Design, construction, commissioning, and early operation of the third-generation n_TOF neutron spallation target at CERN

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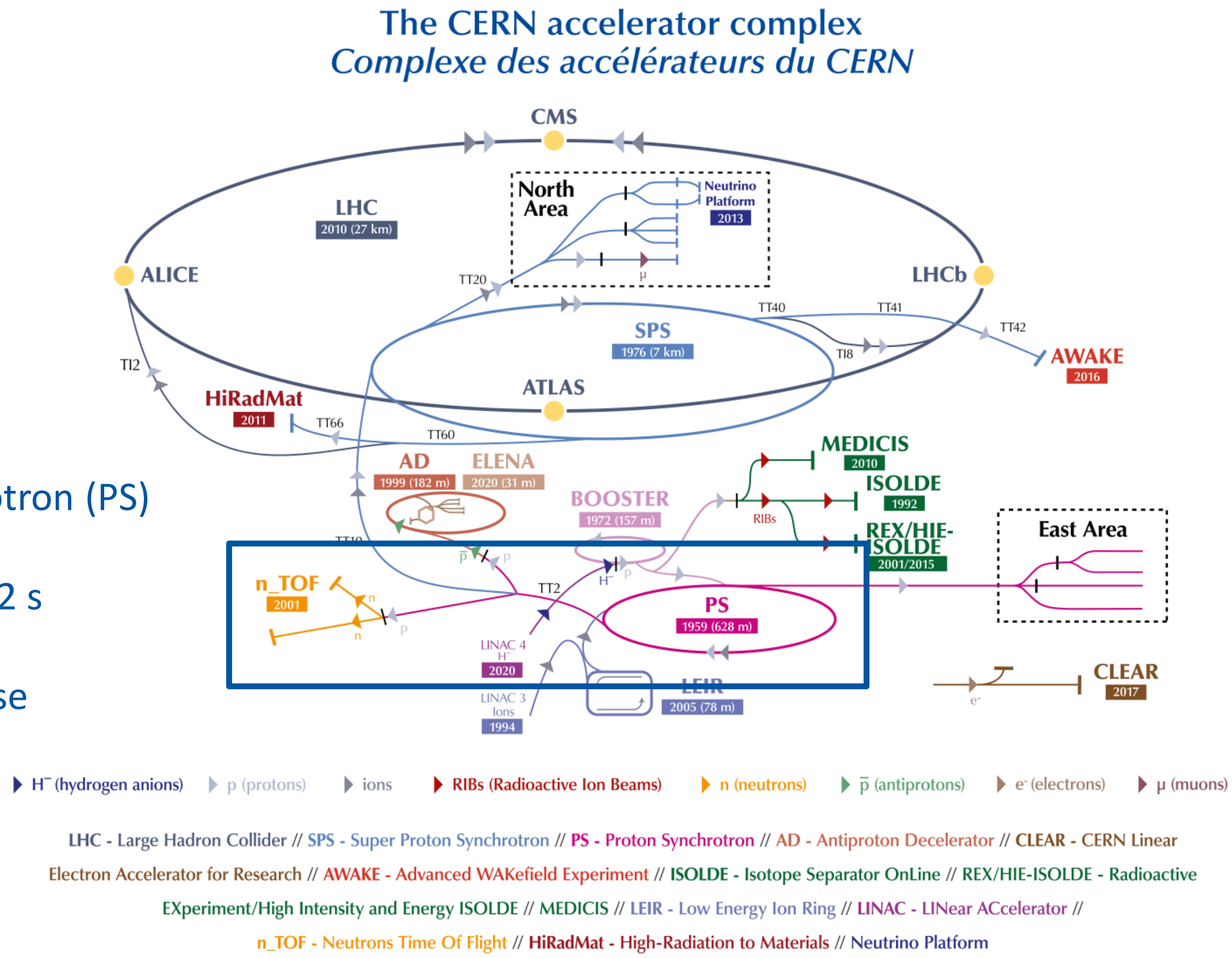
for the n_TOF third-generation spallation target project team

The n_TOF facility at CERN

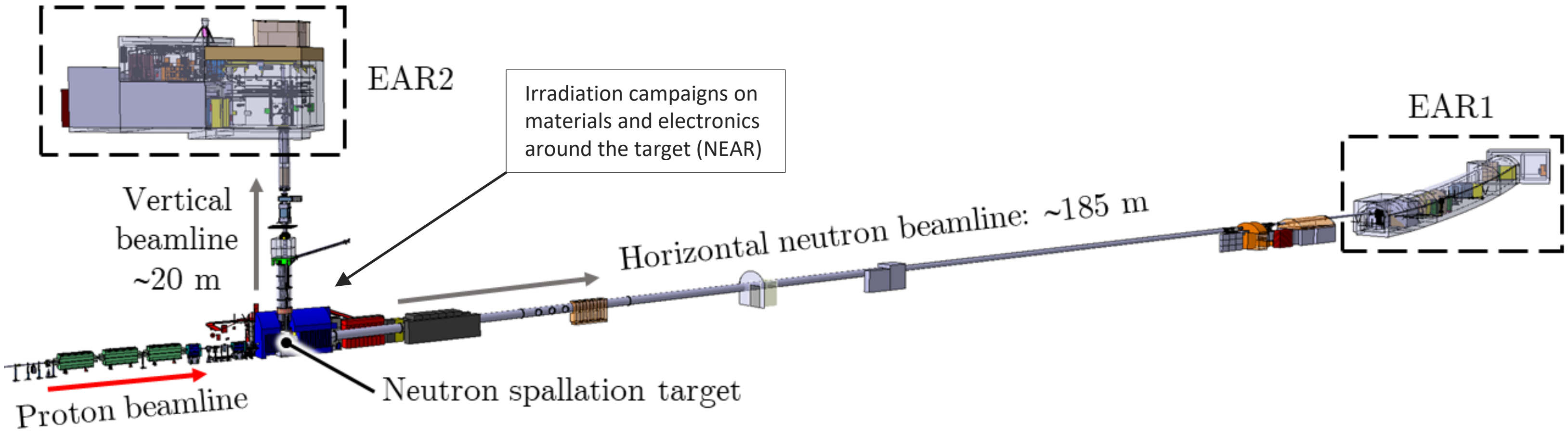


The Proton Synchrotron (PS) can send to n_TOF:

- 1 pulse every 1.2 s
- 20 GeV/c
- 8.5×10^{12} p^+/pulse

The n_TOF facility at CERN

n_TOF: neutron Time Of Flight



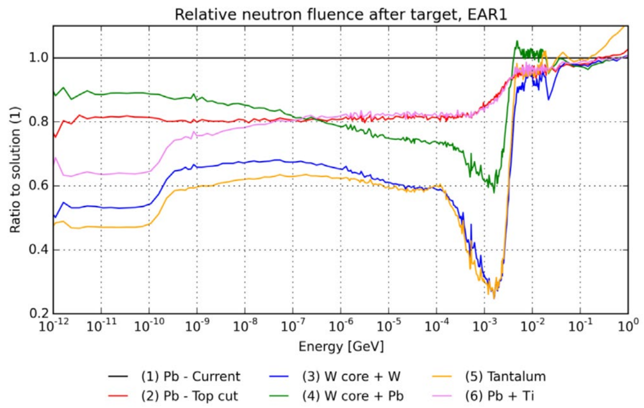
- High instantaneous neutron fluence (10^8 n/cm^2 in a single pulse)
- Wide energy spectrum (sub-thermal to 1 GeV)
- High energy resolution ($\Delta E/E = 10^{-4}$)

Ideal for high signal-to-background ratio neutron cross-section measurements on radioactive isotopes available only in small amounts

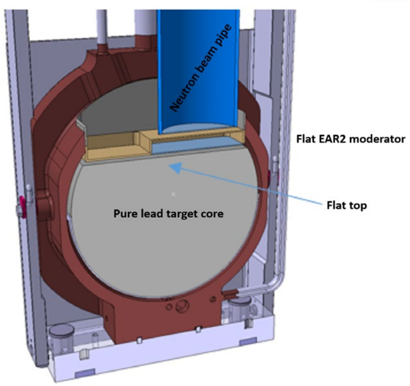
Design studies for the 3rd-gen target

Many different design solutions investigated:

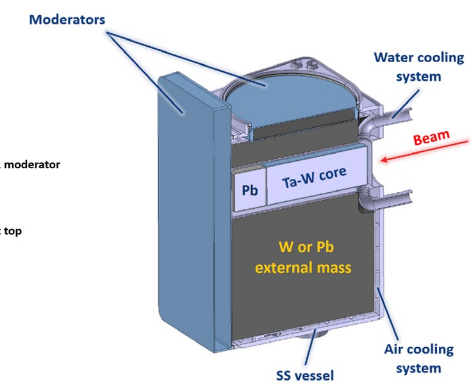
- Core materials (Pb, Ta, W, …)
- Cladding materials (Ta, Ti64, Inconel, …)
- Cooling fluids (water, N_2, Ar, …)



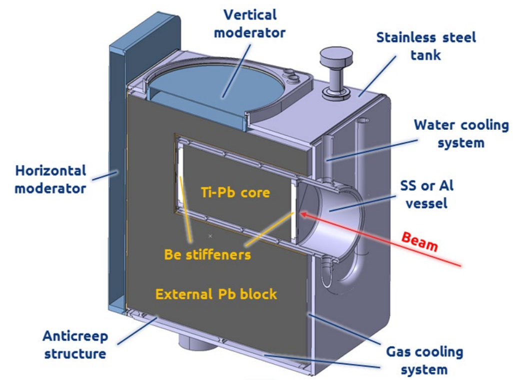
Examples:



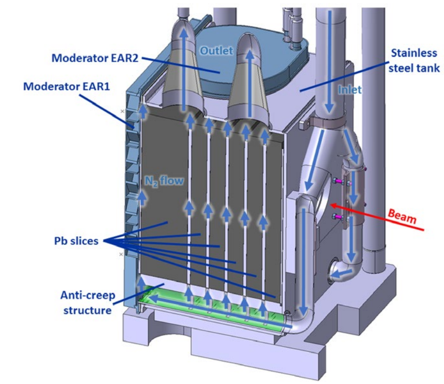
Water-cooled
single Pb block



Water-cooled
Ta-clad W core



Water-cooled
Ti-clad Pb core

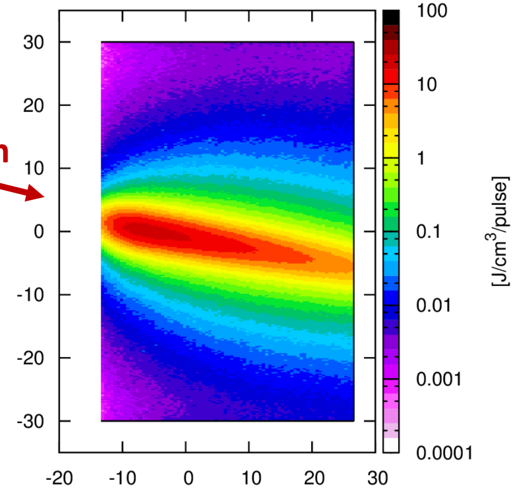


N_2 gas-cooled
Pb plates

Design studies for the 3rd-gen target

Energy deposition (Monte Carlo)

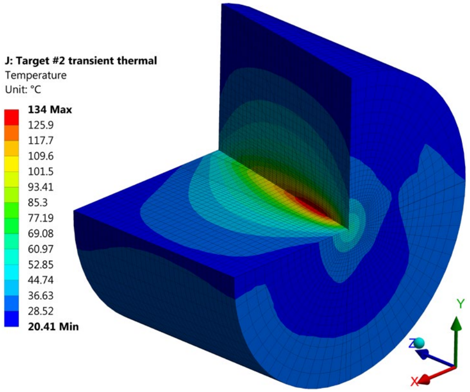
beam



heat source

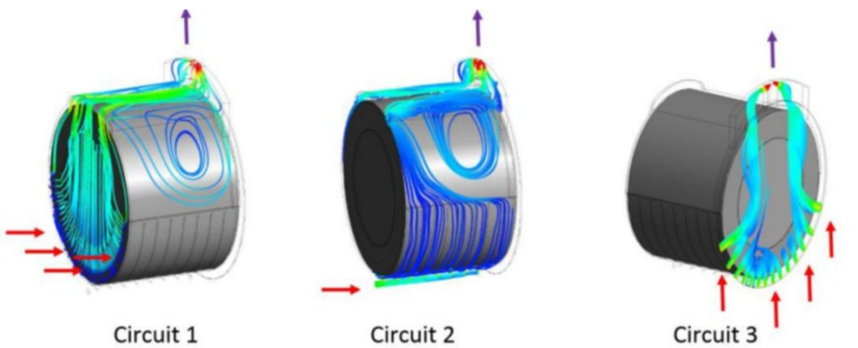
heat sink

Temperature (thermal FEM)

