Beam Intercepting Devices at CERN
PSI visit

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5th April 2023

Outline

- General introduction
- Overview of challenges and focused examples
- Selected choices:
  - n_TOF spallation target
  - Beam Dump Facility
  - SPS internal dumps
- Conclusions

SY/STI: Sources, Targets and Interactions Group

Sources

Build and operate **all CERN laser**-based particle **sources** and lasers for beam ionization/spectroscopy of short-lived nuclides
→ **~10 laser facilities to operate**
→ **Electron sources for CLIC/AWAKE**

Interactions

Design, produce, operate beam intercepting devices in circular accelerators and transfer lines
→ **More than 250 devices**
→ **LHC collimation systems, dumps, etc…**
→ **Devices for accelerator and personnel safety**

Monte-Carlo Simulations beam-matter interactions
→ **Fluka development and Geant4**

Targets

Design **produce**, operate **all CERN secondary particle** production targets
→ **operation of the ISOLDE/n_TOF facilities and AD-target**
→ **responsible of the use of 75% of CERN protons**

SY-STI

Sources, Targets & Interactions

GL: Simone GILARDONI
DGL: Marco CALVIANI

SY-STI-BMI

Beam Machine Interactions

Francesco CERUTTI

SY-STI-LP

Lasers & Photocathodes

Bruce MARSH

SY-STI-RBS

Radioactive Beam Sources

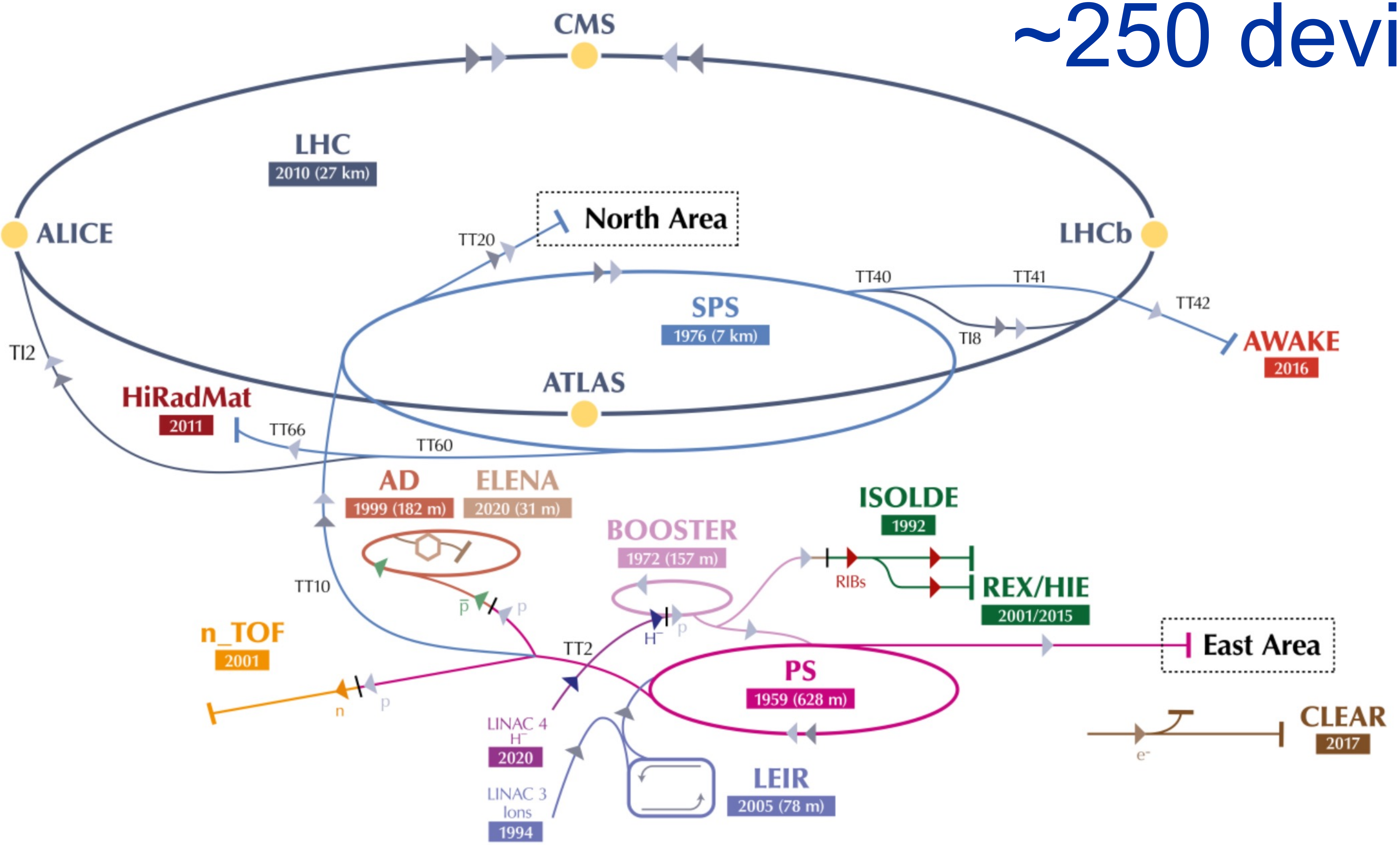
Joachim VOLLAIRE

SY-STI-TCD

Targets, Collimators & Dumps

Marco CALVIANI

~250 devices


CMS
LHC
2010 (27 km)
North Area
ALICE
TT20
LHCb
TT40
TT41
TT42
SPS
1976 (7 km)
TI8
AWAKE
2016
TI2
ATLAS
HiRadMat
2011
TT66
TT60
AD
1999 (182 m)
ELENA
2020 (31 m)
ISOLDE
1992
BOOSTER
1972 (157 m)
RIBs
REX/HIE
2001/2015
TT10
p̄
p
H⁻
n_TOF
2001
TT2
East Area
PS
1959 (628 m)
n
p
LINAC 4
H⁻
2020
CLEAR
2017
e⁻
LINAC 3
Ions
1994
LEIR
2005 (78 m)

0. Introduction to challenges

Beam Intercepting Devices

A beam intercepting device is a component that **intercepts accelerated particle beams** for diverse purposes, such as

- ❑ **Production of secondary particles** ("target")
- ❑ **Protection of sensitive equipment** ("collimator")
- ❑ **Safe disposal** ("dump")

What type of challenges need to be faced? (1/3)

- Devices must be able to withstand operation and accident scenarios & protect delicate equipment
- Mostly employed as “last line of defence” against component damage
- Dependable components, whose failure often leads to long period of downtime
- Usually, the most radioactive components in an accelerator complex

What type of challenges need to be faced? (2/3)

- High energy densities (several **kJ/cm^3/pulse**)
- High power densities (**MW/cm^3**)
- High beam kinetic energy (up **700 MJ**)
- High average deposited power (**hundreds of kW**)

CERNCOURIER.COM

FEATURE SYSTEMS ENGINEERING

INTERCEPTING THE BEAMS

From targets to absorbers, beam-intercepting devices are vital to CERN's accelerator complex.

https://cerncourier.com/a/intercepting-the-beams/

What type of challenges need to be faced? (3/3)

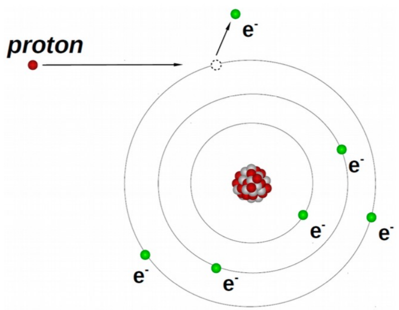
- Ultra High Vacuum requirements (10^{-10} mbar)
- Movable parts with extremely high precision and flatness
- Physics requirements (sometimes implying materials with poor structural properties)
- Impedance (especially for colliders)
- Radiation damage and modification of thermo-physical properties

Beam-matter interaction simulations

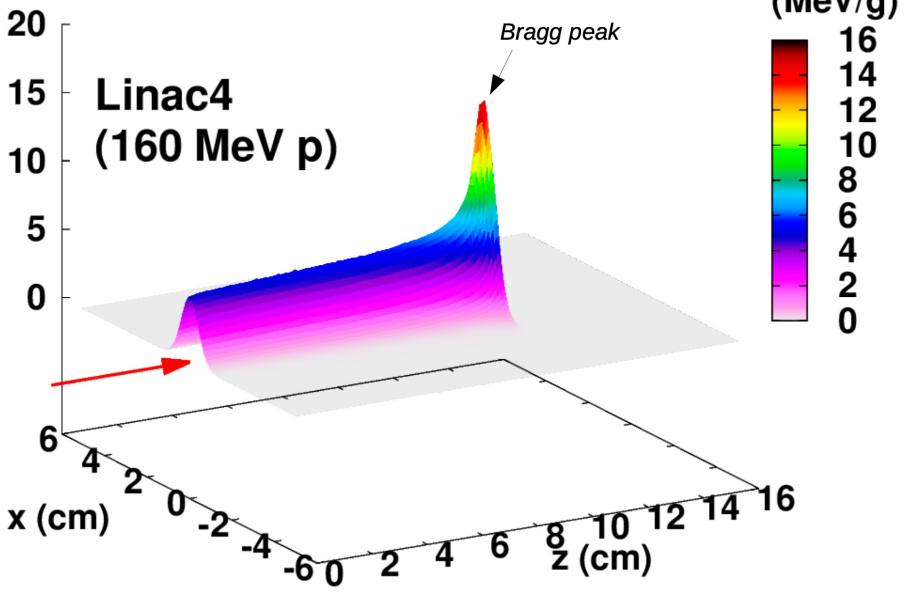
Particles interacts with matter via different mechanisms, depending on species (lepton vs. hadron), energy, impacting material (A, Z and ρ)

http://fluka.cern

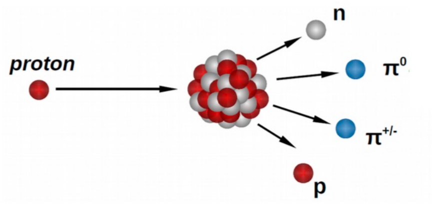
Most protons range out (ionizing energy loss)

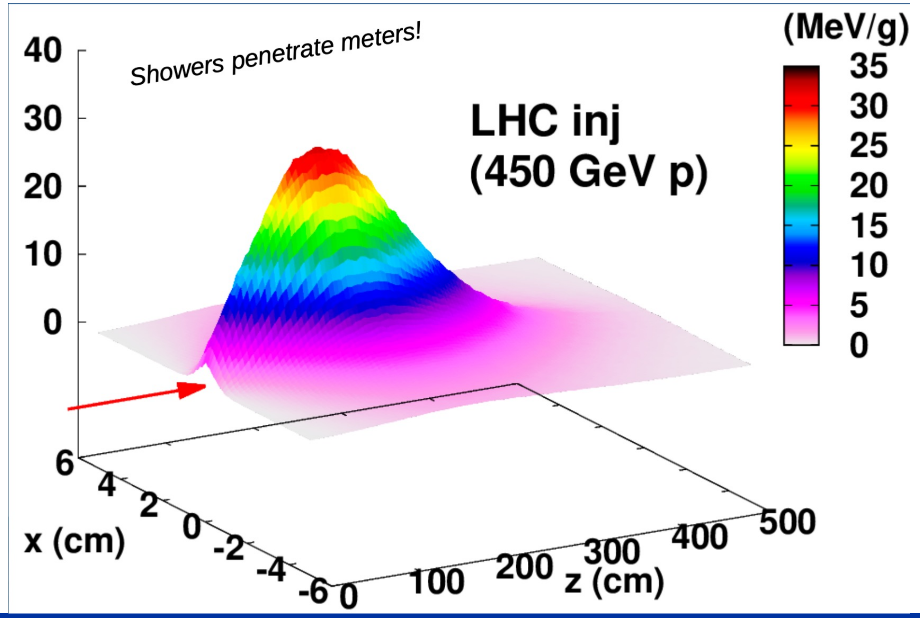


Courtesy A. Lechner



Nuclear interactions, particle cascades (showers)!





What are we talking about?
SPS beam dump

- A proton bunch has typical time duration of 1 ns
- Pulses are constituted by bunches separated by tens of ns (25 ns)

$$\text{Beam kinetic energy} = n_b \times I \times E_b = 288 \times 2.4 \cdot 10^{11} \times 450 = \mathbf{4.9\ MJ}$$

- Dumps (like targets) are made to sustain beam impacts repeatedly – in the case of SPS, every O(7.2) seconds

$$\text{Beam average power} = {}^{Q}/_{t} = \frac{4.9\ \text{MJ}}{21.6\ s} = \mathbf{230\ kW}$$

Need to be carefully dissipated!

What are we talking about?
LHC beam dump

- Beam energy will be 6.8 TeV (6800 GeV) from 2022
- N_b = 2748, with a bunch population up to 1.8×10^{11}

$$\text{Beam kinetic energy} = n_b \times I \times E_b$$
$$= 2748 \times 1.8 \cdot 10^{11} \times 6800 = \mathbf{539\ MJ}$$

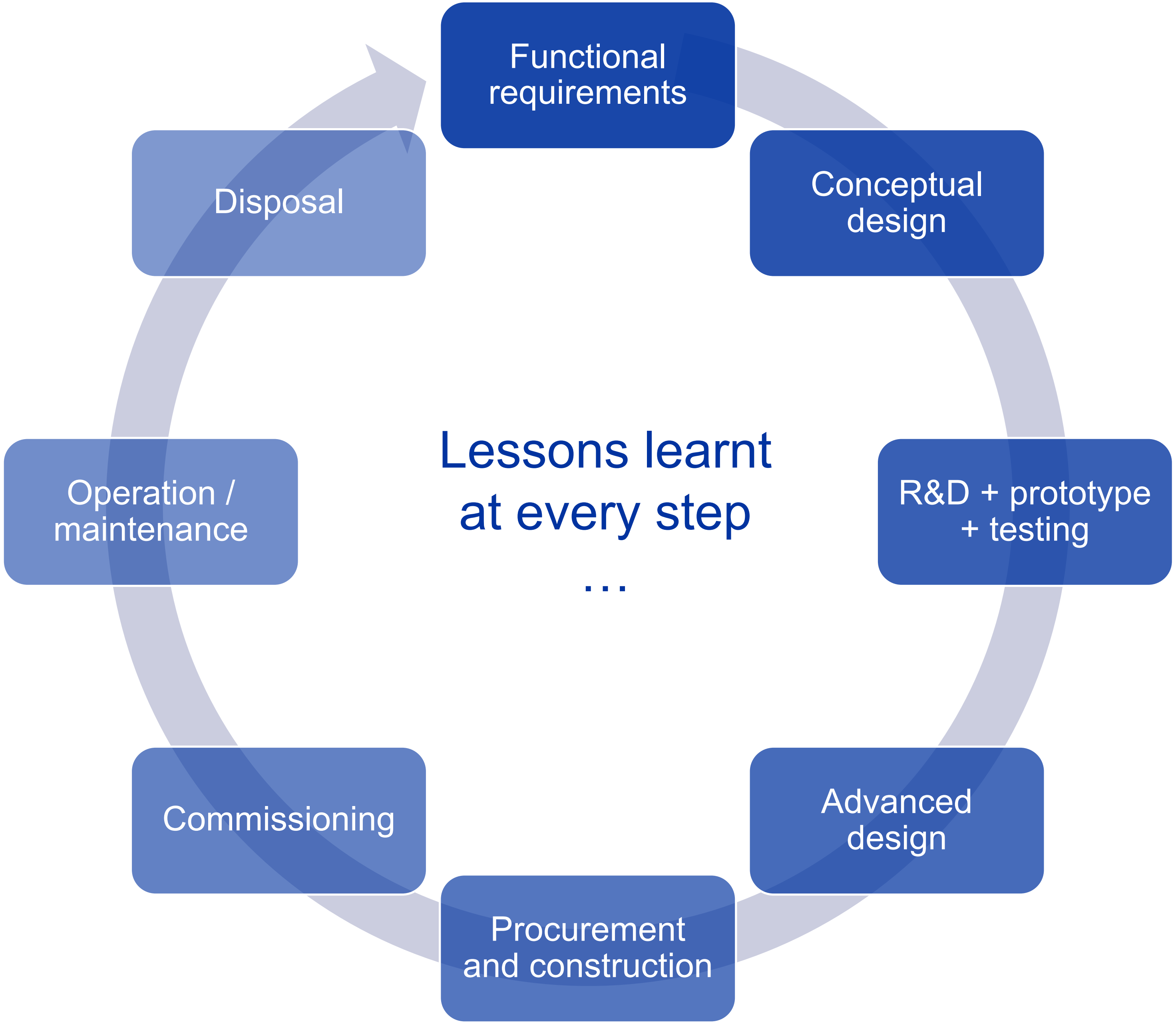
This is really a big value ☺ could **melt 2.5 t of Cu**

- This enormous energy is deposited in 89 μs

$$\text{Beam instantaneous power} = {}^{Q}/_{t} = \frac{539\ \text{MJ}}{89\ \mu\text{s}} = \mathbf{6\ TW}$$

BIDs lifecycle

Lifecycle for the successful construction & operation of BIDs/Target Systems



Functional reliability / integrity

- **Don't want the BIDs to break apart under load!**
- Strength, fatigue, cooling performance
- Erosion, corrosion, wear
- High temperature, high strain-rate performance
- Complexity, repairability, repeatability, Quality Assurance
  - If special materials are employed, make sure your material is available in 5-10 years from now for spares

Ultra High Vacuum design for BIDs

- As for other components that are installed in the machine Ultra High Vacuum, BIDs must also comply to requirements of UHV

- Additional challenges for BIDs are generated by:

1. **Movable parts, no lubrification allowed** → potential source of virtual leaks
2. **High temperatures** during beam impact → increase outgassing
3. Use **graphitic materials** (incorporation of humidity and subsequent outgassing, etc.)

- QA steps and careful control of design processes is a fundamental aspects of BIDs design, construction and reliable operation

Ultra High Vacuum design for BIDs

Vacuum criteria

Leak tightness
(e.g. $1 \cdot 10^{-10}$ mbar·l·s^{-1})

Contamination
(hydrocarbons, CO/CO_2, higher Z – from cleaning or poor design)

Outgassing (from internal components)
(e.g. threshold 10^{-7} mbar·l·s^{-1})

Virtual leaks (e.g. trapped pockets of gas)
(< $5 \cdot 10^{-9}$ mbar·l·s^{-1})

Palette of absorbing materials employed at CERN

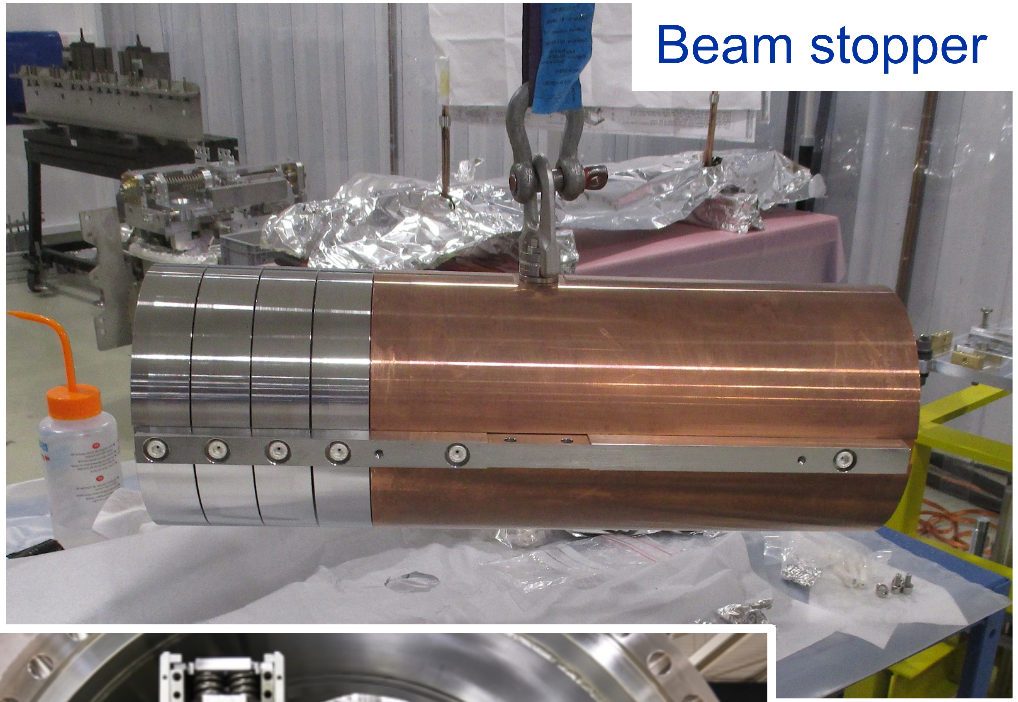
Graphitic materials (and CfC) 1-1.8 g/cm^3	Aluminium alloys 2.7 g/cm^3	Titanium & alloys 4.5 g/cm^3	(Stainless) steels 7.5-8 g/cm^3
Low CTE, good thermal conductivity, low ρ, very high service T, exceptional robustness to beam impact	Light structural materials, good thermal conductivity, low T_m, poor properties at high T	Exceptional strength while light, low CTE, low thermal conductivity	"king" of structural materials, low thermal conductivity

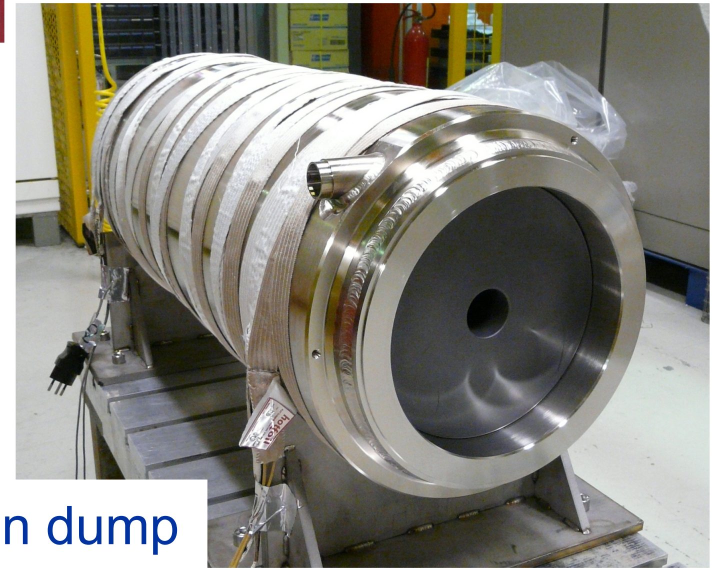
Palette of absorbing materials employed at CERN

CuCrZr1 & Glidcop®	Mo-alloys and TZM	Lead	Tantalum	Tungsten and alloys	Iridium
8.9 g/cm^3	10.2 g/cm^3	11.3 g/cm^3	16.6 g/cm^3	18-19.3 g/cm^3	22.6 g/cm^3
Very good heat conductivity, good strength and stability at high T	Reasonably low CTE, relatively good strength	Target material for neutron production, very low T_m, almost negligible strength	Refractory metal, stable high, ductile, extreme corrosion resistance	High ρ and related absorption power, alloyed-W has good machinability	Target material for pbars, poor mech. performances, very high ρ

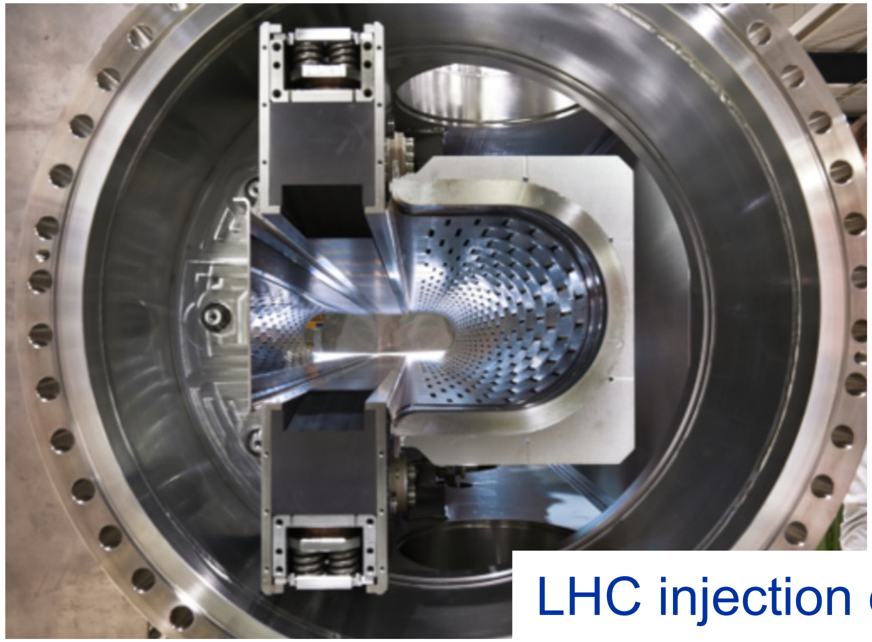
TCAPM

Beam stopper



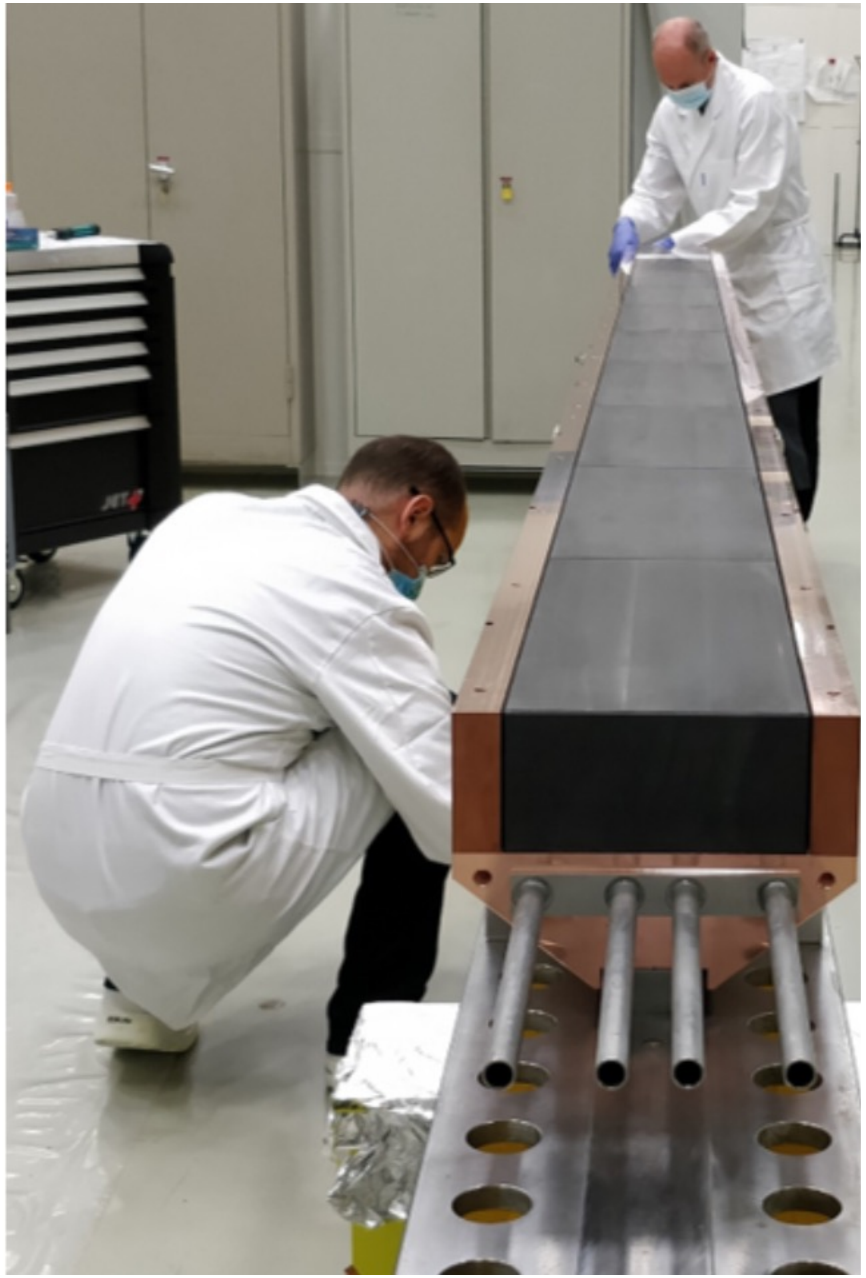


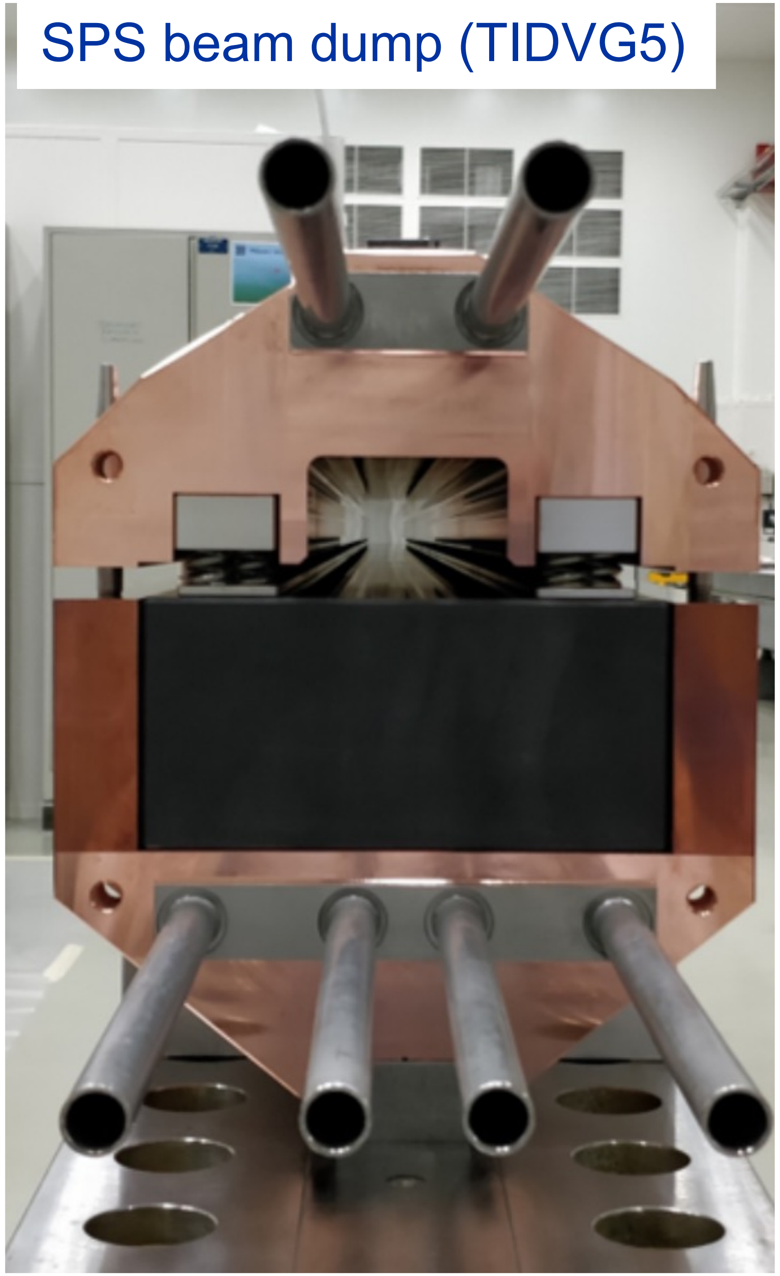
Linac4 main dump



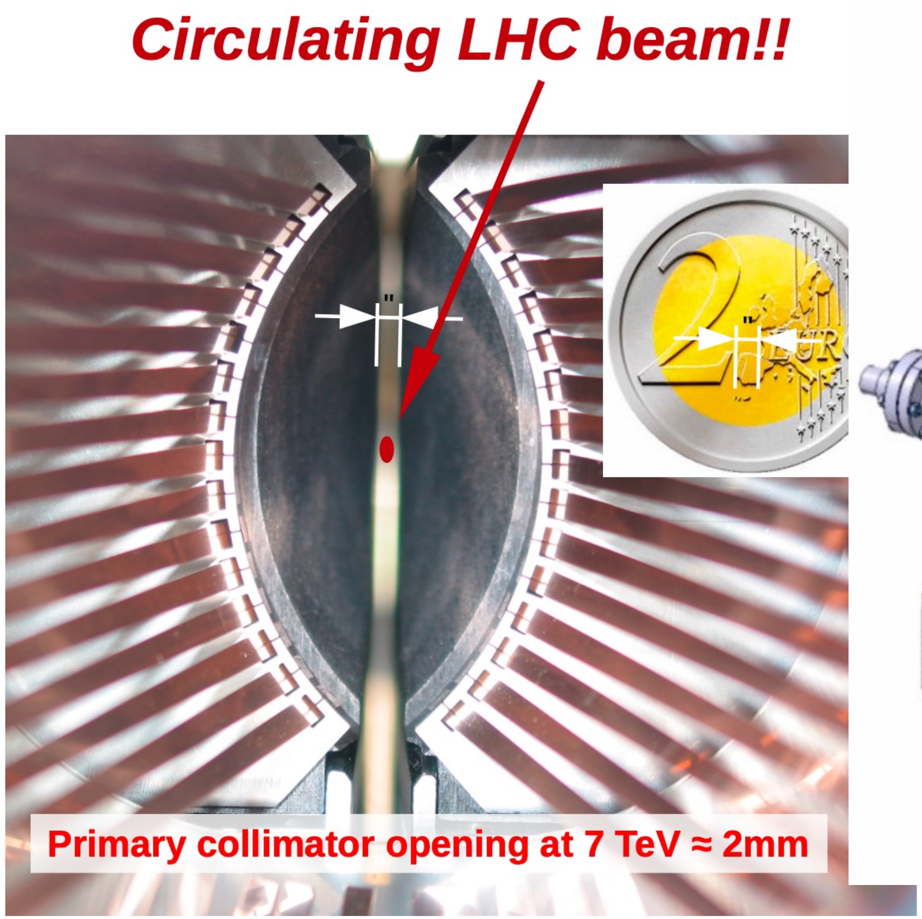
LHC injection dump (TDIS)

