Secondary Beams

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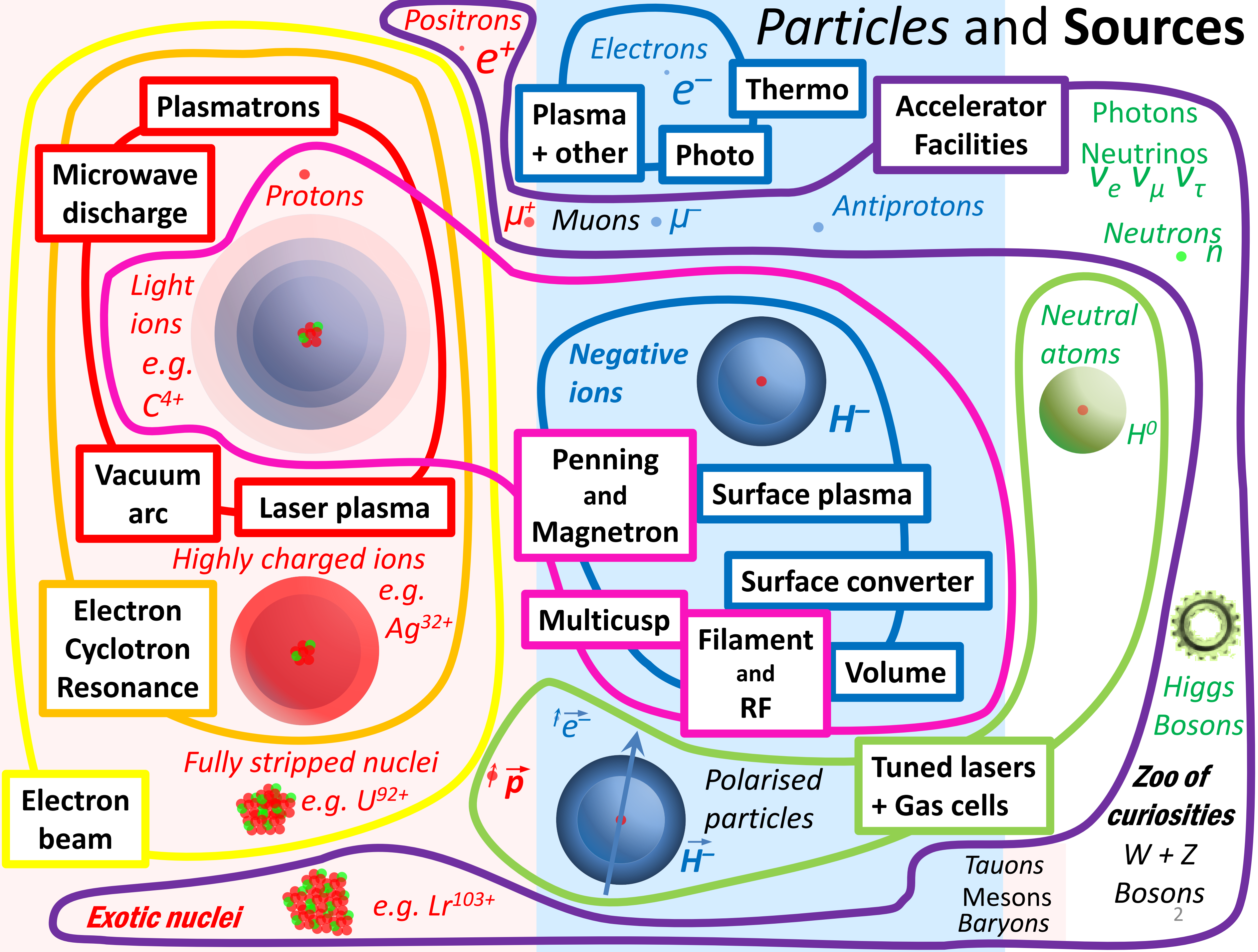
STFC-UKRI

CERN Accelerator School, Introduction to Accelerator Physics
Kaunas, Lithuania,
Saturday 24rd September 2022

Particles and **Sources**



Positrons e^+

Electrons e^-

Plasma + other

Thermo

Photo

Accelerator Facilities

Photons

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

μ^+ *Muons* μ^-

Antiprotons

Neutrons n

Plasmatrons

Microwave discharge

Protons

Light ions e.g. C^{4+}

Vacuum arc

Laser plasma

Highly charged ions e.g. Ag^{32+}

Electron Cyclotron Resonance

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

Electron beam

Exotic nuclei *e.g.* Lr^{103+}

Negative ions H^-

Penning and Magnetron

Surface plasma

Surface converter

Multicusp

Filament and RF

Volume

Neutral atoms H^0

$\vec{e}^-$

$\vec{p}$

$\vec{H}^-$

Polarised particles

Tuned lasers + Gas cells

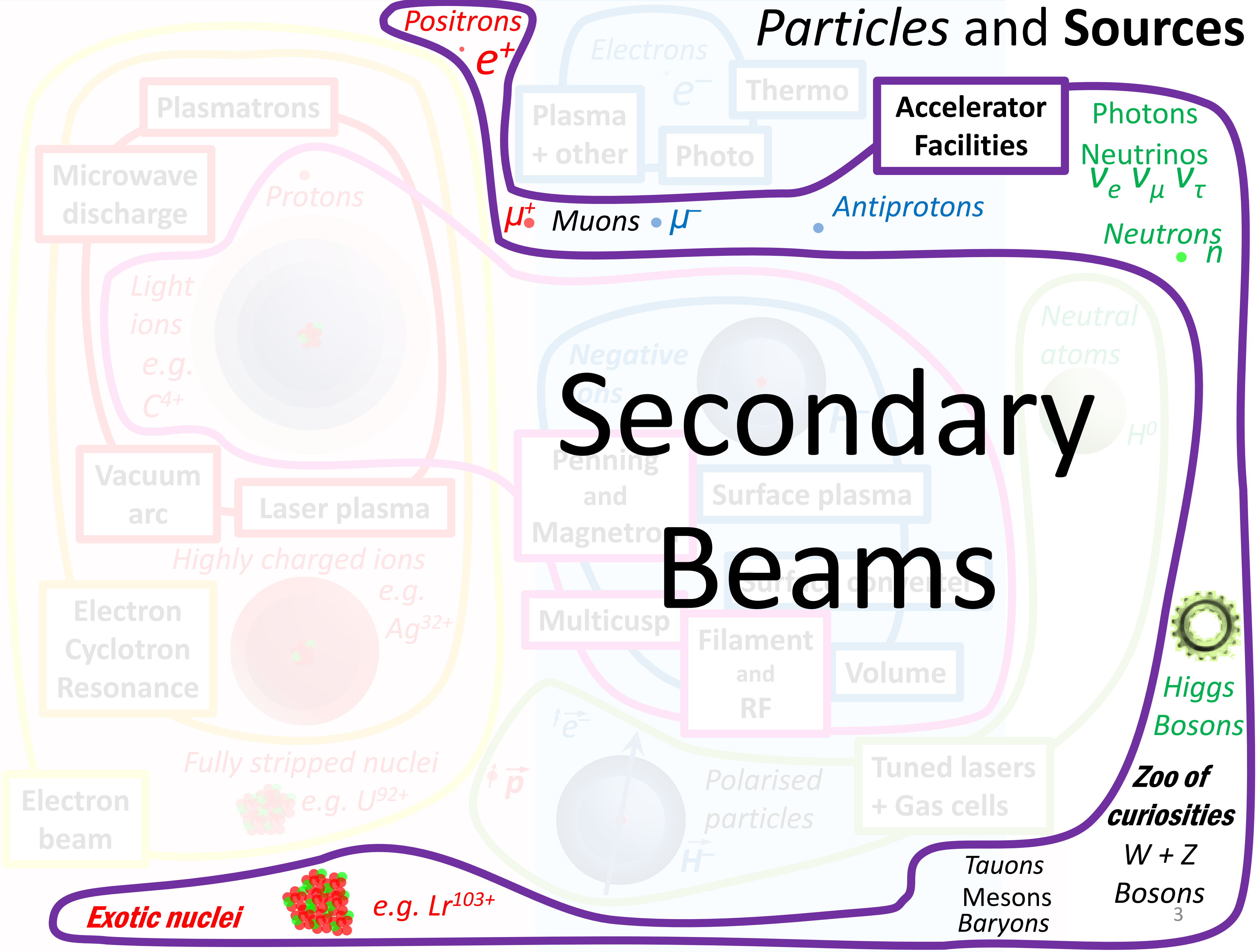
Higgs Bosons

Zoo of curiosities

W + Z Bosons

Tauons Mesons Baryons

Particles and **Sources**



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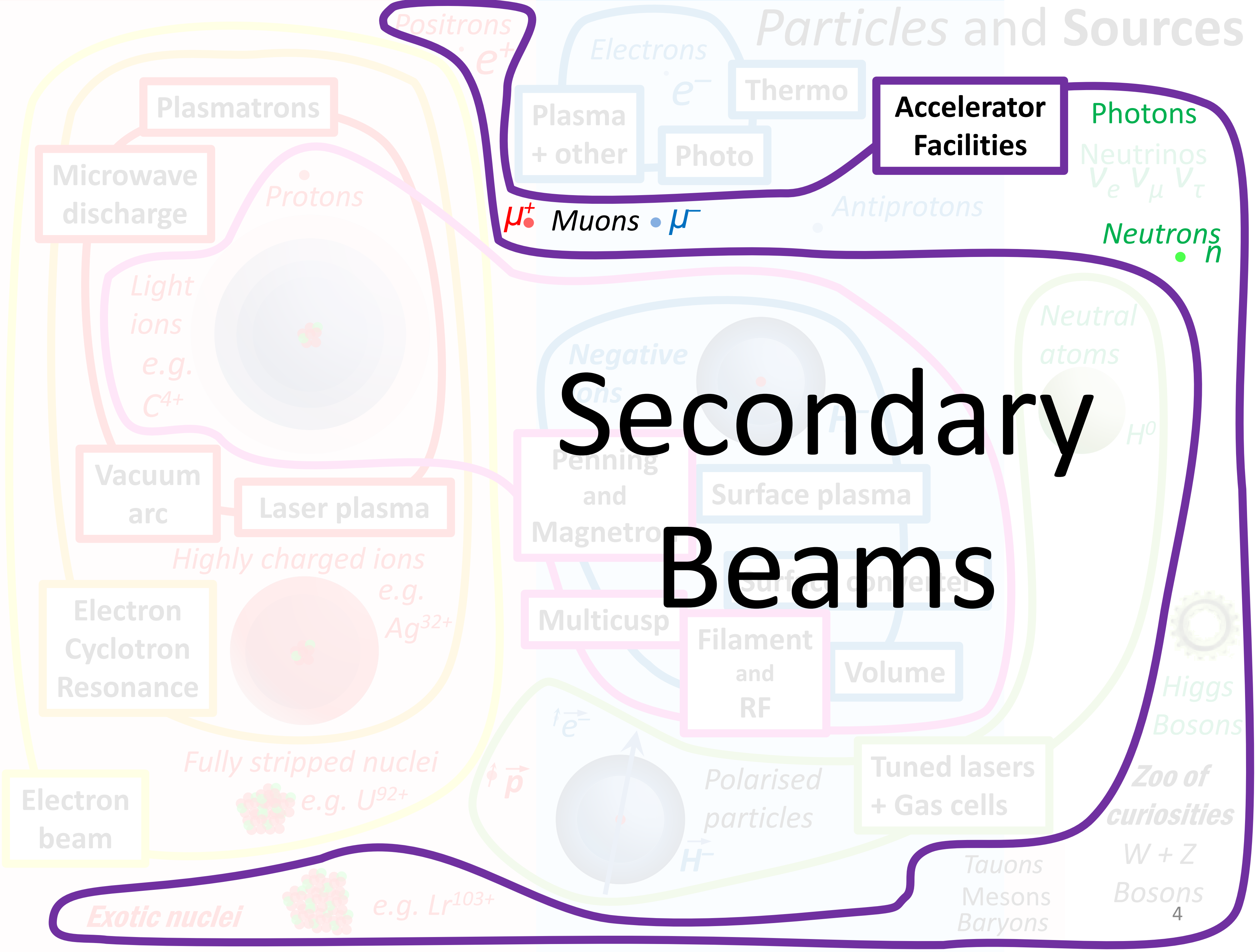

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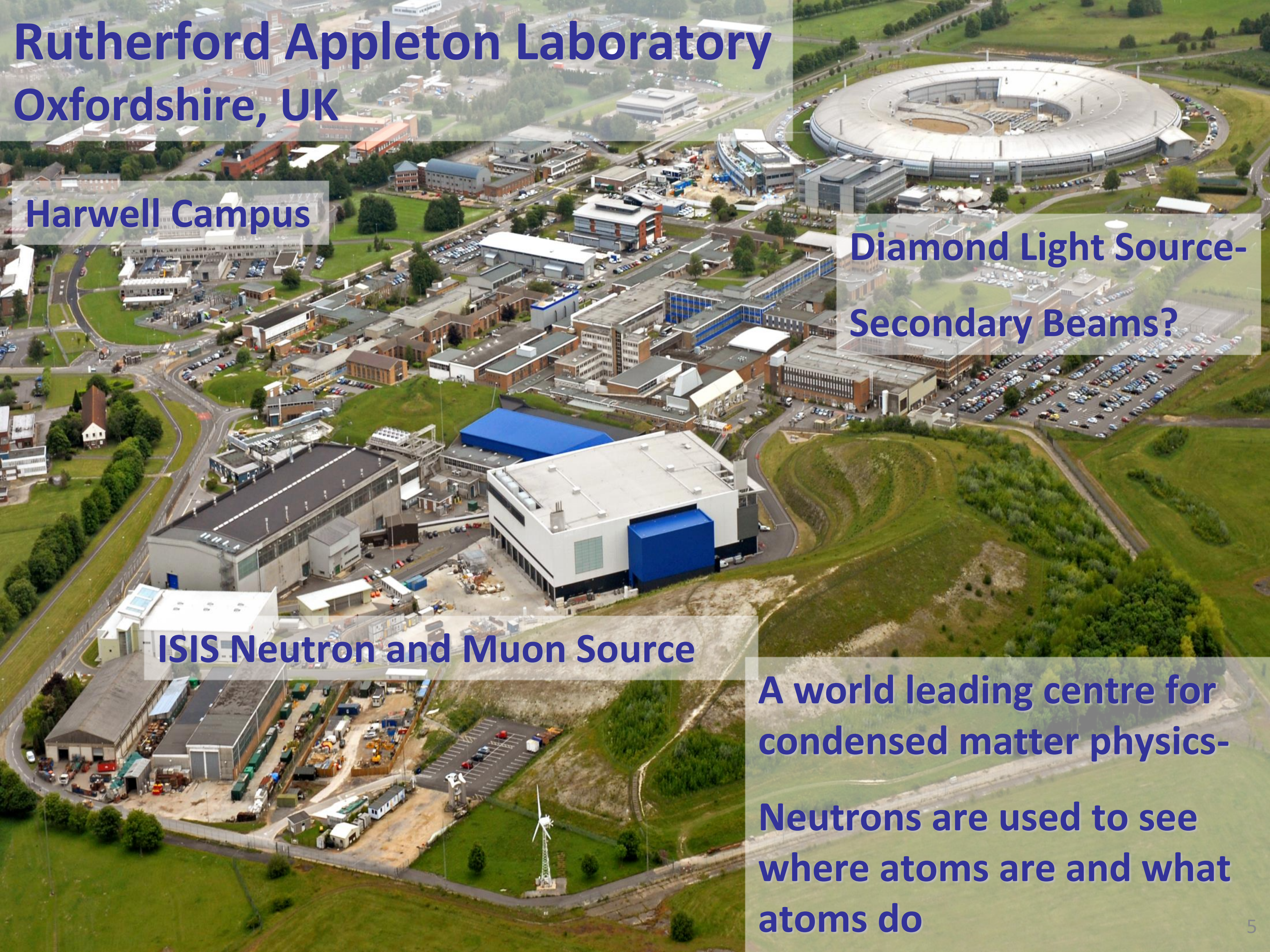
Tauons

Mesons

Baryons

Rutherford Appleton Laboratory
Oxfordshire, UK



Harwell Campus

Diamond Light Source-

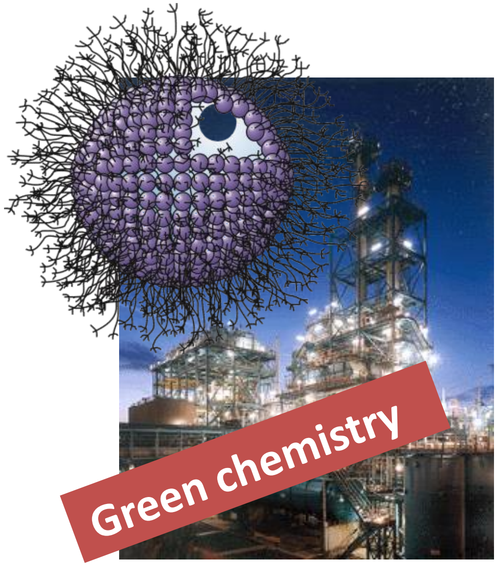
Secondary Beams?

ISIS Neutron and Muon Source

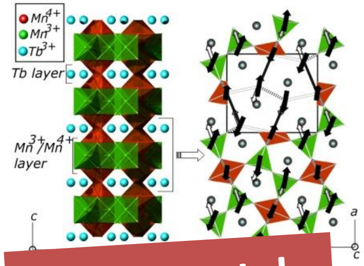
A world leading centre for condensed matter physics-

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

ISIS is used to study everything!

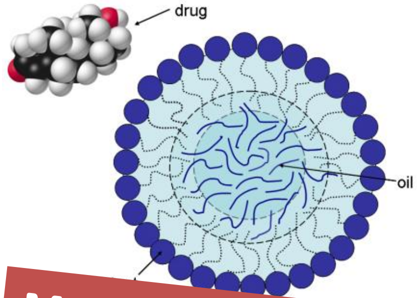


Green chemistry

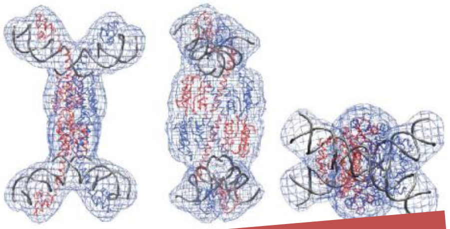


Fundamental magnetism

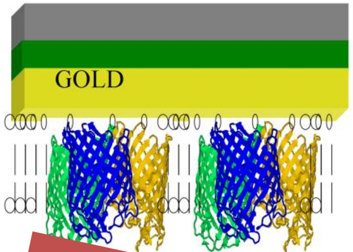
Superconductors



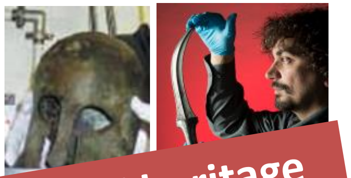
Medical applications



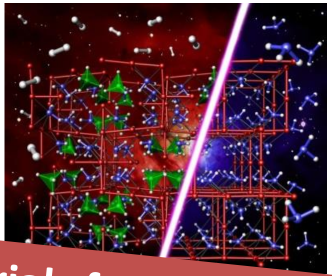
Biological structures



Bio-sensors

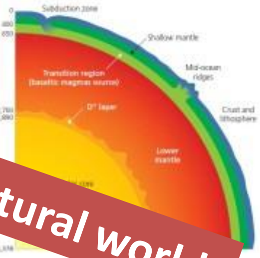


Cultural heritage



Materials for clean energy

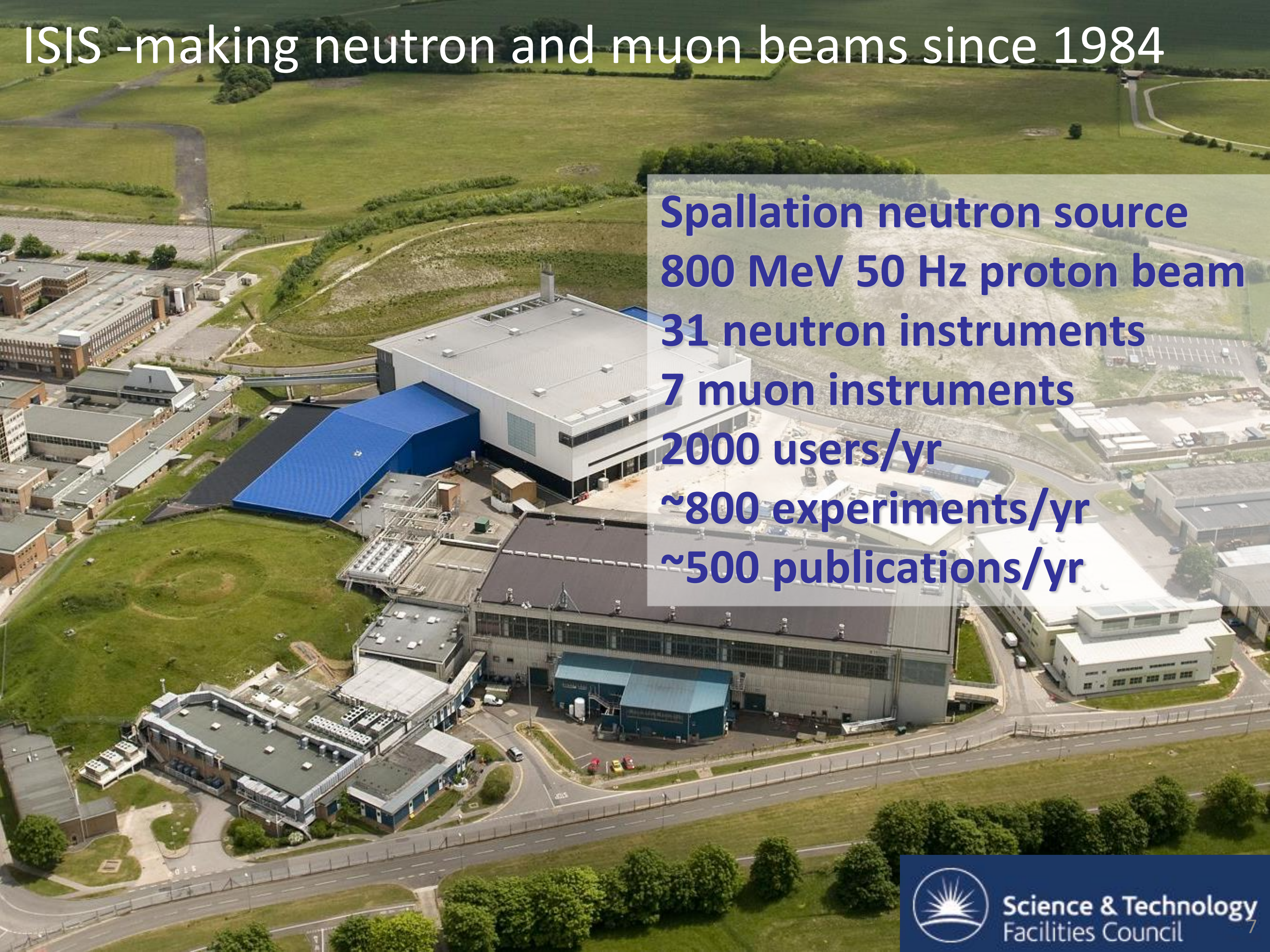
Mechanical Engineering



Natural world

Pollution, energy and the environment

ISIS -making neutron and muon beams since 1984



Spallation neutron source

800 MeV 50 Hz proton beam

31 neutron instruments

7 muon instruments

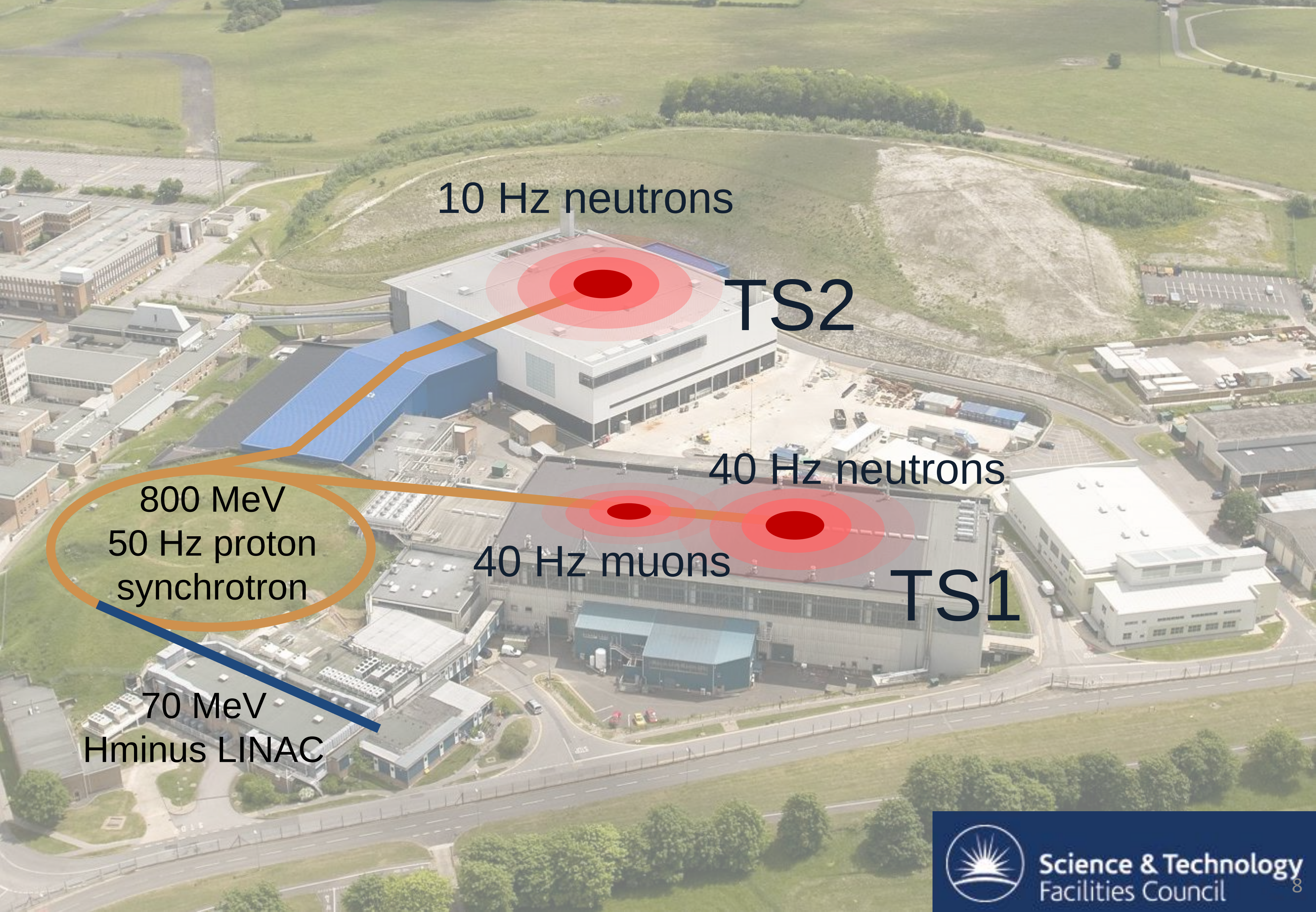
2000 users/yr

~800 experiments/yr

~500 publications/yr

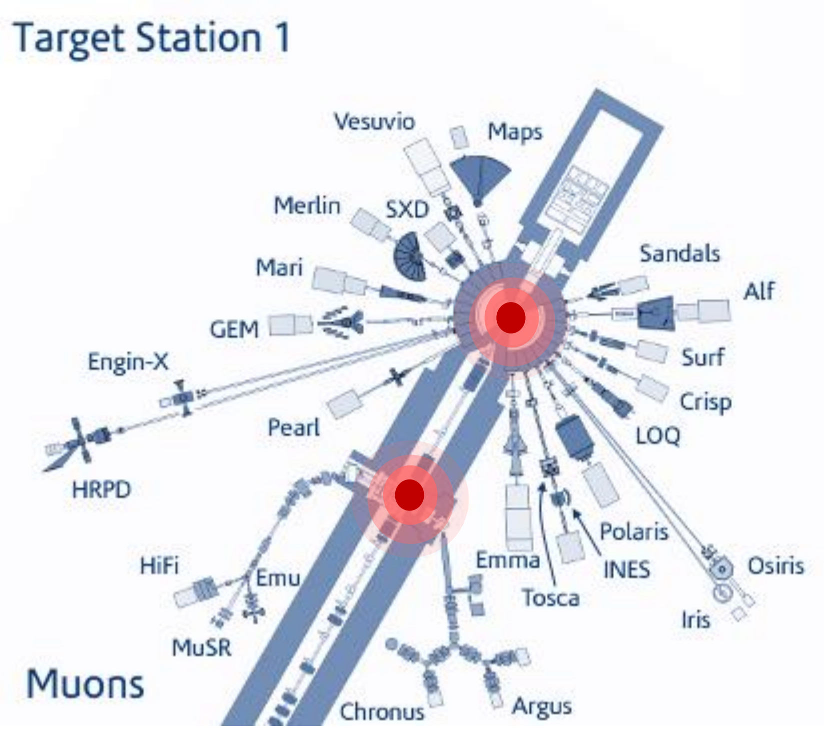
Science & Technology
Facilities Council

ISIS -making neutron and muon beams since 1984

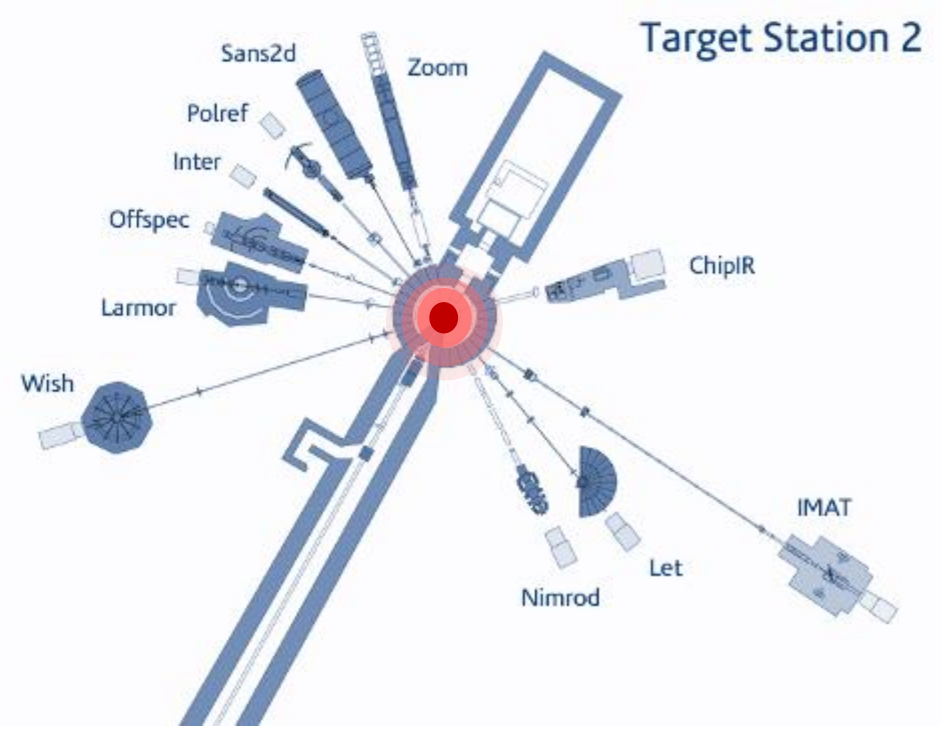


Science & Technology Facilities Council

ISIS has many different types of neutron and muon instruments:



20 neutron instruments
7 muon instruments



11 neutron instruments
(more in the way)