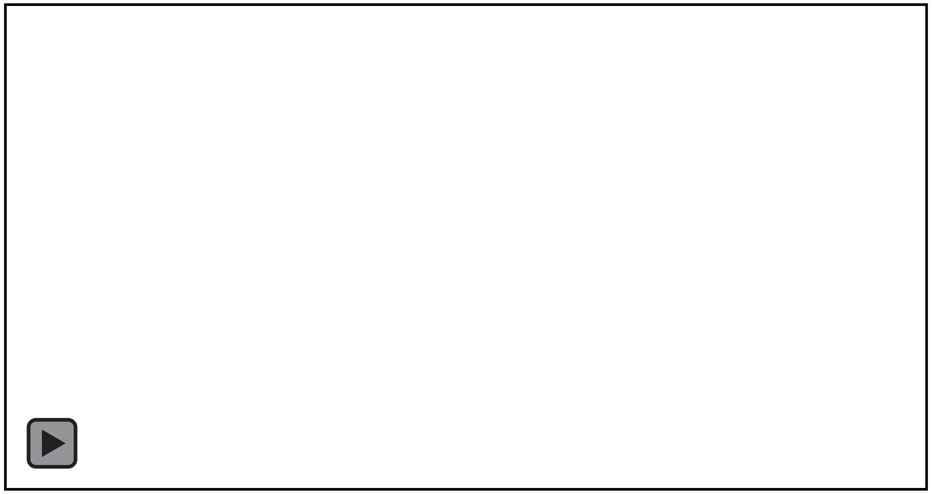


thermal expansion

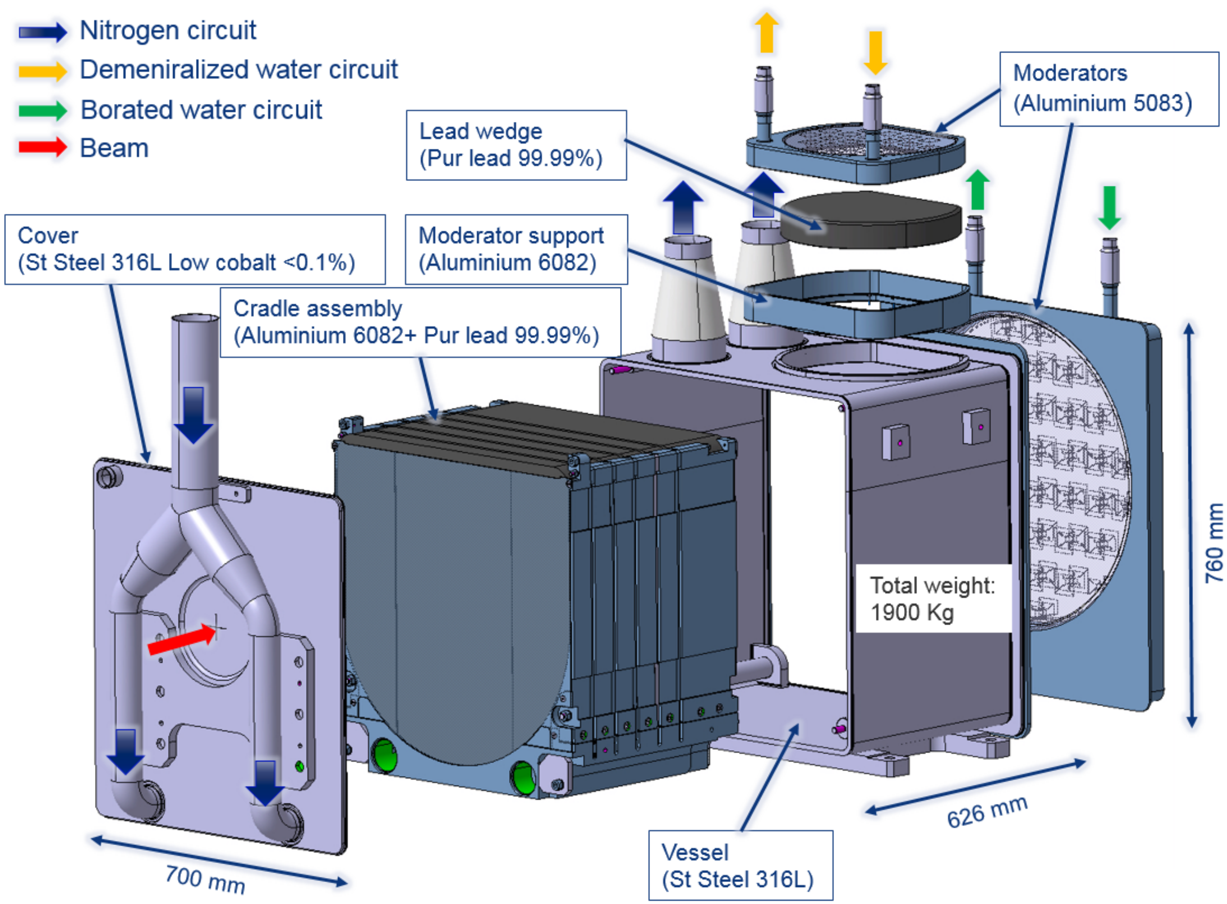
Heat transfer coefficient (CFD)

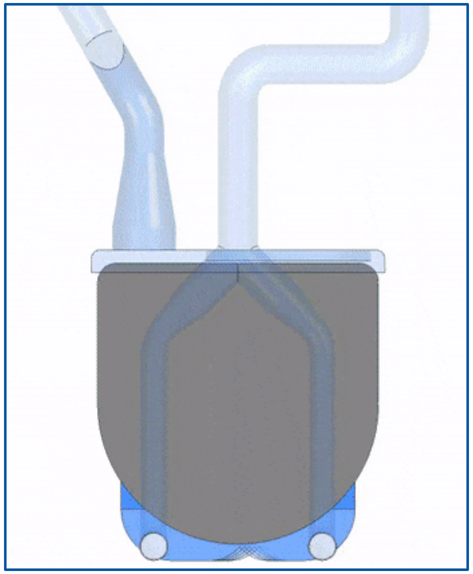


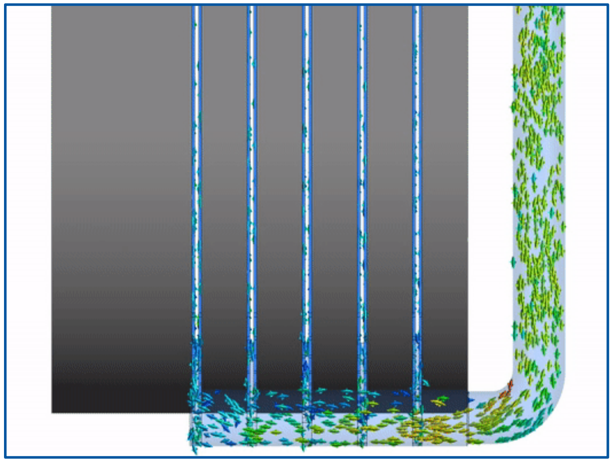
32 kJ in 6-ns (RMS) → Stress wave propagation



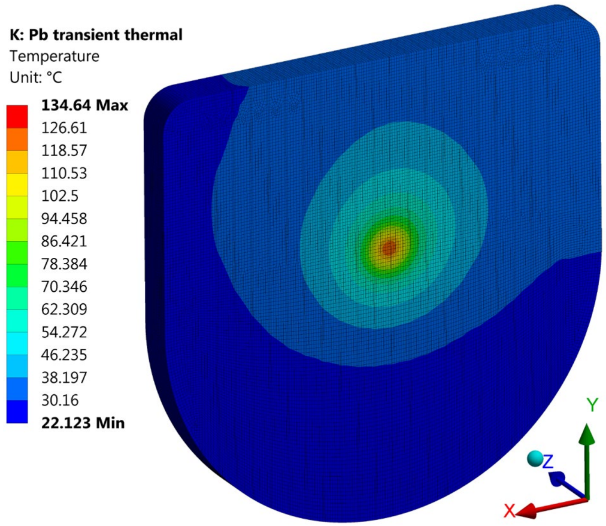
The 3rd-gen n_TOF target

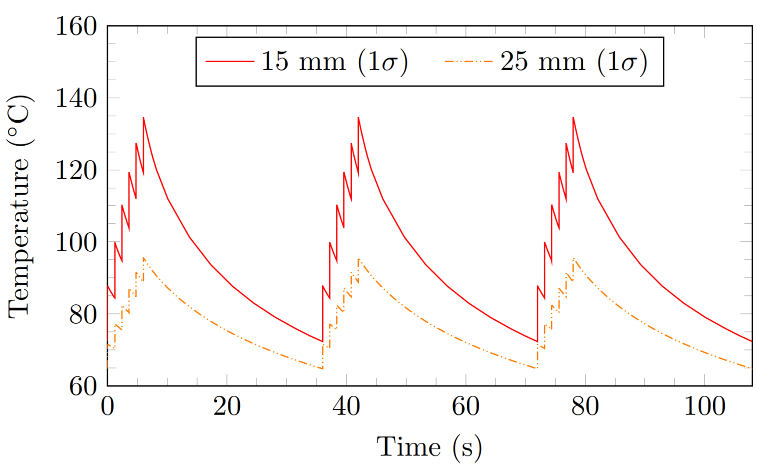






Thermal behaviour





Design parameters

Pulse intensity	10^{13} p$^+$
Beam momentum	20 GeV/*c*
Pulse energy	32 kJ
Pulse length	25 ns (4σ)
Beam size (Gaussian)	15 mm (1σ)
Average intensity	1.67×10^{12} p$^+$/s
Average current	0.27 μA
Average power	5.4 kW
Peak current	91.3 A
Peak power	1.8 TW

- Peak temperature in 2nd slice: 135°C
- Lead melting temperature: 327°C

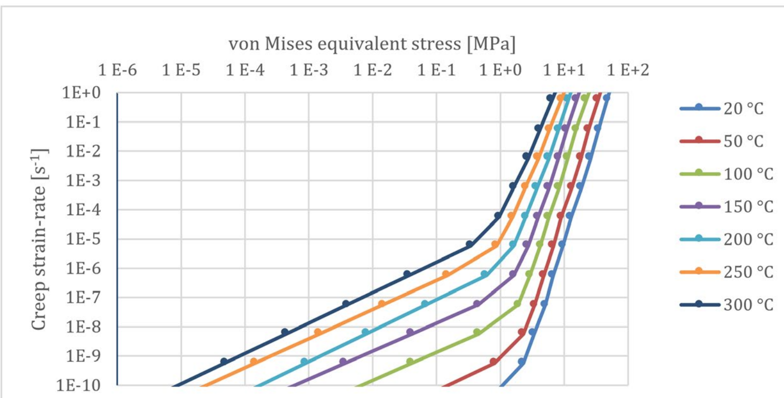
Studies on creep effect

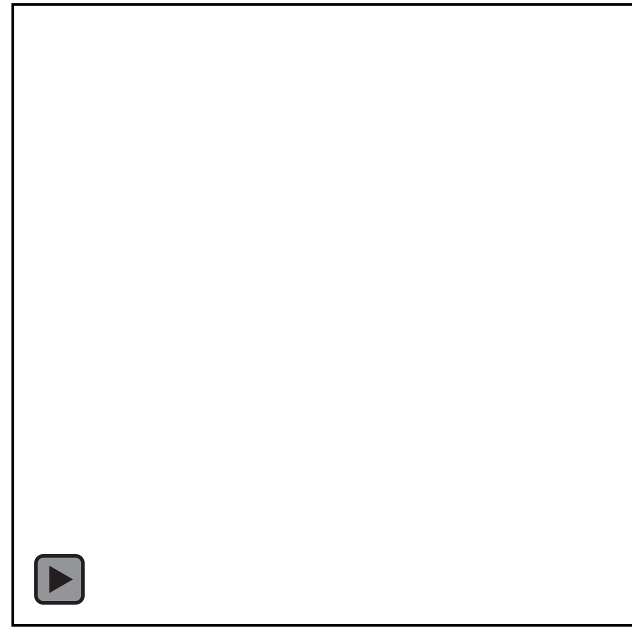
Lead creep → risk of obstructing cooling channels

New User Programmable Feature coded in ANSYS

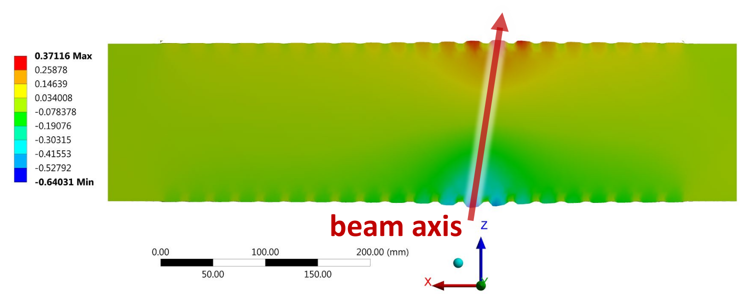
For each segment on a log-log plane:

$$\dot{\varepsilon} = c \cdot \sigma^{m}$$





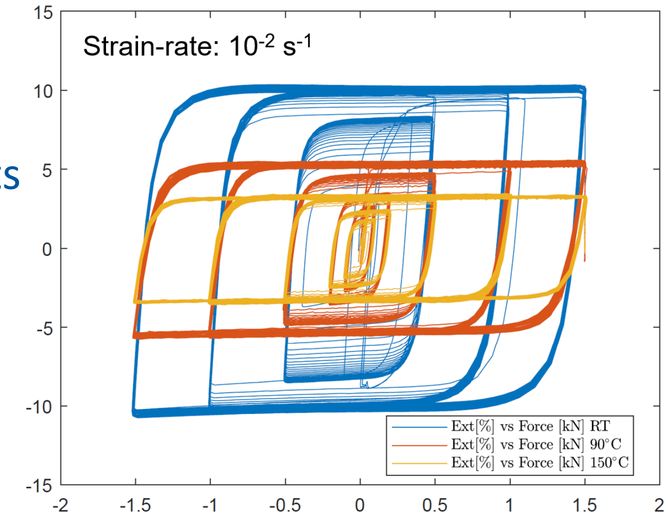
- 2×10^{8} s simulated (6 years and 4 months of continuous operation or twice the target lifetime)
- Also useful to perform CFD simulations in degraded scenarios



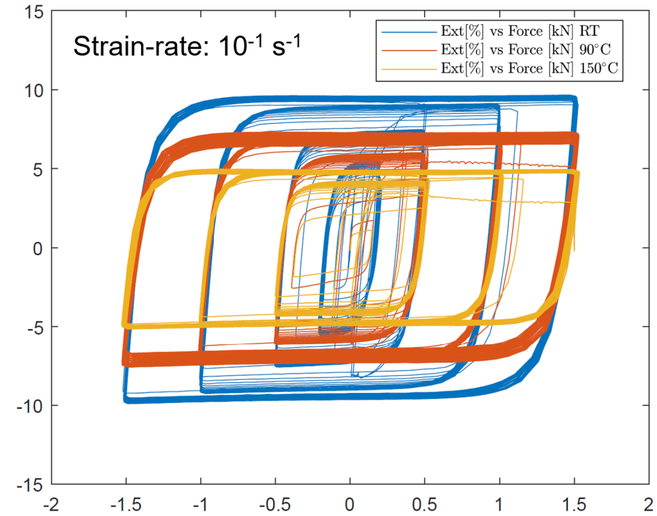
(deformations amplified for better visualization)

