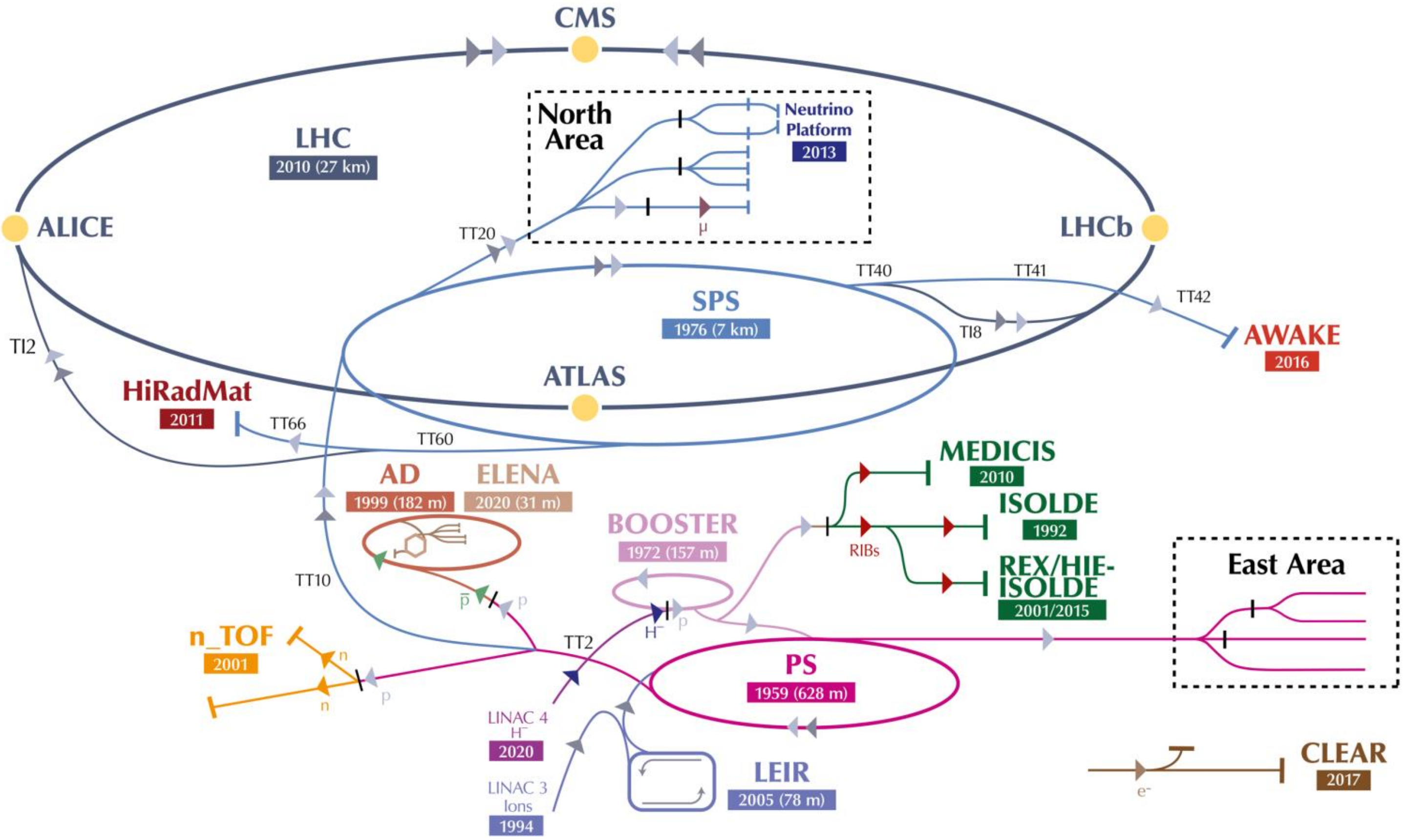
Targets Collimators Dump

Thematic Industry Day – Precision Machining

Marco Calviani, A. Perillo-Marcone (CERN)

22st November 2024

The CERN accelerator complex
Complexe des accélérateurs du CERN



H⁻ (hydrogen anions) p (protons) ions RIBs (Radioactive Ion Beams) n (neutrons) p̄ (antiprotons) e⁻ (electrons) μ (muons)

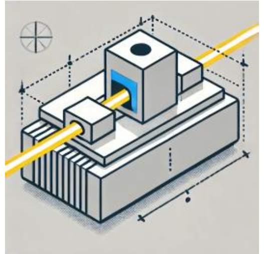
LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive EXperiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform

January 2022

Beam intercepting devices

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

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

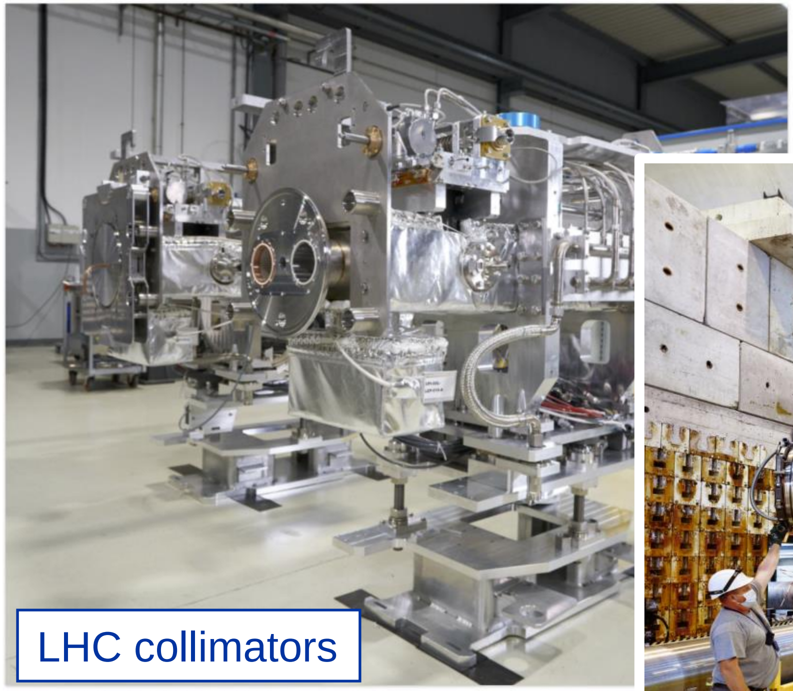


Competences & roles

HiLumi News: protecting the components of CERN's future accelerator

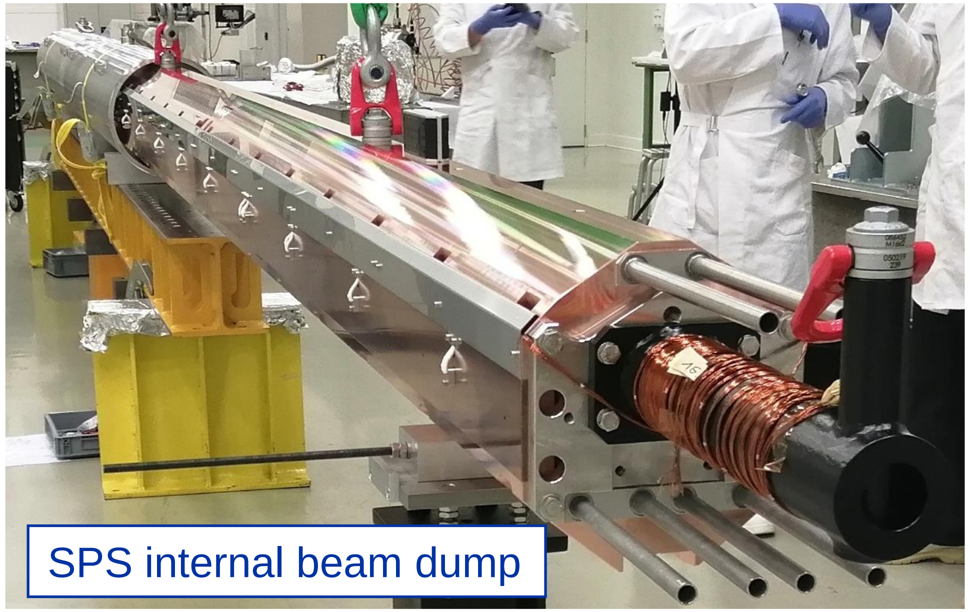
The collimation system of the Large Hadron Collider (LHC), which protects the accelerator's components, needs an upgrade to be able to handle the performance of CERN's future accelerator

31 JANUARY, 2024 | By Anaïs Schaeffer

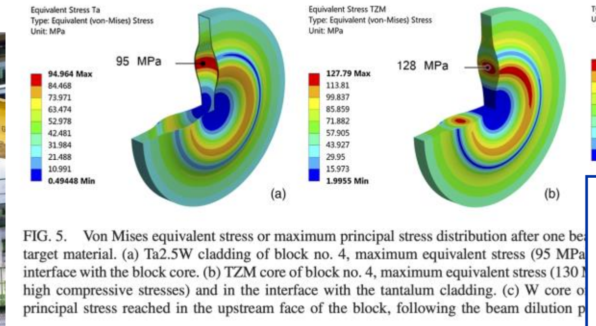


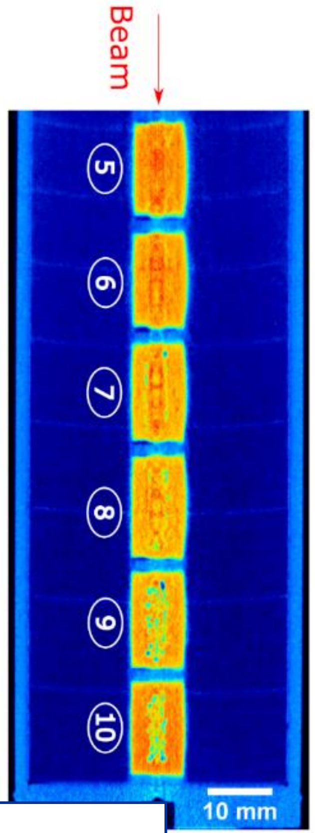
LHC collimators

These two new collimators have been developed at CERN for the future HL-LHC. These models will be installed at LHC in detector) and 5 (CMS detector) during Long Shutdown 3 (LS3). (Image: CERN)



