Proton Driver for Neutrino Factory

Machine Working Group
International Scoping Study

Requirement

- Neutrino factory
  - Useful muon decay 1x10**21 decays/a

    <-- Power requirement for PD
- Other users
  - Superbeam

    beam power >MW (4MW as nominal figure)
  - Muon (PRISM,g-2)

    time structure >kHz

Proton Driver specification

- Beam energy >GeV
  - target, scheme(hardware),cost...
- Beam power >MW (4MW)
  - target (C, Liq.M)
  - beam dump
- Time structure
  - repetition rate <100Hz(NF), ~kHz(Muon)
  - bunch length 1(3)ns(w:cooling)
10ns(w/o:cooling)

Scheme/Hardware

- Proposed schemes
  - Synchrotron (J-PARC, AGS upgrade, Rutherford)
  - Linac (SPL, Fermi lab.)
  - FFAG (Scaling, Semi-scaling)

Issues:

beam loss (instability, activation, maintenance)
beam time strucure (repetition, bunch length)
tolerances (alignment, field errors...)
radiation shield and beam dump design
cost

Synchrotron

Issues to be considered

- Beam power of >MW
- Injection (accumulation)
  - H- stripping, painting, foil lifetime, H0 dump,...
  - space charge
- Acceleration
  - beam loading(RF)
  - beam instability(electron cloud,...)
- Bunch compression
  - nano-second 1-10ns (depends on Mu-acceleration scheme)

Synchrotron

J-PARC (completion ~March,2008)

beam energy 50GeV

beam power 0.4MW(1st stage)-a few MW?

- Linac energy down 0.4GeV -> 0.2GeV

repetition 0.33(0.6)Hz

bunch length 30ns(normal operation)

Features

Imaginary transition gamma : (avoid beam loss caused by transition cross)

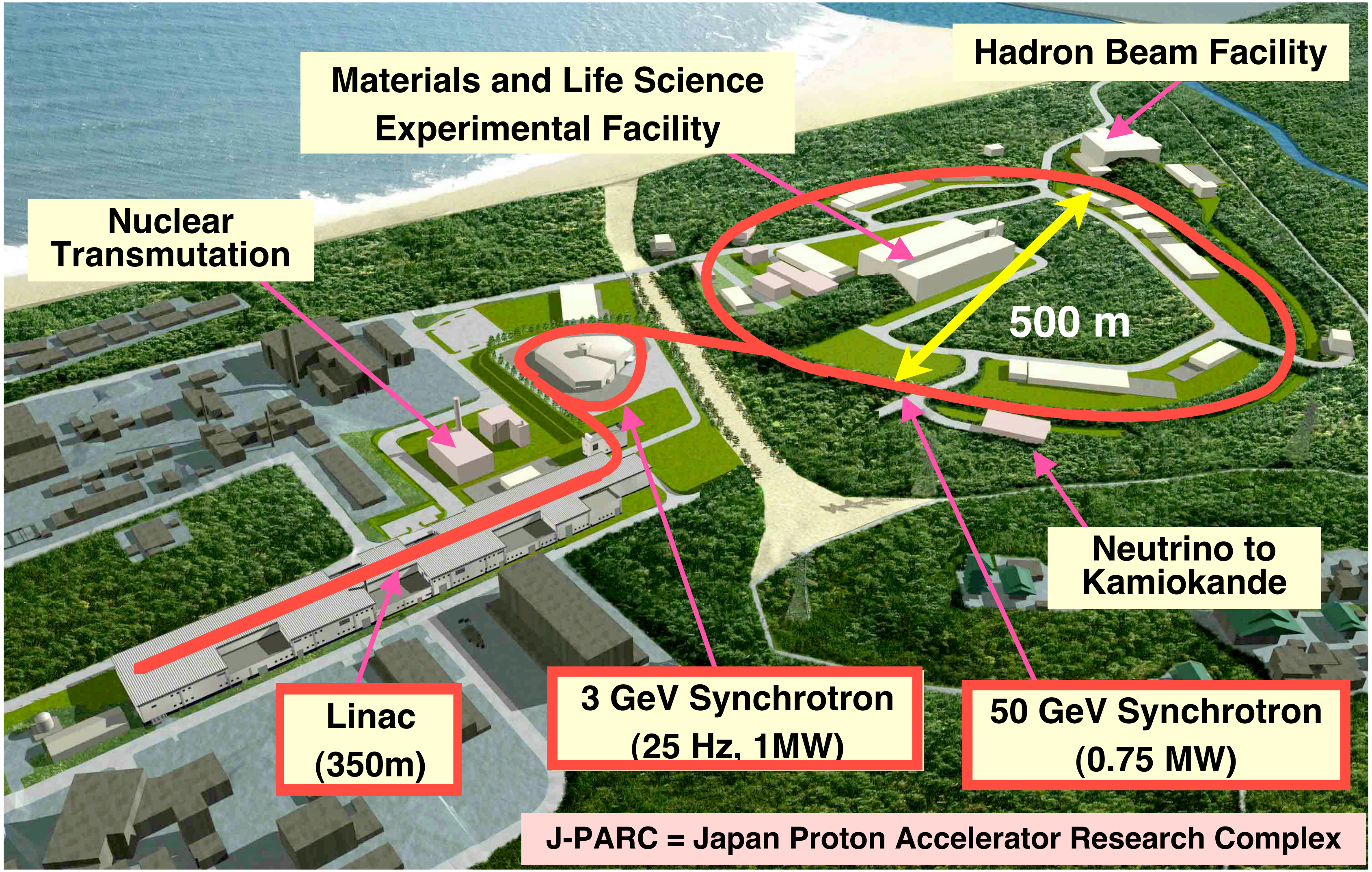
High Gradient Magnetic Alloy loaded RF cavity (5 times shorter cavity compared with ordinary ferrite cavity)