Pb constitutive model for cyclic plasticity

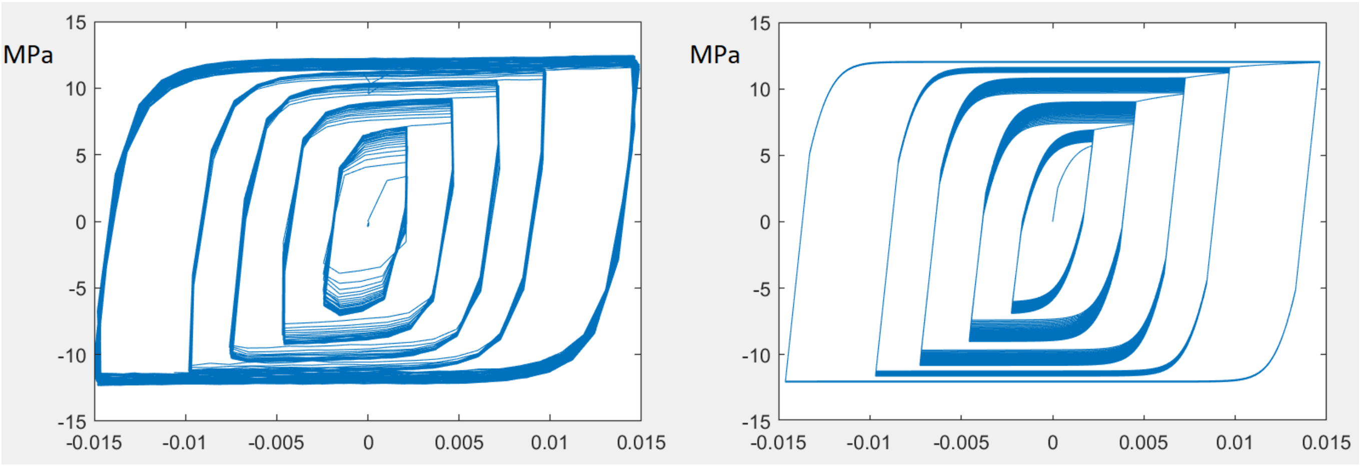
- Cyclic mechanical tests performed at NTNU



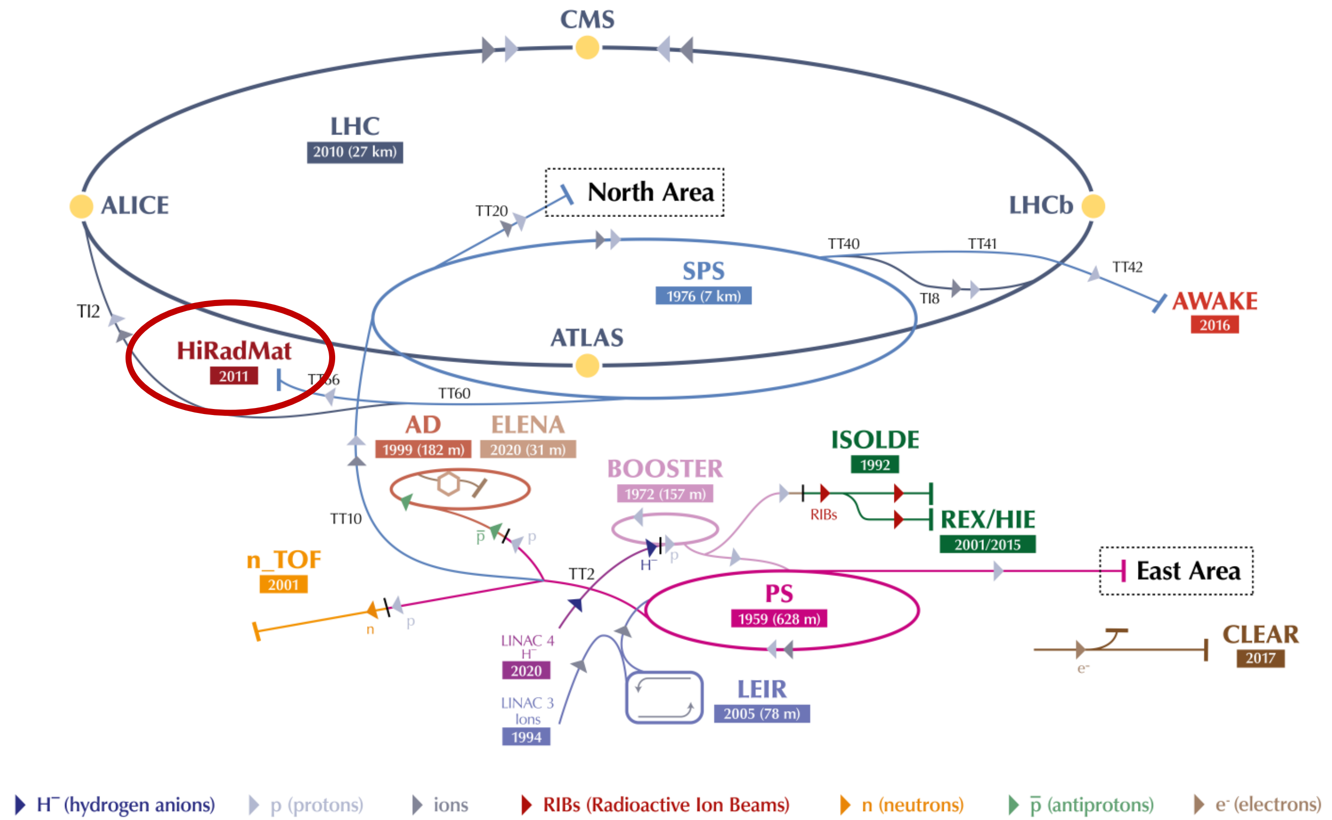
Experimental data



Proposed model



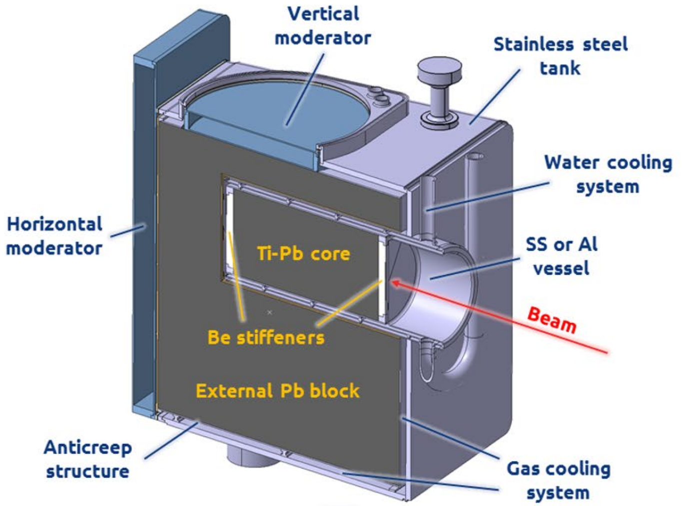
Beam irradiation tests in HiRadMat



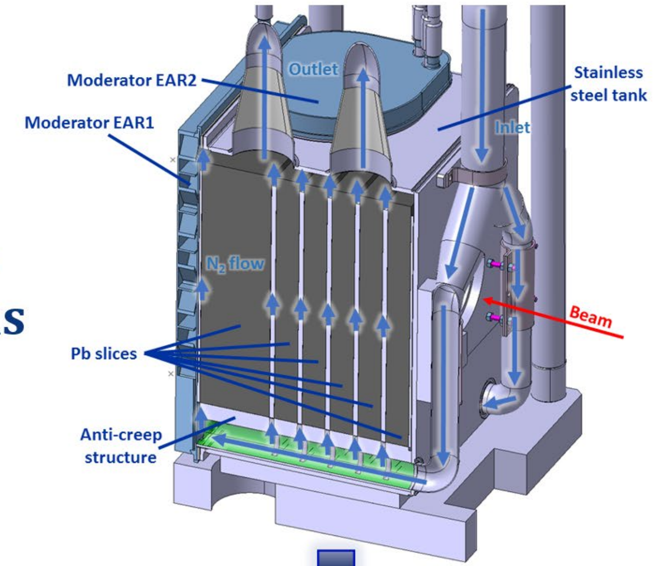
LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE - Radioactive EXperiment/High Intensity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

Beam irradiation tests in HiRadMat

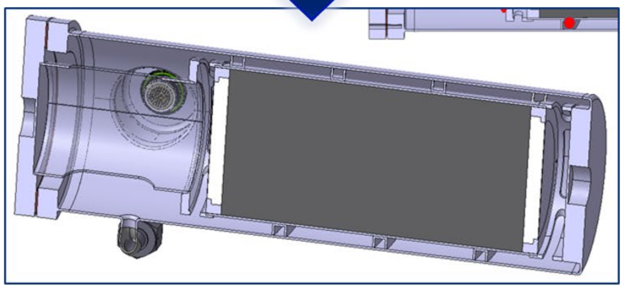
Ti-6Al-4V-clad lead



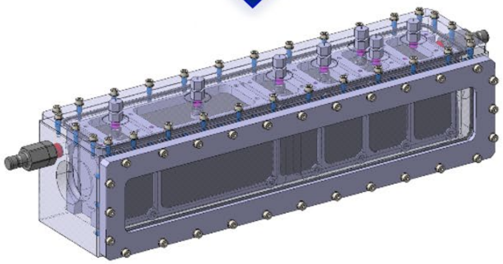
N_2-cooled lead slices



Design solutions



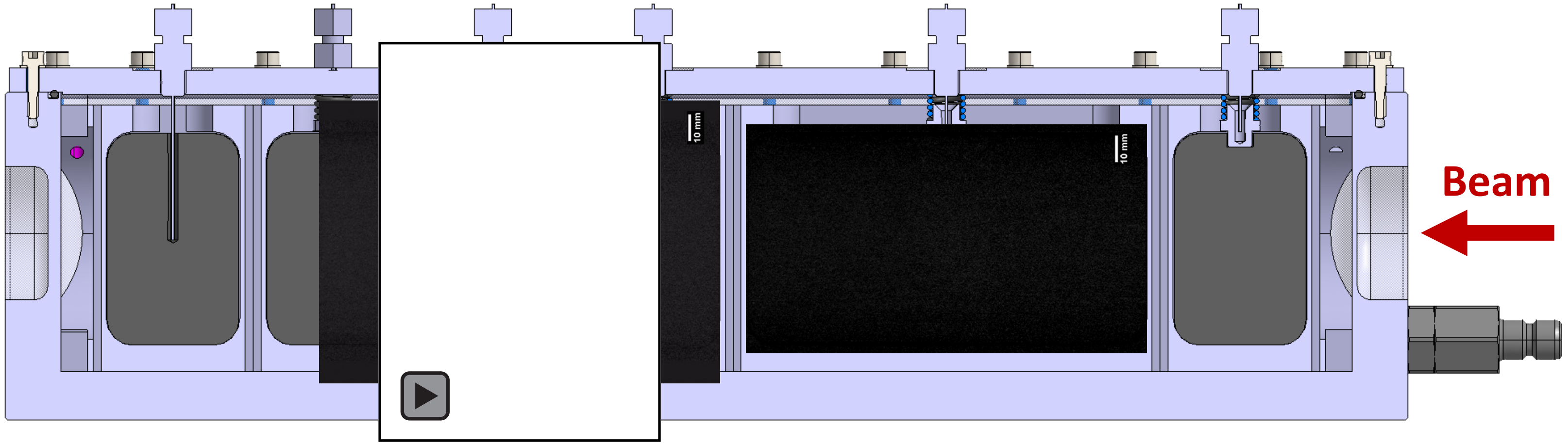
HiRadMat prototypes



Beam irradiation tests in HiRadMat

PIE N_2-cooled Pb prototype

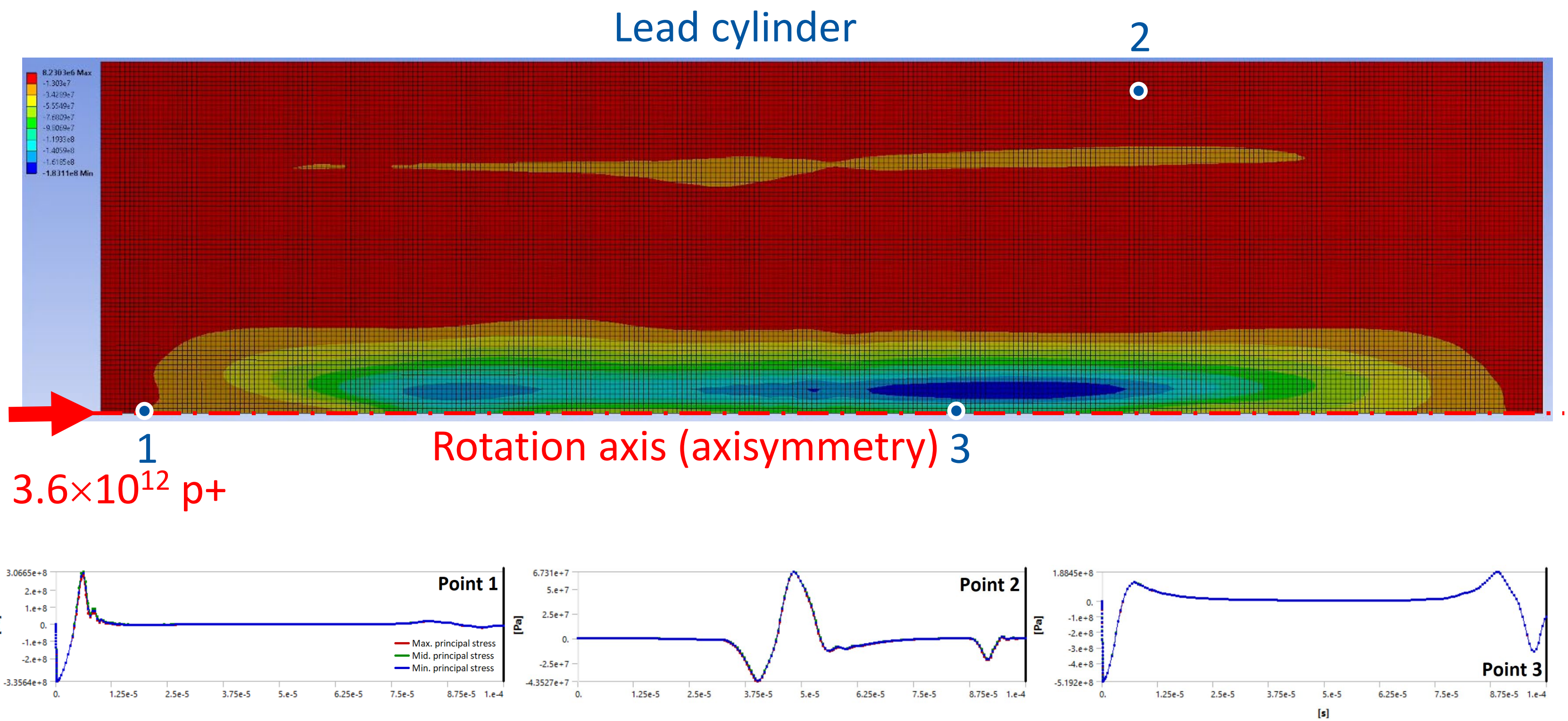
Neutron tomography at NEUTRA (PSI)



