Relativistic Protons and their Applications

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Outline

- Relativistic Electrons vs. Protons
- Example of a 1 GeV Proton RF Accelerator
- Applications
  - Proton Colliders (Tevatron, LHC)
  - Neutron sources (SNS, ESS, *IFMIF*)
  - Neutrino sources (Project X, SPL)
  - Radioactive Ion Beams (FRIB, EURISOL)
  - Accelerator Driven Systems (Ch-ADS, MYRRHA)
- Conclusions

Relativistic Electrons vs. Protons

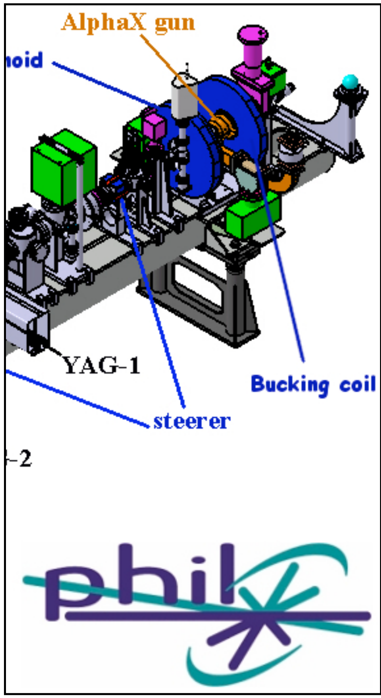
- Electron Mass = 511 keV/c^2
- Proton Mass = 938 MeV/c^2

Standard accelerator technology can produce electrostatic gaps of 100 kV to 500 kV :

$\beta_{e\text{-}(100\ \mathrm{keV})} = 0.548$, $\beta_{e\text{-}(500\ \mathrm{keV})} = 0.863$

By comparison : $\beta_{P(100\ \mathrm{keV})} = 0.0146$

Standard RF Guns can produce 3 to 10 MV accelerating gap $\rightarrow$ $\beta_{e\text{-}(3\ \mathrm{MeV})} = 0.9894$

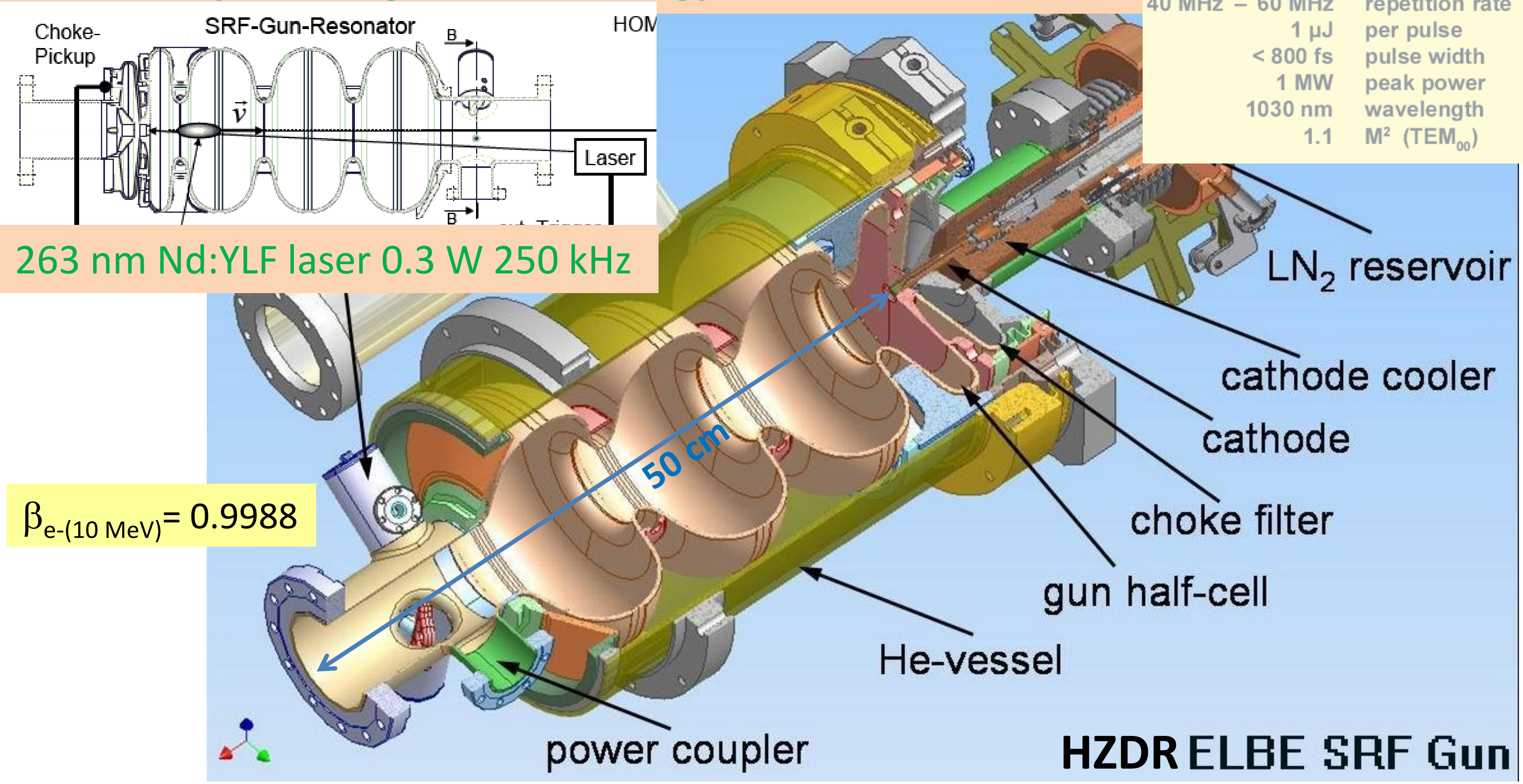


Laser Superconducting RF Gun: 10 MV

- **Laser and Photocathode are driving the bunch charge and emittance.**
- **RF cavity is driving the beam energy**

Laser parameters (BNL)

50 W	output power
40 MHz – 60 MHz	repetition rate
1 µJ	per pulse
< 800 fs	pulse width
1 MW	peak power
1030 nm	wavelength
1.1	M^2 (TEM_{00})

