MW Proton Drivers using Rapid Cycling Synchrotrons

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Outline

1. Definition and Goals of a Proton Driver
2. Existing Machines and Machines under Construction: ISIS, SNS, J-PARC
   - The ISIS Spallation Neutron Source
   - The US Spallation Neutron Source
   - J-PARC 3 GeV and 50 GeV Synchrotrons
3. The synchrotron approach towards achieving the goals
   - RAL RCS Designs for a Proton Driver
   - 30 GeV Slow Cycling Synchrotron
   - Fermilab 8 GeV Synchrotron
   - Development of ISIS into a dual purpose facility
4. Problems & Conclusions

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Definition and Goals

Definition

A proton driver must

1. provide megawatt levels of proton beam power
2. be capable of generating short intense proton bunches

Approaches

1. A full energy linac feeding accumulator and compressor rings (e.g. CERN Neutrino Factory design)
2. An intermediate energy linac with subsequent accumulation, acceleration and compression carried out in a single synchrotron or chain of synchrotrons (RAL, J-PARC, FNAL, BNL)

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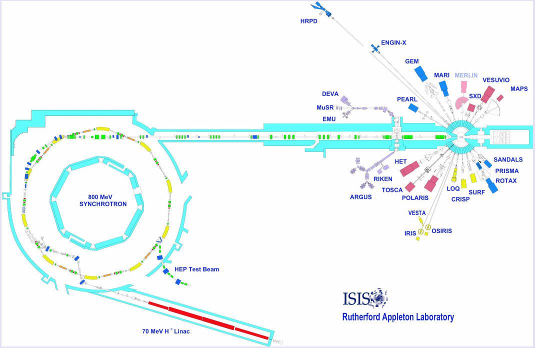
The ISIS Spallation Neutron Source



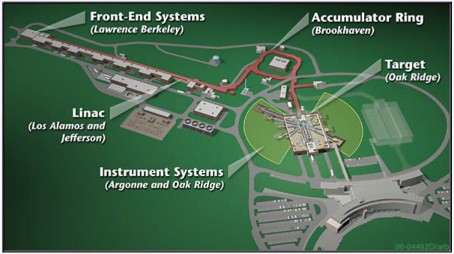
Features

- 70 MeV H^- linac
- Accumulation in synchrotron
- Acceleration to 800 MeV
- 0.16 to 0.24 MW upgrade in progress

- Charge exchange injection into synchrotron via Al_2O_3 foil
- 2.5×10^{13} protons per pulse at 50 Hz
- 2 bunches, each ~100 ns duration at target

Outline

The US Spallation Neutron Source, SNS



- 1 GeV H^- superconducting linac
- 1060 turn charge exchange injection
- 60 Hz rep rate
- 1.5×10^{14} protons accumulated per pulse
- 1.4 MW beam power with $\sim 1\,\mu$s pulses
- Due on line 2006

Outline

J-PARC 3 GeV and 50 GeV Synchrotron System

- 400 MeV H^- linac
- 3 GeV neutron source, 1 MW
- 50 GeV main ring, 0.75 MW
- Facilities for transmutation and neutrino superbeams
- Study of full Neutrino Factory based on FFAGs
- Commissioning 3 GeV ring in 2006

Philosophy behind the Synchrotron Approach

Essential Considerations

- Building up the intensity through multiturn injection is a difficult task
- Bunch compression to nanosecond time durations imposes entirely different demands on the accelerator
- There are severe space charge problems at MW levels of intensity and these levels of bunch compression
- Short bunch requirement means small longitudinal emittance, which is best achieved at lower energy

$$A = \frac{8R\alpha}{hc}\sqrt{\frac{2\gamma(1-\eta_{SC})VE_0}{\pi h|\eta|}} \Longrightarrow \begin{array}{l} \gamma, \frac{1}{h}, \frac{1}{|\eta|} \ \text{min.} \\ \eta_{SC} = \frac{Negh^2}{2\epsilon_0 RF\gamma^2 V} \lesssim 0.4 \end{array}$$

Theoretical Models and Future Plans

- Suggests using separate rings for accumulation and compression
- Fundamentally different beam optics possible in each ring
- Pairs of rings can also be used to split beam and reduce space charge

- RAL designs
  1. 5 GeV, 50 Hz, 4 MW scenario (green field site)
  2. 15 GeV, 25 Hz, 4 MW model (to fit ISR tunnel)
  3. 30 GeV, 8 Hz synchrotron for PS replacement
- Fermilab 8 GeV Synchrotron
- ISIS upgrades
  - Dual purpose neutron/neutrino source

