Introduction to High Power Proton Accelerators

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Outline

1. Two Examples

2. Issues of high intensity beam acceleration

3. Proposals and designs of future facilities
   with megawatt beam power

4. Pros and cons of Linac, Linac-AR, RCS, Cyclotron,
   and FFAG

Two Examples

Why starting with examples?

1. I am most familiar with the works I did

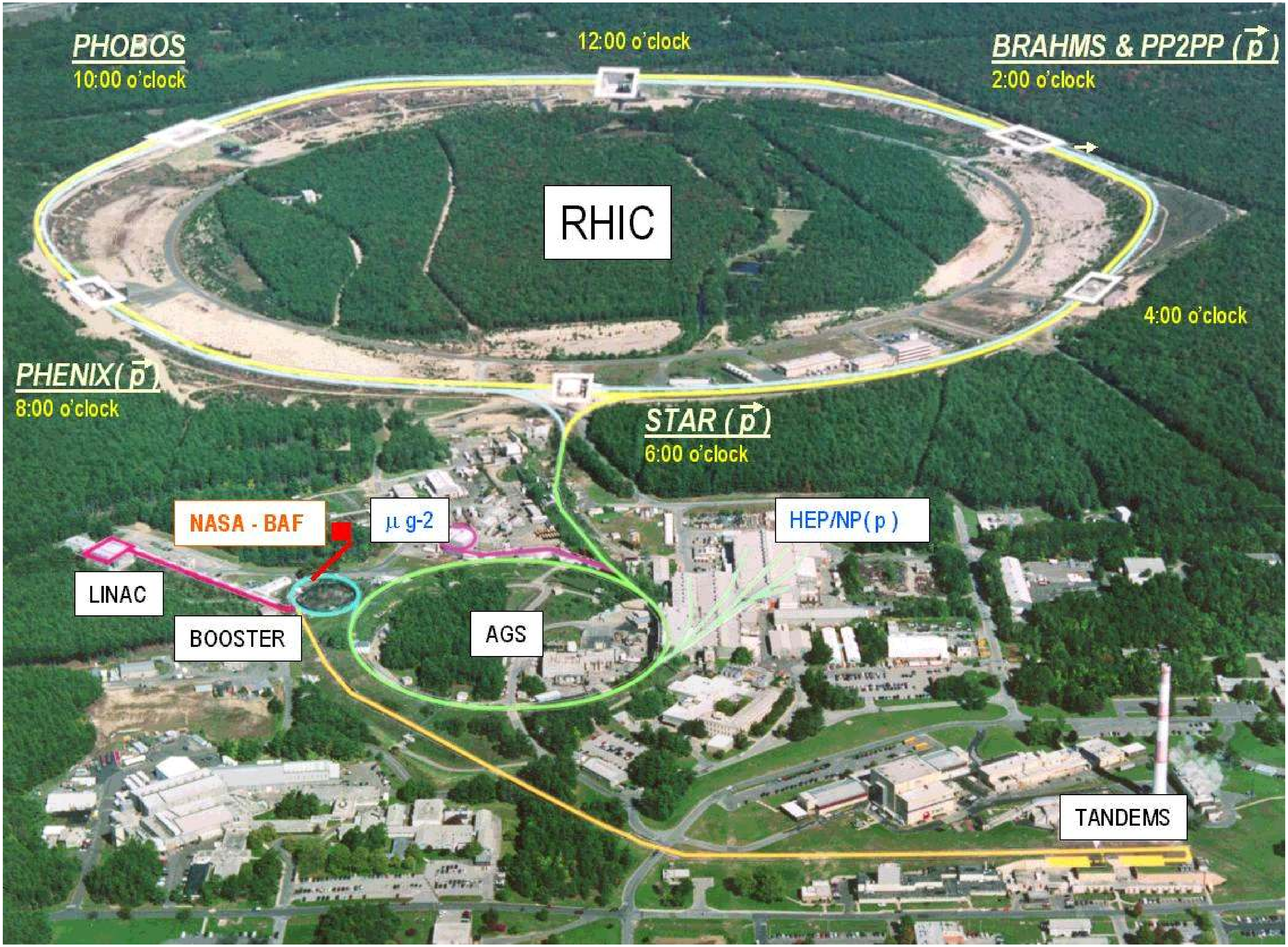
2. To show how to apply the general principles and theories
   you have learned to actual accelerator design and construction

3. To introduce few concepts and world activities of high power proton
   accelerators

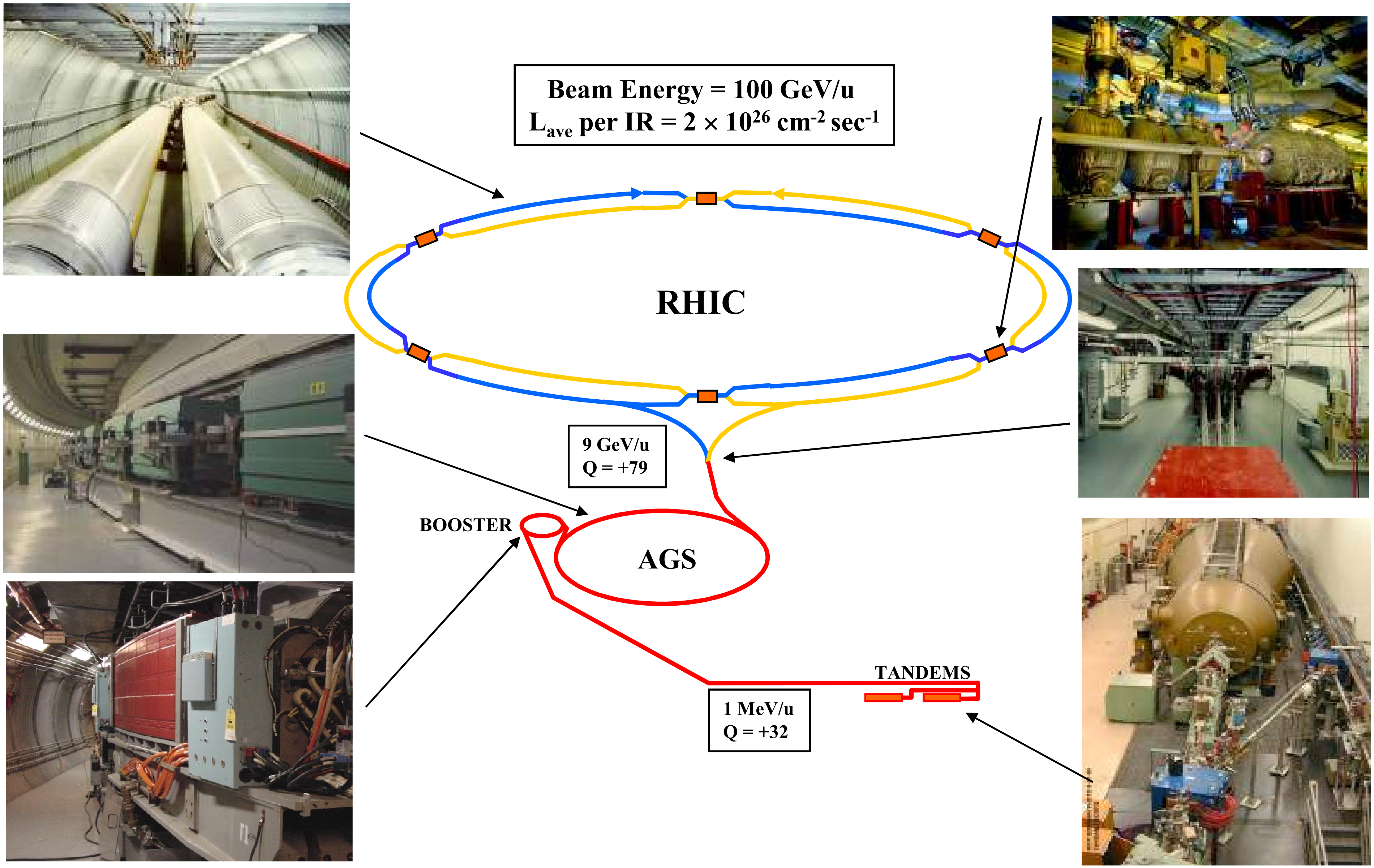
Example 1: Booster Project and AGS Upgrade

Booster was constructed in 1987 – 1990 to

- Increase proton intensity in the AGS
- Raise polarized proton intensity in both AGS and RHIC
- Raise heavy ion mass and intensity in the AGS and RHIC


PHOBOS
10:00 o'clock
12:00 o'clock
BRAHMS & PP2PP ($\vec{p}$)
2:00 o'clock
RHIC
4:00 o'clock
PHENIX($\vec{p}$)
8:00 o'clock
STAR ($\vec{p}$)
6:00 o'clock
NASA - BAF
μ g-2
HEP/NP (p)
LINAC
BOOSTER
AGS
TANDEMS

Gold Ion Collisions in RHIC



Space Charge Tune Shift in Ring

$$\Delta Q = \frac{3\, r_p\, N}{2\pi\, \beta\, \gamma^2\, \epsilon_N\, B_f} < 0.25 \qquad (1)$$

Where:

r_p: Classical proton radius

N: Total number of proton

ϵ_N: Normalized emittance

B_f: Bunching factor

Limited tune spread to avoid resonance loss of beam

Space charge effect of injection energy

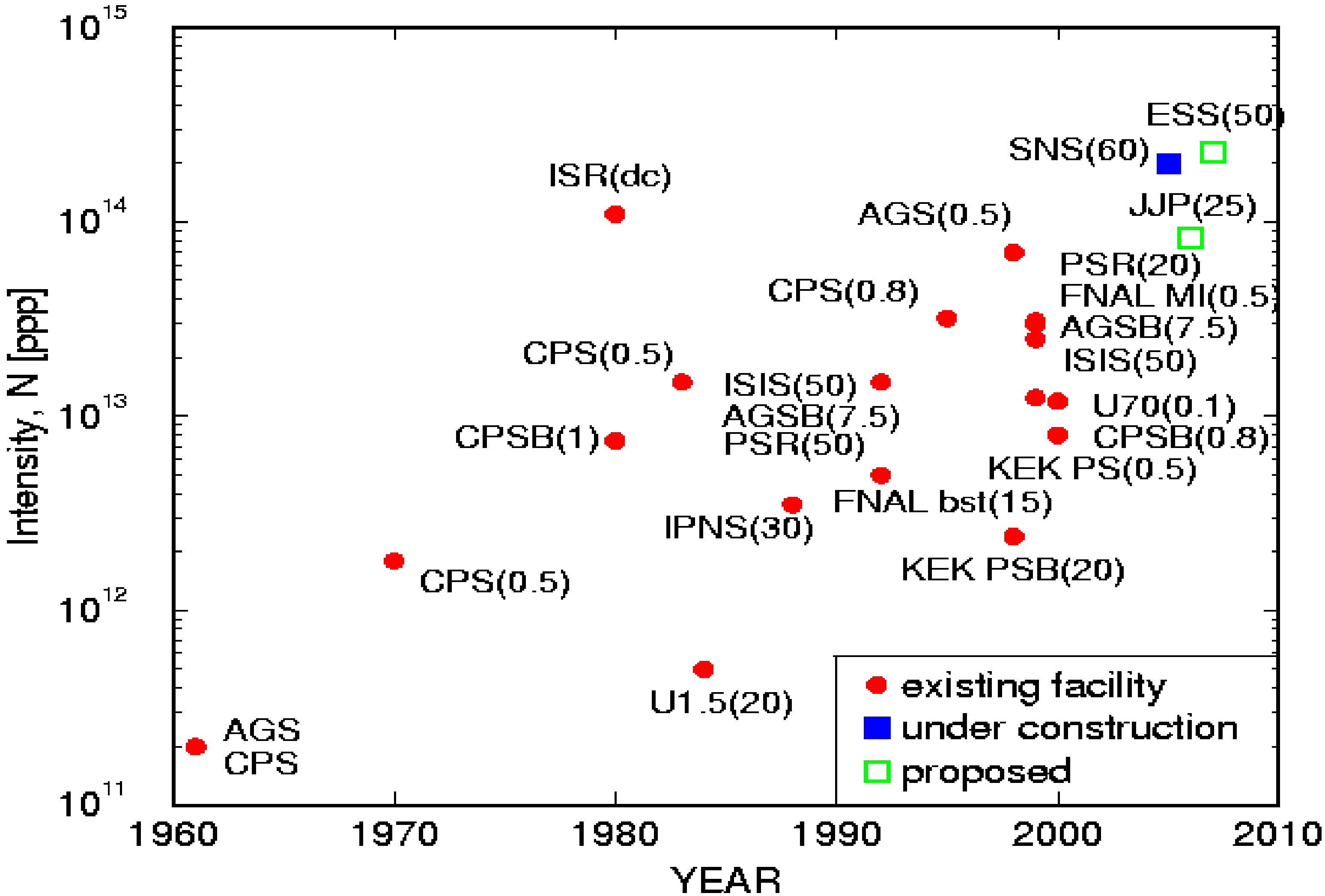
The Booster can raise the AGS injection energy from

E = 200 MeV with $\beta\ \gamma 2 = 0.83$ to

E = 1.5 GeV with $\beta\ \gamma 2 = 6.23$

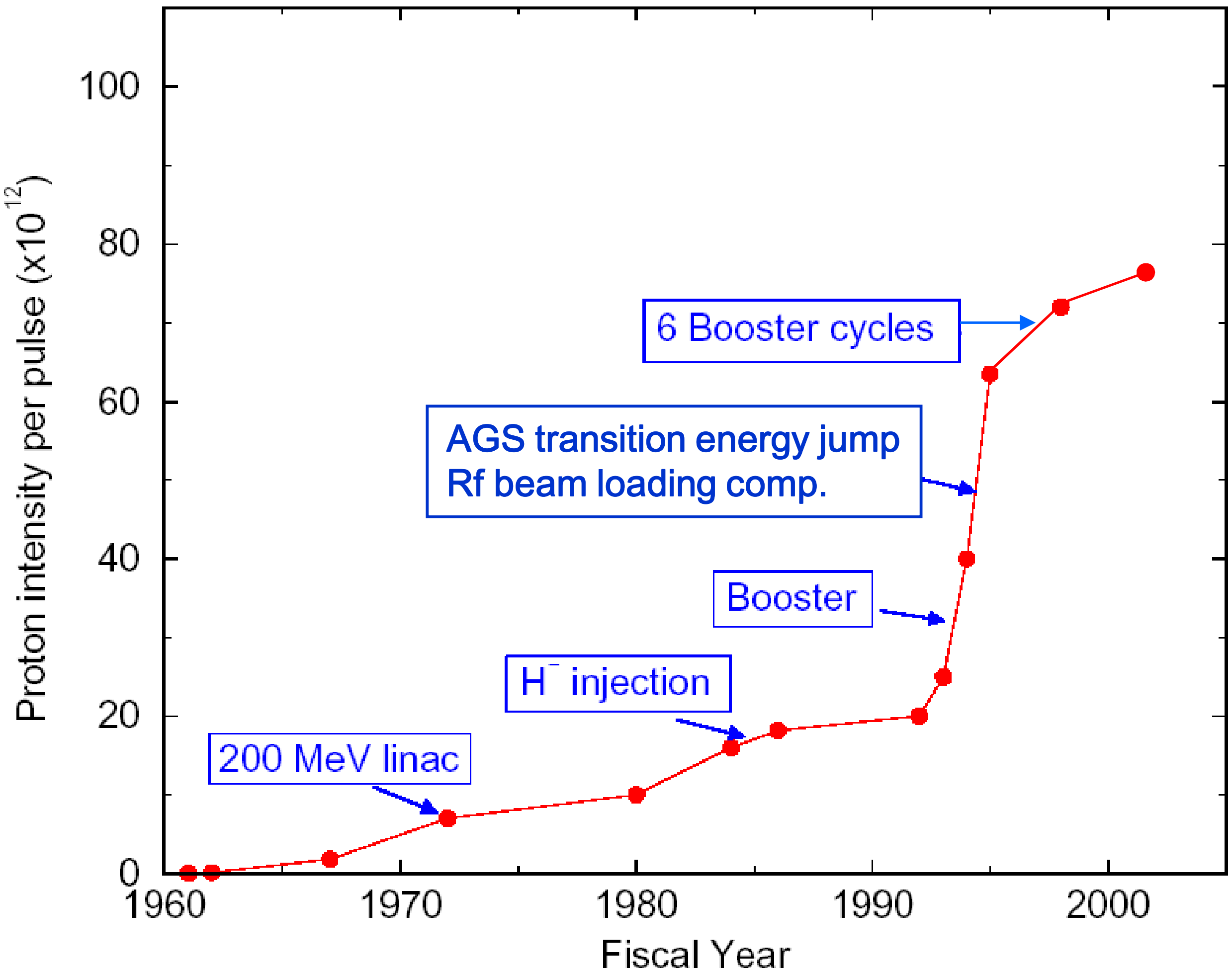
Everything being equal, a factor of about seven increase is possible

Intensity history of multi-GeV proton machines



BNL AGS kept highest intensity record for synchrotron since 1995
That for an AR were kept by ISR and SNS.

