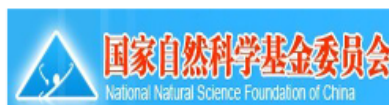




# Congratulations on OCPA2010

July 29 - August 7, 2010

IHEP · Beijing





# The Sixth Overseas Chinese Physics Association **ACCELERATOR SCHOOL** Beijing, China, July 29 - August 7, 2010

## Main Topics

Introduction to accelerators	Design CSNS linac	Vacuum technology
Transverse dynamics	Design of CSNS RCS	Beam instrumentation technology
Longitudinal dynamics	Introduction to hadron therapy	RF technology for hadron linacs
Lattice design	Accelerator design for hadron therapy	RF technology for hadron synchrotrons
Impedance and collective effects	Beam delivery system	Accelerator control
Introduction to hadron linacs	APTF design	Cryogenics & SC technology
Introduction to hadron synchrotrons	Carbon therapy at IMP	Radiation protection
Injection and extraction	Proton therapy in Taiwan	New generation light sources
Beam transport and manipulation	Introduction to ion sources	Advanced acceleration
Introduction to cyclotrons	Magnet technology	Accelerator applications
Introduction to high-power accelerators	Power supply technology	Spallation targets and spectrometers

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Division of Beam Physics,  
Overseas Chinese Physics Association  
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Academy of Sciences

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School website : <http://ocpa2010.ihep.ac.cn/>

- This is the sixth OCPA Accelerator School in its series.
- The first School was held in Hsinchu, Taiwan, August 3-12, 1998
- The second in Yellow Mountain, Anhui, July 18-27, 2000
- The third in Singapore, July 25 to August 3, 2002. The 2004 school was canceled due to SARS .
- The fourth School was held in Yangzhou, Jiangsu, July 27-August 5, 2006 ,
- The fifth in Nantou, Taiwan, September 1-10, 2008.
- The purpose of this school is to provide the students a basic training on modern accelerators.
- The themes of OCPA2010 are spallation neutron sources and particle therapy accelerator facilities.
- The lectures involve basic accelerator physics, technology systems and applications.
- The curriculum for the school is designed as basic topics (10 courses), topics on spallation neutron sources (4 courses), topics on hadron therapy (6 courses), technical topics (11 courses), and seminars (5 courses).
- Professors from U.S., Mainland and Taiwan are invited to give the lectures.





# *OCPA1998*

(August 3-14, 1998, SSRC, Hsinchu)





# 要 求

- 认真听课
- 参加考试
- 完成作业
- 善始善终

祝各位同学取得好成绩  
为今后工作准备好身手



# Program of the Sixth OCPA Accelerator School

TIME	July 29	July 30	July 31	August 1	August 2	August 3	August 4	August 5	August 6	August 7
08:00-09:00	G1: Intro. to Accelerators	G3-Long. Dynamics	G5-Impedance	G7-Hadron synchrotrons	EXCURSION	G8-Injection & extraction	S1-New light sources	H5-IMP carbon therapy	T10-Cryogenics & SC	S4-Targets & spectrometers
09:00-10:00	G1: Intro to Accelerators	G3-Long. Dynamics	G5-Impedance	G7-Hadron synchrotrons		G8-Injection & extraction	S2-Advanced acceleration	H6-Taiwan proton therapy	T10-Cryogenics & SC	S5-Management engineering
Break						Break				
10:15-11:15	G1: Intro. to Accelerators	G3-Long. Dynamics	G6-Hadron linacs	G7-Hadron synchrotrons		G9-Beam transport	H1-Hadron therapy	T7-RF for hadron linac	G10-Cyclotron	S5-Management engineering
11:15-12:15	G2-Transverse Dynamics	G4-Lattice	G6-Hadron linacs	N2-Spall. Neu. sources		G9-Beam transport	H1-Hadron therapy	T7-RF for hadron linac	G10-Cyclotron	Closing
Lunch						Lunch				
14:00-15:00	G2-Transverse Dynamics	G4-Lattice	G6-Hadron linac	N3-Design CSNS linac		N4-Design CSNS RCS	H2-Accel. for hadron therapy	T8-RF for hadron rings	T11-Radiation protection	DEPARTURE
15:00-16:00	G2-Transverse Dynamics	G4-Lattice	N1-High power accel.	N3-Design CSNS linac		N4-Design CSNS RCS	H2-Accel. for hadron therapy	T8-RF for hadron rings	Exam	
Break						Break				
16:15-17:15	T2-Magnet	T1-Ion source	T5-Vacuum	T3-Power supply		T6-Beam Diagnostics	H3-Beam delivery	T9-Control		
17:15-18:15	T2-Magnet	T1-Ion source	T5-Vacuum	T4-Pulsed PS		T6-Beam Diagnostics	H3-Beam delivery	T9-Control		
Super						Super				
20:00-21:00	S3-Accel. applications	Office hours and discussion	Office hours and discussion	Banquet		Office hours and discussion	H4-APTF design	Office hours and discussion	Office hours and discussion	
21:00-22:00	S3-Accel. applications	Homework	Homework			Homework	Homework	Homework	Homework	



G1-A

# ***An Introduction to Particle Accelerators***

*Historical Evolution, Innovative Ideas and  
Prospective in Accelerator Developments*

*C.Zhang*

**6th OCPA Accelerator School**  
**July 29 - August 7, 2010 • Beijing**





孔子  
(公元前551-479)

子曰：  
工欲善其事  
必先利其器

《论语·魏灵公》

*Sharp tools make good work*








# *Preface*

The human's curiosity on the universe has always been the driven force behind the development of telescopes and microscopes. As a type of powerful microscope, particle accelerators play an important role in discovery on the micro-world, which provide a major stimulus for research into the constituents and nature of matter. Traced to its three roots, the history of accelerators is a continuous upgrade towards higher energy, better performance and wider application. Innovative ideas, new methods, and new technologies emerge in endlessly...



# *Outline*

-  **From telescope to microscope**
-  **Historical evolution of accelerators**
-  **Frontiers of modern accelerators**
-  **Future science and accelerators**
-  **Summary**



# **(1) *From telescope to microscope***

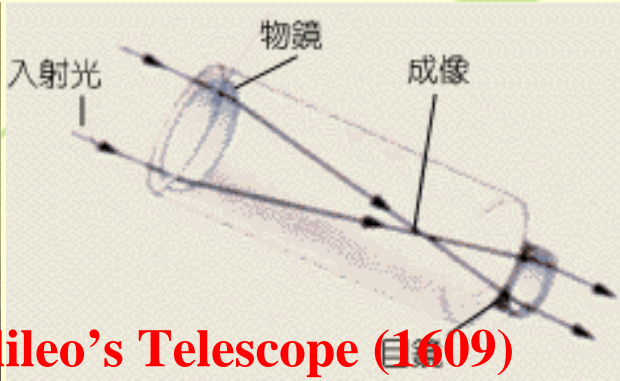
- **400 years of telescopes and microscopes**
- **The Glashow snake and universe**
- **Fundamental particles and interaction**
- **Methods to investigate the micro-world**



# 1.1 400 Years of Telescope

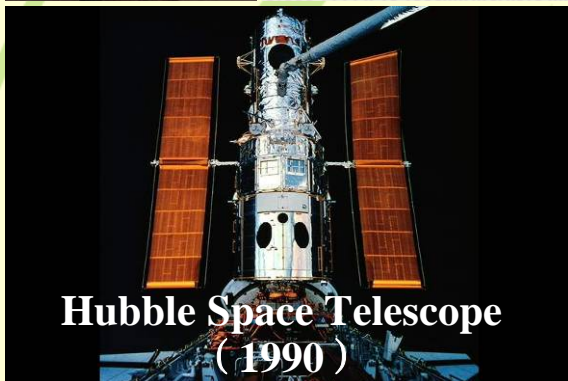


**Galileo's Telescope (1609)**

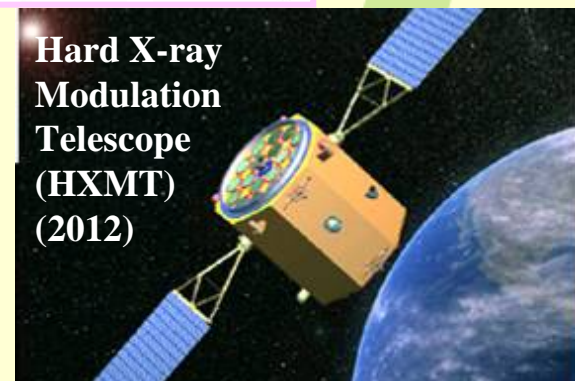


**Galileo's observation on Jupiter & its satellites (1610)**

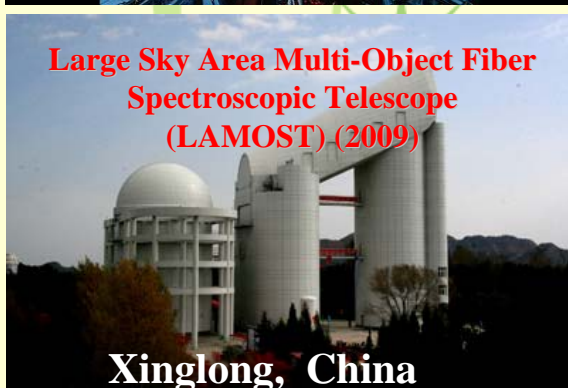
Jan. 8	● ○ ○ ○ II
Jan. 10	• • ● III
Jan. 11	• • ● IV
Jan. 12	○ ○ ● ○ V
Jan. 13	○ ● ○ ○ ○ VI



**Hubble Space Telescope (1990)**

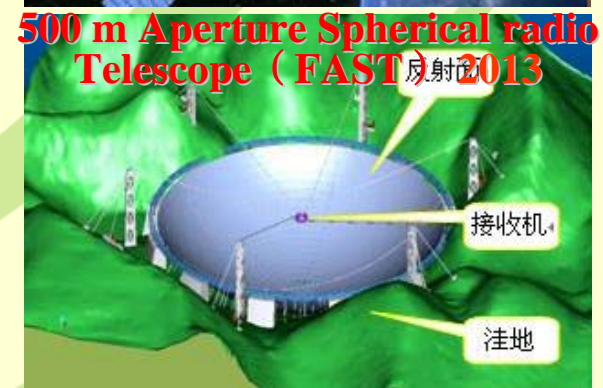


**Hard X-ray Modulation Telescope (HXMT) (2012)**



**Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) (2009)**

**Xinglong, China**

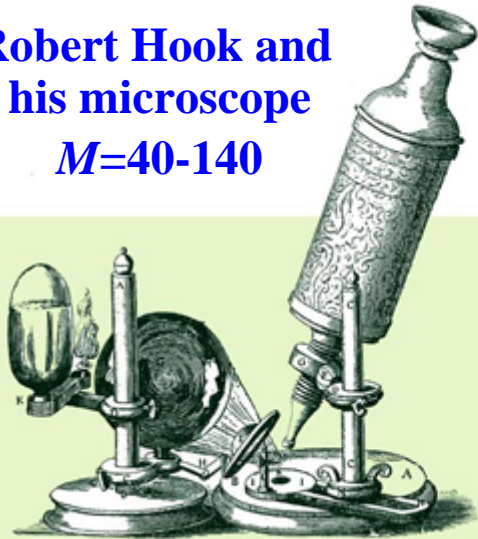


**500 m Aperture Spherical radio Telescope (FAST) (2013)**



# 400 Years of Microscopes

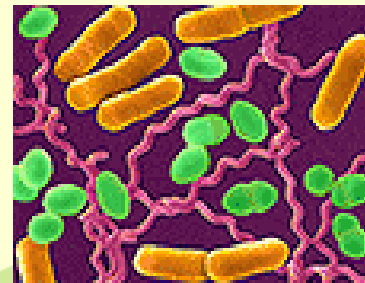
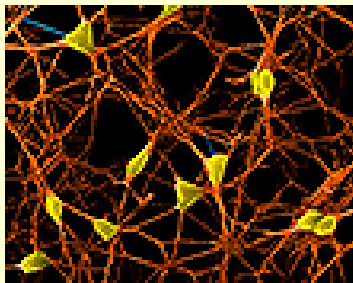
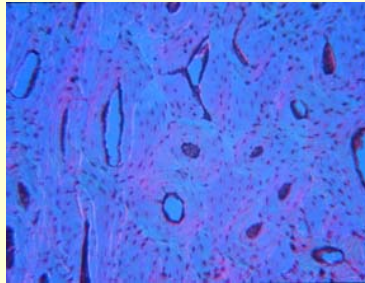
**Robert Hook and  
his microscope**  
 $M=40-140$



**Early Microscope  
(Cuff, 1740)**



**Electron  
microscope  
(1933)**

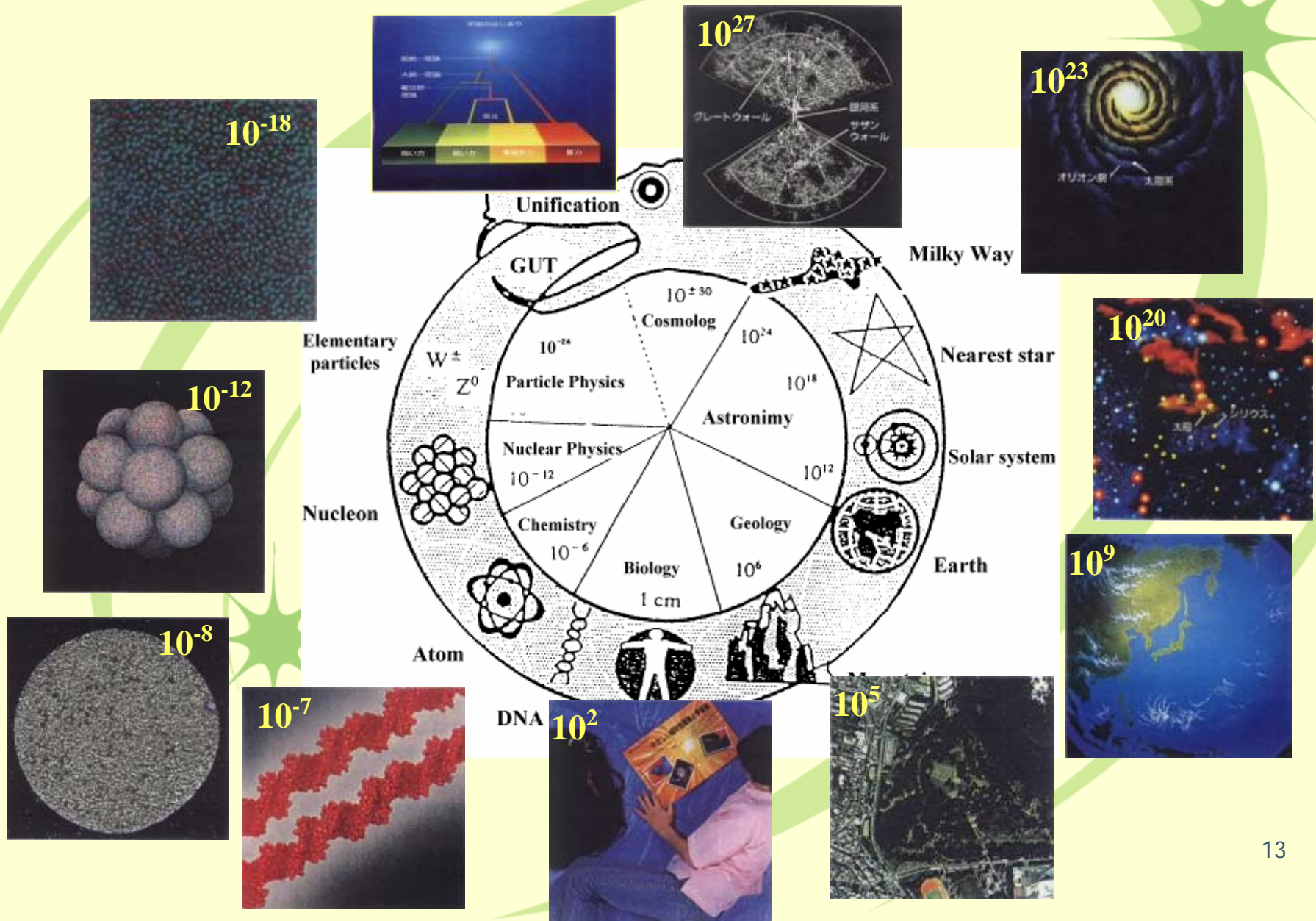


**Sweep Electron  
Microscope (1965)**





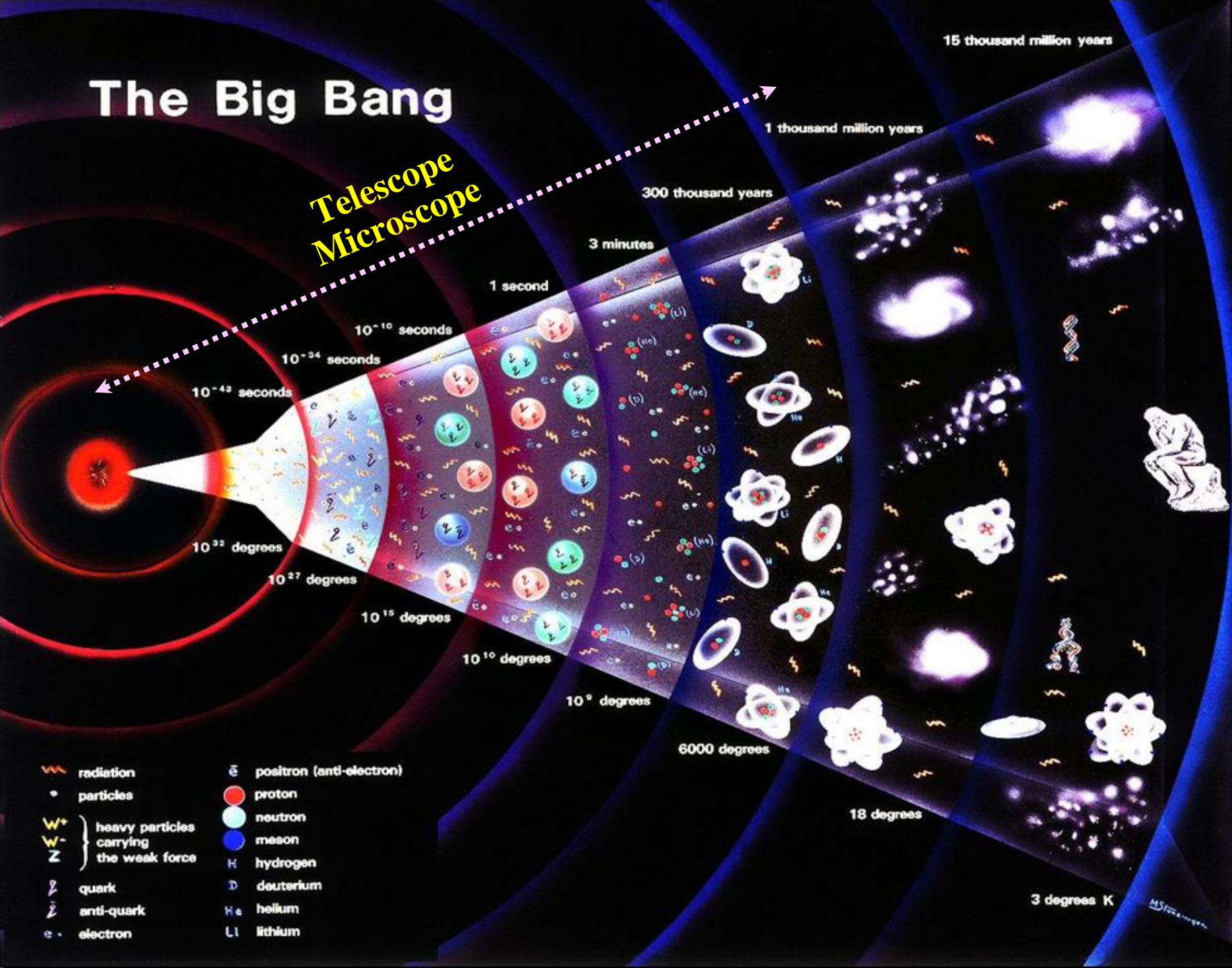
# 1.2 The Glashow Snake and Universe





# The Big Bang

Telescope  
Microscope





# 1.3 Fundamental Particles and Interactions

## Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).

### FERMIONS

matter constituents  
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c <sup>2</sup>	Electric charge	Flavor	Approx. Mass GeV/c <sup>2</sup>	Electric charge
$\nu_L$ lightest neutrino*	(0–0.13) × 10 <sup>-9</sup>	0	<b>u</b> up	0.002	2/3
<b>e</b> electron	0.000511	-1	<b>d</b> down	0.005	-1/3
$\nu_M$ middle neutrino*	(0.009–0.13) × 10 <sup>-9</sup>	0	<b>c</b> charm	1.3	2/3
$\mu$ muon	0.106	-1	<b>s</b> strange	0.1	-1/3
$\nu_H$ heaviest neutrino*	(0.04–0.14) × 10 <sup>-9</sup>	0	<b>t</b> top	173	2/3
<b><math>\tau</math></b> tau	1.777	-1	<b>b</b> bottom	4.2	-1/3

\*See the neutrino paragraph below.

Spin is the intrinsic angular momentum of particles. Spin is given in units of  $\hbar$ , which is the quantum unit of angular momentum where  $\hbar = h/2\pi = 6.58 \times 10^{-25}$  GeV s =  $1.05 \times 10^{-34}$  J s.

**Electric charges** are given in units of the proton's charge. In SI units the electric charge of the proton is  $1.60 \times 10^{-19}$  coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c<sup>2</sup> (remember  $E = mc^2$ ) where  $1 \text{ GeV} = 10^9 \text{ eV} = 1.60 \times 10^{-10}$  joule. The mass of the proton is  $0.938 \text{ GeV}/c^2 = 1.67 \times 10^{-27} \text{ kg}$ .

#### Neutrinos

Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states  $\nu_e$ ,  $\nu_\mu$ , or  $\nu_\tau$ , labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite mass neutrinos  $\nu_1$ ,  $\nu_2$ , and  $\nu_3$  for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.

#### Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or - charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g.,  $Z^0$ ,  $\gamma$ , and  $\eta_c = c\bar{c}$  but not  $K^0 = d\bar{s}$ ) are their own antiparticles.

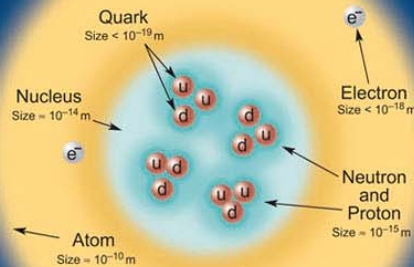
### Particle Processes

These diagrams are an artist's conception. Blue-green shaded areas represent the cloud of gluons.

A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron  $\beta$  (beta) decay.

An electron and positron (antilepton) colliding at high energy can annihilate to produce  $B^0$  and  $B^0$  mesons via a virtual Z boson or a virtual photon.

### Structure within the Atom



If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

### BOSONS

force carriers  
spin = 0, 1, 2, ...

