Beam Intercepting Device Challenges for High Intensity Accelerators

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Contributions from: Fermilab, J-PARC, ORNL, RAL

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Acknowledgements

Many thanks to :

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- **Fermilab:** P. Hurh, K. Yonehara, G. Lolov, B. Paley, Y. He, Z. Liu
- **J-PARC:** K. Haga
- **ORNL:** D. Winder
- **RAL:** C. Densham, D. Wilcox

Beam Intercepting Devices

Safety function	Beam cleaning & control	Physics
Beam stoppers	**Collimators**	**Particle producing targets**
Beam dumps	Scrapers	
	Strippers	
	Slits	

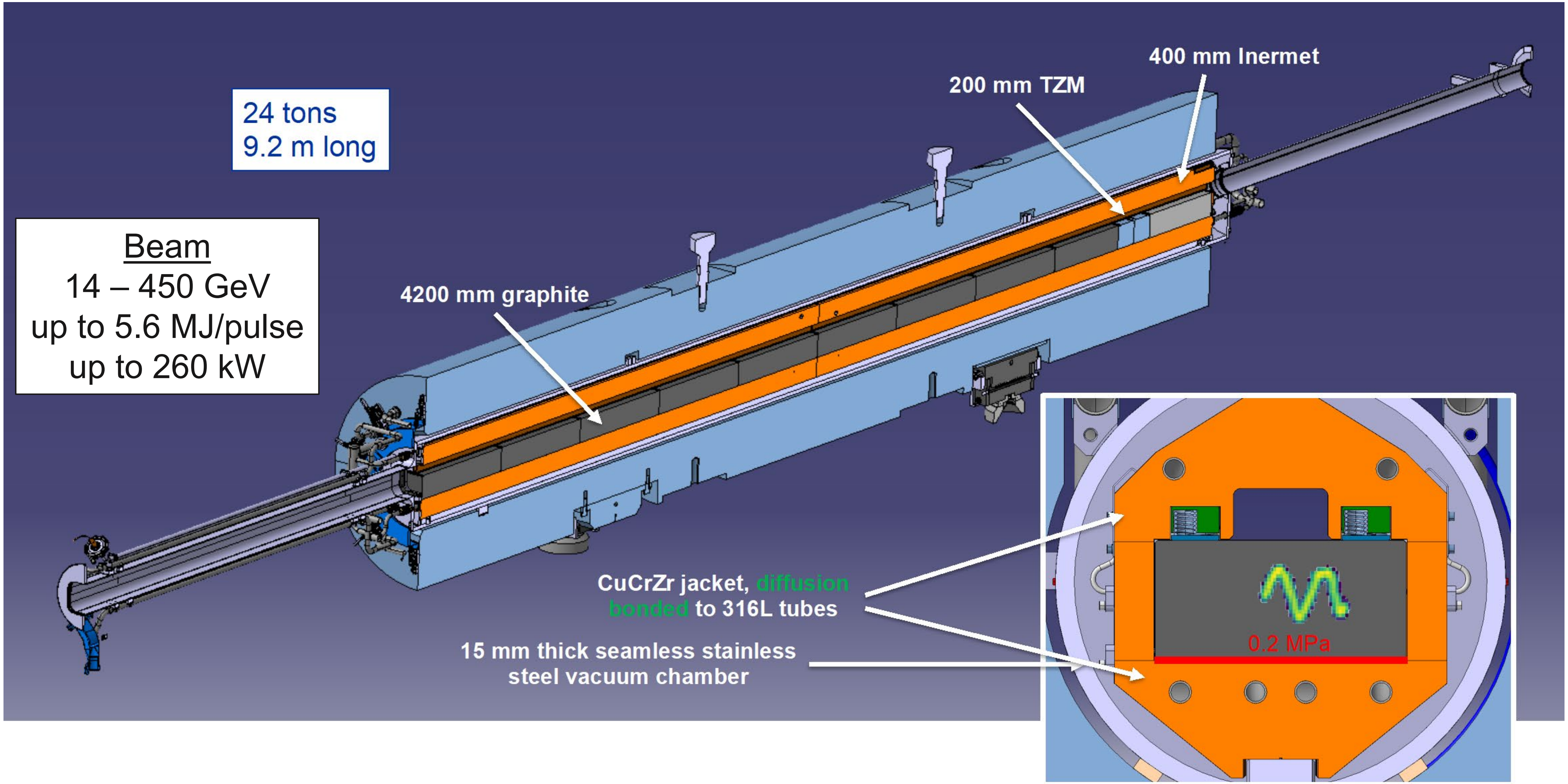
This presentation

NON EXAHUSTIVE compilation of examples of

Beam Intercepting Devices

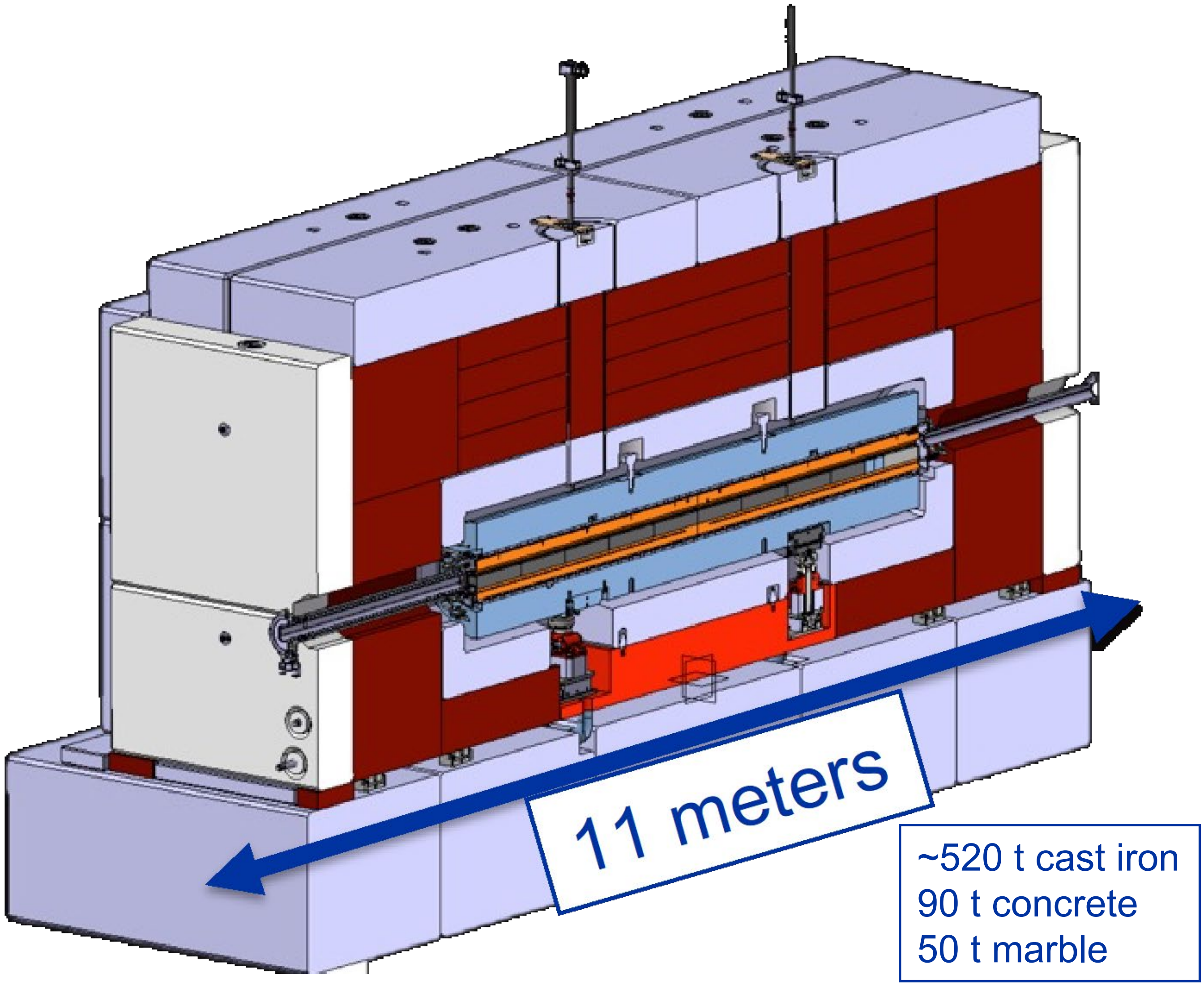
at different laboratories

CERN – SPS Beam Dump (1/3)



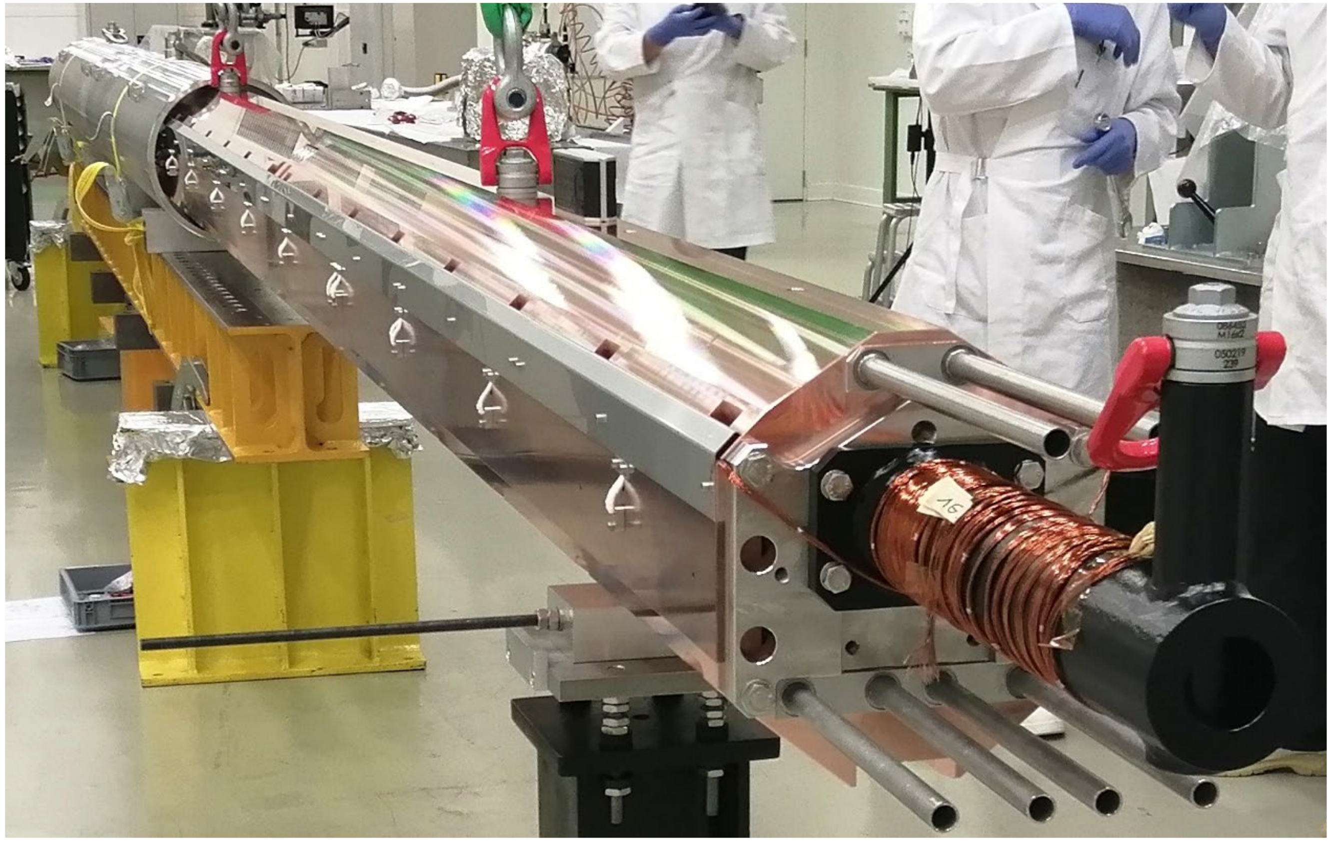
CERN – SPS Beam Dump (2/3)

- **Need to absorb up to 260 kW**
- **Internal dump**
  - In UHV
  - Close to the beam
  - Tight geometrical tolerances
  - Impedance considerations
- **Highly radioactive**
- **Surrounded by massive shielding**
- **No maintenance planned – must be reliable!**

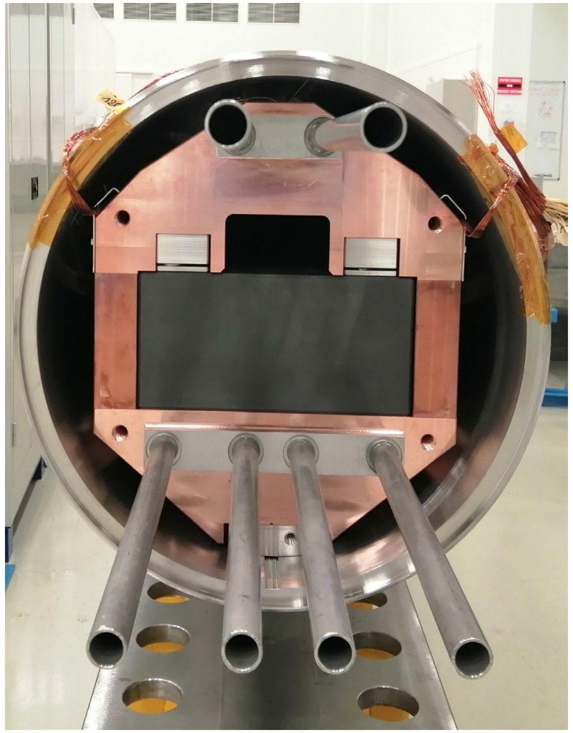


CERN – SPS Beam Dump (3/3)

