Needs for High Intensity Hadron Drivers

Introduction

Issues of high intensity beam facilities

Proposals and designs of future high intensity hadron drivers

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Thomas Roser
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Main challenges for high intensity hadron facilities

Beam power:

$$P = E \times I_{ave} = E \times I_{peak} \times DF$$

[E:Kinetic energy; DF: Duty Factor]

- Peak current (low DF) limited by space charge and beam stability
- Average power limited by beam loss
  - 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 (AGS: ~ 1 %)
  - Need new technologies for efficient beam power production
- High power production targets
  - Material stress and fatigue for pulsed beams (low DF)

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High hadron beam power applications

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)

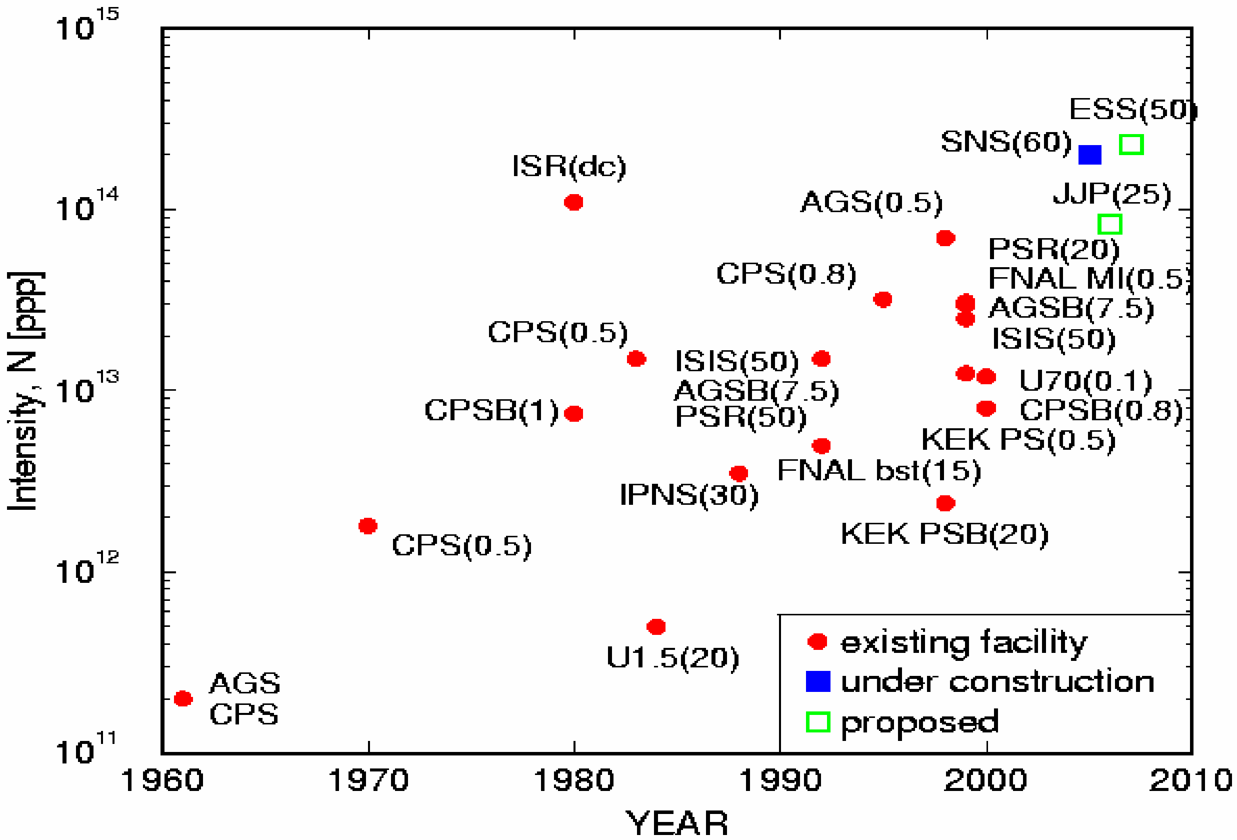
Production of intense secondary beams:

- 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)
- Radioactive Isotope (RI) production: DF: CW - 10^{-4}, E: ~ 1 GeV (ISOL facility, reacceleration of RI)

Production of RI beams by fragmentation:

- Heavy ion drivers: DF: CW - 10^{-4}, E: 0.5 - 3 GeV/n

Intensity history of multi-GeV proton machines



Exp. Growth (similar to max. energy history)

BNL AGS and CERN PS are leading high intensity accelerators for more than 40 years!

New record from SNS for storage rings.

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Progress in high intensity beam acceleration

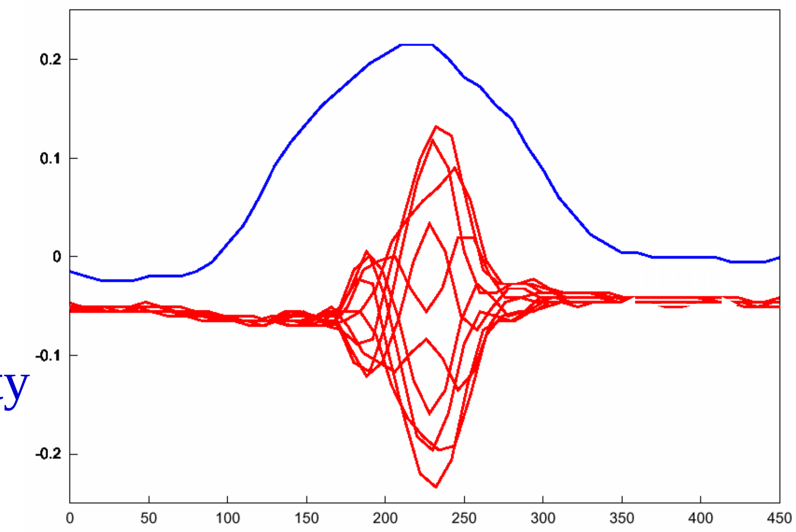
Technologies developed for high intensity beams:

- Low loss charge exchange injection (PSR, SNS, …
- Boosters (CERN, FNAL, BNL, KEK, …
- Rapid cycling synchrotrons (FNAL, ISIS, …
- (CW) RFQs (LEDA,…
- Super-conducting linac (SNS, …
- Transition energy jump or avoidance (CERN, AGS, J-Parc, …
- RF beam loading compensation (AGS, …
- Electron cloud cures (LANL PSR,…

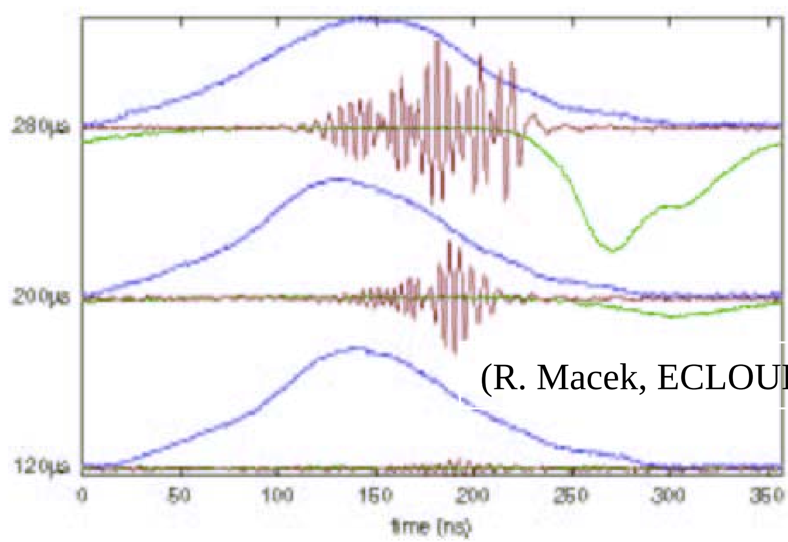
Need both machines and simulations to make progress!

Single bunch transverse instabilities – I_{peak} limitation

- AGS Injection (1.9 GeV)
- 12×10^{12} ppb, ~ 3 eVs
- Single bunch
- Transverse pick-up bandwidth limited
- Cured with non-zero chromaticity



- LANL PSR (0.8 GeV)
- 50×10^{12} ppb
- Cured with high rf voltage



(R. Macek, ECLOUD 2004)

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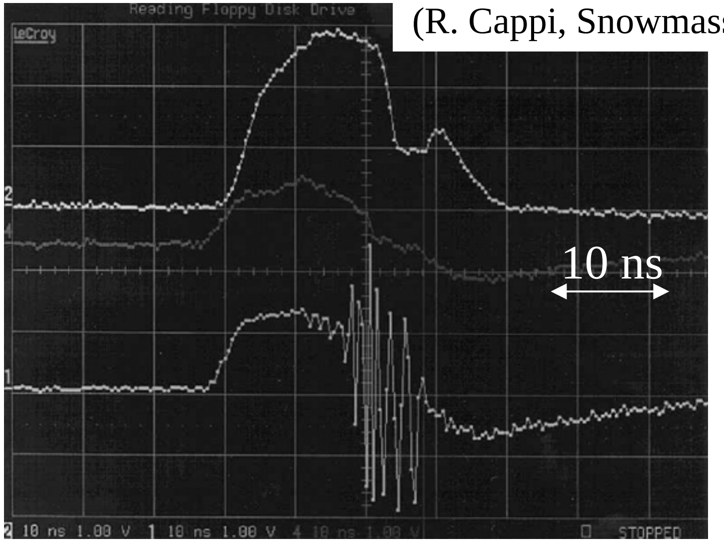
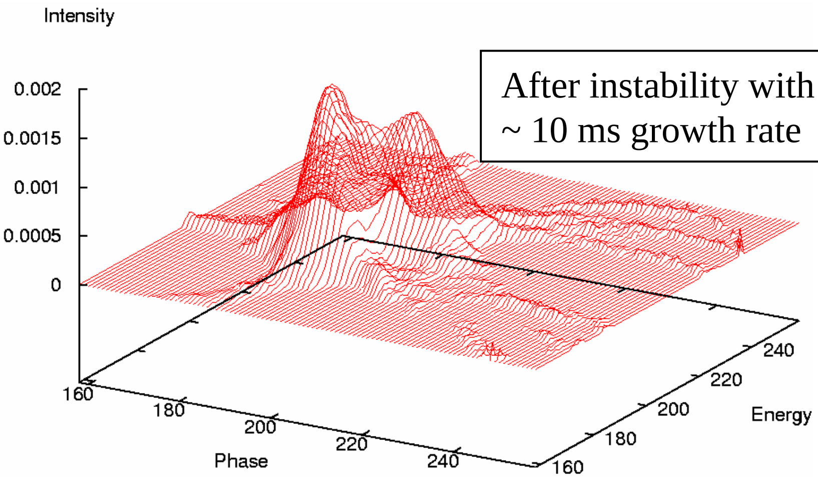
Single bunch transverse instabilities (2)

- CERN PS transition (~ 7 GeV)
- 7×10^{12} ppb, > 2.2 eVs
- Occurs close to transition
- Cured with long. blow-up and non-zero chromaticity



