

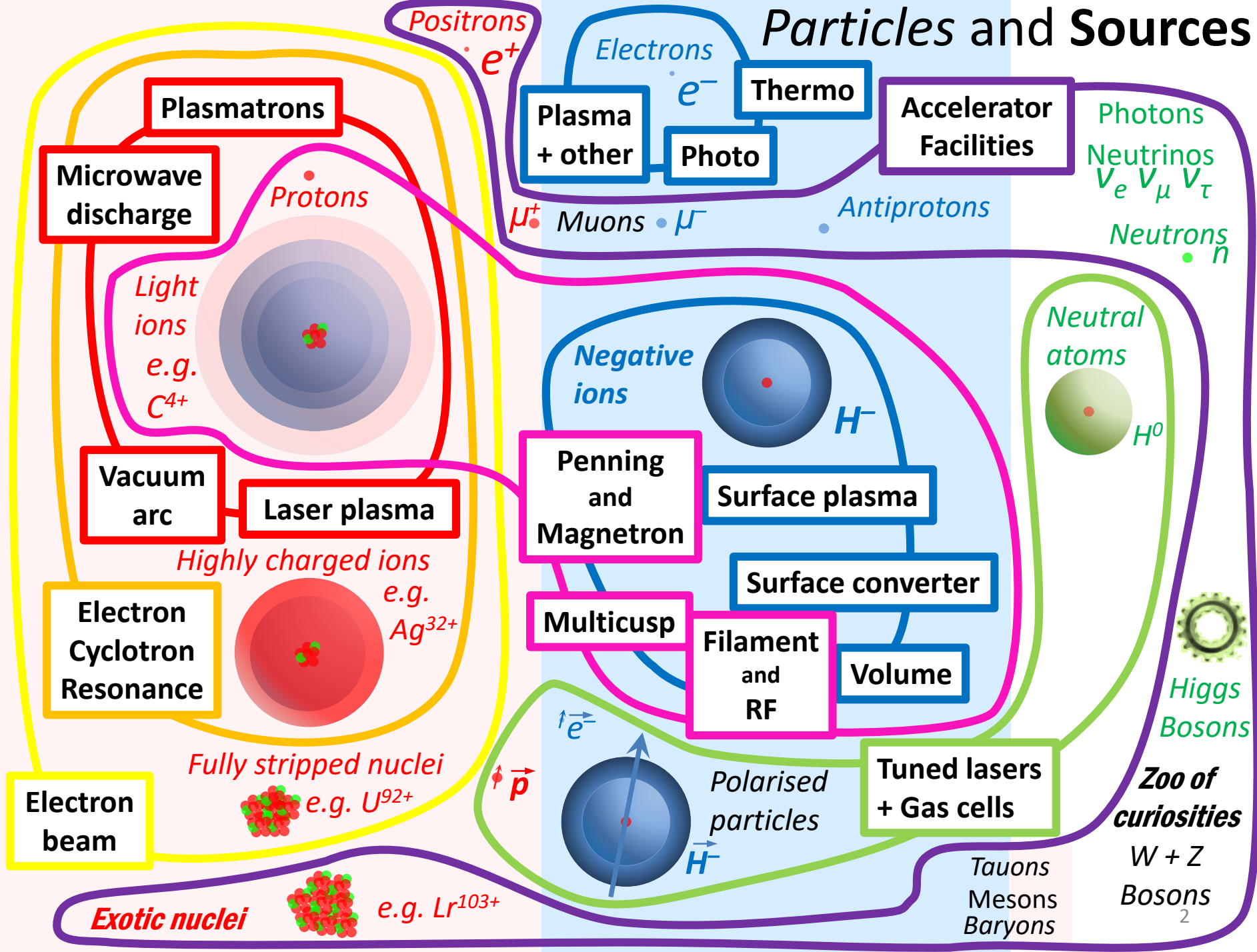
Secondary Beams

Dan Faircloth

ISIS Low Energy Beams Group Leader

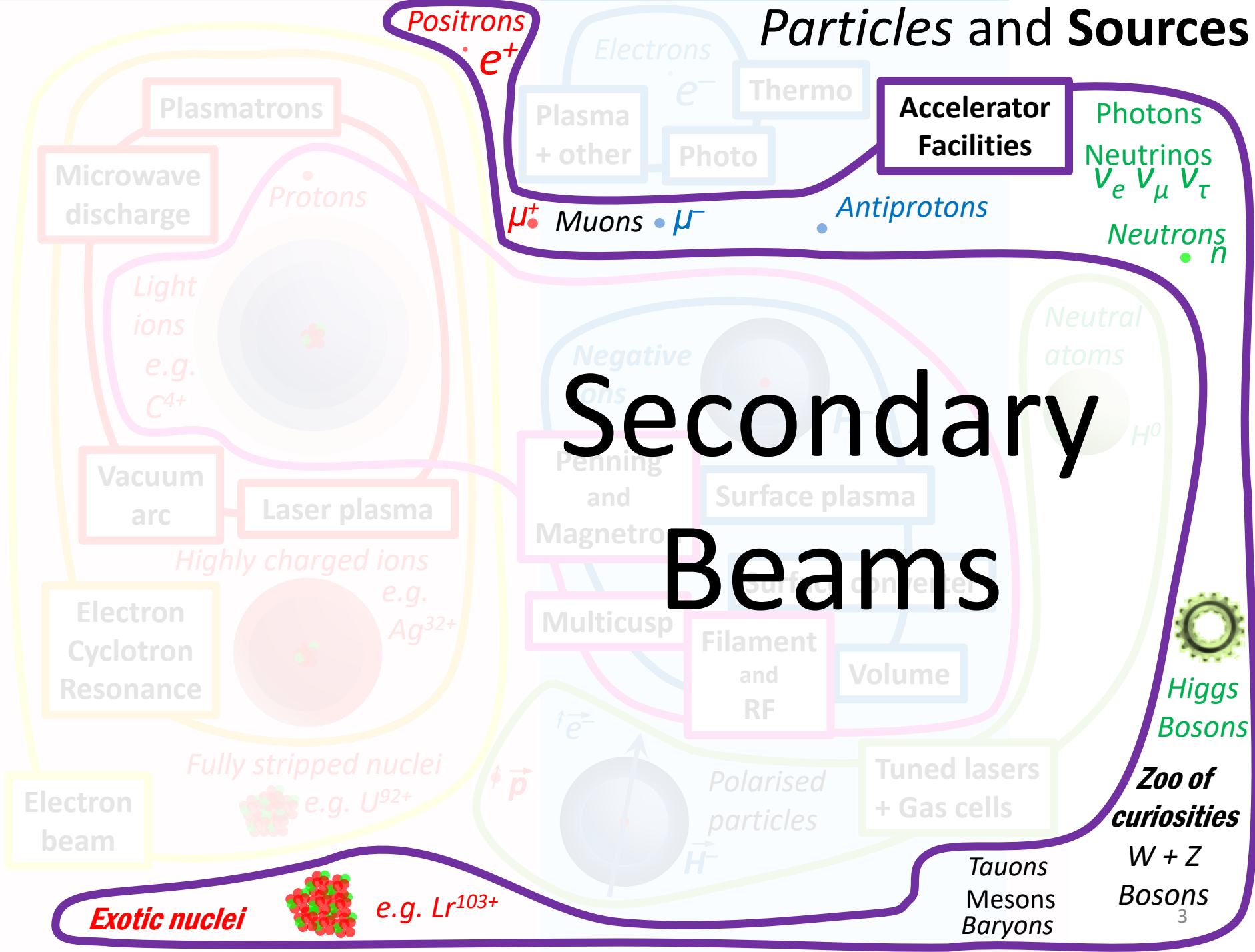
Rutherford Appleton Laboratory

Particles and Sources

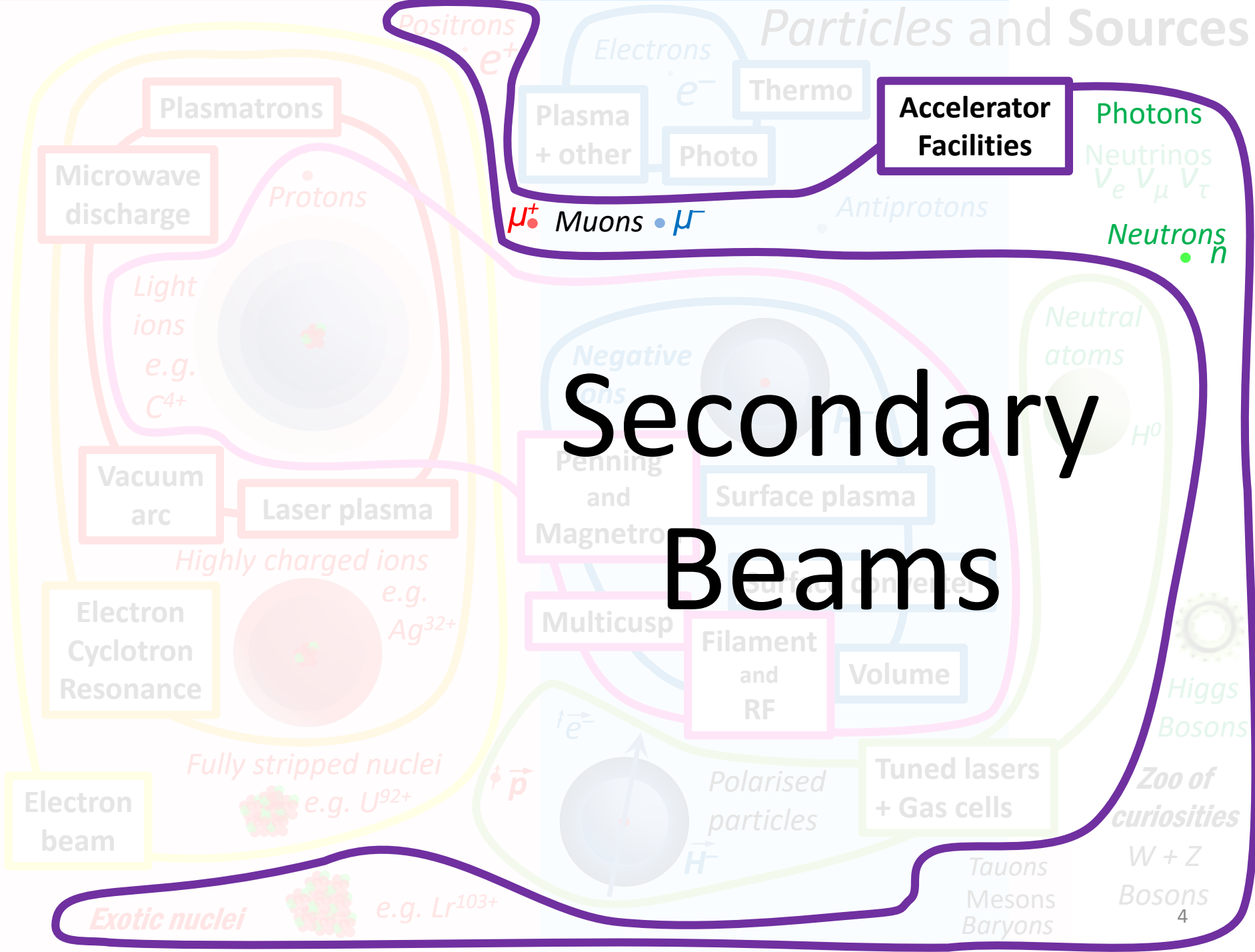


Particles and Sources

Secondary Beams



Particles and Sources



Rutherford Appleton Laboratory Oxfordshire, UK

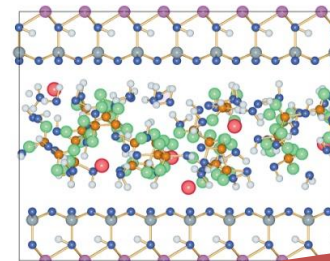
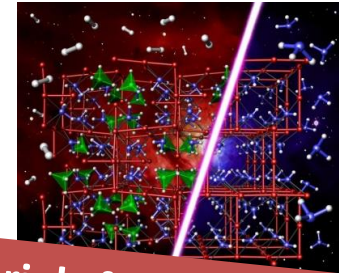
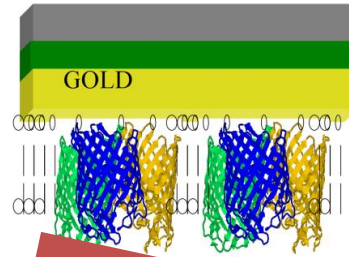
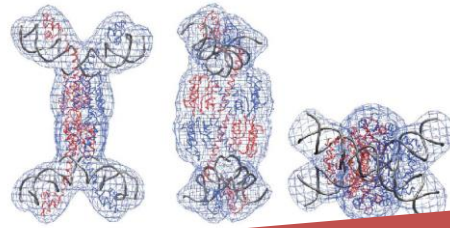
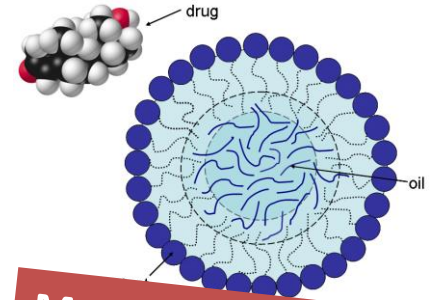
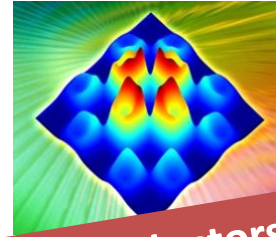
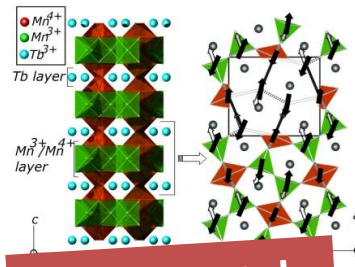
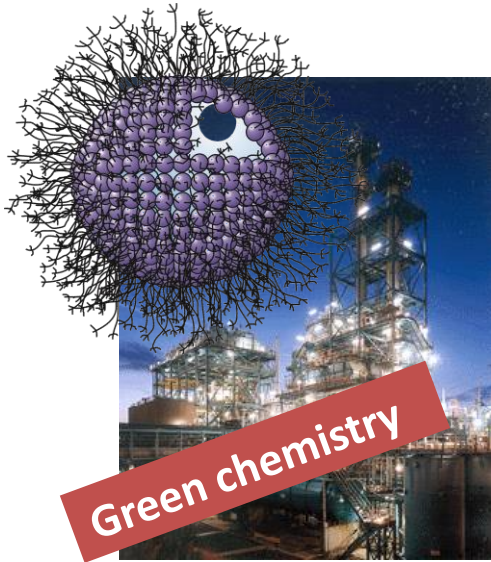
Harwell Campus

Diamond Light Source-
Secondary Beams?

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 is used to study everything!

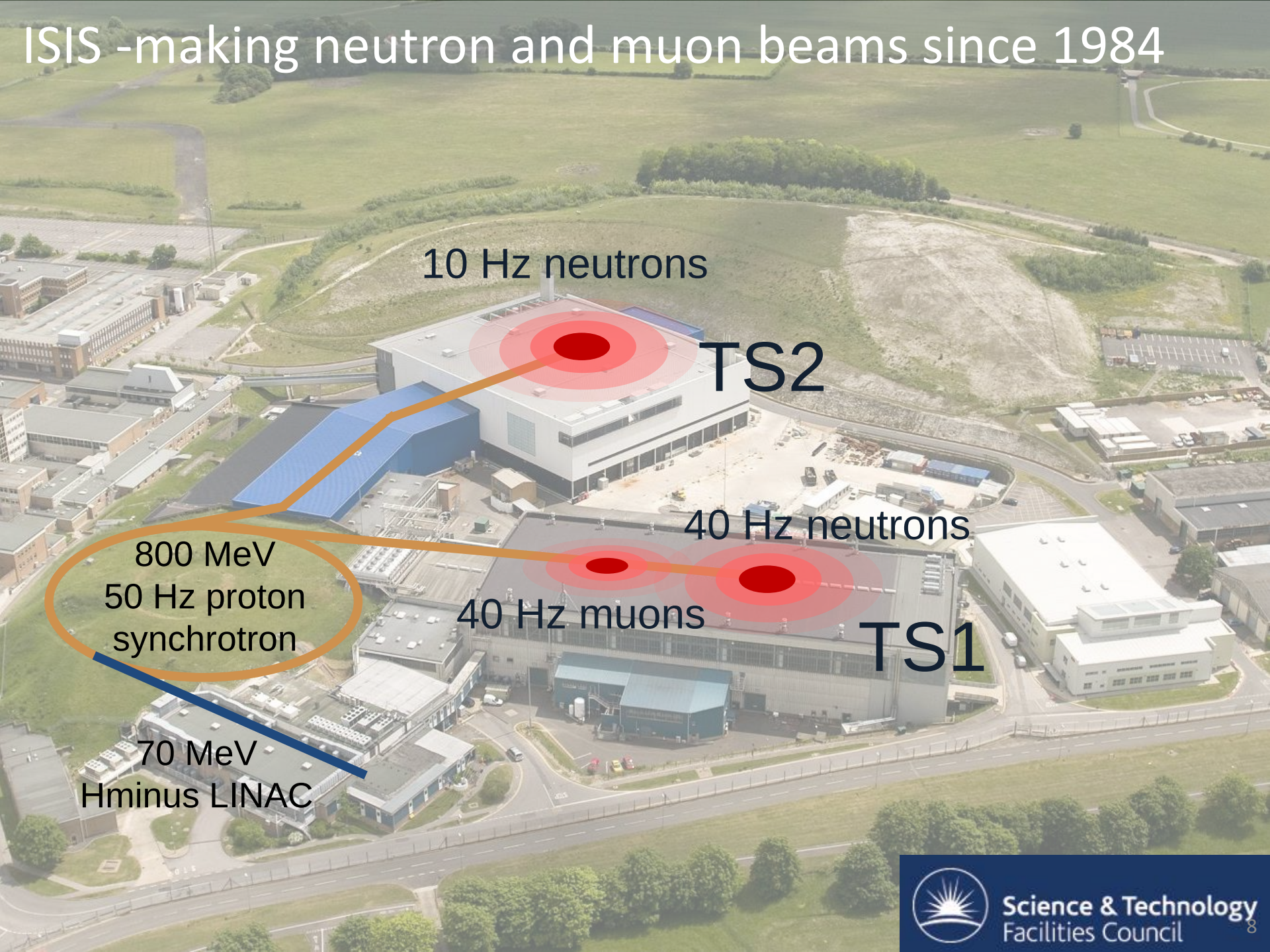


ISIS - making neutron and muon beams since 1984

Spallation neutron source
800 MeV 50 Hz proton beam
31 neutron instruments
7 muon instruments
2000 users/yr
~800 experiments/yr
~500 publications/yr



ISIS - making neutron and muon beams since 1984



10 Hz neutrons

TS2

40 Hz neutrons

40 Hz muons

TS1

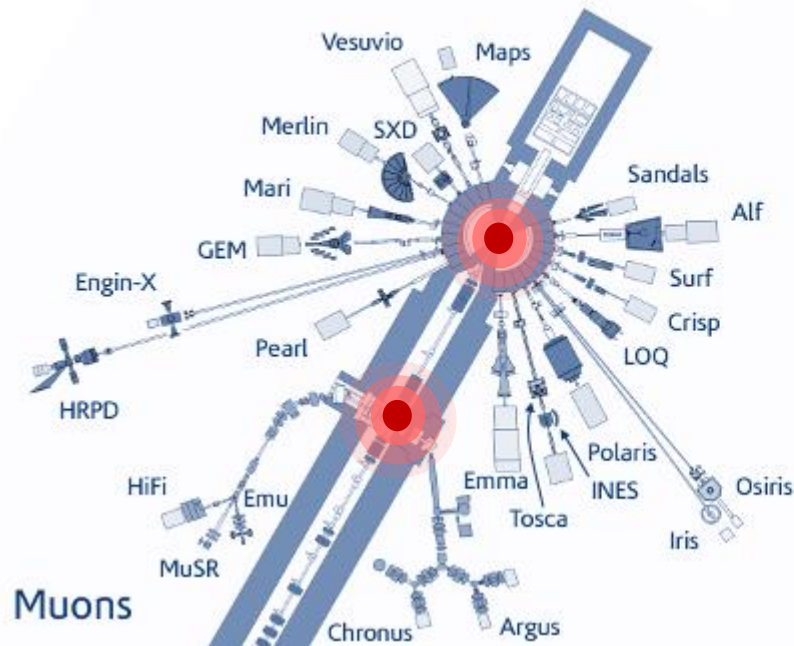
800 MeV
50 Hz proton
synchrotron

70 MeV
Hminus LINAC



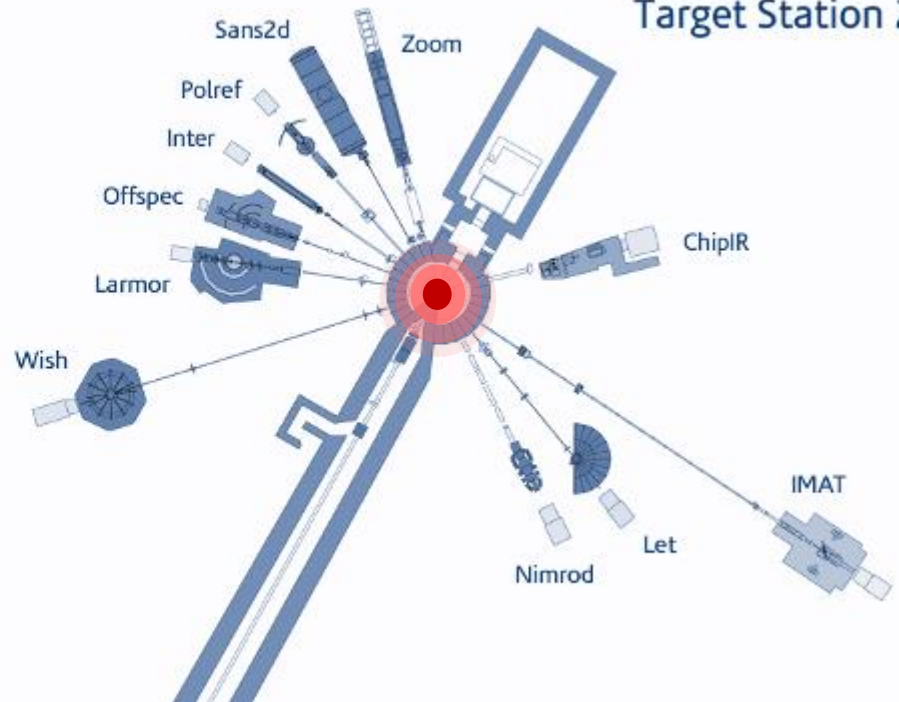
ISIS has many different types of neutron and muon instruments:

Target Station 1



20 neutron instruments
7 muon instruments

Target Station 2



11 neutron instruments
(more in the way)

LET Spectrometer



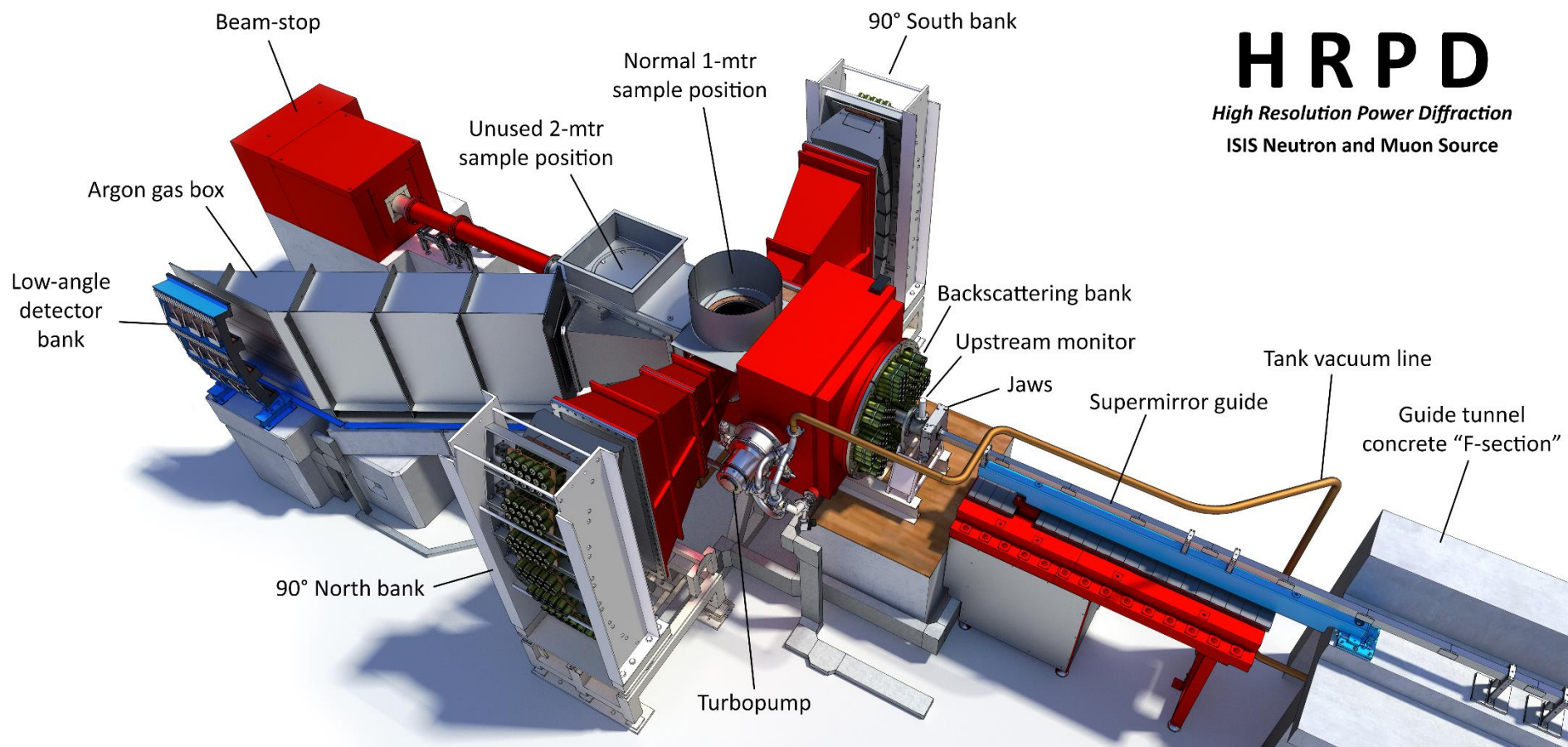
... some
are very
big

...some are smaller and movable

OFFSPEC Reflectometer

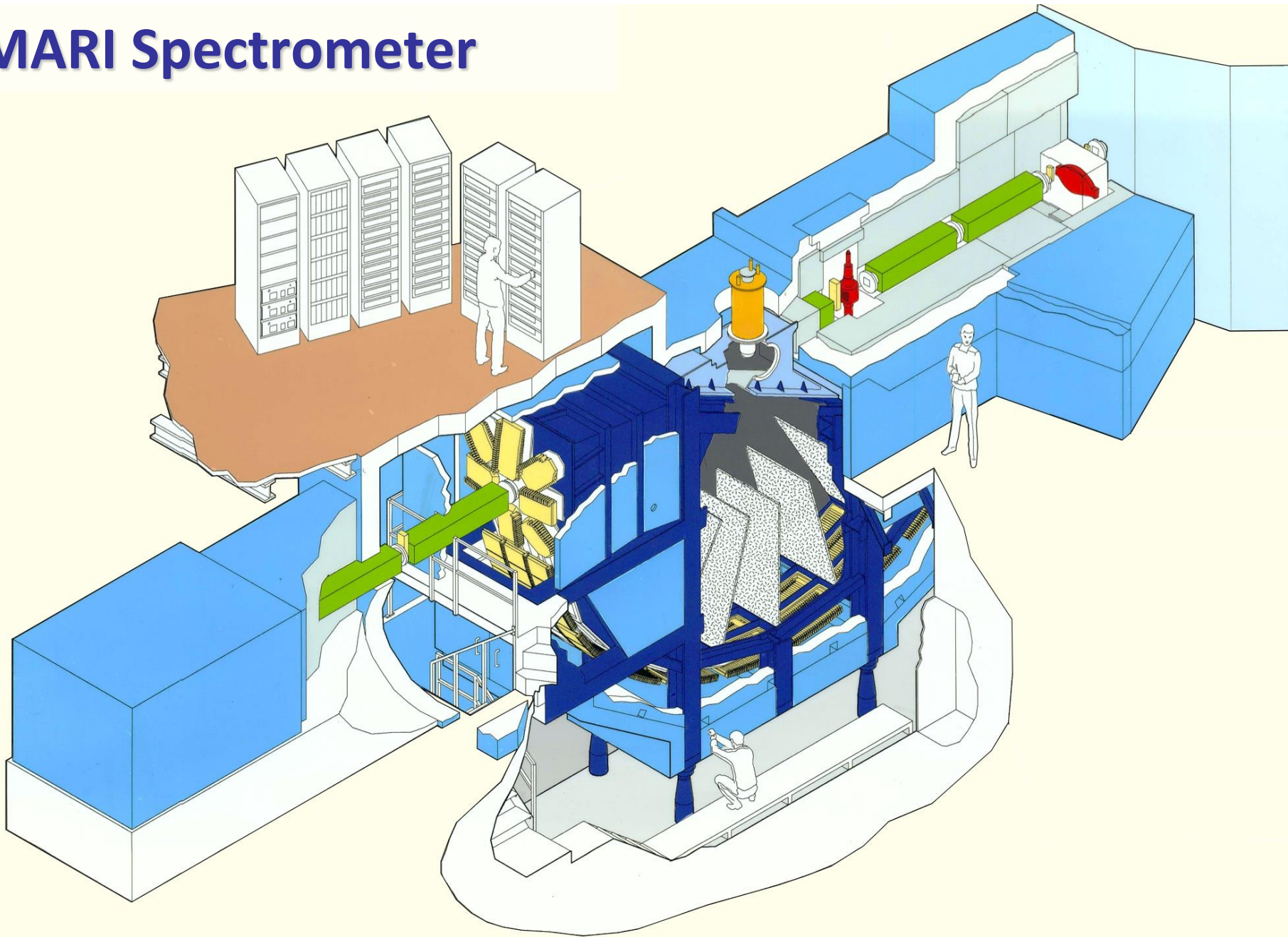


Each instrument is unique and complex...

