High Intensity Accelerators - an overview

Chris Prior

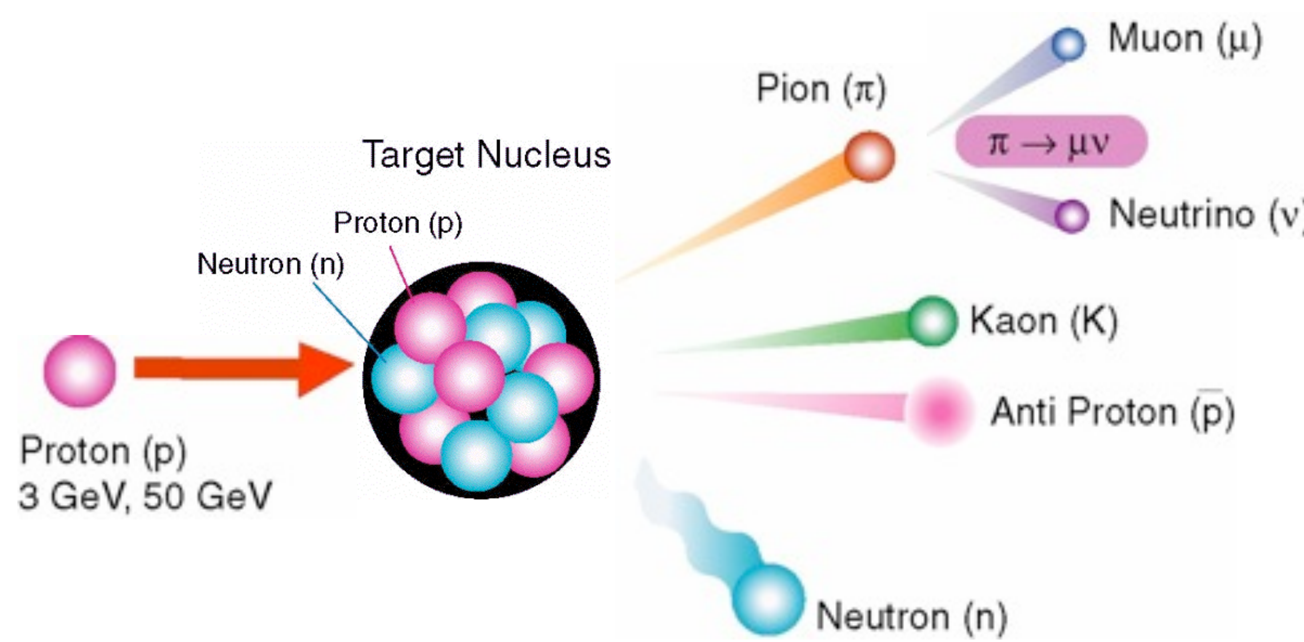
ASTeC, Rutherford Appleton Laboratory, U.K.

and

Trinity College, Oxford

High Intensity Accelerators

- A high intensity driver delivering several MW of average beam power to a production target
- Applications to
  - spallation neutron sources
  - nuclear waste transmutation
  - energy amplifier
  - radioactive ion beams
  - secondary particle production
  - neutrino superbeams
  - neutrino factories
- For a Neutrino Factory:
  - 4 MW at ~50 Hz, ~10 GeV
  - bunches of ~1 ns rms duration.
- For a Neutron Source
  - 4-5 MW at ~50 Hz, 1-3 GeV
  - bunches of ~1 μs to ~2 ms



Materials & Life Sciences at ~3 GeV

Nuclear & Particle Physics at ~50 GeV

R&D for ADS at ~0.5 GeV

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Beam Power

$$\text{Power} = \text{average beam current} \times \text{kinetic energy}$$

$$P = IE = (Nef)E$$

$N =$ number of particles in bunch, $f =$ frequency of bunches

or

$N =$ number of particles in machine, $f =$ repetition rate

- Beam power is a balance of energy against current
  - depends on purpose of the machine (the application/science)
  - takes account of general accelerator limitations
  - also allows for economic considerations

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Multiple Applications

		Power	Energy
Condensed matter studies	spallation neutrons	~1-5 MW	~1 GeV
Materials irradiation	neutrons with stripping reaction	2×5 MW	40 MeV
Secondary beams, particle physics	muons, neutrino production	4 MW	5-15 GeV
RIBS for nuclear & astro-physics	with neutrons	4 MW	~1 GeV
Sub-critical reactors for energy generation and transmutation	MYRRHA demonstrator; thorium cycle	5-10 MW	0.6-1 GeV

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BOEING 757

Projects Worldwide

- Multi-purpose facilities
  - LANSCE (*US*), J-PARC (*Japan*), PEFP (*Korea*), FAIR (*GSI*)
- Spallation neutron sources
  - SINQ@PSI (*Switzerland*), ISIS (*UK*), SNS (*US*), CSNS (*China*), ESS (*Sweden*)
- Radioactive ion beams
  - FRIB (*US*), EURISOL (*Europe*), RIKEN (*Japan*), SPIRAL2 (*France*), SPES (*Italy*), SARAF (*Israel*) …….
- Secondary beams (Neutrino/muon factories)
  - Linac4+SPL (*CERN*), Project-X (*US*), IDS-NF
- Irradiation facilities
  - IFMIF (*Europe/US/Japan*) + prototype EVEDA (*CEA*)
- Accelerator Driven Systems (ADS)
  - EUROTRANS (*Europe*), TRASCO (*Italy*), ADS (*China*), ThorEA (*UK*)

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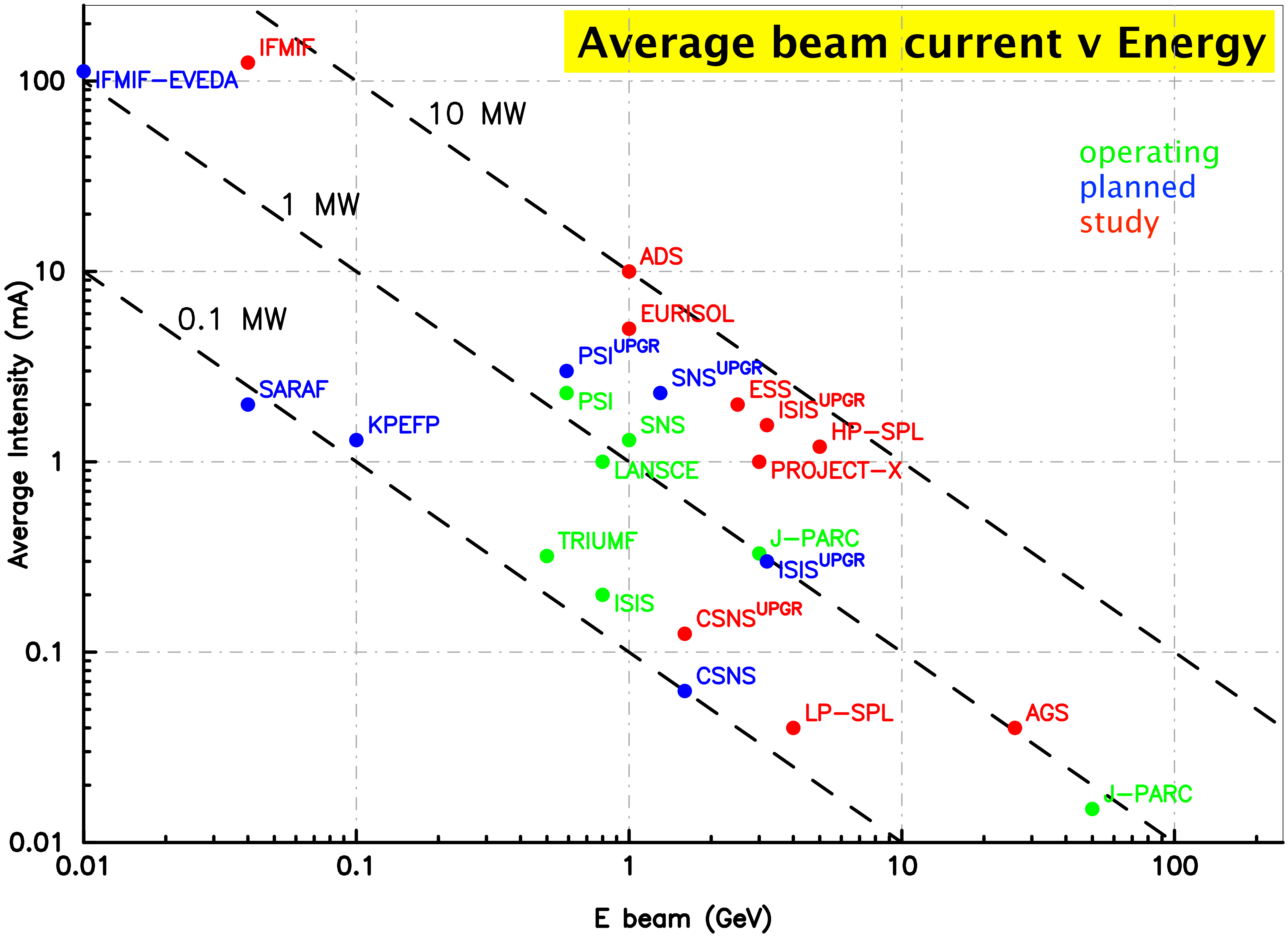
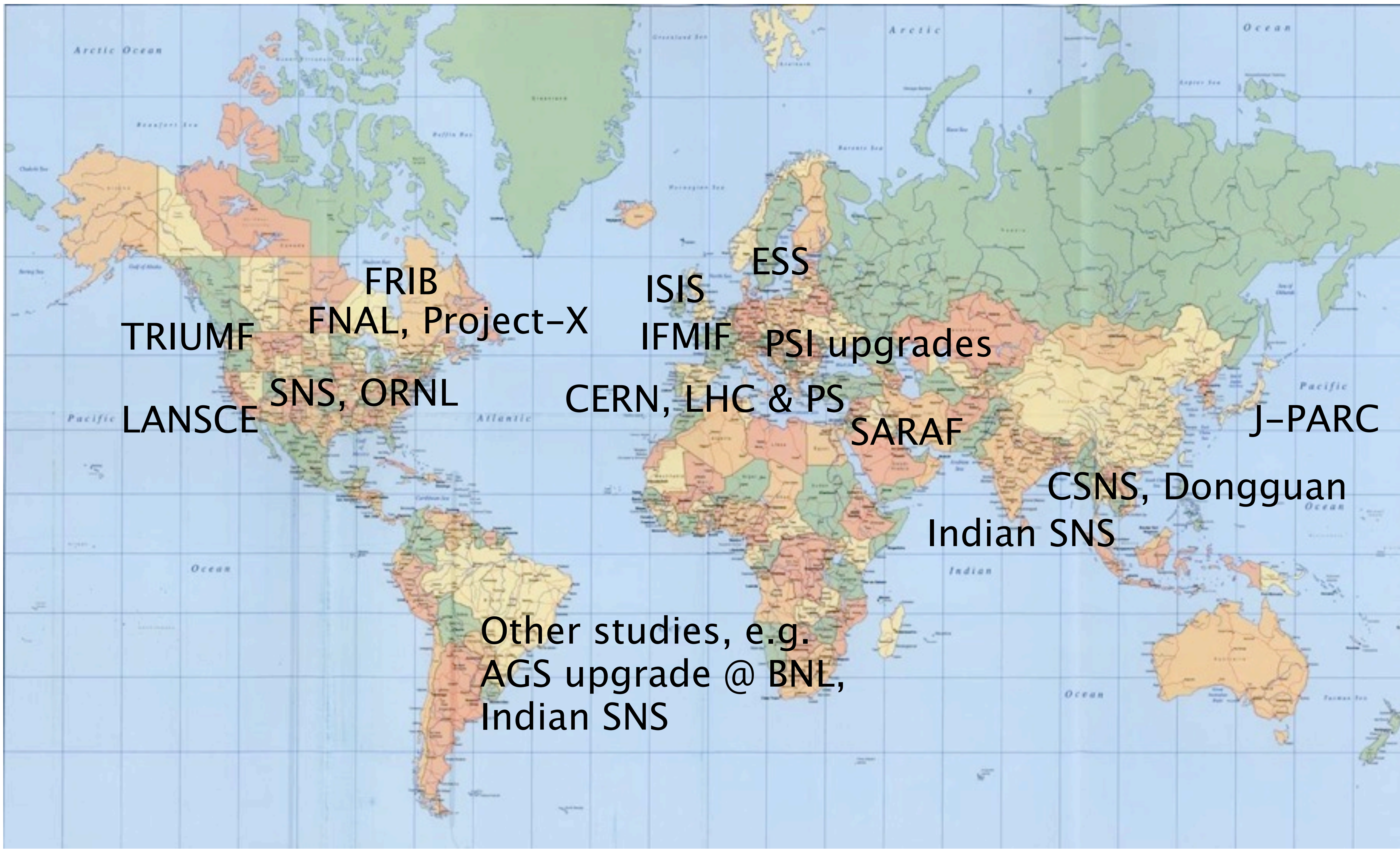
Beam Power Frontier



- Huge step from current status to the level of anticipated future facilities
- Developments at each laboratory take advantage of progress at other laboratories around the world



Different Approaches

- Linac or cw/high rep rate ring directing beam onto a target
  - technological challenges
  - beam dynamics issues
- Linac injecting into accumulator ring
  - additional challenges from accumulation and intensity

Safety paramount: very low beam loss, minimise radiation hazards. Hence demand for very good quality beam. 1 W/m is the accepted goal for uncontrolled beam loss.

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SNS, Spallation Neutron Source

- A short-pulse neutron source, driven by a 1.4 MW proton accelerator
- 1 GeV superconducting H^- linac
- Accumulator ring with ~1000 turn charge exchange injection
- 60 Hz rep. rate
- Operation started October 2006
- Now routinely operating at ~1 MW for almost 5000 hrs/yr, with 85% availability
- 13 neutron scattering instruments

A stepping stone to other high power facilities

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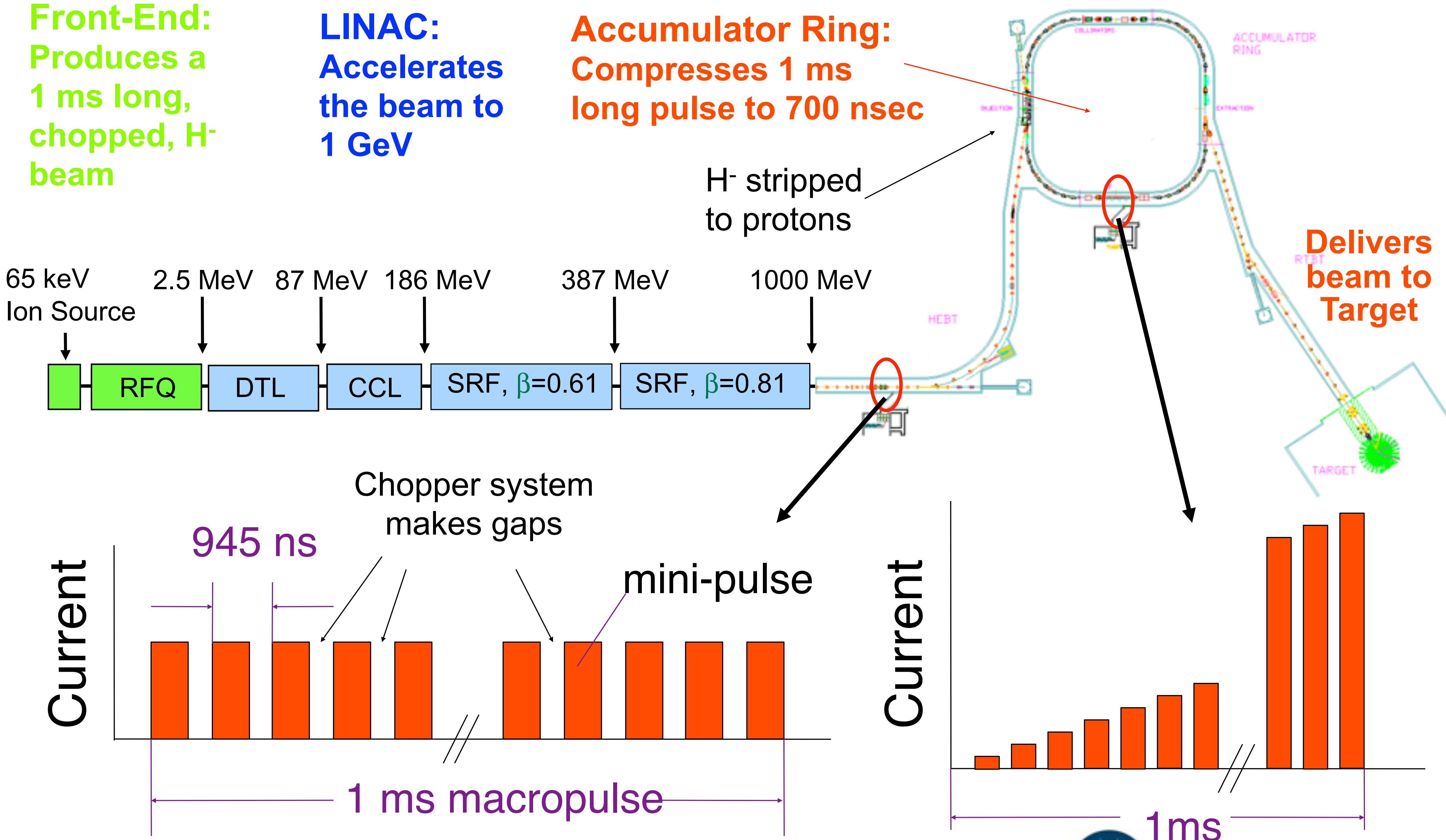
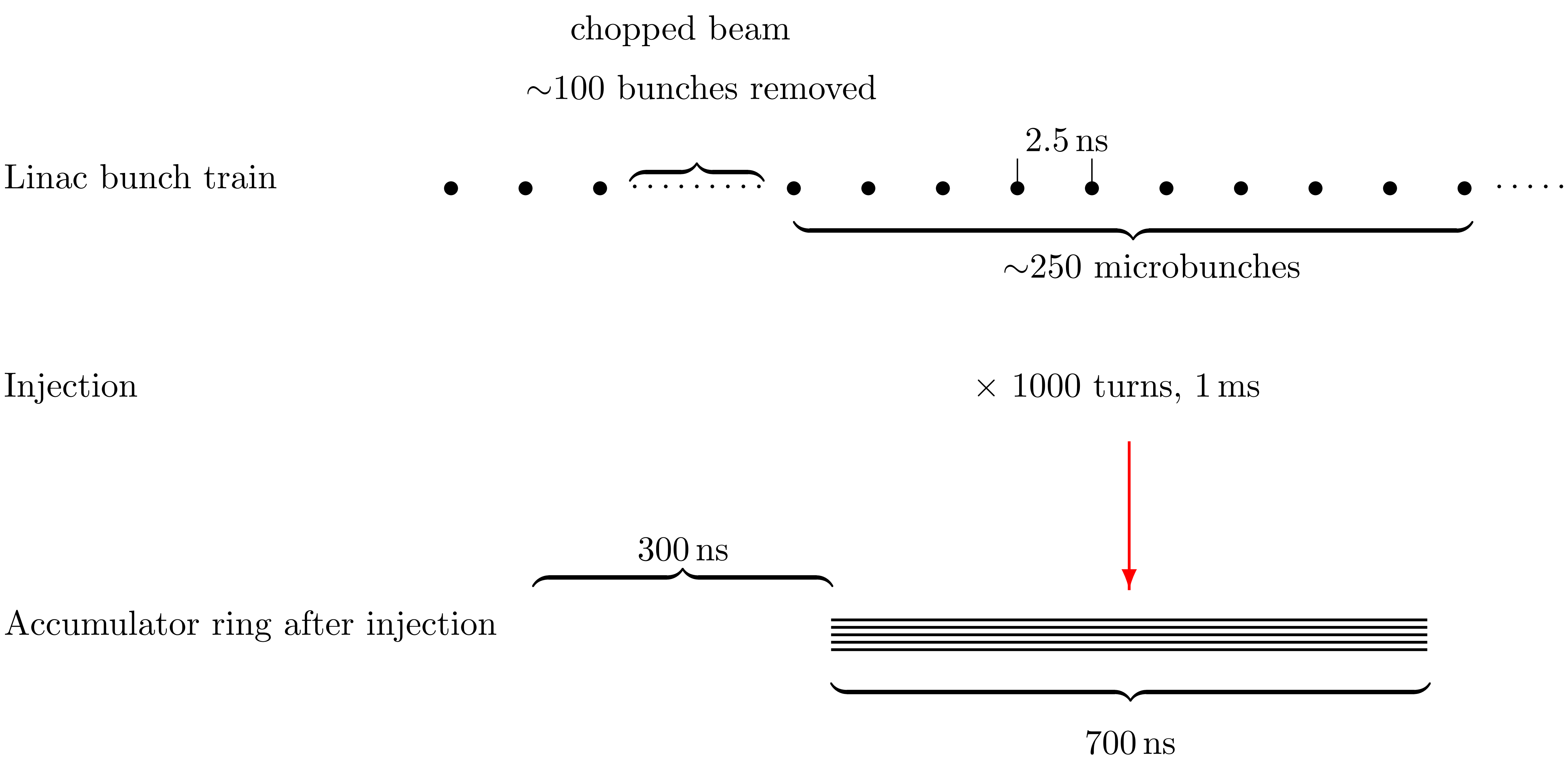
SNS Accelerator Operation





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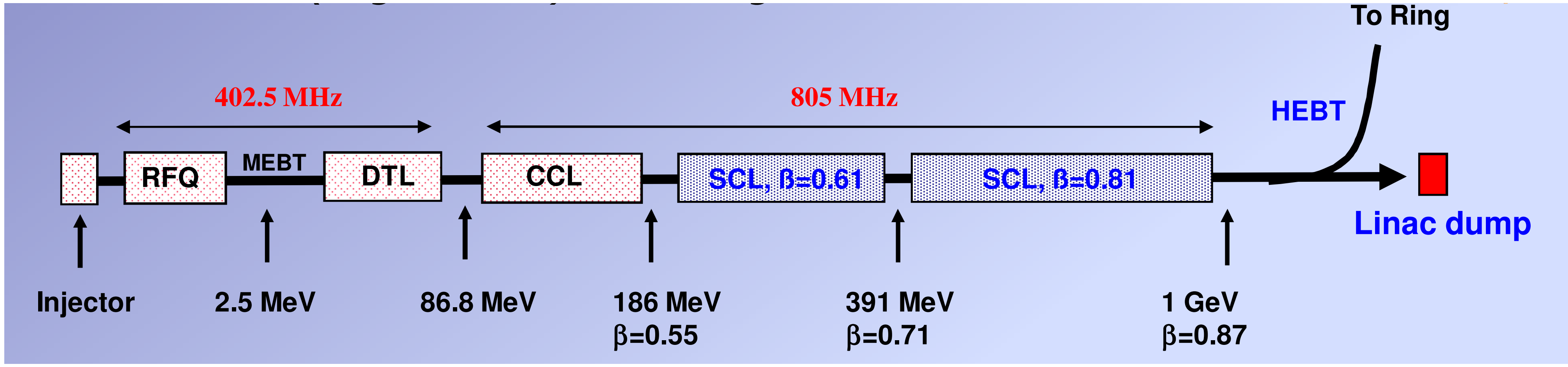
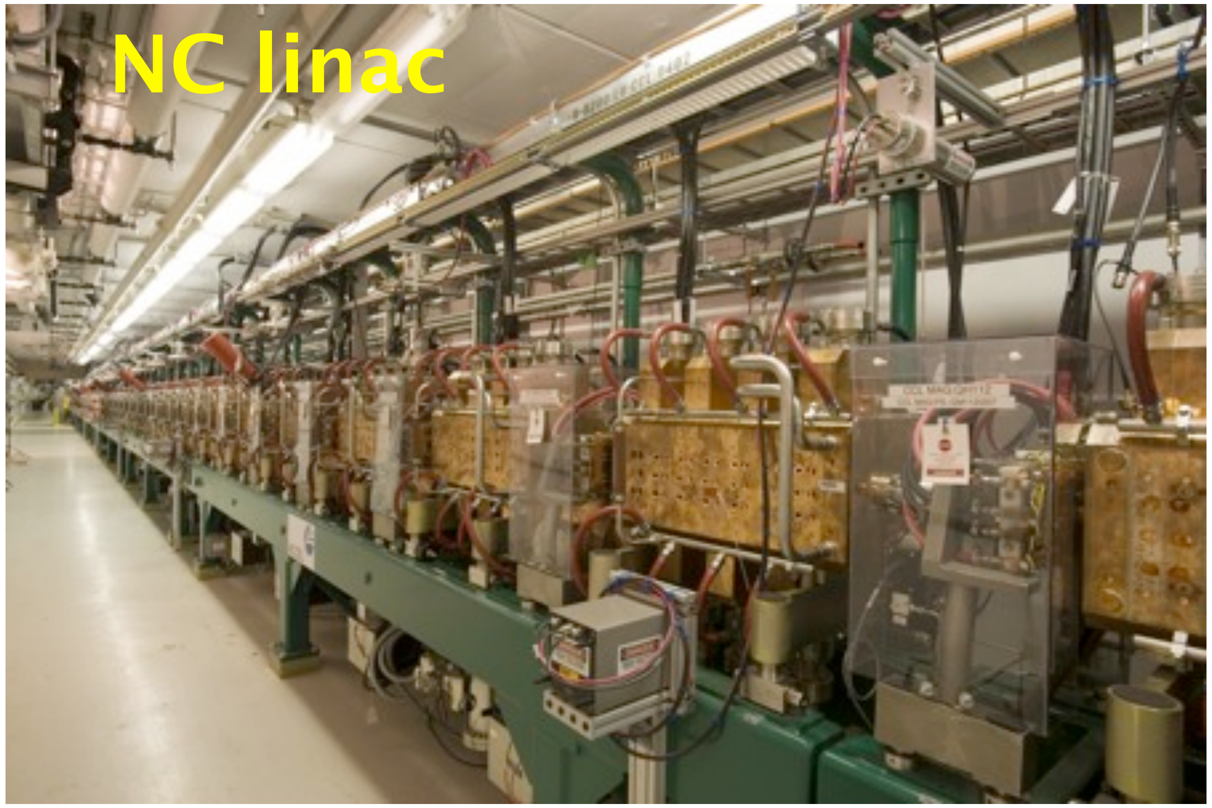
SNS Linac Overview

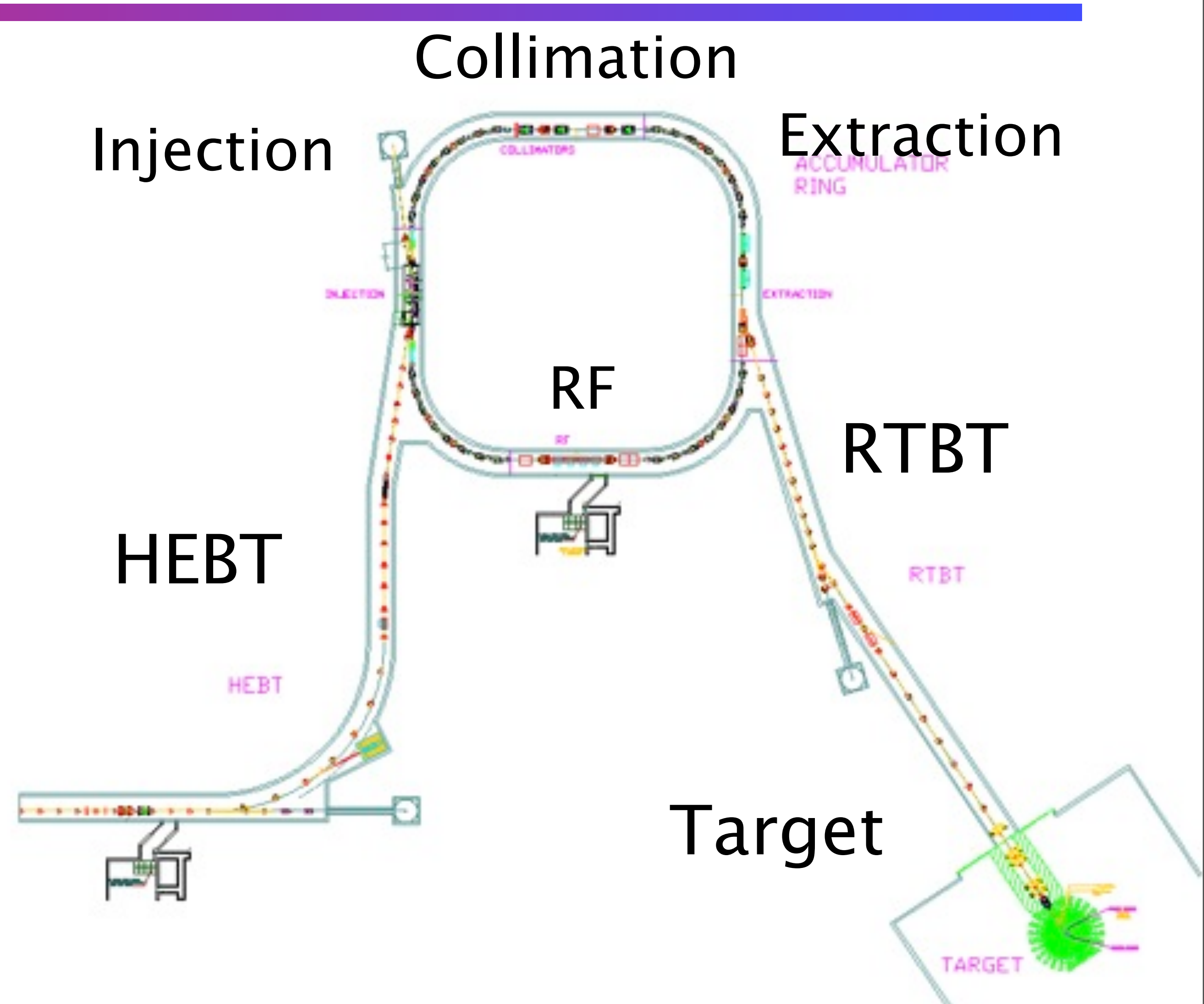


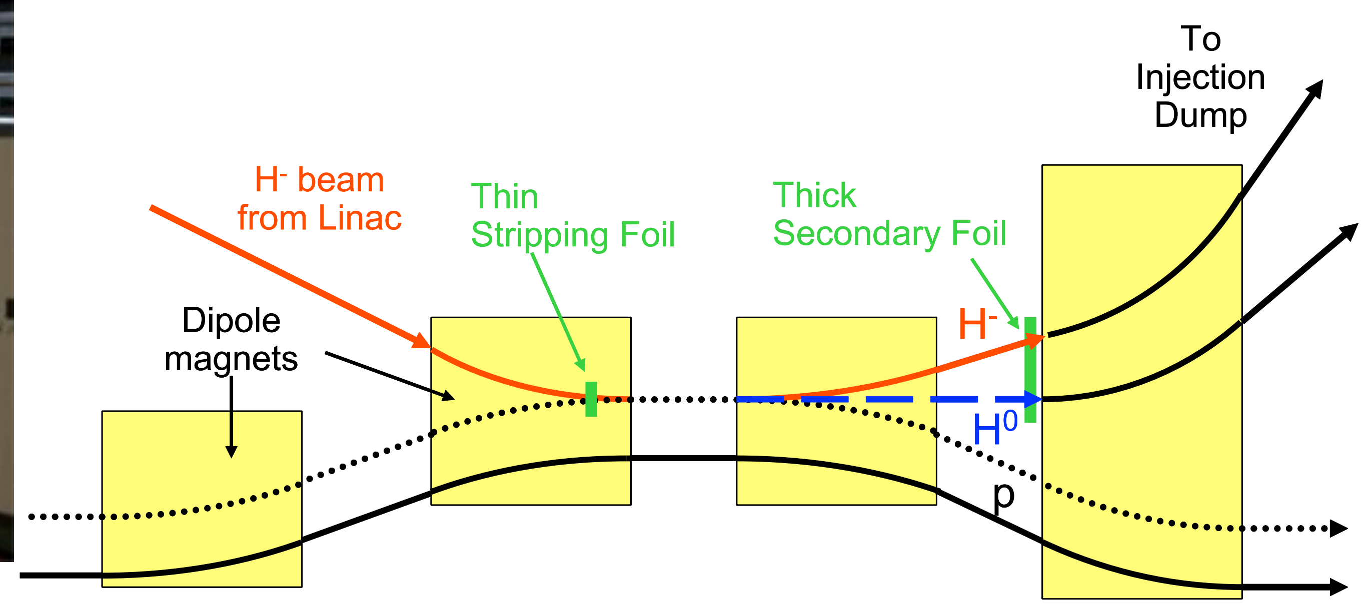
- Linac 260 m, 96 independently phased RF cavity/tanks
- Normal conducting from H^- ion source to 186 MeV
- Superconducting from 186 MeV to 1 GeV



SNS Accumulator Ring

- 90° achromat for transverse and longitudinal collimation.
- Ring circumference 248 m
- Beam injected over ~1000 turns via charge exchange injection.
- Final intensity 1.5×10^{14} ppp
- Pulse 0.2-1.0 ms compressed to ~700 ns.



