5/08/2011

Protons Drivers for ν Beams and other High Intensity Applications

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[using material from:
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- K. Gollwitzer, S. Nagaitsev (FNAL)
- J. Thomason (ISIS)
- M. Aiba, E. Benedetto, M. Benedikt, I. Efthymiopoulos, R. Steerenberg (CERN)]

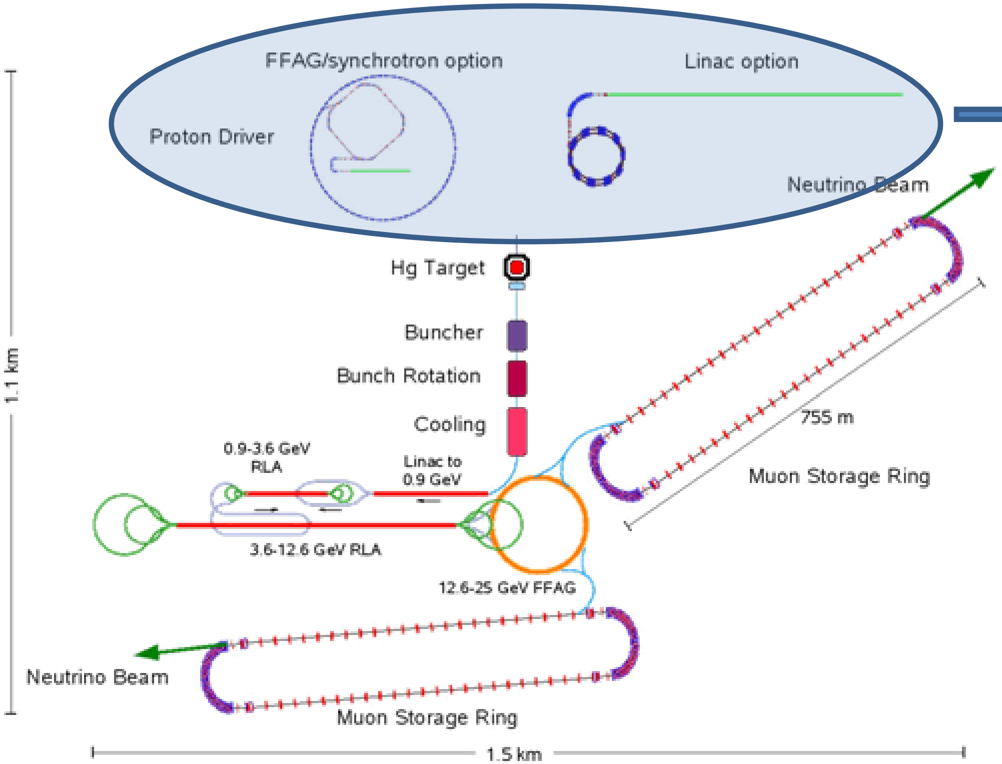
Introduction

- This talk will focus on the favoured proton drivers options for the generation of neutrino beams at FNAL, RAL, CERN and J-PARC.

- HPPAs for other applications at other places are not treated (e.g.: neutron spallation sources, ADS for waste treatment and/or nuclear power generation, medical isotope production etc…).

- «Green field» solutions are not covered.

- A proton driver:
  - is necessary for (almost) all types of neutrino facilities,
  - can be used (and present ones have been built) for other purposes.
- A Neutrino Factory is the most demanding application*, although the proton driver remains a modest part of the whole facility.
- Two types of set-ups are favoured:
  - Ring-based
  - SRF linac-based.



<u>* IDS NF specifications:</u>
- 4 MW proton beam power
- Proton kinetic energy 5 – 15 GeV
- RMS bunch length 1 – 3 ns
- 50 Hz repetition rate
- 3 bunches, extracted > 80 μs apart

Reference IDS NF Design

Status and plans at:

- ***FermiLab***
- RAL
- CERN
- J-PARC

FNAL plans (1/10)

Project X : Mission Goals

- A neutrino beam for long baseline neutrino oscillation experiments
  - 2 MW proton source at 60-120 GeV
- High intensity, low energy protons for kaon and muon based precision experiments
  - Operations simultaneous with the neutrino program
- A path toward a muon source for possible future Neutrino Factory and/or a Muon Collider
  - Requires ~4 MW at ~5-15 GeV .

- Possible missions beyond HEP
  - Standard Model Tests with nuclei and energy applications

FNAL plans (2/10)

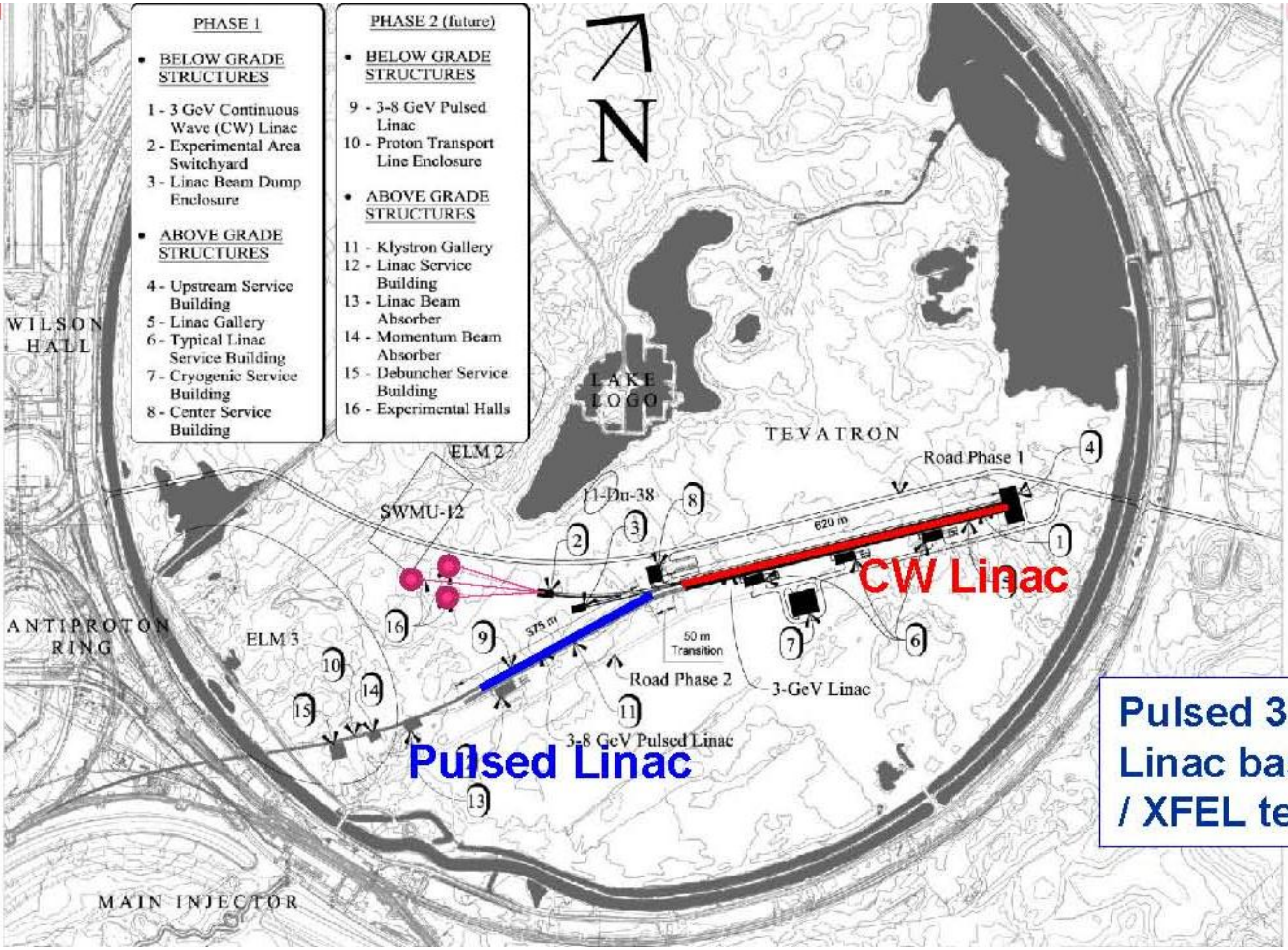
Project X : Reference Design Capabilities

- 3 GeV CW superconducting H- linac with 1 mA average beam current.
  - Flexible provision for variable beam structures to multiple users
    - CW at time scales >1 μsec, 15% DF at <1 μsec
  - Supports rare processes programs at 3 GeV
  - Provision for 1 GeV extraction for nuclear energy program
- 3-8 GeV pulsed linac capable of delivering 300 kW at 8 GeV
  - Supports the neutrino program
  - Establishes a path toward a muon based facility
- Upgrades to the Recycler and Main Injector to provide ≥ 2 MW to the neutrino production target at 60-120 GeV.
- Day one experiment to be incorporated utilizing the CW linac

⇒ Utilization of a CW linac creates a facility that is unique in the world, with performance that cannot be matched in a synchrotron-based facility.

FNAL plans (3/10)