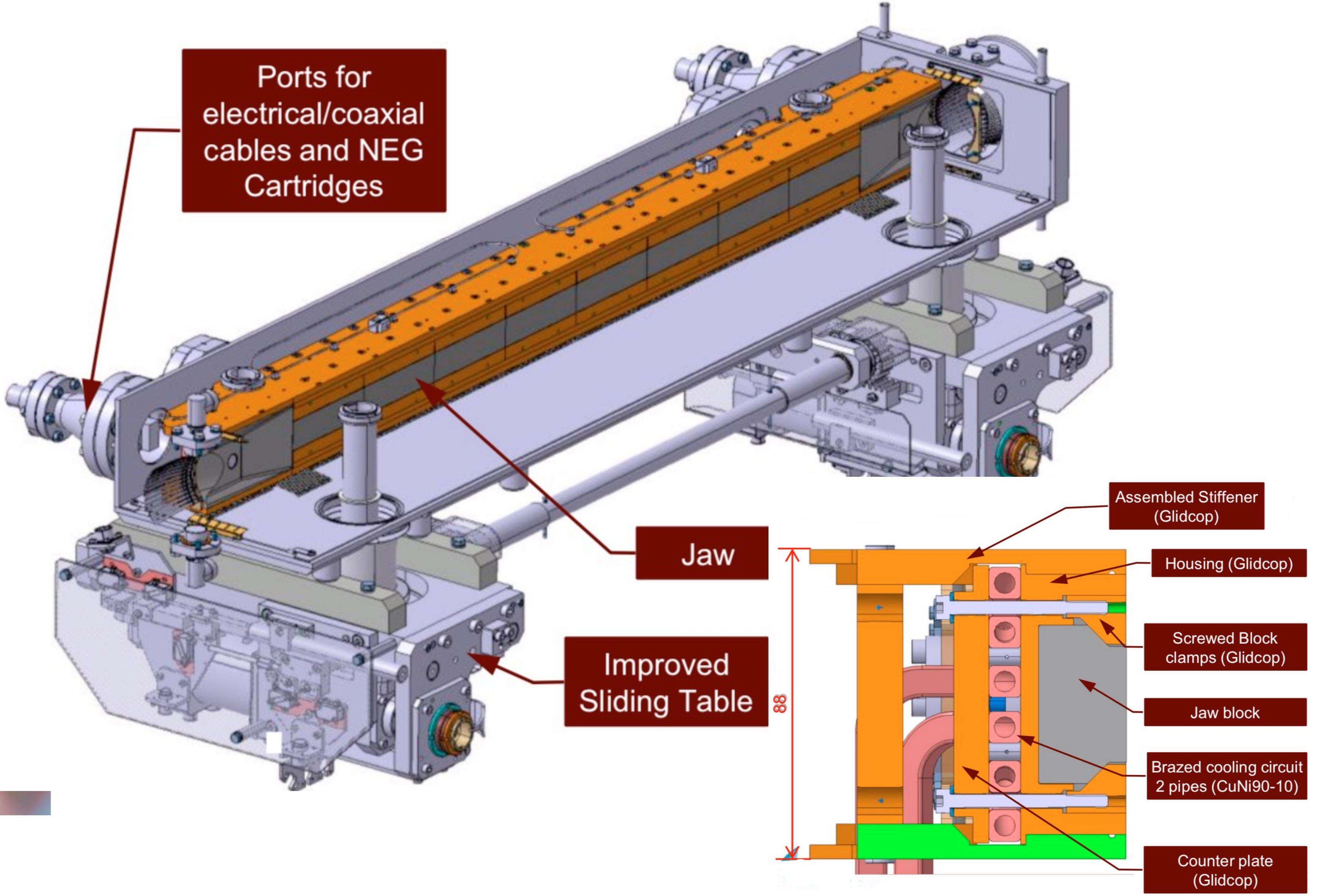
SPS beam dump (TIDVG5)



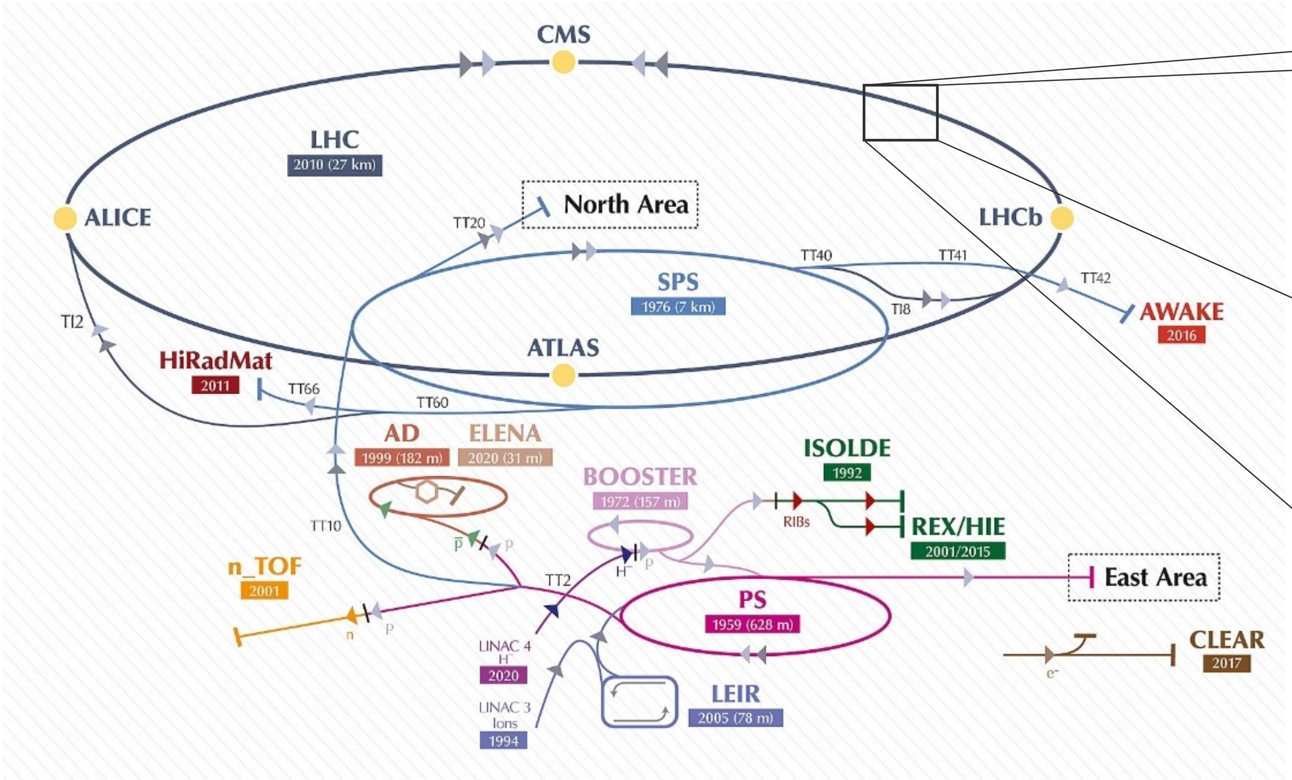


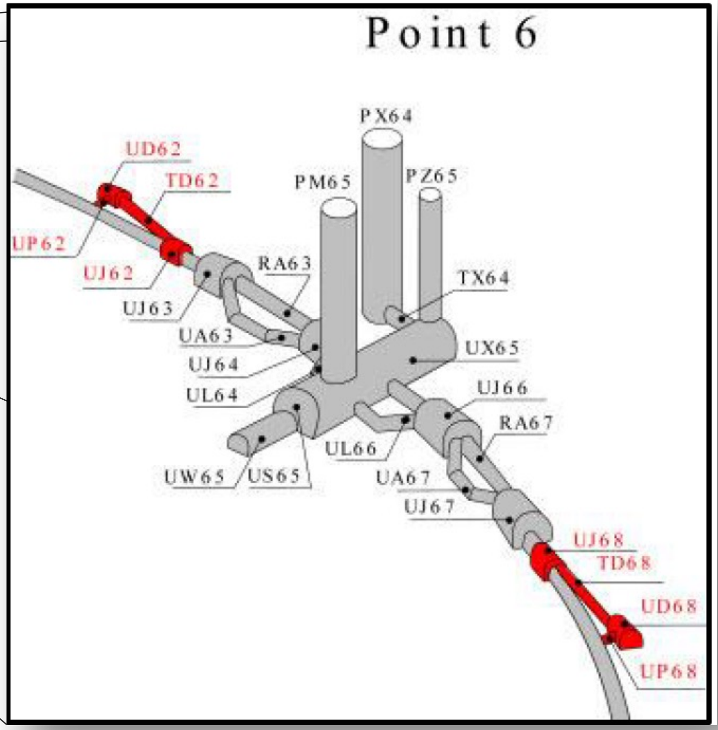
Large Hadron Collider collimation: multi-stage



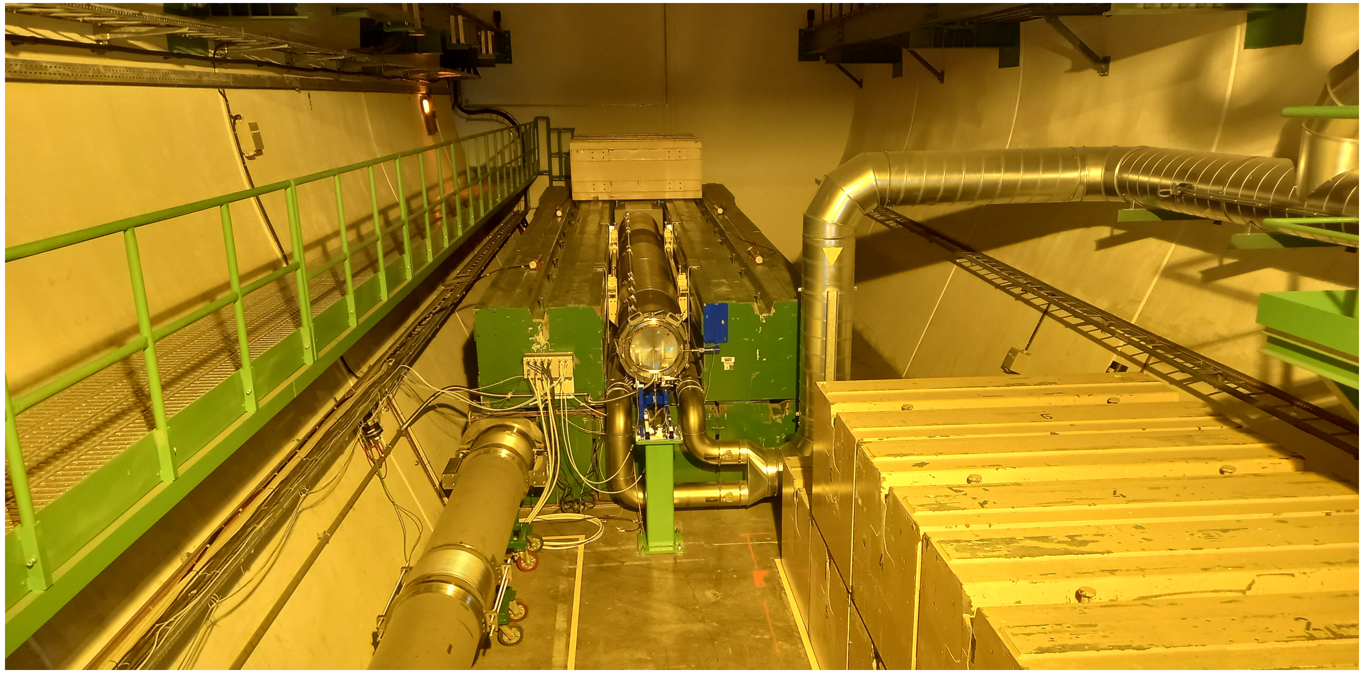


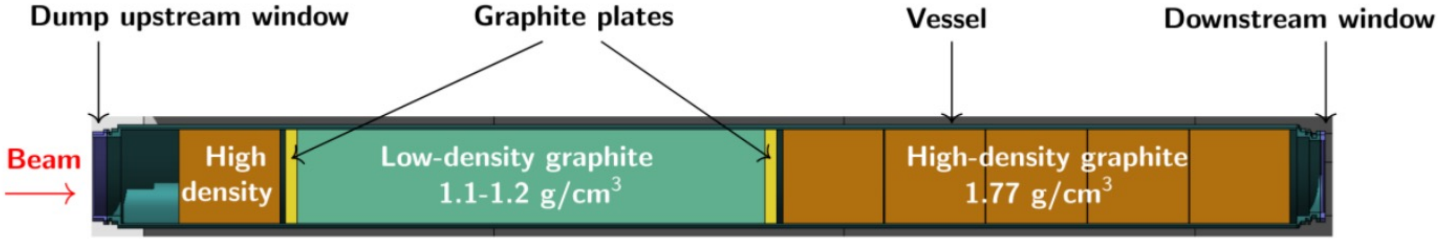
LHC dumps: Where What Why





LHC dumps: Where What Why

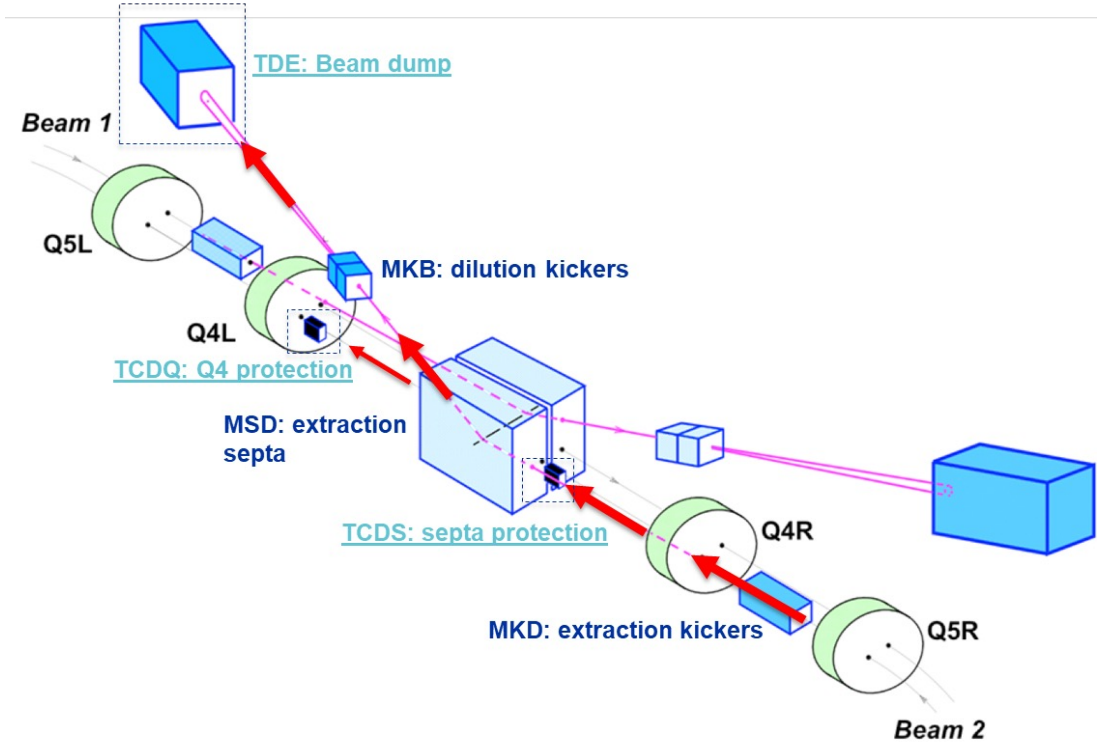




LHC-TDE: LHC Target Dump External

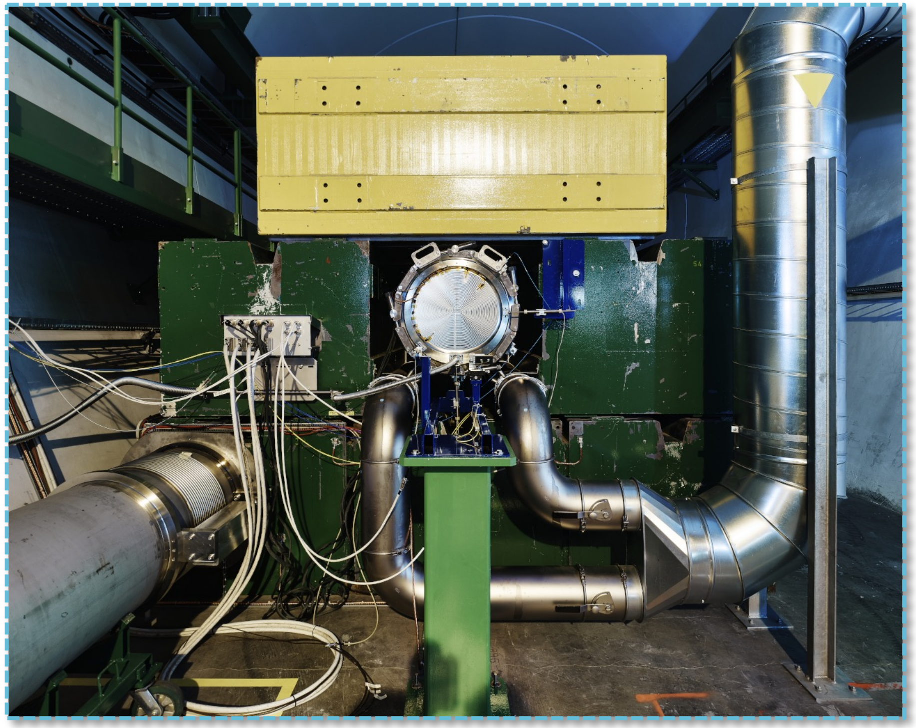
LHC dumps: Where What Why

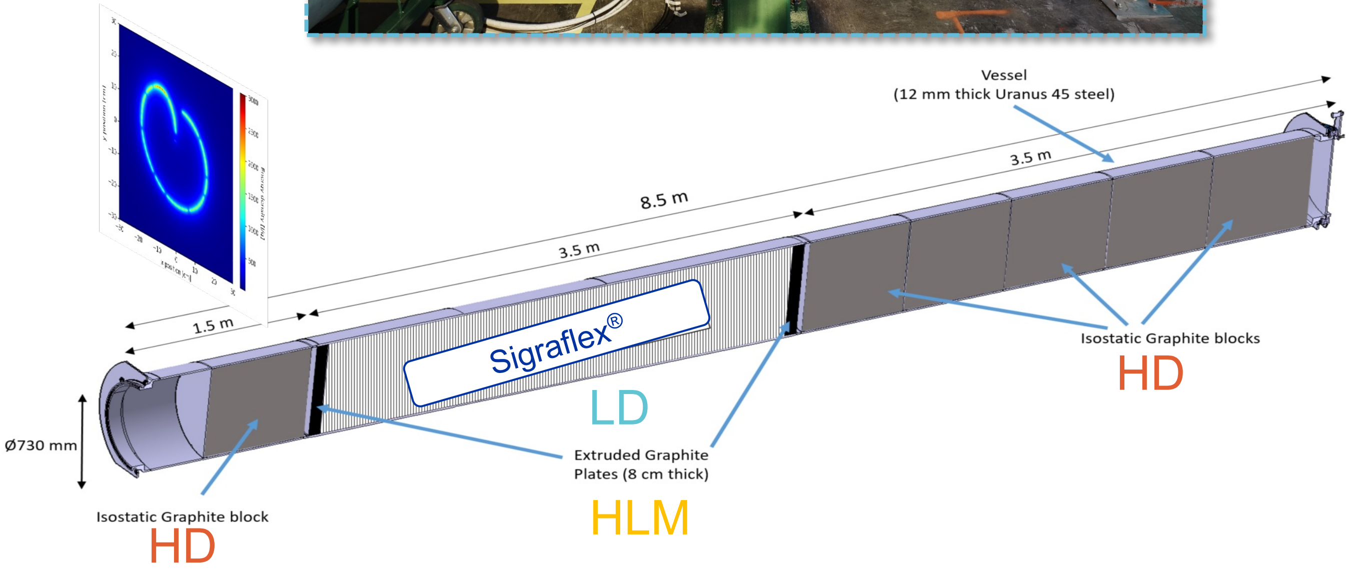
- Essential device of the LHC Beam Dumping System (LBDS)
- To repeatedly absorb the energy of the LHC dumped beam → without breaking
- LHC HW Failures (including other LBDS equipment), beam commissioning, beam instabilities, end of physics beam → Any LHC filled beam in fact.



Some key figures

- Uranus-45 steel tube 8.5 m length and 12 mm thickness (2 Tons)
- ⌀0.7m & 7.6 m C-based core (4.4 Tons):
  - High density (HD) isostatic graphite
  - Low density (LD) Sigraflex stack of sheets
  - Extruded graphite (HLM) plates





Some key figures

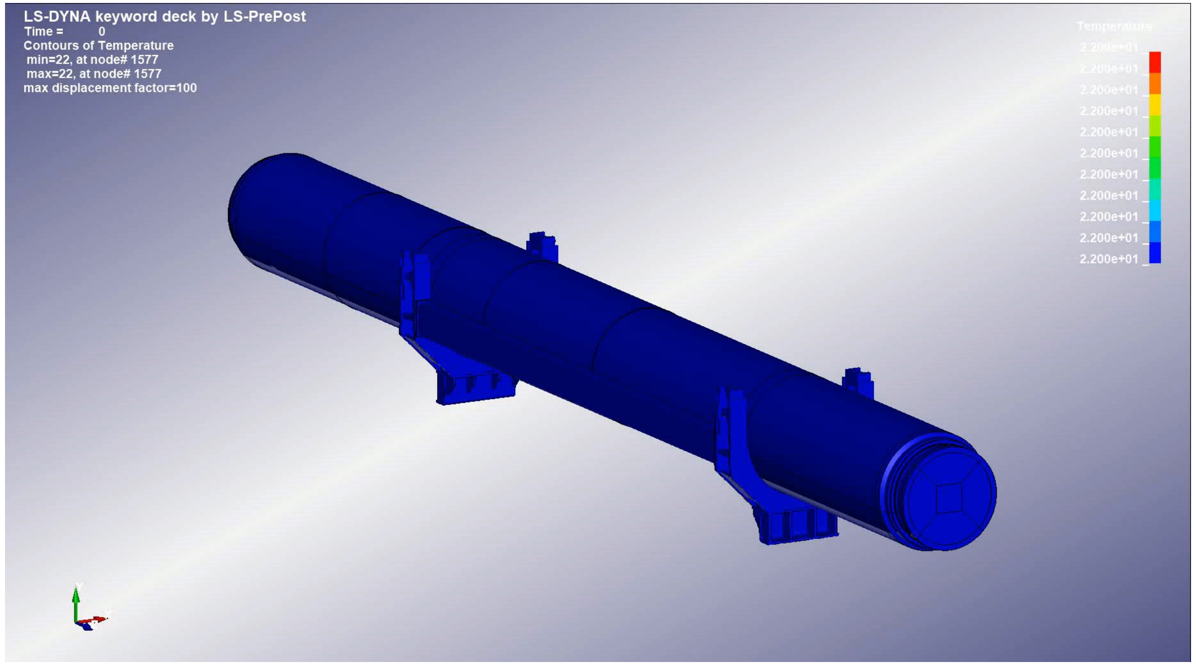
- Operating under high temperature and high structural dynamic loads
  - Up to 539 MJ in 86μs (Run3)

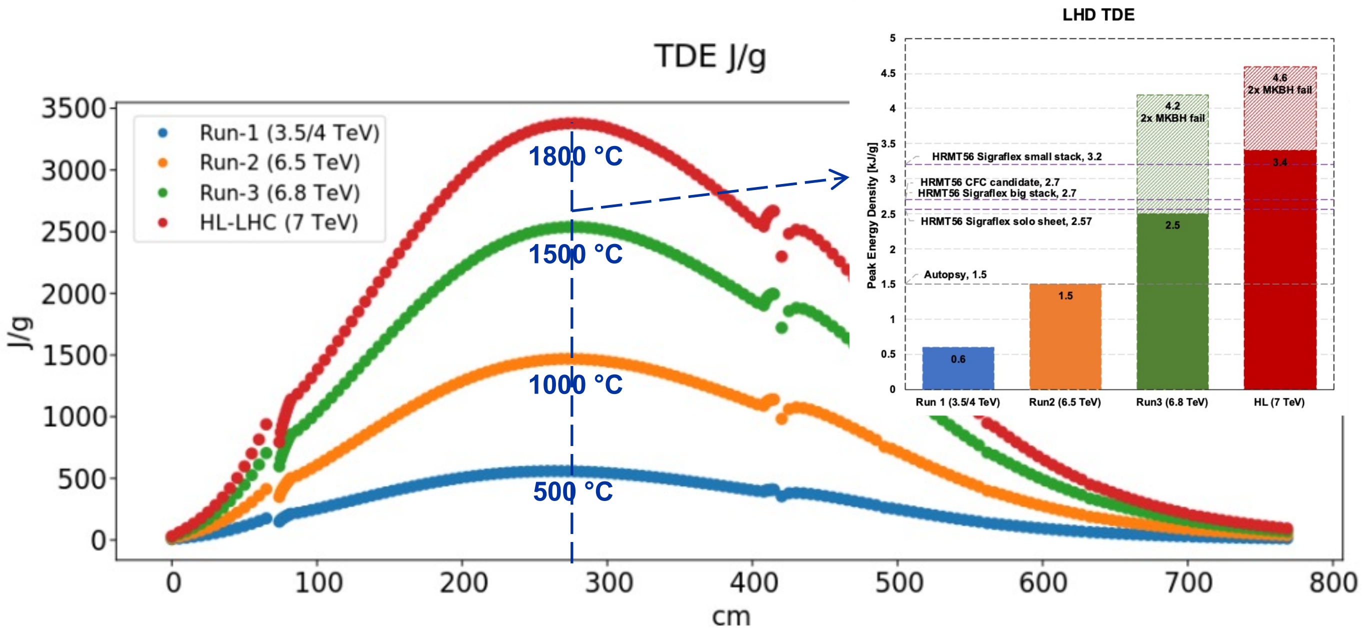
Particularly on the vessel

  - Displacements 5(O)mm
  - Temperatures 170(O)°C
  - *Acceleration 10^2-10^3(O) g*

	Run 1 (2009-2013)	Run 2 (2015-2018)	Run 3 (2022-2025)	HL-LHC (2028-)
E_{prot} (TeV)	4	6.5	6.8	7
Δt_b (ns)	50	25	25	25
N_b	1380	2556	2748	2760
I_b (p)	1.7×10^{11}	1.2×10^{11}	1.8×10^{11}	2.2×10^{11}
E_{beam} (MJ)	150	320	539	680
ε_n (μm rad)	≈2.5	≈2	1.8-2.5	2.5

https://doi.org/10.1088/1748-0221/16/11/P11019

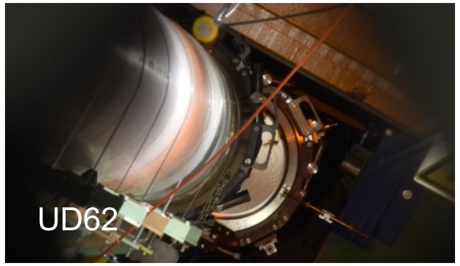




LS2 upgrades in a nutshell

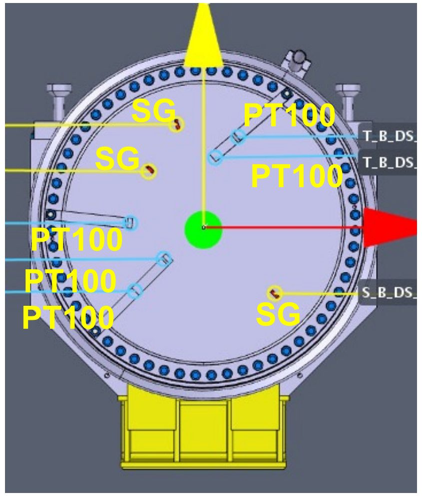
Following Run 2 issues (N2 leaks, movement and vibration findings (FEM)) & Run 3 operational conditions:

- Removal of N2-filled connection between LHC machine vacuum and dumps
- New upstream window
- New downstream window
- New support structure
- N2 line extension
- **New Instrumentation package**

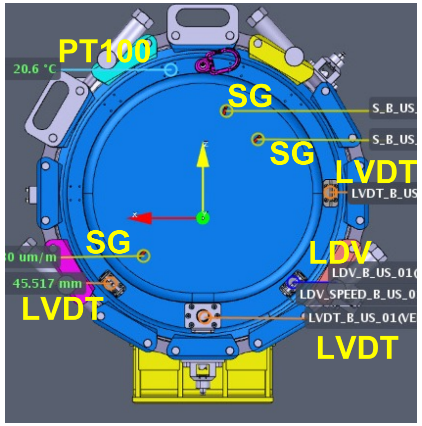


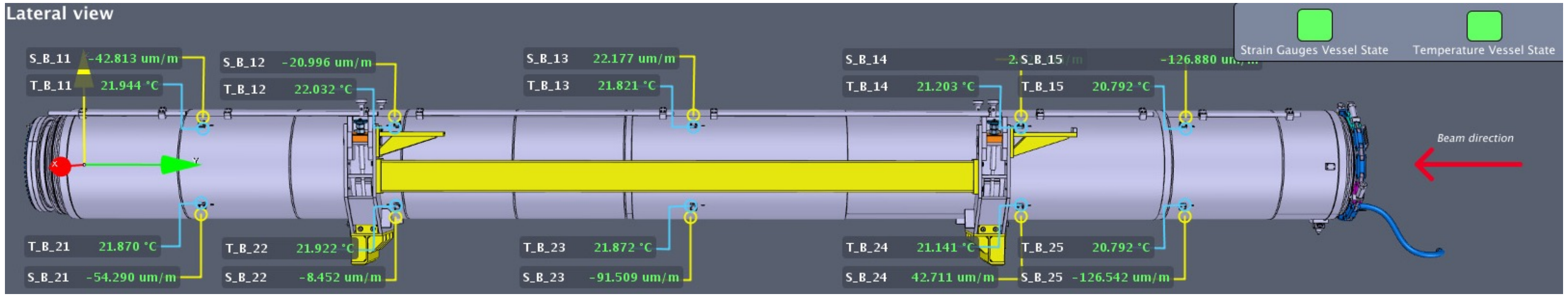
Feature	Instrument	Details	
		Position	N. elements
Thermal Response	PT100s	UpW	1
		Vessel	10
		DwnW	5
Dynamic Response	Strain Gauges	UpW	3
		Vessel	10
		DwnW	3
	LDV	UpW	1
	Accelerometers	UpW	3
	Trigger	Acquisition system	1
Slow Movement	LVDT	UpW - Horz	1
		UpW - Ver	1
		UpW - long	1
General Monitoring	Microphone	Cavern (UD62)	1
	Camera	Cavern	1
	N_2 Pressure	N_2 Injection Line	1

Downstream window

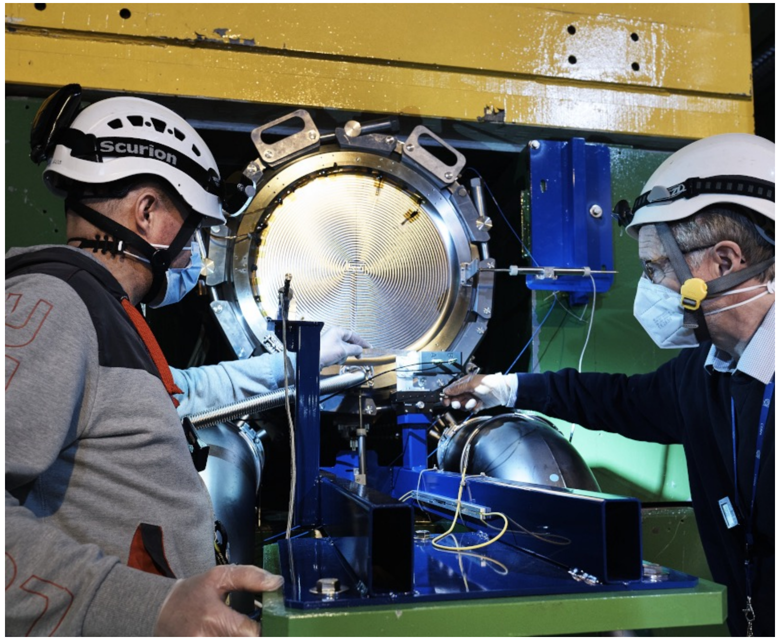


Upstream window

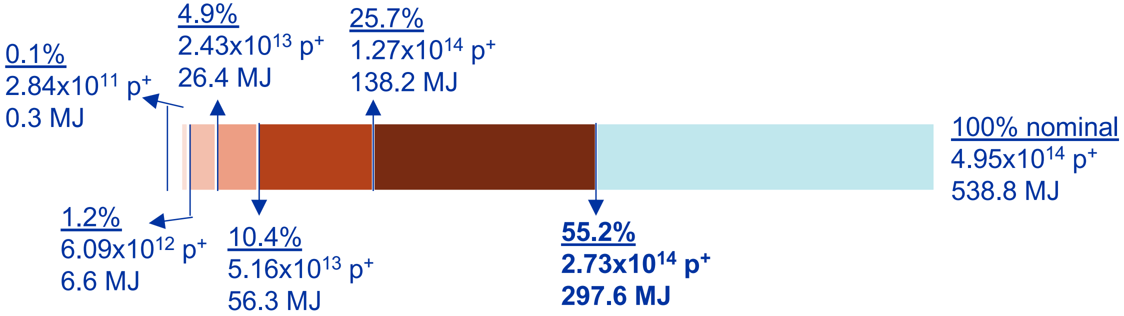




LS2 upgrades in a nutshell



LHC-TDE operation update

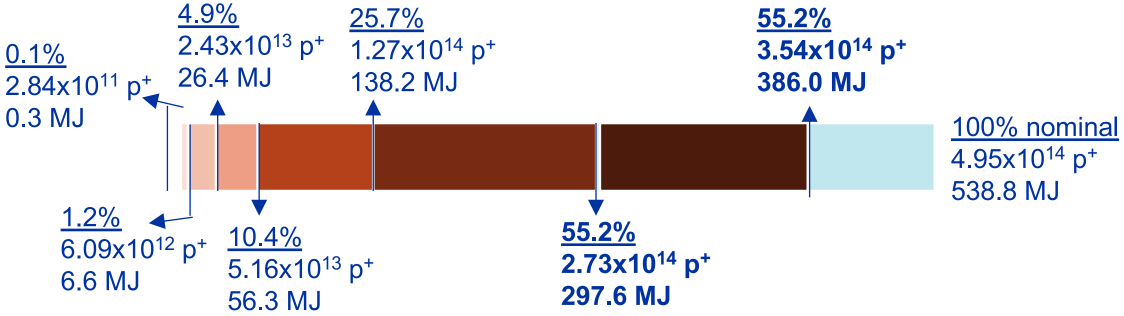


The sound of the LHC-Dump

UD62 @ 2022-08-18T21_18_35+02_00

0.3MJ –1h of 32 Inch LCD TV
6.6MJ – 1 dishwasher cycle
26.4MJ – heat 20 C to 65C 125l water tank
56.3MJ - 31km with e-smart
138.2 MJ - 30kg of TNT (energy content)
297.6 MJ – melt 1.25 tonnes of gold
…in 86μs

