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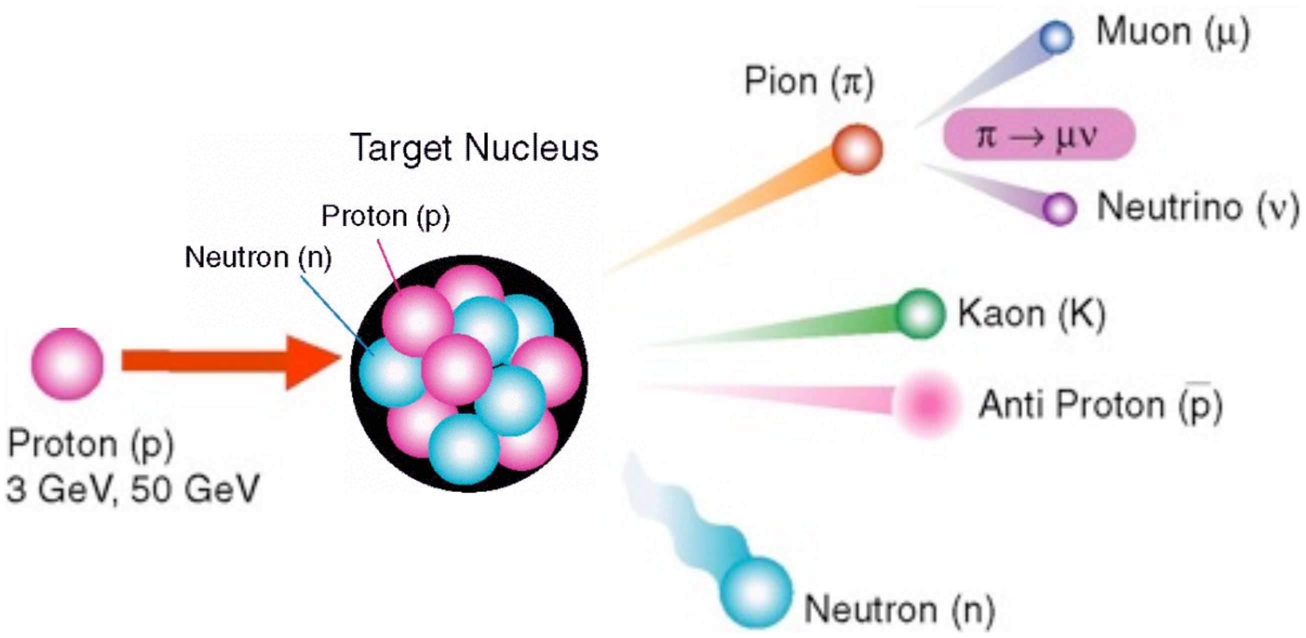
Overview of High Intensity Accelerator Projects

Chris Prior

ASTeC, Rutherford Appleton Laboratory, U.K.

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



Materials & Life Sciences at ~3 GeV

Nuclear & Particle Physics at ~50 GeV

R&D for ADS at ~0.5 GeV

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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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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
- Irridiation facilities
  - IFMIF (*Europe/US/Japan*) + prototype EVEDA (*CEA*)
- Accelerator Driven Systems (ADS)
  - EUROTRANS (*Europe*), TRASCO (*Italy*), ADS (*China*), ThorEA (*UK*)

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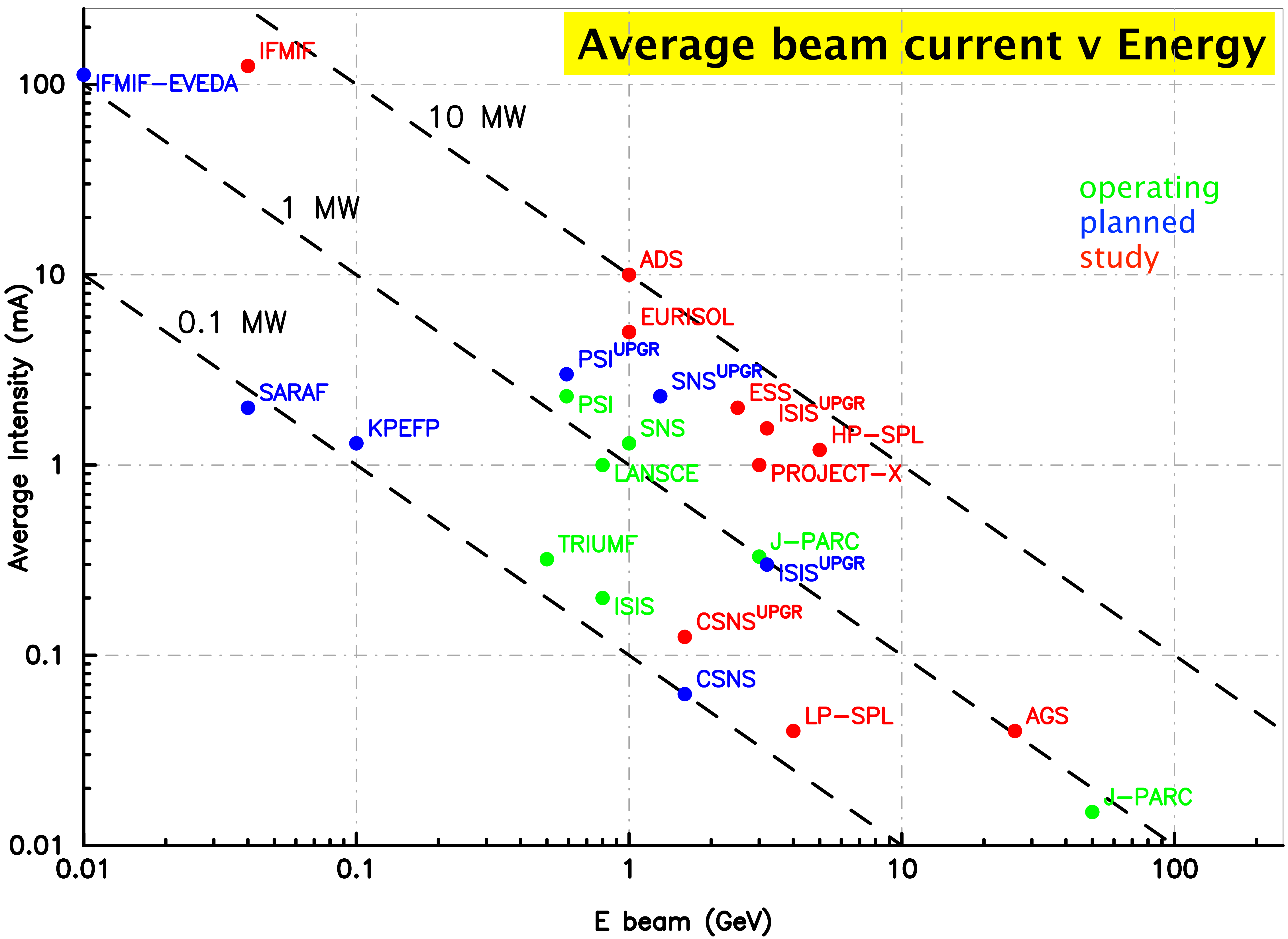
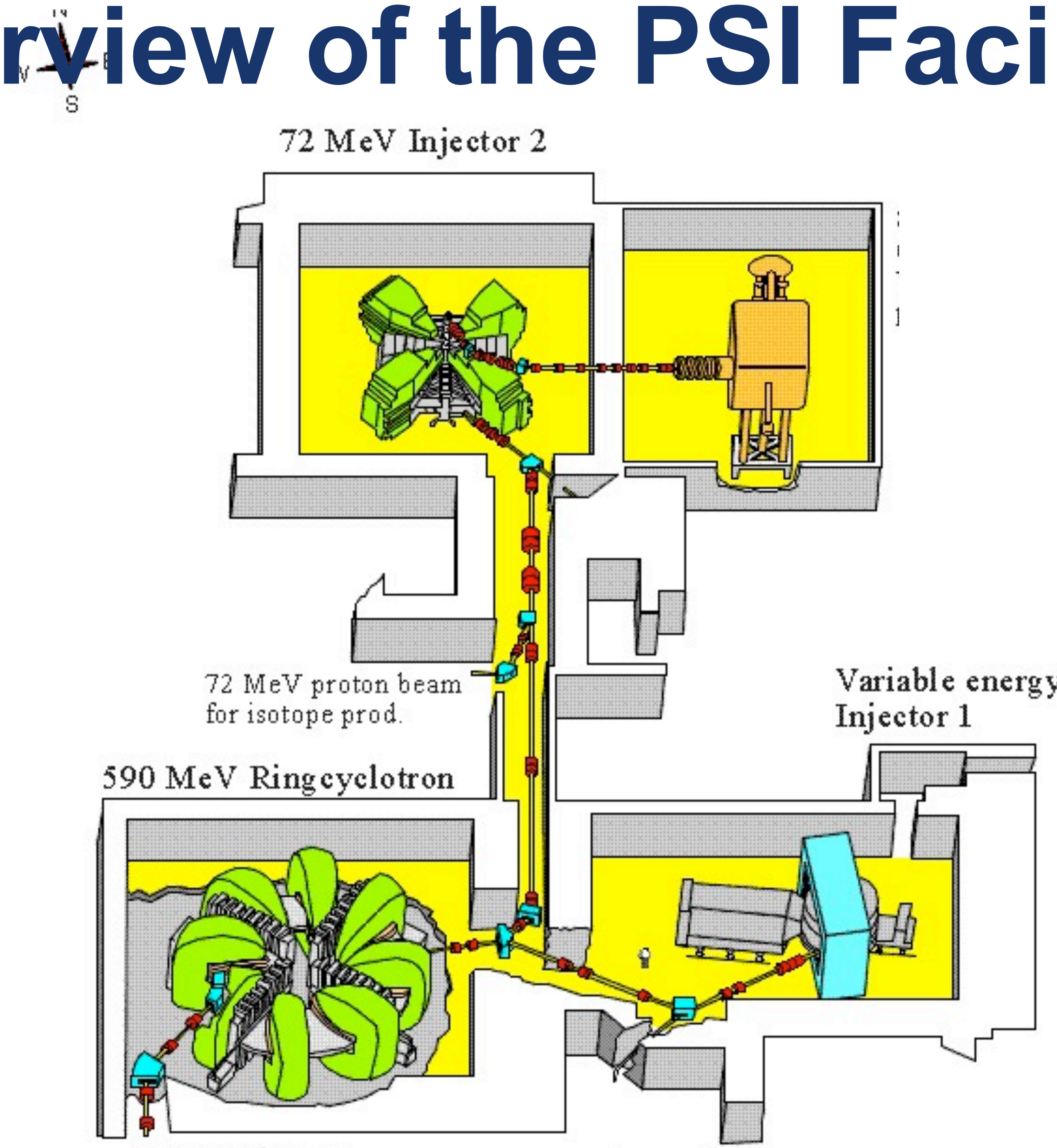
Beam Power Frontier



- 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


Accelerator Facilities at PSI
p-Therapy
250 MeV,
<1μA
central
control room
SINQ
Swiss Light
Source
2.4 GeV, 400mA
High Intensity
Proton Accelerator
590 MeV, 2.2mA
XFEL
Injector
250 MeV

Overview of the PSI Facility



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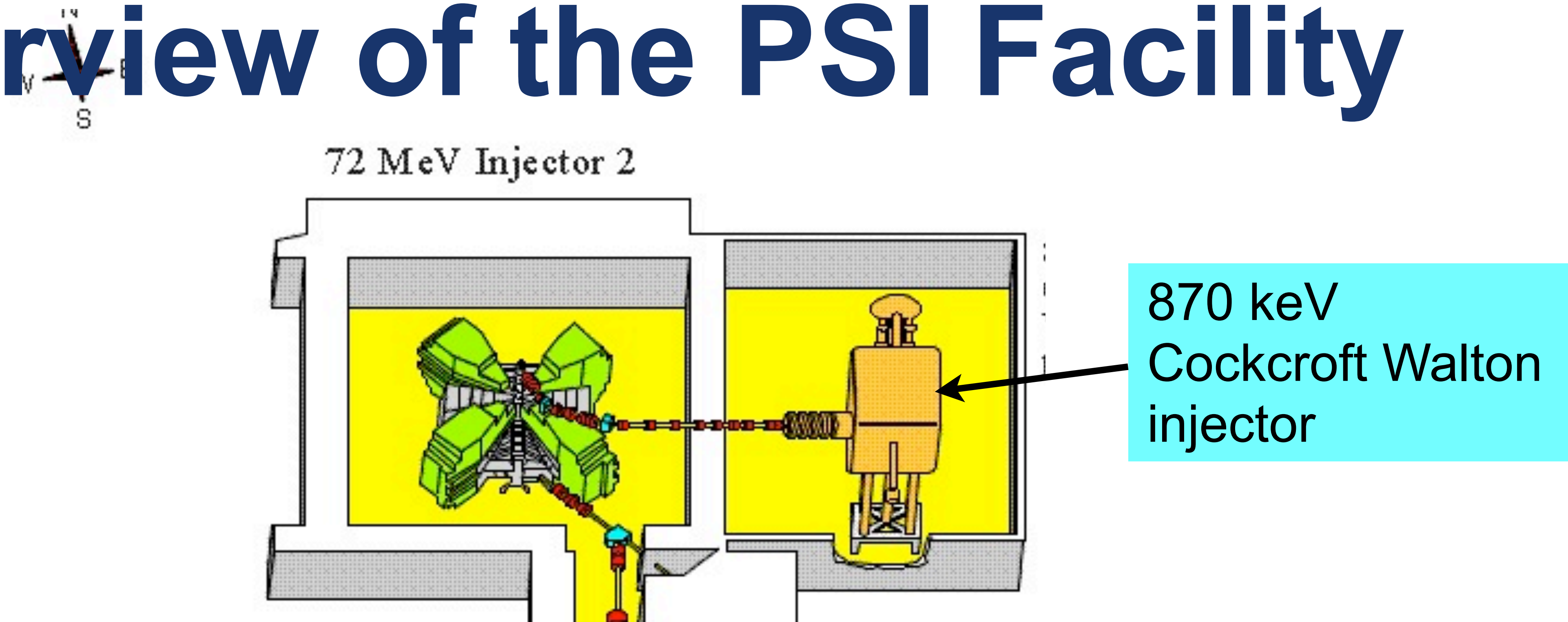
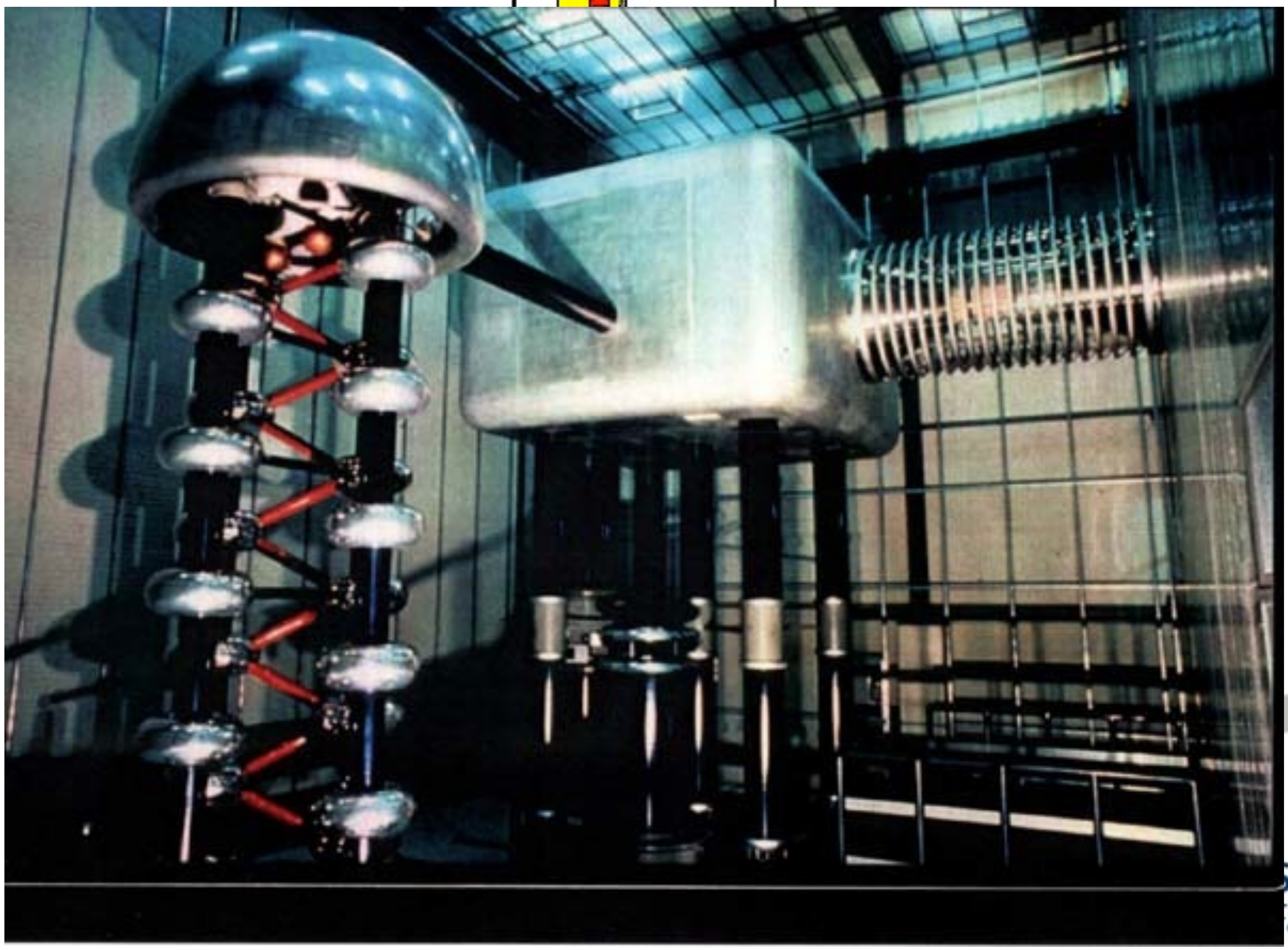
Overview of the PSI Facility





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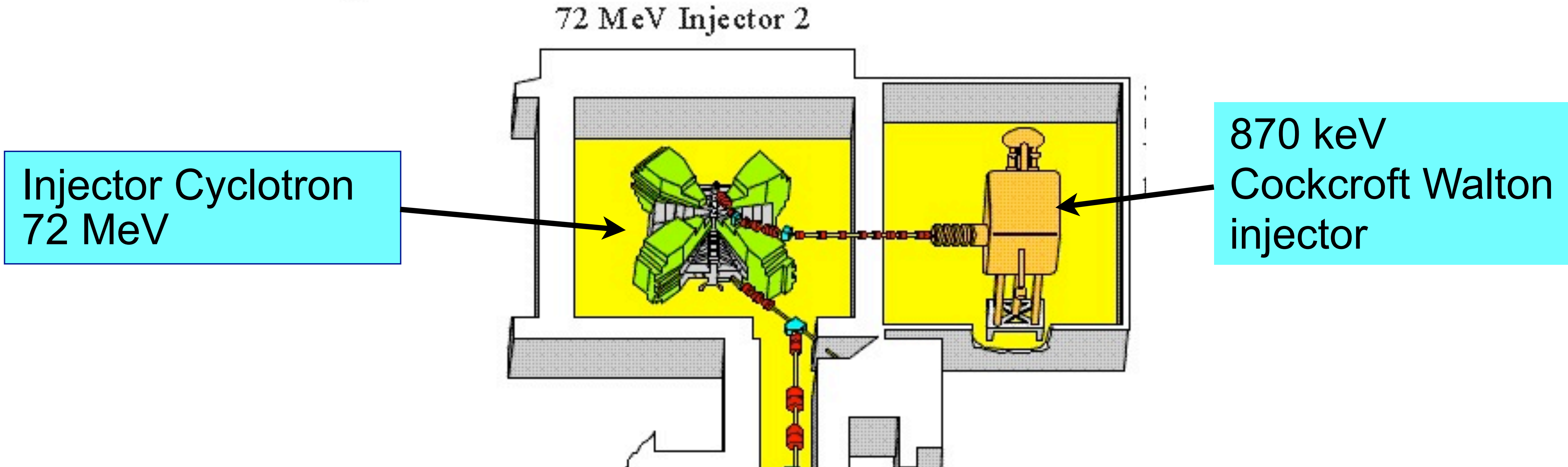
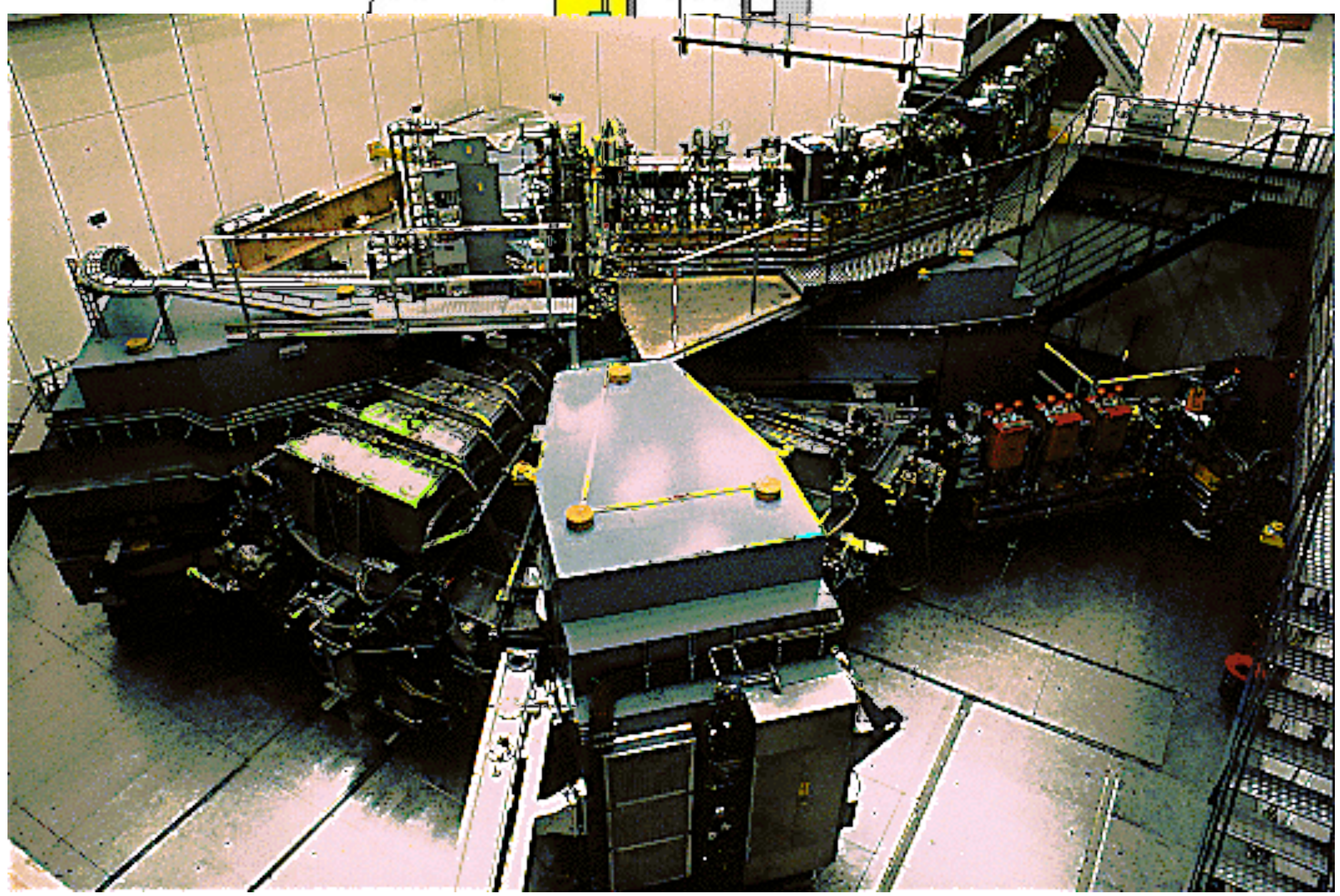
Overview of the PSI Facility



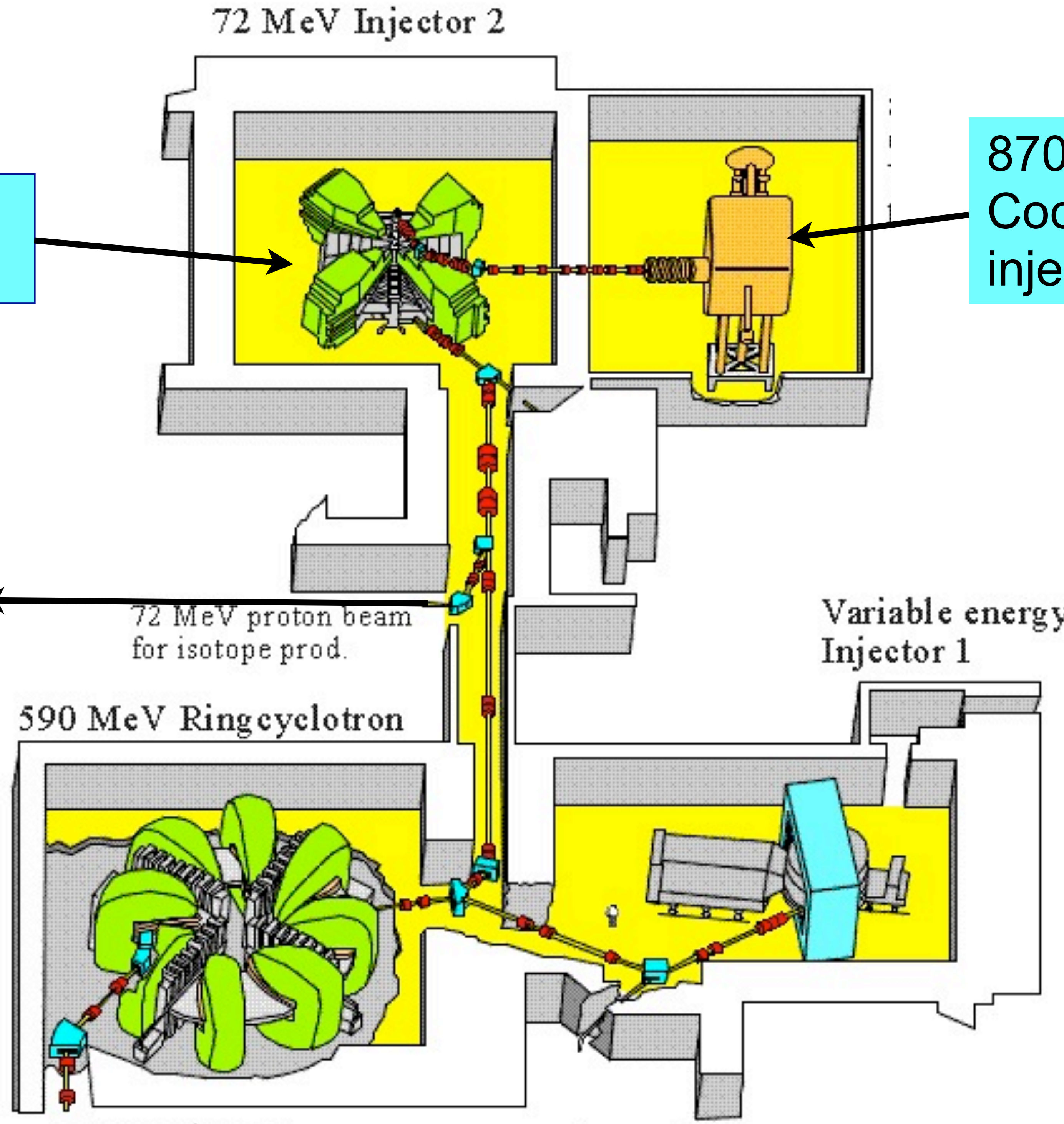


Overview of the PSI Facility

Injector Cyclotron
72 MeV

870 keV
Cockcroft Walton
injector

Isotope
production
(I_b < 100 μA)



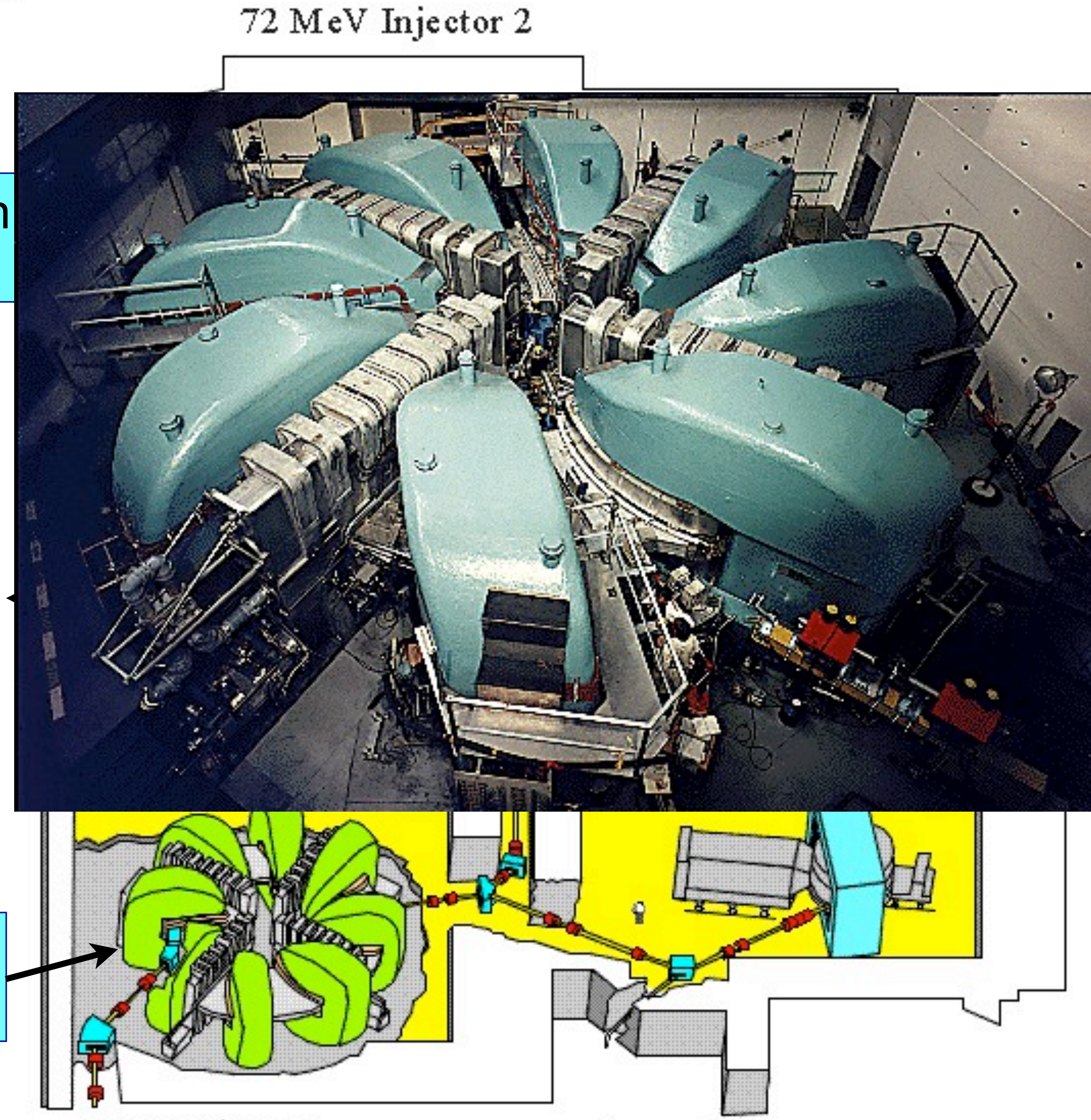
Overview of the PSI Facility

Injector Cyclotron
72 MeV

keV
kcroft Walton
ctor

Isotope
production
(I_b < 100 μA)

Ring Cyclotron
590 MeV



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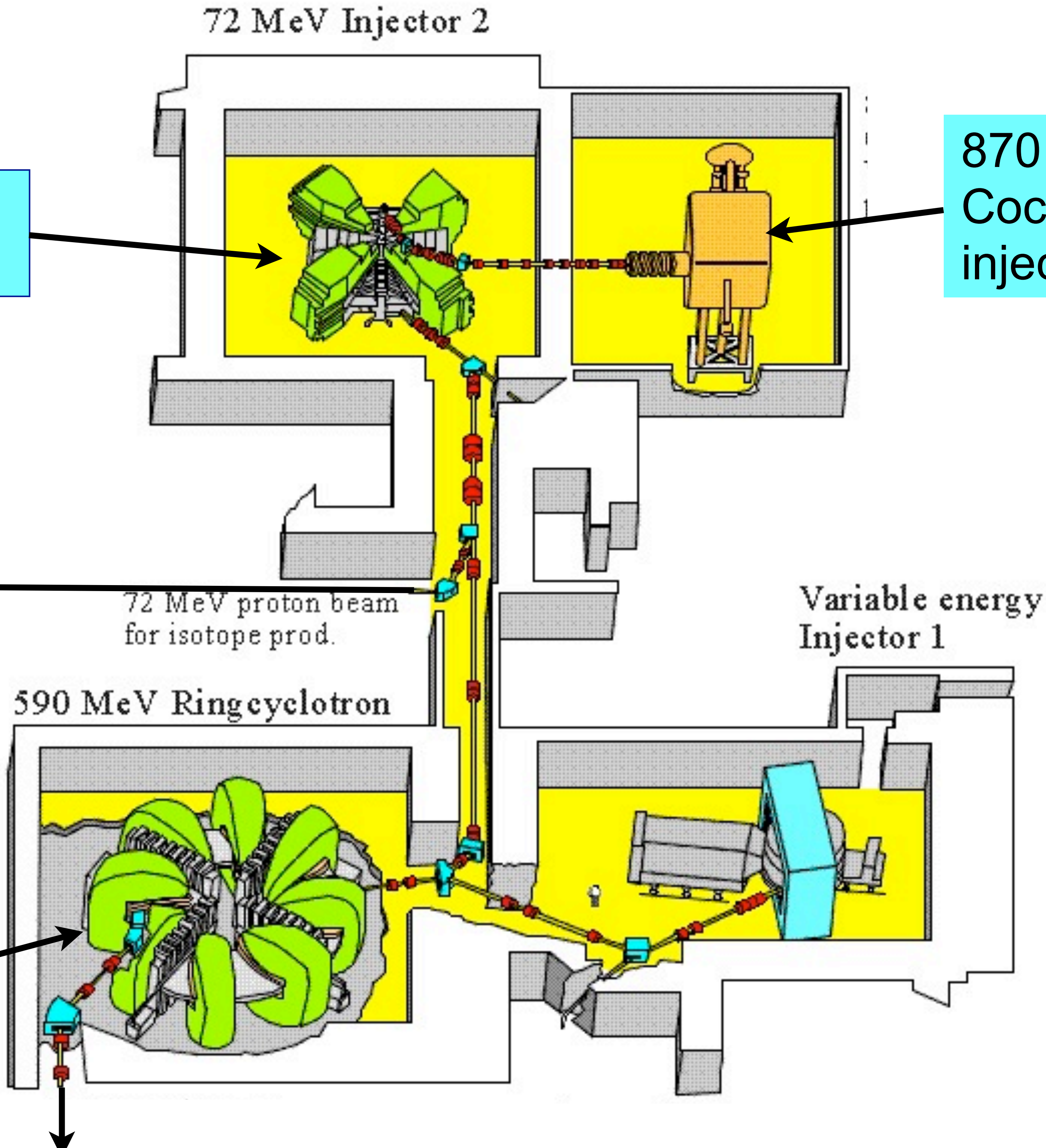
Overview of the PSI Facility