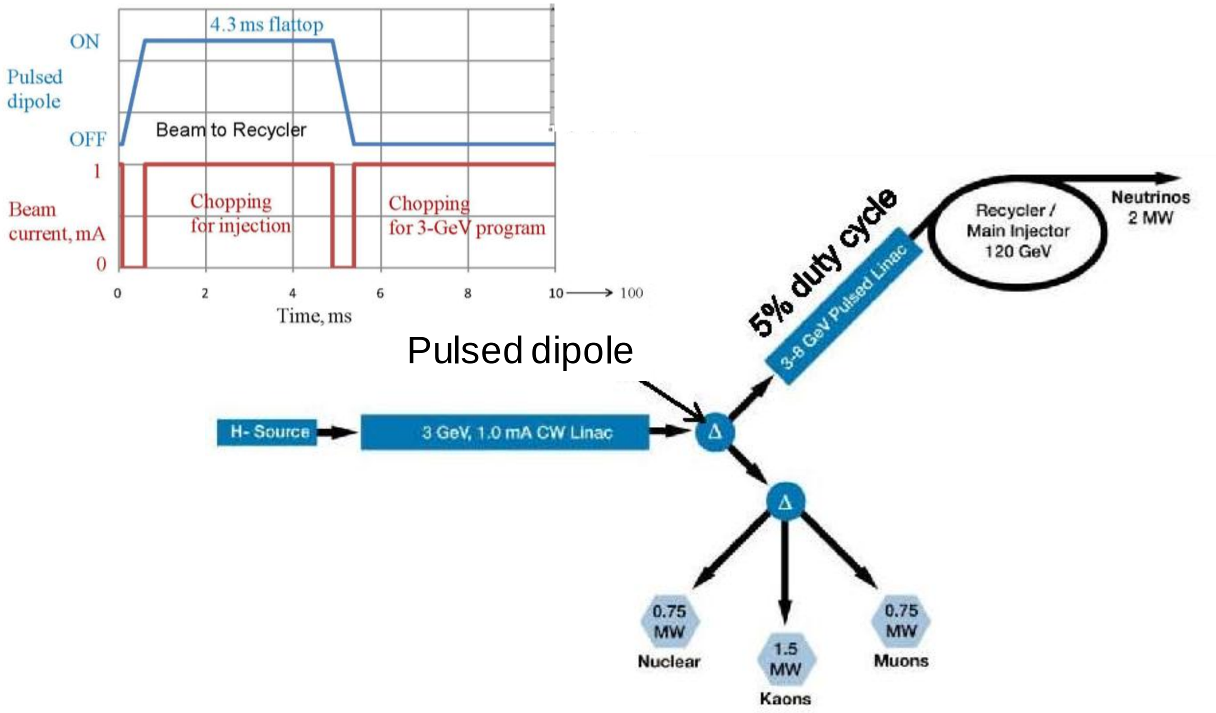
Project X : Provisional Siting



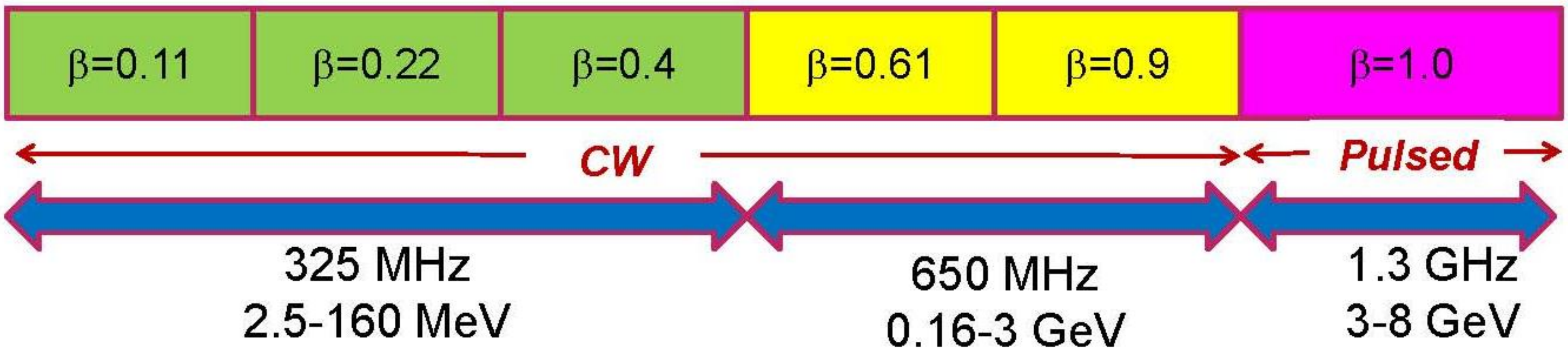
Pulsed 3-8 GeV Linac based on ILC / XFEL technology

Project X : Reference Design Accelerators

- Warm cw front end 162.5 MHz, 5 mA (H- ion source, RFQ, MEBT, chopper)
- 3-GeV cw SCRF linac (325, 650 MHz), 1-mA ave. beam current
- Transverse beam splitter for 3-GeV experiments
- 3-8 GeV: pulsed linac (5% duty cycle), 1.3 GHz
- Recycler and MI upgrades
- Various beam transport lines



Project X : Superconducting RF H^- Linacs

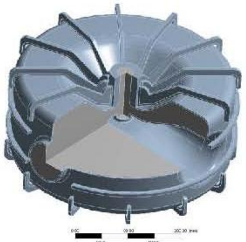


Section	Freq	Energy (MeV)	Cav/mag/CM	Type
SSR0 (β_G=0.11)	325	2.5-10	18 /18/1	SSR, solenoid
SSR1 (β_G=0.22)	325	10-42	20/20/ 2	SSR, solenoid
SSR2 (β_G=0.4)	325	42-160	40/20/4	SSR, solenoid
LB 650 (β_G=0.61)	650	160-460	36 /24/6	5-cell elliptical, doublet
HB 650 (β_G=0.9)	650	460-3000	160/40/20	5-cell elliptical, doublet
ILC 1.3 (β_G=1.0)	1300	3000-8000	224 /28 /28	9-cell elliptical, quad

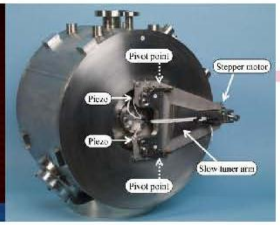
FNAL plans (6/10)

Project X : SRF cavities development

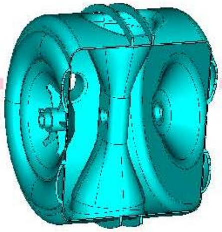
Spoke cavities



SSR0 – design, prototyping



SSR1 – prototyping, testing

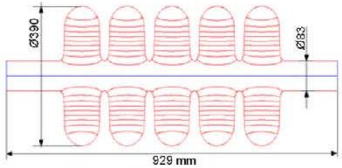


SSR2 - design

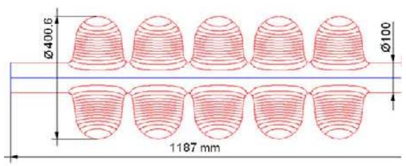
Parameters of the single-spoke cavities

cavity type	β_G	Freq MHz	$U_{acc, max}$ MeV	E_{max} MV/m	B_{max} mT	R/Q, Ω	G, Ω	$^*Q_{0,2K}$ $\times 10^9$	$P_{max,2K}$ W
SSR0	β=0.114	325	0.6	32	39	108	50	6.5	0.5
SSR1	β=0.215	325	1.47	28	43	242	84	11.0	0.8
SSR2	β=0.42	325	3.34	32	60	292	109	13.0	2.9

650 MHz cavities



650 MHz: β=0.61

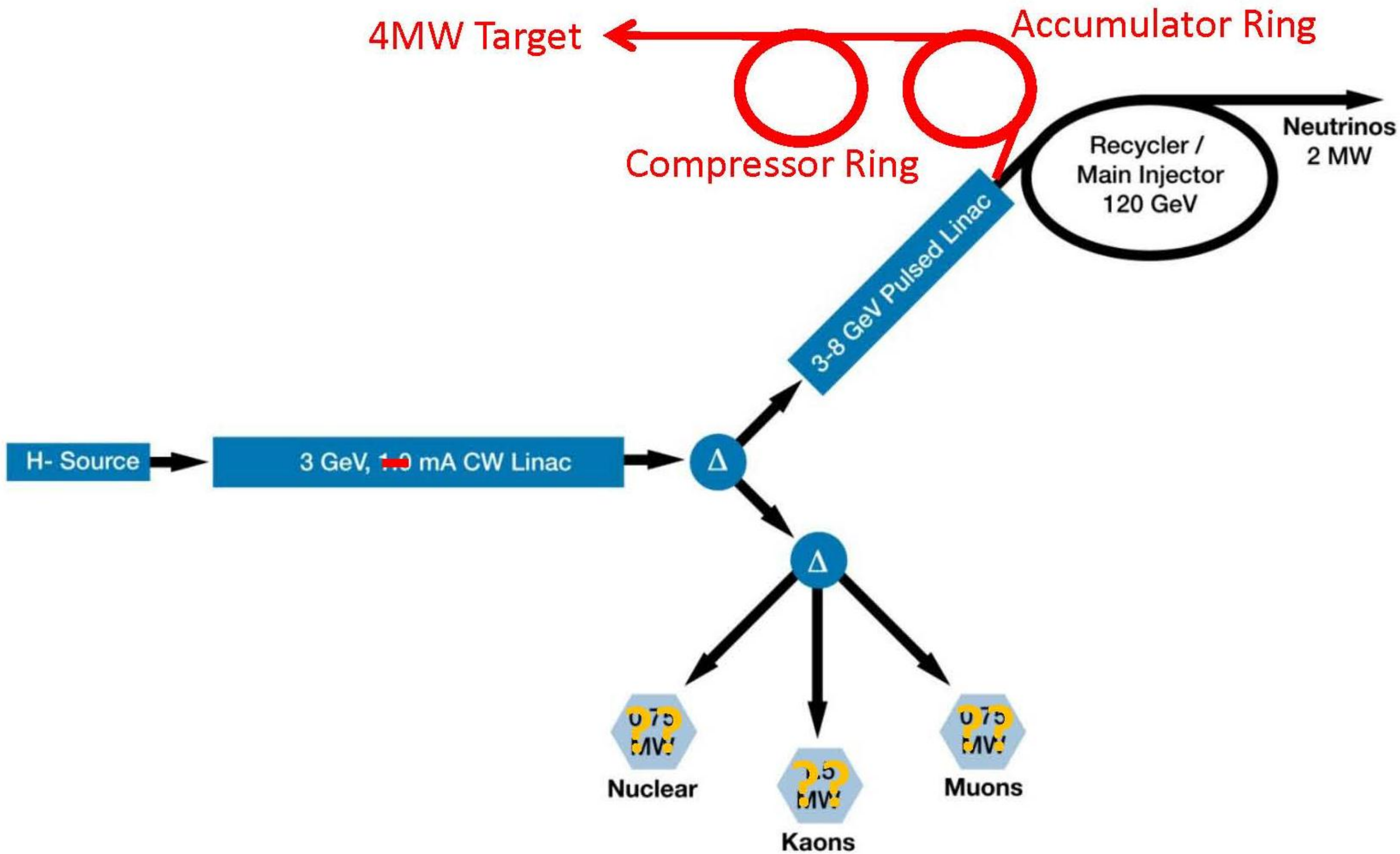


650 MHz: β=0.9

Parameter		LE650	HE650
β_geom		0.61	0.9
R/Q	Ohm	378	638
G-factor, Ohm		191	255
Max. Gain/cavity (on crest)	MeV	11.7	19.3
Acc. Gradient	MV/m	16.6	18.7
Max surf. electric field	MV/m	37.5	37.3
Max surf. magnetic field,	mT	70	70
Q_0 @ 2° K	$\times 10^{10}$	1.5	2.0
P_{2K} max	[W]	24	29

FNAL plans (7/10)