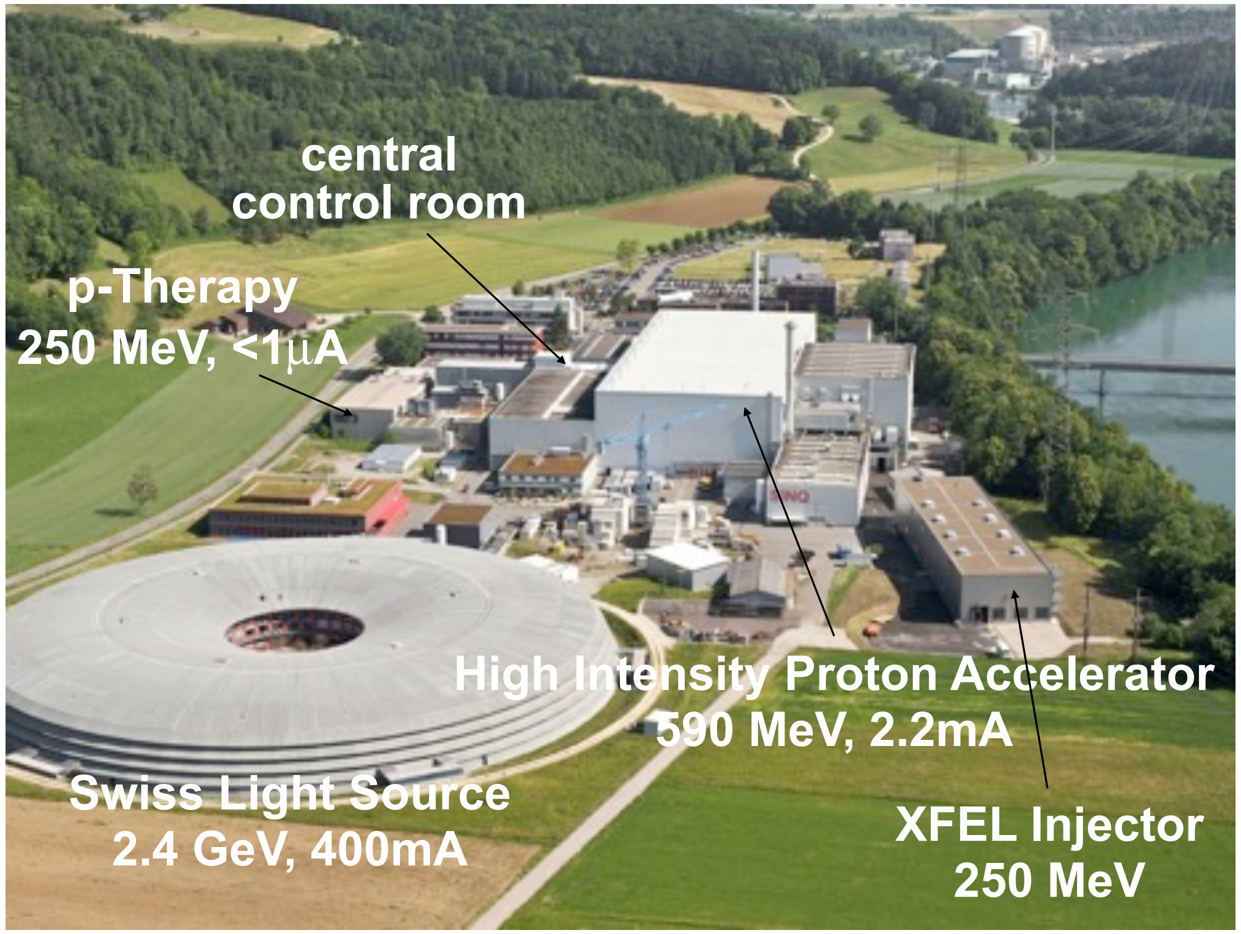


SNS Power Upgrades

- Plans in place to increase the beam power and availability to design values of 1.4 MW and 90% over the next two years.
- Number of instruments to be increased to 16.
- Two upgrade projects at the planning stage
  - increase beam power to ~3 MW by increasing beam energy to 1.3 GeV and increase beam current by 60% (1.4 mA to 2.3 mA)
    - requires additional high ß cavities and ion source upgrade
  - construct a second target powered by sharing beam pulses with the first target station
    - 40 short pulses TS1(2 MW)
    - 20 long pulses TS2 (1 MW, no accumulation)

PSI - Highest Power Neutron Source

- Operates CW
- Optimised for high intensity
- Based on cyclotrons
  - 870 keV Cockcroft Walton Injector
  - 72 MeV injector cyclotron
  - 590 MeV main cyclotron
- Delivers 2.2 mA to spallation neutron target



- 2009 new maximum current: 2.3 mA achieved (1.36 MW).
- Upgrade plans to 1.8 MW by 2013 by improving rf systems.
- Major efforts to improve reliability above 90% and reduce beam loss to 10^{-4}.

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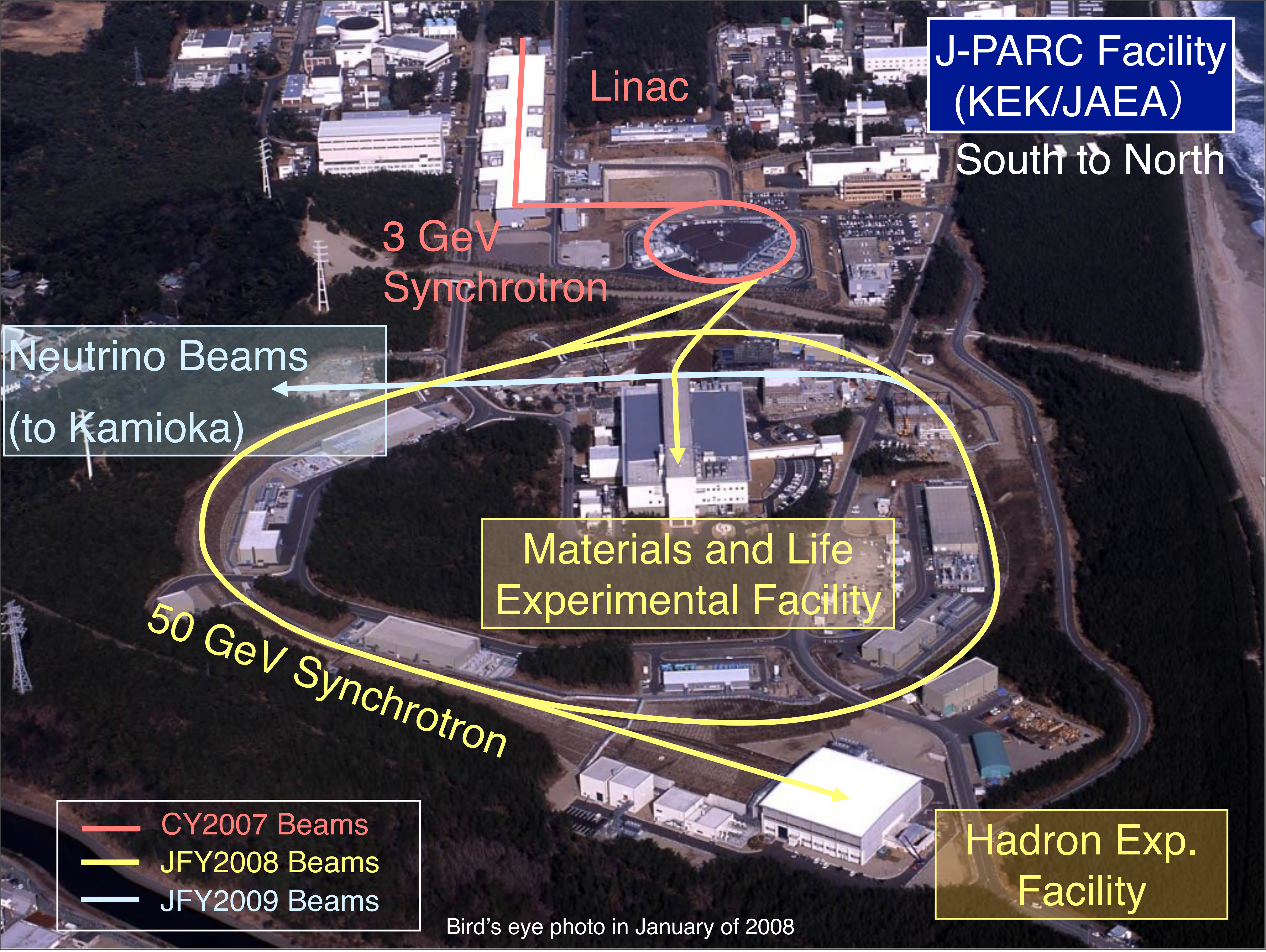
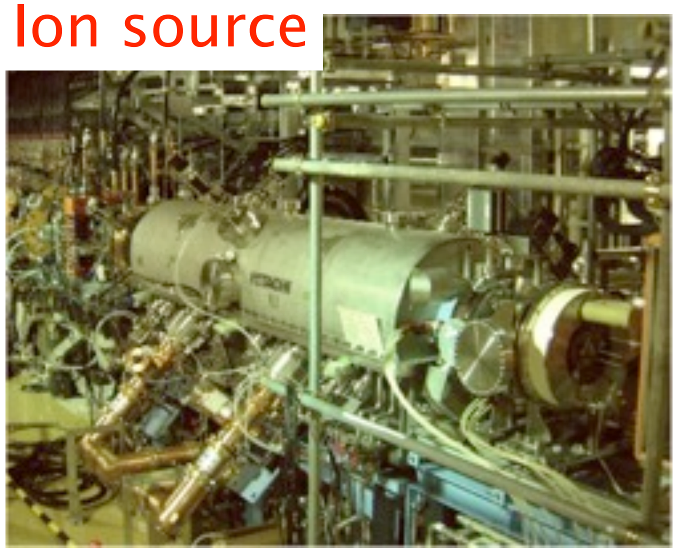

J-PARC Facility
(KEK/JAEA)
South to North
Linac
3 GeV
Synchrotron
Neutrino Beams
(to Kamioka)
Materials and Life
Experimental Facility
50 GeV Synchrotron
Hadron Exp.
Facility
CY2007 Beams
JFY2008 Beams
JFY2009 Beams
Bird's eye photo in January of 2008

J-PARC H^- Linac

Phase I: 181 MeV, peak current 30 mA ⇒ 0.6 MW from RCS at 25 Hz

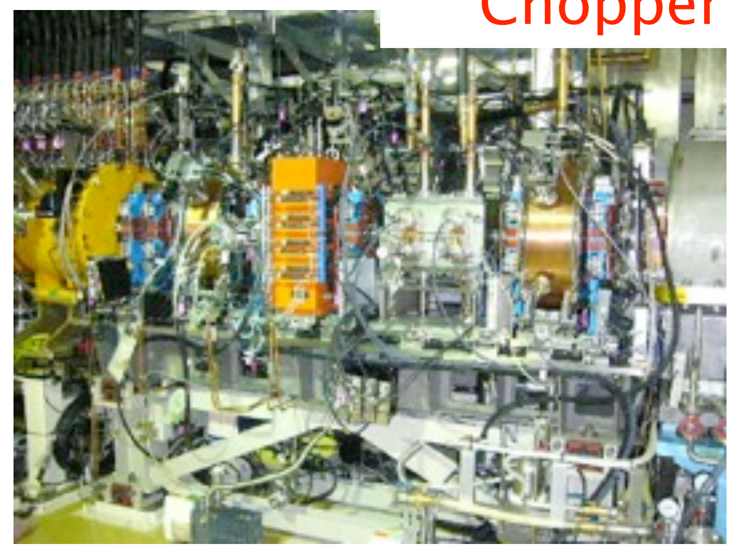
Phase II: 400 MeV, 50 mA ⇒ 1 MW from RCS

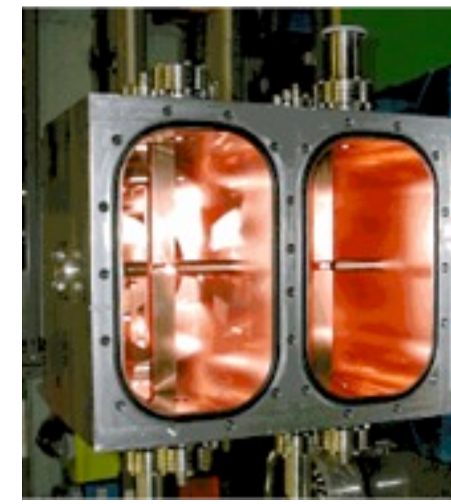
Ion source



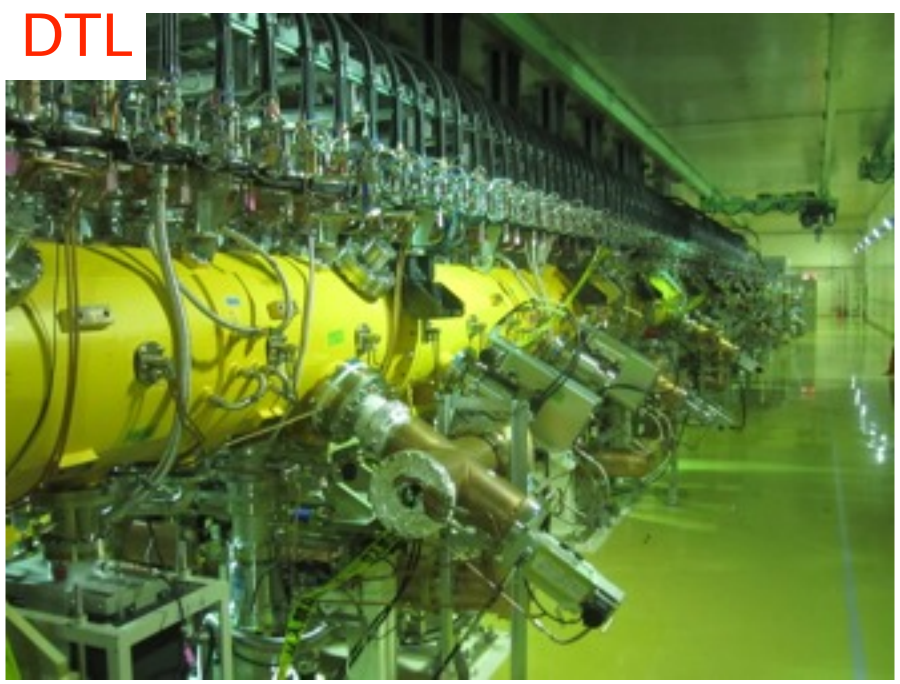
RFQ

Chopper and MEBT



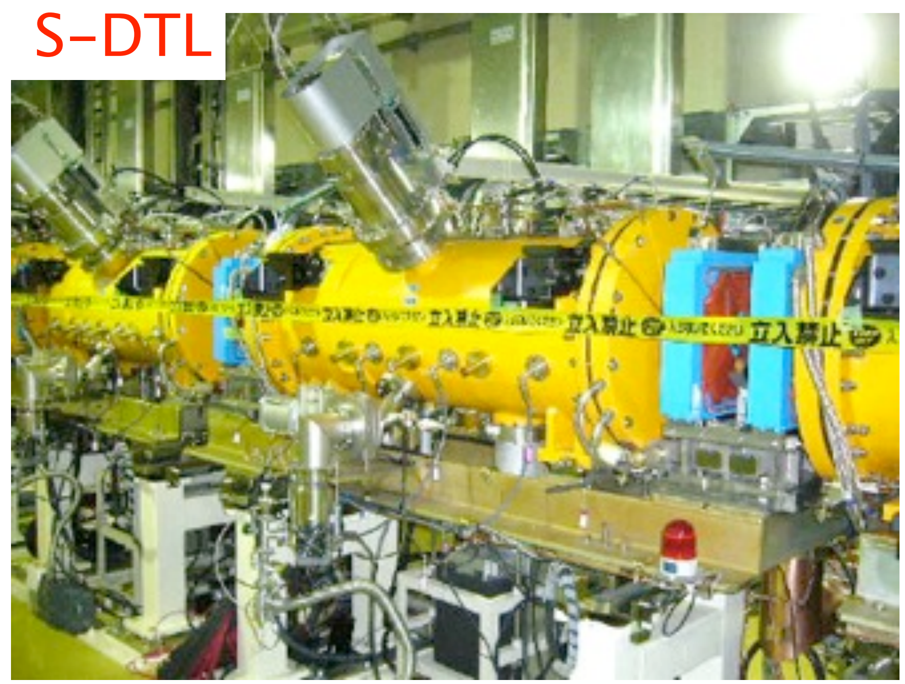


DTL



DTL: Linac commissioned June 2007

S-DTL



Additional structures to 400 MeV (2012), superconducting to 600 MeV

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Quadrupole transfer line from
180 MeV linac being removed

New ACS accelerating structures
for 180-400 MeV section;
currently being installed.

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3 GeV Rapid Cycling Synchrotron Ring

Booster synchrotron, 25 Hz, 333 μA, 1 MW, fast extraction

50 GeV Main Ring

Slow cycling, 0.3 Hz, 15 μA, 50 GeV, 0.75 MW proton beam to hadron and neutrino beam facilities.

Beam commissioned May 2008. 30 GeV in Phase I. Eventual upgrade path to 5 MW

gy

ESS, European Spallation Source

ESS: A Long Pulse Facility

Collaboration of European countries

Expected construction 2013–2018

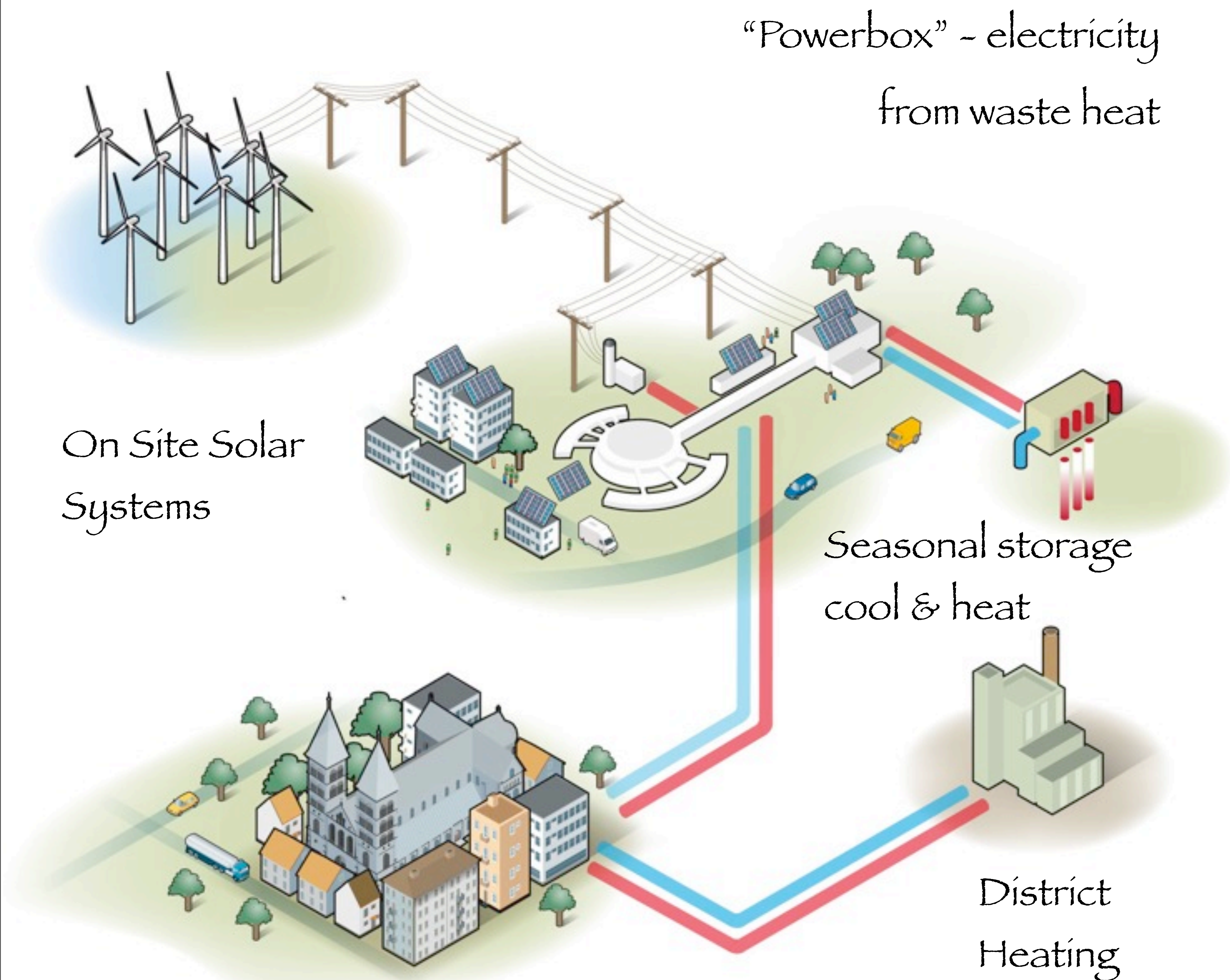
First neutrons 2019

- Optimised for 5 MW (upgradeable to 7.5 MW)
- 2.9 ms pulses of protons
- 14 Hz rep. rate (➟17 Hz?)
- 2.5 GeV energy (➟3.5 GeV?)
- 60 mA ion source current (➟100 mA?)
- Low losses <1 W/m
- High reliability, ≥ 95%
- Single target station; upgrade could include a second target with interleaved 40 Hz operation

Facility cost 1377 M€ with 22 instruments + 101 M€ site specific costs

Operating costs 89 M€$_{2008}$ per year

ESS: A Green Facility



Include research, development & demonstration of emerging energy technologies.

Goal: carbon neutrality.

E.g. options on wind turbine farms

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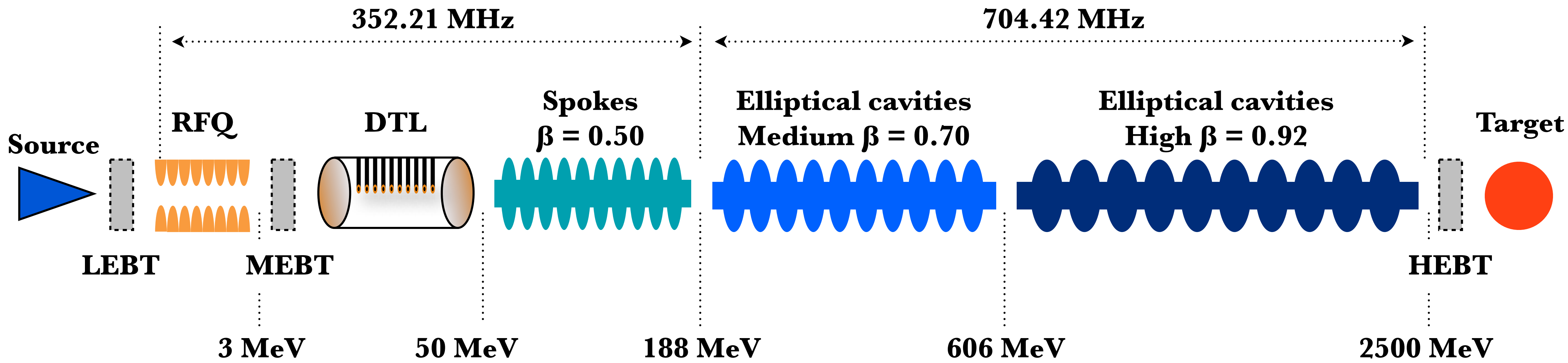
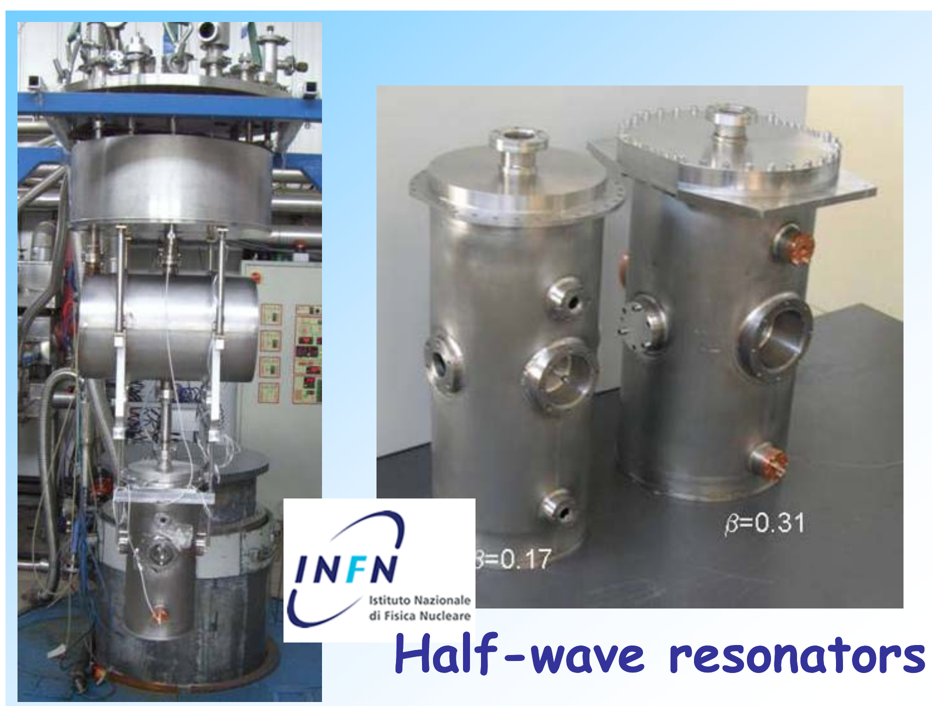
ESS Linac



Energy 2.5 GeV
Ion source current 60 mA (upgrade to 100 mA)



Half-wave resonators

Spoke resonators

ESS prototyping: two half-wave resonators @325 MHz (β=0.17, β=0.31) and two spoke resonators @325 MHz (β=0.15, β=0.35) fabricated and successfully tested

