

Secondary Beams

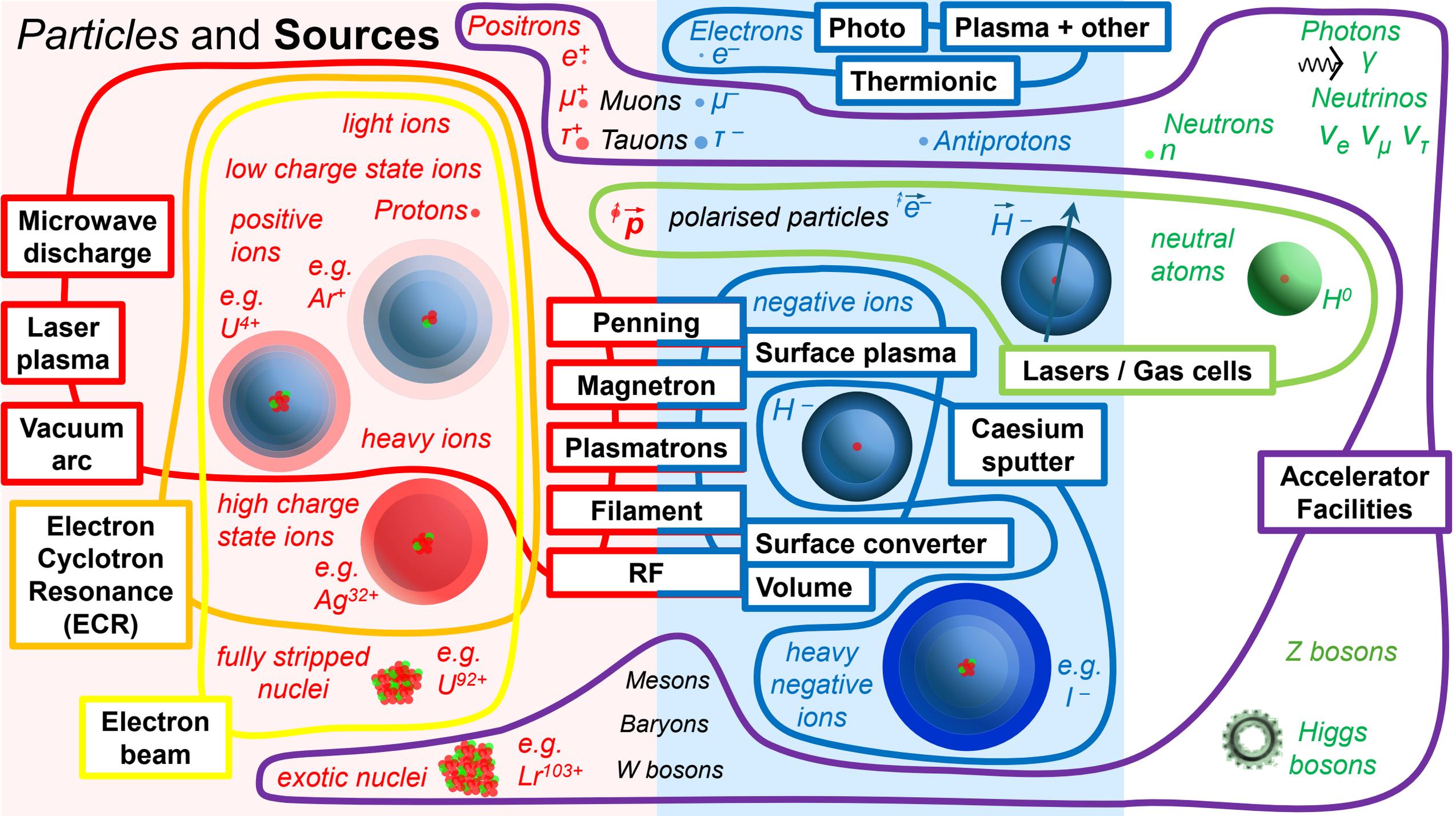
Dan Faircloth

ISIS Low Energy Beams Group Leader

Rutherford Appleton Laboratory

STFC-UKRI

Particles and Sources



Secondary Beams

Positrons e^+
Muons μ^+
Tauons τ^+

Electrons e^-
Photo
Plasma + other
Thermionic

Antiprotons

Neutrons n

Photons γ
Neutrinos $\nu_e \nu_\mu \nu_\tau$

Microwave discharge

Laser plasma

Vacuum arc

Electron Cyclotron Resonance (ECR)

Electron beam

light ions
low charge state ions

positive ions
e.g. Ar^+
 U^{4+}

heavy ions

high charge state ions
e.g. Ag^{32+}

fully stripped nuclei
e.g. U^{92+}

Penning

Magnetron

Plasmatrons

Filament

RF

Surface plasma

Surface converter

Volume

Lasers / Gas cells

Caesium sputter

Mesons
Baryons
W bosons

exotic nuclei



e.g. Lr^{103+}

Accelerator Facilities

Z bosons



Higgs bosons

Rutherford Appleton Laboratory (RAL), Oxfordshire, UK

Harwell Campus

Diamond Light Source

Synchrotron Light Sources-
Secondary Beams?

ISIS Neutron and Muon Source



Science and
Technology
Facilities Council

Positrons e^+

e^+

μ^+ Muons μ^-

τ^+ Tauons τ^-

Electrons e^-

Photo

Plasma + other

Thermionic

Photons γ



Neutrinos $\nu_e \nu_\mu \nu_\tau$

Neutrons n

Antiprotons

Secondary Beams and Targets

Accelerator Facilities

Microwave discharge

Laser plasma

Vacuum arc

Electron Cyclotron Resonance (ECR)

Electron beam

light ions

low charge state ions

positive ions

e.g. Ar^{16+}

U^{4+}

heavy ions

high charge state ions

e.g. Ag^{32+}

fully stripped nuclei

e.g. U^{92+}

exotic nuclei



e.g. Lr^{103+}

Mesons

Baryons

W bosons

Z bosons



Higgs bosons

Penning

Plasmatrons

Filament

RF

Surface plasma

Surface converter

Volume

Caesium sputter

Lasers / Gas cells

heavy negative ions

e.g. I^-

neutral atoms



H^0

Particles and Sources



ISIS -making neutron and muon beams since 1984

Spallation neutron source
31 neutron instruments
7 muon instruments
2000 users/yr
~800 experiments/yr
~500 publications/yr

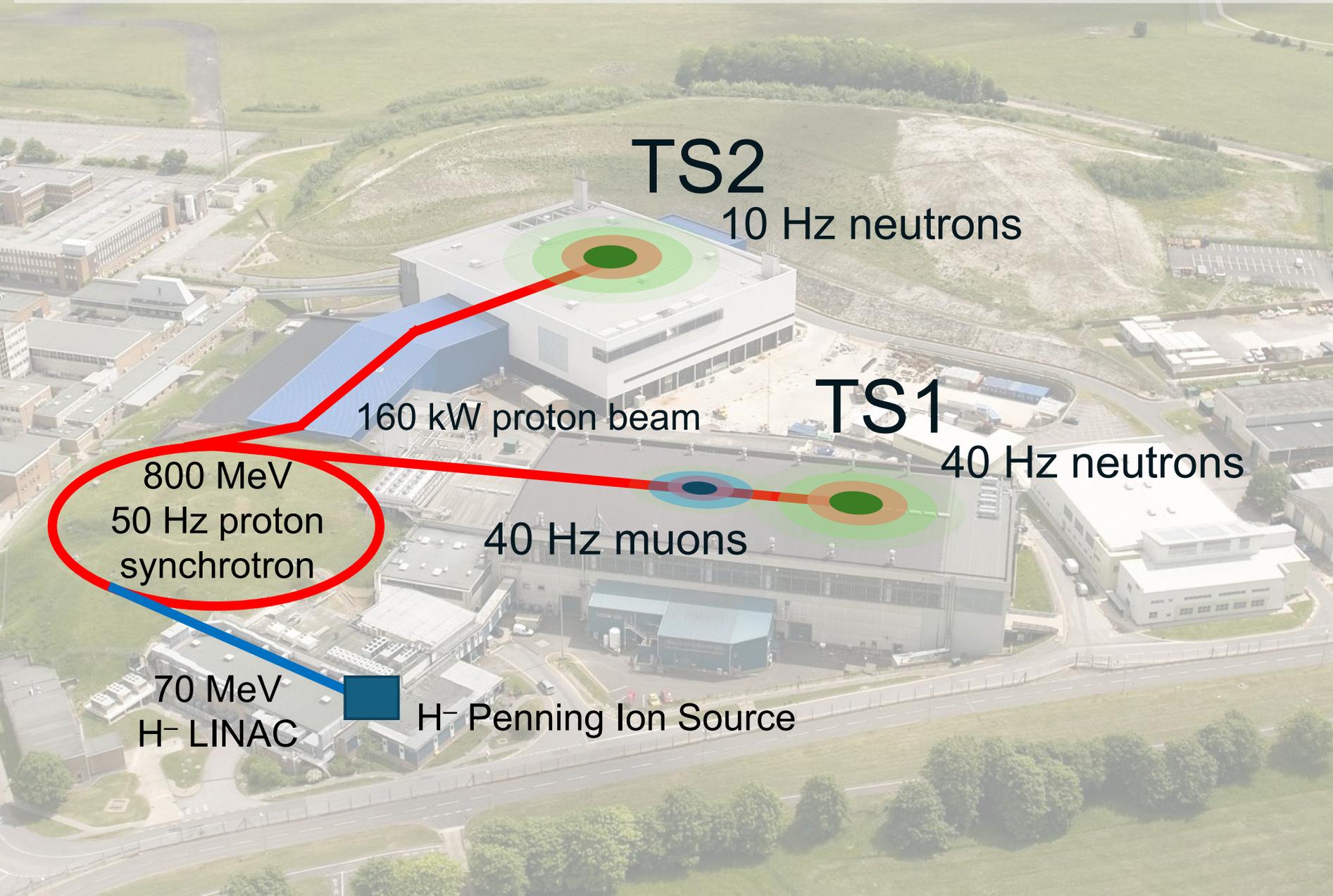


ISIS Neutron and Muon Source

A world leading centre for condensed matter physics-

Neutrons are used to see where atoms are and what atoms do

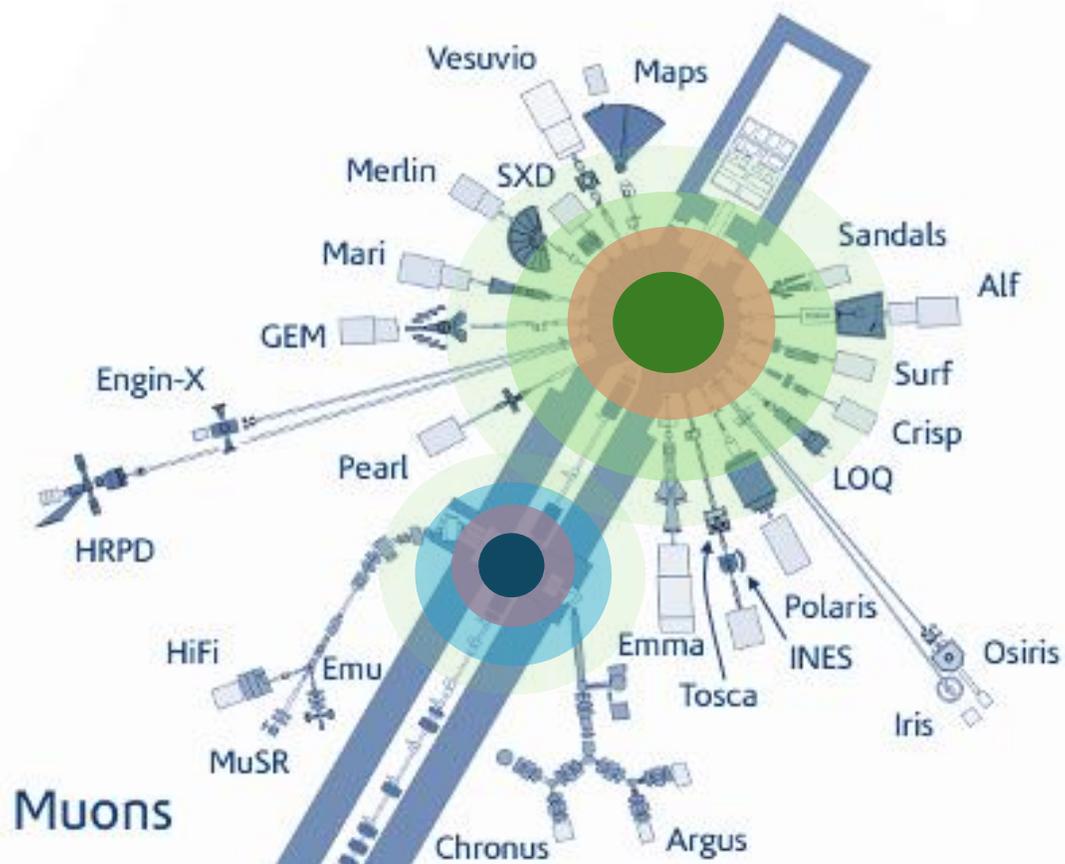
ISIS - making neutron and muon beams since 1984



ISIS Neutron and Muon Source

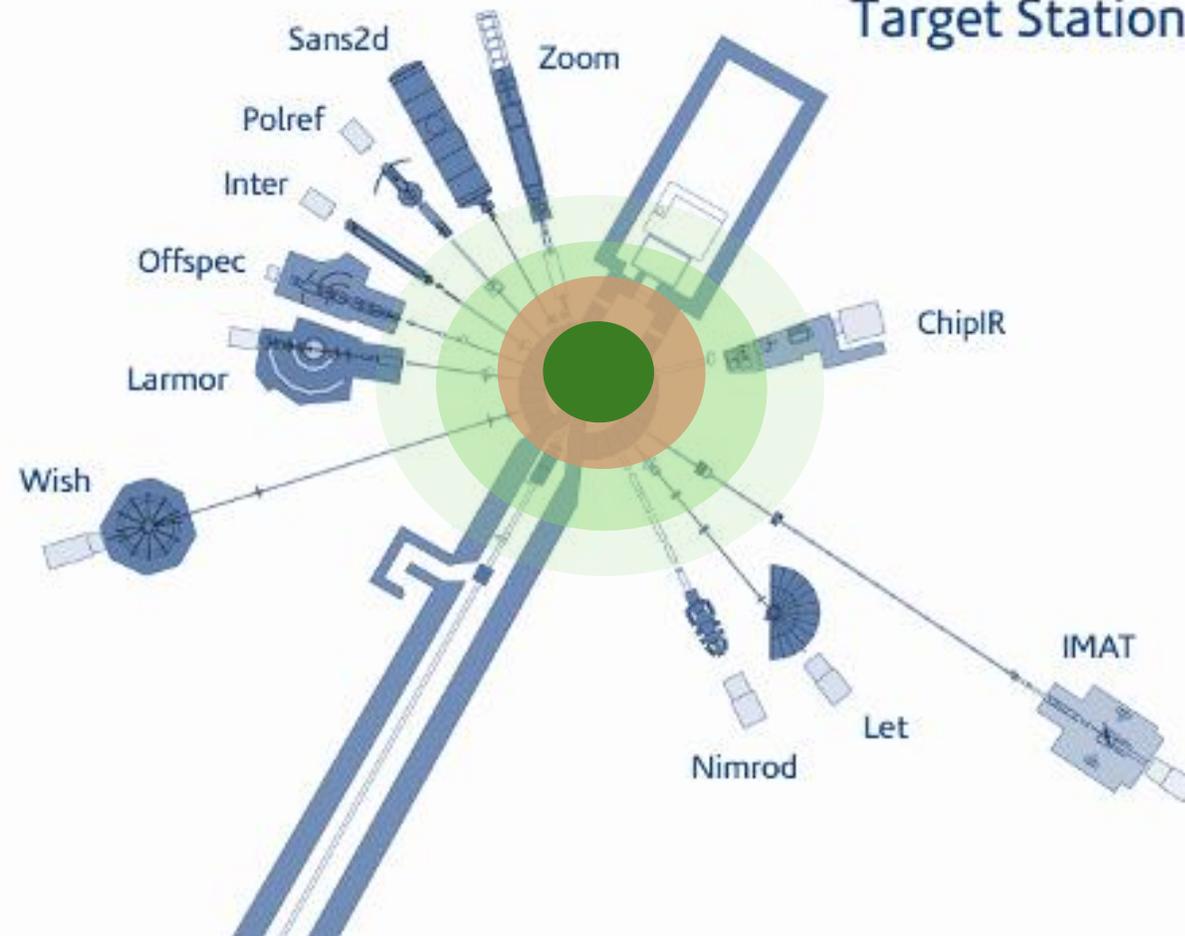
ISIS has many different types of instruments:

Target Station 1



20 neutron instruments
7 muon instruments

Target Station 2



11 neutron instruments
(more in the way)

LET Spectrometer



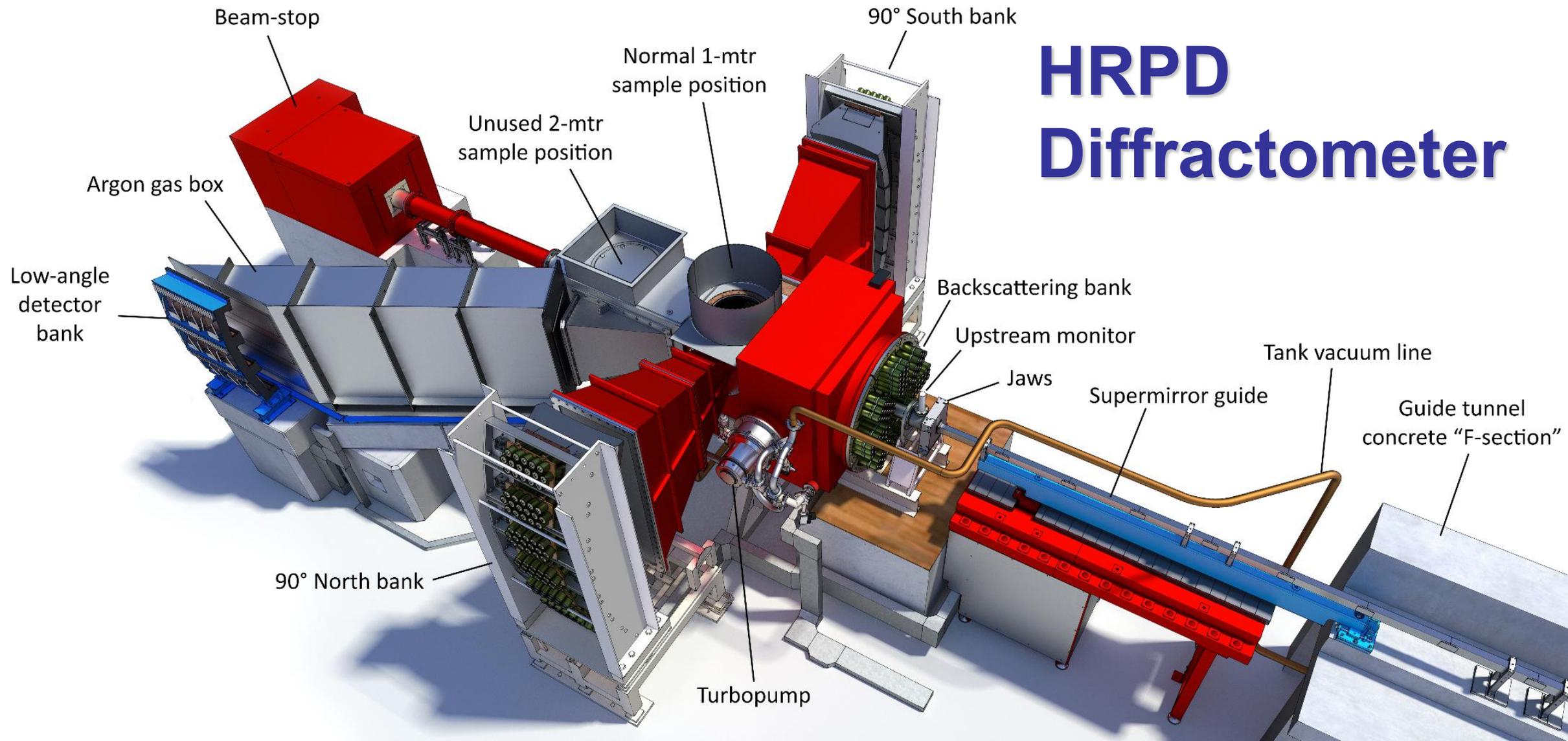
... some instruments
are very big

OFFSPEC Reflectometer

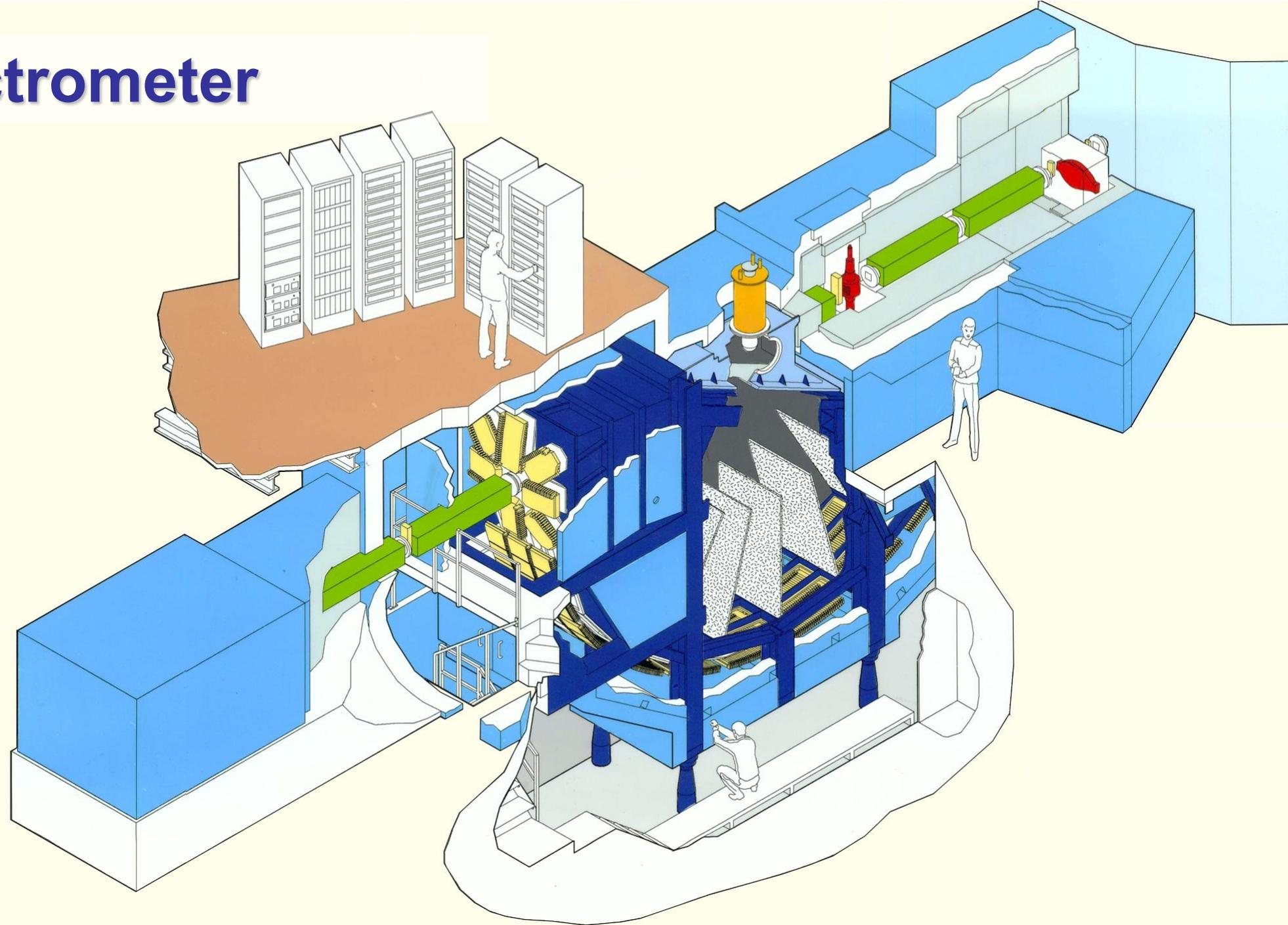
...some are smaller
and movable



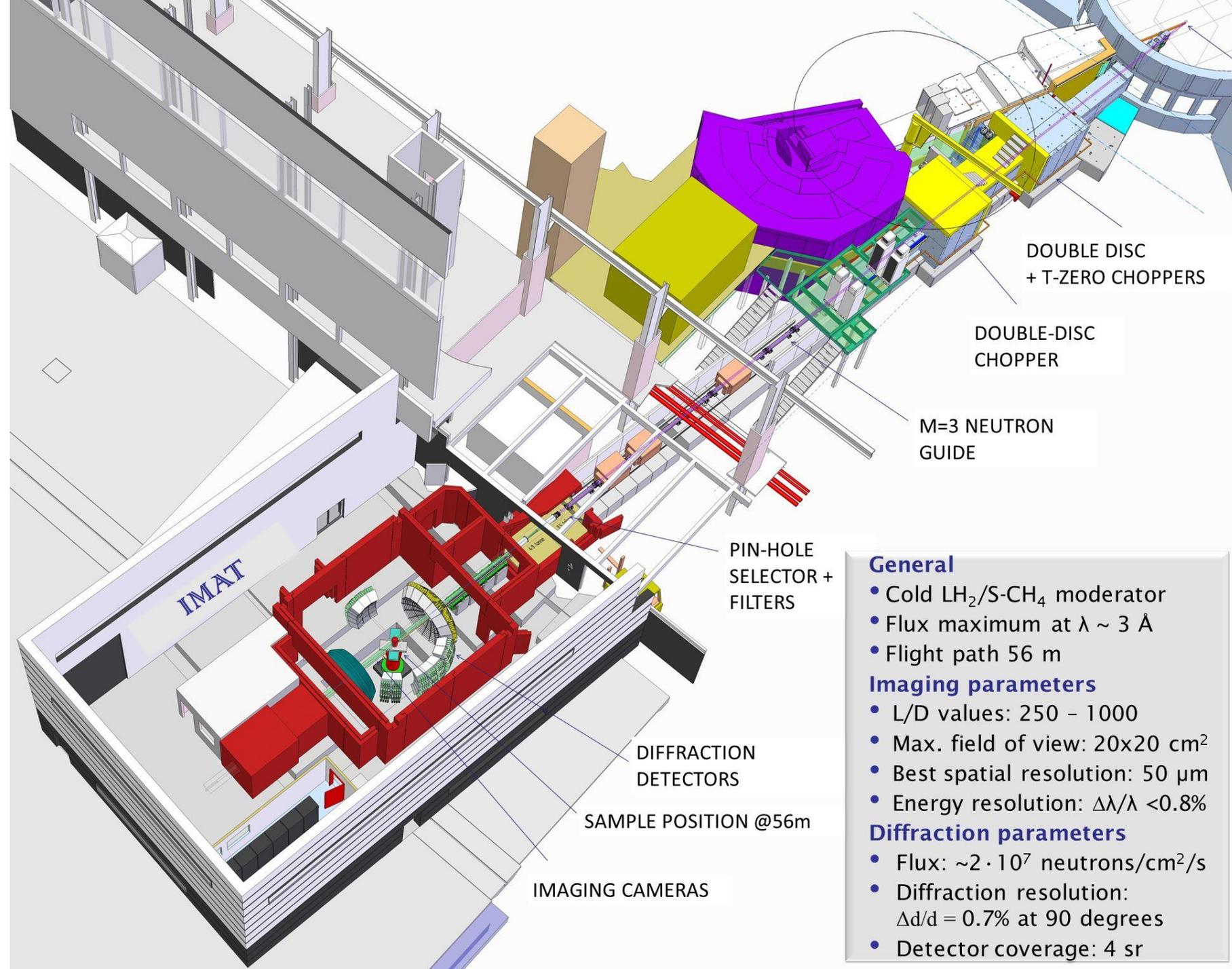
Each instrument is unique and complex...