Injector Cyclotron
72 MeV

870 keV
Cockcroft Walton
injector

Isotope
production
(I_b < 100 μA)

Ring Cyclotron
590 MeV

590 MeV beam to meson production target and spallation neutron source

Beams for low energy experiments

PSI Cyclotron

Sector cyclotron (magnets/resonators)

Optimised for high intensity

E=590 MeV, I_{max}=2.2 mA (1.3 MW)

B_{max}=1.1 T, R_{extr}=4.5 m, N_{turn}=186

Extraction efficiency 99.98%

Loss: < 200W

- The PSI accelerator delivers 1.3 MW beam power
  - loss ~10^{-4}
  - average reliability is 90%
  - 25-50 trips per day
  - grid-to-beam power conversion efficiency is 32% considering RF systems only; ~ 15% including everything
- An upgrade to 1.8 MW is in progress
  - new resonators Injector II cyclotron
  - new 10th harmonic buncher
  - completion planned for 2013
- **Based on experience at PSI, the cyclotron concept is regarded as an effective option for generating high power beams, for example for ADS applications [~ 1GeV/10MW]**

PSI: 2009 New Beam Intensity Record

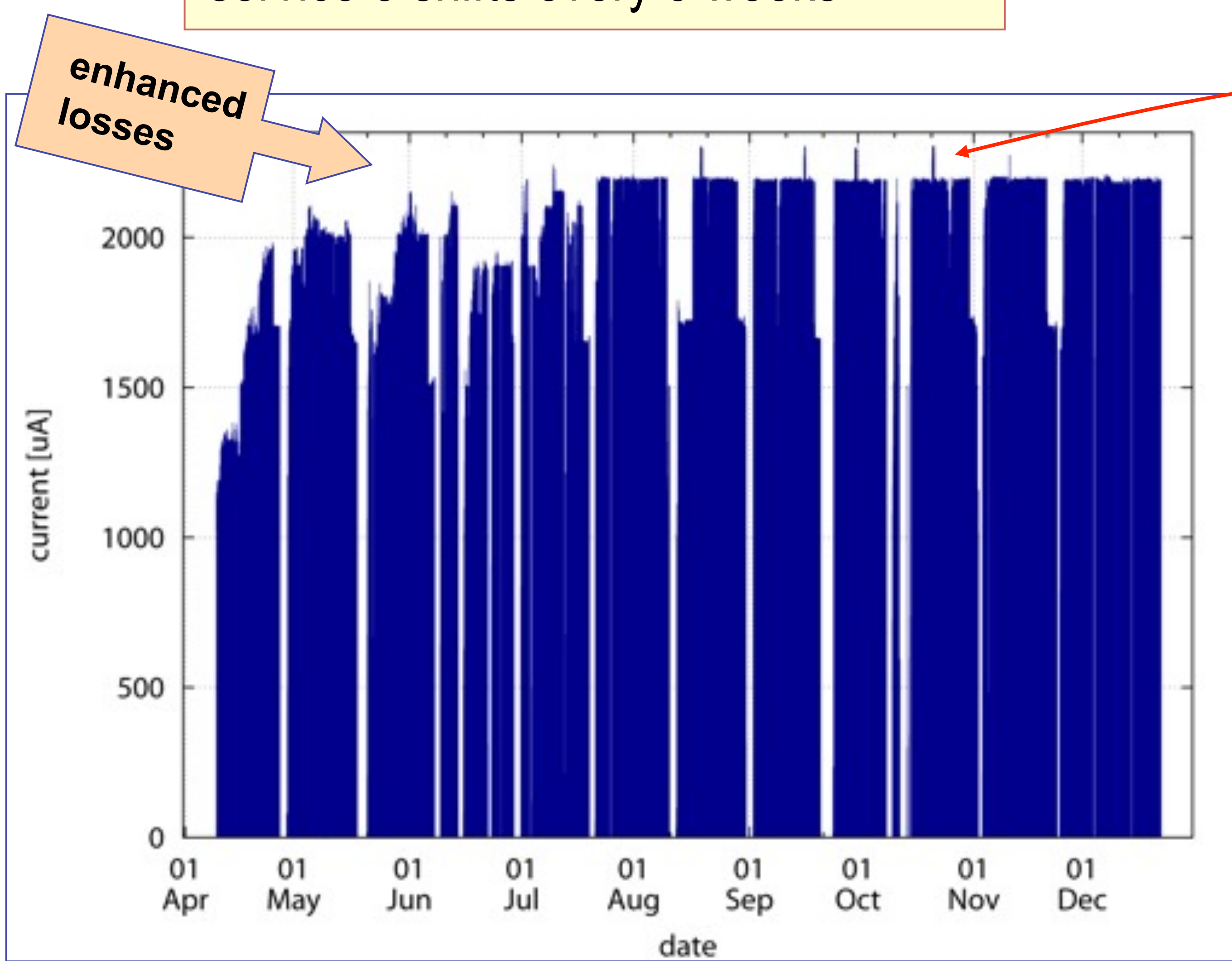
- Since 2009 license for **standard operation 2.2 mA** (*cf* 2.0mA); test operation at 2.4 mA
- New maximum current: 2.3 mA (1.36 MW)

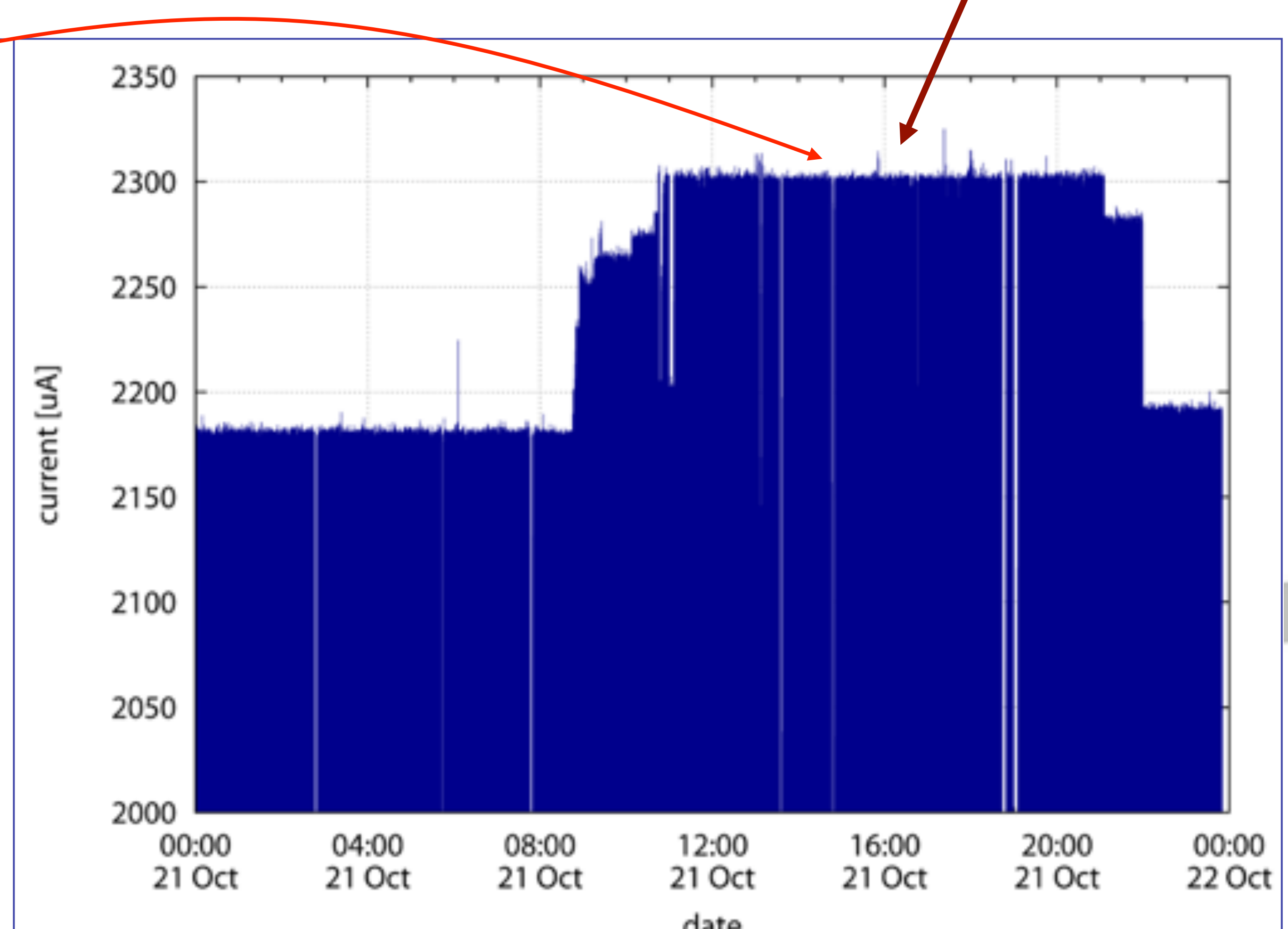
beam operation in 2009 –

service 8 shifts every 3 weeks

test run:

stable operation at 2.3mA





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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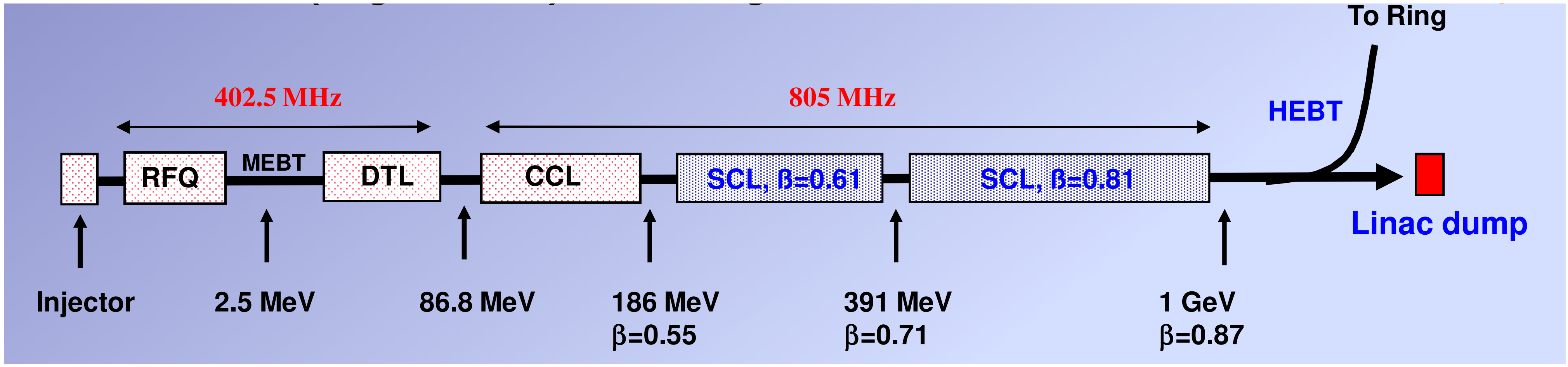
SNS Linac Overview



- 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
- Charge exchange injection into accumulator ring

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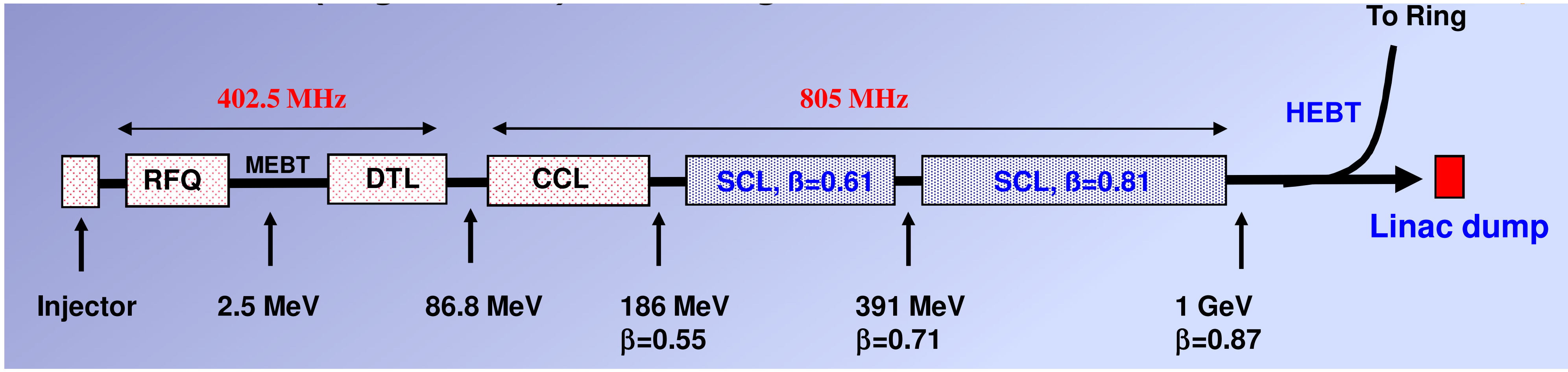
SNS Linac Overview



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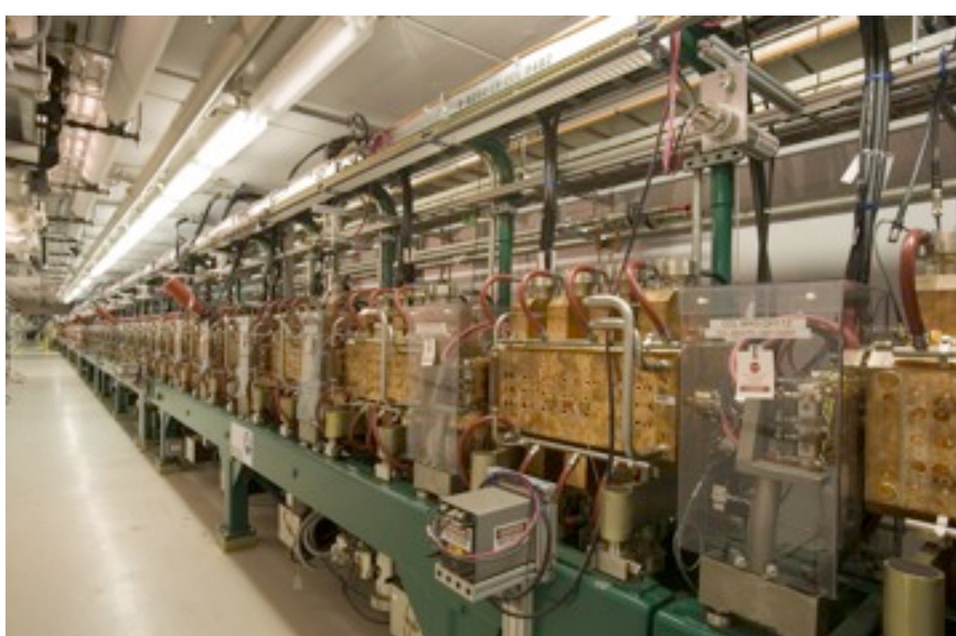

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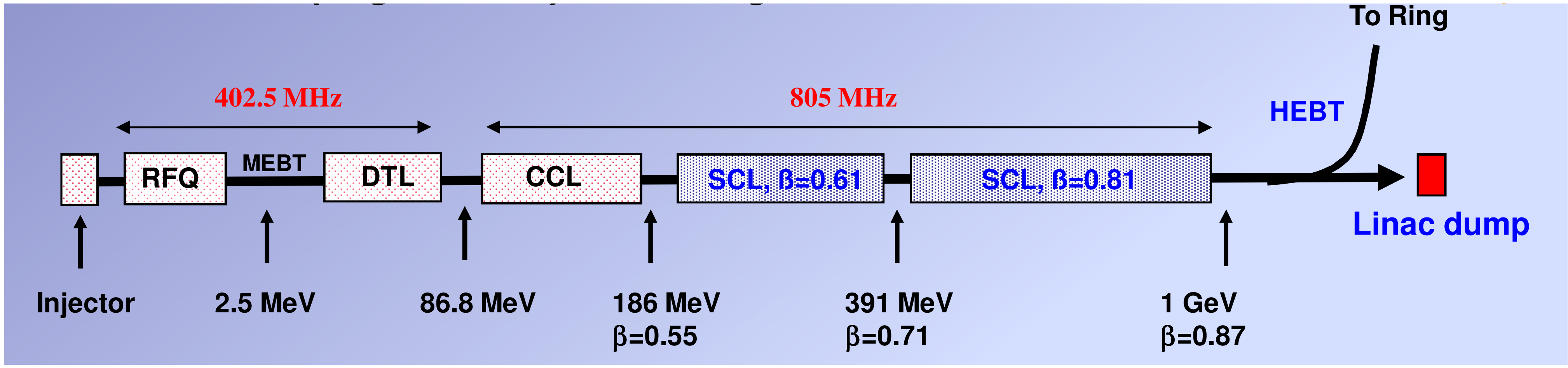
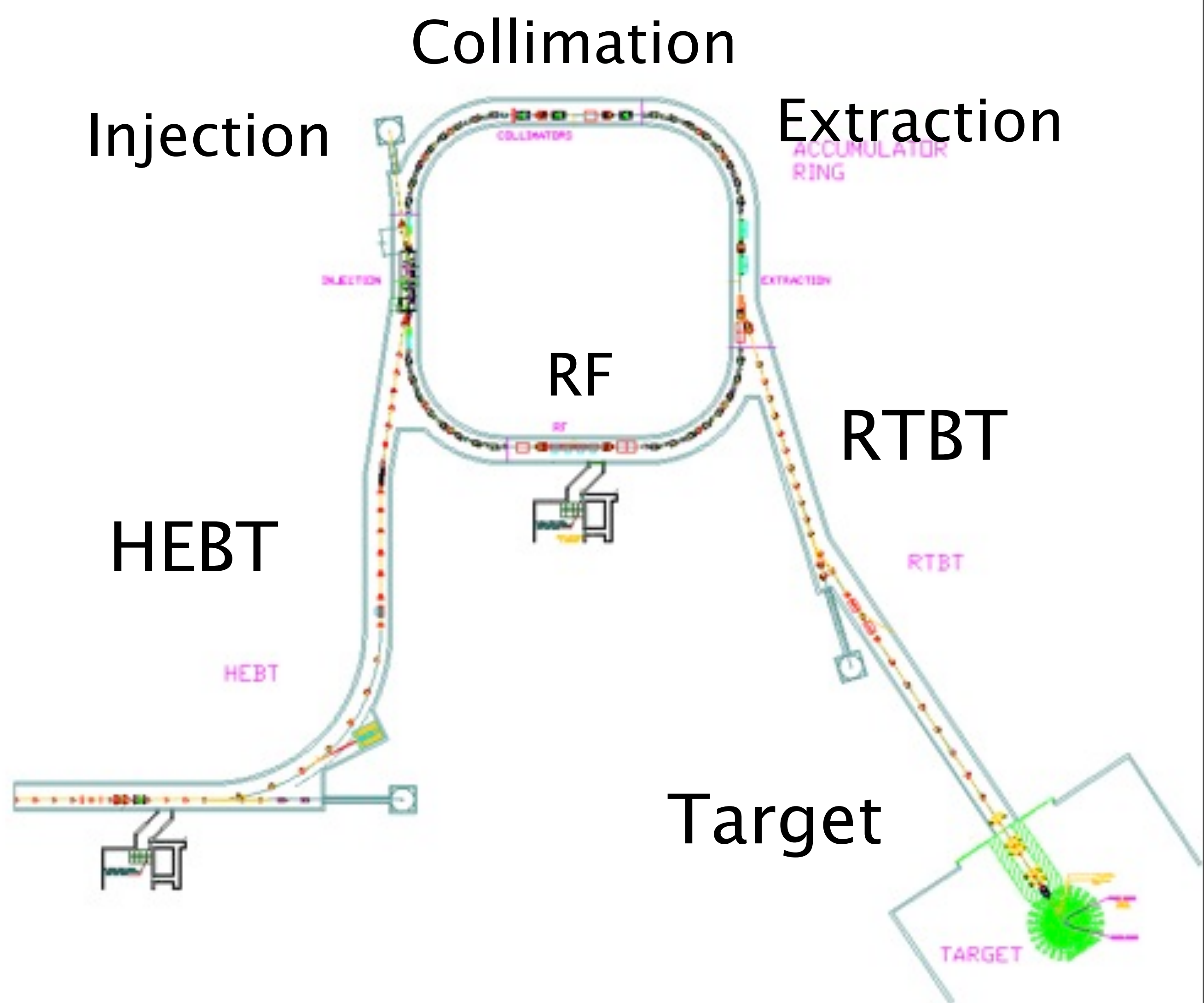
SNS Linac Overview

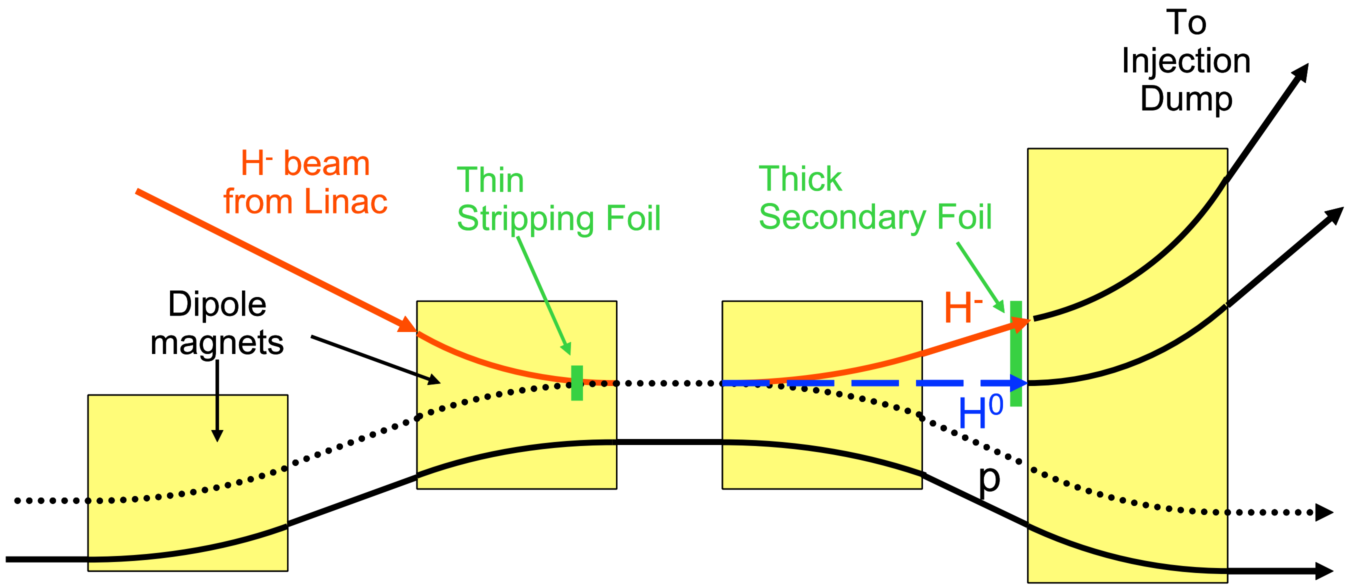


- Linac 260 m, 96 independently phased RF cavity/tanks
- Normal conducting from H^- ion source to 186 MeV
- Superconducting from 186 MeV to 1 GeV
- Charge exchange injection into accumulator ring

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 ~500 ns.



