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Accelerators for neutrons

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John Adams Institute, Oxford, 14 February 2013

Neutrons used in: reactors, fusion, condensed matter physics, security screening, radiopharmaceutical production, …

But neutron $t_{½}$ ~10 mins.
→ must make when wanted

Radioisotope sources (*e.g.* Am/Be, Cf-252, Sb/Be)

D-T accelerators and D-T tubes (14 MeV)

Electron accelerator sources (*e.g.* Harwell linacs (final one, 90 kW))

Proton accelerator sources (*e.g.* ISIS, J-PARC, LANL, PSI, SNS, *ESS*)

Heavier ion accelerator sources (*e.g.* IFMIF, FAFNIR)

Radioisotope sources	Am/Be	(α,n)	4.2 MeV mean energy	Up to ~10^7 – 10^8 n/sec
	Cf-252	(sf)	2.2 MeV	
	Am/Li	(α,n)	0.45 MeV	
	Sb/Be	(γ,n)	0.025 MeV	

D-T sources 14 MeV (deuterons on tritiated target)
RTNS-II, 1–4×10^{13} n/sec (LLNL)
D-T tubes, ~10^{10} n/sec, ~1000 hours
(limits are heating, inventory)

Electron accel. sources (γ,n) + (γ,f) on U, Ta, … ~few × 10^{14} n/sec

Proton accelerator sources (*e.g.* ISIS, J-PARC, LANL, PSI, SNS, *ESS*)
spallation, ~10^{16} – 10^{17} n/sec

Heavier ion accelerator sources (*e.g.* IFMIF, FAFNIR)
deuteron beams, (d,n)
~3×10^{16}, ~0.5–5×10^{15} n/sec

~1 inch

Radioisotope sources

~1 m

D-T tubes

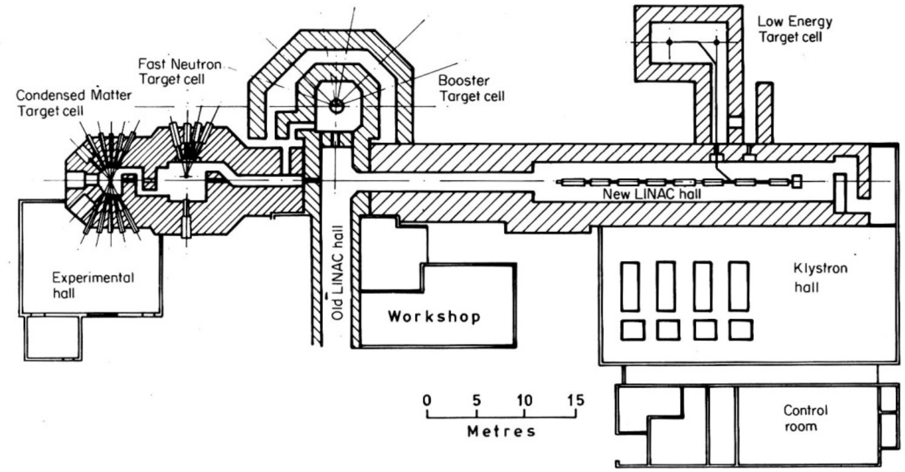


Fig. 1. General plan of HELIOS facilities.

~100 m

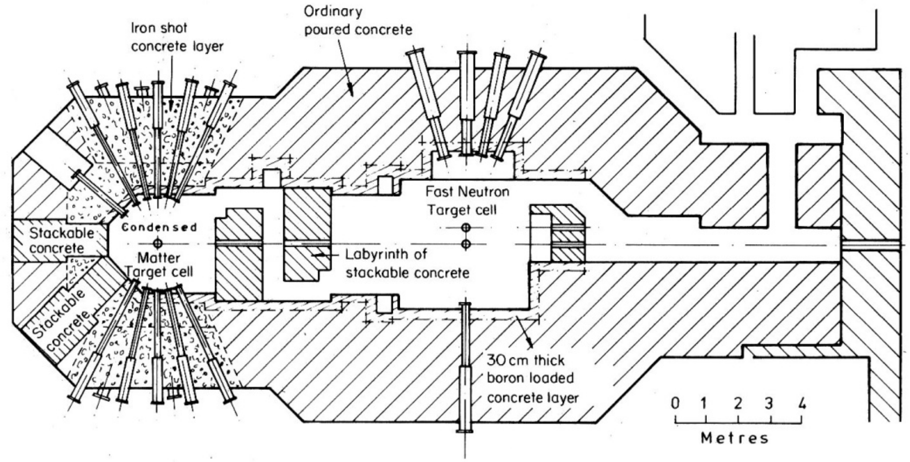
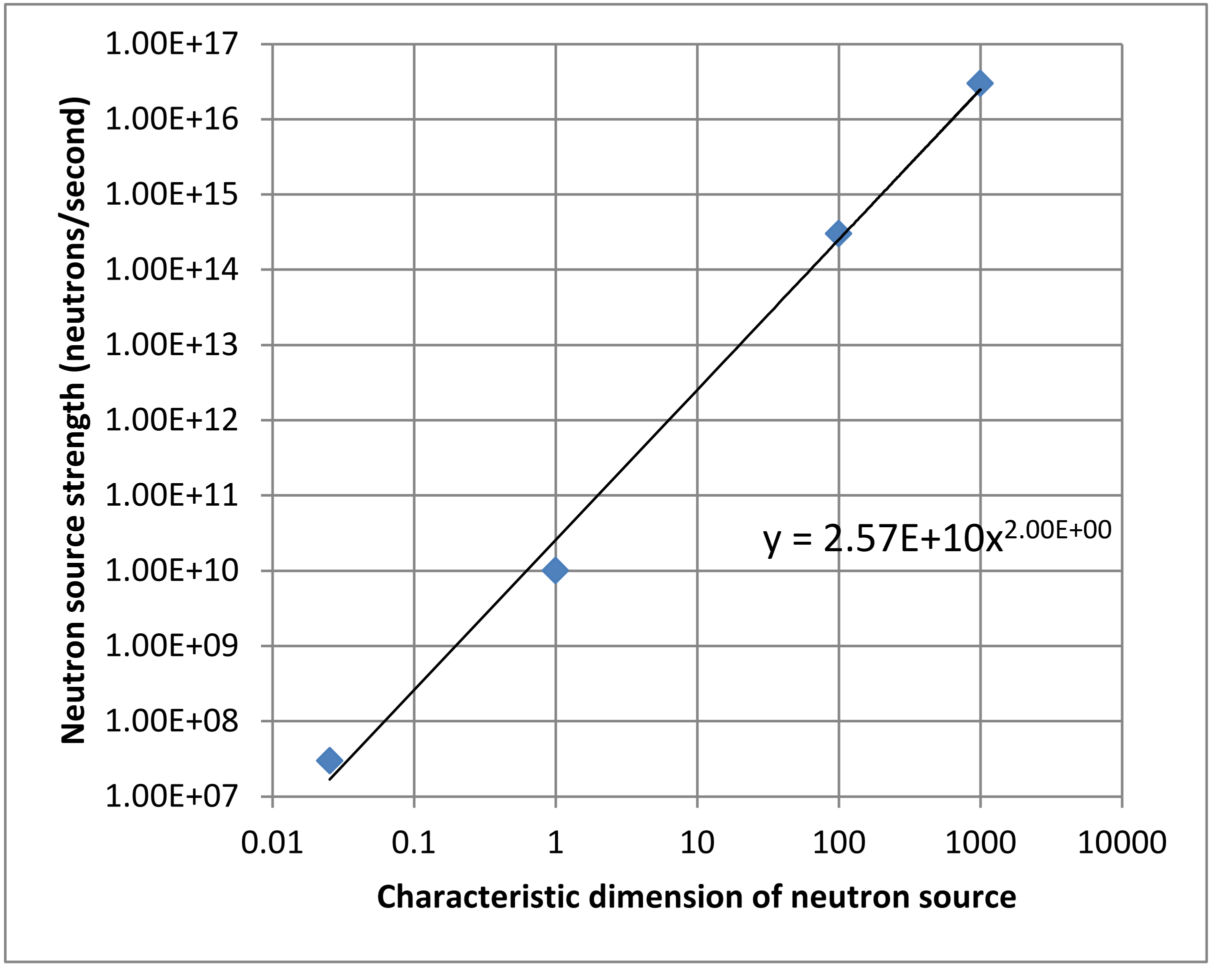


Fig. 2. Detailed plan of the Fast Neutron and Condensed Matter Target Cells.

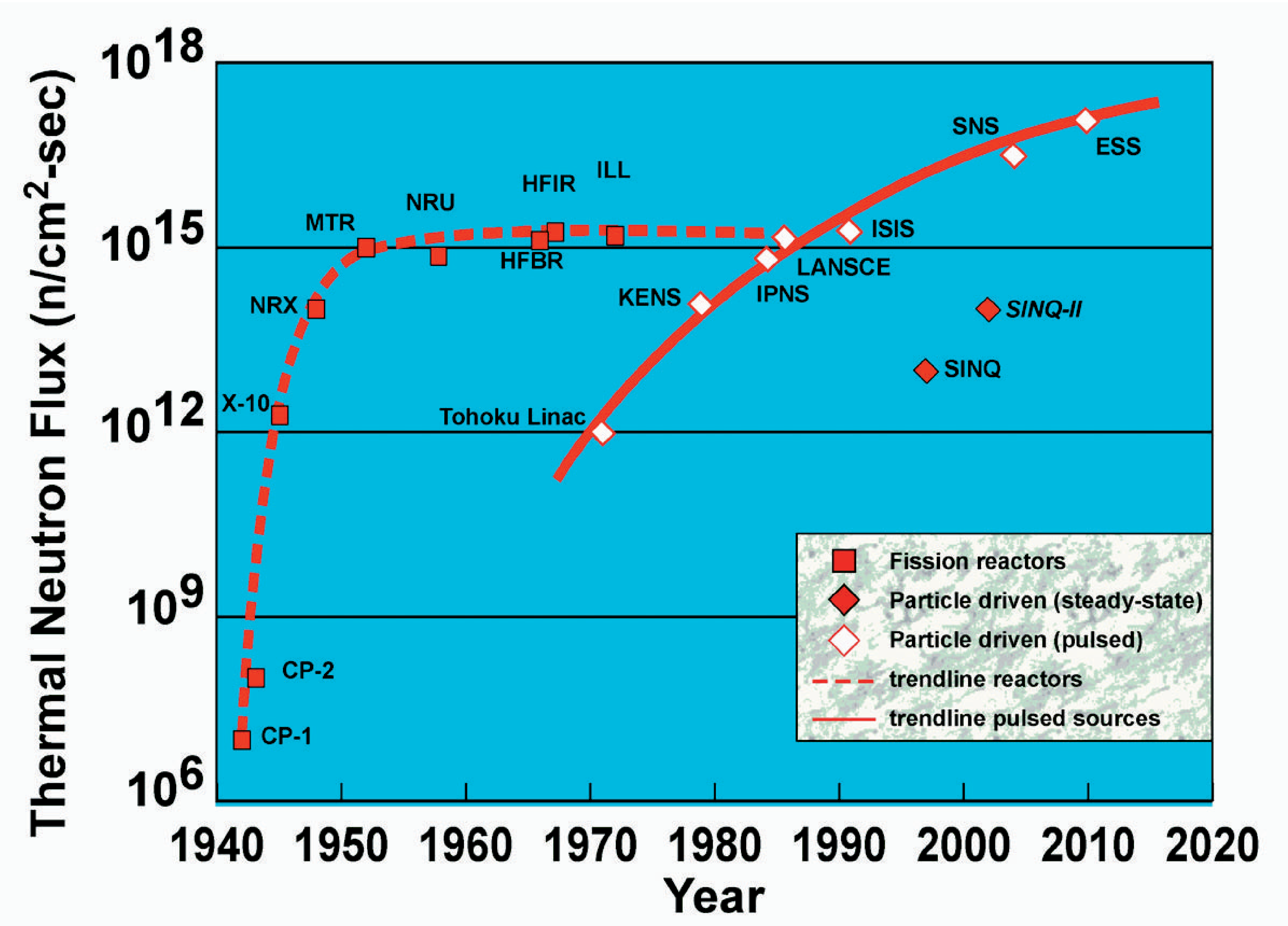
Harwell electron linear accelerator neutron source, 90 kW

~1 km

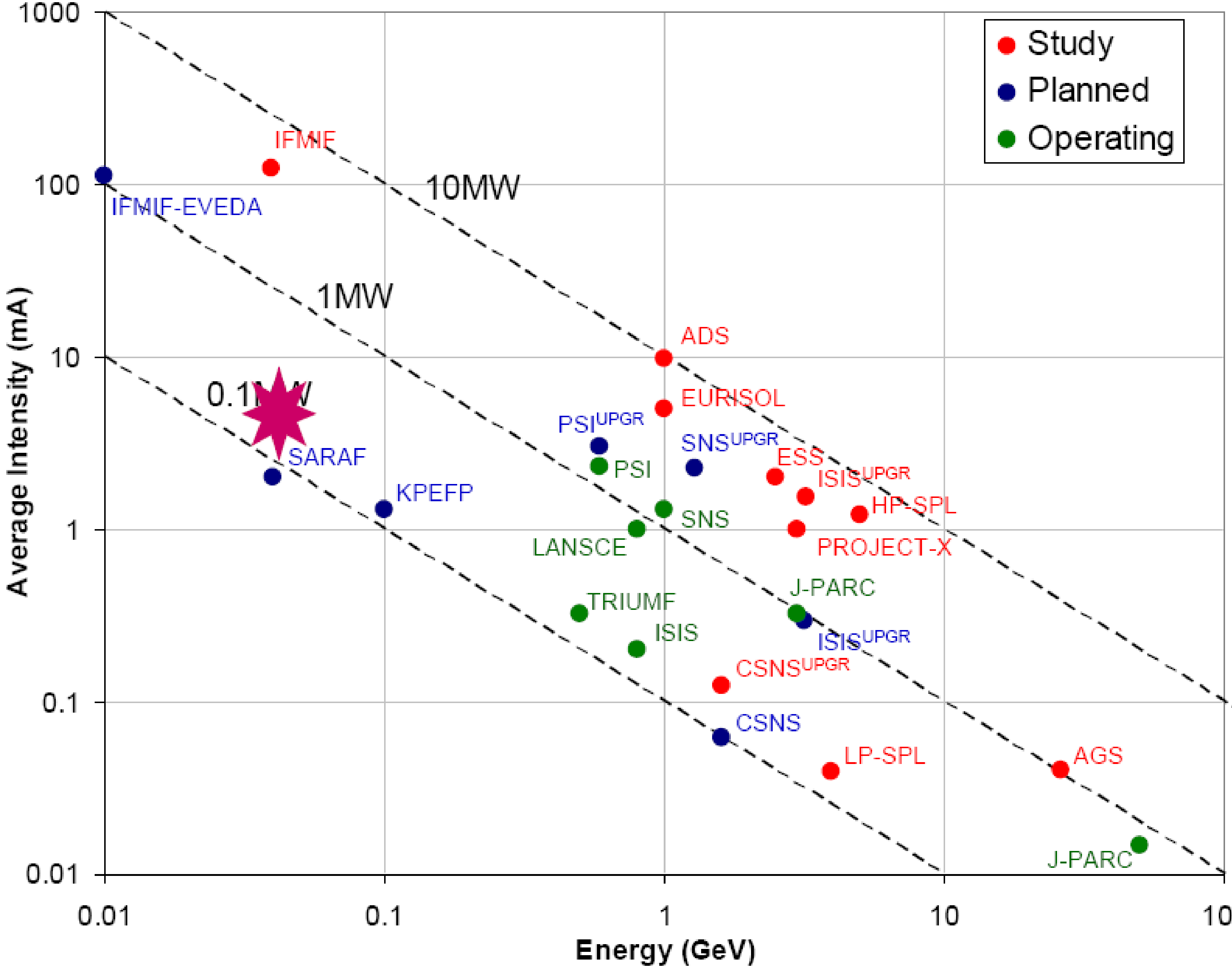
SNS spallation neutron source, Oak Ridge, 1 MW



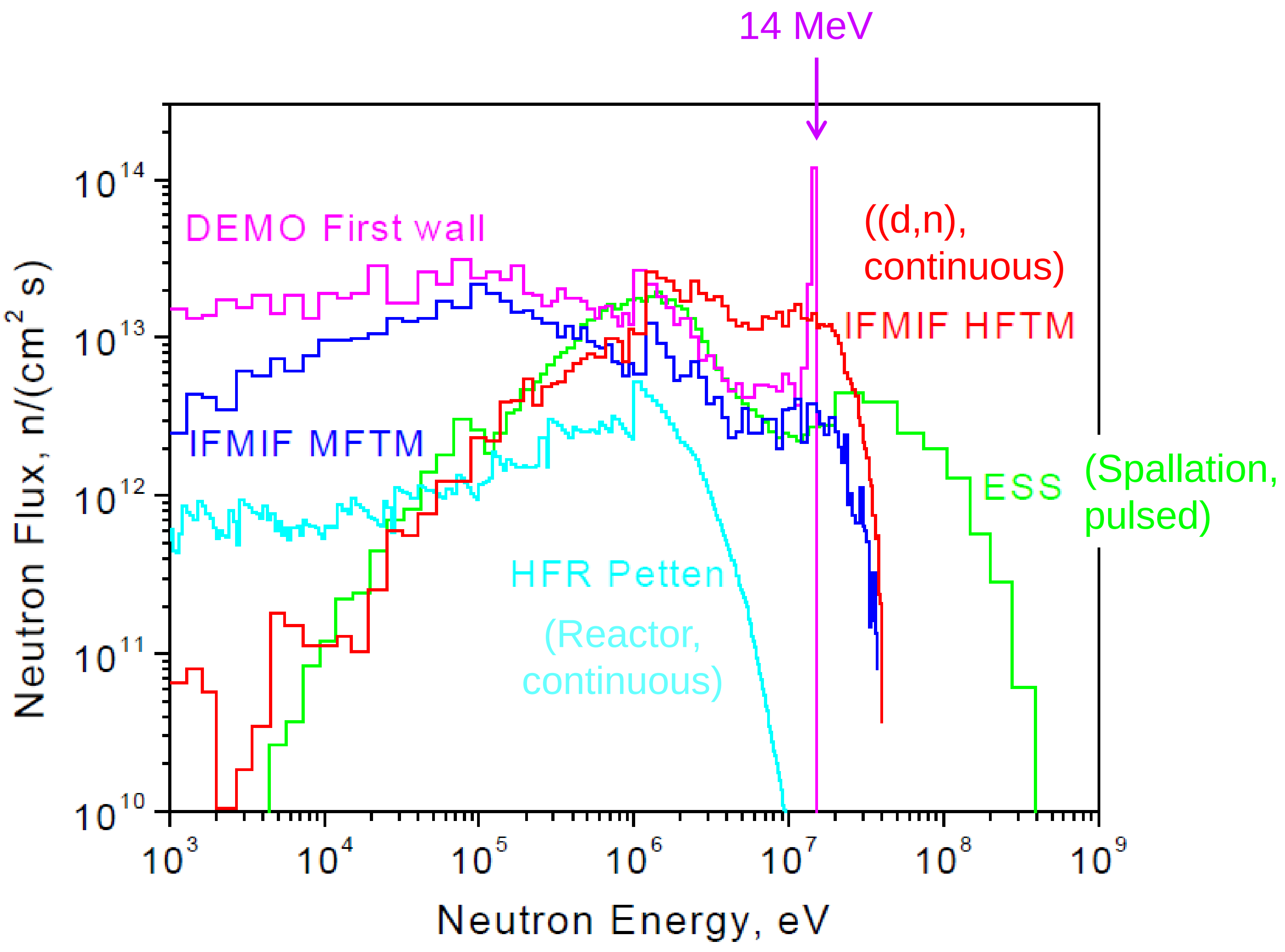
Neutron output $\propto$ size ^{2}



Thermal Neutron Flux (n/cm^2-sec)
10^{18}
10^{15}
10^{12}
10^{9}
10^{6}
1940
1950
1960
1970
1980
1990
2000
2010
2020
Year
CP-1
CP-2
X-10
NRX
MTR
NRU
HFIR
ILL
HFBR
Tohoku Linac
KENS
IPNS
LANSCE
ISIS
SNS
ESS
SINQ-II
SINQ
Fission reactors
Particle driven (steady-state)
Particle driven (pulsed)
trendline reactors
trendline pulsed sources



