7th High Power Targetry Workshop

Facility for Rare Isotope Beams
Michigan State University

Design and prototyping of the CERN Proton Synchrotron Internal Dump in the Framework of the LHC Injectors Upgrade Project

Summary
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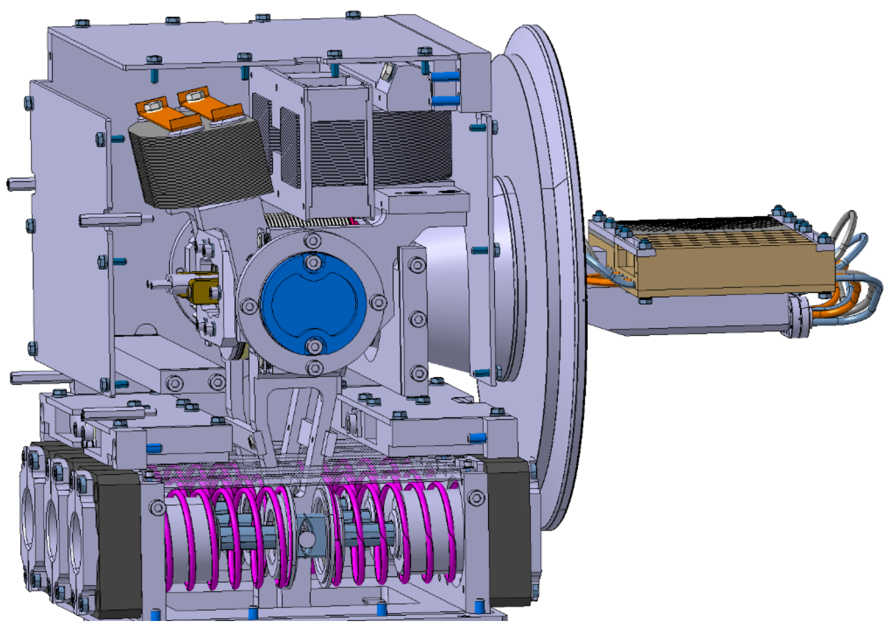
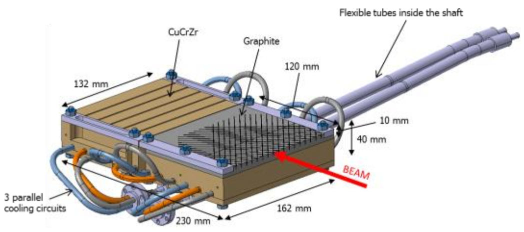


- **Introduction**

Operation and PS dump description

Requirements



- **New Dump Core**

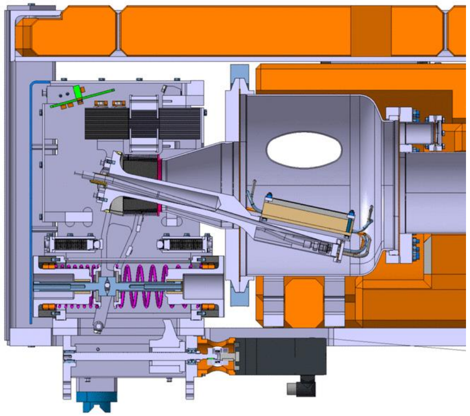
Description

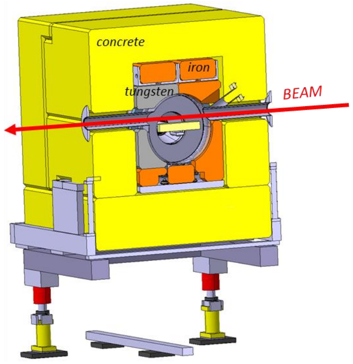
Energy deposition studies

Thermo-mechanical simulations

Prototyping

Analysis



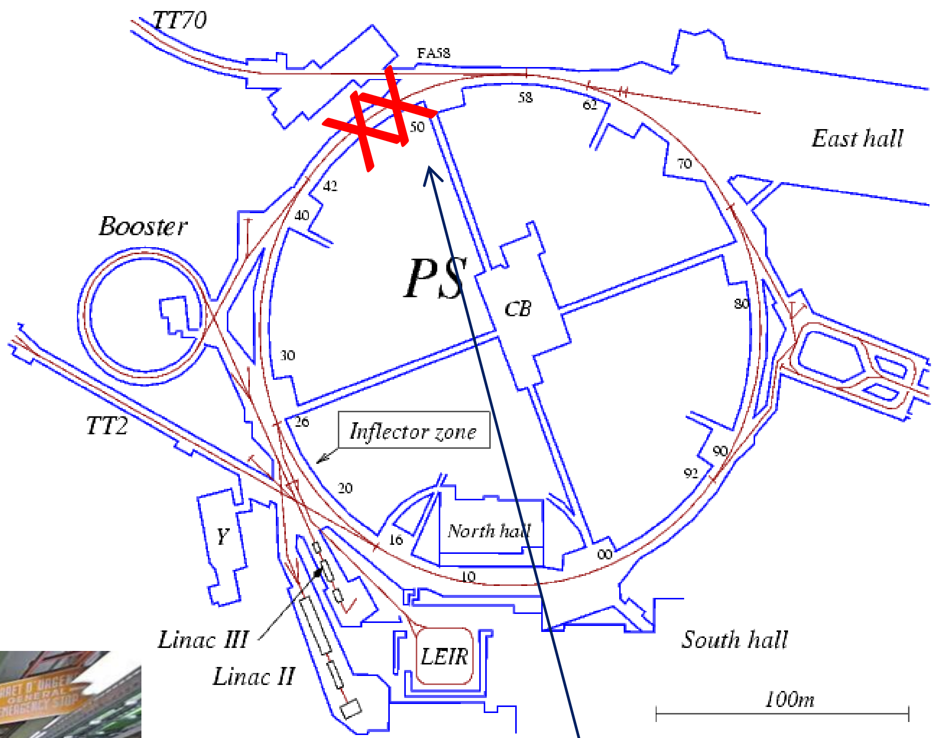


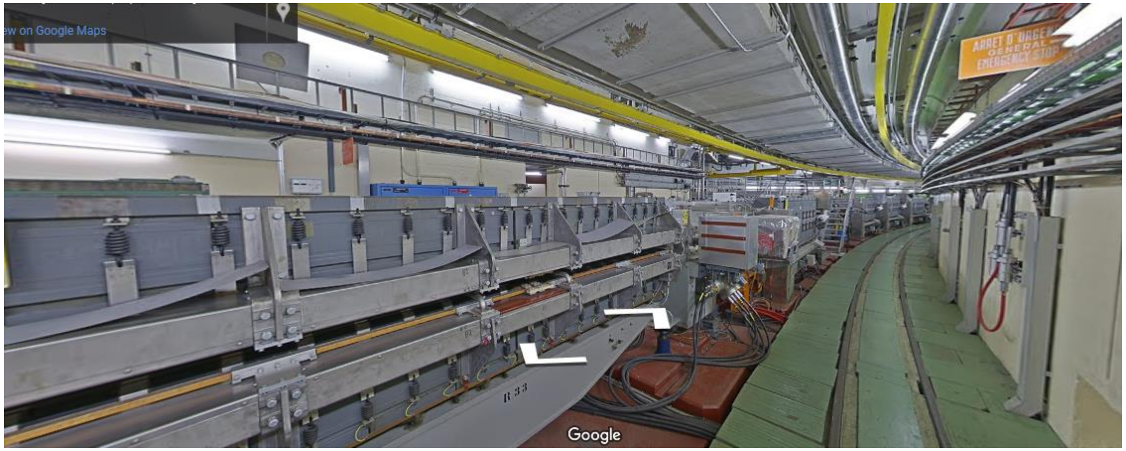
The LHC Injectors Upgrade should plan for delivering reliably to the LHC the beams required for reaching the goals of the HL-LHC.

Timeline: Mai 2020 (PS closing)

PS Machine:

628 m circumference
100 Main dipoles
Max proton momentum: 26 GeV/c



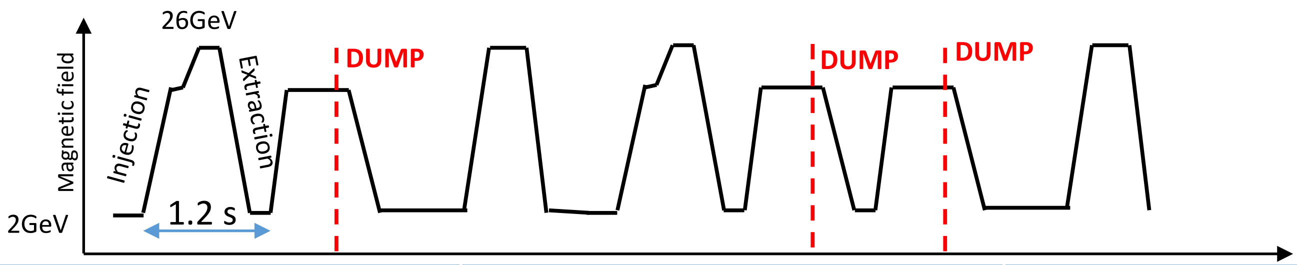


New Dumps: Operation Modes

Reference: PS Ring Internal Dump Functional Specifications, EDMS 1582110 v.2.0.