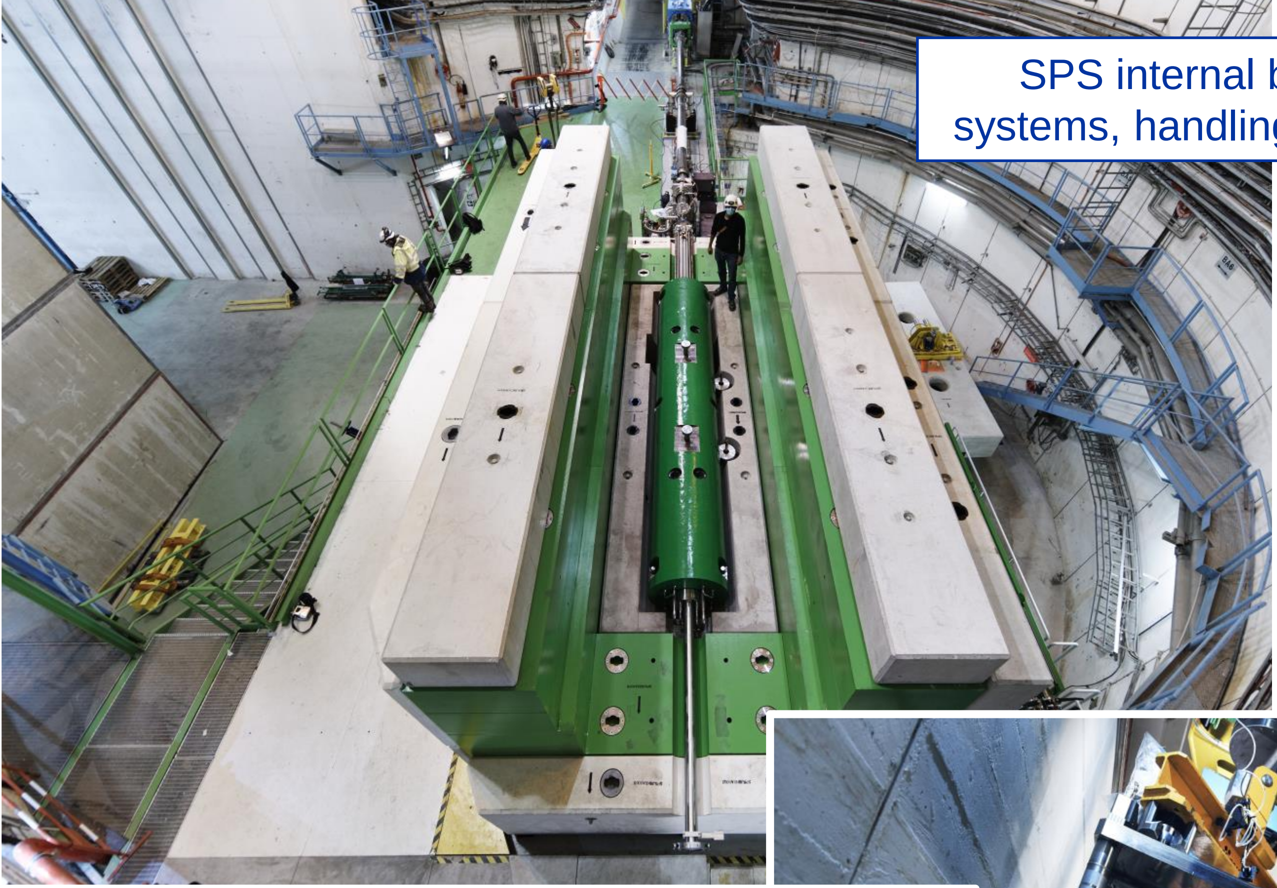
SPS internal beam dump

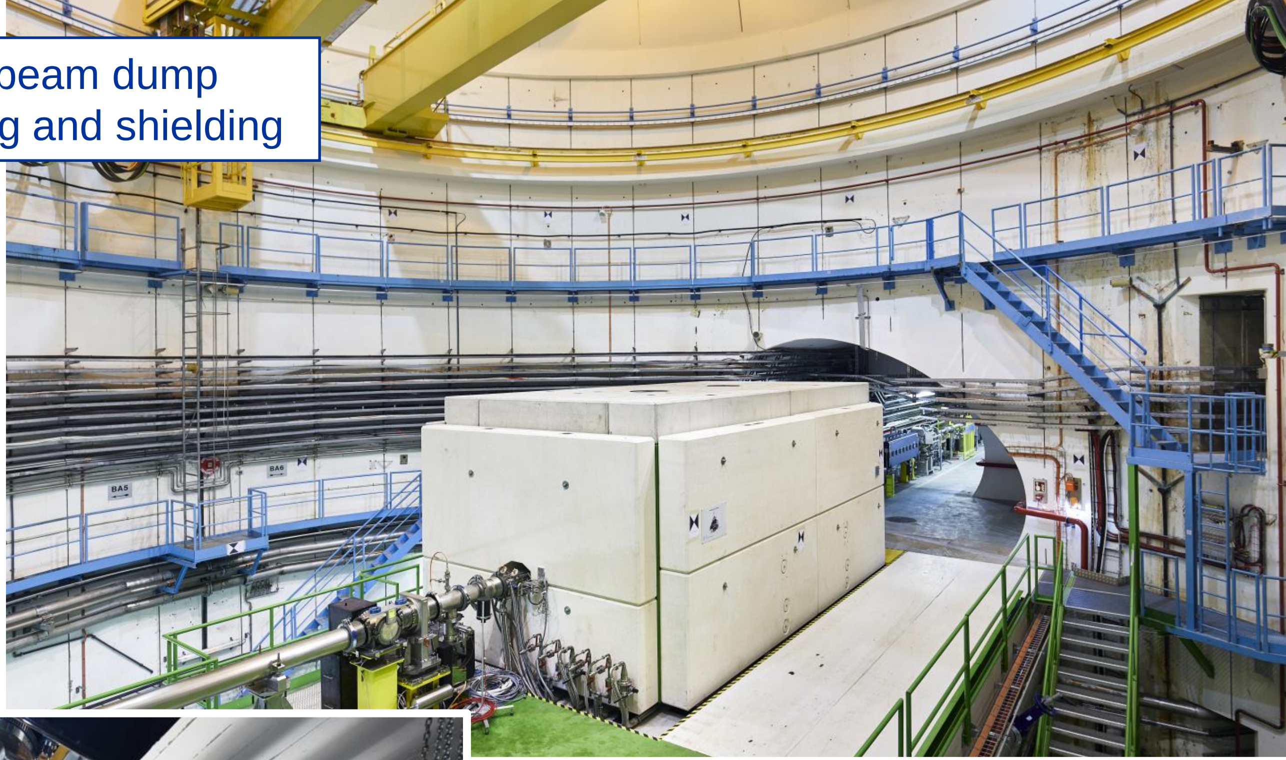




FEM, neutron imaging, cladding technologies

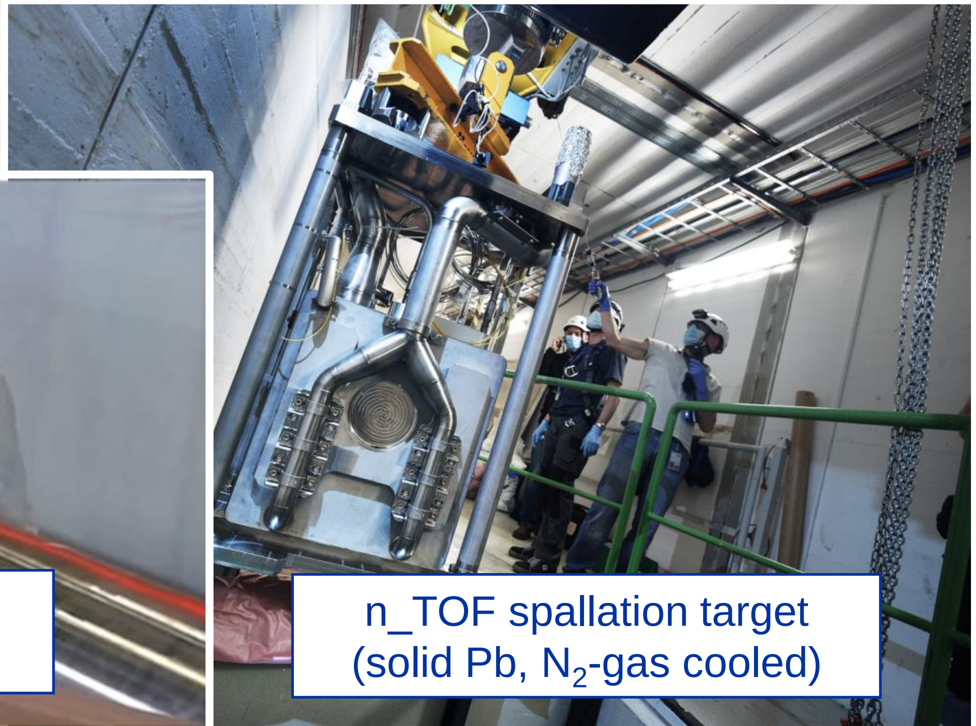
LHC external beam dump



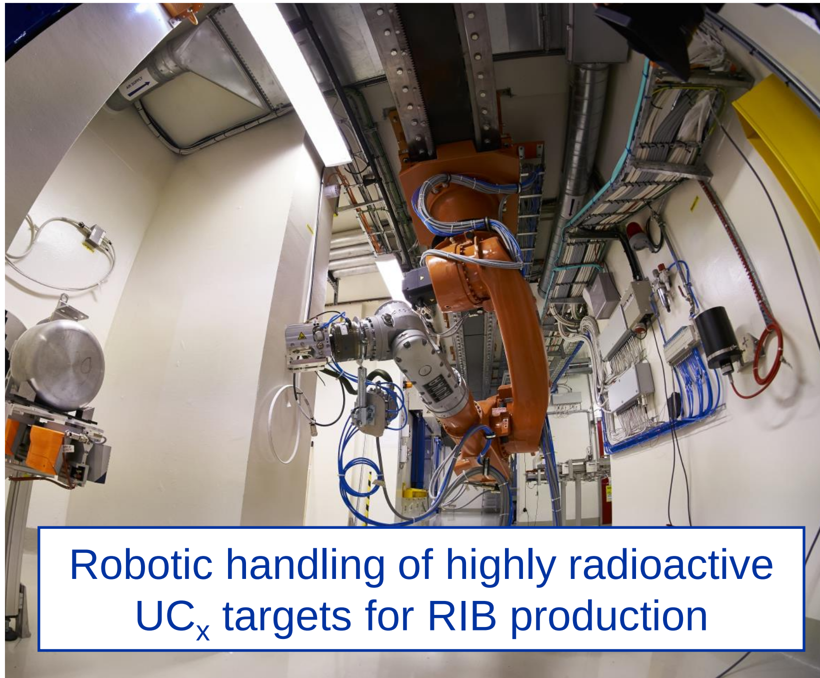


SPS internal beam dump systems, handling and shielding

Radioactive waste packaging capabilities & autopsies



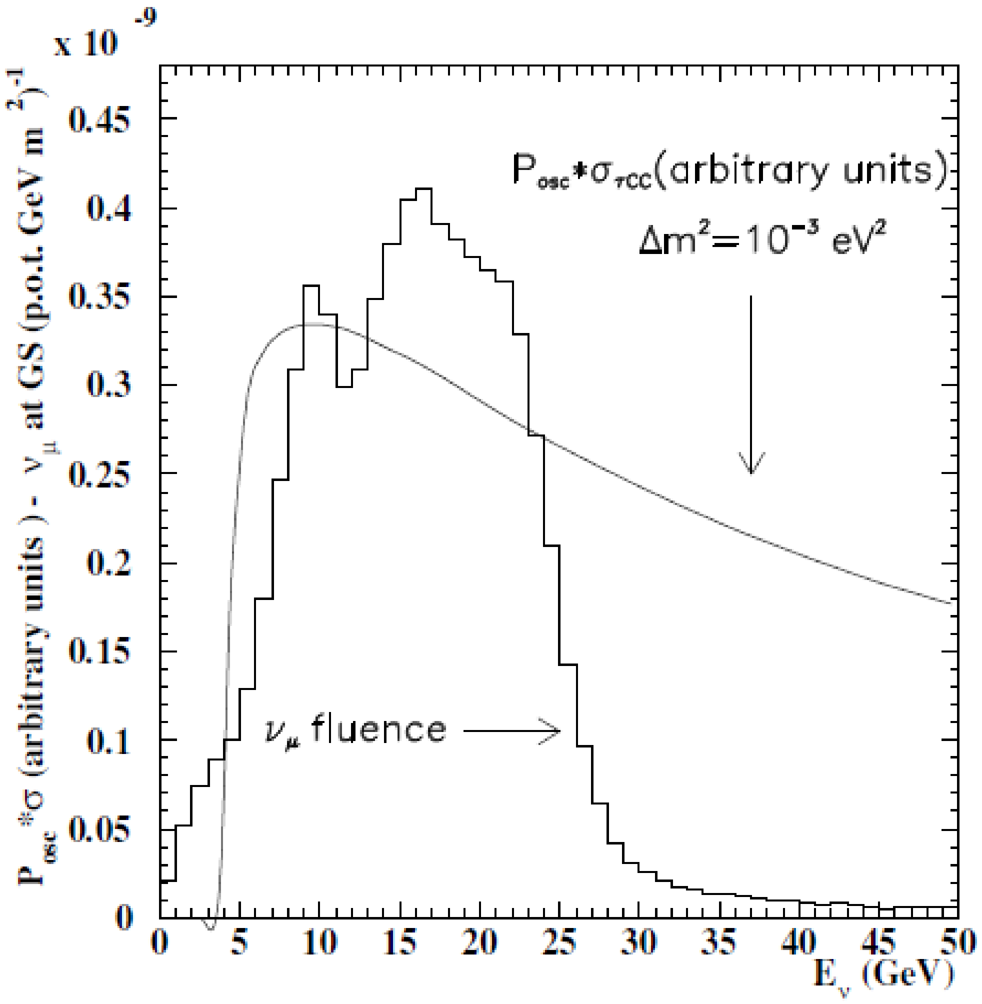
n_TOF spallation target (solid Pb, N_2-gas cooled)

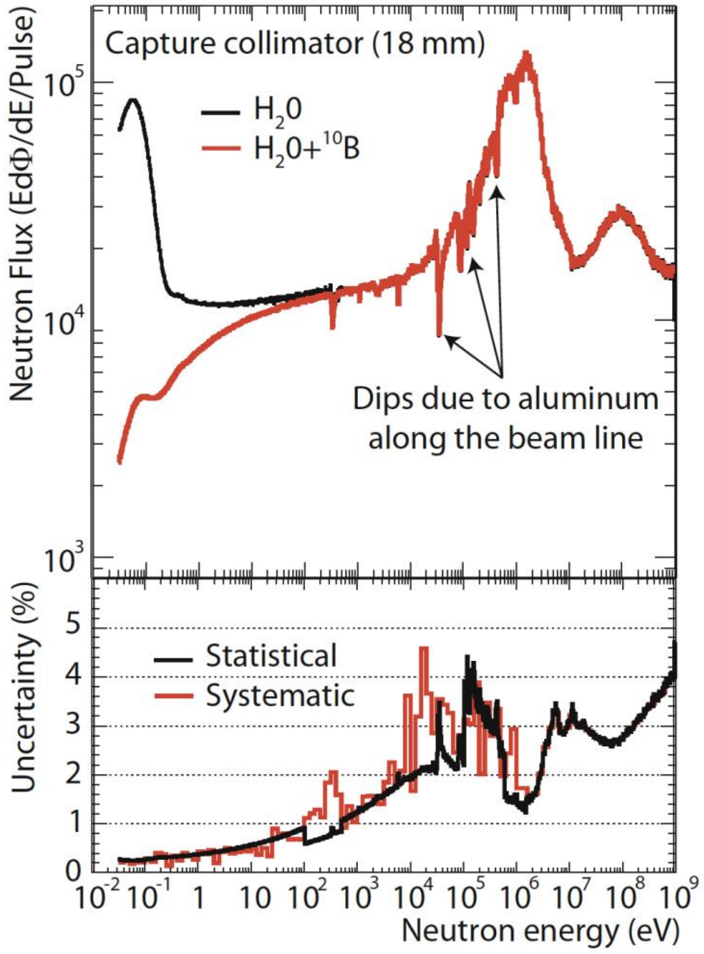


Robotic handling of highly radioactive UC_x targets for RIB production

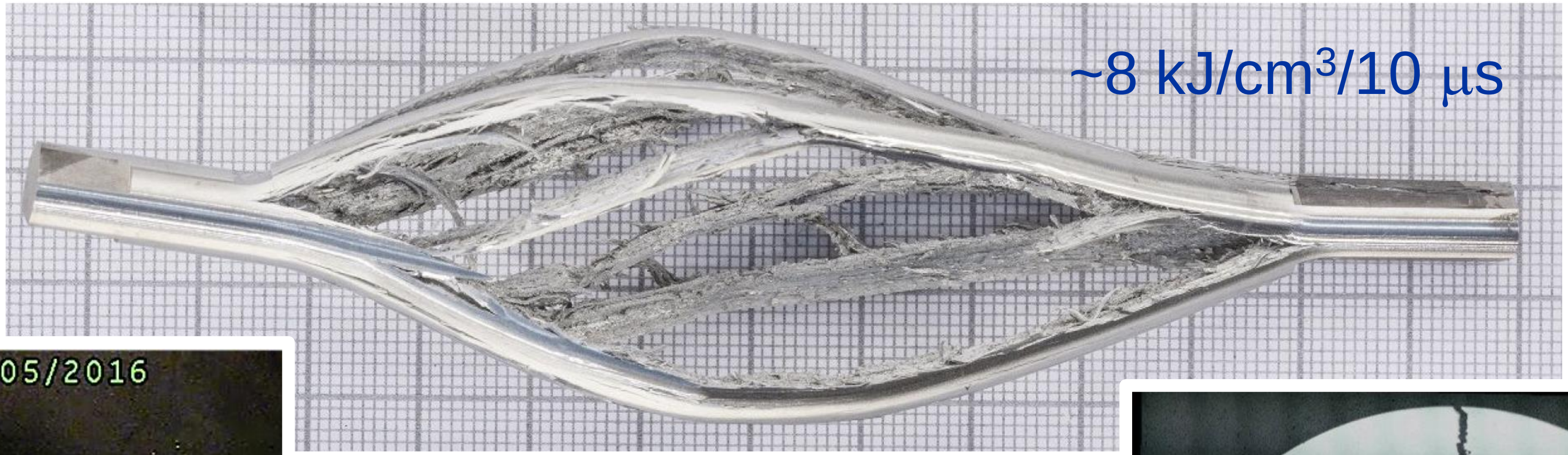
What is effect of beam impacting a BID?

Physics!

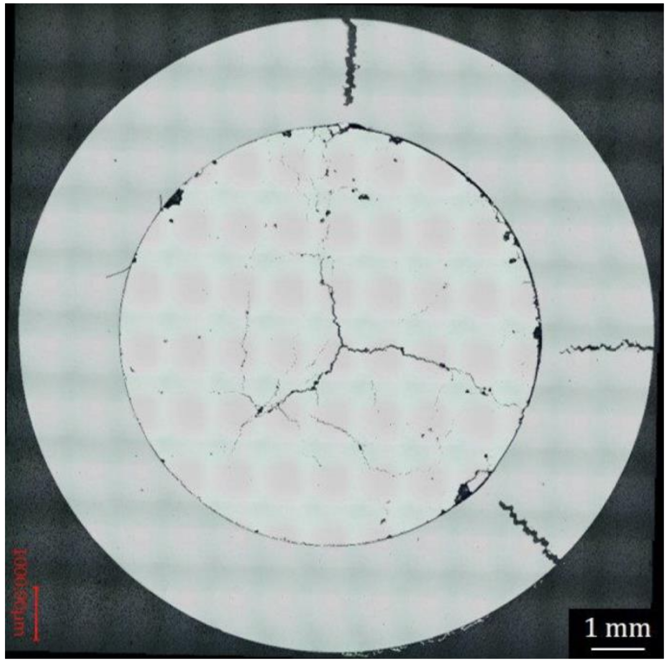




What is effect of beam impacting a BID?



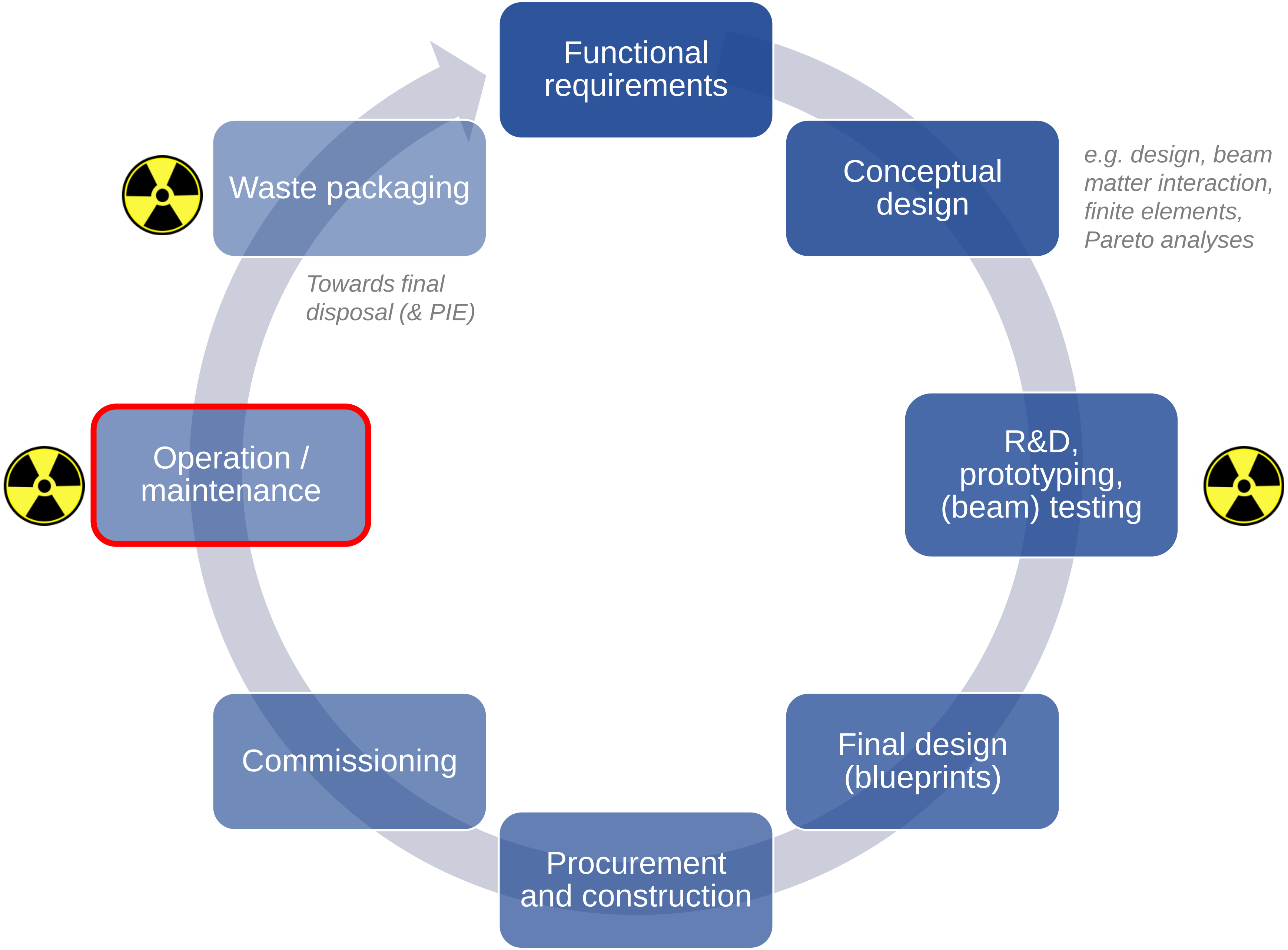
But also damage!



