Beam Intercepting Devices at CERN Types, Challenges, Design, R&D and Operation

M. Calviani (SY-STI)

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Lecture 1/2

Disclaimer

These lectures will present a **phenomenological** and **broader approach** in the design, construction and operation of beam intercepting devices, focusing on **requirements**, **technologies** and **operational constraints**

Dedicated Accelerator Schools (CAS, USPAS, JAS, etc.) are available to expand the calculation part

Structure of the lectures

Lecture 1 will be focused on general concepts, definition and challenges in the design of beam intercepting devices

Lecture 2 will provide specific examples of advanced components recently built, in commissioning & in operation at CERN

Acknowledgments

Many thanks to several colleagues for their contribution and material

A. Perillo-Marcone, A. Lechner, C. Torregrosa, R. Ximenes, F.-X. Nuiry, L. Salvatore Esposito, R. Rossi, O. Aberle

And material from A. Bertarelli, P. Hurh, B. Riemer, M. Wohlmuther & many others

Beam Intercepting Device – a possible definition

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

☐ **Production of secondary particles** (“target”)

☐ **Protection of sensitive equipment** (“collimator”)

☐ **Safe disposal** (“dump”)

Safety function

Beam stoppers

Beam dumps

Beam cleaning & control

Collimators

Scrapers

Strippers

Slits

Physics

Particle producing targets

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

- Devices must be able to withstand operation and accident scenarios & protect delicate equipment
- Sometimes employed as “last line of defence” against component damage
- Operational teams rely heavily on dependable components, whose failure often leads to long period of downtime
- Usually, the most radioactive components in an accelerator complex (cool down, ALARA)

FEATURE SYSTEMS ENGINEERING

INTERCEPTING THE BEAMS

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

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

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

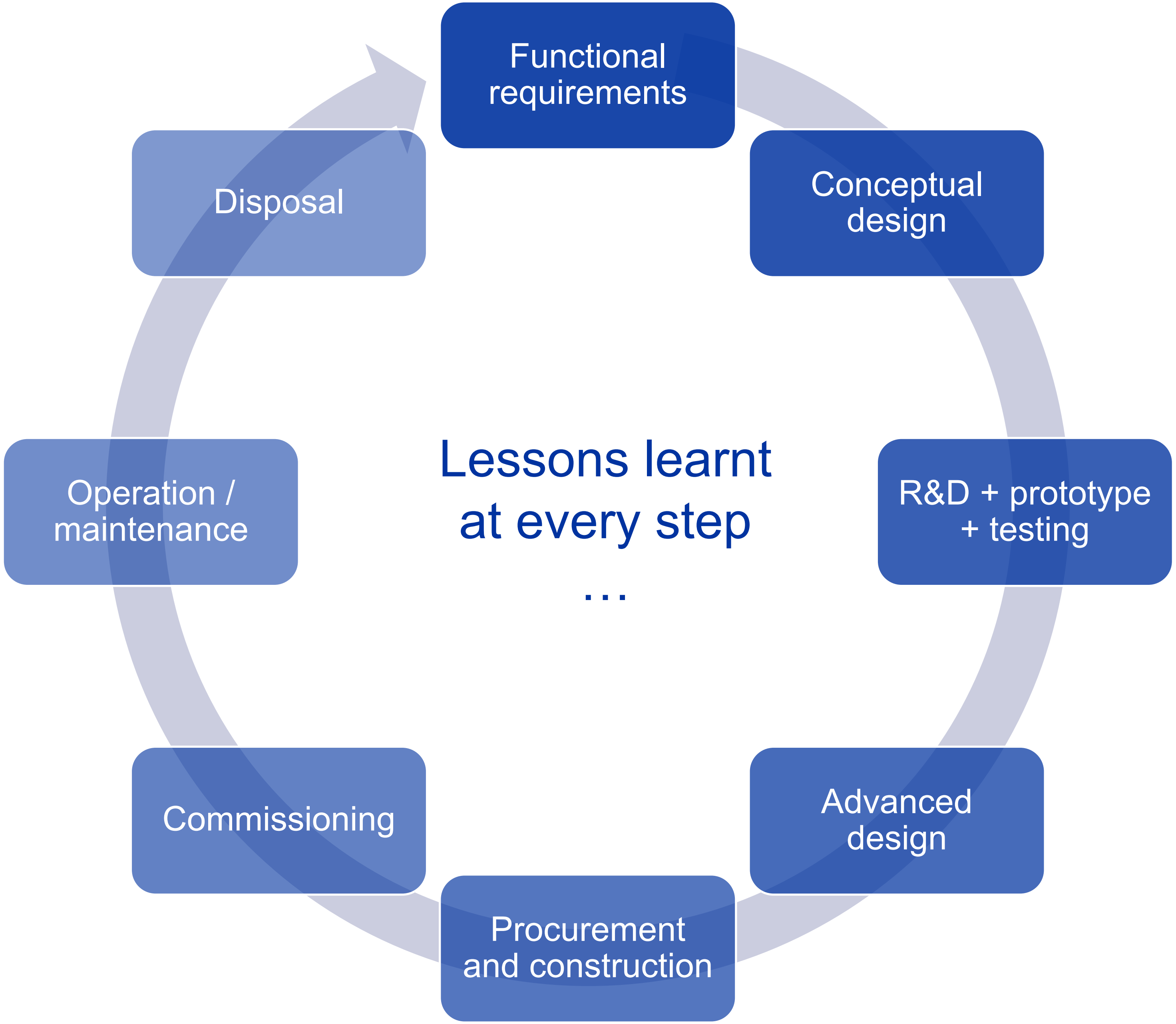
- Ultra High Vacuum requirements (10^{-10} mbar)
- Movable parts with extremely high precision and flatness requirements
- High energy densities (several kJ/cm^3/pulse)
- High power densities (±MW/cm^3)

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

- High beam kinetic energy (up 700 MJ)
- High average deposited power (several hundreds of kW)
- Physics requirements (sometimes implying materials with poor structural properties)
- Impedance (especially for colliders)
- Radiation damage and modification of thermo-physical properties

BIDs lifecycle

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



Functional requirements

Conceptual design

R&D + prototype + testing

Advanced design

Procurement and construction

Commissioning

Operation / maintenance

Disposal

Lessons learnt at every step

…

Boundary conditions & constraints

Design is a complex and iterative process, which must satisfy multiple requirements with – in most cases – incomplete data to start with

- Integration and localisation constraints (tunnels, alcoves, etc.)
- Thermo-mechanical stability
- Material damage (lifetime & reliability)
- Operational availability
- Safety for personnel and for machine
- Handling, accessibility & maintenance considerations

Boundary conditions & constraints

Design is a complex and iterative process, which must satisfy multiple requirements with – in most cases – incomplete data to start with

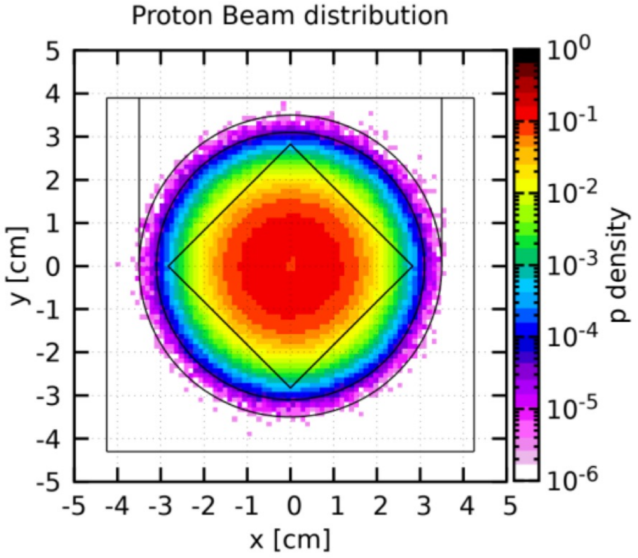
Warning:

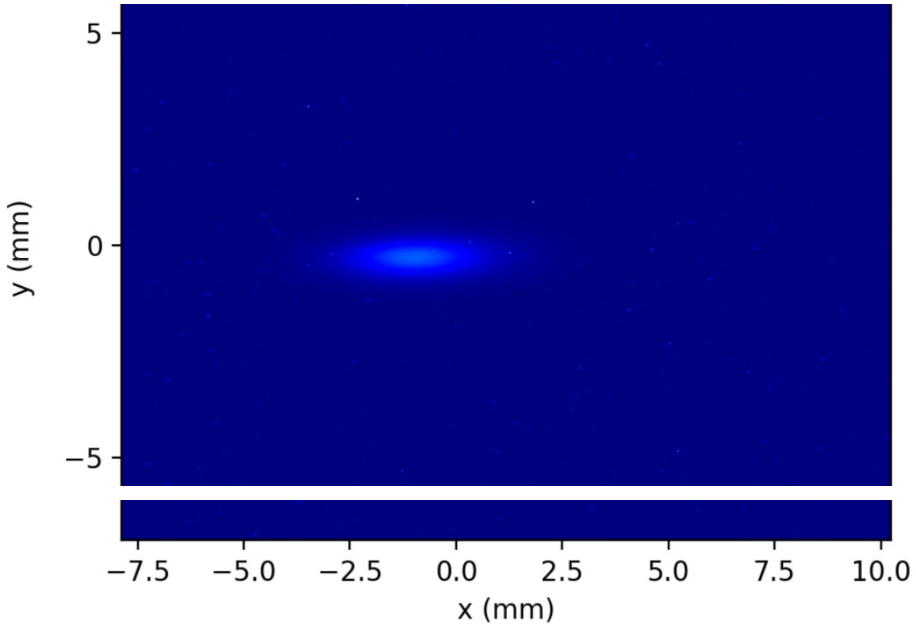
- Unclear functional requirements may later affect performances, safety, reliability/maintainability and inspectability
- Initial cost estimate must be careful thought albeit lack of clear specifications

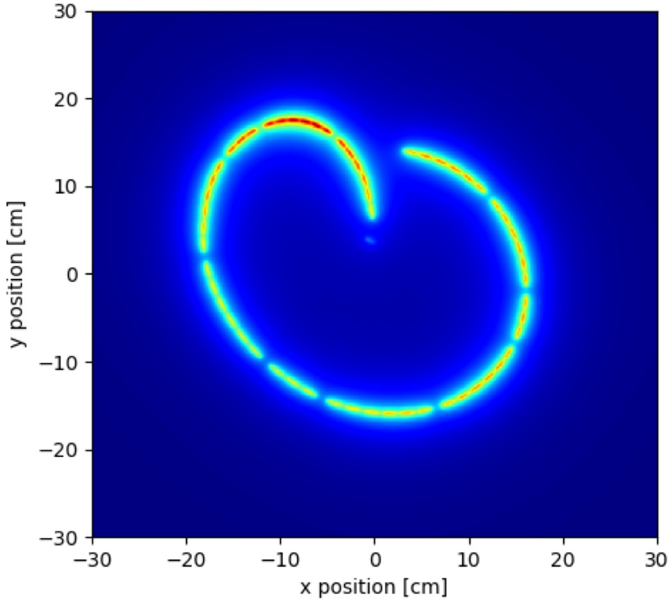
Knowledge of beam parameters impacting on BID

- BID design parameters and constraints generally scale with particle peak intensity (e.g., protons per unit area)

- Peak value can be very dependent on the **beam profile** (e.g. gaussian, flat, or a combination, sweeps or rastered)



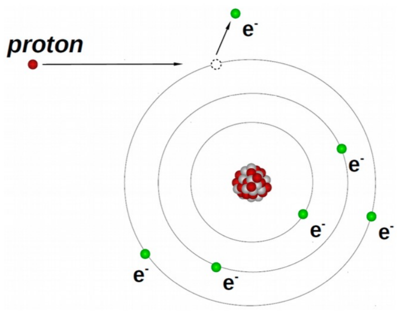


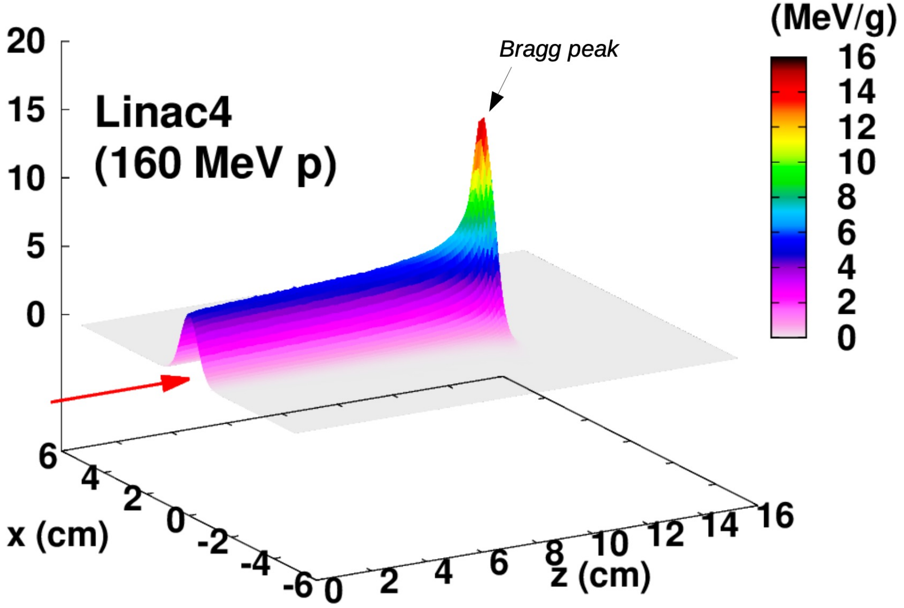


Beam-matter interaction simulations

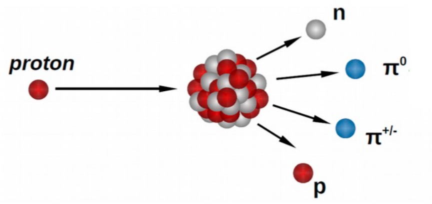
Particles interacts with matter via different mechanisms, depending on species (lepton vs. hadron), energy, impacting material (A, Z and ρ)

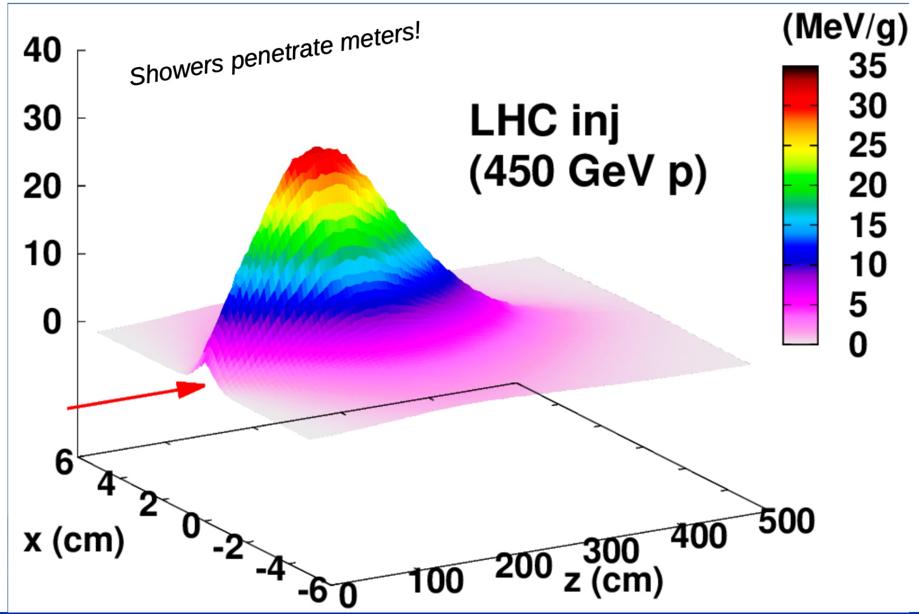
Most protons range out (ionizing energy loss)