LHC-TDE operation update



The sound of the LHC-Dump

UD62 @ 2022-08-18T21_18_35+02_00

0.3MJ –1h of 32 Inch LCD TV
6.6MJ – 1 dishwasher cycle
26.4MJ – heat 20 C to 65C 125l water tank
56.3MJ - 31km with e-smart
138.2 MJ - 30kg of TNT (energy content)
297.6 MJ – melt 1.25 tonnes of gold
386 MJ - …..just add more gold
…in 86µs

Beam impact experimental testing and validation

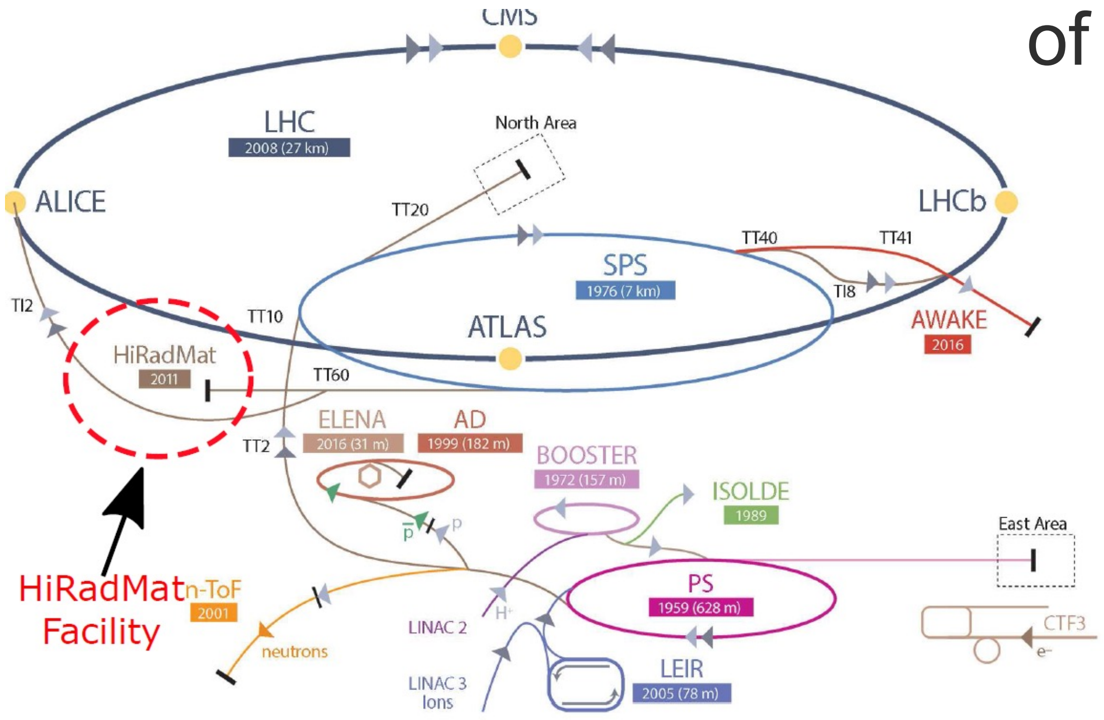
- Validation of design often include the possibility of **testing components or integral devices under beam impact**
- Sometimes devices and materials operate at the extreme – **uncharted territory of temperature and stress** (where EOS are not available)
- Existing material constitutive models at extreme conditions are limited and mostly drawn from military research (e.g. Ta, Ir, W).
- **Dedicated tests allows for numerical vs. experimental cross-check**

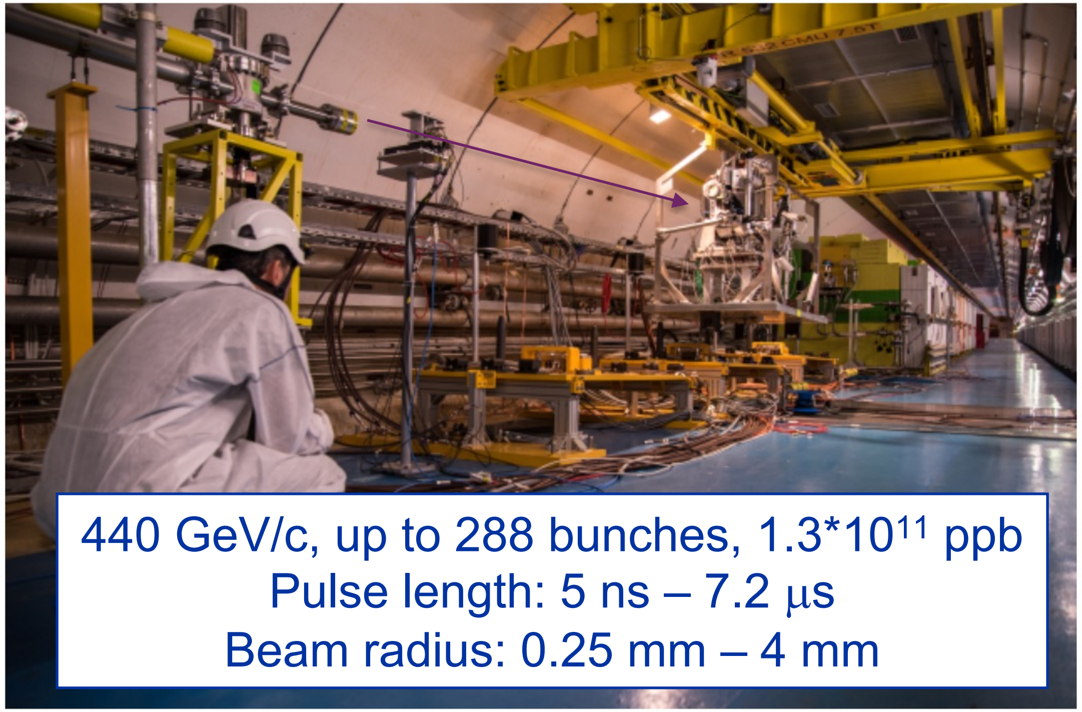
Integral and material testing at CERN

J. Phys.: Conf. Ser. 1350 012162

HiRadMat facility

Dedicated facility for studying the impact of intense pulsed beams on materials



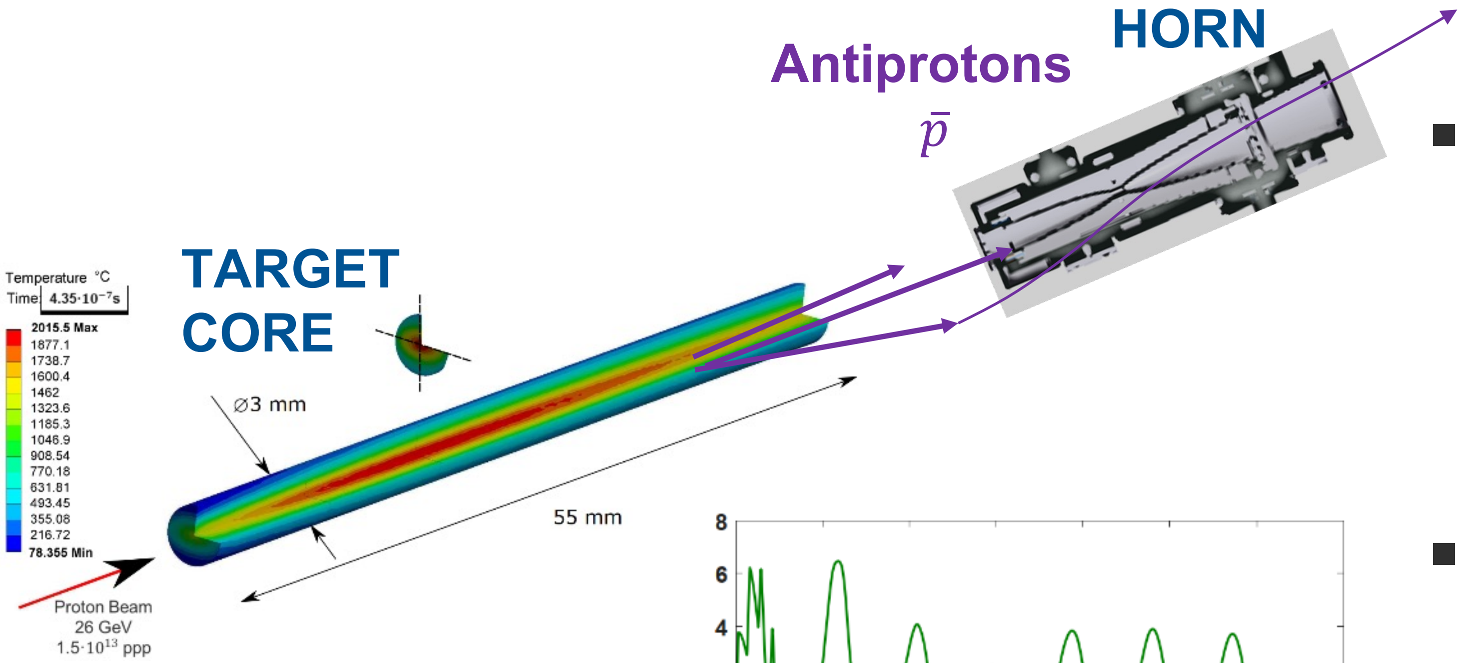


440 GeV/c, up to 288 bunches, $1.3 \cdot 10^{11}$ ppb
Pulse length: 5 ns – 7.2 μs
Beam radius: 0.25 mm – 4 mm

$$\text{Beam kinetic energy} = n_b \times I \times E_b$$
$$= 288 \times 1.3 \cdot 10^{11} \times 440 = \mathbf{2.6\ MJ}$$

$$1.3\ {}^{\text{GJ}}/_{\text{cm}^3}$$

Application of HiRadMat to antiproton production

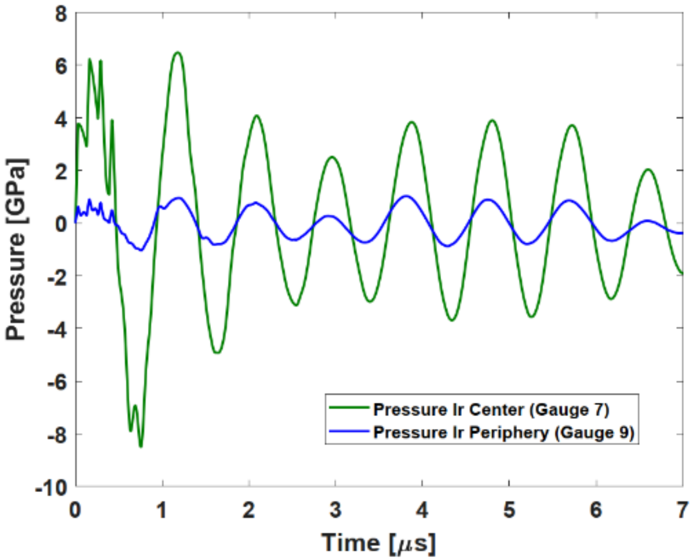


Phys. Rev. Accel. Beams 19, 073402 (2016)

- Efficient pbar production requires maximizing interaction in a short distance
- AD-T core made of Ir (22.3 g/cm^3), 3 mm diameter, 55 mm length
- 2000 ºC in 0.43 μs

$\dot{\varepsilon}_{max} \approx 5 \cdot 10^4 \text{ s}^{-1}$

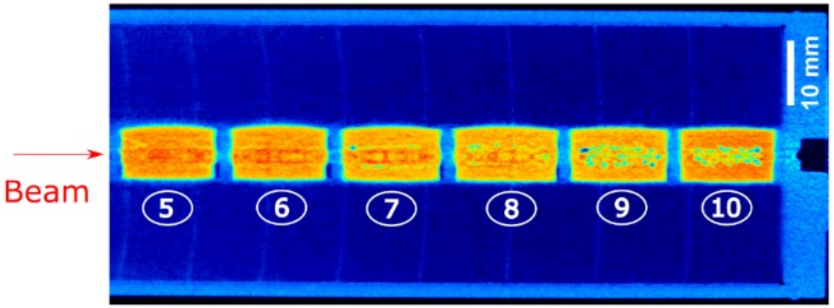
Extreme dynamic response!

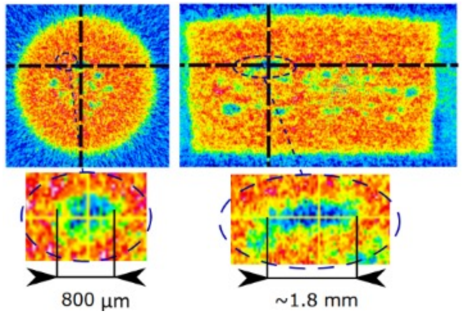


Post Irradiation Examination of Ta-irradiated sample

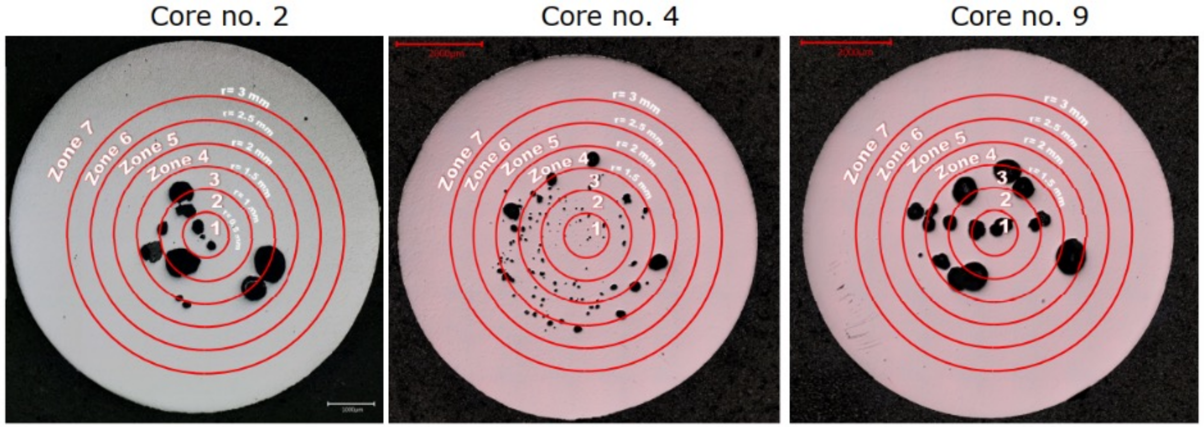
Phys. Rev. Accel. Beams 21, 073001 (2018)
European Journal of Mechanics / A Solids 85 (2021) 104149

- Neutron Tomography @PSI (NEUTRA)





- Target opening and slicing cores at CERN

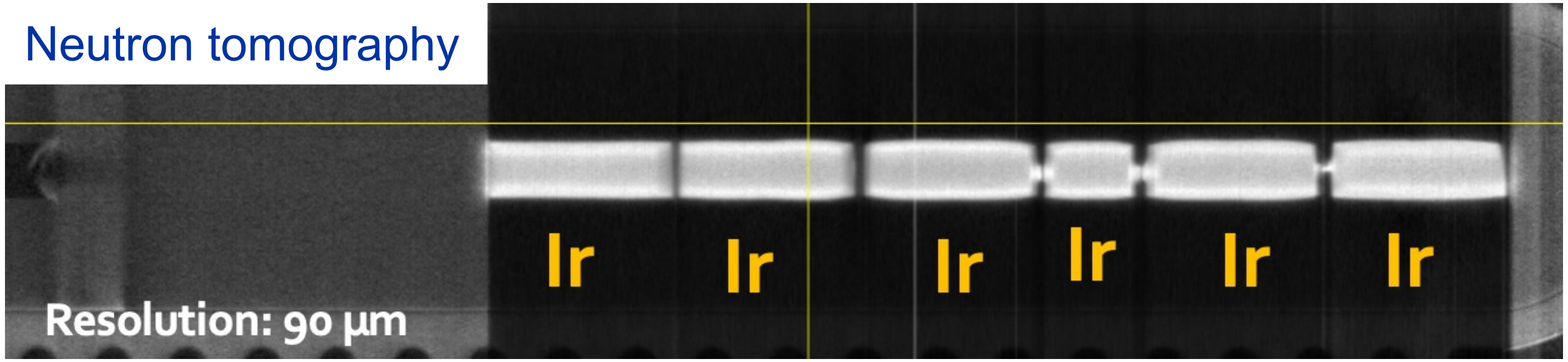


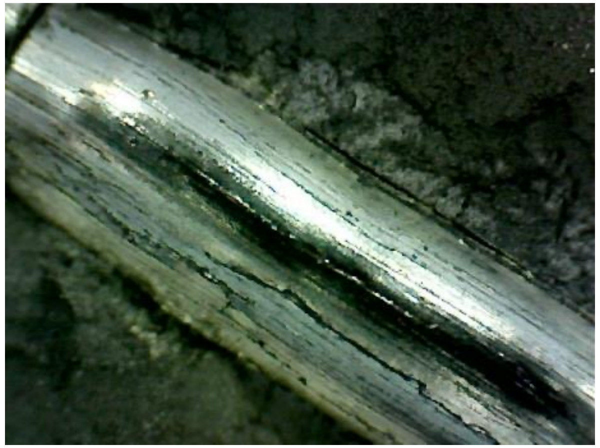
Observation of spalling voids

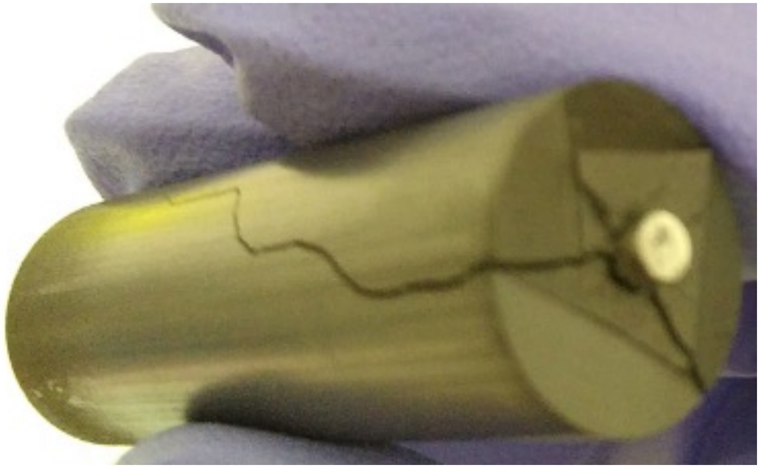
Tensile pressure shall be kept <2-3 GPa to avoid void nucleation

Application of HiRadMat to antiproton production
Some results

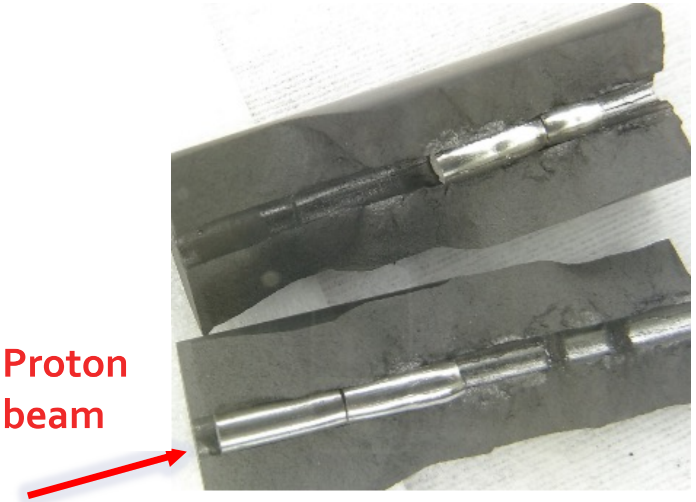
Neutron tomography

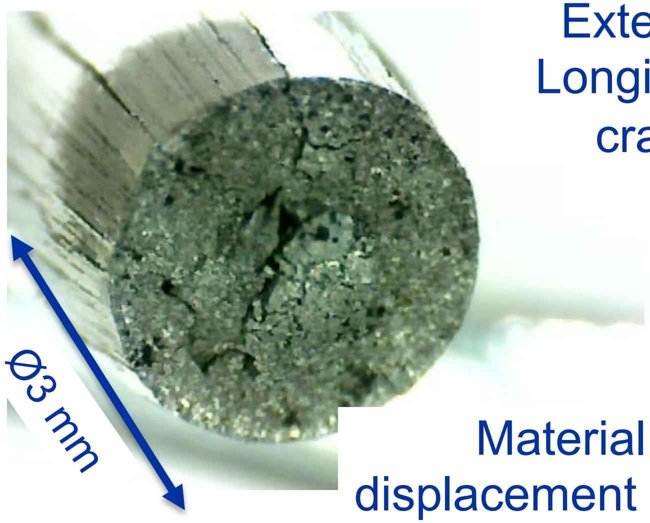






Longitudinal cracks in the isostatic-graphite matrix!





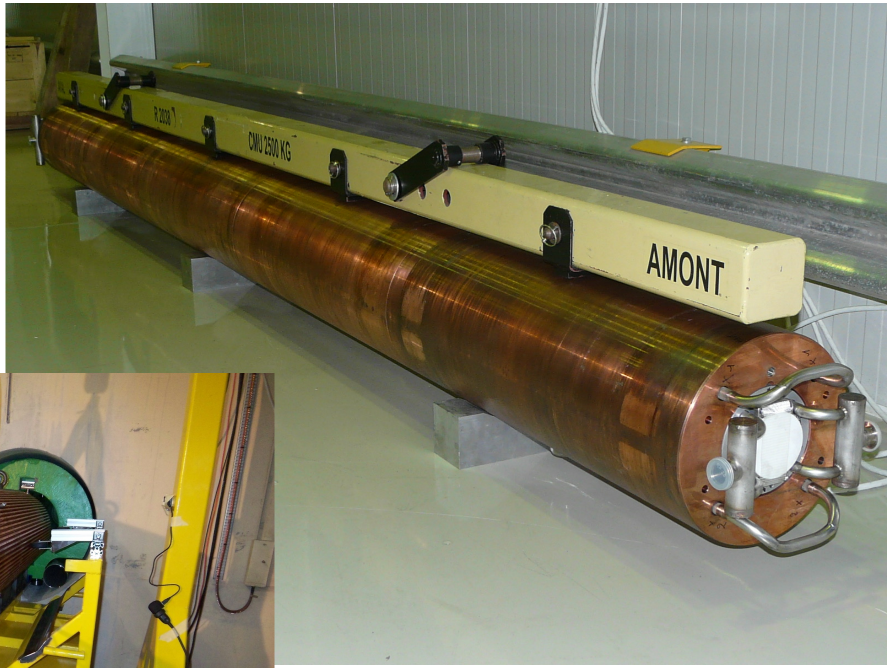
Extensive Longitudinal cracks

Material displacement along the face

Cuprous materials for BIDs

Copper OF – Used mostly as heat-sink in older devices.

- Maximum thermal conductivity
- Easily available
- Low price
- Poor mechanical properties
- For T < ~100 ^{o}C

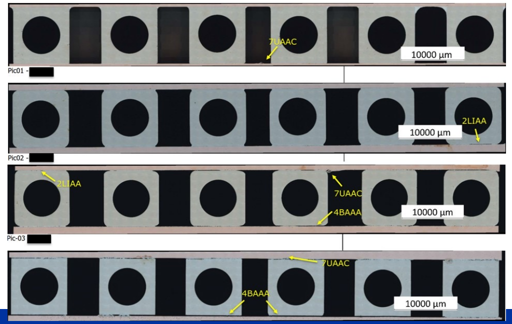


CuCr1Zr – Heavily used in the last ~10 years

- Good thermal conductivity
- Easily available
- Low price
- Good mechanical properties
- For T < ~500 ^{o}C

Oxide Dispersion Strengthened Copper (e.g. Glidcop) - Used mostly on LHC collimators

- Good thermal conductivity
- Only 2 suppliers known
- High price / long lead times
- Good mechanical properties
- For applications undergoing high T (up to ~900 ^{o}C)



1. n_TOF neutron production

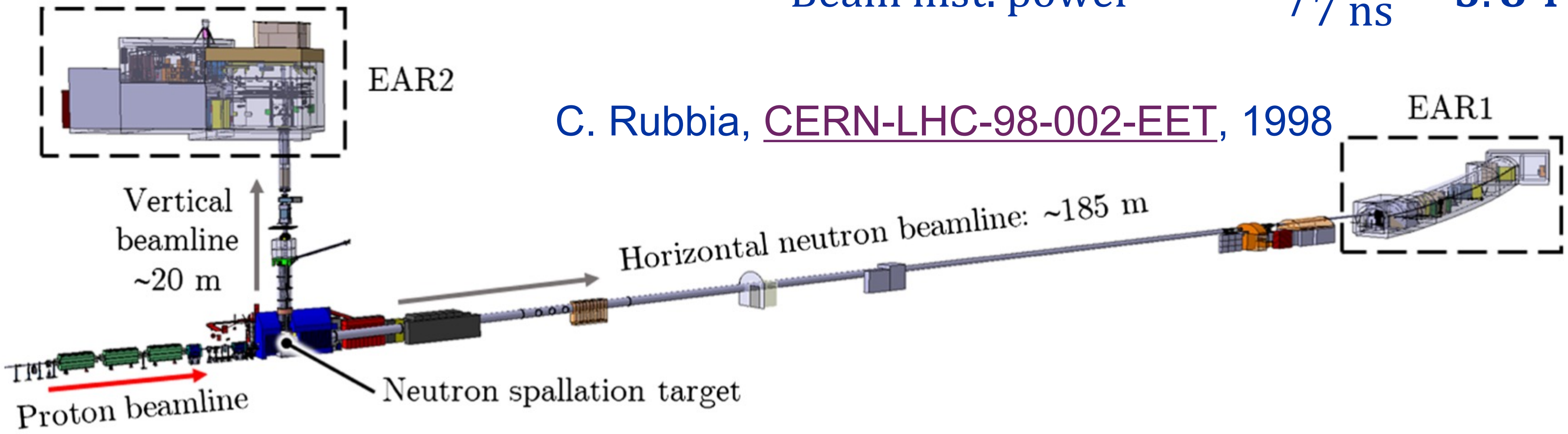
Neutron production at CERN

- n_TOF is a white high-intensity spallation neutron source operating at CERN
- Dedicated to measurement with unmatched S/N ratio for radioactive or low mass samples
- Focus is high intensity per pulse, not average power (limited to around 6 kW)
- Operated with 20 GeV/c proton beam, 8.5*10^{12} ppp, 7 ns 1σ

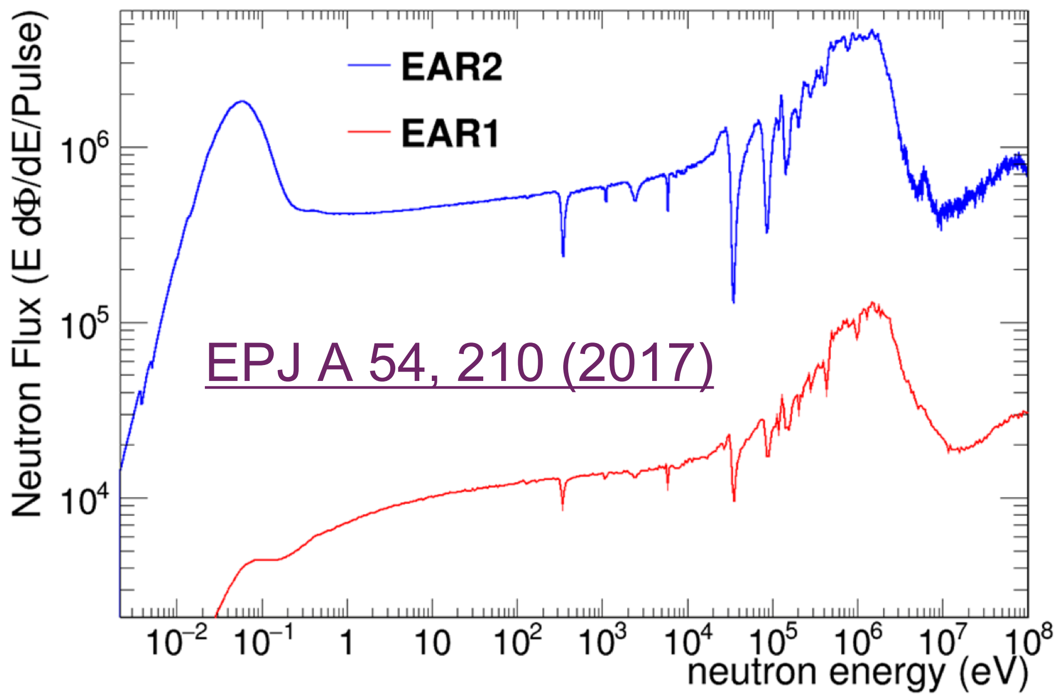
$$\text{Beam kinetic energy} = n_b \times I \times E_b = 1 \times 8.5 \cdot 10^{12} \times 20 = \mathbf{27\ kJ}$$

$$\text{Beam inst. power} = {}^{27\ \text{kJ}}/_{7\ \text{ns}} = \mathbf{3.8\ TW}$$

C. Rubbia, CERN-LHC-98-002-EET, 1998



Neutron production at CERN



- Facility requires **low-γ background** conditions and **high n/p yield**
- Pb best possible target material, due to:
  - **High elastic neutron cross-section**
  - **(very) Low inelastic neutron cross-section**, reducing reabsorption

n_TOF neutron spallation target

- CERN operated two generations of spallation targets

Target #1 (1999-2004)

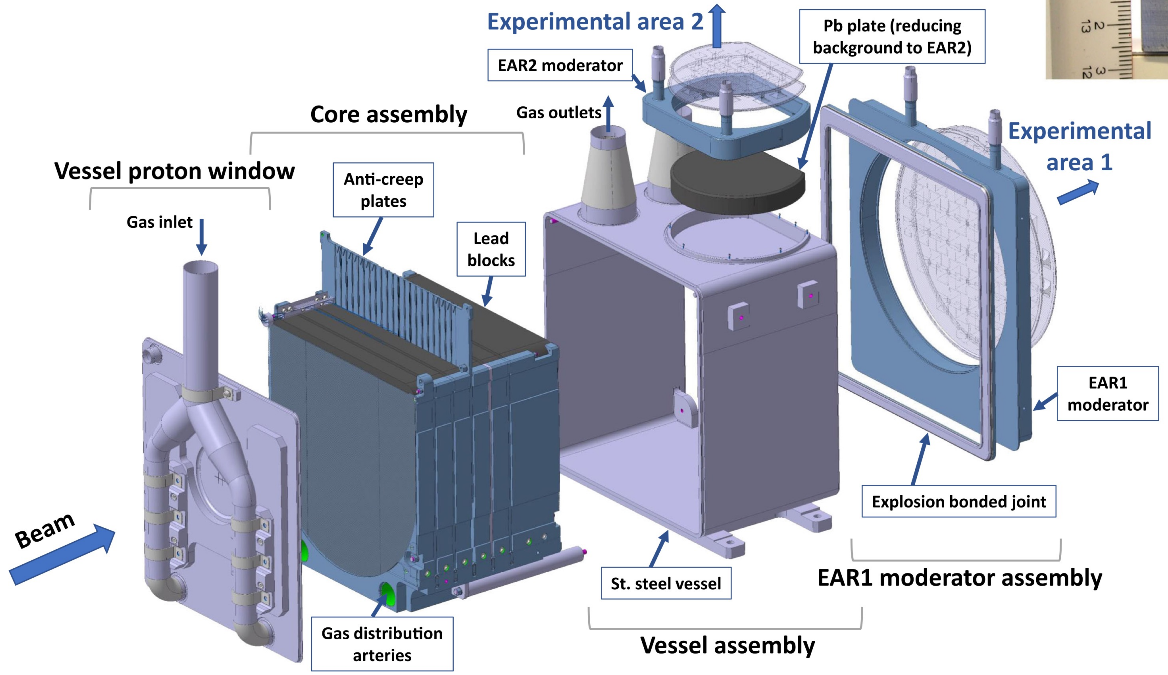
Target #2 (2008-2018)

n_TOF neutron spallation target

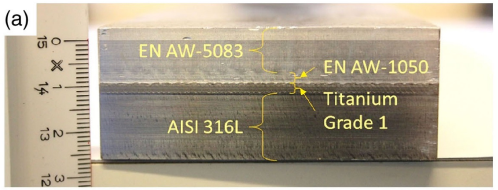
[Phys. Rev. Accel. Beams 24, 093001 (2021)](#)