BIDs lifecycle

Folded with

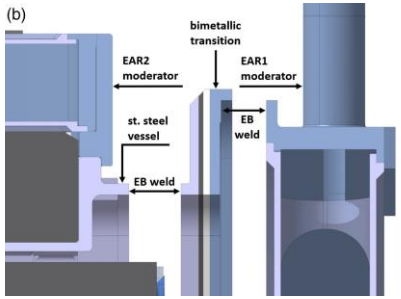
- Operational reliability
- Maintainability
- ALARA design
- QC/QA
- Continuous comparison with experimental data

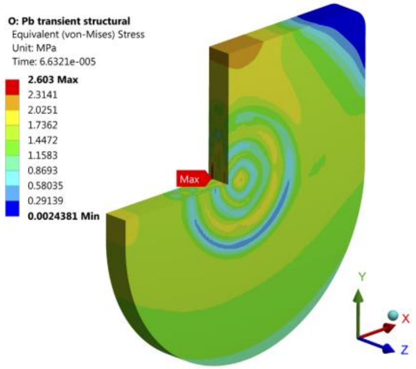


Physics & engineering design processes

Design and **integration** impacts

(e.g. CATIA)

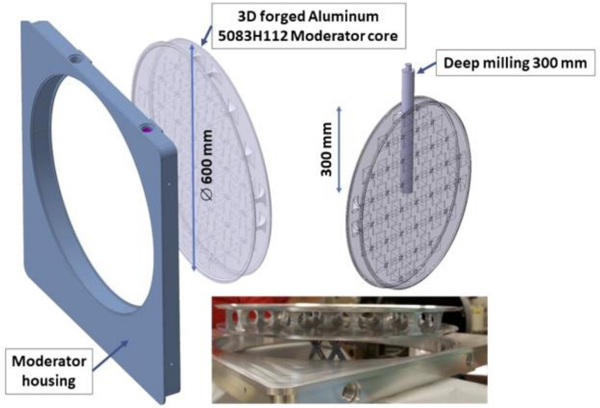




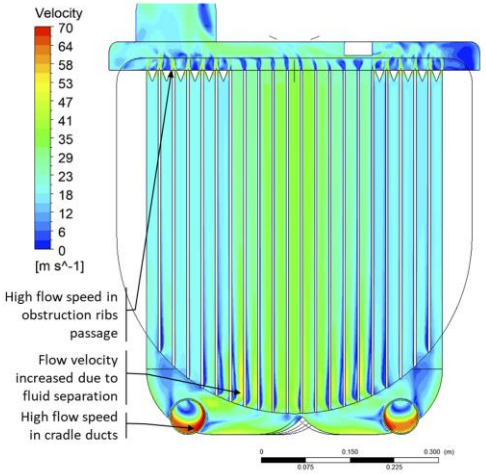
Mechanical performances

(e.g. ANSYS)

Machinability / reliability / feasibility



Target (BID) design progression

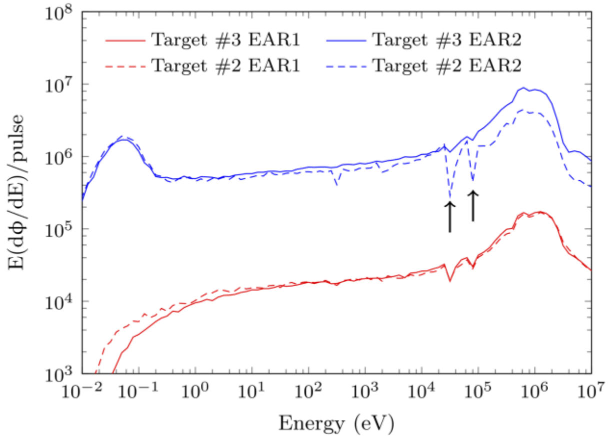


Thermal management

(e.g. ANSYS CFX/Fluent, etc.)

Physics performances

(e.g. FLUKA, PHITS, MCNP)



Heat loads

(e.g. FLUKA, PHITS, MCNP)

Palette of absorbing materials employed for BIDs

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 for BIDs

CuCrZr1 & Glidcop®
8.9 g/cm^3

Very good heat conductivity, good strength and stability at high T

Mo-alloys and TZM
10.2 g/cm^3

Reasonably low CTE, relatively good strength

Lead
11.3 g/cm^3

Target material for neutron production, very low T_m, almost negligible strength

Tantalum
16.6 g/cm^3

Refractory metal, stable high, ductile, extreme corrosion resistance

Tungsten and alloys
18-19.3 g/cm^3

High ρ and related absorption power, alloyed-W has good machinability

Iridium
22.6 g/cm^3

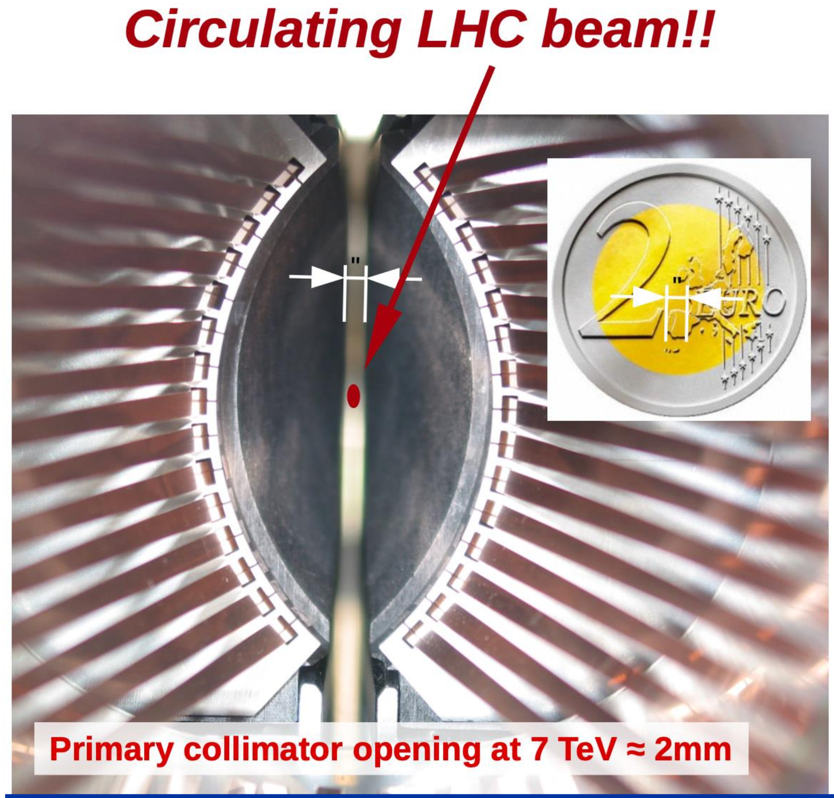
Target material for pbars, poor mech. performances, very high ρ

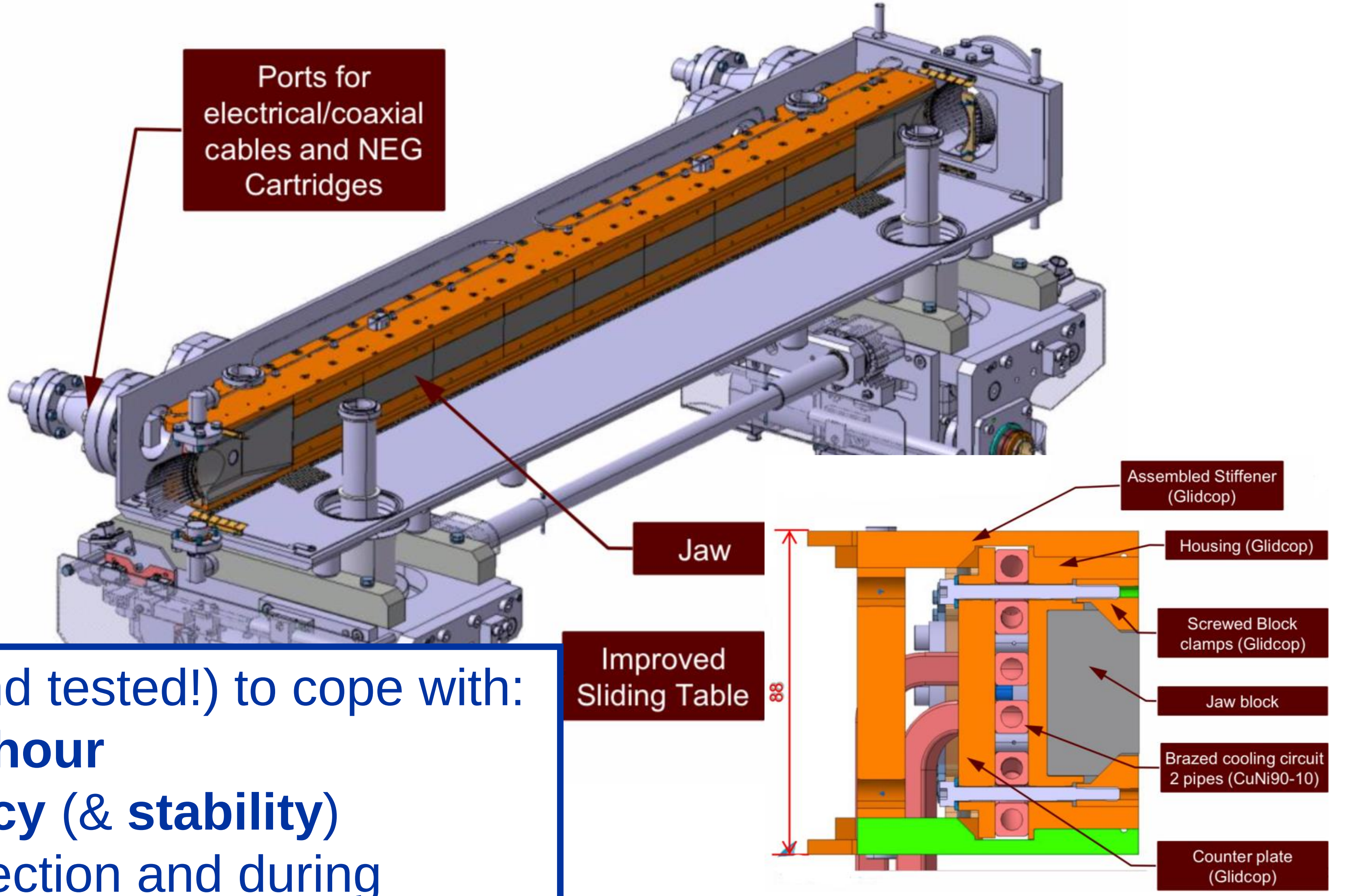
Is precision machining needed?

- **Yes, in many (not all) cases**

- Since we need to respect mechanical tolerances (i.e. planarity of a jaw), or for functional (physics) requirements
- Or also in very innovative use (e.g. crystal collimators)

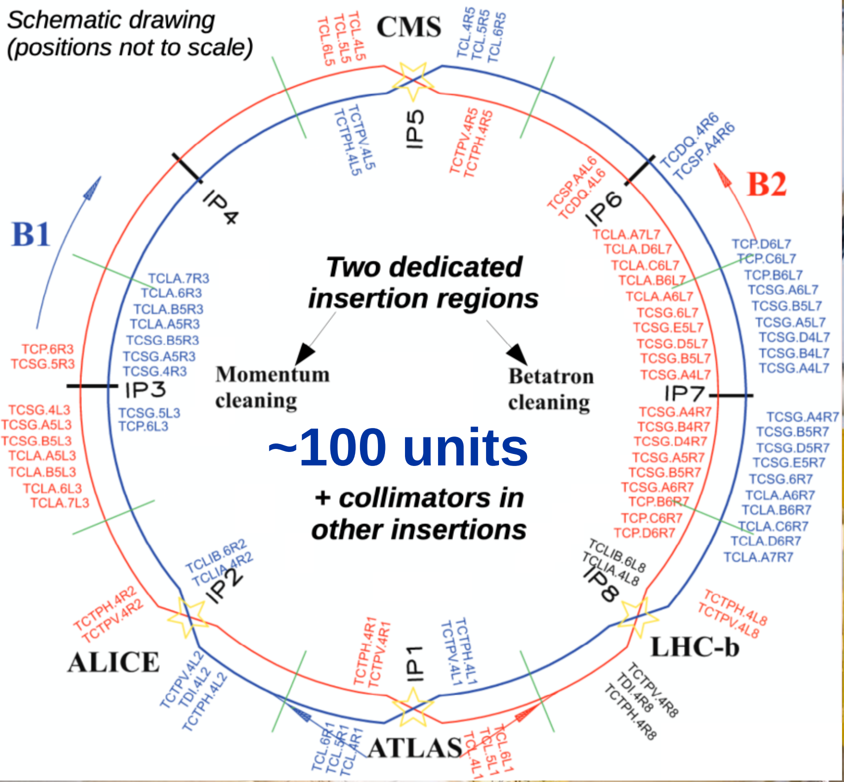
Large Hadron Colliders collimators



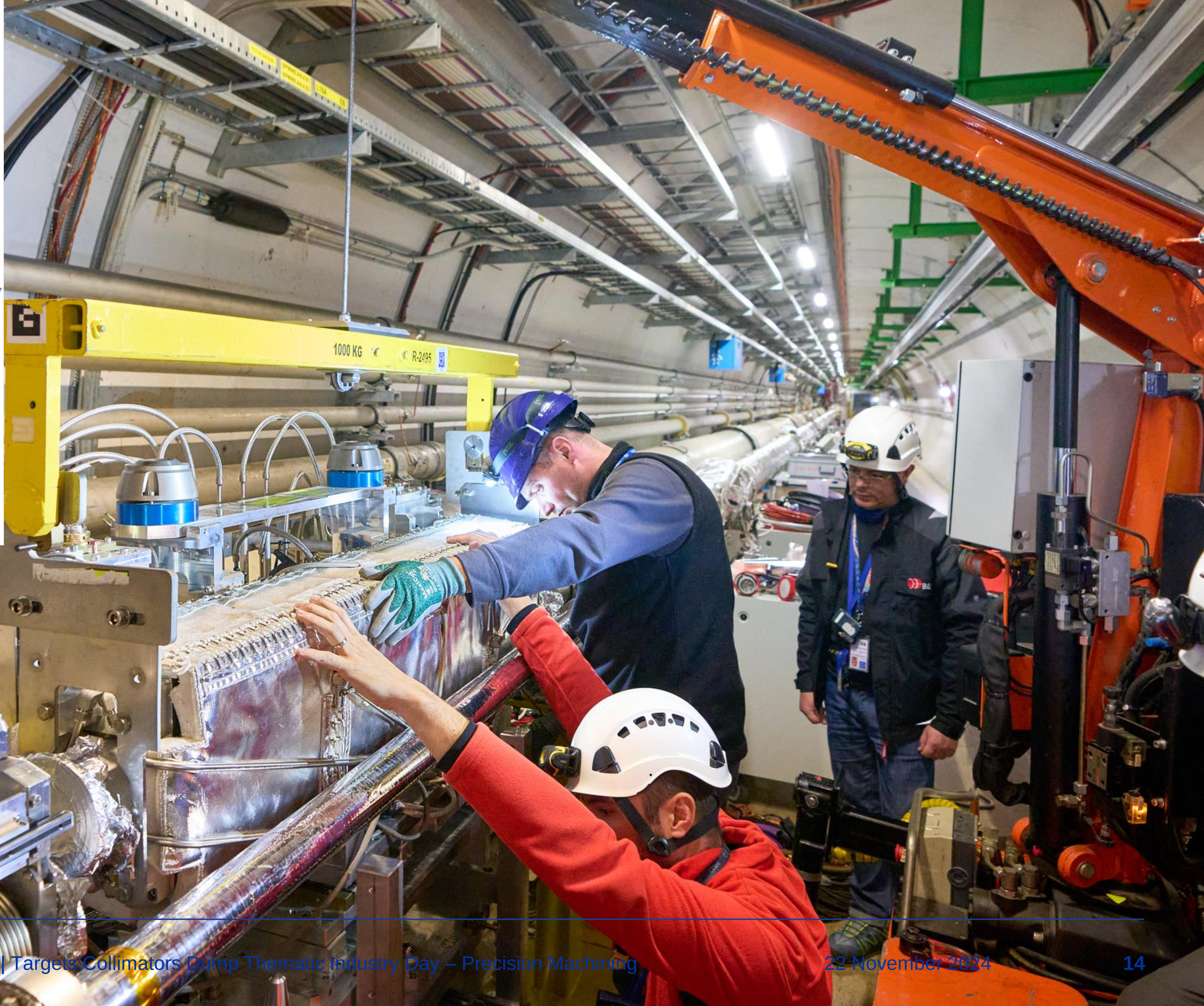


Collimator jaws designed (and tested!) to cope with:

- **10 kW** steady losses of **1 hour**
- **10 µm** positioning **accuracy** (& **stability**)
- **Direct beam** impact at injection and during asynchronous beam dumps at 6.8/7 TeV



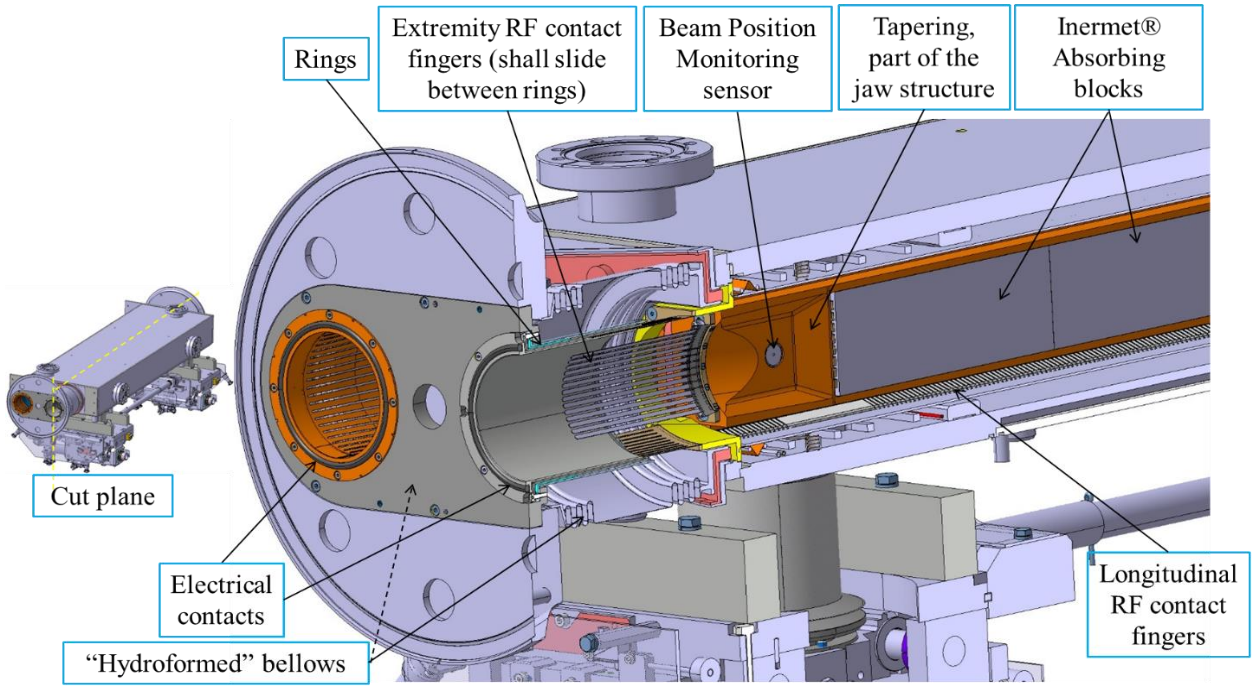
Schematic drawing
(positions not to scale)
CMS
TCL.4L5
TCL.5L5
TCL.6L5
TCL.4R5
TCL.5R5
TCL.6R5
IP5
TCTPV.4L5
TCTPH.4L5
TCTPV.4R5
TCTPH.4R5
IP4
IP6
TCDQ.4R6
TCSP.A4R6
TCSP.A4L6
TCDQ.4L6
B1
B2
Two dedicated
insertion regions
Momentum
cleaning
Betatron
cleaning
~100 units
+ collimators in
other insertions
TCLA.7R3
TCLA.6R3
TCLA.B5R3
TCLA.A5R3
TCSG.B5R3
TCSG.A5R3
TCSG.4R3
TCP.6R3
TCSG.5R3
IP3
TCSG.5L3
TCP.6L3
TCSG.4L3
TCSG.A5L3
TCSG.B5L3
TCLA.A5L3
TCLA.B5L3
TCLA.6L3
TCLA.7L3
TCLA.A7L7
TCLA.D6L7
TCLA.C6L7
TCLA.B6L7
TCLA.A6L7
TCSG.6L7
TCSG.E5L7
TCSG.D5L7
TCSG.B5L7
TCSG.A4L7
TCP.D6L7
TCP.C6L7
TCP.B6L7
TCSG.A6L7
TCSG.B5L7
TCSG.A5L7
TCSG.D4L7
TCSG.B4L7
TCSG.A4L7
IP7
TCSG.A4R7
TCSG.B4R7
TCSG.D4R7
TCSG.A5R7
TCSG.B5R7
TCSG.A6R7
TCP.B6R7
TCP.C6R7
TCP.D6R7
TCSG.A4R7
TCSG.B5R7
TCSG.D5R7
TCSG.E5R7
TCSG.6R7
TCLA.A6R7
TCLA.B6R7
TCLA.C6R7
TCLA.D6R7
TCLA.A7R7
TCLIB.6R2
TCLIA.4R2
IP2
TCTPH.4R2
TCTPV.4R2
ALICE
TCTPV.4L2
TDI.4L2
TCTPH.4L2
TCLIB.6L8
TCLIA.4L8
IP8
TCTPH.4L8
TCTPV.4L8
LHC-b
TCTPV.4R8
TDI.4R8
TCTPH.4R8
TCTPH.4R1
TCTPV.4R1
IP1
TCTPH.4L1
TCTPV.4L1
ATLAS
TCL.6R1
TCL.5R1
TCL.4R1
TCL.6L1
TCL.5L1
TCL.4L1



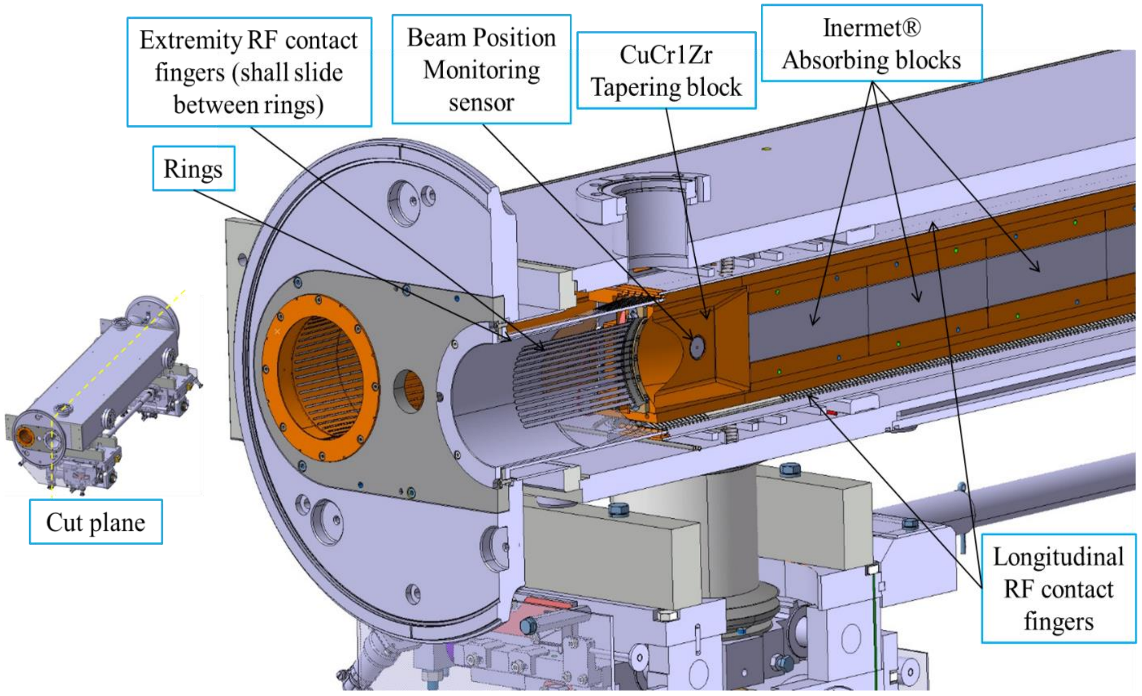
1000 KG
R-2495

Collimators subcomponents

TCLPX collimator

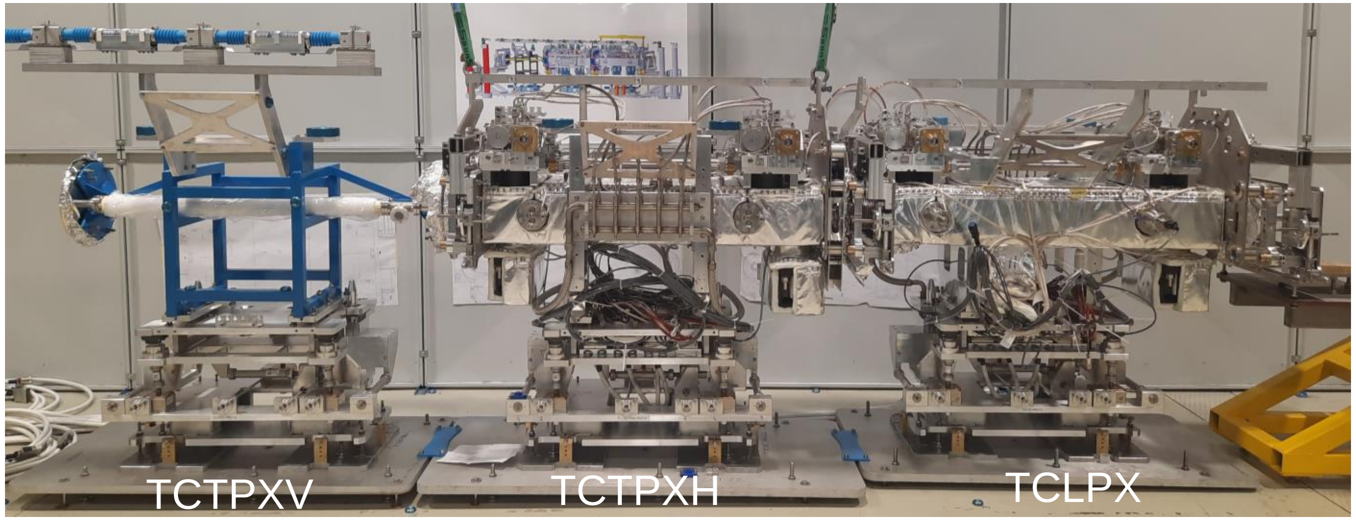


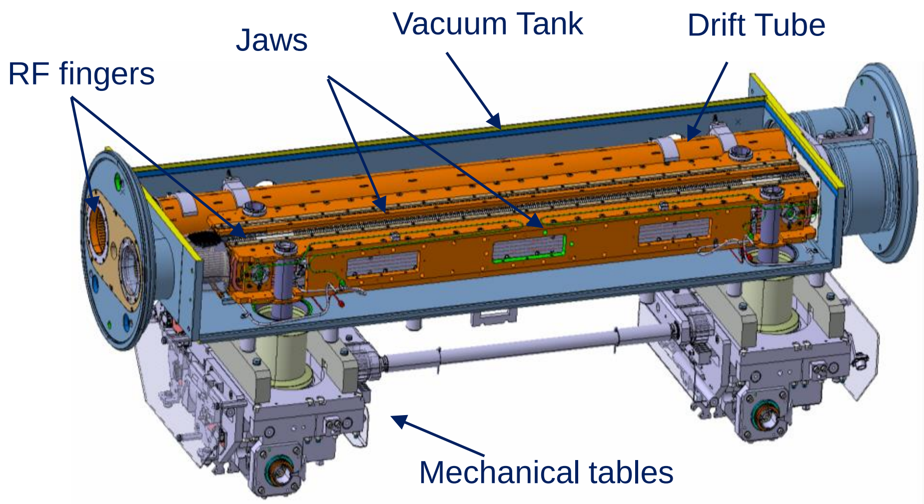
TCTPXH collimator



Collimator prototypes

- Two collimators' prototypes fully built, quality controlled and validated at CERN
  → validation of production method for series production

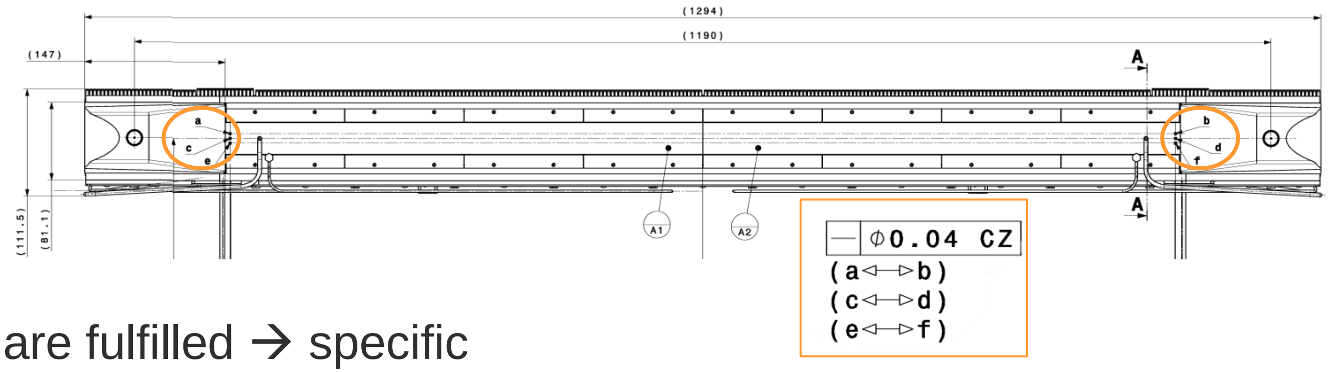




a) Need of high **precision machining of each individual sub-component**
b) Need of high **precision assembly together**
c) Need of high **precision assembly reliable over time** (following operation, transports, and bake out processes)

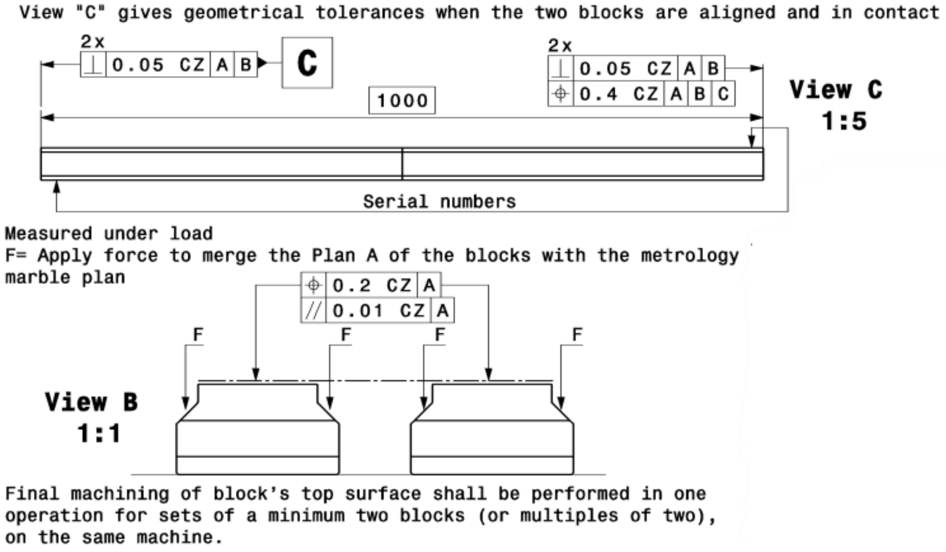
Coll. jaws assembly

Tolerances on the jaw assembly:



- To guarantee that tolerances on the jaw assembly are fulfilled → specific geometrical tolerances on graphite blocks are requested (and achieved)
- Blocks produced by external supplier;
- Blocks were machined in pairs (and metrology controlled in pairs at CERN);

Tolerances on the graphite blocks:

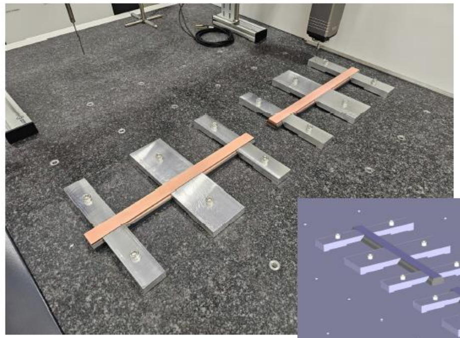


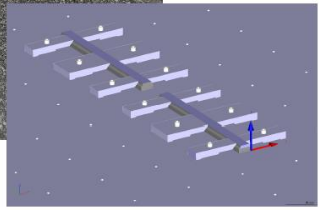
Machine: ZEISS Prismo Ultra 12-24-10
Précision des mesures: 1,2 µm + L/500mm
Température: 20°C ±1°C

N° de pièce: S12-2 et S25-1
Valeurs rouges: 0

Commentaire:

Nom du programme: Block-2x500mm



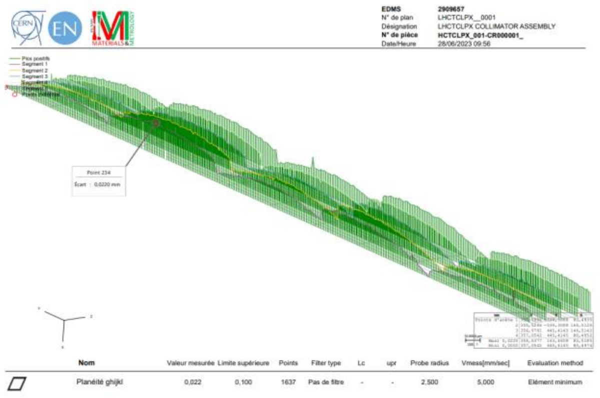


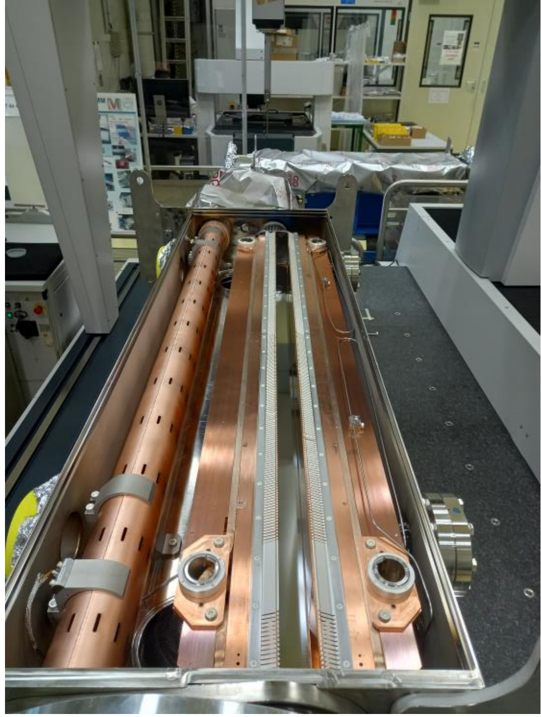
Nom	Valeur mesurée	Valeur nominale	Dimension supérieure	Dimension inférieure	Deviation	+/-
Flatness1	0,0023	0,0000	0,0050	0,0000	0,0023	
Localisation1	0,0219	0,0000	0,2000	0,0000	0,0219	
Localisation1.Z	25,0109	25,0000	0,1000	-0,1000	0,0109	
Parallélisme1	0,0087	0,0000	0,0100	0,0000	0,0087	

Prototype jaws assembly

- TCTPXH jaws' flatness metrology controls:

TCTPXH Jaw straightness target (over 990 mm length)	Straightness measured via CMM at CERN	
	Left jaw	Right jaw
<100 µm	22 µm	63 µm

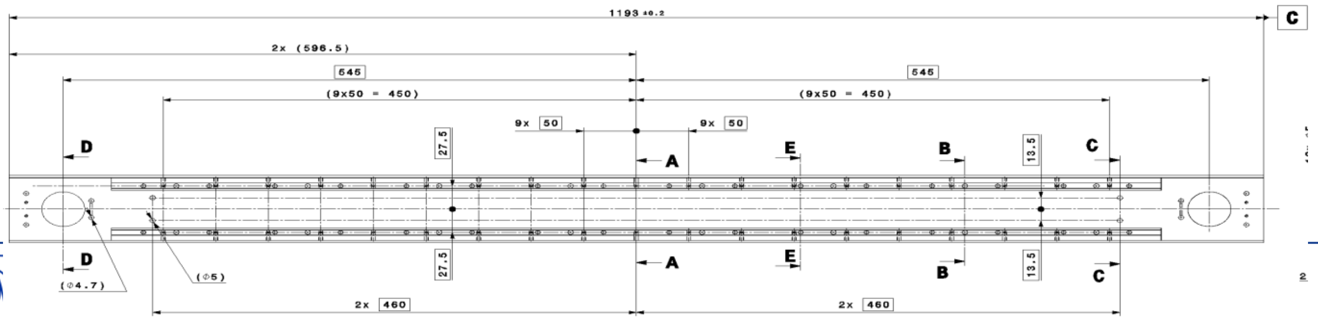


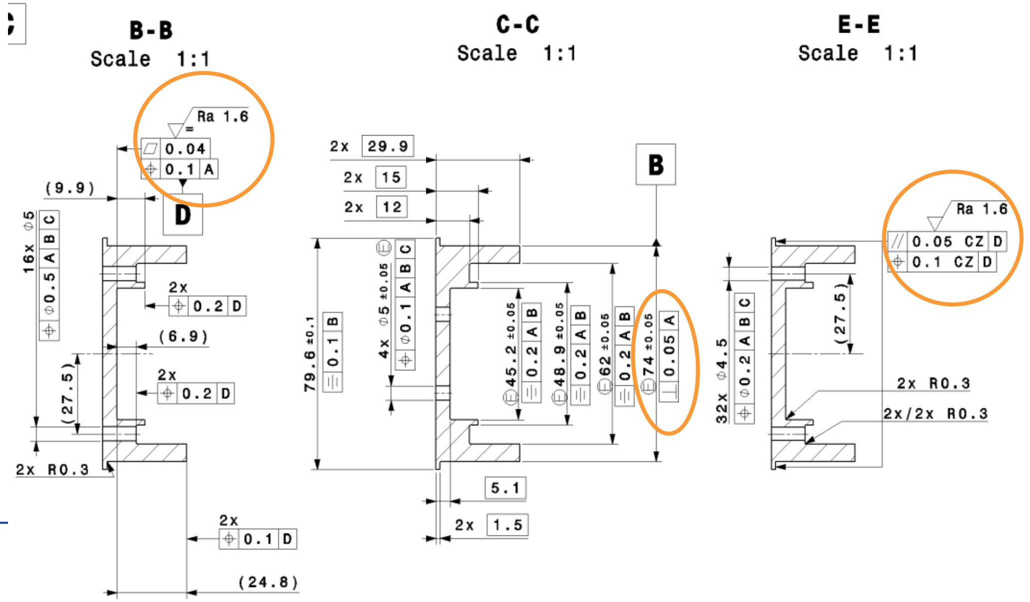


a) Need of high precision machining of each individual sub-component, particularly the structural part (made of CuCr1Zr CW106C according to EN 12420) as well as high precision assembly;

b) Stress relief heat treatments of to guarantee dimensional stability of structural components;

c) Need of high-quality raw material to fulfil tight geometrical tolerances, structural stability, UHV conformity → close follow up of raw material production and quality controls;





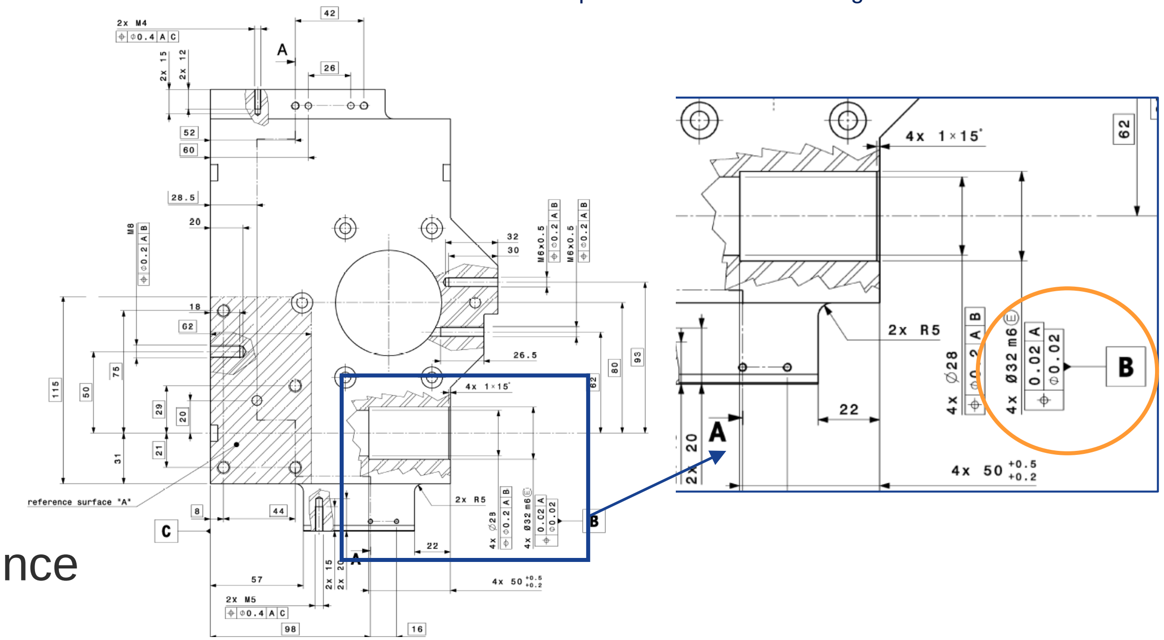
Coll. mechanical tables

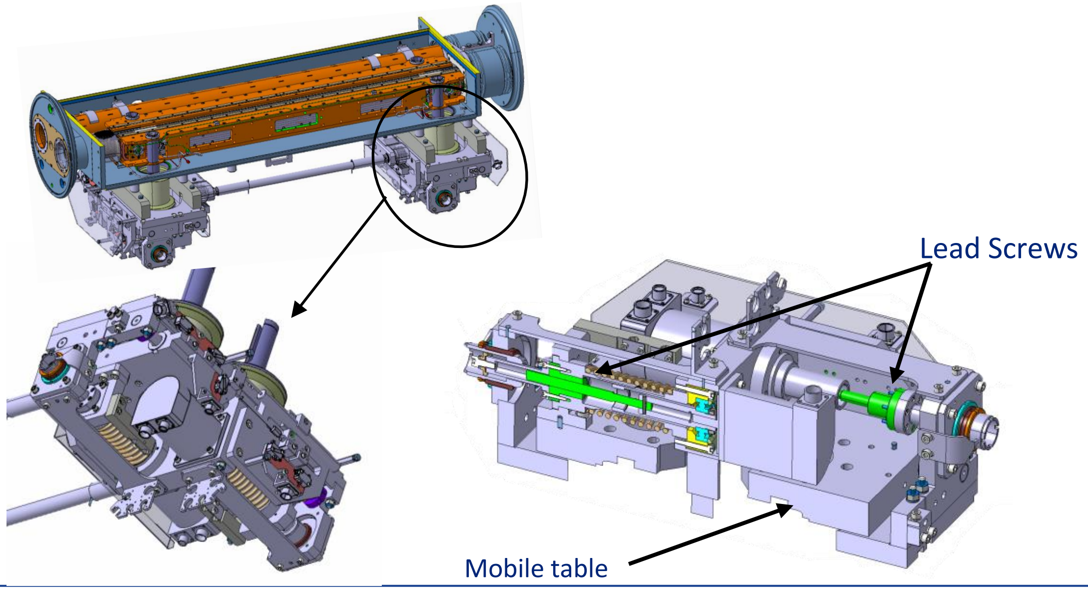
- Mechanical table: Precise mechanical assemblies - actuated by stepper motors and leadscrews → allows the movement of jaw during operation
- **Mobile table**: directly connected to leadscrew. Material: Alu EN AW-6082 T6

↓

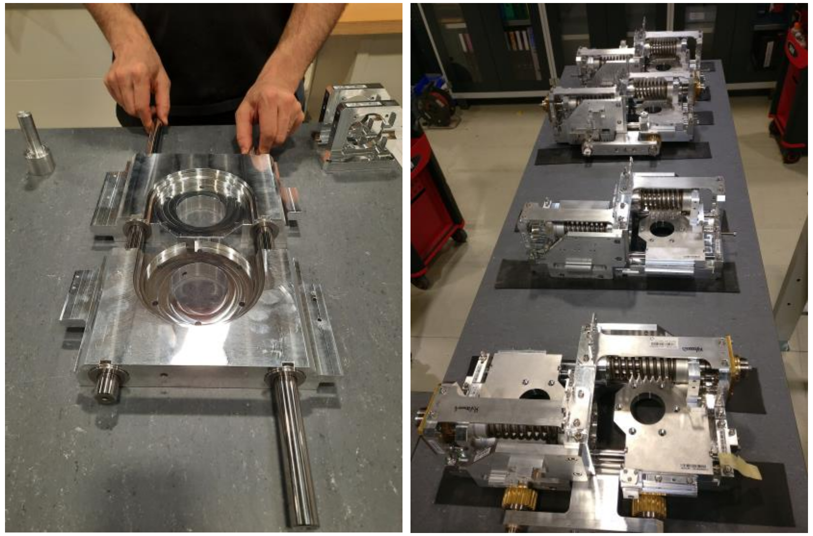
Positioning tolerance of **20 μm** between holes axes and reference surface to guarantee precise and reliable movements.