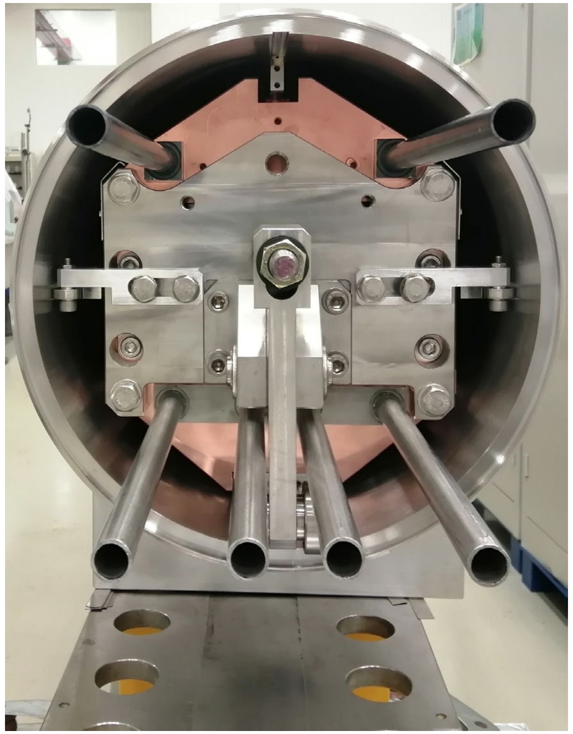
core insertion into the vacuum chamber



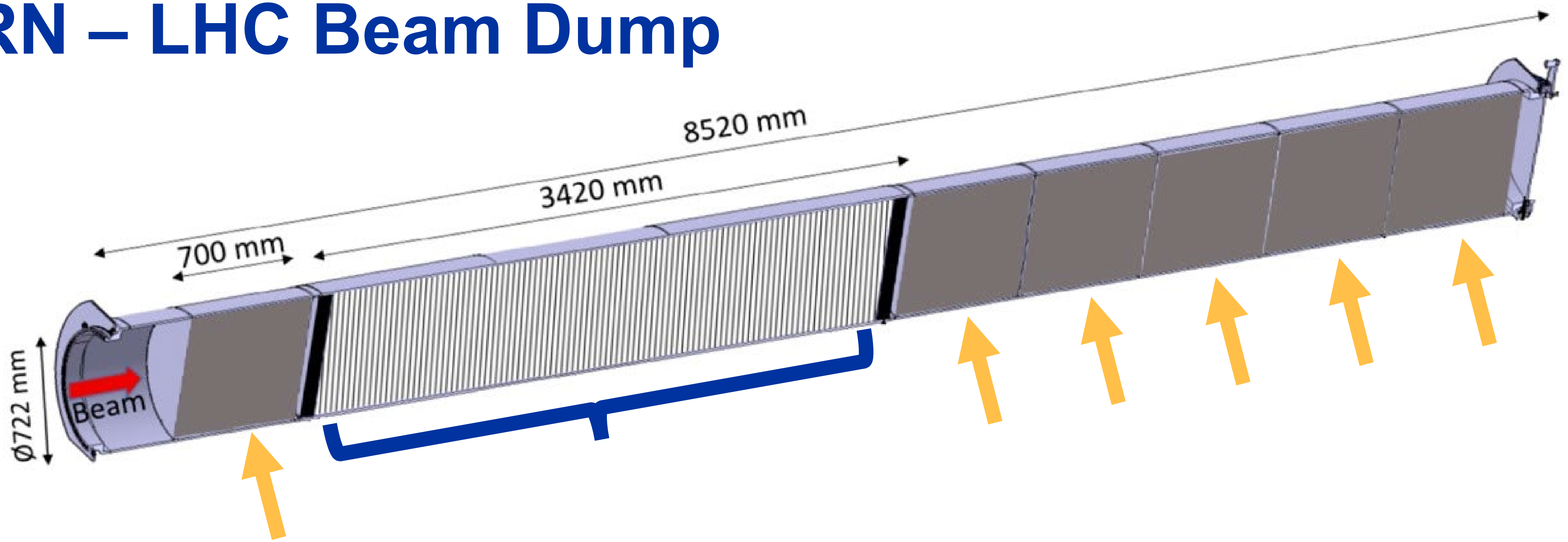
Upstream



Downstream



CERN – LHC Beam Dump



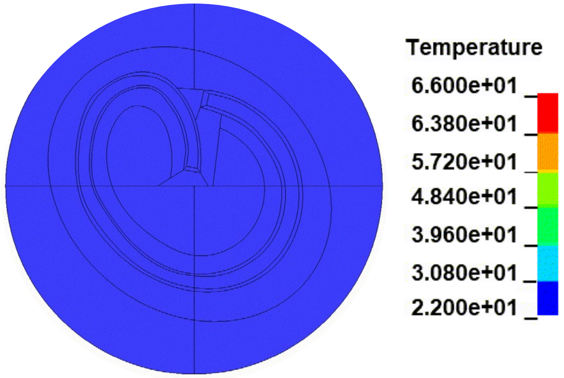
Series of graphitic materials inside 8.5 m-long 318LN duplex stainless-steel vessel

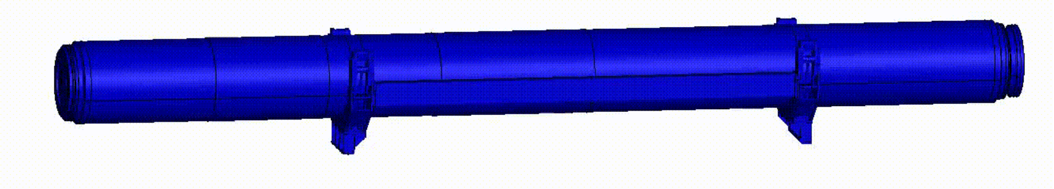
- 6 High-density (1.73 g/cm^3) blocks ***shrink fitted*** inside
- 3.5 m-long Low-density (1.2 g/cm^3) Sector: expanded graphite sheets ***placed*** inside the vessel with radial play

Thanks to N. Solieiri and M. Calviani

CERN – LHC Beam Dump

Beam painted onto the dump face in 86 μs

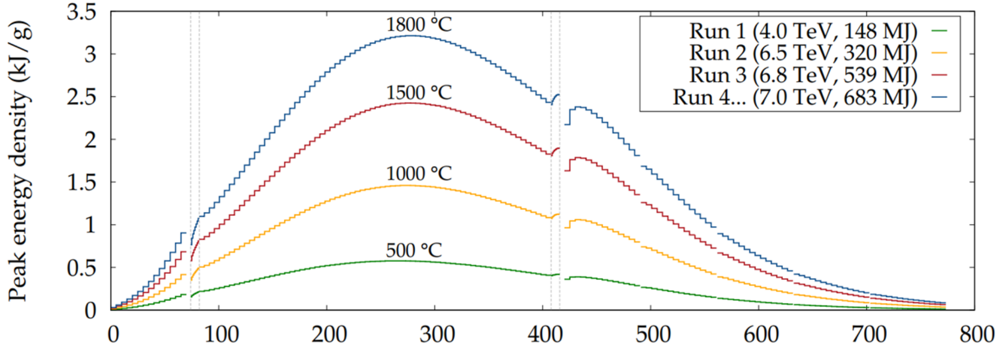




LHC beam kinetic energy will reach **680 MJ** with HL Upgrade

	Run 1 (2009–2013)	Run 2 (2015–2018)	Run 3 (2022–2024)	HL-LHC (2027–)
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

501 MJ in graphite
29 MJ in vessel



Thanks to N. Solieiri and M. Calviani

CERN – LHC Beam Dump

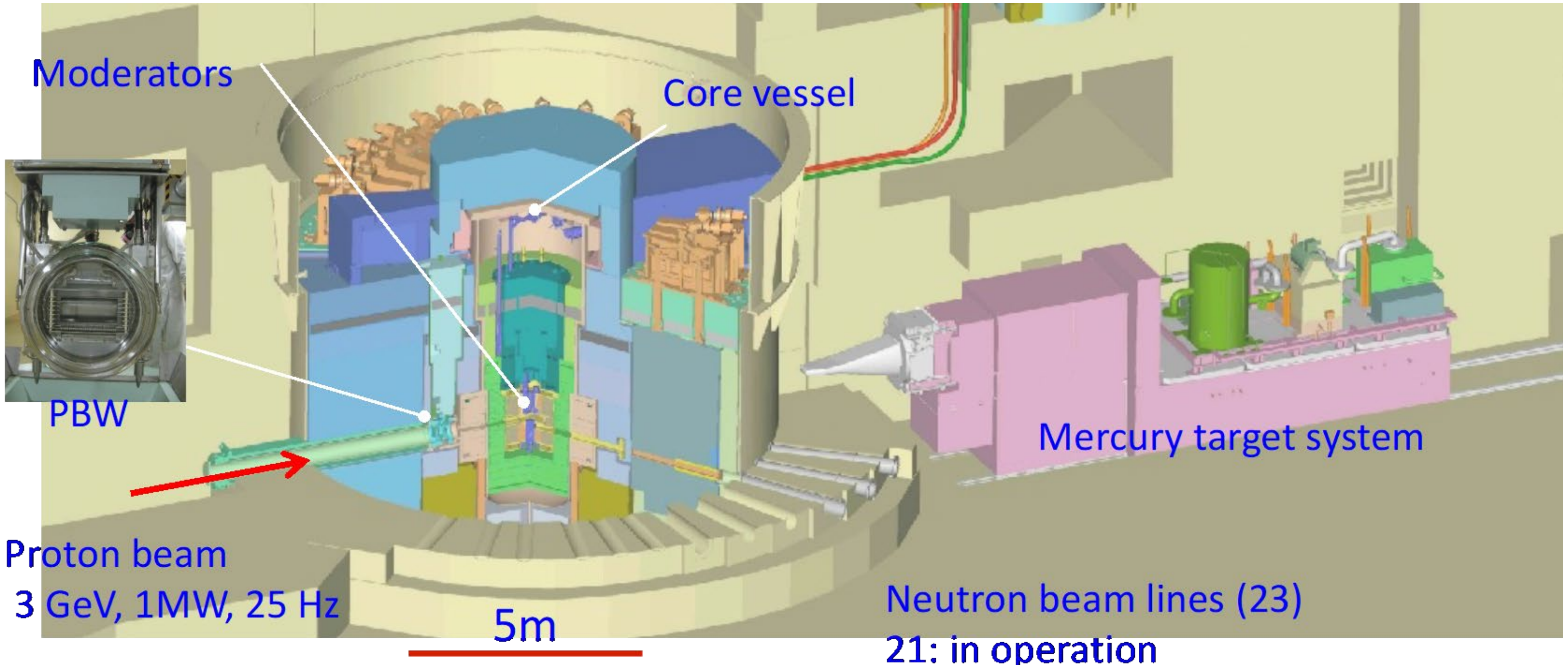
Thanks to N. Solieiri
and M. Calviani

Main challenges for upgraded version

- Predict carbon-based material behaviour under such conditions → select the most adapted materials
- Vessel material / manufacturing techniques (Ti6Al4V or 318LN, EBW or TIG)
- Instrumentation
- Cooling

J-PARC – 1MW SNS (Mercury Target)

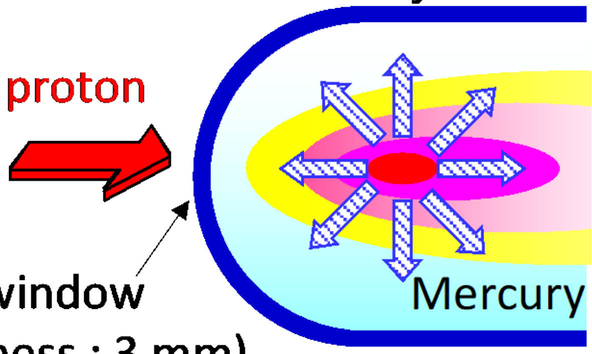
- Cavitation damage induced by pressure wave of mercury degrades structural integrity of the target vessel extremely faster than lifetime estimated by radiation dose (Design : 2500 MWh at 5 dpa)
- Damage increases with beam power
- Development of damage mitigation technology is one of the key Issues to achieve 1 MW operation.



Thanks to K. Haga

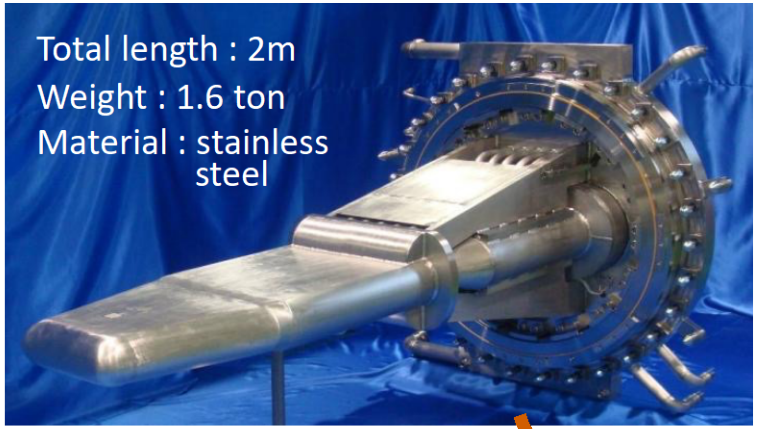
J-PARC – SNS Target

Pulsed proton beam

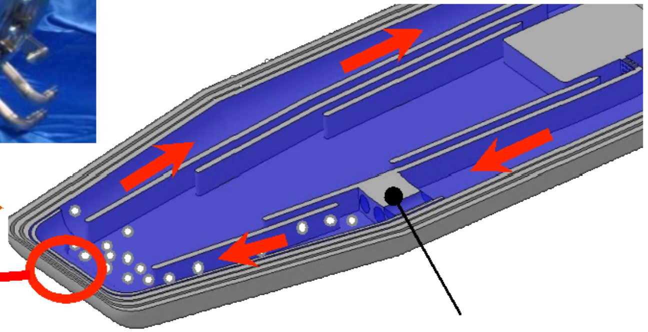


Beam window
(Thickness : 3 mm)
Most vulnerable to pitting damage

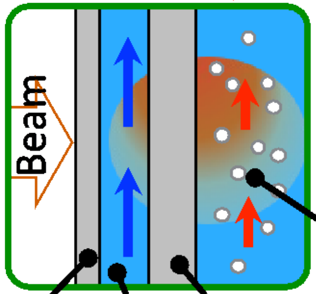
Abrupt heating of mercury
Thermal expansion
Pressure wave
Cavitation damage of the wall



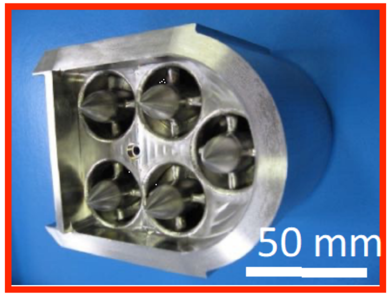
Damage mitigation by micro-bubble injection technology and double walled structure