Unified Electroweak spin = 1			Strong (color) spin = 1		
Name	Mass GeV/c <sup>2</sup>	Electric charge	Name	Mass GeV/c <sup>2</sup>	Electric charge
$\gamma$ photon	0	0	<b>g</b> gluon	0	0
<b>W<sup>-</sup></b>	80.39	-1			
<b>W<sup>+</sup></b>	80.39	+1			
<b>Z<sup>0</sup></b>	91.188	0			

#### Color Charge

Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

#### Quarks Confined in Mesons and Baryons

Quarks and gluons cannot be isolated – they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.

Two types of hadrons have been observed in nature: **mesons**  $q\bar{q}$  and **baryons**  $qqq$ . Among the many types of baryons observed are the proton (uud), antiproton ( $\bar{u}\bar{u}\bar{d}$ ), neutron (udd), lambda  $\Lambda$  (uds), and omega  $\Omega^-$  (sss). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion  $\pi^+$  ( $u\bar{d}$ ), kaon  $K^-$  ( $s\bar{u}$ ),  $B^0$  ( $d\bar{s}$ ), and  $\eta_c$  ( $c\bar{c}$ ). Their charges are +1, -1, 0, 0 respectively.

Visit the award-winning web feature *The Particle Adventure* at

**ParticleAdventure.org**

This chart has been made possible by the generous support of:

U.S. Department of Energy

U.S. National Science Foundation

Lawrence Berkeley National Laboratory

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**CPEPweb.org**

### Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	<b>W<sup>+</sup></b> <b>W<sup>-</sup></b> <b>Z<sup>0</sup></b>	$\gamma$	Gluons
Strength at {				
$10^{-16} \text{ m}$	$10^{-41}$	0.8	1	25
$3 \times 10^{-17} \text{ m}$	$10^{-41}$	$10^{-4}$	1	60

### Unsolved Mysteries

Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, mini-black holes, and/or evidence of string theory.

#### Universe Accelerating?

The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

#### Why No Antimatter?

Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

#### Dark Matter?

Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?

#### Origin of Mass?

In the Standard Model, for fundamental particles to have masses, there must exist a particle called the Higgs boson. Will it be discovered soon? Is supersymmetry theory correct in predicting more than one type of Higgs?



# 1.4 Methods to investigate the micro-world

$$\lambda^{-1} = \frac{E\beta}{hc}$$

**Crystal**  
~ 1 cm

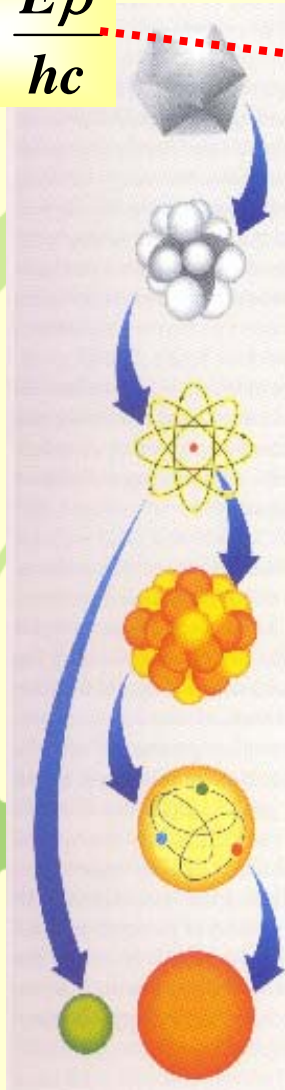
**Molecule**  
~  $10^{-7}$  cm

**Atom**  
~  $10^{-8}$  cm

**Nucleus**  
~  $10^{-12}$  cm

**Proton**  
~  $10^{-13}$  cm

**Lepton, Quark**  
<  $10^{-16}$  cm



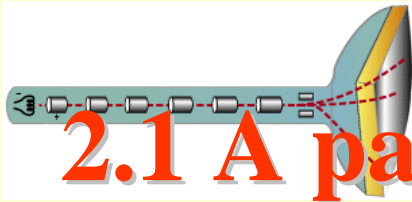
Observed Substance	Size (cm)	Beam Energy $E=hc/\lambda\beta$	Method
<b>Cell/Bacteria</b> <i>= Aggregate of molecule</i>	$10^{-3} \sim 10^{-5}$	$0.1 \sim 10 eV$	Optical microscope
<b>Molecule</b> <i>= Aggregate of atoms</i> ex) Water = $H_2O$	$\sim 10^{-7}$	$\sim 1 keV$	Electron microscope
<b>Atom</b> <i>= Nucleus + Electrons</i>	$\sim 10^{-8}$	$\sim 10 keV$	Synchrotron radiation
<b>Nucleus</b> ex) Oxygen = $8p+8n$	$\sim 10^{-12}$	$>100 MeV$	Low-energy electron or proton accelerators
<b>Hadron</b> <i>= Aggregate of quarks</i> ex) $p=u+u+d$ , $J/\psi=c+\bar{c}$	$\sim 10^{-13}$	$>1 GeV$	High-energy proton accelerators
<b>Quark, Lepton ...</b> (u,d) (s,c) (b,t) ( $e,\nu_e$ ) ( $\mu,\nu_\mu$ ) ( $\tau,\nu_\tau$ )	$<10^{-16}$	$>1000 GeV$	High-energy electron or proton colliders
.....	.....	.....	.....



## *(2) Historical evolution of accelerators*

- **A particle accelerator at your home**
- **Historical roots of accelerators**
- **Main development**
- **Evolution of acceleration principle**
- **Step up to modern accelerators**





## 2.1 A particle accelerator at your home

Television:  
a particle accelerator  
in your house



A television set has almost all the basic features  
of CERN's machines - a source of particles and ways  
of accelerating, guiding and detecting them

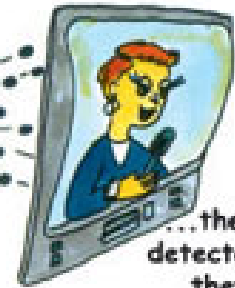
...electromagnetic fields  
accelerate them...



Electrons are  
set free by heating  
a filament...



...and guide them...



...they are  
detected when  
they hit  
the screen





## 2.2 Historical Roots

### *The birth of an era*

1919 Rutherford induced a nuclear reaction with natural alphas.

1928 Gamov predicted tunnelling and 500 keV might be suffice to split atom.



*I have long hoped for a source of positive particles more energetic than those emitted from natural radioactive substances.*

*Ernest Rutherford, 1928*



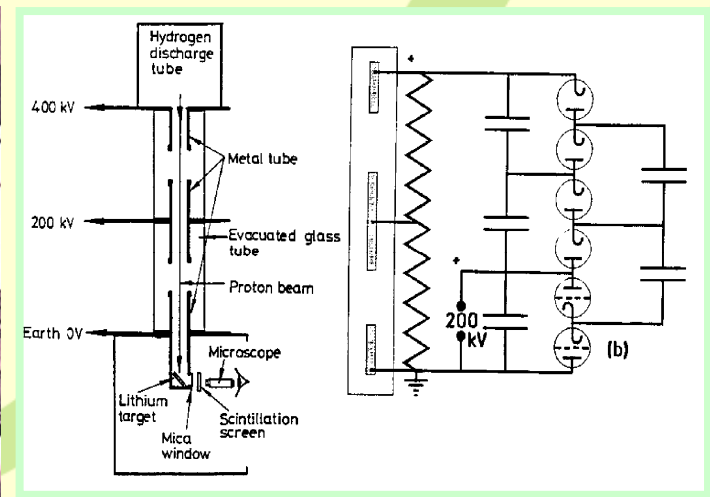
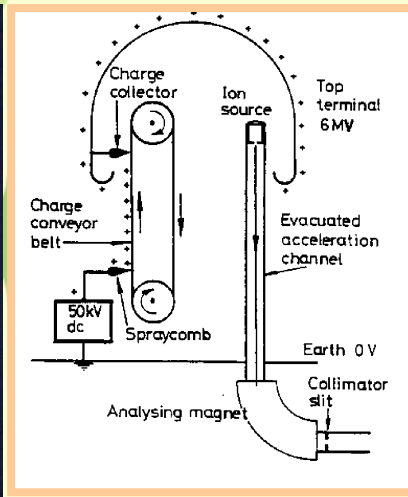
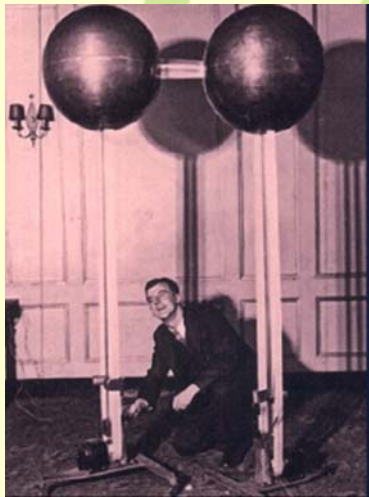
## 2.2 Historical Root 1

### High-voltage acceleration

**1928** Cockcroft & Walton started designing an 800 keV generator encouraged by Rutherford.

**1931** Van de Graaff invented electrostatic generator.

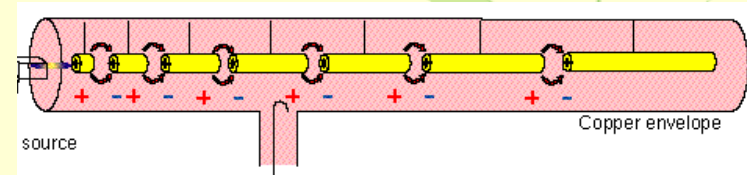
**1932** The rectifier generator reached 700 kV and Cockcroft & Walton split lithium atom with 400 keV proton.





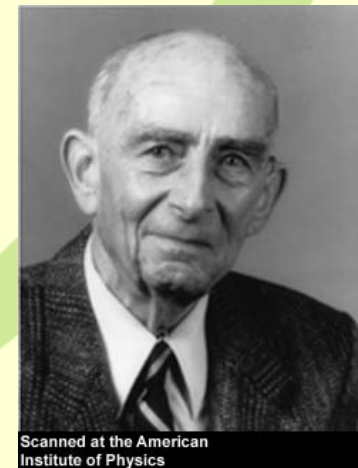
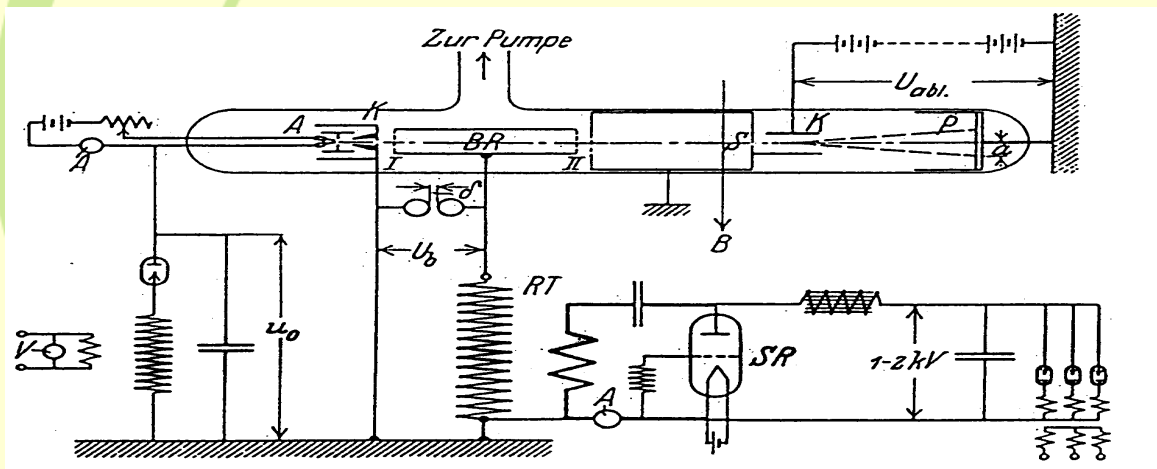
# *Historical Root 2*

## *Resonant acceleration*



**1924 Gustav Ising proposed time-varying fields across drift tube.**

**1928 Rolf Wideroe demonstrated Ising's principle with 1 MHz, 25 kV oscillator to make 50 keV potassium ions.**

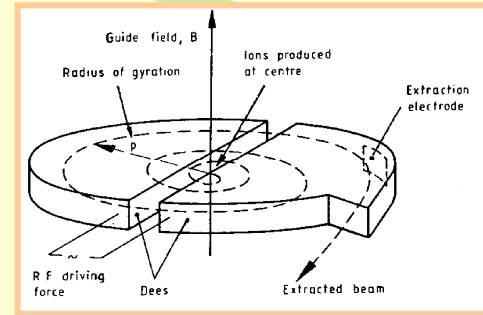


Scanned at the American  
Institute of Physics

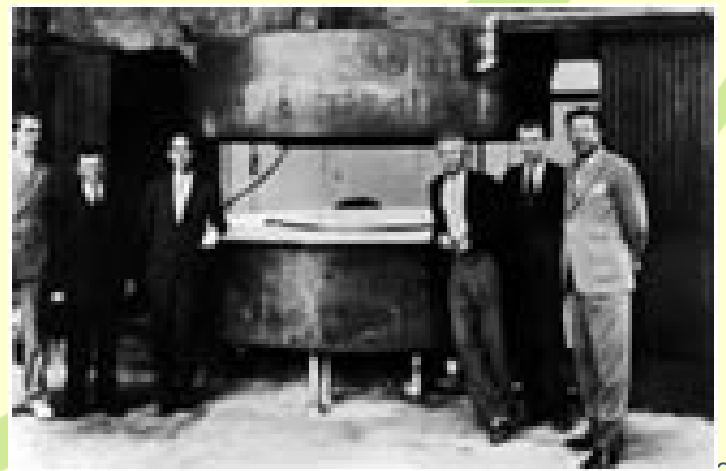
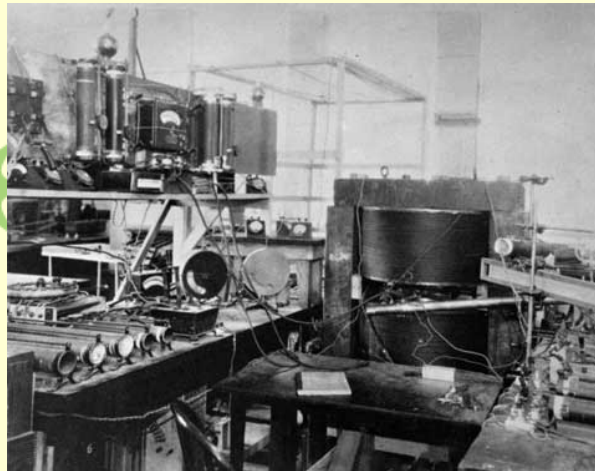
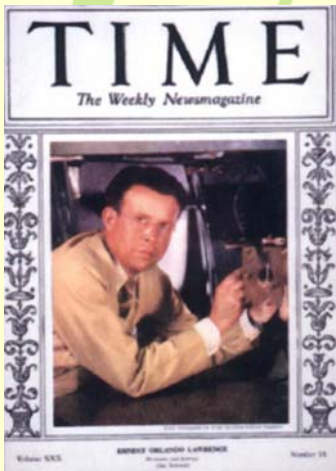


# *Historical Root 2 (cont.)*

## *Resonant acceleration*



- 1929 Lawrence, inspired by Wideroe and Ising, conceived the cyclotron.
- 1931 Livingston demonstrated the cyclotron by accelerating protons to 80 keV;
- 1932 Lawrence's cyclotron produced 1.25 MeV protons and split the atom just few weeks after Cockcroft & Walton.



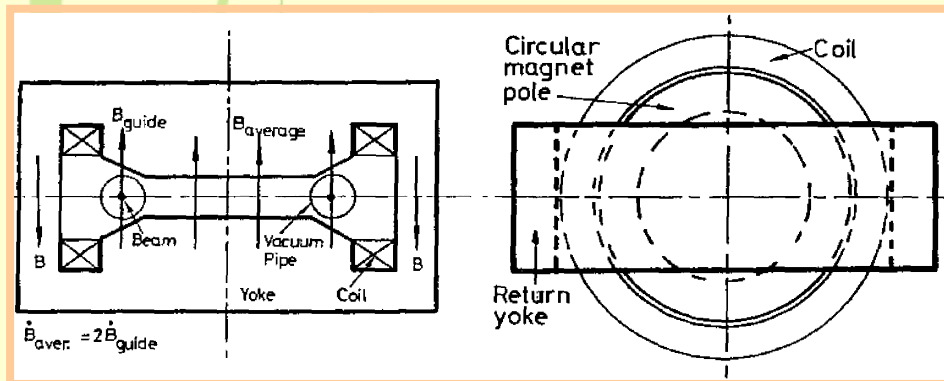


# Historical Root 3

## Betatron acceleration

$$\frac{dB_0(t)}{dt} = \frac{1}{2} \frac{d\bar{B}(t)}{dt}$$

- 1923** Wideroe, a young Norwegian student, drew in his laboratory notebook the design of the betatron with 2-1 rule. Two years later he added the condition for radial stability but not publish.
- 1927** Wideroe made a model betatron, but it did not work. Discouraged he changed course and built a linear accelerator.
- 1940** Kerst re-invents the betatron and built the first working machine for 2.2 MeV electron.
- 1950** Kerst built the world's largest betatron of 300 MeV.





# 1.3 *Main Development*

1944 V.Veksler & E.Mcmillan discovers principle of phase stability and invent the synchrotron.

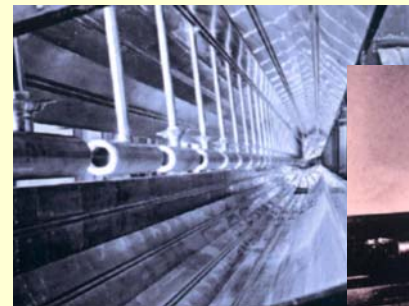
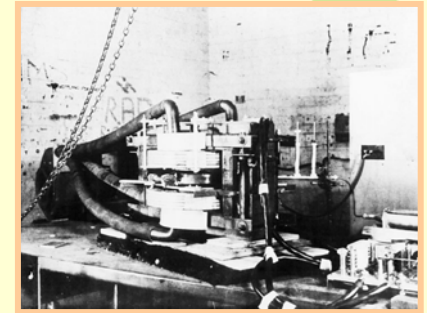
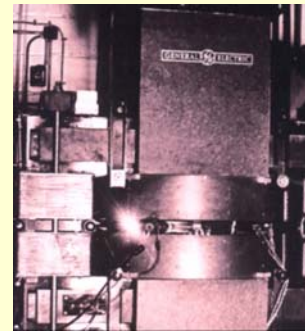
1944 Veksler proposes an idea of microtron.

1945 Energy loss due to synchrotron radiation is measured in an betatron;

1946 F.Goward & D.Barnes make a synchrotron works.

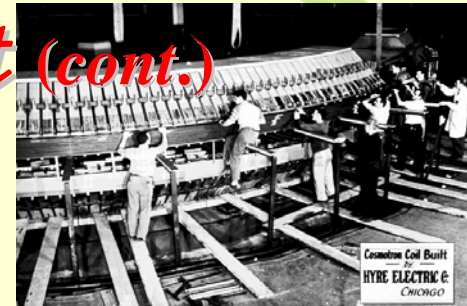
1946 First proton linear accelerator of 32 MeV is built at Berklay.

1946 First electron linear accelerators are studied at Stanford and MIT.





# *Main Development (cont.)*



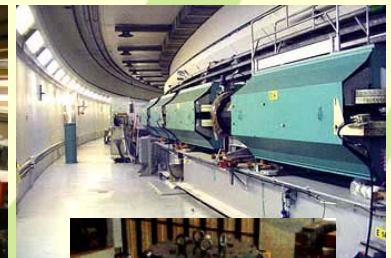
**1952 BNL builds 3 GeV Cosmitron.**

**1952 E.Courant, M.Livingston & H.Snyder propose the principle of strong focusing.**

**1959 CERN builds 28 GeV CPS;  
BNL builds 33 GeV AGS (1960);**

**1960's Several SR facilities are set up  
on rings initially for HEP;**

**1962 First single-ring  $e^+e^-$  collider  
AdA of  $2 \times 250$  MeV is built at  
Frascati.**





# 1.3 Main Development (cont.)

1970 V. Teplyakov and I. Kapchinski invent radio frequency quadrupole linac (RFQ);

1971 J. Madao invented first free electron laser;

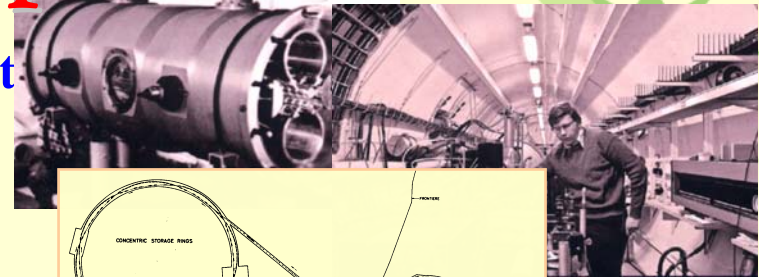
1972 First double-ring proton collider ISR  $2 \times 28$  GeV is built at CERN;

Since 70's A number of  $e^+e^-$  colliders constructed;

Since 80's A number of SR facilities and spallation neutron sources constructed;

1989 First linear collider SLC of  $2 \times 50$  GeV is built at SLAC

2008 First beam from LHC;

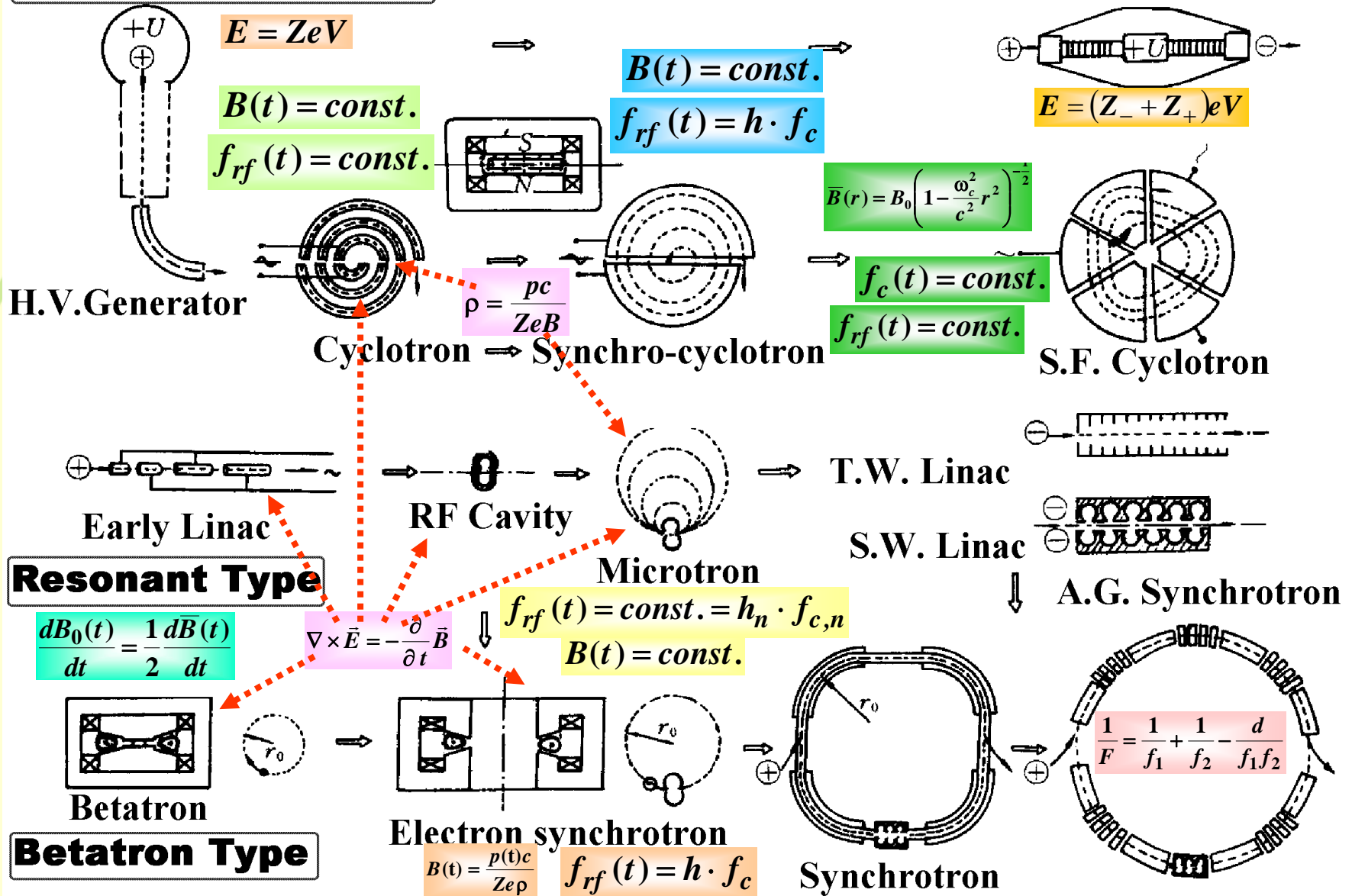


.....