Small Loss Slow Extraction Scheme

Both Side Fast Extraction for Neutrino and Abort line

hands on maintenance scheme for small radiation exposure

J-PARC Facility

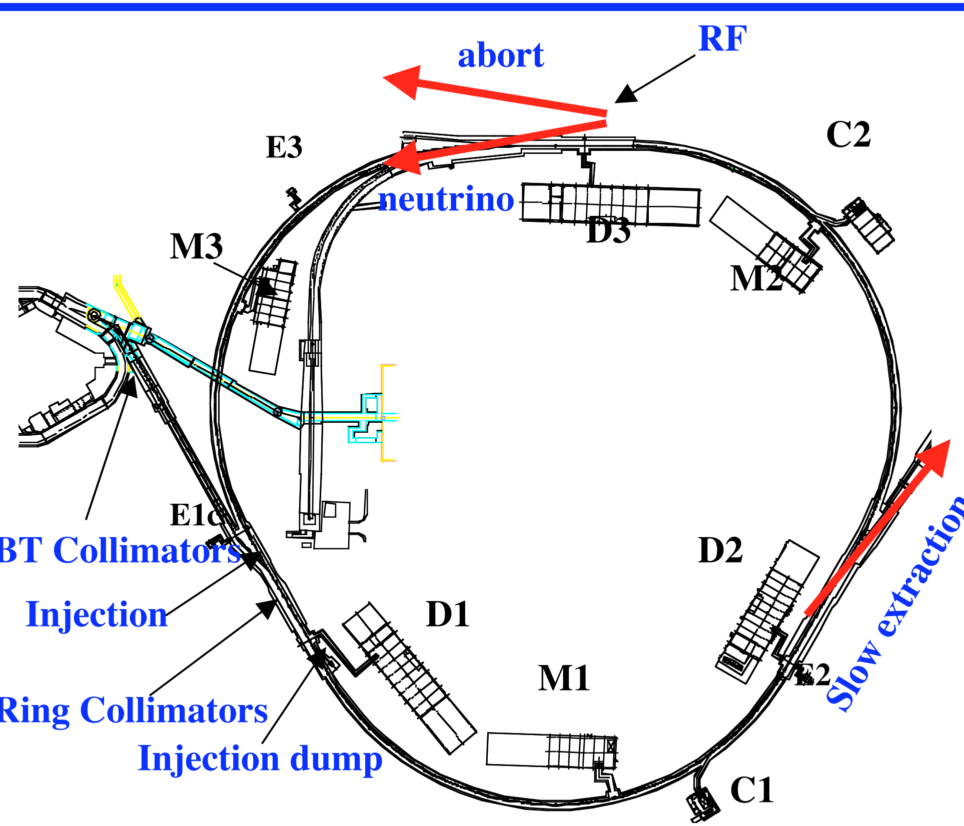


Joint Project between KEK and JAERI

50 GeV Synchrotron (Main Ring)

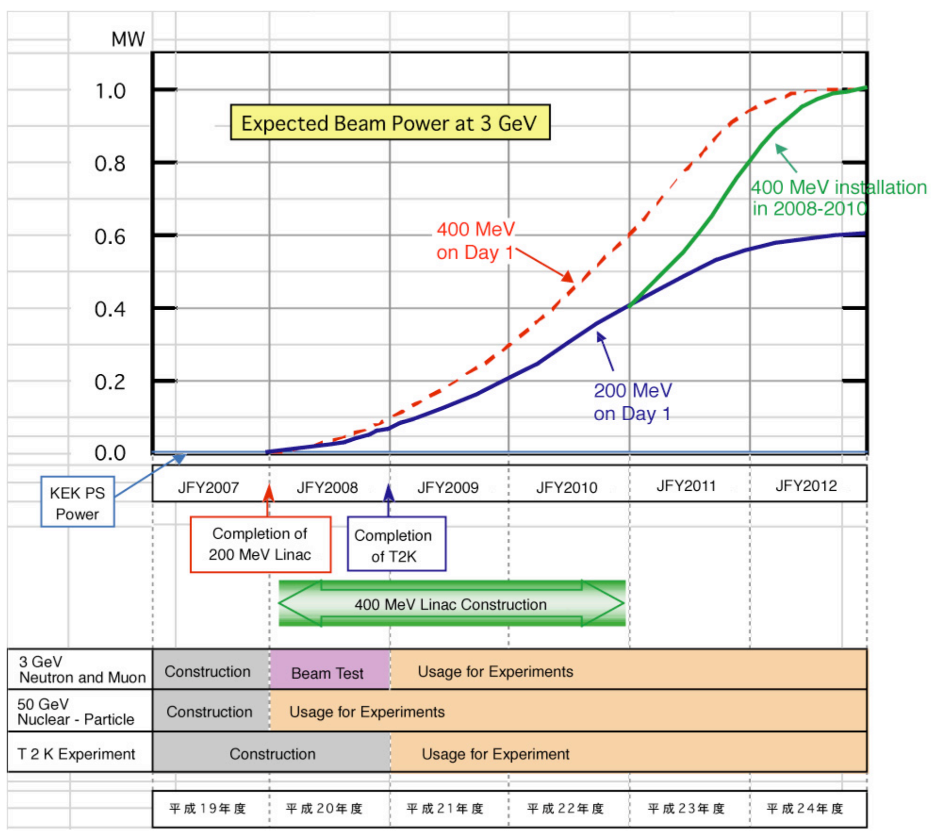
- Imaginary Transition γ
- High Gradient Magnetic Alloy loaded RF cavity
- Small Loss Slow Extraction Scheme
- Both Side Fast Extraction for Neutrino and Abort line
- hands on maintenance scheme for small radiation exposure

•Injection Energy	3GeV
•Output Energy	30GeV (slow) 40GeV (fast) 50GeV (Phase II)
•Circumference	1567.5m
•Beam Power	0.75MW (Phase II) **>2MW(future)**
•Particles	3.3×10^{14} ppp
•Repetition	0.3Hz
•Harmonic	9
•Bunch Number	8
•Nominal Tune	(22.4, 20.8)



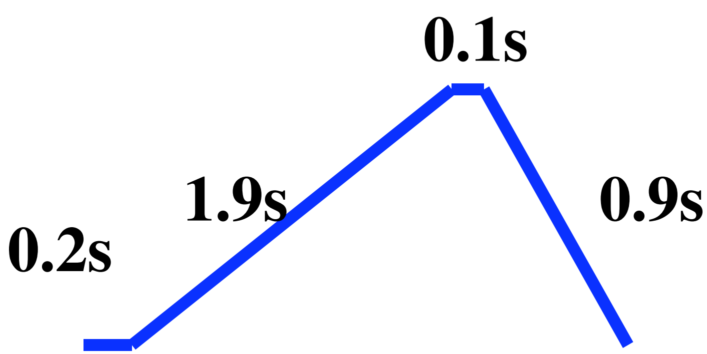
Impact of Lower Energy

- Original design
  - 400 MeV Linac with 50 GeV → 0.75 MW.
- Scenario has been changed
  - Linac: 200 MeV → 3 GeV: 0.6 MW → 50 GeV (40 GeV operation): → 0.4 MW.

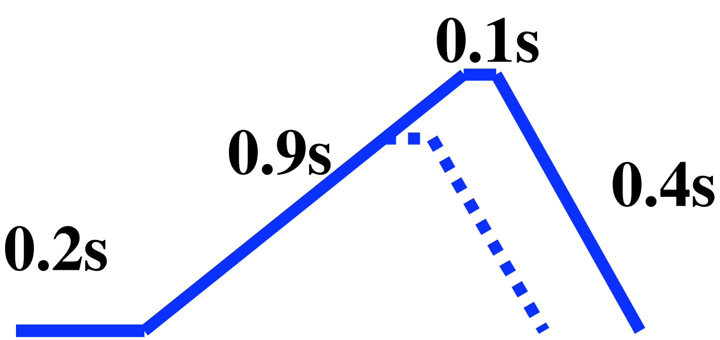


Upgrade Paths

- Possibility of a few MW power at J-PARC
  - Increase of repetition rate rather than increase of particles per pulse is preferable.
  - Following modifications are necessary for higher rep. rate.
    - Energy storage system
    - Additional magnet power supply
    - More rf cavities
    - Additional water cooling system



total 3.1s



total 1.6s

Synchrotron

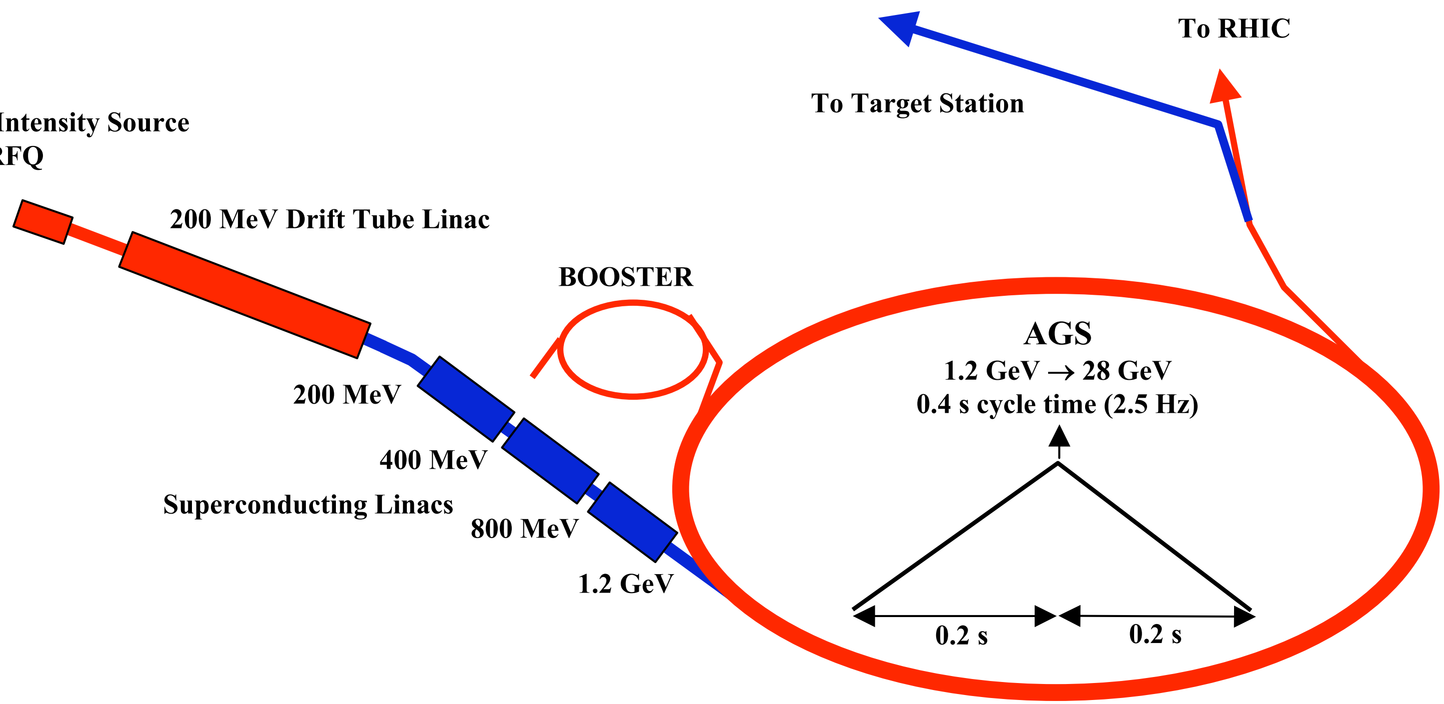
AGS upgrade (under discussion)

