# Ion Sources for Accelerator and Research

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# Outline

1. **Concept, Basics, and Brief Introduction**
2. ***Single Charged Ion Sources***

   *$H^-$ source , $H^+$ source*

3. **Multiply Charged Ion Sources**

   *LIS, EBIS,ECRIS*

# 1. Concept , Basics and Brief Introduction

# Ion Source Applications

- **Accelerators**
- **Nuclear physics, atomic physics , surface physics, material science…..**
- **Fusion application**
- **Nuclear analysis**, such as microprobe trace analysis, ….
- **Industry,** such as ion implantation, etching , lithography ,material modification, film production, Nano-fabrication, industrial polymerization , food sterilization….
- **Medical application**
- **Space thrusters**
- …….

# Many Ion Sources

- Bayard-Alpert type ion source
- Electron Bombardment ion source
- Hollow Cathode ion source
- Reflex Discharge Multicusp source
- Cold- & Hot-Cathode PIG
- Electron Cyclotron Resonance ion source (ECR)
- Electron Beam Ion Source (EBIS)
- Surface Contact ion source
- Cryogenic Anode ion source
- Metal Vapor Vacuum Arc ion source (MEVVA)
- Sputtering-type negative ion source
- Plasma Surface Conversion negative ion source
- Electron Heated Vaporization ion source
- Hollow Cathode von Ardenne ion source
- Forrester Porus Plate ion source
- Multipole Confinement ion source
- EHD-driven Liquid ion source
- Surface Ionization ion source
- Charge Exchange ion source
- Inverse Magnetron ion source
- Microwave ion source
- XUV-driven ion source
- Arc Plasma ion source
- Capillary Arc ion source
- Von Ardenne ion source
- Capillaritron ion source
- Canal Ray ion source
- Pulsed Spark ion source
- Field Emission ion source
- Atomic Beam ion source
- Field Ionization ion source
- Arc Discharge ion source
- Multifilament ion source
- RF plasma ion source
- Freeman ion source
- Liquid Metal ion source
- Beam Plasma ion source
- Magnetron ion source
- Nier ion source
- Bernas ion source
- Nielsen ion source
- Wilson ion source
- Recoil ion source
- Zinn ion source
- Duoplasmatron
- Duopigatron
- Laser ion source
- Penning ion source
- Monocusp ion source
- Bucket ion source
- Metal ion source
- Multicusp ion source
- Kaufman ion source
- Flashover ion source
- Calutron ion source
- CHORDIS

Ion source list from SNS M.Stockli's report

# For ion source details, please read:

1. *Ion Sources,* *Huashun S. Zhang,Jianrong Zhang, Springer-Verlag, 2000, $119.00*
2. *Electron Beam Ion Sources and Traps and Their Applications, Krsto Prelec, Springer-Verlag, 2001*
3. *Electron Cyclotron Resonance Ion Sources, R. Geller, IOP Pub, 1996, $210.00*
4. *Focused Ion Beams from Liquid Metal Ion Sources, P. D. Prewett,G. L. Mair, Wiley, 1991*
5. *Handbook of Ion Sources, Bernhard H. Wolf, CRC Press, 1995, $194.95*
6. *International Symposium on Electron Ion Beam Sources and Their Applications, Ady Hershcovitch, American Institute of Physics, 1989, $85.00*
7. *Physics and Technology of Ion Sources, Ian G. Brown, Wiley, 1989.*
8. *Polarized Ion Sources and Polarized Gas Targets, L. W. Anderson, American Institute of Physics, 1994, $288.00*
9. *Polarized Proton Ion Sources, G. Roy & P. Schmor, American Institute of Physics, 1983, $37.00*
10. *Polarized Proton Ion Sources, Alan D. Krisch & A. M. Lin, American Institute of Physics,1981, $30.00*

From http://shop.barnesandnoble.com

**The book list from SNS M.Stockli's report**

**Ion source conference , workshop, symposium proceedings.**
**ICIS; ECR, EBIS, MEVA, Negative source……**

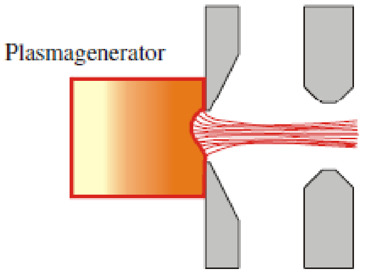
# What is an ion source?

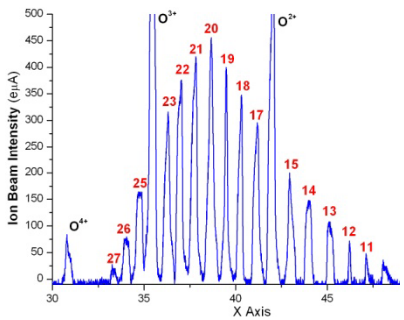
***A device for producing ions: a device that produces a*** *stream of ions, especially for use in particle accelerators or ion implantation equipment****. Ion source is a plasma device.***

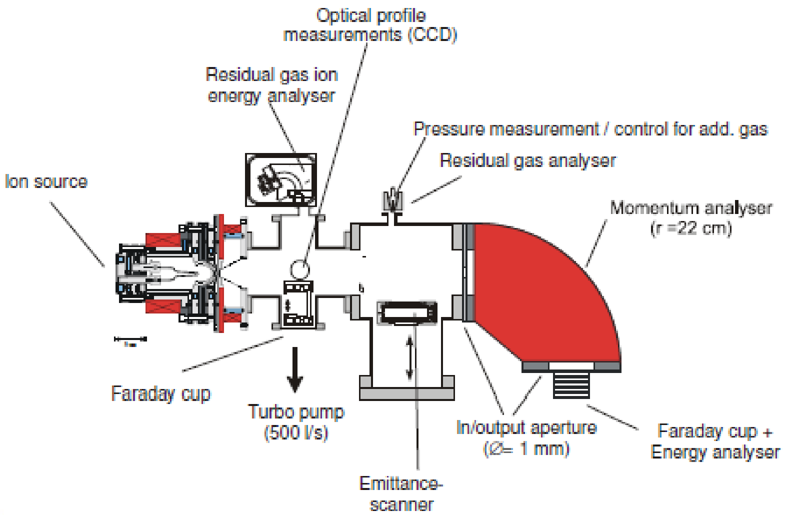
## What are the most important parameters for an ion-source user ?

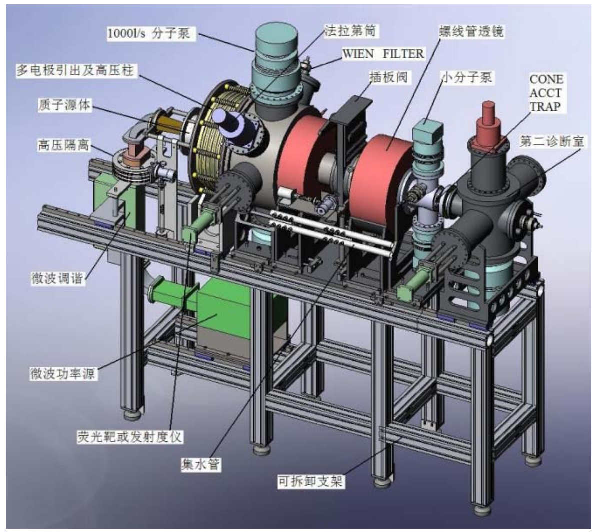
**Beam intensity and beam emittance(beam brightness):** related to ion source itself (plasma parameters), beam extraction system and LEBT.

**Ion source system**: ion source, extraction, beam transport and analyzing , beam diagnostics, control, power supply, vacuum, …..



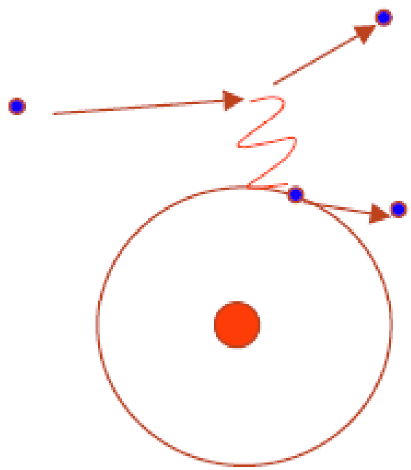



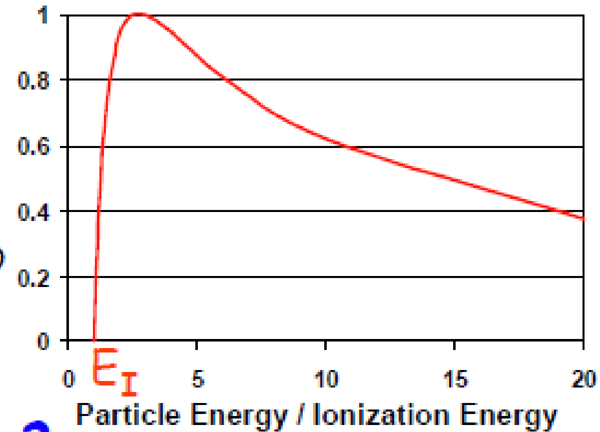
# Ionization of Atoms and Molecules in Gases

- *Ionization in gases, the removal of an electron from an atom or molecule, requires an electric field in excess of $10^{10}$ V/m, only possible within atomic distances typically reached in collisions with charged particles [$F_C = (4\pi\epsilon_o)^{-1} \cdot q_1 \cdot q_2 / r_{12}^2$].*
- *The conservation of energy and momentum favors electrons as the most efficient ionizing particles, and therefore most ion sources use electron impact ionization.*
- *The conservation of energy is responsible for an absolute threshold, the ionization energy $E_I$, the minimum energy which needs to be transferred for successful ionization.*



- *Gases have ionization energies between 12.1 eV for $O_2$ and 24.6 eV for He, e.g. 15.4 eV for $H_2$ molecules and 13.6 eV for H atoms.*
- *The electron impact ionization cross sections are typically $10^{-16}$ cm², roughly the size of the atoms.*
- *The ionization cross section has a maximum close to 3 times the ionization energy $E_I$ and therefore electrons with an energy between 50 and 100 eV can ionize all gases efficiently.*

ionization cross section




***How do we produce ionizing electrons?***

Slide from SNS M.Stockli's report

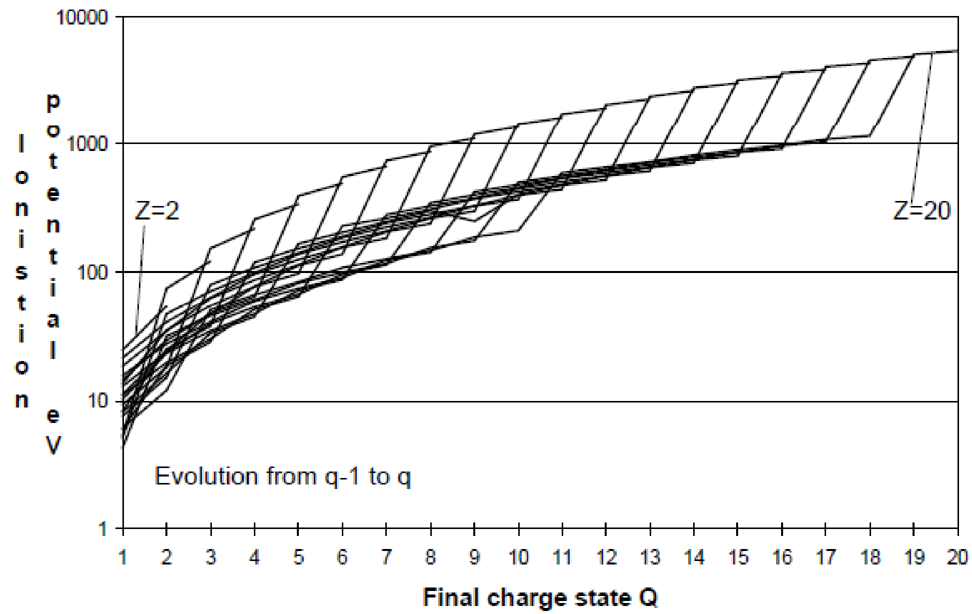
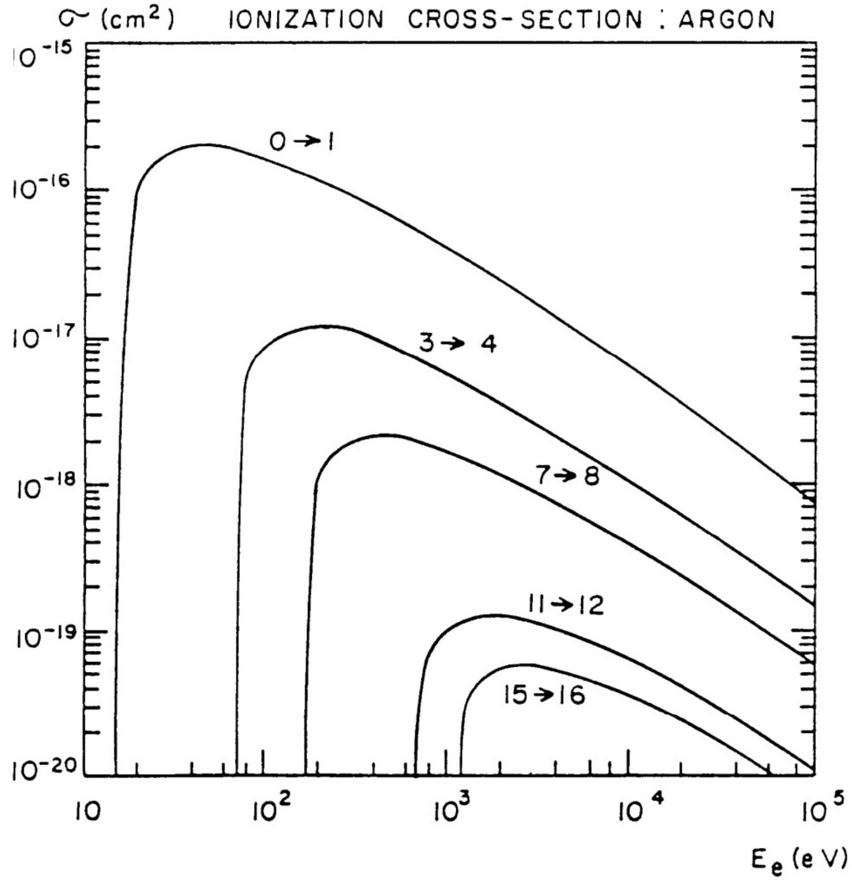



Fig. 1 Evolution of ionisation potentials for the lower atoms



**Ionization needs electrons, electrons can be from:**

- **Thermal or field emission**

  filament, cathode….

- **Discharge**

  electrical discharge, penning discharge, microwave discharge,……

- **External electron source**

  Electron gun, plasma, …..

- ……

# Thermionic Generation of Free Electrons

- *The core of metal atoms keeps the conduction electrons trapped inside the metal with the potential $\Phi$, the work function. This is the energy required to remove one electron from the metal, normally between 4.5 and 6 eV.*
- *When heated to a temperature T [in °K] some of the electrons get enough energy to overcome the work function and escape the metallic filament (Thermionic Emission).*
- *Applying sufficient negative (arc) voltage to the filament allows the electrons to be removed with a current density j [A•m$^{-2}$]:* $\boldsymbol{j = A \cdot T^2 \cdot \exp(-e\Phi/kT)}$

  *with $A \sim 600{,}000\ A \cdot m^{-2} \cdot K^{-2}$*

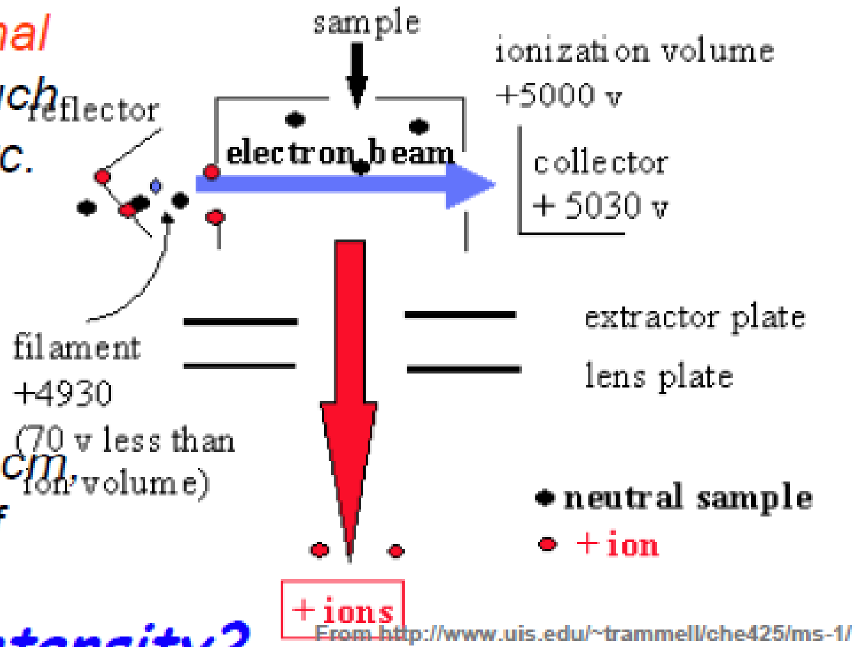
- *High currents require high temperature*
- *High currents require large filaments*

Slide from SNS M.Stockli's report

# The Electron Bombardment Ion Source

- *A simple application of the discussed concepts is the Electron Bombardment Ion Source. Some people call it Electron Impact Ion Source.*
- *This ion source uses thermionic emission from a very hot wire, the filament, to generate an abundance of electrons.*
- *Applying roughly -70 Volts to the filament allows the electrons to gain enough energy to effectively ionize all atoms and molecules.*
- *This ion source is preferred when the ionization rate should be proportional to the gas density, the pressure, such as in gas analyzers, ion gauges, etc.*
- *The filament lifetime is limited by vaporization and sputtering, especially at higher pressures.*
- *At 1 mT pressure, it takes roughly 300 electrons to produce 1 ion per cm. not well suited for the production of high intensity ion beams.*

***How do we increase the intensity?***

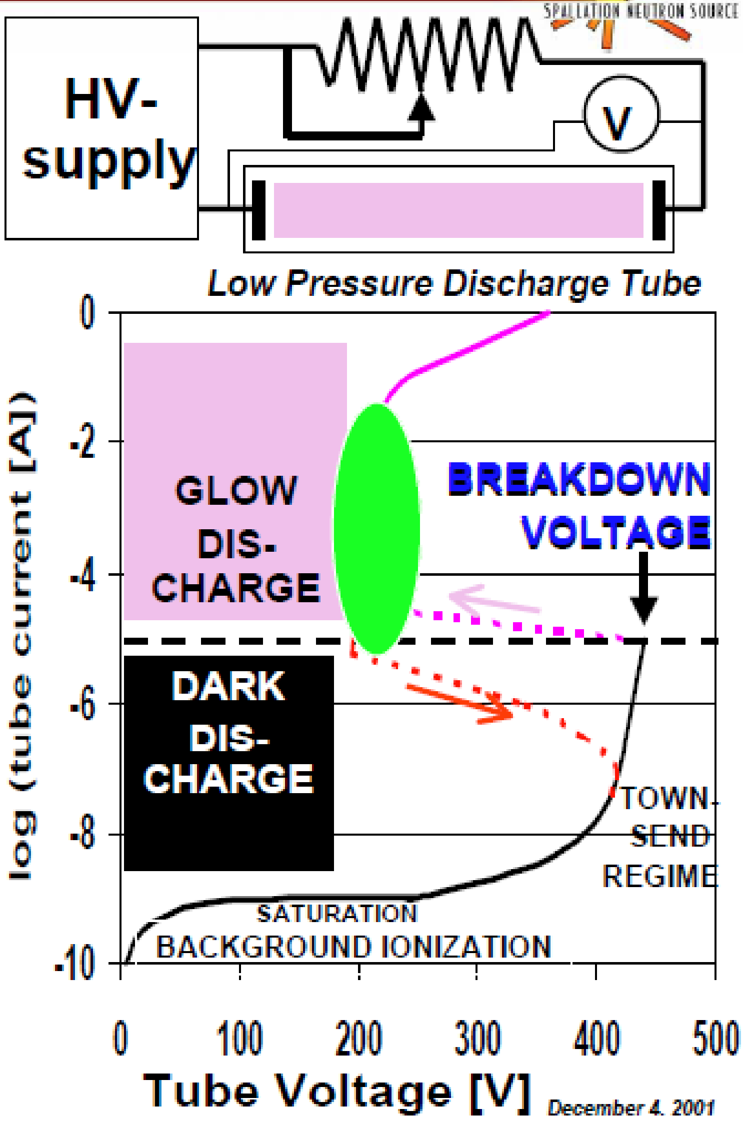



From http://www.uis.edu/~trammell/che425/ms-1/

Slide from SNS M.Stockli's report

## Electrical Discharges in Low Pressure Gases

- *Applying a small voltage to a discharge tube typically results in nA's of current produced by background ionization.*
- *When the voltage is raised significantly the current starts to grow exponentially up to many μA due to Townsend multiplication and the onset of corona.*
- *Further increasing the voltage, suddenly the gas starts to glow and the current grows up to many mA at a much reduced voltage. The glow discharge is maintained and amplified by secondary electrons emitted when the ions impact on the cathode.*
- *As glowing plasma covers a growing fraction of the volume, a growing voltage increase is needed to increase the current.*
- *Most discharge ion sources operate at the low current end of glow discharges.*

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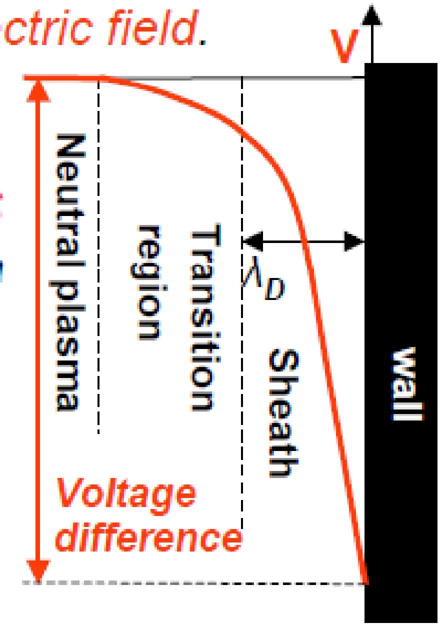
# The Plasma Physics of Ion Sources

- A plasma is composed of neutrals, electrons and ions with densities $n_n$, $n_e$, and $n_i$, typically in the range between $10^{10}$ to $10^{16}$ particles per $cm^3$ corresponding to a **pressure between** $10^{-6}$ and 0.1 Torr.
- The repulsive nature of equal charges requires that essentially all plasmas are practically neutral (quasi-neutral): $e \cdot \Sigma Q_i \cdot n_i = e \cdot n_e$
- Plasma physics dominates if degree of ionization $n_i/(n_i+n_n)>0.1$.
- The average particle speed is $v_p = (8kT_p/\pi m_p)^{1/2}$ with $T_e \geq T_i > T_n$, which means $v_e \geq 43 \cdot v_i$. The rapidly moving electrons leave behind the ions and their space charge creates a or modifies the existing electric field.
- Charges interact with other charges only within a distance $\lambda_D$, the Debye length: $\lambda_D^2 = \epsilon_o kT_e/e^2 n_e$ or $\lambda_D[cm] = 743\,(T_e[eV]/n_e[p/cm^3])^{1/2}$ (A few µm for the SNS ion source). The surface charges on electrodes create a plasma sheath with a thickness $\lambda_D$ which maintains most of the potential difference between electrodes.




- The plasma frequencies are $f_P^2 = n_p \cdot e^2/(4\pi^2 \epsilon_o m_P)$. The SNS ion source has plasma frequency of ~ 100 GHz for the electrons and ~ 2 GHz for the ions and hence the RF interacts with the individual particles.

December 4, 2001

Slide from SNS M.Stockli's report

# Pressure and Vacuum issues of ion sources

- *The non-ionized, neutral particles with density $n_p$ and mass m randomly collide with each other and the walls. For a wall temperature T (in °K) the average particle velocity is $v_p = (8kT_p/\pi m_p)^{1/2}$, with $H_2$ at 1.1 miles/s being about 4-times faster than $N_2$.*
- *Ion sources need an opening to extract the low-energy ions. The SNS ion source has a 7 mm diameter, circular extraction aperture with a 0.38 cm² area. Through this area A, neutral particles escape at a rate of $Q = \frac{1}{4} v_p n_p A$, which is about $10^{19}$pps from the SNS ion source, or* ***about 1,000 neutrals for each extracted ion.*** *The pressure is maintained by adding about 1 Torr•ℓ/s Hydrogen gas.*
- *The particles have to be removed from the LEBT to limit ion beam charge exchange losses to ~10%. Three pumps, each with a speed $S_p$ of 1500 l/s, keep the LEBT pressure $P_L$ below $10^{-4}$ Torr ($P_L = Q/S_p$).*
- *Most ion sources have discharge gaps of a few mm, featuring the highest discharge current at a few Torr. The highest extracted ion currents, however, are found at substantially lower pressures. The SNS ion source operates at 20-30 mTorr, 0.003 % standard atmospheres, a particle density $n_p$ of $10^{15}$cm$^{-3}$.*

December 4, 2001

Slide from SNS M.Stockli's report

# Confinement of Charged Particles

*Time-constant magnetic fields are unaffected by plasmas and therefore are perfectly suited to confine ions and electrons.*

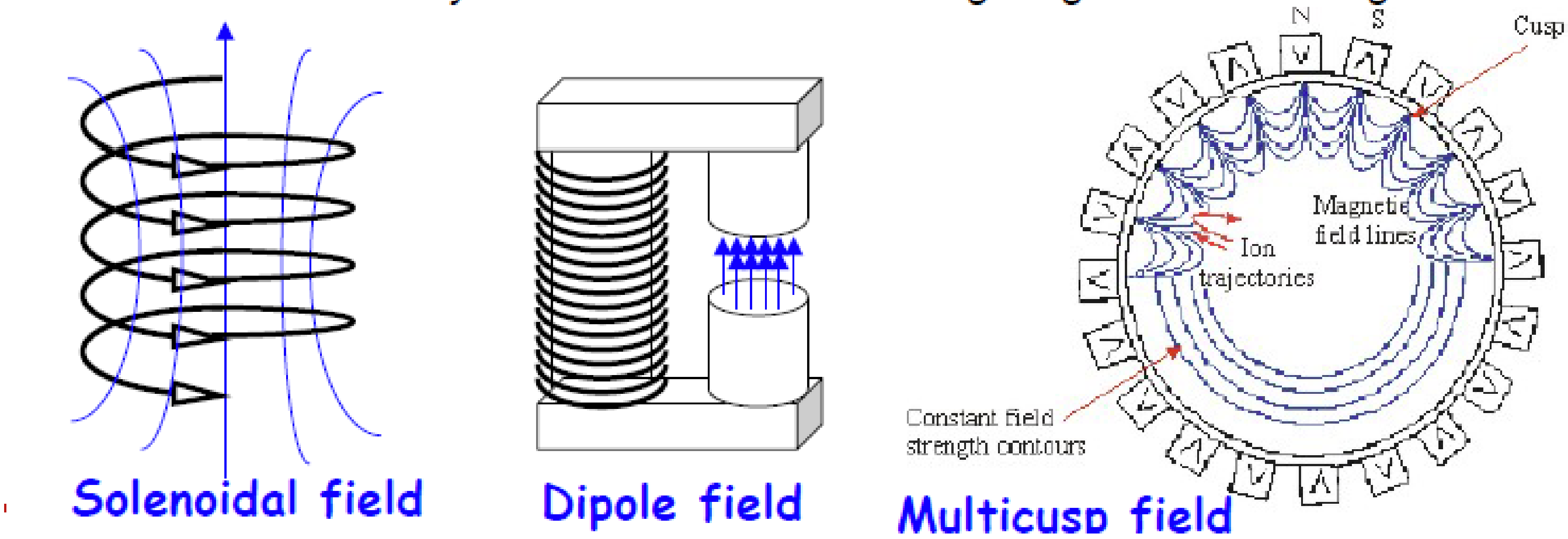
*Charged particles move unimpeded in the direction of the magnetic field.*

*A particle with mass m, charge q, and a velocity v perpendicular to the magnetic field B undergoes a circular motion with a radius $r = mv/qB$.*

*e.g: if B=1 kG, for 10 eV electrons r=0.1mm, for 1 eV protons r = 1.4mm.*

*The resulting helical particle motion reduces the wall losses of the ions and increases the path length of the electrons and their ionization rate.*

*Confinement is normally achieved with the following magnetic field configurations:*




Slide from SNS M.Stockli's report

# What are the most important parameters for an ion-source plasma

$$n_e \, , \, T_e \, , \, \tau_i \, , \, n_i$$

*What an ion source physicist always tries his best to do :*

- **Increase all these parameters to produce intense beam.**
- **Reduce beam emittance with lower $T_i$**

# 2. Single Charged Ion Sources

*$H^-$ source , $H^+$ source*

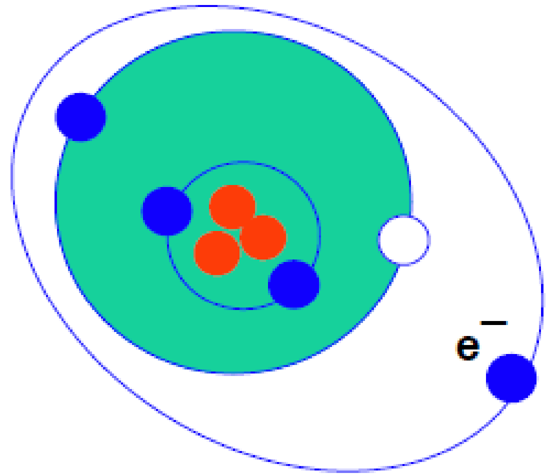
# *$H^-$ source*

**SNS and other neutron source; Proton accelerator**

# Negative Ions; What is that?

SPALLATION NEUTRON SOURCE

- *Some atoms with an open shell can attract an extra electron and form a stable ion with a net charge of –e.*
- *The stability is quantified by the electron affinity, the minimum energy required to remove the extra electron.*
- *The electron affinities are substantially smaller than the ionization energies, covering the range between 0.08 eV for $Ti^-$ and 3.6 eV for $Cl^-$, e.g. 0.75 eV for $H^-$.*
- *For electron energies above 10 eV, the $H^-$ ionization cross section is ~ $30 \cdot 10^{-16}$ cm$^2$, 30 times larger than for a typical neutral atom!!*
- *For $H^+$ energies below 1 keV, the recombination cross section is larger than 100 • $10^{-16}$ cm$^2$.*
- *Charged particle collisions destroy $H^-$ ions easily!!*



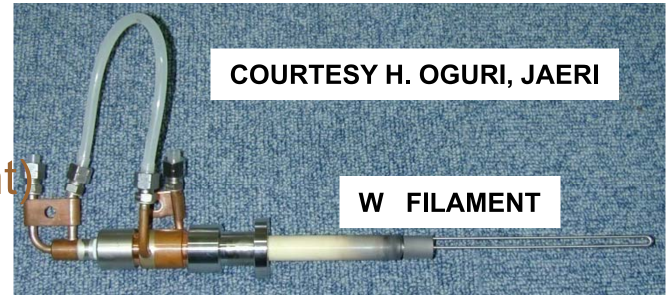

$H^-$ ions are fragile !

Slide from SNS M.Stockli's report

# H⁻ source and Discharge chambers

**FILAMENT** : W, Ta, $LaB_6$

(LIFETIME 500-700h,sputtering of filament)

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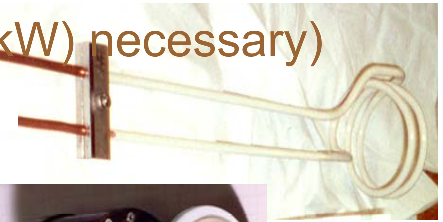
**RF : ANTENNA COIL** (IGNITION and high rf power (10 kW) necessary)

INNER COIL

COURTESY R. THOMAE, LBL



OUTER COIL (LONG LIFETIME >Years clean discharge)

**PIG $H^-$ source**

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**ECR Source**

**➔R. Gobin, CEA /➔D.Küchler, CERN**

**7x ECRs /➔ M. Bacal, LPTP, Ecole Polytechnique**

**S. Bechu➔ PC31.**

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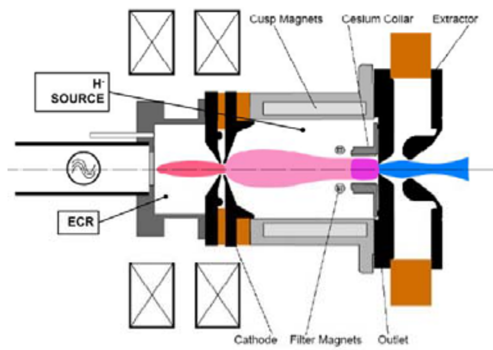
HELICON DISCHARGE

MICROWAVE EXITATION

**➔R. Welton, SNS –> O05**

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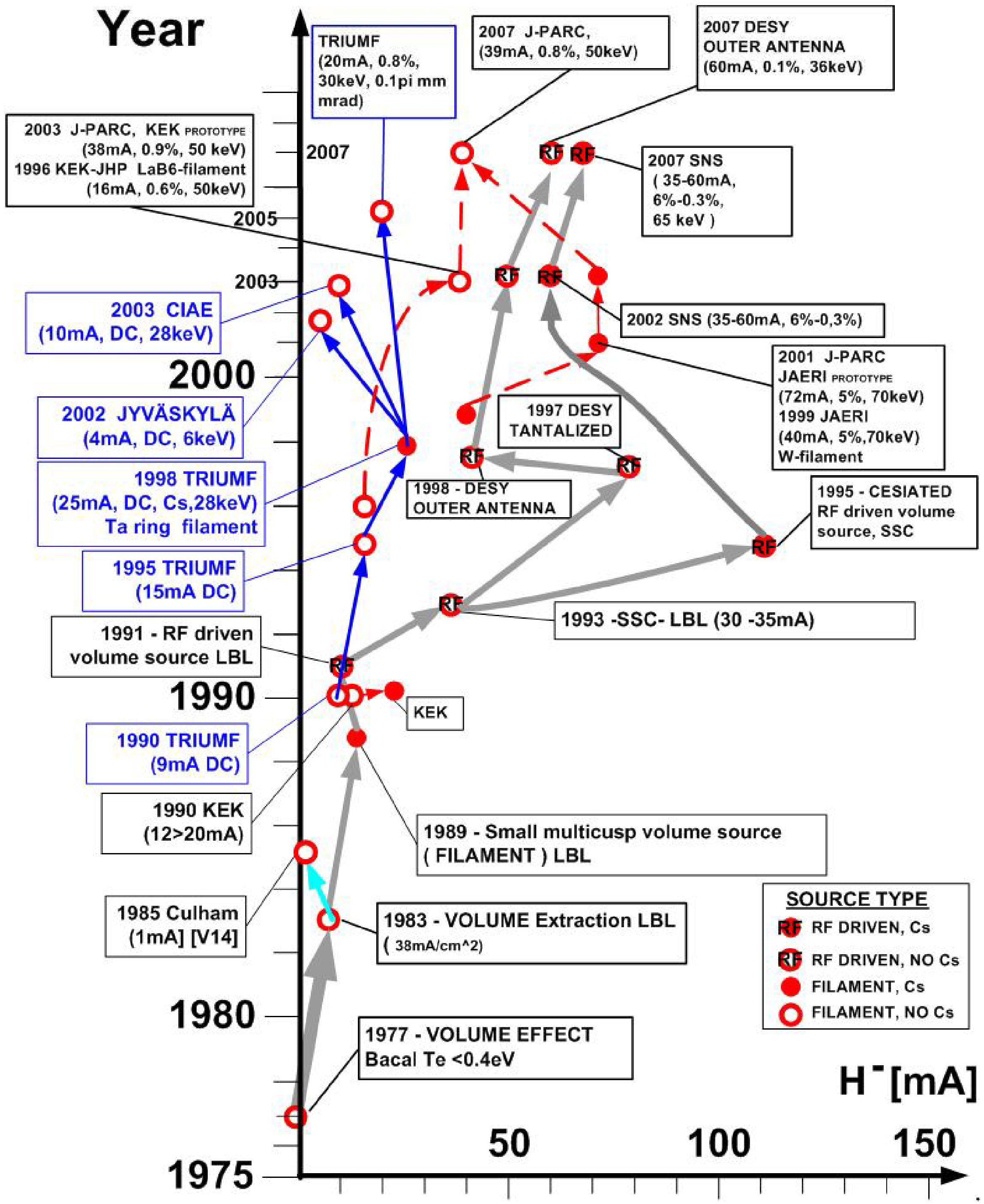
COMBINATIONS

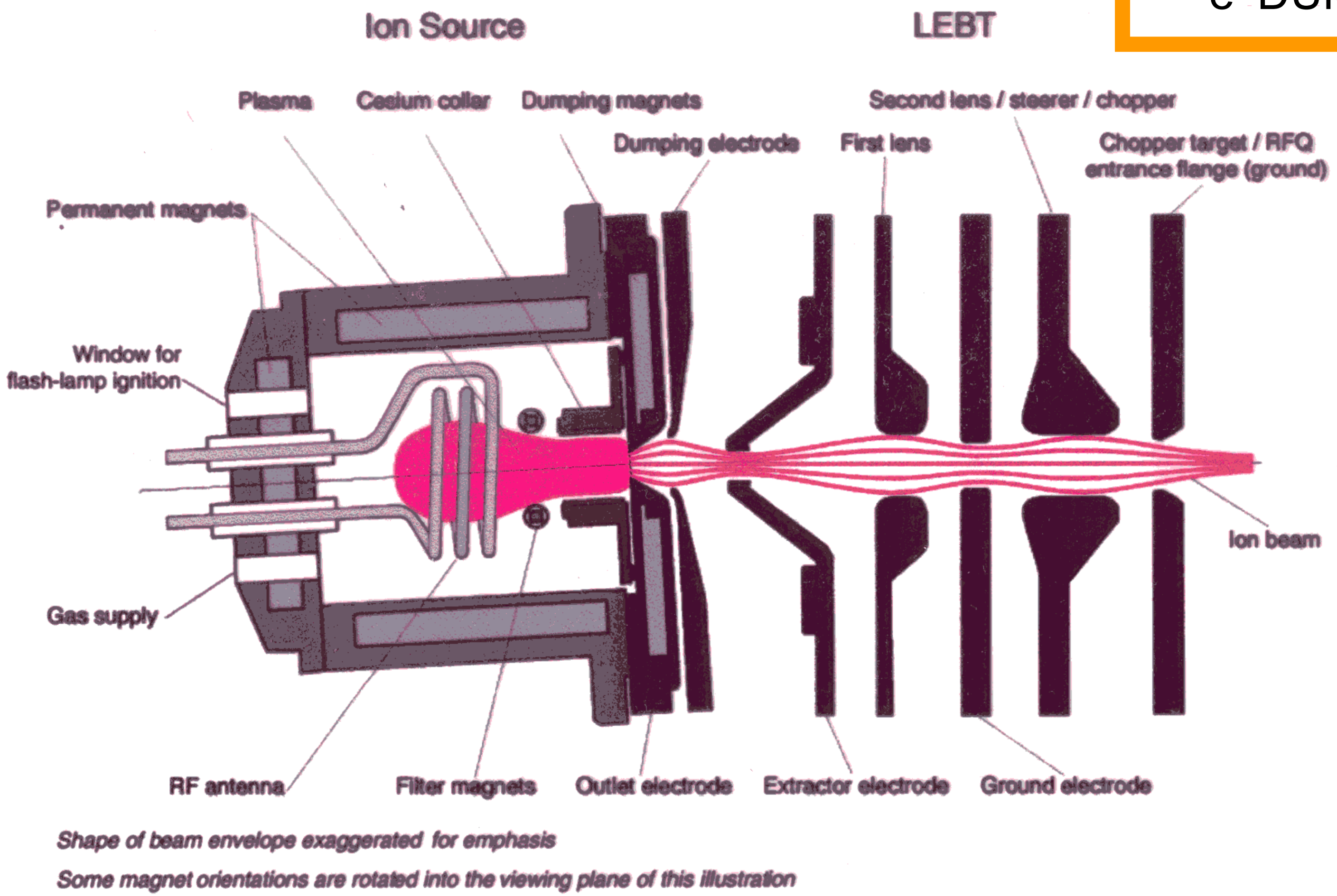
**➔R. Keller , LBL,**
**HYBRIS Source, PAC05**




**HISTORY**
Jens Peters, DESY

# SNS RF H$^-$ SOURCE

- INTERNAL RF COUPLING
- INTERNAL FILTERFIELD
- COLLAR
- Cs
- e$^-$ DUMP before EXTR.