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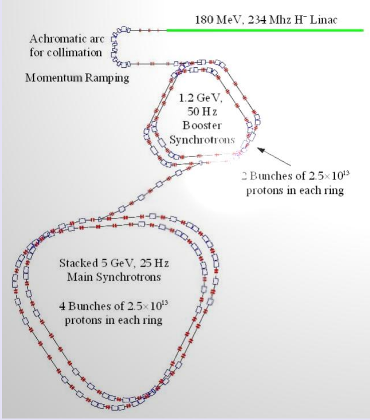
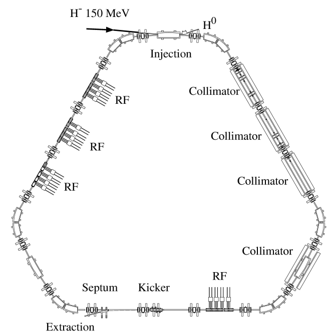
RAL 5 GeV, 50 Hz, 4 MW Driver



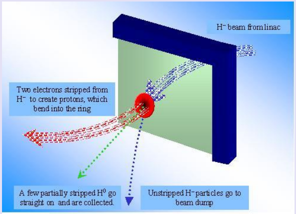
- "Proof of Principle Study"
- Based on double rings of radii in ratio 1:2, frequencies 2:1
- Beam prepared for injection in linac and achromatic arc
- Charge exchange injection via Al_2O_3 foil in booster rings: loss at 10^{-4} level mainly from scattering in foil
- Acceleration in main synchrotrons with ns bunch compression achieved with combination of RF harmonics

1.2 GeV Booster Synchrotron

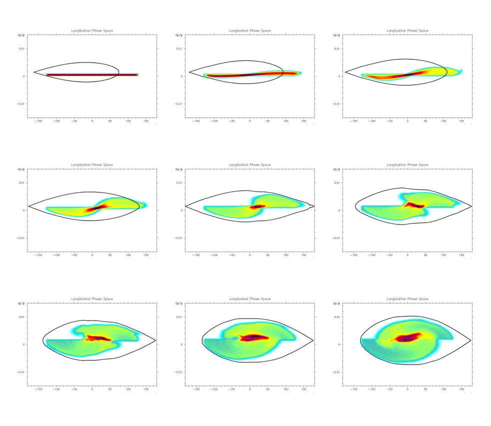
- Triplet booster lattice
  - separate superperiods for collimation, RF and extraction
  - injection in low field dipole ($\sim 0.05\,$T) with $\frac{D_x}{\sqrt{\beta_x}} = 1.6$



Foil heating from stripping and subsequent proton traversals is a concern, particularly in full-energy linac-accumulator ring designs, where temperatures can reach ∼2500K.

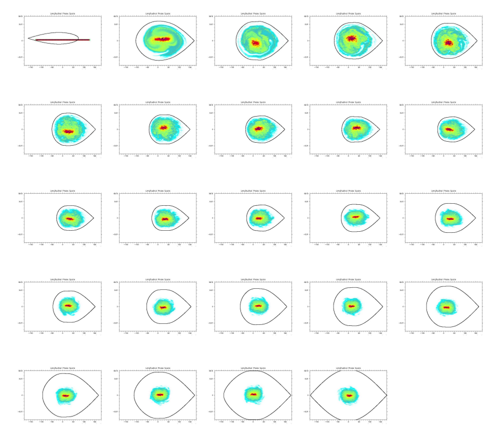


Simulation of Injection at 180 MeV

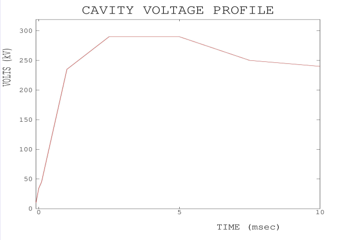


- Chopped beam allows full capture as longitudinal bucket increases with time.
- $\frac{\Delta p}{p}$ painting, RF steering and variable peak cavity voltages assist trapping and help control bunching factor (transverse space charge)