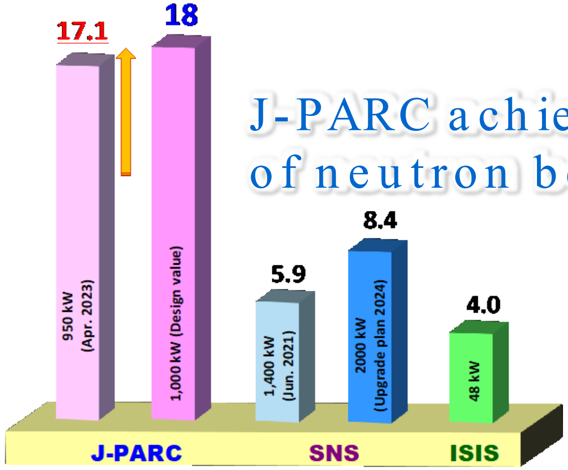


Double-walled structure



Swirl-type bubbler developed in J-PARC





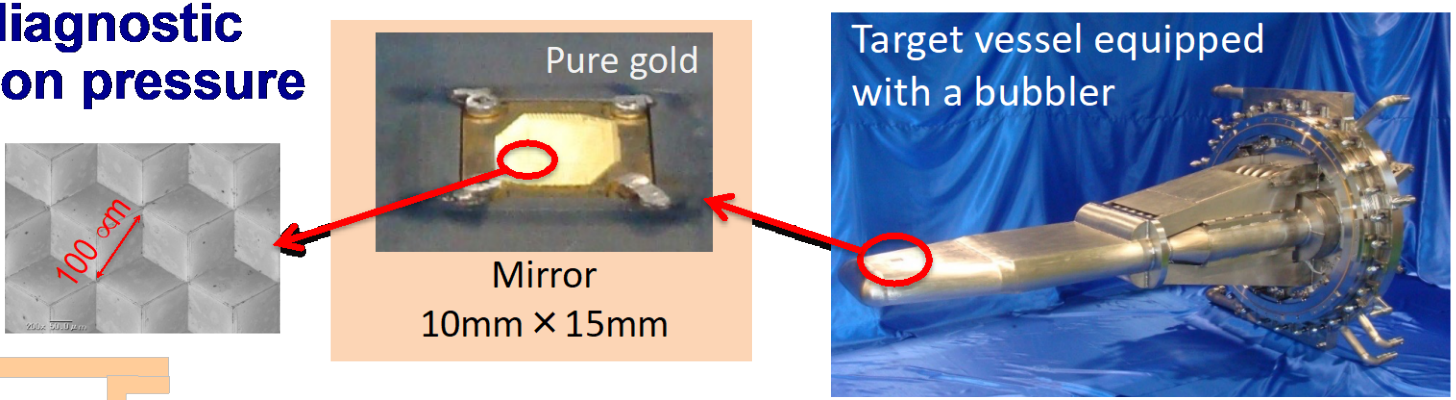
J-PARC achieved the world record of neutron beam intensity !

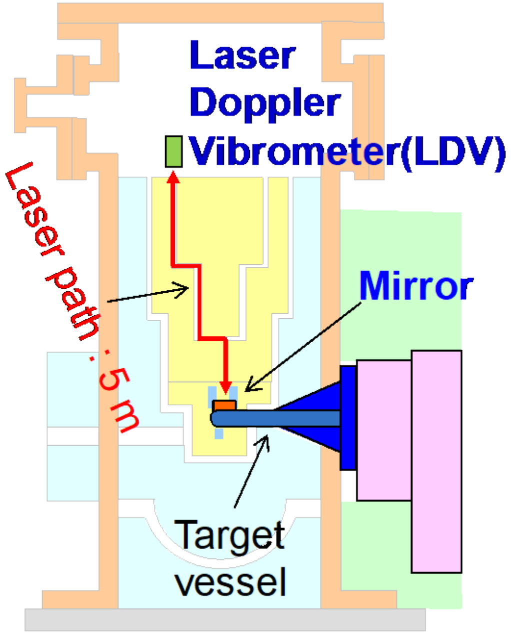
unit: 10^{12} n/(sr□ pulse)

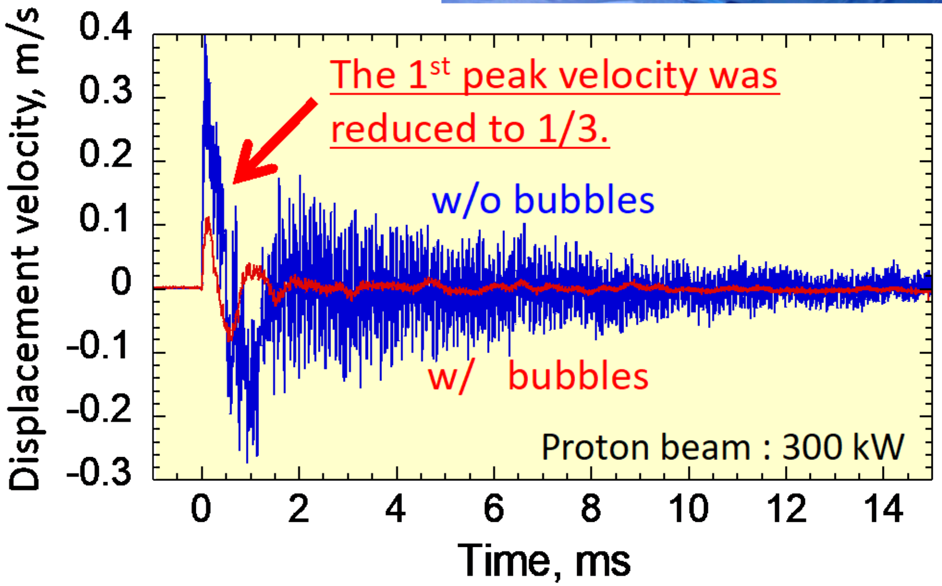
Thanks to K. Haga

J-PARC – SNS Target

In-situ diagnostic system on pressure waves







Excellent bubbling effect to mitigate pressure waves was demonstrated.

Thanks to K. Haga

ORNL – SNS Target Stations

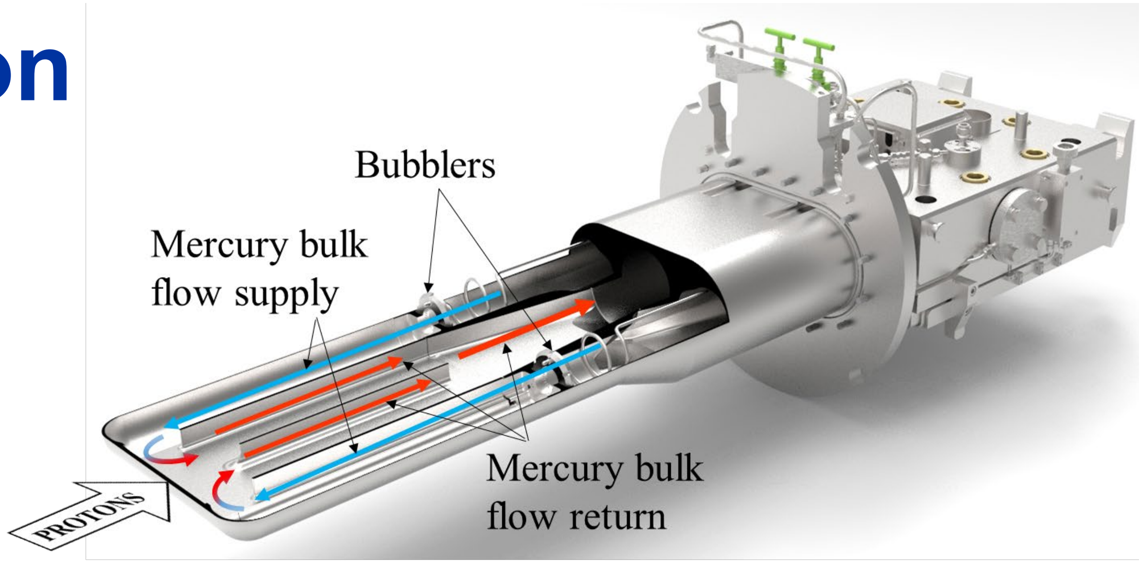
- SNS being upgraded to 2.8 MW, 1.3 GeV protons, 0.7 μs pulses at 60 Hz
  - 1st target station – 2 MW, liquid mercury spallation target, operating since 2006
  - 2nd target station – ~0.7 MW, solid target, design underway
- Main Challenges
  - Smaller, more compact targets are generally better, but provide more challenges to target reliability
  - Lack of comprehensive testing – Can’t replicate the complete target environment anywhere except in operation
- System reliability – The SNS aims at operating >5,000 hours/year, with >90% availability

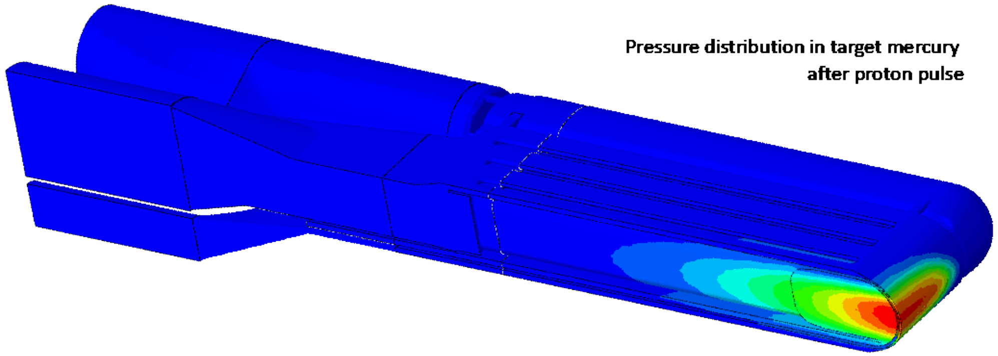
2 MW Target Module
(1st target station)

Thanks to D. Winder

ORNL – SNS 1st Target Station

- Pulsed beam leads to fatigue and cavitation
  - Gas injection pioneered at J-PARC has been a major improvement
- Radiation damage leads to material embrittlement
- Activation and mercury hazards make maintenance difficult
  - 17 years of operation means obsolescence and reliability challenges
- Successful (after many lessons learned) at 1.4 MW, now ramping to 2 MW

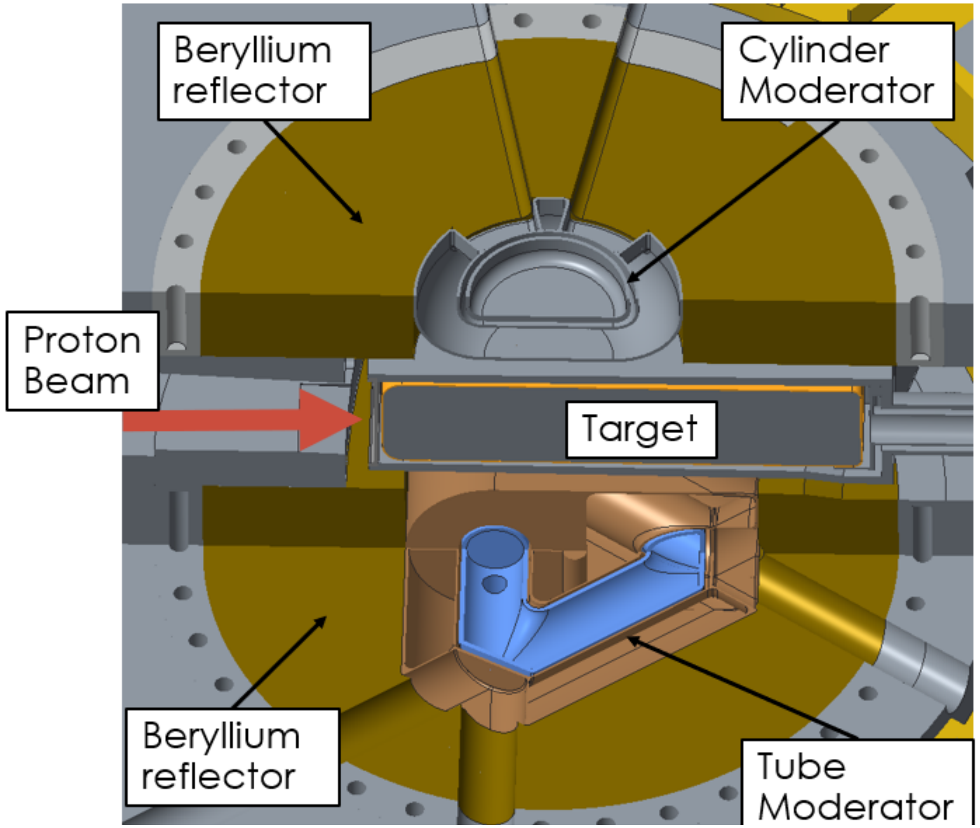


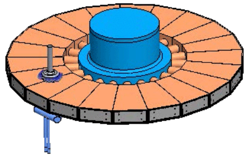


Each beam pulse spikes pressure in the mercury to over **250 atm** (25 MPa or 3,700 psi).