Machine Development

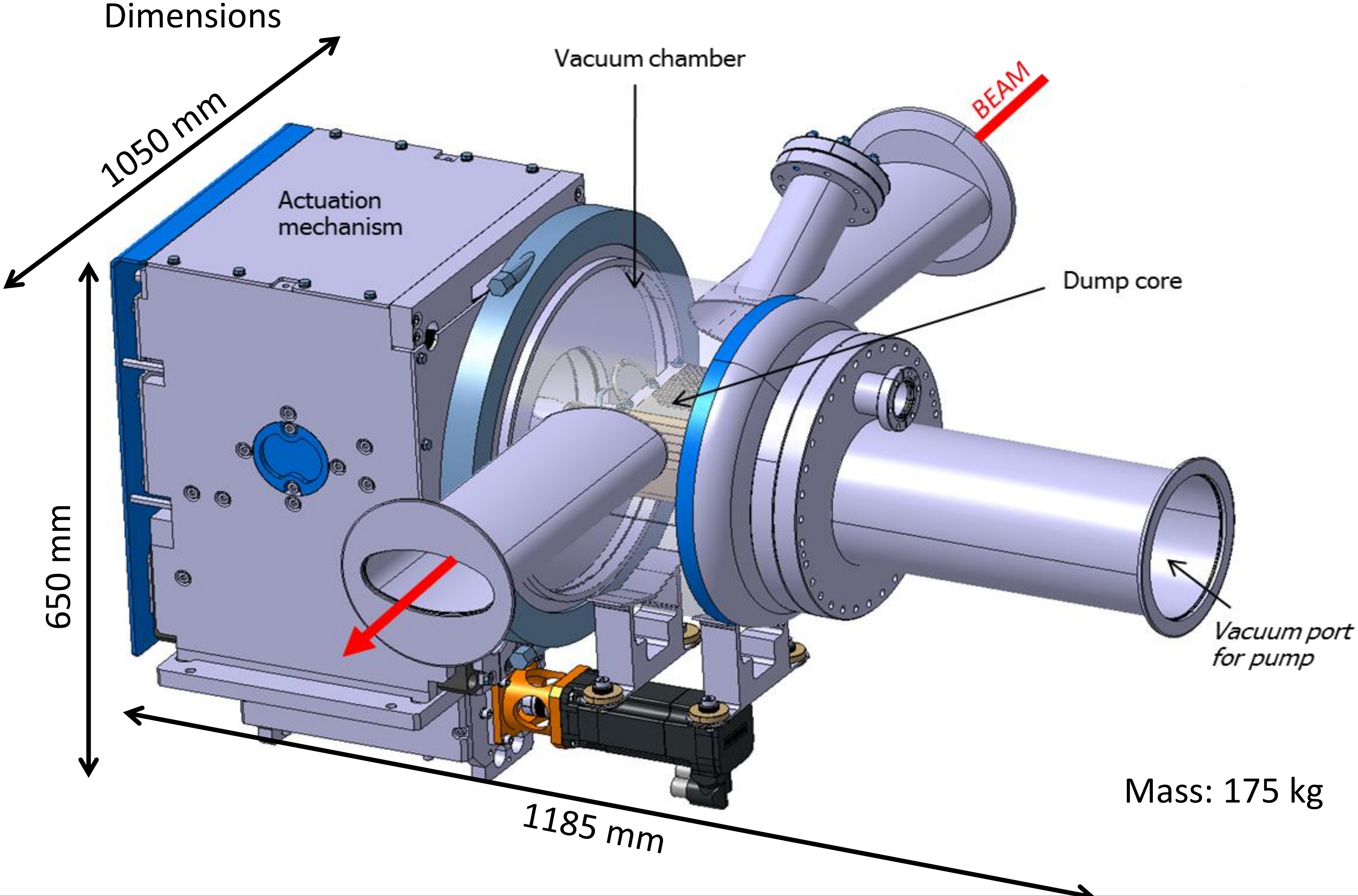
Cycle in the **supercycle** not requested for extraction



BEAM	LHC 25 ns 2015	LHC25ns HL
Particles	Protons, for LHC	
Pulse Intensity:	8.7×10^{12}	2.4×10^{13}
Continuous pulses to study	Minimum 4 pulses	Minimum 4 pulses
Beam revolution time:	2.1 µs	2.1 µs
Pulse Period (Basic Period):	3.6 s	3.6 s
Beam rms size (σ_h x σ_v) odd section [mm × mm]	1.85 x 0.98	1.74 x 0.87
Max momentum	26 GeV/c	26 GeV/c
Intensity density*	76	252
Total shaving time	approx. 4 ms	approx. 4 ms
Total beam energy	**35 kJ**	**96.3 kJ**
Total energy on the dump	**3.2 kJ**	**8.3 kJ**
T_{max} on dump	**415°C**	**1154°C**

*Intensity density $I_{max} = \frac{I_{tot}}{2\pi \cdot \sqrt{\sigma_{horiz}{}^2 \cdot \sigma_{vert}{}^2}}$

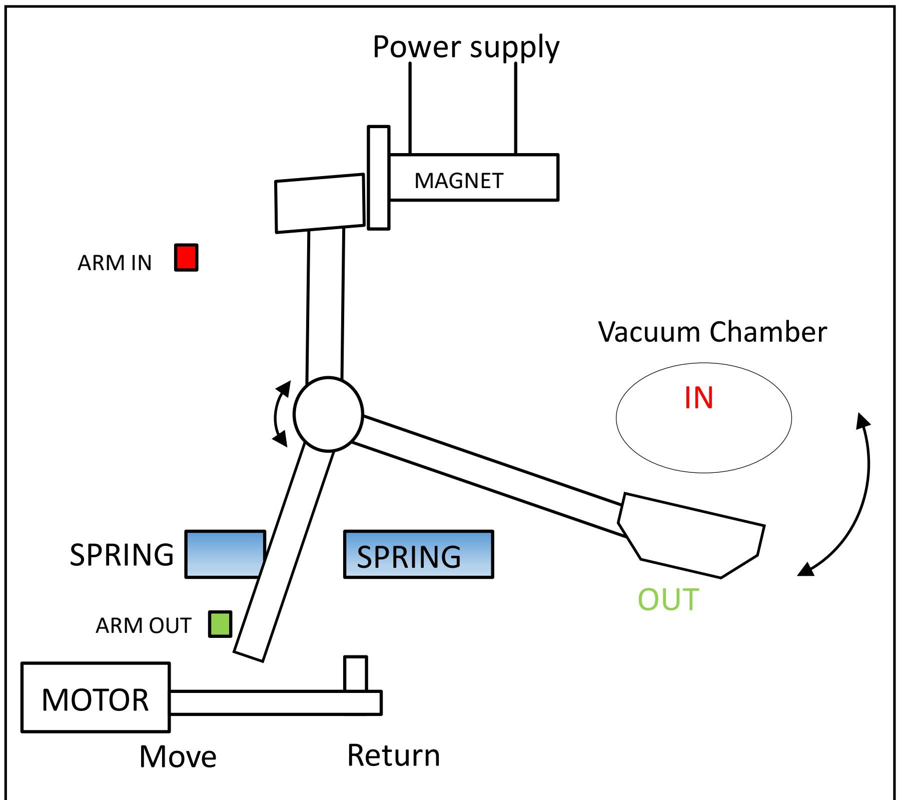
New PS Dump Description

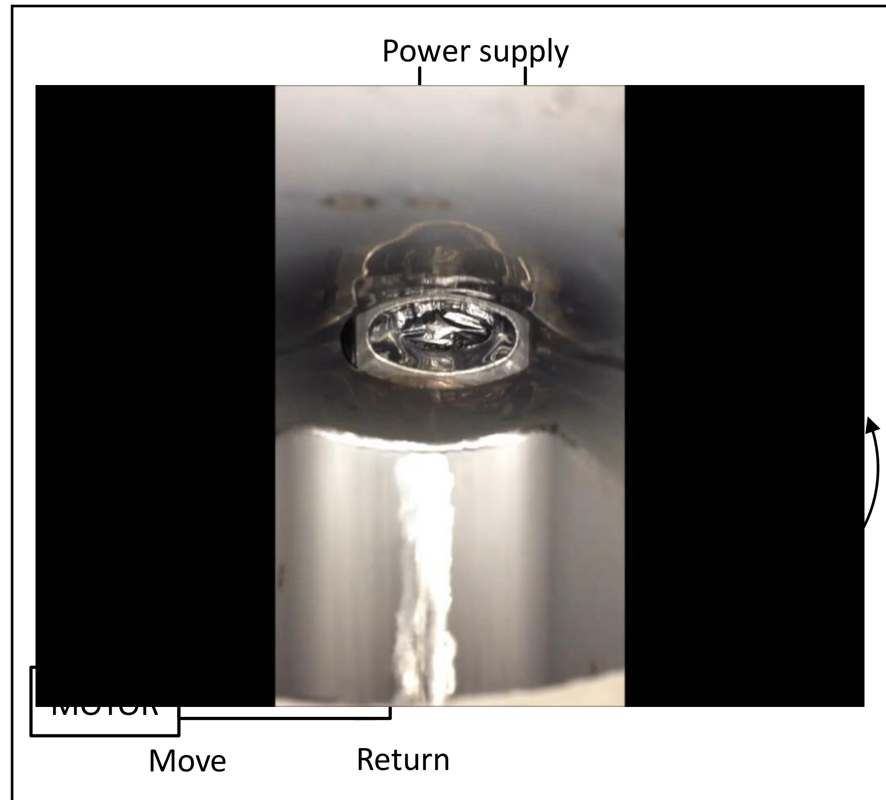


Mass: 175 kg

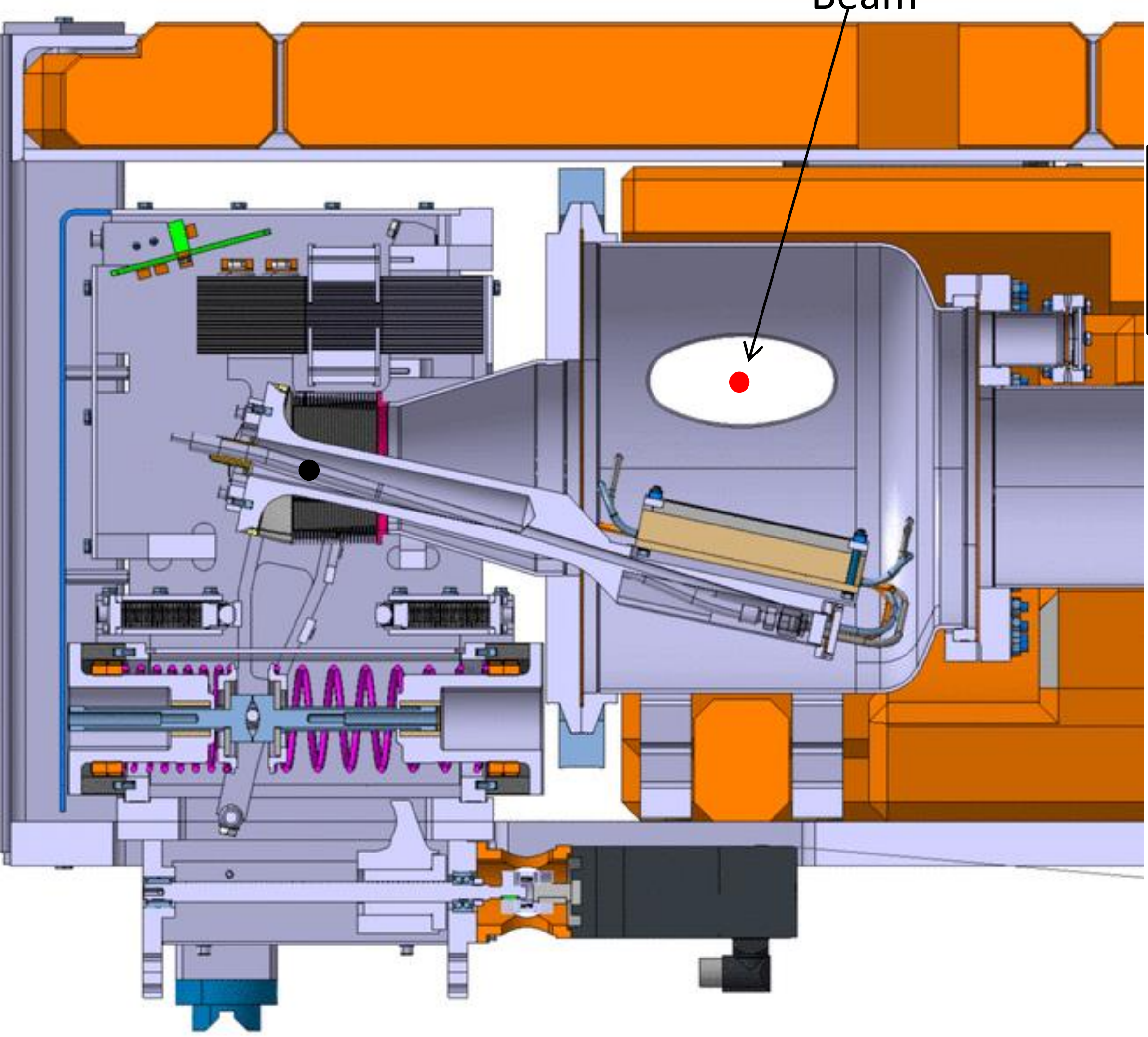
PS Internal Dumps – Actuation System

- Magnetic field keeps the dump arm close to the magnet
- Magnet current cut → springs pushes the dump in the beam position
- Back springs push back the dump in the initial position
- If problem (magnet current) → safety motor pushes away the dump from the chamber