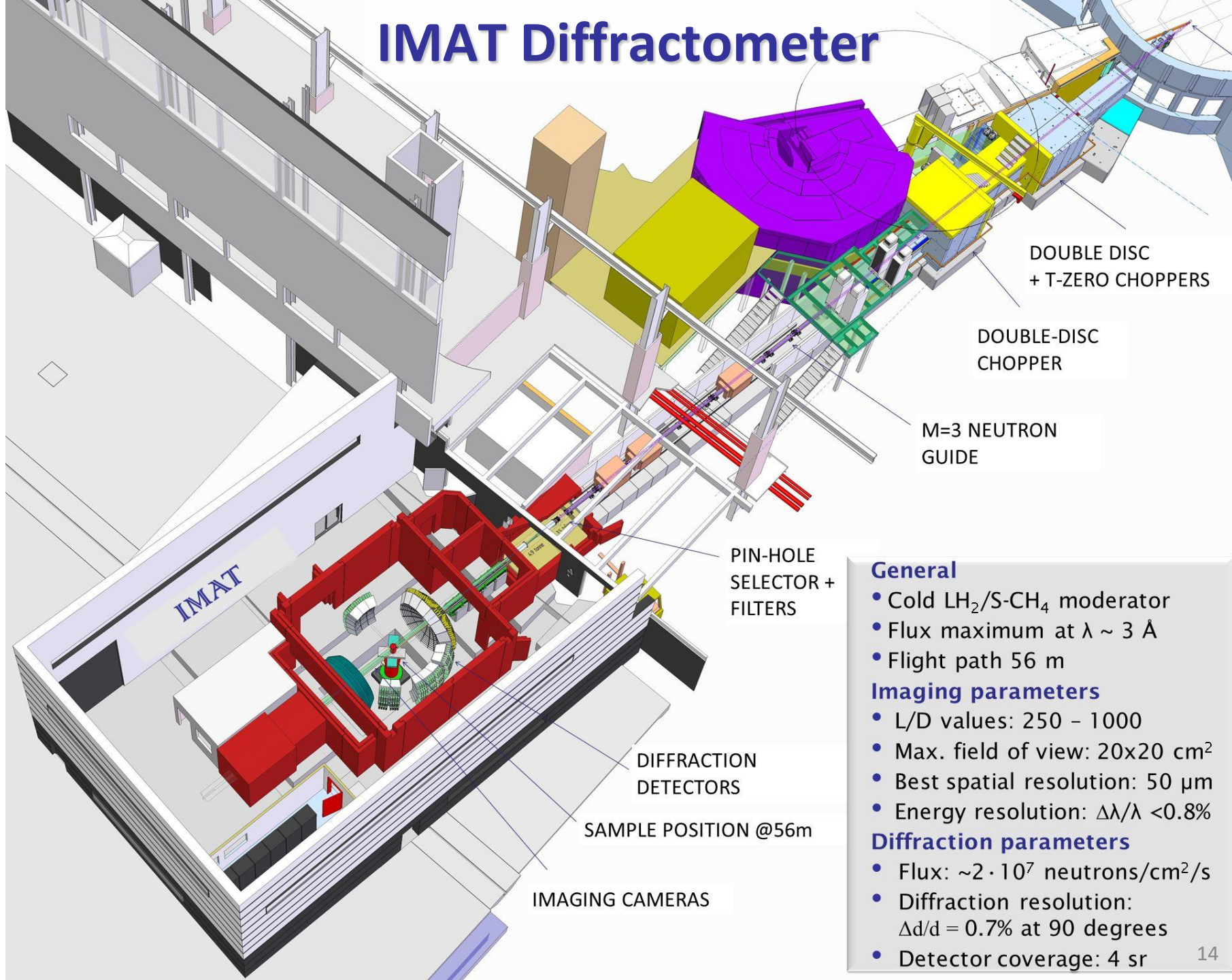


HRPD Diffractometer

MARI Spectrometer



IMAT Diffractometer



DOUBLE DISC
+ T-ZERO CHOPPERS

DOUBLE-DISC
CHOPPER

M=3 NEUTRON
GUIDE

PIN-HOLE
SELECTOR +
FILTERS

DIFFRACTION
DETECTORS

SAMPLE POSITION @56m

IMAGING CAMERAS

General

- Cold $\text{LH}_2/\text{S-CH}_4$ moderator
- Flux maximum at $\lambda \sim 3 \text{ \AA}$
- Flight path 56 m

Imaging parameters

- L/D values: 250 – 1000
- Max. field of view: $20 \times 20 \text{ cm}^2$
- Best spatial resolution: $50 \text{ \mu m}$
- Energy resolution: $\Delta\lambda/\lambda < 0.8\%$

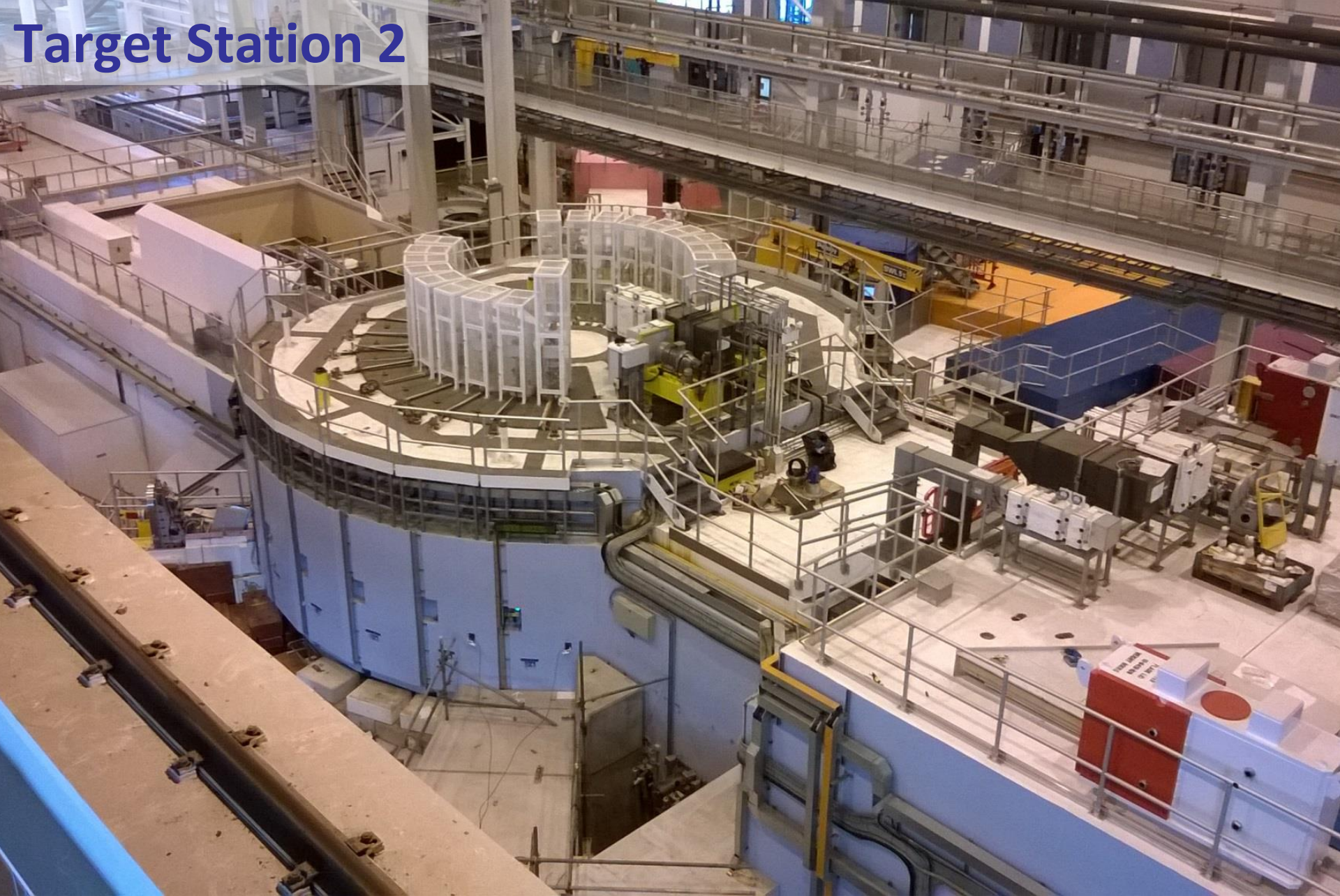
Diffraction parameters

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

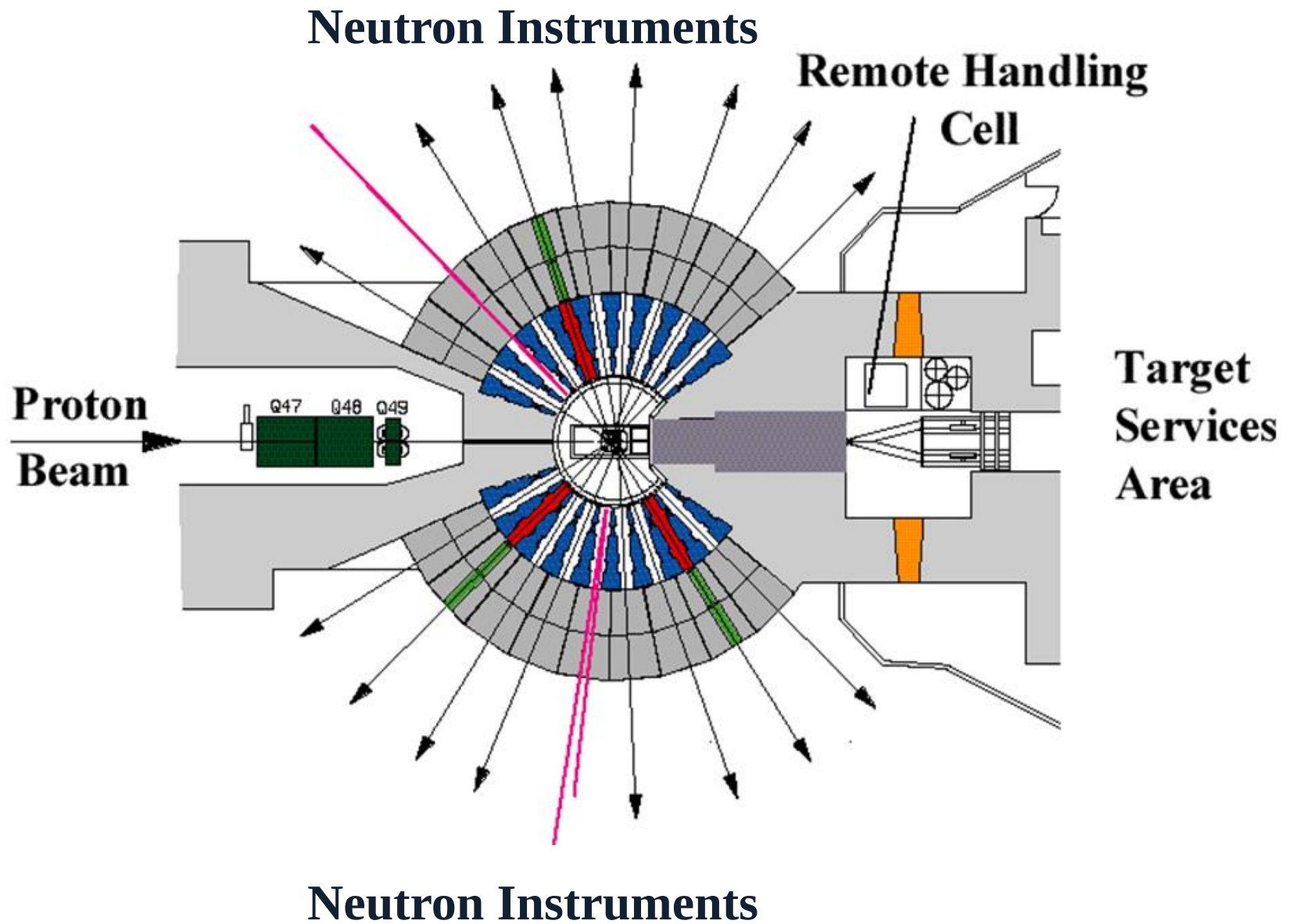
Target Station 1



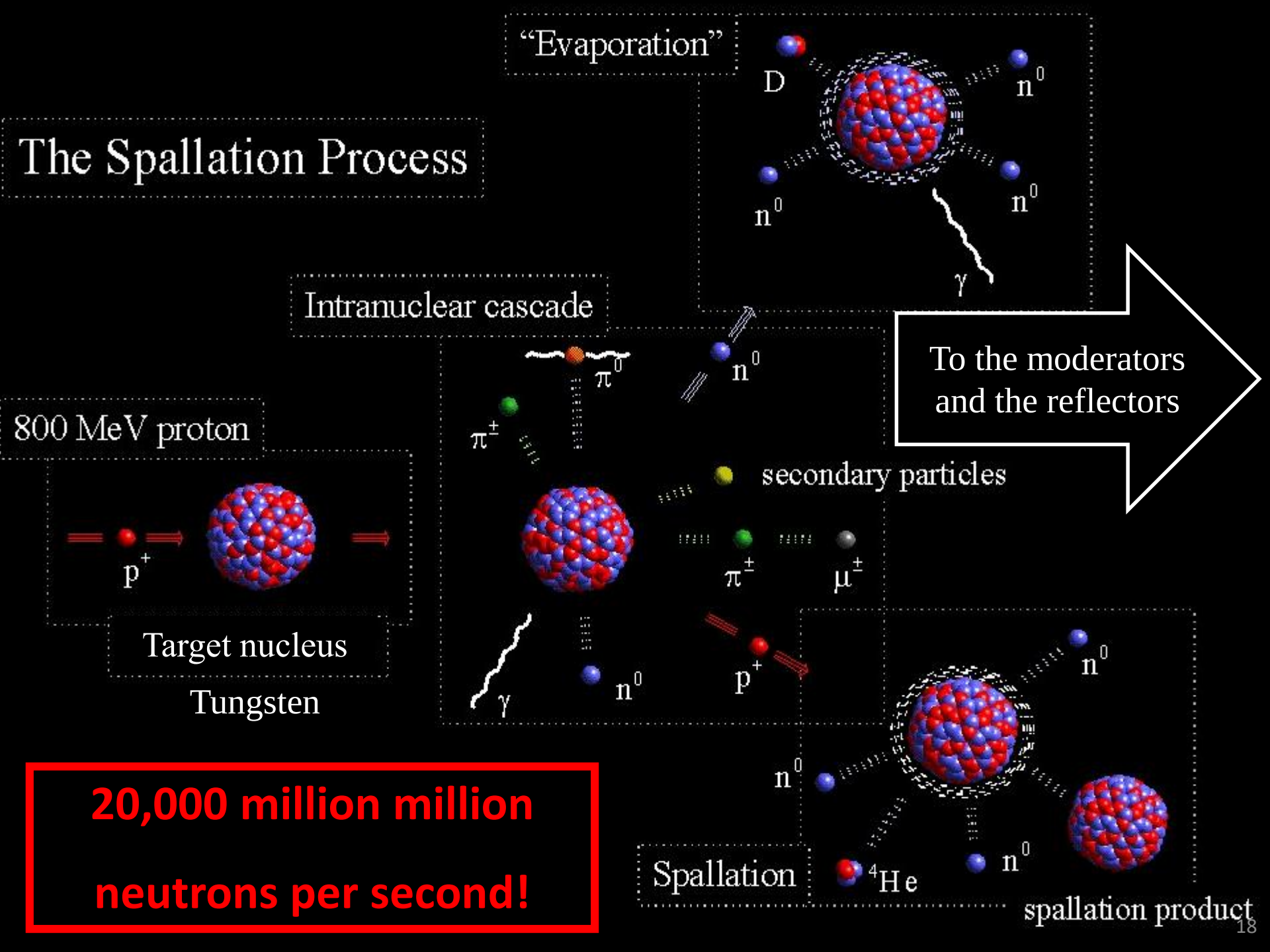
Target Station 2



Basic Layout of ISIS Target Stations

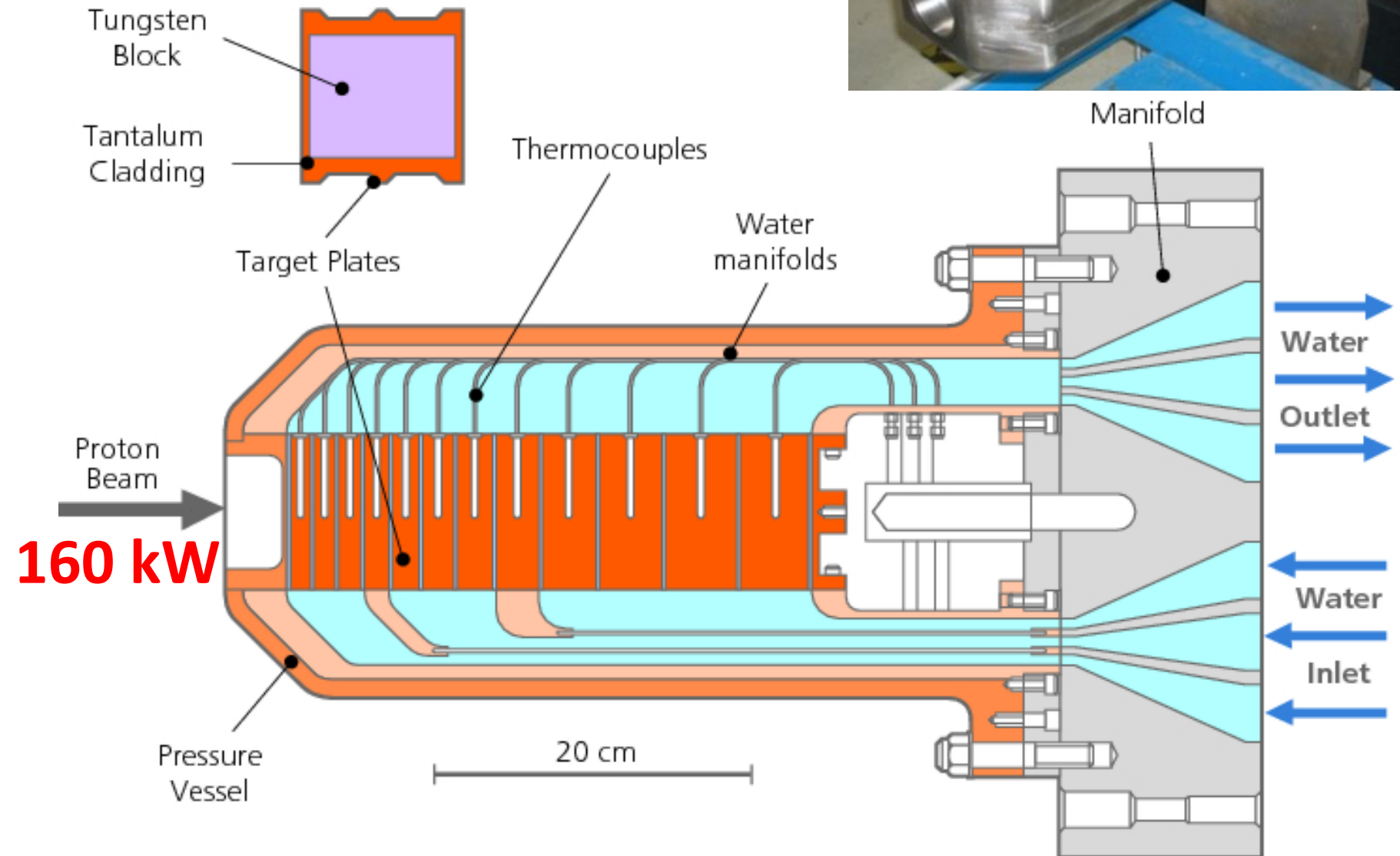


The Spallation Process



**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)

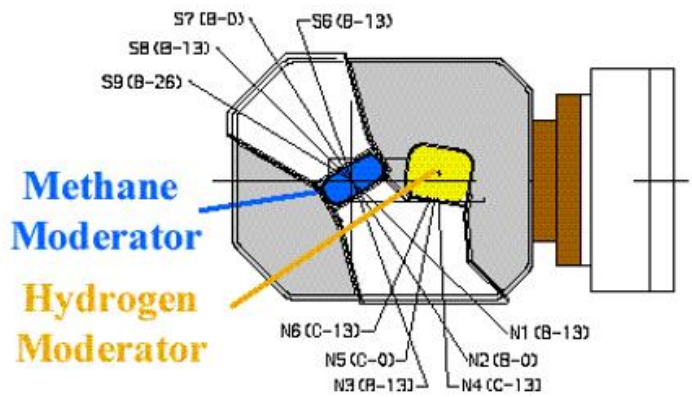
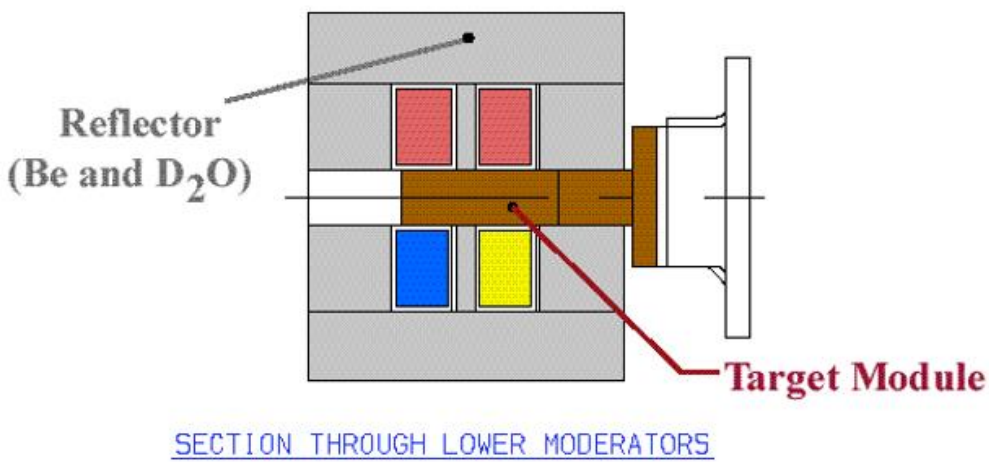
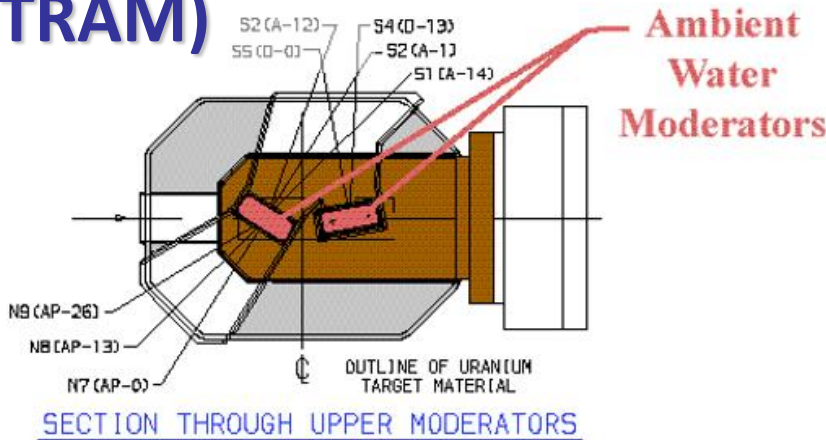
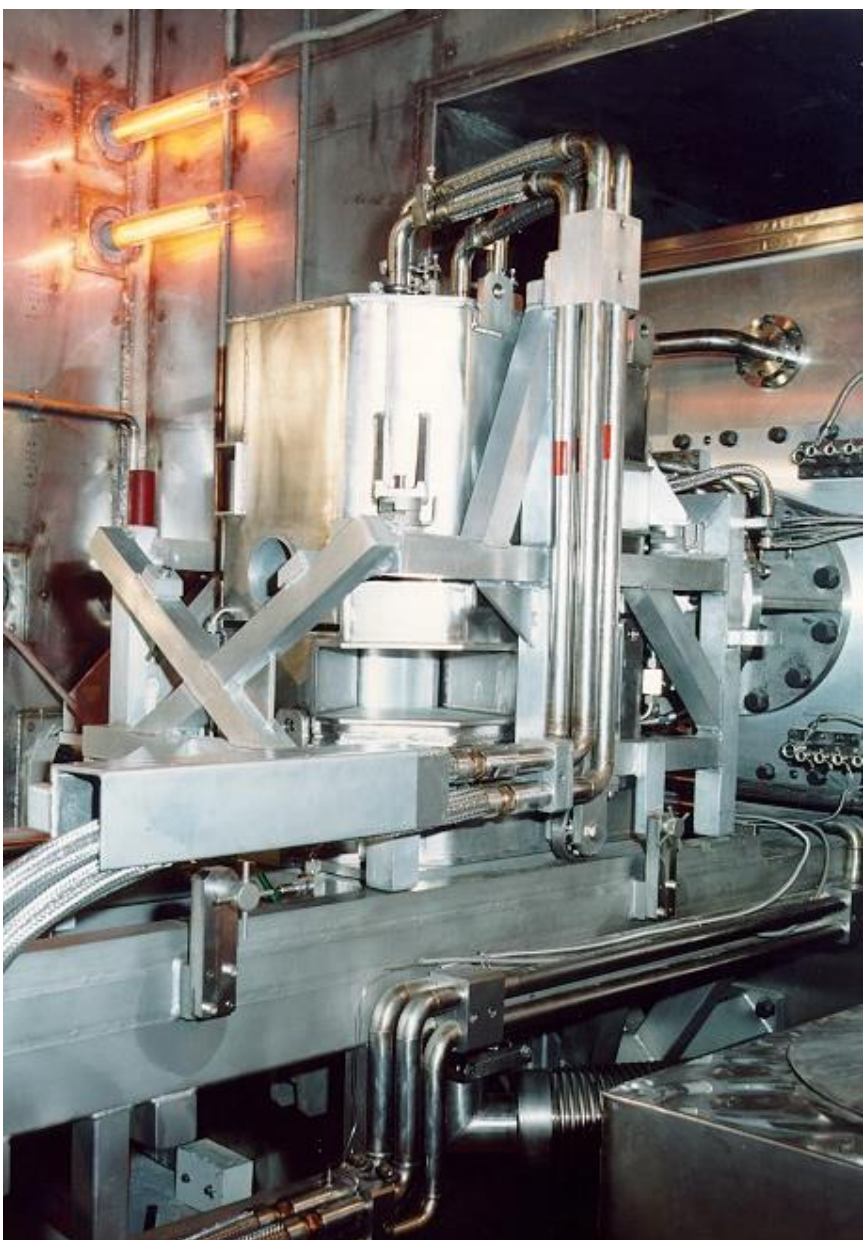
800 MeV
protons



slow
neutrons

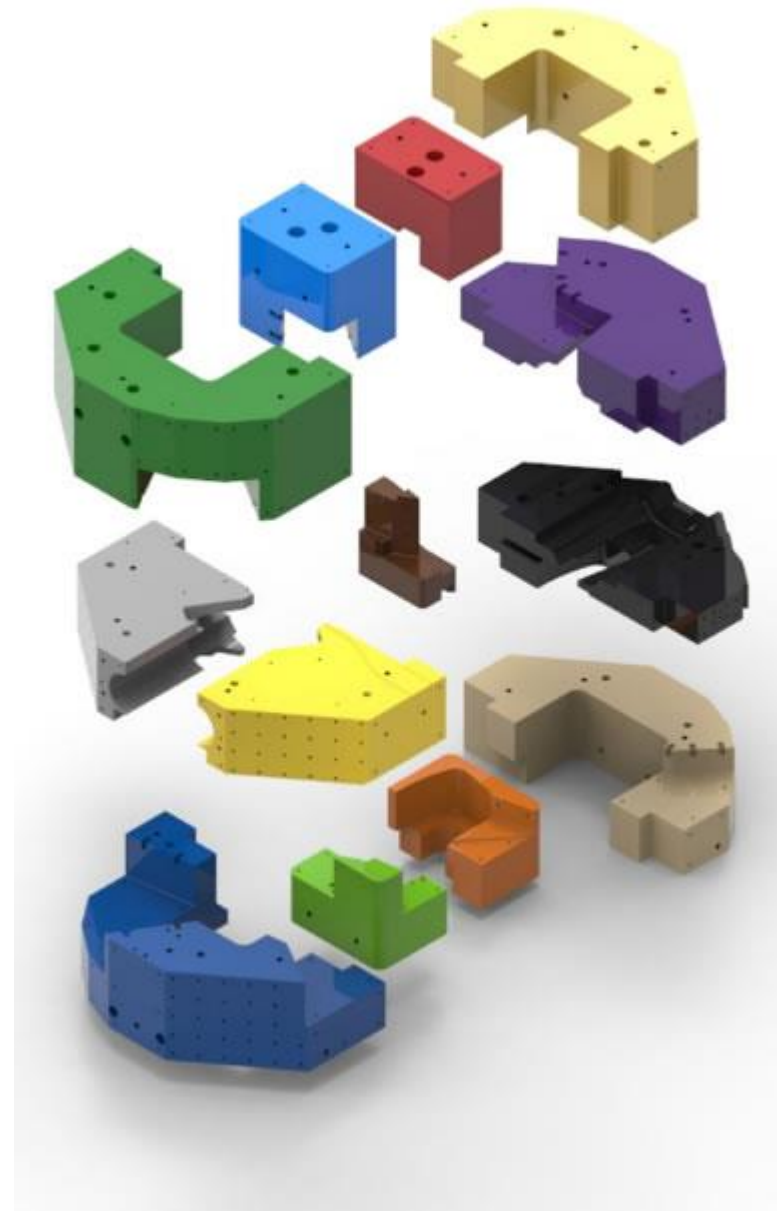
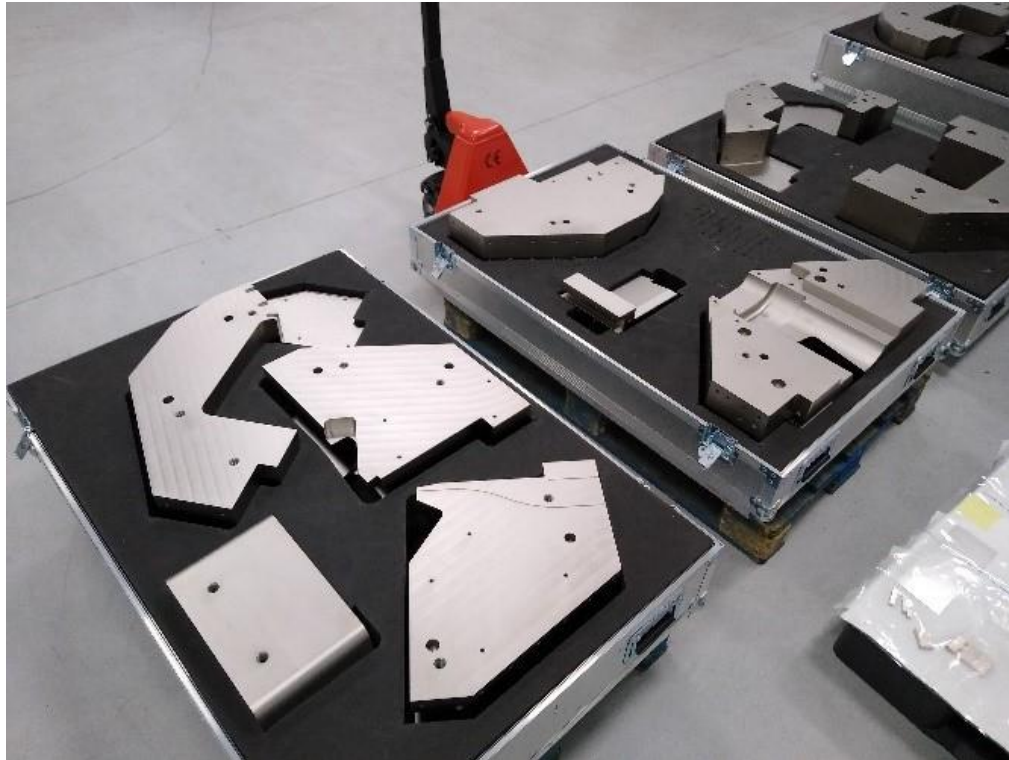


