Overview of High Power Proton Drivers

J. Pasternak
on behalf of IDS-NF

IHEP, Beijing, Nufact'2013,
19.08.2013

Imperial College London

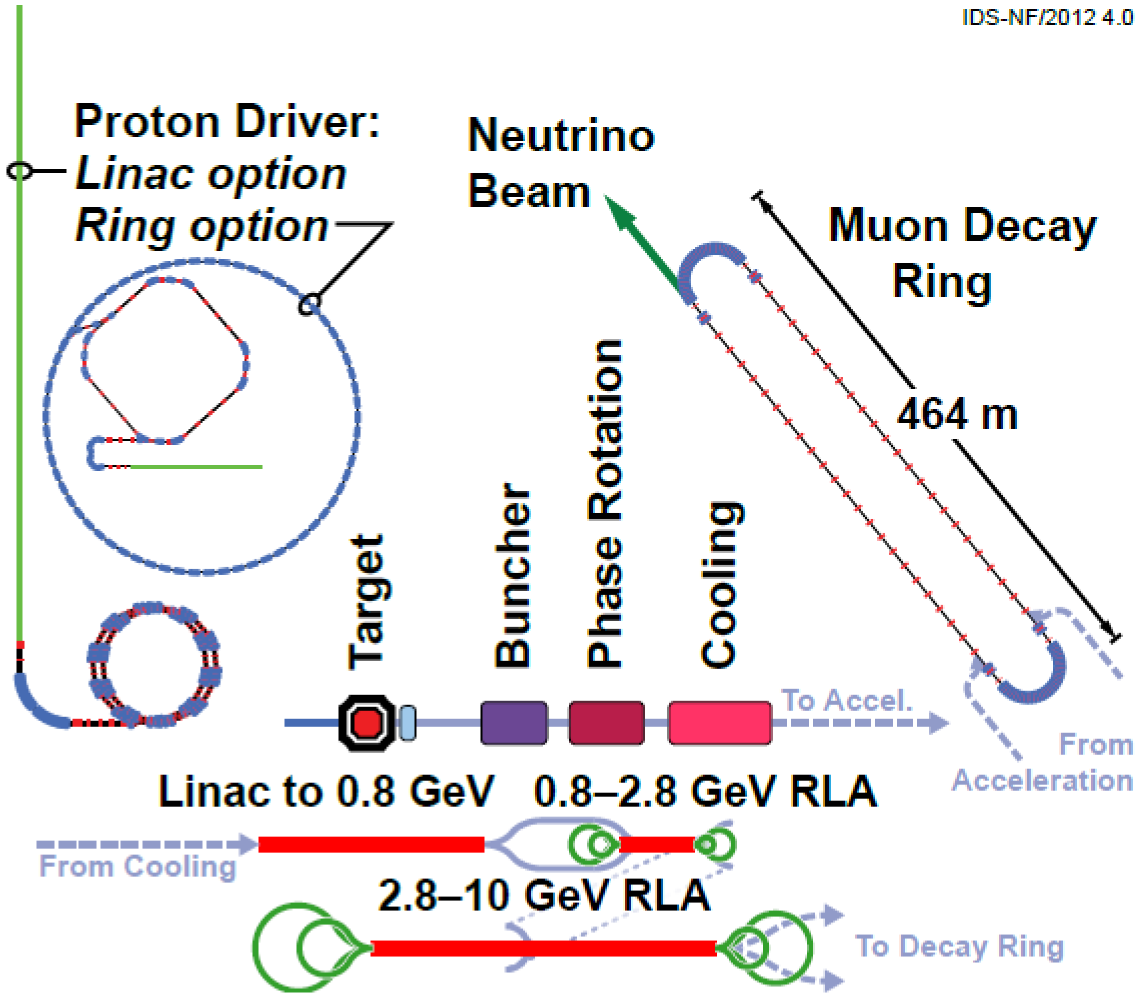
Science & Technology Facilities Council ISIS

Outline

1. Introduction.
2. Studies on ISIS upgrade at RAL.
3. Solution based on SPL at CERN.
4. Project-X at Fermilab.

Talk will be focused on solutions currently envisaged for the Neutrino Factory in the framework of the IDS-NF.

IDS-NF Neutrino Factory Baseline Design

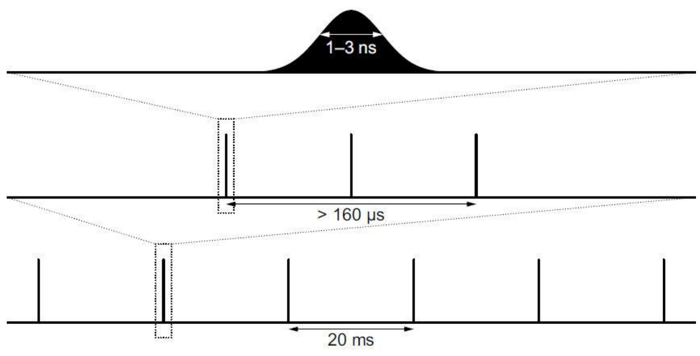


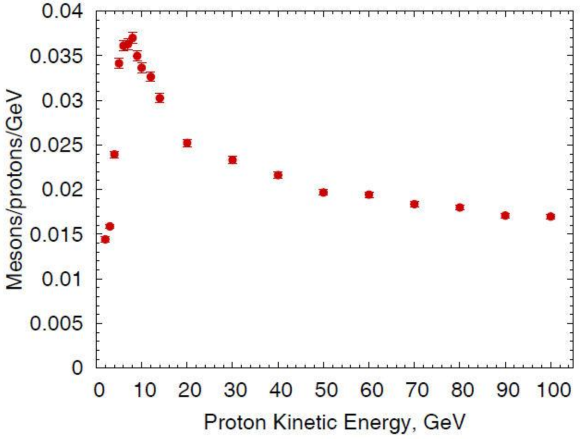
Proton Driver Upgrades

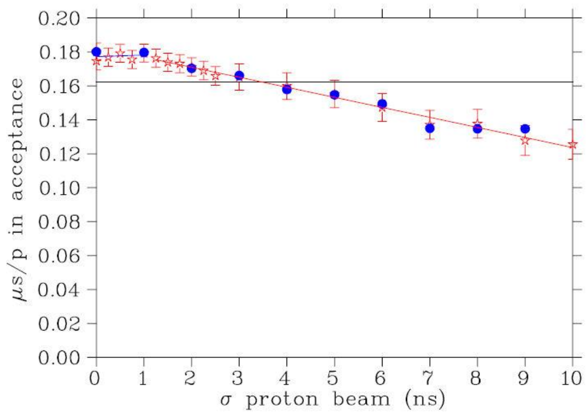
Base	Upgrades	Final Energy
ISIS	RCS Compressor?	9.6 GeV
SPL	Upgrade Linac Additional GeV of Linac Accumulator Compressor	5 GeV
Project X	Upgrade Linacs Accumulator Compressor	8 GeV

High Power Proton Driver Requirements

- Supply protons to target to produce pions
- Basic specifications:
  - 4 MW proton beam power
  - Proton kinetic energy 5 – 15 GeV
  - RMS bunch length 1 – 3 ns
  - 50 Hz repetition rate
  - Three bunches, extracted > 80 μs apart







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Green Field Solution

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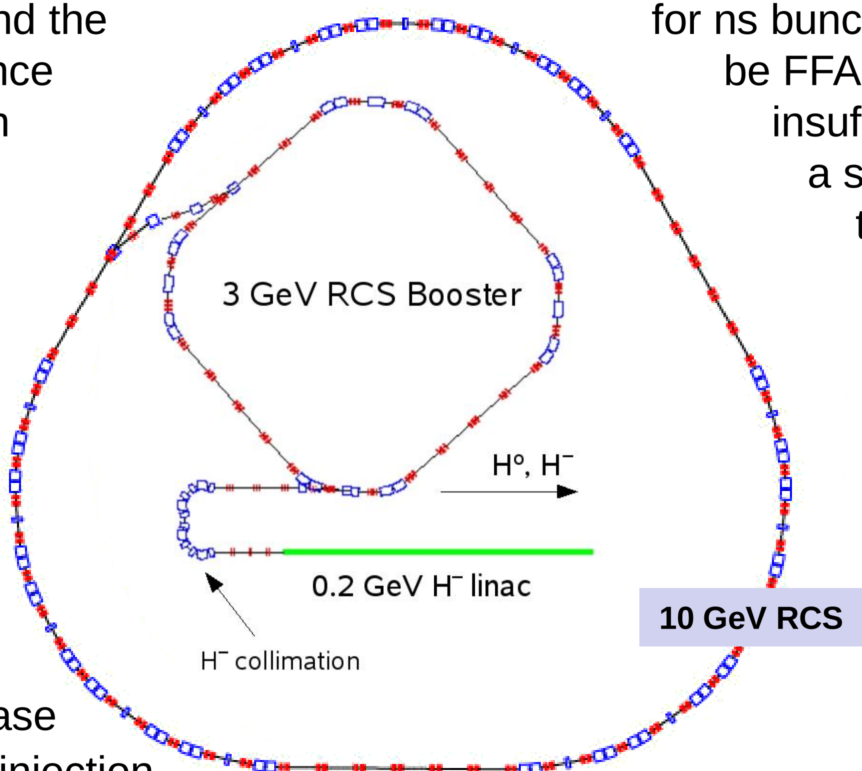
Chris Prior, Grahame Rees,
Shinji Machida (Science & Technology Facilities Council ASTeC)

Proton Driver for a Neutrino Factory

- Lower injection energies provide smaller bucket area in the ring and the small longitudinal emittance needed for final ns bunch compression. Studies show that 180 MeV is a realistic energy for NF
- Special achromat for collimation (longitudinal and transverse) and momentum ramping for injection
- Separate booster ring designed for low loss phase space painting for beam injection and accumulation. Synchrotron moving buckets give flexibility to capture all of the injected beam



- Separate main ring with optics chosen for ns bunch compression. Could be FFAG (cheaper but insufficiently developed) or a synchrotron (reliable, tried and tested)
- Compressed bunches need to be held and sent to target at intervals of ~100 μs. Possible in FFAG and also synchrotron with flat top

ISIS Upgrade + NF Solution

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ISIS Synchrotron Group

and (amongst others)

I S K Gardner, Y Irie[3], S J S Jago, L J Jenner[4], A P Letchford,
J Pasternak[2], D C Plostinar[1], C R Prior[1], G H Rees[1] , J Thomasson

ISIS and [1]ASTeC, Rutherford Appleton Laboratory, UK
[2]ISIS and Imperial College, London, UK
[3]KEK and J-PARC, Japan
[4]Imerpial College and Fermilab