MARI Spectrometer



IMAT Diffractometer



General

- Cold LH₂/S-CH₄ moderator
- Flux maximum at $\lambda \sim 3 \text{ \AA}$
- Flight path 56 m

Imaging parameters

- L/D values: 250 – 1000
- Max. field of view: 20x20 cm²
- Best spatial resolution: 50 μm
- Energy resolution: $\Delta\lambda/\lambda < 0.8\%$

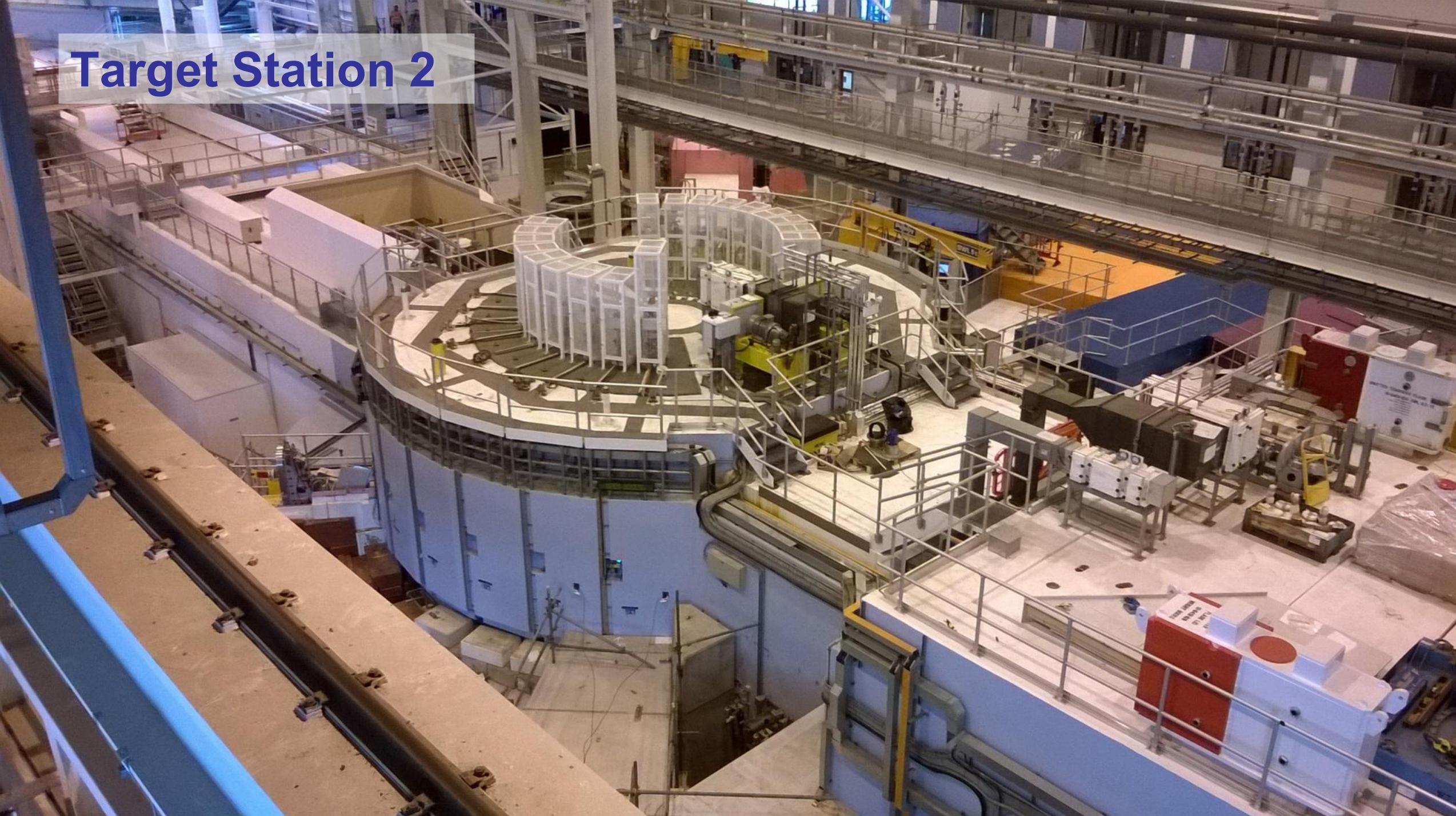
Diffraction parameters

- Flux: $\sim 2 \cdot 10^7$ neutrons/cm²/s
- Diffraction resolution: $\Delta d/d = 0.7\%$ at 90 degrees
- Detector coverage: 4 sr

Target Station 1

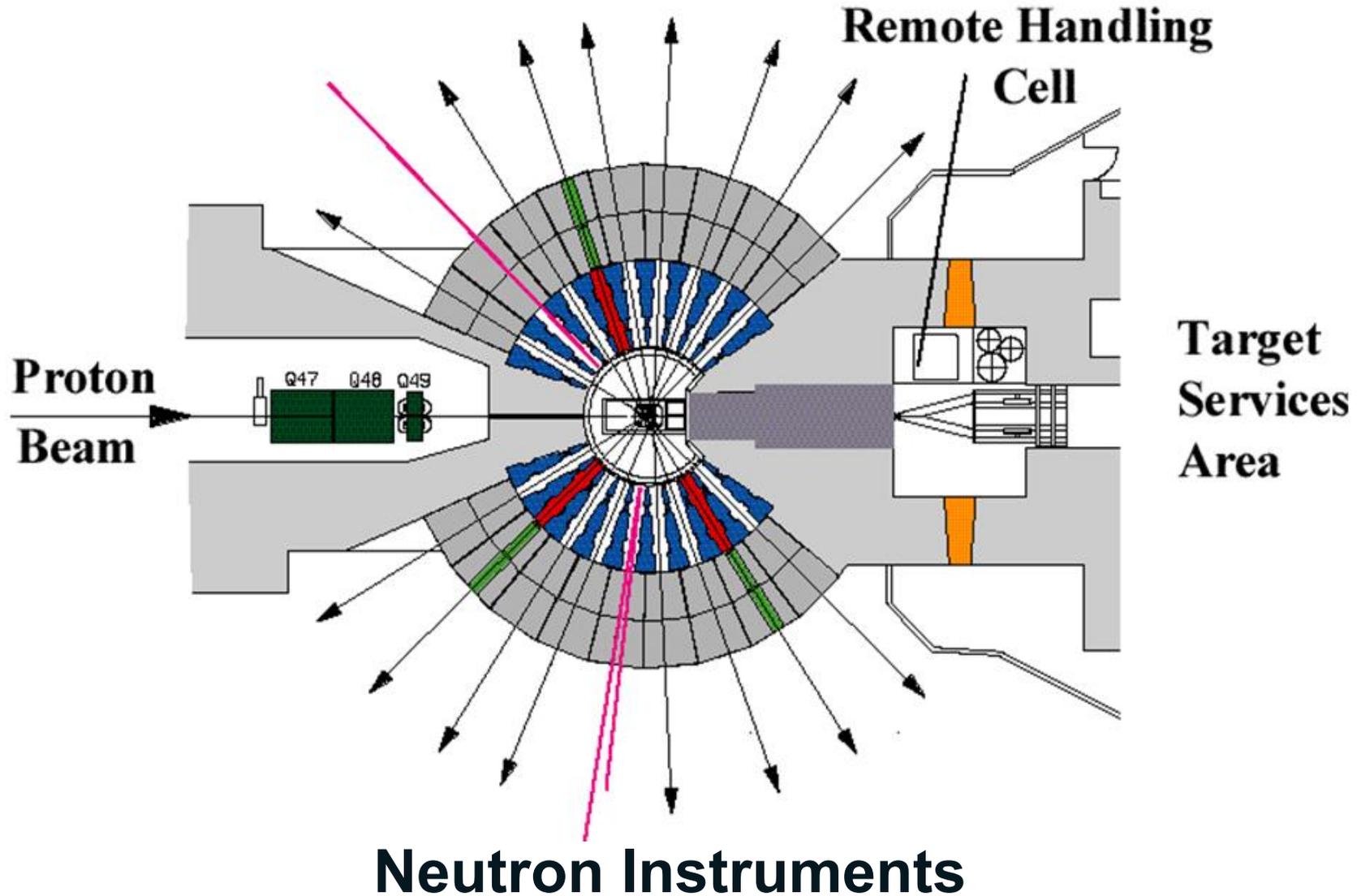


Target Station 2



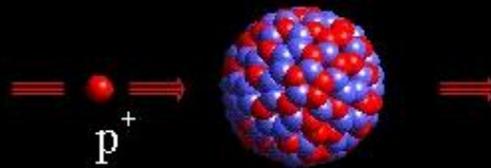
Basic Layout of ISIS Target Stations

Neutron Instruments



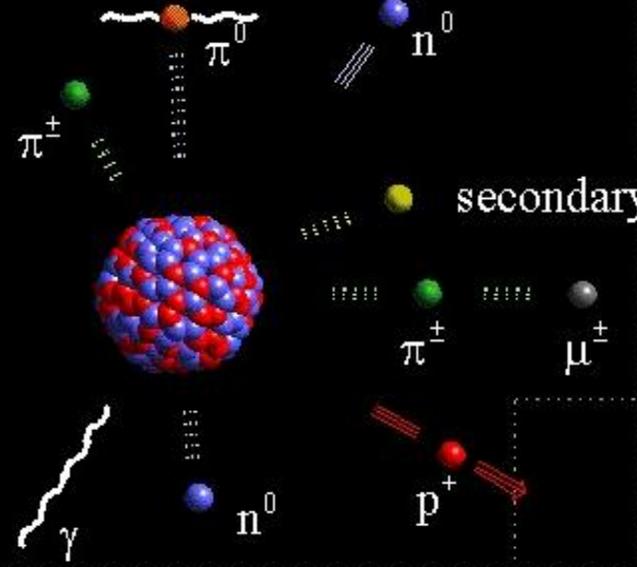
The Spallation Process

800 MeV proton



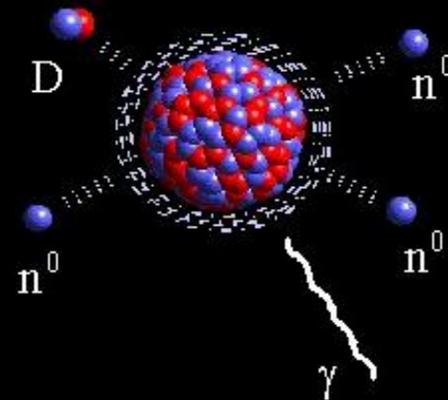
Target nucleus
Tungsten

Intranuclear cascade

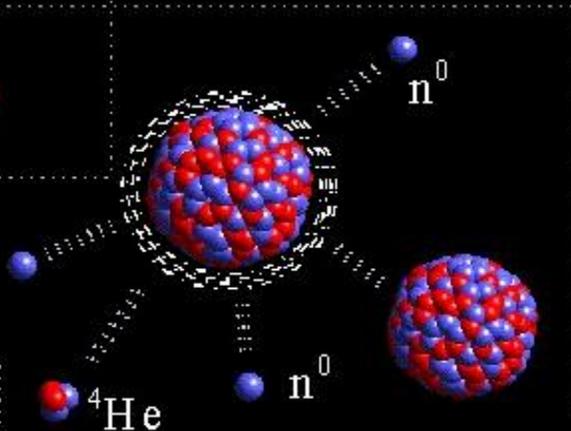


secondary particles

“Evaporation”



Spallation

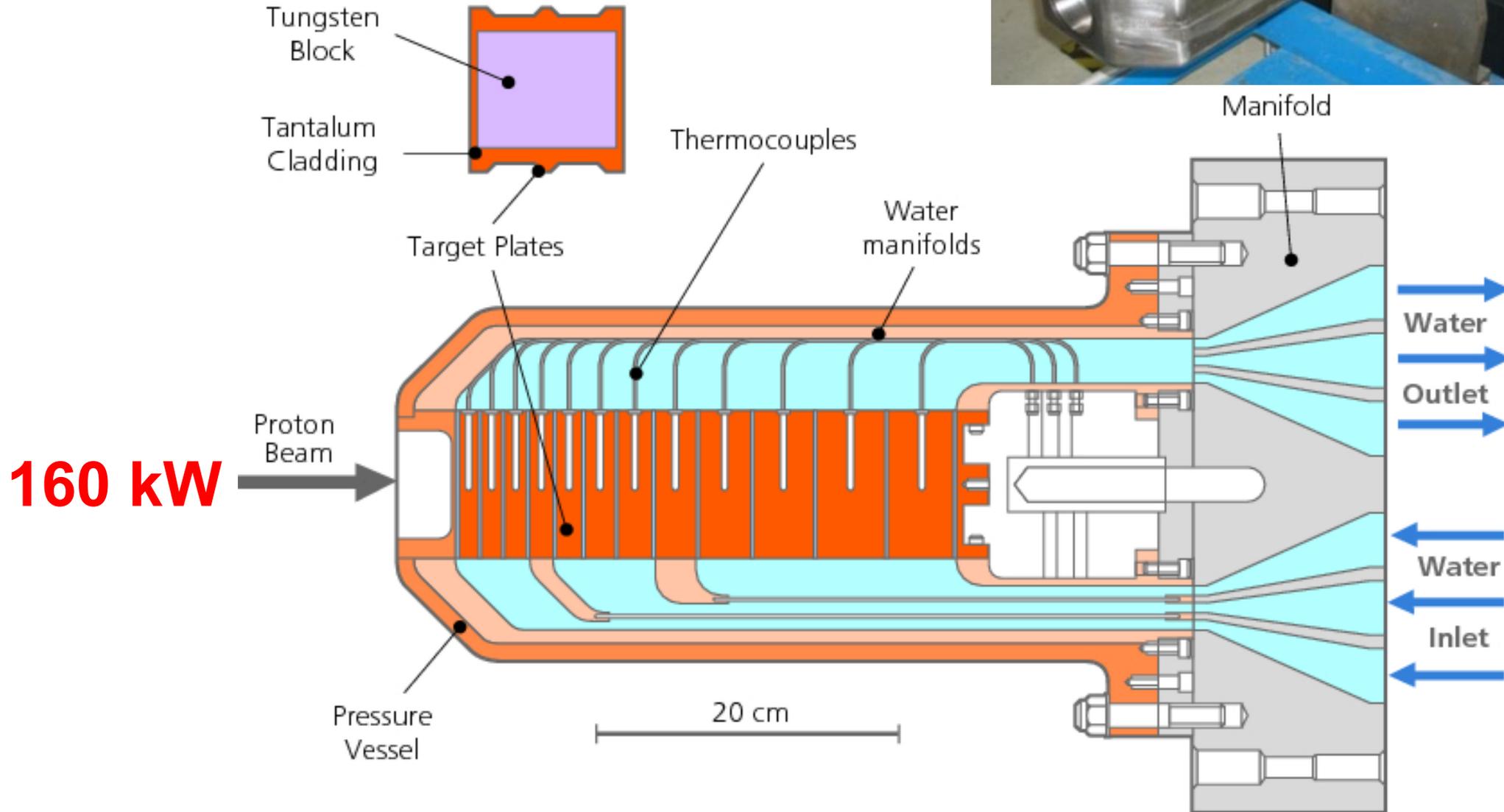


spallation product

To the moderators
and the reflectors

**20,000 million million
neutrons per second!**

Section view of ISIS TS1 target



ISIS target and bottom moderator and reflector assembly (top reflector assembly removed)

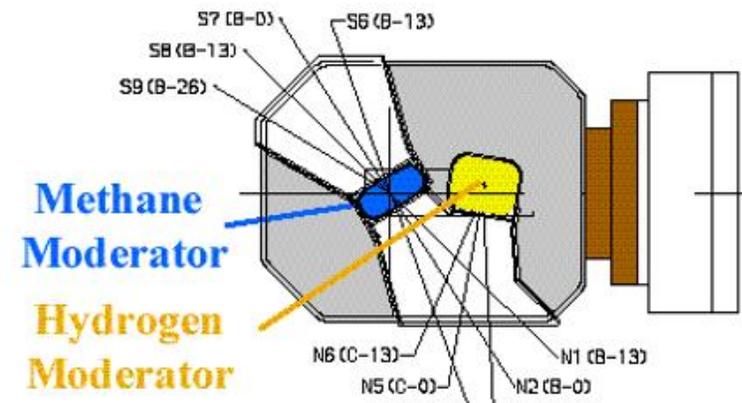
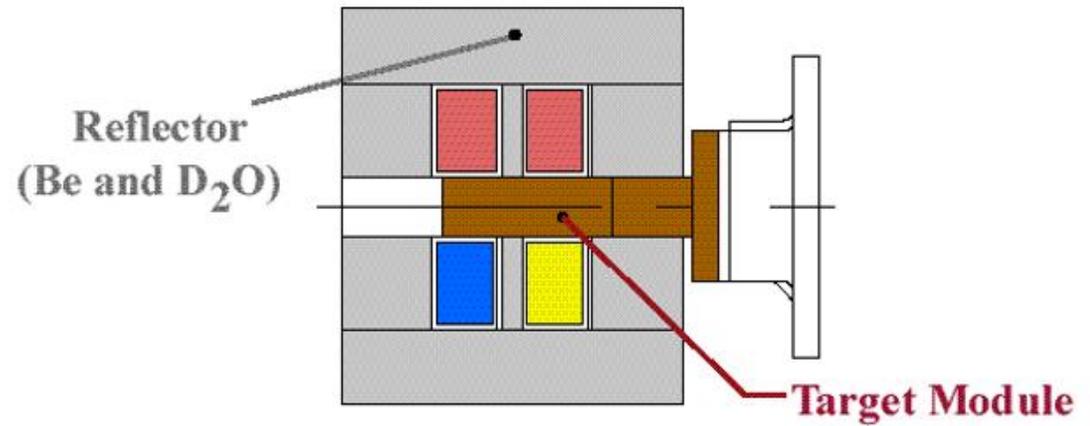
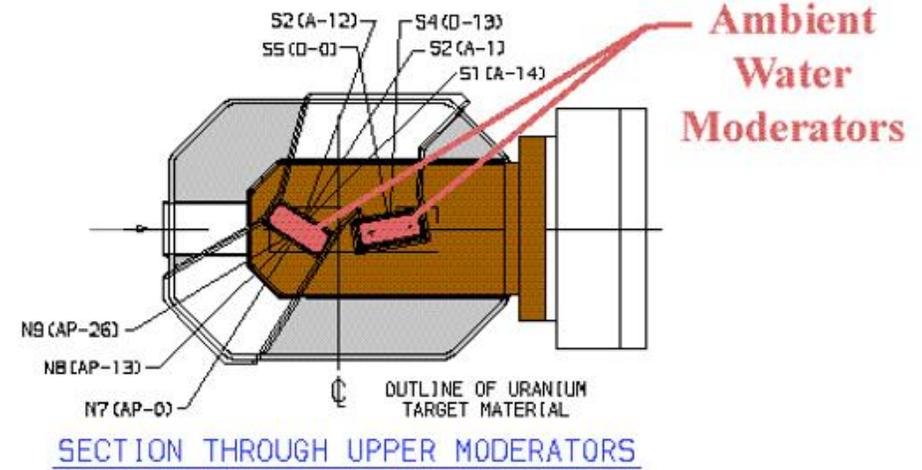
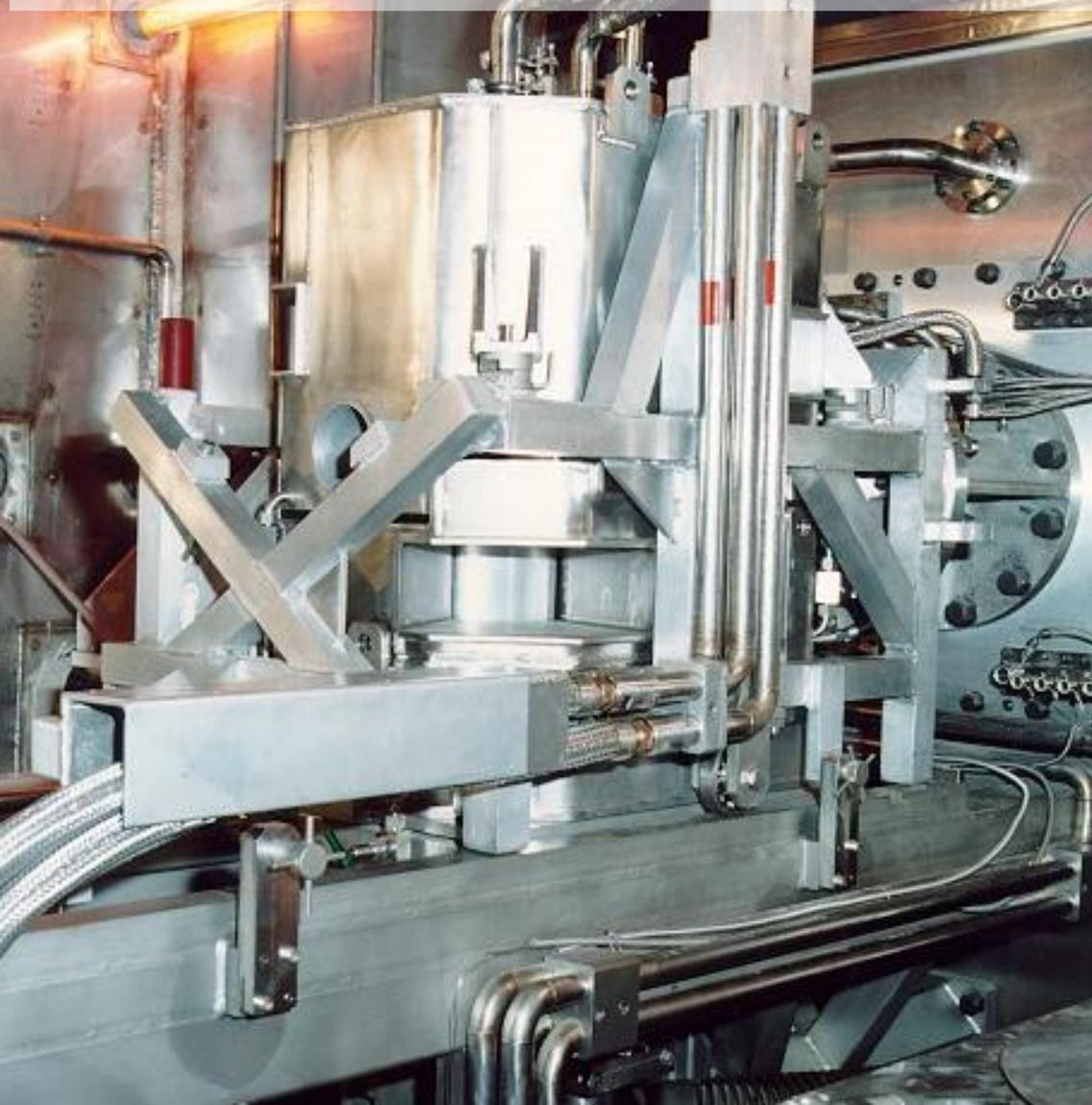
800 MeV
protons



slow
neutrons



Target Reflector And Moderators (TRAM)



ISIS TS1 target and moderators (reflector assembly removed)

Water moderators

heat load 380 W
25 litres/min 30°C demin water
Moderator depth defined
by Al clad Gadolinium poisoning layer

