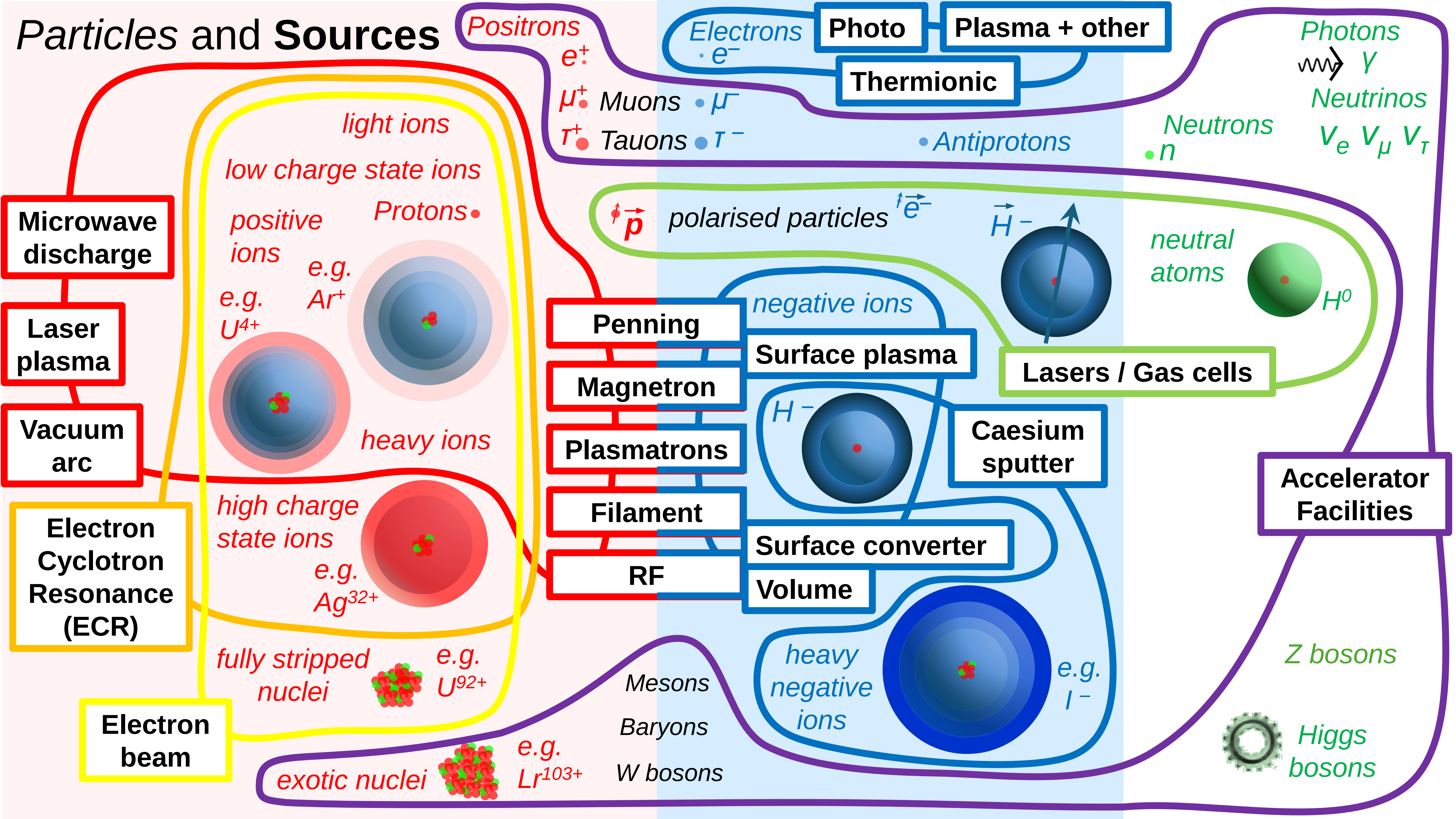
Secondary Beams

Dan Faircloth
ISIS Low Energy Beams Group Leader
Rutherford Appleton Laboratory
STFC-UKRI

CERN Accelerator School, Introduction to Accelerator Physics
Santa Susanna, Spain
Tuesday 24th September 2024

Particles and **Sources**



Positrons e^+

μ^+ Muons μ^-

τ^+ Tauons τ^-

Electrons e^-

Photo

Plasma + other

Thermionic

Antiprotons

Photons γ

Neutrinos ν_e ν_μ ν_τ

Neutrons n

$\vec{p}$ polarised particles $\vec{e}^-$

$\vec{H}^-$

neutral atoms

H^0

Lasers / Gas cells

light ions

low charge state ions

positive ions

Protons

e.g. Ar^+

e.g. 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

negative ions

H^-

heavy negative ions

e.g. I^-

Z bosons

Higgs bosons

Microwave discharge

Laser plasma

Vacuum arc

Electron Cyclotron Resonance (ECR)

Electron beam

Penning

Magnetron

Plasmatrons

Filament

RF

Surface plasma

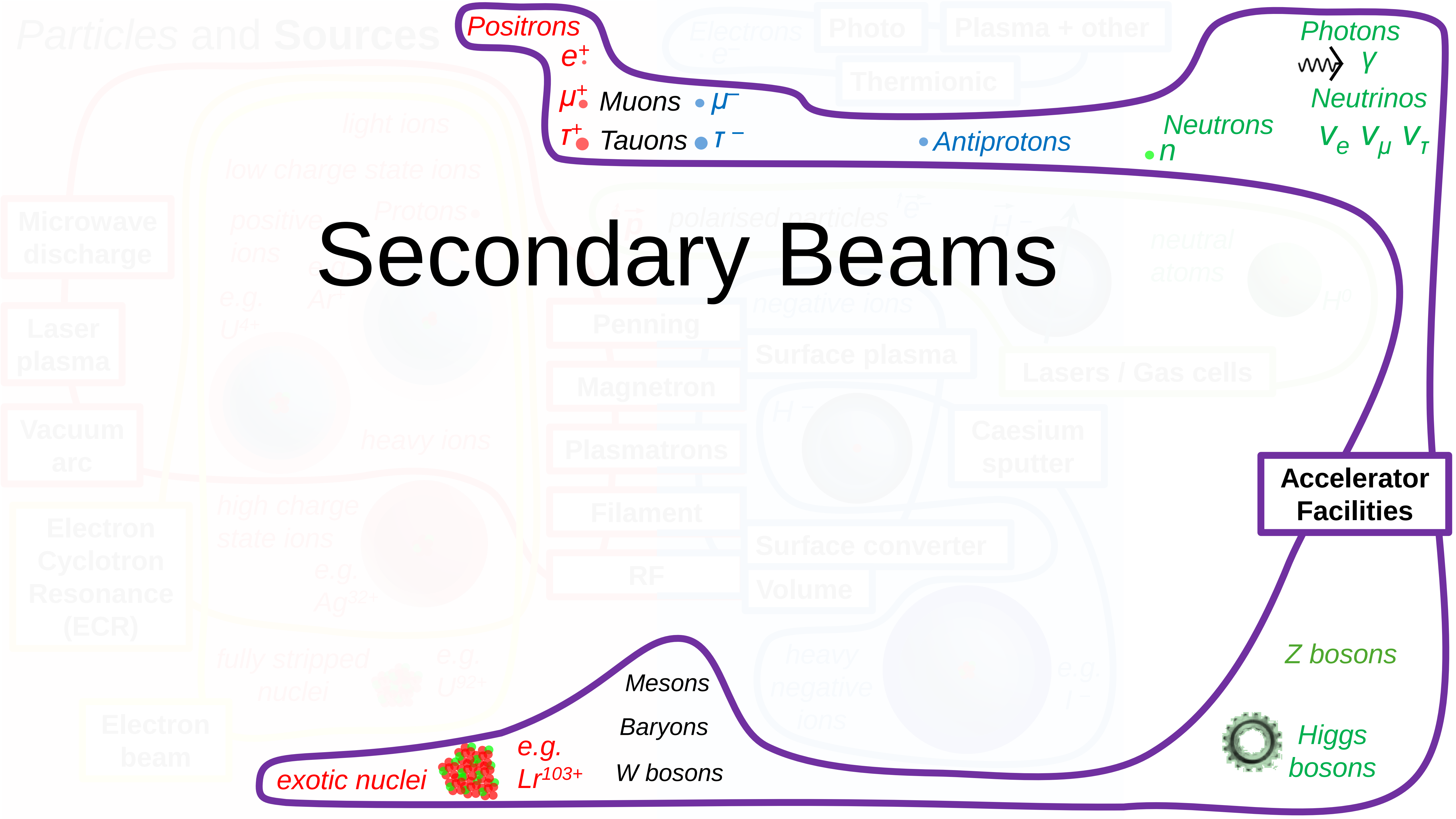
Caesium sputter

Surface converter

Volume

Accelerator Facilities

Secondary Beams



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Accelerator Facilities

Z bosons

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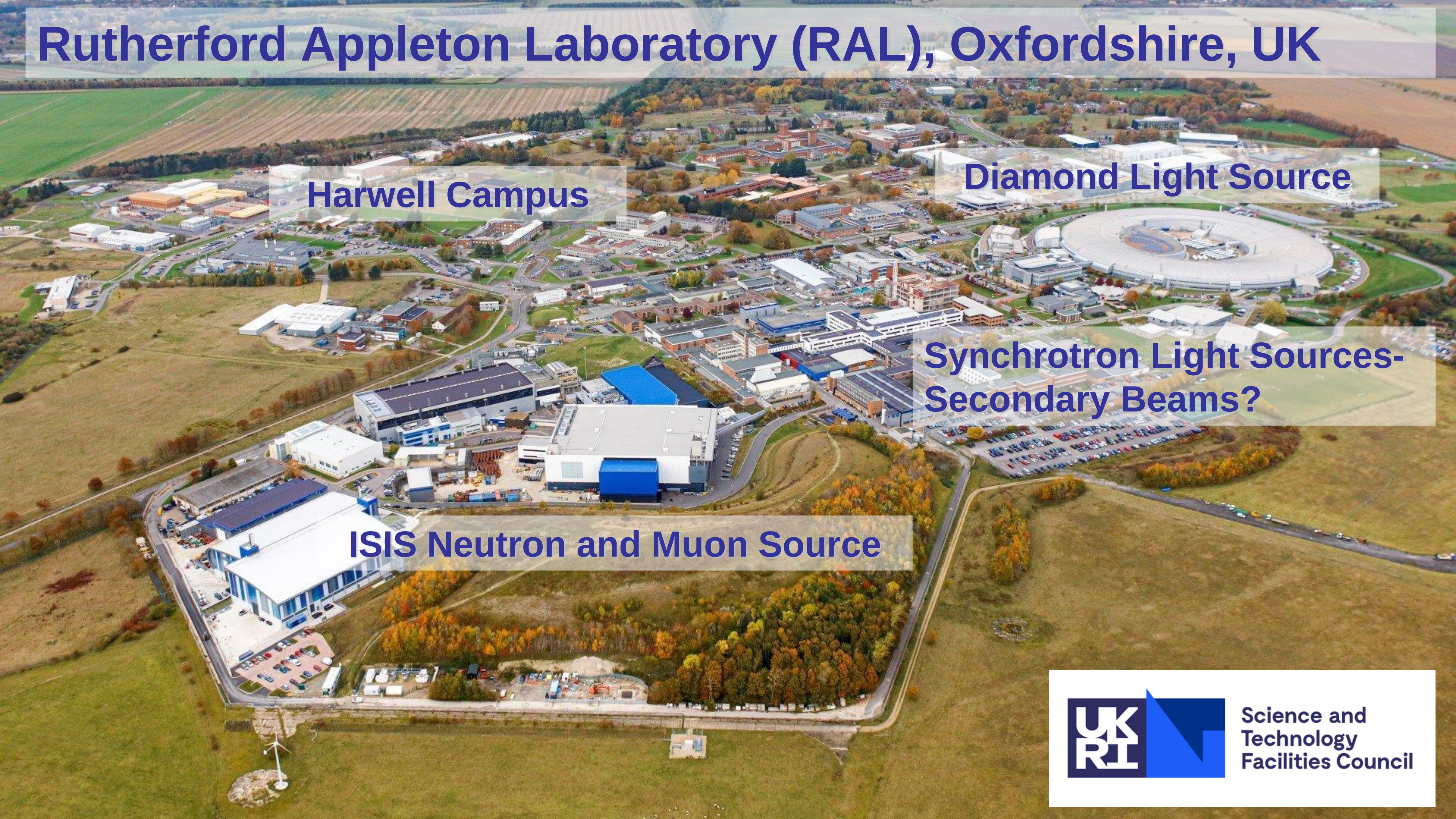
W bosons

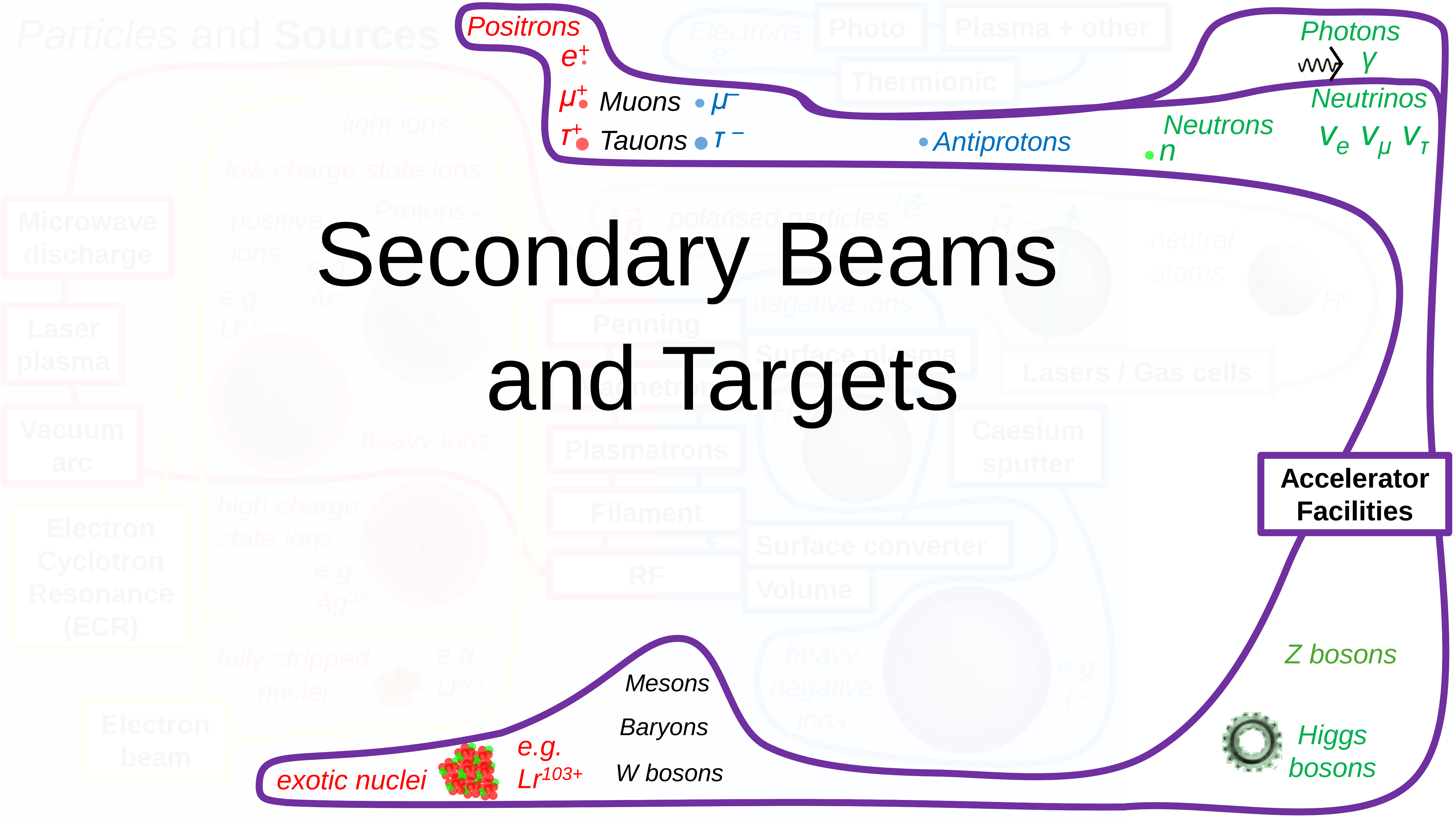
exotic nuclei e.g. Lr^{103+}

Rutherford Appleton Laboratory (RAL), Oxfordshire, UK

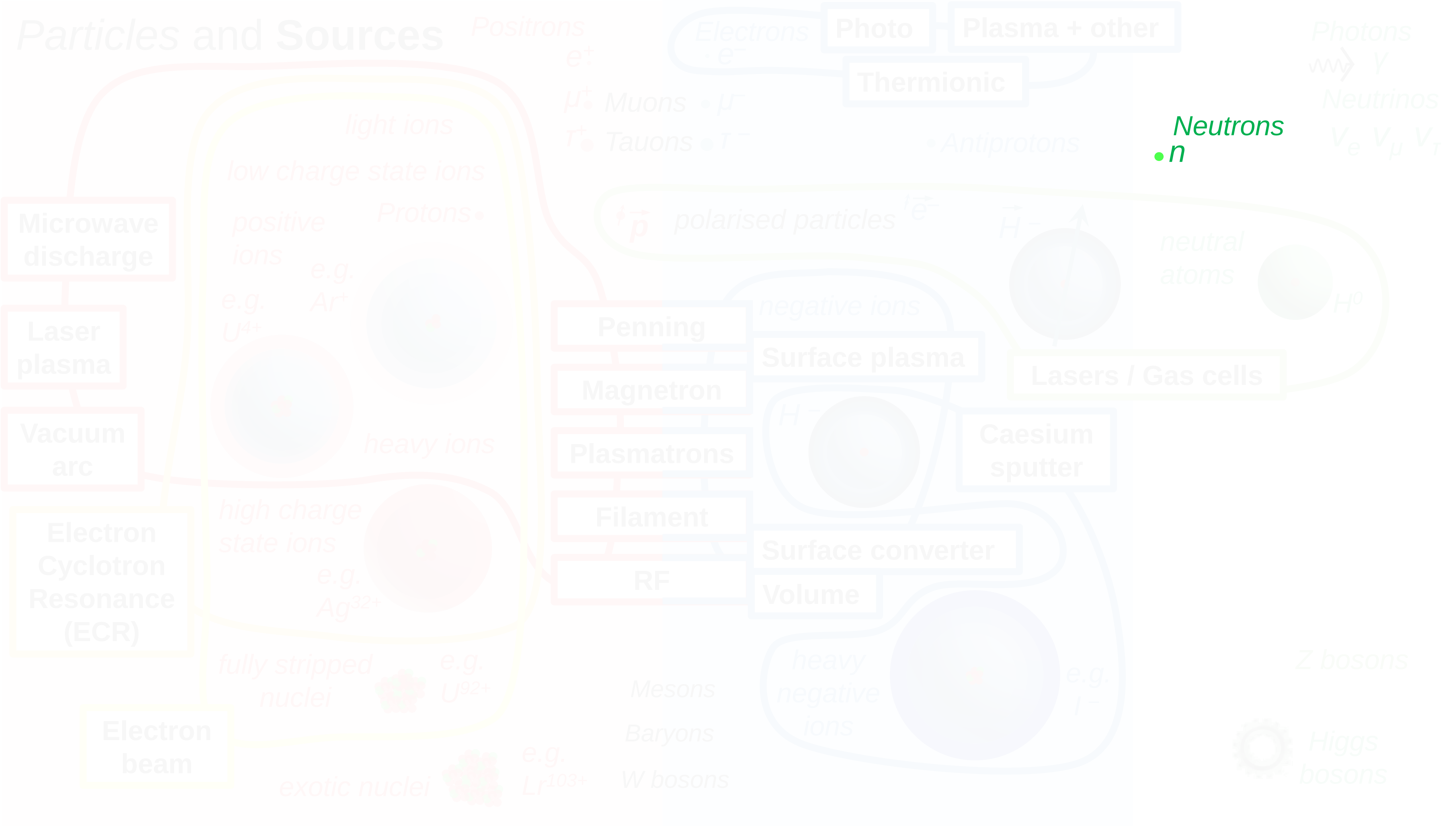


UKRI Science and Technology Facilities Council

Secondary Beams and Targets



Particles and **Sources**



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Plasma + other

Thermionic

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H^-

Caesium sputter

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Volume

heavy negative ions

e.g. I^-

Mesons

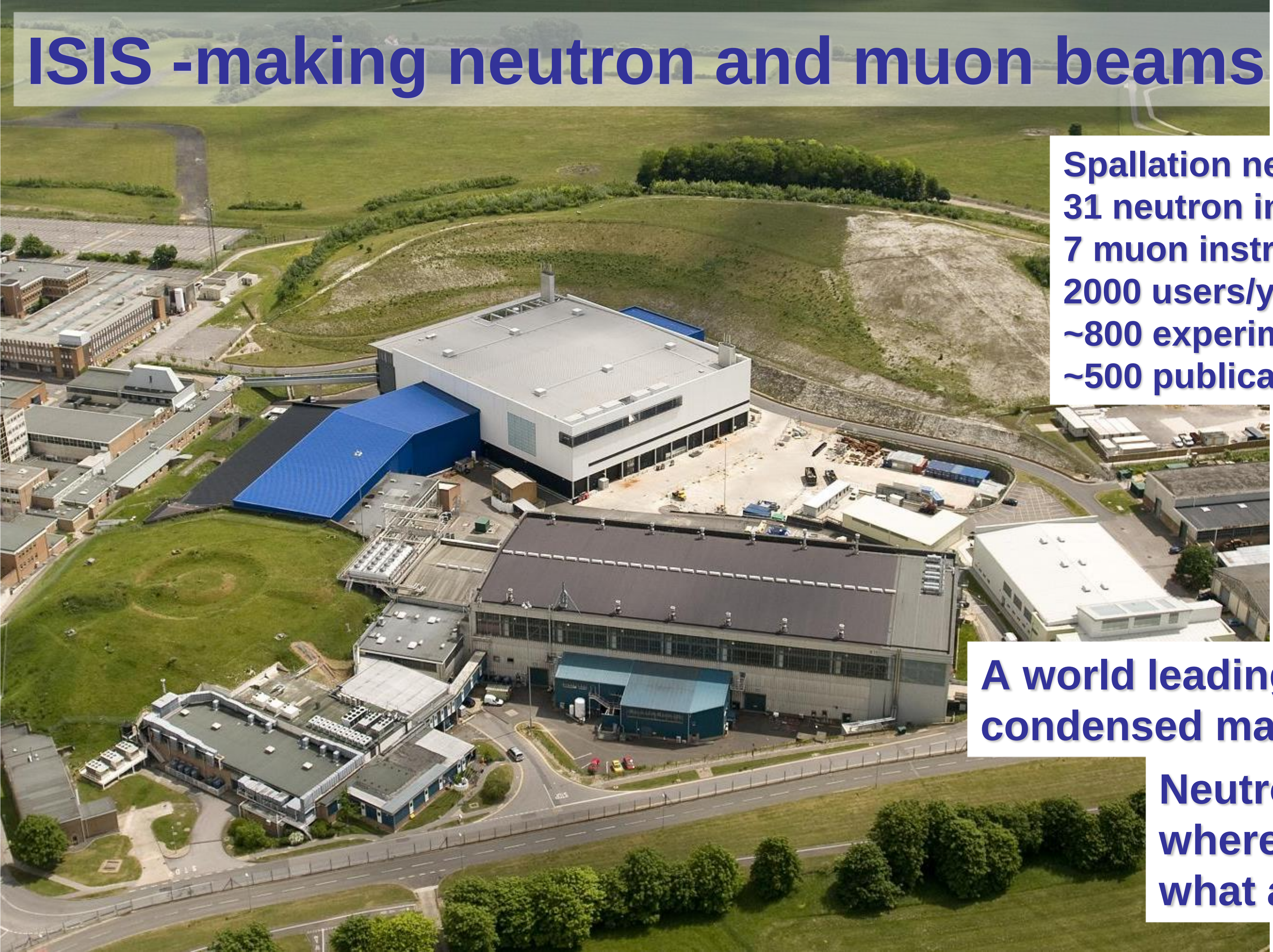
Baryons

W bosons

Z bosons

Higgs bosons

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

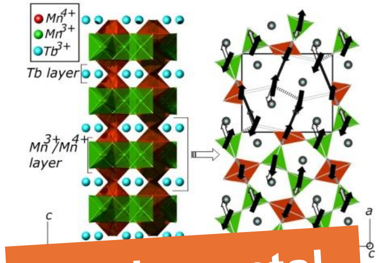
UKRI Science and Technology Facilities Council
ISIS Neutron and Muon Source

A world leading centre for condensed matter physics-

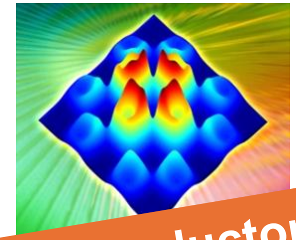
Neutrons are used to see where atoms are and what atoms do

ISIS is used to study everything!

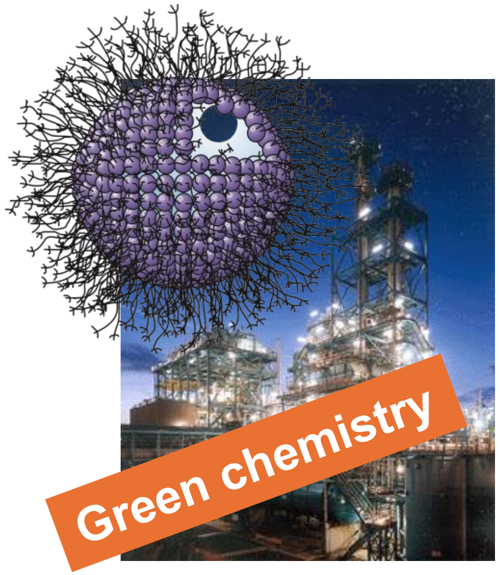
Biological structures



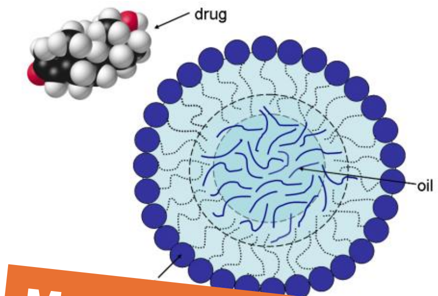
Fundamental magnetism



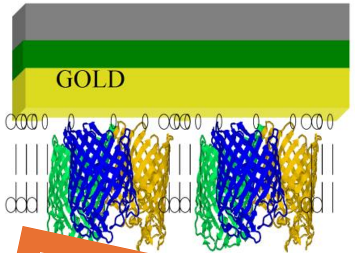
Superconductors



Green chemistry

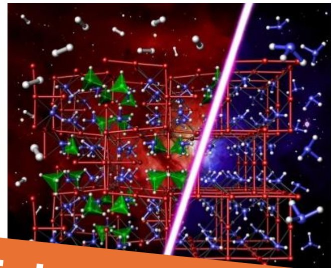


Medical applications



Bio-sensors

Mechanical Engineering



Materials for clean energy

Cultural heritage

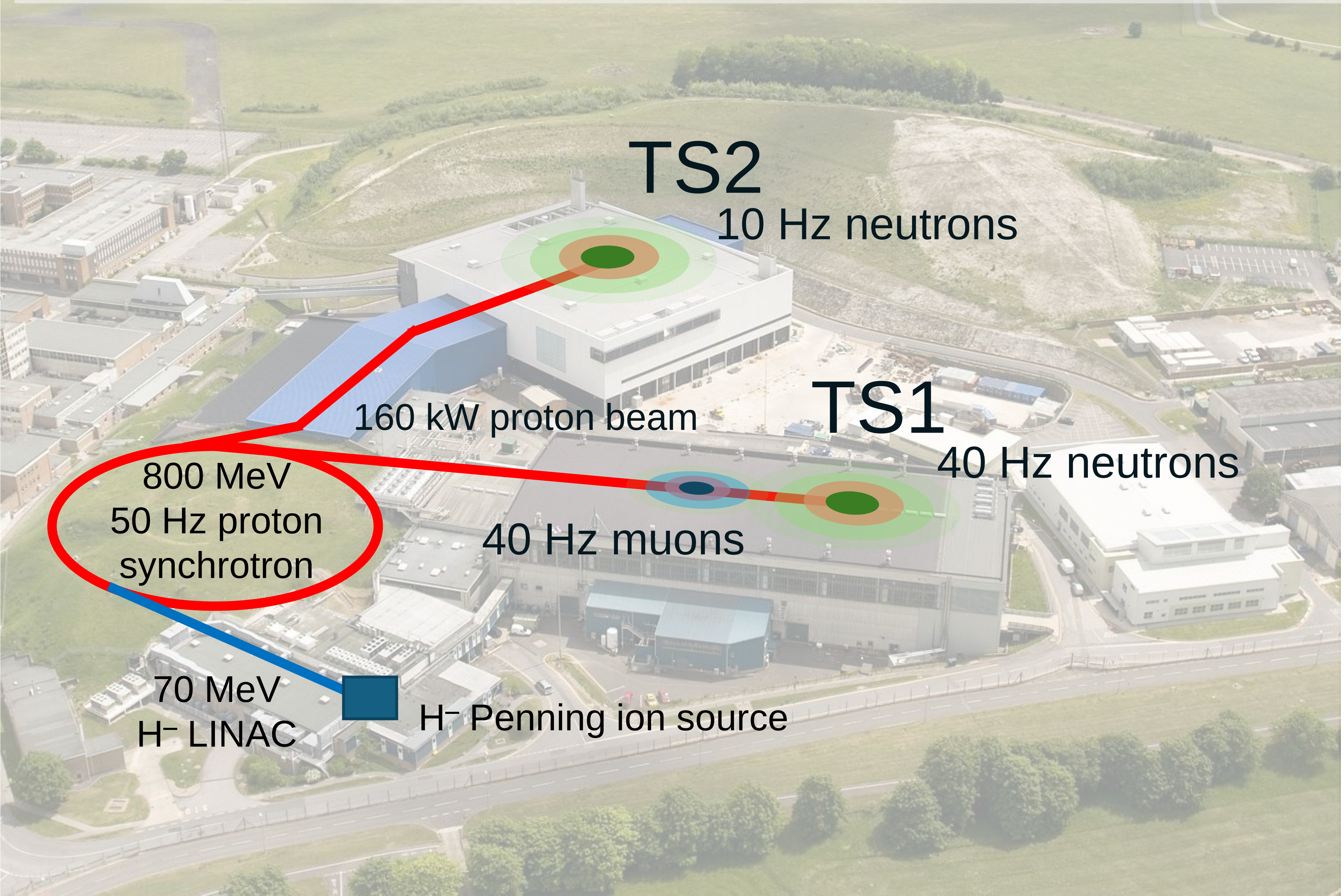
Natural world

Pollution, energy and the environment

UKRI Science and Technology Facilities Council

ISIS Neutron and Muon Source

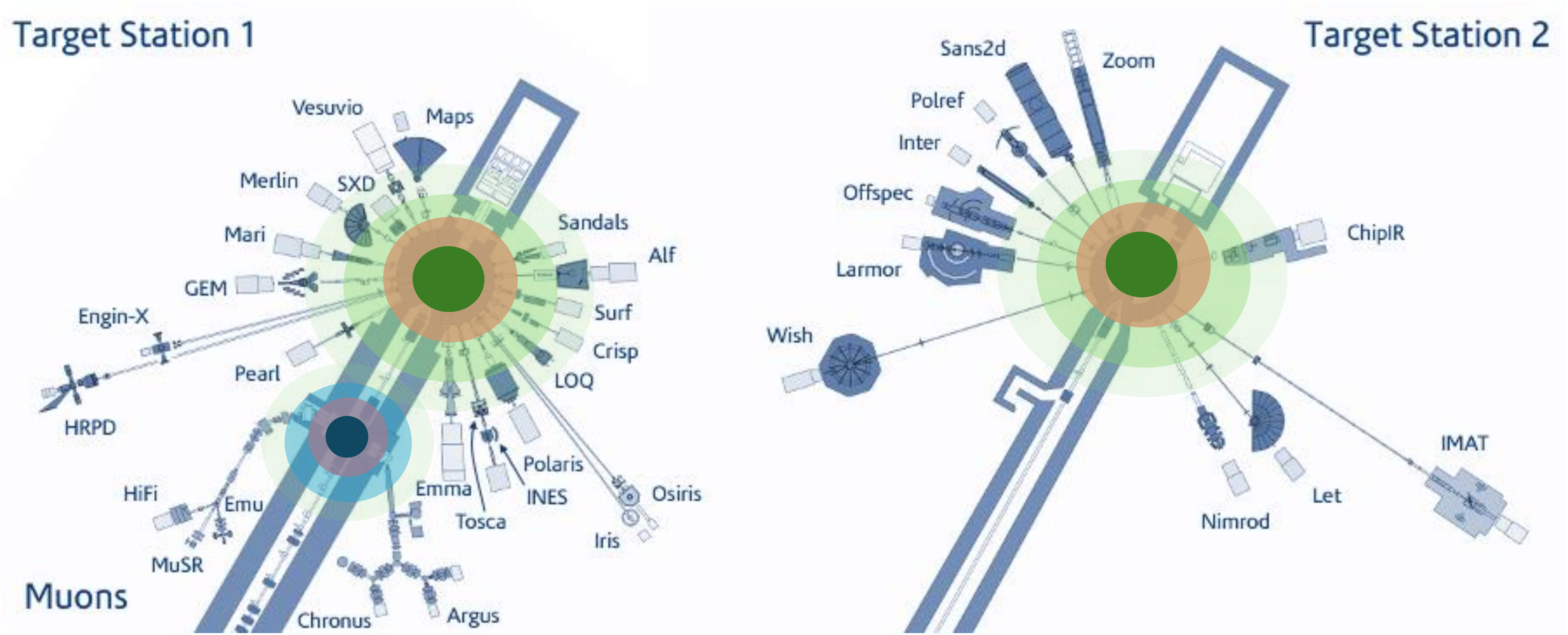
ISIS -making neutron and muon beams since 1984



Science and Technology Facilities Council

ISIS Neutron and Muon Source

ISIS has many different types of instruments:



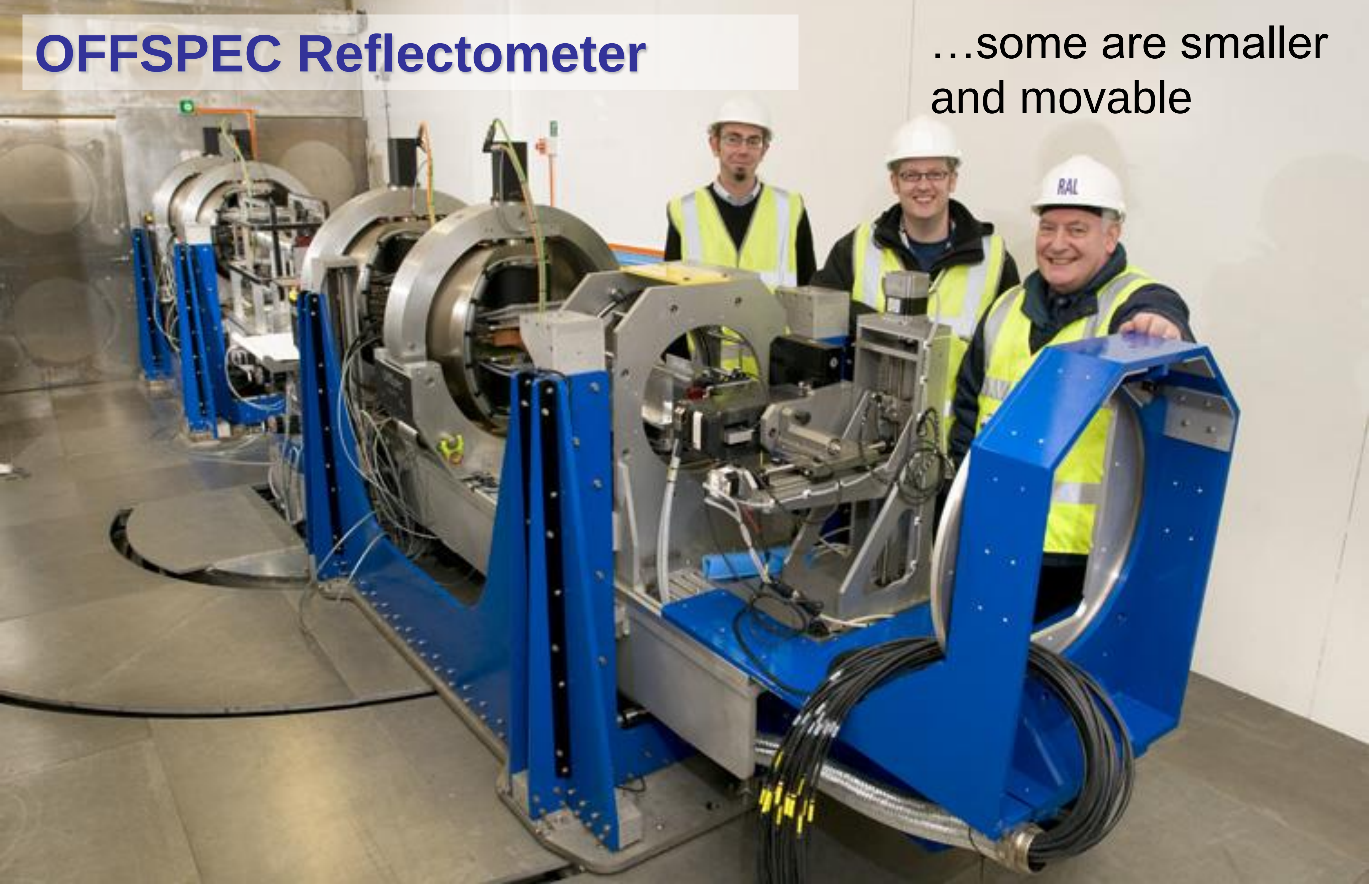
20 neutron instruments
7 muon instruments

11 neutron instruments
(more in the way)