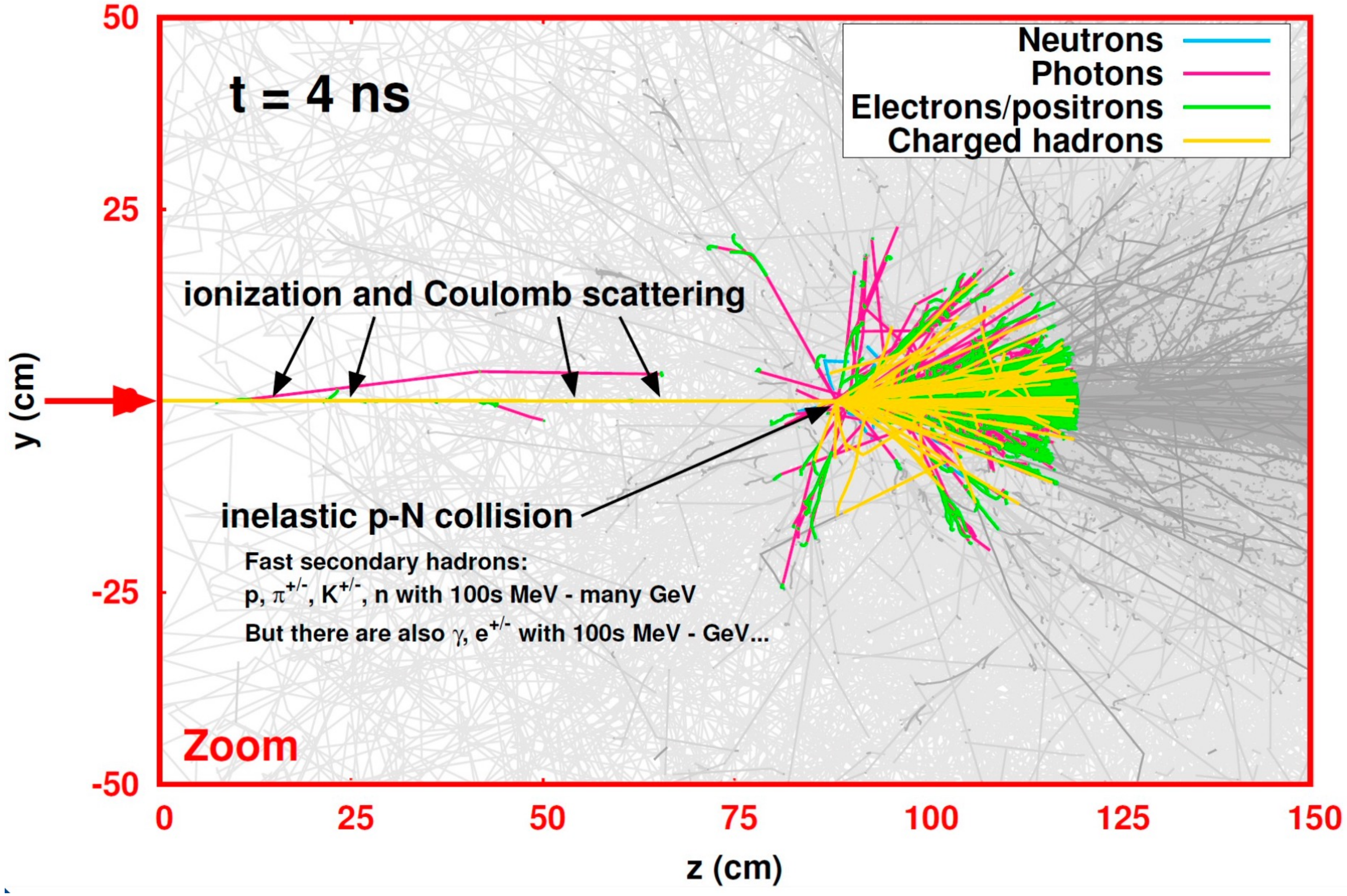
Nuclear interactions,
particle cascades (showers)!





Courtesy A. Lechner

Beam-matter interaction simulations



t = 4 ns

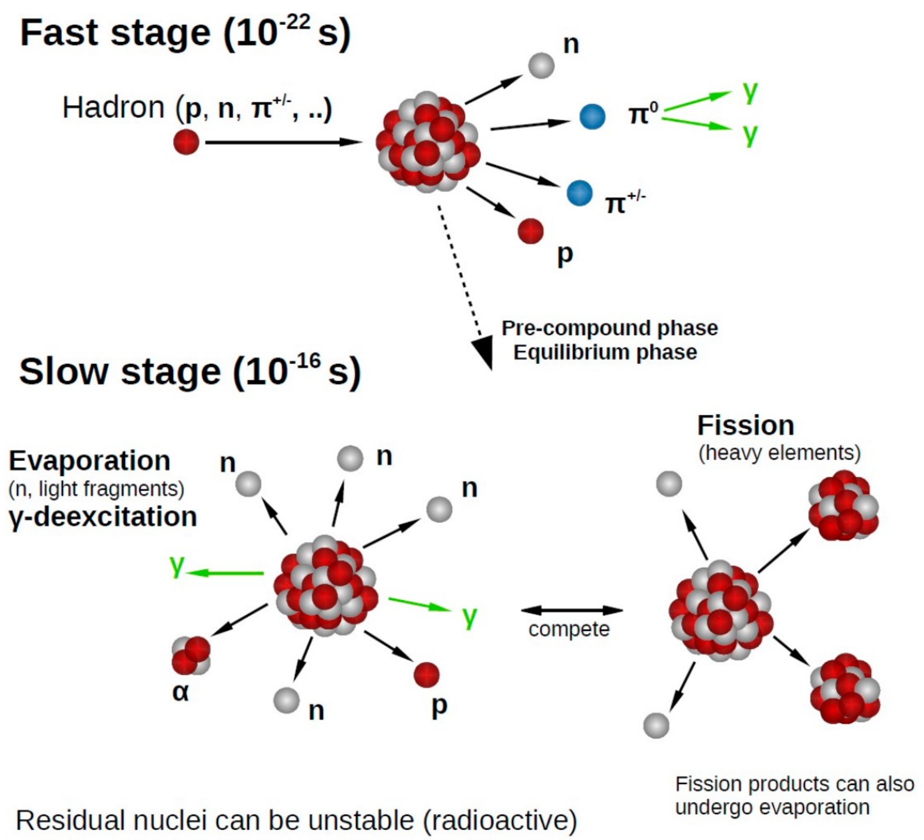
ionization and Coulomb scattering

inelastic p-N collision

Fast secondary hadrons:
p, $\pi^{+/-}$, $K^{+/-}$, n with 100s MeV - many GeV

But there are also γ, $e^{+/-}$ with 100s MeV - GeV...