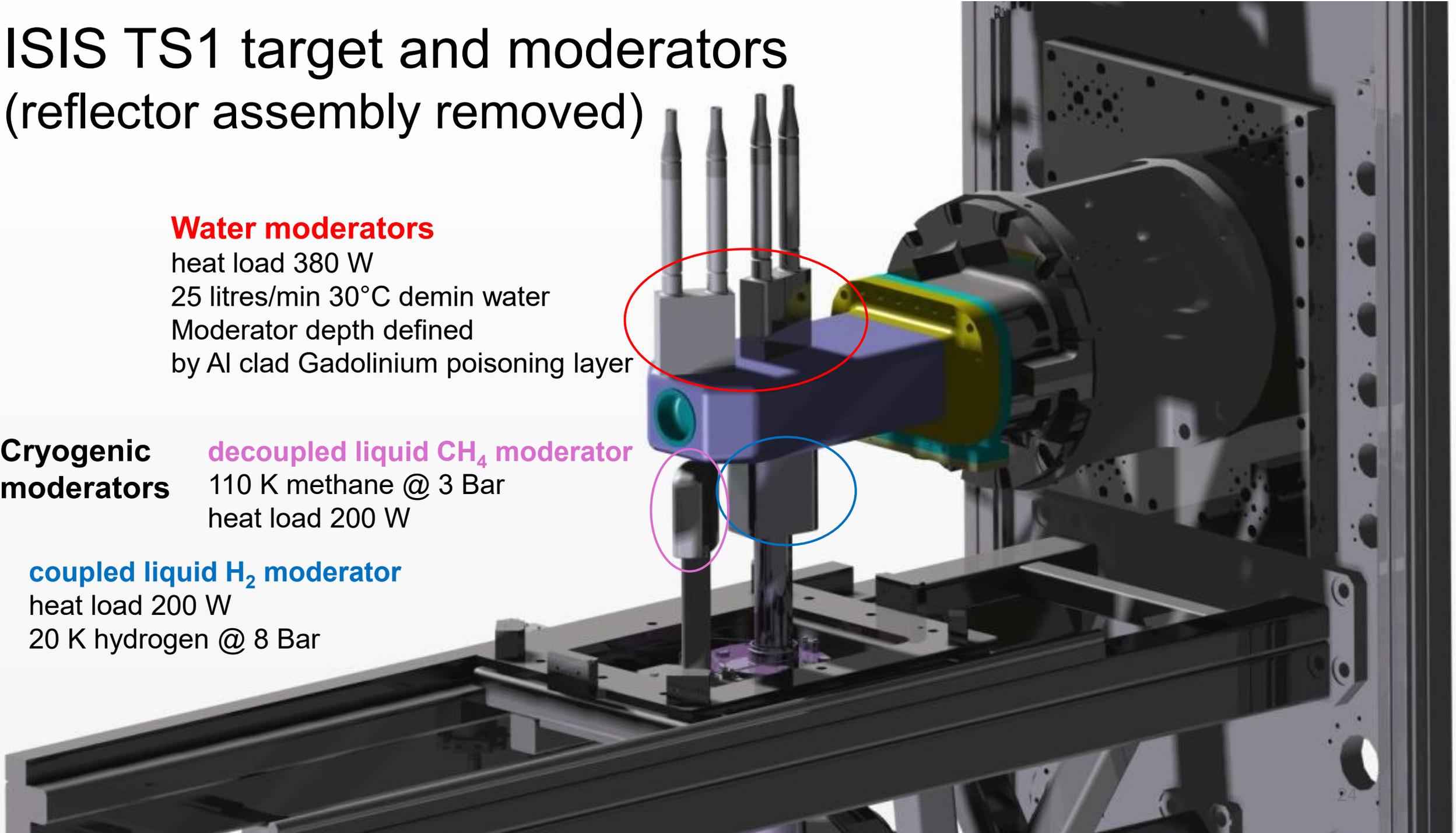
Cryogenic moderators

decoupled liquid CH₄ moderator

110 K methane @ 3 Bar
heat load 200 W

coupled liquid H₂ moderator

heat load 200 W
20 K hydrogen @ 8 Bar



ISIS Target Station 2 TRAM

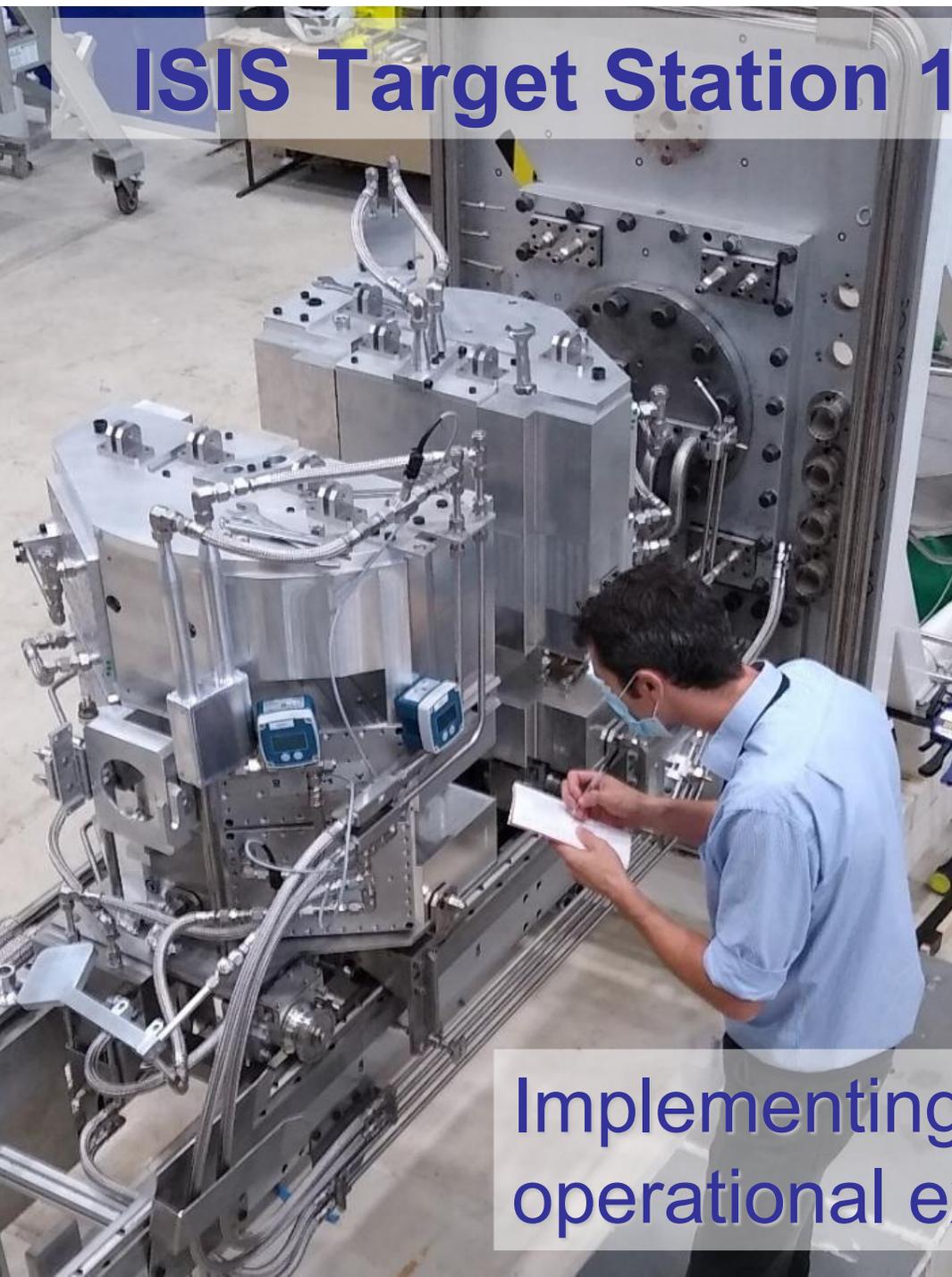
target

decoupled moderator:
solid CH_4 @ 45 K

coupled moderator:
liquid H_2 @ 20 K 4 bar

beryllium reflector open
in maintenance mode

ISIS Target Station 1 New TRAM Project

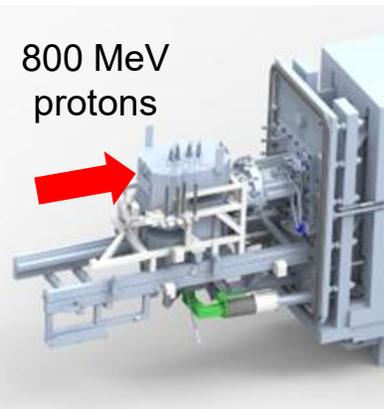


£20M Project
Operational in
2025

Implementing 40 years of
operational experience

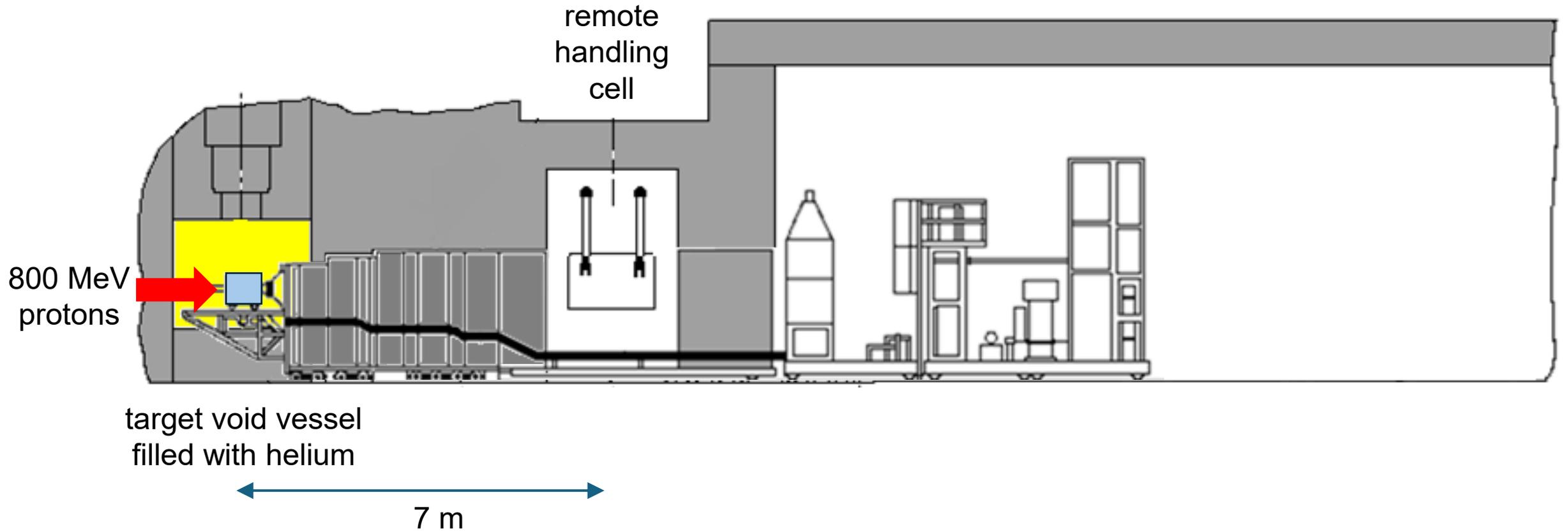


ISIS Target Trolley

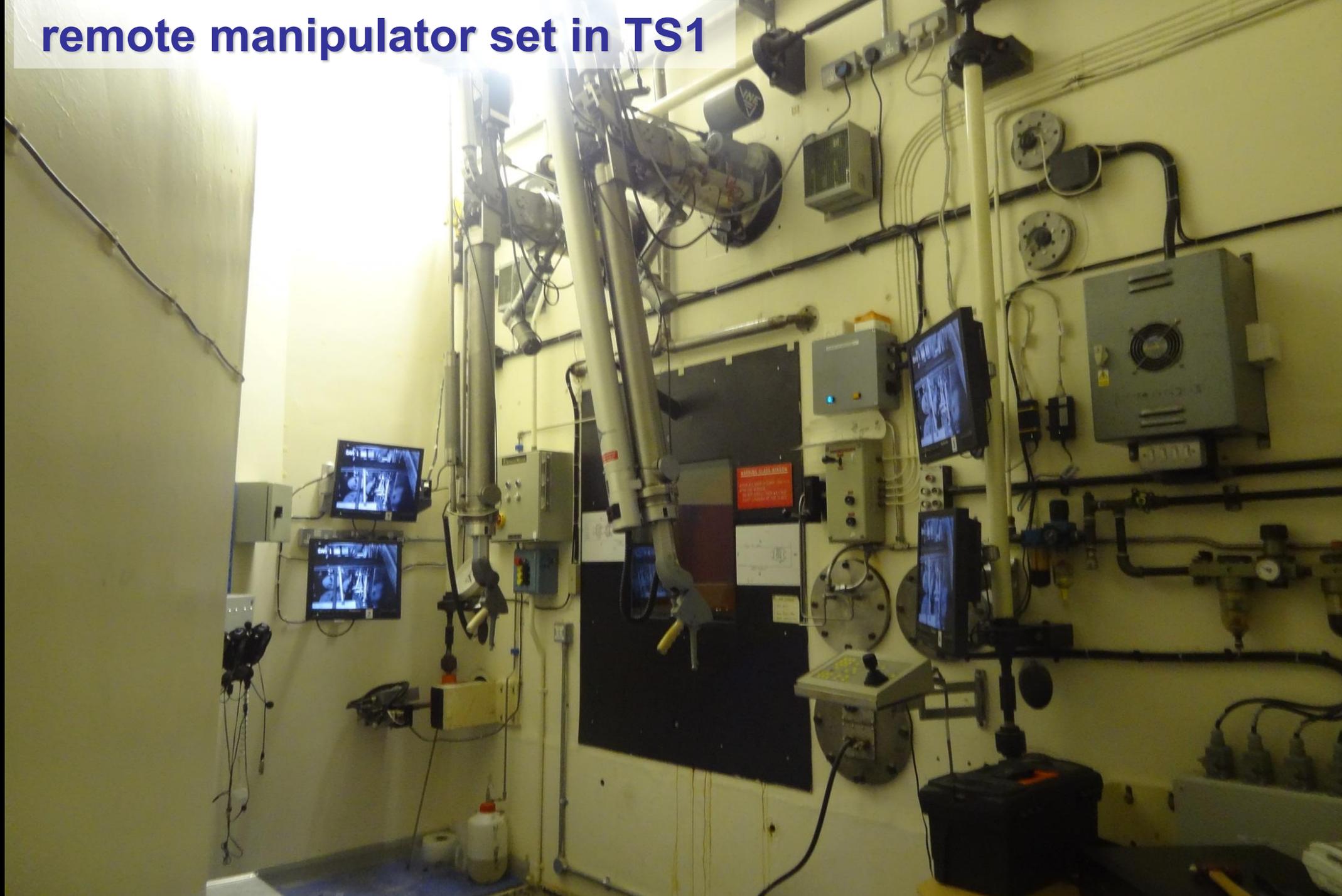


The TRAM is just one part
of the target trolley

ISIS Target Trolley



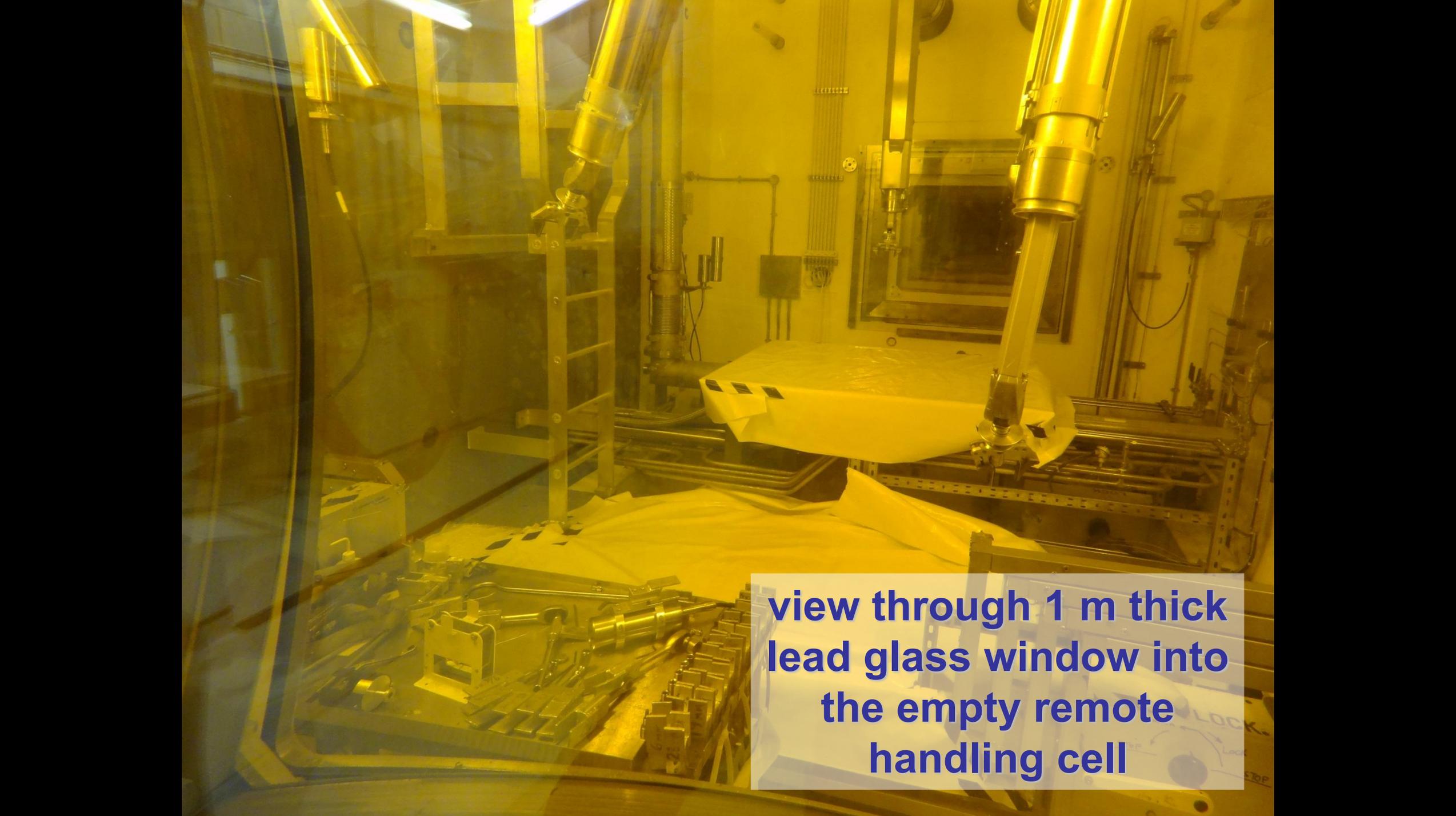
remote manipulator set in TS1



staff in contact by headset

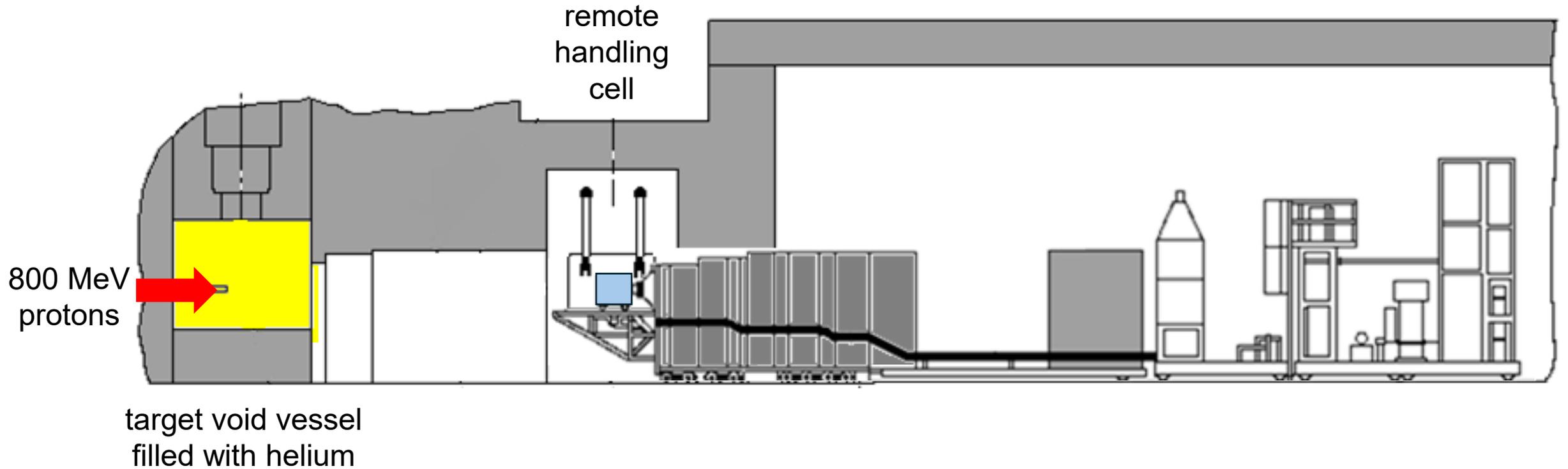
remote manipulator sets on both sides of the remote handling cell





**view through 1 m thick
lead glass window into
the empty remote
handling cell**

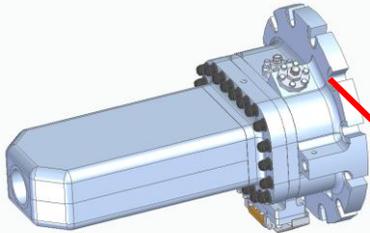
ISIS Target Trolley



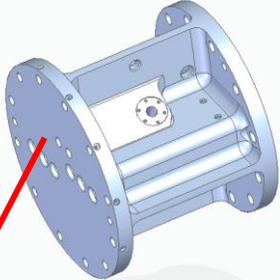
ISIS Target Trolley



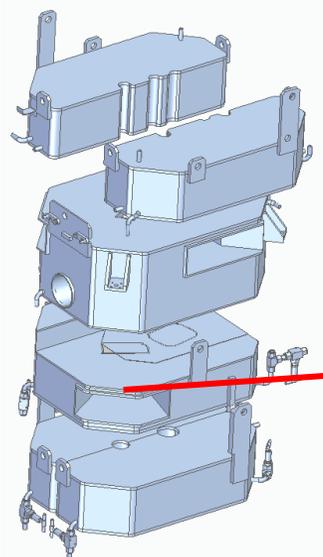
ISIS TS1 Target, Reflector and Moderator- Activity levels



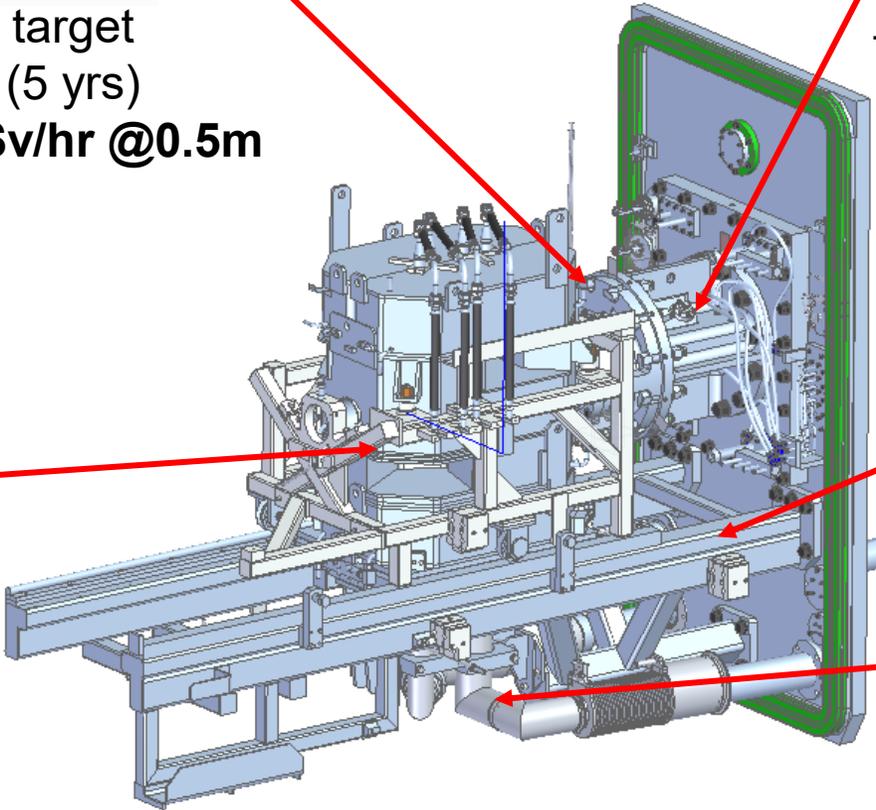
target
(5 yrs)
125 Sv/hr @0.5m



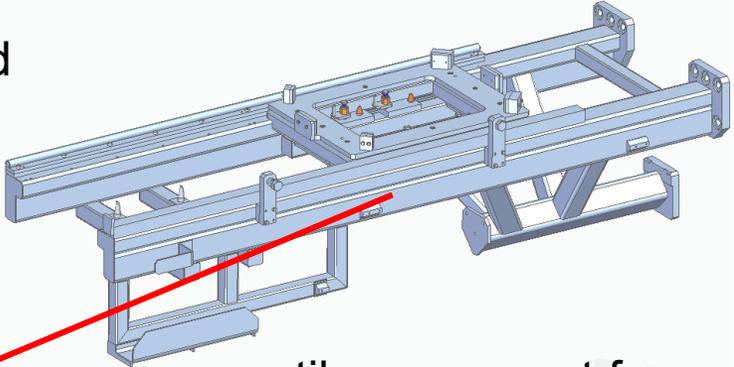
target manifold
5.6 Sv/hr



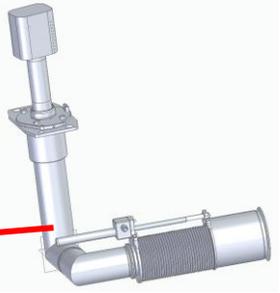
beryllium reflector
(18 yrs)
21.4 Sv/hr



contact doses (unless specified)



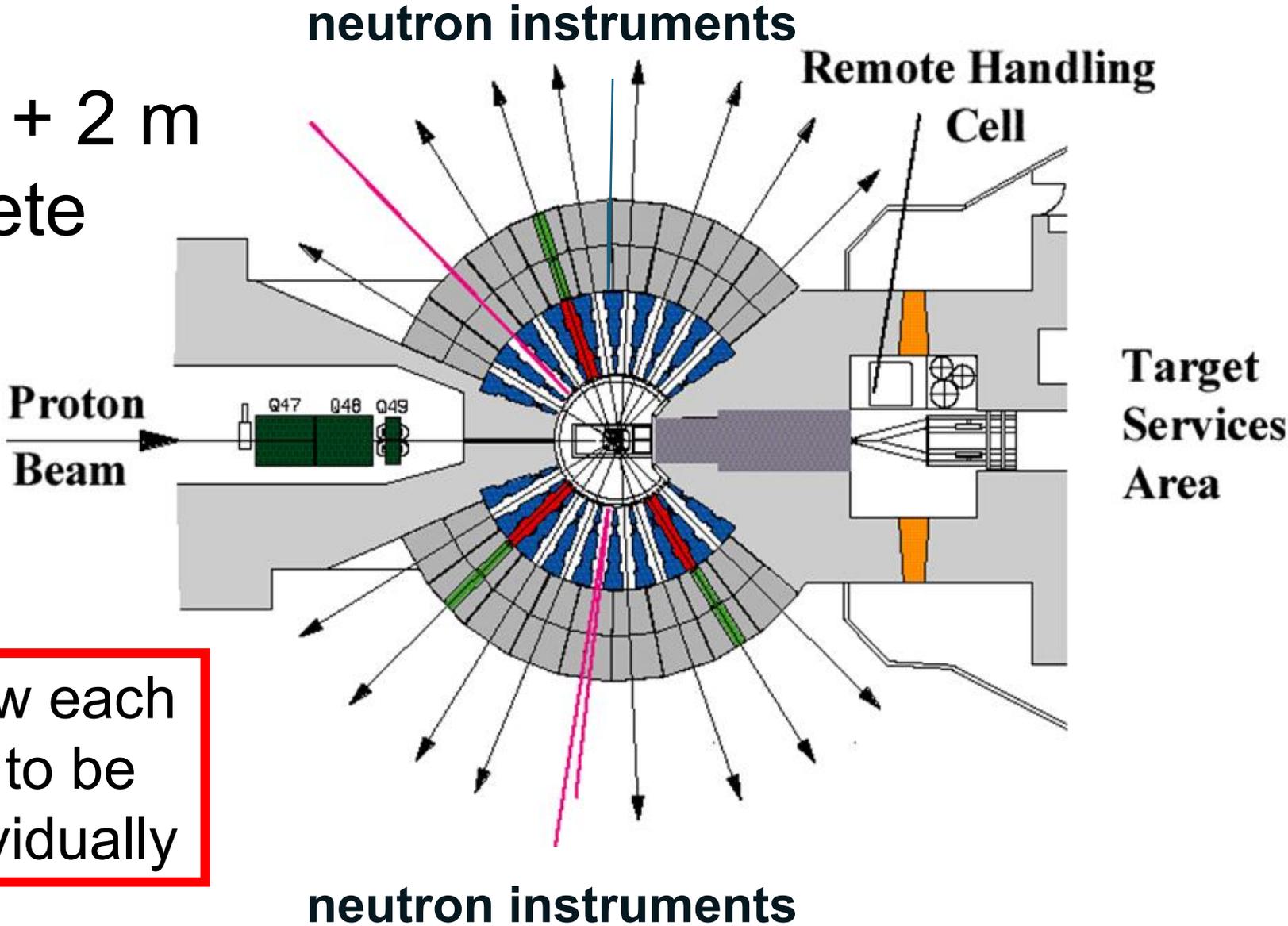
cantilever support frame
(37 yrs)
4.31 Sv/hr



hydrogen moderator
(14 yrs)
6.15 Sv/hr

Shielding

2 m steel + 2 m concrete

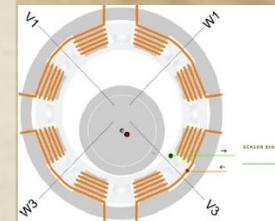


Choppers



**spinning
shielding
shutters**

**magnetically
levitating
bearings**



**precise
timing**

Choppers

Fermi (17)

7.3 kg payload

36,000 rpm

$\pm 0.05^\circ$ phase control

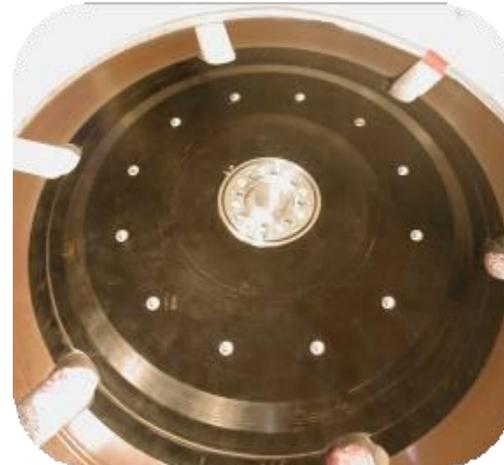
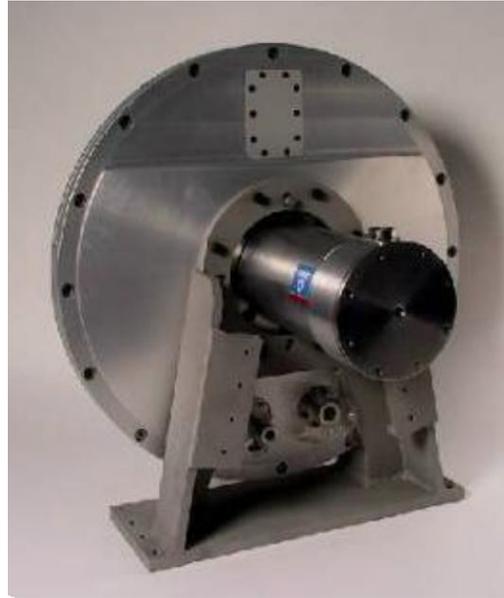


Disk (56)

30 kg payload

20,000 rpm

$\pm 0.05^\circ$ Phase Control



T-Zero (4)

68 kg payload

10,800 rpm

$\pm 0.43^\circ$ phase control



Methane moderator replacement



The main remote handling task is CH₄ moderator replacement
Every 3-4 cycles (more than once a year)



Target replacement

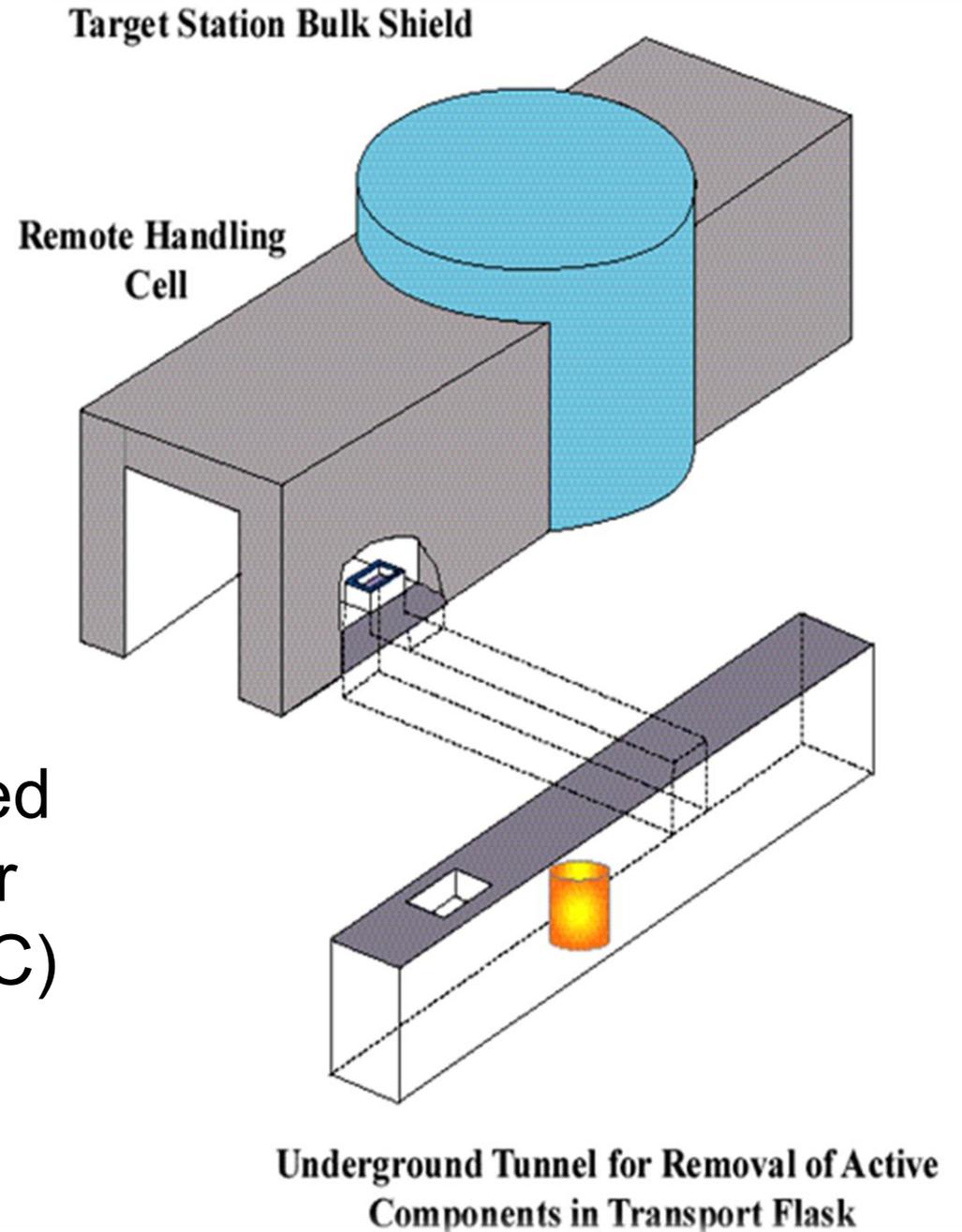


Targets also need to be replaced every 4-5 years

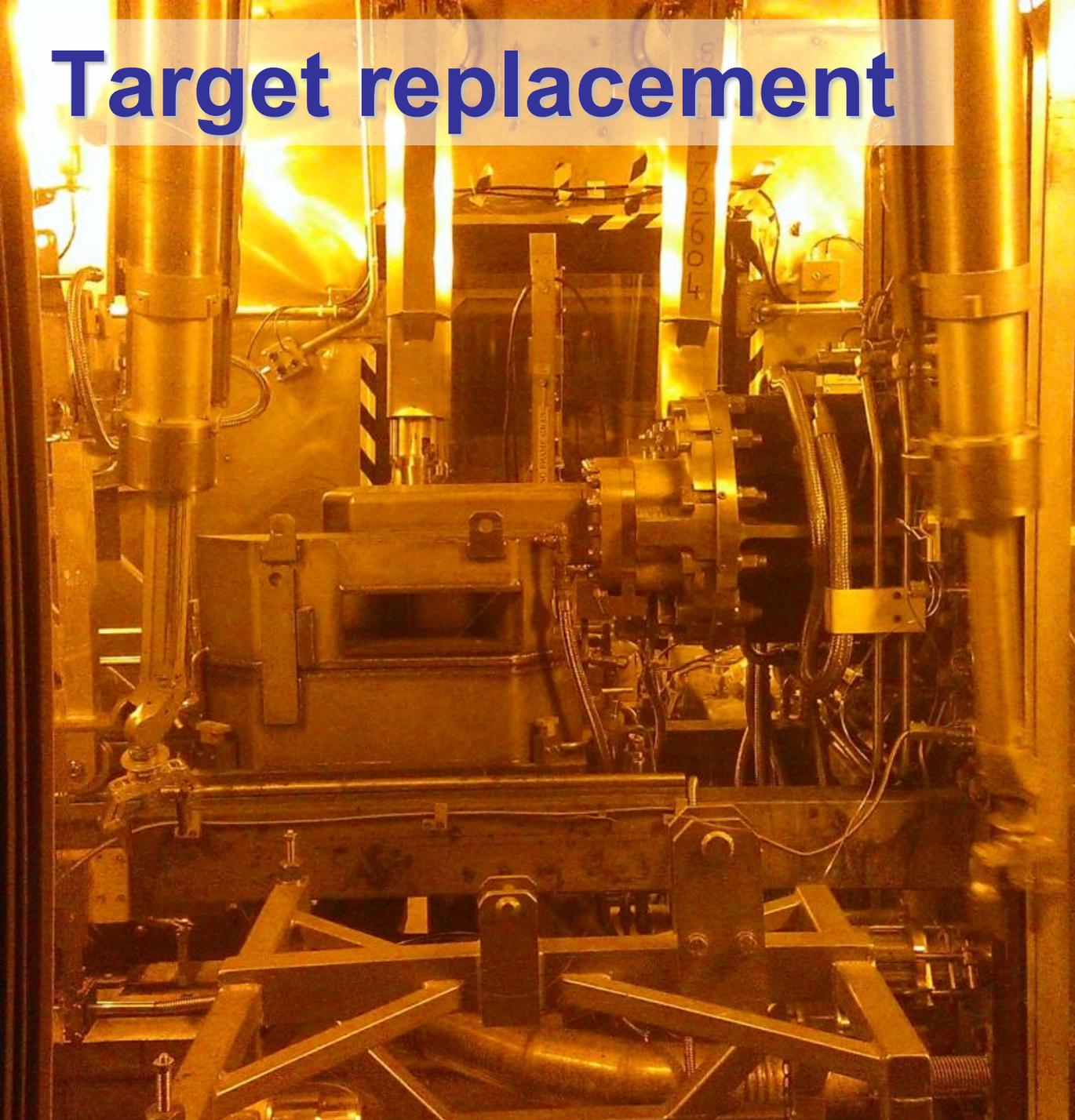
TS1 Tungsten
Target #4 on flow
test rig

Target replacement

Active components are removed using the tunnel system under the Remote Handling Cell (RHC)



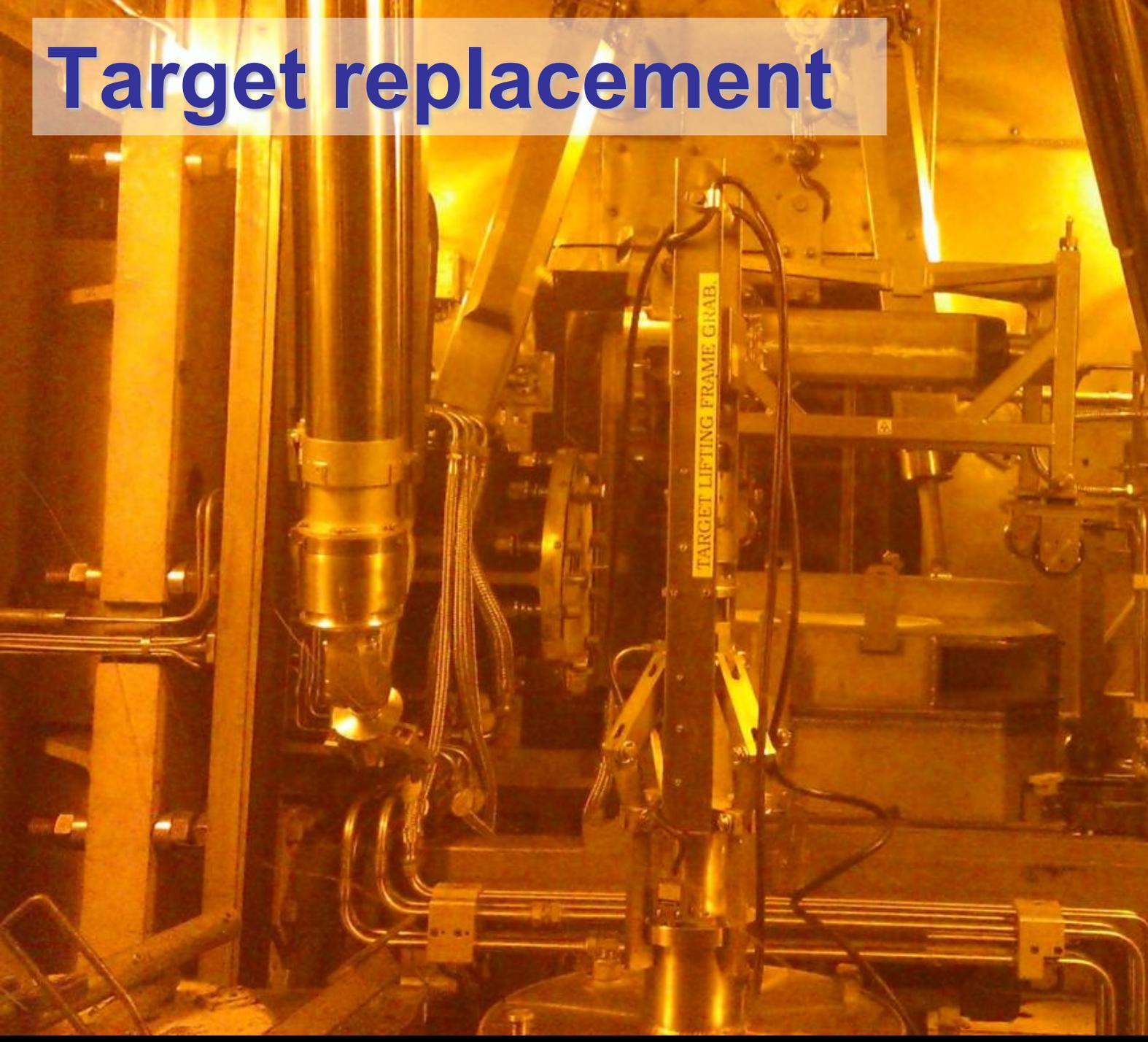
Target replacement



View of the TS1 TRAM
withdrawn into the RHC

The reflector top
section is rolled forward
to expose the target

Target replacement



The target has been disconnected and is being lifted away from its working position

Target replacement



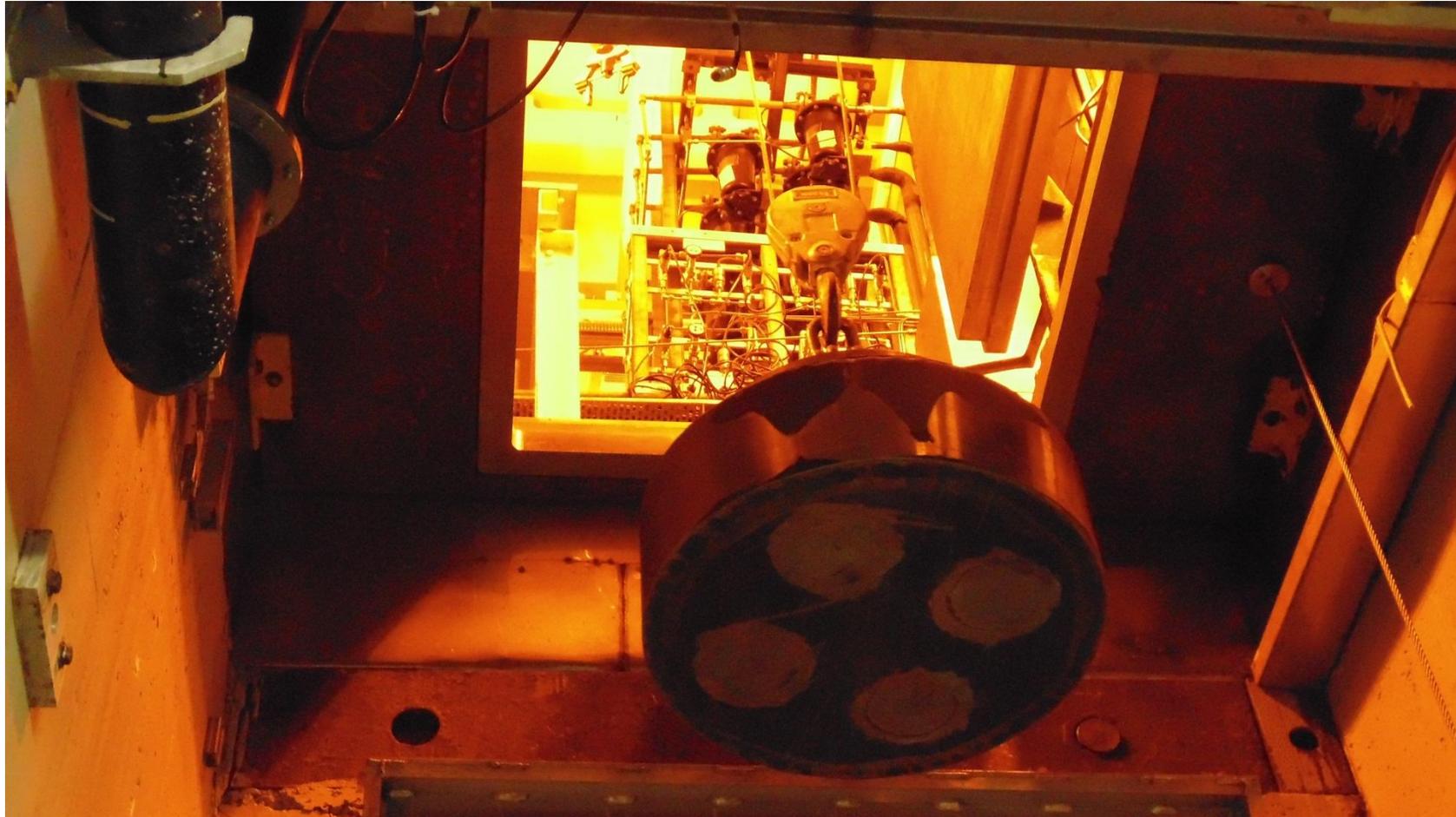
The target being lifted over to the disposal can on the south side of the RHC