LET Spectrometer

… some instruments are very big

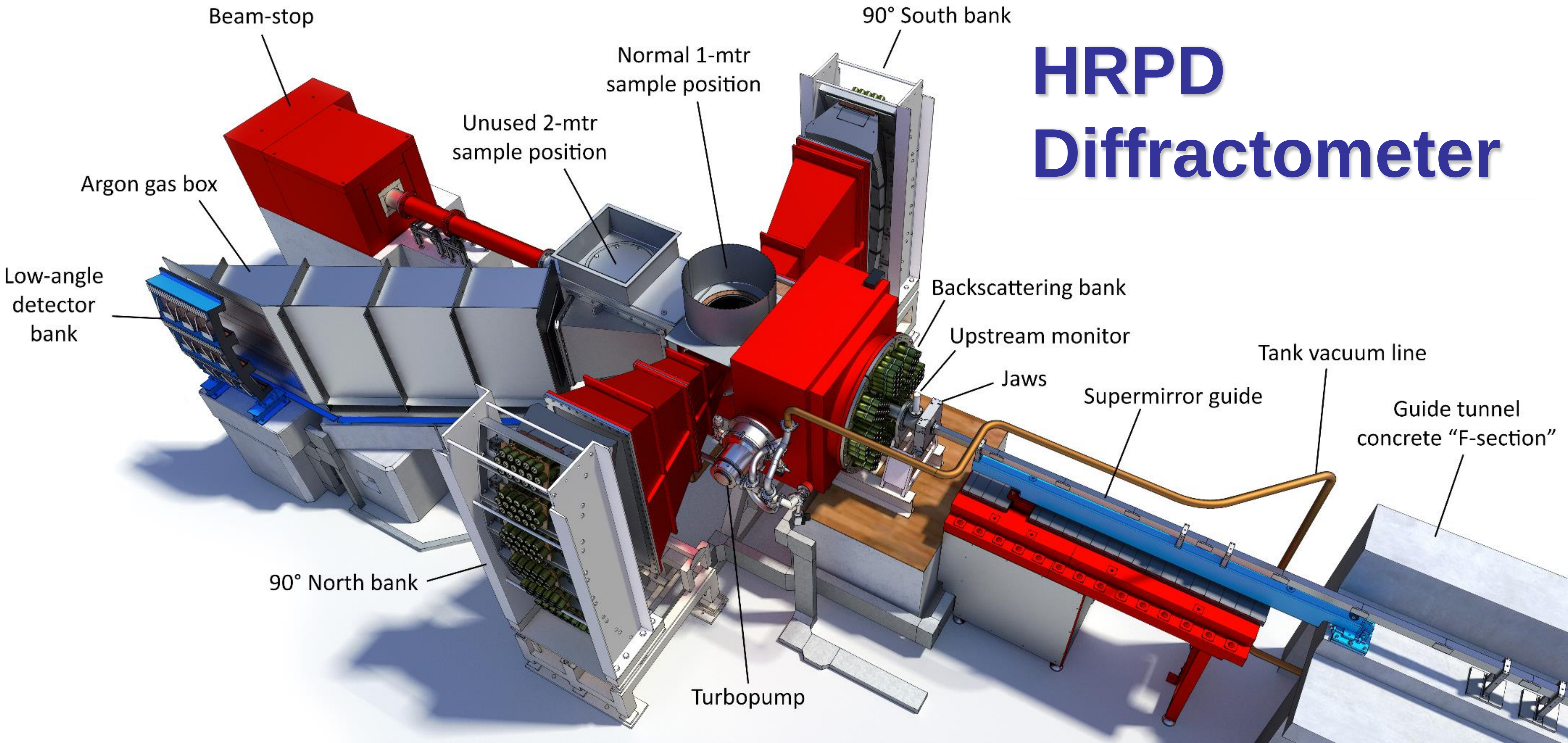
OFFSPEC Reflectometer



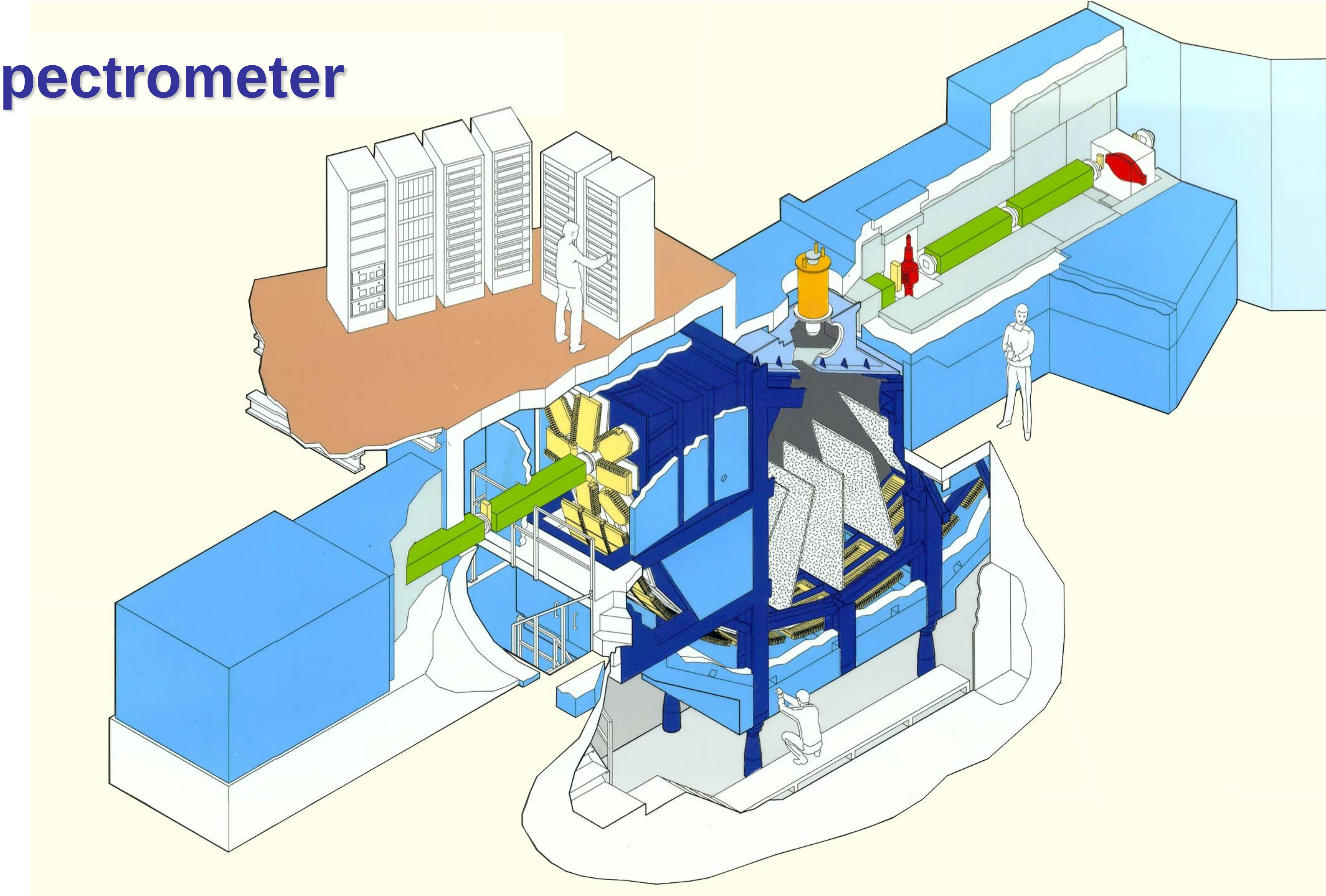
…some are smaller and movable

Each instrument is unique and complex…

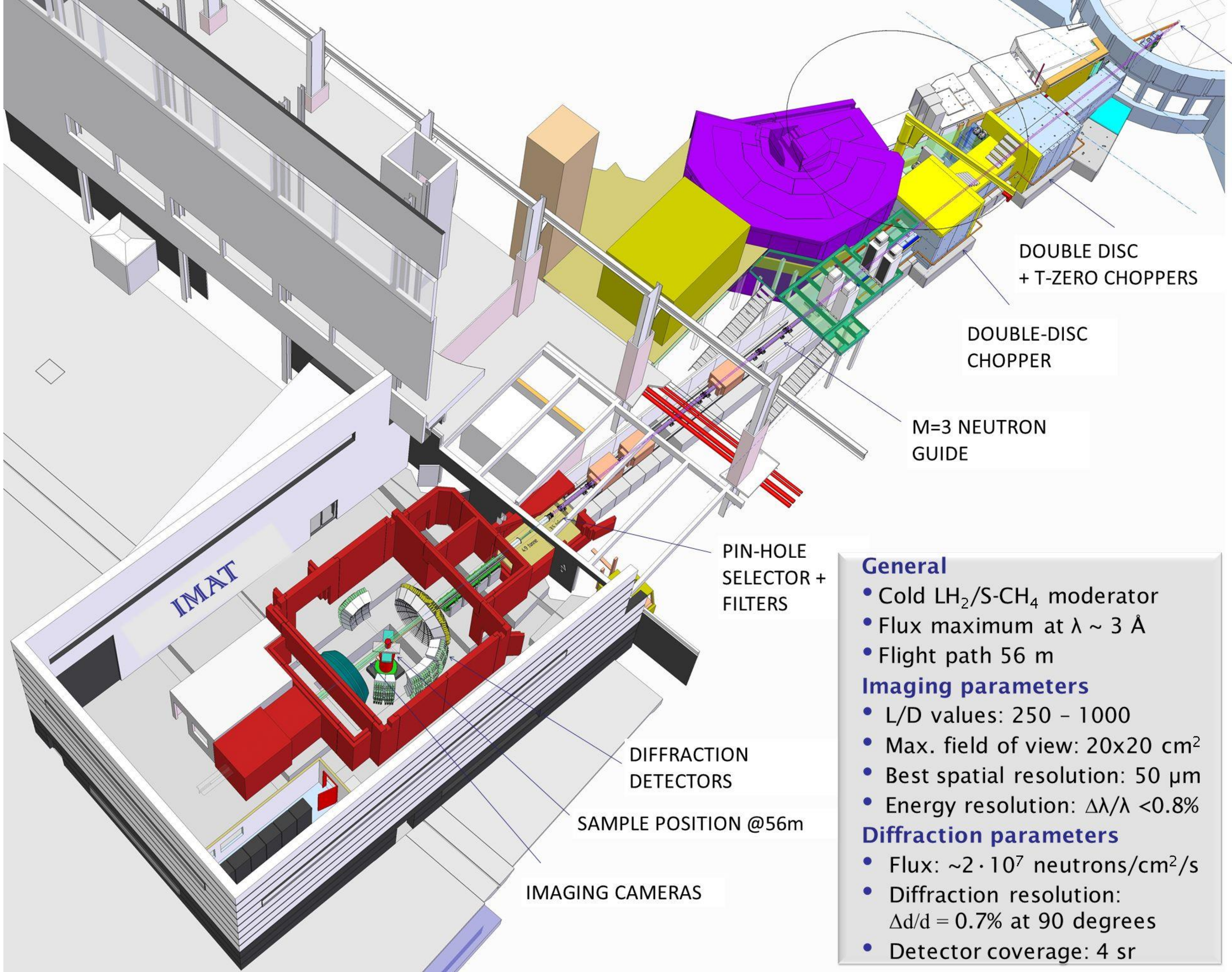
HRPD Diffractometer



MARI Spectrometer



IMAT Diffractometer



General

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

Imaging parameters

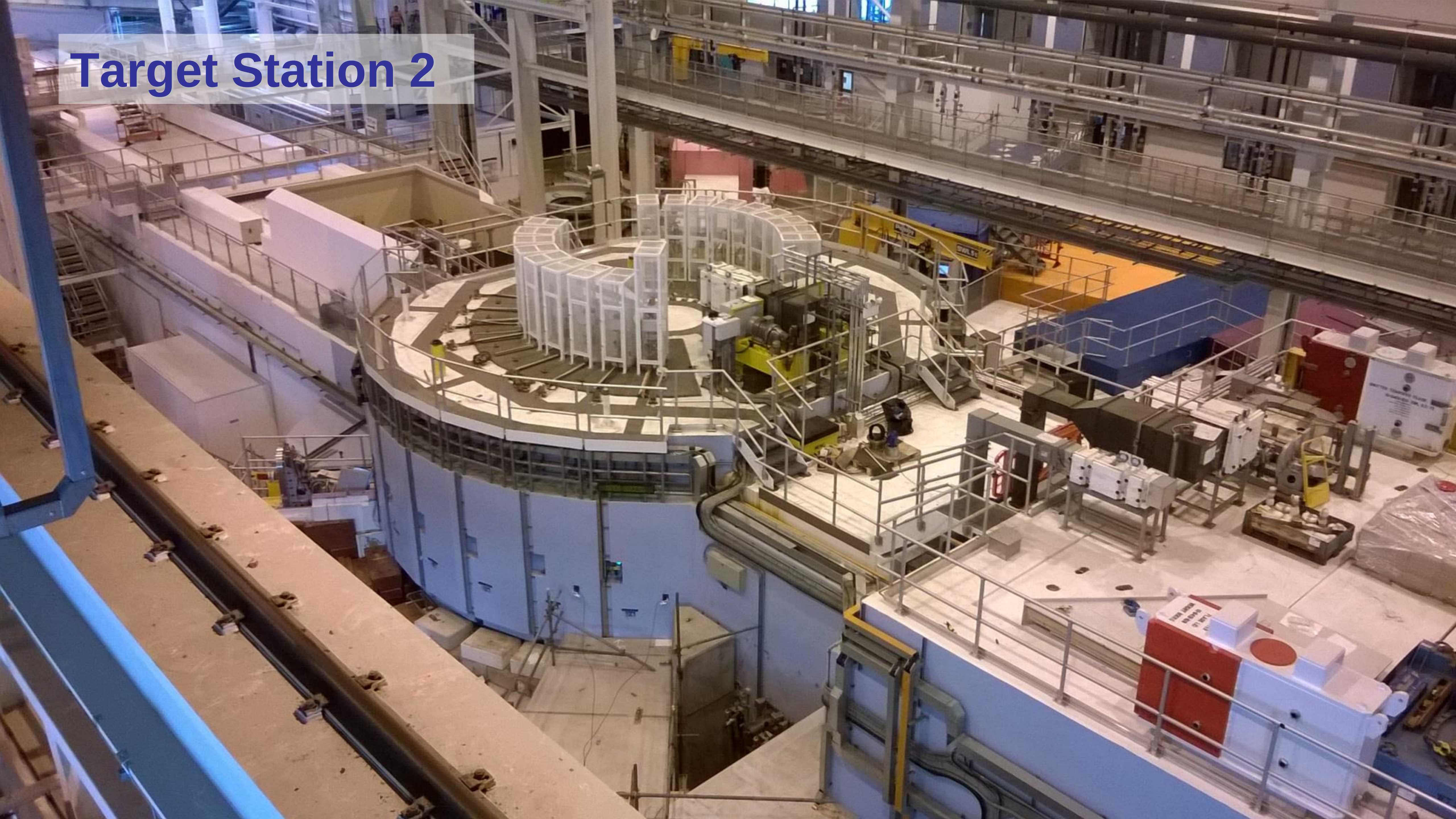
- L/D values: 250 – 1000
- Max. field of view: 20x20 cm^2
- Best spatial resolution: 50 μm
- Energy resolution: $\Delta\lambda/\lambda$ <0.8%

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

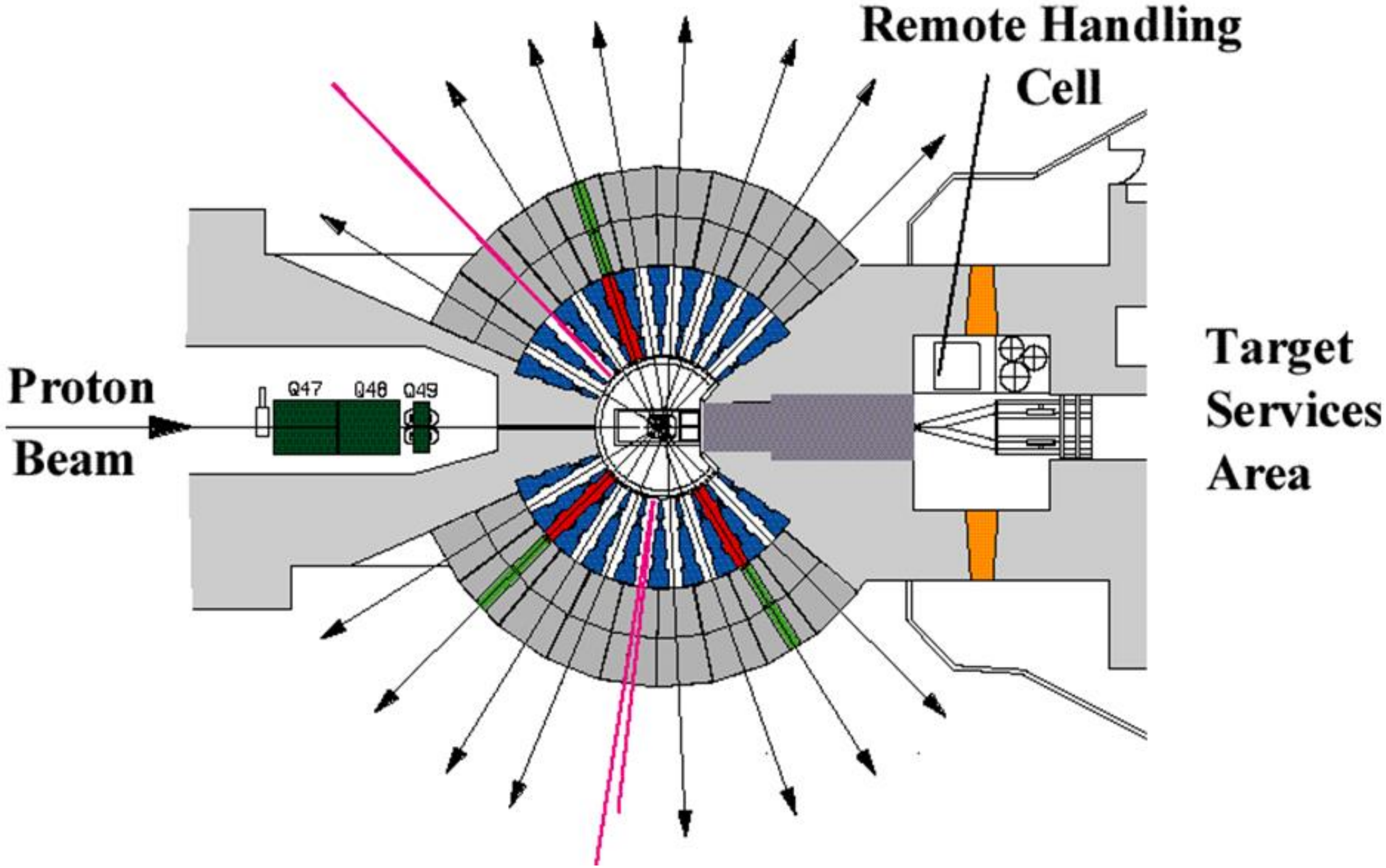
Target Station 1

Target Station 2



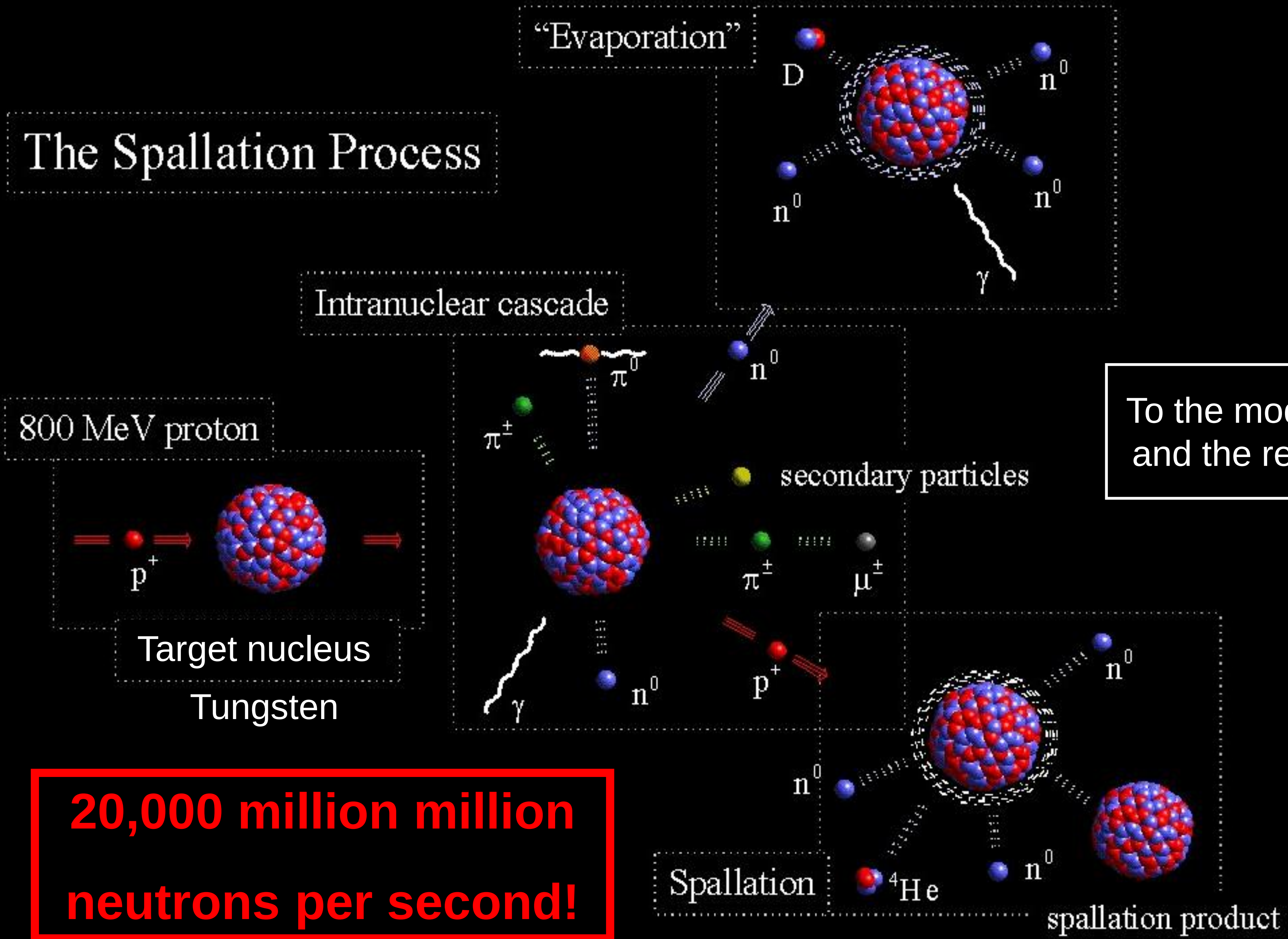
Basic Layout of ISIS Target Stations

Neutron Instruments



Neutron Instruments

The Spallation Process



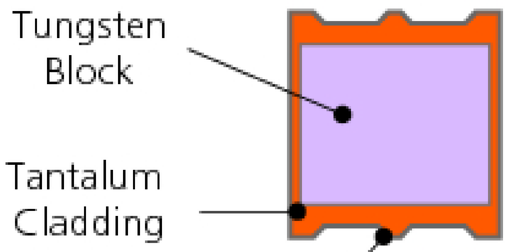
Target nucleus

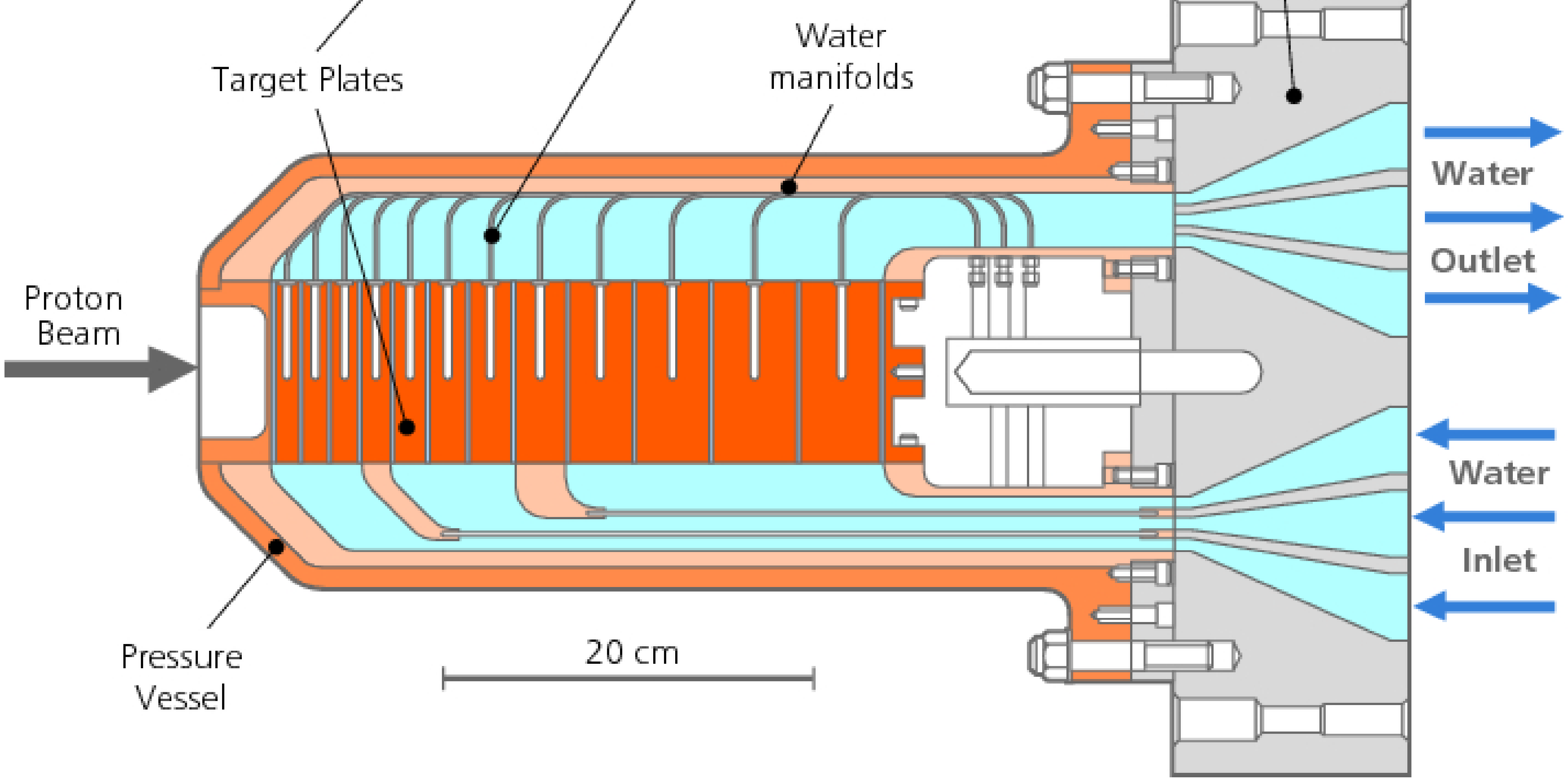
Tungsten

To the moderators and the reflectors

20,000 million million neutrons per second!

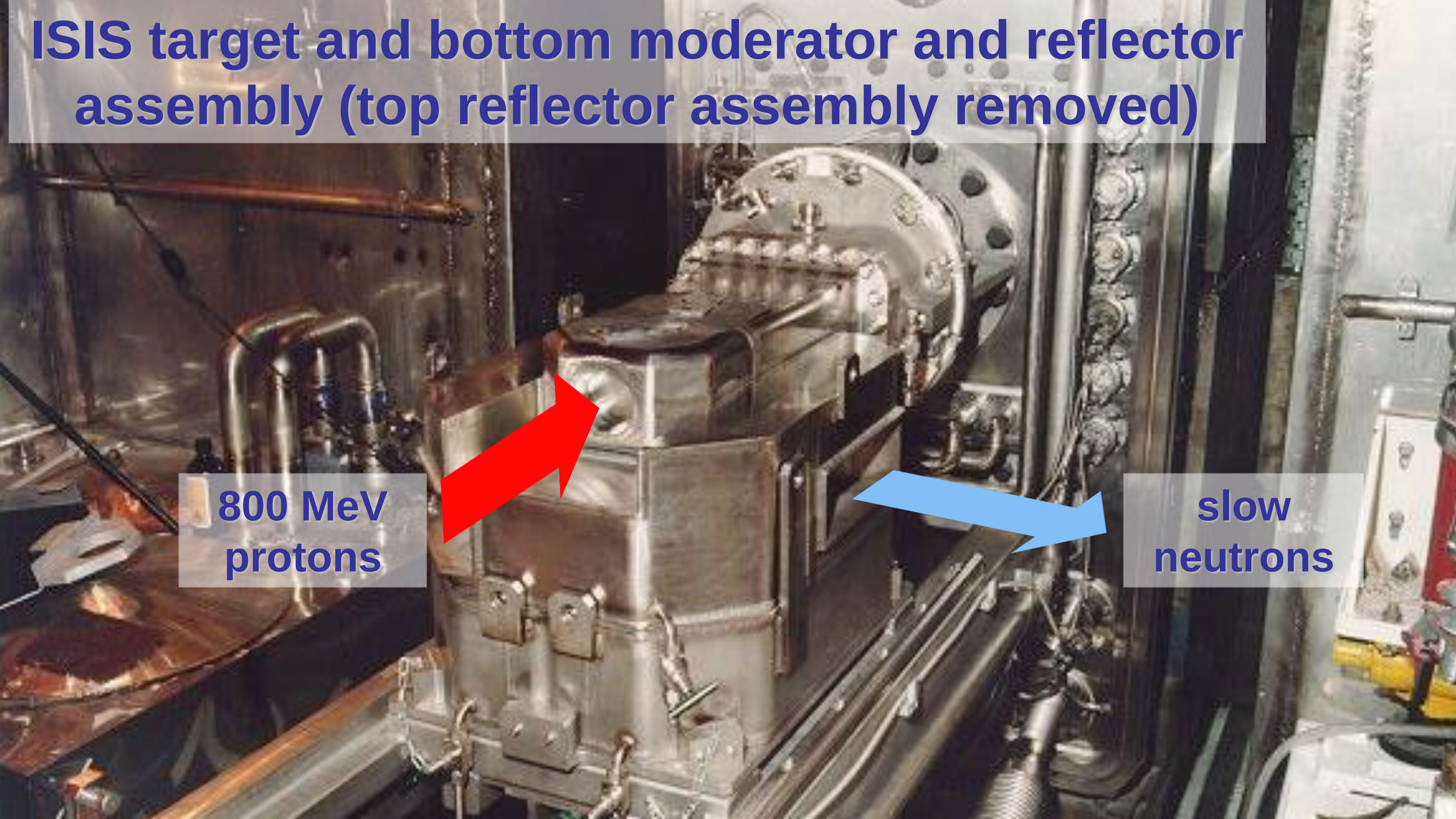
Section view of ISIS TS1 target





160 kW

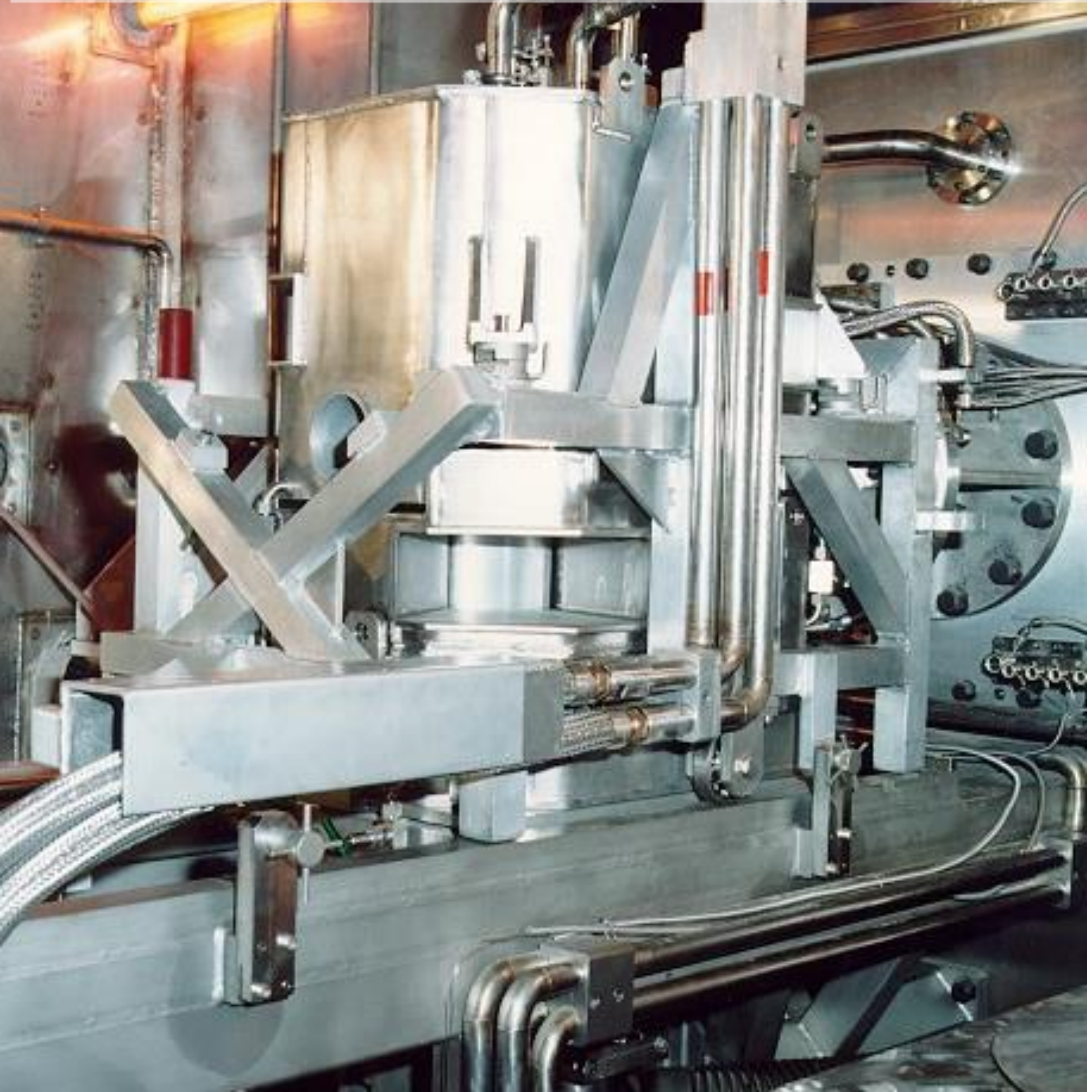
ISIS target and bottom moderator and reflector assembly (top reflector assembly removed)

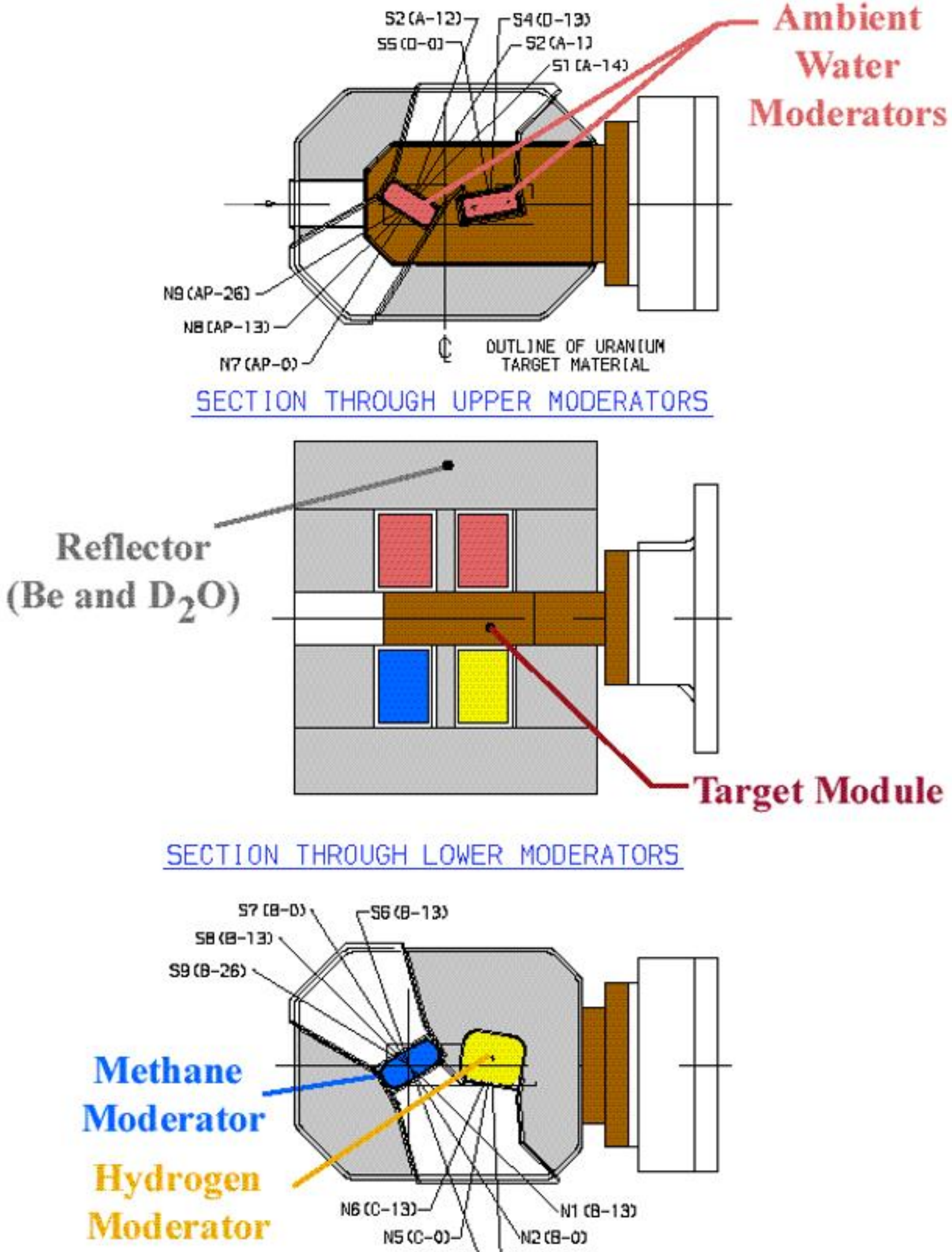


800 MeV protons

slow neutrons

Target Reflector And Moderators (TRAM)





Ambient Water Moderators

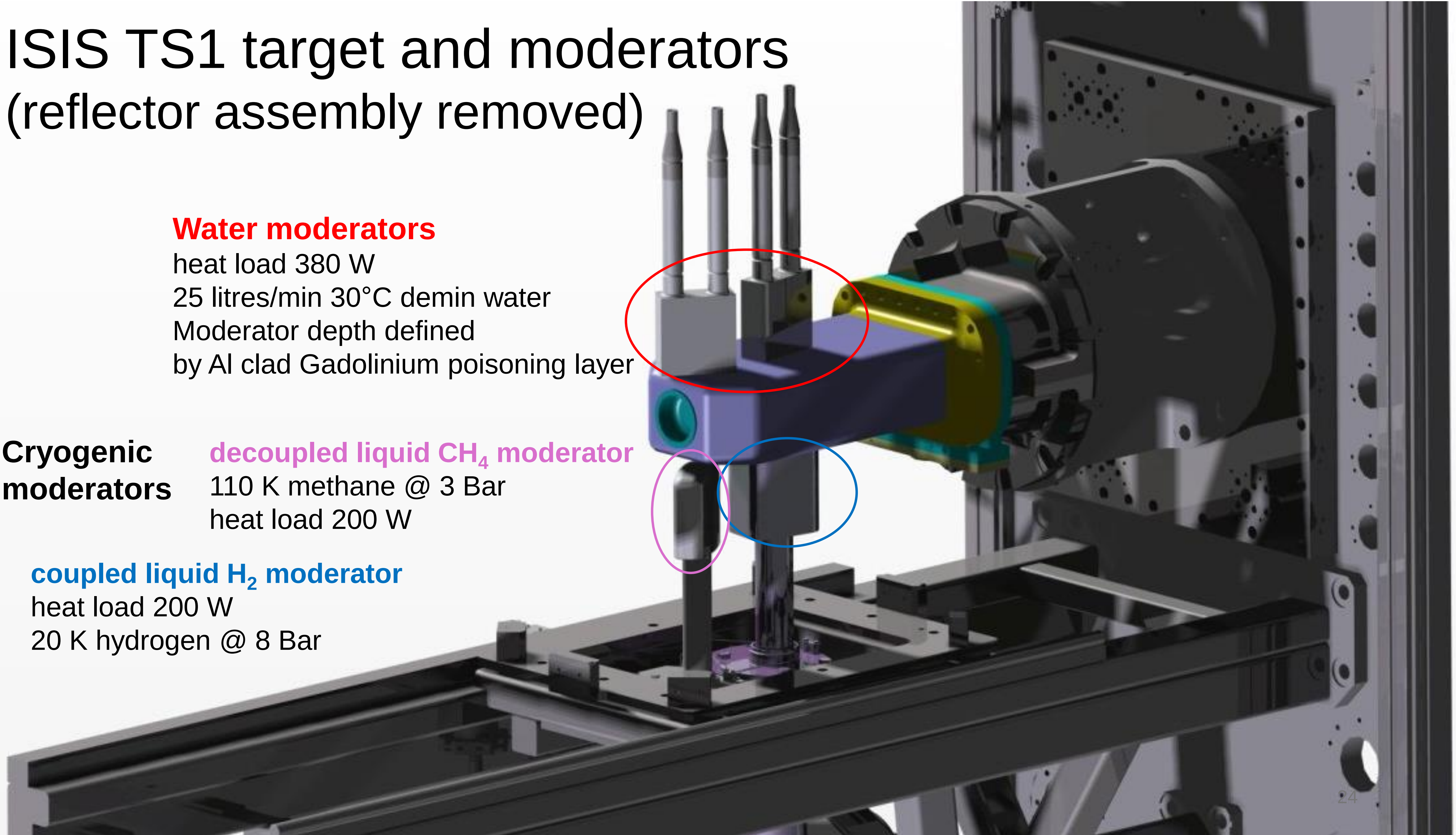
Reflector (Be and D_2O)