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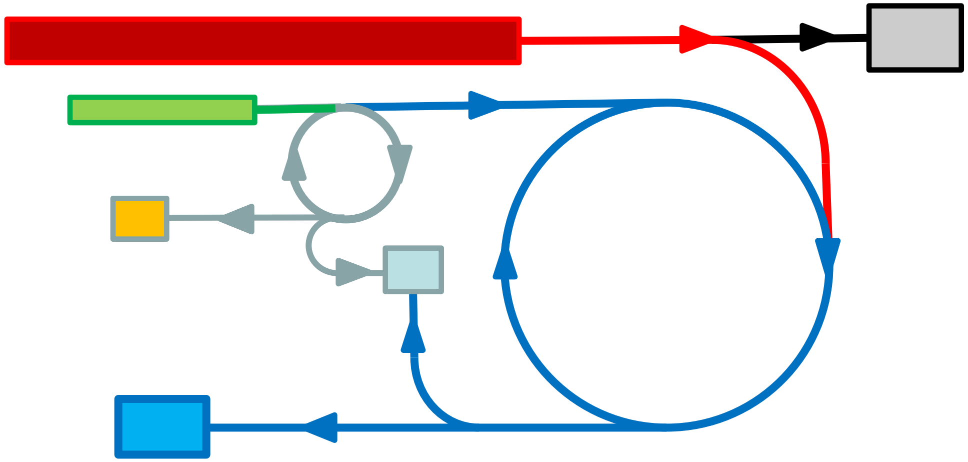
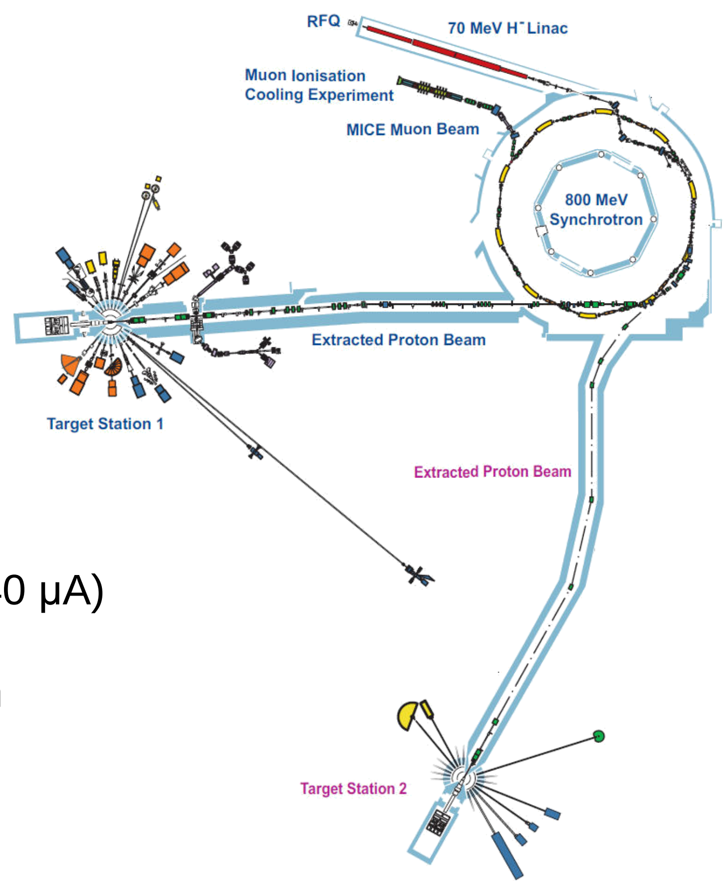
ISIS Upgrades

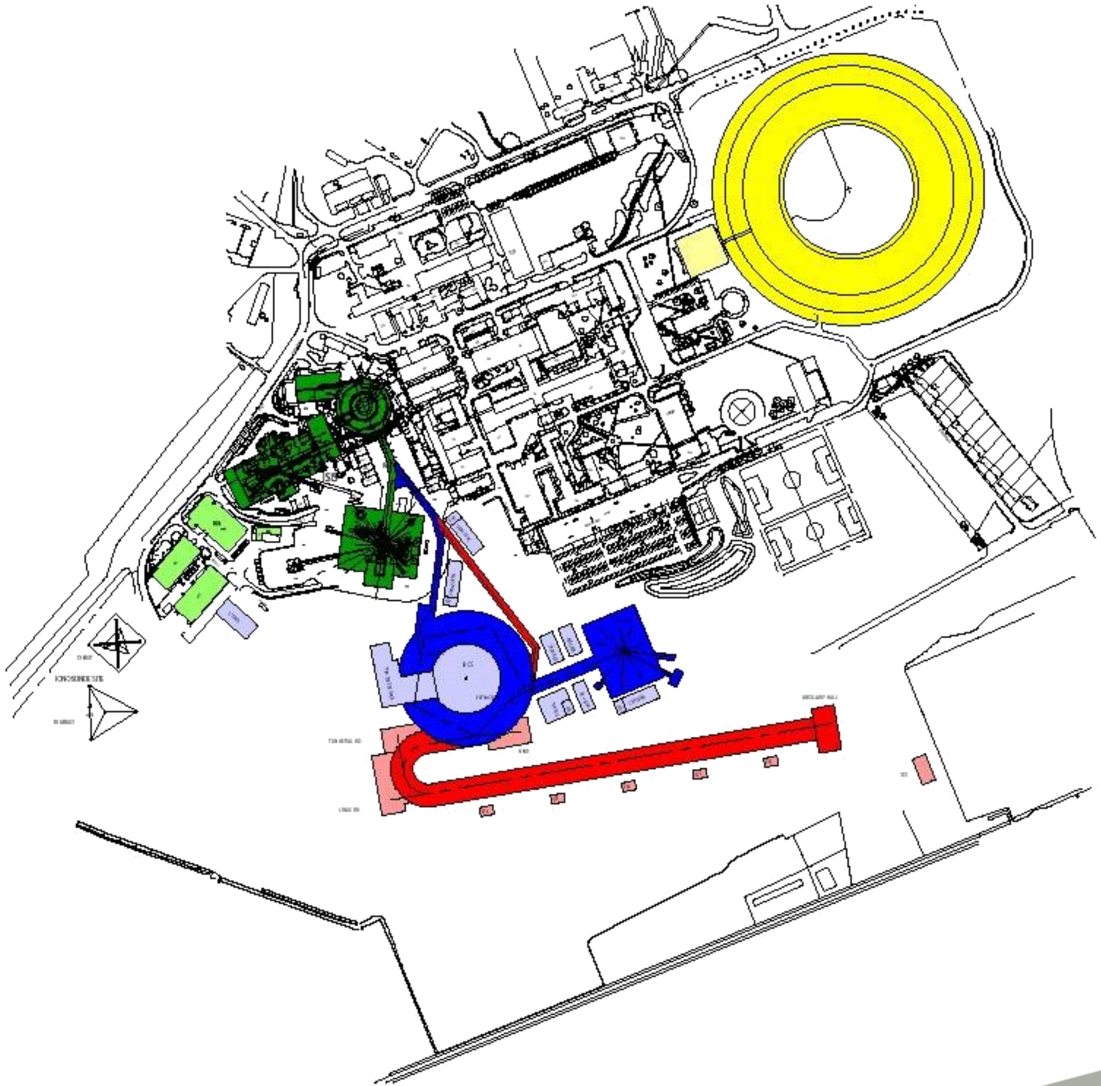




- Present operations for two target stations
  - Operational Intensities: 220 – 230 μA (185 kW)
  - Experimental Intensities of 3×10^{13} ppp (equiv. 240 μA)
  - DHRF operating well: High Intensity & Low Loss
  - Now looking at overall high intensity optimisation
- Study ISIS upgrade scenarios
  - 0) Linac and TS1 refurbishment
  - 1) Linac upgrade leading to ~0.5 MW operations on TS1
  - 2) ~3.3 GeV booster synchrotron: MW Target
  - 3) 800 MeV direct injections to booster synchrotron: 2 – 5 MW Target
  - 4) Upgrade 3) + long pulse mode option

Overlap with NF proton driver

ISIS MW Upgrade Scenarios

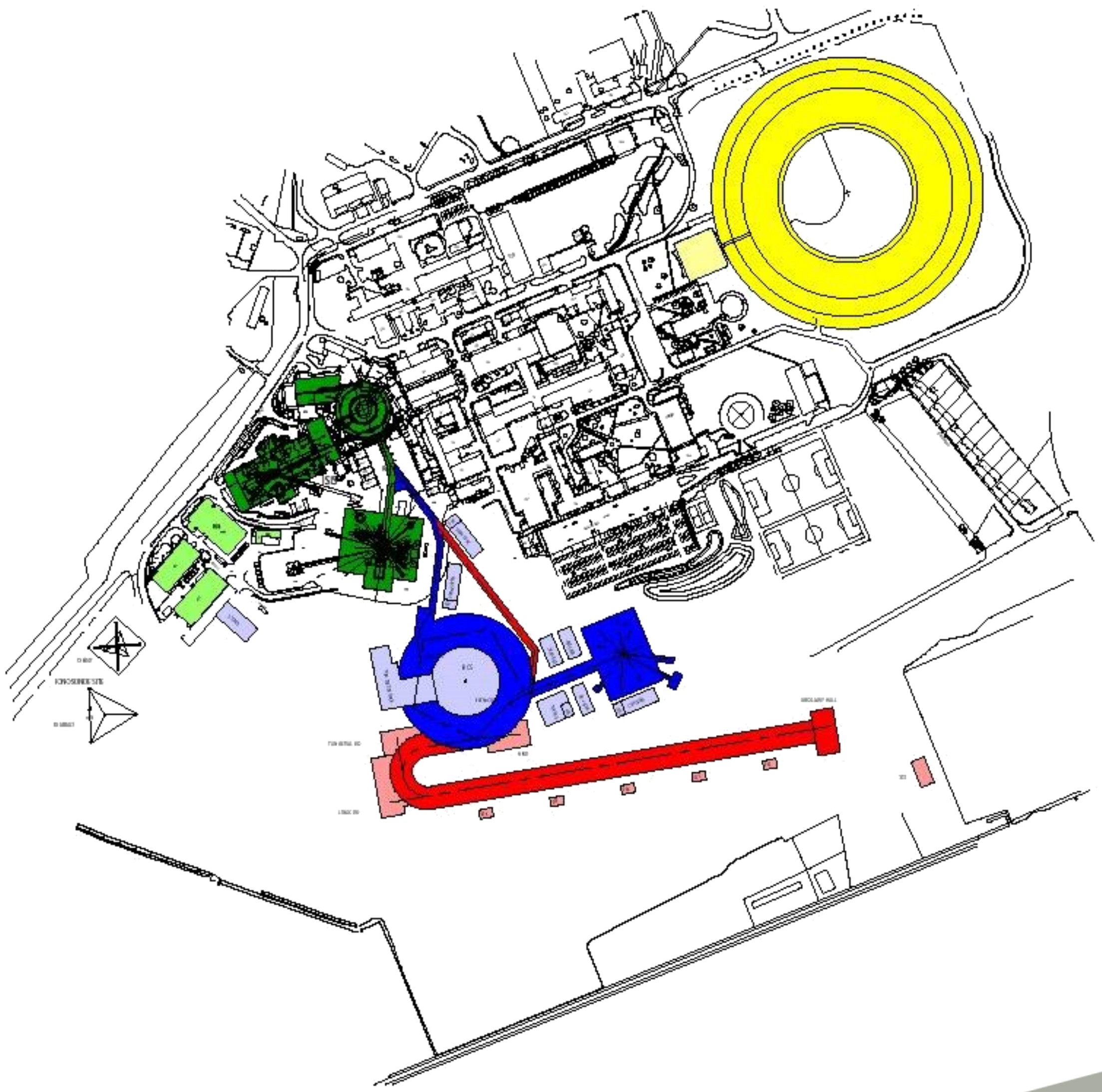


1) Replace ISIS linac with a new ≈ 180 MeV linac (≈ 0.5MW)

2) Based on a ≈ 3.3 GeV RCS fed by bucket-to-bucket transfer from ISIS 800 MeV synchrotron (1MW, perhaps more)

3) RCS design also accommodates multi-turn charge exchange injection to facilitate a further upgrade path where the RCS is fed directly from an 800 MeV linac (2 – 5 MW)