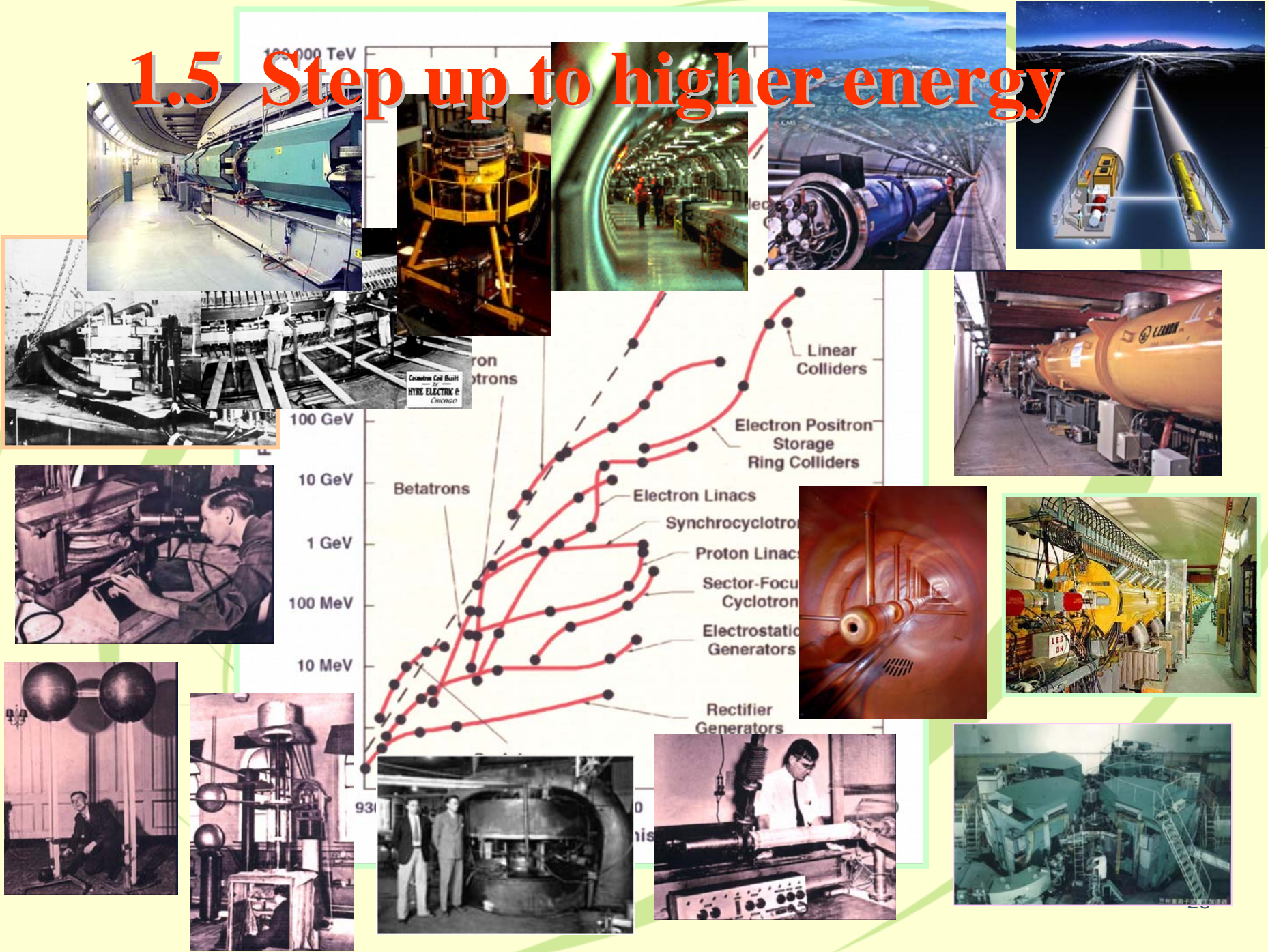
# 1.4 Evolution of acceleration principle

## Direct-Voltage Type





# 1.5 Step up to higher energy



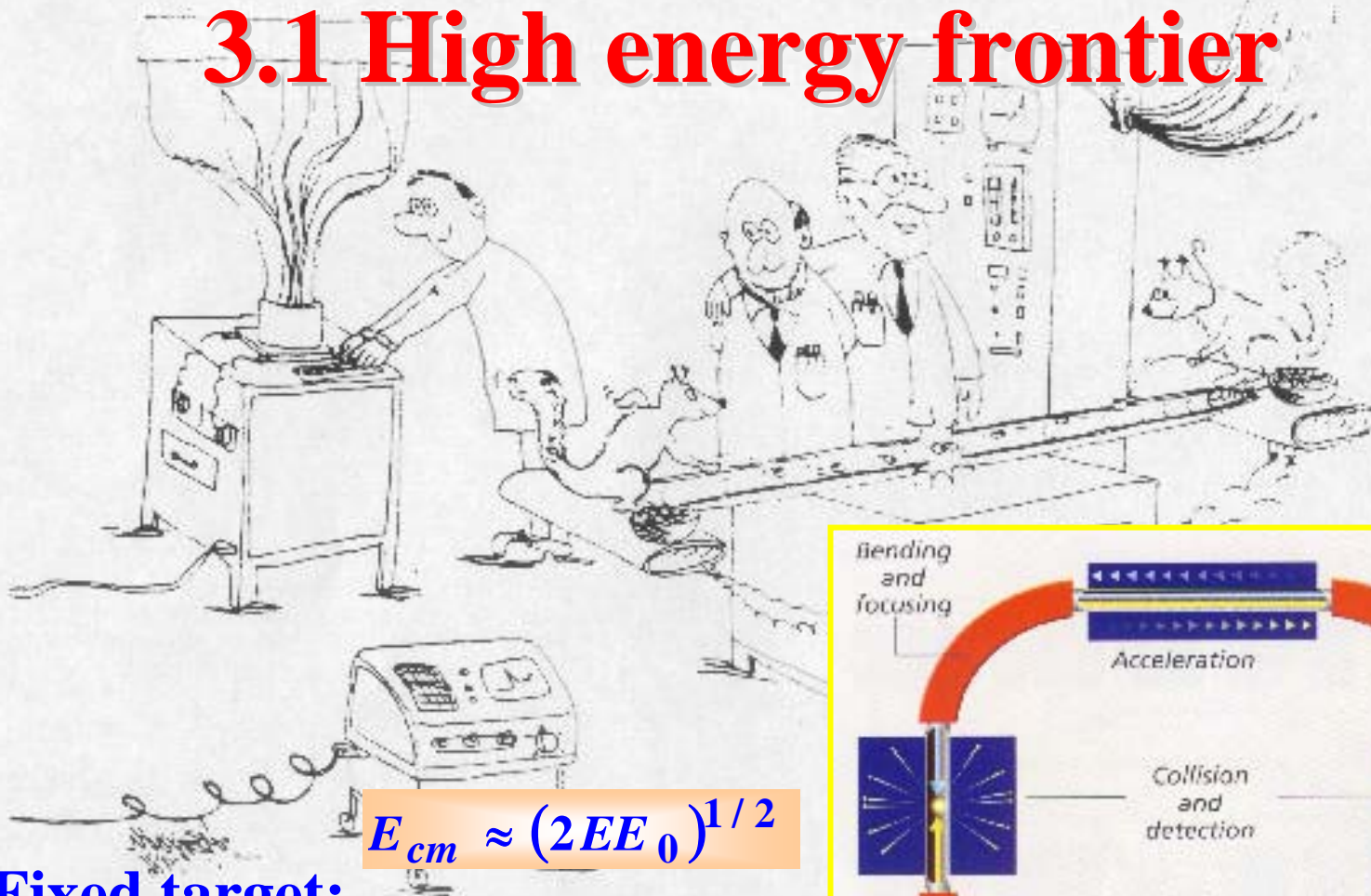


### ***(3) Frontiers of modern accelerators***

- **High energy frontier**
- **High luminosity frontier**
- **Multidisciplinary platforms**
- **Application of accelerators**
- **Novel acceleration methods**



# 3.1 High energy frontier

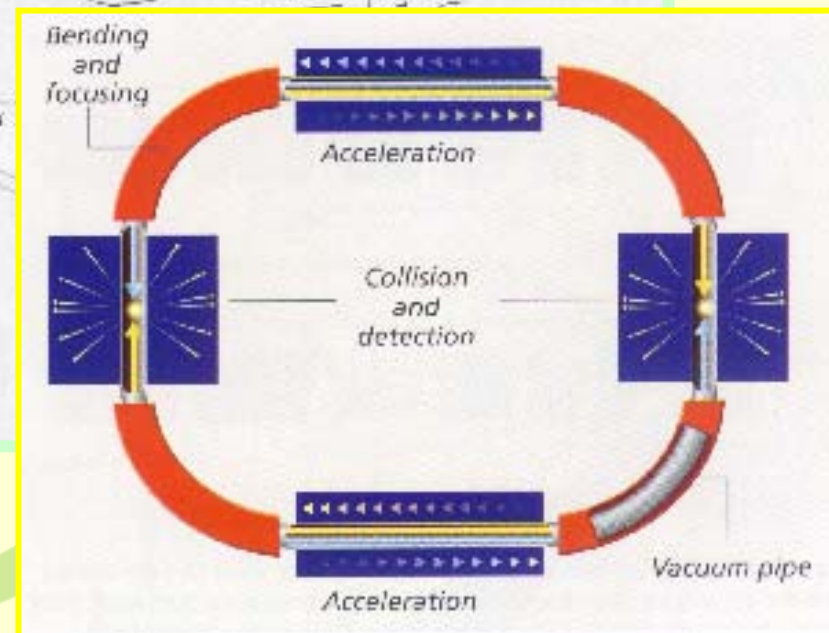


$$E_{cm} \approx (2EE_0)^{1/2}$$

Fixed target:

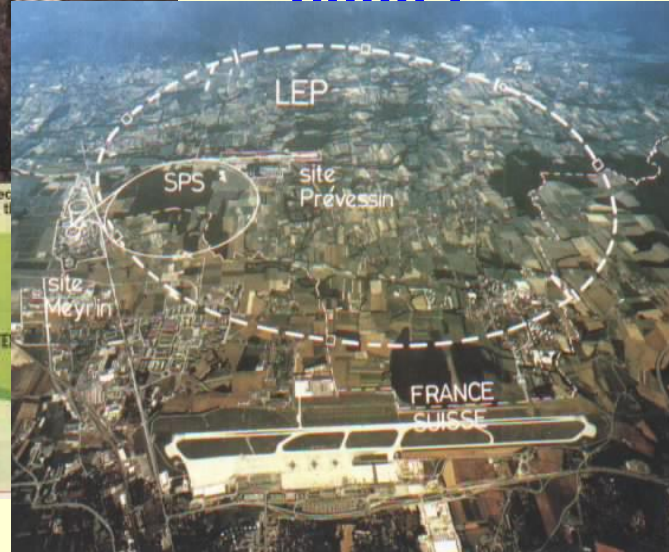
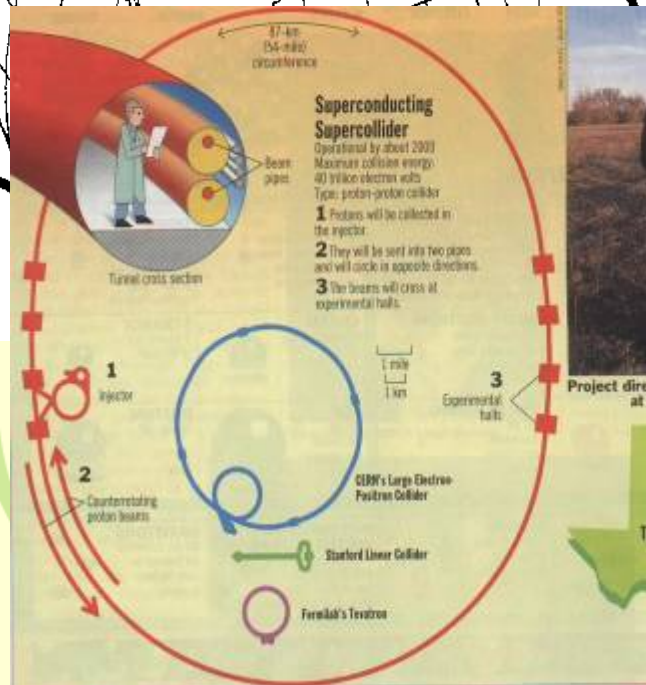
Collider:

$$E_{cm} = 2E$$





# Fermi's Dream (1954)



## Fermi's Dream SSC (LHC)

$E_{beam}$  5000 TeV 20 (7.0)

$E_{C.M.}$  3 TeV 40 (14)

2 T 6.6 (8.3)

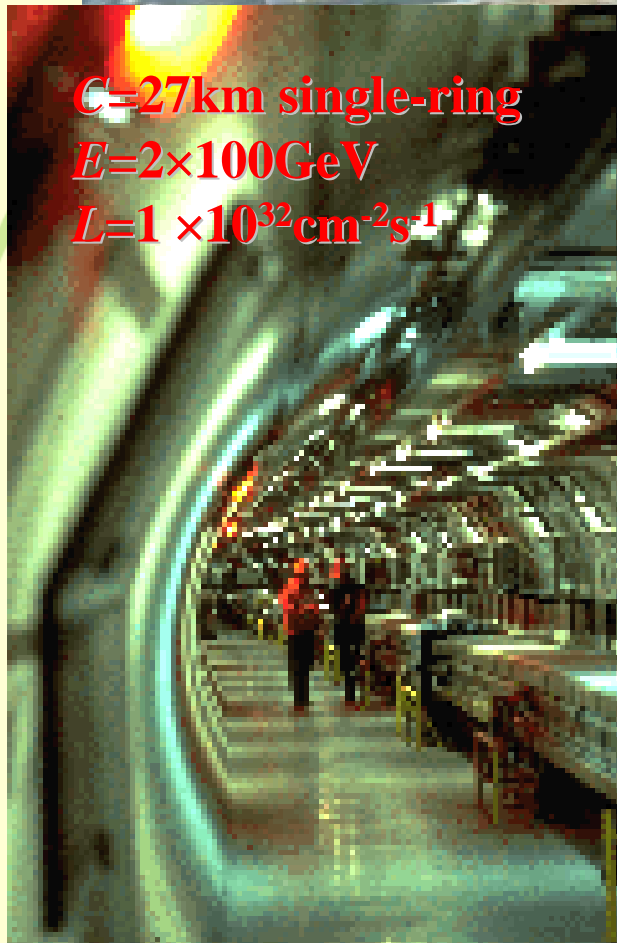
13 (4.3)

8 ? (5)

9 ? (10)



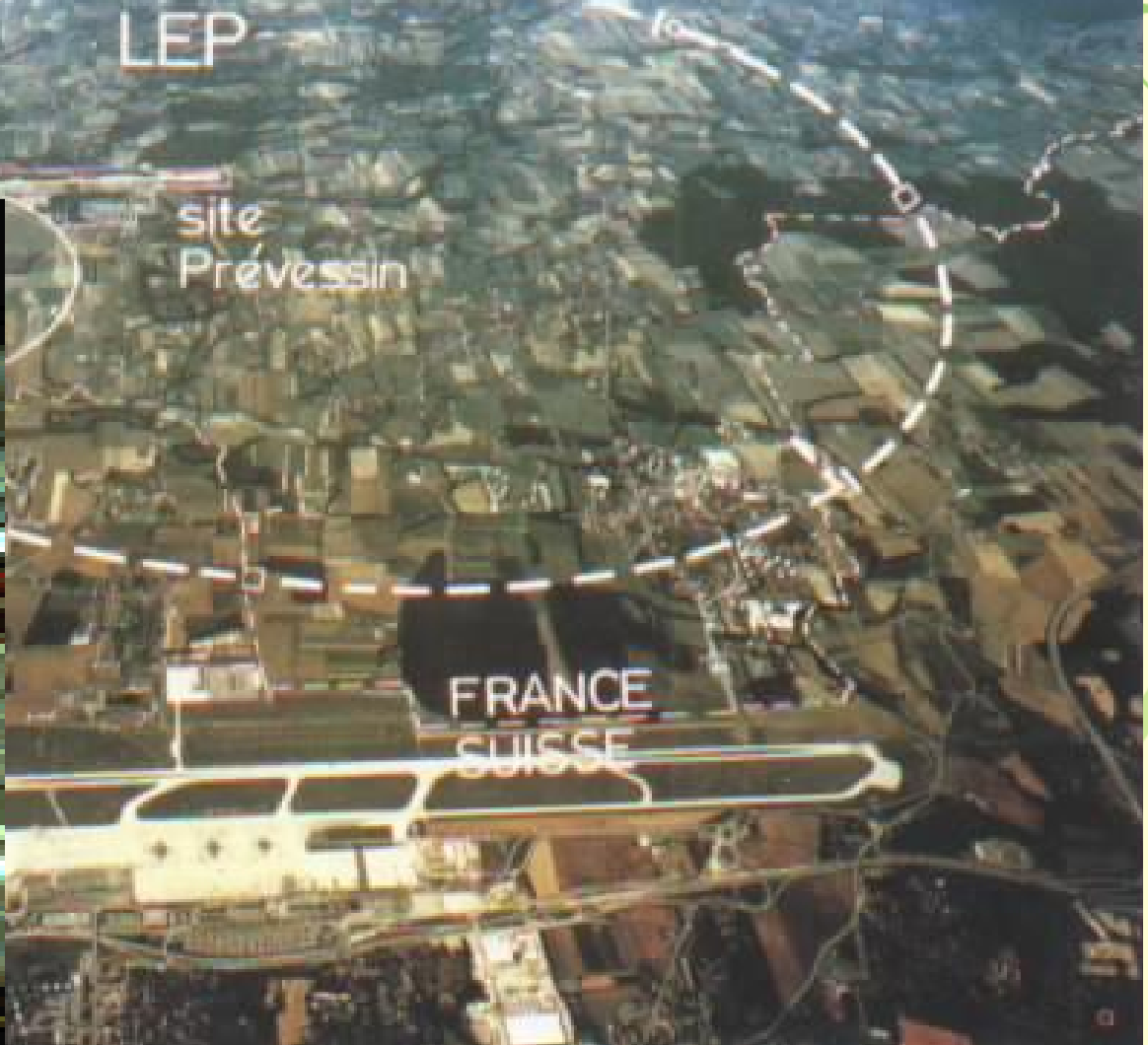
# LEP: *Large Electron Positron collider*



$C=27\text{km}$  single-ring

$E=2\times 100\text{GeV}$

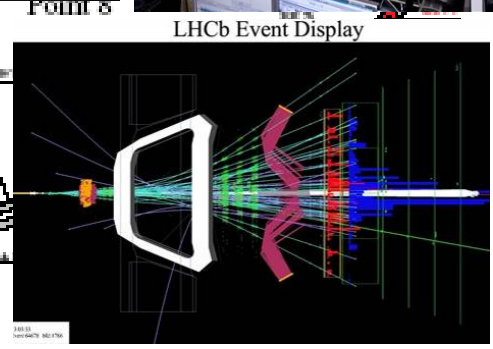
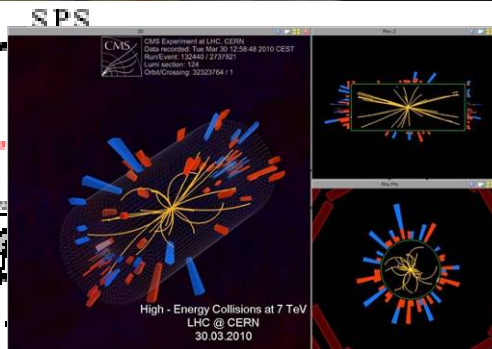
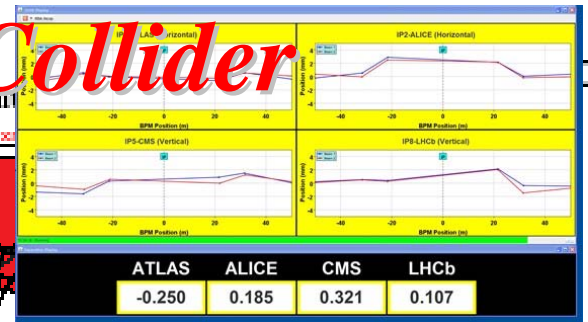
$L=1 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$







# LHP: Large Hadron Collider



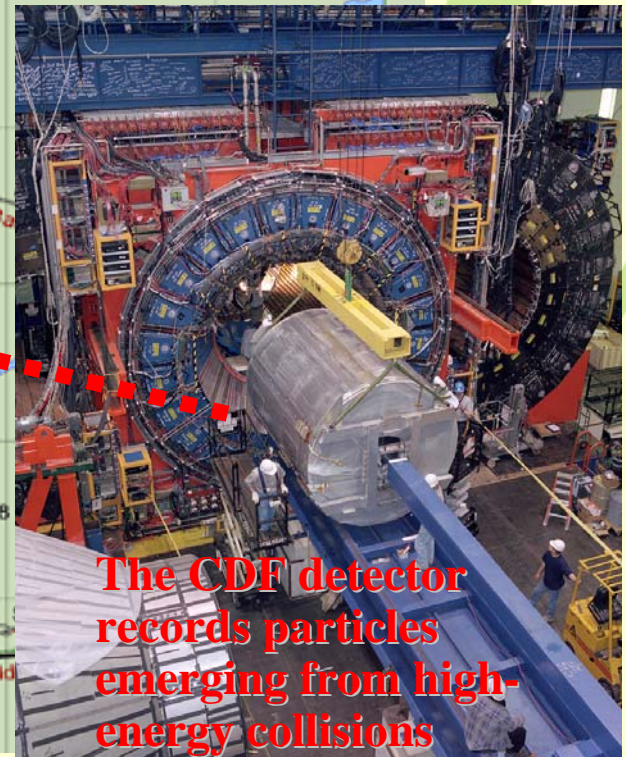
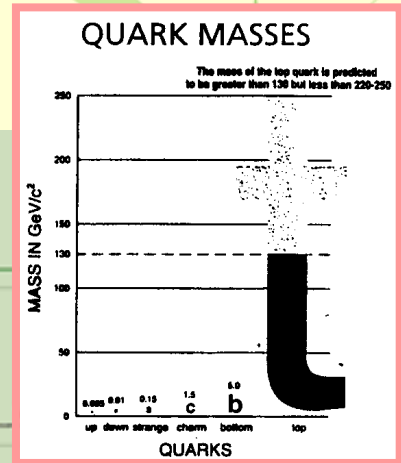
ATLAS