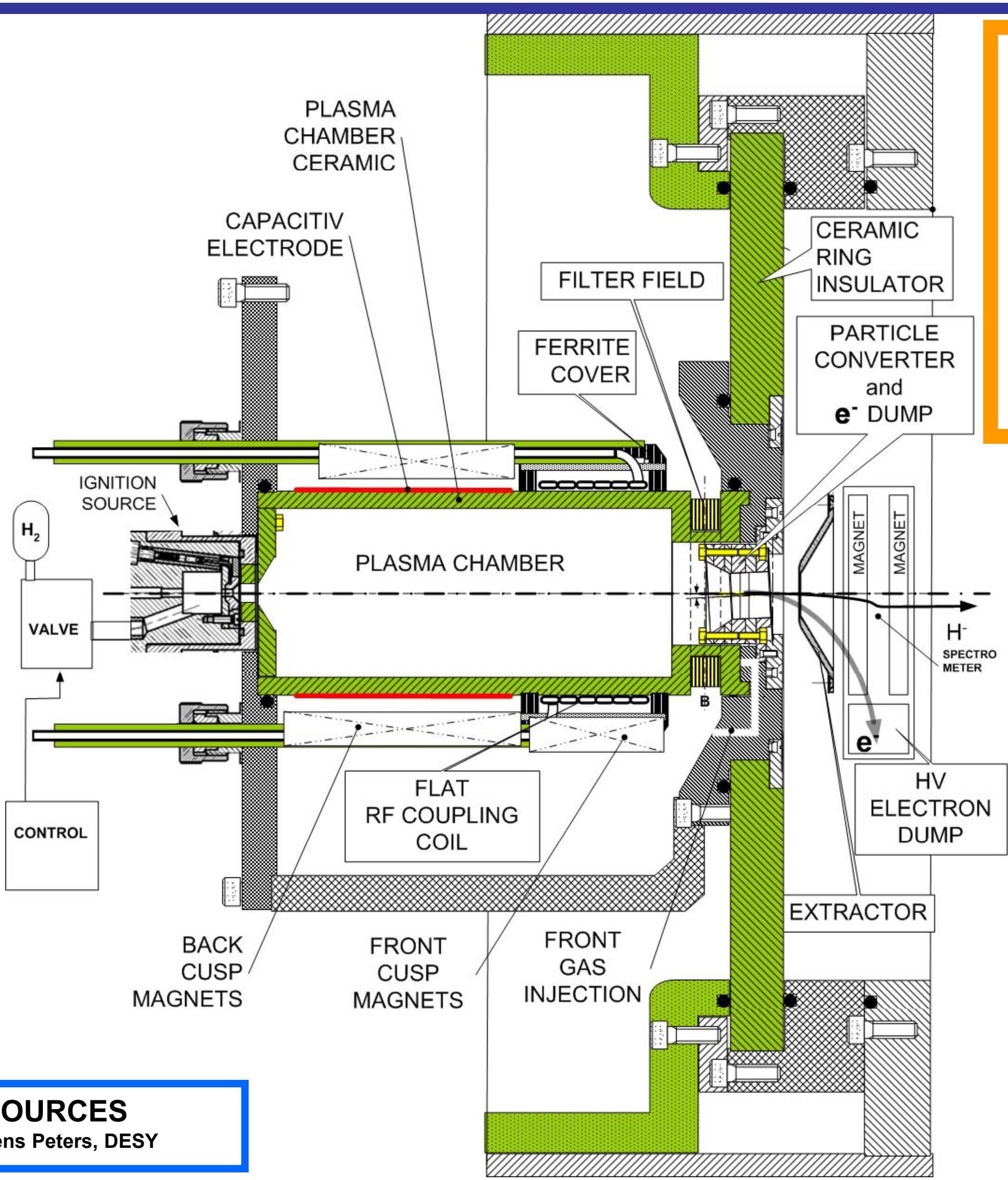



SNS

35-60mA

65 keV

# DESY RF H⁻ SOURCE



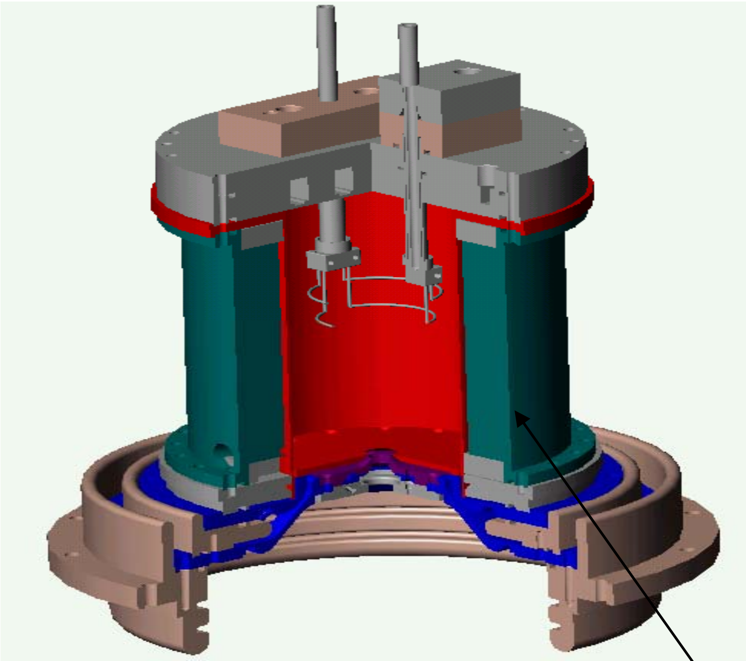

- EXTERNAL RF COUPLING
- EXTERNAL FILTERFIELD
- INSULATED PLASMA CHAMBER
- COLLAR
- NO Cs
- e⁻ DUMP after EXTR.

60 mA
35 keV
lifetime ~ Years
NO Cs

**Brightness Award 2007**

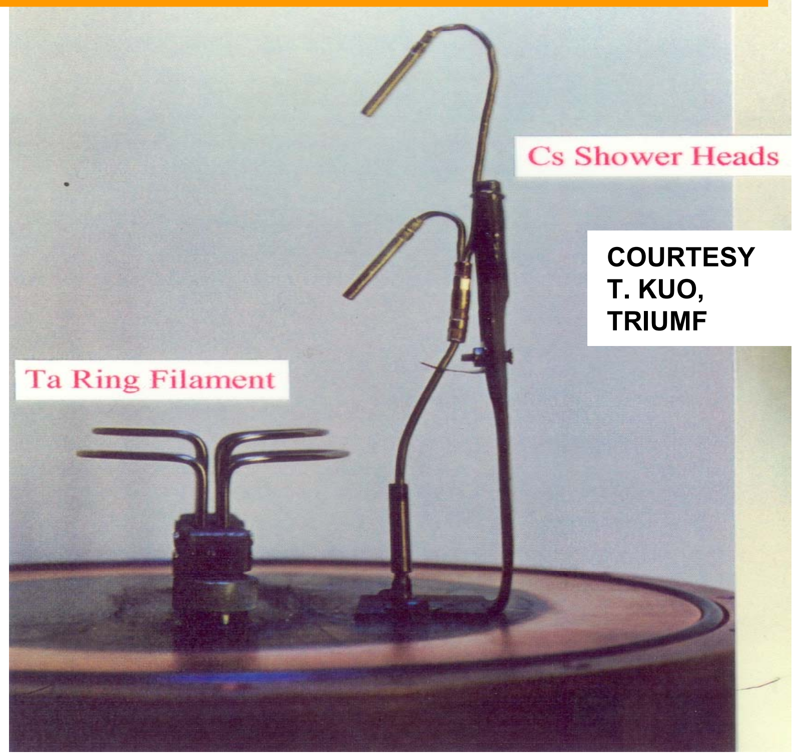
**SOURCES**
**Jens Peters, DESY**

# TRIUMF H$^-$ SOURCE



COURTESY T. ZHANG, CIAE

- FILAMENT
- EXTERNAL FILTERFIELD
- NO COLLAR
- Cs and NO Cs
- e$^-$ DUMP before EXTRACTOR
- with 10 cm EXTENSION
  ~ 0.1 π mm mrad at 20 mA
  without Cs

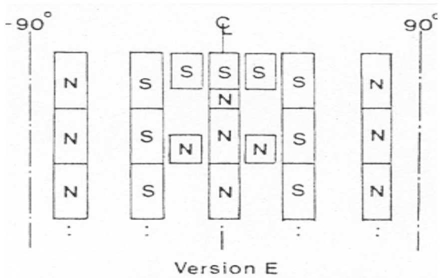



COURTESY
T. KUO,
TRIUMF

OUTSIDE

FILTER

FIELD

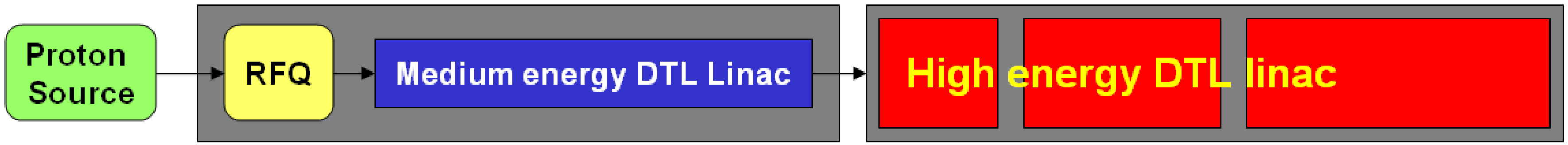



**SOURCES**
Jens Peters, DESY

# Proton source ($H^+$)

# 50-100mA/50-100keV $H^+/D^+$ Source (CW/Pulsed)
# Important Applications

| Application | Max beam power | Energy | Average current |
|---|---|---|---|
| Accelerator Driven Systems<br>100 MW demonstrator<br>Industrial Facility | ~ 5 MW<br>~ 50 MW | ~ 500 MeV<br>~ 1 GeV | ~ 10 mA<br>~ 50 mA |
| Irradiation Material tool (IFMIF) | 5-10 MW | ~ 40 MeV | ~ 125 × 2 mA |
| Compact Neutron Source for Various Studies | 10kW-50kW | 10-20 MeV | 1-5 mA |
| Condensed Matter Studies (SNS) | 1-5 MW | 1-5 GeV | 1-5 mA |
| Radioactive Beams | > 200 kW | > 200 MeV | ~ 1 mA |
| Muons, Neutrinos | 4 MW | 2 GeV | 2 mA |




**Beam intensity and quality are determined by source and LEBT!**

**from R.Gobin's report**

# General Requirements to $H^+/D^+$ Source

and also the most important issues for design and test

- Intense Beam (50-140 mA)
- High Reliability and Availability
- Low Emittance (<0.2 $\pi$ mm mrad)
- High Proton Fraction (>85%)
- Low Beam Noise(<5%)
- Long-life Time (months)

**2.45GHz ECR Ion Source**

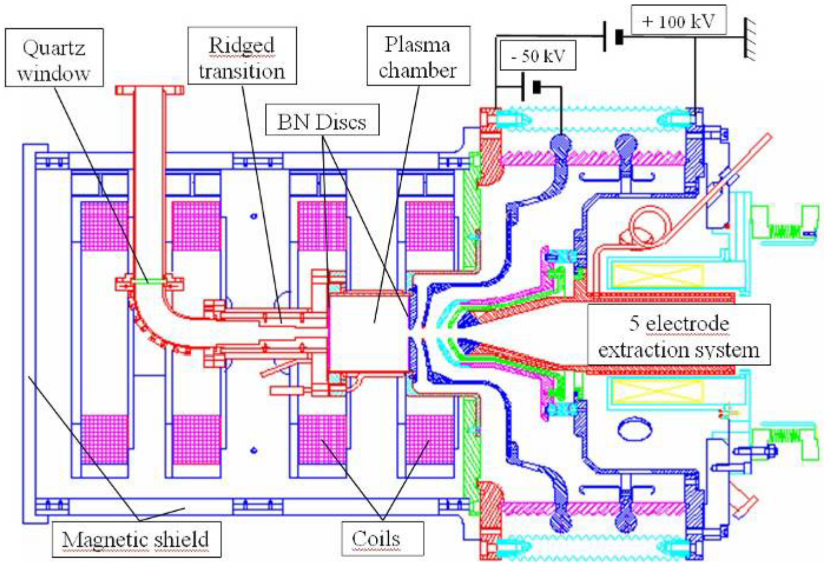
**It is a challenge to fulfill all these requirements!**

## Advantages of 2.45GHz ECR Ion Source

- **Long-life time and high reliability: no filament and no antenna**
- **High proton fraction**

# Microwave Discharge Ion Source-2.45GHz ECR Ion Source

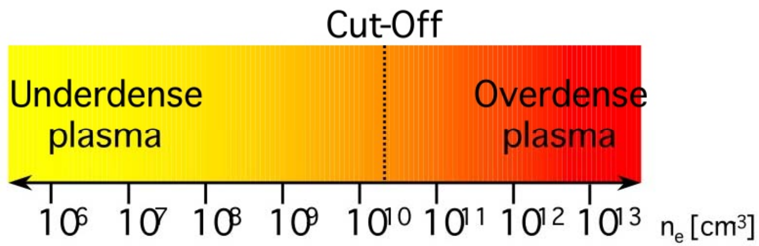
## for proton beam production

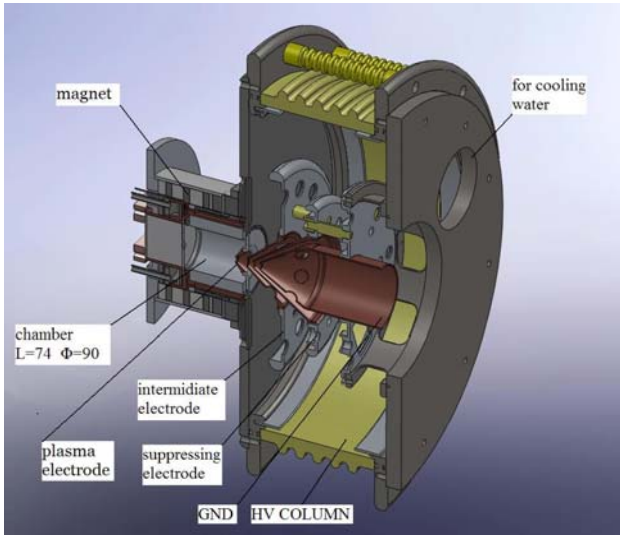



Graph from R.Gobin's slide

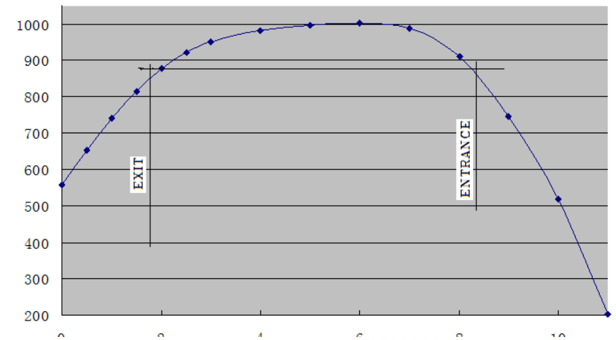
***High currents of proton beam (mA- level)***
***High efficiency ionization of 1+ ions***:

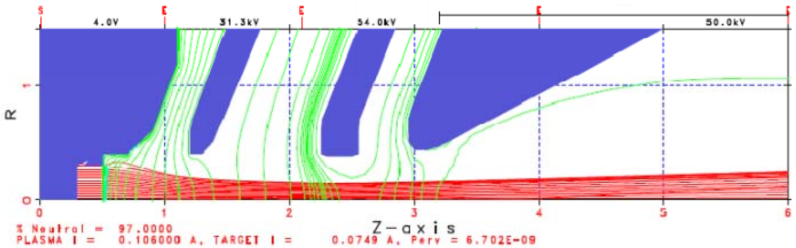
- high electron density (overdenseplasmas)
- low plasma confinementtime
- 2.45 GHz frequency
- low magneticfield




Proton source designed by IMP Lanzhou

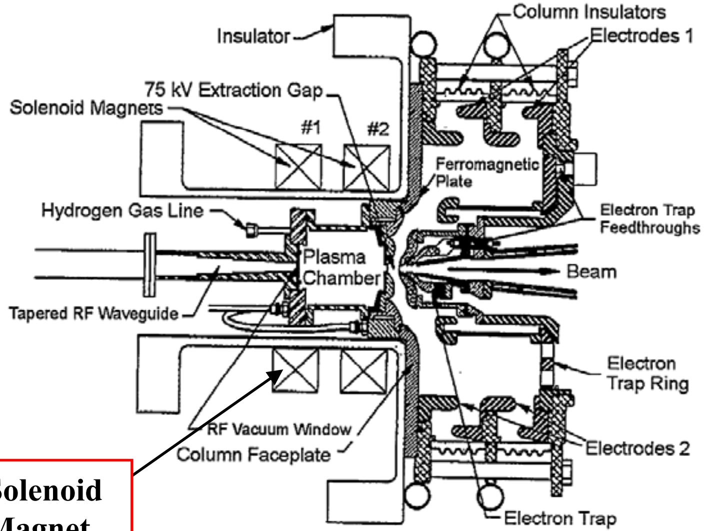



**ECR Source**
$\omega = e\,B / m$
**2.45 GHz →**
875 Gauss

# The Most Successful 2.45GHz ECR Ion Sources in 1995-2007

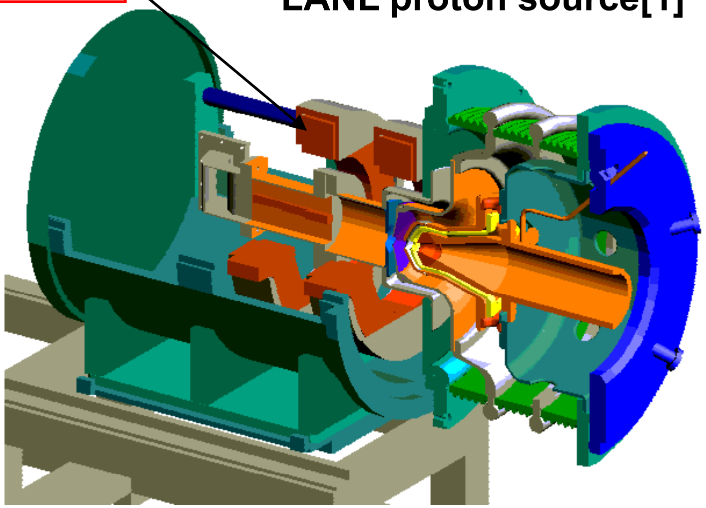
LANL Proton Source and SILHI Source at CEA/Saclay for IFMIF, 100-140mA,CW
(More than 30 labs ever built 2.45GHz ECR ion source)



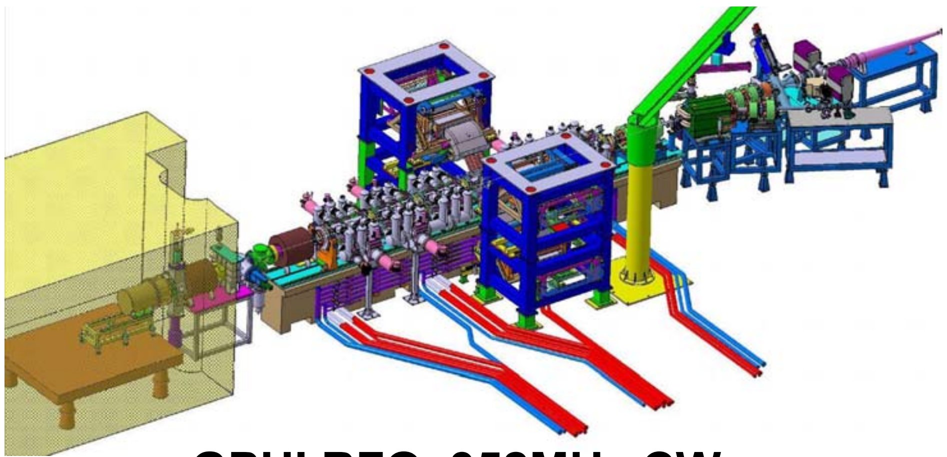

Solenoid Magnet

LANL proton source[1]

LEDA RFQ
350 MHz CW
110 mA $H^+$
6.7 MeV, 8 m
LANL



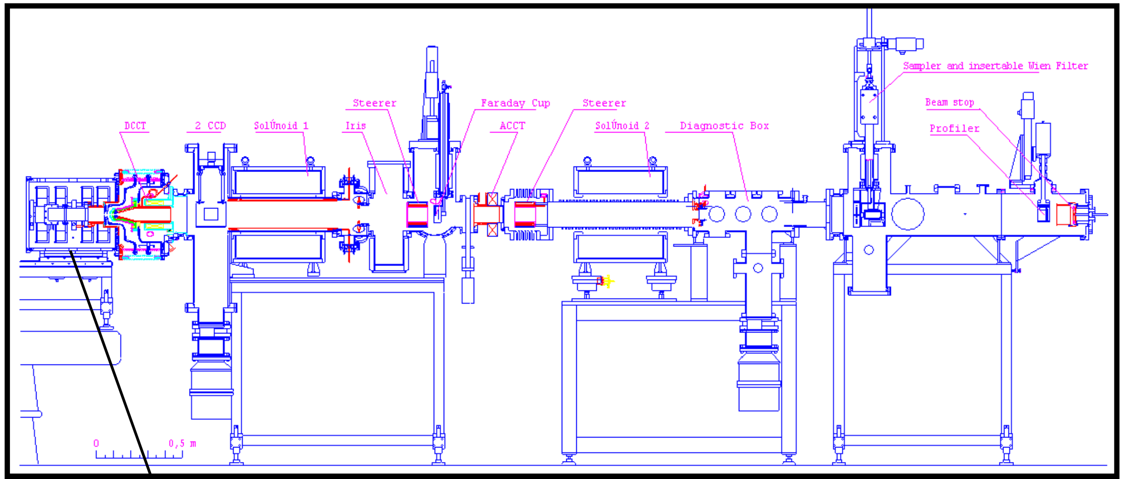
SILHI Source[2]

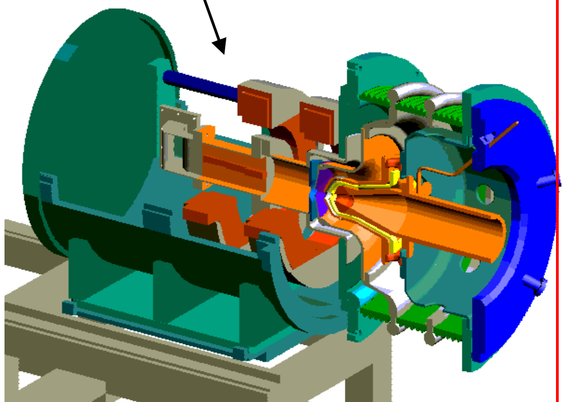


GPHI RFQ, 352MHz CW
120 mA $H^+$, 5MeV, CEA/Saclay

[1] Joseph D. Sherman *et al.*, Rev. Sci. Instrum. 73, 917 (2002).
[2] R.Gobin, Rev. Sci. Instrum. 79, 02B303 (2008).

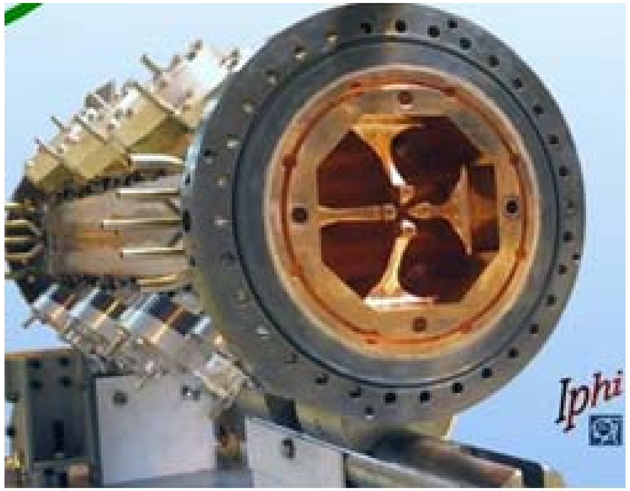
# SILHI/SACLAY Source and LEBT



Since 1996, SILHI produces $H^+$ beams with good characteristics:

$H^+$ Intensity >100 mA at 95 keV
$H^+$ fraction > 80 %
Beam noise < 2%
95 % < Reliability < 99.9 %
Emittance < 0.2 $\pi$ mm.mrad
CW or pulsed mode

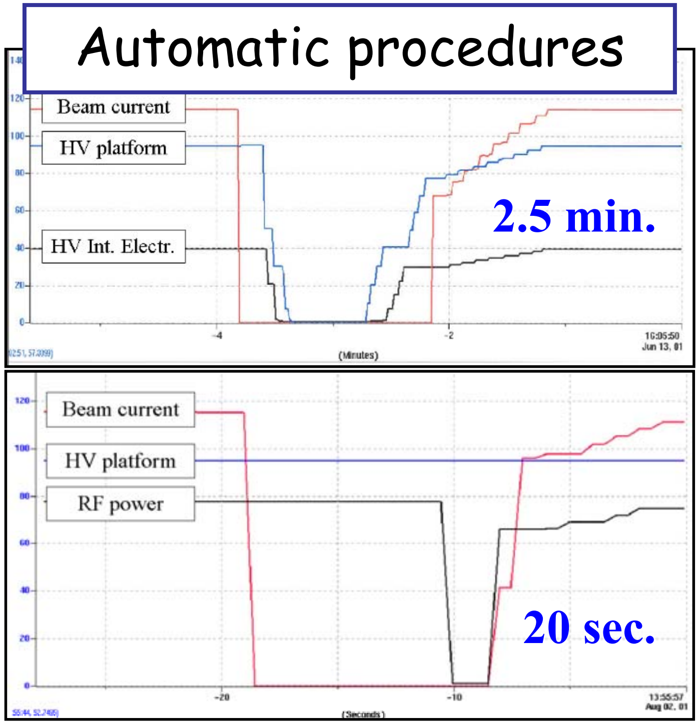


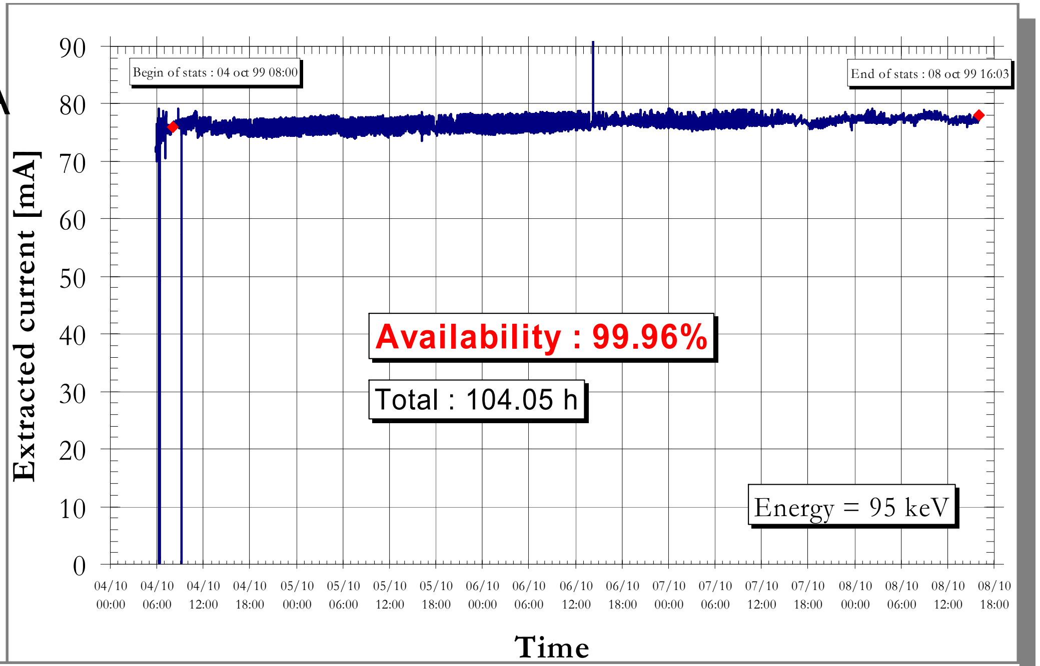

R.Gobin's slides at ECRIS06

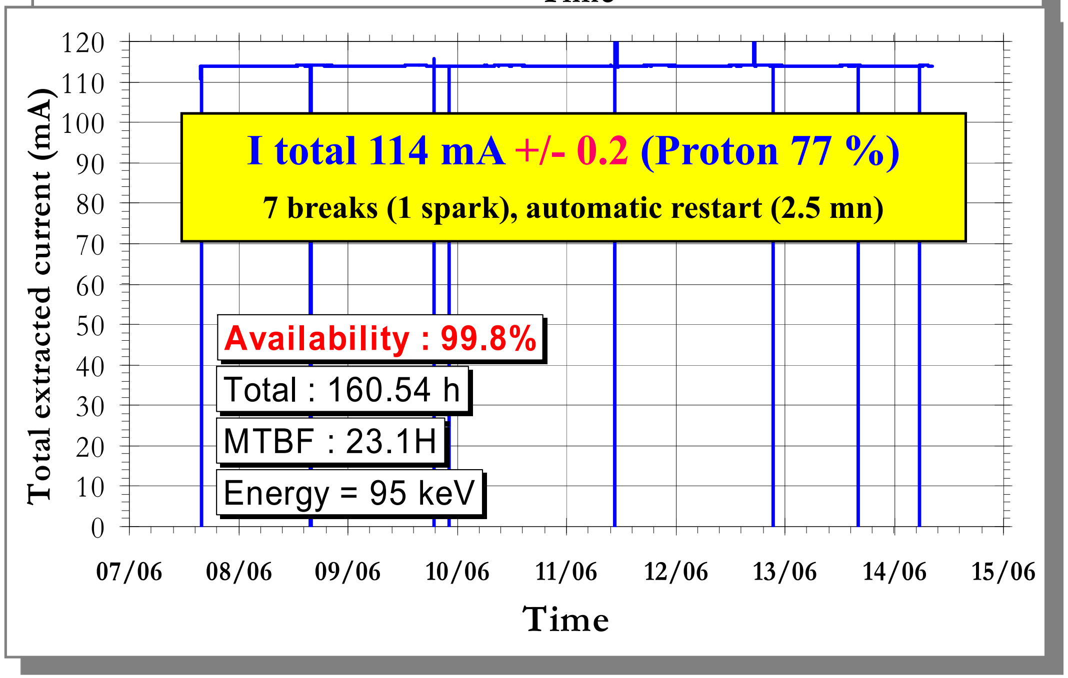
# Reliability Saclay/CEA

**ECR sources are especially well known for the reliability**

**It is a challenge !**

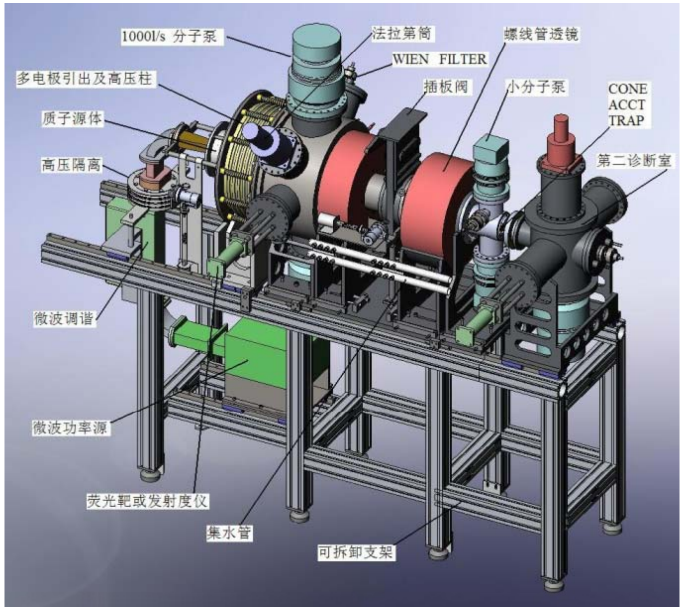


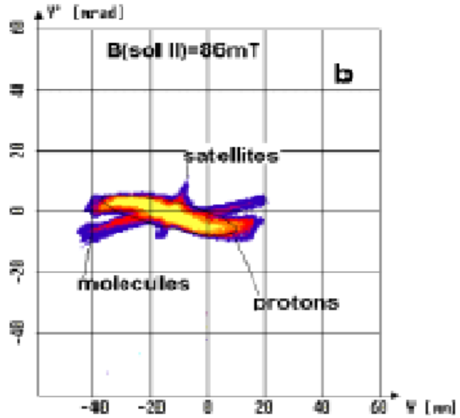



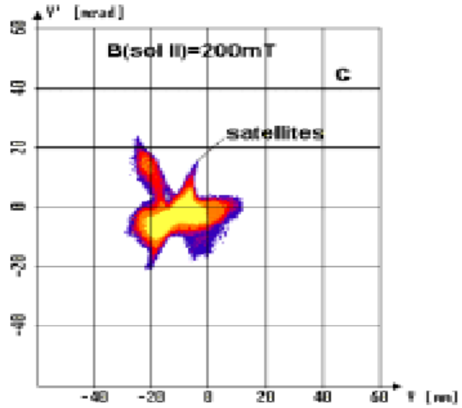



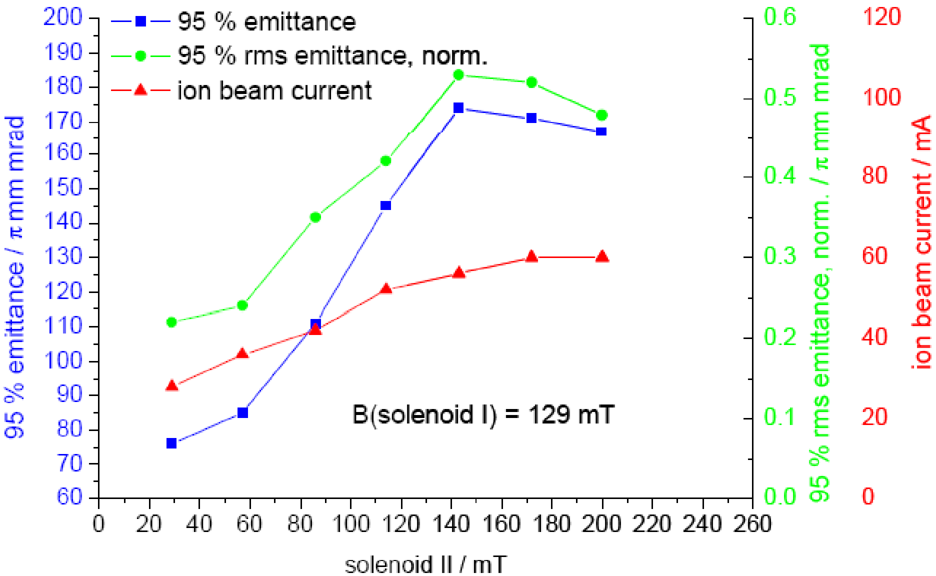

Figures from R.Gobin's slides at ECRIS06

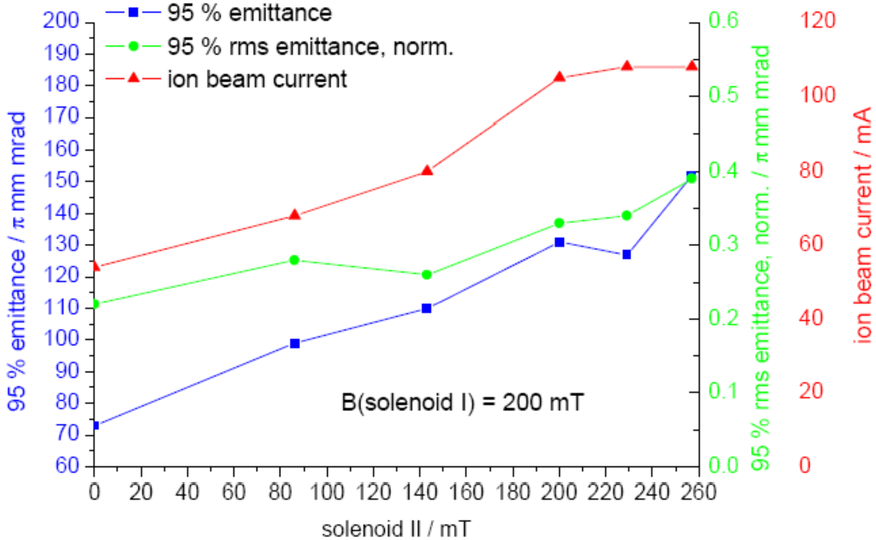
# Beam Emittance Growth due to Space Charge Effect



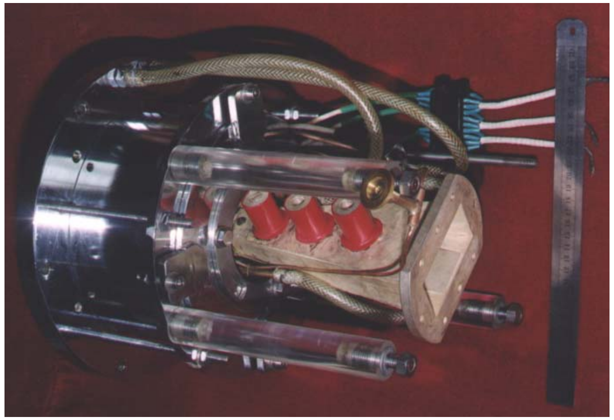



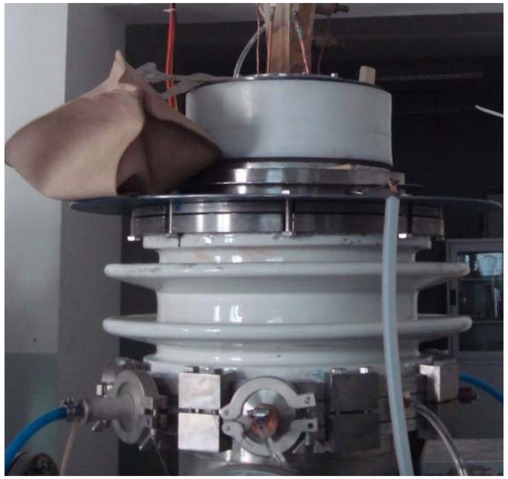

**R.Holinger, TU3001, Linac2006**

# Proton Sources developed by IMP

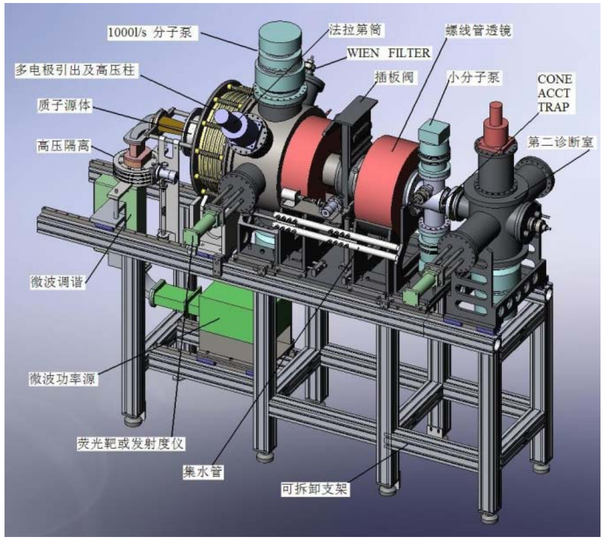


**90-100 mA Proton source developed by IMP in 1999.**

**10 mA proton source developed by IMP in 2006**



IMP, CIAE, Peking Univ. in China



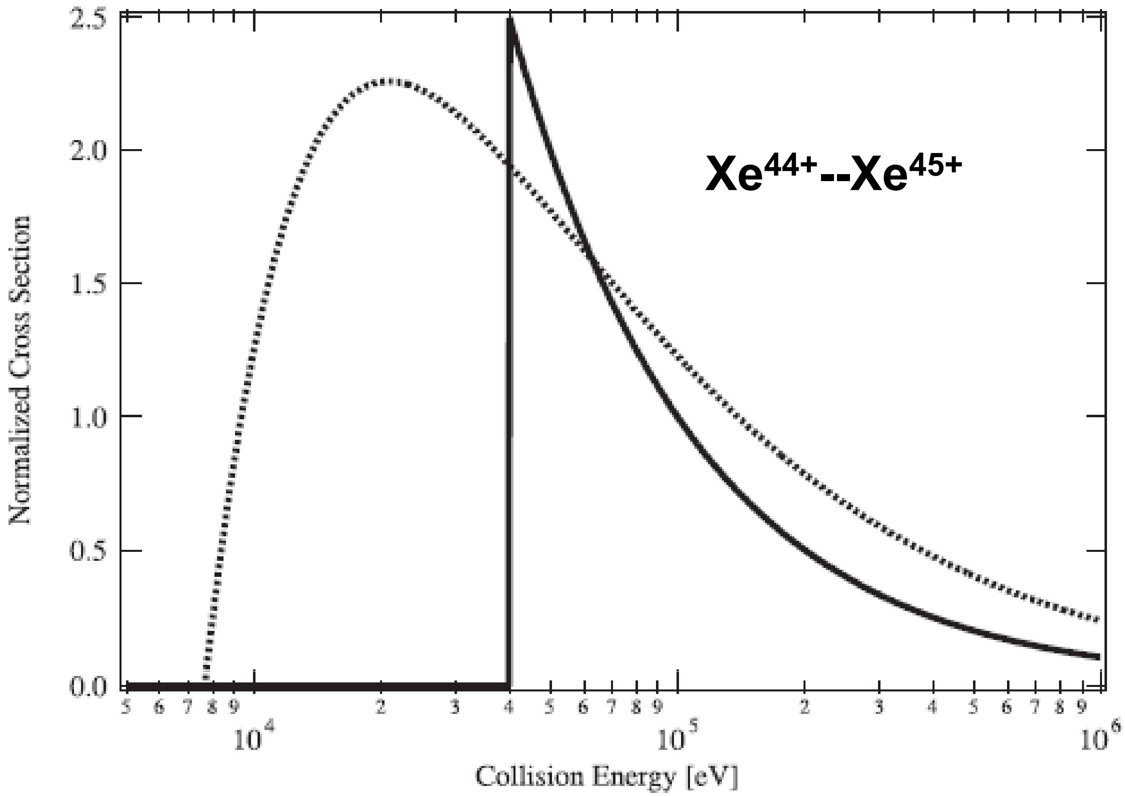

**Proton source and LEBT for ADS and neutron source**

# 3. Multiply Charged Ion Sources

**LIS,EBIS,ECRIS**

# Multiply or Highly Charged Ions

- If an orbiting electron at the external shell of an atom gains sufficient energy, it
- The minim most external sh
- Multiply ch oving n electrons
- **Electron-i** erate multiply ch
- Electron-in trons that are re lt as the charge e more ener se.