Target Reflector And Moderators (TRAM)



TS1 Project – Major Refurbishment

New £3.4M 0.5 T 13-piece beryllium reflector



ISIS TS1 target and moderators with 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

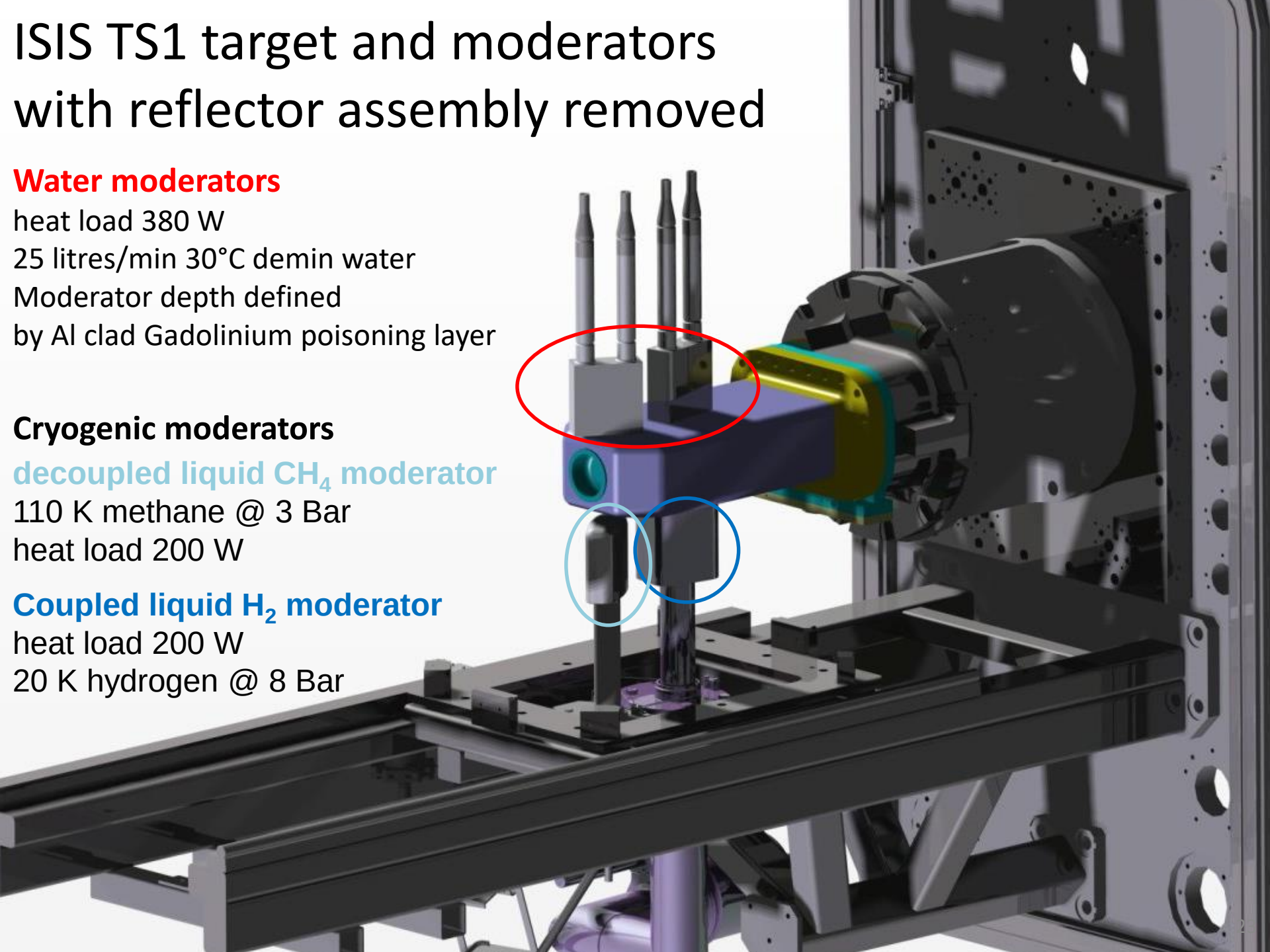
Cryogenic moderators

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



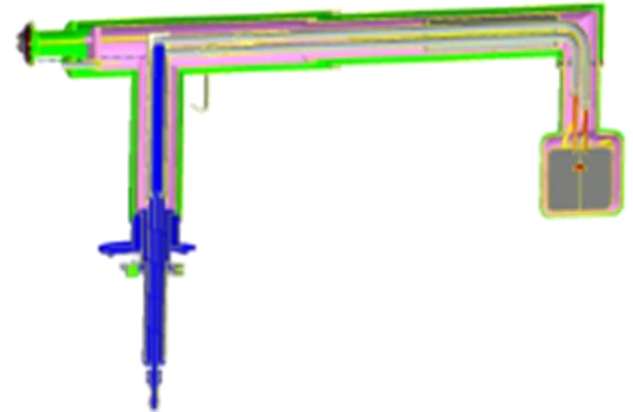
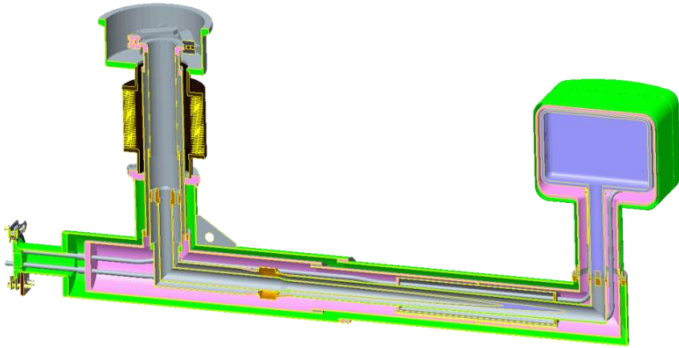
ISIS Target Station 2 TRAM with the edge cooled beryllium reflector open in maintenance mode



TS2 Cryogenic Moderators



coupled moderator: liquid H_2
@ 20 K 4 Bar



decoupled moderator: solid CH_4 @ 45 K



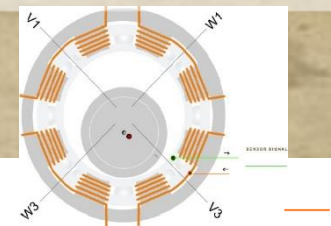
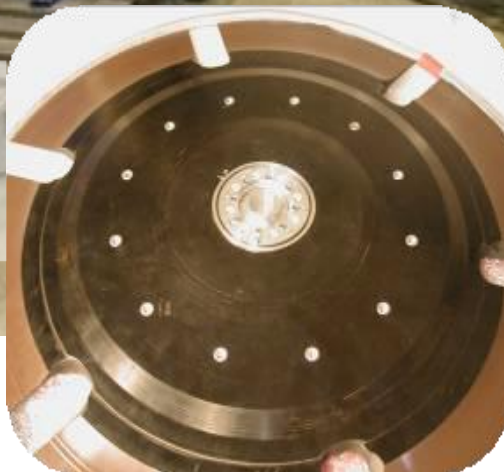
Choppers- spinning shielding



precise
timing

slotted
shielding

magnetically
levitating
bearings



Choppers- spinning shielding

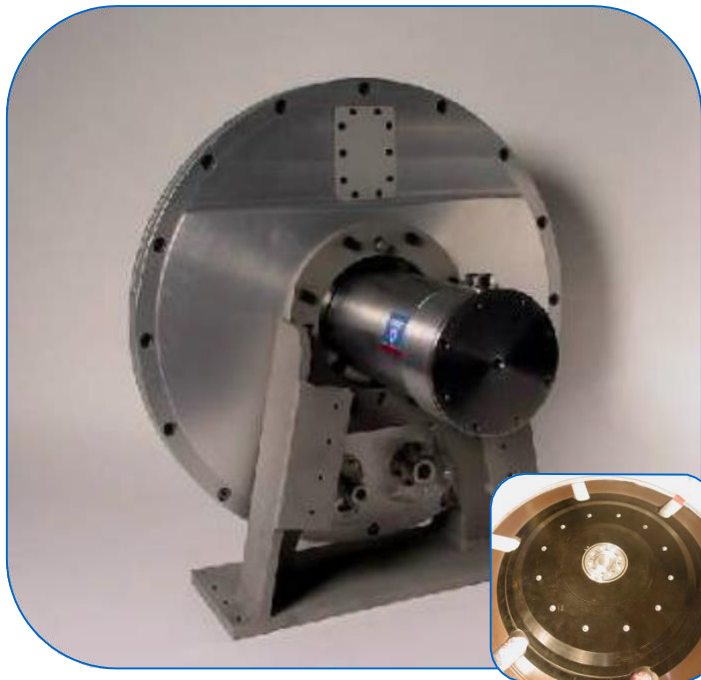
Fermi (17)

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

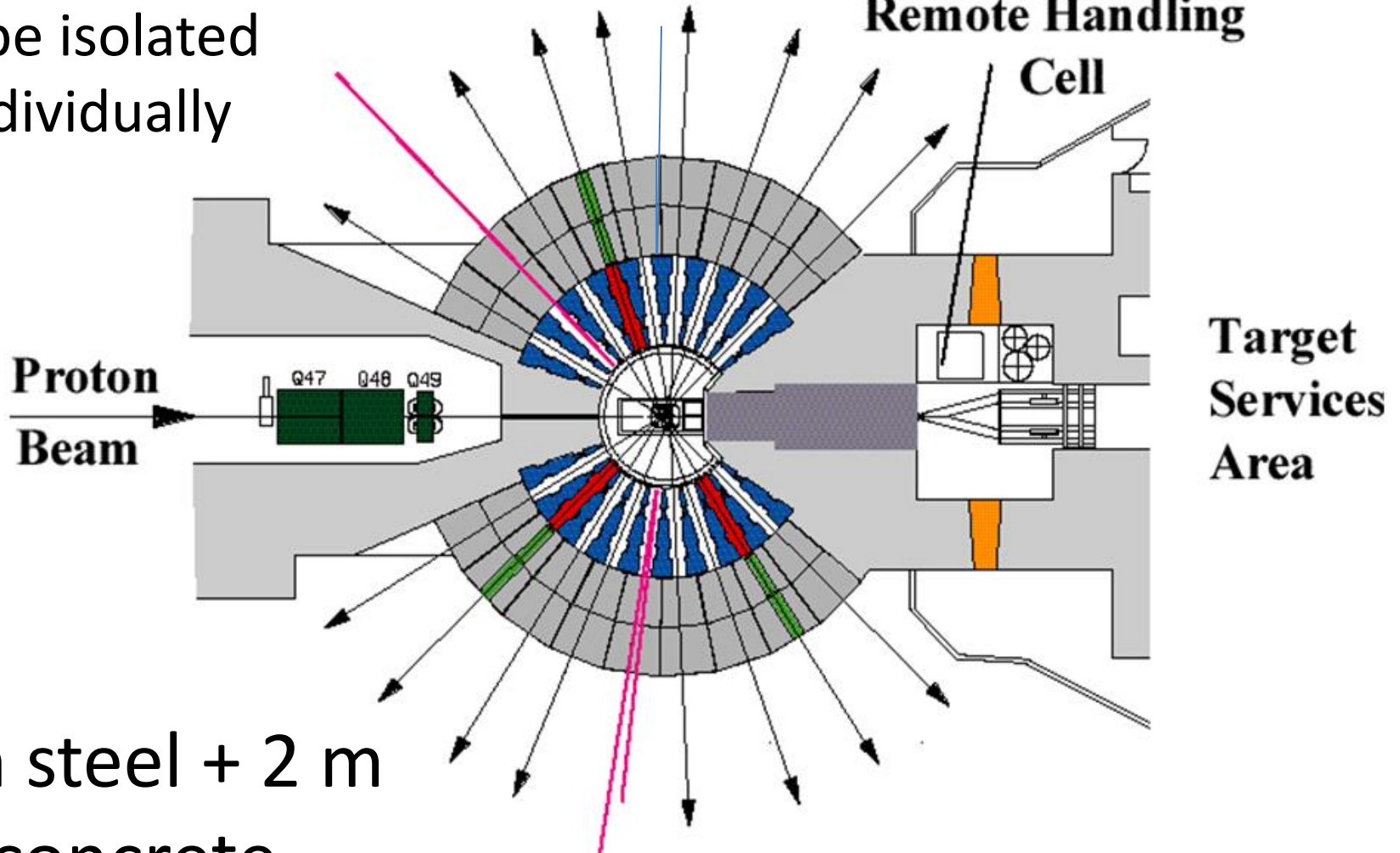


Shielding

Shutters allow
each instrument
to be isolated
individually

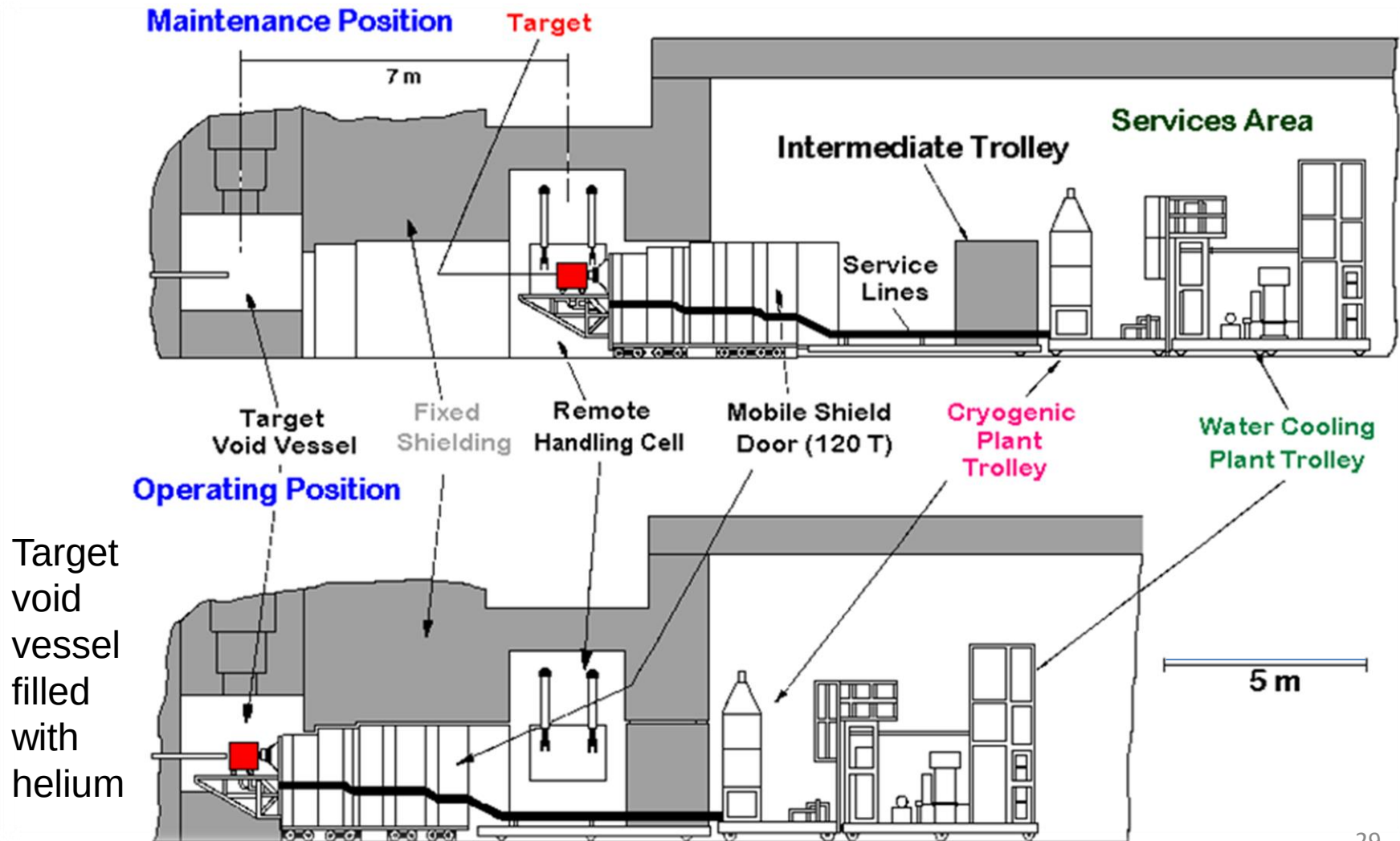
Neutron Instruments

**Remote Handling
Cell**



Neutron Instruments

The services trolley moves to position the TRAM for operation or maintenance



TS1 Services Trolley Cooling Plant



TS2 Services Trolley Cooling Plant



**remote
manipulator
set in TS1**





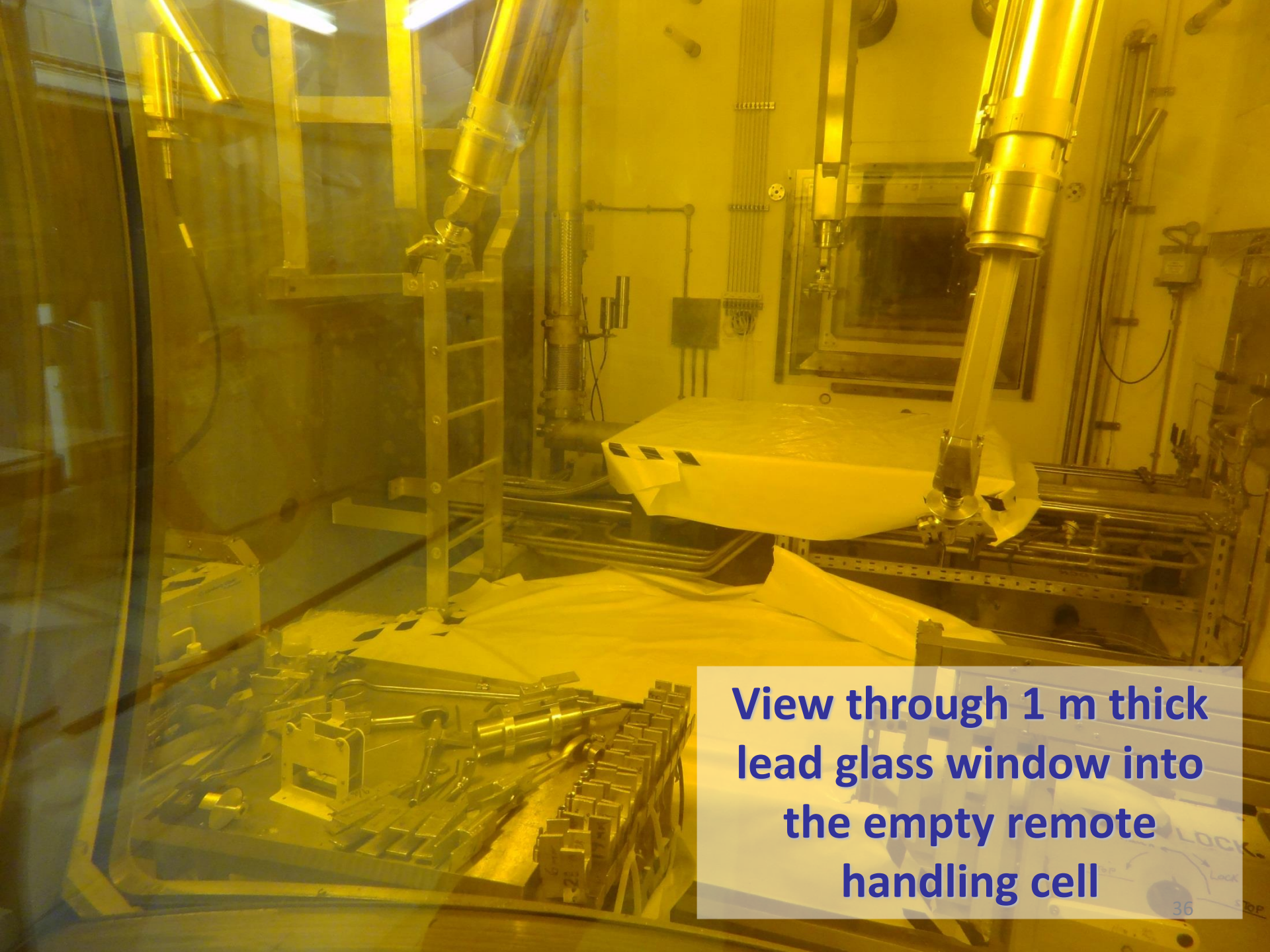
remote
manipulator
set in TS2

remote manipulator sets on both
sides of the remote handling cell



A photograph of two men in a control room. The man in the foreground is wearing a dark blue polo shirt with a NASA logo, a headset, and a wristwatch. He is holding a large, silver, articulated robotic arm. The man in the background is also wearing a headset and is looking at a computer monitor. The room has a blue pegboard on the wall, a clock in the top left corner, and various cables and equipment. A semi-transparent text box is overlaid on the bottom left of the image.

**Crews in contact with
other areas by headset**



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



window failure!



The main remote handling task carried out is CH4 moderator replacement
Every 3-4 cycles



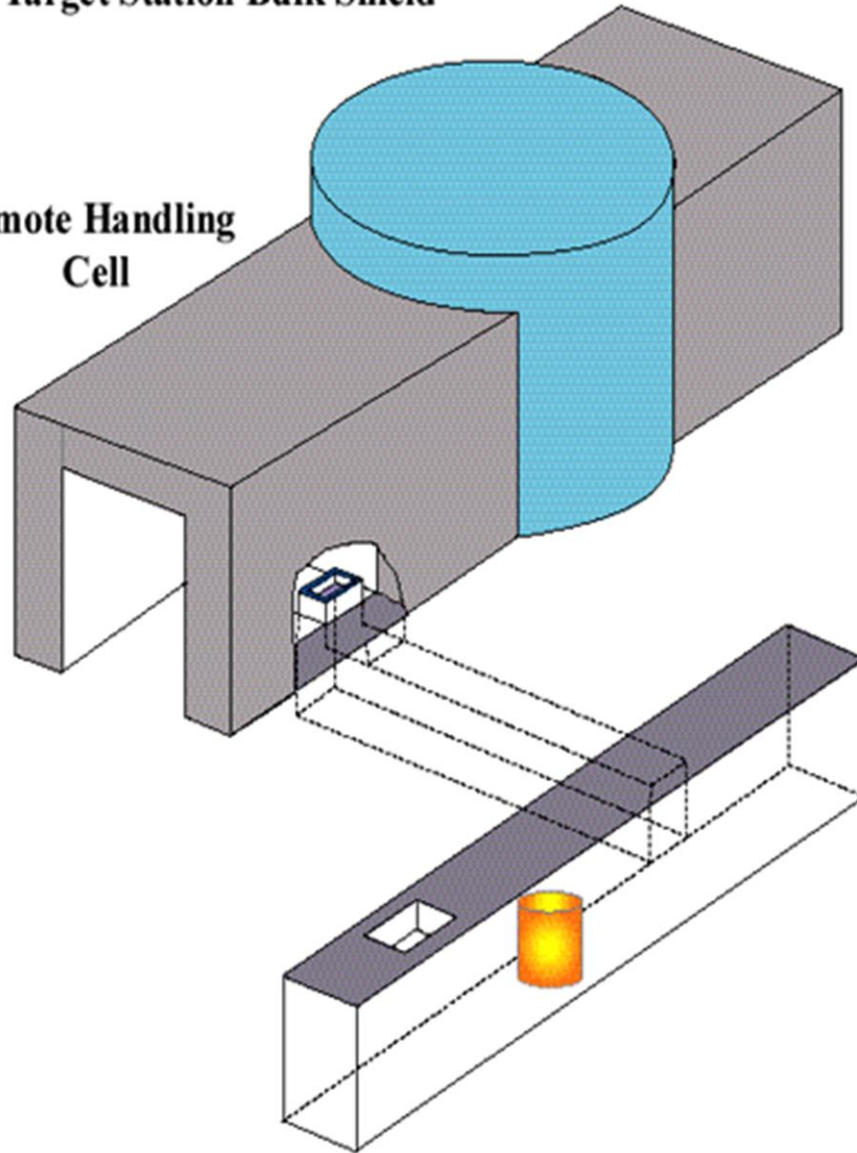
Targets also need to be replaced every 4-5 years

TS1 Tungsten
Target #4 on flow
test rig



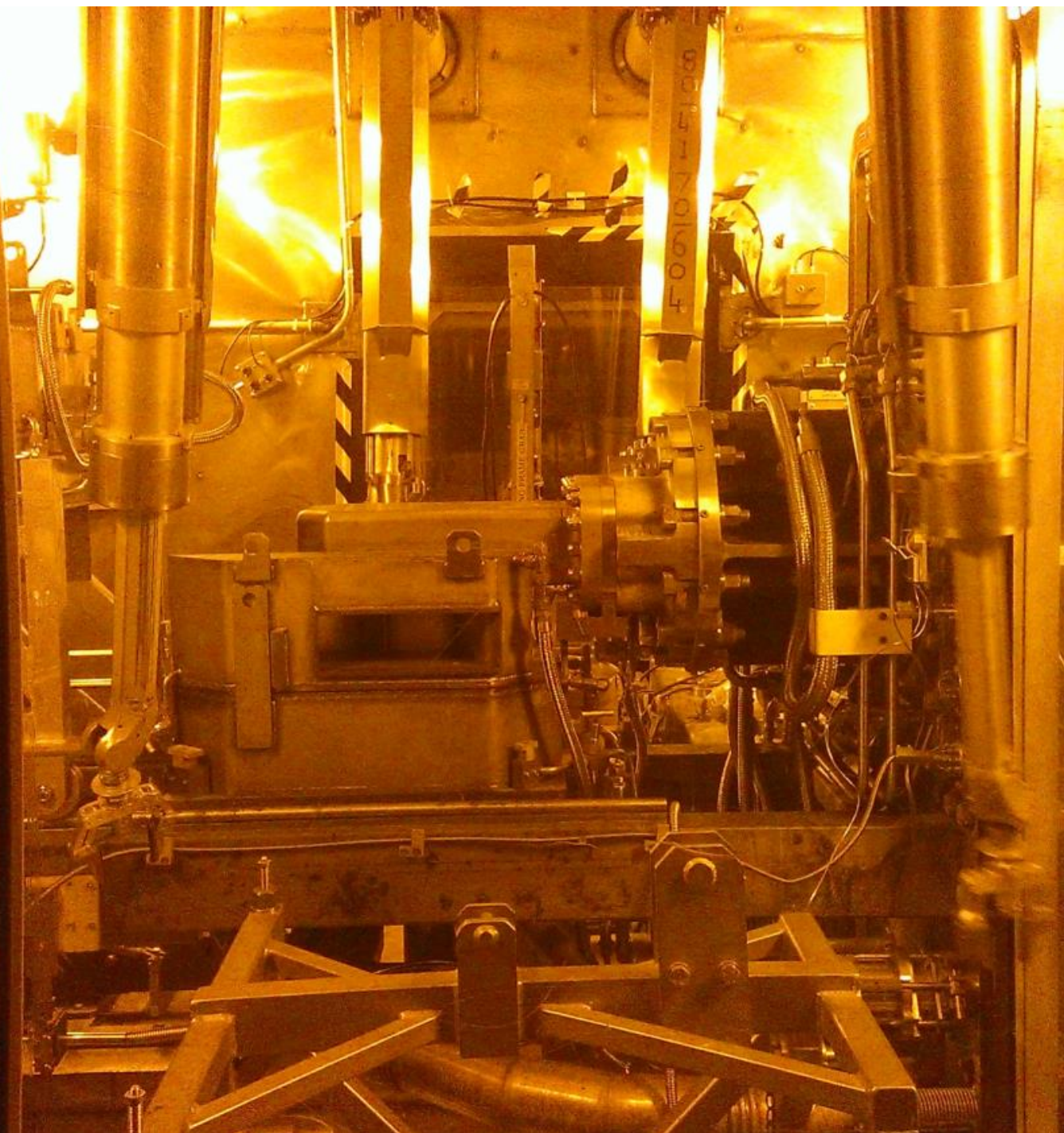
Target Station Bulk Shield

**Remote Handling
Cell**



Active components
are removed using
the tunnel system
under the RHC

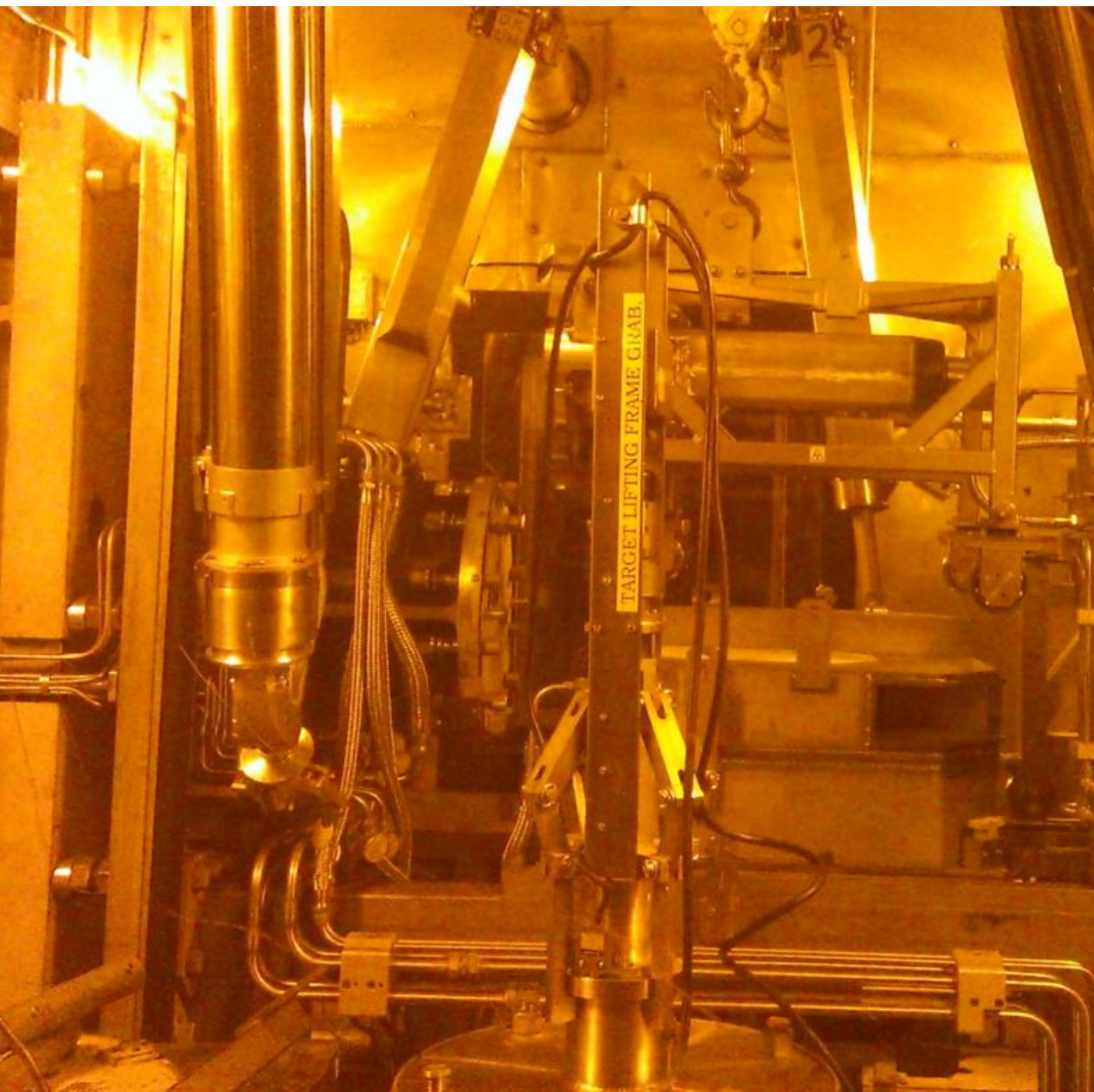
**Underground Tunnel for Removal of Active
Components in Transport Flask**