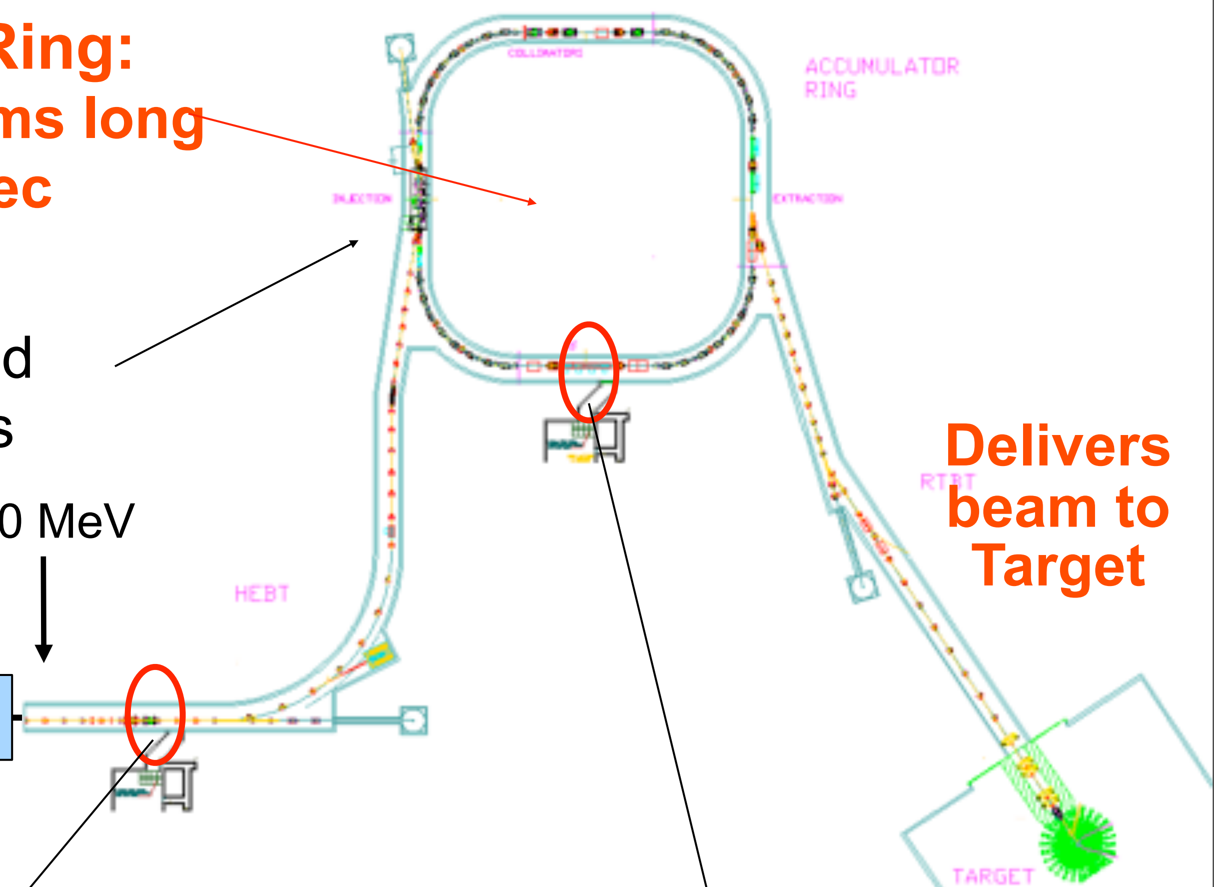


SNS Accelerator Operation

Front-End: Produces a 1 ms long, chopped, H^- beam

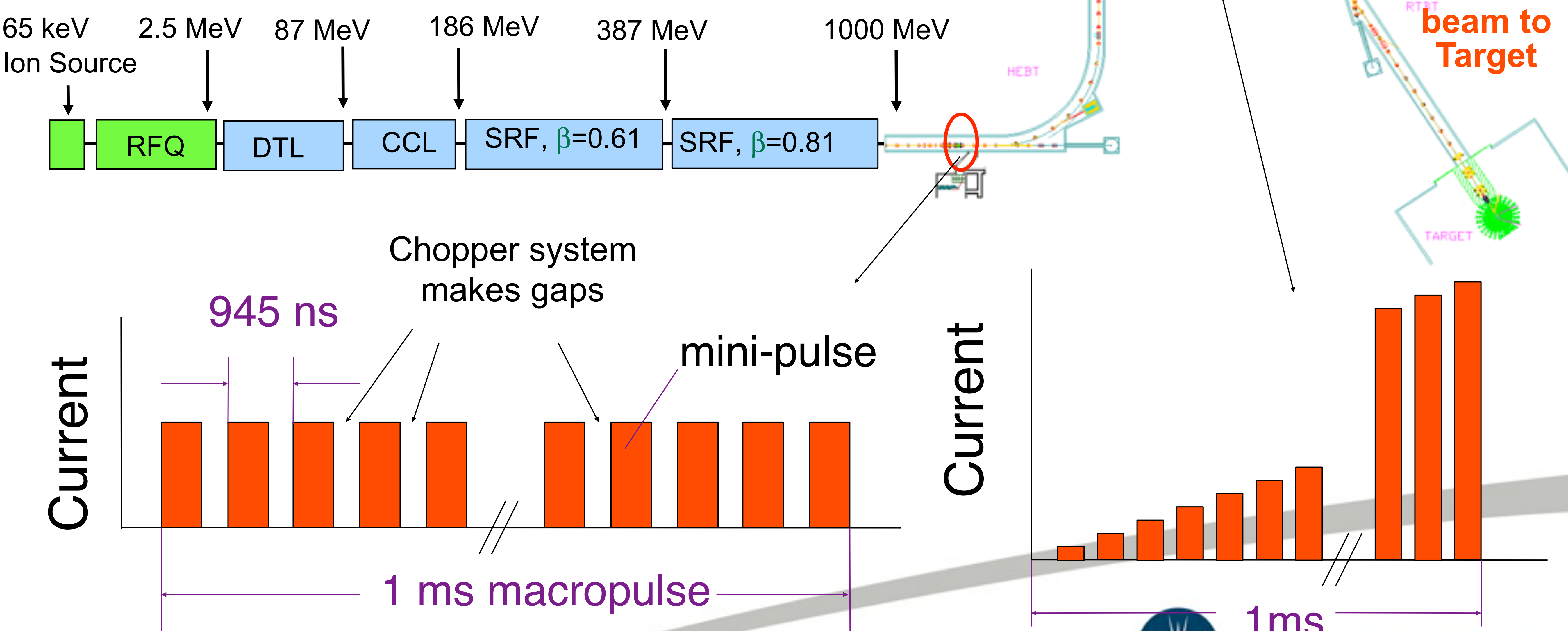
LINAC: Accelerates the beam to 1 GeV

Accumulator Ring: Compresses 1 ms long pulse to 700 nsec



H^- stripped to protons

Delivers beam to Target



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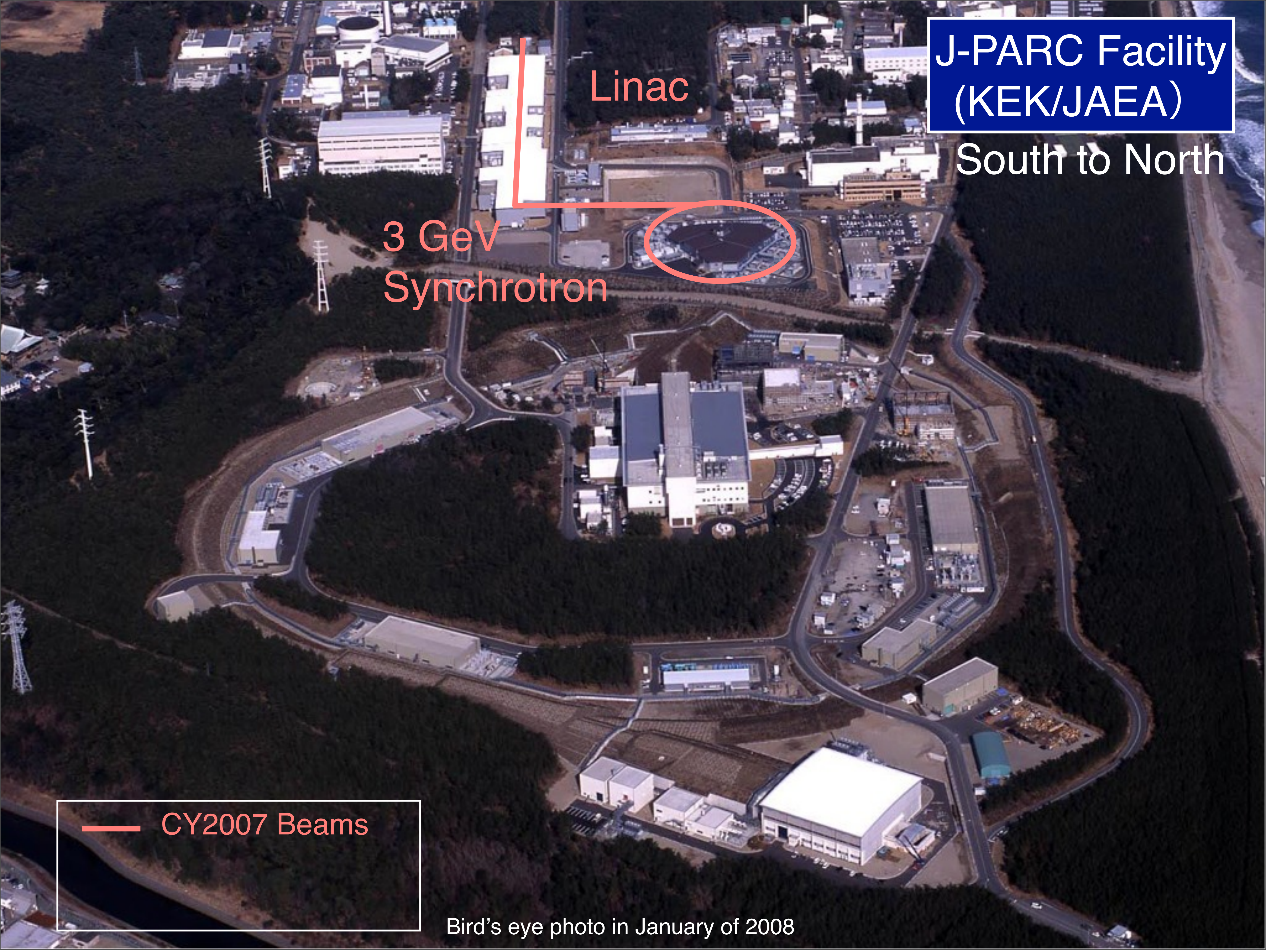
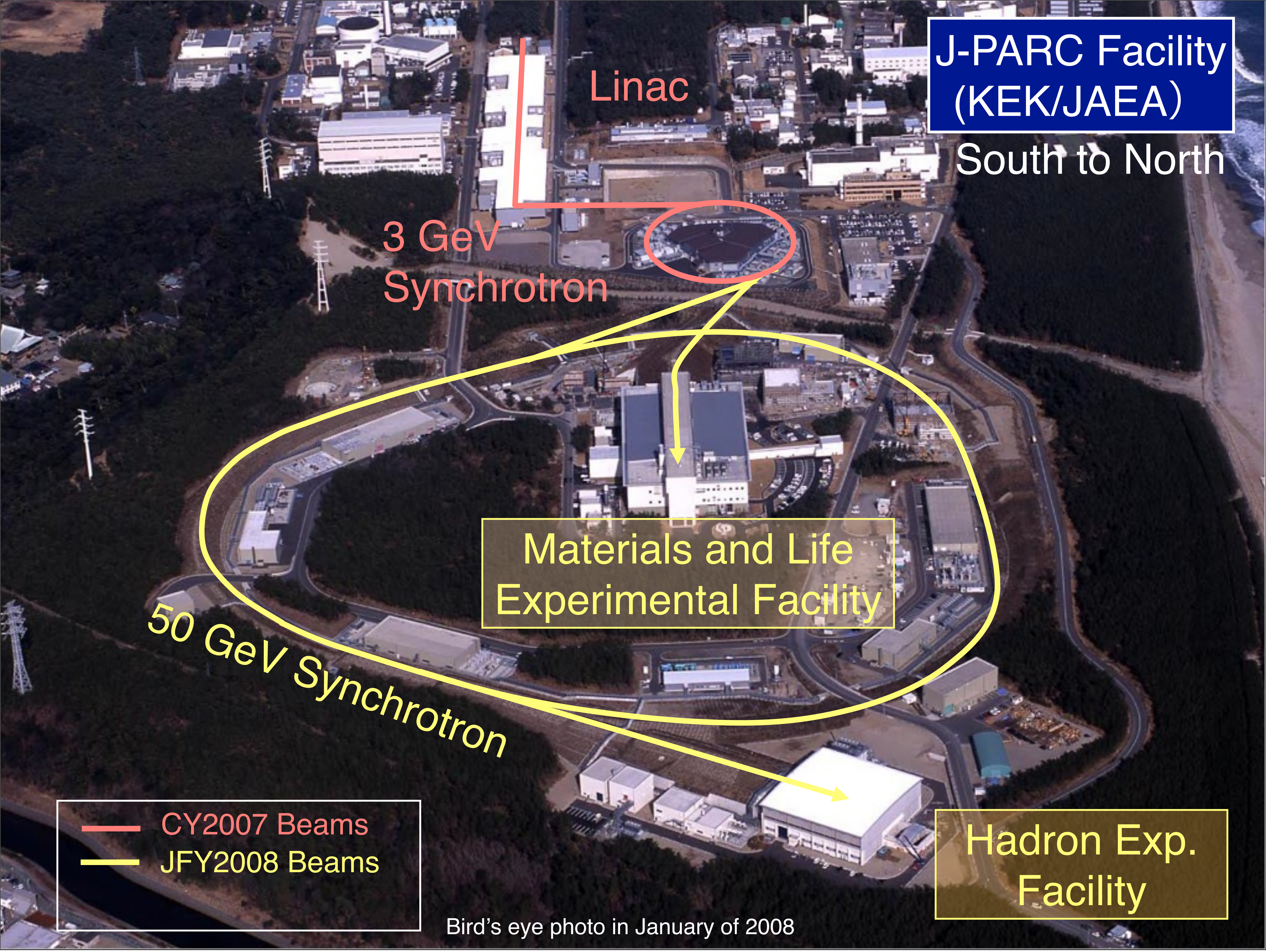
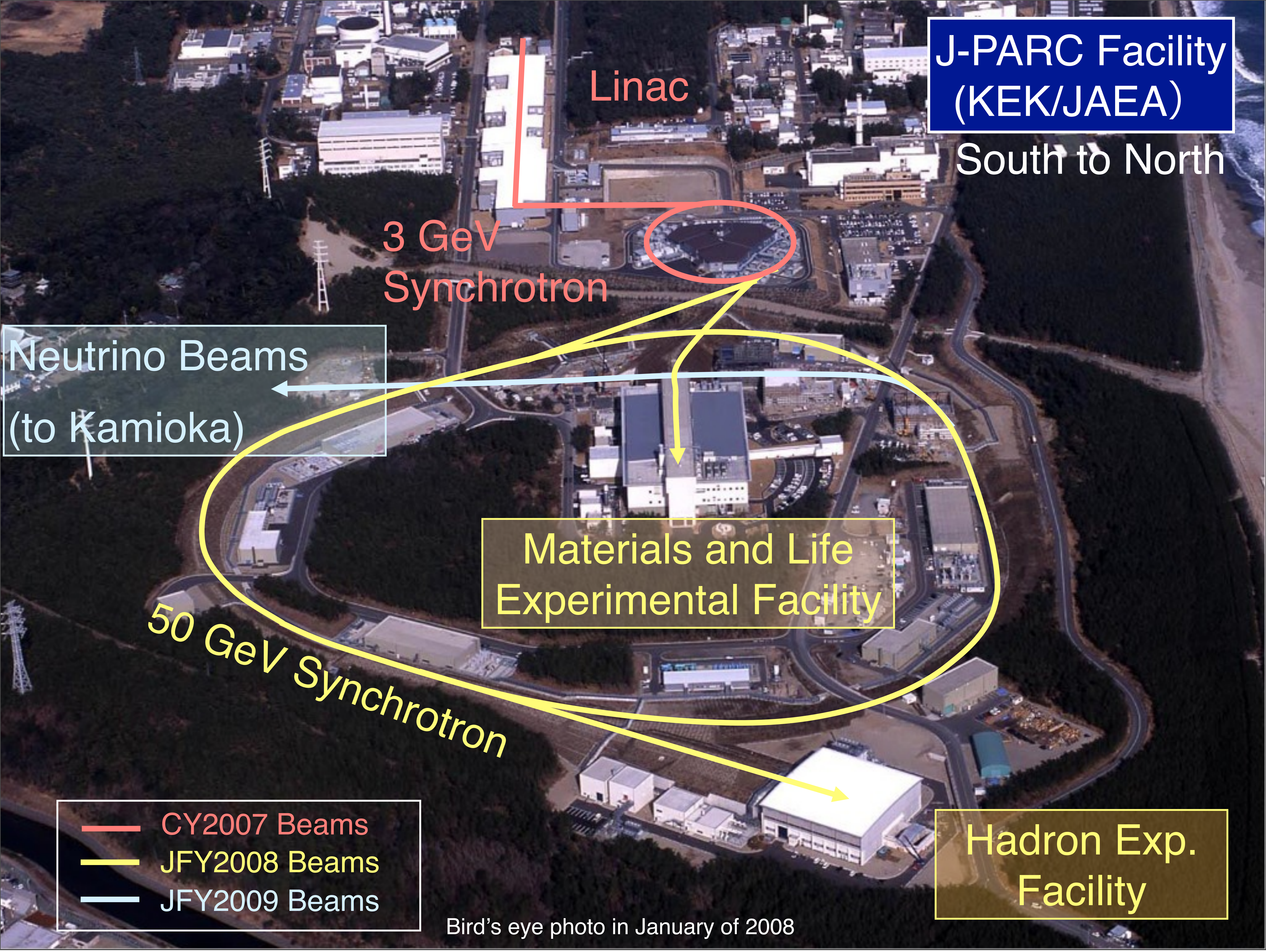
SNS Power Upgrades

- 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 by 2010.
- 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)

Bird's eye photo in January of 2008


J-PARC Facility
(KEK/JAEA)
South to North
Linac
3 GeV
Synchrotron
CY2007 Beams
Bird's eye photo in January of 2008


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

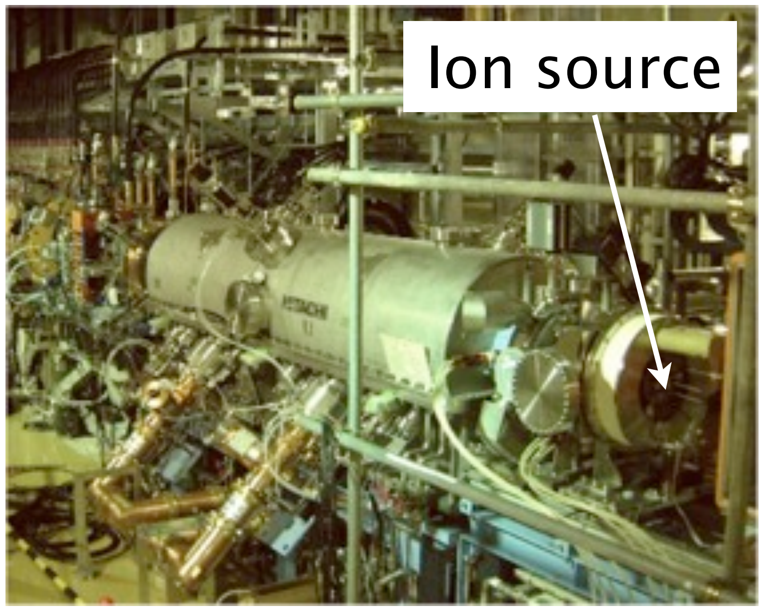

J-PARC Facility
(KEK/JAEA)
South to North
Linac
3 GeV
Synchrotron
Neutrino Beams
(to Kamioka)
Materials and Life
Experimental Facility
50 GeV Synchrotron
Hadron Exp.
Facility
CY2007 Beams
JFY2008 Beams
JFY2009 Beams
Bird's eye photo in January of 2008

J-PARC H^- Linac

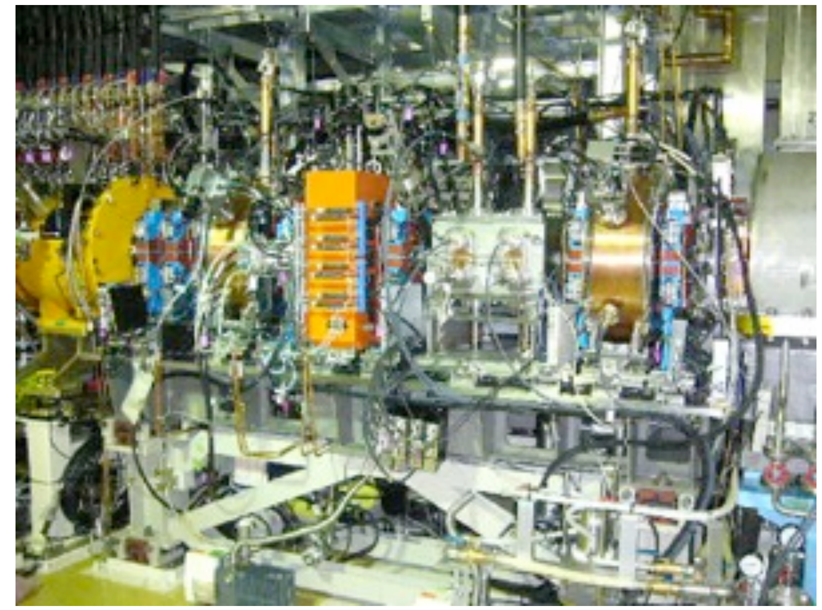
Phase I: 181 MeV, peak current 30 mA ⇒ 0.6 MW from RCS at 25 Hz

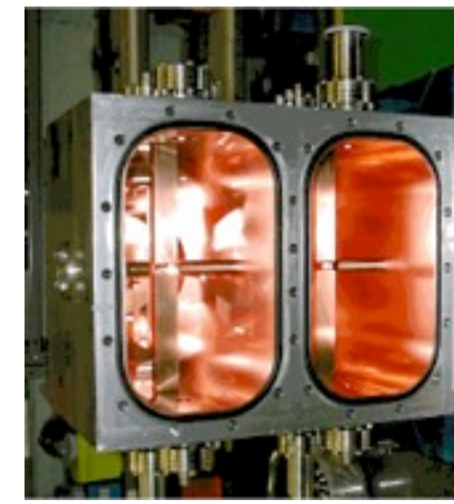
Phase II: 400 MeV, 50 mA ⇒ 1 MW from RCS

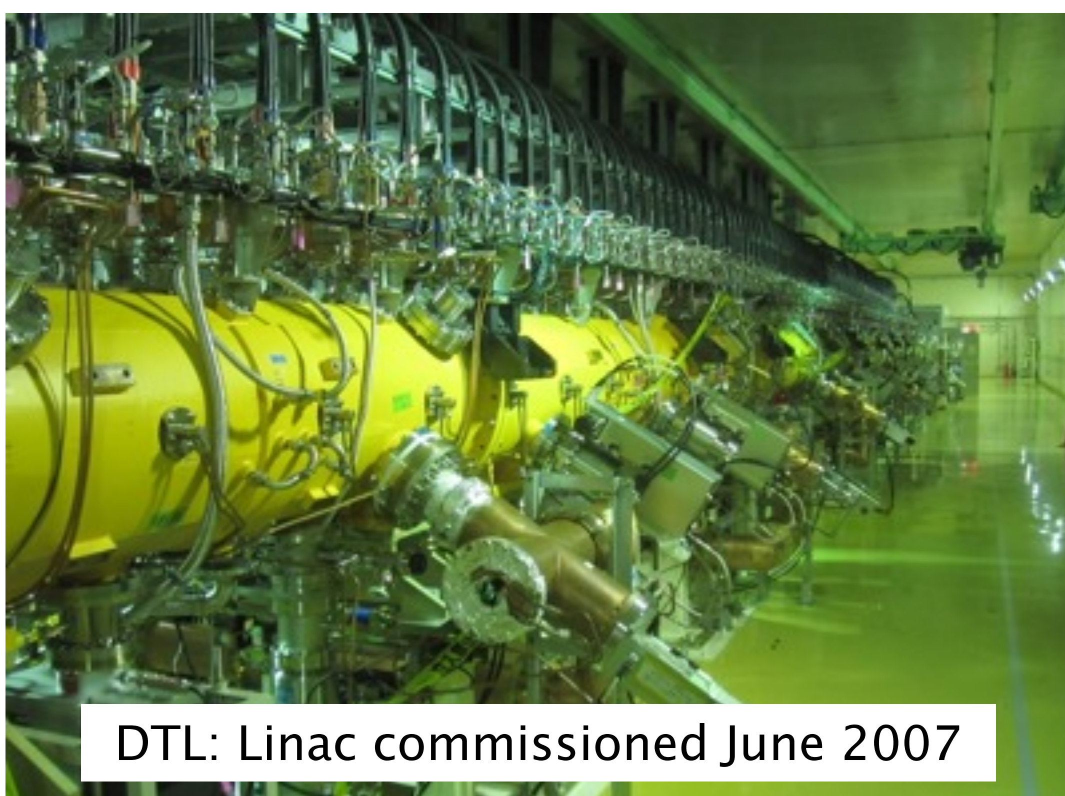
RFQ



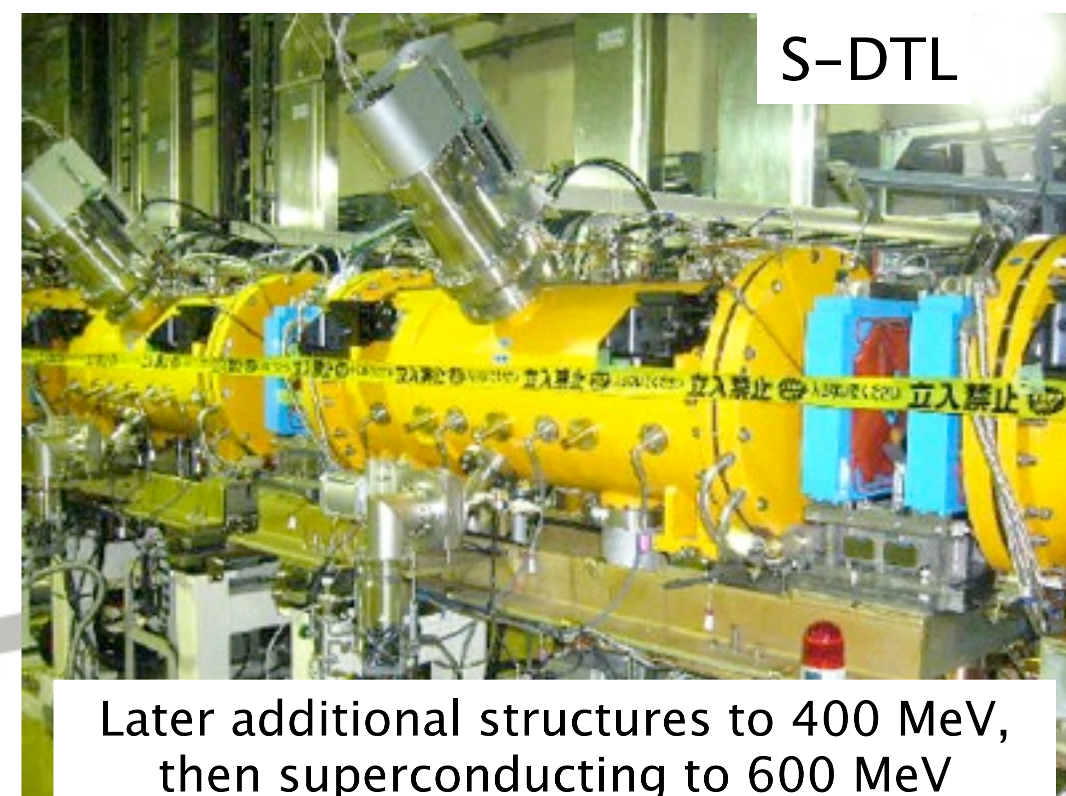
Chopper and MEBT







DTL: Linac commissioned June 2007



Later additional structures to 400 MeV, then superconducting to 600 MeV

Quadrupole transfer line from 180 MeV linac, about to be removed

New ACS accelerating structures for 180-400 MeV section

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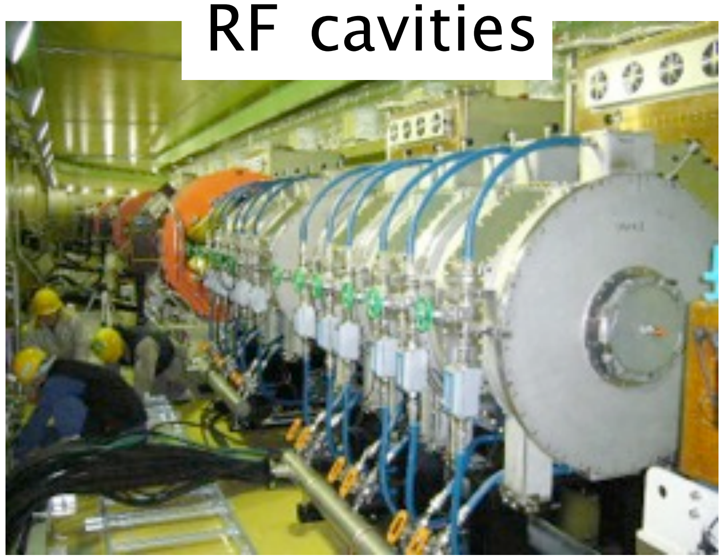
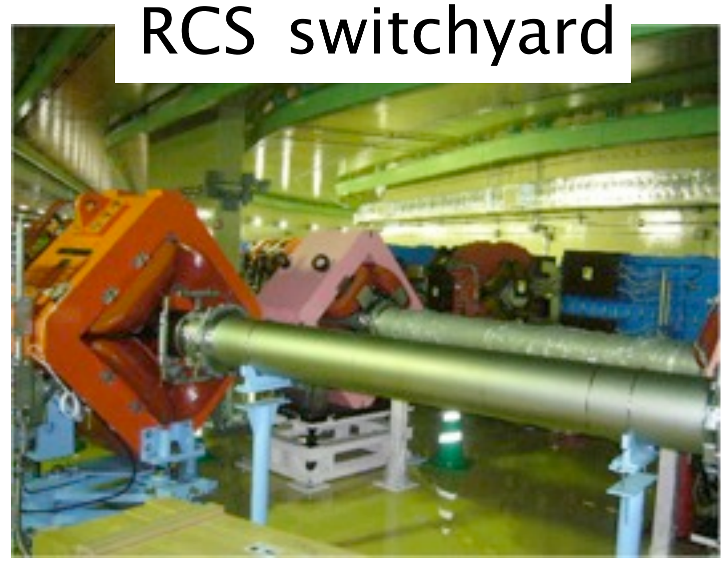
3 GeV Rapid Cycle Synchrotron (RCS)

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

ESS, European Spallation Source

ESS: A Long Pulse Facility

Collaboration of European countries

Expected construction 2013–2018

First neutrons 2018–19

- Optimised for 5 MW (upgradeable to 7.5 MW)
- 2 ms pulses (➟1.5 ms?)
- 20 Hz rep. rate (➟17 Hz?)
- 2.5 GeV energy
- 60 mA ion source current (➟75 mA➟90 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

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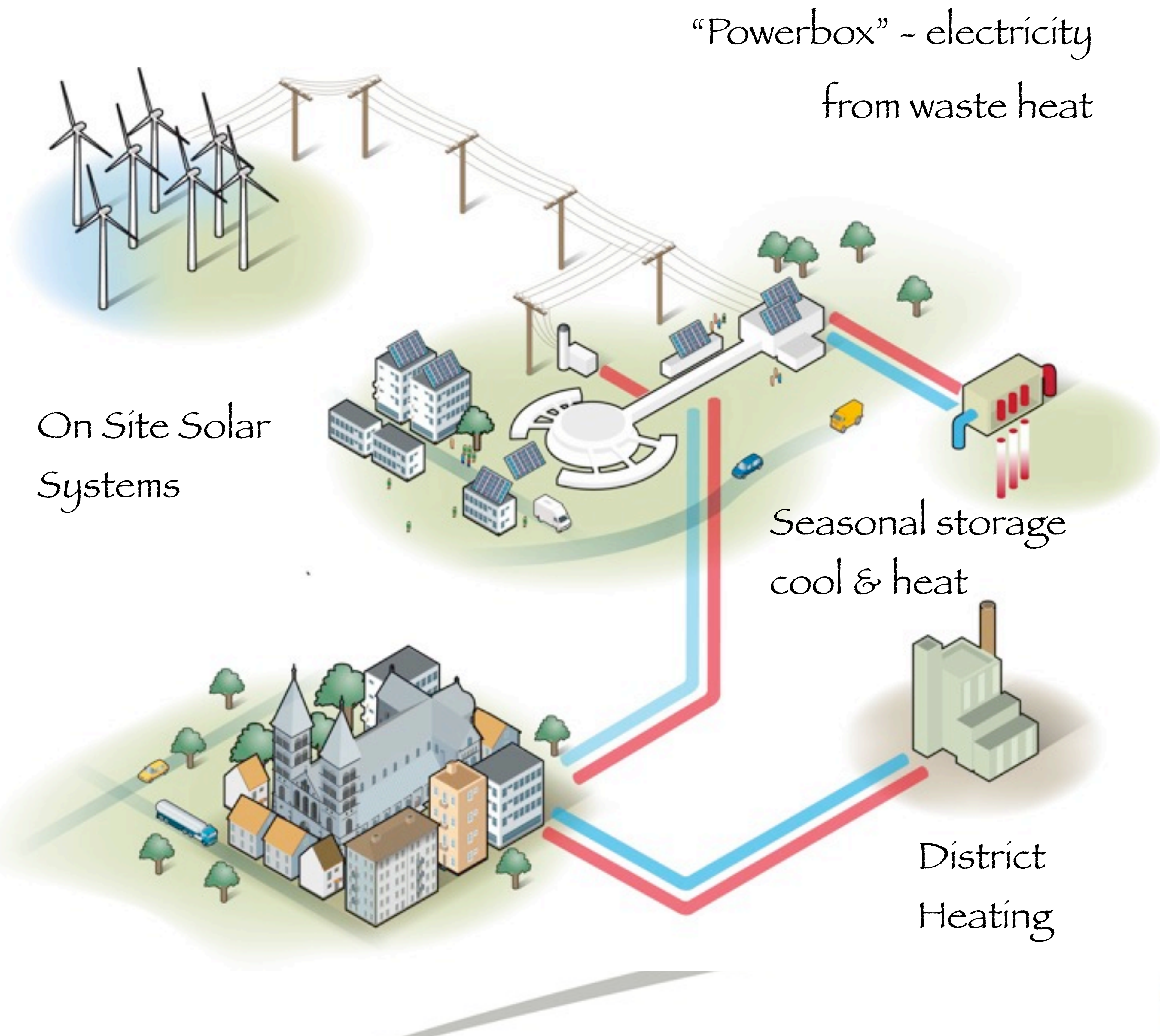
ESS: A Green Facility



Include research, development & demonstration of emerging energy technologies.

Goal: carbon neutrality.

Eg options on wind turbine farms

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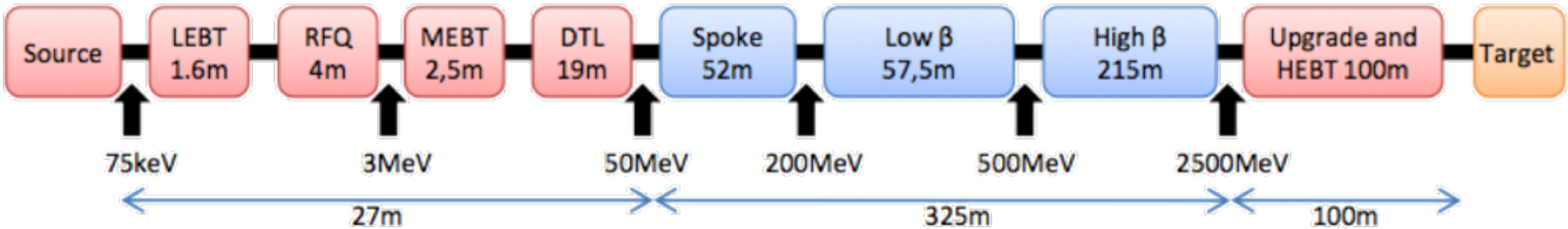
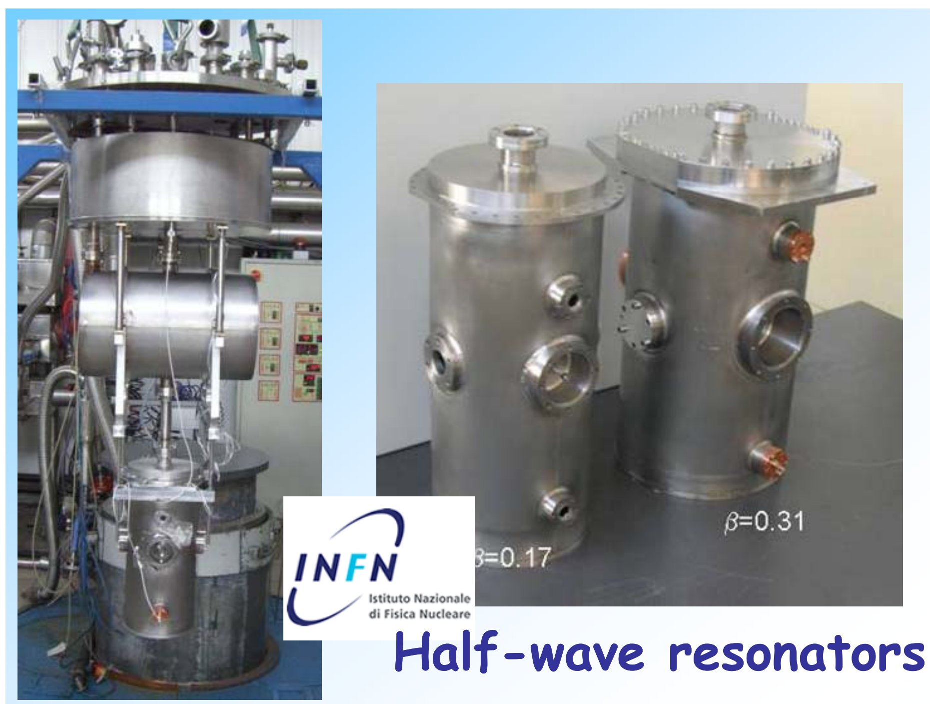
ESS Linac



Energy 2.5 GeV
Ion source current 60 mA (upgrade to 90 mA)

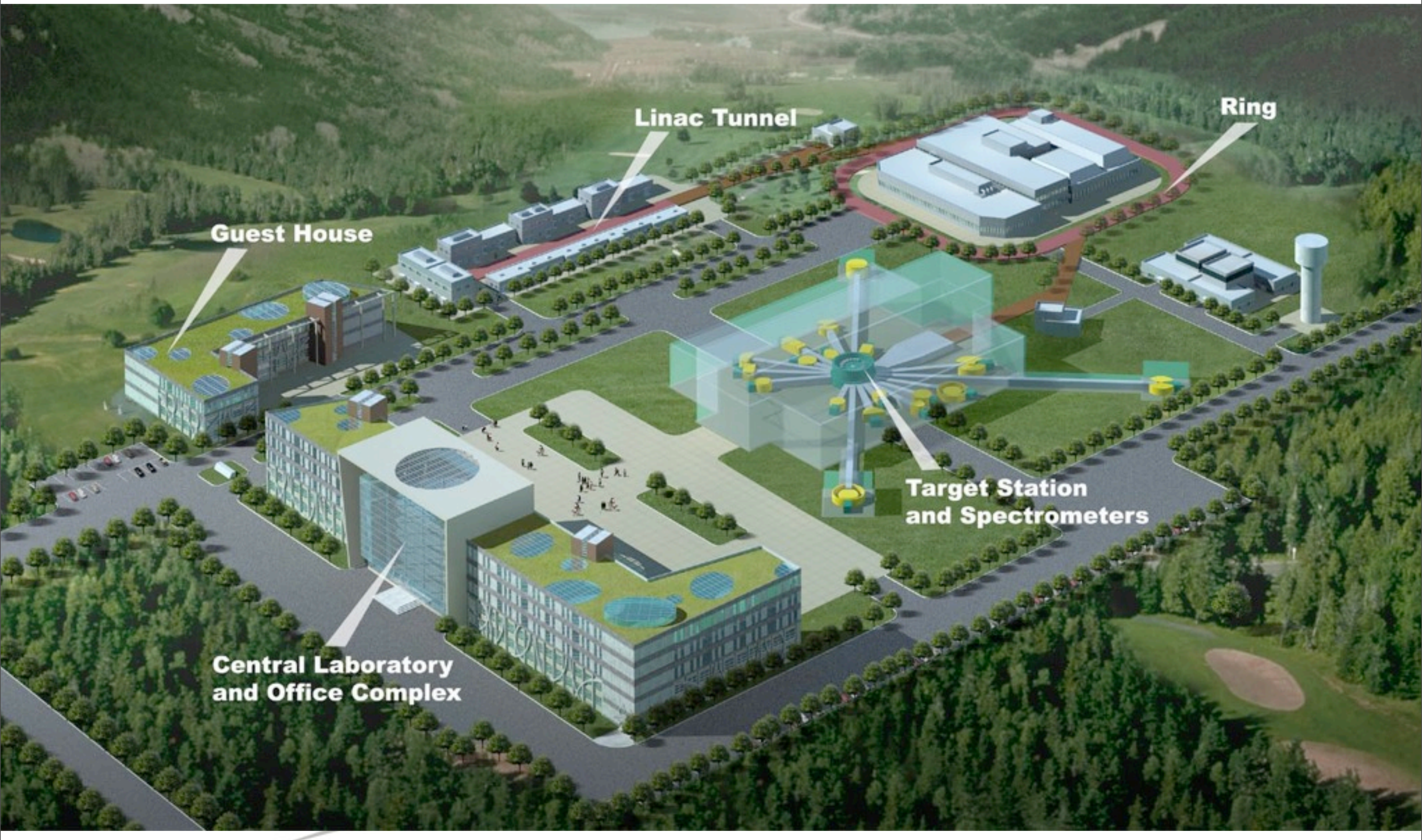


Half-wave resonators

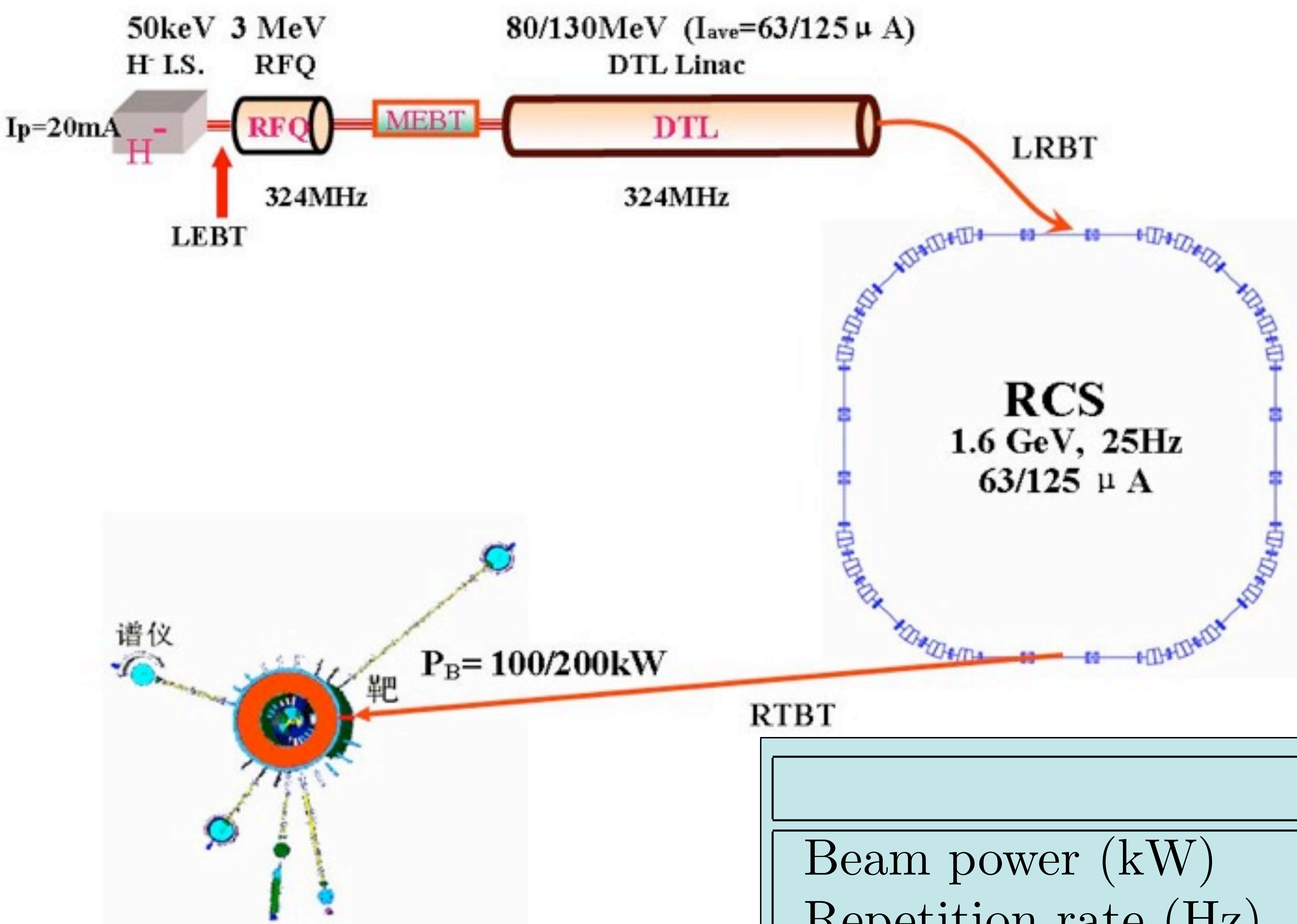
Spoke resonators

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



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 system
- **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