Target Module

Methane Moderator

Hydrogen Moderator

ISIS TS1 target and moderators
(reflector assembly removed)



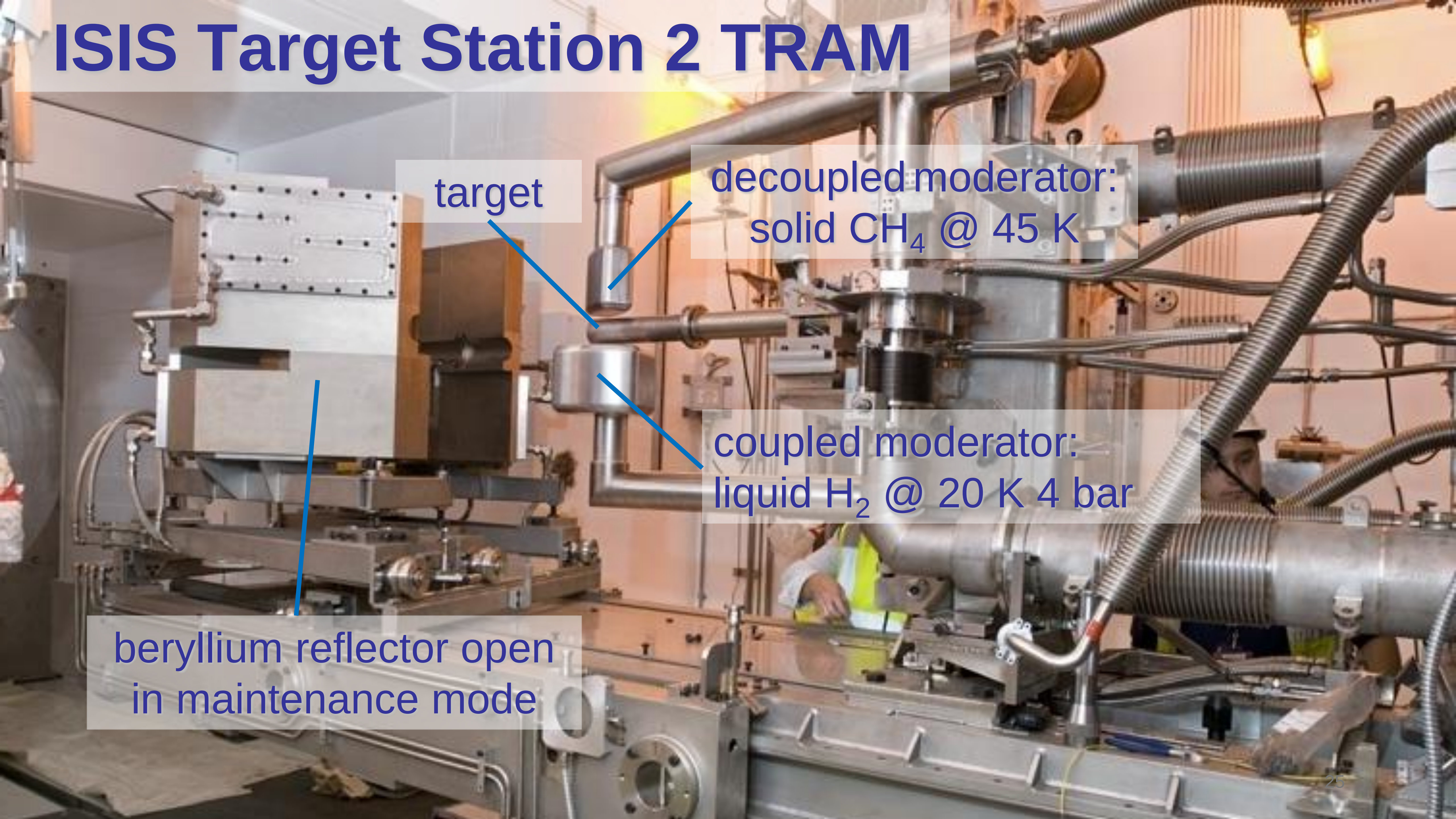
Water moderators
heat load 380 W
25 litres/min 30°C demin water
Moderator depth defined
by Al clad Gadolinium poisoning layer

Cryogenic moderators

decoupled liquid 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



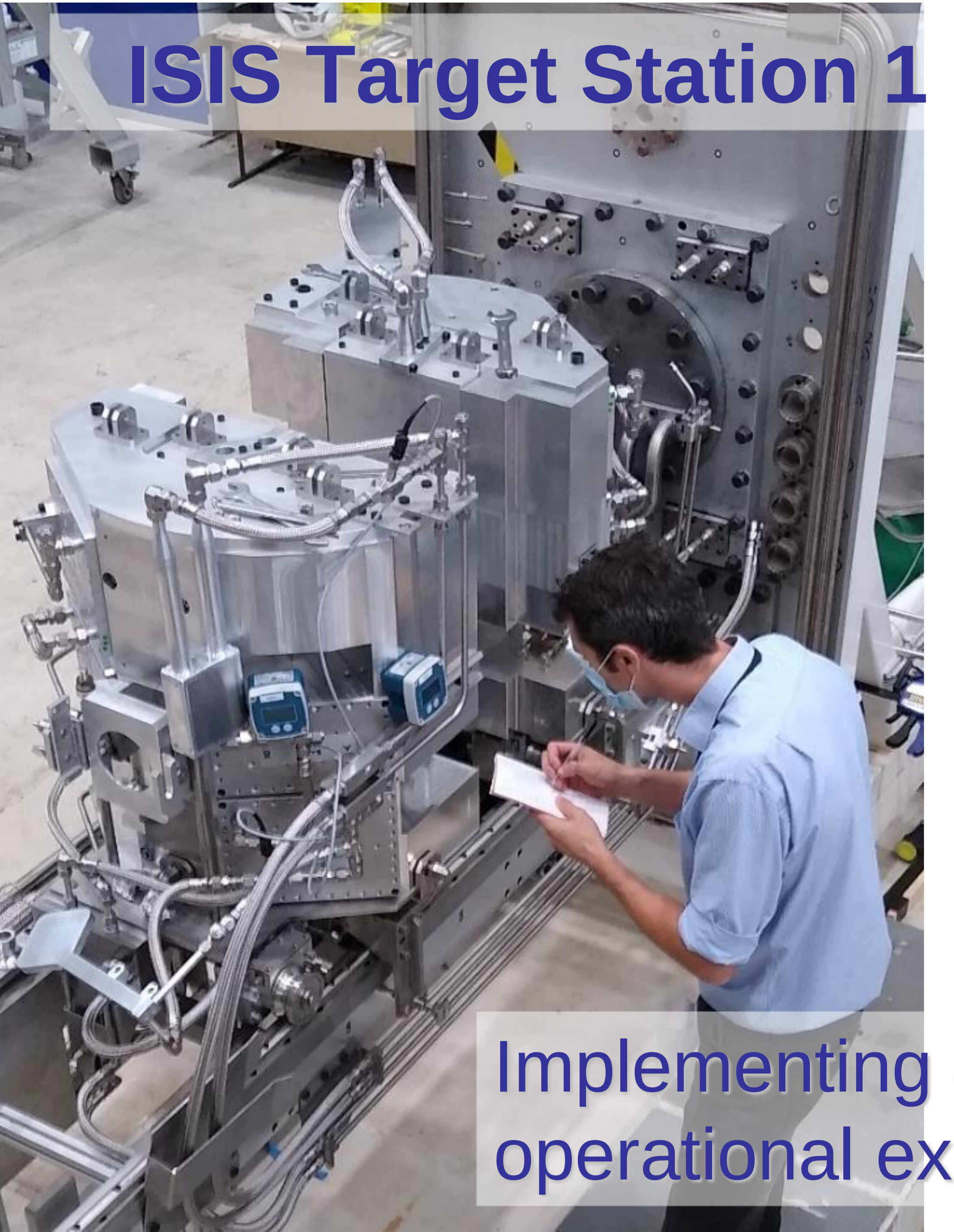
target

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

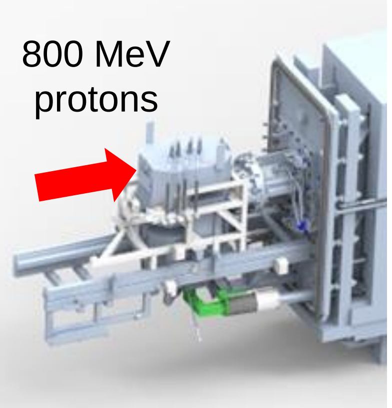


£20M Project

Operational this year!

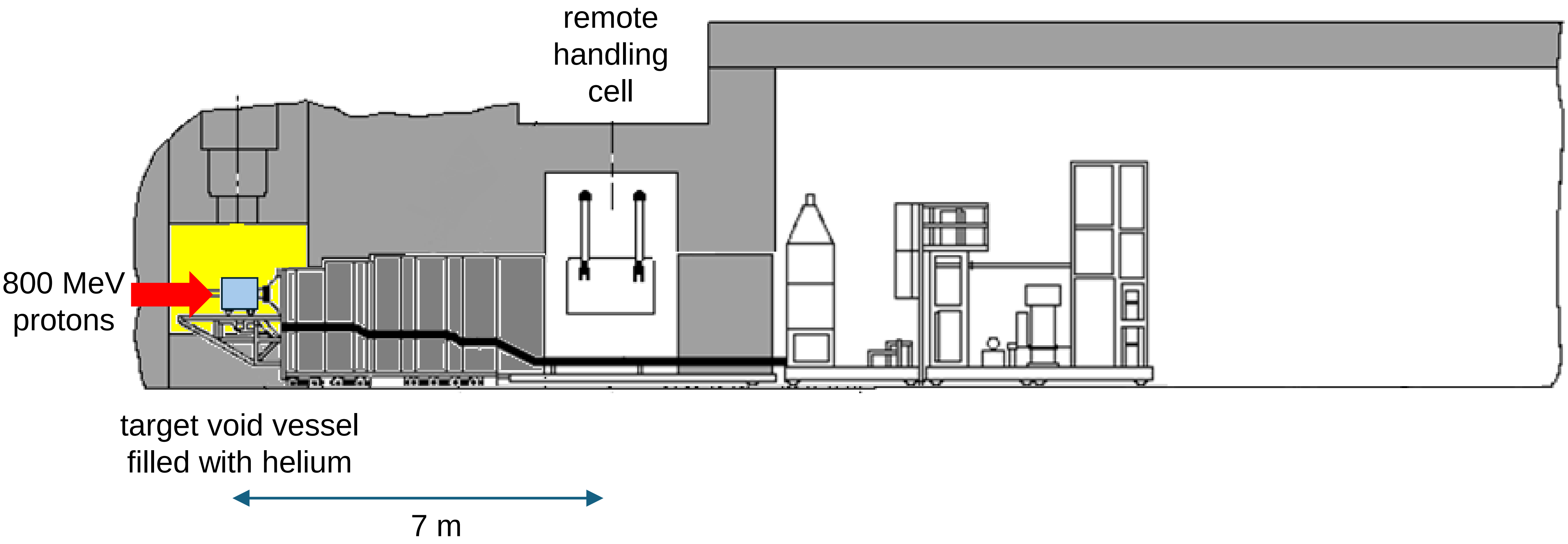
Implementing 40 years of operational experience

ISIS Target Trolley

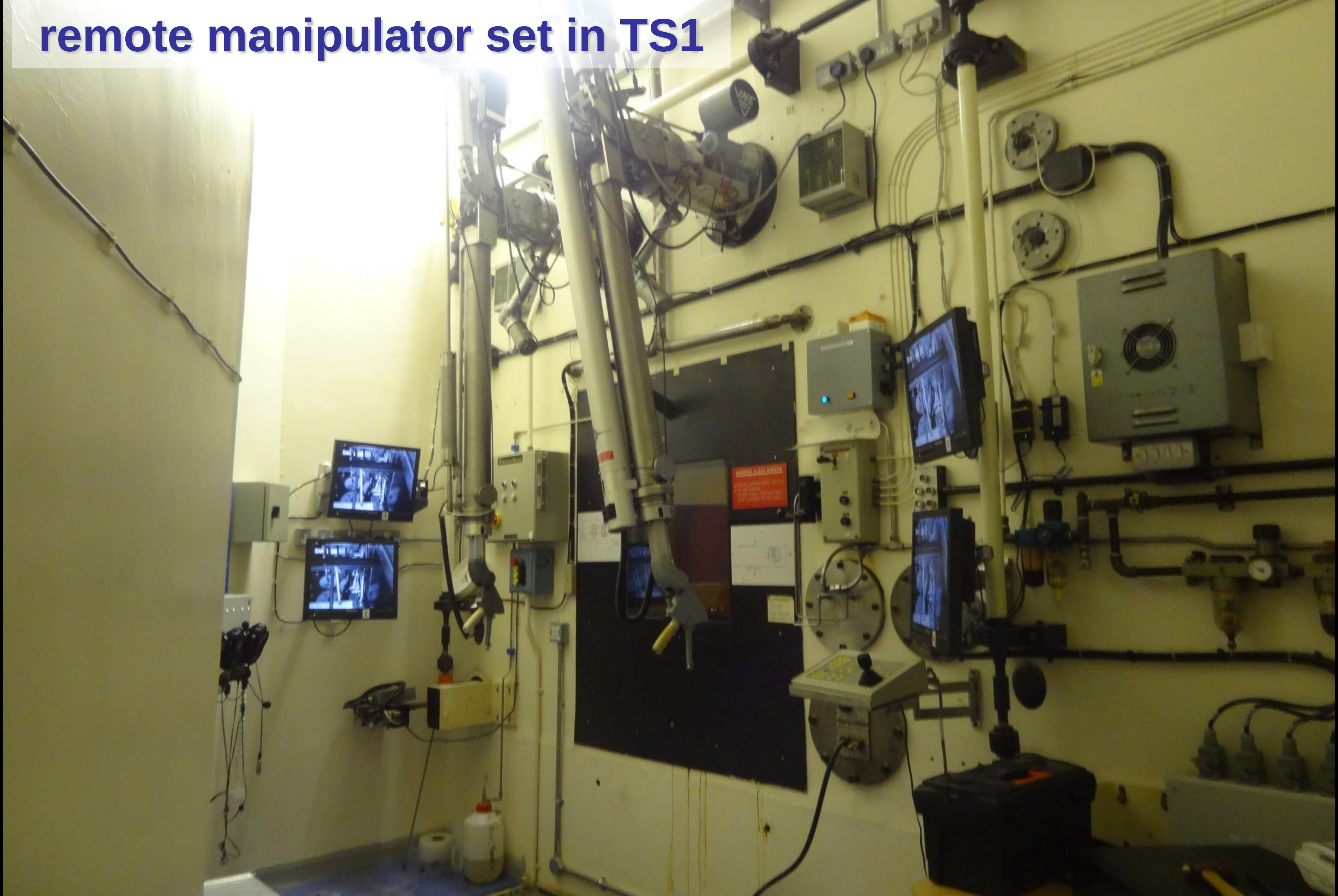


The TRAM is just one part of the target trolley

ISIS Target Trolley

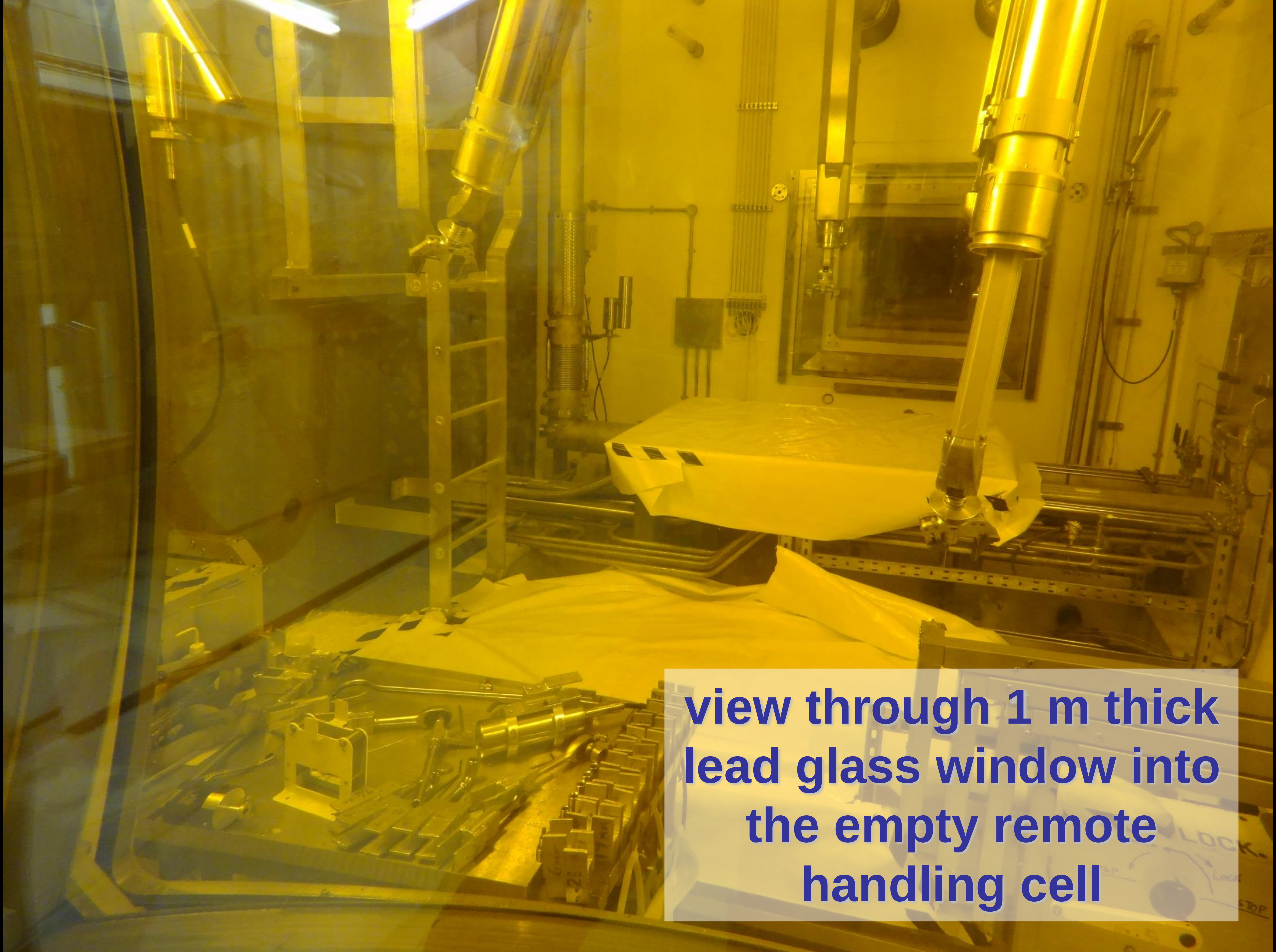


remote manipulator set in TS1



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

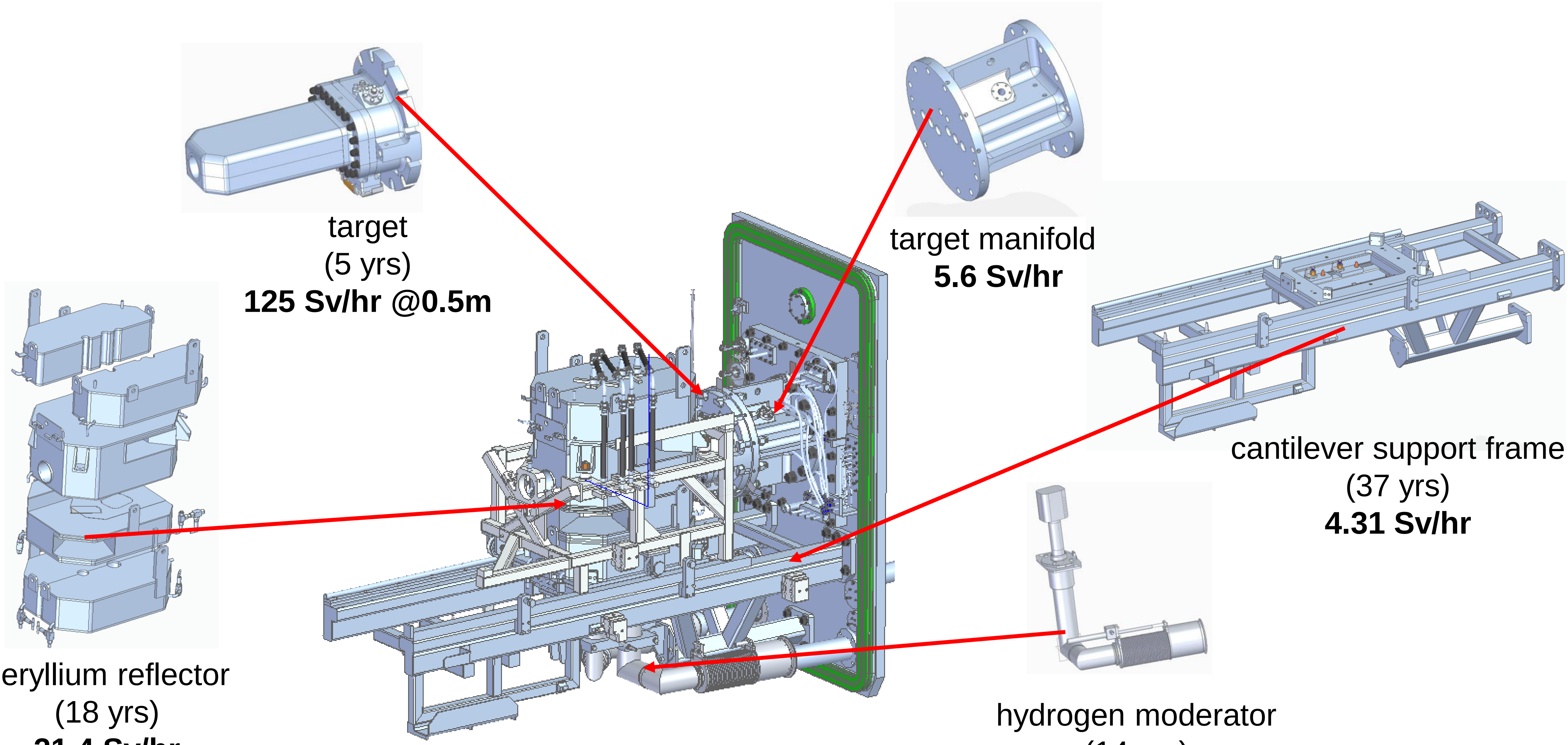
remote handling cell

800 MeV protons

target void vessel filled with helium

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

cantilever support frame
(37 yrs)
4.31 Sv/hr

beryllium reflector
(18 yrs)
21.4 Sv/hr

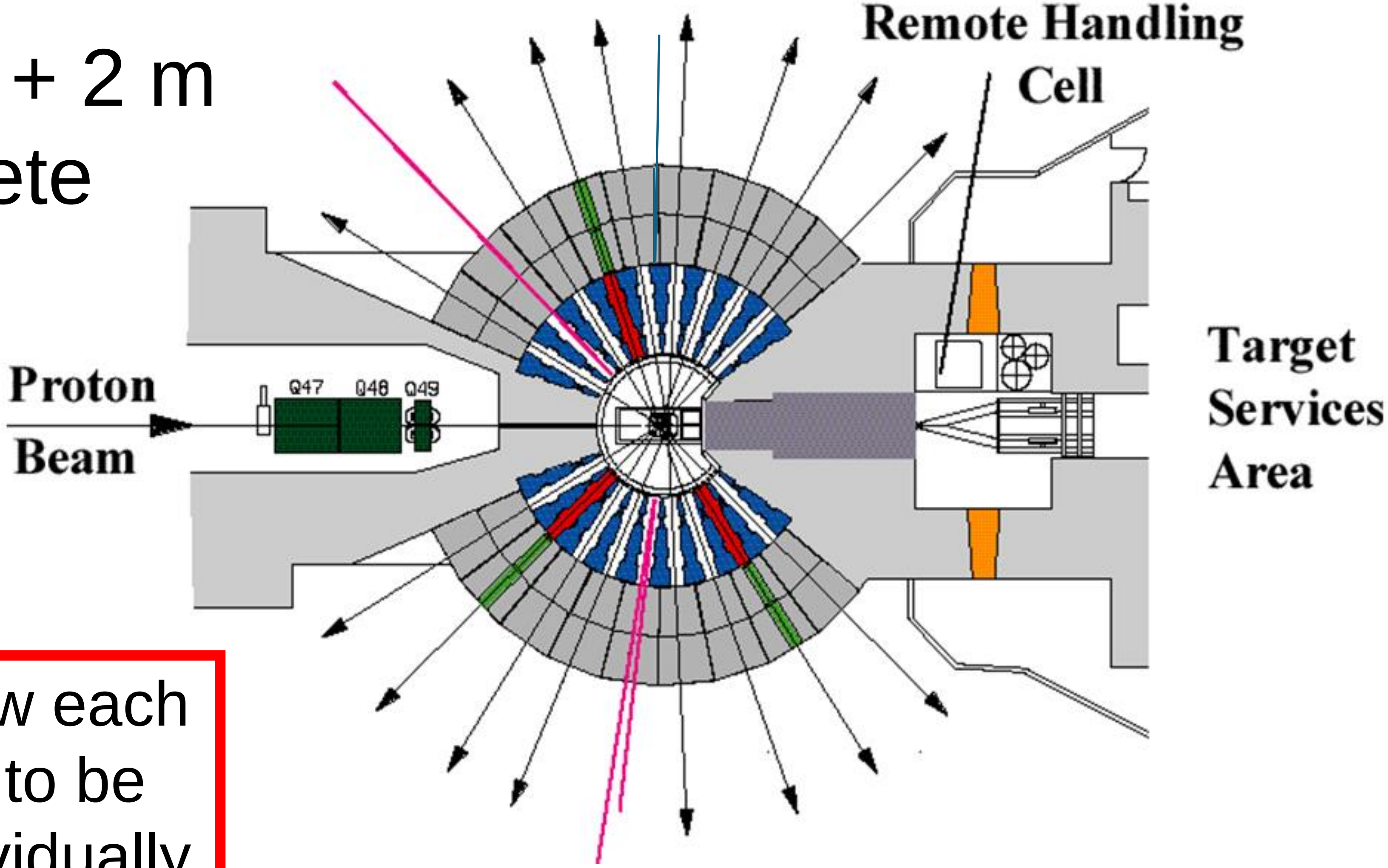
hydrogen moderator
(14 yrs)
6.15 Sv/hr

contact doses (unless specified)

Shielding

2 m steel + 2 m concrete

neutron instruments



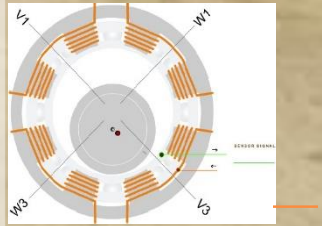
neutron instruments

shutters allow each instrument to be isolated individually

Choppers

spinning shielding shutters

magnetically levitating bearings

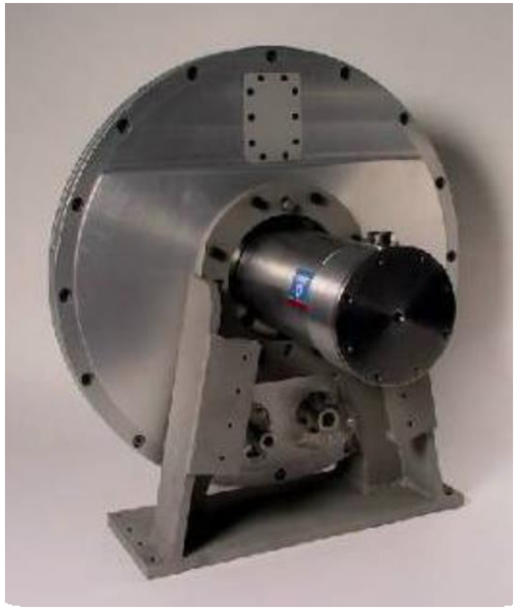


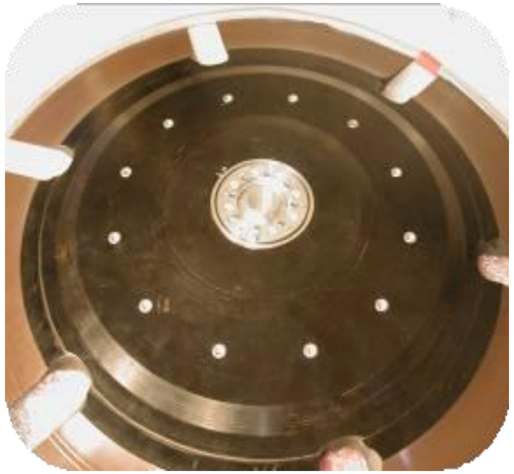
precise timing

Choppers

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

Methane moderator replacement

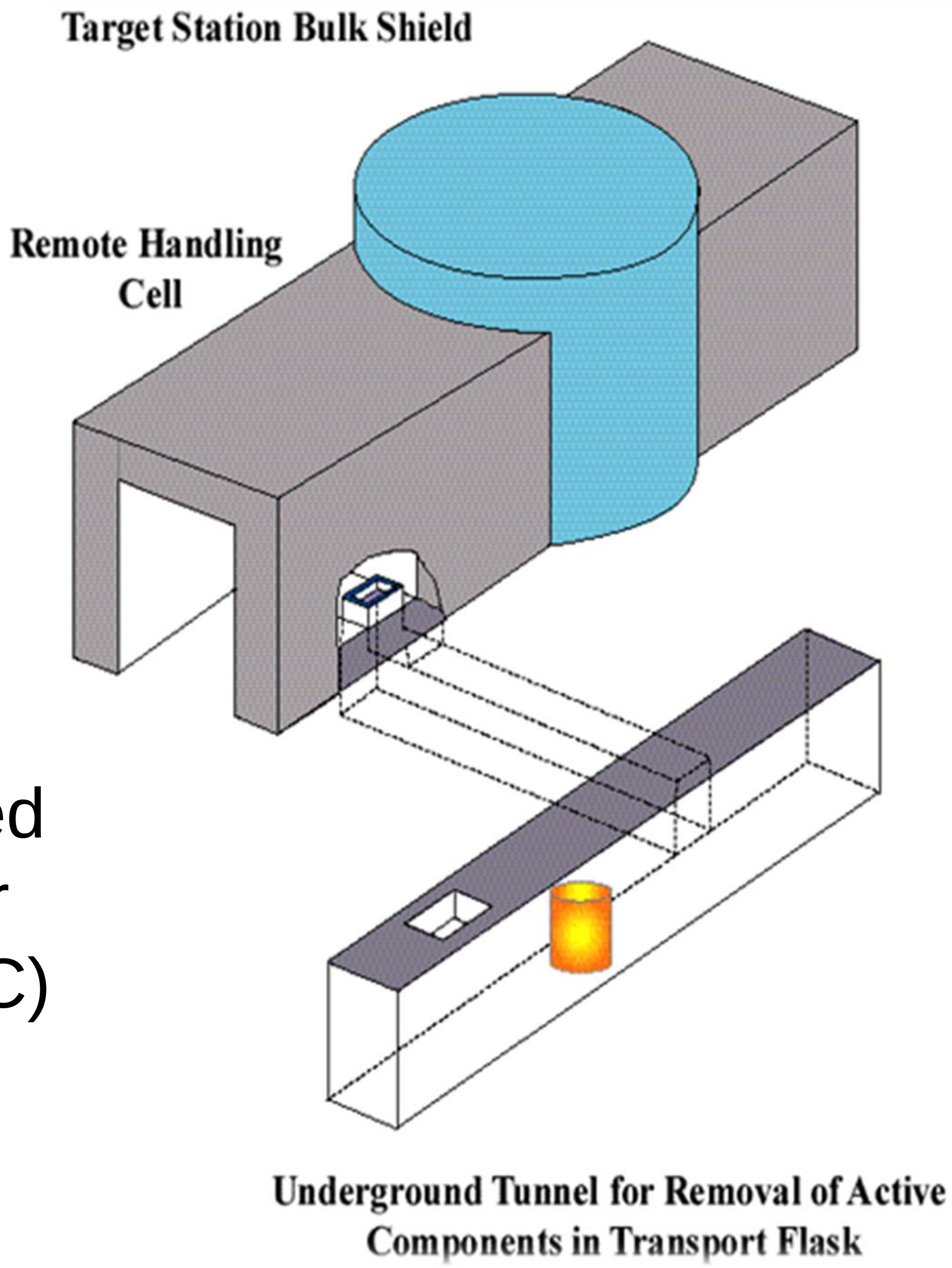
The main remote handling task is CH_4 moderator replacement
Every 3-4 cycles (more than once a year)

Target replacement

Targets also need to be replaced every 4-5 years

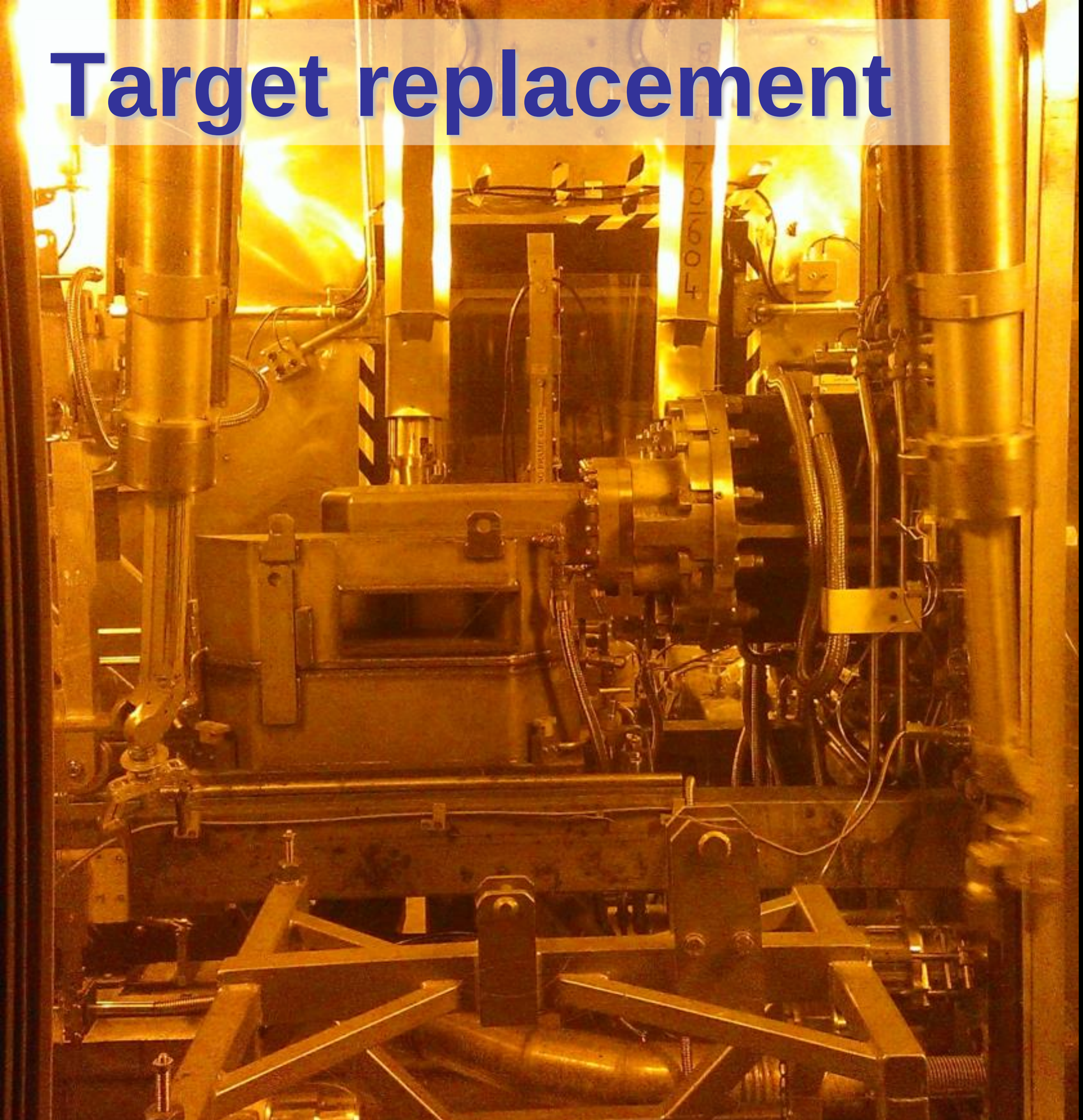
TS1 Tungsten Target #4 on flow test rig

Target replacement



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

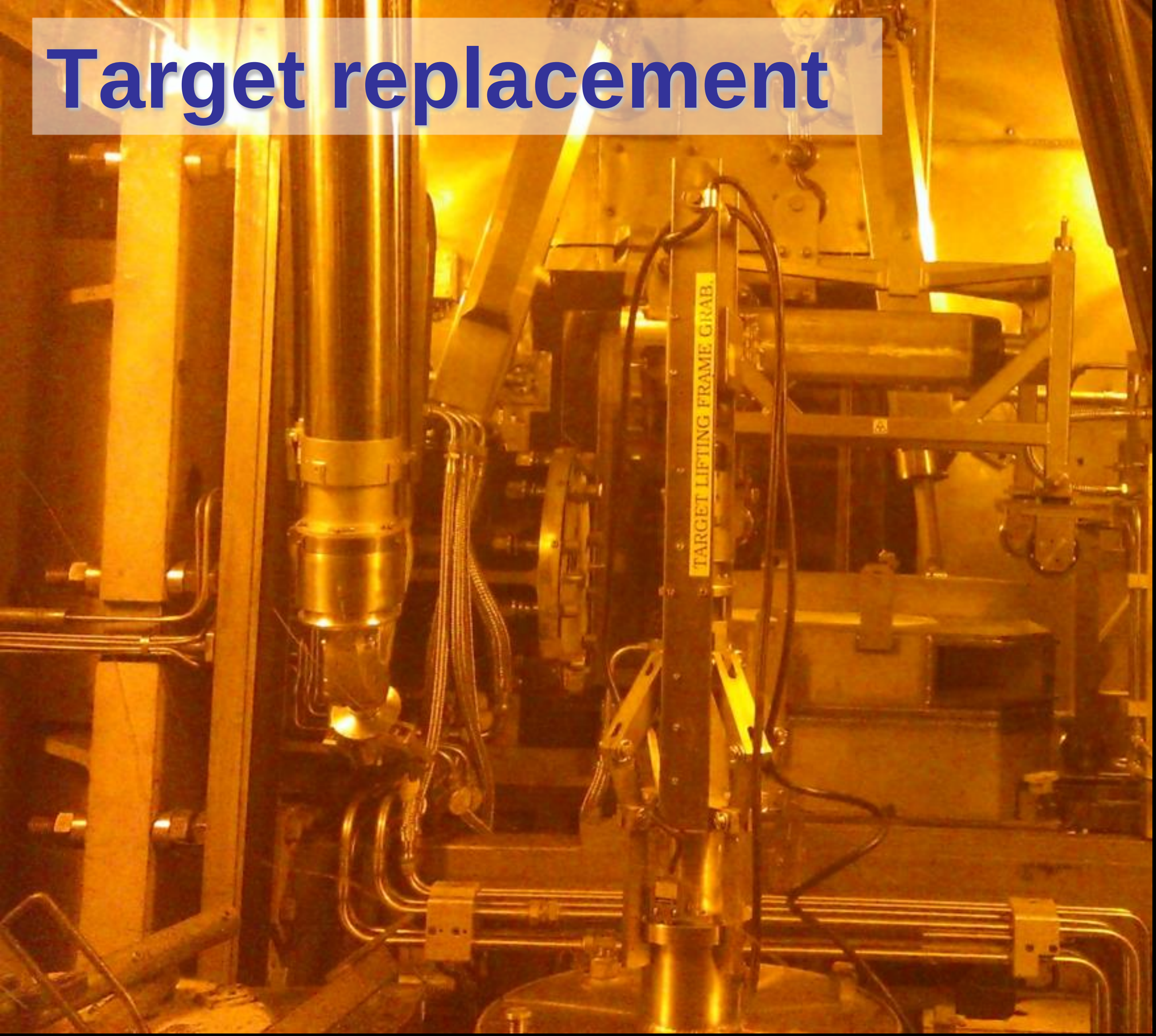
Target replacement



View of the TS1 TRAM withdrawn into the RHC

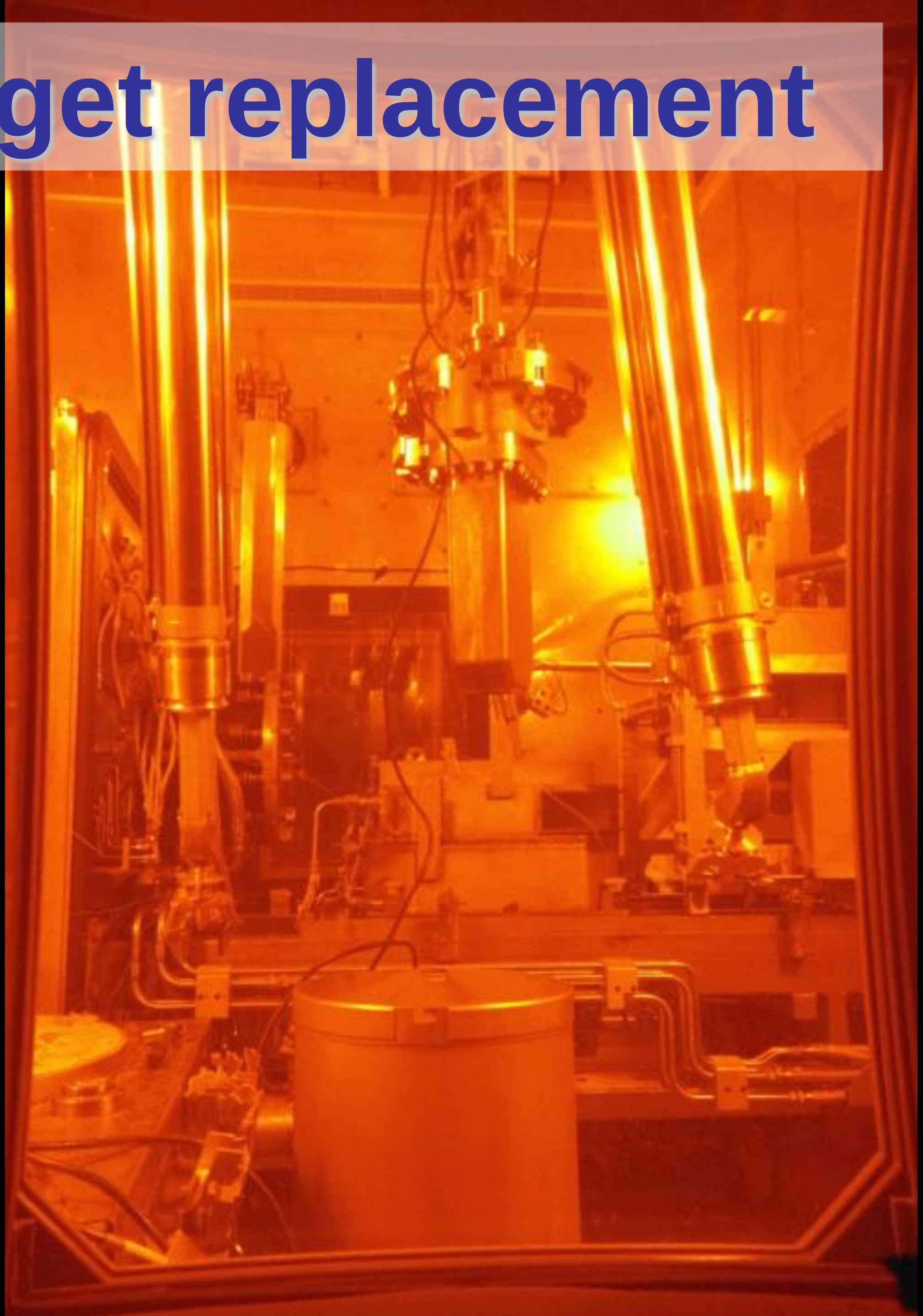
The reflector top section is rolled forward to expose the target