AGS Intensity History

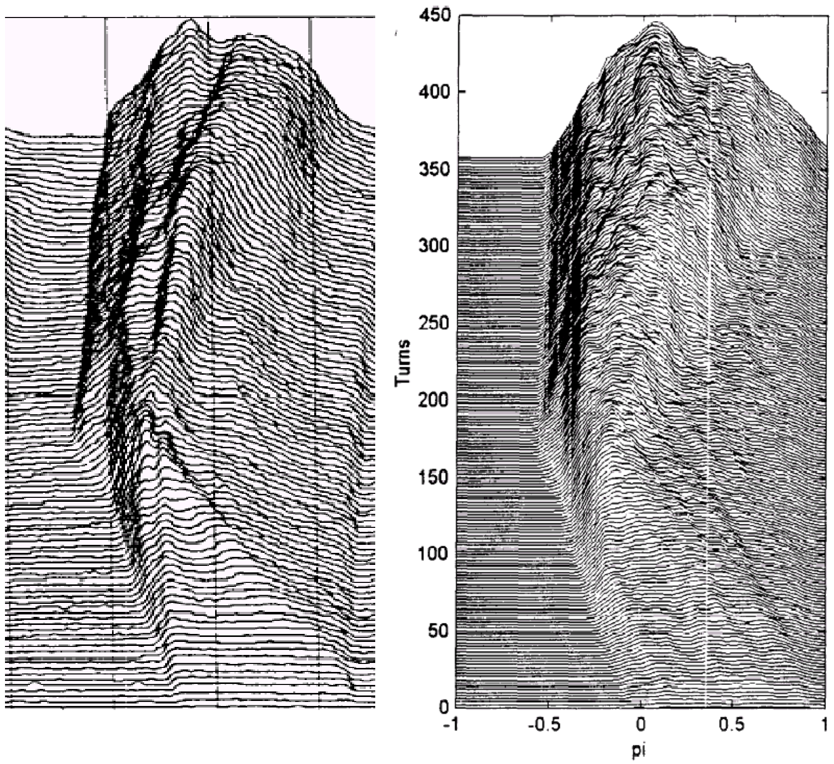


Technologies developed for high intensity beams:

- Low loss charge exchange injection (AGS, SNS, …
- High current ion source
- Boosters (CERN, FNAL, AGS, KEK, …
- Rapid cycling synchrotron (FNAL, ISIS, …
- Pulsed and CW RFQs (LEDA, AGS, SNS,..
- Super-conducting Linac (SNS, …
- Transition energy jump or avoidance (CERN, AGS, J-Parc, …
- Beam loading compensation and 2nd harmonic cavity (AGS, ISIS, …
- Electron cloud cures (PSR, SNS…
- Beam Collimation (SNS,
- Damping of collective instability (AGS, SNS, ..

H^- injection into the Booster

Measurement Simulation



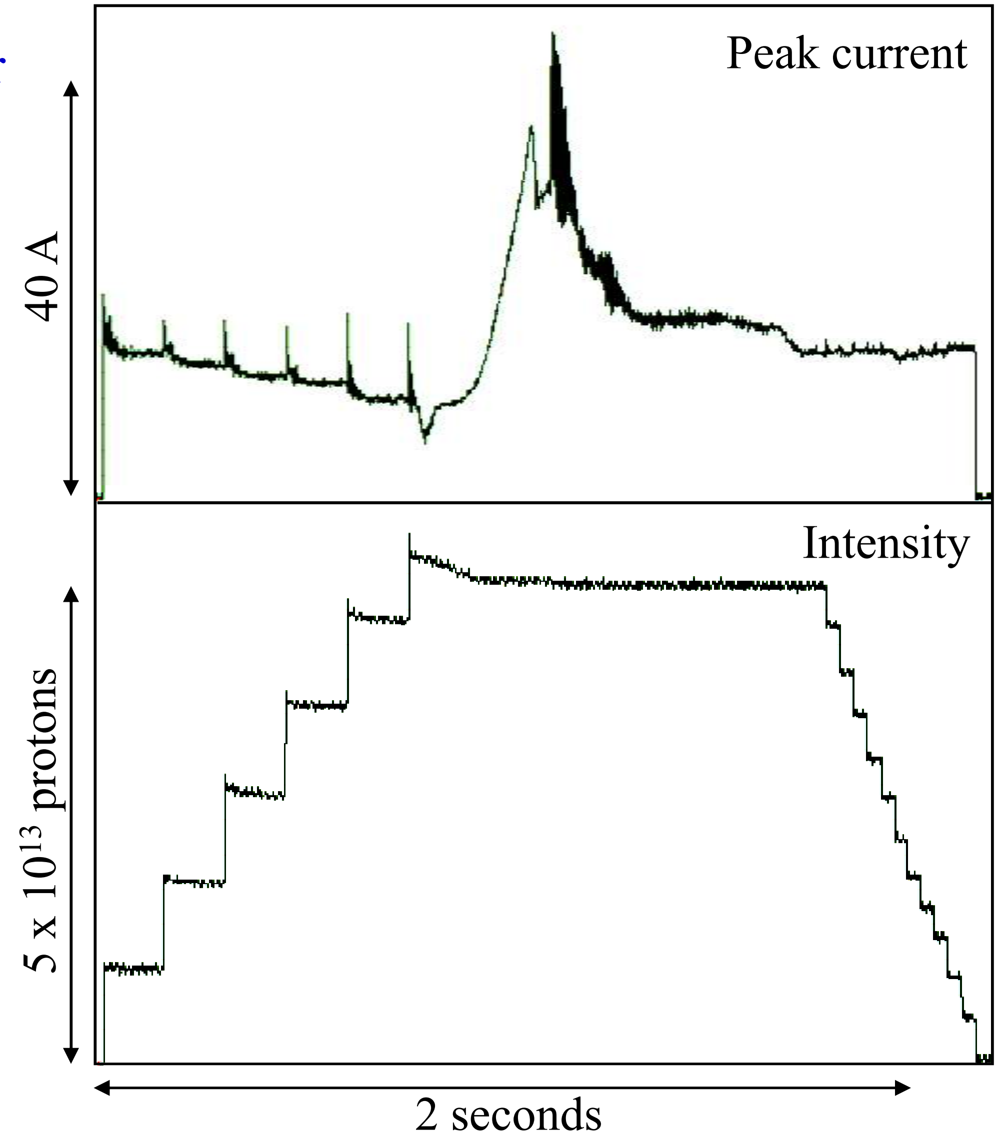
Injected:
23×10^{12} ppb
1.3 eVs

Circulating:
17×10^{12} ppb
3.0 eVs

- 90 mA H^- magnetron source, about 100 turns accumulation
- High B dot gives effective longitudinal phase space painting.
- Injection period is approx. equal to synchrotron period.

AGS High Intensity Performance

- 6 single bunch transfers from Booster
- Peak intensity reached: 72×10^{12} ppp
- Bunch area: 3 eVs at injection
  10 eVs at extraction
- Intensity for FEB ops: 60×10^{12} ppp
- Strong space charge effects during accumulation and energy transition in AGS
- 2nd order transition energy jump limits available momentum aperture.
- Chromatic mismatch at transition causes emittance dilution



Example 2: The Spallation Neutron Source

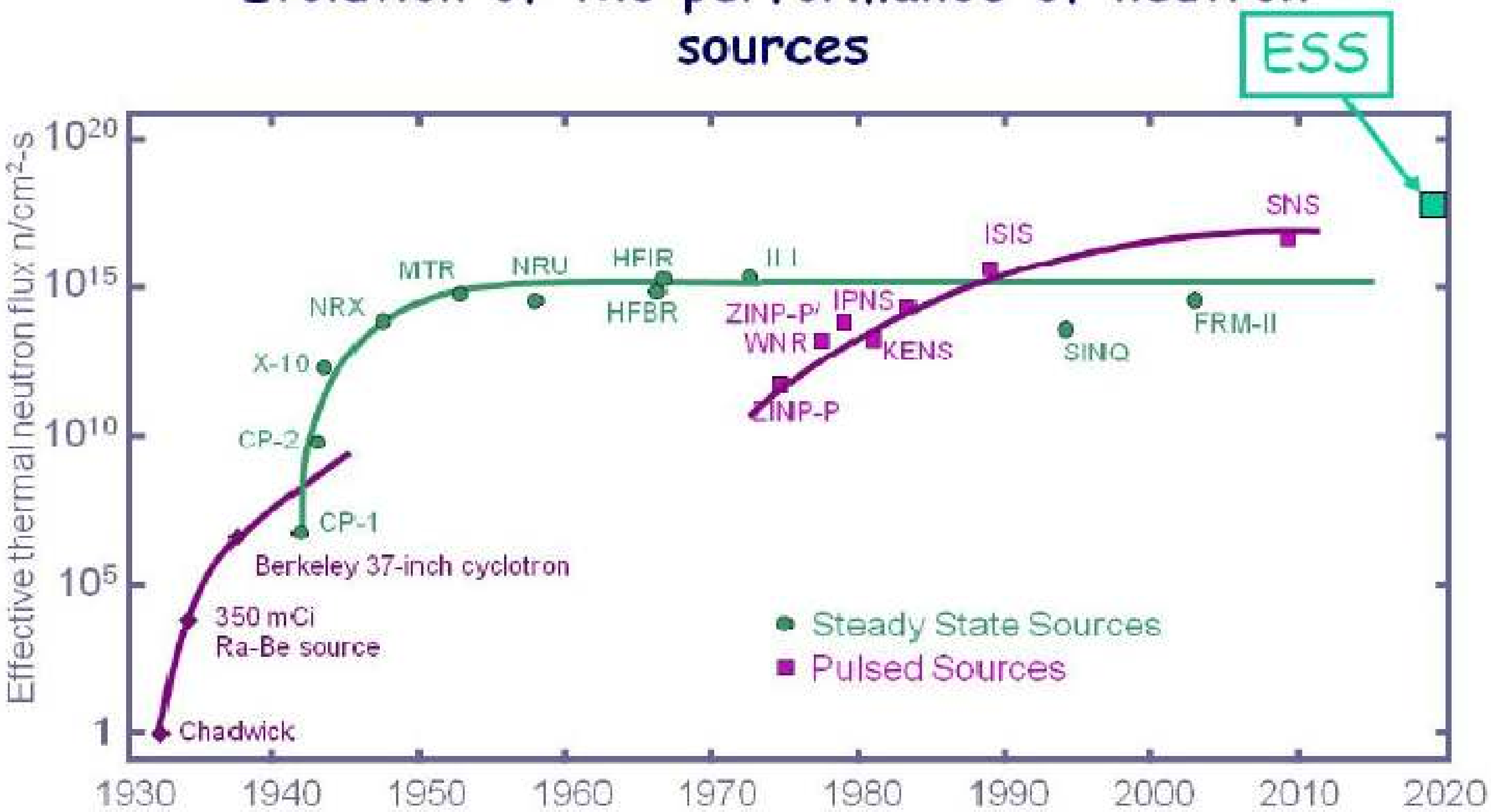
The SNS is a short-pulse neutron source, driven by a 1.4 MW proton accelerator

SNS will be the world's leading facility for neutron scattering research with peak neutron flux ~20–100x ILL, Grenoble

SNS is funded through DOE-BES at a cost of 1.4 B$

- The Project is a collaboration of six US DOE laboratories
- SNS will be 8x ISIS, the world's leading pulsed source
- Stepping stone to other high power facilities

Evolution of the performance of neutron sources



(Updated from *Neutron Scattering*, K. Skold and D. L. Price, eds., Academic Press, 1986)

Evolution of Neutron Sources

1. Reactors, 1940 –
2. ISIS/RAL 1980 ---
3. LAMF/LANL, 1980 ---
4. IPNS/ANL, 1985 -- 2005
5. ANS/ORNL(R&D), 1985 ---1996, followed by SNS
6. ESS R&D, 1990 – 2003, 2005-2010
7. Individual US Spallation Neutron Source R&D(1990 – 1996)
   LANL, ANL, BNL, ..
8. US joint R&D/ORNL, 1996 – 1999
9. US SNS/ORNL construction, 1999 – 2005
10. J-PARC/KEK R&D, 1992 – 1999, construction, 2001-- 2008