Chinese SNS, Dongguan

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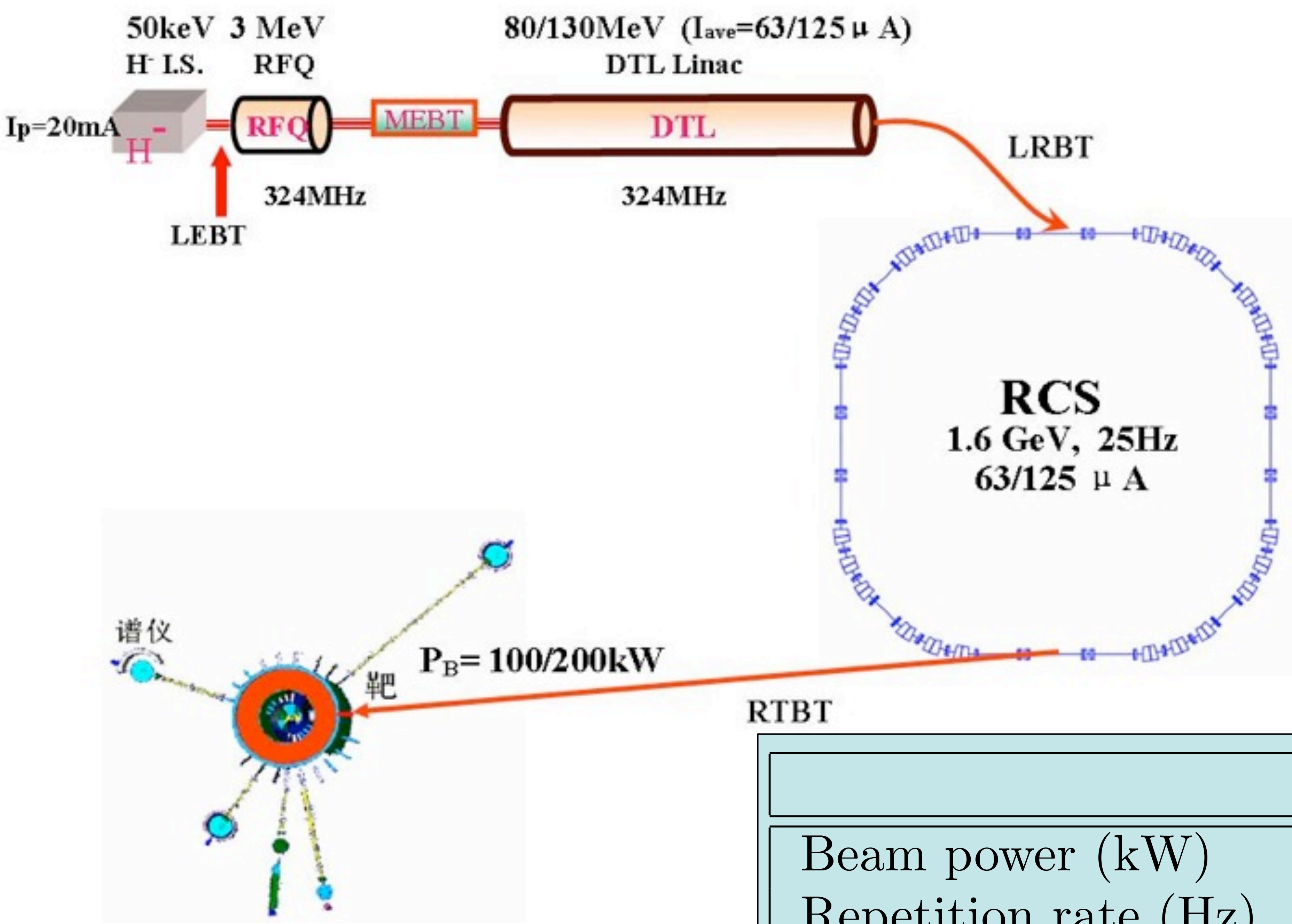
324 MHz RF linac providing 80 MeV H⁻ beam to 1.6 GeV RCS



- ✳ Penning ion source under construction
- ✳ RFQ technology developed in ADS study
- ✳ Upgrade path to 200 kW

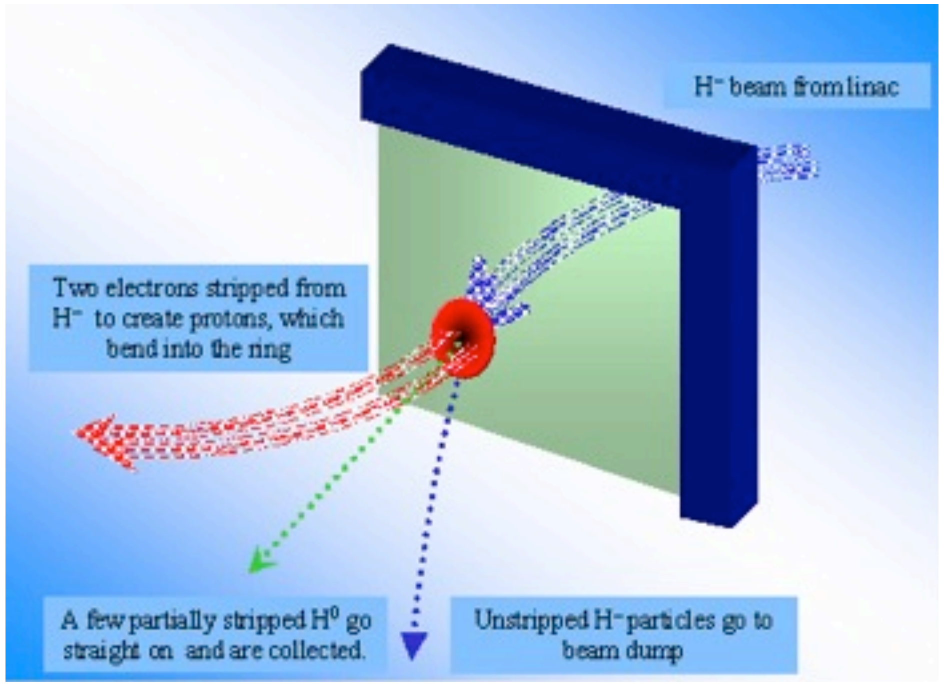
	CSNS-I	CSNS-II
Beam power (kW)	100	200
Repetition rate (Hz)	25	25
Average current (μA)	62.5	125
Proton energy (GeV)	1.6	1.6
Linac energy (MeV)	80	132

Main Issues (1)

- Accelerator **design options**
  - Cyclotrons (PSI) or FFAGs
  - Full energy linac and accumulator/storage rings (e.g. SNS, ESS)
  - Low/intermediate energy linac, booster RCS, main accelerating ring (synchrotron or FFAG) (e.g. J-PARC, CSNS, ISIS)
- Requirement for **very low uncontrolled beam loss** throughout machine (0.1-1 W/m average)
  - fast beam chopper in linac, achromats and advanced collimation systems
- **Beam characterisation**, especially in the low energy stages
  - advanced diagnostics
- **Halo formation**, emittance growth and control in linacs
  - minimise longitudinal halo
- **RF**: Linac frequencies, choice of cavities, frequency jump, HOM, damage to SC cavities from beam loss
- Operational beam loss: Intra-beam stripping in H^- linacs

Main Issues (2)

- **Transverse and longitudinal matching**
- **Charge exchange injection H⁻→H⁺**
  - Foil issues: Stripping efficiencies, Multiple Coulomb scattering, Large angle and Nuclear scattering, Energy straggling, Heating, Stress and buckling, Lifetime, Radiation, Stripped Electrons, Emittance Growth
  - Laser stripping (incl. cw beams)
  - Unstripped beam (H^0, H^-)
- Beam accumulation, phase space painting
  - Transverse and longitudinal coupling, options for transverse painting, options for longitudinal painting
- Trapping and acceleration in rings
  - instability studies, space charge mitigation, halo, emittance growth, electron cloud



Main Issues (2)

- **Transverse and longitudinal matching**
- **Charge exchange injection $H^- \rightarrow H^+$**
  - Foil issues: Stripping efficiencies, Multiple Coulomb scattering, Large angle and Nuclear scattering, Energy straggling, Heating, Stress and buckling, Lifetime, Radiation, Stripped Electrons, Emittance Growth
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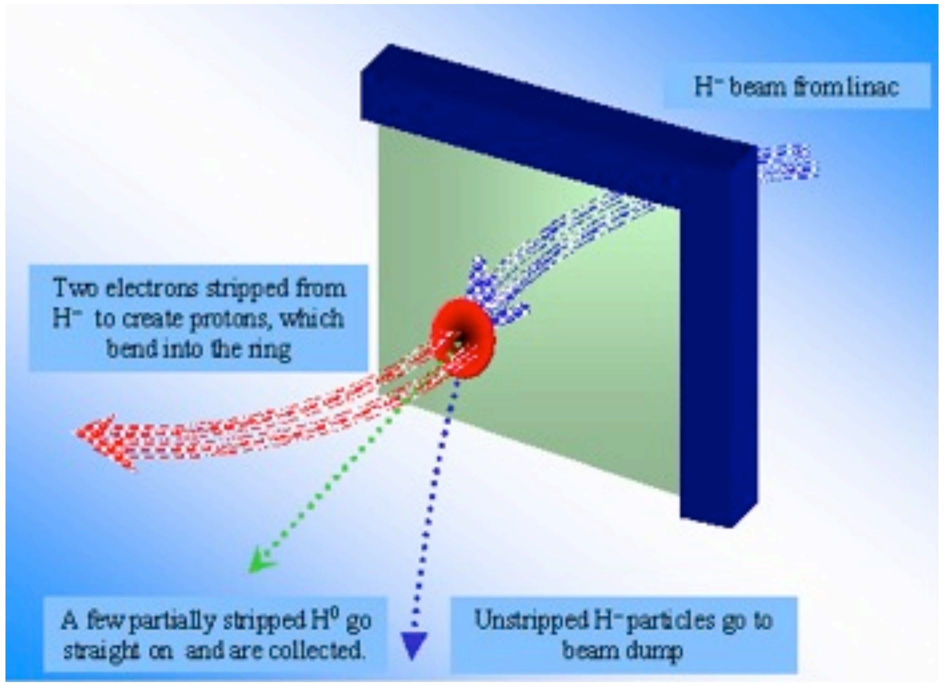
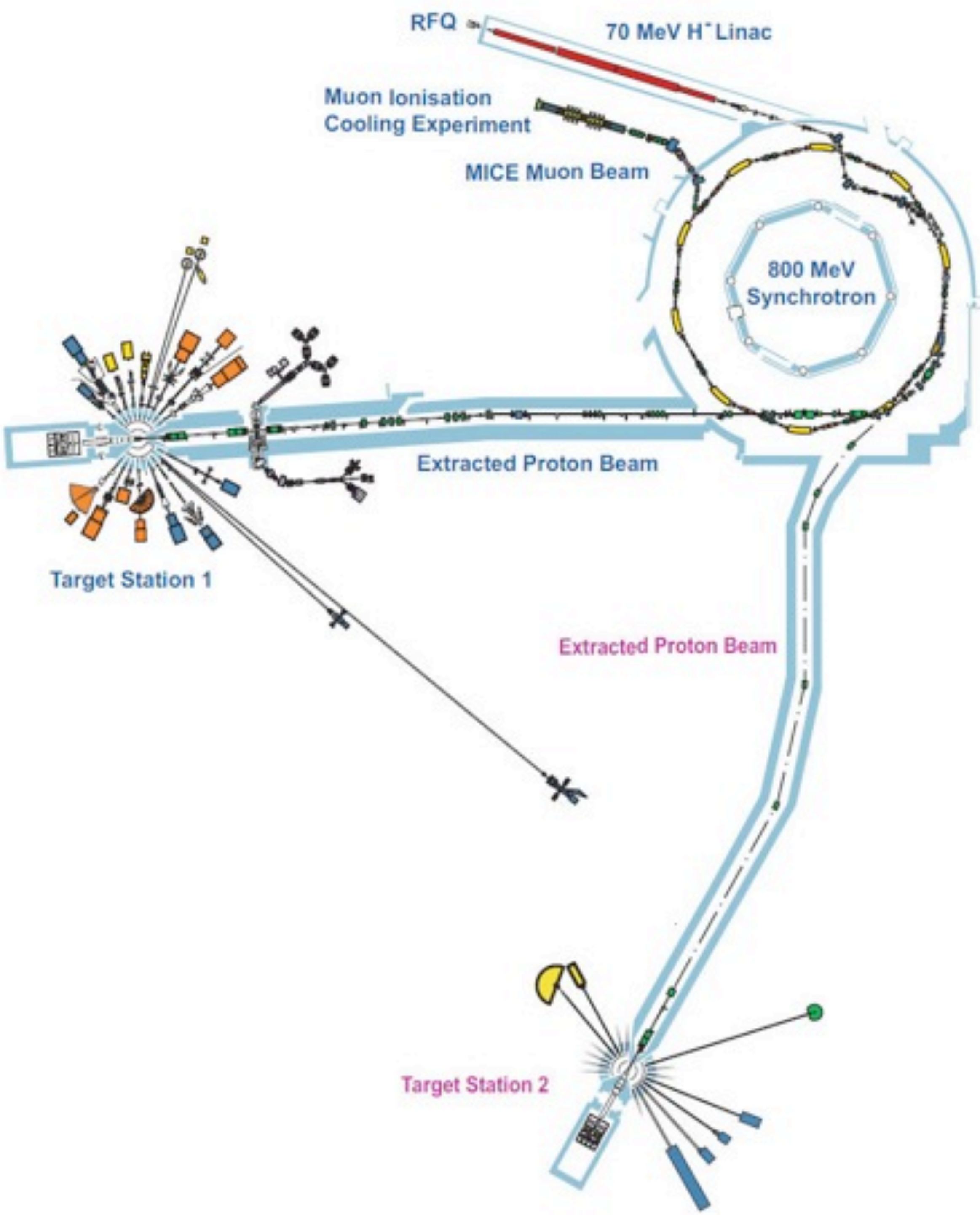


- Trapping and acceleration in rings
  - instability studies, space charge mitigation, halo, emittance growth, electron cloud

ISIS
Spallation Neutron Source

ISIS - present



- 70.44 MeV H^- linac
- Charge exchange injection into 800 MeV RCS
- 50 Hz operation
- 200 µA, 160 kW
- Two target stations, at 40 Hz and 10 Hz
- Dual harmonic RF system to upgrade to ~240 kW
- Otherwise intensity limited by space charge

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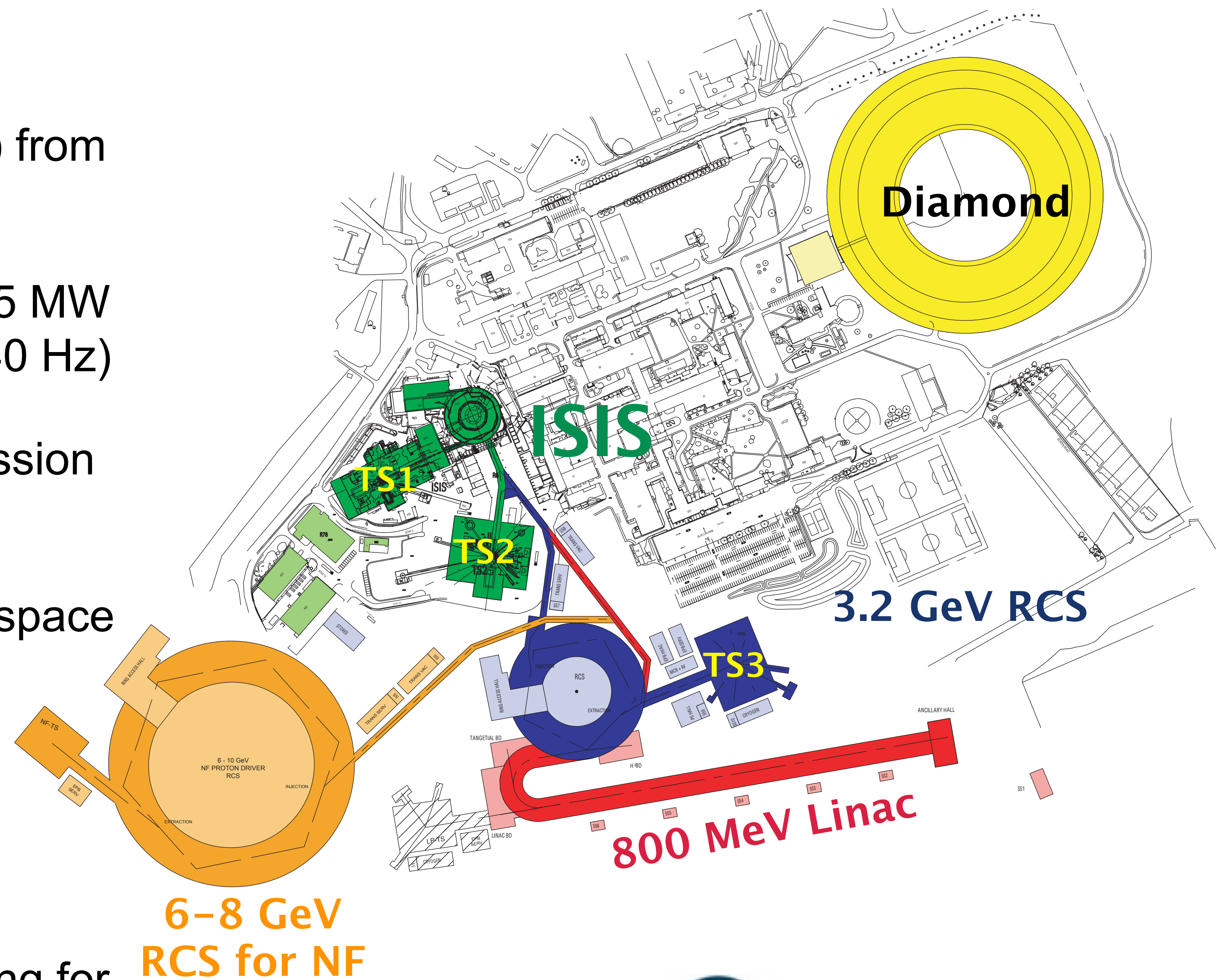
ISIS Power Upgrades

- Replacement linac with increase in injection energy to ~180 MeV
- Add new 3.2 GeV synchrotron
  - Bucket-bucket transfer (2 bunches) from ISIS
  - Simple energy increase gives ~0.75 MW to new neutron production target (40 Hz)
- Add new 800 MeV H^- linac (decommission the old ISIS?)
  - Charge exchange injection, phase space painting
  - 2 MW at 30 Hz, ~5 MW at 50 Hz
  - All bunches for neutron production
  - or transfer some bunches to new ring for neutrino factory driver



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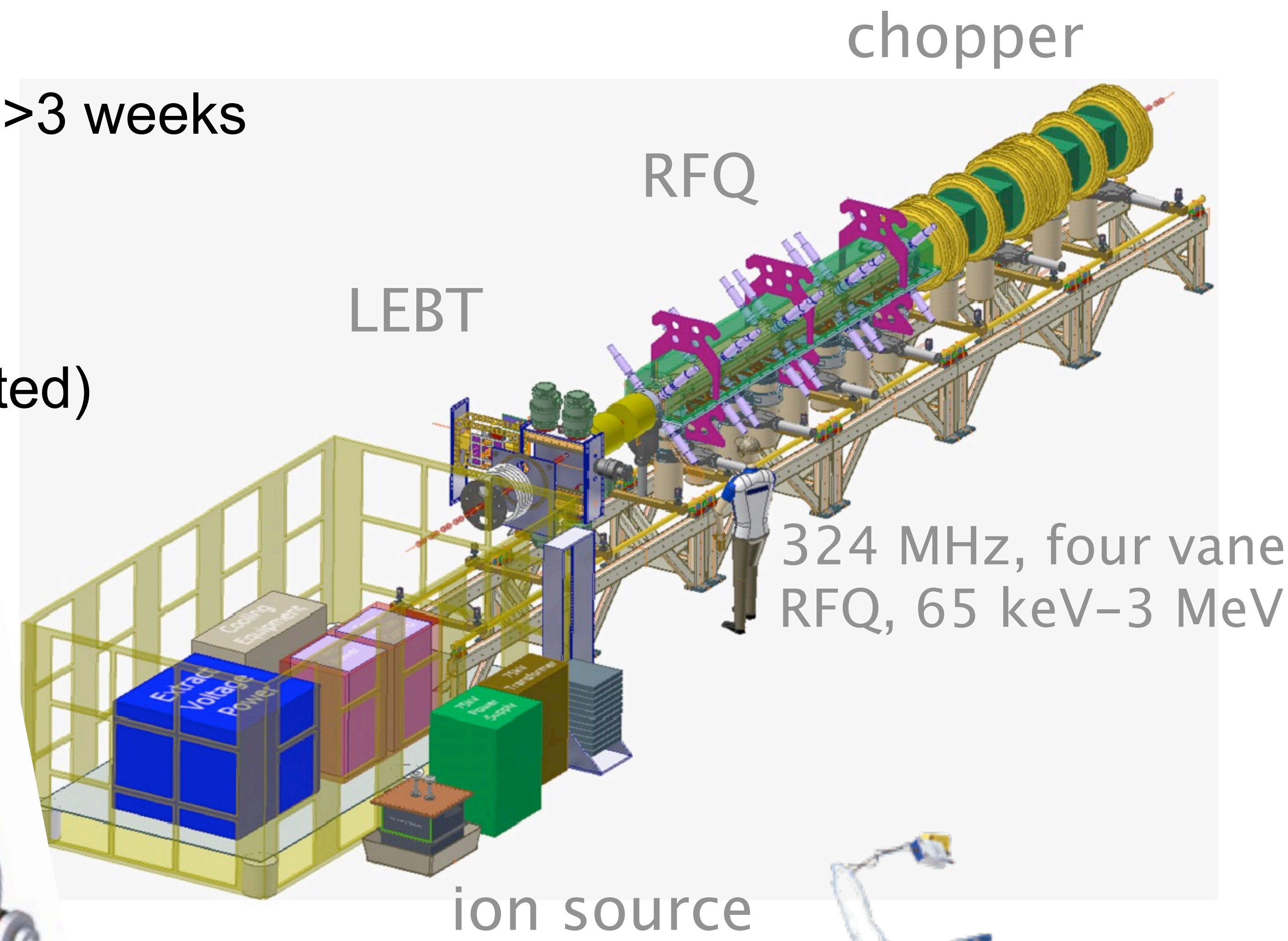
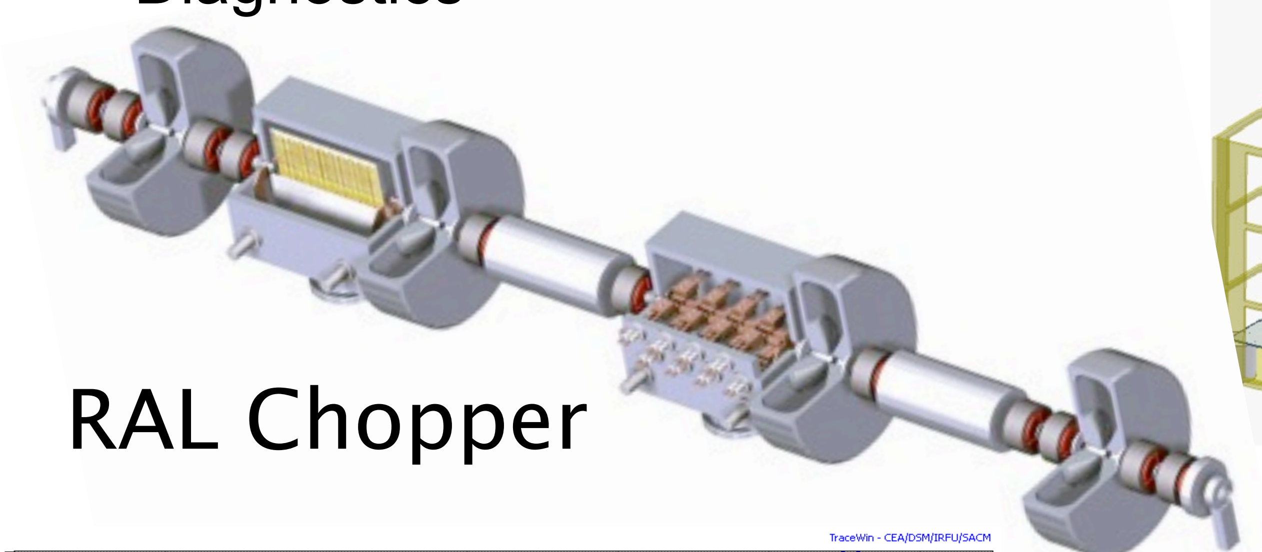
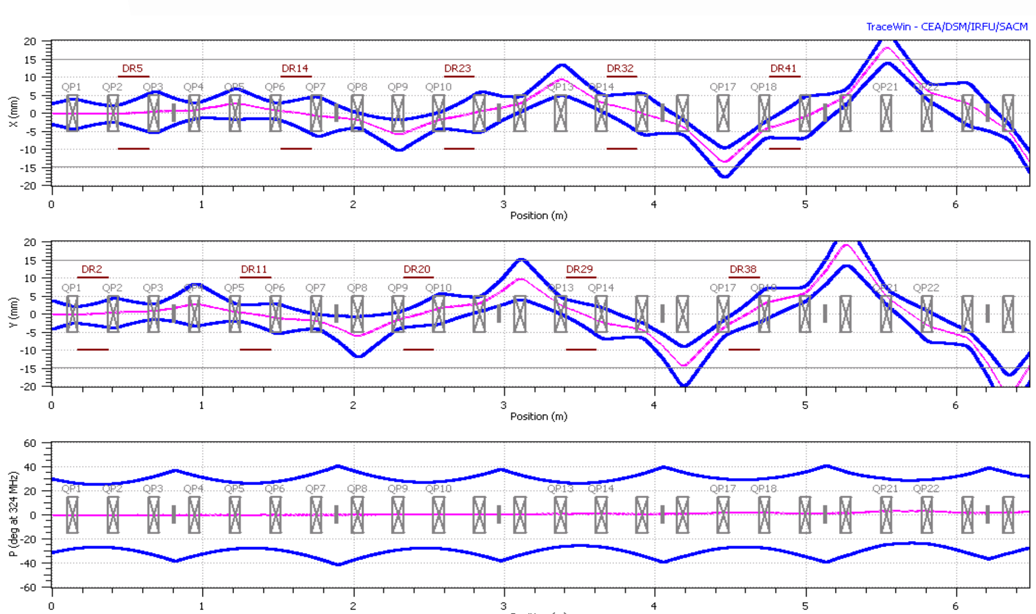
Linac Front-End Project, FETS

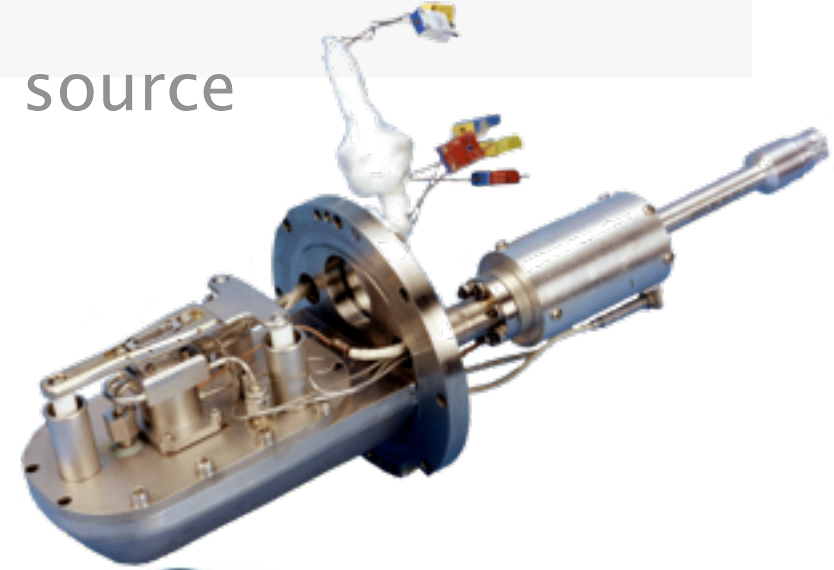
- H^- Ion source development
  - 60 mA, up to 2 ms pulse, lifetime >3 weeks
- RFQ design
  - 4 vane, 324 MHz
- Fast beam chopper (tandem, distributed)
- Diagnostics





RAL Chopper

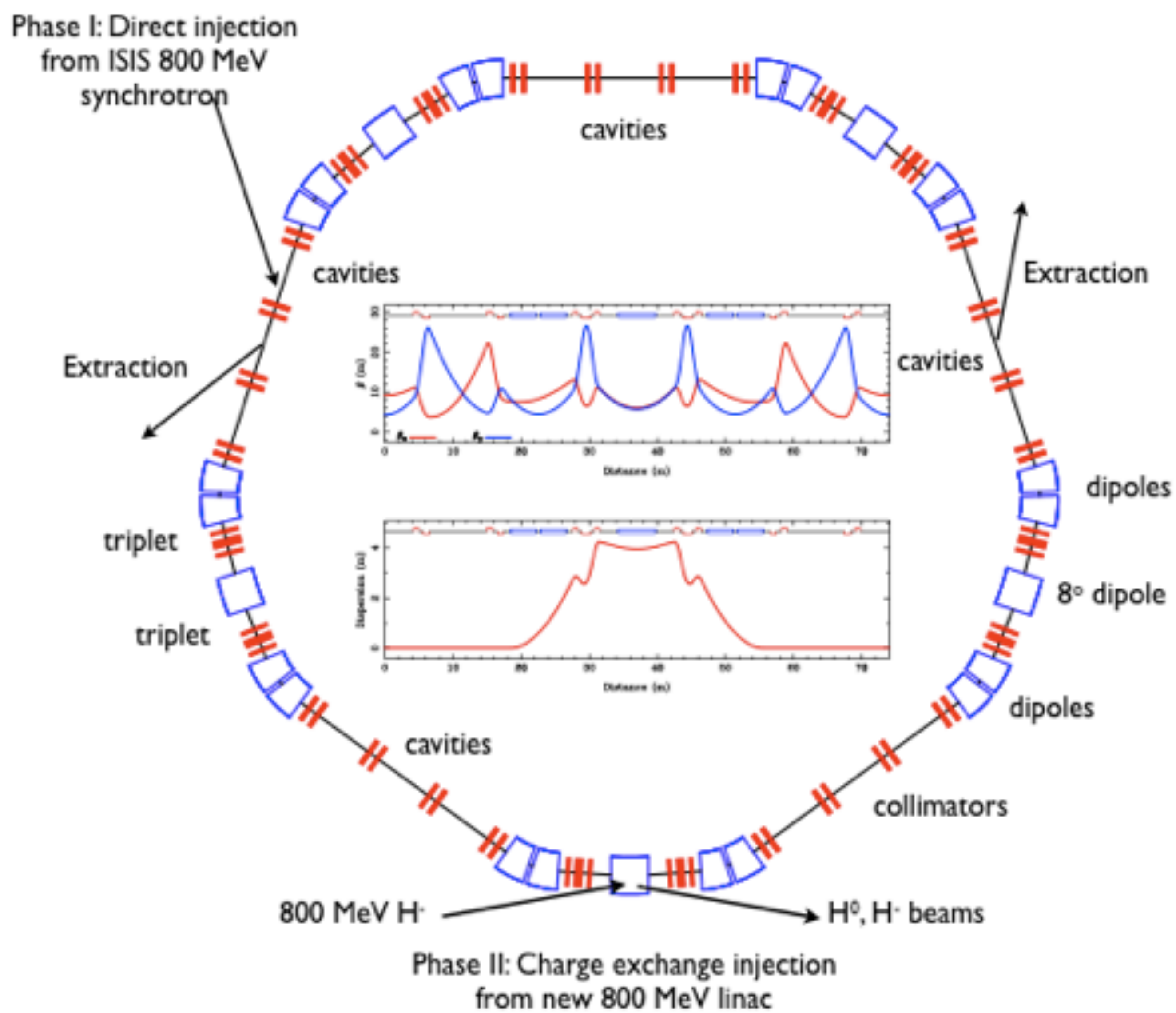




Penning H^- ion source,
60 mA, 2 ms, 50 Hz

Rapid Cycling Synchrotron Upgrade Ring

Energy	0.8-3.2 GeV
Repetition Rate	50 Hz
Circumference (2.5× ISIS)	408.4 m
Transition γ_t	7.2
Harmonic number h	5
RF sweep f_{RF}	6.1-7.1 MHz
Peak RF voltage V_{RF}	$\sim$750 kV
Peak tune depression ΔQ_{sc}	$\sim$ 0.1
Longitudinal emittance ϵ_L	$\sim$1.5 eV.s
Magnetic guide field $B(t)$	sinusoidal