Target replacement



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

Target replacement

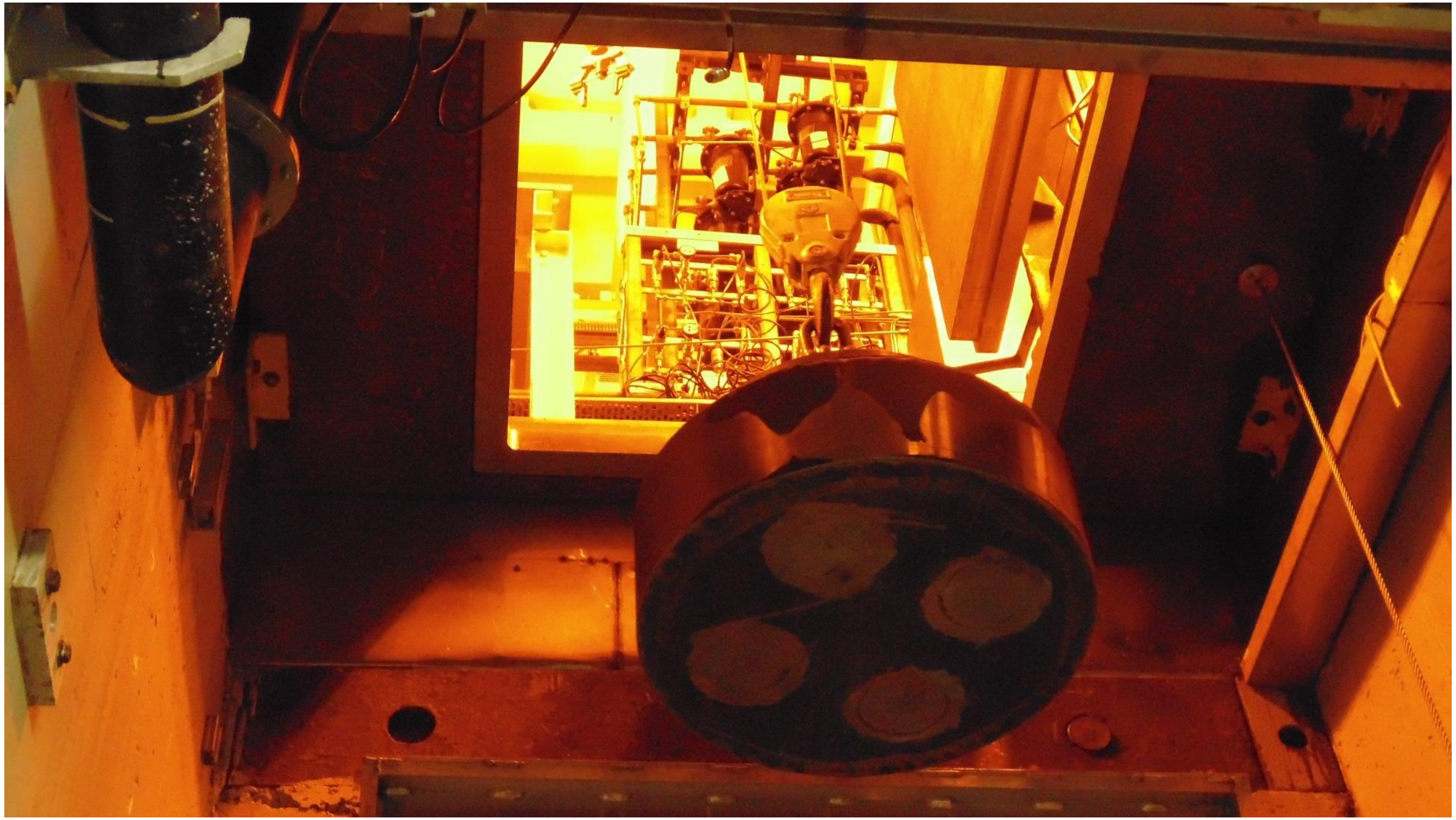


The target being lifted over to the disposal can on the south side of the RHC

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

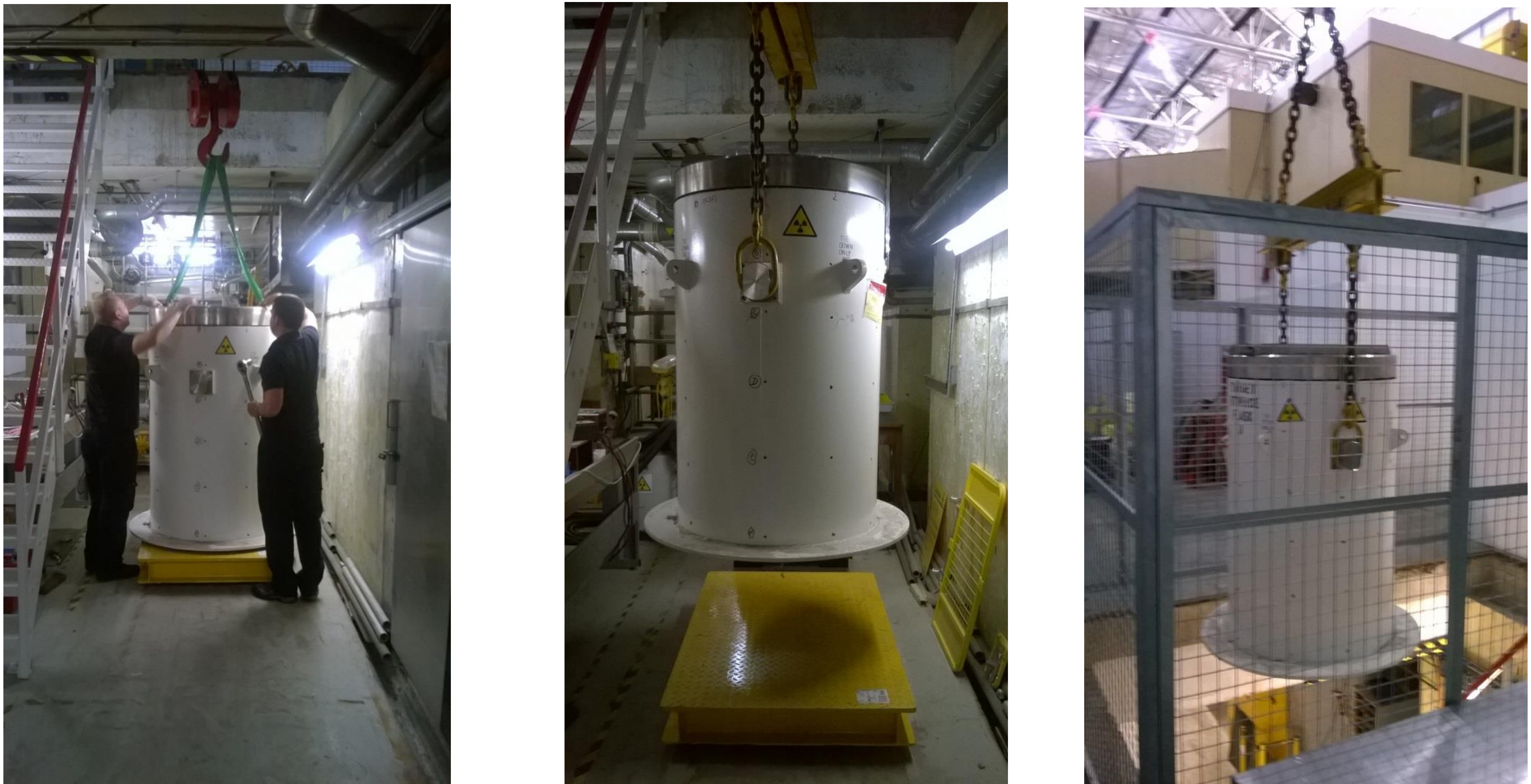
Target replacement

Storage flask total weight is 9 Tonnes

Flask is moved on a ‘MasterMover’ powered pallet truck

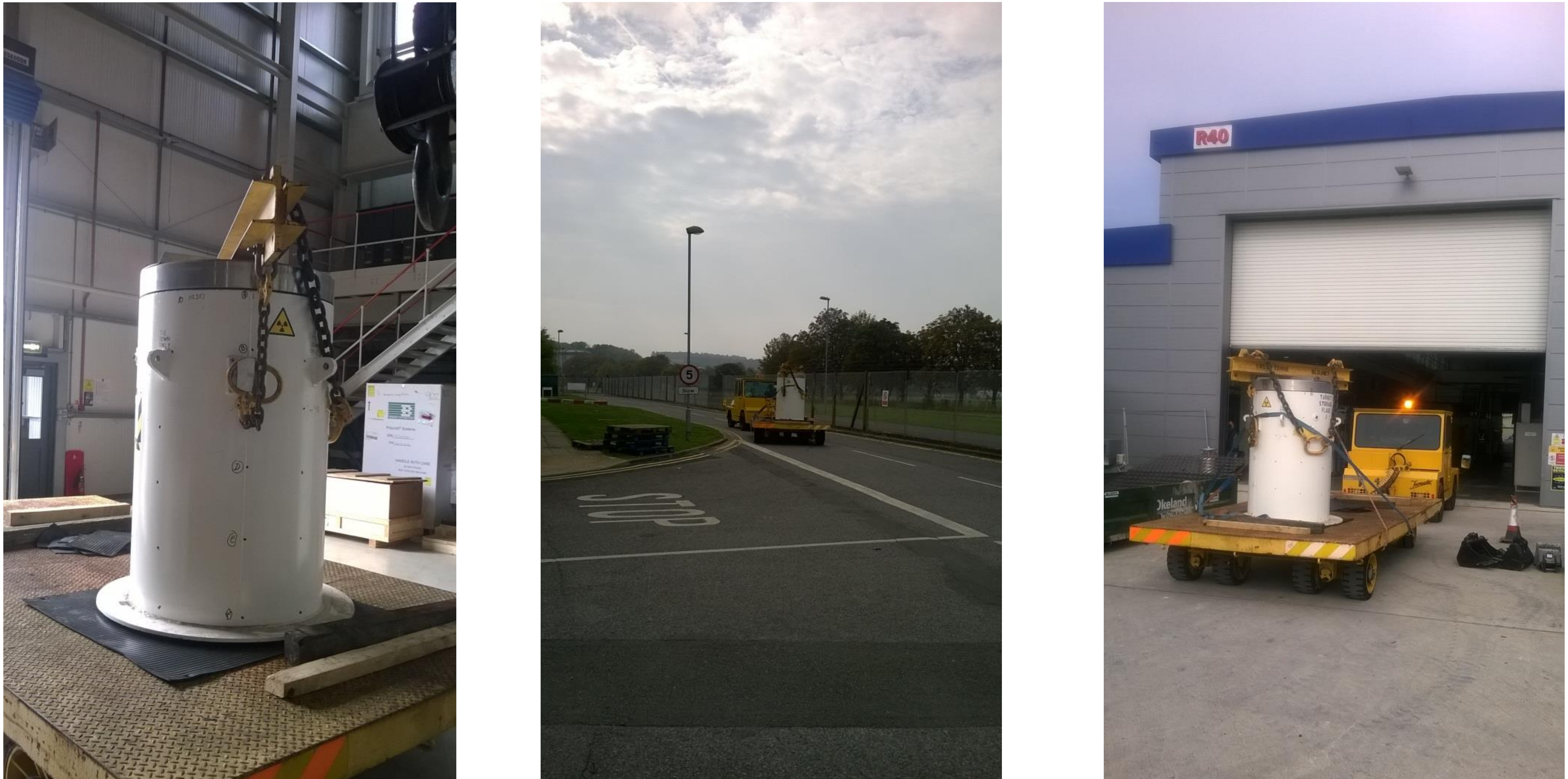
Target replacement

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

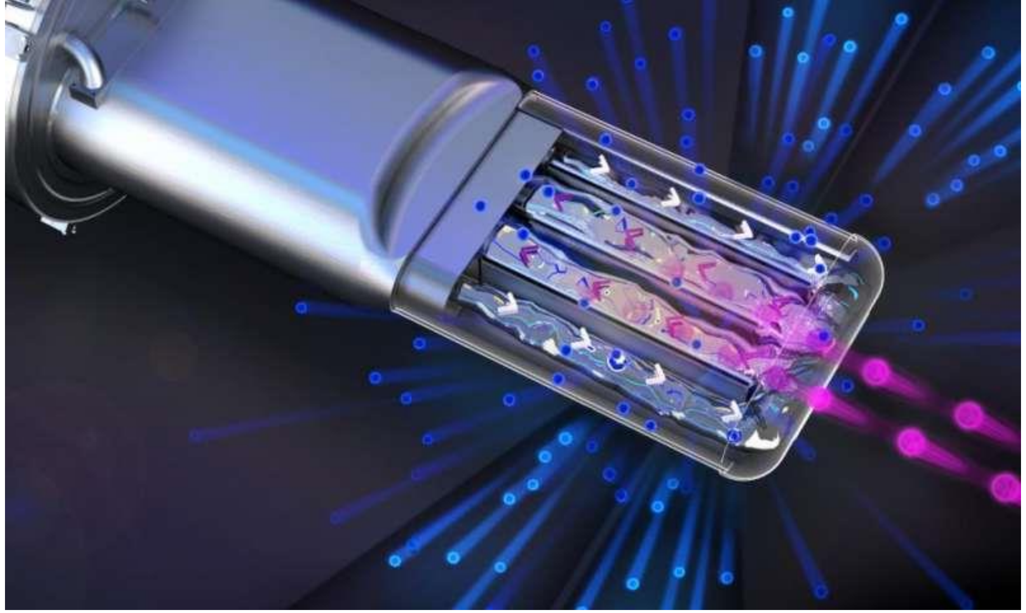
Target replacement

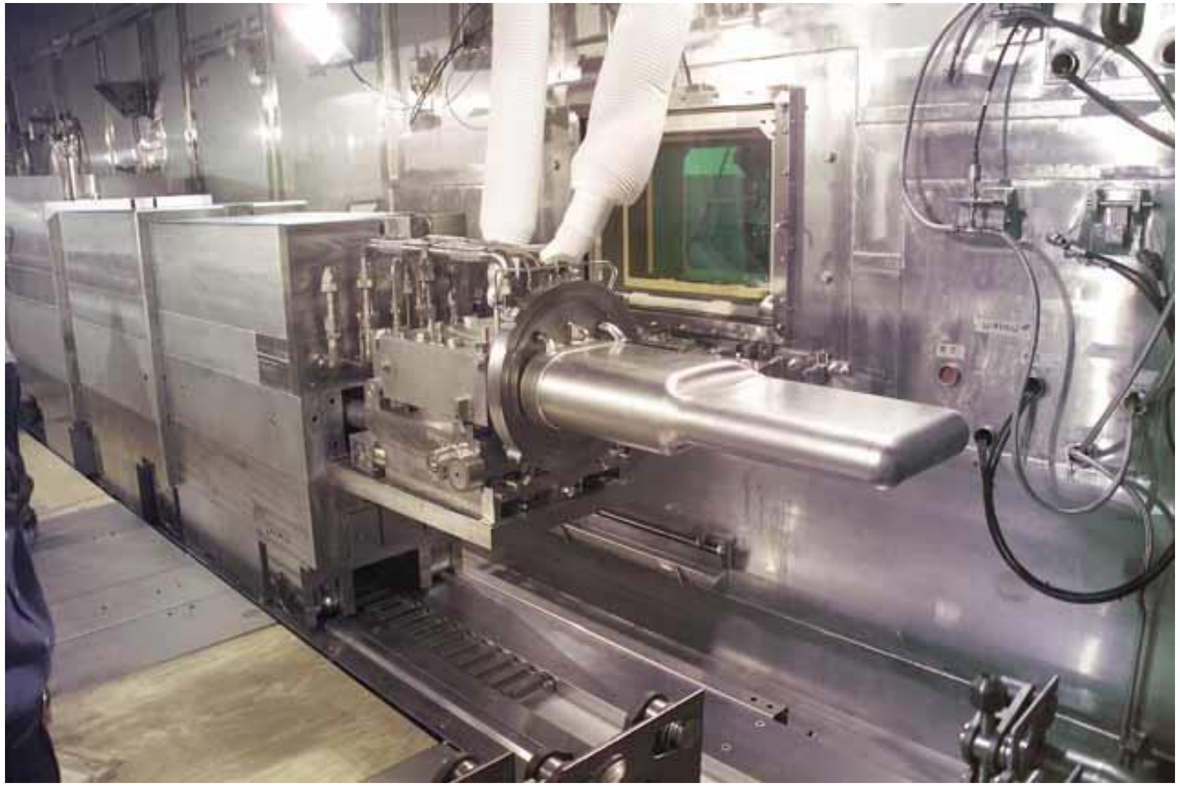
For final disposal the target is transferred to a registered and licenced Type B package and transported to Sellafield (the UK's nuclear waste storage facility)

More neutrons!

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

SNS
SPALLATION NEUTRON SOURCE

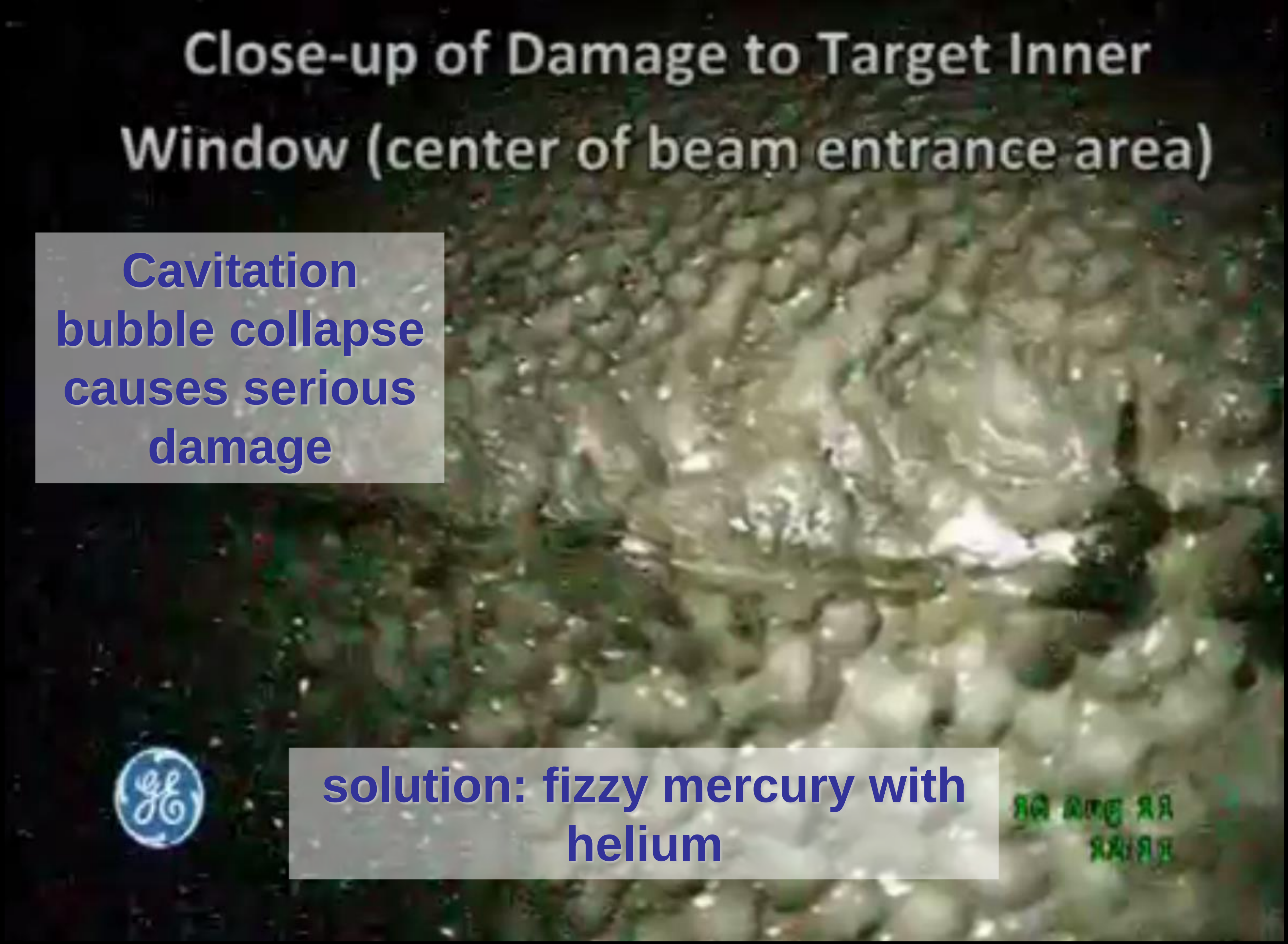




1.4 MW liquid mercury target

SNS
SPALLATION NEUTRON SOURCE

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

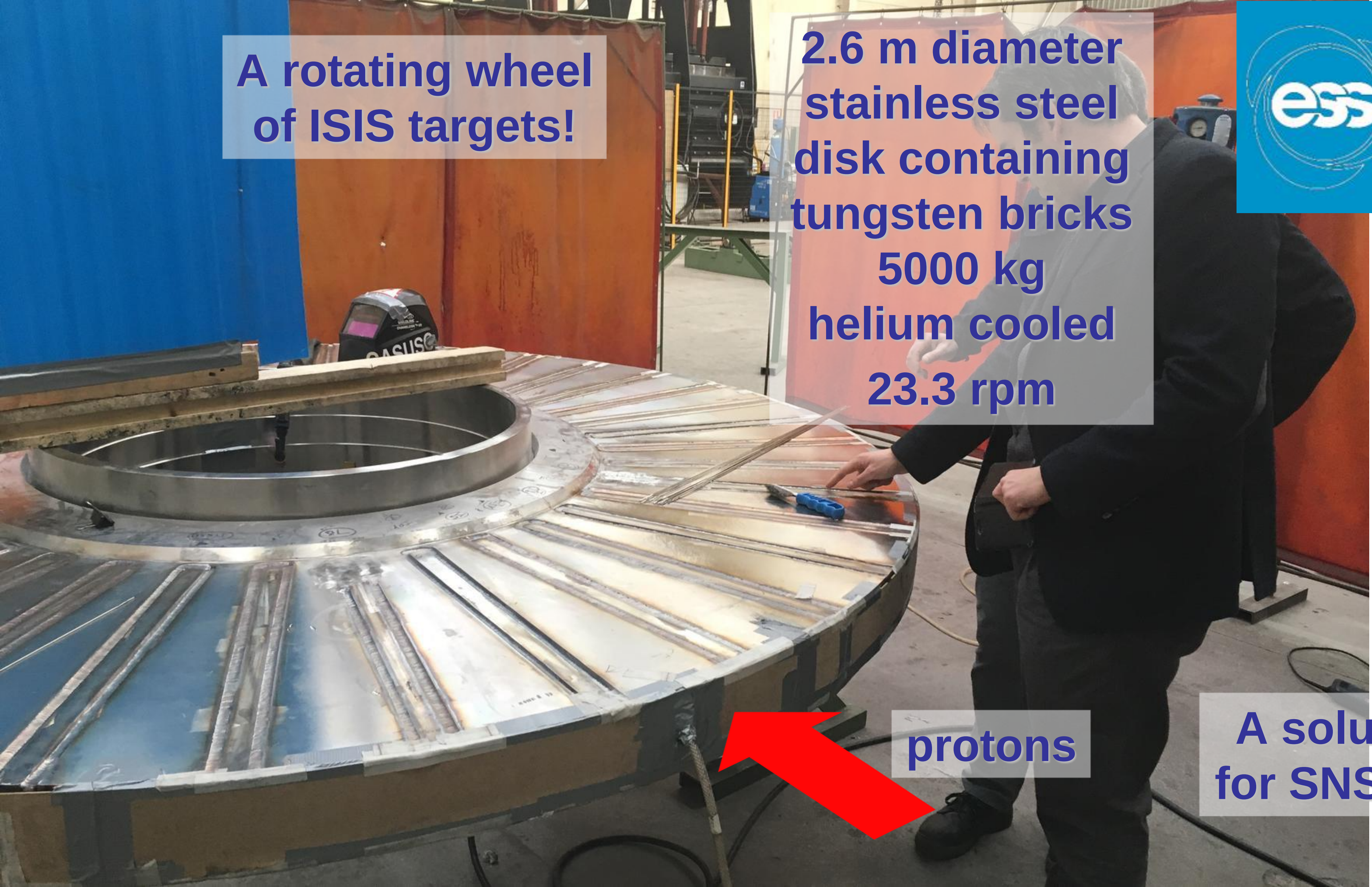


Cavitation bubble collapse causes serious damage

solution: fizzy mercury with helium

ESS currently under construction
3 MW on target!

EUROPEAN SPALLATION SOURCE



A rotating wheel of ISIS targets!

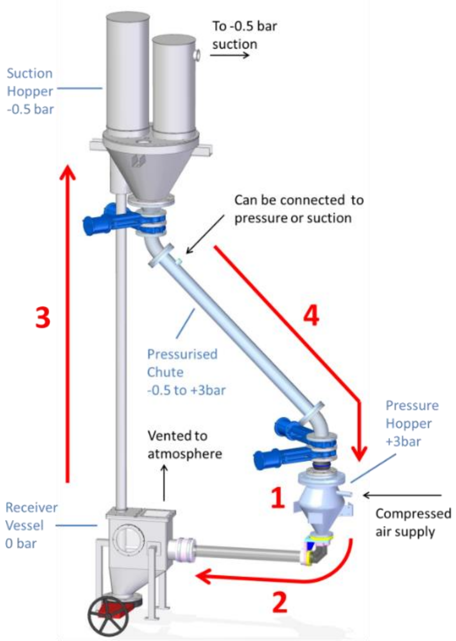
2.6 m diameter
stainless steel
disk containing
tungsten bricks
5000 kg
helium cooled
23.3 rpm

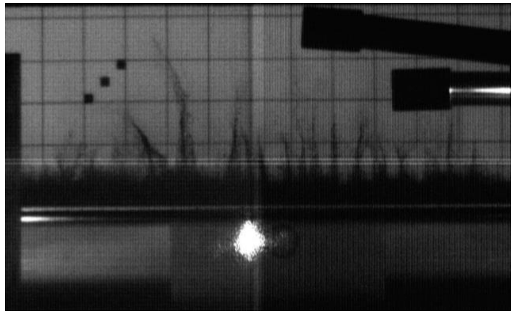
protons

A solution
for SNS TS2

Even more power!

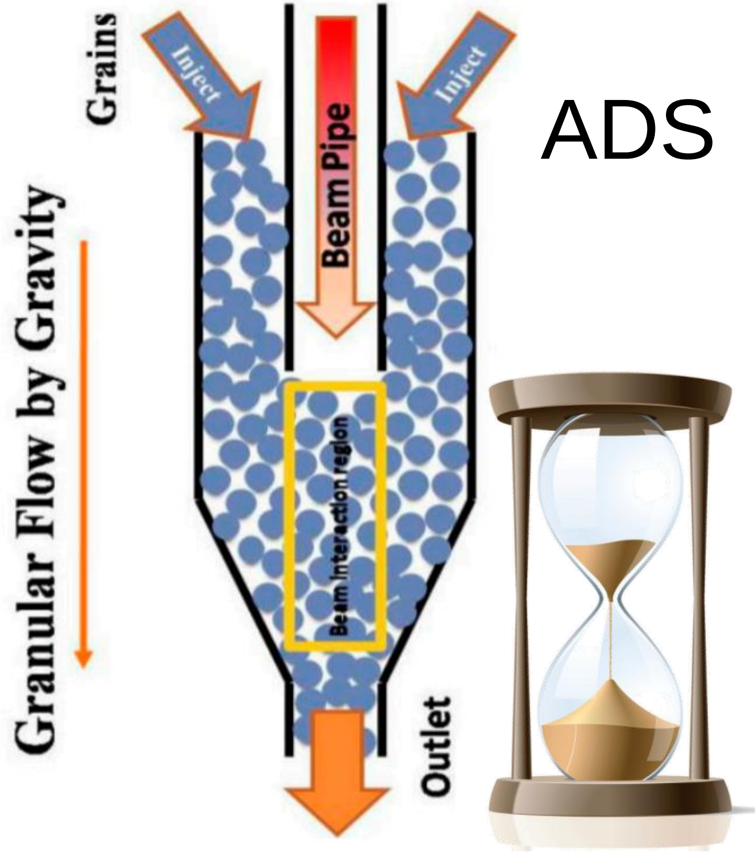
Tungsten powder handling system developed at RAL





Tests at CERN

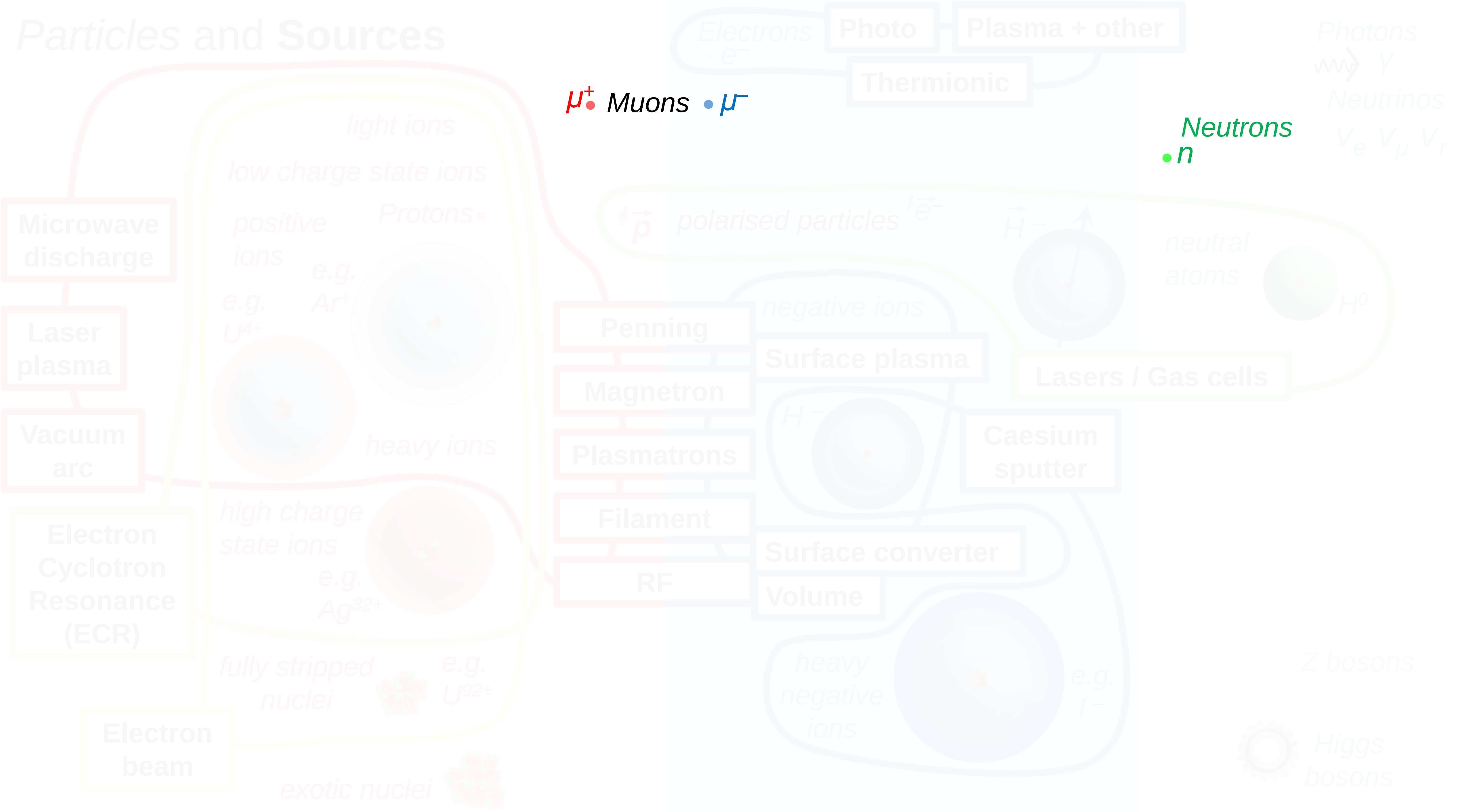
ADS



IMP 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



Electrons e^-

Photo

Plasma + other

Thermionic

Photons γ

Neutrinos ν_e ν_μ ν_τ

μ^+ Muons μ^-

Neutrons n

light ions

low charge state ions

positive ions

Protons

e.g. Ar^+

e.g. U^{4+}

heavy ions

high charge state ions

e.g. Ag^{32+}

fully stripped nuclei

e.g. U^{92+}

exotic nuclei

Microwave discharge

Laser plasma

Vacuum arc

Electron Cyclotron Resonance (ECR)