Simulation of Acceleration Cycle 0.18 to 1.2 GeV

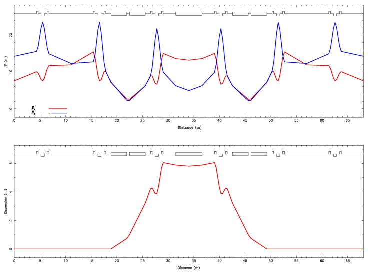


- 0% beam loss predicted
- Output bunch length ∼100 ns

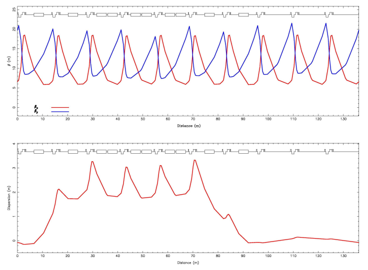


5 GeV Model: Optical Details

Booster Lattice

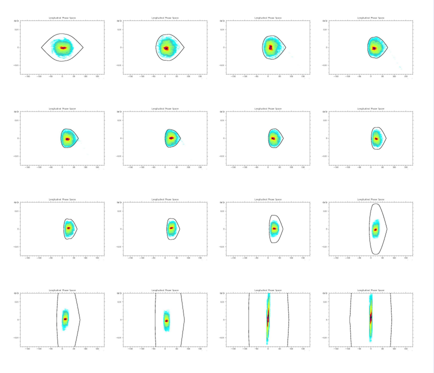


Main Ring

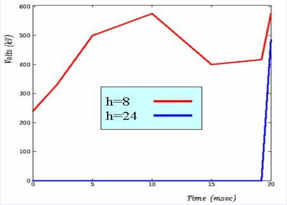


- Main ring uses simple FODO lattice
- Compression to 1 ns achieved as $\gamma \rightarrow \gamma_t$
- Main ring resistant to optical effects of severe space charge ($I \sim 1000$ A)

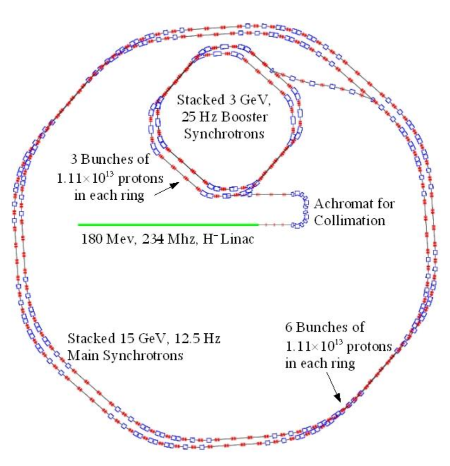
Simulation of Main Acceleration and Compression 1.2 to 5 GeV



- 0.2% beam loss on transfer
- Final bunch length ∼2 ns
- Achieved with combination of $h = 8/h = 24$ RF harmonics



RAL 15 GeV, 25 Hz, 4 MW Driver



- Main ring 151 m mean radius to fit ISR tunnel
- Principles similar to 5 GeV driver
- Await results from HARP for optimal final beam energy

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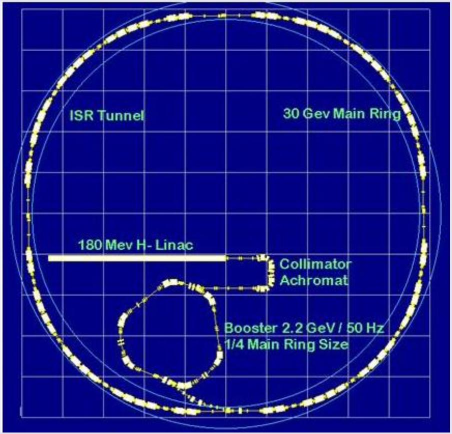
A 30 GeV, 8 Hz Synchrotron as Possible Replacement for CERN PS



- 180 MeV H^- Linac with 2.5 MeV fast beam chopper
- Achromatic arc with high normalised dispersion
- Momentum ramping for injection painting
- bunch compression

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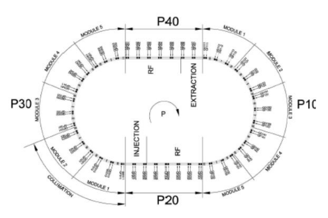
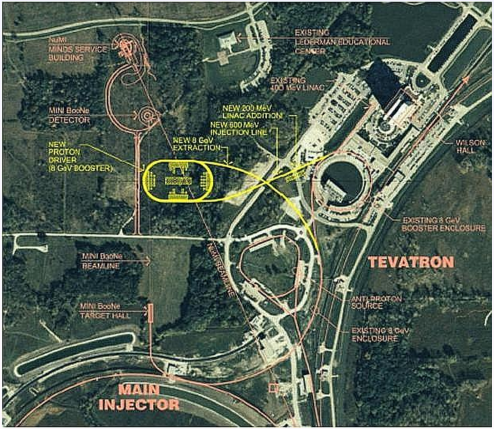
Fermilab 8 GeV Synchrotron-based Proton Driver

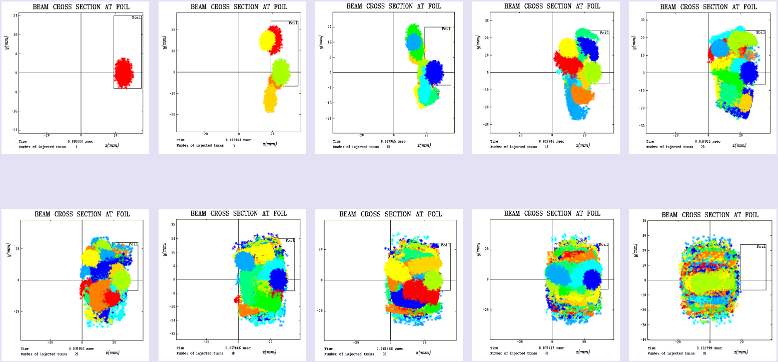
- Improved booster for main injector
- Racetrack lattice, 75 m mean radius
- Based on RAL design