Study
Planned
Operating
10MW
1MW
0.1MW
IFMIF
IFMIF-EVEDA
ADS
EURISOL
PSIUPGR
SNSUPGR
ESS
ISISUPGR
HP-SPL
PROJECT-X
SARAF
KPEFP
PSI
SNS
LANSCE
TRIUMF
ISIS
J-PARC
ISISUPGR
CSNSUPGR
CSNS
LP-SPL
AGS
J-PARC
Average Intensity (mA)
Energy (GeV)
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
100



14 MeV
DEMO First wall
((d,n),
continuous)
IFMIF HFTM
IFMIF MFTM
ESS
(Spallation,
pulsed)
HFR Petten
(Reactor,
continuous)
Neutron Flux, n/(cm² s)
Neutron Energy, eV
10¹⁰
10¹¹
10¹²
10¹³
10¹⁴
10³
10⁴
10⁵
10⁶
10⁷
10⁸
10⁹

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Accelerator production of neutrons — some challenges

Neutron factories — not accelerator R&D projects

Not

Machine parameters	
Mean radius (3 × ISIS)	78.0 m
Repetition frequency	50 Hz
Injection energy from ISIS	0.8 GeV
Extraction energy (option of 8 GeV)	3 GeV
Number of circulating protons	3.75×10^{13}
Ring acceptance	304 π mm mrad
Magnet lattice type	racetrack
Number of ring superperiods	2
Number of 3-cell periods per arc	5
Number of arc cells	2 × 15
Number of straight section cells	2 × 7
Number of main B dipoles	2 × 10
Number of secondary b dipoles	2 × 5
Number of main D quadrupoles	2 × 22
Number of trim d quadrupoles	2 × 12
Number of main F quadrupoles	2 × 22
Number of trim f quadrupoles	2 × 12
Gamma transition	13.8
Horizontal betatron tune	11.7
Vertical betatron tune	7.4
Bending angle for B dipoles	16.5°
Bending angle for b dipoles	3.0°
Bending angle for 3-cell arc periods	36.0°
Length of main B dipoles	5.940 m
Length of secondary b dipoles	1.080 m
Length of main D quadrupoles	1.036 m
Length of main F quadrupoles	1.200 m
Length of trim quadrupoles	0.200 m
RMS unnorm. injection trans. emittance	19 π mm mrad
100% unnorm. injection trans. emittance	125 π mm mrad
100% unnorm. 3 GeV trans. emittance	50 π mm mrad
100% unnorm. 8 GeV trans. emittance	25 π mm mrad
100% norm. longitudinal emittance	<1.0 eV sec

but Reliability

Output

Accelerator operations

Beam losses

Induction of radioactivity in machine

Hands-on maintenance — usually ~few mSv/year limit

Typical beam loss criterion ~1 W/m — challenging with MW

Knowledge of haloes very important in high-power machines

→ beam dynamics critical

Example — ISIS (0.2 MW)

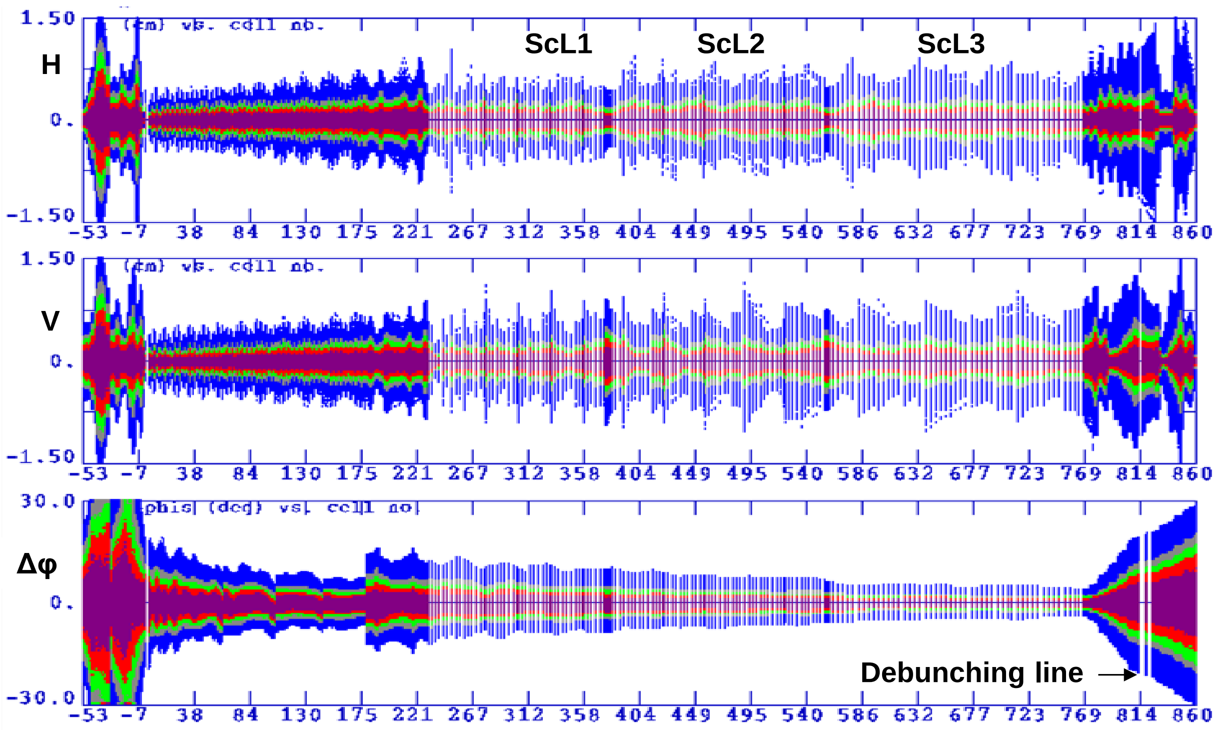
~0.3–1.0 kW lost at injection into 163-m-circumfer. synchrotron
→ ~3 W/m

But some people clock up 2–3 mSv/year

If beam losses inevitable, lose beam in one place, *e.g.* on collimators

Accelerator operations must be integrated into design process
— retro-fitting is very expensive

Design is more than

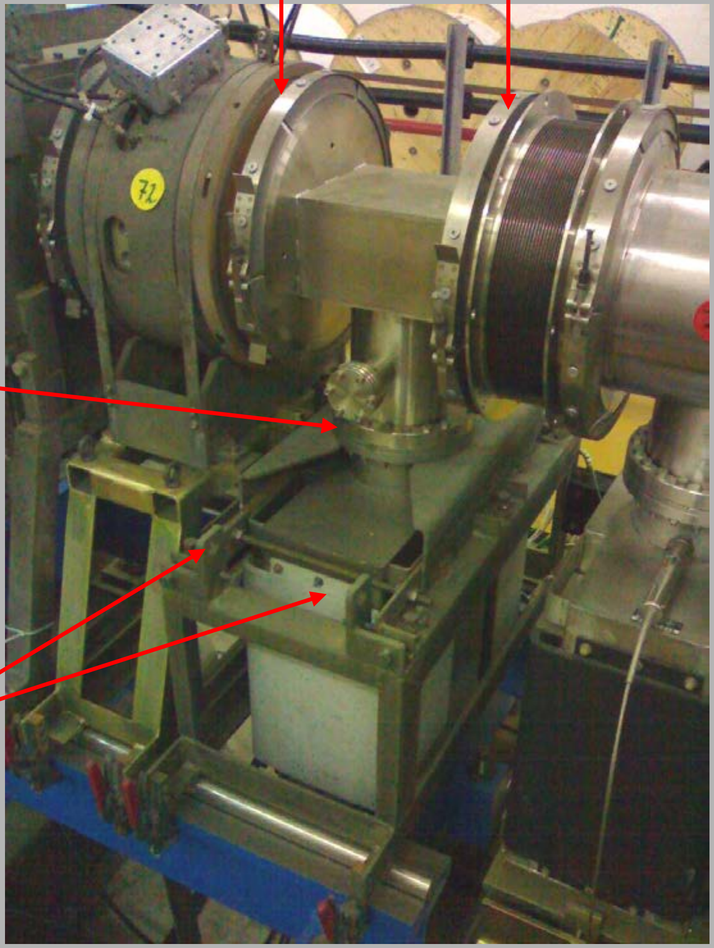


E.g. designing for maintenance → "time, distance, shielding"

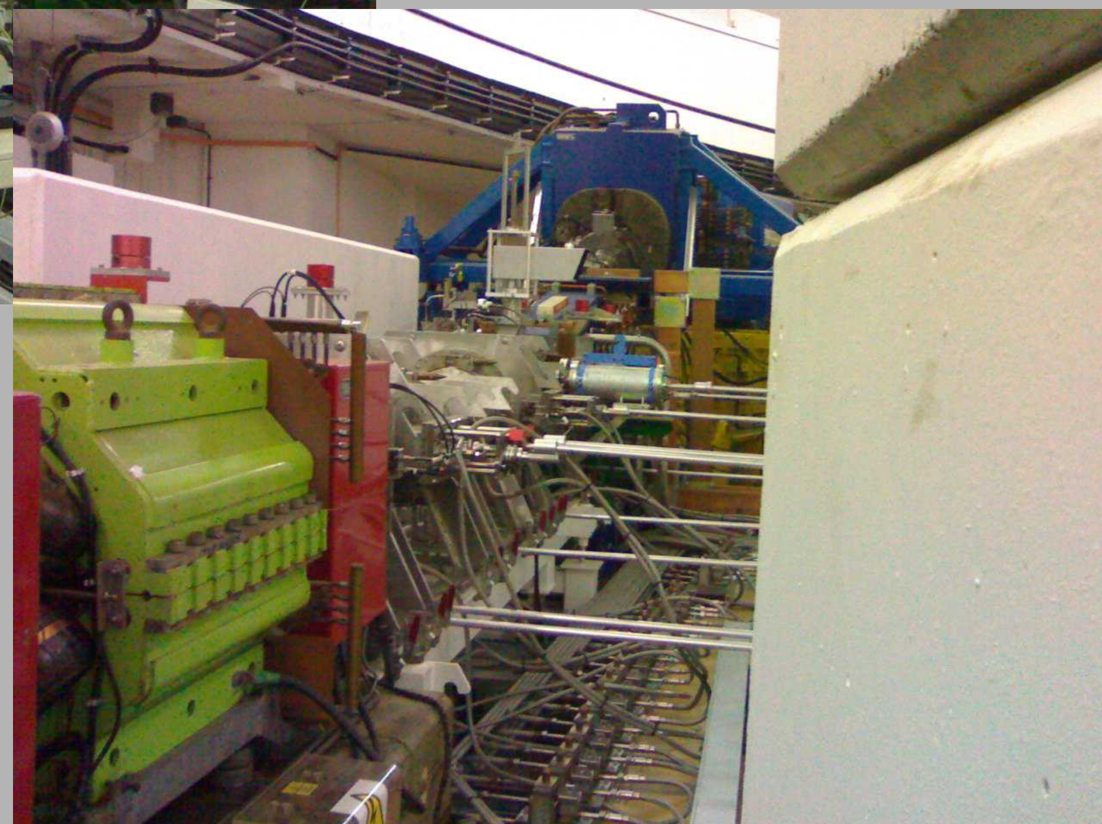
V-band vacuum seals

Conflat seals

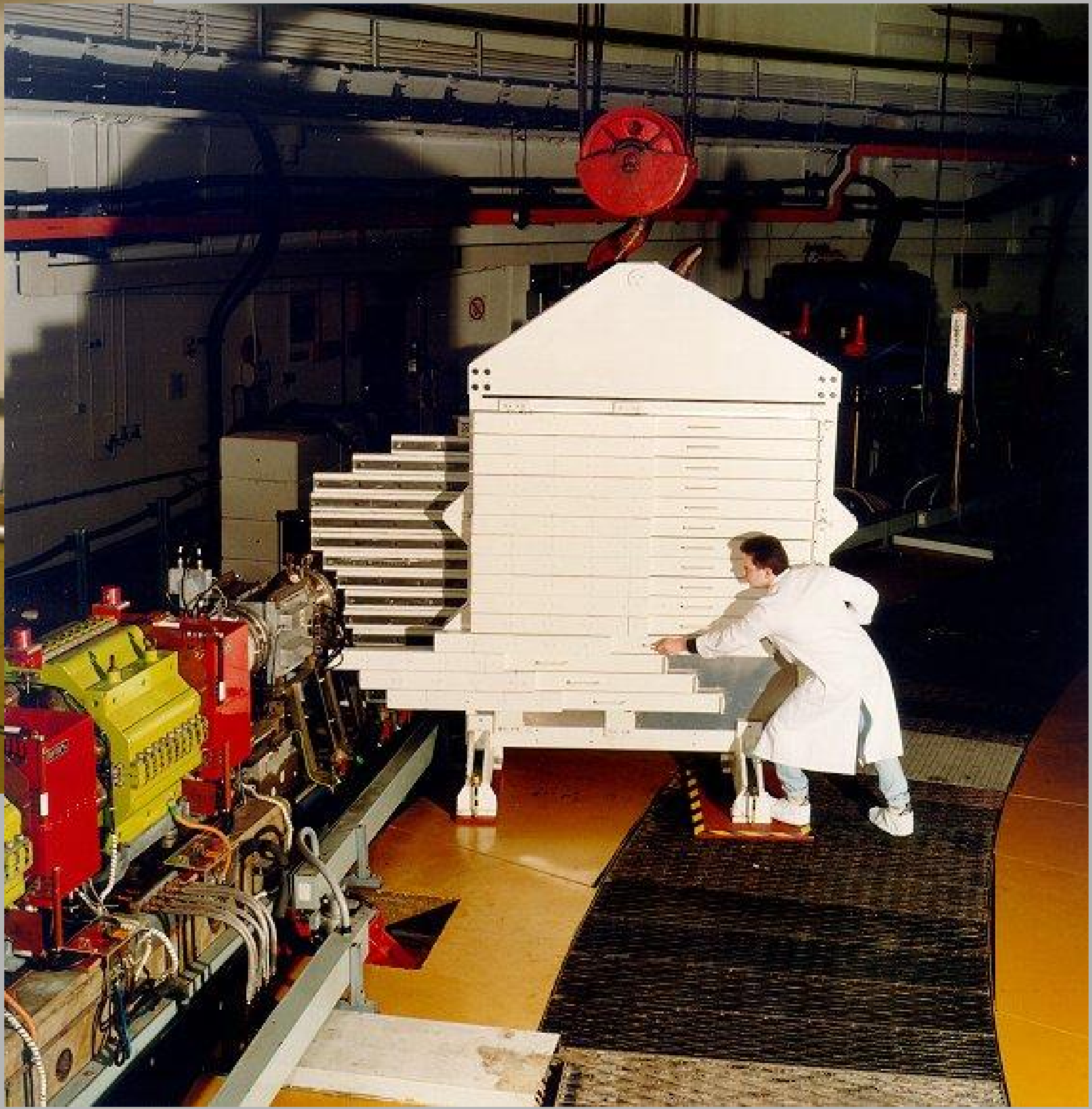
Lifting lugs



Time



Distance



Configurable shielding

ISIS synchrotron room — originally built for Nimrod

Ample space essential for repairs, exchange of large components, etc.