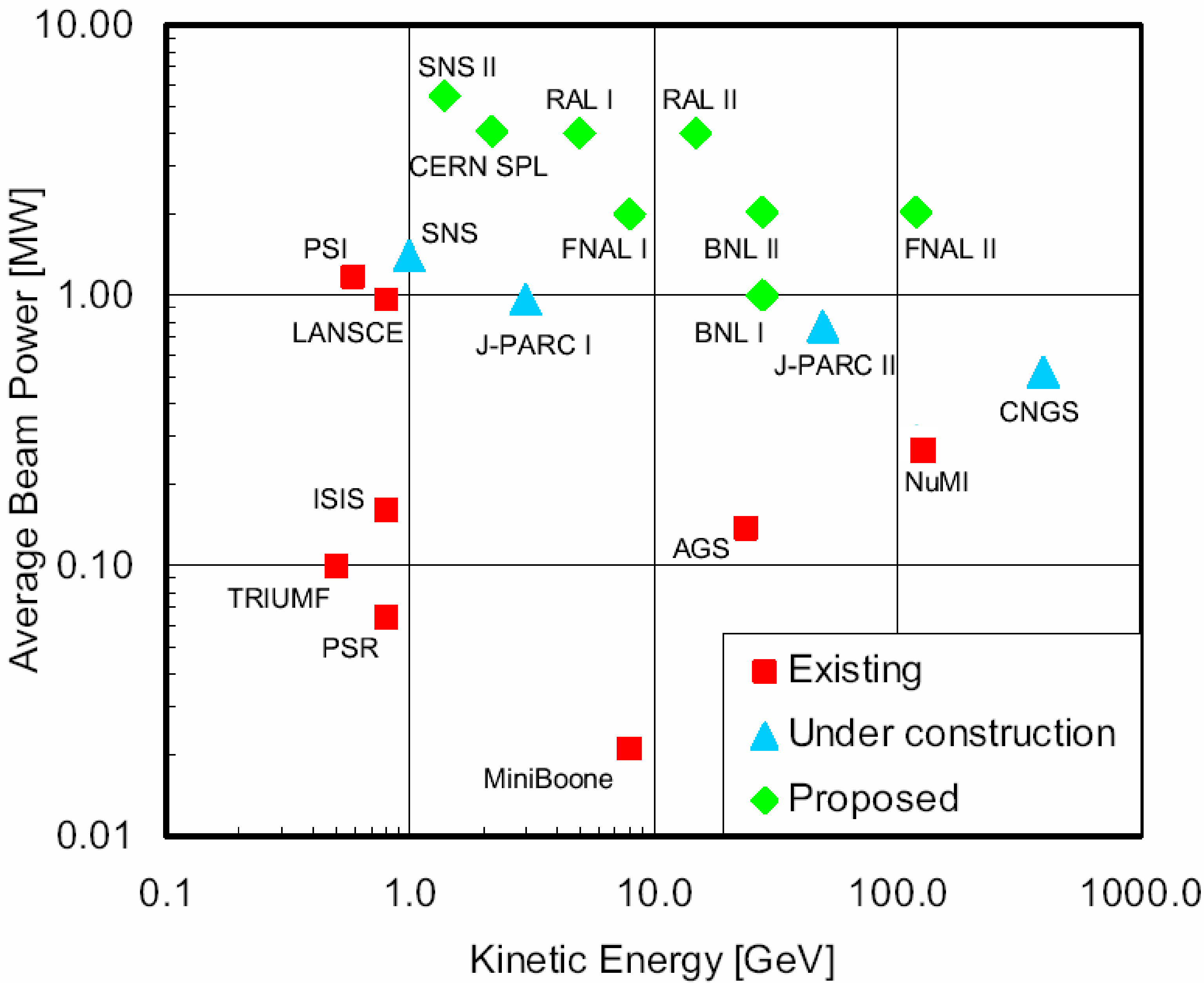
(R. Cappi, Snowmass 2001)

- RHIC transition (~ 20 GeV/n)
- 7×10^{10} cpb, ~ 0.3 eVs/n
- Occurs close to transition
- Cured with octupoles and non-zero chromaticity



E-cloud and/or broadband impedance

High Beam Power Proton Machines



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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

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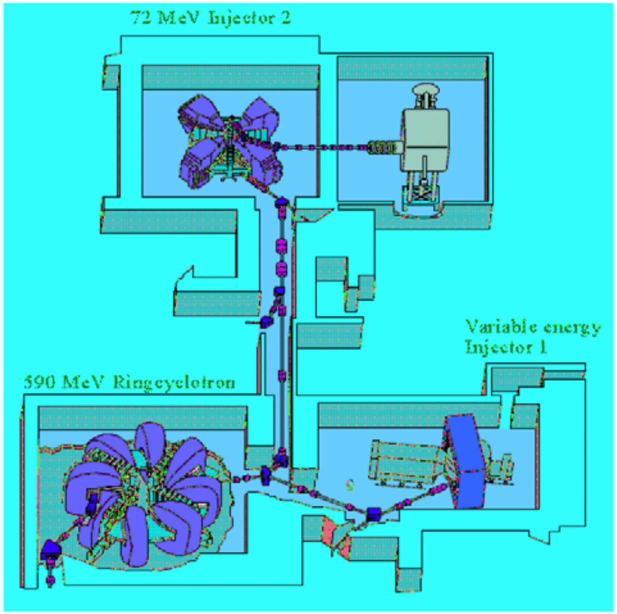
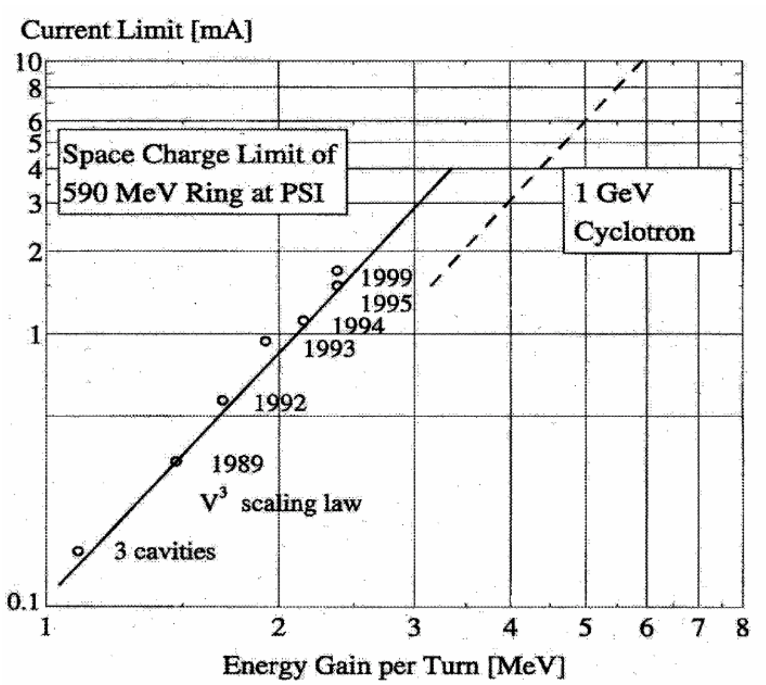
PSI SINQ Cyclotron Facility