ORNL – SNS 2nd Target Station

- Design criteria for target materials and systems
  - Past experience from other facilities can be a guide, but need to improve on the state-of-the-art
  - Tungsten material properties is a challenge. Addressed by planned encapsulation
- Compact beam for high neutron brightness
  - Balancing design risk with performance gains





Thanks to D. Winder

CERN – n_TOF Spallation Neutron Target

Thanks to M. Calviani

- 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

Beam kinetic energy = 27 kJ , beam pulse = 7 ns → Instantaneous power = 3.8 TW

Target #1 (1999-2004)

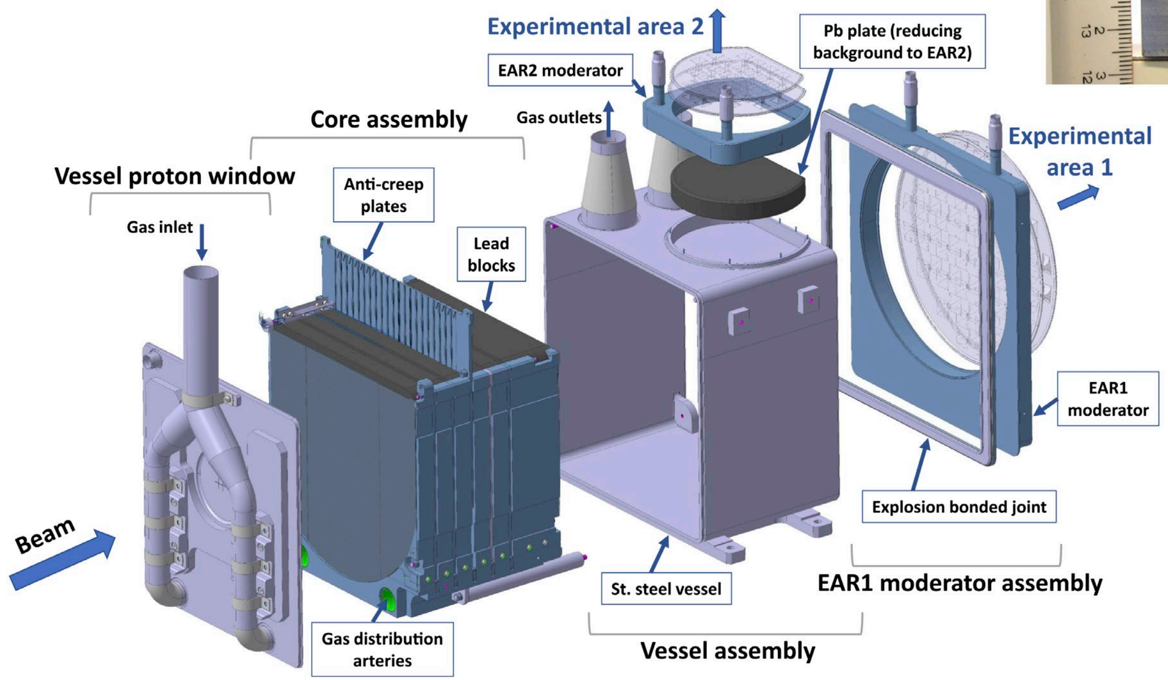
Pure Pb used as target material

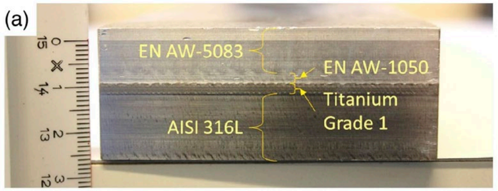
Target #2 (2008-2018)

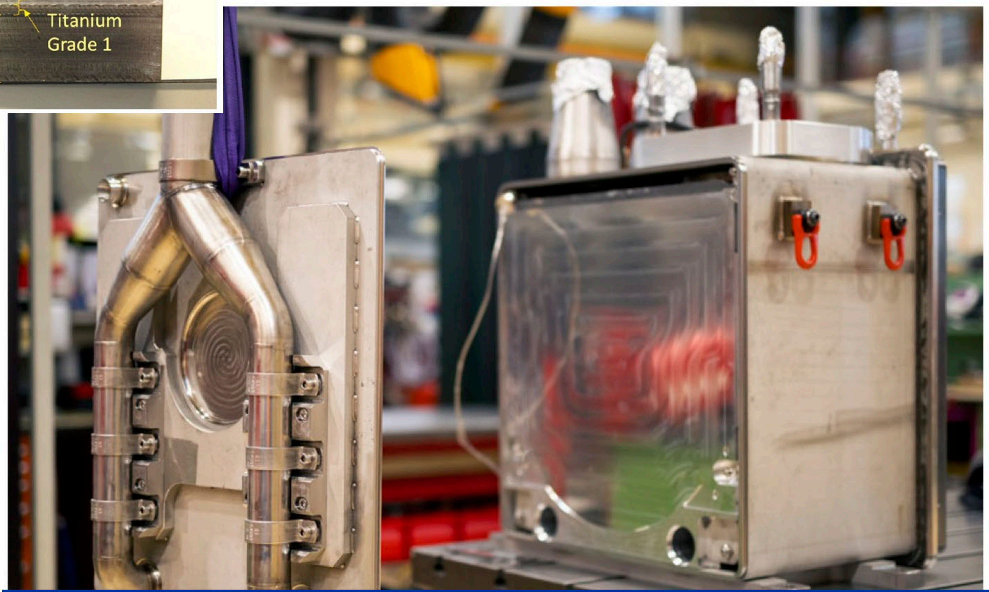
CERN – n_TOF Target (3rd generation)

Thanks to M. Calviani

- 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







Focus – **reliability** & **physics performance**

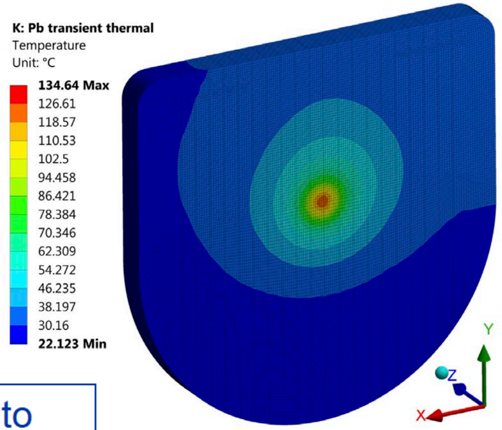
Phys. Rev. Accel. Beams 24, 093001 (2021)

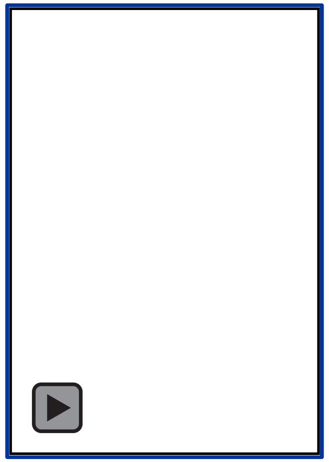
N_TOF Target challenges/limitations

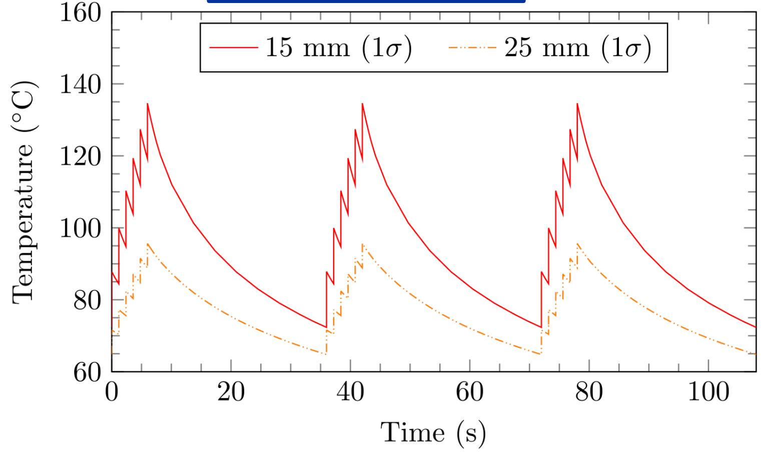
Thanks to M. Calviani

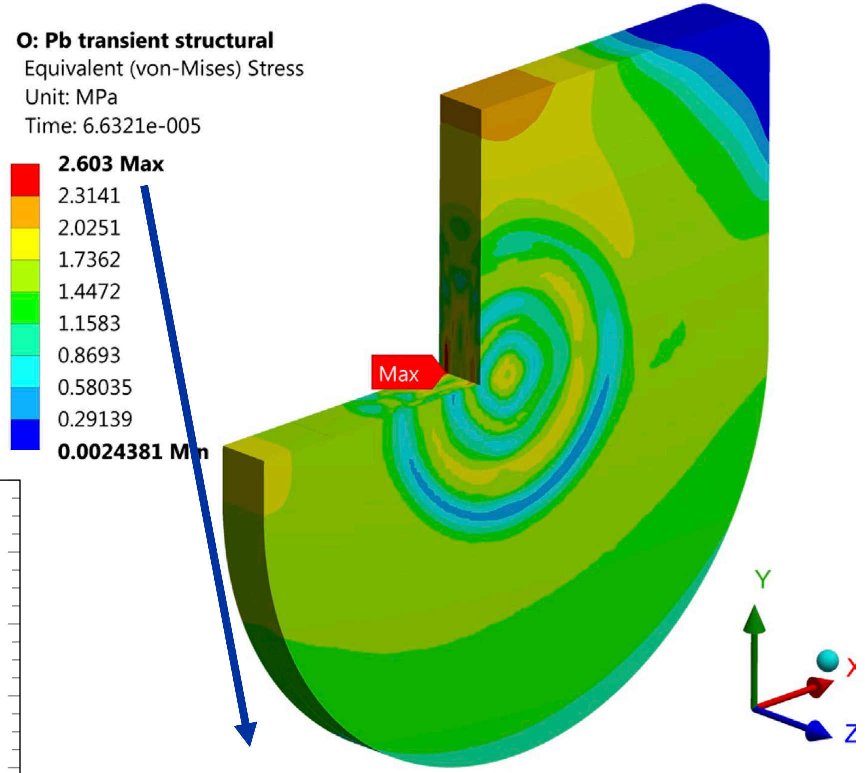
- Pb is a non-structural material, low melting point, very low yield stress

0.7 T_m

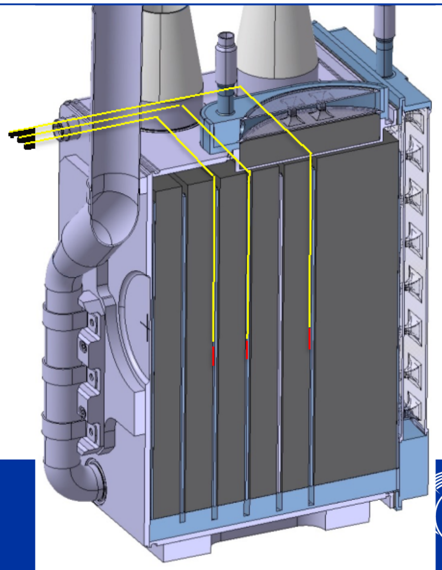








6 type-K thermocouples to monitor Pb surface temperature

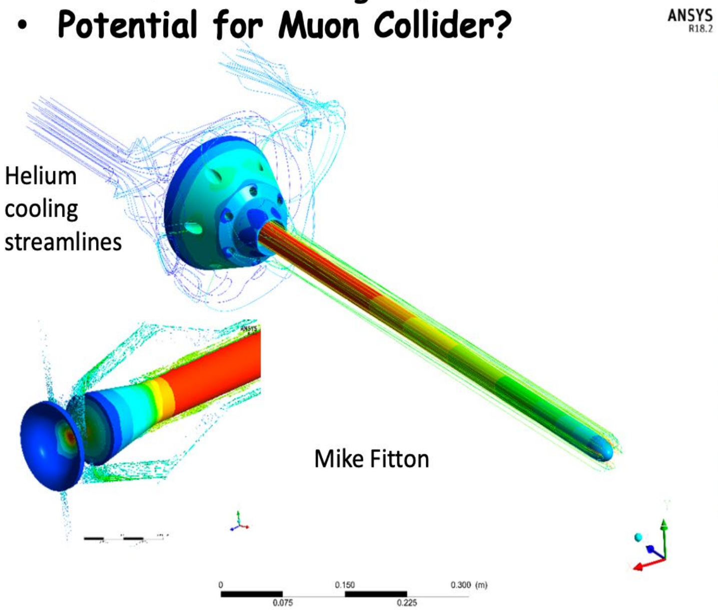


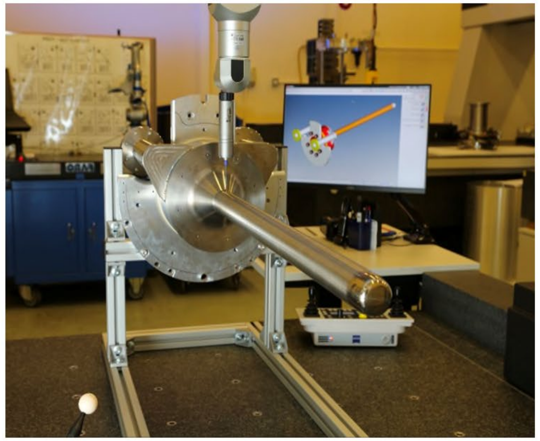
2.6 MPa vs. 1 MPa (plastic flow onset)

Neutrino Targets (T2K & LBNF)

T2K helium cooled graphite target
- 12 years good experience

- Stable operation at 500 kW at 30 GeV
- 1.3 MW prototype constructed and ready for installation
- Basis for LBNF target for 1.2 MW at 120 GeV (2.4 MW upgrade planned)
- **Potential for Muon Collider?**





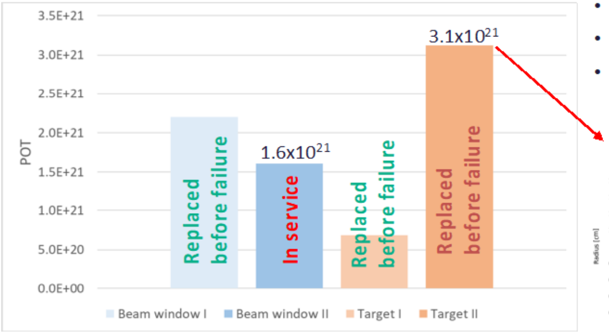
Survey of T2K target using Co-ordinate Measuring Machine (CMM) at RAL.