Power of a Proton Beam

$$P(MW) = E_k(Gev) * I_{ave}(Amp) \qquad (2)$$

$$I_{ave} = Ne/\tau = 1.5 \times 10^{14} \times 1.6 \times 10^{-14} \times 60$$
$$= 1.4 \text{ mA}$$

$$P_{SNS} = 1.0 \times 1.4 = 1.4 \text{ MW}$$

High power accelerator needs both high intensity and high repetition rate

Neutron Yield

$$n = 0.1 \times (A + 20) \times E \text{ (Gev)} \qquad (3)$$

$$\approx 20$$

For SNS mercury target at 1 Gev

$$N_n = n \times N_p = 0.1 \times (A + 20) \times P \qquad (4)$$

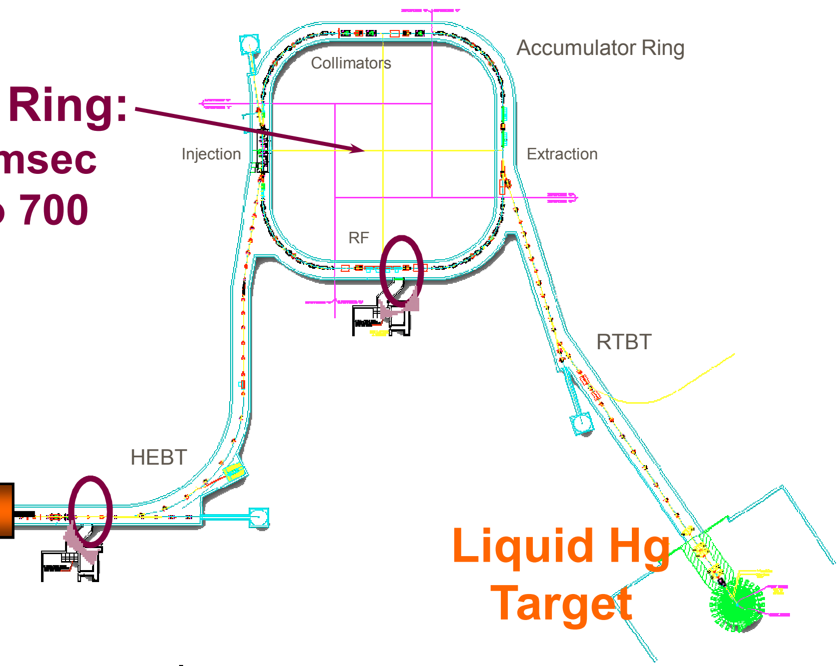
Means that total neutron flux is proportional to total proton beam power

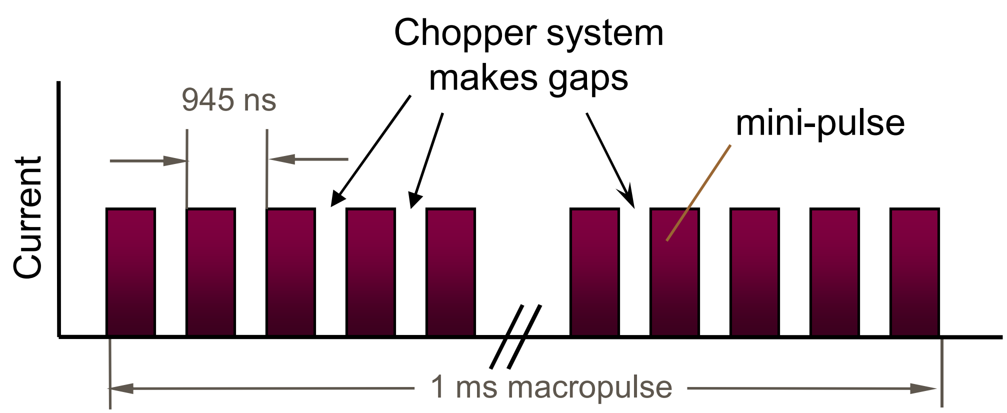
SNS Accelerator Complex

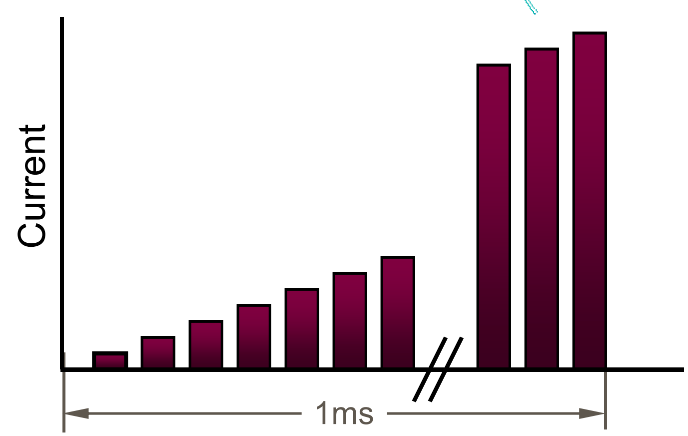
Front-End:
Produce a 1-msec long, chopped, H- beam

1 GeV LINAC

Accumulator Ring:
Compress 1 msec long pulse to 700 nsec



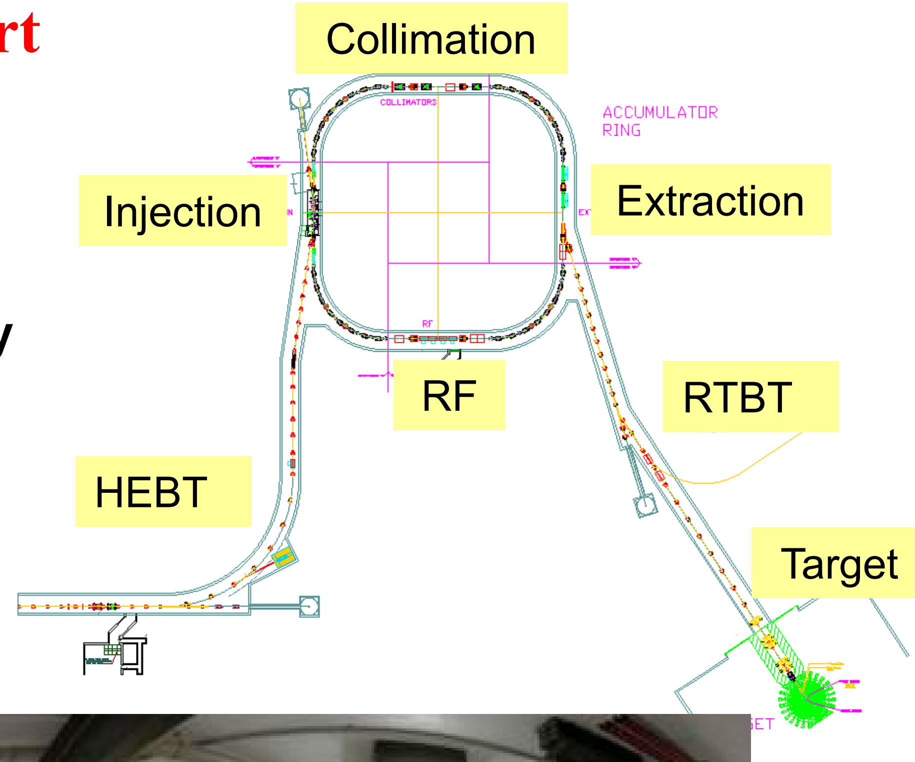


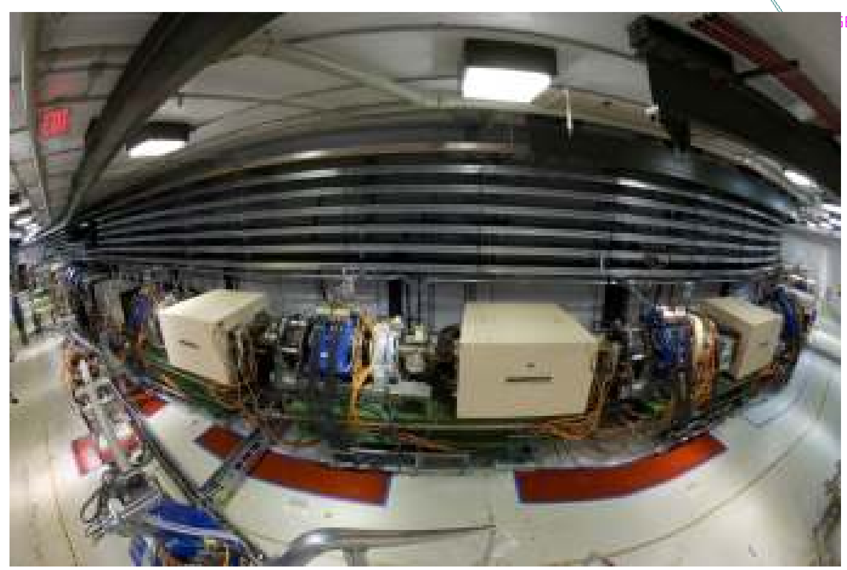


Accumulator Ring and Transport Lines

- **Designed and built by Brookhaven National Lab**
- **Accumulates 1-msec long beam pulse by multi-turn charge exchange injection**

Circum	248 m
Energy	1 GeV
Accum turns	1060
Final Intensity	1.5×10^{14}
Current	26 A

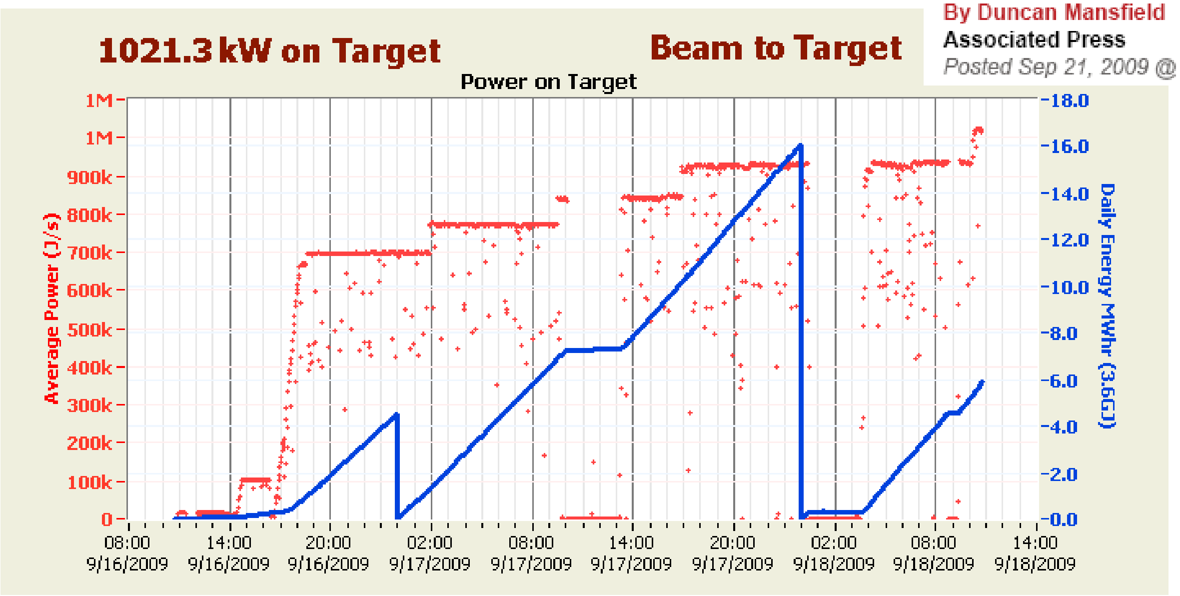




1 MW Beam Power Achieved!

Neutron facility achieves 1-megawatt power

By Duncan Mansfield
Associated Press
Posted Sep 21, 2009 @ 09:00 AM



Dream delivered: SNS pushes past one megawatt

Stuart Henderson said he was ready to get some sleep. Whether he meant for the first time since April 28, 2006, he didn't say. But the director of the Research Accelerator Division was obviously relieved.

The Spallation Neutron Source, which is supported by Stuart's division, on September 18 became the first spallation neutron source to break the one-megawatt barrier. SNS is now the most powerful spallation neutron source in the world, topping the continuous-beam SINQ at the Sherrer Institute in Switzerland, which currently runs at 900 kilowatts.

Much as the day the SNS was first turned on in April 2006, the milestone came with a control-room whoop as the power reading on the instrument panel rolled over to seven figures.

The SNS was ramping up for its latest operational run following a maintenance shutdown that included the installation of a brand new target module to replace the original target, which outlasted most expectations of service life.

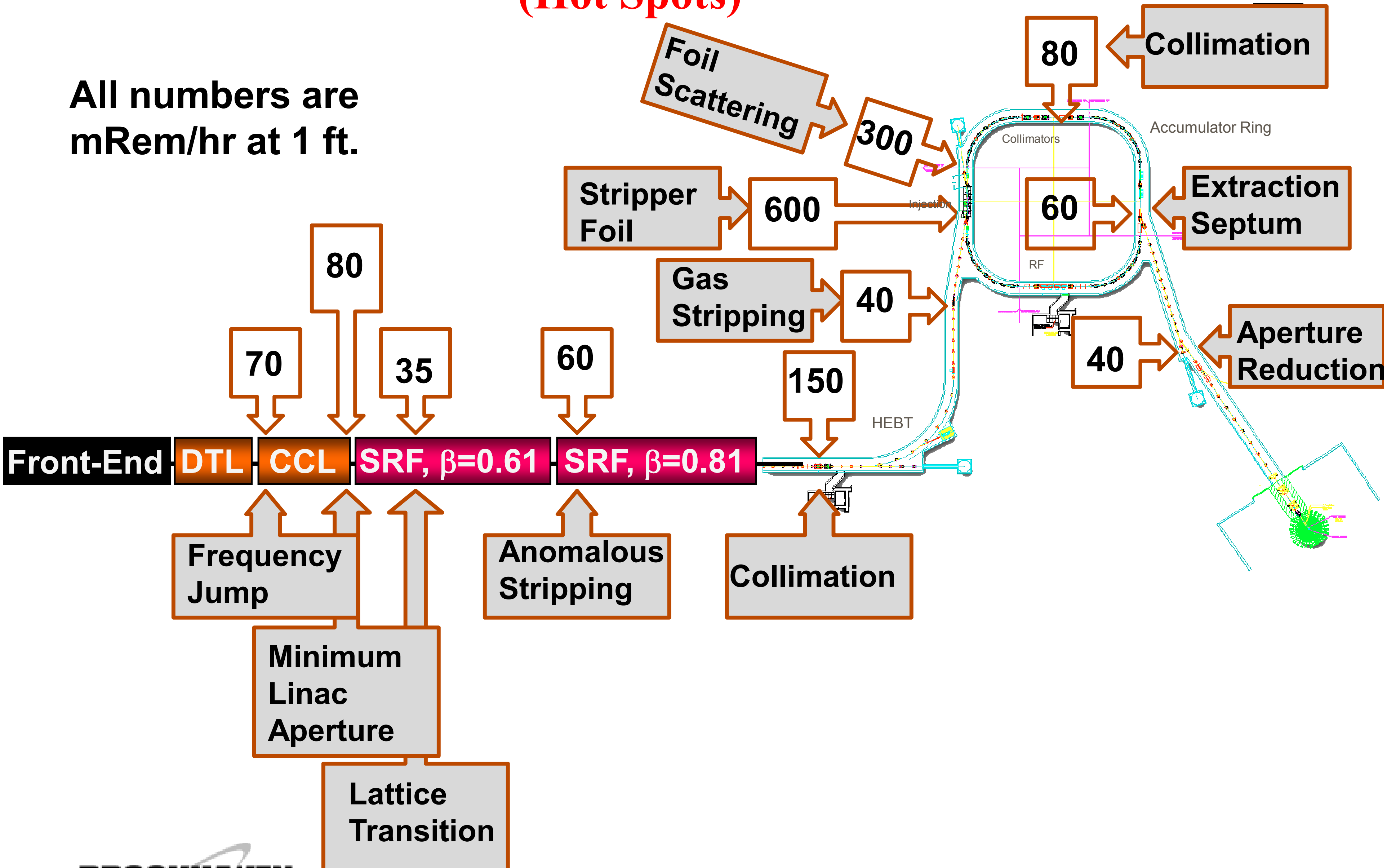
"It's been a long time in the making and the dream of a lot of people to make a megawatt-class pulsed spallation neutron source, and today we've finally delivered on that dream," said Stuart just after the deed was done.