Example of mobile table drawing:



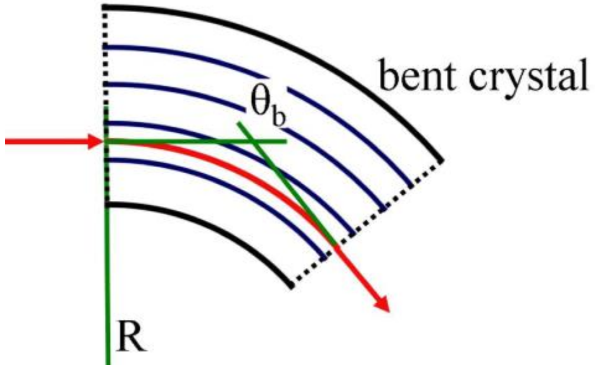


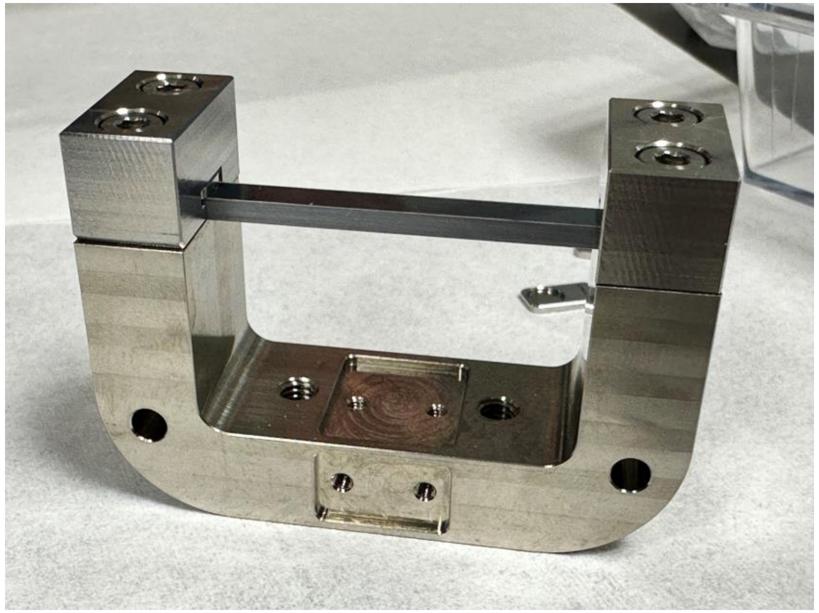
Mechanical table for prototype collimators:

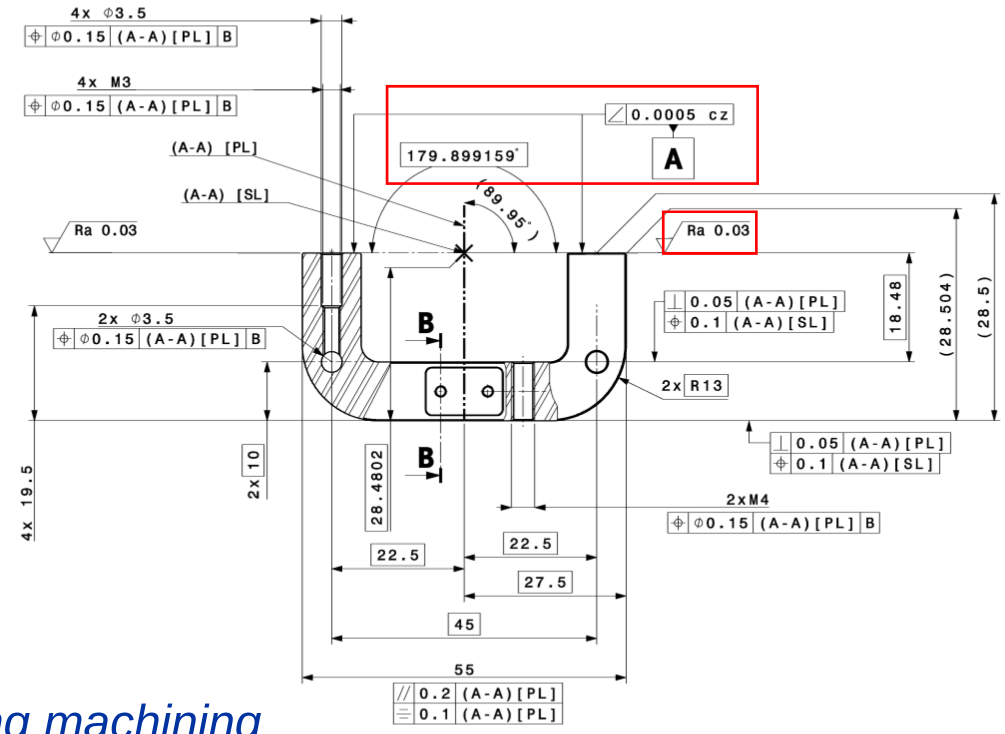


Crystal collimators

Delicate and very precise systems to "channel particles" through crystal planes in a silicon wafer





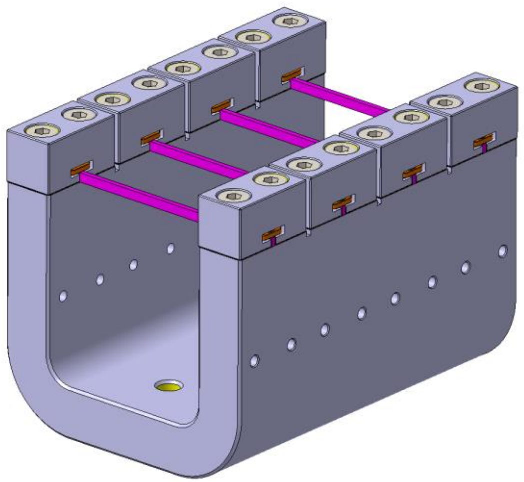


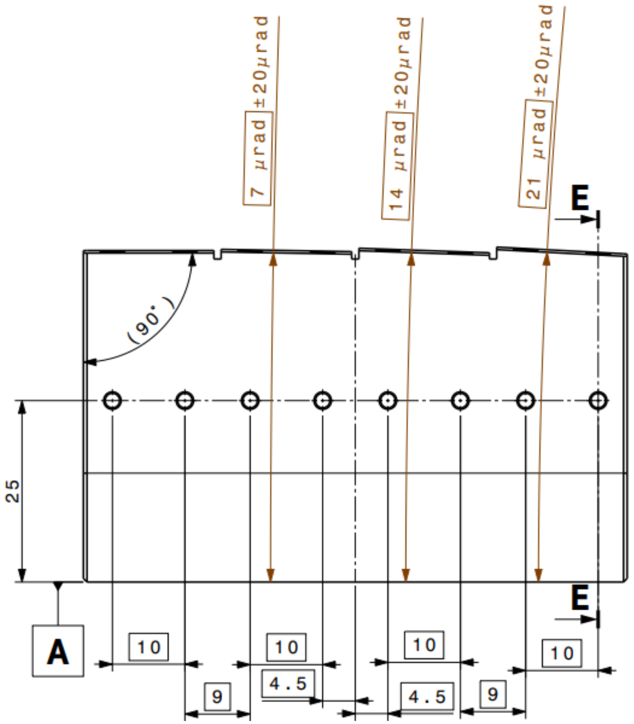
(very) high precision requirements:

- Surface **R_a ~30 nm**
- **Angular orientation precision < 50 μrad**

Titanium grade 5 *e.g. free-form single-point diamond turning machining*

Crystal collimators





Extreme precision requirements:

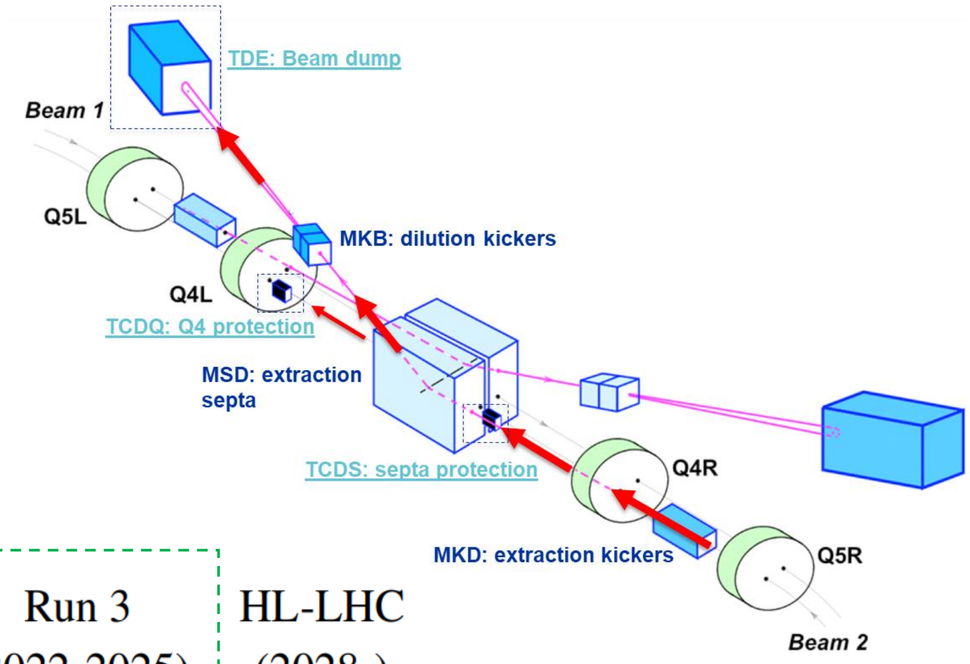
- Surface roughness **< 40 nm from peaks to valleys**
- **Angular orientation precision < 20 µrad**

Titanium grade 5 very challenging to machine with such accuracy. Possible solutions:

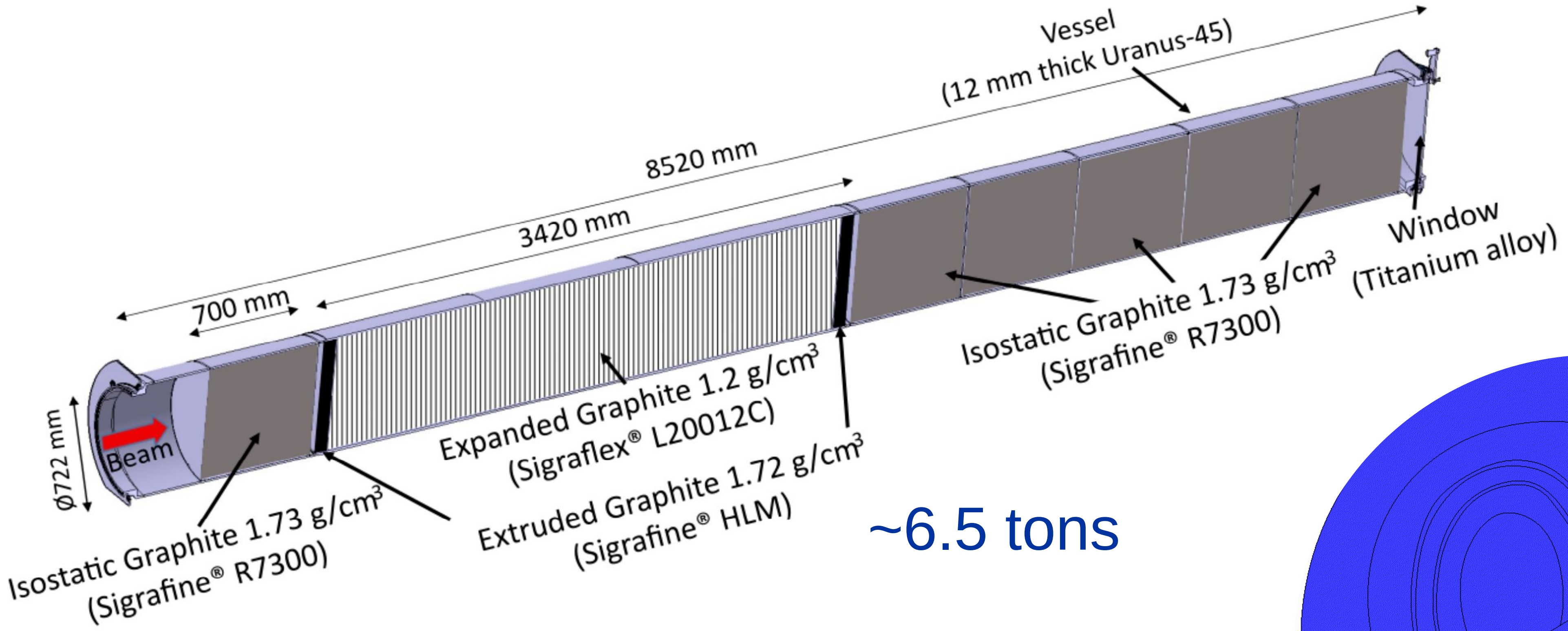
- Use a more machinable material
- Apply a coating on the surfaces to be machined

LHC external beam dump – where, what, why

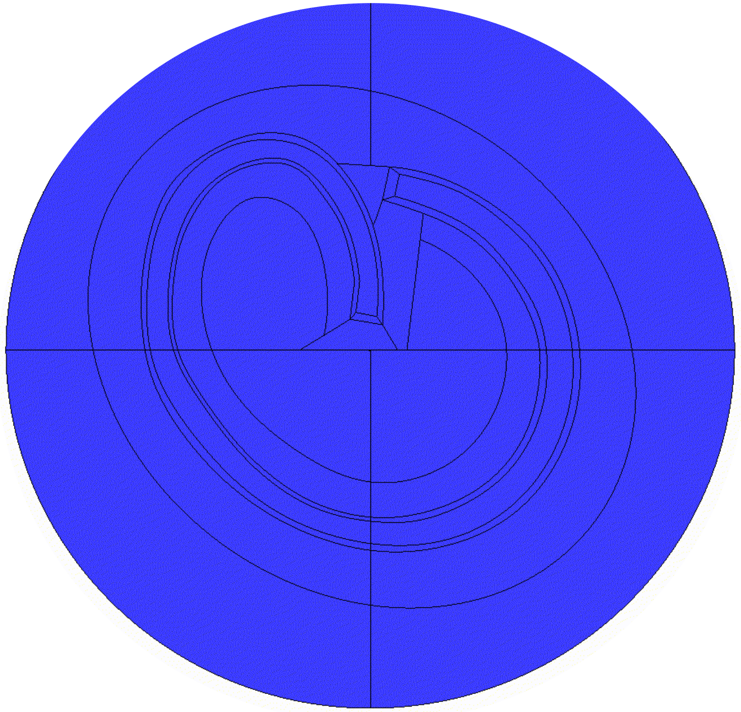
- Essential device of the LHC Beam Dumping System (LBDS)
- **Repeatedly absorb the energy of the LHC dumped beam, without damage**



	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


Vessel
(12 mm thick Uranus-45)
8520 mm
3420 mm
700 mm
Ø722 mm
Beam
Window
(Titanium alloy)
Isostatic Graphite 1.73 g/cm3
(Sigrafine® R7300)
Expanded Graphite 1.2 g/cm3
(Sigraflex® L20012C)
Extruded Graphite 1.72 g/cm3
(Sigrafine® HLM)
Isostatic Graphite 1.73 g/cm3
(Sigrafine® R7300)

~6.5 tons



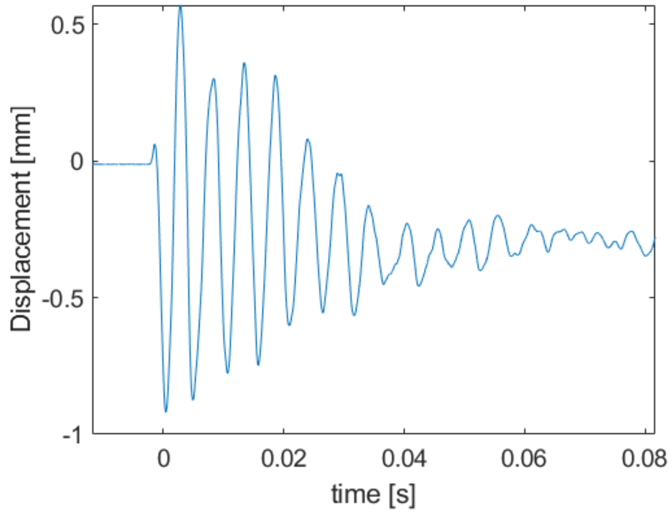
What the challenges?

- In the last few years, we noticed **several operational challenges** (N_2 leaks, massive (~cm) movements, etc.)
- What do we saw with instrumentation?