Electron beam

Penning

Magnetron

Plasmatrons

Filament

RF

negative ions

Surface plasma

Surface converter

Volume

H^-

Caesium sputter

heavy negative ions

e.g. I^-

$\vec{p}$ polarised particles $\vec{e}^-$

$\vec{H}^-$

neutral atoms

H^0

Lasers / Gas cells

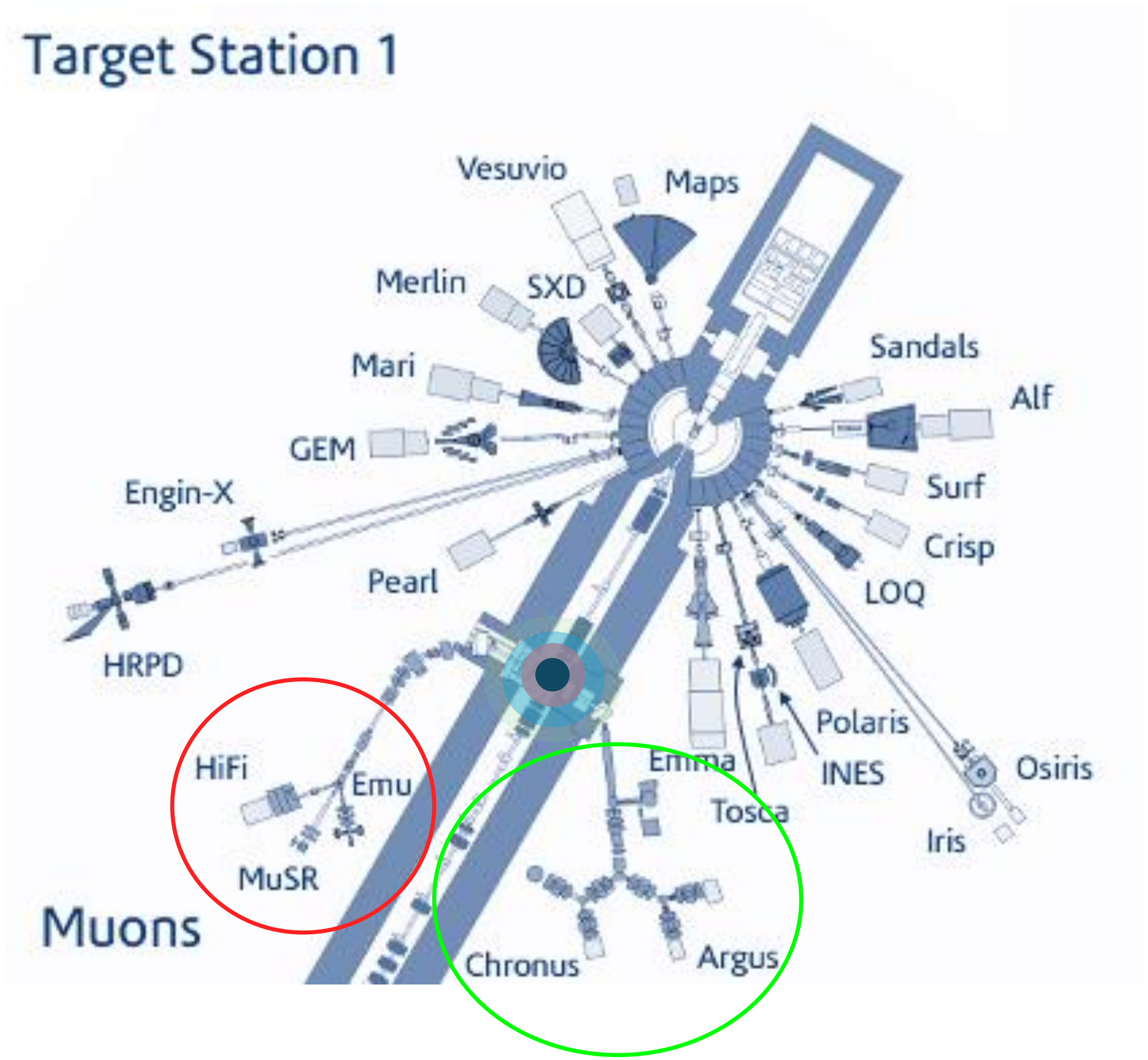
Z bosons

Higgs bosons

Muons at ISIS

Science and Technology Facilities Council

ISIS Neutron and Muon Source



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

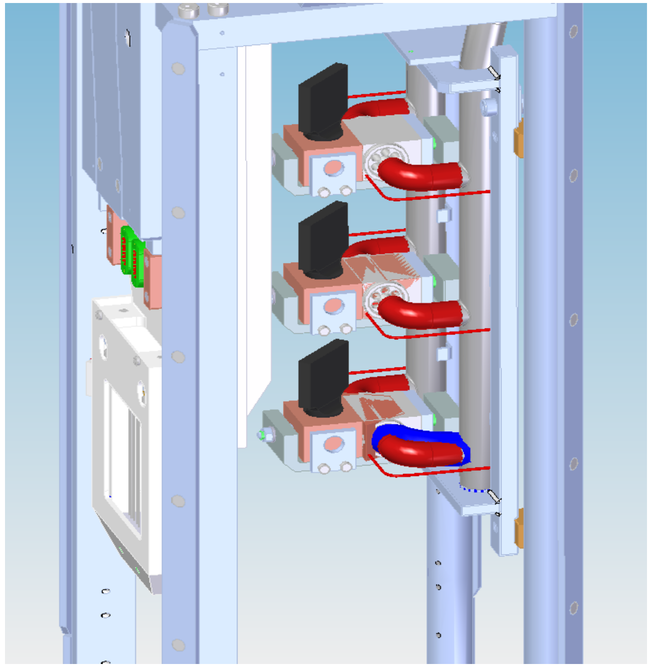
ISIS Muon Target

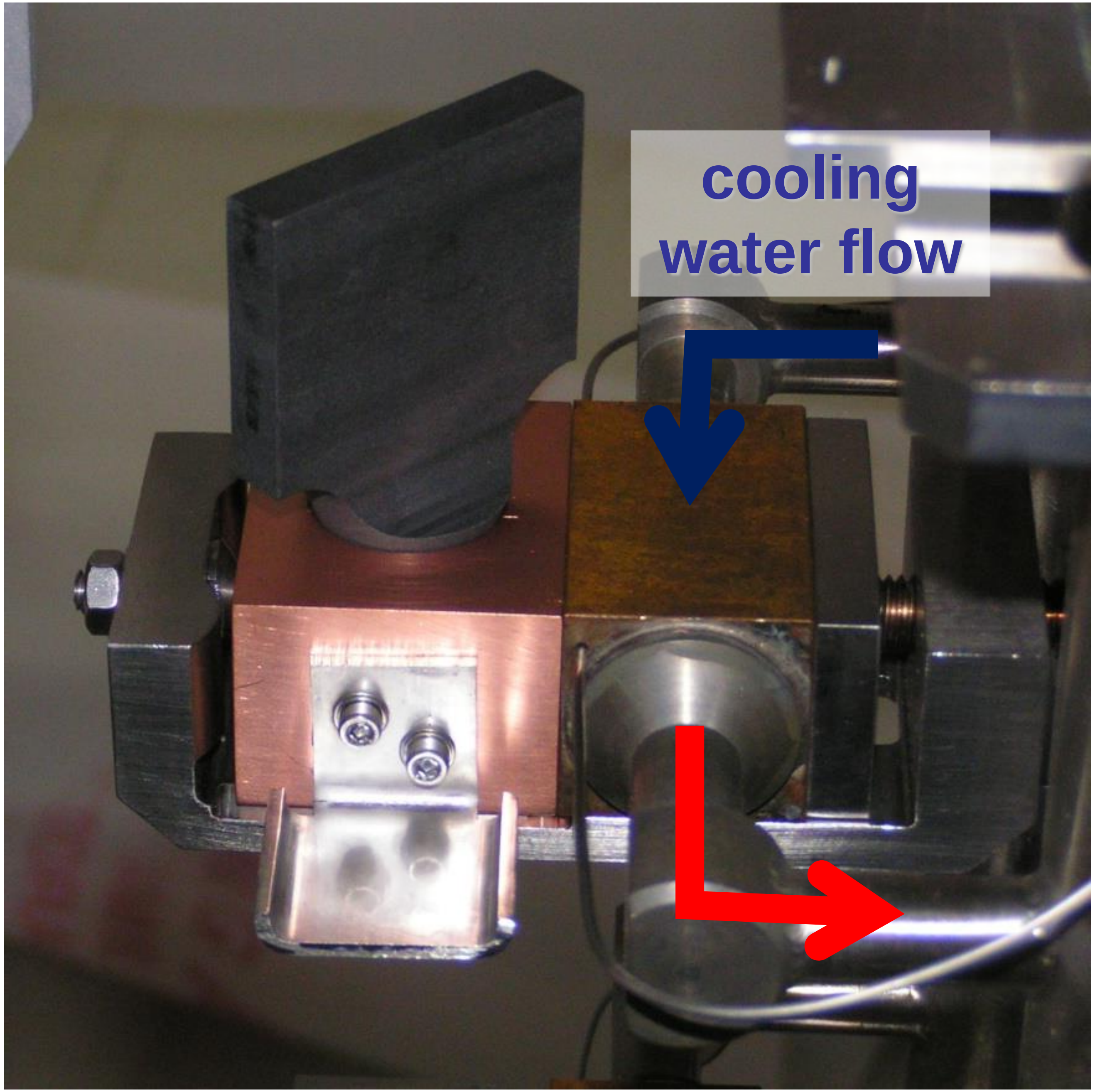
10 mm thick graphite target at 45° to the 800 MeV proton beam

About 5% beam lost

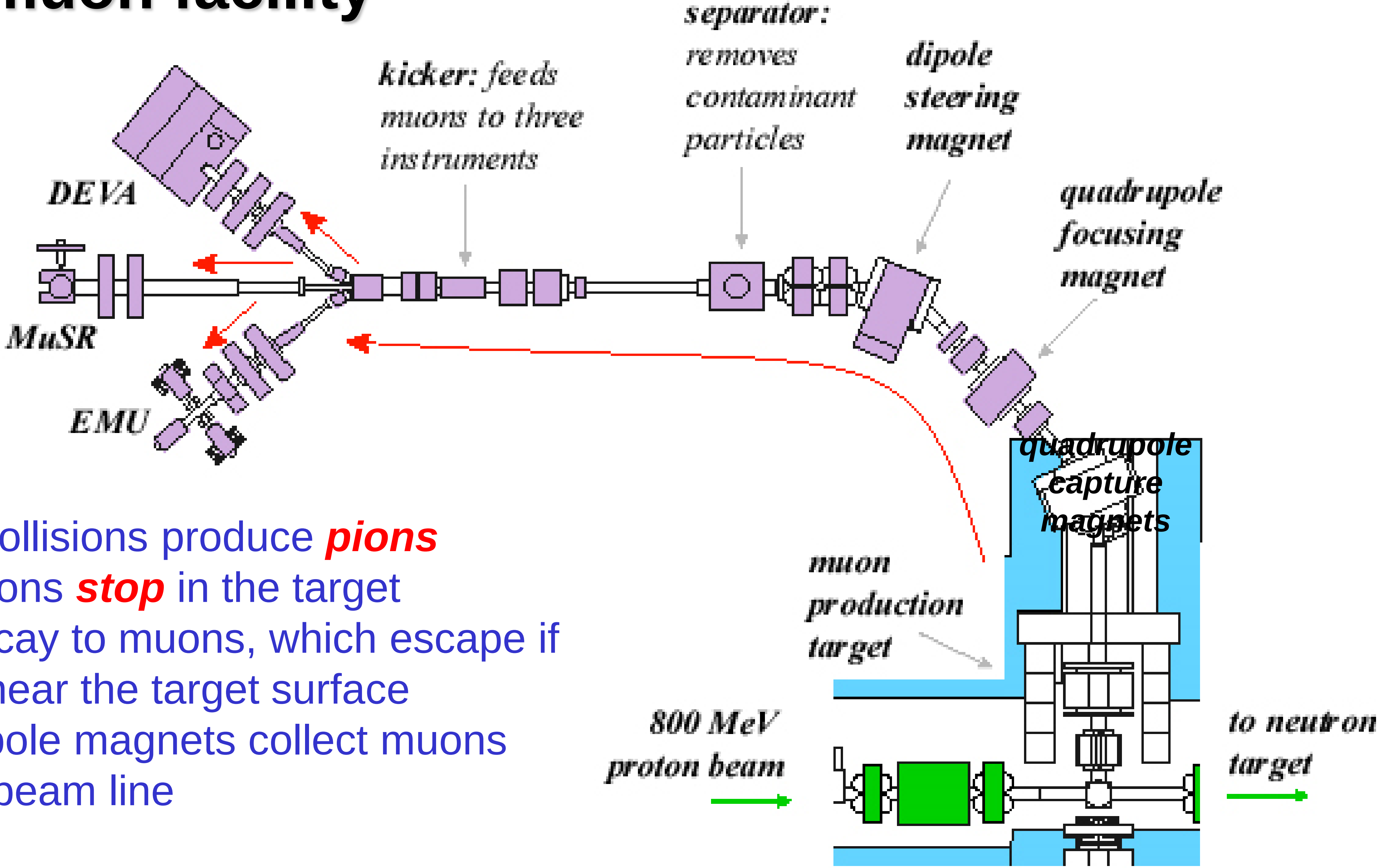
Diffusion bonded to copper to maximise thermal contact

10 kW maximum heat load



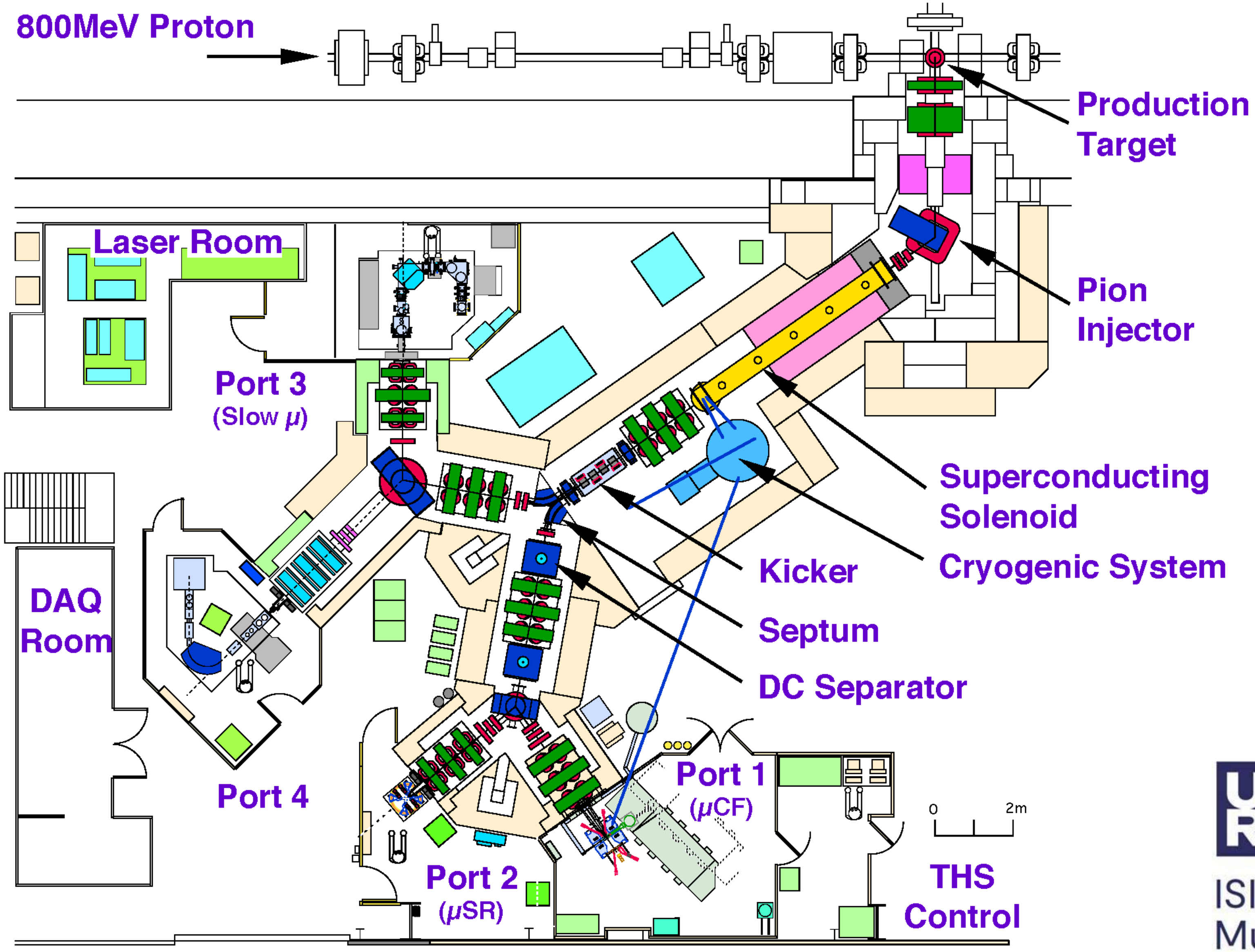


The EC muon facility



- 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

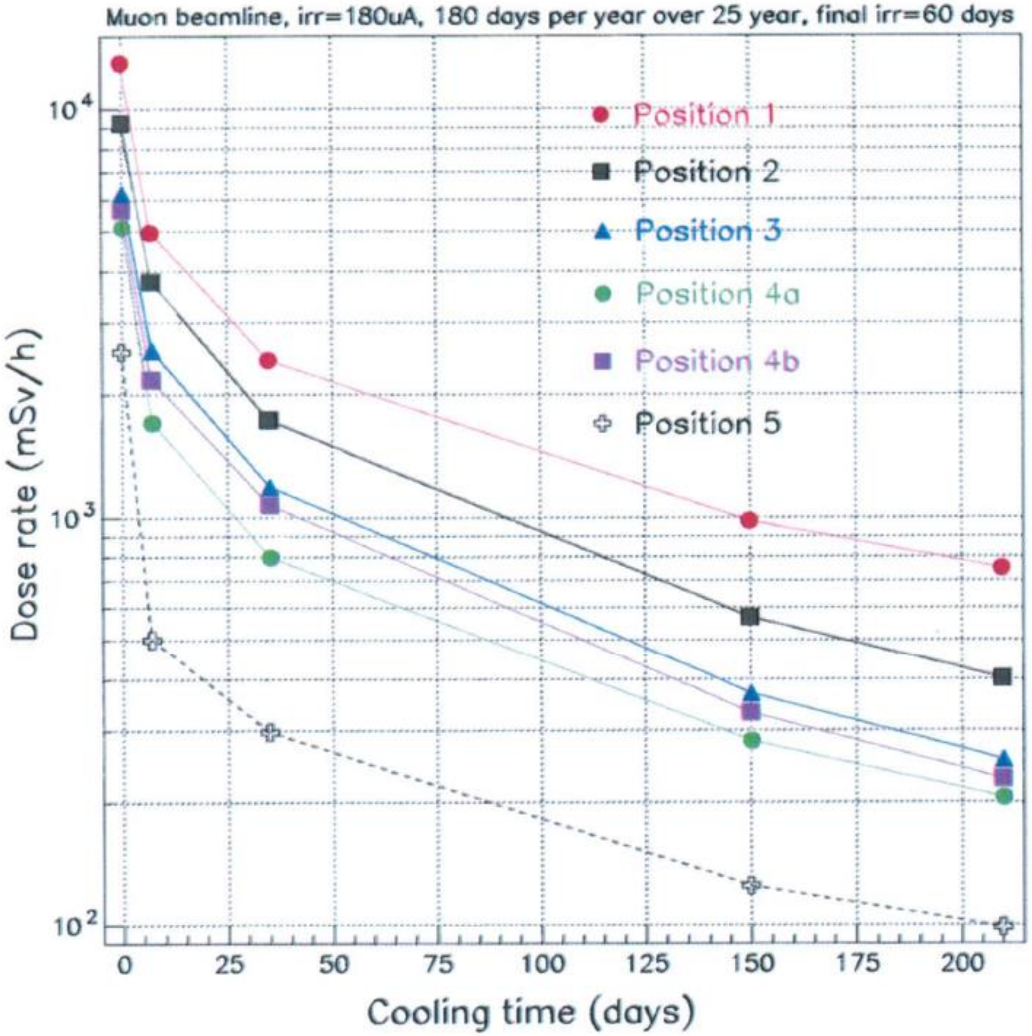
RIKEN-RAL muon facility

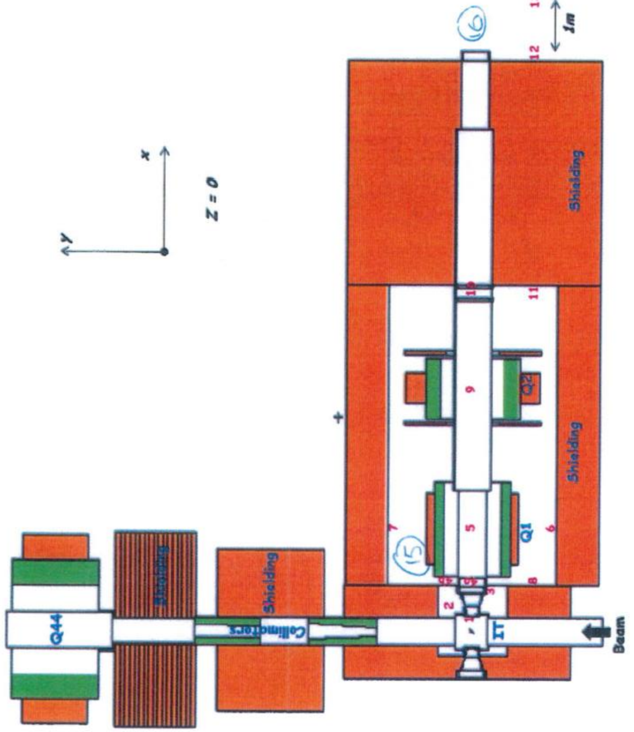


Science and Technology Facilities Council

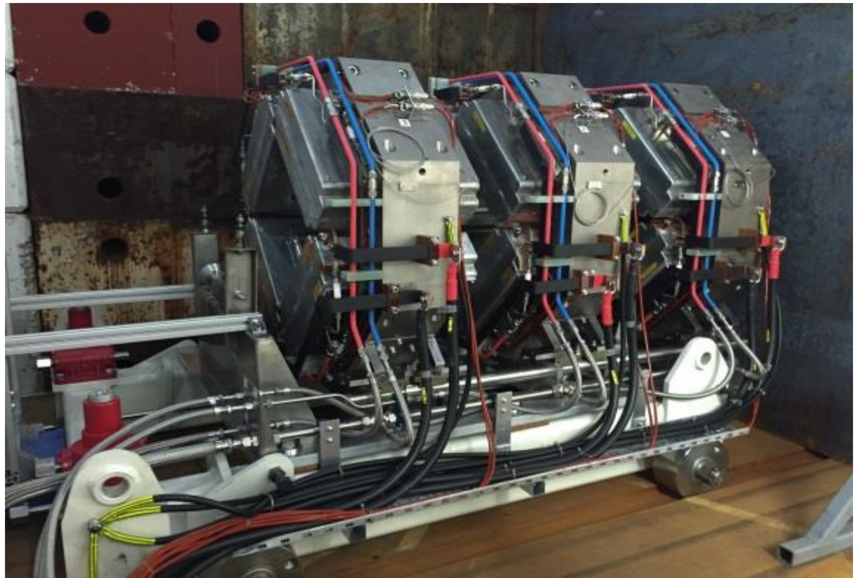
ISIS Neutron and Muon Source

Radiation levels



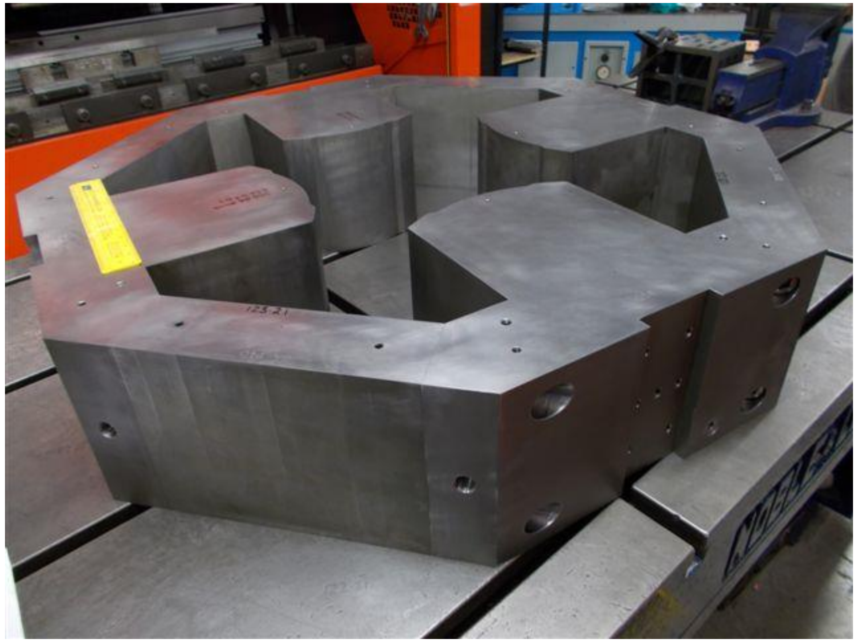


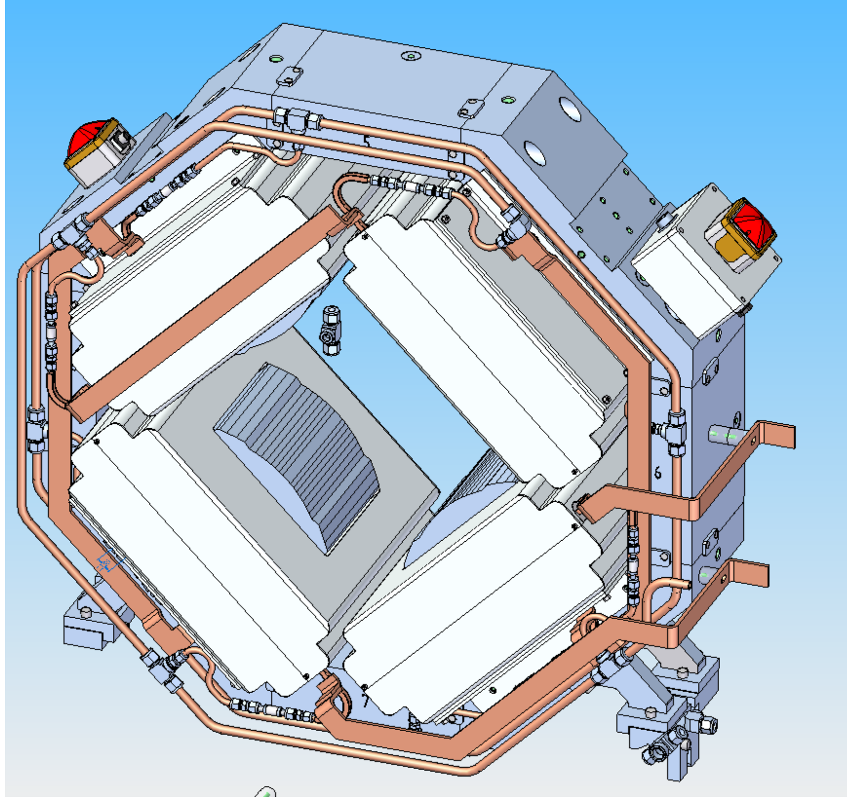
Radiation Hard Magnets

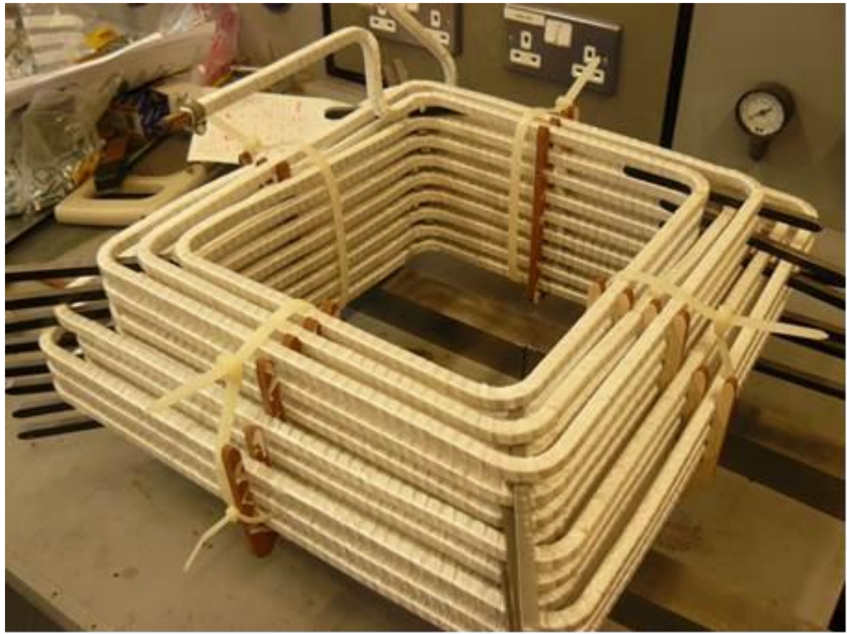


Radiation Hard Magnet Design

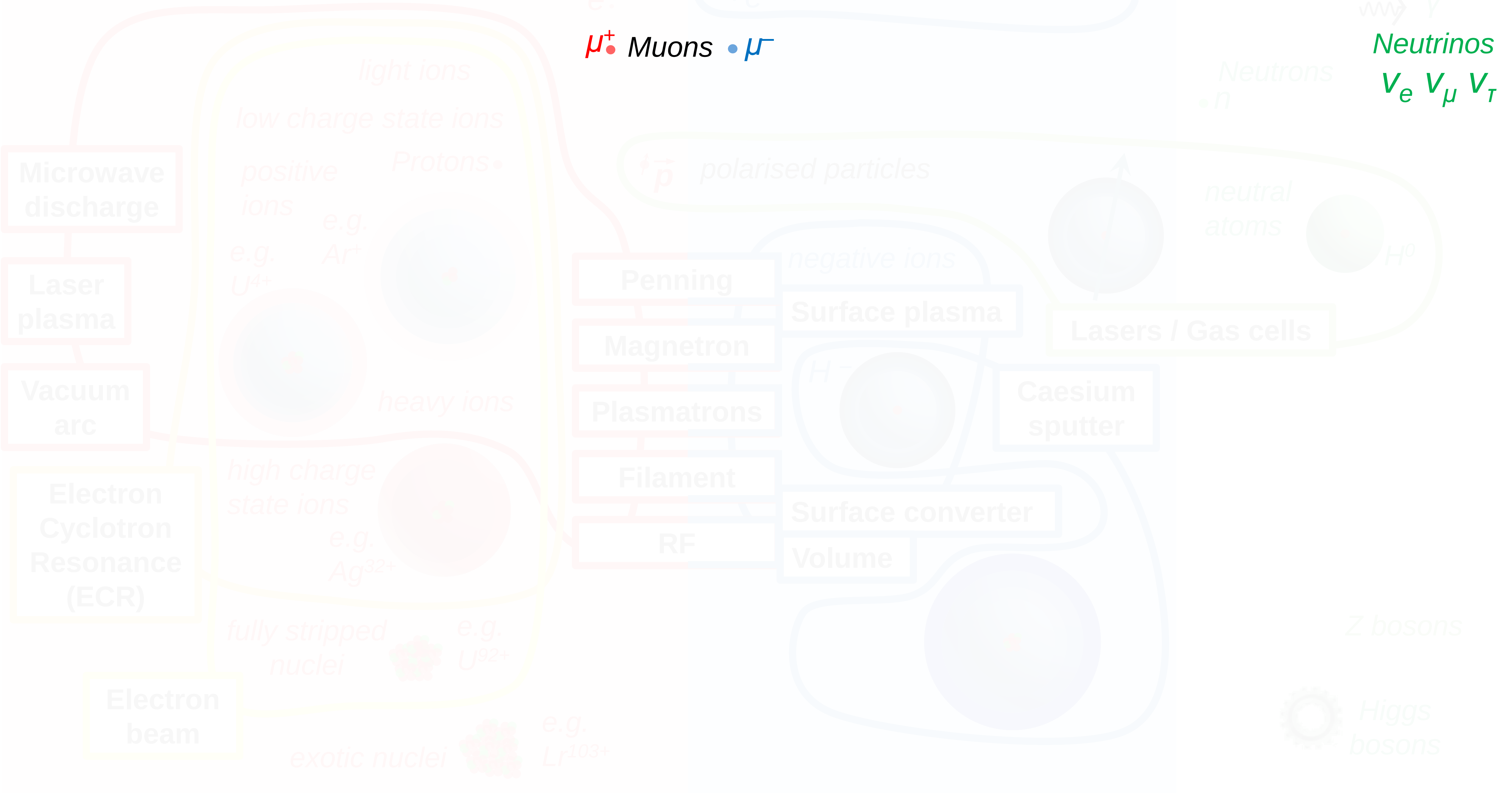
- In-house concrete magnet design
- Coils potted in concrete
- Water cooled







Particles and Sources



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Electrons e^-

Photo

er

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

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RF

Surface plasma

Surface converter

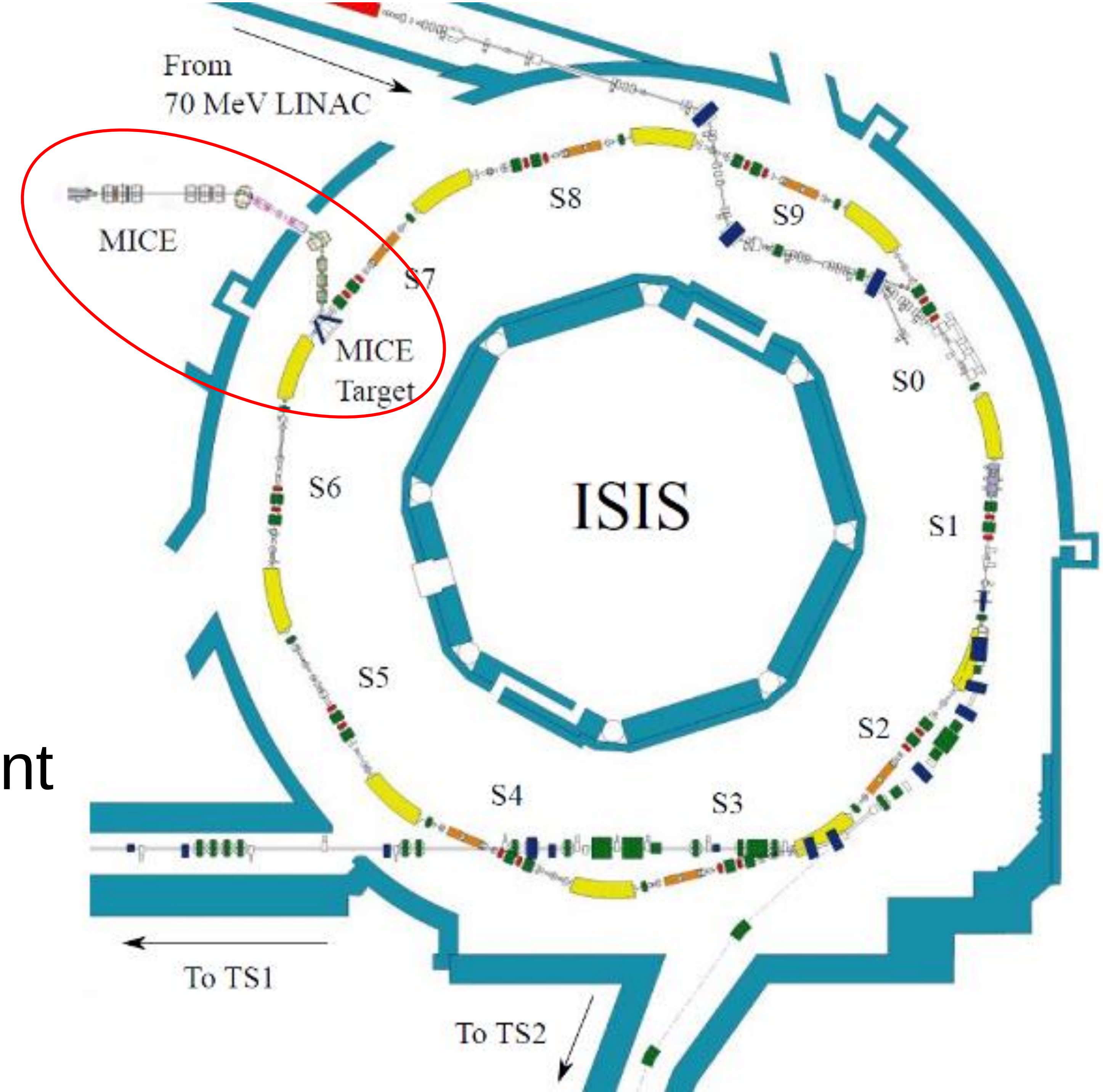
Volume

Caesium sputter

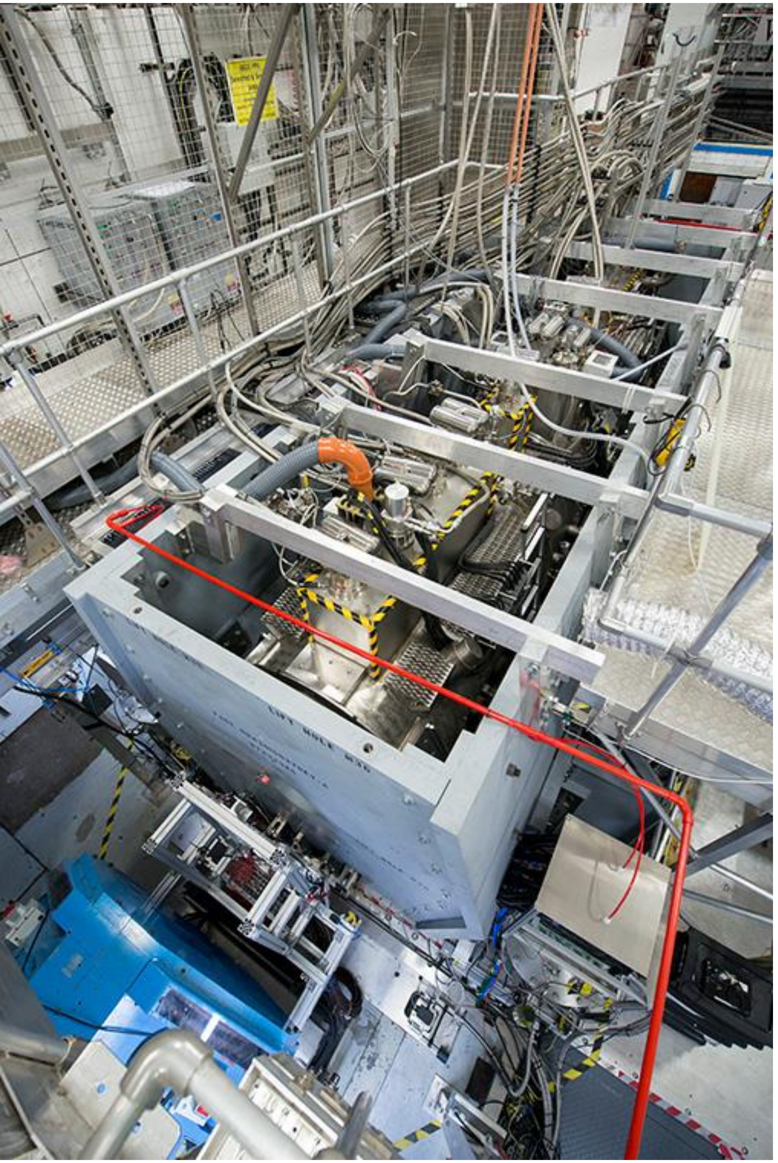
Lasers / Gas cells

MICE @ ISIS

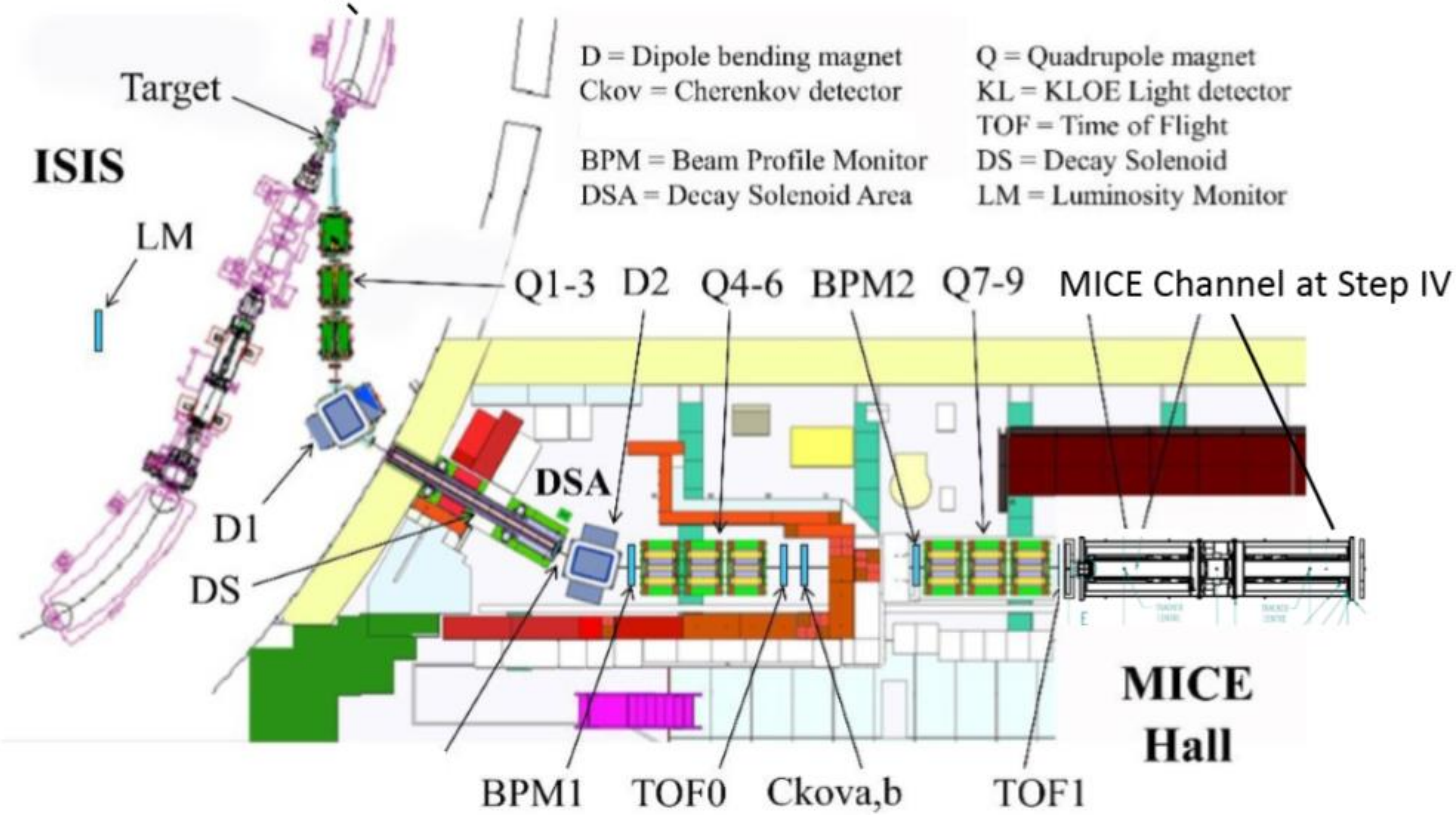
Muon
Ionisation
Cooling
Experiment
(MICE)