No detectable voids down to 100 μm

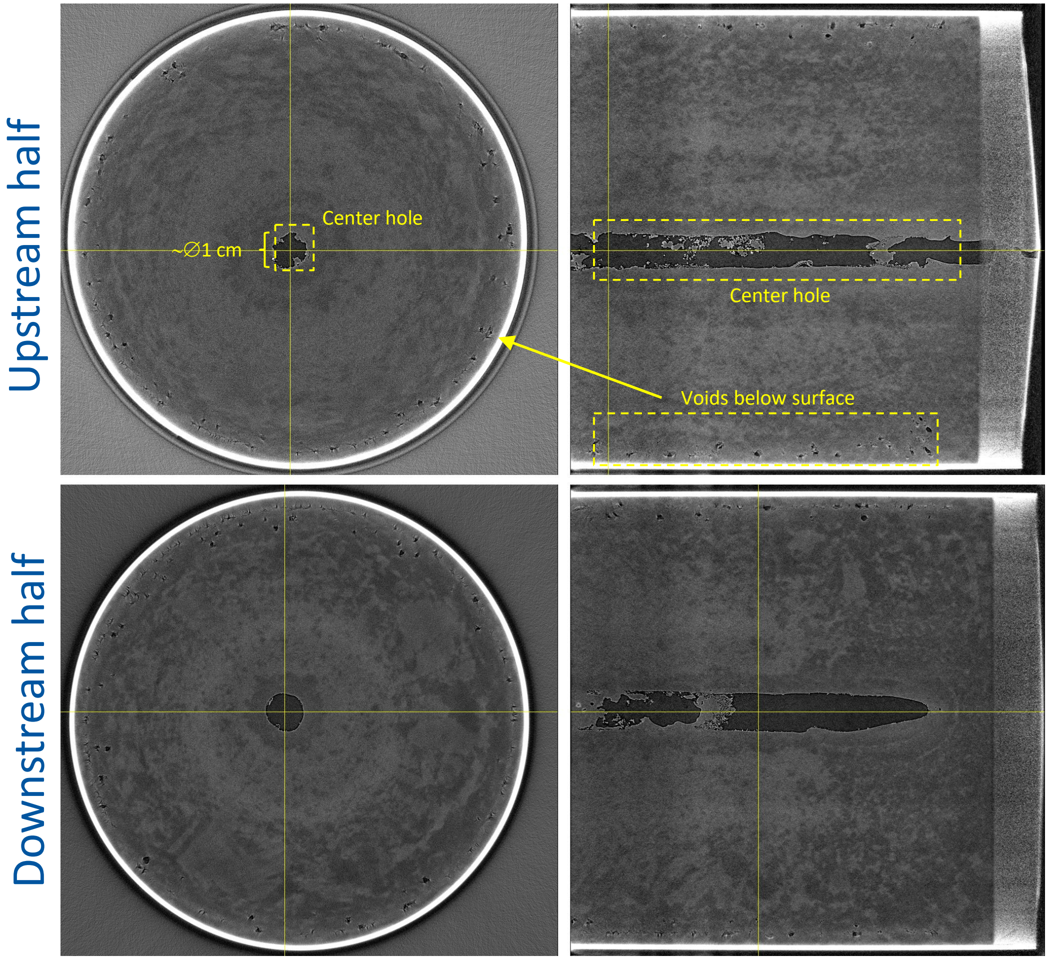
Beam irradiation tests in HiRadMat

Ti64-clad Pb prototype



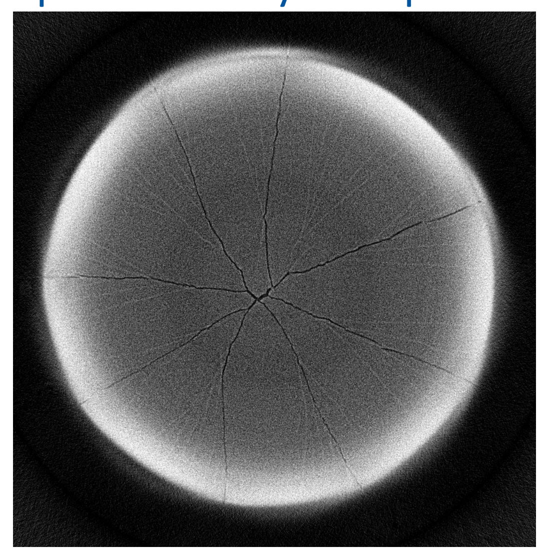
Huge oscillations of stress on the beam axis and below the cylindrical surface

Beam irradiation tests in HiRadMat

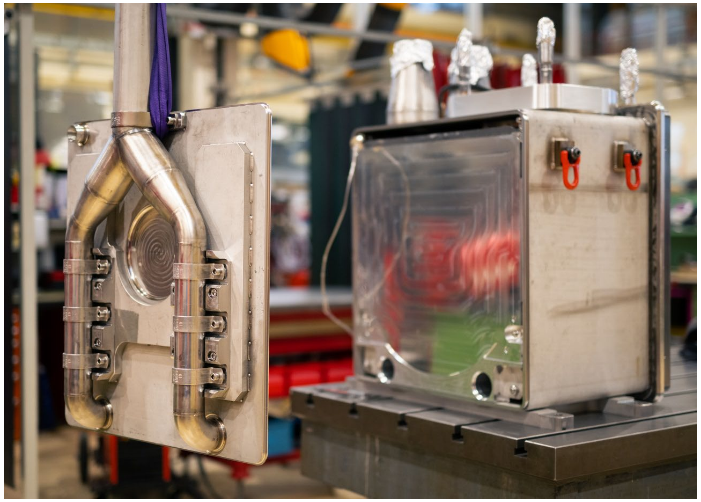


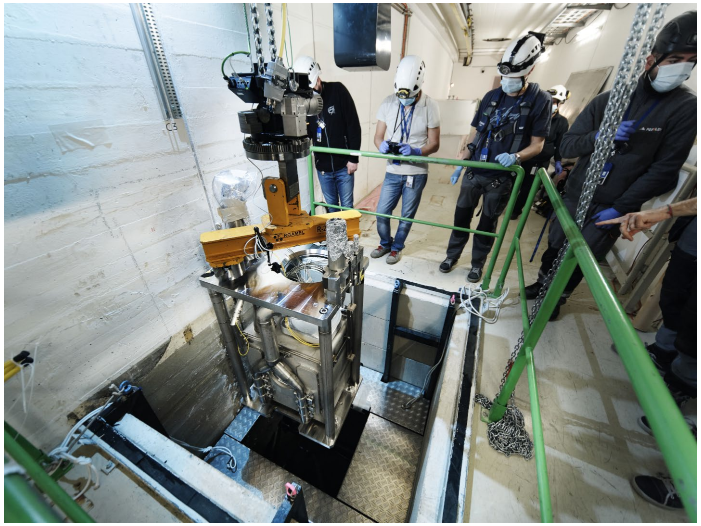
- After 1000 pulses of 3.6×10^{12} p^+
- Neutron tomography at ILL (Grenoble)
- Voids in the lead cylinder
- Ti-6Al-4V cladding intact and content sealed