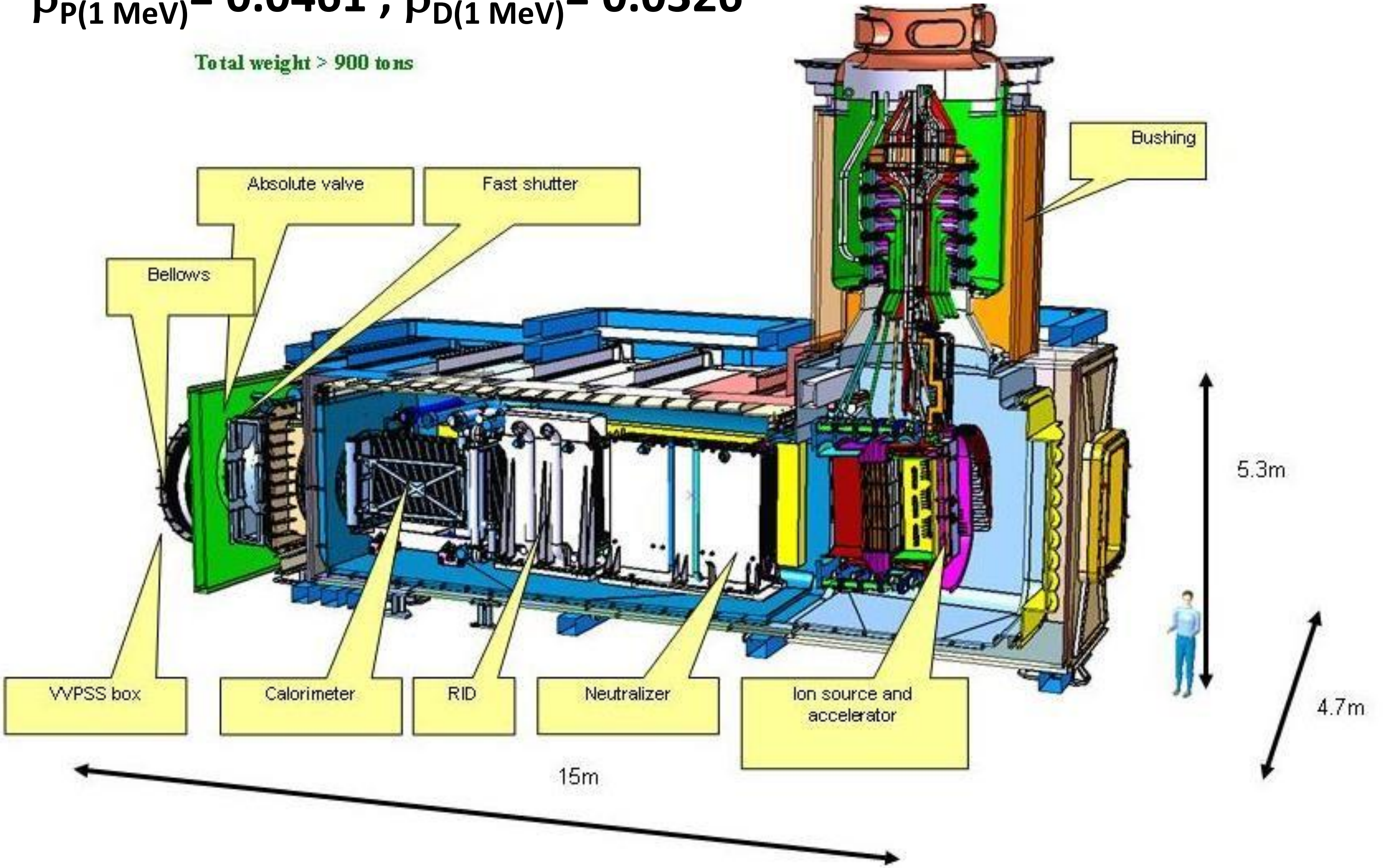


263 nm Nd:YLF laser 0.3 W 250 kHz

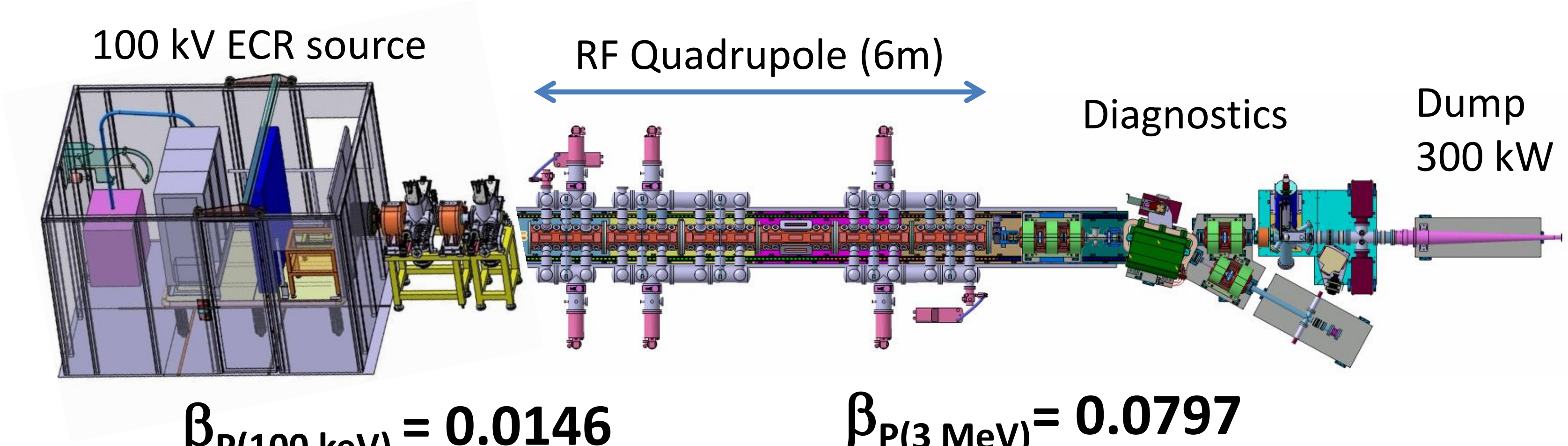
$\beta_{e-(10\ MeV)} = 0.9988$

ITER Neutral Deuteron Injection: 1 MV

$\beta_{P(1\,\mathrm{MeV})} = 0.0461$; $\beta_{D(1\,\mathrm{MeV})} = 0.0326$



A 3 MeV Proton Injector : IPHI

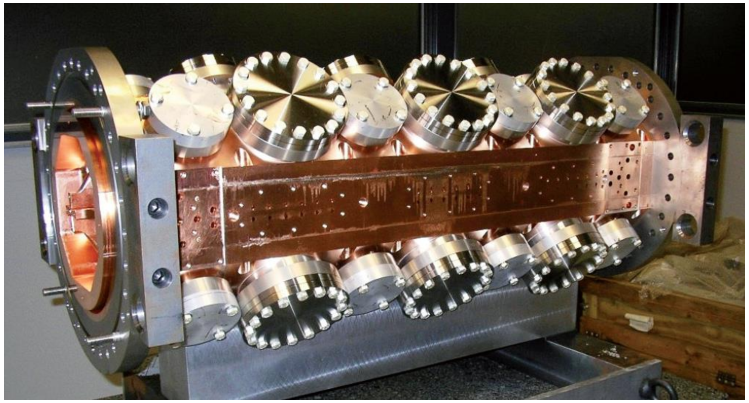


$\beta_{P(100\ \mathrm{keV})} = \mathbf{0.0146}$

$\beta_{P(3\ \mathrm{MeV})} = \mathbf{0.0797}$

Overall efficiency is about 300 kW/4 MW ~ 10 %

100 kV electrostatic extraction

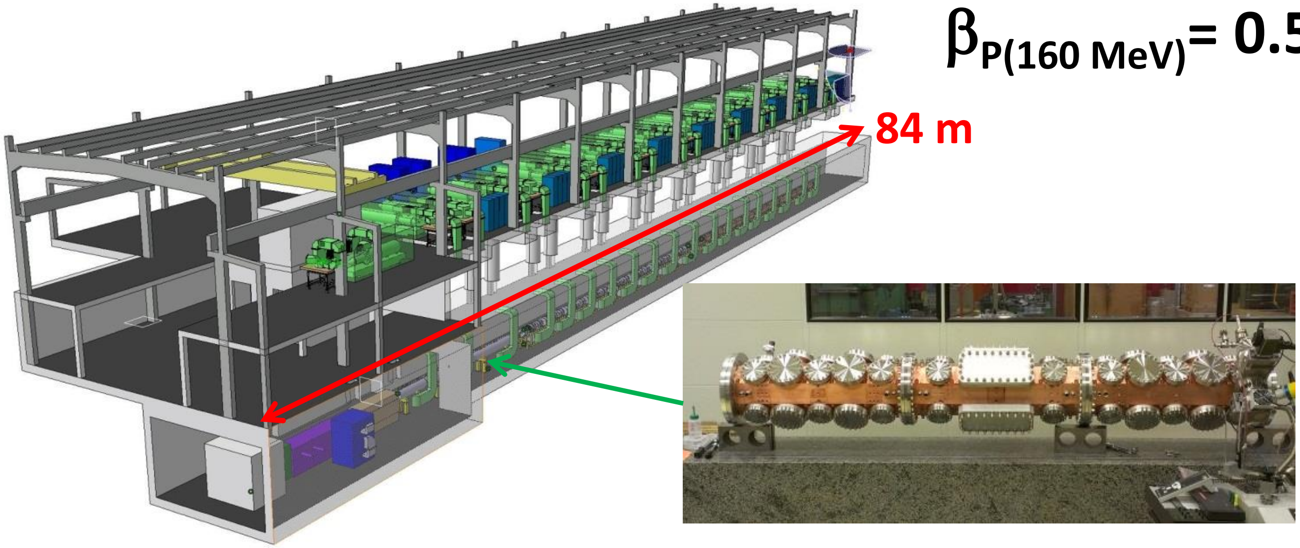


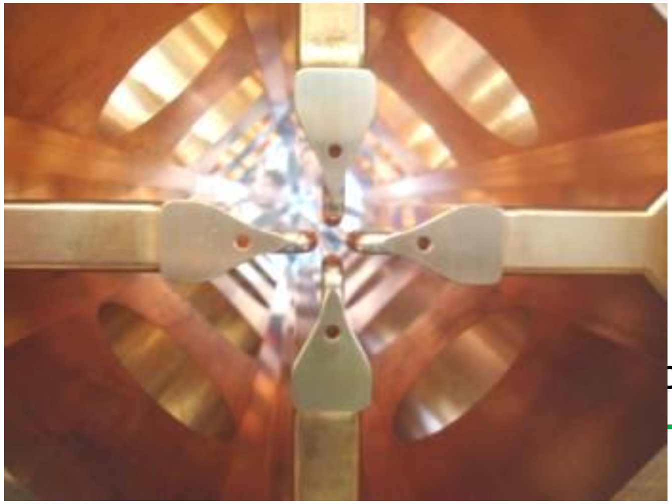
One RFQ sector (1m)

RF distribution:
2 MW CW 352 MHz

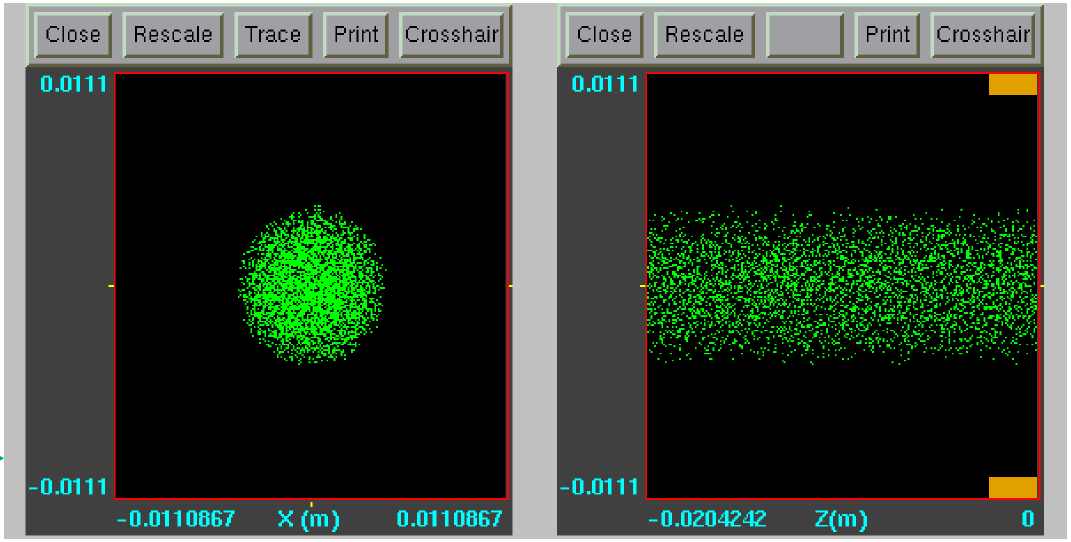
A 160 MeV Proton Facility: LINAC4

$\beta_{P(160\ \mathrm{MeV})} = 0.520$

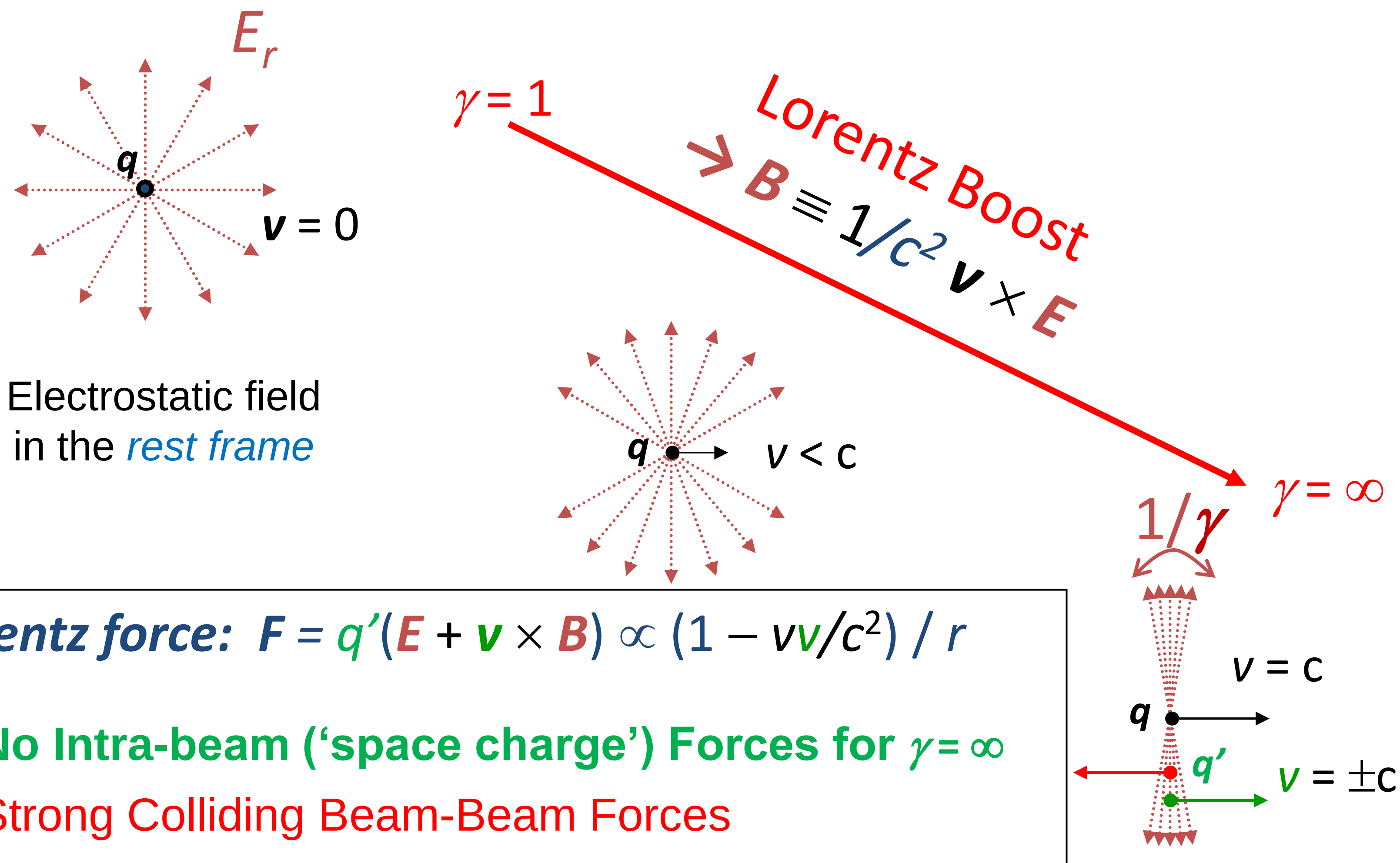




on



The Electromagnetic Field of a Relativistic Charge *q*



Electrostatic field
in the *rest frame*

“Shock Wave”
in the *lab frame*

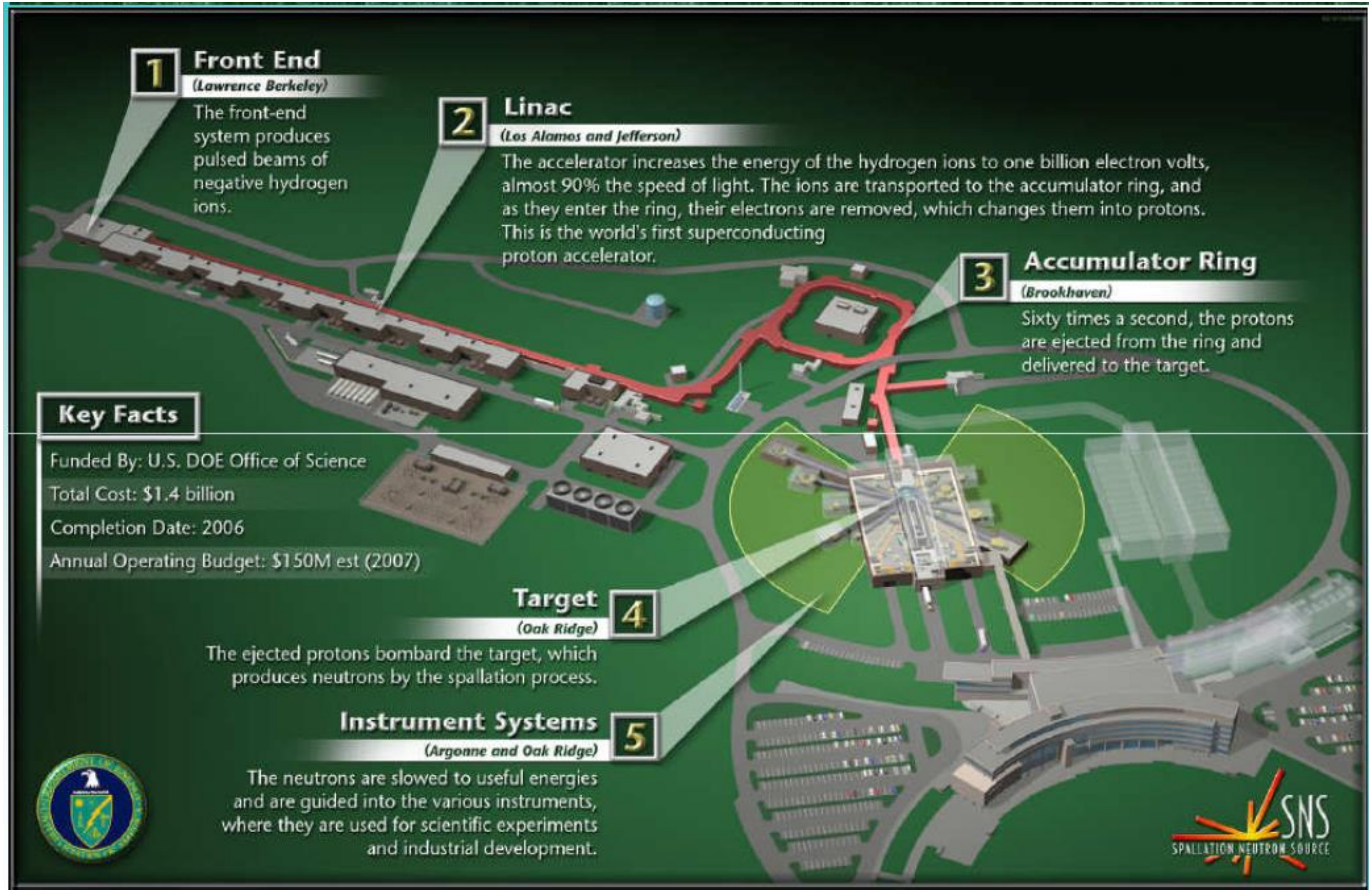
Lorentz force: $\mathbf{F} = q'(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \propto (1 - vv/c^2) / r$

⇒ No Intra-beam (‘space charge’) Forces for $\gamma = \infty$

⇒ Strong Colliding Beam-Beam Forces

Main Message: space charge forces are dominating the low-energy high-charge proton bunches transport

A 1 GeV Proton Facility : SNS



1 Front End

(Lawrence Berkeley)

The front-end system produces pulsed beams of negative hydrogen ions.