CT scans of prototype 1.3 MW target

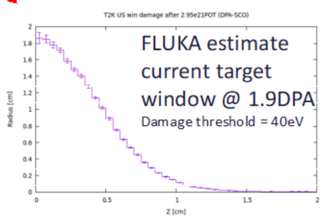
International UON Collider Collaboration

Science & Technology Facilities Council
Rutherford Appleton Laboratory

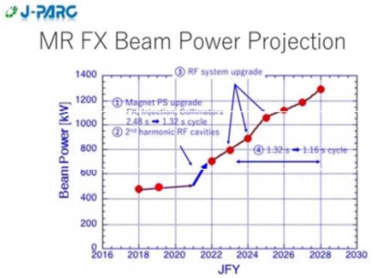
Titanium beam windows:
Good experience so far on T2K at 500 kW



- How long will a Ti-6Al-4V window/target last?
- Target currently has highest POT ~3 x 10^{21} POT
- C.2 DPA – c.10x BLIP sample data so far(c.0.24 DPA)



Future plans	PPP	rep rate	current (A)	Beam power (kW)	Run time (mths)	POT/yr
2021	2.64E+14	2.48	1.71E-05	512	4	7.28E+20
2022	2.20E+14	1.32	2.67E-05	801	3	8.55E+20
2023	2.48E+14	1.32	3.01E-05	903	4	1.29E+21
2024	2.24E+14	1.16	3.09E-05	928	4	1.32E+21
2025	2.80E+14	1.16	3.87E-05	1160	2	8.26E+20
2026	2.96E+14	1.16	4.09E-05	1227	4	1.75E+21
HK	3.20E+14	1.16	4.42E-05	1326	6	2.83E+21



Similar DPA/year for LBNF at 1.2 MW

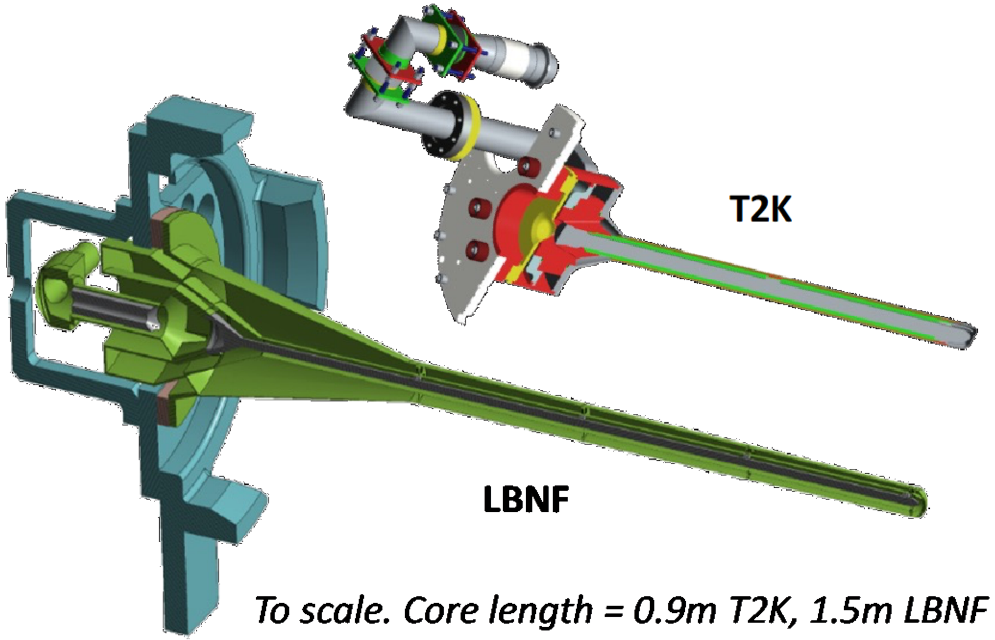
Thanks to C. Densham and D. Wilcox

Comparison LBNF vs T2K

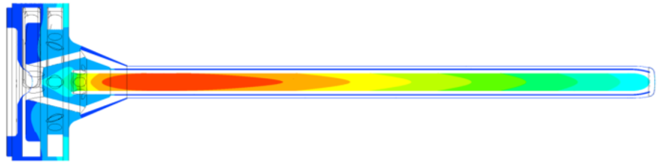
Thanks to C. Densham and D. Wilcox

Parameter	LBNF Design (1 Year Design Life)	T2K Experience (Target 2 History)
Beam Power (MW)	1.2	0.51
Proton Energy (GeV)	120	30
Beam Current (µA)	10	17
Beam Sigma (mm)	2.7	4
Radiation Damage Severity (p/cm^2)	2.5E+21	3.1E+21
Thermal Shock Severity (p/cm^2/pulse)	1.7E+14	2.6E+14

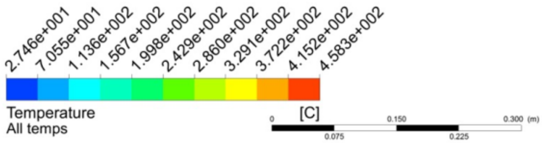
- Higher beam power but lower current and smaller beam spot = lower proton fluence and thermal shock than T2K
- Longer target will require optimised design of cantilever support

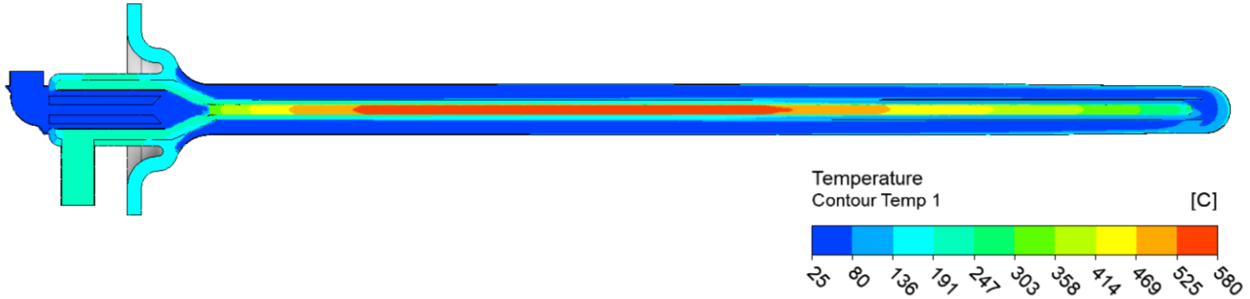


To scale. Core length = 0.9m T2K, 1.5m LBNF



NB current experience up to 500 kW



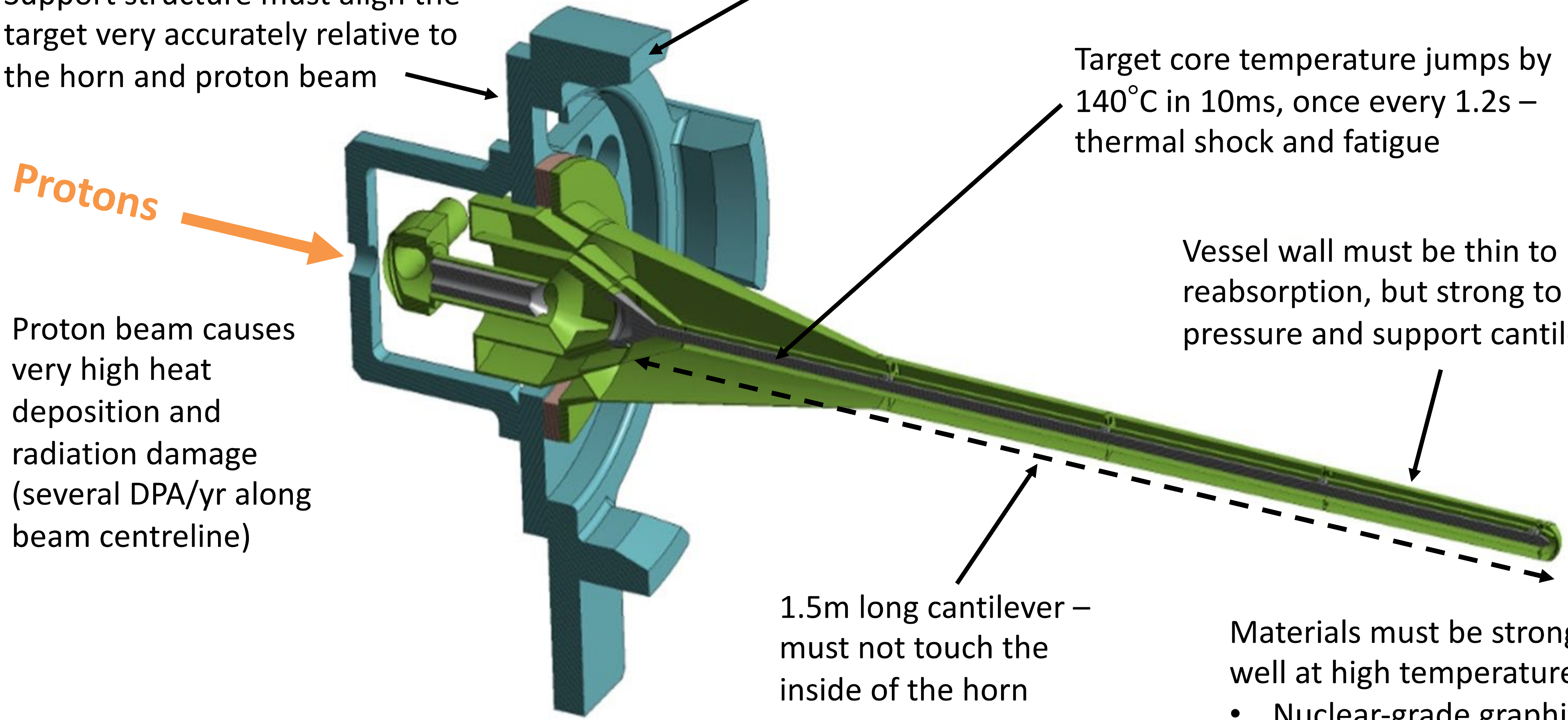


LBNF Target – Engineering Challenges

Thanks to C. Densham and D. Wilcox

Vibrations transmitted from horn to target mount

Support structure must align the target very accurately relative to the horn and proton beam



Target core temperature jumps by 140°C in 10ms, once every 1.2s – thermal shock and fatigue

Vessel wall must be thin to prevent pion reabsorption, but strong to contain pressure and support cantilever

Proton beam causes very high heat deposition and radiation damage (several DPA/yr along beam centreline)

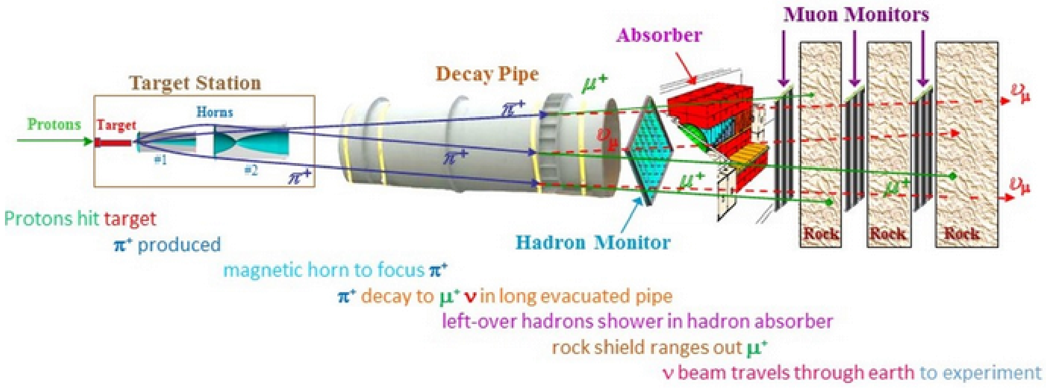
1.5m long cantilever – must not touch the inside of the horn

Materials must be strong and perform well at high temperature:

- Nuclear-grade graphite core
- Titanium alloy outer container

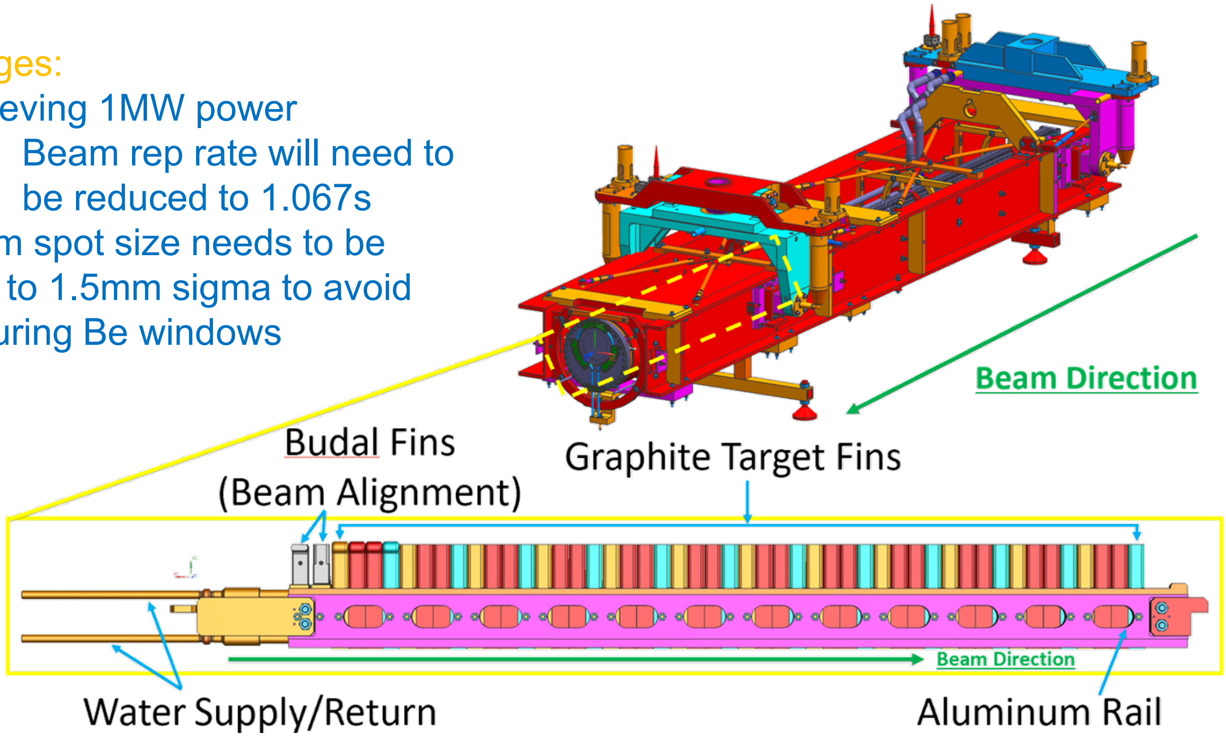
Fermilab – NuMi (Neutrino Target)

- 1 MW capable neutrino production target
- TA-06 achieved average beam power of 923kW in 2023
- Next 3 targets currently in production – possibly the last targets that will ever be built for NuMI
- Run to 1MW will be attempted in FY24



Challenges:

- Achieving 1MW power
  - Beam rep rate will need to be reduced to 1.067s
- Beam spot size needs to be held to 1.5mm sigma to avoid rupturing Be windows