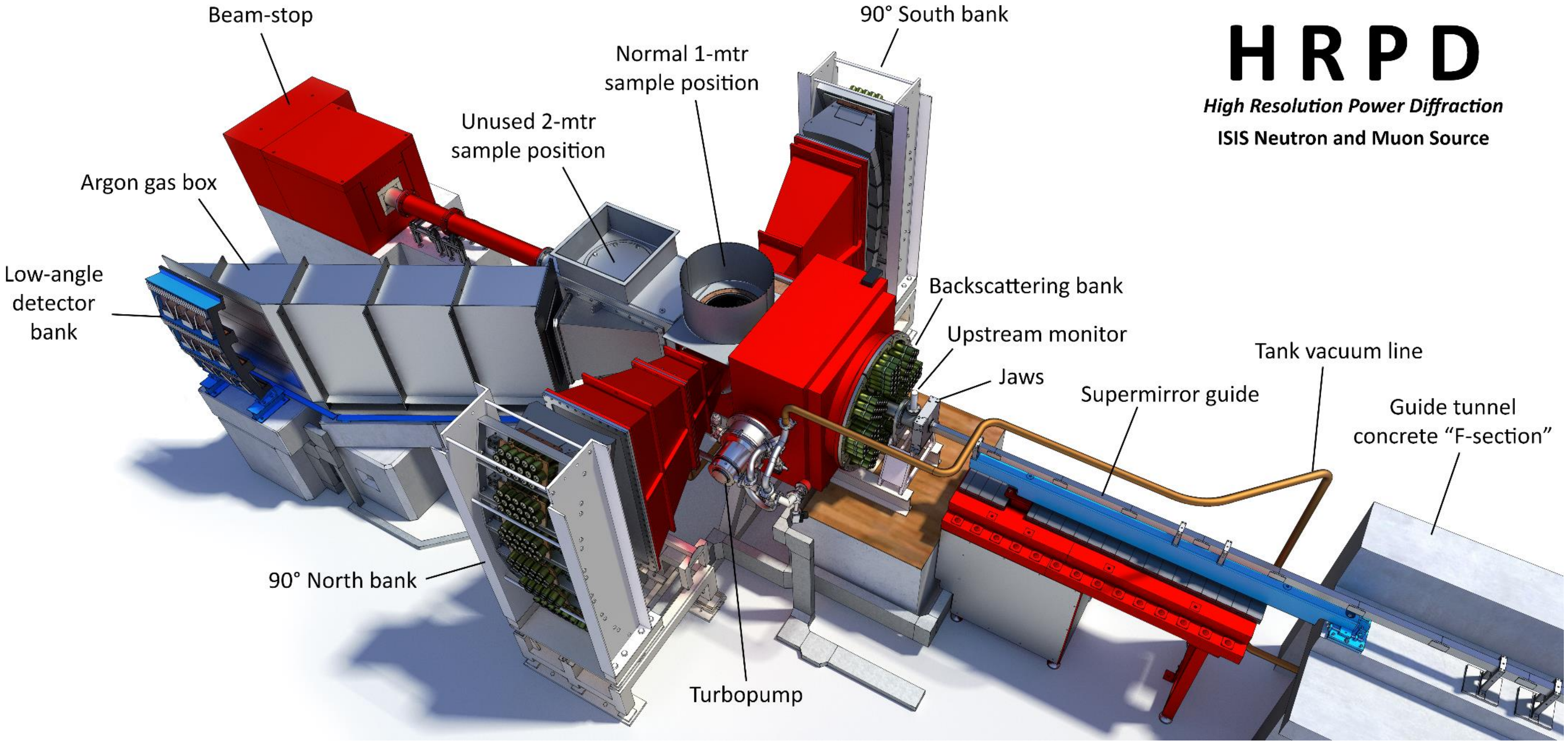
LET Spectrometer

… some are very big

…some are smaller and movable

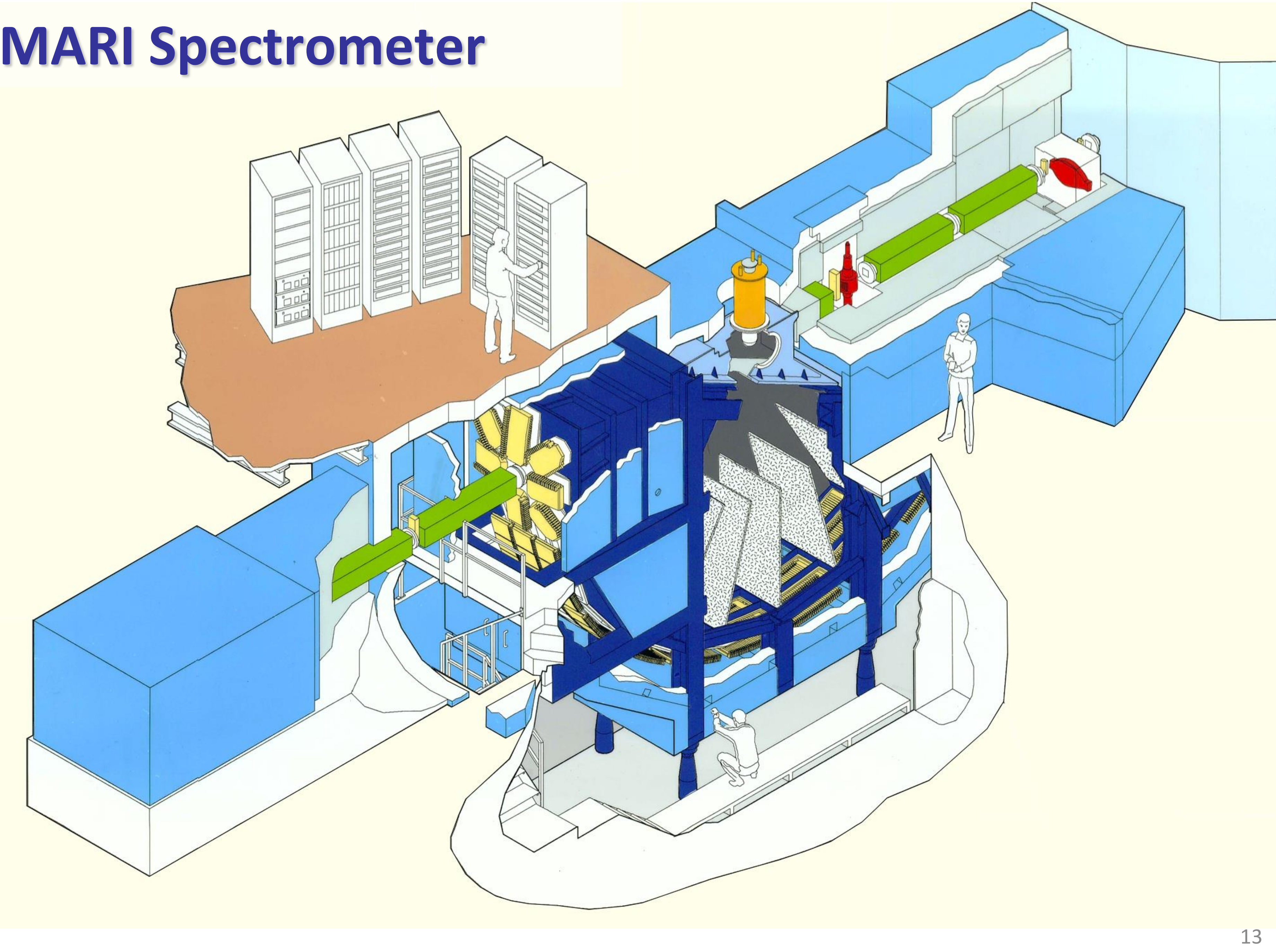
OFFSPEC Reflectometer

Each instrument is unique and complex…

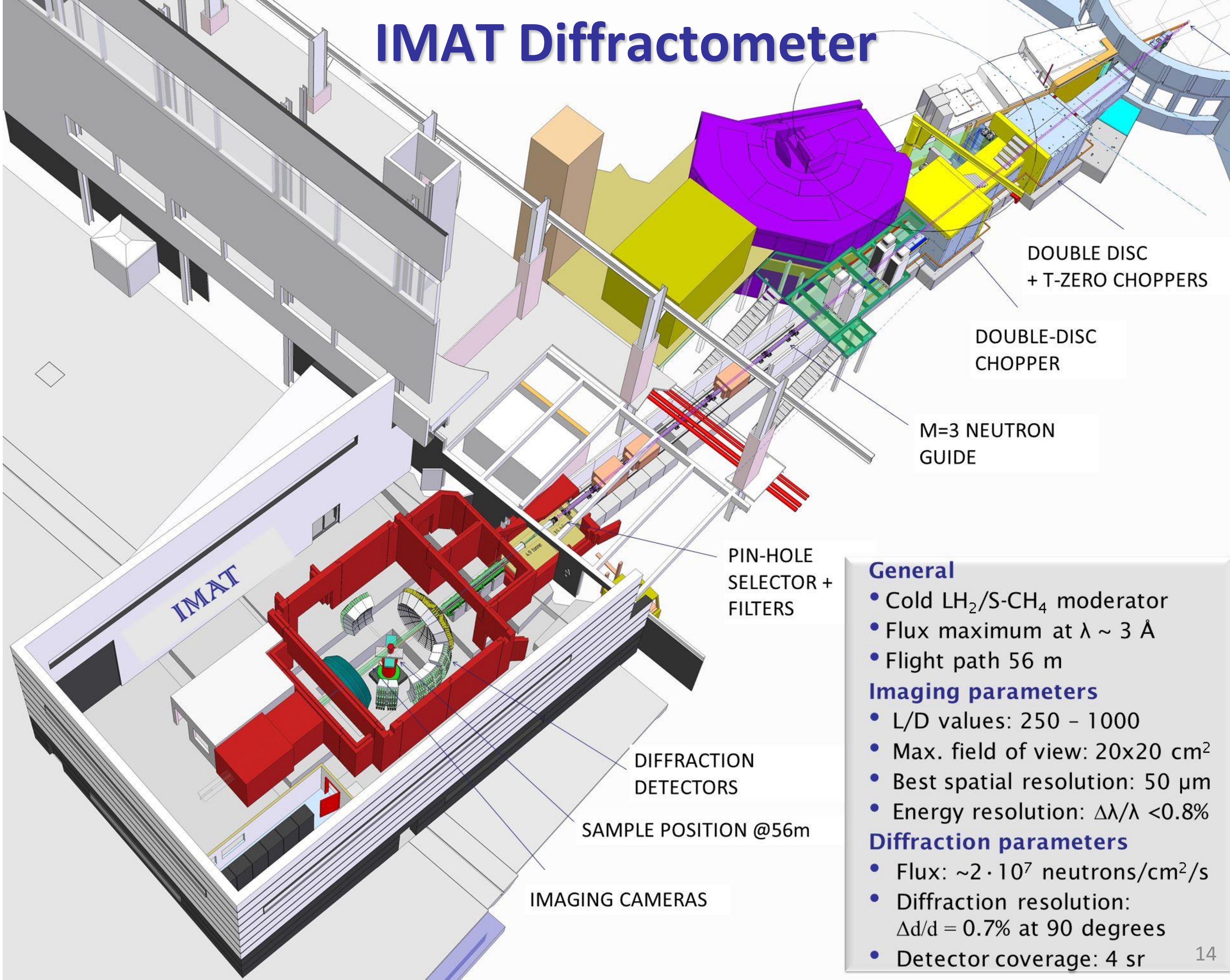


HRPD Diffractometer

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 LH_2/S-CH_4 moderator
- Flux maximum at λ ~ 3 Å
- Flight path 56 m

Imaging parameters

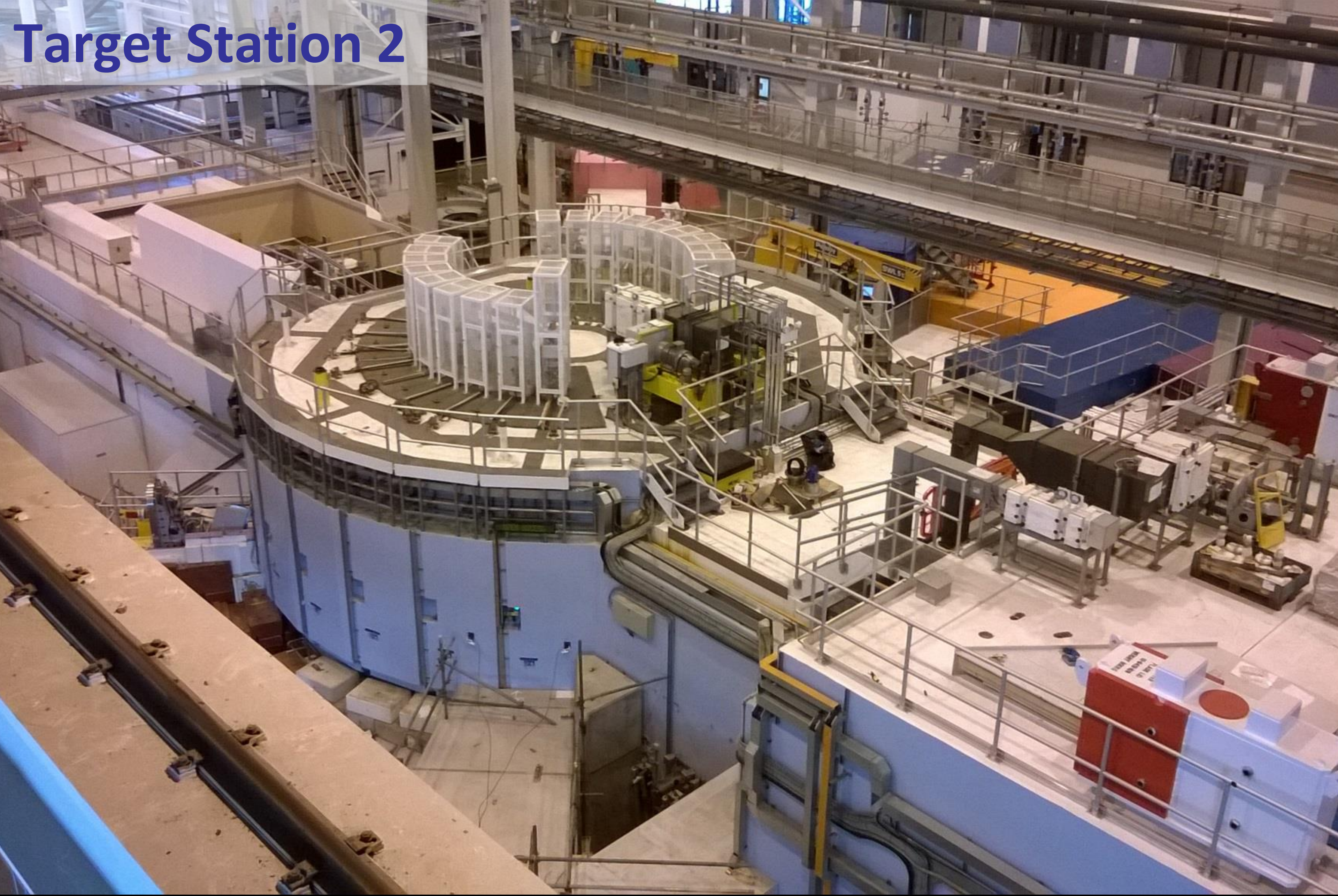
- L/D values: 250 – 1000
- Max. field of view: 20x20 cm^2
- Best spatial resolution: 50 μm
- Energy resolution: $\Delta\lambda/\lambda$ <0.8%

Diffraction parameters

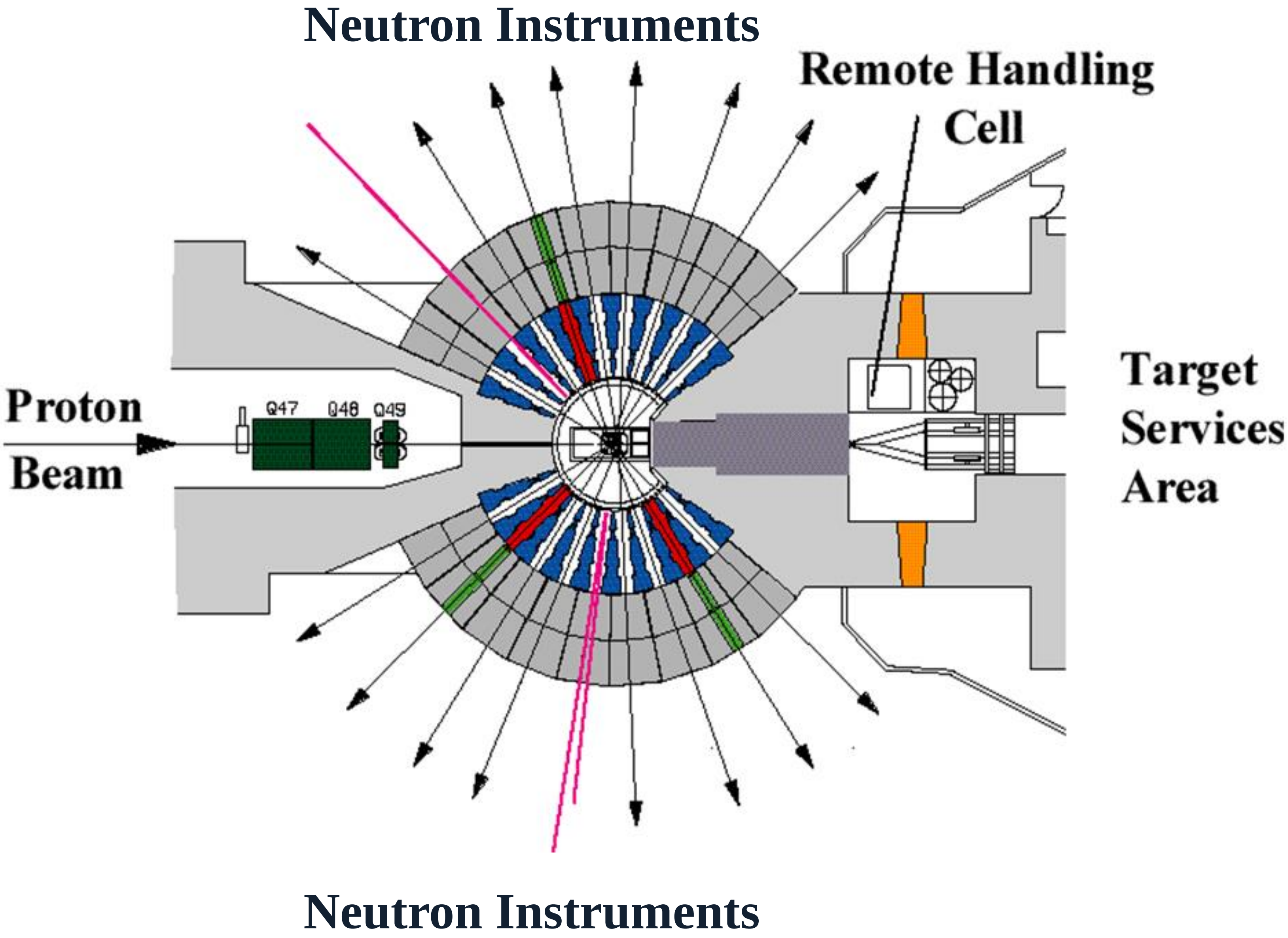
- Flux: ~$2 \cdot 10^7$ neutrons/cm^2/s
- Diffraction resolution:
  $\Delta d/d$ = 0.7% at 90 degrees
- Detector coverage: 4 sr

Target Station 1

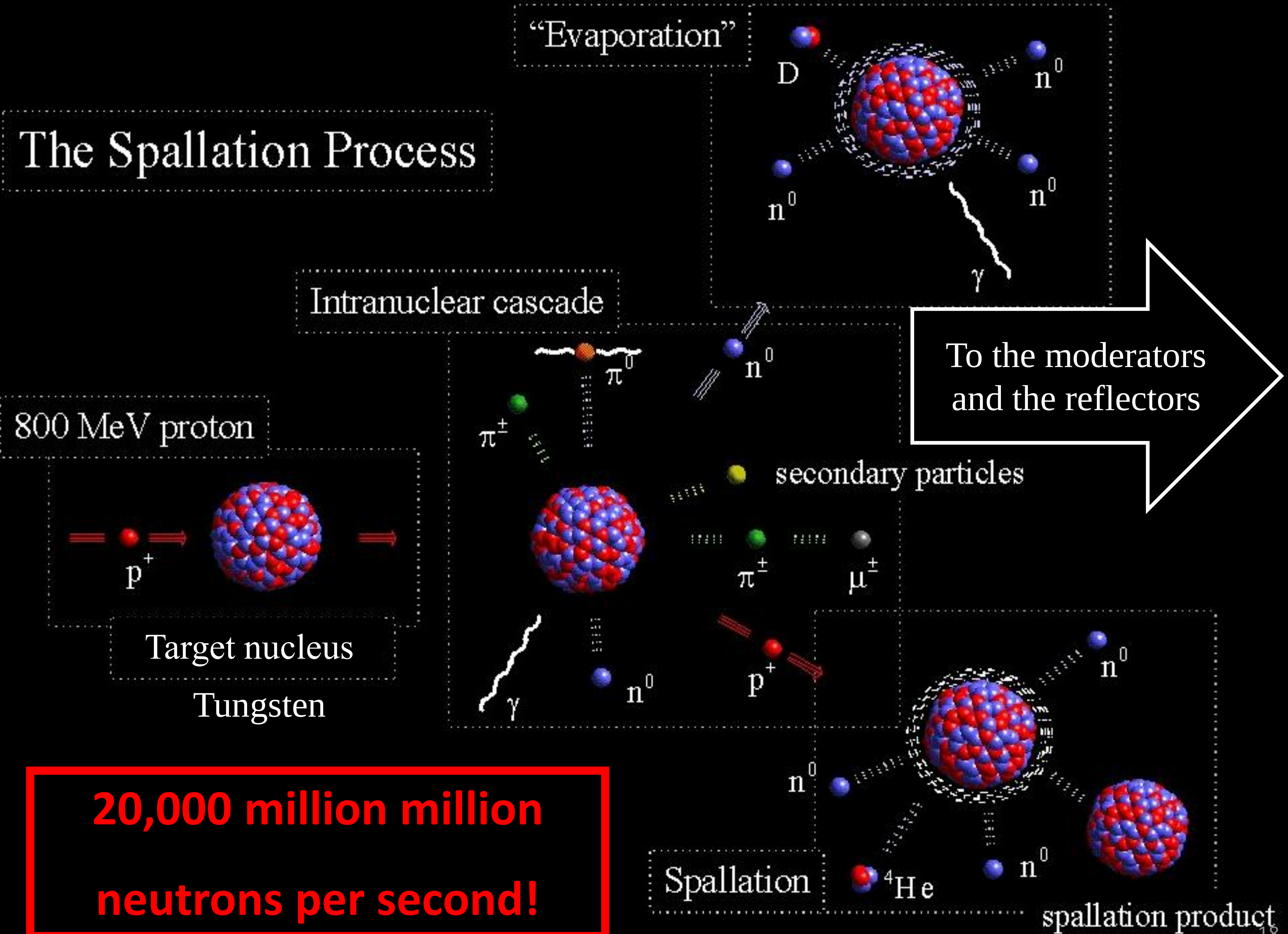
Target Station 2



Basic Layout of ISIS Target Stations



The Spallation Process

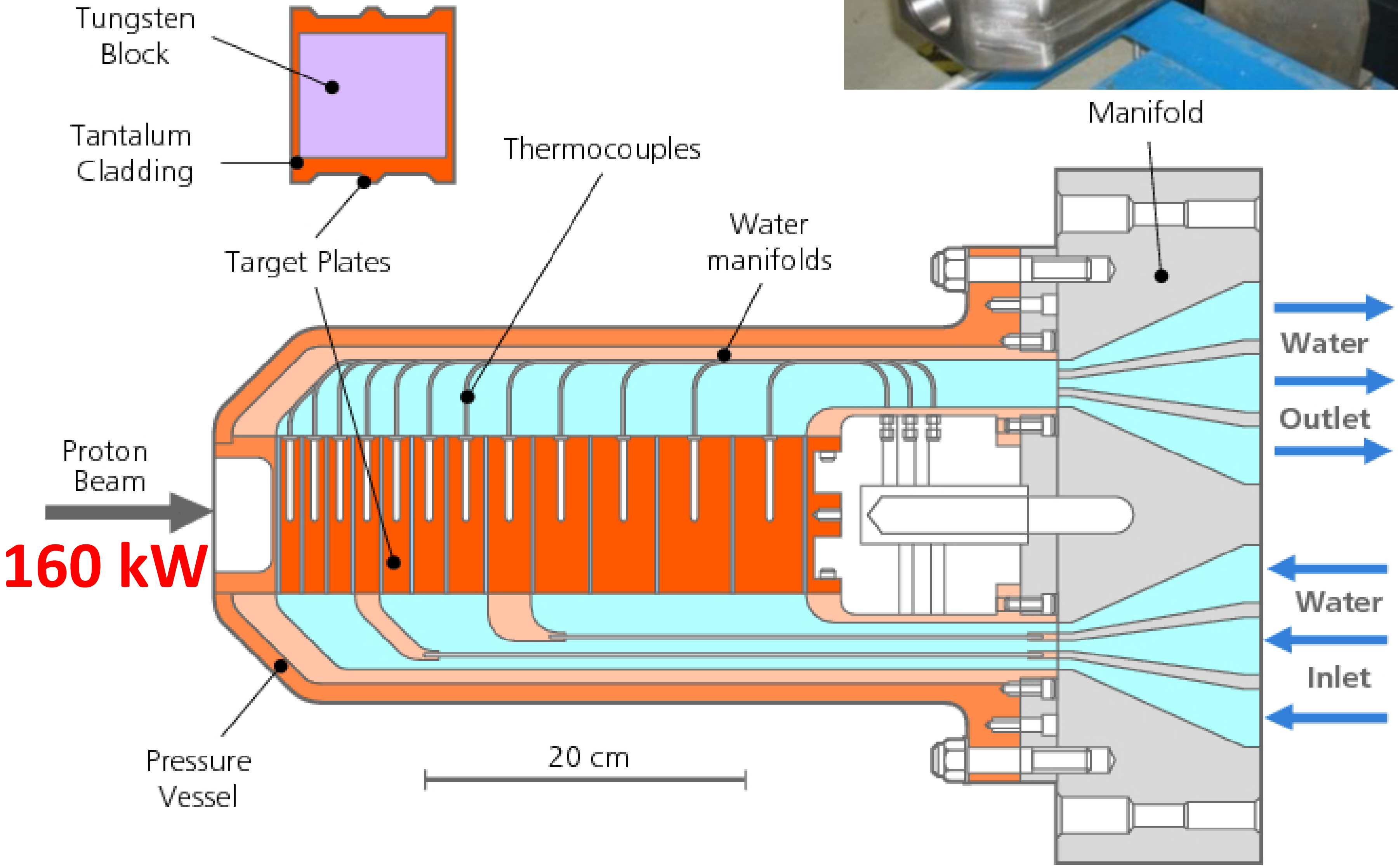


To the moderators and the reflectors

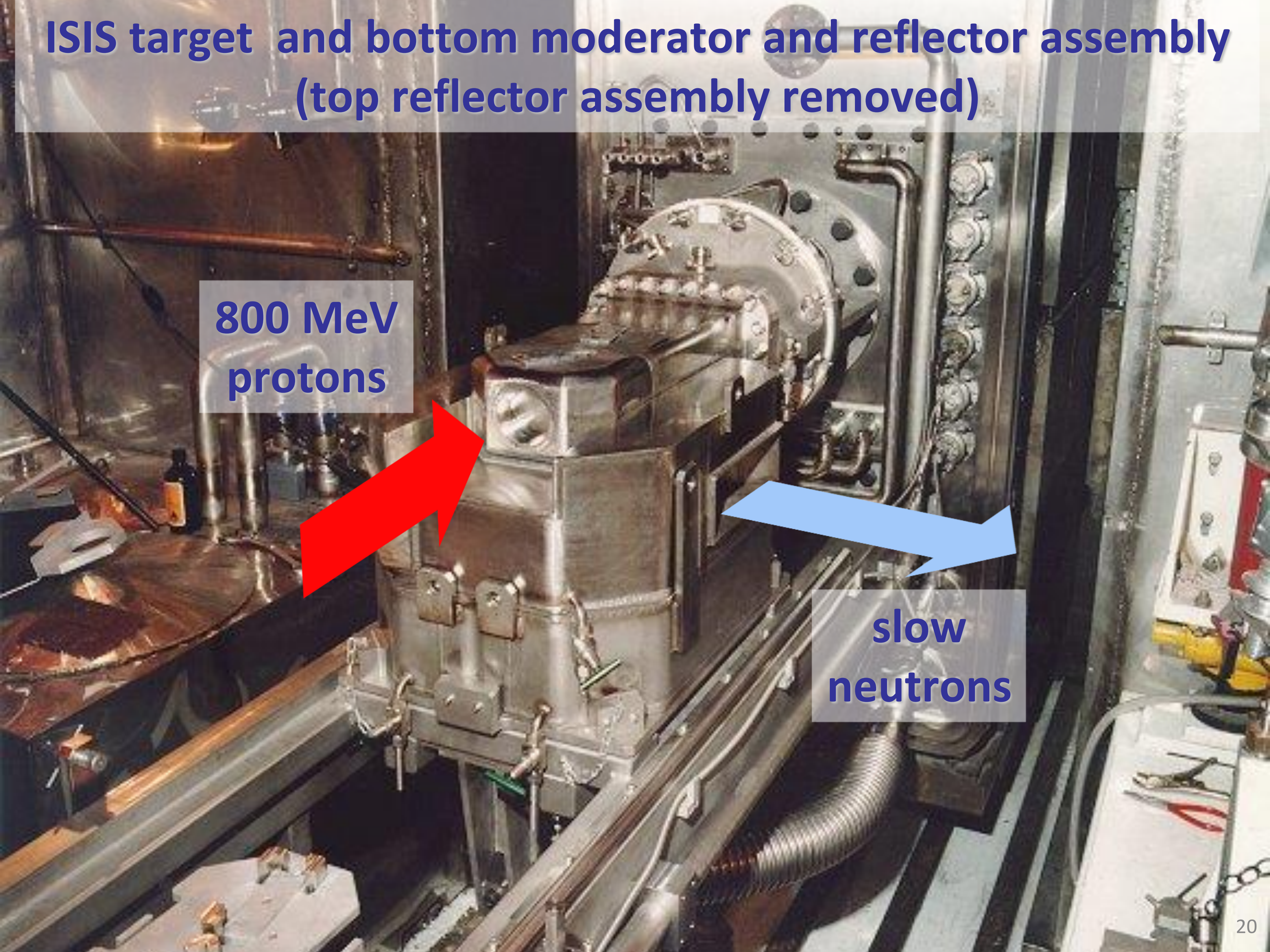
Tungsten

20,000 million million neutrons per second!

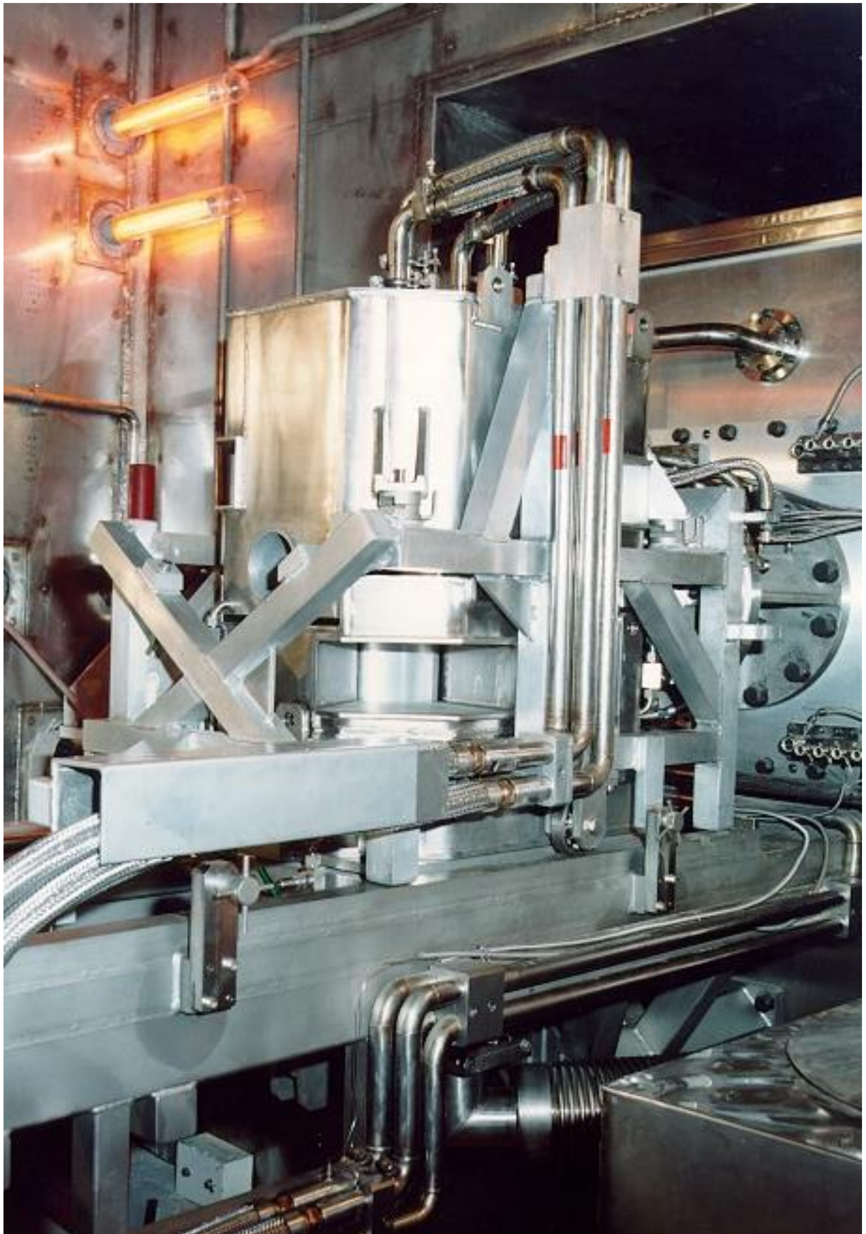
Section view of ISIS TS1 target

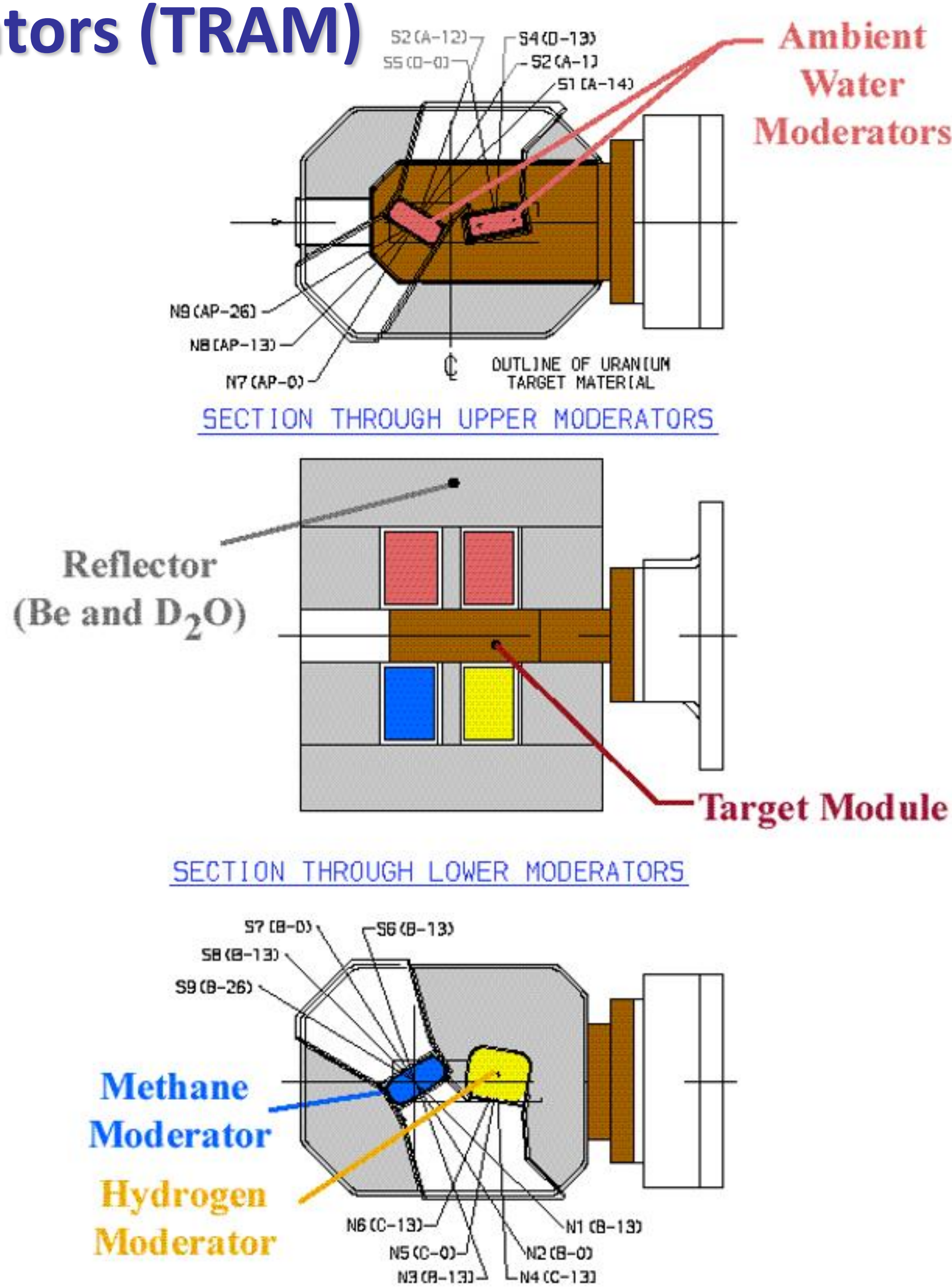


ISIS target and bottom moderator and reflector assembly (top reflector assembly removed)