High-energy hadron on nucleus:



Fast stage (10^{-22} s)

Hadron (**p**, **n**, **$\pi^{+/-}$**, **..**)

Pre-compound phase
Equilibrium phase

Slow stage (10^{-16} s)

Evaporation
(n, light fragments)
γ-deexcitation

compete

Fission
(heavy elements)

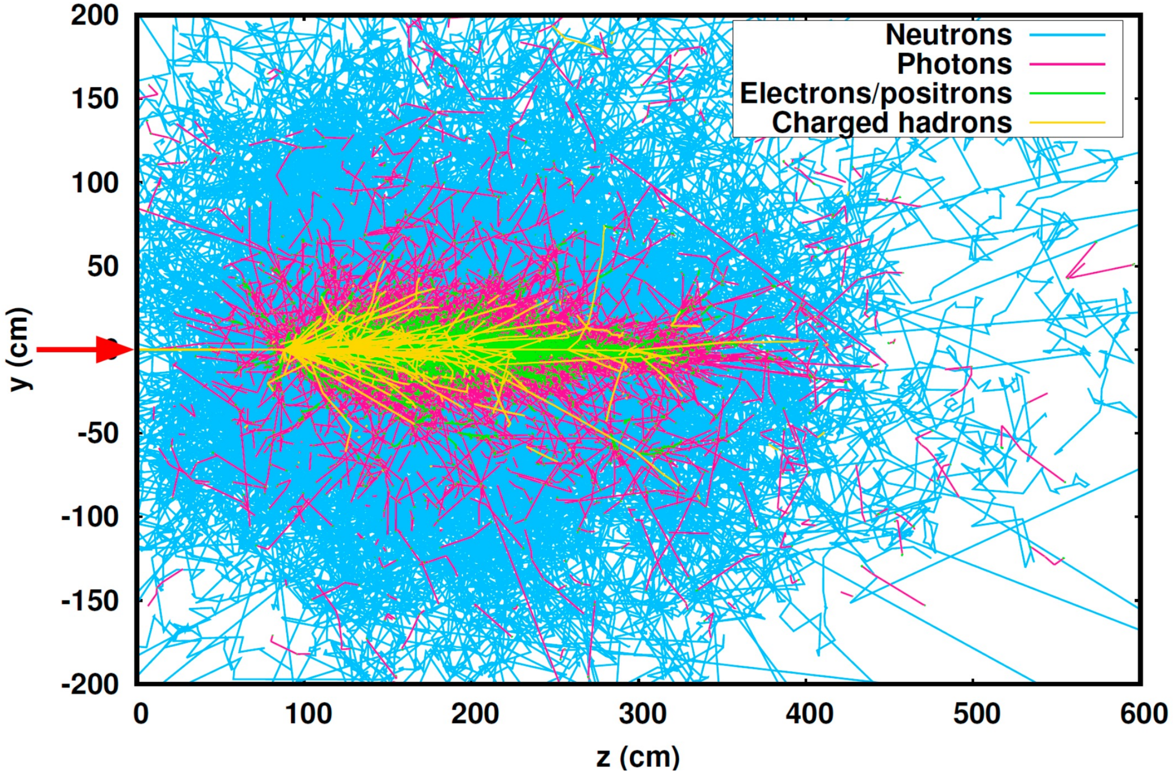
Residual nuclei can be unstable (radioactive)

Fission products can also undergo evaporation

Courtesy A. Lechner

Beam-matter interaction simulations

- Following material Coulomb interactions during the cascade, atoms & molecules vibrate and therefore T increase!
- In engineering terms: part of the energy is lost in the BID and **converted into thermal energy** (heat!) – this occurs almost instantaneously



Deposited energy (per unit volume) [J cm^{-3}]

$$\Delta T_{adiab} \cong \frac{Q_V}{\rho \cdot Cp}$$

Specific heat [J g^{-1} K^{-1}]

Density [g cm^{-3}]

Courtesy A. Lechner

Beam-matter interaction simulations

- Monte Carlo codes (such as FLUKA, MCNP, PHITS, MARS) are employed to simulate beam-matter interaction and extract the physics information

- These codes include:
  - High accurate description of cross-section, particle production modes, particle yields over a large spectrum of energies and varying primary particle (protons, electrons, ions, etc.)
  - Reliable production of π^0, K^0 and modelling of electromagnetic showers ($\pi^0 \rightarrow \gamma\gamma$, etc.), hadron photoproduction, muons, etc.
  - Description of energy loss processes for different particles (ionisation losses, Bremsstrahlung, pair production, etc.)
  - Production, transport and moderation of neutrons from high energy to thermal energies
  - Nuclide inventories after irradiation, DPA, H and He production

What are we talking about?

SPS beam dump

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

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

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

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

Need to be carefully dissipated!

What are we talking about?
LHC beam dump

- Beam energy will be 6.8 TeV (6800 GeV) from 2022
- N_b = 2748, with a bunch population up to 1.8x10^{11}

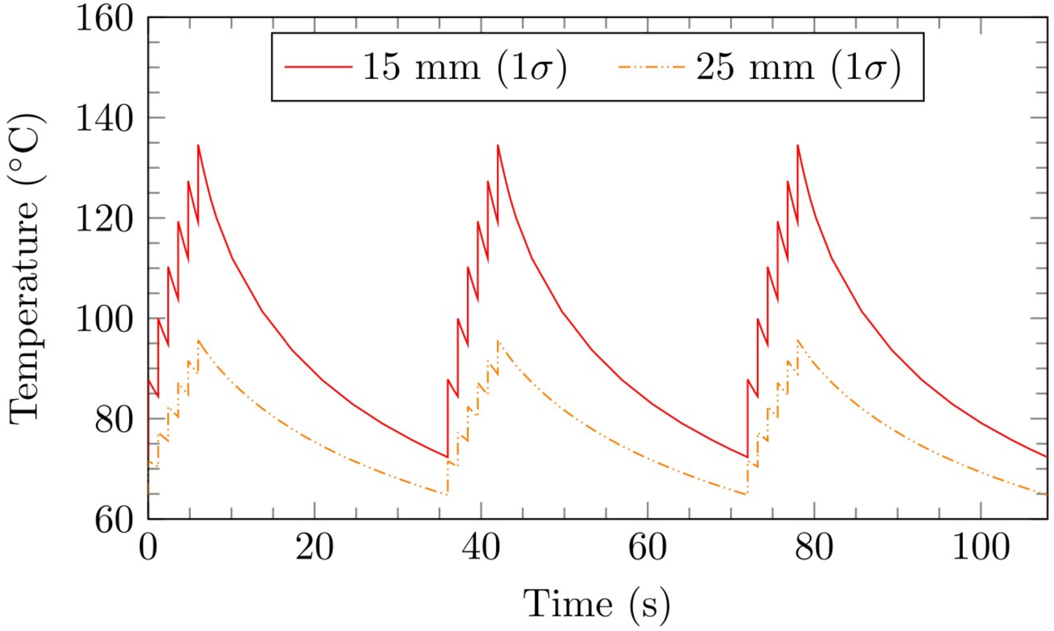
Will see tomorrow what are the effects of these quantities on large components and how to tackle them from an eng. standpoint

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

Thermal behaviour of BIDs

- For a pulsed beam, energy is generally deposited in a target material in a very short time

$$\Delta T \cong \frac{Q_V}{\rho \cdot Cp(T)}$$



- After the pulse, the energy diffuses through the material and the peak temperature drops

- After several repeated pulses, the temperatures will rise until a “pseudo steady state” is reached ➔ quasi-static temperature profile