Target replacement

Target and can being lowered into the transport flask



Target replacement



Shield plug is lowered onto flask
After the plug is fitted personnel can approach the loaded flask

Target replacement

The loaded flask is checked by ISIS Health Physics for external radiation and contamination



Target replacement



Storage flask total weight is 9 Tonnes

Flask is moved on a 'MasterMover'
powered pallet truck

Target replacement

The loaded flask is lifted out of the tunnel



Target replacement

The loaded flask is transported back to R40 for storage



Target replacement



After work in the RHC is complete the area must be cleared and checked

Personnel can enter the RHC when the TRAM is in the forward position

Full suit, gloves, overshoes and respirator are required for this work



Target replacement

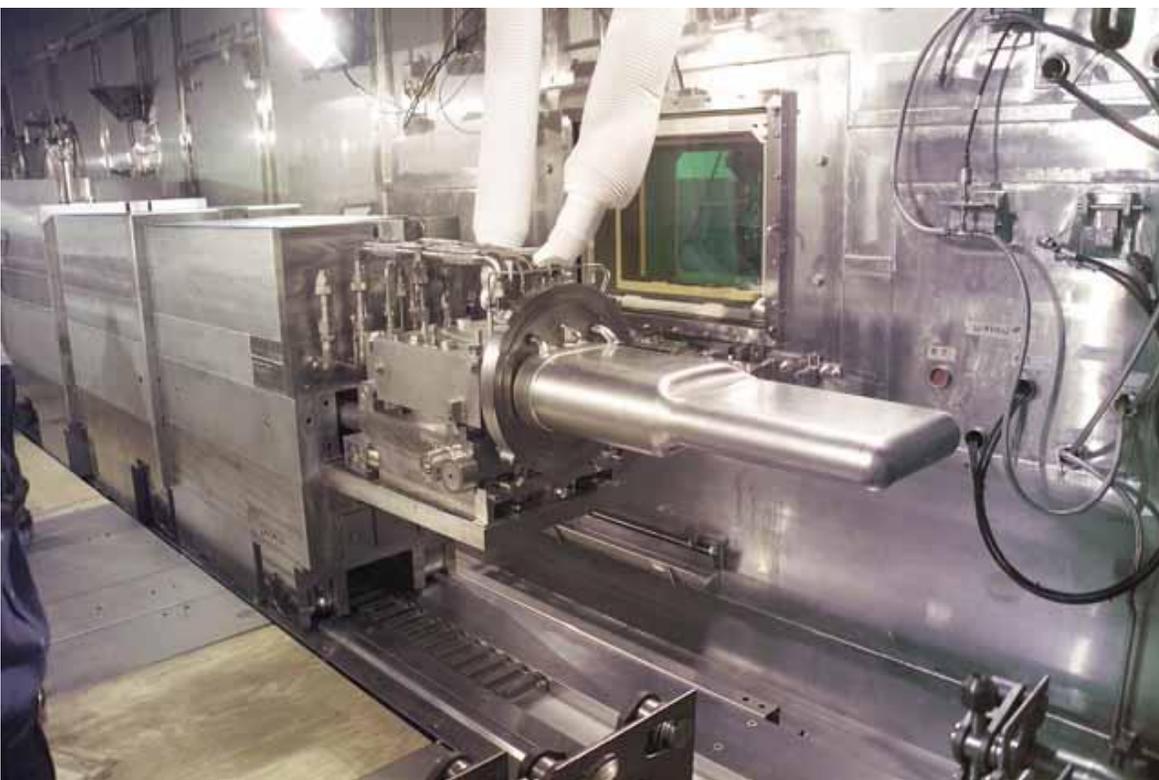
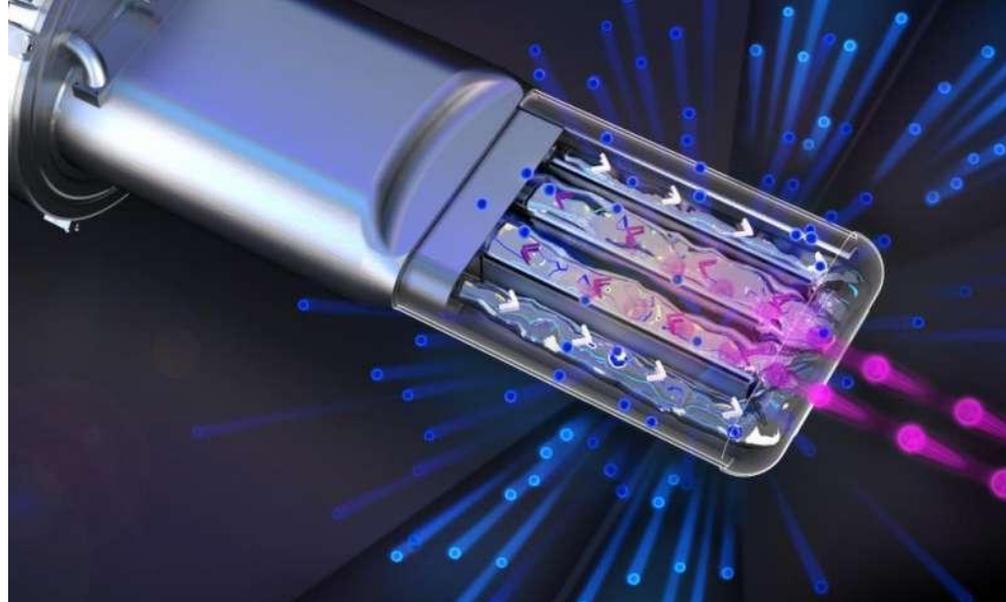


For final disposal the target is transferred to a registered and licenced Type B package and transported to Sellafield the UK's nuclear waste storage facility

More neutrons!

- ISIS 160 kW on target
- More power = more neutrons
- The power must be removed somehow
- SNS Oakridge USA = 1.4 MW





1.4 MW liquid mercury target





AR 500
AR 500

Close-up of Damage to Target Inner Window (center of beam entrance area)

**Cavitation
bubble collapse
causes serious
damage**



**solution: fizzy mercury with
helium**

RR 010 RR
RR RR

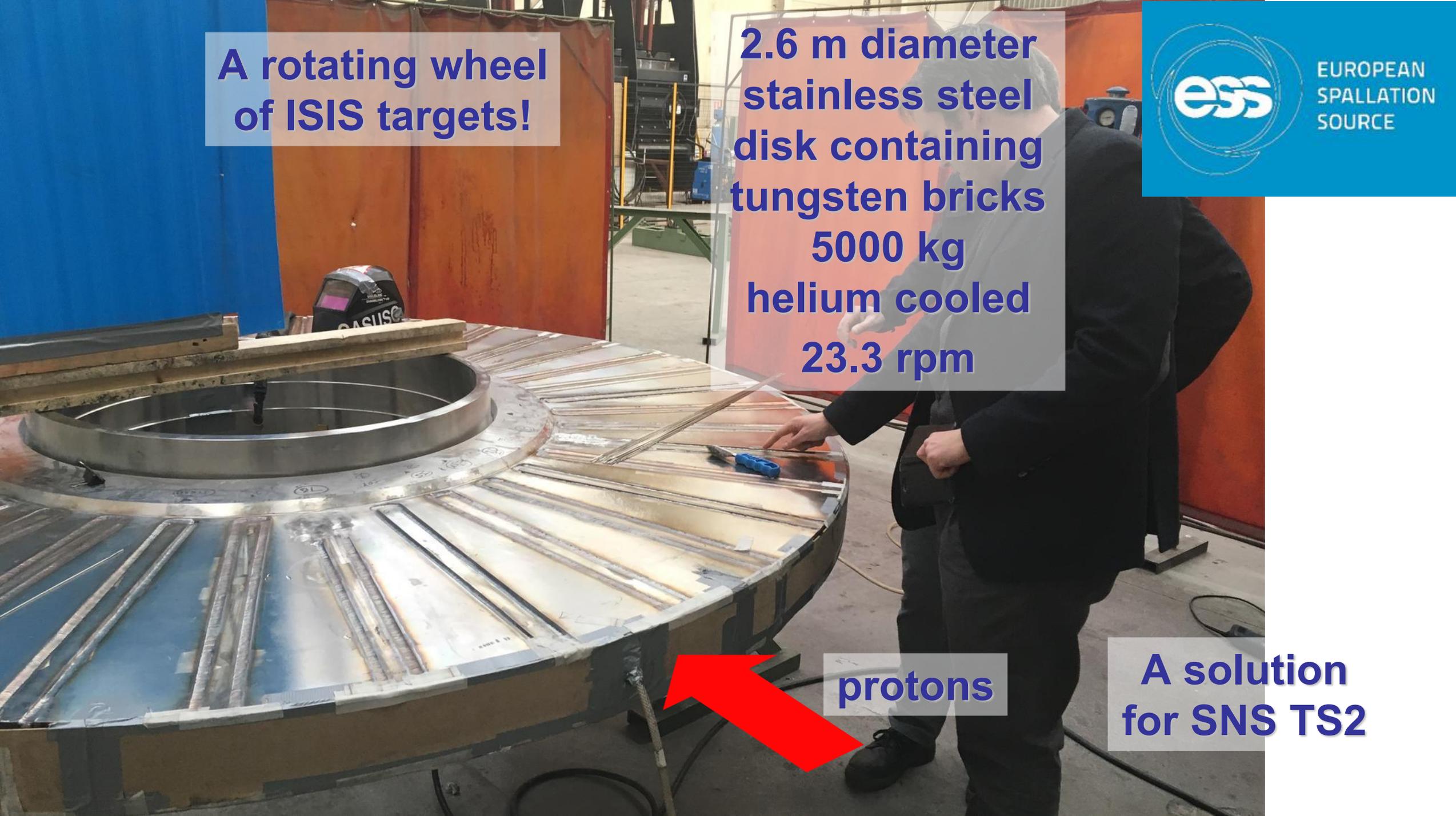
ESS currently under construction

3 MW on target!



**A rotating wheel
of ISIS targets!**

**2.6 m diameter
stainless steel
disk containing
tungsten bricks
5000 kg
helium cooled
23.3 rpm**



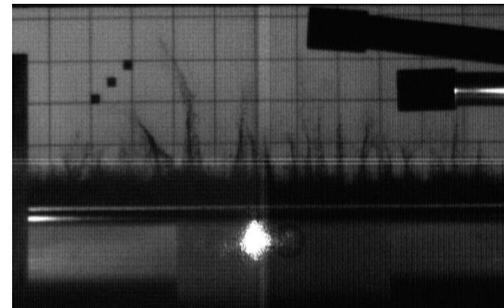
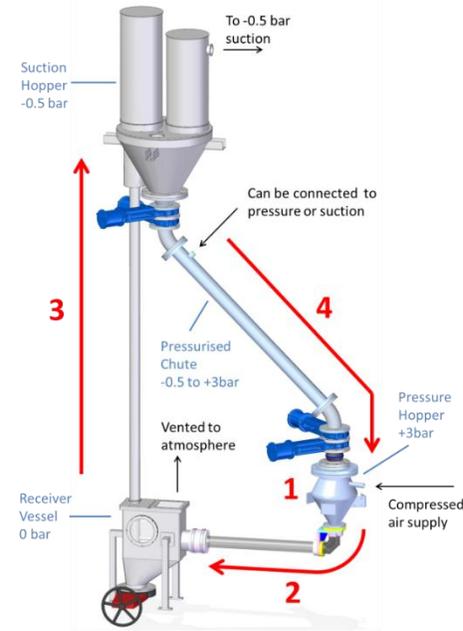
protons

**A solution
for SNS TS2**

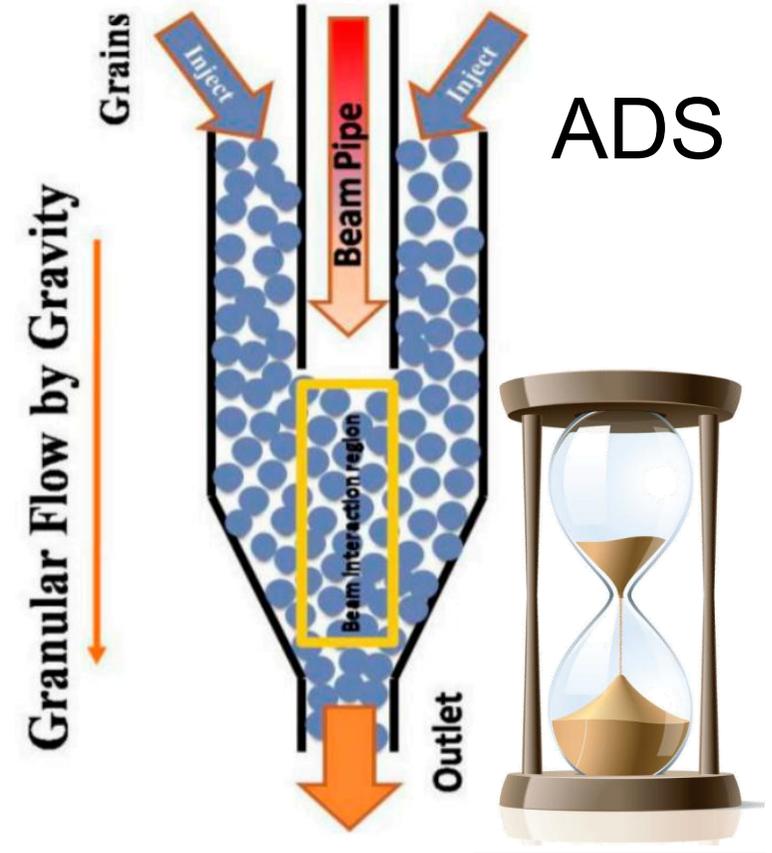
Even more power!



Tungsten powder handling system developed at RAL



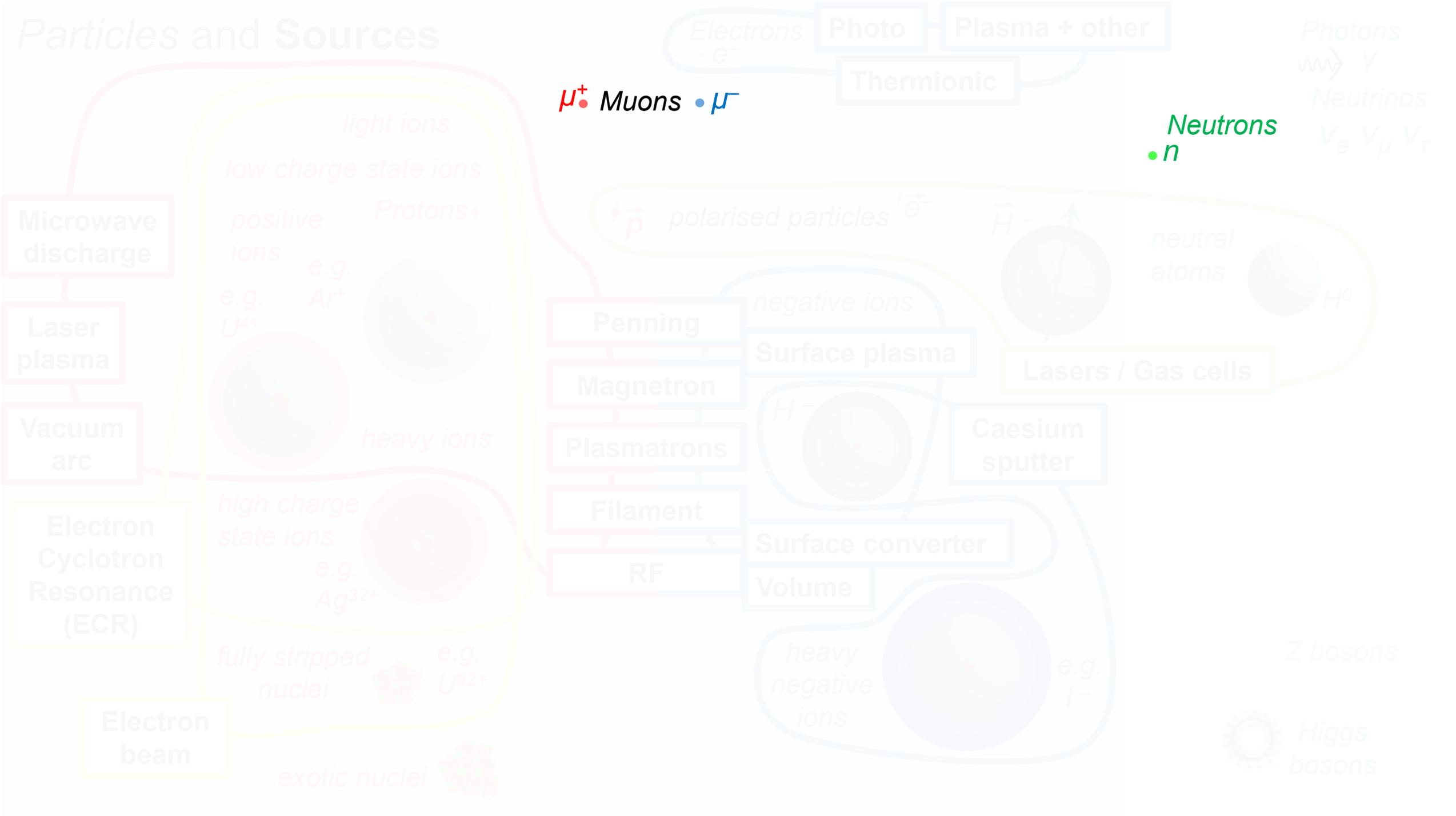
Tests at CERN



中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

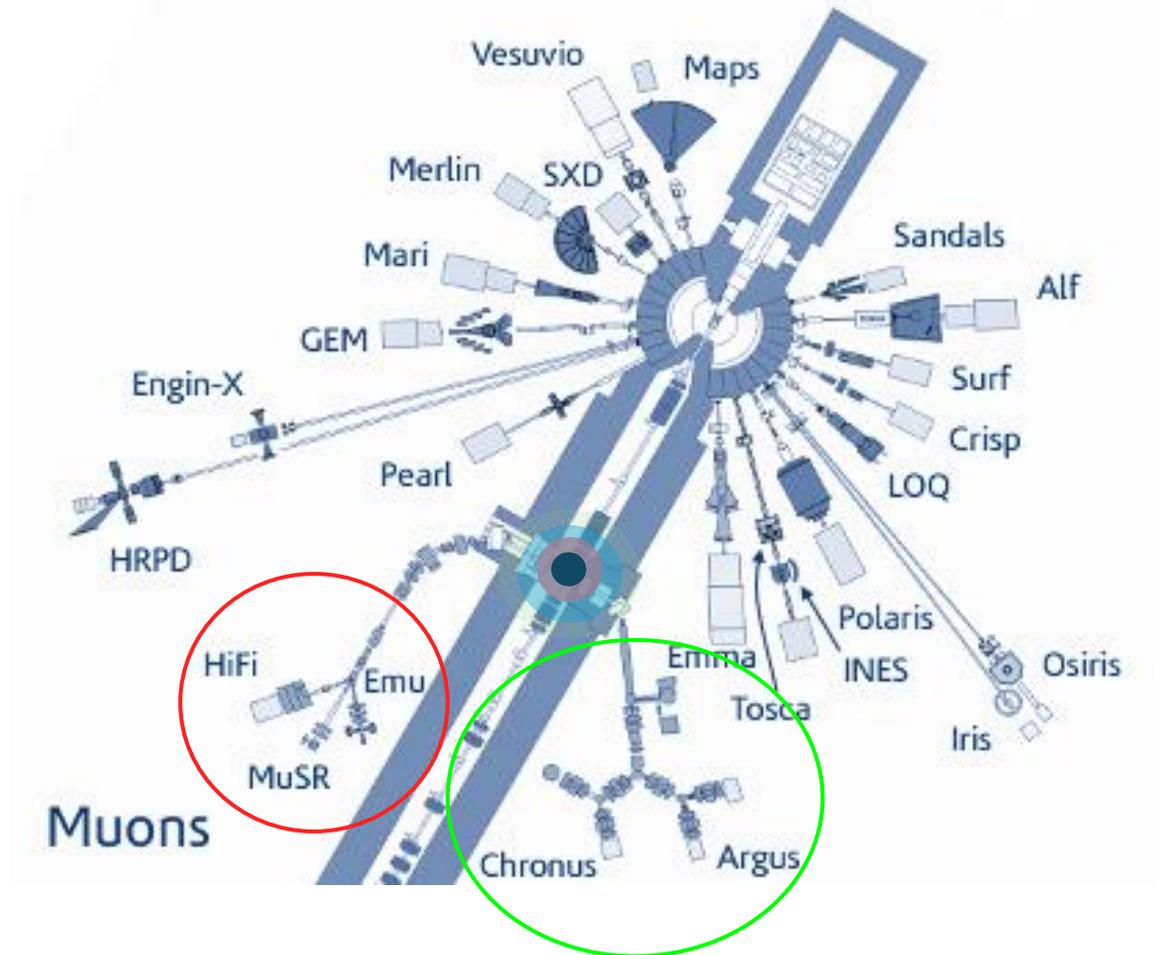
10 -100 MW!

Particles and Sources



Muons at ISIS

Target Station 1



7 muon instruments

EC muon facility:

- +ve muons
- Three spectrometers for materials studies

RIKEN-RAL muon facility:

- +ve or -ve muons
- Variable momentum
- Two spectrometers for materials studies
- Low energy muon development
- Other fundamental muon physics experiments

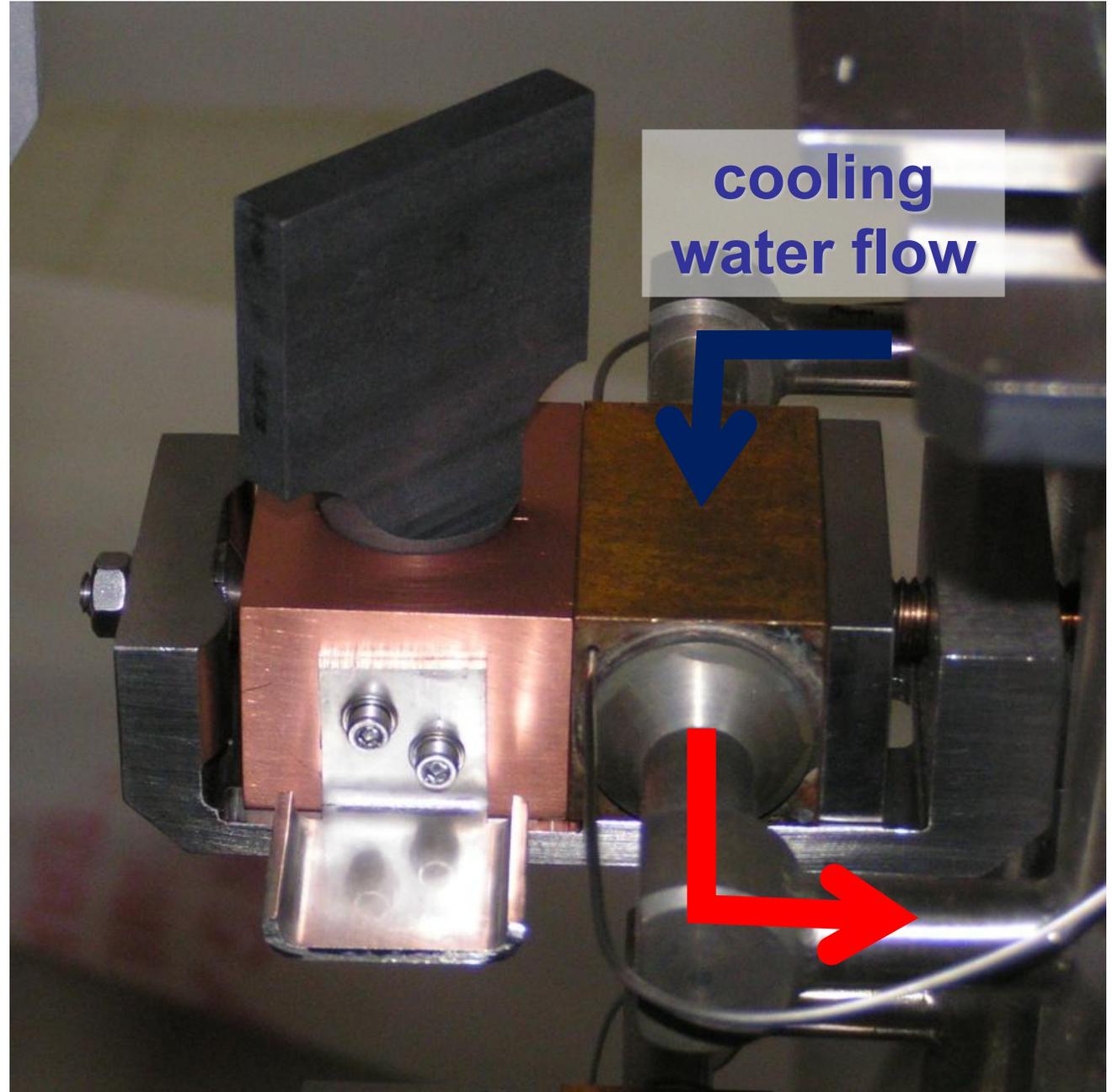
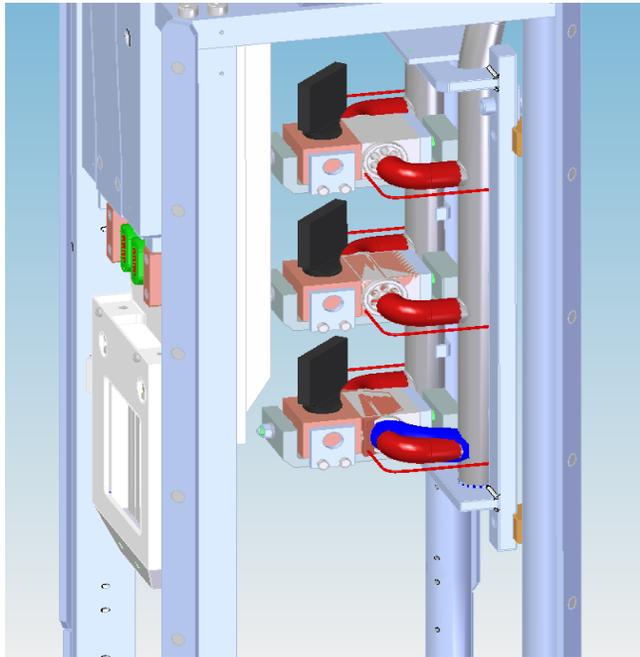
ISIS Muon Target