(See MEGAWATT, page 5)

Michael Plum (sitting) and Viatcheslav Danilov (standing) react as the SNS beam power readout goes to seven figures.

Beamloss: SNS Residual Activation after 1 MW Operation (Hot Spots)

All numbers are mRem/hr at 1 ft.



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- **We plan to double the SNS beam power by**
  - **Increasing beam energy with 9 additional cryomodules (SNS Power Upgrade Project)**
  - **Increasing peak current from the source (Operational improvements)**
  - **modifying injection and extraction regions to accommodate higher beam energy (all other power supplies support 1.3 GeV operation)**
- **Anticipate PUP "CD-2" Approval (Baseline) in 2011; Construction Timeline 2012-2017**
- **Active R&D: Laser-stripping, target cavitation damage mitigation, electron-proton instability damping, source development, …**

	Baseline	Upgrade
Kinetic Energy	1.0 GeV	1.3 GeV
Beam Power	1.44 MW	3.0 MW
Linac Beam Duty Factor	6%	6%
Peak Linac Current	38 mA	59 mA
SRF Cavities	81	117
Ring Bunch Intensity	1.5×10^{14}	2.5×10^{14}
Ring Space Charge Tune Spread	0.15	0.15

3. Possible Applications of HPPA

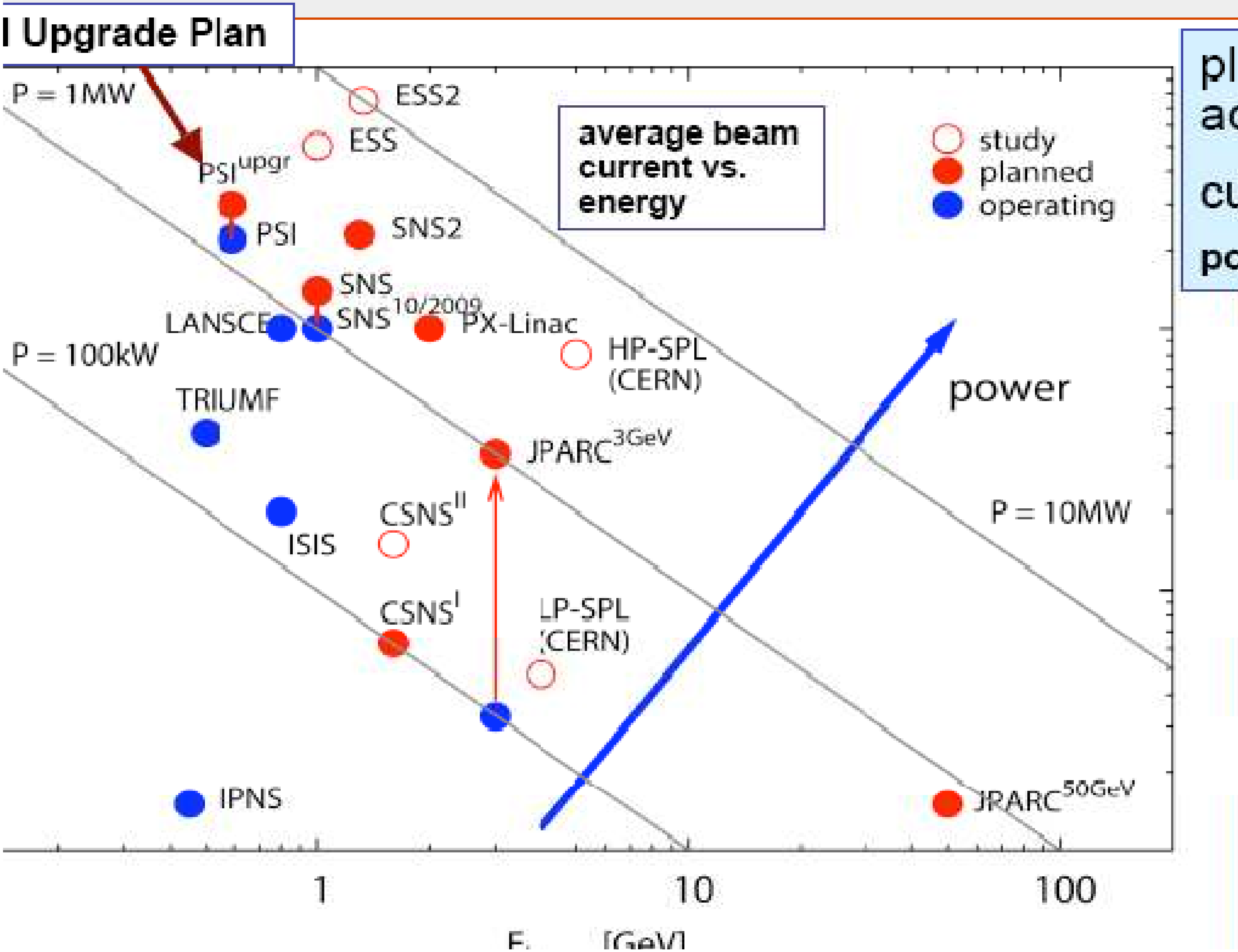
Nuclear waste transmutation and accelerator driven sub-critical reactors:

- CW or high DF to minimize mechanical shock
- E: 1 – 10 GeV (minimize power deposition in window, fully absorb beam in reactor)

Production of intense secondary beams:

- Neutrons: DF: CW - 10^{-4}, E: 0.5 - 10 GeV (neutron production ~ prop. to beam power)
- Kaons: DF ~ 0.5 (minimize pile-up in detector), E: > 20 GeV
- Neutrino super-beam: DF: ~ 10^{-5}(suppress background), E: > 1 GeV (depends on neutrino beam requirements)
- Muons for neutrino factory: DF: ~ 10^{-5} (pulsed cooling channel), E: > 10 GeV (for 5MW, I_{peak} > 50A)
- Muons for muon collider: DF: ~ 10^{-7} (maximize luminosity), E: ~ 20 – 30 GeV (for 5MW, I_{peak} = 1.7 – 2.5 kA)

High Power Proton Accelerators



plot: selecte
accelerators

current vs. e

power ∝ curre

Design options for high power facilities

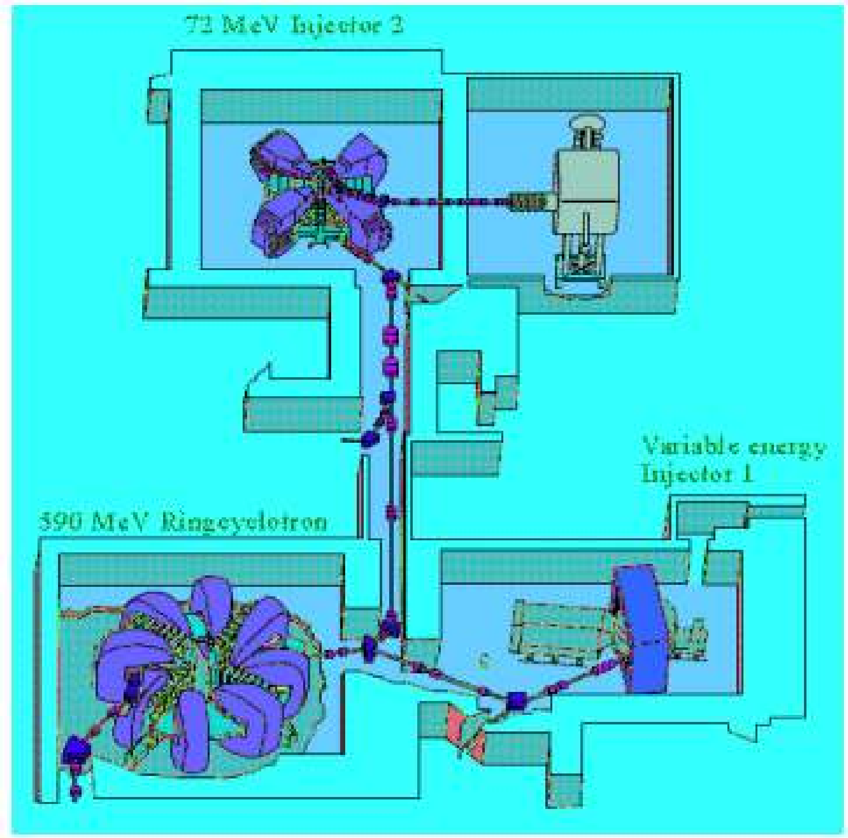
	design:	issues/challenges:
CW or high DF:	Cyclotron + p source	$E \leq 1$ GeV
	SC Linac + p source	CW front end (RFQ, DTL)
Low DF:	Linac + accum. ring	$E \leq 5$ (8?) GeV (H^- stripping)
	Linac + RCS	Rep. rate < 100 Hz, $P_{RSC}/P_{Linac} \leq 10$
	Linac + FFAG	Rep. rate ≤ 1 kHz, $P_{RSC}/P_{FFAG} \leq 3$
	Linac + n × RCS	For high energy Bunch-to-bucket transfers High gradient, low frequency rf

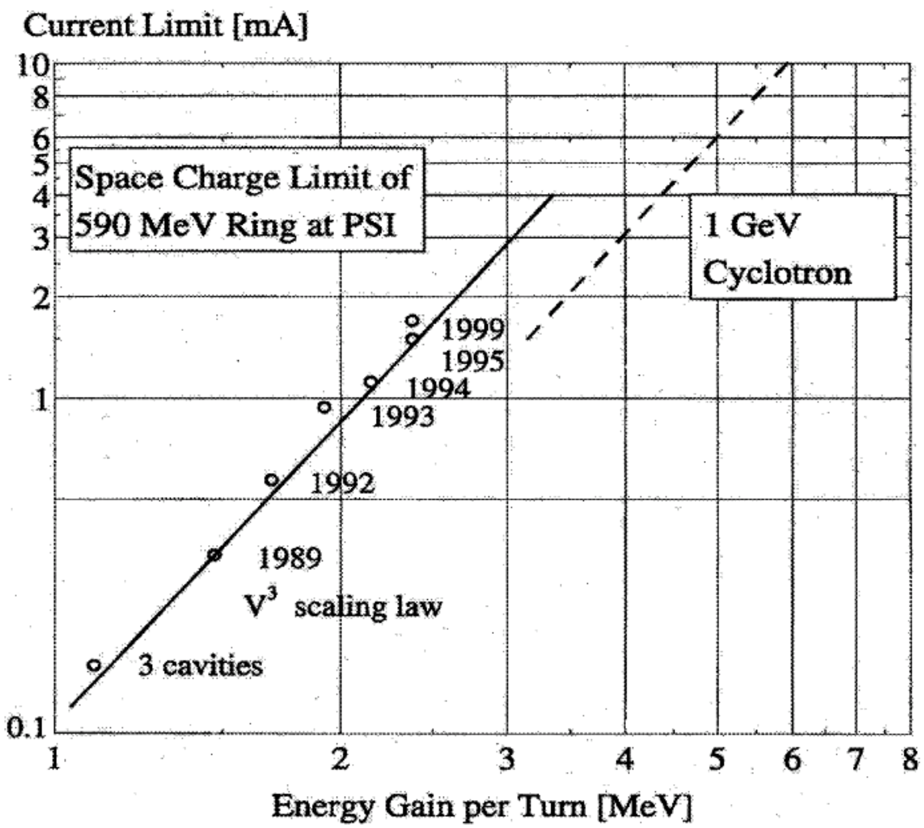
Achieved: 590 MeV, 2 mA, 1.2 MW

Upgrade: 590 MeV, 3 mA, 1.8 MW

Possible: 1000 MeV, 10 mA, 10 MW

[M. Humbel (PSI)]

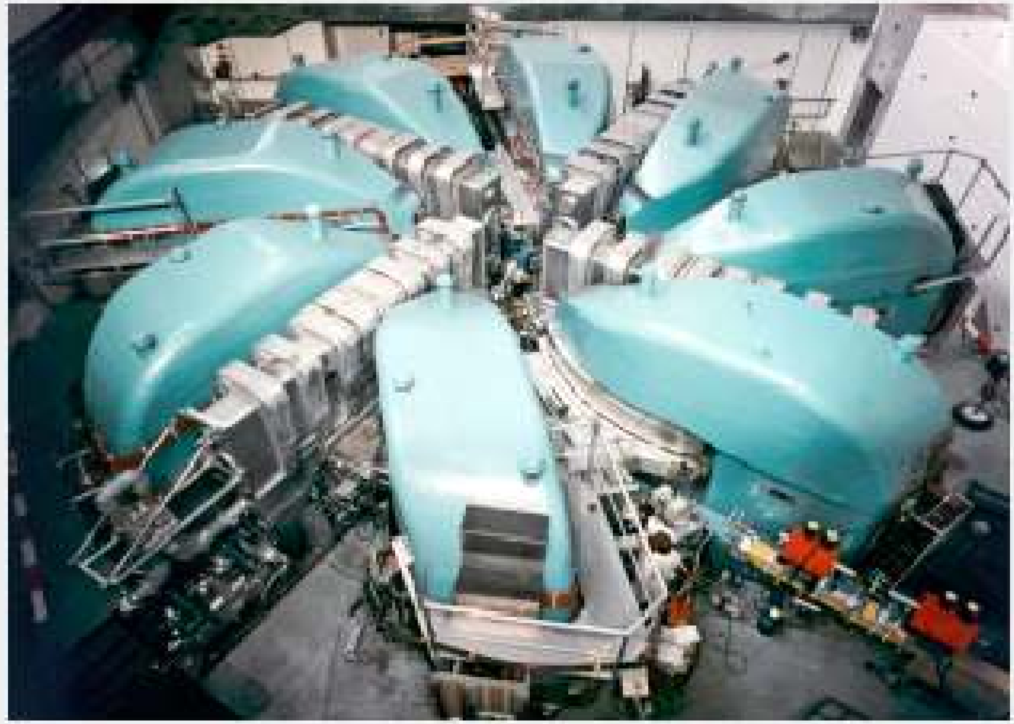




Space charge current limit scales with third power of rf voltage.

PSI Ring Cyclotron

ector Magnets:	1 T
gnet weight:	~250 tons
ccelerator Cavities:	850 kV (1.2 MV)
lat-Top Resonator	150 MHz
rection coil circuits:	15
celerator frequency:	50.63 MHz
monic number:	6
etic beam energy:	72 → 590 MeV
m current max.:	2.2 mA
raction orbit radius:	4.5 m
er diameter:	15 m
tive Losses @ 2mA:	$-\sim 1..2 \cdot 10^{-4}$
nsmitted power:	0.26-0.39 MW/Res.