Achieved: 590 MeV, 2 mA, 1.2 MW

Upgrade: 590 MeV, 3 mA, 1.8 MW

Possible: 1000 MeV, 10 mA, 10 MW





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

CW Super-conducting Linac

Several proposals, but no existing facility

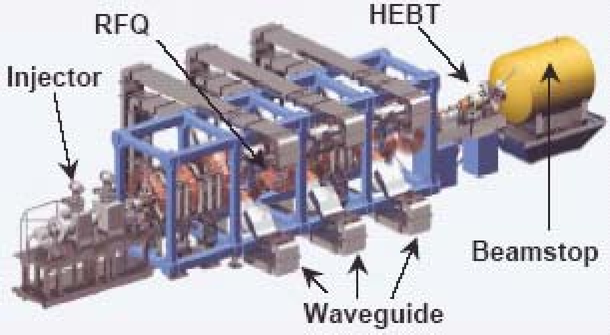
Issues: CW front end (RFQ, DTL), operating efficiency of SC cavities/rf system

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, 3 MeV test stand at CERN)

3.0 MeV, 100 mA CW (0.3 MW)

First beam in 2007, 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)

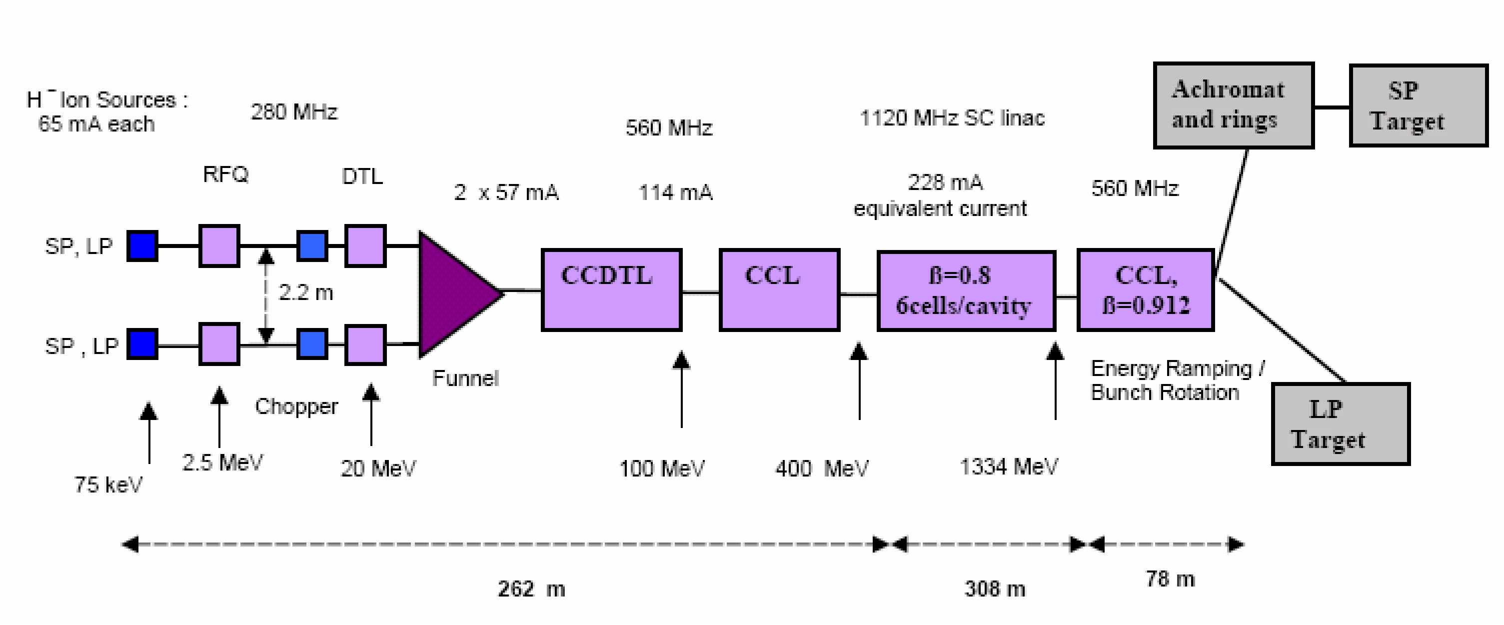
Start 2009 (?)

CW Super-conducting Linac (2)

Super-conducting Linac designs: APT Linac, ESS (Long Pulse)

ESS – Long Pulse Reference Design: 1334 MeV, 3.7 mA (3.3% DF), 5 MW

Beam / AC power (LP): 24% (NC 19%, SC 28%)



Radioactive Isotope Facilities

2 types of radioactive beam production:

- Isotope Separator On-line (ISOL): high intensity (~ 1 GeV) proton beam on high Z production target and extract and maybe reaccelerate radioactive nuclei

- Examples: ISOLDE (CERN), ISAC (TRIUMF), …

- Fragmentation facility (FF): high intensity (~ 300 MeV/n) heavy ion beam on “thin” target and study beam fragments in flight or stop the fragments and extract and maybe reaccelerate.