Project X upgrade (MC / NF): draft layout



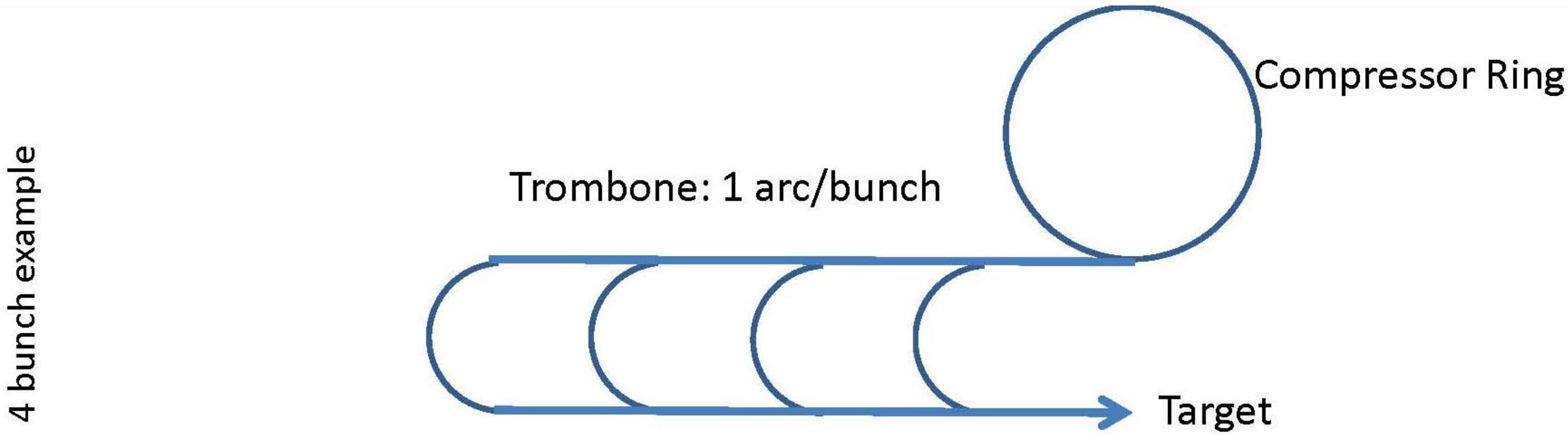
FNAL plans (8/10)

Project X upgrade (MC / NF): actions' list

- Upgrade Project X
  - 4 MW at 8 GeV
    - Increase particles per linac bunch
    - Increase pulse linac duty factor
- Repackage linac beam for 12-15 Hz delivery
  - Accumulator Ring
    - Collect linac beam into bunches
  - Compressor Ring
    - Narrow bunches to <= 3 ns
  - Delivery as a single bunch (trombone system)
    - Multiple bunches arrive at target at same time

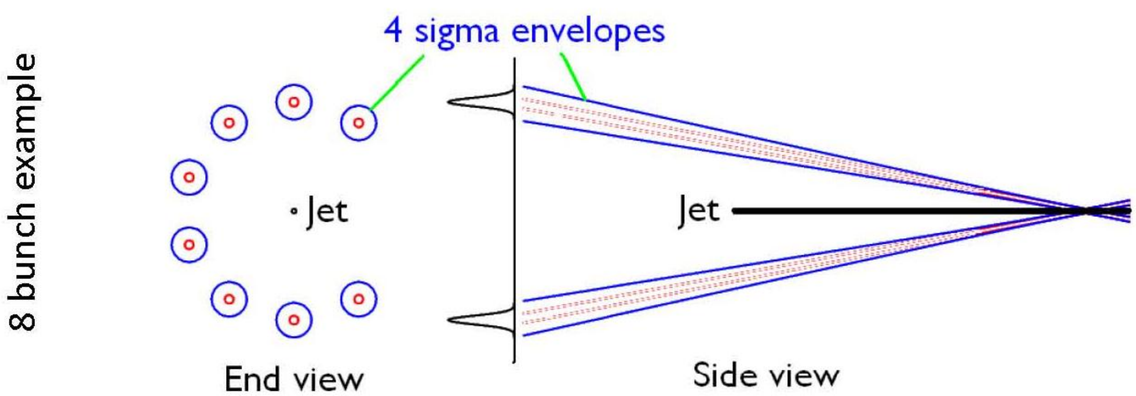
– Increase beam current during the 8 GeV pulse to 5 mA (10 mA_{peak});
– Increase rep. rate to 15 Hz;
– Increase beam pulse length to 6.7 ms (10% duty cycle).

Project X upgrade: Combining bunches on target



Muon Collider Proton Driver Trombone Schematic

(not to scale; bunches arrive simultaneously on target)



Each beam line provides different trajectory to target

FNAL plans (10/10)

Project X upgrade: Main subjects of concern (!)

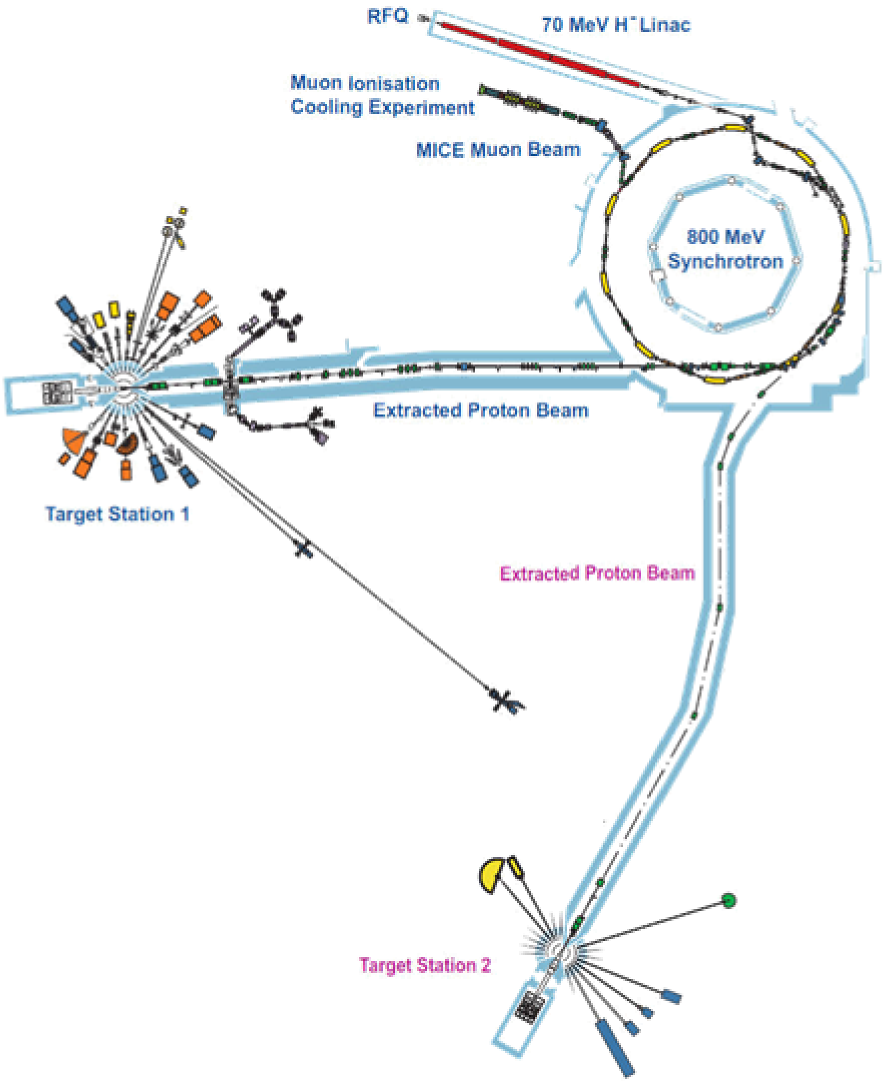
- Accumulator Ring
  - Striping
  - Instabilities
- Compressor Ring
  - Bunch Rotation
  - Dipole aperture and large momentum spread
- Delivery
  - Trombone
  - Beam sizes and angles at target

Status and plans at:

- FermiLab
- ***RAL***
- CERN
- J-PARC

ISIS plans (1/9)

Current (upgraded) ISIS (0.24 MW)



- Assumes an optimised 2RF system giving 300 µA in the synchrotron
- 4/5 pulse pairs to TS-1 (192 kW) and 1/5 pulse pairs to TS-2 (48 kW)
- Must keep beam to TS-2 for the foreseeable future

ISIS plans (2/9)

Science & Technology Facilities Council

ISIS MW upgrade scenarios

Further developments of the ISIS accelerator and target stations are possible with each stage giving of order a factor 2 enhancement of the neutron source characteristics

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

overlap with NF proton driver

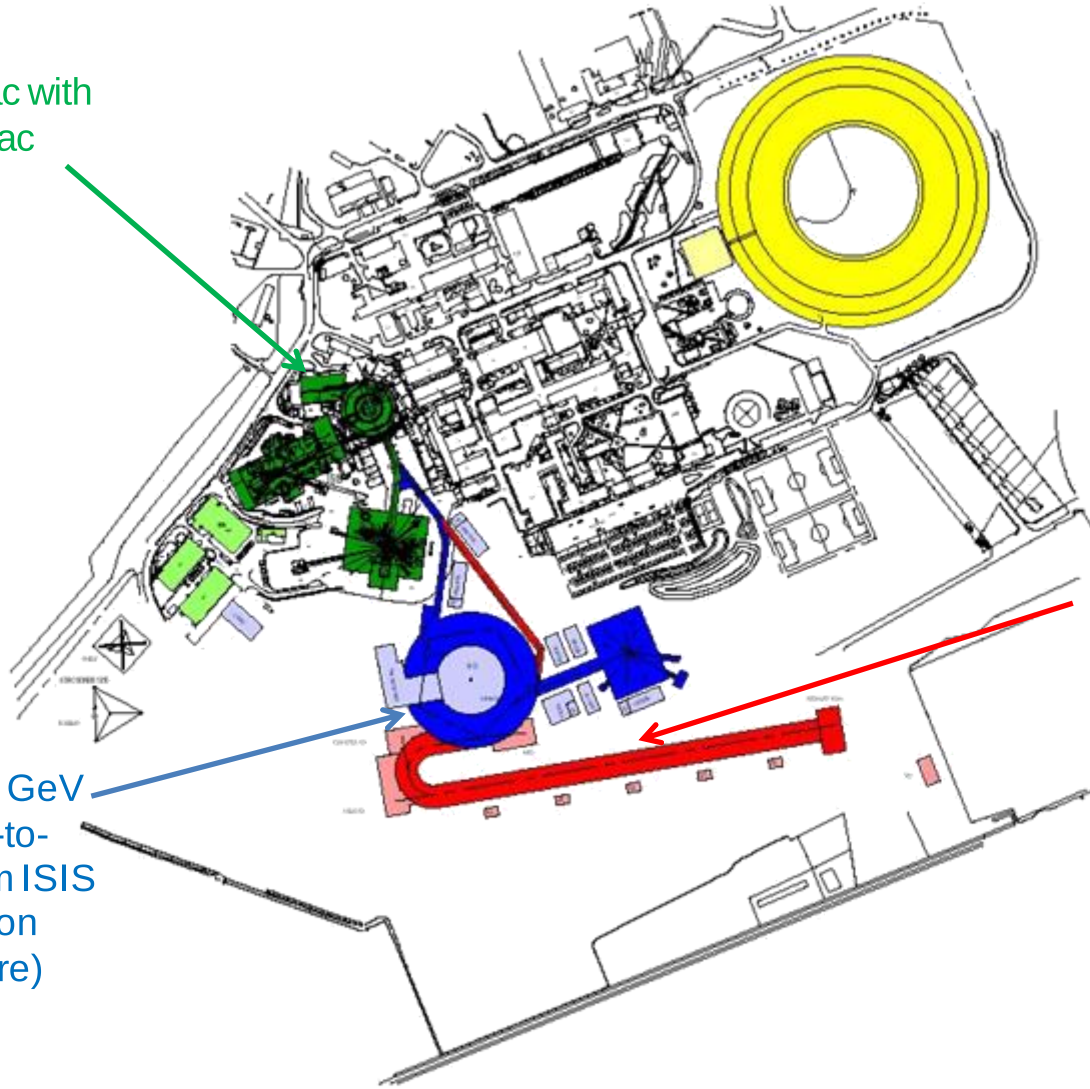
4) 800 MeV direct injections to booster synchrotron
   + long pulse mode option