Nimrod sector

Space

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FAFNIR (FAcility for Fusion Neutron Irradiation Research)

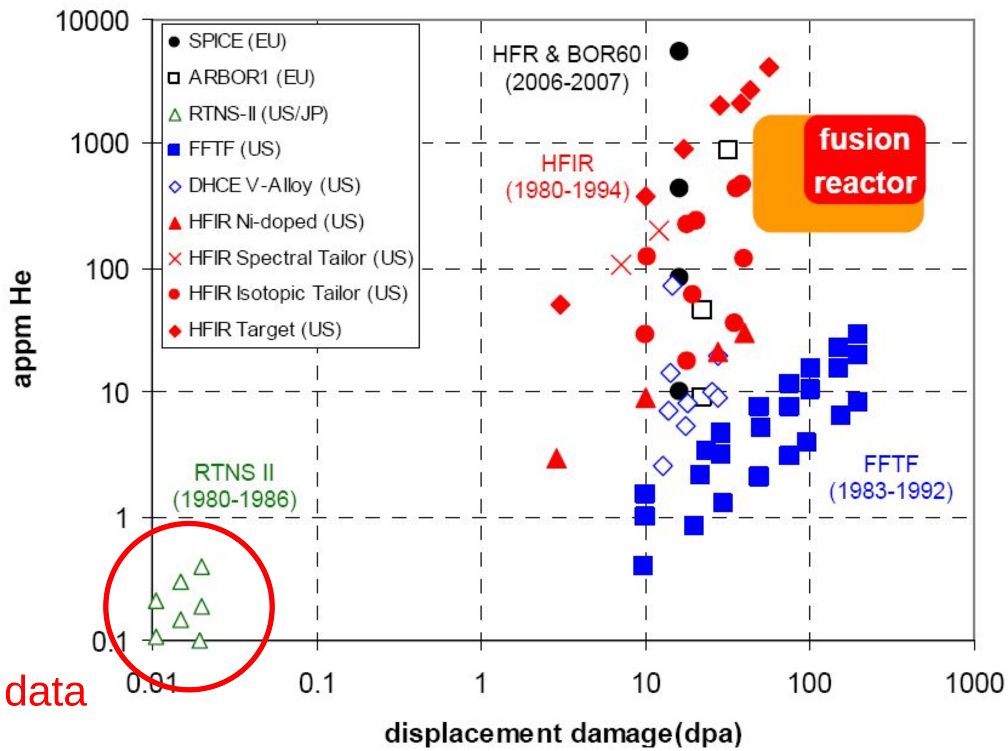
Neutron source for materials damage tests for fusion reactors
- 14 MeV neutrons from deuterium-tritium
- $d + {}^3H \rightarrow {}^4He + n + 17.6$ MeV

Poor database of radiation damage effects by 14 MeV neutrons

FAFNIR

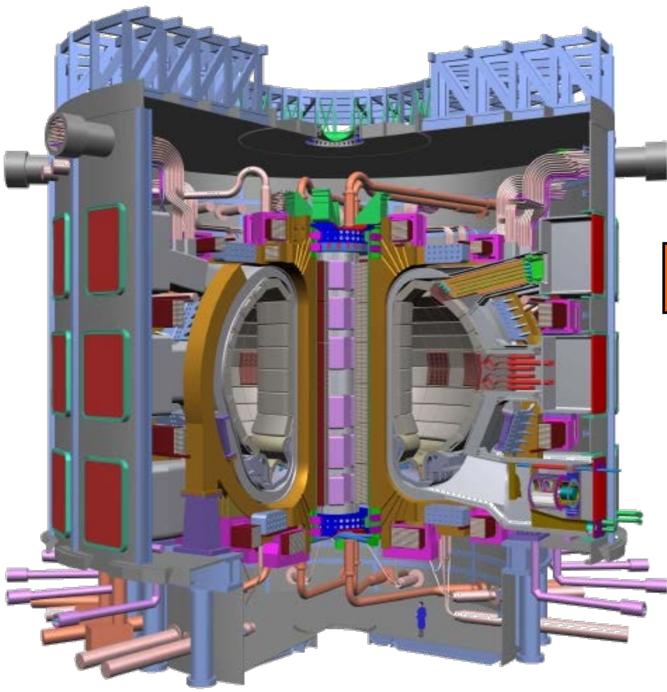
40 MeV deuteron linac
~ 3–30 mA CW
~ 100 kW – 1 MW
Rotating carbon target
C(d,n) reaction
14-MeV-like spectrum

Can be built relatively easily

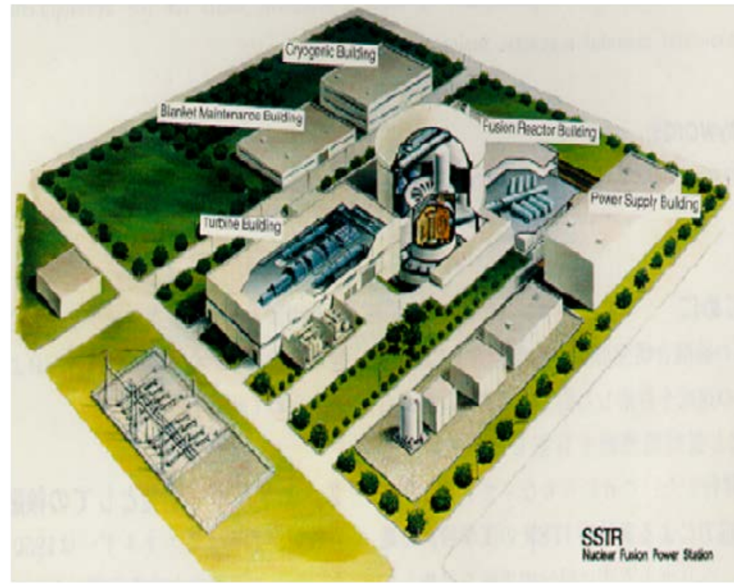


Only true 14 MeV data

ITER (~now)



DEMO Power Plant (2030–40)



Commercial utilisation

- Long-burn
  $Q \geq 10$ 300 ~ 500 sec
  $Q \sim 5$ Steady State
- Integration of fusion technology

Advanced Tokamak Research

Materials Development & IFMIF

- Electric Power Generation
  ex. $Q = 30 \sim 50$
  Steady State

IFMIF (International Fusion Materials Irradiation Facility)

Designed as ideal machine for 14 MeV radiation damage studies

2 × 5 MW 40 MeV deuterium beams

Liquid Li target

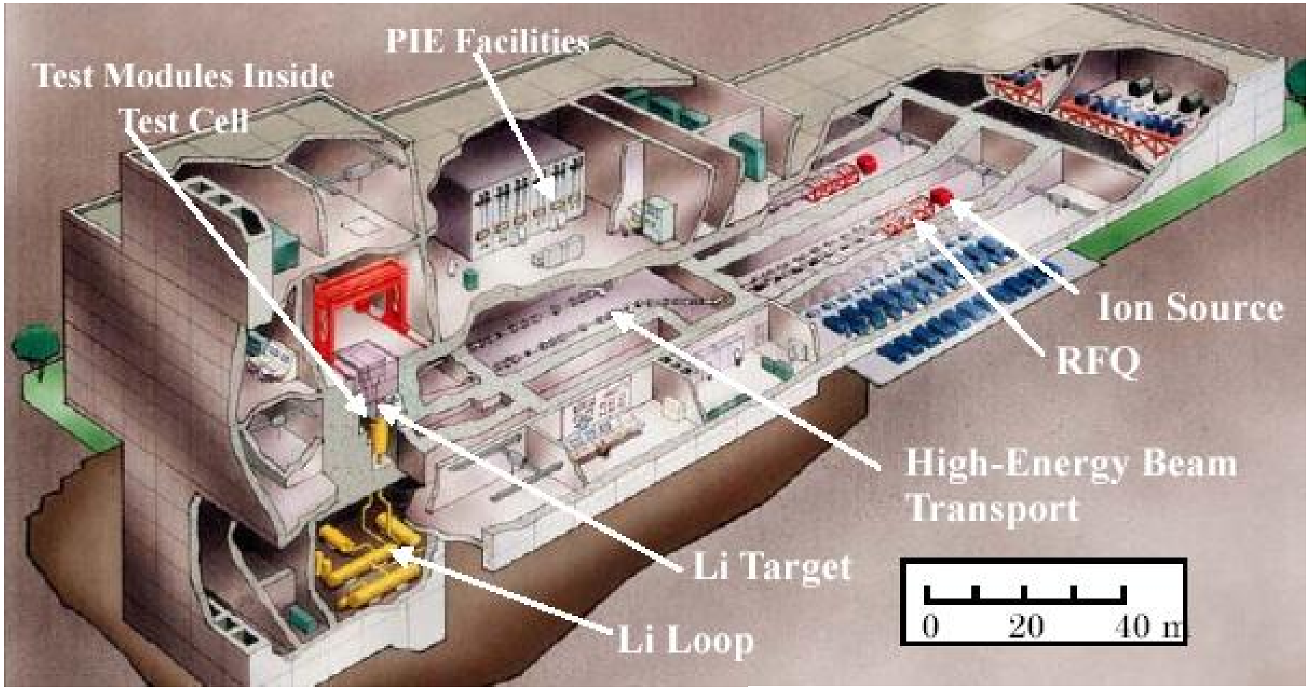
But both accelerator and target challenging

long time scales

politically difficult

Relaxed test requirements, improved interpretation of data, …

→ can relax machine requirements



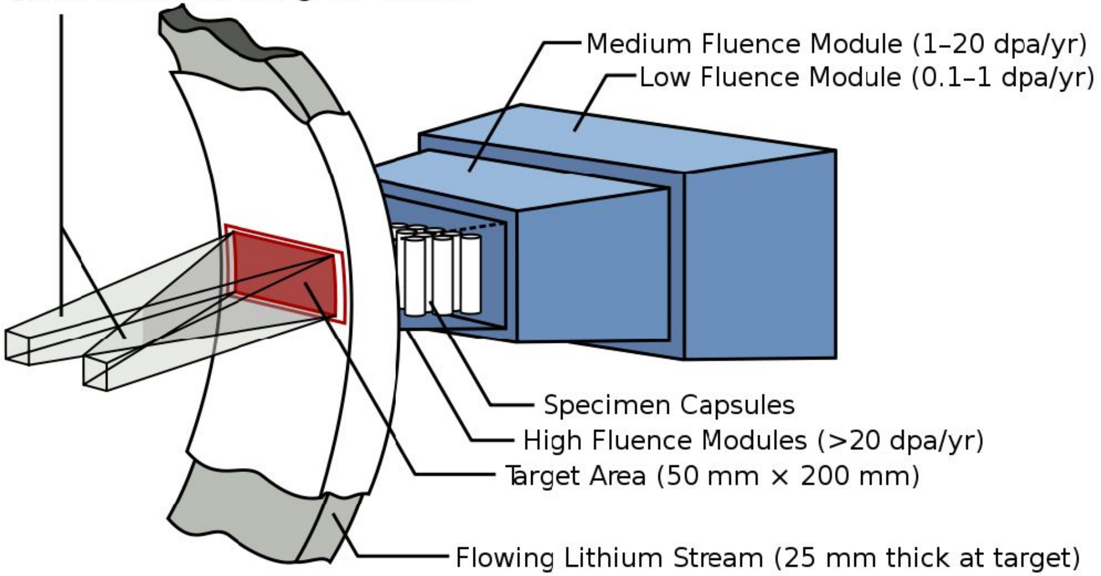
IFMIF

(International Fusion Materials Irradiation Facility)

~40 kW/cm³

Vacuum coupling to accelerator

Beam profile on target critical



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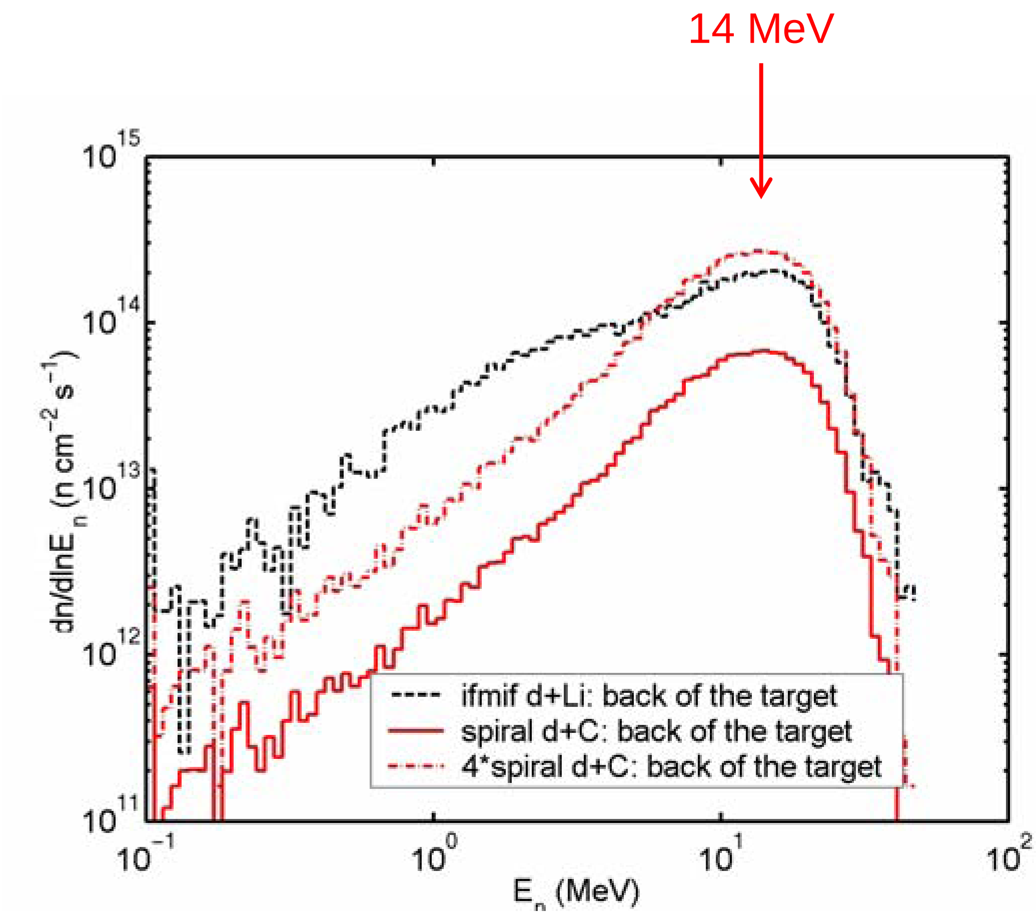

40 MeV deuterons on lithium (IFMIF) and carbon (FAFNIR)

FAFNIR — being promoted by CCFE (Culham)

40 MeV D+ on C target, 3 – 30 mA mean beam current
→ CW machine

40 MeV? Cyclotron, FFAG, RFQ + linac

Cyclotron	Well-established technology, but current too low
FFAG	Immature, decades from "factory" use, if ever
RFQ + linac	Only practical choice

Other considerations

- Superconducting? Adds complications (*e.g.* engineering, He)
- Low beam losses essential — suggests big-aperture structures
- Good beam diagnostics very important — not easiest in a DTL
- Beam transport to target
- Scanning issues?

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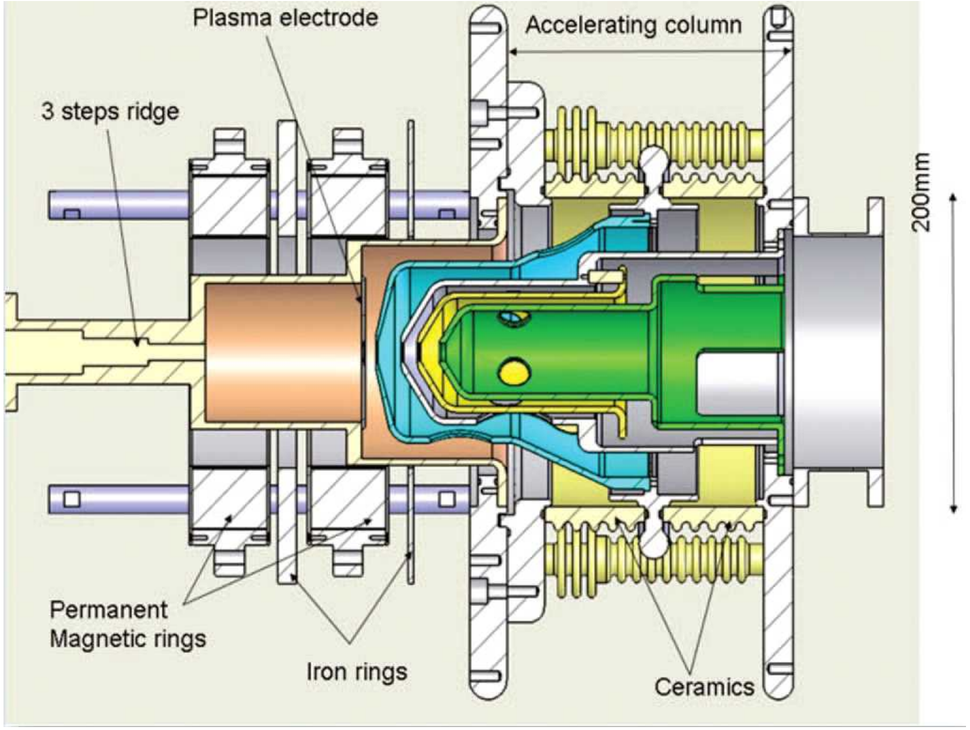
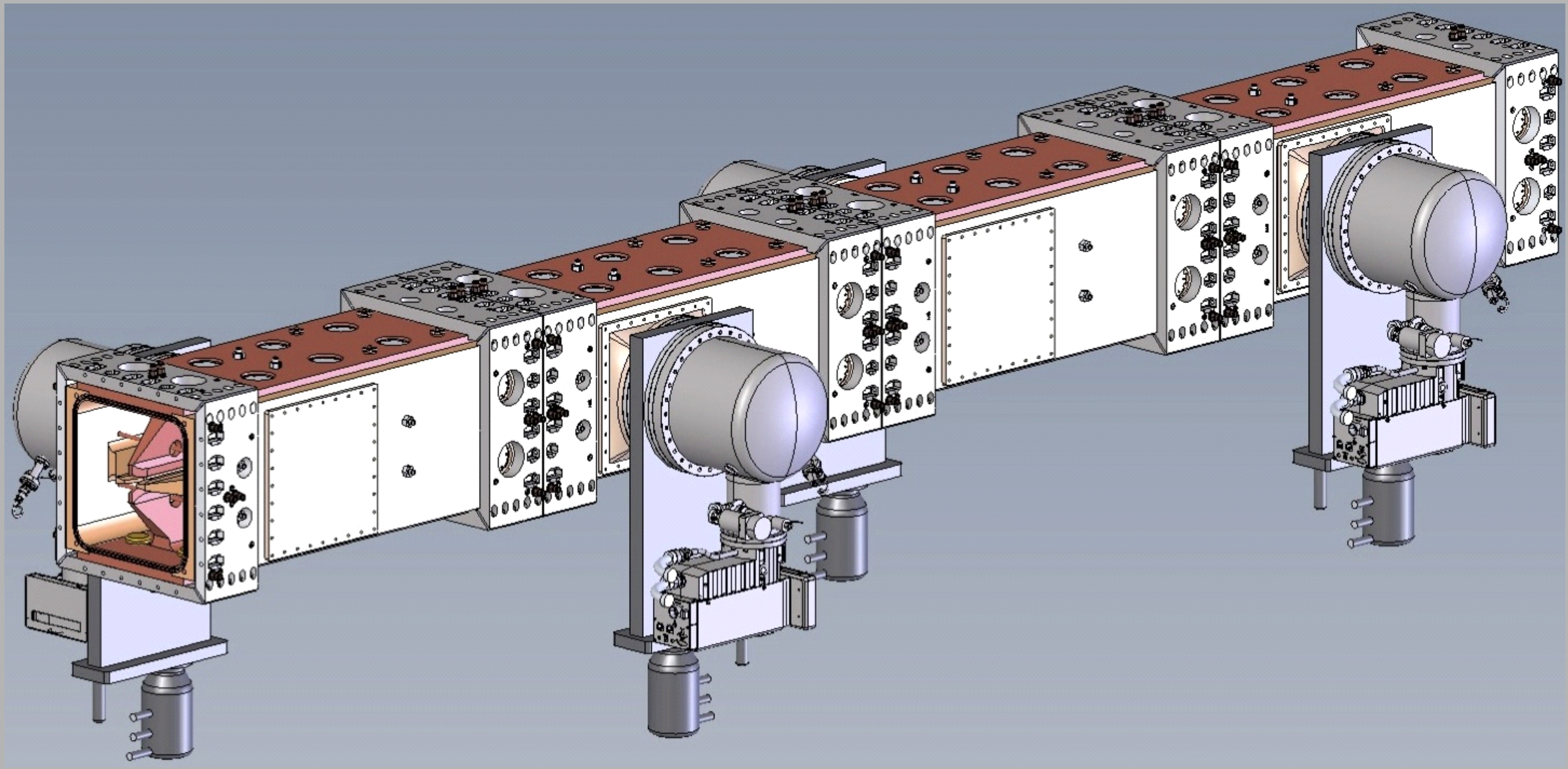
Ion source

- Base deuteron ion source on proven proton ion source
- SILHI microwave discharge source, 2.45 GHz, 1.2 kW magnetron
- 140 mA protons, CW, 0.2π mm-mrad, several months lifetime
- Deuteron ion source already demonstrated

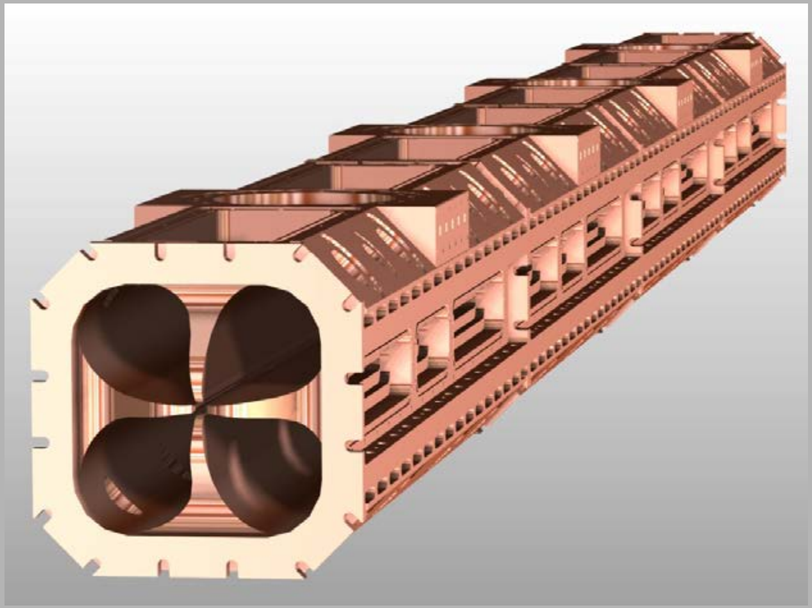


RFQ

- CW, whereas RFQs mostly pulsed hitherto
- “Normal” RFQ, but liberal water-cooling
  - *e.g.* IPHI and IFMIF CW RFQs, 120–130 kW/m heat
- “Reduced gradient” RFQ
  - *e.g.* PXIE CW RFQ, 50–60 kW/m heat
  - ~30% smaller acceleration gradient, longer structure, more conservative
  - Structure power $\propto$ accelerating field ^{2}
- For ~30 mA, match into linac at 2–3 MeV



CAD model of PXIE RFQ (FNAL)
162.5 MHz, 4.45 m long, four-vane CW structure



4-vane, 324 MHz, 60 mA, RFQ
Front End Test Stand, RAL

Linac

Beam dynamics for ~30 mA not especially challenging, but CW *is* challenging

Availability of RF sources — strong driver for frequency choice
$\rightarrow$ triodes, tetrodes — probably $\leq$200 MHz

Superconducting or normally conducting?