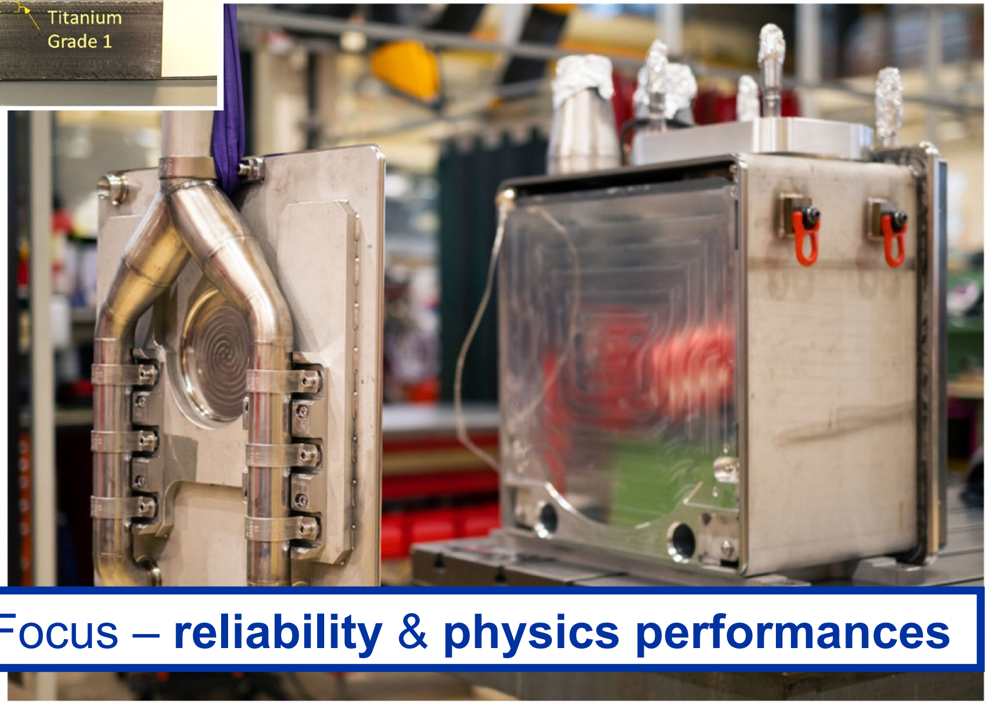
- 3rd generation spallation target, pure Pb based, N_2-gas cooled, water moderated, operational since July 2021

- Several innovations introduced, including bimetallic transitions & nitrogen gas cooling



(a)



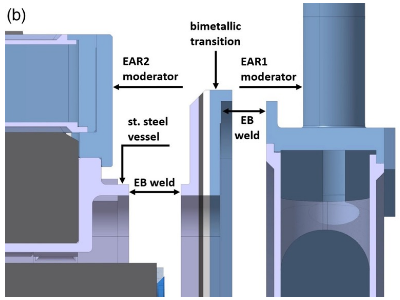


Focus – **reliability** & **physics performances**

Physics/engineering design process

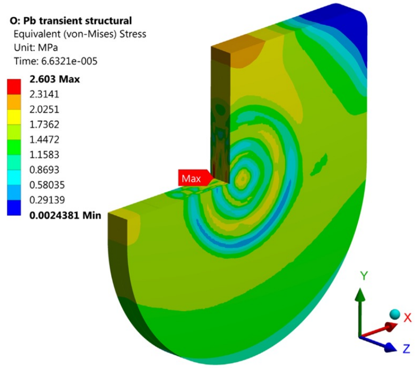
Design and **integration** impacts

(CATIA v5)



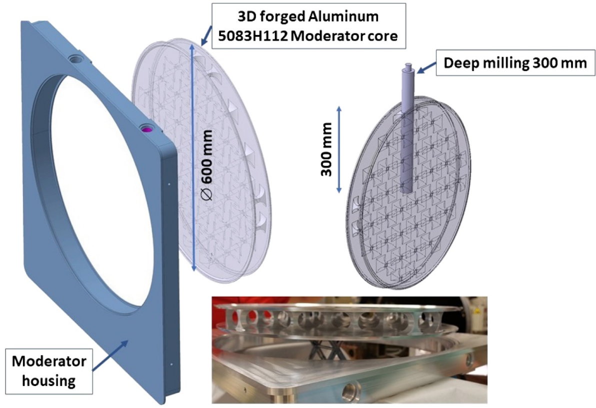
Mechanical performances

(ANSYS)



Machinability / reliability / feasibility

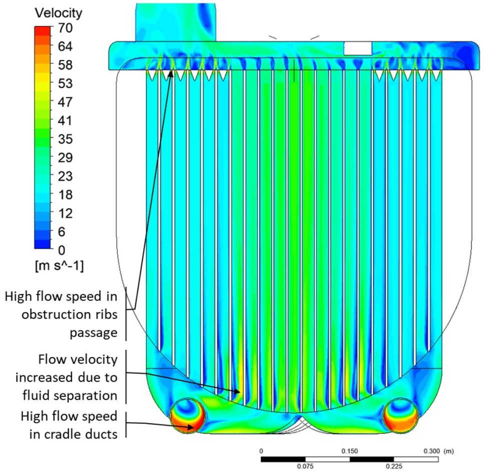
(Workshop)

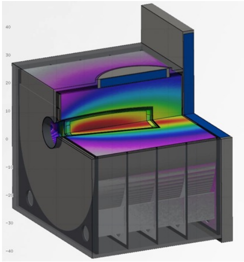


Target (BID) design progression

Thermal management

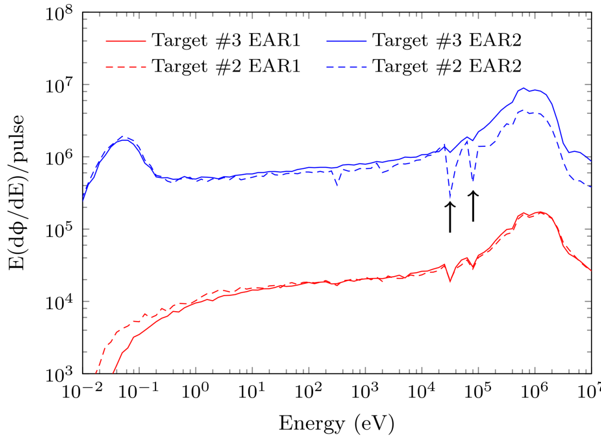
(ANSYS CFX)





Physics performances

(FLUKA)



Heat loads

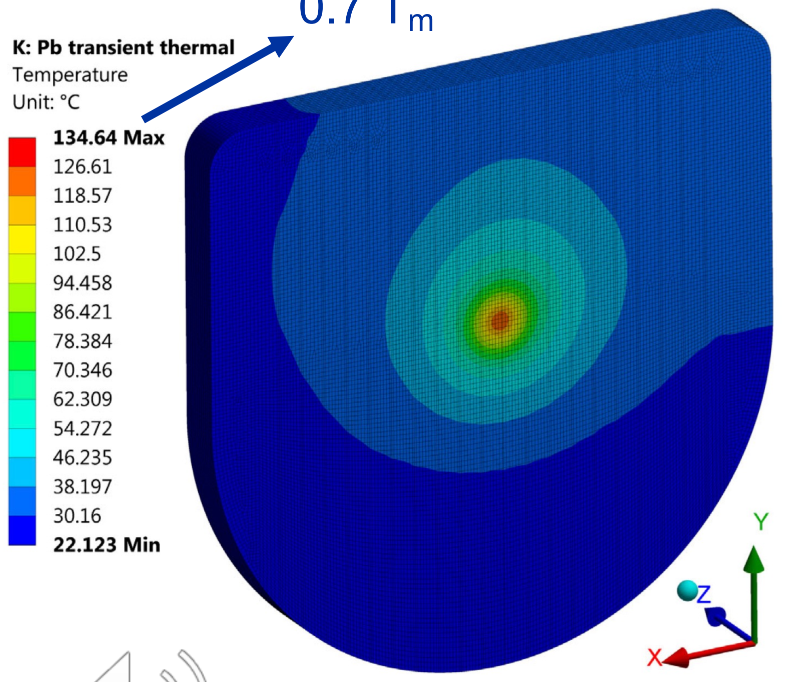
(FLUKA)

n_TOF neutron spallation target

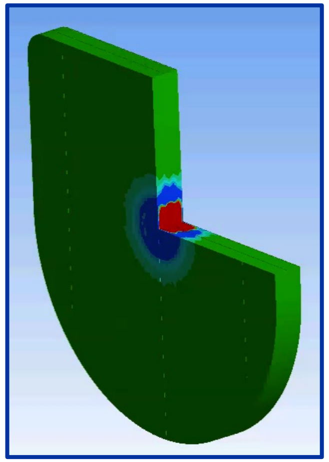
Phys. Rev. Accel. Beams 24, 093001 (2021)

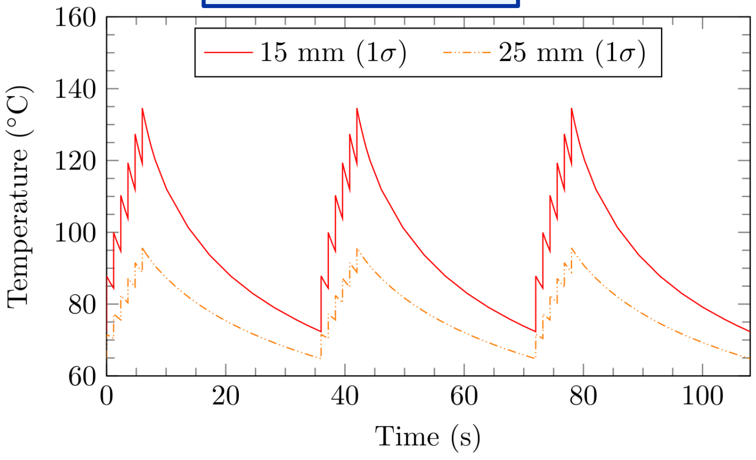
- Pb is a non-structural material, low melting point, very low yielding point

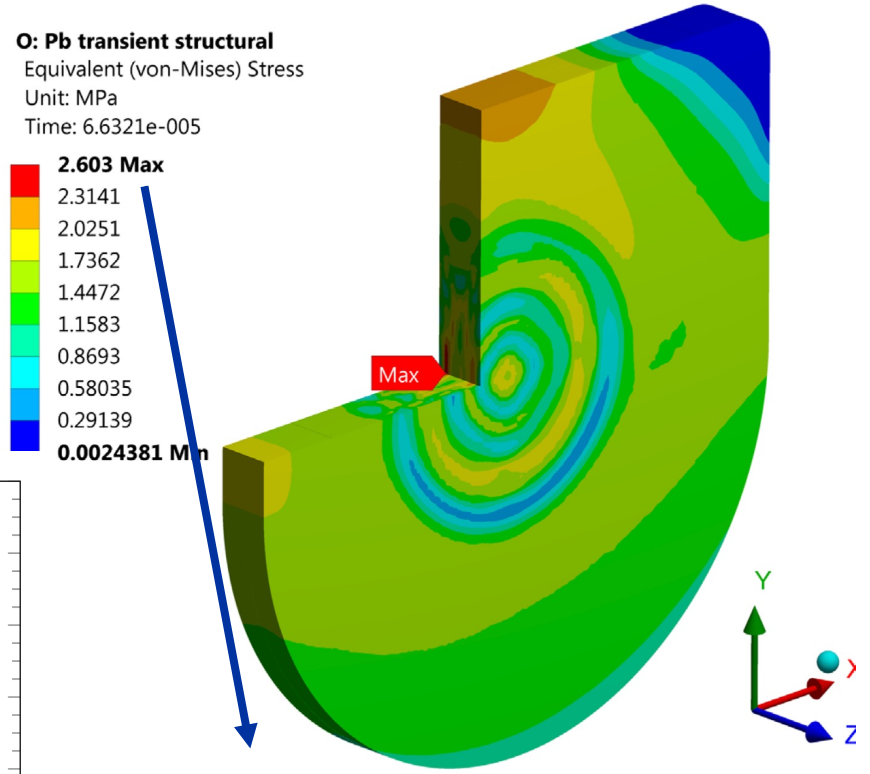
0.7 T_m



(listen for ±kJ impacting on Pb)







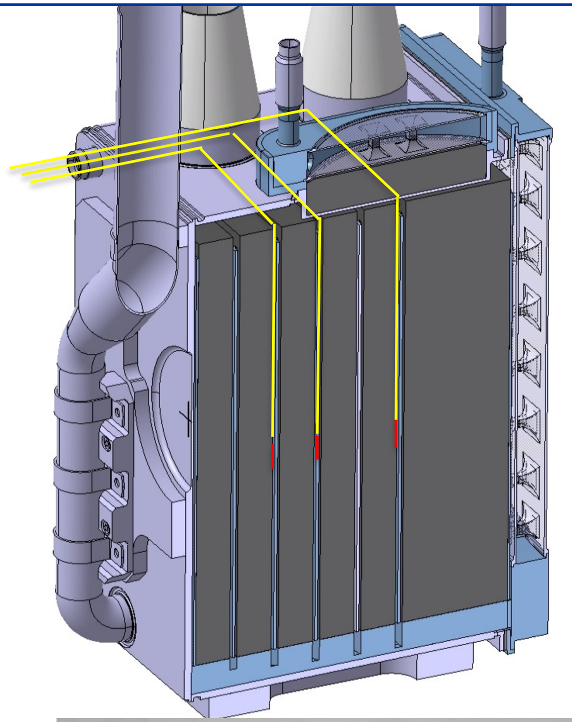
2.6 MPa vs. 1 MPa (plastic flow onset)

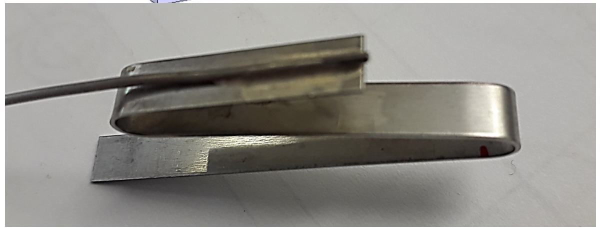
Target monitoring system

6 type-K thermocouples to monitor Pb surface temperature

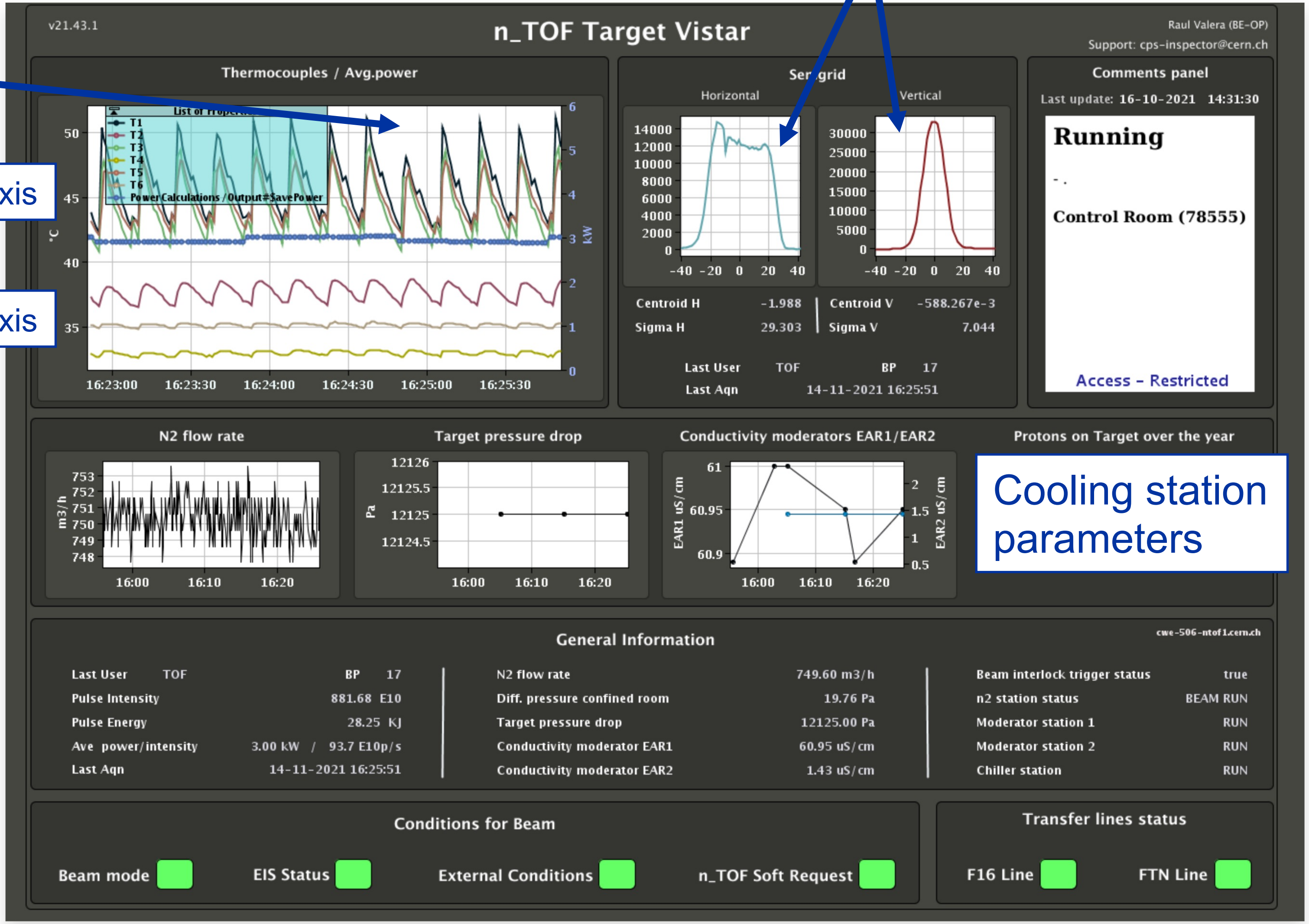
On axis

Off axis



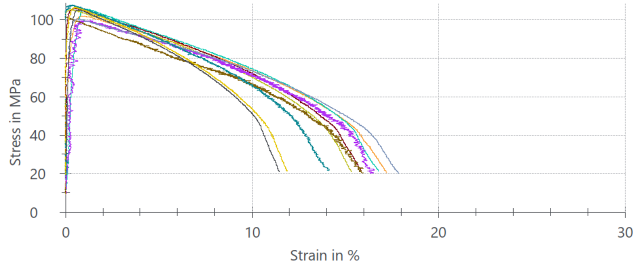


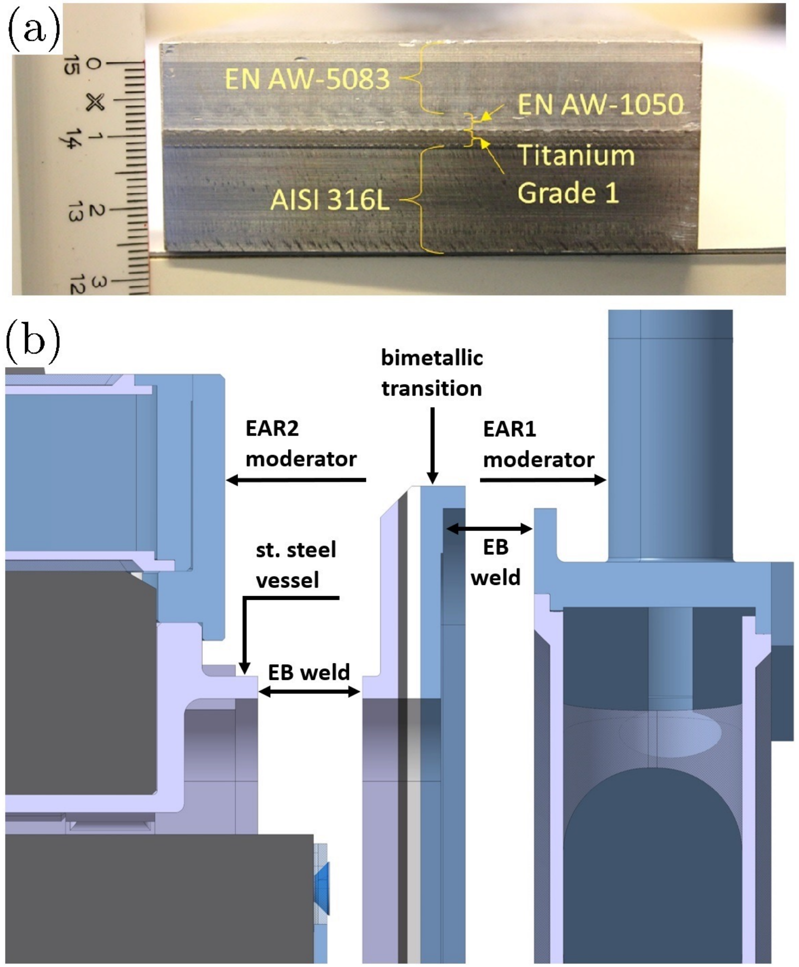
Beam size on target



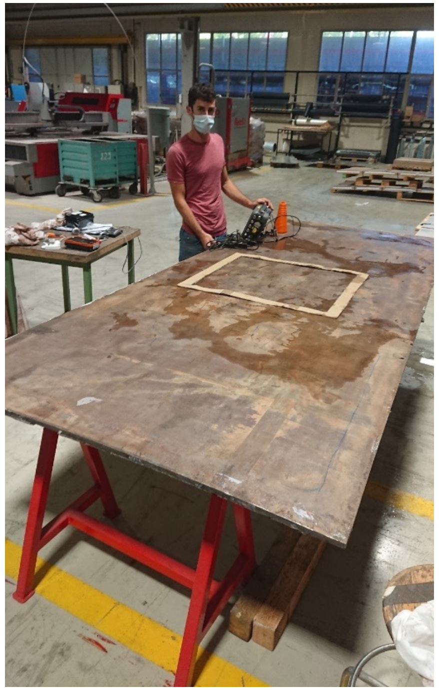
Cooling station parameters

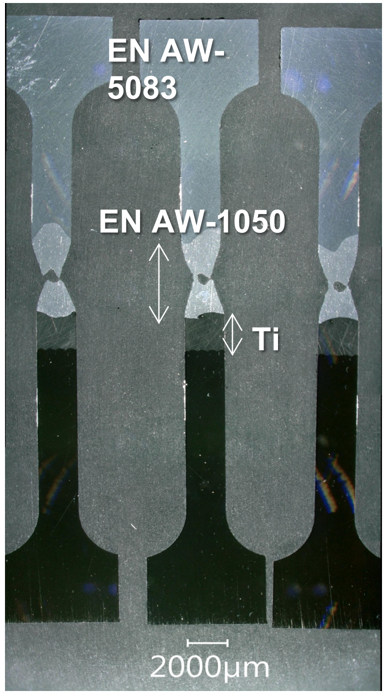
n_TOF spallation target R&D
Bimetallic transition

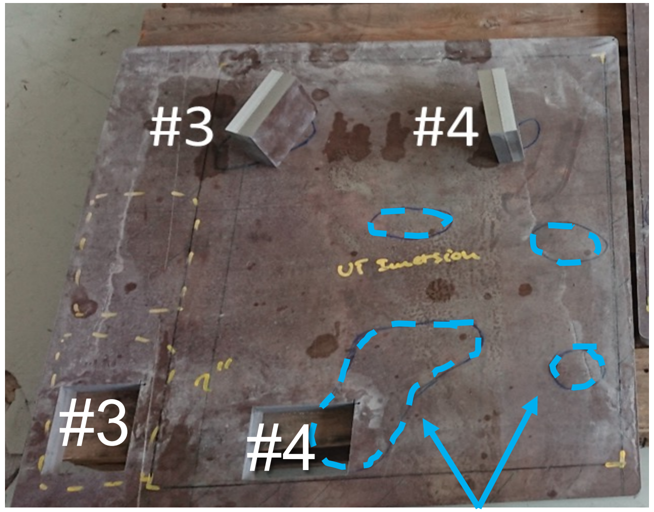




- Bimetallic transition was acquired based on tight specifications by CERN → Nobelclad (DE) was the selected contractor





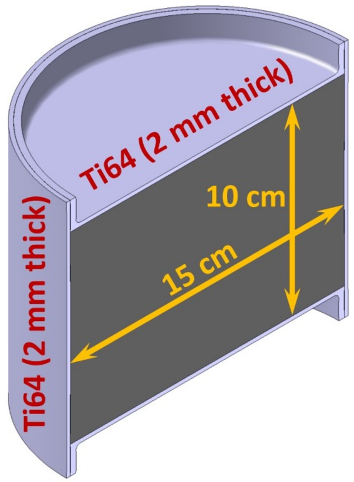


Areas marked with higher density of indications during the full plate inspection by contact UT

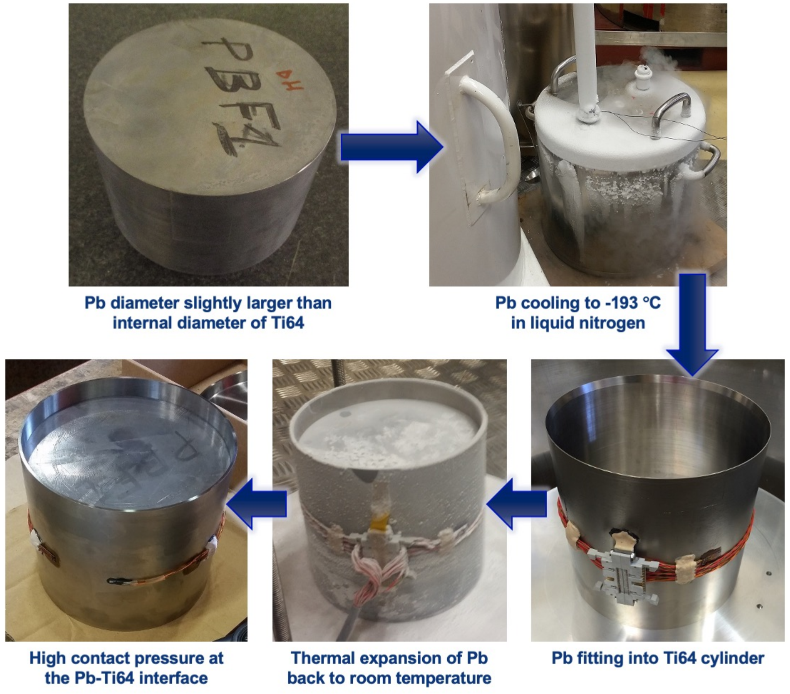
n_TOF spallation target R&D

- Before getting to this final design, several other options were investigated

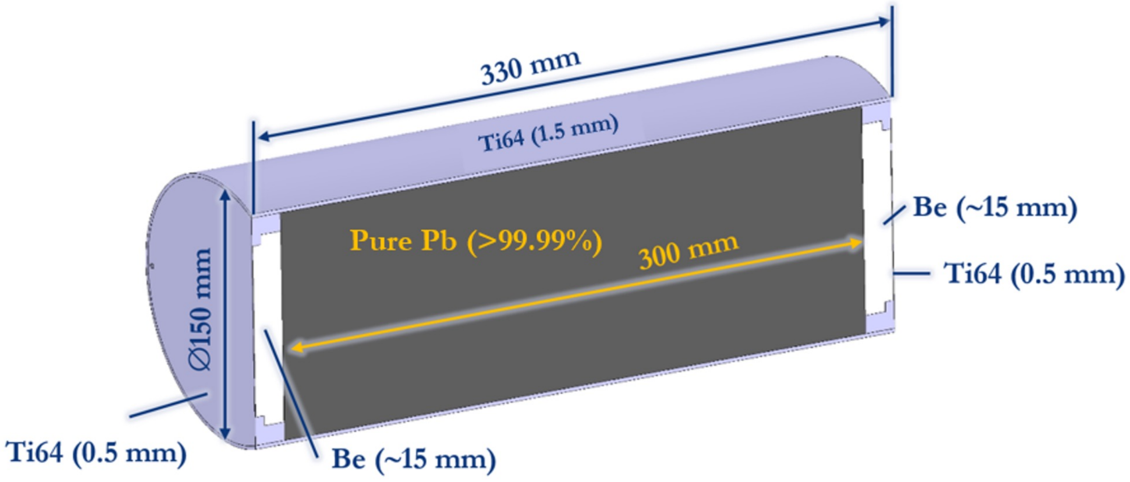
Ti64-clad Pb prototype: cryogenic shrink fitting



Ti64-contained Pb prototype 1

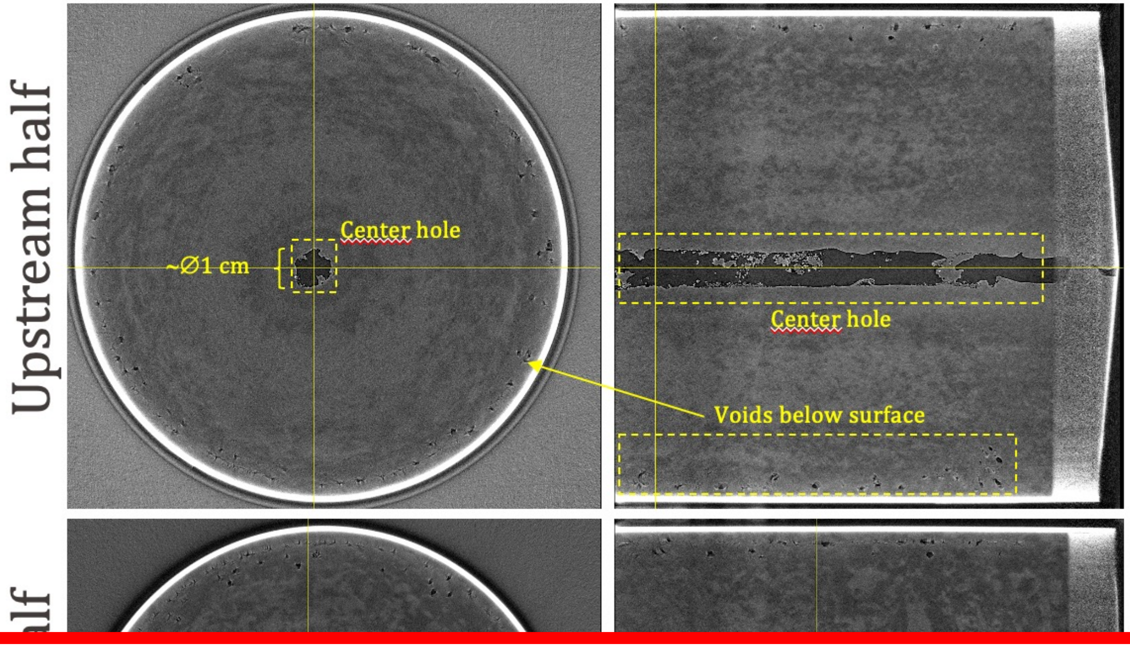


Ti64-clad Pb cylinder with Be inserts



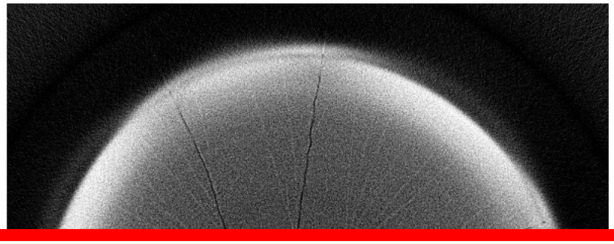
Also tested in HiRadMat…

Neutron tomography after irradiation test in HiRadMat



- After 1000 pulses of 3.6×10^{12} p^+
- Neutron tomography at ILL (Grenoble)
- Voids in the lead cylinder
- Ti-6Al-4V cladding intact and content sealed

Upstream beryllium plate cracked



- Voids in lead where peak stress oscillations were found during stress wave reflection in simulations (beam axis and below cylindrical surface).
- Titanium Grade 5 envelope intact and content sealed despite extensive damage in lead (test conditions more extreme than real target operation).
- Cracks in upstream beryllium plate probably not caused by direct beam impact but by bending stresses induced by cumulated deformations in lead cylinder and change of pressure profile at the Pb-Be interface.