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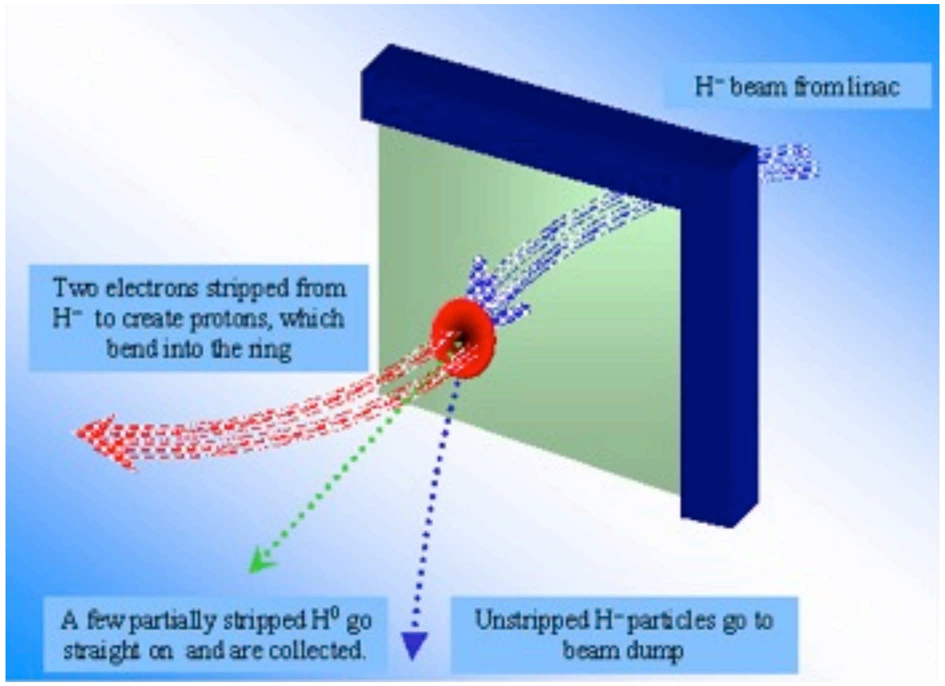
Main Issues (2)

- **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
  - 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

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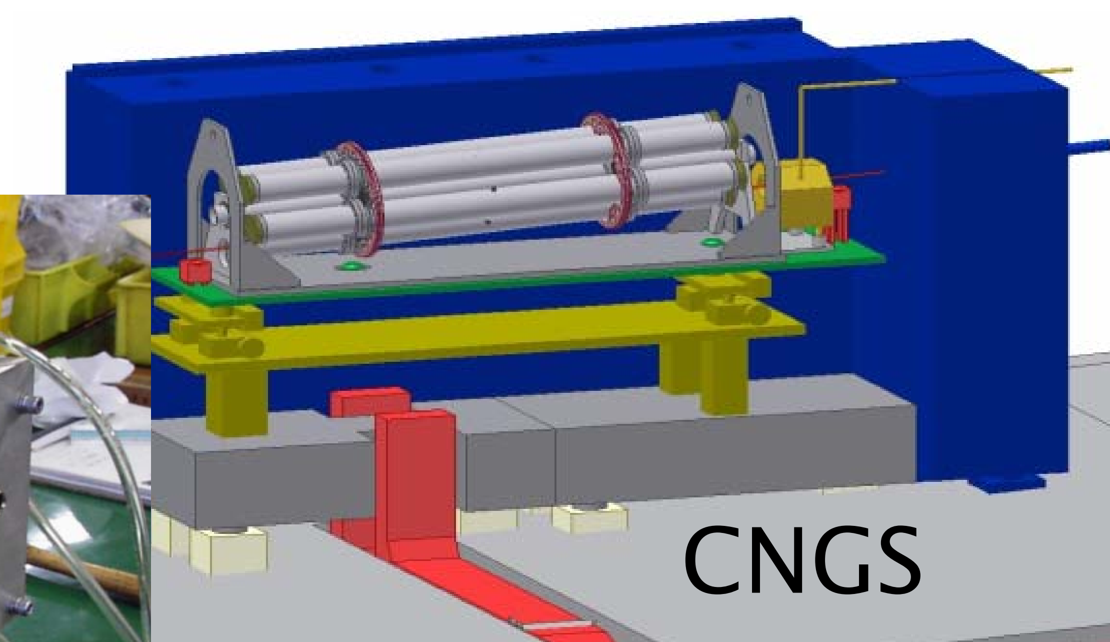
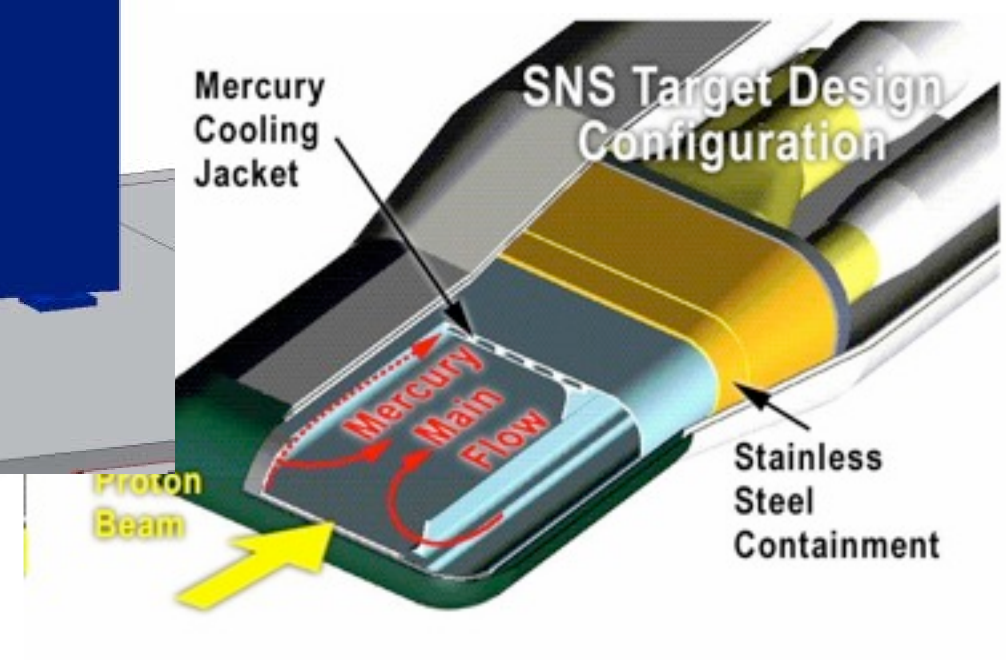
Main Issues (3)

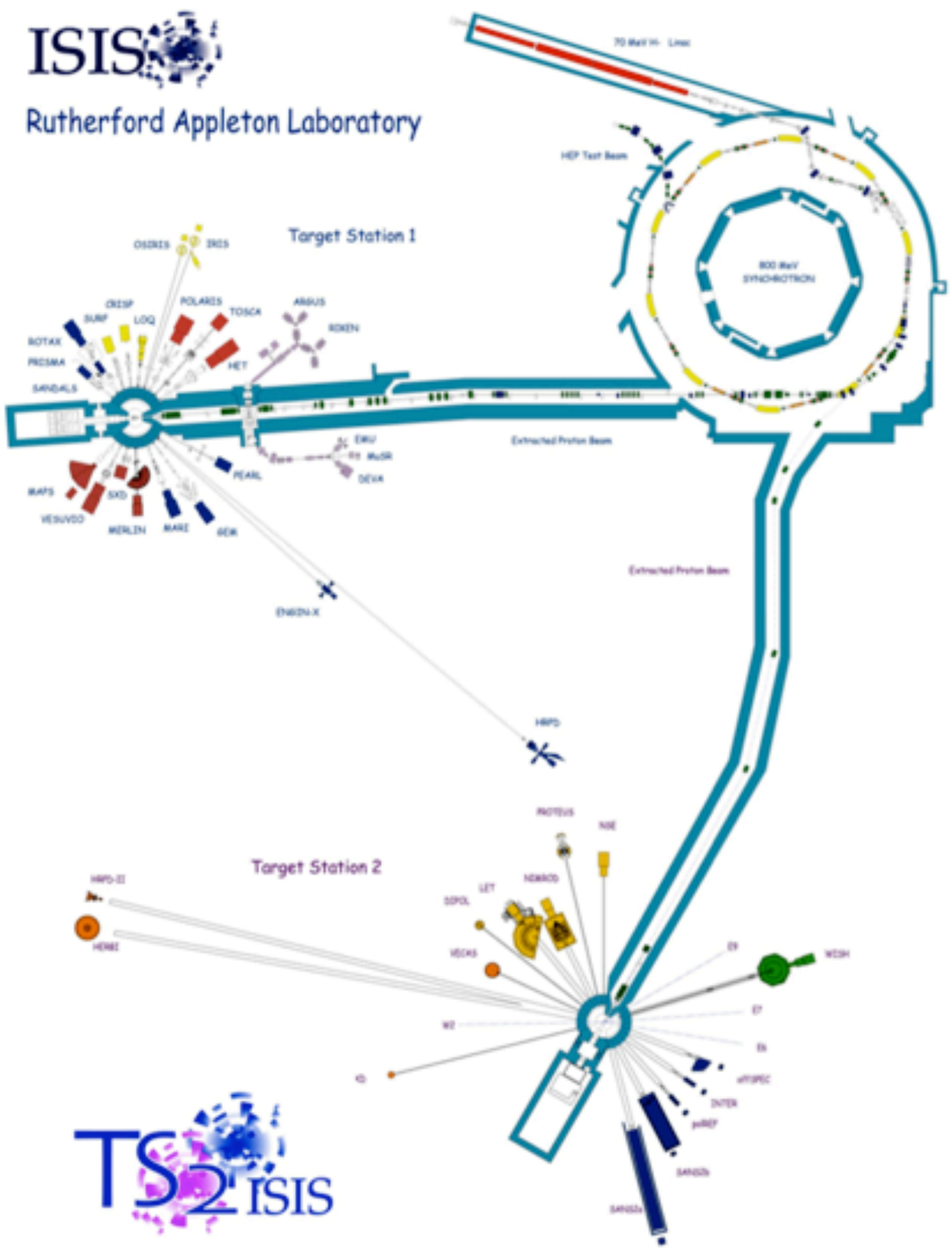
- **Nanosecond bunch compression** for Neutrino Factory/Muon Collider
  - imposes additional considerations beyond (say) a neutron source.
- **Multi-megawatt targets**
  - solid targets, liquid mercury, powder jets
- **High intensity proton FFAG ring development**





ISIS
Spallation Neutron Source

ISIS Now



- 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 system to upgrade to ~240 kW
- Otherwise intensity limited by space charge

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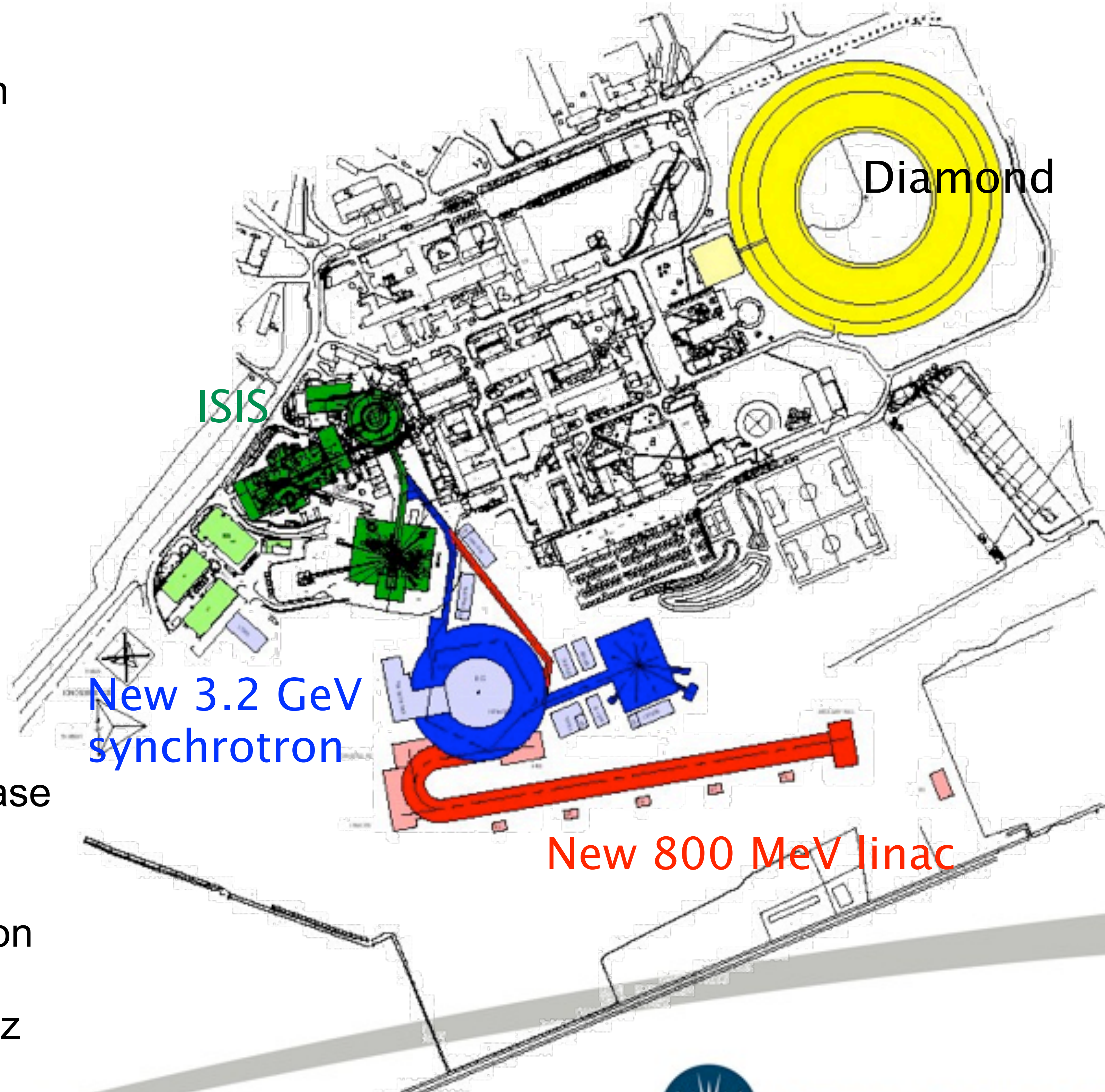
ISIS Power Upgrades

- 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
  - 5 bunches for neutron production
  - 2 MW at 30 Hz, ~5 MW at 50 Hz



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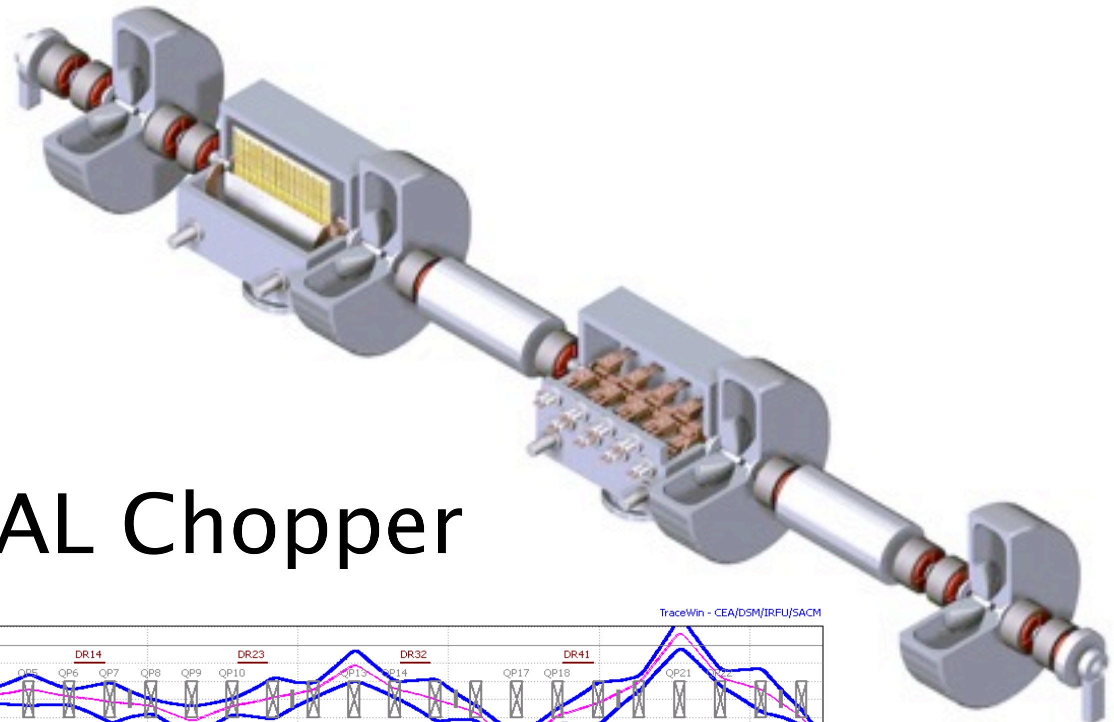
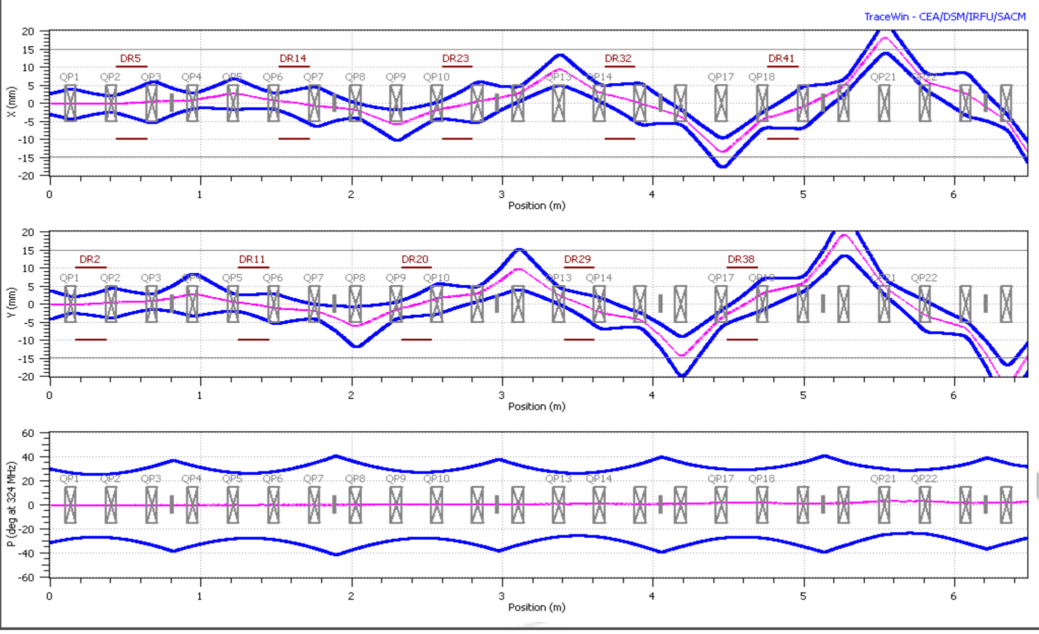
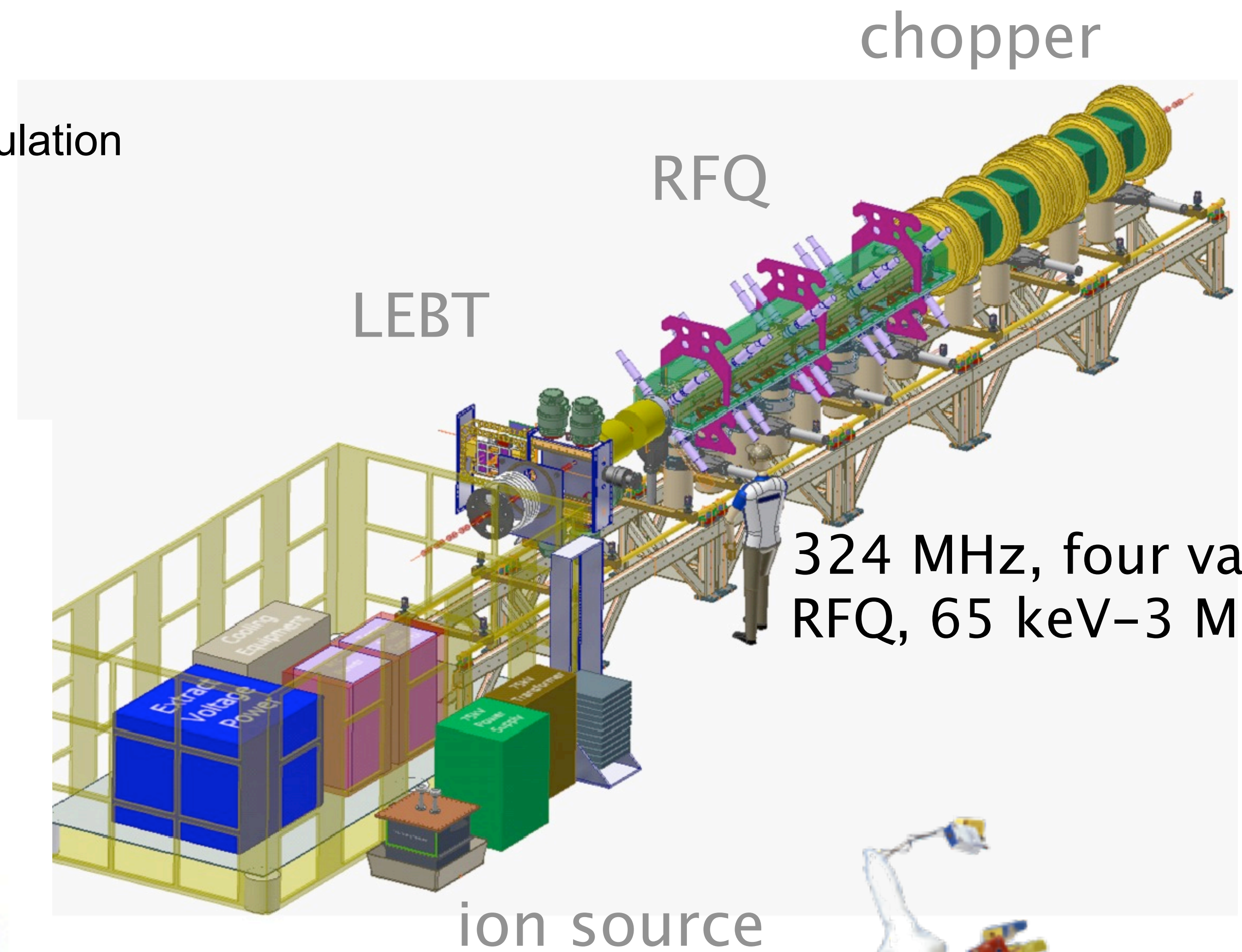
Linac Front-End Project, FETS

- EU/FP6/CARE/HIPPI
  - Linac architectures (nc + sc) to 200 MeV
  - Diagnostics/measurements (UNILAC) and simulation
  - Code comparison
- CERN and RAL test stands
  - Ion source, RFQ and chopper development

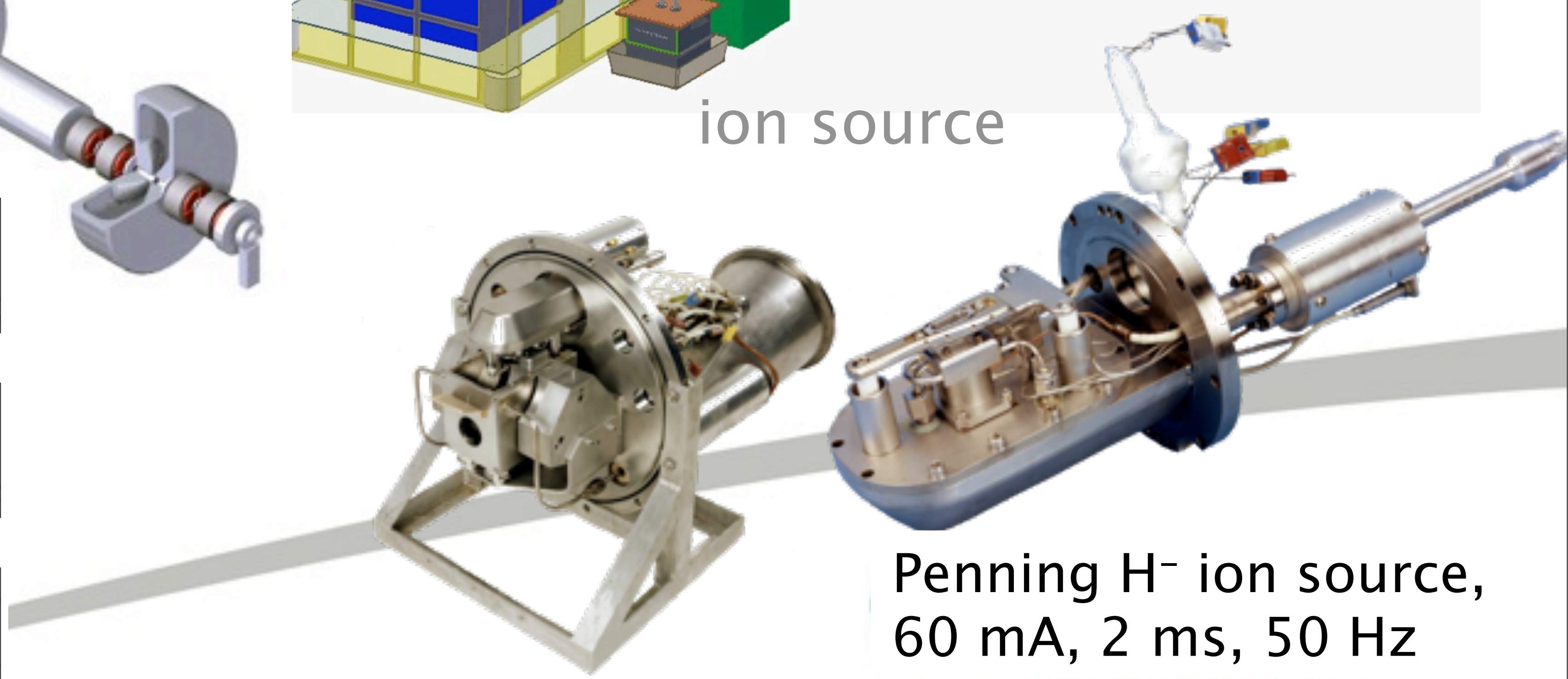


RAL Chopper





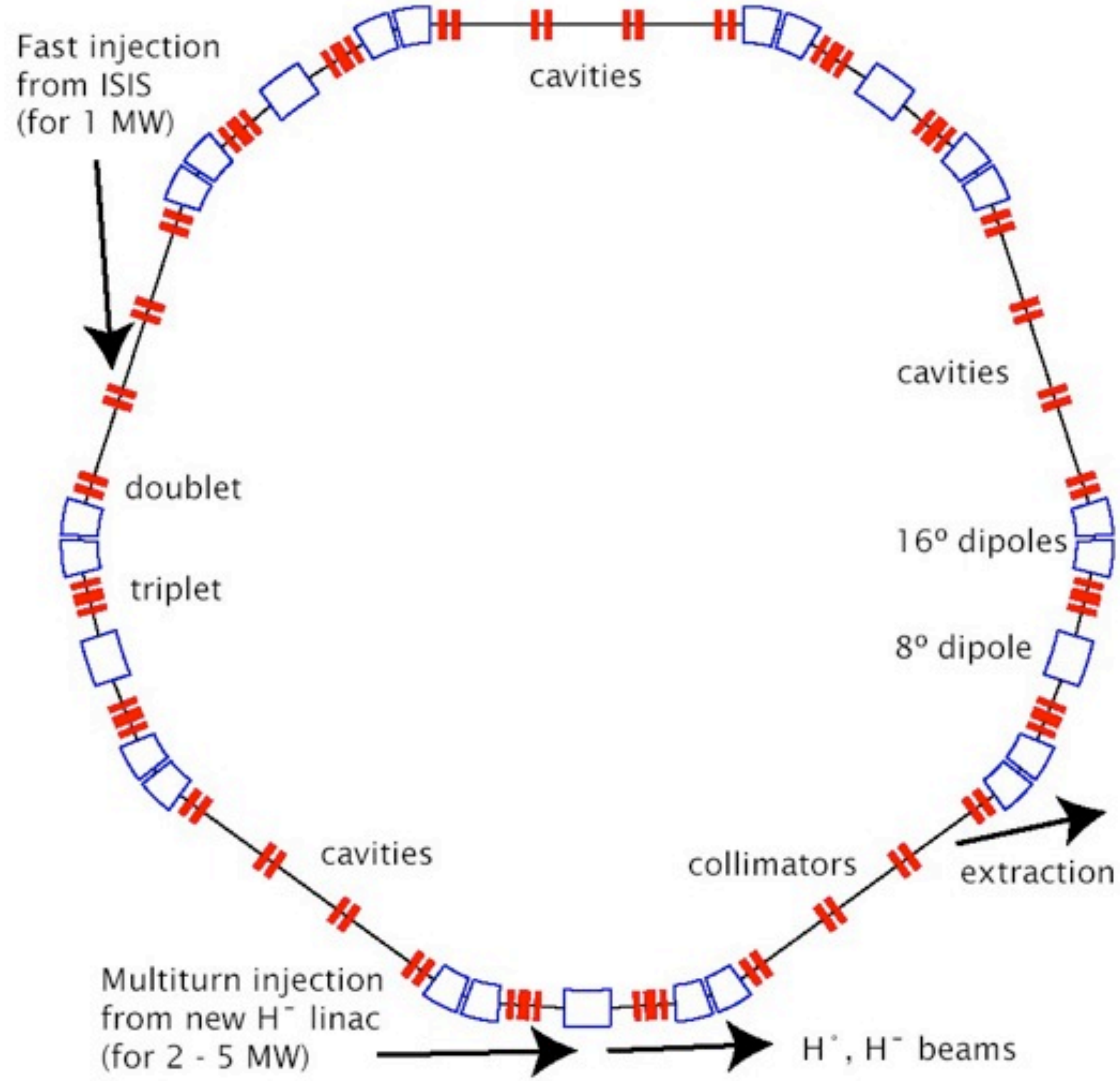
324 MHz, four vane RFQ, 65 keV–3 MeV



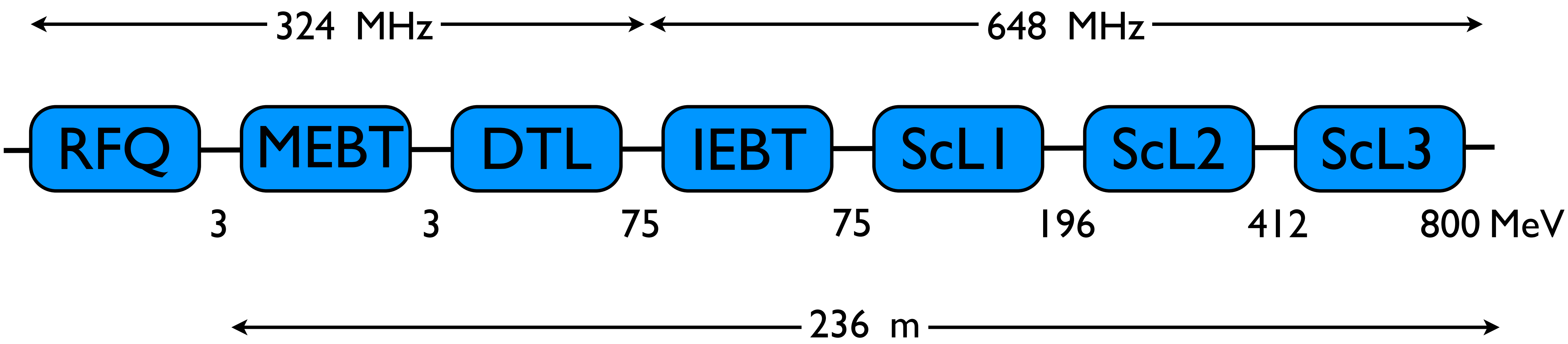
Penning H^- ion source, 60 mA, 2 ms, 50 Hz

5 Superperiod RCS Ring

Energy	0.8 – 3.2 GeV
Rep Rate	50 Hz
Circum, R:R_{ISIS}	408.4 m, 5:2
Gamma-transition	7.2
h	5
f_{rf} sweep	6.1-7.1 MHz
Peak V_{rf}	~ 750 kV
Peak ΔQ_{sc}	~ 0.1
ε_l per bunch	~ 1.5 eV s
B [t]	sinusoidal



800 MeV H^- ISIS Upgrade Linac

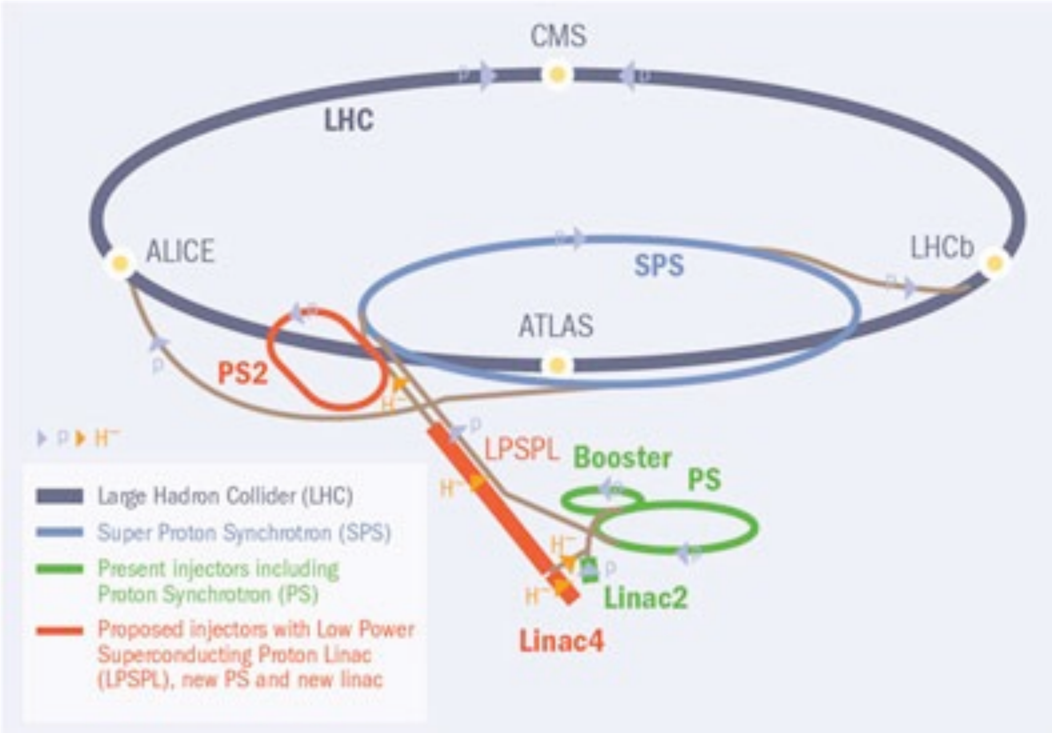


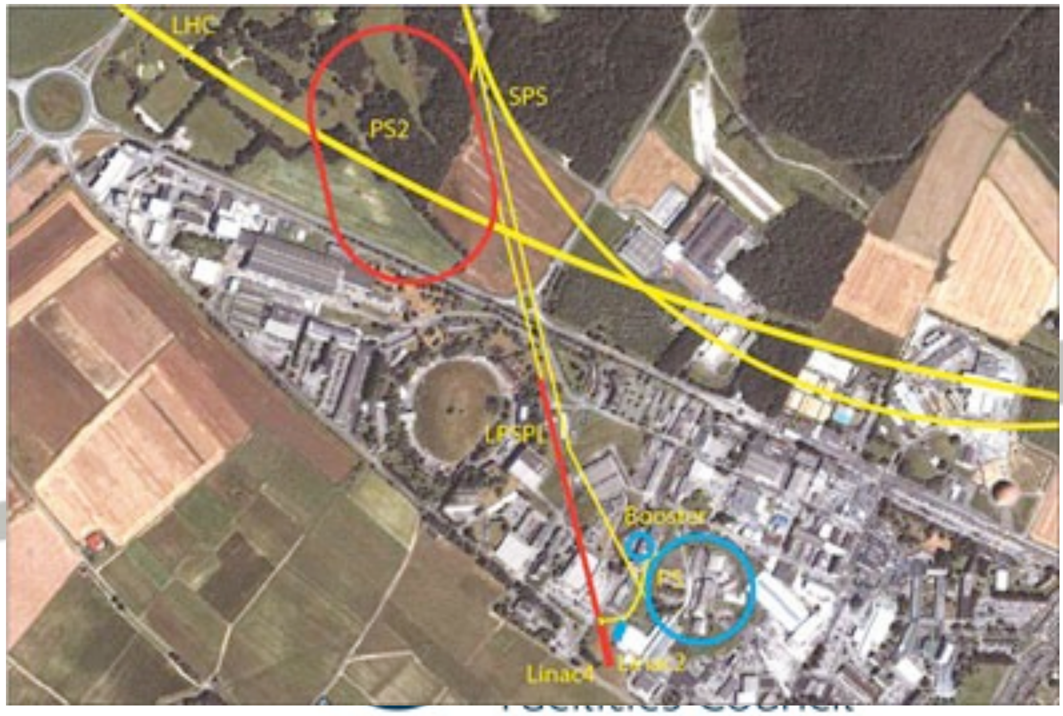
- Based on J-PARC frequency, 324 MHz
- Intermediate energy beam transport section to remove longitudinal halo
- Superconducting from 75 MeV
- RFQ and MEBT chopper based on FETS