Fermilab: Simulation of Transverse Injection

S-bend Model; 20 turns, 26 revolutions



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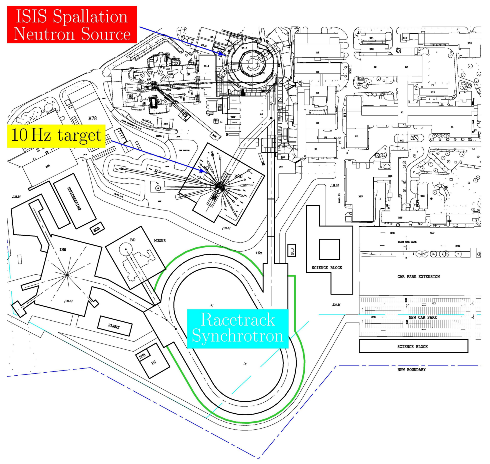
Phased Upgrade of ISIS

Phase 1

- Addition of new synchrotron, 78 m radius (*cf* FNAL)
- 1 MW neutron source at 3 GeV (50 Hz) and NF test-bed at 6 or 8 GeV (16.7 Hz)
- Test of bunch compression and NF target experiments



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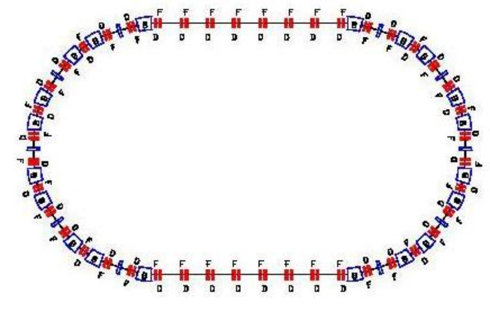


Acceleration using combined harmonic magnetic field to reduce peak RF

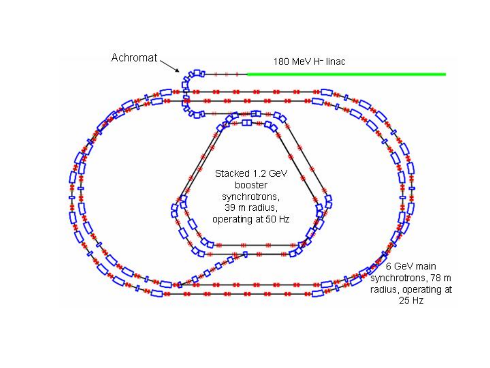
$$B(t) = B_0 - B_1 \cos 2\pi f t + \frac{B_1}{\sqrt{6}} \sin 4\pi f t$$

Phases 2

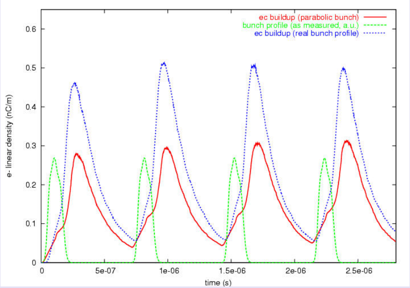
- Replacement of current ISIS synchrotron with new booster
  - two stacked rings, 39 m radius
  - 180 MeV to 1.2 GeV

Phase 3

- Construction of second main synchrotron
- Full 4-5 MW proton driver



The Electron Cloud Study at ISIS



- A major concern for high intensity proton drivers
- Limits intensity at LANL PSR
- Not seen at ISIS but why not?
- Many ISIS features built into RCS MW designs
  - RF shields in dipoles and quadrupoles
  - Tapered vacuum chambers (rectangular)
- Computational/experimental study in progress

Summary of Problems Facing an RCS-based Proton Driver

- Very low uncontrolled beam loss for hands-on maintenance: requires carefully designed collimation system
- Injection trapping: low energy fast beam chopper in linac and controlled RF voltages
- Excessively high stripping foil temperatures: injection painting
- Instabilities, particularly electron cloud
- Multiple harmonic accelerating magnet design to reduce $\dot{B}$ and V_{peak}

Conclusions

- A 4 MW RCS-base proton driver appears feasible and provides a flexible solution to accumulation and bunch compression
- Following development work over the past decade on ESS, SNS and J-PARC, there are no obvious show-stoppers
- The phased upgrade of ISIS is an attractive option with a minimum disruption to user facilities
- BUT the step from 0.16 MW to 4 MW is huge.
- Preliminary cost estimates suggest RCS and LAR scenarios are roughly the same price, but the cost depends on the site and existing infra-structure

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