View of the TS1
TRAM withdrawn
into the RHC

This view is from
the north side of
the RHC

The reflector top
section is rolled
forward to expose
the Tungsten
Target



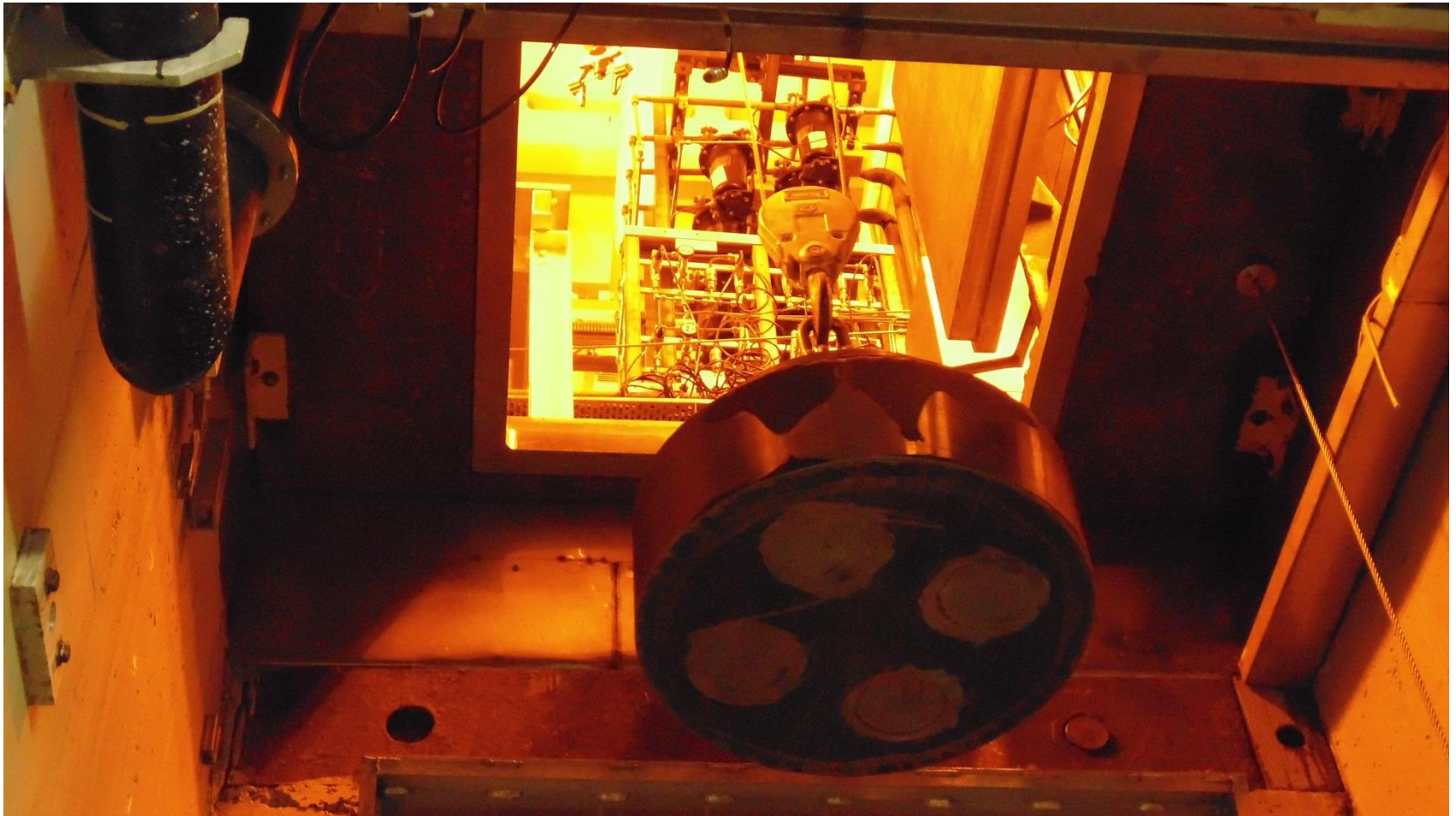
The target has been disconnected and is being lifted away from its working position



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



Target and can being lowered into the transport flask



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

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





Storage flask total weight is 9 Tonnes

Flask is moved on 'MasterMover' powered pallet truck

The loaded flask is lifted out of the tunnel



The loaded flask is transported back to R40 for storage



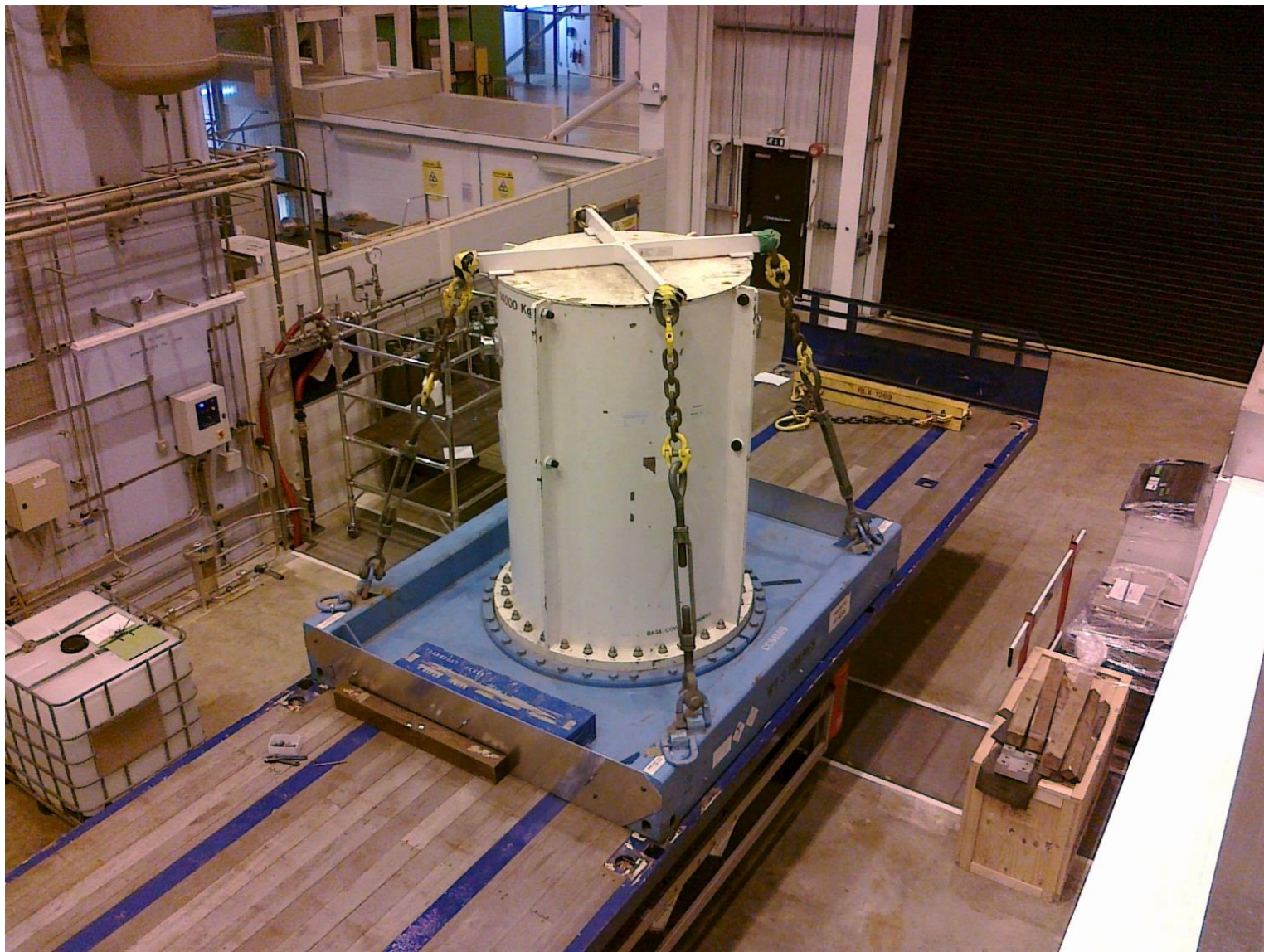


After work in the RHC is complete the area must be cleared and checked

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

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



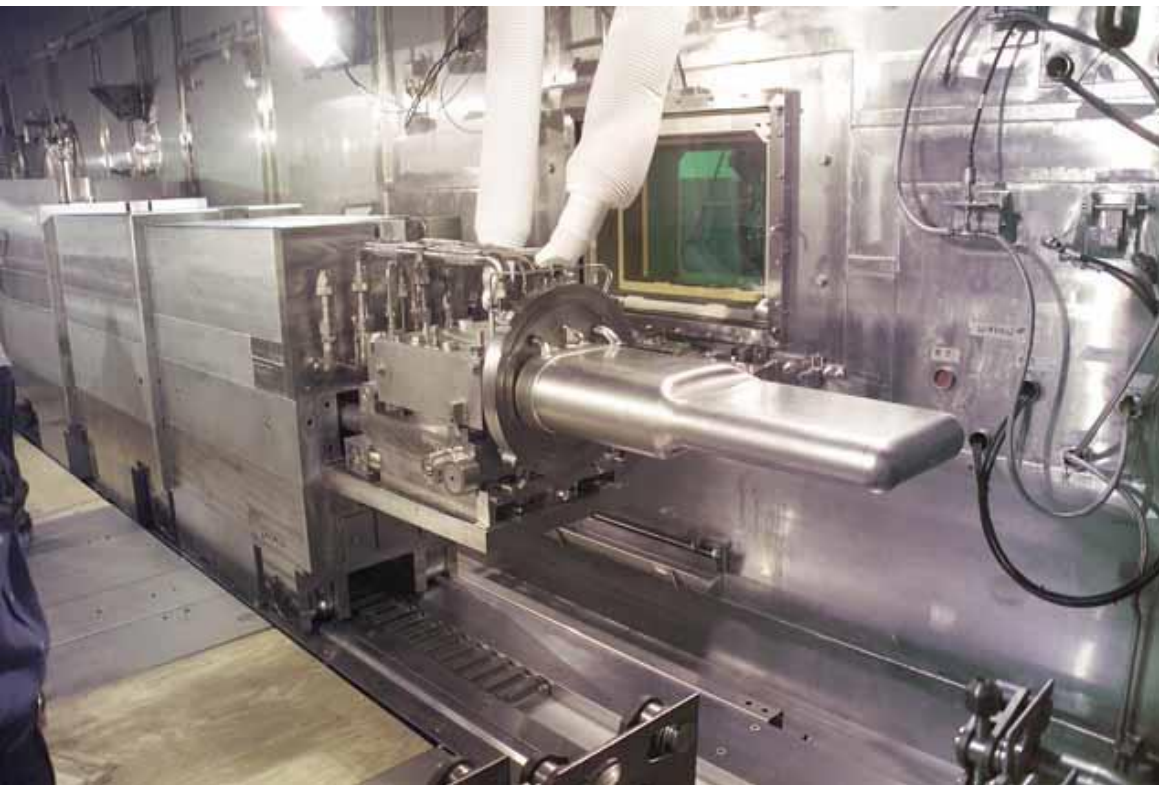
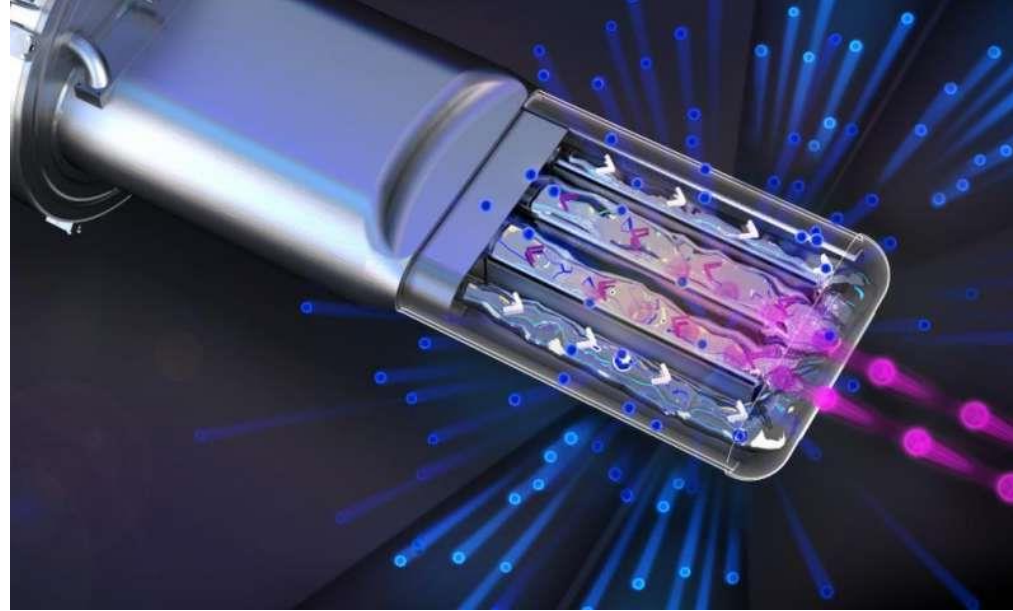


For final disposal the target is transferred to a registered and licenced Type B package and transported to Sellafield the UK's nuclear waste storage facility

More power!

- 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





100 500 1000
1000

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

Cavitation bubble collapse causes serious damage



solution: fizzy mercury with helium



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**

**A solution for
SNS TS2**

protons

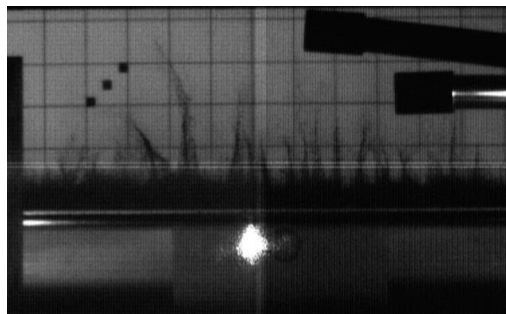
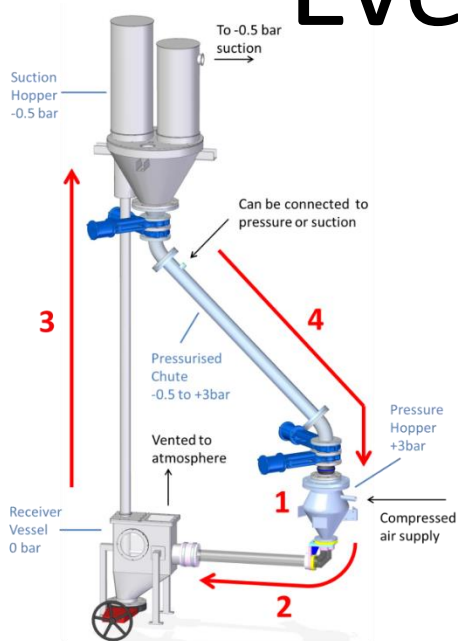




Tungsten powder
handling system
developed at RAL

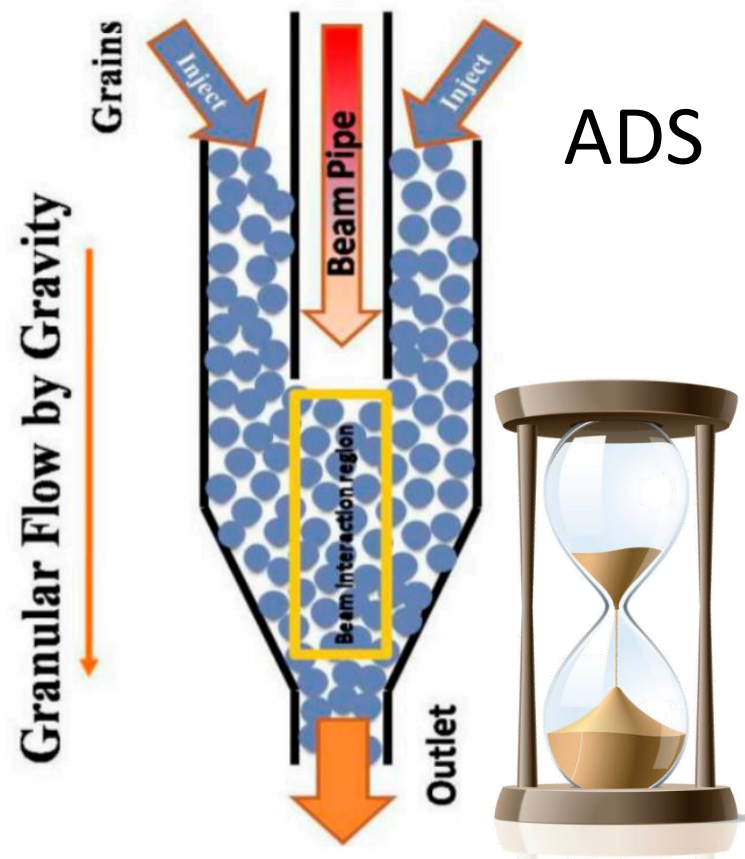


Science & Technology
Facilities Council



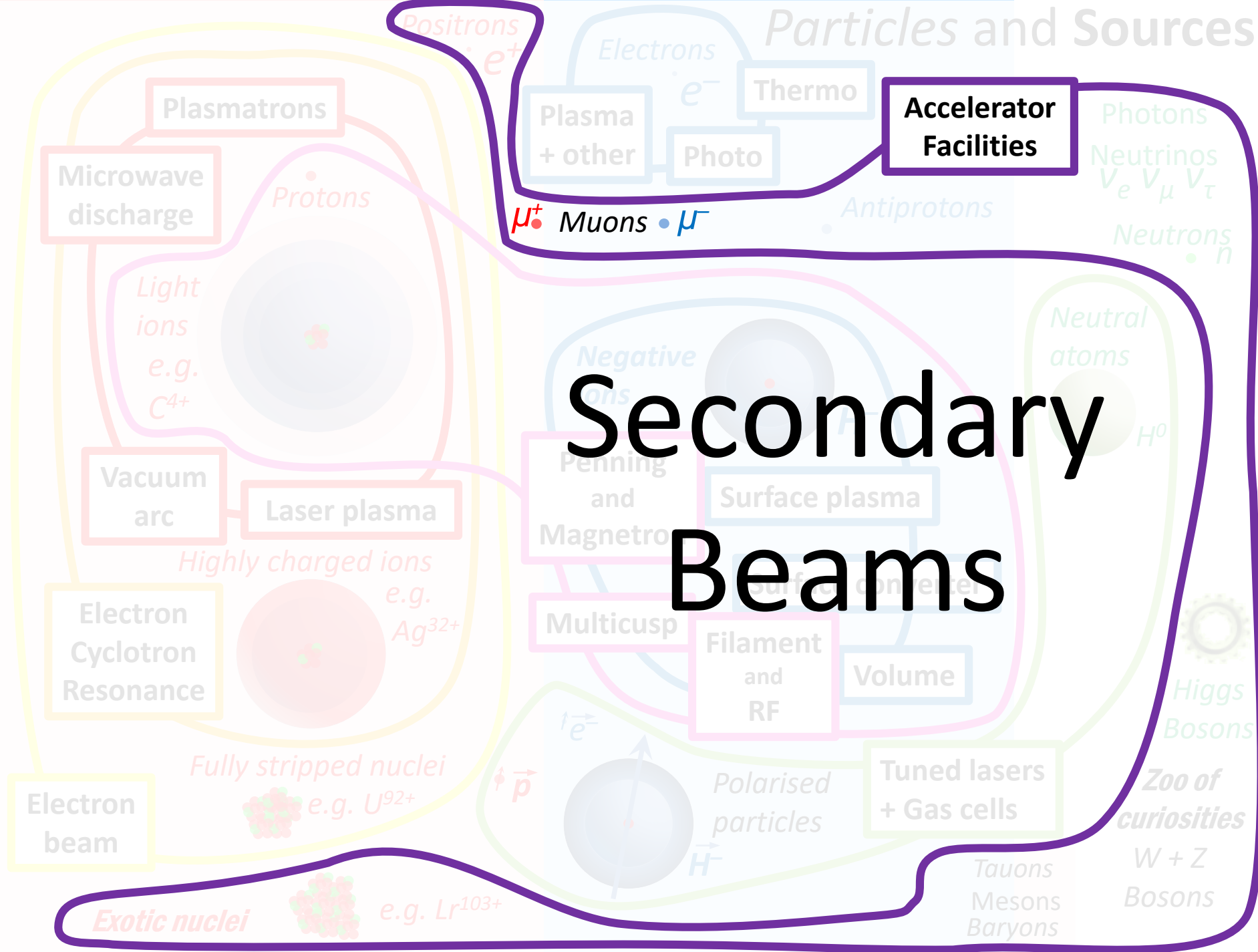
Tests at CERN

Even more power!



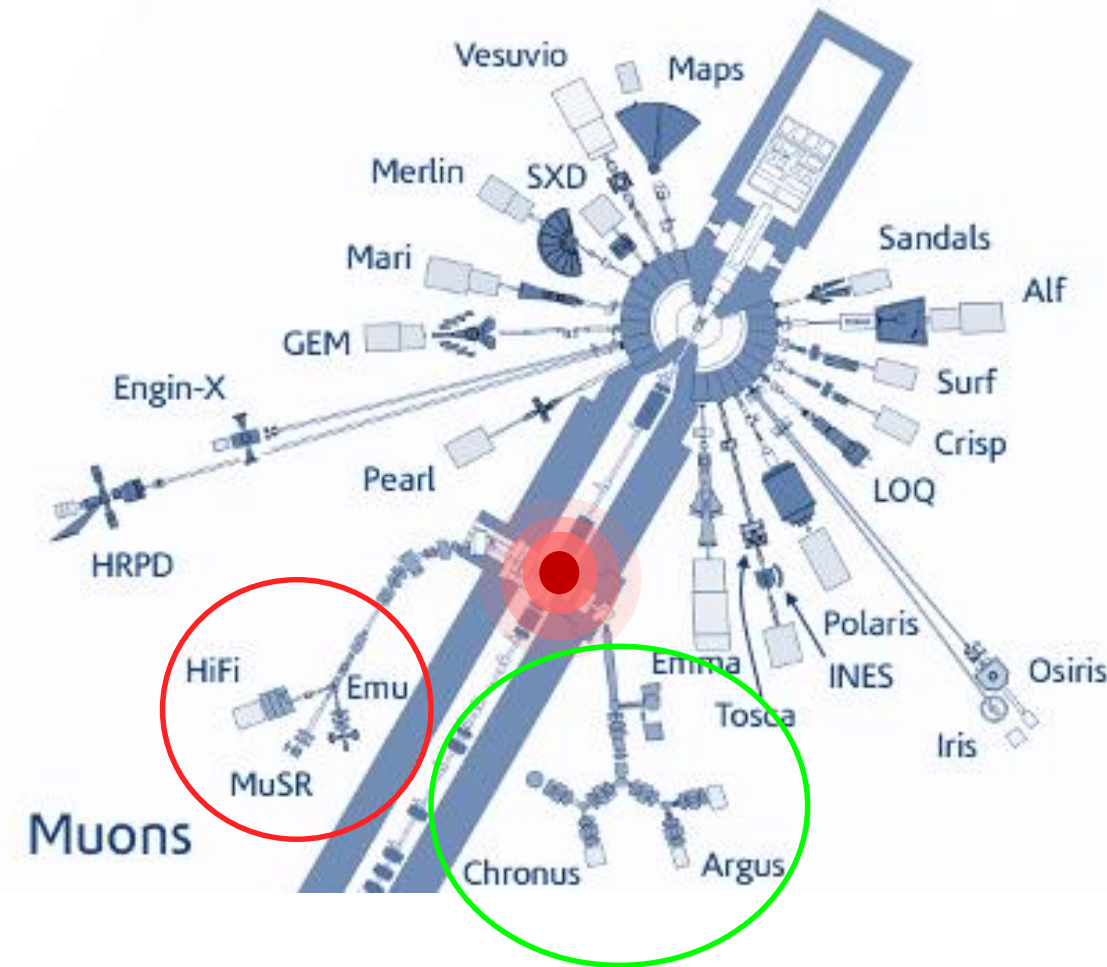
中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

10-100 MW!



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

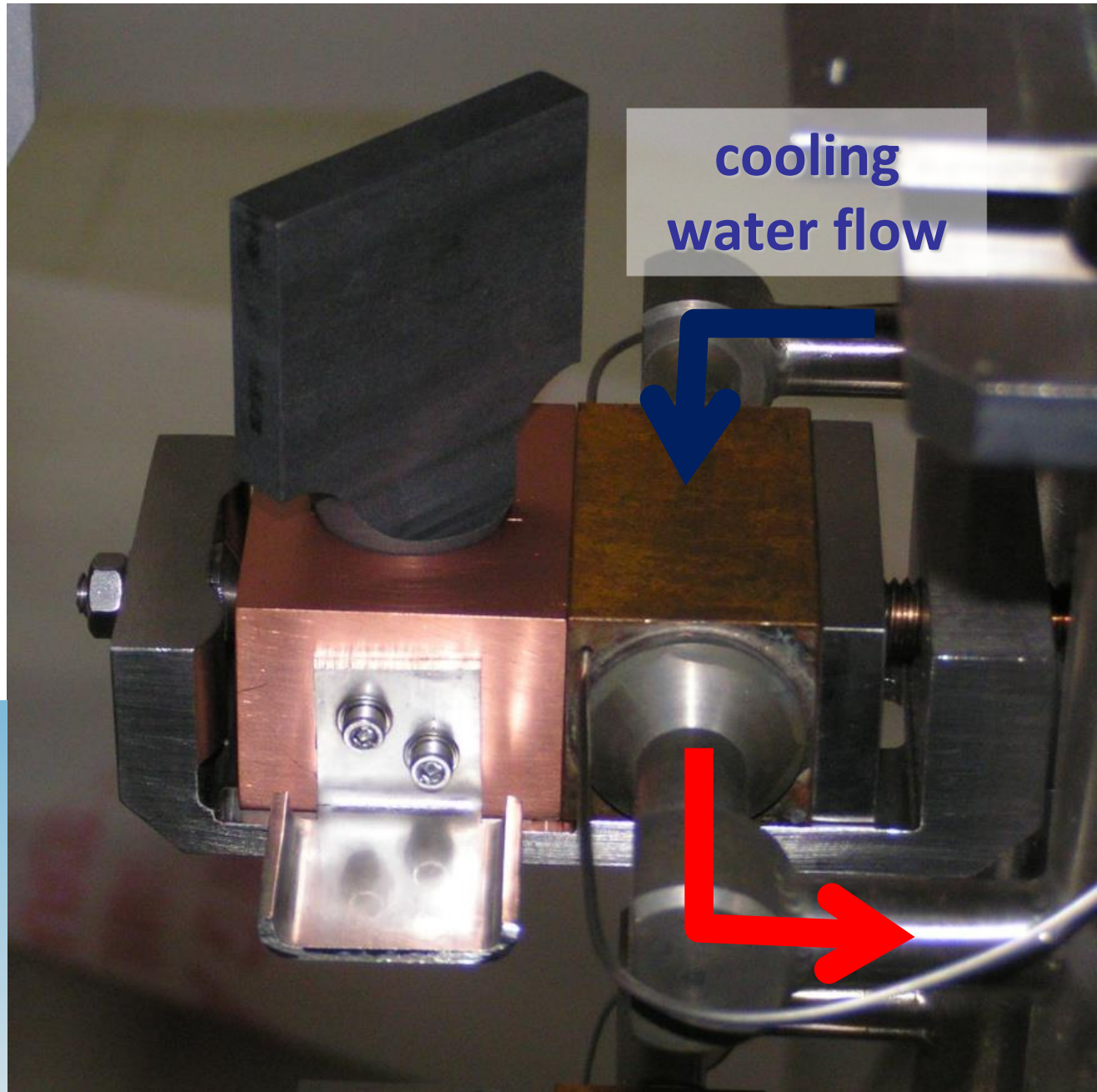
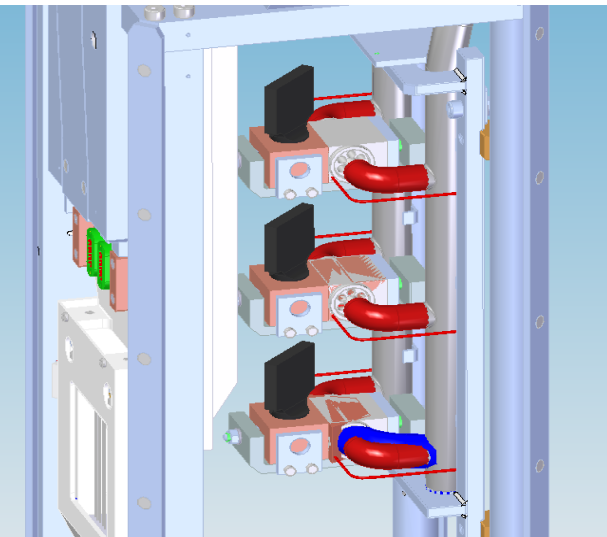
ISIS Muon Target

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

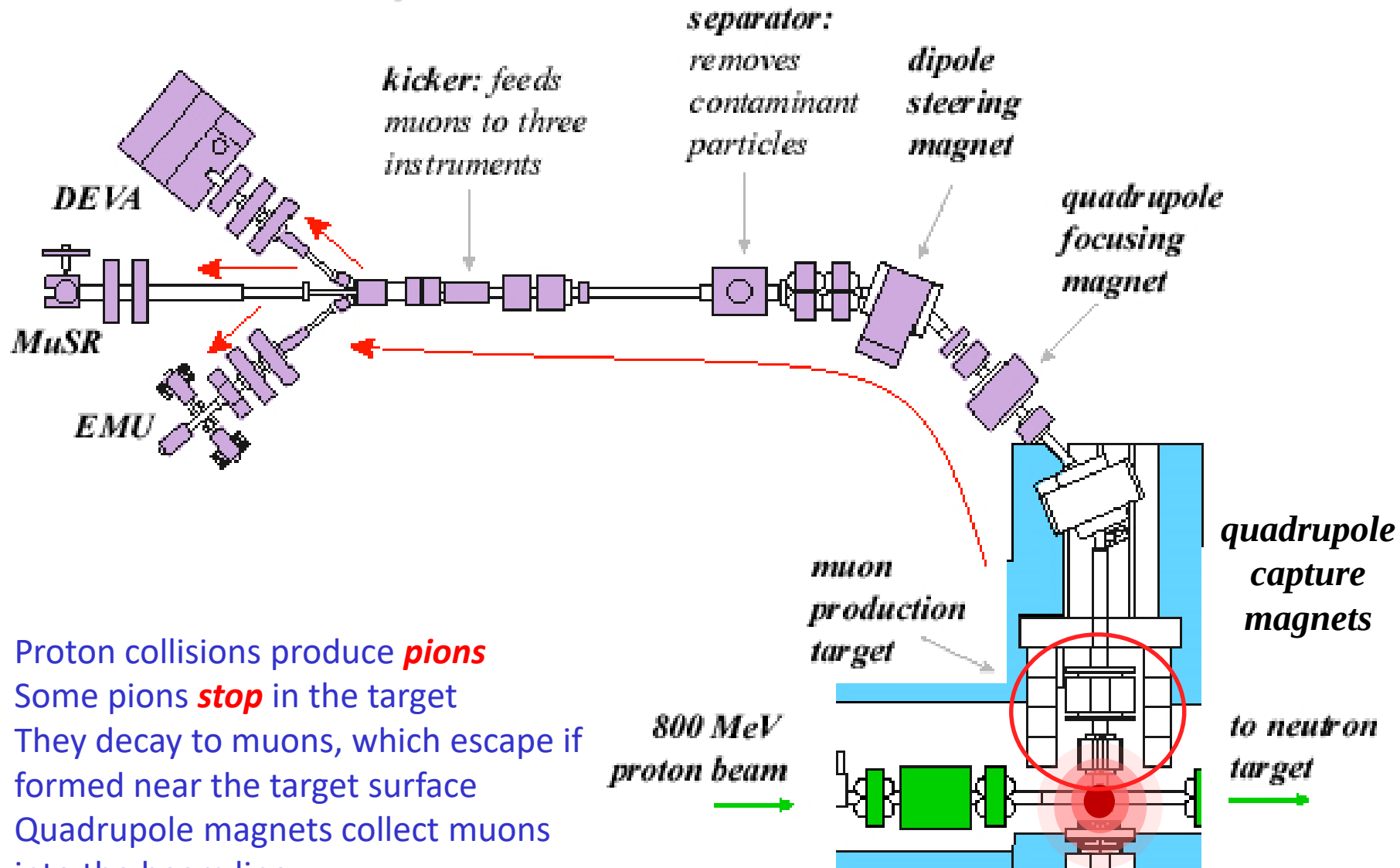
About 5% beam lost.