CERN

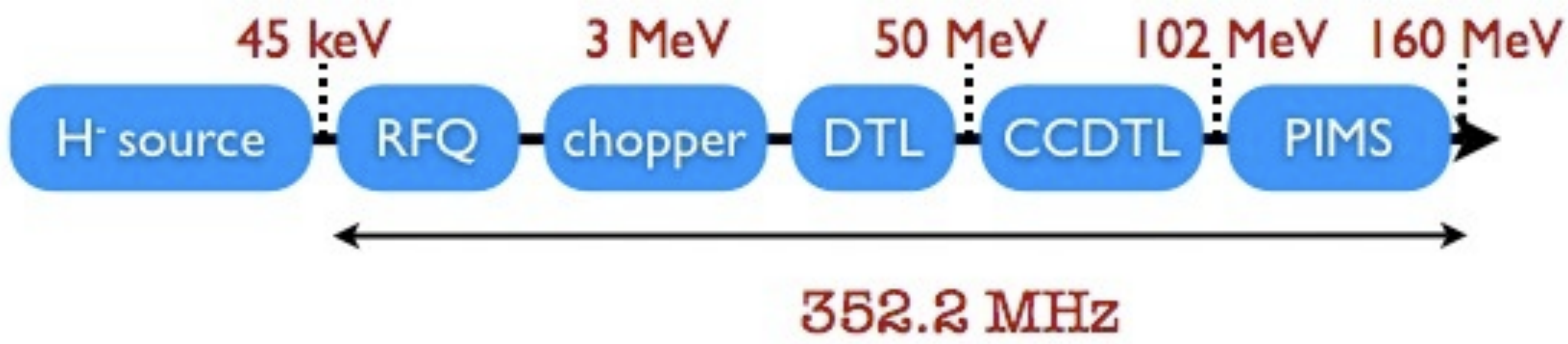
CERN Linac4 and SPL

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



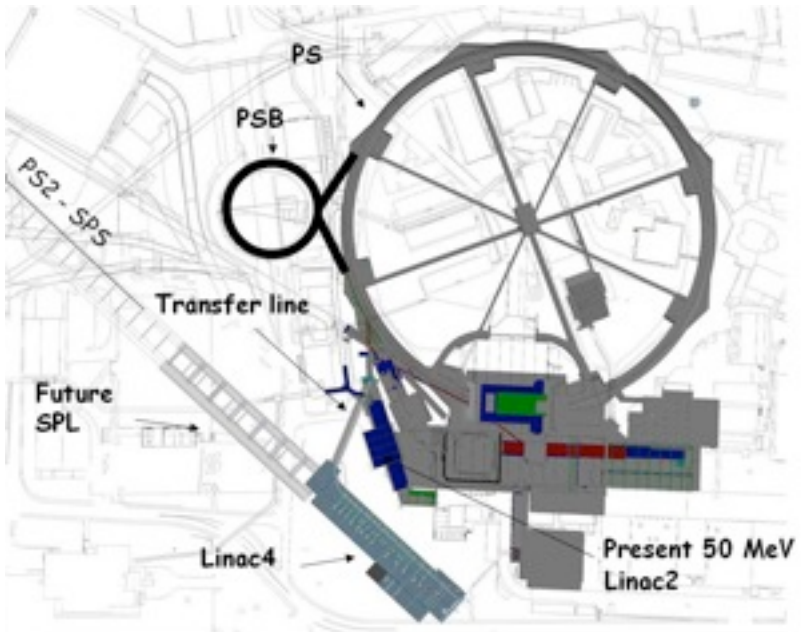


CERN LINAC4



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.



Science & Technology Facilities Council

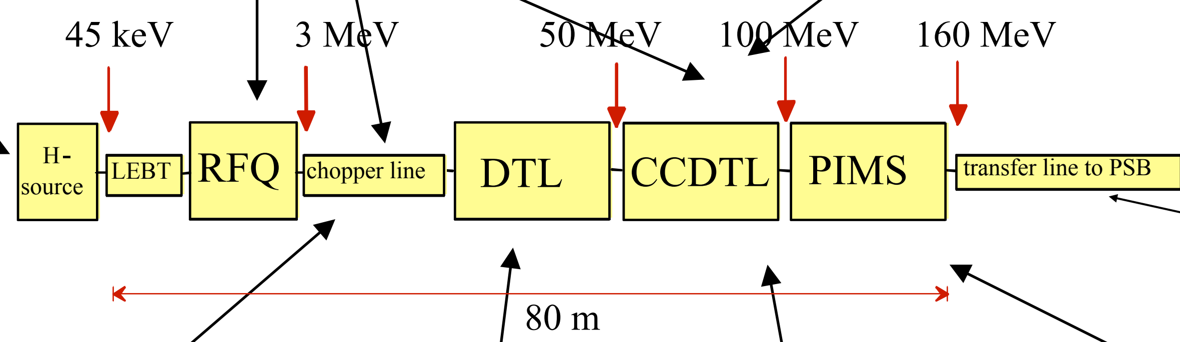
Linac4 – External Contributions

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

RFQ RF design, RF amplifiers, modulator construction from French Special Contribution. *started.*

Prototype modulator, RF tuners, couplers, waveguides from India, *in progress*

Agreement with DESY to access drawings of H- source *completed*



Transfer line vacuum chambers and supports from Pakistan, *agreed*

Chopper line built in a EU Joint Research Activity *completed*

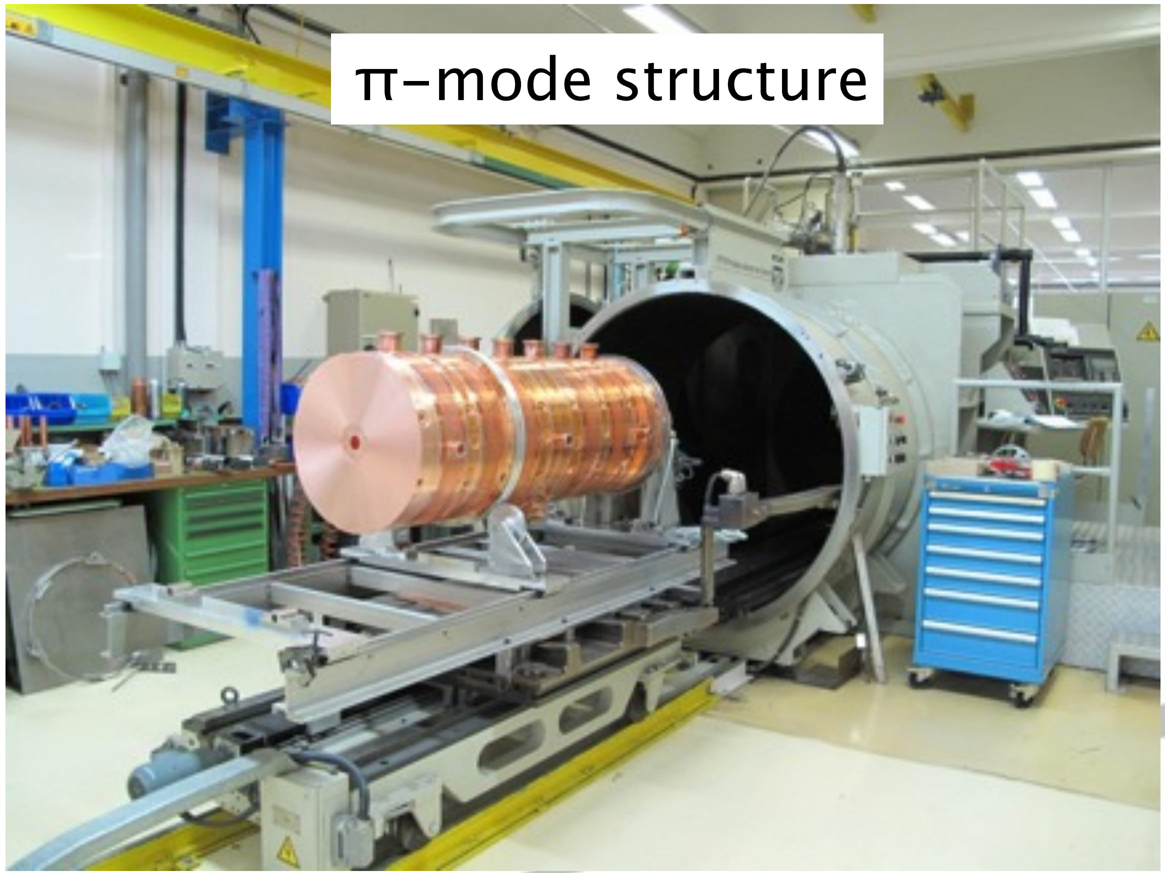
Participation of ESS-Bilbao in DTL construction, *started*

Construction of CCDTL in Russia, via an ISTC Project *started*

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

LINAC4

- **H^- ion source**: 2 MHz RF volume source delivers 40 mA at 45 keV (400 μs at repetition rate of 2 Hz)
- **Radio Frequency Quadrupole** (3 m): bunches and accelerates to 3 MeV
- **Chopper line** (3.6 m): 11 quads, 3 bunchers, 2 sets of deflecting plates, removes 113 bunches from every 355.
- **Drift tube linac** (19 m): acceleration to 50 MeV in 3 tanks
- **Cell-coupled DTL** (25 m): acceleration to 100 MeV, 21 tanks (3 cells each)
- **π-mode structure** (22 m): acceleration to 160 MeV, 12 tanks (7 cells)



Building construction

“Mount-Citron”, September 2008

Building construction

Status end of August 2010

Building construction

Status end of August 2010

Civil construction - status

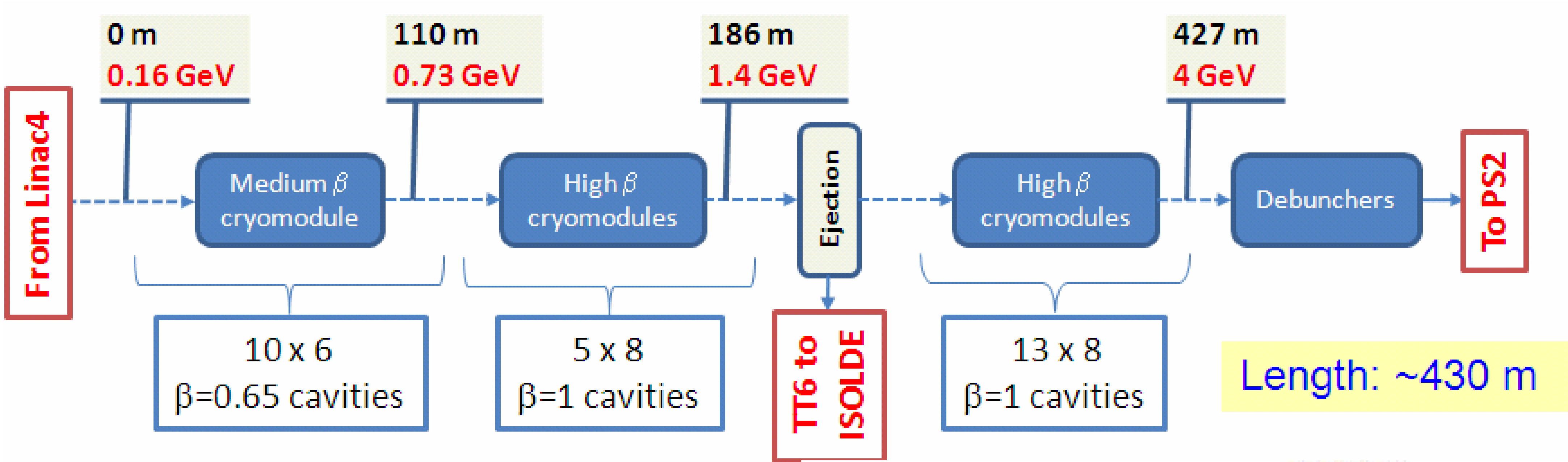
Delivery of tunnel and surface building, planned for 15.10.2008, Exactly to the day 2 years after groundbreaking

Civil construction - status

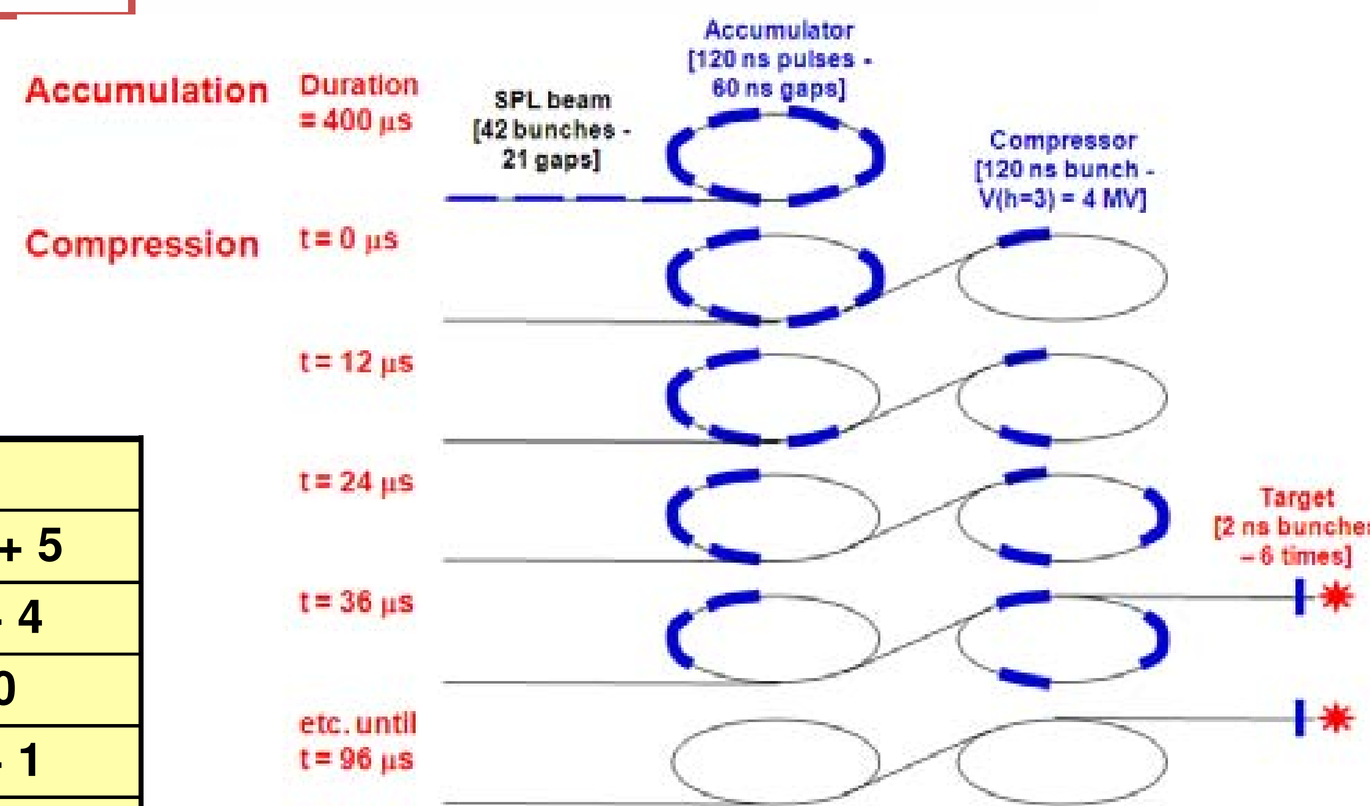
Status Friday September 10th

Delivery of tunnel and surface building, planned for 15.10.2008,
Exactly to the day 2 years after groundbreaking

CERN SPL



- Extend Linac4 to 4 or 5 GeV
- Low and High Power options



	LP-SPL	HP-SPL	
Energy (GeV)	4	2.5 or 5	2.5 + 5
Beam power (MW)	0.16	3 or 6	4 + 4
Rep. Frequency (Hz)	≤ 2	50	50
Protons/pulse (x 10^{14})	1.5	1.5	2 + 1
Av. Pulse Current (mA)	20	20	40
Pulse duration (ms)	1.2	1.2	0.8 + 0.4

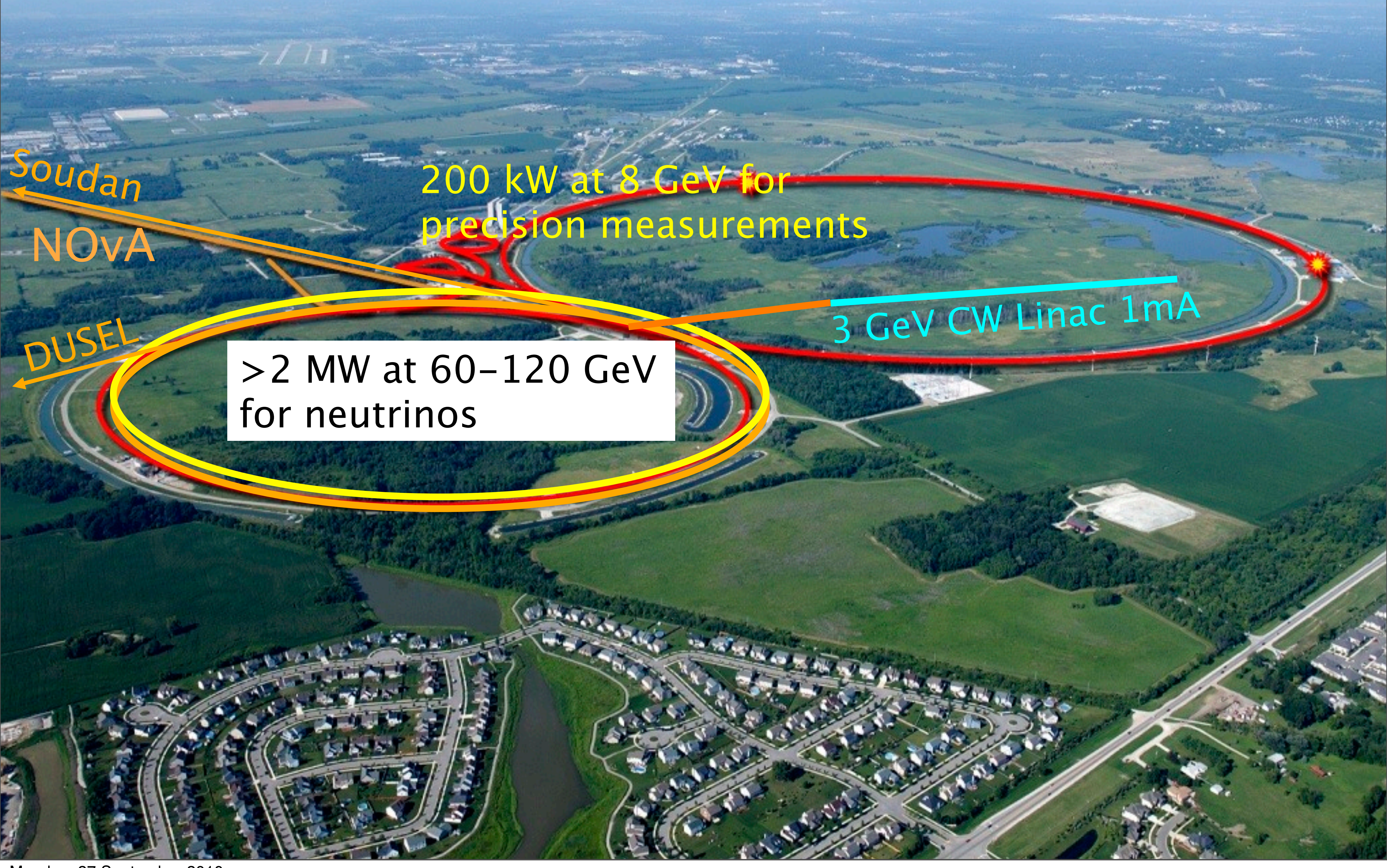
Accumulation/Compression for Neutrino Factory

The Intensity Frontier: Present

The Intensity Frontier: Early This Decade

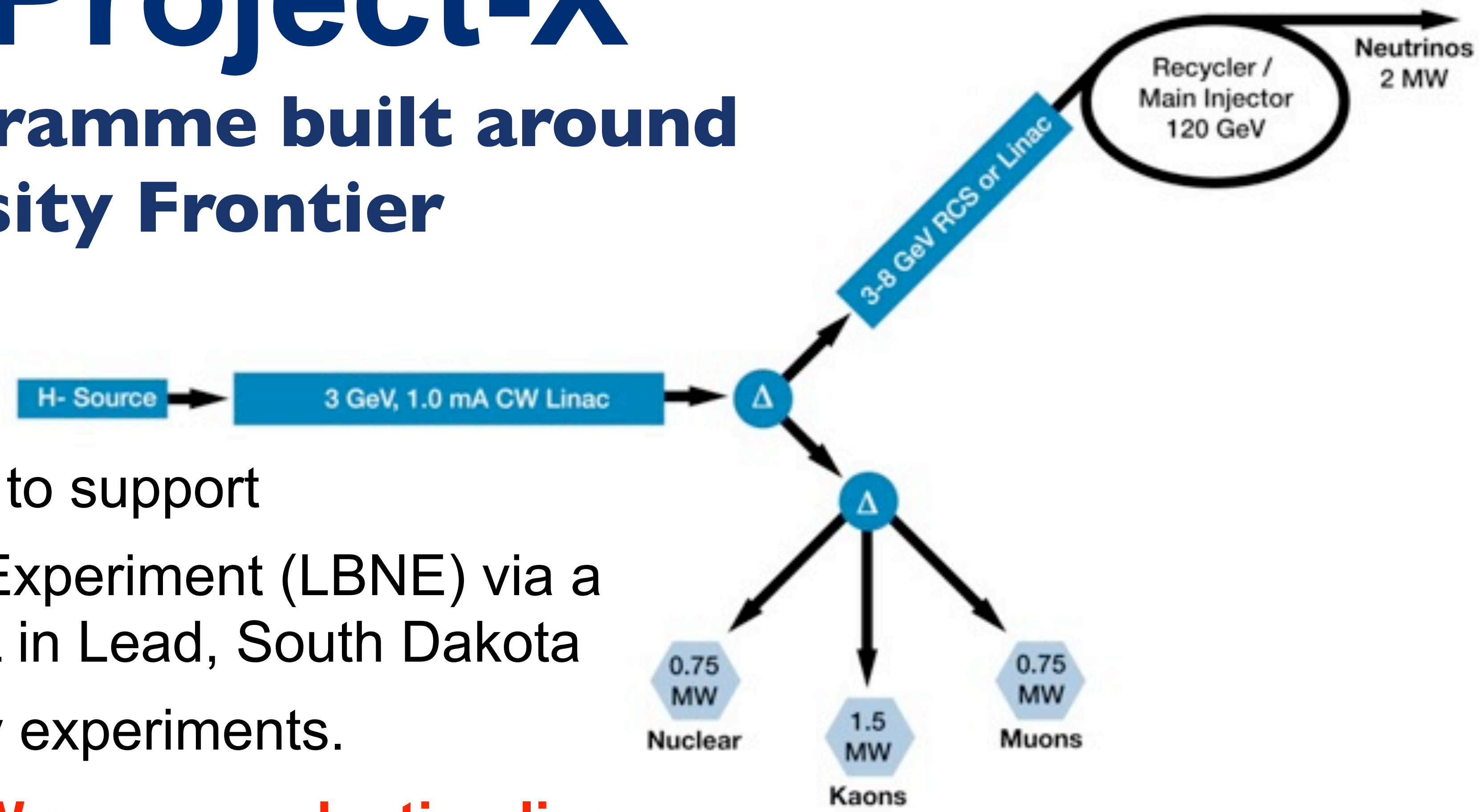
The Intensity Frontier: Project X

(National Project with International Collaboration)



Project-X

An experimental programme built around Fermilab's High Intensity Frontier

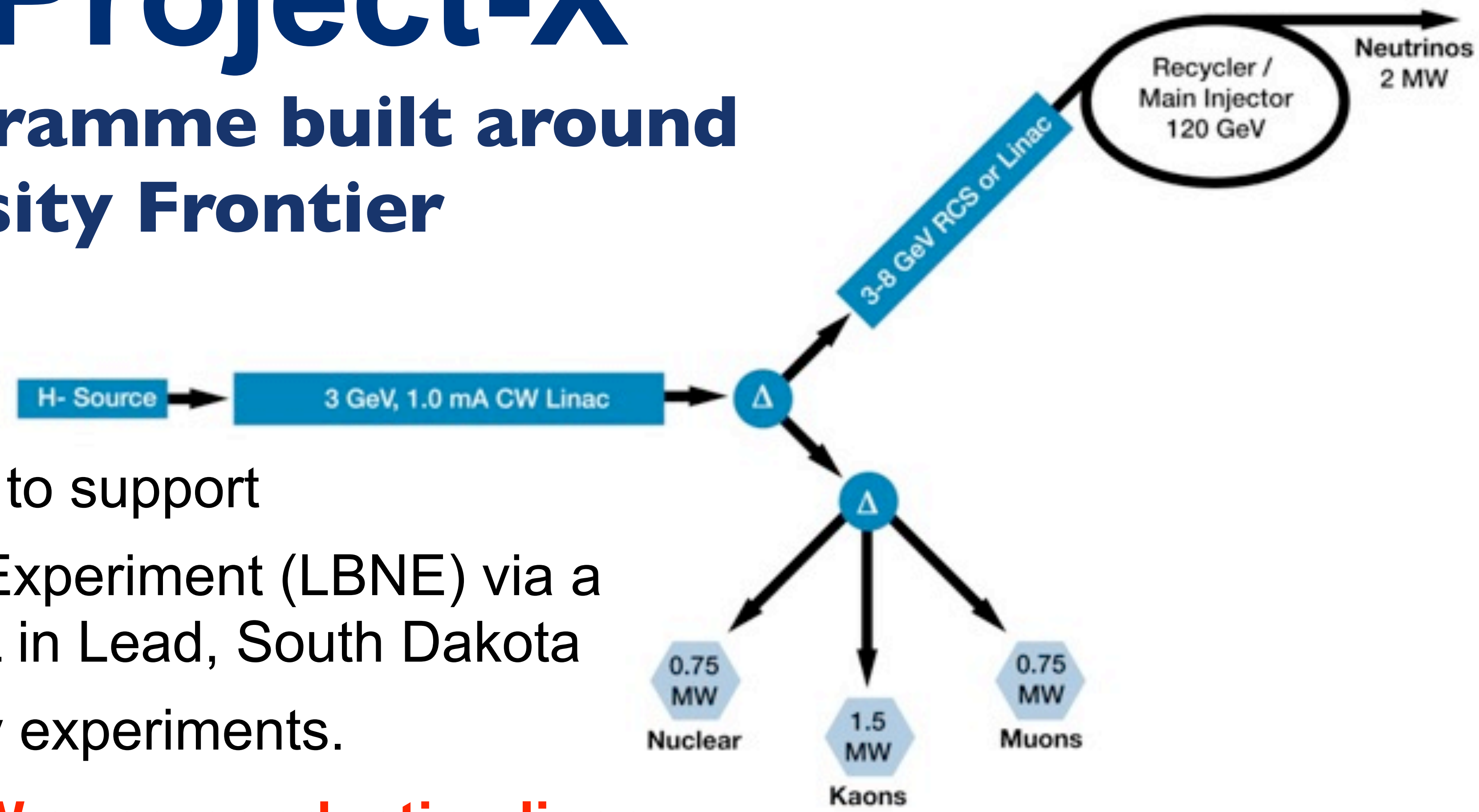


- A **multi-MW proton source** to support
  - Long Baseline Neutrino Experiment (LBNE) via a new beam line to DUSEL in Lead, South Dakota
  - Broad suite of rare decay experiments.
- Based on a **3 GeV, 1 mA CW superconducting linac**
  - Warm CW front end (H^- ion source, RFQ, MEBT, chopper)
- Part (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**

Science & Technology Facilities Council

Project-X

An experimental programme built around Fermilab's High Intensity Frontier



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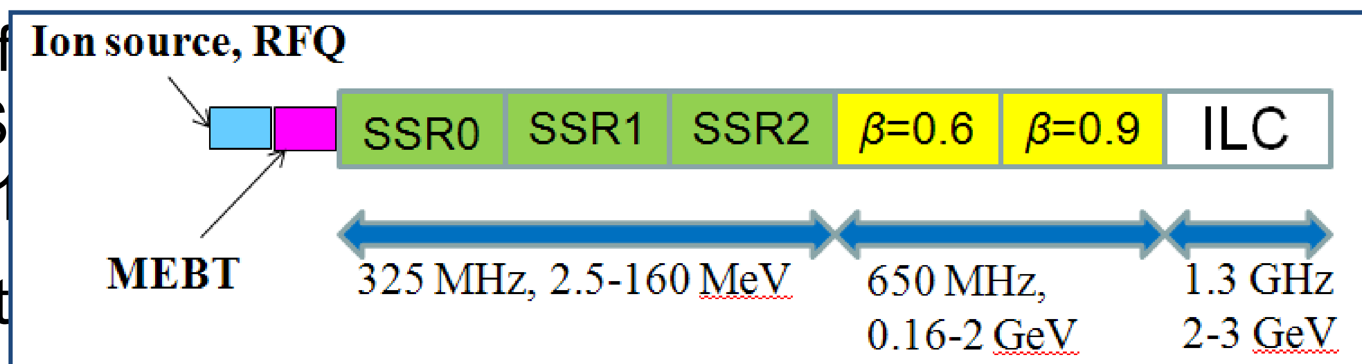

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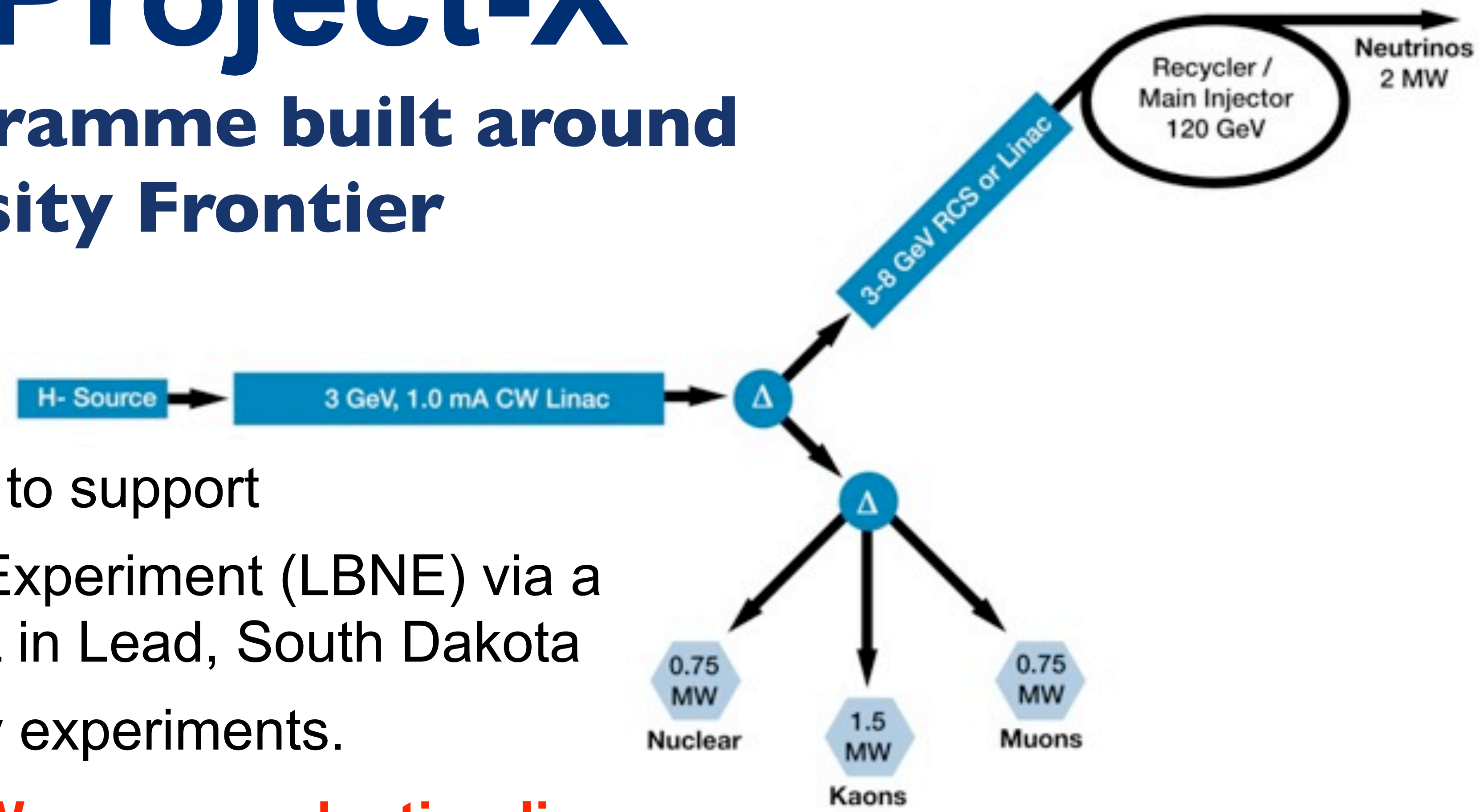