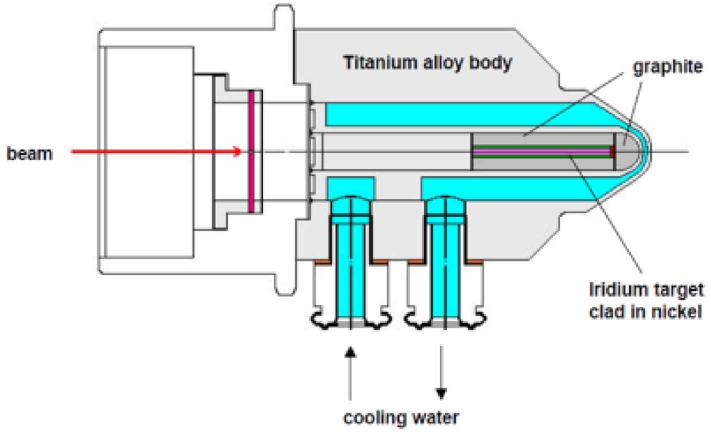
- 48 Graphite Target Fins of grade POCO ZXF-5Q
- The hottest location on the fins reaches a temperature of 997 degrees Celsius

Thanks to G. Lolov

CERN – Antiproton Decelerator Target

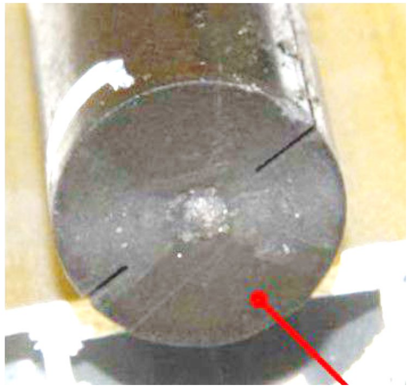
PS Proton Beam

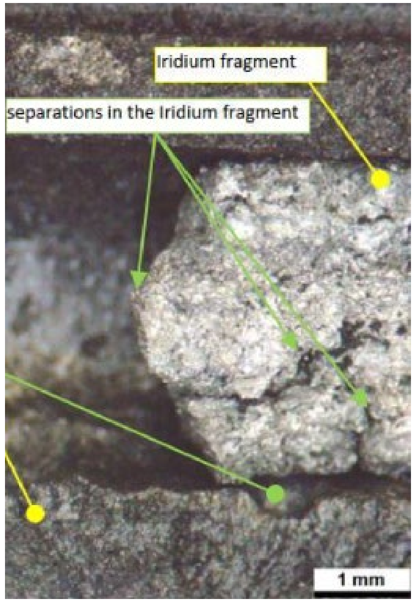
- 26 GeV/c
- Primary beam
  0.5 mm x 1 mm
- 1.45e13 ppp
- **430 ns pulse length**

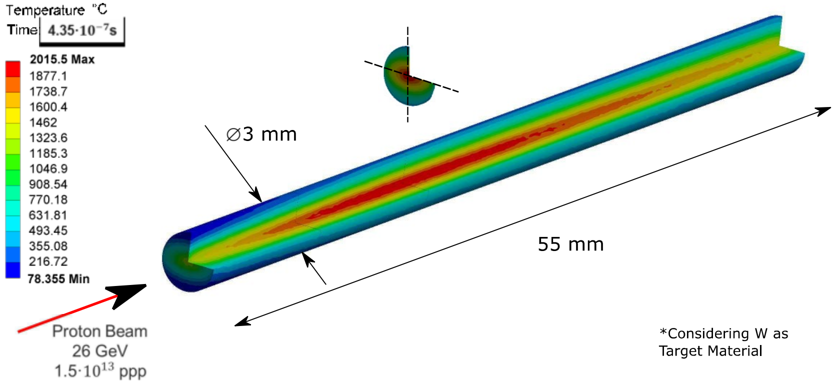


Target core made of
ø 3 mm x 55 mm
length
rod of **Iridium**

$\rho = 23\ g/cm^3$





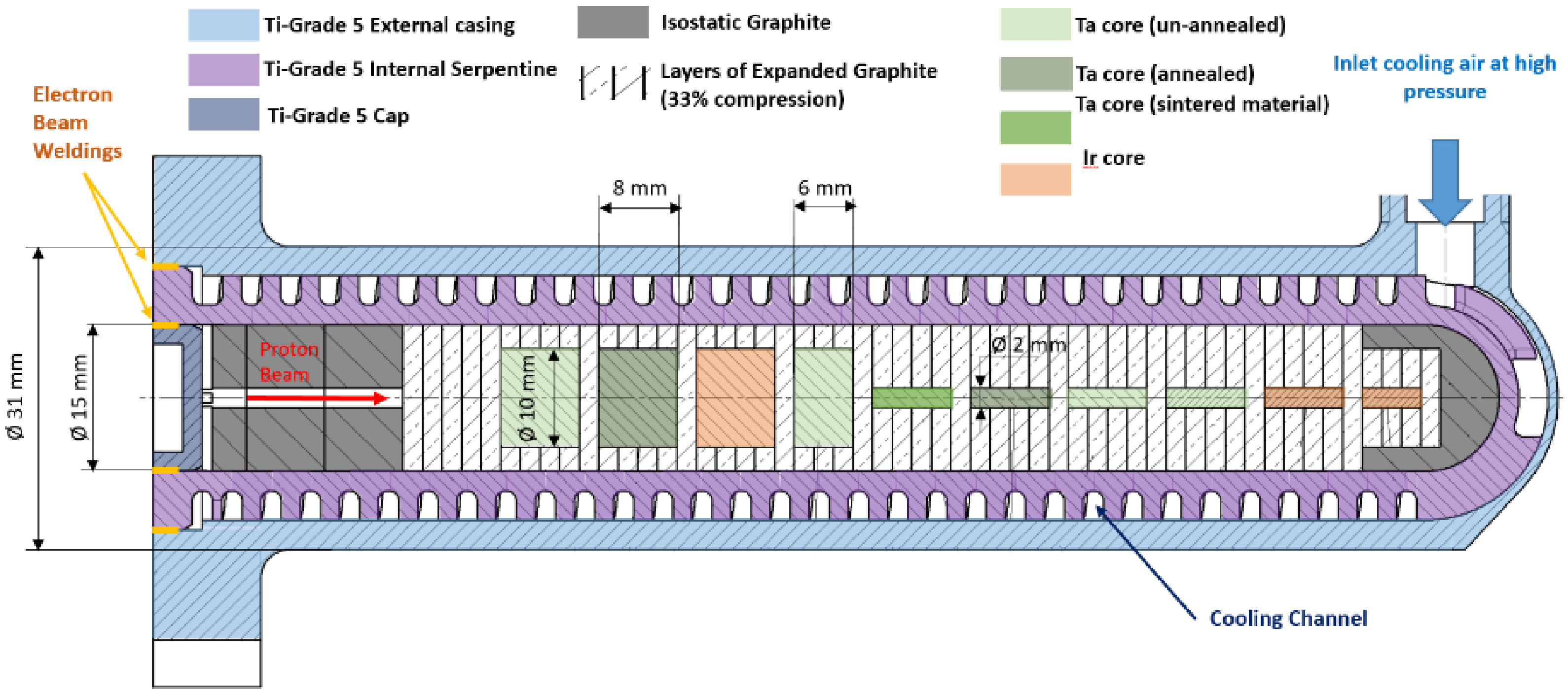


Adiabatic T rise at target core: $\Delta T > 2000$ °C

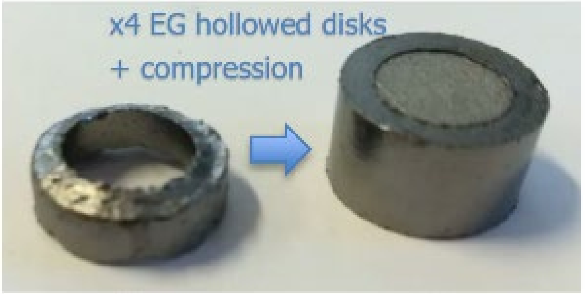
Iridium core is an amalgam of broken, melted & re-solidified fragments

Thanks to M. Calviani and C. Torregrosa

CERN – AD Target new design

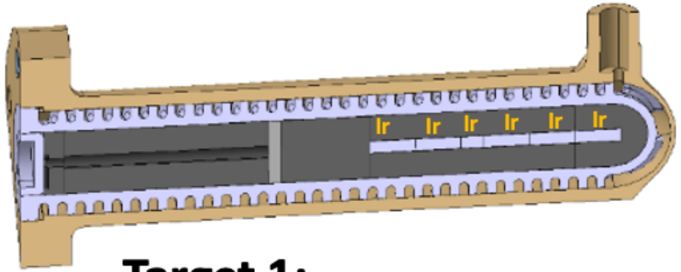


- Air cooled target
- Sliced core, with different diameter and length
- Matrix of different graphitic materials



Thanks to M. Calviani and C. Torregrosa

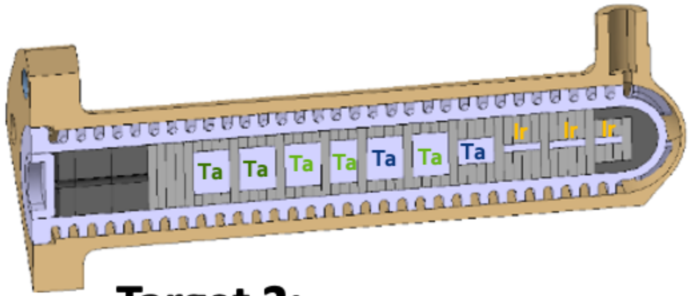
CERN – AD Target New Design Tests



Target 1:

Core: Ø 3 mm Ir

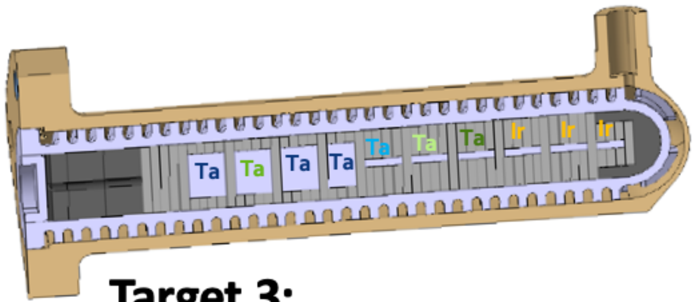
Matrix: Isostatic graphite



Target 2:

Core: Ø 10 mm Ta + Ø 2 mm Ir

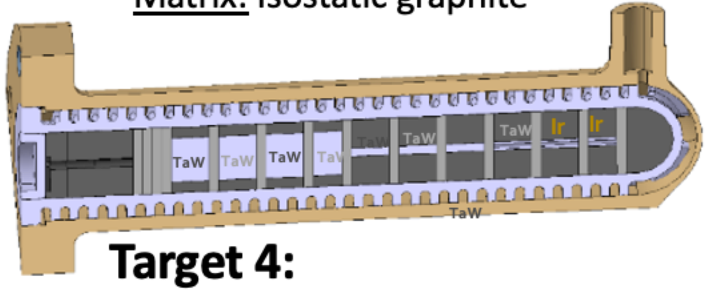
Matrix: **Compressed EG**



Target 3:

Core: Ø 10 mm Ta + Ø 2 mm Ta + Ø 2 mm Ir

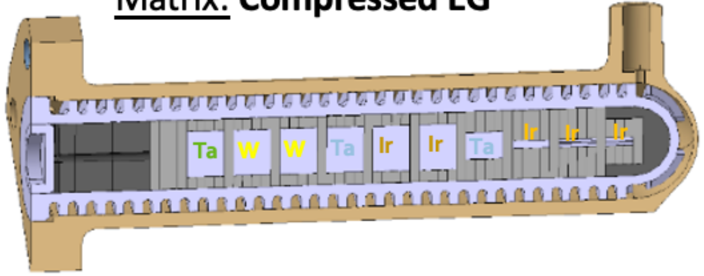
Matrix: Compressed EG



Target 4:

Core: Ø 10 mm Ta2.5W + Ø 2 mm Ta2.5W + Ø 2 mm Ir tube

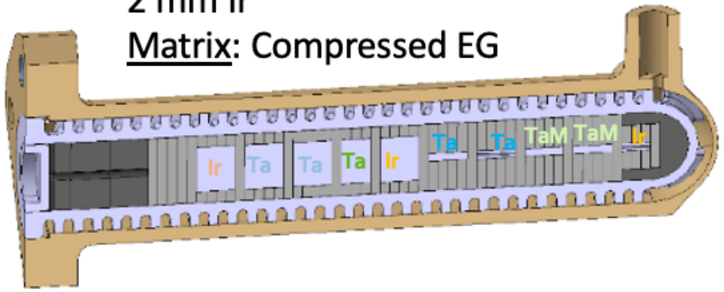
Matrix: Isostatic graphite



Target 5:

Core: Ø 10 mm Ta + Ø 10 mm W + W-1.1TiC + Ø 10 mm Ir +Ø 2 mm Ta tube

Matrix: Compressed EG



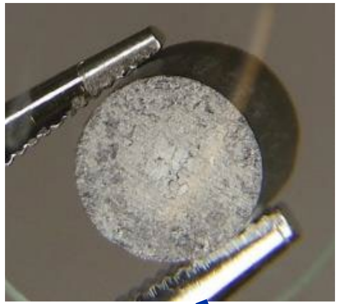
Target 6:

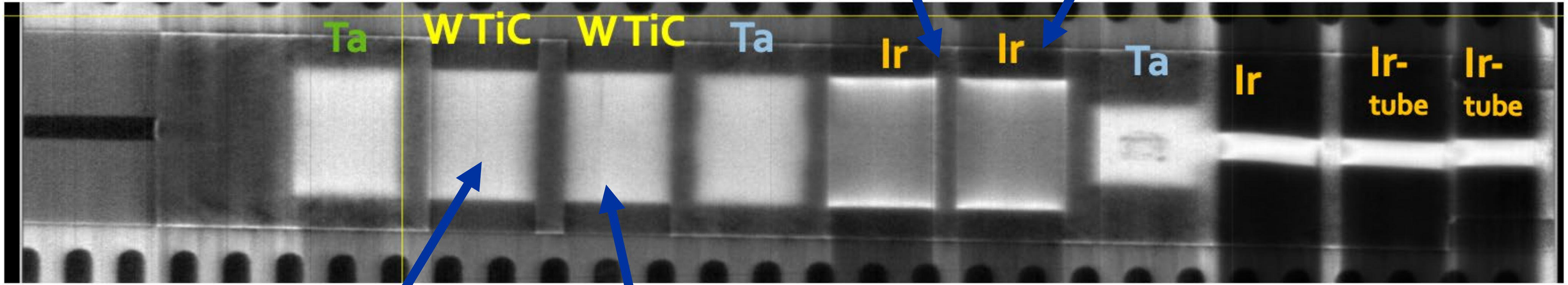
Core: Ø 10 mm Ir Ø 10 mm Ta + Ø 2 mm Ta tube