PS Dump Kinematics

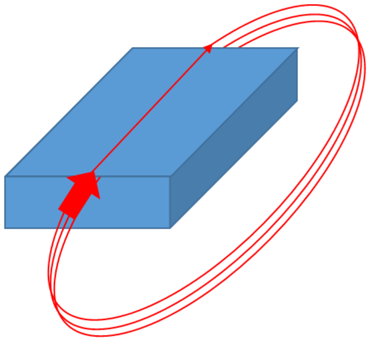


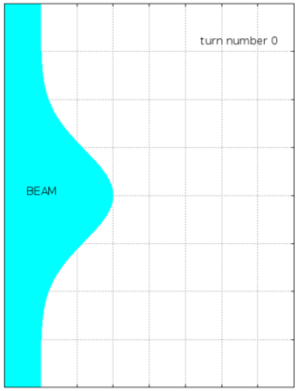
Courtesy: Yannick Coutron (CERN)

- Cycle time: <300 ms
- Angular movement: +/-6°

→dump tangential velocity ~0.8 m/s

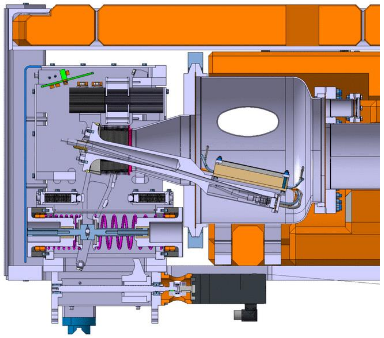
Beam turn after beam turn, the dump intercepts a small fraction of the beam protons





PS Dump Shaving Impact

Dump movement



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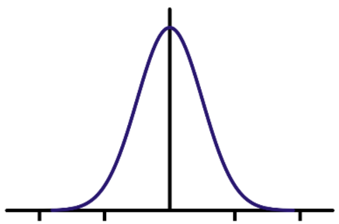
Gaussian beam intensity distribution



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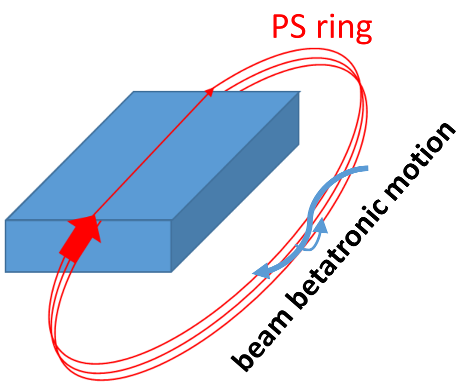
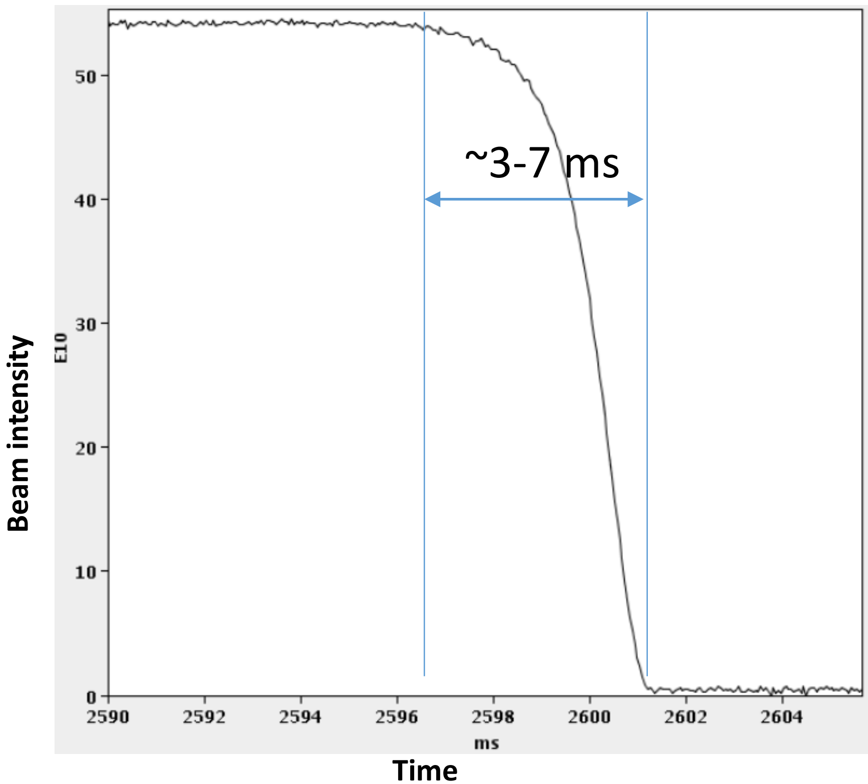
Beam dynamics

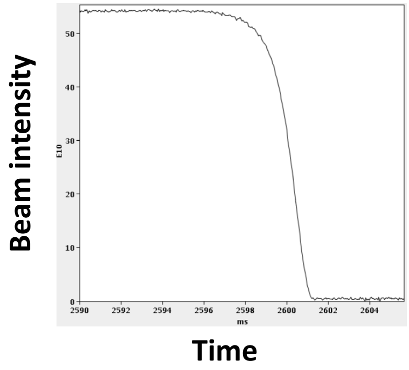


Nonlinear beam intensity drop over time*:

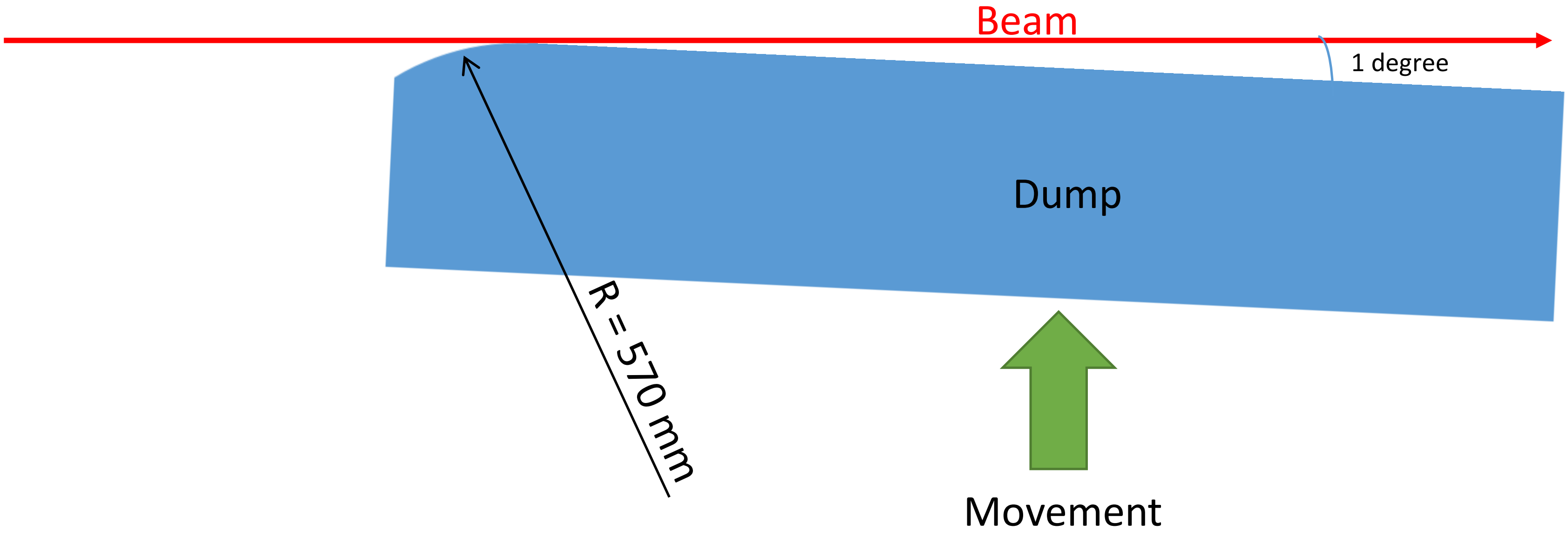


*PS Wall Current Monitor measurement

Nonlinear beam intensity drop over time:



→On a very thin layer of the dump core surface (few tens of microns thick);
→A 1 degree angle is set in order to control the position of the primary impact location.