MICE @ ISIS

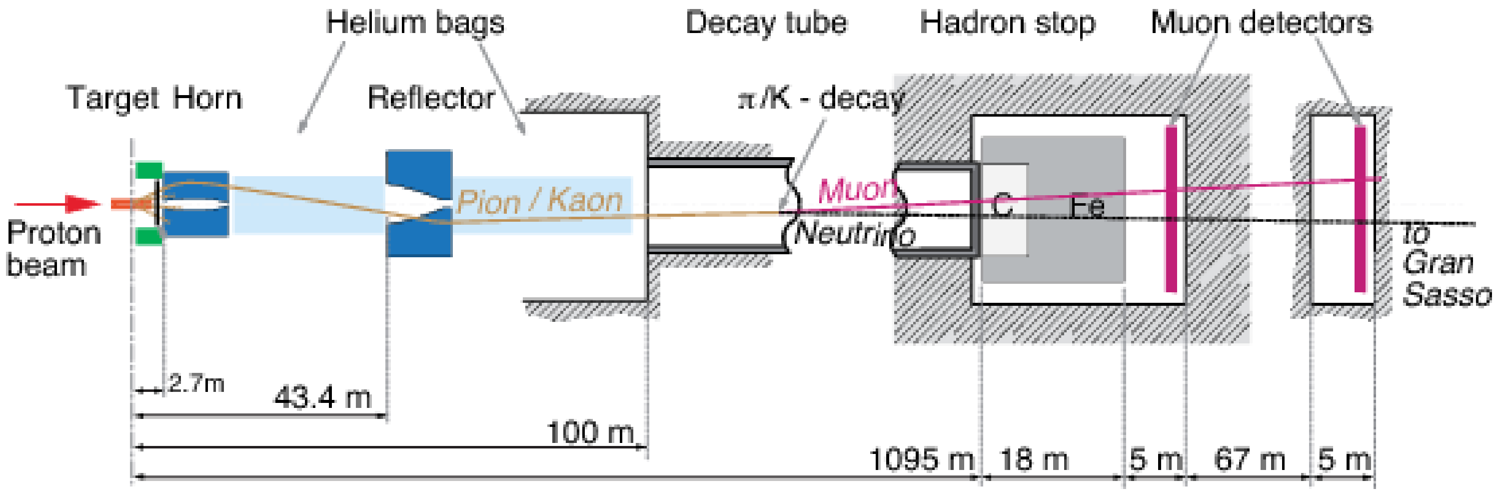


MICE Beamline

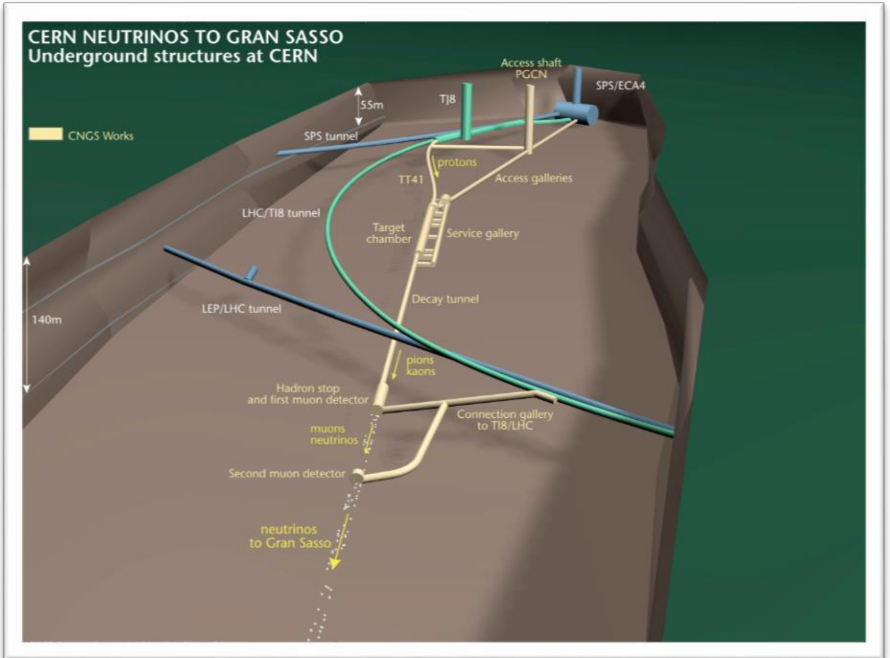


MICE demonstrated 1D muon cooling

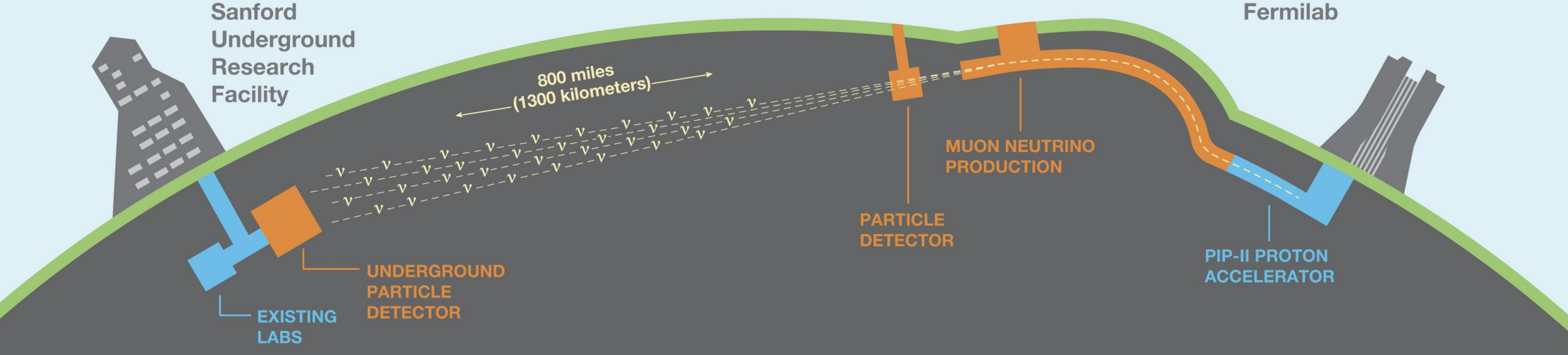
CERN Neutrinos to Gran Sasso (**CNGS**)



732 km



Deep Underground Neutrino Experiment



Sanford Underground Research Facility

Fermilab

800 miles
(1300 kilometers)

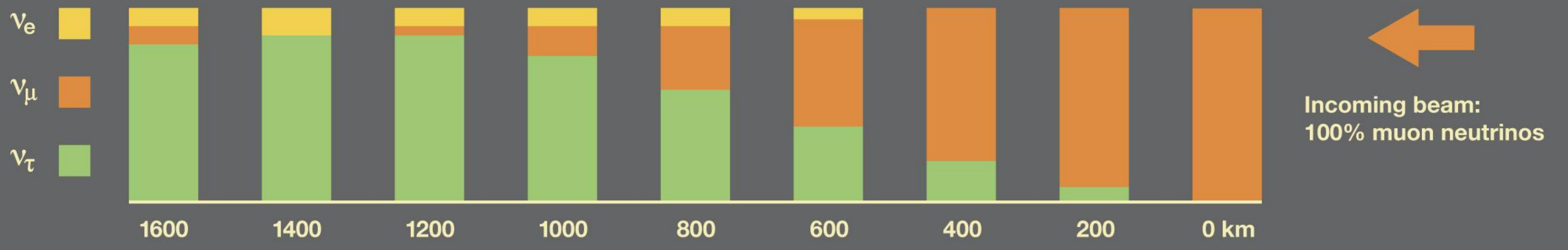
MUON NEUTRINO PRODUCTION

PARTICLE DETECTOR

PIP-II PROTON ACCELERATOR

UNDERGROUND PARTICLE DETECTOR

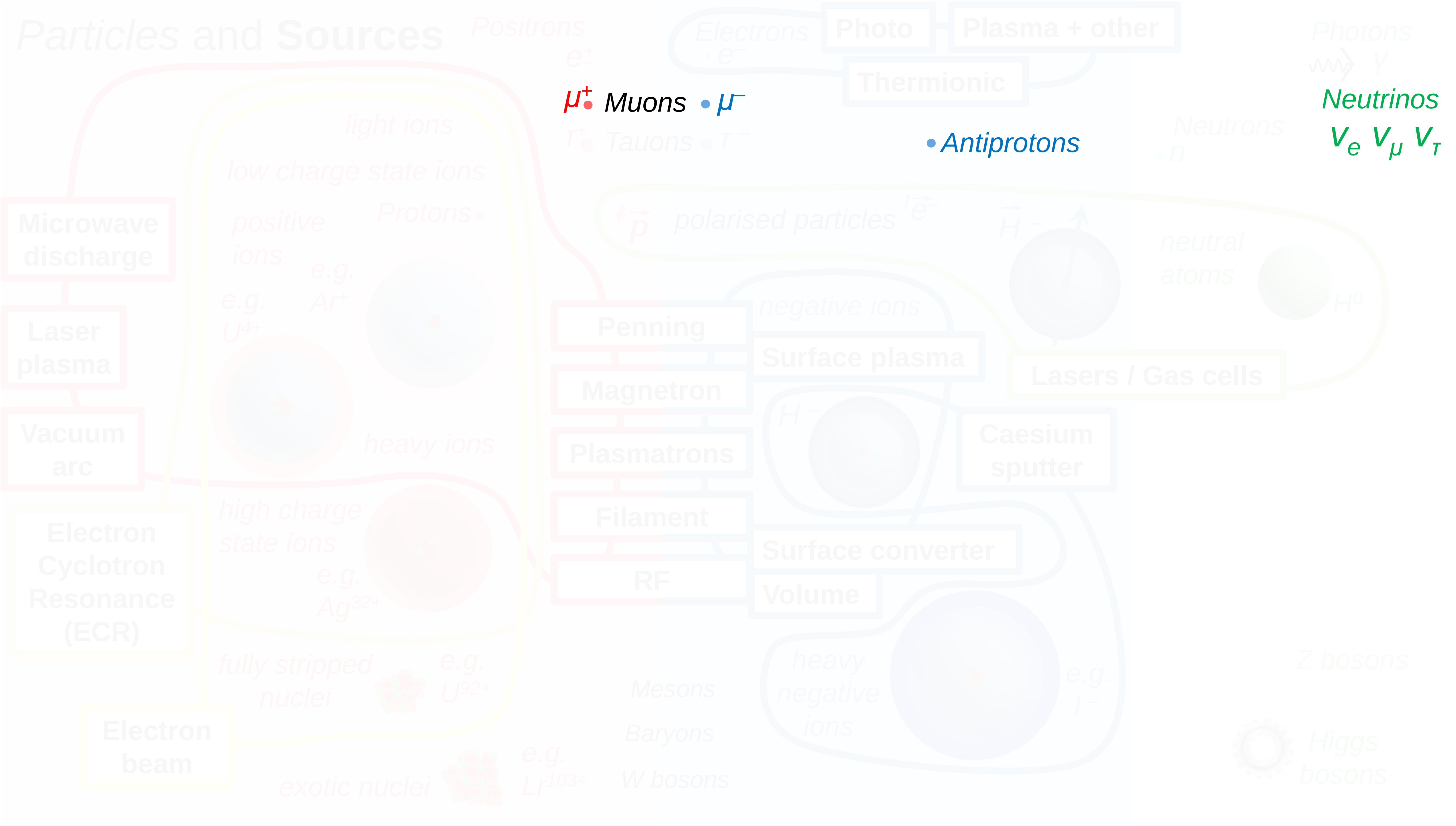
EXISTING LABS



Incoming beam:
100% muon neutrinos

Probability of detecting electron, muon and tau neutrinos

Particles and Sources



Positrons e^+

Electrons e^-

Photo

Plasma + other

Thermionic

Photons γ

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ν_e ν_μ ν_τ

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$\vec{p}$ polarised particles $\vec{e}^-$

$\vec{H}^-$

negative ions

Surface plasma

H^-

Caesium sputter

Surface converter

Volume

heavy negative ions

e.g. I^-

neutral atoms

H^0

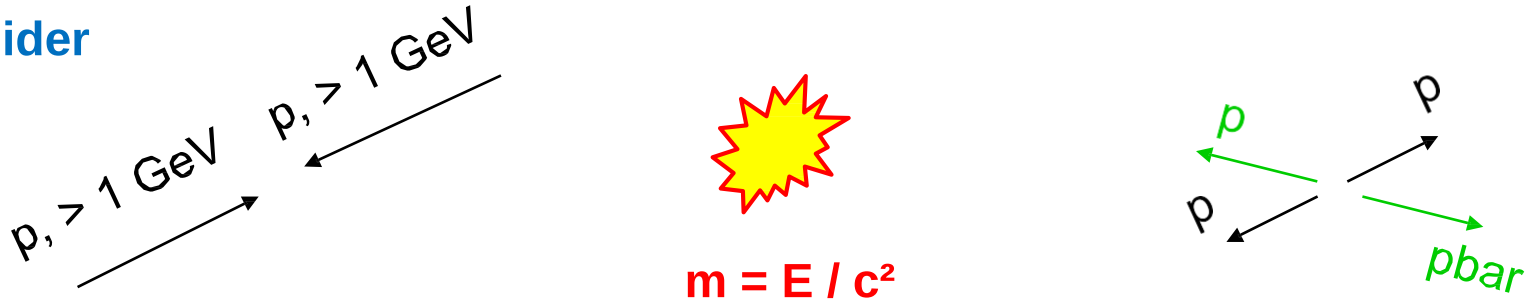
Lasers / Gas cells

Z bosons

Higgs bosons

Creation of Antiprotons

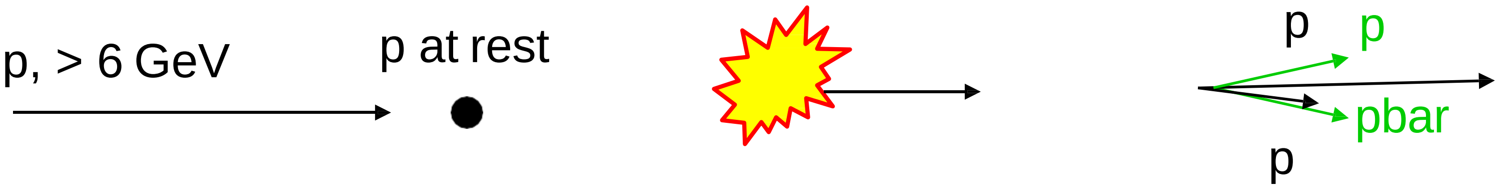
Collider



$m = E / c^2$

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

Target



$m = E / c^2$

$T_{pbar} > 6\ GeV$

Magnetic horn

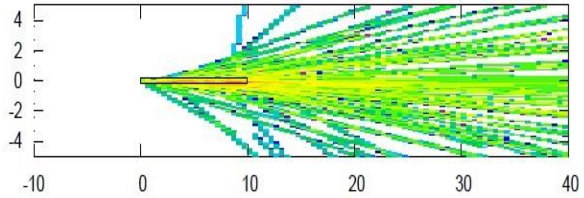
Simon van der Meer 1960s

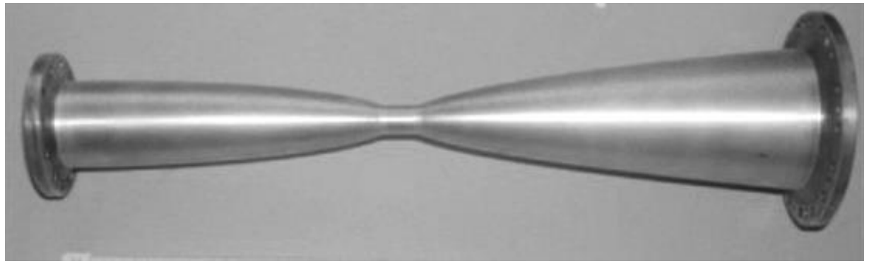
1.4 mm Al 400 kA 15 µs

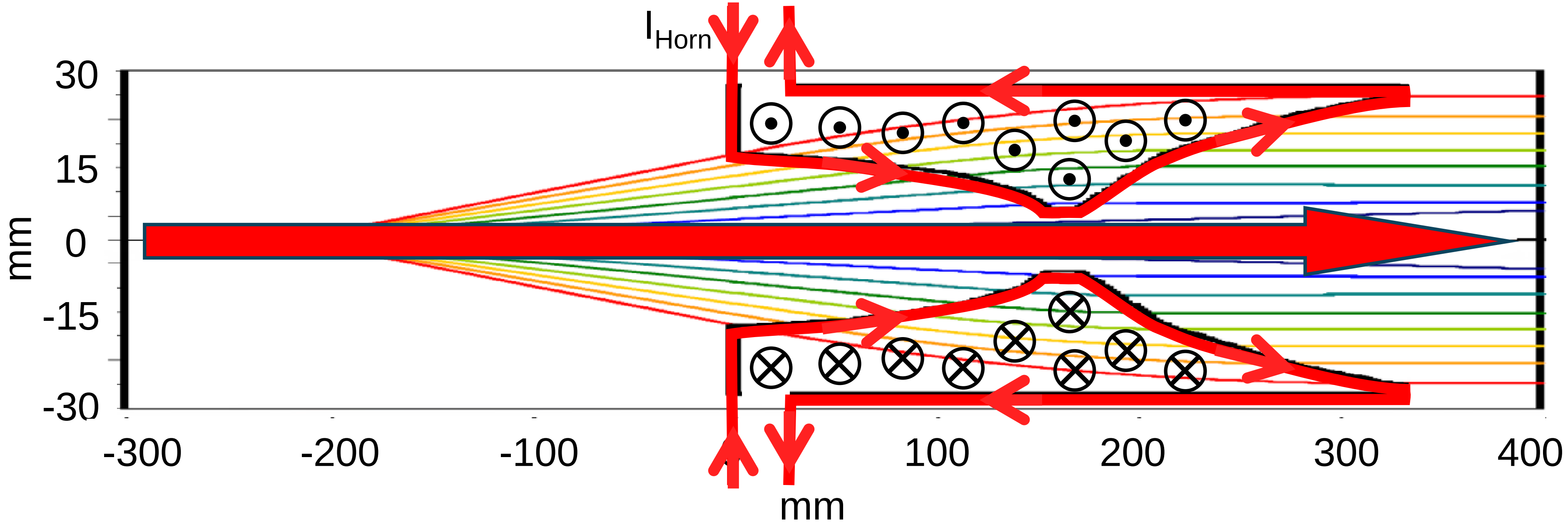
"current sheet lens"

originally developed for neutrino beams then for antiprotons

Magnetic horn



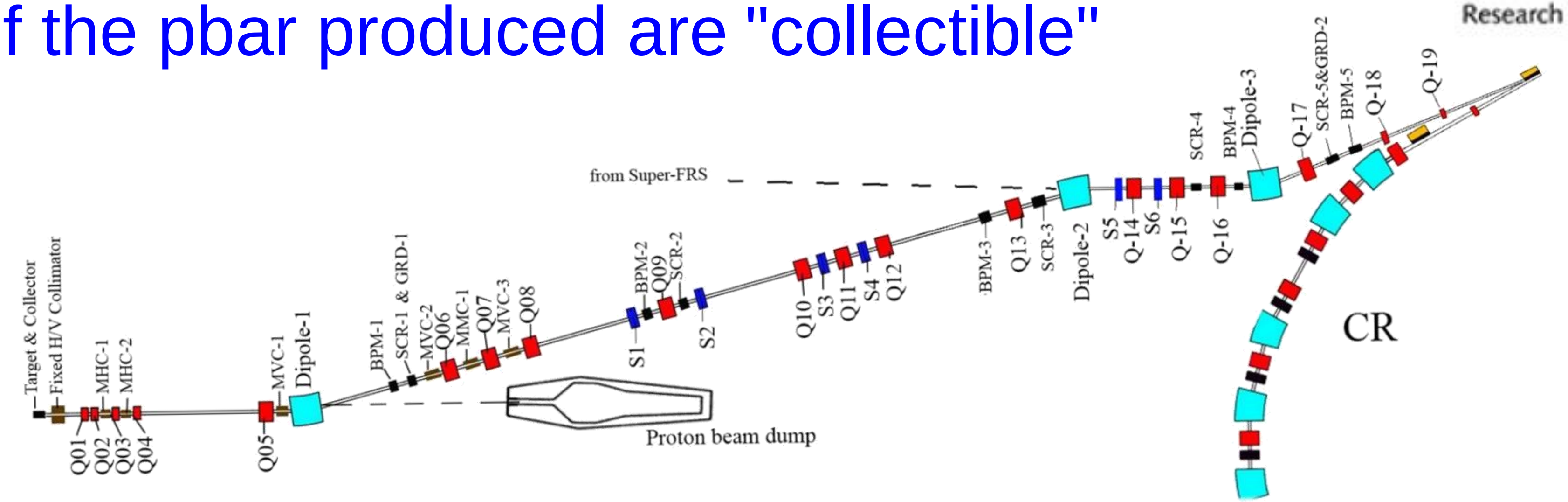




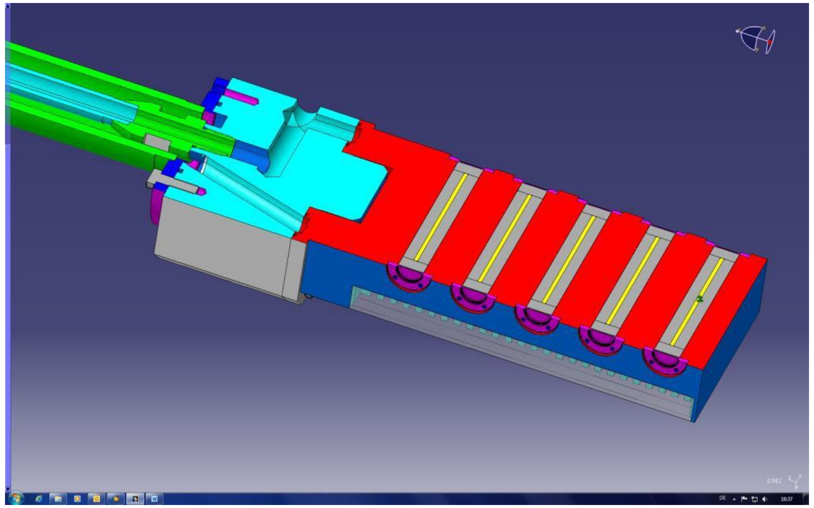
Beam Separation

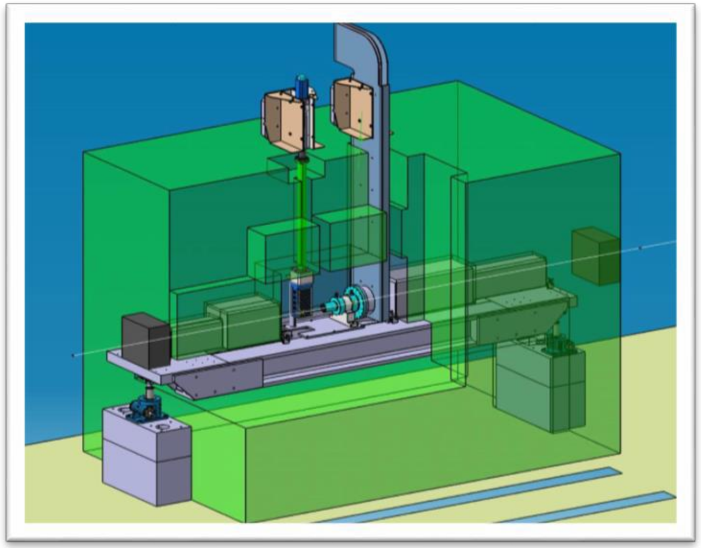
FAIR — Facility for Antiproton and Ion Research in Europe

Only 2% of the pbar produced are "collectible"

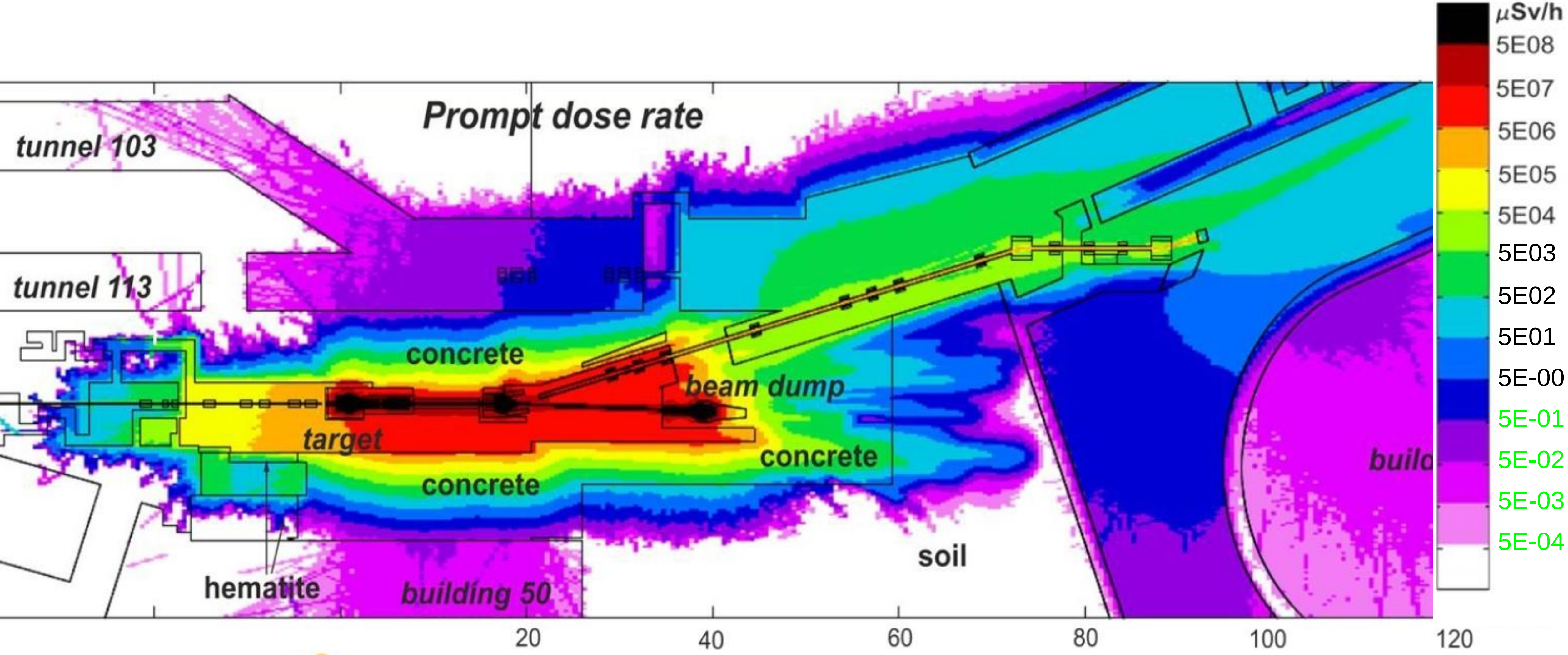


target





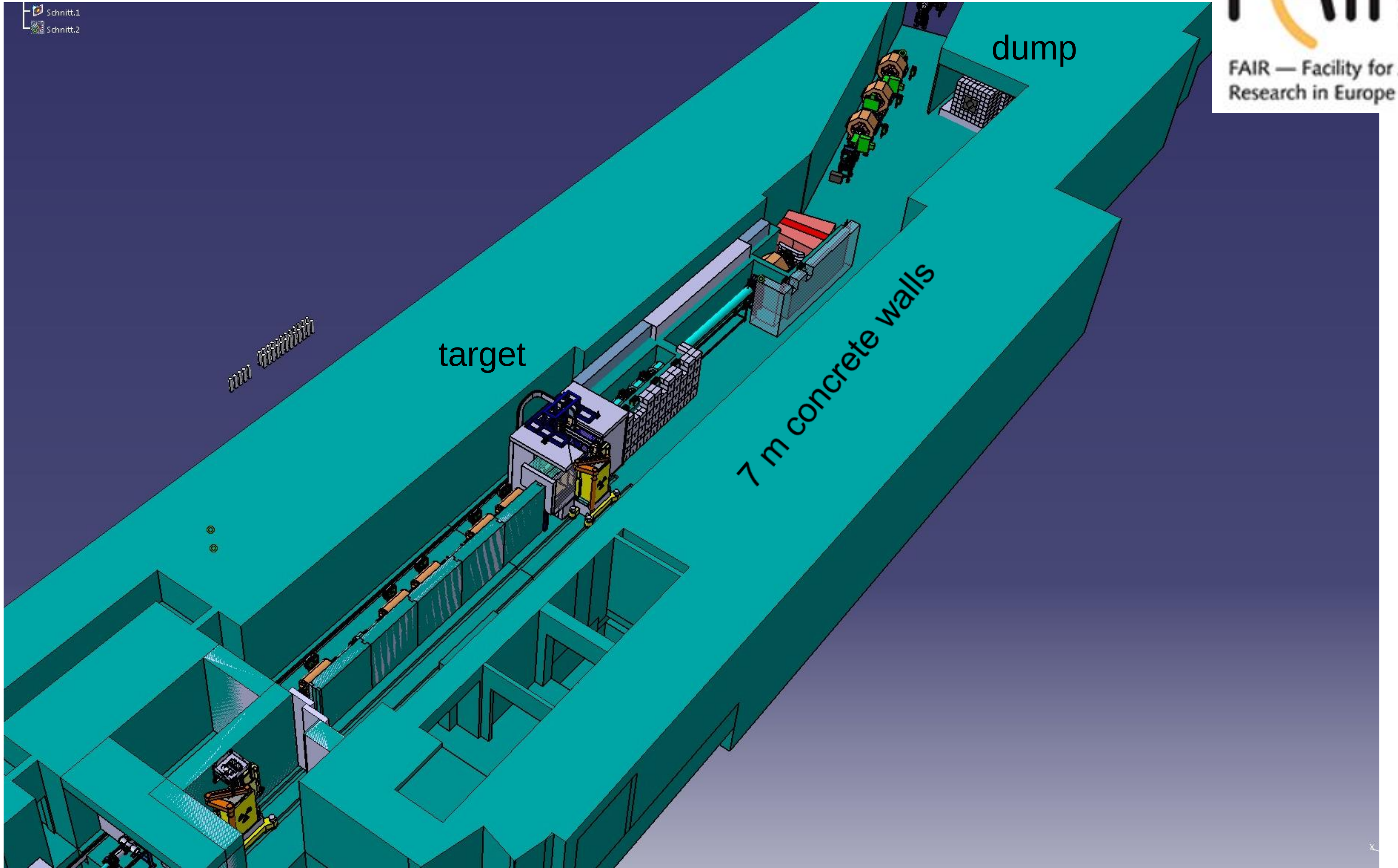
separator



FAIR — Facility for Antiproton and Ion Research in Europe

Shielding Required

FAIR — Facility for Antiproton and Ion Research in Europe



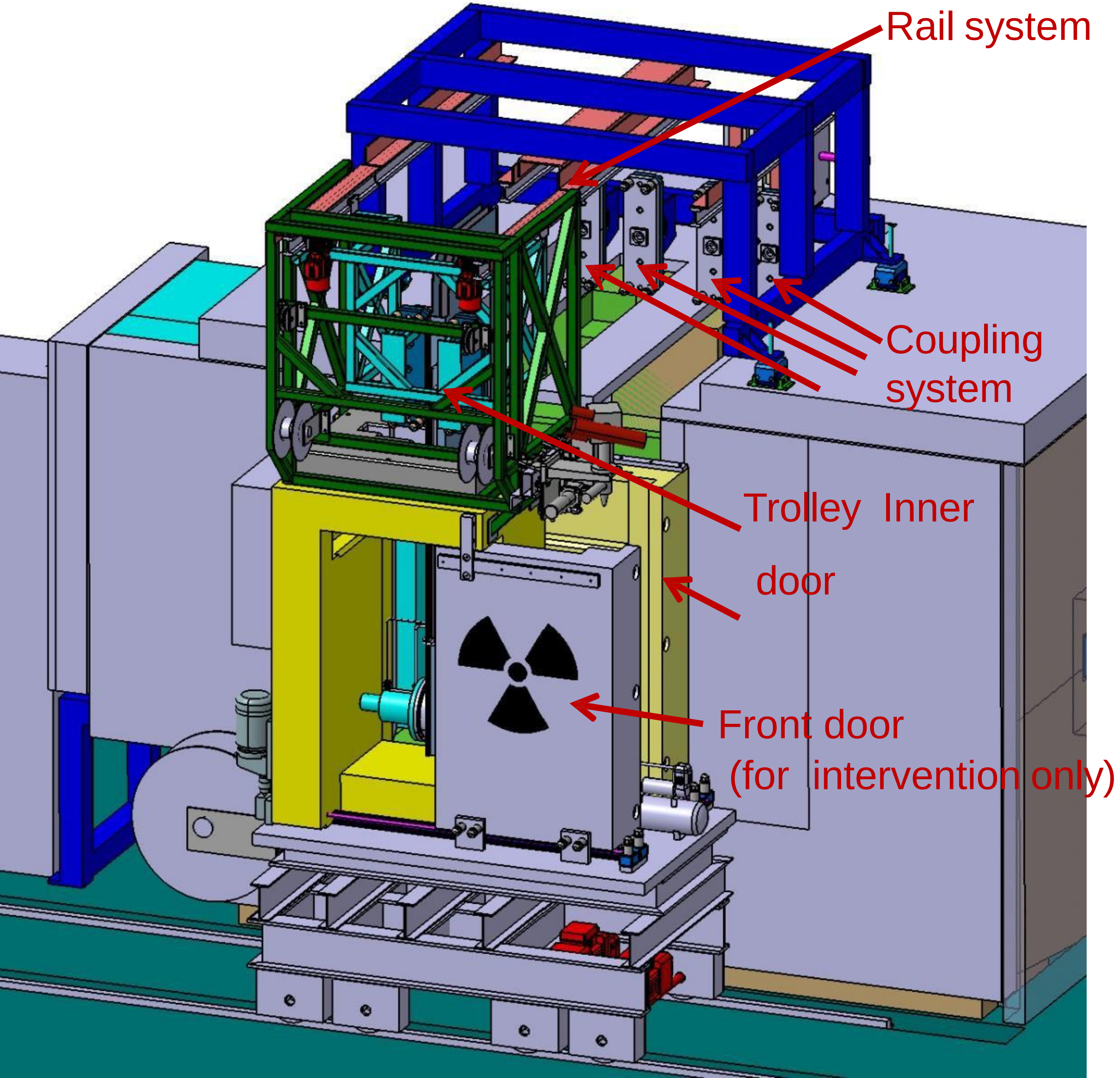
dump

target

7 m concrete walls

Target station and transport container

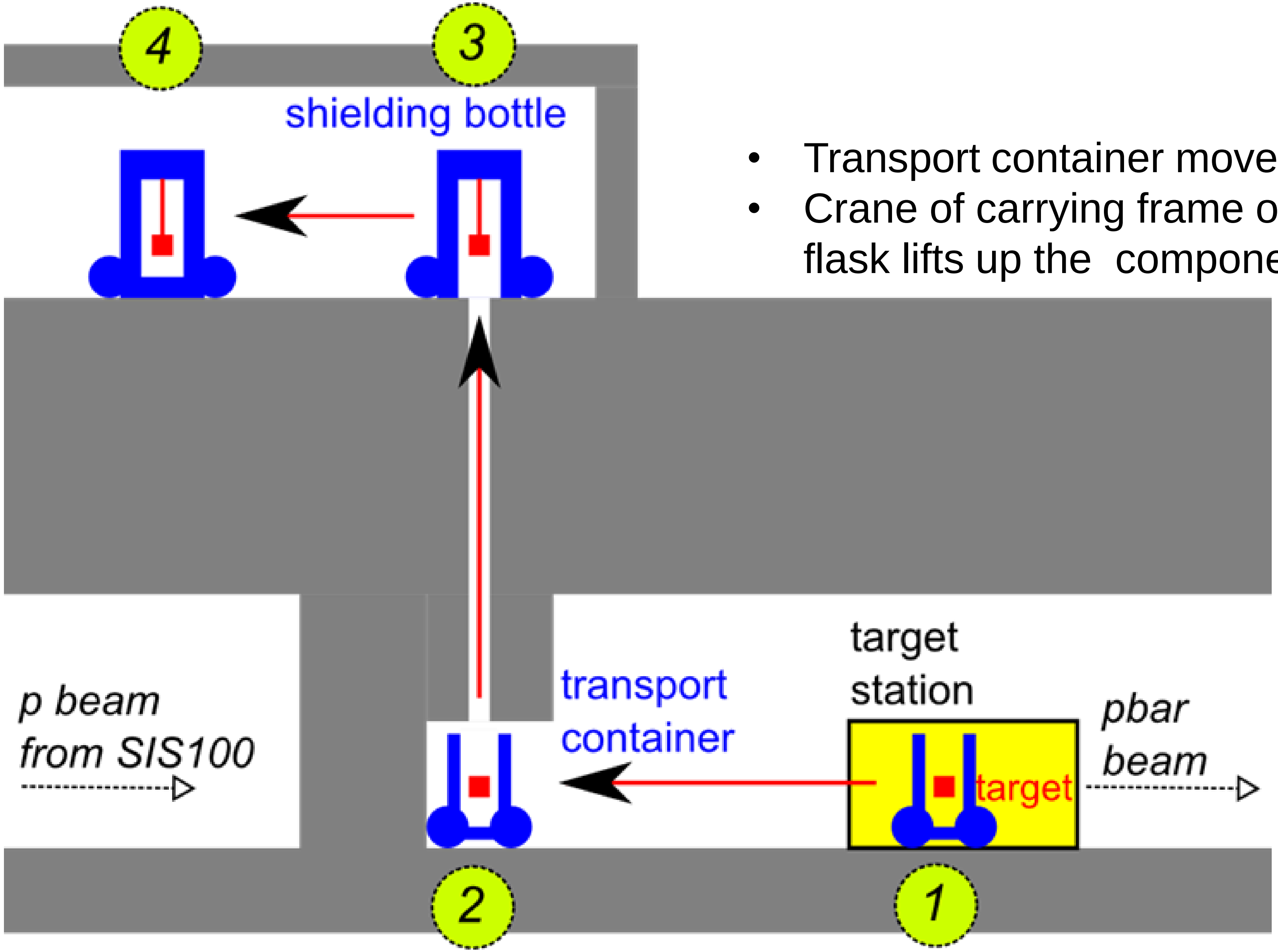
FAIR — Facility for Antiproton and Ion Research in Europe



- 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.