Digression – dismantling and reinstallation

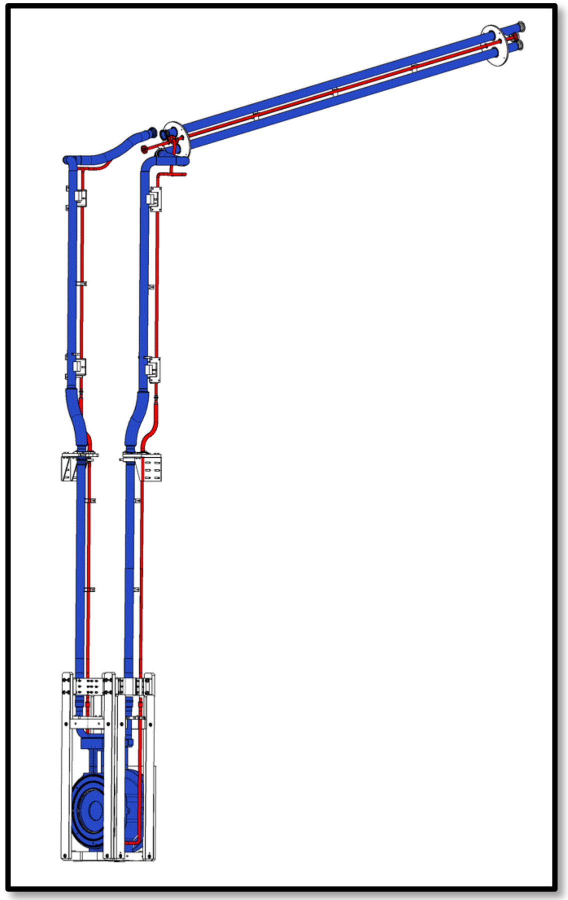
- At CERN facilities are upgraded and devices exchanged in already existing areas – **maximize reuse of existing infrastructure** – n_TOF is an example

- However, challenges are present due to high residual dose rates and potential contamination risks

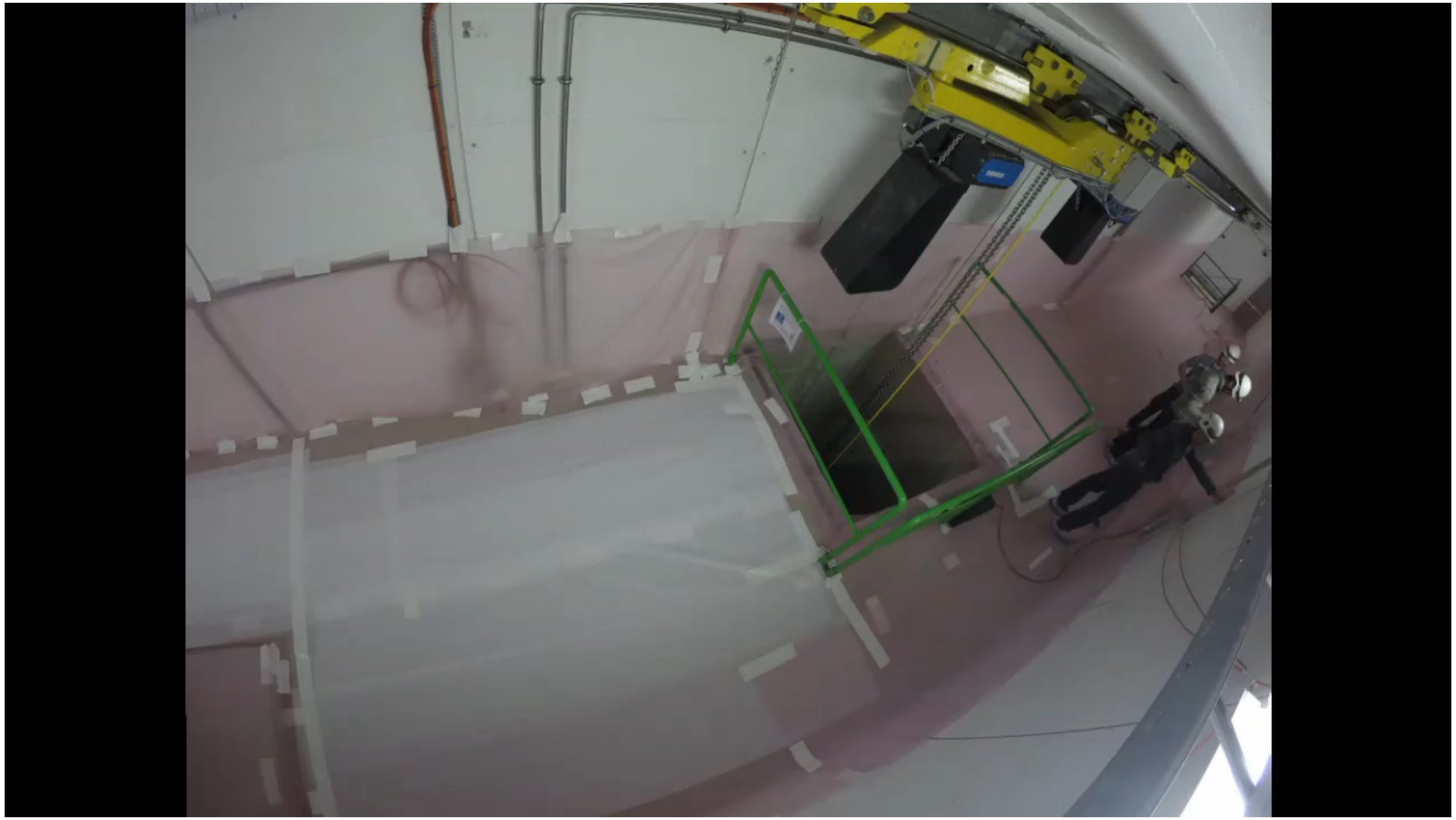
- E.g., **dismantling of n_TOF Target #2** in order to make space for Target #3

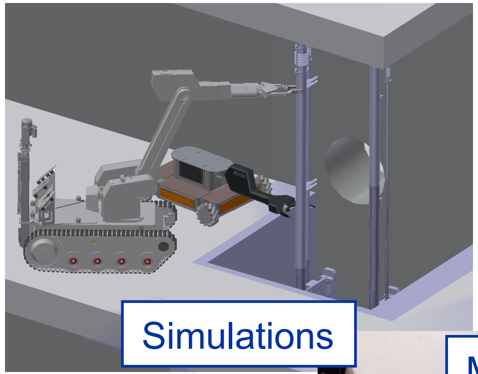
- Maximize use of ALARA processes (remote handling and telemanipulation)

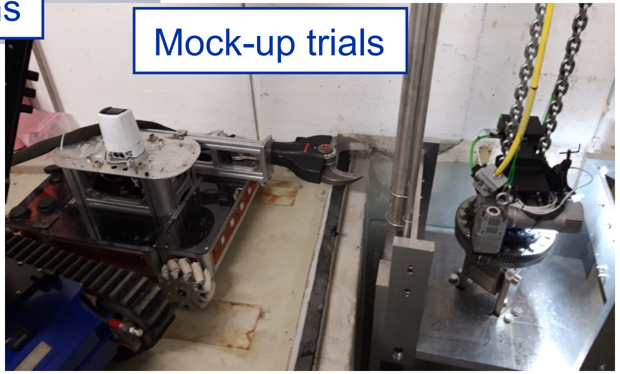
Target #2 cooling & moderator pipes removals



Target #2 water pipes cutting (robotics)







Target #2 removal, sampling and packaging

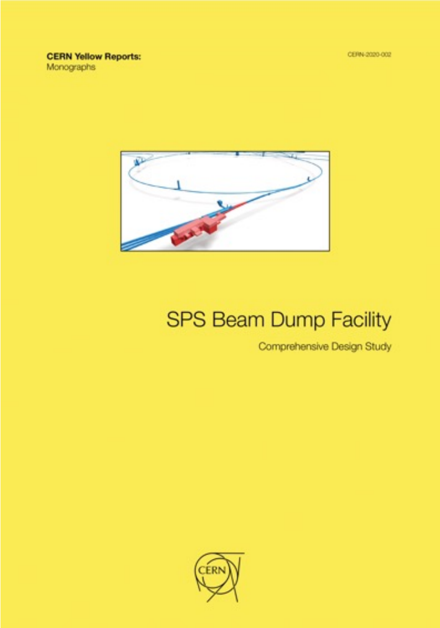
2. Beam Dump Facility

https://doi.org/10.23731/CYRM-2020-002

SPS Beam Dump Facility

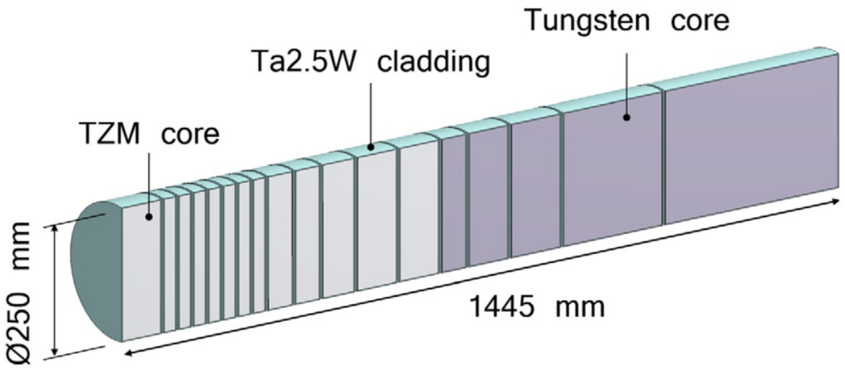
Looking towards the mid-term potential future

- Facility being design at CERN for hidden sector searches
- Requirement: high-Z material (short nuclear inelastic scattering length) & high energy protons & high POT



$$\text{Beam kinetic energy} = I \times E_b = 4 \cdot 10^{13} \times 400 = \mathbf{2.6\ MJ}$$

$$\text{Beam avg. power} = {}^{2.6\ \text{MJ}}/_{7.2\ \text{s}} = \mathbf{360\ kW}$$



- TZM and W core, water-cooled
- Cladding w/ Ta alloys to avoid corrosion/erosion effects

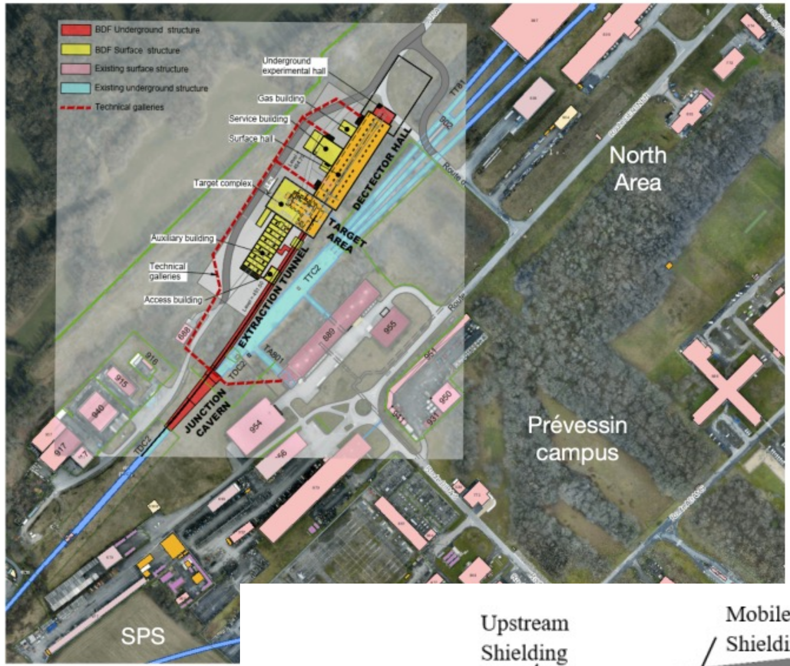


Fig. 1.1: Overview of the proposed imp
campus.

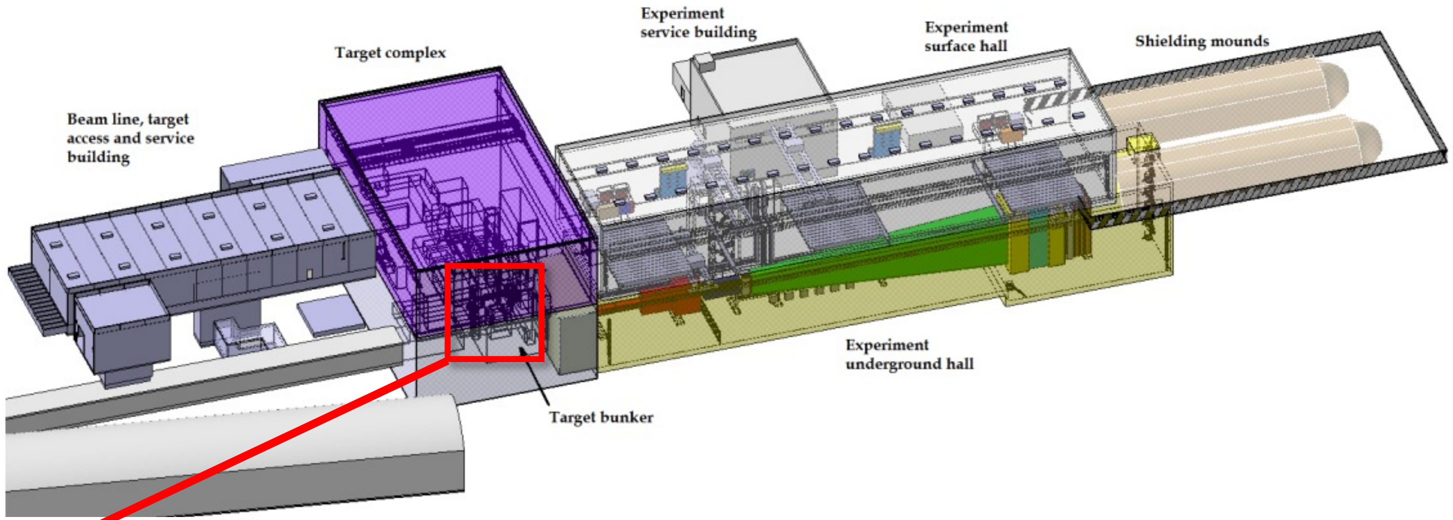


Fig. 1.2: Overview of the target complex and experimental area

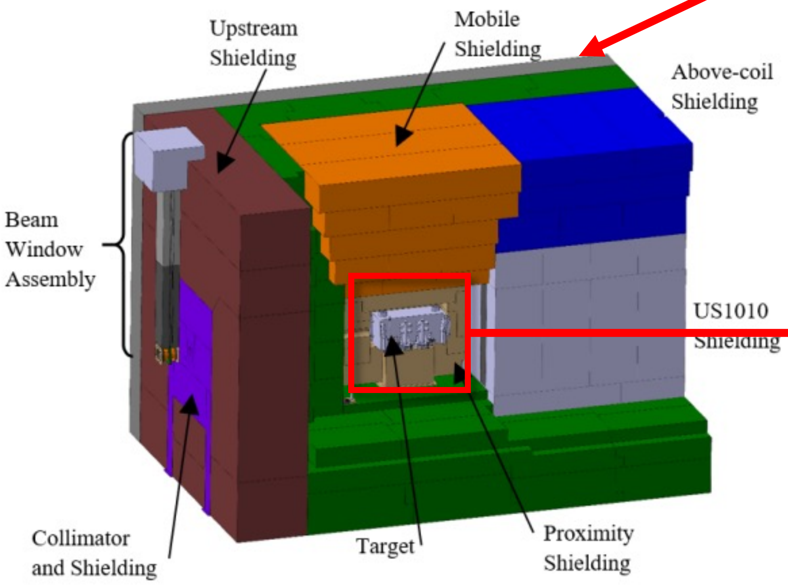


Fig. 6.7: Isometric cutaway view of crane concept equipment in the helium vessel

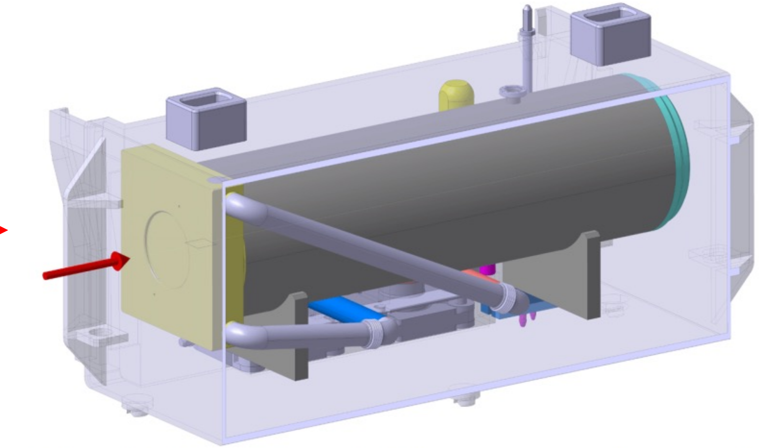


Fig. 5.61: Full assembly of BDF target: view of the helium container, outer tank, upstream and downstream flanges, and inlet and outlet pipes.

SPS beam dump facility

R. Ximenes, IWSMT15 (2023)

BDF Target

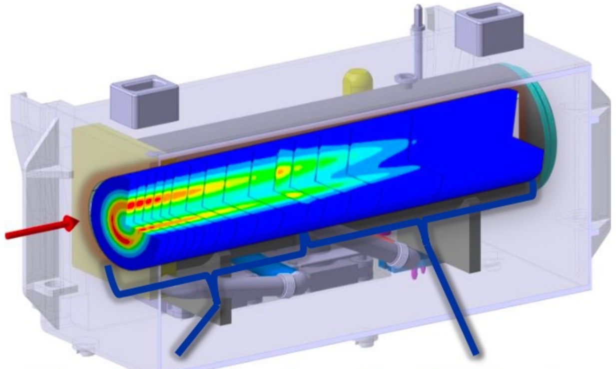
- High thermal power (300 kW) → cooling needs
- High POT → radiation damage
- Slow extraction but high spill power density → Quasi-static thermal-induced stresses

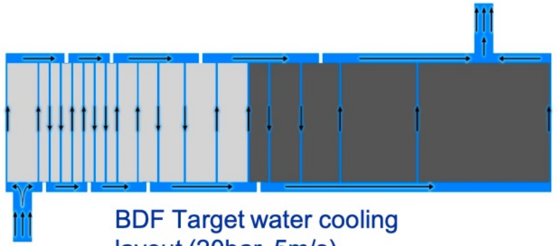
TZM & W core Target as reasonable physics & engineering compromise. **Ta2.5W HIPed cladding** (Baseline design)

Baseline beam parameters of the BDF Target operation. https://doi.org/10.23731/CYRM-2020-002

Proton momentum (GeV/c)	400
Beam intensity (p^+/cycle)	4×10^{13}
Cycle length (s)	7.2
Spill duration (s)	1.0
Beam dilution pattern	Circular
Beam sweep frequency (turns/s)	4
Dilution circle radius (mm)	50
Beam sigma (H, V) (mm)	(8, 8)
Average beam power (kW)	356
Average beam power deposited in target (kW)	305
Average beam power during spill (MW)	2.3

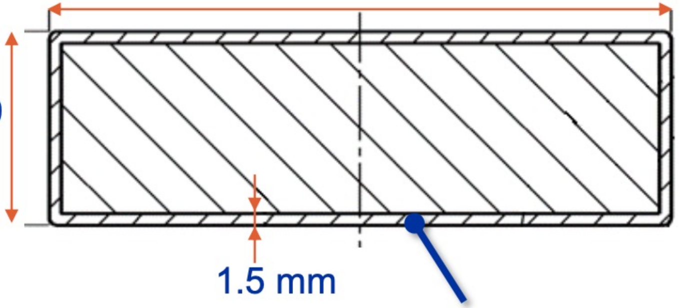
~ 4.0×10^{19} p^+/y





BDF Target water cooling layout (20bar, 5m/s)

https://doi.org/10.1103/PhysRevAccelBeams.22.113001



Ta2.5W cladding

R. Ximenes, IWSMT15 (2023)

Tantalum

- ✓ Refractory with high melting point, conductivity, strength and ductility
- ✓ High density
- ✓ Low CTE
- ✓ Full solubility with Molybdenum and Tungsten
- ✓ Very good corrosion-erosion resistance in water medium
- ✓ Sound experience in other Targetry applications (ISIS, LANSCE, KENS…)

Ta-2.5W: Solution strengthened Ta alloy with W

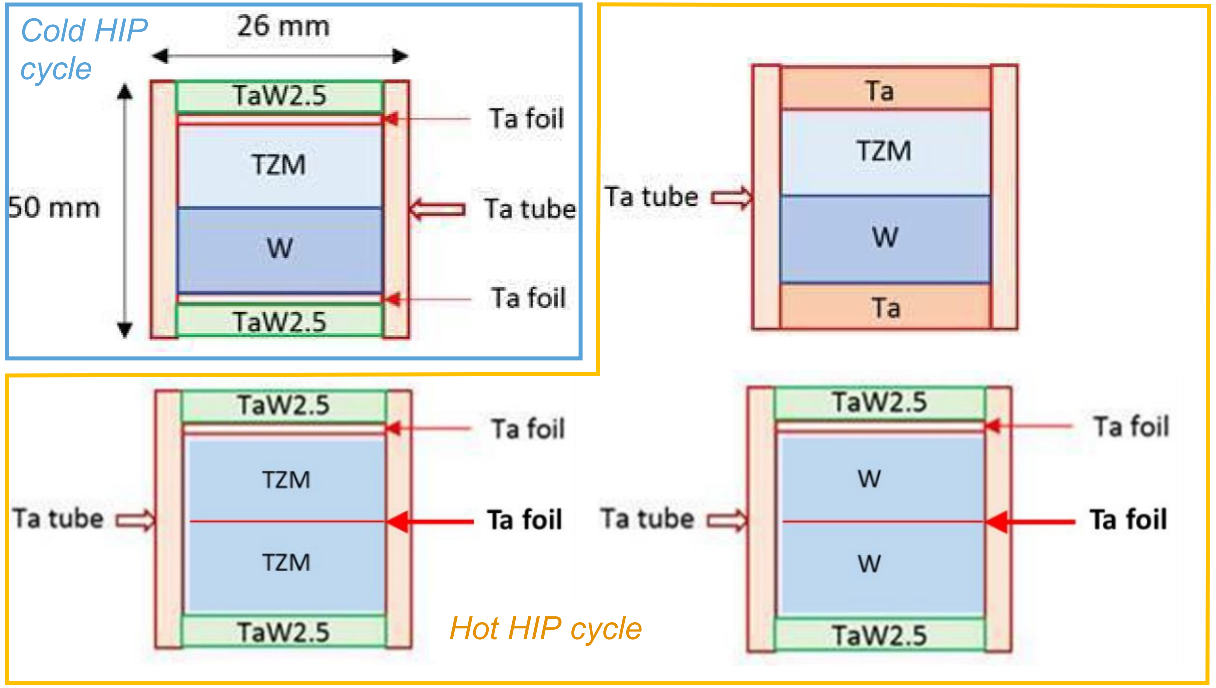
- Higher strength yet still ductile
- Enhanced hydrogen embrittlement resistance

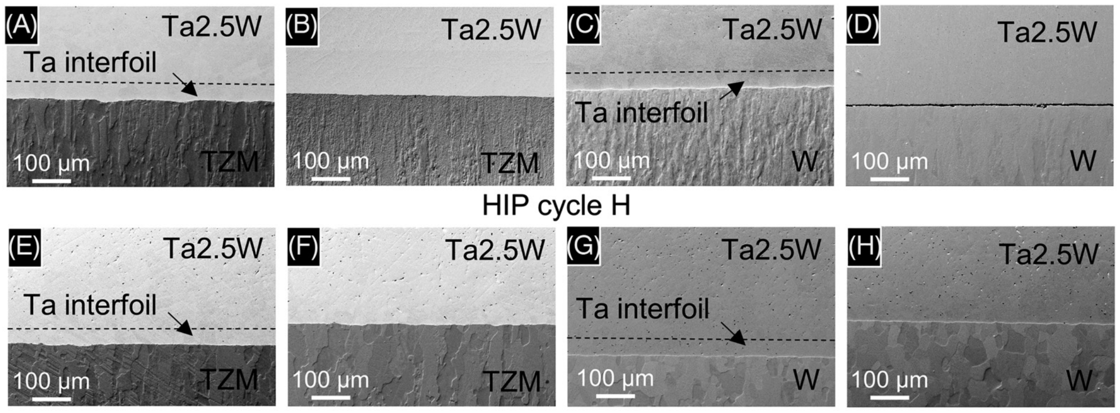
- **Preliminary HIP and SPS Cladding trials w/ Ta2.5W & core materials**
- ***Prototype manufacturing**
- **Extensive material & HIPed cladding characterization**
- ***Prototype beam tests**
- ***Post Irradiation Examination**

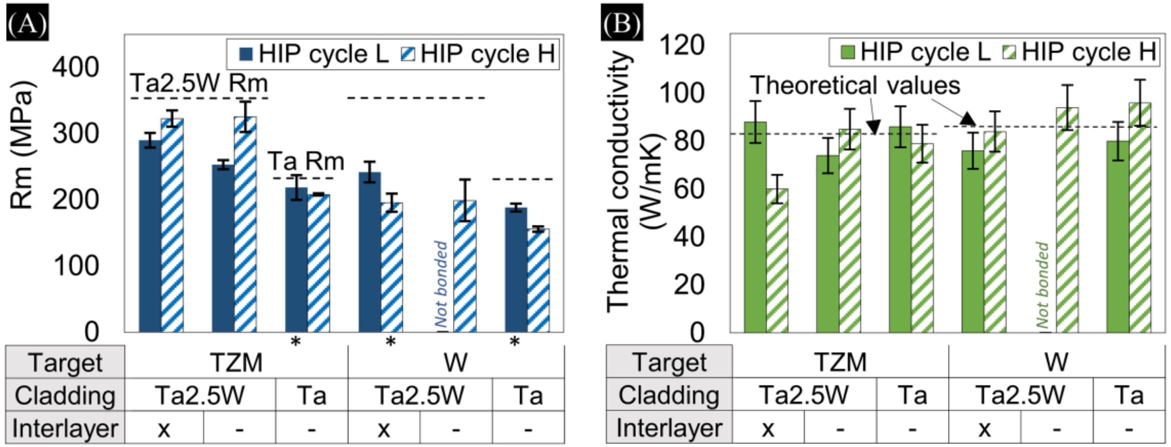
*Other presentation in IWSMT-15

SY Accelerator Systems | 15 IWSMT | 5-9th March 2023 | Rui Franqueira Ximenes | Beam Dump Facility production target at the European Laboratory for Particle Physics (CERN) and advanced cladding technological R&D | 6

Summary of Ta, Ta2.5W cladding R&D





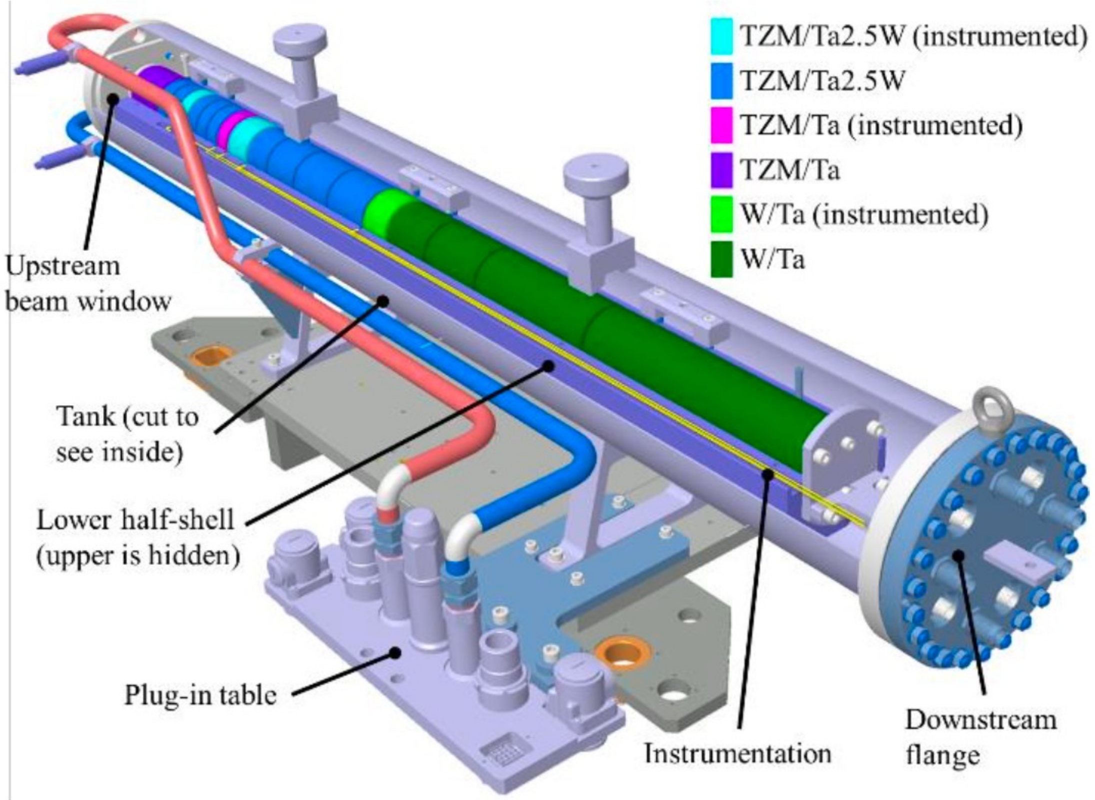


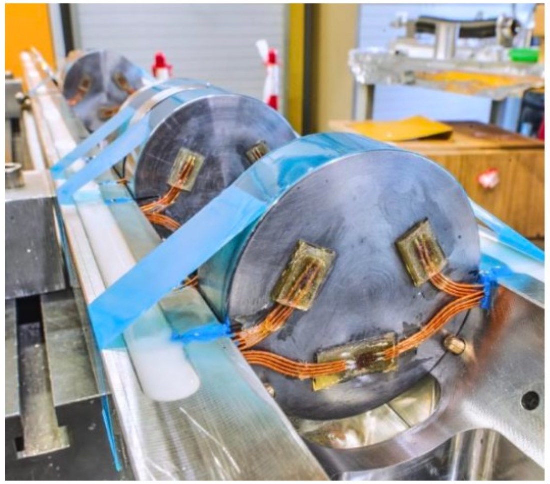
Microstructural observations, tensile strength and conductivity measurements for some of the studied interfaces (https://doi.org/10.1002/mdp2.101)

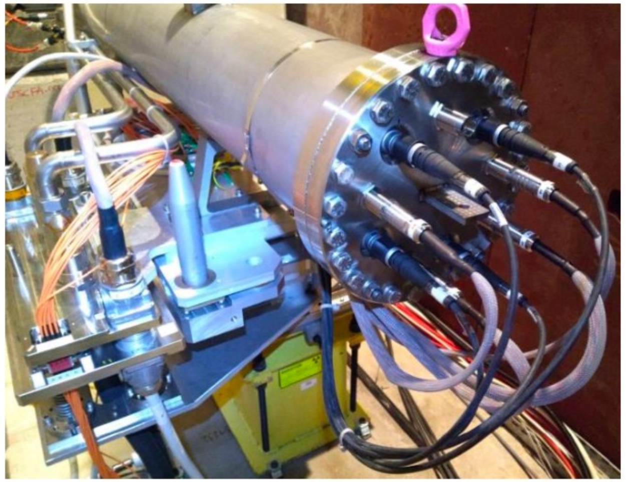
BDF Target Prototype

R. Ximenes, IWSMT15 (2023)

Design summary:







- 4 blocks instrumented with strain gauges and temperature sensors
- Target blocks two half-shell parts which allow free expansion while guiding the 20-bar cooling water.
- Shells inserted in a cylindrical SS tank. Water connections on the upstream side of the tank. Instrumentation on the downstream.
- Collimator-like plug-in table, allowing fully remote handling. The prototype was designed to be the first complete remotely dismountable device of its type at CERN

BDF Target Prototype beam tests (2018)

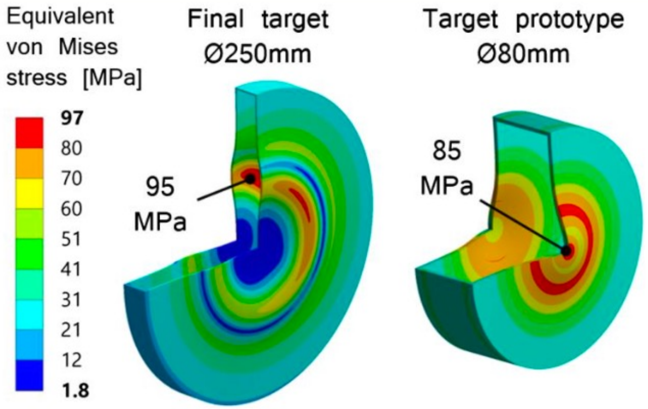
R. Ximenes, IWSMT15 (2023)

Final target (at 4 × 10^{13} *p+/cycle) :*

- Expected (FEM) Max von Mises stress of 95 MPa & max T of 160 °C on Ta2.5W. (180 & 150 °C on TZM & W respectively)

	Final target	Target prototype
Proton momentum [GeV/c]	400	
Beam intensity [p+/cycle]	4×10^{13}	$3\text{-}4\times10^{12}$
Beam dilution	four circular sweeps	no
Beam extraction	7.2 s cycle with 1s of beam extraction	
Average beam power [kW]	355	27-35
Average power on target [kW]	300	18-23

FEM calculation (with 3 × 10^{12} p+/cycle on the prototype)



Prototype (at *3.75 × 10^{12} p+/cycle*) :

- Expected (FEA) max stress amplitude(σ_a) of 50 Mpa (105 MPa von Mises equivalent) and max temperature of 250 °C on the Ta2.5W
- **σ_a @r=20mm: 37 MPa (FEA) vs 43 MPa (SG) on the Ta2.5W**
- **T@r=20mm: 40 °C (FEA) vs 38.8 °C (Pt100) on the Ta2.5W**

Maximum[1] temperatures, strains measured (Transverse & Radial) and equivalent stress amplitudes vs calculated via FEA for 3.75 × 10^{12} p+/cycle

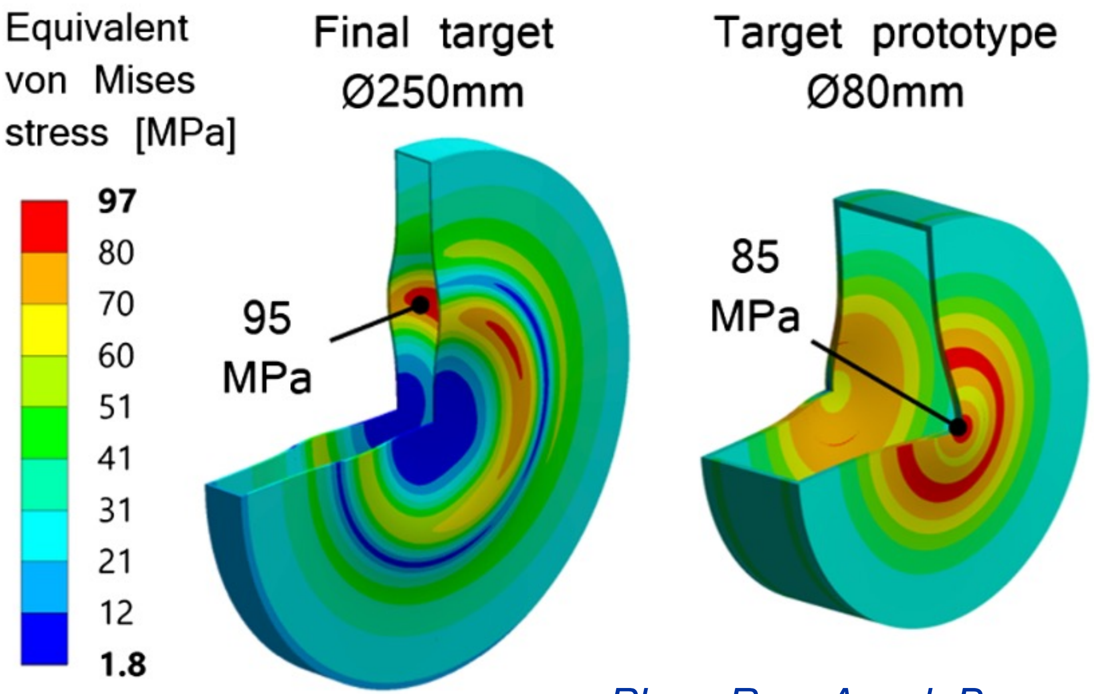
Cladding Material (block)	T_{Pt100} [°C]	T_{FEA} [°C]
Ta2.5W (4)	38.8±0.5	40
Ta (8)	46±0.5	43.8

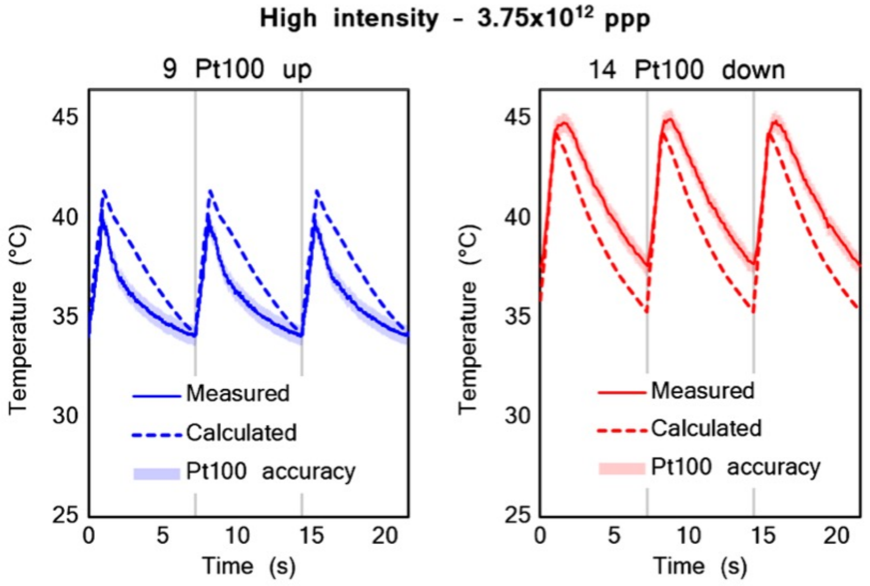
Cladding Material (block)	$\Delta\varepsilon_{SG}$ [μm/m]	$\sigma_{a,SG}$ [MPa]	$\Delta\varepsilon_{FEA}$ [μm/m]	$\sigma_{a,FEA}$ [MPa]
Ta2.5W (4)	190 |-450	43	170 | 390	37
Ta (8)	100 |-230	22	87 |-250	23

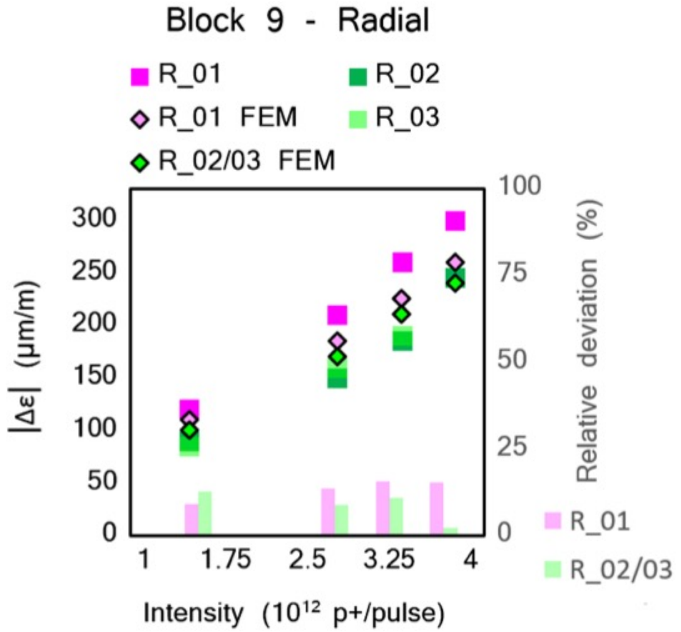
[1] Maximum within all the measured values by the instrumentation. The FEA values are at the same location of the PT100 and SG. The actual maximum temperatures in the blocks are higher but were not directly measured.