2 Linac

(Los Alamos and Jefferson)

The accelerator increases the energy of the hydrogen ions to one billion electron volts, almost 90% the speed of light. The ions are transported to the accumulator ring, and as they enter the ring, their electrons are removed, which changes them into protons. This is the world's first superconducting proton accelerator.

3 Accumulator Ring

(Brookhaven)

Sixty times a second, the protons are ejected from the ring and delivered to the target.

Key Facts

Funded By: U.S. DOE Office of Science

Total Cost: $1.4 billion

Completion Date: 2006

Annual Operating Budget: $150M est (2007)

4 Target

(Oak Ridge)

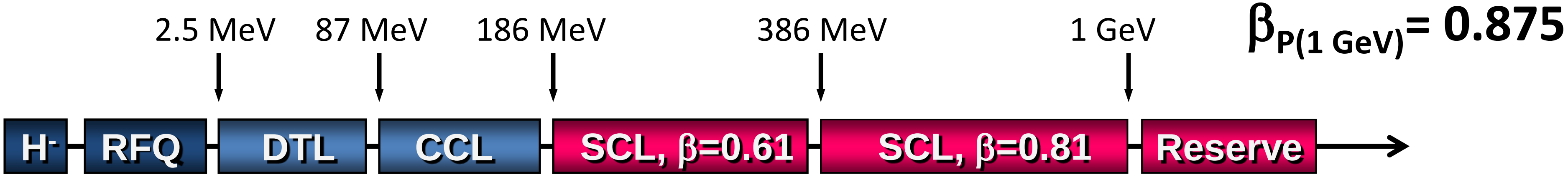
The ejected protons bombard the target, which produces neutrons by the spallation process.

5 Instrument Systems

(Argonne and Oak Ridge)

The neutrons are slowed to useful energies and are guided into the various instruments, where they are used for scientific experiments and industrial development.

SNS Linac RF Structures : **331 m**

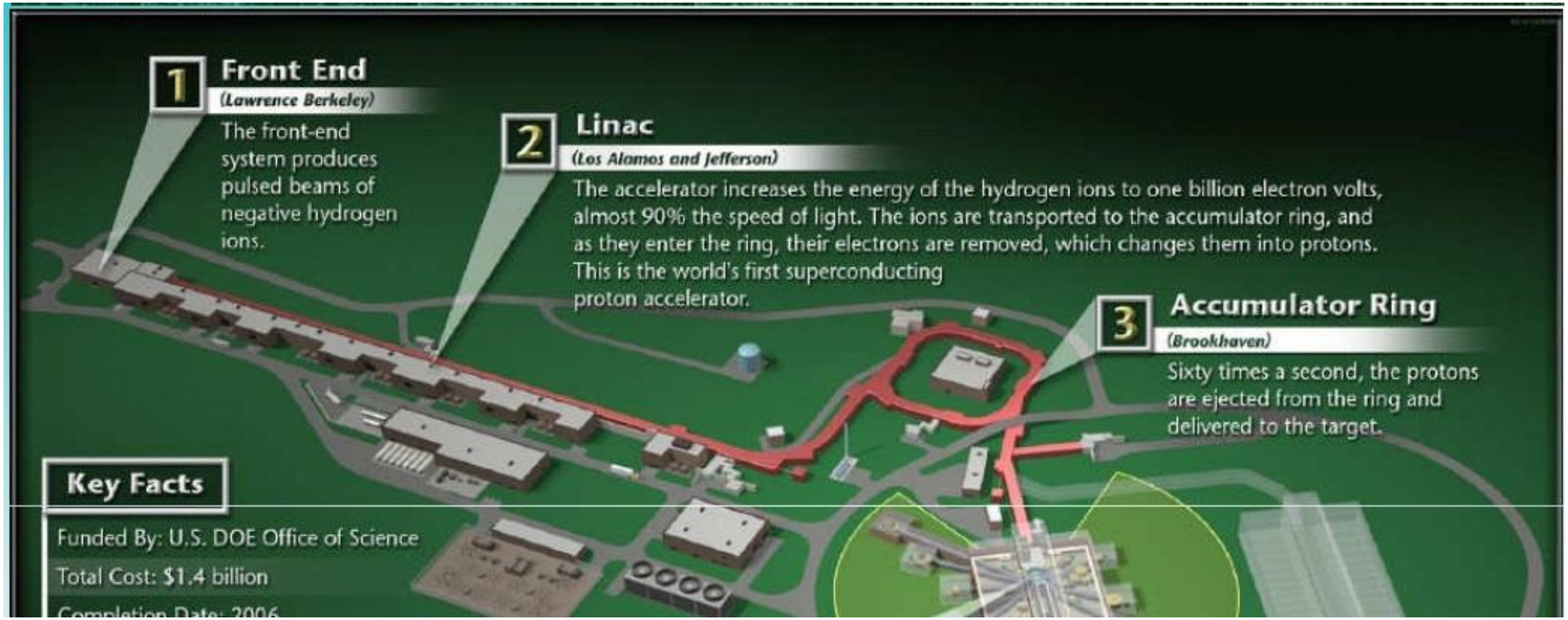


2.5 MeV 87 MeV 186 MeV 386 MeV 1 GeV **$\beta_{P(1\,GeV)}$= 0.875**

H^- **RFQ** **DTL** **CCL** **SCL, β=0.61** **SCL, β=0.81** **Reserve**

- MW class: 1.5 MW in the linac, 26 mA average in the 1 ms pulse (65 pC@400 MHz), 60 Hz (6%)

Neutron Facility Application: SNS



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Proton parameters, from the neutron target standpoint:

- Kinetic energy : 1 GeV
- Pulse repetition : 60 Hz
- Proton short-pulse length: 695 ns
- Total charge : 24 µC (*about 65 pC @ 0.57 THz*)

Applications

- Applications
  - Proton Colliders (Tevatron, LHC)
  - Neutron sources (SNS, ESS, *IFMIF*)
  - Neutrino sources (Project X, SPL)
  - Radioactive Ion Beams (FRIB, EURISOL)
  - Accelerator Driven Systems (Ch-ADS, MYRRHA)

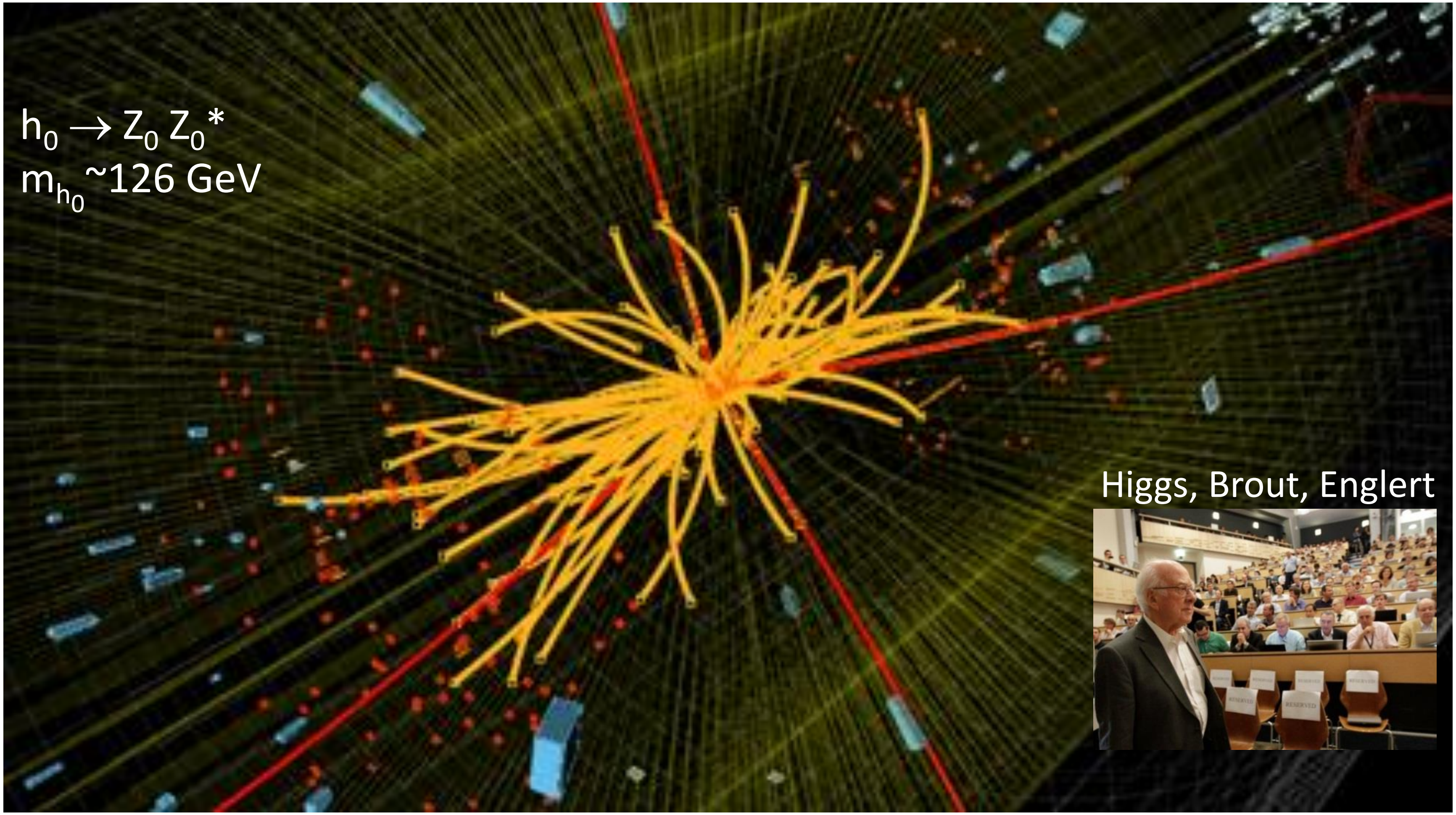
Only colliders are using protons as the particles of interest for physics processes.

For the other 4 applications, proton (or deuteron) beams are used to drive the production of the secondary beams of interest: neutrons or neutrinos.

$\Rightarrow$ Proton beam ‘high level’ parameters may lead to different beam requirements on standard vs. laser-based driver accelerators.

High Energy Proton Colliders

The discovery of the Higgs Boson, at the LHC and the TeVatron



$h_0 \rightarrow Z_0\, Z_0{}^*$

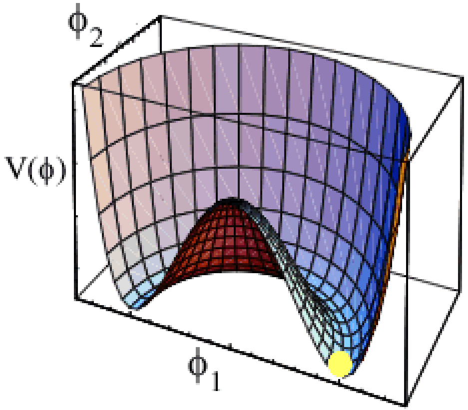
m_{h_0}~126 GeV

Higgs, Brout, Englert

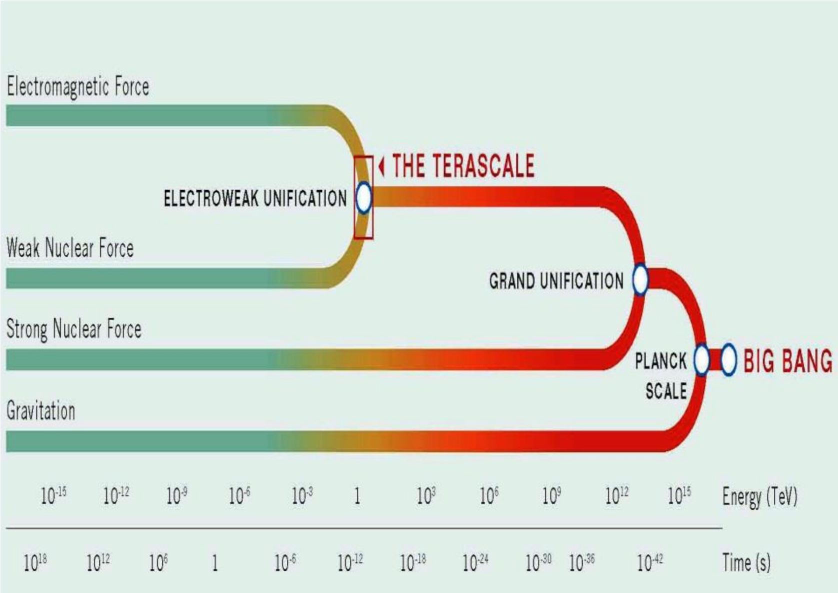
High Energy Proton Colliders

Like the major past scientific findings, the discovery of the Higgs boson elevates **Mankind’s Perspective**: *our world obeys U(2)-symmetric laws of dynamics, despite the so-far resolved U(1) symmetry*.