S/C advantages:
- reduced RF requirements
- lower operating costs
- larger structure apertures

S/C disadvantages:
- cryogenic systems
- lower maturity of cavity technology (especially at low energies)
- more challenging engineering
- increased complexity
- longer repair times

If superconducting —

Accelerating structures for ~3–40 MeV limited to half-wave and spoke resonators — but operational experience limited

Cold or warm focussing elements?

- Cold quadrupoles or solenoids enable better accelerating gradients but are considerably more complex
- Warm focussing elements lead to more cryo-modules and reduced accelerating gradients

If normally conducting —

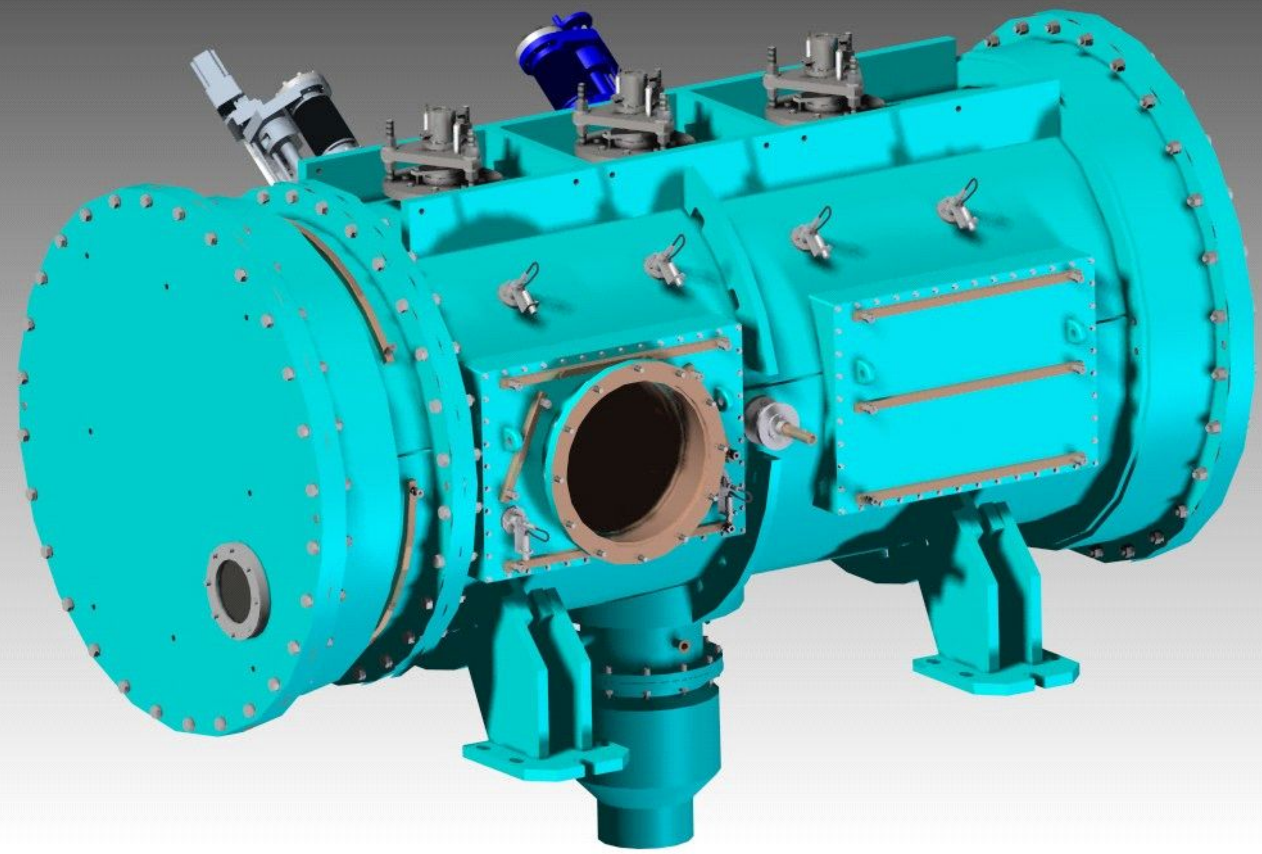
Room-temperature drift tube linac (DTL) conservative option

Usual pulsed DTL design → ~200 kW/m heat
→ difficult since heat mostly in drift tubes

But if halve usual accelerating gradient → ~50 kW/m

E.g. 10-metre-long cavity
→ ~15 MeV energy gain, ~500 kW beam power,
~500 kW structure power

Permanent or electromagnetic quadrupoles in drift tubes?
→ electromagnetic to tune for minimum beam losses



2-metre-long test section of 202.5 MHz linac tank for testing at full RF power at RAL — currently out for manufacture

High-energy beam transport (HEBT) [to target]

Nothing particularly challenging

- Focussing structure probably FODO (like recently constructed 140-metre beam line to ISIS TS-2)

Double-bend achromat to eliminate “shine back” from target to linac

Air-cooled elements wherever possible — avoids water problems

Gaussian beam profile on target not difficult — could make squarer using octupoles

Beam diagnostics

High-power low-energy beam $\rightarrow$ non-invasive diagnostics

Beam currents: DC toroidal current transformers

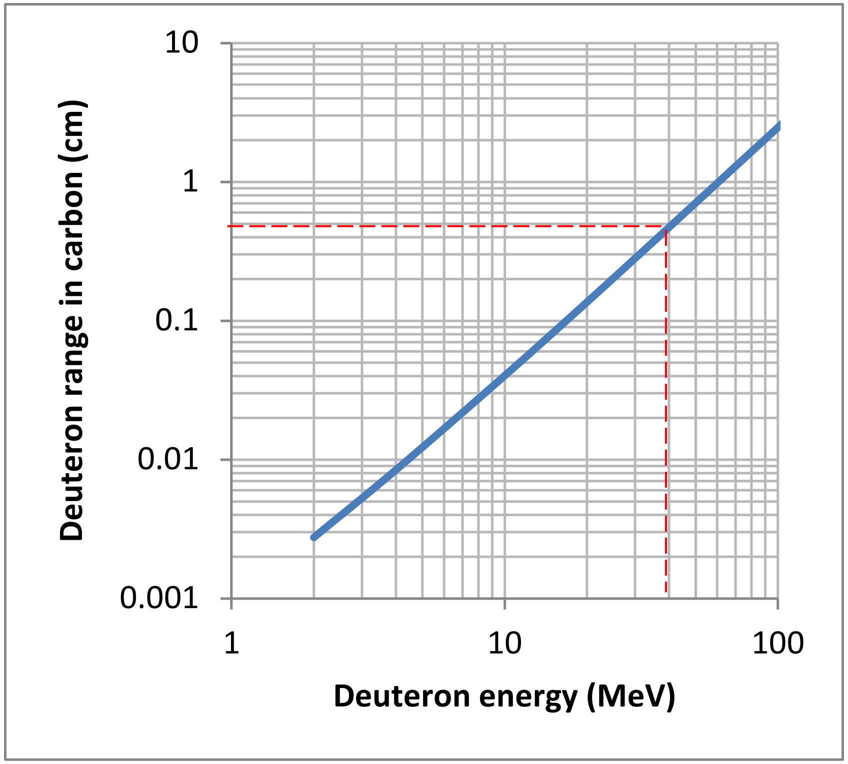
Beam positions and profiles: residual gas ionisation monitors

Beam losses: ionisation chambers, plastic scintillators

Comprehensive beam dilution system to facilitate set-up and fault diagnosis

Target (1)

Range of 40 MeV deuteron in carbon = 0.94 g/cm² → 0.5 cm



Range of deuteron = twice range of proton of half energy

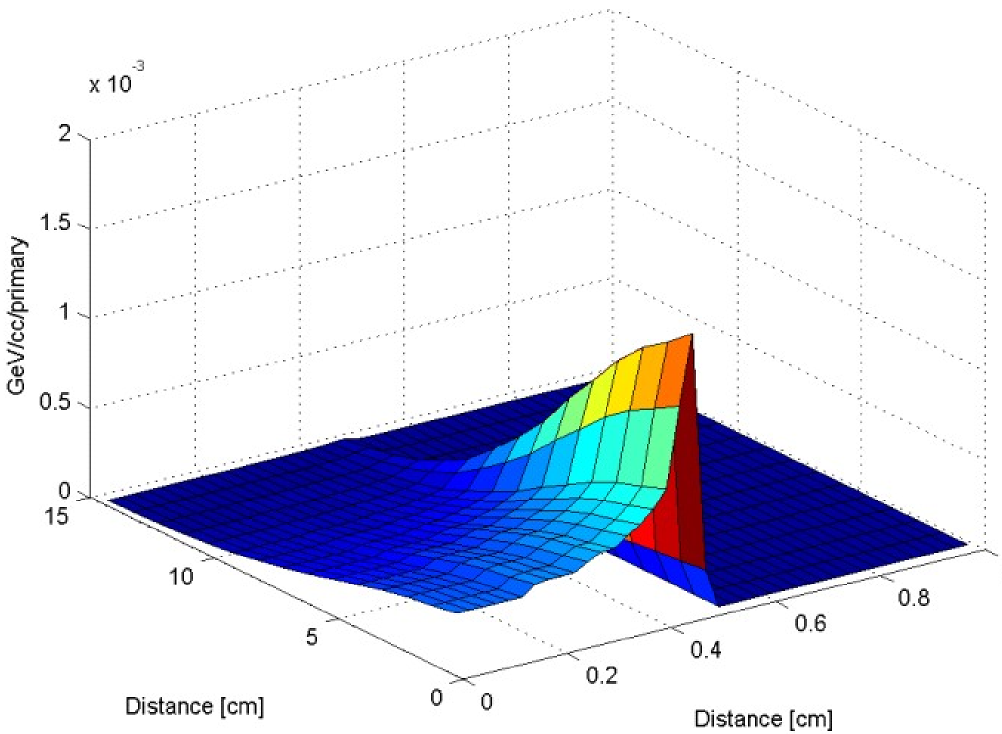
Target (2)

40 MeV D, 6 mA, 1/e-radius 14 mm (σ = 10 mm), carbon

→ ~230 kW/cm³

→ rotation essential

→ ~2000°K



σ = 10 mm, 231 kW/cm³

25 mm, 37 kW/cm³

50 mm, 9.3 kW/cm³

GeV/cm³/deuteron for σ = 50 mm

Target (3)

Single-slice rotating targets already accommodate ~100 kW (*e.g.* PSI)

→ 40 MeV, ~3 mA — starting specification

Later — multi-slice target for higher beam currents

Radiation damage / graphite strength considerations

Optimisation of irradiation geometry
numbers and sizes of samples to be irradiated
fluences required
fluxes deliverable
neutronics
thermal issues
stresses, *etc.*

Current situation

EFDA (European Fusion Development Agreement) setting up review of 14 MeV neutron sources for radiation damage measurements

Options — IFMIF-lite and FAFNIR

Awaiting conclusion of review

University of Oxford
Manchester 1824, The University of Manchester
University of Huddersfield
Imperial College London
University of Birmingham
JAI John Adams Institute for Accelerator Science
Science & Technology Facilities Council
CCFE Culham Centre for Fusion Energy

ISIS upgrades

ISIS — spallation neutron source

World-leading centre for research in the physical and life sciences
— world's most productive spallation neutron source

~30 neutron and muon instruments for properties of materials in terms of molecular structure

National and international community of >2000 scientists

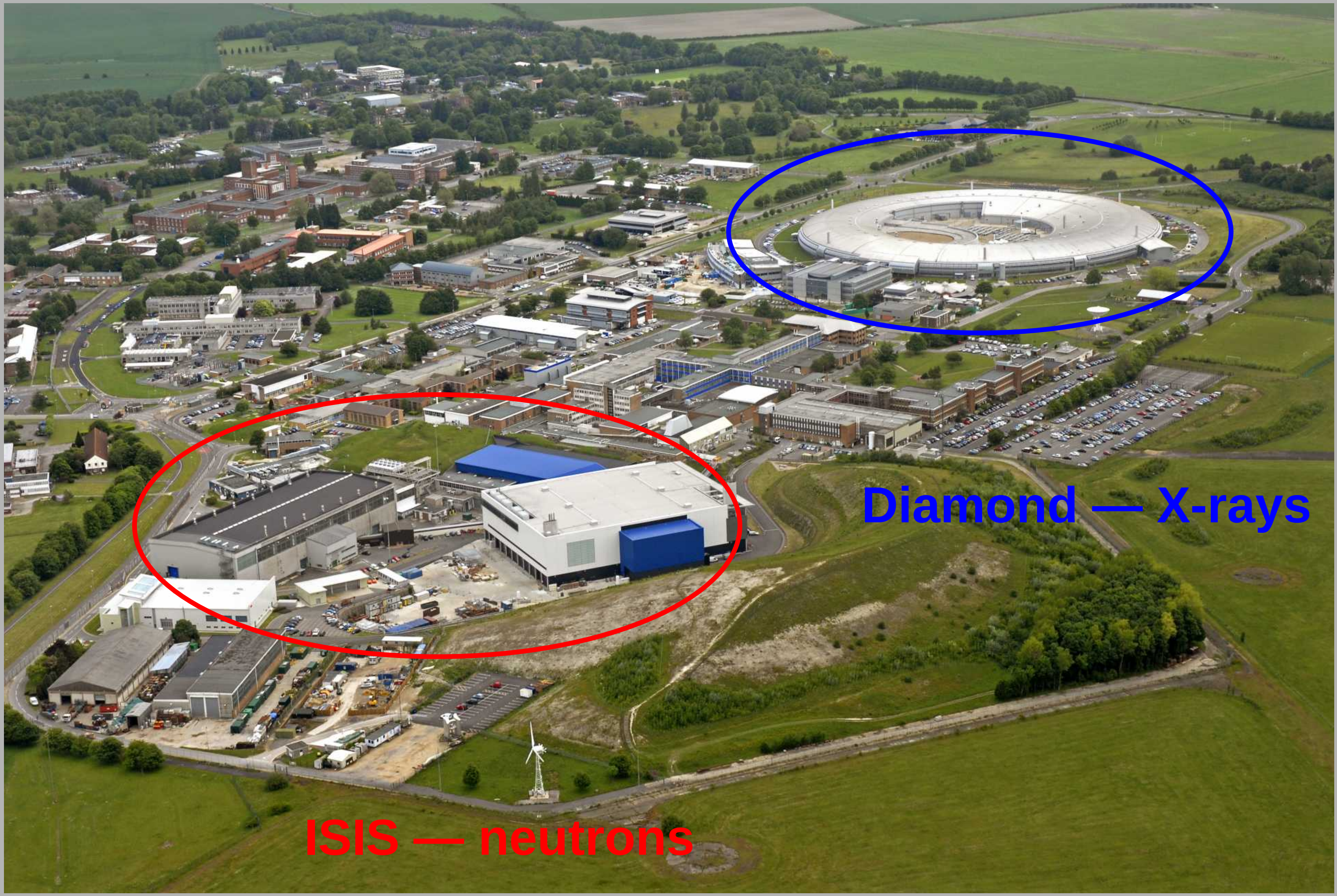
Driven by UK's high-power proton accelerators

Research fields include clean energy, environment, pharmaceuticals and health care, nanotechnology, materials engineering and IT

~450 publications/year (~10000 total over 28 years)

MICE (Muon Ionisation Cooling Experiment)