ISIS MW Upgrade Scenarios



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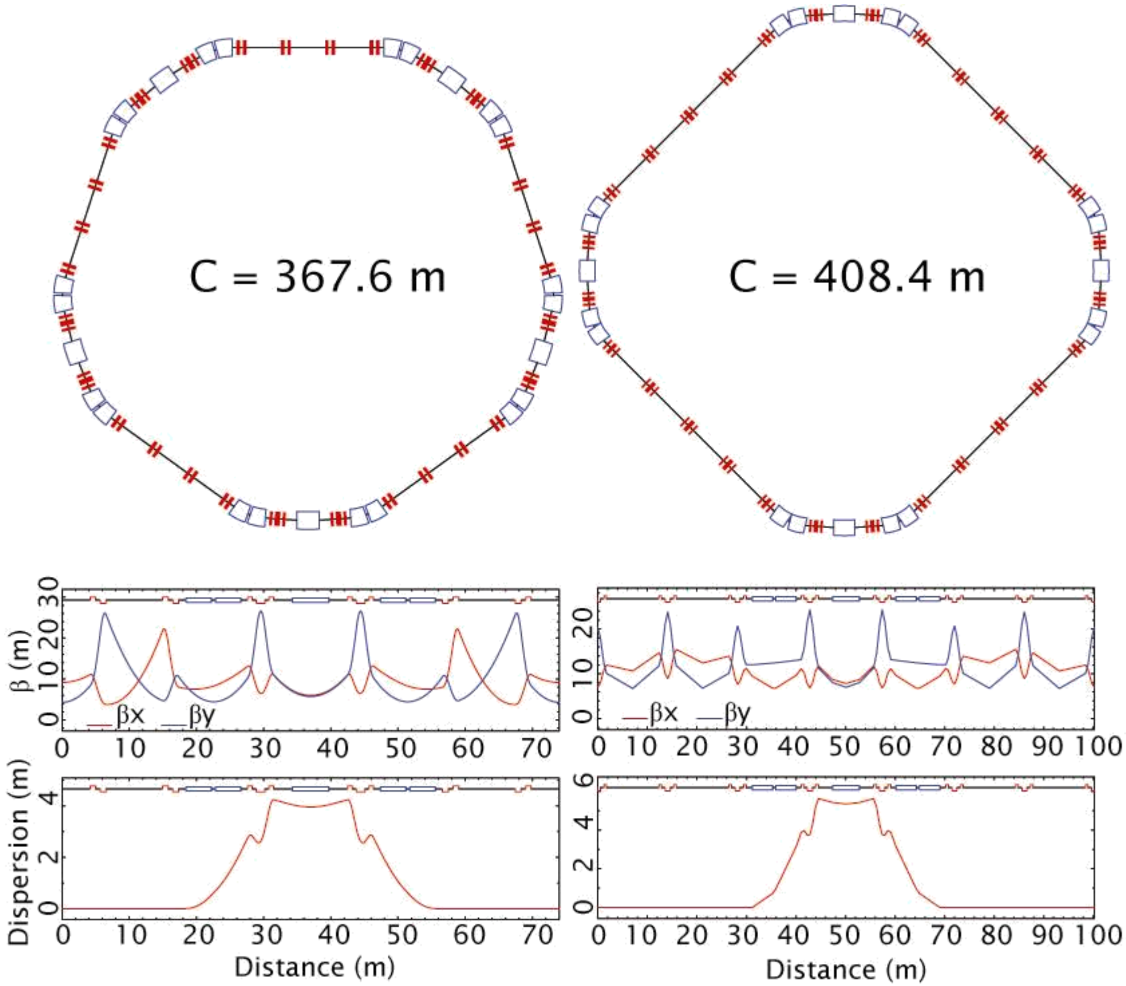
Possible ≈ 3.3 GeV RCS Rings



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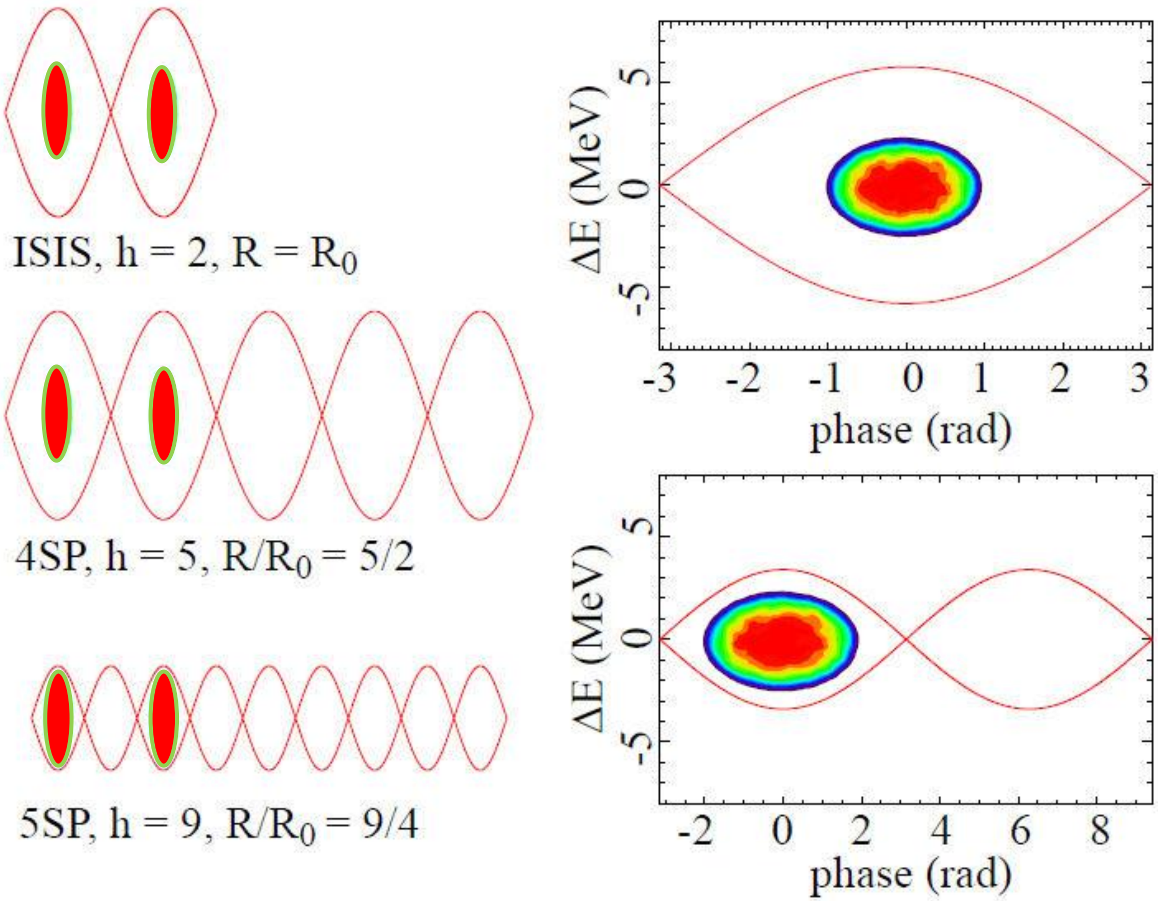

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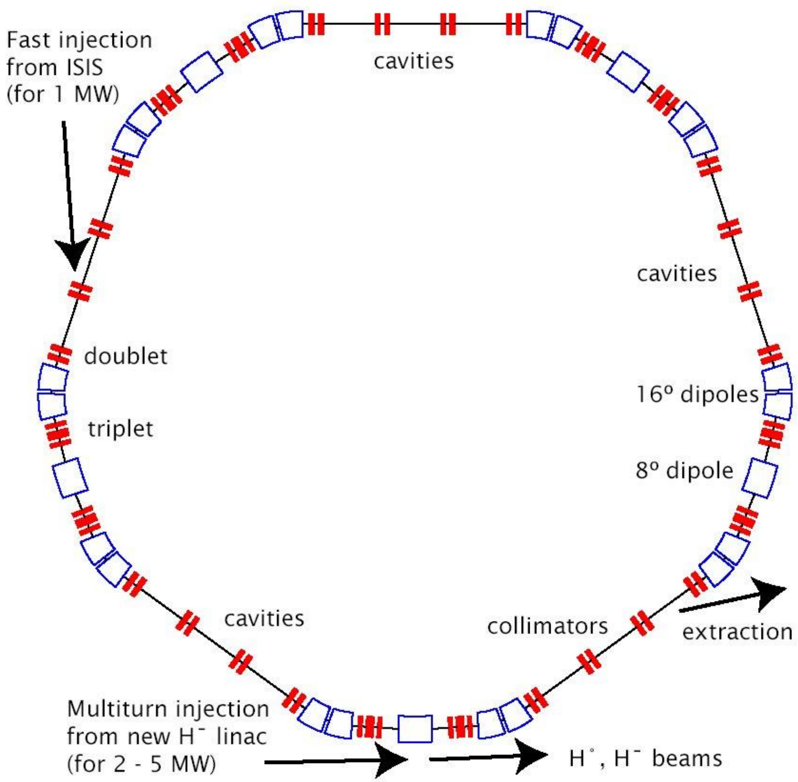
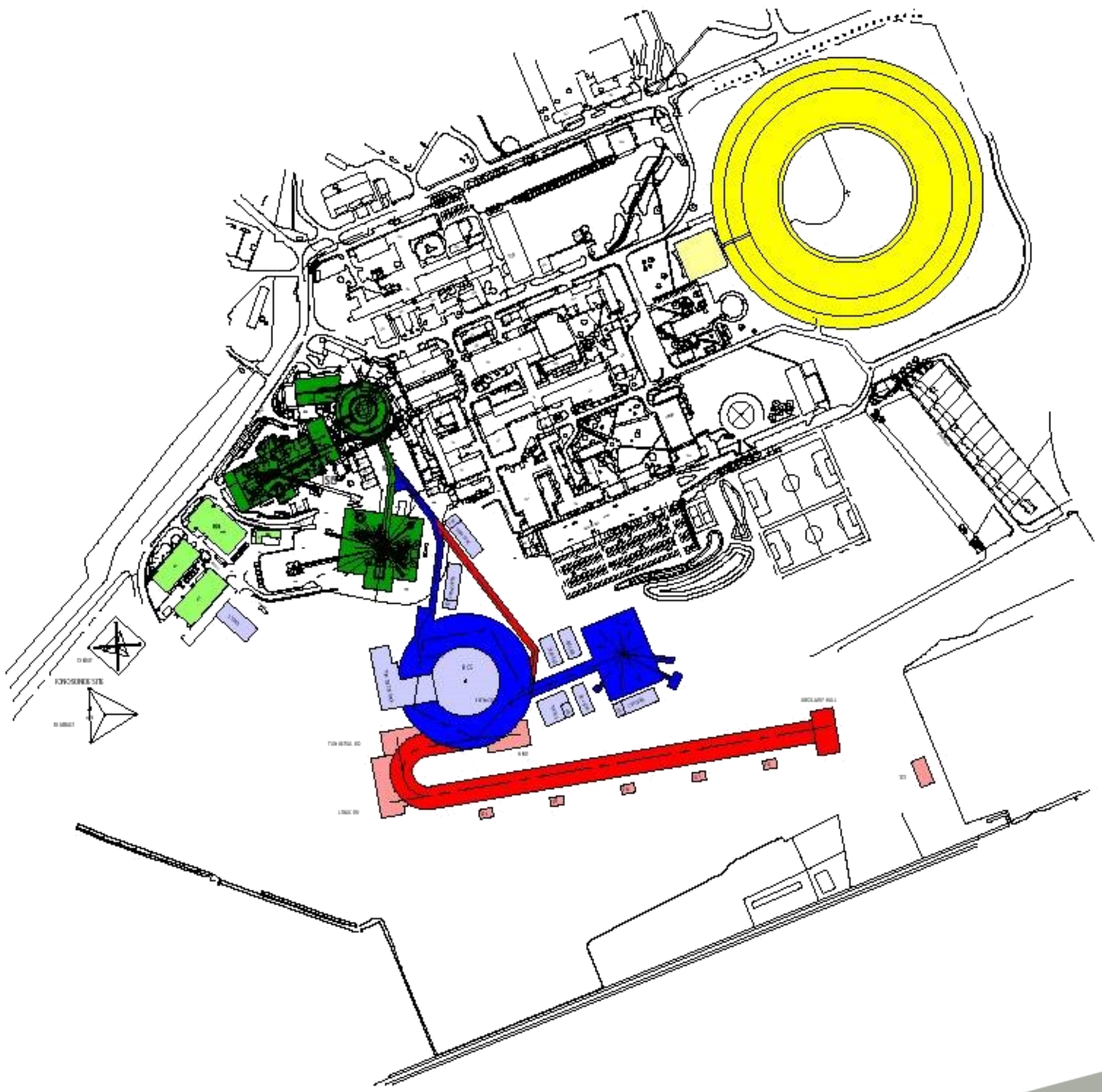
5SP RCS Ring