ISIS plans (3/9)

Science & Technology Facilities Council

ISIS MW upgrade scenarios

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

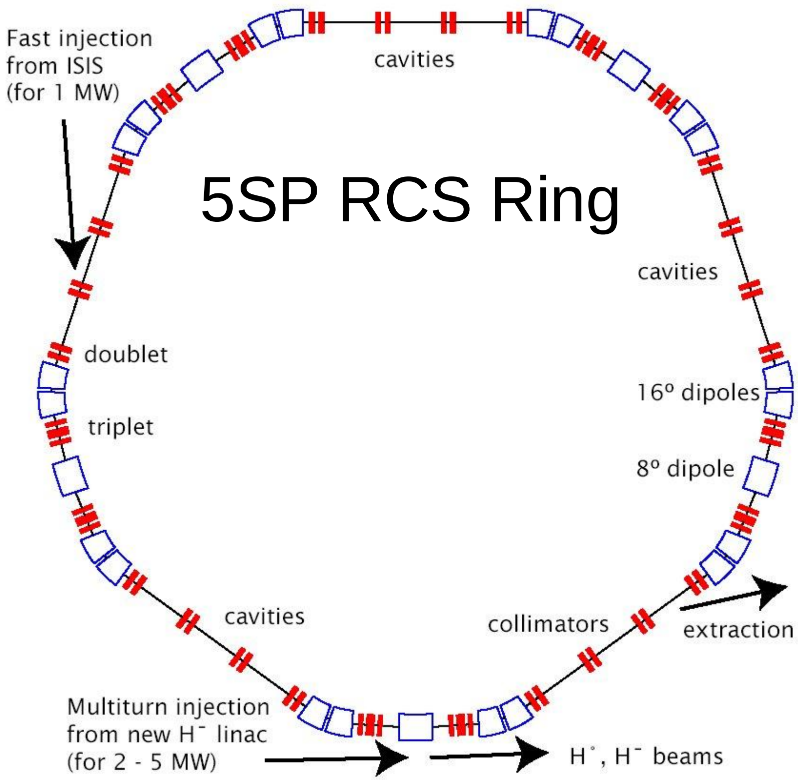


3) RCS design also accommodates multi-turn charge exchange injection to facilitate a further upgrade path where the RCS is fed directly from an 800 MeV linac (2 – 5 MW)

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

ISIS plans (4/9)

ISIS MW upgrade: «typical» 3.2 GeV RCS



Main RCS characteristics

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 plans (5/9)

Science & Technology Facilities Council

ISIS MW upgrade: 800 MeV linac

Main characteristics

Beam power for 2 MW, 30 Hz, 3.2 GeV RCS	0.5 MW
Beam pulse current before MEBT chopping	43.0 mA
Beam pulse current after MEBT chopping	30.0 mA
Number of injected turns for 370 m RCS	~500 turns
Beam pulse duration at the 30 Hz rep rate	~730.0 μs
Duty cycle for the extent of the beam pulse	~2.2 %
MEBT(out) normalised rms emittances	0.30, 0.42 (π) mm mr

Draft architecture

*74.8 MeV stage 1 (common to all options)

RFQ – MEBT – DTL – IEBT – **74.8 MeV**

Options*	F (MHz)	Stage 2	Stage 3	Stage 4
1	648	ScL 1	ScL 2	ScL 3
2	648	CCL	ScL 2	ScL 3
3	(324) 972	(ScL a)	ScL b	ScL c

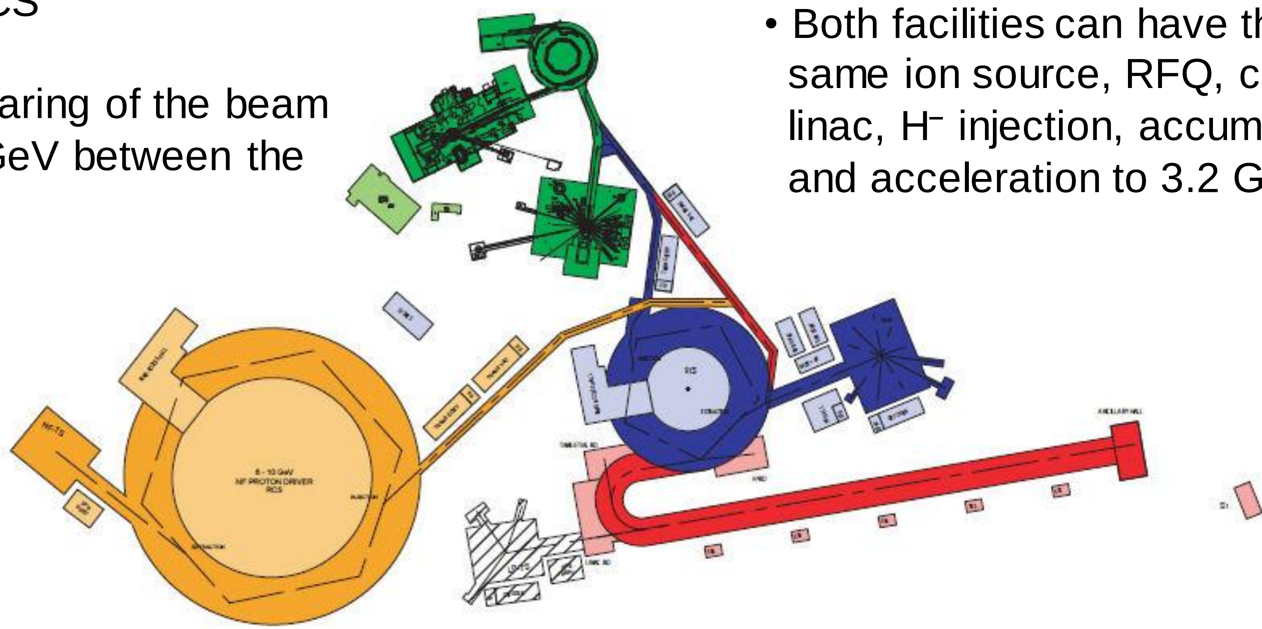
~200 MeV **800 MeV**

CERN

ISIS plans (6/9)

ISIS Common Proton Driver for neutrons and NF

- 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



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

- Requires additional RCS machine in order to meet the power and energy needs of the Neutrino Factory

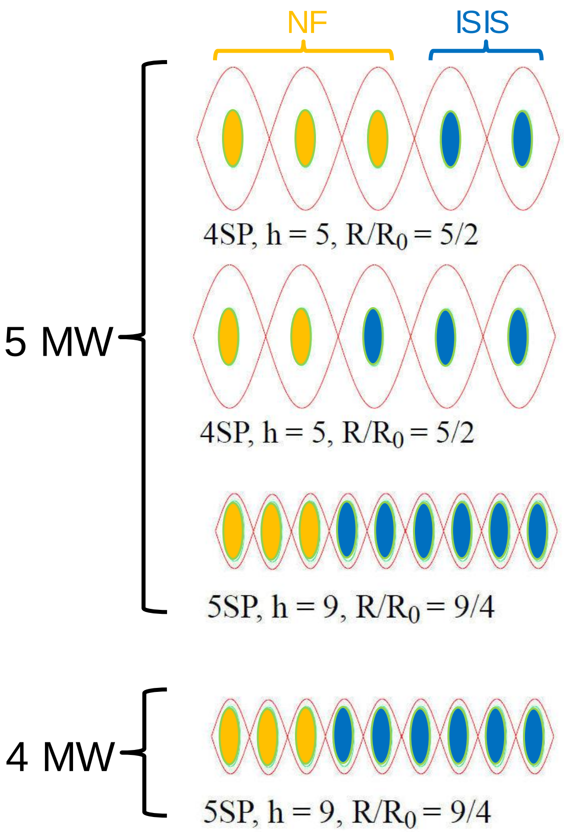
ISIS plans (7/9)

Science & Technology Facilities Council

ISIS Common Proton Driver: RCS beam sharing

- 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

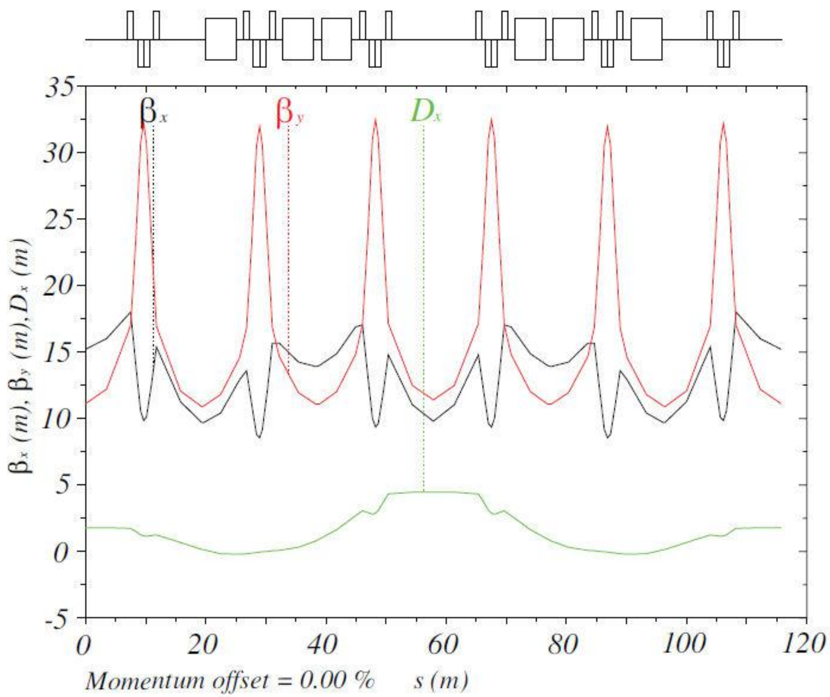
3 bunches, 2.2×10^{13} protons/bunch, 7.7 GeV
3⅓ MW to ISIS

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

ISIS plans (8/9)

Science & Technology Facilities Council

ISIS Common Proton Driver: 2nd RCS design



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
Betatron tunes (Q_H, Q_V)	(8.72, 7.82)
Gamma transition	13.37 (flexible)
Beam power at 9.6 GeV	4 MW for 3 bunches
Injection energy	3.2 GeV
Extraction energy	9.6 GeV
RF voltage per turn	≈ 3.7 MW
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

ISIS plans (9/9)

Science & Technology Facilities Council

ISIS MW Proton Driver: Necessary 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

Status and plans at:

- FermiLab
- RAL
- ***CERN***
- J-PARC

CERN plans (1/11)

Current PS-based Proton Driver

[from EDMS Document No.**1108369 rev 1.1**]