Project Main Requirements

→ *PS Ring Internal Dump Functional Specifications, EDMS 1582110 v.2.0.*

Main Requirements

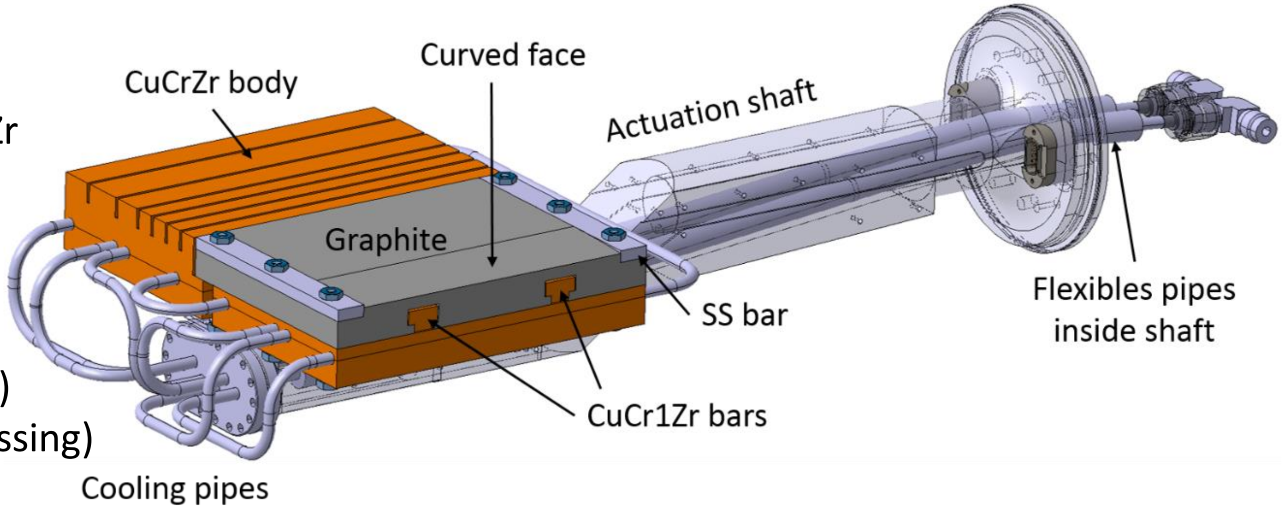
- Dumping time shall be 300 ms
- Beam impact every 1.2 s or 2.4 s for several minutes
- 200 000 cycles / year / dump
- High vacuum (2 x 10^{-8} mbar after 24 h of pumping)
- Geometrical constraints (max 955mm space in Z)
- Short and punctual maintenance (1 per year)
- Lifetime until 2035

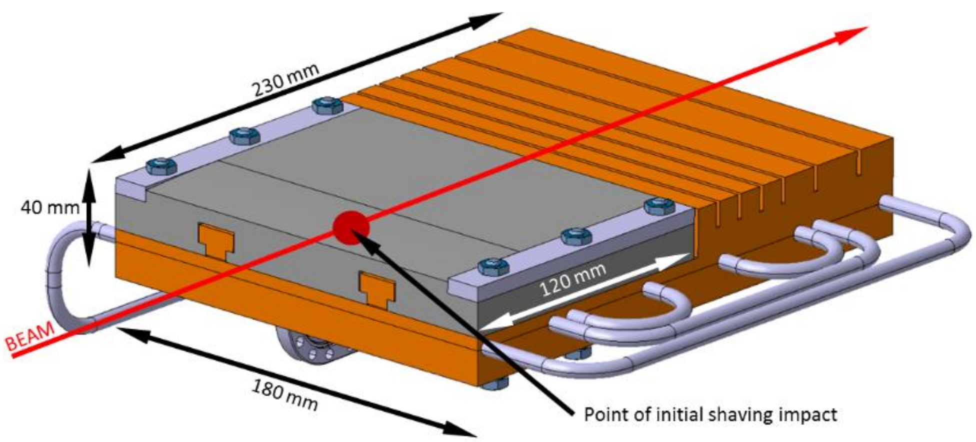
Engineering challenges

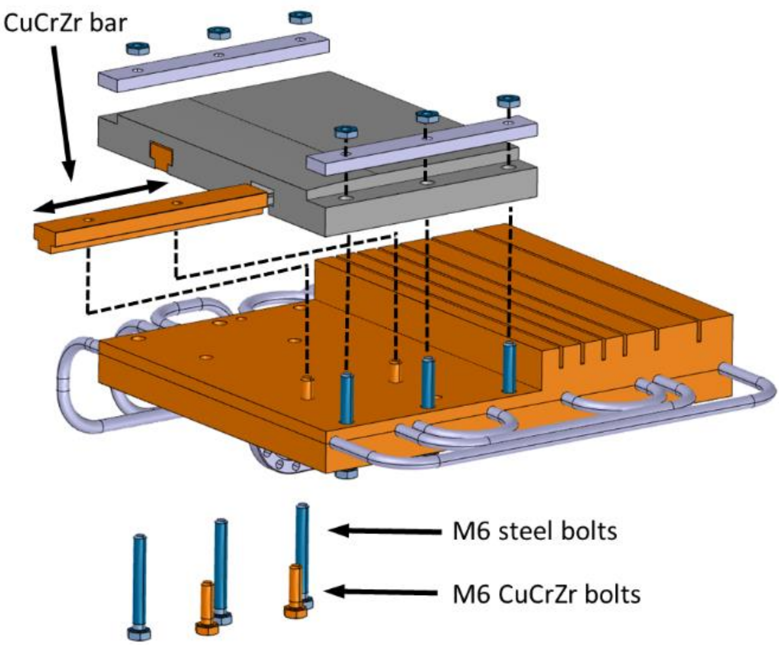
- Minimized dump core mass, considering also proton leakage
- **Thermal management**
- Stress evaluation
- Cooling system inside the vacuum chamber
- **Reliable mechanism**
- Fatigue (mechanism, bellow…)
- **Highly radioactive environment**
- Precise mechanical dimensioning
- Efficient modular shielding
- Material ageing (Gas production and DPA)

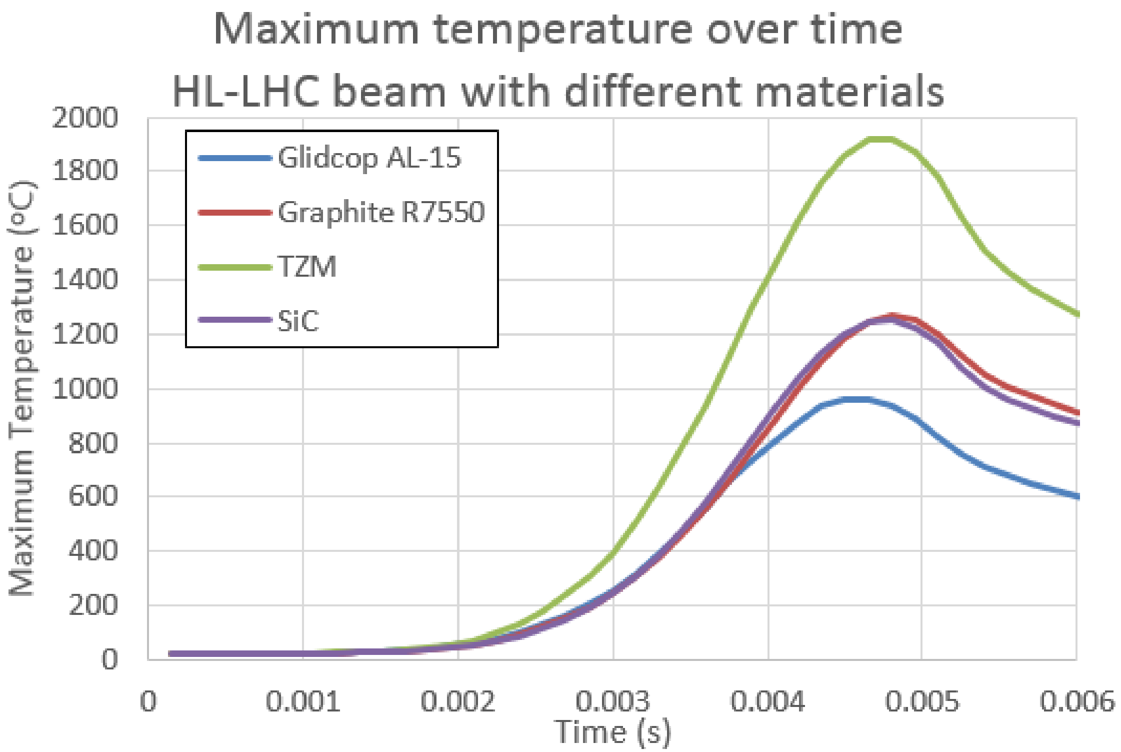
Concept:
Isostatic graphite followed by CuCrZr
Seamless cooling tubes

Two designs studied:
Clamped tubes (mechanical contact)
Diffusion bonding (Hot Isostatic Pressing)







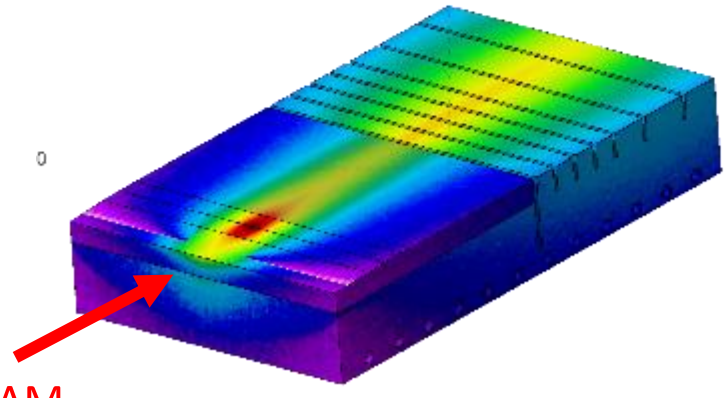


Some low density materials:

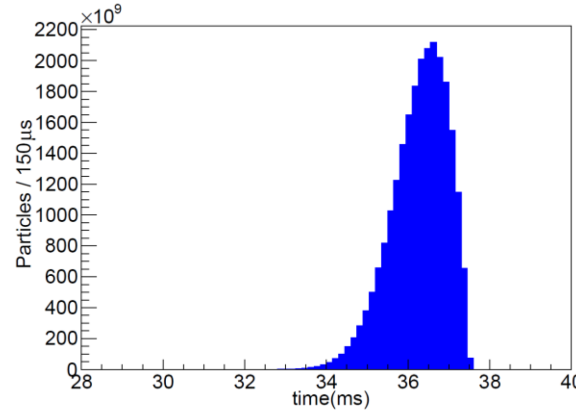
- Graphite R7550
- ~~Silicon Carbide~~ High elastic modulus (~400 GPa) → high stresses. R7550 better known.
- ~~Glassy Carbon~~ Low thermal conductivity ~7 W/(m K)

Energy Density Distribution (Fluka)