Need to plan for upgrades



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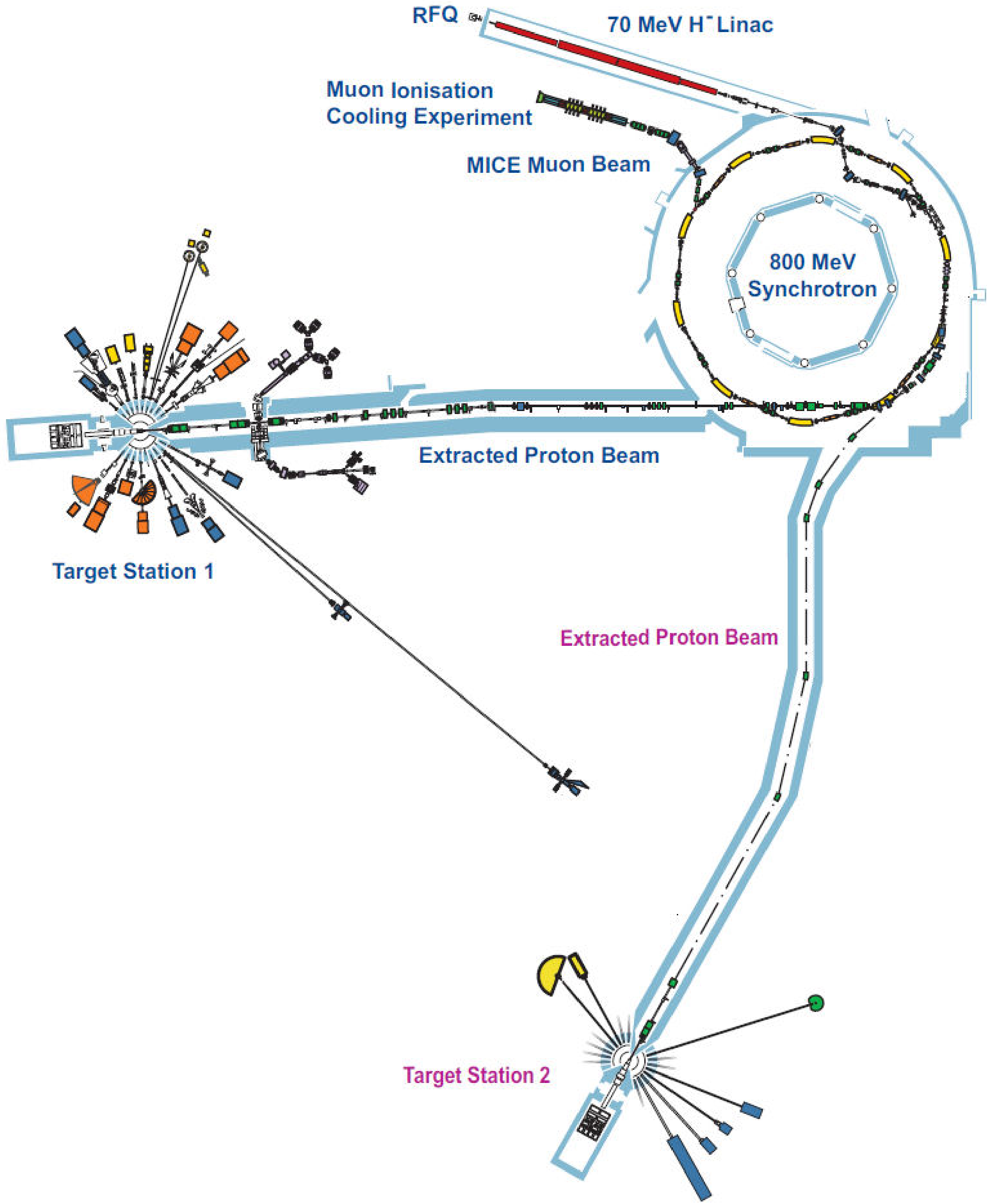
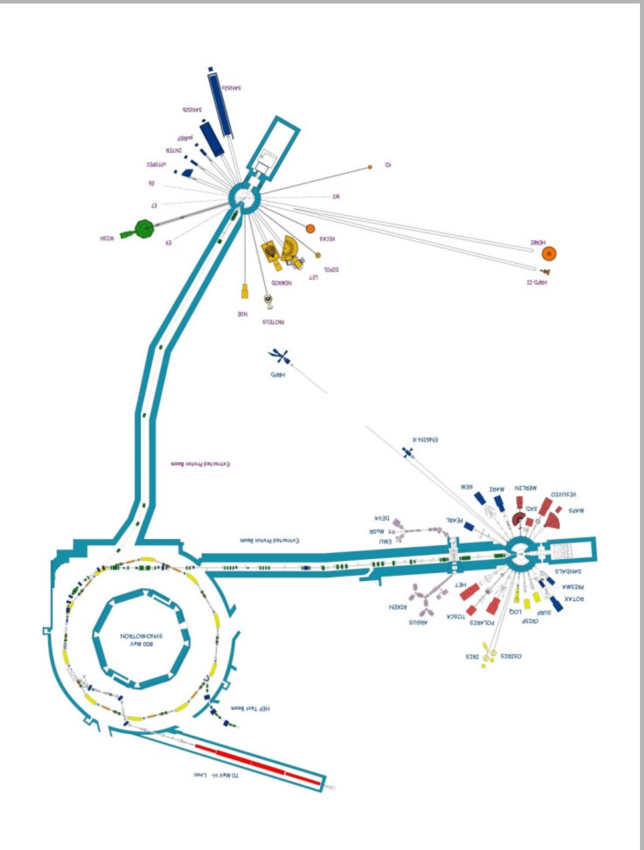


RFQ
70 MeV H⁻ Linac
Muon Ionisation
Cooling Experiment
MICE Muon Beam
800 MeV
Synchrotron
Extracted Proton Beam
Target Station 1
Extracted Proton Beam
Target Station 2

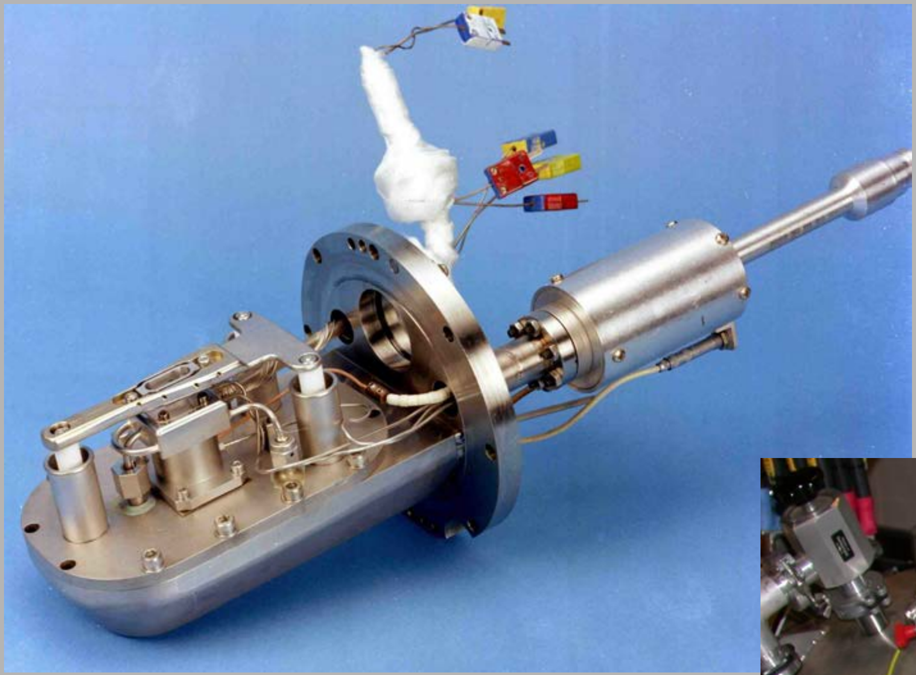


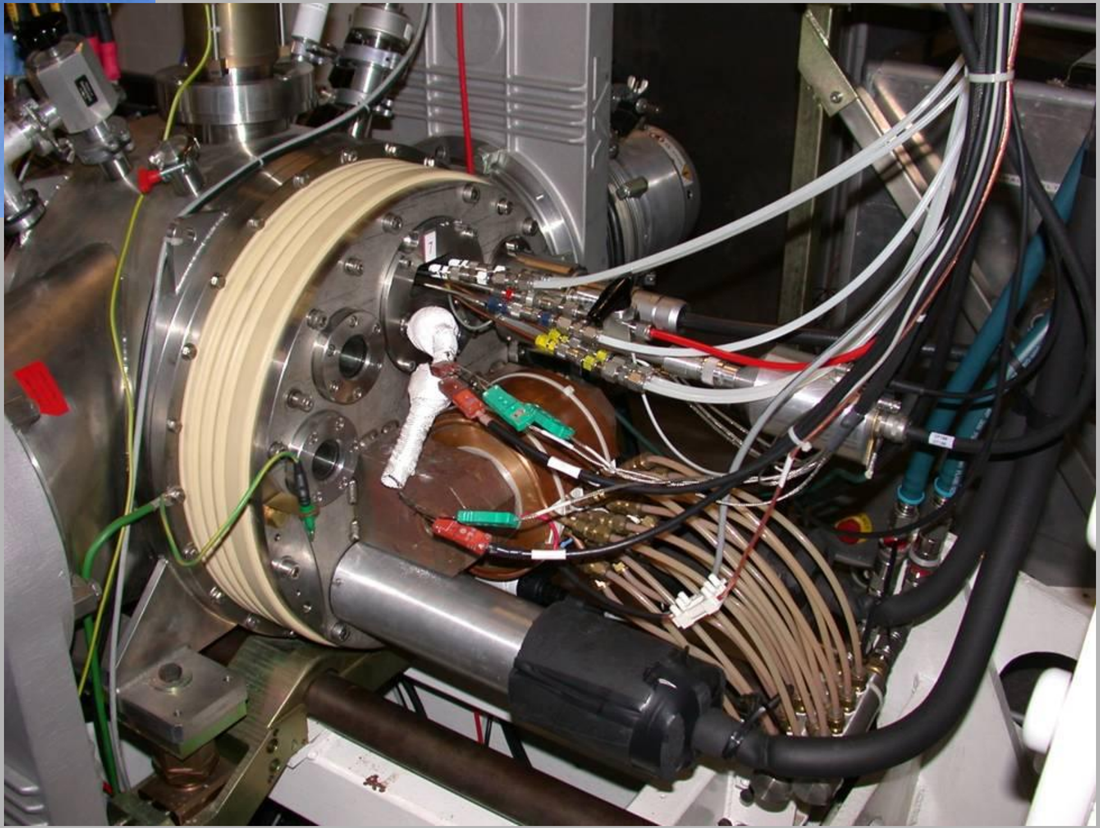
ISIS from air

RFQ: 665 keV H^-, 4-rod, 202 MHz

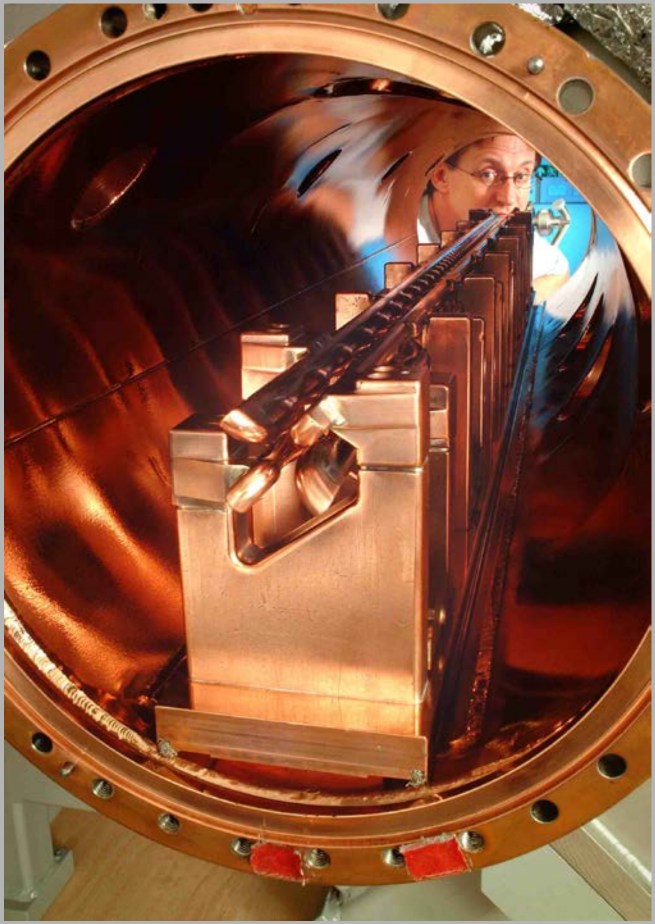
Linac: 70 MeV H^-, 25 mA, 202 MHz, 200 µs, 50 pps

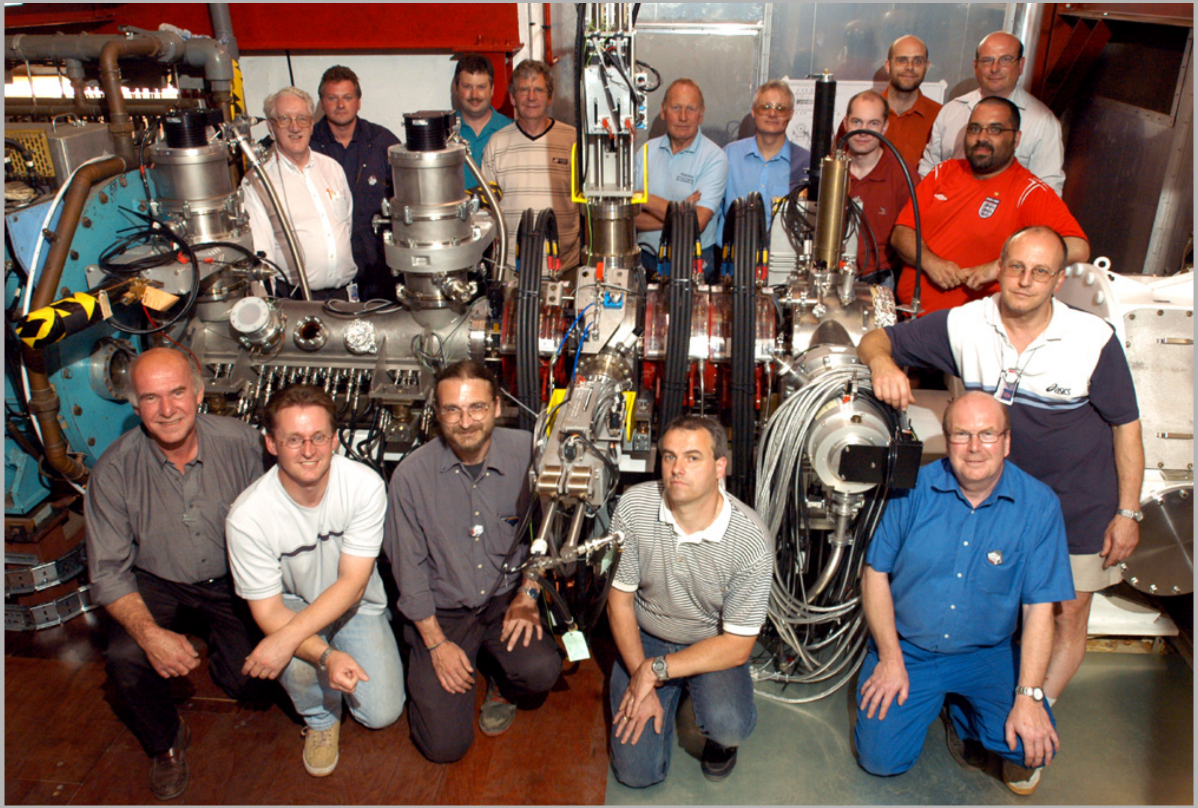
Synchrotron:	800 MeV proton, 50 Hz 5 µC each acceleration cycle Dual harmonic RF system
Targets:	2 × W (Ta coated) Protons: 2 × ~100 ns pulses, ~300 ns apart TS-1, 40 pps TS-2, 10 pps
Moderators:	TS-1: 2 × H_2O, 1 × liq. CH_4, 1 × liq. H_2 TS-2: 1 × liq. H_2 / solid CH_4, 1 × solid CH_4
Instruments:	TS-1: 20 TS-2: 7 (+ 4 more being built)