# Production of Multiply Charged Ions by electron-impact ionization

## 1. Single step ionization

$$A + e \longrightarrow A^{n+} + (n+1)e$$

## 2. Stepwise single ionization

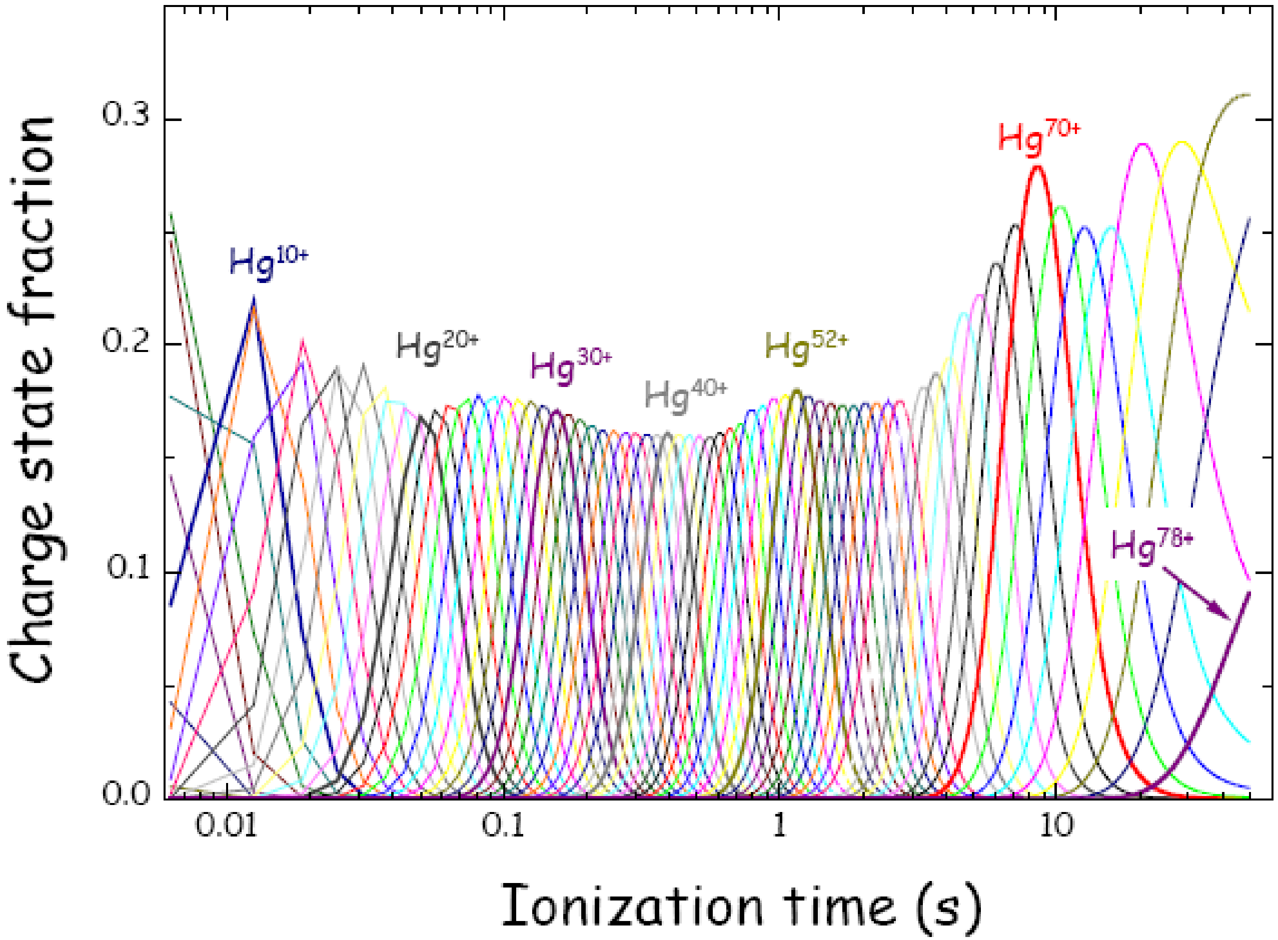
$$A + e \longrightarrow A^{+} + 2e$$

$$A^{+} + e \longrightarrow A^{2+} + 2e$$

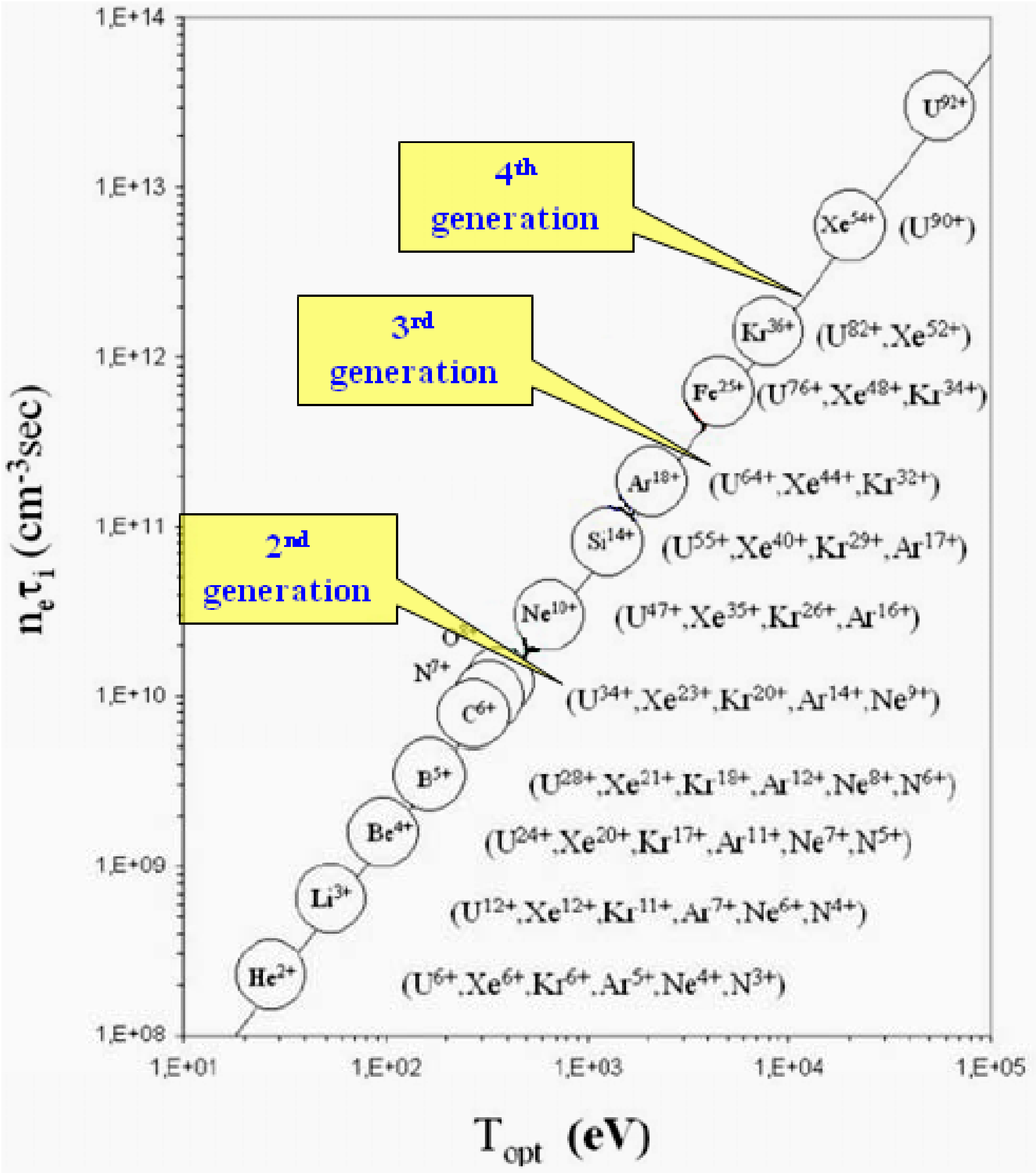
………

$$A^{(n-1)+} + e \longrightarrow A^{n+} + 2e$$

# Time evolution of the ions' charge state




In highly charged ion sources, very important:
ion confinement time » ionization time



4th generation
3rd generation
2nd generation
U92+
Xe54+ (U90+)
Kr36+ (U82+,Xe52+)
Fe25+ (U76+,Xe48+,Kr34+)
Ar18+ (U64+,Xe44+,Kr32+)
Si14+ (U55+,Xe40+,Kr29+,Ar17+)
Ne10+ (U47+,Xe35+,Kr26+,Ar16+)
O
N7+ (U34+,Xe23+,Kr20+,Ar14+,Ne9+)
C6+
B5+ (U28+,Xe21+,Kr18+,Ar12+,Ne8+,N6+)
Be4+ (U24+,Xe20+,Kr17+,Ar11+,Ne7+,N5+)
Li3+ (U12+,Xe12+,Kr11+,Ar7+,Ne6+,N4+)
He2+ (U6+,Xe6+,Kr6+,Ar5+,Ne4+,N3+)
1,E+14
1,E+13
1,E+12
1,E+11
1,E+10
1,E+09
1,E+08
1,E+01
1,E+02
1,E+03
1,E+04
1,E+05
$n_e \tau_i$ (cm$^{-3}$sec)
$T_{opt}$ (eV)

# Loss Processes of Multiply Charged Ions

**1. Loss by charge exchange**

$$A^{n+} + A \longrightarrow A^{(n-1)+} + A^{+}$$

$$A^{n+} + A^{m+} \longrightarrow A^{i+} + A^{(n+m-i)+}$$

**2. Loss by recombination**

$$A^{n+} + e \longrightarrow A^{(n-1)+} + h\gamma$$

**3. Loss by diffusion**

# Ion Sources for Multiply or Highly Charged Beam

- **ECRIS**

  CW and pulsed beam (～10ms), *I*: eμA-emA

- **EBIS-** Electron Beam Ion Source

  Only pulsed beam (10-50 μs), *I*: few emA-tens emA

- **LIS-** Laser Ion Source

  Only pulsed beam (a few μs), *I*: few emA-tens emA

# Why Multiply or Highly Charged Ion Beams (Q: Charge Sate)

- **Higher Q, higher energy. E $\propto$ Q or $Q^2$**

- **Higher Q, higher energy gain, accelerator more compact and lower cost**

-2001, RIA project, $U^{28+}$, 400MeV/u, 400kW, cost range 950M$

-2009, FRIB project, $U^{33+}+U^{34+}$ , 200MeV/u, 400 kW, cost range 550M$

- **Higher Q, more intense beam without stripping**

- RIKEN ECRIS is running $U^{35+}$ directly for RIBF

- IMP SECRL is running $Bi^{31+}$ directly for HIRFL

# Applications of Highly Charged Ion Beams

- **Heavy ion accelerators for high energy physics and nuclear physics**

- **Atomic Physics and surface physics**

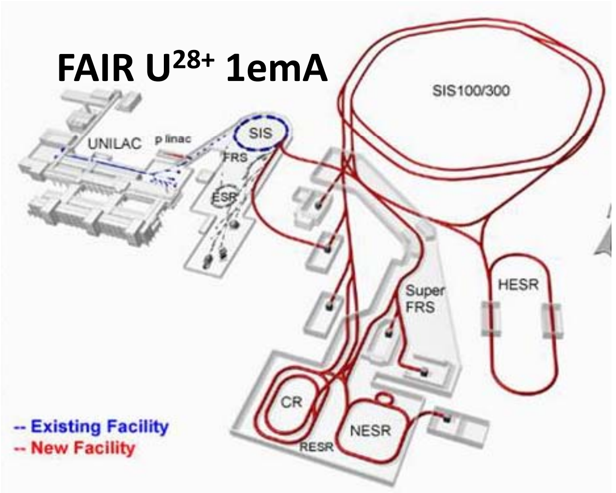
  Atomic physics data and various processes; X-ray astophysics;Cosmic Chronometer; Structure of the vacuum; Solar physics and earth-sun connection;……

- **Microelectronic and nanotechnology**

  Ion Implantation; Material modification; Ion lithography; Ion microprobe and X-ray microscope…..

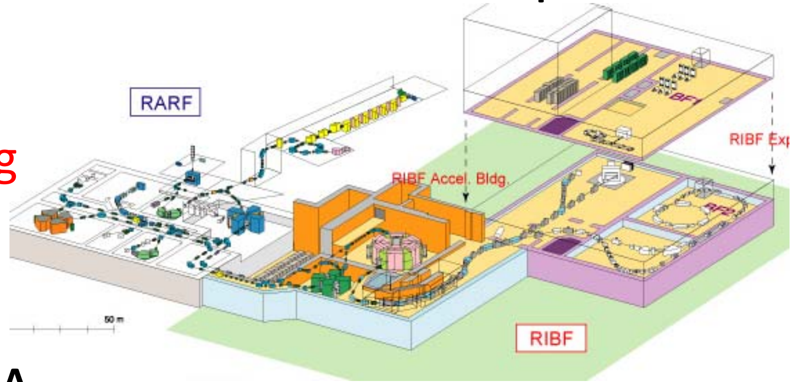
# High Power Heavy Ion Accelerator is driving force for Intense Highly Charged Ion beams (atomic physics, surface physics …)

FAIR $U^{28+}$ 1emA

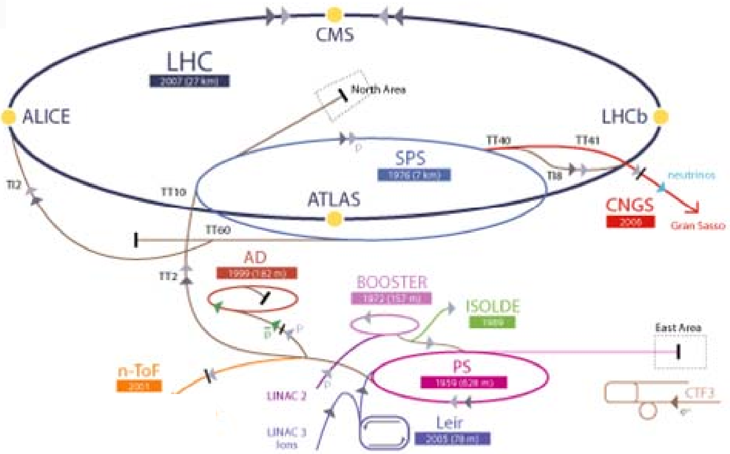



Demands to intense highly charged ion beams are increasing

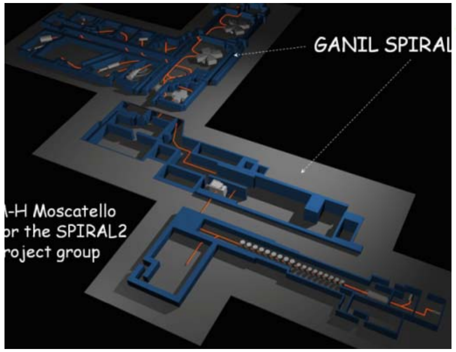
RIKEN RIBF $U^{35+}$ 525eμA



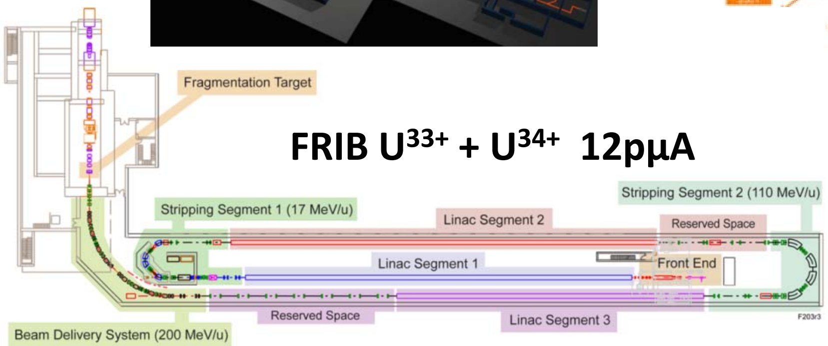

LHC $Pb^{27+}$ 1 emA



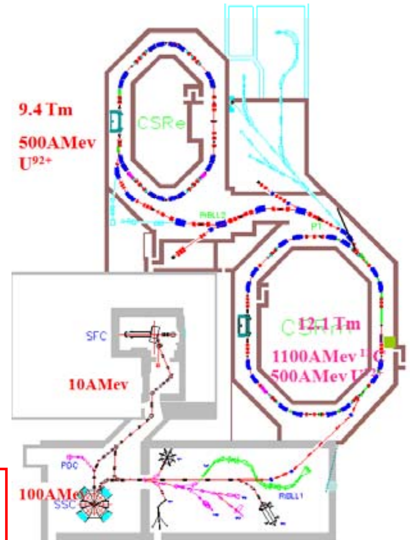

SPIRAL2 $Ar^{12+}$ 1emA




FRIB $U^{33+}$ + $U^{34+}$ 12pμA



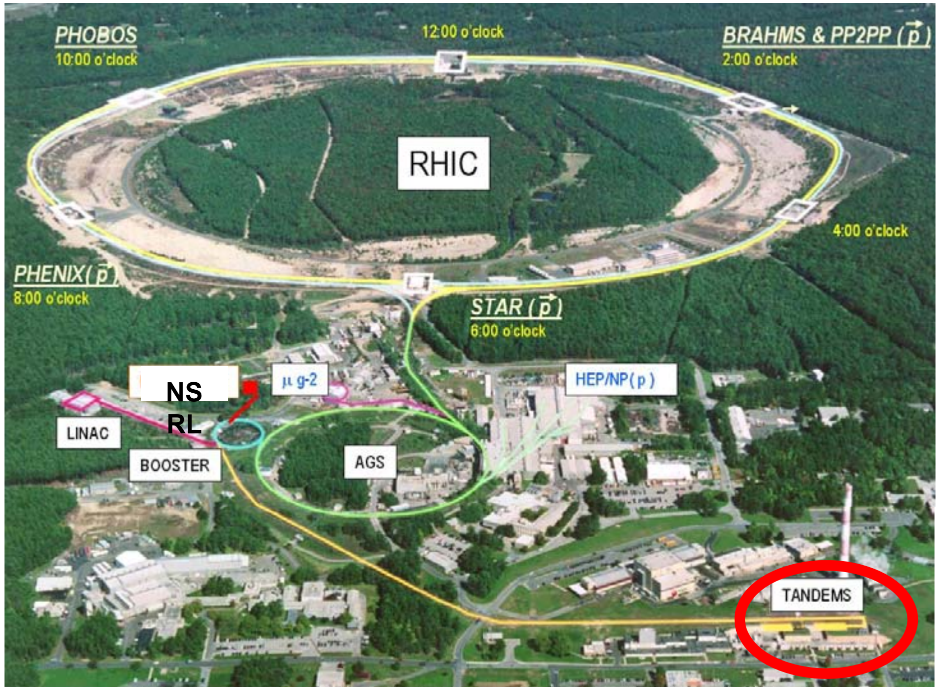

Except $U^{33+}$ and $U^{34+}$, these beam intensities have not been achieved by any existing ECRIS .

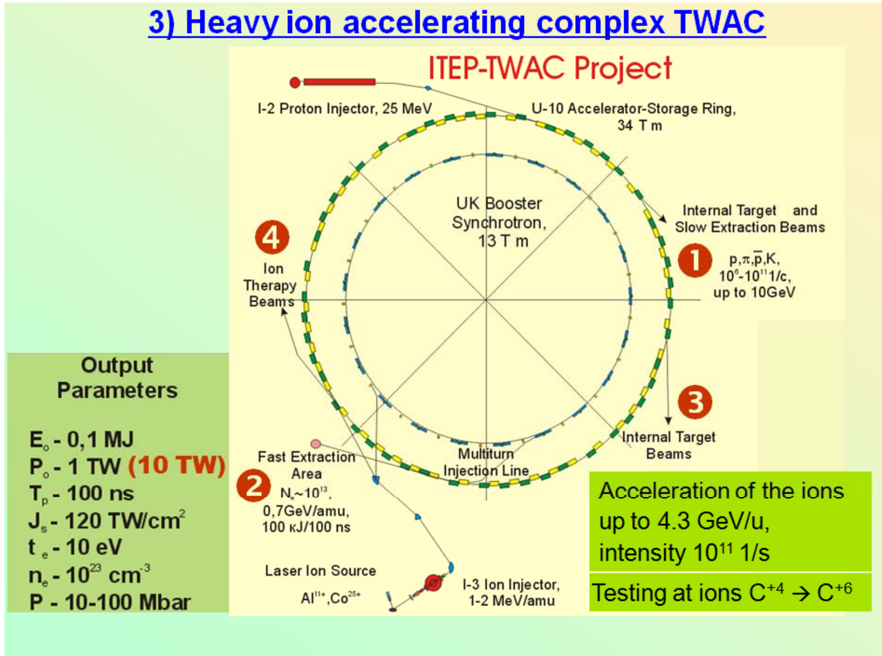



IMP HIRFL $U^{41+}$ 100eμA

# BNL RHIC(EBIS)

# ITEP TWAC (LIS)



# LIS--Laser Ion Source

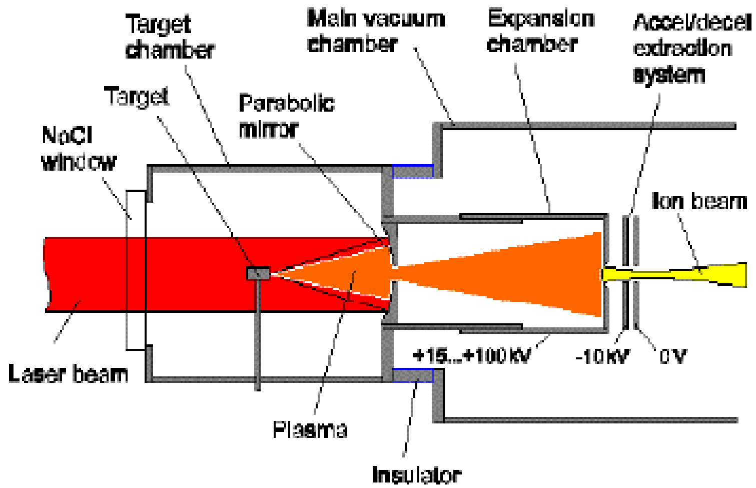
## History

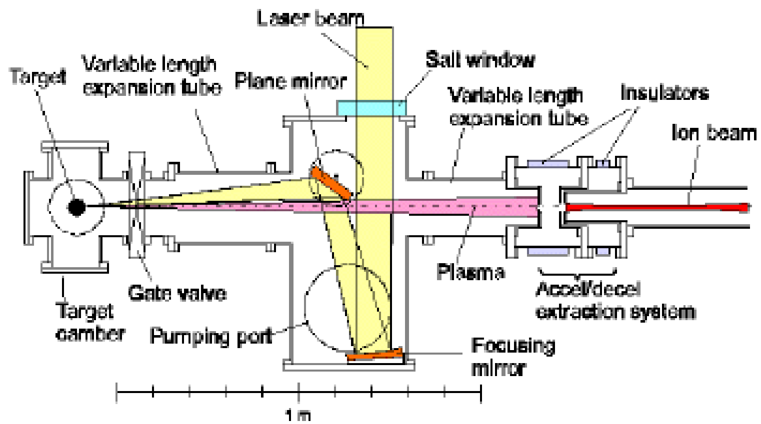
- 1969 First idea was proposed by Byckovsky, Peacock and Pease.
- 1977 -1984 JINR Dubna $Cr^{13+}$
- 1988 Technical University of Munich, ITEP
- 1992-2002, ITEP,GSI, CERN
- 2002-2005, HIMAC,RIKEN

In China, 1990， 2005-2010, at IMP, LIS.

# LIS Principle

- The plasma is generated by a laser beam.
- A short pulsed and high power laser beam is focused to a small spot on a solid target Containing the desired beam species.
- The laser evaporates the target material.
- The plasma electrons are produced during the evaporation process.
- The plasma expands normal to the target.
- The electrons are heated to high energy by the laser radiation.
- The plasma ions are stepwise ionized to high Charge states.
- Electron energy and ion charge state are determined by the laser power density and the wavelength.
- Low charge state: $10^{9}$-$10^{10}$ w/cm$^{2}$, High charge state: >$10^{12}$ w/cm2
- The ion pulse duration is determined by the space between the target and the extraction plane.




**The most important:**
**Laser generator;**
**Laser focusing system**
**Target and the ion source parts**

# LIS Advantages and Drawbacks

1. Advantage:
- Simple system
- High charge states
- High beam current
- Short pulse

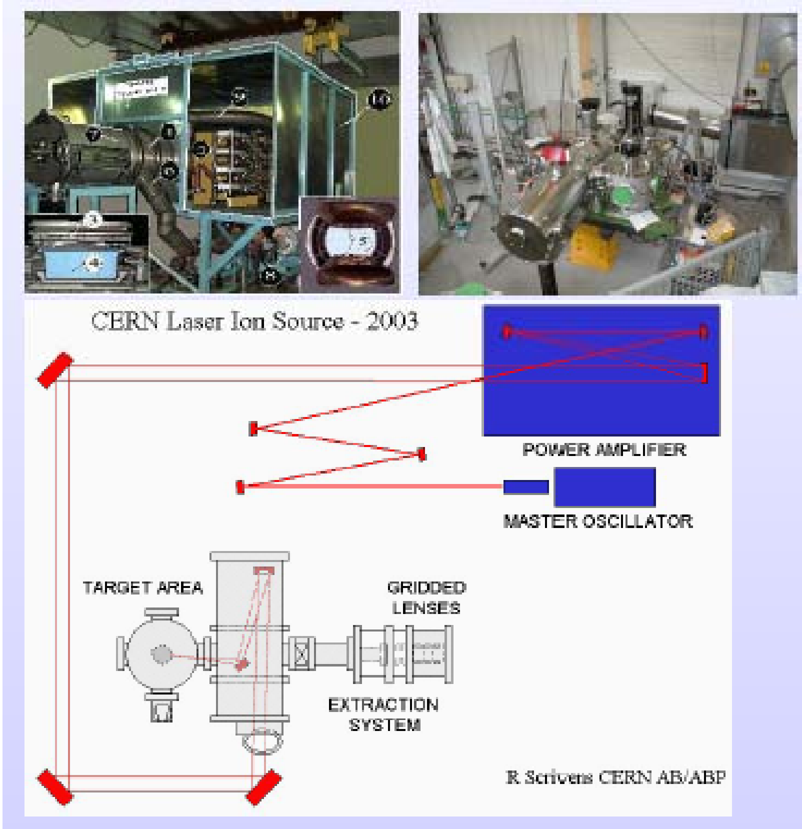
2. Drawbacks:
- Low reliability and stability.
- Pulse to pulse beam current fluctuations
- Target erosion and low lifetime.
- Coating of optics by the evaporated target material
- Beam species is limited to the solid target
- Large emittance and energy spread.

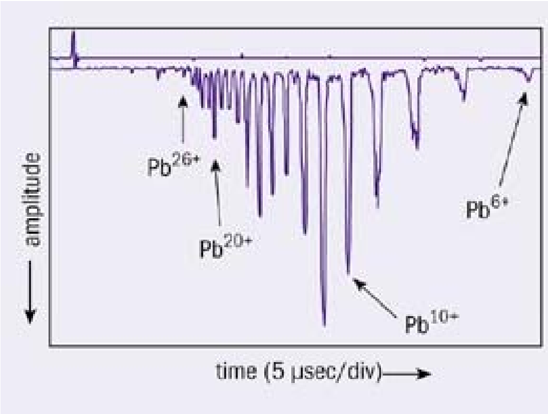
# CERN/ITEP LHC LIS

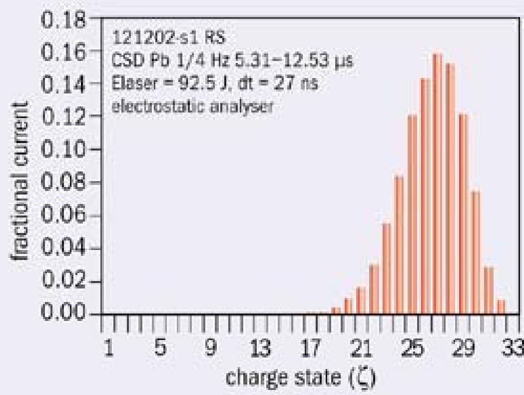
1992-2002

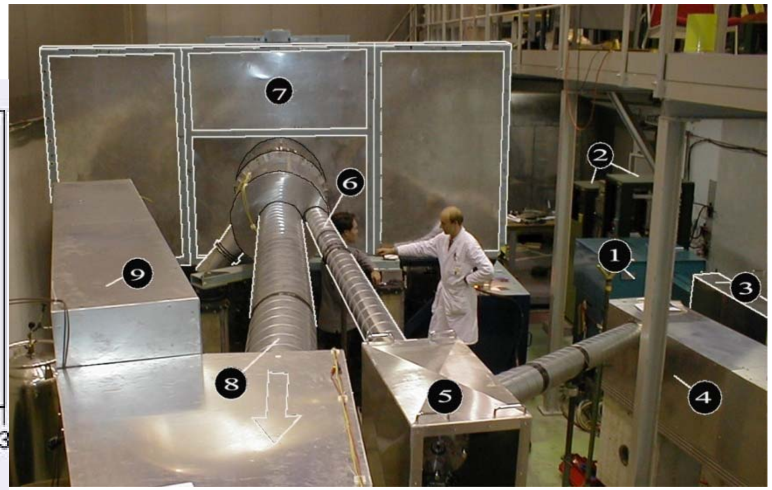
**CERN LIS: $CO_2$ laser**
**$\lambda$=10.6 $\mu$m, 100 J, 1 Hz**
**Laser pulse 15-30 ns**
**Power density $10^{13}$ W/cm$^2$**
**Ion pulse 1-10 $\mu$s**

- Statistical fluctuations in pulse amplitude and pulse width from shot to shot were less than ±15%. 1 Hz pulse trains lasting more than 60-70 minutes.
- 1-2 x $10^{10}$ Pb $^{27+}$ in a pulse of 3-4 μs.



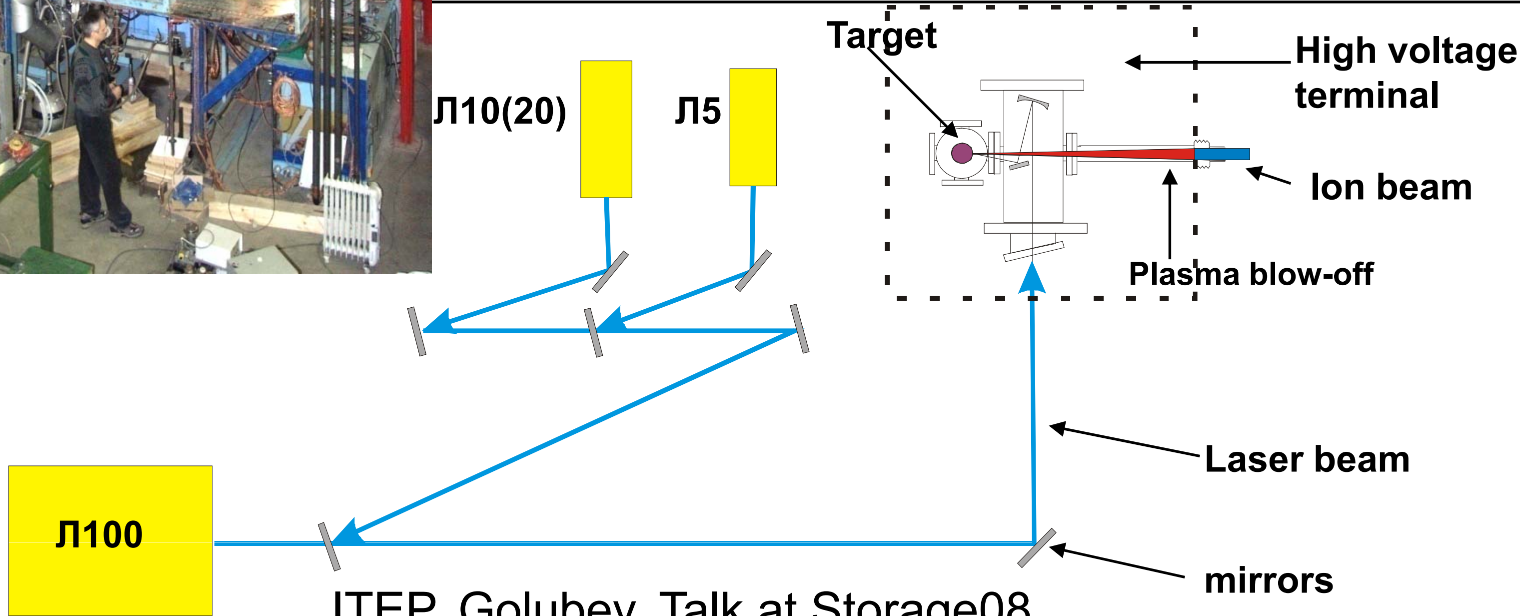
# Key element: New triple - laser ion source pre-injection system (L5, L10, L100)

**Laser L100**

**3 mA 80 MeV $Fe^{16+}$ Measured !**

Target with diameter of *150mm* and height of *200mm* for more than *2*10⁶* shots

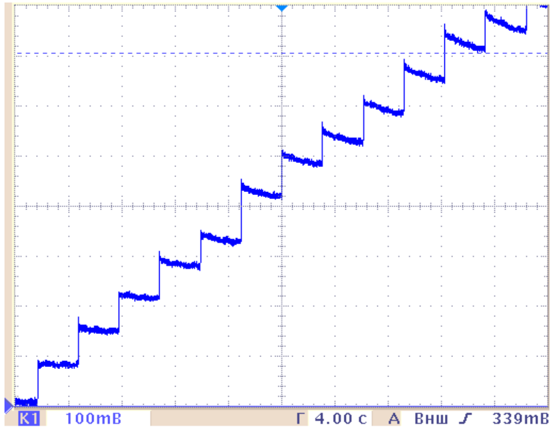
| | |
|---|---|
| Wavelength, μm | 10,6 |
| Pulse energy, J | 5/20/100 |
| Pulse duration, ns | 100/80/30 |
| Repetition rate, Hz | 0,5 /1/1 |
| Number of shots | ~$10^6$ |

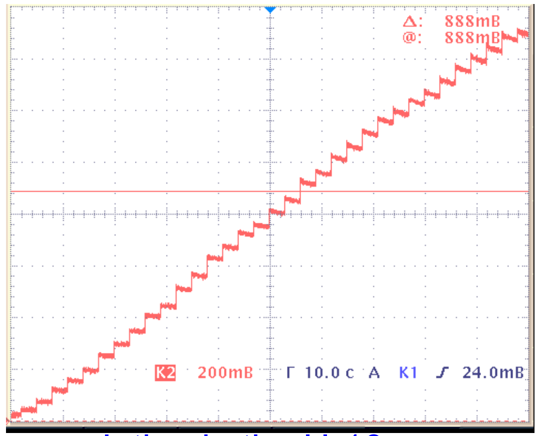



ITEP, Golubev, Talk at Storage08

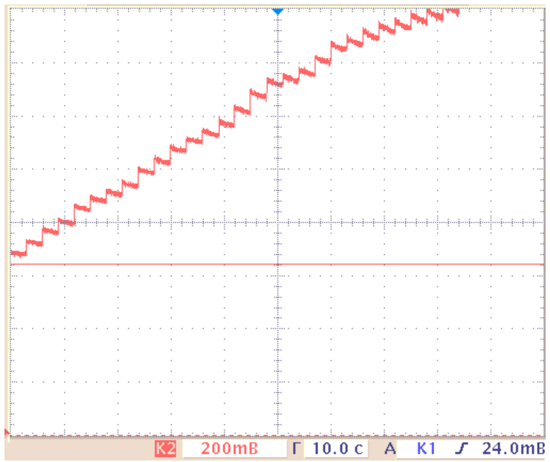
# Ion accumulation $C^{6+}$ in U-10 (213 MeV/u)