SPS Beam Dump Facility

Beam tests







Phys. Rev. Accel. Beams 22, 123001 (2019)

Excellent agreement between data and simulations results

Nb-alloys cladding R&D

R. Ximenes, IWSMT15 (2023)

Ta alloys →non-negligible decay heat w/ BDF operational conditions. RP concern w/ LOCA

➢ **Search for alternative cladding materials (Zircaloys, Nb-alloys): Nb, Nb1Zr, Nb10Hf1Ti**

- Less activation, less decay heat
- Refractory. Share outstanding thermo-mechanical properties of Ta and good corrosion-erosion resistance
- Lower cost

Preliminary 'bondability' study ✓
- Phase diagrams
- Diffusivity
- Ductility
- Creep

Quick FEM checks ✓
- Thermo-mechanical compliance

New cladding candidates manufacturing tests & characterization ✓ ...

Cladding (bulk) material characterization ✓

FEM assessment ✓
- Operation
- Decay heat / LOCA

Yet to be fully addressed

Radio Protection aspects
- Nb-94 ? Other? ...

Residual stress ...

Fatigue ...

Oxidation

QA of cladding material

Radiation damage

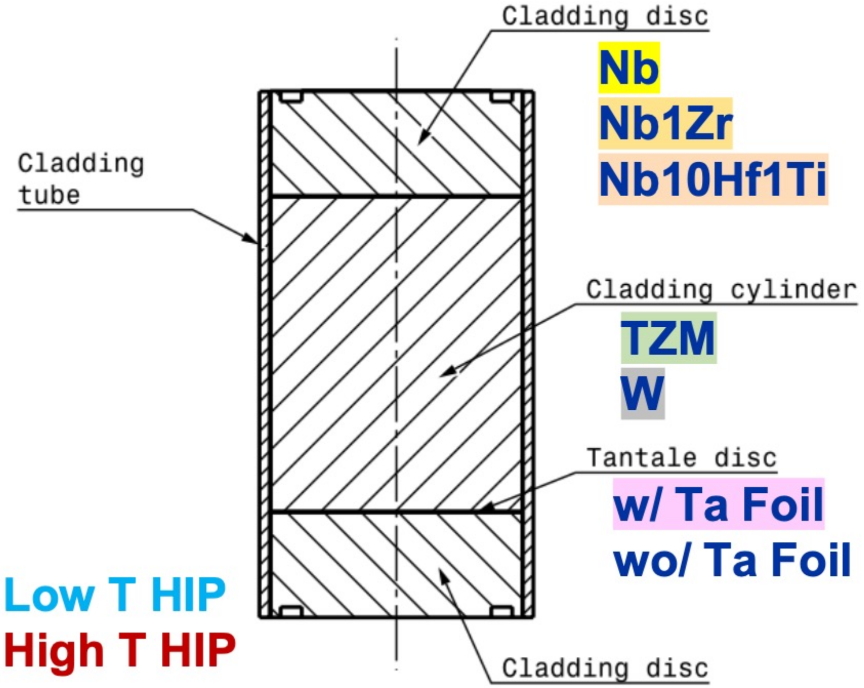
Beam tests

Nb-alloys cladding R&D

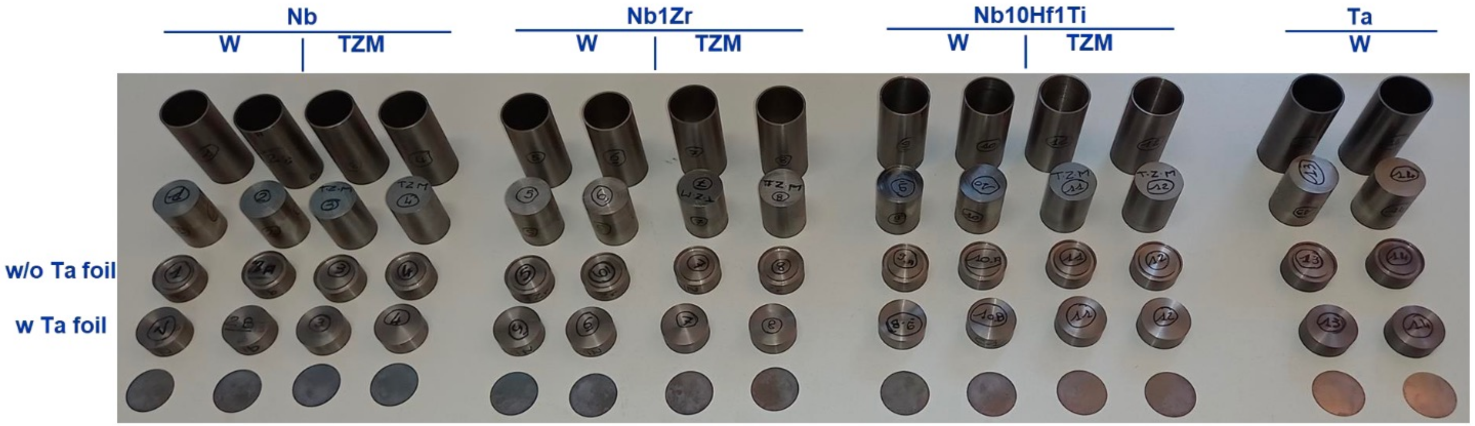
New cladding candidates manufacturing tests & characterization

Procurement of alloys → EBW + Leak test → HIP 1 + UT → Metallography → HIP 2 + UT → Metallography + characterization

- **Purpose:** assess the viability of cladding Nb-alloys on TZM and W via Hot Isostatic Pressing (HIP) & build the appropriate material models, fed from interface characterization



Low T HIP
High T HIP



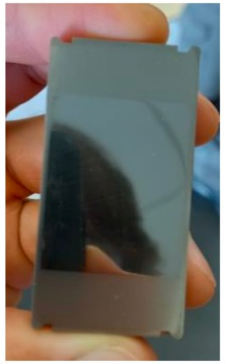
R. Ximenes, IWSMT15 (2023)

Nb-alloys cladding R&D

New cladding candidates manufacturing tests & characterization

Procurement of alloys | EBW + Leak test | HIP 1 + UT | **Metallography** | HIP 2 + UT | Metallography + characterization

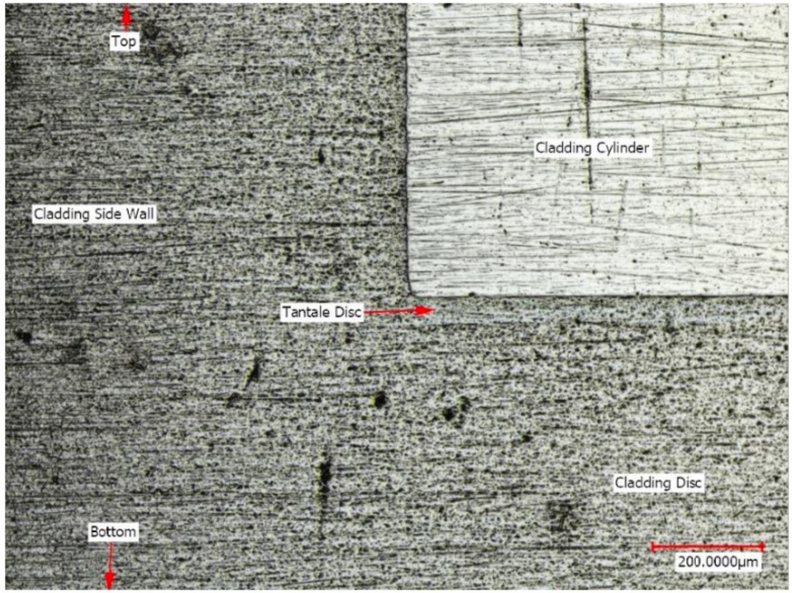
R. Ximenes, IWSMT15 (2023)

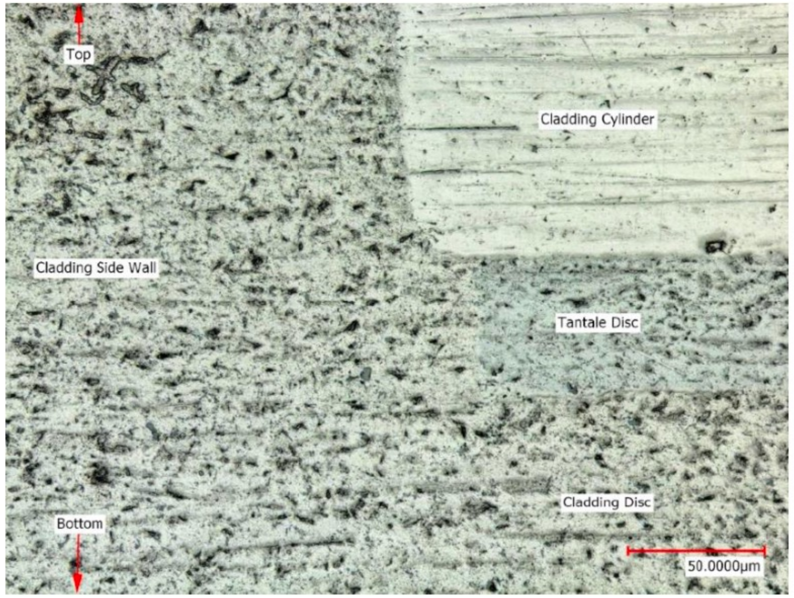


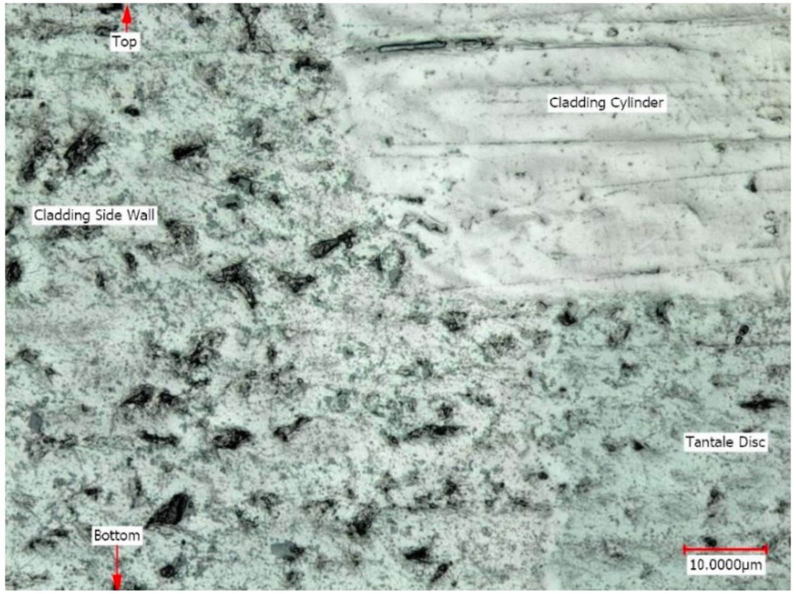
OM to visually check the bonding interface

- ✓ Evident successful plastic deformation of the parts against each other (in preliminary OM)
- ✓ Bonding visually ok

Example of Nb//W capsule after Low T HIPing







Take home message

- Project approval is expected early 2024 depending on management decisions during 2023
- Large (60 MCHF) infrastructure and strong physics case
- High power production target and target systems will be built in an existing underground cavern
- **Lots of critical R&D and plans ahead in the next few years**

3. SPS Beam Dumps

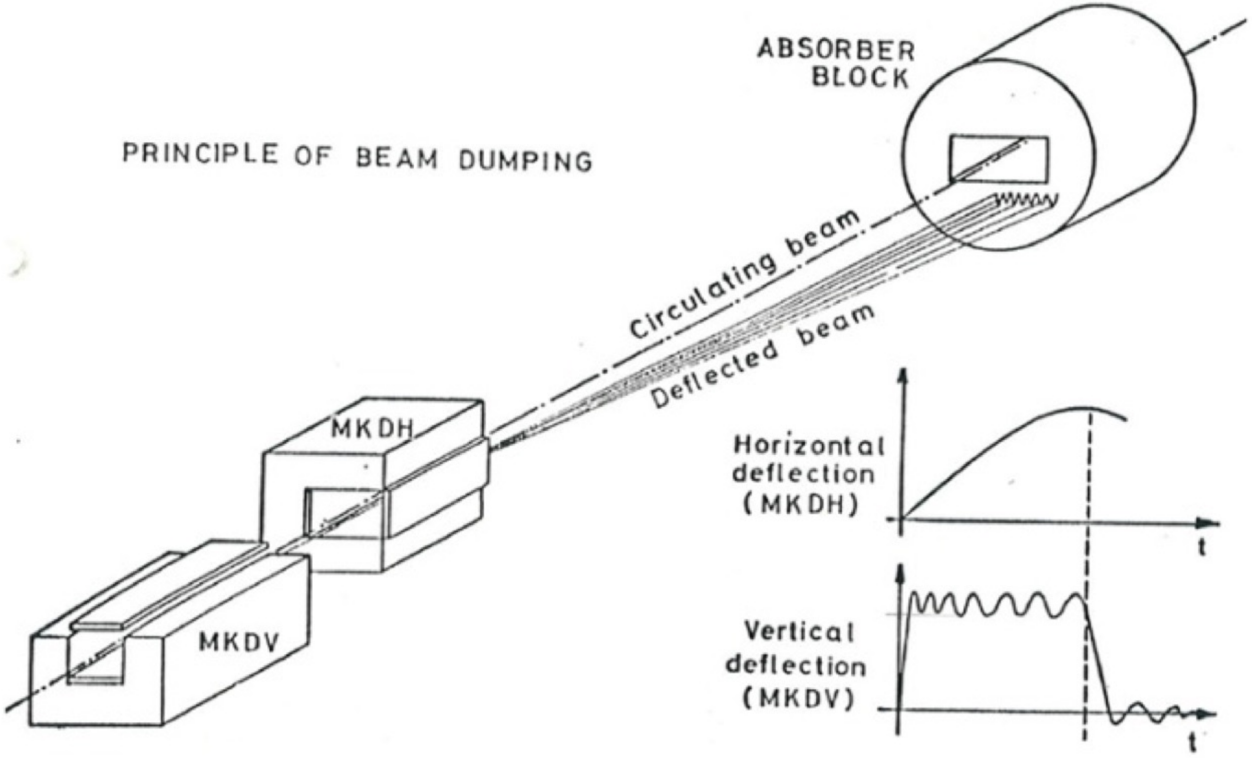
Internal vs. external dumps

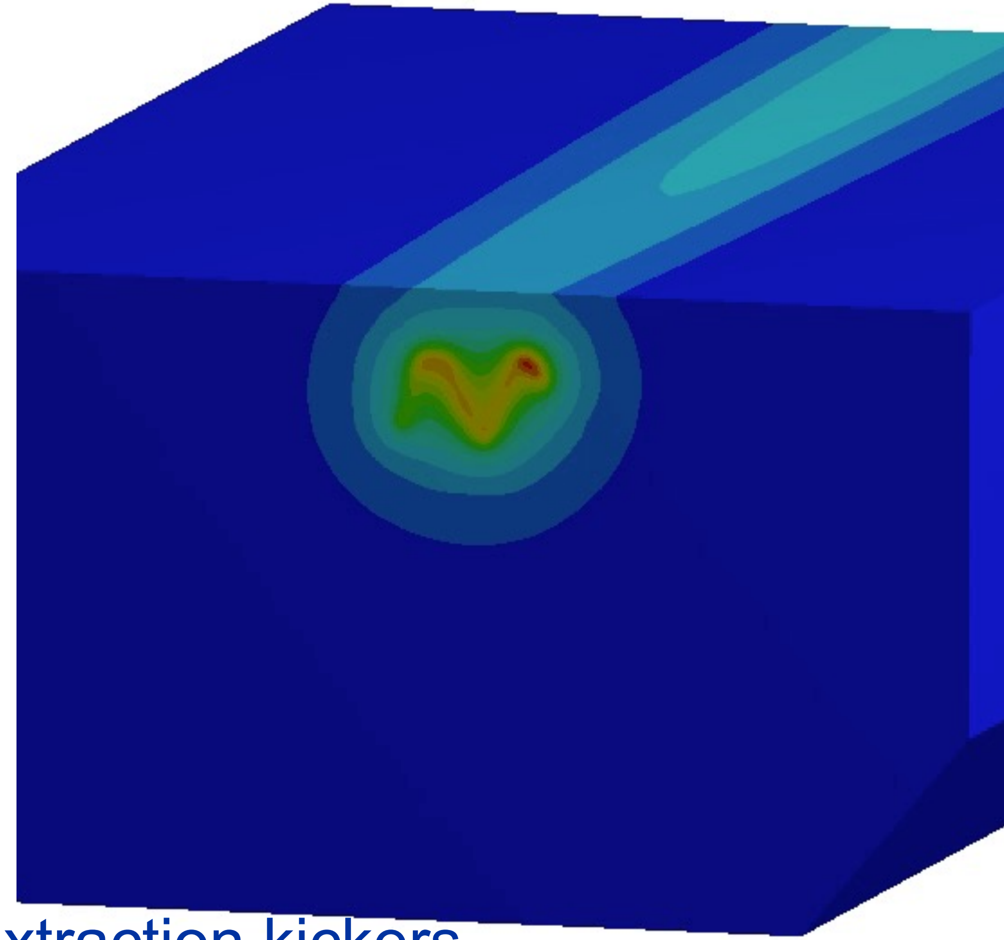
- Dumps are designed to withstand **all potential beam scenarios**, **safety devices** for machine components
- They can be located **internally** or **externally** to the machine vacuum depending on the geometry and external requirements
- Internal dumps have the extra challenge of having to comply with the strict UHV requirements despite the high T
- External dumps usually requires dedicated caverns or line components

SPS Internal Beam Bump
History, challenges and technology

- Due to the specific design of the SPS, the dump is **internal**
- Heavily used in the machine (not only during exceptional case), to allow flexibility and setting up beams
- Reliability is a key parameter for operation

SPS beam dumping





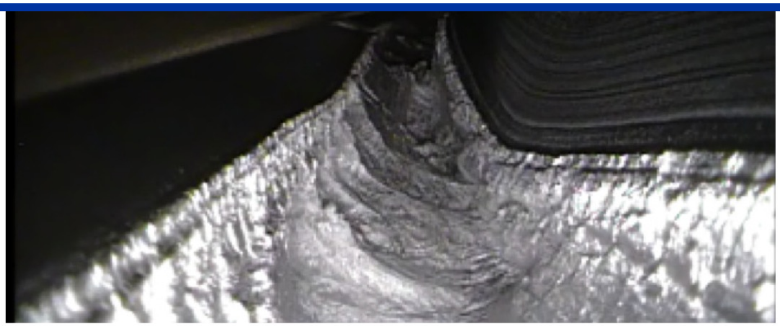
- Beam is diluted during 7.2 μs with dilution and extraction kickers
- Asymmetry in the energy deposition results in asymmetric stress distribution

SPS Internal Beam Bump
History, challenges and technology

- Historically (up to 2000), SPS dumps were including only **aluminium** as absorber
- From 2000 onwards (“millennium” dump) – due to the higher intensities – **graphite** was introduced, keeping Al for the downstream part – earlier generation were Ti-coated
- It was a good idea, but…

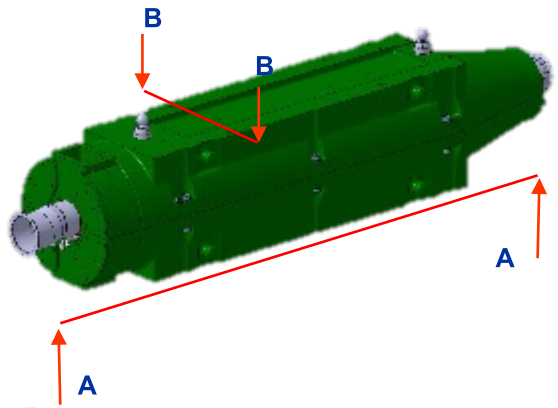
What happens with insufficient cooling?

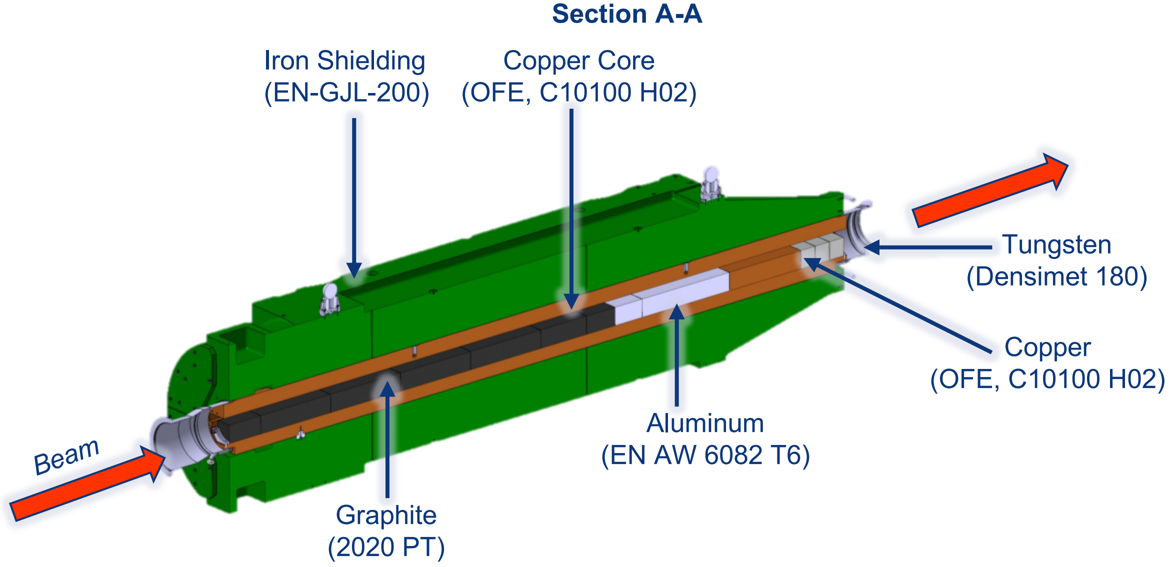
- Molten aluminium coming from insufficient cooling
- Lesson learnt: **complete removal of Al and focus on improving thermal contact with Cu sink**

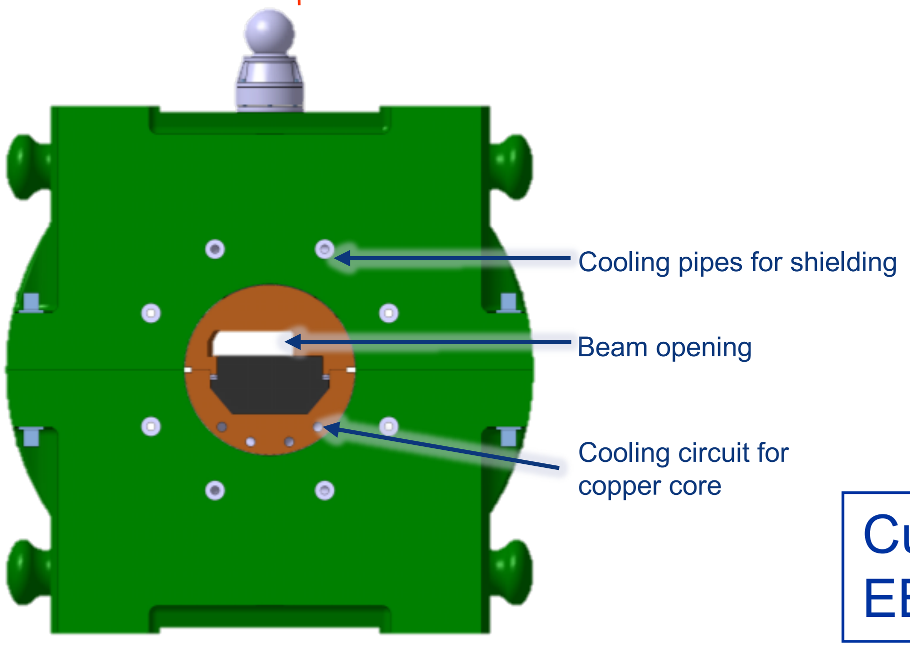


Third generation dump

< 2016



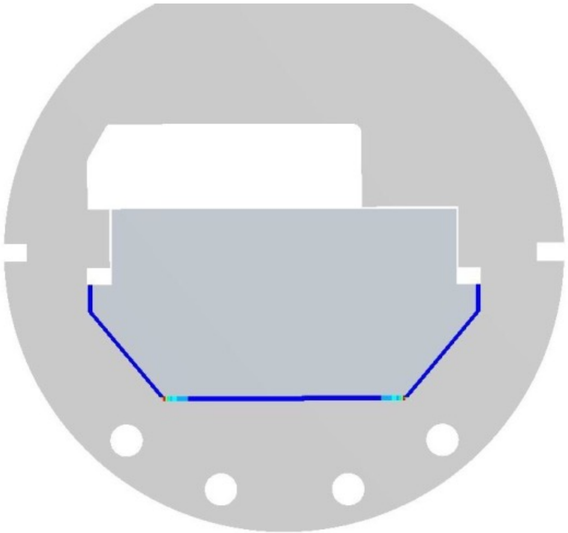




Cu-OFE 3D forged core
EB welded half shells

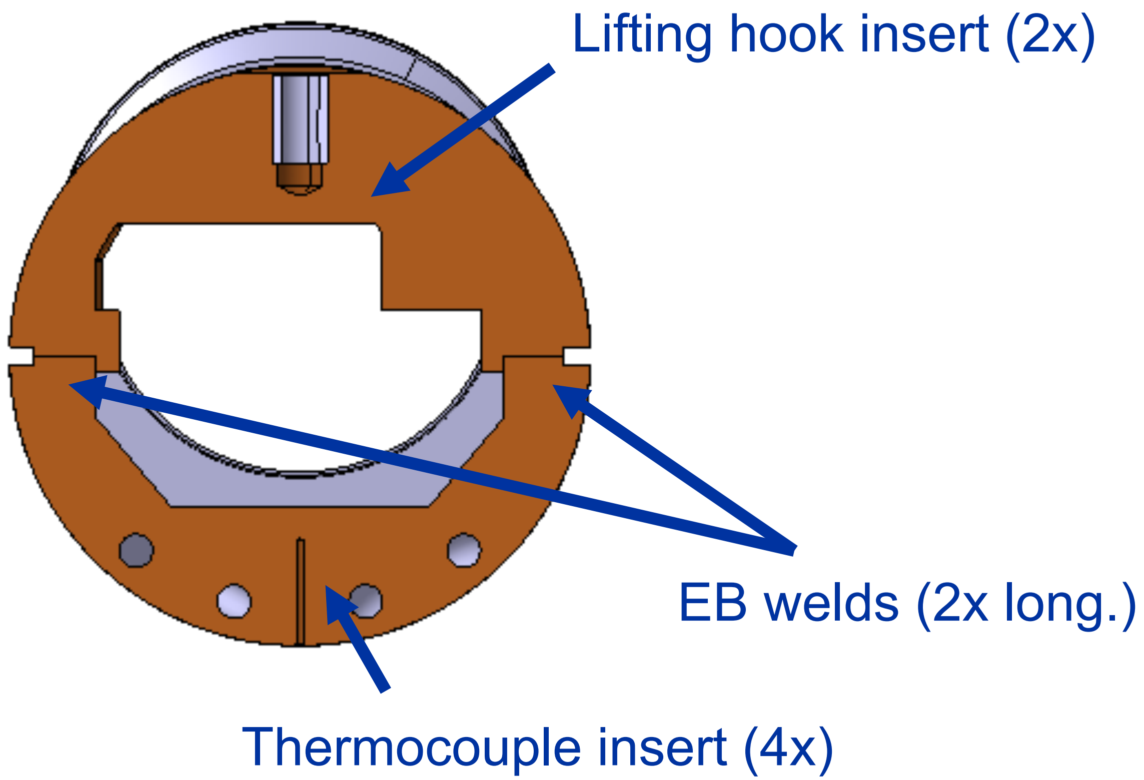
Issues with previous designs

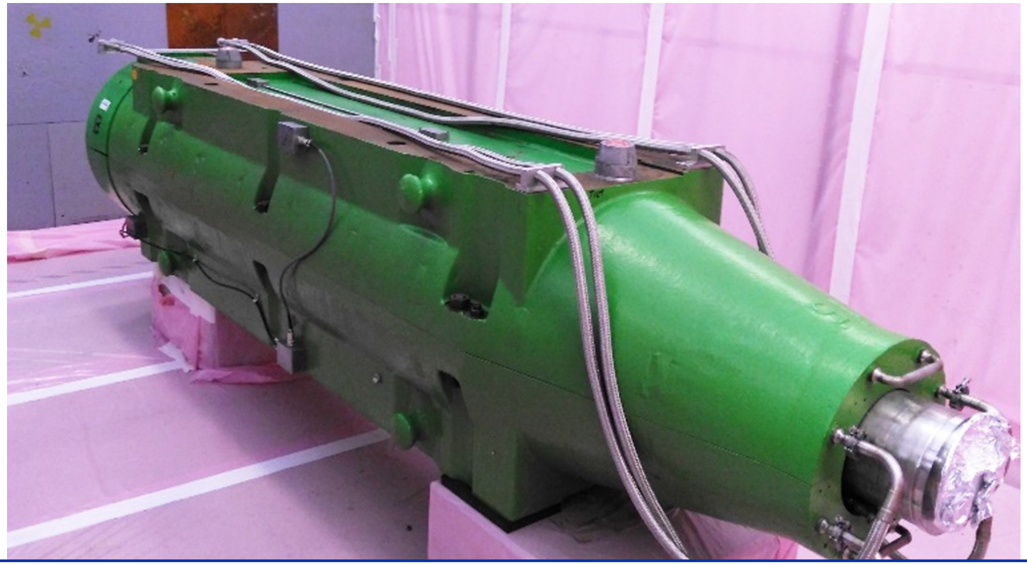
- Limited internal instrumentation (blind during operation)
- Unpredictable contacts between absorbing blocks and Cu core
- Extremely long manufacturing time of 3D forged Cu-OFE
- Aluminium as beam absorbing materials
- Vacuum leaks at EB welds due to asymmetric energy deposition