‘U(2) rotation’
symmetric Higgs
Lagrangian.



‘U(2) rotation’
asymmetric
ground state.



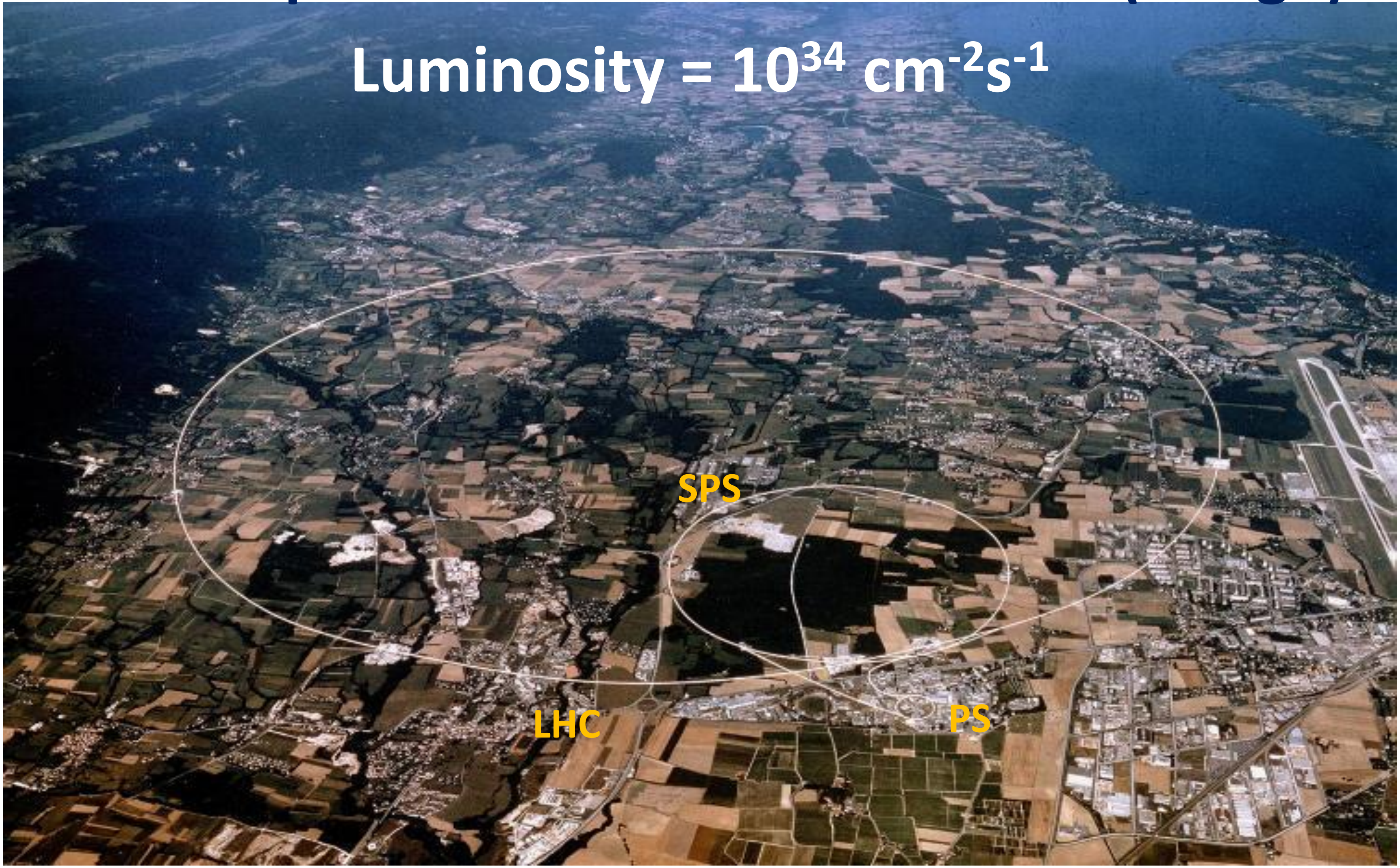
courtesy P. Oddone

The Tevatron at Fermilab (Chicago)

Proton-antiproton collider 1 TeV x 1 TeV

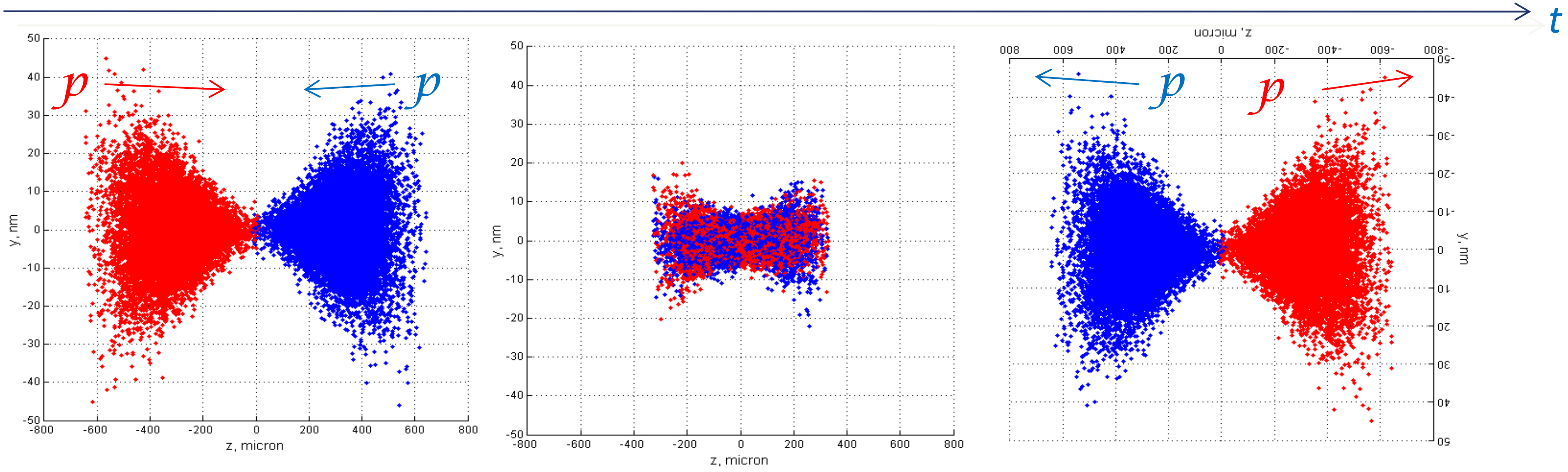
The LHC at CERN (Geneva)

Proton-proton Collider 7 TeV x 7 TeV (design)



Luminosity = 10^{34} $cm^{-2}s^{-1}$

Collider Luminosity



The counting rate $N_{\mathcal{E}}$ of physical events $\mathcal{E}$ created during the collision of two proton bunches is given by:

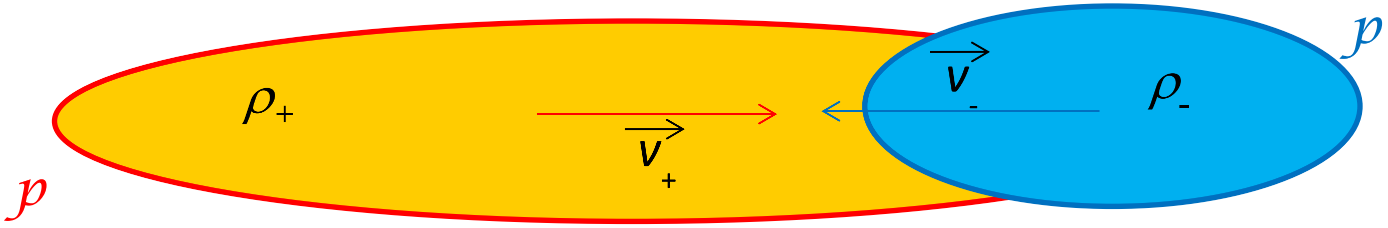
$$N_{\mathcal{E}} = \overline{\mathcal{L}} \cdot \sigma_{\mathcal{E}}$$

where

- $\sigma_{\mathcal{E}}$ is the cross-section of the event pp $\rightarrow \mathcal{E}$
- $\overline{\mathcal{L}}$ is the **integrated luminosity** over the collision.

$N_{\mathcal{E}}$, $\sigma_{\mathcal{E}}$, et $\overline{\mathcal{L}}$ are Lorentz invariant quantities

Integrated Luminosity over Bunch Collision



For relativistic protons $\gamma_+, \gamma_- \rightarrow \infty$:

$$\boxed{\overline{\mathcal{L}} = \frac{1}{c^2}\int c\,dt\, d^3x\, \mathbf{J}_+ \cdot \mathbf{J}_- = \frac{1}{c^2}\int c\,dt\, d^3x\, \rho_+\rho_-(c^2 - \vec{v}_+ \cdot \vec{v}_-)}$$

For instance : head-on collisions $\vec{v}_+ = -\vec{v}_- = c\hat{z}$ of Gaussian bunches :

$$\rho_\pm(\vec{x},t) = \frac{N_\pm}{(2\pi)^{3/2}\sqrt{\sigma_x^\pm \sigma_y^\pm \sigma_z^\pm}} \exp -\frac{1}{2}\left(\frac{x^2}{\sigma_x^{\pm 2}} + \frac{y^2}{\sigma_y^{\pm 2}} + \frac{(z \pm ct)^2}{\sigma_z^{\pm 2}}\right)$$

leads to $\boxed{\overline{\mathcal{L}} = \frac{N_+ N_-}{4\pi \Sigma_x \Sigma_y}}$ **int^{ed} luminosity per collision**, with $\Sigma^2 = \frac{1}{2}(\sigma_+^2 + \sigma_-^2)$

In the LHC, there is one collision of two 23 nC proton bunches every 25 ns

Proton Beams for LHC Injection

Proton beam specifications for injection in the Booster ring

Ions species: H-

Energy: 160 MeV

Bunch intensity: 40 mA

Bunch frequency: 352.2 MHz

Beam Power: 5.1 kW

Duty cycle: 0.1 % (222/133 transmitted bunches/empty buckets)