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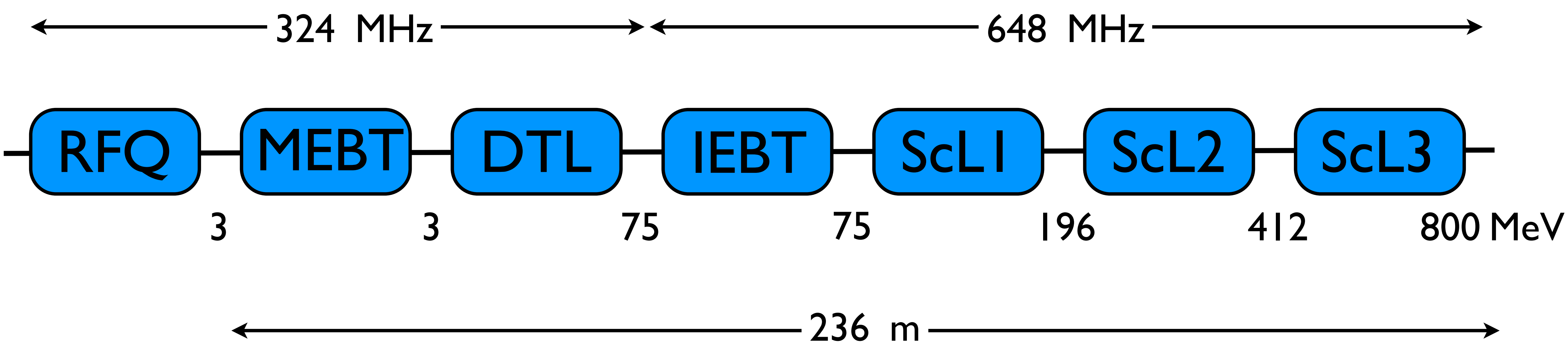
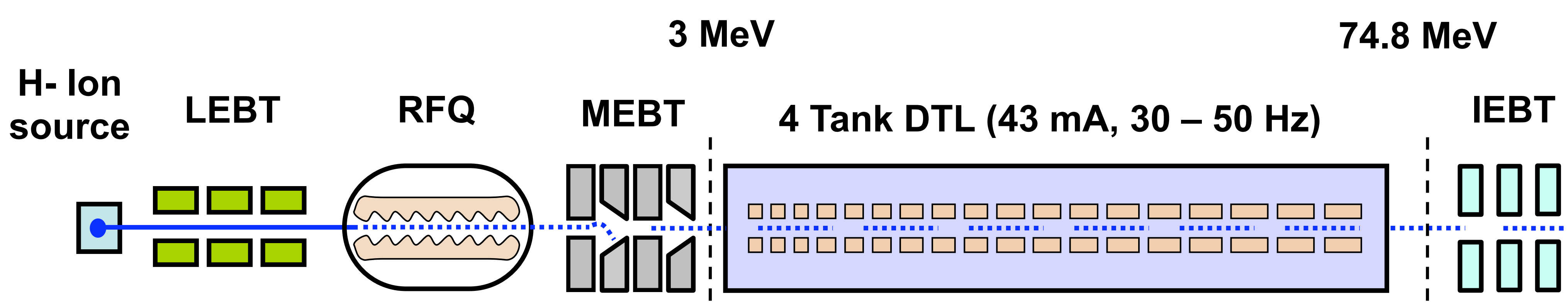
800 MeV H- ISIS Upgrade Linac



- Based on J-PARC frequency, 324 MHz
- Intermediate energy beam transport section to remove longitudinal halo
- Superconducting from 75 MeV
- RFQ and MEBT chopper based on FETS



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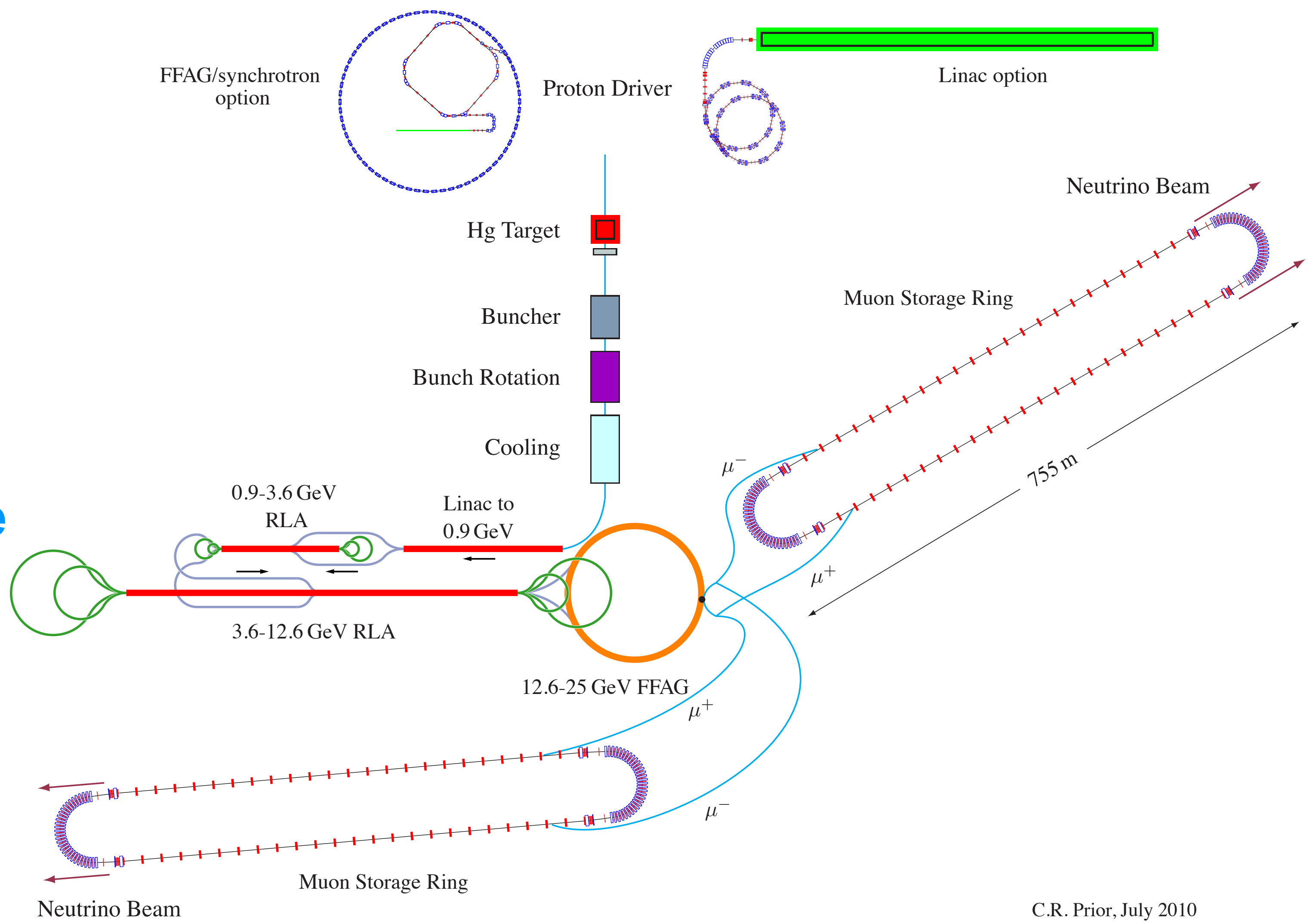
Neutrino Factory

- Proton driver
  - **Primary beam on production target**
- Target, capture channel
  - **Create π, decay to μ**
- Cooling
  - **Reduce transverse emittance**
- Muon acceleration
  - **130 MeV to 10-50 GeV**
- Decay ring(s)
  - **Store for ~500 turns**
  - **Long production straights**



Additional requirements are that the proton pulse contains 1-3 bunches and the driver must compress the proton bunches to 1-3 ns, then hold in a compressed state for ~150 μs.

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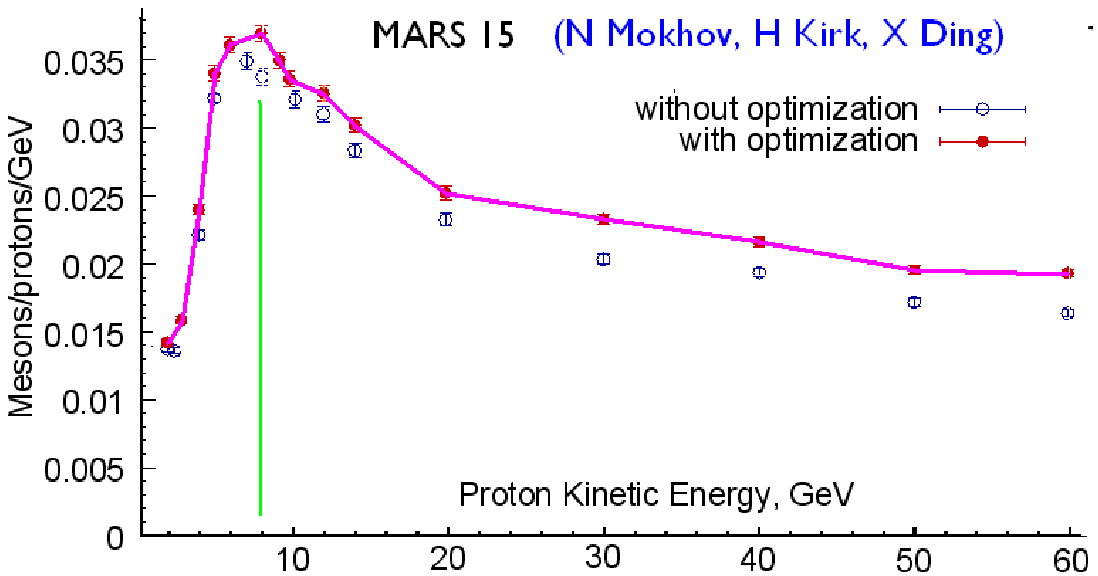
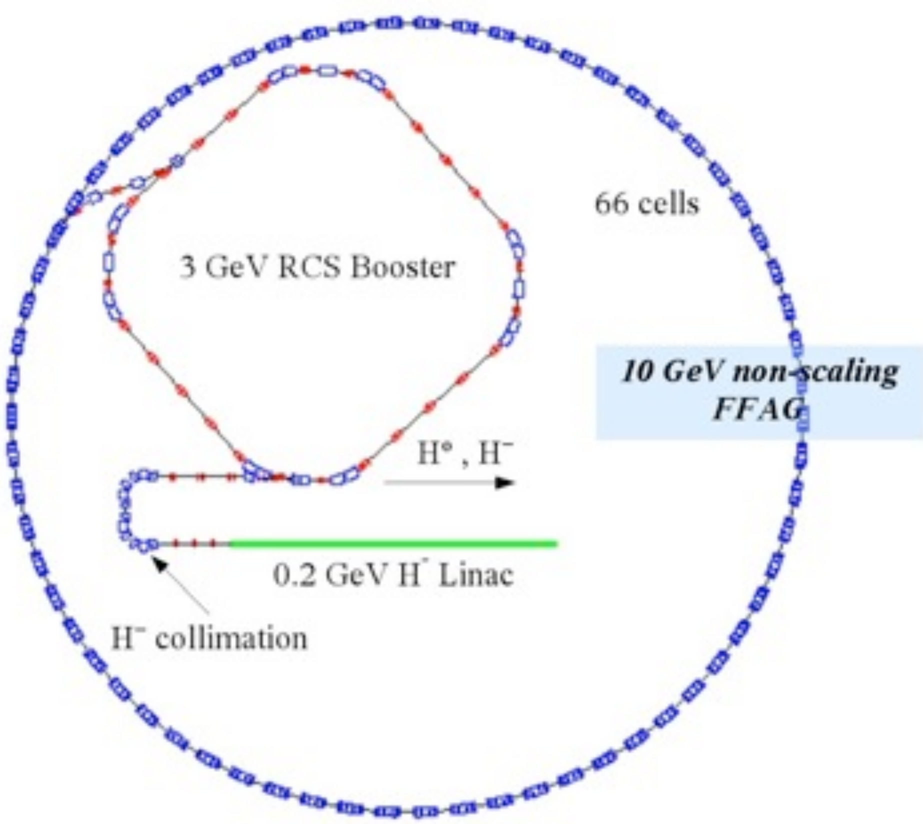
NF Proton Drivers

4 MW, 50 Hz, energies in range 5–15 GeV





- Choice of energy dictated by pion production from target
- Specific models developed for NF/MC purposes
- Meet specific pulse structure requirements
  - 3 bunches per pulse
  - compressed to ~2 ns
  - held in driver and sent to target at required time separation
- Could be linac plus accumulator and compressor rings (CERN) or combination of RCS booster (for accumulation) and synchrotron or FFAG main ring (for acceleration and compression) ideally have a purpose-built design for NF
  - **but economic considerations may lead to compromise by adapting/extending existing machine**

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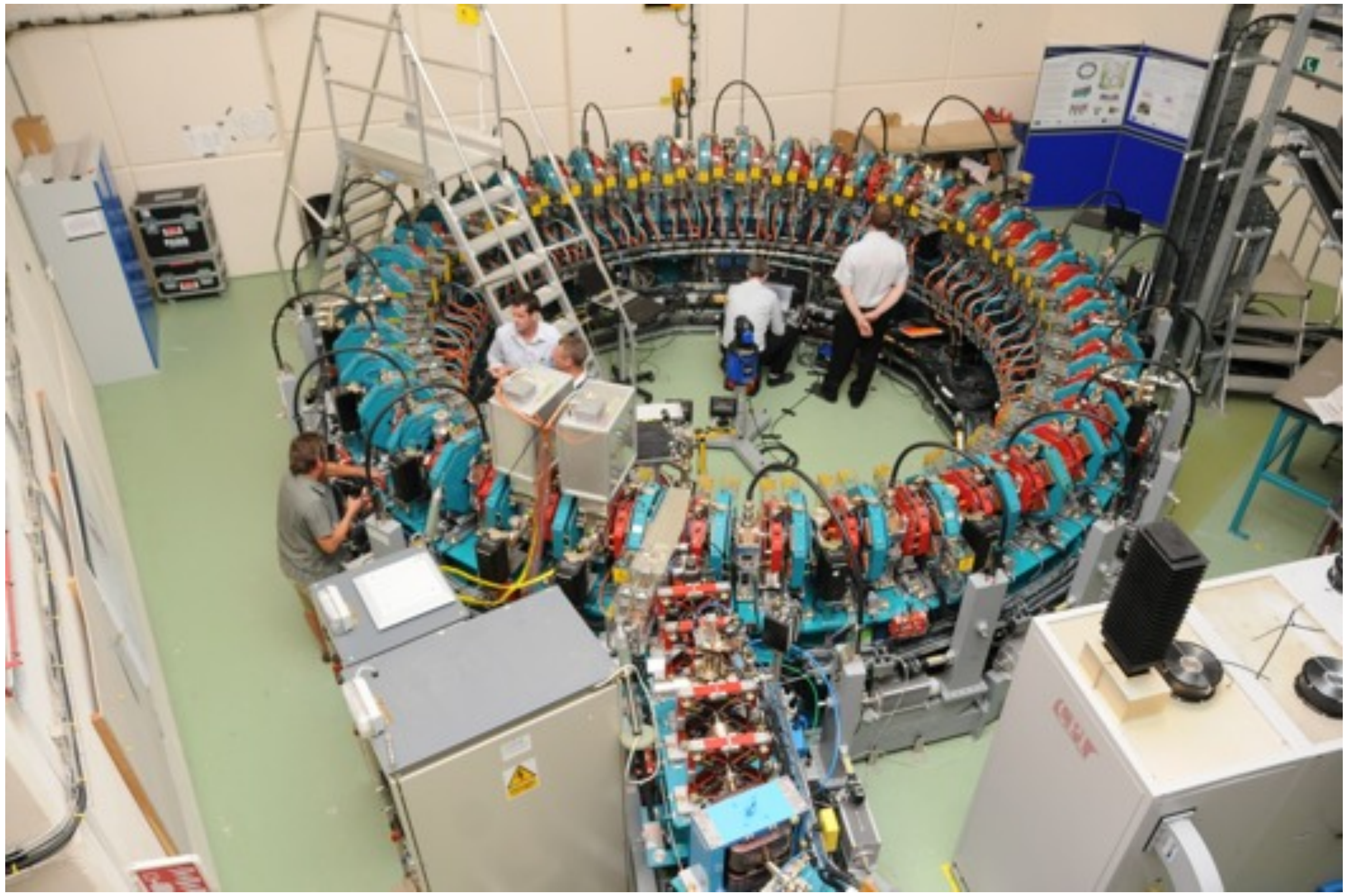
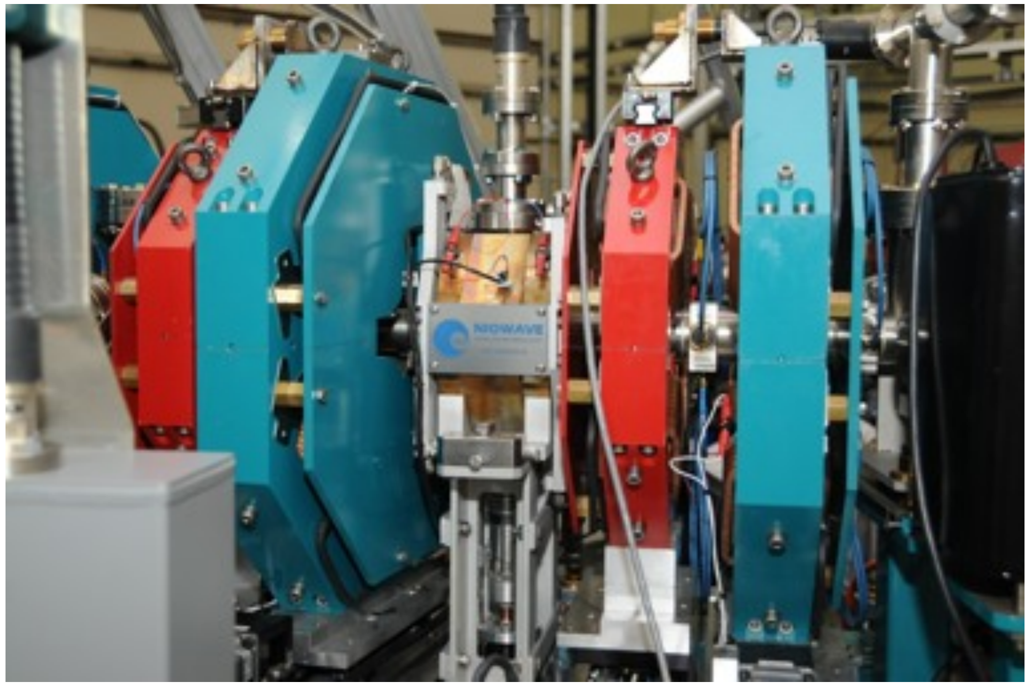
FFAG Acceleration

- Fixed-Field Alternating Gradient accelerator
- Avoids magnet ramping so good for unstable particles (e.g. muons)
- Betatron tune varies; resonance crossing
- Likely to be robust; high power proton/ion applications?
- Much R&D needed.

EMMA - electron model of non-scaling muon FFAG at Daresbury Laboratory, UK





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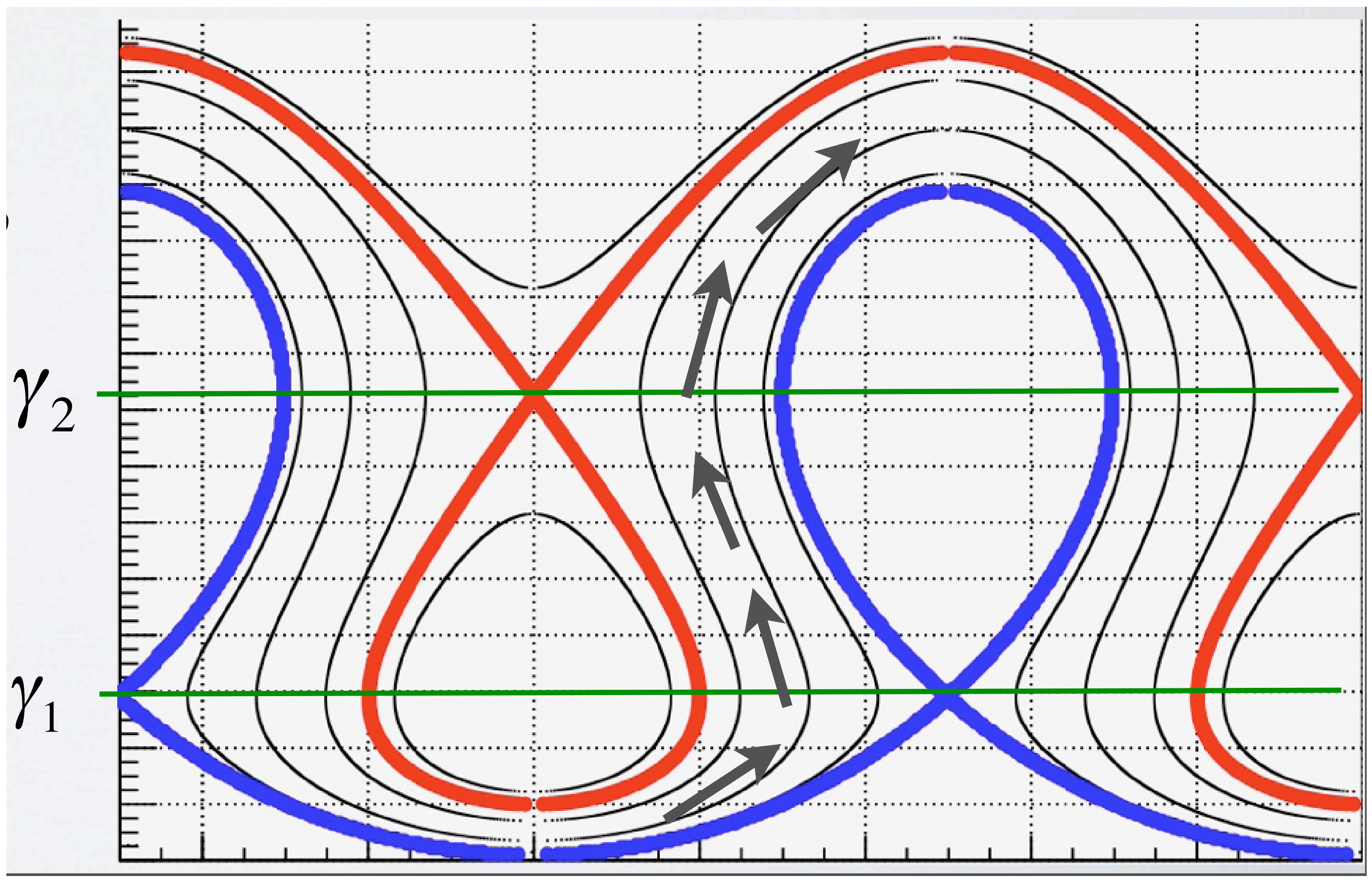
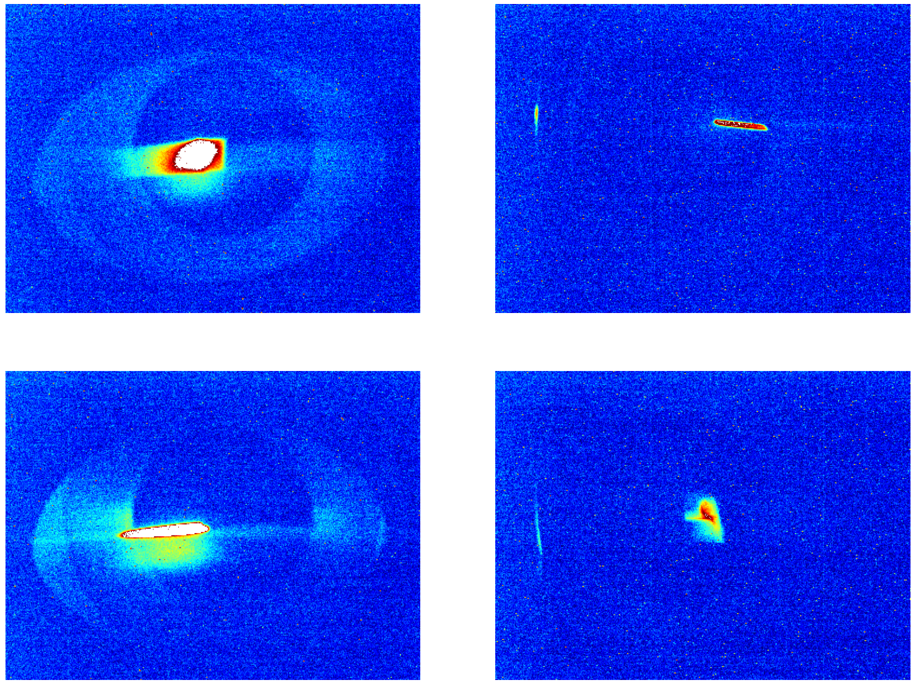
EMMA Results





EMMA demonstrated novel Serpentine (out of bucket) acceleration

Published March 2012 as cover article in Nature Physics

Lecture by S. Machida, Thursday

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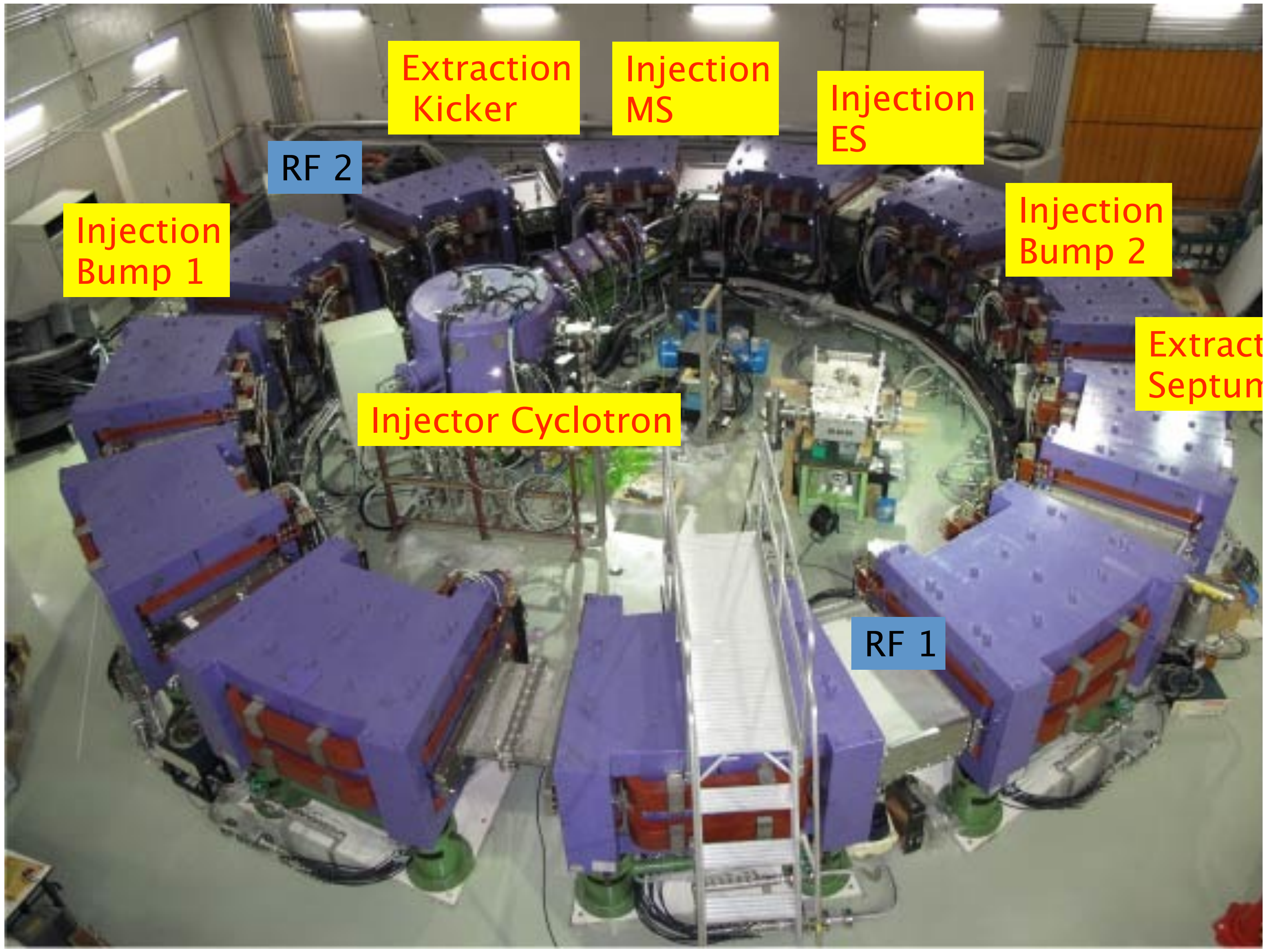
FFAG Development



International collaboration established to carry out experimental tests on 150 MeV FFAG at Kyoto University.