Diffusion bonded to copper to maximise thermal contact

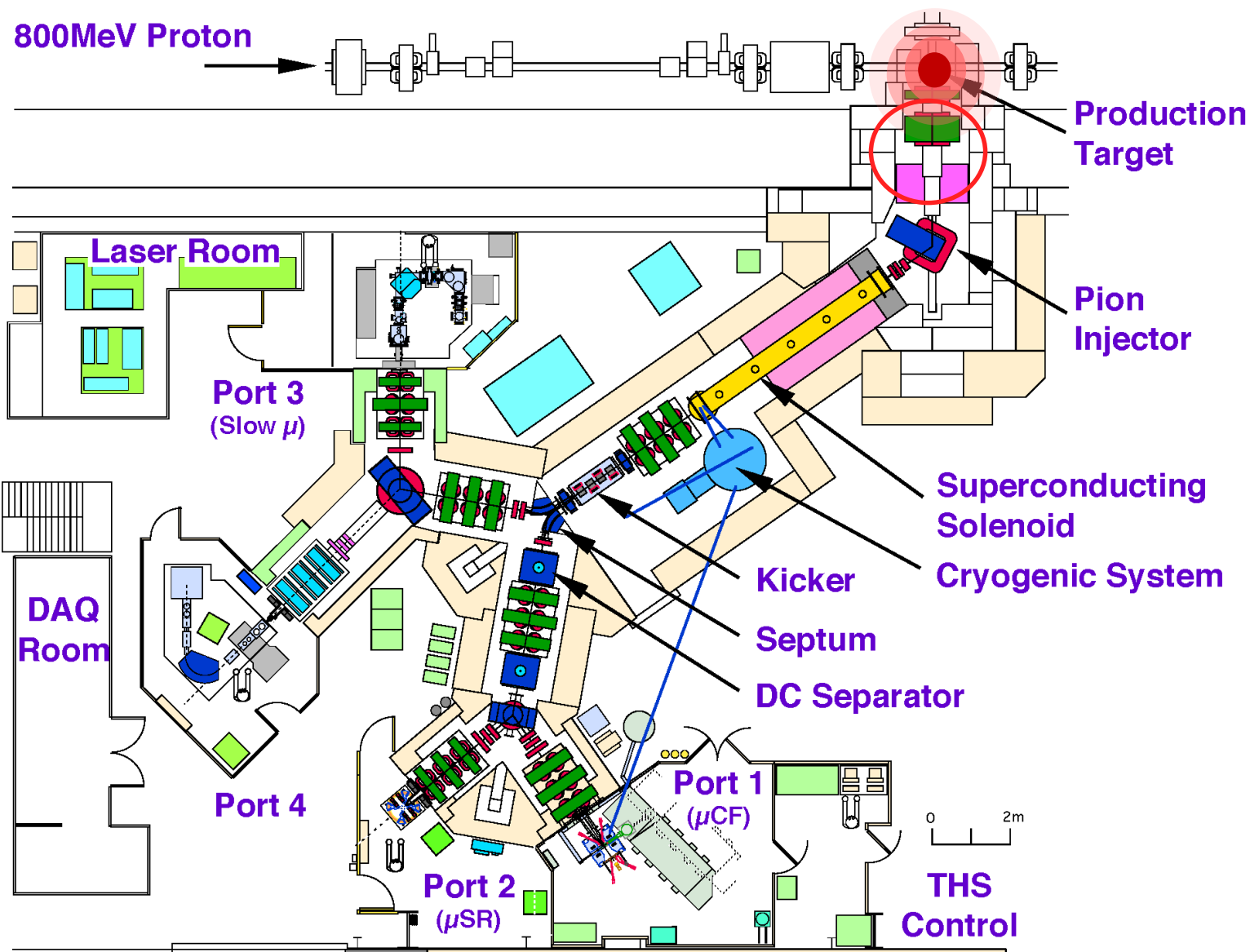
10 kW maximum heat load



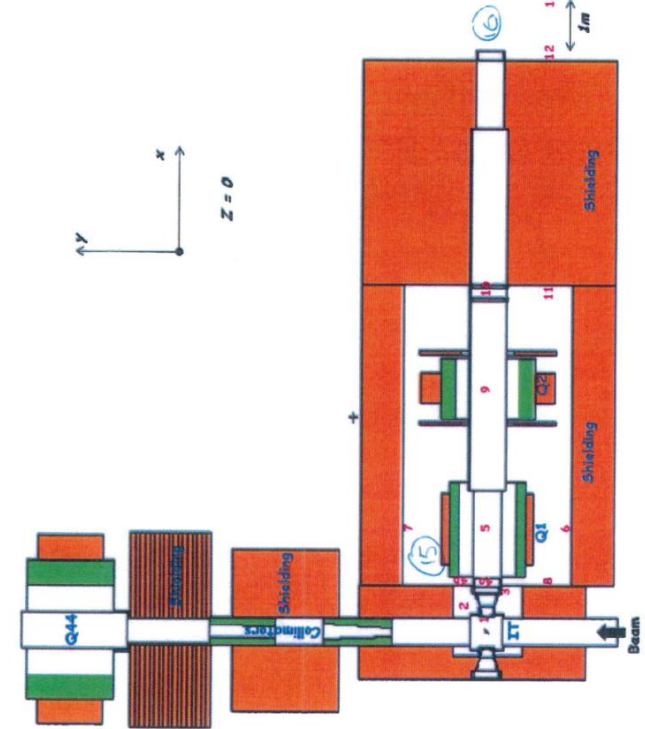
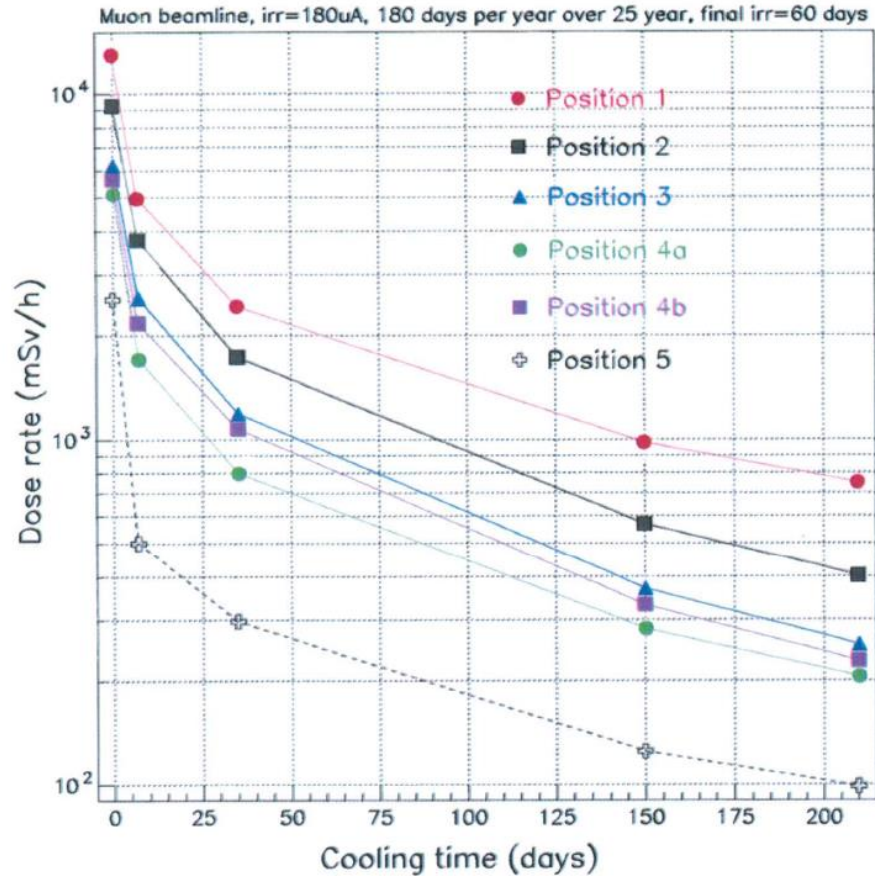
The EC Muon Facility



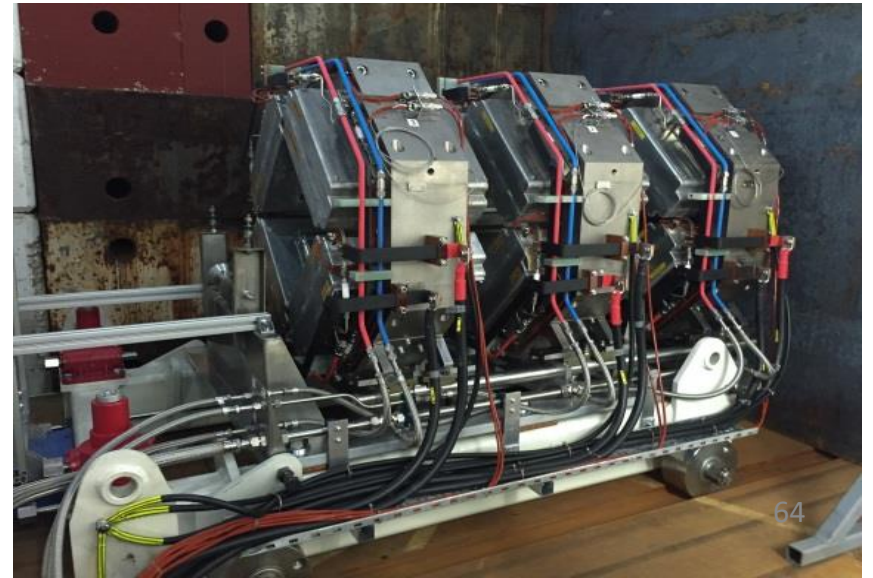
- Proton collisions produce **pions**
- Some pions **stop** in the target
- They decay to muons, which escape if formed near the target surface
- Quadrupole magnets collect muons into the beam line



Radiation Levels

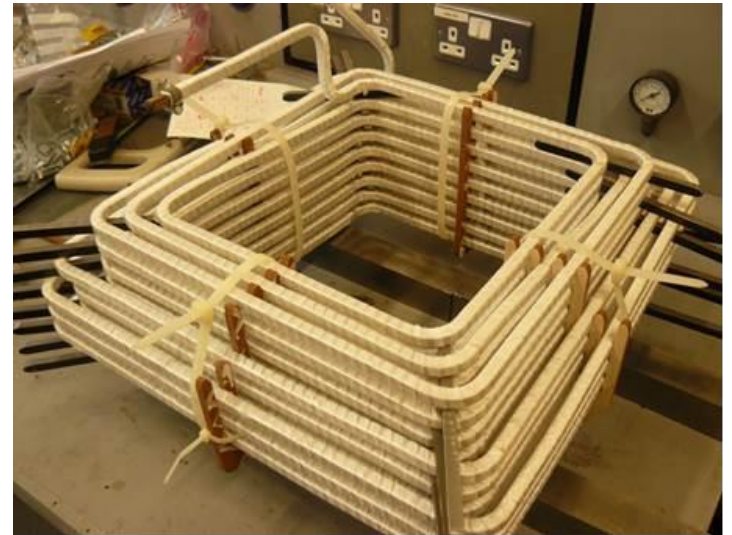
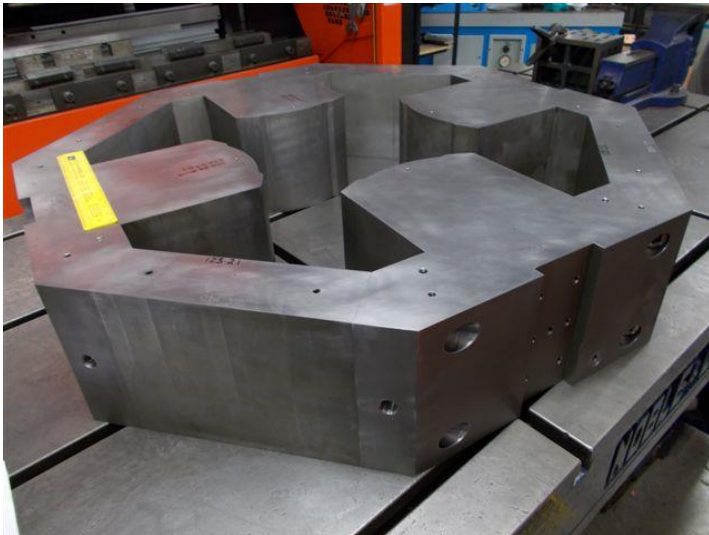
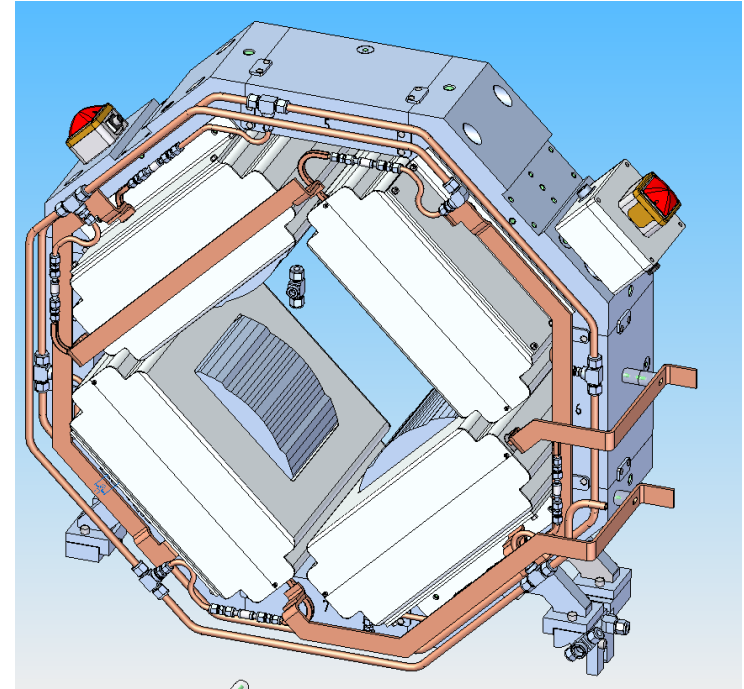


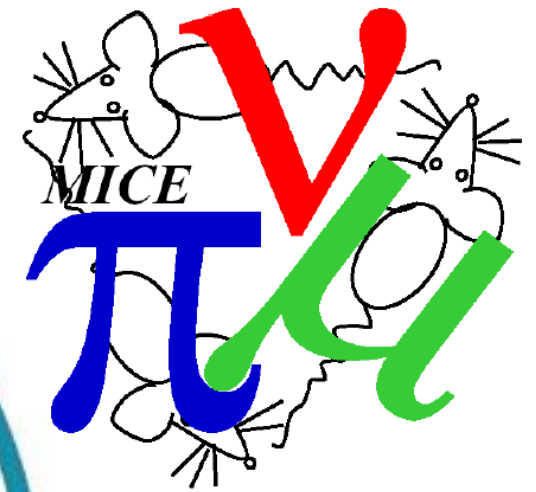
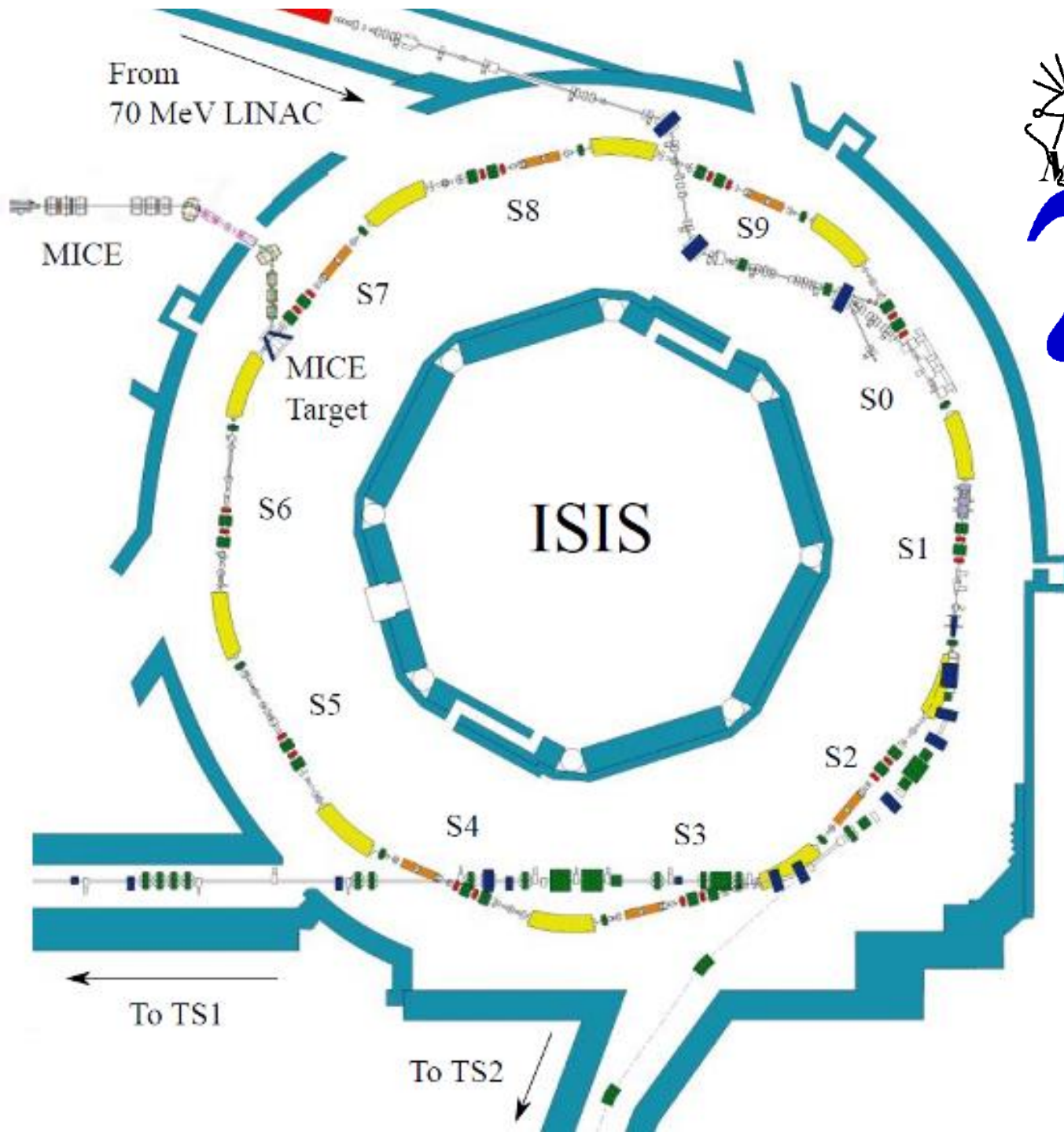
Radiation Hard Magnets



Radiation Hard Magnet Design

- In house concrete magnet design
- Coils Potted in concrete
- Water Cooled

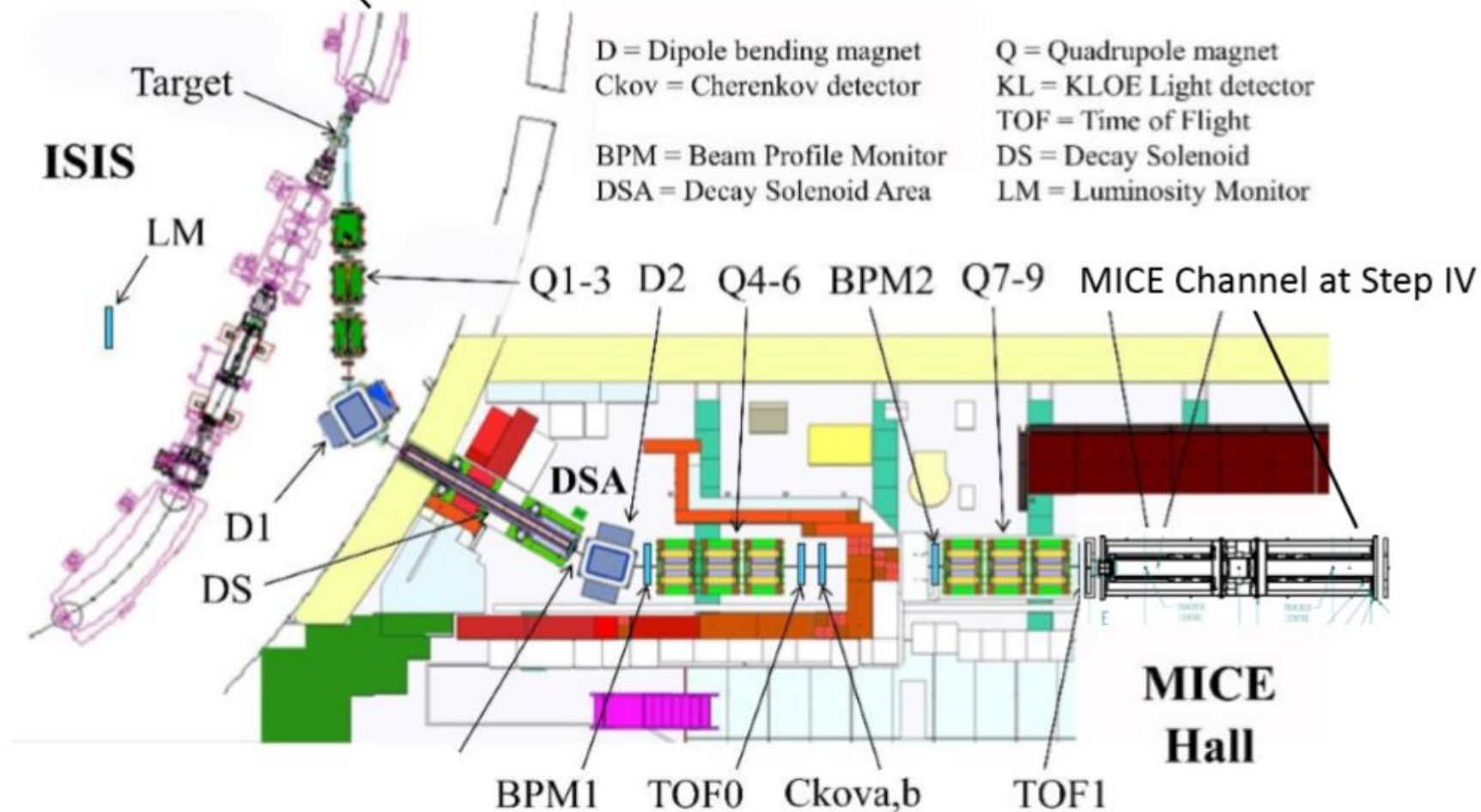




Muon
Ionisation
Cooling
Experiment



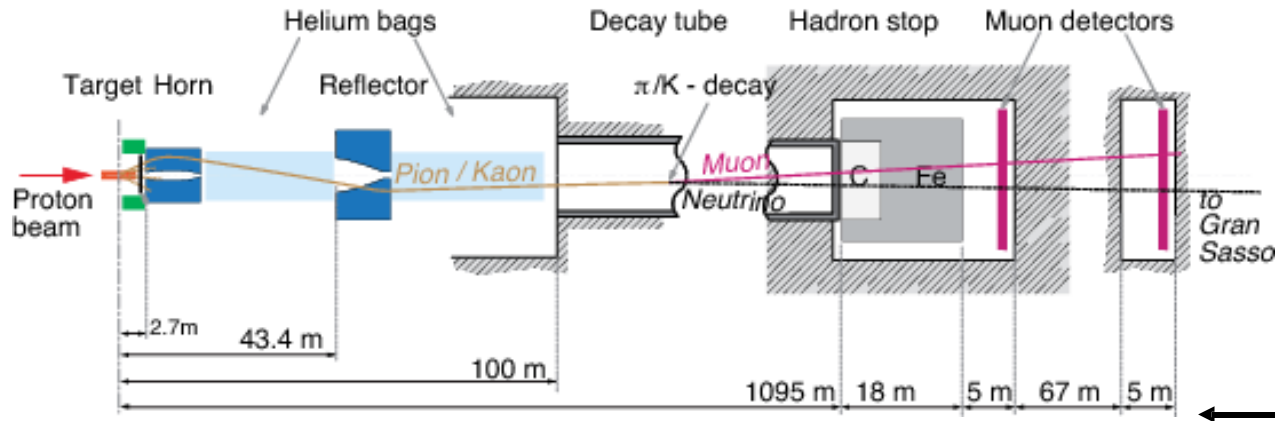
MICE Beamline



MICE Beamline
Conceptual Layout

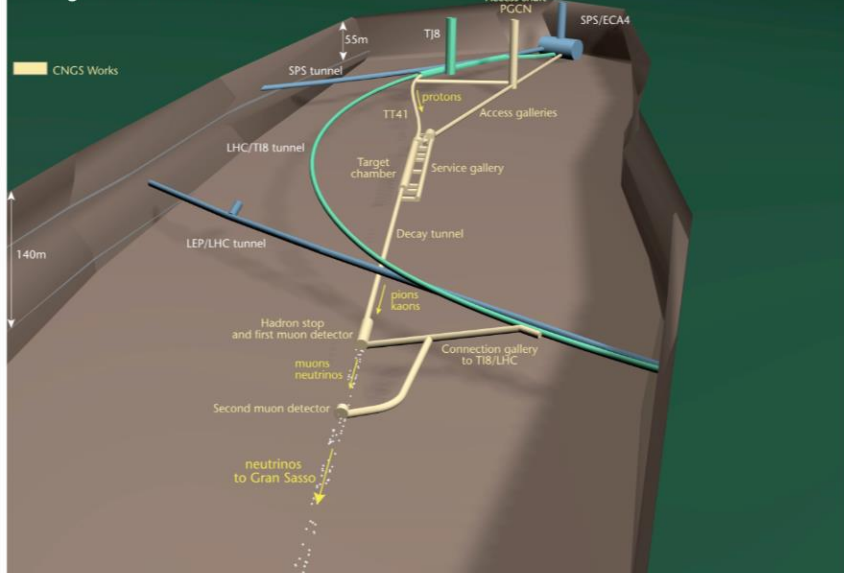
Mice demonstrated muon
cooling in 1D

CERN Neutrinos to Gran Sasso (CNGS)