- beam energy 24GeV
- beam poweer 1MW
- repetition 50Hz
- bunch length ~1ns

Features

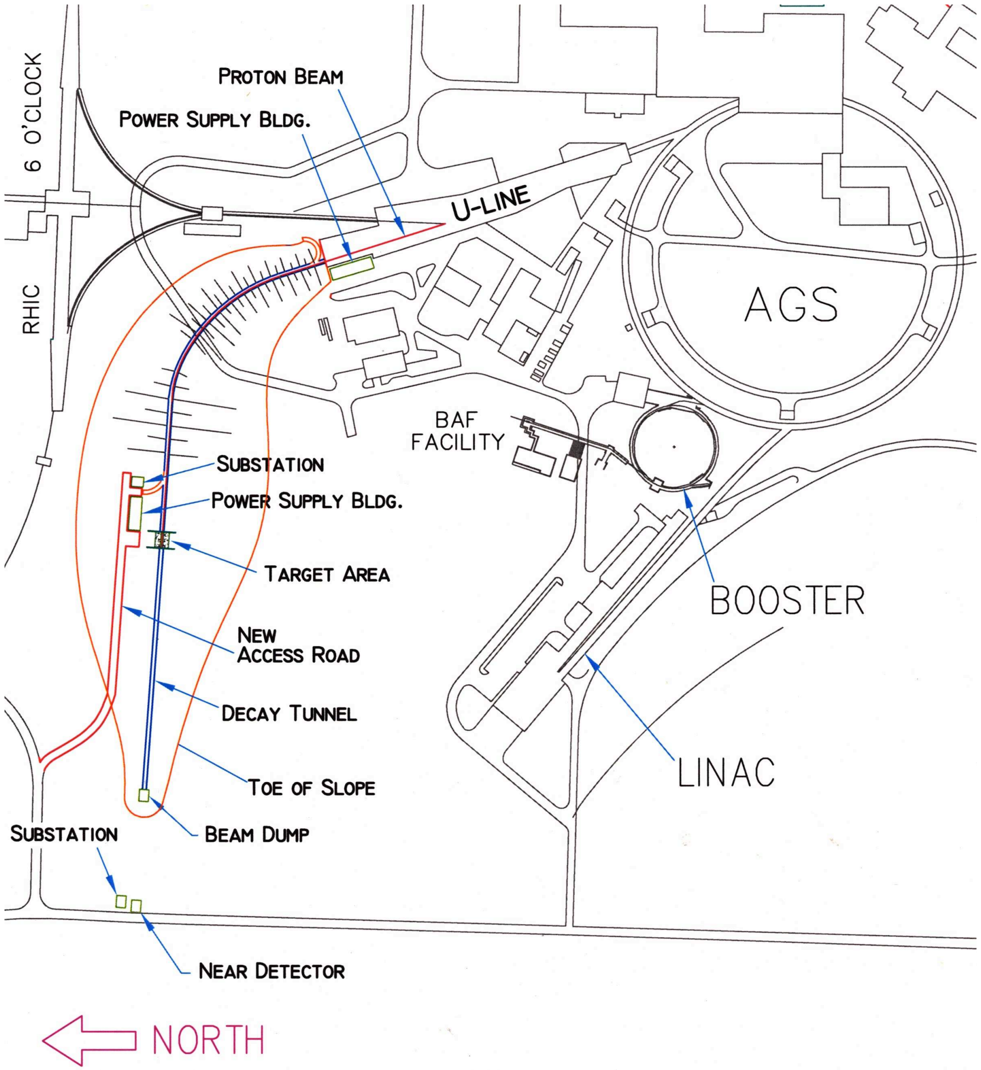
- Use 1.2GeV SC Linac instead of booster
- Increase rep. rate
- New mag. PS and RF cavities

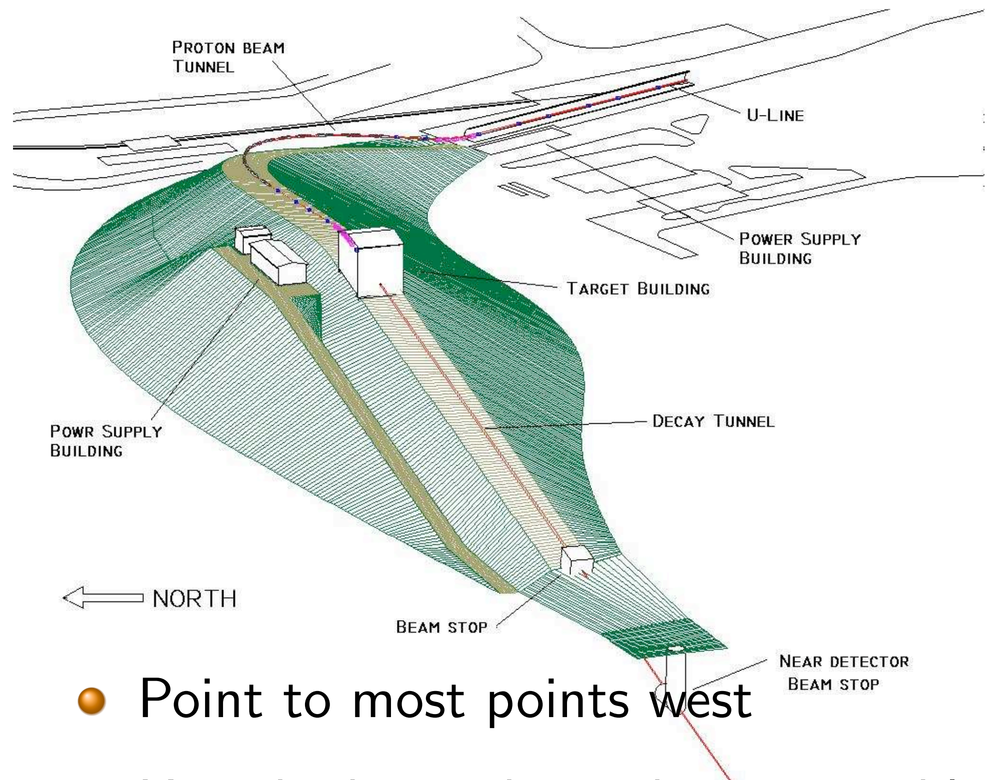
Upgrade to AGS for Super Beam



- Use 1.2 GeV SC Linac instead of booster
  - $7 \times 10^{13} \rightarrow 9 \times 10^{13}$ ppp
  - Fill time 0.6 sec $\rightarrow$ 1.0 msec
- Increase rep. rate 0.5 $\rightarrow$ 2.5 Hz   50Hz (NF)
- New mag. PS and RF cavities
- Further improvements on design being worked on.

BNL Site Development





- Point to most points west
- Keep hadrons above the water table
- Room for a (very) near detector
- Hill cheaper than tunnel

Synchrotron

Rutherford Lab. (RCS-ISIS experience, ISIS upgraded, under discussion)

3 options:

1)5GeV, 50Hz, 4MW

2)6-8GeV, 50Hz, 4MW

3)15GeV, 25Hz, 4MW

bunch length 1-3ns

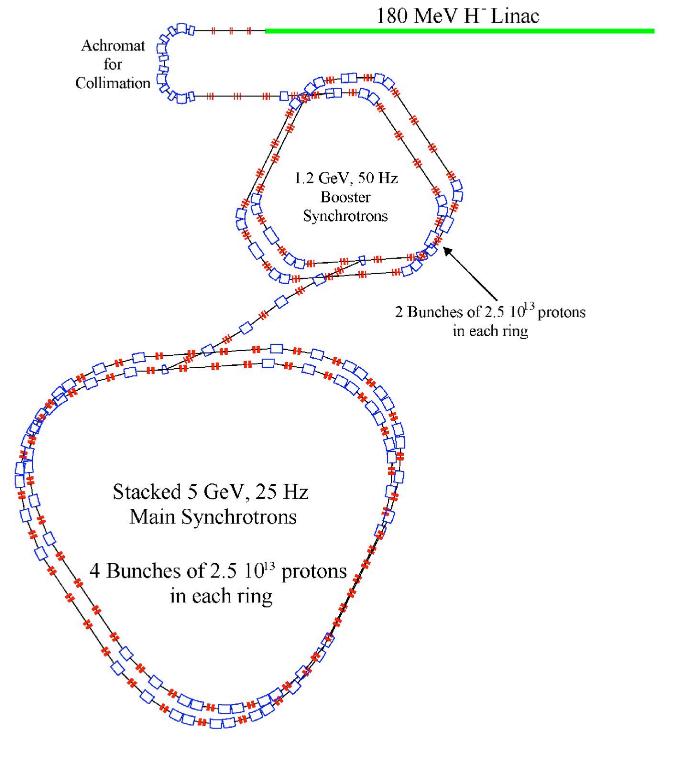
Features

bunch compression with converging isochronous conditions

FETS(Front End Test Stand)R&D:Ion Sorce, Chopper,...