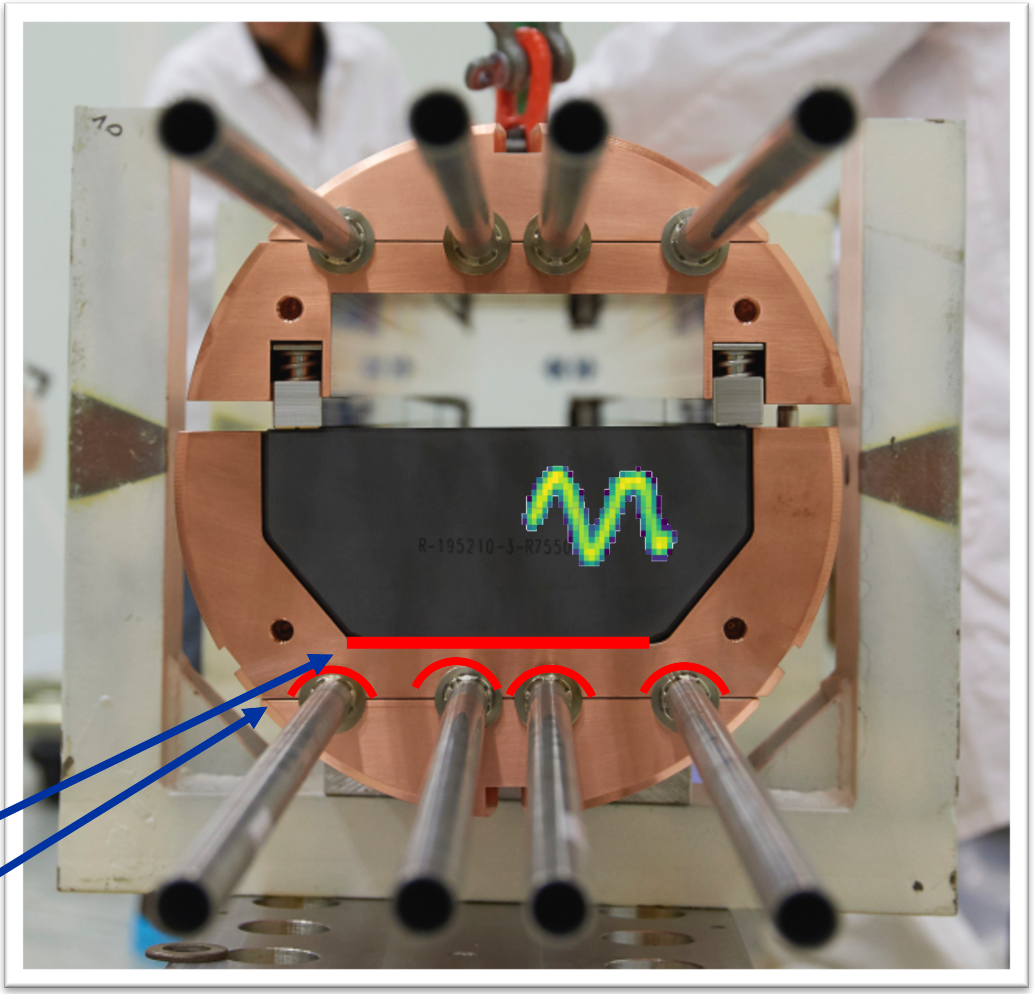
Heat diffusion mechanisms - conduction

- Almost all BIDs use **conduction** to remove heat from heated volume to surface for cooling
- Conduction is diffusion of heat via random molecular and/or atomic interactions

Heat flux

Heat conductivity

$$q'' = k \cdot (T_{out} - T_{in})$$



1st interface graphite/CuCrZr

2nd interface CuCrZr/316LN

Other (conventional) heat transfer methods

- **Convection**
  - Transfer heat from a surface into a fluid
  - Motion of the fluid & diffusion inside fluid

HTC = heat transfer coefficient

$$q'' = \overset{\uparrow}{h} \cdot \left(T_{surf} - T_{flu}\right)^{b}$$

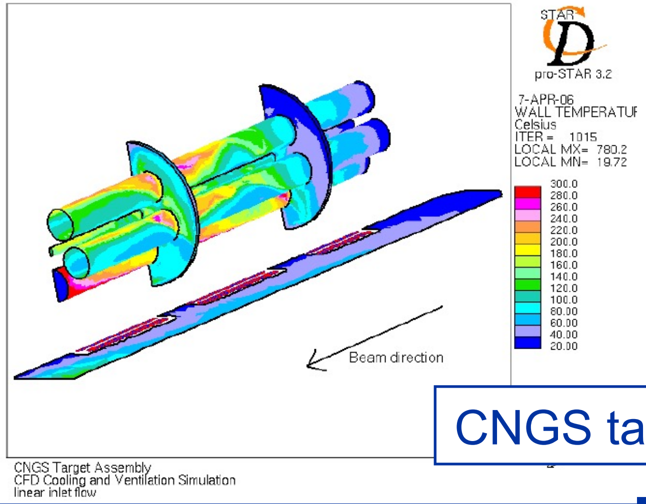
- **Radiative cooling**
  - Via electromagnetic radiation → only effective at high T & ΔT

$$q'' = \sigma \cdot \epsilon \cdot \left(T_{sou}^{4} - T_{out}^{4}\right)$$

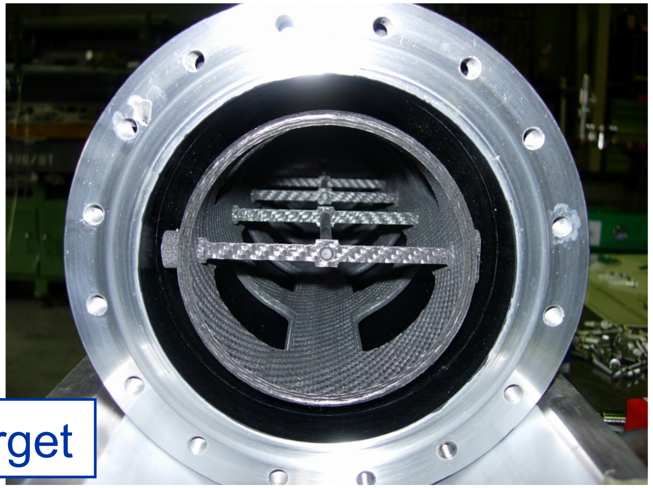
Stefan-Boltzmann constant

emissivity

- **Convective boiling**
  - E.g., hypervapotron systems
  - Not extensively employed in BID