10 mm thick graphite target at 45° to the 800 MeV proton beam

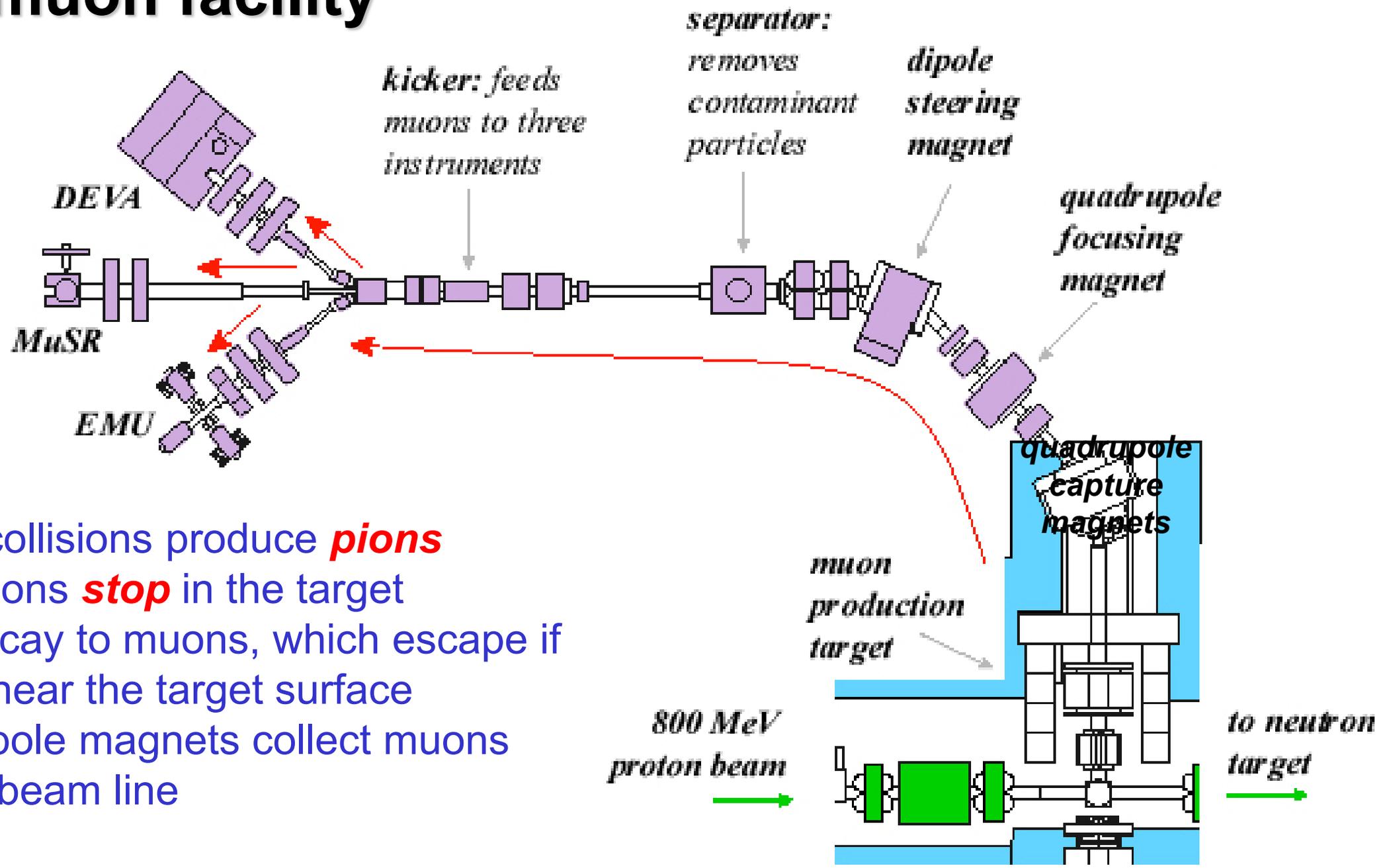
About 5% beam lost

Diffusion bonded to copper to maximise thermal contact

10 kW maximum heat load

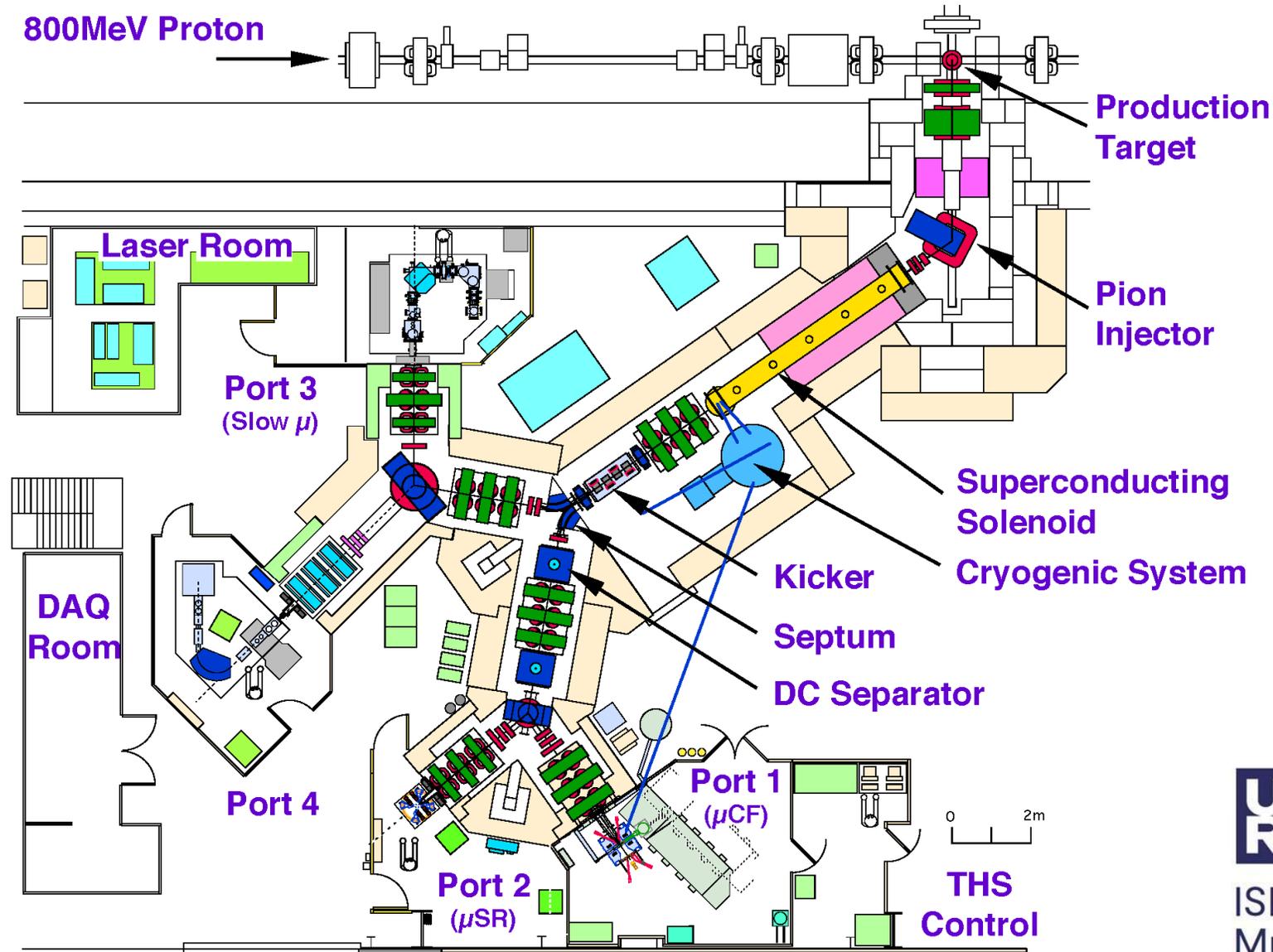


The EC muon facility

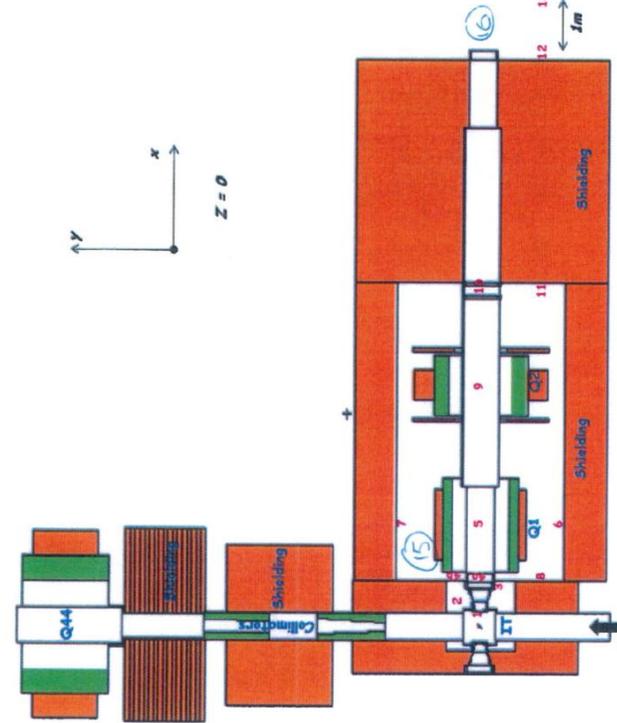
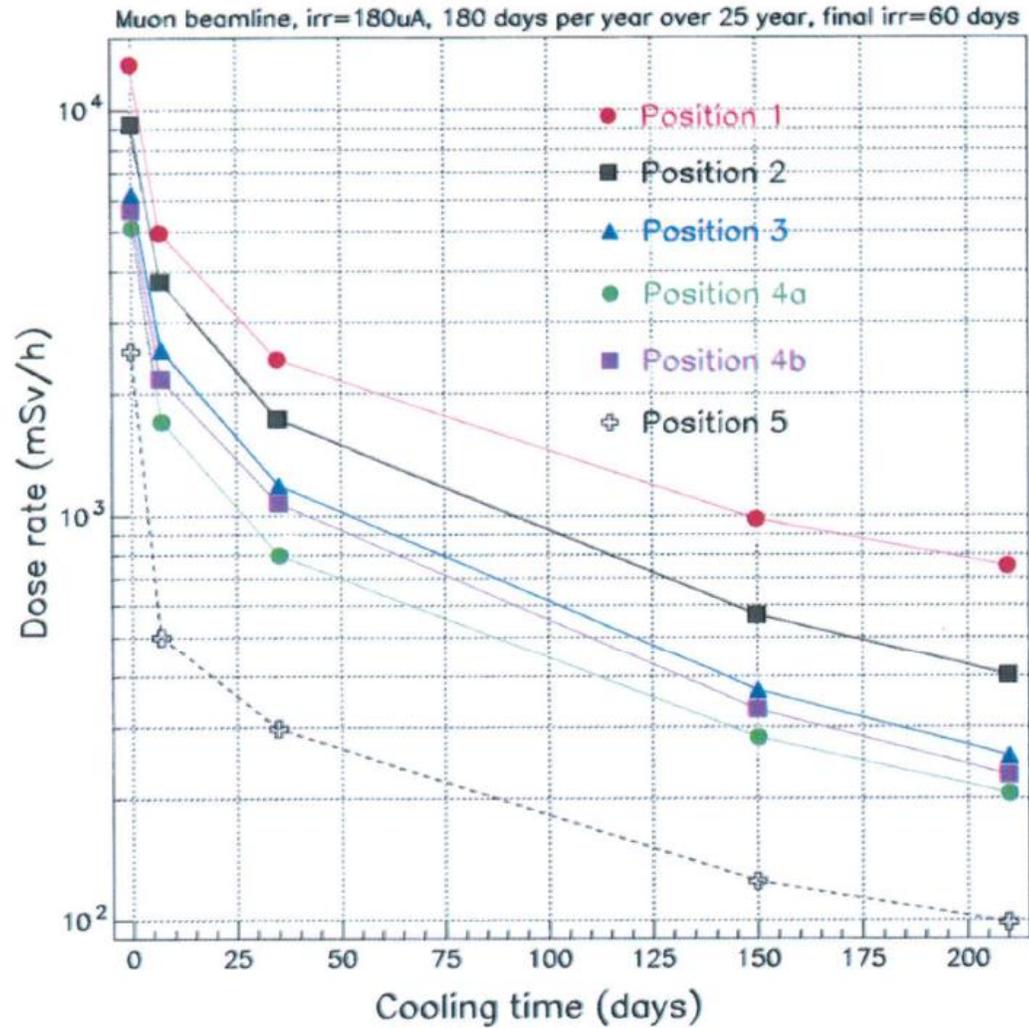


- Proton collisions produce **pions**
- Some pions **stop** in the target
- They decay to muons, which escape if formed near the target surface
- Quadrupole magnets collect muons into the beam line

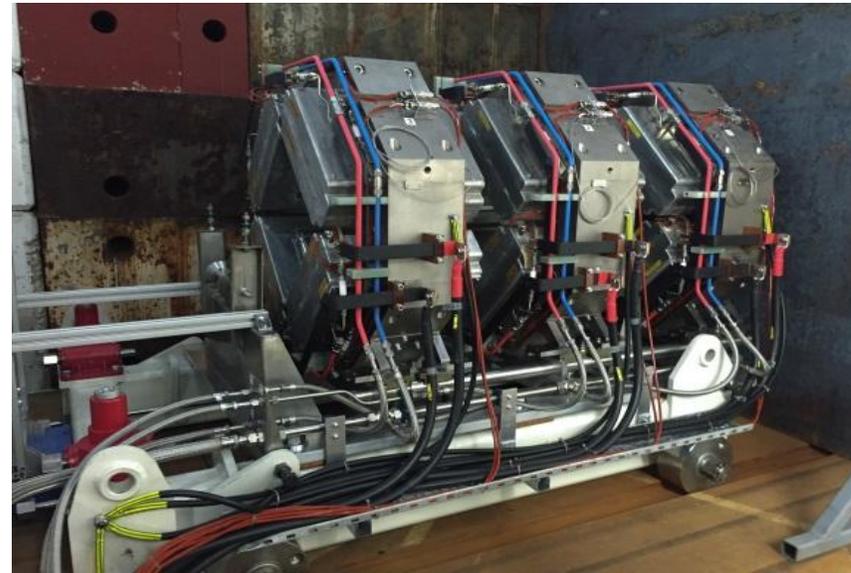
RIKEN-RAL muon facility



Radiation levels

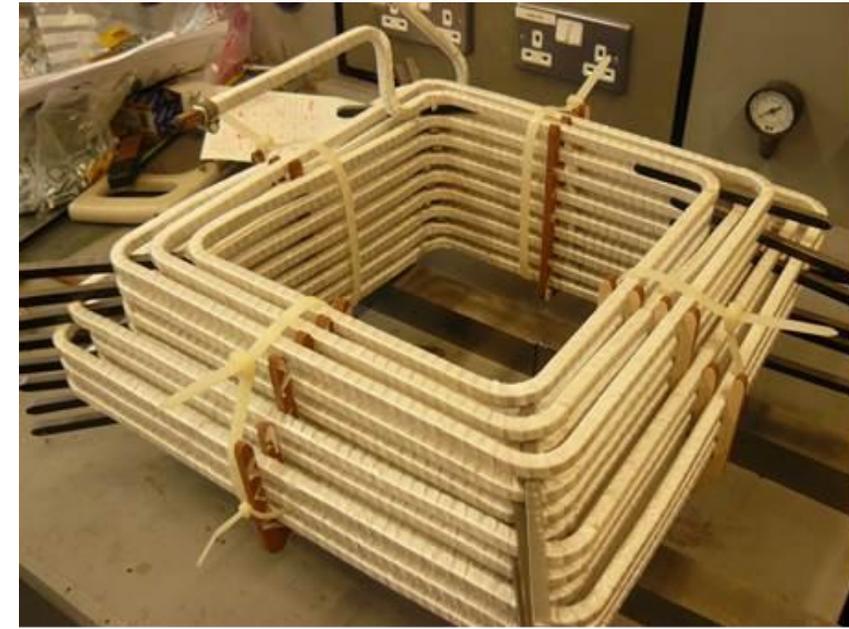
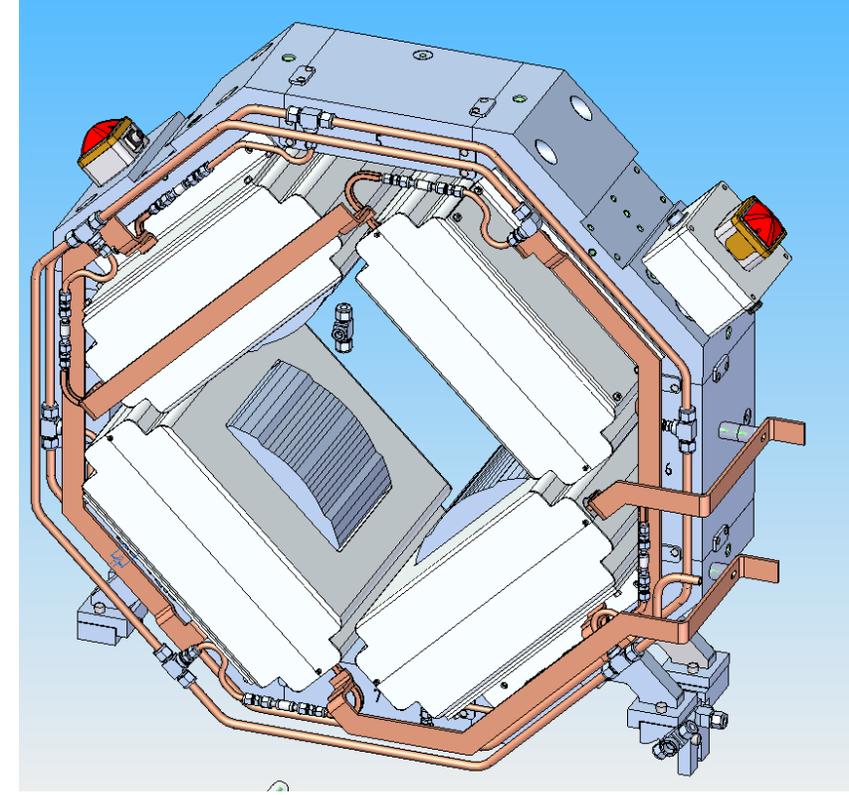
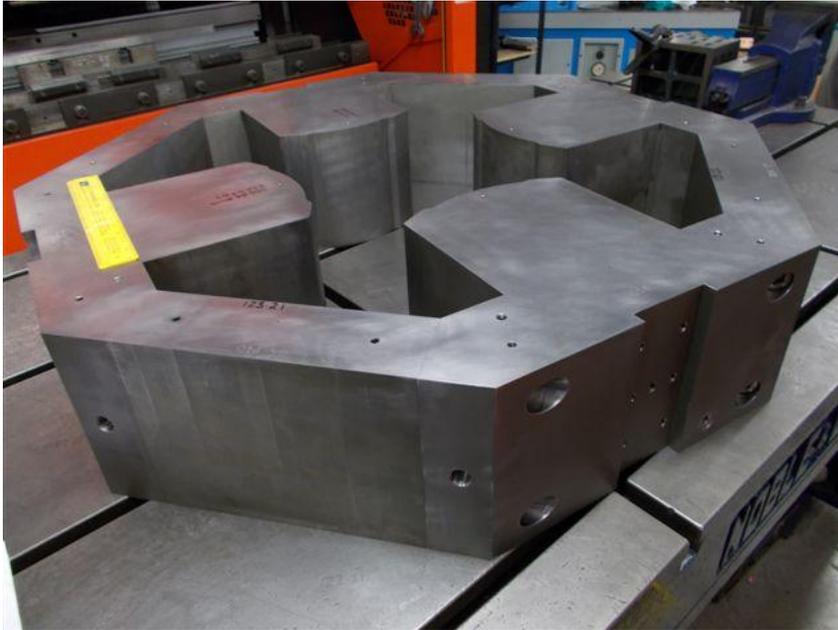


Radiation Hard Magnets

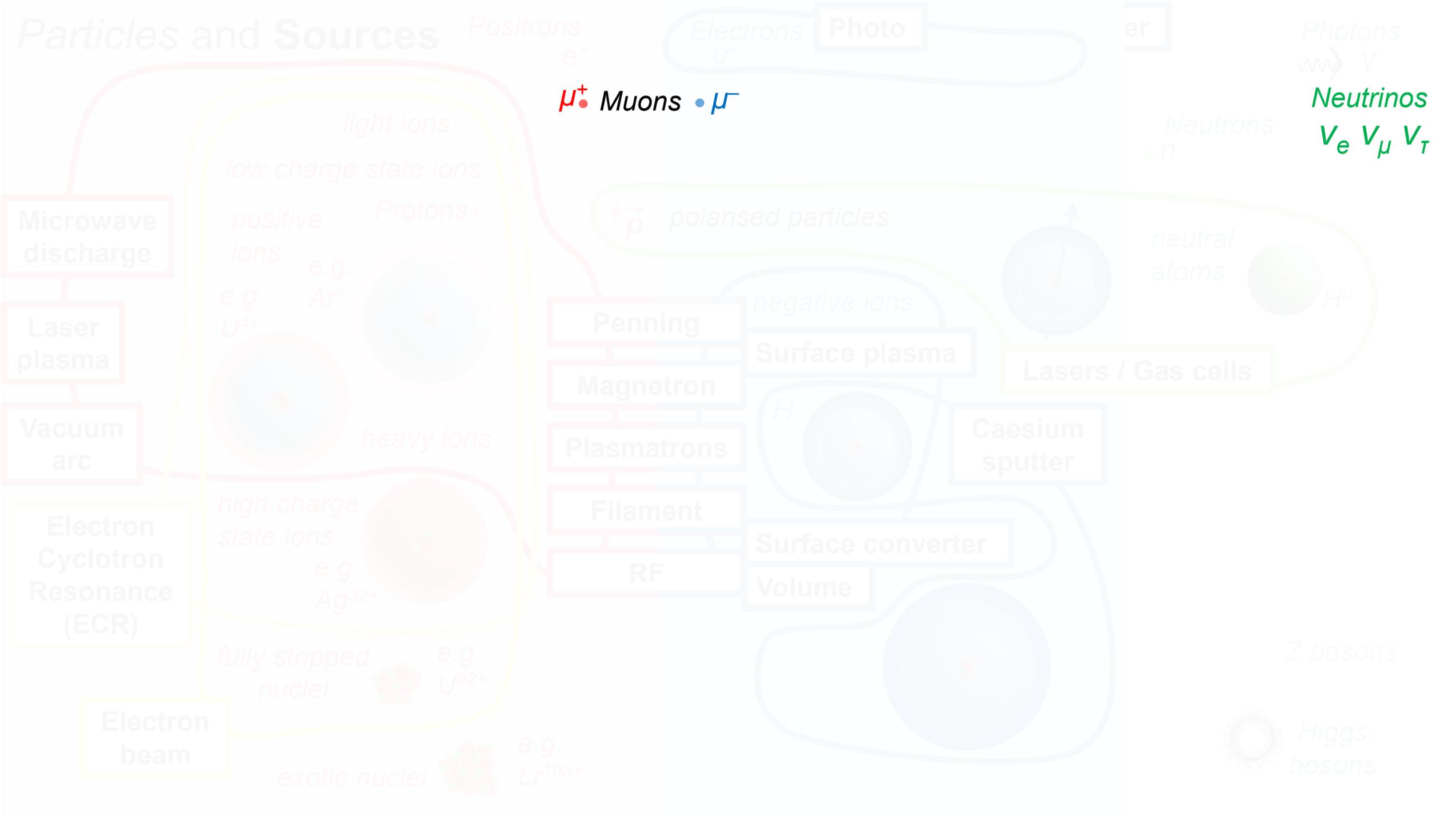


Radiation Hard Magnet Design

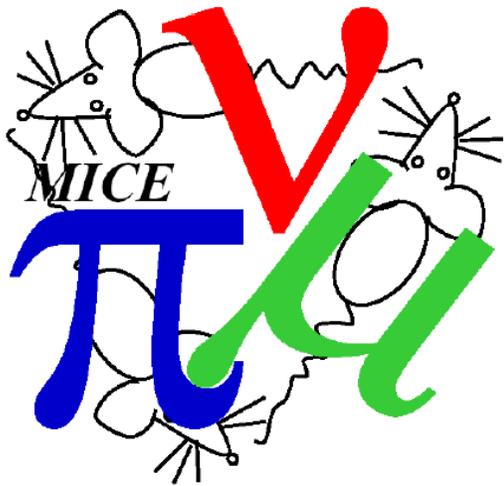
- In house concrete magnet design
- Coils potted in concrete
- Water cooled



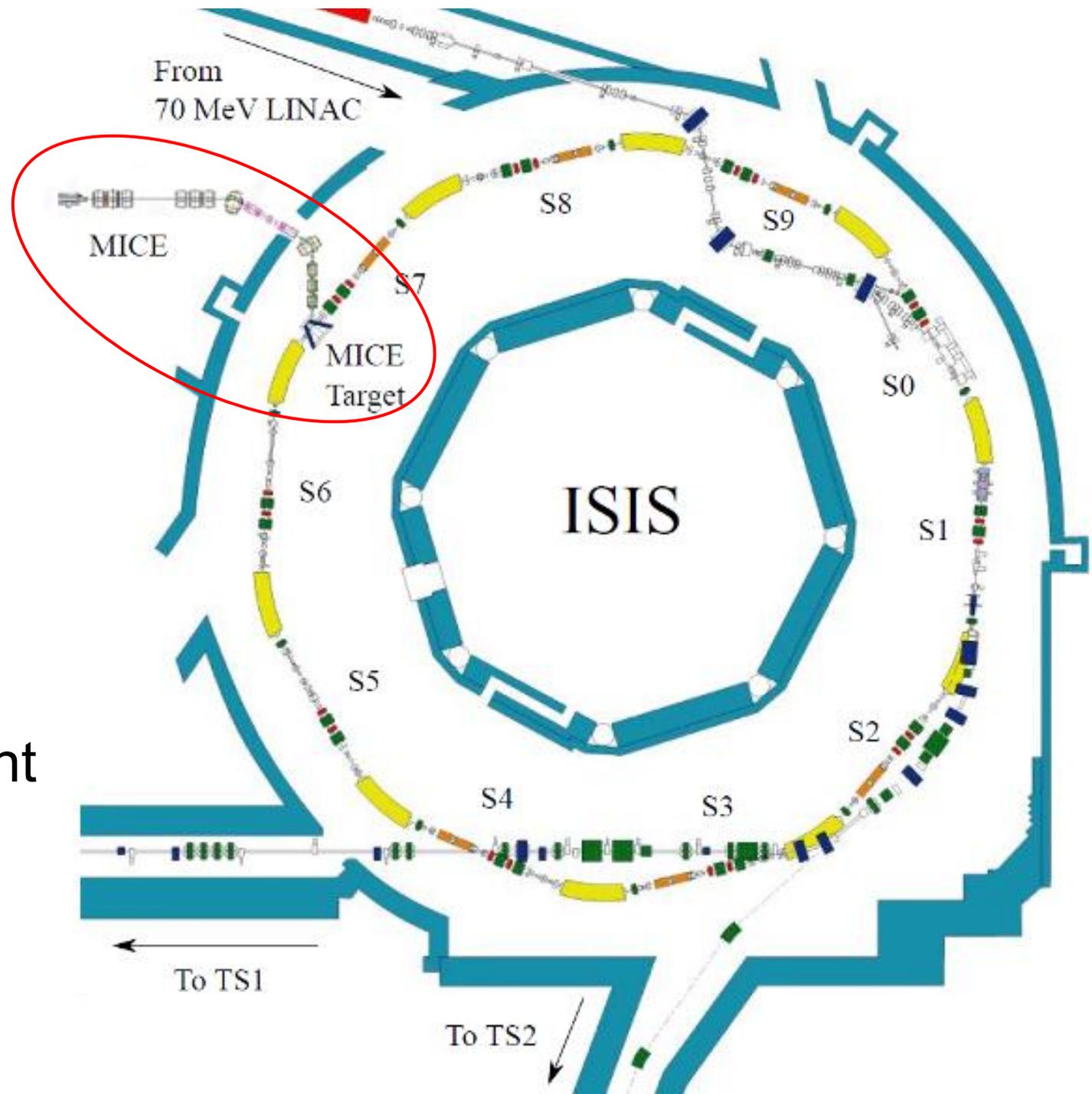
Particles and Sources



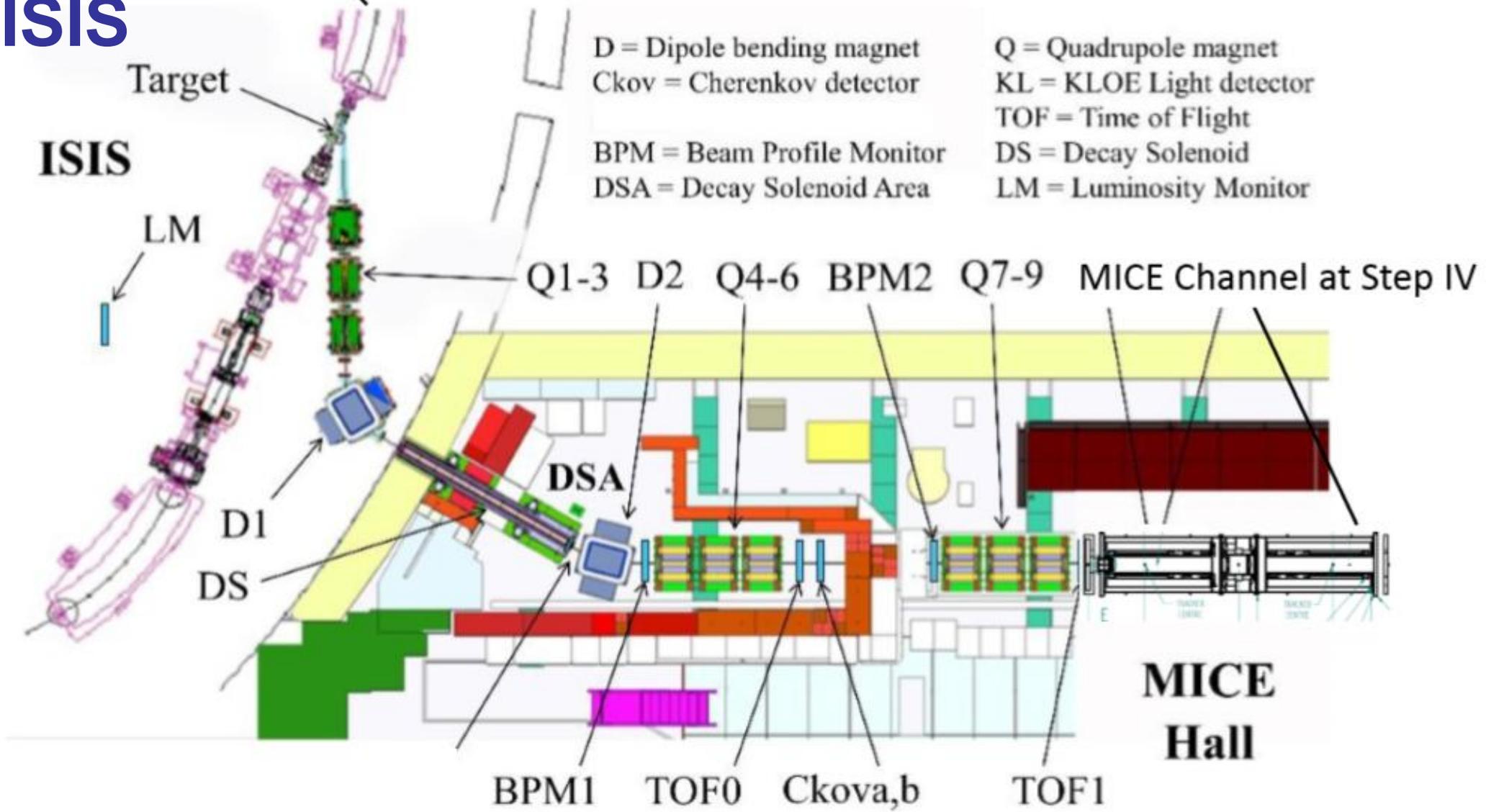
MICE @ ISIS



Muon
Ionisation
Cooling
Experiment



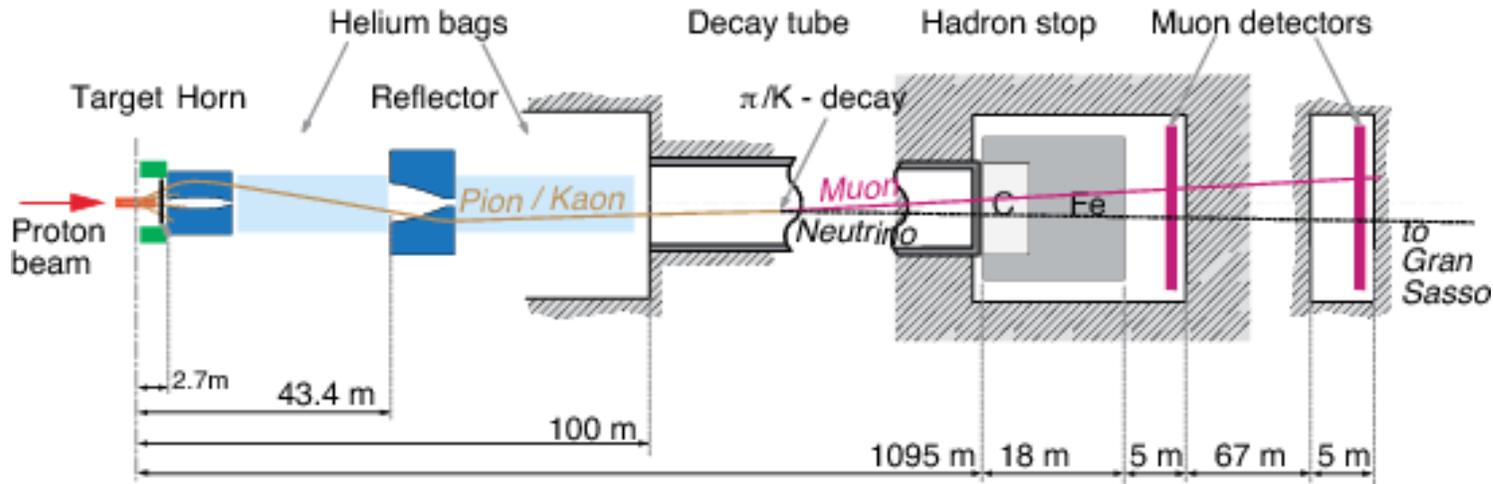
MICE @ ISIS



MICE Beamline
Conceptual Layout

Mice demonstrated muon cooling in 1D

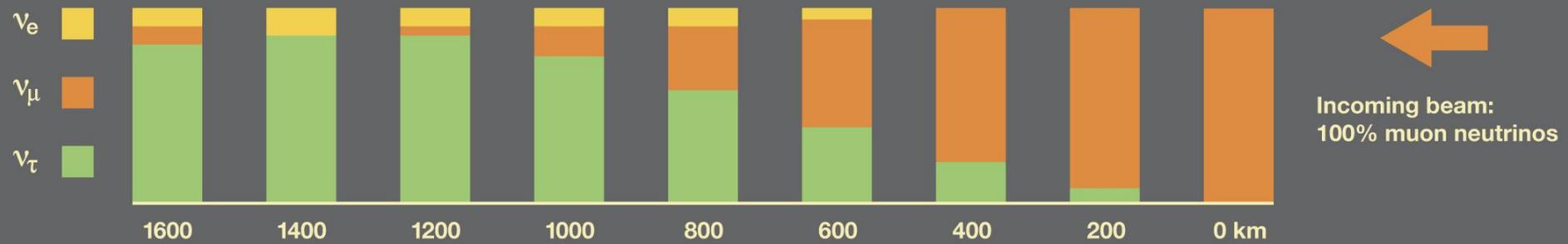
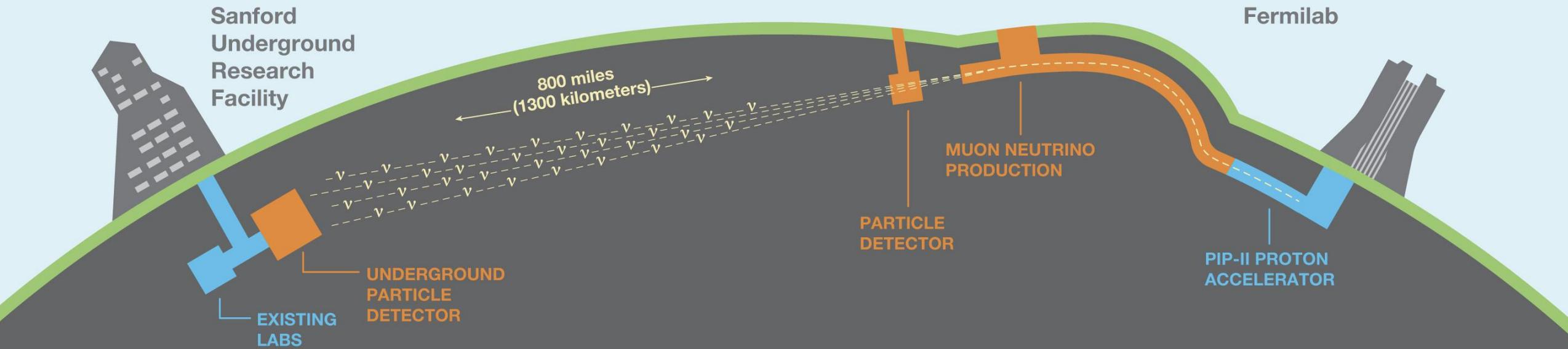
CERN Neutrinos to Gran Sasso (CNGS)