Energy	0.8 – 3.2 GeV
Rep Rate	50 Hz
C, R/R_0	367.6 m, 9/4
Gamma-T	7.2
h	9
f_{rf} sweep	6.1-7.1 MHz
Peak V_{rf}	≈ 750 kV
Peak K_{sc}	≈ 0.1
ε_l per bunch	≈ 1.5 eV s
$B[t]$	sinusoidal

ISIS MW Upgrade Scenarios



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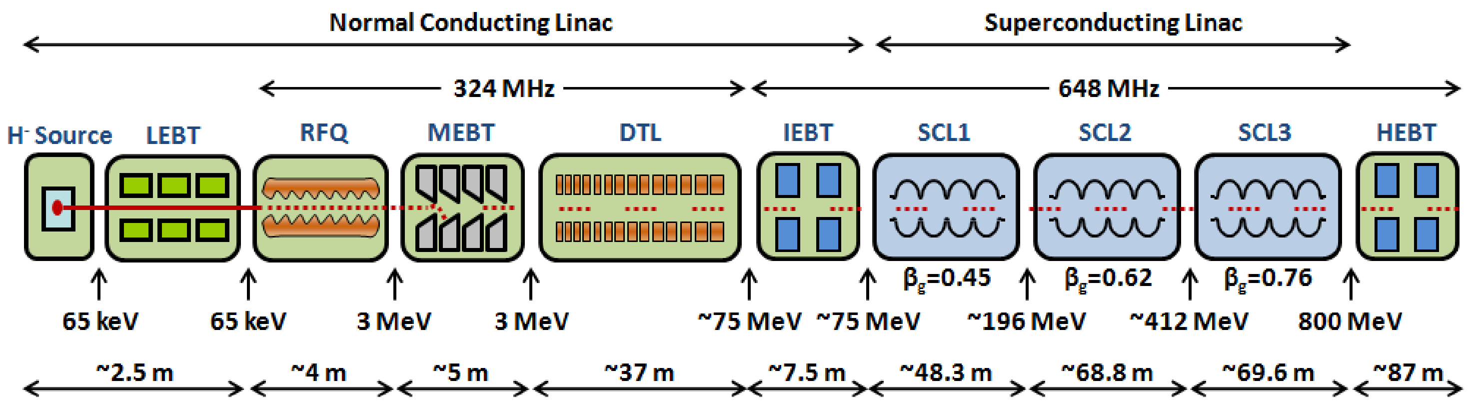
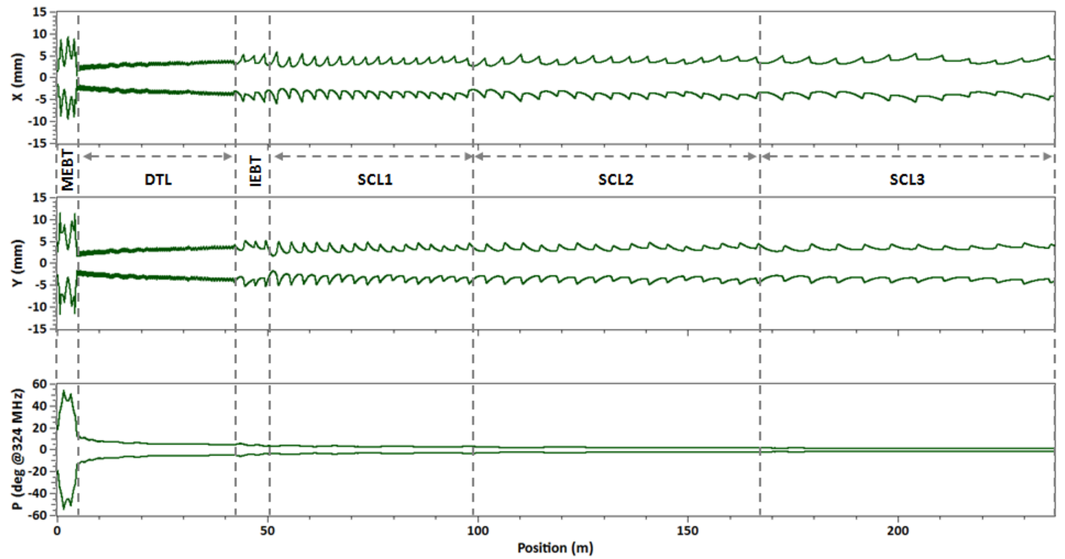
Grahame Rees,
Ciprian Plostinar (ASTeC)

800 MeV, H^- Linac Design Parameters

Ion Species	H^-
Output Energy	800 MeV
Accelerating Structures	DTL/SC Elliptical Cavities
Frequency	324/648 MHz
Beam Current	43 mA
Repetition Rate	30 Hz (Upgradeable to 50)
Pulse Length	0.75 ms
Duty Cycle	2.25 %
Average Beam Power	0.5 MW
Total Linac Length	243 m

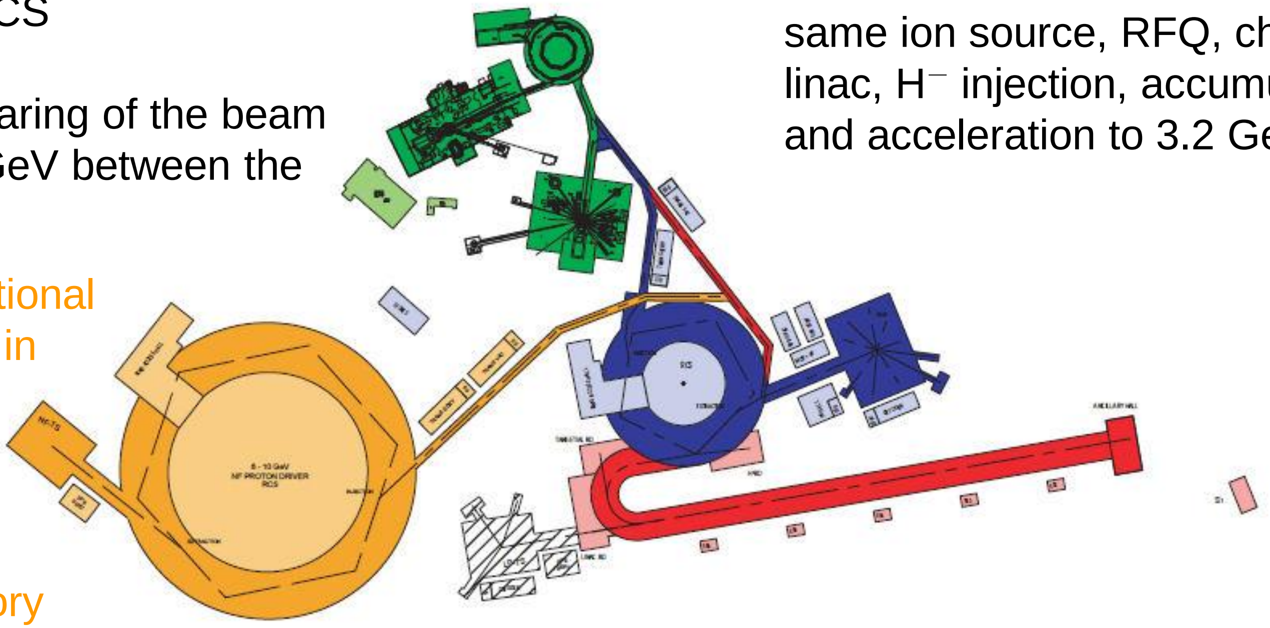
Design Options





Common Proton Driver for the Neutron Source and the Neutrino Factory

- Based on MW ISIS upgrade with 800 MeV Linac and 3.2 (≈ 3.3) GeV RCS
- Assumes a sharing of the beam power at 3.2 GeV between the two facilities
- Requires additional RCS machine in order to meet the power and energy needs of the Neutrino Factory



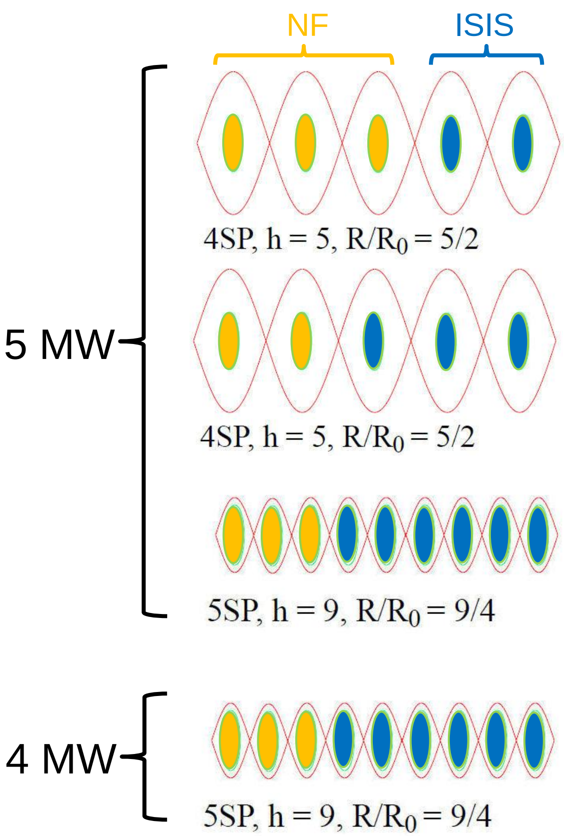
- Both facilities can have the same ion source, RFQ, chopper, linac, H^- injection, accumulation and acceleration to 3.2 GeV

- Options for the bunch compression to 1 – 3 ns RMS bunch length:
  - adiabatic compression in the RCS
  - ‘fast phase rotation’ in the RCS
  - ‘fast phase rotation’ in a dedicated compressor ring

Summary of Assumptions for the Common Proton Driver

- Bunches will be transfered from the booster RCS at ≈ 3.2 GeV, 50 Hz

Assume 4 – 5 MW from booster RCS, and 4MW required from NF proton driver :



3 bunches, 3.9×10^{13} protons/bunch, 4.3 GeV
2 MW to ISIS

2 bunches, 3.9×10^{13} protons/bunch, 6.4 GeV
3 MW to ISIS

3 bunches, 2.2×10^{13} protons/bunch, 7.7 GeV
3⅓ MW to ISIS

3 bunches, 1.76×10^{13} protons/bunch, 9.6 GeV
2⅔ MW to ISIS

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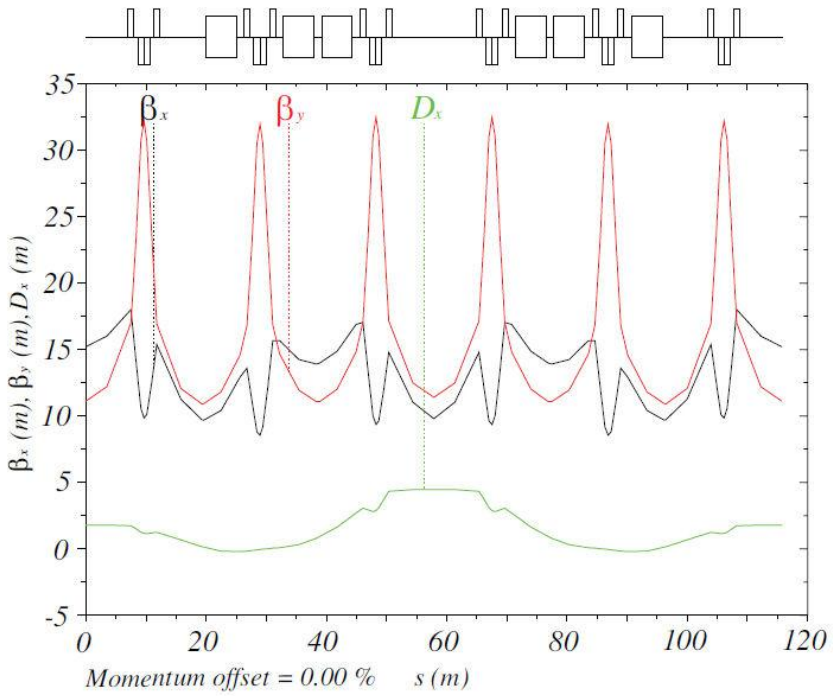
Jaroslaw Pasternak, Leo Jenner
(Imperial College London , Science & Technology Facilities Council ISIS , Fermilab)

Preliminary design of the second RCS



Parameters of 3.2 – 9.6 GeV RCS

Number of superperiods	6
Circumference	694.352 m
Harmonic number	17
RF frequency	7.149 – 7.311 MHz
Gamma transition	13.37
Beam power at 9.6 GeV	4 MW for 3 bunches
Injection energy	3.2 GeV
Extraction energy	9.6 GeV
Peak RF voltage per turn	≈ 3.7 MV
Repetition rate	50 Hz
Max B field in dipoles	1.2 T
Length of long drift	14 m

- Present-day, cost-effective RCS technology
- Only three quadrupole families
- Allows a flexible choice of gamma transition
- Up to 3.7 MV/turn?