*Linear intensity growth ~ 100 s (> 40 cycles)*

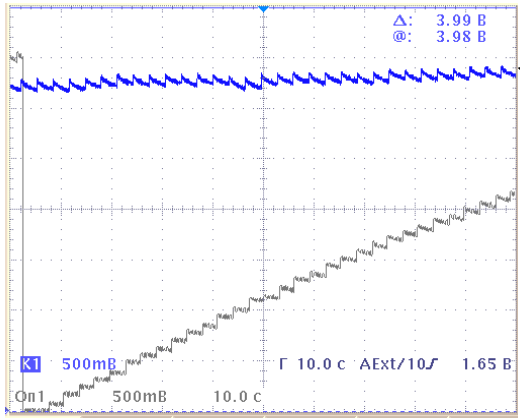



Oscillograms for the intensity of the $C^{+6}$ during accumulation in the U-10




*Accumulation drawdown*



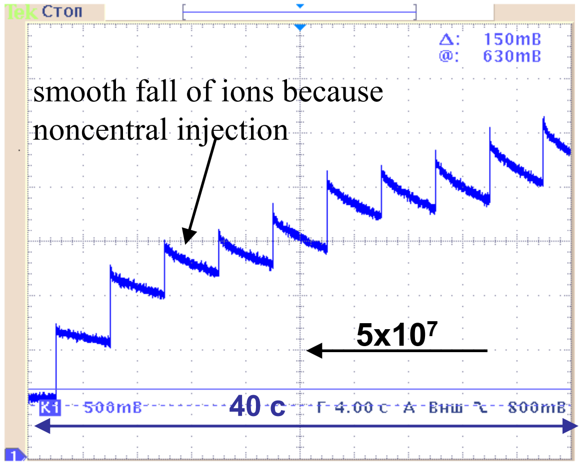

$4{\cdot}10^{10}$

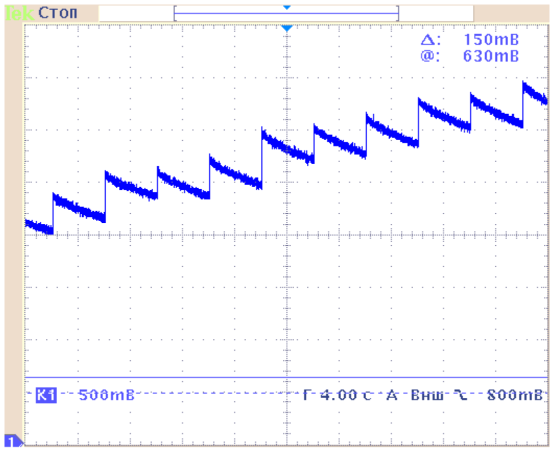
*Maximum intensity of accumulated beam*

ITEP, Golubev, Talk at Storage08

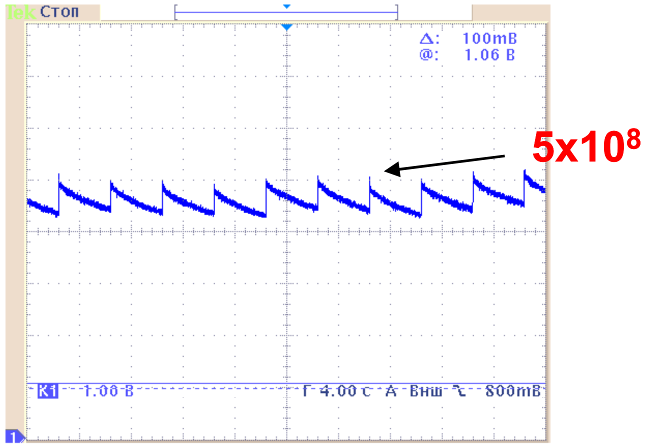
# First experience with $Fe^{16+} \Rightarrow Fe^{26+}$ stacking

**Stacking of the $Fe^{16+} \Rightarrow Fe^{26+}$ beam in U-10 Ring**



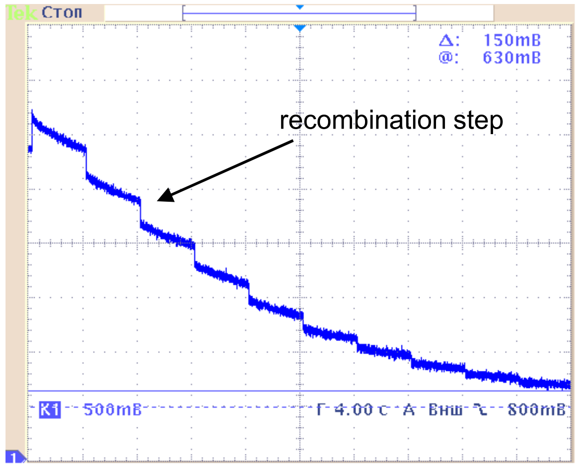




**Maximuml intensity of $Fe^{26+}$ stacked beam $k_{\propto} \Rightarrow 10$**



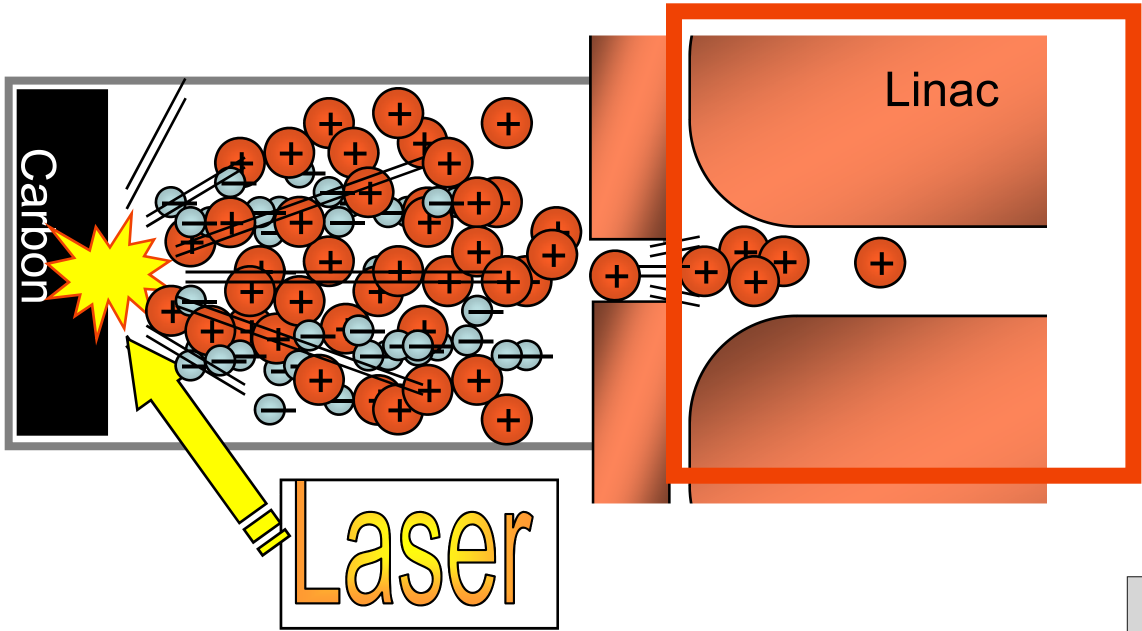

| | |
|---|---|
| Beam energy | 165 MeV/u |
| Target material | Mylar |
| The thickness of the target | 1,5 mg/cm$^2$ |
| The target size | 10x20 mm$^2$ |
| The cross section of ionization | ~3x10$^{-21}$ cm$^2$ |
| The cross section of recombination | ~7x10$^{-23}$ cm$^2$ |
| The frequency of injection | 0,25 Hz |

**Stacked beam life time in the U-10 Ring at kickers on, $\tau$o=16 s**

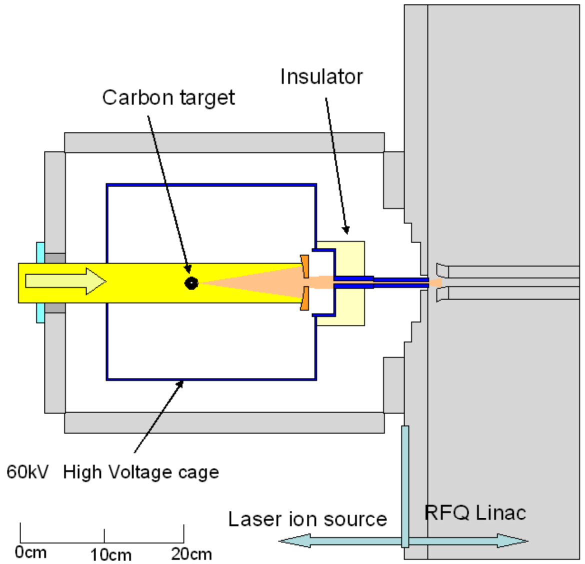



ITEP, Golubev, Talk at Storage08

# Direct laser-plasma injection into RFQ at HIMAC and RIKEN




- Dense plasma can be induced from solid target hit by laser.
- Since ions are in plasma state, space charge effect can be neglected.
- No LEBT
- Very simple structure.

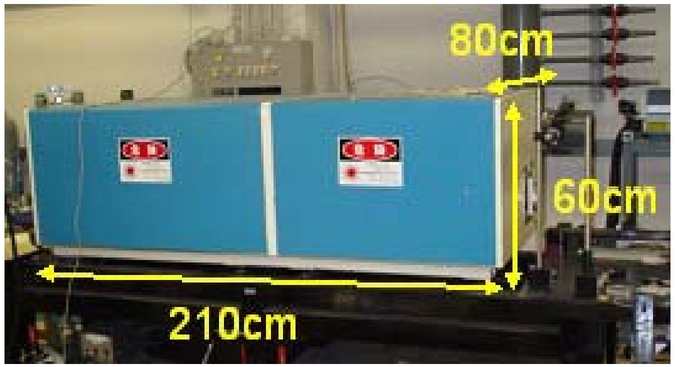


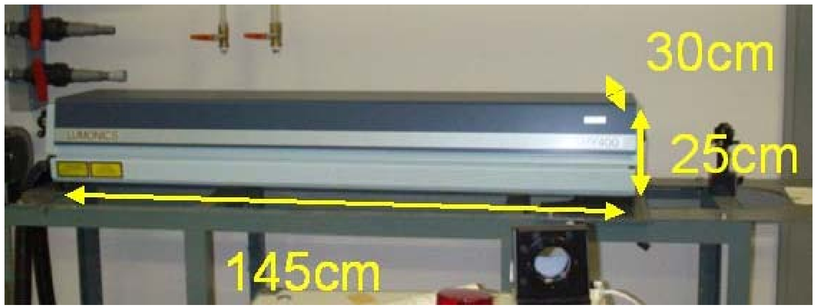
# Laser systems

Two types of laser systems had been used for plasma production.

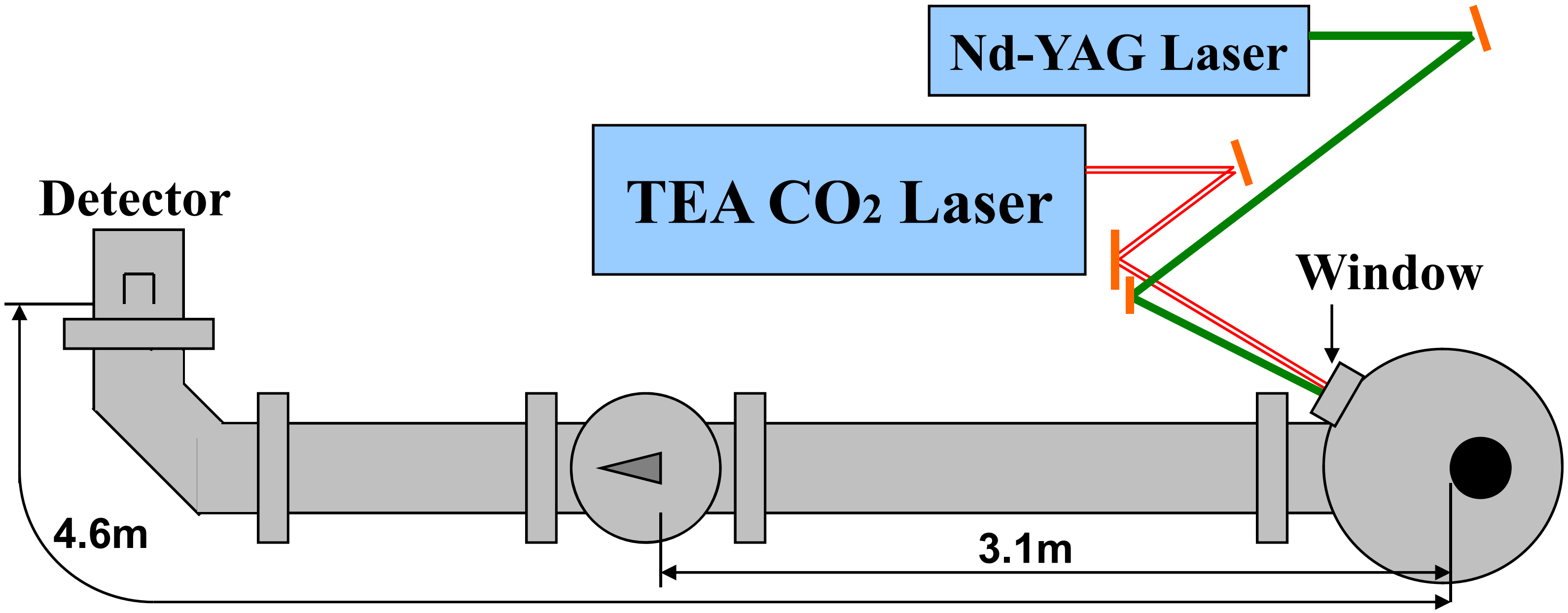
•CO2 laser
8J (1.2 J on the target)
$C^{4+}$ is mainly induced
Longer pulse duration
High intensity

•Nd-YAG laser
300 mJ
$C^{6+}$ (50 %)
Easy to use.
Highly charged states

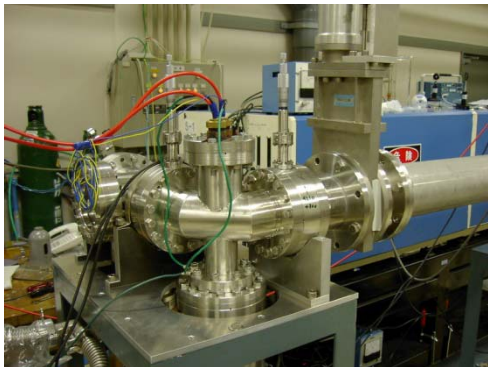


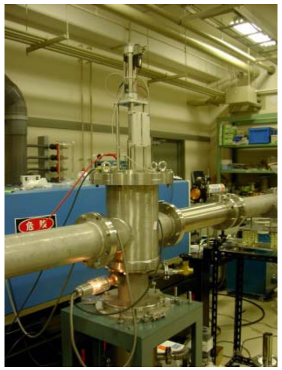
# Measurement of charge states distributions



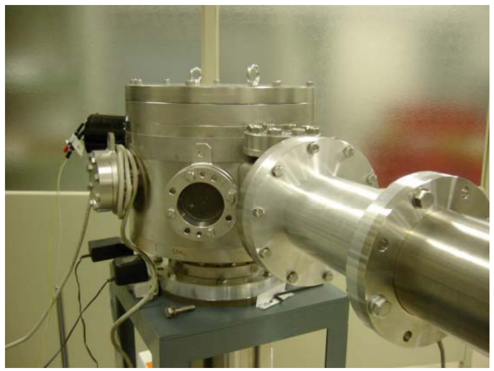

**Analyzer**



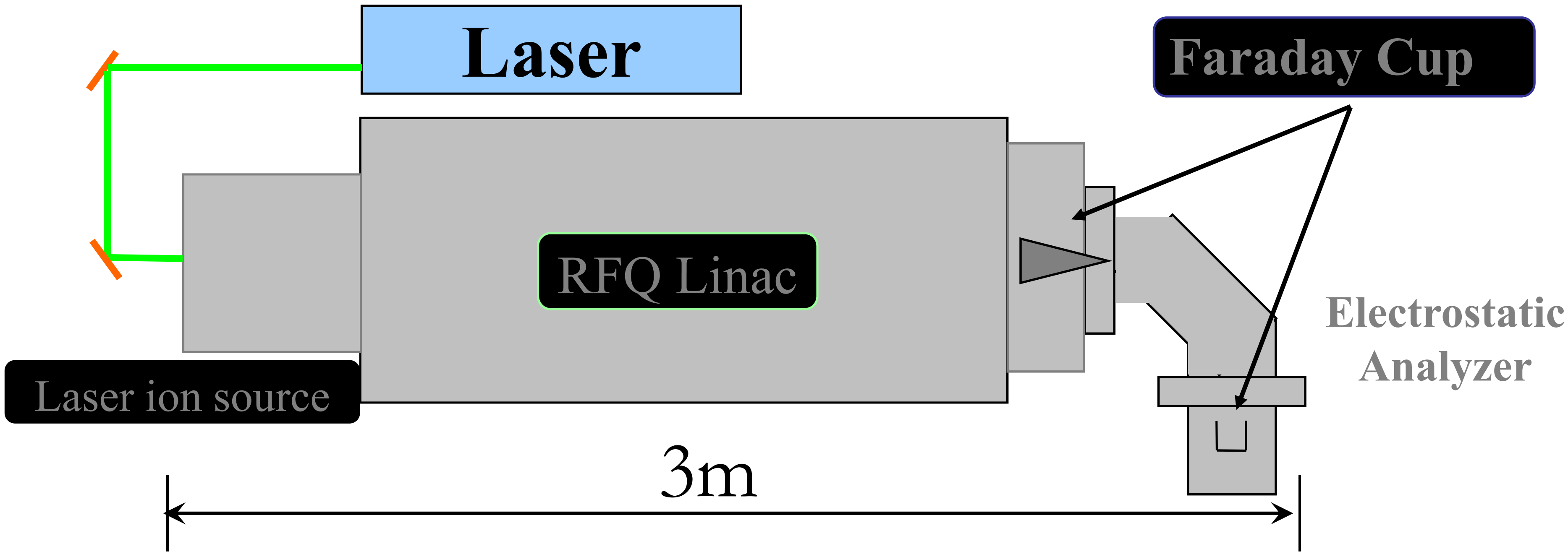
**FC Chamber**

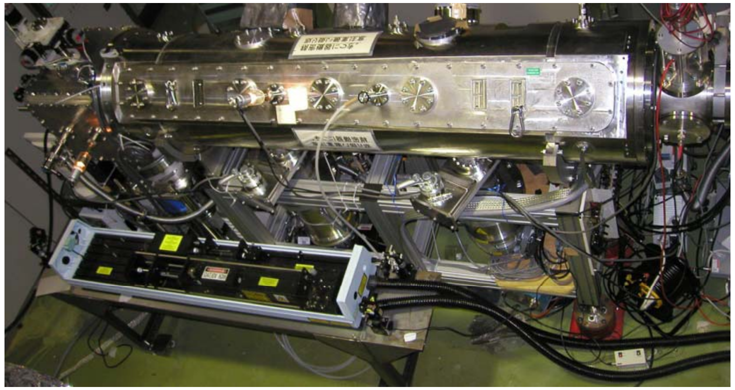


**Target Chamber**

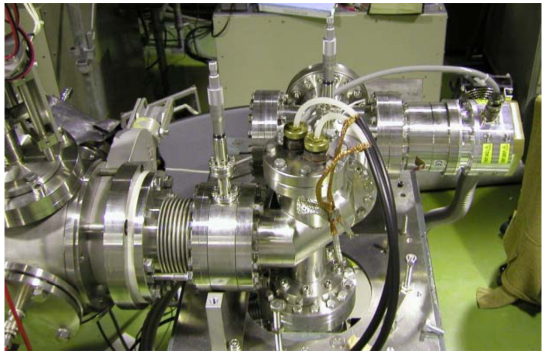


# Acceleration Test



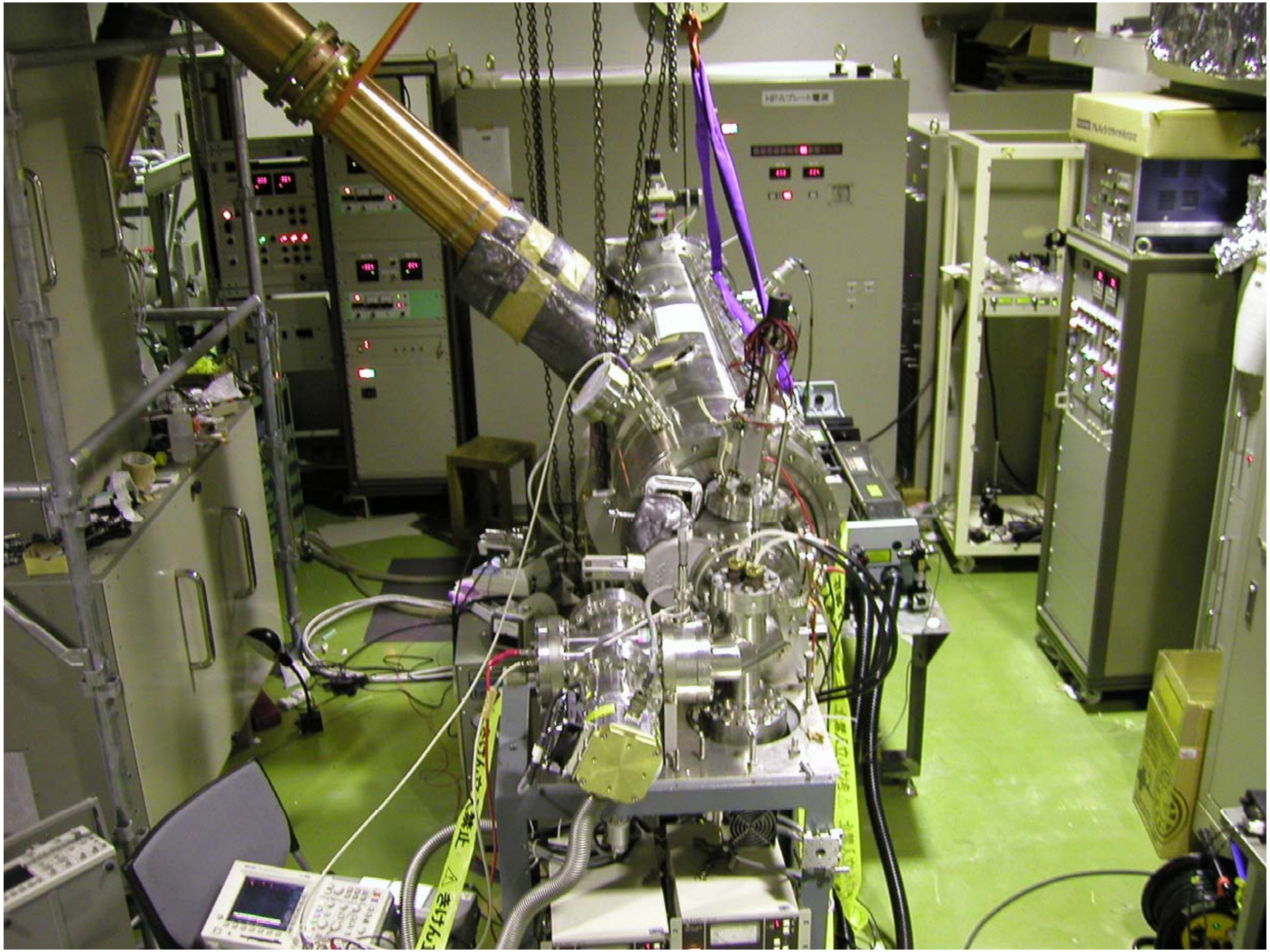



RFQ linac + laser ion source



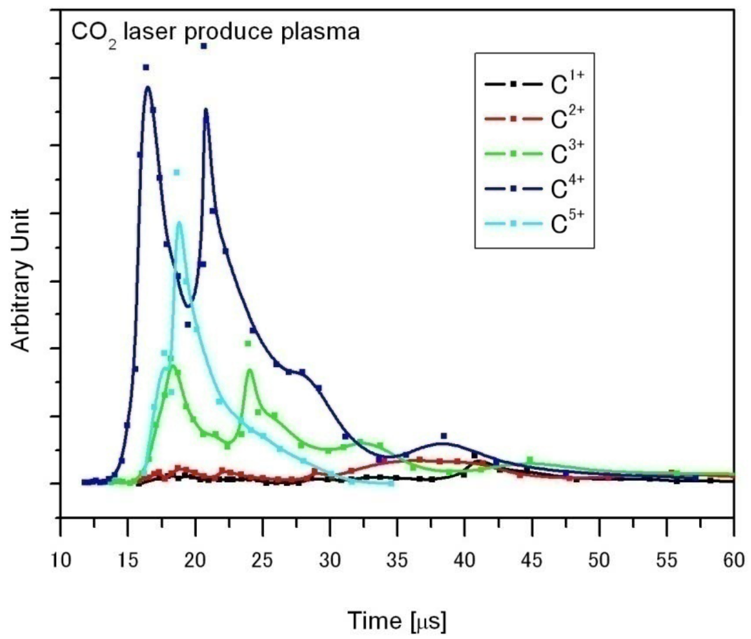
Electrostatic analyzer

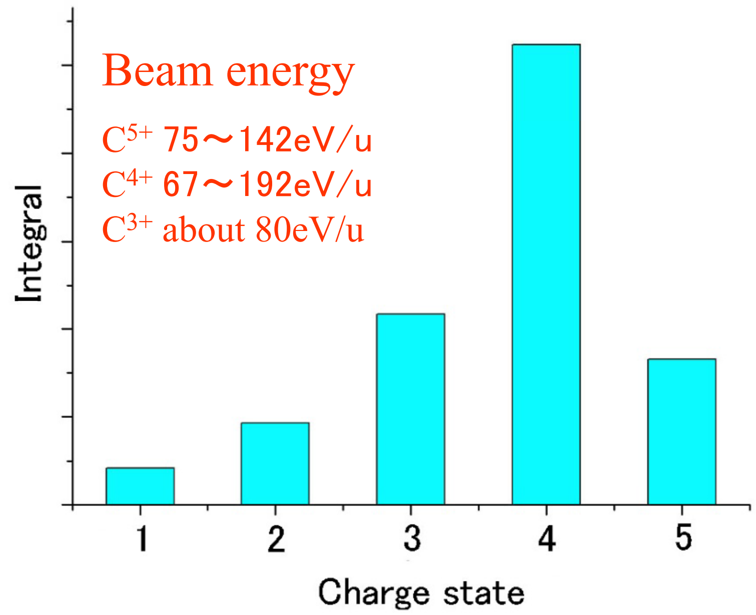
# RFQ Linac and electrostatic analyzer



# Charge states distribution

## of Carbon plasma by $CO_2$ laser

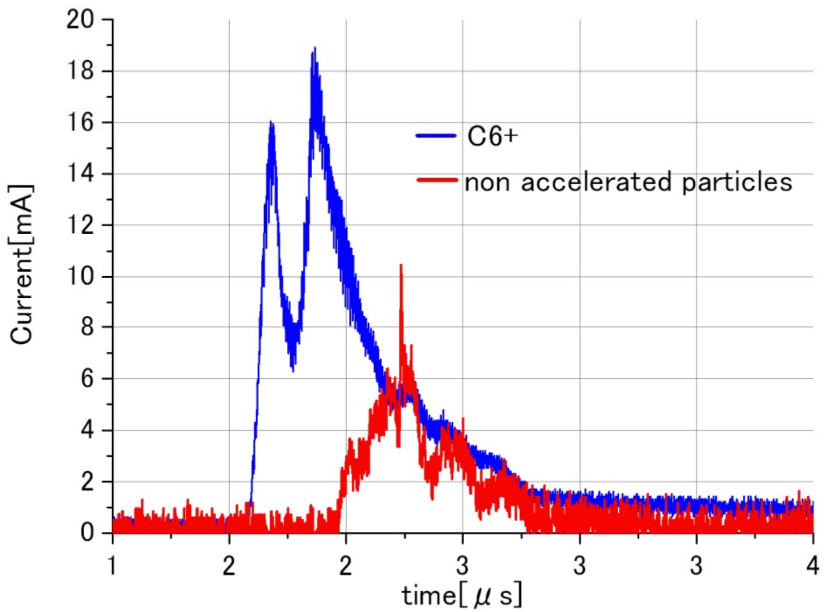



$C^{4+}$ is mainly produced

⇒$C^{4+}$ acceleration experiment

# Results (Nd-YAG)




| | |
|---|---|
| 17mA | Accelerated C6+ peak current |
| $6.0 \times 10^9$ | Number of particles C6+ |

# Comments to DLPI

- Large emittance and energy spread
- Long-term reliability and stability to be tested.
- Well designed target system.
- Improve injection efficiency.
- $C^{4+}$ or $C^{6+}$ may be OK!, but for other metallic ion beams ?

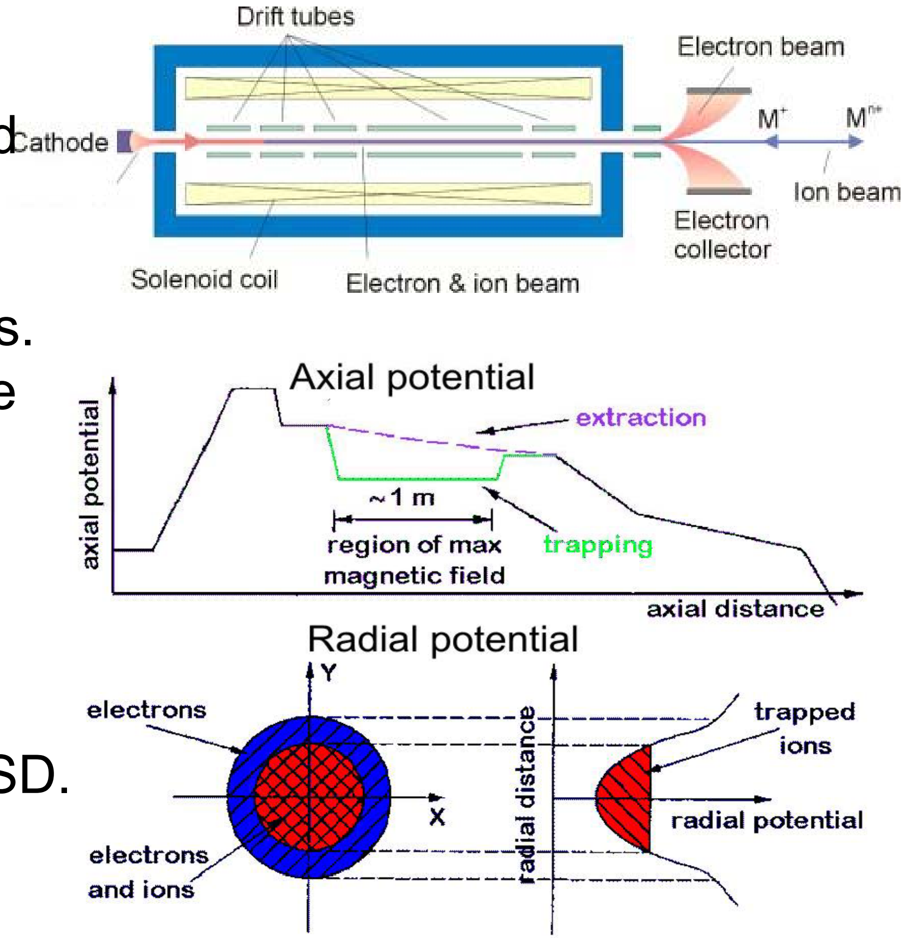
# EBIS--Electron Beam Ion Source

## History

- Invented by Donets at JINR,Dubna in 1965. $Au^{19+}$ beam in 1969.
- 1970-1985, in Dubna, cryogenic version of EBIS KRYON-I,II,II,
  bare ions C, N, O, Ne, Ar, Kr, Xe.
- 1970-1985, Europe, US, Japan, a lot of EBIS (*EBIS time*), **$U^{90+}$ !**
- 1982, at Bekerley, EBIT, from EBIS, 1990s, SuperEBIT, $U^{92+}$ !
- Since 1985, in accelerator fields, ECRIS time
- 2001-2005, breakthrough of EBIS at JINR, new idea of ESIS by Donets, and high current EBIS at BNL.
- In China, Shanghai EBIT, no EBIS.

# Principle of EBIS

- High current electrons are produced by cathode (10 A/cm$^2$), compressed to high density(1000A/cm$^2$ )by the solenoids, and decelerated and stopped by a collector.
- Ions are trapped axially by electrostatic potentials applied to cylindrical electrodes.
- Ions are trapped radially by space charge of the electrons.
- The trapped ions undergo stepwise ionization by the electrons.
- The longer confinement time, the higher charge states, *ms- hundreds s*.
- The desired charge state is at peak of CSD.
- The electrostatic barrier is dropped, the ions are escaped from the trap and extracted.
- The extracted current can be accurately predicted and calculated.
- Ultrahigh vacuum 10$^{-10}$ mbar.



# Advantage and Drawbacks of EBIS

## 1. Advantages:

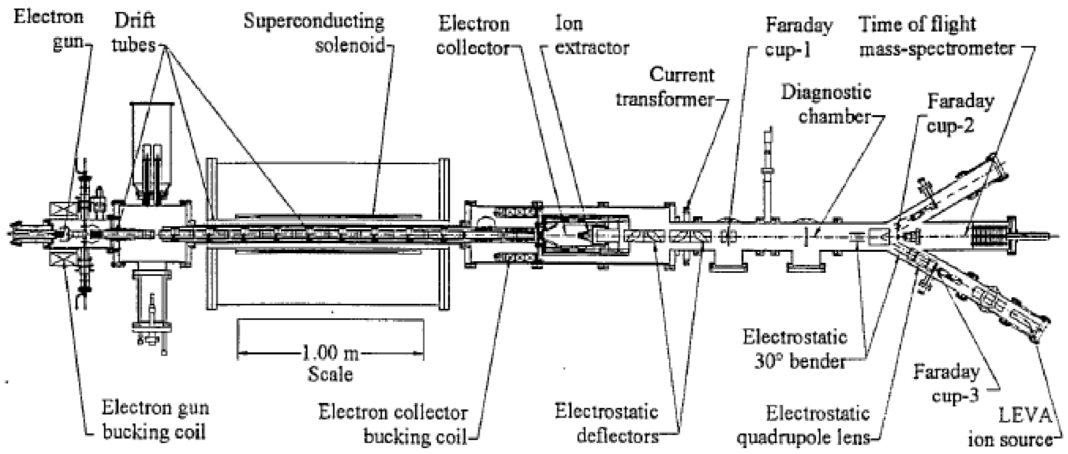
- Highest charge state
- Narrow CSD and the desired charge state is at the peak of CSD
- Ion intensity almost independent of species, and beam pulse can be controlled easily.

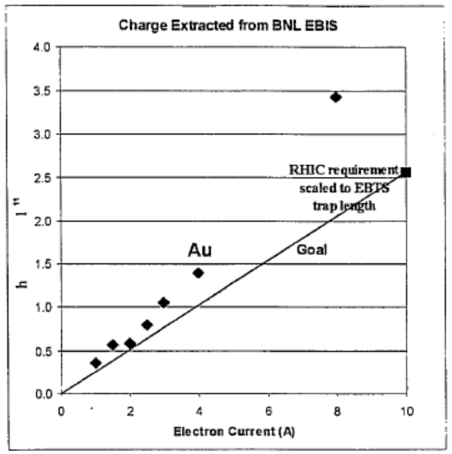
## 2. Drawbacks:

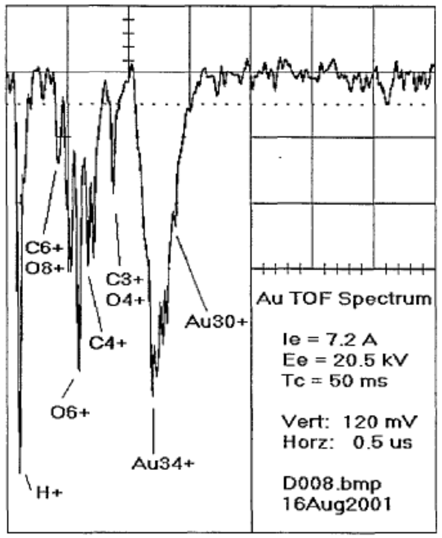
- Low beam intensity
- High technology (ultrahigh vacuum, superconducting solenoid…)
- Instability of high current electrons
- High energy spread
- Injection of solid-material ions from external source