HL-LHC beam

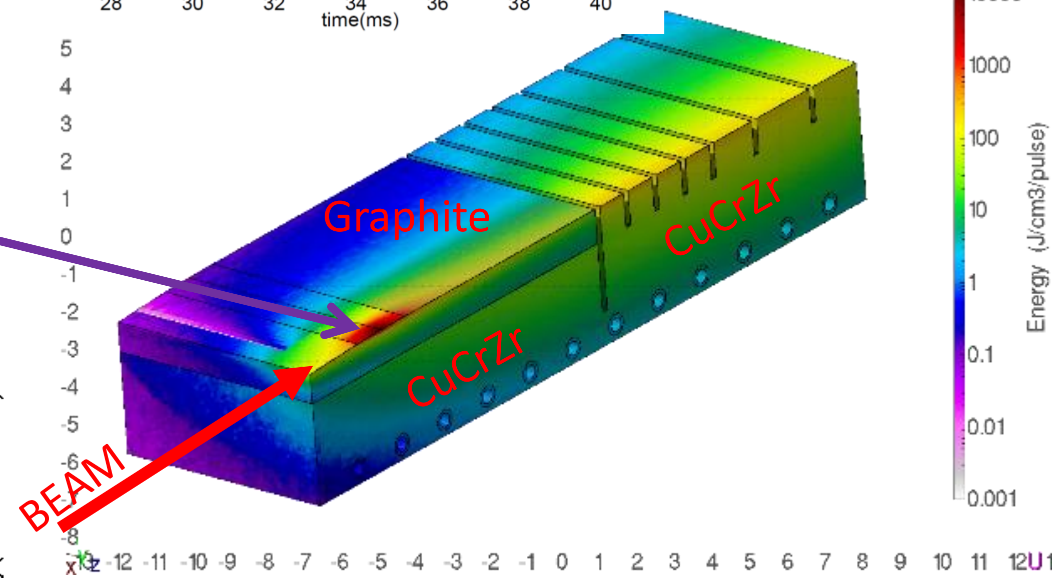


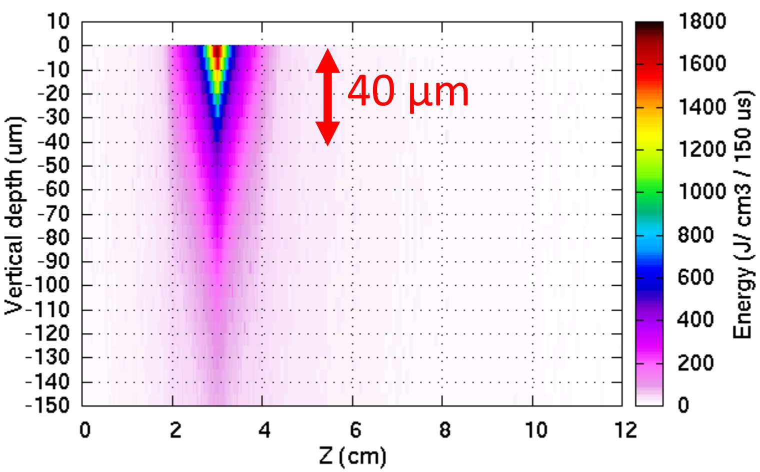
BEAM



Values shown are accumulated per pulse

1800 J/cm³/150 µs
At the surface only





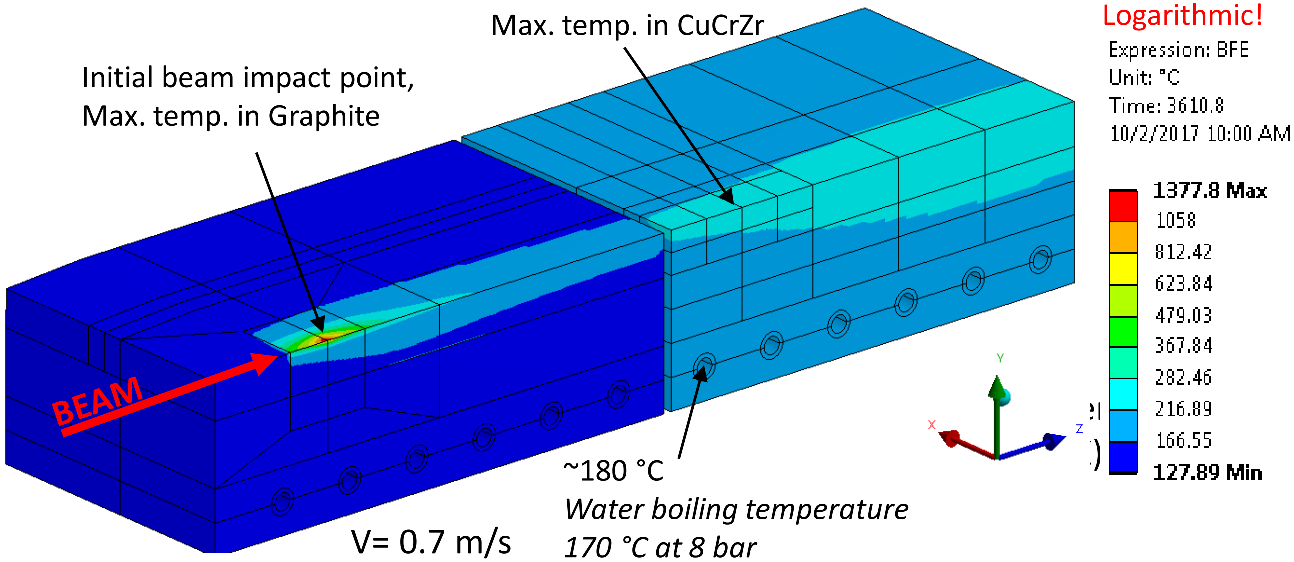
Courtesy: Jose Briz Monago

Thermal Simulation

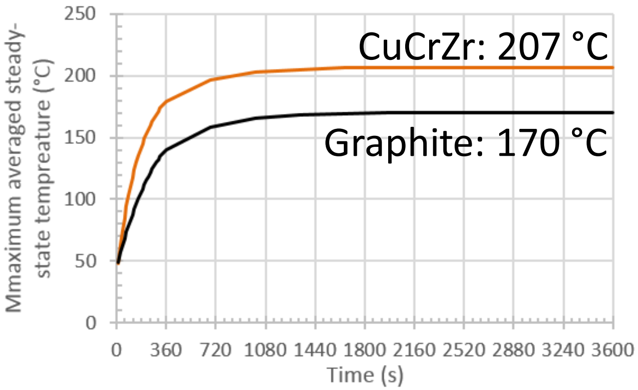
2400×10^{10} protons/3.6 s → 6 8323 joules/3.6 s → 2.3 kW

Beam:	LHC25ns HL-LHC
Intensity	2.4×10^{13}
Momentum	26 GeV/c
Size	1.74 × 0.87 mm×mm
Pulse	Steady-state + 4. pulse

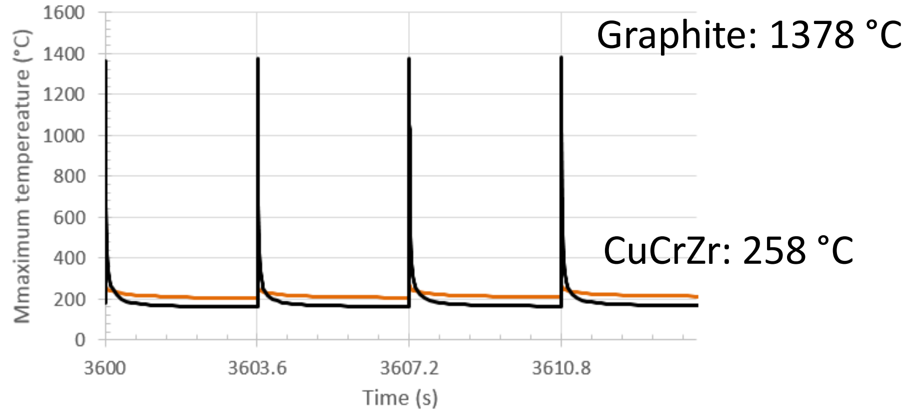
Graphite – CuCrZr
TCC: 1000 W/(m^2 K)



Steady-state

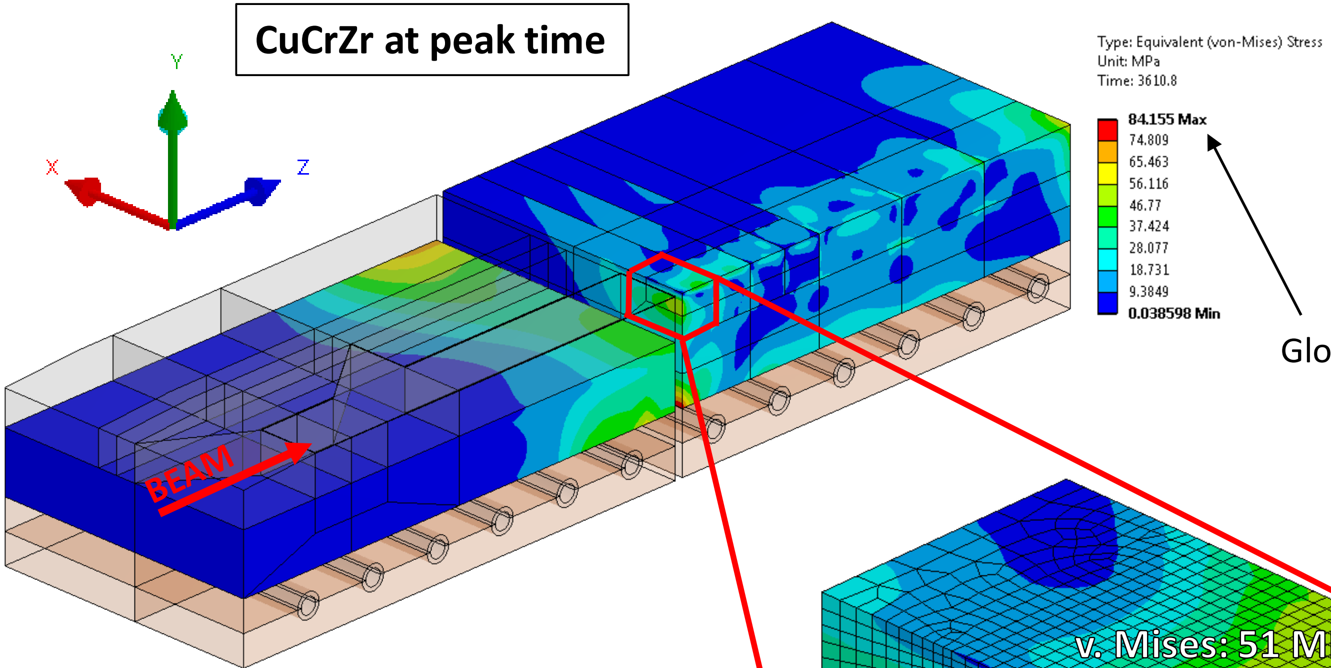


4 pulses – HL-LHC



For boundary condition calculations see: Upgrade of the PS Internal Dump in the Framework of the LHC Injectors Upgrade Project. EDMS No. 1845424 Rev. 0.1