- Examples: NSCL (MSU), GSI (GERMANY), RIKEN (JAPAN), …

Radioactive Isotope Facilities

Future high power facilities:

- RIKEN upgrade (superconducting cyclotron) FF
  (300 MeV/n, 100kW U, CW, completed 2007)

- GSI FAIR (Rapid cycling synchrotron) FF
  (0.4 – 1.5 GeV/n, 60 kW U, pulsed, approved for construction)

- NSCL upgrade (cyclotron + superconducting linac) FF
  (200 MeV/n, 100 kW U, CW)

- RIA (superconducting linac for heavy ions and protons) FF (+ ISOL)
  (400 MeV/n, 100 kW U, CW)

Low Duty Factor Facilities – Accumulator vs. RCS/FFAG

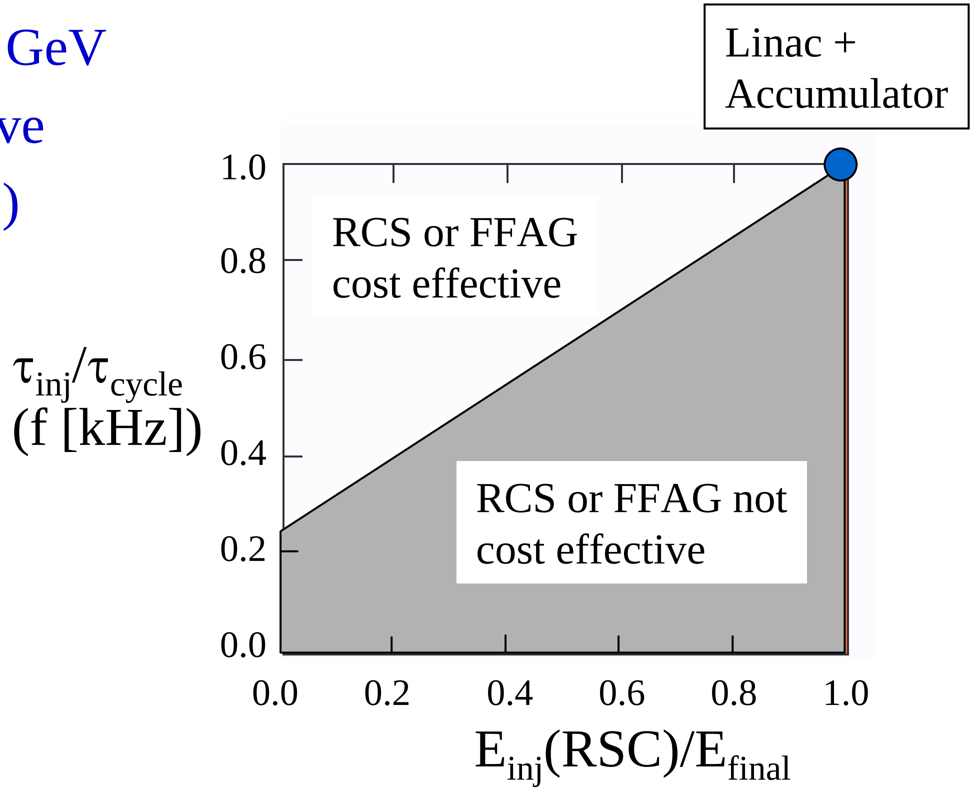
Linac + accum. ring	$E \leq 5$ (8?) GeV (H^- stripping)
Linac + RCS	Rep. rate < 100 Hz, $P_{RCS}/P_{Linac} \leq 10$
Linac + FFAG	Rep. rate $\leq$ 1 kHz, $P_{FFAG}/P_{Linac} \leq 3$

Maximum beam power if cost scales with total length (linac + ring):

For 1 ms linac pulse length and $E_{final} \sim 5$ GeV

→ Accumulator ring is more cost effective

unless rep. rate > 200 Hz (→ FFAG ?)