Upstream beryllium plate cracked

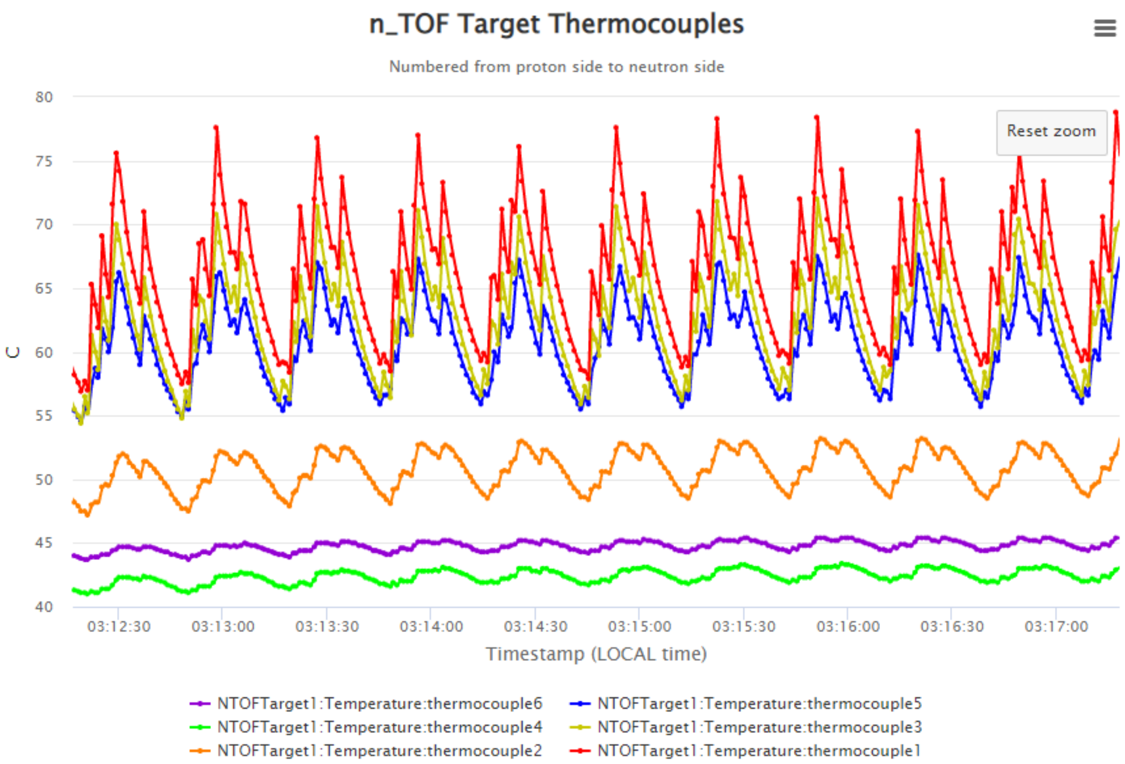


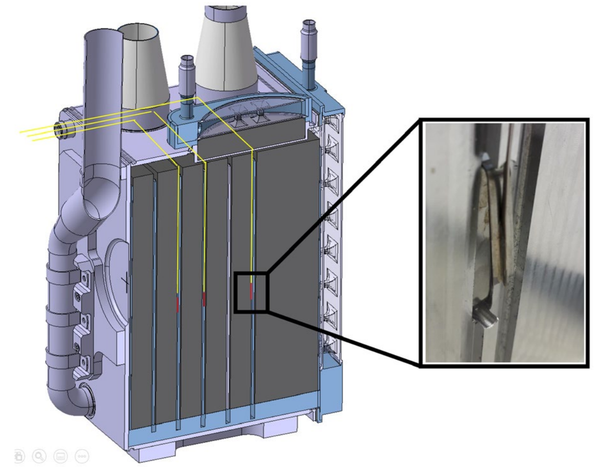
3rd gen target installed in 2021

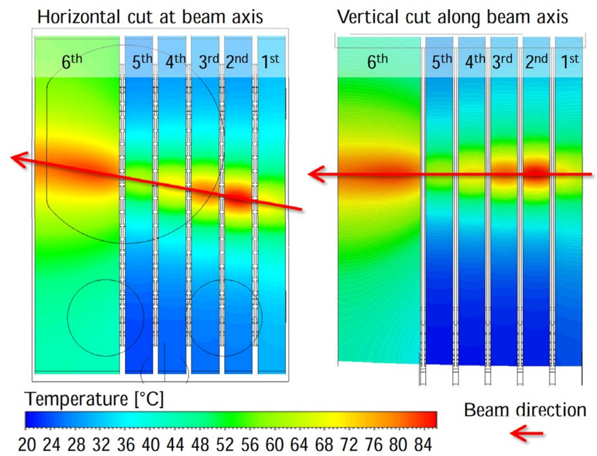




Target operation in 2021-2022

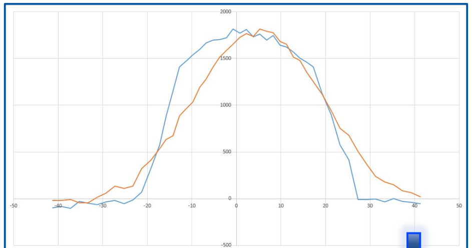




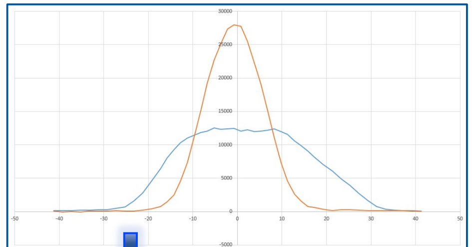


Target operation in 2021-2022

15×15 mm² RMS

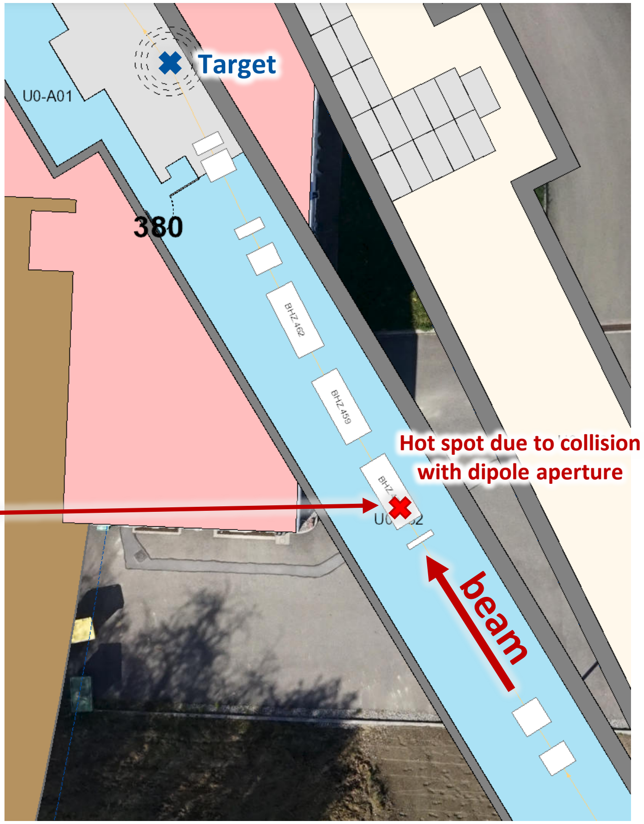


16×7 mm² RMS

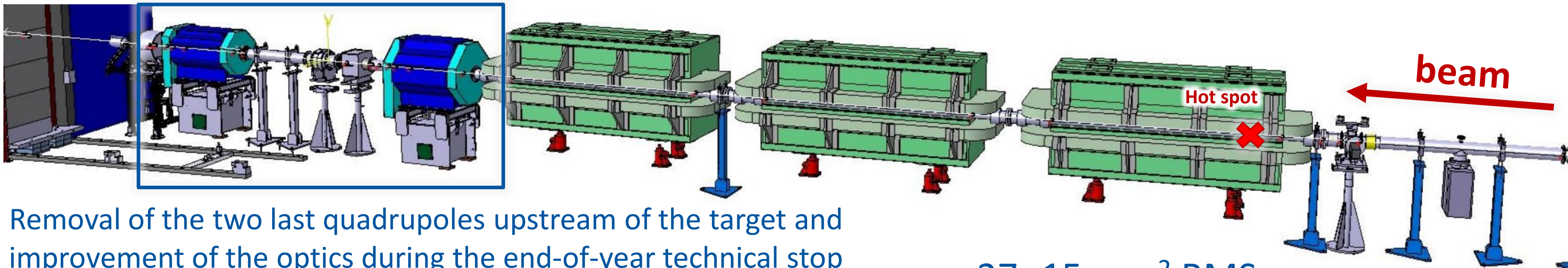


Dose rate (measured at 1 m) after modifications in the beam line with improved optics during the end-of-year technical stop

ID	Reference	Position	Dose rate [µSv/h] Date: 15-09-21 Cool down time: 30 h	Dose rate [µSv/h] Date: 28-09-21 (8:15) Cool down time: 30 h	Dose rate [µSv/h] Date: 16-11-21 (14:50) Cool down time: 30 h	Dose rate [µSv/h] Date: 17-05-22 (13:15) Cool down time: 30 h	Dose rate [µSv/h] Date: 13-09-22 (17:50) Cool down time: 31 h
1	-	Start of FTN	3	2.5	1	0.8	4
2	QFO.435	UPSTREAM	4	2.5	2	1.7	38
3	QFO.435	DOWNSTREAM	4	3.5	2	3	46
4	DHZ.436	DOWNSTREAM	3.5	1.7	2	1.3	26
5	QDE.450	UPSTREAM	33	18	12	12	33
6	QDE.450	DOWNSTREAM	38	18.5	13	15	37
7	DVT.451	DOWNSTREAM	13	3.6	4	10	25
8	-	Between DVT.451 and FTN.BTV454	-	30 (below)	-	-	-
9	-	Between DVT.451 and FTN.BTV454	-	-	-	-	12
10	FTN.BTV454	UPSTREAM	97	32	20	15	20
11	FTN.BTV454	DOWNSTREAM	193	42	25	14	32
12	BHZ 456	MIDDLE	360	76	45	20	35
13	BHZ 456	DOWNSTREAM	116	35	25	17	22
14	BHZ 459	DOWNSTREAM	74	28.5	19	36	47
15	BHZ 462	DOWNSTREAM	70	26	20	60	100
16	*old QFO.465*	DOWNSTREAM	50	25	21	-	-
17	UWB.474	UPSTREAM	-	-	-	67	69
18	UWB.474	DOWNSTREAM	62	25.7	32	64	76
19	*old QDE.480*	UPSTREAM	83	53.5	56	-	84
20	*old QDE.480*	DOWNSTREAM	126	82	93	-	-
21	BSG.484	UPSTREAM	-	-	-	154	170
22	BSG.484	DOWNSTREAM	127	100	99	150	193
23	-	Vacuum chamber in the wall	-	-	-	124	170



Target operation in 2021-2022



Removal of the two last quadrupoles upstream of the target and improvement of the optics during the end-of-year technical stop

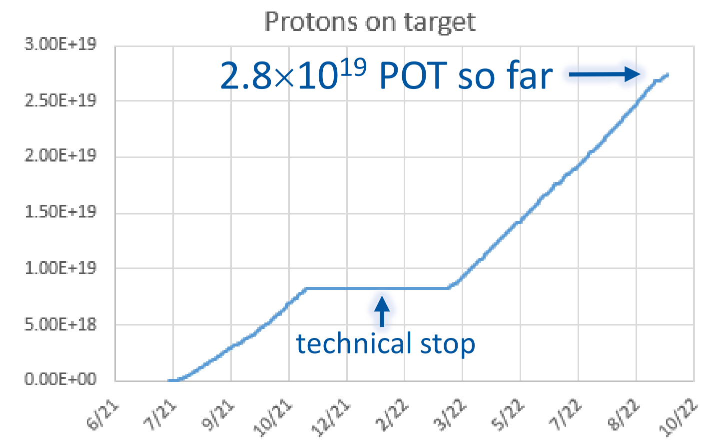
27×15 mm^2 RMS

Beam spot even larger than design assumptions

possible to increase intensity

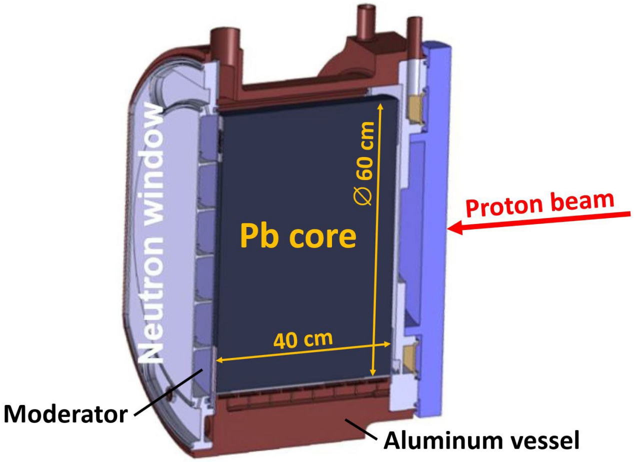
11	FTN.BTV454	DOWNSTREAM	193	42	25	14	32
12	BHZ 456	MIDDLE	360	76	45	20	35
13	BHZ 456	DOWNSTREAM	116	35	25	17	22

Dose rate at hotspot back to acceptable values

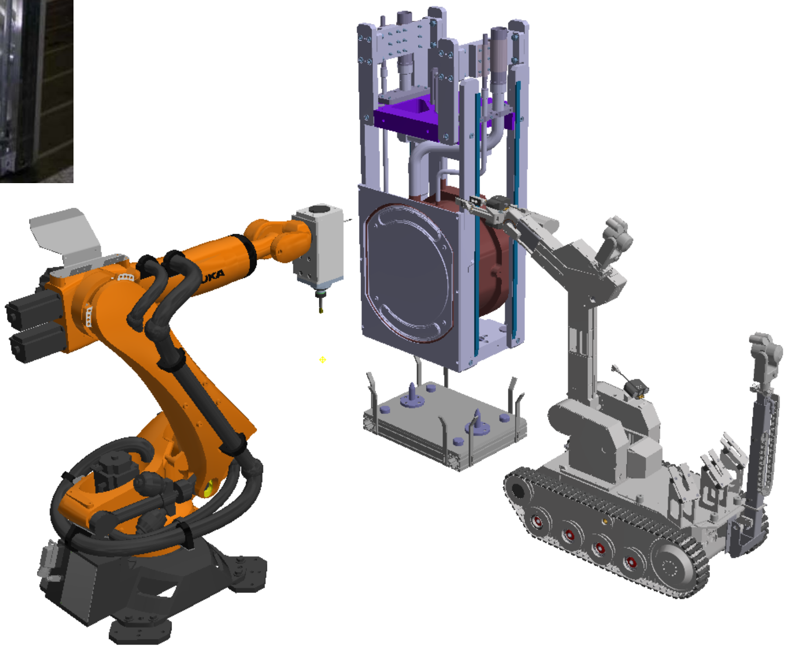


2nd gen target autopsy

- Single lead cylinder (∅60×40 cm²) in aluminium vessel, water-cooled
- In operation from 2009 to 2018

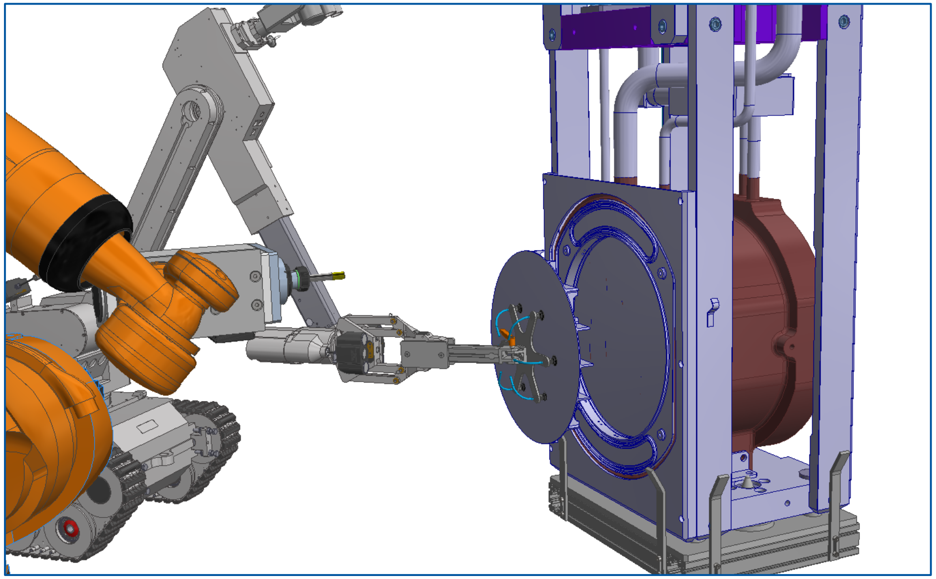


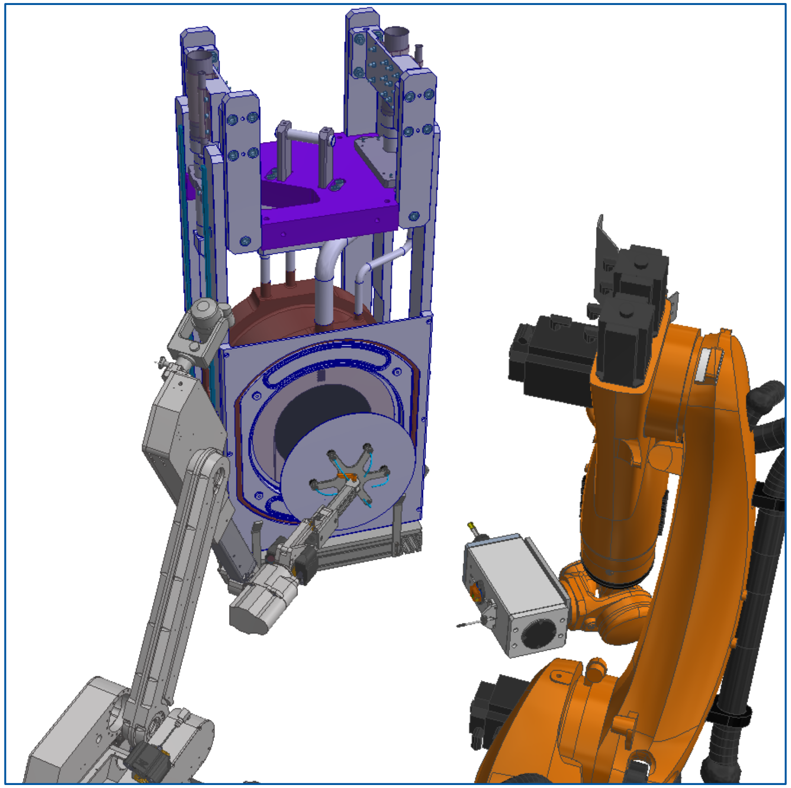
- Autopsy and radioactive waste packaging planned for summer 2023
- Executed with KUKA and Telerob robots