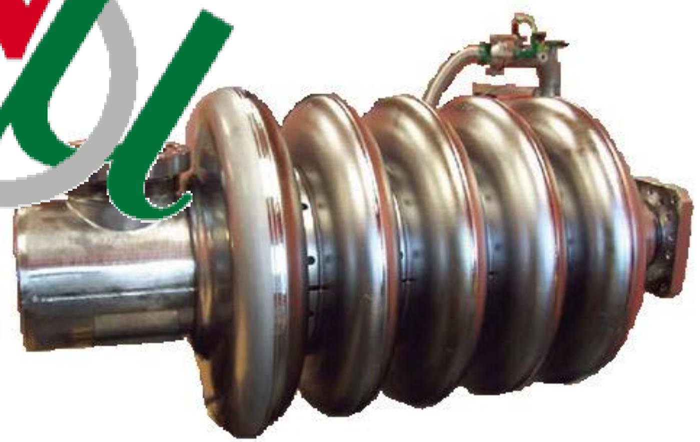
Necessary Hardware R&D

To realise ISIS MW upgrades, NF and generic high power proton driver development, common hardware R&D will be necessary in key areas:

- High power front end (FETS)
- RF Systems
- Stripping Foils
- Diagnostics
- Targets
- Kickers
- *etc.*

- In the neutron factory context SNS and J-PARC are currently dealing with many of these issues during facility commissioning and we have a watching brief for all of these
- Active programmes in some specific areas

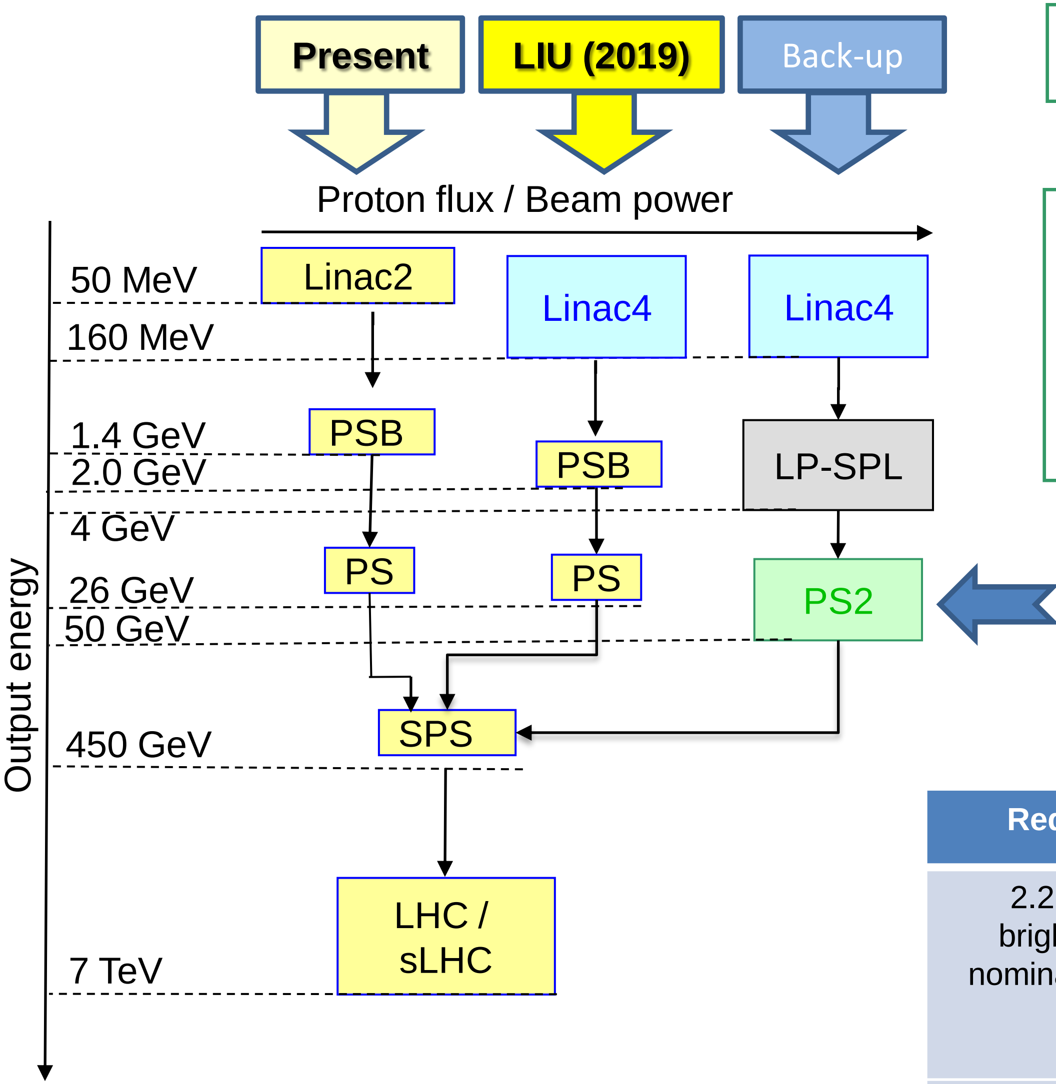
SPL-Based NF Proton Driver



Information from

(amongst others)

Roland Garoby, Simone Gilardoni,
Gersende Prior, Frank Gerigk



LP-SPL: Low Power-Superconducting Proton Linac (4 GeV)

HP-SPL: Upgrade of infrastructure (cooling water, electricity, cryogenics etc.)

Replacement of klystron power supplies

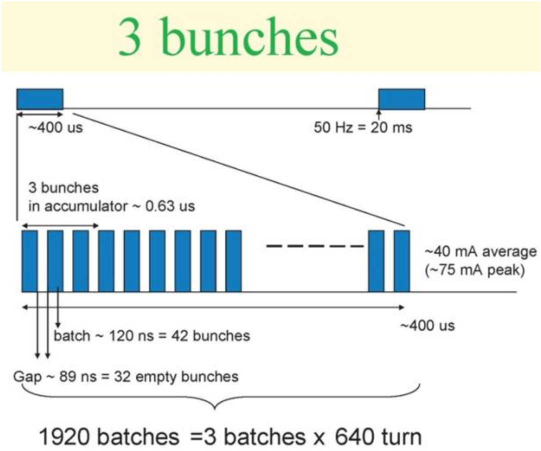
Addition of 5 high β cryomodules to accelerate up to 5 GeV

Main requirements of PS2 on its injector:

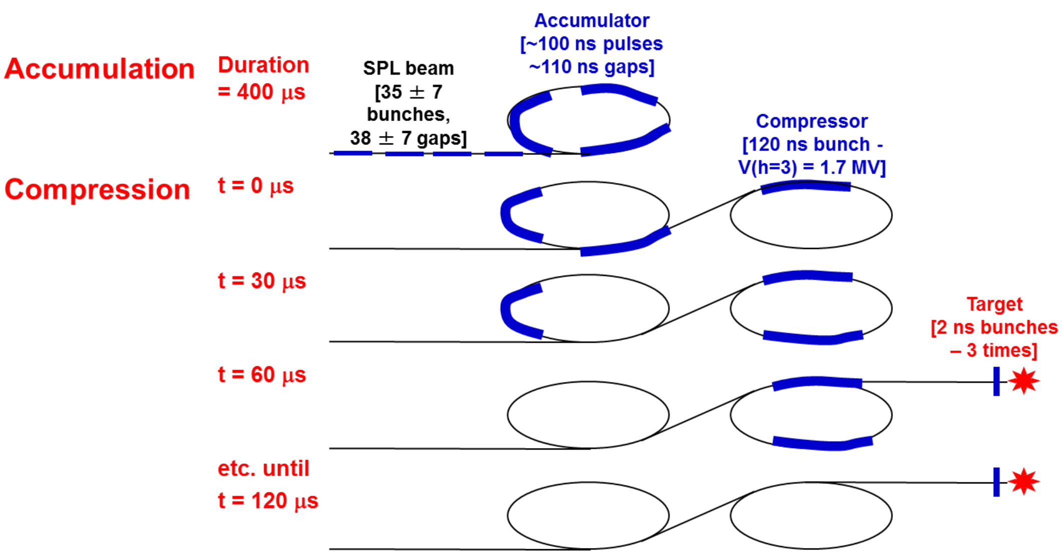
Requirement	Parameter	Value
2.2 x ultimate brightness with nominal emittances	Injection energy	4 GeV
	Nb. of protons / cycle for LHC (180 bunches)	6.7×10^{13}
Single pulse filling of SPS for fixed target physics	Nb. of protons / cycle for SPS fixed target	1.1×10^{14}

SPL-Based NF Proton Driver: Principle

- Accumulation of beam from the High Power SPL in a fixed energy Accumulator (5 GeV, 4MW beam power).
- Bunch compression («rotation») in a separate Compressor ring



	3 bunches / 1 bunch
Accumulator	
circumference	185.8 m
no. of accumulation turn	640 / 1920
transition gamma	6.33 (isochronous)
no. of simultaneous bunches	3 / 1
Compressor	
circumference	200 m
rf voltage	1.7 MV
no. of compression turn	86
transition gamma	2.84
no. of simultaneous bunches	2 / 1
Beam on target	
bunch spacing	30 μs / -
burst duration	60 μs / -
bunch length	2 ns
beam energy	5 GeV
beam power	4 MW
repetition	50 Hz



HP-SPL: Main Characteristics

Ion species	H^-	
Output Energy	5	GeV
Bunch Frequency	352.2	MHz
Repetition Rate	50	Hz
High speed chopper (rise & fall times)	< 2	ns