CERN Superconducting Proton Linac Proposal

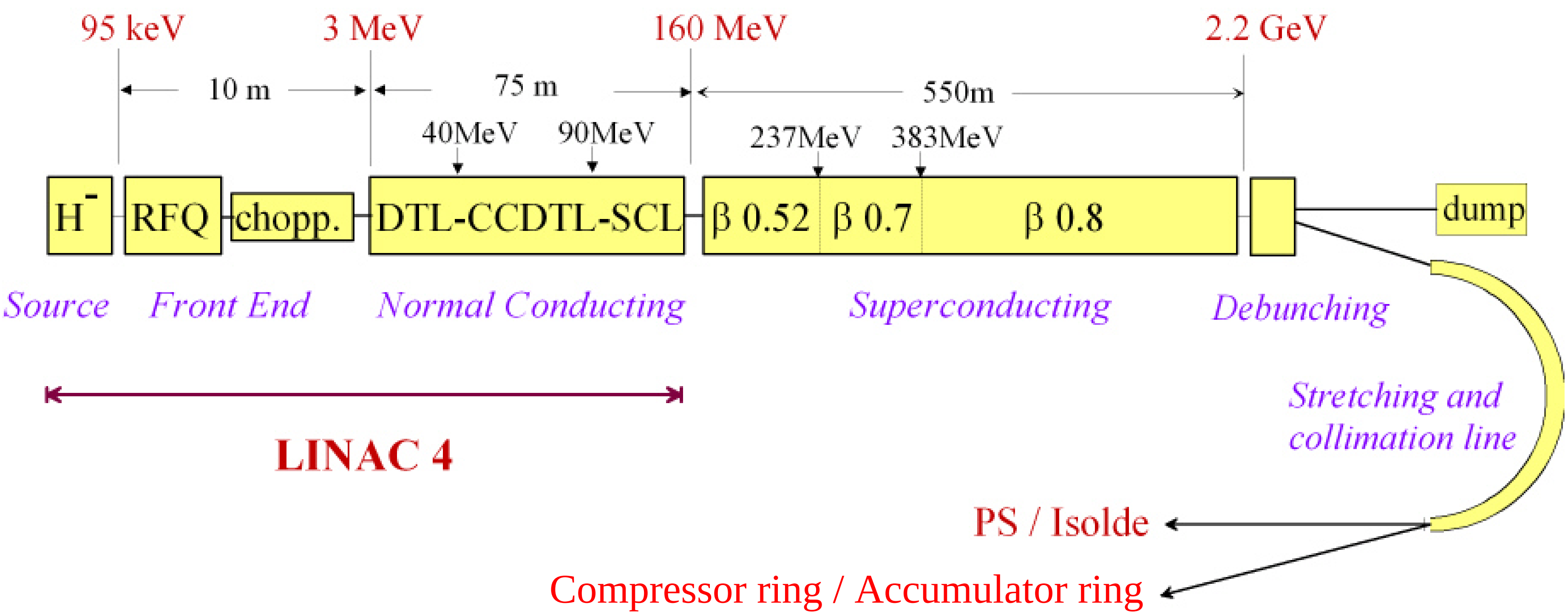
2.2 (3.5) GeV, 1.8 mA , 4 MW, 50 Hz

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



FNAL SCL Proton Driver Proposal

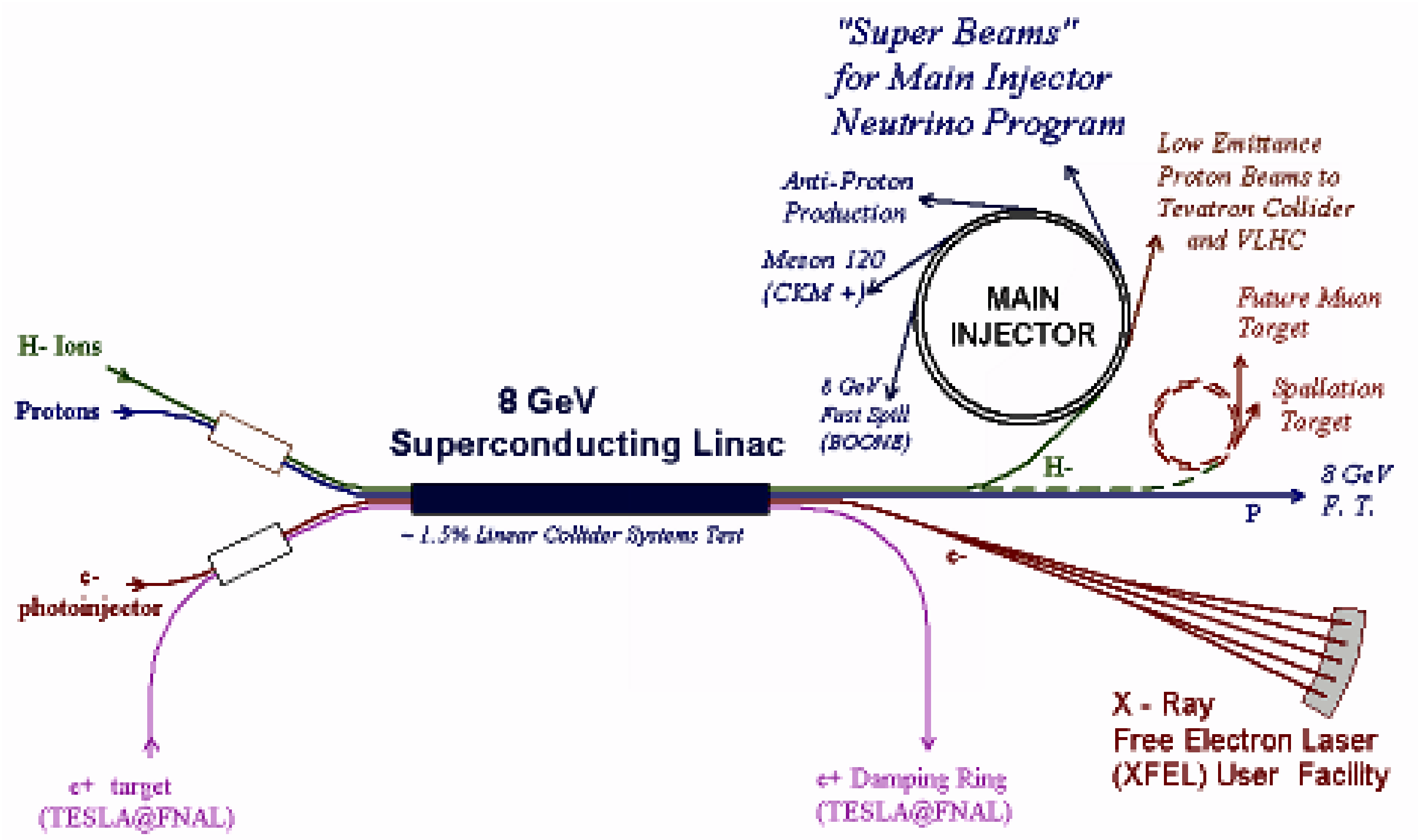
Super-conducting linac: 8.0 GeV, 0.25 mA , 2 MW, 10 Hz

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)