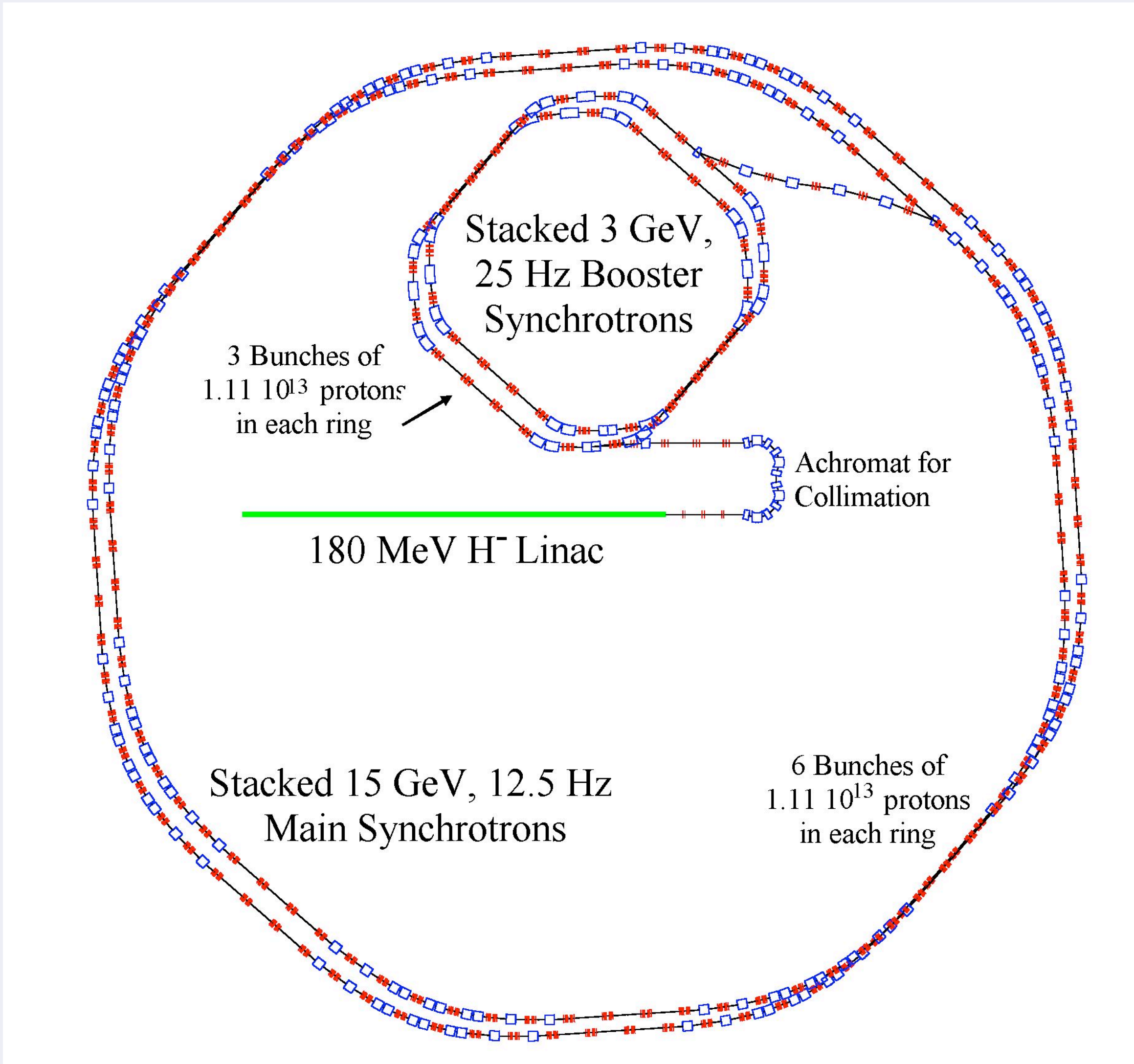
5 GeV, 50 Hz, 4 MW RCS design

5 GeV, 50 Hz



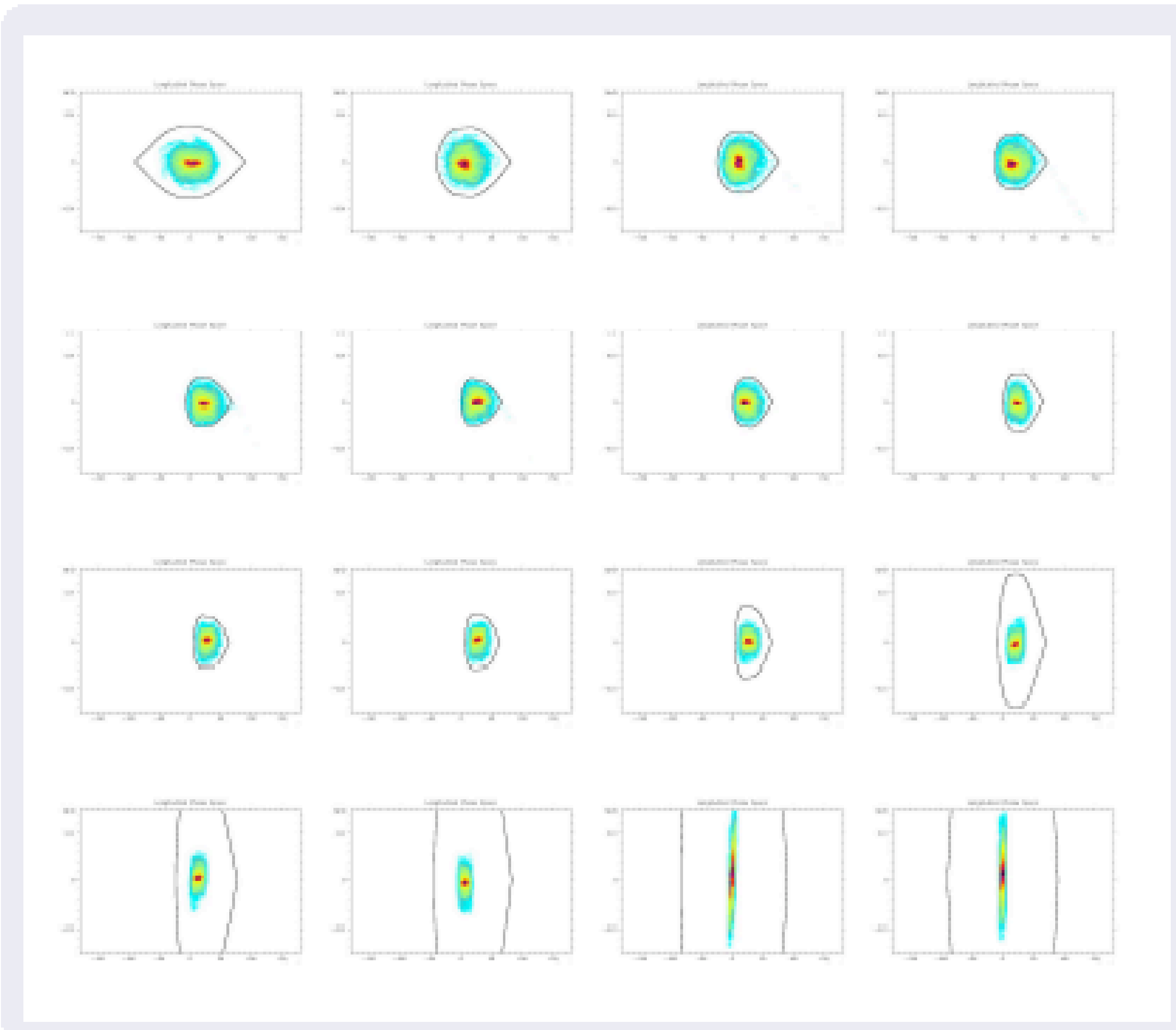
- Booster rings for proton accumulation and initial acceleration
- Main rings for remaining acceleration and bunch compression
- Pairs of rings reduce space charge
- Doubling radius, halving frequency leads to acceptable $\frac{\mathrm{d}B}{\mathrm{d}t}$ and RF voltages
- Repetition rate restored by extracting on alternate half cycles.
- Compression at 5 GeV relies on $\gamma \to \gamma_t -$ and addditional 0.5 MV of RF at $h = 24$.