2nd gen target autopsy

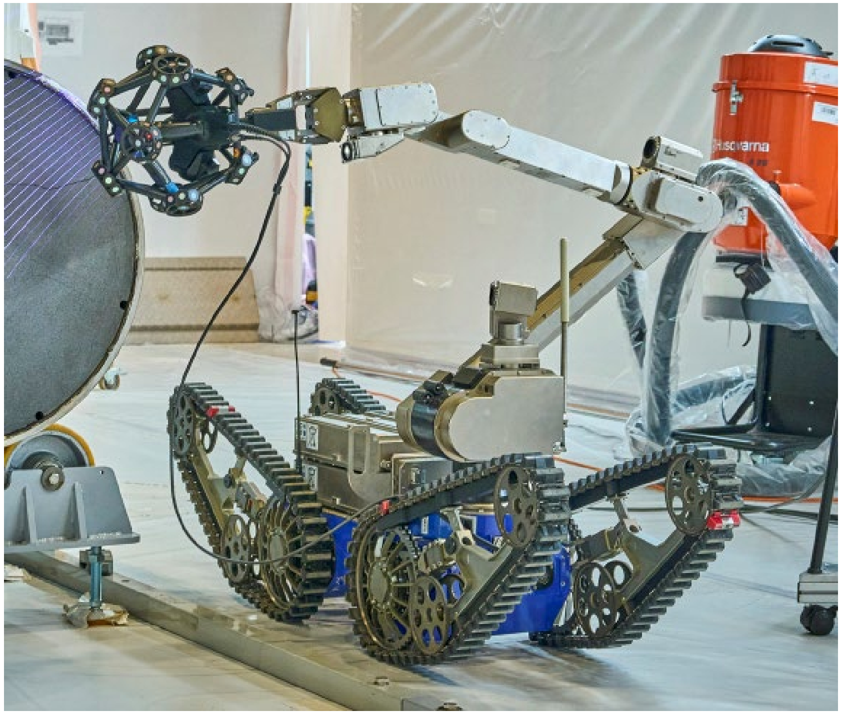
- The borated-water moderator casing will be cut out and inspected to assess the presence of boron deposits
- The downstream window will also be cut out to expose the surface of the Pb core
- The upstream face of the Pb core will also be exposed with a similar procedure

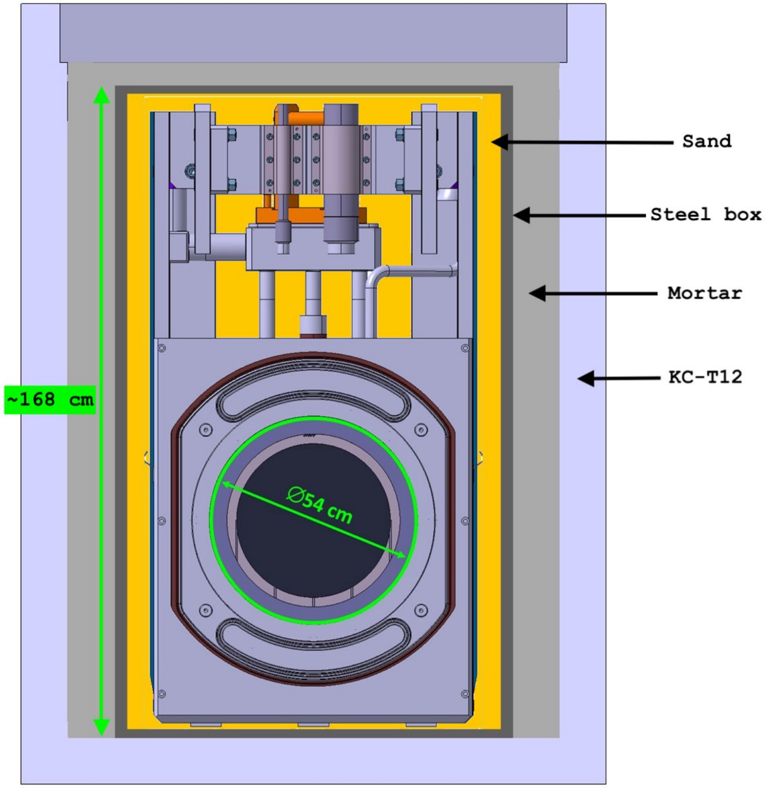




2nd gen target autopsy

- Scanning of Pb surface by 3D scanner to quantify plastic deformation due to beam interaction and creep
- Cutting of the target frame for compact package in KC-T12 container for disposal in Swiss repository





Summary

- The n_TOF Target #3 successfully operates since July 2021 with a new design based on N_2-cooled pure Pb plates. The new design is the result of 5 years of studies including material characterization activities, constitutive modelling, and beam irradiation tests.
- The new target is equipped with instruments for live monitoring of temperature, beam profile, and cooling parameters, also used for beam interlocks.
- Improvements in proton beam line and optics led to contained dose and thermo-mechanical loads opening possibility for further improvement in target performance
- An autopsy of the spent 2nd generation target is planned for summer 2023 to provide feedback on the long term structural effects on the target, after a decade of target operation
- Additional references:

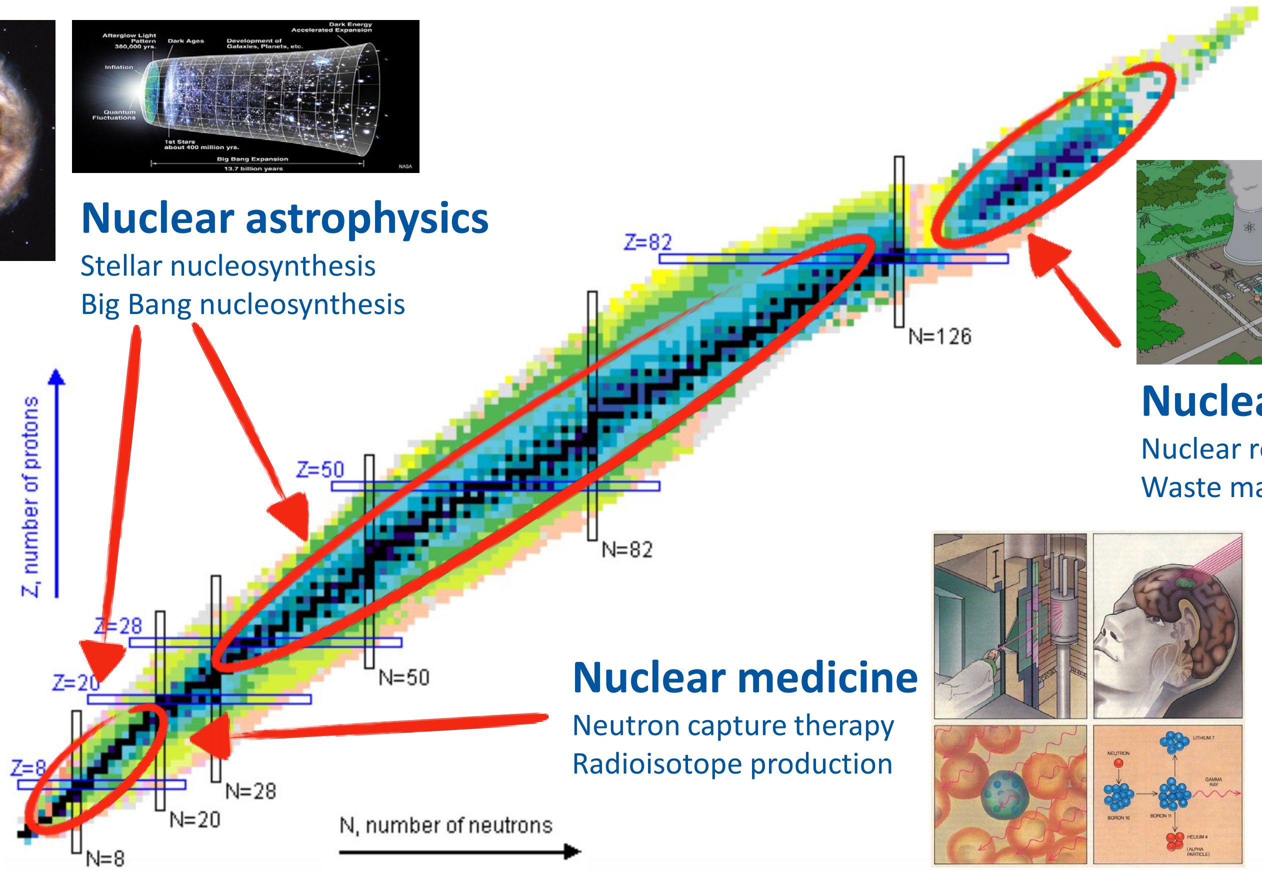
  - R. Esposito *et al.*, *Phys. Rev. Accel. Beams* **24**, 093001 (2021)
  - R. Esposito *et al.*, *J. Neutron Res.* **22**, 221 (2020)
  - R. Esposito, *Design, prototyping, and thermo-mechanical modelling of a neutron spallation target impacted by high-energy proton-beam pulses in the n_TOF facility at CERN*, Ph.D. dissertation, EPFL, Lausanne, Switzerland (2022)

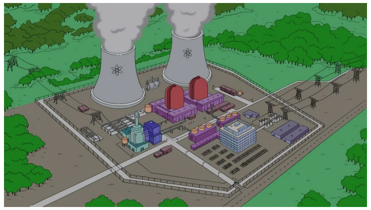
Additional slides

The n_TOF facility at CERN

Chart of nuclides

Nuclear astrophysics
Stellar nucleosynthesis
Big Bang nucleosynthesis





Nuclear technology
Nuclear reactors (energy)
Waste management

Nuclear medicine
Neutron capture therapy
Radioisotope production

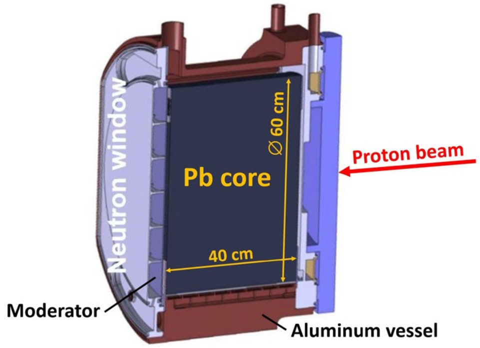
The n_TOF facility at CERN

Target #1 and target #2

- Target #1 operated from 2000 to 2004
- Target #2 operated from 2009 to 2018
- Based on pure lead cooled by water
- Abnormal increase of radioactivity in the cooling circuit
- Erosion/corrosion issues
- Cooling water contamination with radioactive products from target