Intermezzo: importance of PIE

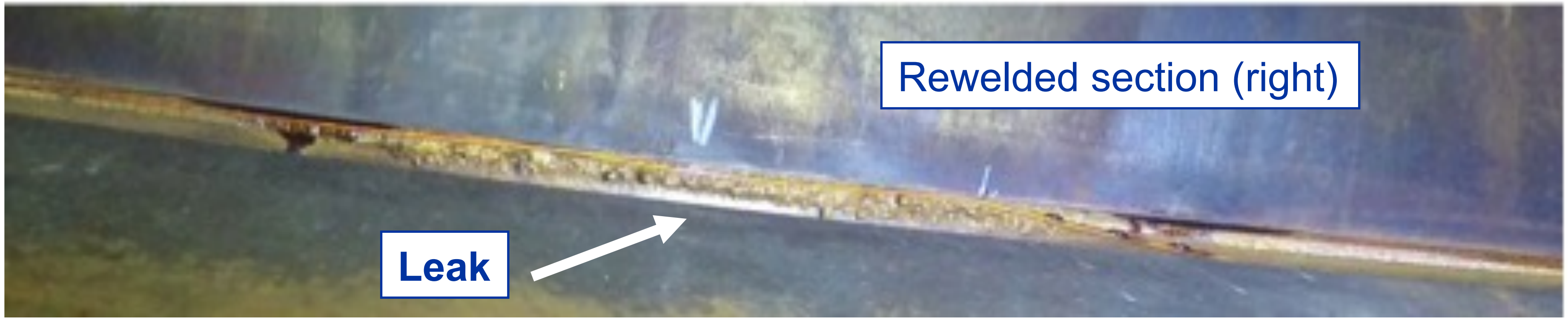
- Third generation dump was inspected post-mortem at CERN in order to confirm position of leak and correct in fourth generation dump





Few mSv/h with shielding close
±50 mSv/h core open
➔ Robotic means employed to inspect

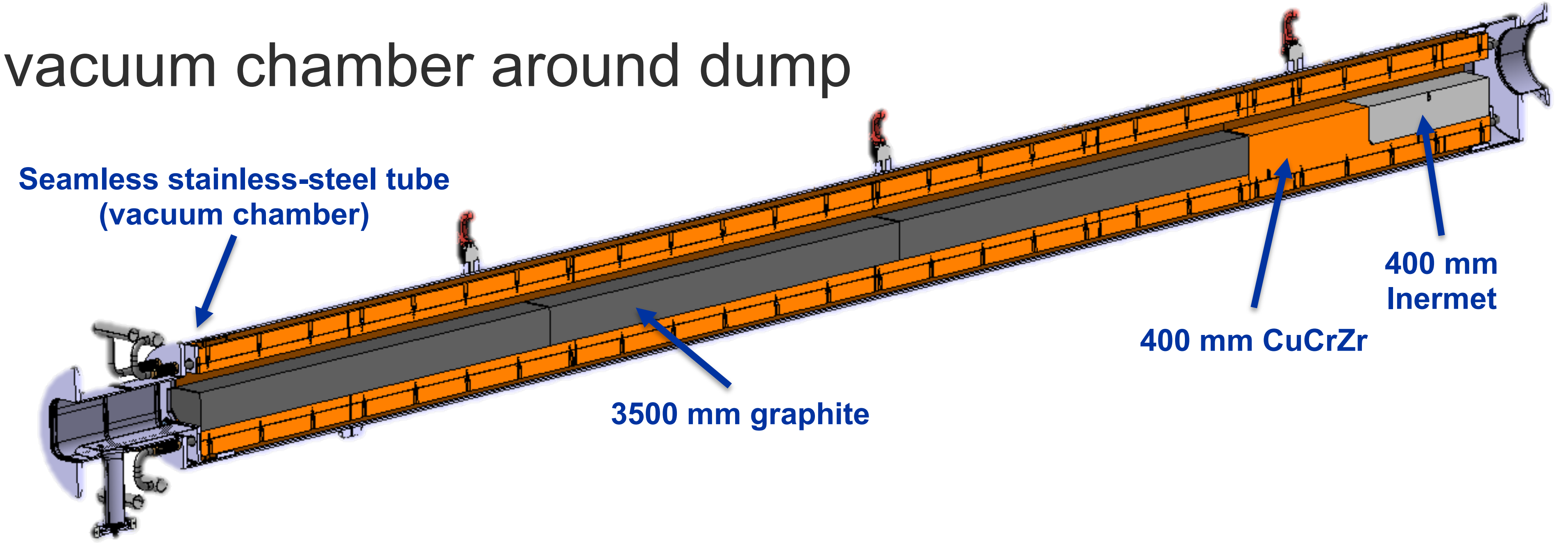

Good quality weld (left)


Rewelded section (right)
Leak

Fourth generation dump (2017-2018)

- Eradication of aluminium
- CuCrZr as absorber (integrated with heat sink)
- Better springs to improve TCC
- Seamless SS vacuum chamber around dump
- T sensors

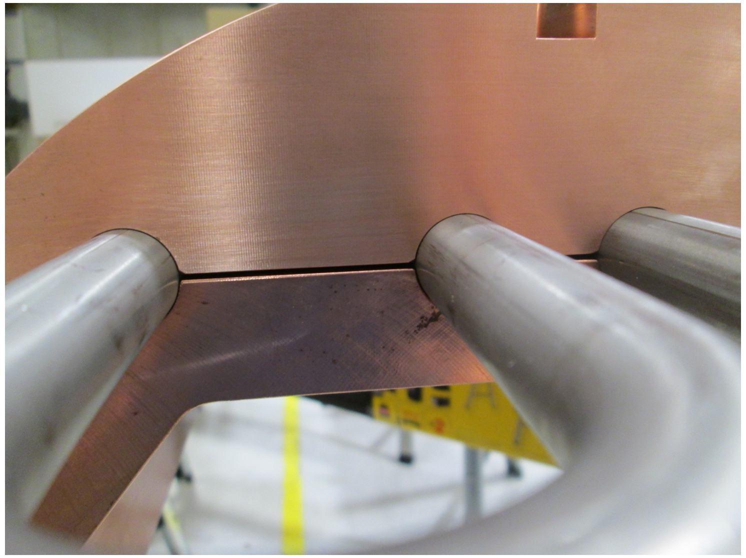
P_{dep}=60 kW
E_{beam}=4.2 MJ

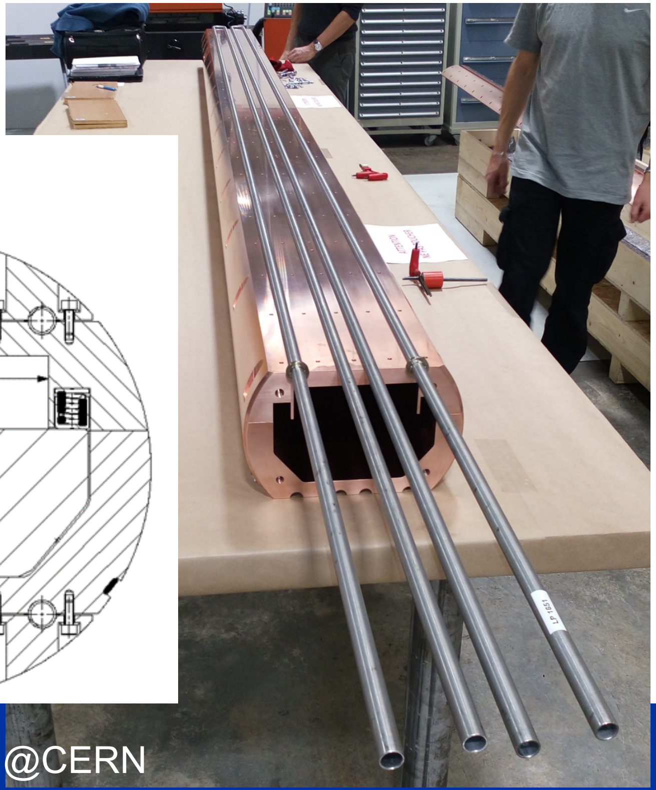


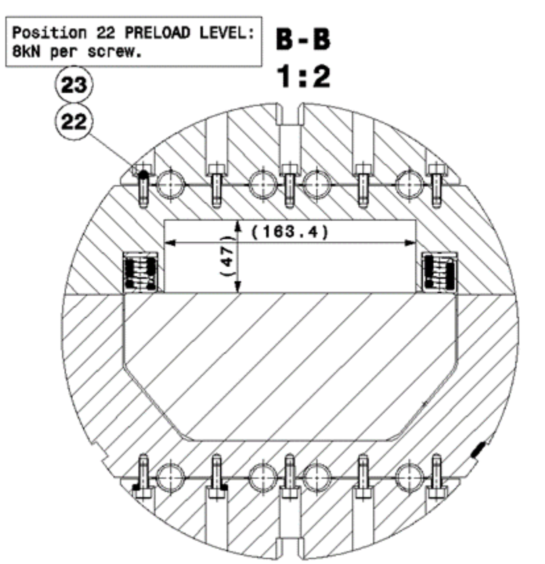
Mechanical clamping

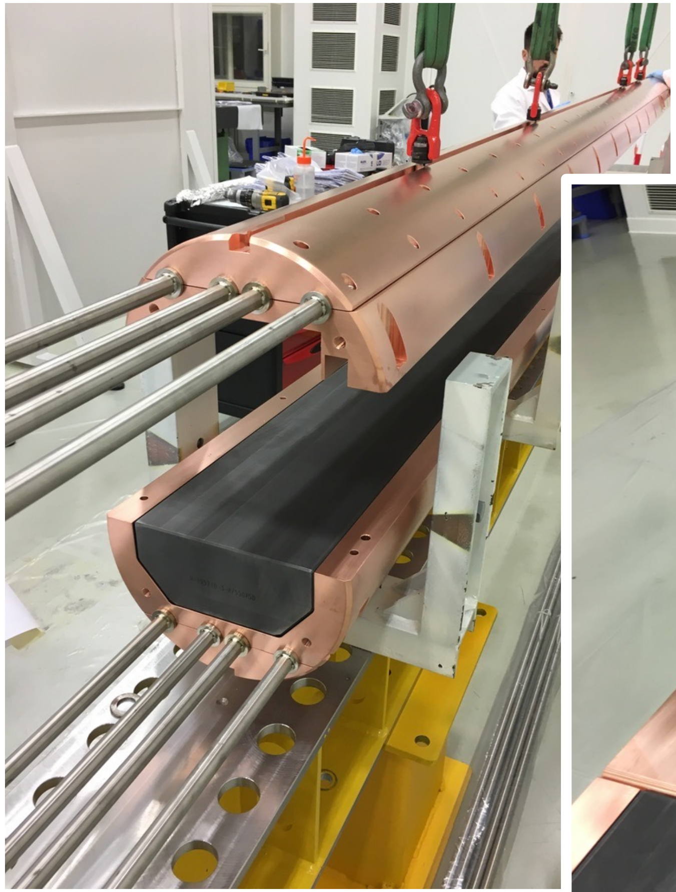
- Due to the short time available for design and construction, mechanical clamping was chosen to dissipate heat from CuCrZr to stainless steel tubes

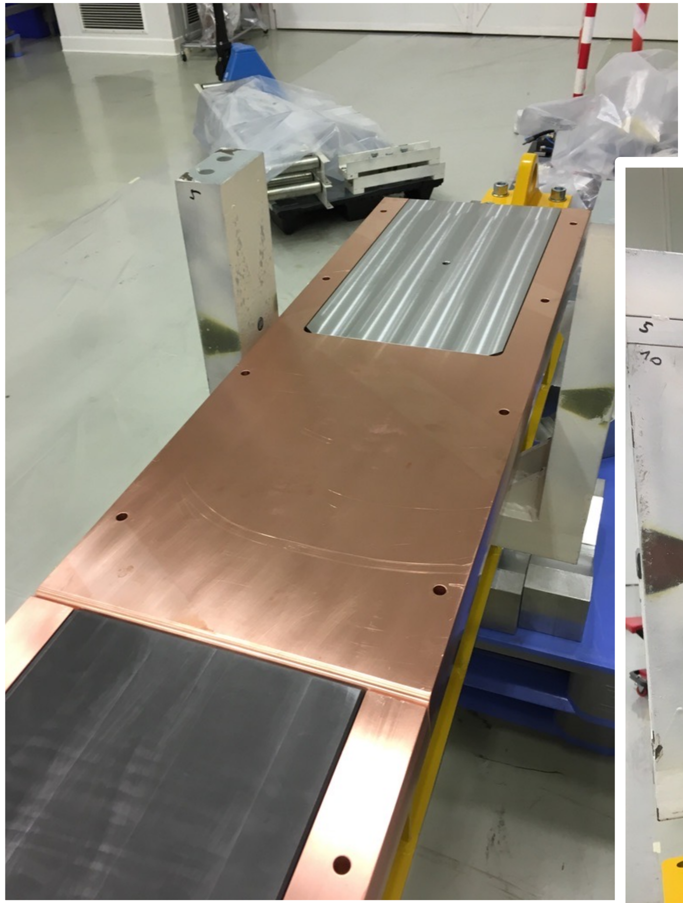
- UHV compatible, high precision machining required, but thermal contact difficult to estimate

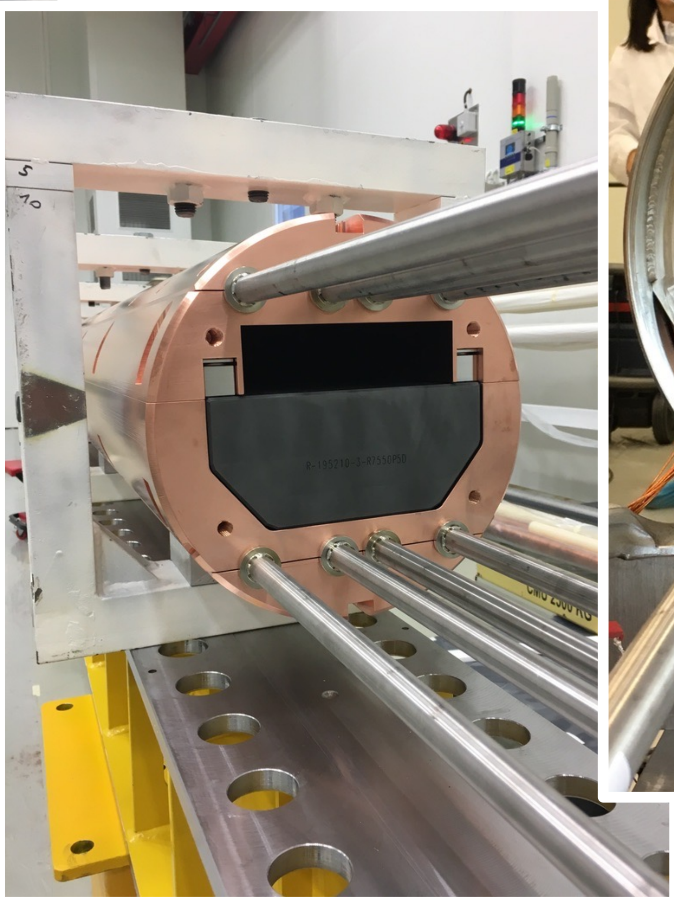


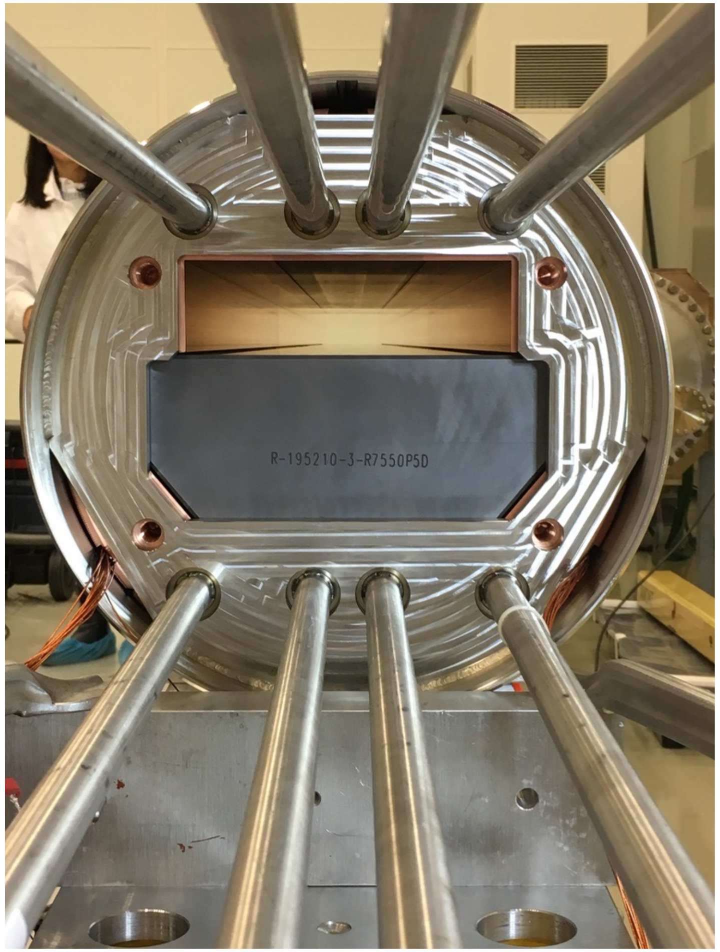











R-195210-3-R7550P5D

Fifth generation dump (→ 2021)
LHC injectors upgrade

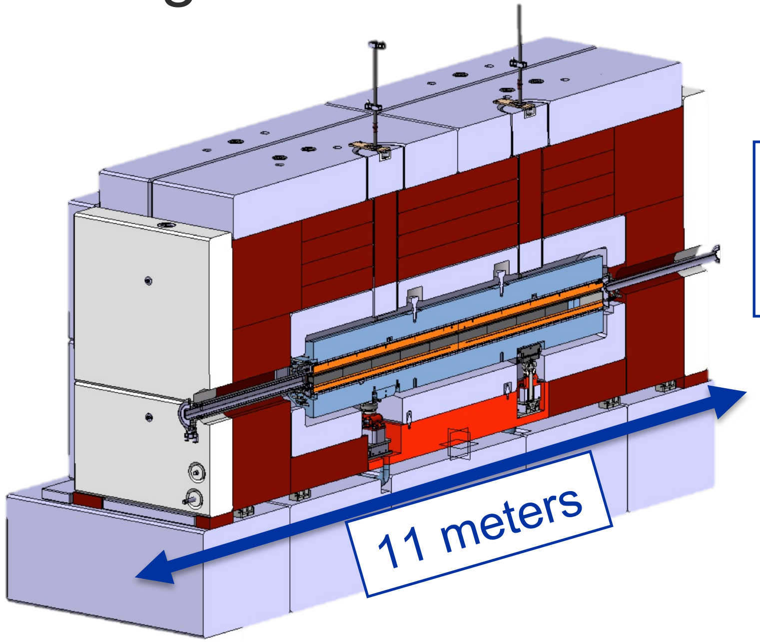
- Incremental upgrades were not possible anymore → **revolutionary design**

1. Need to cope with higher beam power (70 kW → 260 kW)

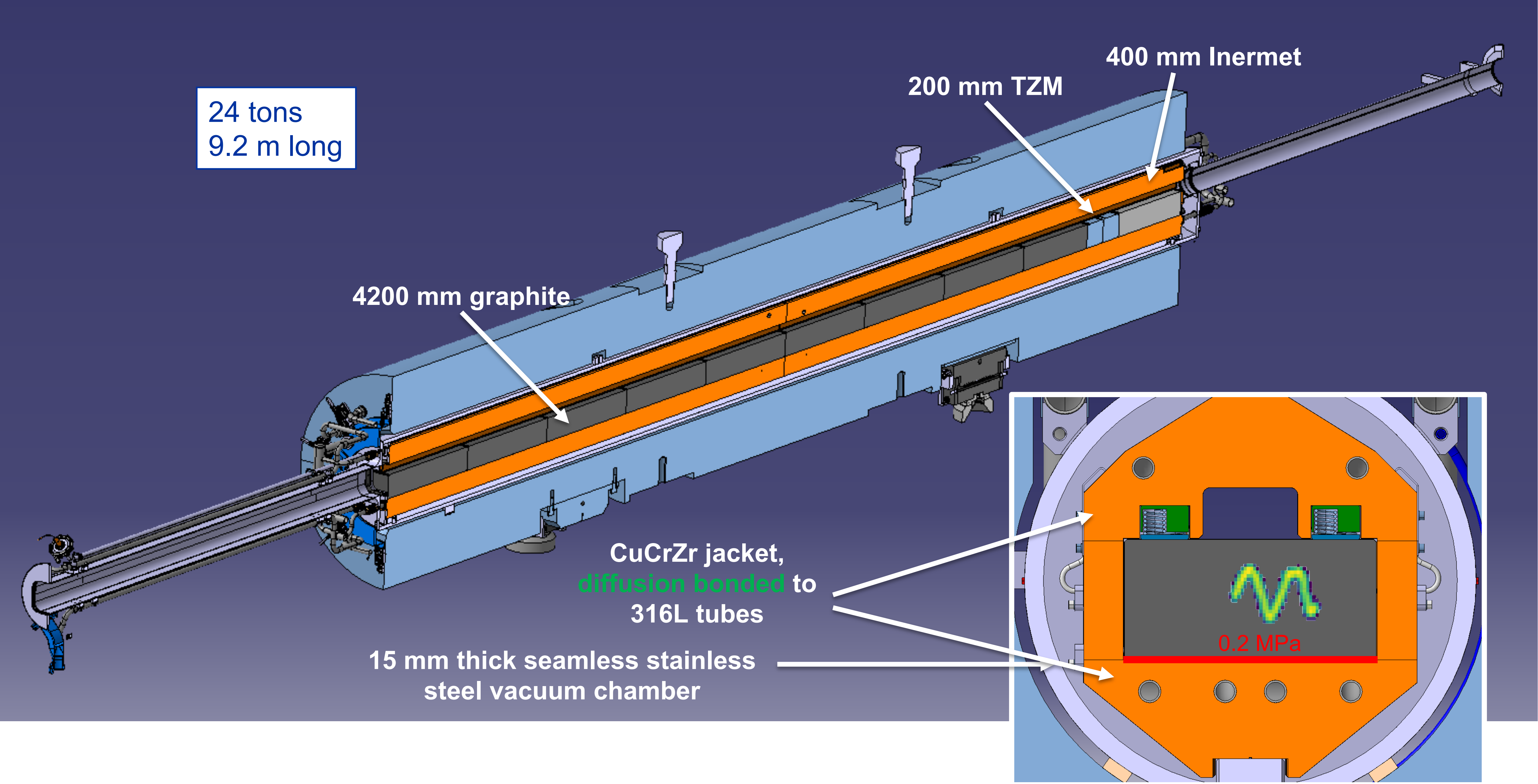
2. Need to comply with strict radiation protection regulations

Table 3: HL-LHC beam load parameters for internal dump

Parameter	Unit	HL-LHC Standard		LIU-SPS 80b		HL-LHC BCMS	
		Low Energy	High Energy	Low Energy	High Energy	Low Energy	High Energy
Energy	GeV	26	450	26	450	26	450
Brightness	e13 p+/μm	3.92	3.70	4.35	4.11	4.93	4.67
Stored energy / pulse	MJ/pulse	0.30	5.04	0.34	5.60	0.30	5.04
Pulse period	s	21.6		21.6		28.8	
Max. dumps / hour		167		167		125	
Average power	kW	14.3	233.6	15.9	259.6	10.7	175.2
Consecutive dumps		>1h(1, 2)		>1h(1, 2)		>1h(1, 2)	

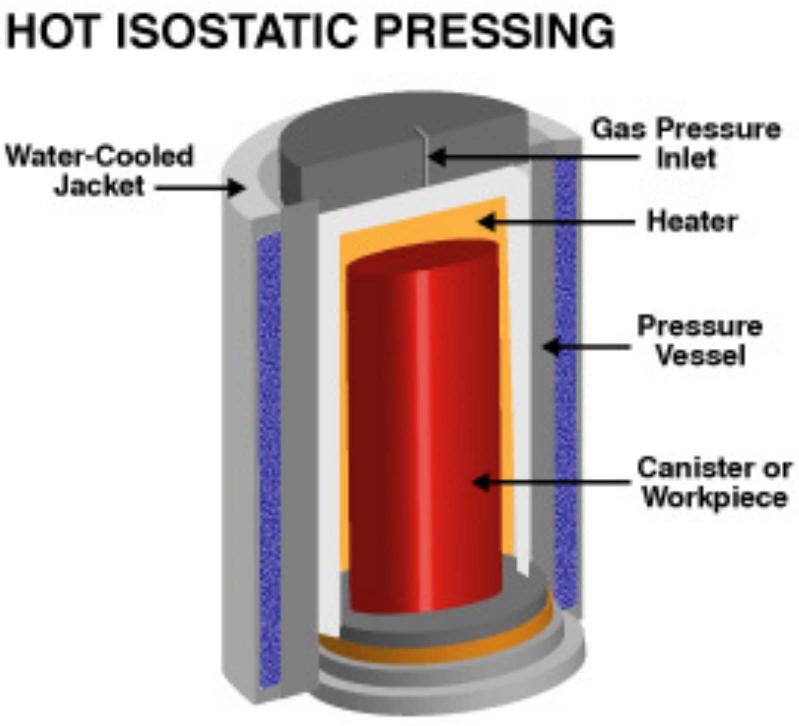


~520 t cast iron
90 t concrete
50 t marble


24 tons
9.2 m long
400 mm Inermet
200 mm TZM
4200 mm graphite
CuCrZr jacket,
diffusion bonded to
316L tubes
15 mm thick seamless stainless
steel vacuum chamber
0.2 MPa

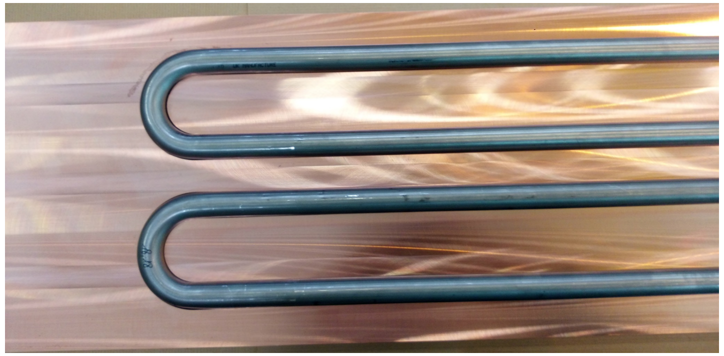
Diffusion bonding via HIP

Phys. Rev. Accel. Beams 24, 043001 (2021)



- Material densification technique
- Enclosures often of large size (operate under high pressure of inert gas and can reach high temperatures)
- Treatment of parts containing residual defects, giving them improved mechanical properties (foundry, powder metallurgy)...
- Allows to obtain a diffusion welding = perfect contact
- Compatible with UHV
- Different geometries possible
- Reproducible procedure

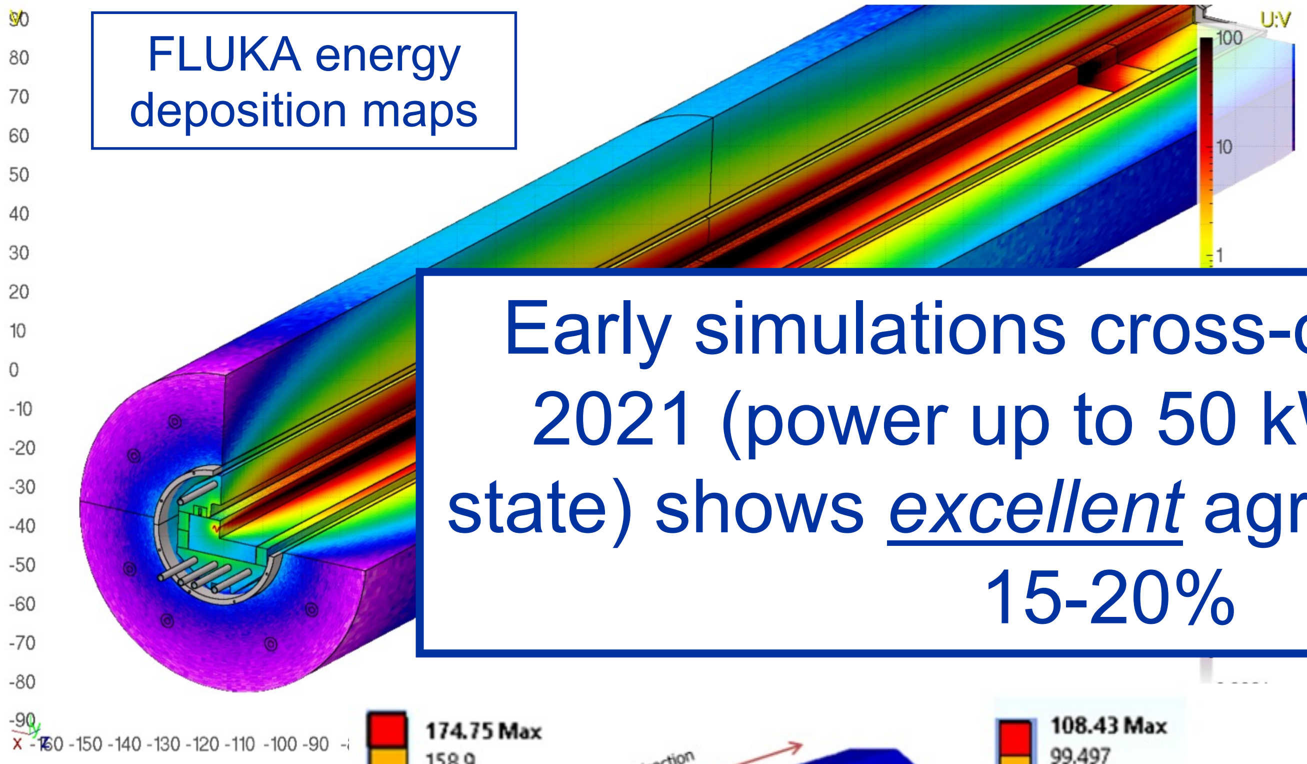
Custom development for CuCrZr diffusion to 316LN



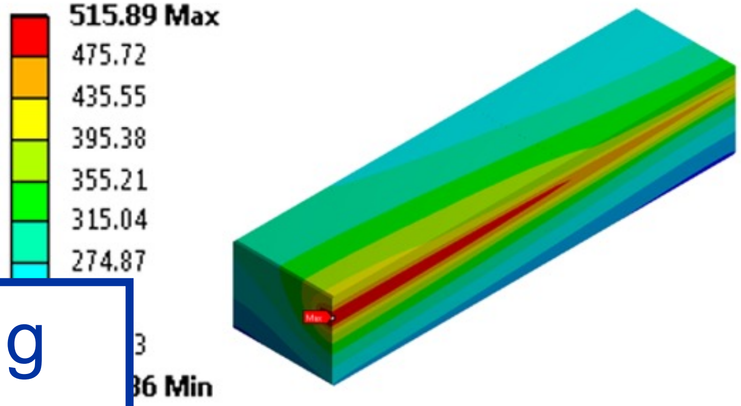
Courtesy CERN FLUKA team, D. Carbajo, A. Romero

Multiphysics simulations for the core

FLUKA energy deposition maps

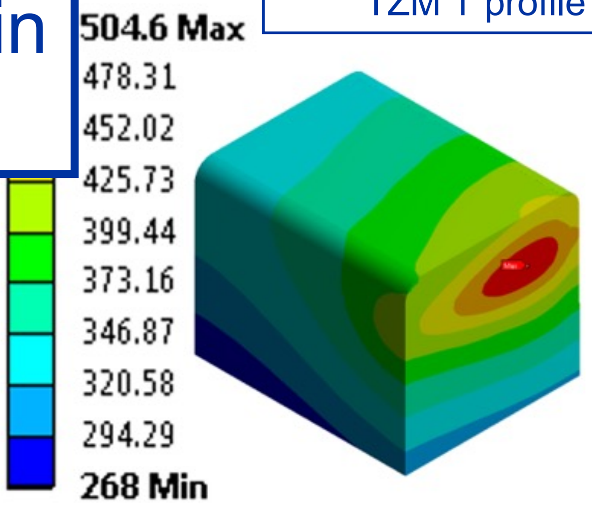


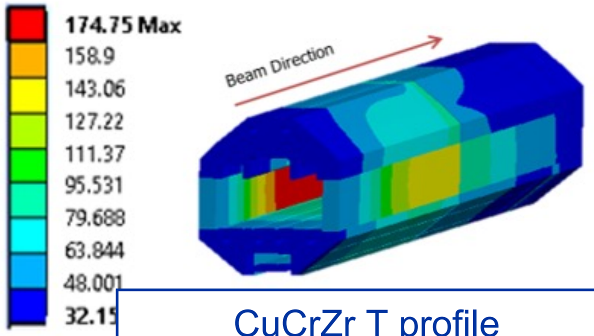
Graphite T profile



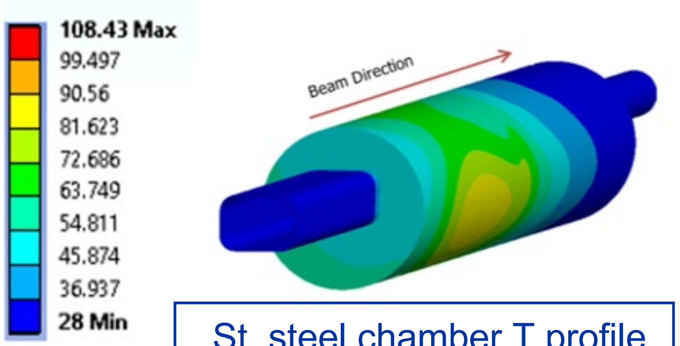
Early simulations cross-check during 2021 (power up to 50 kW in steady state) shows *excellent* agreement within 15-20%