15 GeV, 25 Hz, 4 MW RCS Driver

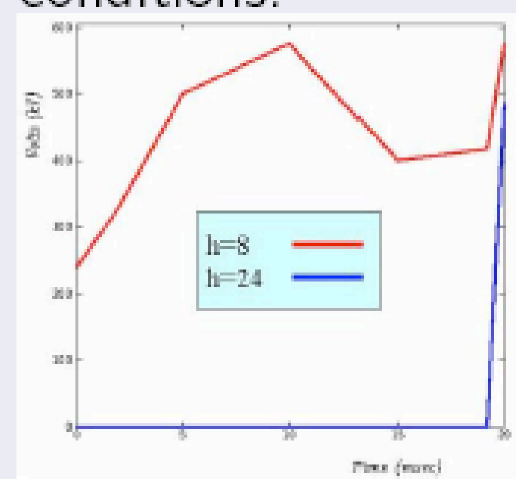


Same general principles and similar procedure for injection painting. Normal bunch rotation achieves ns compression.

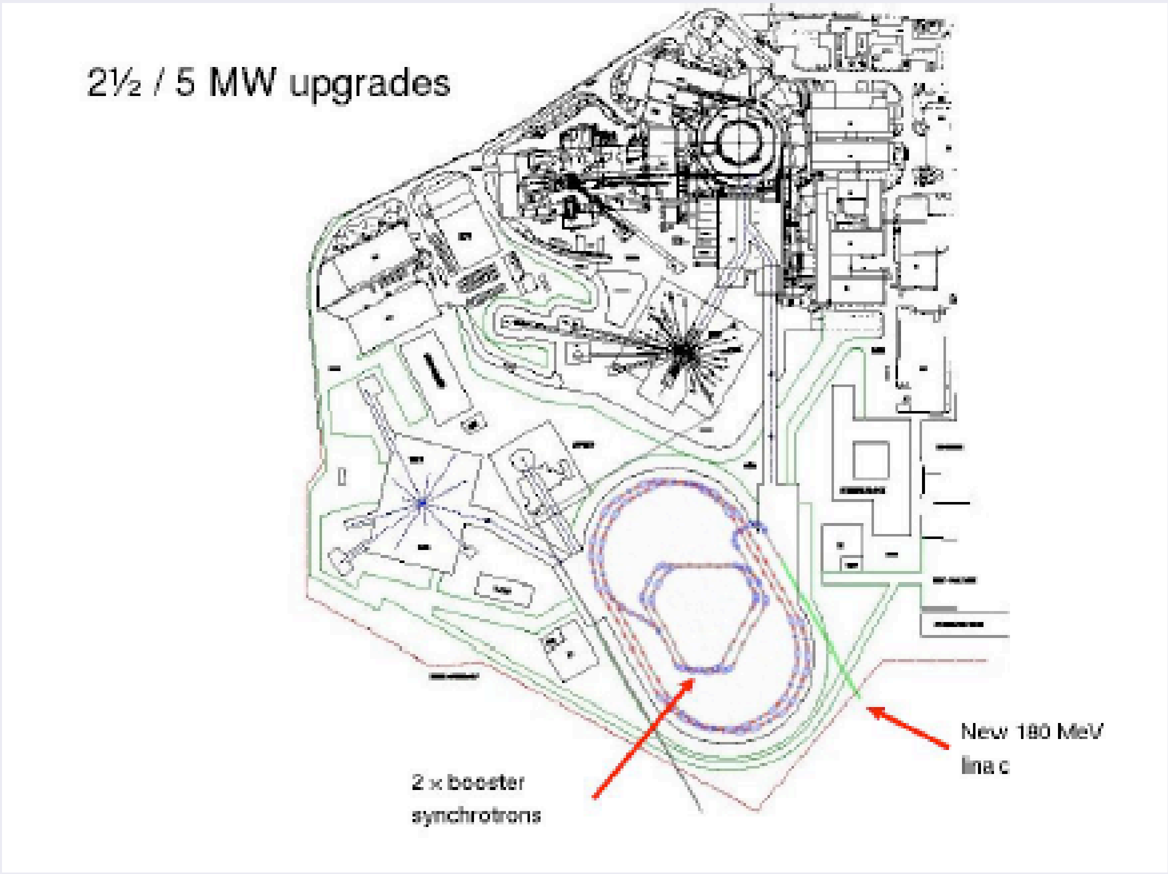
Bunch compression 5GeV



Final compression enhanced by addition by $h = 24$ voltage and achieved by converging on isochronous conditions.



ISIS upgraded to a 4MW PD



Progressive development 0.5 MW to 1 MW to 2.5 MW to 5 MW, with phases for bunch compression and target testing, resulting in a combined neutron/neutrino facility

Linac

Issues to be considered

- Maximum Energy? Higher energy is better but,
  - For accumulation and bunch compression, a synchrotron(fixed or variable energy) is necessary.
  - Space charge limit: 8GeV/2GeV=28times better

    Almost all machine issues are common.
  - Other users?: Linac +PSR ---> machine dedicated to NF
  - Cost estimation

Linac

- CERN SPL(CDR2)
  - beam energy 3.5GeV
  - beam power 4MW
  - repetition rate 50Hz
- Features
  - 704MHz bulk Nb cavity
  - 3 families;beta=0.5,0.8,1.0 :15,18,30MV/m
    5,6,7 cells per cavity

SPL & PDAC [1/3]

SPL (CDR2) characteristics

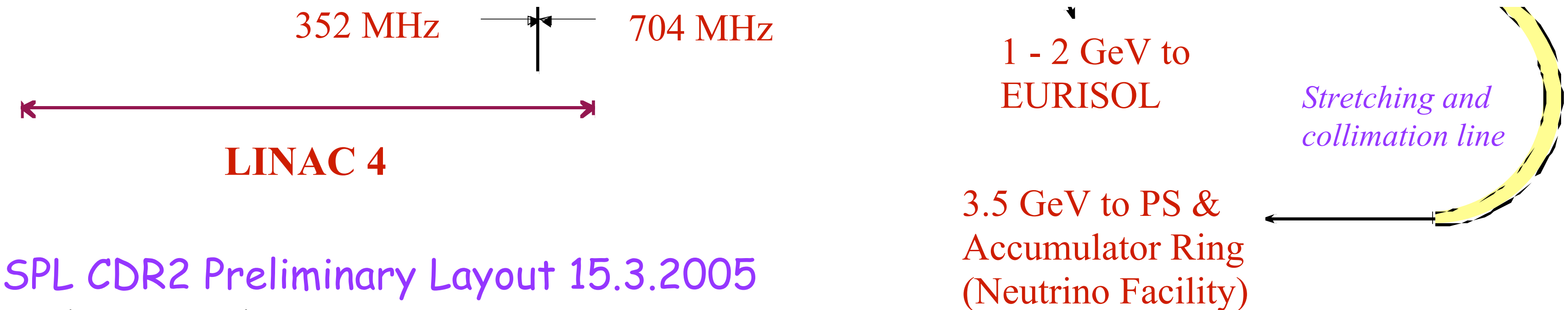
Ion species	H^-	
Kinetic energy	3.5	GeV
Mean current during the pulse	40 (30 ?)	mA
Mean beam power	4	MW
Pulse repetition rate	50	Hz
Pulse duration	0.57 (0.76 ?)	ms
Bunch frequency	352.2	MHz
Duty cycle during the pulse	62 (5/8)	%
rms transverse emittances	0.4	π mm mrad
Longitudinal rms emittance	0.3	π deg MeV

SPL & PDAC [2/3]

SPL main goals:

- increase the performance of the CERN high energy accelerators (PS, SPS & LHC)