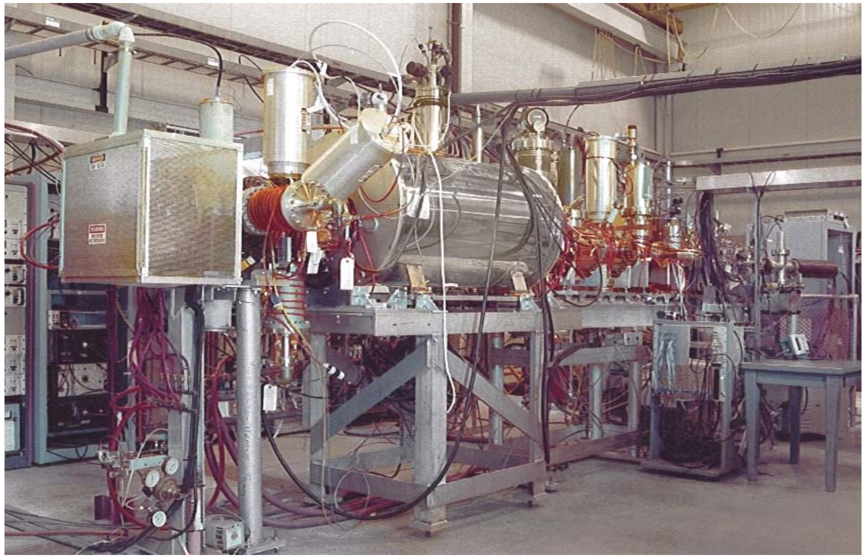
# BNL RHIC, EBIS

$I_e$ 8-10 A
B: 5 T
Trap length: 0.7 m
$Au^{32+}$ 550 eμA
Beam pulse: 15 μs

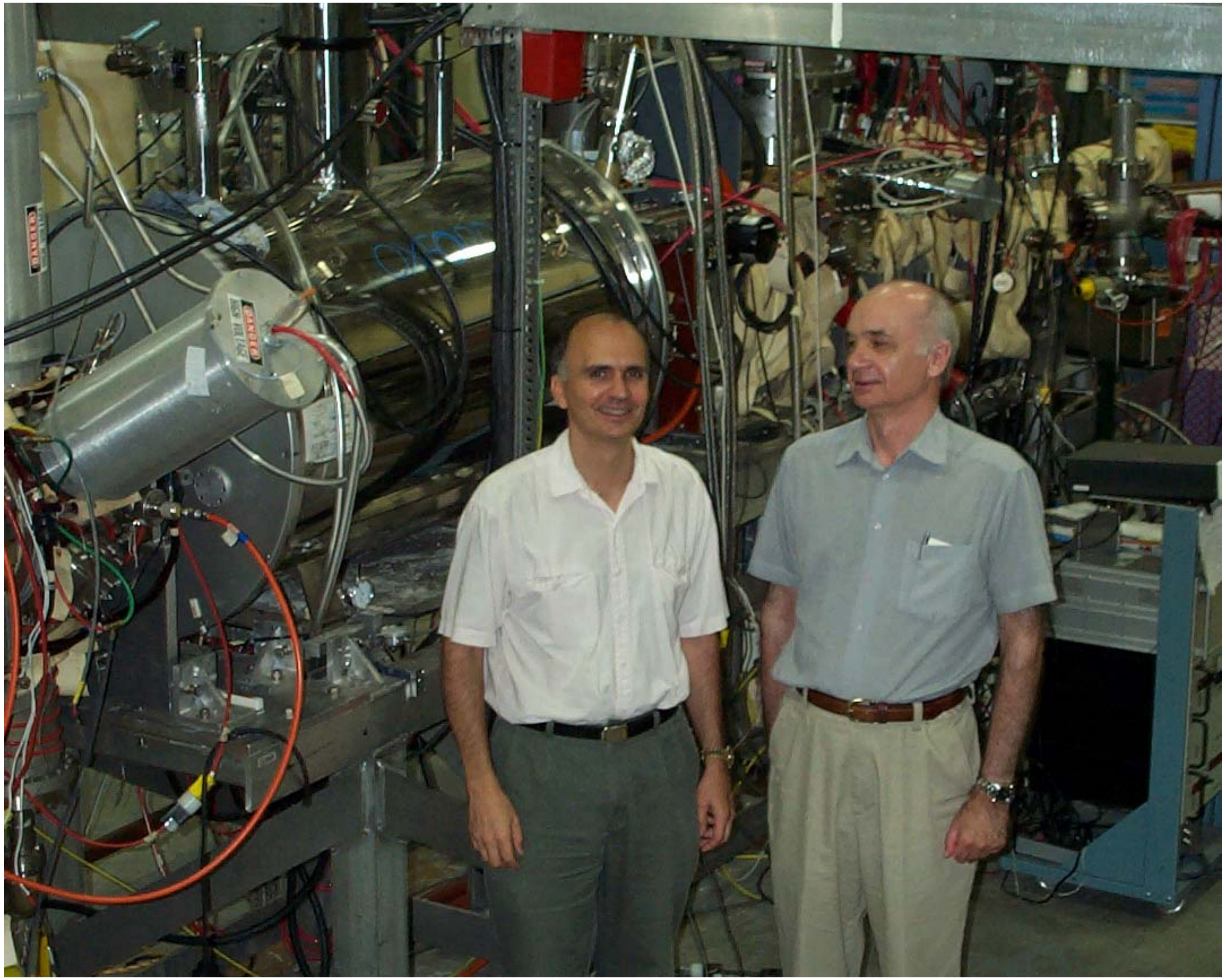


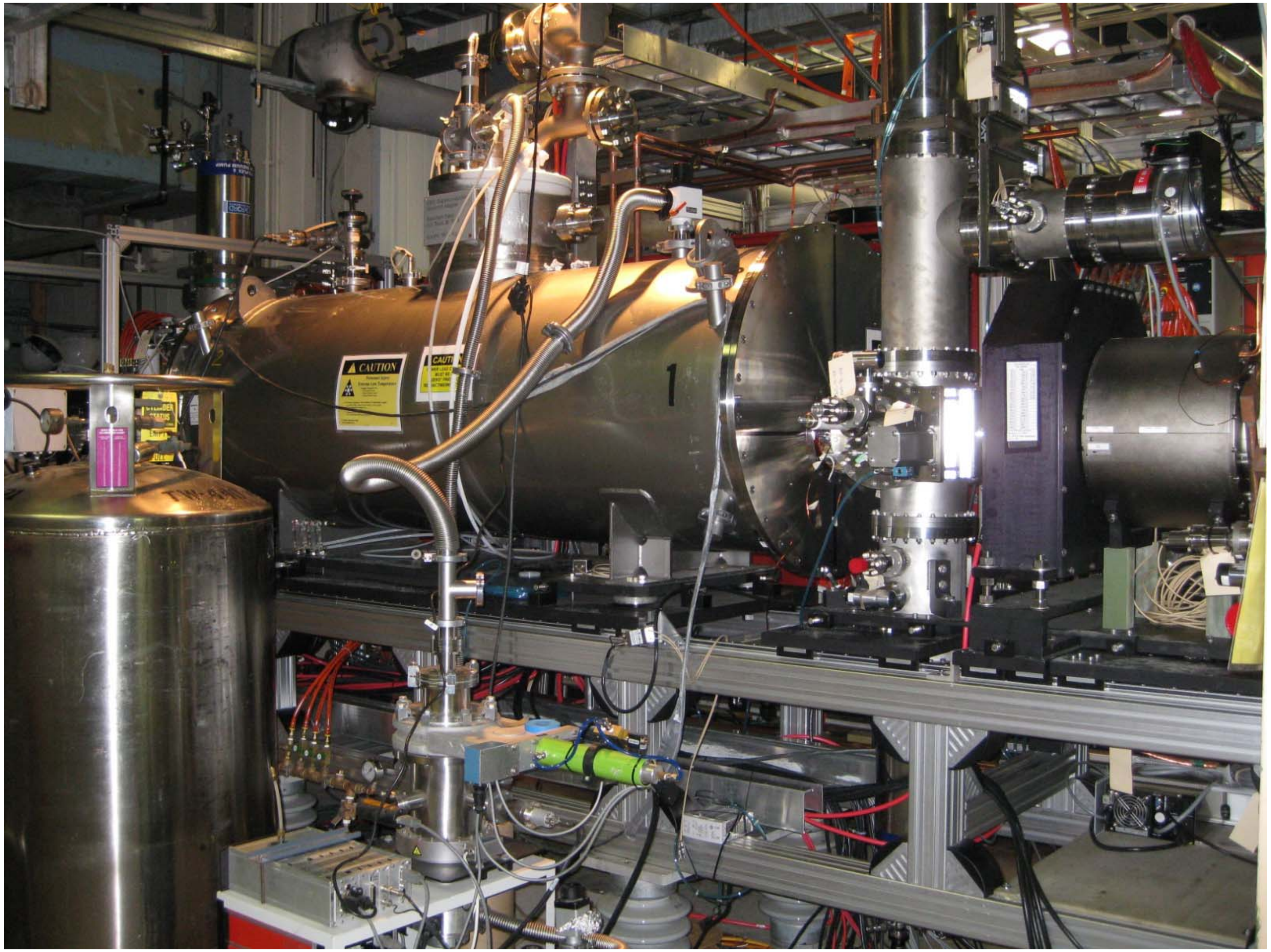



# Brightness Award in 2003 (first award )



# BNL New EBIS



Magnet was cooled down….run at full field on Saturday

Final pumping & leak checking in process

Final check of ps's and controls

**Au$^{32+}$ - tens mA**

# A Significant Breakthrough of EBIS
# →Electron String Ion Source

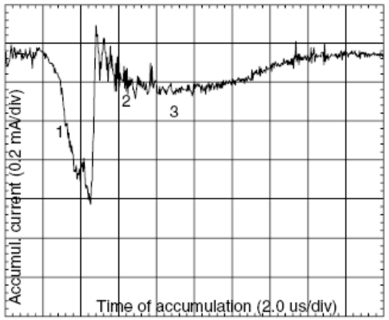
- Discovered by Donets recent years (firstly observed in late 70s).
- Under Reflex Operation Mode of EBIS
- The electron gun and the collector are designed specially so that the electrons could be reflected.
- Electron string can arise if the electron number stored in the drift tubes exceeds a threshold value (energy issue: $E_{es}$ 30% < $E_{einj,,}$ $E_{es}$ 10% > $E_{einj}$) .
- Electron string formation passes three phases: quiet accumulation, instability, quiet accumulation.
- Electron string related to $B^3$ ( $I_e$ hundreds uA ).
- Reduce more than 95% power consumption of EBIS

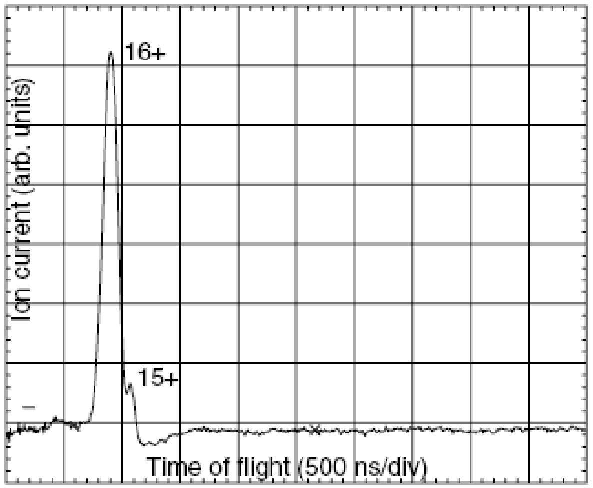
**$Ar^{16+}$ 200 eμA**

**$Fe^{24+}$ 150 eμA**

**Beam pulse: 8 μs**

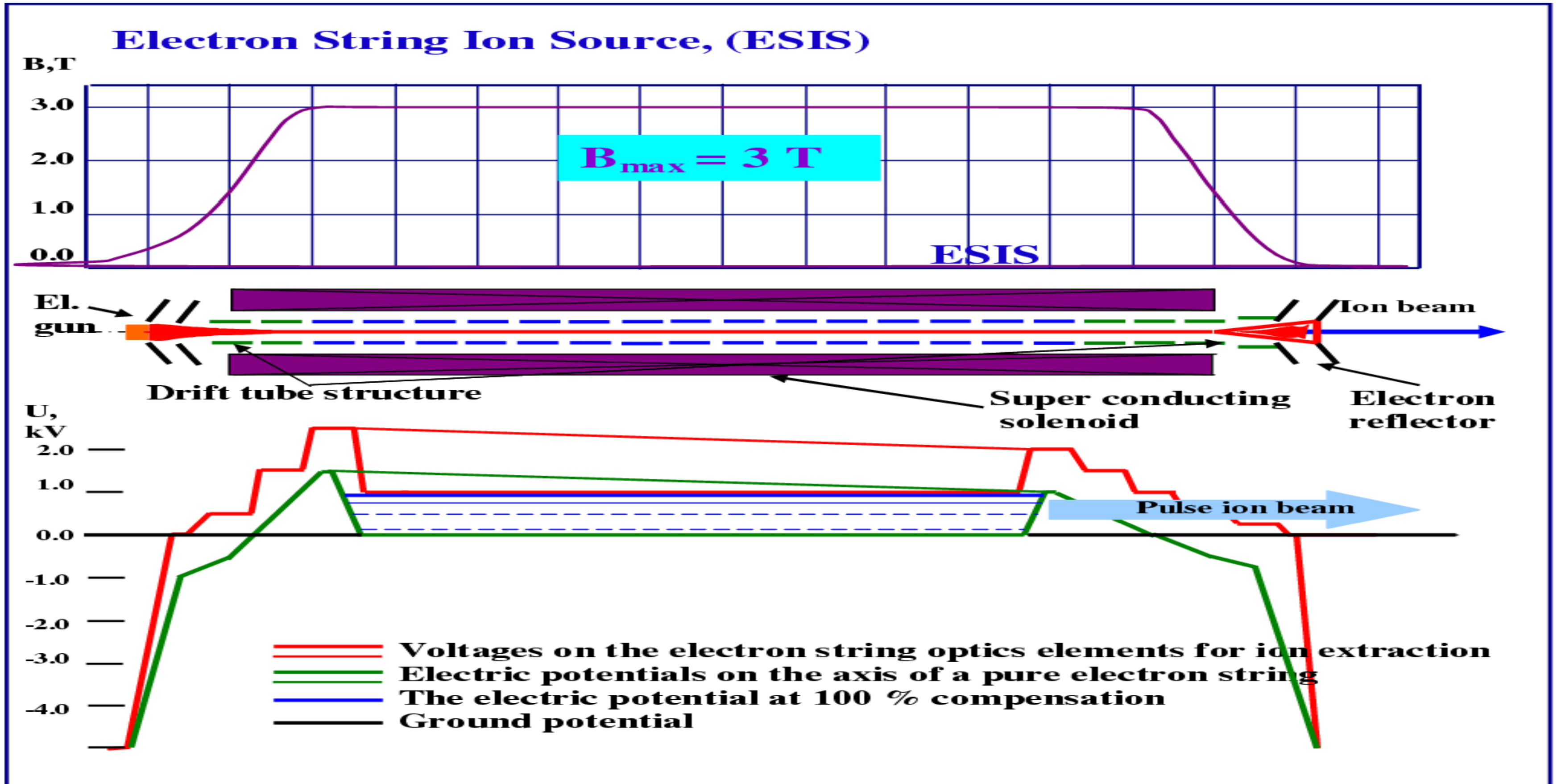
**Injected into JINR synchrotron**



b)

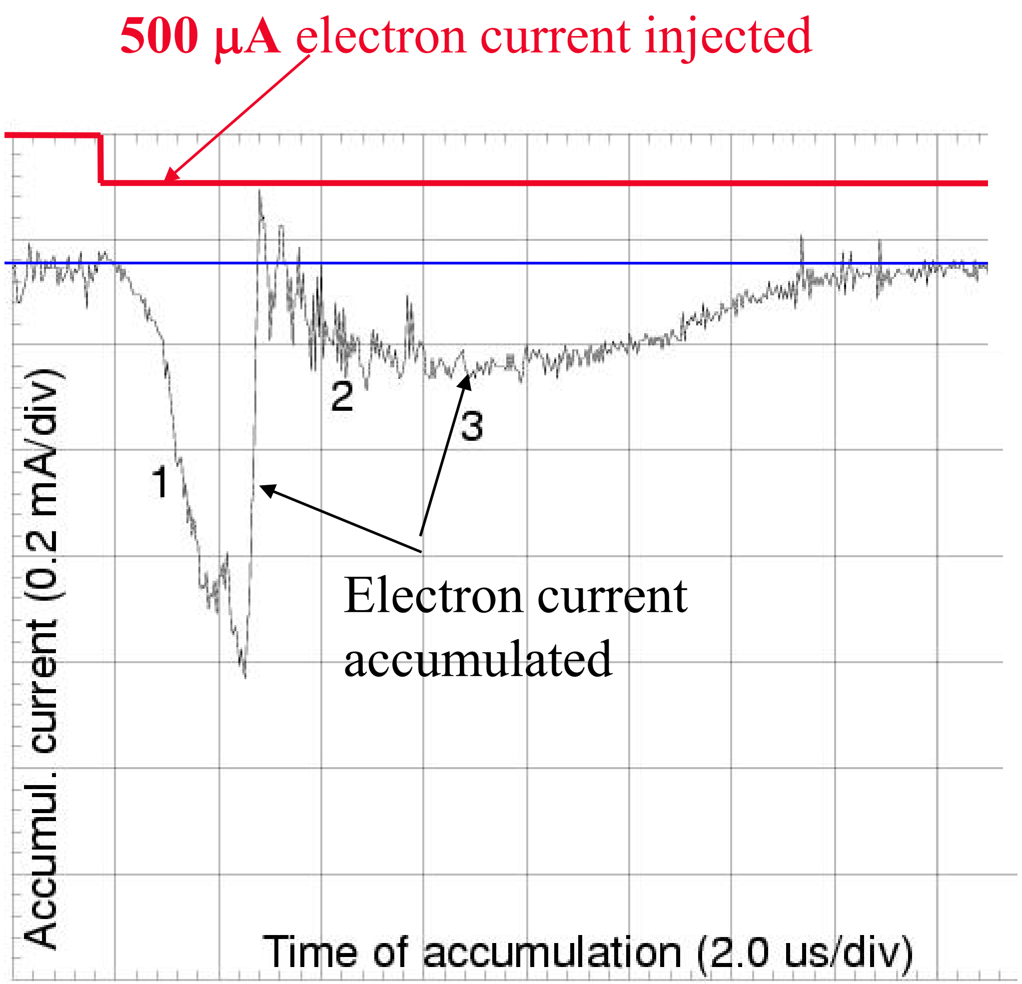
**Comments to Donets Brightness Award 2005**

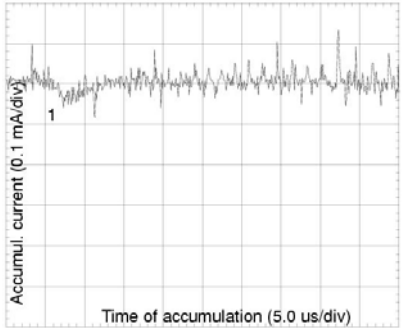


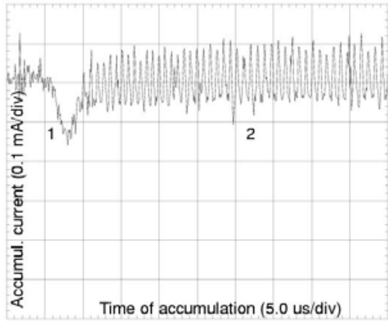

*EBIS in the electron reflex mode of operation*

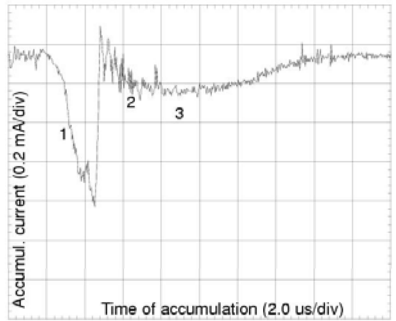

V. Shutov
SAIP2008

JINR




Injection electron current: **500 µA**

V. Shutov
SAIP2008

# Comments to ESIS

只有坚持不懈、长期积累和实验中敏锐思维，才能有重大创新和突破！

# ECR Ion Source History and Development

- In the Beginning Supermafios in 1974
- First generation 6 to 10 GHz sources
  - Minimafios, ECRVIS , LBL ECR, RT-ECR …
- Second generation 14 to 18 GHz
  - CAPRICE, AECR-U, LECR ………
  - RIKEN 18 GHz
  - SERSE 18 GHz Superconducting
  - A-PHOENIX
  - GTS 18 GHz Grenoble
- Third Generation 24 to 35 GHz
  - VENUS Operating at 28 GHz  Berkeley
  - SECRAL Operating at 18 -24GHz Lanzhou
  - MS-ECRIS Under construction for 28 GHz for FAIR
  - RIKEN SC-ECR Operating  at 18 GHz for RIBF
  - MSU-NSCL   SUSI Operating  at 18 GHz
- Fourth Generation ,35GHz-60GHz??

**Typical beam intensity enhancement in the last 10-30 years**

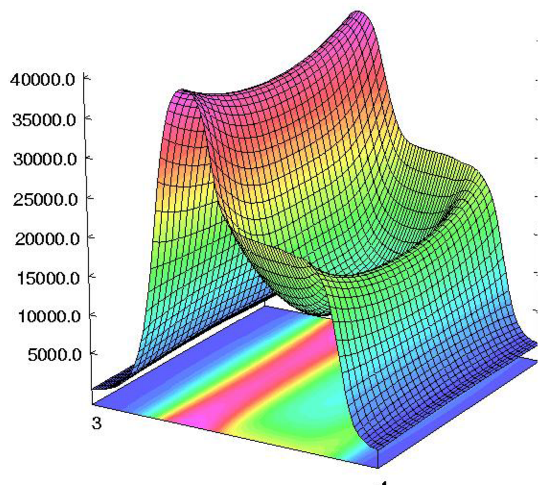
| Ions | Year Intensity By ECRIS | Year Intensity By ECRIS | By factor |
|---|---|---|---|
| $O^{6+}$ | 1974, 15 eμA Supermafios | 2004-2006, >2000 eμA IMP SECRAL LBNL VENUS | 30 ys >130 |
| $Xe^{30+}$ | 1997-1998, 10-15 eμA, RIKEN 18 GHz, LBNL AECR-U | 2008, >150 eμA, IMP SECRAL | 10 ys >10 |
| $Xe^{35+}$ | 1997, 1.5 eμA LBNL AECR-U | 2009, >45 eμA IMP SECRAL | 10 ys >30 |
| $U^{34+}$ | 1997, 20 eμA, LBNL AECR-U | 2006, >200 eμA LBNL VENUS | 10 ys >10 |

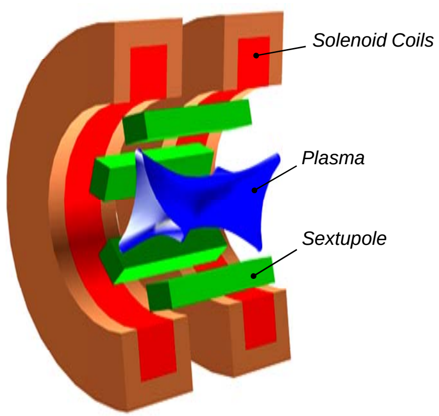
# ECRIS--ECR Ion Source

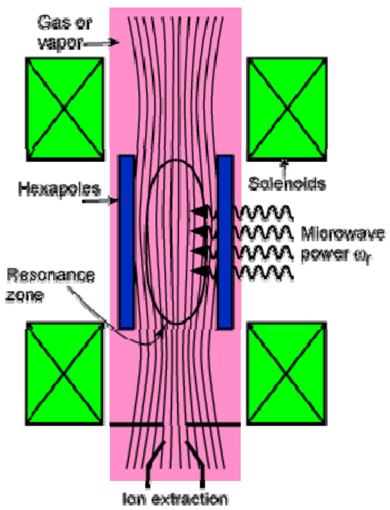
- **Plasma device to produce intense highly charged ion beams**
- **Plasma is produced and heated by microwave (6 GHz-28GHz)**
- **Plasma is confined by minimum B structure－solenoids+sextupole**
- **Highly charged ions are produced by stepwise ionization process**
- **A resonant interaction between electrons and RF takes place when :**

$$\omega_{HF} = \frac{eB(\mathbf{r})}{m}$$

- **Plasma parameters:** $n_e$ - $10^{12}$ $cm^{-3}$ Te – tens keV, $\tau_{ion}$ - ms
- **To produce HCI beams, need high $n_e$, long $\tau_{ion}$ and low $n_0$**

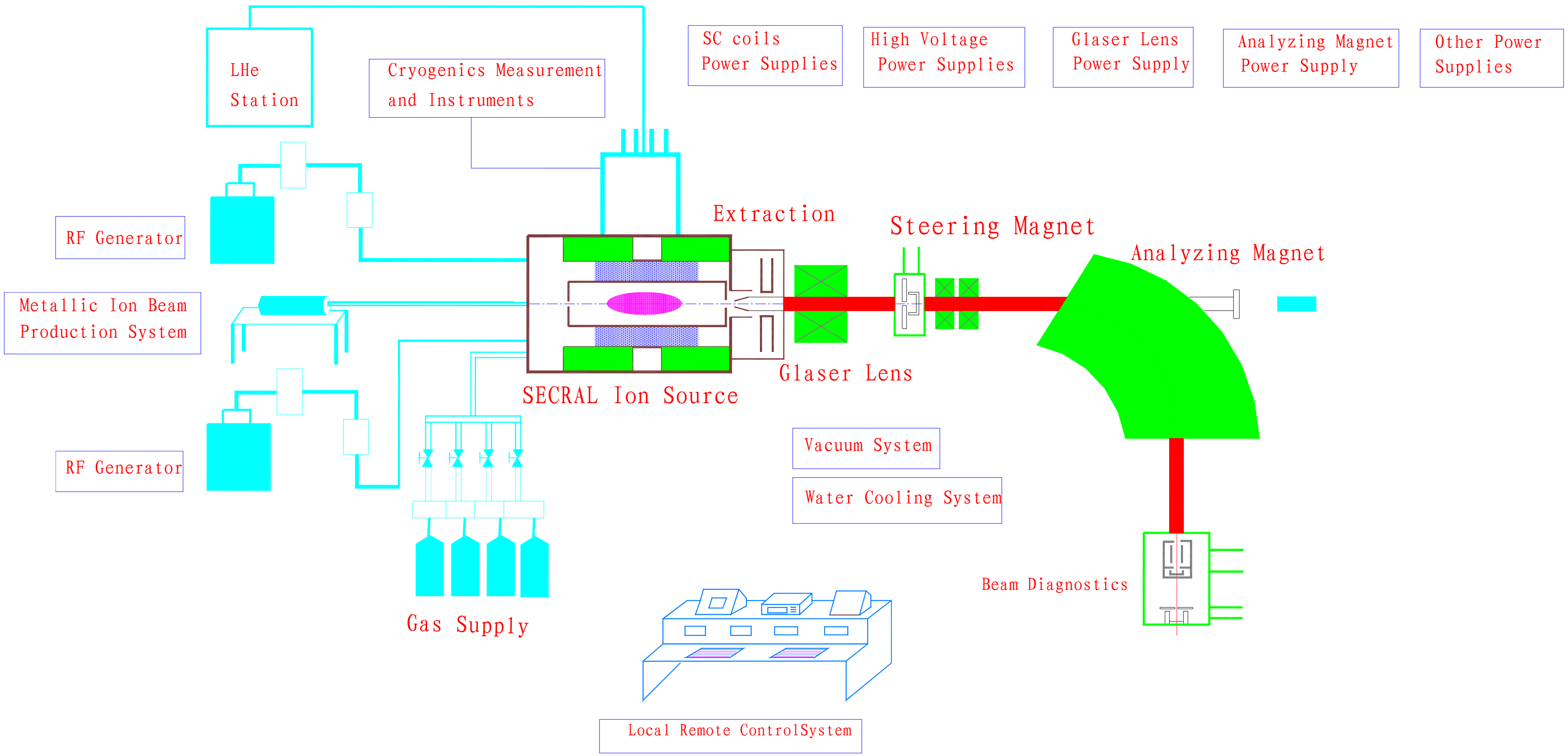



**ECRIS physics is not completely understood!**

# An ECRIS System Layout



# Advantages and Drawbacks of ECRIS

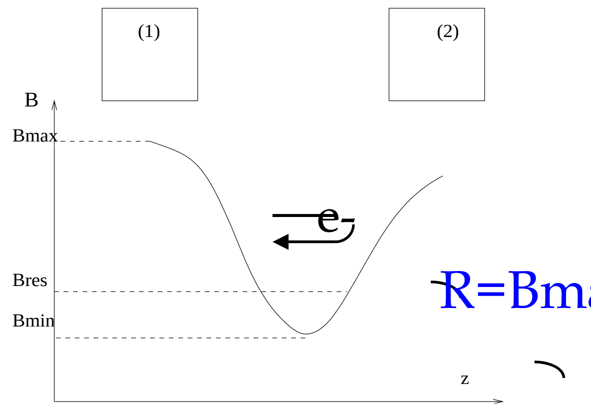
## 1. Advantages

- High intensity for highly charged ion beams,
  $O^{6+}$ 2emA, $^{238}U^{48+}$ >1 eμA
- Long-term stability and reliability
- Low energy spread ($-10^{-4}$ ) and low emittance (30-150 )
- High ionization efficiency
- Very long-life time and no consumable components.

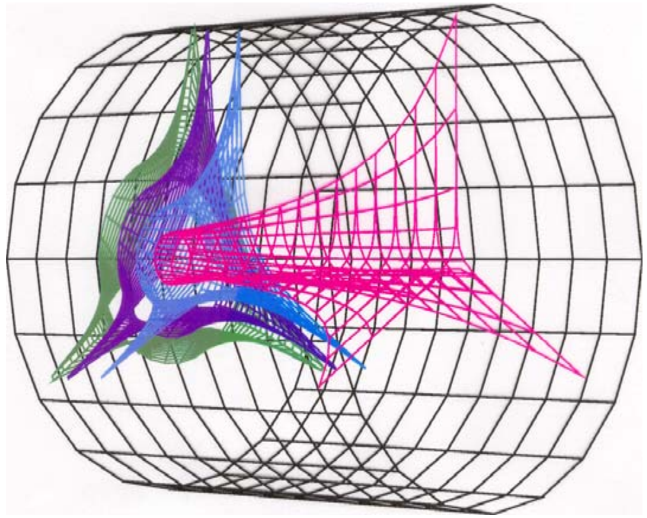
## 2. Drawbacks:

- Lower beam intensity for highly charged ion beams of refractory material .
- Can not produce short pulsed beam (μs-ns)

# Physics of ECR plasmas: electron heating and confinement

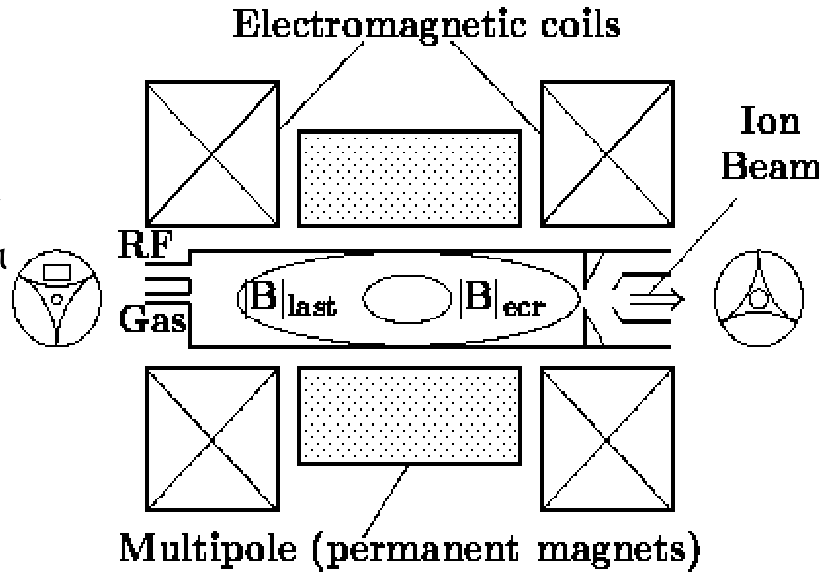



R=Bmax/Bmin



<u>Electrons interact</u> with the RF wave when: $w_{RF} = w_c + k_{//} v_{//}$ (resonance surface $w_{RF} = wc$ *), electron motion and losses…..*

<u>Mirror effect:</u> the electrons bounce between the maxima of the magnetic field
It was shown early that only the mirror confinement is <u>unstable</u> versus the interchange instability (curvatu of field lines is not correct) => a hexapole is added




<u>The hexapole</u> changes the shape of the field lines, and induces a drift of the electrons; however this drift occurs along equal-B lines => criterion of the last closed mod B line.

# Physics of ECR plasmas: ion production and confinement

Ions are produced via step by step ionization. Some recombination processes should be avoided (charge exchange => low pressure is needed)

As they are ionized step by step, ions should be kept enough time in the plasma => confinement

As the ions are cold (less than a few eV), as the mean charge of the plasma is high (heavy ions), it can be shown that the ions are not magnetized (hence not mirror confined), have all the same temperature. This result can be shown by this hierarchy of times (Ar9+):

| $\tau_{ij}$ | $T_{cycl}$ | $\tau_{conf}$ | $\tau_{eq\ e/i}$ |
|---|---|---|---|
| 2,3 $10^{-8}$ | 6,7 $10^{-7}$ | $10^{-3}$ | 3,6 |

Two transport processes push the ions out of the plasma:
diffusion through thermal motion, and through an ambipolar electric field

$$\tau_q = 7.1\ 10^{-20} L^2 q^2\, Ln\Lambda\, \sqrt{A}\,\frac{n_e q_{eff}}{T_i^{5/2}} \quad (\mathrm{s, cm, cm^{-3}, eV})$$

$$\tau_q = 7.1\ 10^{-20} L\, q\, Ln\Lambda\, \sqrt{A}\,\frac{n_e q_{eff}}{T_i^{3/2} E} \quad (\mathrm{s, cm, cm^{-3}, eV, V/cm})$$

## Rate equation

Electron density

Ion confinement time

$$
\begin{cases}
\dfrac{dn_0}{dt} = -n_e \chi^{\text{ion}}_{0\to 1} n_0 + n_{\text{gas}} \xi^{\text{ex}}_{1\to 0} n_1 - \dfrac{n_0}{\tau_0} \\
\quad \vdots \\
\dfrac{dn_i}{dt} = +n_e \chi^{\text{ion}}_{i-1\to i} n_{i-1} - n_e \chi^{\text{ion}}_{i\to i+1} n_i - n_{\text{gas}} \xi^{\text{ex}}_{i\to i-1} n_i + n_{\text{gas}} \xi^{\text{ex}}_{i+1\to i} n_{i+1} - \dfrac{n_i}{\tau_i}
\end{cases}
$$

Electron temperature

**ionization**

$$\chi^{\text{ion}}_{i\to i+1} = \left\langle \sigma^{\text{ion}}_{i\to i+1}(v_e) v_e \right\rangle$$

$$\chi^{\text{ion}}_{i\to i+1} = \int \sigma^{\text{ion}}_{i\to i+1} v_e \frac{2}{\sqrt{\pi}} \left( \frac{E_e^{1/2}}{T_e^{3/2}} e^{-E_e/T_e} \right) dE_e$$

$$= \frac{9.37\times 10^{-6}}{I_i T_e^{1/2}} \int_{I_i}^{\infty} \ln \frac{E_e}{I_i} e^{-E_e/T_e} \frac{dE_e}{T_e} \left[\text{cm}^3\text{s}^{-1}\right]$$

**Charge exchange**

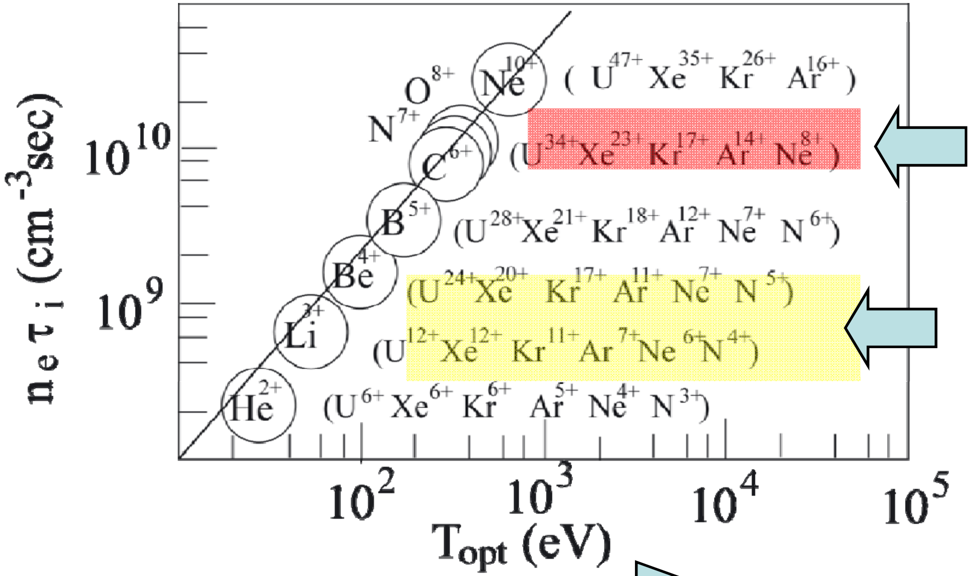
$$\xi^{\text{ex}}_{i\to i-1} = \left\langle \sigma^{\text{ex}}_{i\to i-1}(v_i) v_i \right\rangle$$

$$\xi^{\text{ex}}_{i\to i-1} = \int_0^{\infty} \sigma^{\text{ex}}_{i\to i-1} v_i \frac{2}{\sqrt{\pi}} \left( \frac{E_i^{1/2}}{T_i^{3/2}} e^{-E_i/T_i} \right) dE_i$$

$$= 3.15\times 10^{-6} i^{1.17} I_{\text{gas}}^{-2.76} \sqrt{\frac{T_i}{A_i}} \quad \left[\text{cm}^3\text{s}^{-1}\right]$$

**Slide from RIKEN Nakagawa's talk**

# ECR plasma condition




$U^{35+}$($10^{10}$cm$^{-3}$sec)

High Performance ECRIS
($10^{9}$ cm$^{-3}$sec)

Beam intensity

$$I_q = \frac{n_q\, q\, V}{\tau_c}$$

$n_q$ : ion density

$q$ : charge state

$V$ : plasma volume

$\tau_c$ : ion confinement time

| | |
|---|---|
| $n_e$ | *Larger* |
| $V$ | *Larger* |
| $\tau_c$ | *Shorter and longer* |
| $n_e\tau_c$ | *Higher ($10^{10}$(cm$^{-3}$ms)* |
| $n_0$ | *lower* |

**Slide from RIKEN Nakagawa's talk**

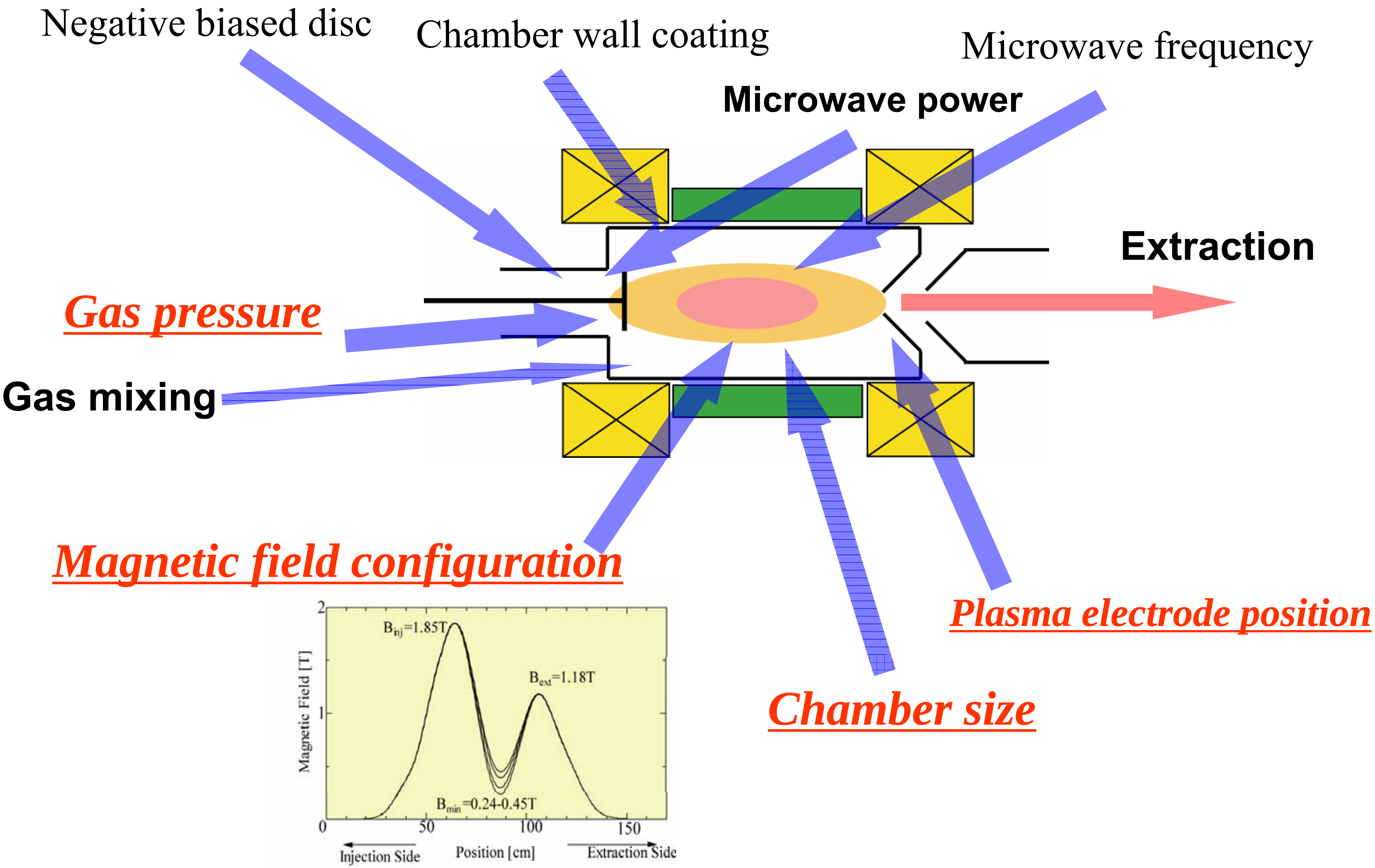
# Magic ECRIS

## Geller’s Words:

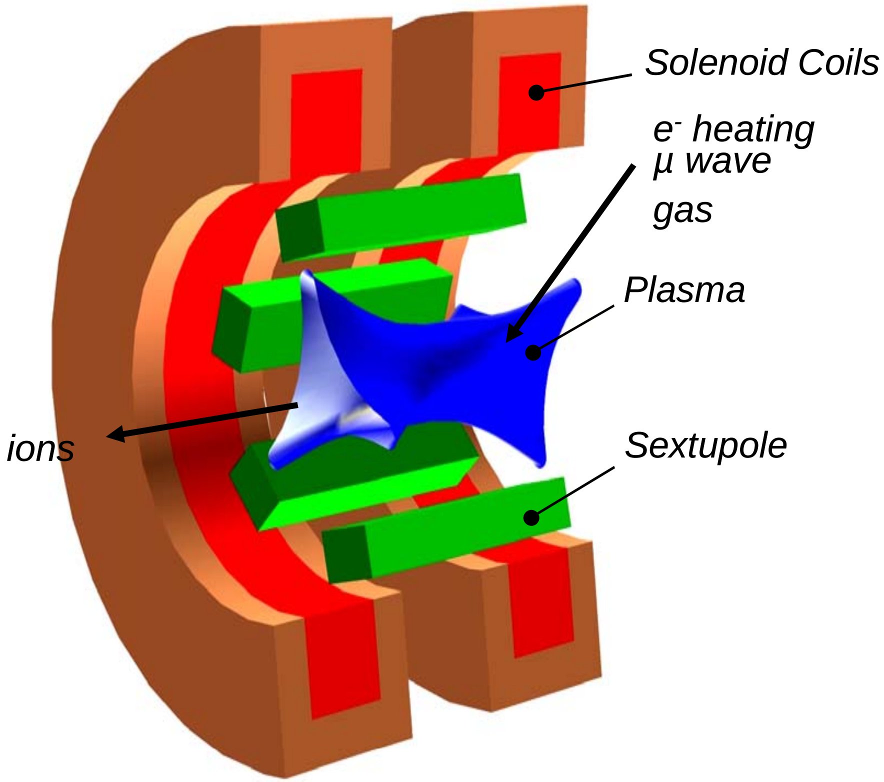
A joke by accelerator people in 80s-90s:

“EBIS experts at least understand why their source performs so poorly, whereas the poor ECRIS people do not even understand why the ECRIS performs so well”.