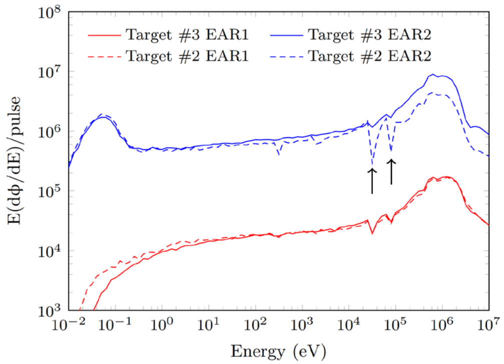
Target #1

Target #2

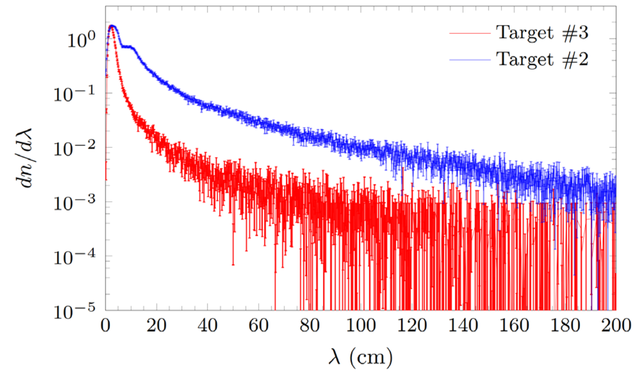


Target #3: physics performance

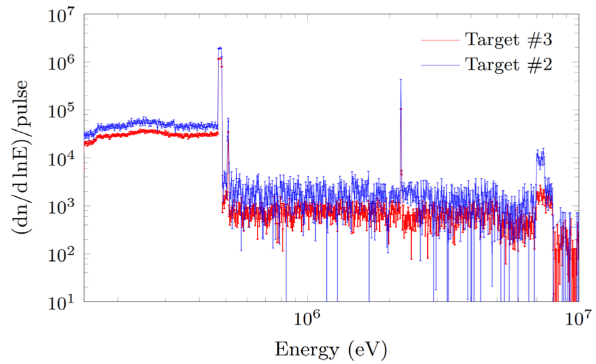
Neutron flux



Resolution function

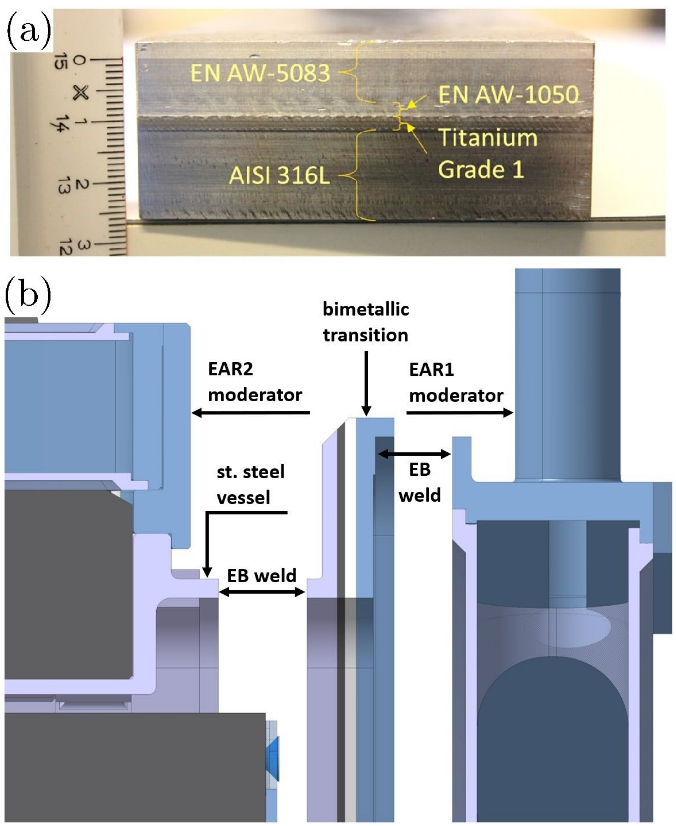


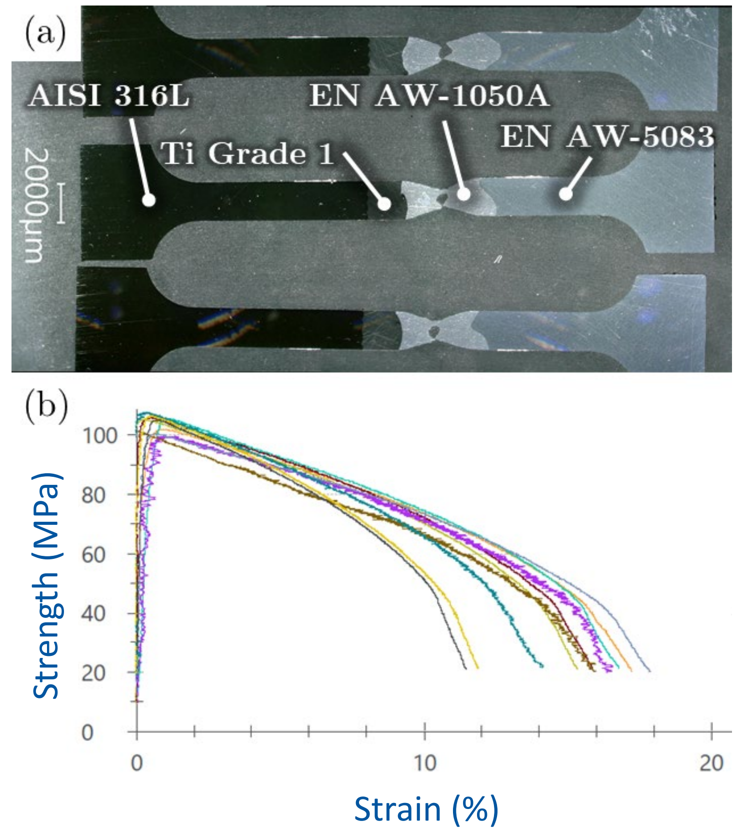
Photon background



Neutron moderators

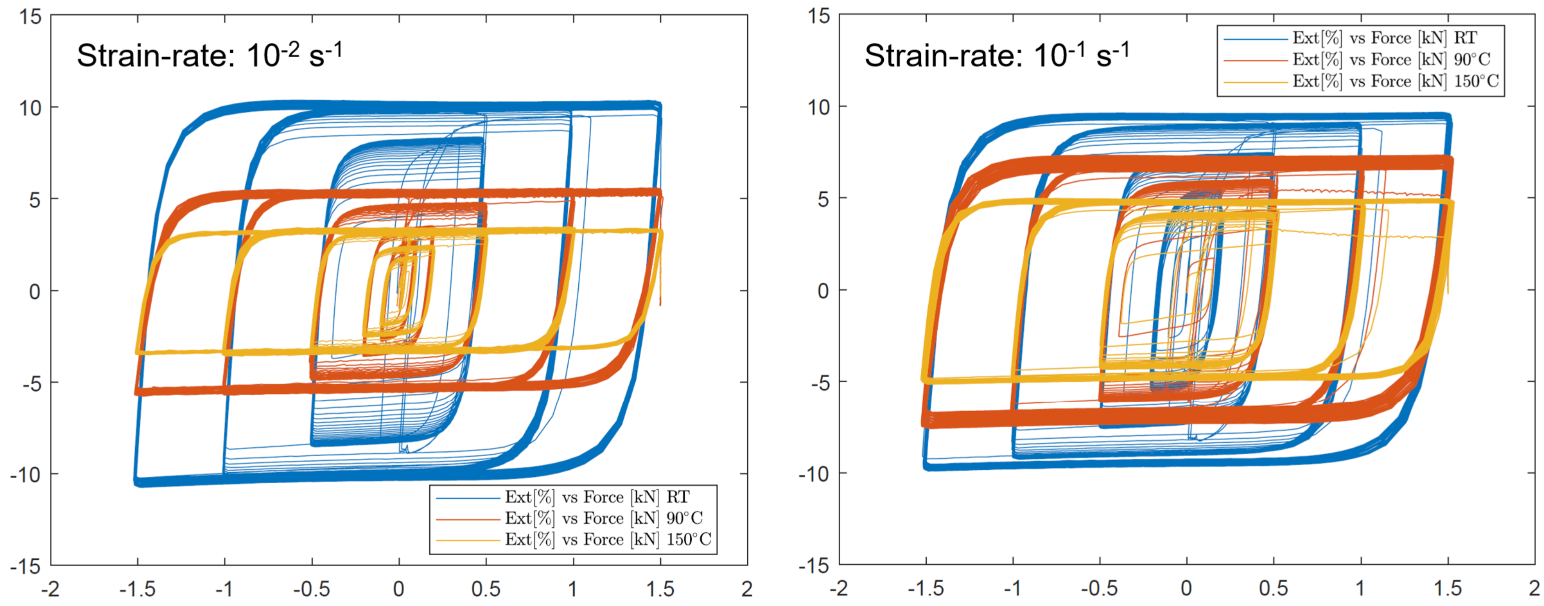
Explosive-welded bond between stainless steel vessel and Al-5083 moderator





Pb constitutive model for cyclic plasticity

- Better predictions of long term Pb behaviour → Multi-pulse simulations →
  → Pb constitutive behaviour under cyclic plasticity
- Strain-controlled cyclic tests at different temperatures and strain-rates (collaboration with Norwegian University of Science and Technology)
- Observed: Bauschinger effect, cyclic-hardening, non-Masing behaviour.
- Non reproducible by traditional models generally available in commercial FEM software



Pb constitutive model for cyclic plasticity

- *Incremental plasticity* model proposed
- Able to reproduce Bauschinger effect, cyclic hardening, and non-Masing behaviour.

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^{\mathbf{e}} + \boldsymbol{\varepsilon}^{\mathbf{p}} + \boldsymbol{\varepsilon}^{\mathbf{th}}$$

$$\boldsymbol{\sigma} = \mathbb{E} : \boldsymbol{\varepsilon}^{\mathbf{e}}$$

$$f = \sqrt{\frac{3}{2}(\boldsymbol{\sigma}' - \mathbf{X}) : (\boldsymbol{\sigma}' - \mathbf{X})} - R - \sigma_{y0} = 0$$

$$\dot{\boldsymbol{\varepsilon}}^{\mathbf{p}} = \dot{\lambda}\mathbf{N} = \dot{\lambda}\frac{\frac{3}{2}(\boldsymbol{\sigma}' - \mathbf{X})}{\sqrt{\frac{3}{2}(\boldsymbol{\sigma} - \mathbf{X}) : (\boldsymbol{\sigma} - \mathbf{X})}}$$

$$\dot{\lambda} = \sqrt{\frac{2}{3}\dot{\boldsymbol{\varepsilon}}^{\mathbf{p}} : \dot{\boldsymbol{\varepsilon}}^{\mathbf{p}}}$$

$$\dot{\mathbf{X}} = \frac{2}{3}C\dot{\boldsymbol{\varepsilon}}^{\mathbf{p}} - \gamma\mathbf{X}\dot{\lambda}$$ Bauschinger effect [1]

$$\dot{R} = b(Q - R)\dot{\lambda}$$ Cyclic hardening

Strain memory model [2]

$$F = \sqrt{\frac{2}{3}(\boldsymbol{\varepsilon}^{\mathbf{p}} - \boldsymbol{\zeta}) : (\boldsymbol{\varepsilon}^{\mathbf{p}} - \boldsymbol{\zeta})} - q = 0$$

$$\dot{q} = \frac{1}{2}(\mathbf{N} : \mathbf{n}^*)\dot{\lambda}$$

$$\dot{\boldsymbol{\zeta}} = \frac{1}{2}(\dot{\boldsymbol{\varepsilon}}^{\mathbf{p}} : \mathbf{n}^*)\mathbf{n}^*$$

$$\mathbf{n}^* = \frac{\sqrt{\frac{2}{3}}(\boldsymbol{\varepsilon}^{\mathbf{p}} - \boldsymbol{\zeta})}{\sqrt{\frac{3}{2}(\boldsymbol{\varepsilon}^{\mathbf{p}} - \boldsymbol{\zeta}) : (\boldsymbol{\varepsilon}^{\mathbf{p}} - \boldsymbol{\zeta})}}$$

$$Q = Q_M - (Q_M - Q_0)\, e^{-2\mu q}$$

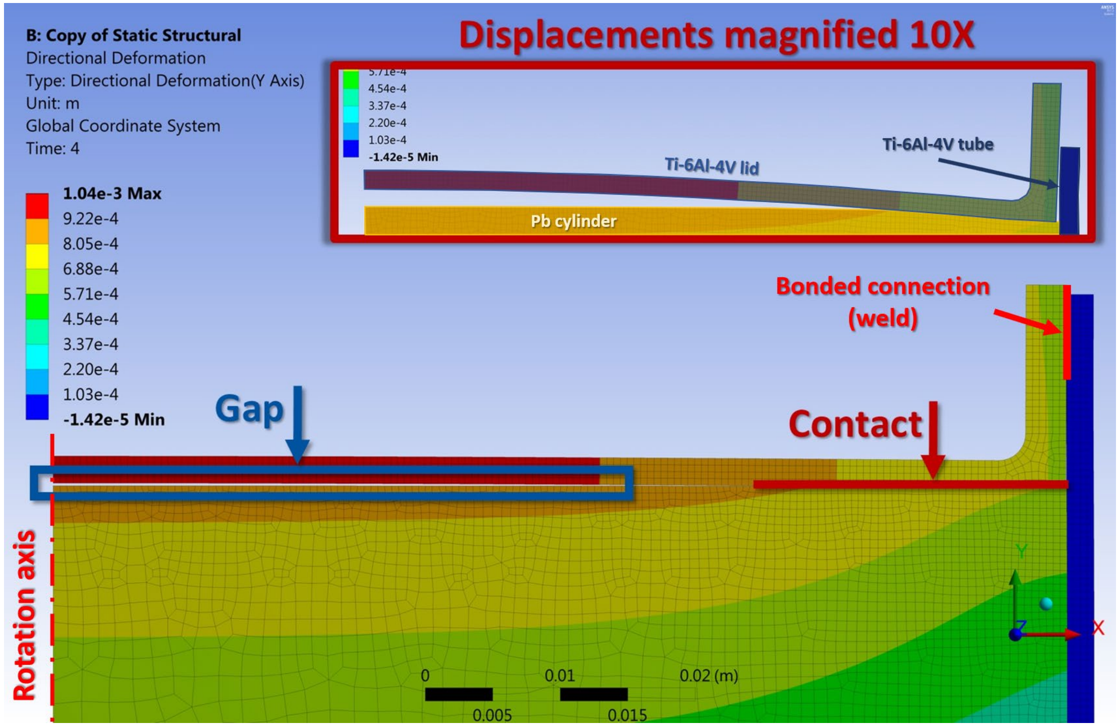
Non-Masing behaviour

[1] P. J. Armstrong, C. O. Frederick, C.E.G.B. Report RD/B/N731, Berkeley, UK, 1966
[2] J. Lemaitre et al., *Mécanique des matériaux solides*, 3rd ed., Dunod, 2009

The Ti64-clad Pb prototypes

Deformation Ti-6Al-4V lid → Loss of contact with lead → Loss of conductivity and cooling efficiency

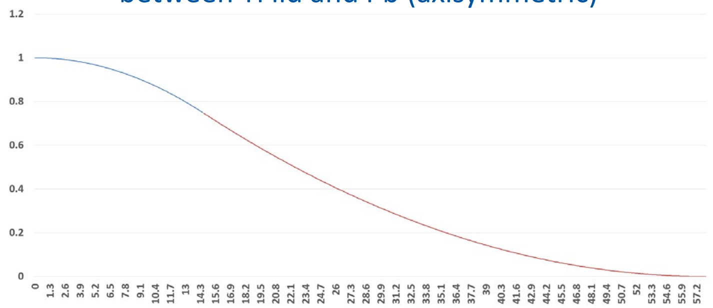
Prototypes manufactured:
Pb cylinder with
Ti-6Al-4V cladding



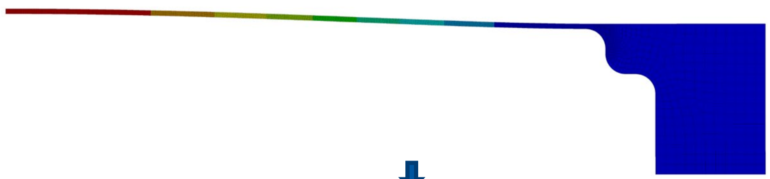
Axisymmetric simulation

The Ti64-clad Pb prototypes

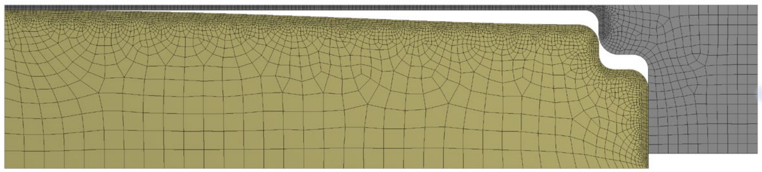
Desired contact pressure profile
between Ti lid and Pb (axisymmetric)