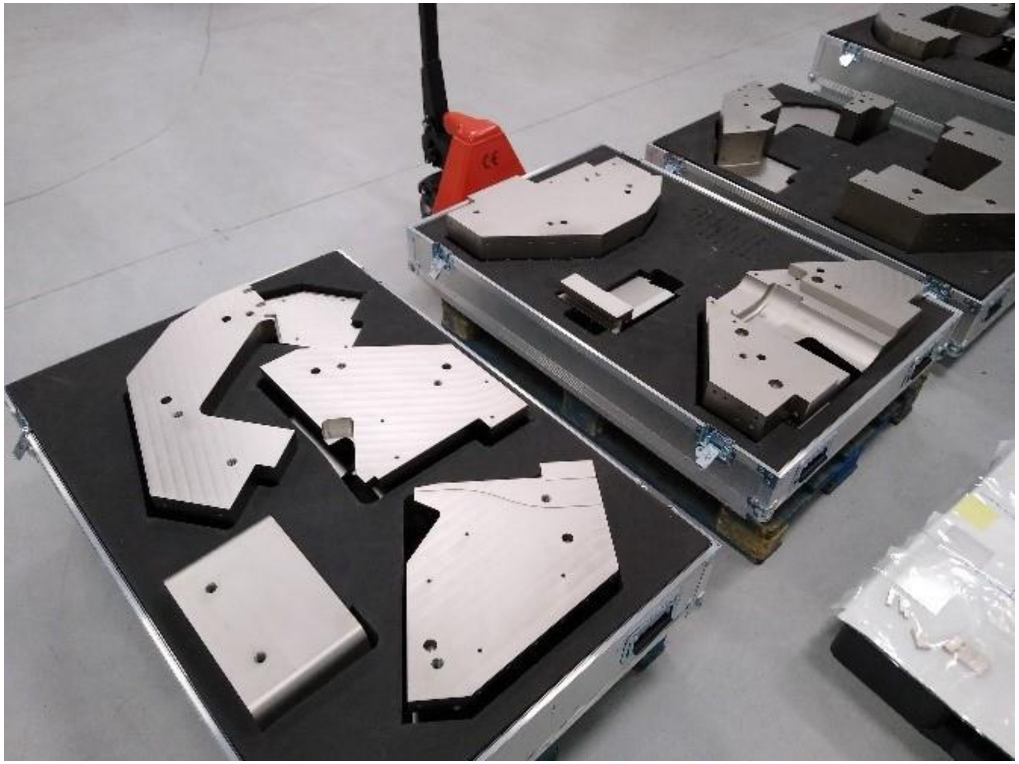
Target Reflector And Moderators (TRAM)

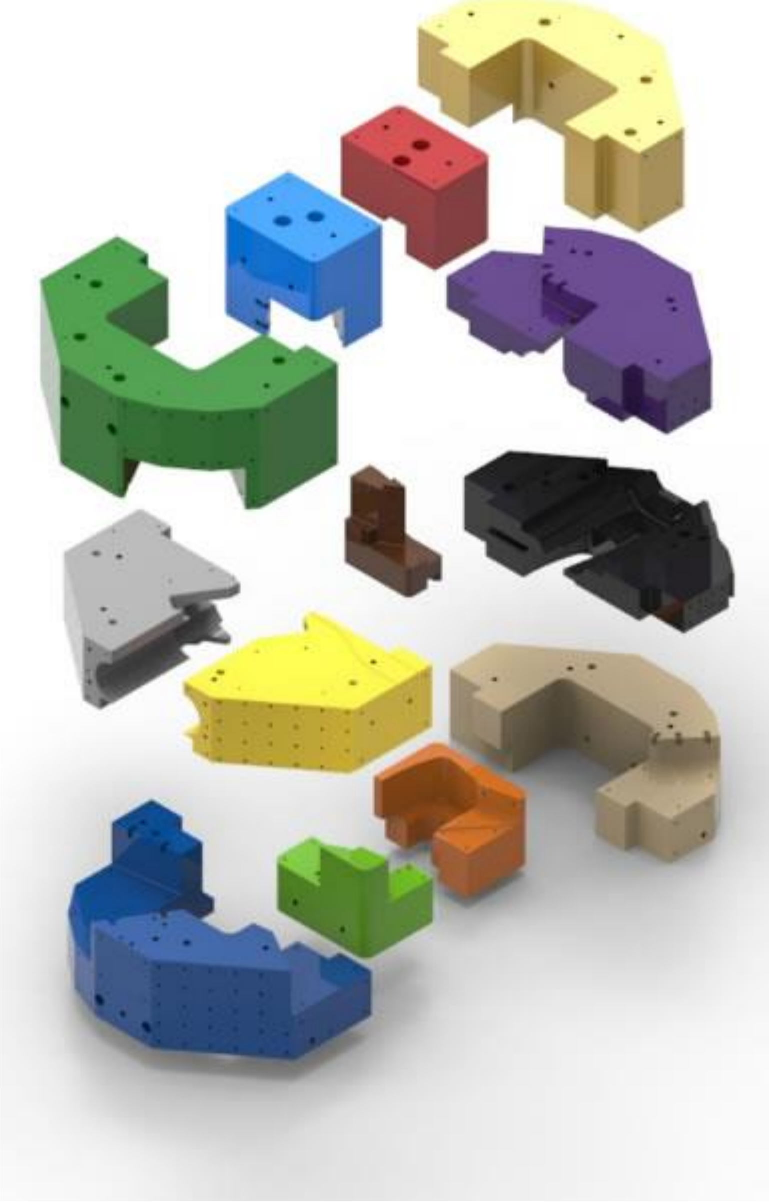




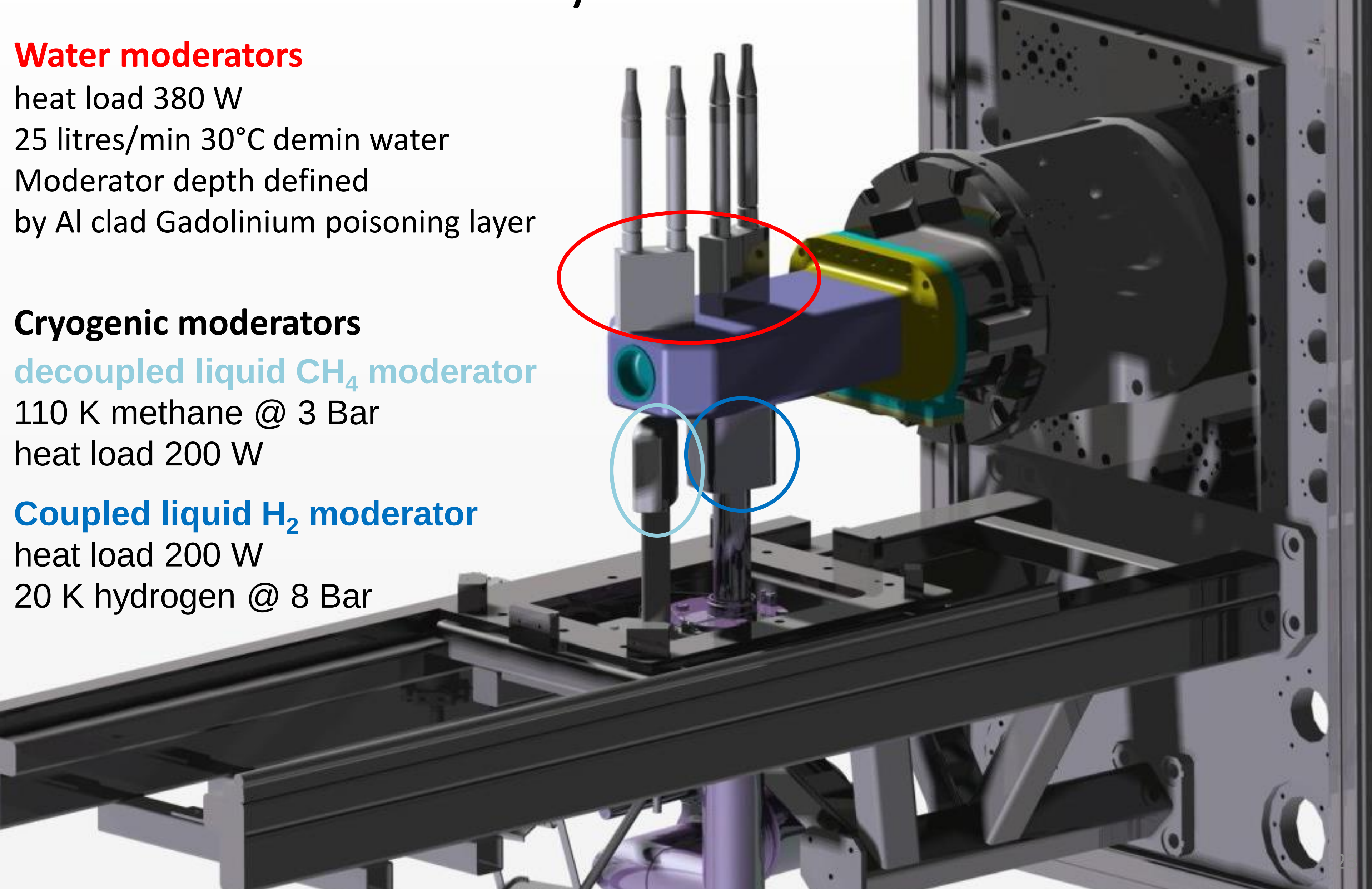
TS1 Project – Major Refurbishment

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 CH_4 moderator

110 K methane @ 3 Bar

heat load 200 W

Coupled liquid H_2 moderator

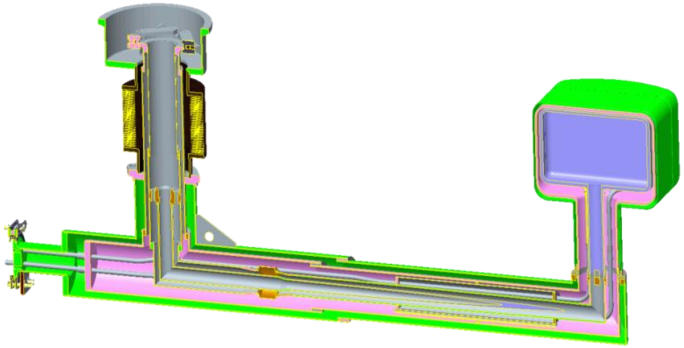
heat load 200 W

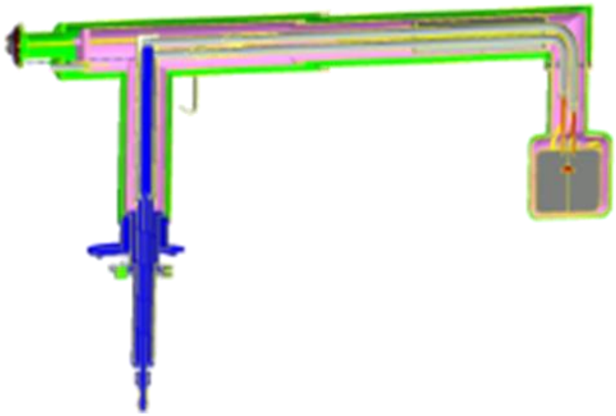
20 K hydrogen @ 8 Bar

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

magnetically levitating bearings

slotted shielding

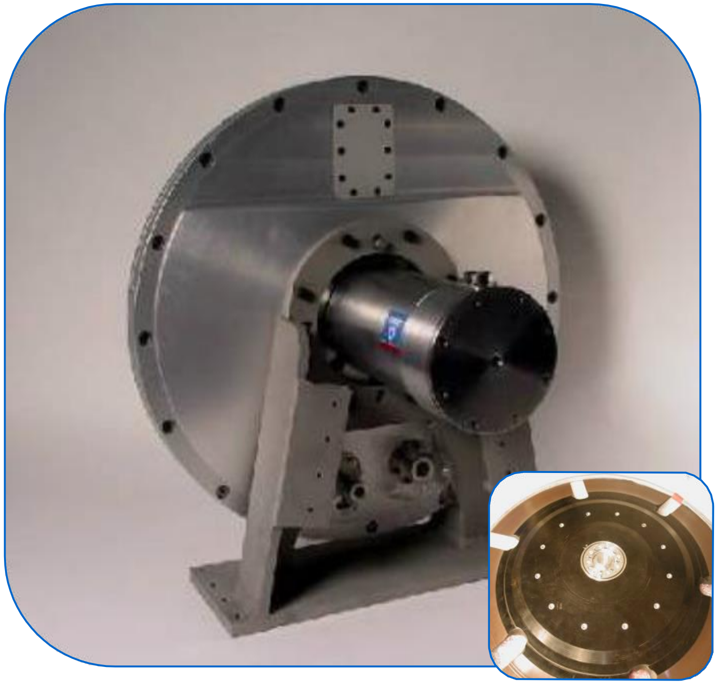
Choppers- spinning shielding

Fermi (17)

7.3 kg Payload
36,000 rpm
±0.05° Phase Control

Disk (56)

30 kg Payload
20,000 rpm
±0.05° Phase Control

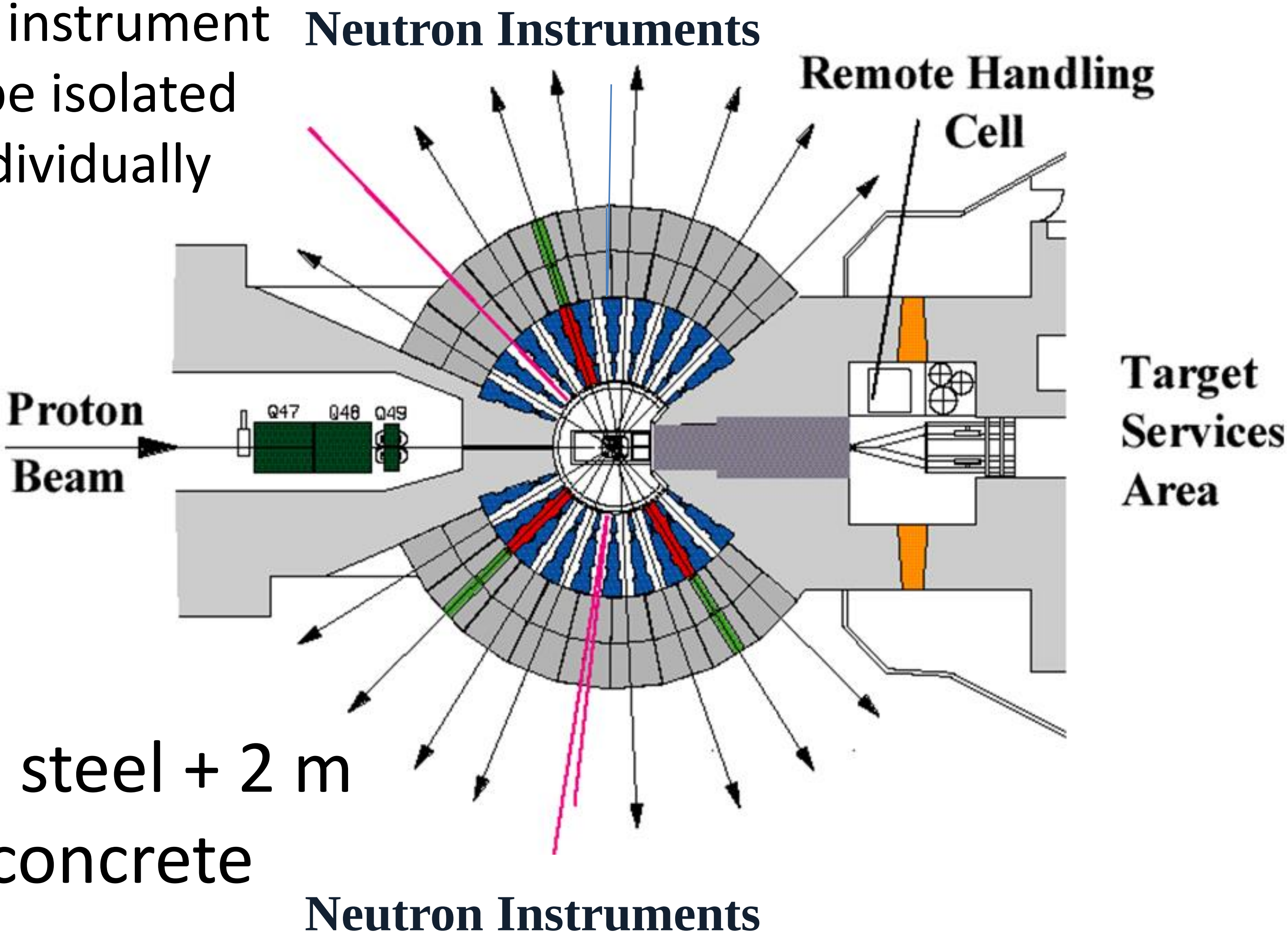


T-Zero (4)

68 kg Payload
10,800 rpm
±0.43° Phase Control

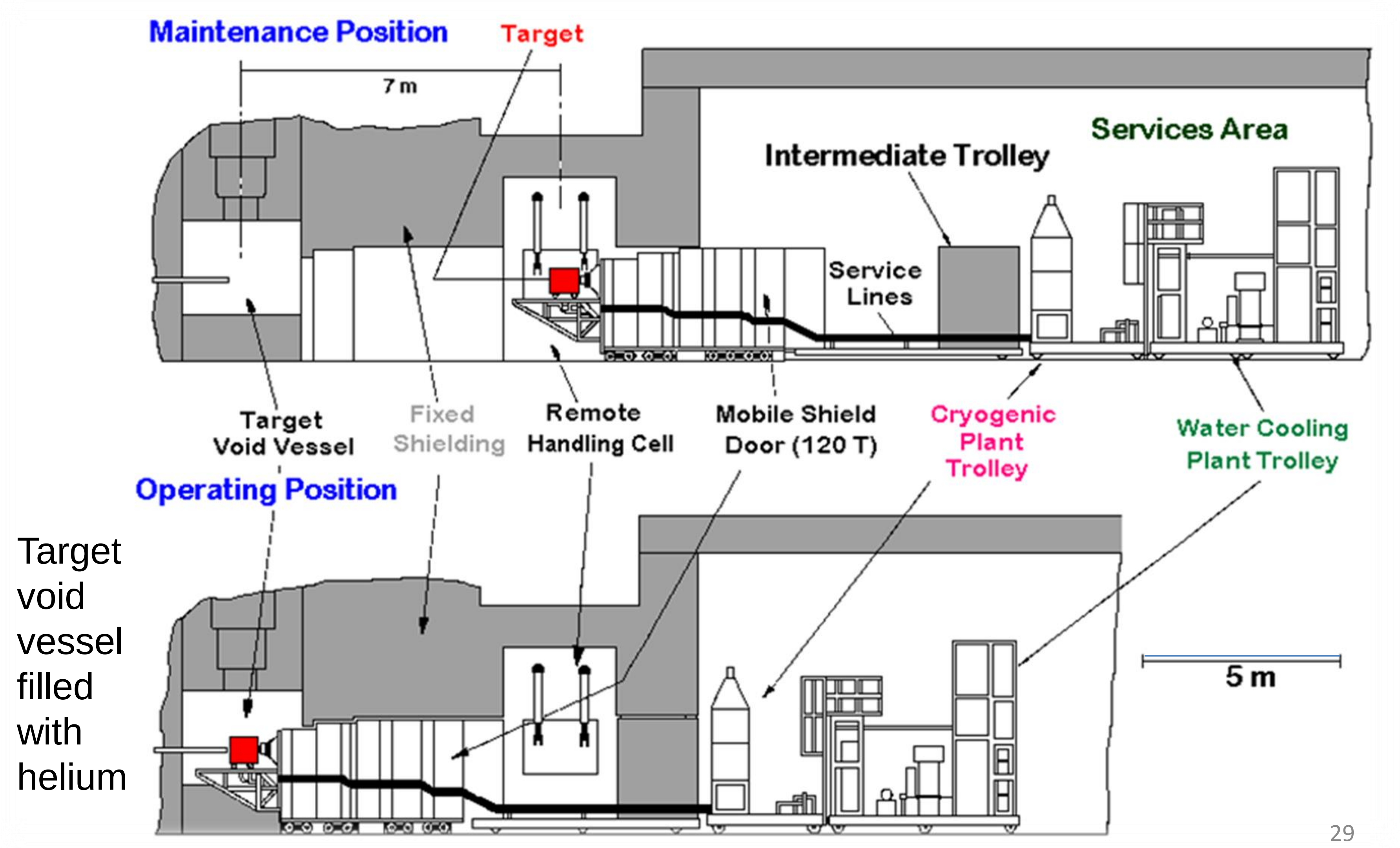
Shielding

Shutters allow each instrument to be isolated individually



2 m steel + 2 m concrete

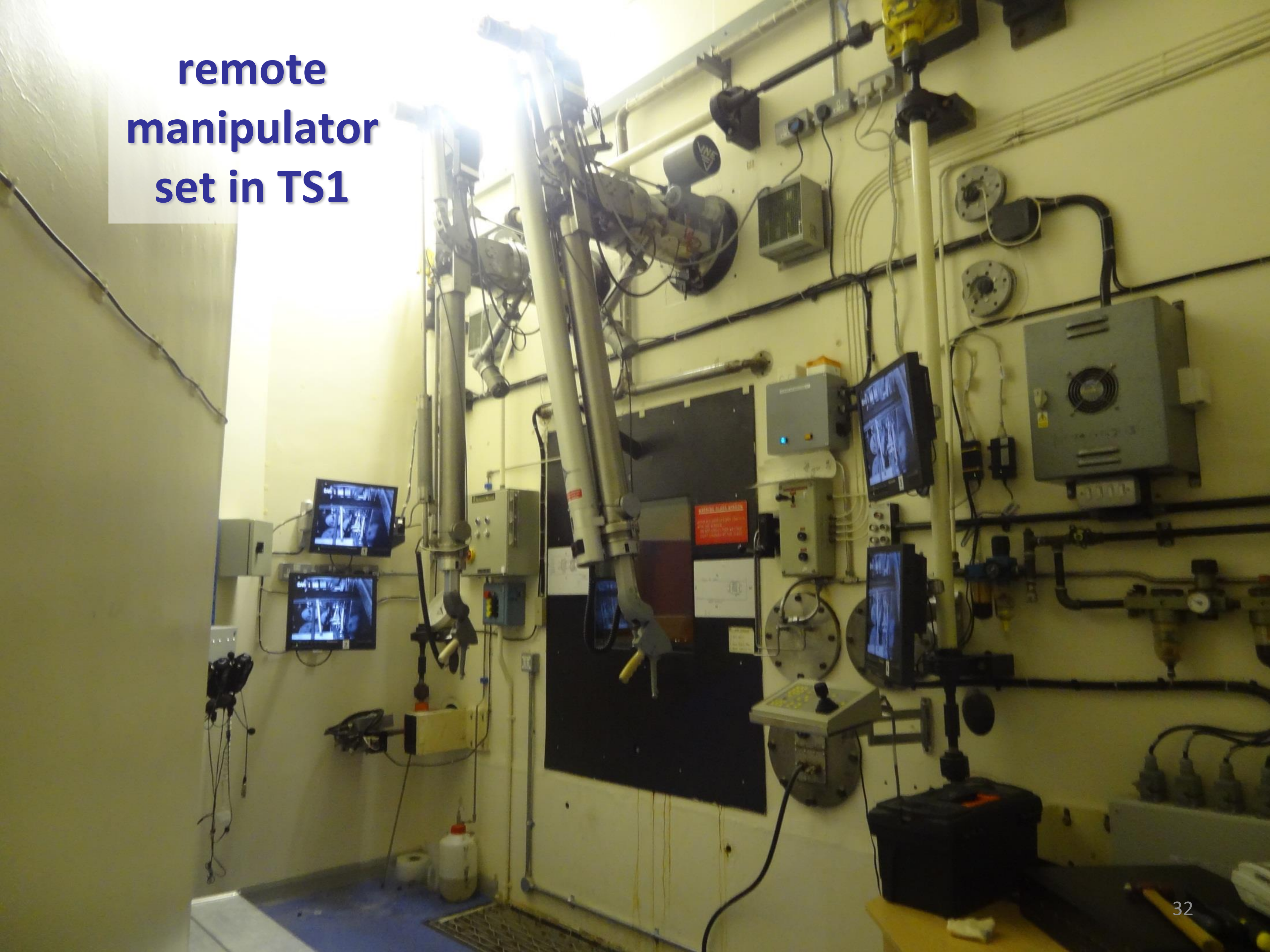
The services trolley moves to position the TRAM for operation or maintenance



Target void vessel filled with helium

TS1 Services Trolley Cooling Plant

TS2 Services Trolley Cooling Plant

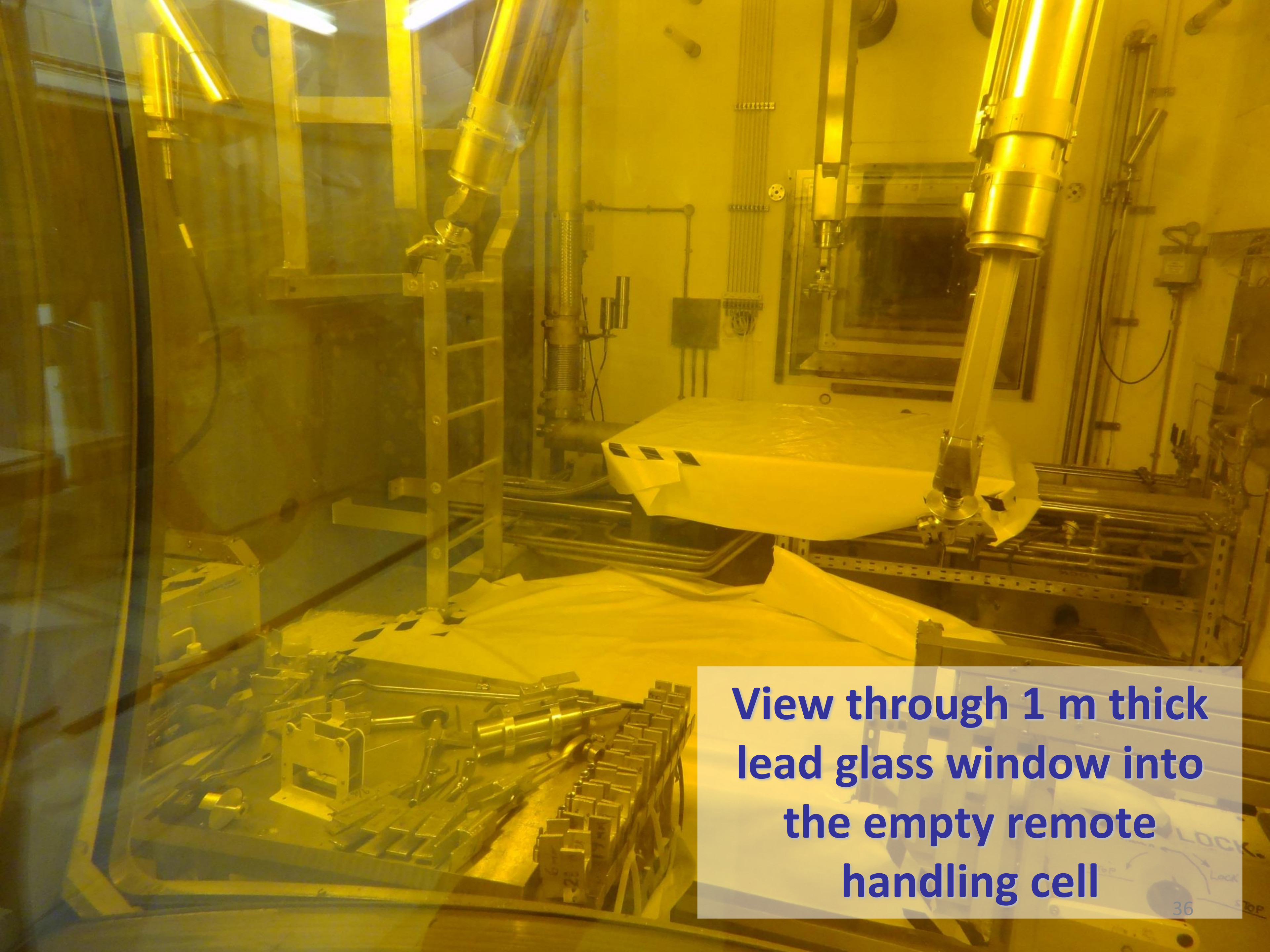


remote manipulator set in TS1

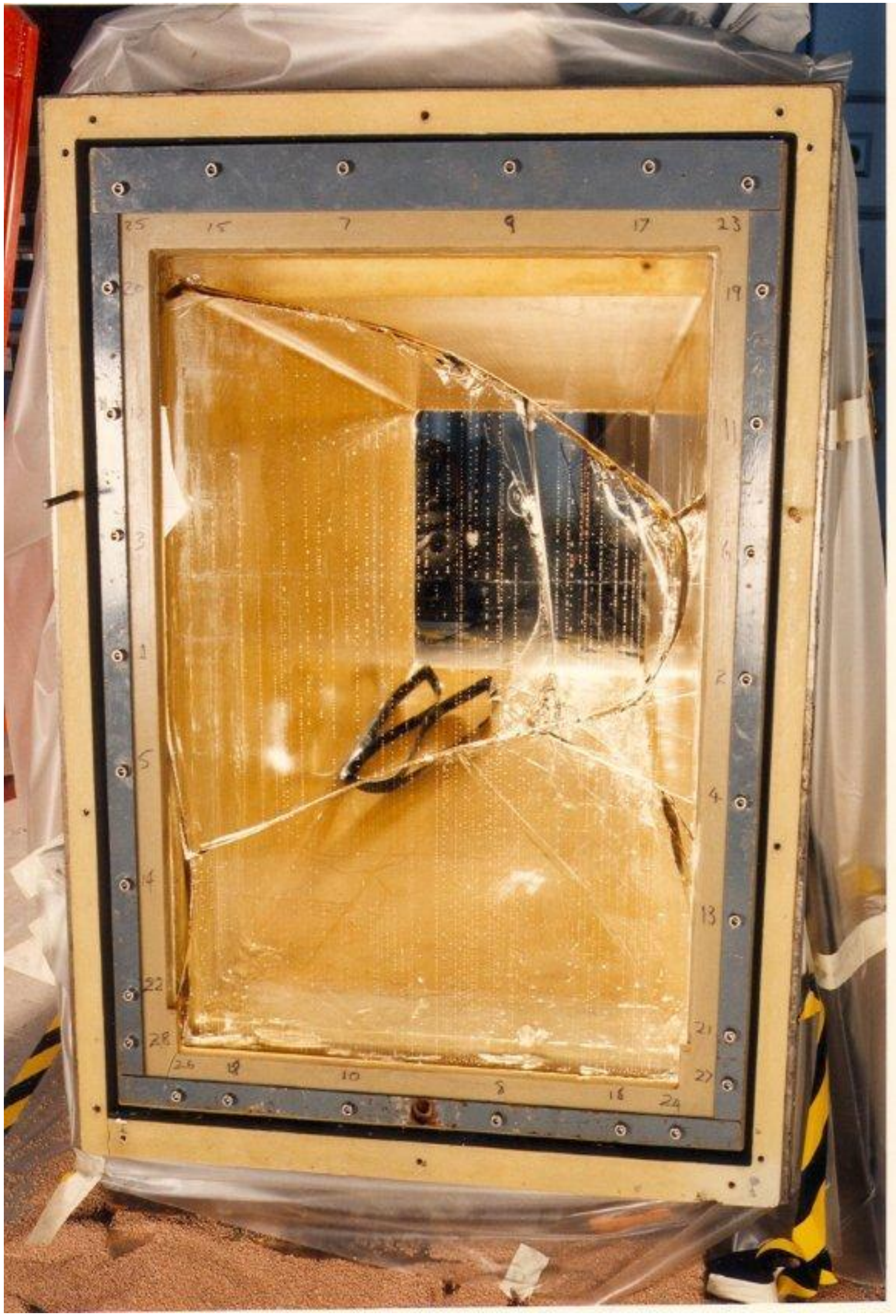
remote manipulator set in TS2

remote manipulator sets on both sides of the remote handling cell

Crews in contact with other areas by headset



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

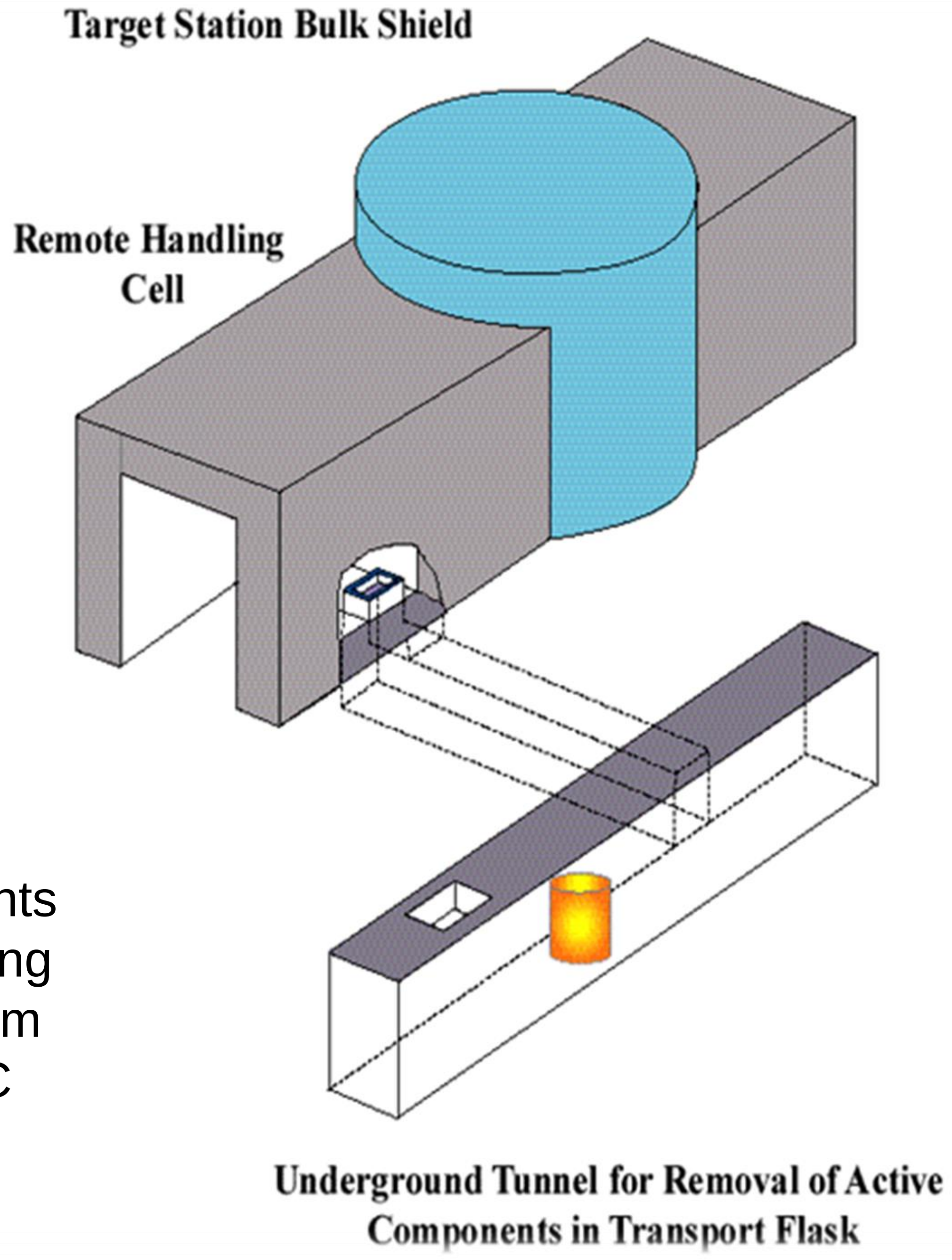


window failure!