# Tevatron at FNAL



**$C=6.3\text{km}$  single-ring**  
 **$E_{CM}=2\times 0.98\text{ TeV}$**   
 **$L=3.55\times 10^{32}\text{cm}^{-2}\text{s}^{-1}$**





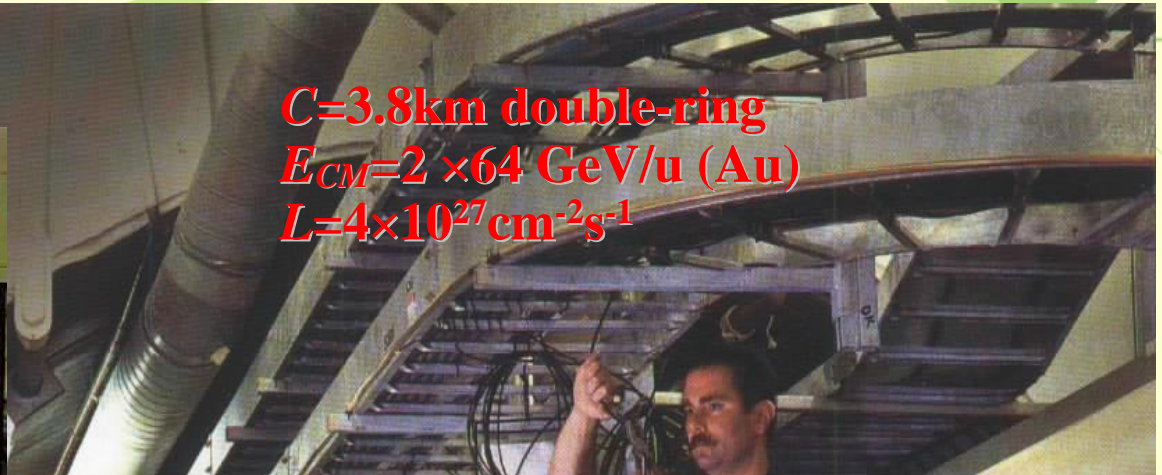
# DESY and HERA



$C=6\text{km}$  double-ring  
 $E=820\text{ GeV}(p)+30\text{ GeV}(e)$   
 $L=2\times 10^{31}\text{ cm}^{-2}\text{ s}^{-1}$

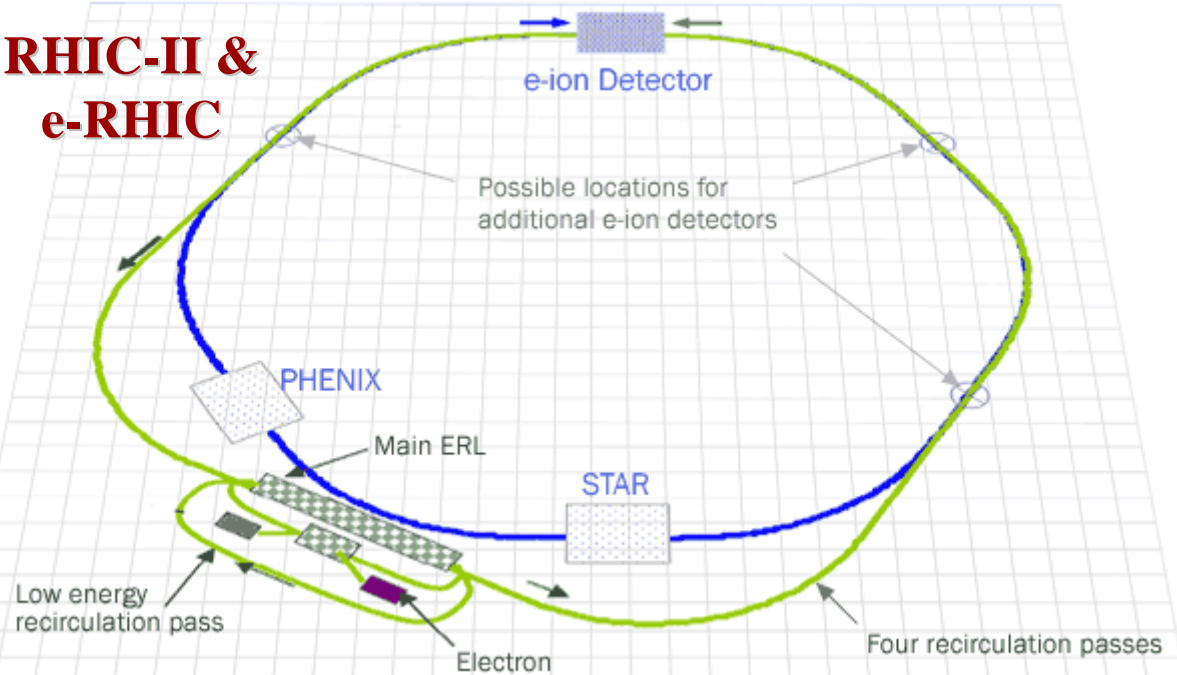


# RHIC of BNL



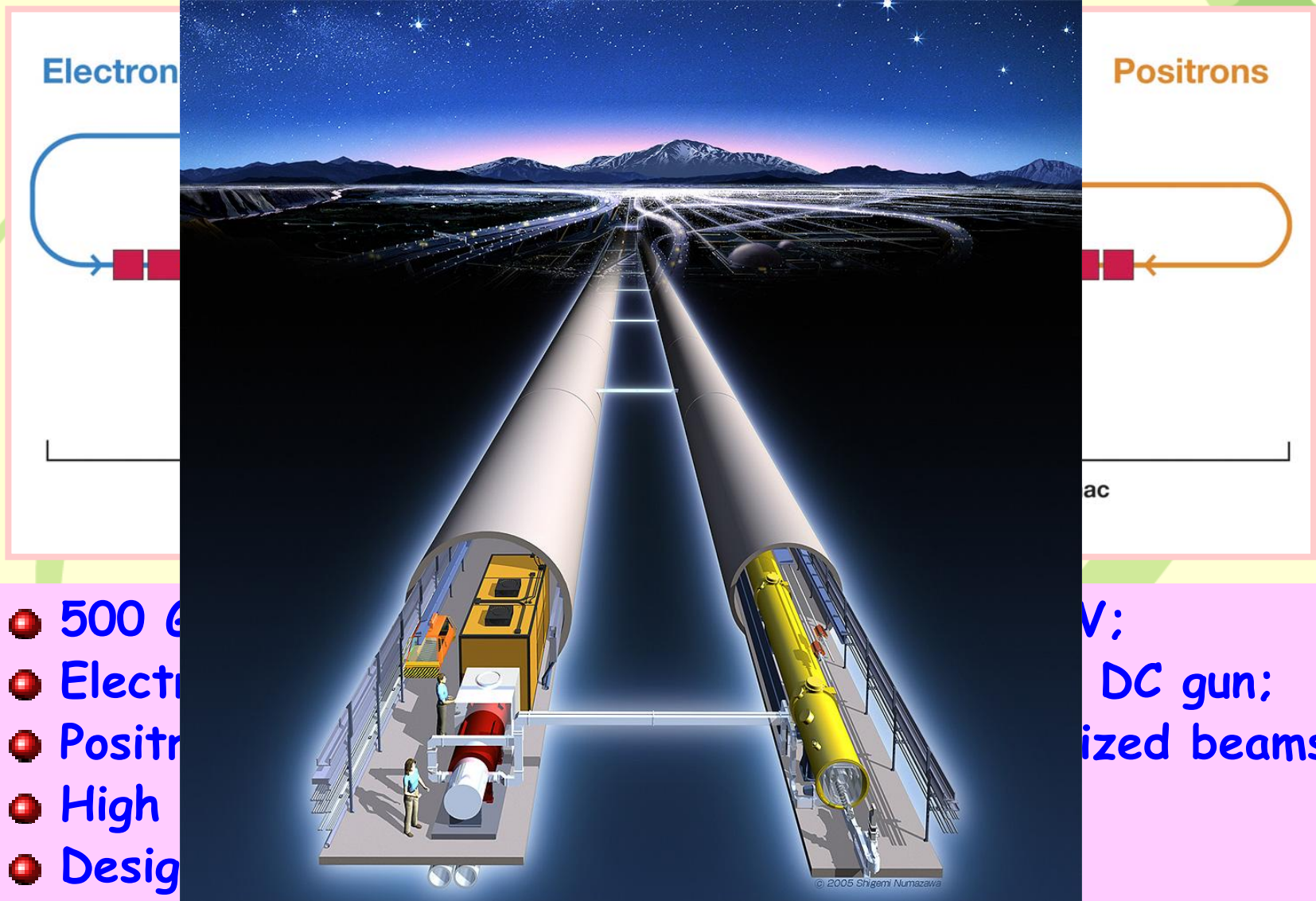
$C=3.8\text{km}$  double-ring  
 $E_{CM}=2 \times 64 \text{ GeV/u (Au)}$   
 $L=4 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$

## RHIC-II & e-RHIC





# International Linear collider

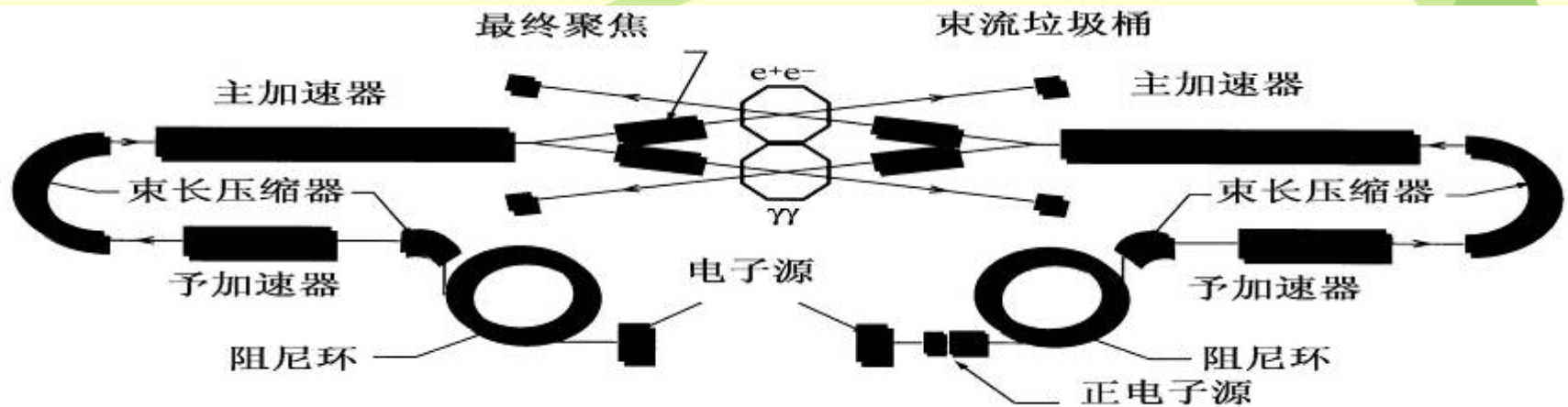


- 500 GeV
- Electron
- Positron
- High
- Design

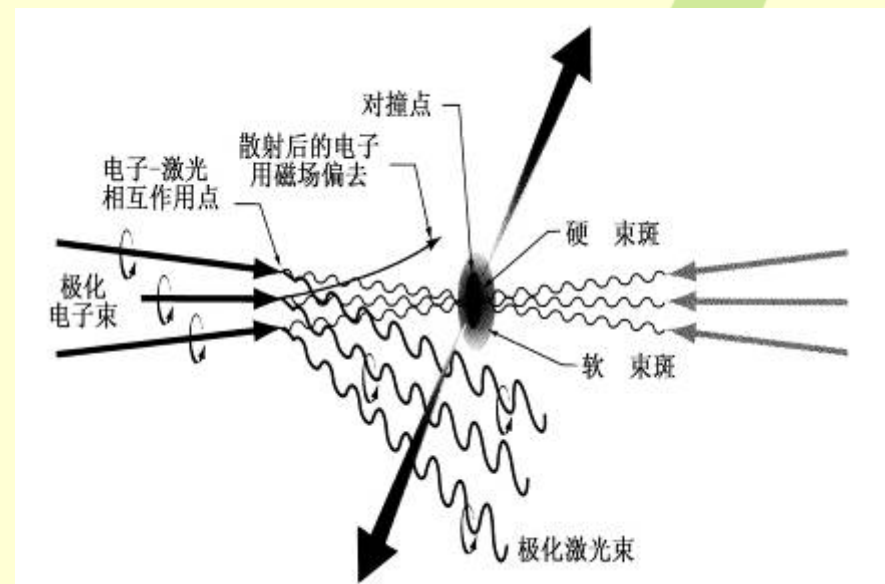
V;  
DC gun;  
ized beams;



# $\gamma\text{-}\gamma$ Collider



Beam Energy $E$	250 GeV
Particle per bunch	$0.65 \times 10^{10}$
Overall Length	$\sim 10$ km
Repitition	180Hz
Bunch Length	0.1 mm
Beam Size at IP	$71\text{nm} \times 9\text{nm}$
Polarization	All and adjustable
Distance if X-e IP and $\gamma\text{-}\gamma$ IP	5 mm
$e^+e^-$ Luminosity	$\sim 1 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$
$\gamma\text{-}\gamma$ Luminosity	$\sim 1 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$





# $\mu^+ - \mu^-$ Colliders

Exotic

Same as electron,  $m^\pm$  is lepton, but unstable  $t_{m0} \approx 2\text{ms}$

Reasonable

$$m_m = 105 \text{ MeV}, \quad \frac{m_\mu}{m_e} = 206.8$$

$$P_{SR} \propto \frac{1}{\rho} \left( \frac{E}{E_0} \right)^4, \quad \frac{P_{SR,\mu}}{P_{SR,e}} \approx 10^{-9}, \quad \text{which is negligible}$$

$\Rightarrow m^\pm$  storage ring  $\Rightarrow$  smaller and more effective

$$t_m = g t_{m0}, \quad E = 2\text{TeV}, \quad g = 20000, \quad t_m = 40\text{ms}, \quad N = t_m / T_{rev} \approx 1500$$

$$\sigma(\mu^+, \mu^- \rightarrow \text{Higgs}) \propto m^2 \Rightarrow \frac{\sigma_{\mu^\pm}}{\sigma_{e^\pm}} \approx 40000$$

hadrons,  $m, n, K \dots \Rightarrow$  Chance for new physics discovery

Challengeable

$$t_{m0} \approx 2\text{ms}, \quad t_m = 40\text{ms} \quad @ 2\text{TeV}$$

$$\Rightarrow V_{RF} \propto dE/dt, \quad \text{difficulty, cost...}$$

very fast cooling  $\Rightarrow$  Ionization cooling

$m^\pm$  Decay  $\Rightarrow$  Background, shielding issues.....

neutrino pollution  $D \propto E^3 \Rightarrow$  very serious @  $E = 2\text{TeV}$

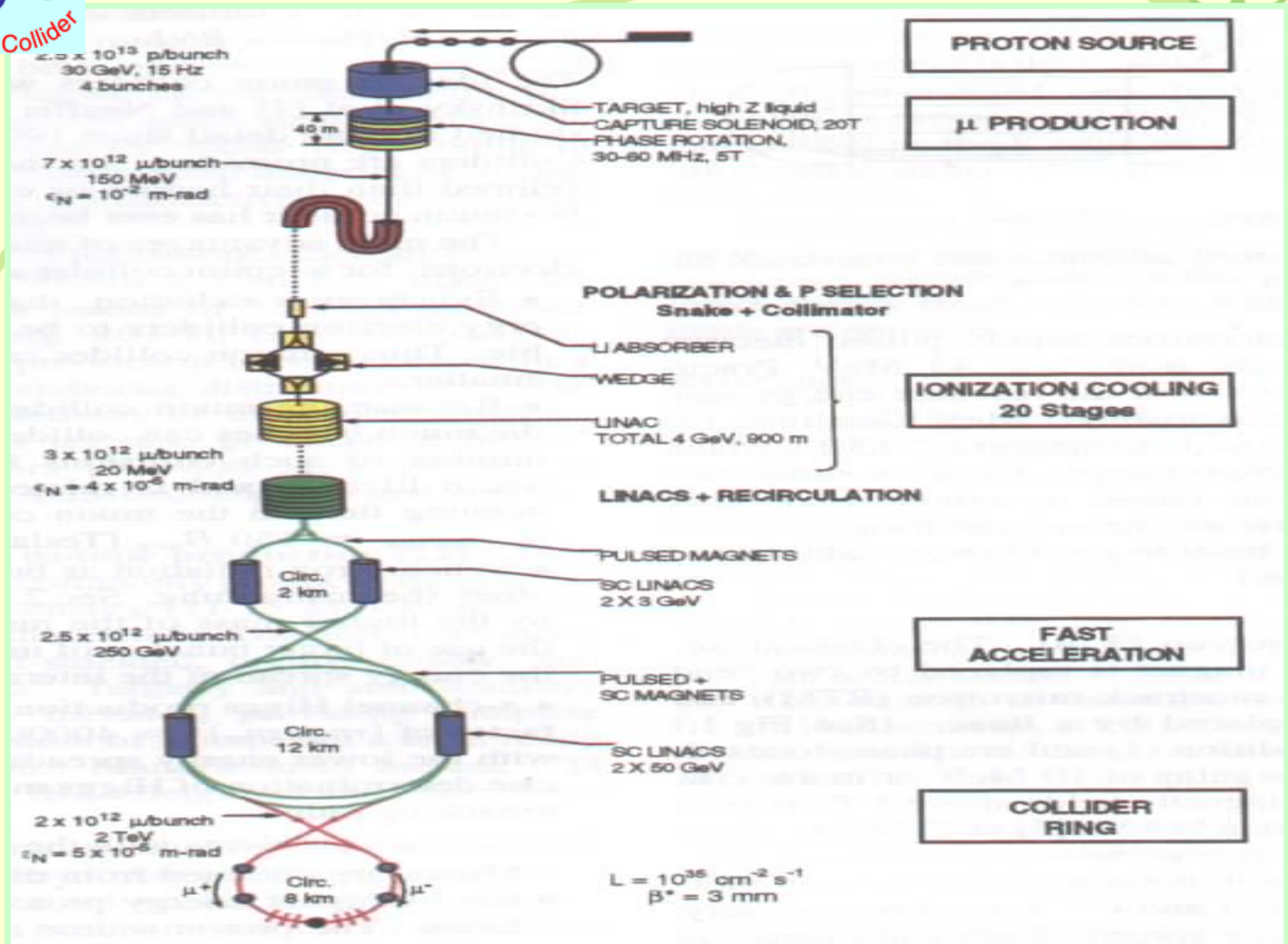
.....

Being studied

P.Chen (SLAC), Y.Cho(ANL) K.Y.Ng, Z.Qian (FNAL),  
Y.Zhao, H.Wang, H.Ma (BNL), Q.S.Shu (CEBAF), D.Li (LBL) .....



# A schematic diagram of $E=2 \times 2 \text{ TeV } \mu^+ \mu^-$ Collider



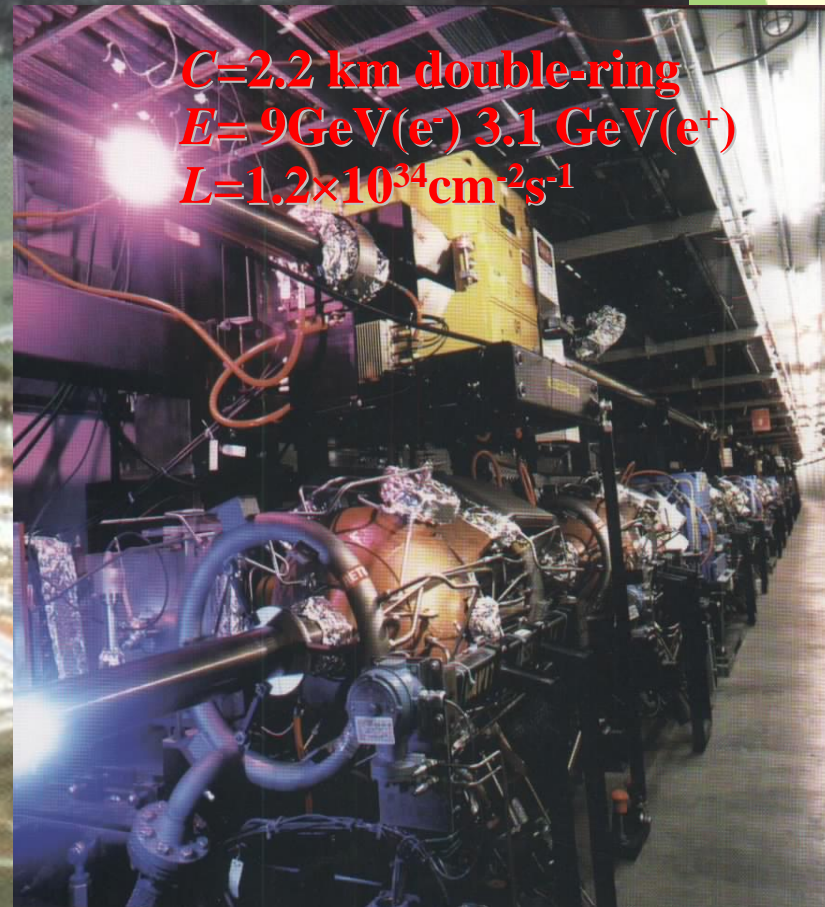


## 3.2 High luminosity frontier

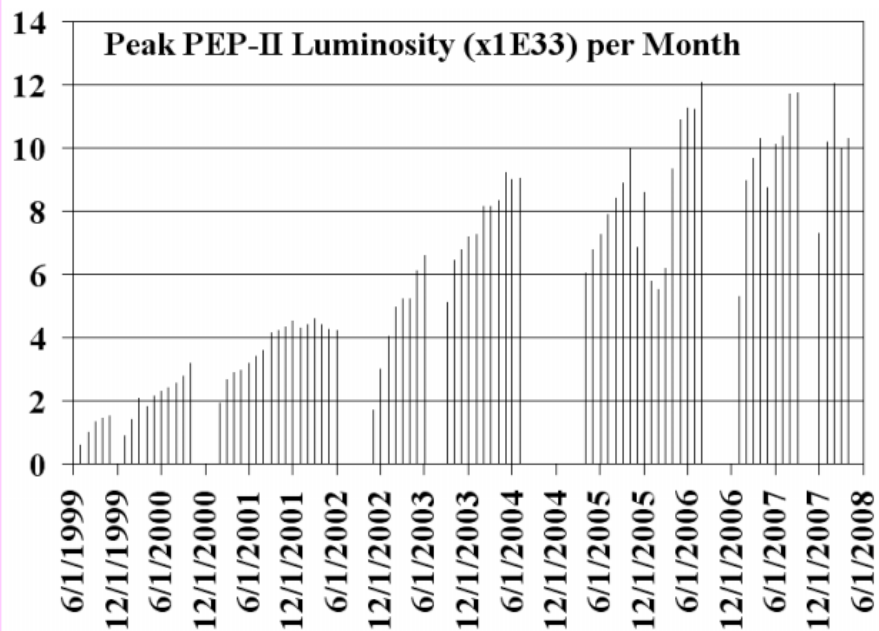
- ✚ After discovery made with pioneer accelerators, more detail and accurate investigation need to be made in order to extend the discovery with higher statistics, which needs higher luminosity machines;
- ✚ Higher luminosity calls for higher performance colliders with higher current, better final focusing, and usually double-ring structure...
- ✚ Challenge to accelerator physics and technology: beam instabilities and impedance, injection, interaction region, vacuum, accurate bunch monitoring ...