Pulse length: 400 µs

Transverse emittance (XX'): 0.4 Pi.mm.mrad

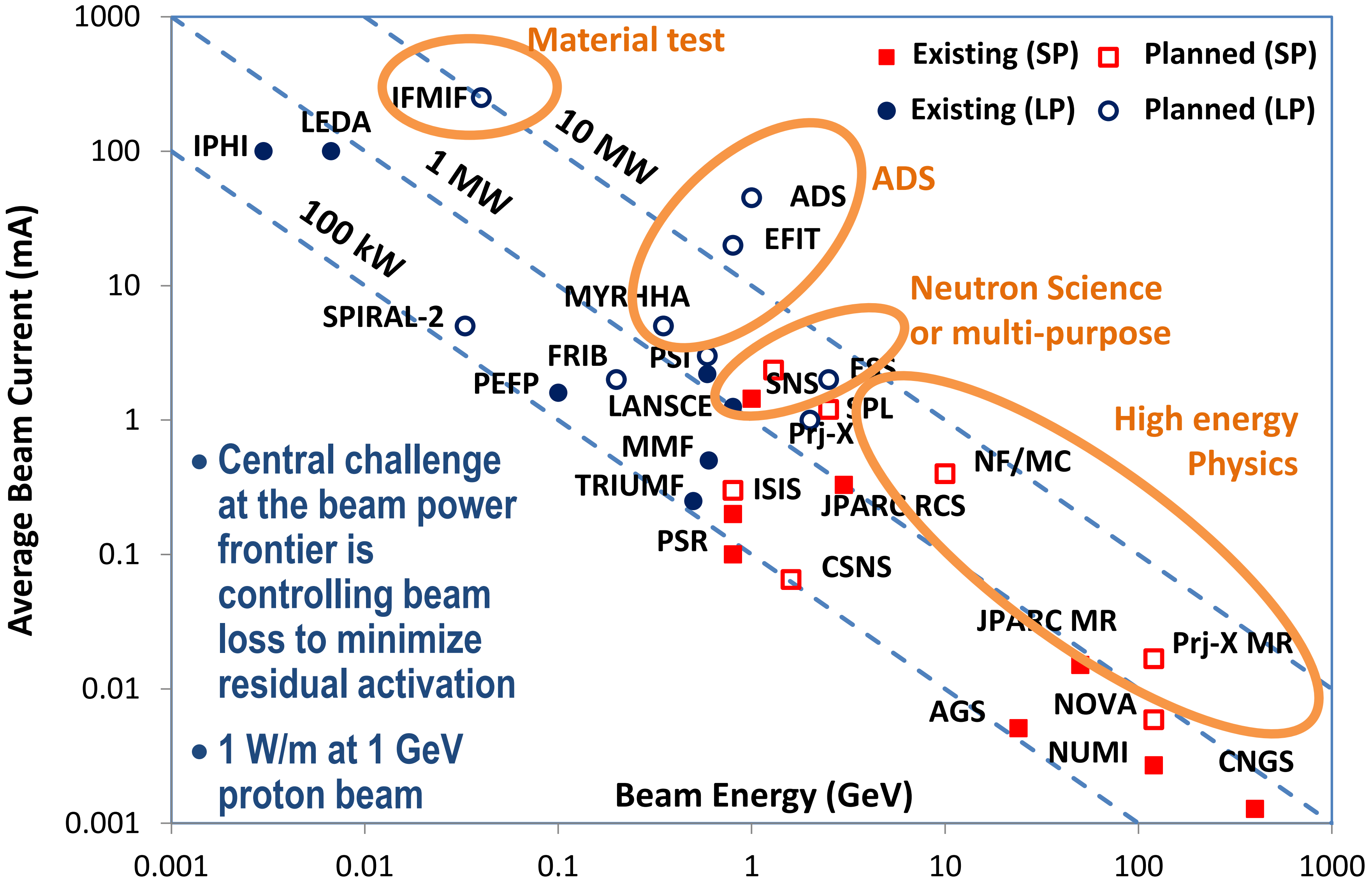
Bunch length: 60 ps

Bunch dispersion DE/E ~0.1%

N. particles per bunch: $1.14 \cdot 10^9$

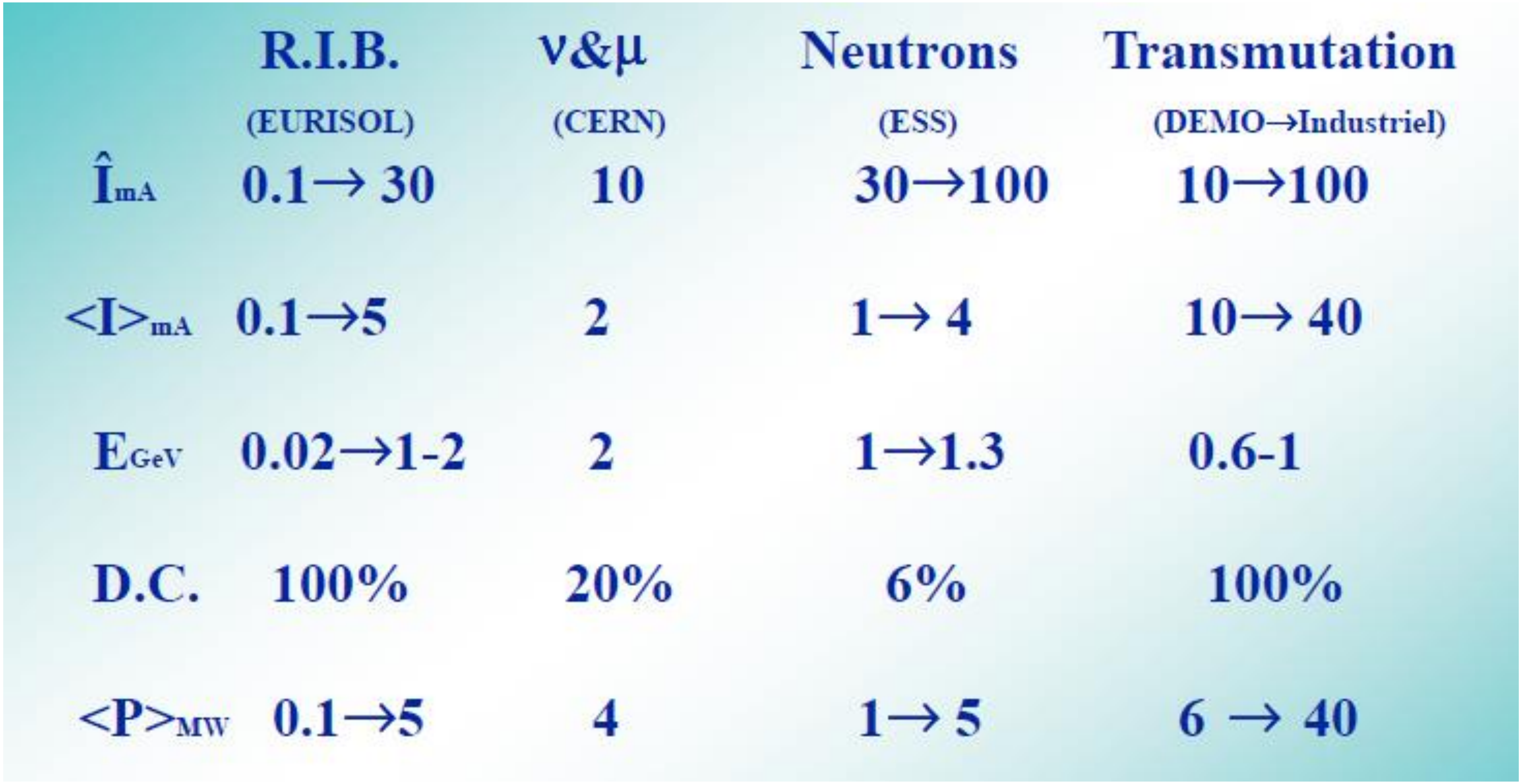
There are later stages of injection in the PS and SPS synchrotrons. **Ultimately, about 2600 proton bunches (400 GeV, 23 nC/25 ns) will be injected in each of the two LHC storage rings, about every 10 hours.**

Beam Power Frontier for Ion Beam Facilities



- Central challenge at the beam power frontier is controlling beam loss to minimize residual activation
- 1 W/m at 1 GeV proton beam

High Level Parameters for High Power Proton Accelerators (HPPA)

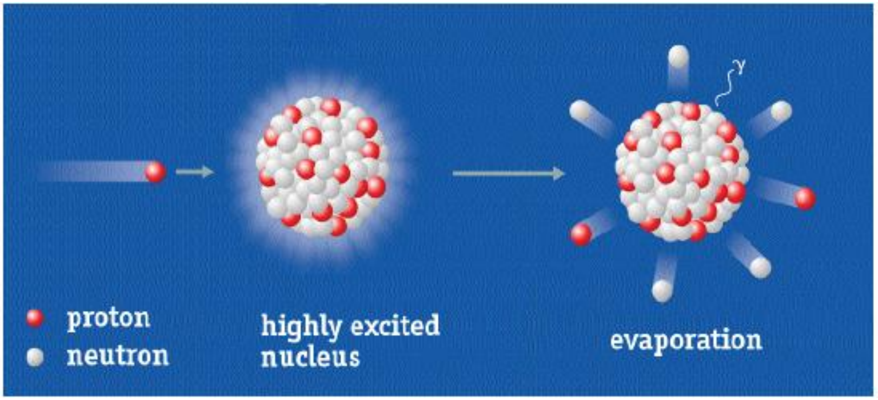


	R.I.B. (EURISOL)	ν&μ (CERN)	Neutrons (ESS)	Transmutation (DEMO→Industriel)
$\hat{I}_{mA}$	0.1→ 30	10	30→100	10→100
$<I>_{mA}$	0.1→5	2	1→ 4	10→ 40
E_{GeV}	0.02→1-2	2	1→1.3	0.6-1
D.C.	100%	20%	6%	100%
$<P>_{MW}$	0.1→5	4	1→ 5	6 → 40

(Courtesy of J. Wei and S. Henderson)

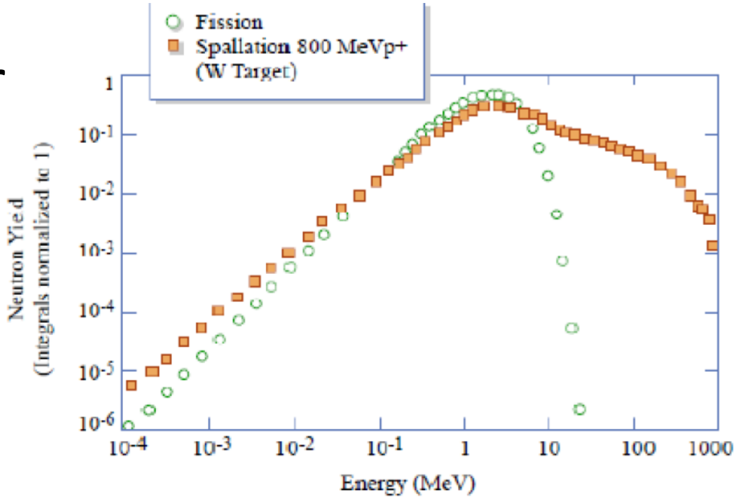
Neutron sources

Neutrons are produced through the **spallation process** on heavy nuclei:



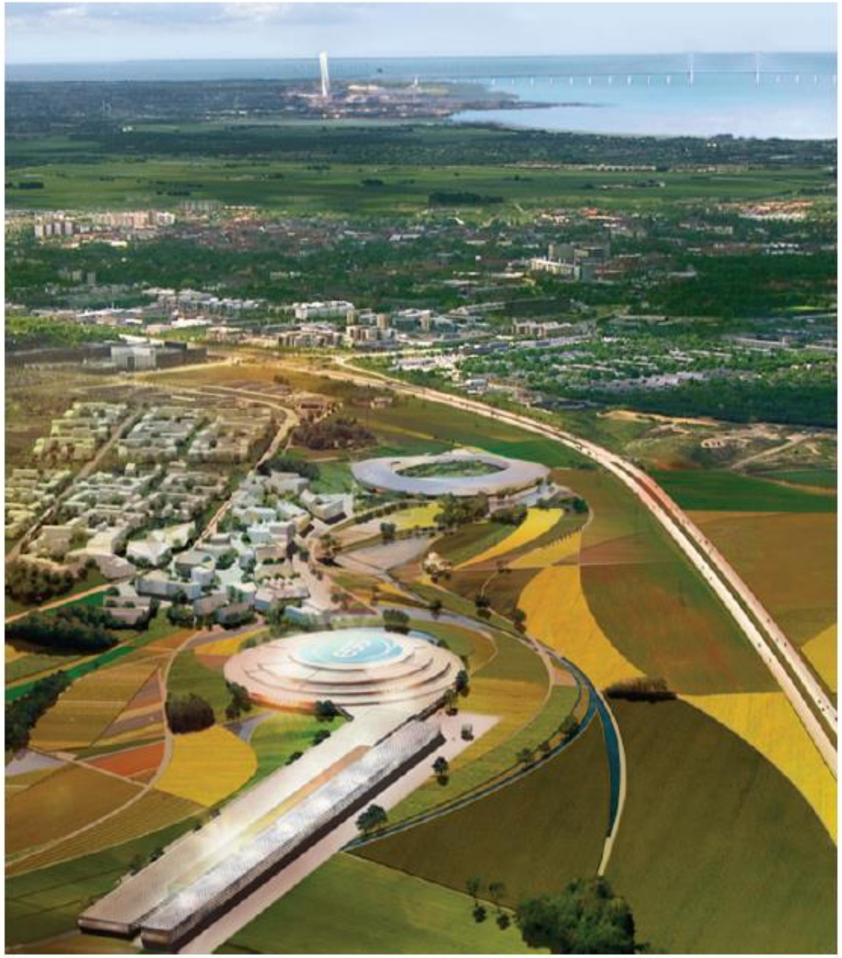
Spallation: A nuclear process in which a high energy proton excites a neutron rich nucleus which decays sending out neutrons (and other particles).

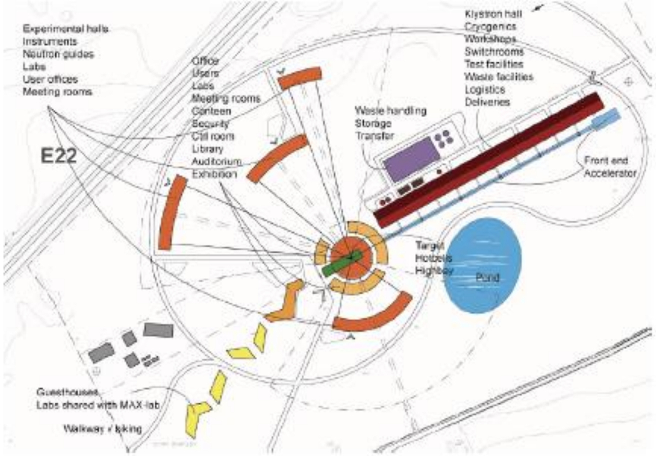
- The average energy deposited on the target, about 50 MeV/n, is lower than for deuteron induced nuclear processes.
- About 20-40 neutrons are produced per primary proton.
- Neutrons with a broad energy spectrum, peaked on 1 MeV.