H^- injection, stripping, proton acceleration, beam dynamics issues (resonances, emittance growth, space-charge

Should demonstrate/verify theory/codes and indicate possible use for high power and/or high rep.rate (~cw) use.

Further theoretical studies of isochronous proton FFAGs ongoing

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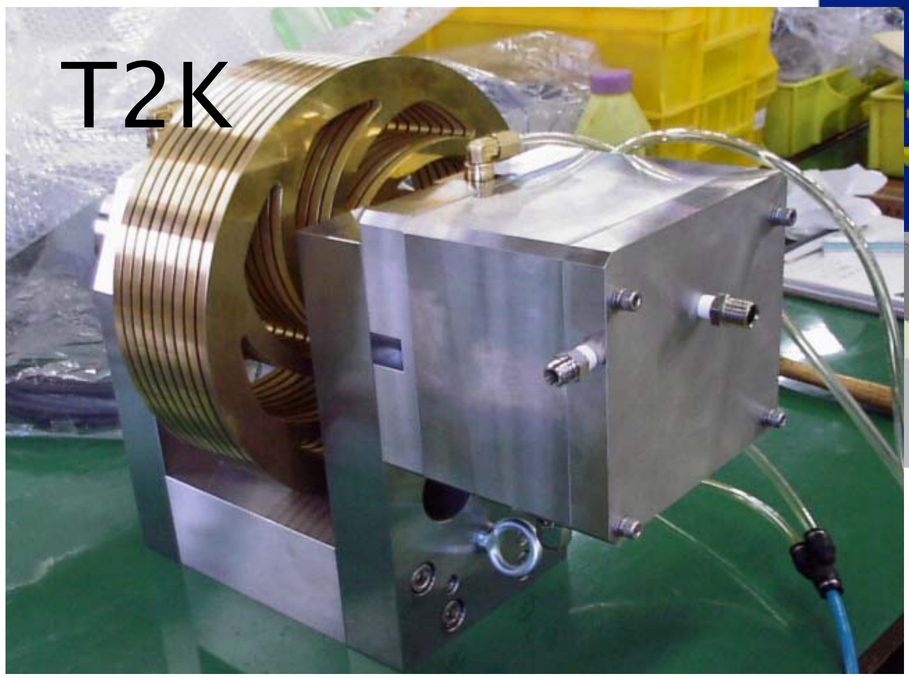
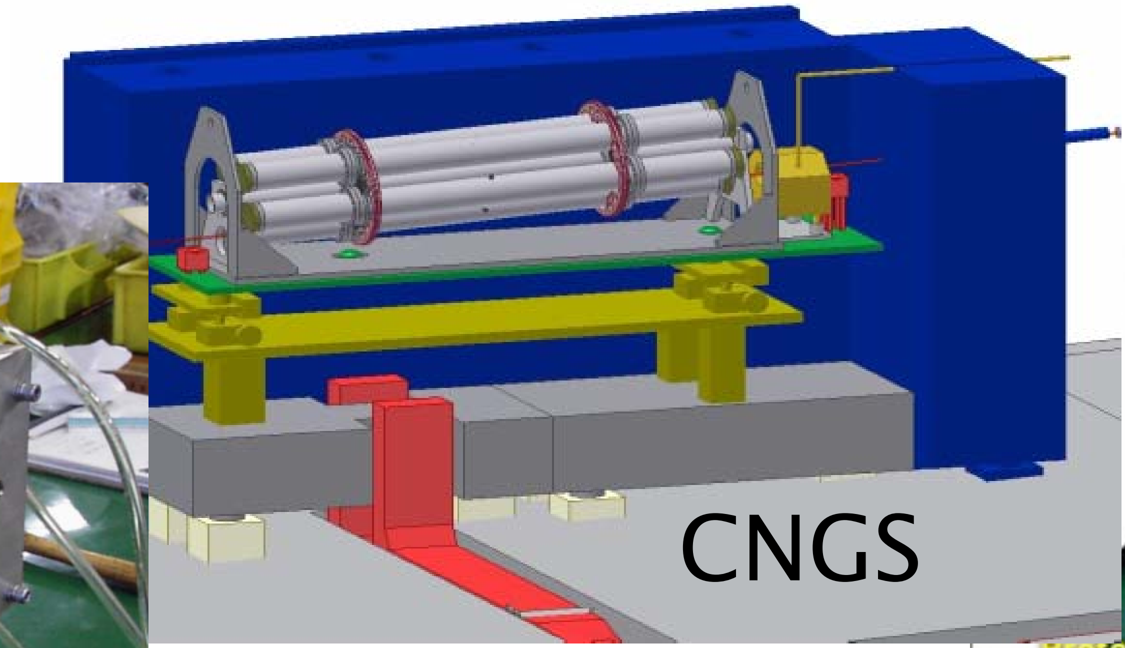
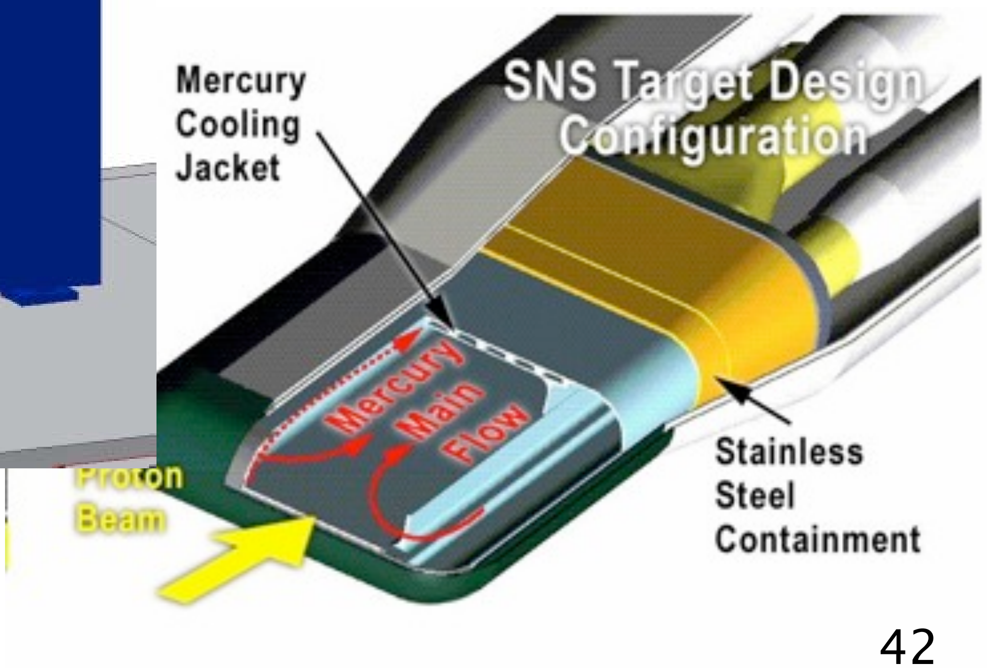
Main Issues (3)

- **Nanosecond bunch compression** for Neutrino Factory/Muon Collider
  - imposes additional considerations beyond (say) a neutron source.
- **Multi-megawatt targets**
  - solid targets, liquid mercury, powder jets
- **High intensity proton FFAG ring development**



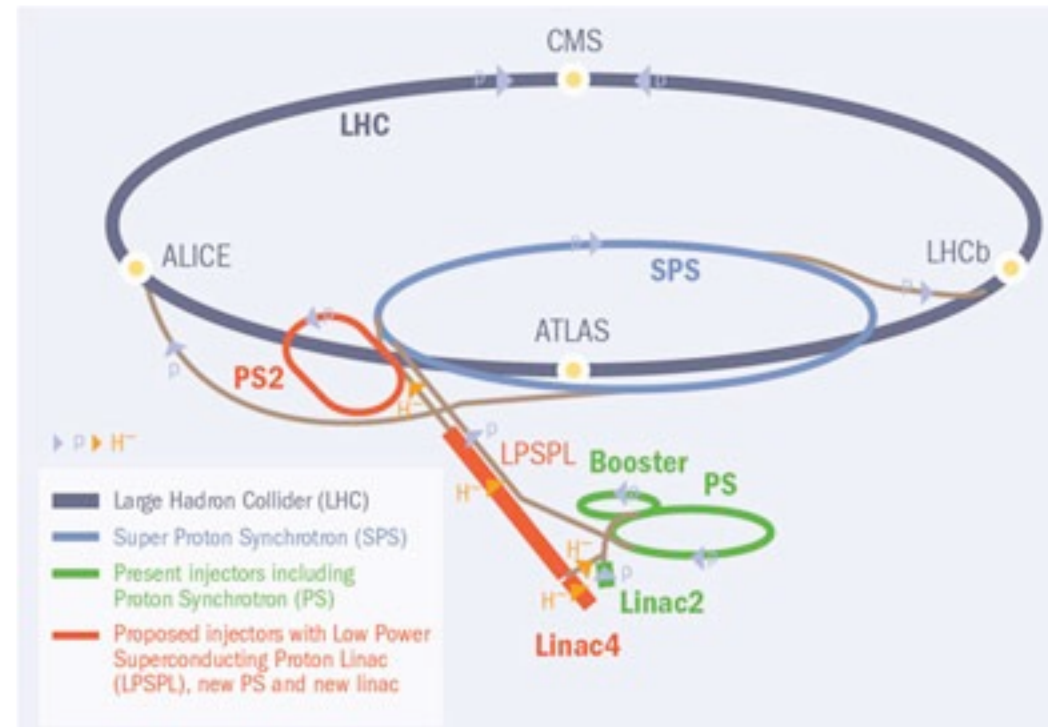




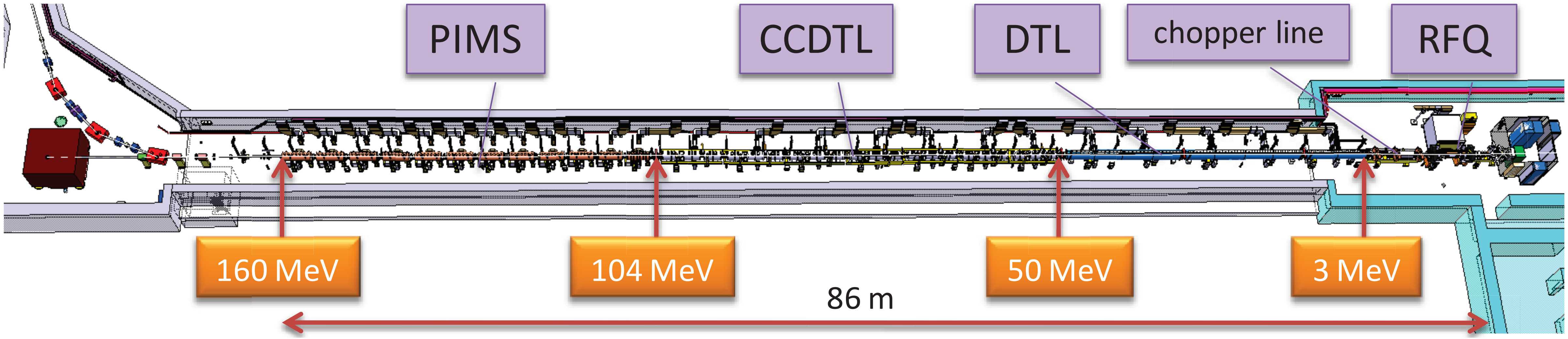

CERN

CERN Linac4 and SPL

- **Upgrade to CERN injector complex**
- Linac4 under construction to feed PS-Booster
- Proposals to extend to SPL, initially configured for low power as injector for new 50 GeV synchrotron
  - **ISOLDE, EURISOL**
  - **Neutrino physics, radioactive ion beams**
- Could later be configured for high power to serve as a multi-megawatt facility for future physics needs

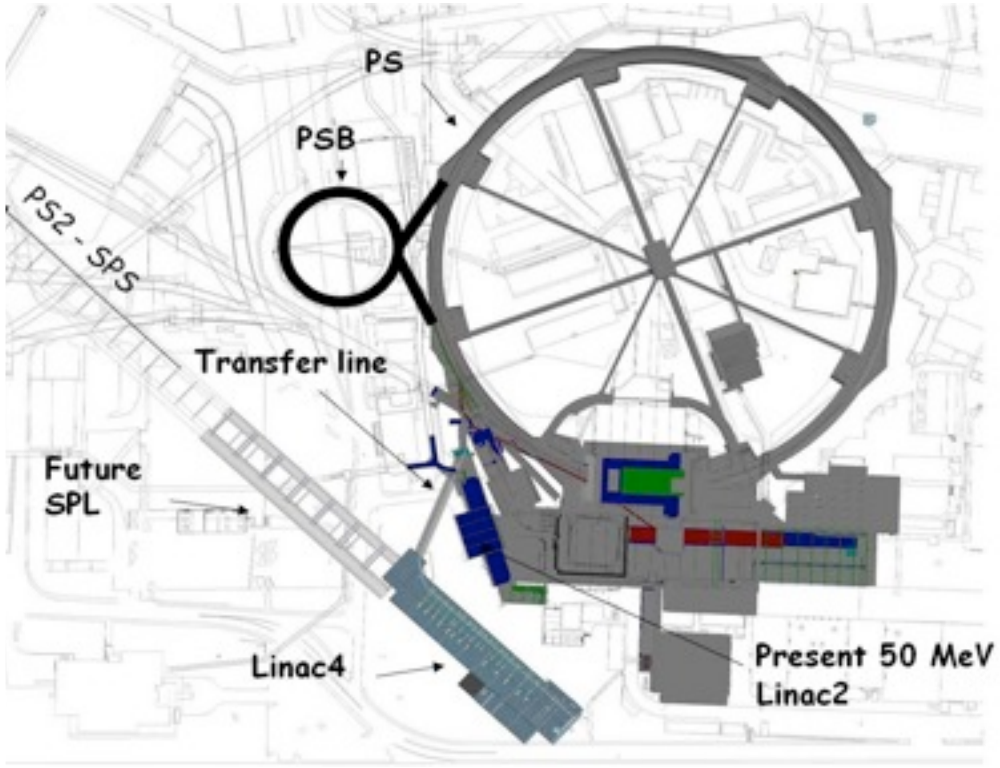


CERN LINAC4



New linac to inject into PS-Booster, replacing Linac2

- Length 86 m
- 4 different accelerating structures
- H^- beam, chopped 62.5%
- 40 mA average current
- Focusing with 111 PM and 33 EM quadrupoles
- Transfer line and charge exchange into PSB.
- Designed to allow for future operation as part of high-power SPL.



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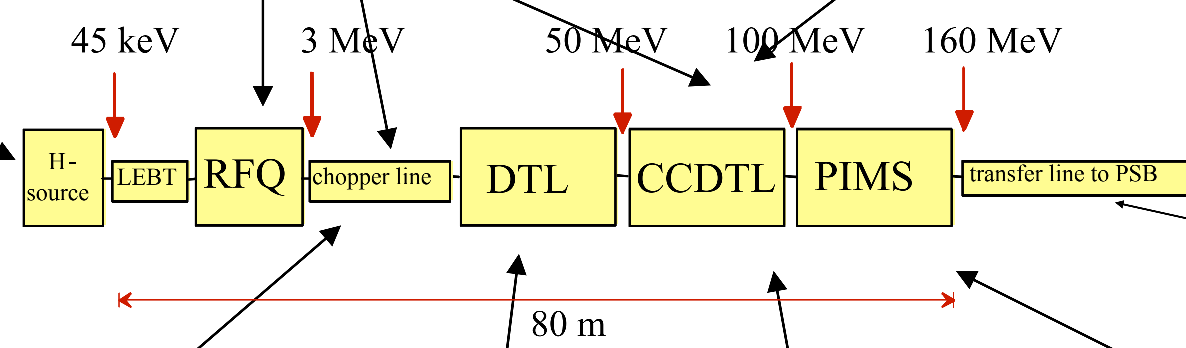
Linac4 – An International Project

Network of agreements to support Linac4 construction. Relatively small fraction of the overall budget, but access to specialised manpower ! Integration at the component level.

RFQ RF design, RF amplifiers, modulator construction from French Special Contribution

Prototype modulator, RF tuners, couplers, waveguides from India

Agreement with DESY on H- ion source



Transfer line vacuum chambers and supports from Pakistan

Chopper line built in a EU Joint Research Activity

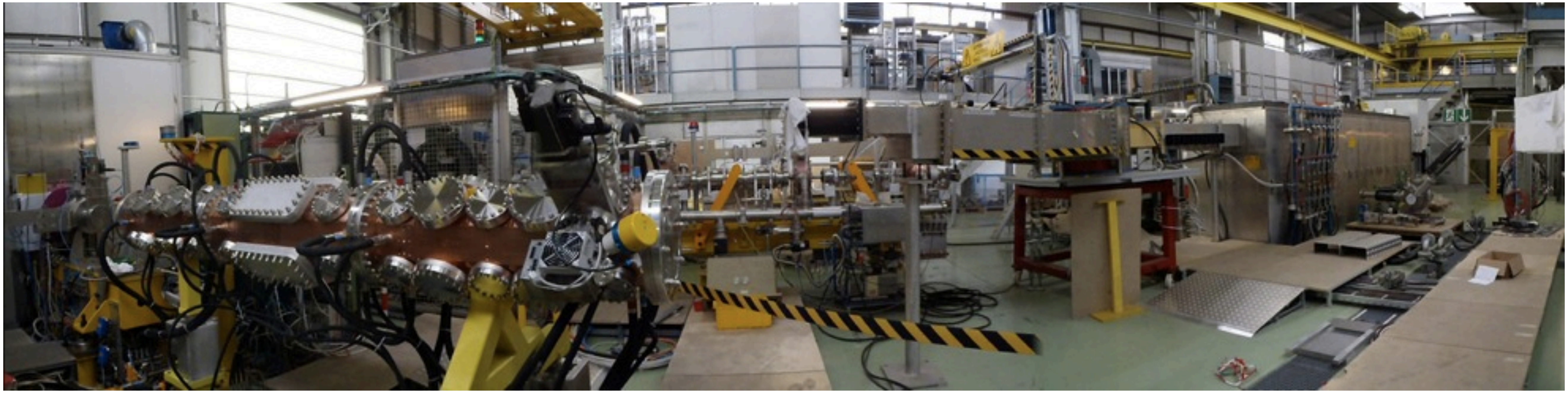
Participation of ESS-Bilbao in DTL construction

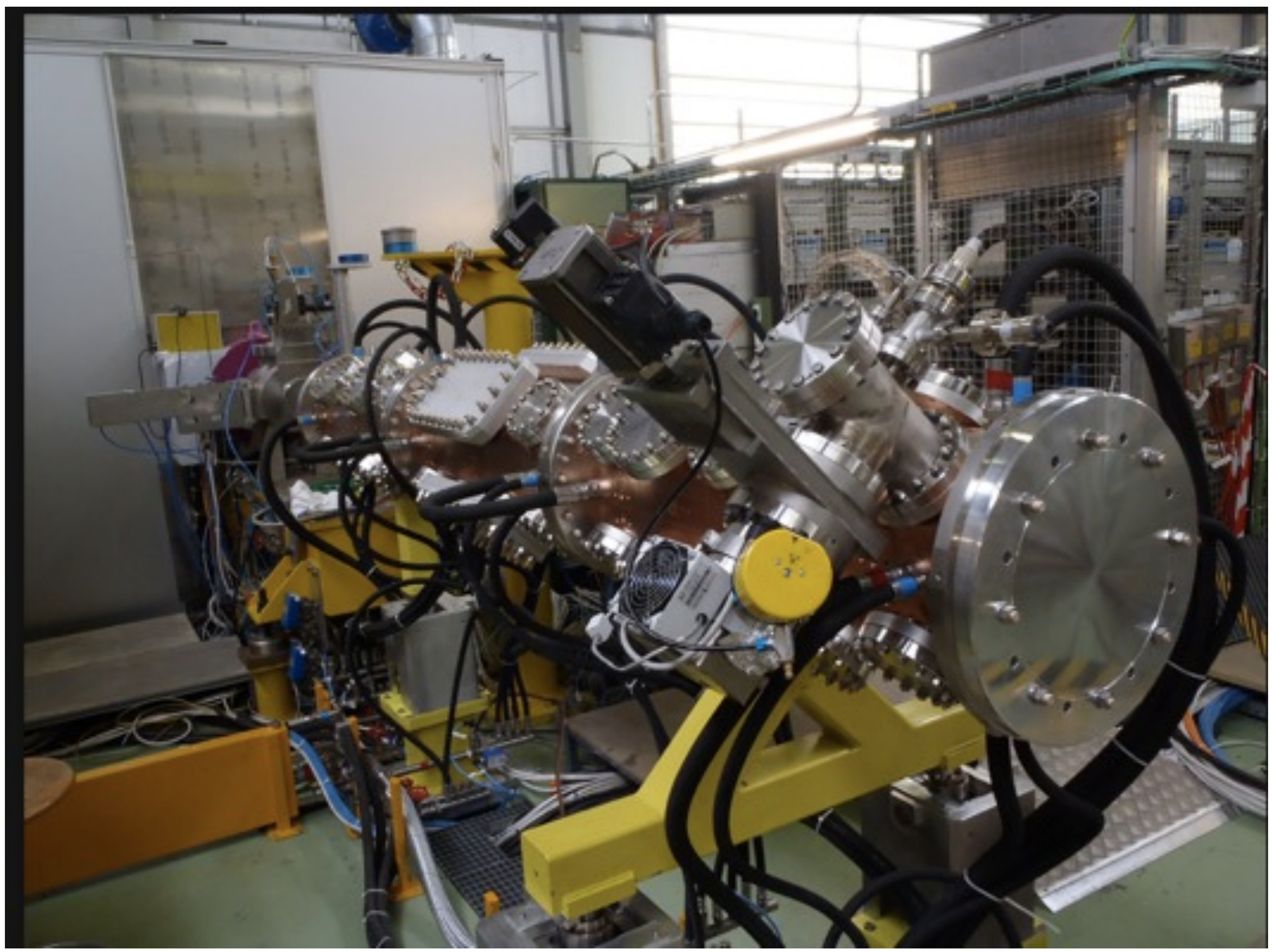
Construction of CCDTL in Russia, via an ISTC Project

Collaboration agreement with Soltan Institute (Poland) and FZ Julich (D) for PIMS construction.

Linac4 Construction Status

Linac4 Construction Status





π-mode structure

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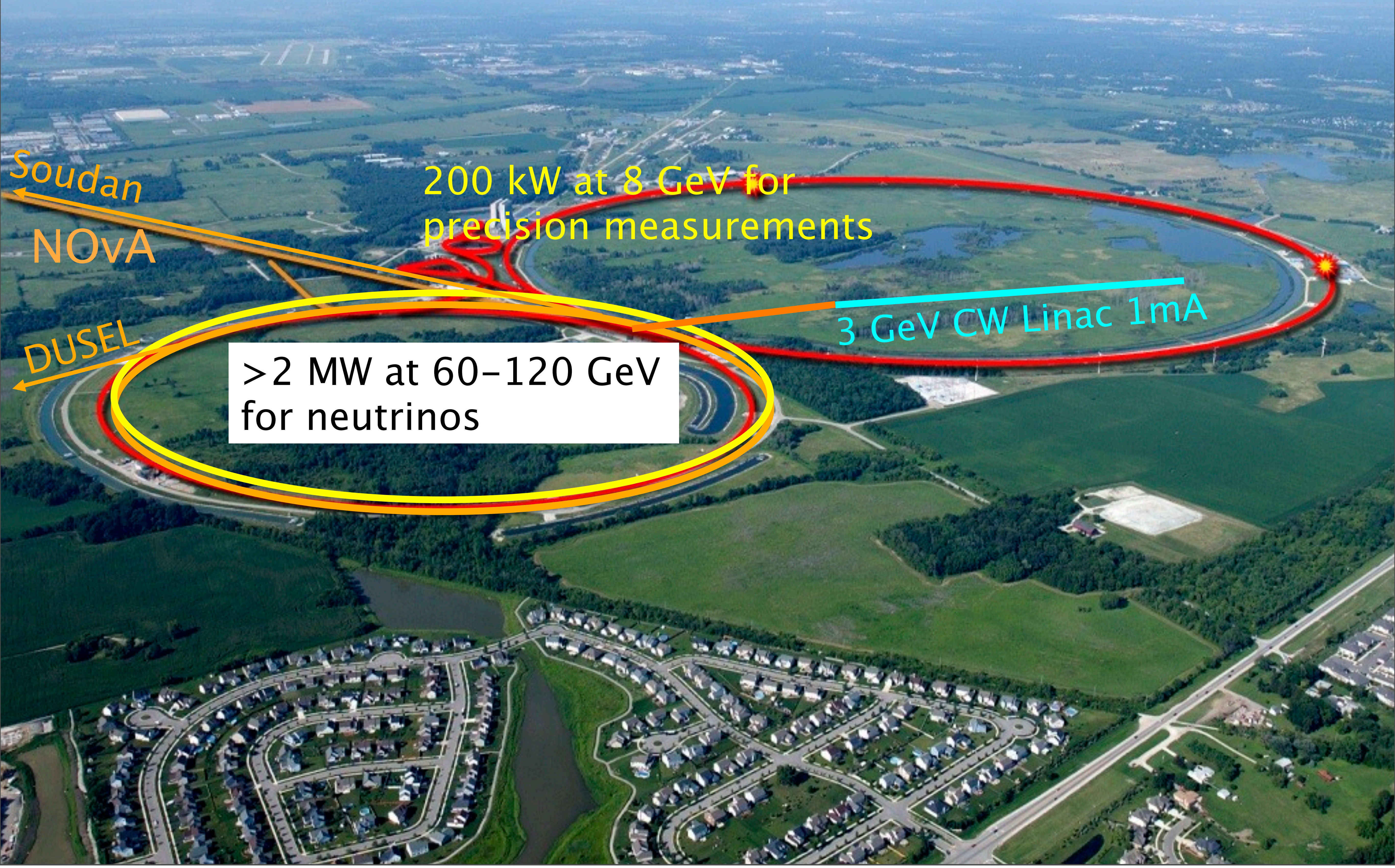
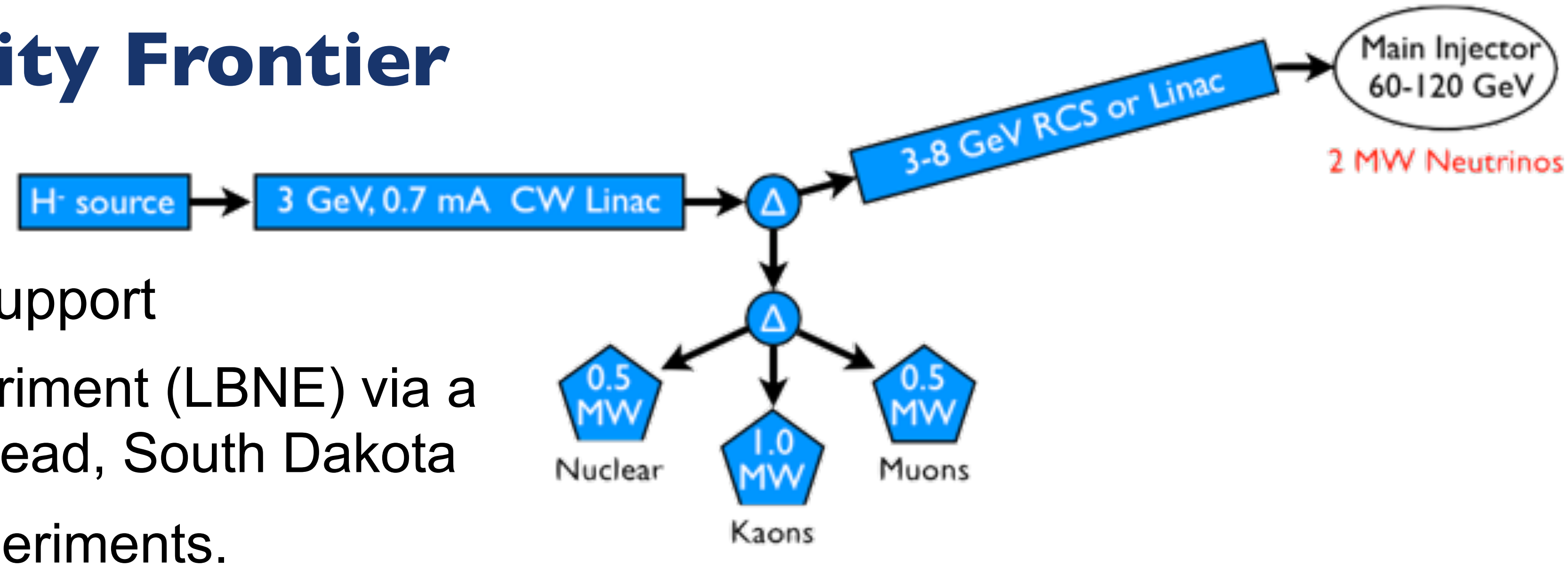
The Intensity Frontier: Project X

(National Project with International Collaboration)



Project-X

An experimental programme built around Fermilab's High Intensity Frontier



- A **multi-MW proton source** to support
  - Long Baseline Neutrino Experiment (LBNE) via a new beam line to DUSEL in Lead, South Dakota
  - Broad suite of rare decay experiments.
- Based on a **3 GeV, 1 mA CW superconducting linac**
  - Warm CW front end (H^- ion source, RFQ, MEBT, chopper)
- Part (5-9%) of the H^- beam will be accelerated in a SRF pulsed linac (5% duty cycle) or RCS (10 Hz) for injection to Recycler/Main Injector for multi-MW beams at 60-120 GeV.
- The main portion of H^- beam from the 3 GeV linac will be directed to three different experiments at lower energies
- Flexible timing characteristics
- Project-X will also support development of a **Muon Collider** and **Neutrino Factory**