CuCrZr Structural Results, HIP design



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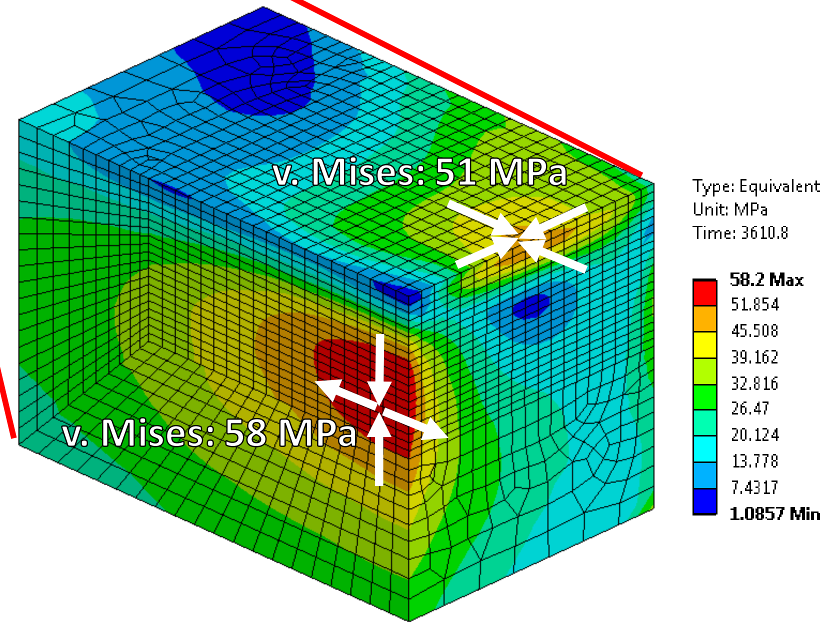
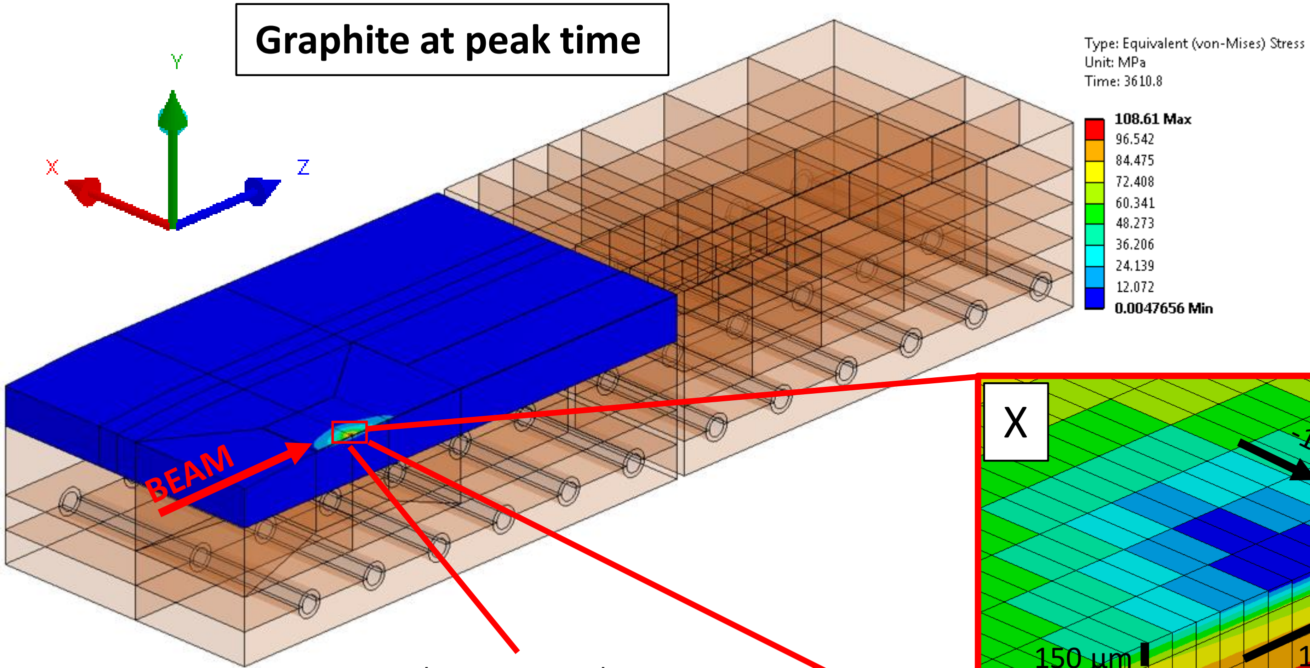


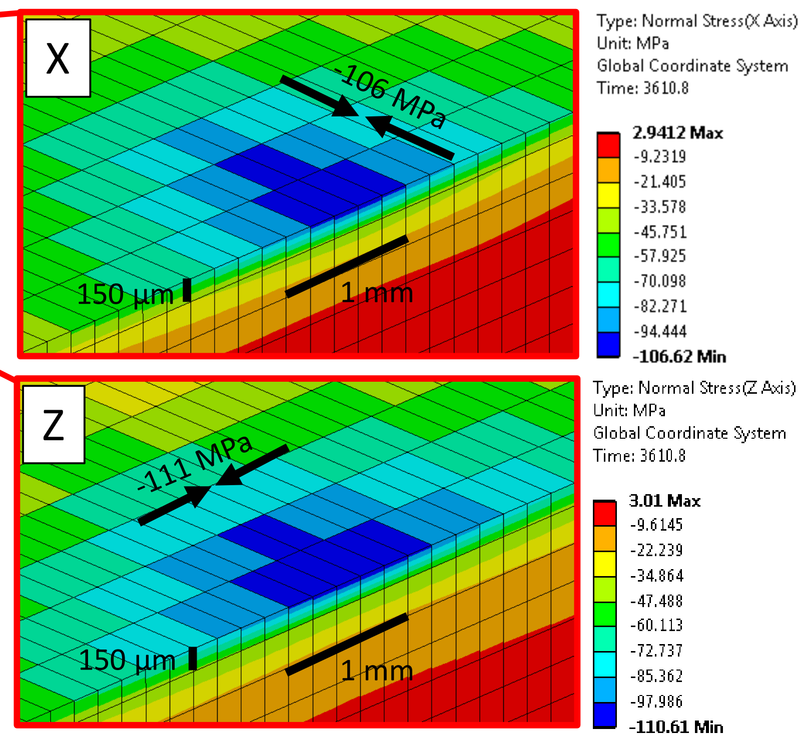
Yield strength (300 °C)	230 MPa
Representative stress	58 MPa
Safety Factor	3.96

Graphite Structural Results, HIP design

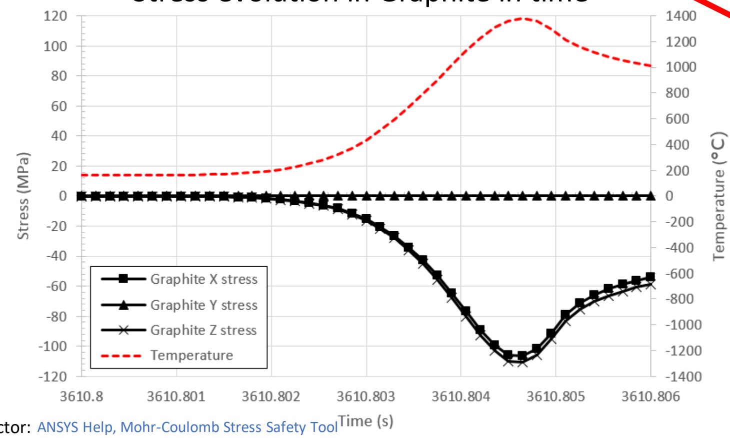
Graphite at peak time



Tensile strength	40 MPa
Comp. strength	130 MPa
Mohr-Coulomb SF	1.17



Stress evolution in Graphite in time



Mohr-Coulomb Safety Factor: ANSYS Help, Mohr-Coulomb Stress Safety Tool

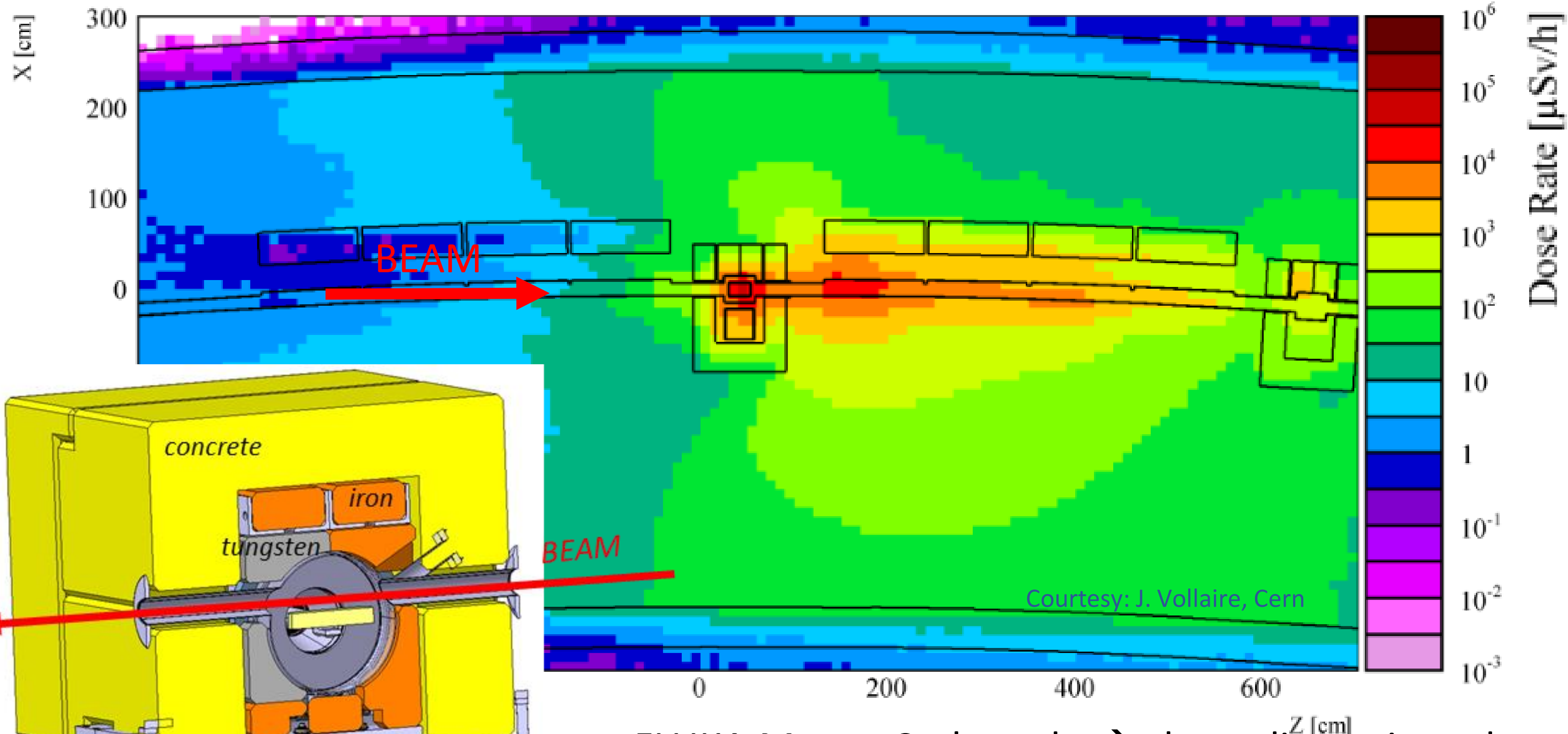
$$F_s = \left[\frac{\sigma_1}{S_{tensile\,limit}} + \frac{\sigma_3}{S_{compressive\,limit}} \right]^{-1}$$