TZM T profile



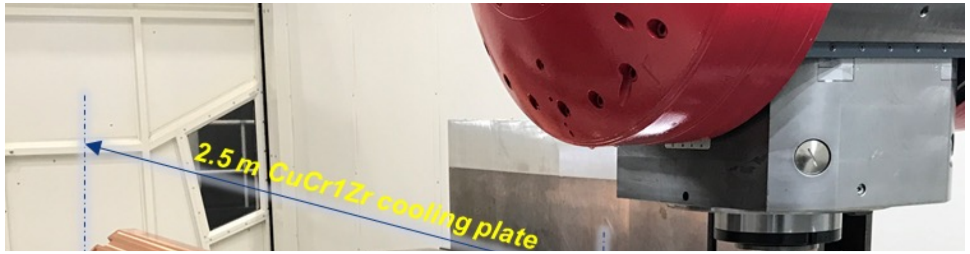


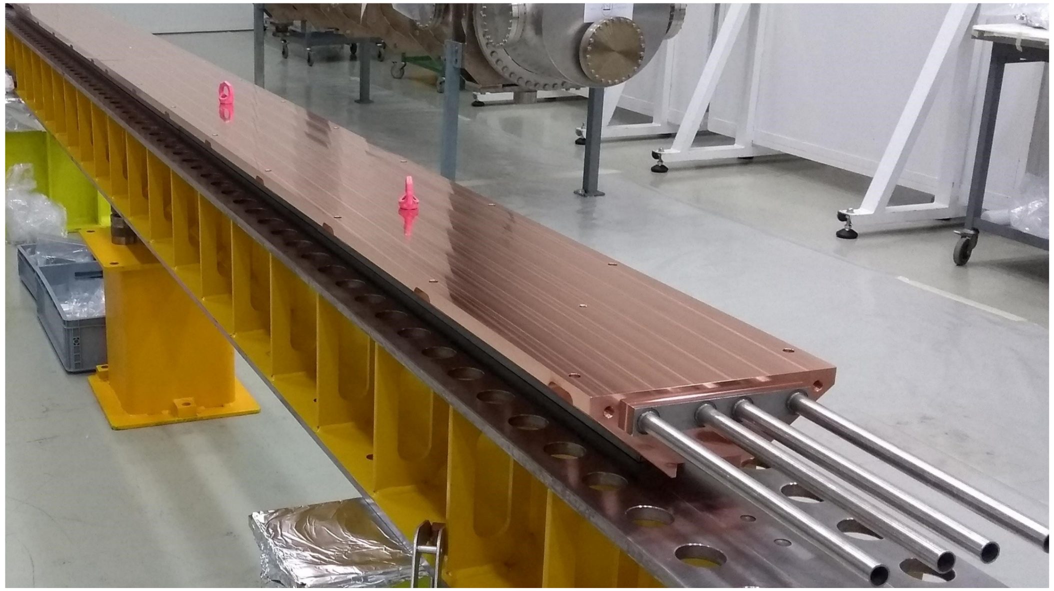
CuCrZr T profile

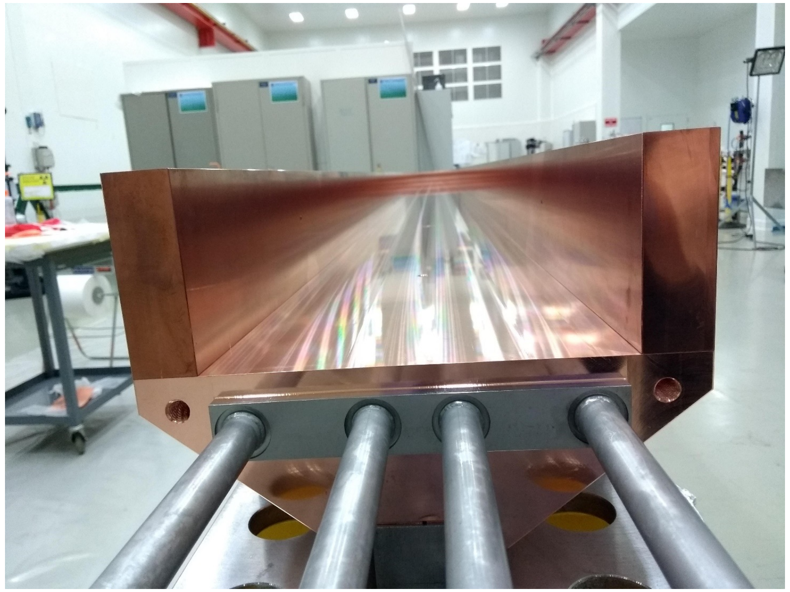


St. steel chamber T profile

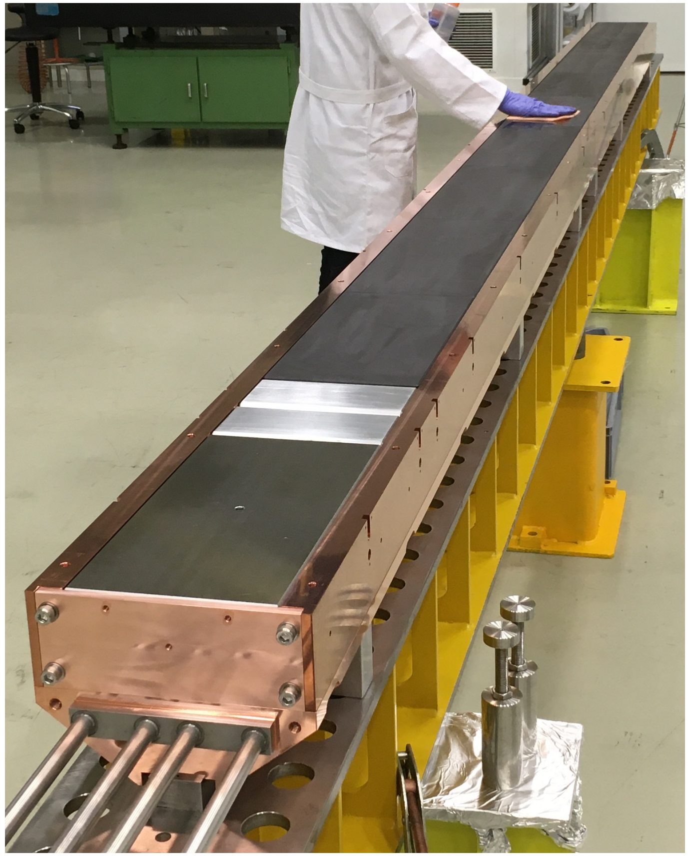
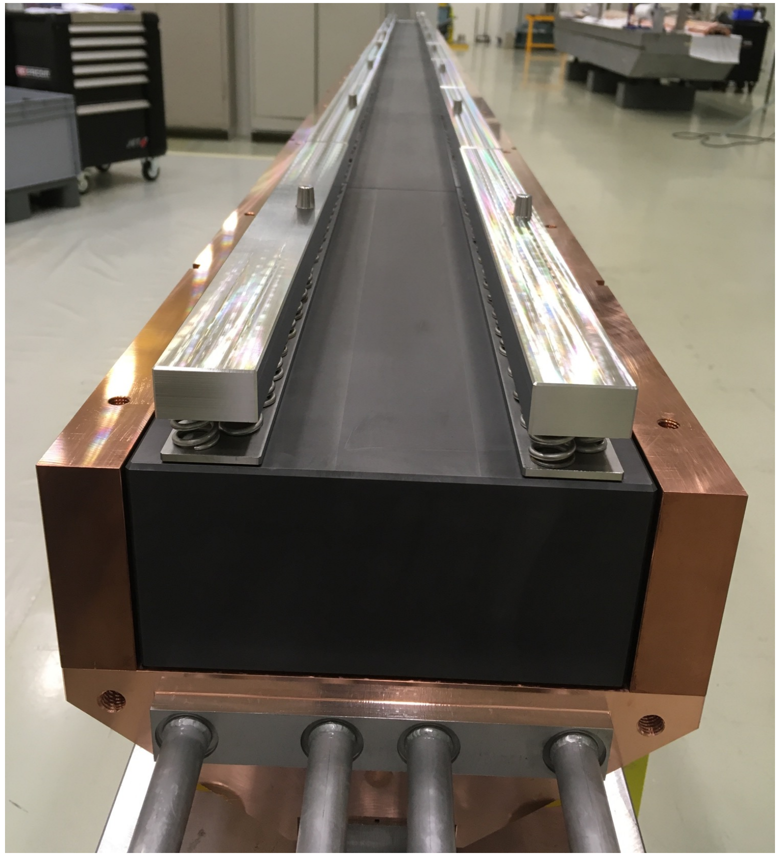
Fifth generation dump – assembly & installation



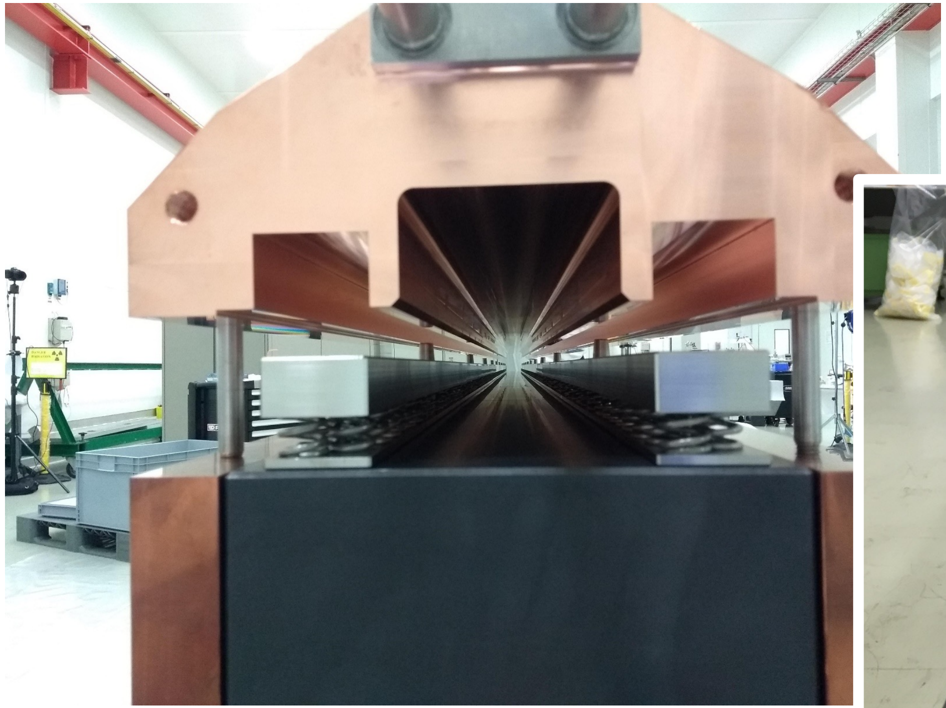


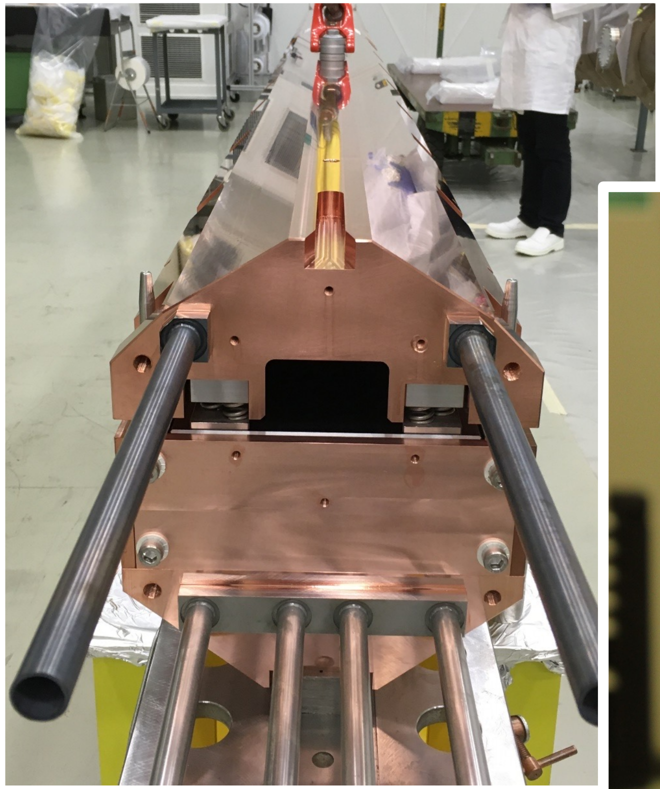


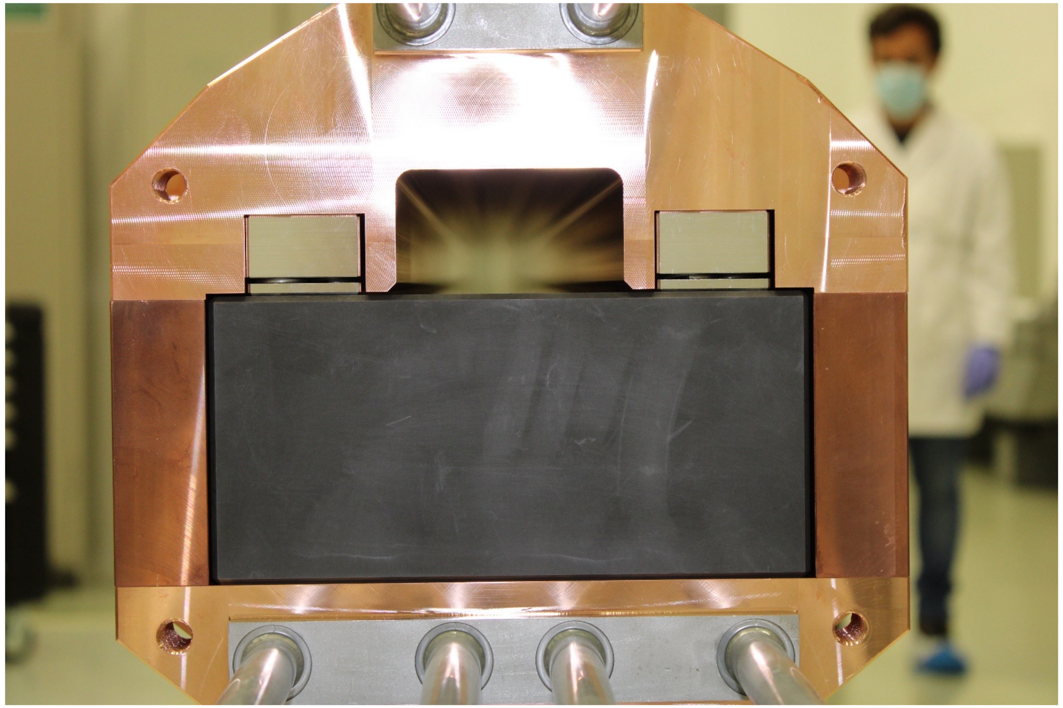
Fifth generation dump – assembly & installation

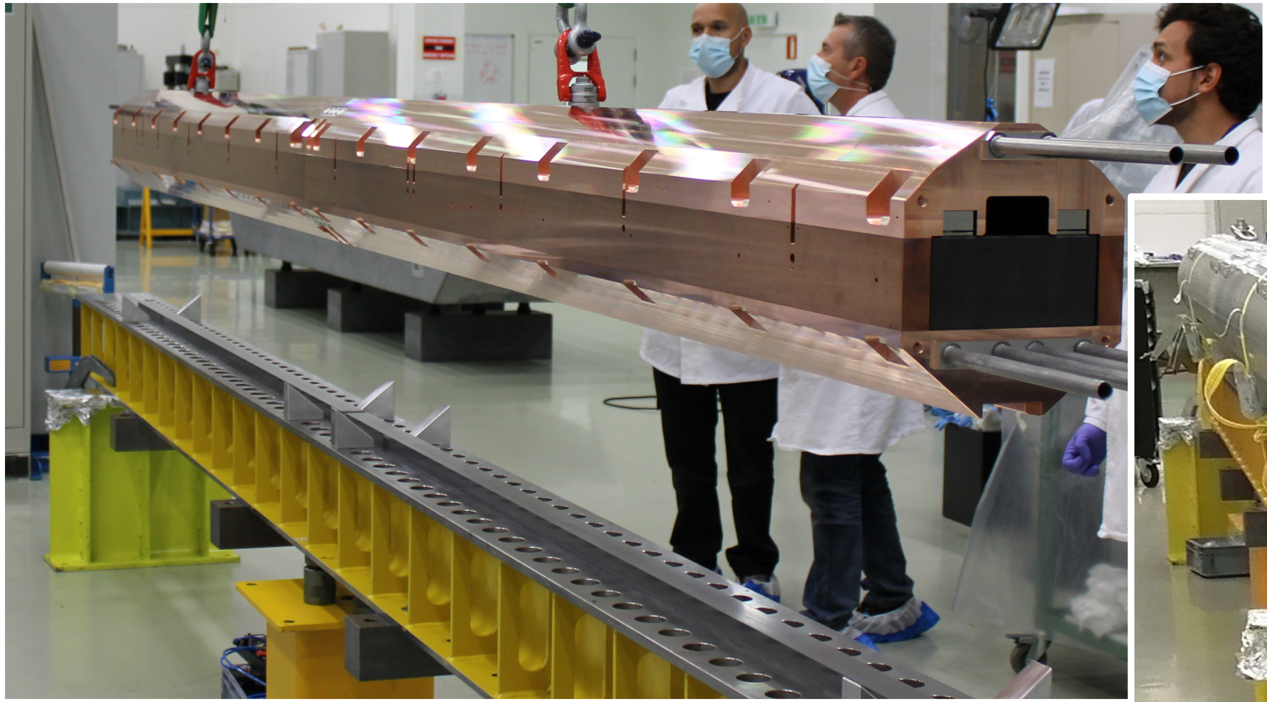

Fifth generation dump – assembly & installation

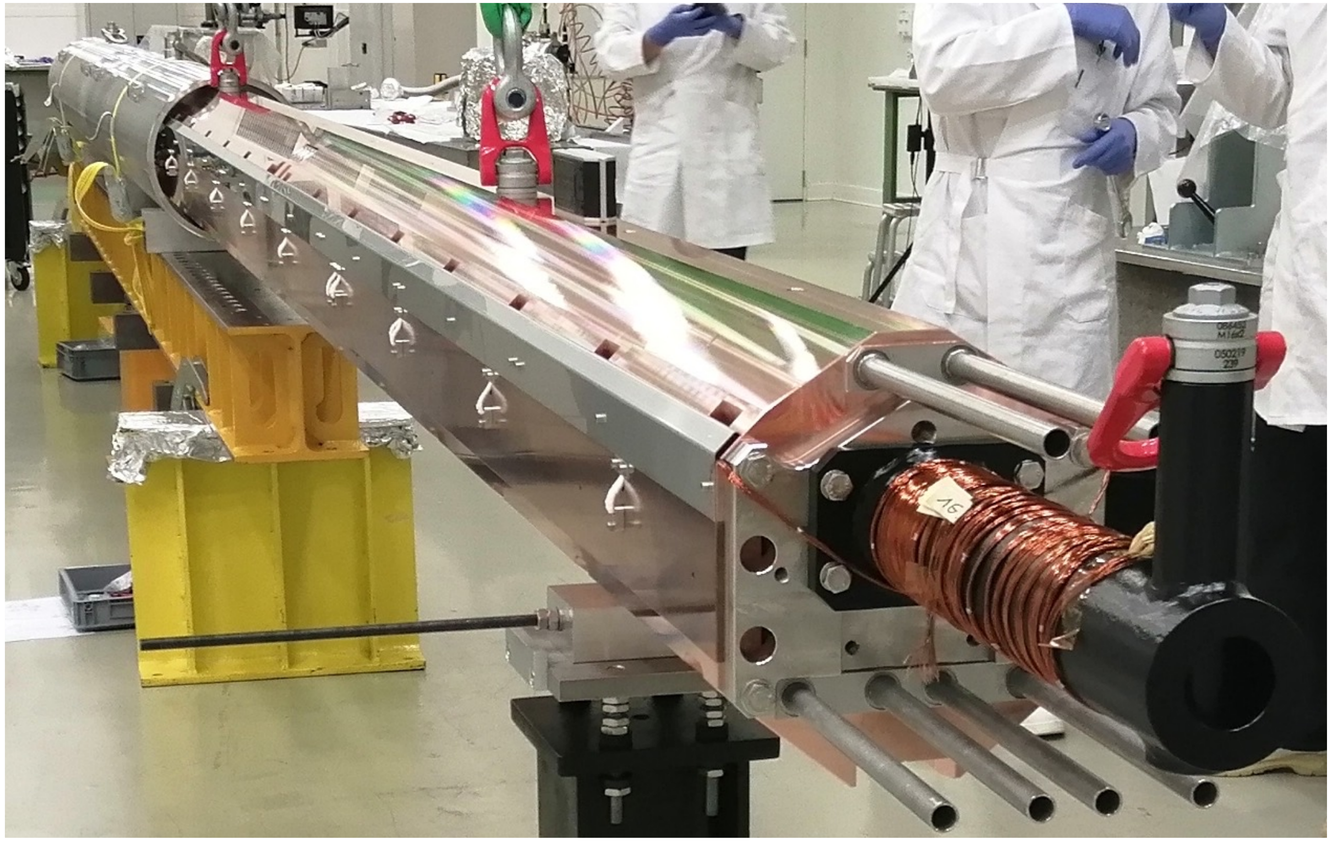






Fifth generation dump – assembly & installation

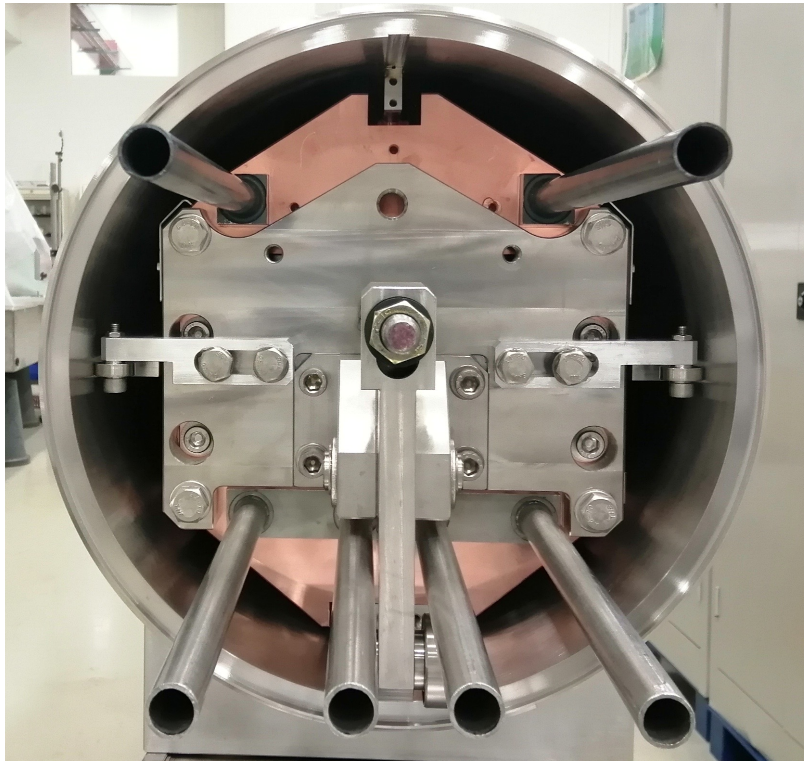


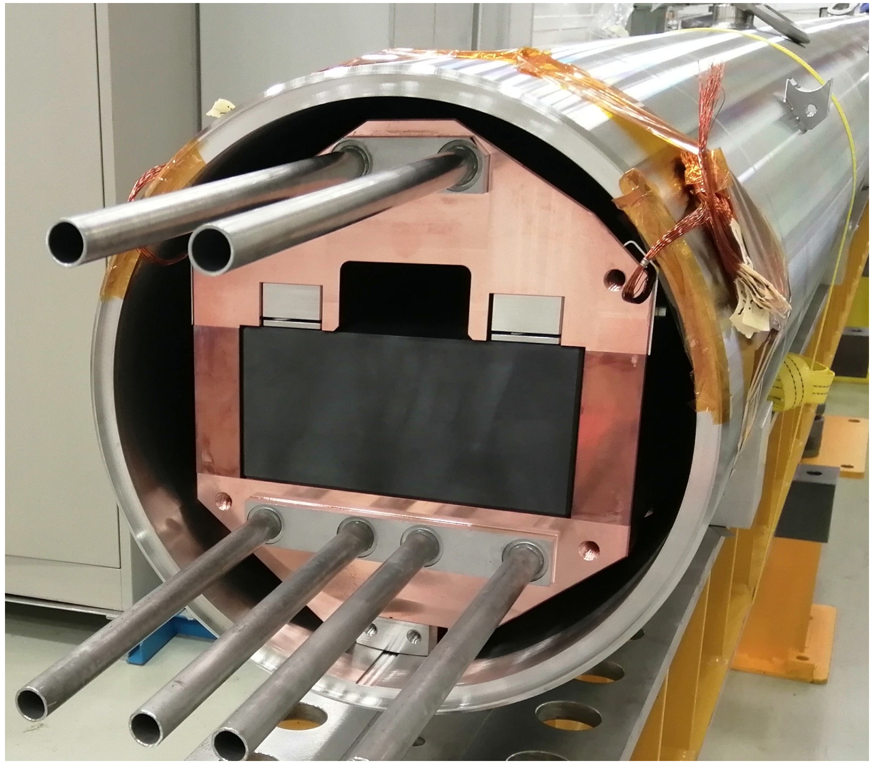


Fifth generation dump – assembly & installation

(a)

(b)



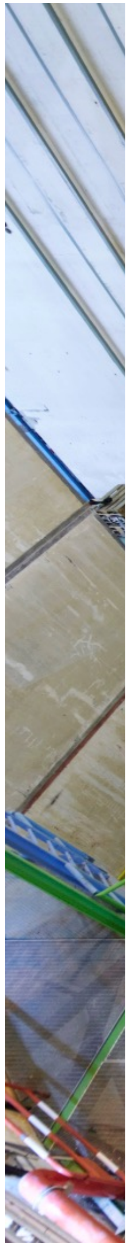


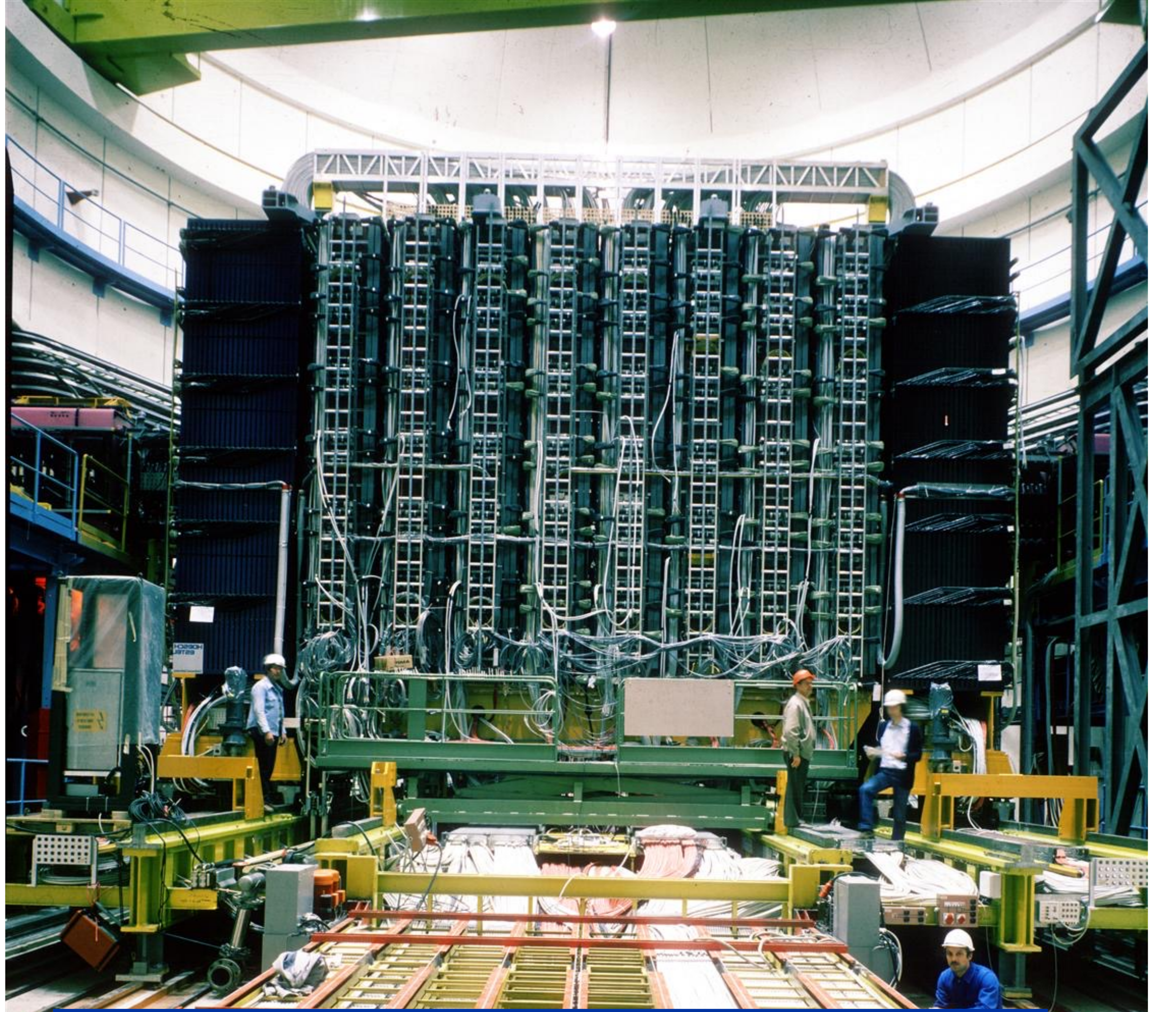
Construction of seamless vacuum chamber from forging

Fifth generation dump – assembly & installation

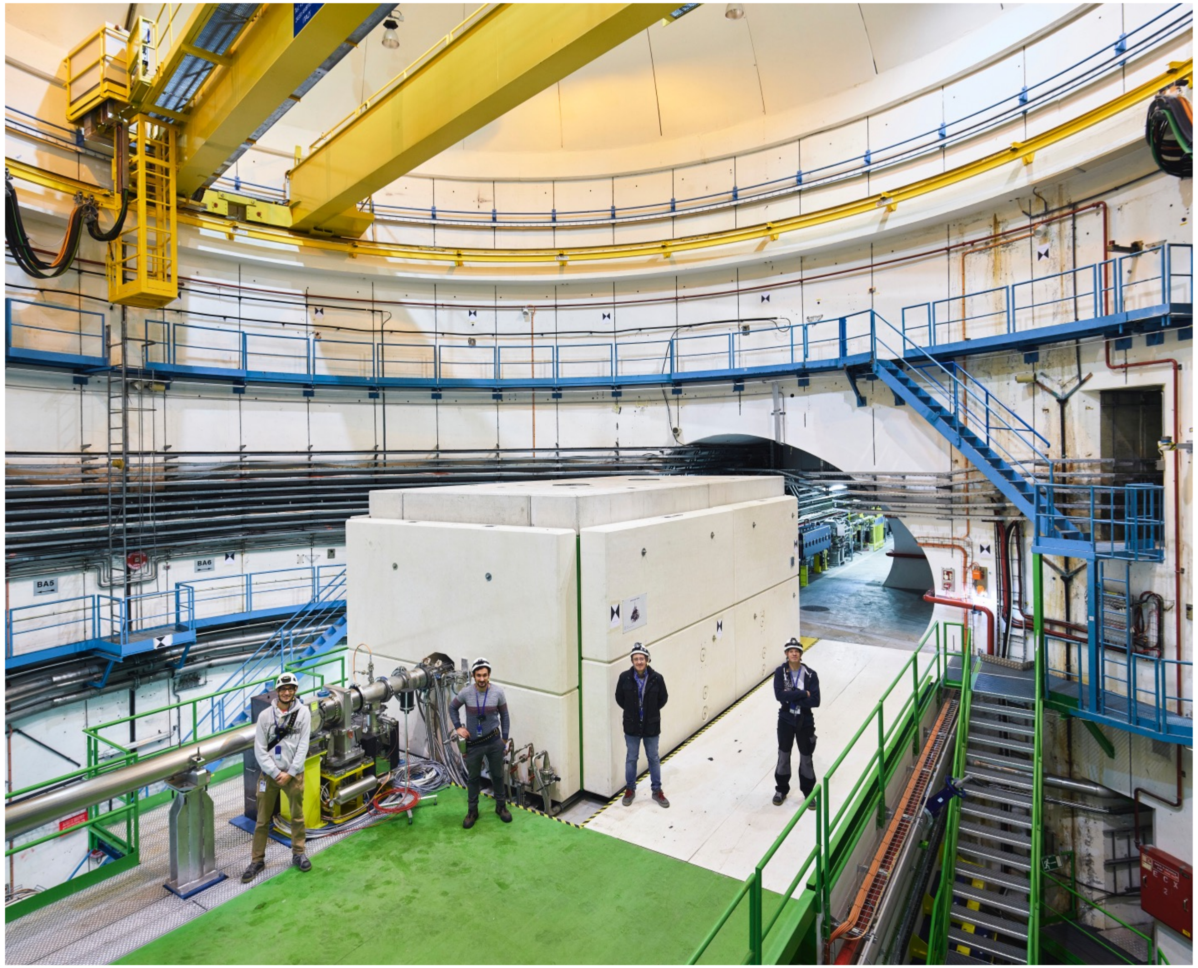
Welding of cooling channels and beam pipe

Installation of external shielding and final welding of yoke cooling





A new life for the hall that saw the UA1 experiment $Sp\bar{p}S$!
W and Z bosons discovery in 1983 & Nobel to C. Rubbia and S. var der Meer



Successful installation of dump in readapted caverns in SPS LSS5

Many topics were not mentioned/discussed…

- Targets and technologies for radioactive ion beam production (ISOLDE, MEDICIS…)
- Crystal-assisted beam manipulation
- Laser for RIBs excitation
- Operational feedbacks from antiproton production targets, etc.
- Challenges and plans for beam intercepting devices for future lepton machines (e.g. 650 kW photon dump for FCCee…)
- Targetry for Muon Collider machines (1.5 MW)

Conclusions

- Beam Intercepting Devices are a **multi-physics**, **multi-expertise** and **cross ”cultural”** systems
- Reliable construction relies on a delicate balance of different requirements and constraints
- Operational experience is a key aspect in the feedback loop

THANKS, marco.calviani@cern.ch

home.cern