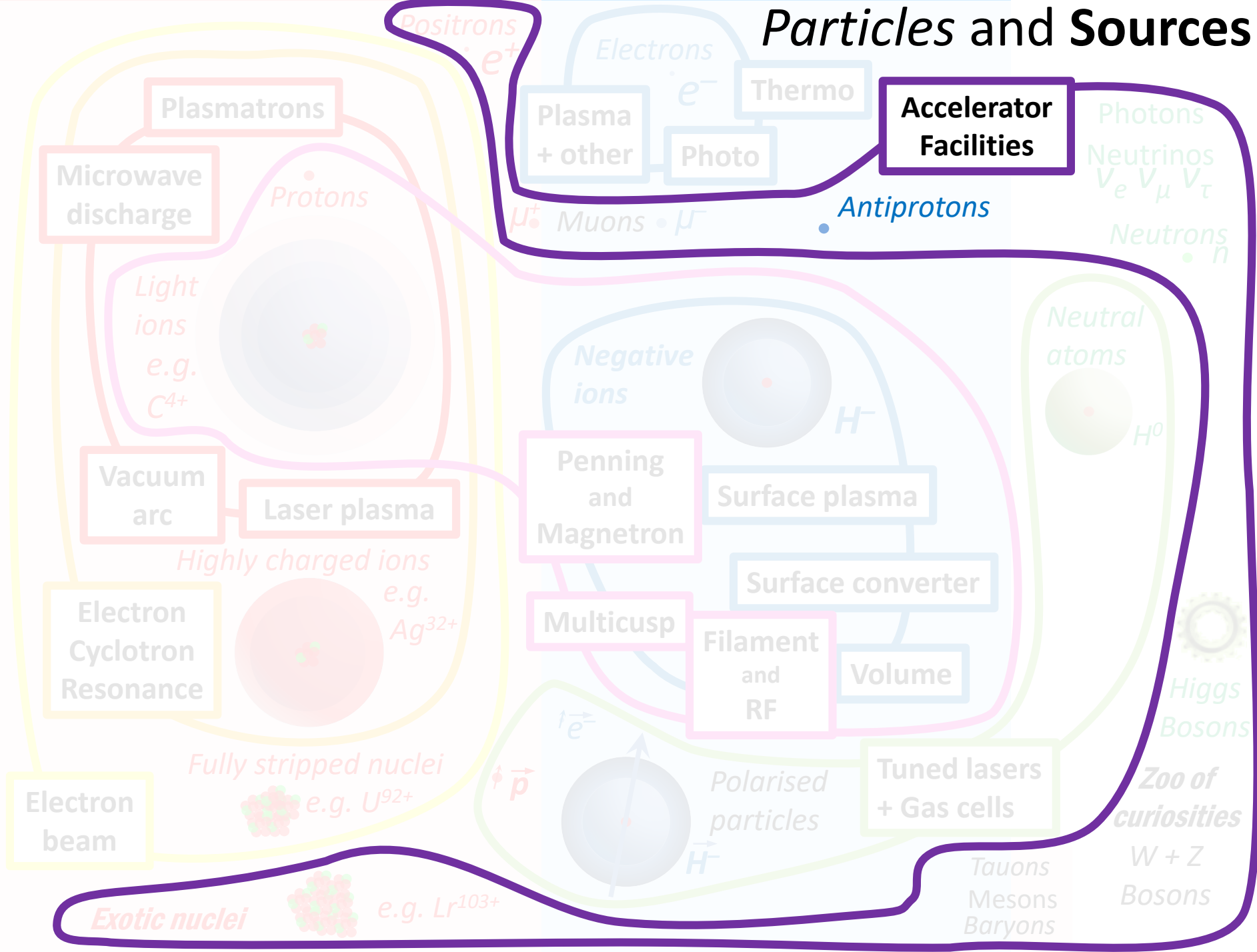


732 km

CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN

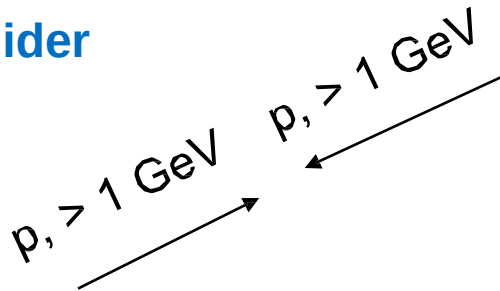


Particles and Sources



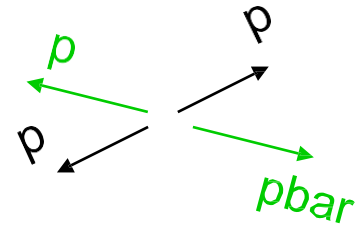
Creation of Antiprotons

Collider

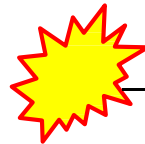
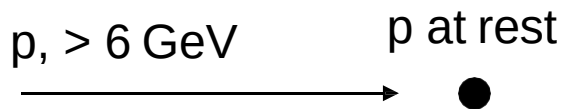


$$m = E / c^2$$

$$m_p = m_{p\text{bar}} \approx 1 \text{ GeV} / c^2$$

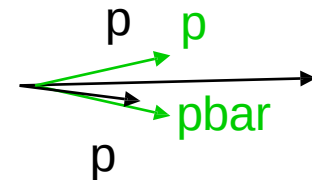


Target

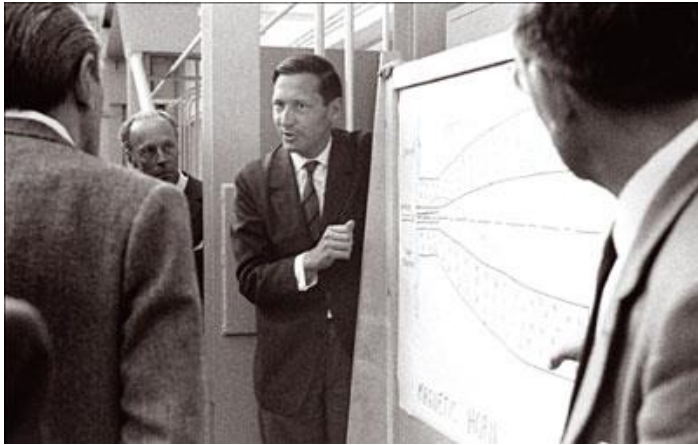


$$m = E / c^2$$

$$T_{p\text{bar}} > 6 \text{ GeV}$$



Magnetic Horn



Simon van der Meer

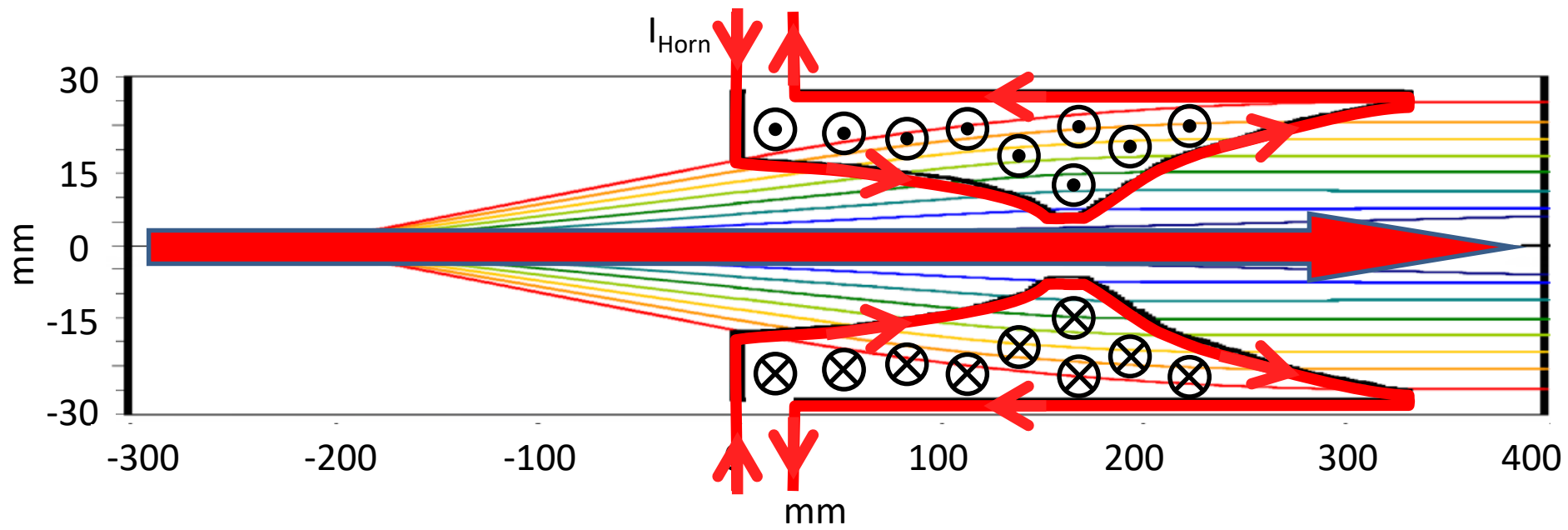
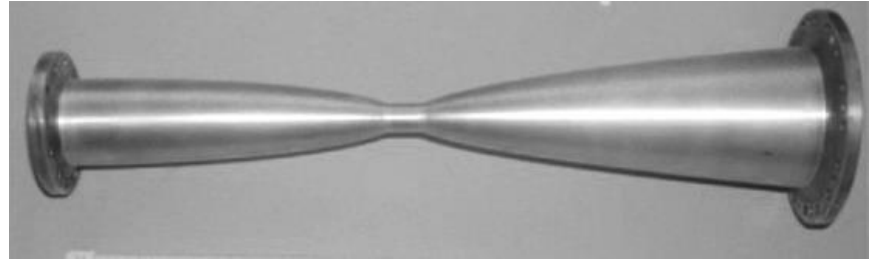
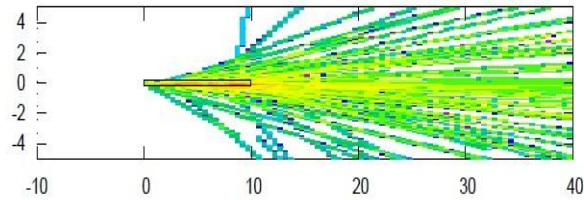


1960s "current sheet lens"
originally for neutrino beams
then for antiprotons

1.4 mm Al 400 kA 15 μ s
(half-sine)



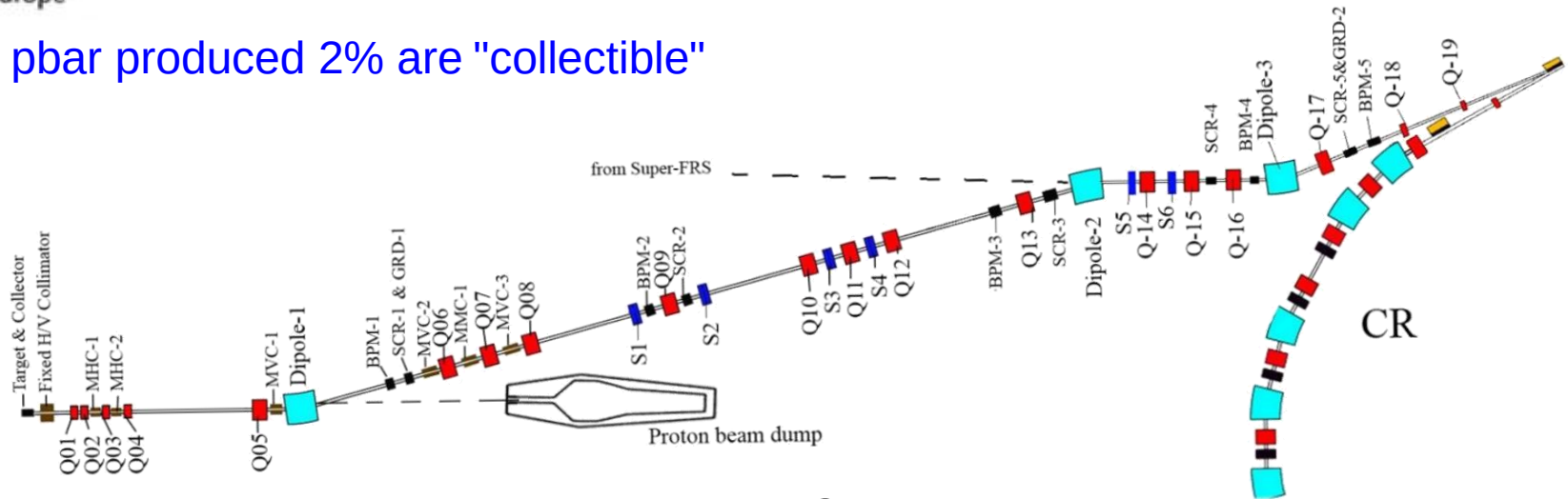
Magnetic Horn



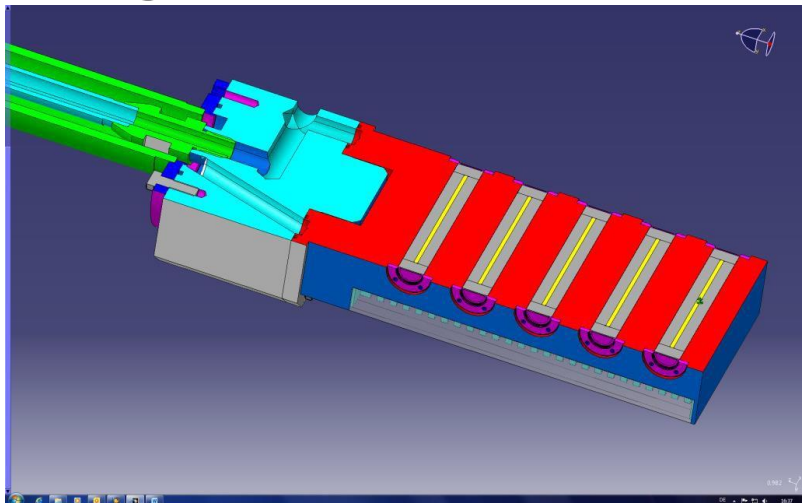
Beam Separation

FAIR — Facility for Antiproton and Ion Research in Europe

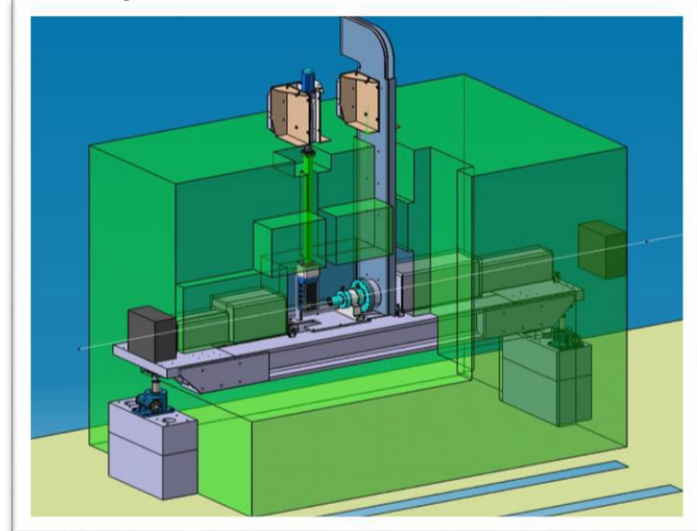
Of the pbar produced 2% are "collectible"



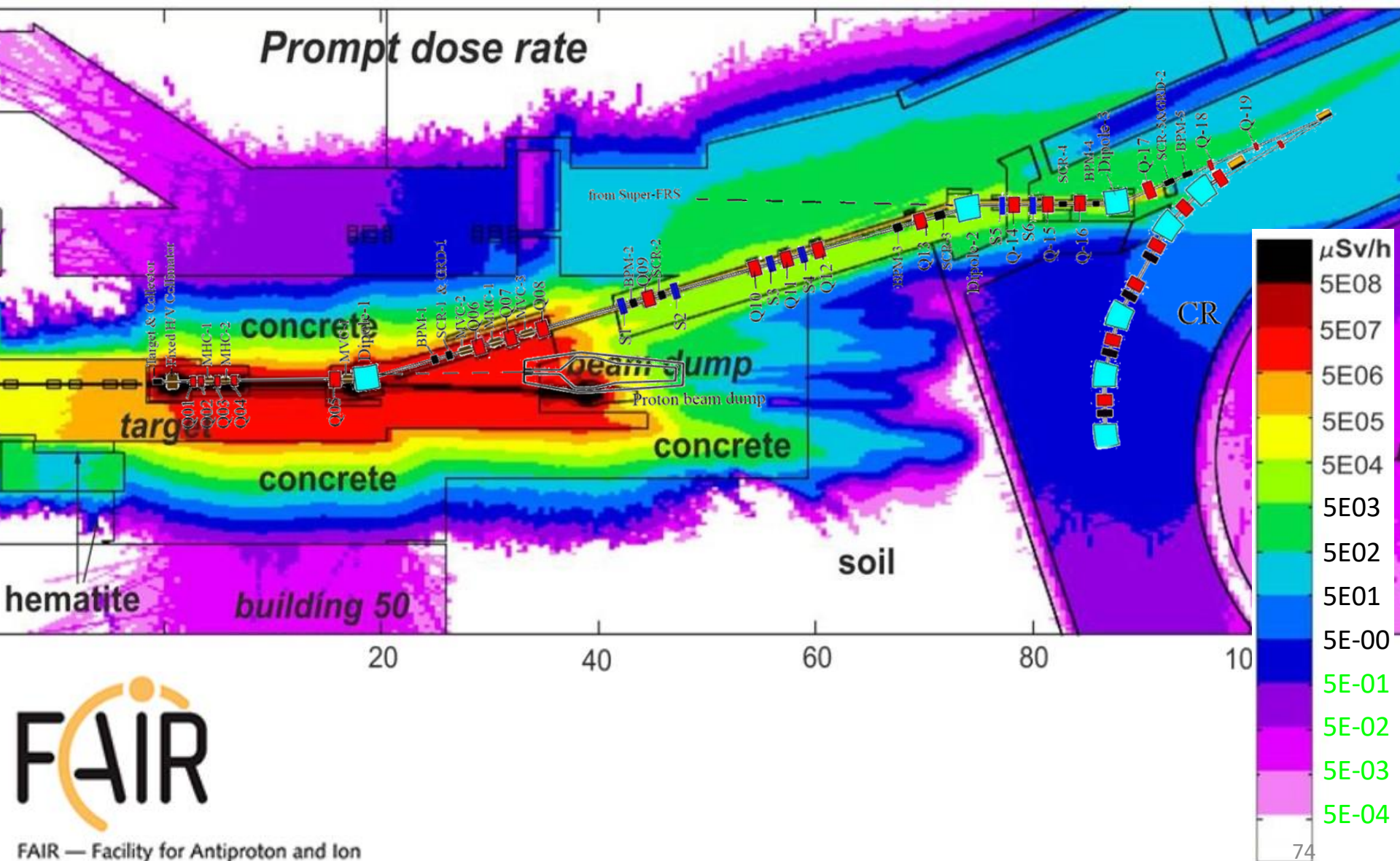
Target



Separator

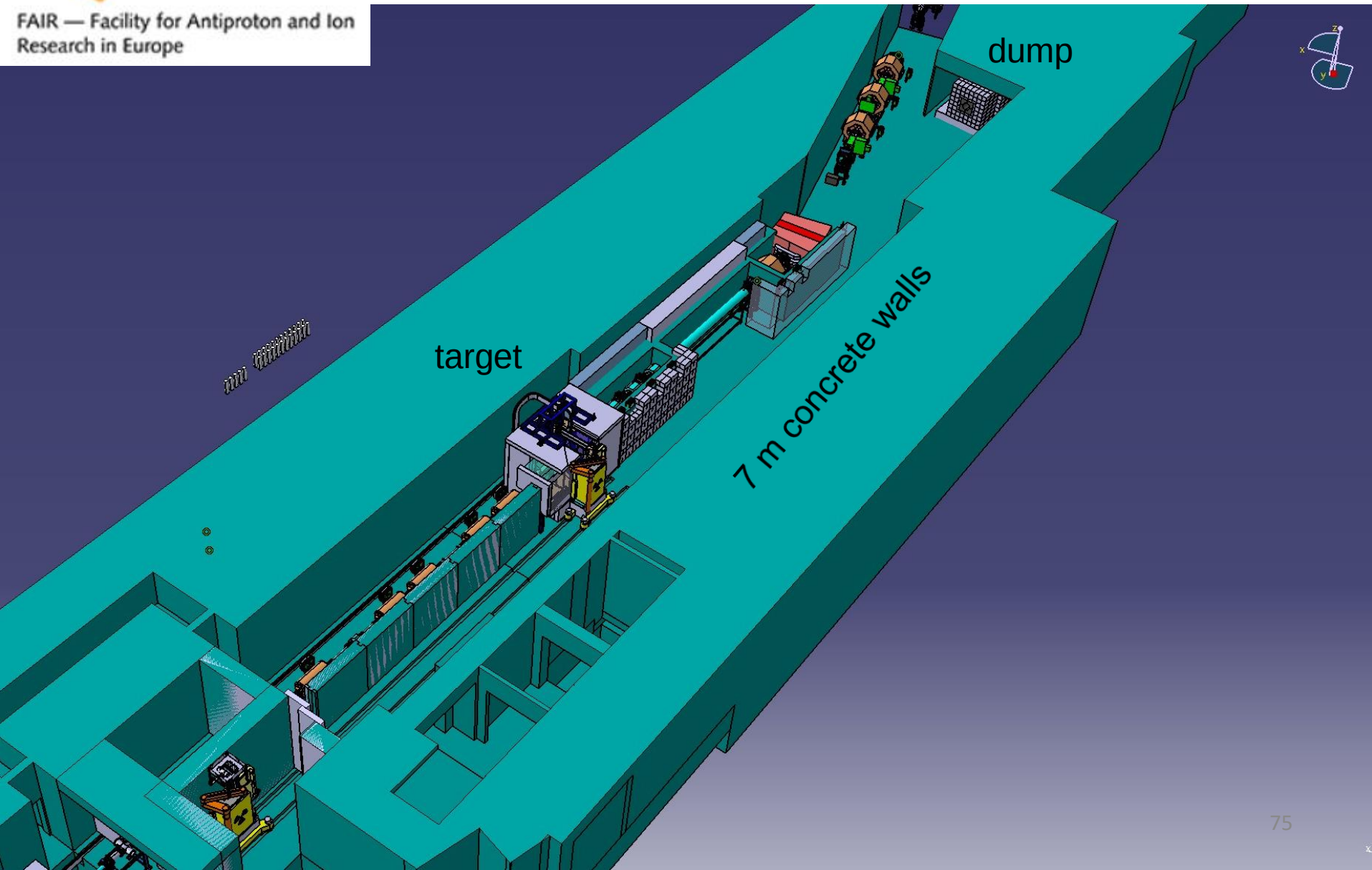


Beam Separation



Shielding Required

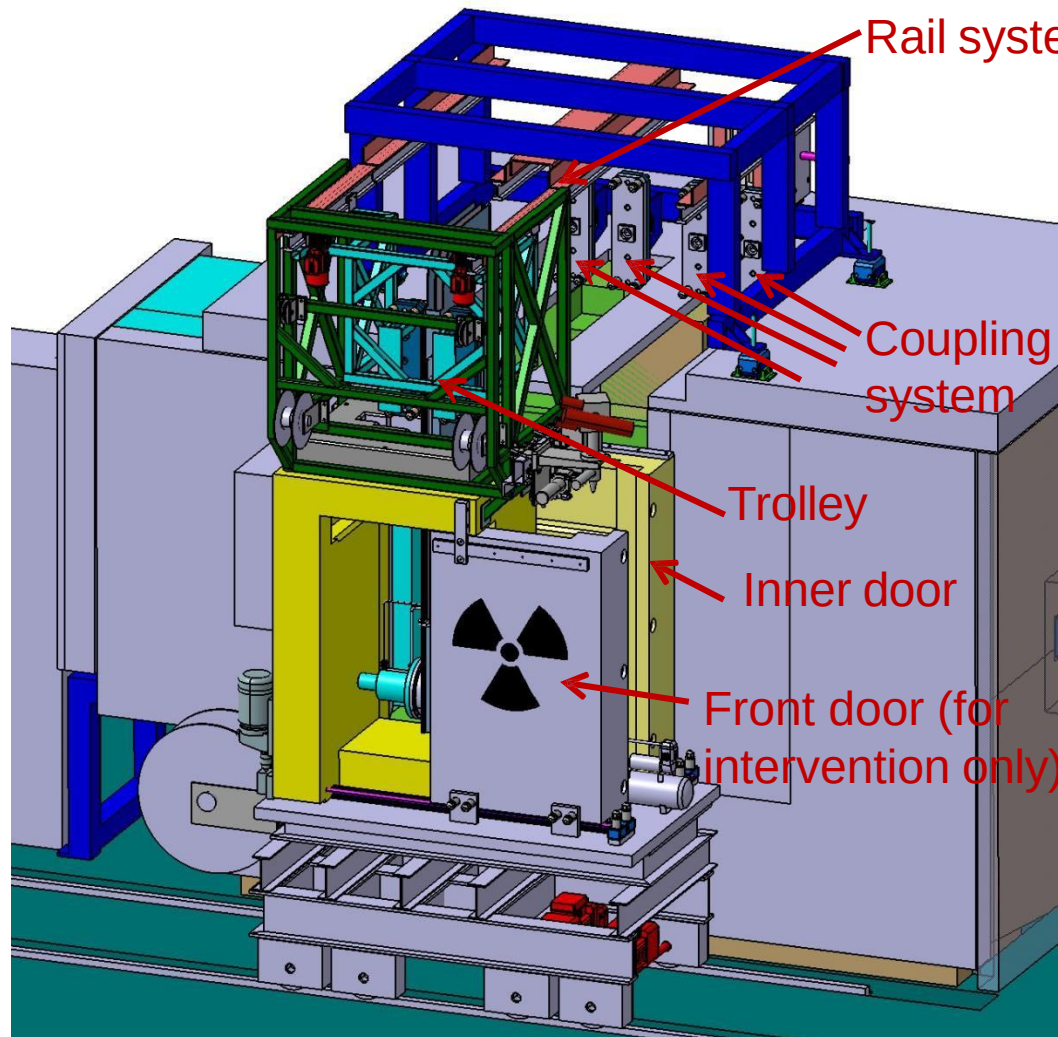
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Target station and transport container

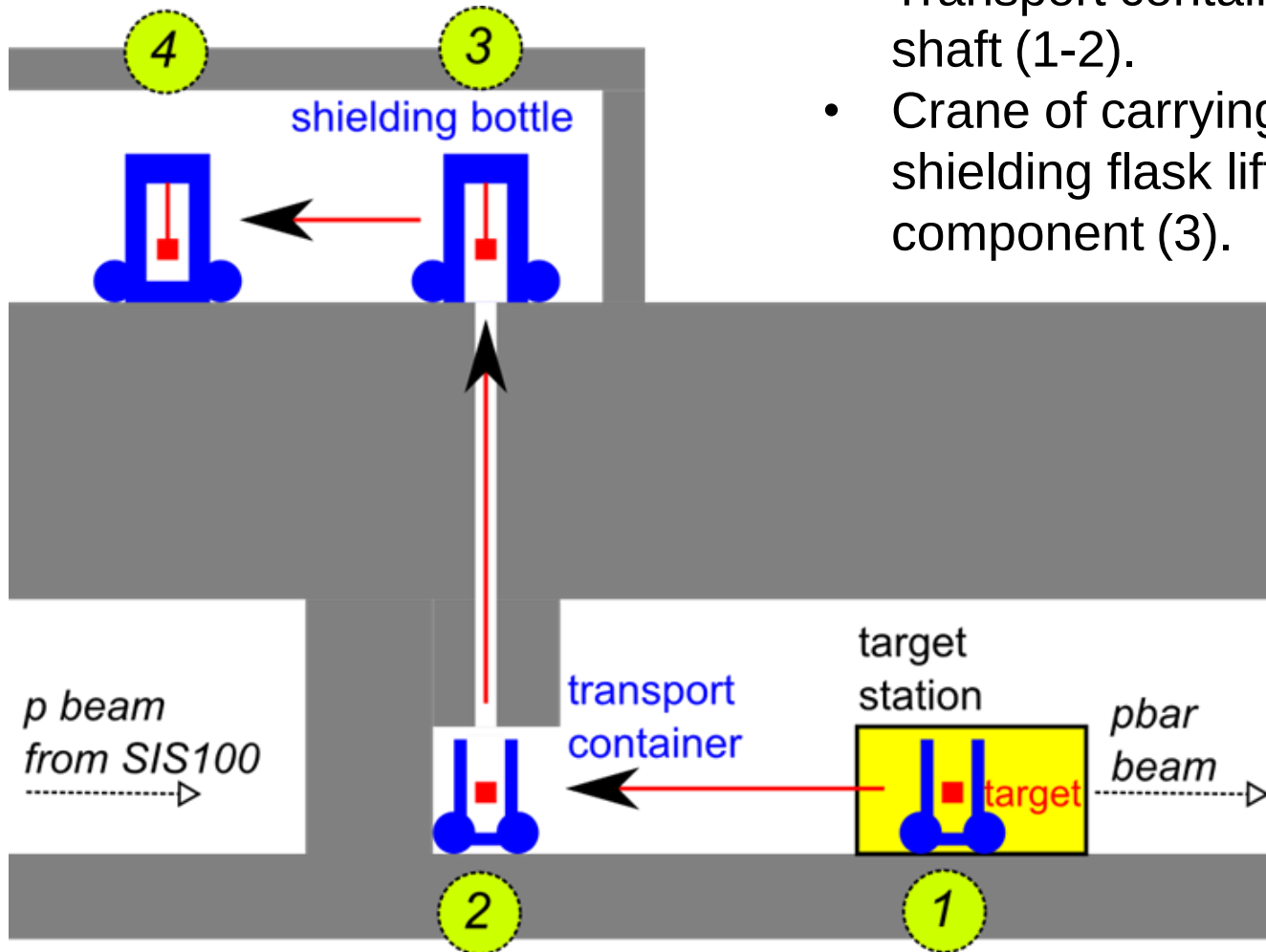


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Research in Europe



- 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



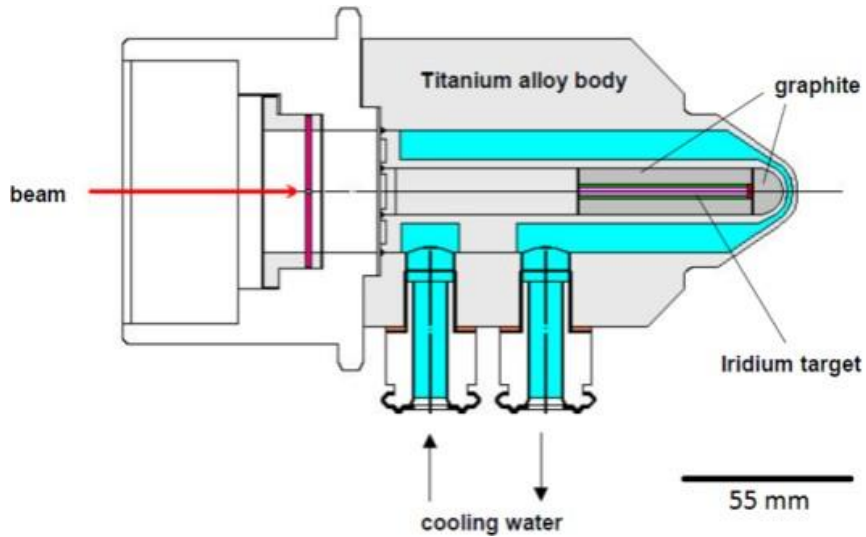
- Transport container moves to the shaft (1-2).
- Crane of carrying frame of the shielding flask lifts up the component (3).