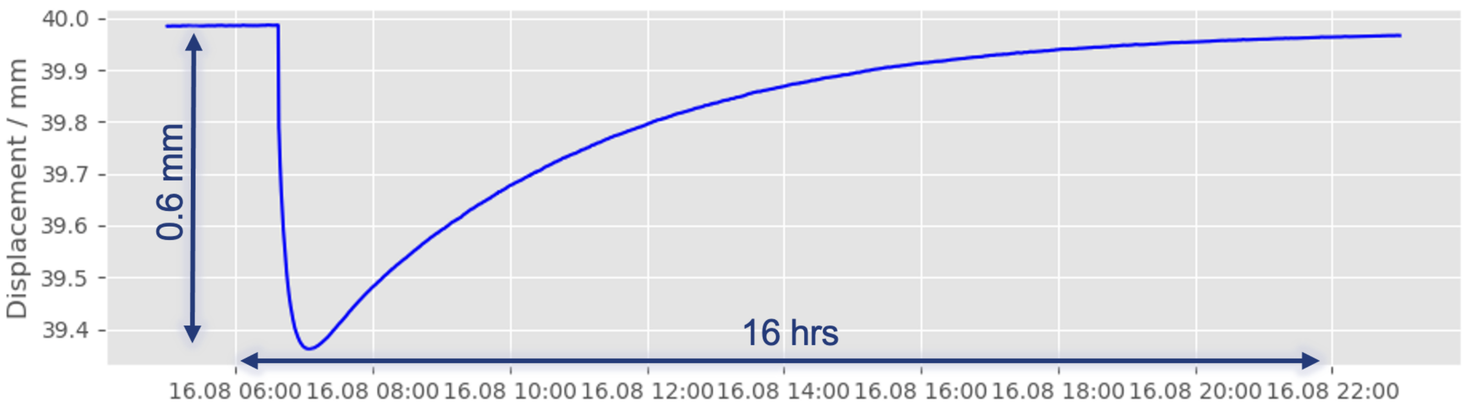
Could **melt roughly 2 t of Cu**

55.2% nominal Run3
2.73×10^{14} p^+
297.6 MJ

Time scale of 100 ms

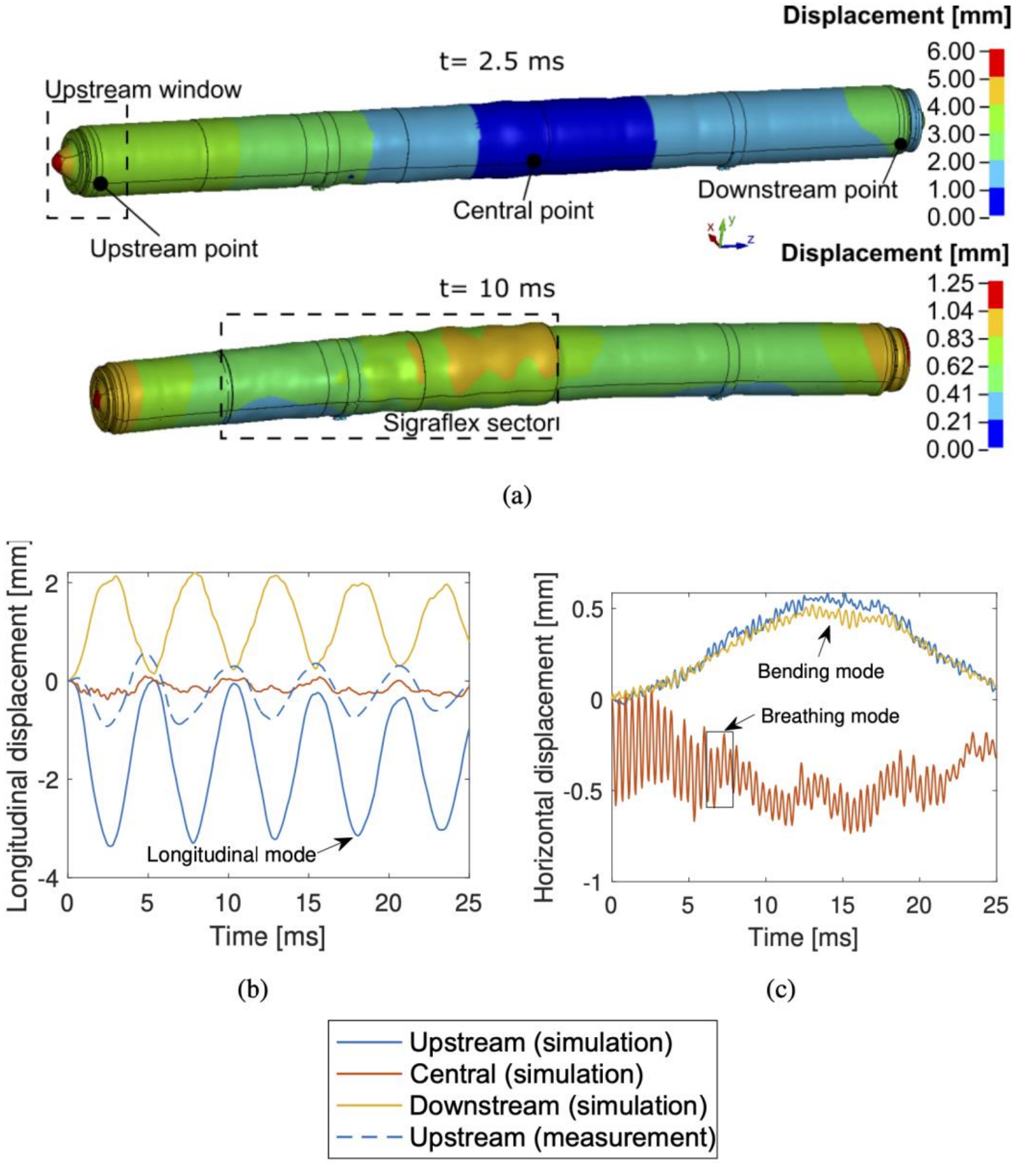


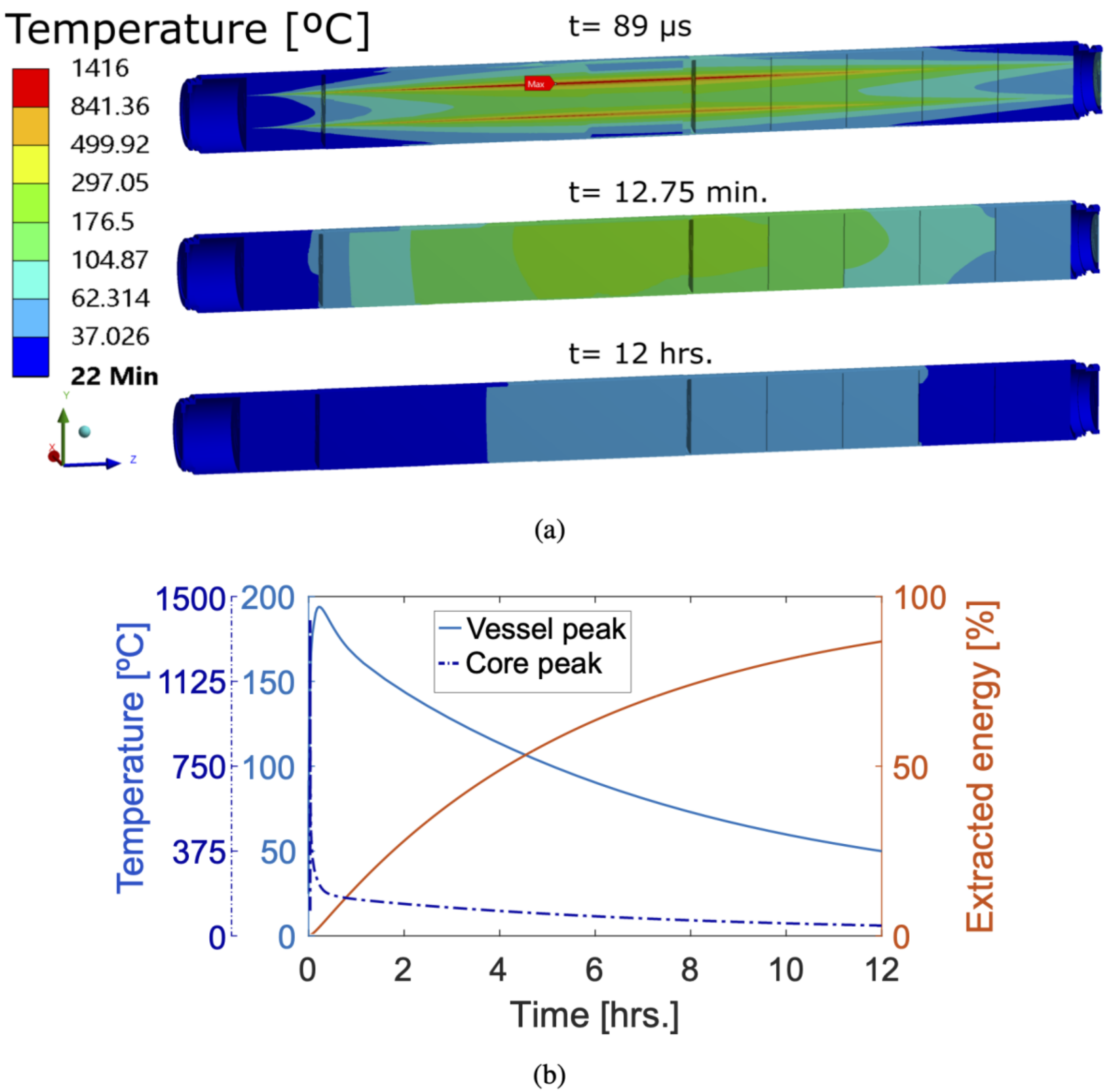
Time scale of >10 hours (!)



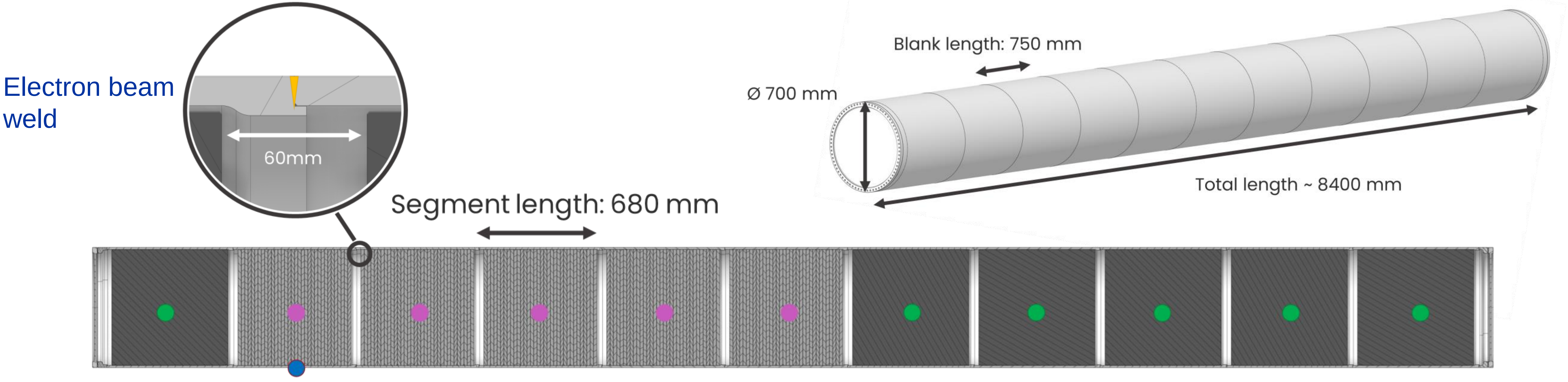
Timescale of a dumping event

ms ⟷ 10 h

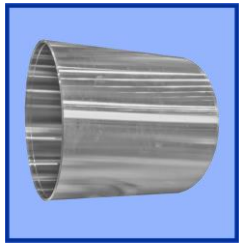




New generation LHC beam dump being developed

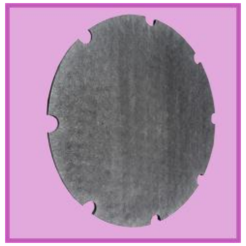


Titanium Grade 5 seamless blanks



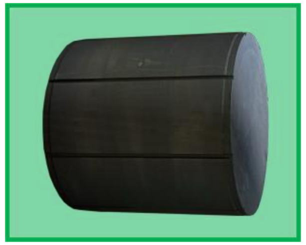
CFC Composite plates

- New material for HL dumps
- Superior thermal shock resistance
- Stack of 15 x 45 mm thick plates must be shrink fitted inside titanium blanks



Isostatic Graphite blocks

- Previously shrink fitted in stainless steel blanks
- Possible to achieve ± 0.05 tolerance on 700 mm diameter



Shrink fitting graphitic materials – under assessment

Vessel is heated using heating blankets to give **1 mm minimum gap** on diameter
*400ºC required for titanium

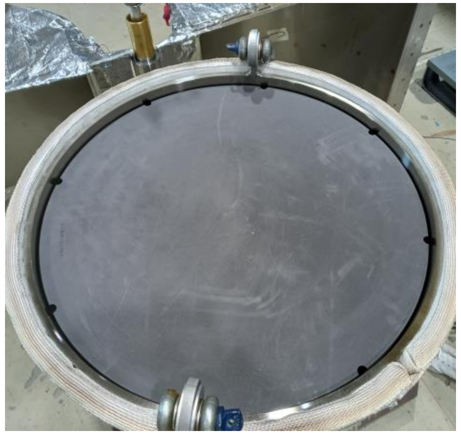
Blank is carefully lowered over the core

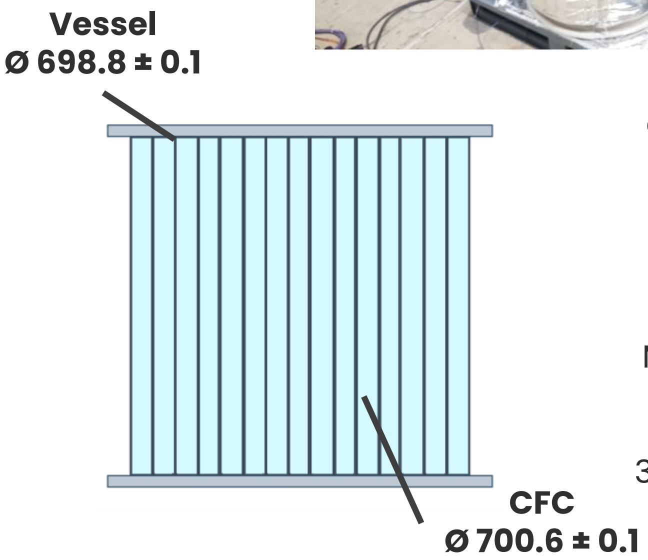
Once cooled to room temperature the shrink fit is complete

1

2

3



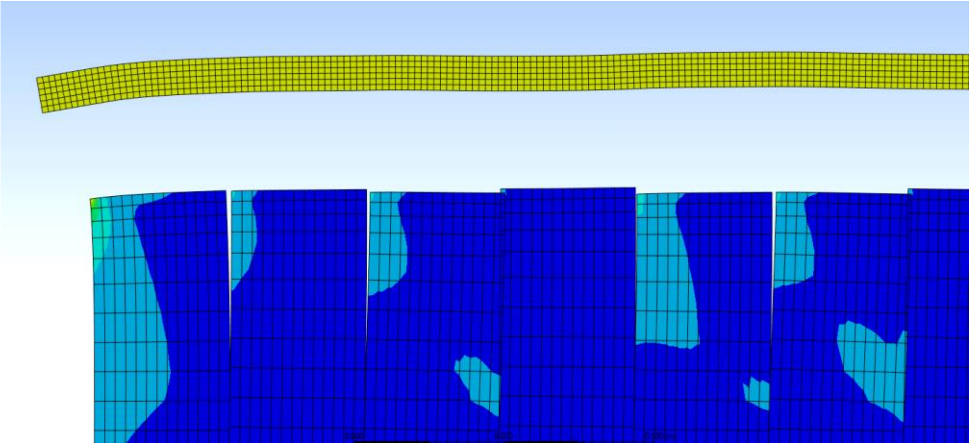


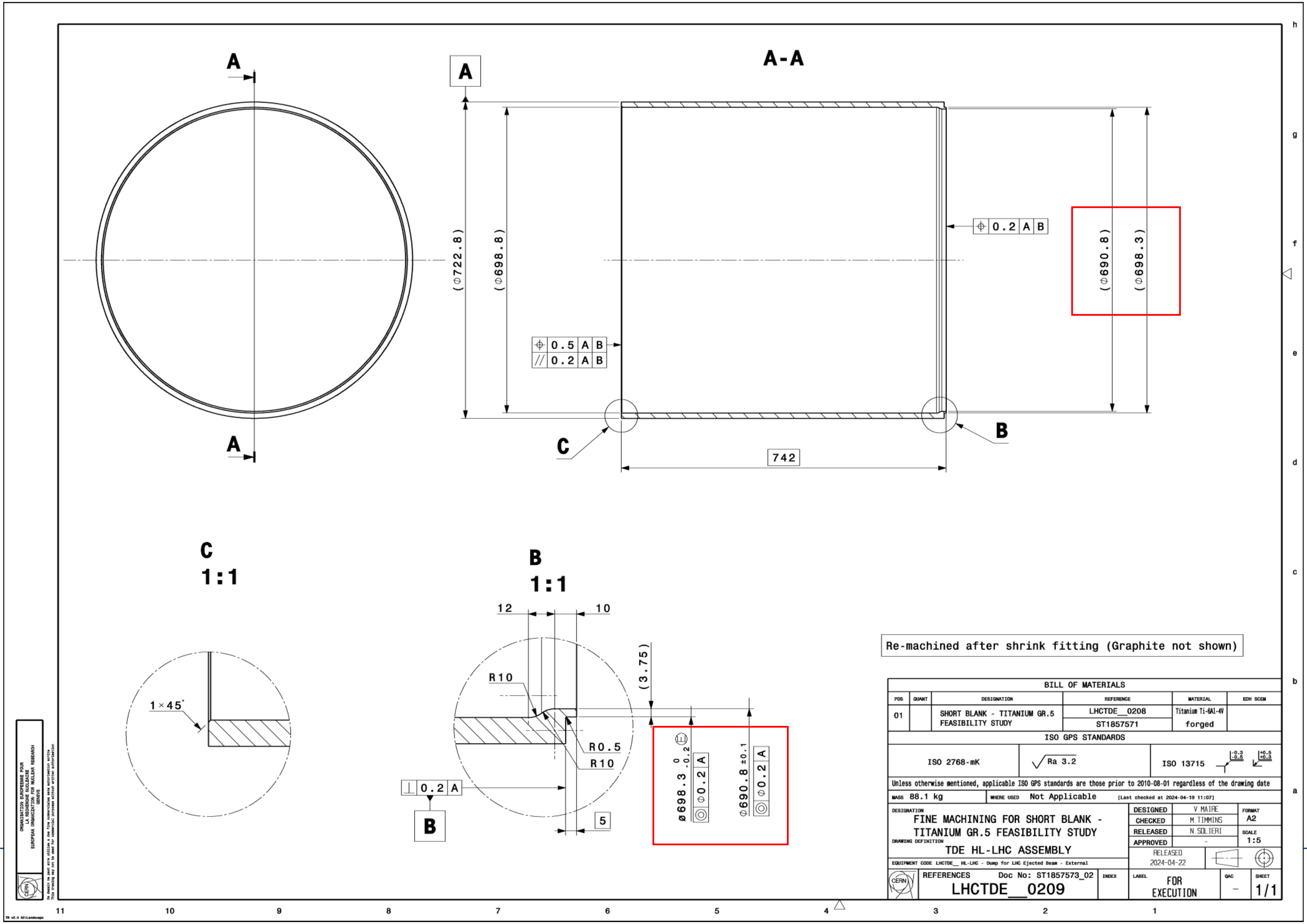
CFC is more challenging to machine accurately than isostatic graphite - depends on CFC type