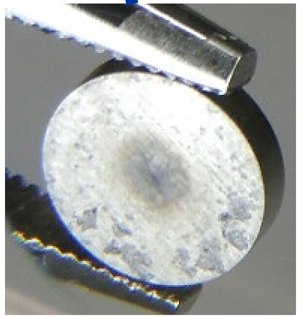
Matrix: Compressed EG

Thanks to M. Calviani and C. Torregrosa

CERN – AD Target New Design Tests (some results)



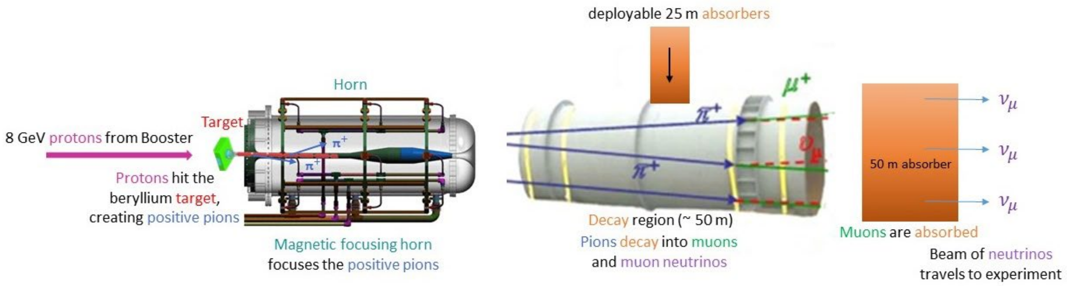


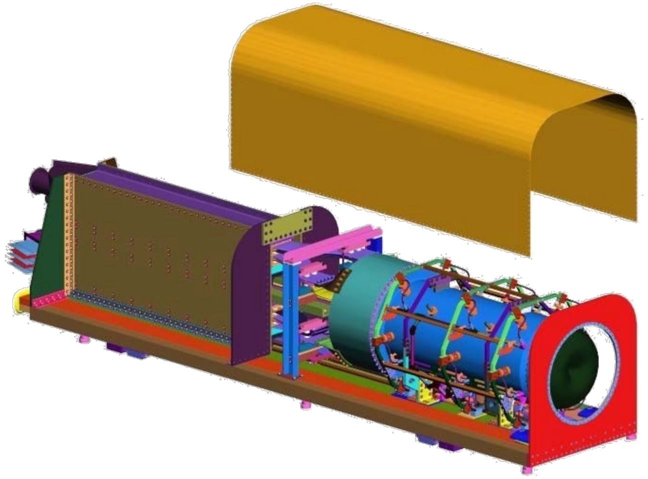


Good behaviour of advanced materials
TFGR W-TiC in two different configurations

Thanks to M. Calviani and C. Torregrosa

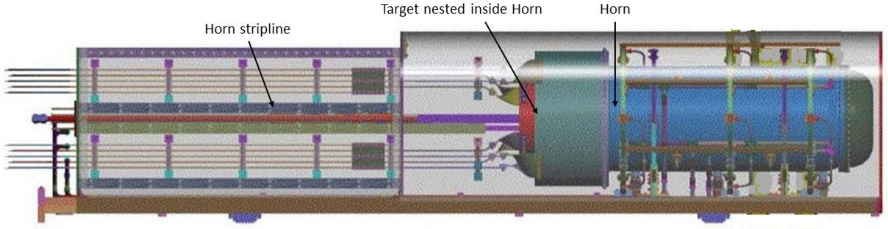
Fermilab – BNB Target/Horn



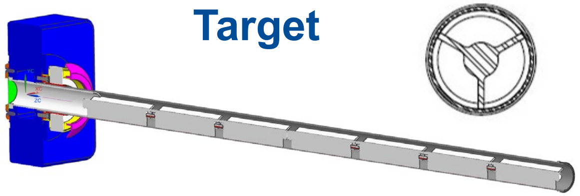


The BNB (Booster Neutrino Beam) beamline converts the 8 GeV proton beam from the Booster into a focused neutrino beam. It is currently in operating for the **SBND** experiments.

Air around the horn is contained within an enclosure which contains the most radioactive air for a minimum of 4 hours. The air is recirculated in a closed loop to cool both the horn power supply stripline and the target slugs.

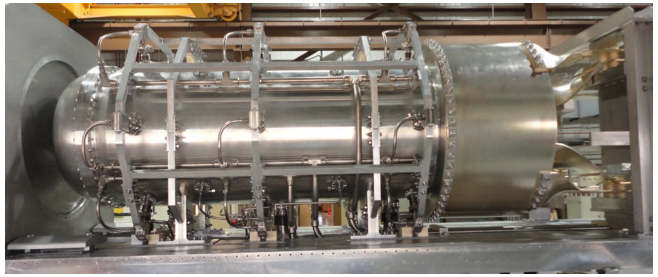


Target



The target consists of seven beryllium target slugs contained within a beryllium tube which is in turn cantilevered from an aluminum manifold. The target is inserted within the horn inner conductor.

Horn and Spare Fabrication

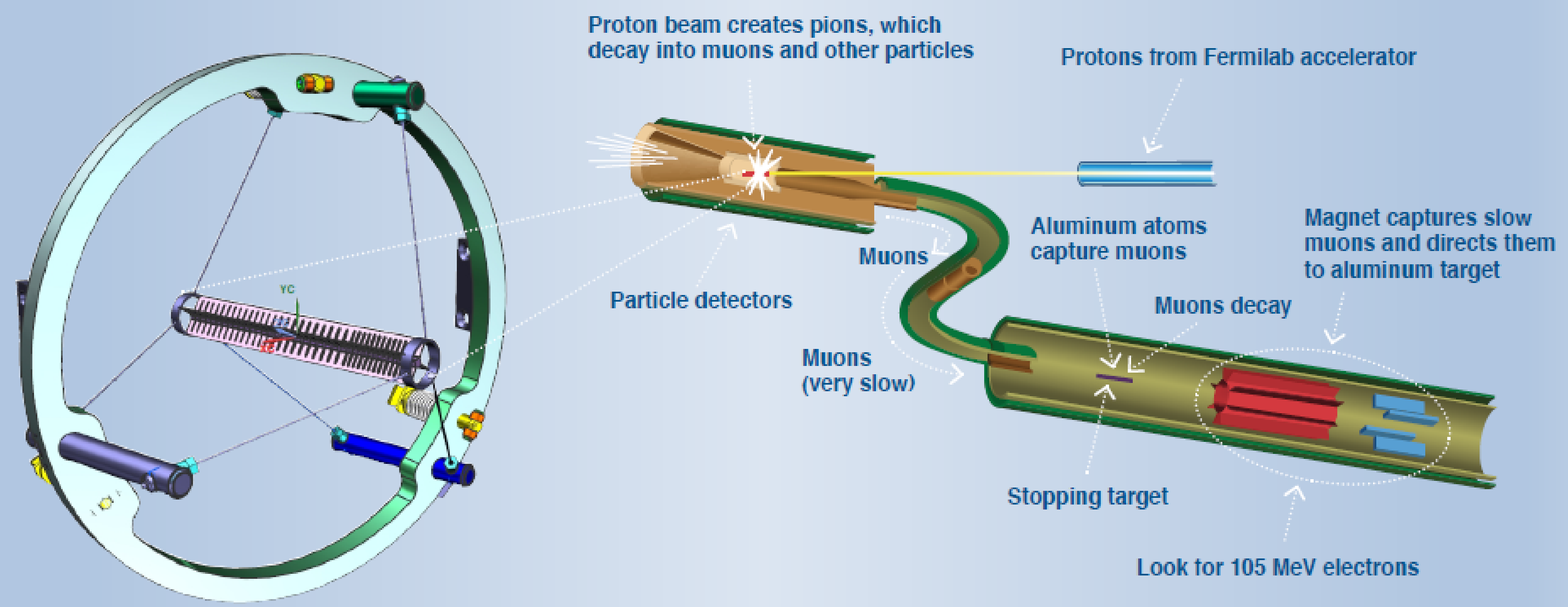


Horn was optimized to run at 170 kA to produce a maximum magnetic field of 1.5 Tesla

Horn conductors are water cooled.
1st Horn developed leak
2nd Horn had plugged cooling lines
3rd horn was installed in 2015
4th horn is currently in the final stage of assembly

Thanks to B. Paley and Y. He

Fermilab – Mu2e



Production Target

The Mu2e production target is suspended by spokes within a bicycle wheel structure. The current version of the tungsten production target has circular rings at the ends and its core is finned and segmented to allow for sag minimization and temperature control.

Plans for a Muon Conversion Experiment

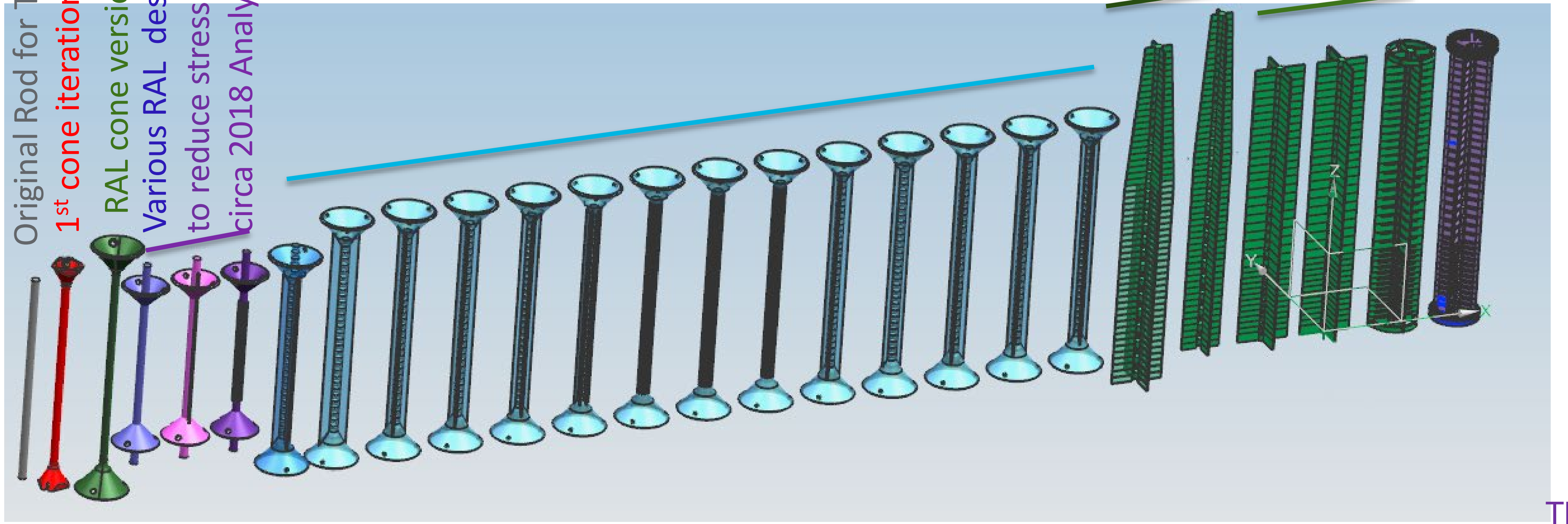
The proposed Mu2e experiment will test a fundamental symmetry of the quantum world. Scientists have observed the transformation of one type of quark into another, as well as the transition of one type of neutrino into another. The question remains: Can the muon, a charged lepton, change into another type of charged lepton? In particular, can a muon turn into an electron? The discovery of this process would revolutionize scientists' understanding of elementary particles and the principles that govern their interactions.

Thanks to Z. Liu

Fermilab - Mu2e Target Evolution

Various FNAL/ RAL iterations with fins (n_{fins} = 3 to 18) to augment cooling with increased surface area during 2018. Includes the T1 Milestone target (CRR in April 2018) (rightmost blue target)

Starting in 2018 Analysis included emissivity as a function of temperature, non-uniform time dependent Energy Deposition (Edep) (380 msec of Edep, 1.02 sec of no heating).

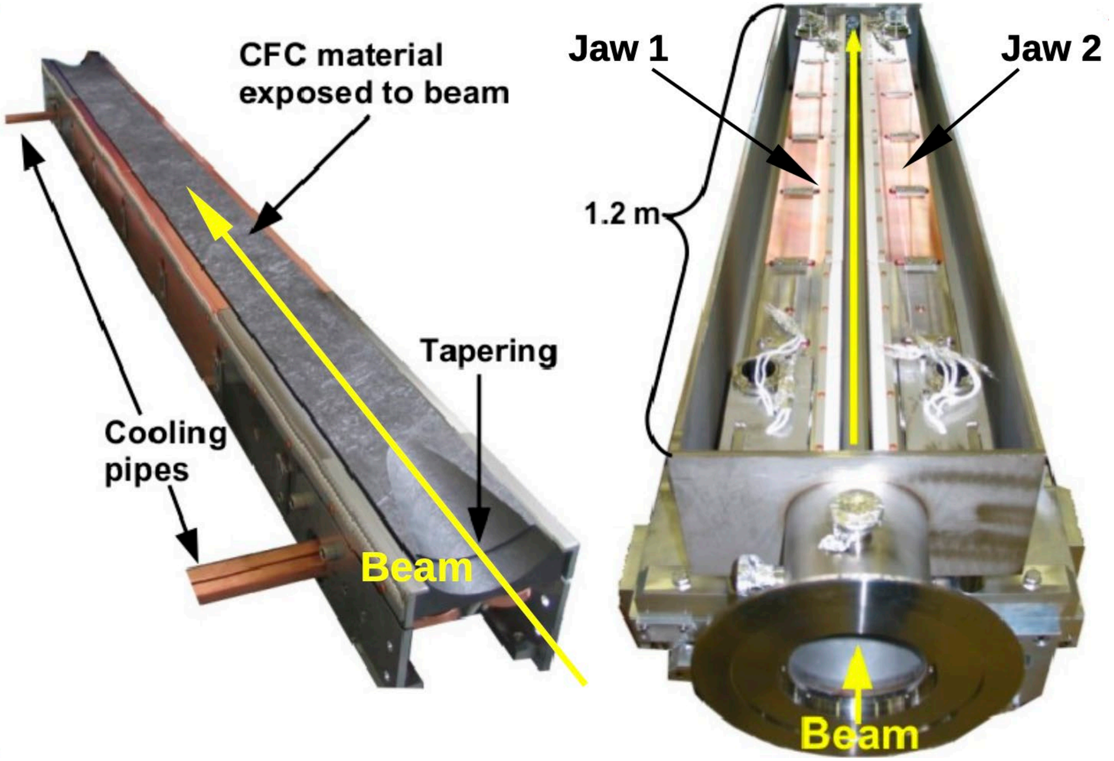


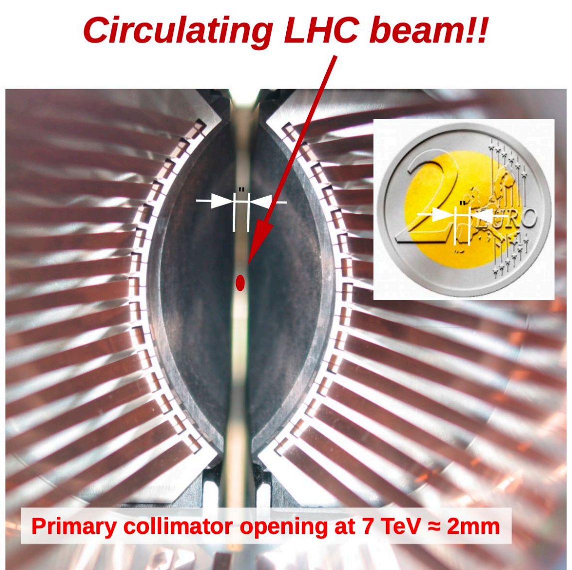
Thanks to Z. Liu

CERN – LHC Collimators

Functions of a collimation system

- Quench mitigation for superconducting magnets (mW/cm^3!)
- Protection against long-term radiation damage to magnets (passive masks)
- Concentration of losses/activation in controlled areas
- Cleaning physics debris (for colliders)
- Optimise background in the experiments
- Beam tail/halo scraping, halo diagnostics