Draft layout

Short baseline experiment

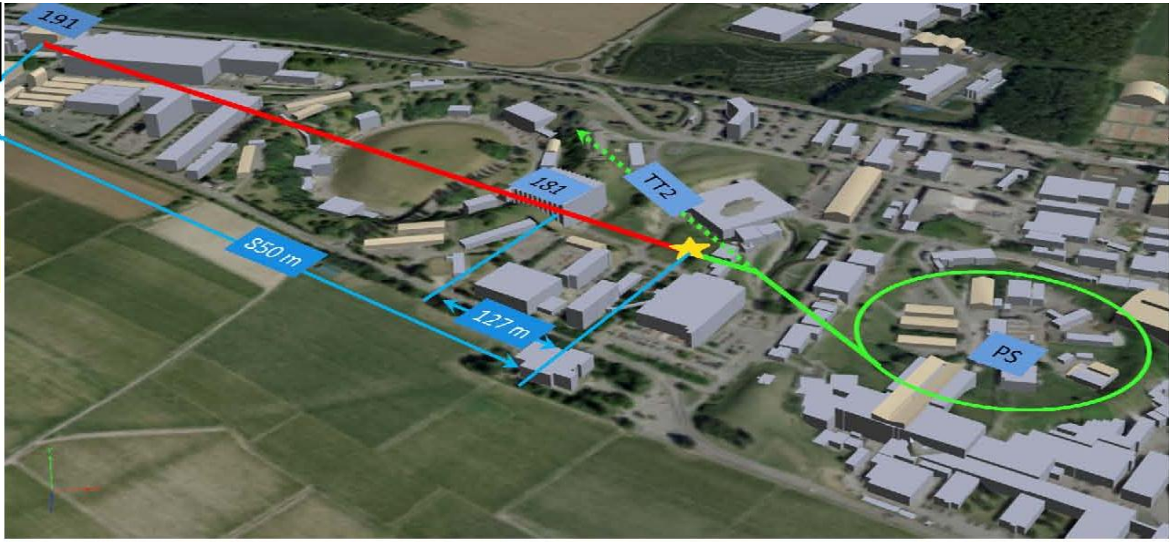


Figure 1.3: The foreseen neutrino beam path (red) on the Meyrin site. The green lines represent the primary protons beam in the PS, TT2, TT1 and TT7.

Proton beam characteristics

	Old neutrino facility		New neutrino facility		
	PS dedicated Feb-Mar 1983	PS parallel 1983 - 1984	PS dedicated	PS parasitic	PS ultimate[3]
Proton Momentum	19.2 GeV/c	19.2 GeV/c	20 GeV/c	20 GeV/c	26 GeV/c
Protons/pulse	1.25×10^{13}	1.2×10^{13}	3×10^{13}	2.6×10^{13}	4×10^{13}
Max. rep. rate	1.2 s	14.4 s	1.2 s	1.2 s	1.2
Beam energy	38 kJ	38 kJ	96 kJ	84 kJ	166 kJ
Average beam power	**32 kW**	**2.5 kW**	**80 kW**	**70 kW**	**140 kW**

?

CERN plans (2/11)

SPS-based Proton Driver

e.g. LAGUNA-LBNO DS (EU-FP7)

CERN-AB-2007-013 PAF

POT/year [10^{19}] for 200 days of operation with 80% machine efficiency

	SPS cycle length	6 s	
	Injection Energy	14 GeV	
	Beam sharing / Max SPS intensity @ 400GeV [$x10^{13}$]	0.45	0.85
Present injectors + machines' improvement	4.8	5	9.4
	5.7	5.9	11.1

1.3 x nominal CNGS performance

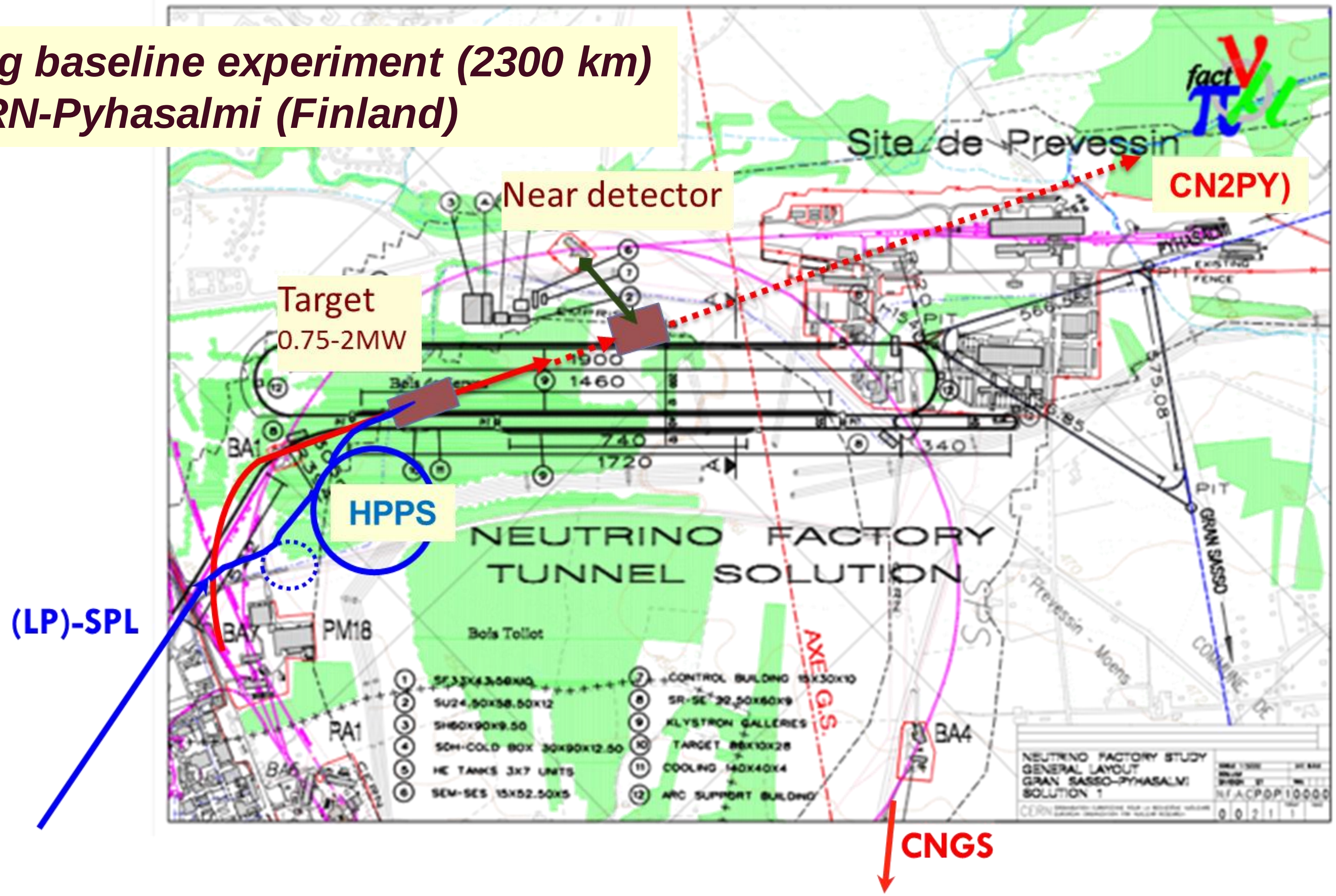
Long baseline experiment (2300 km) CERN-Pyhasalmi (Finland)

CERN plans (3/11)

New High Power PS-based Proton Driver

- New High Power PS (30-50 GeV, 2MW beam power) using the Low Power SPL (LP-SPL) as injector.
- Future Feasibility Study based on the work for LP-SPL and PS2 to be supported within the LAGUNA-LBNO DS (EU-FP7)

Long baseline experiment (2300 km)
CERN-Pyhasalmi (Finland)



CERN plans (4/11)

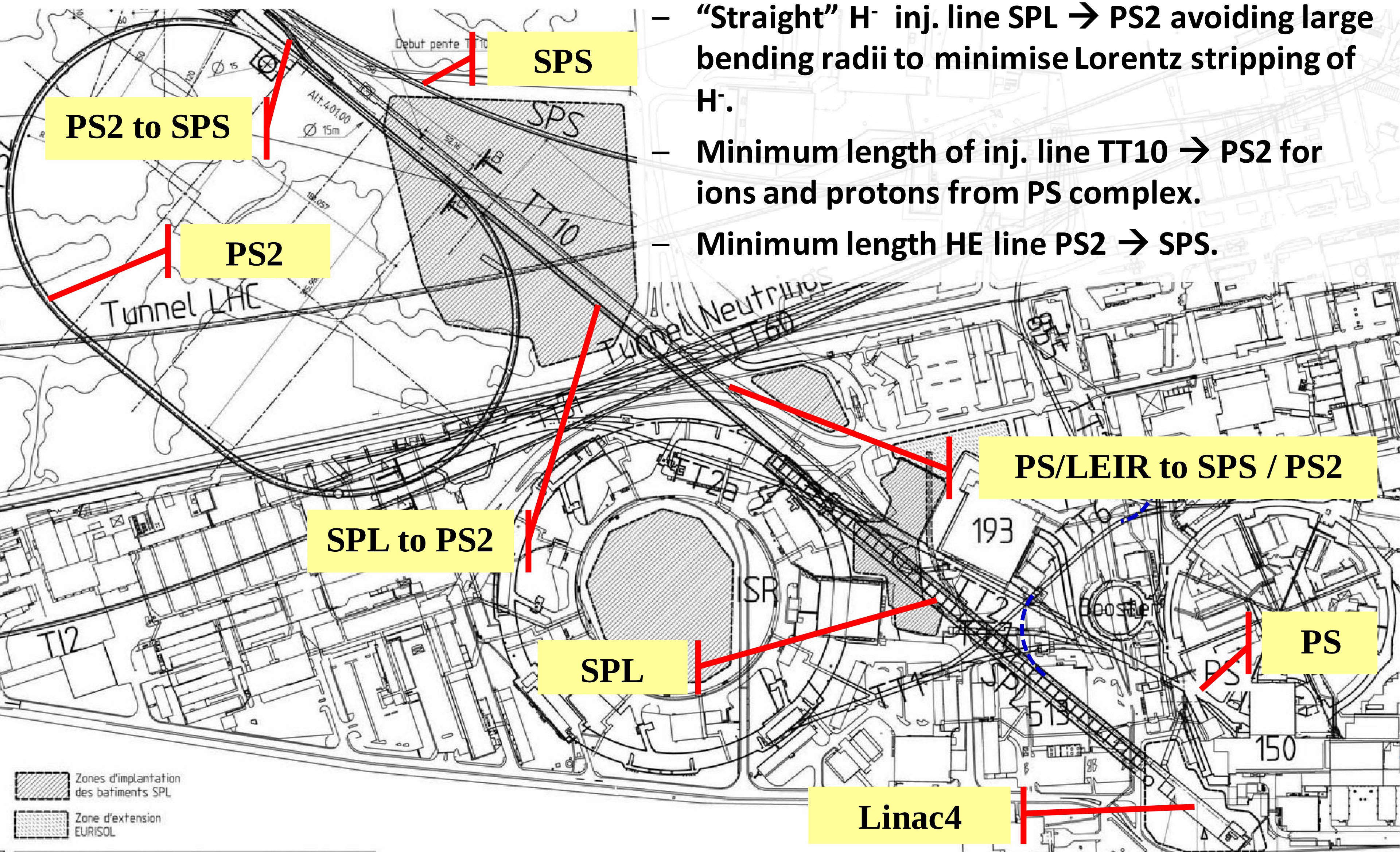
Reminder: PS2 main parameters…

Parameter	unit	PS2	PS
Injection energy kinetic	GeV	4.0	1.4
Extraction energy kinetic	GeV	20 - 50	13 - 25
Circumference	m	1346	628
Max. bunch intensity LHC (25ns)	ppb	4.0×10^{11}	1.7×10^{11}
Max. pulse intensity LHC (25ns)	ppp	6.7×10^{13}	1.2×10^{13}
Max. pulse intensity FT	ppp	1.0×10^{14}	3.3×10^{13}
Linear ramp rate	T/s	1.5	2.2
Repetition time (50 GeV)	s	~ 2.5	1.2/2.4
Max. stored energy	kJ	800	70
Max. effective beam power	kW	320	60