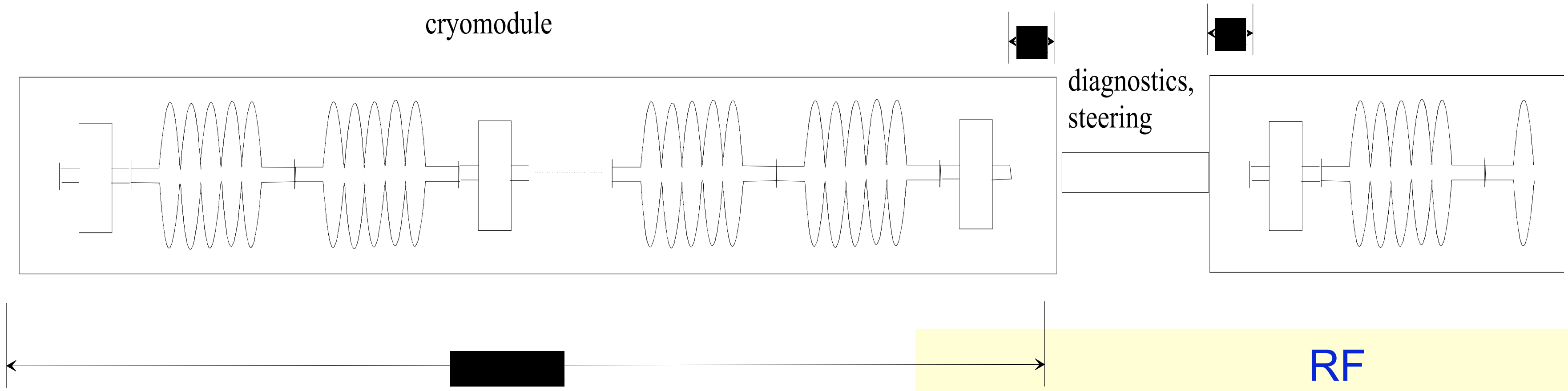
- address the needs of future experiments with neutrinos and radio-active ion beams



SPL CDR2 Preliminary Layout 15.3.2005

Work in progress!

The present R&D programme concentrates on low-energy (Linac4) items, wherever possible in collaboration with other laboratories.



quadrupole length to be determined, indicatively 300 mm (including bellows)

RF

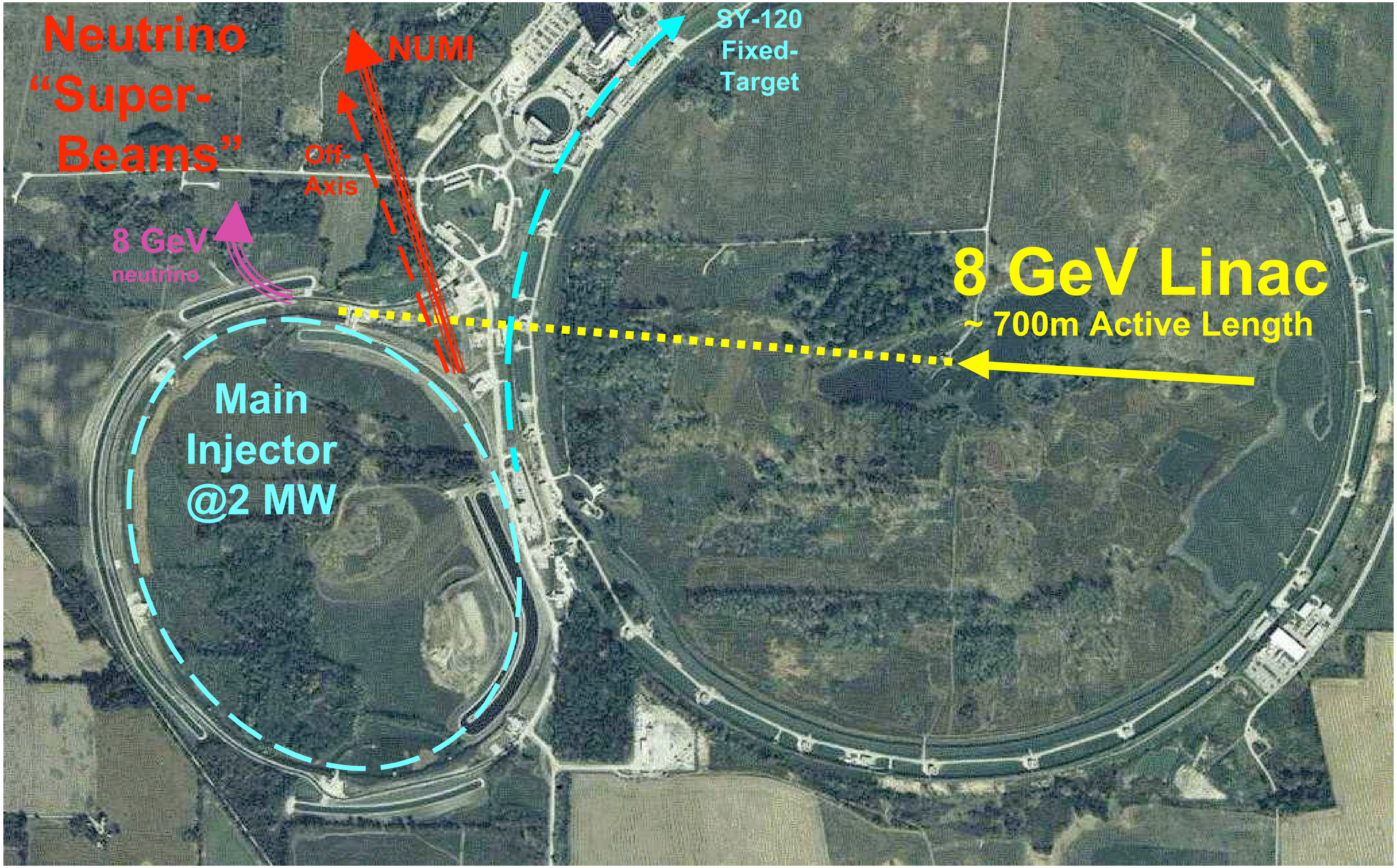
- 704 MHz bulk Niobium cavities
- 3 families of cavities : beta =0.5,0.85,1.0
- gradients : 15, 18, 30 MV/m
- 5, 6 and 7 cells per cavity

- Cold (2K) quadrupoles in the cryomodules, independently aligned from the cavities (to minimize cold/warm transitions and maximize real estate gradient).
- Cryomodules of maximum length (between 10 and 15 m), containing n cavities and (n+1) quadrupoles. Diagnostics, steering etc. between cryomodules.
- Length of the cavities limited by fabrication and handling considerations. Proposed number of cells per cavity is therefore 5, 6 and 7 for the three sections.
- 2 MW max power /coupler
- Standardisation of the design after 2 GeV

Linac

- 8GeV SC linac + Main Injector(FNAL)
  - beam energy 30-120GeV
  - beam power 2MW (>2MW further MI upgrade)
  - repetition rate 1.5s(0.67Hz);120GeV
    0.5s(2Hz);40GeV
- Features
  - 1300MHz/325MHz
  - Cu-SC transition:15MeV
  - Ultimate parameters:25mAx1msecx10Hz)

8 GeV Superconducting Linac



Two Design Points for 8 GeV Linac

<u>Initial:</u> 0.5 MW Linac Beam Power (BASELINE)

8.3 mA x 3 msec x 2.5 Hz x 8 GeV = 0.5 MW

Twelve Klystrons Required

<u>Ultimate:</u> 2 MW Linac Beam Power

25 mA x 1 msec x 10 Hz x 8 GeV = 2.0 MW **Power limit?**

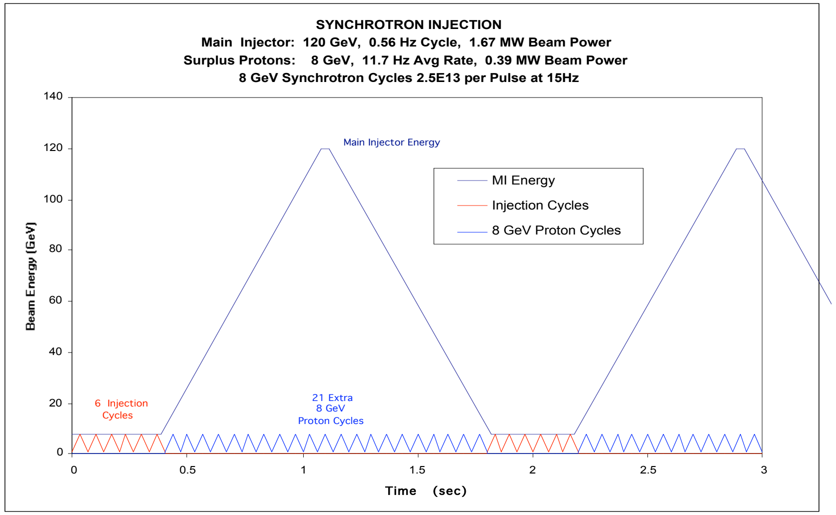
33 Klystrons Required

<u>Either Option Supports</u>:

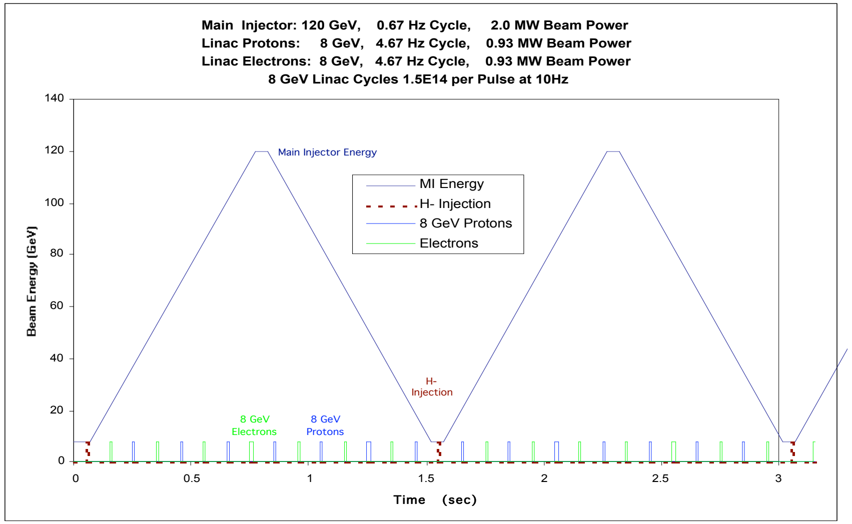
1.5E14 x 0.7 Hz x 120 GeV

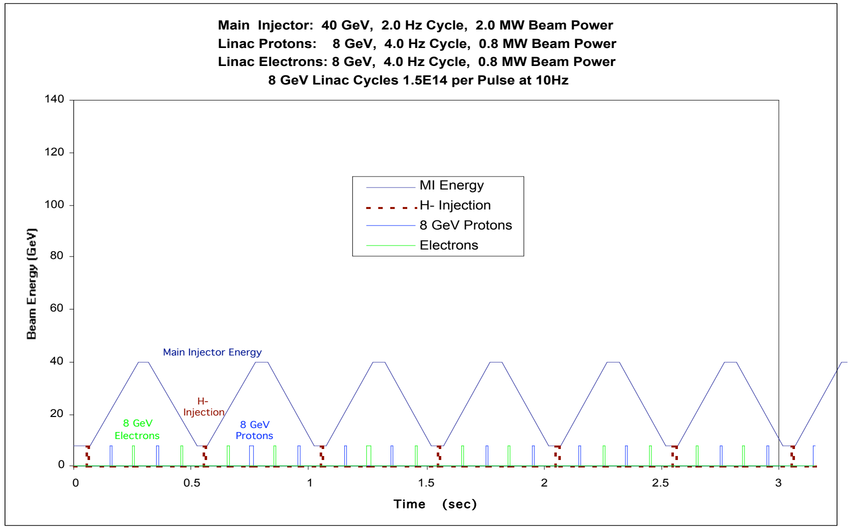
= 2 MW Beam Power from Fermilab Main Injector

MI with Synchrotron. vs. MI with SCL



- **MI maintains 2 MW Beam power at lower energy**
  - # of ν not strongly dependent on E
  - Reduces tails at higher ν energies
- **Allow flexible ν Program**





FFAG

- FFAG
  - Scaling

    zero chromaticity; Tunes are const.

    non-linear field
  - Semi-scaling

    non-zero chromaticity; Tunes are varied but the beam does not cross structure resonances.

    non-linear field cf. "Isochronous" ring
  - Non-scaling

    non-zero chromaticity

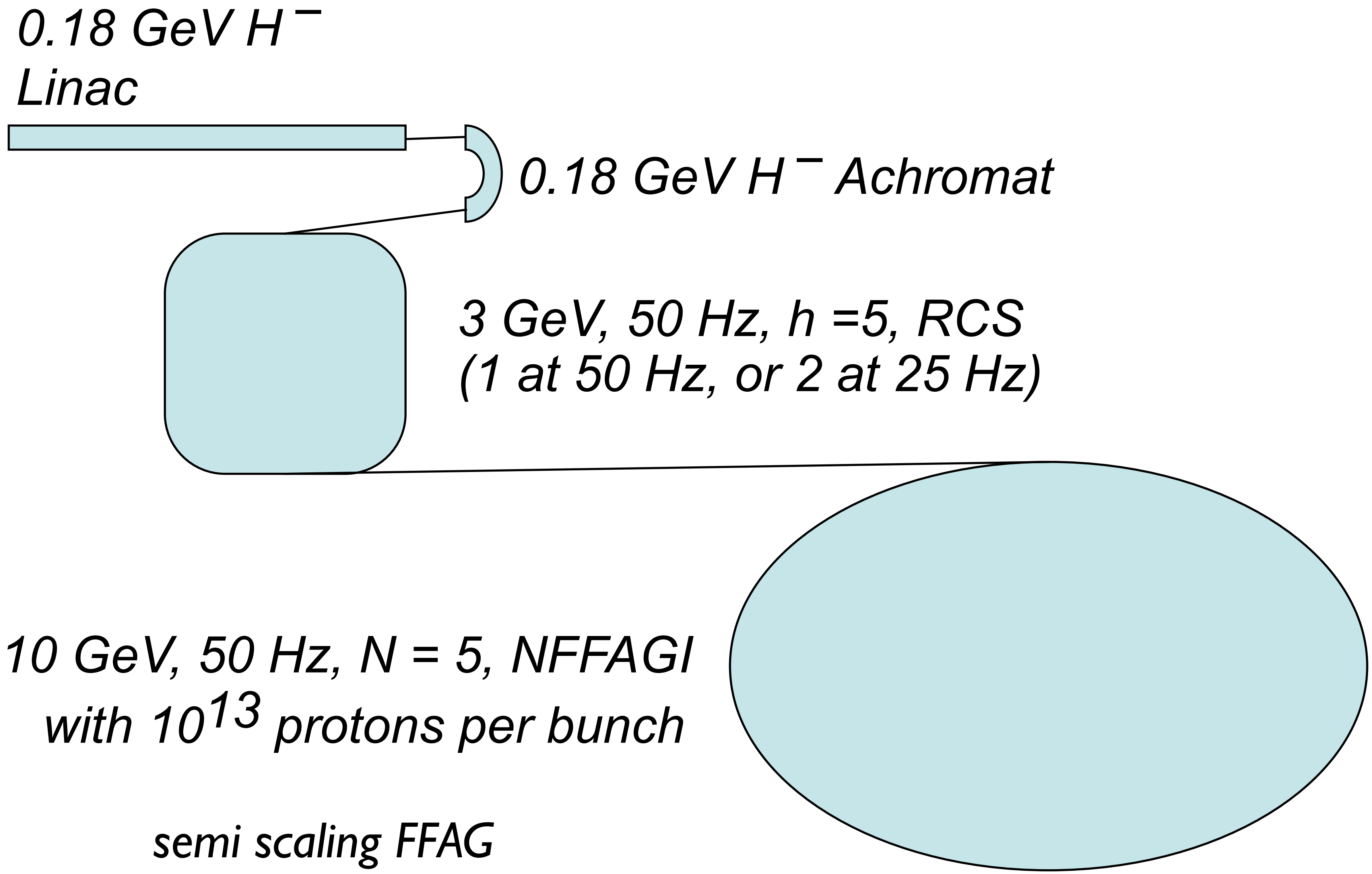
    linear field; The beam cross the structure resonances

Proton driver looks possible with scaling or semi-scaling FFAGs.