European Spallation Source (ESS)

ESS is a long pulse (3 ms) neutron source





- European Spallation Source, SC LINAC, 2019, 5 MW, 2.5 GeV, 50 mA, 2.86 ms, 14 Hz
- Examples of challenges: Footprint of RF sources, Energy efficiency

Proton Beams for ESS

Proton beam specifications

Energy: 2.5 GeV

Average Beam Power: 5 MW

Number of protons per bunch: $0.88 \cdot 10^9$

Bunch repetition frequency: 352.21 MHz

Pulse intensity: 50 mA

Pulse length: 2.86 ms

Repetition rate: 14 Hz

Duty cycle: 4 %

Transverse normalized emittance (XX’): 0.22 Pi.mm.mrad

Bunch length: 10 ps

Bunch dispersion DE/E ~0.04%

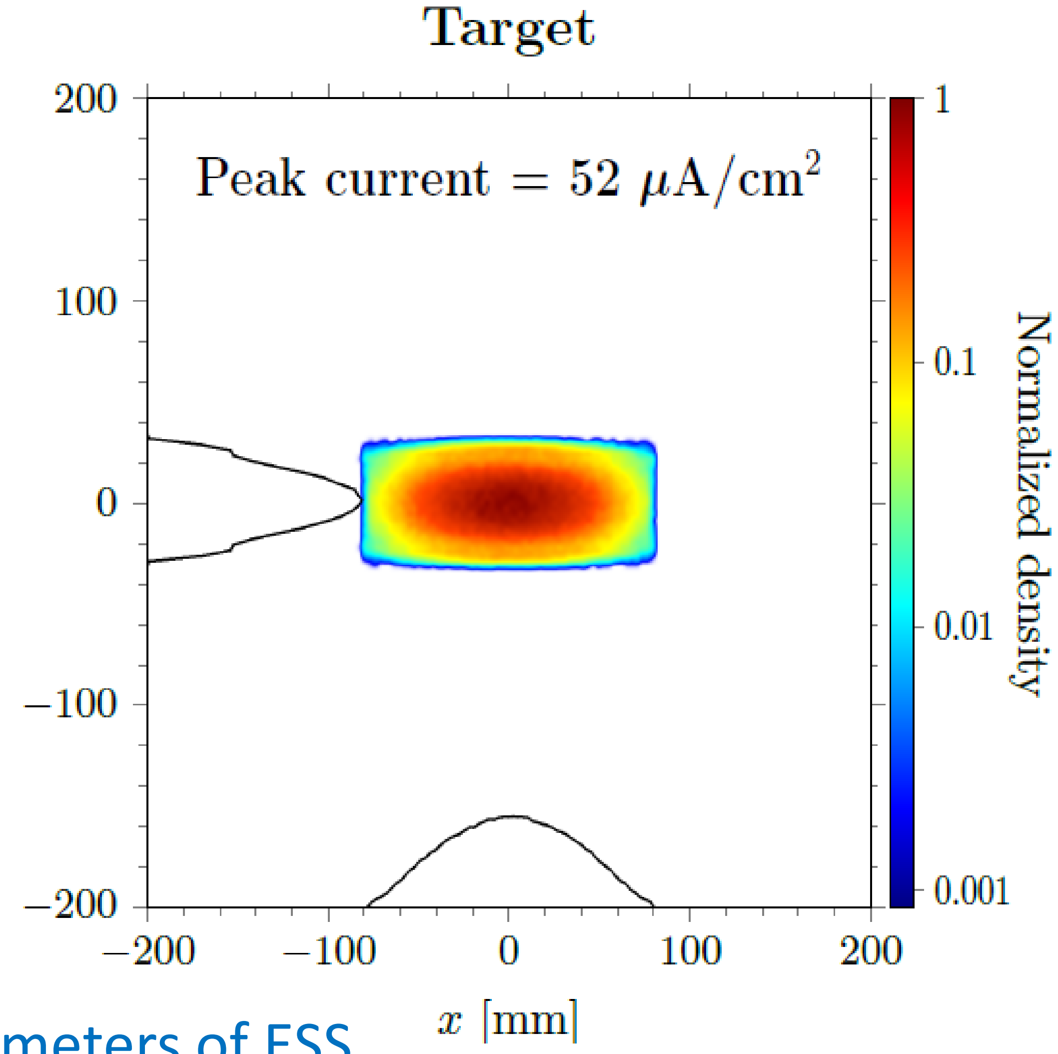
These are the RF-accelerator ‘biased’ parameters of ESS.

ESS: Beam Density on Target

Proton beam :
Energy: 2.5 GeV
Pulse: 3 ms@14 Hz
Footprint: 160×60 mm^2

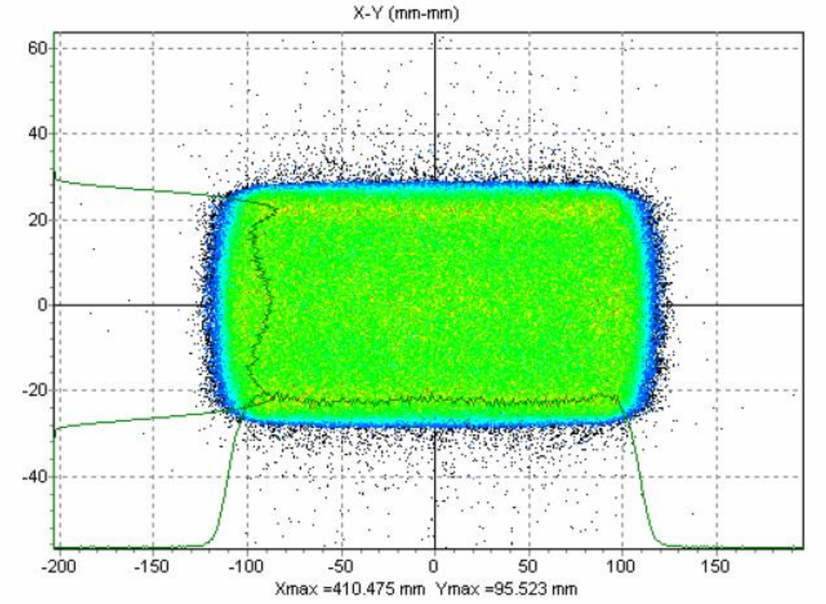
Transverse profile flattening is needed to reduced the time-average peak intensity on target from :
250 µA/cm^2 to 52 µA/cm^2

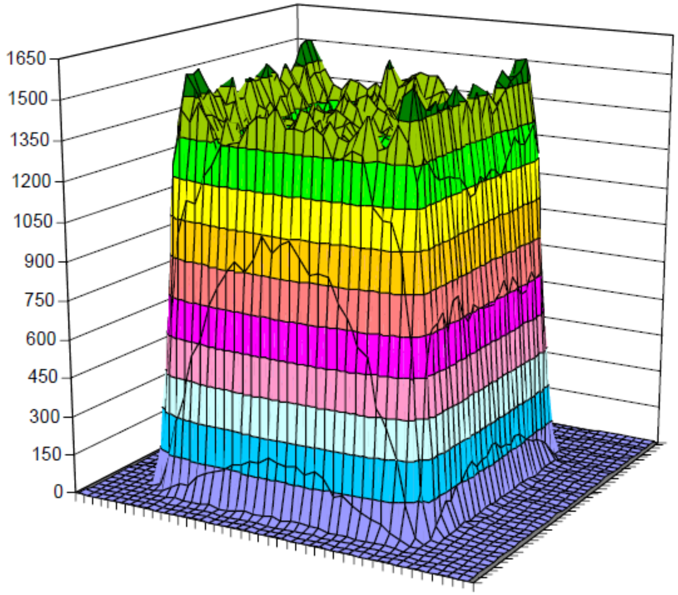
Homogeneity is not an issue



These are the high level parameters of ESS

International Fusion Material Irradiation Facility (IFMIF)





Deuteron beam profile

Energy: 40 MeV (*hardly relativistic*), CW

Cross-section : 220×70 mm^2

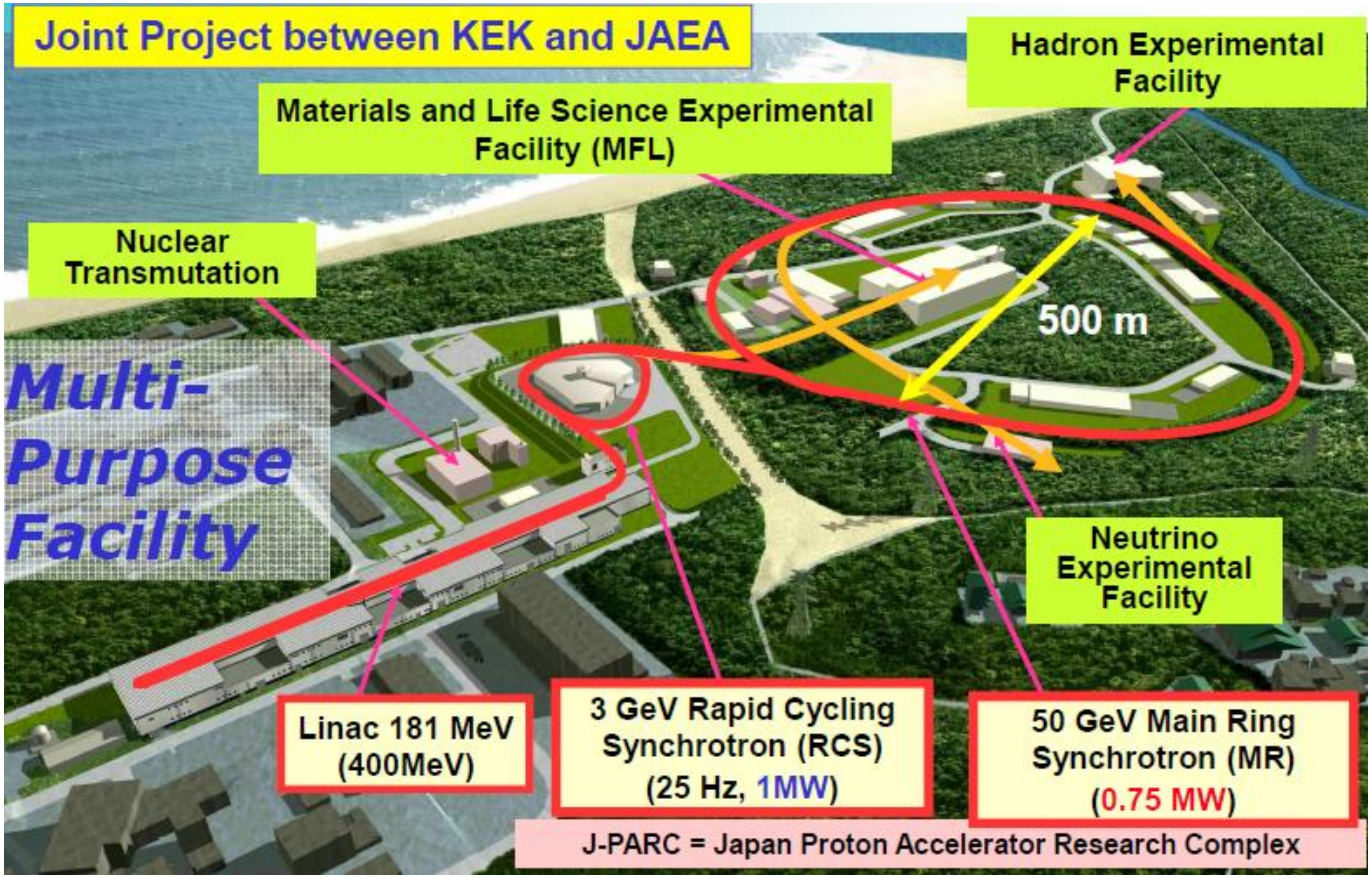
Average intensity on target : 1 mA/cm^2

Homogeneity : < 5%

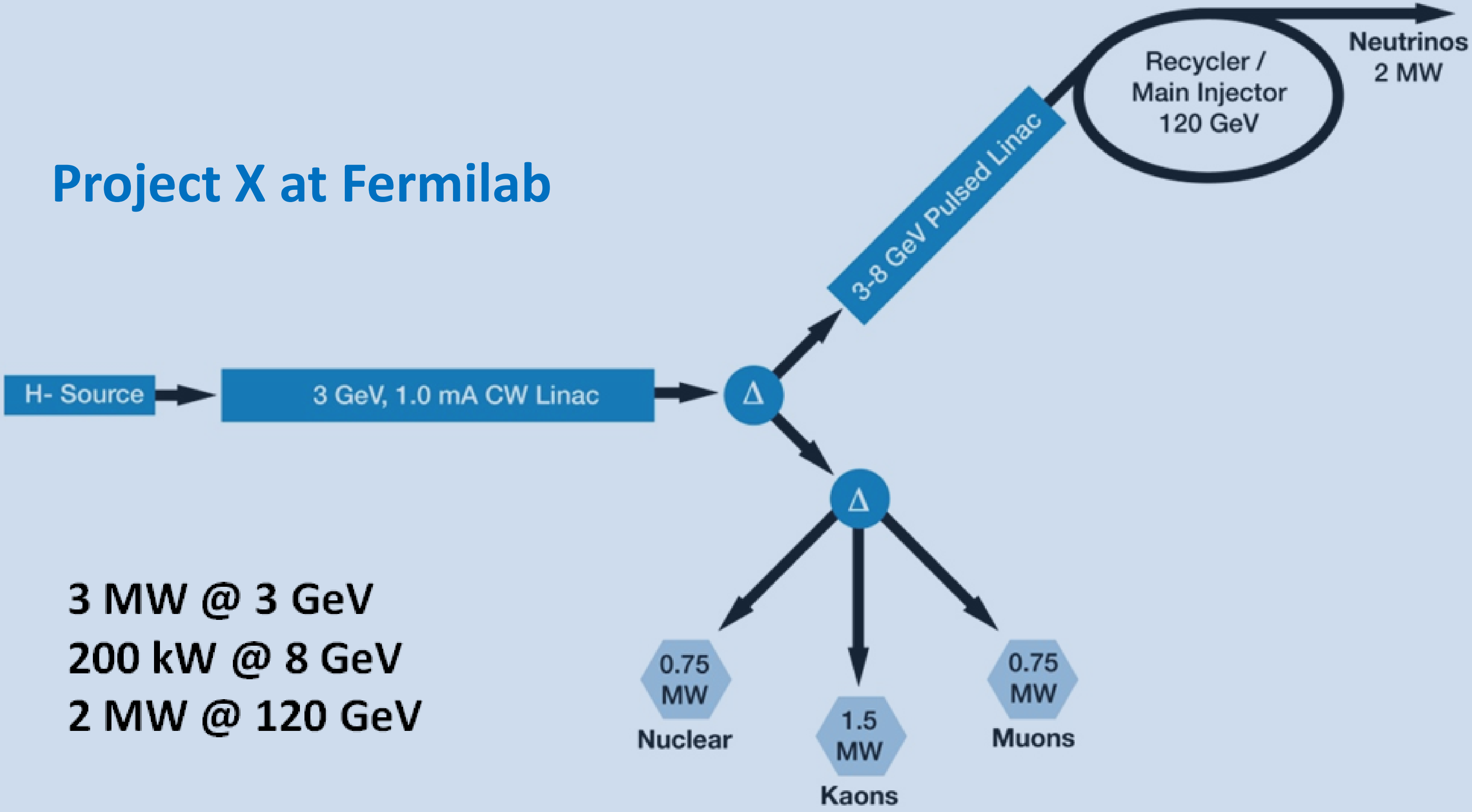
These are the high level parameters of IFMIF