CERN plans (5/11)

Reminder: PS2 integration…

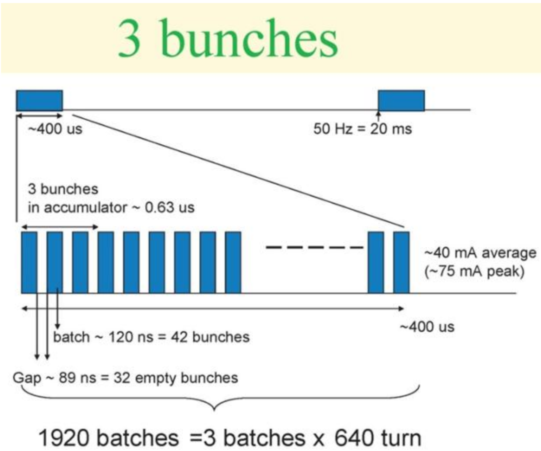
- "Straight" H^- inj. line SPL → PS2 avoiding large bending radii to minimise Lorentz stripping of H^-.
- Minimum length of inj. line TT10 → PS2 for ions and protons from PS complex.
- Minimum length HE line PS2 → SPS.



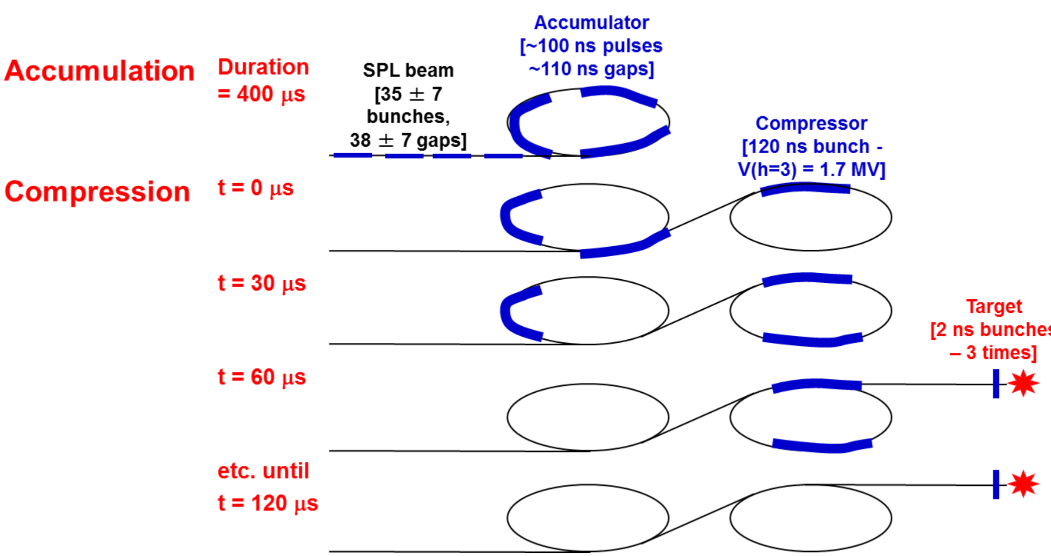
CERN plans (6/11)

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



CERN plans (7/11)

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 (H⁻)

Required for muon production (5 GeV)

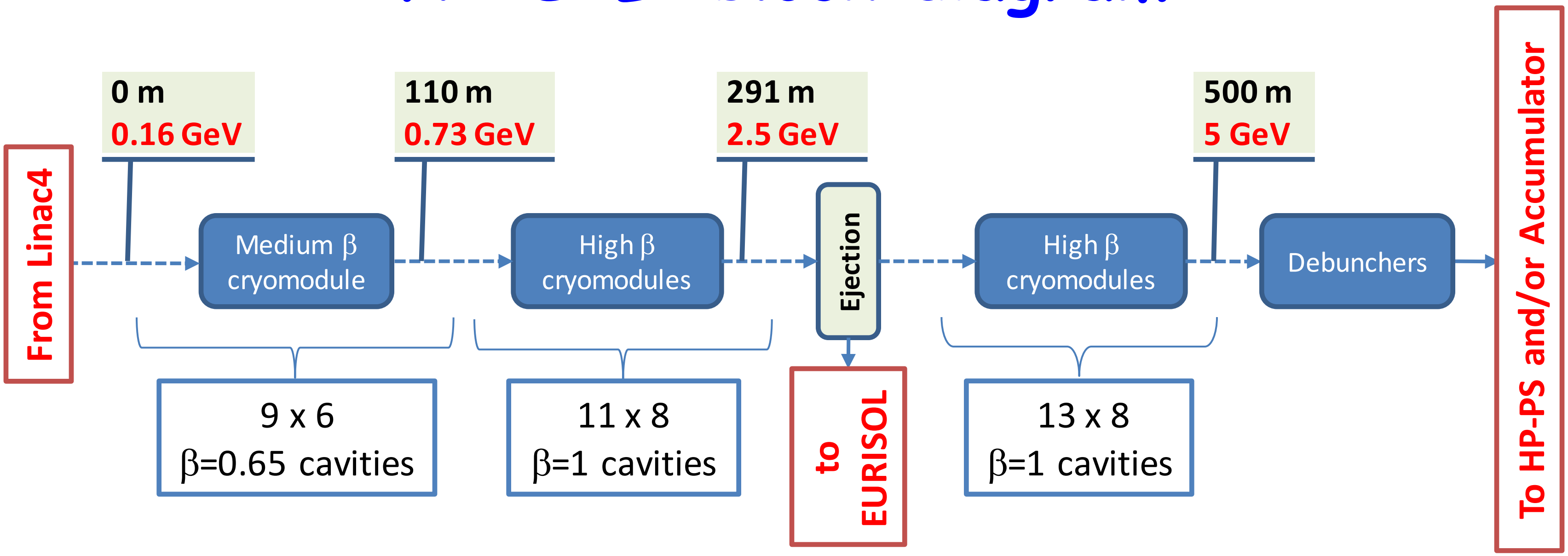
Required for flexibility and low loss in accumulator (< 2 ns chopper)

	Option 1	Option 2
Energy (GeV)	2.5 or 5	2.5 and 5
Beam power (MW)	2.25 MW (2.5 GeV) <u>or</u> 4.5 MW (5 GeV)	5 MW (2.5 GeV) <u>and</u> 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)

$2 \times$ beam current $\Rightarrow 2 \times$ nb. of klystrons etc .

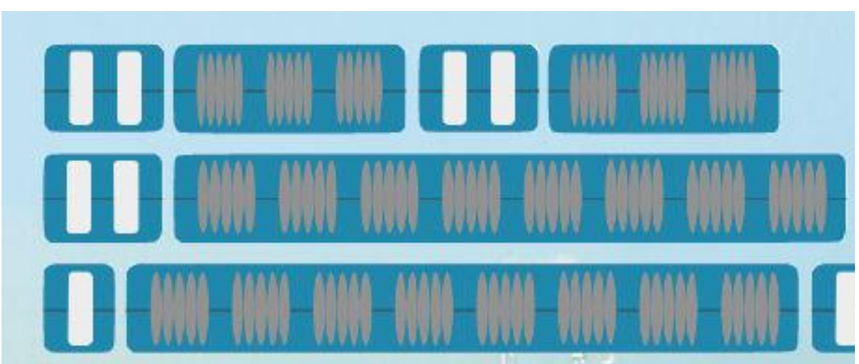
CERN plans (8/11)

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

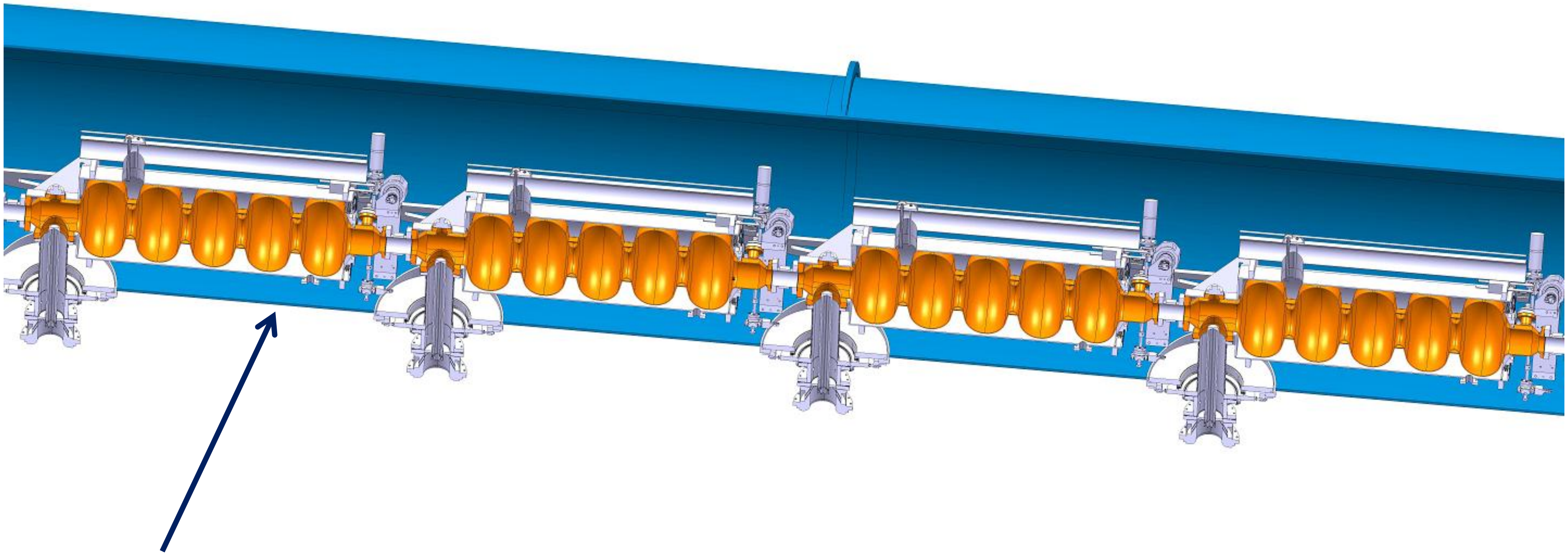
Intermediate energy

High energy

CERN plans (9/11)

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 before the end of 2014 tested in 2014.