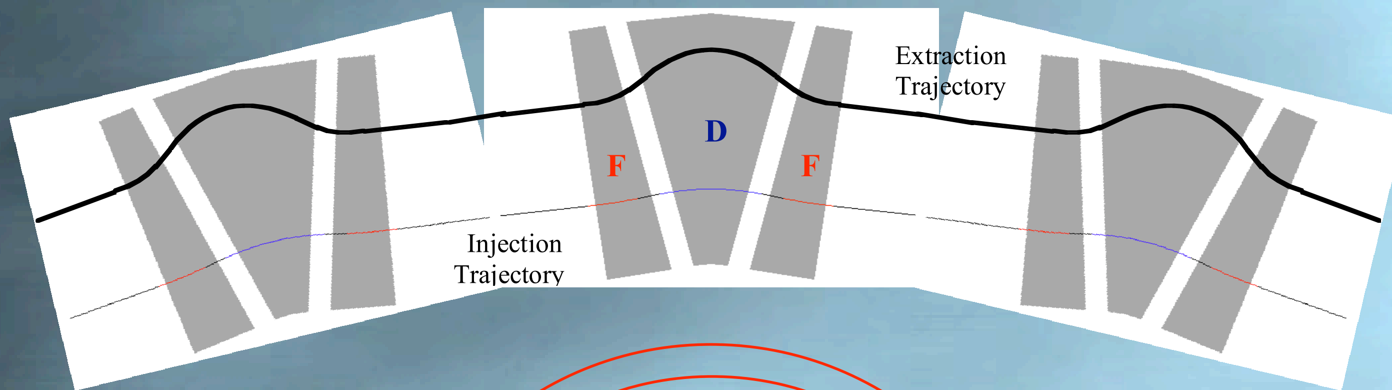
FFAG

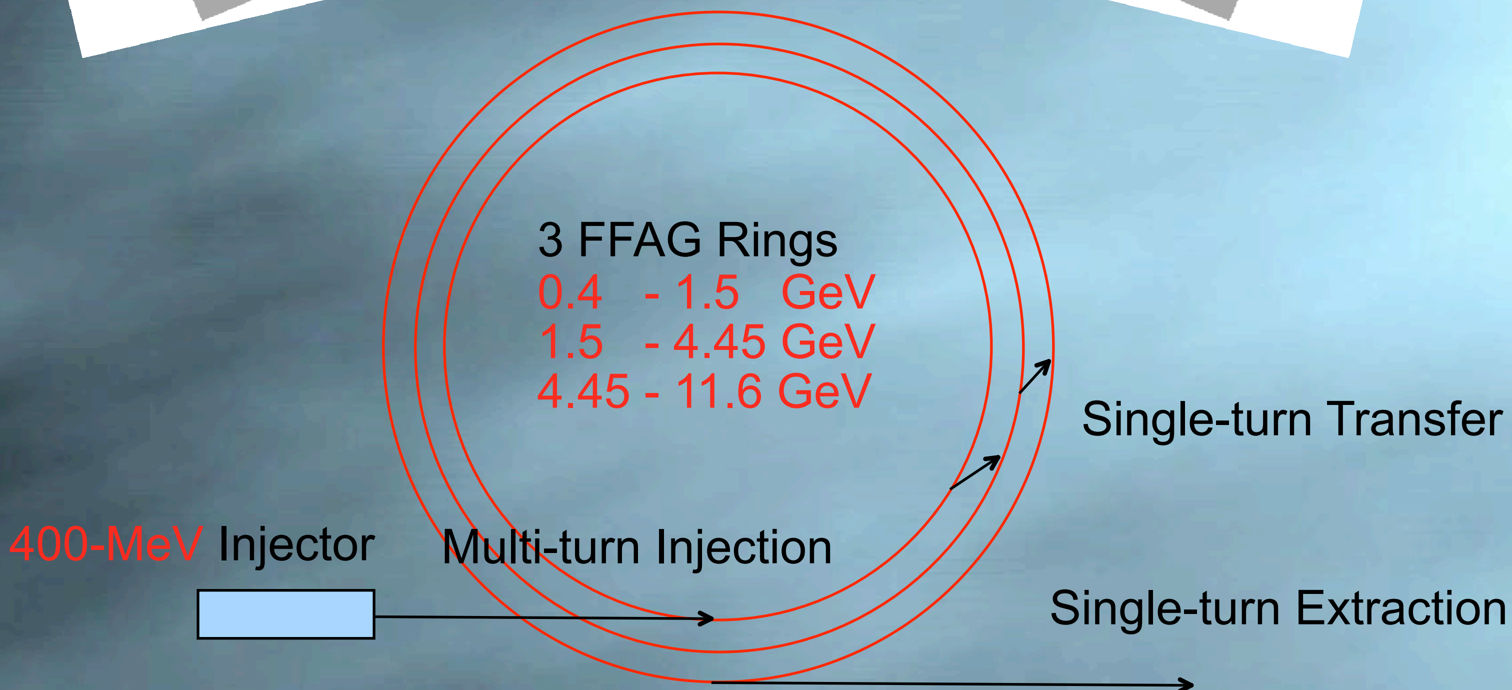
1. Rutherford
   - E=10GeV, P=4MW, 50Hz
   - isochronous, semi-scaling (non-scaling, non-linear)
2. BNL
   - E=11.6GeV, P=18MW, 100Hz
   - semi-scaling (non-scaling, non-linear)
3. KEK/Kyoto U
   - E=1(3)GeV, P=1MW, 10(1)kHz
   - scaling (scaling, non-linear)

4 MW, Proton Driver Layout
Rutherford Lab.



18MW FFAG Accelerators for Proton Drivers BNL



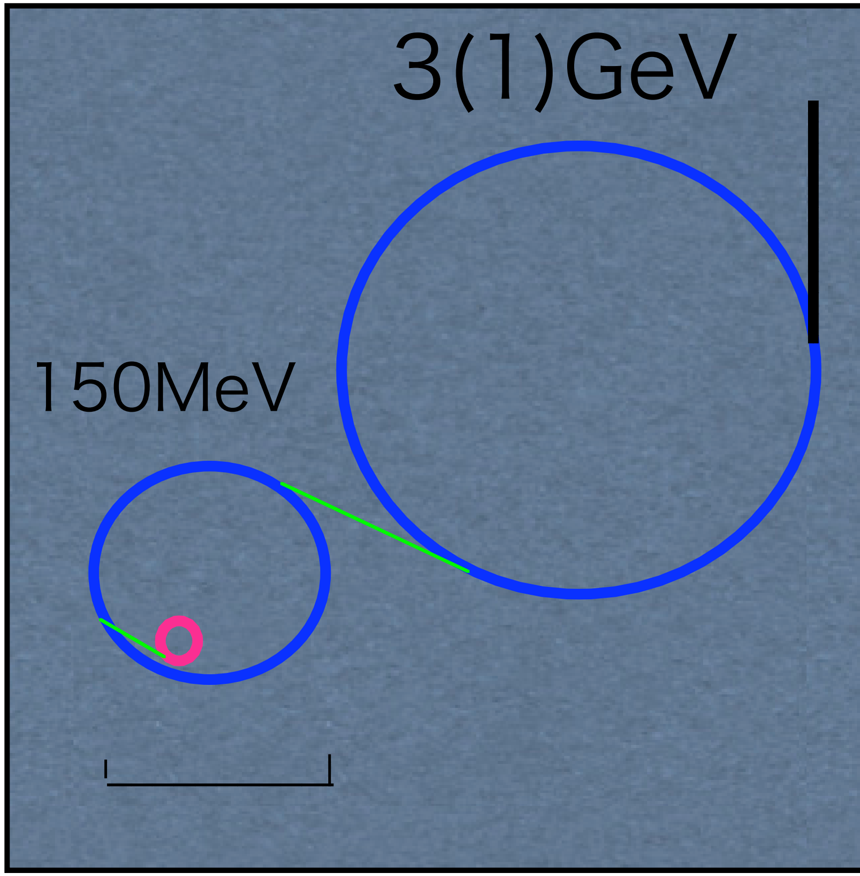


Scaling FFAG (KEK/Kyoto U.)

beam energy ~3(1)GeV
beam power ~1MW (Iave. ~ 0.3(1)mA)
bunch width ~10ns
beam rep. rate ~3(10)kHz

FFAG

Energy 150MeV-3(1)GeV
ntensity 6x10**11ppp
Rep. Rate 3(10)kHz
Ave. Current 0.33(1)mA (Beam Power 1MW)
Radius ~25(16)m
rf frequeny 5.43MHz - 8.08MHz
rf voltage ~600kV
bunch width ~10ns



Compact, less Expensive

Summary

- Main parameters
  - beam energy
  - beam power
  - time structure
- Specifications for different Schemes
  - Synchrotron, Linac, FFAG
- Need more studies for optimization