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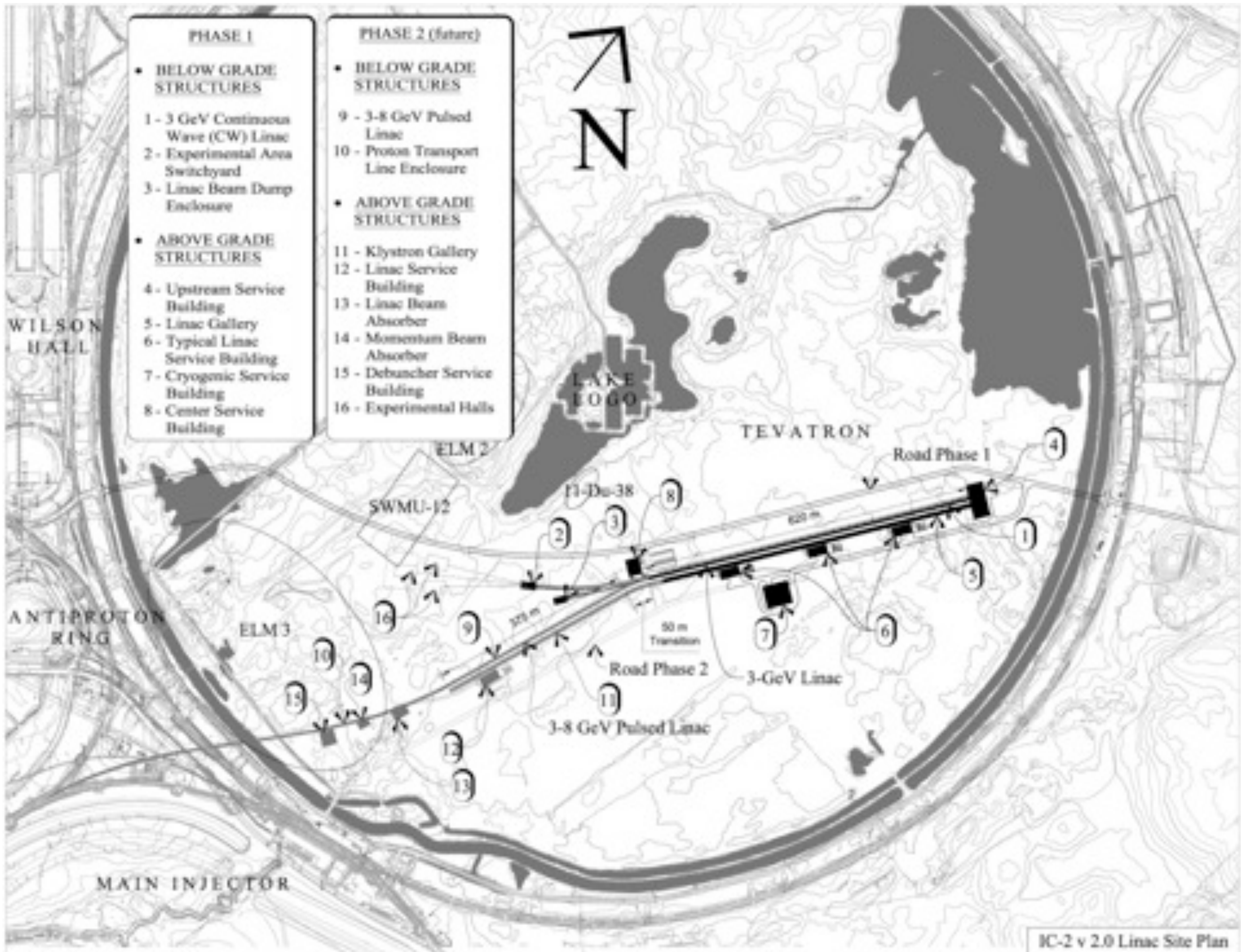
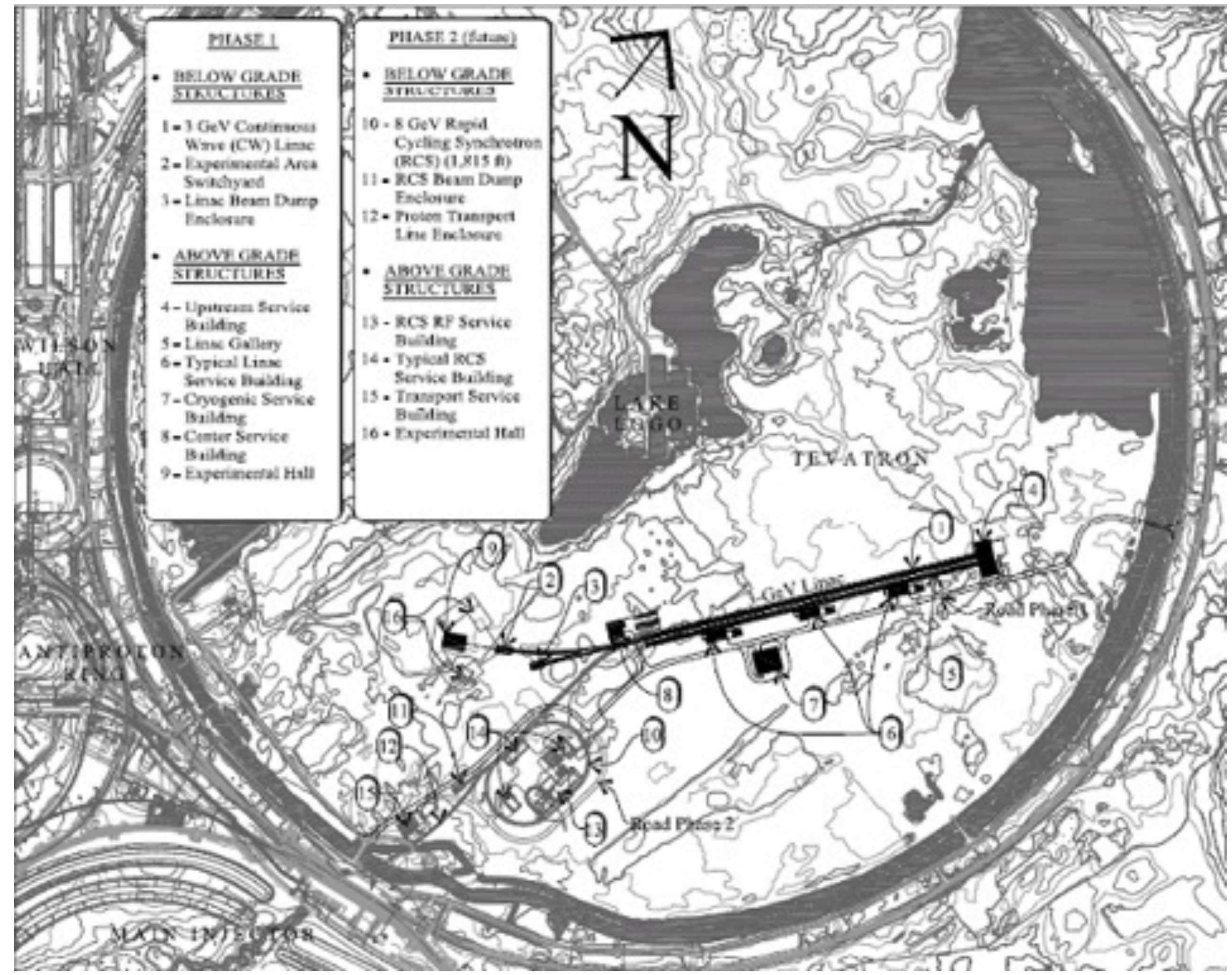
3-8 GeV Pulsed Linac and RCS Options

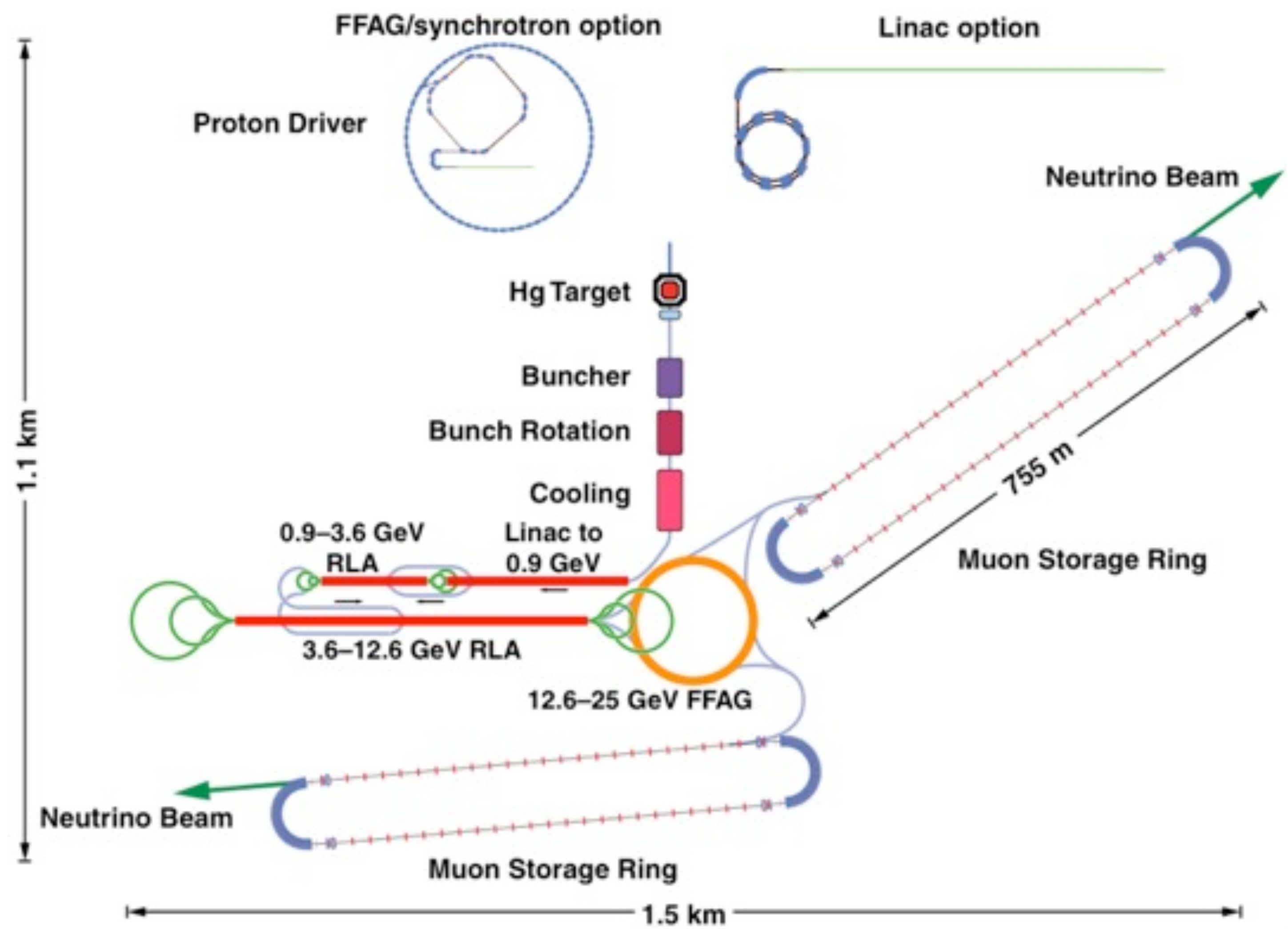




- RCS to 3-8 GeV under study but looks to have a limited upgrade potential (for Muon collider and Neutrino Factory)
- Present work concentrated on a pulsed linac
  - 1.3 GHz, 25 MV/m gradient, ≤5% duty cycle,1-30 ms pulse length
  - ~250 cavities (28 ILC-type cryomodules) needed.

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 20-50 GeV
- Decay ring(s)
  - Store for ~500 turns
  - Long production straights



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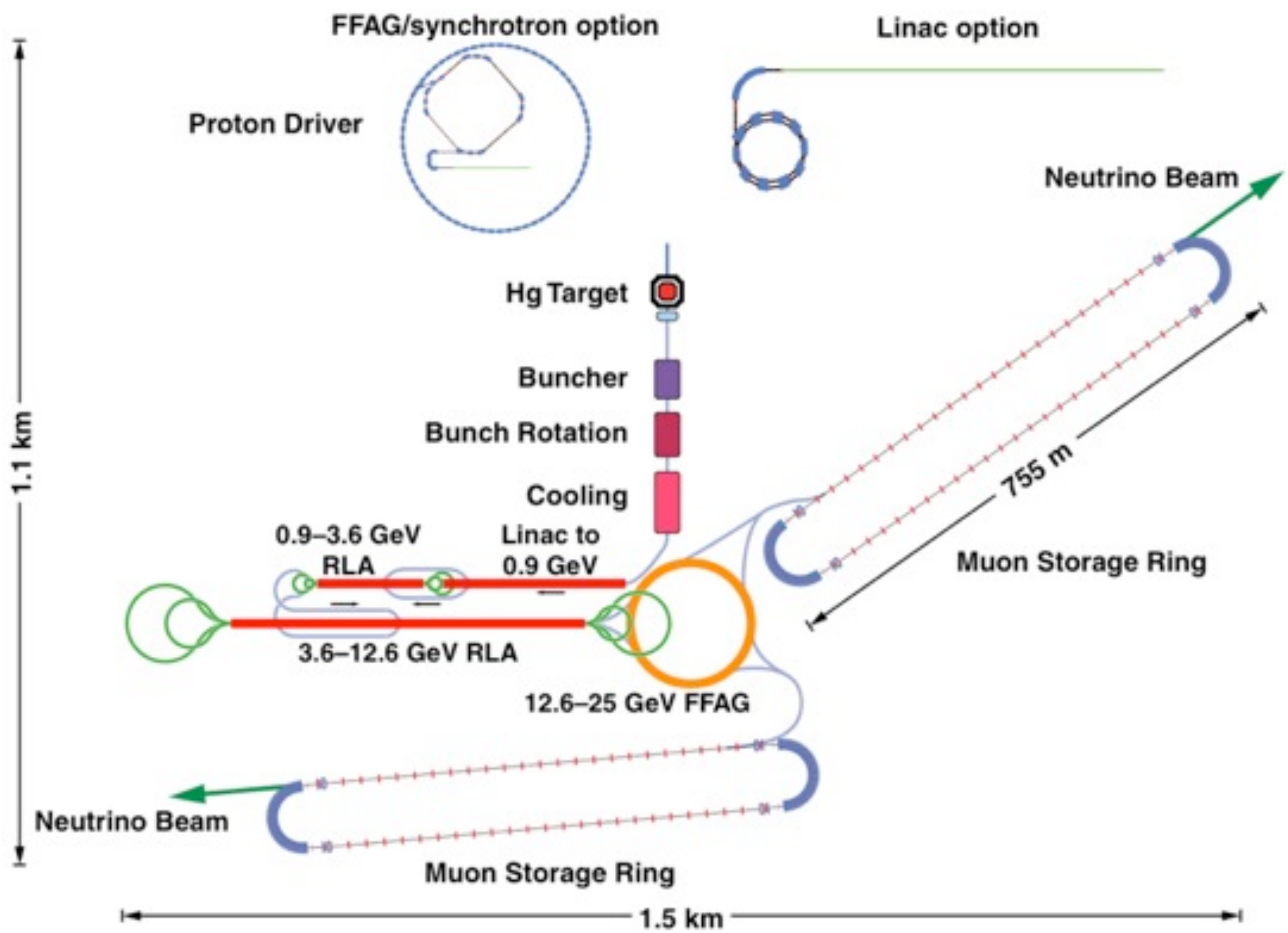

Additional requirements are that the proton pulse contains 1-3 bunches and the driver must compress the proton bunches to 1-3 ns, then hold in a compressed state for ~150 μs

Project-X Neutrino Factory/Muon Collider Strategy

- Project X shares many 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 capable of this beam pulse format
- New accumulator and compressor ring will be needed to produce the correct beam format on a NF or MC target. Possible idea of “trombone” delay lines and funnel to combine bunches at target.

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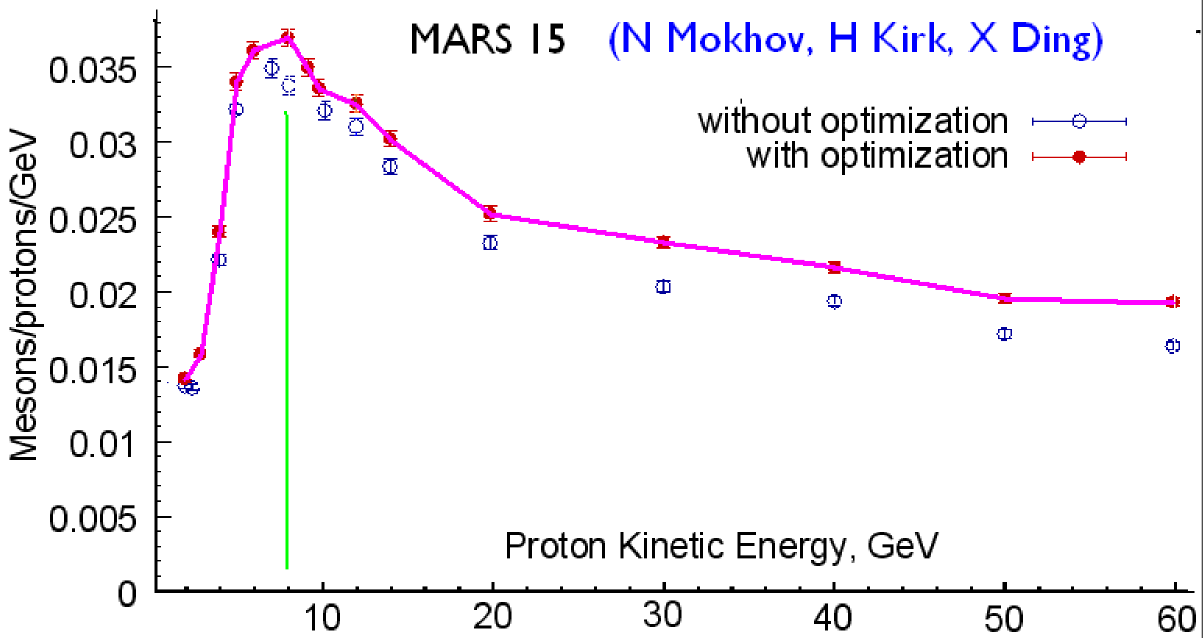

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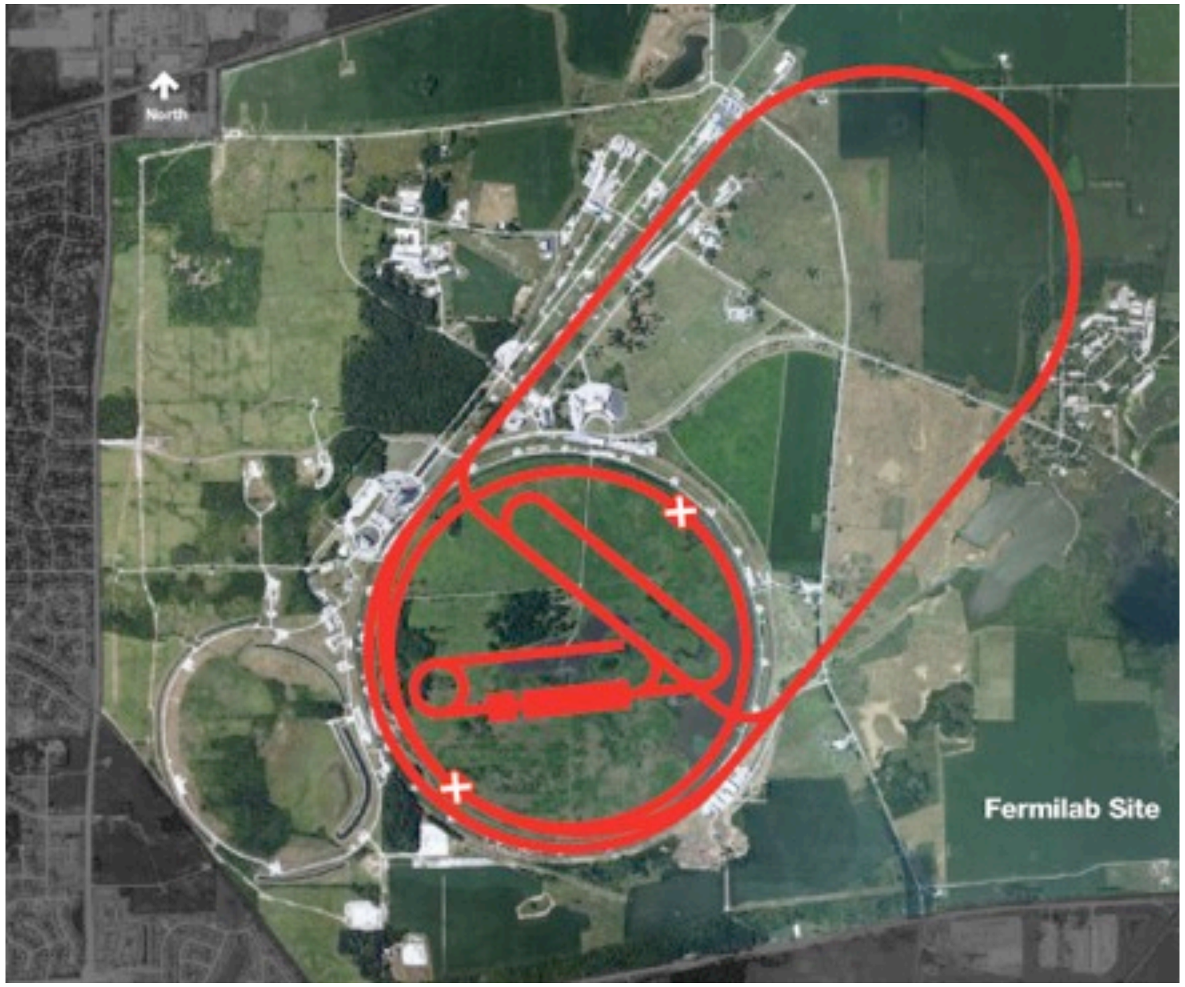

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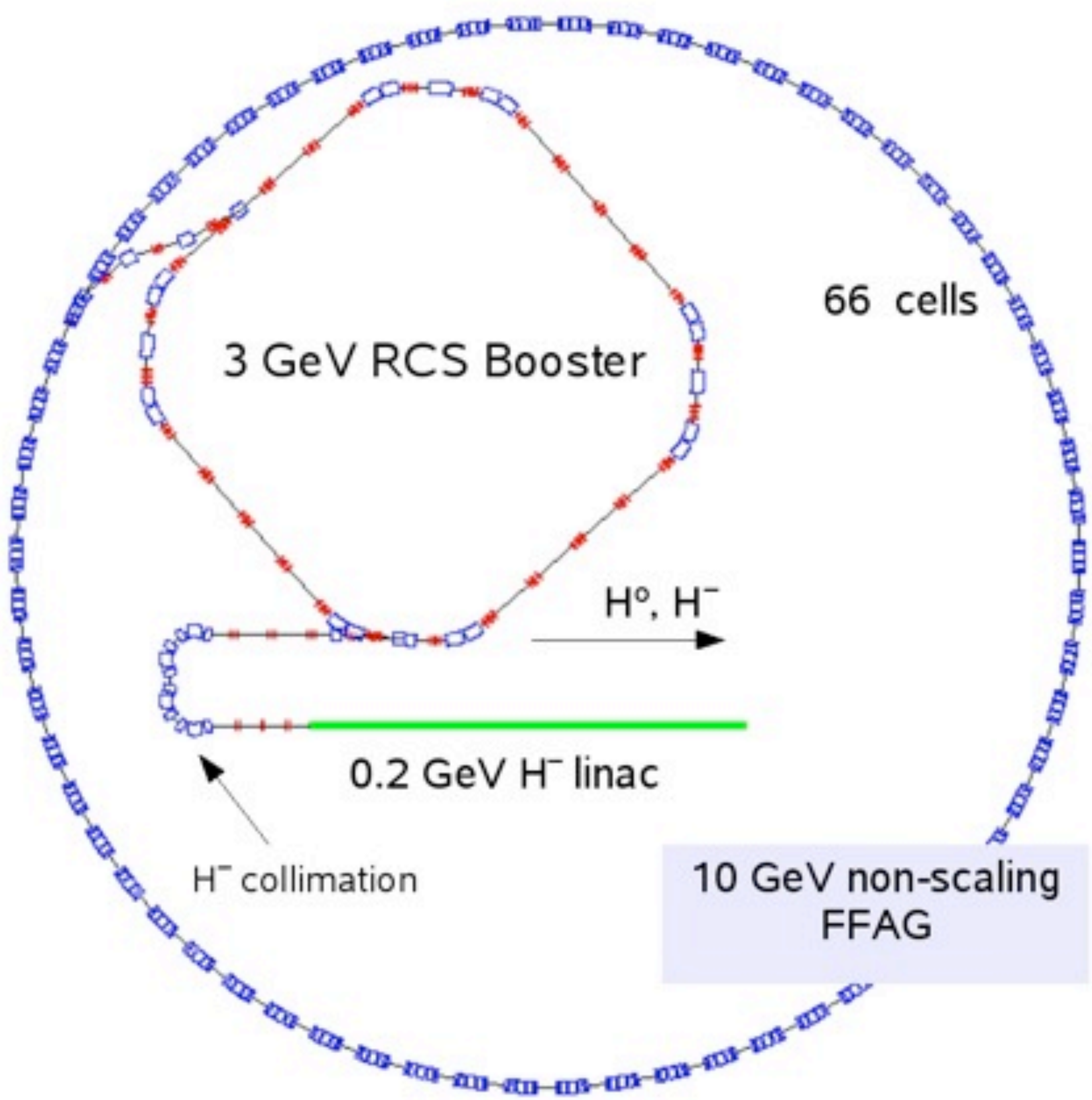
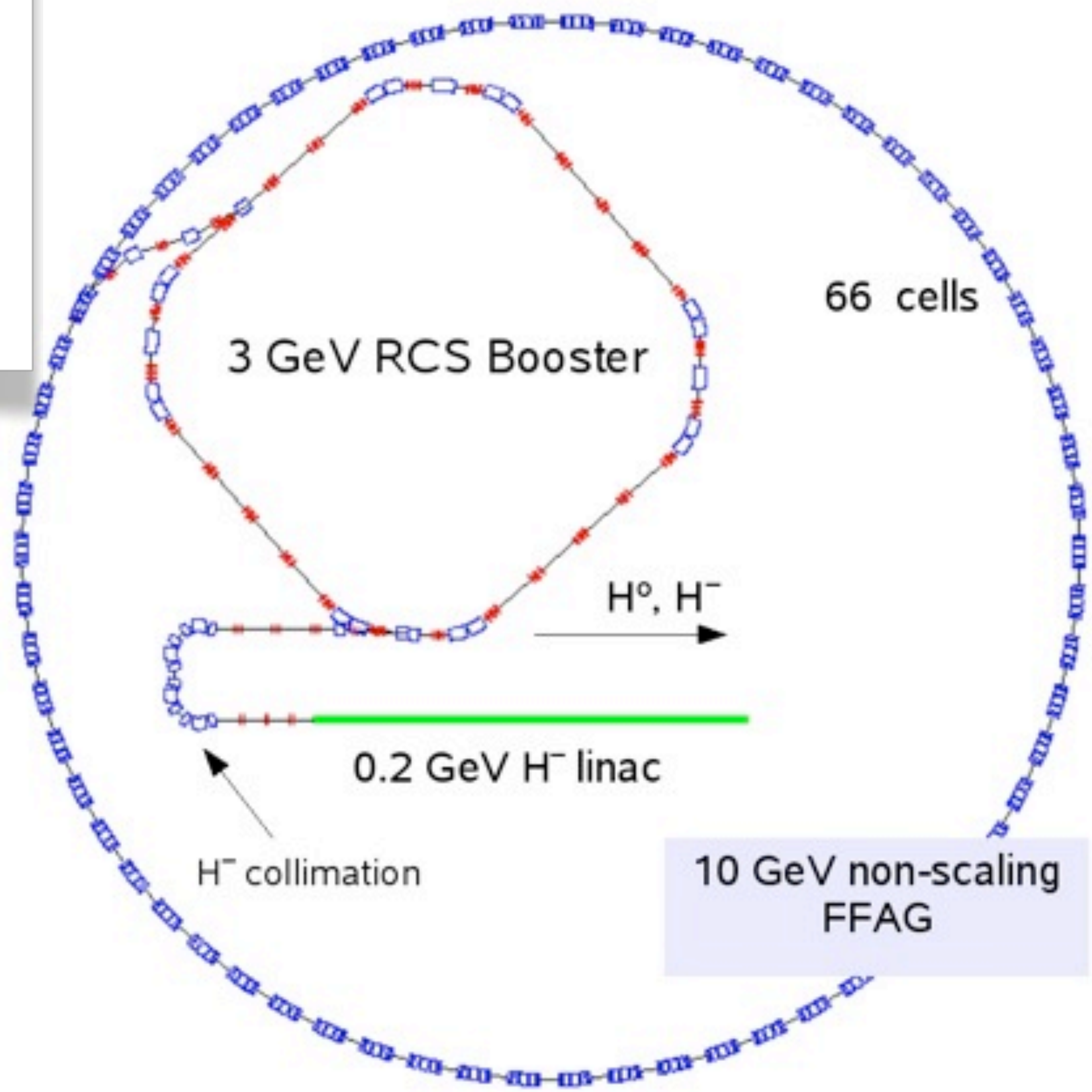
Green-Field Model of a 4 MW, 50 Hz, 10 GeV Proton Driver for a Neutrino Factory



Green-Field Model of a 4 MW, 50 Hz, 10 GeV 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.



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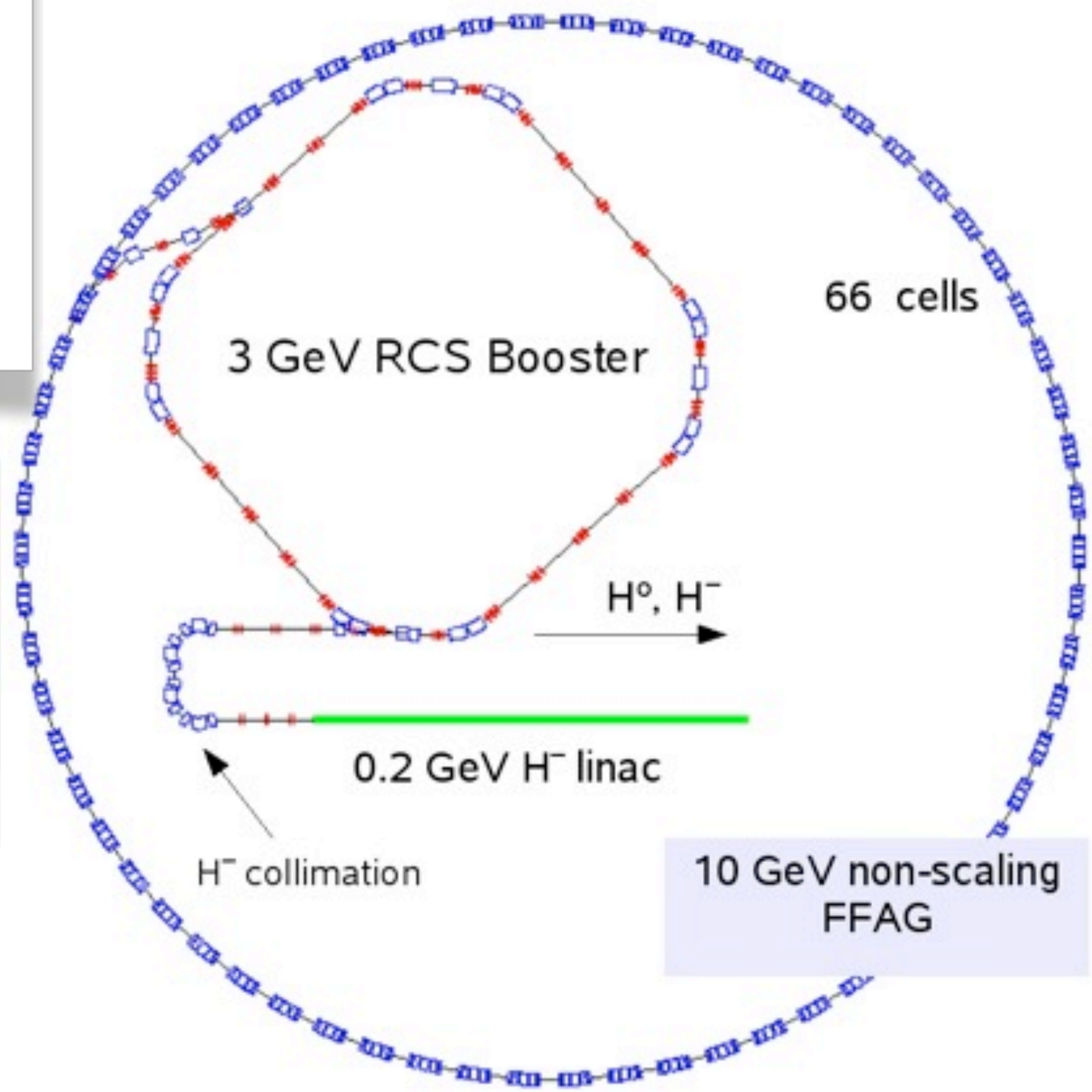
Special achromat for collimation (longitudinal and transverse) and momentum ramping for injection



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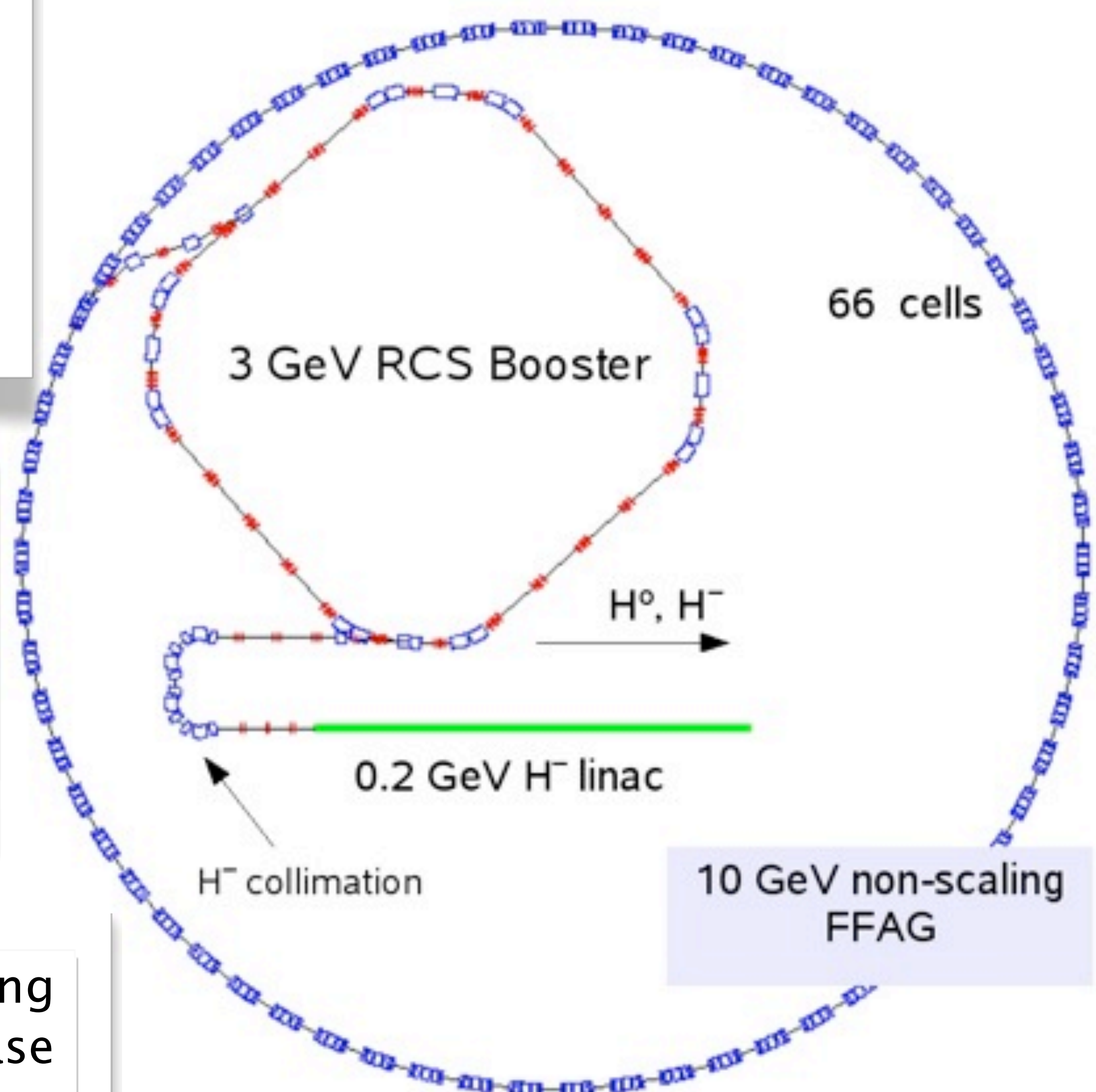
Separate booster ring designed for low loss phase space painting for beam injection and accumulation. Synchrotron moving buckets give flexibility to capture all of the injected beam.