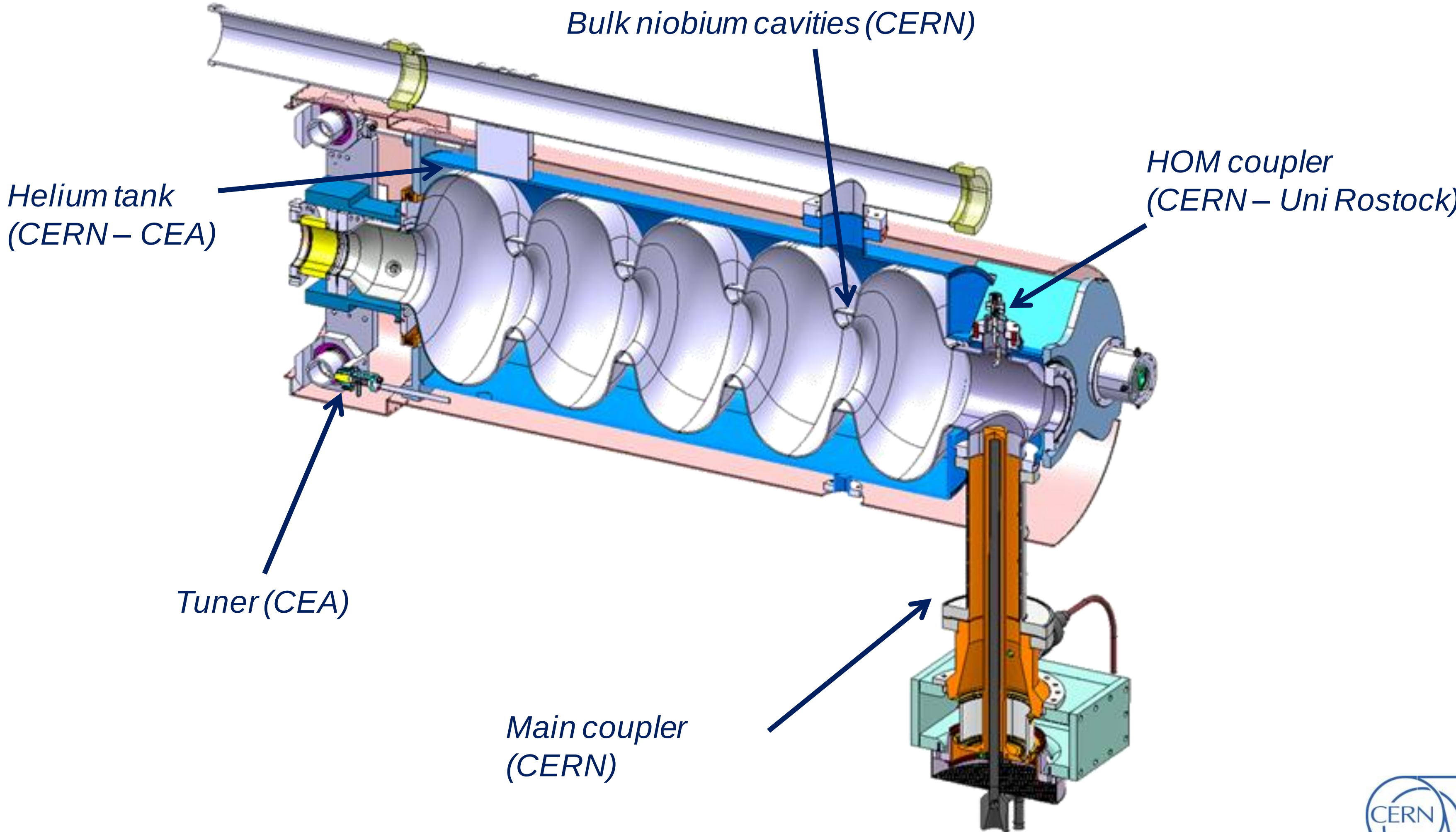


Cryomodule (CERN – CNRS)

CERN plans (10/11)

HP-SPL: Cavity § cryomodule design

SPL β = 1 cavity + helium tank + tuner + main coupler



CERN plans (11/11)

Summary of supporting activities

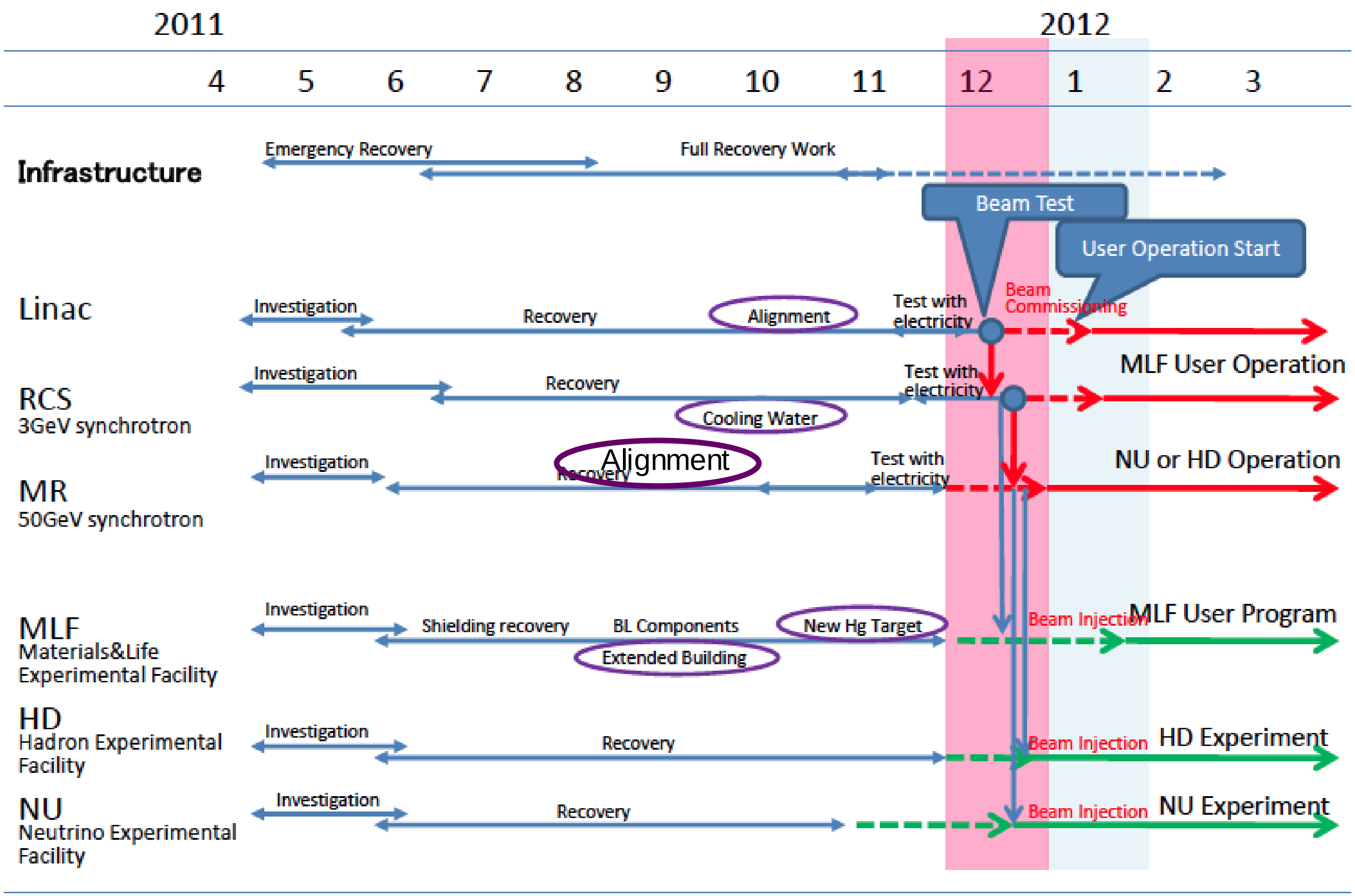
- **Current PS-based Proton Driver:**
  - Needs extensive investigation of impact on infrastructure (~on-going)
  - Requires more resources if current PS beam performance is insufficient (closely linked to the LHC Injectors Upgrade Project)
- **SPS-based Proton Driver:**
  - Study of beam ejection/Xfer line/target/decay tunnel foreseen within LAGUNA-LBNO DS
  - LAGUNA-LBNO DS expected to support investigation of SPS potential for higher intensity/flux (closely linked to the LHC Injectors Upgrade Project)
- **New High Power PS (with LP-SPL as injector):**
  - Conceptual Design Study foreseen within LAGUNA-LBNO DS
- **SPL-based Proton Drivers (LP-SPL as well as HP-SPL):**
  - Approved R § D on main SRF components, in collaboration with ESS and a number of EU laboratories/institutions, with some support from Brussels
  - Study of ring(s) foreseen within LAGUNA-LBNO DS

Status and plans at:

- FermiLab
- RAL
- CERN
- ***J-PARC***

J-PARC plans (1/4)

Earthquake recovery schedule



- Start of beam commissioning: December 2011.
- User program: 50 days of beam time until the end of March 2012.

J-PARC plans (2/4)

Power Upgrade for MR fast extracted beam

Achieved before the earthquake:
145 kW beam delivery to the T2K experiment
-> Recovery of the 145 kW beam is the first target of the FX operation

For higher beam power :

1. Increase beam loss capacity in ring collimator and reduction of activation
   - Additional shielding in ring collimators

2. Increase injected number of particles per pulse
   - Second harmonic cavity for manipulation of longitudinal bunch form to reduce the effect of space charge force
   - Lower emittance beam of the RCS by adopting 400 MeV injection

3. Increase repetition rate
   - Improvement/replacement of main magnet power supplies and rf system
     → R&Ds of high rep. time magnet power supply and high field gradient cavity are well in progress .