Neutrino Sources

The JPARC facility includes a high energy, short pulsed, proton beam on Hg or W targets to produce neutrinos beams from pions and muon decays → neutrino oscillations at SuperKamiokande



Project X Reference Design



Project X at Fermilab

3 MW @ 3 GeV
200 kW @ 8 GeV
2 MW @ 120 GeV

H- beams are used whenever the beam is injected (and stripped to H+) in a compressor ring to produce short pulses, e.g. SNS, NuFact, …

Proton Beams for Neutrino Beams

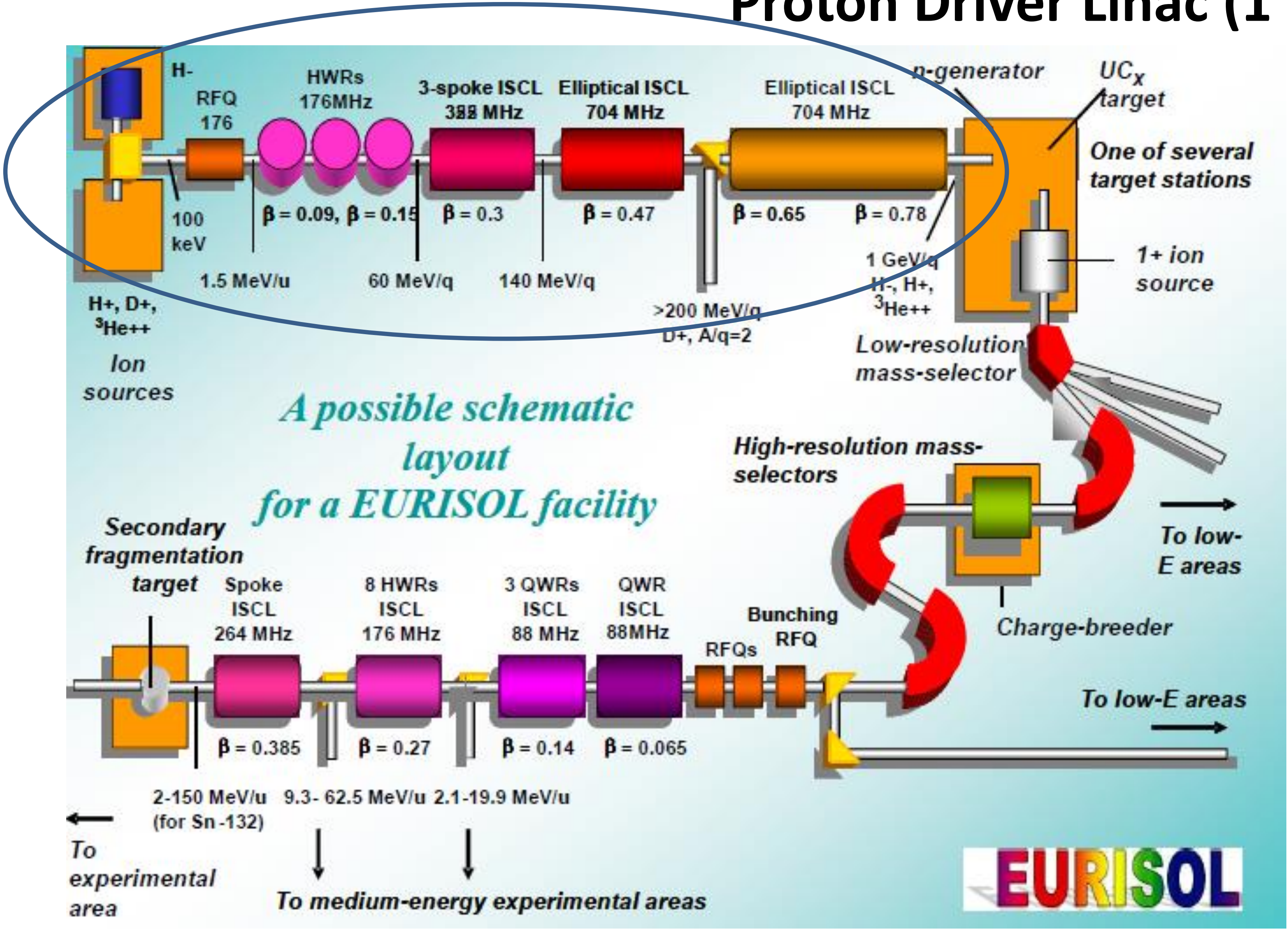
Proton beam specifications at injection in pulse-compressor ring (e.g. SPL)

Energy : 3.5 GeV
Bunch intensity: 40 mA
Bunch frequency: 352 MHz
Beam Power: 4 MW
Duty cycle: 3 % (52% during pulse)
Pulse length: 0.57 ms
Transverse emittance (XX'): 0.4 Pi.mm.mrad
Longitudinal emittance (ZZ'): 0.6 Pi.mm.mrad
Bunch length: 10 ps
Bunch dispersion DE/E ~0.04%
Number of particles per bunch: $1.14 \cdot 10^9$

These parameters are required for beam injection in the ring.

Radioactive Ion Beams (RIB)

Proton Driver Linac (1 GeV)



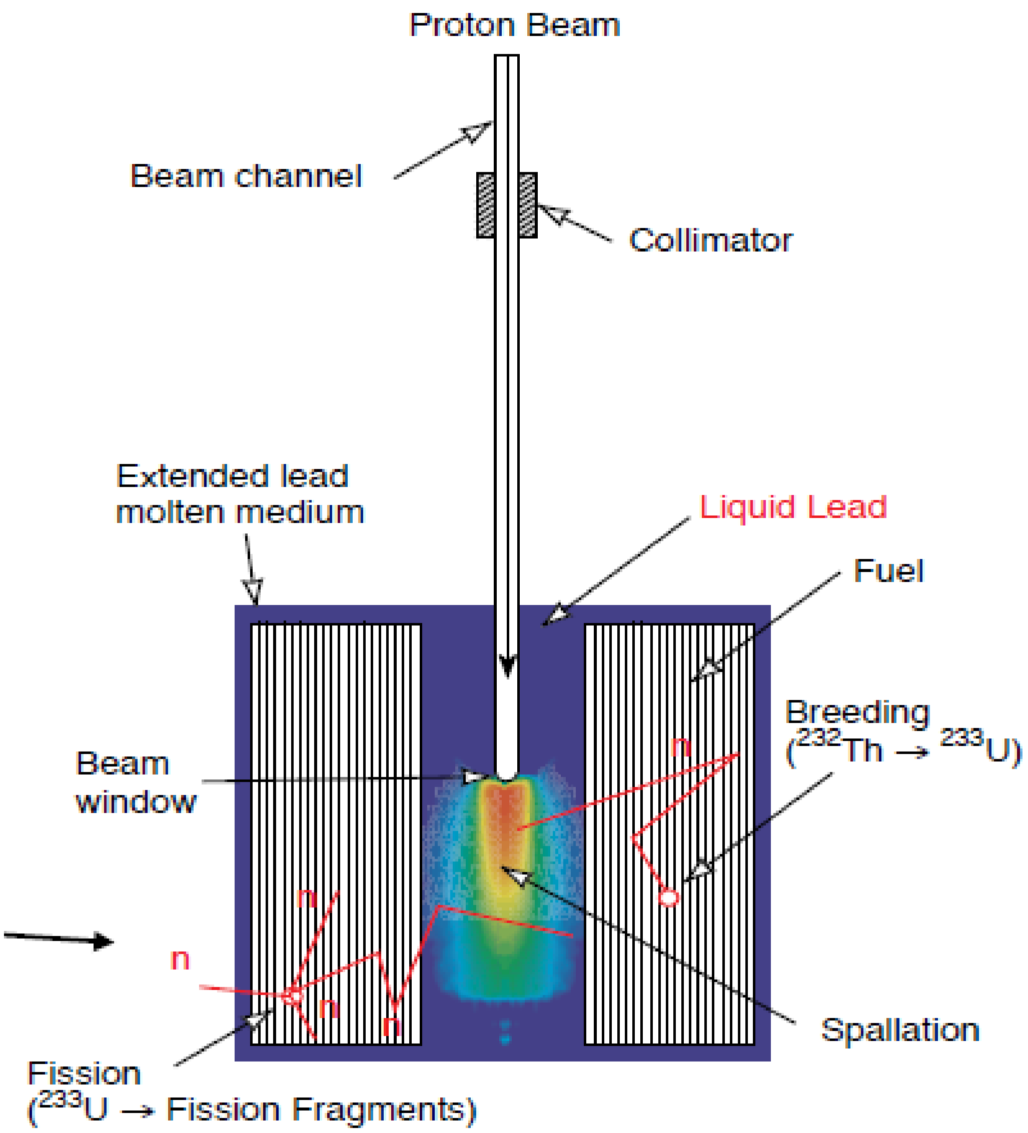
Proton Beams for RIB

Proton beam specifications for Eurisol

Energy : 1 GeV
Beam Power: 5 MW
Bunch intensity: 5 mA
Bunch frequency: 176 MHz
Number of particles per bunch: $1.8 \cdot 10^8$ (28 pC)
Duty cycle: 100 %
Transverse emittance (XX’): 0.25 Pi.mm.mrad
Longitudinal emittance (ZZ’): 0.4 Pi.mm.mrad
Bunch length: 30 ps
Bunch dispersion DE/E ~0.1%

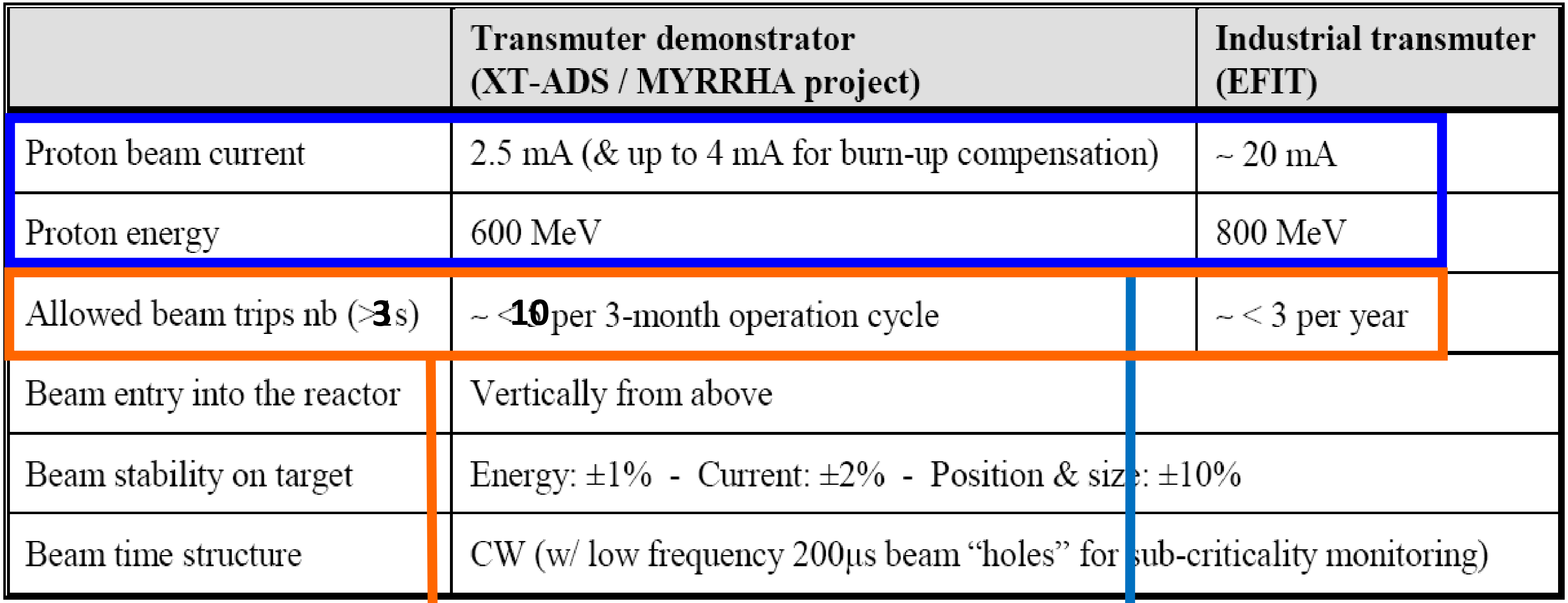
These are the RF-accelerator ‘biased’ parameters of EURISOL.
High level parameters on the UCx target (sorry, next time !).

Accelerator Driven System Principle



Proton Beams for ADS

Proton beam specifications



	Transmuter demonstrator (XT-ADS / MYRRHA project)	Industrial transmuter (EFIT)
Proton beam current	2.5 mA (& up to 4 mA for burn-up compensation)	~ 20 mA
Proton energy	600 MeV	800 MeV
Allowed beam trips nb (>3 s)	~ <10 per 3-month operation cycle	~ < 3 per year
Beam entry into the reactor	Vertically from above	
Beam stability on target	Energy: ±1% - Current: ±2% - Position & size: ±10%	
Beam time structure	CW (w/ low frequency 200μs beam "holes" for sub-criticality monitoring)	

Challenge #2: very high reliability !