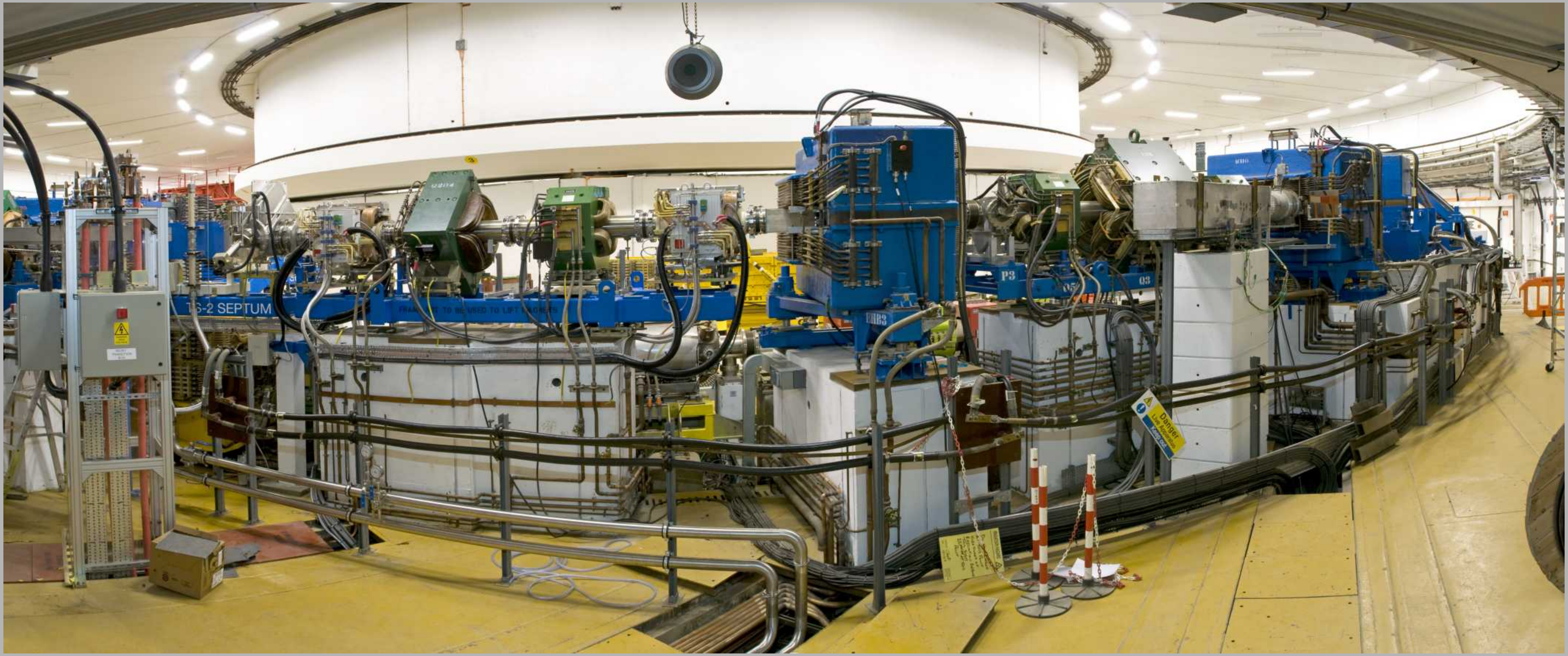
–35 kV H^{-} ion source





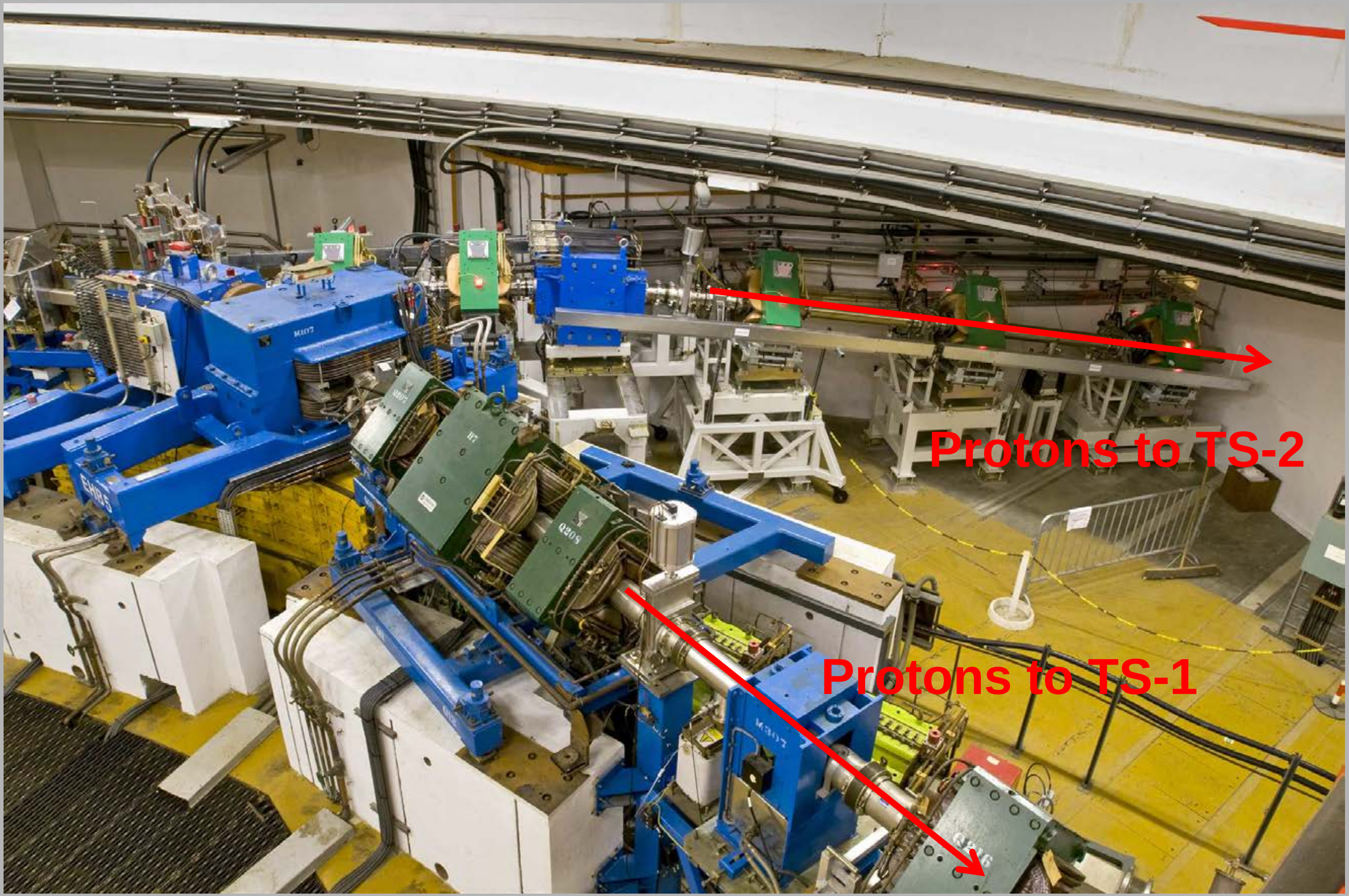
665 keV 4-rod 202 MHz RFQ


70 MeV 202 MHz 4-tank H^- linac



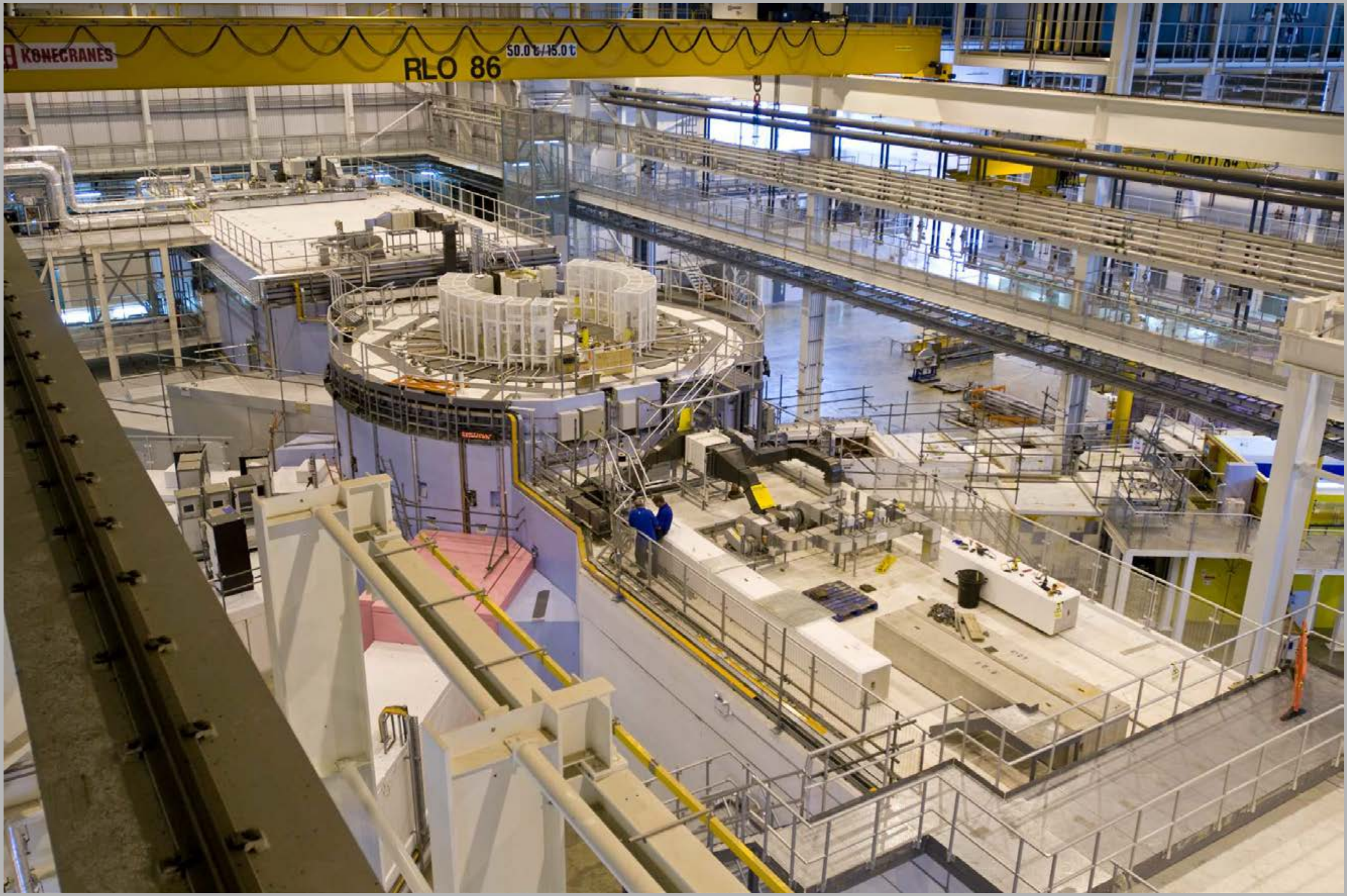
1.3–3.1 + 2.6–6.2 MHz 70–800 MeV proton synchrotron

Superperiods 9, 0 and 1 of 800 MeV proton synchrotron

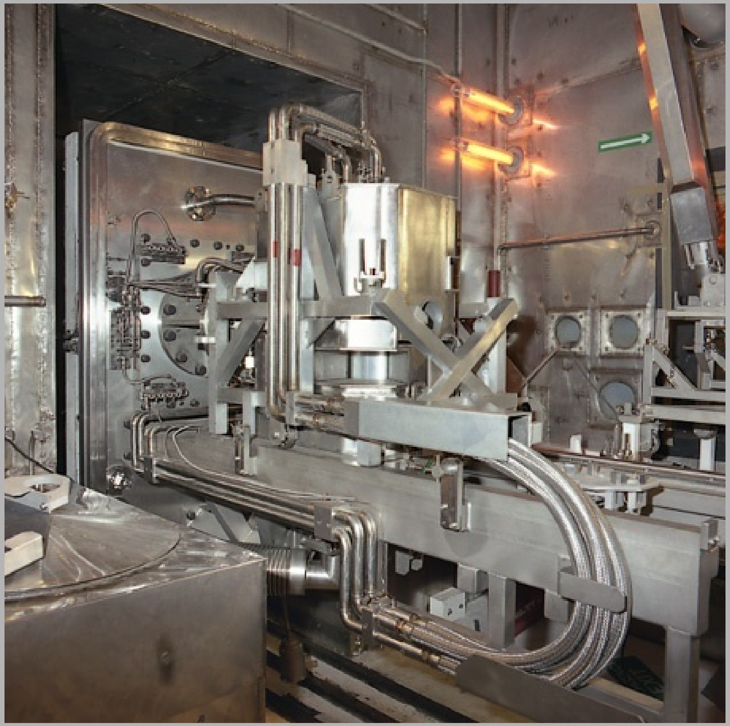


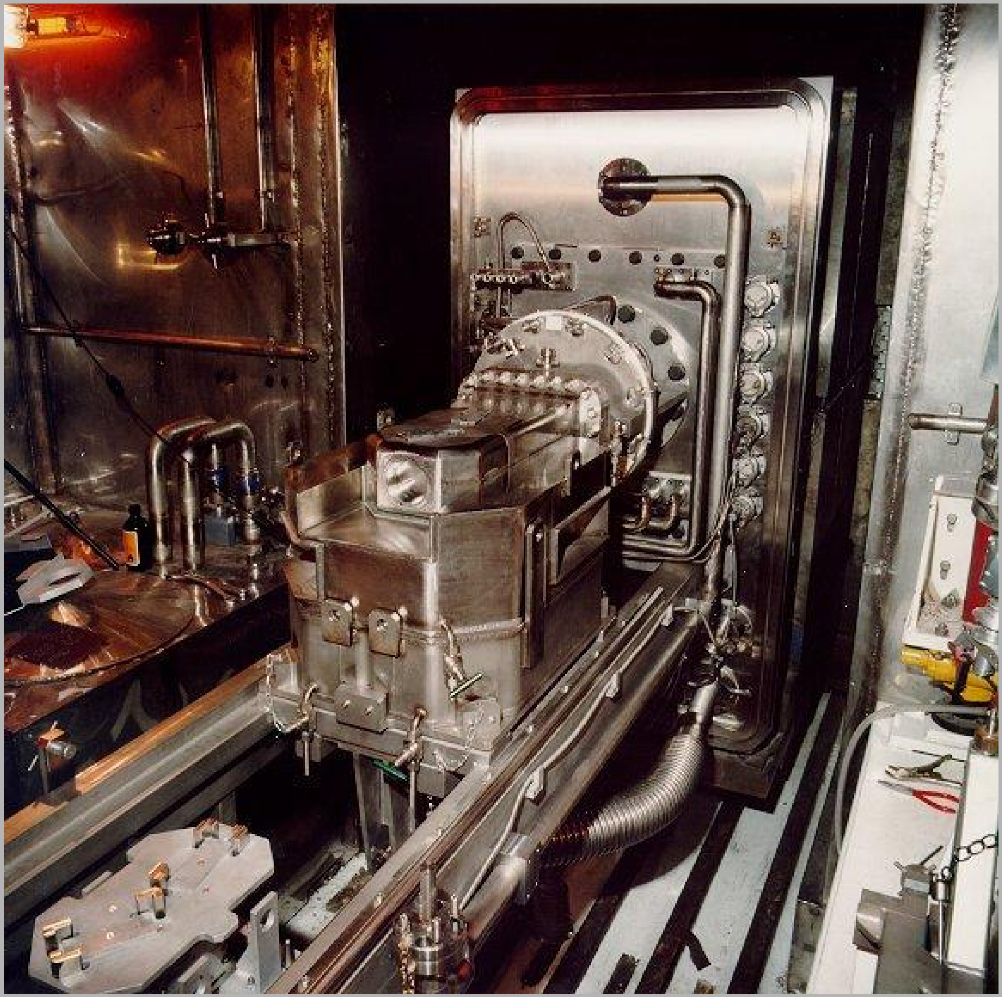
EPB1 and EPB2 to TS-1 and TS-2 above synchrotron

ISIS TS-1 experimental hall, 20 instruments

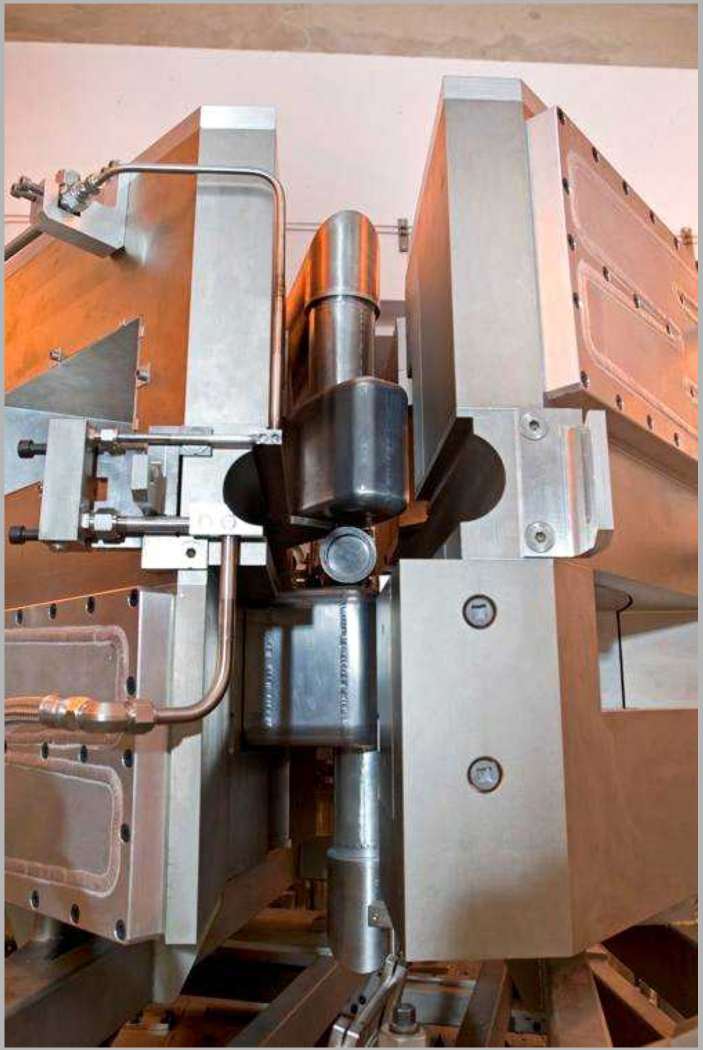


ISIS TS-2 experimental hall, 7 instruments + 4 under way





TS-1 tungsten target
(plate target)



TS-2 tungsten target (solid cylinder)

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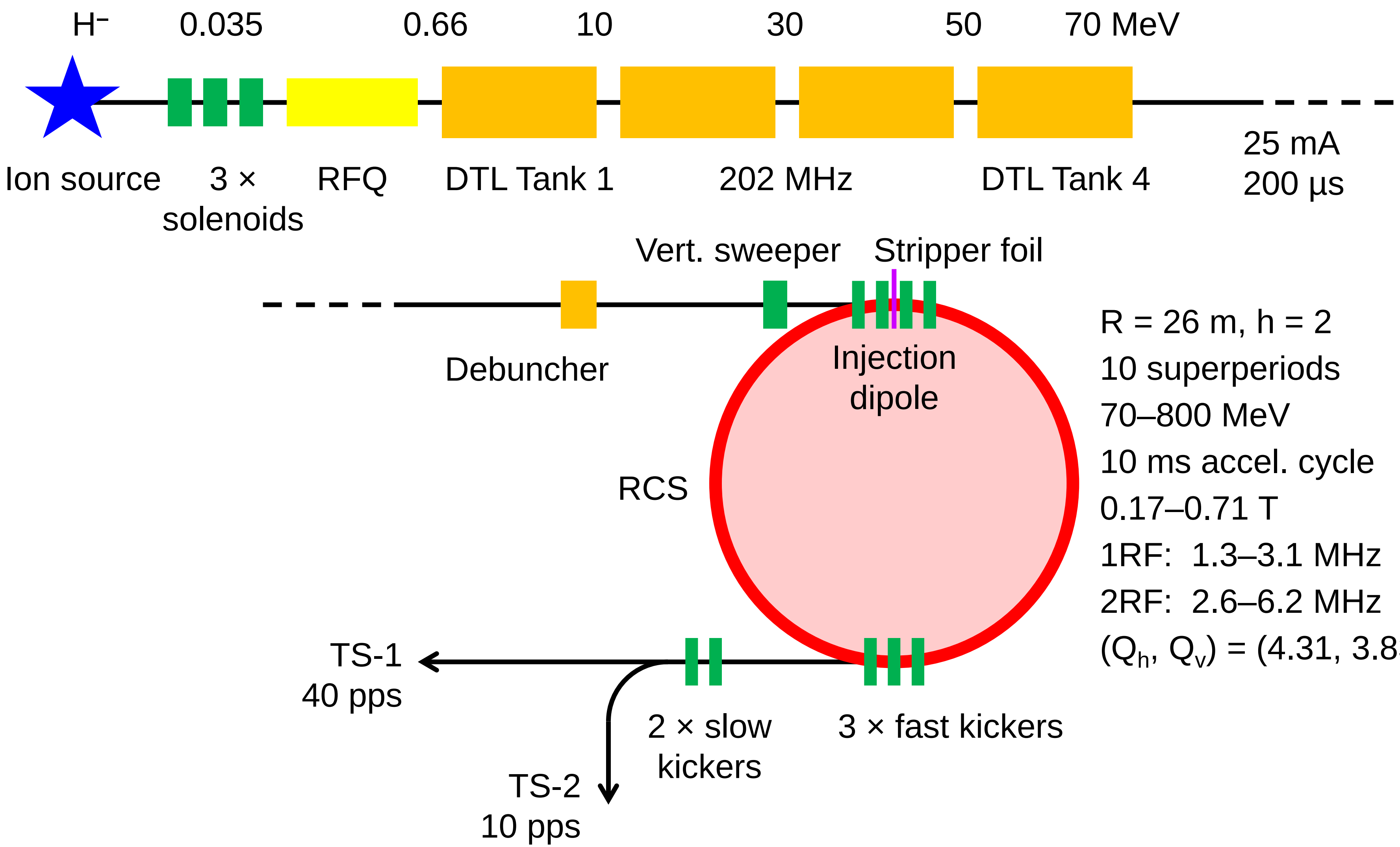
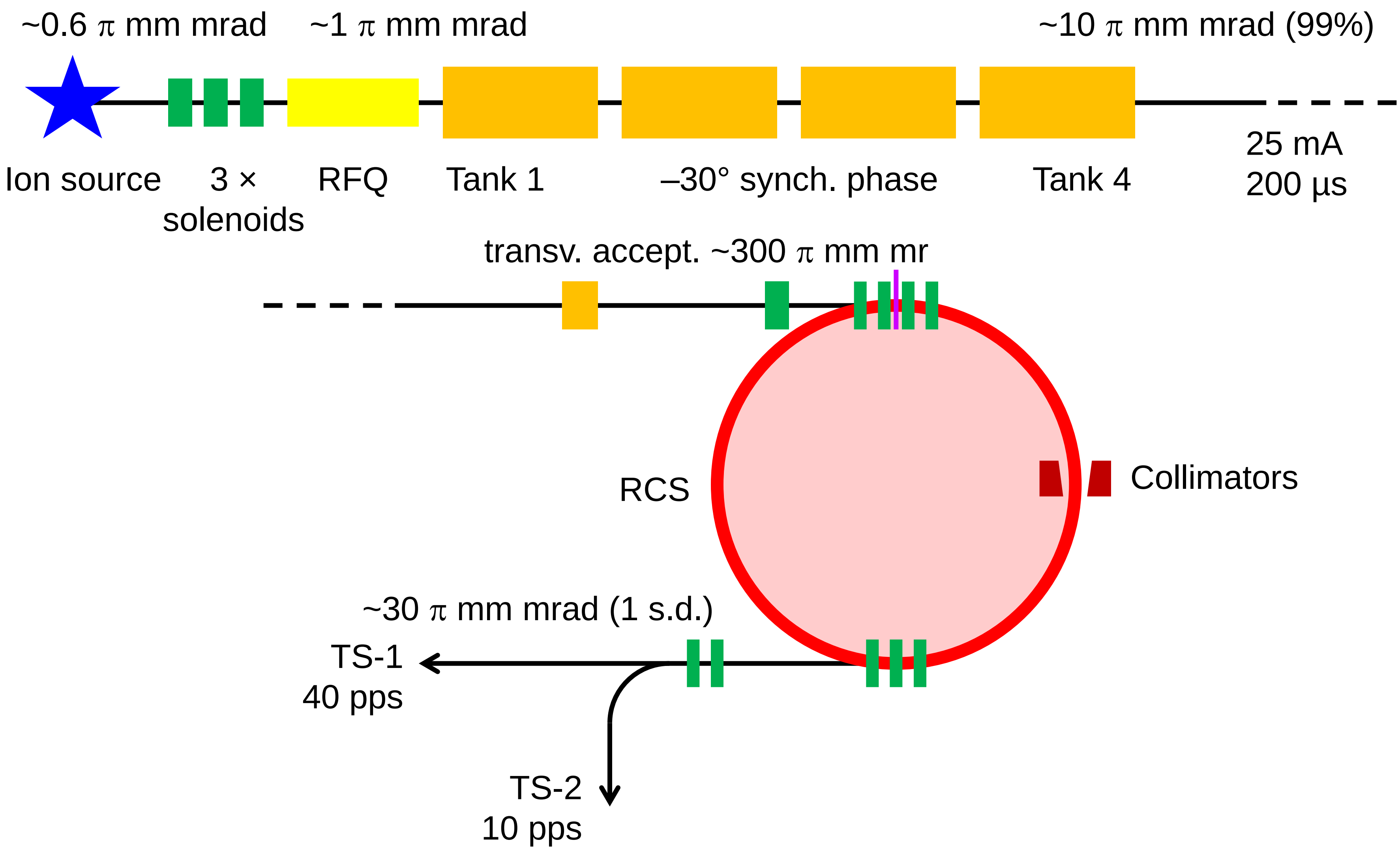
ISIS linac and synchrotron