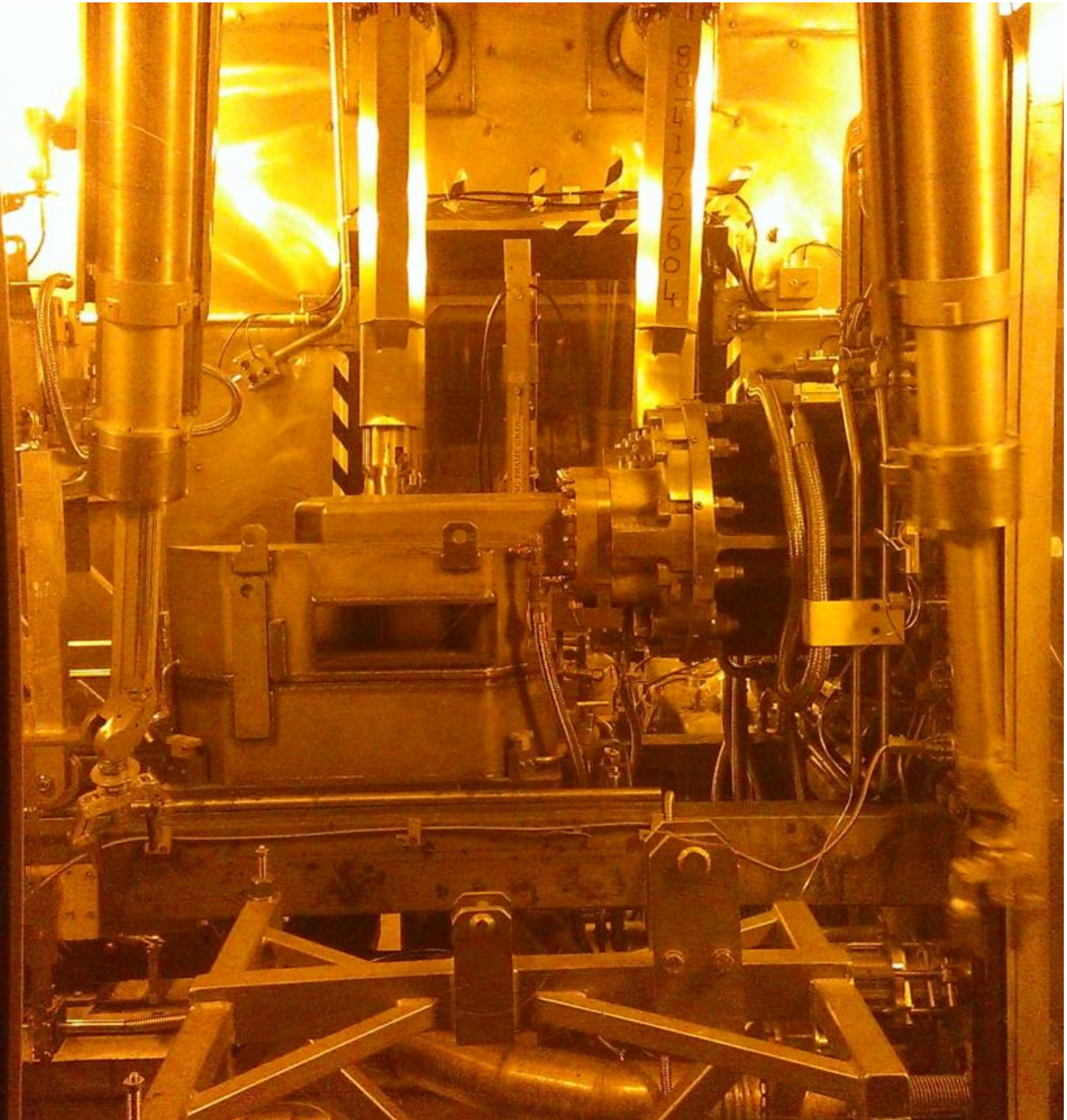
The main remote handling task carried out is CH4 moderator replacement Every 3-4 cycles

Targets also need to be replaced every 4-5 years

TS1 Tungsten
Target #4 on flow
test rig



Active components are removed using the tunnel system under the RHC

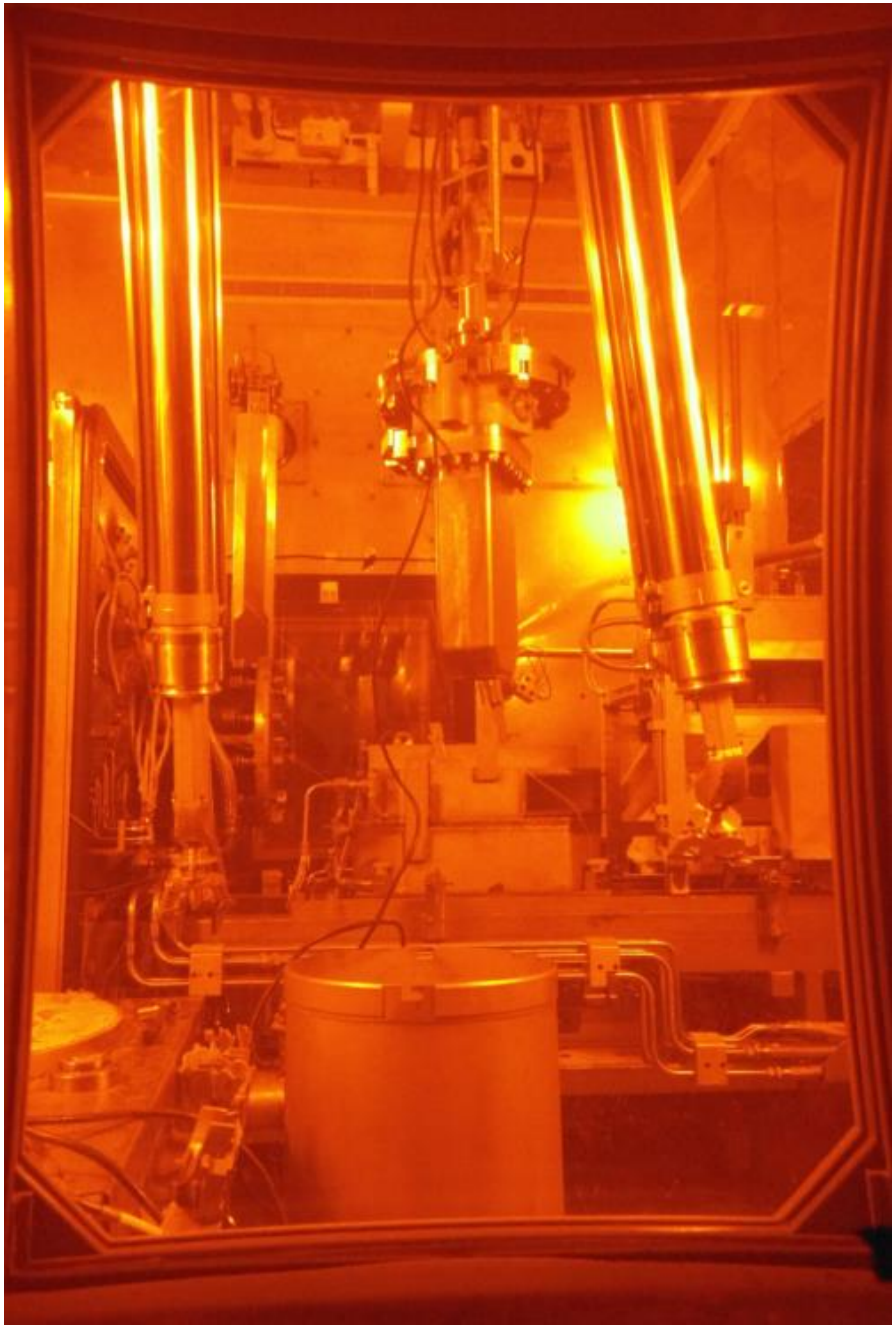


View of the TS1 TRAM withdrawn into the RHC

This view is from the north side of the RHC

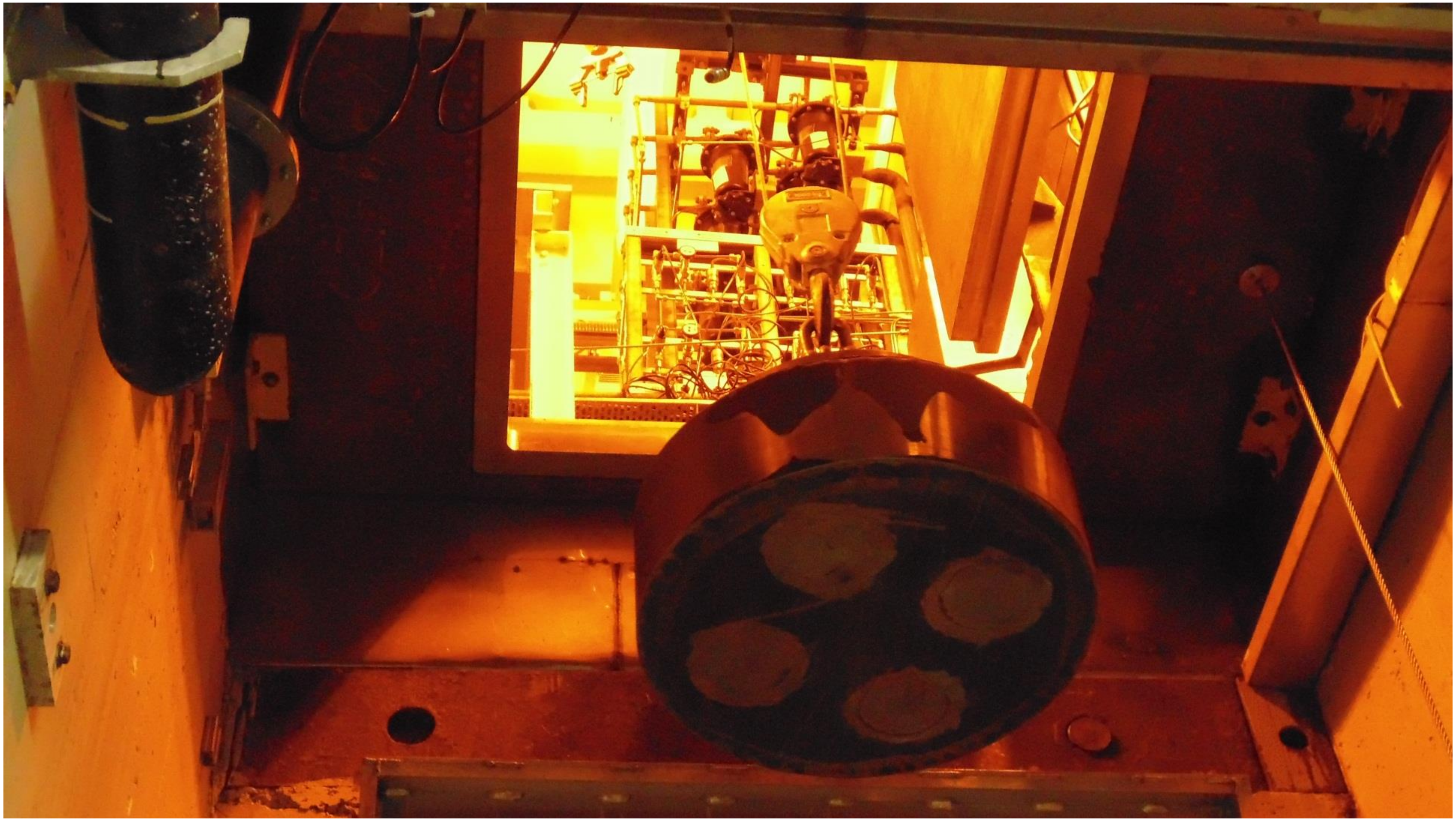
The reflector top section is rolled forward to expose the Tungsten Target

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

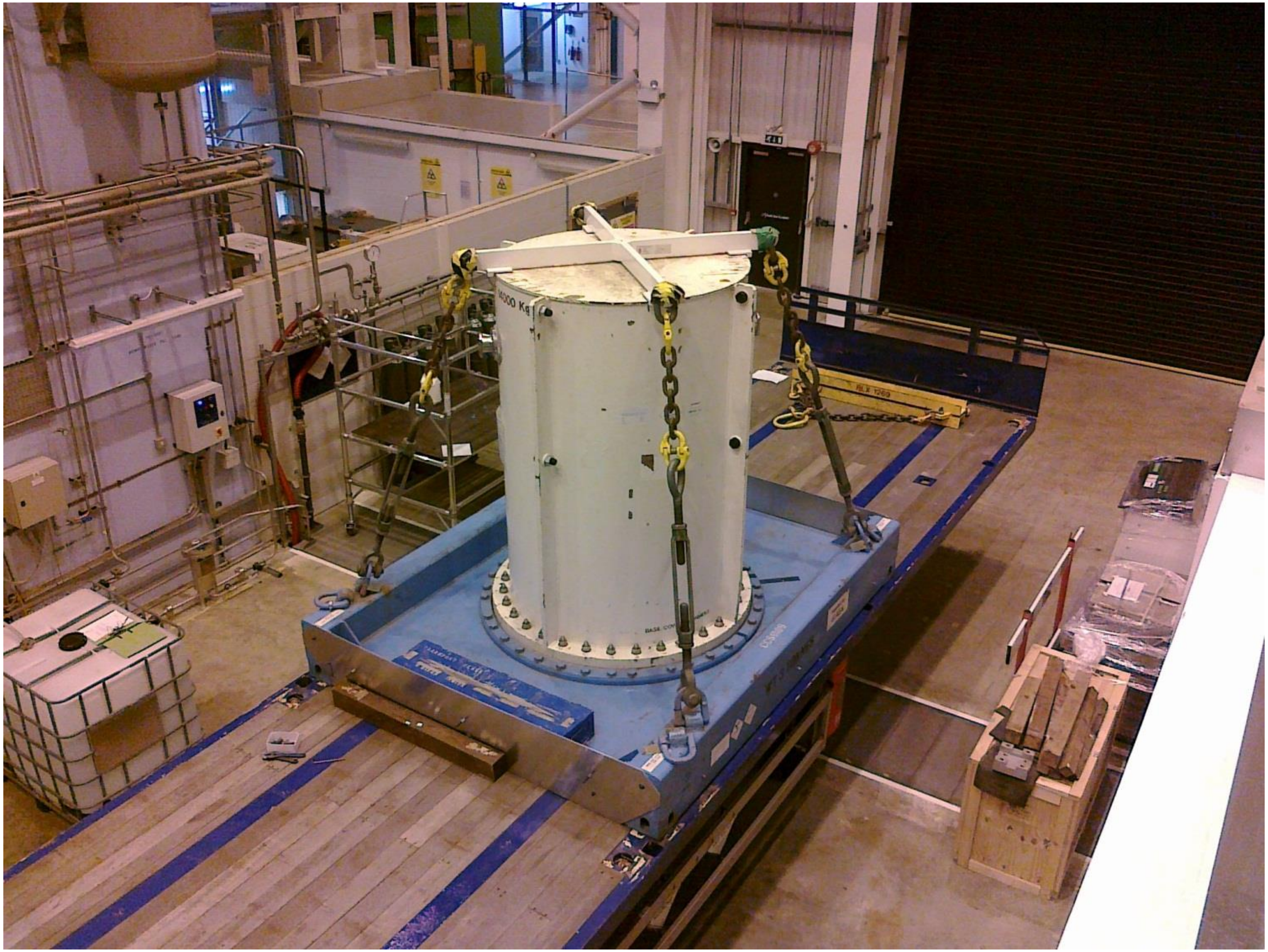
The loaded flask is lifted out of the tunnel

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

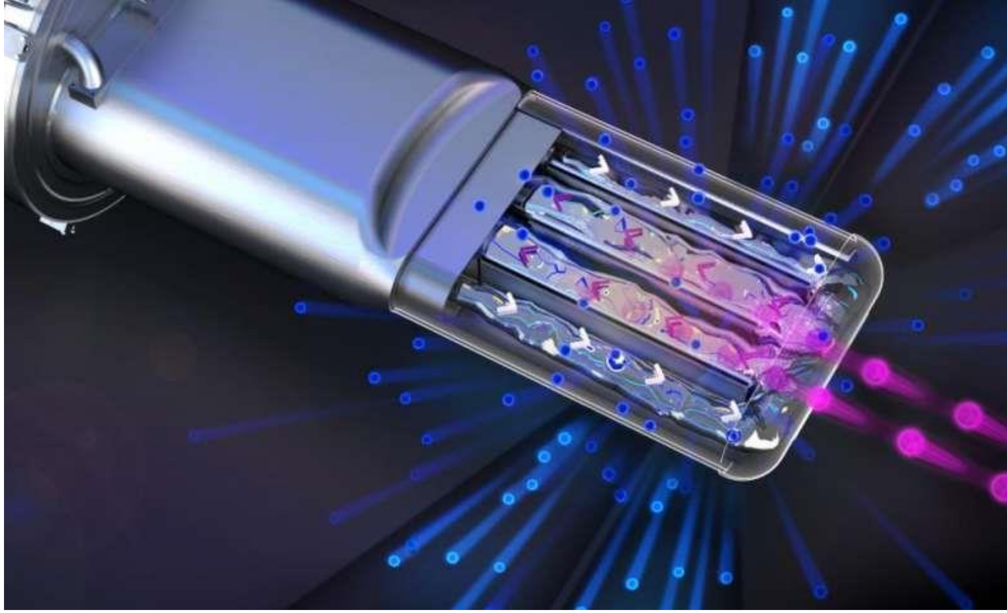
Full suit, gloves, overshoes and respirator are required for this work

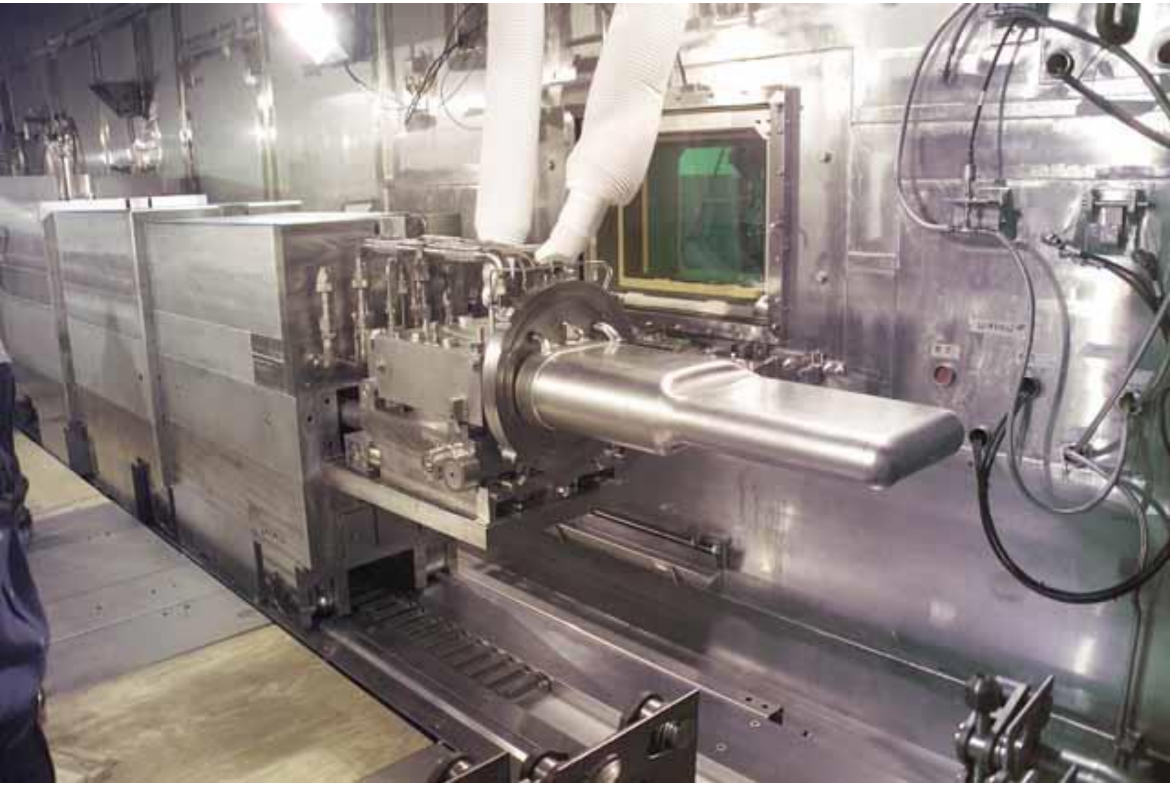


For final disposal the target is transferred to a registered and licenced Type B package and transported to Sellafield the UK's nuclear waste storage facility

More power!

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



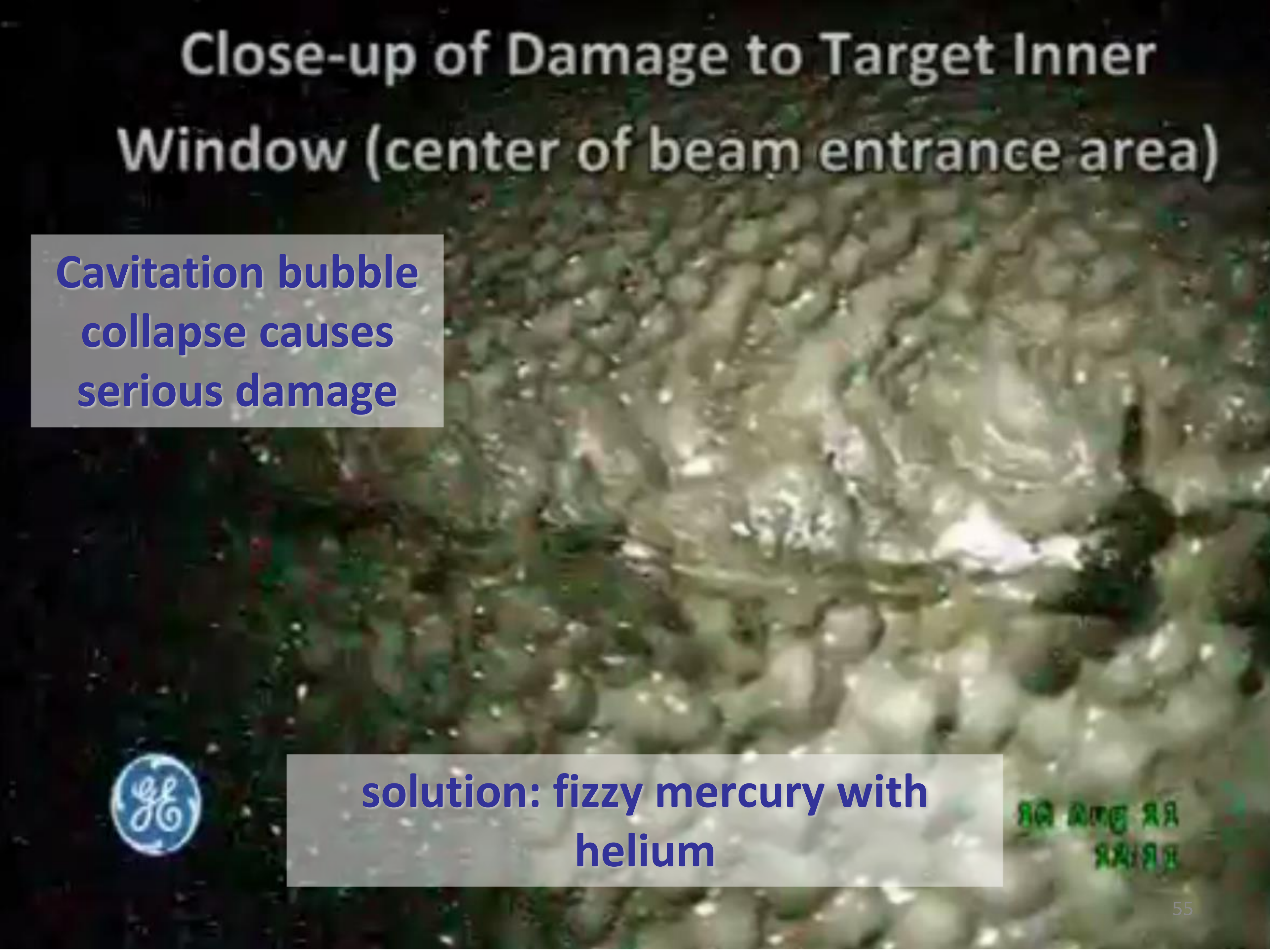


1.4 MW liquid mercury target

SNS

SPALLATION NEUTRON SOURCE

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!

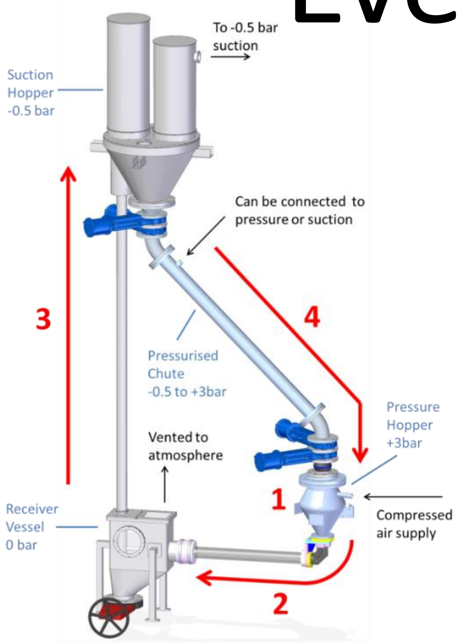
EUROPEAN SPALLATION SOURCE

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

A solution for SNS TS2

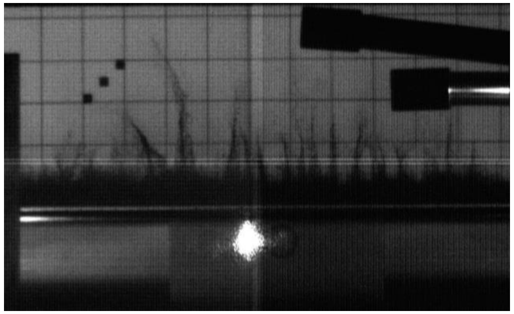
protons

Even more power!

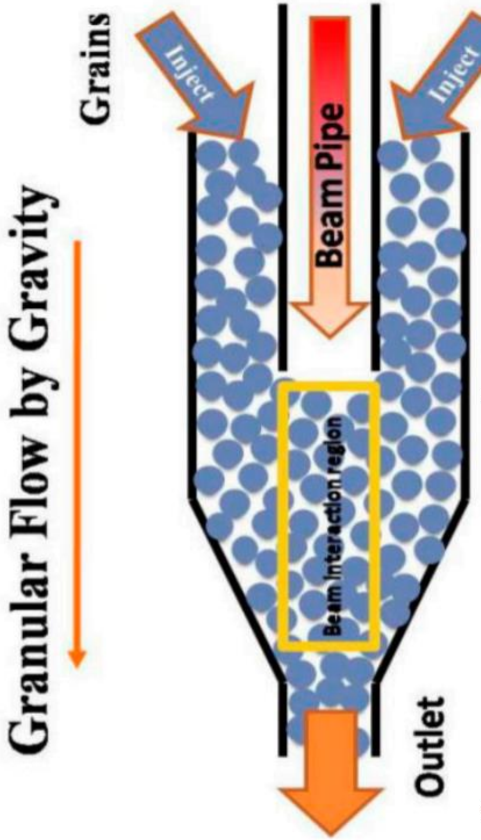


Tungsten powder handling system developed at RAL

Science & Technology Facilities Council



Tests at CERN

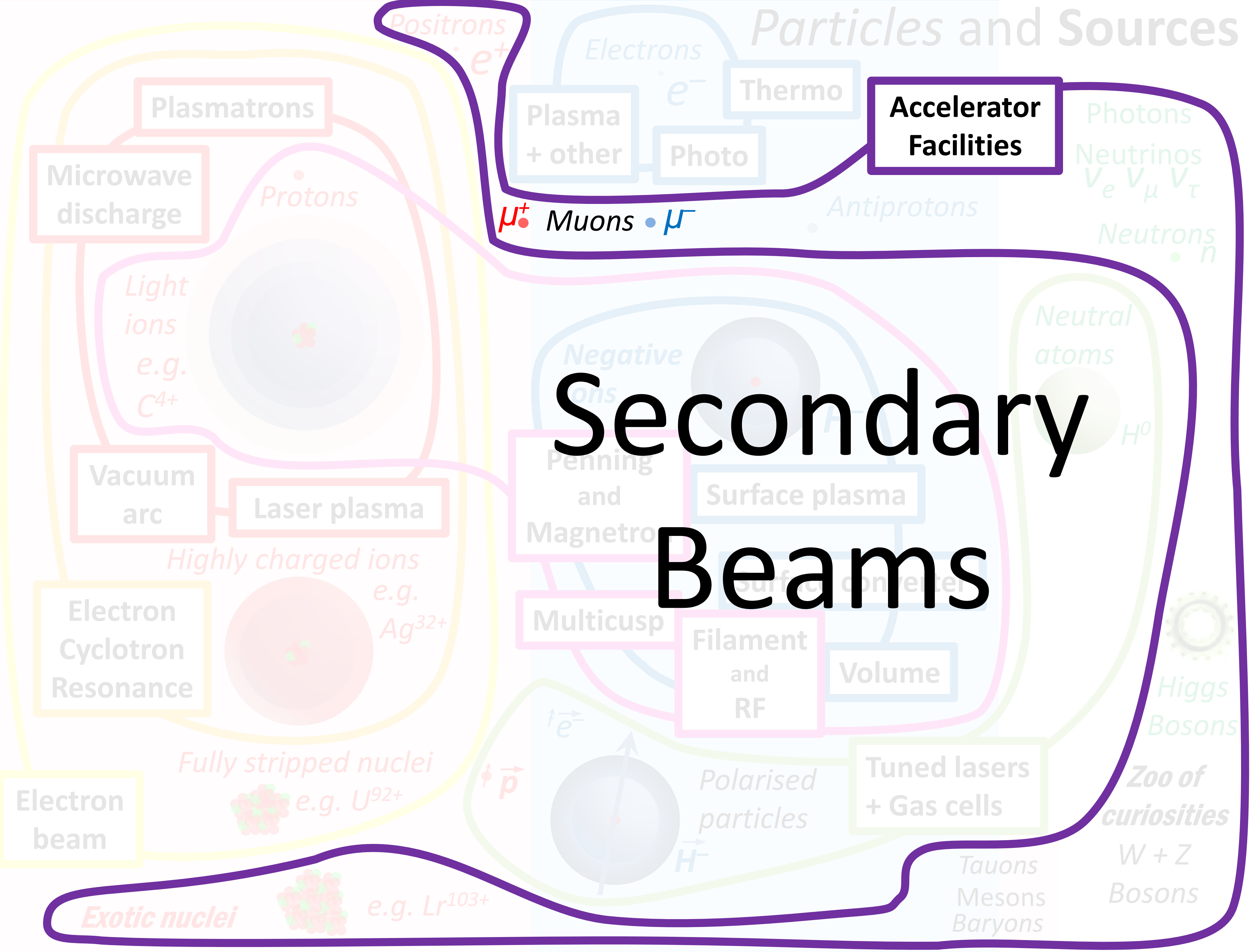


ADS

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

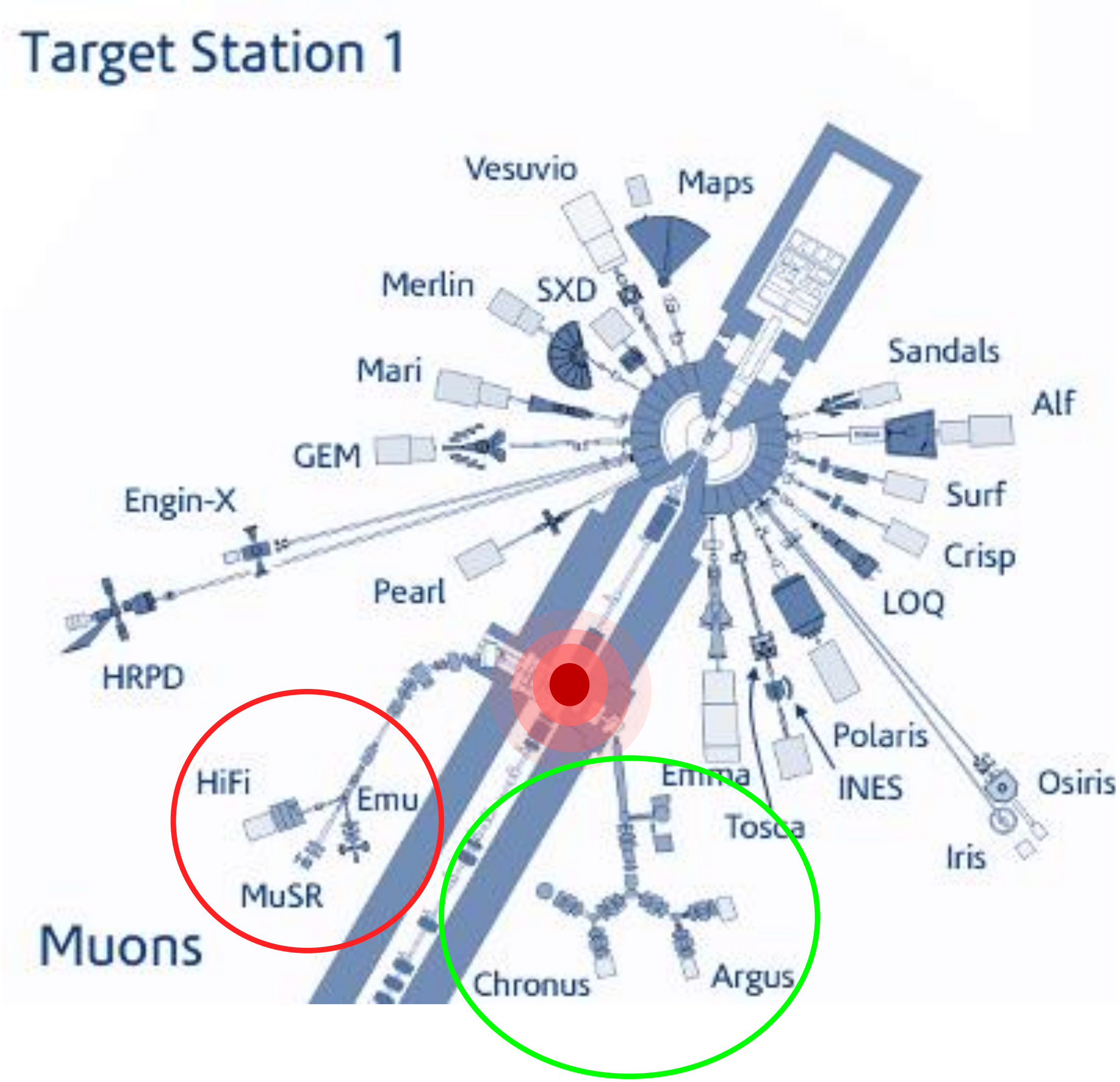


Accelerator Facilities

μ^+ *Muons* μ^-

Secondary Beams

Muons at ISIS



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

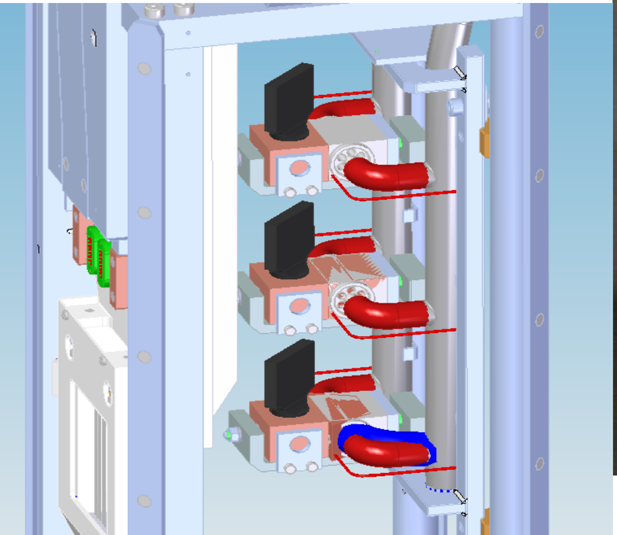
ISIS Muon Target

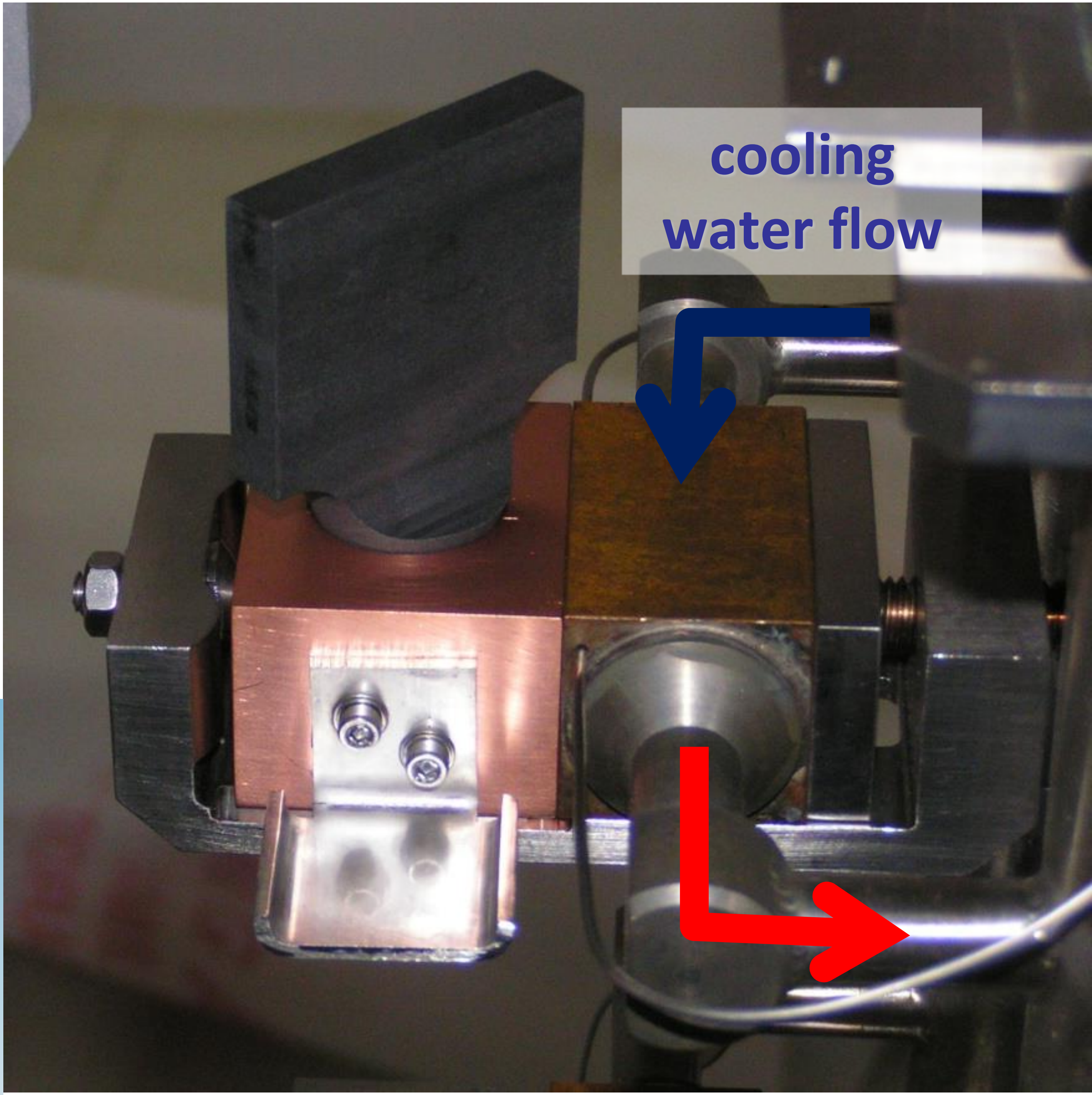
10 mm thick graphite target at 45° to the 800 MeV proton beam

About 5% beam lost.