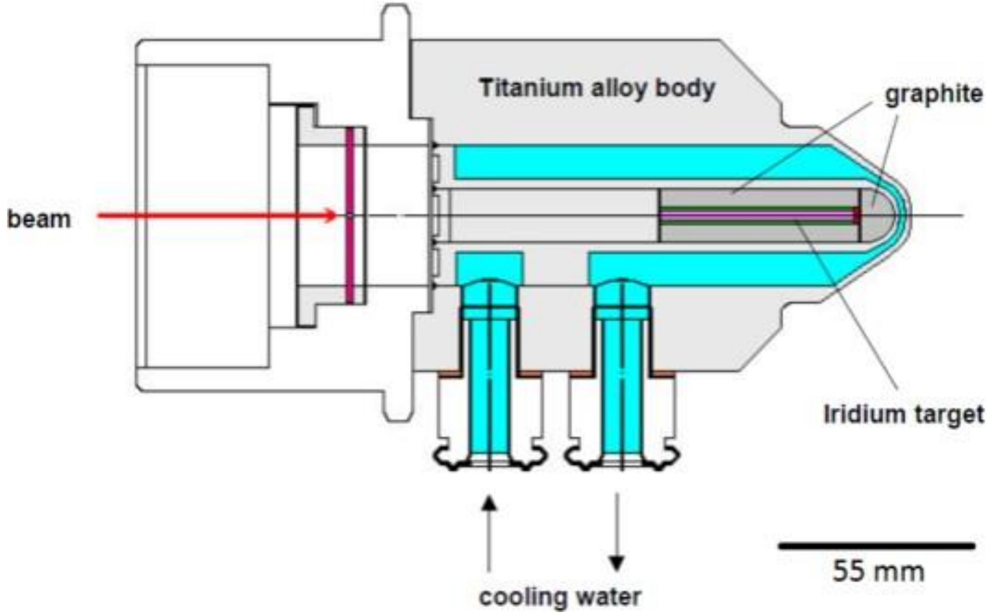
Target transport

FAIR — Facility for Antiproton and Ion Research in Europe

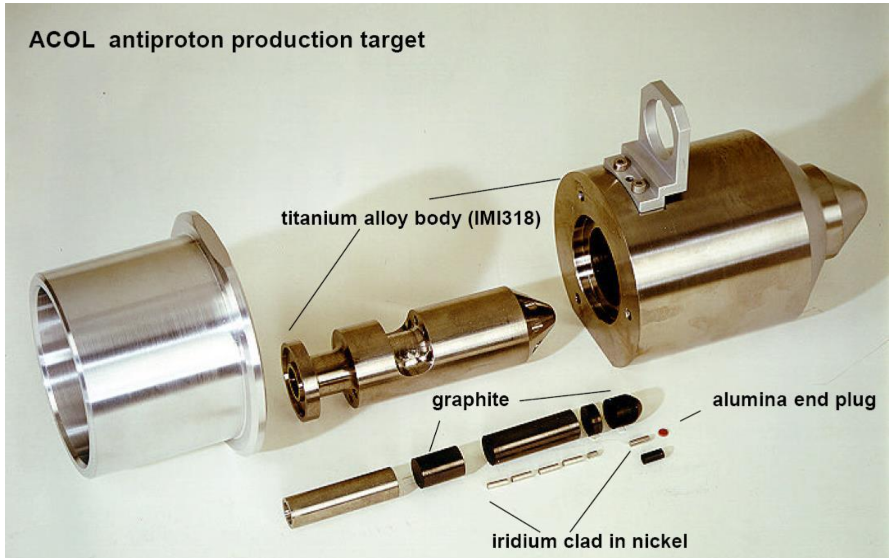


- Transport container moves to the shaft (1-2).
- Crane of carrying frame of the shielding flask lifts up the component (3).

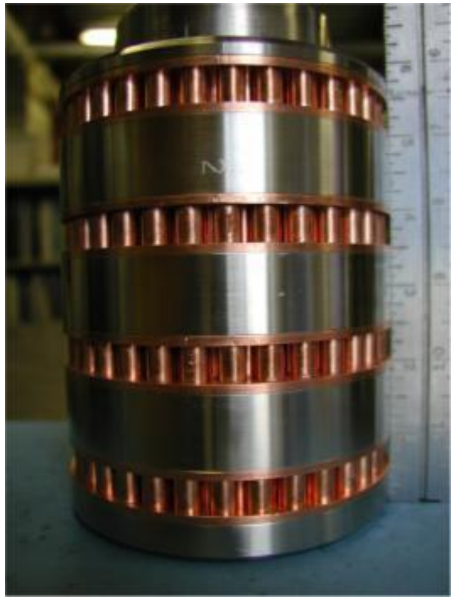
CERN and Fermilab pbar Targets



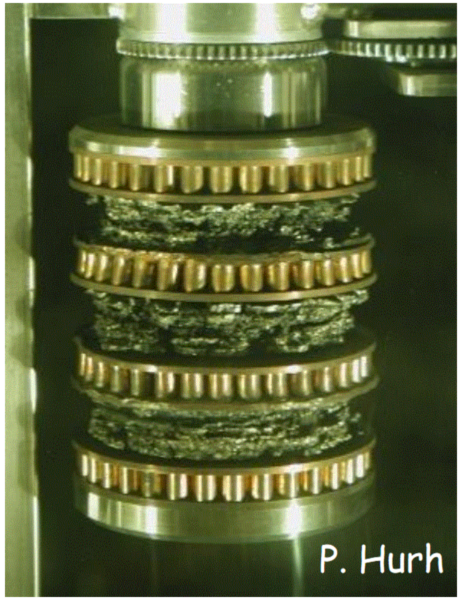
CERN target (Ir or Cu)



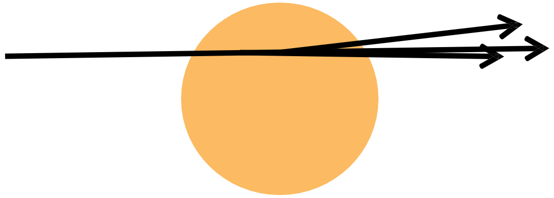
Fermilab rotating target



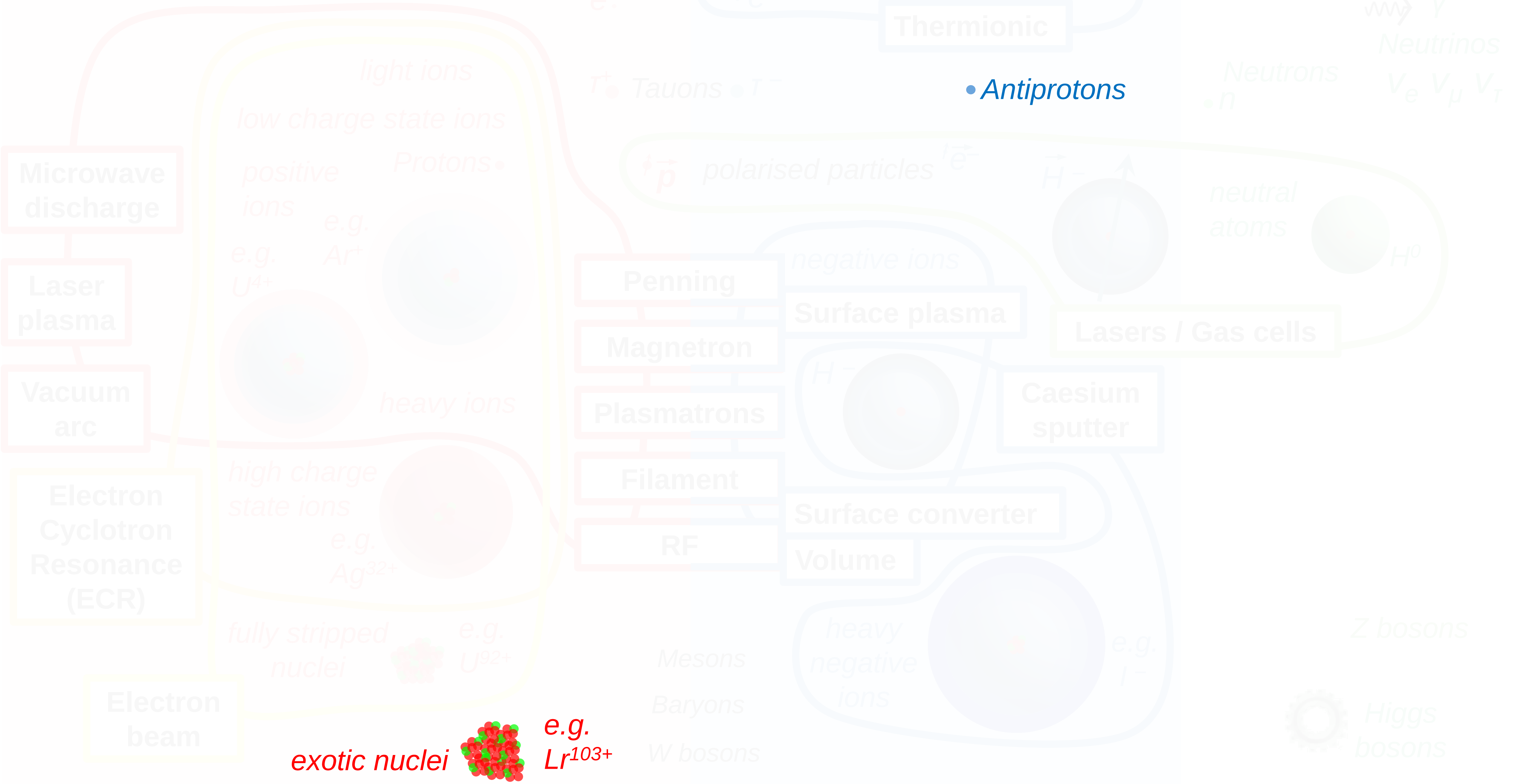
new



used



Particles and Sources



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Z bosons

Electron beam

Baryons

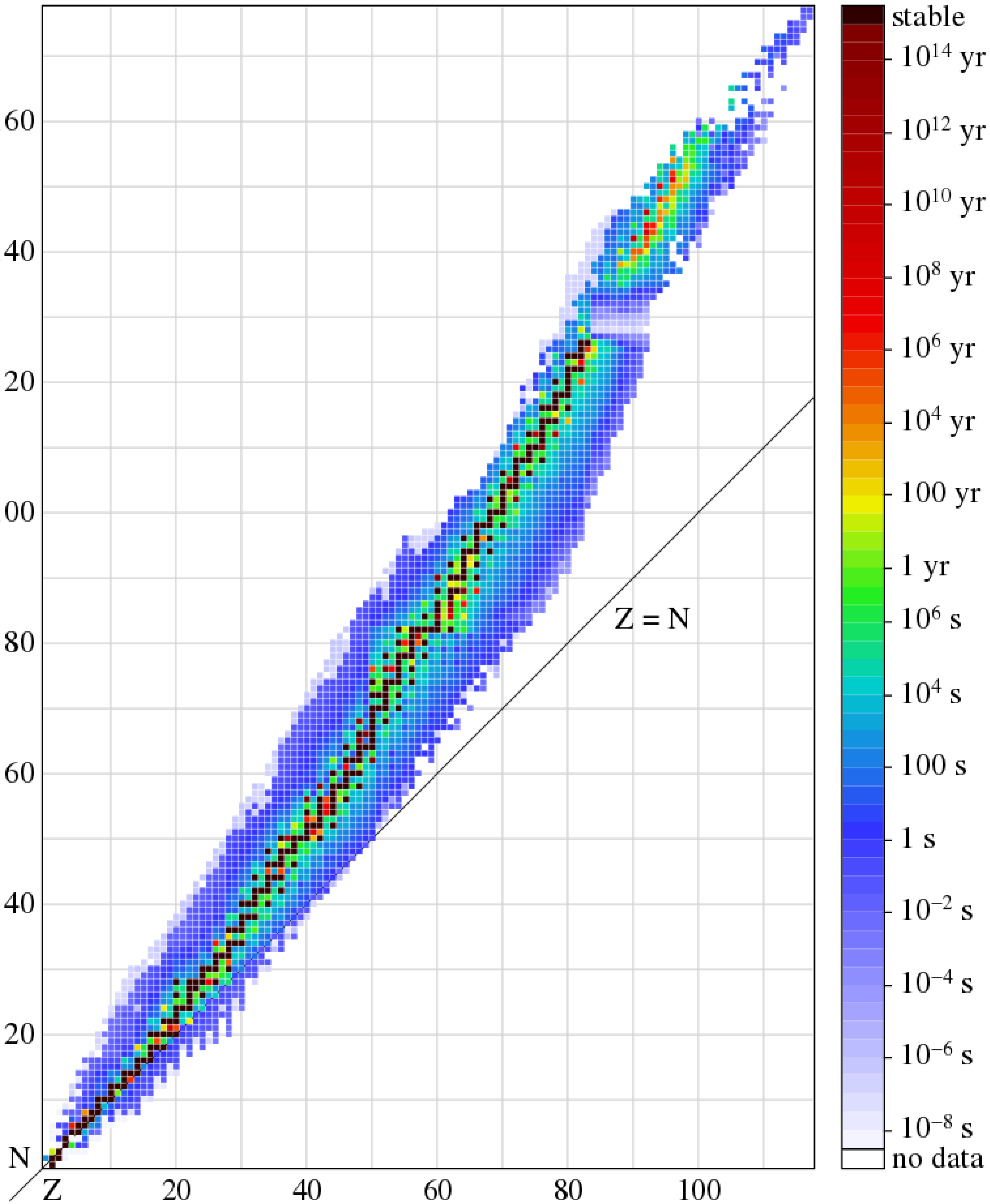
Higgs bosons

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

W bosons

Radioactive Ion Beams

A powerful way of studying the atomic nucleus



TRIUMF

Rare Isotope Facilities World-Wide

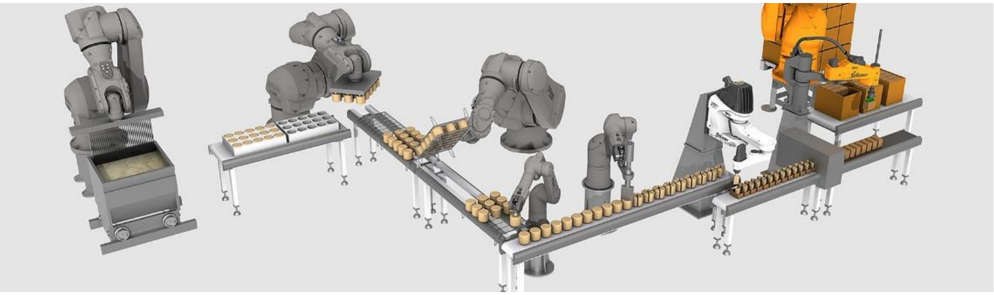
- ● ISOL-type Facilities
- ■ In-Flight-type Facilities

* planned or in construction

covery, celerated

ISOL vs In Flight Fragmentation

Isotope Separation On Line (ISOL): A production line

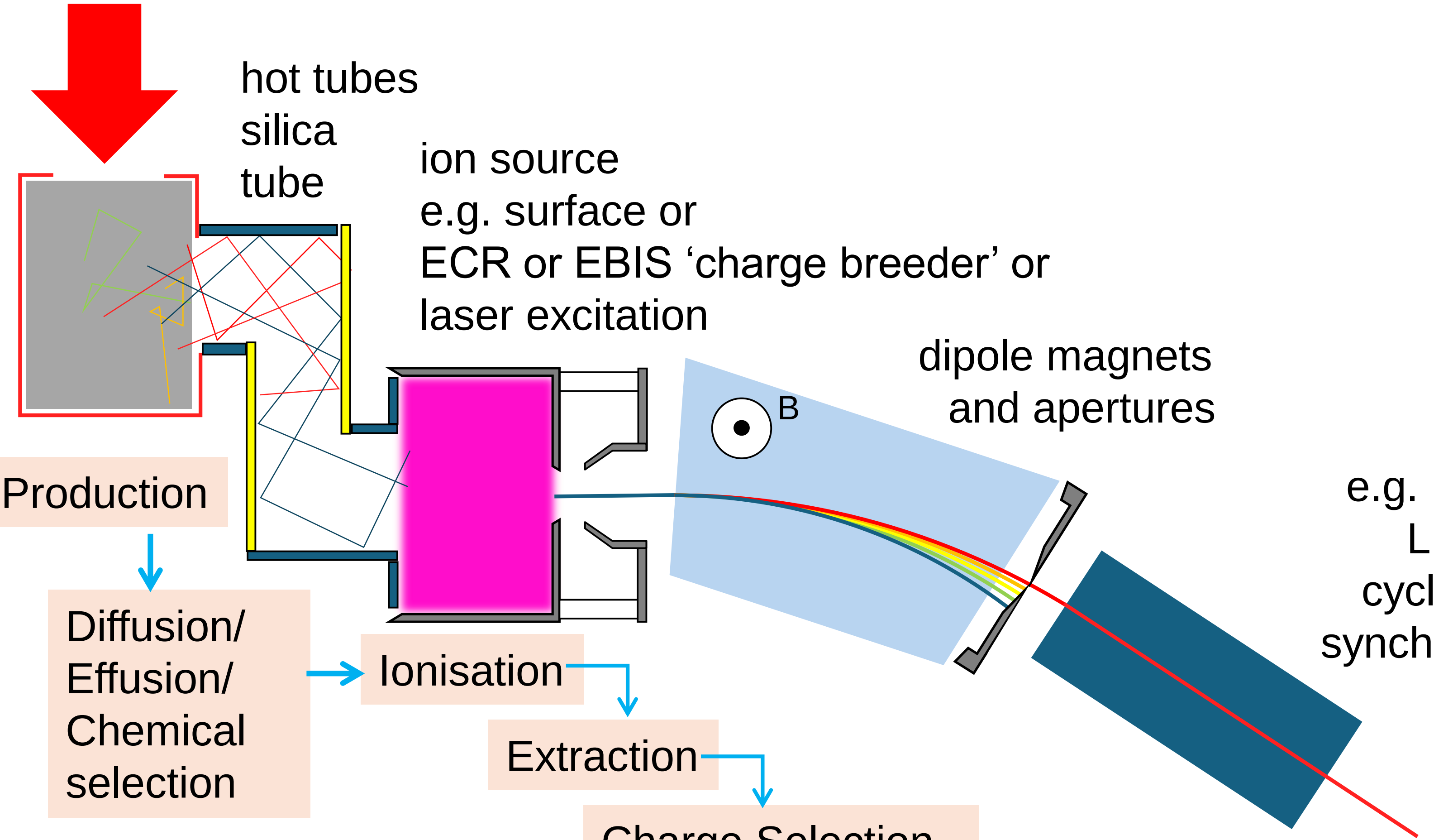


A → B → C → D → E → F

Very complicated chains of acceleration and separation have been created

In Flight Fragmentation: Filtering an explosion

ISOL: common components



primary beam

hot thick target

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

seconds
to
release

Production

Diffusion/
Effusion/
Chemical
selection

Ionisation

Extraction

Charge Selection

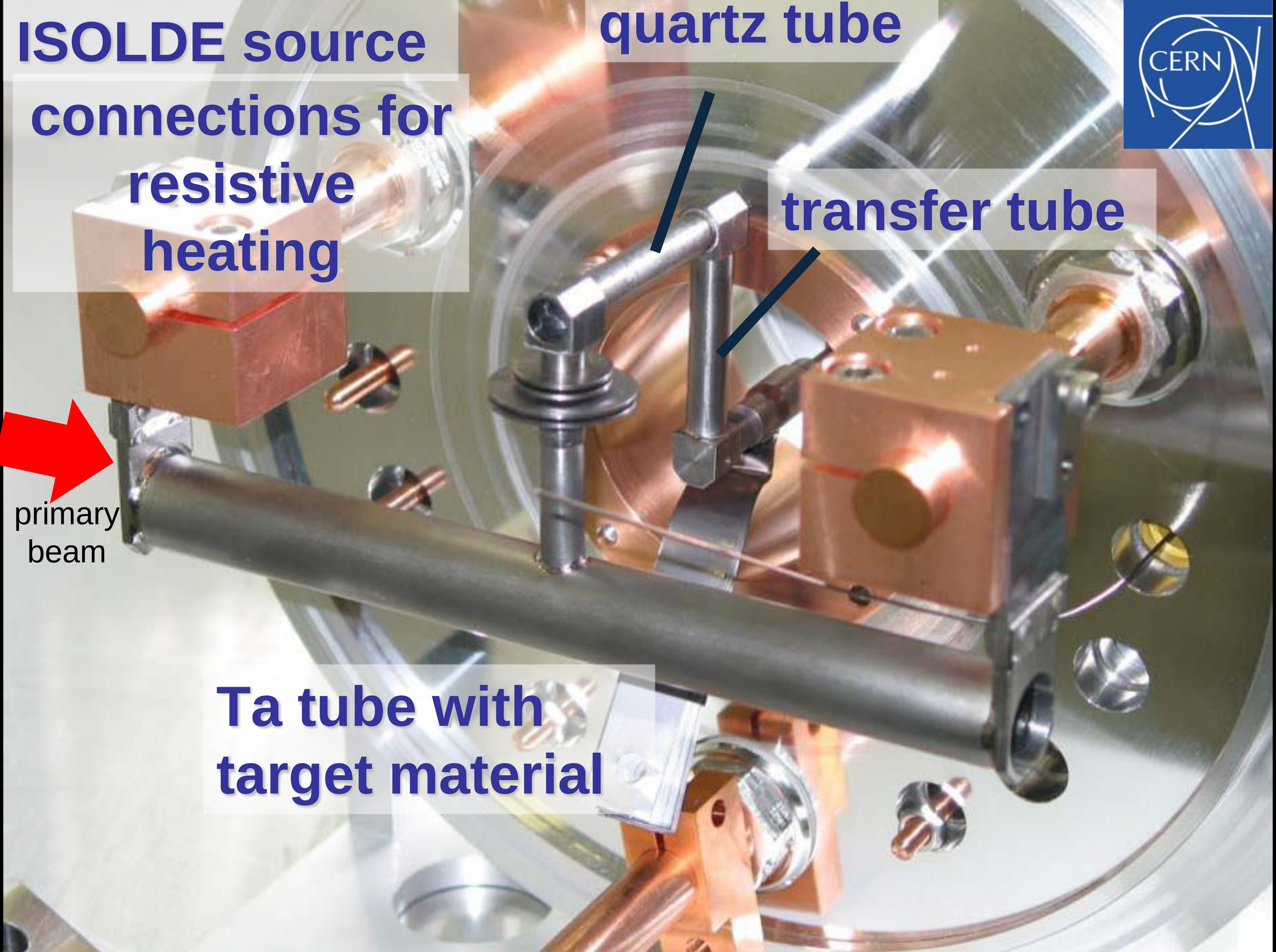
Acceleration

pure isotope and
charge state beam

Efficiencies can be as low as 1E-8

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

TRIUMF

RIB Intensity

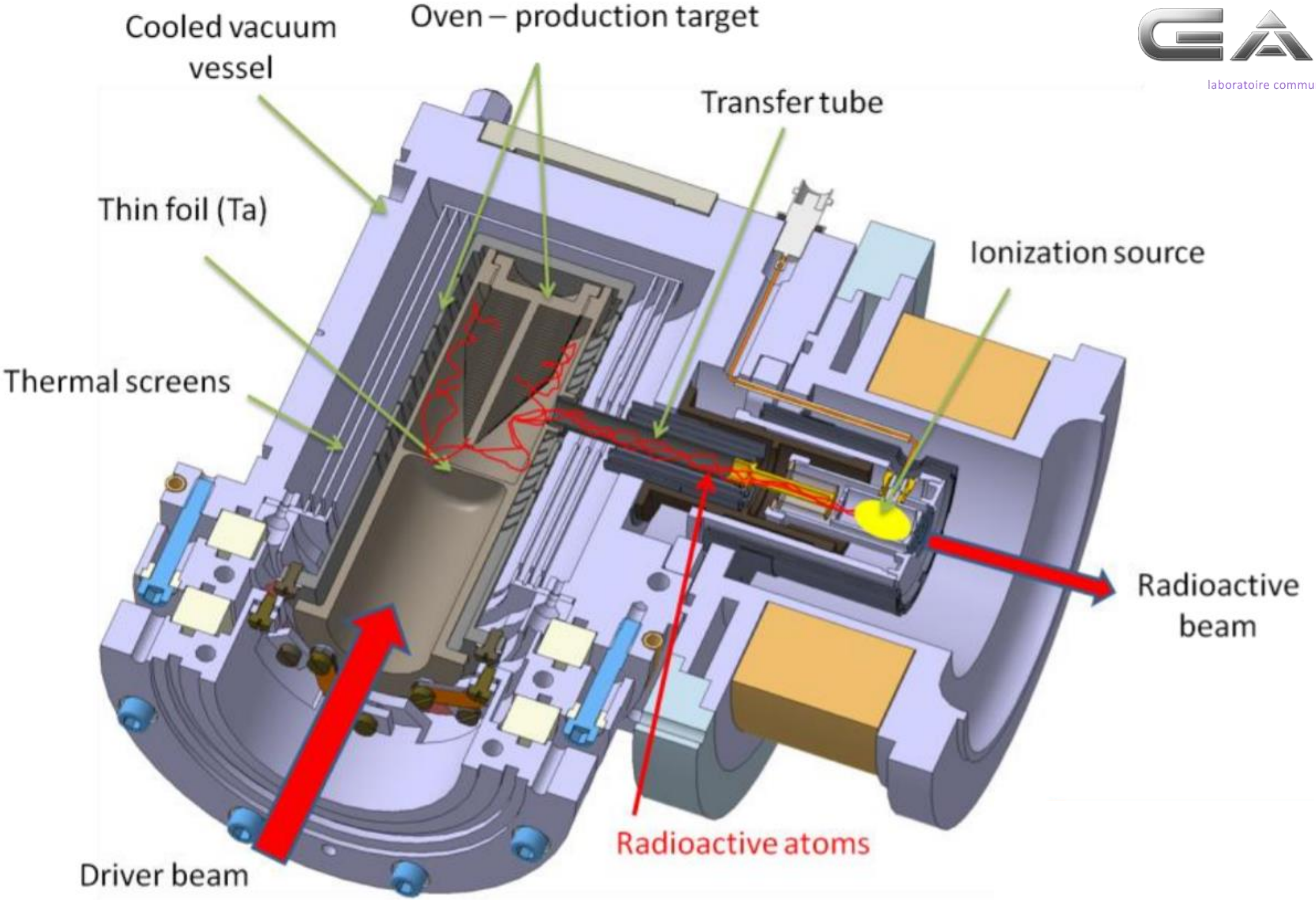
$$I_{\text{RIB}} = \varepsilon \cdot I_{\text{prod}} = \varepsilon \cdot \int_{\text{target}} \sigma(E)\, N_{\text{target}}\,(l)\, I_{\text{primary}}(l)\, dl$$

verview

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 $[\text{barn} = 10^{-24}\mathrm{cm}^2]$
N_{target} - target atoms per exposed area $[\mathrm{cm}^{-2}]$
$I_{primary}$ - primary beam intensity

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

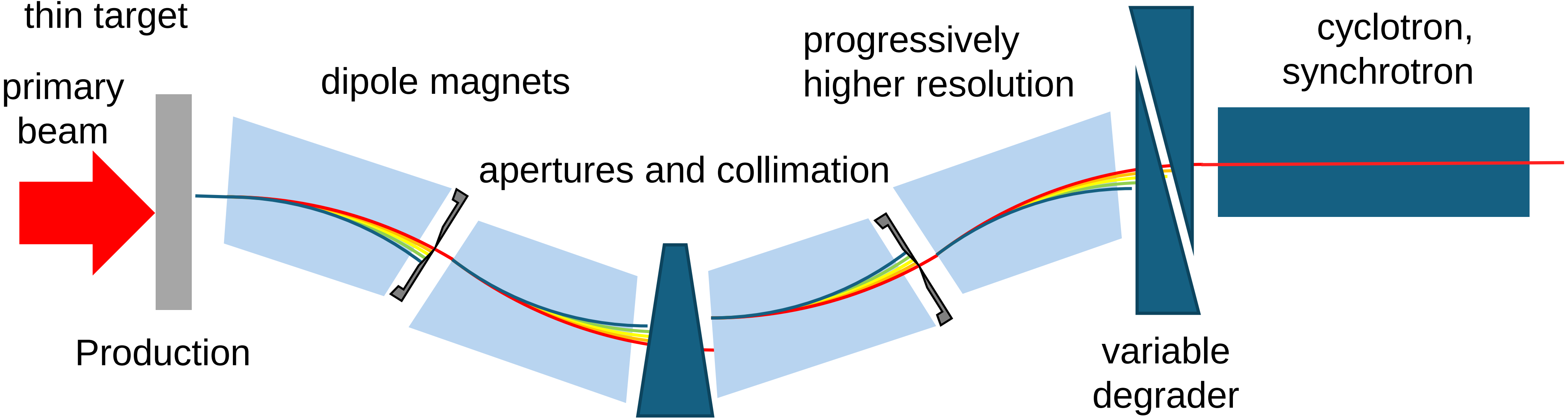
$\varepsilon_{\text{release}}$ - probability of not-decaying during the time of extraction from the target/ion source unit
$\varepsilon_{\text{ionization}}$ - probability of ionization of desired species by chosen ionization mechanism
$\varepsilon_{\text{transport}}$ - efficiency of mass selection and 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



laboratoire commun CEA/DSM CNRS/IN2P3

In Flight Fragmentation: common components

Fragment separator:



thin target

primary beam

dipole magnets

progressively higher resolution

RFQ,
LINAC,
cyclotron,
synchrotron

apertures and collimation

single isotope beam

Production

variable degrader

q/m selection

wedge shape degrader

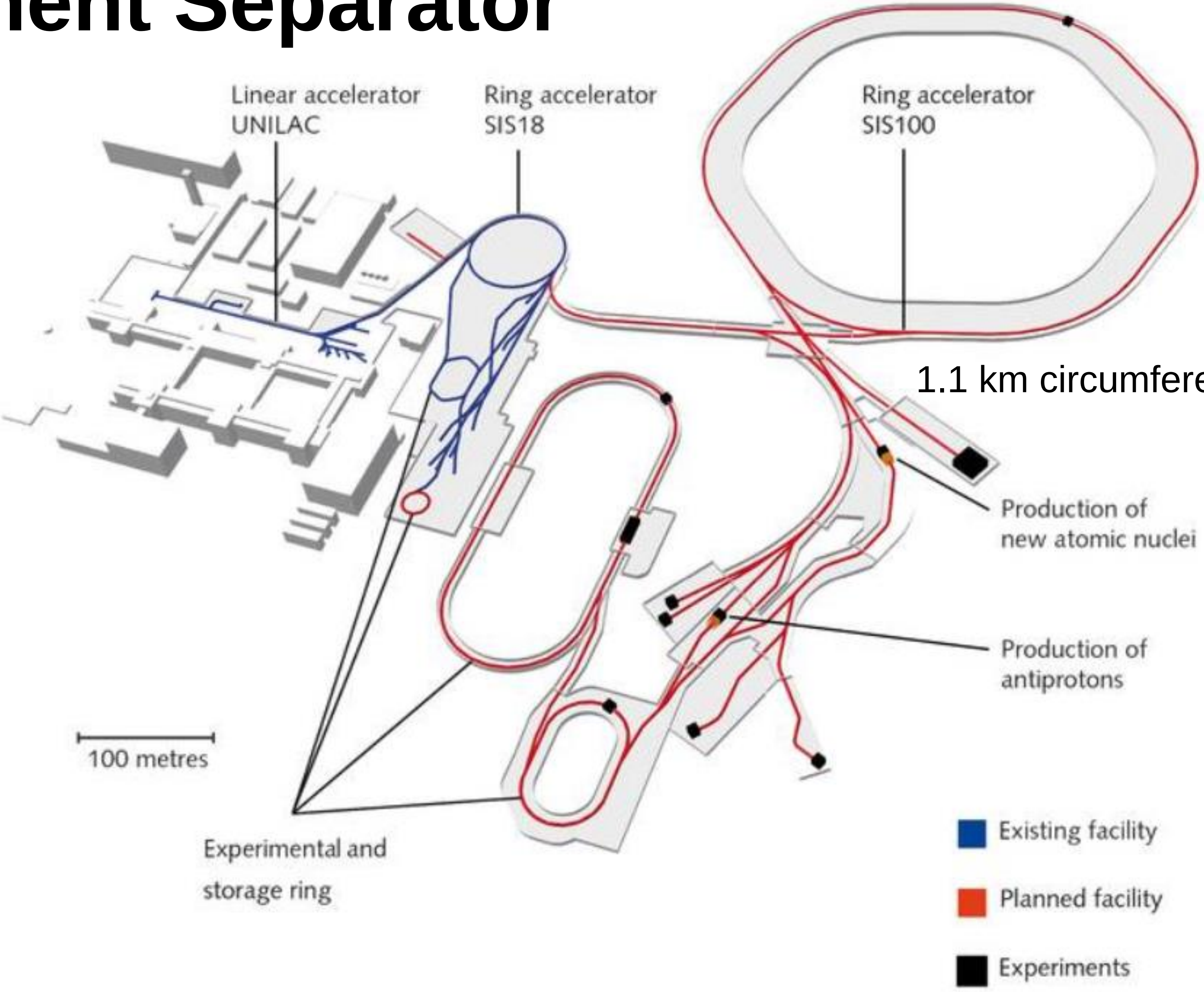
Wein filters also used

Degrader: *d**E**/dx* depends on projectile’s ***Z***

In flight fragmentation is suitable for very short half life beams

The Super Fragment Separator

2.7 GeV/nucleon
U^{28+}

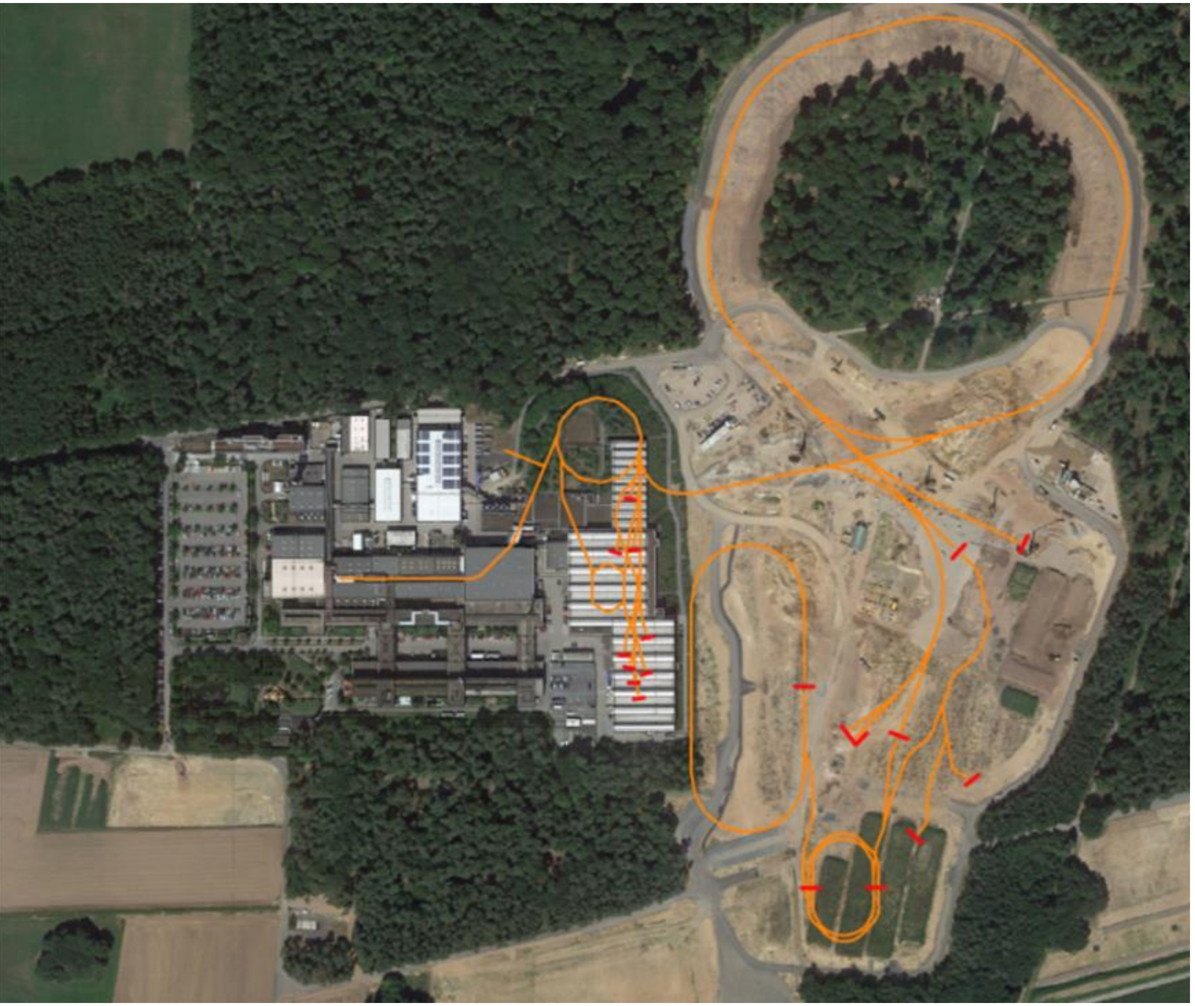


1.1 km circumference

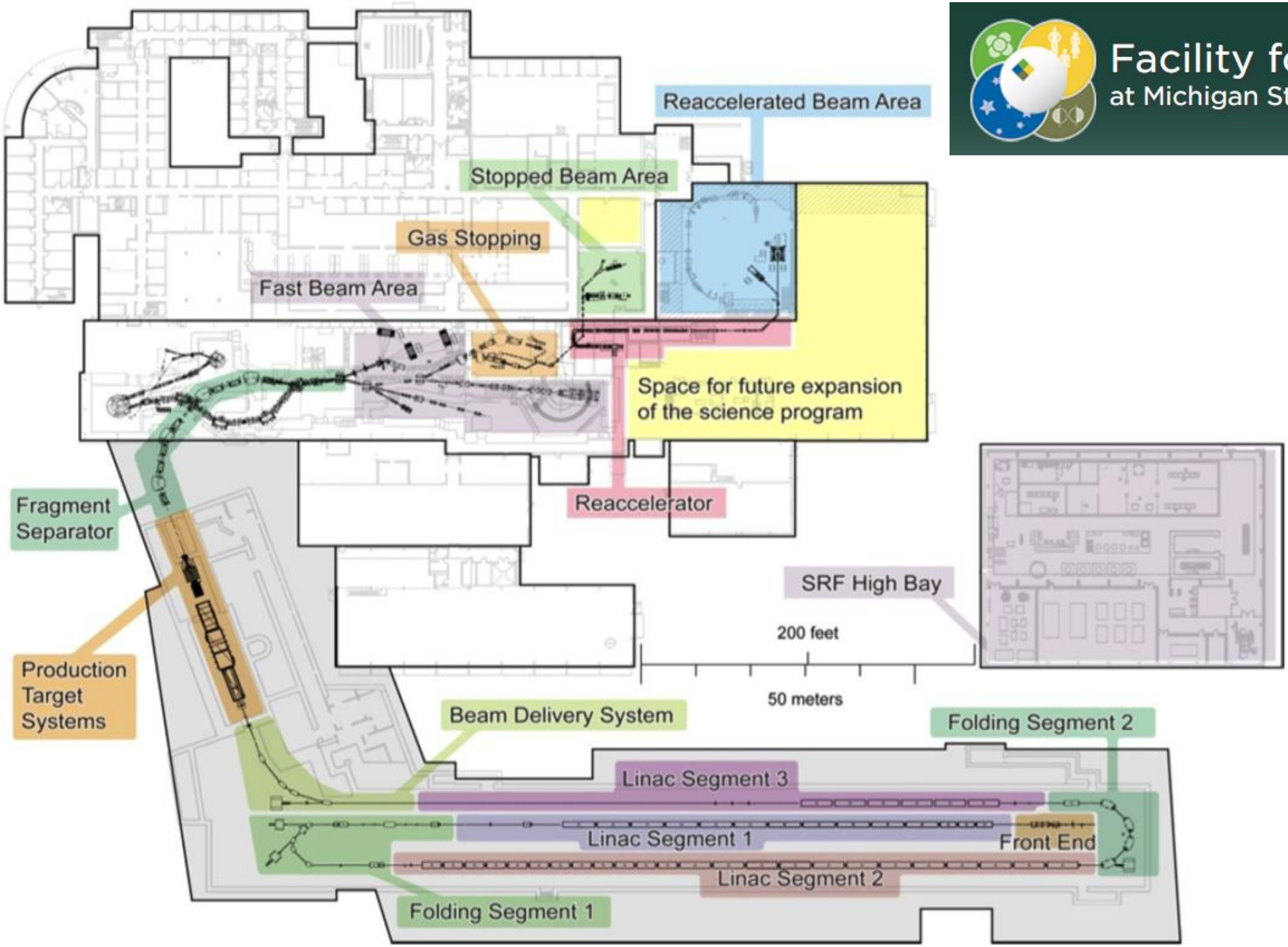
FAIR — Facility for Antiproton and Ion Research in Europe