R = 26 m, h = 2
10 superperiods
70–800 MeV
10 ms accel. cycle
0.17–0.71 T
1RF: 1.3–3.1 MHz
2RF: 2.6–6.2 MHz
$(Q_h, Q_v) = (4.31, 3.83)$

ISIS linac and synchrotron

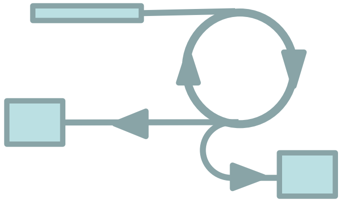


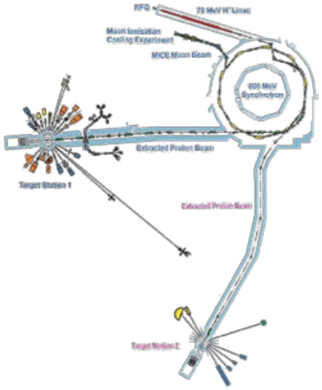
Upgrades to ISIS

Why upgrade? Basically, to host more user experiments

Success of spallation neutron source user facility depends on

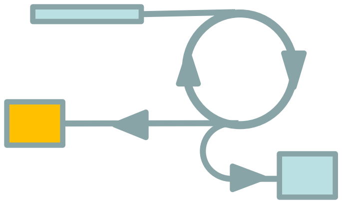
- Source strength ← wrong to put emphasis just on this (ESS)
- Proton conversion to neutrons
- Reliability
- Instrumentation
- Innovation
- Investment
- Support facilities
- Support staff
- Cost effectiveness
- User community

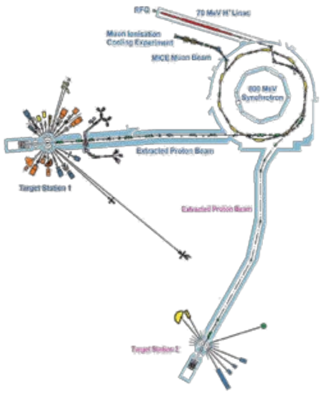




ISIS upgrades

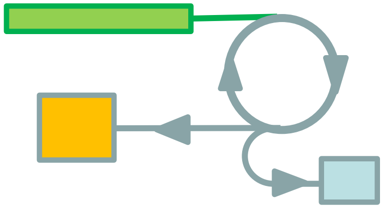
0) Linac refurbishment

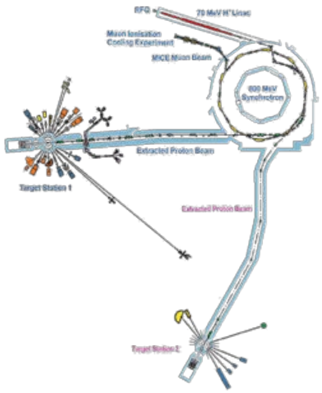




ISIS upgrades

0) Linac refurbishment and TS-1 upgrade

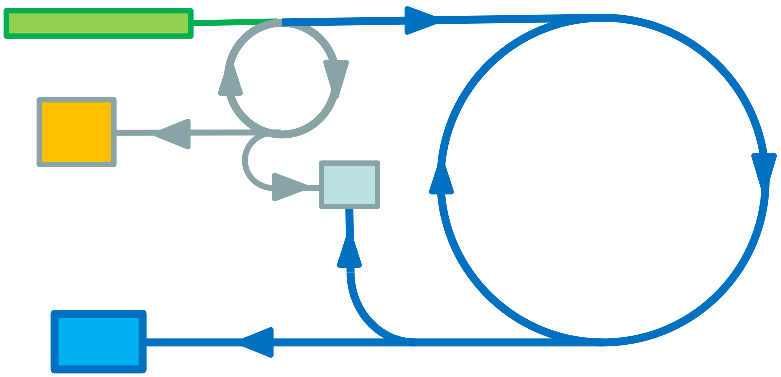


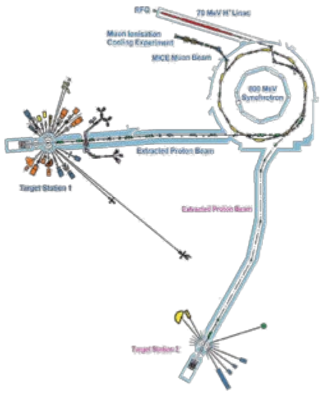


ISIS upgrades

0) Linac refurbishment and TS-1 upgrade

1) Linac upgrade, ≤0.5 MW on TS-1



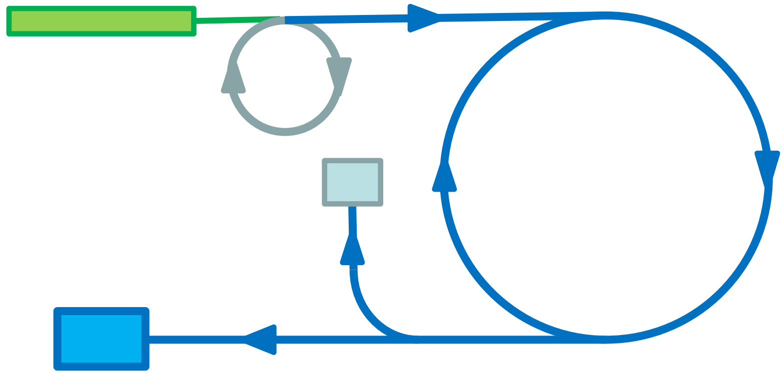


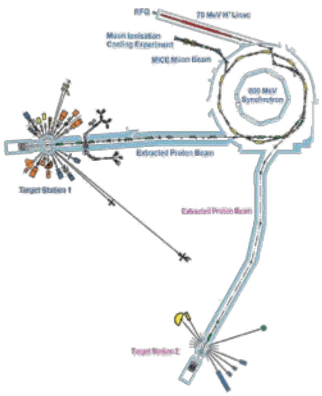
ISIS upgrades

0) Linac refurbishment and TS-1 upgrade

1) Linac upgrade, ≤0.5 MW on TS-1

2) 3 GeV booster synchrotron: MW target





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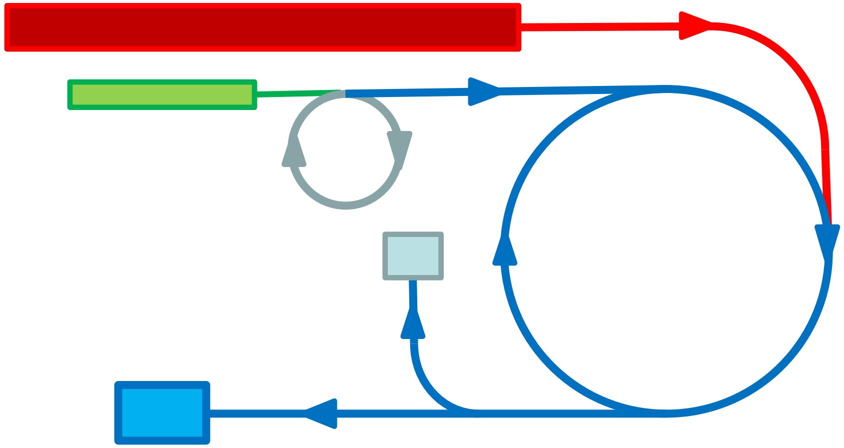
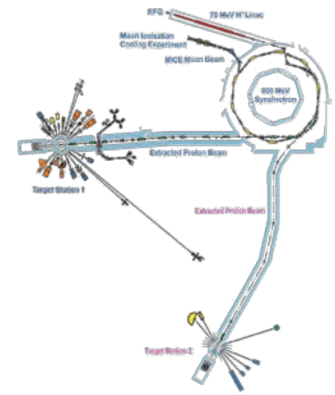




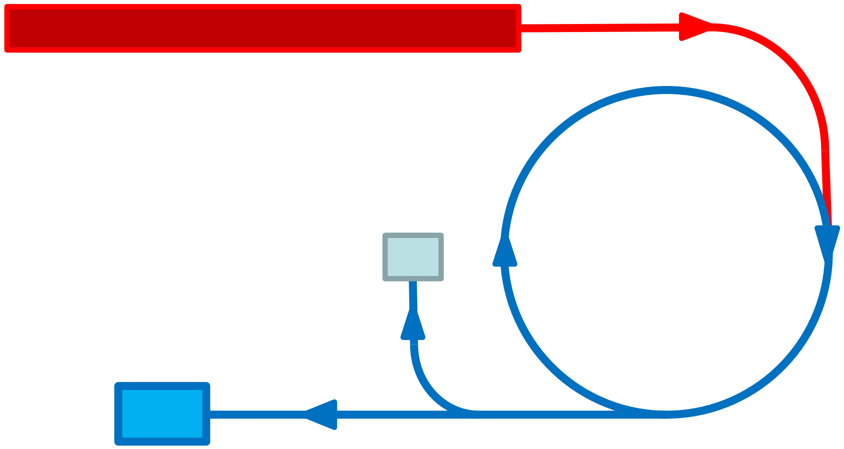
ISIS upgrades

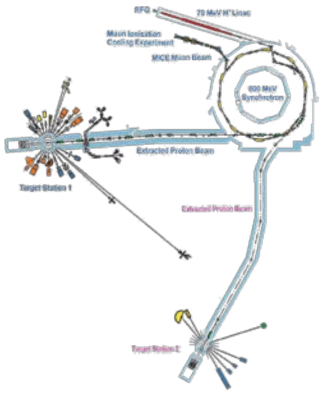
0) Linac refurbishment and TS-1 upgrade

1) Linac upgrade, ≤0.5 MW on TS-1

2) 3 GeV booster synchrotron: MW target

3) 800 MeV direct injection: 2–5 MW target





ISIS upgrades

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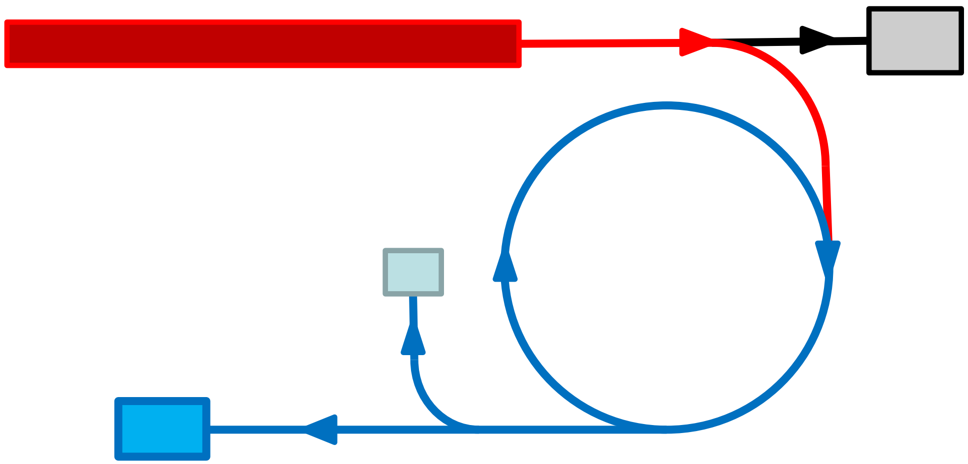

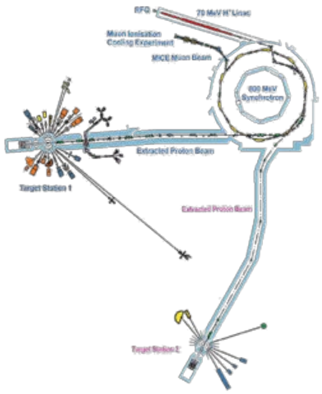

ISIS upgrades

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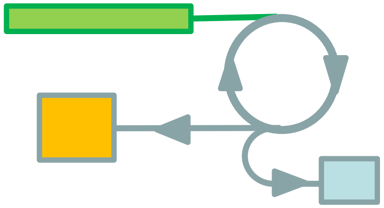
1) Linac upgrade, ≤0.5 MW on TS-1

2) 3 GeV booster synchrotron: MW target

3) 800 MeV direct injection: 2–5 MW target

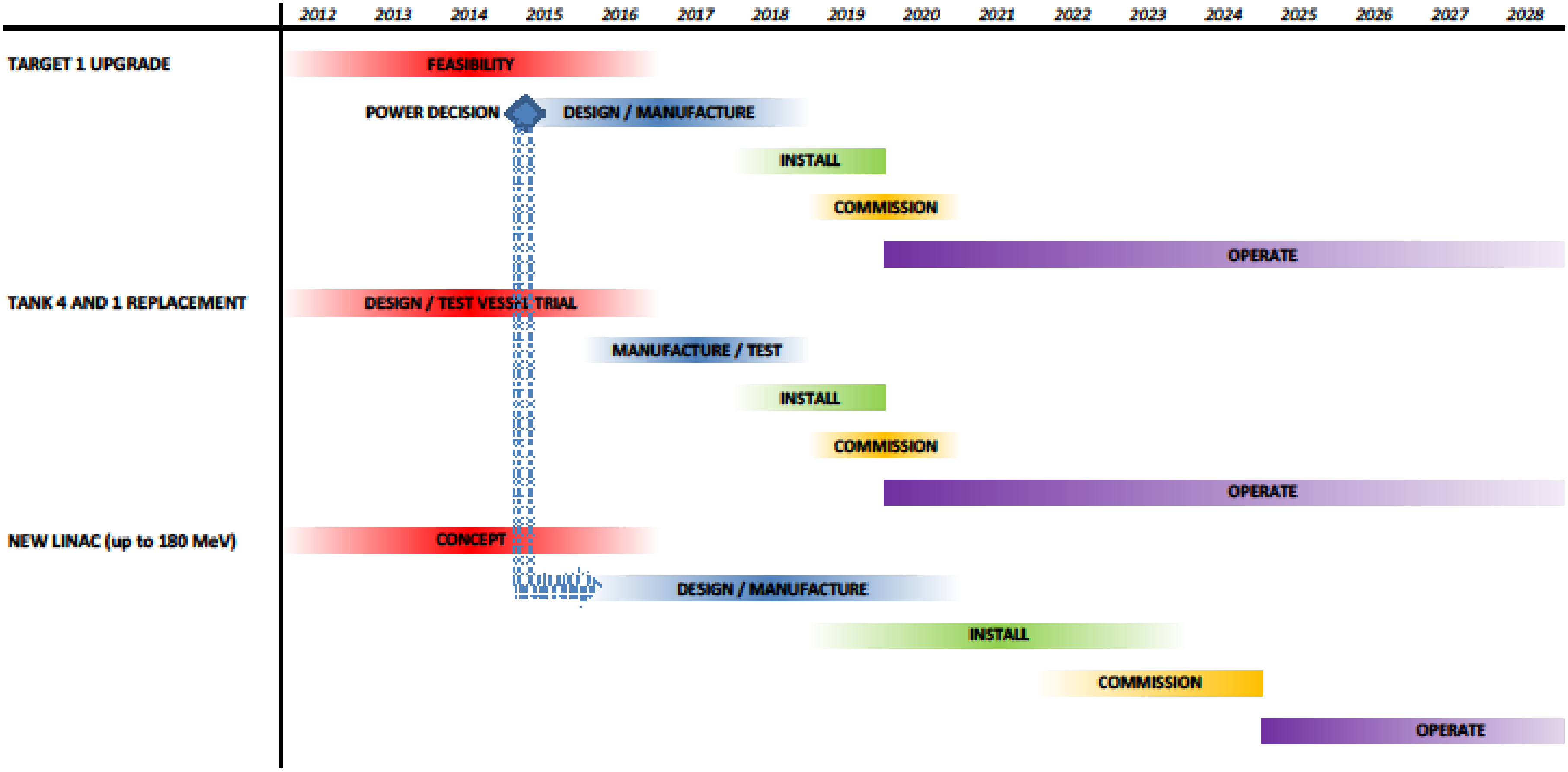
4) Upgrade 3) + long pulse mode option



0) Linac refurbishment and TS-1 upgrade

1) Linac upgrade, ≤180 MeV, ≤0.5 MW

Most cost-effective in short-to-medium term



Time line for TS-1 and linac upgrade

Advantages of upgraded target

Better neutronics, more useful neutrons per proton

TS-1 target is conservative 1970s design

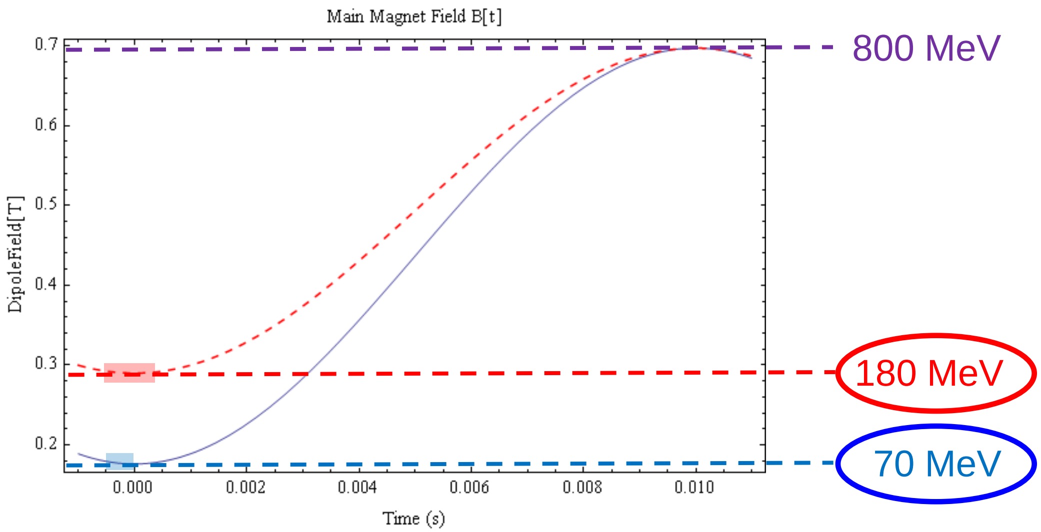
Advantages of new higher energy linac

New

Inject into synchrotron at higher energy
— space charge limitations less
— so can get more charge into synchrotron and higher beam currents out of synchrotron