# PEP-II at SLAC



$C=2.2$  km double-ring  
 $E=9\text{ GeV}(e^-) 3.1\text{ GeV}(e^+)$   
 $L=1.2\times 10^{34}\text{ cm}^{-2}\text{ s}^{-1}$

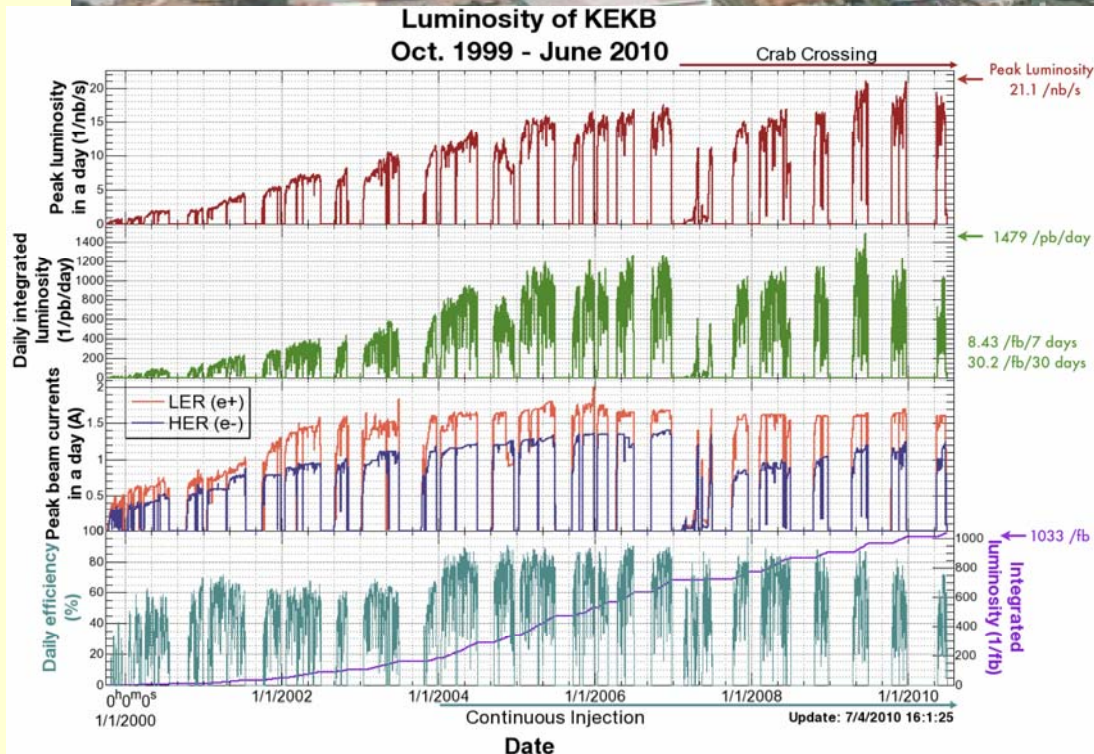




# KEK and KEKB



**$C=3$  km double-ring**  
 **$E=8\text{GeV}(e^-) 3.5\text{GeV}(e^+)$**   
 **$L=2\times 10^{34}\text{cm}^{-2}\text{s}^{-1}$**





# Super B-Factories



Crab cavity

Crab crossing  
small  $\beta$

Ante-chamber

[NEG Pump]

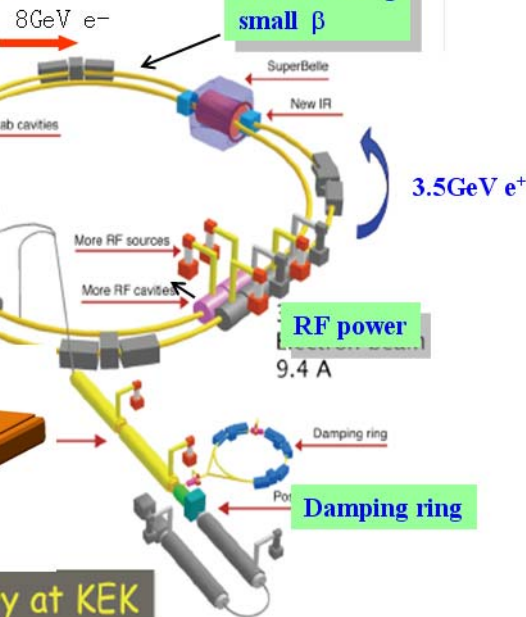
beam

SR

[SR Channel]

[Beam Channel]

Super B Factory at KEK

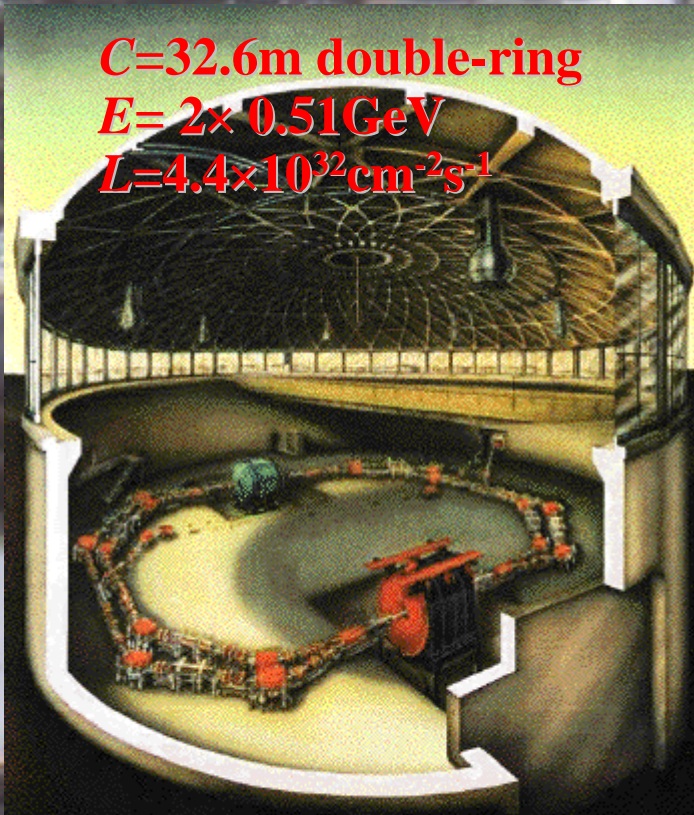


Tune shift x		0.0021	0.0033	0.0017	0.0025	0.0044	0.0067	0.0052	0.0080
Tune shift y		0.097	0.097	0.0891	0.0892	0.0684	0.0687	0.0909	0.0910
Total RF Wall Plug Power	MW	16.38		12.37		28.83		2.81	



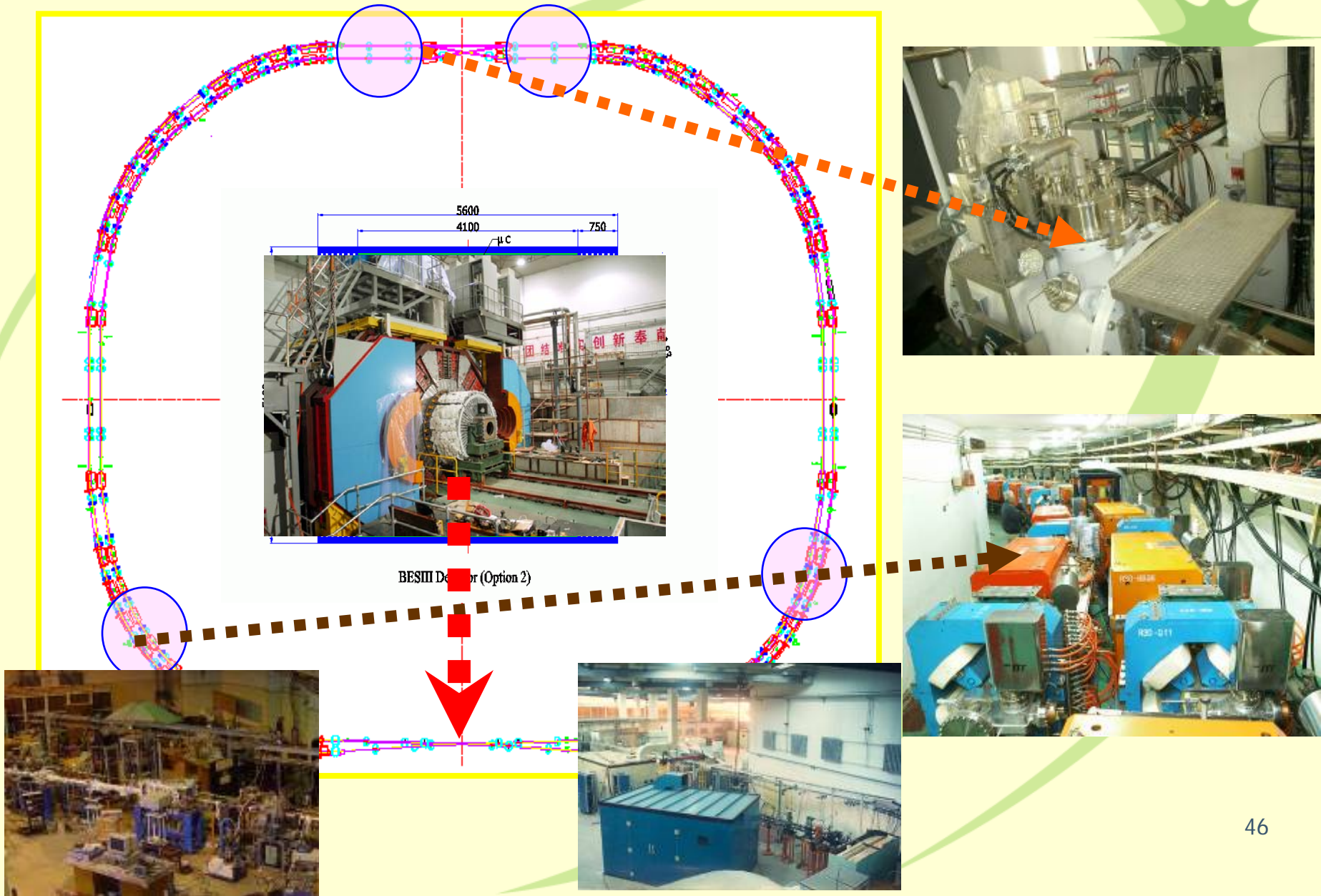
# LNF-DAFNE

$C=32.6\text{m}$  double-ring  
 $E=2\times 0.51\text{GeV}$   
 $L=4.4\times 10^{32}\text{cm}^{-2}\text{s}^{-1}$





# BEPCII: a double-ring $e^-e^+$ collider for charm- $\tau$ physics









## **3.3 Multidisciplinary platforms**

- **Synchrotron radiation sources**
- **Free electron lasers**
- **Energy Recovery Linac**
- **Spallation neutron sources**



## 3.3.1 Synchrotron Radiation Sources



- *Energy loss per turn:*

$$U_0(\text{keV}) = 88.5 \frac{E(\text{GeV})^4}{\rho(\text{m})}$$

BEPC:  $E=2.8\text{GeV}$ ,  $r=10.345\text{m}$ ,  
 $U_0=526\text{keV}$

- *Critical energy:*

$$u_c(\text{keV}) = 0.665 E^3(\text{GeV}) B(\text{T})$$

- *Radiation damping*

- $z$ : Higher the  $E$  more the  $U_0$

- $x$  &  $y$ :  $\Delta x', \Delta y' \neq 0$ ,  $(\Delta x', \Delta y')_{\text{RF}} = 0$

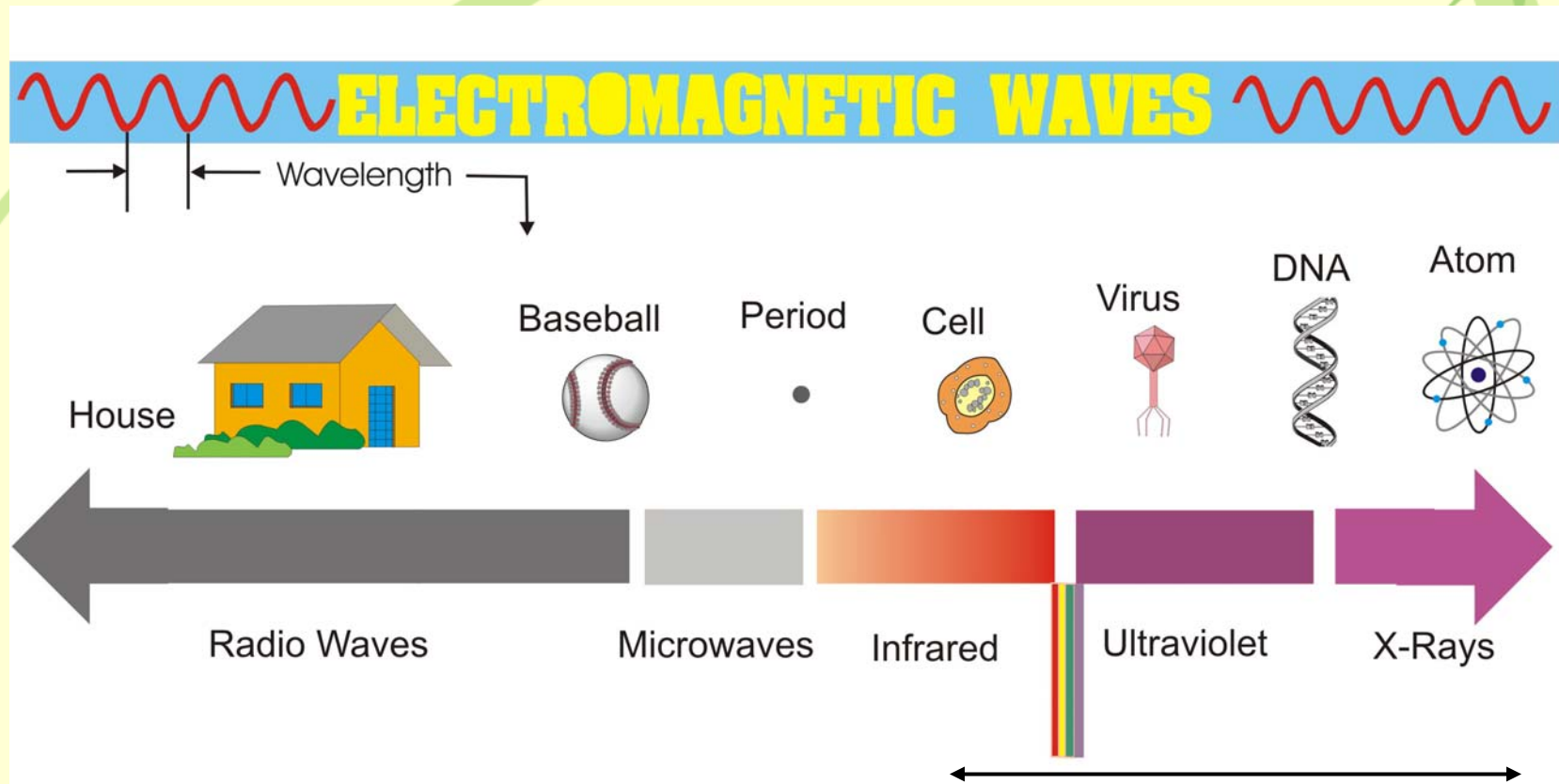
- *The Damping time*

$$\tau_{x,y,e}(\text{ms}) = \frac{C(\text{m})\rho(\text{m})}{13.2 J_{x,y,e} E^3(\text{GeV})}$$



# Electromagnetic Radiation

## *How it relates to the world we know*



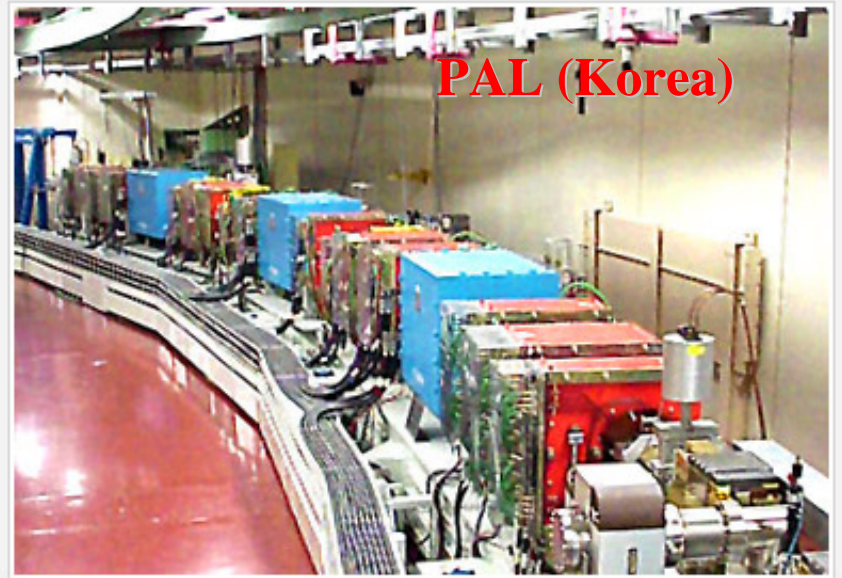
Synchrotron radiation is  
used for experiments  
typically over this region



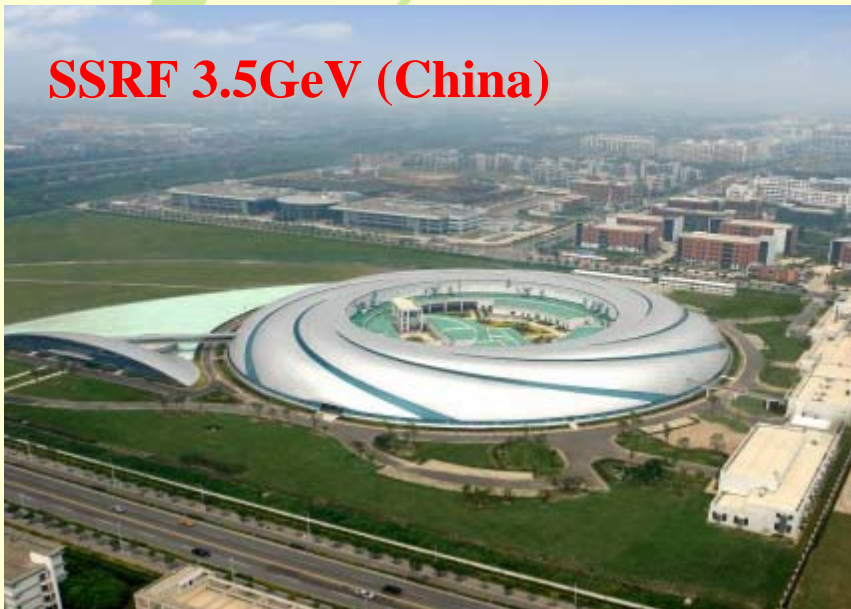
**Spring-8 8GeV (Japan)**



**PAL (Korea)**



**SSRF 3.5GeV (China)**



**SSRC 1.5GeV (Taiwan)**





**Indus-2 2.5GeV (India)**



**SIAM 1GeV (Thailand)**



**SSLS 0.5GeV (Singapore)**



**SESAME 2.5GeV (Jordan)**



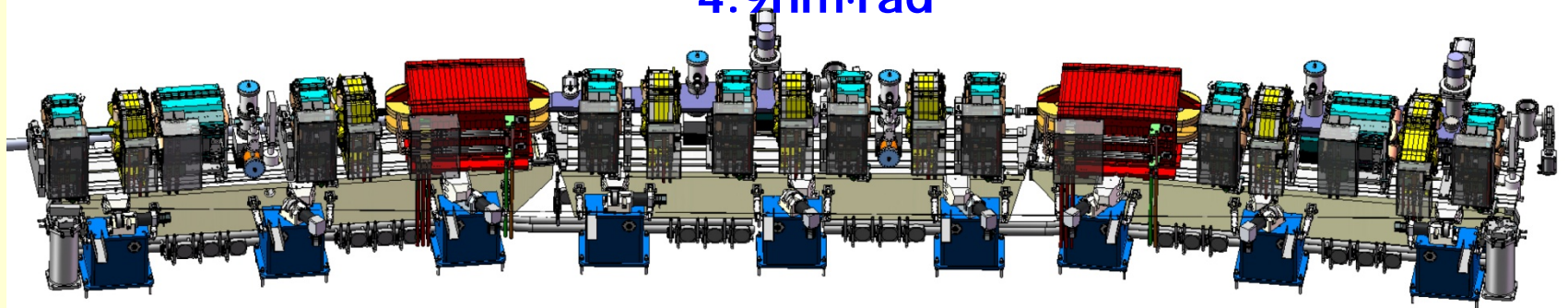


TPS



**TPS** 台灣光子源規劃構想  
*Taiwan Photon Source*

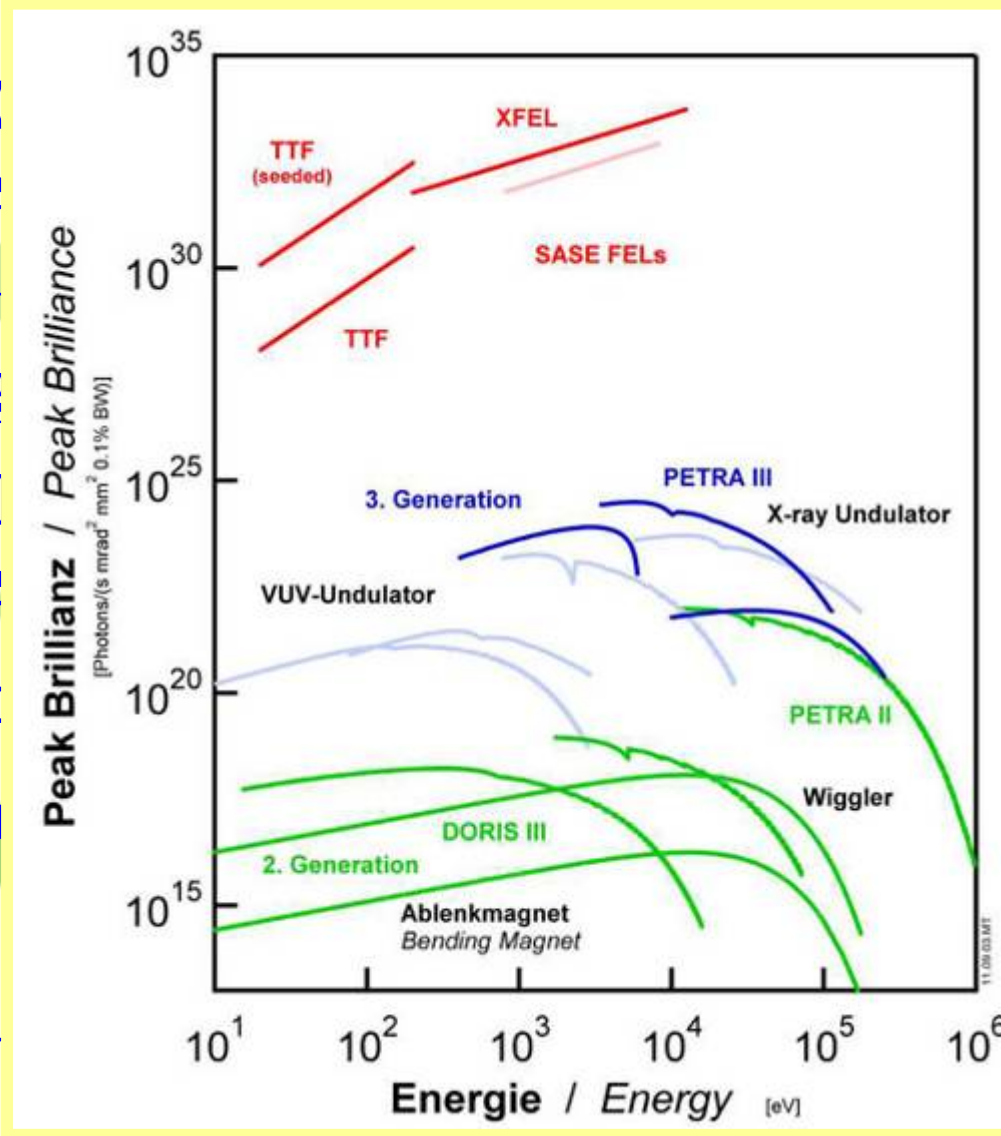
3GeV, 1.6–  
4.9nm·rad





## 3.3.2 Free Electron Lasers (FEL)

- FEL (Free Electron Laser) accelerates electrons to high energies (GeV) and then passes them through a series of bending magnets (BMs) and wigglers (WGs) to produce a beam of light (photons) of a specific wavelength (from the IR to the X-ray).
- The “third generation” FELs (3. Generation) are the most powerful and brightest (peak brilliance) in the world.
- Two of the most powerful and brightest (peak brilliance) in the world are the PETRA III and DORIS III.
- China is building a new FEL (Free Electron Laser) in Shanghai.
- From 1960 to 1990, many FELs were built in the US, Europe, and Japan.



rons of  
e electrons  
e ...  
ne IR and  
d X ray).  
on.  
GHG.