Grid to Beam Power Conversion Efficiency

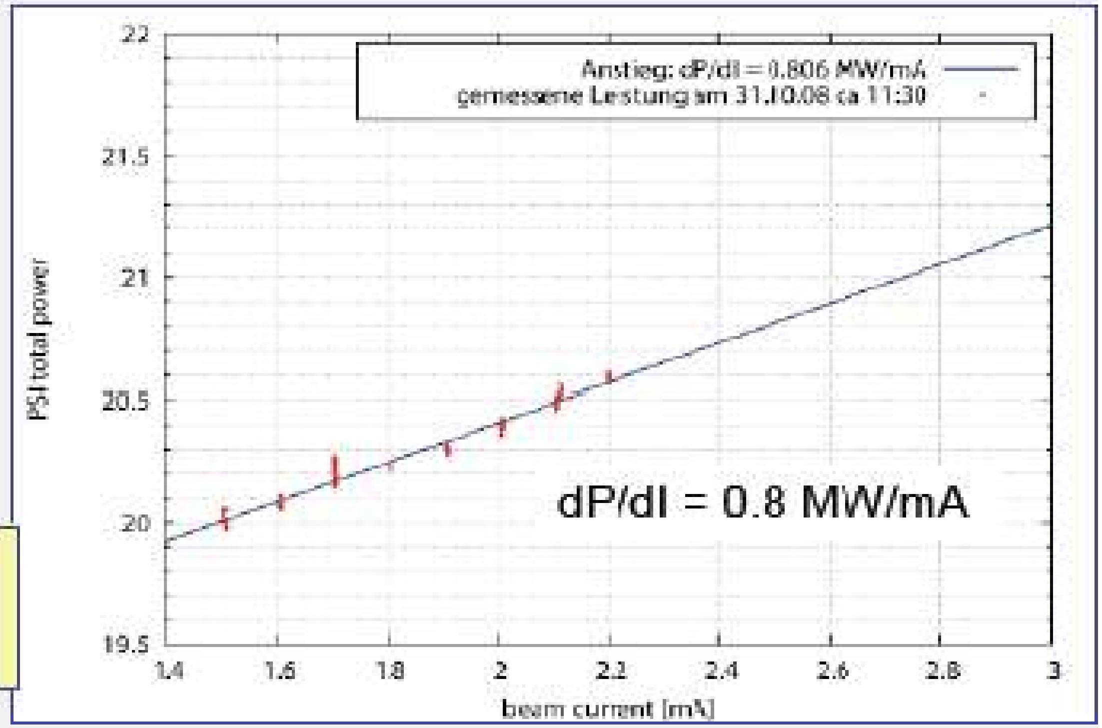
for industrial application, transmutation etc., the aspect of **efficient usage of grid power** is very important

PSI: ~10MW Grid → 1.3MW Beam

$$P_{\mathrm{grid}}(I) \approx (8.0 \pm 0.5)\mathrm{MW} + 0.81\mathrm{MW} \cdot I[\mathrm{mA}]$$

contains many loads not needed for ADS !

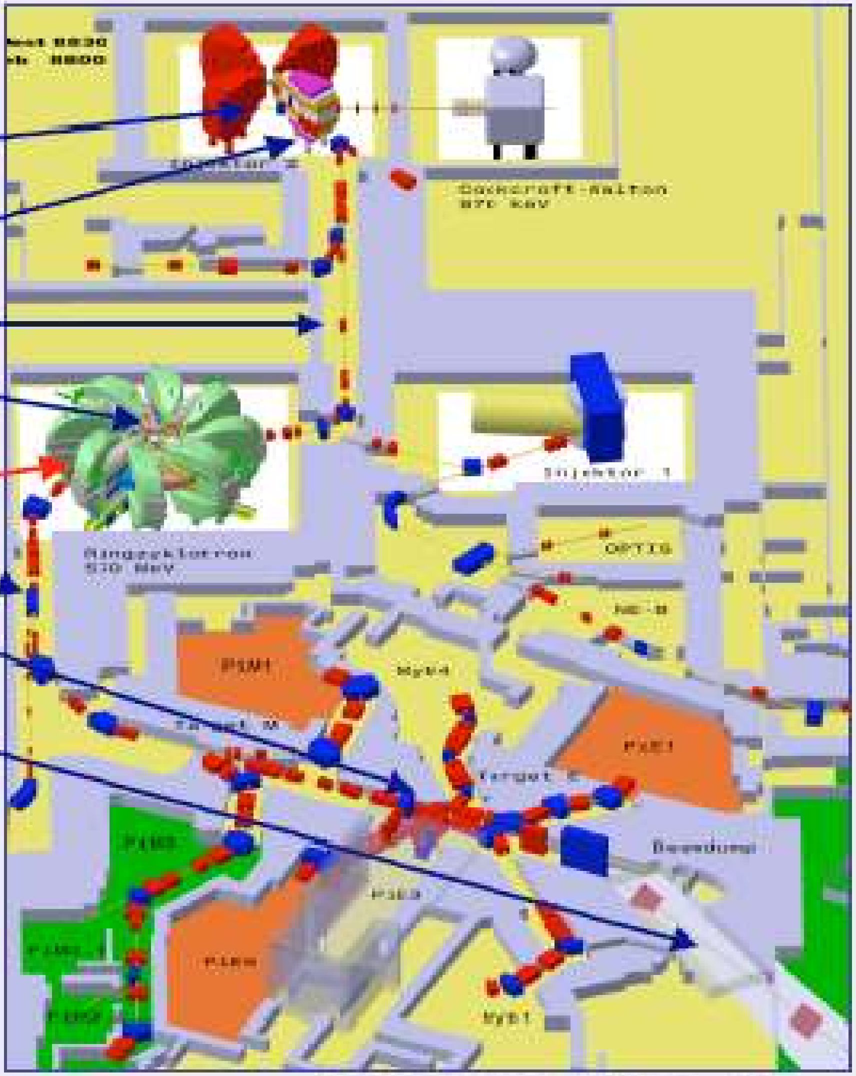
▶ **differential measurement of electrical power vs. beam power (total PSI power shown)**



M.Seidel, HIPA 2009, Fermilab

Particle losses along the accelerator

Accelerator Section	kin. energy [MeV]	max.loss [µA]	typ. loss [µA]
Injector II, extraction	72	5	0.3
collimator FX5 (shielded)	72	10	5
transport channel II (35m)	72	0.1	
Ring Cyc., Injection	72	2	0.3
Ring Cyc., Extraction	590	2	~0.4
transport channel III	590	0.1	0.02 (est)
target E+M (shielded)	590	30%	30%
transport channel IV	575	0.1	
SINQ target (shielded)	575	70%	70%

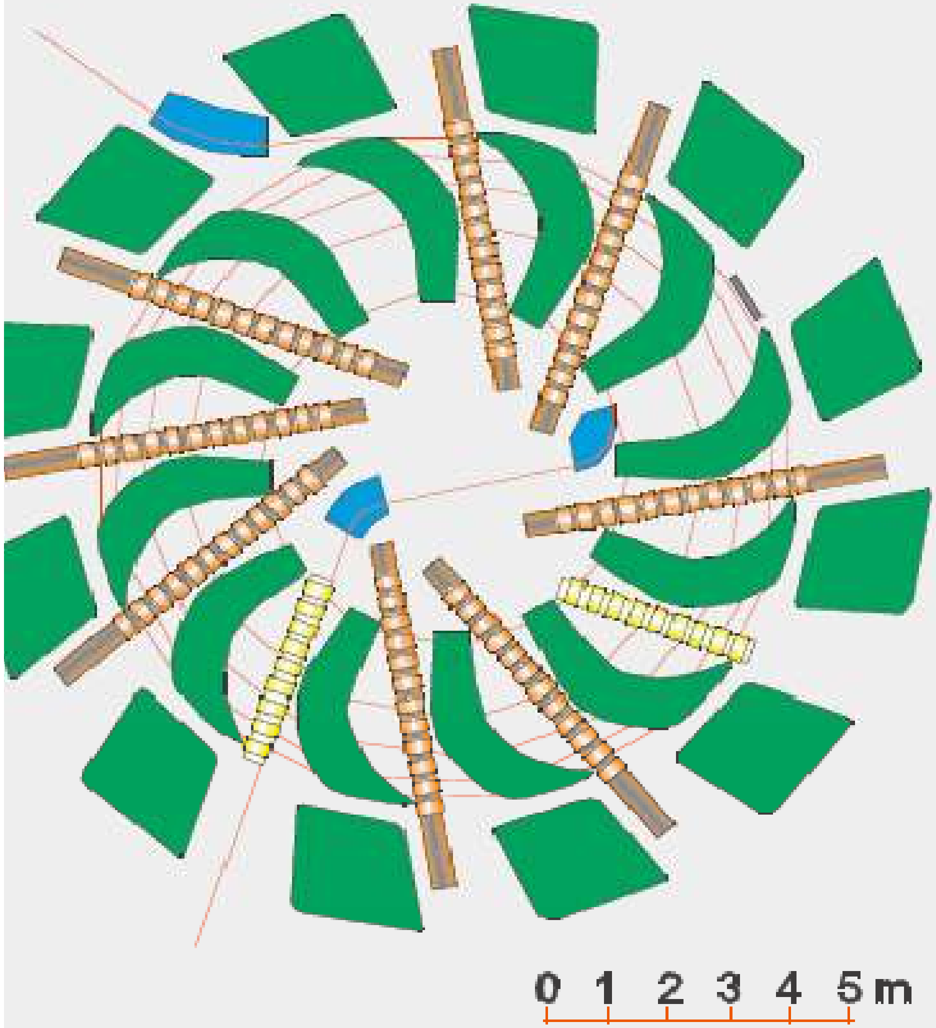


acceptable for service:

~ $2\cdot10^{-4}$ relative losses per location (@590MeV)

Parameter Set for a 10 MW Cyclotron

[1997, Th.Stammbach et al]



parameters	1 GeV Ring	PSI Ring
Energy	1000 MeV	590 MeV
Injection energy	120 MeV	72 MeV
Magnets	12 (B_{max} = 2.1 T)	8 (B_{max} = 1.1
Cavities	8 (1000 kV)	4 (800 kV)
Frequency	44.2 MHz	50.63 MHz
Flat tops	2 (650 kV)	1 (460 kV)
Injection radius	2.9 m	2.1 m
Extraction radius	5700 mm	4462 mm
Number of turns	140	186
Energy gain at extraction	6.3 MeV	2.4 MeV
DR/dn	11 mm	5.7 mm
Turn separation	7 s	7 s
Space charge limit	10 mA	2.2 mA (3.0 @ MV/turn)
Beam power	10 MW	1.3 MW

Several proposals, but no existing facility

Issues: CW front end (RFQ, DTL), operating efficiency of SC cavities/rf system

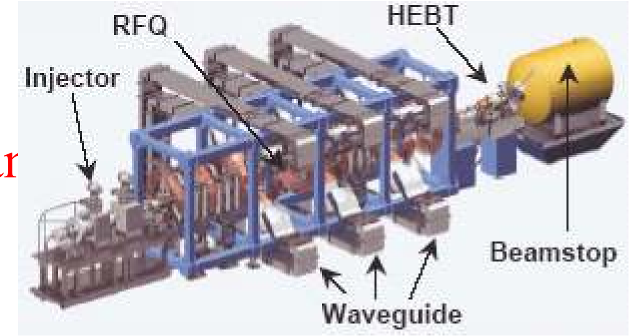
Low Energy Demonstration Accelerator (LEDA):

6.7 MeV, 100 mA CW (0.7 MW)

Successful demonstration of CW front-end

Bench-marking of halo simulation codes

High Intensity Proton Injector (IPHI, CEA) [R. Ferdinar



3.0 MeV, 100 mA CW (0.3 MW)

First beam in 2006, to be used for SPL (CERN)

International Fusion Materials Irradiation Facility (IFMIF):

2 x 125 mA D^+, 5 MeV (RFQ), 40 MeV (DTL) (2 x 0.6 MW, 2 x 5 MW)

Start 2009 (?)

Waste Storage Times

ssion Products are
orter lived (~30
ars half life) than
tinides(~10^5 years).
actinide wastes
ed storage for
ological periods of
ne - Yucca mountain
lution. EA produces
ss actinide waste so
e storage time is
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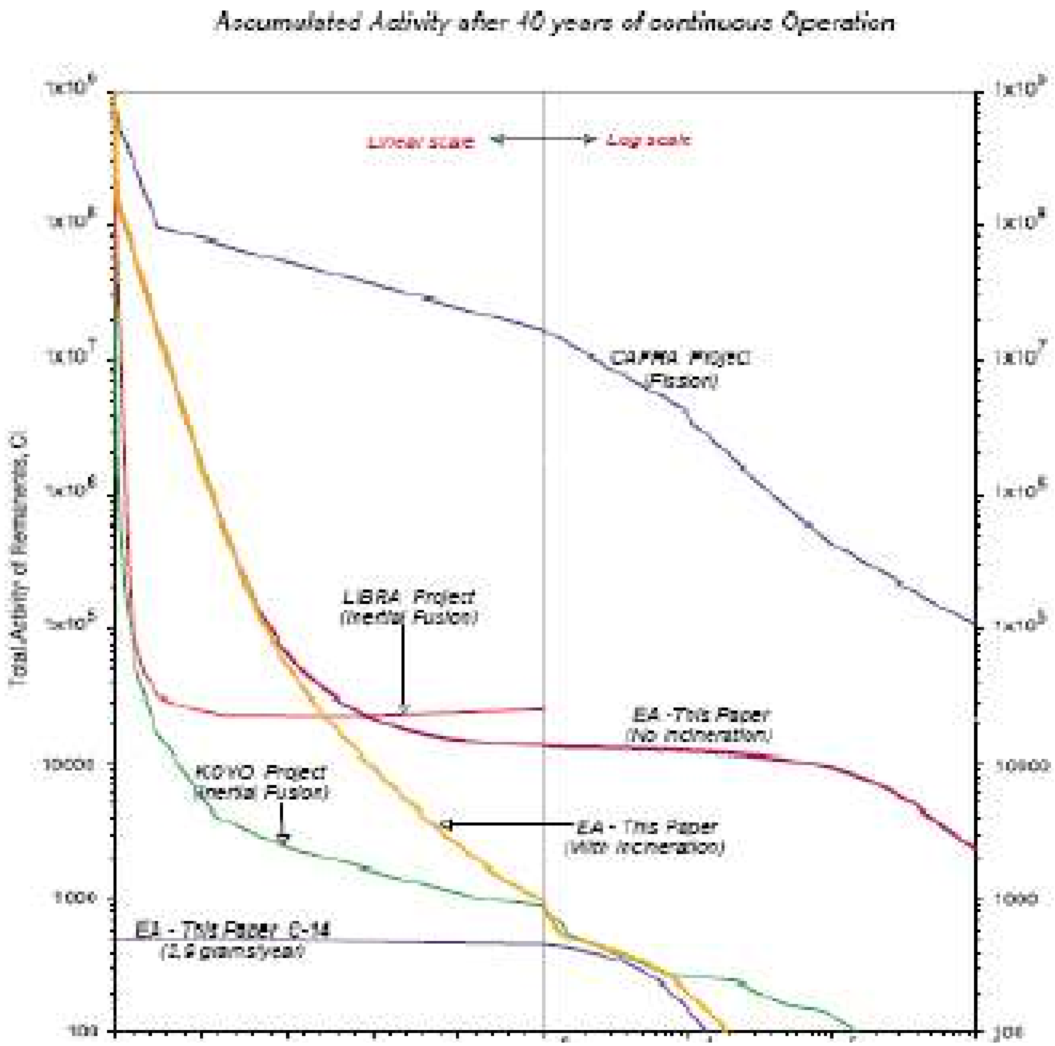