Required for low loss in accumulator

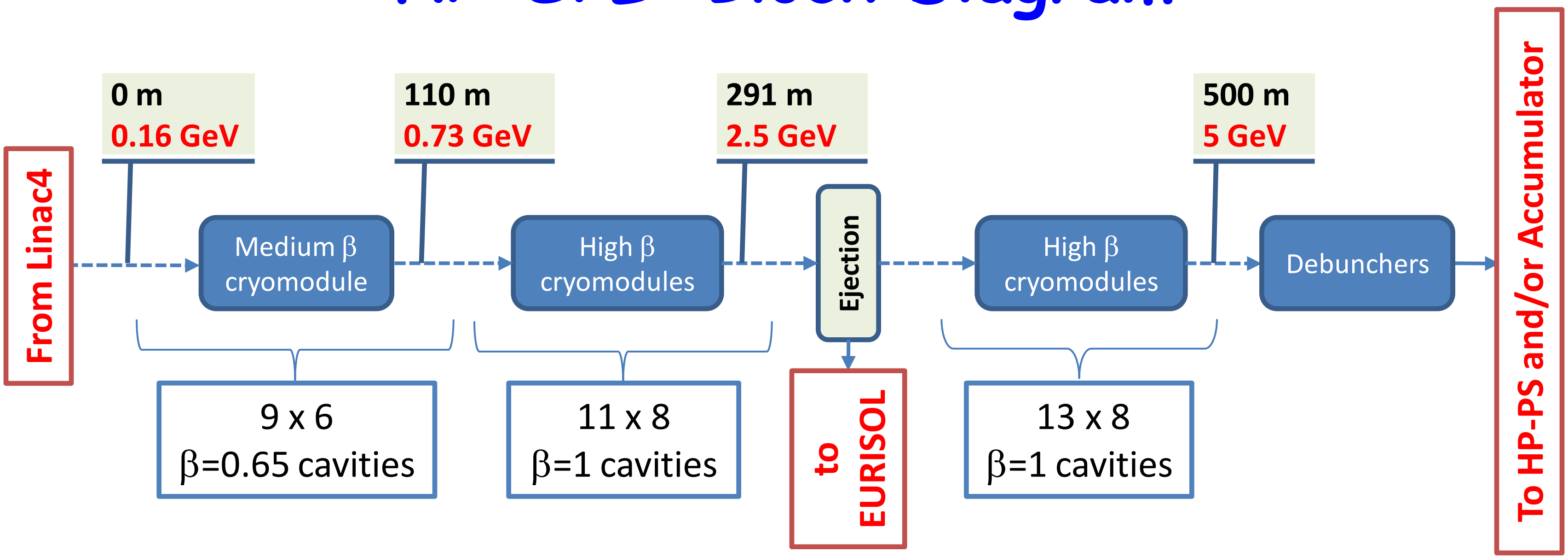
Required for muon production

Required for flexibility and low loss in accumulator

	Option 1	Option 2
Energy (GeV)	2.5 or 5	2.5 and 5
Beam power (MW)	2.25 MW (2.5 GeV) or 4.5 MW (5 GeV)	5 MW (2.5 GeV) and 4 MW (5 GeV)
Protons/pulse (x 10^{14})	1.1	2 (2.5 GeV) + 1 (5 GeV)
Av. Pulse current (mA)	20	40
Pulse duration (ms)	0.9	1 (2.5 GeV) + 0.4 (5 GeV)

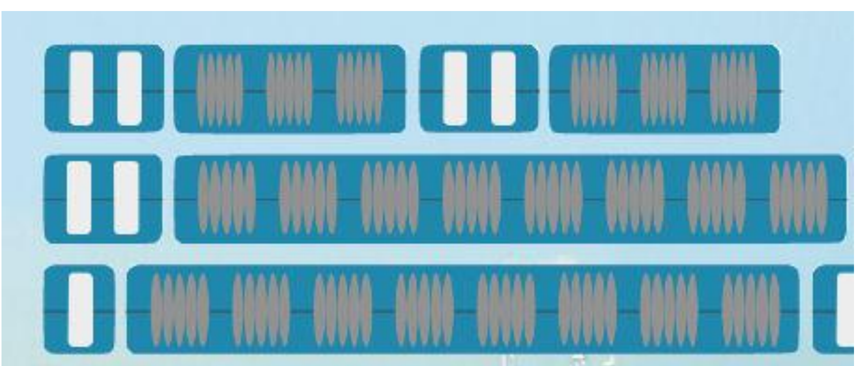
2 × beam current ⇒ 2 × nb. of klystrons etc .

HP-SPL: Block Diagram



Segmented cryogenics / separate cryo-line / room temperature quadrupoles:

- Medium β (0.65) – 3 cavities / cryomodule
- High β (1) – 8 cavities / cryomodule



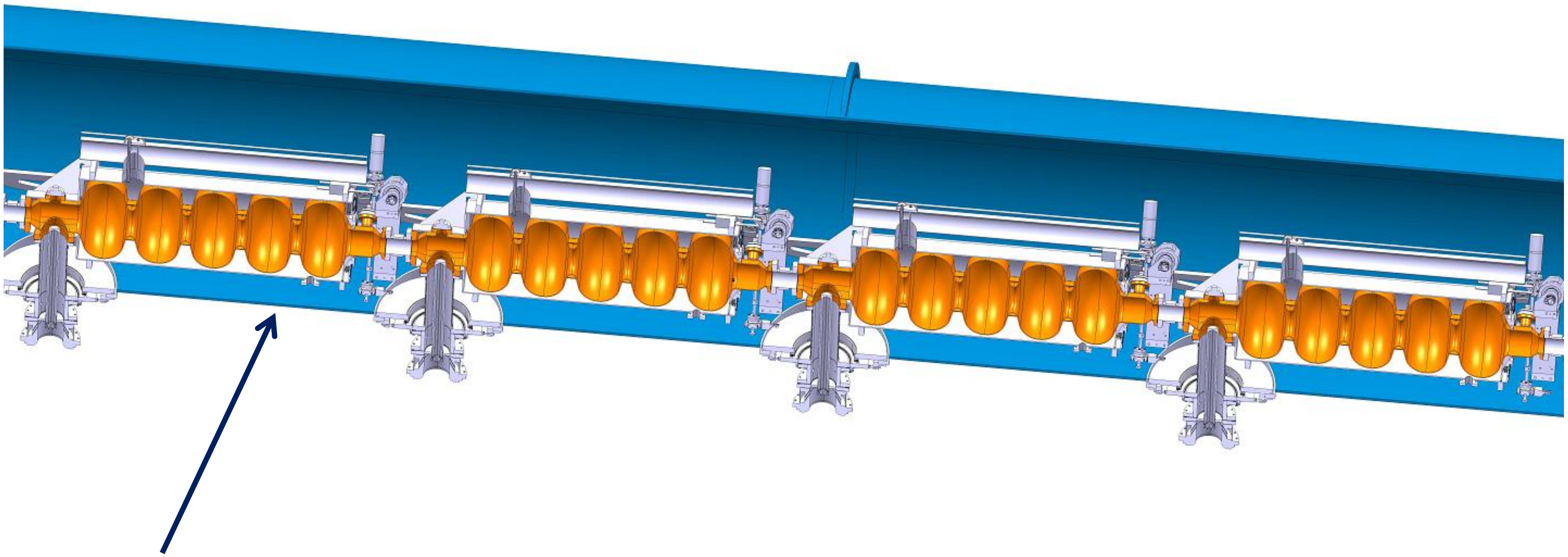
Low energy

Intermediate energy

High energy

HP-SPL: R&D Objective

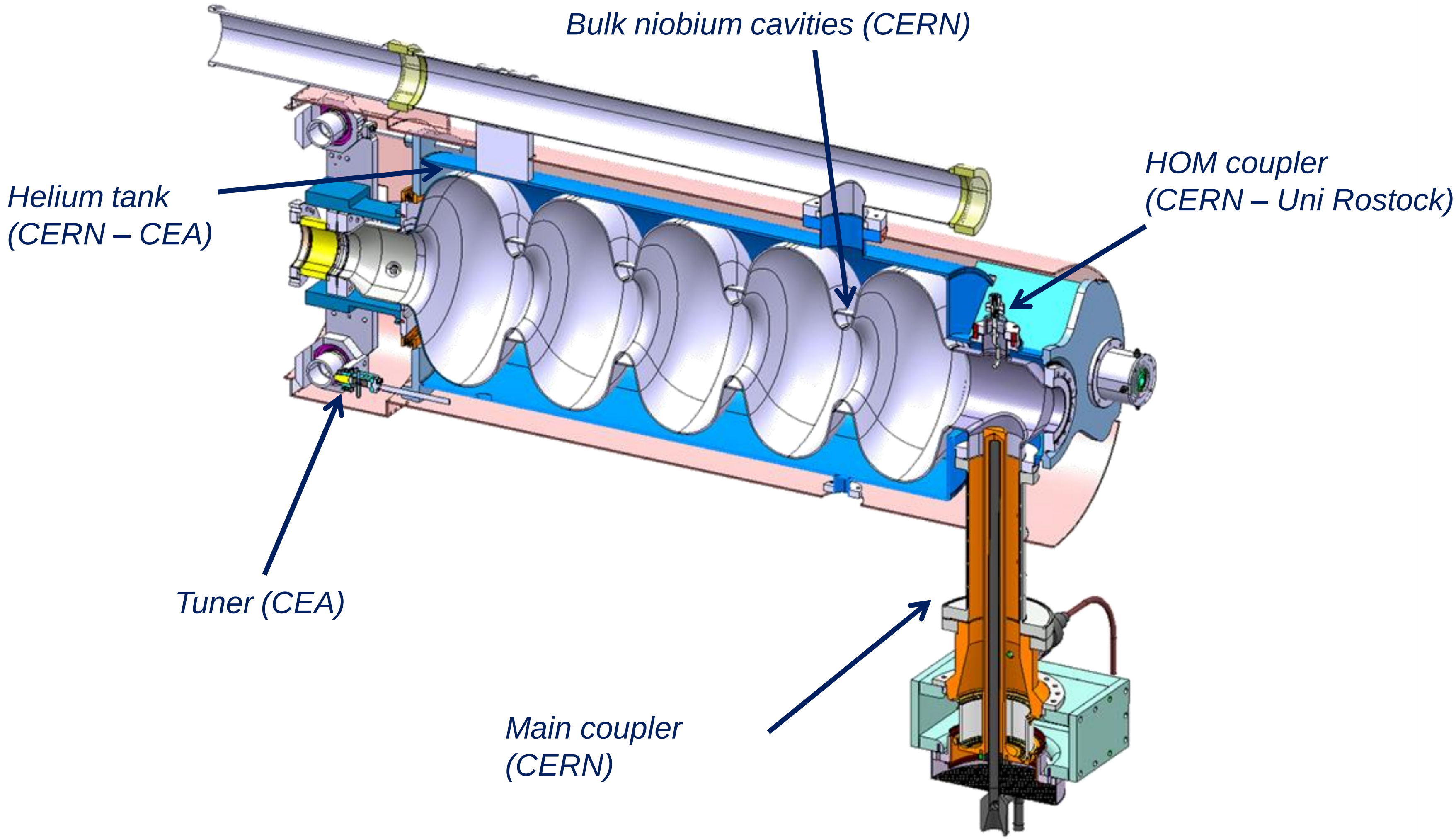
Design, construction and test of a string of 4 β=1 cavities equipped with main couplers & tuners inside a "short" prototype cryo-module to be tested in 2014.