Challenge #1: high CW beam power (2-16 MW)

Proton Beams for ADS

Proton beam specifications

Energy: 600 MeV to 1 GeV

Bunch intensity: 5 mA to 20 mA

Bunch frequency: 704 MHz

Duty cycle: 99.98% (CW, 200 μs hole every 1s)

Transverse emittance (XX'): 0.25 Pi.mm.mrad

Longitudinal emittance (ZZ'): 0.4 Pi.mm.mrad

Bunch length: 30 ps

Bunch dispersion DE/E ~0.1%

These are the RF-accelerator 'biased' parameters of EURISOL.
The High level parameters on the target must be derived from the following requirements:

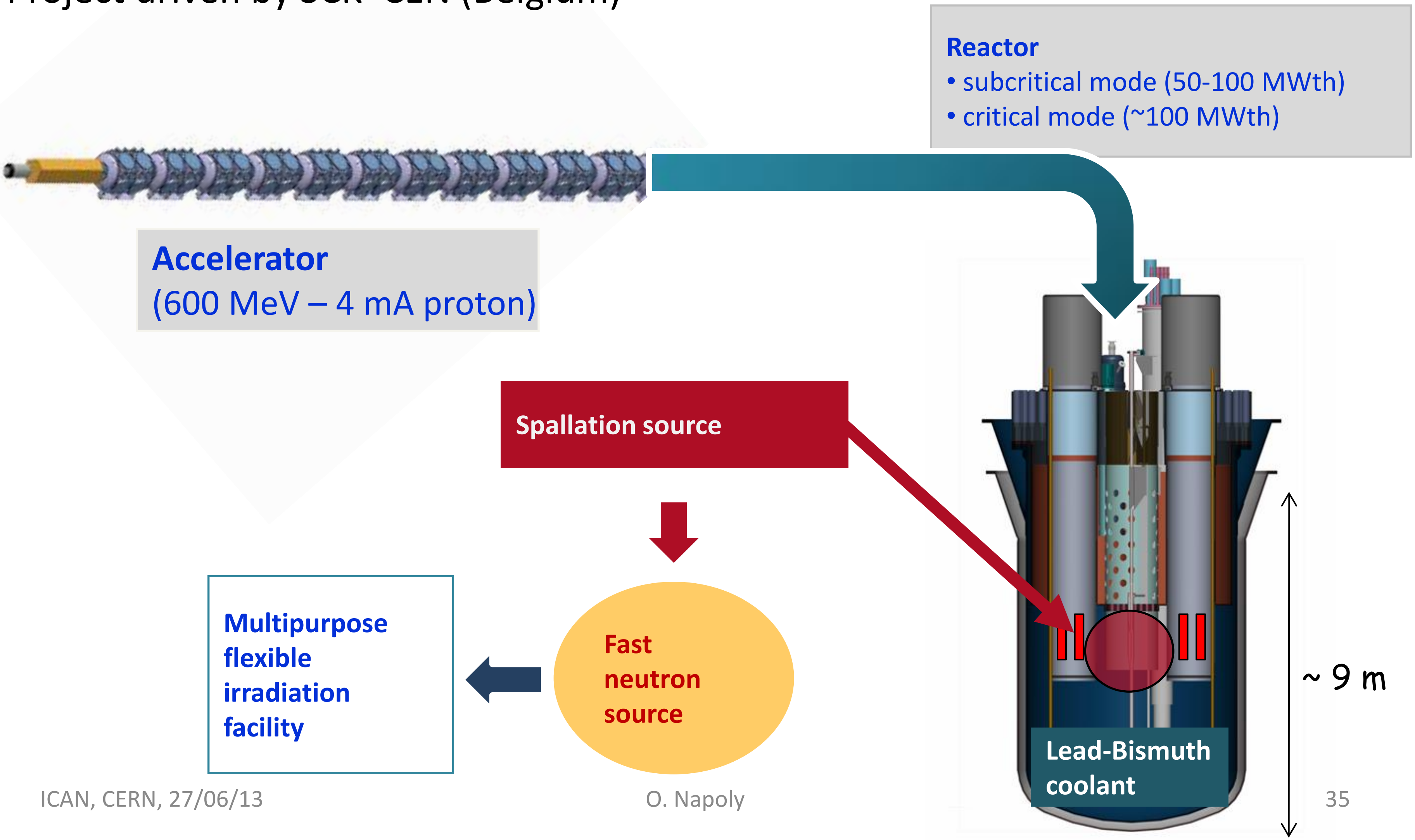
Beam power stability: 1%

Reliability: very high, a few beam trips < 3s per years

Objective at target: fast neutron flux 10^{15}n/(cm^2 s) at En > 0.75 MeV

MYRRHA Project

- MYRRHA (Multi-Purpose hYbrid Research Reactor for High-tech Applications)
- Project driven by SCK•CEN (Belgium)



Reactor
- subcritical mode (50-100 MWth)
- critical mode (~100 MWth)

Accelerator
(600 MeV – 4 mA proton)

Spallation source

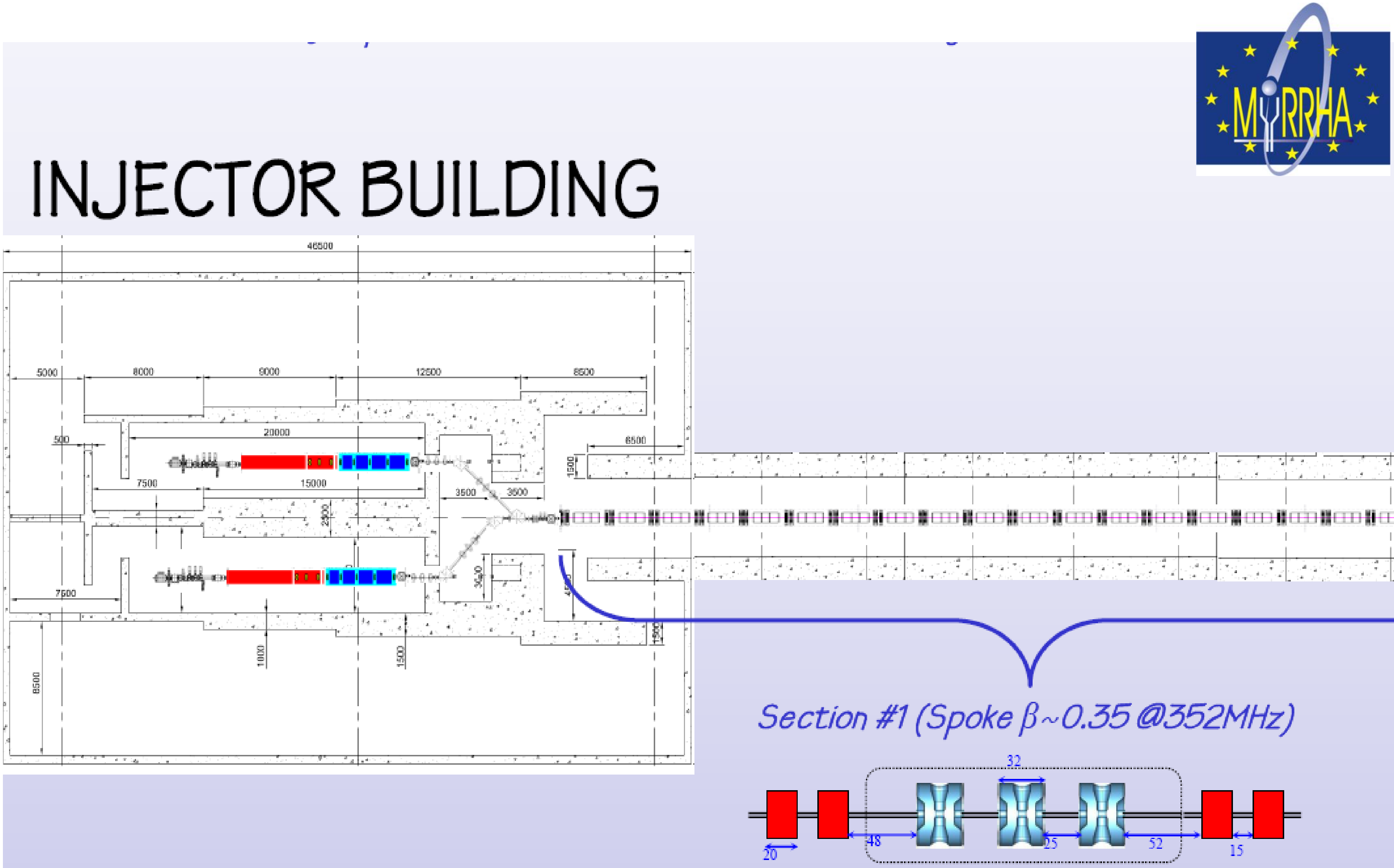
Fast neutron source

Multipurpose flexible irradiation facility

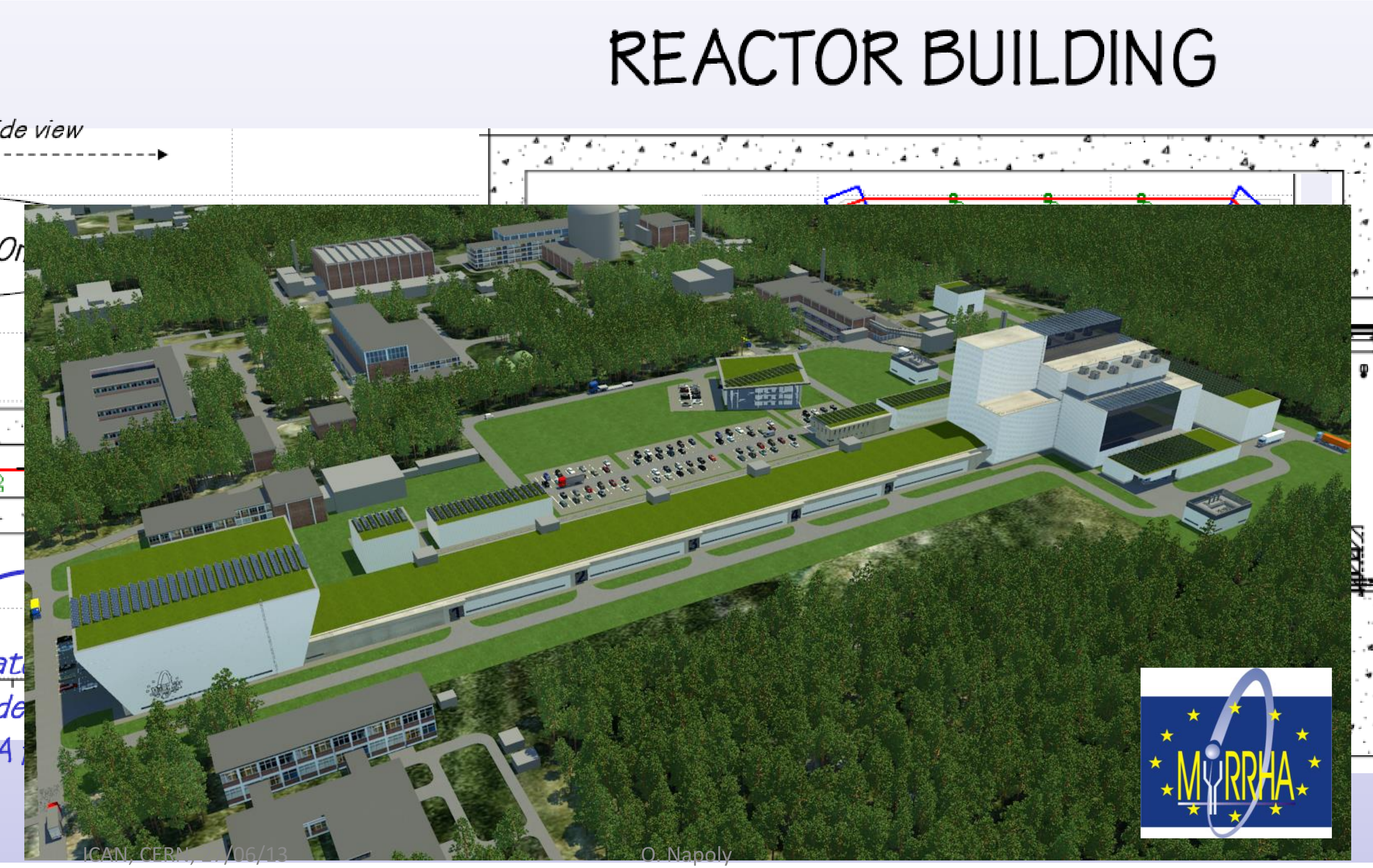
Lead-Bismuth coolant

~ 9 m

MYRRHA Linear Accelerator



The Accelerator and Reactor Buildings



Conclusions

- Producing relativistic proton beams meets the needs of many applications to pure and applied research, and to societal needs.
- In most cases, Proton beams are only used to generate the secondary beams of interest: neutrons or neutrinos. LHC is the exception.
- Producing relativistic proton beam by standard accelerator technology is very demanding in accelerating structures, real estate, and power:

→a Laser based proton injector (~1 GeV) would be a 'modest' but paying first step.

- High average intensity or luminosity is a must.