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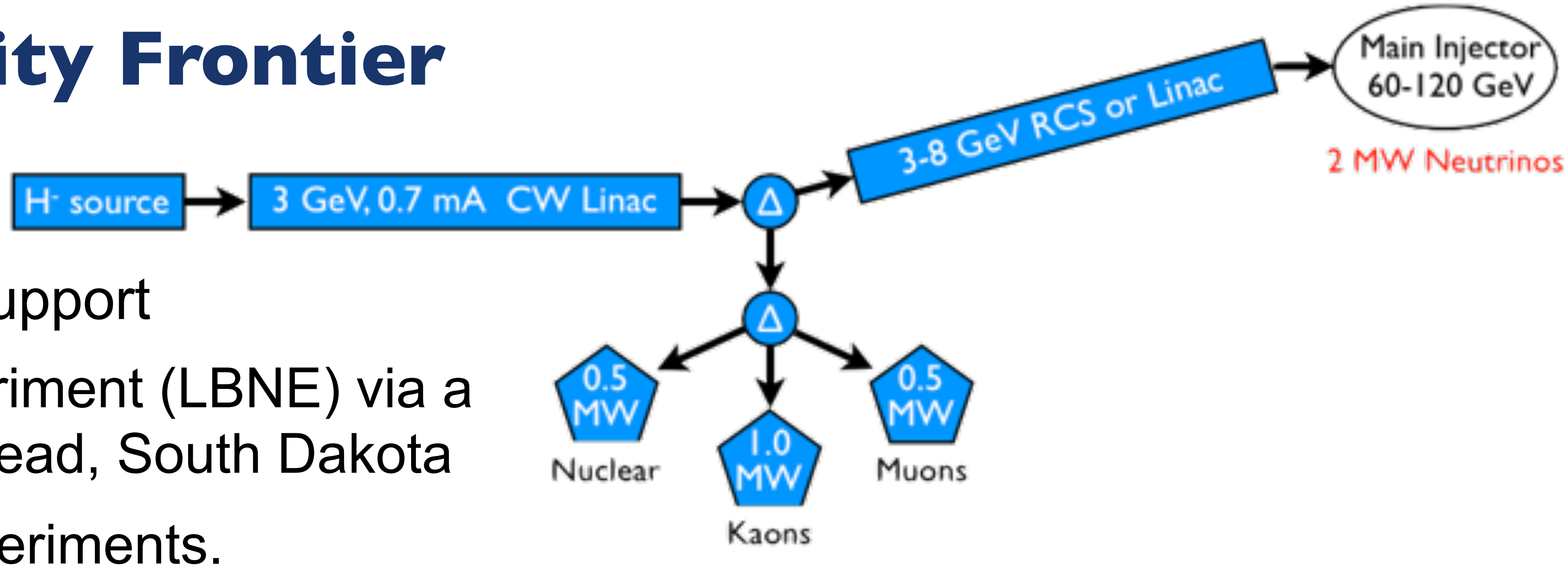
Project-X

An experimental programme built around Fermilab's High Intensity Frontier



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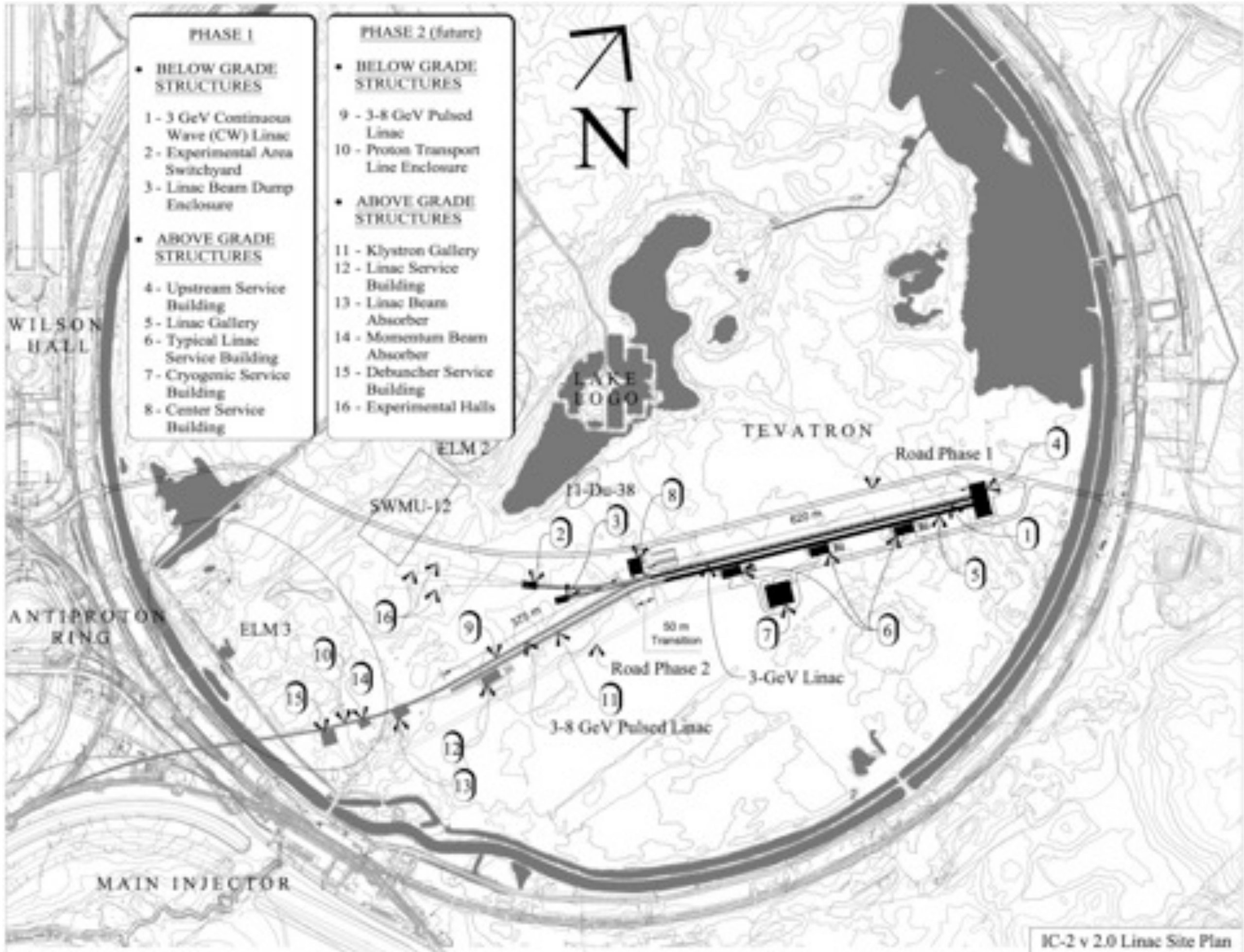
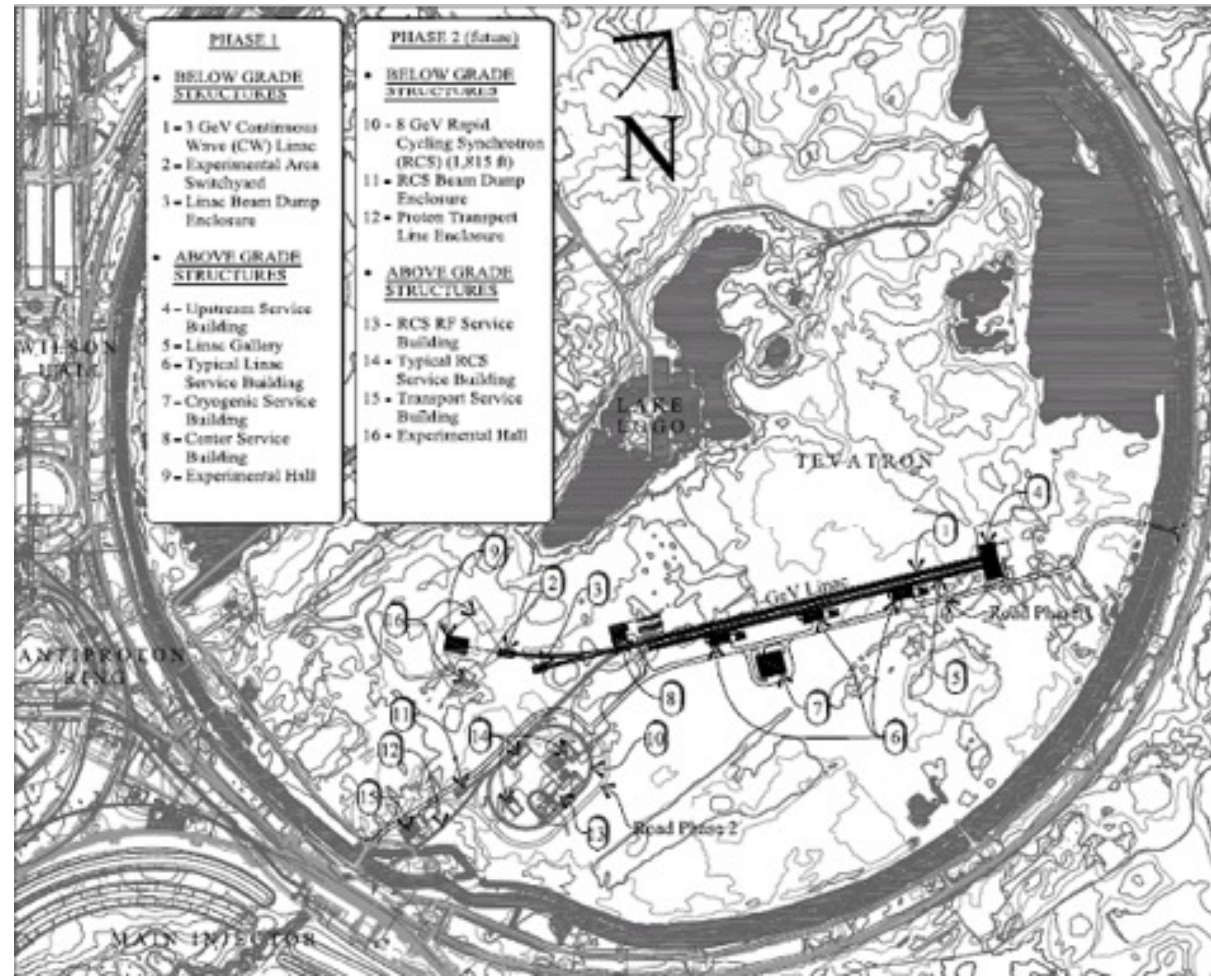
3-8 GeV Pulsed Linac and RCS Options

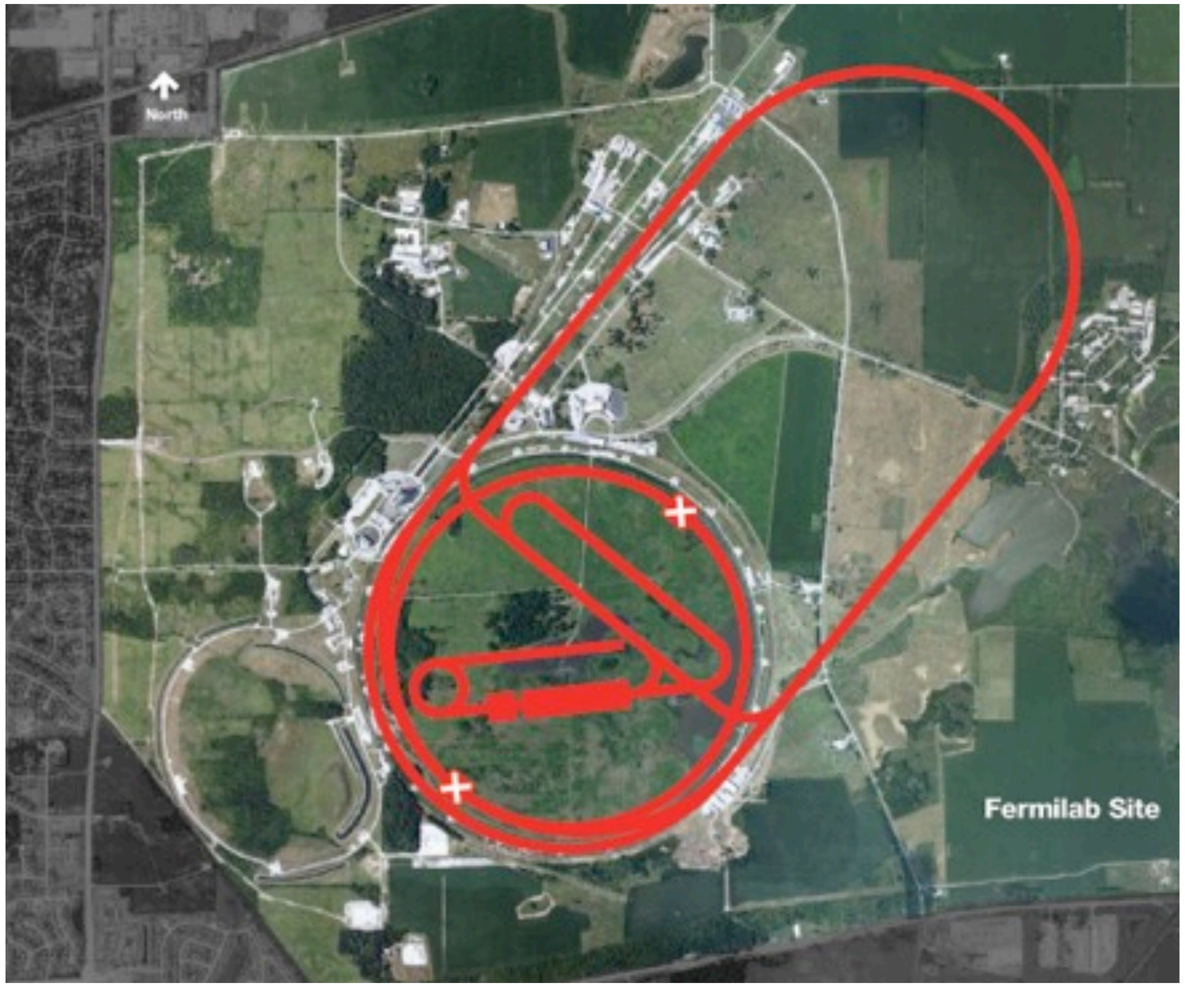




- RCS to 3-8 GeV under study but looks to have a limited upgrade potential (for Muon collider and Neutrino Factory)
- Present work concentrated on a pulsed linac
  - 1.3 GHz, 25 MV/m gradient, ≤5% duty cycle,1-30 ms pulse length
  - ~250 cavities (28 ILC-type cryomodules) needed.

Project-X Neutrino Factory/Muon Collider Strategy

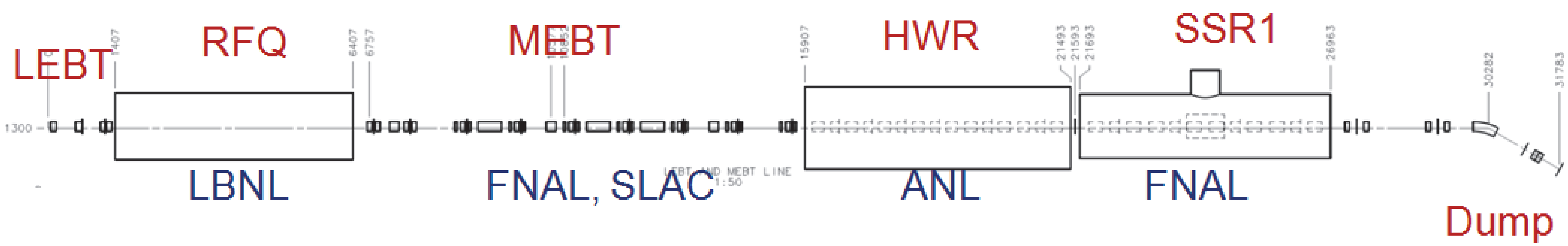
- Project X shares features with the proton driver required for a Neutrino Factory or Muon Collider
  - NF and MC require ~4 MW @ 5-15 GeV
- Primary issues are related to beam pulse structure
  - NF wants proton beam on target consolidated in 1-3 bunches, separated by ~150 μs
  - Muon Collider requires single bunch
- Project X linac will deliver 4 MW (with upgrades) but is not directly capable of this beam pulse format.



- New accumulator and compressor ring will be needed to produce the correct pulse structure on a NF or MC target. Possible idea of “trombone” delay lines and funnel to combine many bunches simultaneously at target.

Fermilab PXIE

- Project-X Injector Experiment: Prototype for front-end
- Will accelerate 1 mA (average) H- beam to ~25 MeV
- Test reliable operation of a CW 2.1 MeV RFQ accelerator



- Demonstrate bunch-by-bunch chopping
- Test low-β acceleration in SRF cryomodules
- Show sufficiently small emittance growth during initial acceleration
- Good particle extinction for the removed bunches

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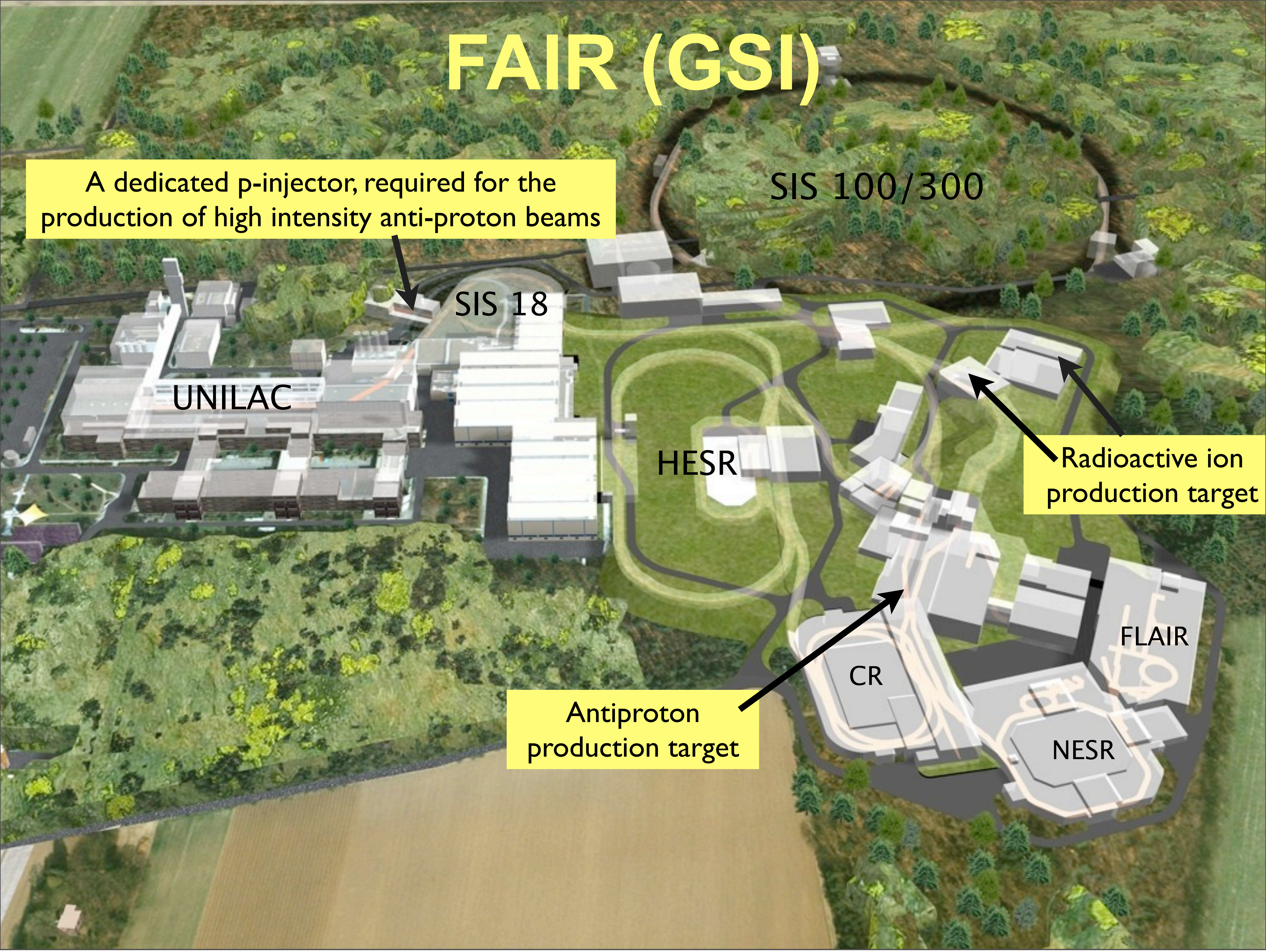
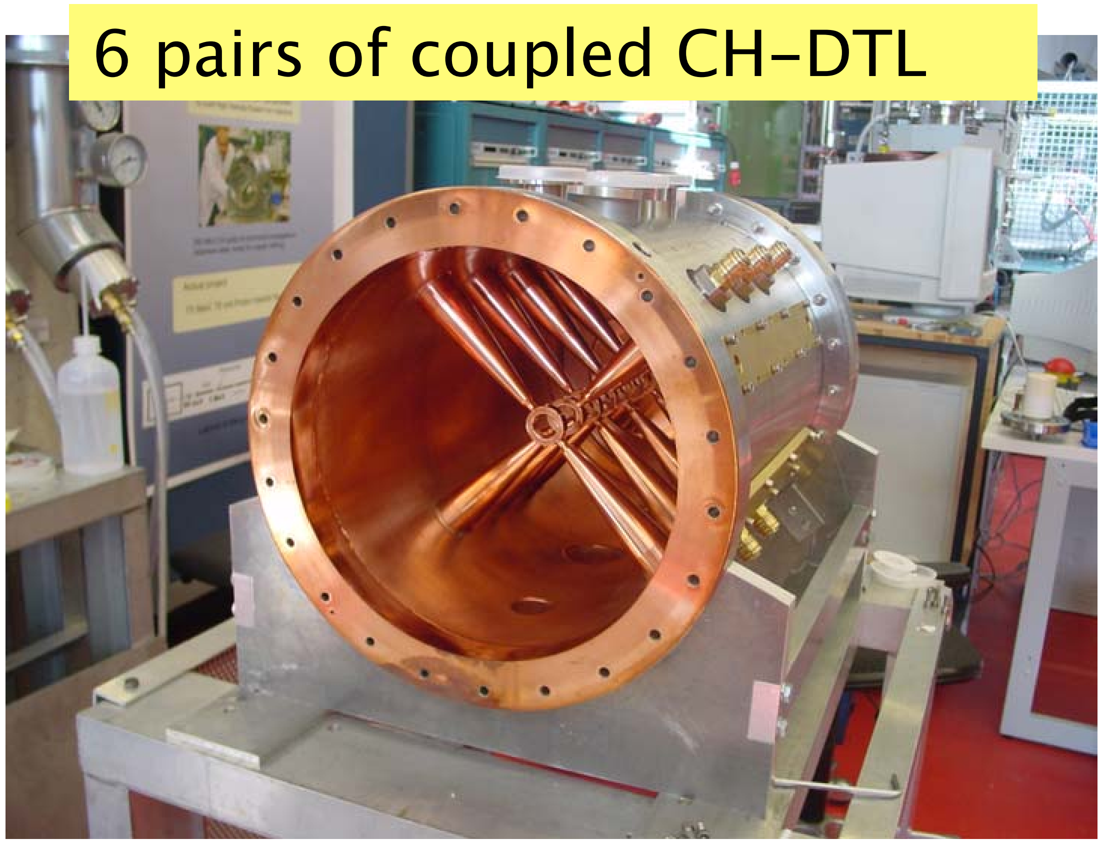
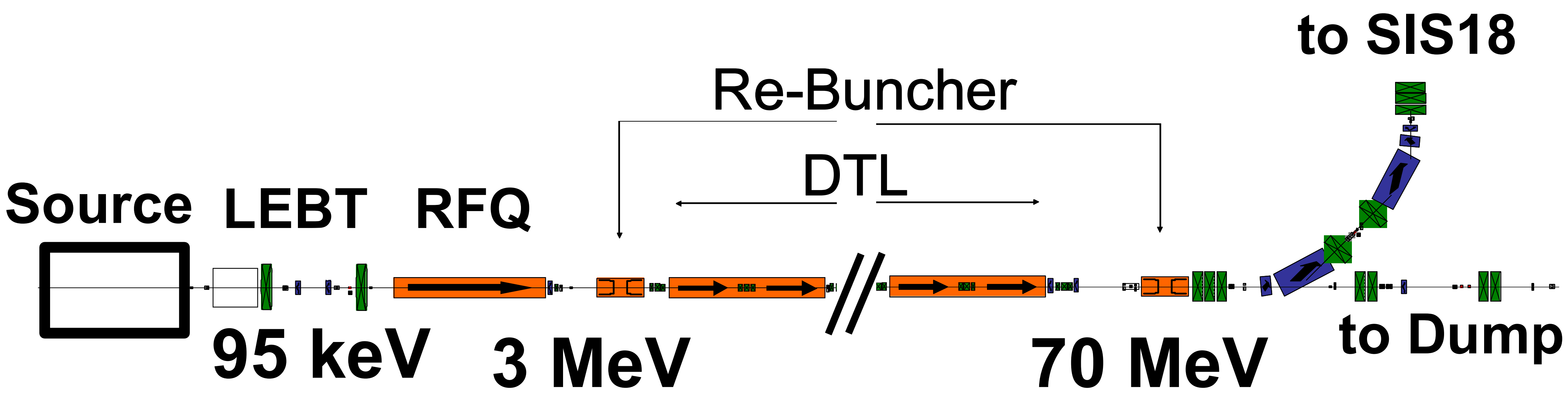
FAIR (GSI)


A dedicated p-injector, required for the production of high intensity anti-proton beams
SIS 100/300
SIS 18
UNILAC
HESR
Radioactive ion production target
FLAIR
CR
Antiproton production target
NESR

FAIR Proton Injector

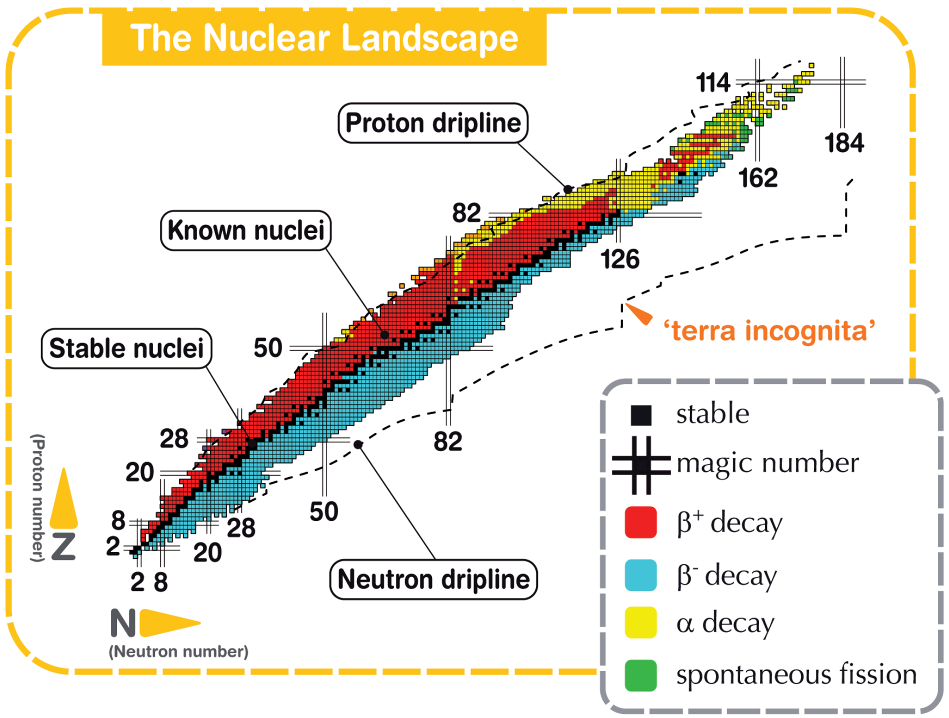
- GSI proton injector - 70 MeV, 70 mA, 352 MHz, 4 Hz repetition, 36 μs beam pulse length
  - first linac based on coupled H-Mode cavities combined with KONUS beam dynamics
- Tolerances comparable with other high intensity linacs
- Under construction. Commissioning 2013?

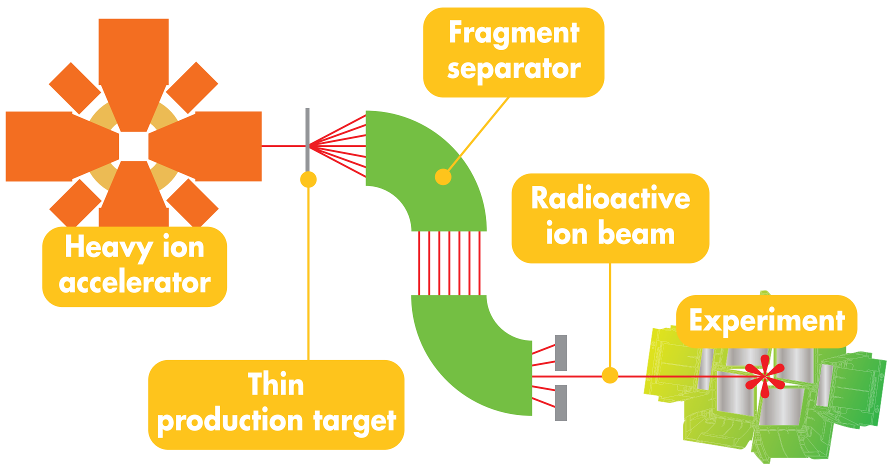




Radioactive Ion Beams

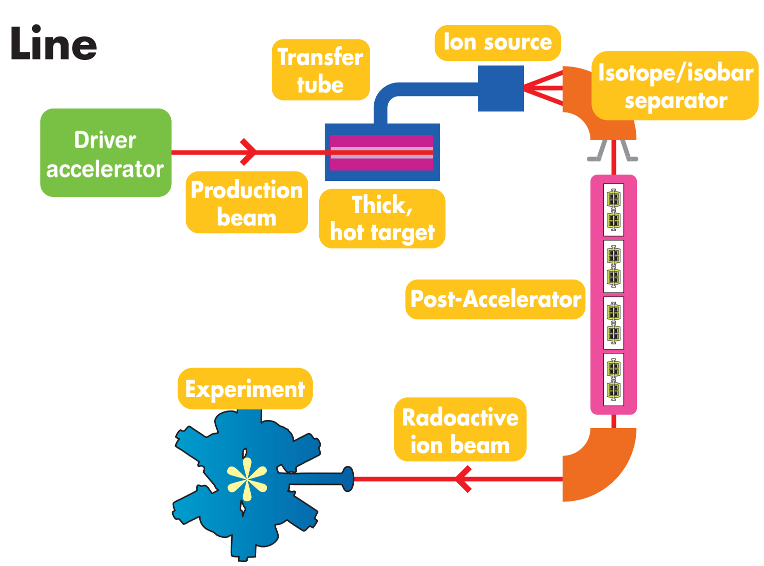
To explore ever-more exotic regions of the nuclear chart, towards limits of stability of nuclei.