CNGS Target Assembly
CFD Cooling and Ventilation Simulation
linear inlet flow



CNGS target

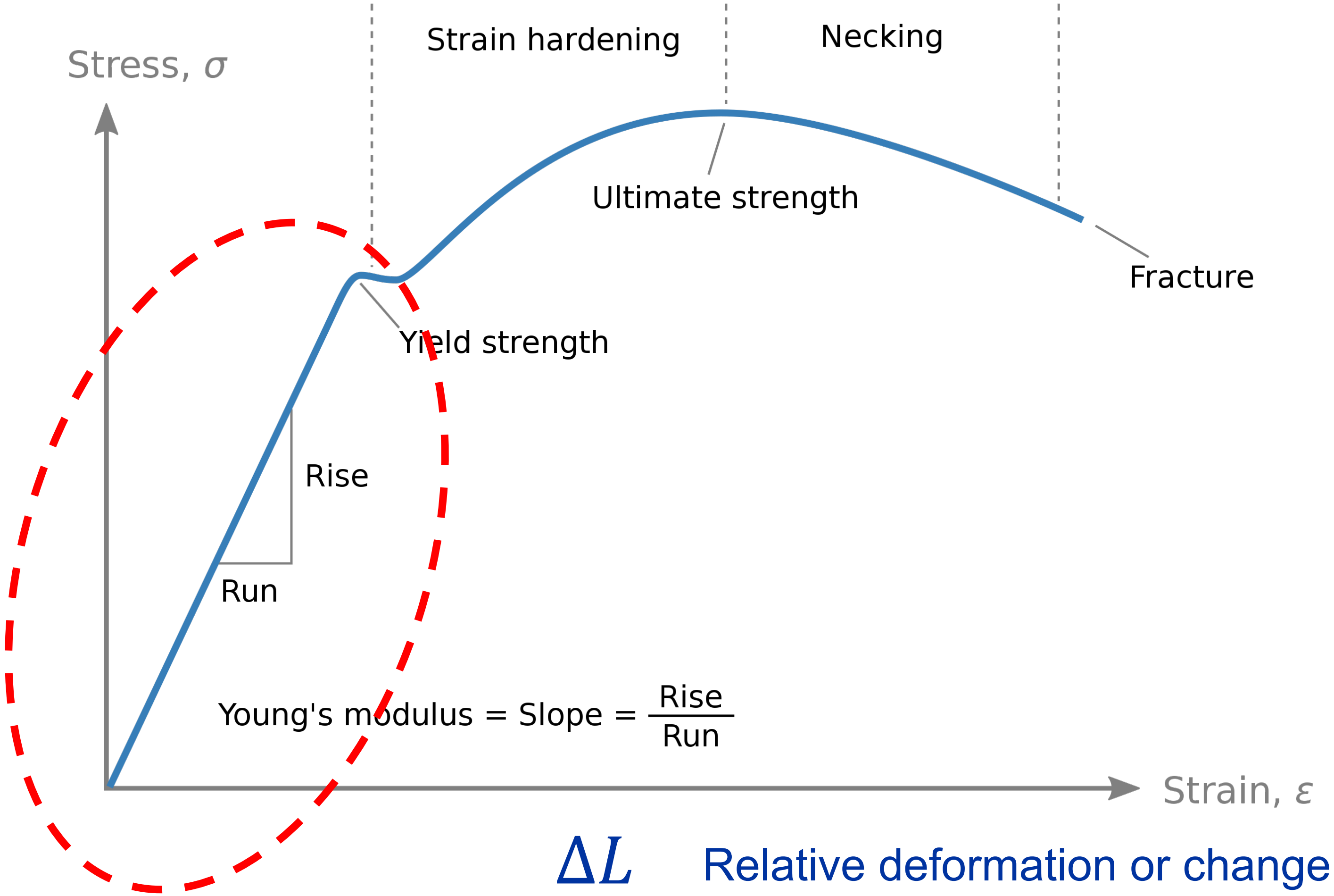
Selection of cooling methods for BIDs

- Several considerations add up in the selection – all are **related to each other and must be considered at the same time & links to material selection**:

1. **Operational** requirements (what is the average power?)
2. **Cooling** requirements (heat removal, operating temperature)
3. **Robustness** (what are the risk associated with the cooling media)
4. **Chemical** reactions between fluid and material (corrosion, erosion, radiolysis)
5. **Safety** (radiological and conventional, water vs. air)

Basic mechanical property concepts

- Young’s modulus describe a material stiffness (deformation for a given stress)
- Material strength referred as:
  - **Yield**
  - **Ultimate**



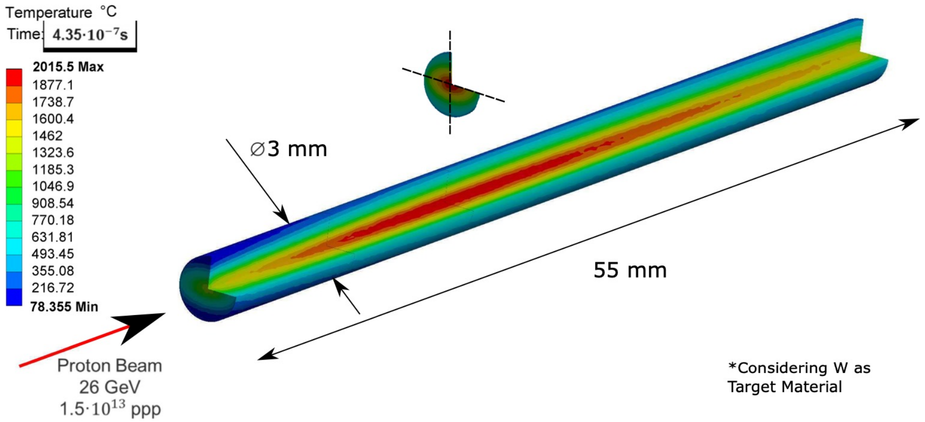
We want typically BIDs to operate here

$$\varepsilon = \frac{\Delta L}{L_0}$$

Relative deformation or change in shape and size of elastic, plastic, and fluid materials under applied forces

Finite Elements Methods for BIDs

- Total stresses (force per unit area!) inside a material can be induced by:
  - Mechanical loads
  - Thermal gradients
  - Geometrical restraints



*Considering W as Target Material

- In BIDs, the main source of stress is generally the **non uniform temperature distribution** generated by beam impact

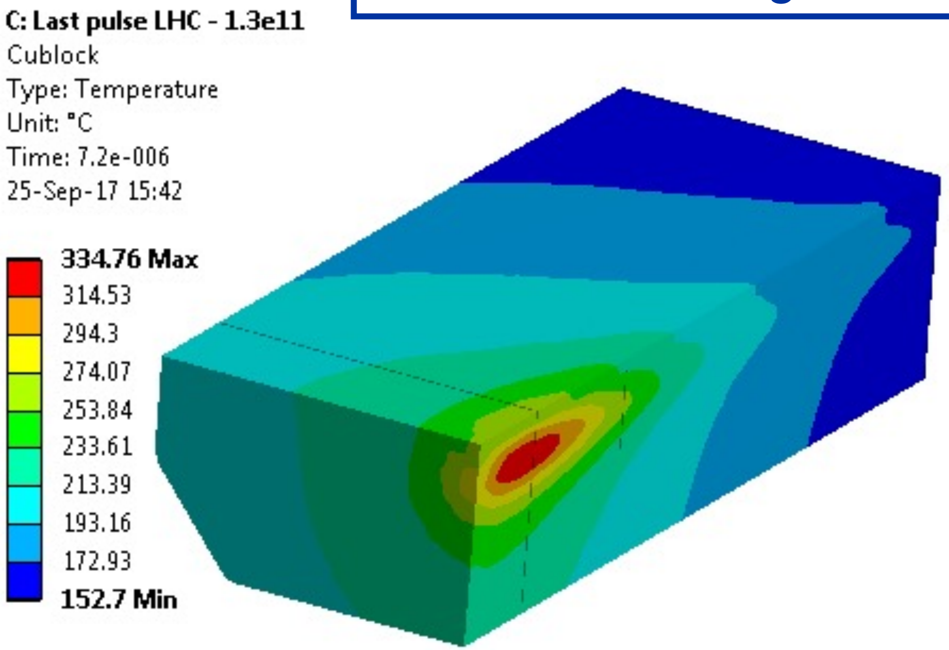
- Analytical methods exist for simple shapes, but generally dedicated codes are used (ANSYS, COMSOL, etc.)

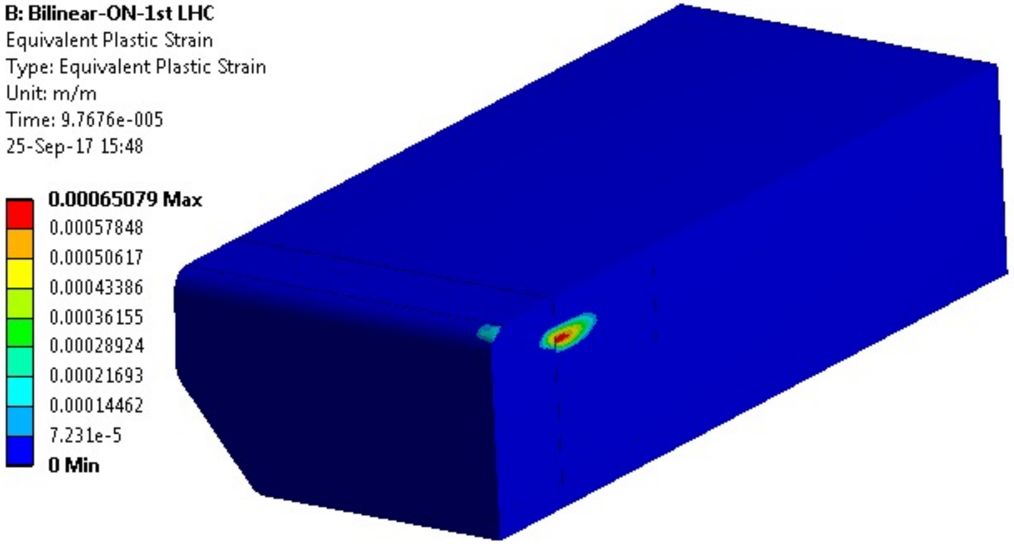
Steps for Finite Element Analysis Modelling