# Optimization of Intense Highly Charged Ion Beam Production at ECRIS



# Key parameters and scaling law




Minimum-B field Confinement

Graph from C.Lyneis and D. Leitner at LBNL

- **Magnetic field configuration:**

$B_{inj} \approx 4\ B_{ECR}$ $B_{ext} < B_{rad} \approx 2\ B_{ECR}$

$B_{min} \approx 0.8\ B_{rad}$

Semi-empirical Scaling law

- **Microwave frequency:**

$\omega_e = qB_{ecr}/m = \omega_{rf}$

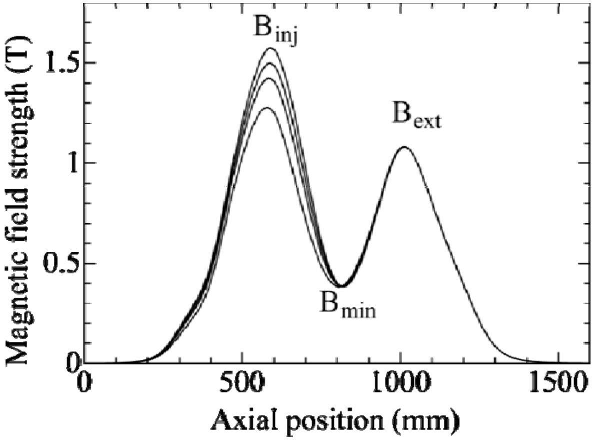
$I \propto \omega_{rf}^2\ M^{-1}\tau^{-1}$

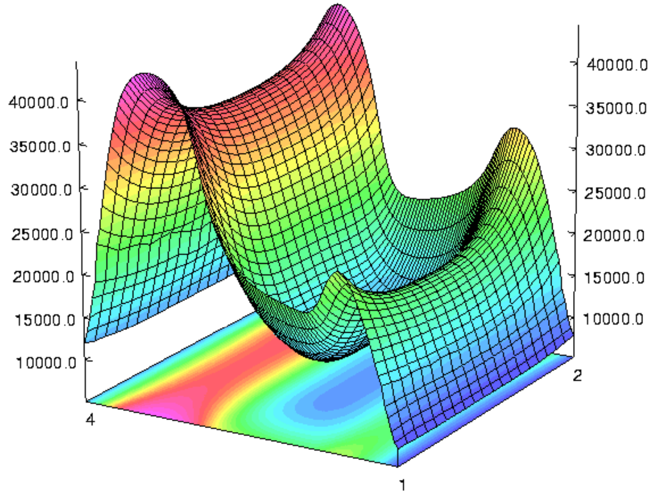
- Extraction voltage:

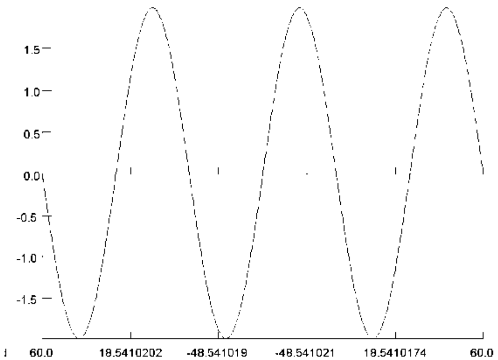
$I \propto U_{ext}^{3/2}$

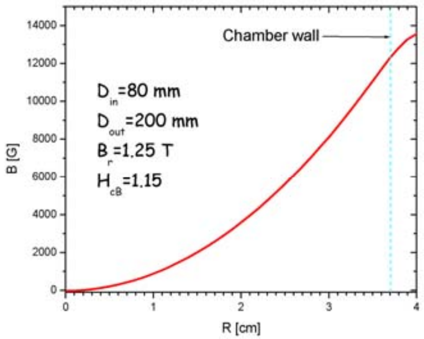
- Plasma chamber geometry (length, diameter) and wall material
- Extraction system (gap, voltage, plasma electrode position)
- Biased disc (voltage, position)

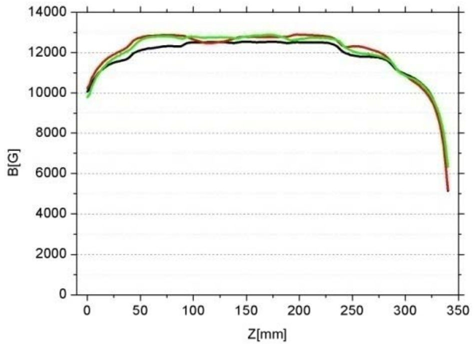
# Design of Magnetic Field Distribution for ECRIS

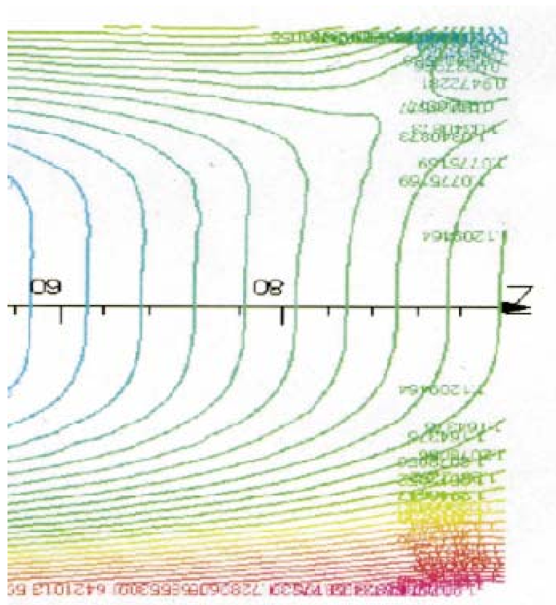






# Key Issues of Highly Charged ECRIS Design

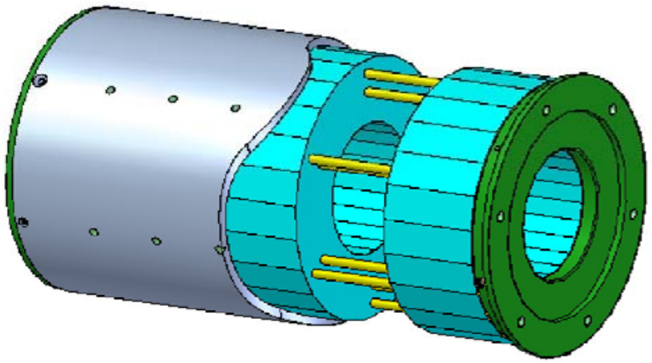
- **Be able to be operated at 14-18-28 GHz, 1.5-5 -10 kW RF power and 20-30 kV extraction voltage.**
- **Particular emphasis is put on optimum design and compromise among:**

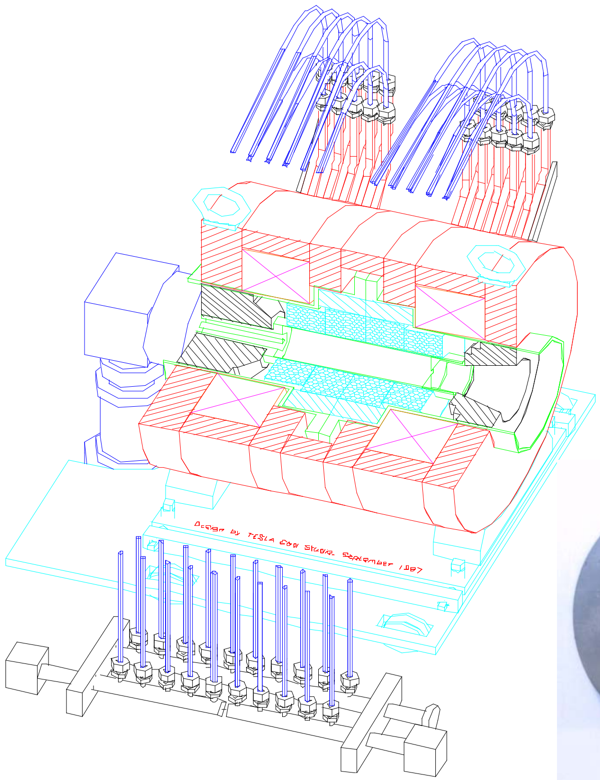
  **magnetic field distribution, plasma volume, RF power density in the chamber, big space for injection components and extraction, lower price, but high reliability and stability.**
- **Very good cooling to the chamber and other components inside chamber.**
- **Provide an extra source of cold electrons through aluminum chamber and biased disk.**
- **Minimize possible leakage and losses of the RF power.**
- **Maximum the pumping conductance at the extraction and injection side.**
- **Beam transport line be able to operate at maximum 10-20 mA total beam for multiply charged ions with a high transmission efficiency and high Q/m resolution.**

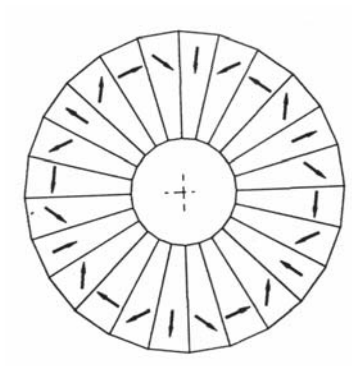
# Highly Charged ECR Ion Sources

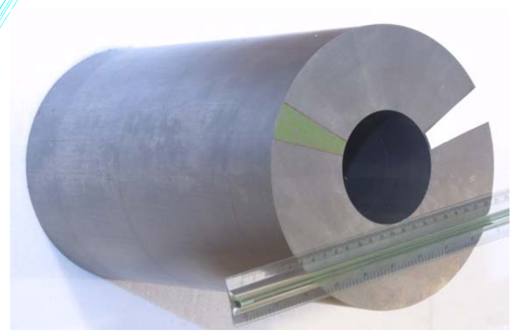
## In terms of method to produce the needed magnetic field configuration :

- **Standard ECRIS**
- **All permanent ECRIS**
- **Superconducting ECRIS**



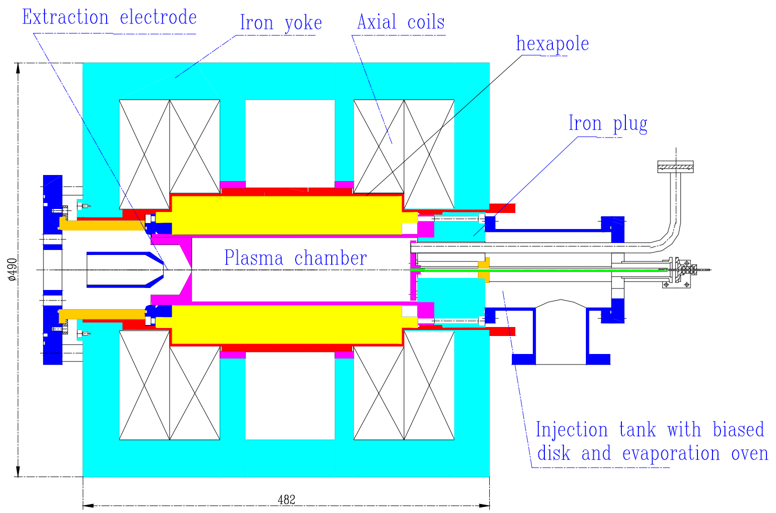


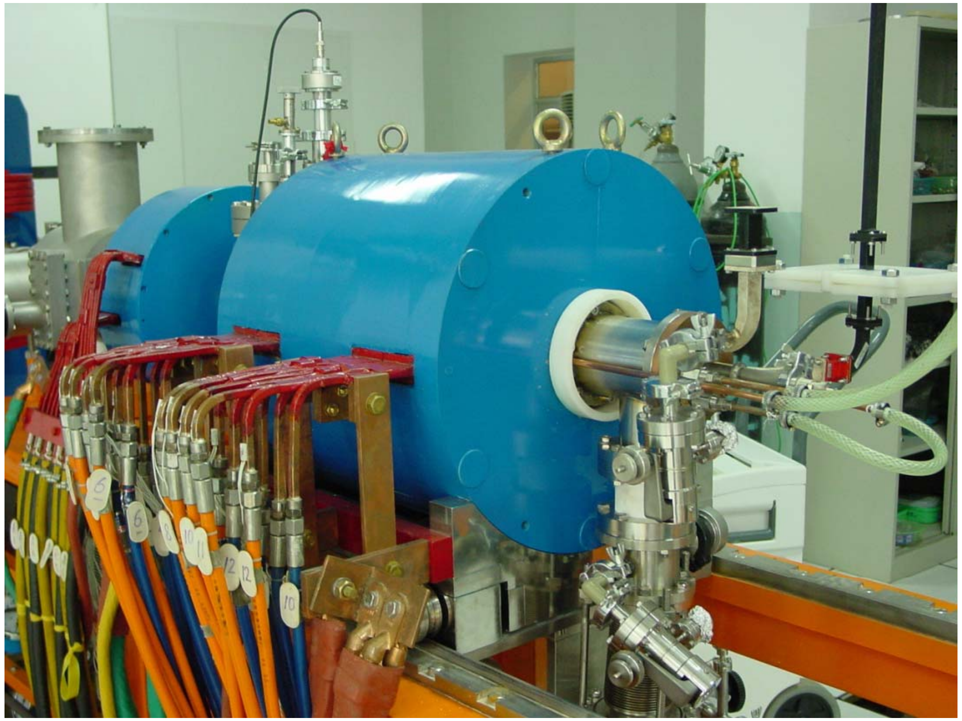




# IMP LECR3 at 14.5 GHz

**Magnetic field: 1.5-1.7T, 1.1T**
**RF : 14.5 GHz, 800-1000 W**
**Extraction: φ8-9mm, 20 -25kV**
**Slit: 10-15 mm**
**Faraday-cup: -150 V**



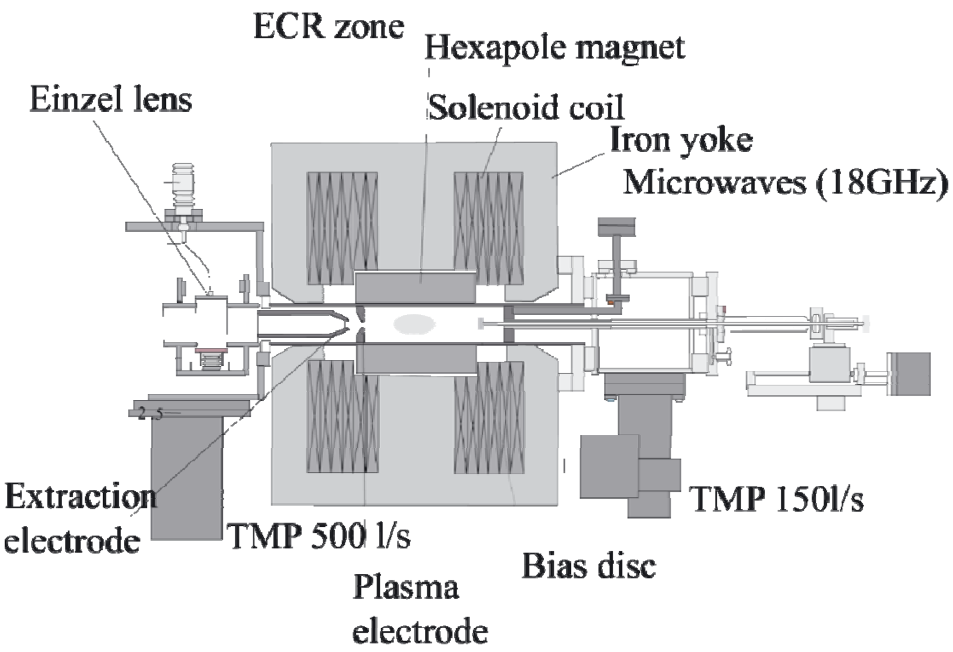



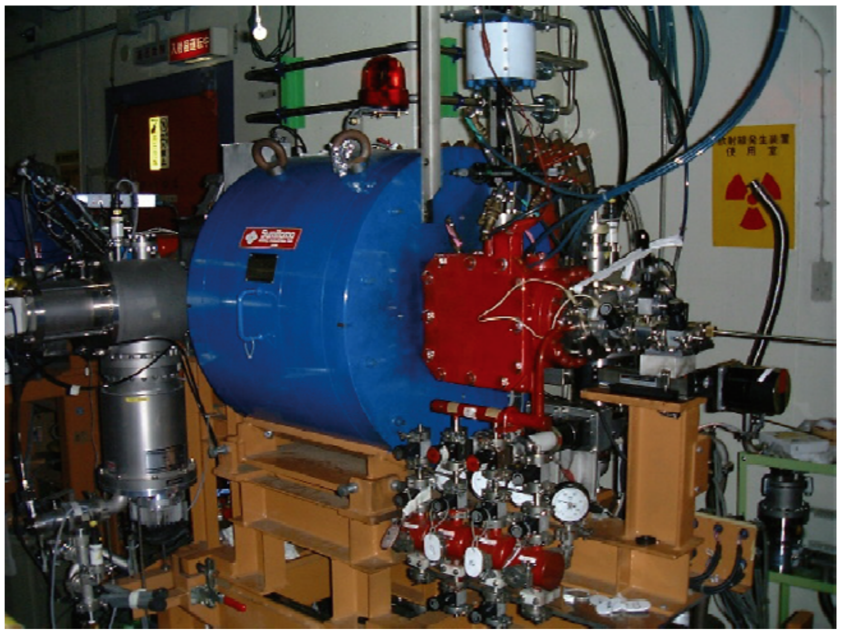
**$Ar^{11+}$ 240 eμA , $Ar^{14+}$ 30 eμA**

**$^{129}Xe^{20+}$ 160 eμA , $Xe^{26+}$ 95 eμA, $Xe^{30+}$ 7 eμA**

**$Ni^{12+}$ 75 eμA , $Ni^{13+}$ 57 eμA, $Ni^{15+}$ 31 eμA**

$Fe^{11+}$ 210 **eμA , $Fe^{12+}$ 175 eμA, $Fe^{13+}$ 141 eμA, $Fe^{16+}$ 25 eμA**



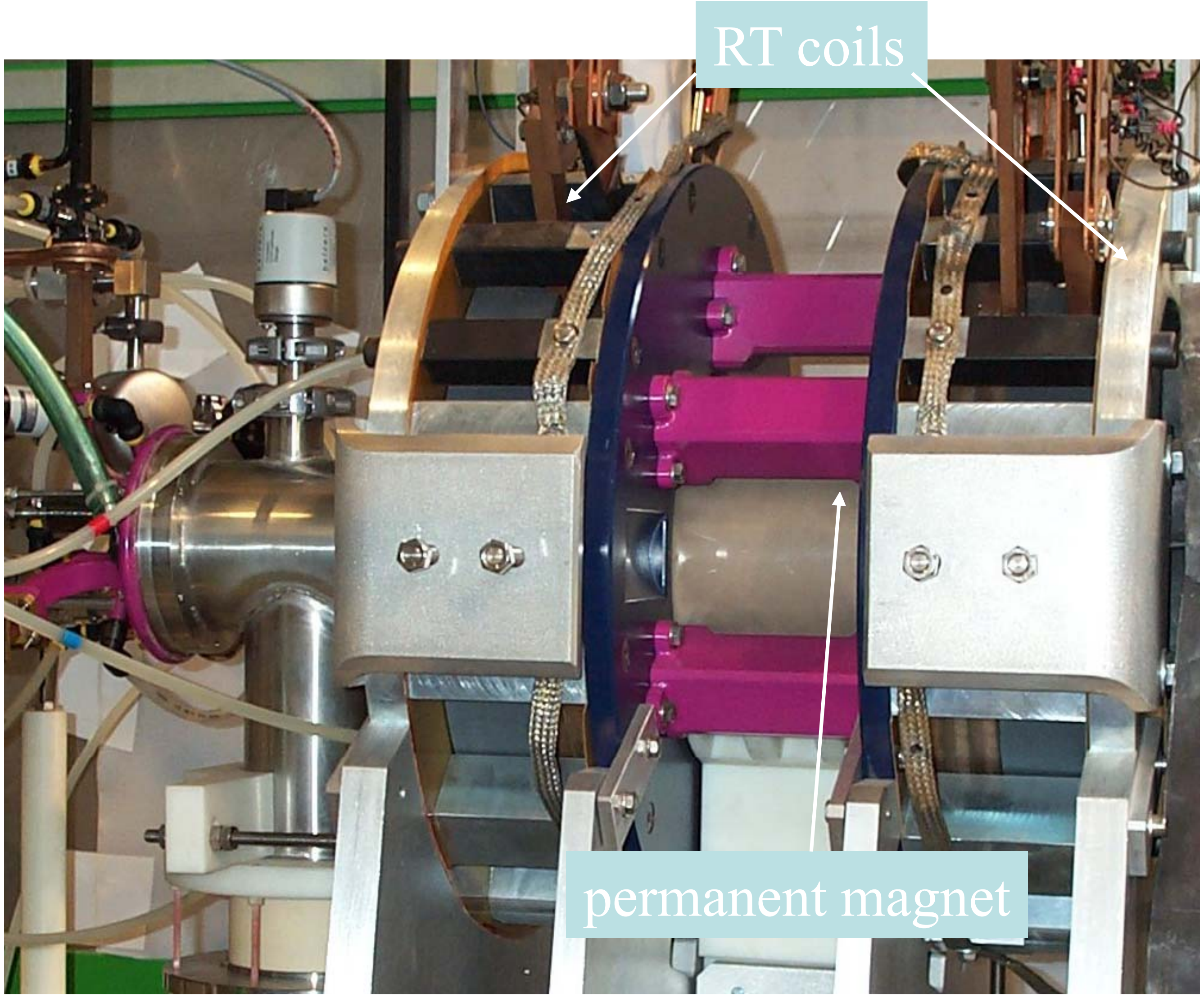



# RIKEN 18 GHz ECRIS

## Main Parameters of the RIKEN 18 GHz ECRIS

| | |
|---|---|
| **Mirror coil** | |
| Maximum current | 800 A |
| Maximum field on axis | 1.4 T |
| Mirror ratio | 3.0 |
| **Hexapole magnet** | |
| Inner diameter | 80 mm |
| Outer diameter | 170 mm |
| Length | 200 mm |
| Material | Nd-Fe-B |
| Field strength on surface | 1.4 T |
| **Micro wave** | |
| Frequency | 18 GHz |
| Maximum power | 1.5 kW |
| **Plasma chamber** | |
| Inner diameter | 75 mm |
| Length | 270 mm |
| **Vacuum** | |
| Turbo-molecular pumps | 150 and 500 l/s |
| **Extraction** | |
| Maximum voltage | 20 kV |
| Hole diameter Orifice | 10 mm |
| Electrode | 13 mm |

# Grenoble ECRIS: GTS



# Permanent magnet ECR Ion sources

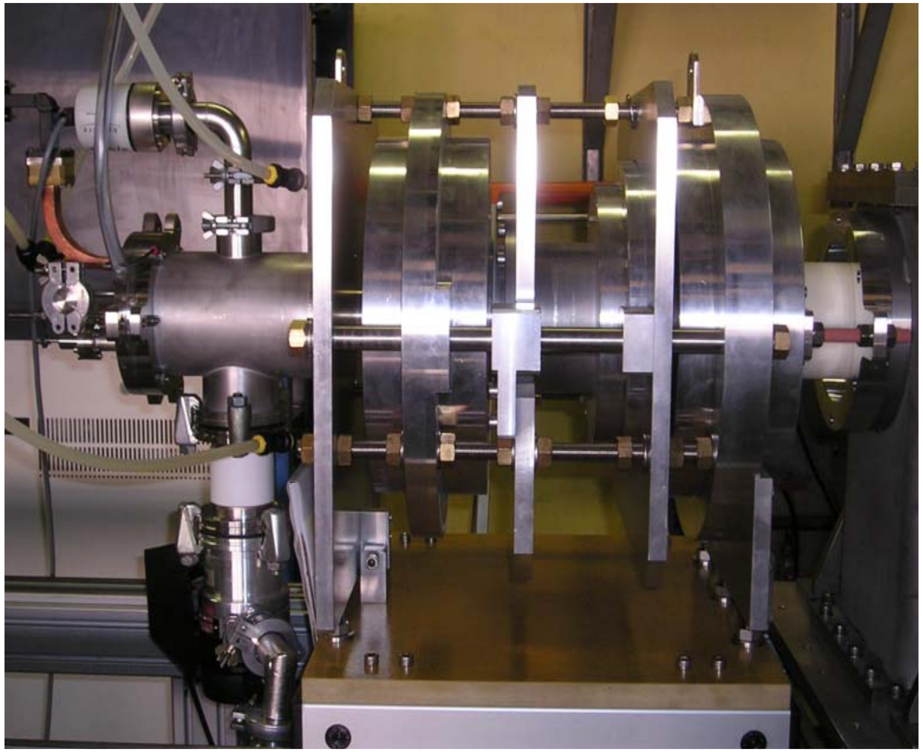
Totally built with permanent magnets (mirror + cusp fields)

These sources can reach performances of earlier « hybrid sources ». They are ideally suited to operation on HV platforms (few electrical power required)

Highest magnetic field ~ 1 tesla
⇒Well suited to 10 to 14 GHz operation

Size of the plasma chamber:
•Radius from 1.5 to 3 cm (the larger, the better for confinement)
•Length ~ 10 to 20 cm

The Nanogan series is well known.
New development: for the PISI project.

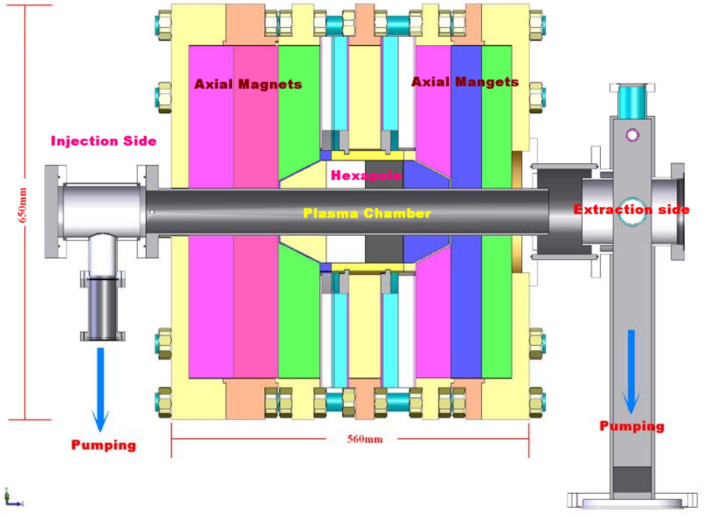


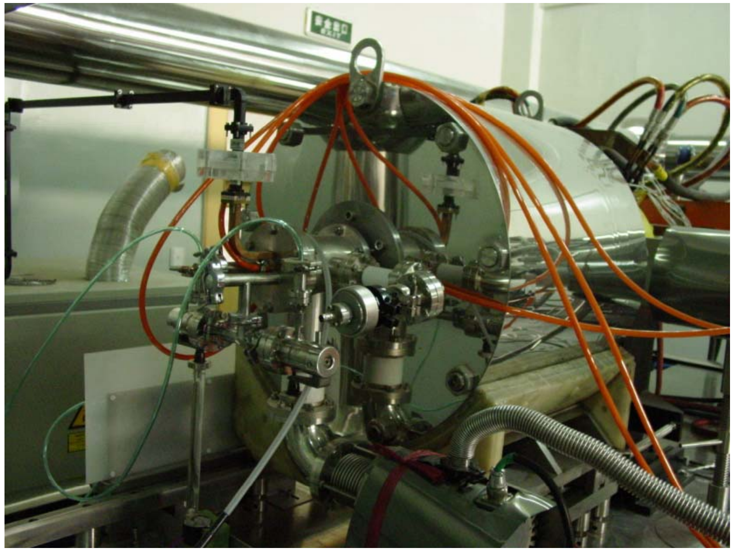
The PISI source built by CEA Grenoble (operating with a TWT from 12.5 to 14.5 GHz)

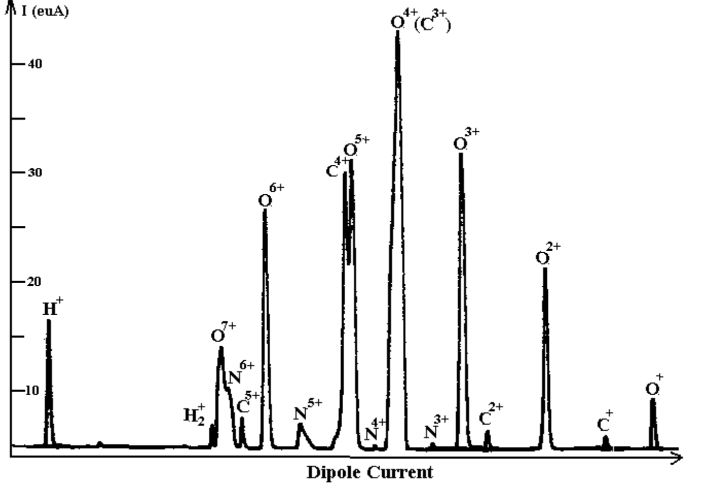
**$B_{inj}$ : 2 T, $B_{min}$ : 0.38 T**
**$B_{ext}$ : 0.93 T, $B_{rad}$ : 1 T**

# IMP LAPECR2

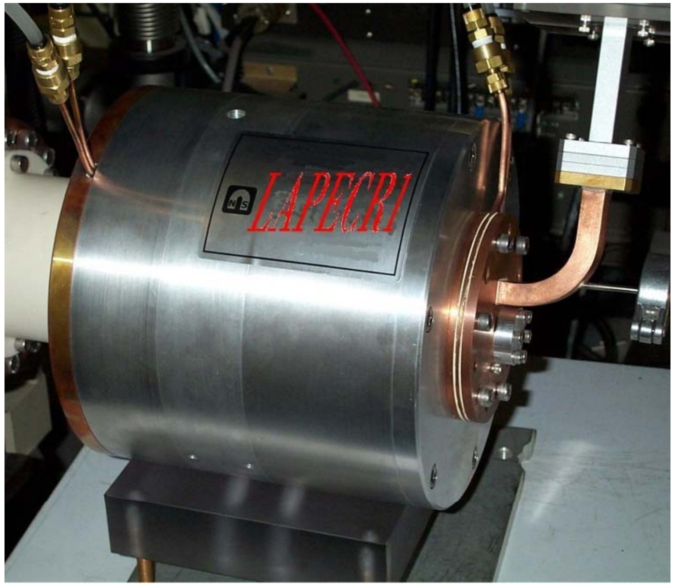
**Geller Prize**

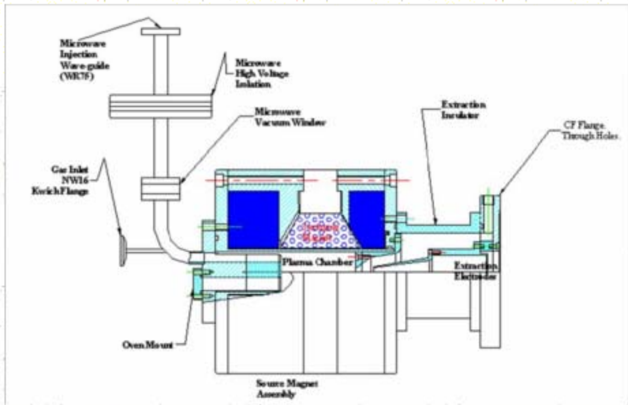




# IMP LAPECR1




Sectional plot of LAPECR1 source

| | |
|---|---|
| **Binj** | 0.62T(1.0T) |
| **Bext** | 0.56T |
| **Hexapole pole surface** | 1.1T |
| **Plasma chamber ID** | 45mm |
| ***f*** | 14.5GHz |
| **RF power** | 1kW |
| **Dimension** | $\varphi$102mm×296mm |
| **Weight** | ~25kg |
| **Permanent material** | N45M NdFeB |
| **Lmirror** | 74mm |
| **Lecr** | 55mm |
| **HV** | 30~50kV |

- **Built for industry application.**
- **Built for a US company and IMP**

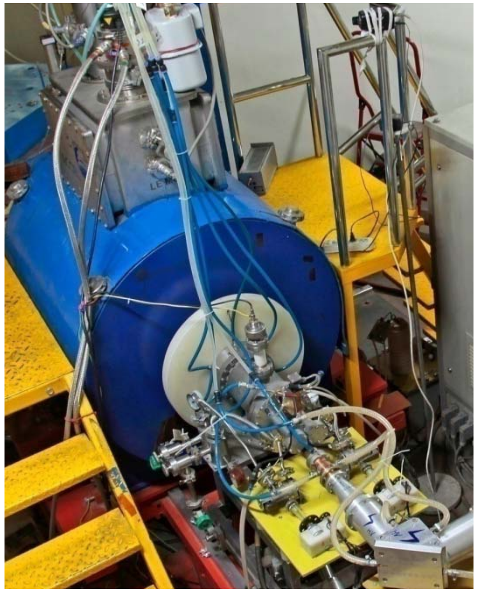
mAs,  He+, He2+, B+, C+, C2+, O+, O2+, N+, N2+, Ar+…

# IMP ECRIS Evolution from Normal Conducting to Superconducting Magnet

Xe Beam Current from IMP ECRIS

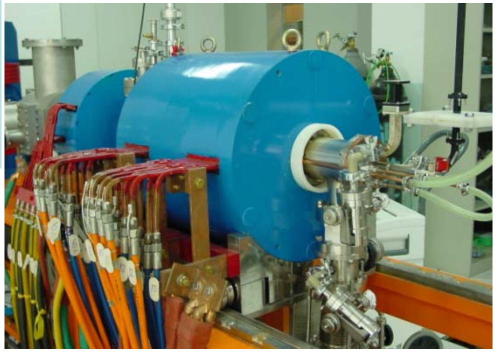
| Ions | LECR1 10GHz eμA | LECR3 14.5GHz eμA | SECRAL 18-24GHz eμA |
|---|---|---|---|
| $Xe^{20+}$ | 20 | 160 | 505 |
| $Xe^{27+}$ | * | 50 | 455 |
| $Xe^{30+}$ | * | 7 | 152 |
| $Xe^{35+}$ | * | * | 45 |
| $Xe^{42+}$ | * | * | 3 |

Superconducting

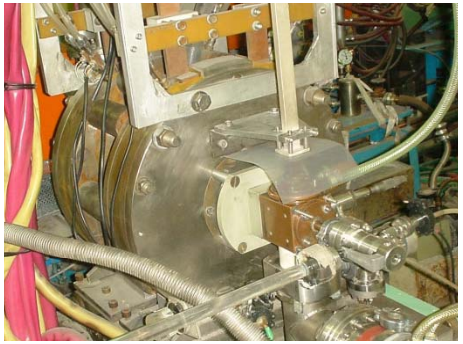


SECRAL(2005), 3.7T, 5-7 kW, 18-24GHz

Normal Conducting

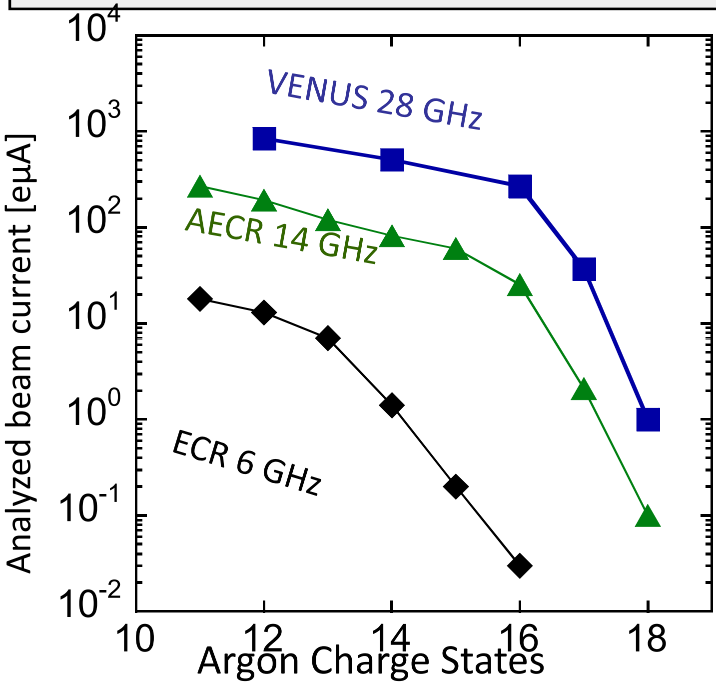


LECR3(1999), 1.5T, 1.5 kW, 14.5GHz



LECR1(1991), 0.8T, 0.5 kW, 10GHz

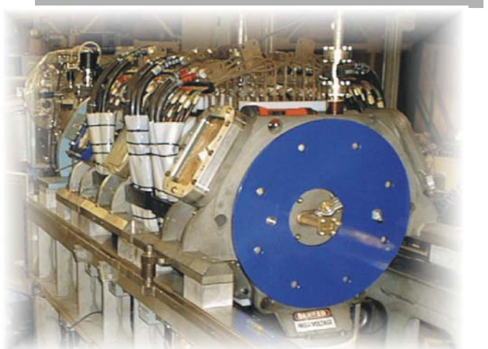
# LBNL ECRIS Evolution from Normal Conducting to Superconducting Magnet