Fragmentation
RIBs produced by fragmentation of a projectile on a thin target. Radioactive nuclei created are separated in flight.
Secondary beam: high energy and selectivity, but low intensity

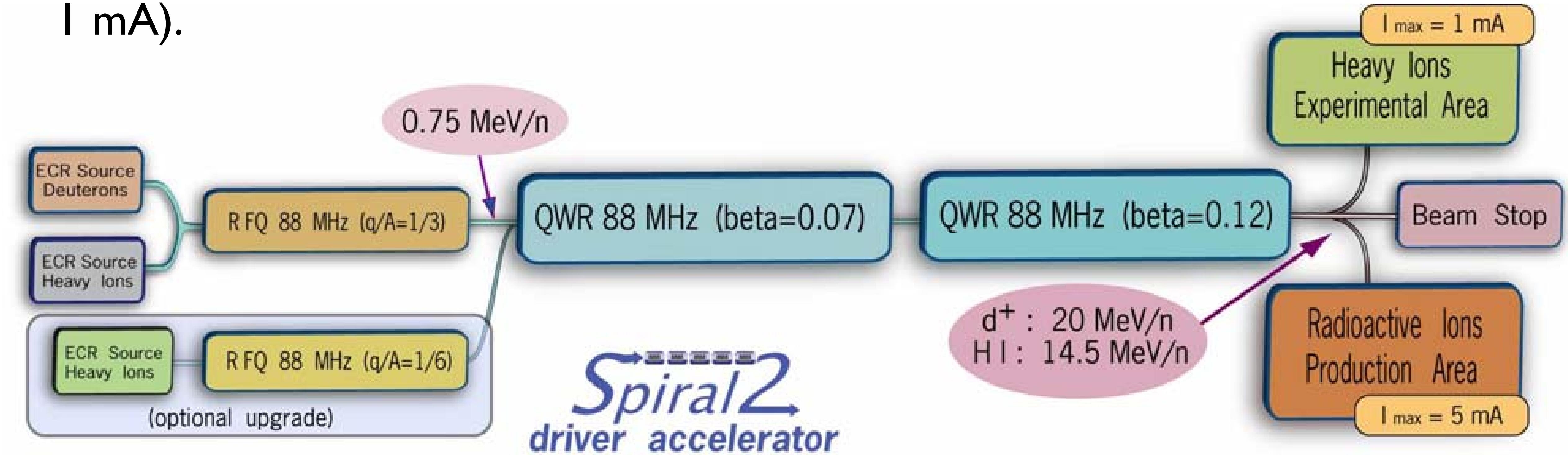
ISOL: Isotope Separation On-Line
RIBs produced by spallation, fission or fragmentation reactions of a projectile with a thick target. Products of reaction diffuse out of target, are ionised, separated on-line and re-accelerated.
Secondary beams: very intense but short-lived nuclei not reachable



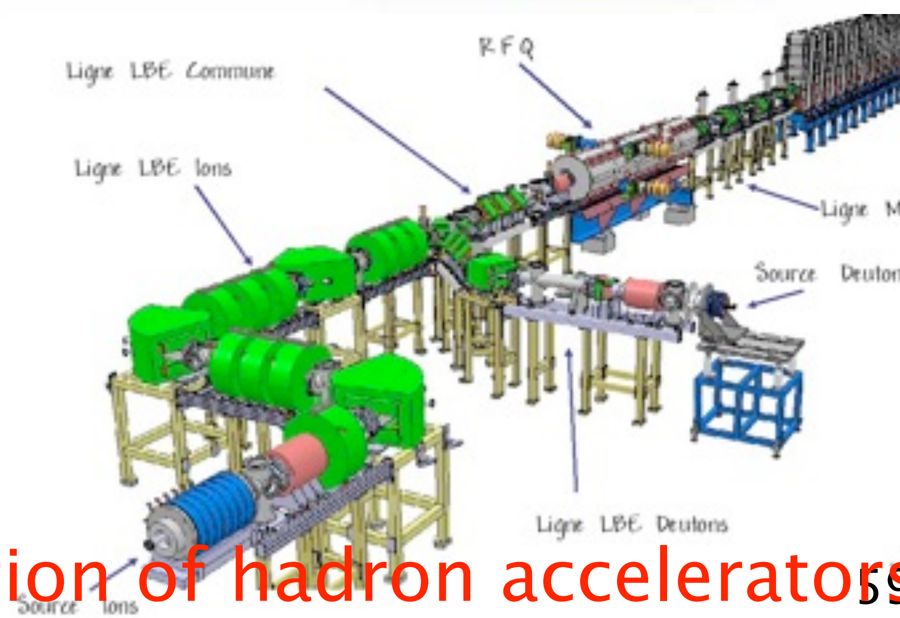
SPIRAL-2

Radioactive beams facility at GANIL, Caen, France

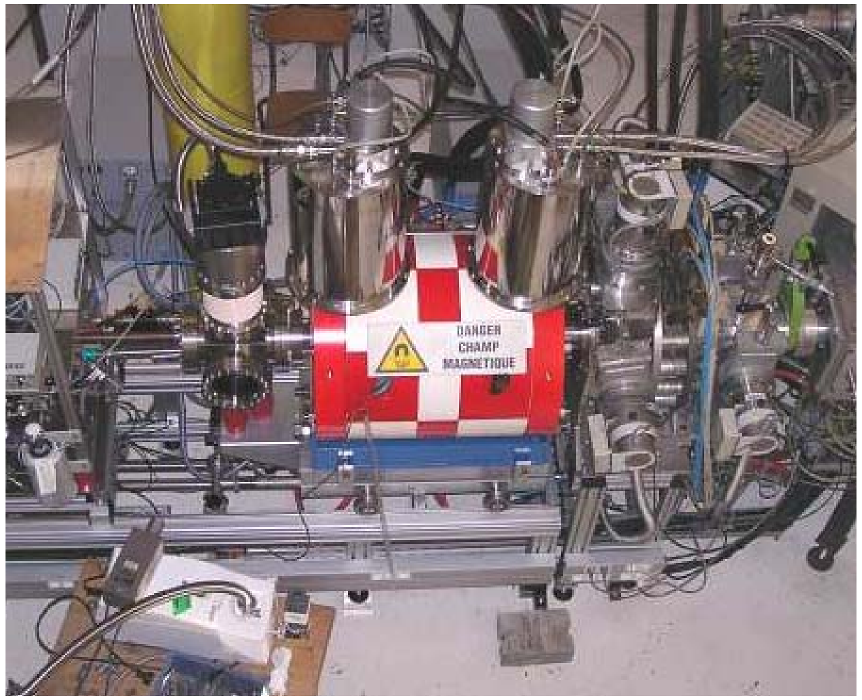
- A superconducting linac driver, delivering **deuterons** with an energy up to 40 MeV (up to 5 mA) and **heavy ions** with an energy up to 14.5 MeV/u (up to 1 mA).



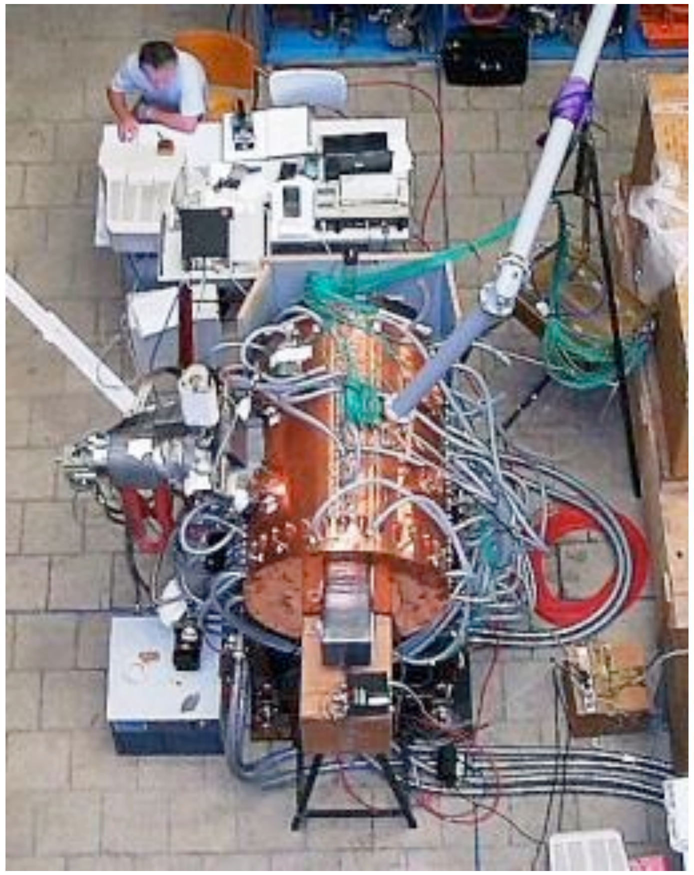
- Two families of quarter wave resonators: type A (optimized for beta=0.07, 1 per cryomodule) and B (beta=0.12, 2 per cryomodule).
- The accelerator is under construction.



Spiral2 is developing a completely new generation of hadron accelerators



ECR heavy ion source



RFQ – full power test

First Type B β=0.12 cryo-module

First Type A β=0.07 cryo-module

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April/May 2012


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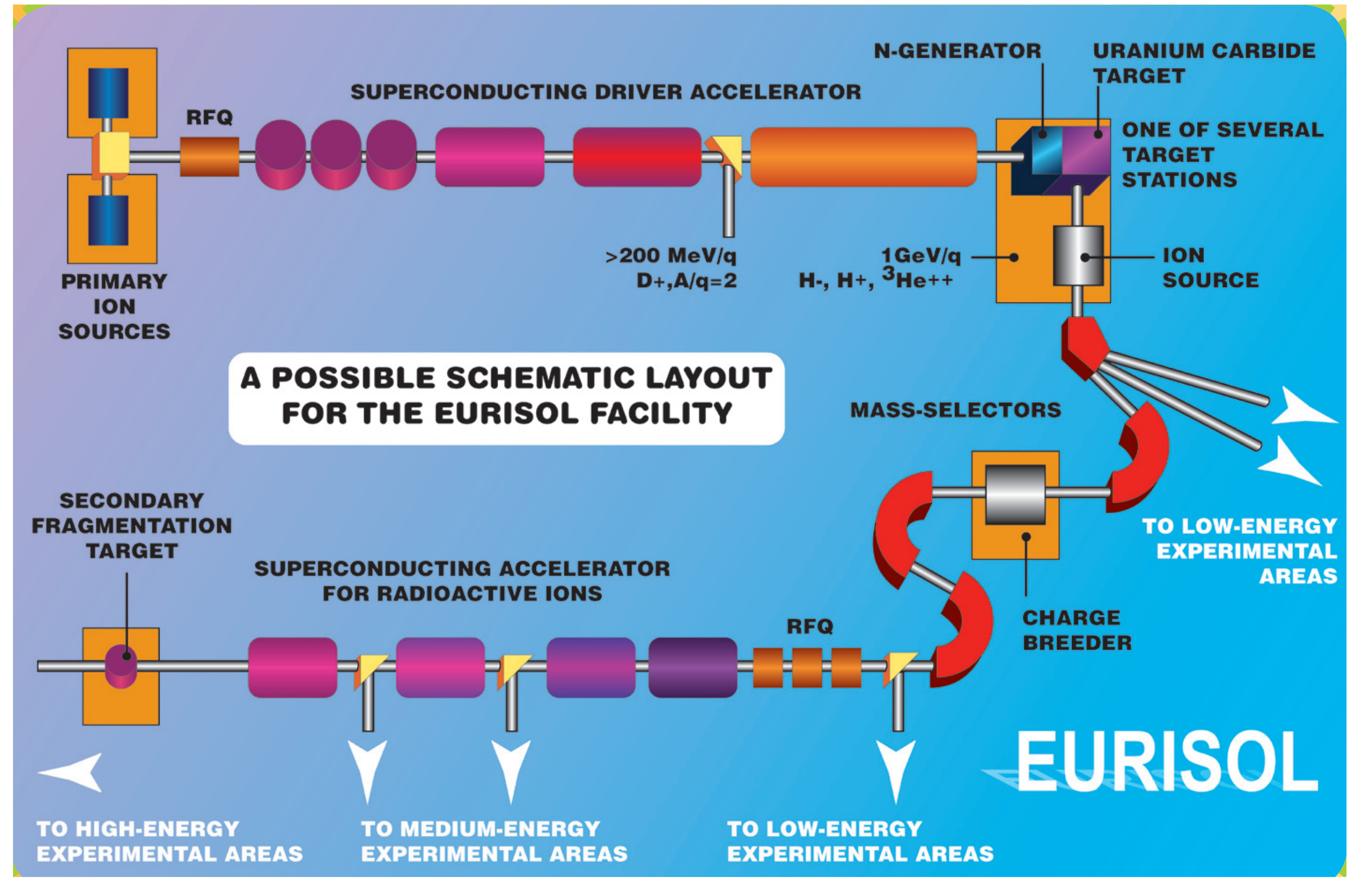
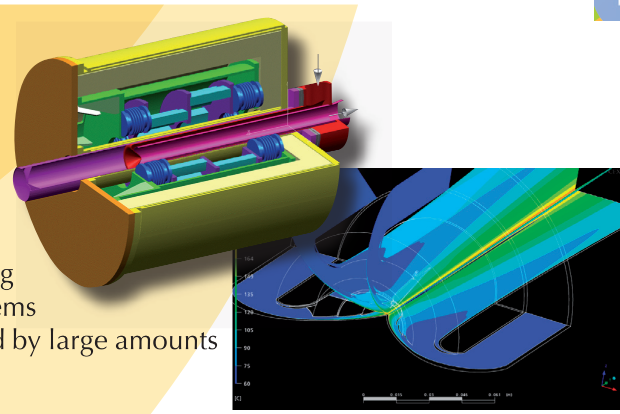
EURISOL (European ISOL Facility)

- 1 GeV superconducting linac, 5MW of protons on neutron converter target
- Also capable of accelerating deuterons, ^{3}He and ions up to mass 40.
- Beams impinge simultaneously on two types of target
  - direct target
  - indirectly after conversion of protons into neutrons through a loop containing 1 ton of mercury surrounded by fissile material.



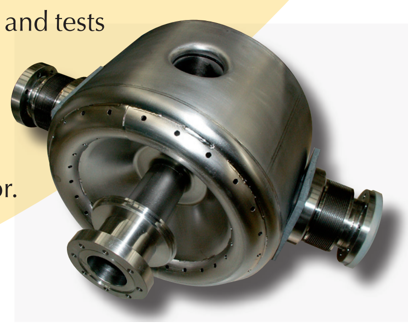
Multi-MW target station

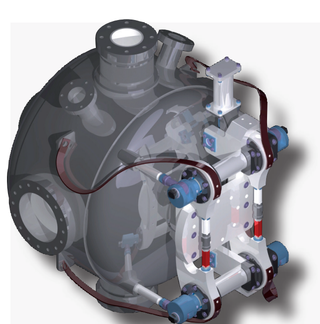
Technical preparatory work and demonstration of principle for a high-power target station for production of beams of fission fragments using the mercury proton-to-neutron converter-target and cooling technology is carried out in collaboration with the communities working on spallation neutron sources, accelerator-driven systems and neutrino factories. The converter will be surrounded by large amounts of fissile material.



Superconducting cavity development

The Design Study includes fabrication and tests of fully-equipped superconductivity cavity prototypes and design, fabrication and test of a multipurpose cryomodule for the low-energy section of the proton driver linear accelerator.





Unstable nuclei diffuse out of the target, are ionized and selected, and can be used directly at low energy or reaccelerated by another linac to energies up to 150 MeV per nucleon in order to induce nuclear reactions.

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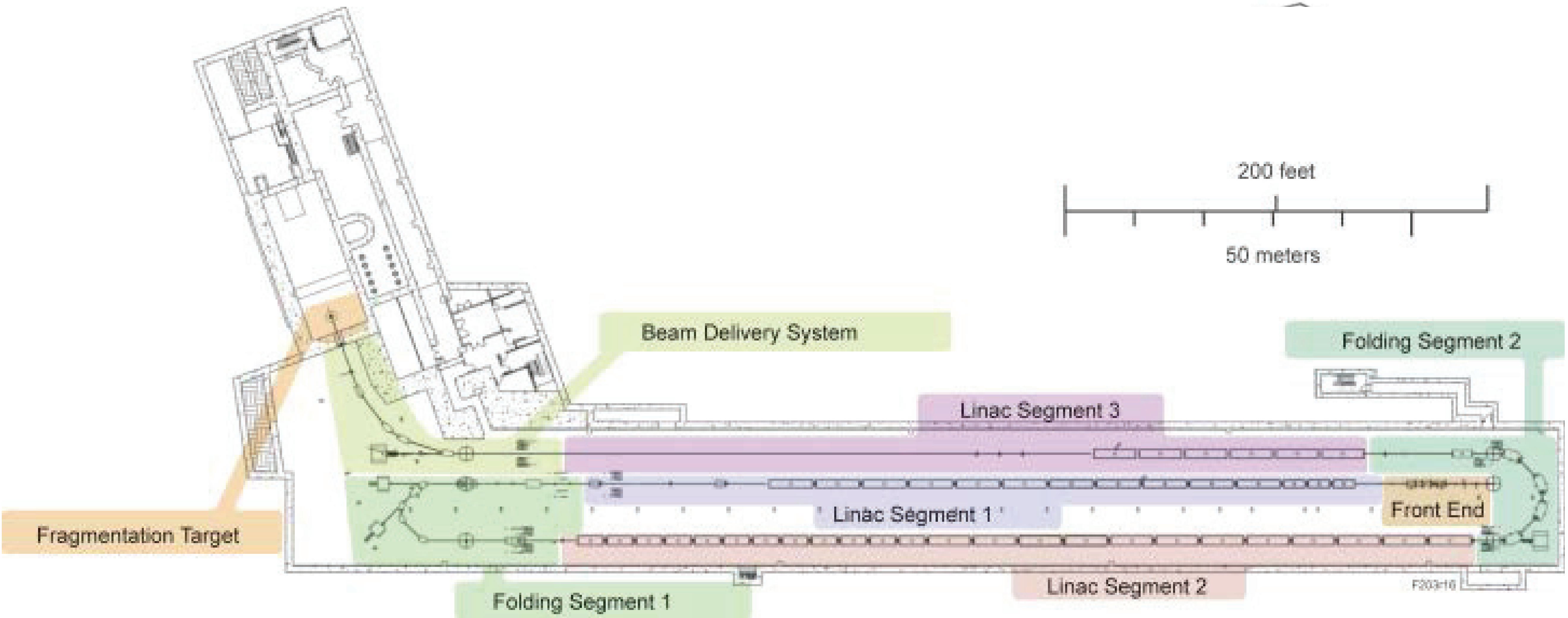
FRIB - Facility for Rare Isotope Beams at MSU

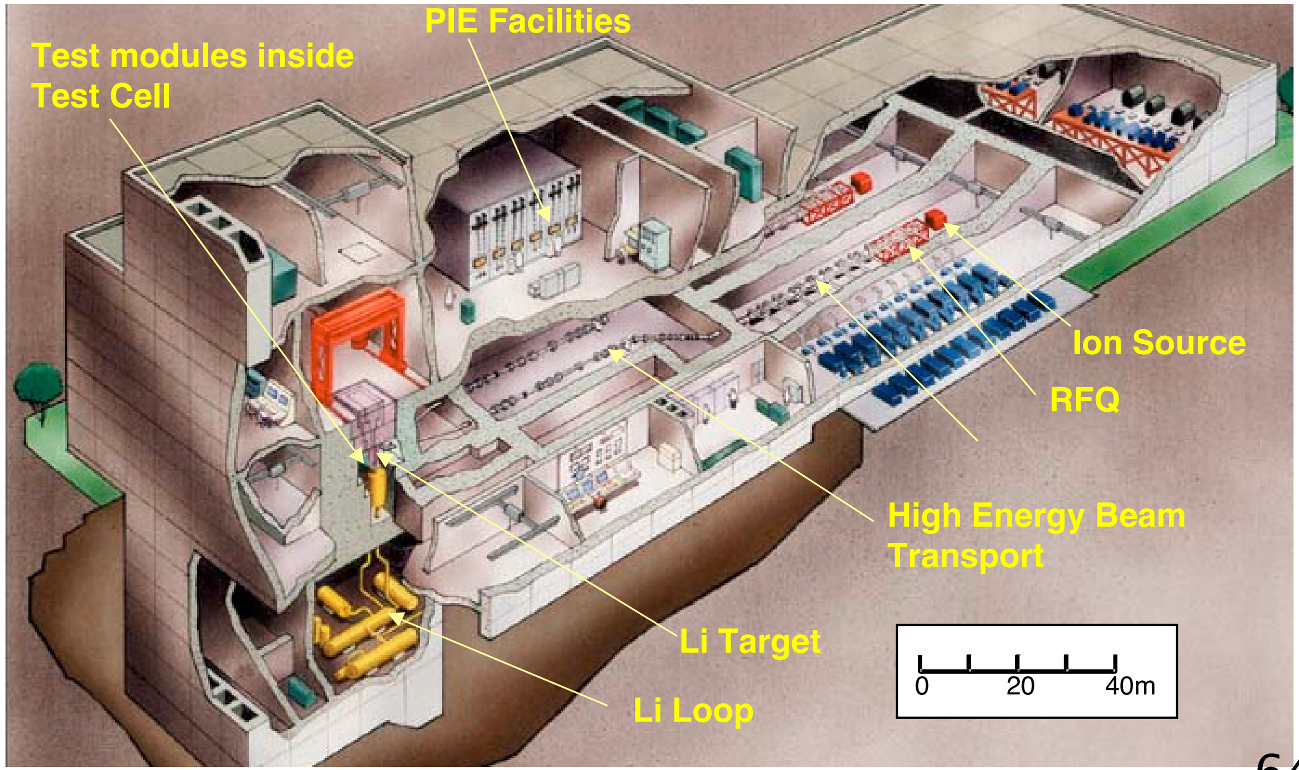
- Agreement signed June 2009. Cost ~$600m and take ~10 years to design and build.
- Superconducting RF driver linac providing 400 kW for all beams with uranium accelerated to 200 MeV/u and lighter ions with increasing energy (protons at 600 MeV).
- Upgrade possibilities to 400 MeV/u for uranium, to 1 GeV for protons



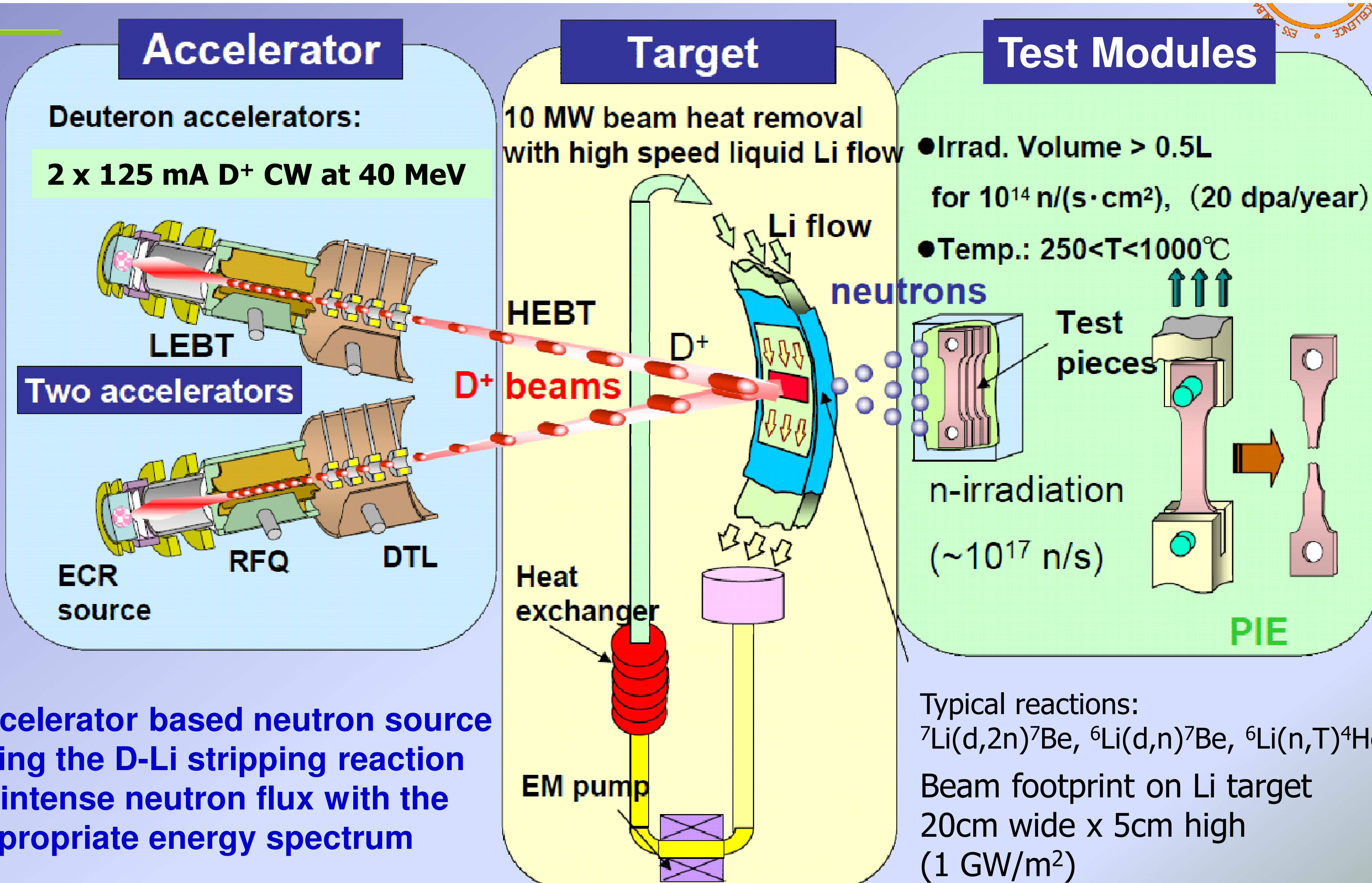
IFMIF and IFMIF-EVEDA

- An international facility planned by Japan, EU, USA and Russia to produce a high energy, neutron-rich, environment to test materials for suitability for use in fusion energy reactors.
- IFMIF will
  - calibrate data from fission reactor and other accelerator-based irradiation tests
  - generate an engineering base of material-specific activation and radiological properties data
  - support the analysis of materials for use in safety, maintenance, recycling, decommissioning, and waste disposal systems.