732 km

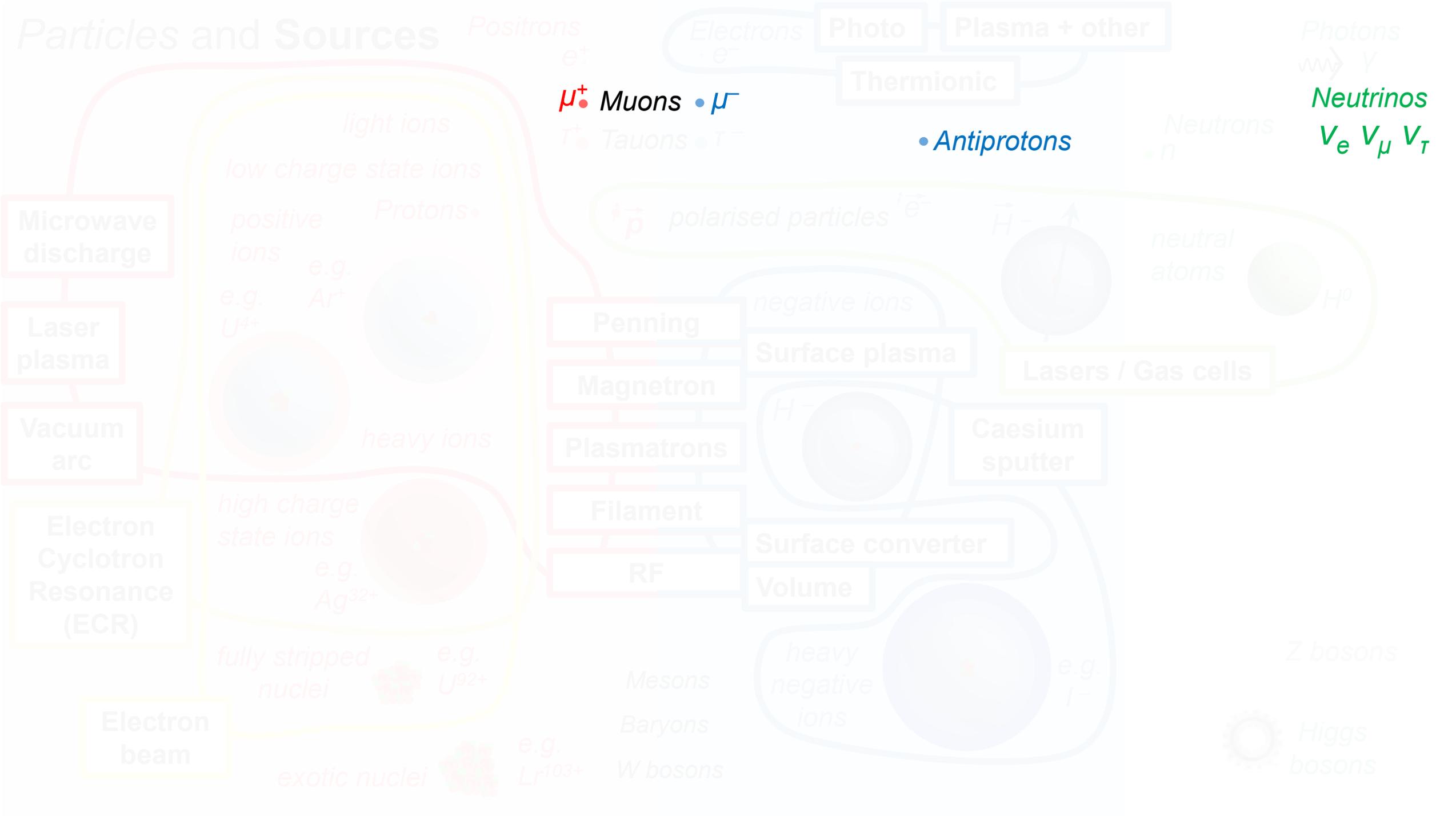


Deep Underground Neutrino Experiment



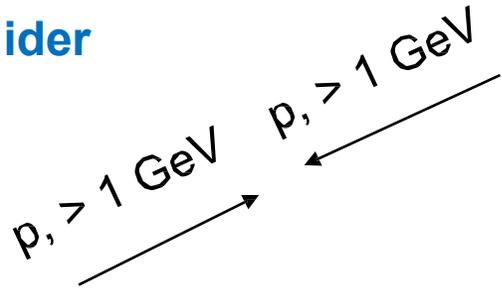
Probability of detecting electron, muon and tau neutrinos

Particles and Sources

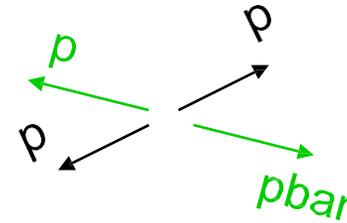


Creation of Antiprotons

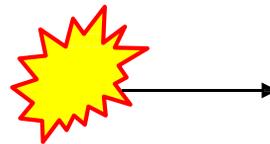
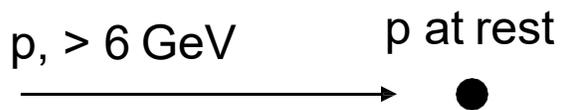
Collider



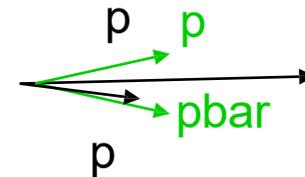
$$m = E / c^2$$
$$m_p = m_{pbar} \approx 1 \text{ GeV} / c^2$$



Target



$$m = E / c^2$$
$$T_{pbar} > 6 \text{ GeV}$$



Magnetic horn



Simon van der Meer 1960s

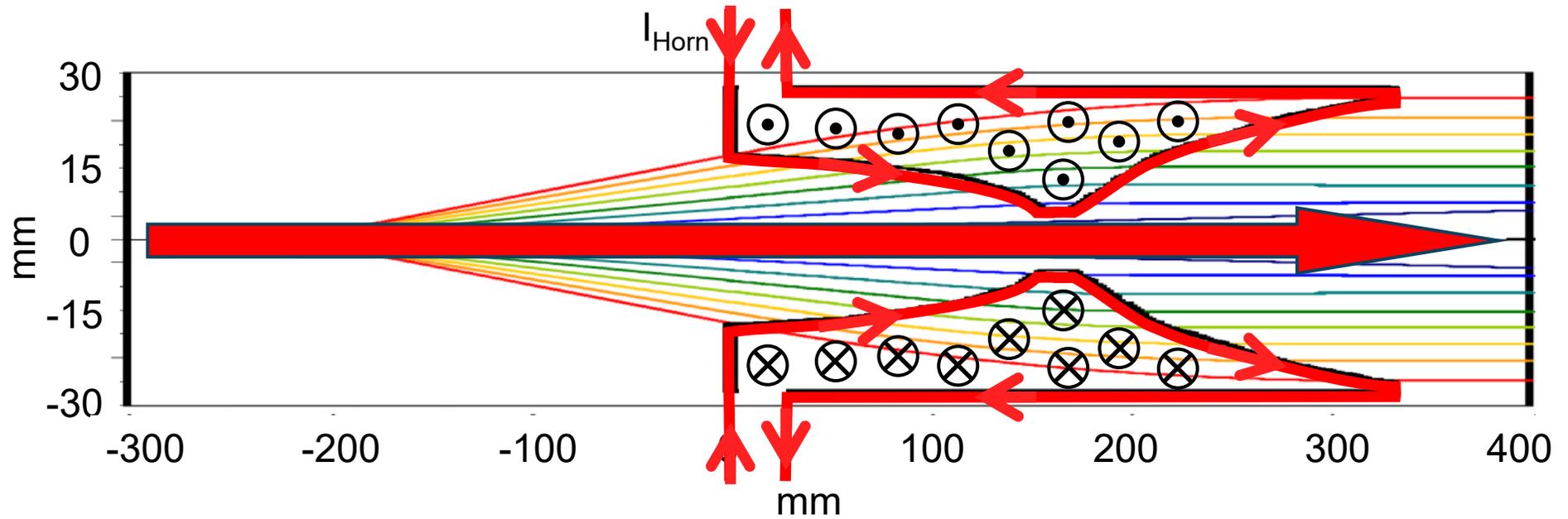
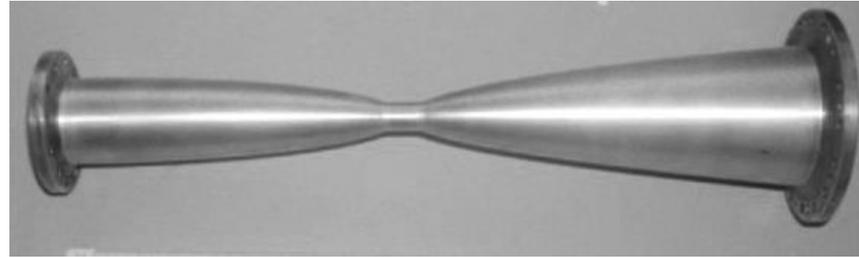
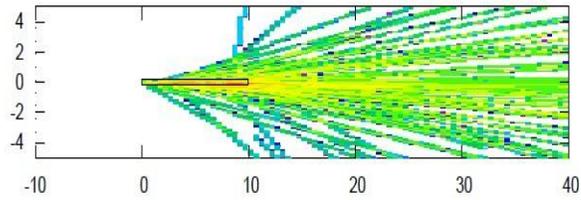


1.4 mm Al 400 kA 15 μ s

"current sheet lens"

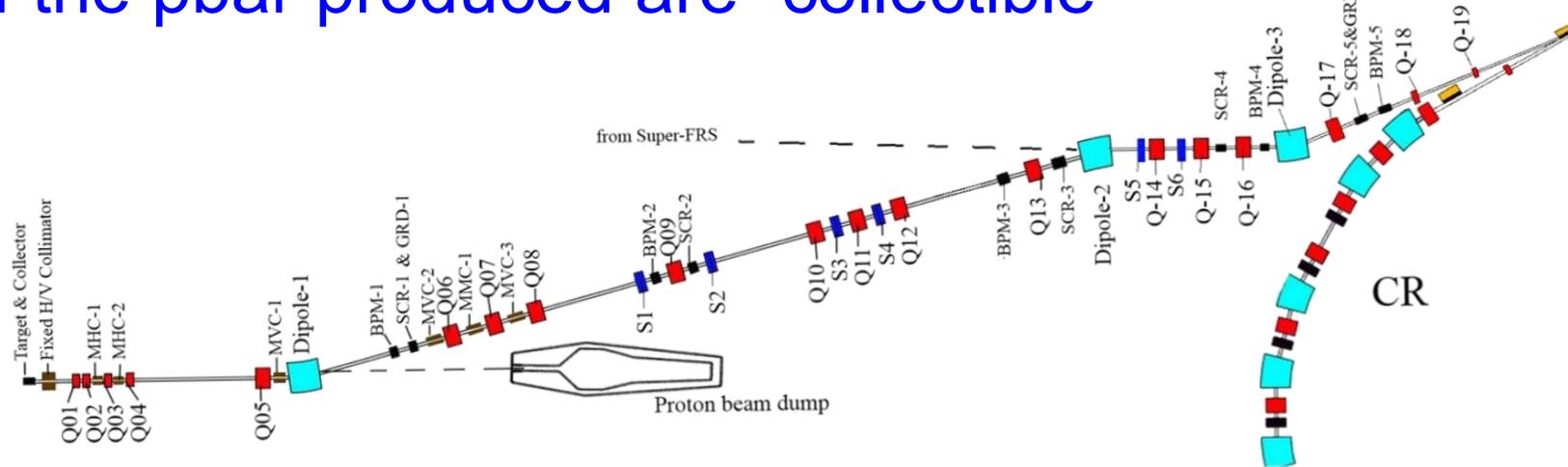
originally developed for neutrino beams then for antiprotons

Magnetic horn

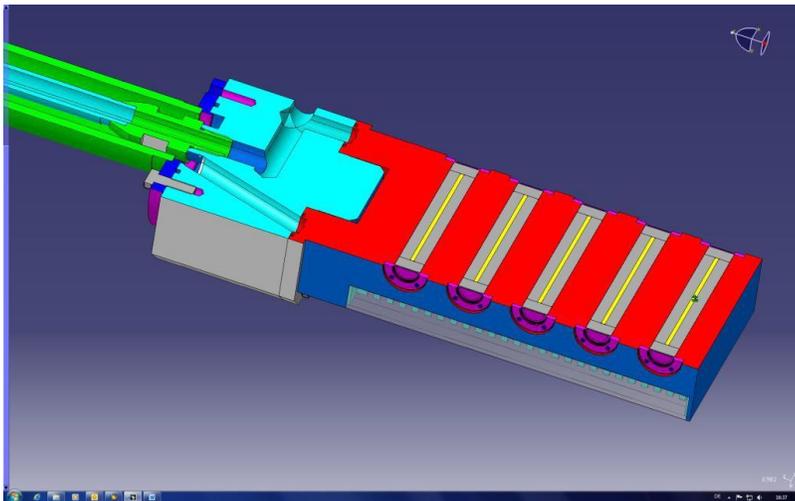


Beam Separation

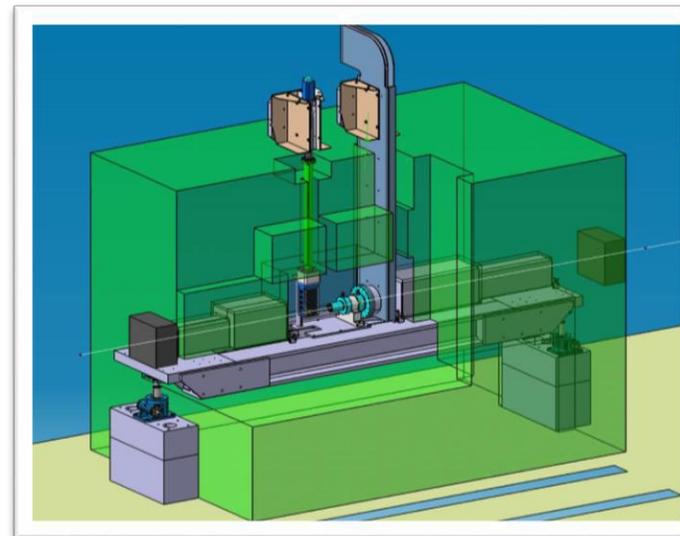
Only 2% of the pbar produced are "collectible"

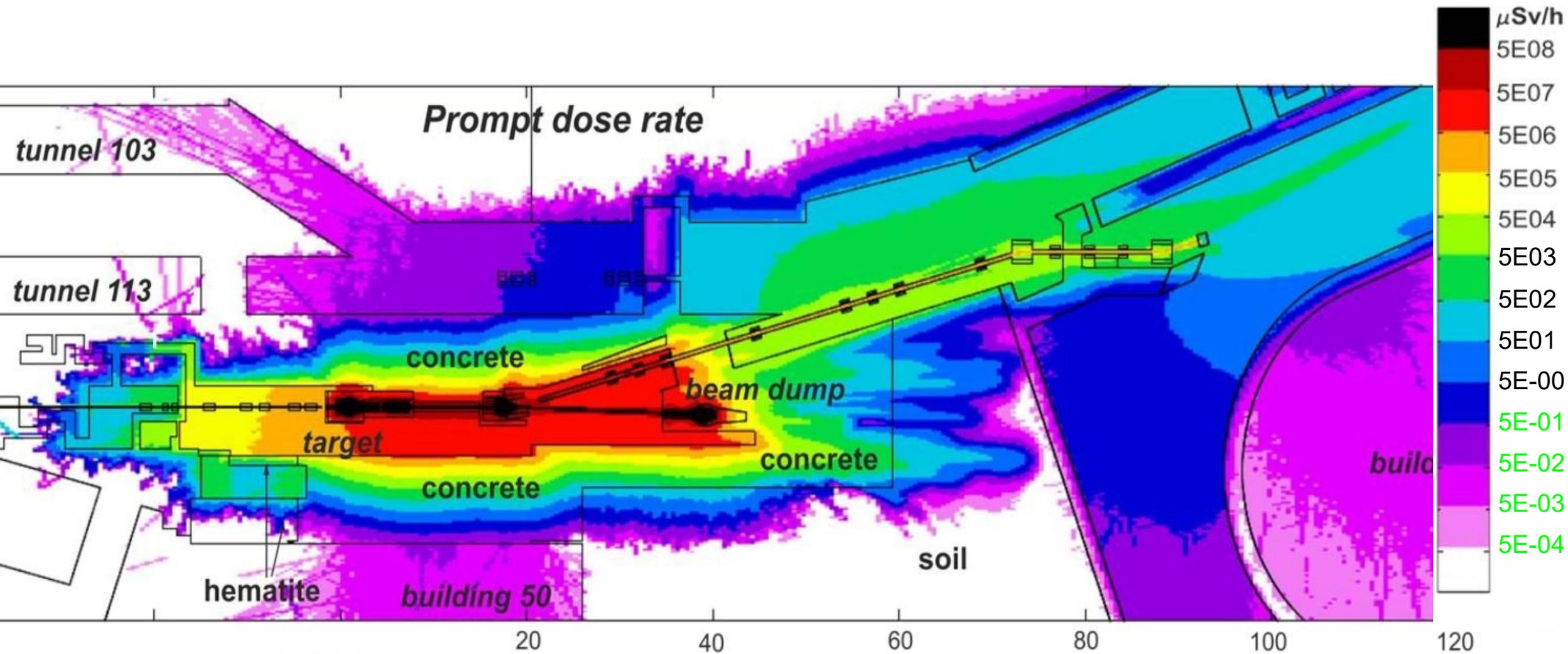


Target



Separator



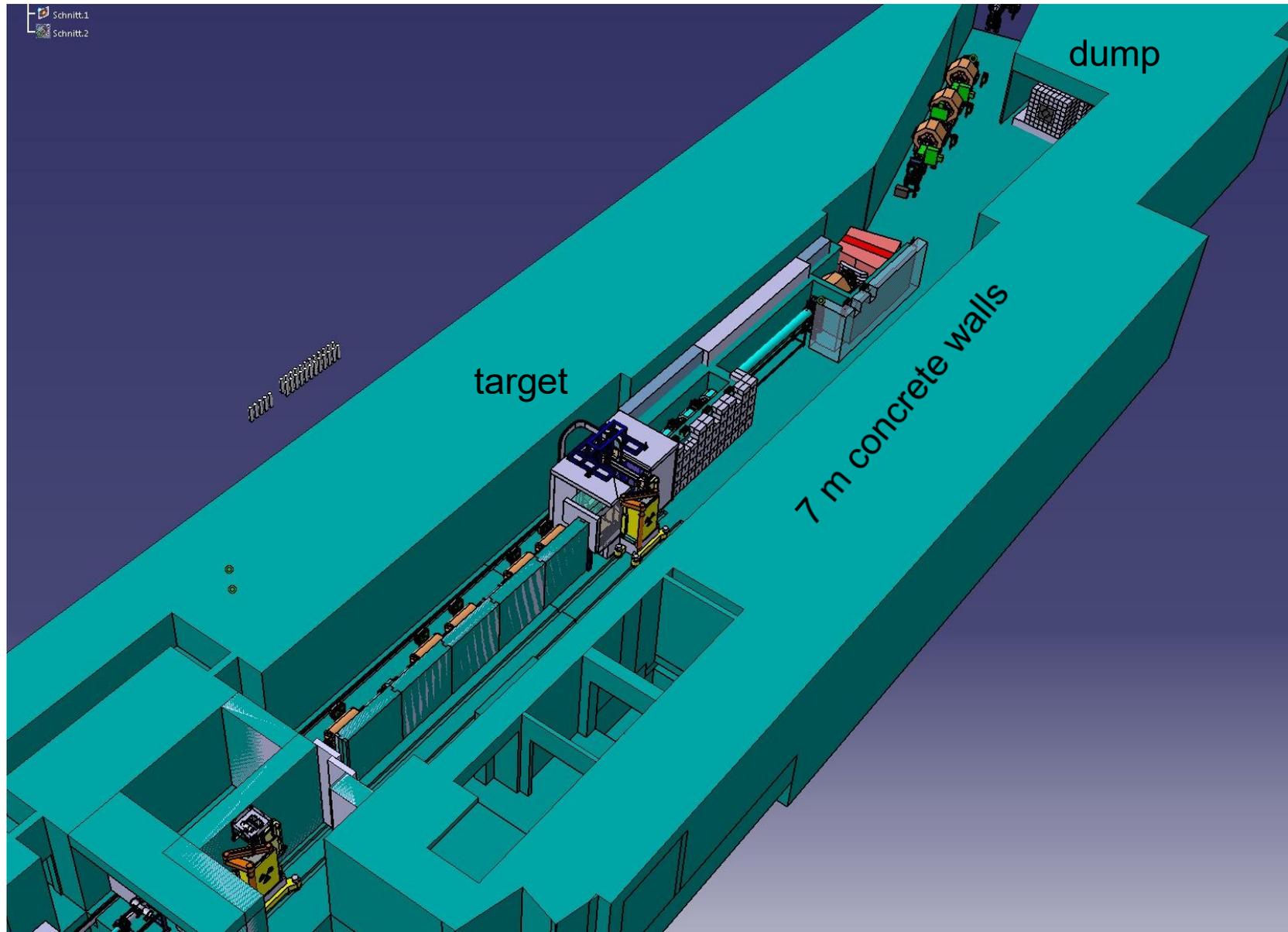


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Research in Europe

Shielding Required



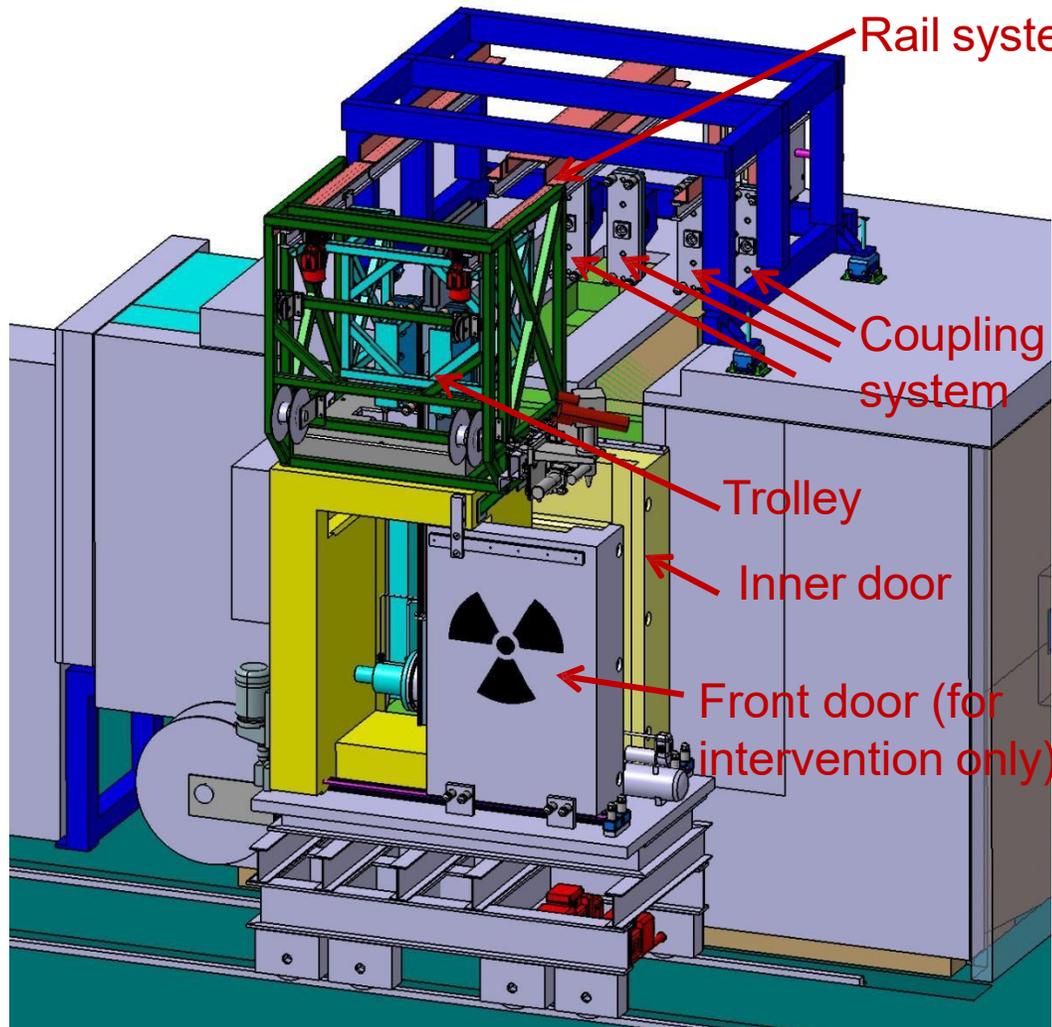
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Research in Europe



Target station and transport container

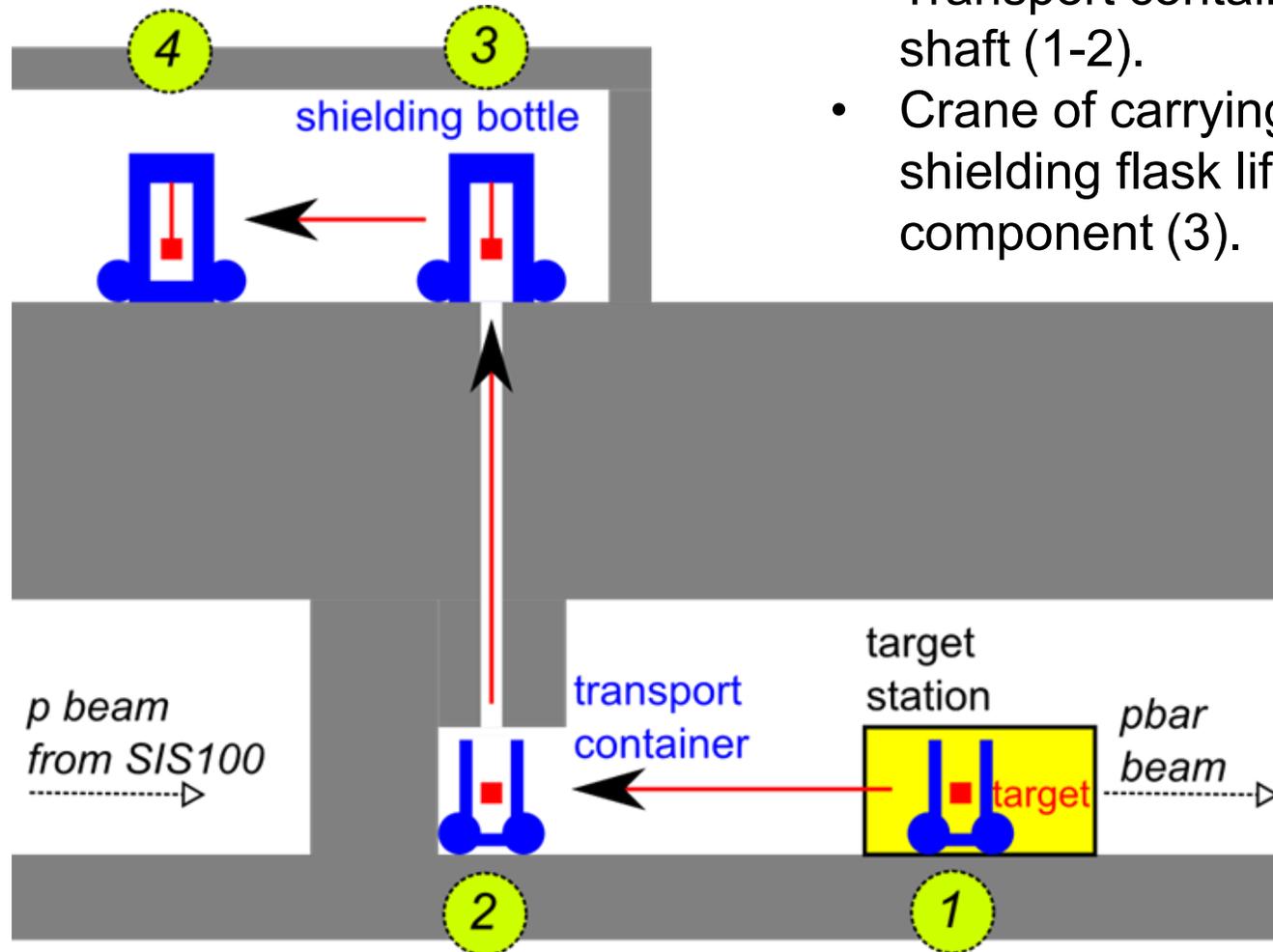


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Research in Europe



- Transport container is placed in front of target station.
- Door of target station and transport container are opened.
- Component is gripped by a quick coupling system.
- Trolley moves the component via rail system into the transport container.
- Doors are closed.

Transport concept



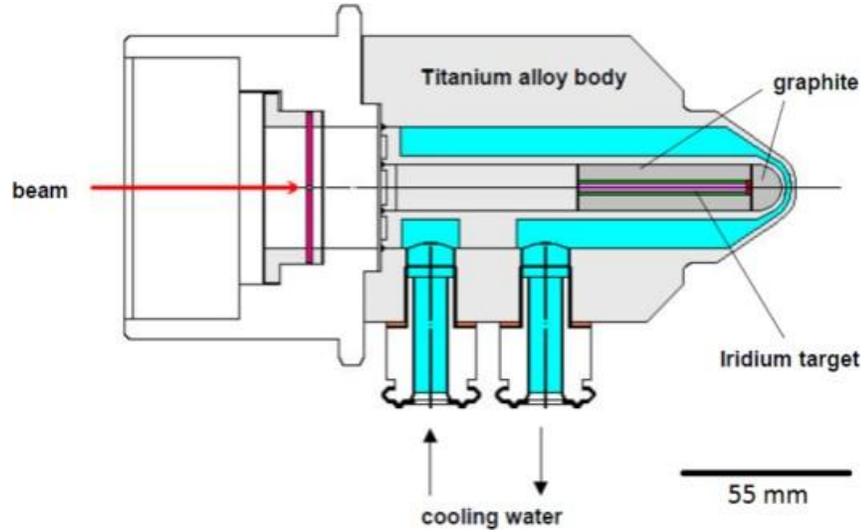
- Transport container moves to the shaft (1-2).
- Crane of carrying frame of the shielding flask lifts up the component (3).