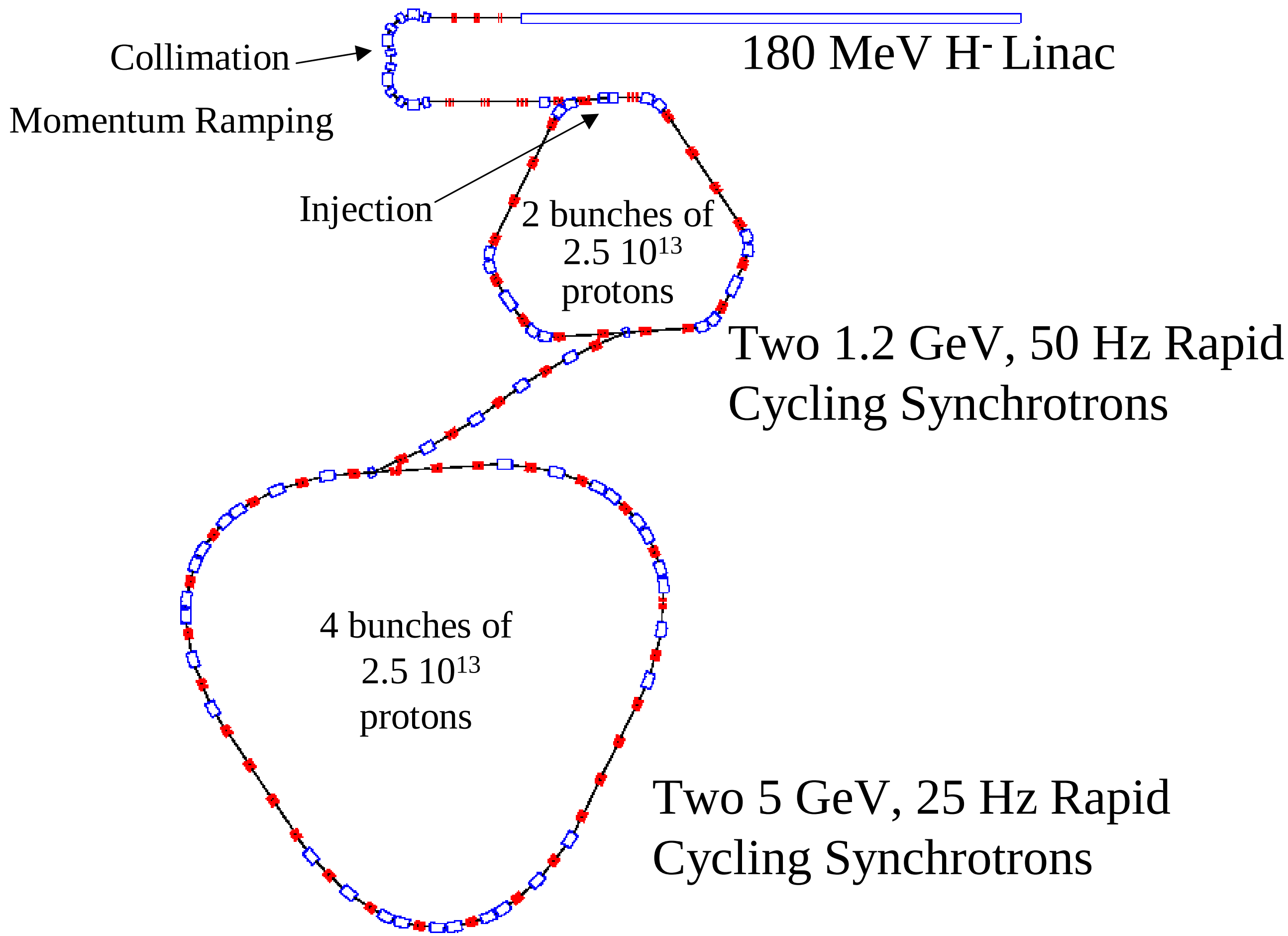


RAL proton driver proposal

5 GeV, 0.8 mA , 4 MW, 50 Hz

After Main Synchrotrons: DF: ~ 8 x 10^{-7}, I_{peak} ~ 1 kA

Bunch compression using transition energy

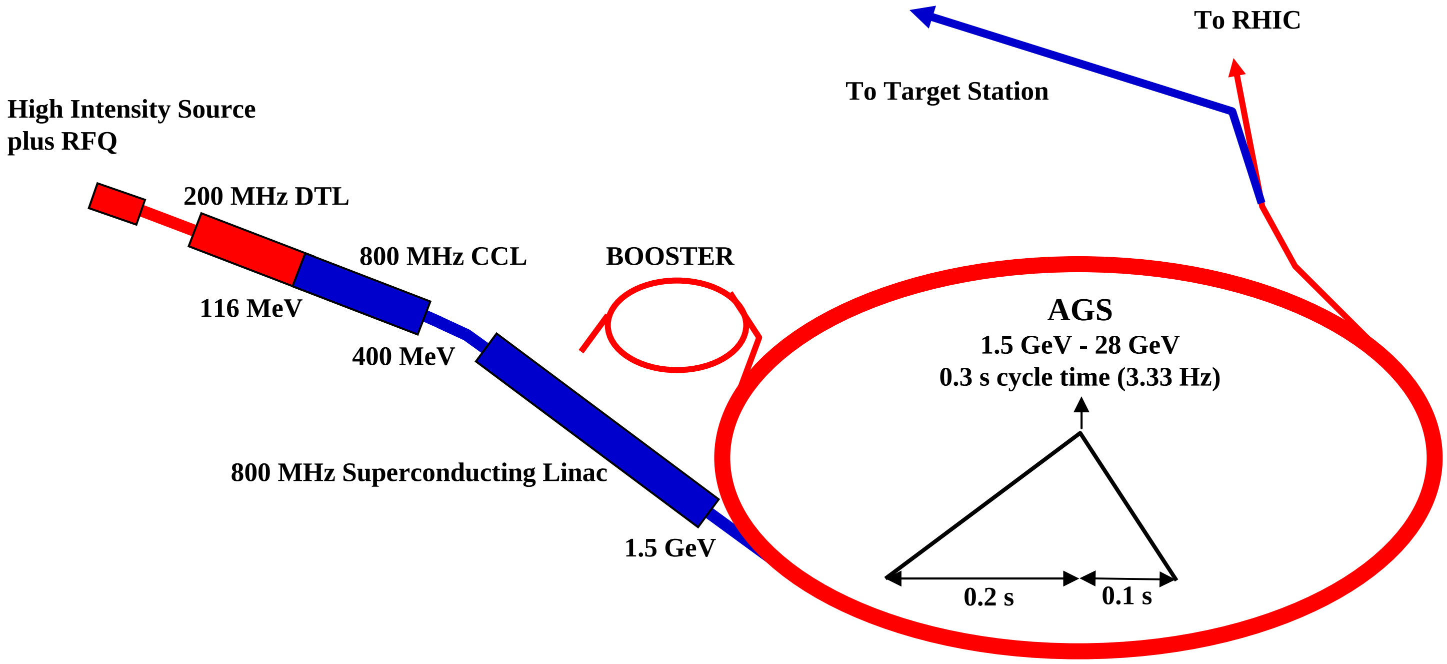


BNL AGS Upgrade to 2 MW

28 GeV, 0.07 mA , 2 MW, 3.33 Hz

After AGS: DF: ~ 4 x 10^{-6}, I_{peak} ~ 16 A

1.5 GeV superconducting linac extension for direct injection of ~ 1.4 × 10^{14} protons



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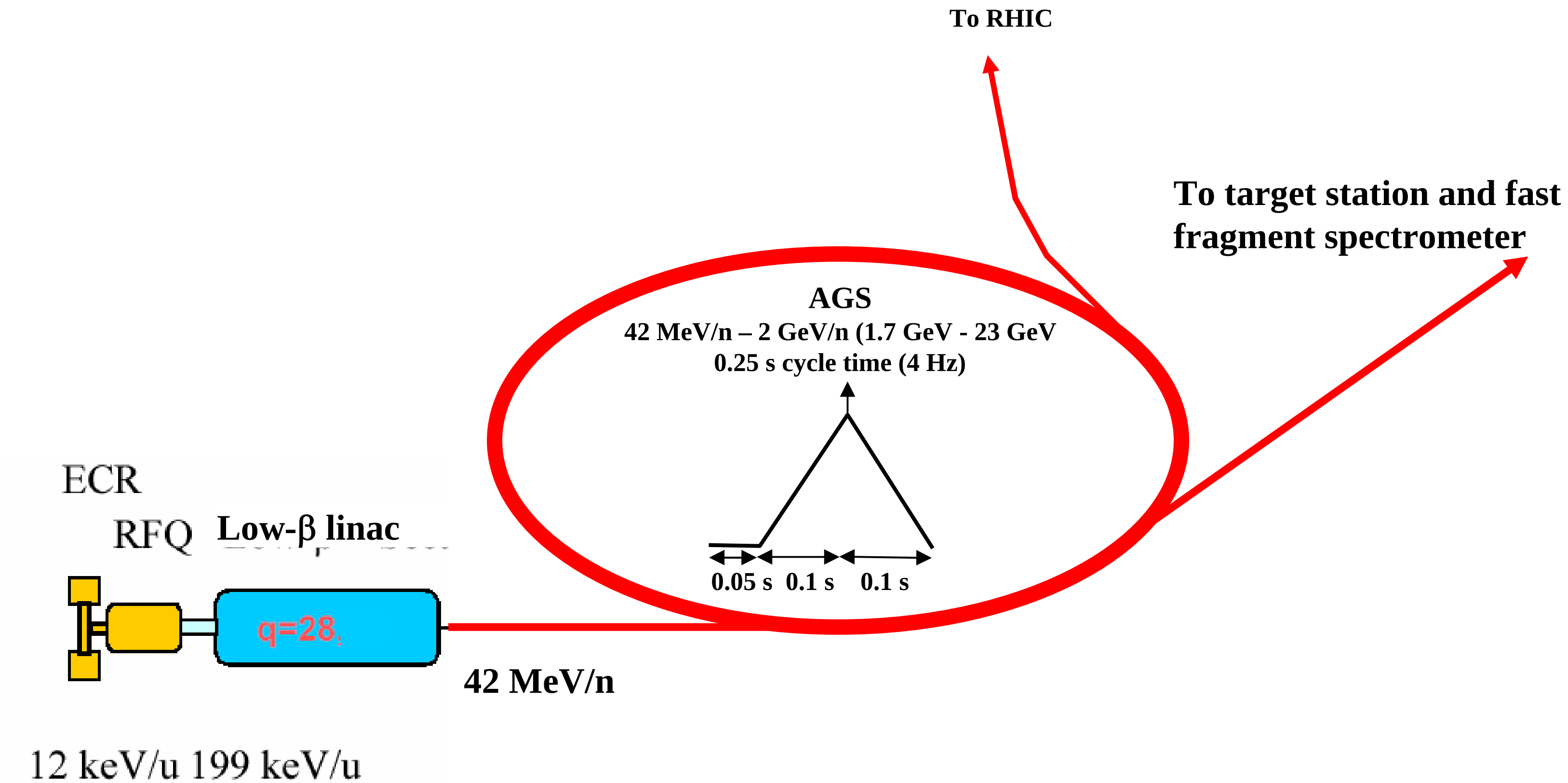
Possible AGS heavy ion driver

2 GeV/n, 100 kW, 4 Hz

“RIA” front end,

Electron cooling at AGS injection (alternatively in separate Accumulator)

Fast and slow extraction at 2 GeV/n (or lower energies)



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FFAG hadron driver

Renewed interest in Fixed Field Alternate Gradient (FFAG) accelerators

Advantages: High repetition rate (~ kHz), final energy > 1 GeV

Successful demonstration of scaling (fixed tune)

Non-scaling designs with small tune variation are being developed

Example: 1 GeV, 10 mA , 10 MW, 1 kHz

After FFAG: DF: ~ 3×10^{-4}, I_{peak} ~ 30 A

Issues: High rf gradient (> 3 MV/turn !!),

Fast frequency tuning (~ 0.5ms) or harmonic number hopping

Conclusions

Multi-MW facilities are being planned with DF from CW to 10^{-6}

Designs for a CW facility with 10 MW beam power are mature. Construction of such a facility should be the next step of the development of high intensity proton accelerators. (SCL can go to even higher power)

Several excellent and detailed designs for Multi-MW low DF facilities exist. The designs will benefit from the experience with projects presently under construction (SNS, J-PARC).

High rep. rate FFAG hadron drivers: Need to solve rf requirements!