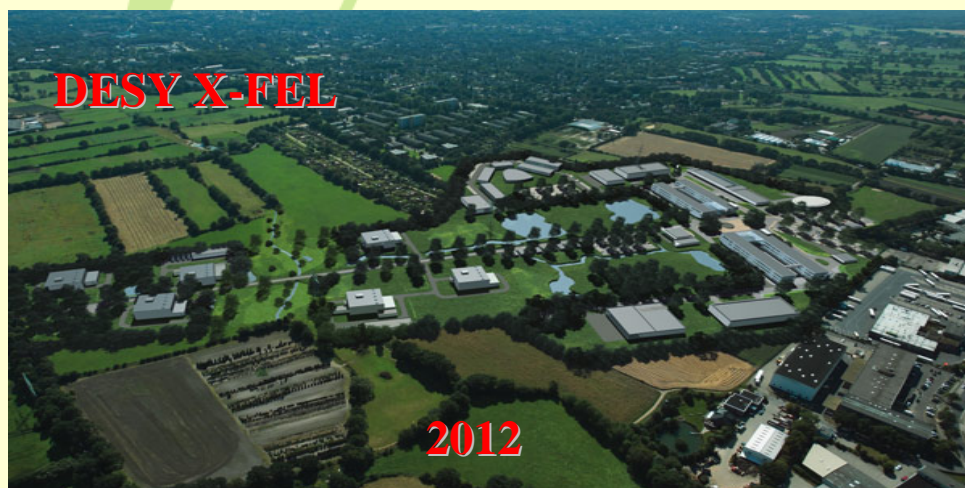
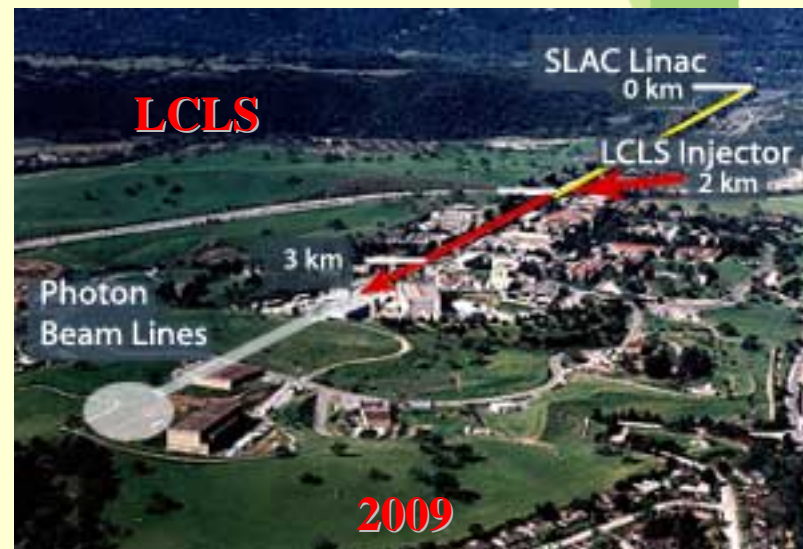


# XFELs coming soon

**X-Ray Free-Electron Laser Projected Parameters**

	LCLS (US)	DESY XFEL (Europe)	SCSS (Japan)
Pulse duration	<230 fs	100 fs	80 fs
Wavelength	1–64 Å	1–15 Å	1–50 Å
Repetition rate	120 Hz	10 Hz	60 Hz
Electron bunches per pulse	1	≤3000	1
Electron beam energy	4–14 GeV	≤20 GeV	≤8 GeV
Photons per pulse ( $\times 10^{13}$ )	1.2 (at 1.5 Å)	1.2 (at 1 Å)	0.76 (at 1 Å)
Linac length	1 km	2 km	350 m
Estimated cost*	\$379 million	\$1 billion	\$330 million
Estimated start date	2009	2012	2010

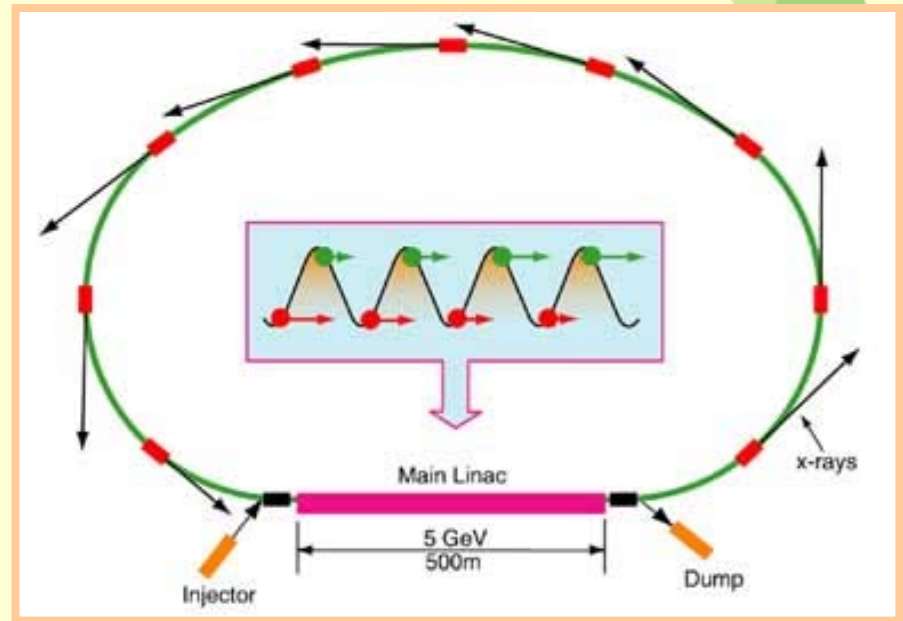
\*Estimates include varying amounts of instrumentation and different methods of accounting.



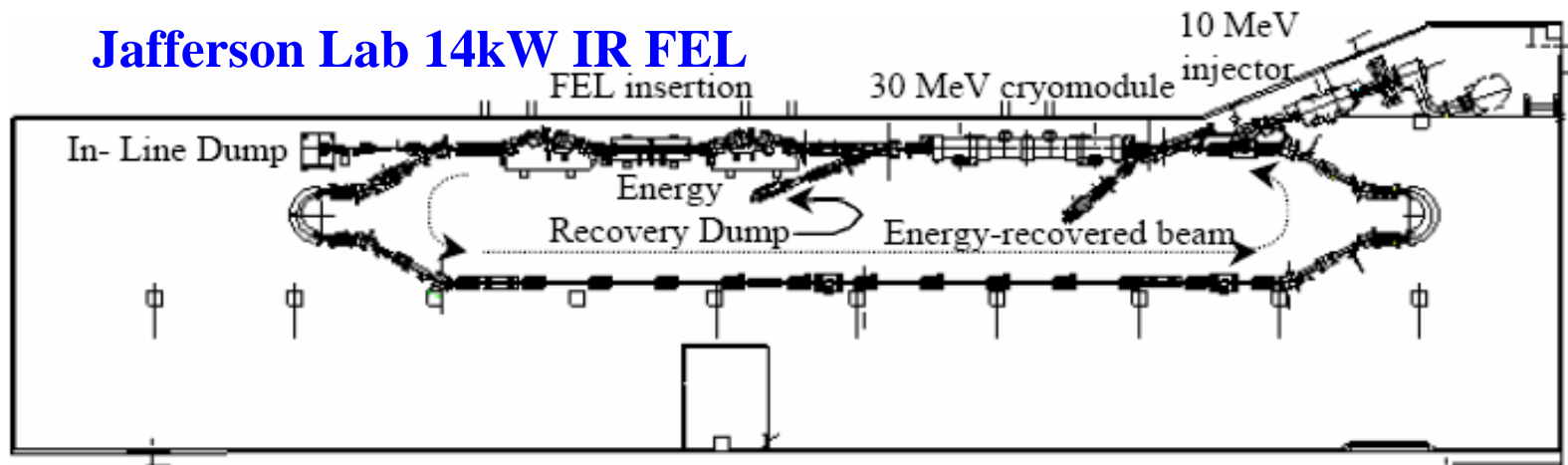


### 3.3.3 Energy Recovery LINAC (ERL)

- Very high average brilliance ➡  $\sim 10^{23}$  ph./mm<sup>2</sup>/mrad<sup>2</sup>/0.1%/s ;
- Many beamlines ➡ more users;
- Femto-second pulse with high repetition ➡ molecular dynamics...
- Coherence ➡ Imaging of non-crystalline materials ...



#### Jafferson Lab 14kW IR FEL

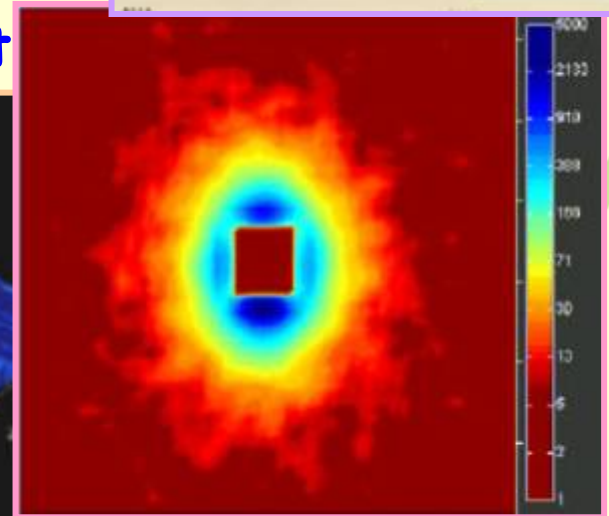
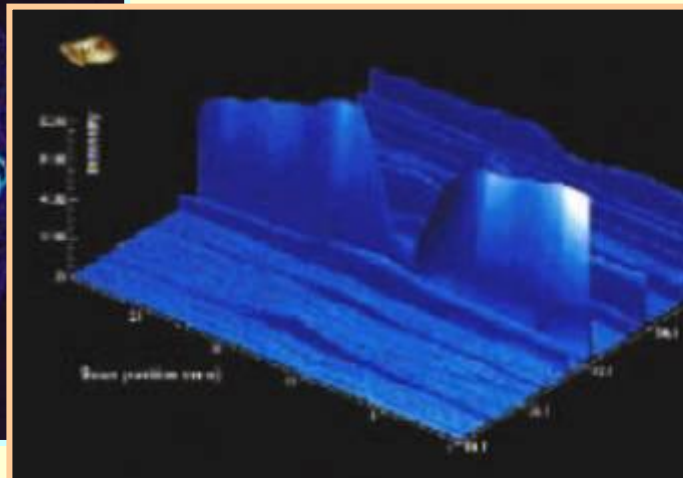
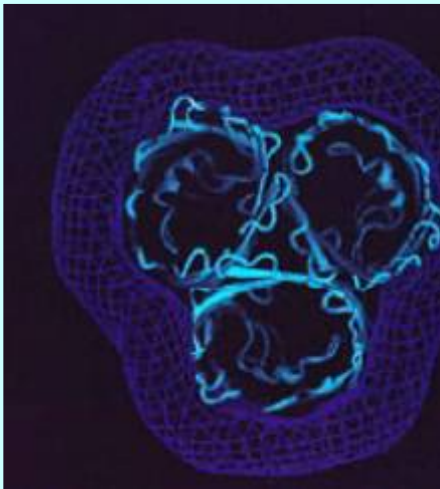
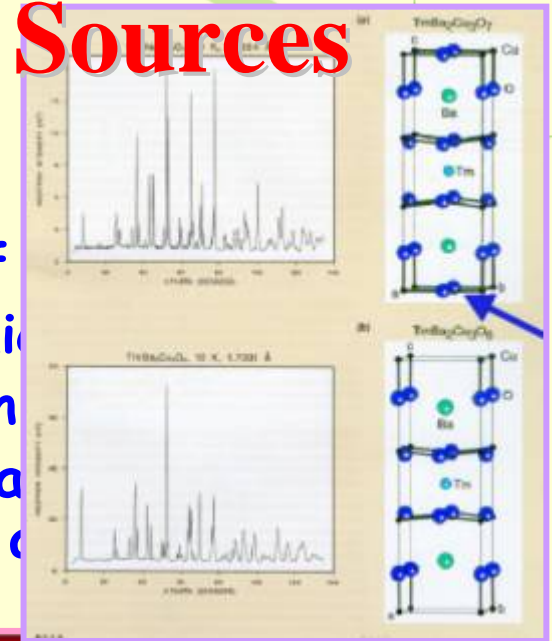
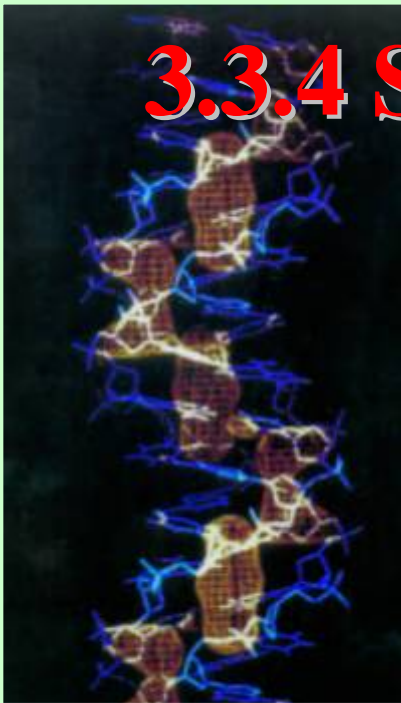




# 3.3.4 Spallation Neutron Sources

neutrons show unique properties:  
 no magnetic moment in spite of  
 length of the order of interatomic  
 able to collective excitations in  
 t to reactor source, SNS is a  
 h resolution, low background  
 energy.

complementary with synchrotron

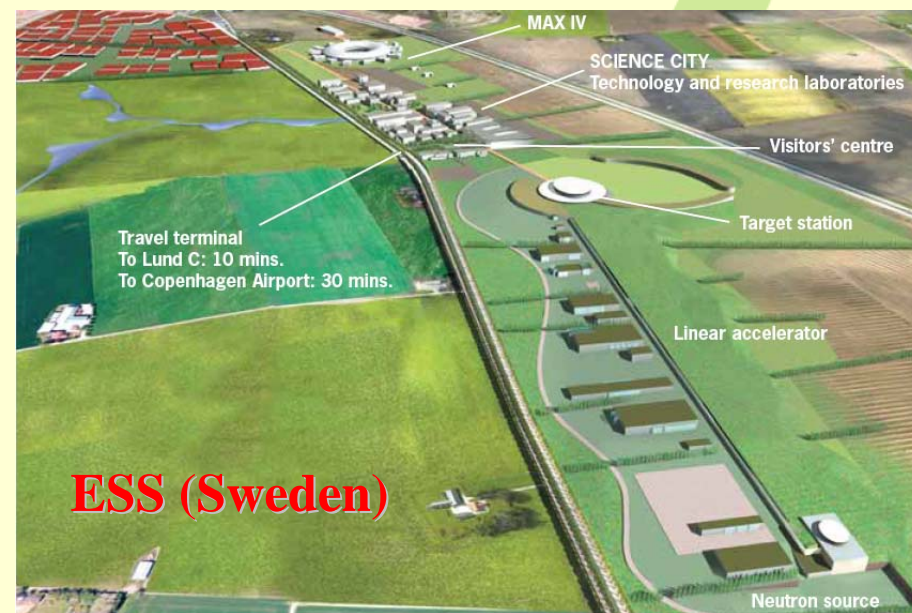
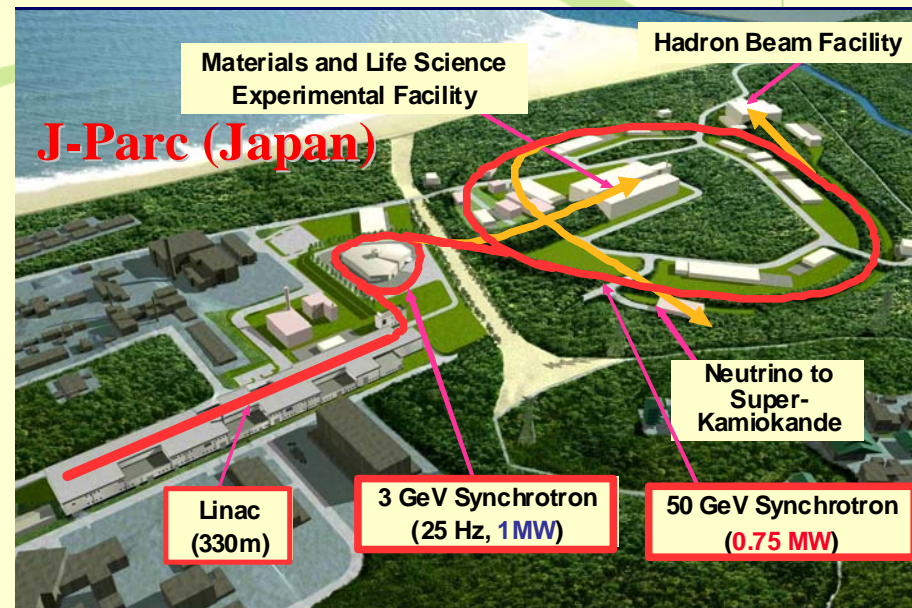




# Existing and planned spallation neutron sources

Name	Status	Beam Energy (GeV)	Ave.Beam Power (MW)	Repetition rate (Hz)	Proton per pulse ( $10^{13}$ )	Pulse length ( $\mu$ s)
IPNS ANL	Operat. 1981	0.05 linac 0.5 RCS	0.0075	30	0.3	0.1
ISIS RAL	Operat. 1981	0.07 linac 0.8 RCS	0.16	50	2.5	0.45
SINQ PSI	Operat. 1981	0.59 Cyclotron	$\leq 0.9$	CW	-	-
LANCE LANL	Operat. 1981	0.8 linac	0.08	20	3	0.27
LANCE II LANL	Plan	0.8 linac	1.0	30	-	1200
SNS US	Operation	1.0 linac A.R.	$1 \rightarrow 5$	60	10	0.55
J-Parc	Operation	0.4 linac 3.0RCS	1.0	25	8.3	<1
ESS Europe	Plan	1.33 linac A.R.	5.0	50	47	1
CSNS China	Plan	0.08 linac 1.6 RCS	$0.12 \rightarrow 0.5$	25	2	0.4