Varying diameter on adjacent plates causes stress concentrations when shrink fitted

Must maintain the alignment of the stack during shrink fitting procedure

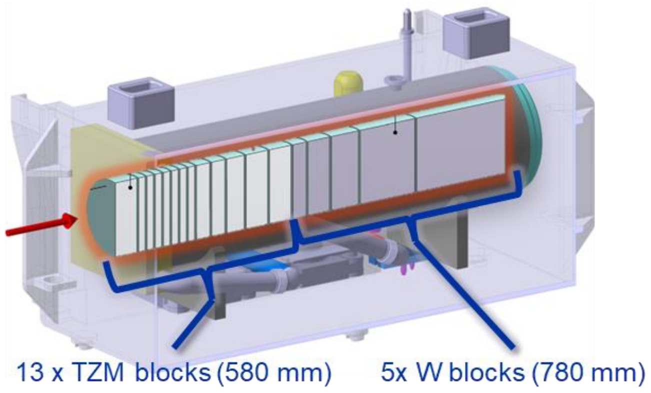
3 mm chamfers on corners of plates will alleviate these issues

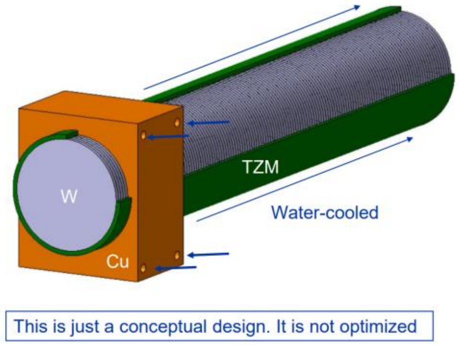




A-A
A
(Ø722.8)
(Ø698.8)
0.2 A B
0.5 A B
0.2 A B
(Ø690.8)
(Ø698.3)
742
C
B
C
1:1
B
1:1
1×45°
12
10
R10
(3.75)
R0.5
R10
0.2 A
5
Ø698.3 0 -0.2
Ø0.2 A
Ø690.8 ±0.1
Ø0.2 A
Re-machined after shrink fitting (Graphite not shown)
BILL OF MATERIALS
POS
QUANT
DESIGNATION
REFERENCE
MATERIAL
EDH SCEM
01
SHORT BLANK - TITANIUM GR.5 FEASIBILITY STUDY
LHCTDE__0208
ST1857571
Titanium Ti-6Al-4V
forged
ISO GPS STANDARDS
ISO 2768-mK
Ra 3.2
ISO 13715
Unless otherwise mentioned, applicable ISO GPS standards are those prior to 2010-08-01 regardless of the drawing date
MASS 88.1 kg
WHERE USED Not Applicable
FINE MACHINING FOR SHORT BLANK - TITANIUM GR.5 FEASIBILITY STUDY
TDE HL-LHC ASSEMBLY
DESIGNED V.MAIRE
CHECKED M.TIMMINS
RELEASED N.SOLIERI
APPROVED
FORMAT A2
SCALE 1:5
RELEASED 2024-04-22
REFERENCES
Doc No: ST1857573_02
LHCTDE__0209
FOR EXECUTION
SHEET 1/1

Design processes for target design





Hybrid TZM/W TaW cladded, water cooled

(2019)

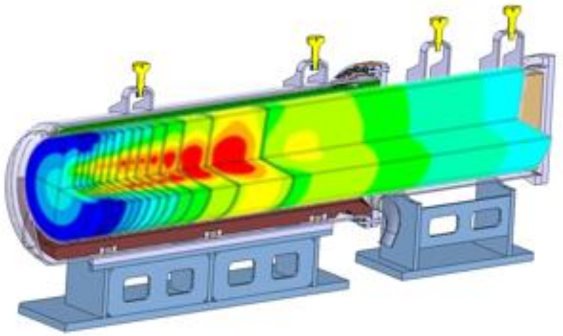
Hybrid TZM/W Nb-alloy cladded, water cooled

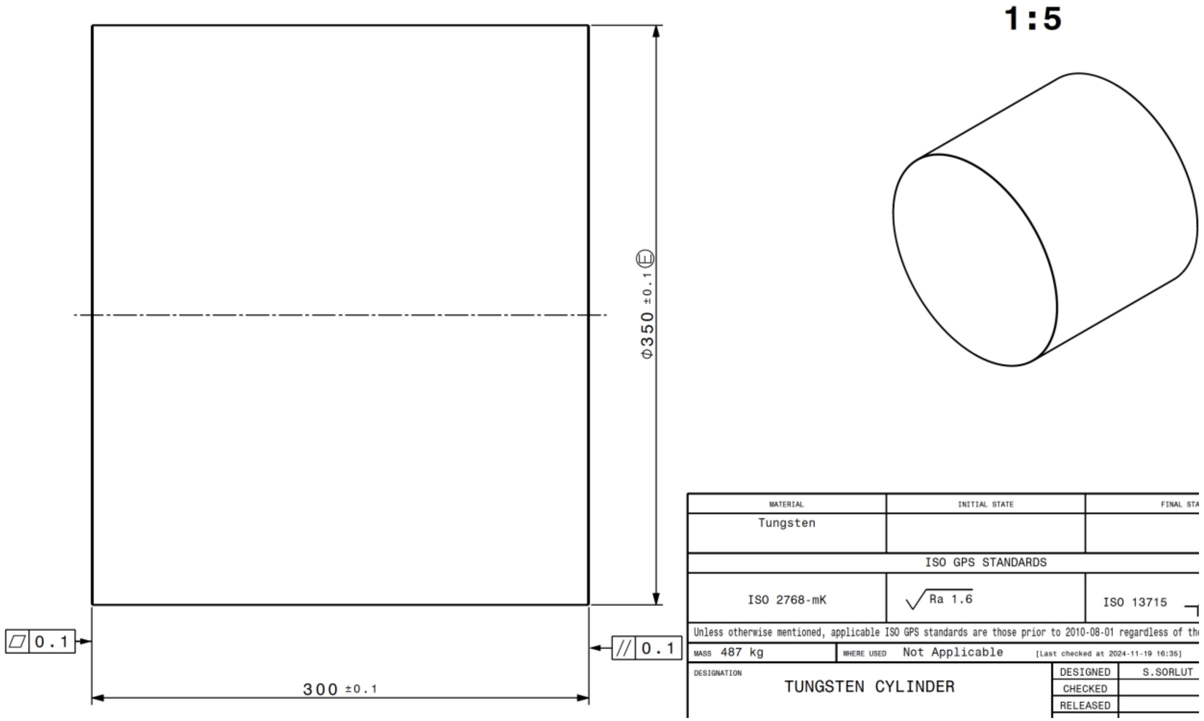
(2020-2022)

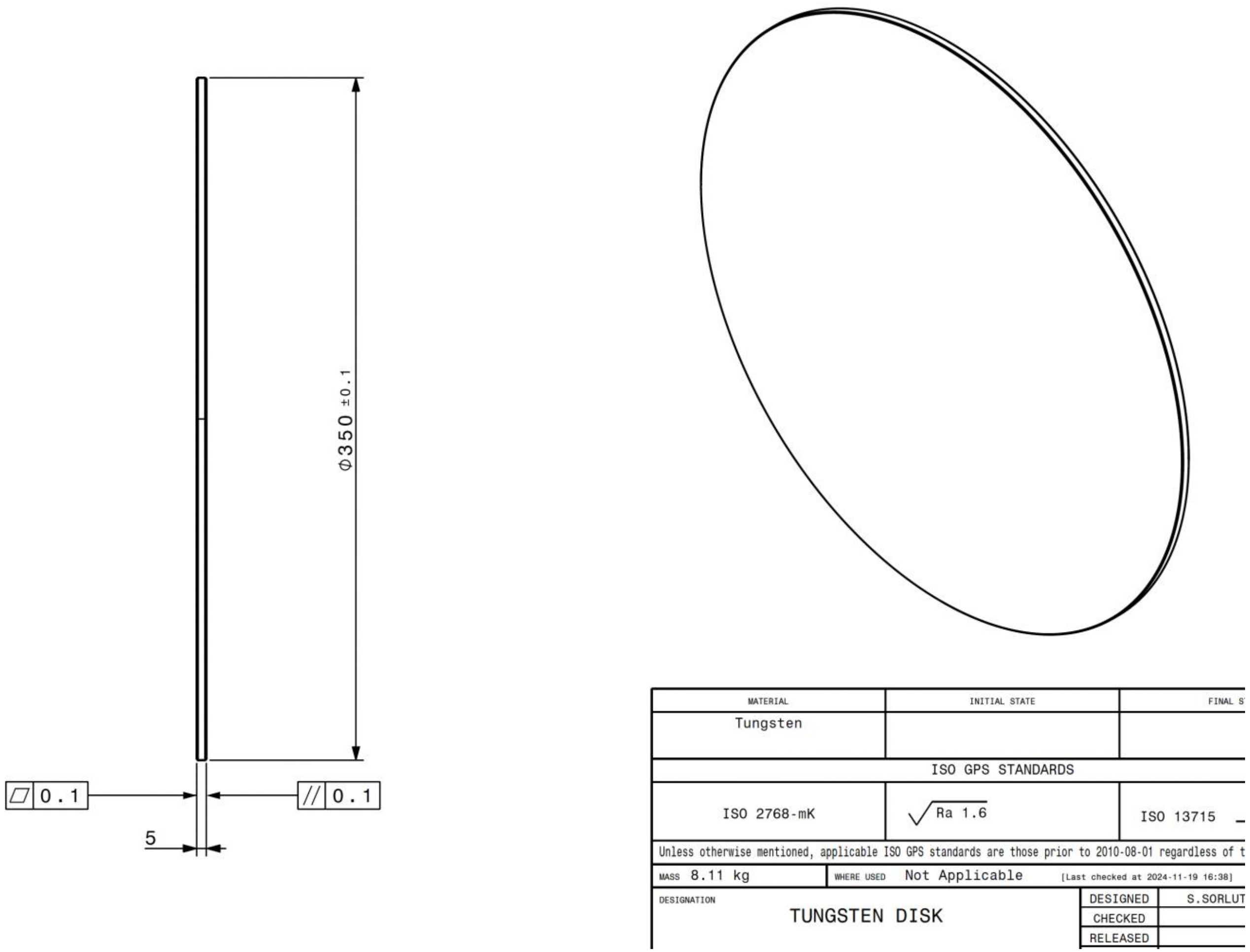
W, TZM cladded, Cu + W Target (2023)

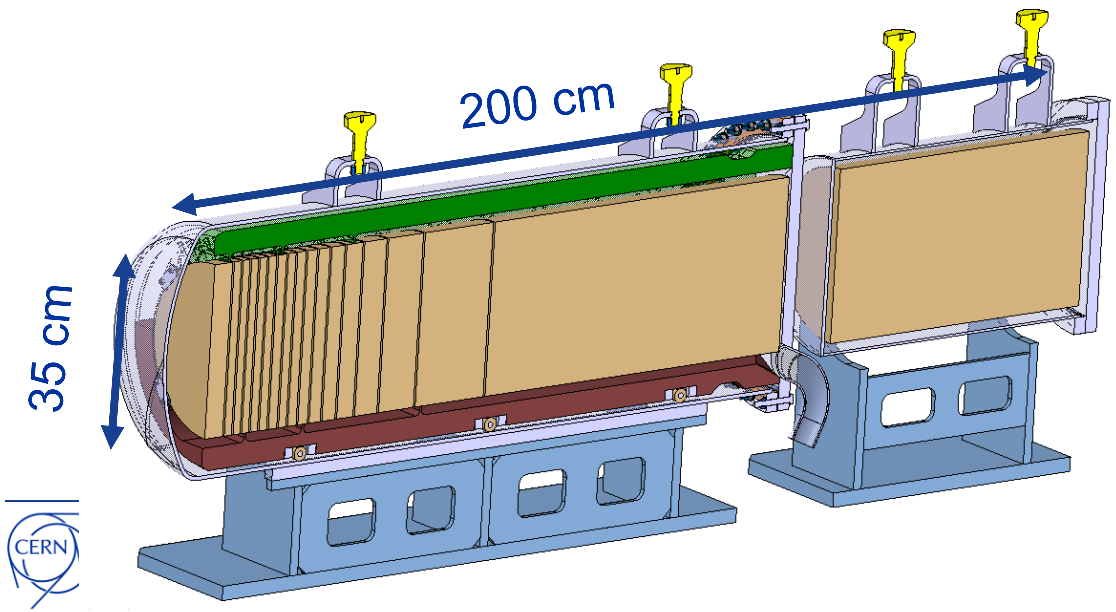
Full W, uncladded, He-cooled

(2024→)





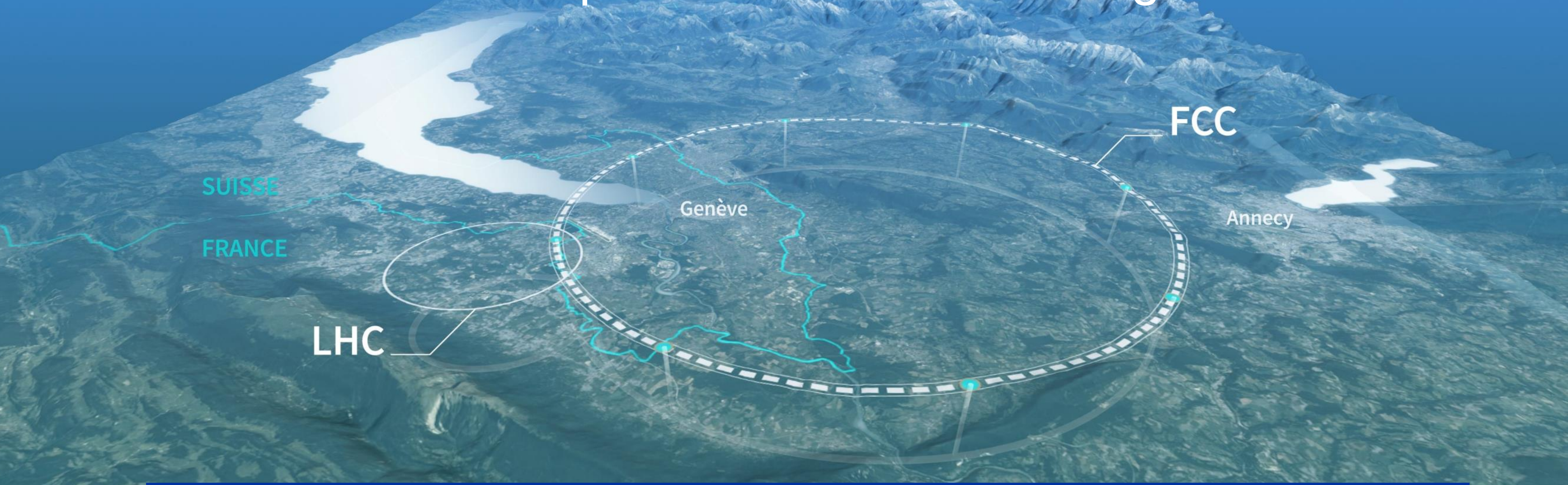




- Hot-rolled W
- Inconel 718 or SS 316LN

Future Circular Collider

electron positron machine 1st stage



A real challenge for BIDs (and other systems)
e.g. 20 MJ with V size of ~20 nm

Conclusions

- **Beam Intercepting Devices** and their **full lifecycle management** is an essential & multi-physics/expertise aspect of CERN's operation
- Some applications required **very precise machining**!
- Looking forward to hearing from you in case you are **interested and willing to contribute to support us in some of our challenges**!

THANKS, marco.calviani@cern.ch

YEARS / ANS CERN

home.cern