Thanks to M. Calviani, F-X. Nuiry and D. Baillard

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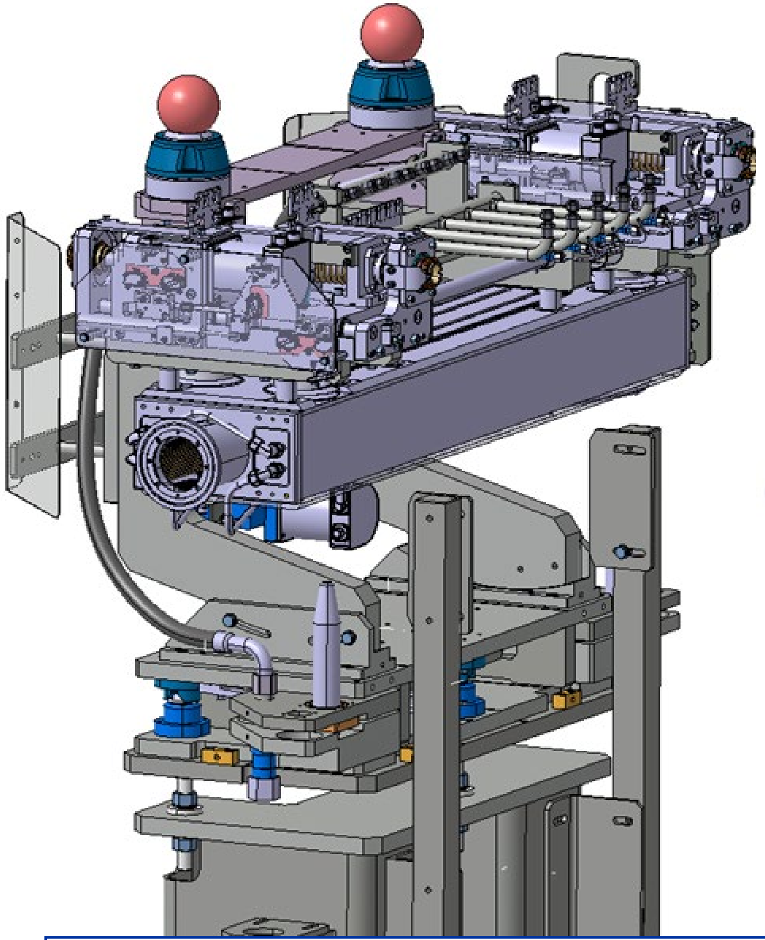
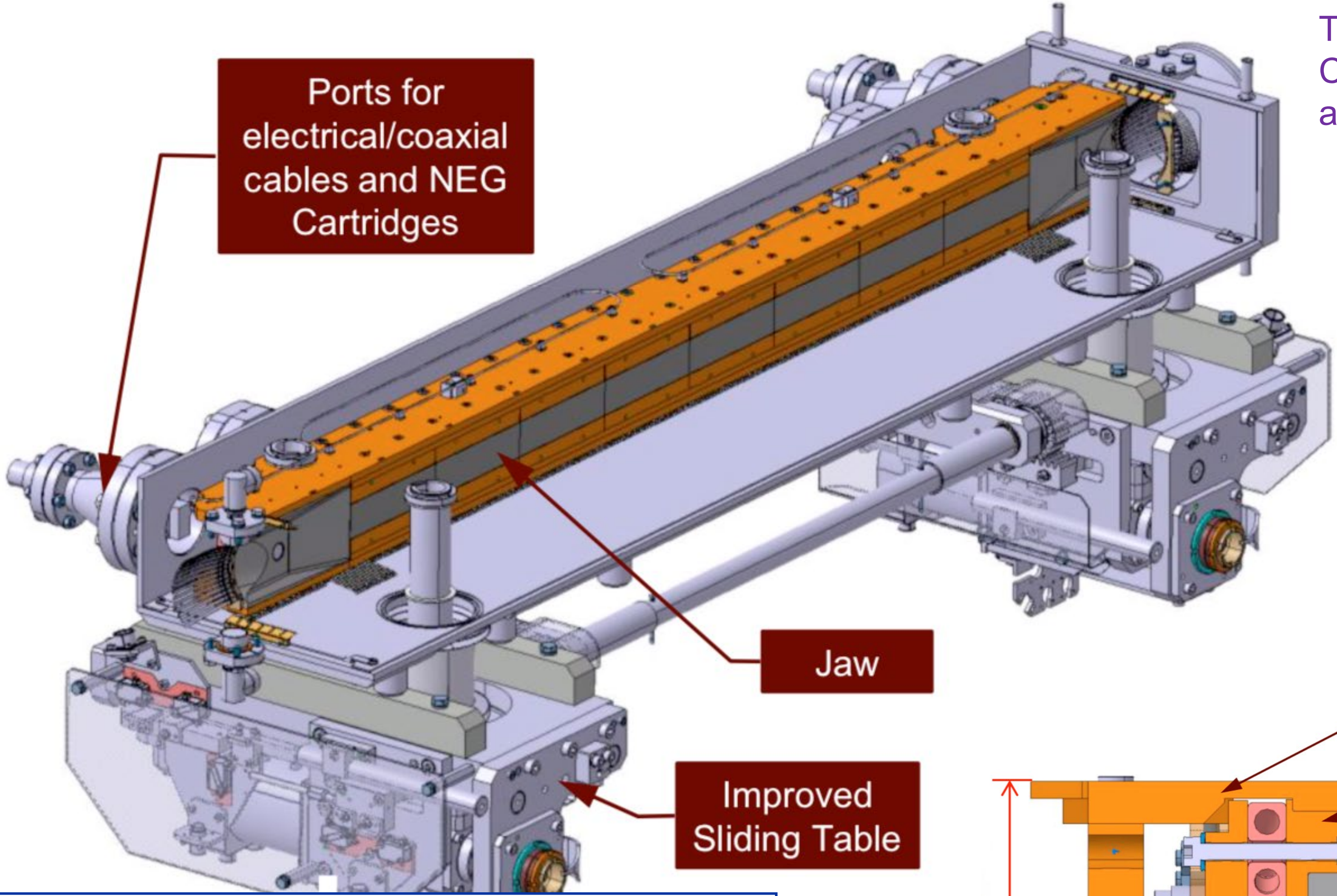
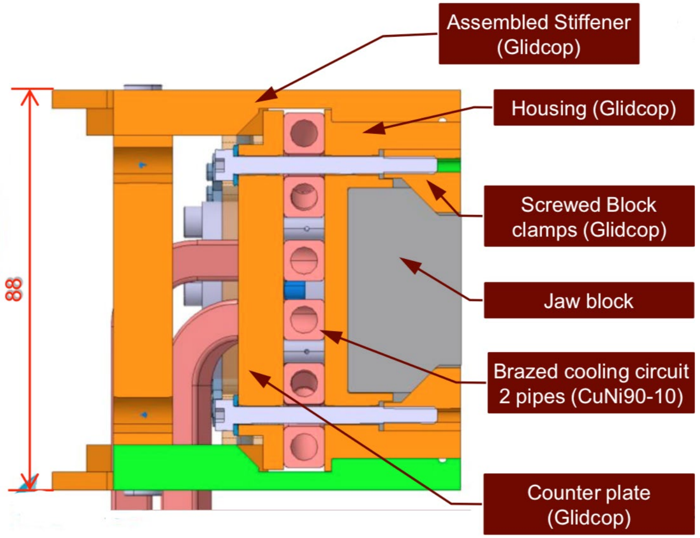






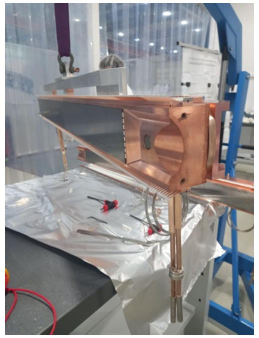
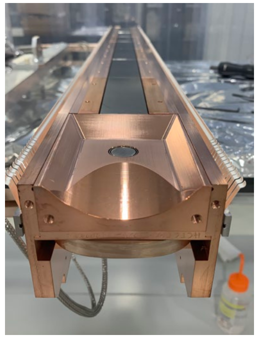
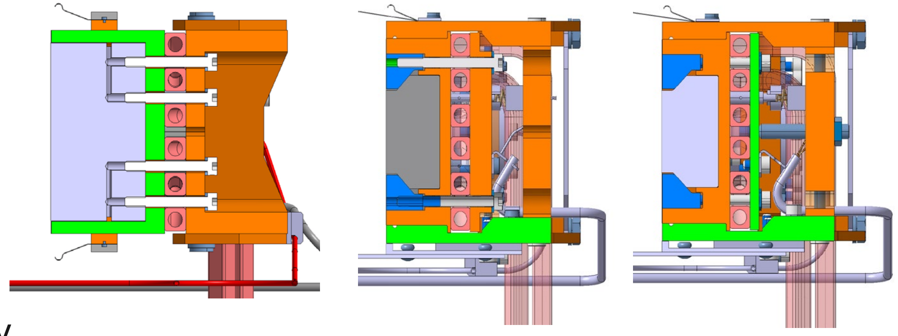
Collimator jaws designed (and tested!) to cope with:

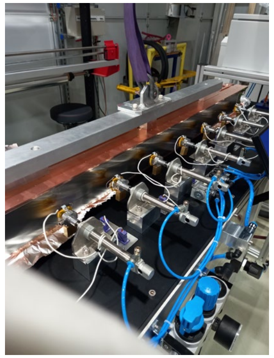
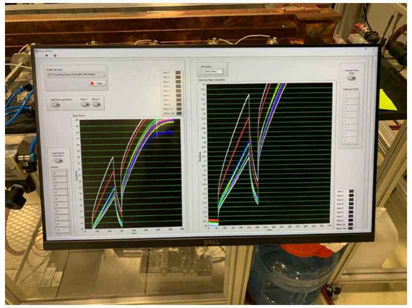
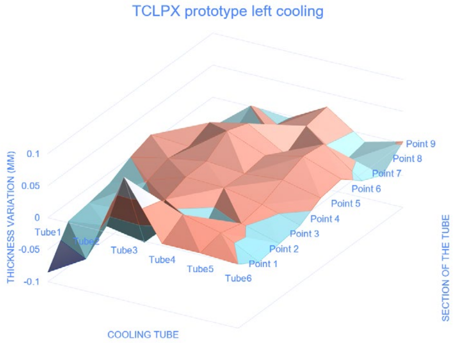
- **10 kW steady losses of 1 hour**
- **Direct beam impact at injection and during asynchronous beam dumps at 7 TeV**

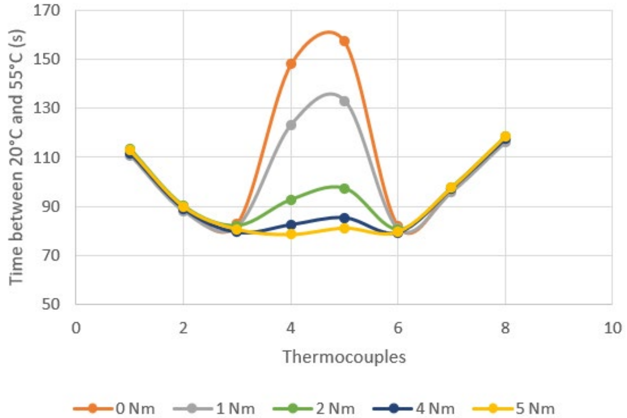
General challenges : Jaw performance

Thanks to M. Calviani, F-X. Nuiry and D. Baillard

- **Absorbing materials choice**
  - Find a materials meeting the operation requirements in term of thermal shock resistance
  - High conductivity to limit impedance
  - Machinability, reproducibility (reliability)
- **Flatness requirements (a few dozen µm)**
  - Hard to obtain because of segmented design accumulating tolerances defect
  - Geometrical tolerances hard to obtain for certain materials (tungsten alloy)
  - Long copper parts and cooling pipes highly flexible wrt required tolerances
- ✓ **Thermal contact conductance**
  - Good thermal contact conductance required between components. Difficult to quantify.
  - Complex testbench to crosscheck simulation and experimental results.



Conclusions

- **Wide variety of challenges found in BIDs**
- **Material specification, characterisation, testing, simulation is critical**
- **Instrumentation necessary to understand the behaviour of BIDs (but often a challenge itself)**
- **Cooling**
- **Operation in UHV**
- **Impedance**
- **Irradiation damage**
- **Manufacturing methods / reliability / fatigue**

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