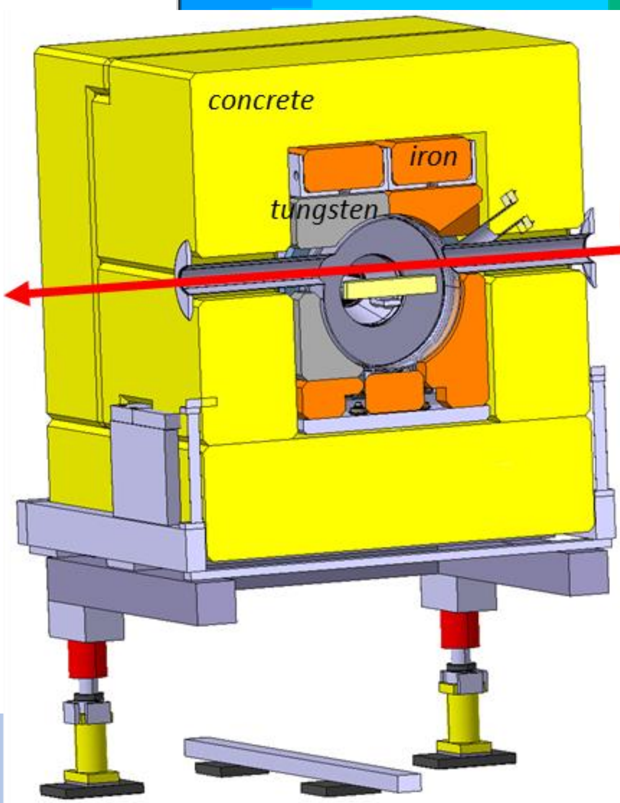
σ1 is maximum principal stress (tensile)

σ3 is minimum principal stress (compressive)

Expected activation after 1 month of cool down

After 10 years of operation: close to 10 mSv/h on the dump, after 1 month of cool down

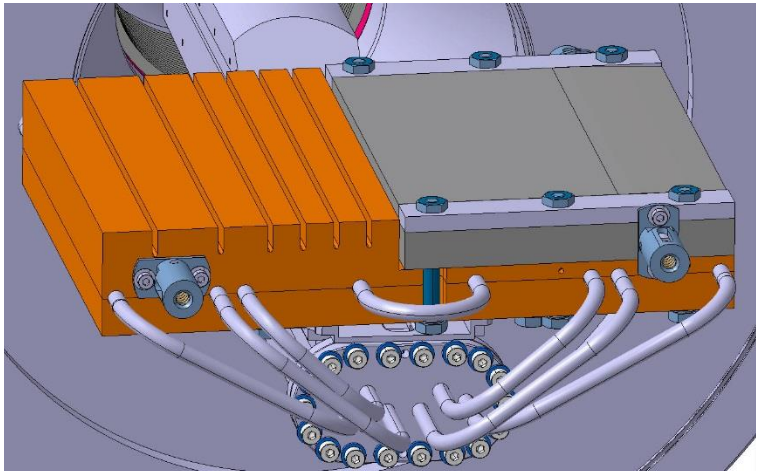
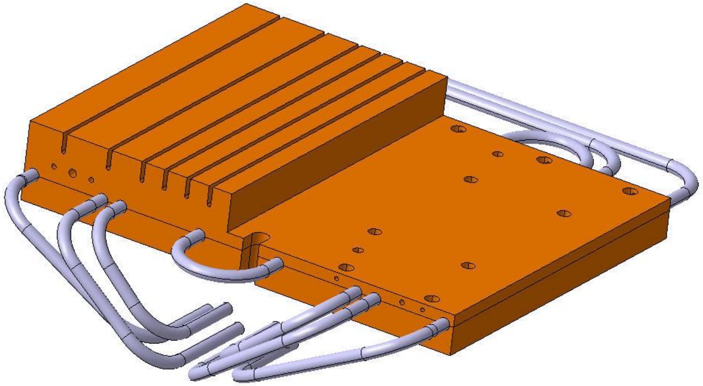




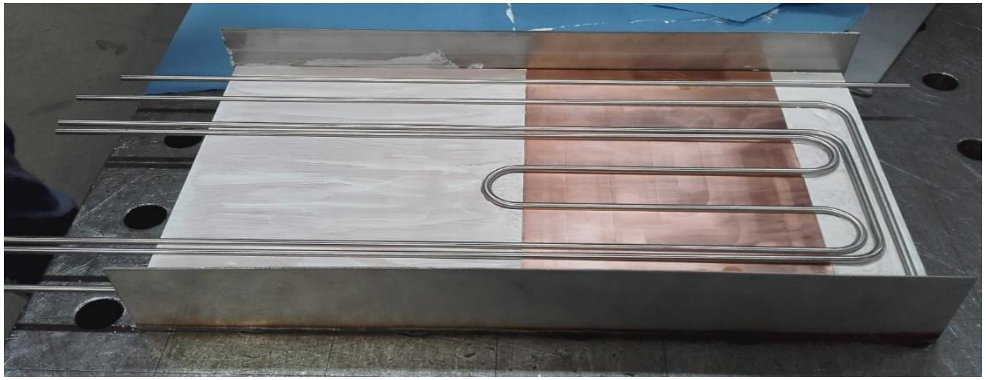
- FLUKA Monte-Carlo code → three dimensions dose rate maps
- Inermet and Concrete as part of the shielding
- For 2.4×10^{17} protons / year to the dump

  →60 kGy / year on mechanism

CuCrZr blocks + 316L tubes
→ HIP process
→ Thermal treatment
→ Final precision machining

Alumina coating of all blocks made of CuCrZr to prevent diffusion bonding to the steel tubes and steel casing during HIP

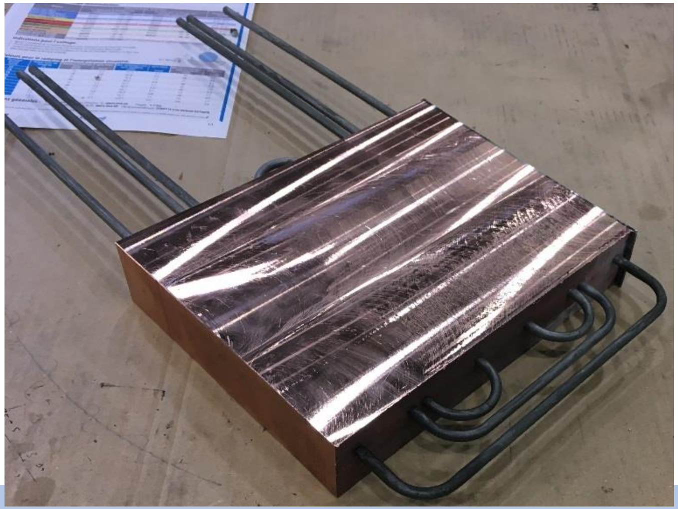
Core Prototyping: HIP Process, Thermal Treatment and Ageing

- Heating and cooling rate of 5 K/min;
- High temperature plateau for 3 h;
- High Argon pressure.

- Solutionizing (high temperature for 30 min in air);
- Water quenching at RT for 10 min (~90º/s);
- Ageing at 500°C for 6h in air.

Steel tubes inner surfaces under vacuum and sealed to limit oxidation during heat treatment

AFTER thermal treatment, ageing and machining



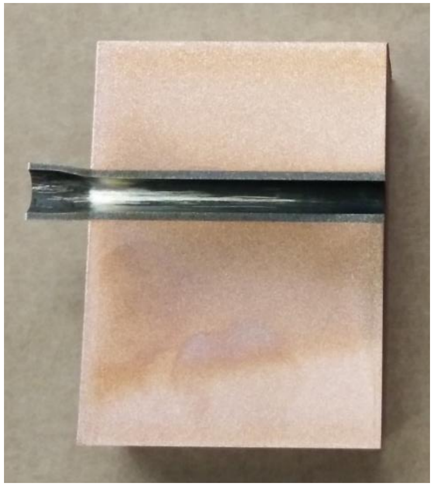
- The CuCr1Zr groove was too large (Ø7 mm, tube → ~Ø6.3 mm)
- At the beginning of the HIP → Pressure increase inside the tube (110 MPa) → tube swelling
- CuCr1Zr housing too large → Tube crack