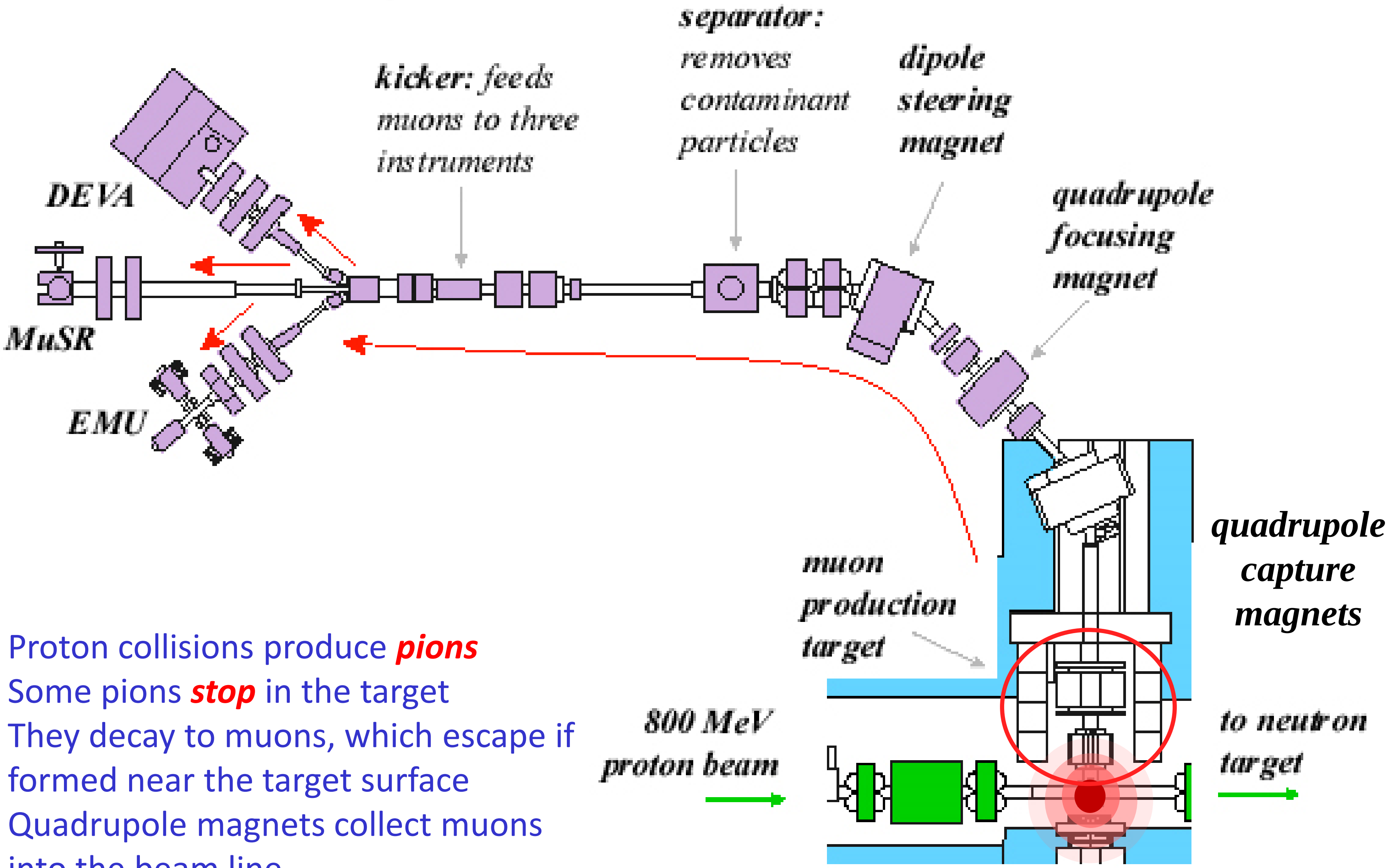
Diffusion bonded to copper to maximise thermal contact

10 kW maximum heat load

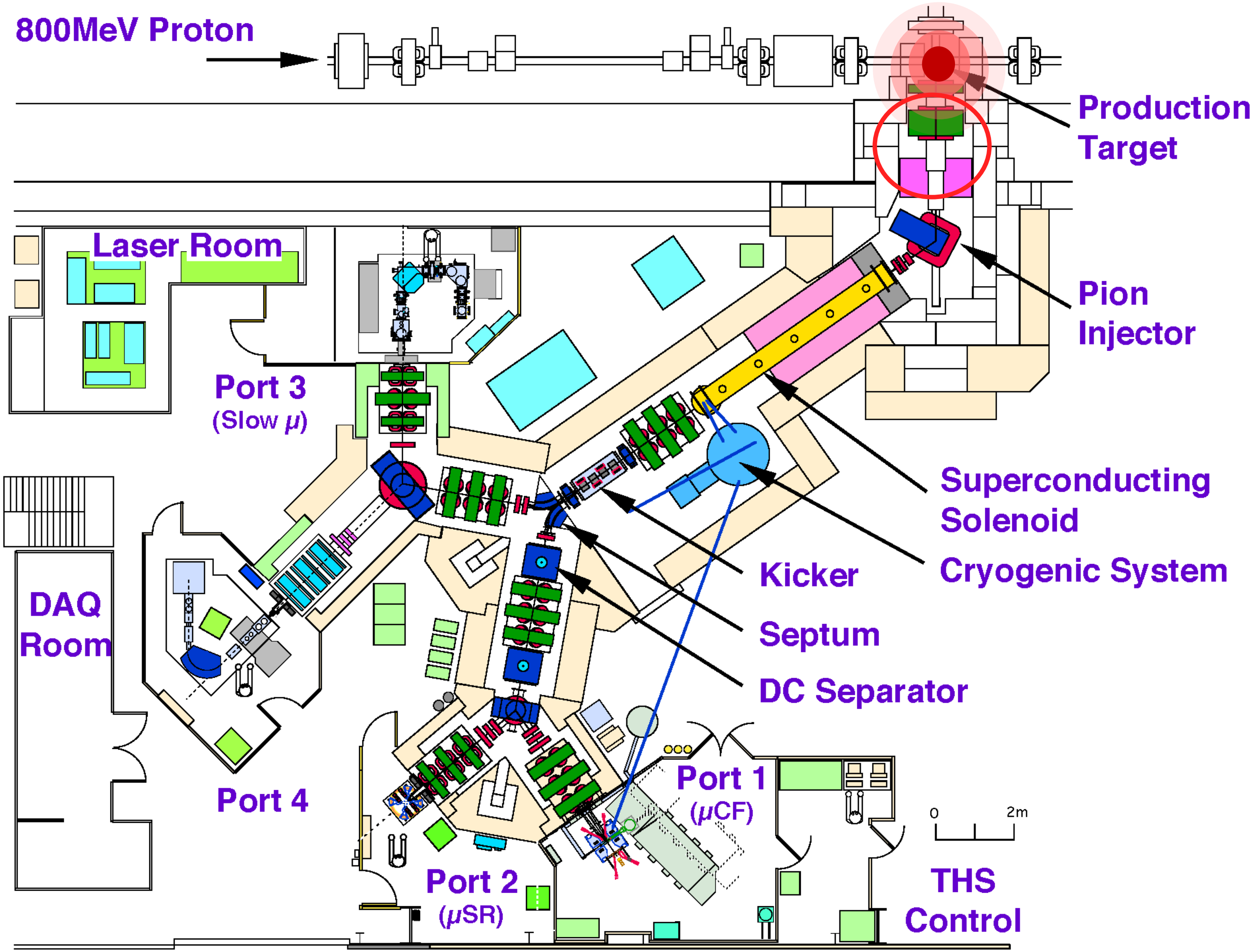




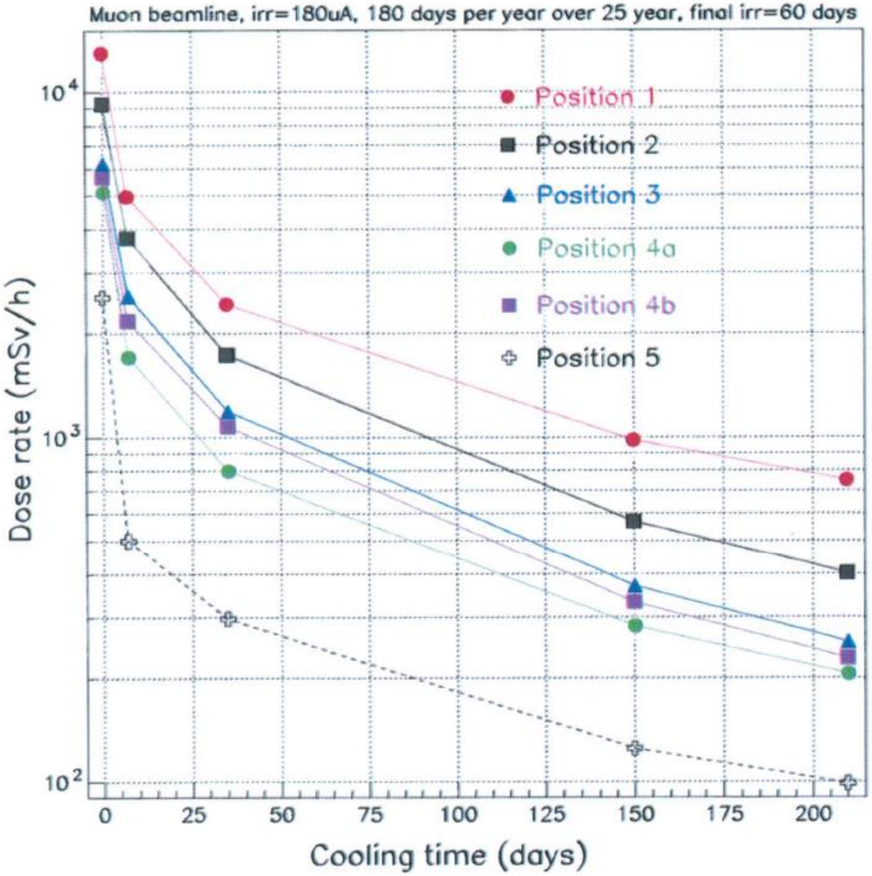
The EC Muon Facility

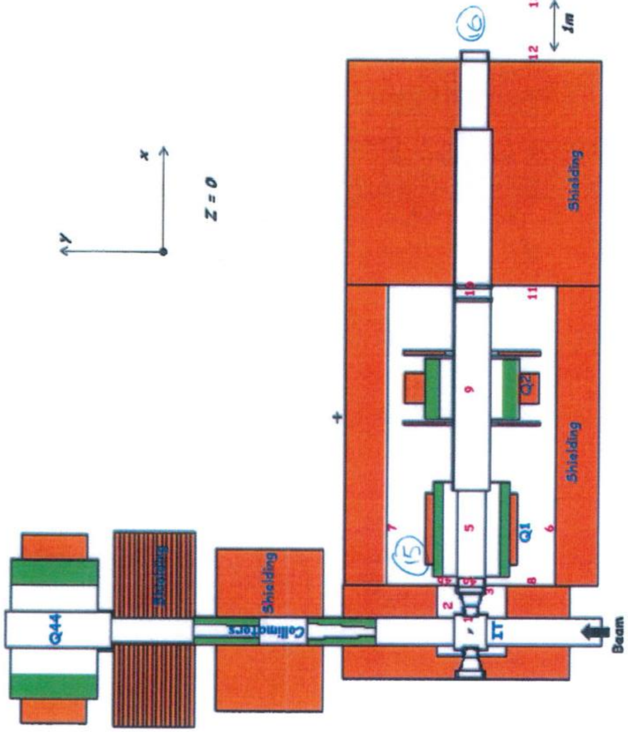


- Proton collisions produce ***pions***
- Some pions ***stop*** in the target
- They decay to muons, which escape if formed near the target surface
- Quadrupole magnets collect muons into the beam line

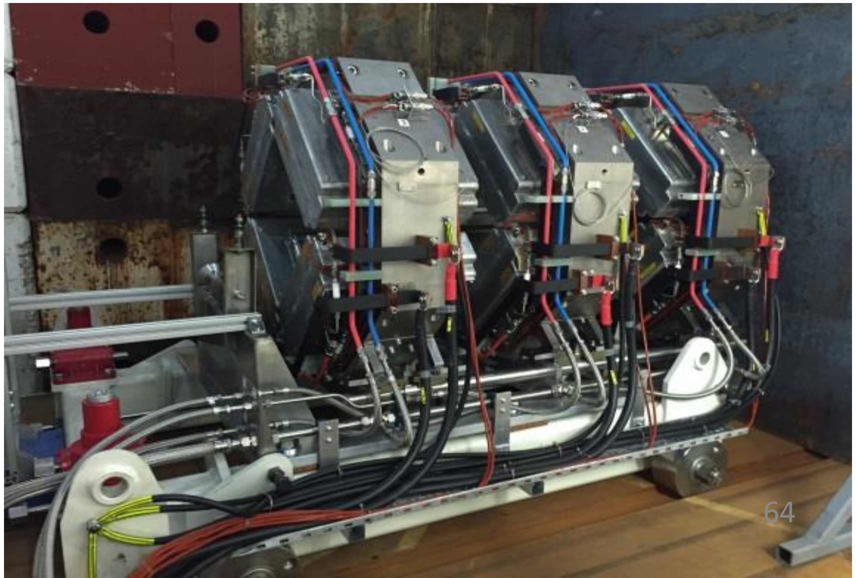

800MeV Proton
Production Target
Laser Room
Pion Injector
Port 3
(Slow μ)
Superconducting Solenoid
Kicker
Cryogenic System
DAQ Room
Septum
DC Separator
Port 4
Port 1
(μCF)
0
2m
Port 2
(μSR)
THS Control

Radiation Levels

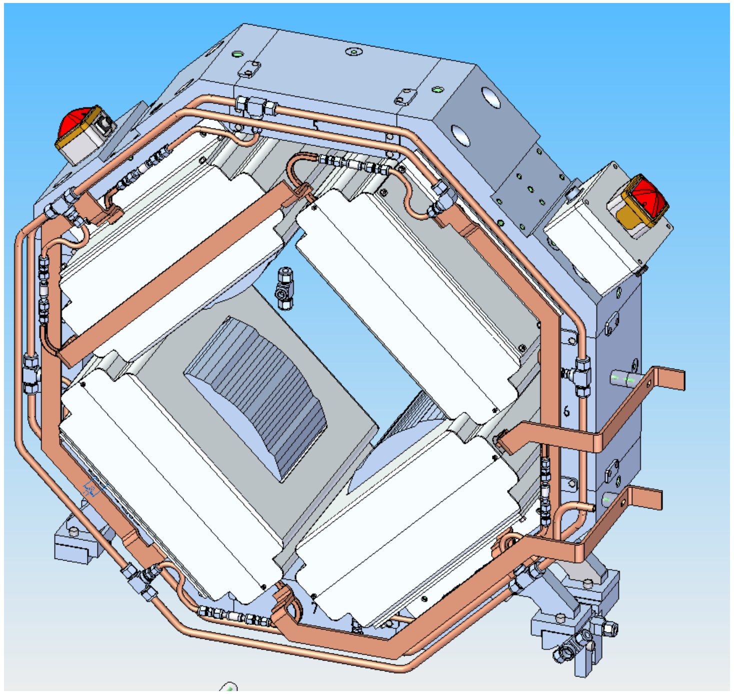




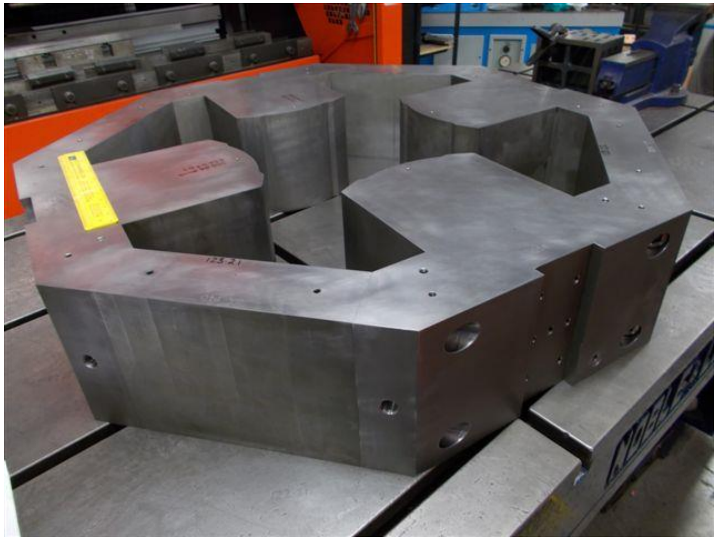
Radiation Hard Magnets

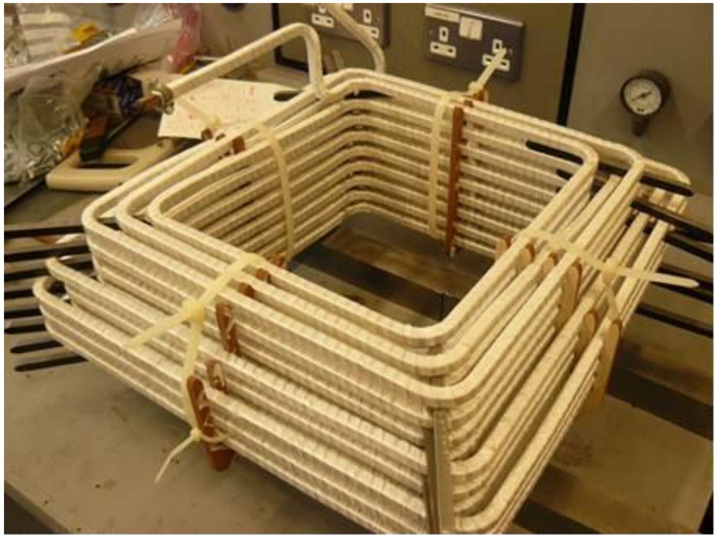


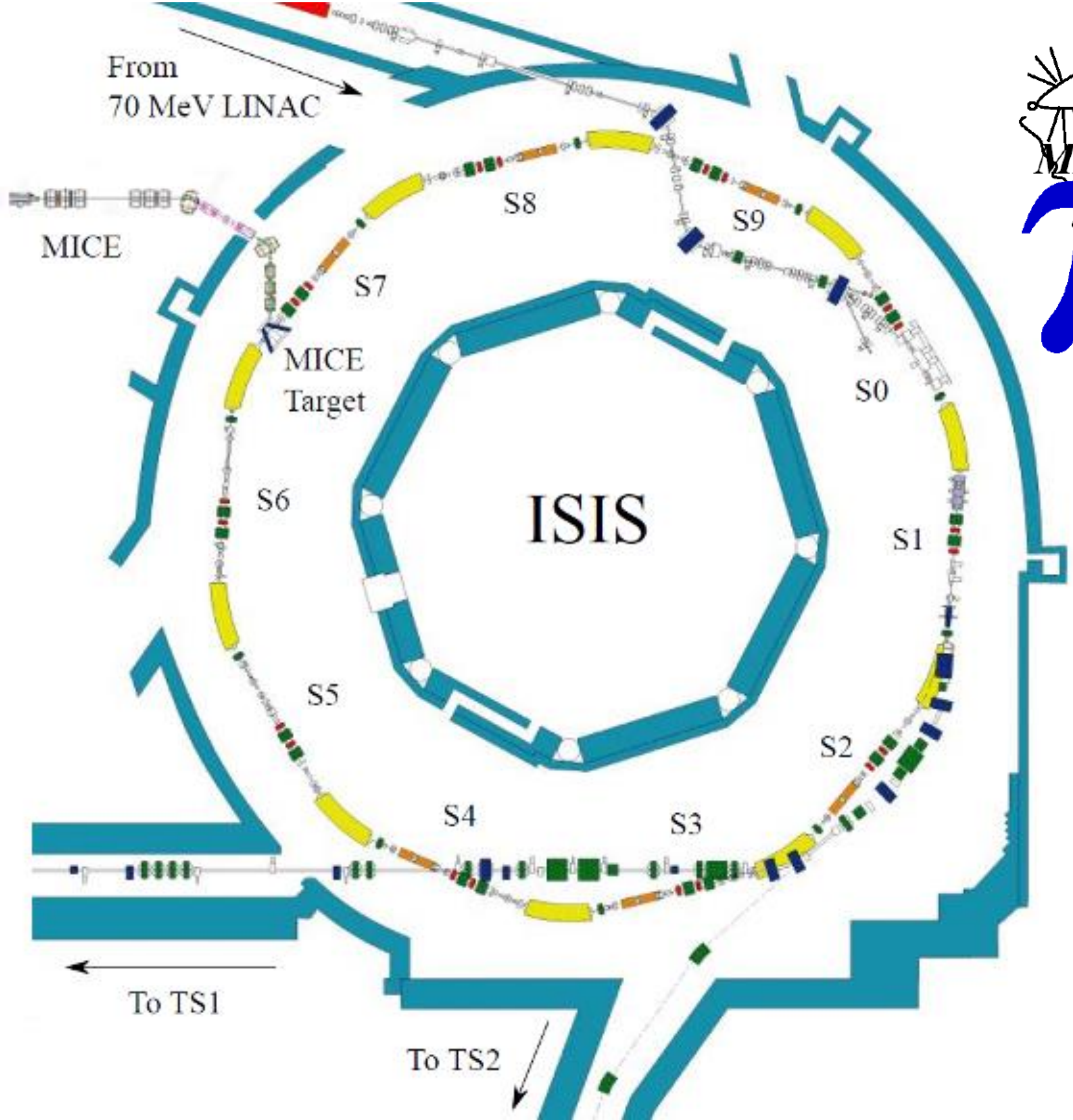
Radiation Hard Magnet Design



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

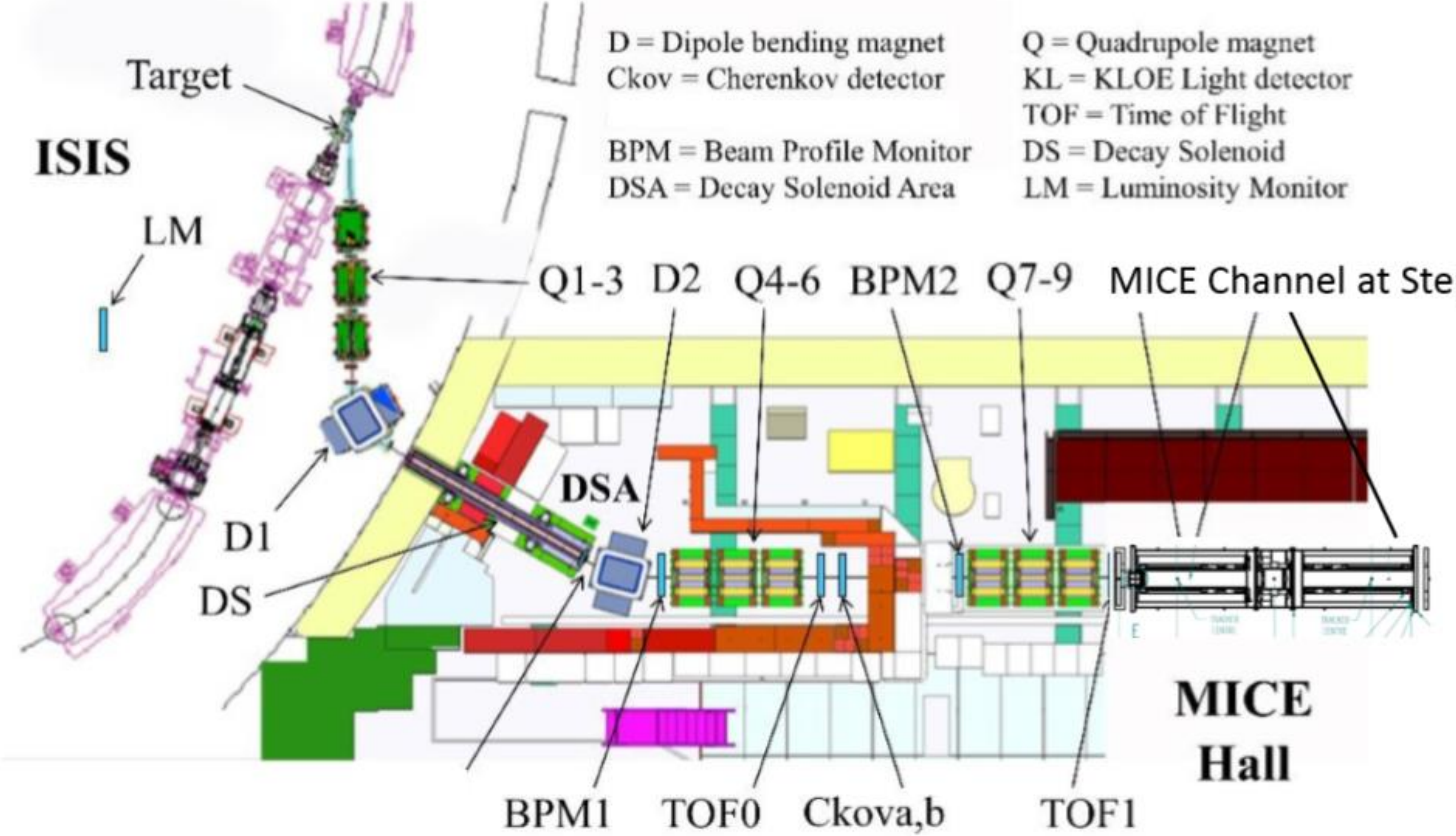






Muon
Ionisation
Cooling
Experiment

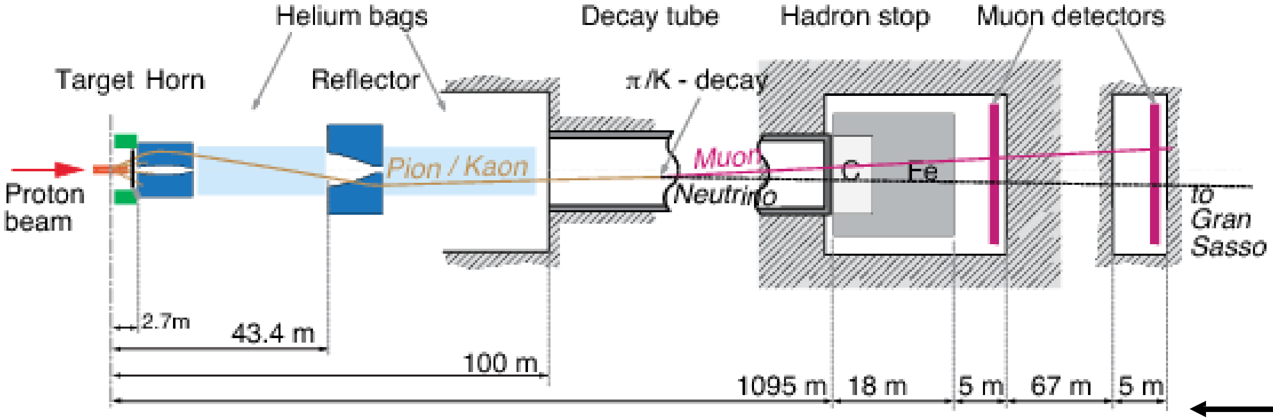
MICE Beamline



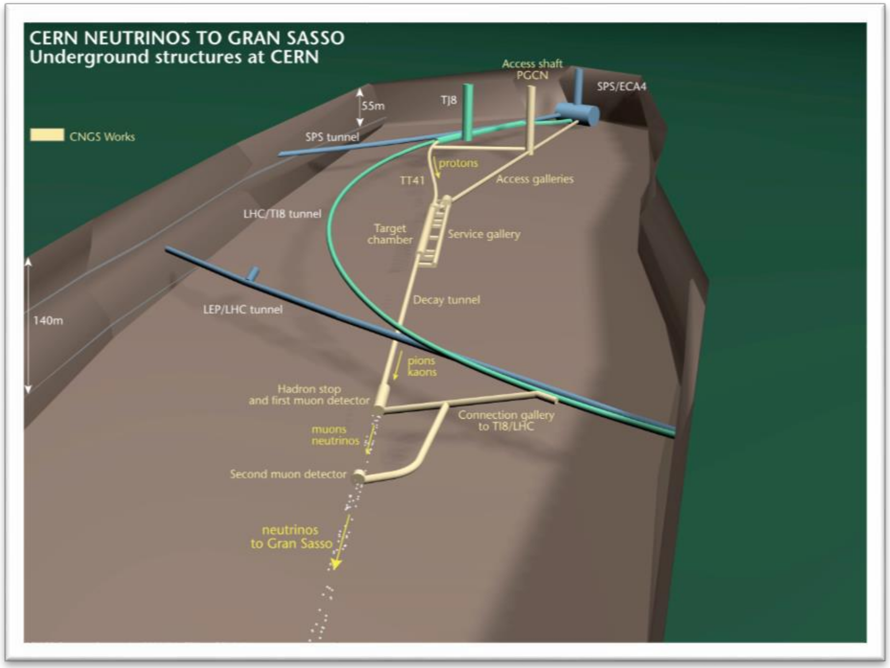
MICE Beamline
Conceptual Layout

Mice demonstrated muon cooling in 1D

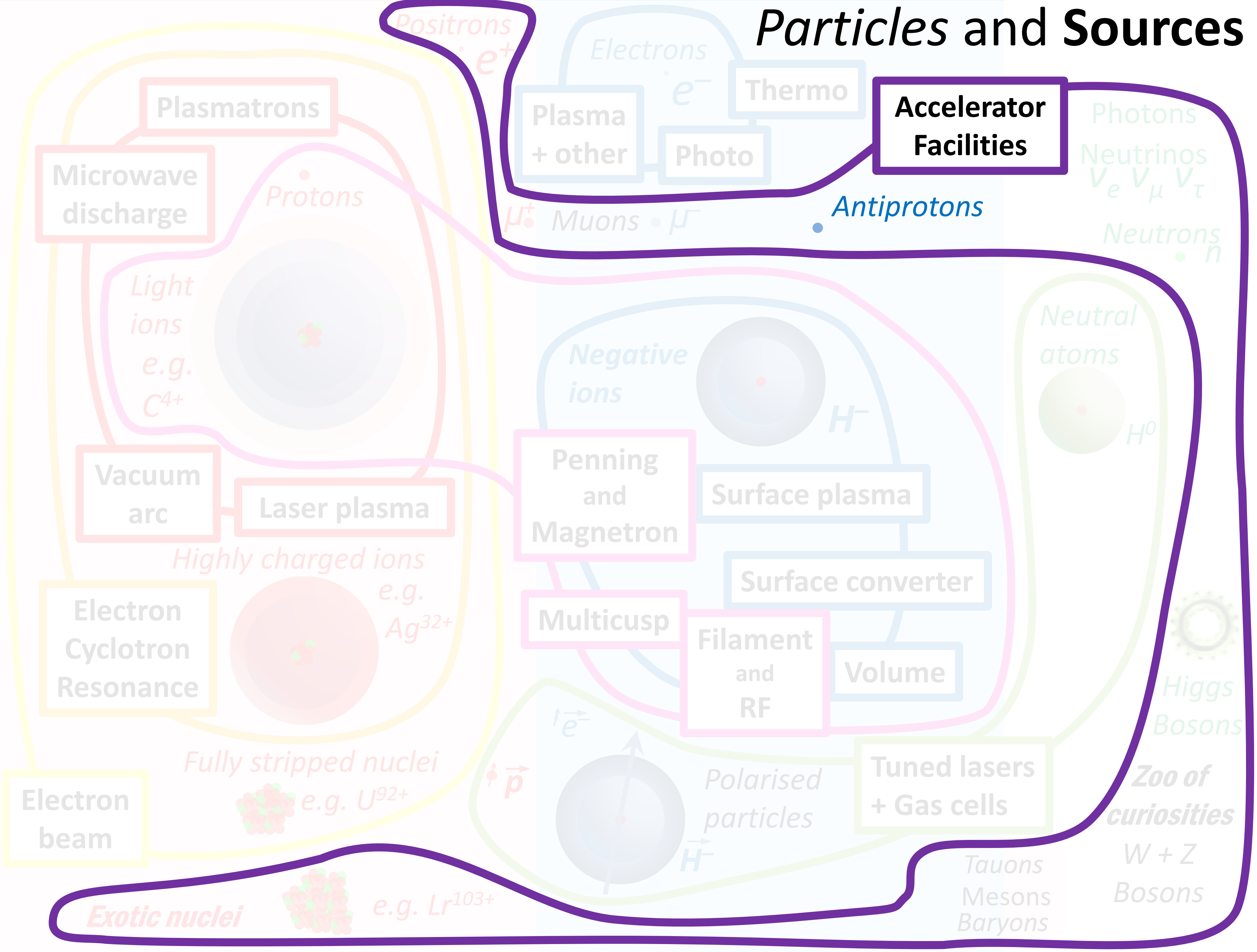
CERN Neutrinos to Gran Sasso (**CNGS**)