- Two deuteron accelerators delivering beams of a total power of 10 MW on a liquid lithium source, generating intense flux of neutrons (10^{17} neutrons/s) at 14 MeV
- IFMIF-EVEDA test facility, single deuteron accelerator to 9 MeV, 125 mA, 1.2 MW. Under development at CEA



IFMIF - Principles

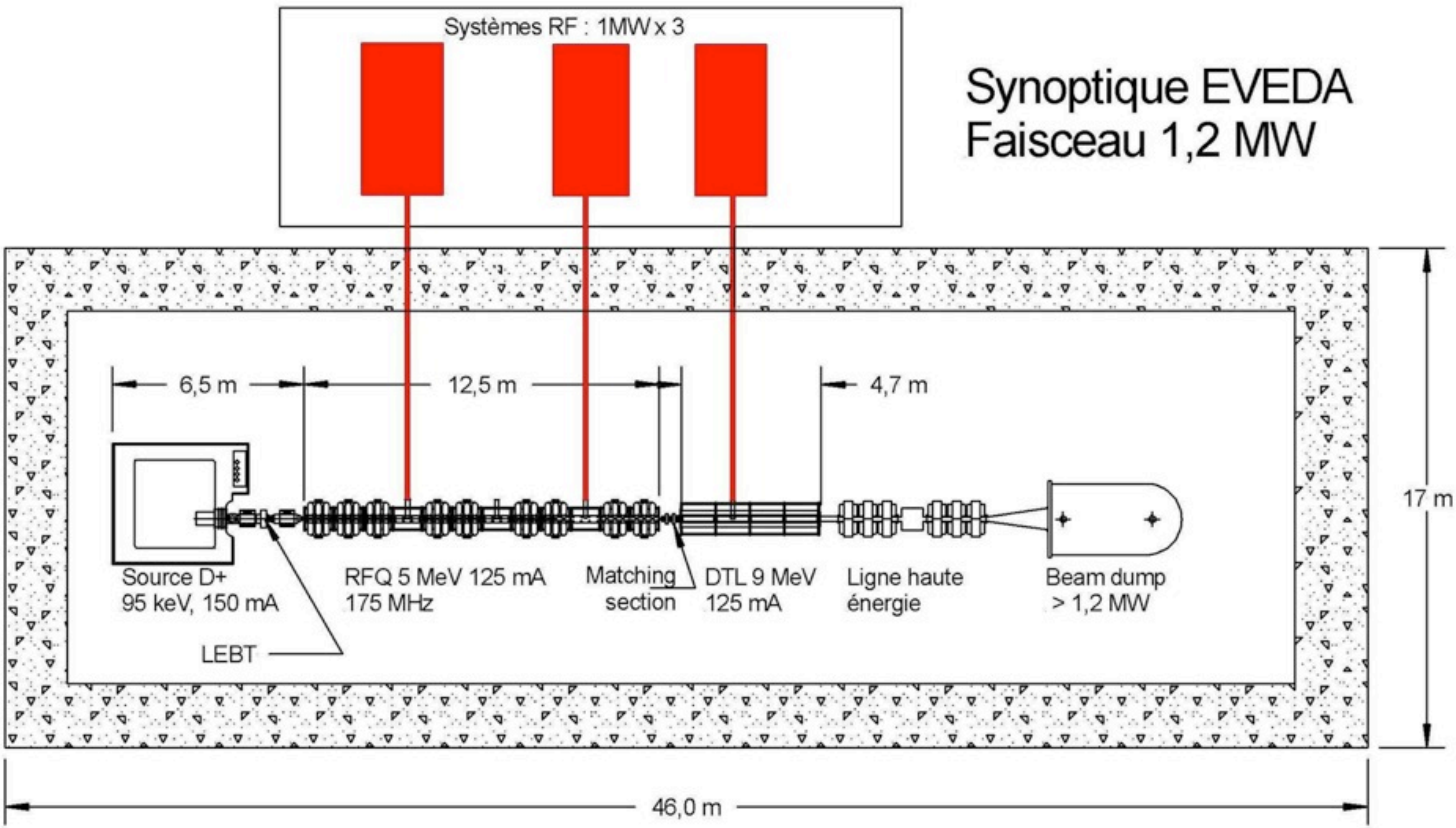


Accelerator based neutron source using the D-Li stripping reaction ⇒ intense neutron flux with the appropriate energy spectrum

Typical reactions:
$^{7}Li(d,2n)^{7}Be$, $^{6}Li(d,n)^{7}Be$, $^{6}Li(n,T)^{4}He$

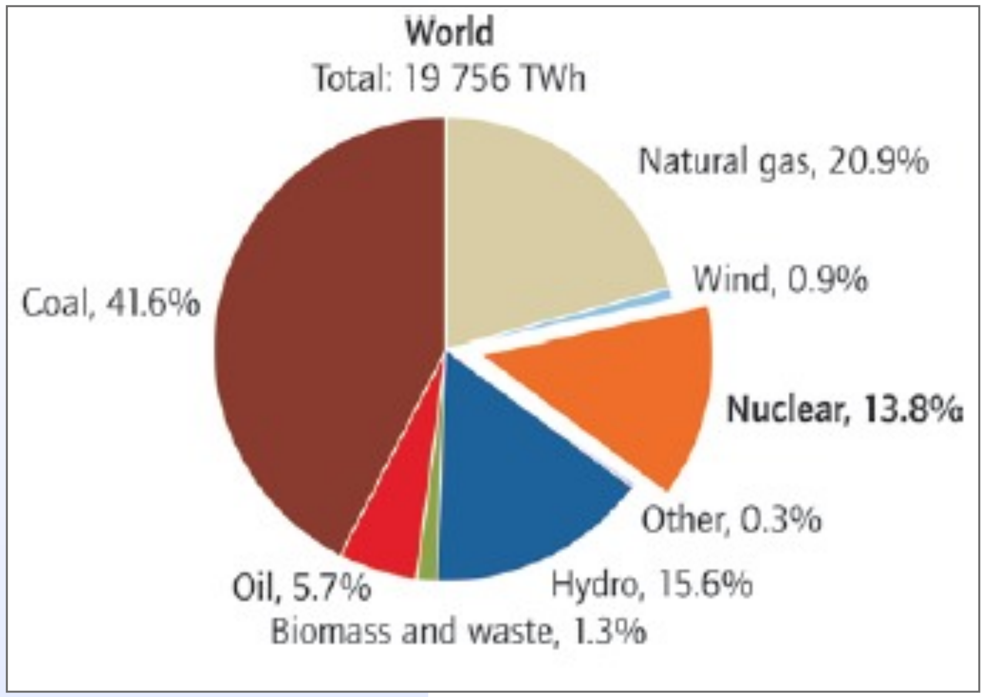
Beam footprint on Li target
20cm wide x 5cm high
(1 GW/m²)

IFMIF-EVEDA
A 9 MeV Test Facility

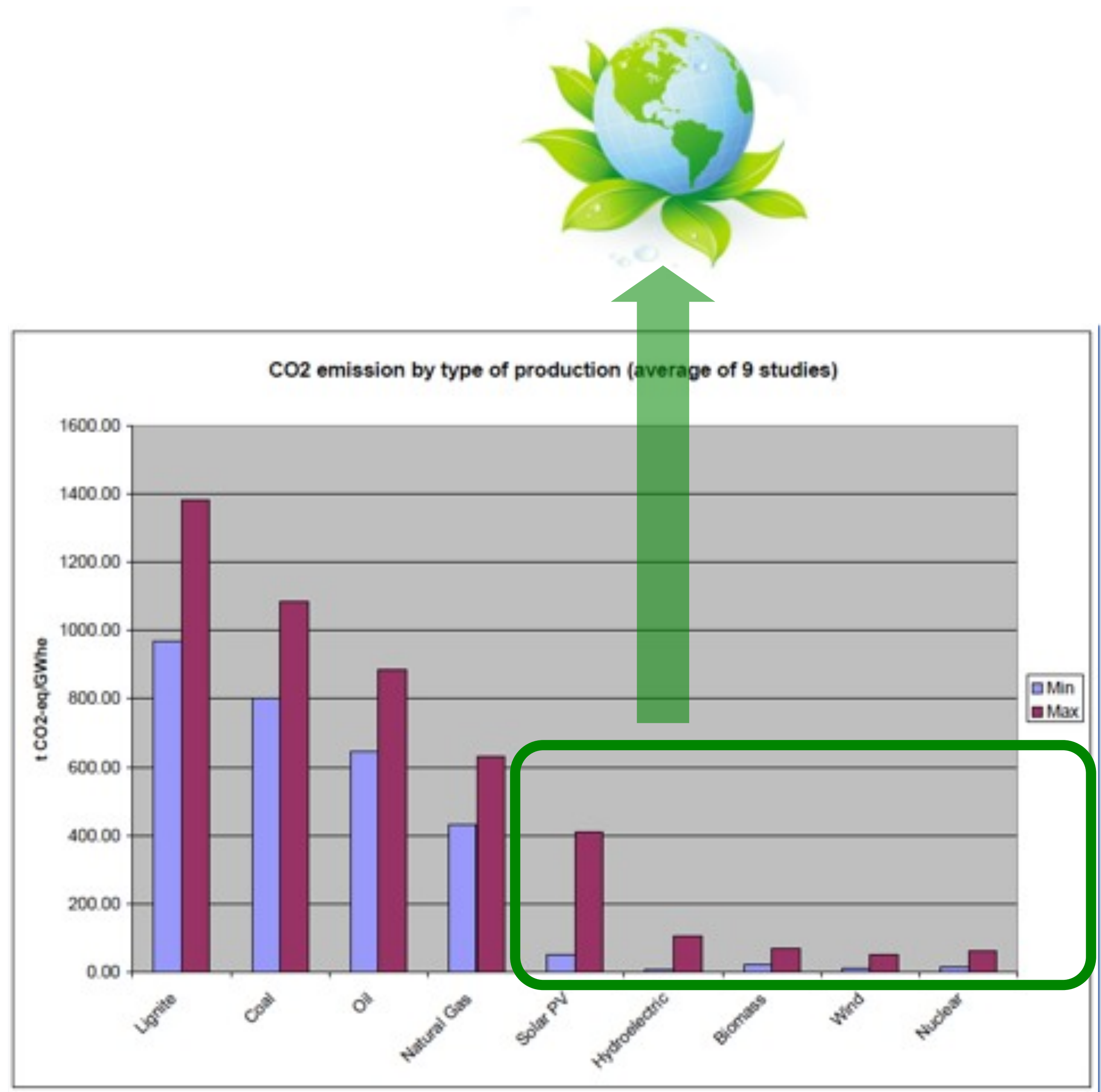


SCK•CEN
STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE

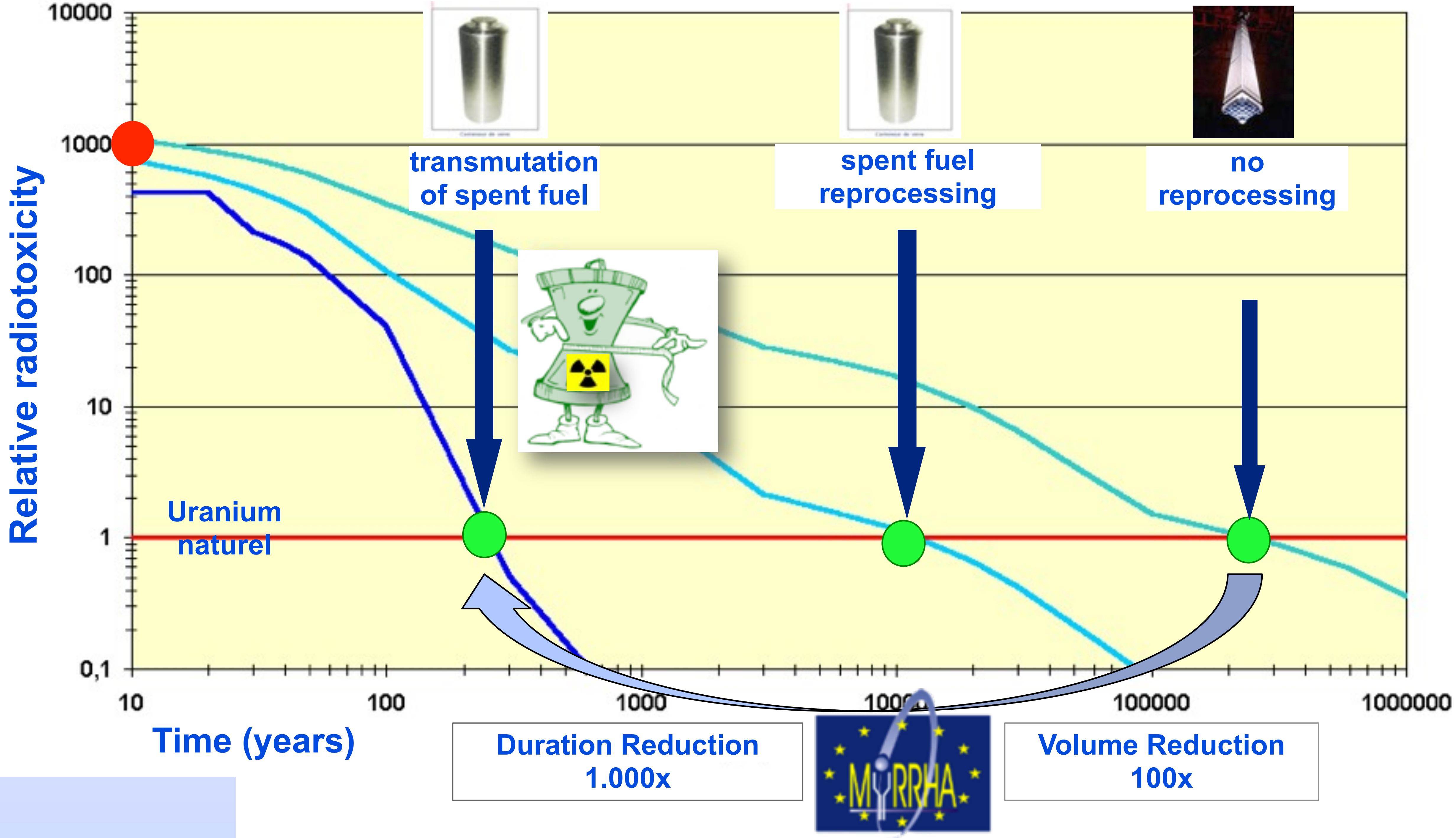
Facing the energy challenge



Electricity generation worldwide
(OECD, 2007)



Motivation for transmutation



Accelerator Driven Systems

- Nuclear waste transmutation and nuclear energy generation using spallation neutron sources
  - intense neutron flux produced from spallation reactions induced by a proton beam on a heavy target
  - neutrons are moderated and used to drive a sub-critical blanket
  - long-lived nuclear waste transmuted to stable or short-lived isotopes

  "ADSRs have the potential to replace carbon-free nuclear power stations with a more sustainable, cost-effective and safer form of nuclear power to the benefit of the consumer and the environment."
- ADSR fuelled with non-enriched thorium (abundant); breeds and burns its own fuel in a plutonium-free cycle
  - safety advantages that reactor is sub-critical and can be shut down very rapidly by switching off the accelerator
- **World's first ADS experiment** March 2009 at KURRI, Japan. 100 MeV FFAG proton beam on heavy metal target; spallation neutrons bombarded into sub-critical fuel core

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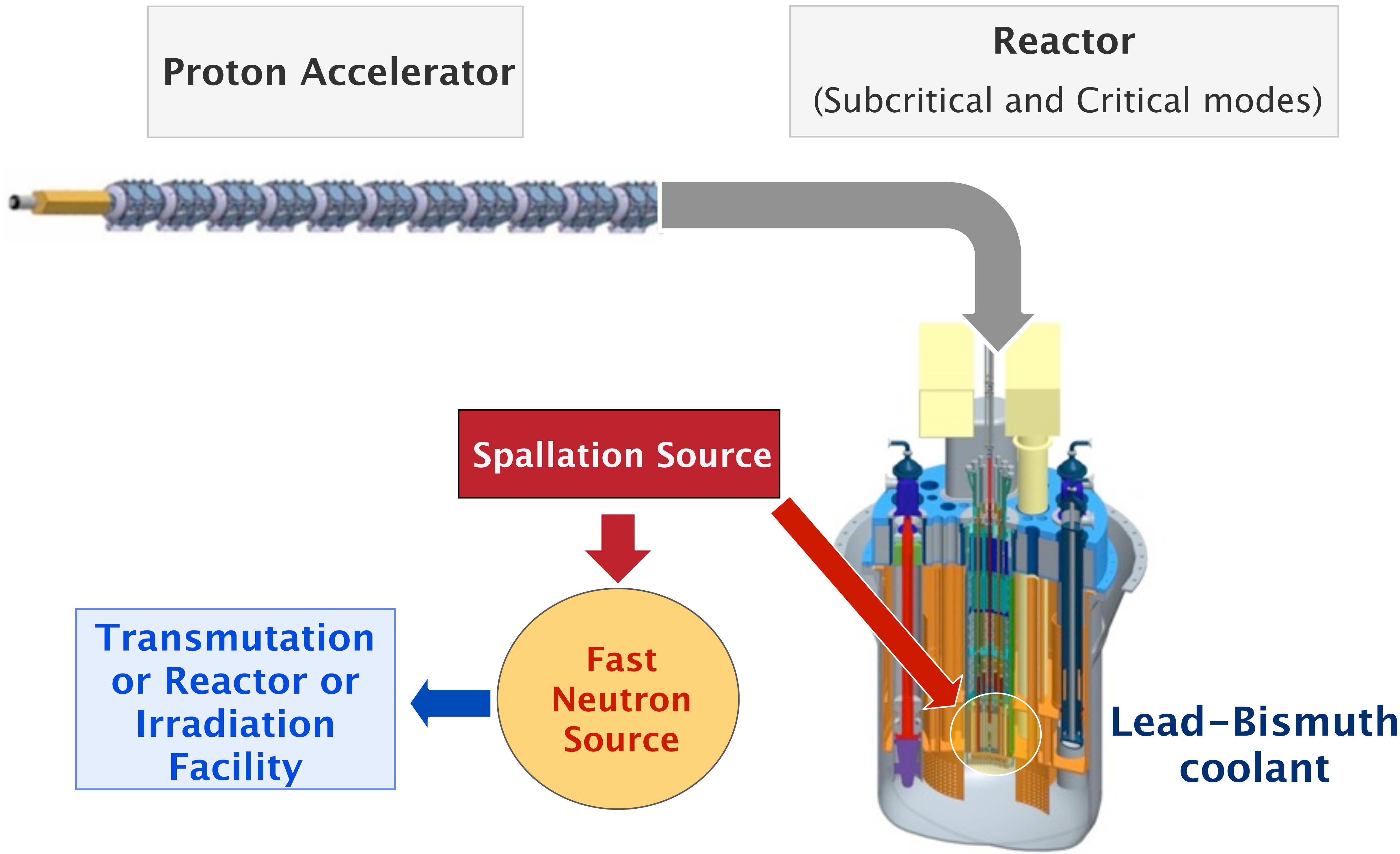
Accelerator Driven Systems



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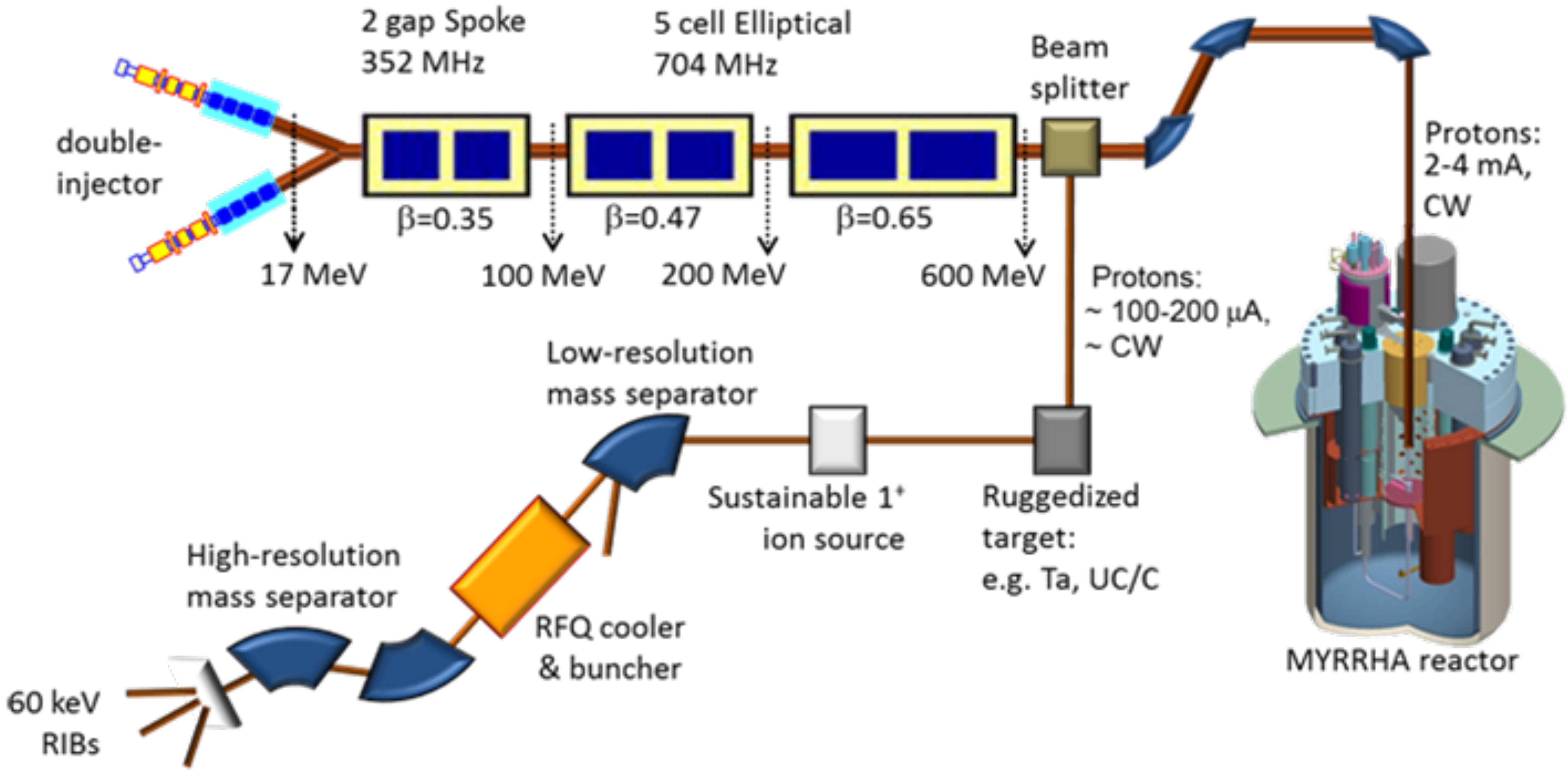
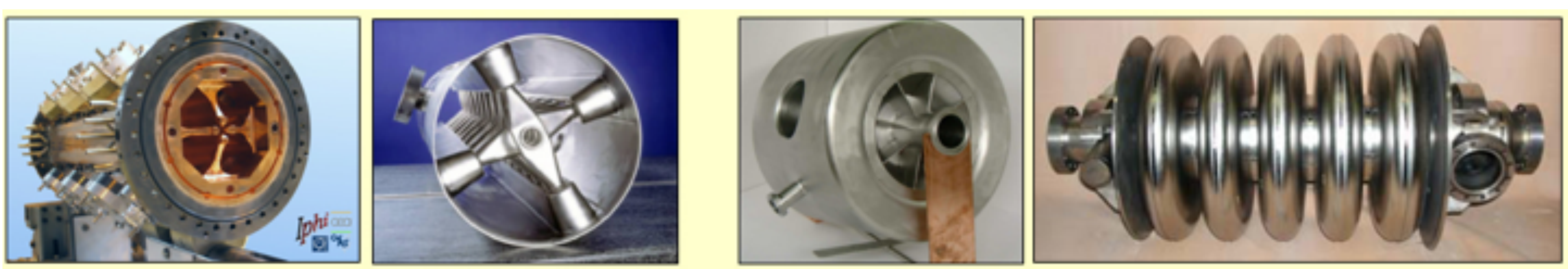
MYRRHA

Belgian Nuclear Research Centre (SCK.CEN); construction planned 2015.
600 MeV, 2.5 mA proton beam on Pb-Bi target





ADSR: Reliability Issues

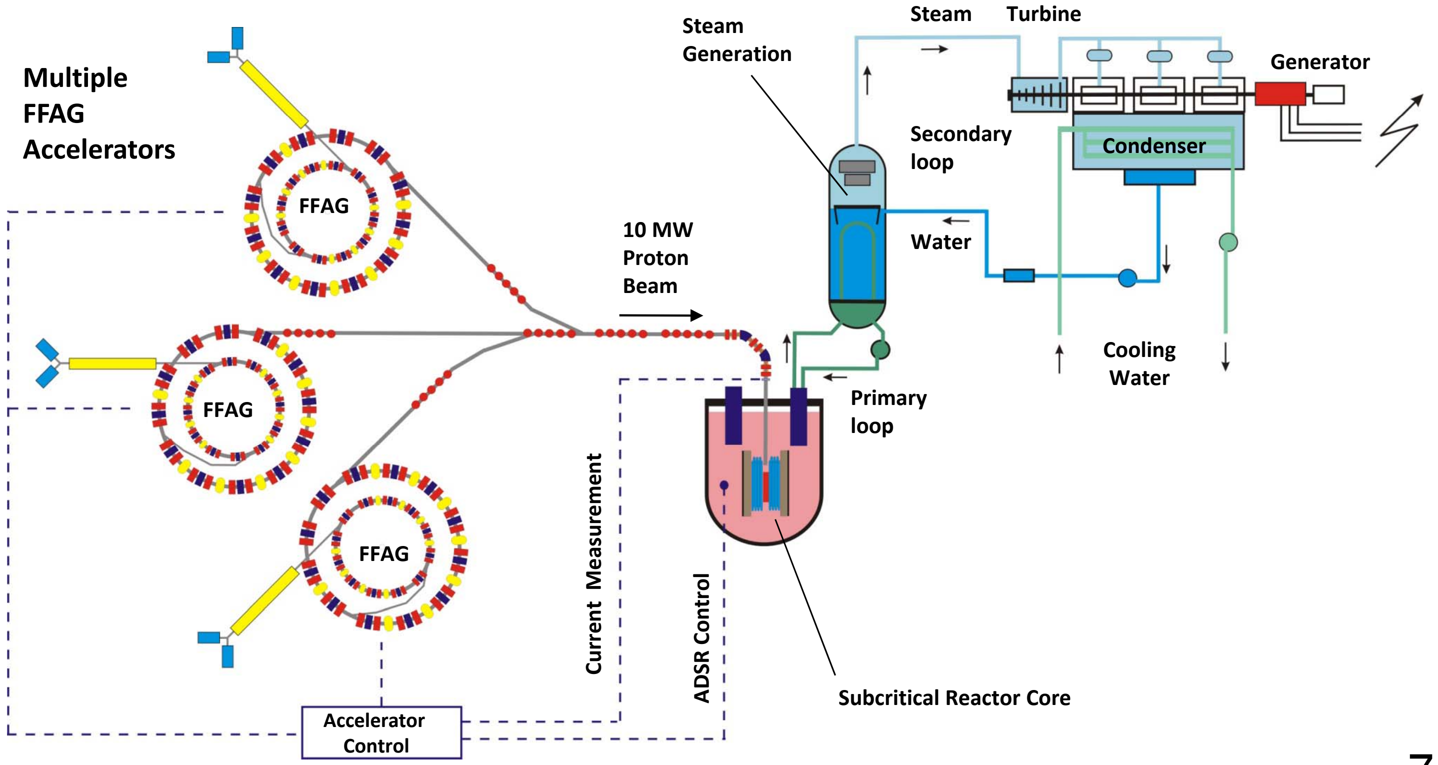
Beam availability: an order of magnitude better than present day state-of-the-art.

- Number of beam trips longer than 3 seconds to be reduced to less than 1 per week.
  - related to the thermal shocks which a beam interruption causes in an ADS, adversely affecting structural materials of the reactor and possibly causing safety issues.
- Operability of the plant requires an extremely high availability of the proton beam.

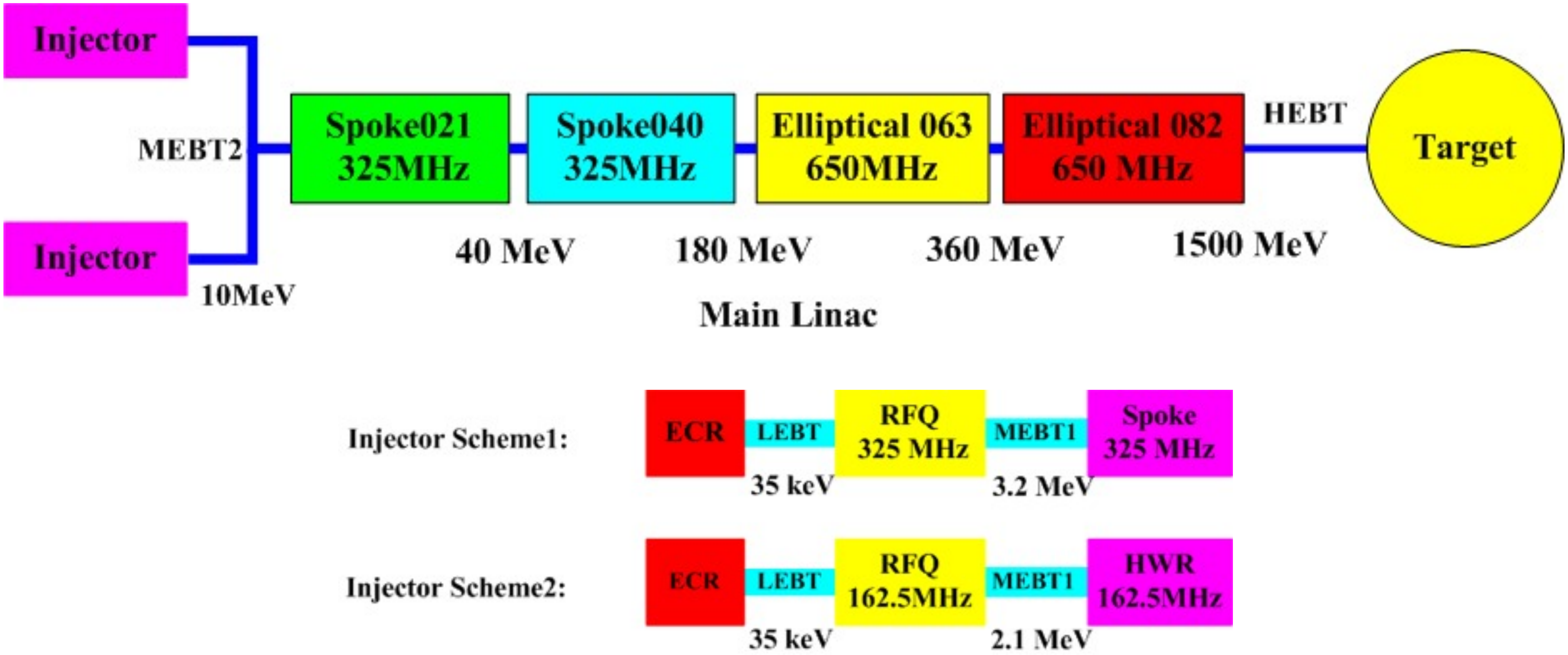
PSI data 2001

Interruption time	$1' - 3'$	$3' - 15'$	$15' - 60'$	1-2h	2-6h	6-12h	12-24h	> 24h
Number	5245	524	93	19	21	6	4	4
Time sum (h)	92	42	42	25	75	45	70	167

UK-ThorEA approach: multiple accelerators with redundancy, current increased if one accelerator goes down. FFAGs proposed for reliability and reduced cost.



Chinese-ADS Study



Energy	1.5 GeV
Current	10 mA
Beam power	15 MW
Beam trips/year	$\begin{cases} 1-10\,\mathrm{s}\ (<25000) \\ 10\,\mathrm{s}-5\,\mathrm{min}\ (<2500) \\ >5\,\mathrm{min}\ (<25) \end{cases}$

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Summary

- There is very strong interest in high power proton and ion accelerators with a wide range of applications
- The designs of the various projects have many features in common (e.g. the use of superconducting RF), leading to large potential synergy between projects
- Two large-scale facilities have recently come into operation (SNS, J-PARC)
- These and others are being upgraded or have upgrade plans (PSI, ISIS, SNS, J-PARC, GSI)
- Many medium-scale facilities are in construction (Linac4, Saraf, Spiral2, PEFP, IFMIF-EVEDA)
- ESS, IFMIF, Project-X, MYRRHA may come into being in the coming decade. C-ADS looks set on an aggressive programme.

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