The Conceptual design

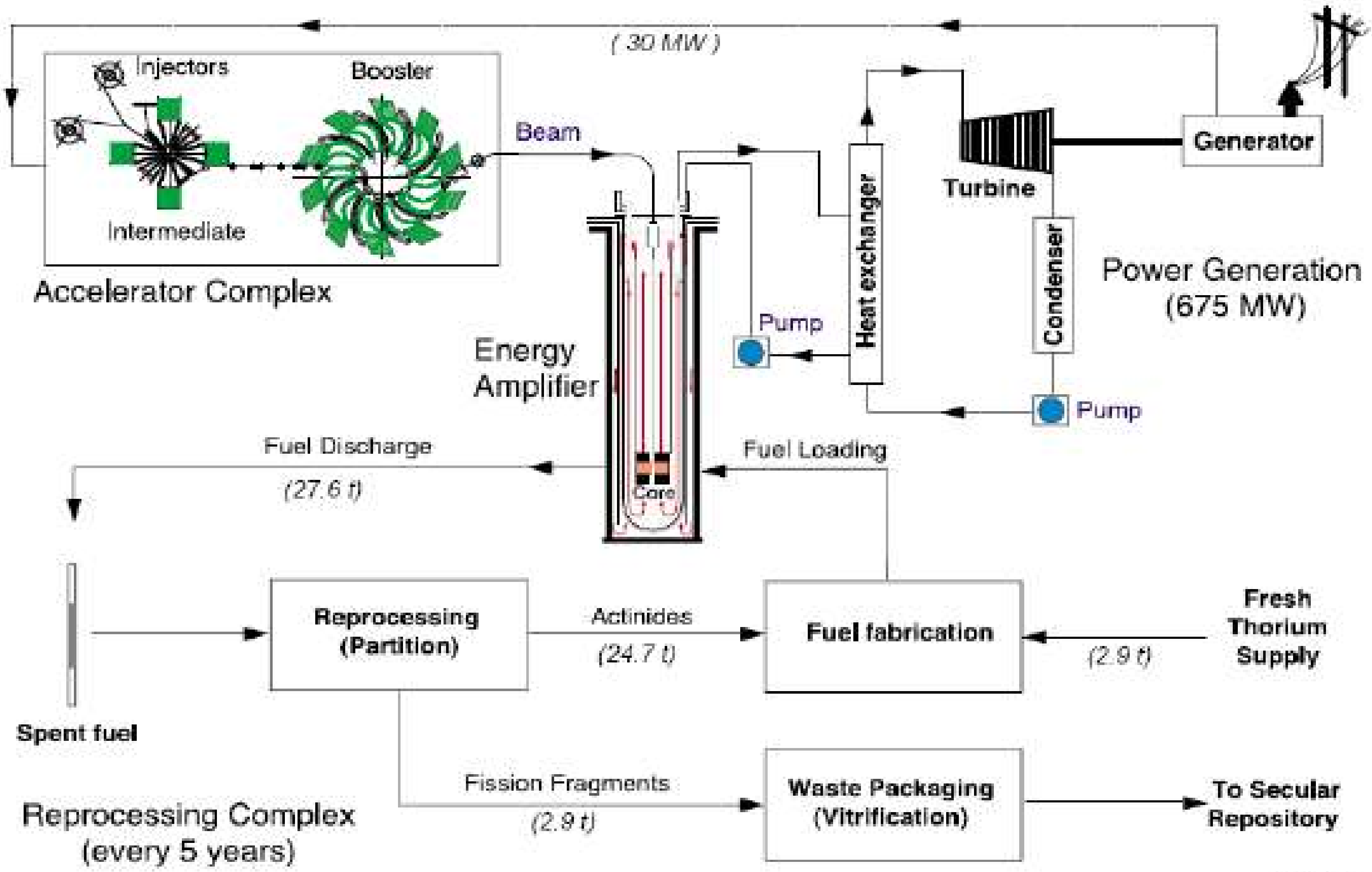
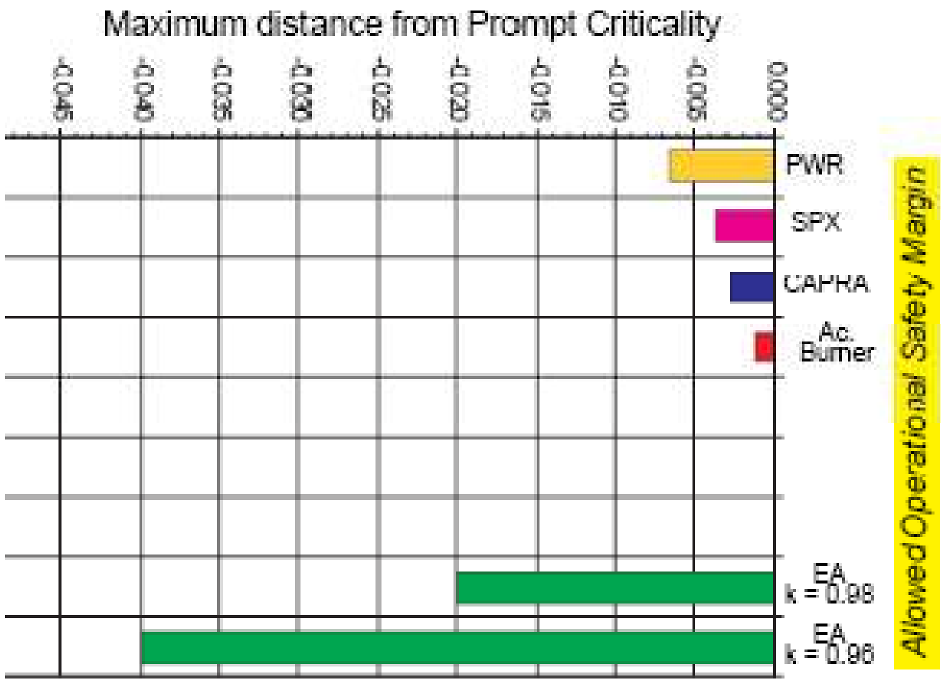
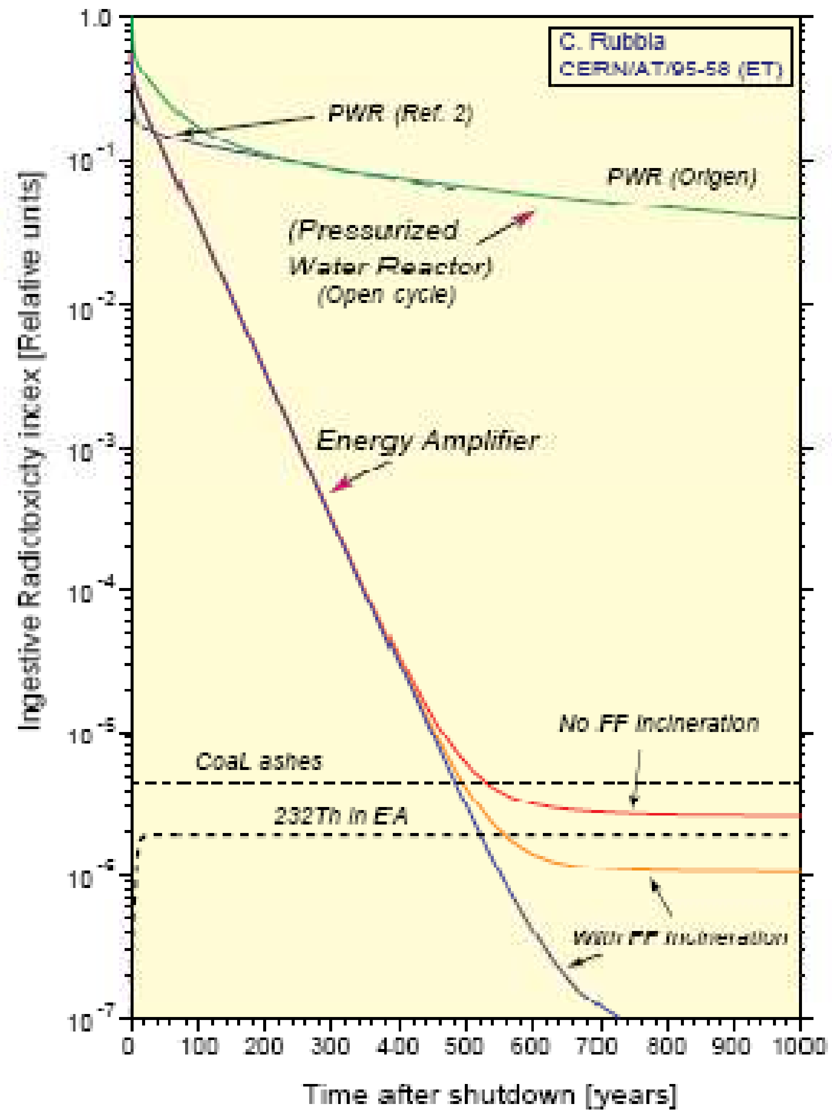


Figure 1.1

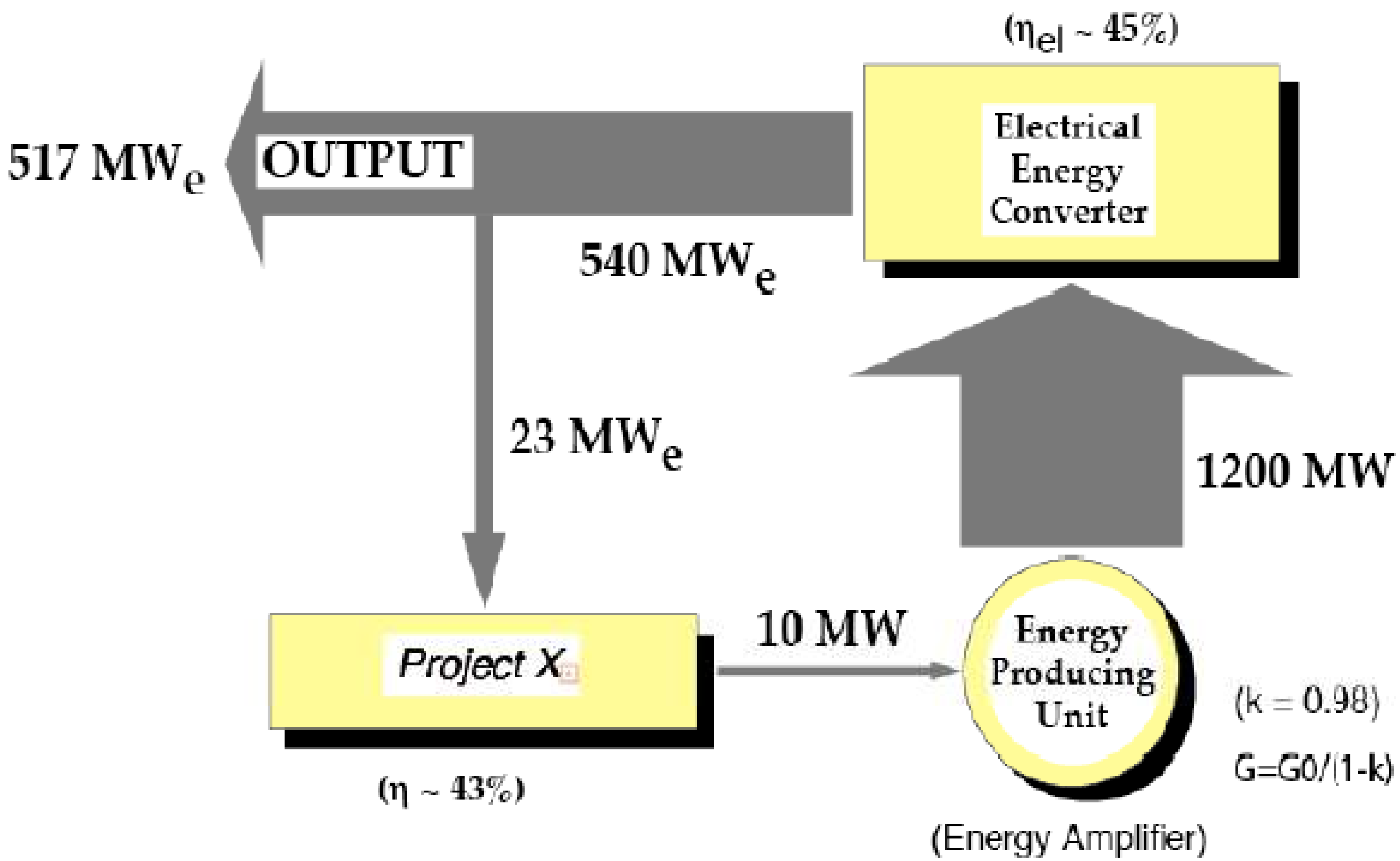
Advantages of the EA:





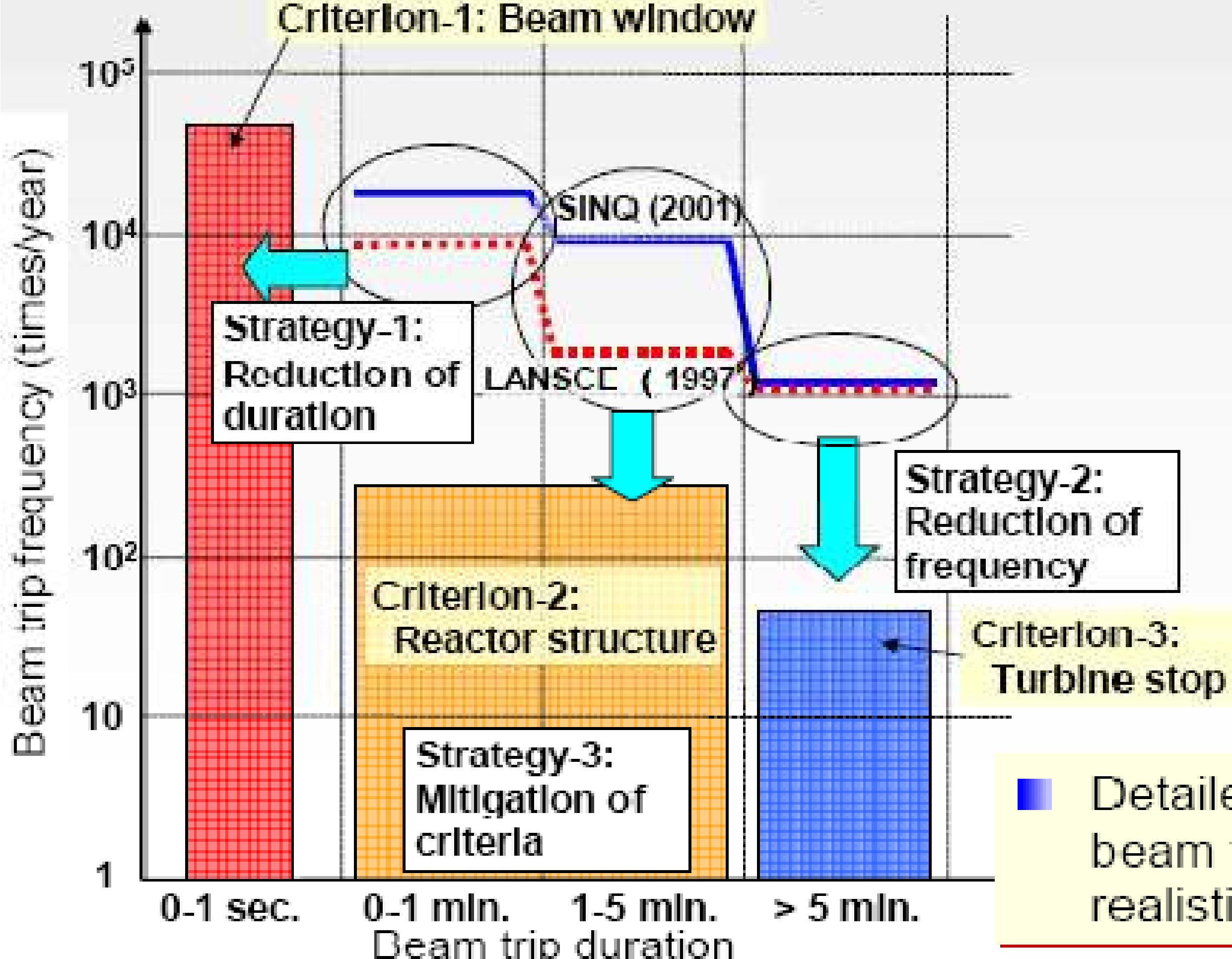
Safety margin with different systems
(fraction of delayed neutrons)
as compared with that of an Energy Amplifier

- Example of a 10 MW beam (Project X?); very close to the power of standard EA unit defined by C. Rubbia.



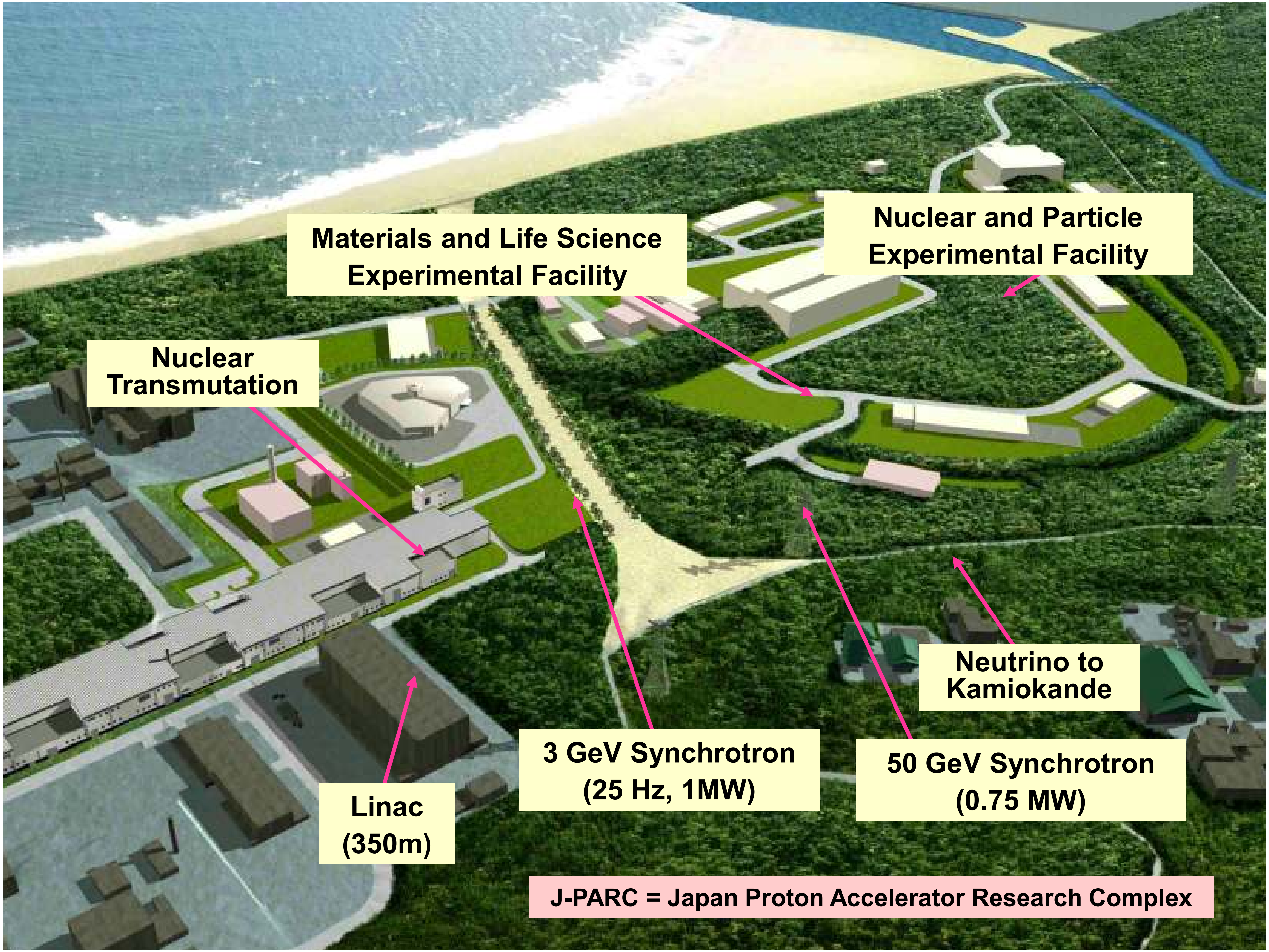
Reliability: Strategy to Reduce Beam Trip Frequency

- SINQ and LANSCE experiences show **1 or 2 orders** of frequency reduction might be necessary to meet the criteria



Three strategies for reduction
1. Reduction of the beam trip **duration** down to 1 sec.
2. Reduction of **frequency** for relatively long beam trip
3. Mitigation of the **criteria** by design consideration and detailed transient analysis.

- Detailed analysis on the causes of the beam trips is underway to explore the realistic solutions for Strategy-1 and 2


Materials and Life Science Experimental Facility
Nuclear and Particle Experimental Facility
Nuclear Transmutation
Neutrino to Kamiokande
3 GeV Synchrotron (25 Hz, 1MW)
50 GeV Synchrotron (0.75 MW)
Linac (350m)
J-PARC = Japan Proton Accelerator Research Complex

2.2 GeV, 1.8 mA , 4 MW, 50 Hz [R. Garoby (CERN)]

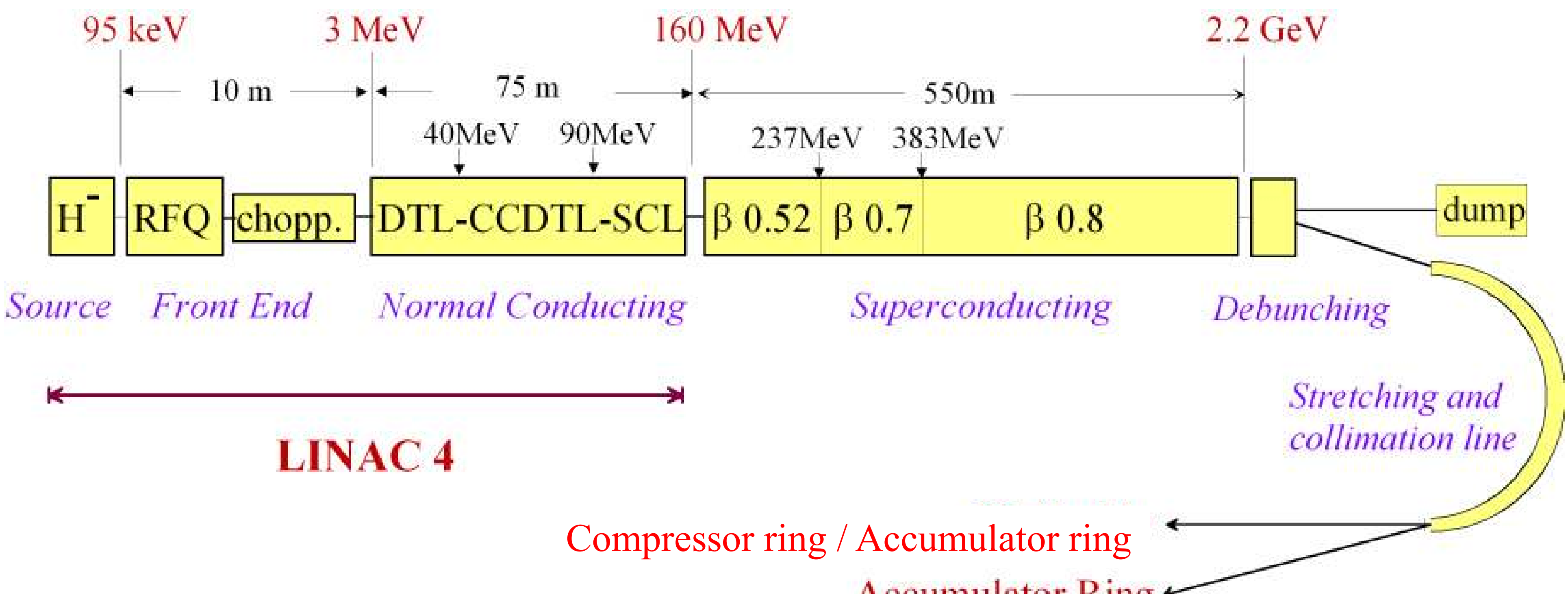
After Linac: DF: 8.2 %, I_{peak} = 22 mA (H^-)

After accumulator: DF: ~ 10^{-4}, I_{peak} ~ 18 A

After compressor: DF: ~ 2 x 10^{-5}, I_{peak} ~ 90 A

Solid Nb super-conducting 704 MHz cavities

New Design
5.0 GeV
G ~ 20 MeV/m



Arguments for a linac-based driver

Motivation

1. Acceleration in a single machine

A linac is largely accepted as the best accelerator at least up to a few hundreds of MeV. Accelerating up to the final energy in a linac avoids beam transfers and guarantees very low beam loss in the accelerator itself.

2. Safe and proven set-up

There is no doubt that an sc linac can be built to reliably deliver multi-MW of beam power up to 4-8 GeV. Proof of existence is given by SNS.

3. “Easy” ring(s)

A synchrotron is needed to transform the long linac pulse (nx100 μs) into a small number of short bunches. It can however be simplified wrt an RCS and it is credible because of:

- no space charge
- no need to accelerate (CW power supply and magnets, ordinary vacuum chamber, simpler RF system, no capture loss…)
- no time for instabilities to develop.

Specifications (from ISS report)

Parameter	Basic value	Range
Beam energy [GeV]	10	5 - 15
Burst repetition rate [Hz]	50	?
Number of bunches per burst (n)	4	1 – 6 ?
Total duration of the burst [μs]	~ 50	40 - 60
Time interval between bunches [μs] (t_{int})	16	~ 50/(n-1)
Bunch length [ns]	2	1 - 3

SPL-based 5 GeV – 4 MW proton drivers have been designed [SPL + 2 fixed energy rings (accumulator & compressor)] which meet these requirements

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SPL-based proton driver: principle [2/2]

Beam accumulation

- **Accumulator ring**
  - **Charge exchange injection**
  - **~nx100μs accumulation time**
  - **Isochronous (η=0): beam frozen longitudinally to preserve $\Delta p/p$**
  - **No RF (=> minimum impedance)**
  - **1-6 bunches of ~120 ns length**

Bunch compression

- **Compressor ring**
  - **Large RF voltage (large stored energy & minimum RF power) (=> bunch rotation on stored energy)**
  - **Large slippage factor η => rapid phase rotation in few x10μs,**
  - **~2ns rms bunch length @ extraction to the target (=> moderate ΔQ because of dispersion)**

Synchronization between rings

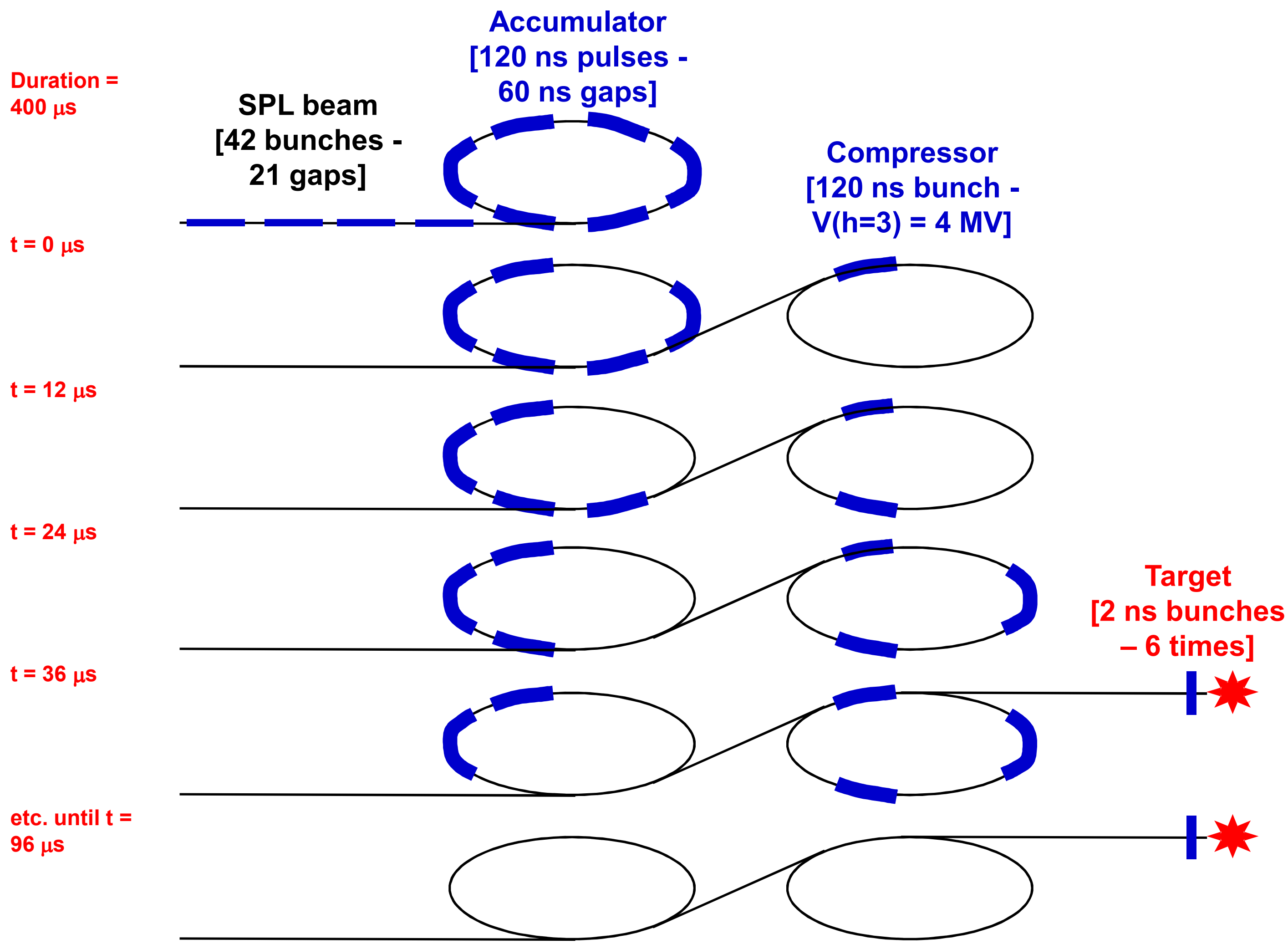
- **Ratio of circumferences guaranteeing correct positioning of successive bunches inside the compressor without energy change in any ring**