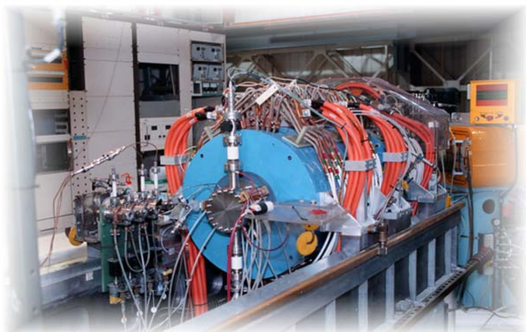

Normal conducting

Super conducting

**ECR (1983)**
**0.4 T, 0.6 kW, 6.4 GHz**



**AECR-U (1996)**
**1.7 T, 2.6 kW, 10 + 14 GHz**

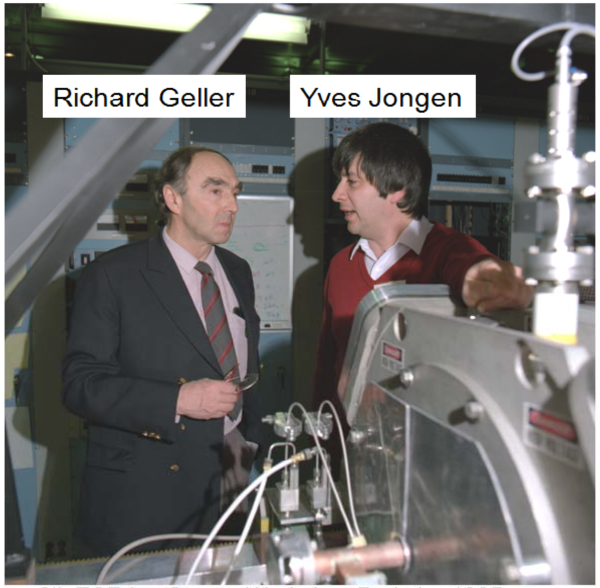


**VENUS (2001)**
**4.0 T, 14 kW, 18 + 28 GHz**

**Slide from C.Lynies and D.Leitner  talk at ICIS09**

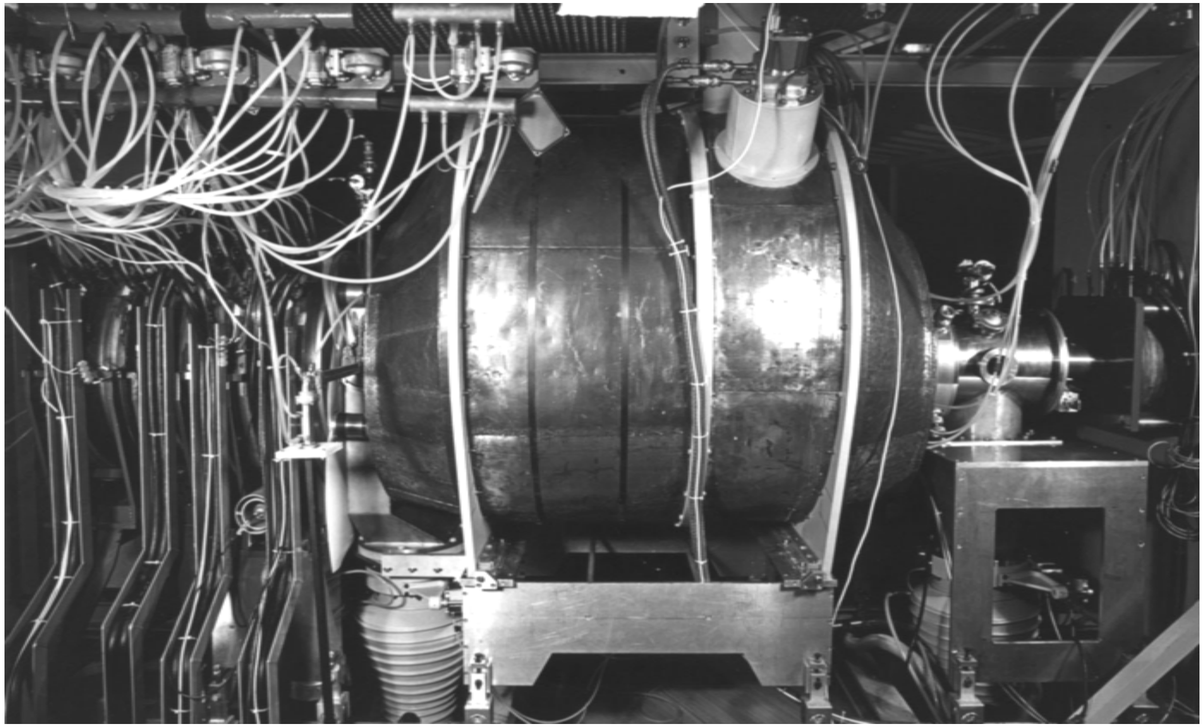
# First successful SC ECR ion source

ECR Ion Source Pioneers




6th ECR Ion Source Workshop Berkeley 1985

ECREVIS circa 1983



Yves Jongen, Louvain-la Neuve, Belgium

**Slide from LBNL C.Lyneis talk at ICIS09**

# SERSE in INFN-LNS Catania

Built by collaboration between CEA-Grenoble and INFN-LNS

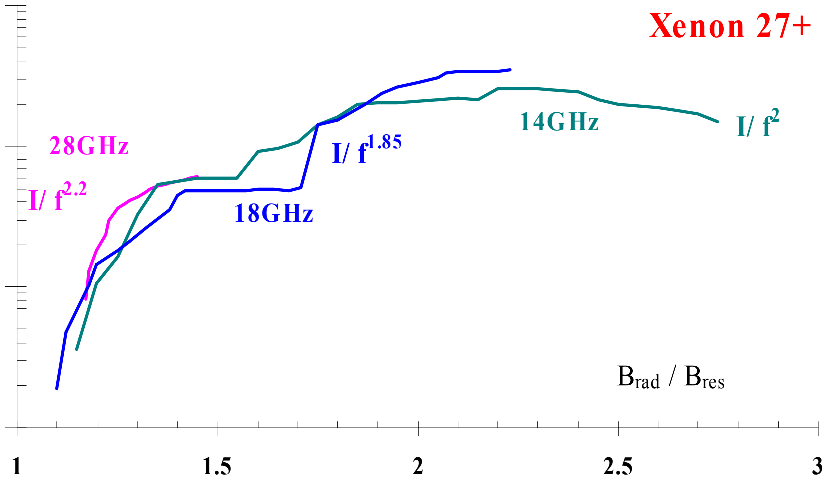
G. Ciavola, S. Gammino,IFN-LNS,Catania

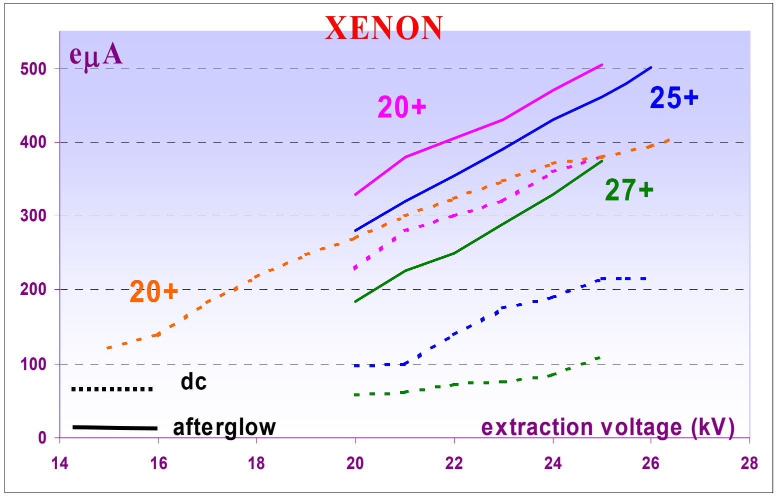
**Superconducting ECR designed for 18 GHz**

**Tested at 28 GHz**

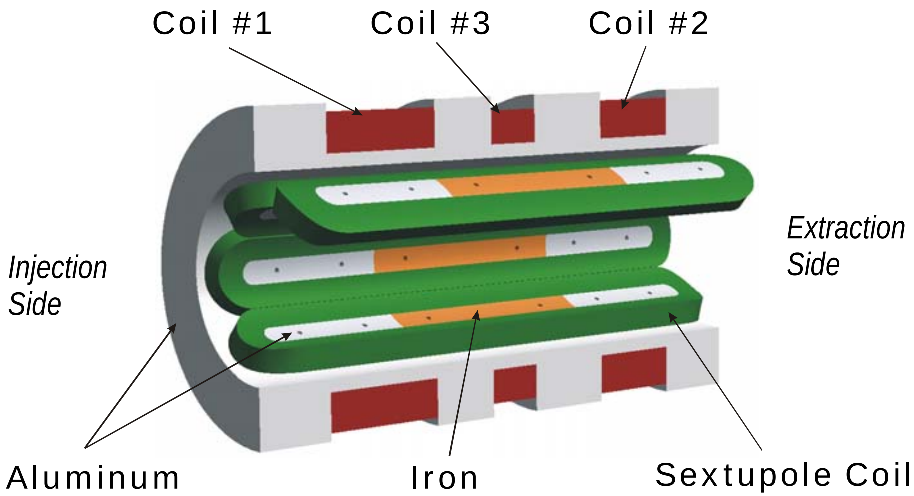
- **I ~ $f^2$ , from 18 GHz to 28 GHz**
- **P≥ 3 kW**
- **Optimum $B_{rad}$ at 28 GHz > 1.45 T**

**First test at 28GHz in 2000 and demonstrated frequency scaling up to 28 GHz**



# LBNL VENUS 28 GHz — The first 3rd generation ECRIS




Sextupole-in-Solenoid
Conventional coil structure

**Achieved magnetic fields**

**$B_{inj} \leq 4$ T, $B_{ext} \leq 3$ T, $B_{rad} \leq 2.2$ T**

**18-28GHz, >9 kW rf power**

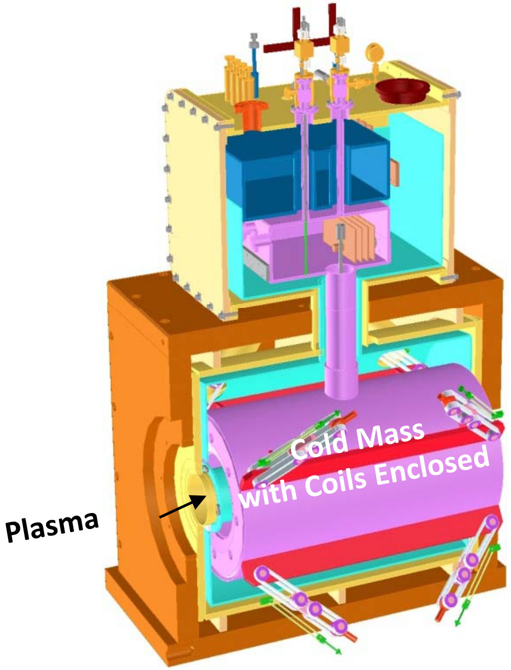
**Courtesy of C.Lyneis and D.Leitnerat LBNL**

- **1997 : Magnet prototype**
- **2002: The first test at 18GHz**
- **2006-2007: The best results achieved at 28GHz**

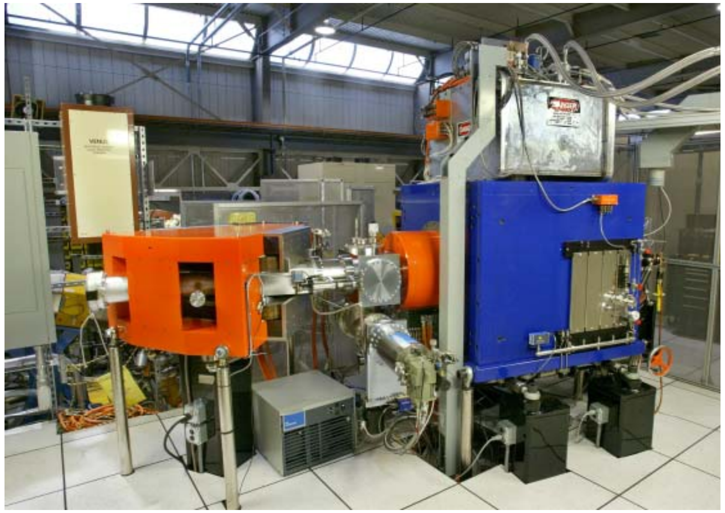
- **10 years from construction to the best results.**
- **Sextupole lead was burned in Jan.2008 and has taken more than two years to repair! It will be online test soon.**

**VENUS has addressed many of technologies and challenges firstly Now being incorporated into other 3rd Generation Sources**

Advanced cryostat with cryocoolers

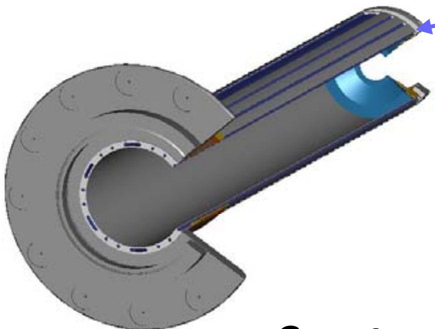



Beam transport with high transmission dipole magnet

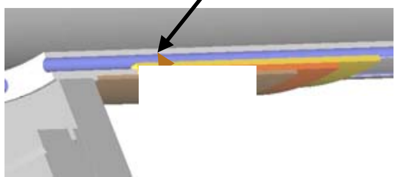


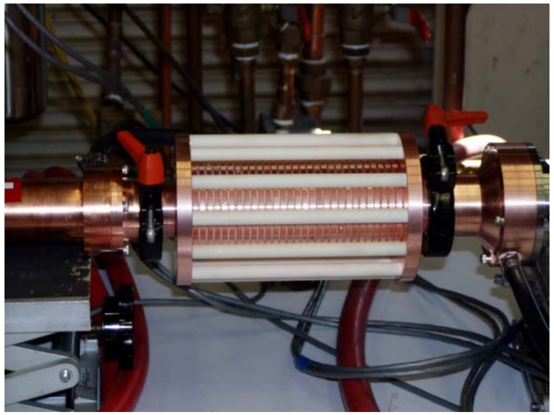
Aluminum plasma chamber for high power operation with incorporated tantalum x-ray shield

Water cooling for high power



Ta X-ray shield





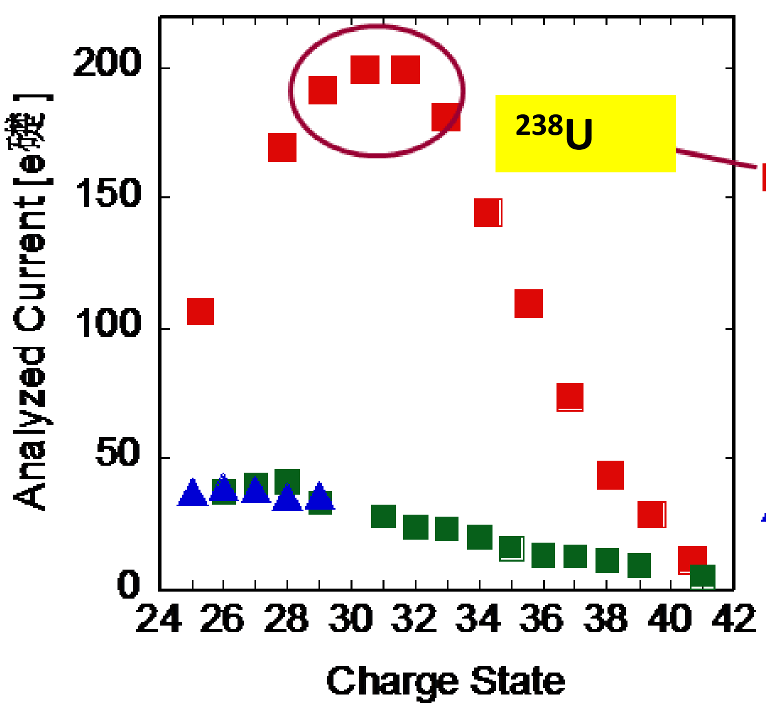
28 GHz ceramic HV break

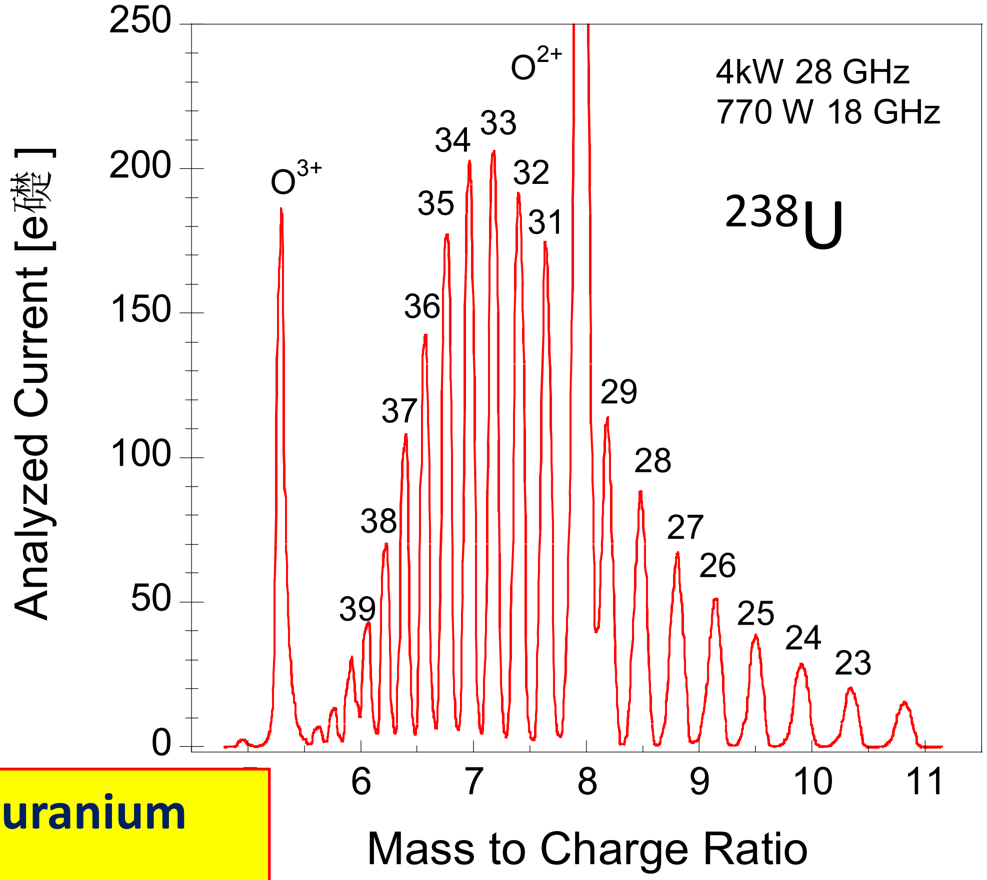


**Courtesy of C.Lyneis and D.Letner at LBNL**

# LBNL VENUS: Achieved the best uranium performance

U$^{34+}$ 200 eμA, U$^{47+}$ 5 eμA



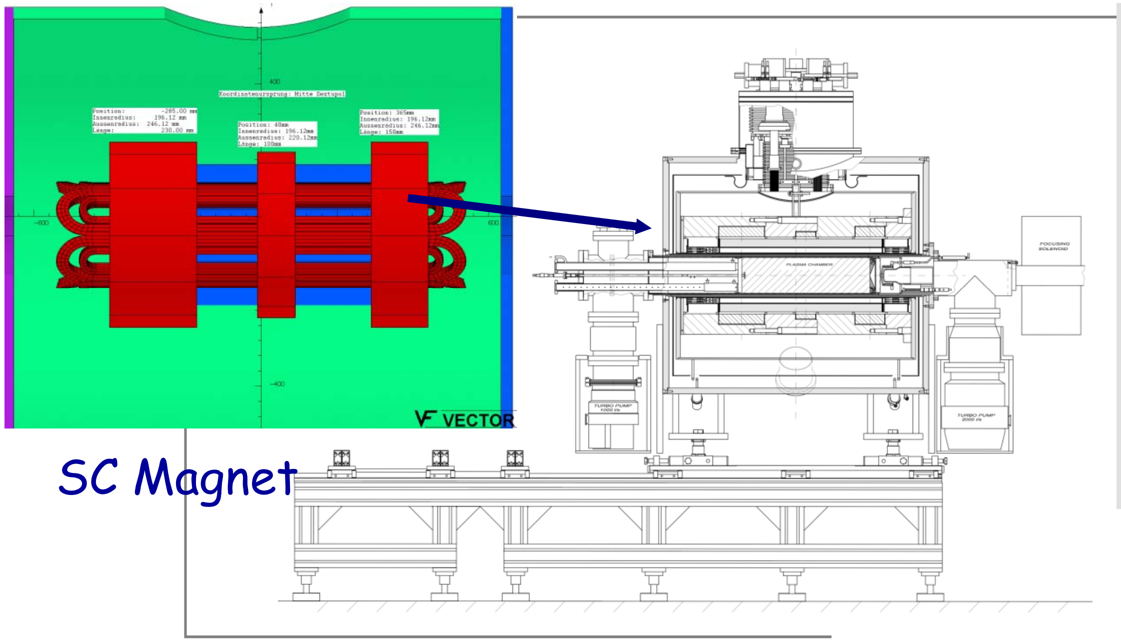




**Production of intense highly charged uranium beams more challenging!**

**C.Lynies and D.Leitner at LBNL, talk at ICIS09**

# MS-ECRIS for FAIR

***— The third Generation ECRIS collaborated by 9 EU institutions***



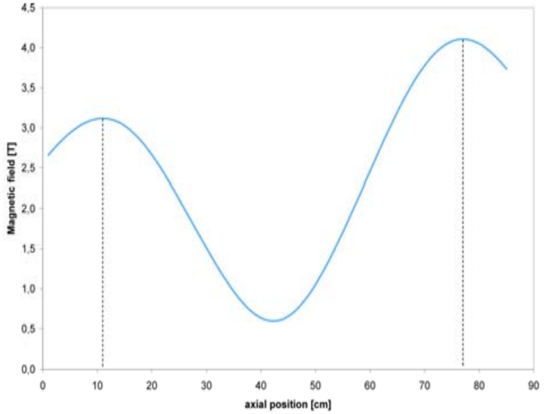

SC Magnet

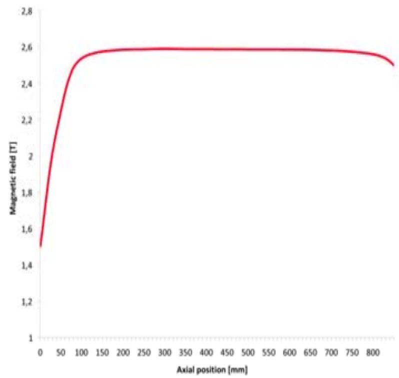
Fabrication of magnet started in 2007

- **Designed specifications**

  **28GHz, $B_{inj}$ 4.5 T, $B_{ext}$ 3.2 T, $B_{rad}$2.7 T**

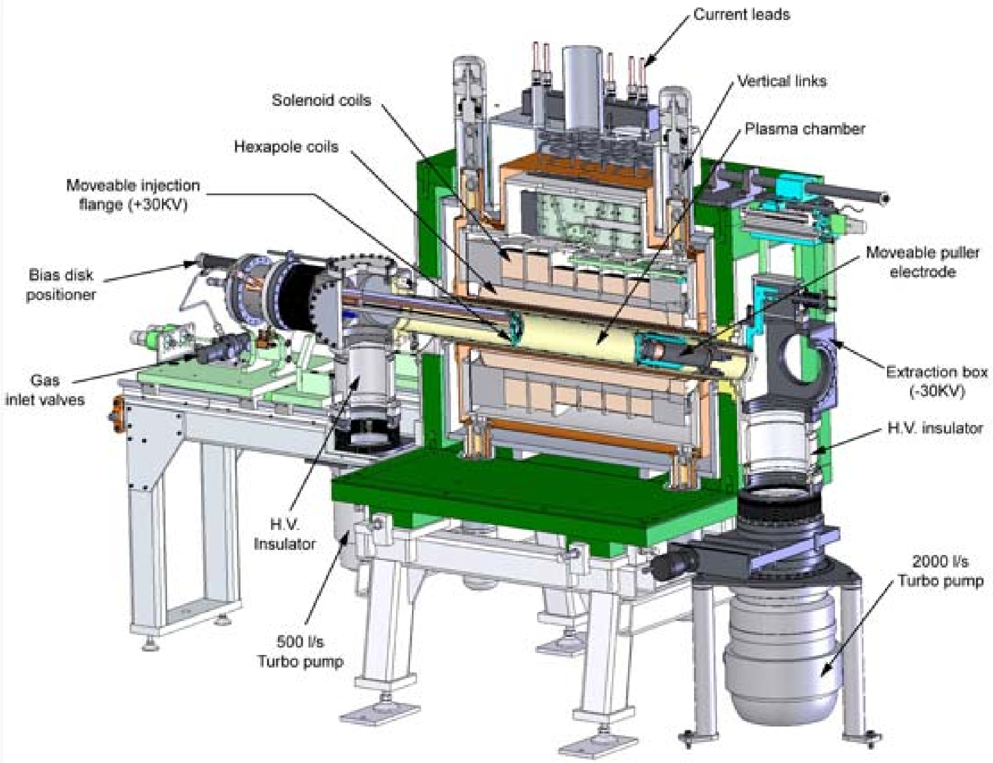
- **All single coils reached the specified demands .**
- **But the whole magnet system quenched randomly with different ramping strategies (50% maximum)**
- **Restarted mechanical modification recently**

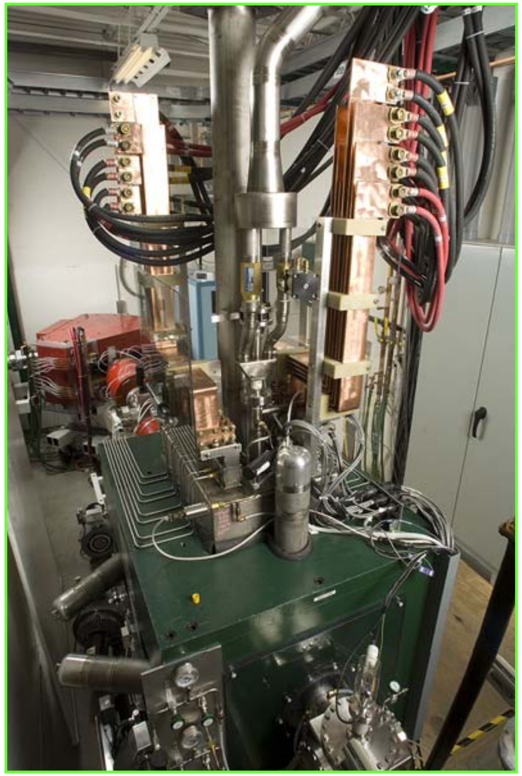



Courtesy G. Ciavola, S. Gammino,IFN-LNS,Catania

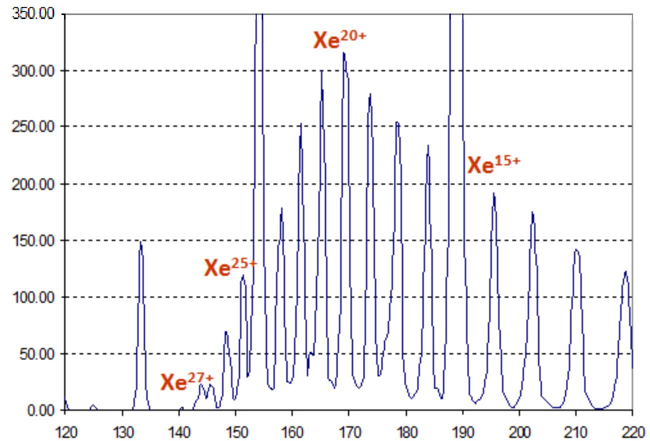
# SUSI ECRIS at NSCL/MSU



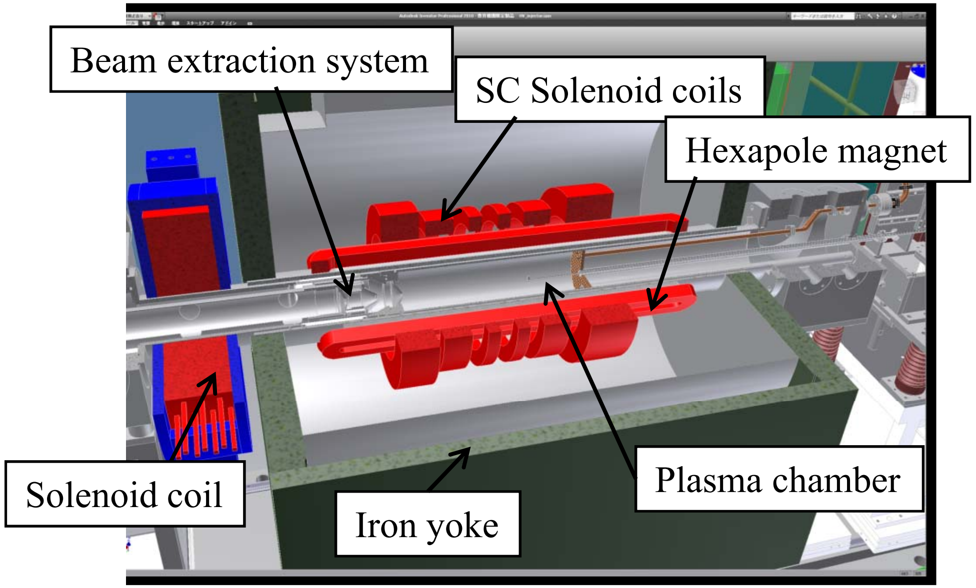
- **Achieved magnet field** (lower field):
  **18- 24GHz, $B_{inj}$ 2.5 T, $B_{ext}$ 1.4 T, $B_{rad}$ 1.5T**
- **Unique feature : Flexible axial field distribution with 6 solenoid coils**
- **chamber volume adjustable from 3.1 to 3.9 l**
- **Started operation for accelerator at 18GHz**

Courtesy of G.Machicoane at MSU

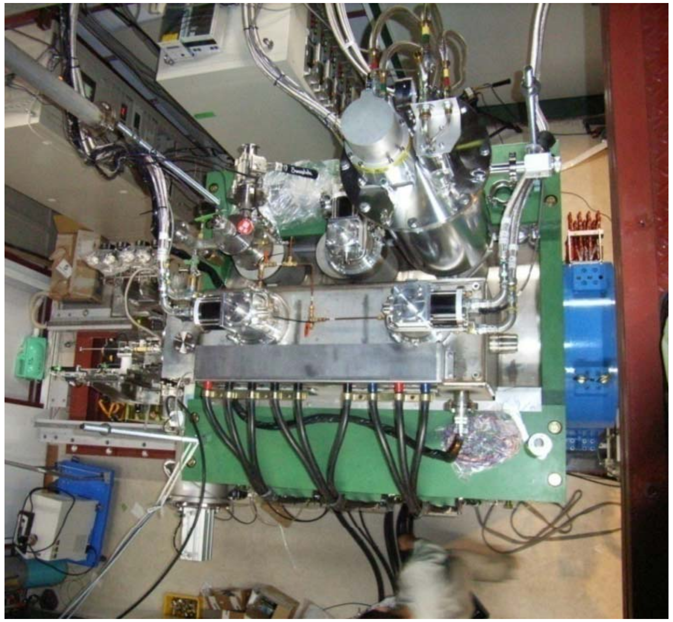


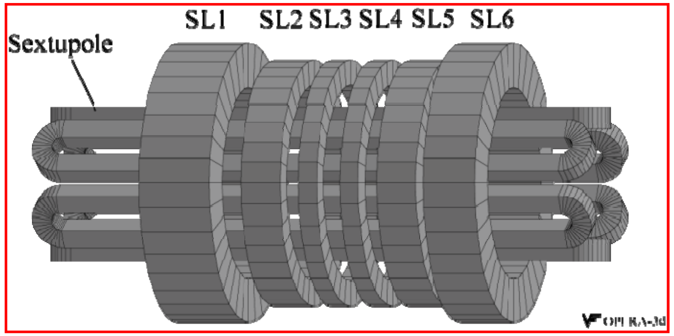

**$^{129}Xe$ : optimized on $Xe^{20+}$ :335euA**
**1.7kW 18GHz, 300W 14.5GHz**

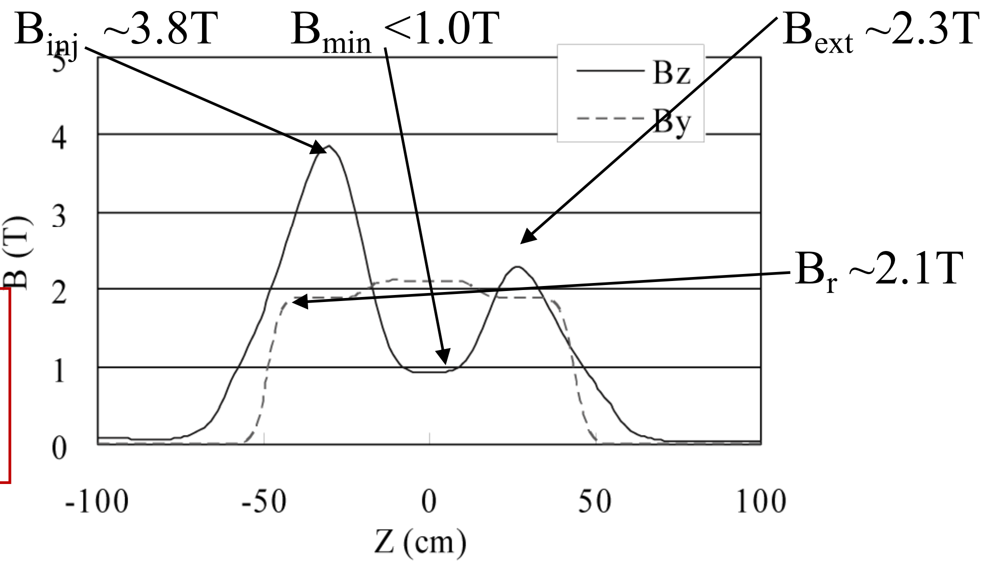
# RIKEN 28GHz SC-ECRIS —The fastest construction 3rd Generation ECR




**2 years from construction to the first beam.**





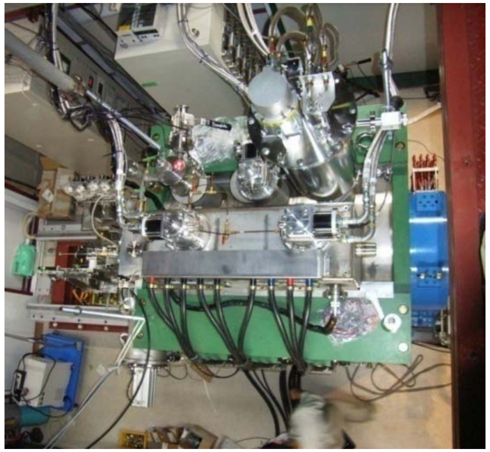

- ■Started operation at 18GHz
- ■28GHz test and operation planed in 2010
- ■6 solenoid coils for flexible field

**Courtesy of T.Nakagawa at RIKEN**

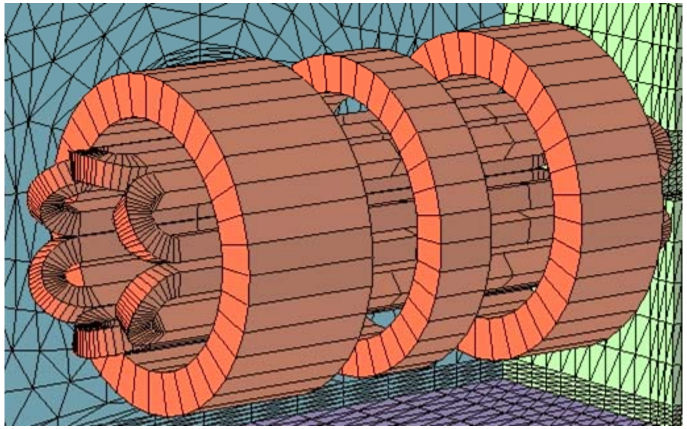
# All existing or under-construction SC-ECRIS utilize conventional magnet structure

ECREVIS, SERSE,VENUS, SUSI, MS-ECRIS, RIKEN SC-ECR....

**Conventional Structure:**
**Sextupole-inside-Solenoid**



RIKEN SC-ECRIS (18-28 GHz)



VENUS in Berkeley (18-28 GHz)

**Advantage:**

- Higher sextuple field;
- Larger plasma chamber;
- Higher rf power.

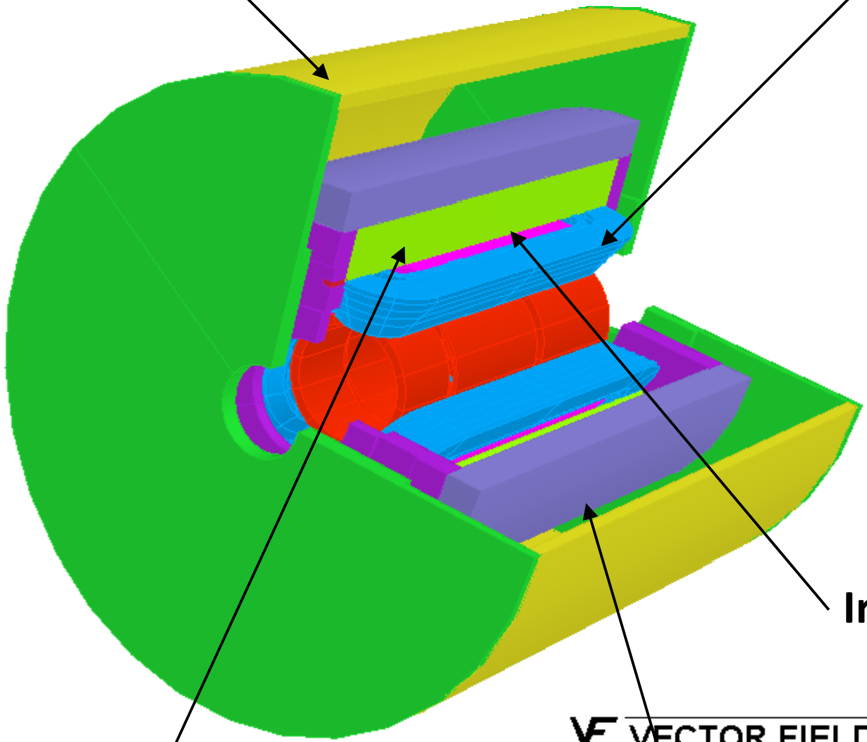
**Disadvantage:**

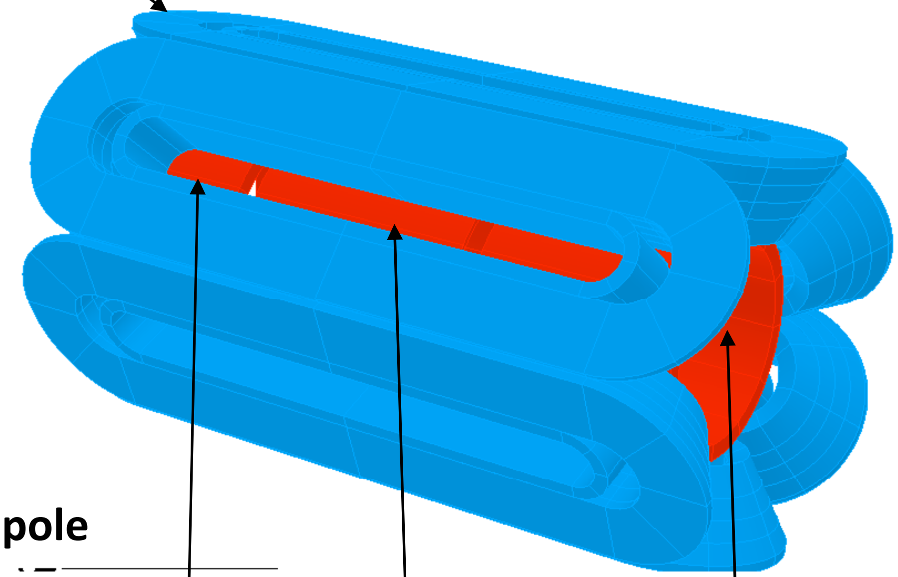
- Very strong interaction forces;
- Much longer sextupole;
- Bigger source body;
- Hard to build

**That is why SERSE and VENUS took so many years to build and MS-ECRIS magnet failed .**

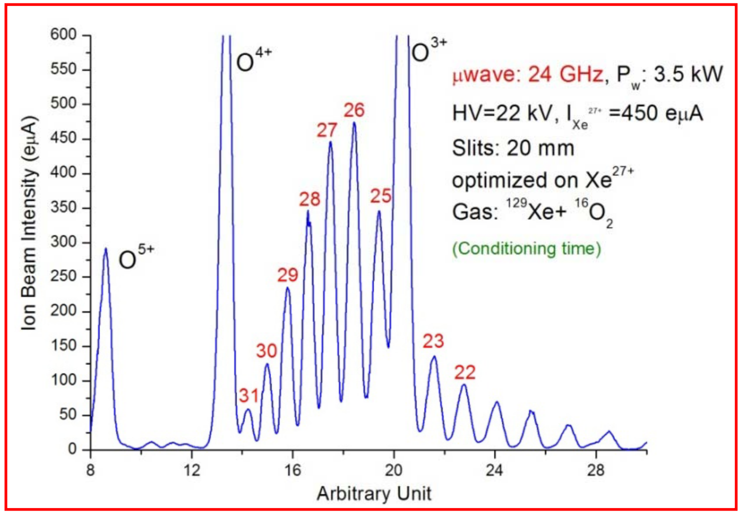
# IMP SECRAL Utilizes a New Magnet Concept and an Innovative Superconducting Coil Configuration

Completely New Design!
Reverse conventional structu
Solenoids-inside-sextupole

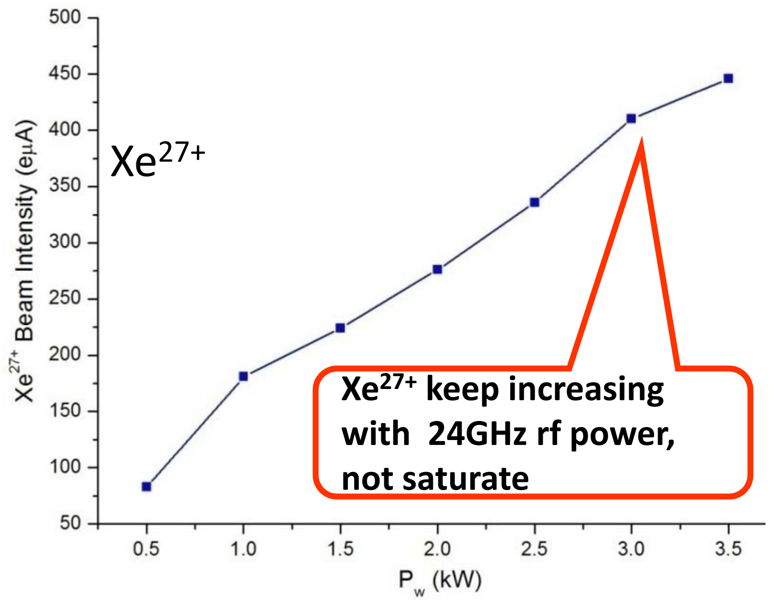


# SECRAL 24GHz/7kW — the first 3rd generation ECRIS being operated to deliver thousands-hours-beam for accelerator

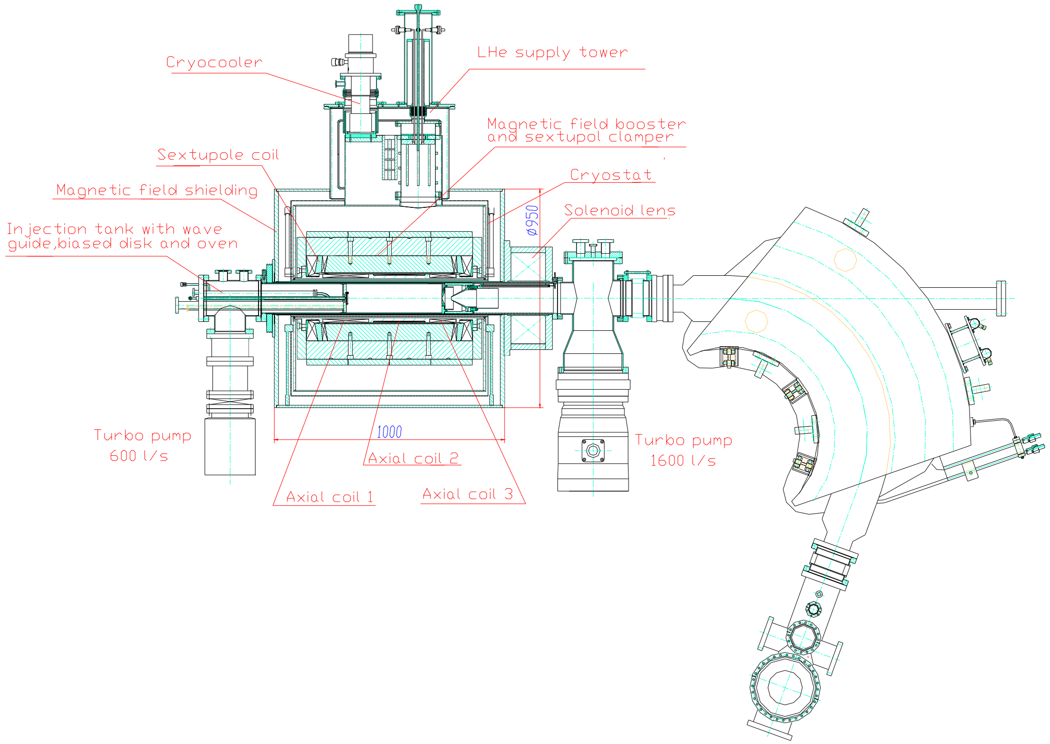


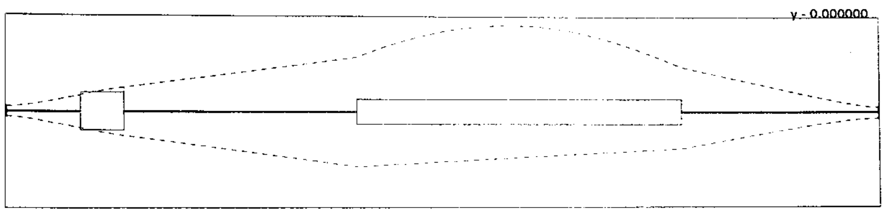

- **Achieved magnet field:**
  **18- 24GHz, $B_{inj}$ 3.7 T, $B_{ext}$ 2.2 T, $B_{rad}$ 2 T**
- **2002, fabrication**
- **2005, the first beam at 18 GHz**
- **2009, the first test at 24 GHz**
- **SECRAL beam commissioning at 24GHz is just at initial stage. Better results will be coming up.**



# SECRAL Beam Transport Line

**Designed for 15-20 mA total beam transmission at 20-30 kV extraction**


**Analyzing magnet:**
**Bending angle: 110 degree**
**Bending radius: 600 mm**
**Pole gap: 120 mm**

# The best results from SECRAL and VENUS

- VENUS and SECRAL have led the way in developing implementations of 3rd Gen ECRIS, and have demonstrated feasibility and the nice source performance of the 3rd Gen ECRIS , and have provided new opportunities for related research and heavy ion accelerators.