732 km

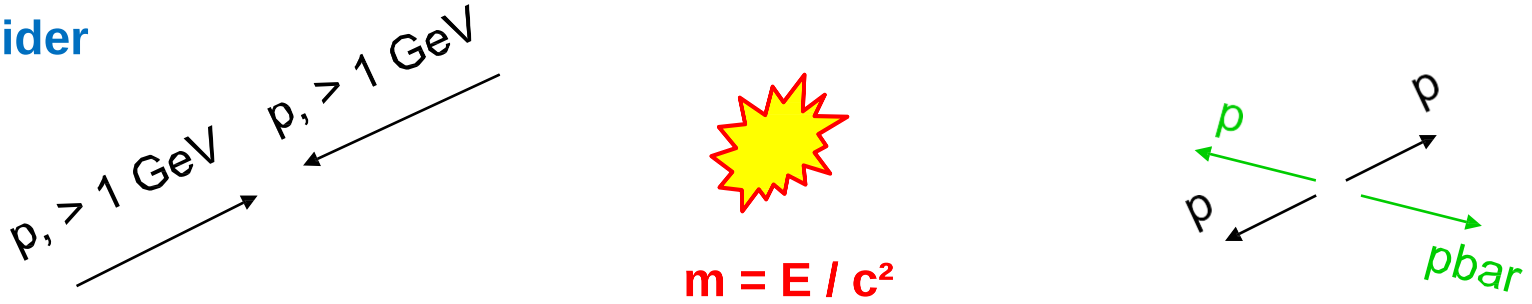


Particles and **Sources**



Creation of Antiprotons

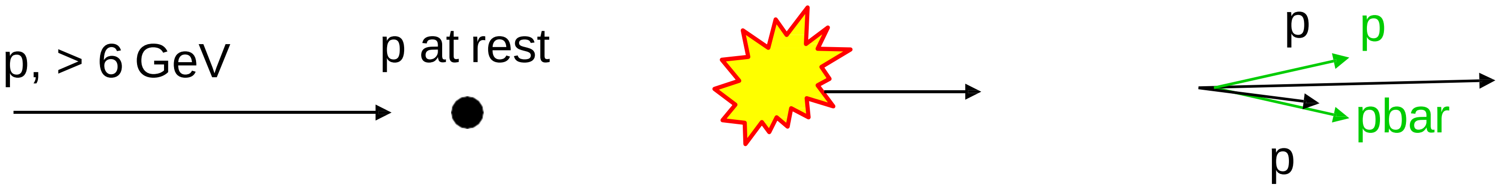
Collider



$m = E / c^2$

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

Target



$m = E / c^2$

$T_{pbar} > 6 \text{ GeV}$

Magnetic Horn

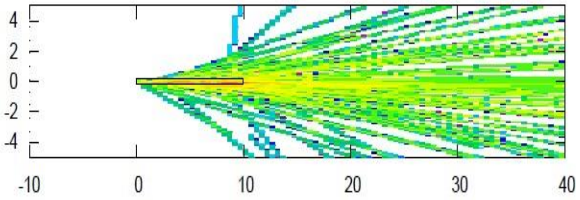
Simon van der Meer

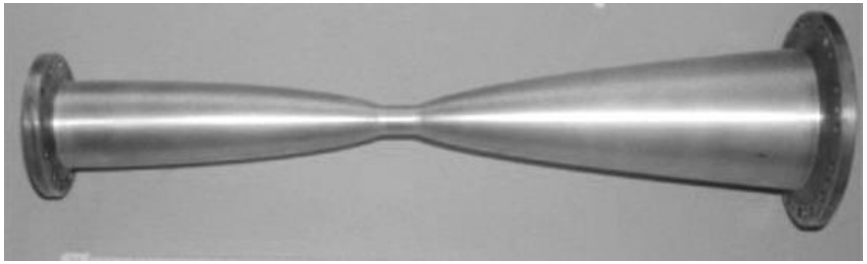
1960s "current sheet lens"
originally for neutrino beams
then for antiprotons

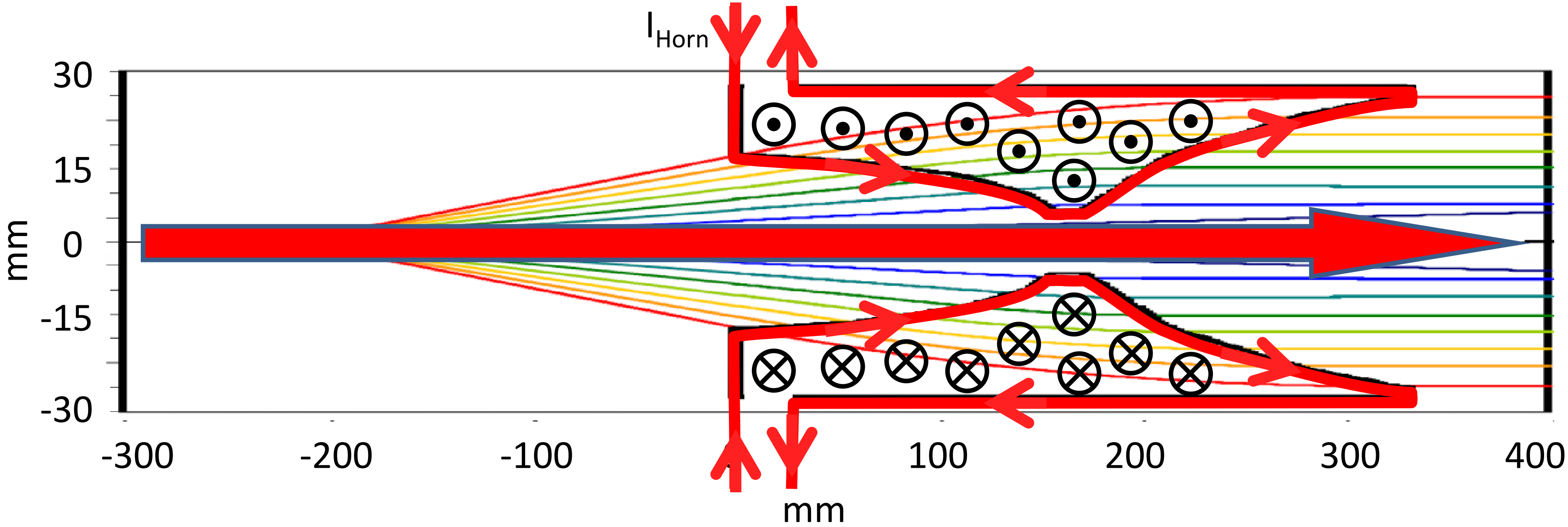
1.4 mm Al 400 kA 15 µs

(half-sine)

Magnetic Horn







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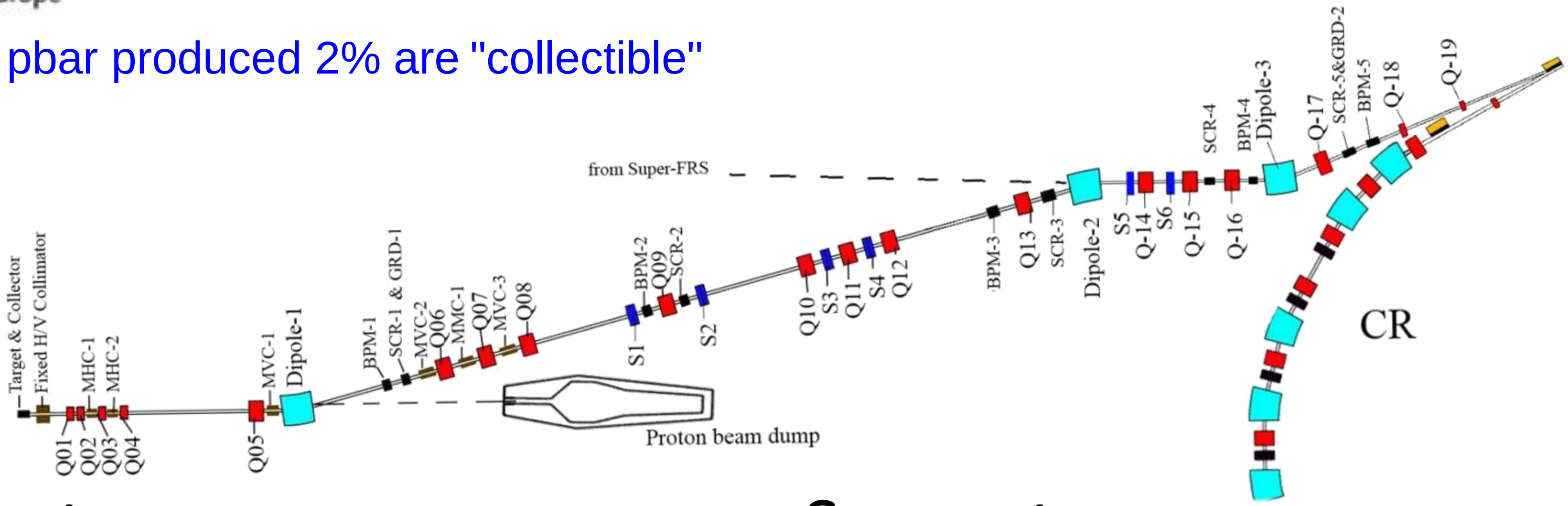
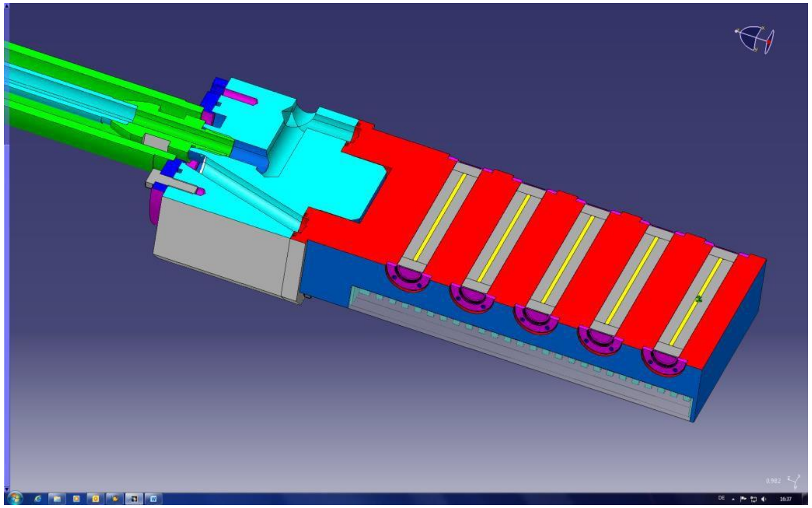
Beam Separation

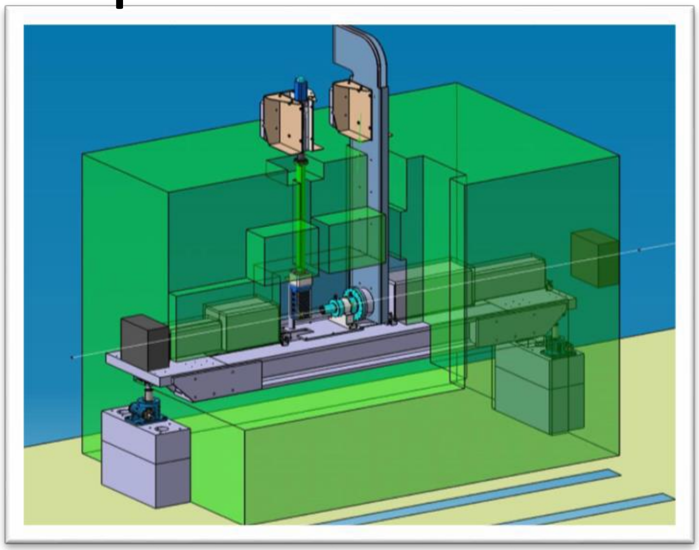
Of the pbar produced 2% are "collectible"



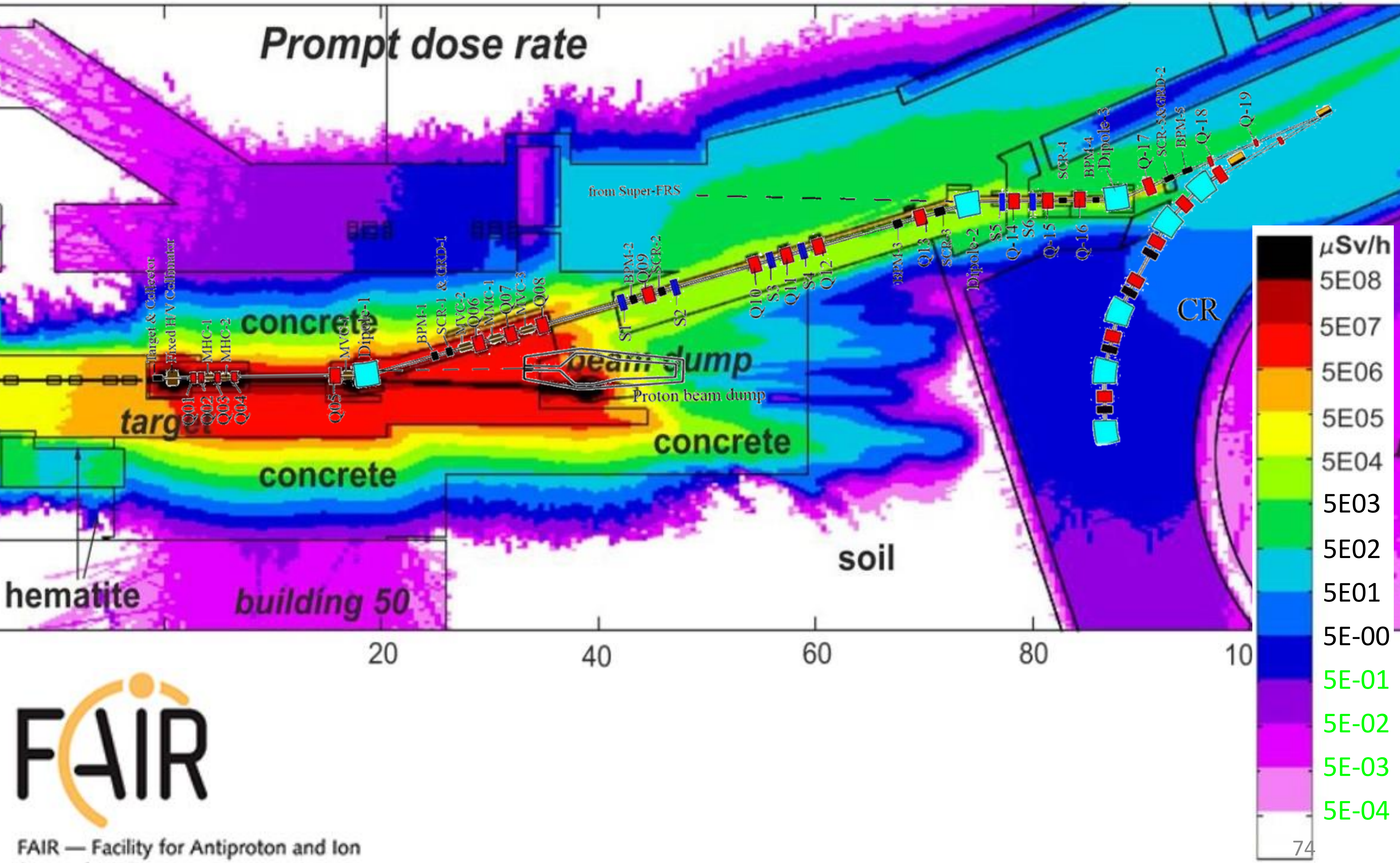
Target



Separator



Beam Separation



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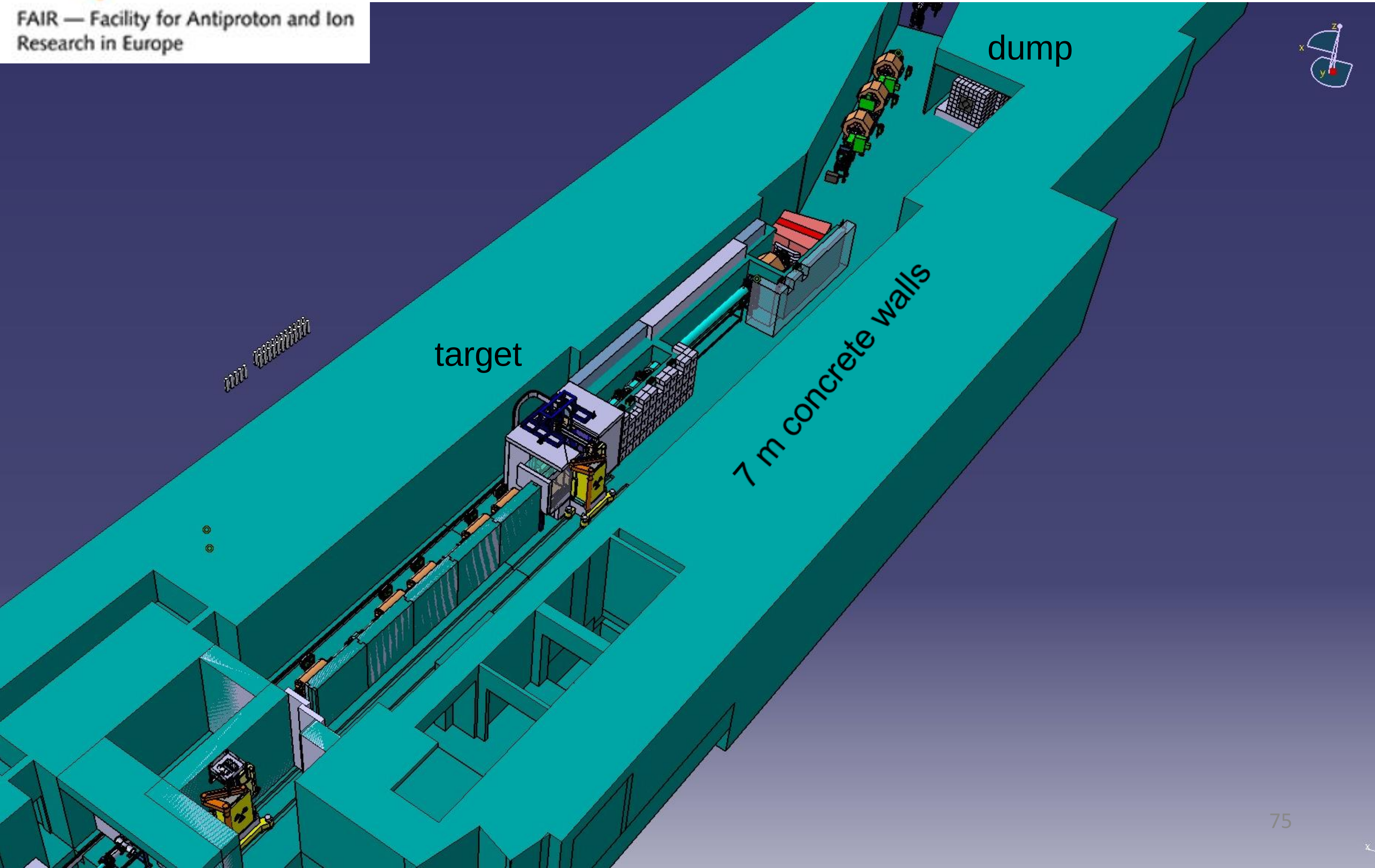
Shielding Required



Target station and transport container

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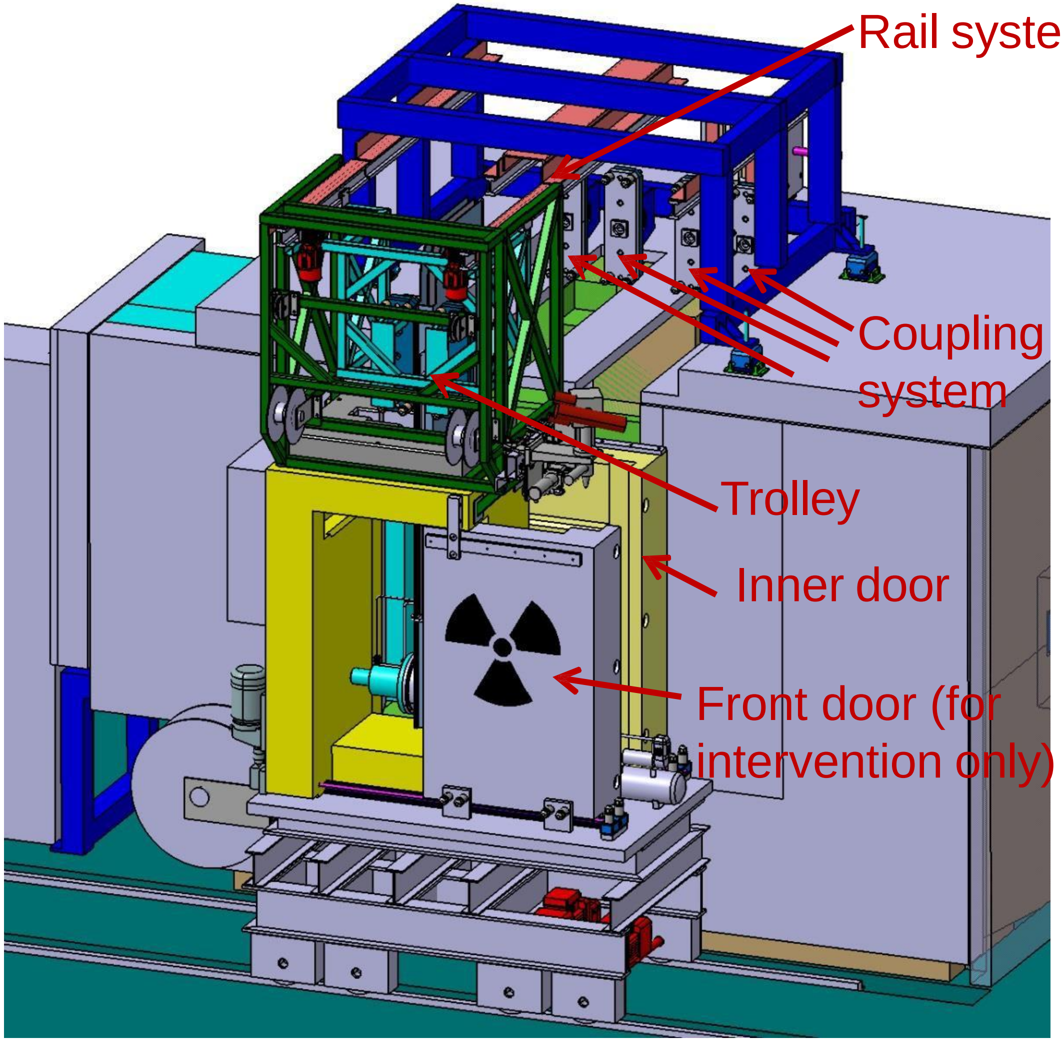
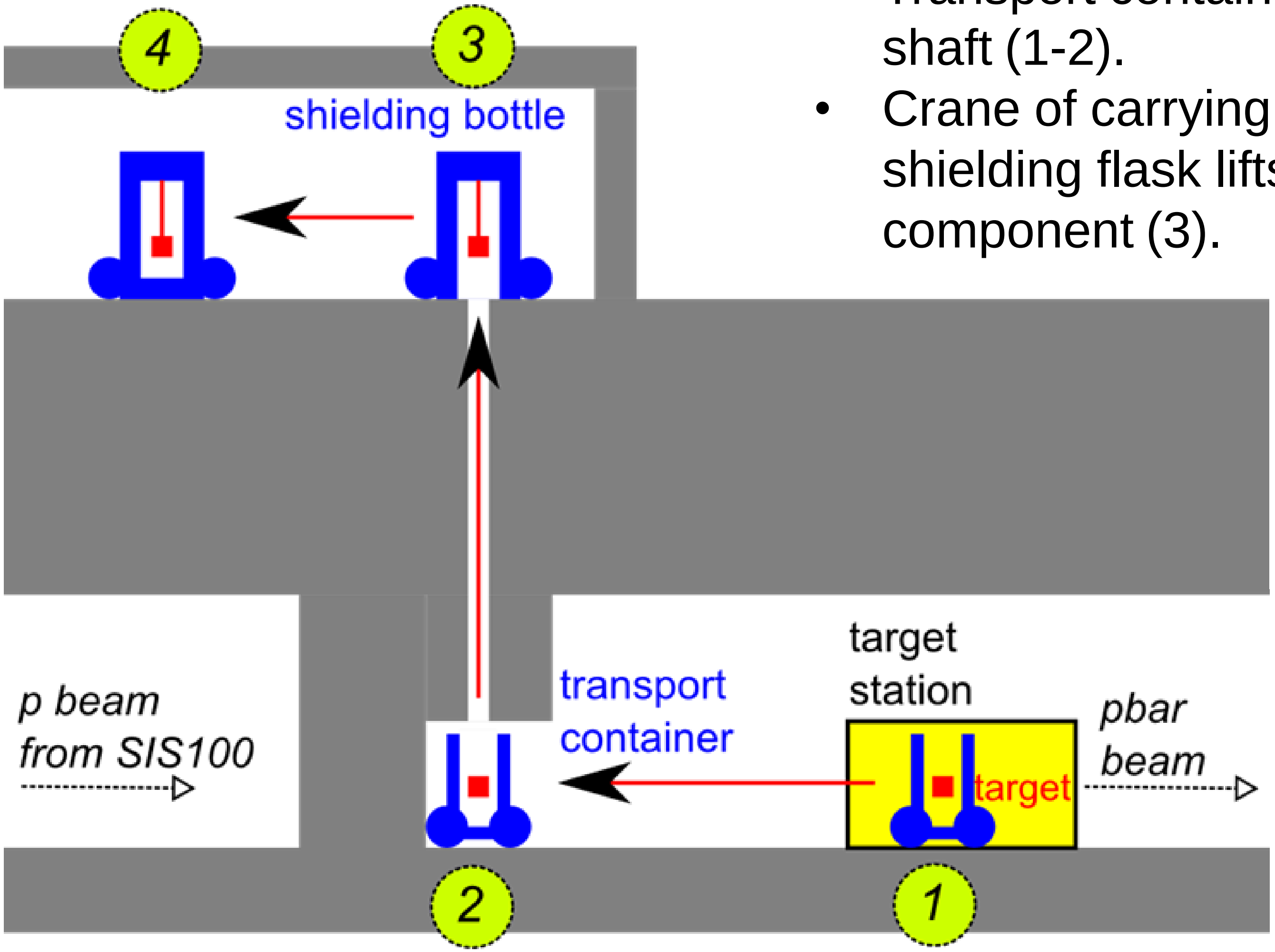


- Transport container is placed in front of target station.
- Door of target station and transport container are opened.
- Component is gripped by a quick coupling system.
- Trolley moves the component via rail system into the transport container.
- Doors are closed.

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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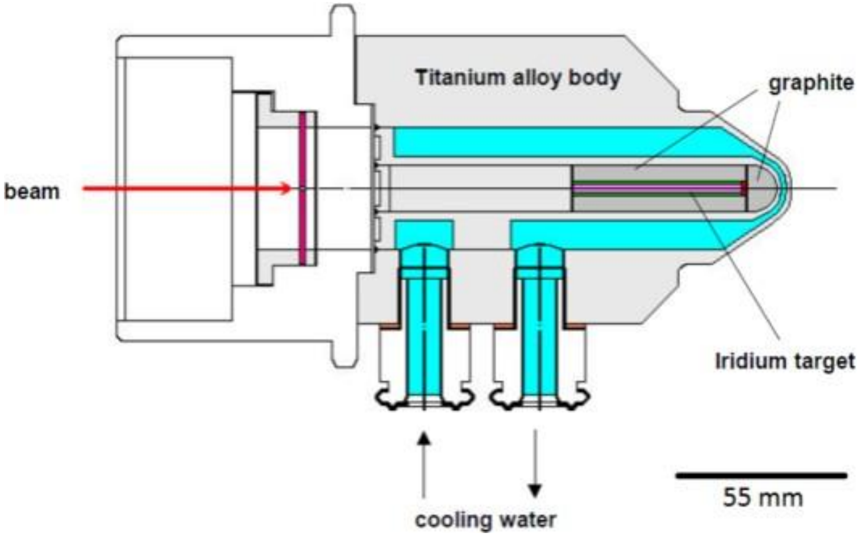
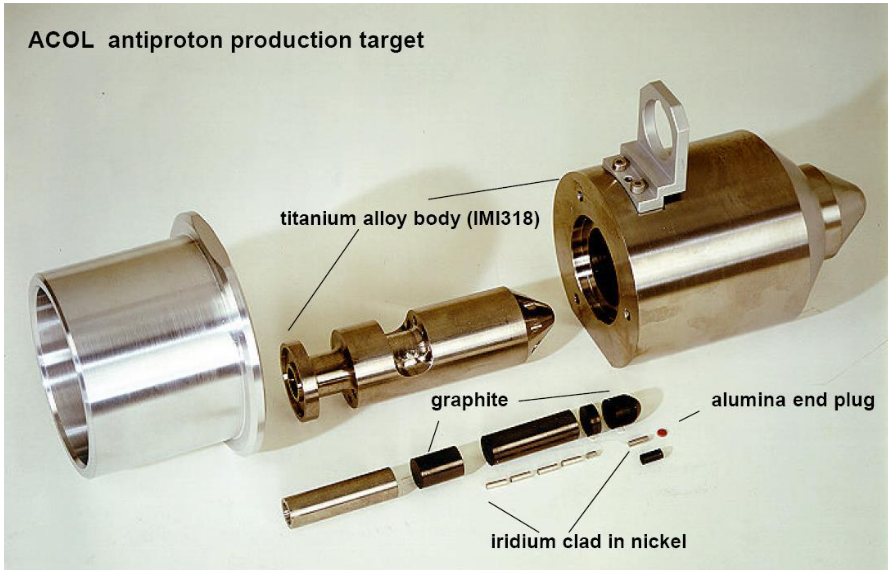
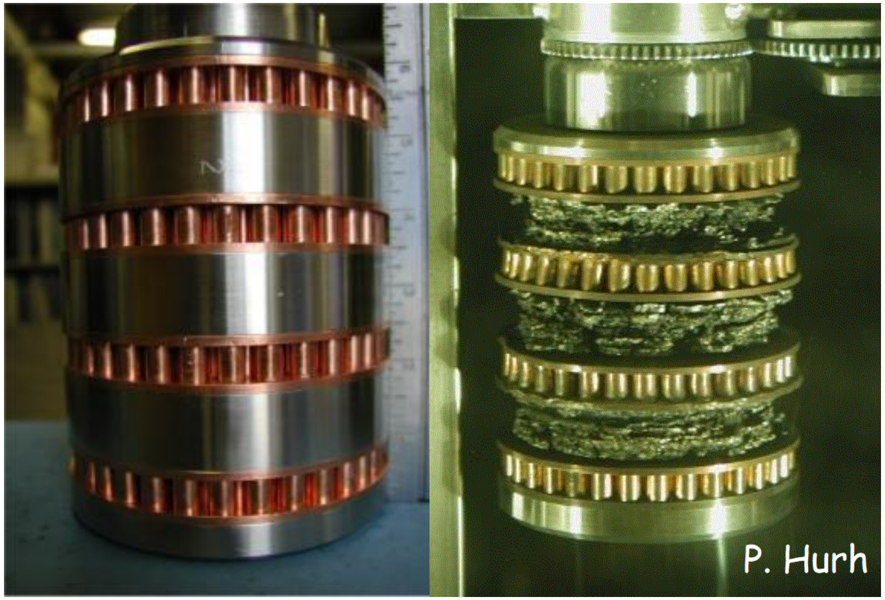
CERN and Fermilab pbar Targets

CERN target (Ir or Cu)