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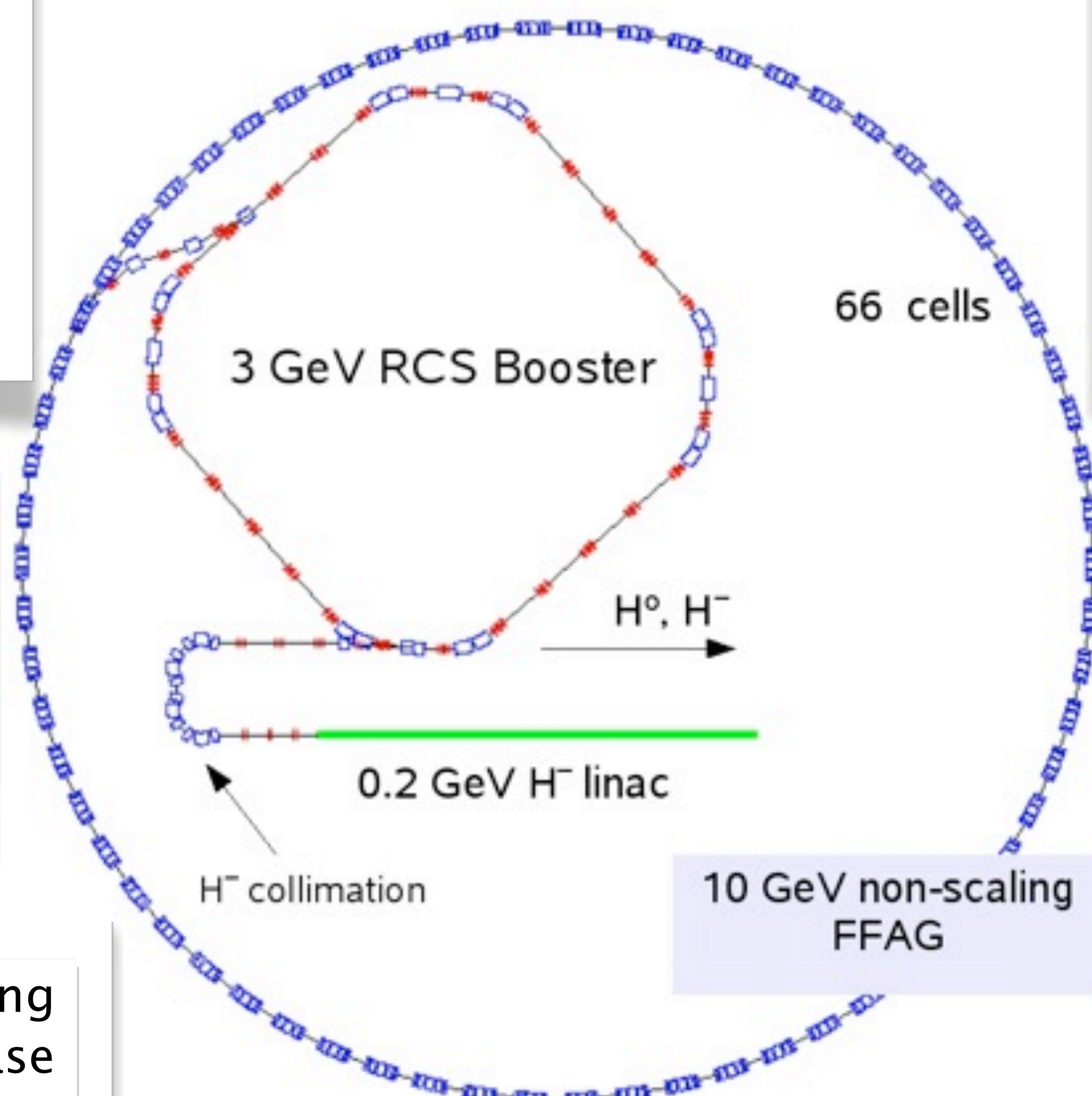

Separate main ring with optics chosen for ns bunch compression.
Could be FFAG (cheaper but insufficiently developed) or a synchrotron (reliable, tried and tested)

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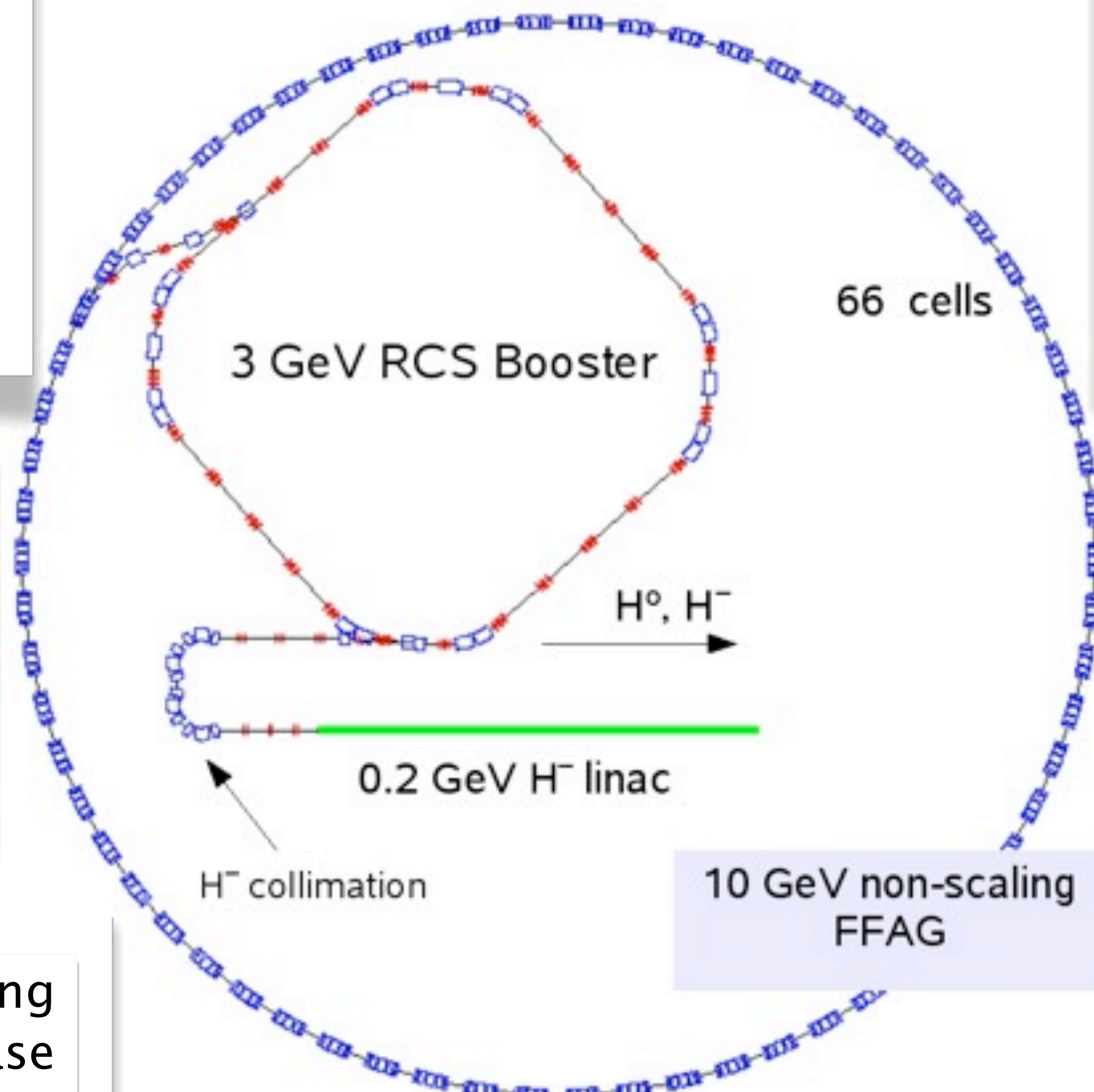

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Compressed bunches need to be held and sent to target at intervals of ~150 μs. Possible in FFAG and also synchrotron with flat top.

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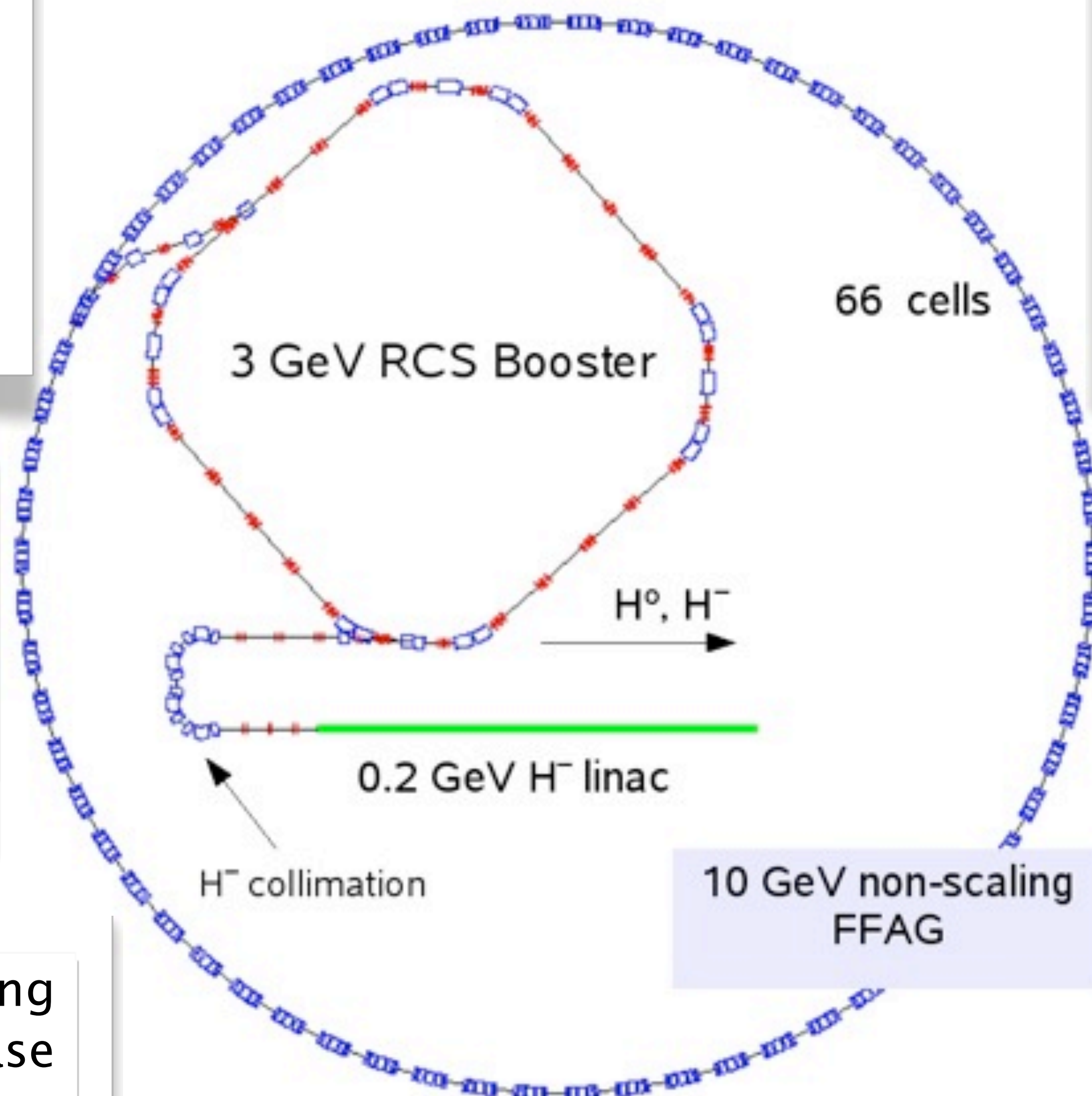

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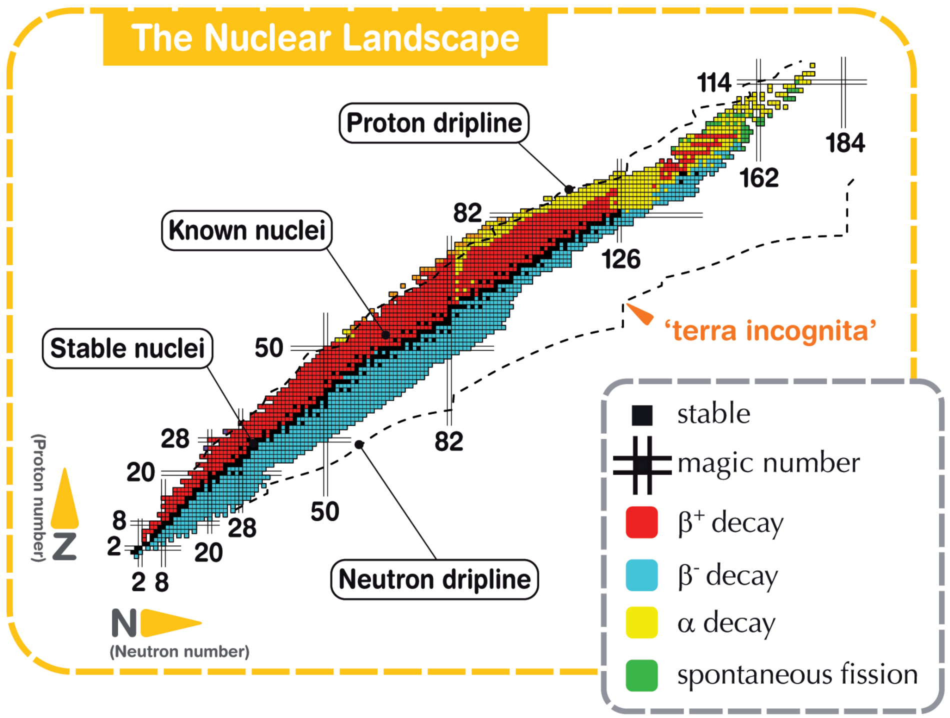
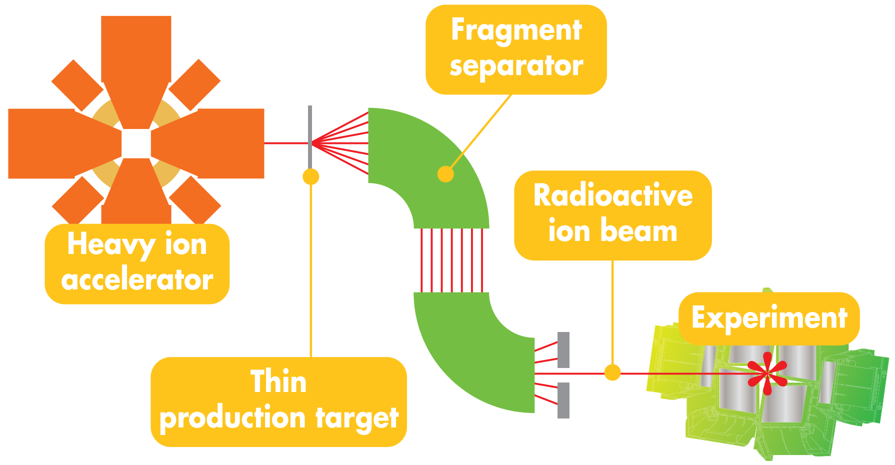
Under study at RAL

Science & Technology Facilities Council

Radioactive Ion Beams

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



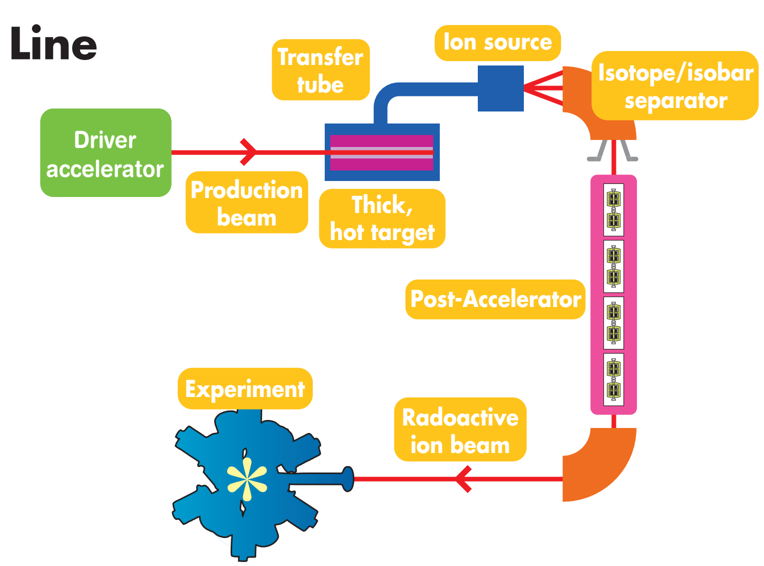


Fragmentation

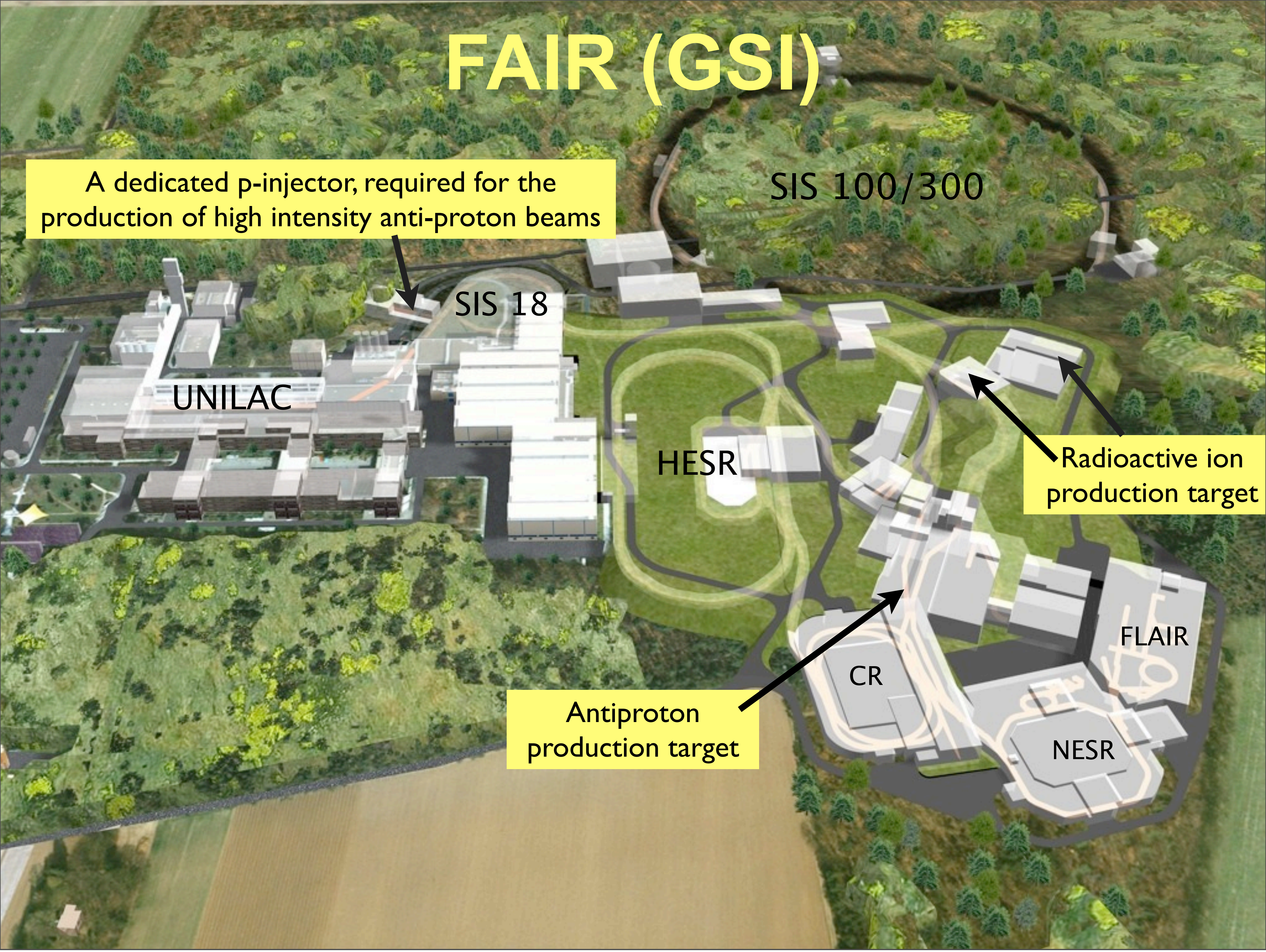
RIBs produced by fragmentation of a projectile on a thin target. Radioactive nuclei created are separated in flight. Secondary beam: high energy and selectivity, but low intensity

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

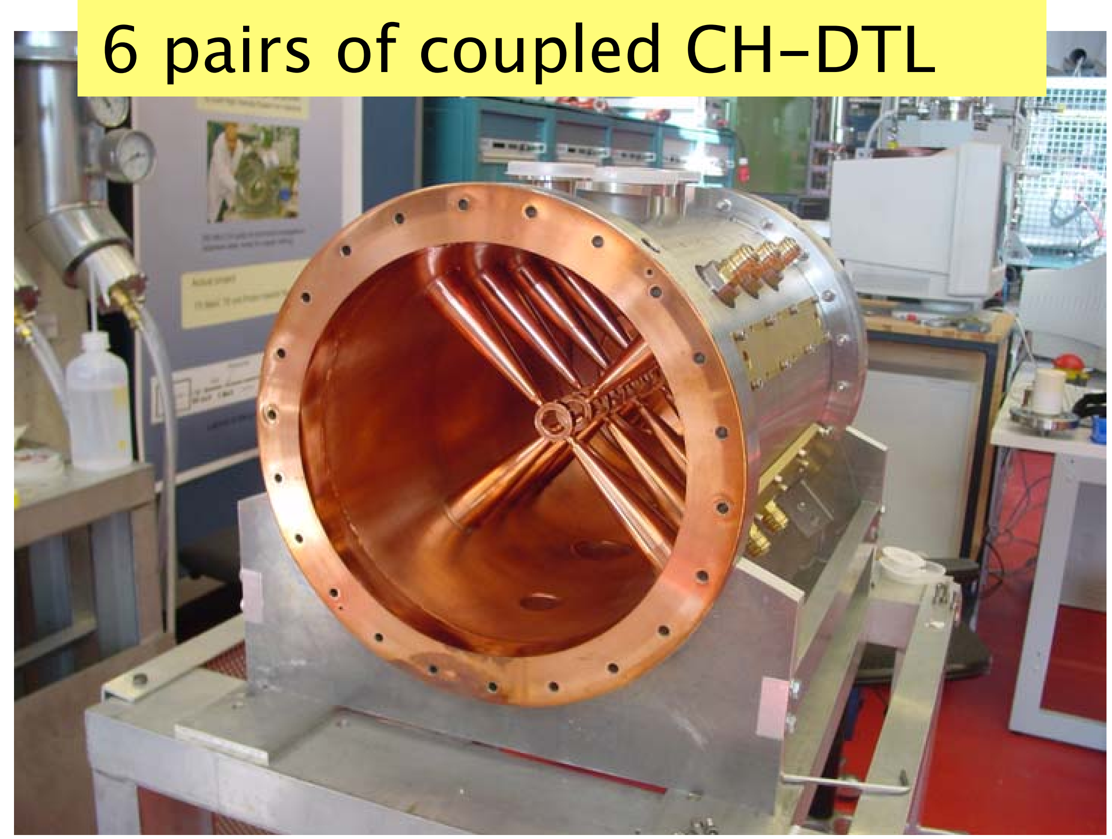


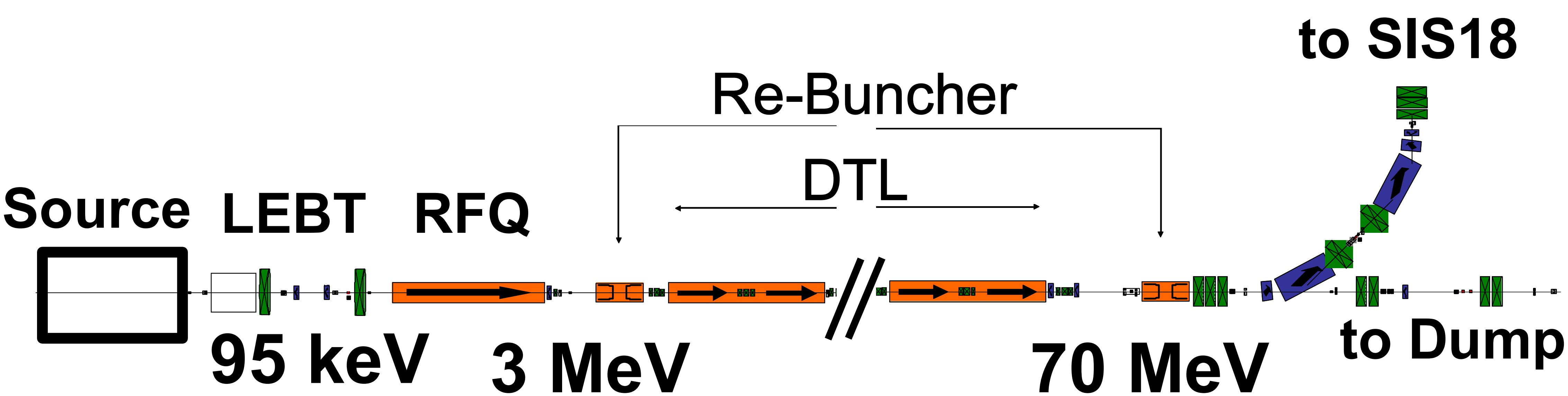
FAIR (GSI)


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
NESR
Antiproton production target

FAIR Proton Injector

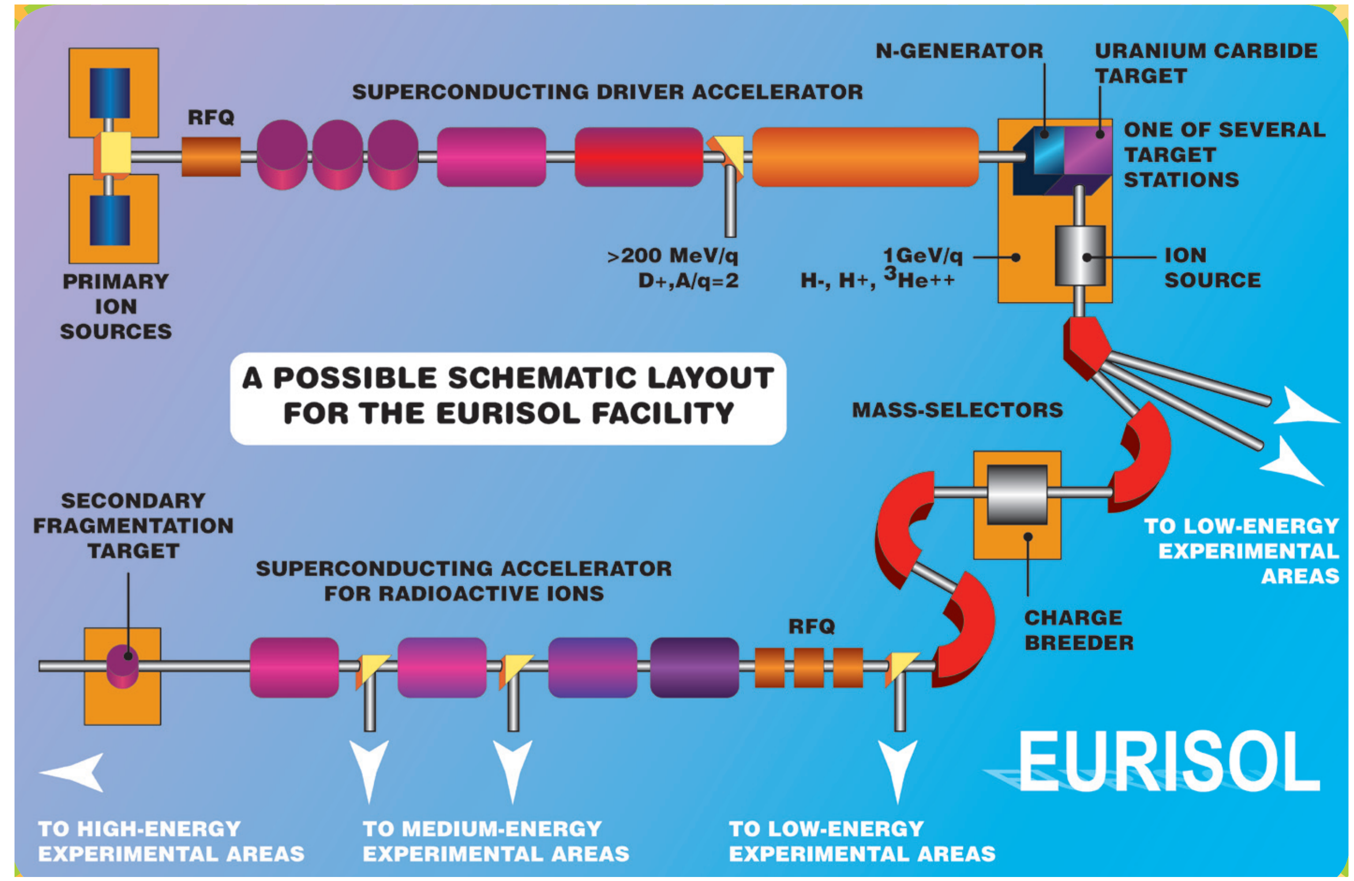
- GSI proton injector - 70 MeV, 70 mA, 352 MHz, 4 Hz repetition, 36 μs beam pulse length
  - first linac based on coupled H-Mode cavities combined with KONUS beam dynamics
- Tolerances comparable with other high intensity linacs
- Construction 2010? Commissioning 2013?





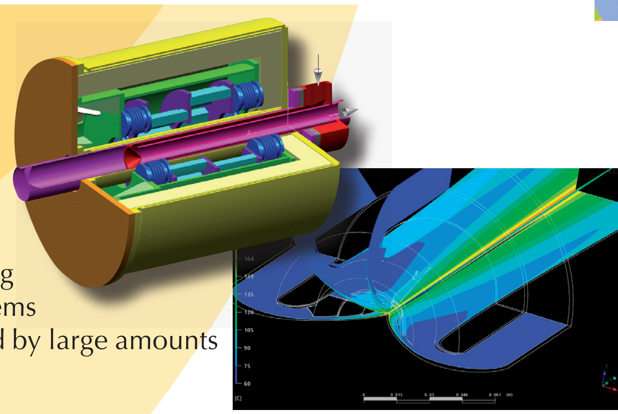
EURISOL (European ISOL Facility)

- 1 GeV superconducting linac, 5MW of protons on neutron converter target
- Also capable of accelerating deuterons, 3He 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.