- Now almost all record beam intensities are produced by SECRAL and VENUS

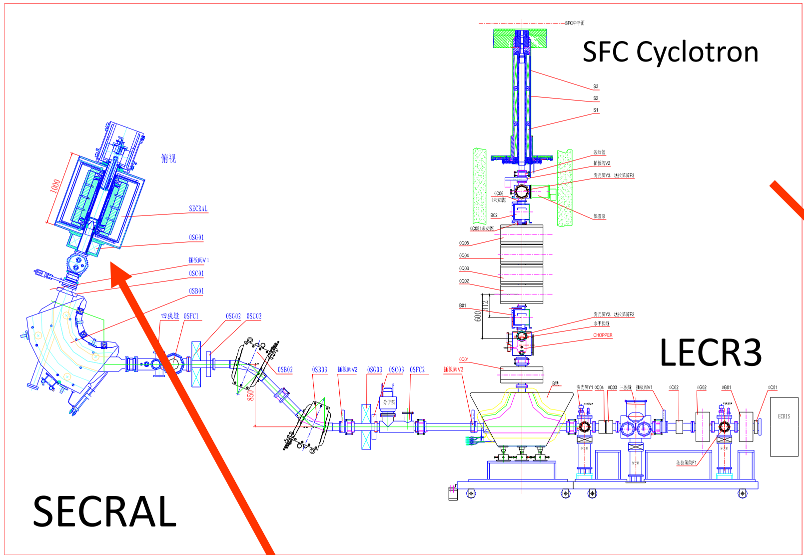
- SECRAL performances at lower frequency and lower power could be comparable or even better than those of higher frequency and higher power ECR sources.

SECRAL with an innovative magnet structure and unique features may open a new way for developing high performance and compact SC ECR ion source.

| | Q | SECRAL 18 GHz <3.2 kW μA | SECRAL 24GHz 3-4 kW μA | VENUS 28 GHz 5-9kW μA |
|---|---|---|---|---|
| $^{16}O$ | 6+ | 2300 | | 2860 |
| | 7+ | 810 | | 850 |
| $^{40}Ar$ | 12+ | 510 | 650 | 860 |
| | 14+ | 270 | 440 | 514 |
| | 16+ | 73 | 149 | 270 |
| | 17+ | 8.5 | 14 | 36 |
| $^{129}Xe$ | 20+ | 505 | | 320 |
| | 27+ | 306 | 455 | 270 |
| | 30+ | 101 | 152 | 116 |
| | 31+ | 68 | 85 | 67 |
| | 34+ | 21 | 60 | 40 |
| | 35+ | 16 | 45 | 28 |
| | 38 | | 17 | 7 |
| | 42+ | 1.5 | 3 | 0.5 |
| | 43+ | 1 | | |
| $^{209}Bi$ | 28+ | 214 | | 240 |
| | 30+ | 191 | | 225 |
| | 41+ | 22 | | 15 |
| | 44+ | 15 | | 7.7 |
| | 48+ | 4.2 | | 1.4 |
| | 50+ | 1.5 | | 0.5 |

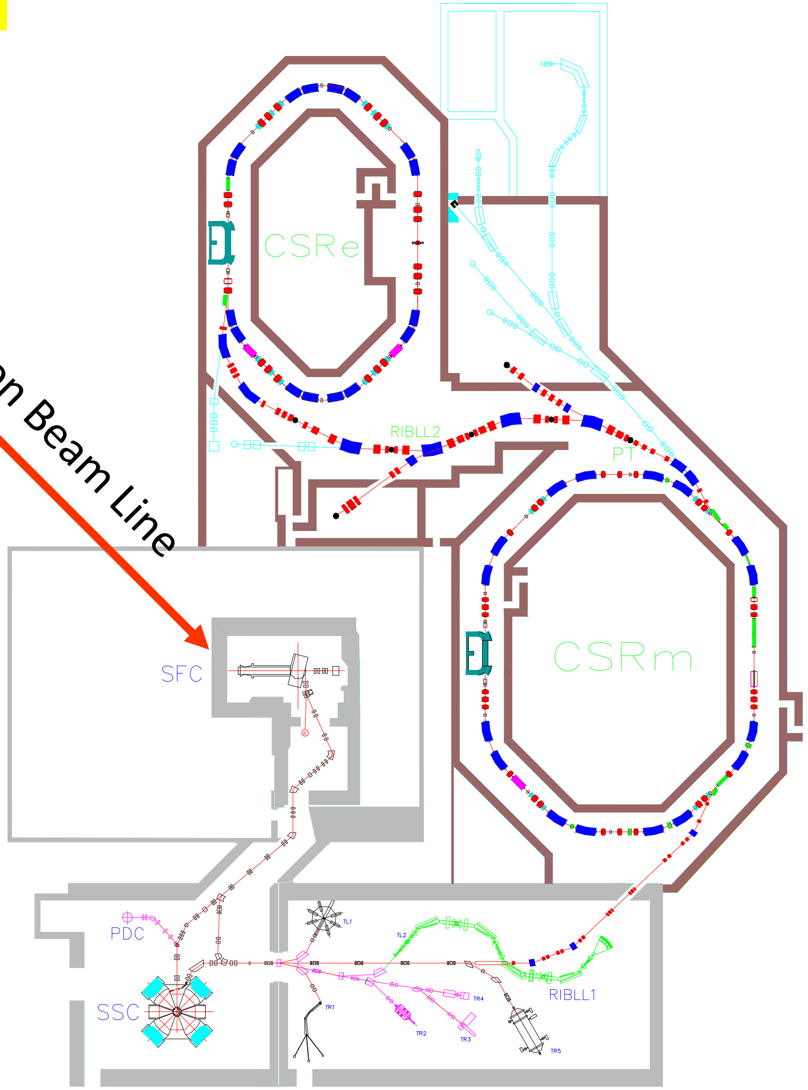
# SECRAL Operation for HIRFL Accelerator since May 2007

**SECRAL is dedicated only for operation of highly charged heavy ion beams.**




Axial Injection Beam Line

**HIRFL Accelerator Complex at IMP lanzhou**



# Significant issues during design , construction and operation of high field high performance SC-ECRIS

- **Only if you need high current and high charge state heavy ion beams, go to superconducting ECRIS.**

- **To build a high performance SC-ECRIS, you have to achieve a good compromise among those key issues, such as rf frequency, rf power, magnetic field configuration, plasma chamber size, expertise of SC magnet and cryogenics , reliability, long-term operation, cost , construction time and risk.**

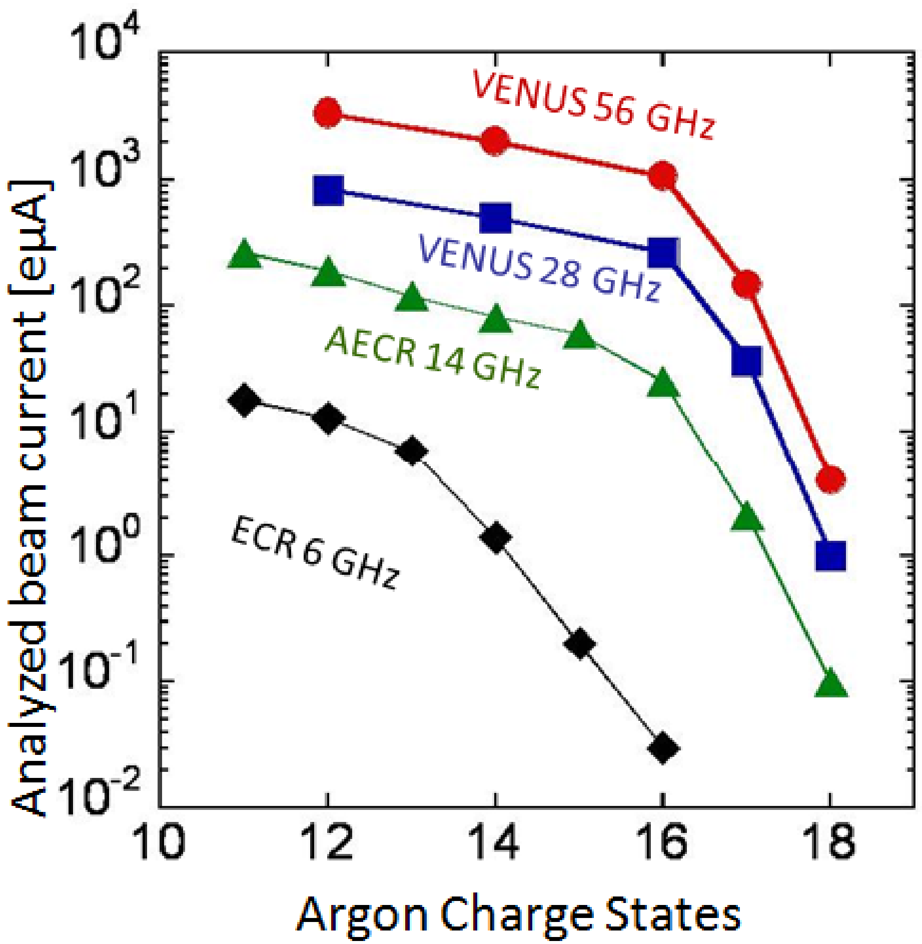
- **Challenges to build high field SC-magnet for the 3$^{rd}$ generation ECR:**

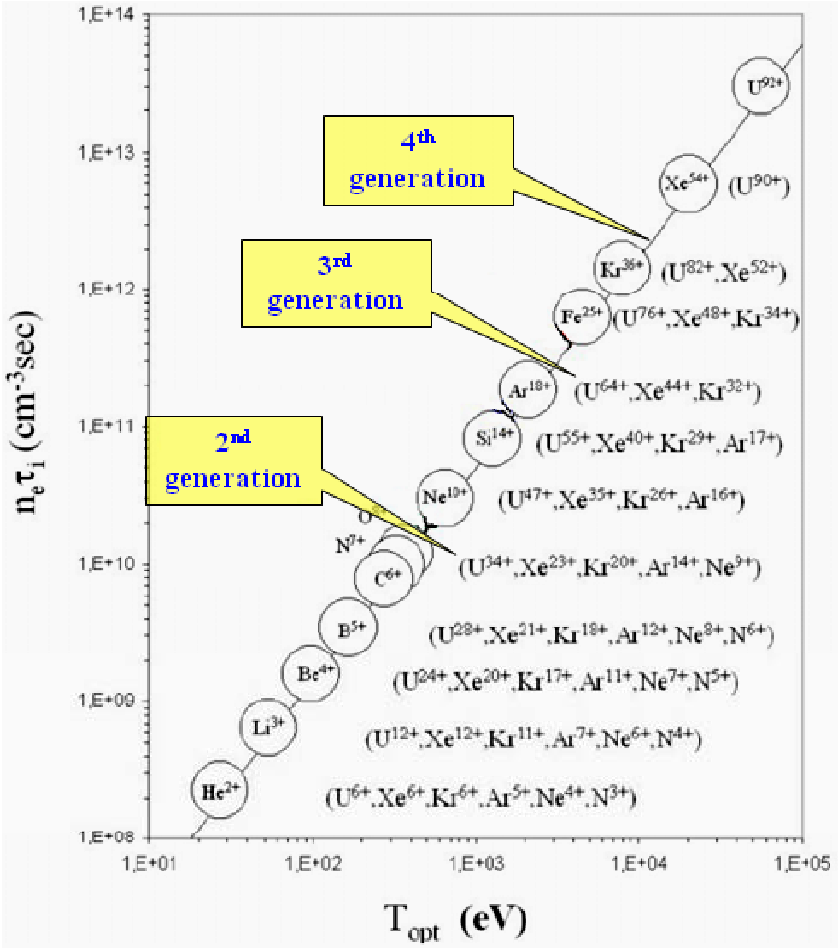
  - Need to keep enough safety margin for maximum fields and critical current
  - Try to reduce the interaction forces and design a reliable clamping system to prevent the wires and the coils from moving.
  - Stability and reliability of the SC-magnet are the most important for SC-ECR

# Significant issues during design , construction and operation of high field high performance SC-ECRIS

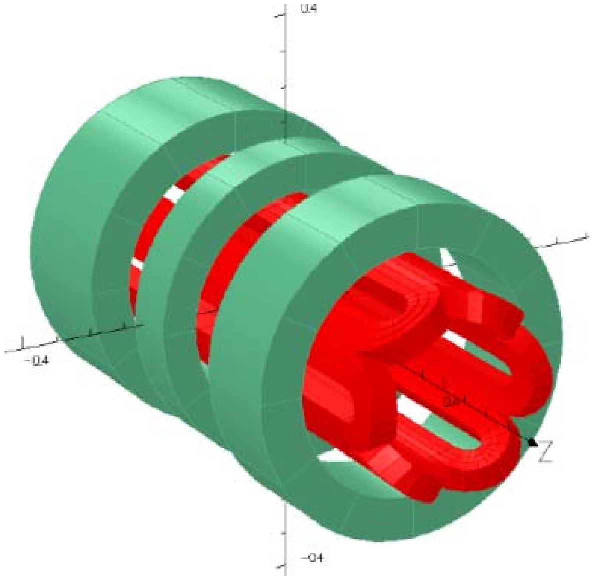
- **Challenges to design and operate cryogenics system for the SC-magnet of the 3rd generation ECRIS.**
  - Very strong x-ray with energy tens keV to MeV has to be taken into account in cryogenics design. Keep in mind that heat load from x-ray: 1 W/kW, much higher than that from magnet itself. X-ray flux and energy increase with rf frequency and power.
  - High power two stage cryocoolers or close-loop liquefy machine must be installed for long-term operation of the 3rd generation ECRIS.
- **Beam quality from the 3rd generation ECRIS and beam formation, beam transmission should be studied carefully. We only need high brightness beam.**
- **Reliable interlock and alarm system is very crucial.**
- **It is hard to build high field 3rd generation ECRIS. Sometimes it may take more than 5 years.**

# The 4th Generation ECRIS—Future Development

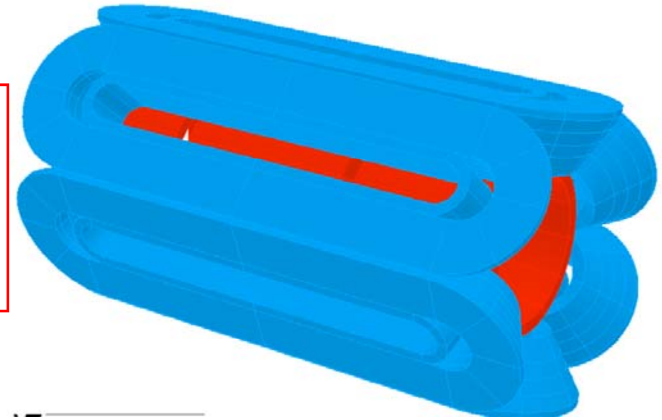


# What SC-magnet structure shall we design for 4$^{th}$ generation ECRIS?




Some new configuration ?



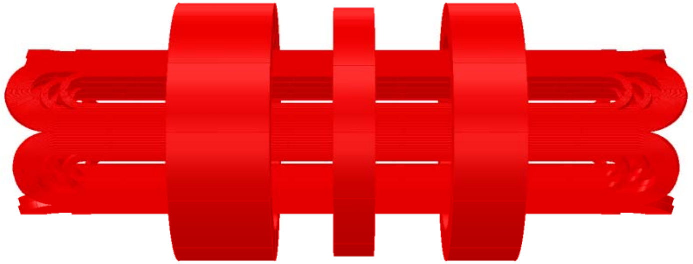
1. Sextupole-inside-solenoid

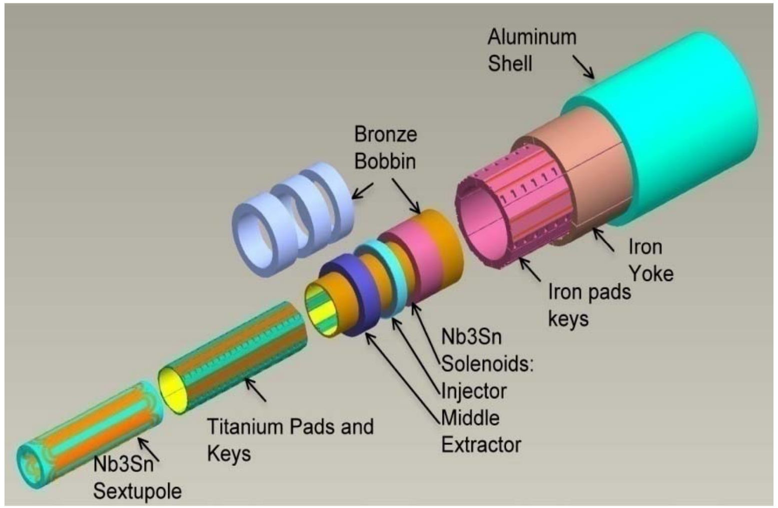
2. Some new structure?

3. Solenoid-inside-sextupole

The **continuing demand of higher beam intensities** makes the development of 4th Generation ECR ion sources necessary

**4th Gen ECRIS 56 GHz design at LBNL**






Study supported by FRIB R&D funds

**Courtesy of D.Leitner at LBNL**

# The most challenging tasks in 4th generation ECRIS

1. SC-magnet with the max field at the coil 15-17 T and the huge interaction forces between the solenoids and the sextupole( >few tens tons).

2. Laboratory available 50-60GHz /10-30 kW gyrotron system operated at both CW and pulse mode. Long-term stability and reliability are crucial.

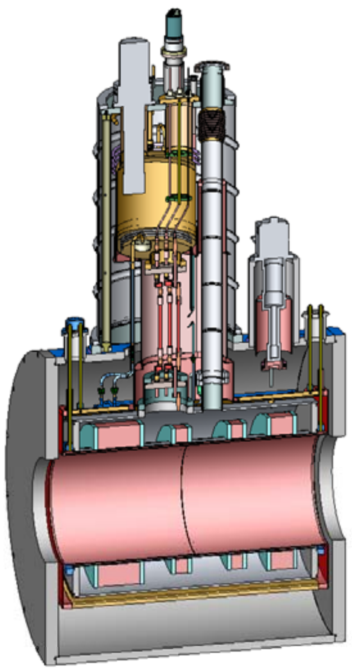
3. Extremely strong X-ray flux to insulation material and very strong head load to the cryogenics system. Online close-loop LHe liquefy machine may have to be utilized.

4. 40-60 mA mixed highly charged ion beam transmission issues.

**Technical R&D is absolutely necessary and should be supported .**

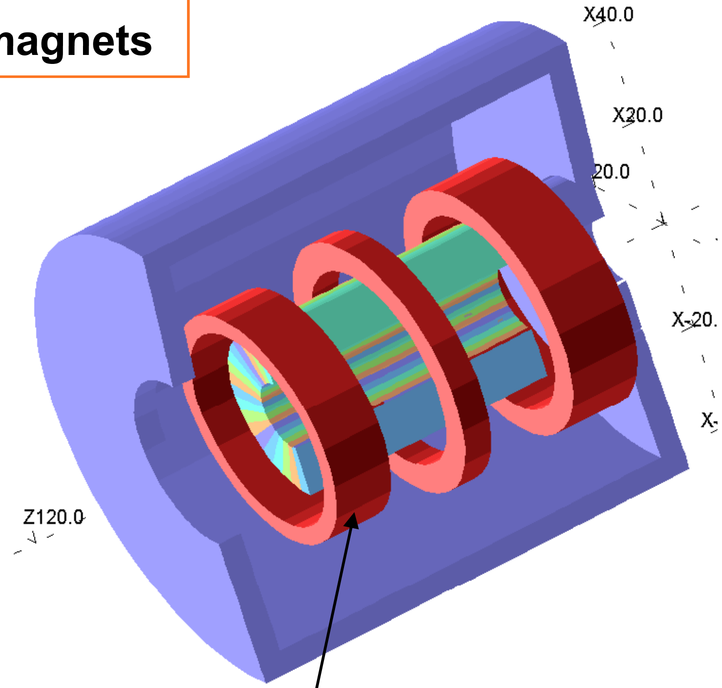
# Hybrid Superconducting ECRIS Concept Design

$n_e \sim \omega_{rf}^2$
$B_{in} \sim 4B_{ecr}$

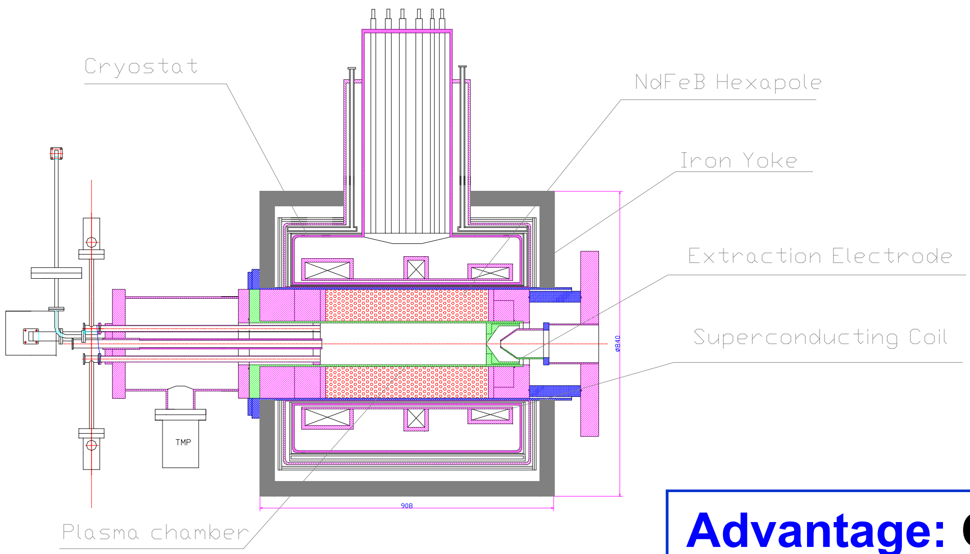


Superconducting solenoids+
Heaxpole using permanent magnets

RF: 18 GHz
$B_{inj}$: 3.0 Tesla
$B_{rad}$: 1.4-1.6 Tesla
$\Phi_{chamber}$: 75-120 mm

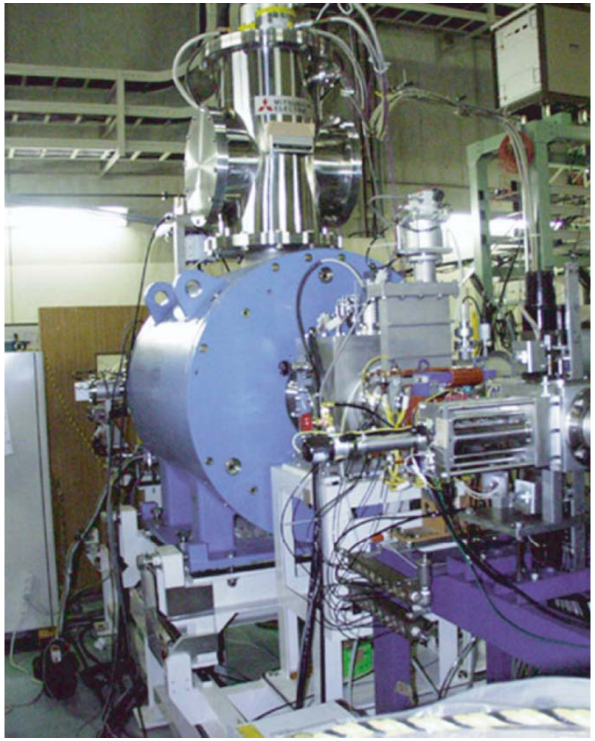



Could be LTS or HTS coils

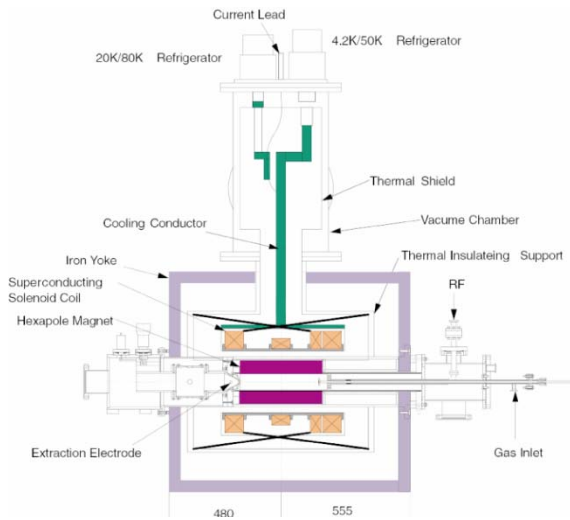



**Advantage:** Compact, lower cost, easier to build.
**Disadvantage**: Lower hexapole field.

# Hybrid SC-ECRIS: SC solenoid+NdFeB sextupole



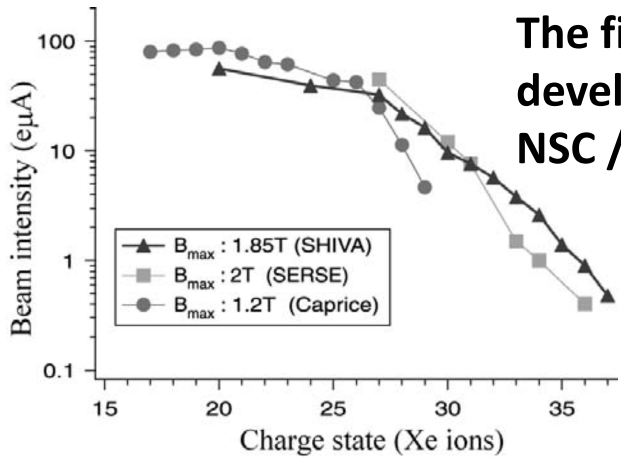
**The first LHe–free hybrid ECRIS developed by RIKEN . 18GHz**




Courtesy of T.Nakagawa at RIKEN
And A.Roy at NSC/New Delhi

**The first high Tc HTS ECRIS developed by Pantechnik and NSC /New Delhi . 18GHz**

- **Performance of such hybrid ECR is nice, but beam current for high Q is not so good because of low field.**
- **Be careful to demagnetization of sextupole due to solenoid Br**



# Theoretical Studies and Modeling of ECRIS

In the past 20 years, a lot of theoretical studies and modeling on ECRIS, still no clear picture. Few totally self consistent codes, including all the physics and using as input parameters and the design parameters.

Input parameters: magnetic configuration;dimensions;incident RF power,gas (or metallic vapour…) input flux.

- Highly charged ion production and losses.

  ionization, recombination, diffusion losses, collisions ……

- ECR heating, interactions with various waves.
- Electron confinement and ion confinement.
- Simulations of those methods or techniques to enhance highly charged ion beam production.

  biased disk, gas mixing, frequency effect, magnetic field effect, after-glow….

# Studies on ECRIS physis for intense highly charged ion beam formation are urgent

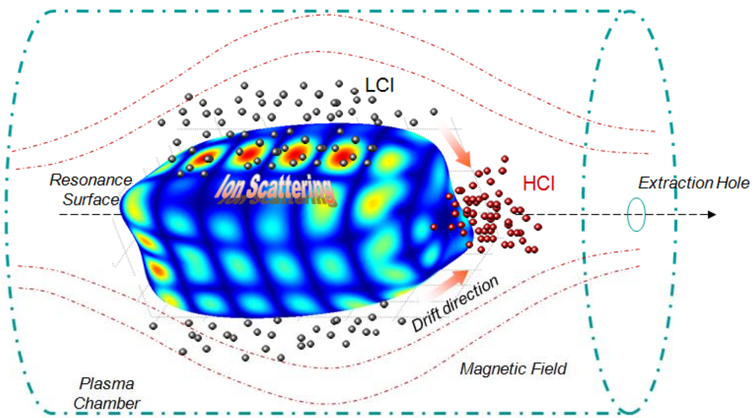
■ECRIS physics for intense highly charged ion beam formation is far from understanding because it is so complicated.

■Design of high performance ECRIS still remains semi-empirical and tricky.

■ECRIS physics study is extremely slower that than experimental progress.

■That is why there has been no big significant breakthrough in the past 20 years although great progress has been made.

■High performance ECR ion source is becoming a very big machine and too much rely on high technology instead of new ideas.




Graph courtesy of S.Gammino at LNS

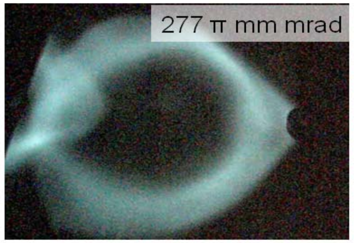
**Original and innovative ideas that may result in great breakthrough for HCI beam production are extremely significant at present**

# ECRIS Beam Quality Studies

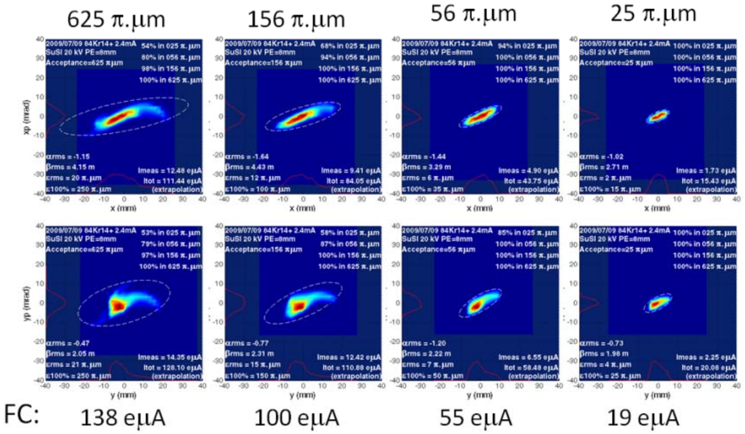
More efforts were focused on beam quality studies in the past few years in ECRIS community because of accelerator requirements.

GANIL, LBNL, ISN, IMP,…..

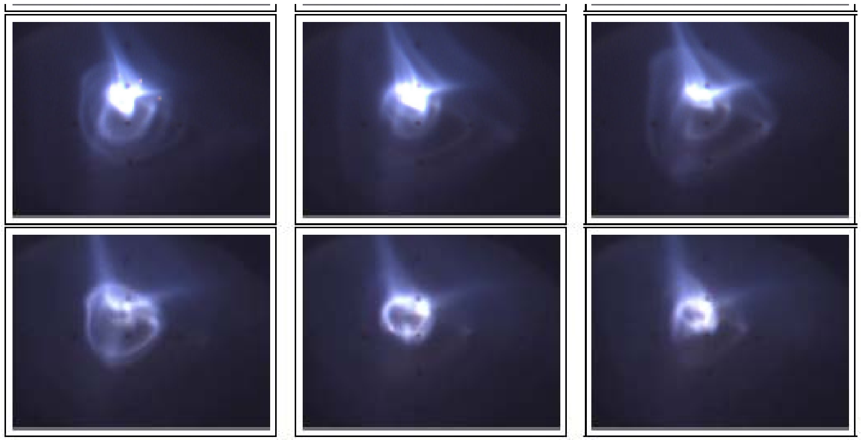
# Beam quality, beam formation and transmission



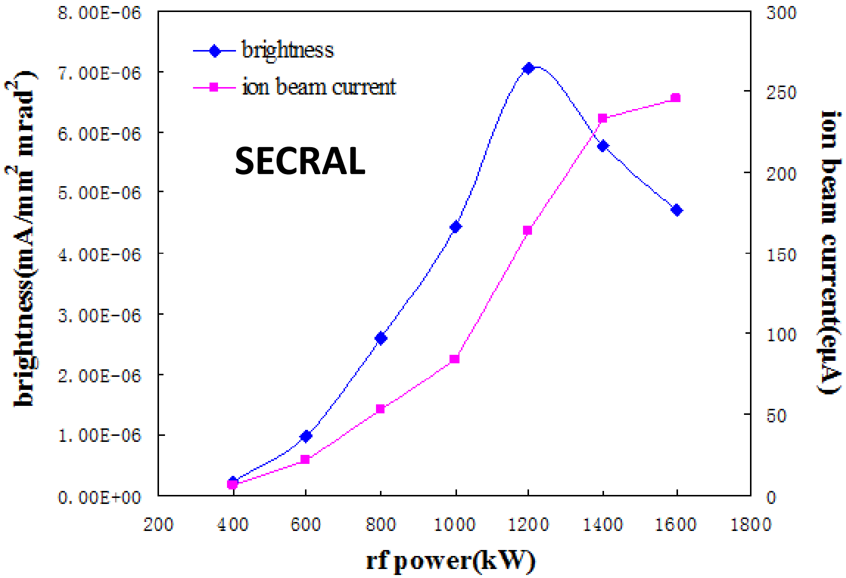

JYFL 14GHz ECRIS, Ar8+ beam, H.Koivisto talk at ICIS09



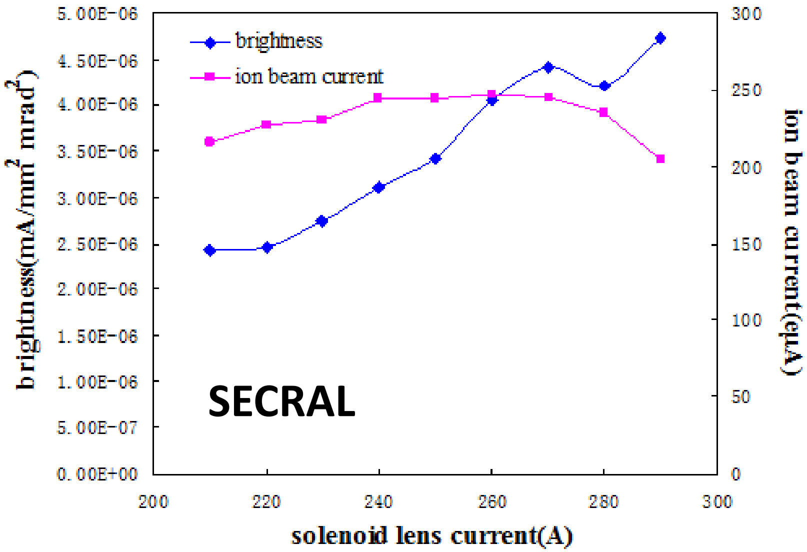

Beam collimation at SUSI beam line



SECRAL Ar beam at different settings of the focusing solenoid.




$Xe^{25+}$ beam current and brightness vs rf power




$Xe^{25+}$ beam current and brightness vs solenoid lens setting

# Conments of Beam Emittance and Beam Image from ECRIS

- Beam emittance from ECR ion source can be increased by a factor 2-3 for different plasma conditions!

- Higher axial magnetic field, higher rf fequency, higher rf power and larger extraction aperture may result in much larger beam emittance of ECR ion source, although much more beam current!

- Beam image and emittance could change a lot when you optimize ECR ion source. So should be very careful to tune an ECR ion source during its operation for a accelerator!

# 结束语

1. 离子源发展的驱动力来自基础研究（核物理，高能物理，原子物理，加速器....）和工业应用。
2. 离子源是个好东西！

- 理论与实验及经验的综合体。
- 非常利于人才培养, 涉及:

  原子物理、等离子体物理、电磁场理论、材料理论和性质、磁铁技术、加速器束流光学、束流诊断、微波和高频理论及技术、真空技术、电源技术、机械设计和加工、高压技术、电子学和控制.......
- 只要你持之以恒去研究，提出新的想法，不断试验，总会有惊喜，总会有新发现和提高，并由此可能带来革命性突破（ECRIS 改写核物理发展历史，EBIS 引发原子物理革命). 庞大的国际离子源队伍之原因。
- 新发现是在长期积累和不断研究的基础上产生的（Geller和Donets，40年只专注一种离子源。PIG, EBIS,LIS都发源于Dubna）。
- 交流、合作和竞争缺一不可。

# Acknowledgement

**I do appreciate for those colleagues in ion source community who sent me their slides. Some of graphs and slides in this lectures are directly from their presentations at international conferences or seminar talks.**

**All slides in this lectures are only used for OCPA2010 accelerator school**

谢谢