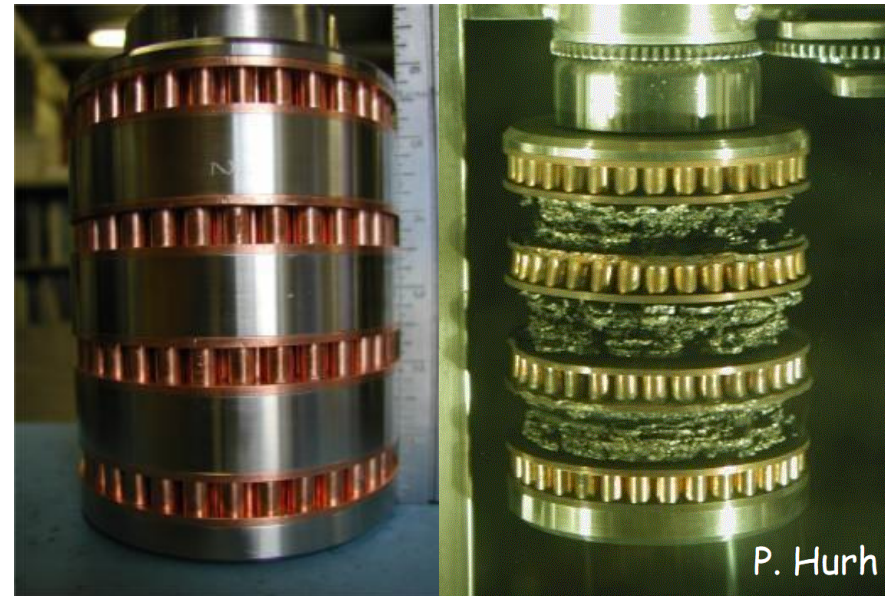
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Research in Europe

CERN and Fermilab pbar Targets

CERN target (Ir or Cu)

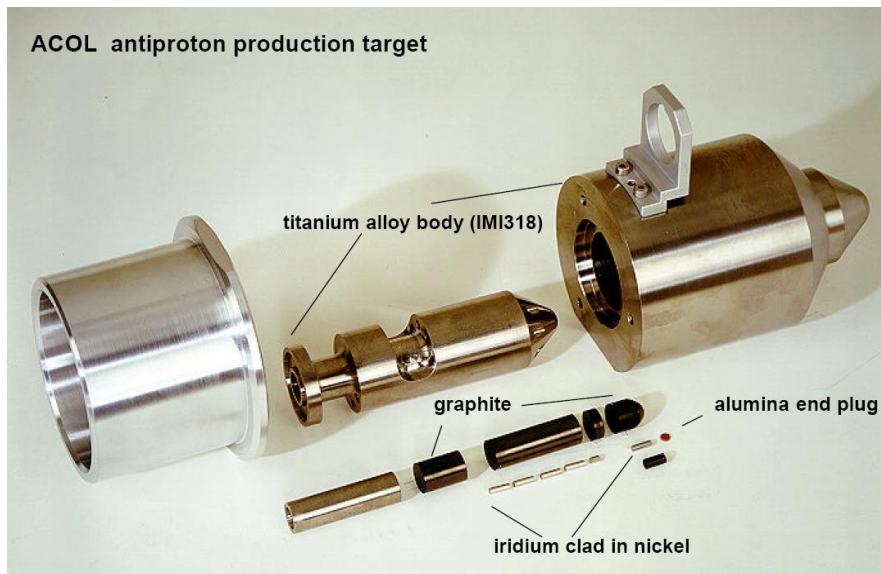


Rotating Fermilab target

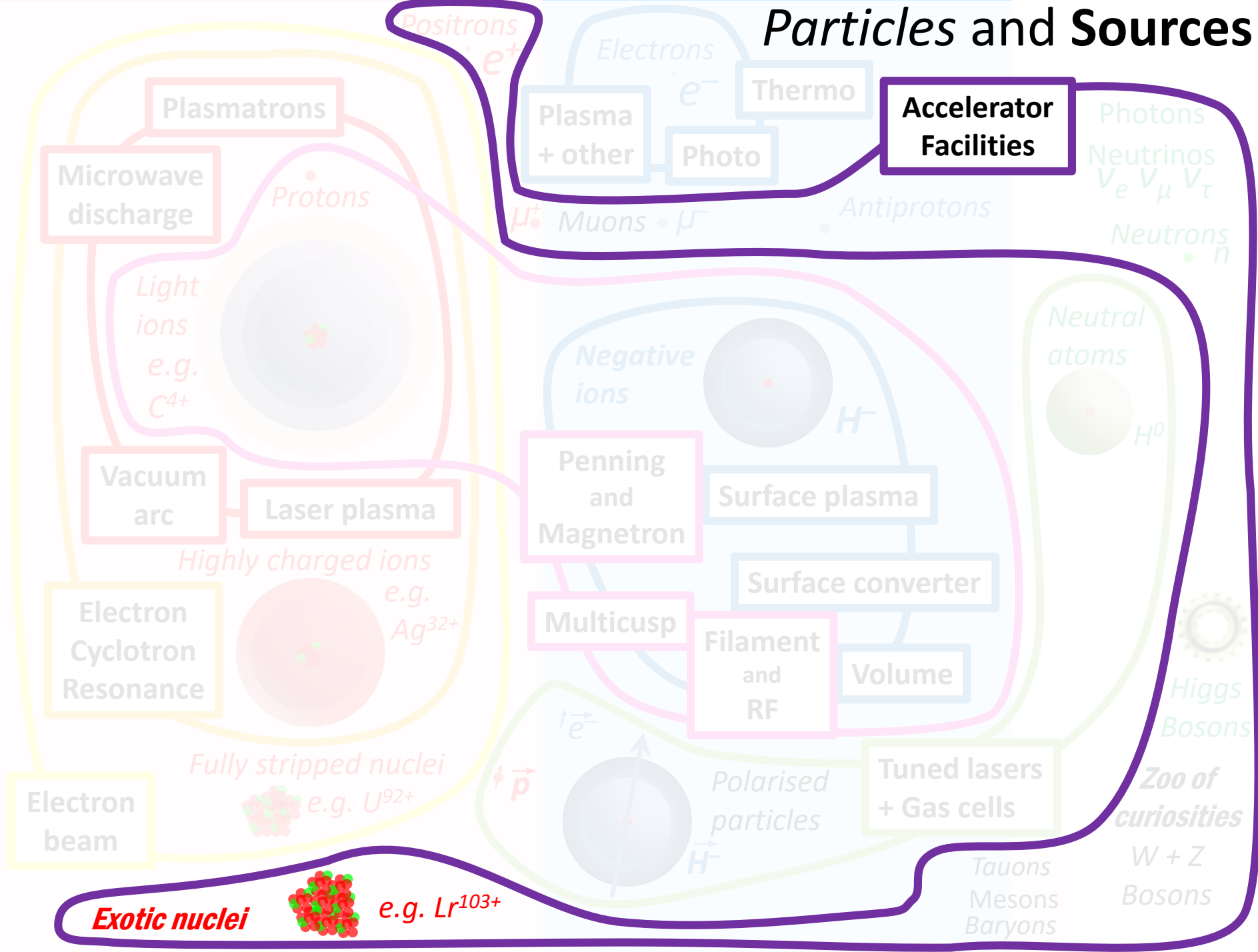


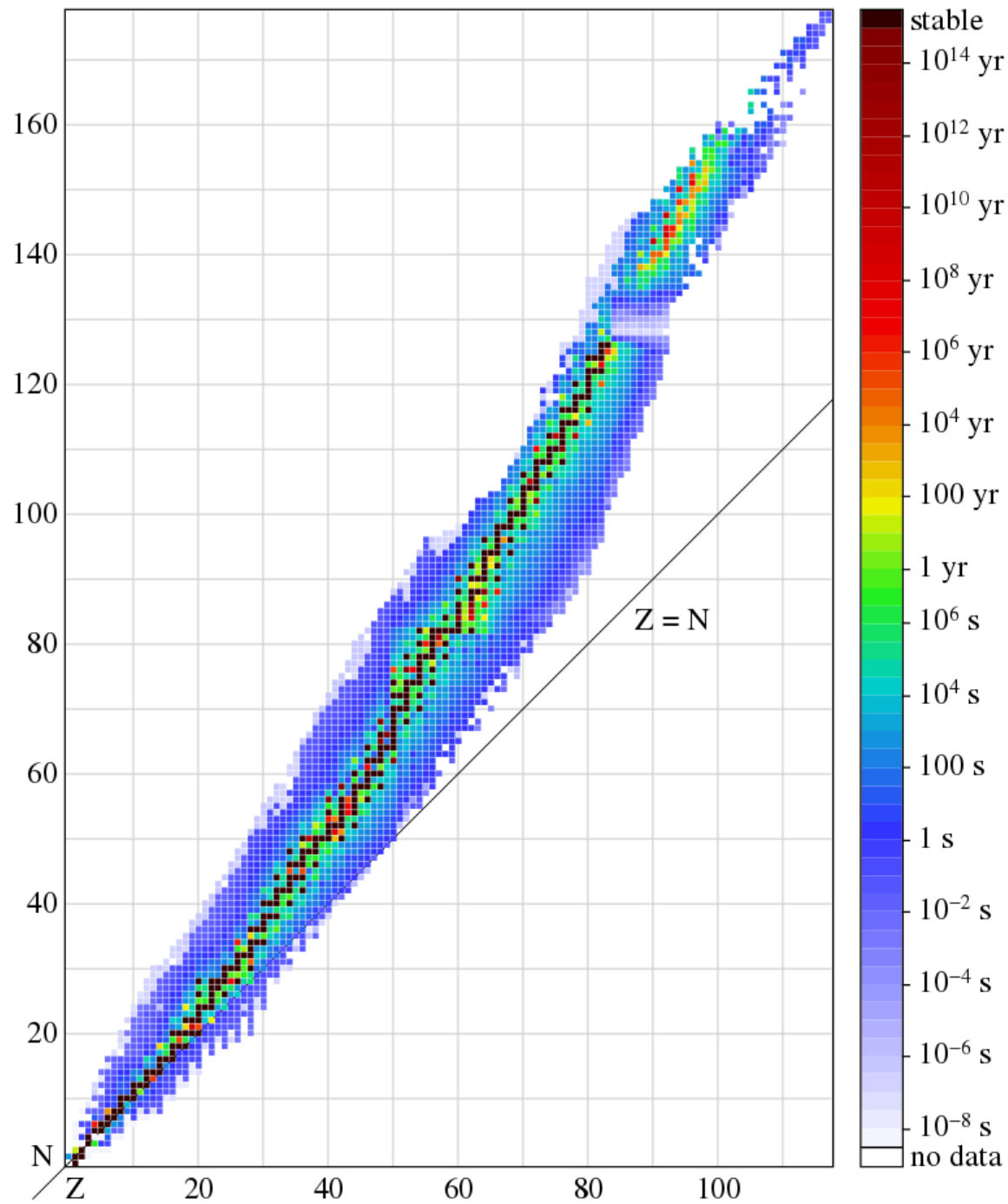
new

used



Particles and Sources





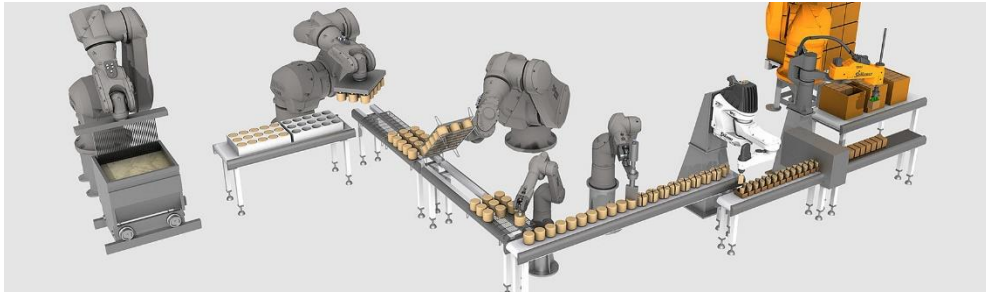
Radioactive Ion Beams

A powerful way of studying
the atomic nucleus



ISOL vs In Flight Fragmentation

Isotope Separation On Line (ISOL): A production line



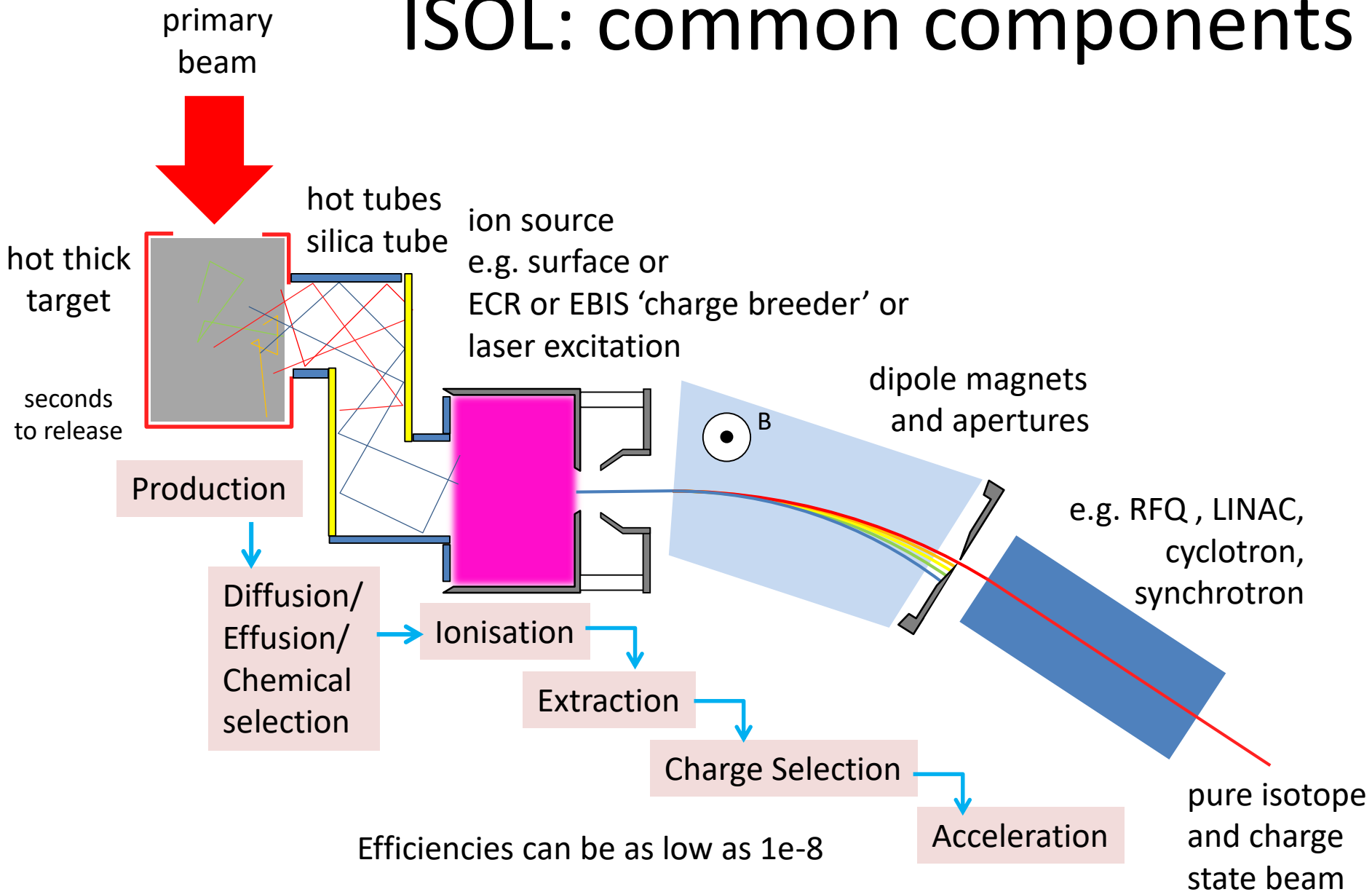
A → B → C → D → E → F

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**

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

view

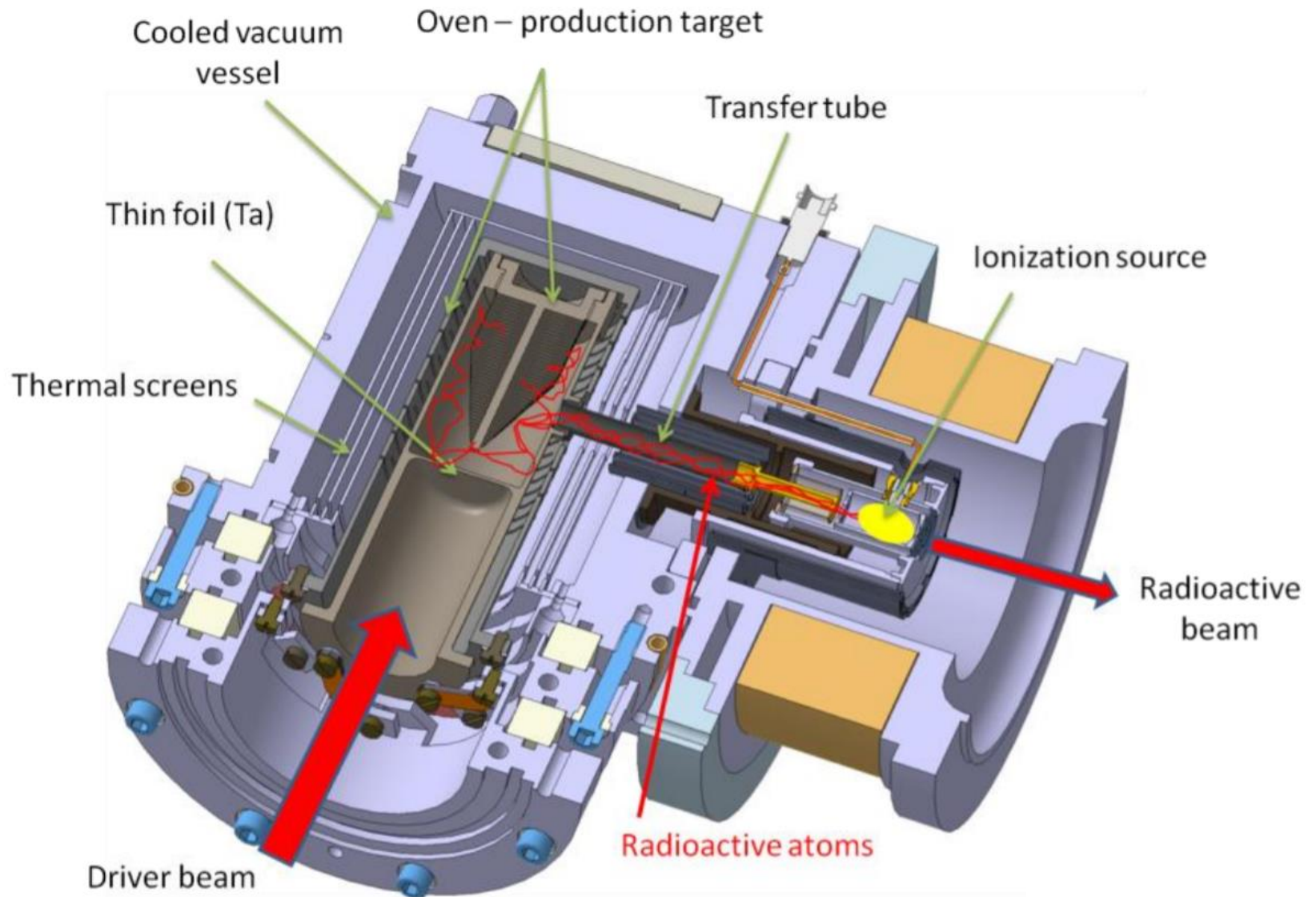
- I_{RIB} - rare ion beam intensity [s^{-2}]
- ε - overall efficiency
- I_{prod} - production rate of a reaction product [s^{-2}]
- σ - reaction cross-section [barn = 10^{-24}cm^2]
- N_{target} - target atoms per exposed area [cm^{-2}]
- I_{primary} - primary beam intensity

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

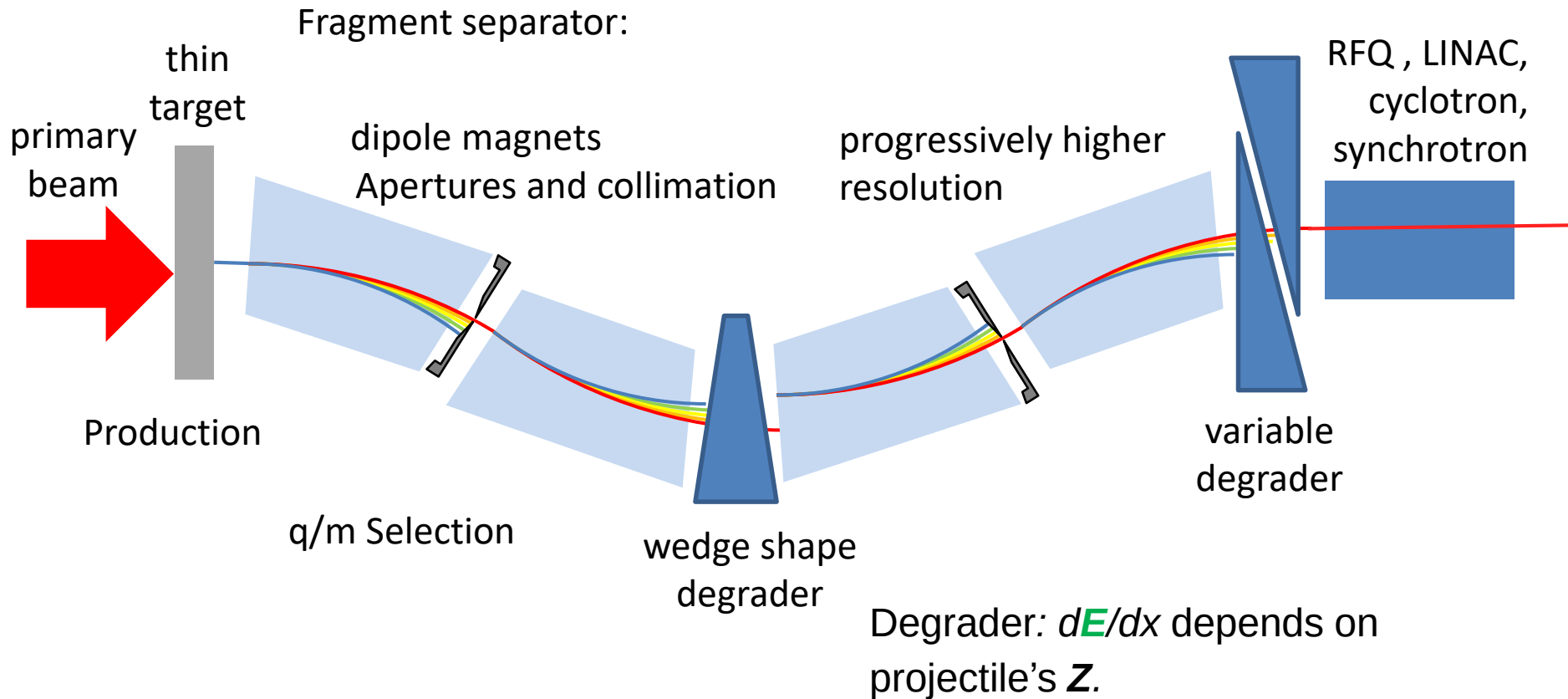
typically 5% to 90%

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

- $\varepsilon_{\text{release}}$ - 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



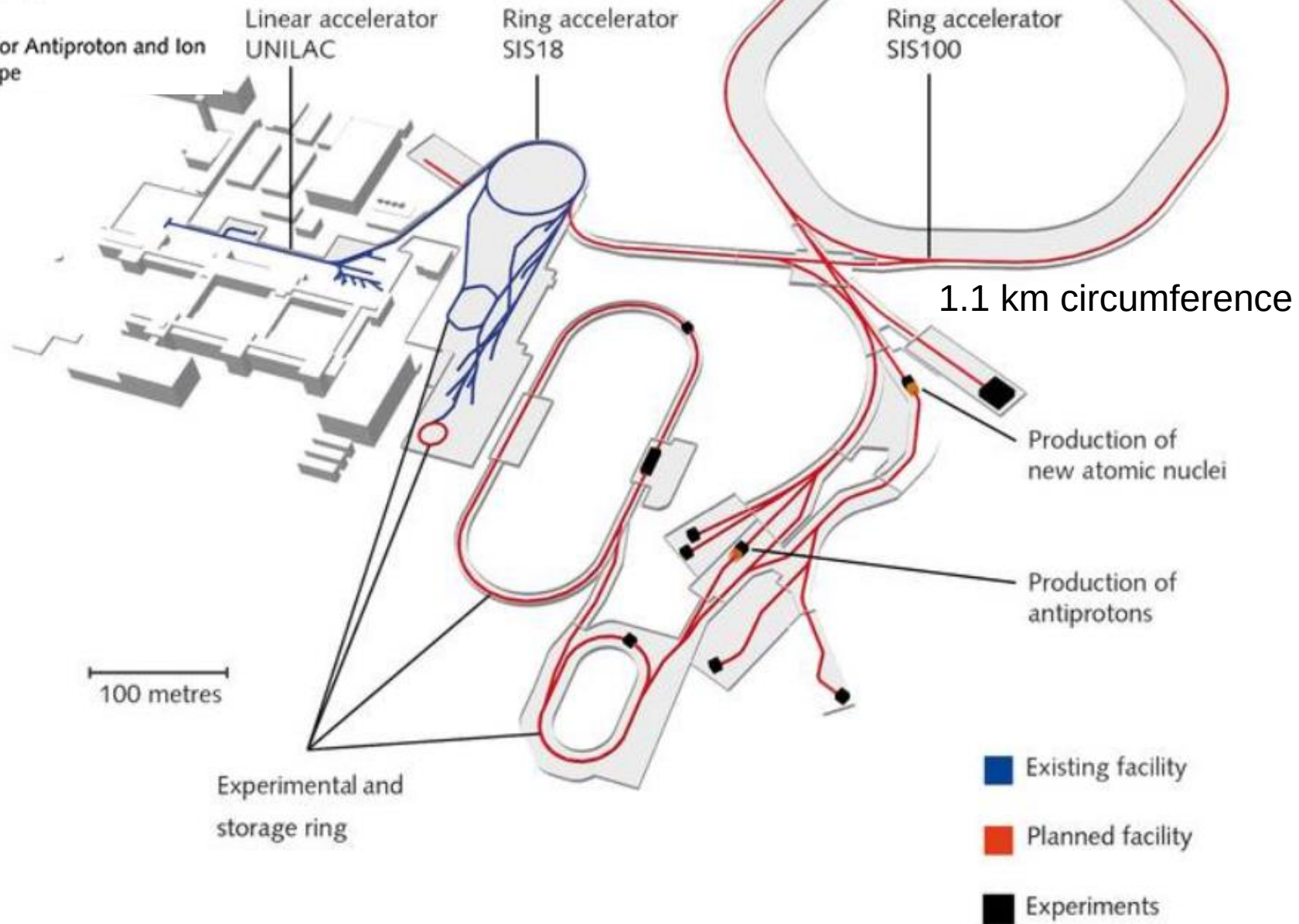
In Flight Fragmentation: common components



In flight fragmentation suitable for very short half life beams



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The Super Fragment Separator