The Super Fragment Separator

FAIR — Facility for Antiproton and Ion Research in Europe



Facility for Rare Isotope Beams
at Michigan State University



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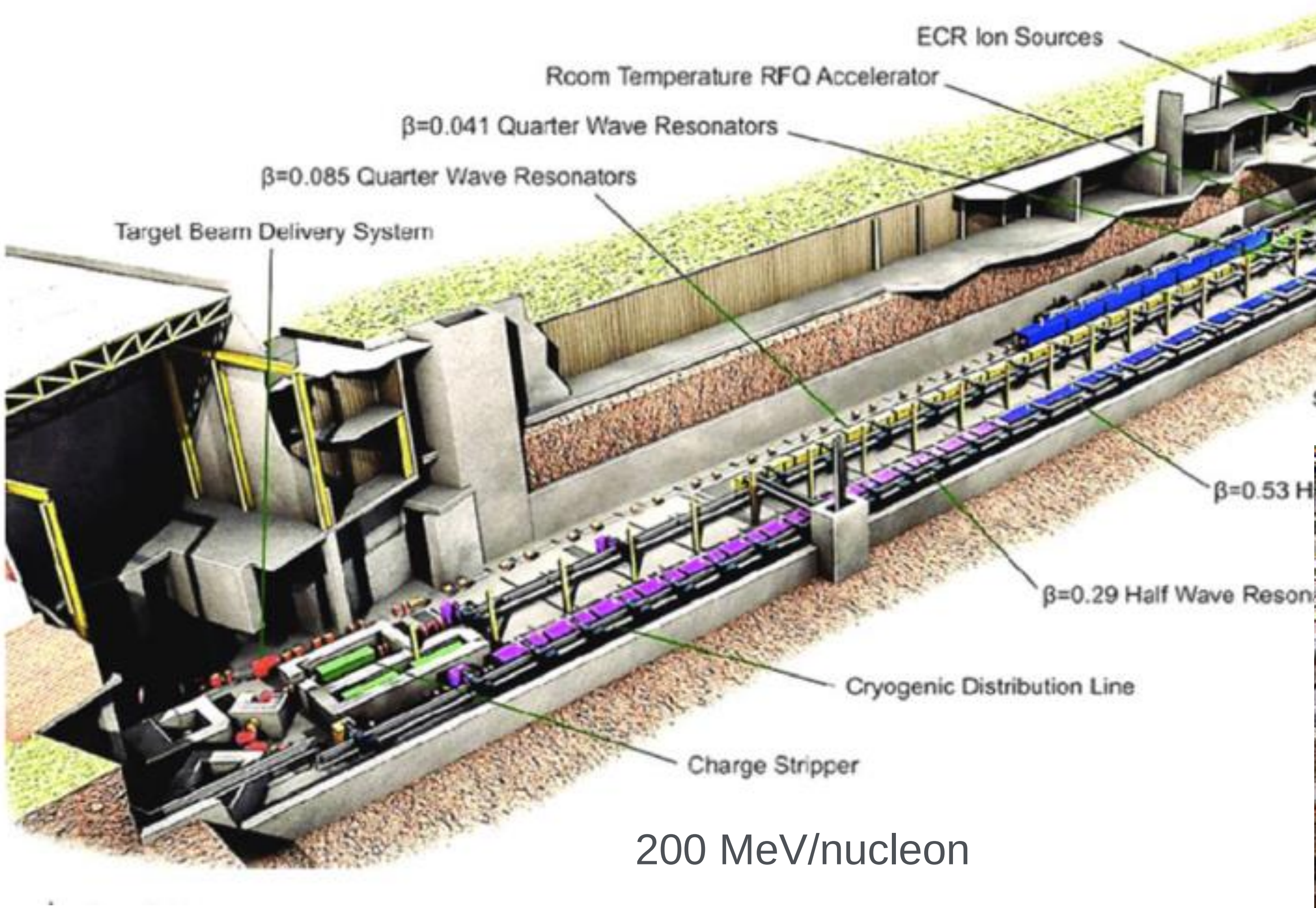
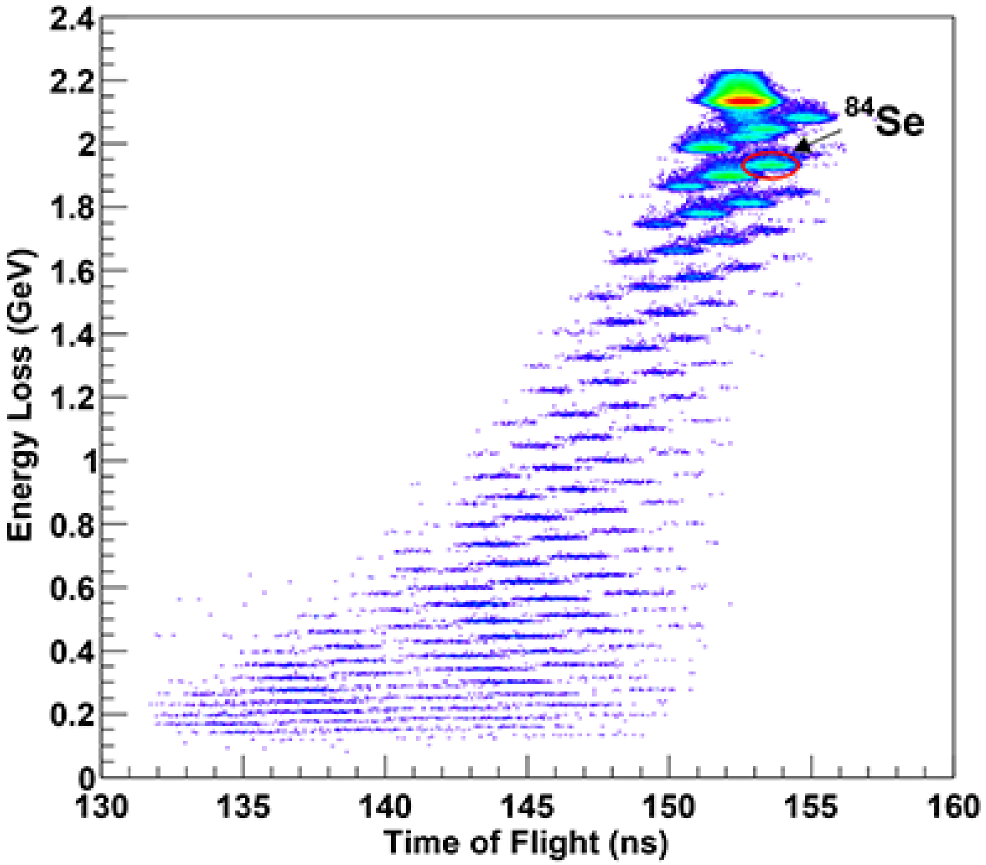


517 m linac

200 MeV/nucleon

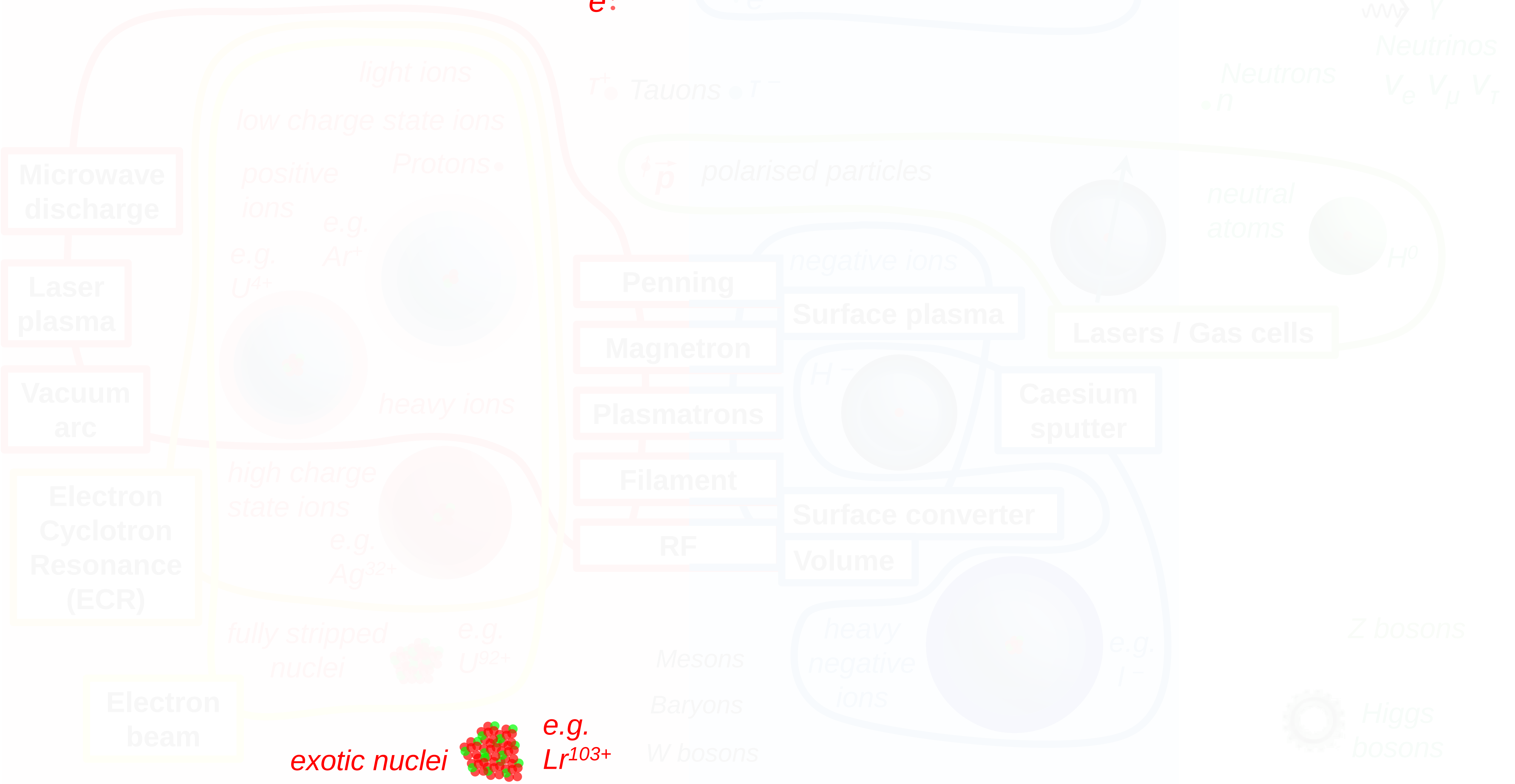
Facility for Rare Isotope Beams
at Michigan State University

first rare isotopes 2021
selenium-84 from a krypton-86 beam.



2022 discovered magnesium-18

Particles and Sources



Positrons e^+

Electrons e^-

Plasma + other

Photons γ

Neutrinos ν_e ν_μ ν_τ

Neutrons n

τ^+ Tauons τ^-

light ions

low charge state ions

Protons

positive ions

e.g. Ar^+

e.g. U^{4+}

$\vec{p}$ polarised particles

neutral atoms

H^0

Microwave discharge

Laser plasma

Vacuum arc

Electron Cyclotron Resonance (ECR)

Electron beam

Penning

Magnetron

Plasmatrons

Filament

RF

negative ions

Surface plasma

Lasers / Gas cells

H^-

Caesium sputter

Surface converter

Volume

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

heavy negative ions

e.g. I^-

Z bosons

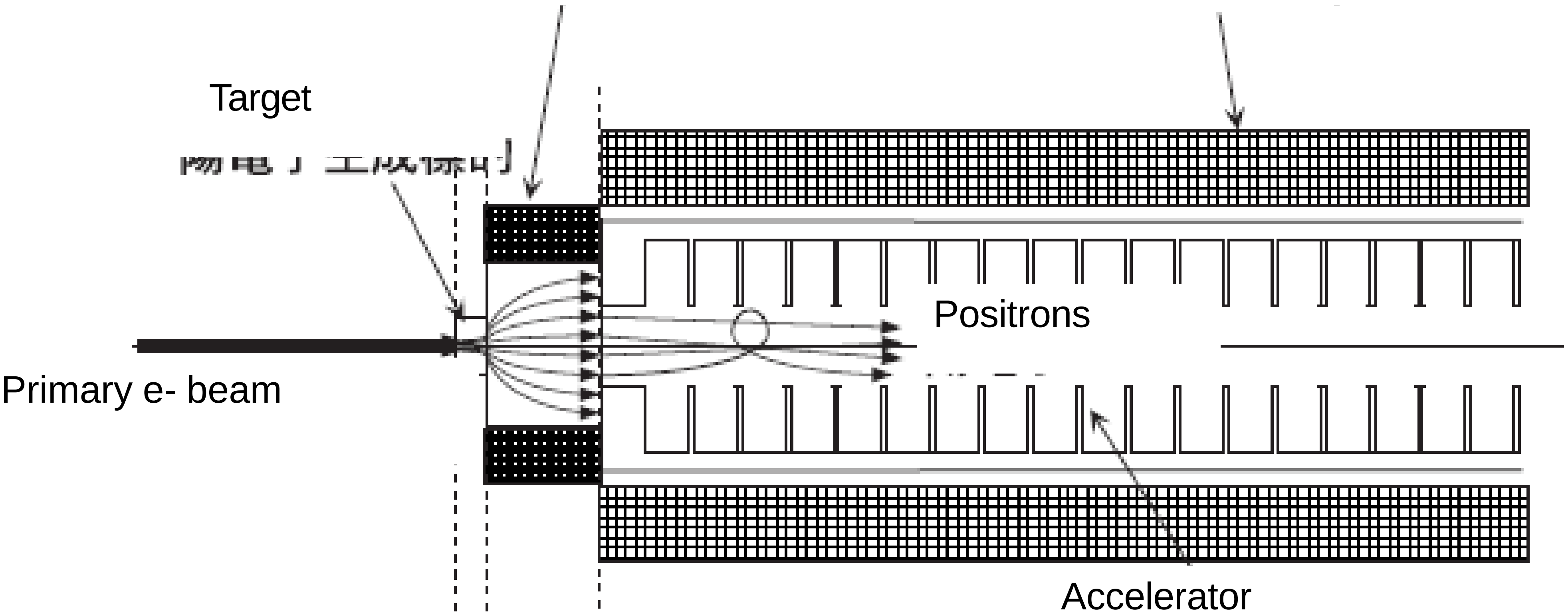
Higgs bosons

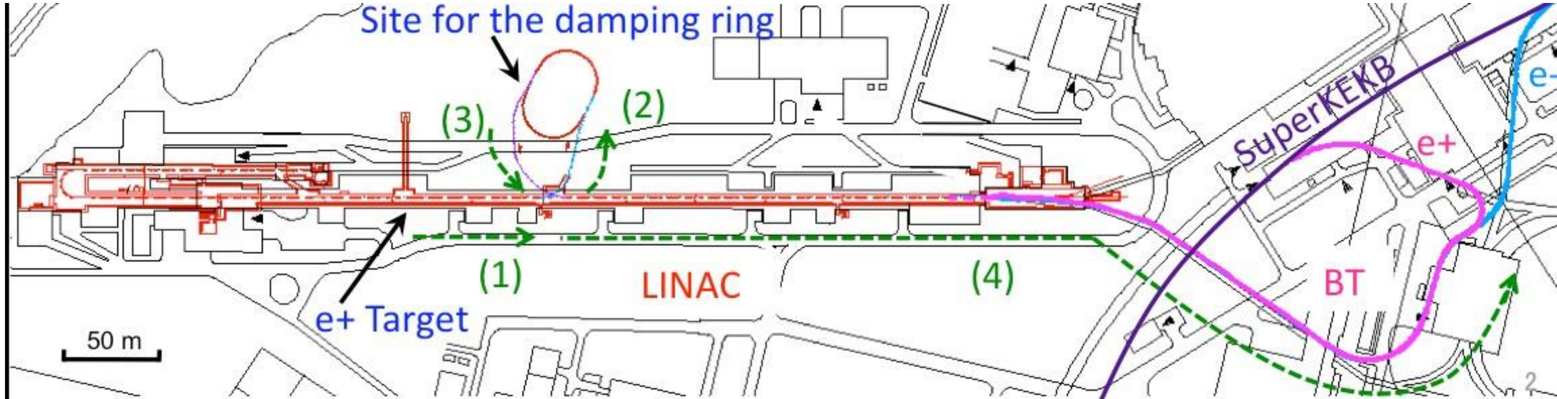
Positron Sources

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 KEKB and Su in Japan





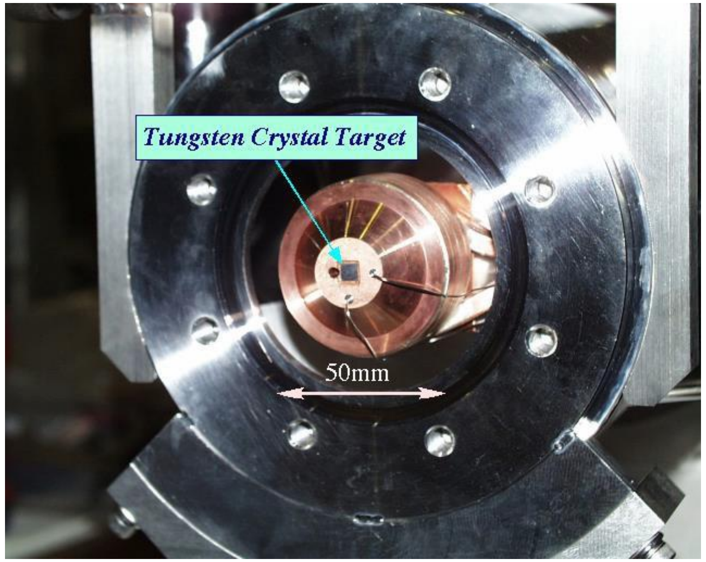
Target material

Requirements:

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

High melting point

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

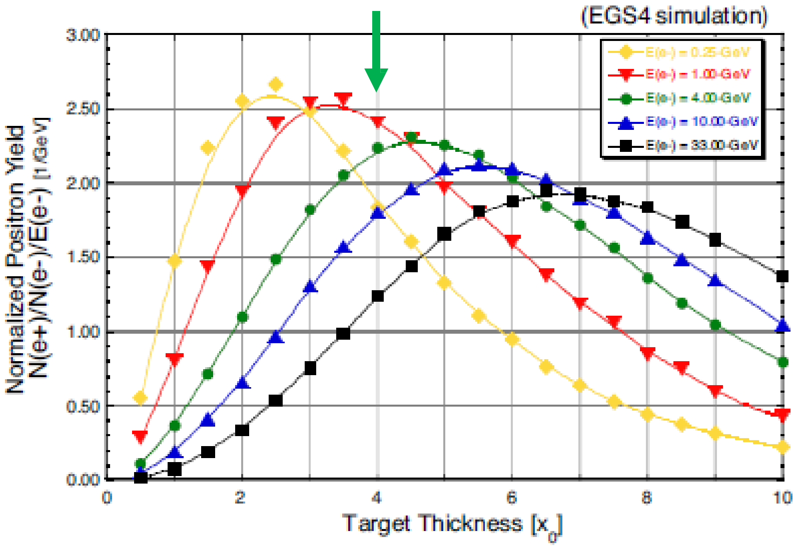


Joining of tungsten crystal to a copper body by a hot isostatic pressing (HIP)

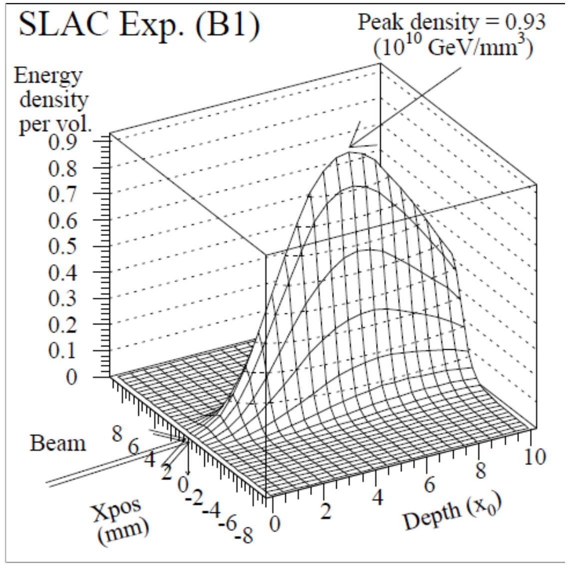
KEKB, SuperKEKB

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

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



Target destruction limit



After the target destruction occurred at SLAC

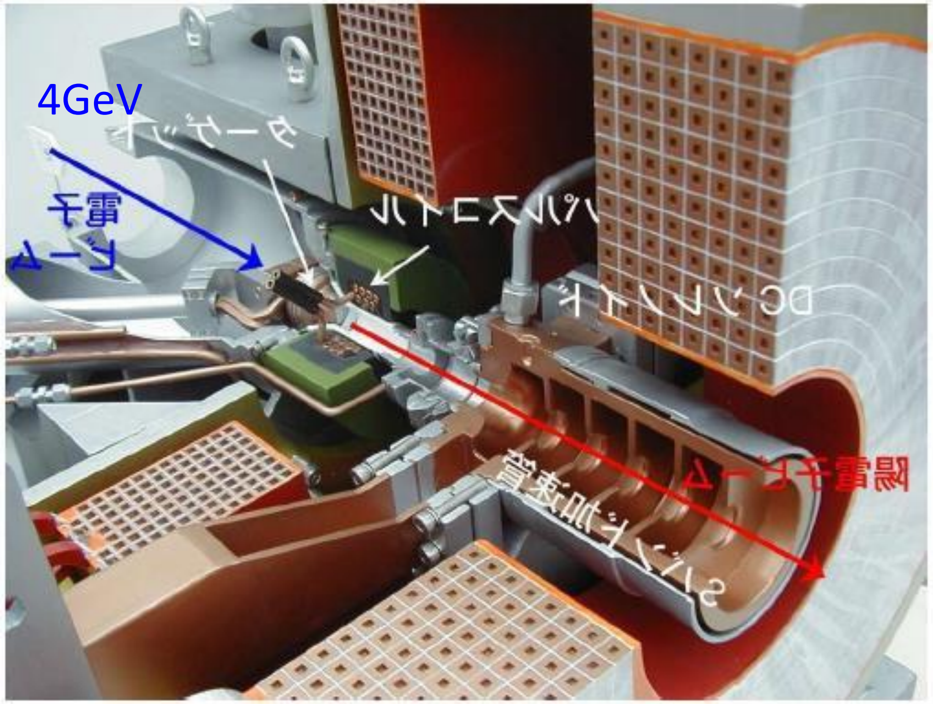
Threshold : 76 → 35 J/g

KEK Positron Sources

KEKB

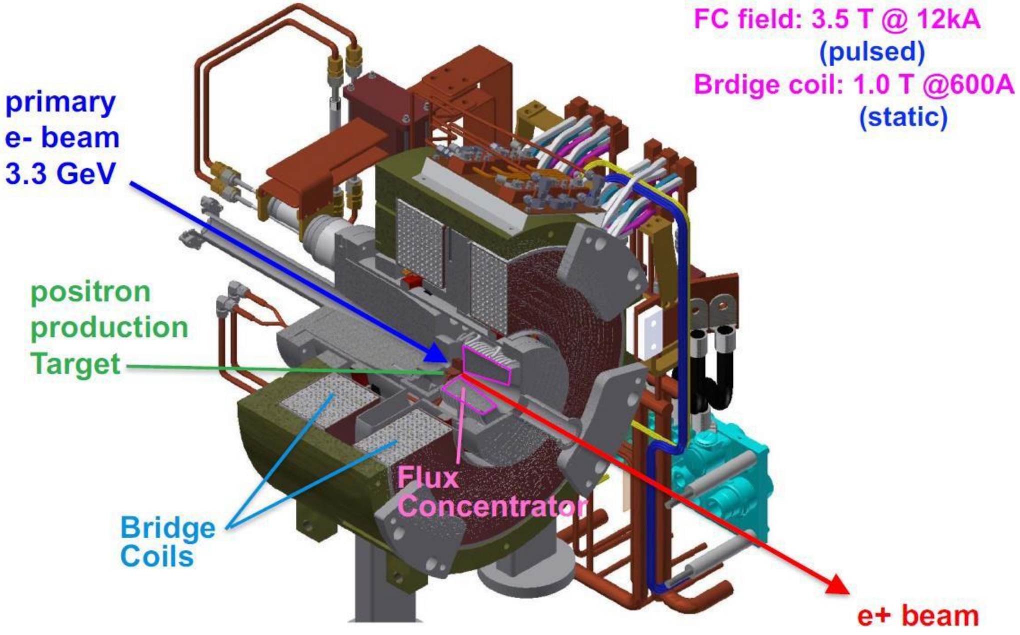
Quarter wave transformer matching device

Pulse coil: 2.3T @ 10kA



SuperKEKB

AMD Flux Concentrator matching device

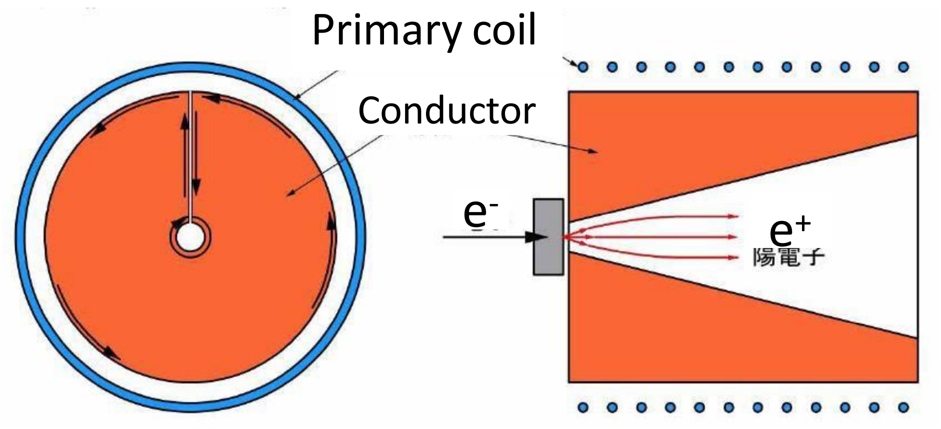


50Hz rep rate with a bunch charge of $2.5\times10^{10} = 2.5\times10^{12}$ e+/s

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.

adiabatic condition

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

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

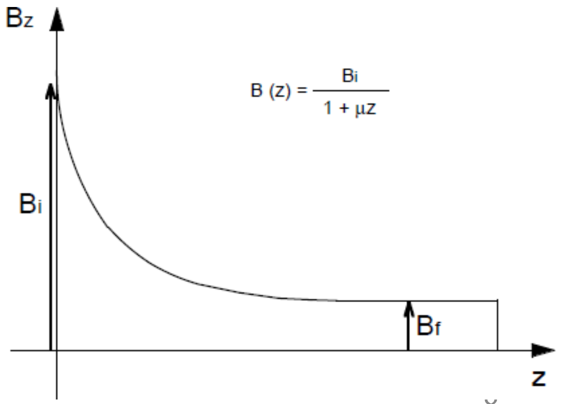
(B0 = 7.0 [Tesla], μ = 60[1/m])

Transverse acceptance

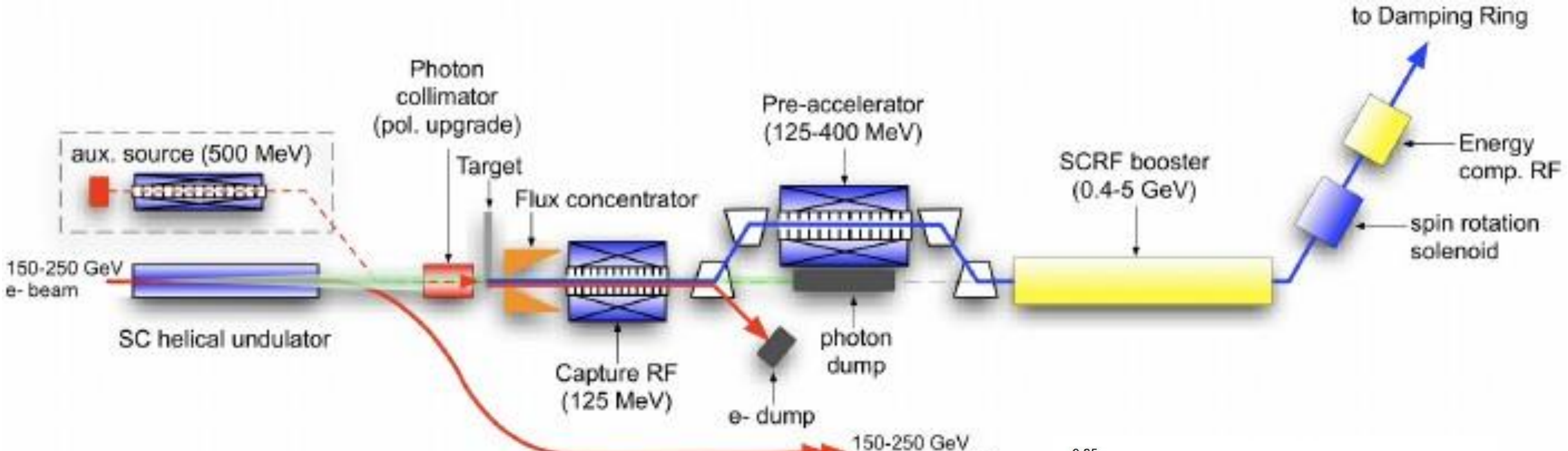
$$p_{t-max} = \frac{e}{2}\sqrt{B_f B_0 a}$$

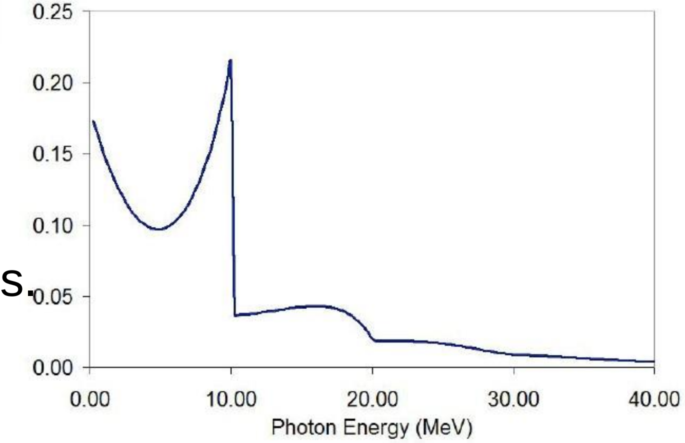
$$r_{max} = \sqrt{\frac{B_f}{B_0}}a$$

a: Diameter of an accelerator iris



Gamma Ray Undulator Source





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

Considered primarily for the ILC

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

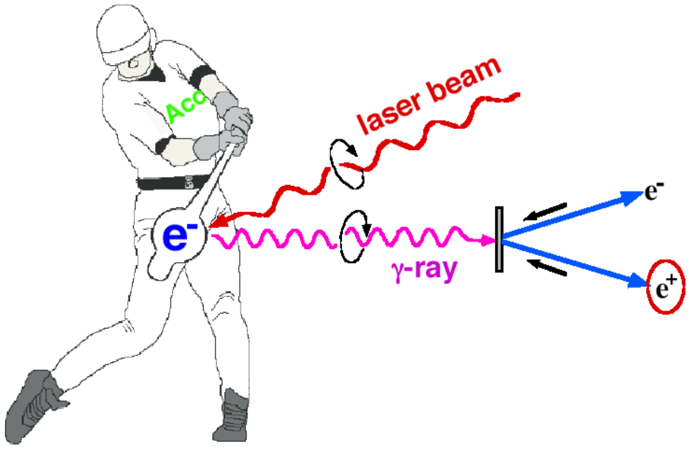
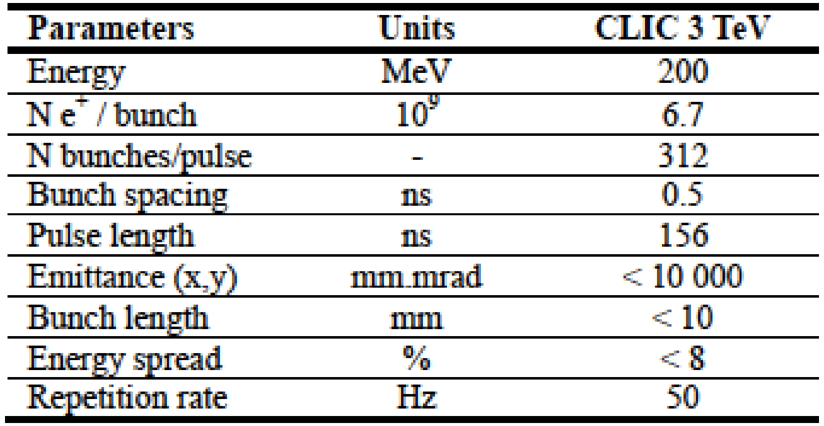


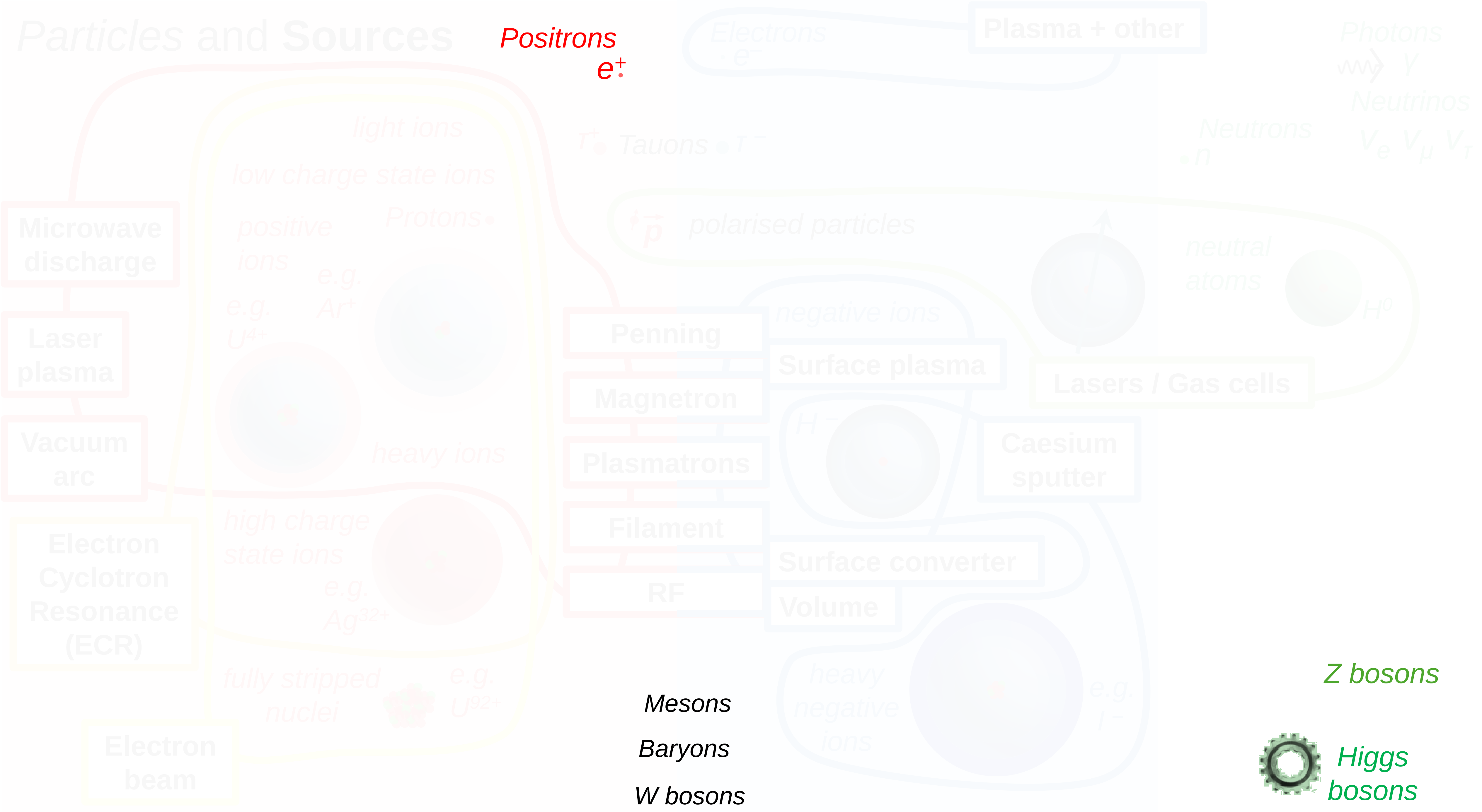
Table 1: CLIC parameters for e+ beam



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



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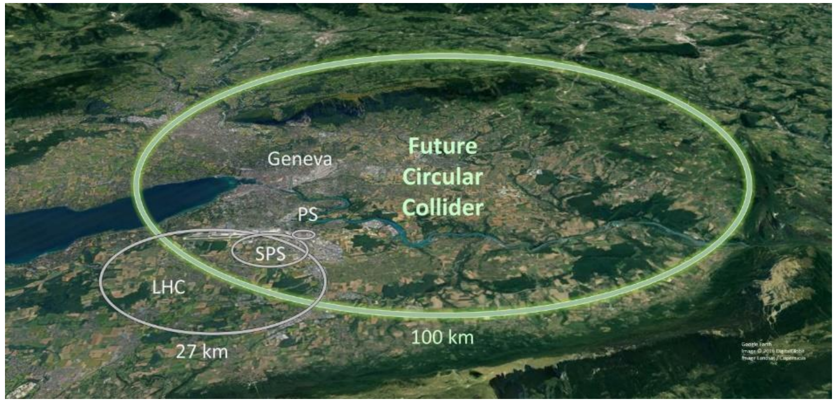
Future Colliders

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?