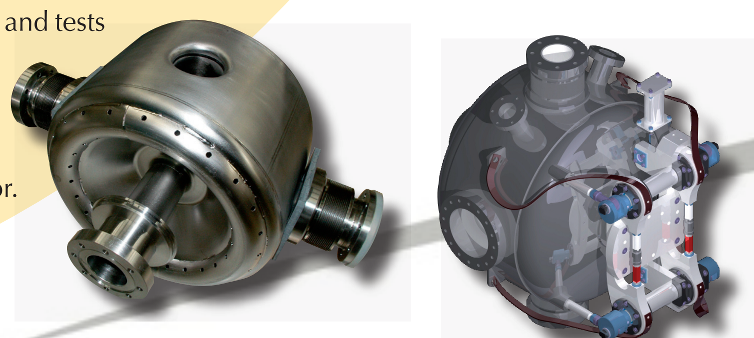
Multi-MW target station

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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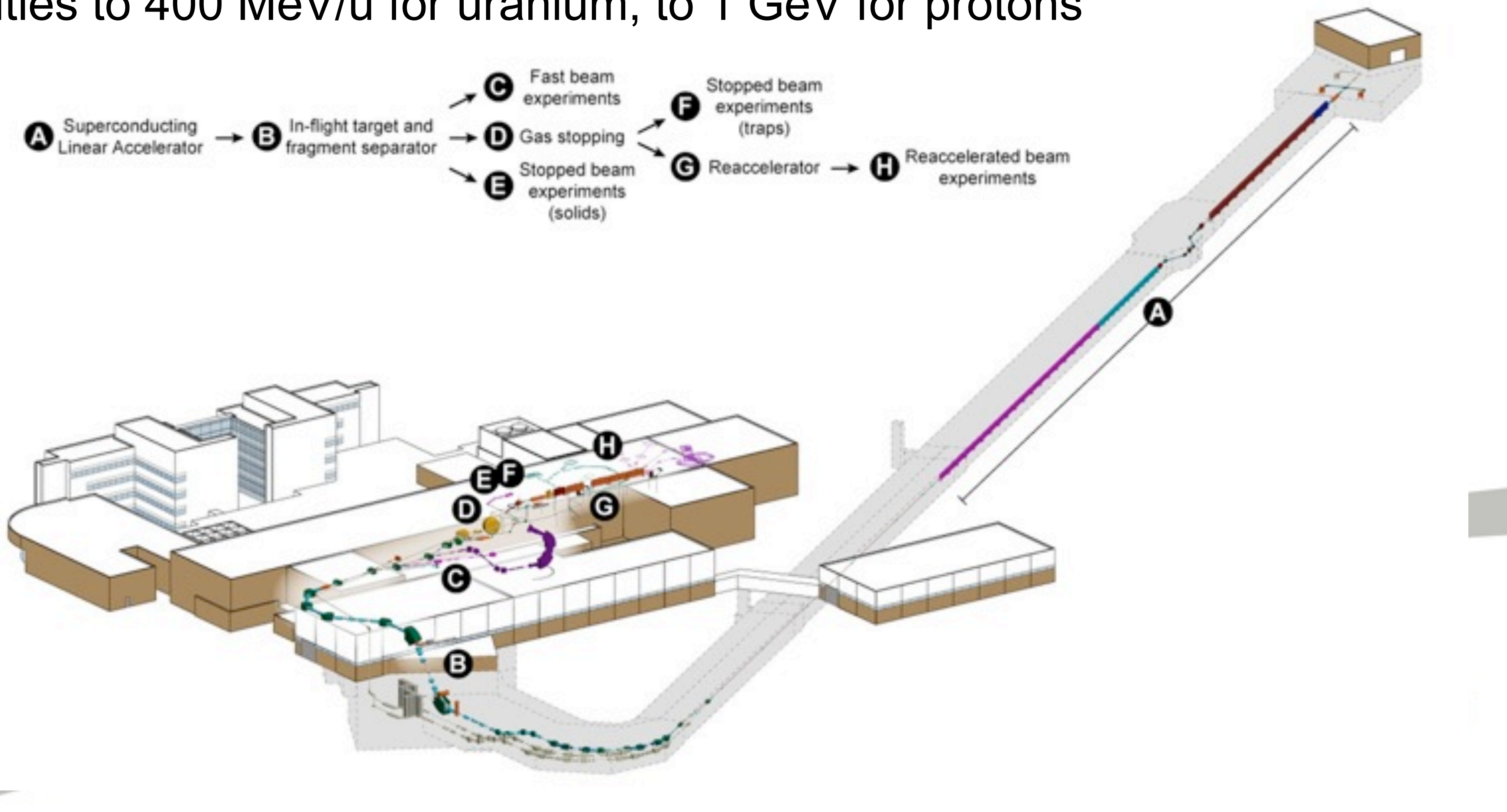
FRIB - Facility for Rare Isotope Beams at MSU

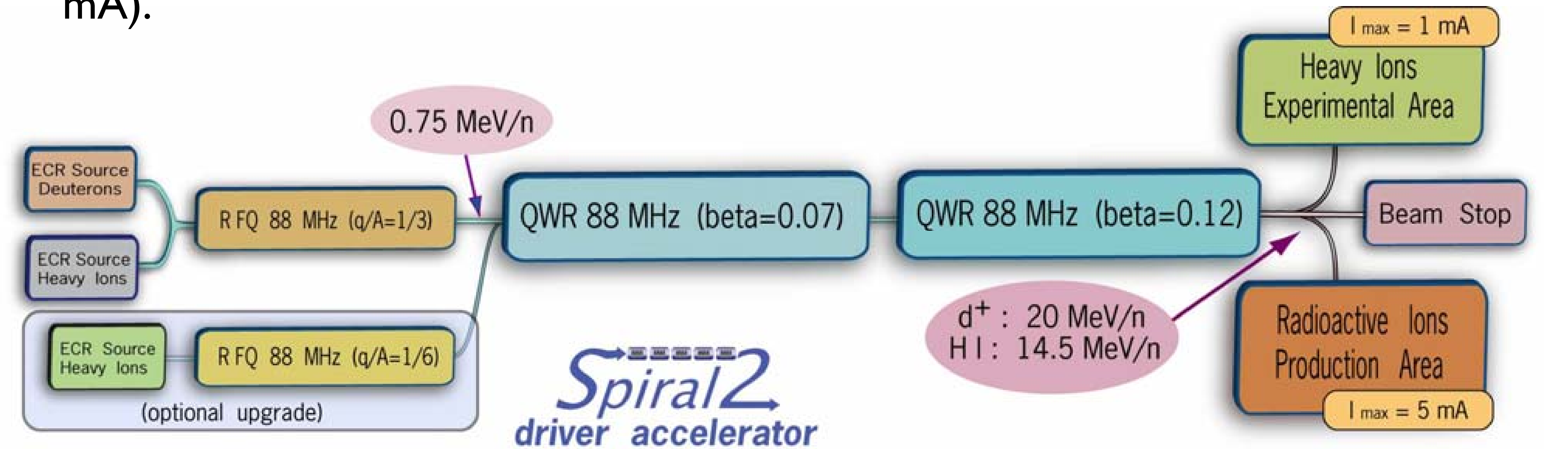
- Agreement signed June 2009. Cost ~$600m and take ~10 years to design and build.
- Superconducting RF driver linac providing 400 kW for all beams with uranium accelerated to 200 MeV/u and lighter ions with increasing energy (protons at 600 MeV).
- Upgrade possibilities to 400 MeV/u for uranium, to 1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



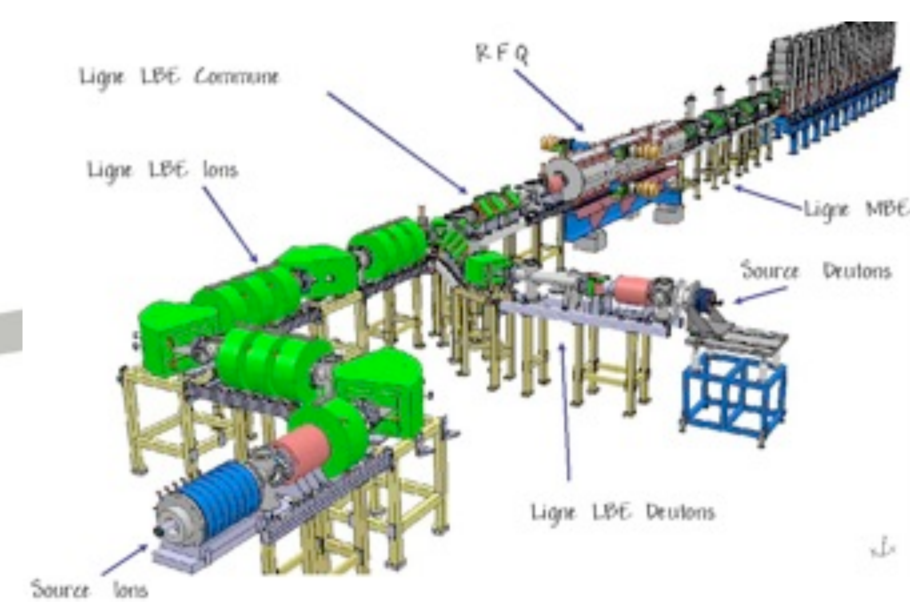
SPIRAL-2

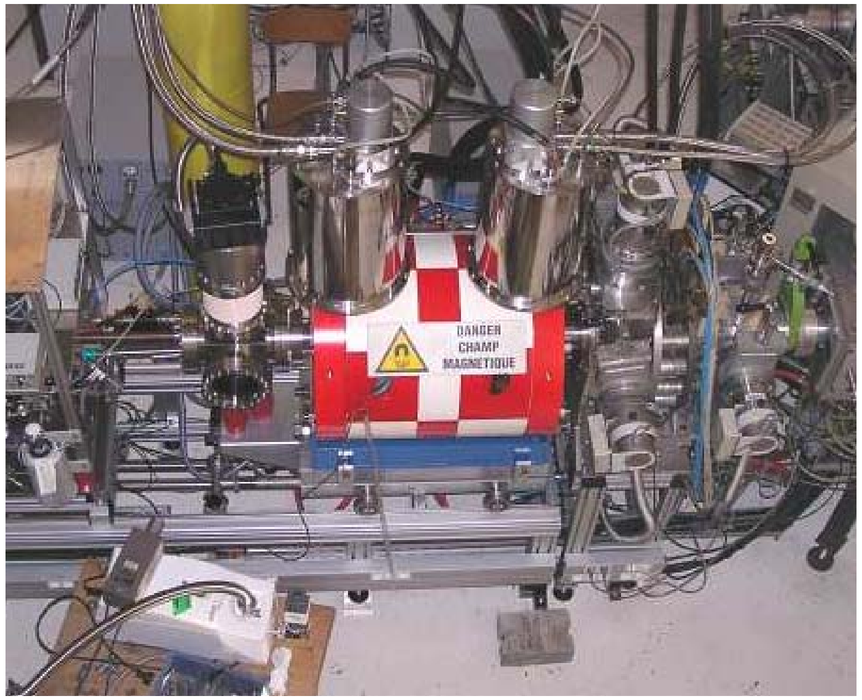
Radioactive beams facility at GANIL, Caen, France

- 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).

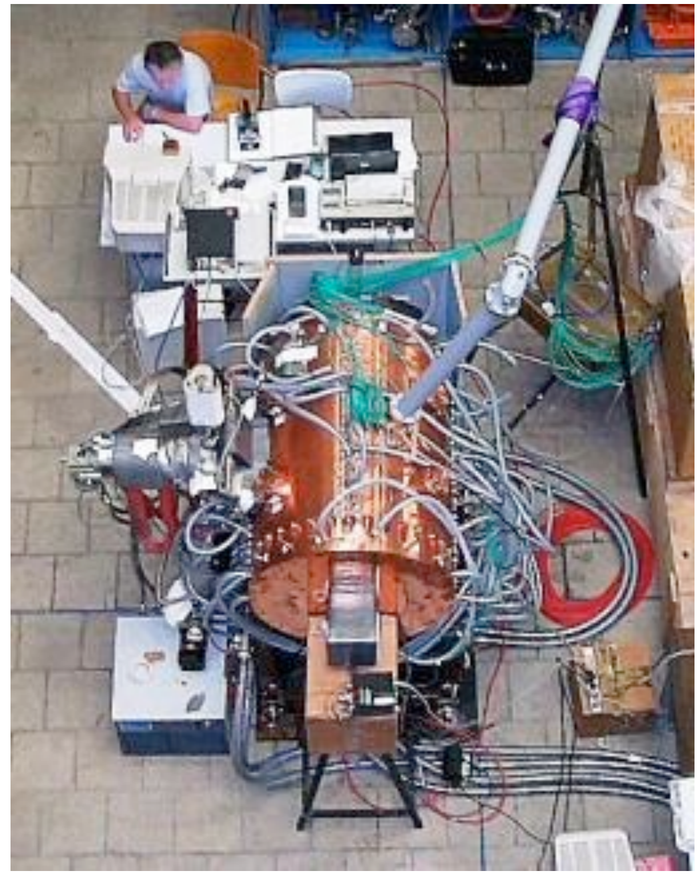


- Two families of quarter wave resonators: type A (optimized for beta=0.07, 1 per cryomodule) and B (beta=0.12, 2 per cryomodule).
- The accelerator is scheduled to be commissioned from mid-2011 onwards.



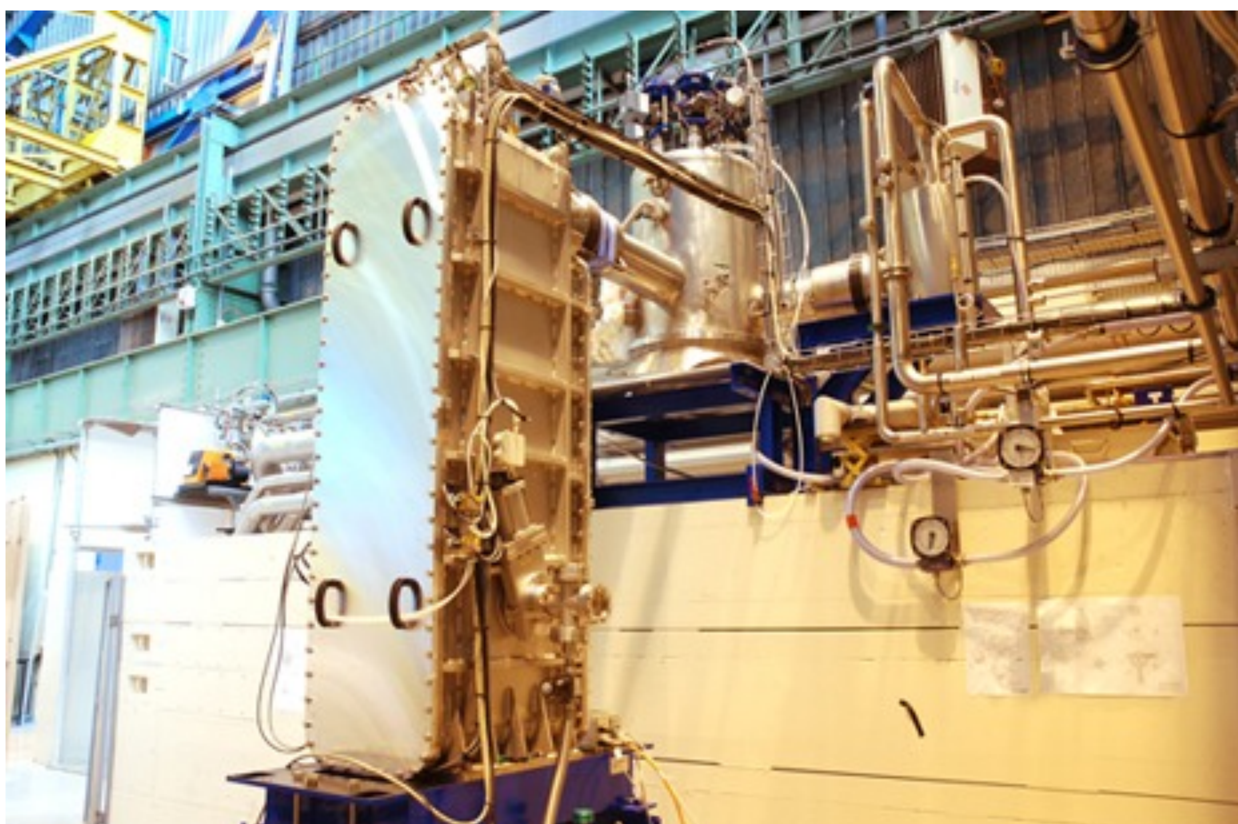


ECR heavy ion source



RFQ – full power test

First Type B ß=0.12 cryo-module



First Type A ß=0.07 cryo-module

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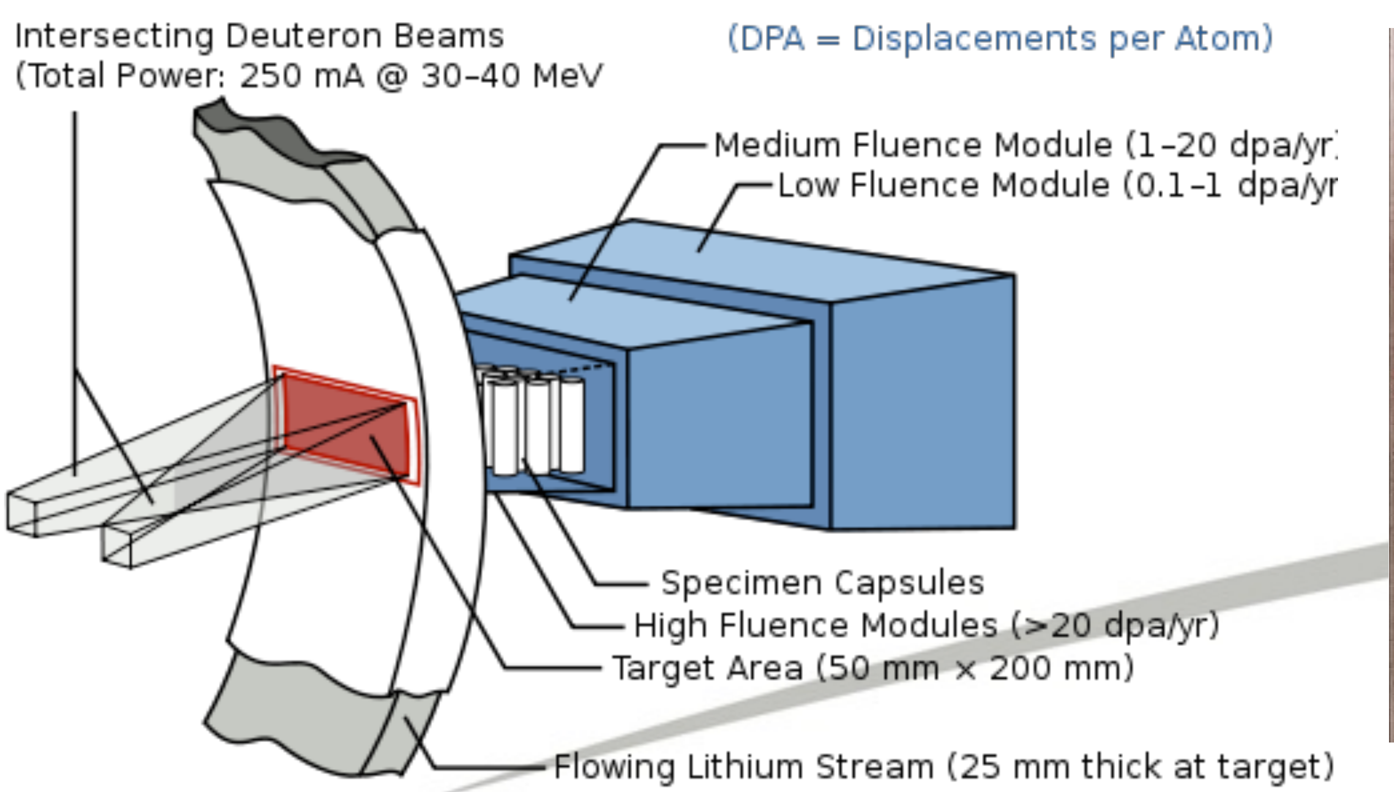
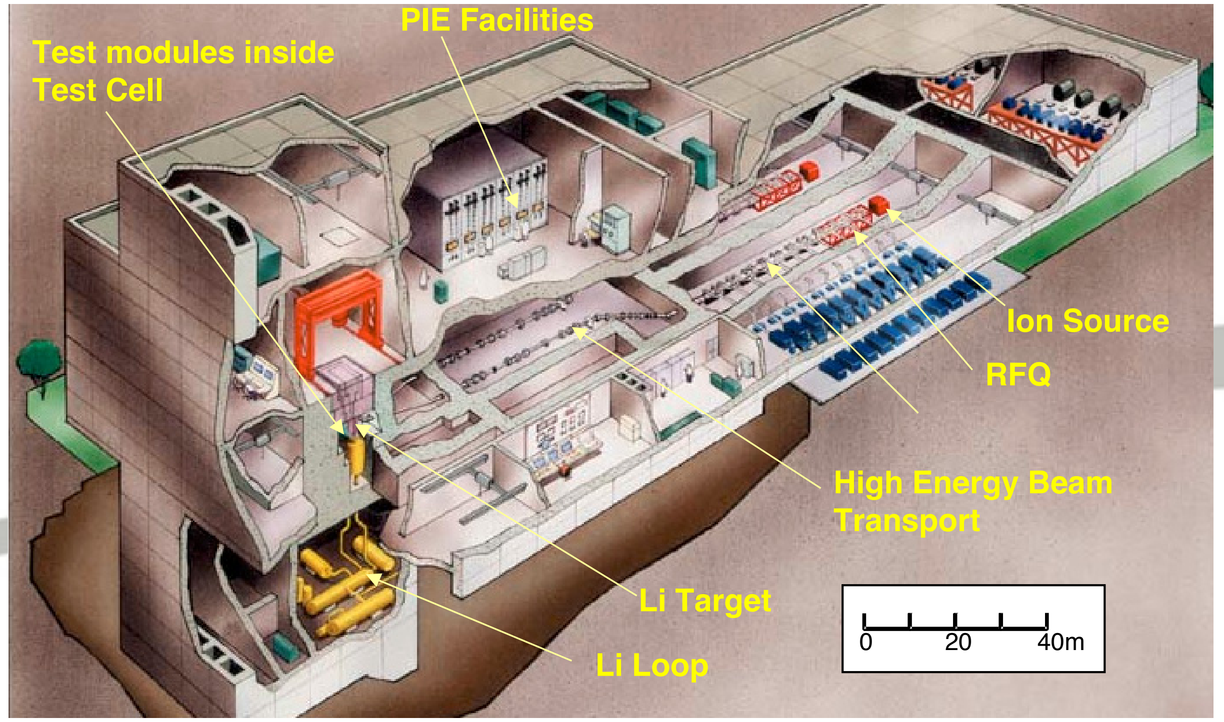
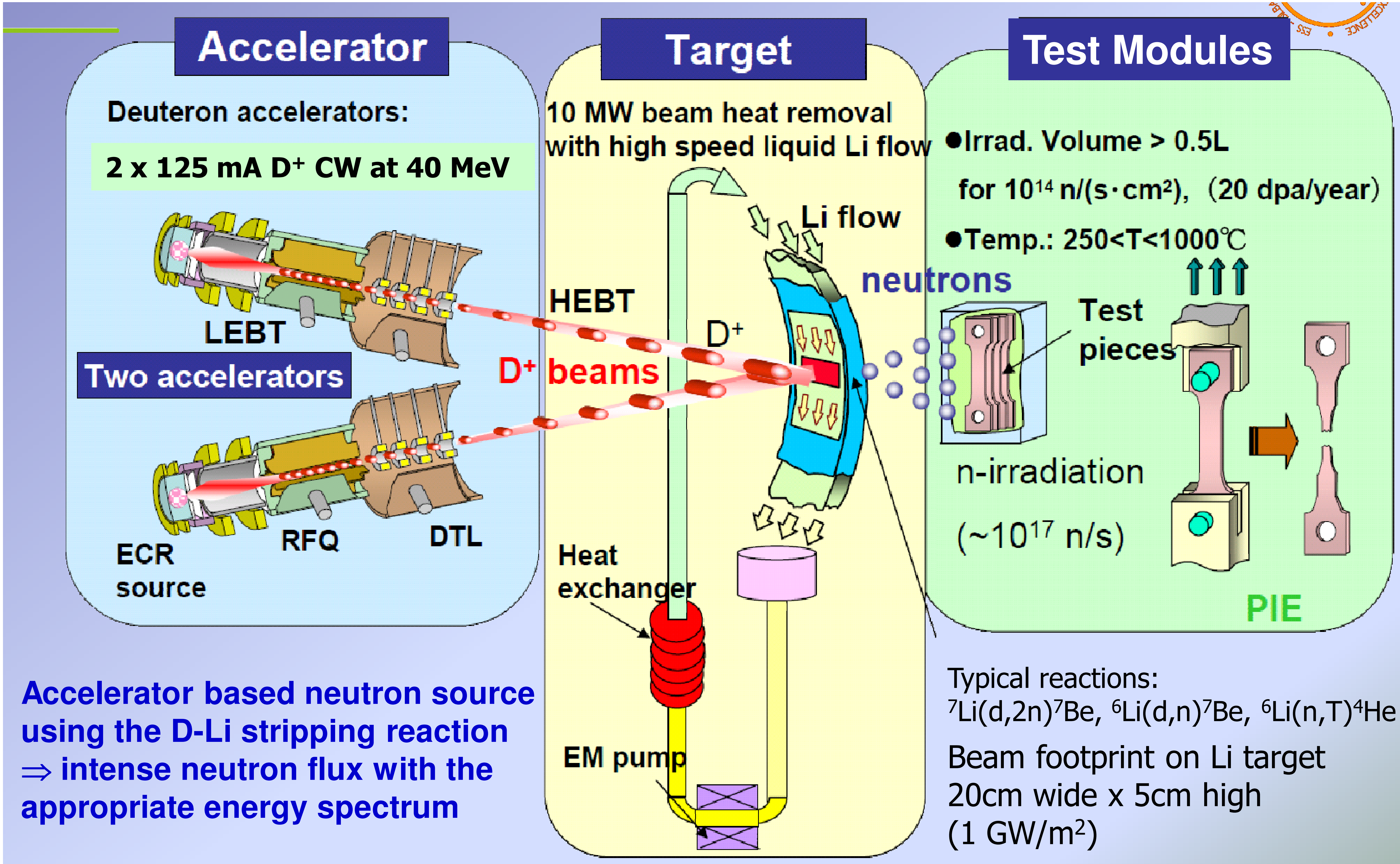
IFMIF and IFMIF-EVEDA

- 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

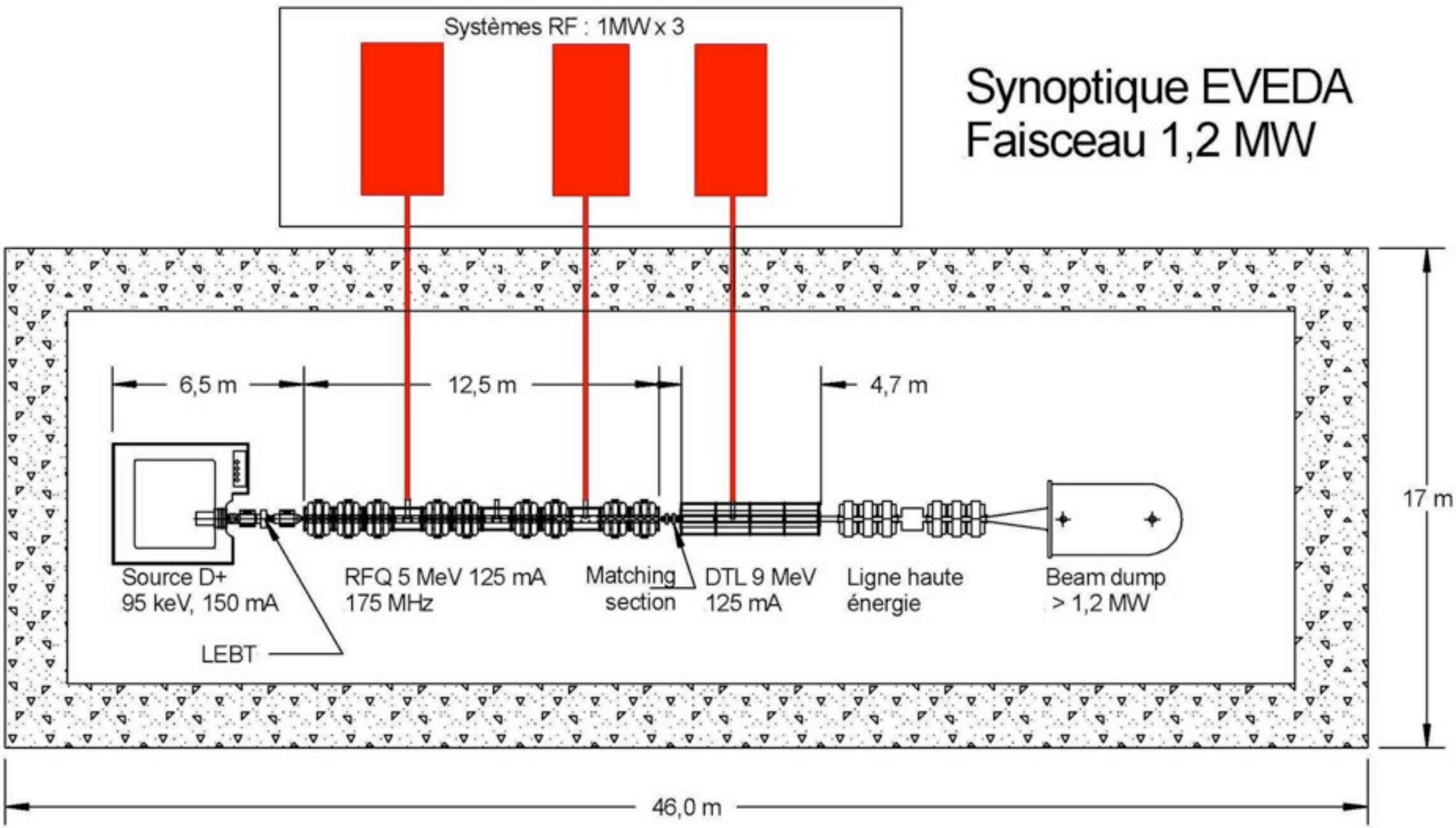




IFMIF - Principles



IFMIF-EVEDA
A 9 MeV Test Facility



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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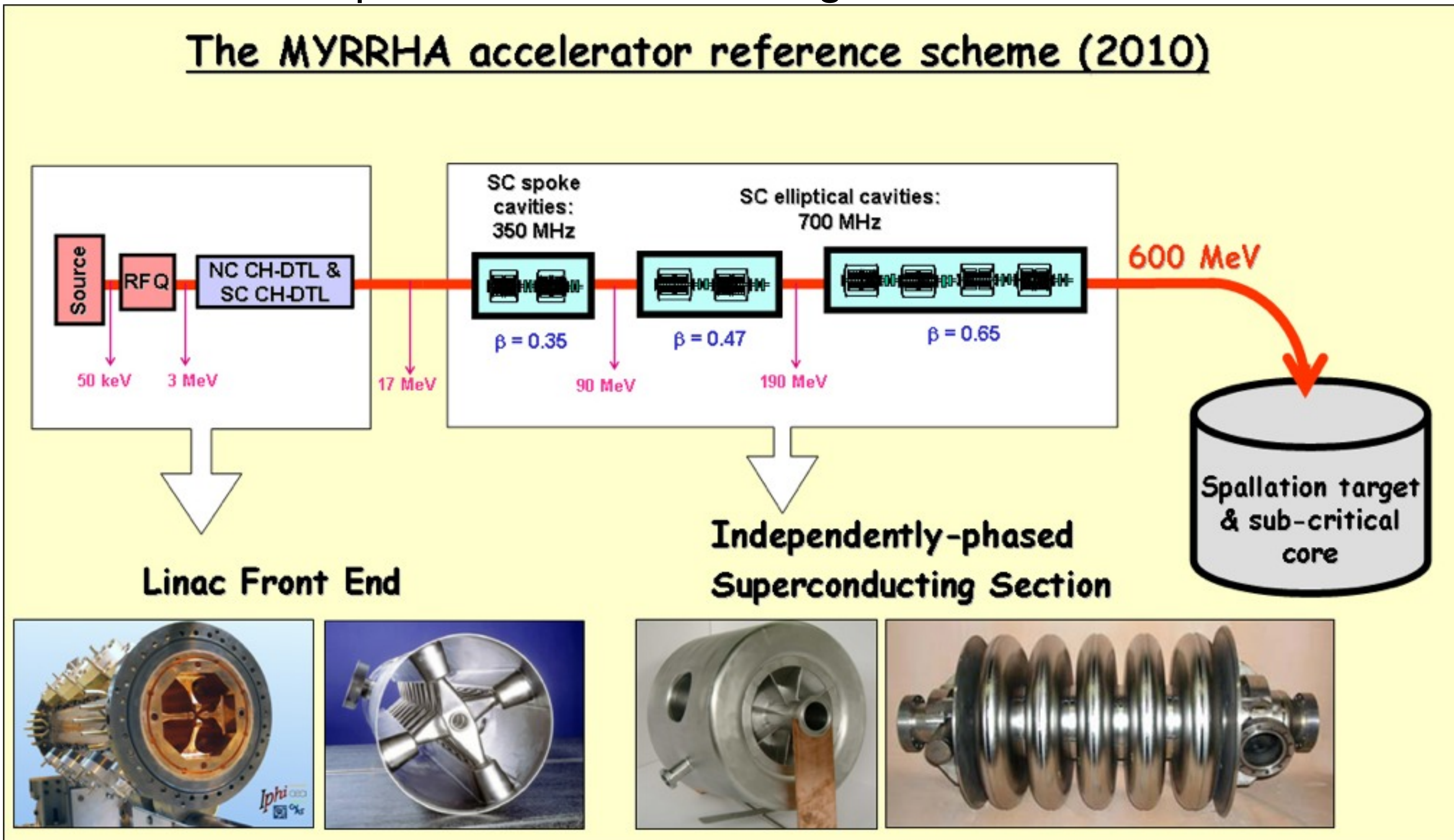
MYRRHA

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



ADSR: Reliability Issues

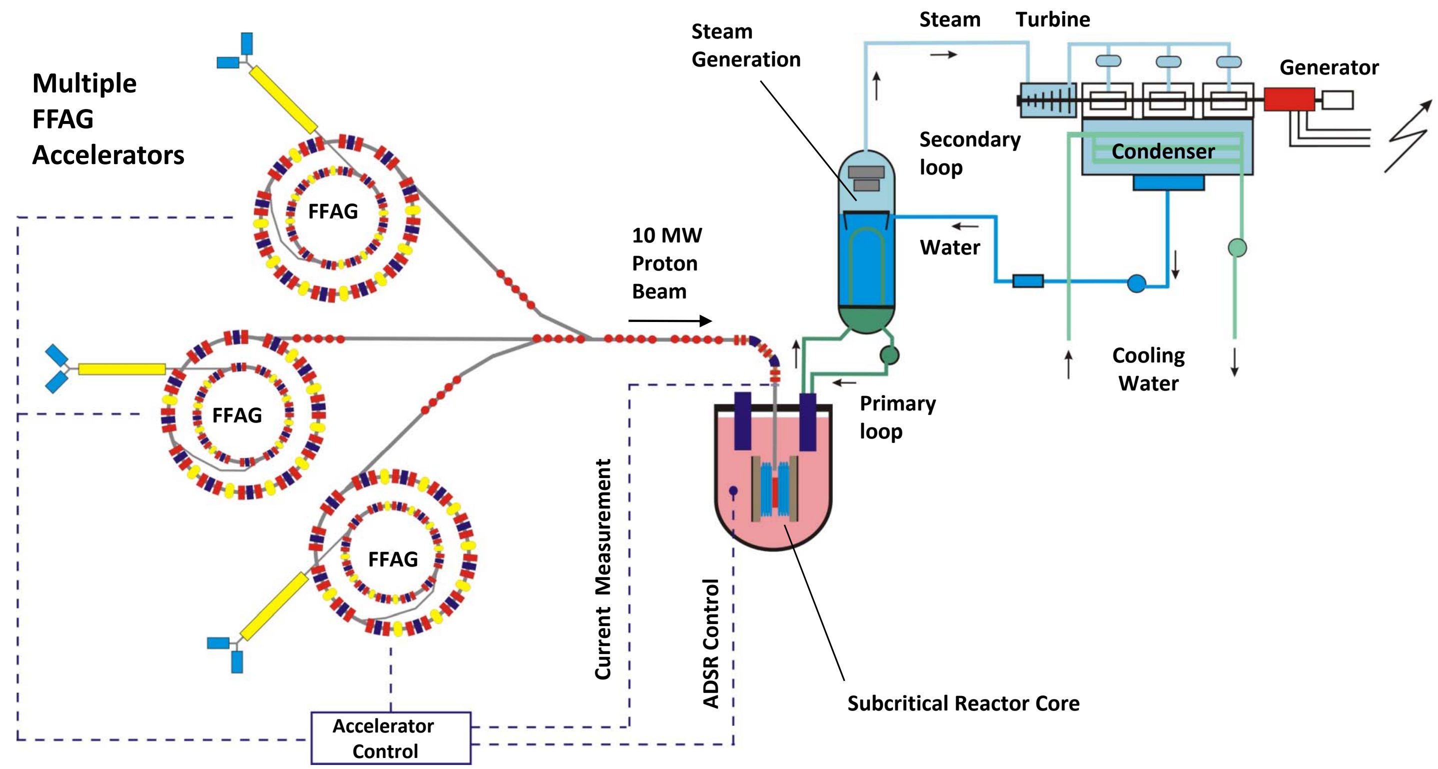
Beam availability: an order of magnitude better than present day state-of-the-art.

- 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

ThorEA approach: multiple accelerators with redundancy, current increased if one goes down



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)
- Others are being upgraded or have upgrade plans (PSI, ISIS, SNS)
- 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

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