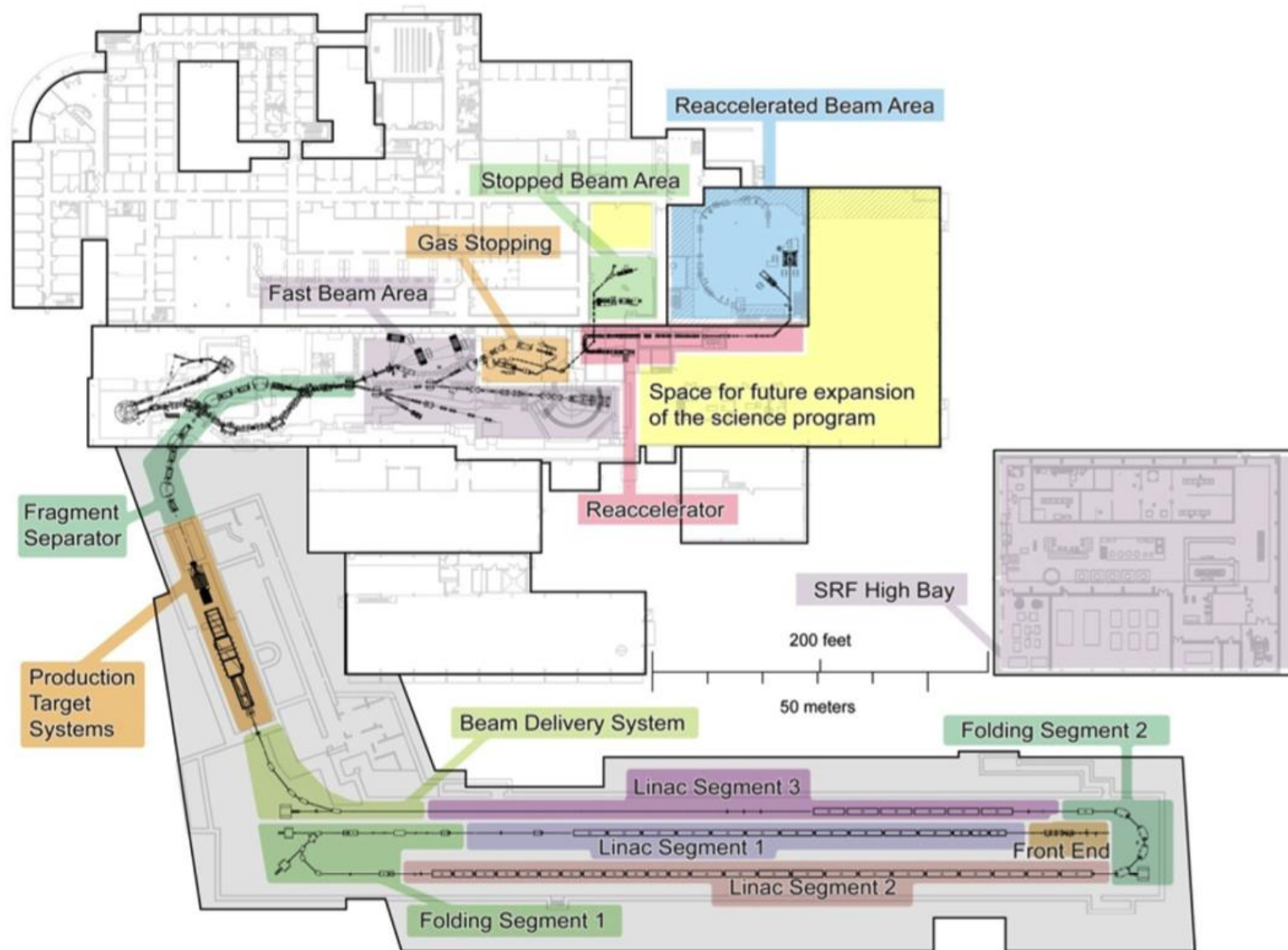


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Research in Europe



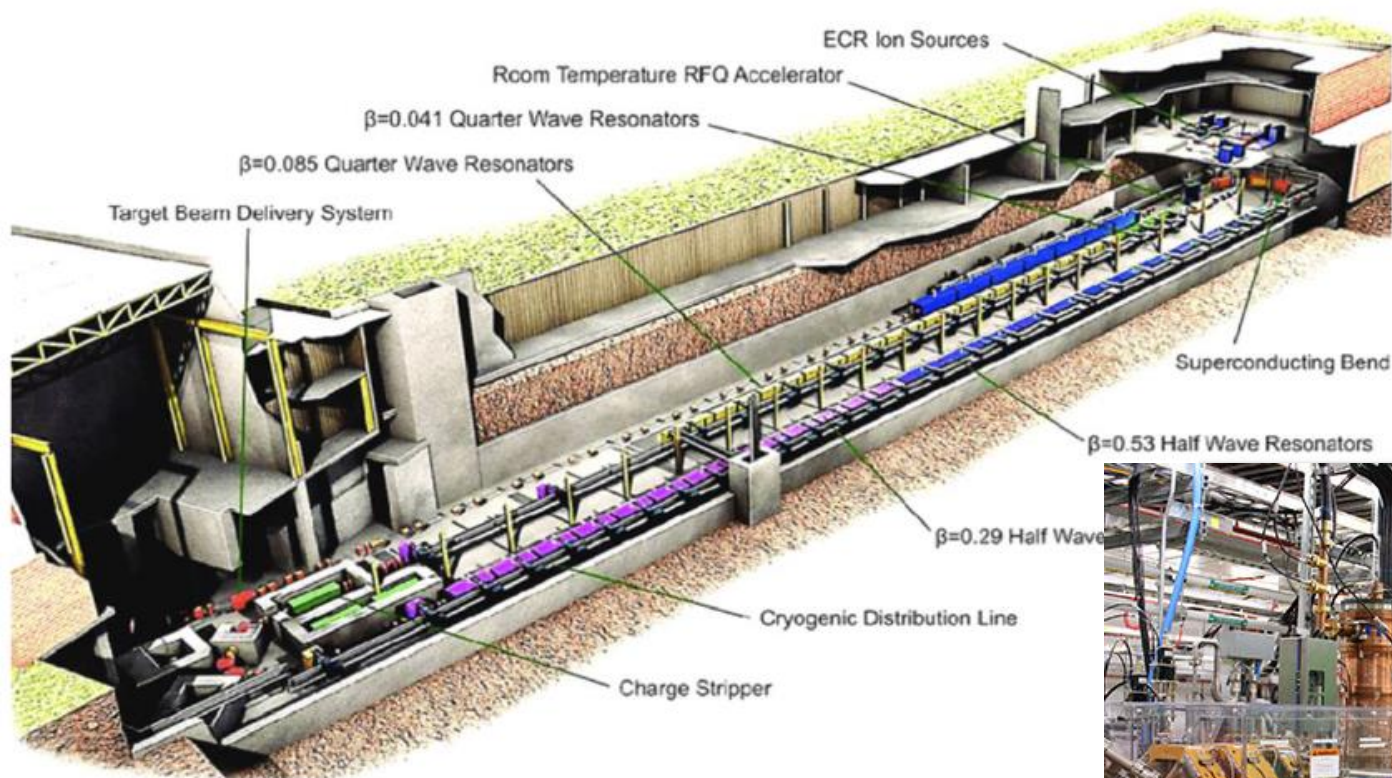


Facility for Rare Isotope Beams at Michigan State University





Facility for Rare Isotope Beams at Michigan State University



517 m linac

200 MeV/nucleon



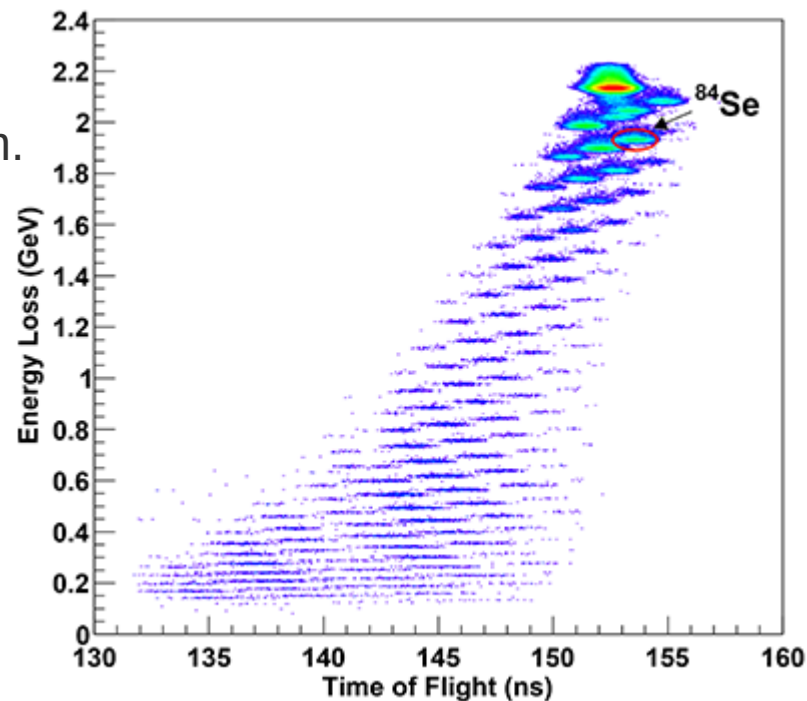


Facility for Rare Isotope Beams at Michigan State University

FIRST RARE ISOTOPES

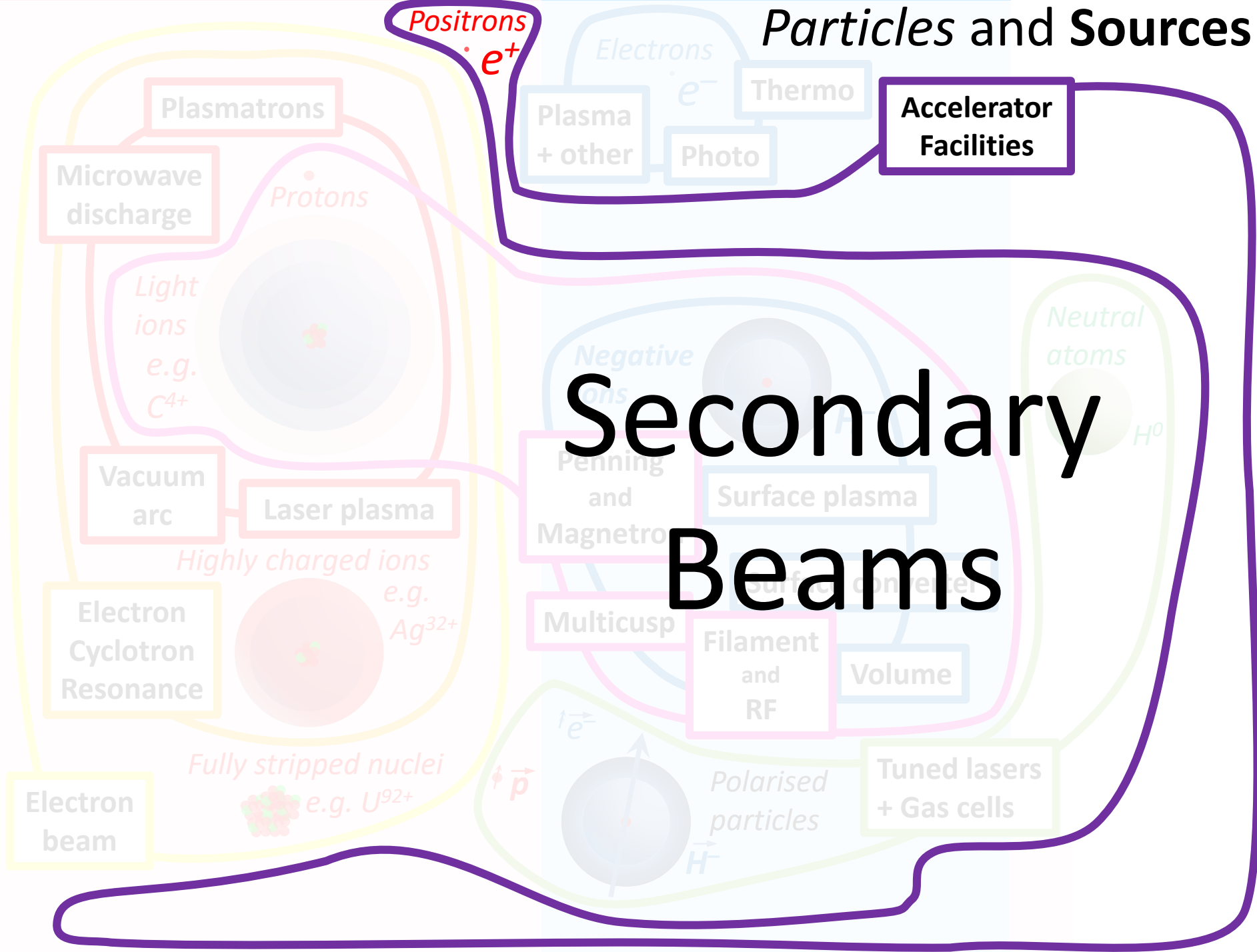
11 December 2021

selenium-84 from a krypton-86 beam.



January 2022 they discovered magnesium-18

Particles and Sources

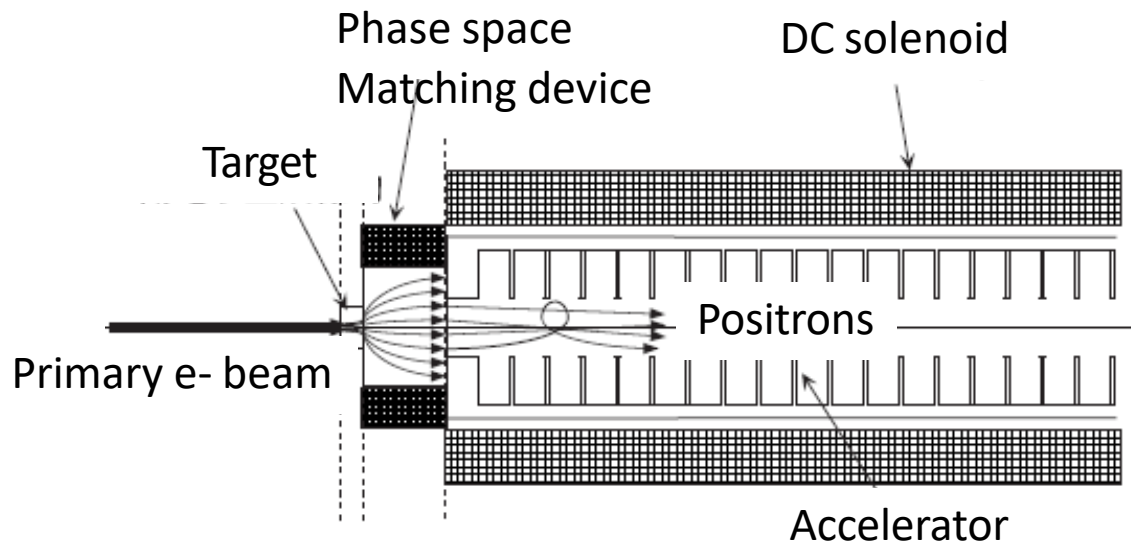
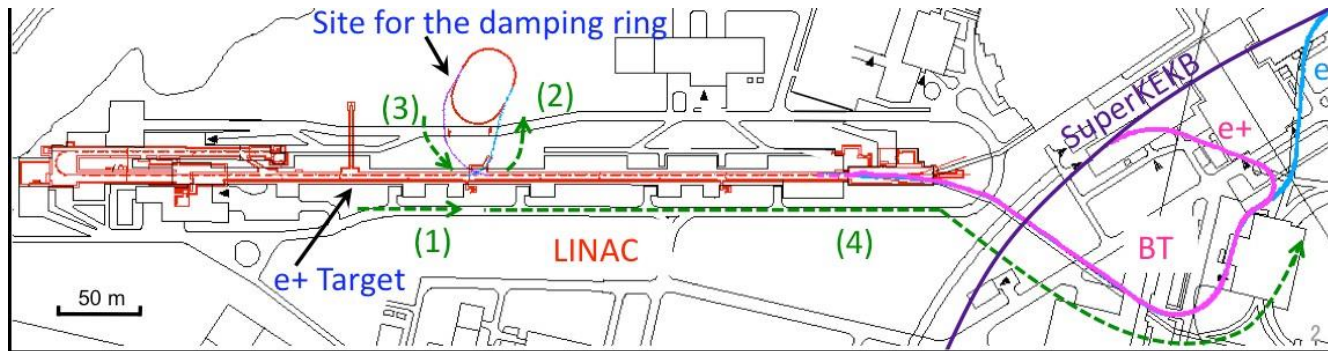


Positron Sources

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
- Gamma ray beam

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),

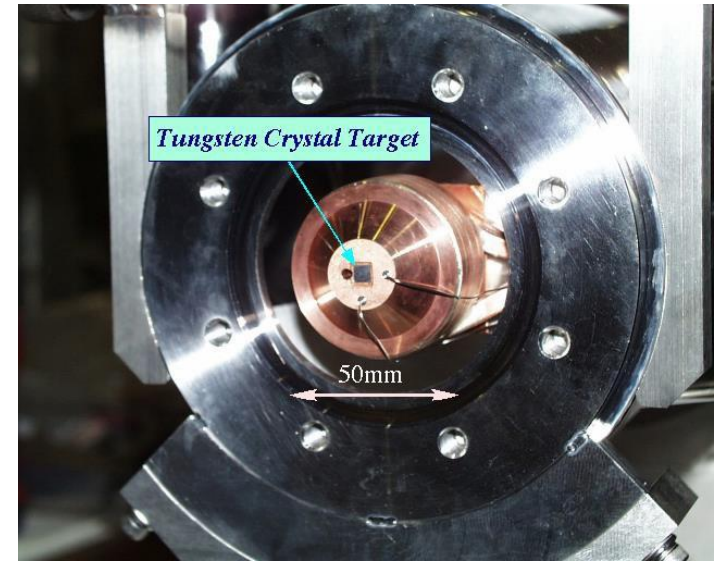
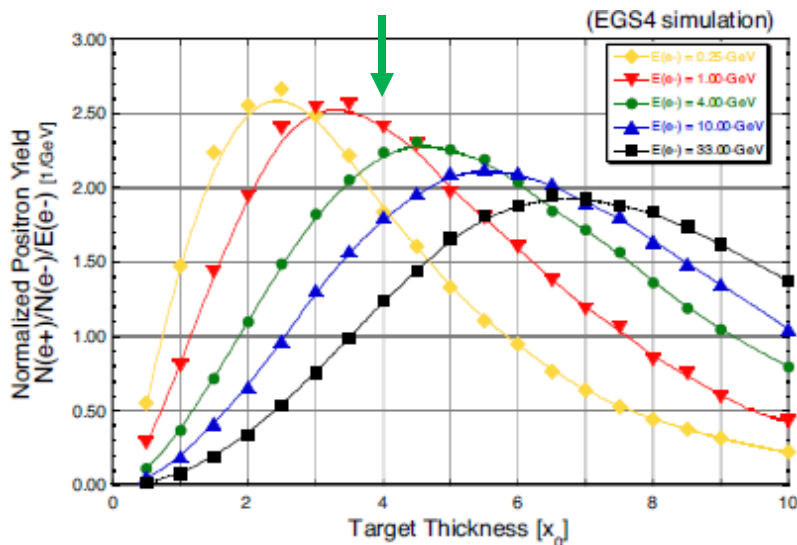
Tungsten- rhenium alloy (W-Re)

KEKB, SuperKEKB

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

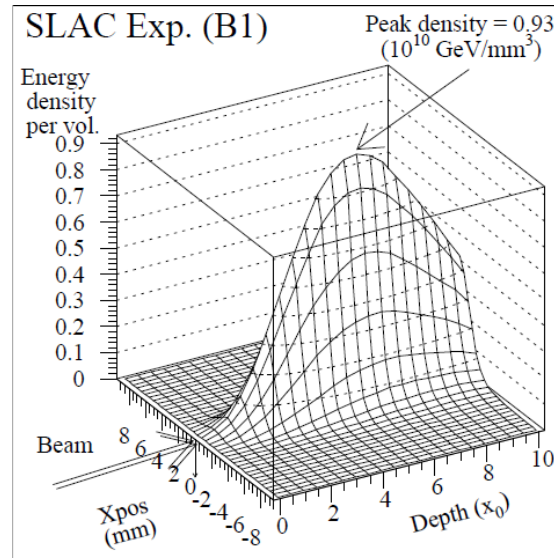
Primary e- beam energy: 4.0 GeV(KEKB)

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

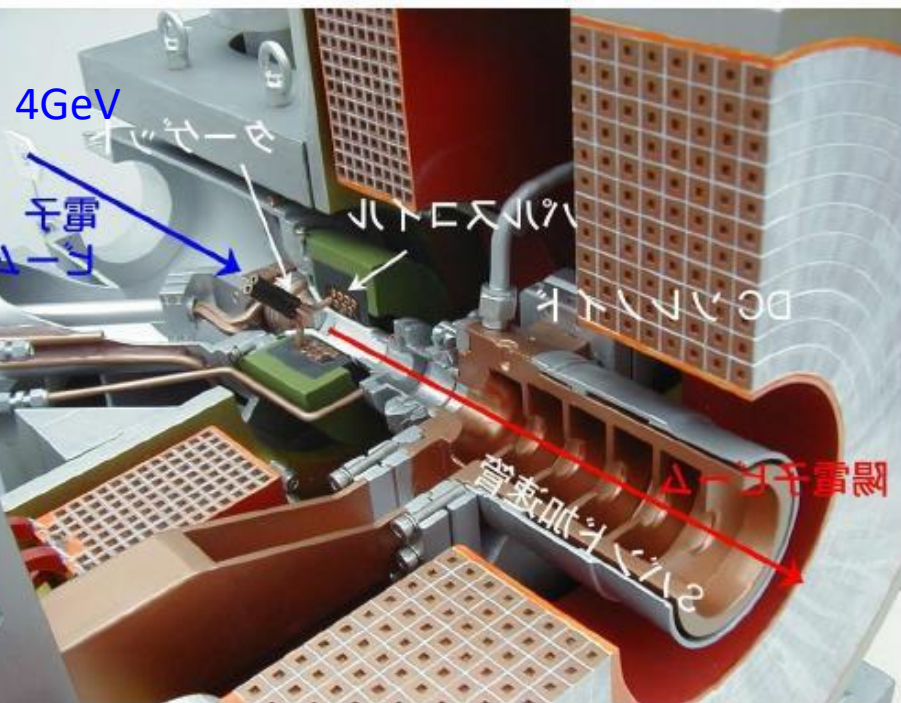
Threshold : $76 \rightarrow 35 \text{ J/g}$

KEK Positron Sources

KEKB

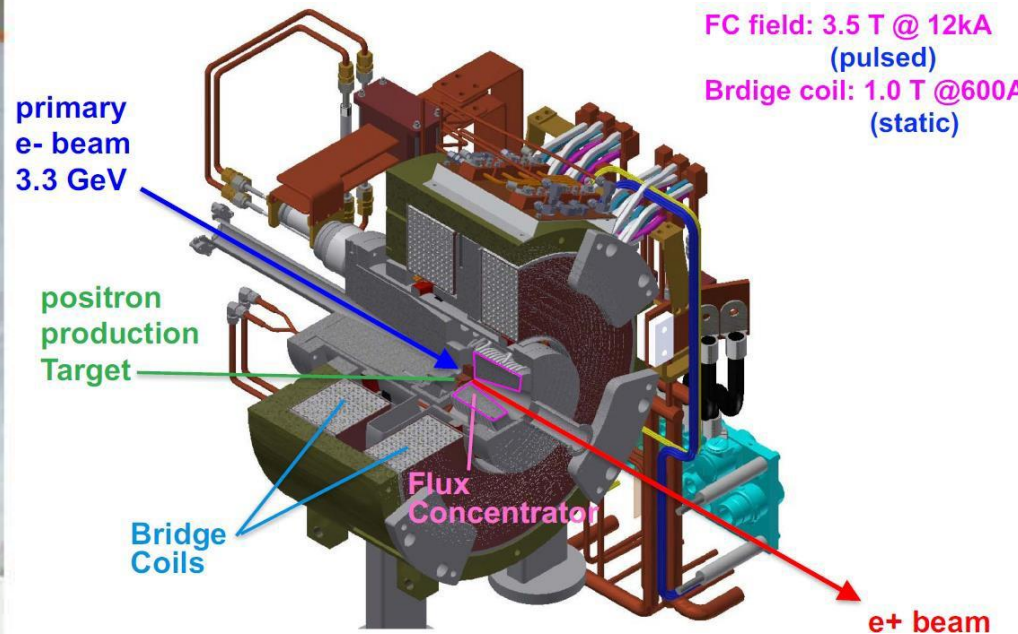
Quarter wave transformer matching device

Pulse coil: 2.3T @ 10kA



SuperKEKB

AMD Flux Concentrator matching device

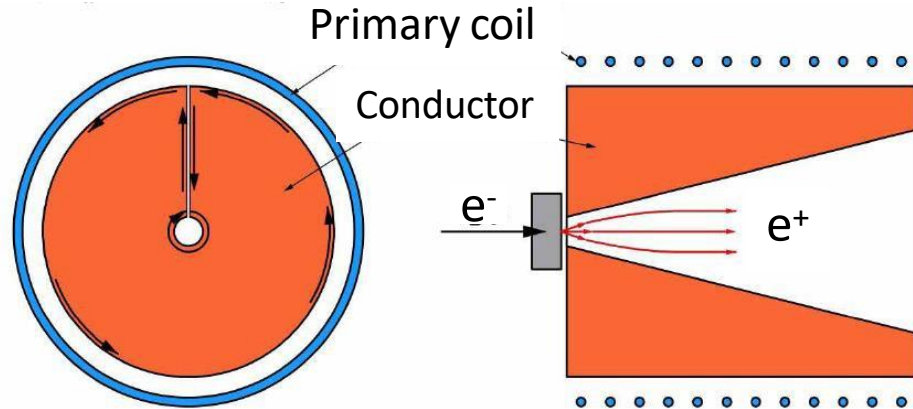


50Hz rep rate with a bunch charge of $2.5 \times 10^{10} = 2.5 \times 10^{12} \text{ e}^+/\text{s}$

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

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

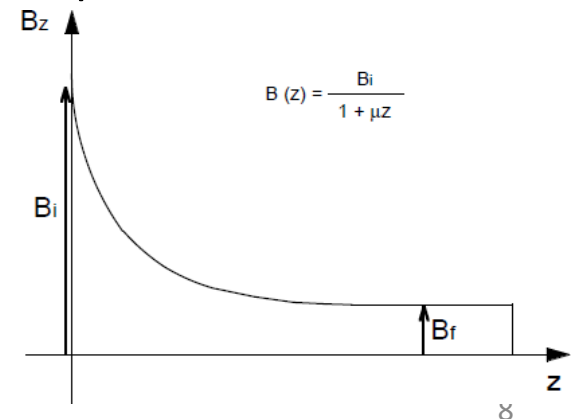
$$p_z \leq 17.5 [MeV/c]$$

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

Transverse acceptance

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

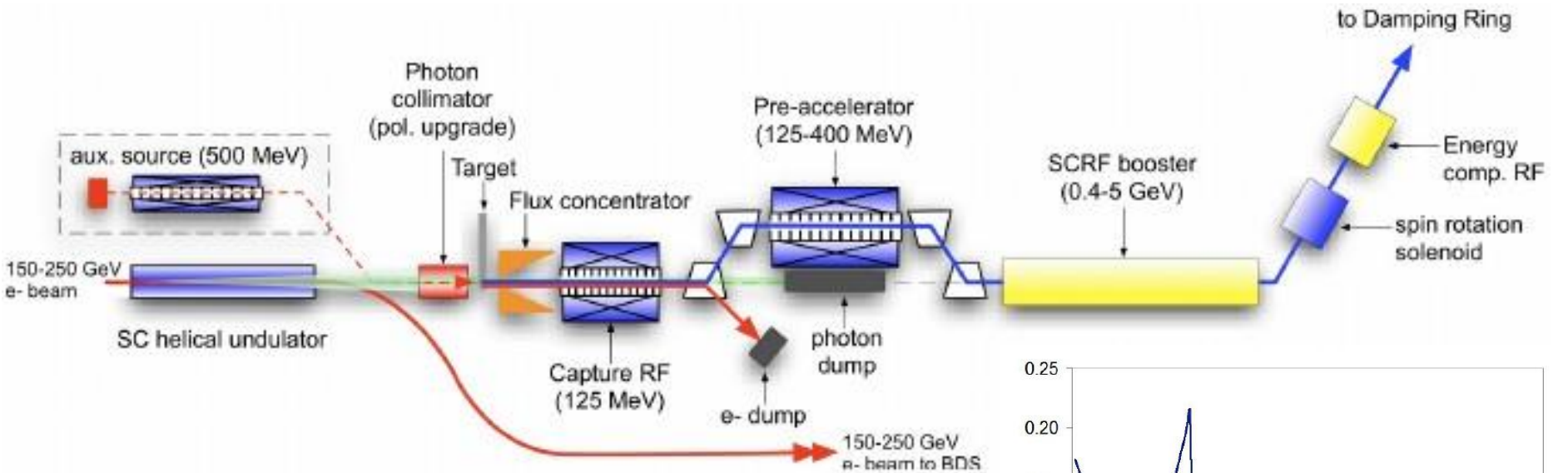
$$r_{max} = \sqrt{\frac{B_f}{B_0}} a$$



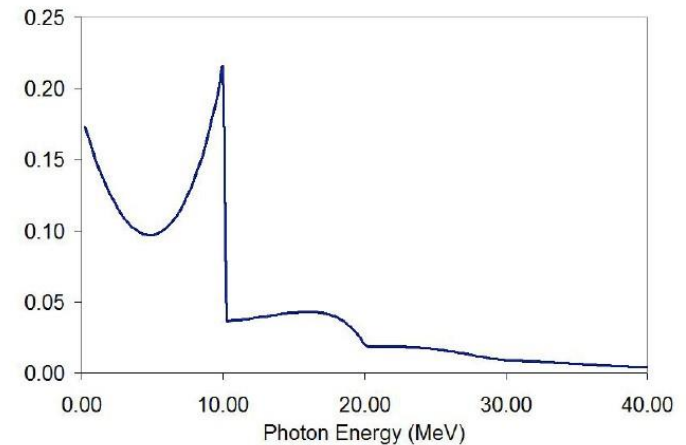
a: Diameter of an accelerator iris

Gamma Ray Undulator Source

Considered primarily for the ILC



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



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

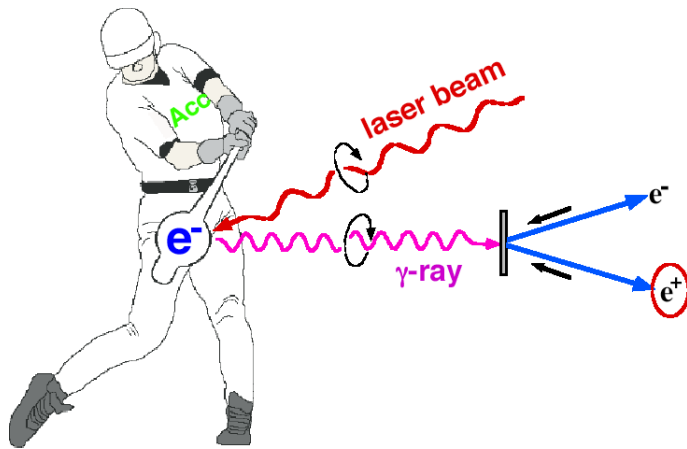
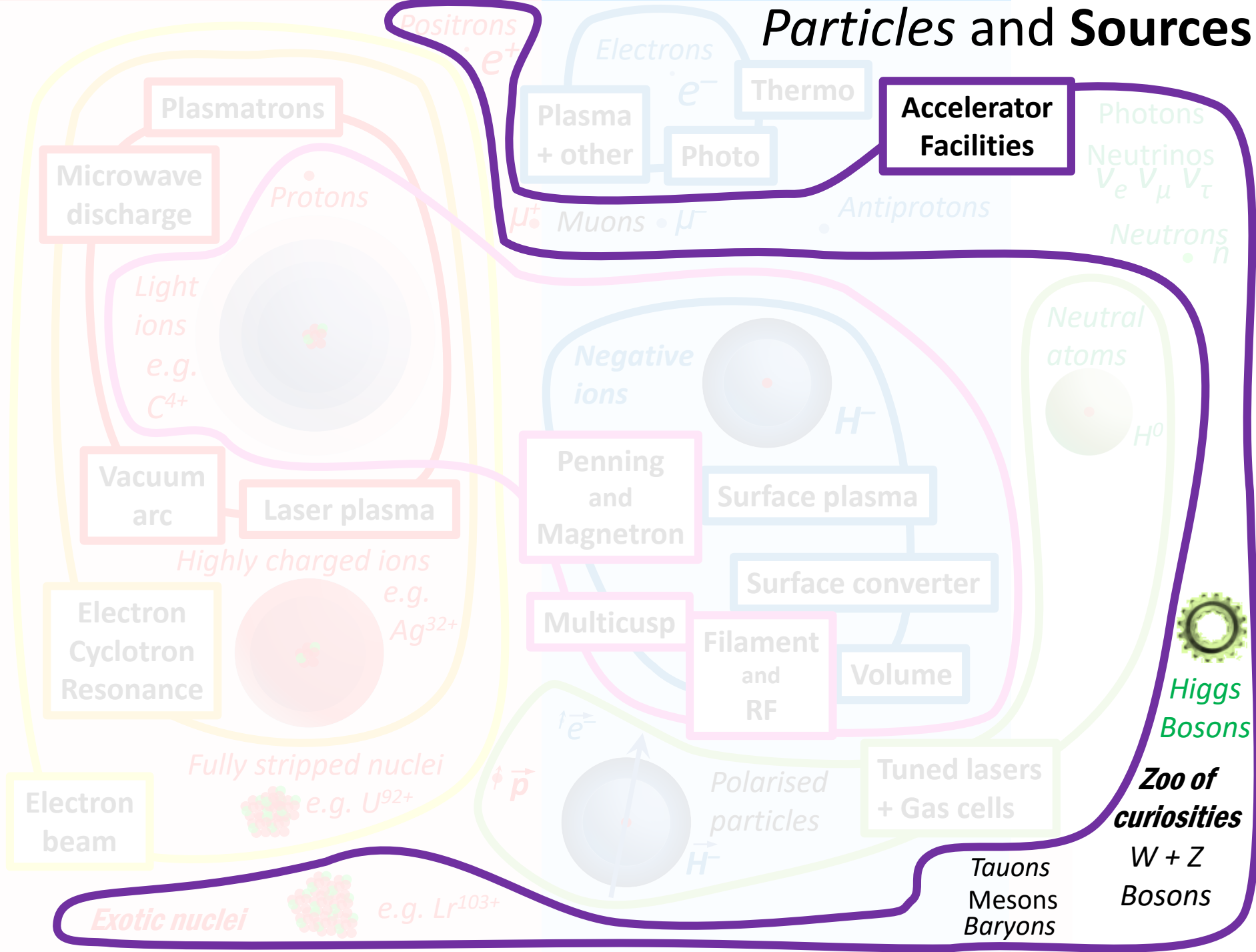


Table 1: CLIC parameters for e+ beam

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



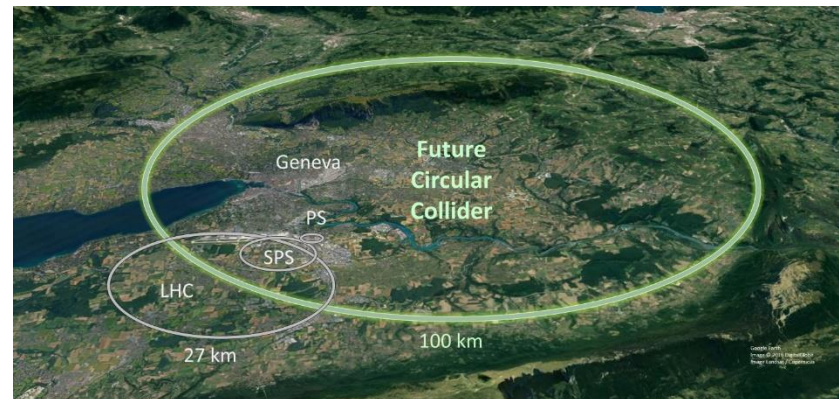
Future Colliders



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?