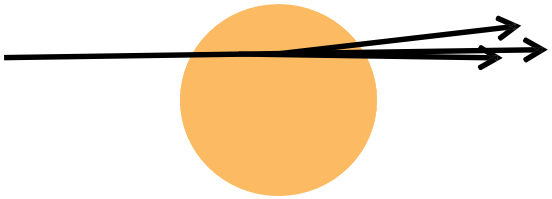




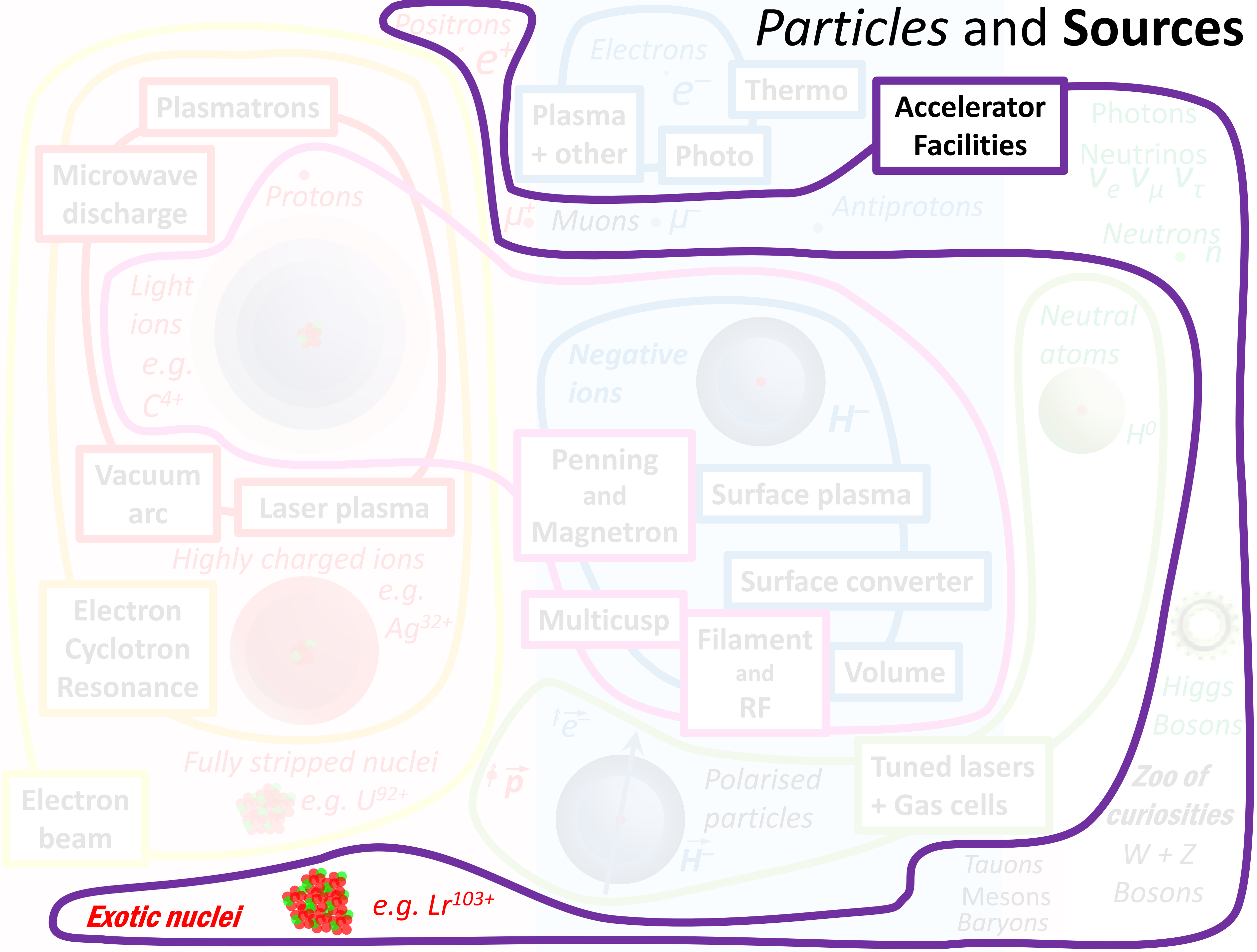
Rotating Fermilab target



new used

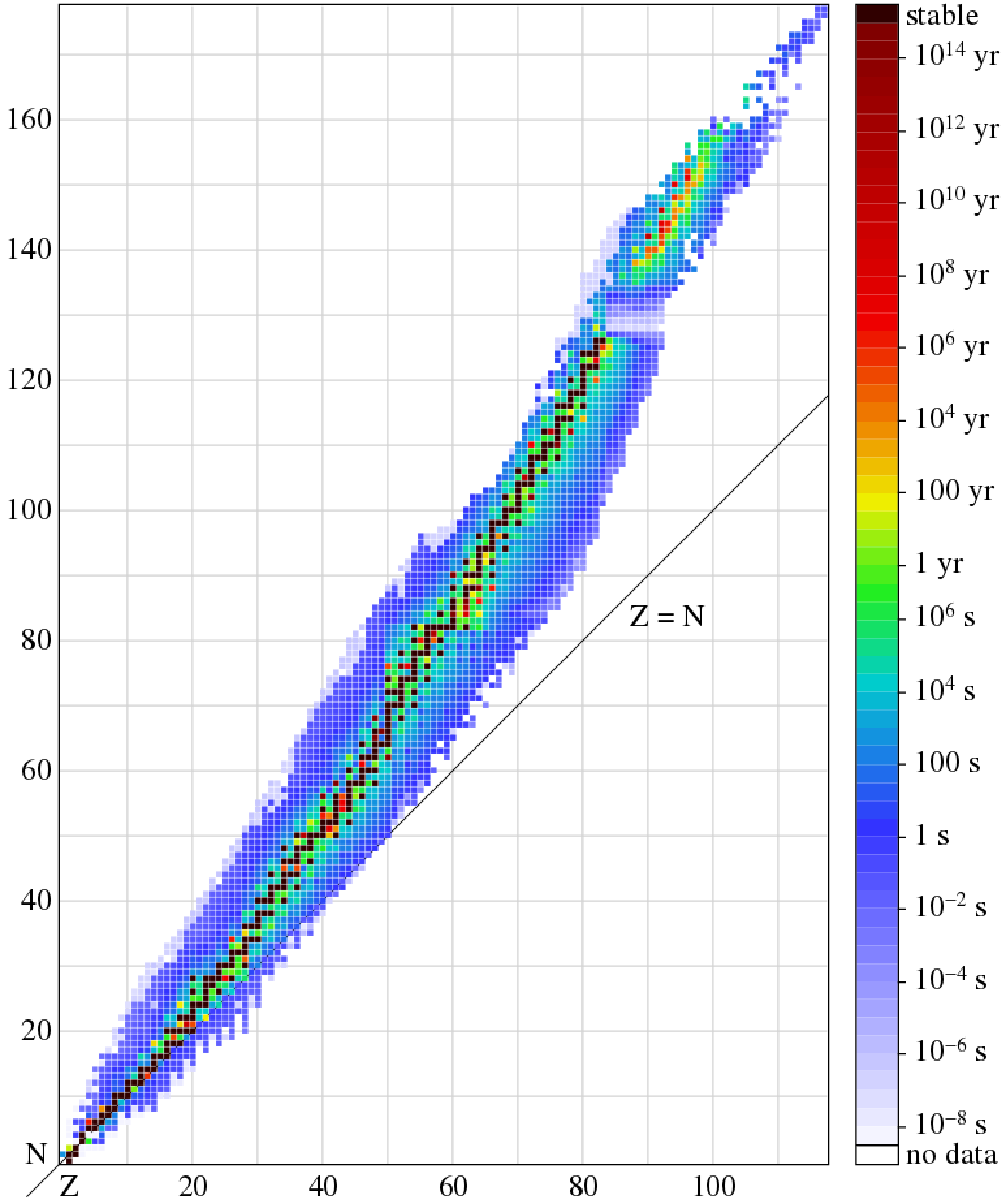


Particles and **Sources**



Accelerator Facilities

Exotic nuclei e.g. Lr^{103+}



Radioactive Ion Beams

A powerful way of studying the atomic nucleus

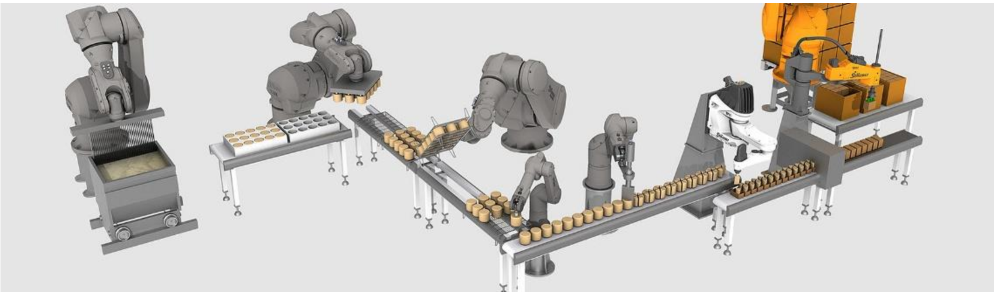
TRIUMF

Rare Isotope Facilities World-Wide

covery,
celerated

ISOL vs In Flight Fragmentation

Isotope Separation On Line (ISOL): A production line

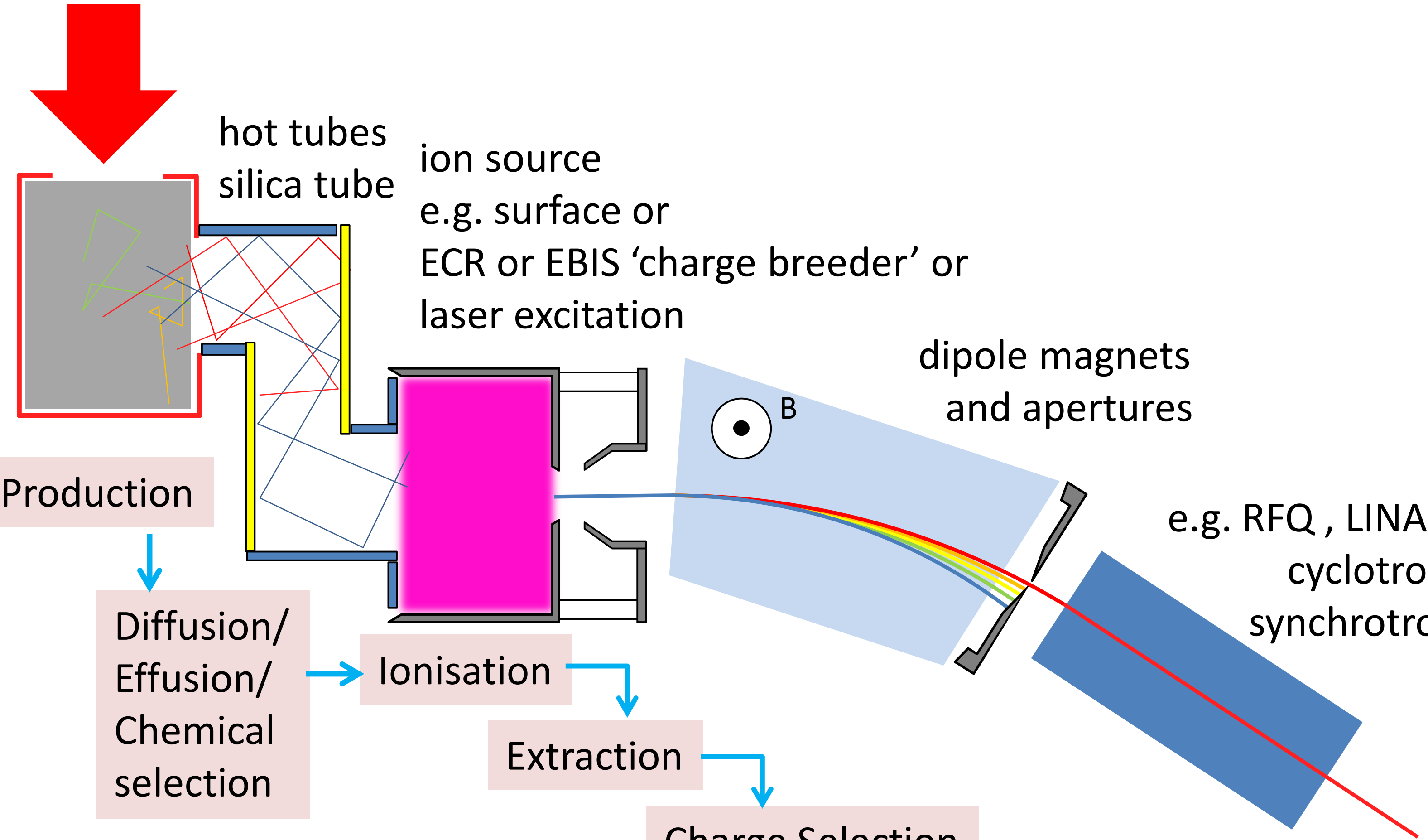


A → B → C → D → E → F

Very complicated chains of acceleration and separation have been created

In Flight Fragmentation:
Filtering an explosion

ISOL: common components



primary beam

hot thick target

seconds to release

hot tubes
silica tube

ion source
e.g. surface or
ECR or EBIS ‘charge breeder’ or
laser excitation

dipole magnets and apertures

e.g. RFQ , LINAC, cyclotron, synchrotron

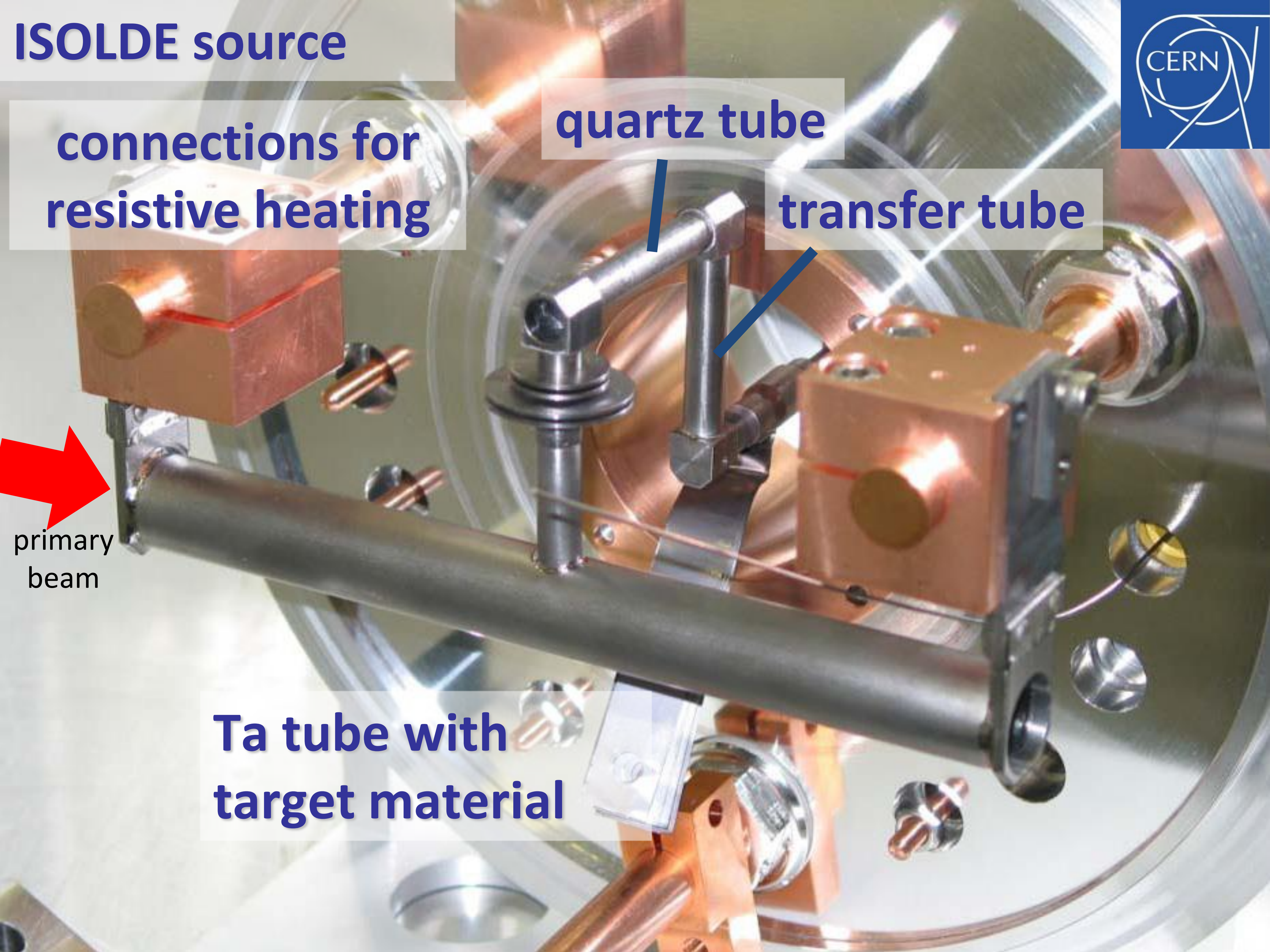
pure isotope and charge state beam

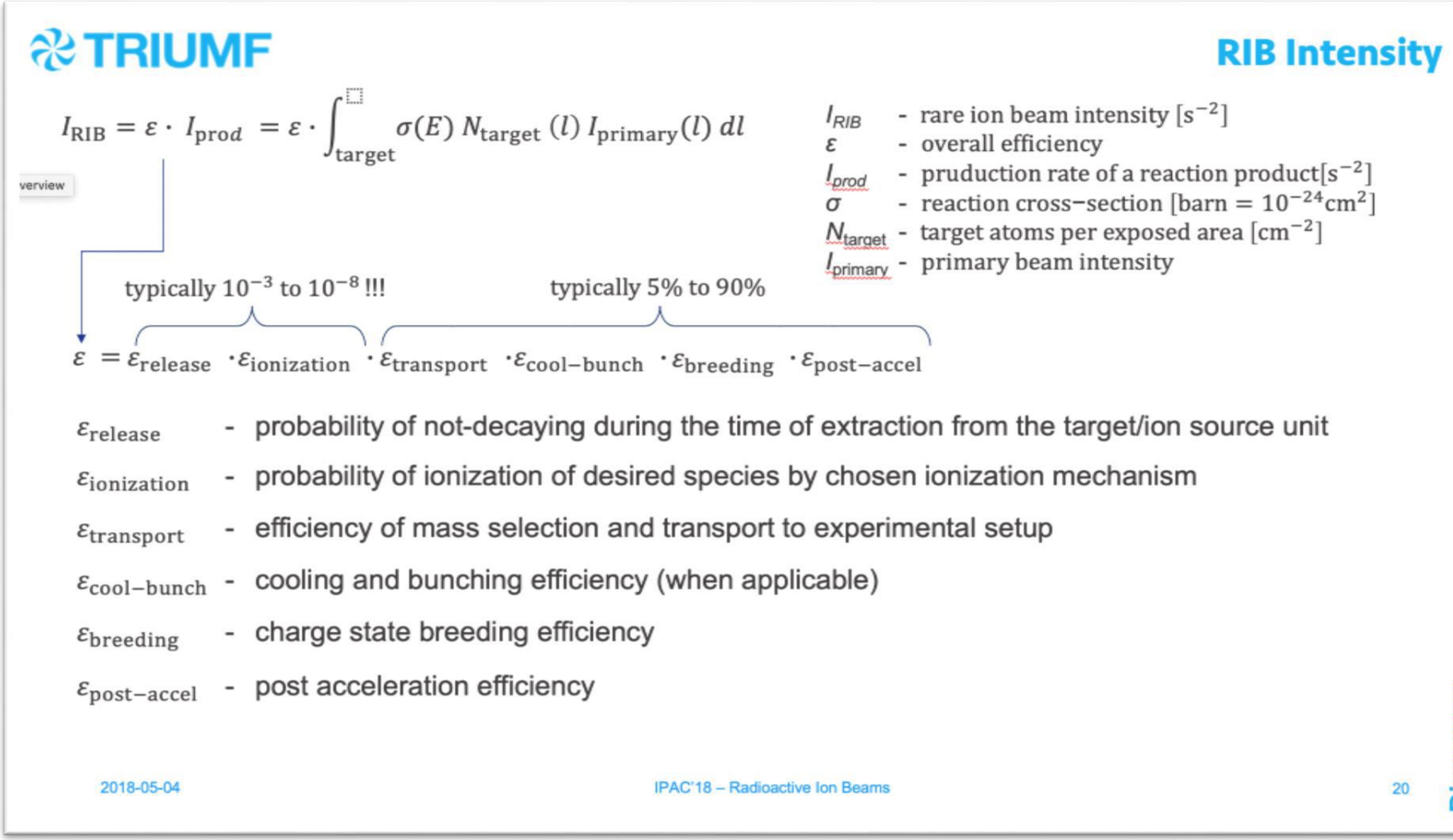
Production → Diffusion/ Effusion/ Chemical selection → Ionisation → Extraction → Charge Selection → Acceleration

Efficiencies can be as low as 1e-8

ISOL produces very pure beams with “long” half life

ISOLDE source





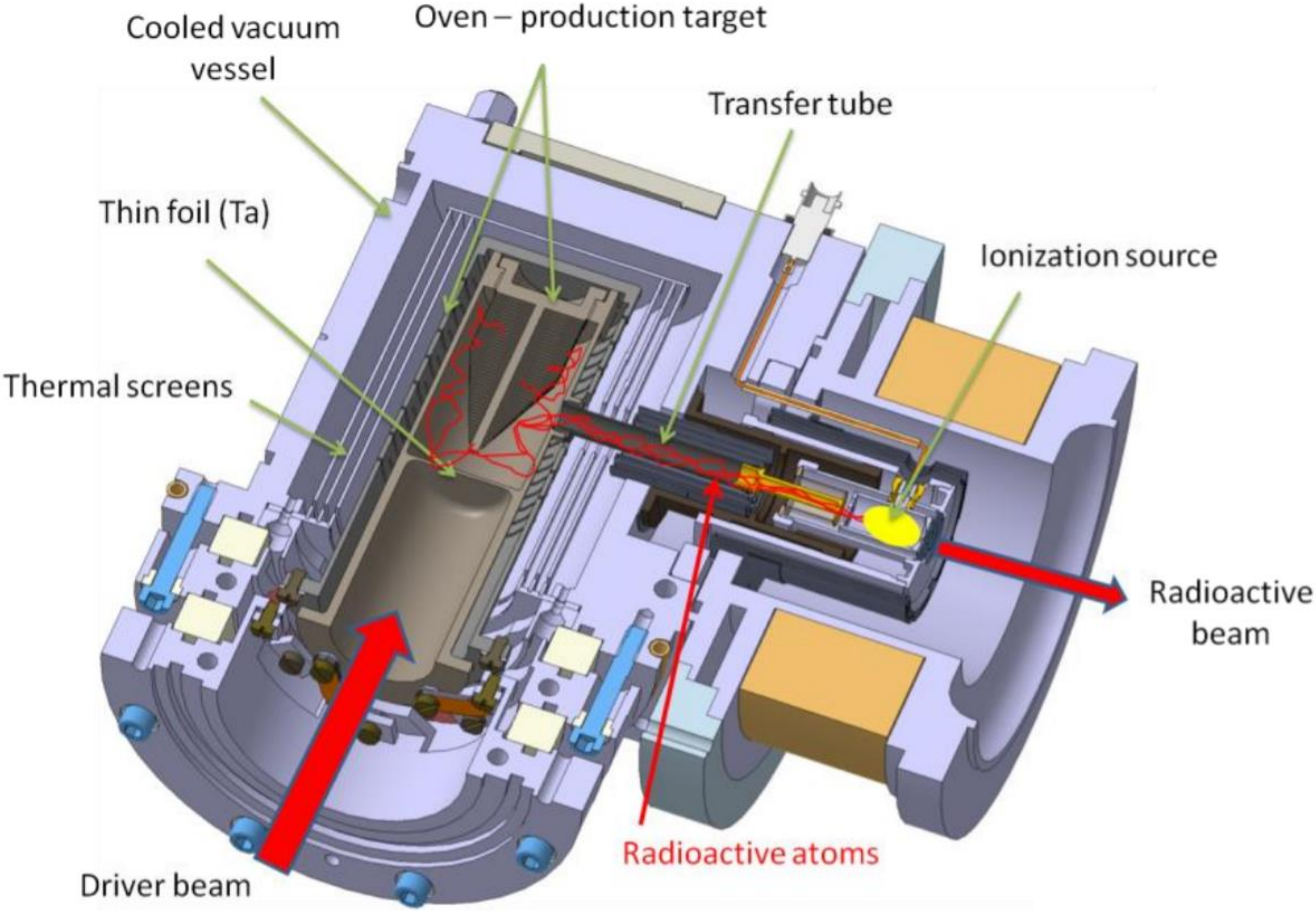
RIB Intensity

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

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

$$\varepsilon = \overbrace{\varepsilon_{\mathrm{release}} \cdot \varepsilon_{\mathrm{ionization}}}^{\text{typically } 10^{-3} \text{ to } 10^{-8} \text{ !!!}} \cdot \overbrace{\varepsilon_{\mathrm{transport}} \cdot \varepsilon_{\mathrm{cool-bunch}} \cdot \varepsilon_{\mathrm{breeding}} \cdot \varepsilon_{\mathrm{post-accel}}}^{\text{typically } 5\% \text{ to } 90\%}$$

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



Cooled vacuum vessel

Oven – production target

Transfer tube

Thin foil (Ta)

Ionization source

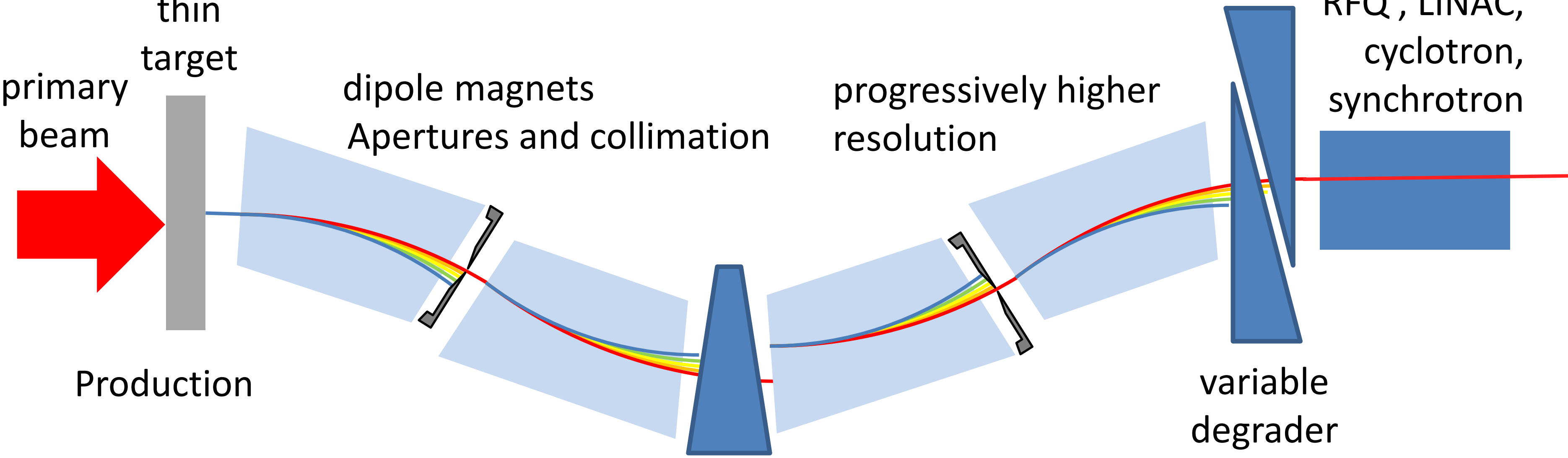
Thermal screens

Radioactive beam

Radioactive atoms

Driver beam

In Flight Fragmentation: common components



Fragment separator:

thin target

primary beam

dipole magnets
Apertures and collimation

progressively higher resolution

RFQ , LINAC, cyclotron, synchrotron

Production

variable degrader

q/m Selection

wedge shape degrader

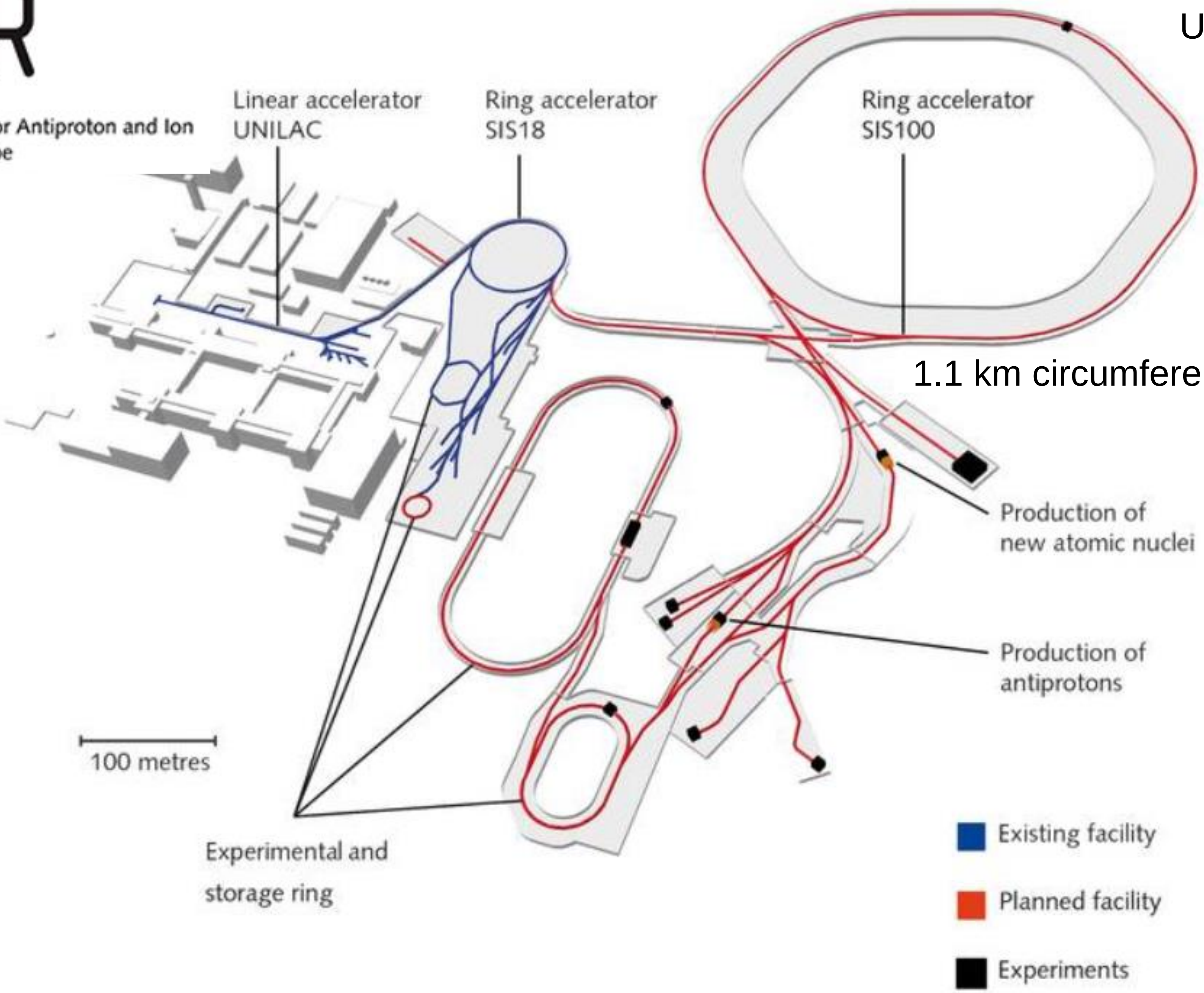
Degrader*: dE/dx* depends on projectile's ***Z****.*

In flight fragmentation suitable for very short half life beams

FAIR — Facility for Antiproton and Ion Research in Europe

2.7 GeV/nucleon

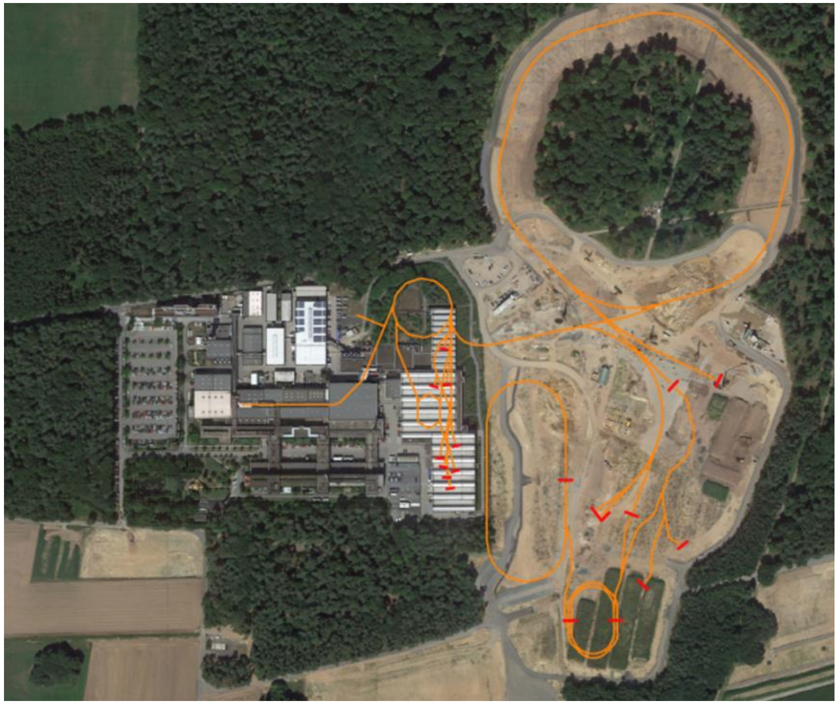
U^{28+}



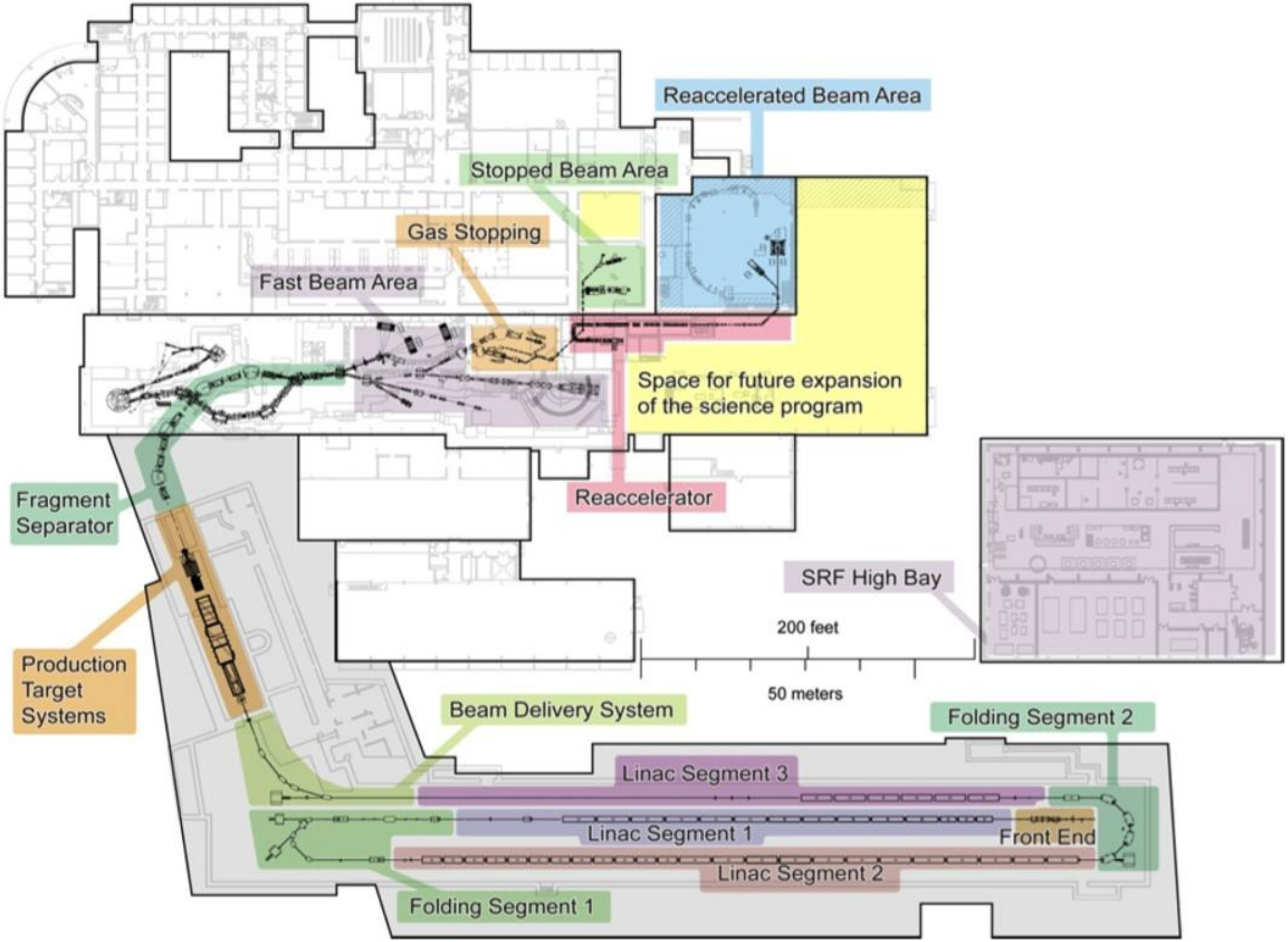
1.1 km circumference

The Super Fragment Separator

FAIR — Facility for Antiproton and Ion Research in Europe



Facility for Rare Isotope Beams
at Michigan State University



Facility for Rare Isotope Beams
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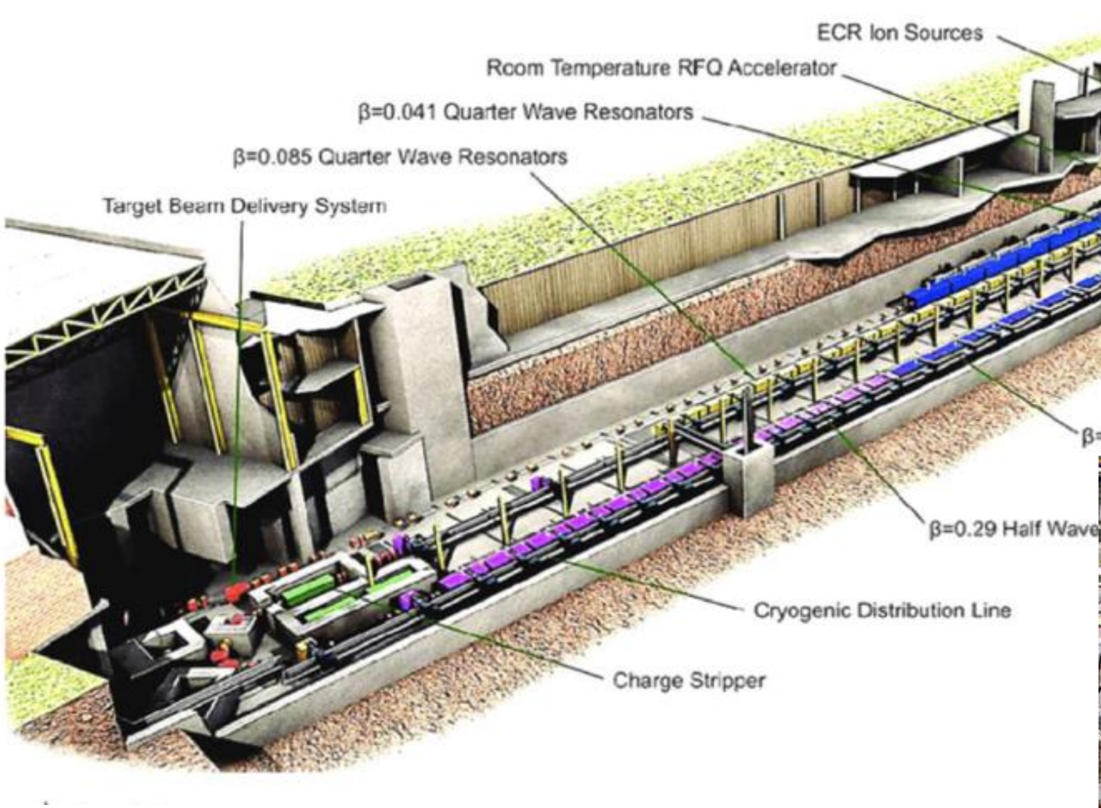
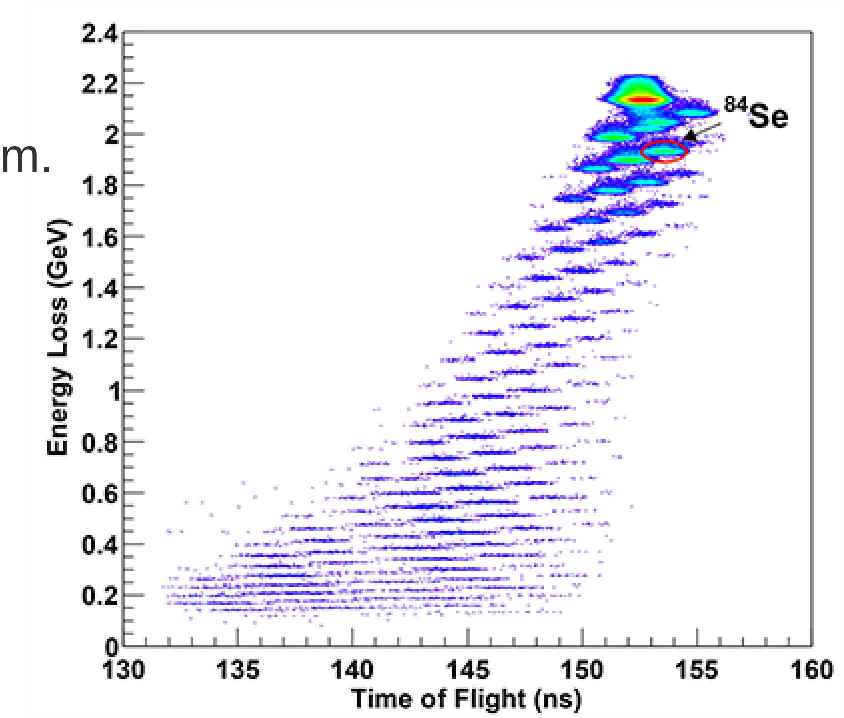