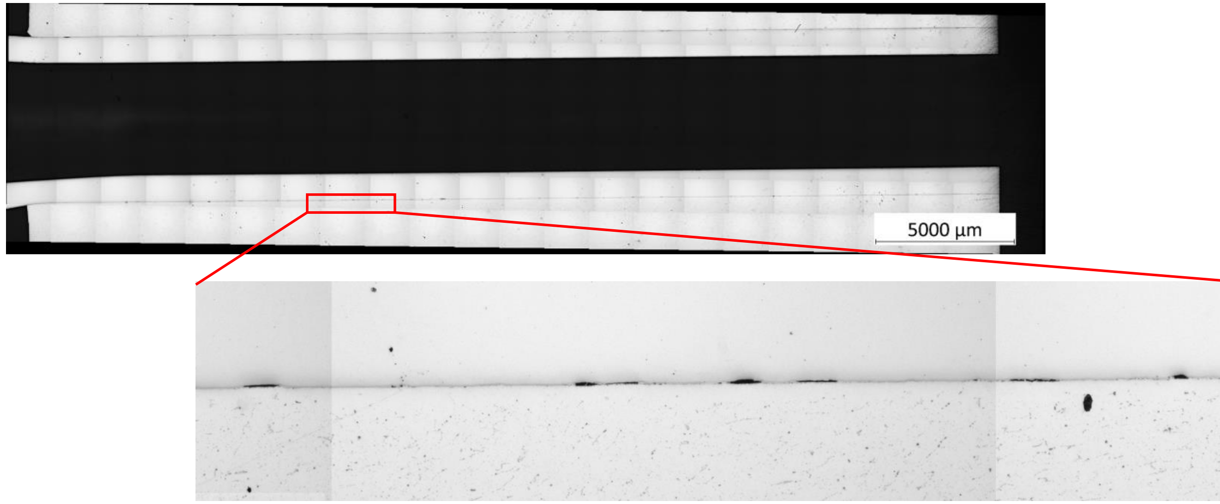
Before HIP

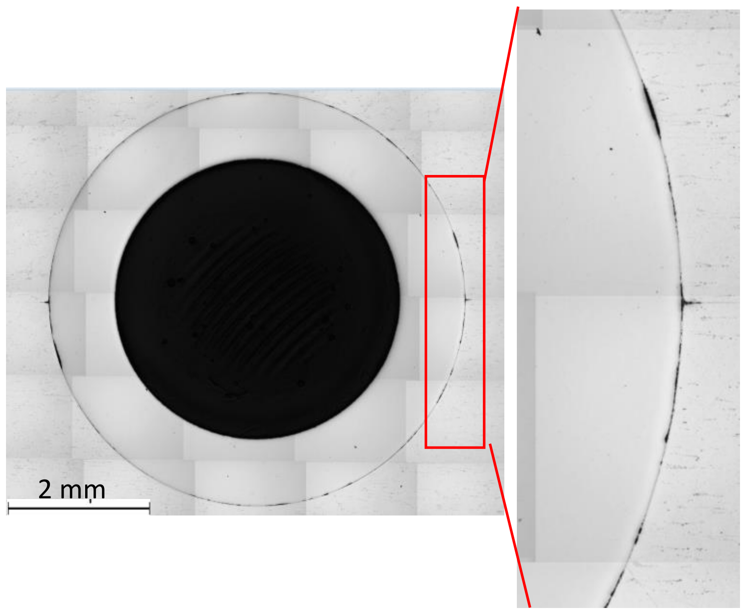
After HIP + Heat treatment

Core Prototyping, Analysis

Optical inspections







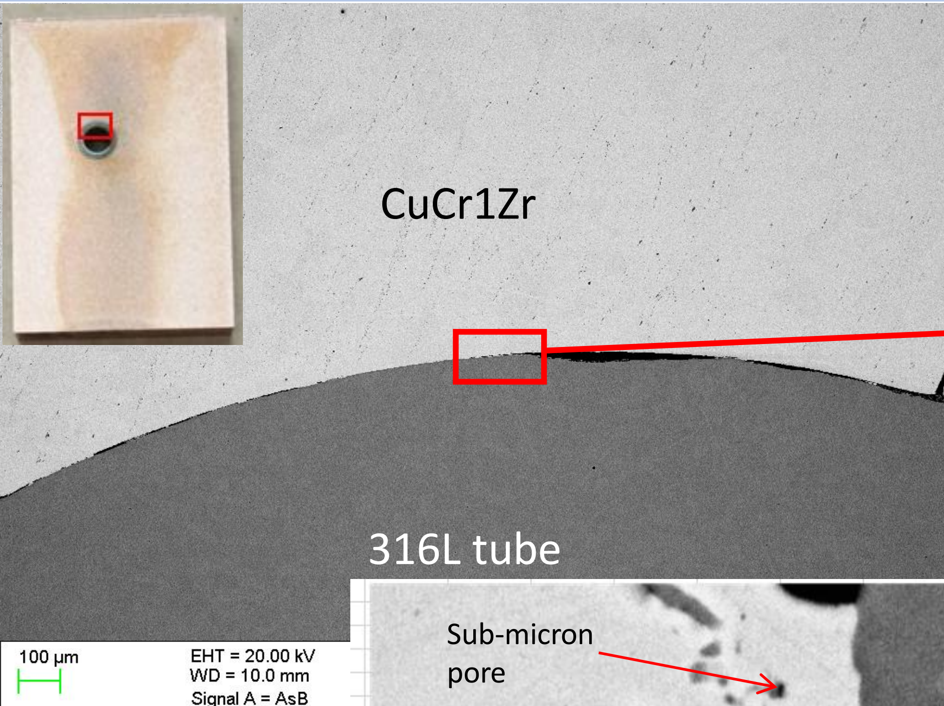
Interface CuCr1Zr-Steel:

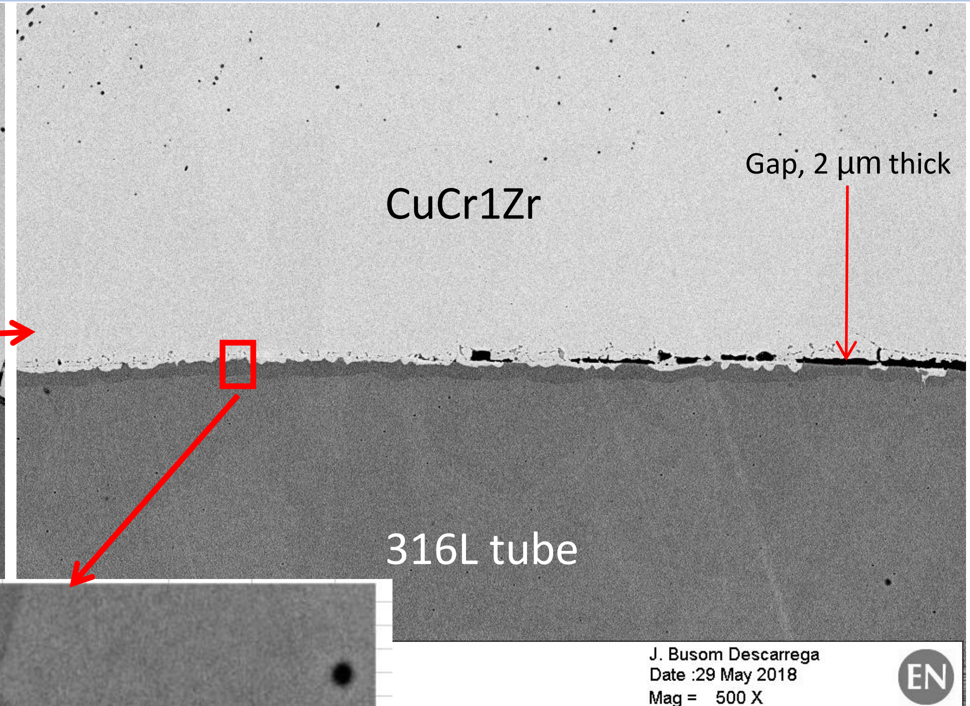
- Clearly visible
- Defects confirmed as voids in the interface (gaps up to 15 µm thick)

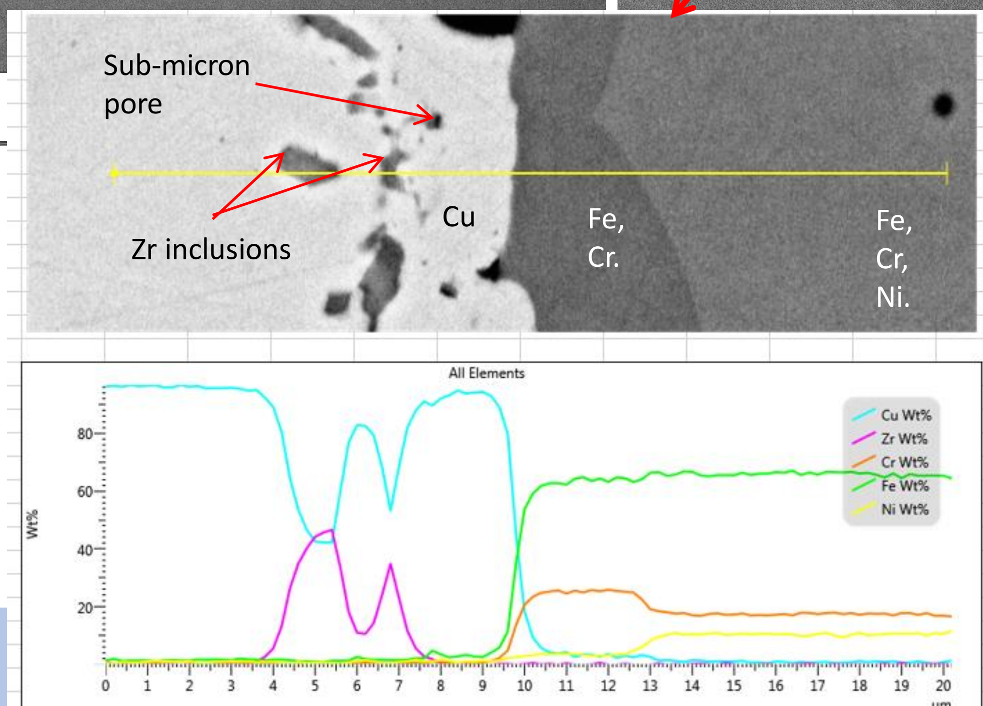
Courtesy: Josep Busom Descarrega

Core Prototyping, Analysis

SEM observations and Energy Dispersive X-ray analysis







At the continuous bonding:

- **10 µm thick interface**
- **Cr and Zr diffusion at the interface**
- **Sub-micrometric pores in the CuCr1Zr due to Kinkerdall effect**

Diffusion bonding accomplished in a part of the interface

Courtesy: Josep Busom Descarrega

PS Internal Dumps – Summary

- Beam Intercepting Device with challenging requirements;

- The **multi-turn shaving** / damping process is a key parameter for the core design;

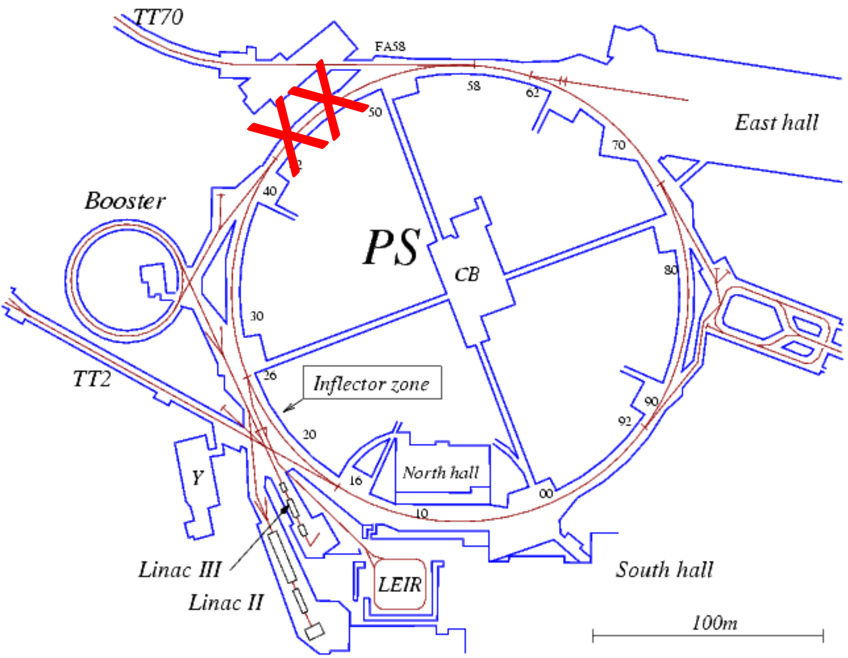
→PS Machine beam circulation simulations output lead to same intensity drop
→4 ms energy deposition time (HL-LHC beam)
→>1000^{o}C temperature gradient over few tens of µm of graphite

- Water cooling is needed as 2.3 kW can be applied for several minutes

- HIP design is challenging but would enhance PS operation from 2020 onwards

- Radiation ageing is not expected to be an issue

- Actuation system is a key sub-system for the equipment reliability



Thanks for your attention