1. **Model** setup
   - Geometry (e.g., from CAD) & definition of **material properties** (mostly varying with temperature) & mesh generation
   - Definition of **loads** (hence internal heat generation from MC codes) & boundary conditions
2. **Thermal** analysis (transient, steady-state…)
3. **Structural** analysis (static, dynamic)
4. **Thermal-Structural** coupling (complex analysis performed in some specific cases)

Example of material response

CuCrZr absorbing block from 4th generation SPS beam dump (see tomorrow)





T_{max}=335°C

~0.07% plastic deformation

$T_{\text{service CuCrZr}}$= 400°C

Yield strength= 280 MPa

Courtesy F.-X. Nuiry

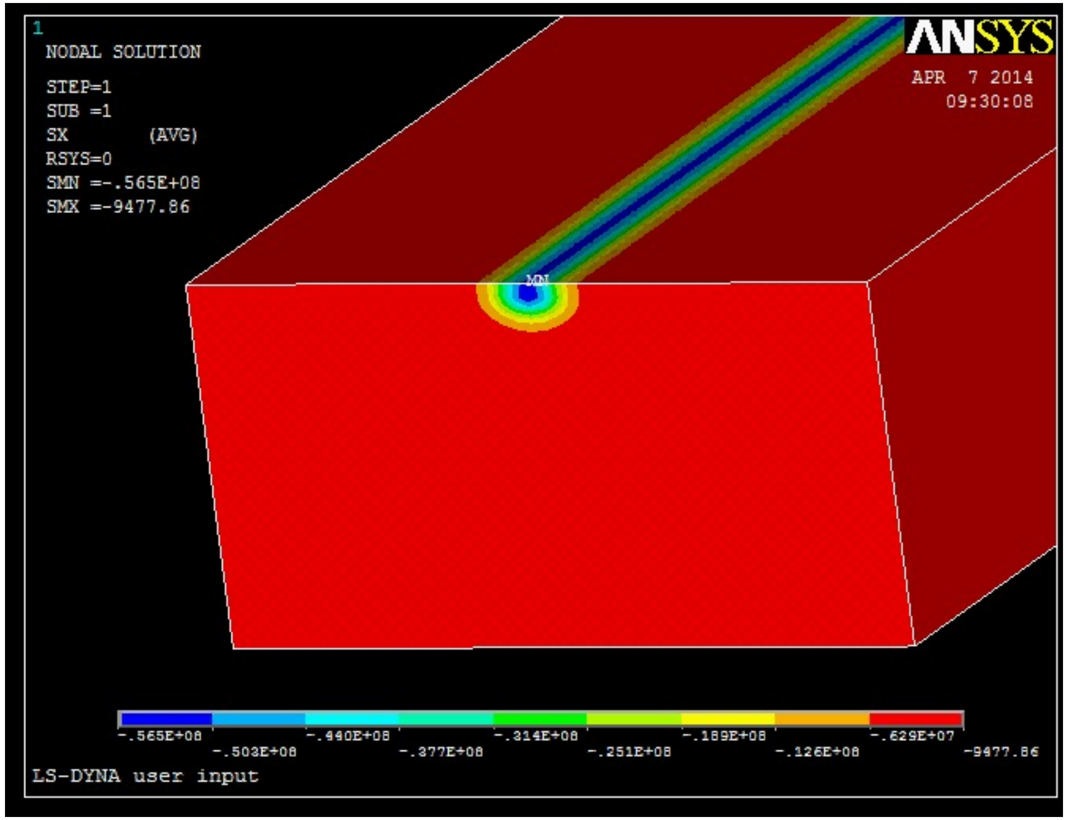
Example of material response

- Elastic stress waves travelling at the speed of sound in the materials

Stiffness coefficient

$$c_0 = \sqrt{\frac{K_s}{\rho}}$$

Density



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1
NODAL SOLUTION

STEP=1
SUB =1
SX          (AVG)
RSYS=0
SMN =-.565E+08
SMX =-9477.86
```

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APR  7 2014
   09:30:08
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LS-DYNA user input
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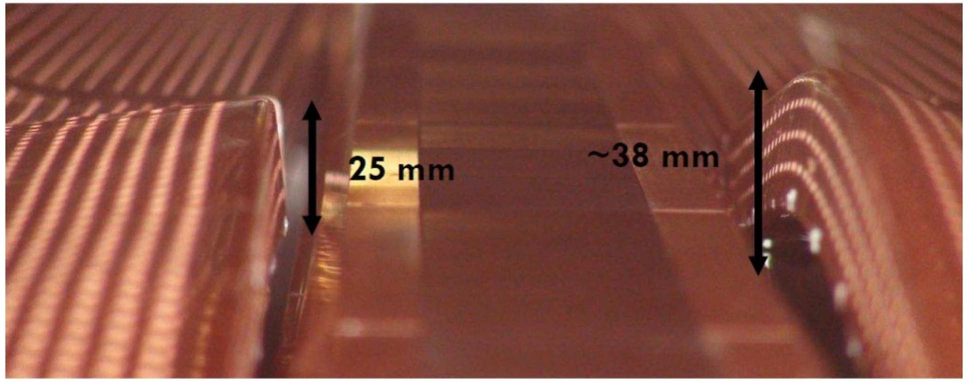
Courtesy F.-X. Nuiry

Dynamic regimes

- BIDs for accelerators are generally designed to work in the **elastic regime** (deformation can recover) → **reliability**

- Beam impact accidents (or even nominal operation) can provoke also permanent deformation of the component → **plastic regimes (irreversible damage)**

- Sometimes the effect is much more catastrophic, if instantaneous power is high enough → quasi **shockwave regime**



Phys. Rev. Accel. Beams 22 013401 (2019)
Journal of Dynamic Behavior of Materials (2019) 5:266–295

Palette of absorbing materials employed at CERN

- BIDs requires a variety of different materials, characterized by wildly different parameters – some generalities of employed materials are reported

Graphitic materials (and CfC)

1-1.8 g/cm^3

Low CTE, good thermal conductivity, low ρ, very high service T, exceptional robustness to beam impact

Aluminium alloys

2.7 g/cm^3

Light structural materials, good thermal conductivity, low T_m, poor properties at high T

Titanium & alloys

4.5 g/cm^3

Exceptional strength while light, low CTE, low thermal conductivity

(Stainless) steels

7.5-8 g/cm^3

“king” of structural materials, low thermal conductivity

Palette of absorbing materials employed at CERN

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

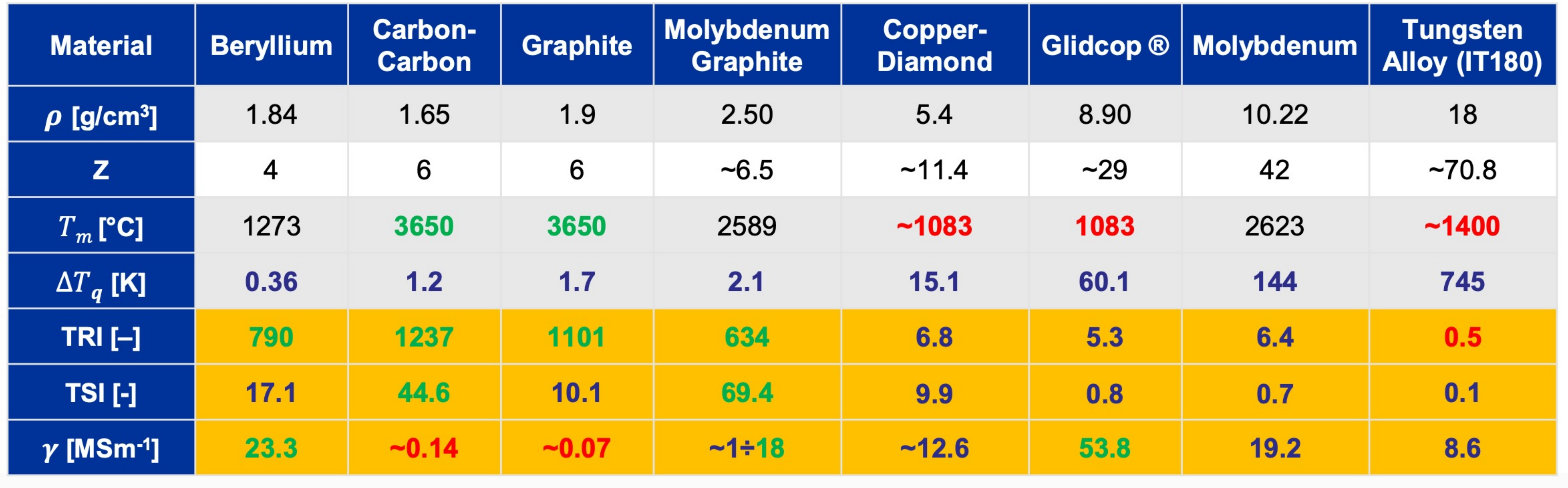
Tungsten and alloys
18-19.3 g/cm^3

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

Figure of Merits



Material	Beryllium	Carbon-Carbon	Graphite	Molybdenum Graphite	Copper-Diamond	Glidcop ®	Molybdenum	Tungsten Alloy (IT180)
ρ [g/cm^3]	1.84	1.65	1.9	2.50	5.4	8.90	10.22	18
Z	4	6	6	~6.5	~11.4	~29	42	~70.8
T_m [°C]	1273	3650	3650	2589	~1083	1083	2623	~1400