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CERN and Fermilab pbar Targets

CERN target (Ir or Cu)

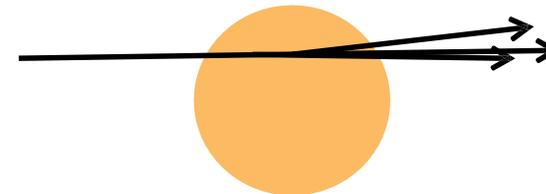
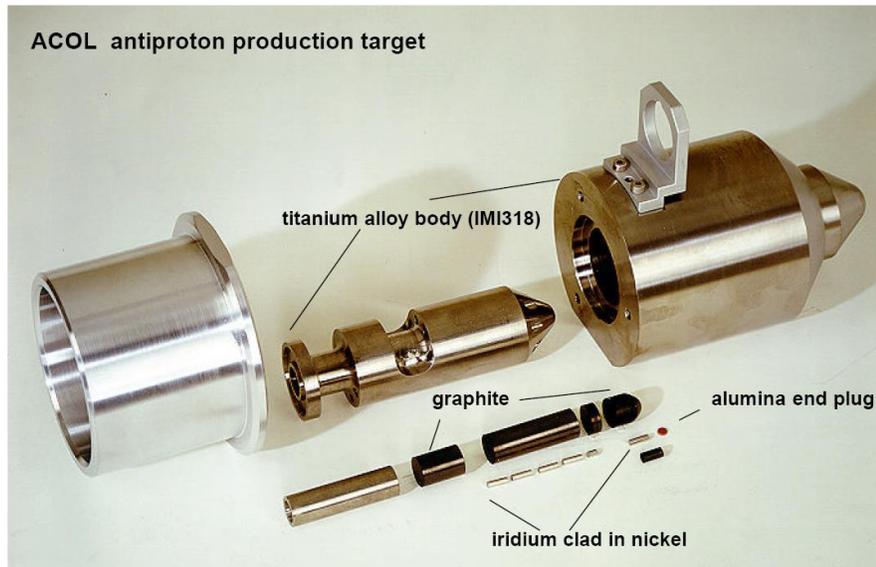


Rotating Fermilab target

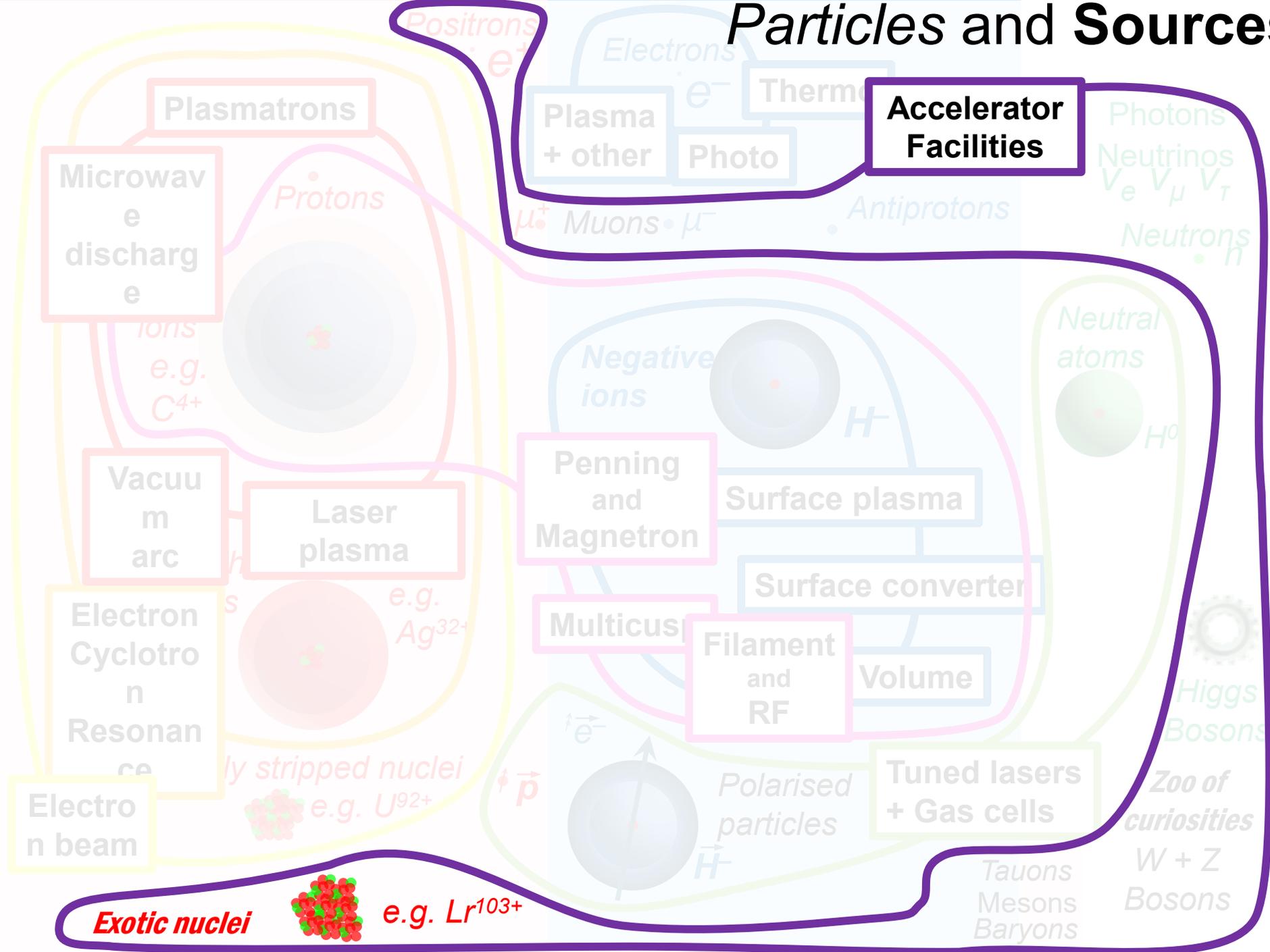


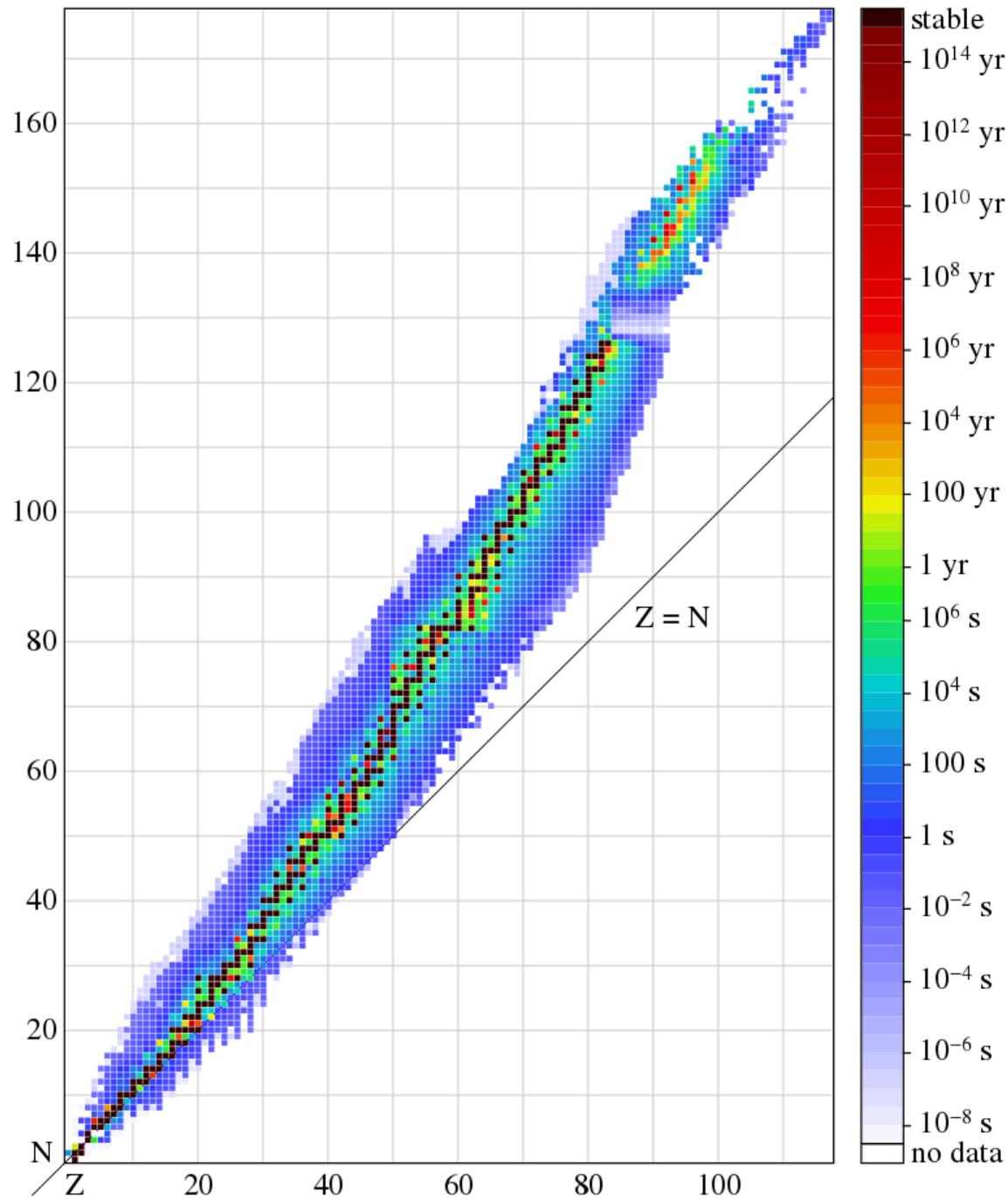
new

used



Particles and Sources





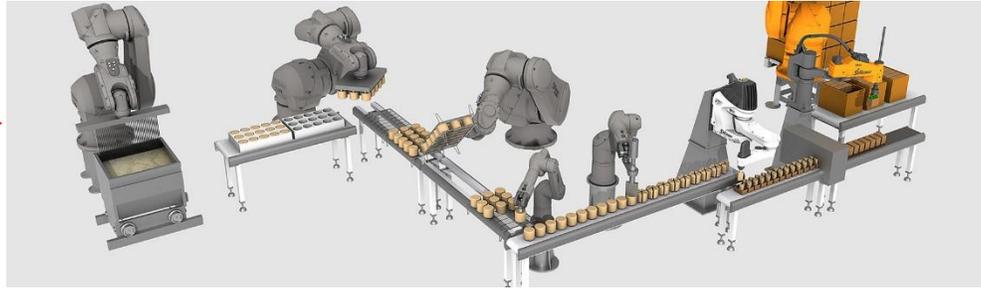
Radioactive Ion Beams

A powerful way of studying the atomic nucleus



ISOL vs In Flight Fragmentation

Isotope Separation On Line (ISOL): A production line



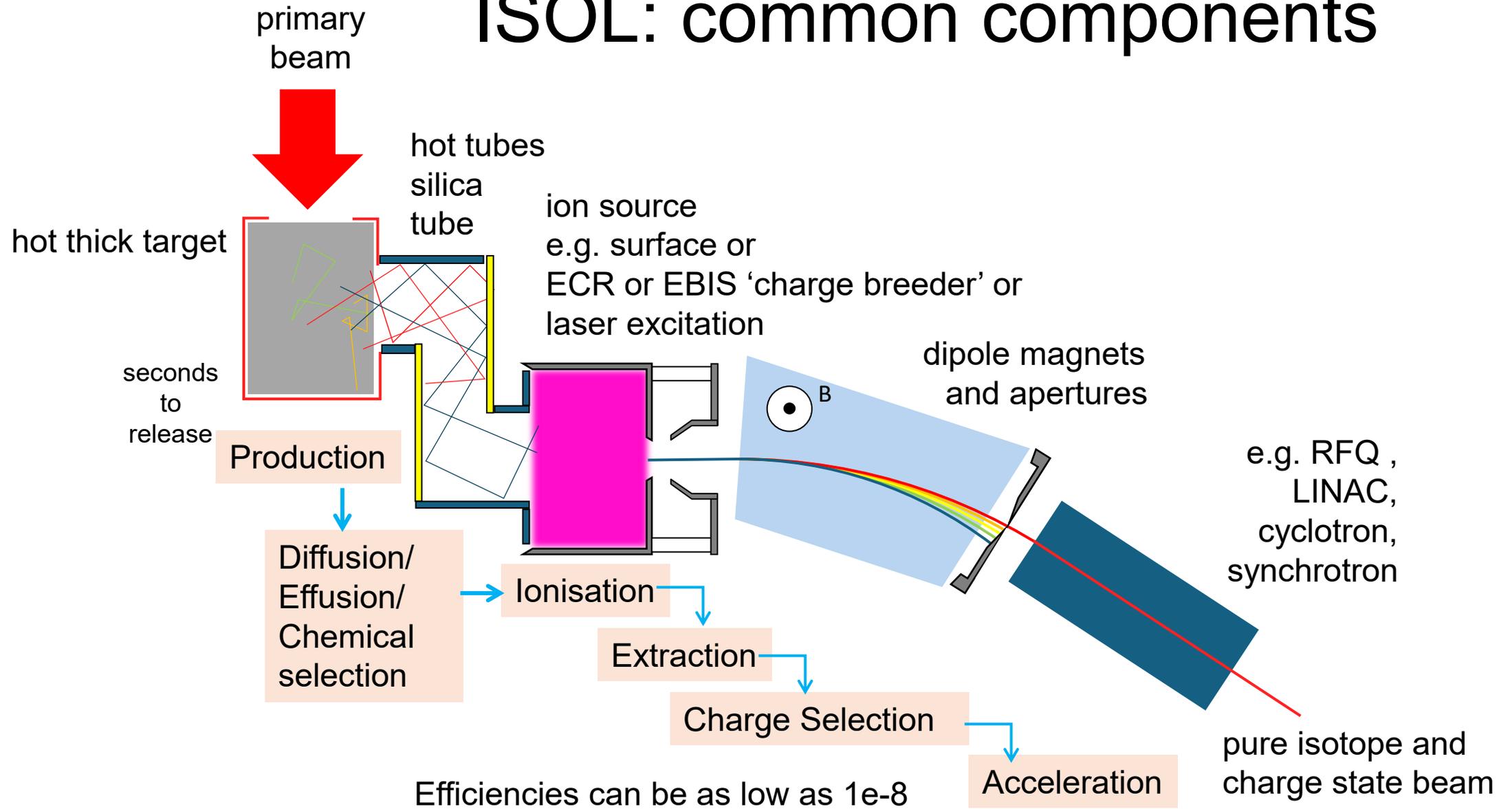
A → B → C → D → E → F

Very complicated chains of acceleration and separation have been created

In Flight Fragmentation:
Filtering an explosion



ISOL: common components



ISOL produces very pure beams with "long" half life

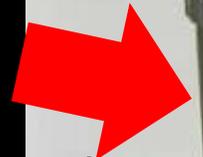


ISOLDE source

**connections for
resistive heating**

quartz tube

transfer tube



**primary
beam**

**Ta tube with
target material**

$$I_{RIB} = \varepsilon \cdot I_{prod} = \varepsilon \cdot \int_{\text{target}} \sigma(E) N_{\text{target}}(l) I_{\text{primary}}(l) dl$$

view

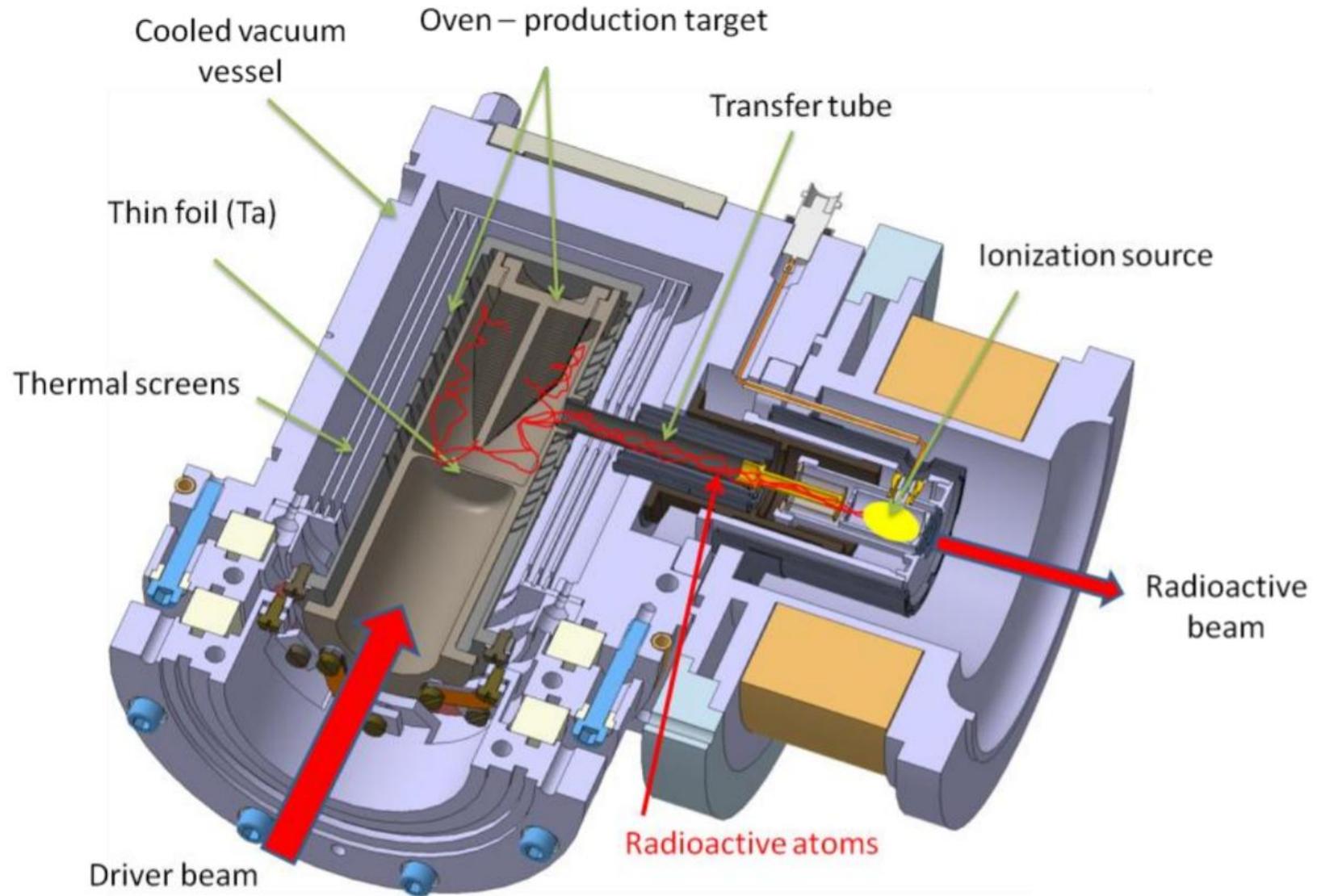
- I_{RIB} - rare ion beam intensity [s^{-2}]
- ε - overall efficiency
- I_{prod} - production rate of a reaction product [s^{-2}]
- σ - reaction cross-section [barn = 10^{-24}cm^2]
- N_{target} - target atoms per exposed area [cm^{-2}]
- I_{primary} - primary beam intensity

typically 10^{-3} to 10^{-8} !!!

typically 5% to 90%

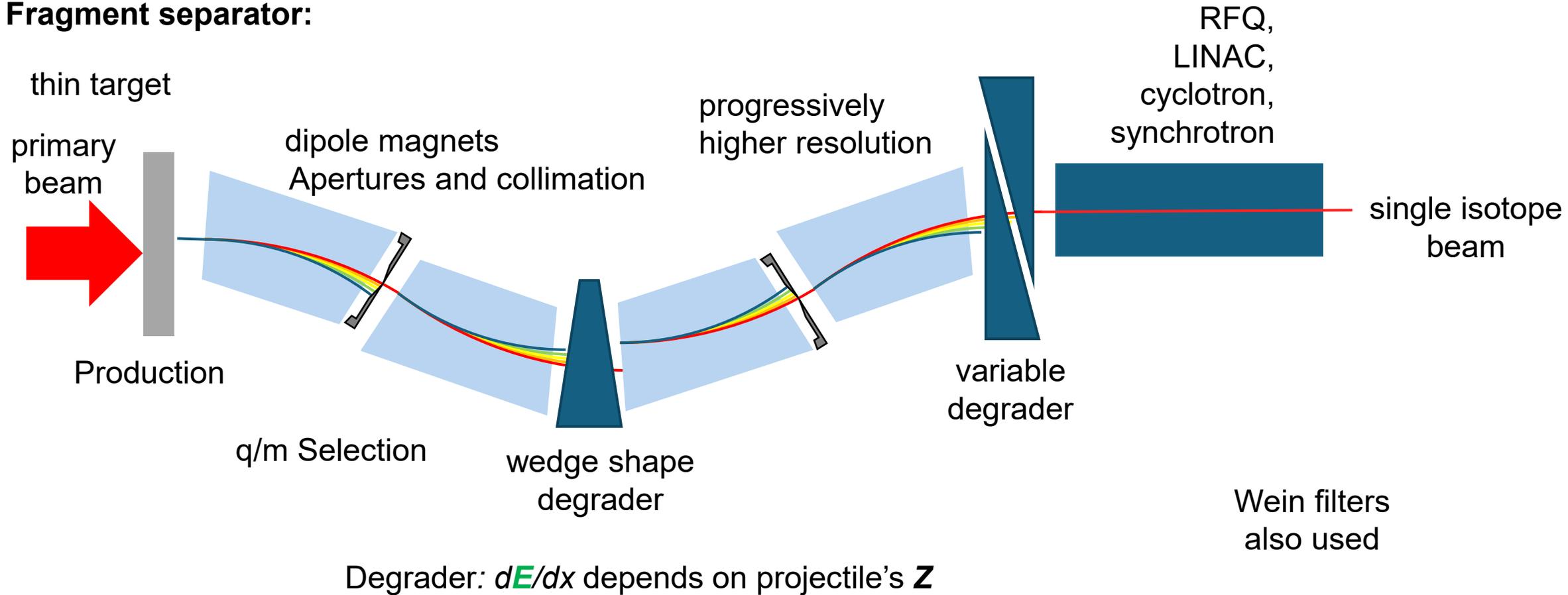
$$\varepsilon = \varepsilon_{\text{release}} \cdot \varepsilon_{\text{ionization}} \cdot \varepsilon_{\text{transport}} \cdot \varepsilon_{\text{cool-bunch}} \cdot \varepsilon_{\text{breeding}} \cdot \varepsilon_{\text{post-accel}}$$

- $\varepsilon_{\text{release}}$ - probability of not-decaying during the time of extraction from the target/ion source unit
- $\varepsilon_{\text{ionization}}$ - probability of ionization of desired species by chosen ionization mechanism
- $\varepsilon_{\text{transport}}$ - efficiency of mass selection and transport to experimental setup
- $\varepsilon_{\text{cool-bunch}}$ - cooling and bunching efficiency (when applicable)
- $\varepsilon_{\text{breeding}}$ - charge state breeding efficiency
- $\varepsilon_{\text{post-accel}}$ - post acceleration efficiency



In Flight Fragmentation: common components

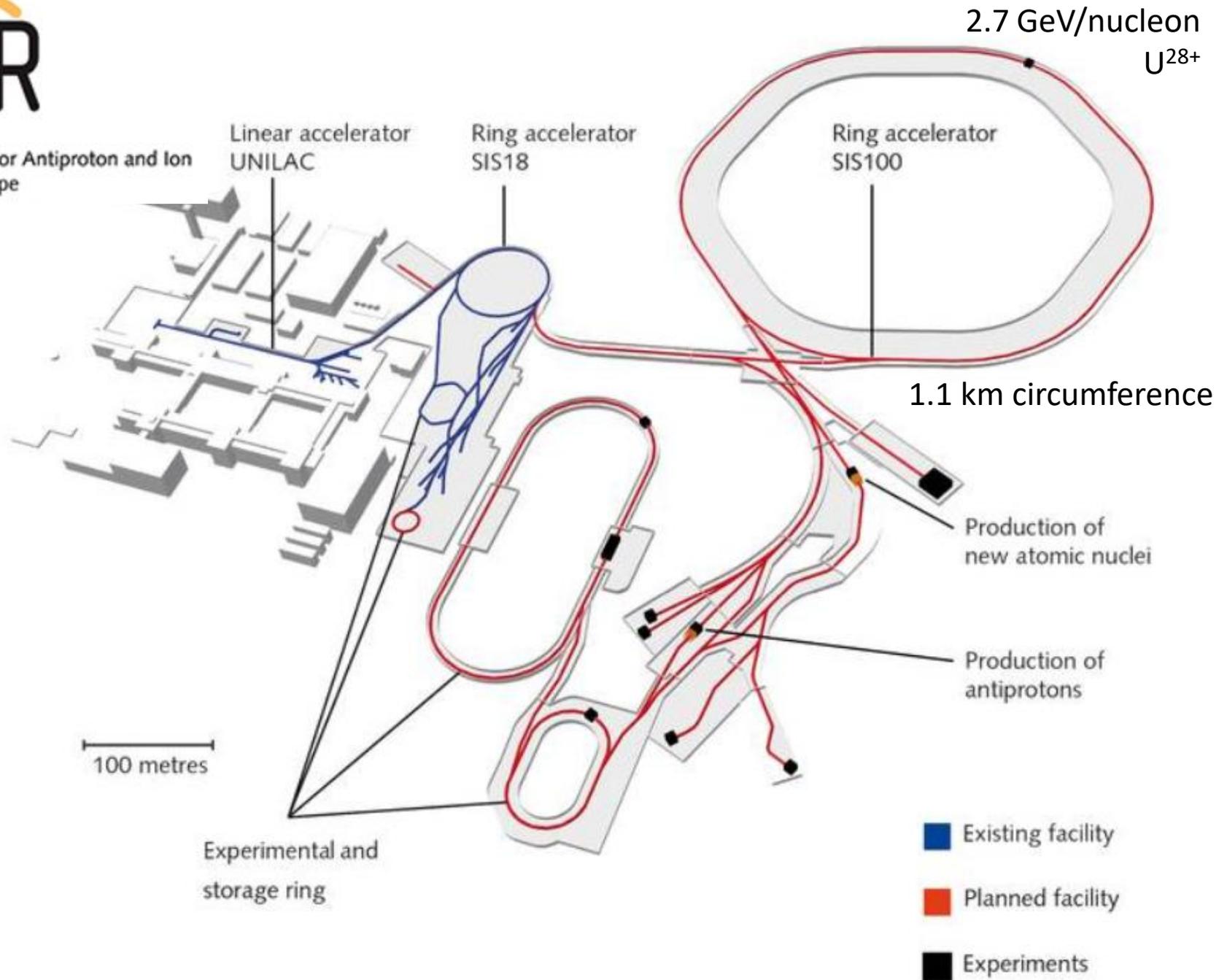
Fragment separator:



In flight fragmentation is suitable for very short half life beams



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The Super Fragment Separator