Cryomodule
(CERN – CNRS)

HP-SPL: Cavity & Cryomodule Design

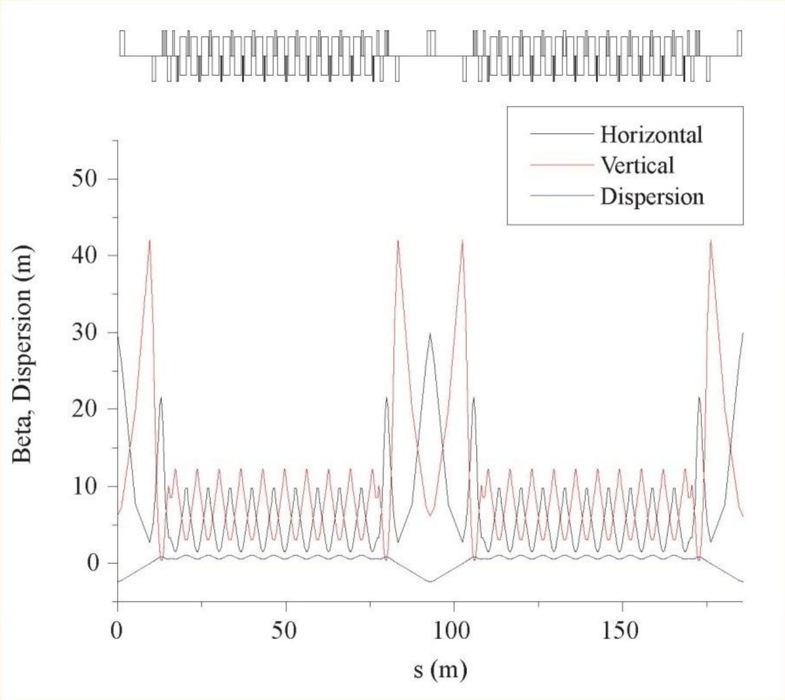
SPL $\beta = 1$ cavity + helium tank + tuner + main coupler



Accumulator/compressor lattices

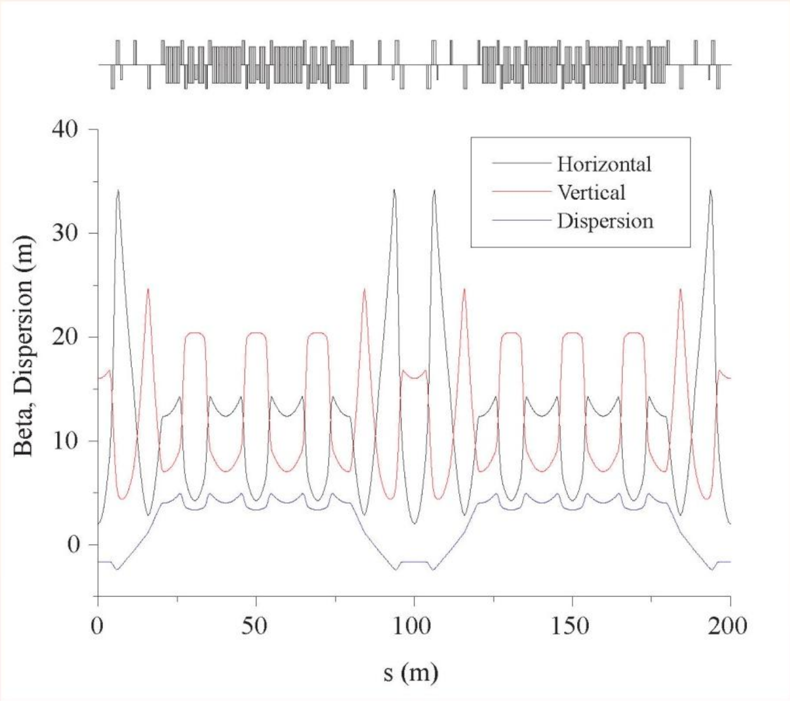
from M. Aiba

Lattice for 1 & 3 bunches



γ_{tr}=6.33 (isochronous)

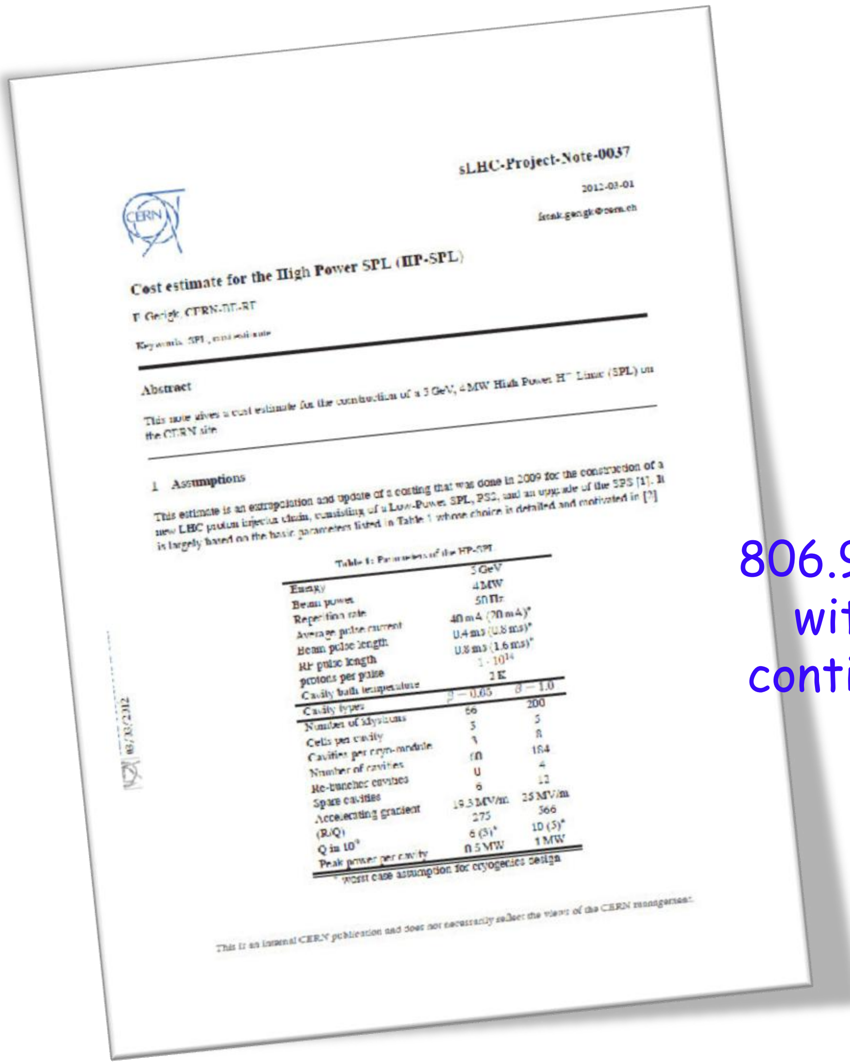
Lattice for 1 & 3 bunches



γ_{tr}=2.8

Collective effect related limitations have also been studied

HP-SPL: Cost Estimate (1/3/12)



sLHC-Project-Note-0037

2012-03-01

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Cost estimate for the High Power SPL (HP-SPL)

F. Gerigk, CERN-BE-RF

Keywords: SPL, cost estimate

Abstract

This note gives a cost estimate for the construction of a 5 GeV, 4 MW High Power H^- Linac (SPL) on the CERN site.

1 Assumptions

This estimate is an extrapolation and update of a costing that was done in 2009 for the construction of a new LHC proton injector chain, consisting of a Low-Power SPL, PS2, and an upgrade of the SPS [1]. It is largely based on the basic parameters listed in Table 1 whose choice is detailed and motivated in [2].

Table 1: Parameters of the HP-SPL

Energy	5 GeV	
Beam power	4 MW	
Repetition rate	50 Hz	
Average pulse current	40 mA (20 mA)*	
Beam pulse length	0.4 ms (0.8 ms)*	
RF pulse length	0.8 ms (1.6 ms)*	
protons per pulse	$1 \cdot 10^{14}$	
Cavity bath temperature	2 K	
Cavity types	$\beta = 0.65$	$\beta = 1.0$
Number of klystrons	66	200
Cells per cavity	5	5
Cavities per cryo-module	3	8
Number of cavities	60	184
Re-buncher cavities	[illegible]	4
Spare cavities	6	12
Accelerating gradient	19.3 MV/m	25 MV/m
(R/Q)	275	566
Q in 10^9	6 (3)*	10 (5)*
Peak power per cavity	0.5 MW	1 MW

* worst case assumption for cryogenics design

This is an internal CERN publication and does not necessarily reflect the views of the CERN management.

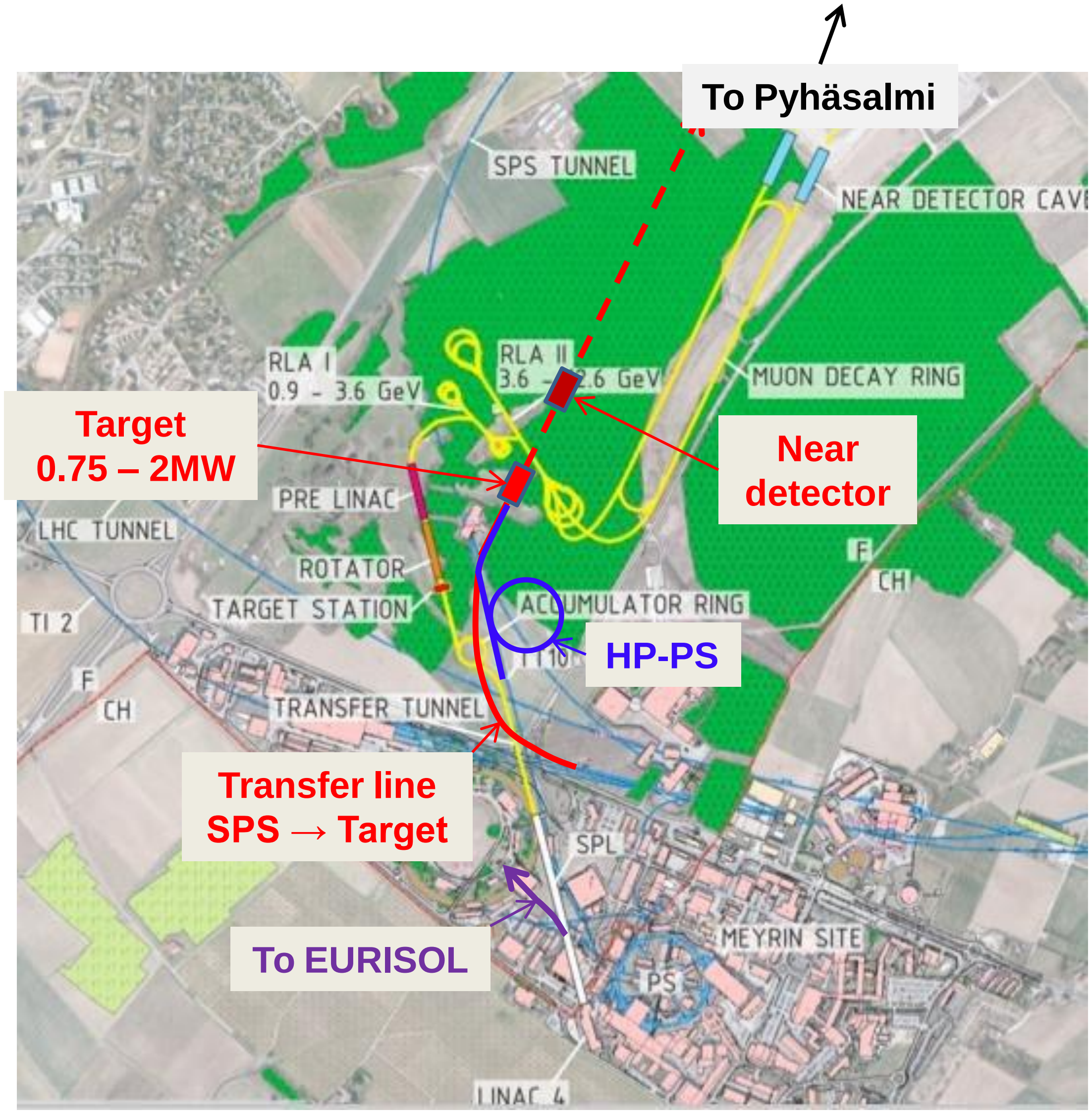
806.9 MCHF
without
contingency

NF on CERN Site

Other potential neutrino physics sources at CERN

Super-beam:
LAGUNA-LBNO SPS (750 kW)
LAGUNA-LBNO HP-PS (2 MW)

Beta-beam:
EURISOL (200kW)



Project-X at Fermilab

Materials from
Keith Gollwitzer
Accelerator Division
Fermilab

Project X main goals

- To provide neutrino beams for long baseline neutrino oscillation experiments
- To provide intense kaon and muon beams for precision experiments;
- To provide MW-class beam at 1 GeV to support a broad rang of materials studies and energy application
- To develop a path toward a muon source for a possible Neutrino Factory and Muon Collider