Generation of 6 bunches [2/2]

Scenario for 6 bunches

Accumulation

Compression



SPL for proton driver		**Output beam**	
Parameters	Values	Parameters	Values
Kinetic beam energy	5 GeV	Kinetic beam energy	5 GeV
Repetition rate	50 Hz	Repetition rate	50 Hz
Average current during the burst	40 mA	No. of bunches per cycle	6
Beam power	4 MW	Bunch length (r.m.s.)	~2 ns
		Bunch spacing	~12 μs
		Transverse emittance (r.m.s., physical)	3 πmm-mrad

Accumulator		**Compressor**	
Parameters	Values	Parameters	Values
Circumference	318.5 m	Circumference	314.2 m
Transition gamma	6.33	Transition gamma	2.3
RF voltage	-	RF voltage	4 MV
Harmonics number	-	Harmonic number	3
No. of arc cells	24	No. of arc cells	6
Super periodicity	2	Super periodicity	2
Nominal transverse tune	7.77/ 7.67	Nominal transverse tune	10.79/5.77
No. of turns for accum.	400	No. of turns for comp.	36
Maximum no. of bunches	6	Maximum no. of bunches	3
Main quadrupole		Main quadrupole	
Bore radius	56 mm	Bore radius	148 mm
Field gradient	5.5 T/m	Field gradient	7.1 T/m
Magnetic length	1.2 m	Magnetic length	1.9 m
Main bending		Main bending	
Full gap	103 mm	Full gap	125 mm
Full width	162 mm	Full width	379 mm
Field stength	1.7 T	Field strength	5.1 T
Magnetic length	1.5 m	Magnetic length	3 m

from M. Aiba

Summary

IT IS CLEAR THAT

there is no show-stopper for a multi-MW proton driver based on a 5 GeV SPL delivering 6 or even 3 proton bunches of ~2 ns rms length on target at 50 Hz.

reducing to a single bunch is probably not impossible, but much more challenging.

HOWEVER

the accumulator and compressor rings remain to be designed in detail (RF system, minimization of beam losses, design of collimation and collimators, H0 & unstripped H- beam dump, …).

R & D on H- stripping and charge exchange injection is mandatory. Laser-based stripping deserves study and experimental tests.

if high beam power and accumulator/compressor rings are implemented as upgrades, the corresponding needs have to be foreseen when initially building the superconducting linac.

ɔulse duration, N_b = number of bunches per pulse, τ_b = final compressed bunch length.

ɿer	Power (MW)	Type	Energy (GeV)	Frequency (Hz)	Protons per pulse ($\times 10^{13}$)	Pulse structure τ_p (μs)	N_b	τ_b (ns)
·-AGS	1	Synch	28	2.5	9	720	24	3
	4	Synch	28	5	18	720	24	3
	4	Synch	40	5	12.5	720	24	3
ιL	2	Synch	8	15	10	1.6	84	1
	2	Linac	8	10	15			
ιL MI	2	Synch	120	0.67	15	10	530	2
꞉N-SPL	4	LAR	2.2	50	23	3.2	140	1
	4	LAR	3.5	50	14	1.7	68	1
ιRC	0.75	Synch	50	0.3	31	4.6	8	6
.	4	Synch	5	50	10	1.4	4	1
	4	Synch	6–8	50	8.3	1.6	6	1
	4	FFAG	10	50	5	2.3	5	1
	4	Synch	15	25	6.7	3.2	6	1
/CERN	4	Synch	30	8.33	10	3.2	8	1
ː/Kyoto	1	FFAG	1	10^4	0.06	0.4	10	10
	1	FFAG	3	$3\,10^3$	0.06	0.5	10	10

FNAL SCL Proton Driver Proposal

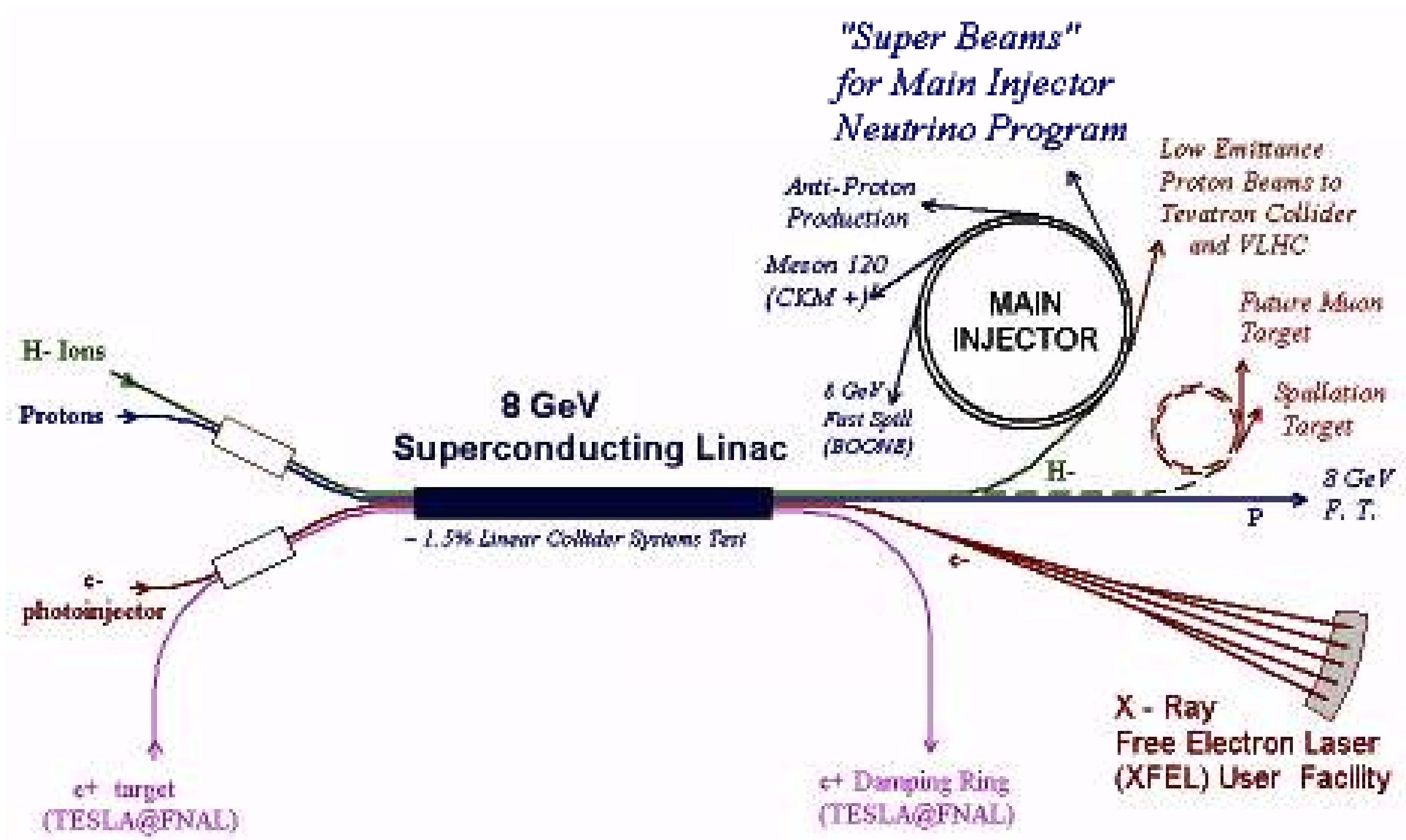
Super-conducting linac: 8.0 GeV, 0.25 mA , 2 MW, 10 Hz [B. Foster (FNAL)]

After Linac: DF: 0.9 %, I_{peak} = 28 mA (H^-)

After MI (accumulator): DF: ~ 6 x 10^{-5}, I_{peak} ~ 5 A

After MI (acceleration): 120 GeV, 2 MW, 0.7 Hz, DF: ~ 4 x 10^{-6}, I_{peak} ~ 5 A

1.3 GHz Tesla cavities, stripping of H^- (all fields < 600 G)

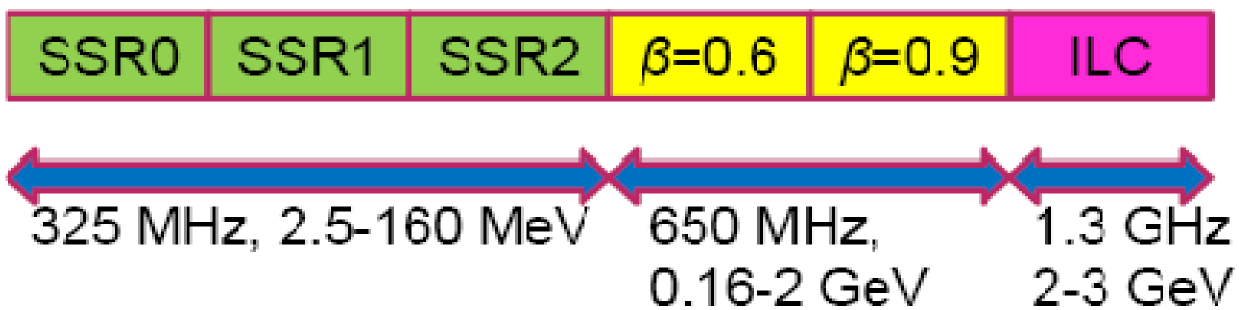


Project X

IC-2v2.0

"Option 4"

- Option 4: a 3-GeV CW linac with a 650 MHz intermediate system, based on 5-cell cavities.



Note: 650 MHz, β=0.9, 5-cell cavities are same physical length as 1300 MHz, β=1.0, 9-cell cavities

IC-2v2.0 "Option 4"

- Total number of cavities in each configuration:
  - IC-2v1.0: 316 cavities (to 3 GeV)
  - IC-2v2.0: 250 cavities (less if β=0.95)
- Total linac length is reduced by ~20% (for 3 GeV)
  - Or, 3 GeV linac (option 4) is ~20% longer than the 2 GeV linac in IC-2v1.0
- Early analysis of cost trade-offs indicate that 1300 MHz cavity becomes more cost effective than 650 MHz somewhere in the range of 2 GeV
- Development of IC-2v2.0 (option 4) will allow us to explore issues related to introduction of a third frequency, and variations on the 1300 MHz cavity shape

Primary parameters

5 MW long pulse source
(upgrade to 7.5 MW?)

≤ 2 ms pulses

≤ 20 Hz

Protons (H+)

Low losses ! 1 W/m

High reliability, >95%

Summary

Beam power efficiency

- Beam power efficiency is an issue for high intensity accelerator.

$$BPE = \frac{\text{beam power } \left(E \times I_{beam}\right)}{\text{total operatonal power}}$$

- BPE>30% for P_b>10MW, otherwise
  - Environment problem:CO2
  - ADSR becomes nonsense ; Creating nuclear wastes more than treating!
- Superconducting magnet
  - High temperature SC is very attractive.

Comparative Advantages of RCS vs LAR

- **Lower Beam Current**

- **Lower Injection Energy**

- **Higher Injection Beam Loss is allowed.**

  (If one increases the beam energy by a factor of 7.5 times, the allowed beam loss during the injection is 7.5 times as high as that for AR with the same beam power.)

- **Perhaps immune against the e-p instability?**

- **SNS debate in 1999 BNL(LAR) design or ANL(RCS) design?**

RCS Challenges

- Lower injection energy in turn implies higher space charge effect.
- Large aperture magnets are required, giving rise to large fringing fields.
- Ceramics vacuum chamber with RF shield to avoid the eddy current effect
- Stranded coil to overcome the eddy current effect on the magnet coils.
- Injection to make large aperture beam and its extraction are hard to manage.
- Precise magnet field tacking is necessary for each family of magnets
- Powerful RF accelerating system for rapid acceleration

Main challenges for future Multi-MW facilities

- Beam Loss and collimation
  - Maintainability requires losses ~ 1 W/m
  - For 1 km/10MW facility: total losses of 1 kW or 10^{-4} at top energy
  - Since losses are not evenly distributed, lower values may be required at some locations

- Power Consumption Efficiency
  - Efficiency = (beam power)/(wall plug AC power)
  - Present facilities have typically low efficiency (few %)
  - Need new technologies for efficient beam power production

- Design and Performance of High Power Production Targets and secondary beams

- Reliability and Availability for Users, especially for commercial power production

Conclusions

- Multi-MW facilities are being planned with DF from CW to 10^{-6}
- Designs for a CW facility with few MW beam power are mature, either by SPL or Cyclotron
- Several excellent and detailed designs for Multi-MW low DF facilities exist. The designs will benefit from the operational experience of recent projects (SNS, J-PARC).
- FFAG is not suitable for high intensity, but can provide high power through high rep rate(`100 to ~ KHz)
- Active R&D needed to improve performance, increase reliability, and reduce cost
- China is entering the field at a critical time for both technological advancement and industrial competitiveness.

References

1. “Ultra-high Intensity Proton Accelerators and their Applications”, W. T. Weng, PAC1997

2. “Upgrading the SNS Compressor Ring to 3 MW”, W. T. Weng, ..et. Al., EPAC2002

3. “Workshop on Applications of High Intensity Proton Accelerators”, FNAL, 2009, http://conferences.fnal.gov/App-Proton-Accelerator/

Exercies

1. Changing one parameter at a time, how to raise SNS proton beam power from 1.0 MW to 2.0 MW by varying

   a. Beam energy
   b. Beam intensity
   c. Beam rep-rate

2. What is the best combination(realistic and cost-effective), by varying all possible parameters to reach 2 MW?

3. Compare the relative advantages of LAR and RCS design of CSNS design, in terms of

   a. Accelerator performance limitation
   b. Required changes of power supply, RF, and Vacuum
   c. Cost and reliability