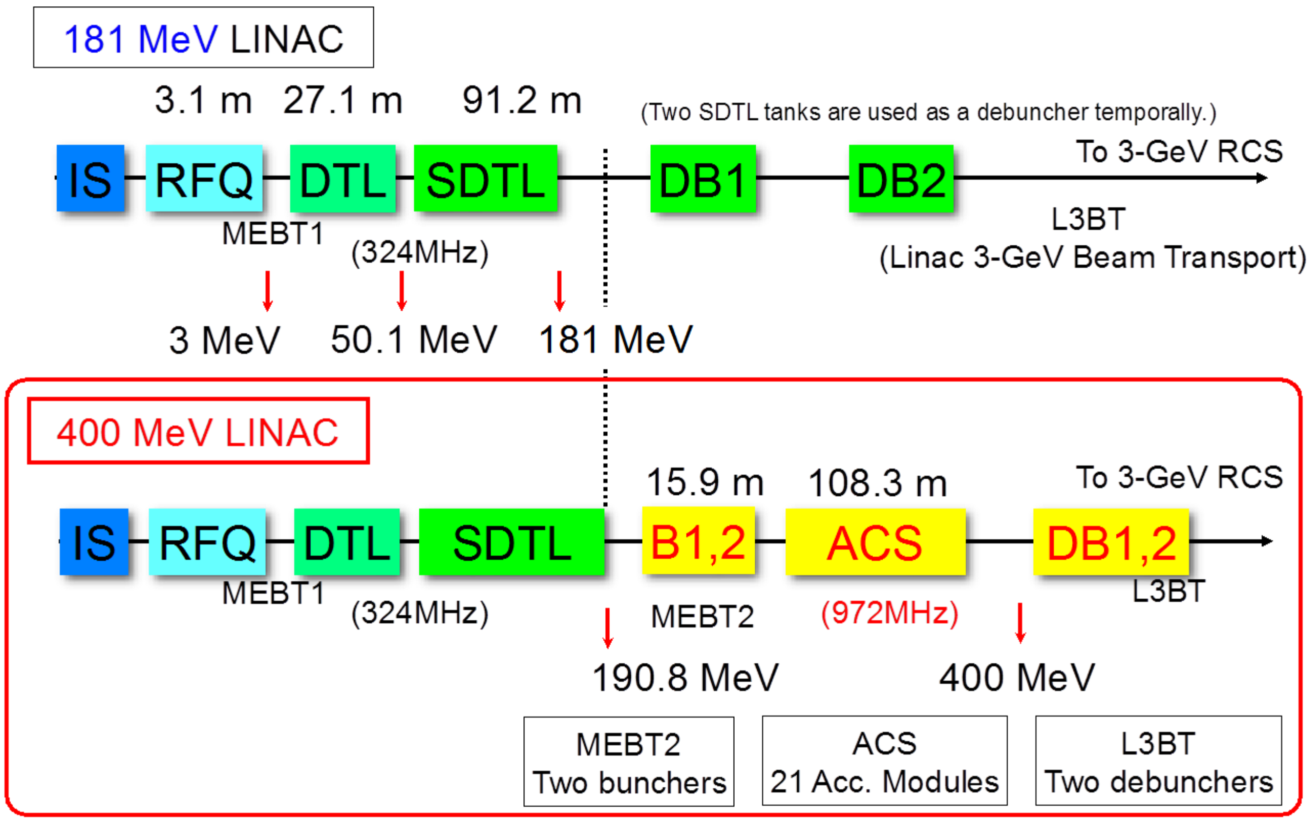
J-PARC plans (3/4)

Linac Energy Upgrade

The full energy (400 MeV) linac is necessary for the J-PARC facility to reach nominal performance (Beam power: 1MW@RCS, 0.75MW@MR)

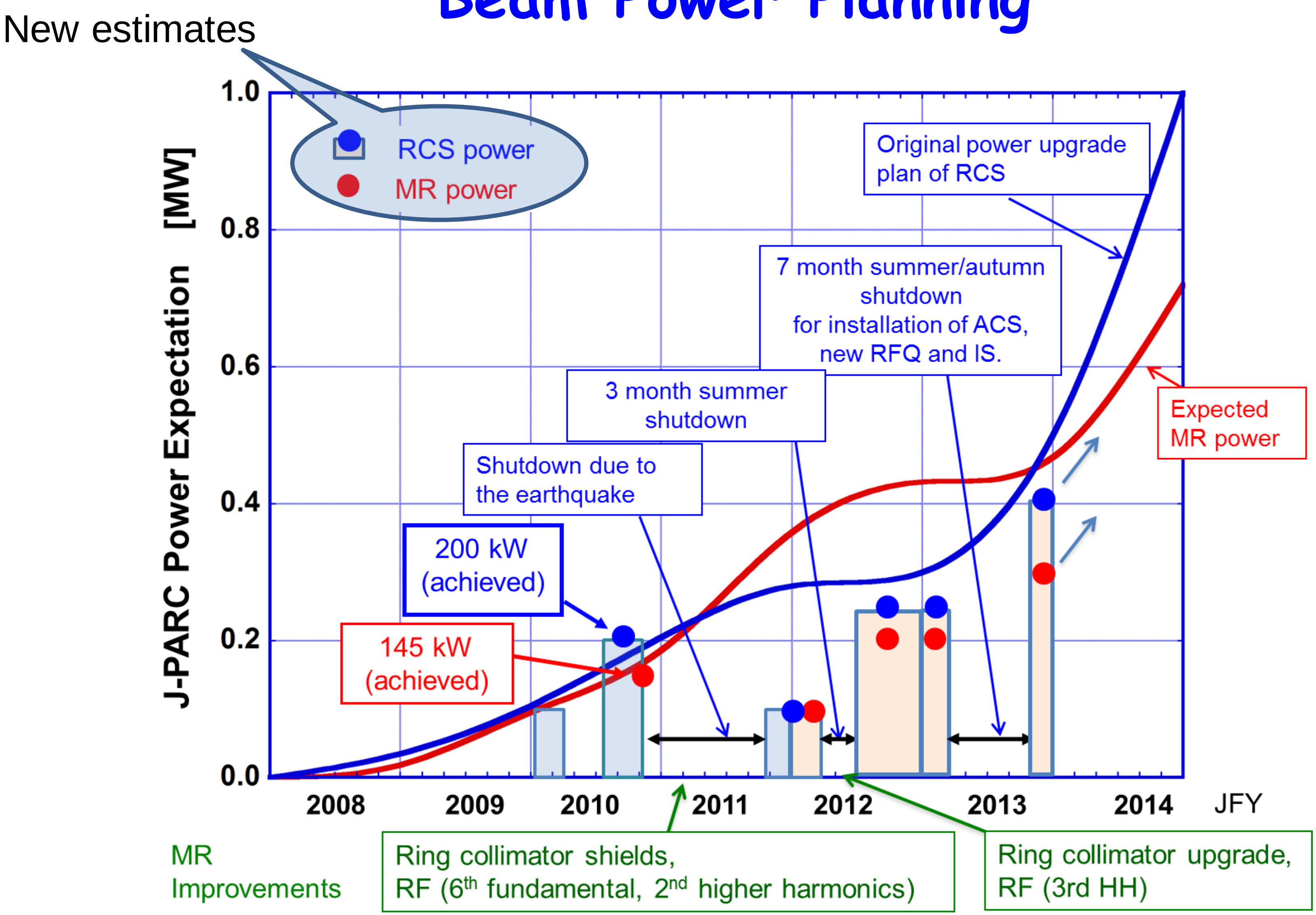
Funding for construction of 181 to 400MeV part of the linac started with supplementary budget of JFY2008.

Installation is scheduled during the Summer 2013.



J-PARC plans (4/4)

Beam Power Planning



Summary

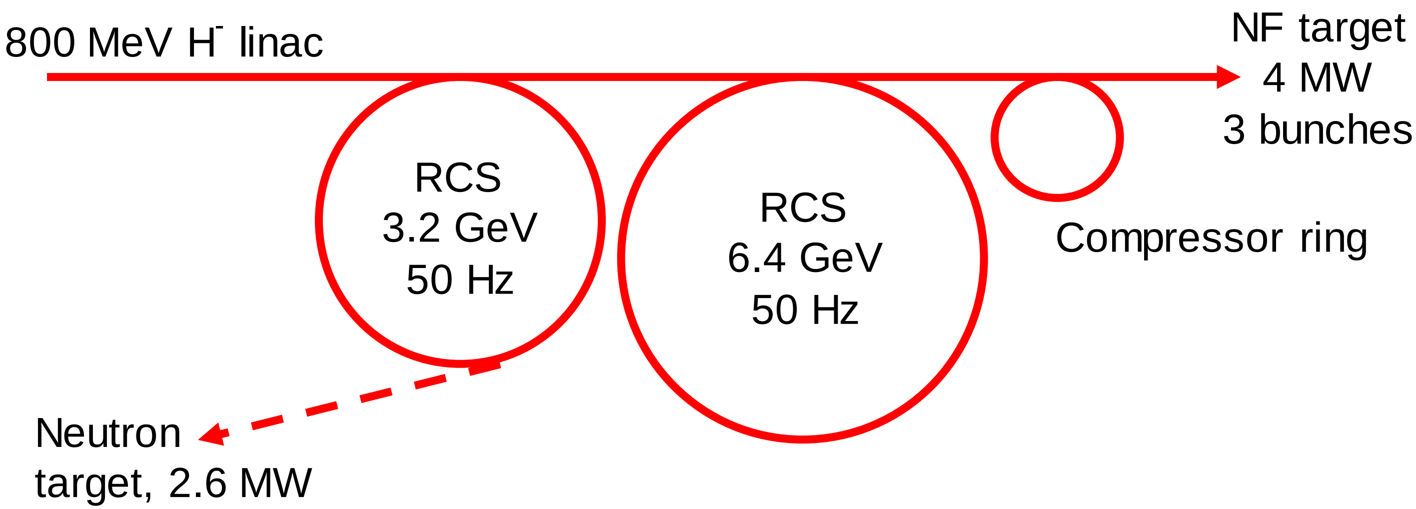
- Many challenges remain for multi-GeV MW-class proton drivers, and even more when adding the requirements of NF and MC.
- For the time-being, neutrino facilities only «piggy-back» on existing or planned projects.
- Projects are at very different degrees of advancement:
  - J-PARC is recovering and getting back with an ambitious power upgrade plan,
  - Project X is at an advanced stage of proposal with extensive R § D,
  - Other projects are at the R§D stage/remote from approval (e.g. LAGUNA, ISIS MW upgrade),
  - 1 MW for conventional neutrino beam should be operational before 2020.
- Collaboration is worth enhancing, including apparented HPPA projects:
  - Many technologies are common (H^- ion source, RFQ, High Power RF, SRF, targets,…),
  - Resources are scarce!

THANK YOU
FOR YOUR ATTENTION!

Spares

Science & Technology Facilities Council

ISIS Common Proton Driver: Alternative option



- Fast phase rotation in the dedicated compressor ring (most economic from the RF point of view, but another ring is needed)
- Bunches will be extracted one by one from the RCS
- Compressor ring works above transition, but the rotation is very fast
- The bunches in the RCS will wait uncompressed for 200 µs
- We do not have a design for the compressor ring at the moment, but CERN design can be adopted

CERN plans

Reminder: PS2 for high beam intensities in SPS…

- PS2 provides up to twice line density of PS high-intensity beam
- Twice circumference gives up to~4 times more intensity in total
  - ~1.0E14 per PS2 cycle (~1E14 with a longer kicker gap)
- Five-turn extraction will fill SPS with single shot instead of two from PS
  - Twice more intensity in SPS via twice higher line density.
  - No injection flat bottom in the SPS (two shot filling from PS presently)
- Clean bunch to bucket transfer PS2 40 MHz to SPS 200 MHz (cf. LHC)
  - ~6E11 protons per PS2 40 MHz bucket → 1.2E11 in every fifths SPS 200 MHz bucket (extraction kicker gap by leaving buckets unfilled at PS2 injection)