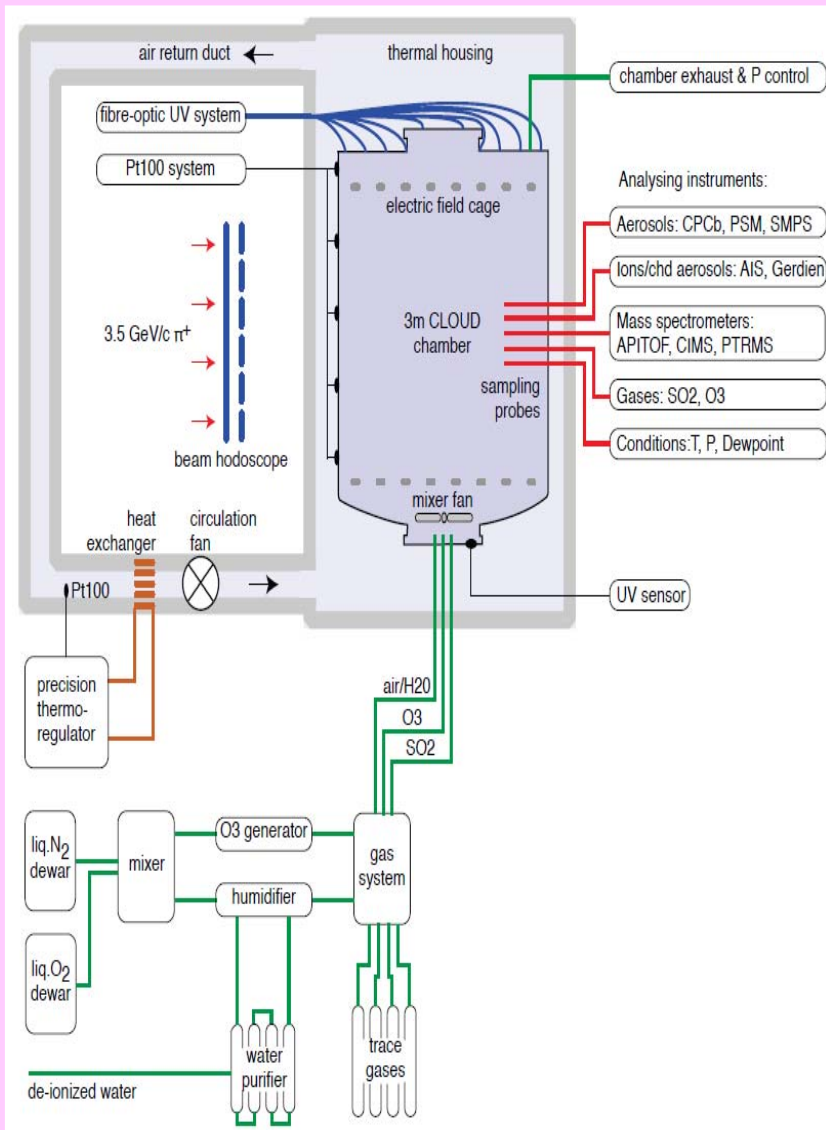
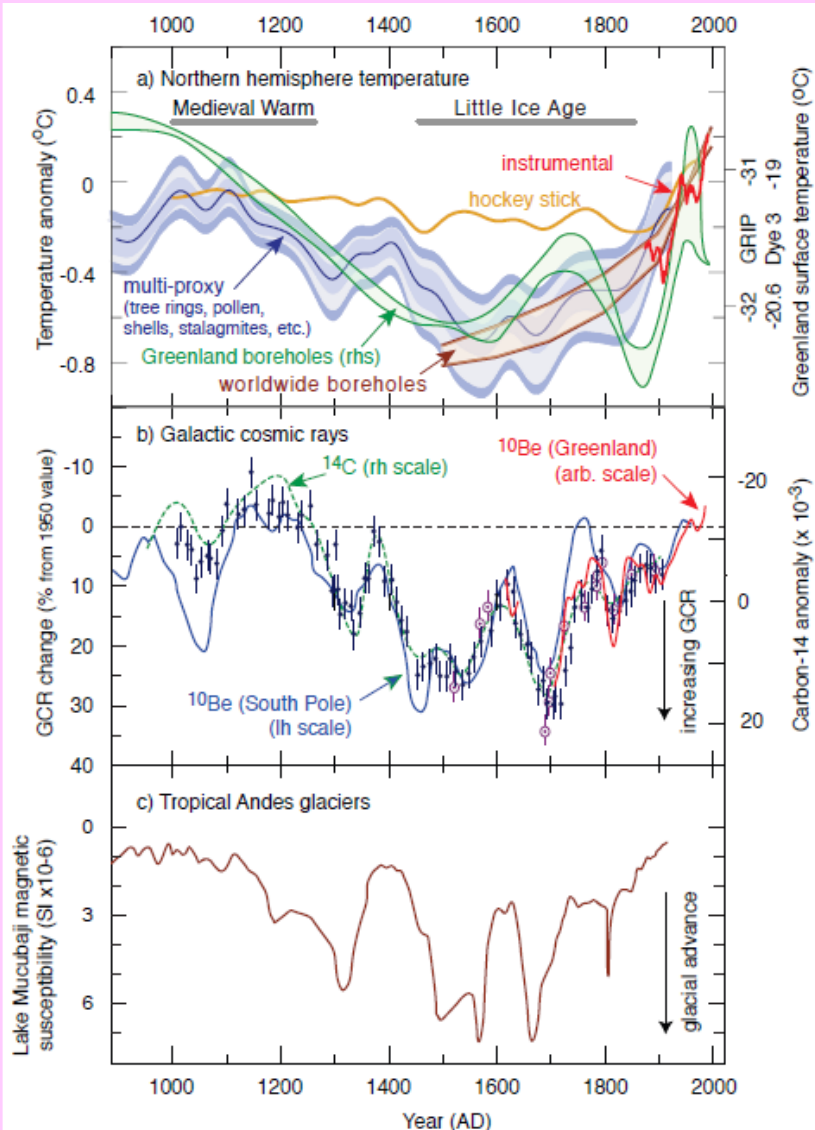
## **3.4 Application of accelerators**

Although accelerators were developed for particle physics, many thousands of them are put to practical uses in other branches of scientific research as well as in industry, agriculture, medicine and many other fields of our society.

- **Accelerator Driven Sub-critical reactor**
- **Nuclear waste transmutation**
- **Medical accelerators**
- **Irradiation**
- **Non-destructive inspection**

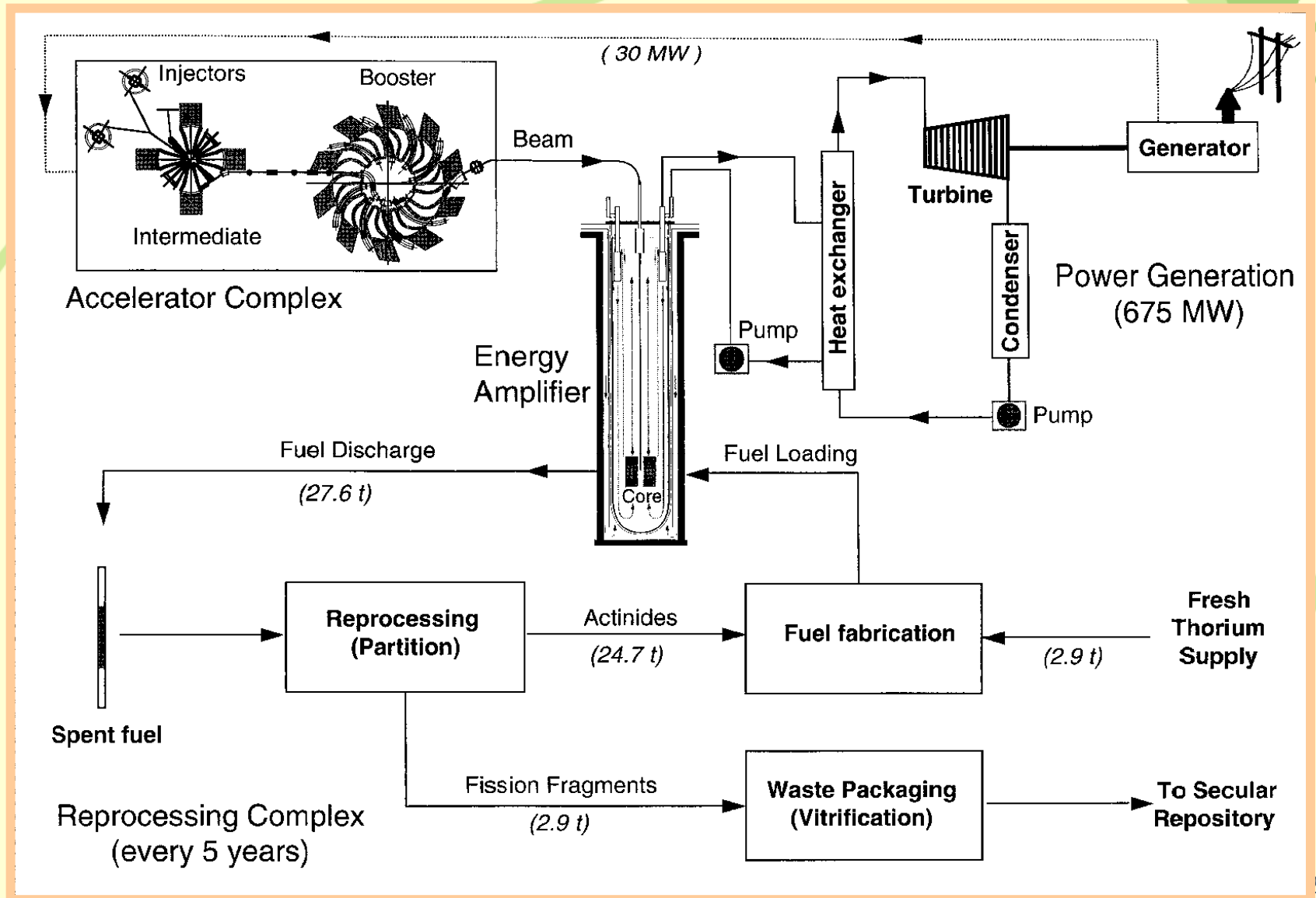


# Messages from IPAC'10



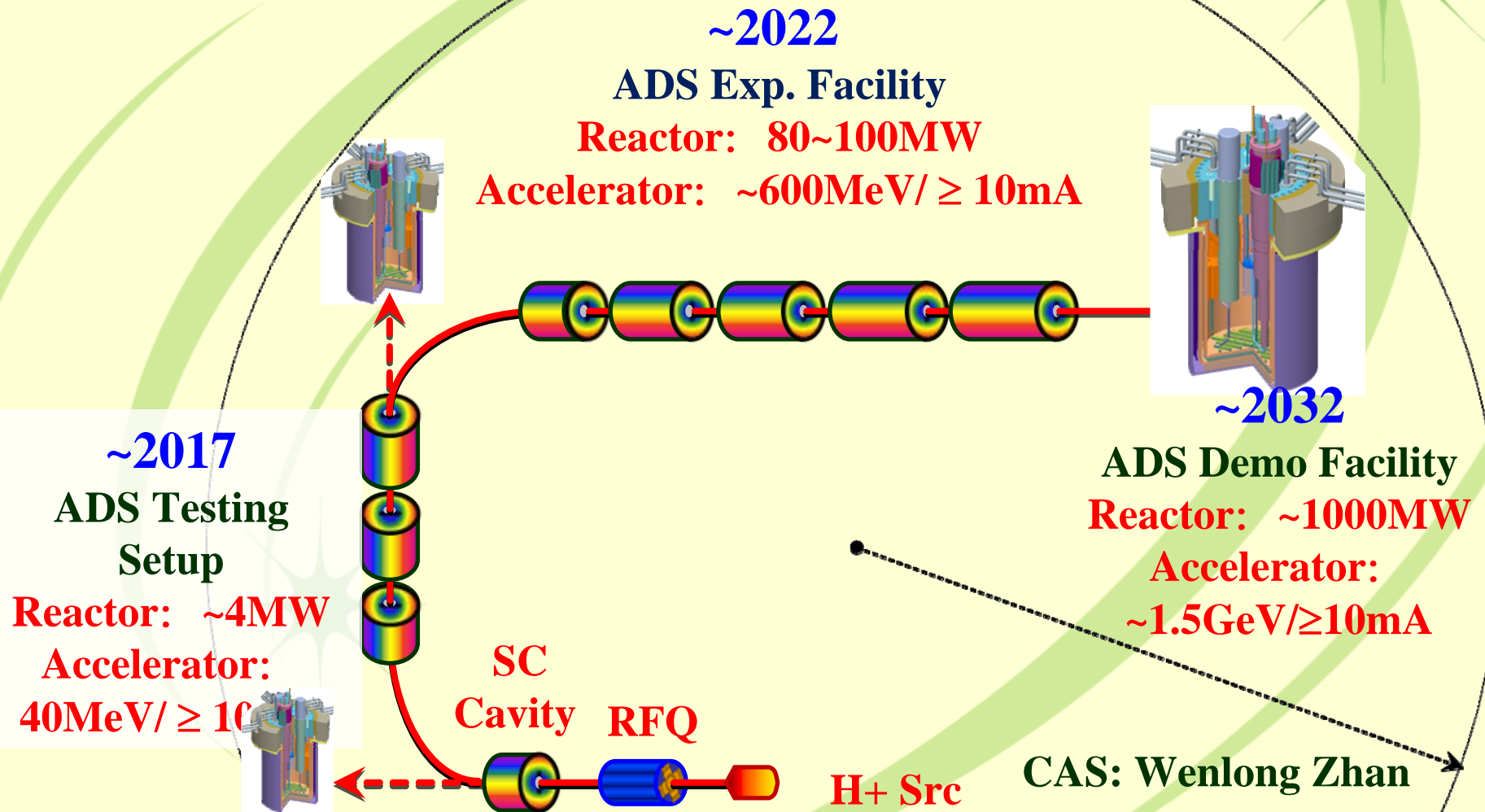


### 3.4.1 Accelerator Driven Sub-critical reactor (ADS)





# China's Roadmap for ADS

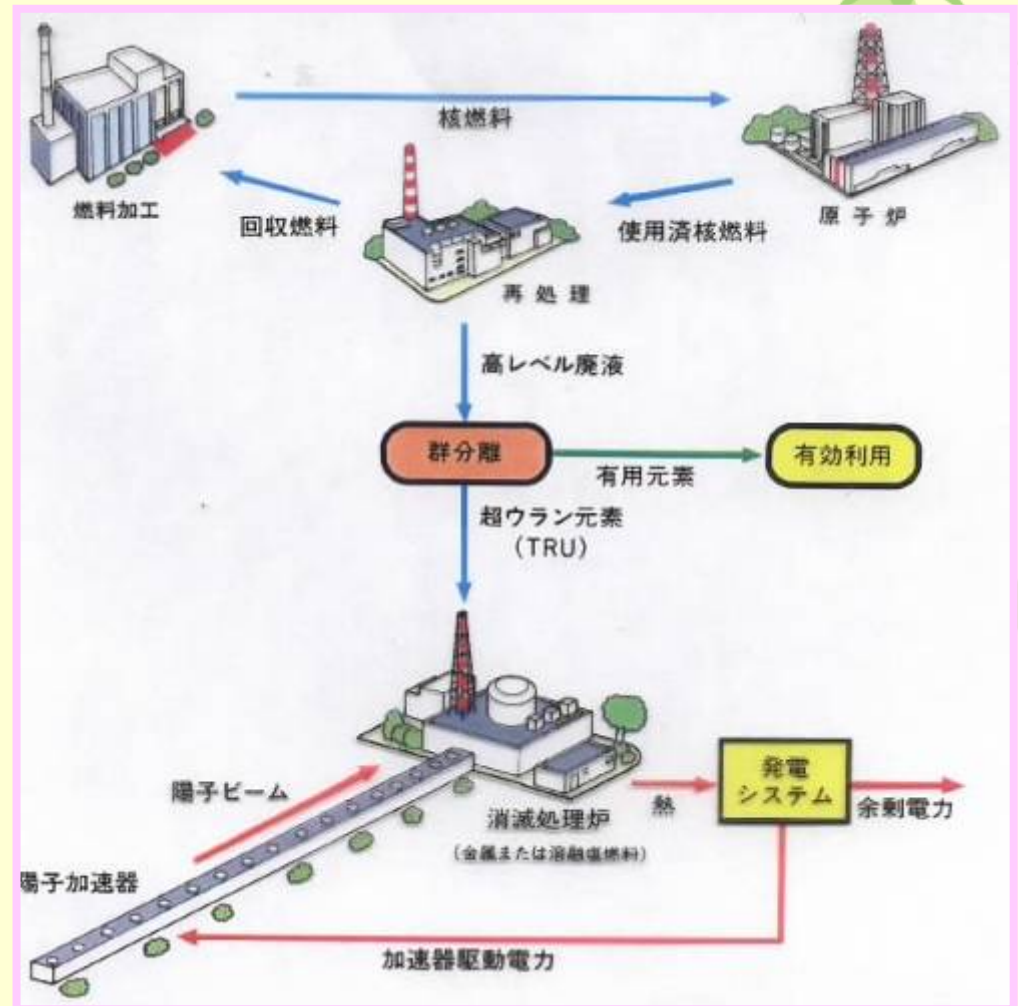


July 7, 2010



## 3.4.2 Nuclear waste transmutation

The concept of energy amplifier is extended to the transmutation of long-lived nuclear waste. The idea is to mix nuclear plutonium waste with the thorium fuel so that it also undergoes fission and breaks up into harmless elements.





### 3.4.3 Medical accelerators





# Heavy Ion Medical Accelerator in Chiba



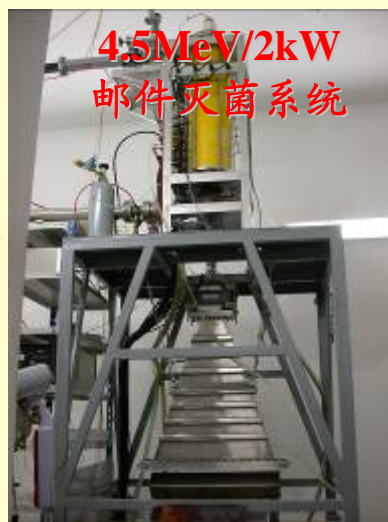
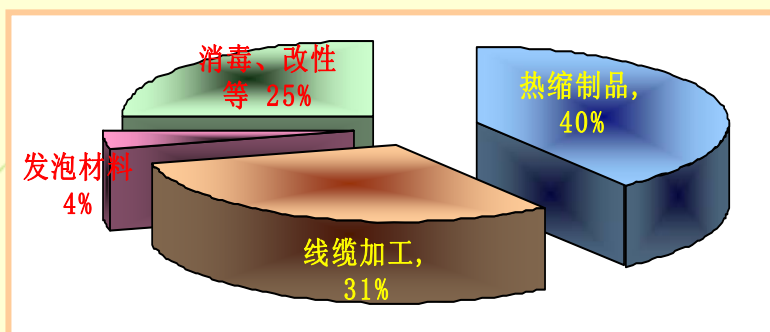


## 3.4.4 Irradiation

据不完全统计，我国已建成的功率在5kW及其以上的工业用电子辐照加速器有100多台，总功率已超过6MW，仅2005年以来的4年里，新增建的加速器辐照生产线约20条。



10MeV/20KW 返波型  
工业辐照加速器



4.5MeV/2kW  
邮件灭菌系统



10MeV大功率  
辐照加速器



2.5MeV/1.2kW车载式电子  
束辐照安全系统

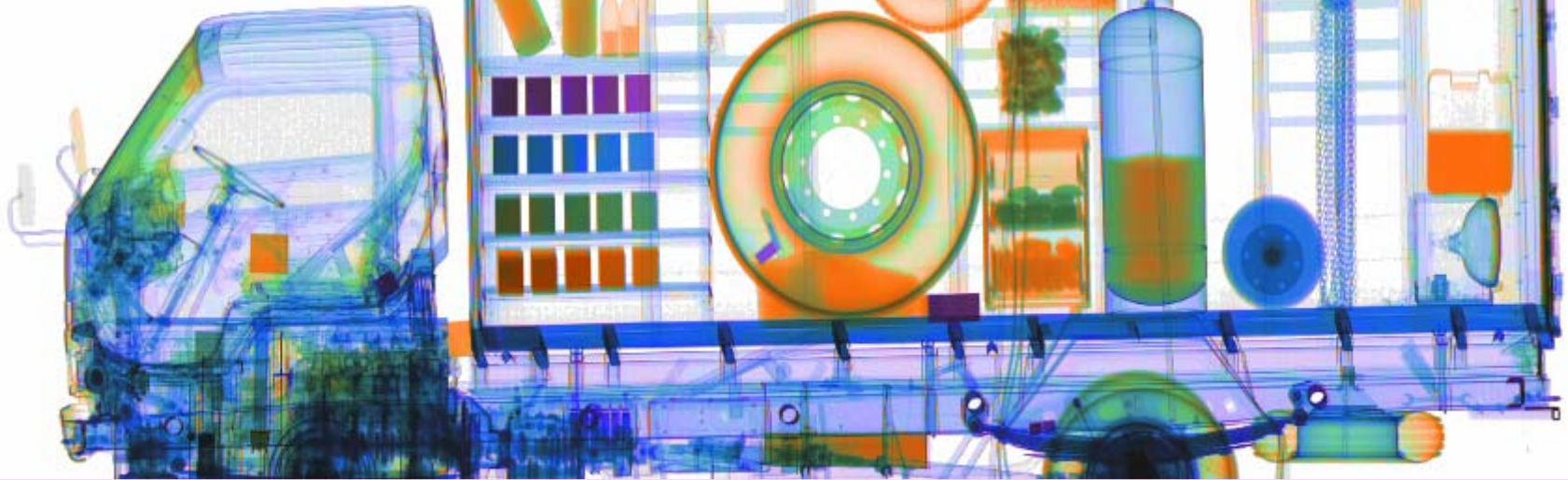


辐照进行时.....



### 3.4.5 Non-destructive inspection e.g. Container inspection facilities

双能量束流成像：根据不同原子量物质的对两种能量束流的吸收特性，鉴别被测物种类。



MT1213LX

RF9066

2006/06/07



## 3.5 New methods and Technologies

The novel acceleration methods proposed so far can be classified into two catalogs;

To transfer energy from photons to particle beams; laser accelerators of different kinds, such as beat-wave accelerators, grating accelerator, inverse Cherenkov effect accelerator, inverse FEL accelerators and others. The maximum electric field in laser can be as high as key issue  $10^5 \sim 10^9$  MV/m, while the key issue is how to obtain the  $E_z$  component at the beam direction.

To transfer energy from one beam to another beam:

- A high-speed moving beam directly drives the accelerated beam: smoke-ring accelerator, linear beam accelerator, etc.
- Wake field accelerators (WFA): laser WFA, plasma WFA, dielectric WFA, coupled wake tube accelerator and two beam accelerator.