Ti lid deformation due to desired contact pressure

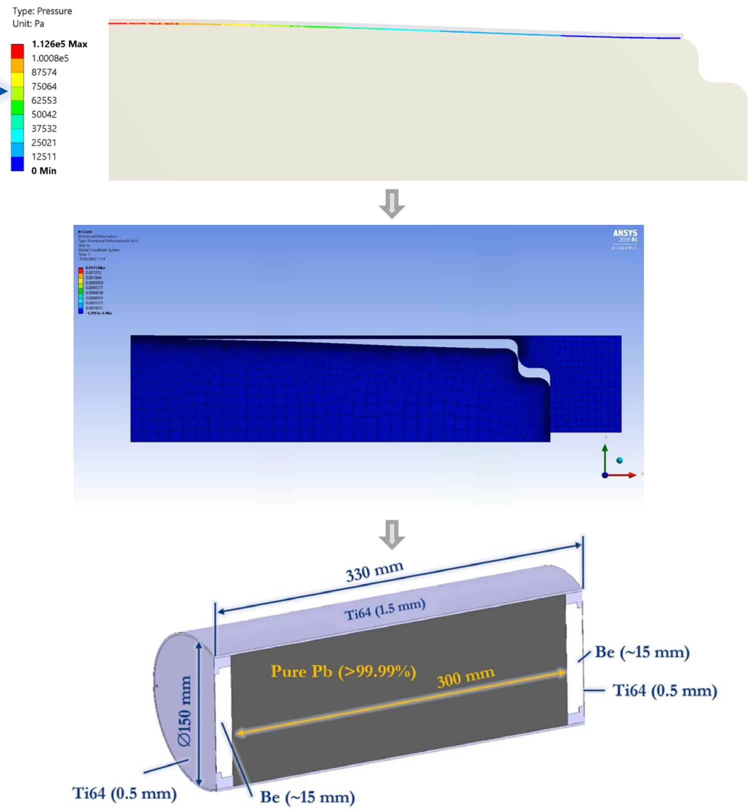


Be plate imposing desired deformation



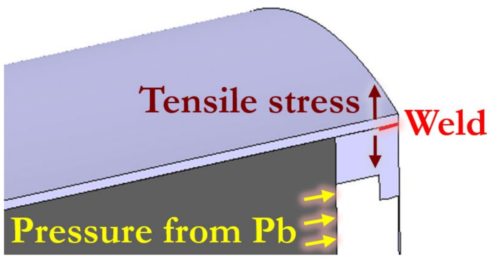
Be transparent to neutrons

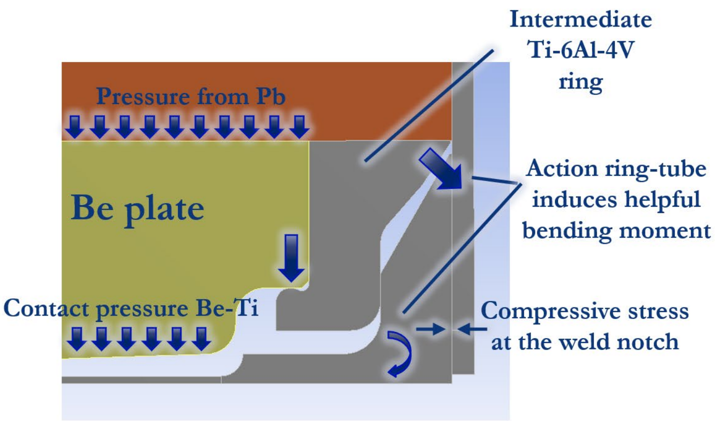
Contact pressure as reaction of imposed deformation



The Ti64-clad Pb prototypes

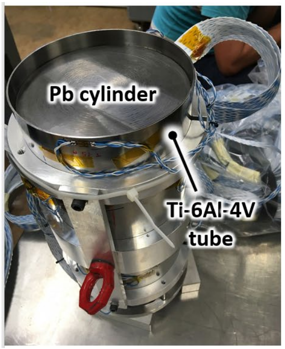
High bending stress (tensile) at the weld notch → Addition of intermediate ring to improve stress distribution

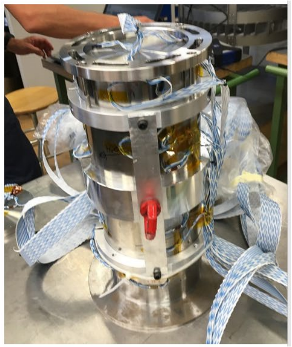
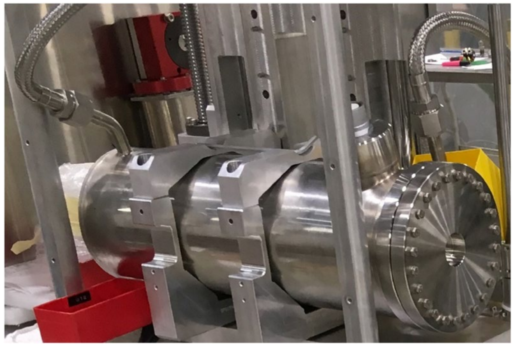




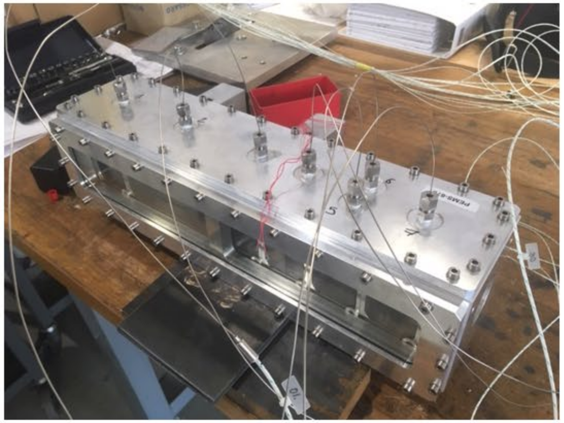
Beam irradiation tests in HiRadMat

Ti-6Al-4V-clad Pb with Be plates

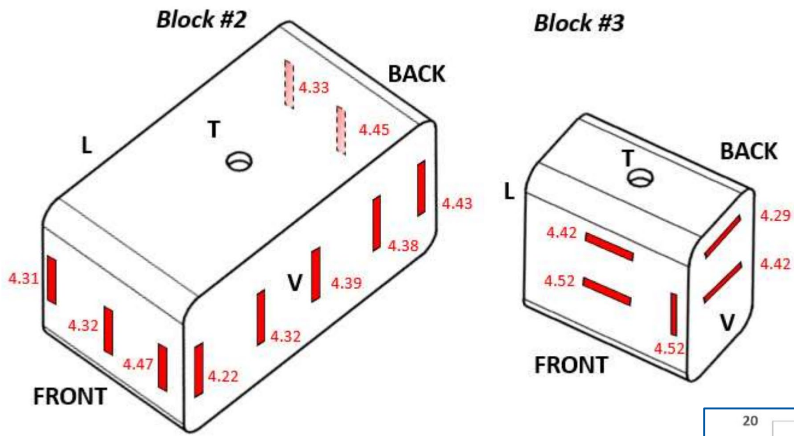


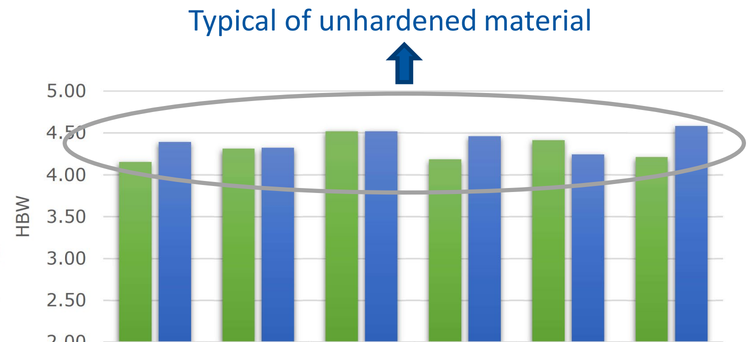



N_2-cooled Pb blocks



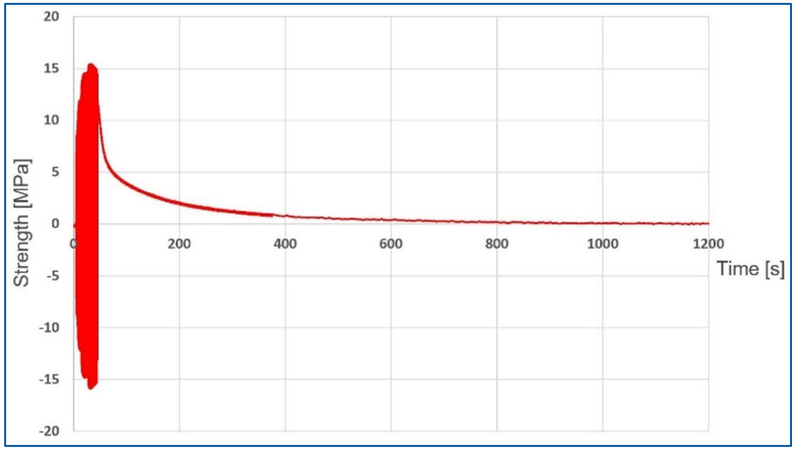

N_2-cooled Pb prototype hardness





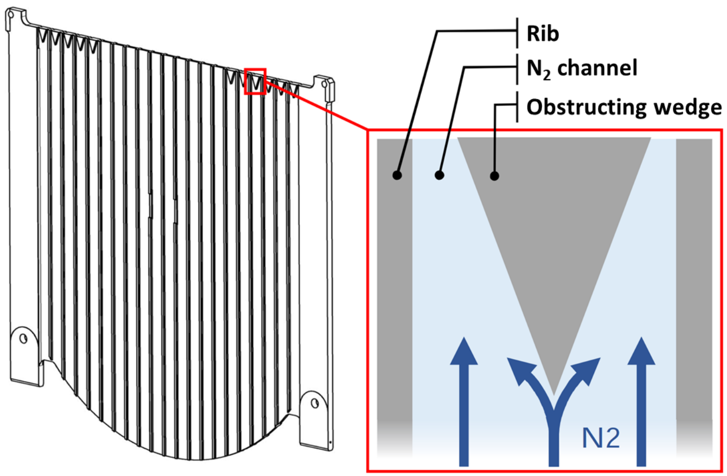
	Block #1	Block #2	Block #3	Block #4	Block #5	Block #6
Edge	4.15	4.31	4.52	4.18	4.41	4.21
Center	4.39	4.32	4.52	4.46	4.24	4.58

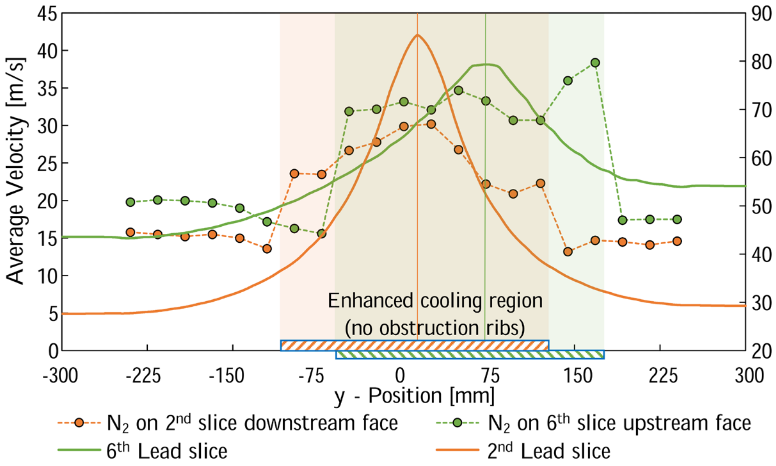
- Compatible with observations of stress relaxation tests
- Total recovery after ~10 min at RT



CFD and cooling optimization

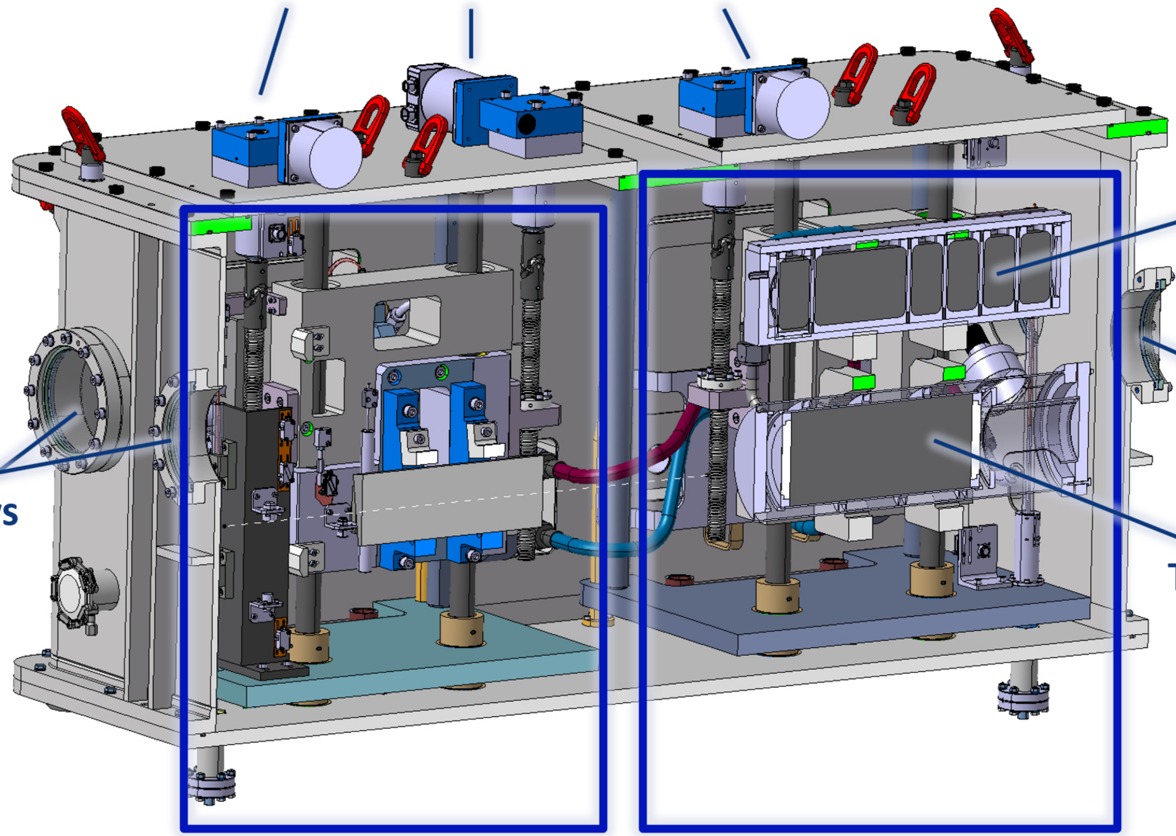
Obstructing wedges to optimize N_2 flow distribution





Average HTC	$63.8\ W\ m^{-2}\ K^{-1}$
Peak HTC	$130\ W\ m^{-2}\ K^{-1}$

Beam irradiation tests



Beam irradiation tests