Project X staging

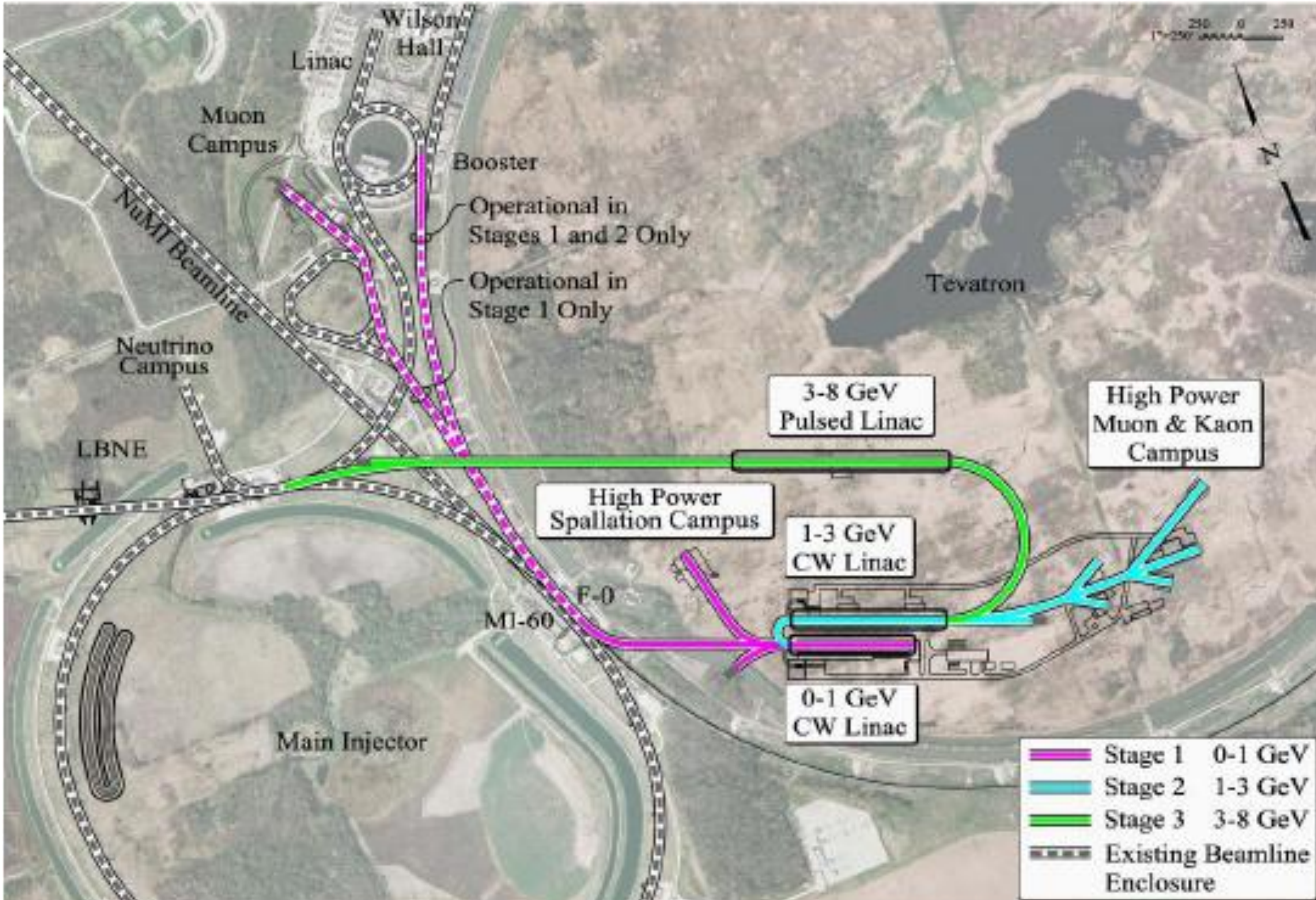
• Construction of a 1~GeV CW linac (average current of 1~mA) to provide beam to the Booster and to a new 1~GeV experimental facility

• 1-3~GeV CW linac with an average current of 1~mA to provide beam to a new 3~GeV experimental facility and upgrading the 1~GeV lianc to 2~mA average current.

•Addition of a 3-8~GeV pulsed linac and accompanying upgrades to the Recycler and Main Injector.

• Addition of new Accumulator and Compressor rings for the Neutrino Factory and Muon Collider.

Project X Layout



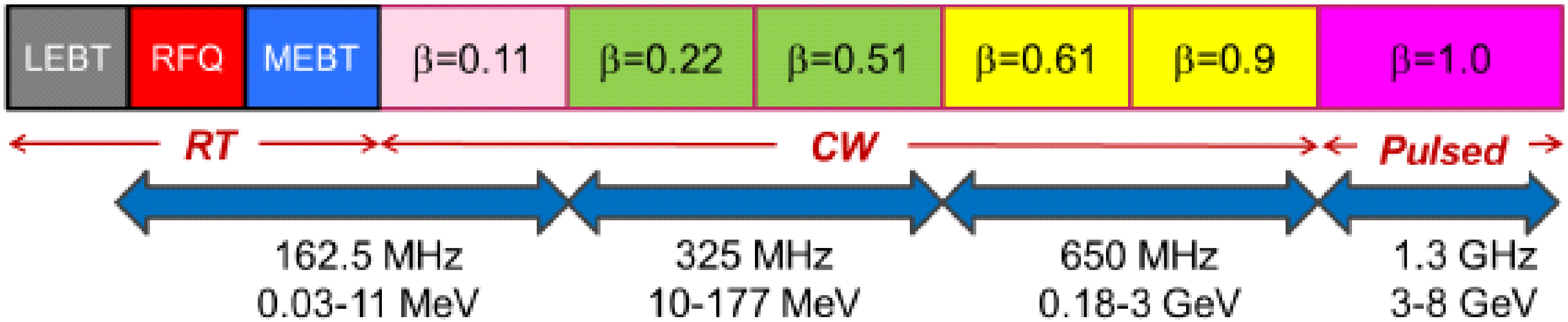
Project X building blocks (1)

- An H^- source consisting of a 30~keV DC ion source, Low Energy Beam Transport (LEBT), 2.1 MeV RFQ, and Medium Energy Beam Transport (MEBT) augmented with a wideband bunch-by-bunch chopper capable of generating bunch trains of arbitrary patterns at 162.5~MHz.
- A 3GeV superconducting linac operating in CW mode, and capable of accelerating an average (>\us) beam current of 2~mA to 1GeV and 1mA to 3GeV, with a peak beam current of 5mA.
- A 3 to 8GeV pulsed superconducting linac capable of accelerating an average current of 43uA with a 4.3 % duty factor.
- A pulsed dipole that can switch the 3GeV beam between injection into the pulsed linac and the 3GeV experimental program.

Project X building blocks (2)

•An RF beam splitter that can extract 1~mA of beam at 1~GeV.
• An RF beam splitter that can deliver 3~GeV beam to multiple experiments.
• Upgrades to the 8~GeV Booster to support injection at 1~GeV (stages~1 and~2).
• Upgrades to the Main Injector/Recycler complex to support a factor of three increase in beam intensity (stage~3).
• Target facilities required to produce secondary particle beams needed by the experimental program.
• Accumulator and compressor rings with their services (circumference ~300 m),

Project X linac schematic



Proton Driver Concerns

- Stripping
  - Accumulation of protons from H^- linac beam
  - Handling of unconverted beam
- Intense particle bunches
  - Instabilities?
    - Example of look at longitudinal parameters

$$P_{\max} \approx 0.72\,\mathrm{MW}\left(\frac{E}{8\,\mathrm{GeV}}\right)^4\left(\frac{f_{rep}}{15\,\mathrm{Hz}}\right)\left(\frac{L_b\sigma_p}{60\,\mathrm{cm}\times 1\%}\right)^2\left(\frac{10\,\mathrm{m}}{L_{init}}\right)$$

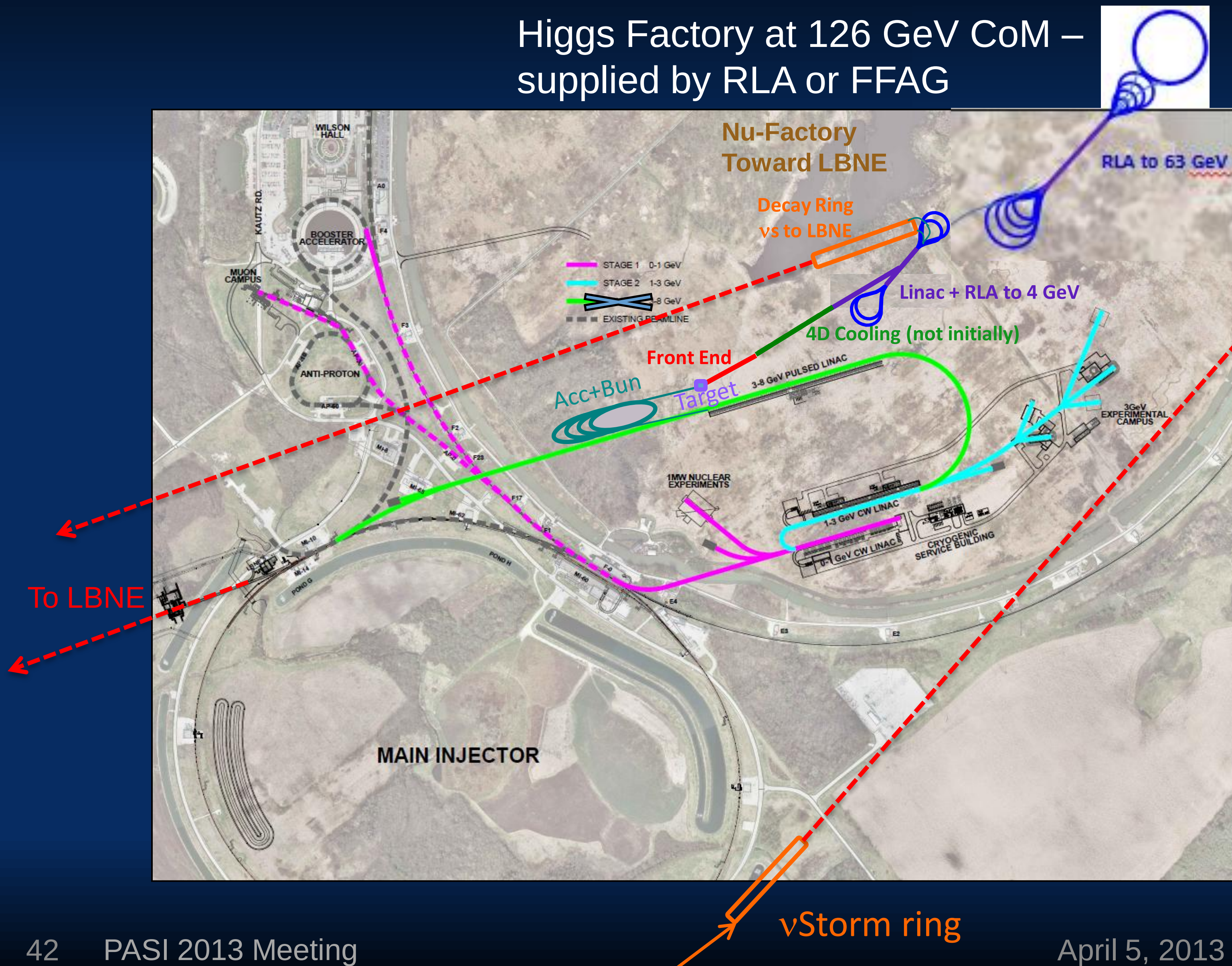
V. Lebedev: maximum power per bunch

Final Bunch Parameters (Compressor Ring)

Initial Ring Bunch Parameters (Accumulator Ring)

NF (L3NF→NF) ⇨ HF at Fermilab

Higgs Factory at 126 GeV CoM – supplied by RLA or FFAG



NOTE:
Option to combine early muon RLA PX final Linac being explored

Thank you