# Various wake field acceleration approaches

WF Device	Max. Grad.	Advantages	Disadvantages	Experimental Status
LWFA Laser WFA	multi-GV/m	High-gradient	Requires powerful short pulse laser. Poor efficiency.	Preliminary experiments underway; electrons are captured and accelerated
PWFA Plasma WFA	$\approx$ GV/m	High-gradient	Requires difficult drive beam, alignments. Same focus problem as LWFA	Acceleration of injected beam at 5-7MeV/m using few nC drive beam
Iris loaded WFA	50MV/m	Simple and well understood	Low gradient, requires good beam-beam alignment.	Similar to PWFA
DWFA Dielectric WFA	100MV/m	Very simple; Deflection modes damped	Requires difficult drive beam, good beam-beam alignment.	Similar to PWFA
CWTA Coupled Wake Tube	500MV/m	Stepped up gradients; beam-beam effects small. Simple extension of acceleration possible.	Requires efficient coupling of RF power,. Drive beam less difficult than DWFA	Experiment under construction



# Laser plasma accelerators produced “Dream beam” followed up by worldwide experiments

## ICL/RAL, UK

*“Monoenergetic beams of relativistic electrons from intense laser-plasma interactions”*  
*S. P. D. Mangles et al., NATURE, 431, 535, 2004.*

## LBNL, US

*“High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding”*  
*C. G. R. Geddes et al., NATURE, 431, 538, 2004.*

## LOA, France

*“A laser-plasma accelerator producing monoenergetic electron beams”*  
*J. Faure et al., NATURE, 431, 541, 2004.*

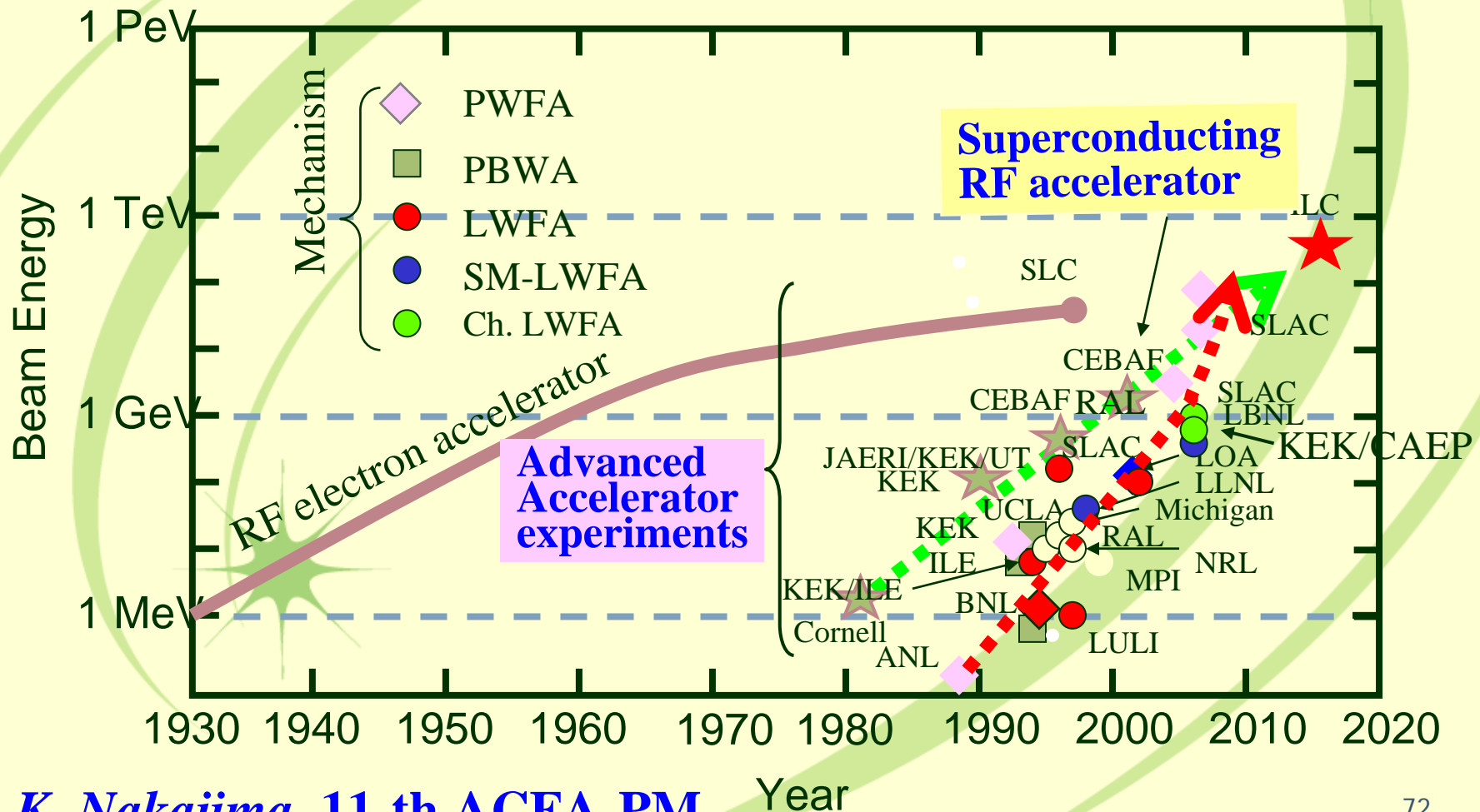
*Thomas Katsouleas, NATURE, 431, 515, 2004*





# History of Accelerators - Livingston chart

Advanced Accelerators gear up to TeV





# International collaboration on High-energy Laser-plasma Acceleration at CAEP, China



## Phase-I:

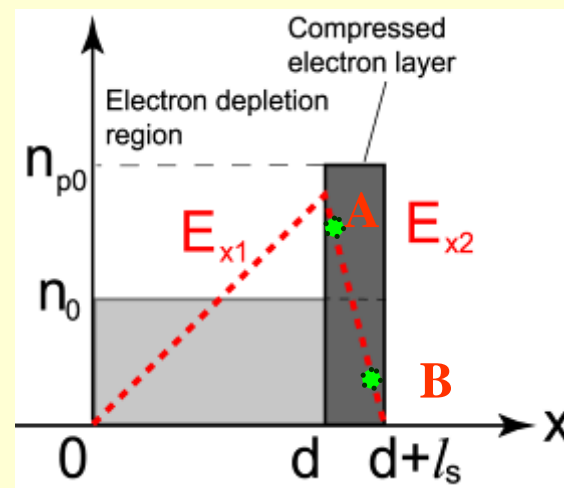
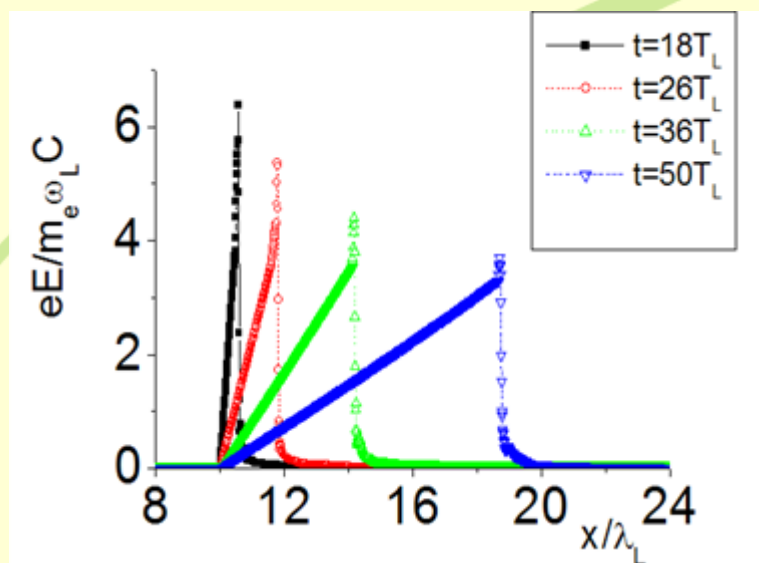
1 GeV monoenergetic electron acceleration with 10 mm size gas jet and a long focusing optics

## Phase-II:

Multi-GeV monoenergetic electron acceleration with a long-range discharge plasma channel

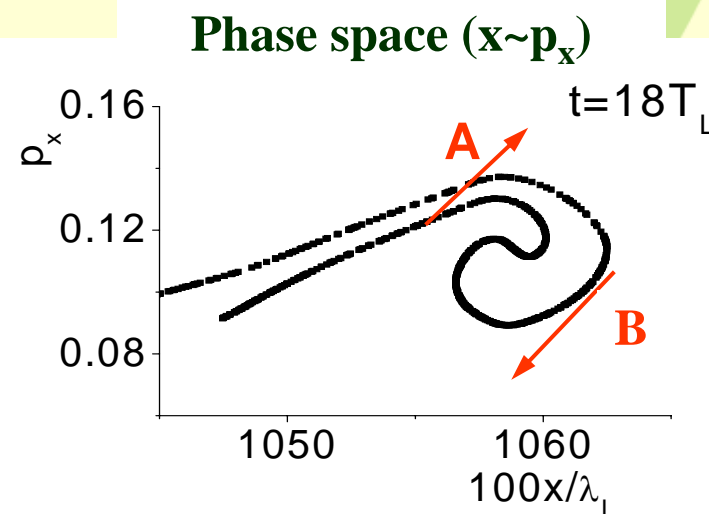


# 北京大学激光加速质子的研究



提出新的激光加速机制—稳相加速

在相稳定加速区内用圆偏振激光脉冲产生单能强流质子束







近物所超导ECR源



清华大学光阴极电子枪



高能所正电子源

# 加速器新技术



北大光阴极注入器



北大超导加速器



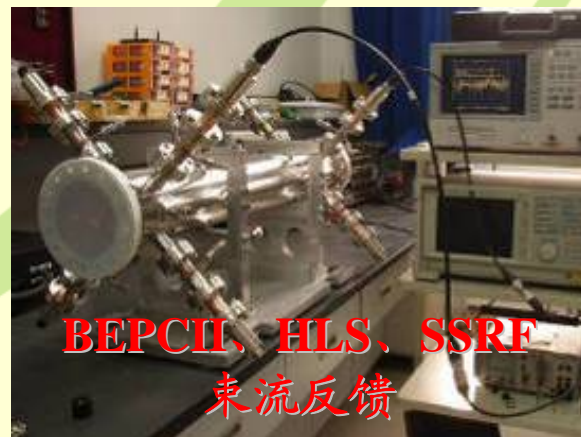
SSRF和BEPCII超导腔



原子能院1/4波长  
超导谐振腔



HIRFL-CSR上的电子冷却



BEPCII、HLS、SSRF  
束流反馈



# 北京大学国产实用型多Cell 射频超导腔发展

我国第一只纯  
铌超导腔



QWR  
腔



北京大学射  
频超导课题  
组成立

1988

1994

2000

2002

2005

2006

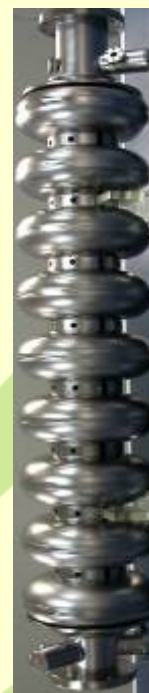
2007

2008

2009

2×9cell

2×3.5cell





## **(4) *Future science and accelerators***

- **Higher beam energy**
- **Higher beam intensity**
- **Higher time resolution**
- **Higher spatial resolution**







1000 times  
higher energy

# Acceleration Technology

1 PeV =  $10^{15}$  eV

Laser-plasma LC

“New paradigm”



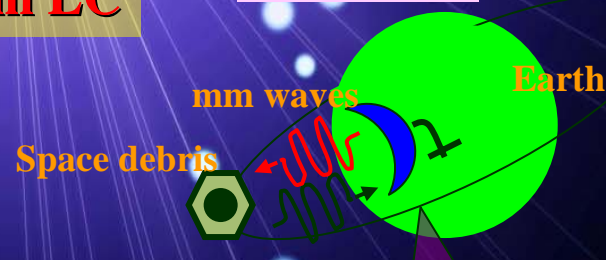
Leptogenesis

SUSY breaking

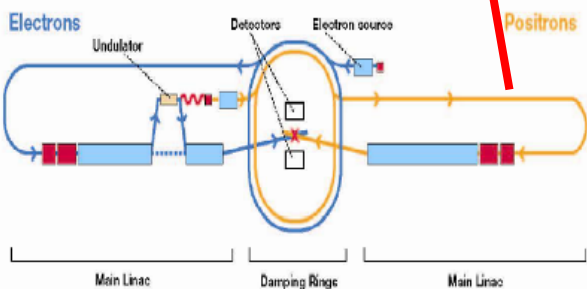
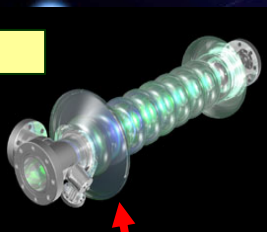
Two-beam LC

Extra dimension  
Dark matter  
Supersymmetry

Earth-based space  
debris radar



Ultra-High  
Voltage STEM  
with  
Superconducting  
RF cavity



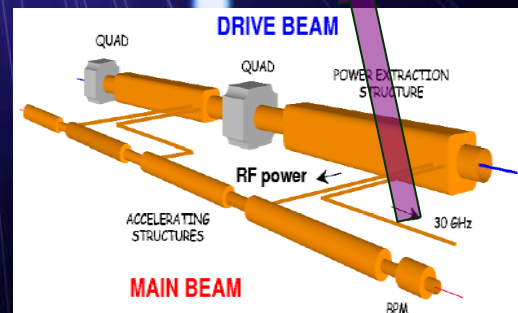
ILC

1 TeV =  $10^{12}$  eV

“Standard model”

Higgs  
Quarks  
Leptons

T. Suzuki  
@ACFA08





1000 times  
more  
powerful  
beam

100 MW Beam Power

Inertial Fusion

Nuclear waste processing

Brighter neutron source

Muon Collider

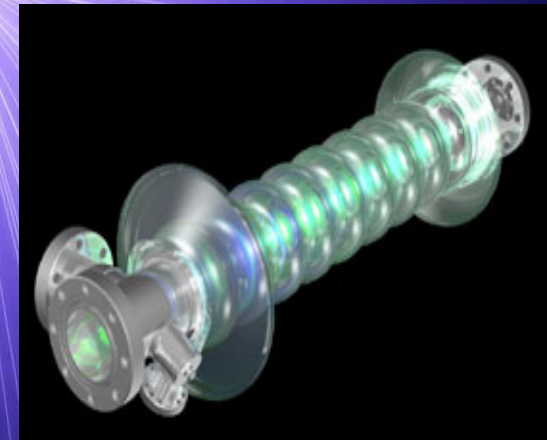
Neutrino Factory

Linear Collider

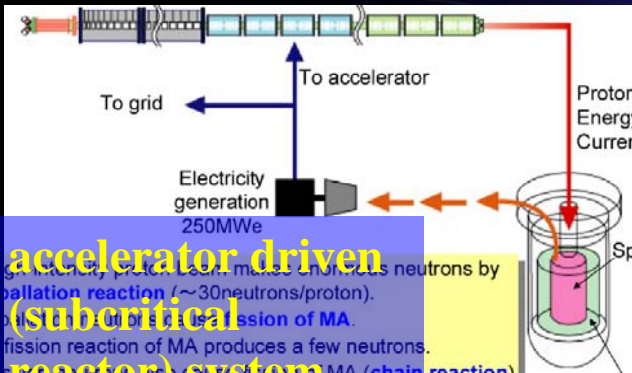
100 kW Beam Power



Muon-collider  
Neutrino Factory

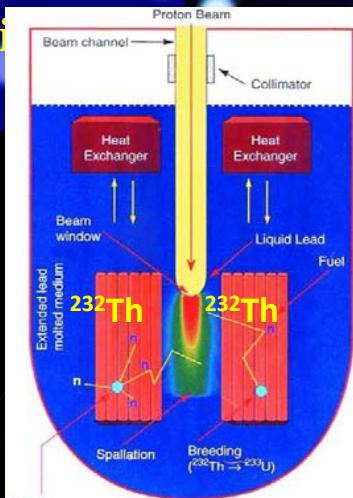


Super-  
conducting  
Accelerator  
Technology

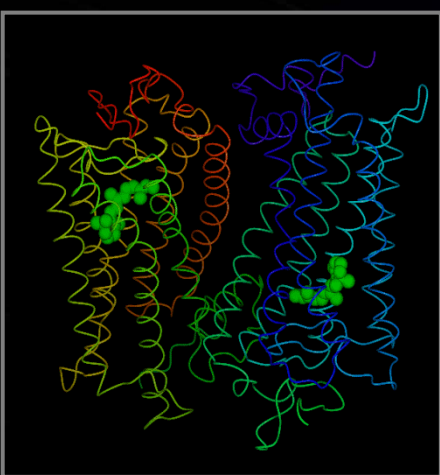


accelerator driven  
(subcritical  
reactor) system

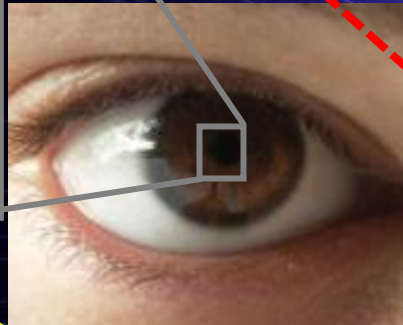
and  
nuclear waste  
transmutation  
system







Rhodopsin  
~200 fs



1 fs =  $10^{-15}$  s

Photosynthetic  
reaction in leaves  
~ 100 fs



bunch-  
slicing

future  
light  
sources

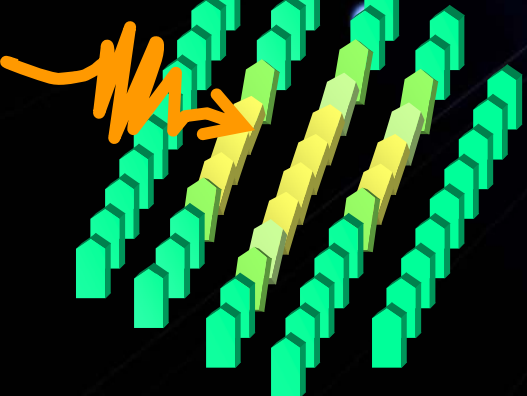
1 ps =  $10^{-12}$  s

current  
light  
sources

1 ns =  $10^{-9}$  s

1000 times  
shorter time  
resolution

Fast photo-switching  
of metal-to-insulator  
phase ~ 1 ps

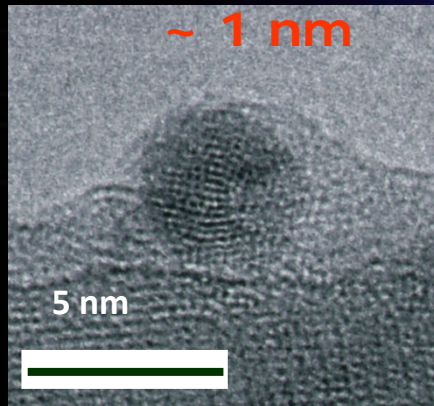


*Femto-sec Beam  
Technology*

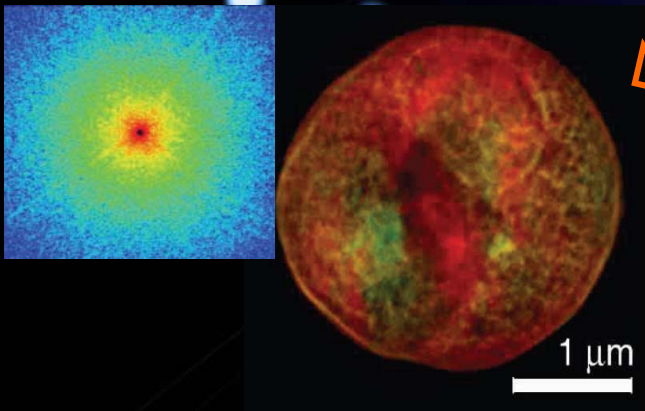


1000 times  
higher spatial  
resolution

catalytic chemistry



cellular structure  
and function ~ (1-10) nm



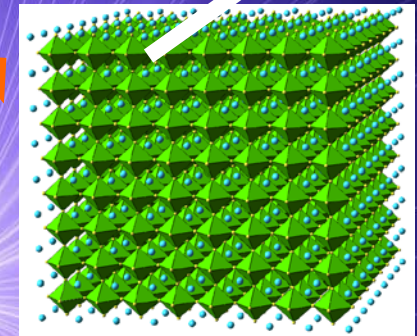
future  
light  
sources

1 nm

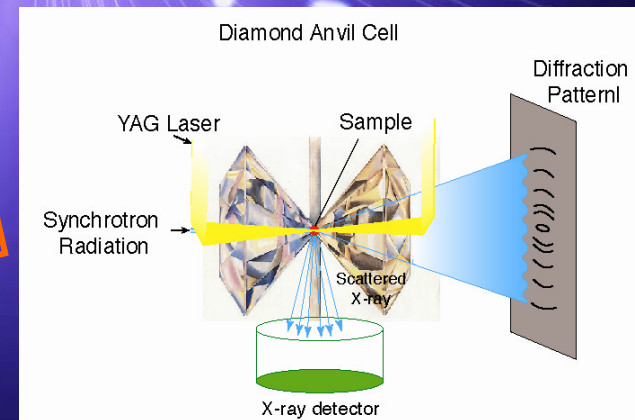
10 nm  
current  
light  
sources

~100 nm

Nano-crystal ~ 1 nm



extreme condition  
~ (1-10) nm



**Nano beam  
Technology**





*Future science calls for  
innovative ideas for  
new generation of  
accelerators*



# Scientific Knowledge from 500 B.C. to 2000 A.D.

## Scientific Knowledge: 500 B.C. to 2000 A.D. The Road to Waxahachie

Waxahachie, Texas, U.S.A. That's where the Superconducting Super Collider (SSC) is being built. A giant scientific tool akin to the telescope or the microscope, the SSC is a 54-mile underground accelerator—shaped like a racetrack—that will enable scientists to smash atomic particles (protons) into tiny pieces to see what makes them work.

By learning about these tiny particles, they—and we—will form a deeper understanding of the building blocks of every material thing in the universe. **The discoveries resulting from the SSC could have as great an impact on our lives—and the lives of future generations—as the discovery of fire had on prehistoric man or as the discovery of electricity has had on our lives.**

The road to Waxahachie began 2400 years ago in the town of Abdera, Greece, where a philosopher named Democritus stated: "Nothing exists except atoms and space; everything else is opinion."

A warning: **knowledge is perishable.**  
From 500 A.D., when the emperor Justinian closed the Academy and the Lyceum in Athens—until 1071 A.D., when Greek-speaking scholars fled west following the fall of Constantinople—scientific activity in Europe virtually ceased. According to Williams and French in *The Book of Science*, "...these times disappeared minds and apparatus disappeared, and trade routes were limited. The period in Europe in which learning and science could develop had nearly to wait."

**Invention of  
Telescope  
& Microscope**

The quest for knowledge has brought us, at last, to Waxahachie, where scientists and engineers are building the next great instrument of discovery—the SSC. They tell us in the midst of controversy. Strident nay-sayers demand to know: what benefits the SSC will bring. They want to ignore the patient curiosity leads to discovery, discovery leads to invention; invention leads to benefit.

Michael Faraday, the British scientist who formulated the basic principles of electricity, understood the pattern well. When the Prime Minister asked the use of a hand-cranked generator that Faraday had built, he replied, "I know not, but I wager that one day your government will tax it." In 1880, England levied a tax on the generation of electricity. The pattern—curiosity, discovery, invention, benefit—held true.

And what about the road from Waxahachie? It is human nature to want to know now what awaits us down the road, to turn away to the next page to see what happens. But we can't. We can only make the journey, trusting in the example of others whose journeys have brought us to this place, this time. Perhaps Shakespeare's Hamlet said it best: "There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy."

This timeline focuses on scientific developments in Western Europe and the United States. It represents a broad, general view of what is known, not what is known in detail. It is not intended to be a comprehensive history of science, but a guide to the major milestones in the history of science.

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© Thomas Shookman 1992



# Summary

- As an powerful tool for acceleration of charged particle beams, particle accelerators have been rapidly developed since it was invented in 1930's aiming at the researches on the micro-world;
- Traced to its three roots, the history of accelerators is a continuous upgrade for higher energy and better performance;
- The higher energy and higher luminosity are two frontiers of the accelerators for high energy physics;
- Synchrotron radiation sources, free electron lasers and spallation neutron sources and etc. are in vigorously growing;



## *Summary* (cont.)

- Variety of low energy accelerators are widely applied in all aspects of our society;
- New methods, and new technologies emerge in endlessly and will present a entirely new appearance of accelerators;
- Future science calls for innovative ideas for new generation of accelerators.
- As “microscope” for micro-world, the accelerators will be further developed in 21<sup>st</sup> century in the world as well as in Asia.



# Question

To line up the following types of accelerators with the characters listed in the right side:

Synchrotron

$$B=\text{const.}, f_{\text{rf}}=h f_c$$

Betatron

$$B=\text{const.}, f_{\text{rf}}=\text{const.}$$

Cyclotron

$$B = \frac{pc}{Ze\rho} , \quad \frac{dB_0(t)}{dt} = \frac{1}{2} \frac{d\bar{B}(t)}{dt}$$

Synchro-cyclotron

$$B = \frac{pc}{Ze\rho} , \quad f_{\text{rf}}=h f_c$$