Will synchrotron accept more charge at higher injection energy?
— detailed studies done up to 180 MeV
— yes, but with care

Upgrade Parameters



- Space charge limit scales as $\beta^2\gamma^3$
- Peak space charge moves from 70 to 180 MeV ≈ factor of 2.60

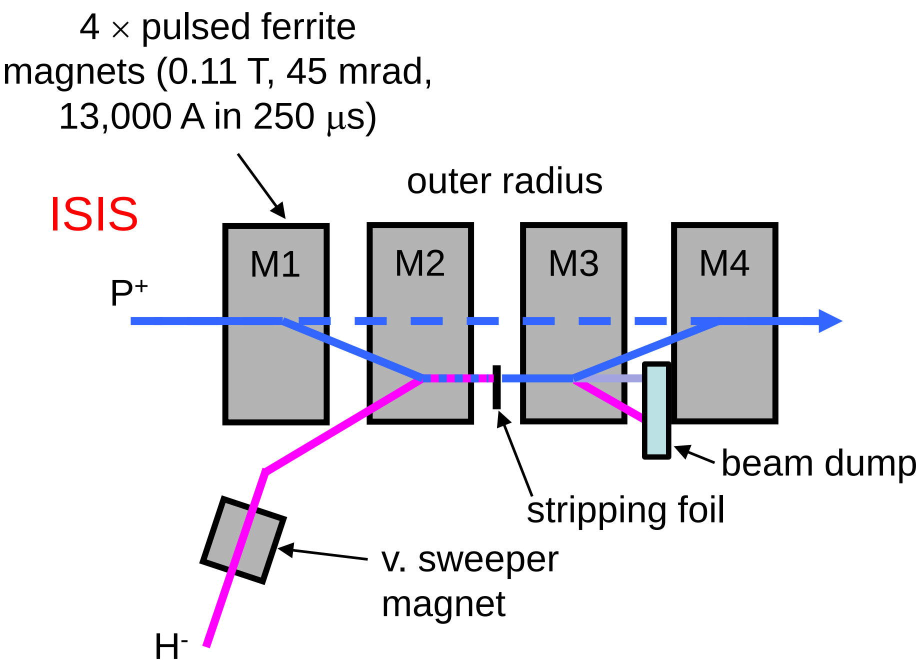
	Present ISIS	Upgrade Idea
Magnet Field	Sinusoidal	Sinusoidal
Energy Range	70 – 800 MeV	180 – 800 MeV
Longitudinal Trapping	"adiabatic capture"	chopped beam
Intensity	2.5 – 3.0×10^{13} ppp	≈ 8.0×10^{13} ppp
Mean Power	160 – 200 kW	≈ 0.5 MW
Injection	H^-, inside, 250 μs	H^-, outside, 500 μs
RF System DHRF: h=2, 4	f_2 = 1.3 – 3.1 MHz V_{pk} = 80, 160 kV	f_2 = 2.0 – 3.1 MHz V_{pk}=80, 160 kV

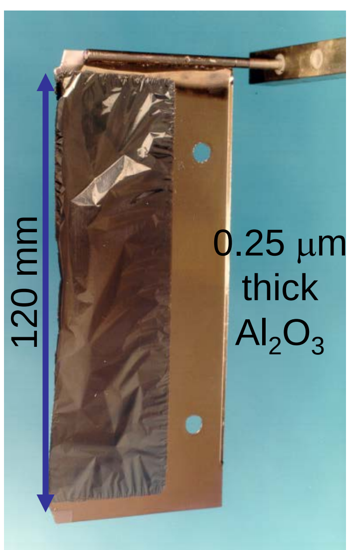
- RF acceleration parameters should be within present ISIS limits
- Possible problems: instabilities, dynamics changes, activation, 180 MeV injection, RF systems, foils, loss, *etc* …

Need to consider

- Injection dynamics, injection straight and foil
- Longitudinal and acceleration dynamics, associated high intensity limits
- Transverse high intensity limitations
- Full cycle, 3-D simulations: checks and optimisations of 3-D parameters
- RF systems
- Activation and collimation
- Diagnostics and damping systems

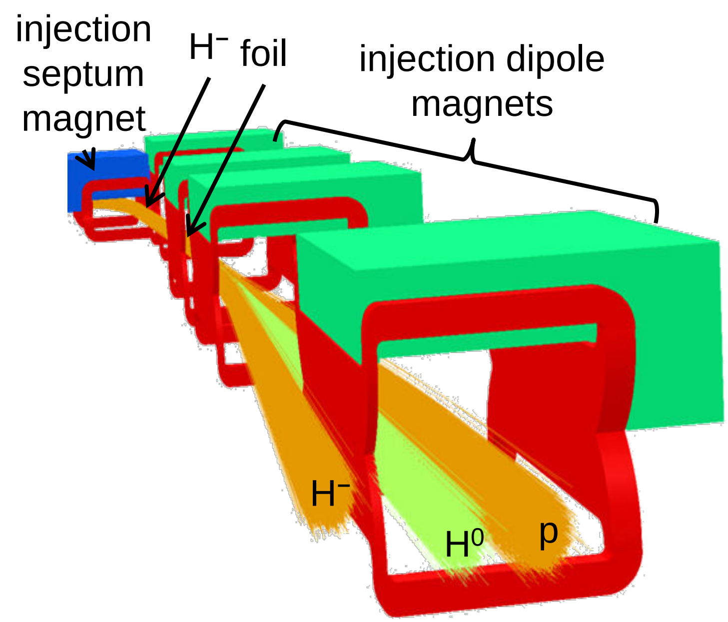
Injection / H^- stripping



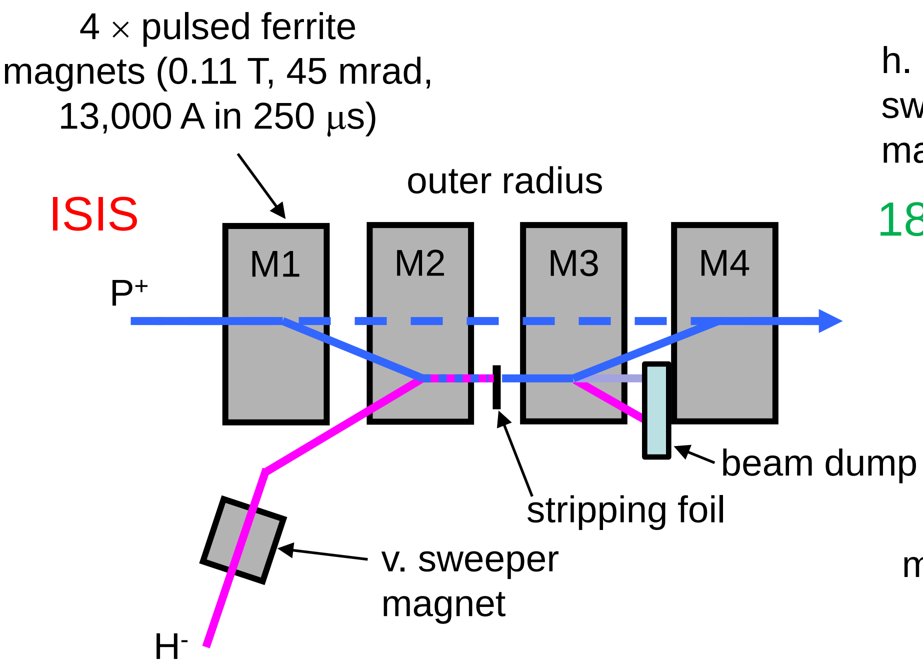


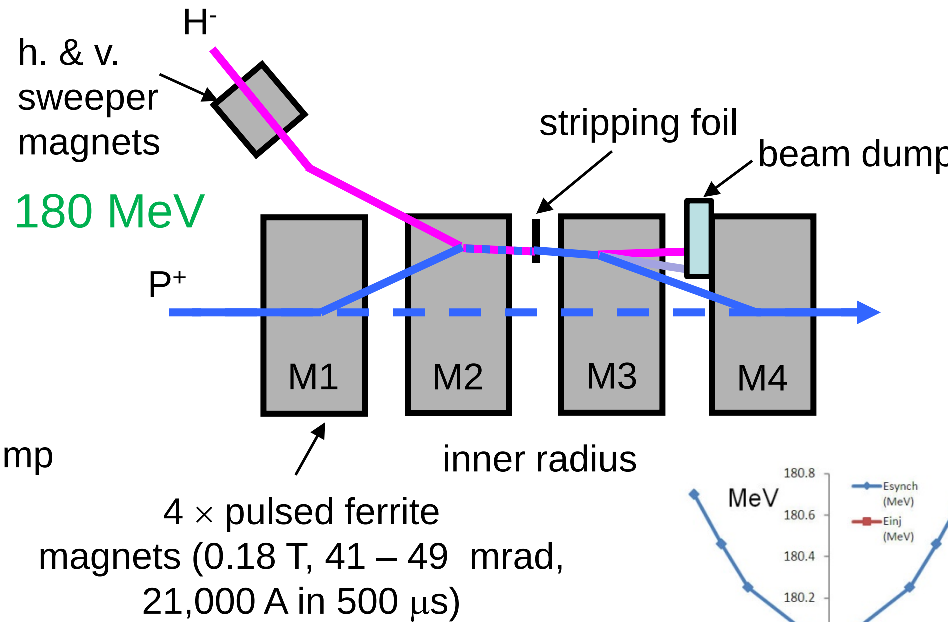
- Injection at 70 MeV over ≈ 250 μs before field minimum
- Symmetric, constant beam bump

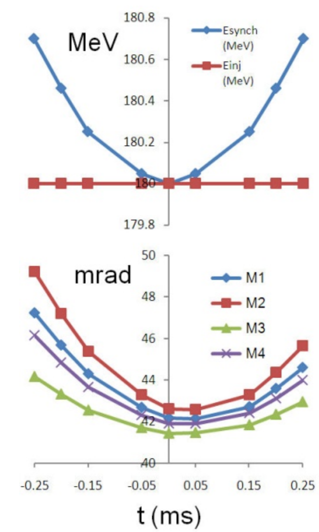
- Model of existing 70 MeV injection – use to benchmark 180 MeV design

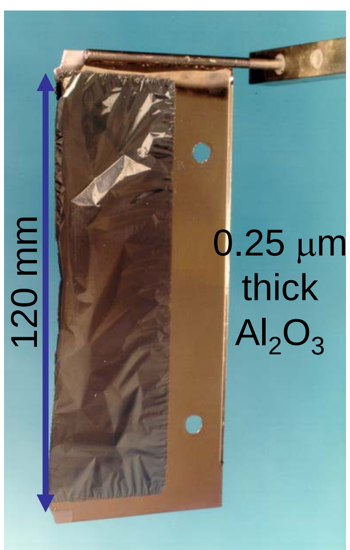


Injection / H⁻ stripping





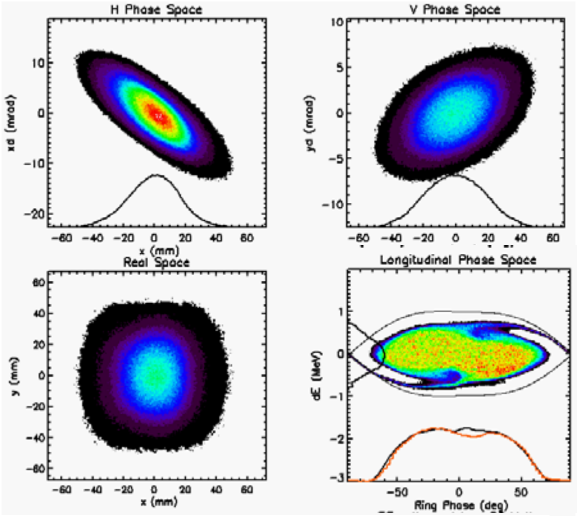




- Injection at 70 MeV over ≈ 250 μs before field minimum
- Symmetric, constant beam bump

- Injection at 180 MeV over ≈ 500 μs before around minimum
- Asymmetric, falling beam bump
- Higher power deposited on foil and dump

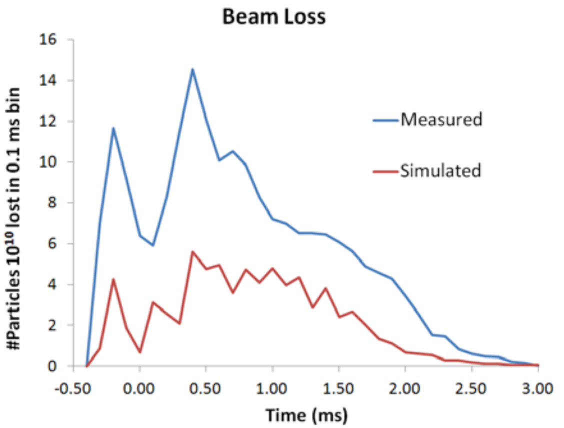
Synchrotron beam simulations

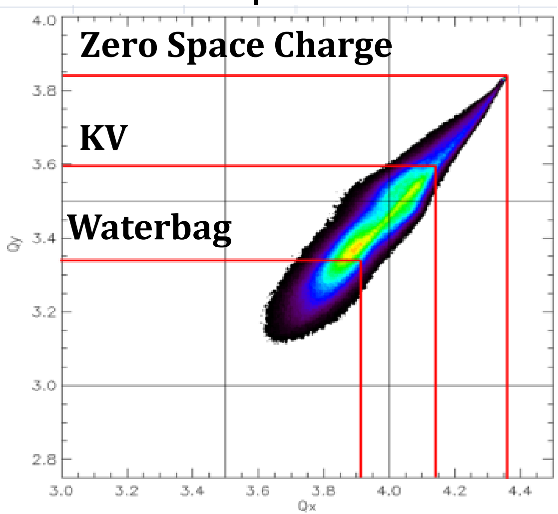


Aim : Simulate synchrotron beam to understand and minimise beam losses.

Model of ring injection and acceleration using 2 million particles tracked over 3000 turns with space charge, foil scattering, collectors, machine apertures and RF errors.   Fitted to transverse and longitudinal profiles.

Result: Measured beam loss 7% , simulated 3 % (right). Need to include envelope and closed orbit errors. Temporal beam loss structure looks good.





Simulation shows many high intensity effects for further study , tune spread (left) , vertical emittance growth mechanisms, moments etc.

Studies of injection painting distributions may minimise some of these effects leading to higher intensity operation.

Conclusion

Linac upgrade can be done

Costs?

Being based on J-PARC 181 MeV linac

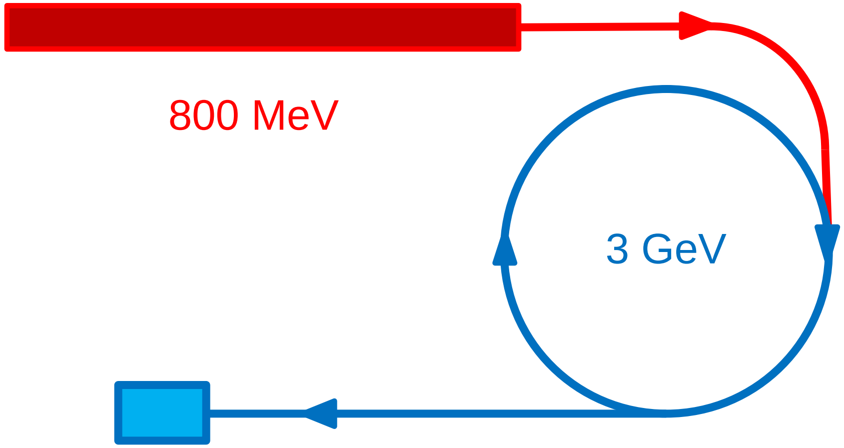
~£80M

Time scales?

Engineering design + preparations ~3 years

Building, installation + commissioning ~4 years

→ 2022 long shutdown



3) 800 MeV direct injection: 2–5 MW target

For longer term — ESS not enough

Green field site — at RAL?

Accelerators for neutrons — to sum up

Continuing need

Always a rôle for proton or heavy-ion accelerators

STFC has stewardship of UK's high-power proton accelerators

Complemented by accelerator institutes

Science & Technology Facilities Council
Rutherford Appleton Laboratory

ISIS

ISIS

Science & Technology
Facilities Council