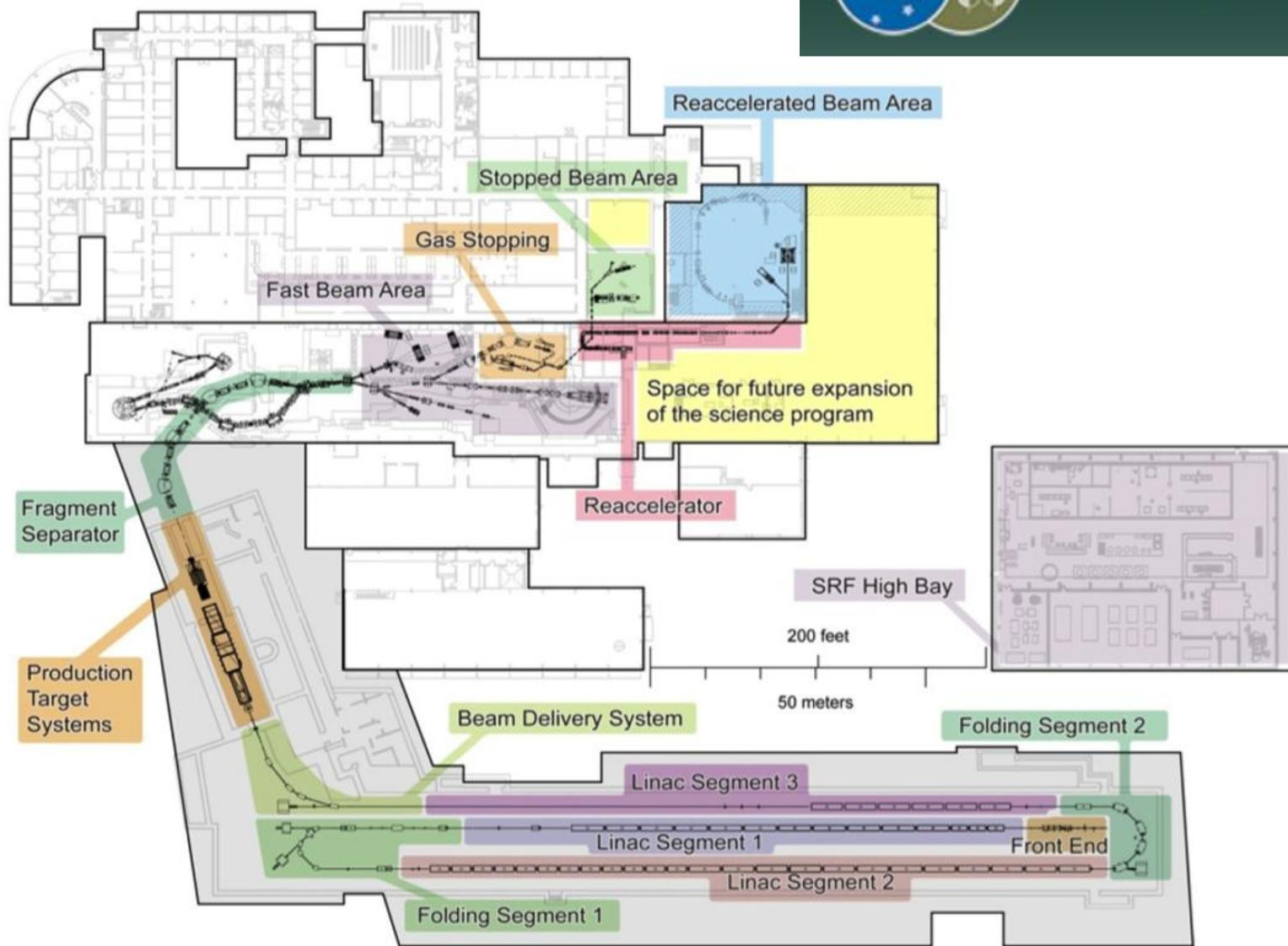


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Research in Europe



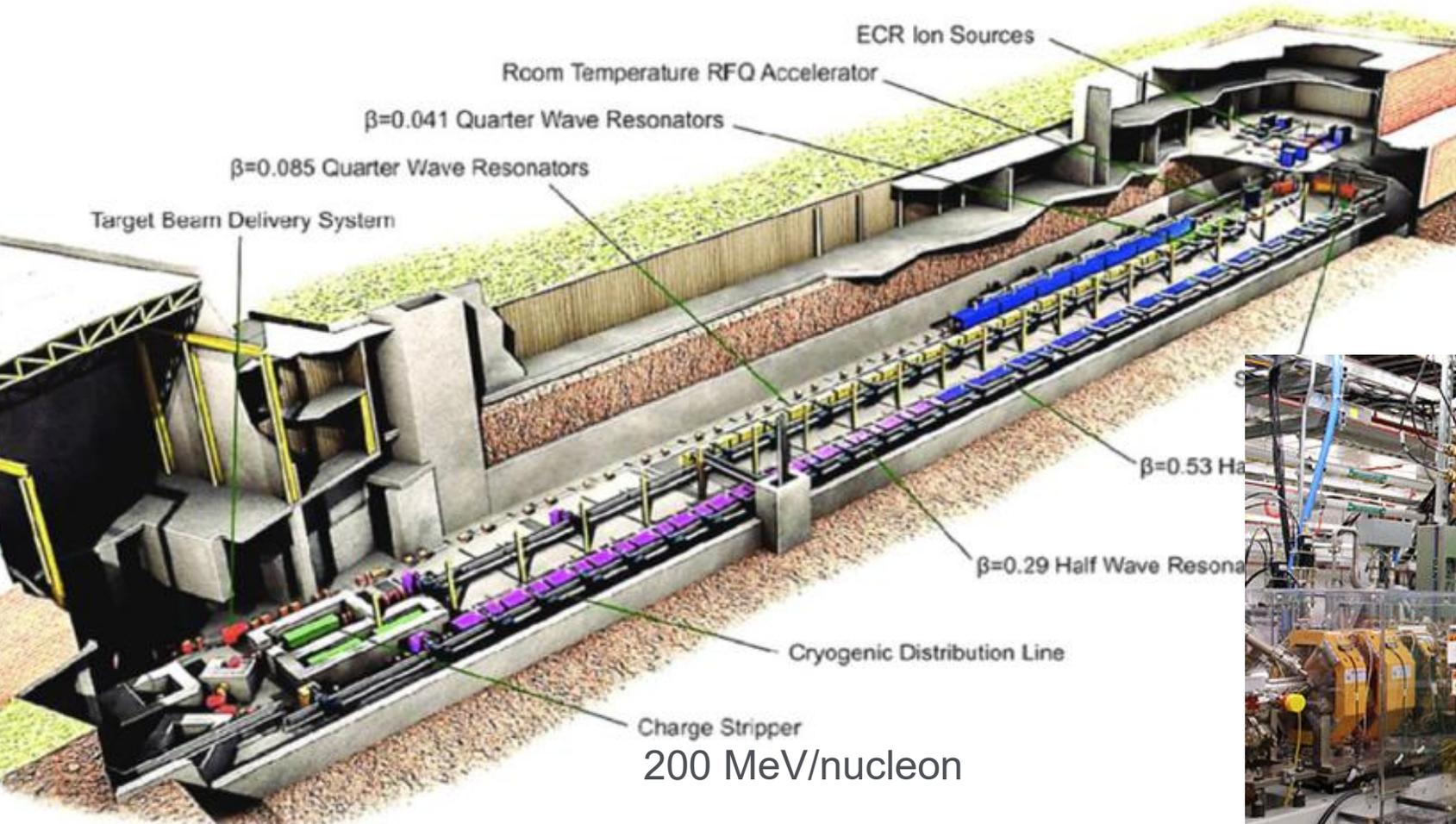


Facility for Rare Isotope Beams at Michigan State University





Facility for Rare Isotope Beams at Michigan State University



517 m linac



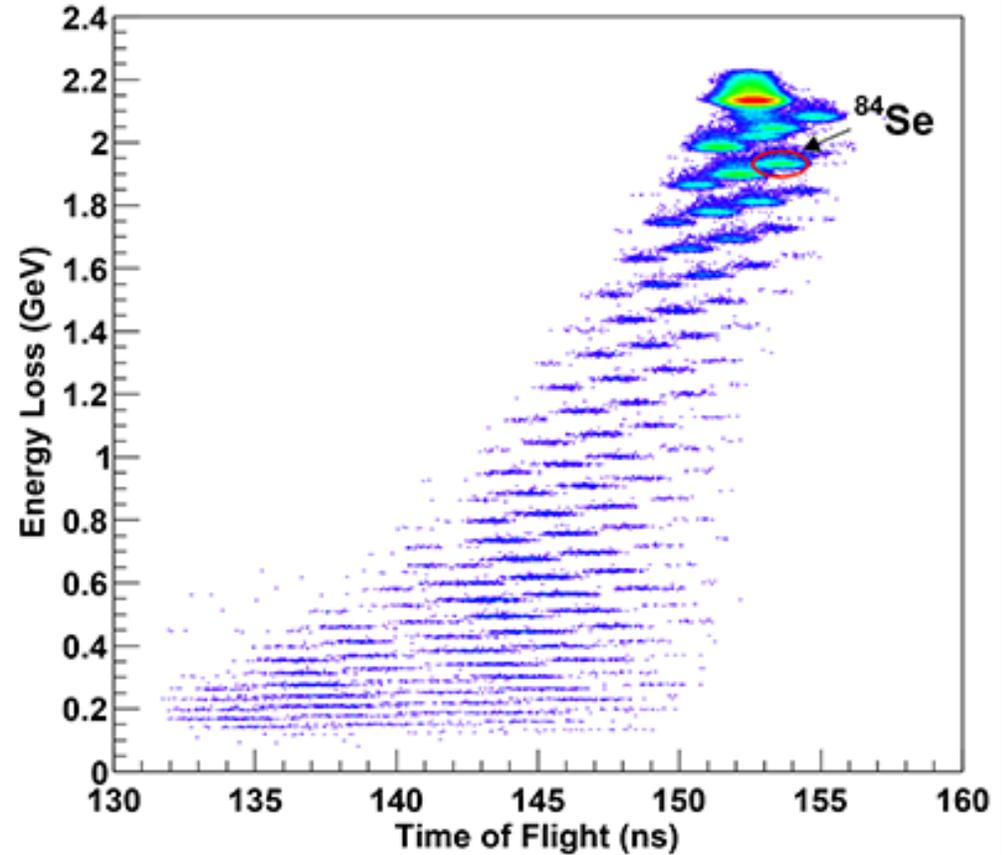


Facility for Rare Isotope Beams at Michigan State University

FIRST RARE ISOTOPES

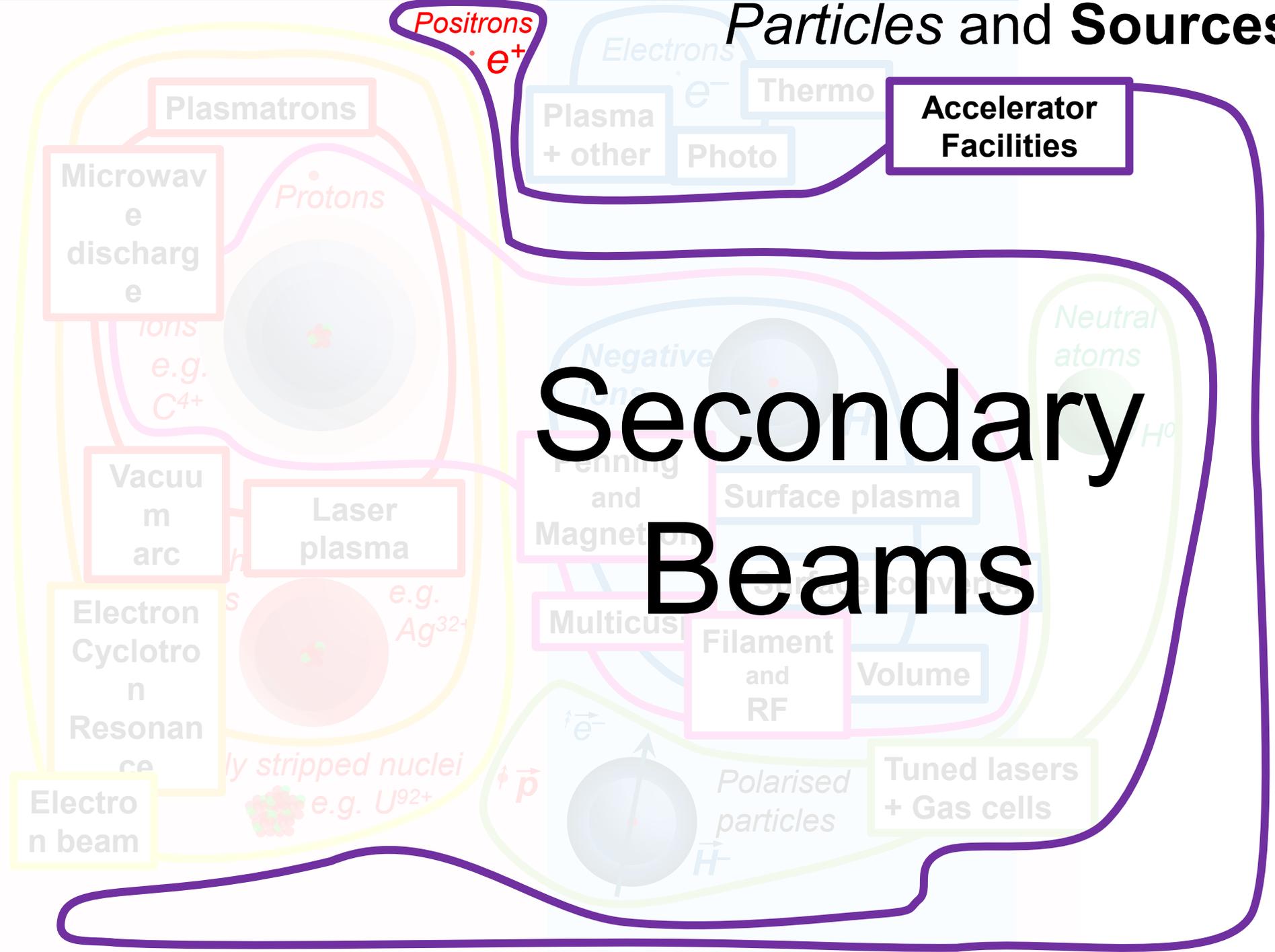
11 December 2021

selenium-84 from a krypton-86 beam.



January 2022 discovered magnesium-18

Particles and Sources

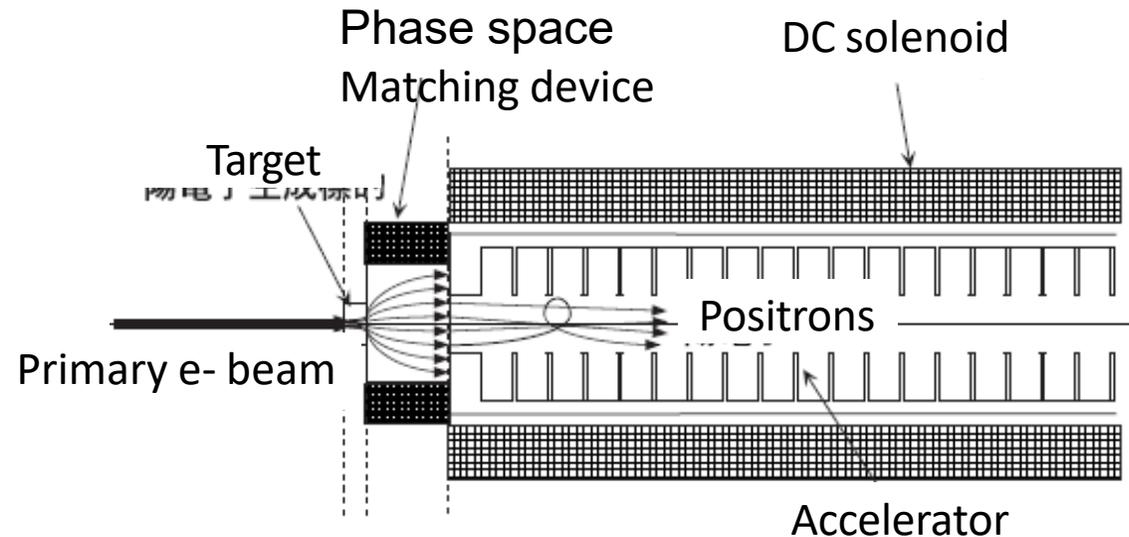
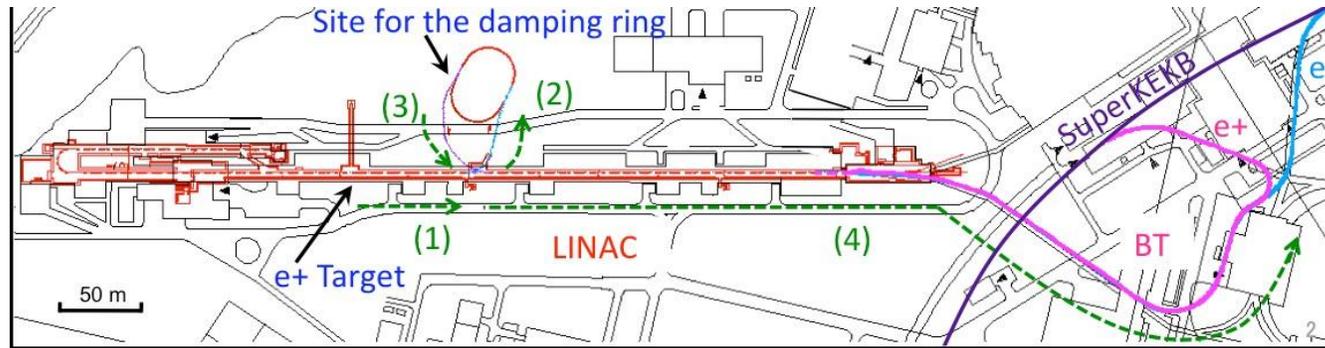


Positron Sources

Techniques:

- Radio-isotope source
 - long-lived e.g. ^{22}Na ($\sim 10^6$ e⁺/s)
 - or beam-induced e.g. ^{13}N ($\sim 10^9$ e⁺/s)
- MeV or GeV electron beam on target
- Gamma ray beam on target
 - Undulator generated
 - Compton backscatter generated

Positron source for the KEKB and the SuperKEKB in Japan



Target material

Requirements:

High Z (Cross section of Bremsstrahlung $\propto Z^2/A$)

High melting point

Tantalum(^{73}Ta),

Tungsten(^{74}W),

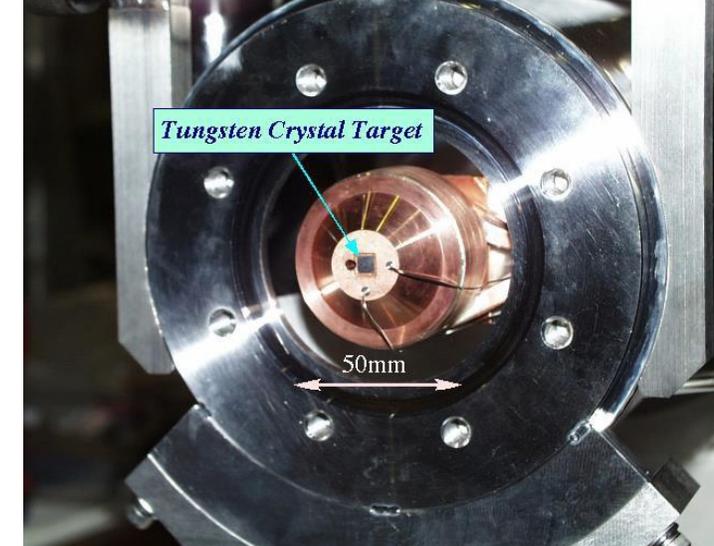
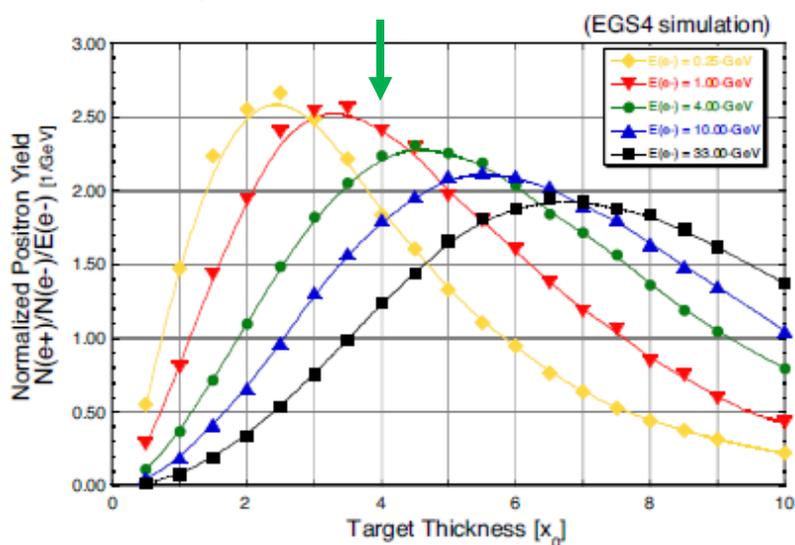
Tungsten- rhenium alloy (W-Re)

KEKB, SuperKEKB

Target material: W 14mm ($4\chi_0$)

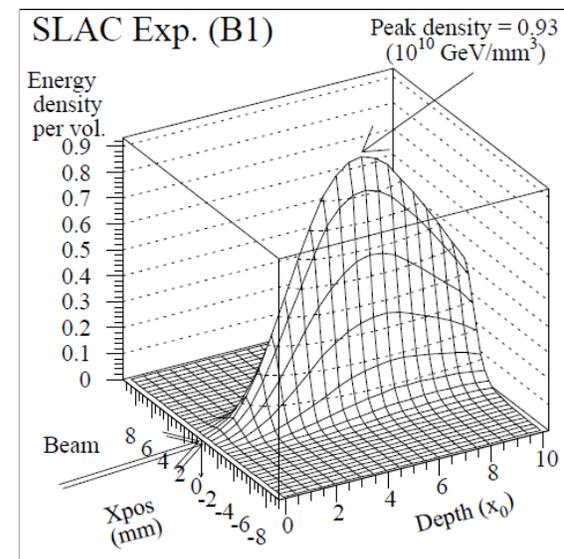
Primary e- beam energy: 4.0 GeV(KEKB)

3.3GeV(SuperKEKB)



Joining of tungsten crystal to a copper body by a hot isostatic pressing (HIP)

Target destruction limit



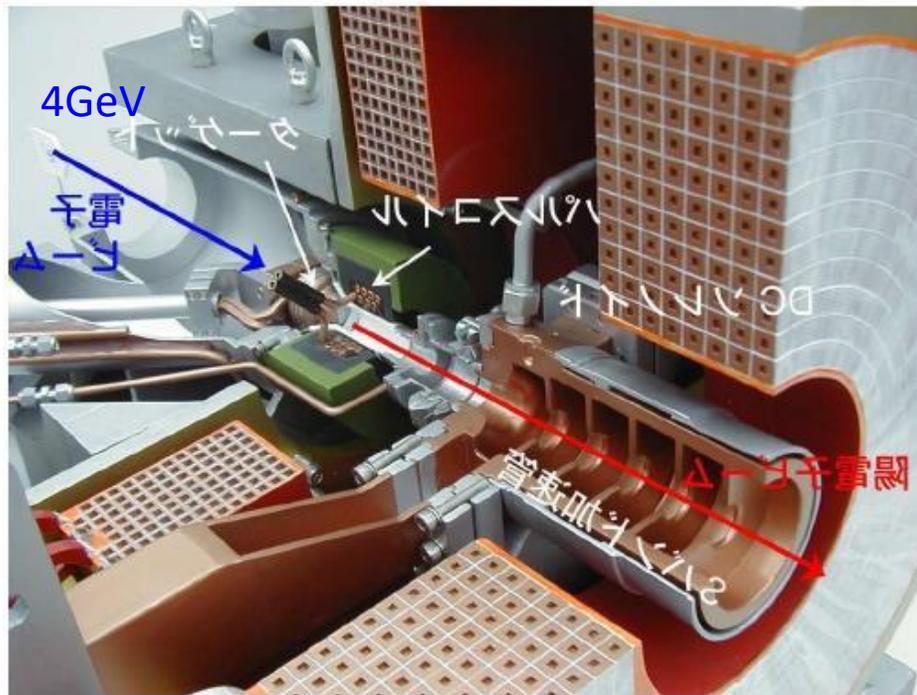
After the target destruction occurred at SLAC
Threshold : $76 \rightarrow 35 \text{ J/g}$

KEK Positron Sources

KEKB

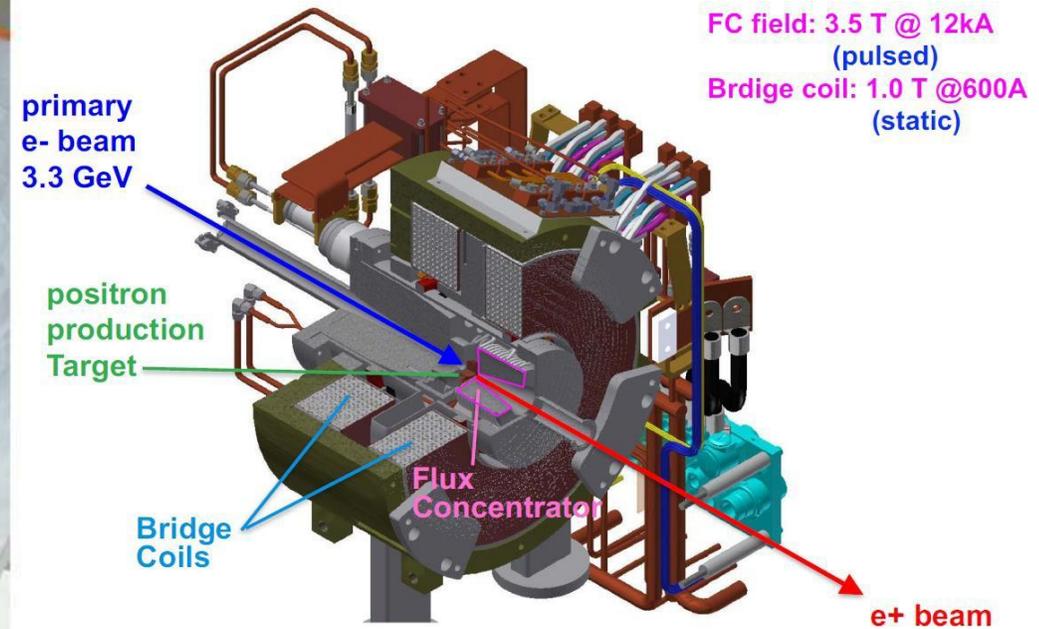
Quarter wave transformer matching device

Pulse coil: 2.3T @ 10kA



SuperKEKB

AMD Flux Concentrator matching device

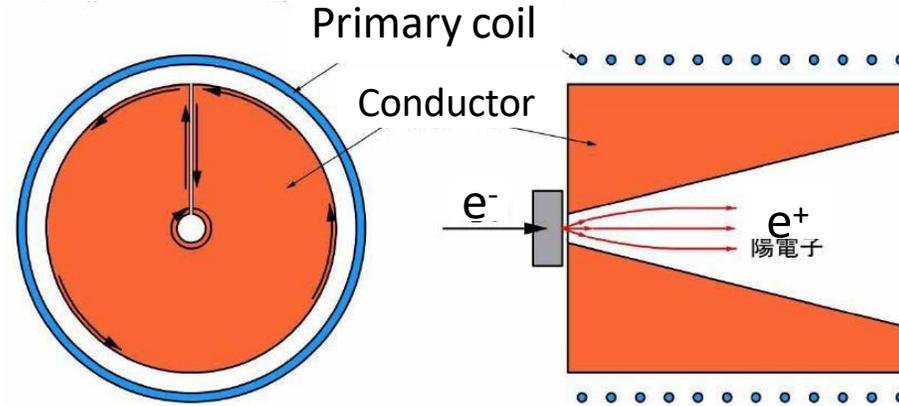


50Hz rep rate with a bunch charge of $2.5 \times 10^{10} = 2.5 \times 10^{12} e^+/s$

Adiabatic Matching Device (AMD)

Adiabatic invariance is constant during the motion.

$$\int \sum_i p_i dq_i = \frac{\pi p_t^2}{eB}$$



AMD field is produced by a flux-concentrator.

The eddy current is induced in the tapered conductor by a changing magnetic field which is made by the primary coil.

The magnetic field is concentrated due to the tapered shape of the FC head.

adiabatic condition

$$\epsilon = \frac{\mu p_z}{eB_0} \leq 0.5$$

$$p_z \leq 17.5 [MeV/c]$$

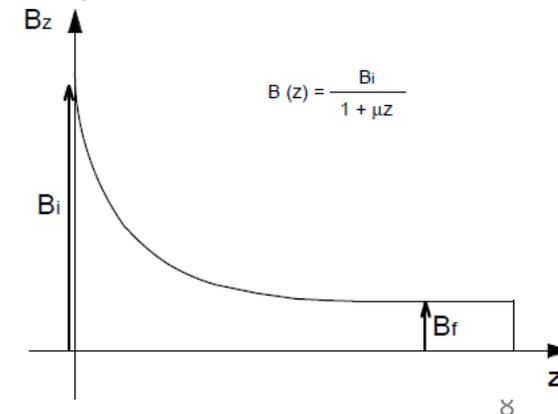
($B_0 = 7.0$ [Tesla], $\mu = 60$ [1/m])

Transverse acceptance

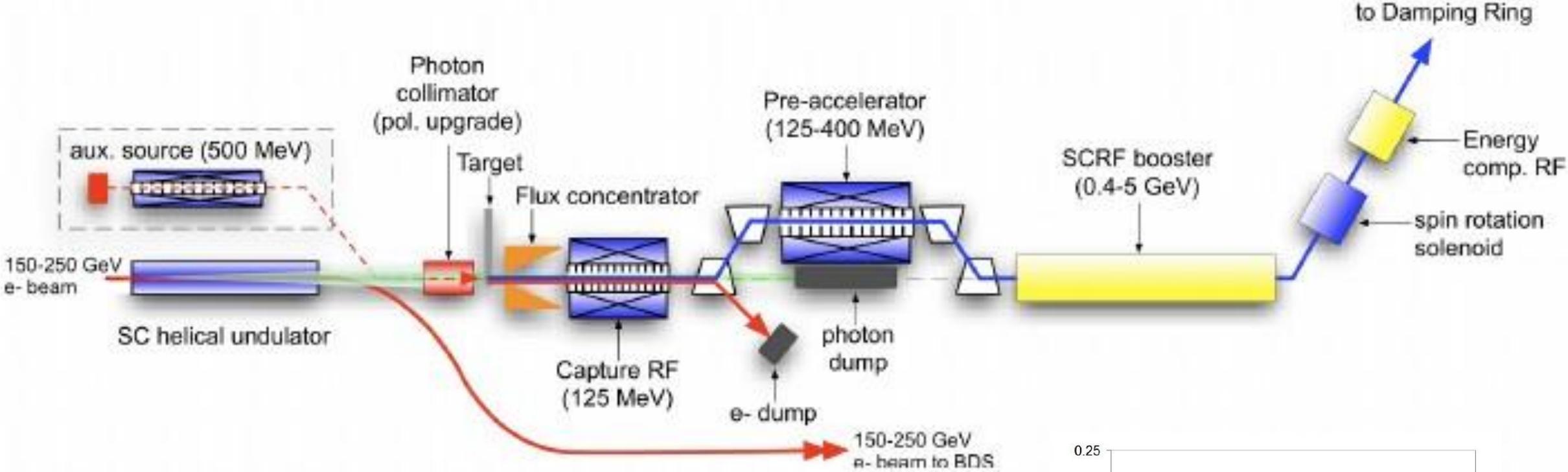
$$p_{t-max} = \frac{e}{2} \sqrt{B_f B_0} a$$

$$r_{max} = \sqrt{\frac{B_f}{B_0}} a$$

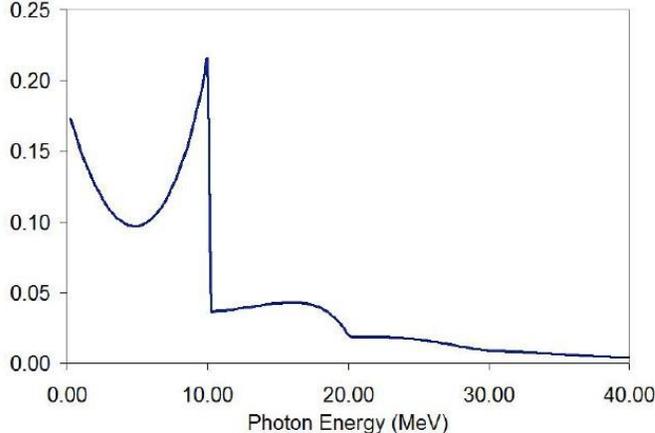
a: Diameter of an accelerator iris



Gamma Ray Undulator Source



The undulator produces a gamma-ray spectrum with a series of harmonic peaks.



Considered primarily for the ILC

Gamma Ray Compton Source

Compton backscattering of a laser beam using an electron beam is used in most intense gamma-ray sources such as ELI-NP.

The laser is typically a YAG laser using one or more high brightness optical cavities

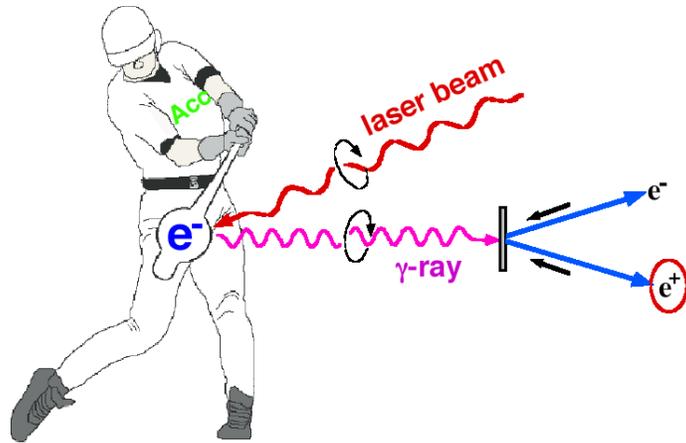
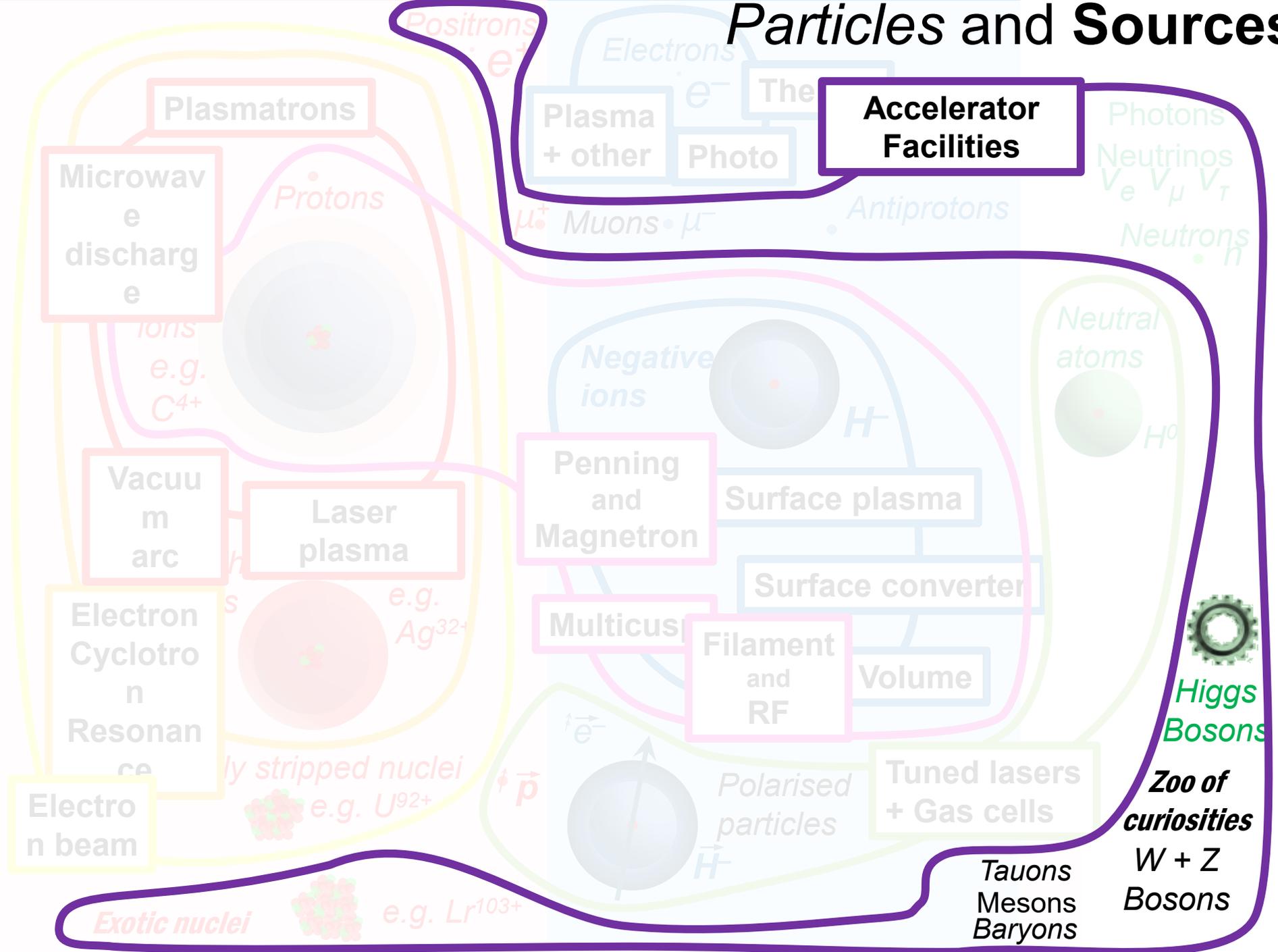


Table 1: CLIC parameters for e^+ beam

Parameters	Units	CLIC 3 TeV
Energy	MeV	200
$N e^+ / \text{bunch}$	10^9	6.7
$N \text{ bunches/pulse}$	-	312
Bunch spacing	ns	0.5
Pulse length	ns	156
Emittance (x,y)	mm.mrad	< 10 000
Bunch length	mm	< 10
Energy spread	%	< 8
Repetition rate	Hz	50

(pre-damping ring)

Particles and Sources



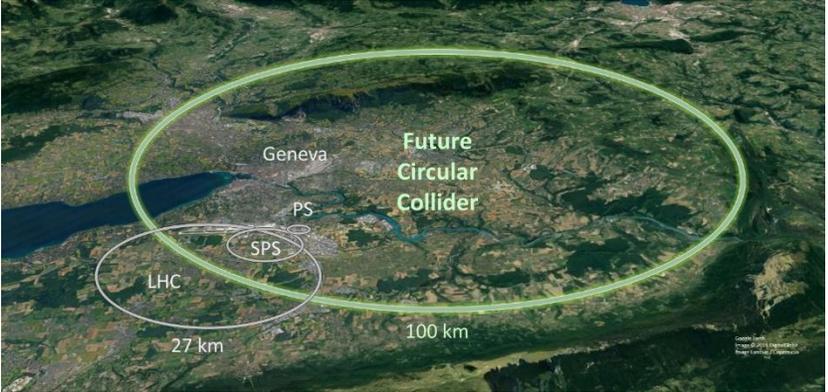
Future Colliders



Compact Linear Collider

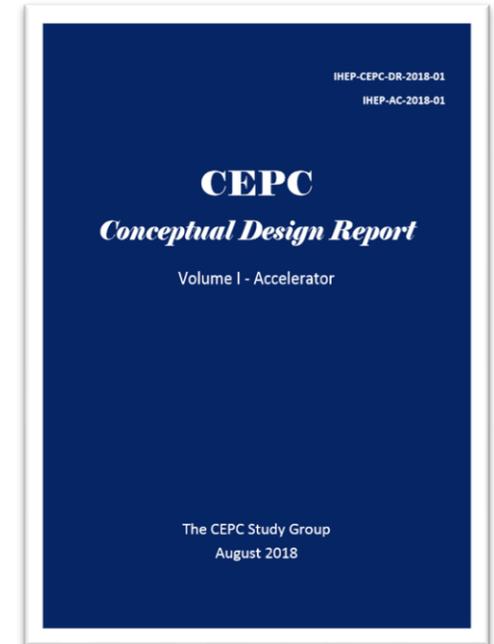


The Next Linear Collider



Higgs Factory

- China Electron Positron Collider (CEPC)
- 100 km underground circular tunnel
- 240 GeV
- \$6bn
- More than million Higgs bosons in 7 years
- \$6000 per Higgs and one Higgs every 3 mins!



Summary

- Secondary beams are incredibly fascinating
- The work they do moves forward our understanding of the universe
- They are at the extreme limit of our:
 - Knowledge of physics
 - Engineering capability
 - Financial and Political ability
- We have only scratched the surface

Thank you for listening
Questions?