517 m linac

200 MeV/nucleon

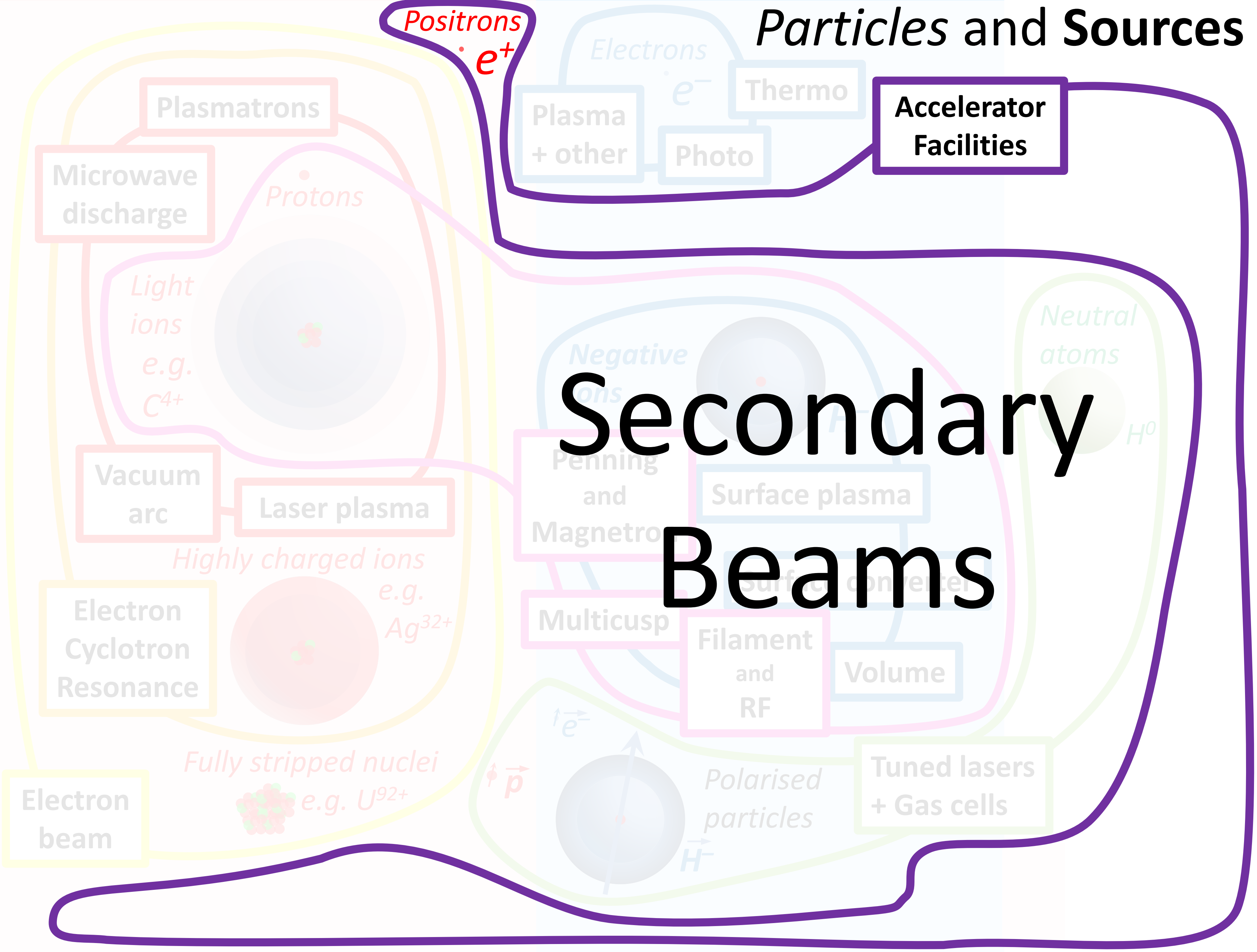
Facility for Rare Isotope Beams
at Michigan State University

FIRST RARE ISOTOPES
11 December 2021
selenium-84 from a krypton-86 beam.



January 2022 they discovered magnesium-18

Particles and **Sources**



Positrons e^+

Accelerator Facilities

Electrons e^-

Thermo

Plasma + other

Photo

Plasmatrons

Microwave discharge

Protons

Light ions e.g. C^{4+}

Vacuum arc

Laser plasma

Highly charged ions e.g. Ag^{32+}

Electron Cyclotron Resonance

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

Electron beam

Negative ions H^-

Penning and Magnetron

Surface plasma

Surface converter

Multicusp

Filament and RF

Volume

Neutral atoms H^0

Tuned lasers + Gas cells

Polarised particles

$\vec{e}^-$ $\vec{p}$ $\vec{H}^-$

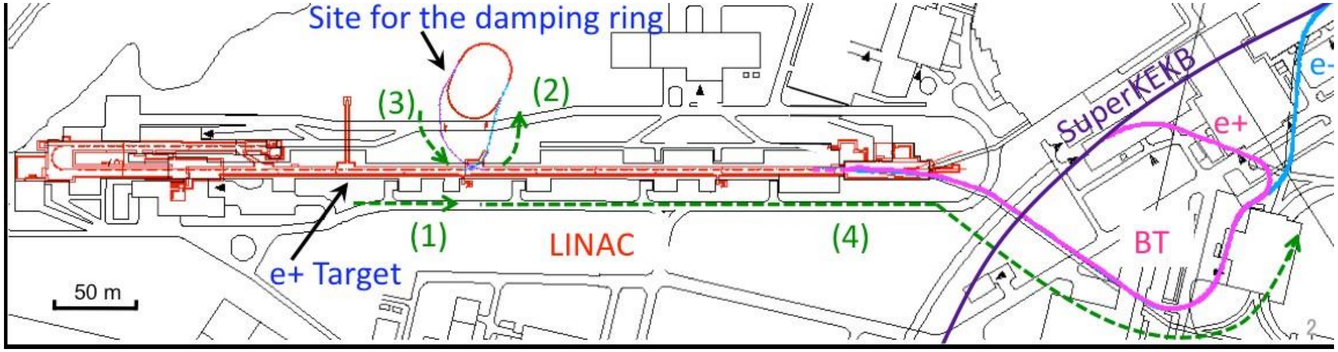
Secondary Beams

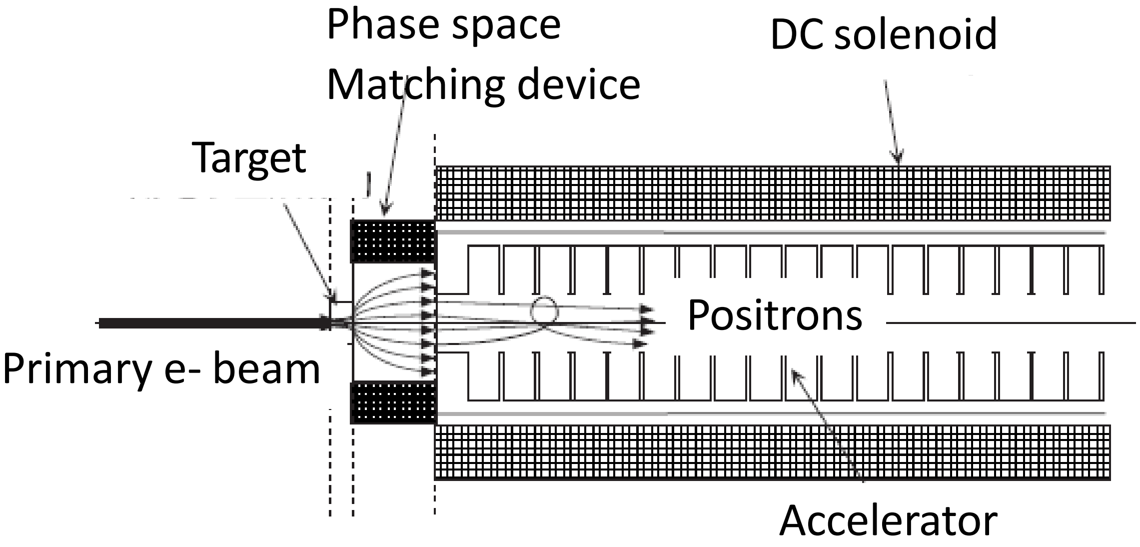
Positron Sources

Techniques:

- Radio-isotope source
  - long-lived e.g. ^{22}Na (~10^6 e^+/s)
  - or beam-induced e.g. ^{13}N (~10^9 e^+/s)
- MeV or GeV electron beam
- Gamma ray beam

Positron source for the KEKB and the SuperKEKB in Japan





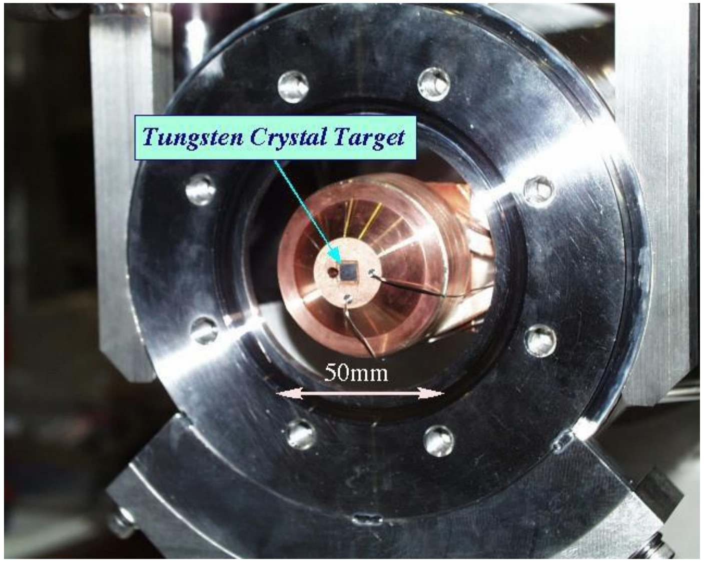
Target material

Requirements:

High Z (Cross section of Bremsstrahlung ∝ Z^2/A)

High melting point

- Tantalum(^{73}Ta),
- Tungsten(^{74}W),
- Tungsten- rhenium alloy (W-Re)

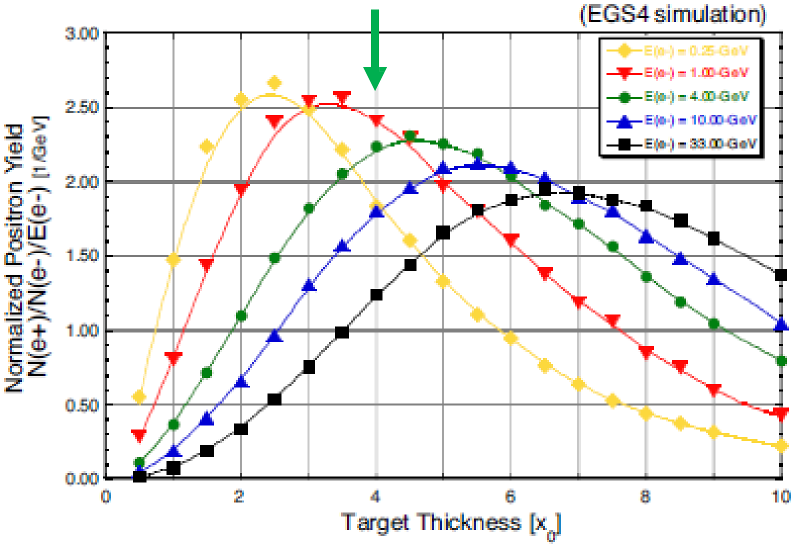


Joining of tungsten crystal to a copper body by a hot isostatic pressing (HIP)

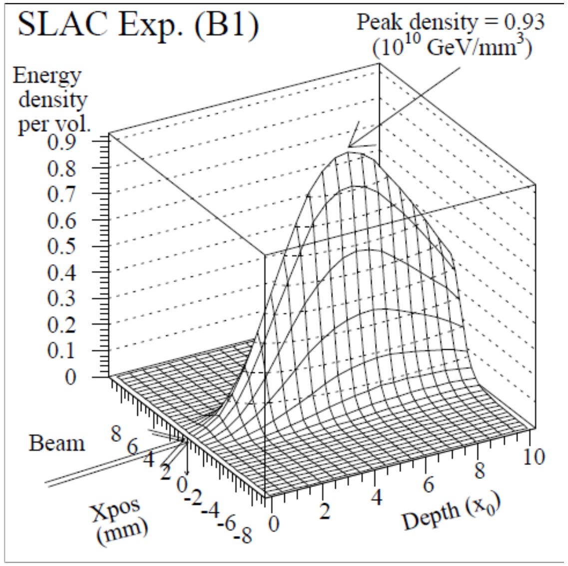
KEKB, SuperKEKB

Target material: W 14mm (4χ_0)

Primary e- beam energy: 4.0 GeV(KEKB) 3.3GeV(SuperKEKB)



Target destruction limit



After the target destruction occurred at SLAC

Threshold : 76 → 35 J/g

KEK Positron Sources

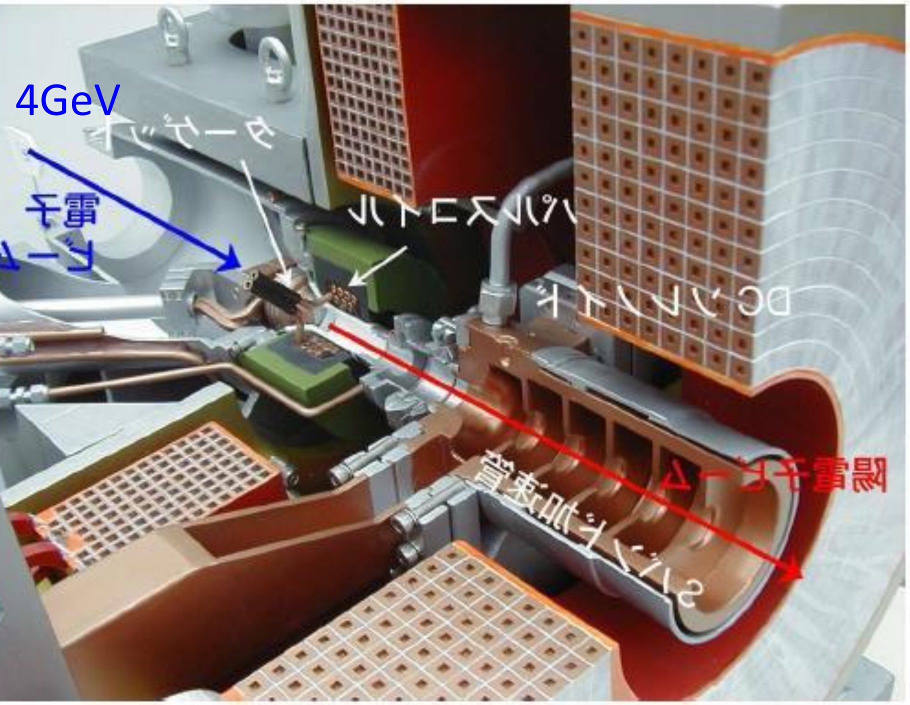
KEKB

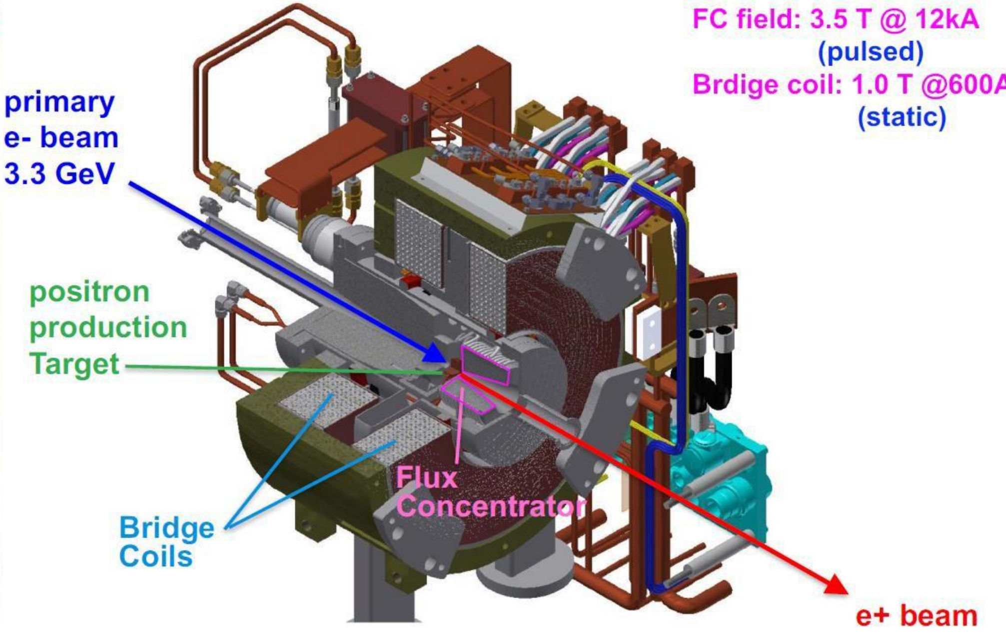
Quarter wave transformer matching device

Pulse coil: 2.3T @ 10kA

SuperKEKB

AMD Flux Concentrator matching device



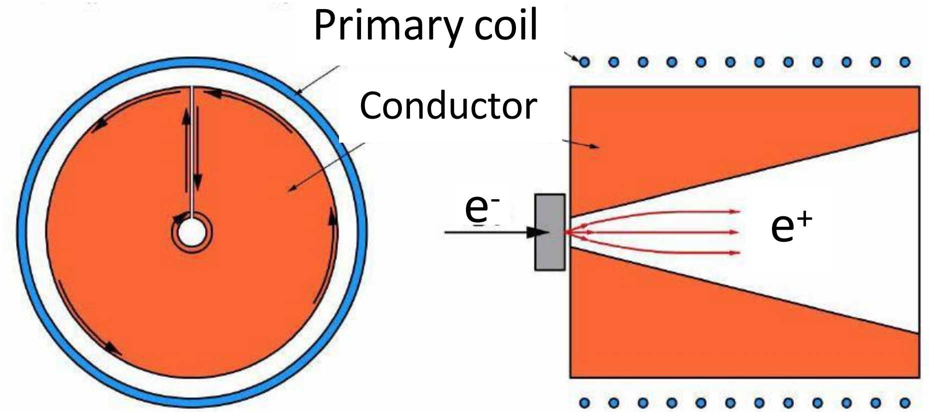


50Hz rep rate with a bunch charge of $2.5\times10^{10} = 2.5\times10^{12}$ e^+/s

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

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

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

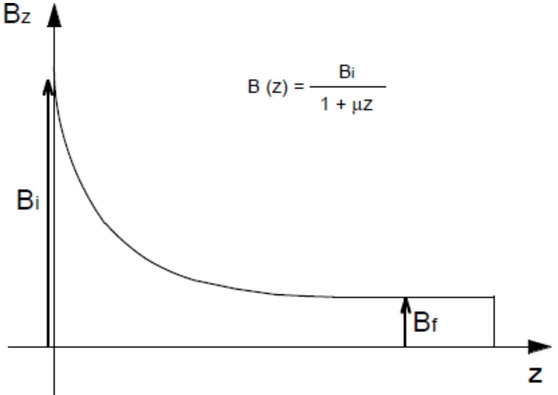
(B0 = 7.0 [Tesla], μ = 60[1/m])

Transverse acceptance

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

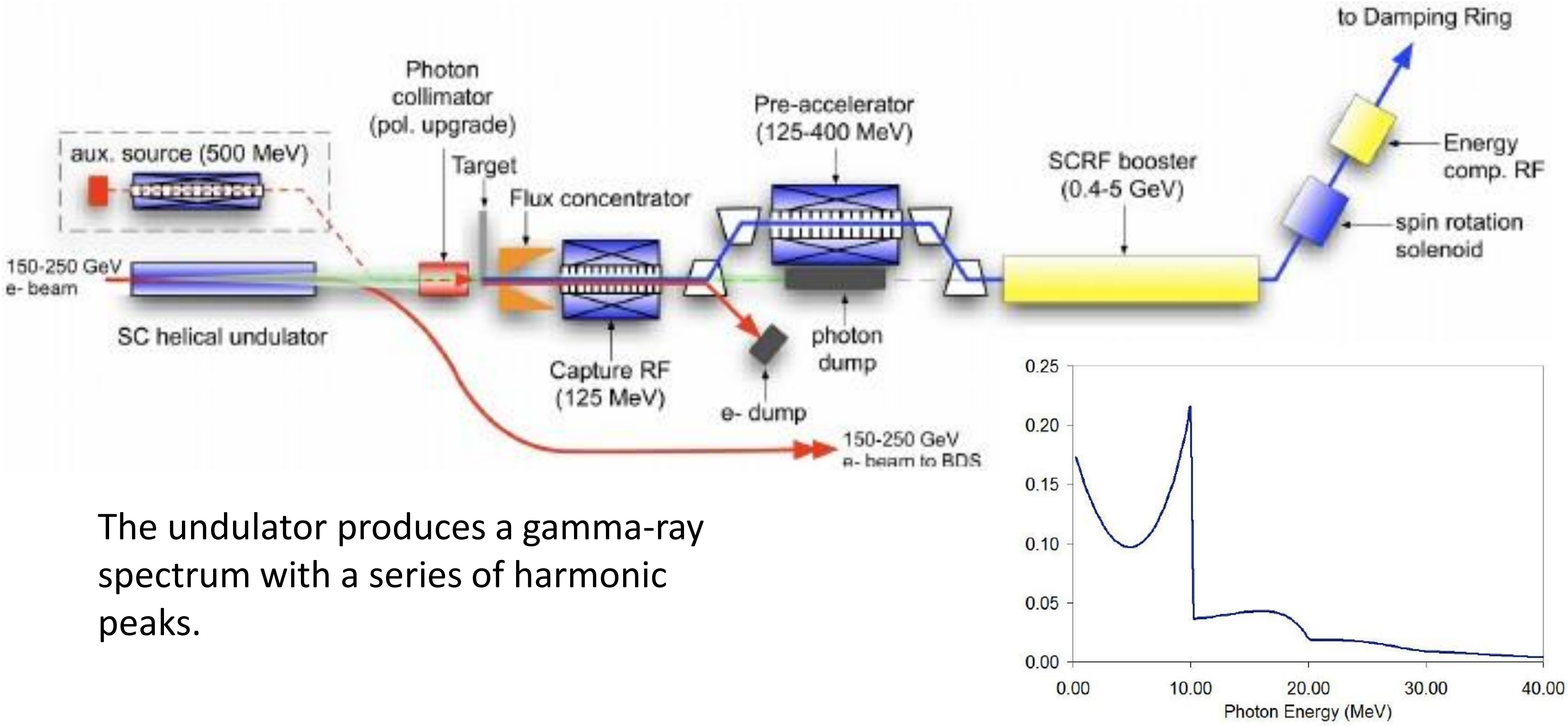
$$r_{max} = \sqrt{\frac{B_f}{B_0}}a$$

a: Diameter of an accelerator iris



Gamma Ray Undulator Source

Considered primarily for the ILC

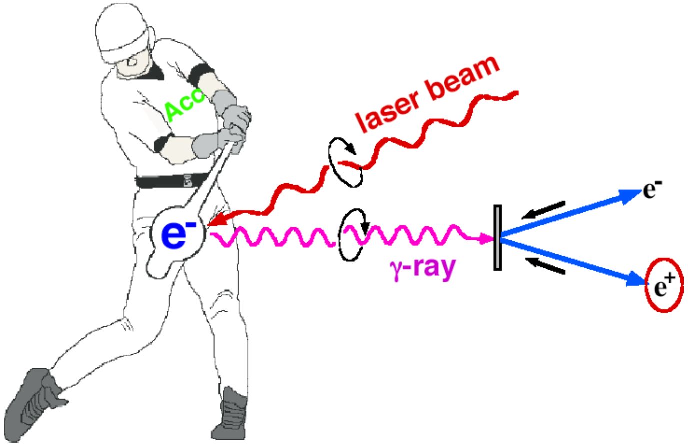


The undulator produces a gamma-ray spectrum with a series of harmonic peaks.

Gamma Ray Compton Source

Compton backscabering 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



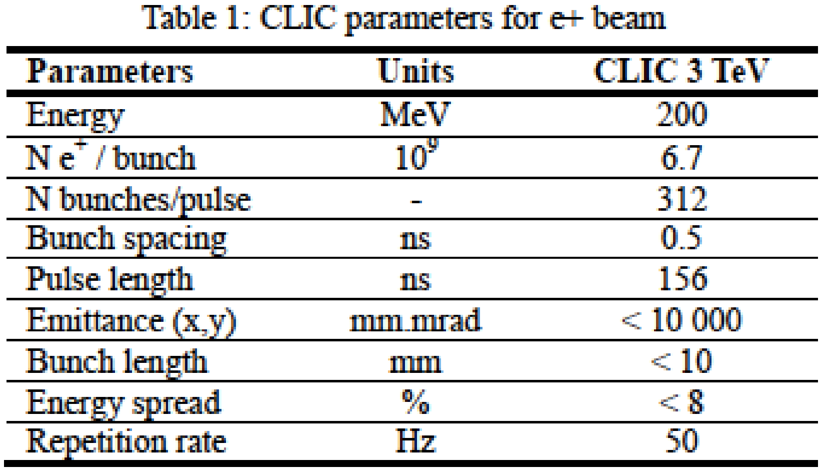
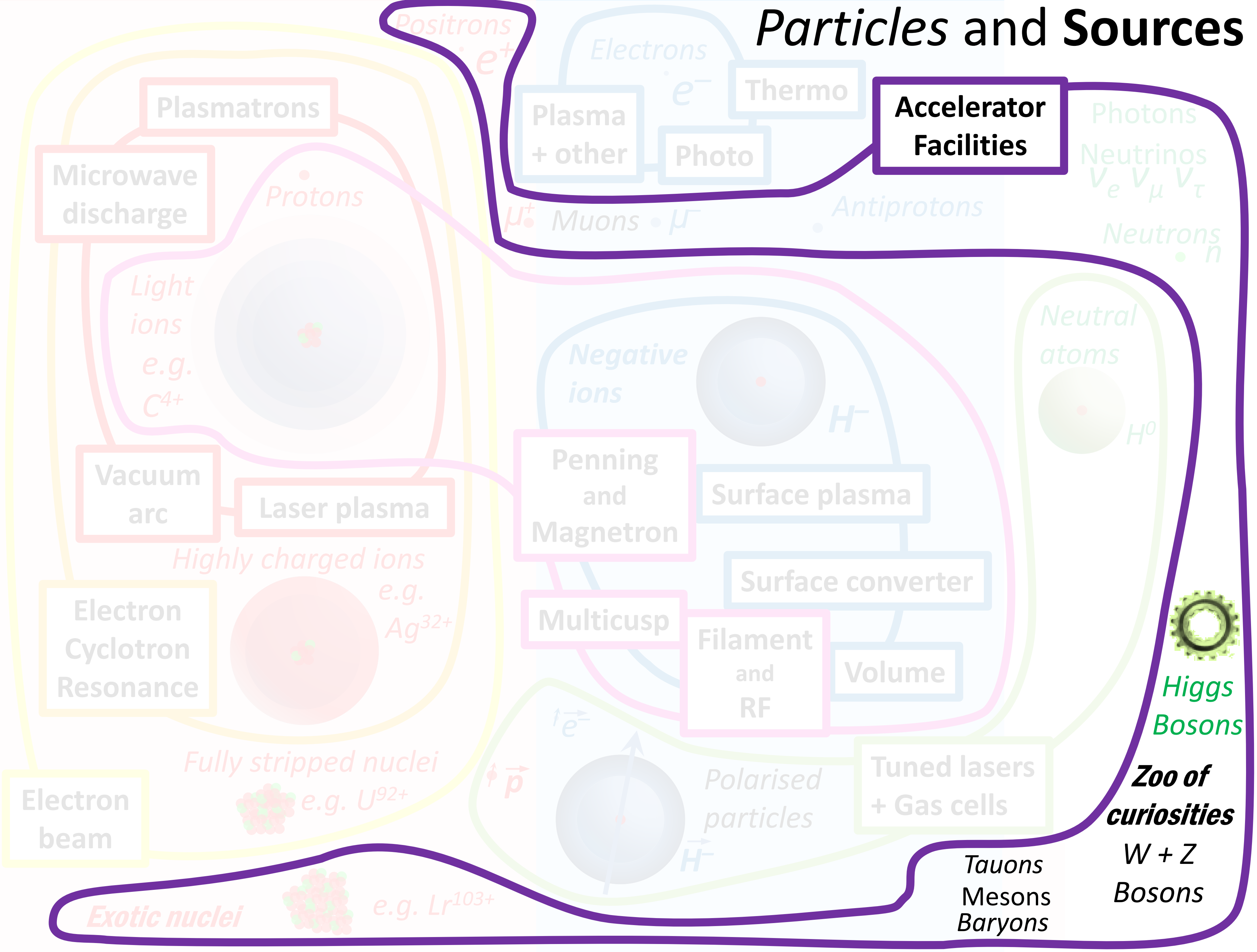


Table 1: CLIC parameters for e+ beam

Parameters	Units	CLIC 3 TeV
Energy	MeV	200
N e^+ / bunch	10^9	6.7
N 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**



Positrons e^+

Electrons e^-

Plasma + other

Thermo

Photo

Accelerator Facilities

Photons

Neutrinos ν_e ν_μ ν_τ

Neutrons n

Antiprotons

μ^+ Muons μ^-

Plasmatrons

Microwave discharge

Protons

Light ions e.g. C^{4+}

Vacuum arc

Laser plasma

Highly charged ions e.g. Ag^{32+}

Electron Cyclotron Resonance

Electron beam

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

Exotic nuclei e.g. Lr^{103+}

Negative ions H^-

Penning and Magnetron

Surface plasma

Surface converter

Multicusp

Filament and RF

Volume

Neutral atoms H^0

Polarised particles $\vec{e}^-$ $\vec{p}$ $\vec{H}^-$

Tuned lasers + Gas cells

Higgs Bosons

Zoo of curiosities

W + Z Bosons

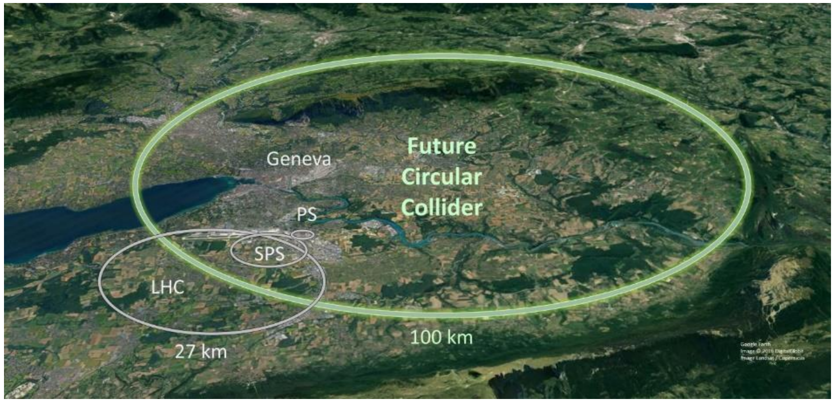
Tauons
Mesons
Baryons

Future Colliders

Compact Linear Collider

NLC

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!

IHEP-CEPC-DR-2018-01
IHEP-AC-2018-01

CEPC
Conceptual Design Report
Volume I - Accelerator

The CEPC Study Group
August 2018

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?