ΔT_q [K]	0.36	1.2	1.7	2.1	15.1	60.1	144	745
TRI [–]	790	1237	1101	634	6.8	5.3	6.4	0.5
TSI [-]	17.1	44.6	10.1	69.4	9.9	0.8	0.7	0.1
γ [MSm^{-1}]	23.3	~0.14	~0.07	~1÷18	~12.6	53.8	19.2	8.6

From: A. Bertarelli, Joint International Accelerator School (2014)

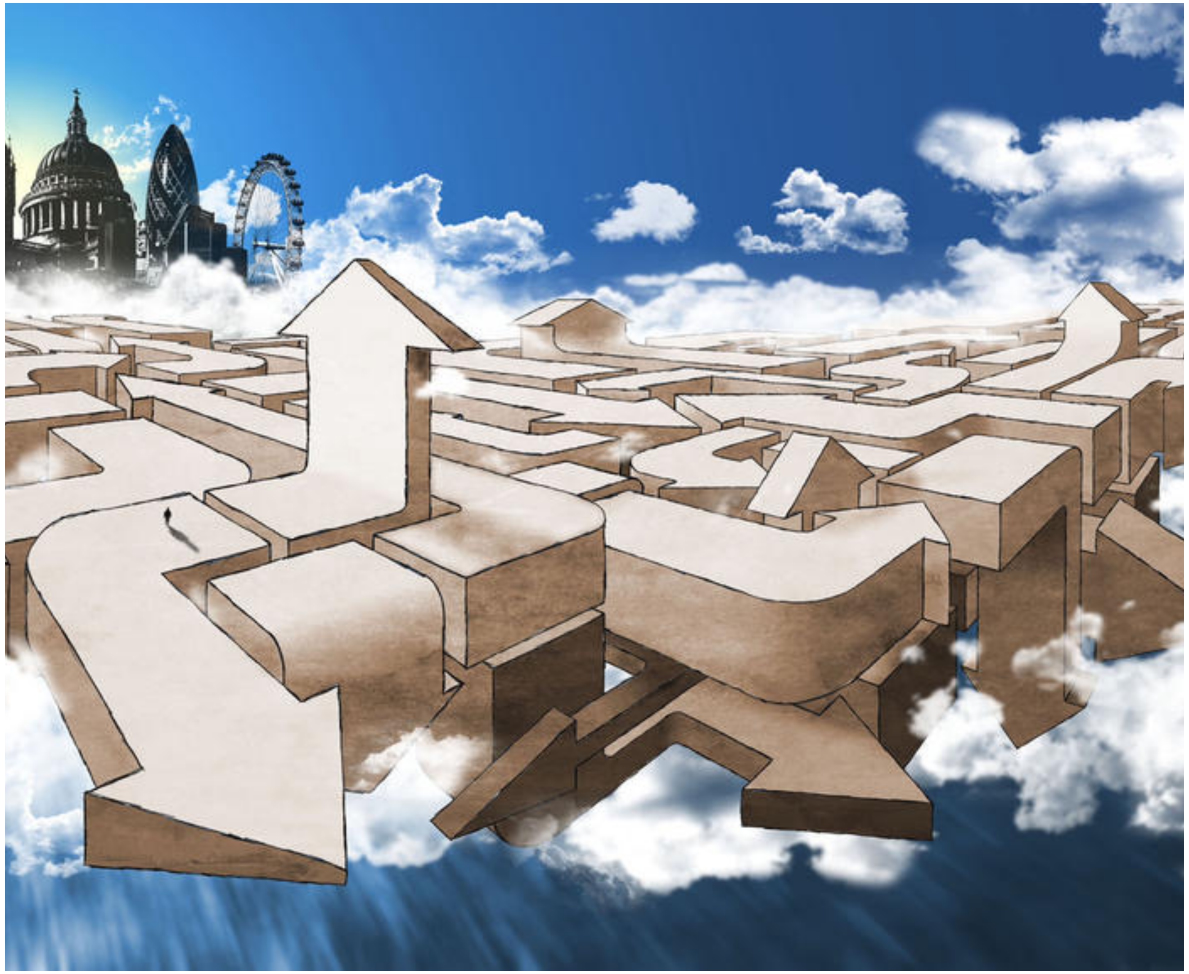
TSI = Thermal Stability Index
TRI = Thermomechanical Robustness Index

Selection for absorbing materials for BIDs

Will see tomorrow what are the effects of these quantities and how to tackle them from an engineering standpoint

Selection for absorbing materials for BIDs

- Physics requirements
- Functional reliability / integrity
- Operational safety (for personnel and machine)



Targets - Physics requirements

- Different type of sources depending on experiments:
  - **“Point-like” source** (e.g., antiproton production), very dense with small physical dimensions
  - **Massive target acting as dump** (e.g., neutron production)
  - **Long, narrow target** (e.g., neutrino production), low density but several nuclear inelastic lengths
  - **Refractory metals** (e.g., RIB production), need to be heated “externally” to maximize effusion
  - Fusion-like neutron sources (14 MeV) need for example deuterons on Li target
  - Medical isotope production & harvesting (from U, water, etc.)

- Constant iterations between physicist and engineers to find the right compromise between availability/reliability and physics output

Functional reliability / integrity

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

Operational safety

- Safety critical components vs. replaceable components
  - Some components in a target facility are **replaceable**, hence **expected to fail at a certain rate**, posing little safety risk (e.g., pbar target)
  - Some components are **part of a safety matrix** (especially for personnel protection) (e.g., beam stoppers)
  - QA and conservative choices should be increased for safety critical components
  - **Safety critical components should be "damage tolerant"**, especially in the case of off-normal events. In these cases, ductility (ability to plastically deform without fracture) is highly desirable

Radiation protection considerations

- Radiation protec l in the design iteration of bean n
  - **Operation** – for owntime
  - **Radioactive wa** t (start to) be part of the items to think to

- General principl
  - Low activation m
  - Toxic materials t
  - Safe disposal

PROMPT AND RESIDUAL RADIATION

AIR AND HE ACTIVATION

RADIATION PROTECTION

WATER AND GROUND ACTIVATION

RADIOACTIVE WASTE

Ultra High Vacuum design for BIDs

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

- Additional challenges for BIDs are generated by:

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

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

Ultra High Vacuum design for BIDs

Vacuum criteria

Leak tightness

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

Contamination

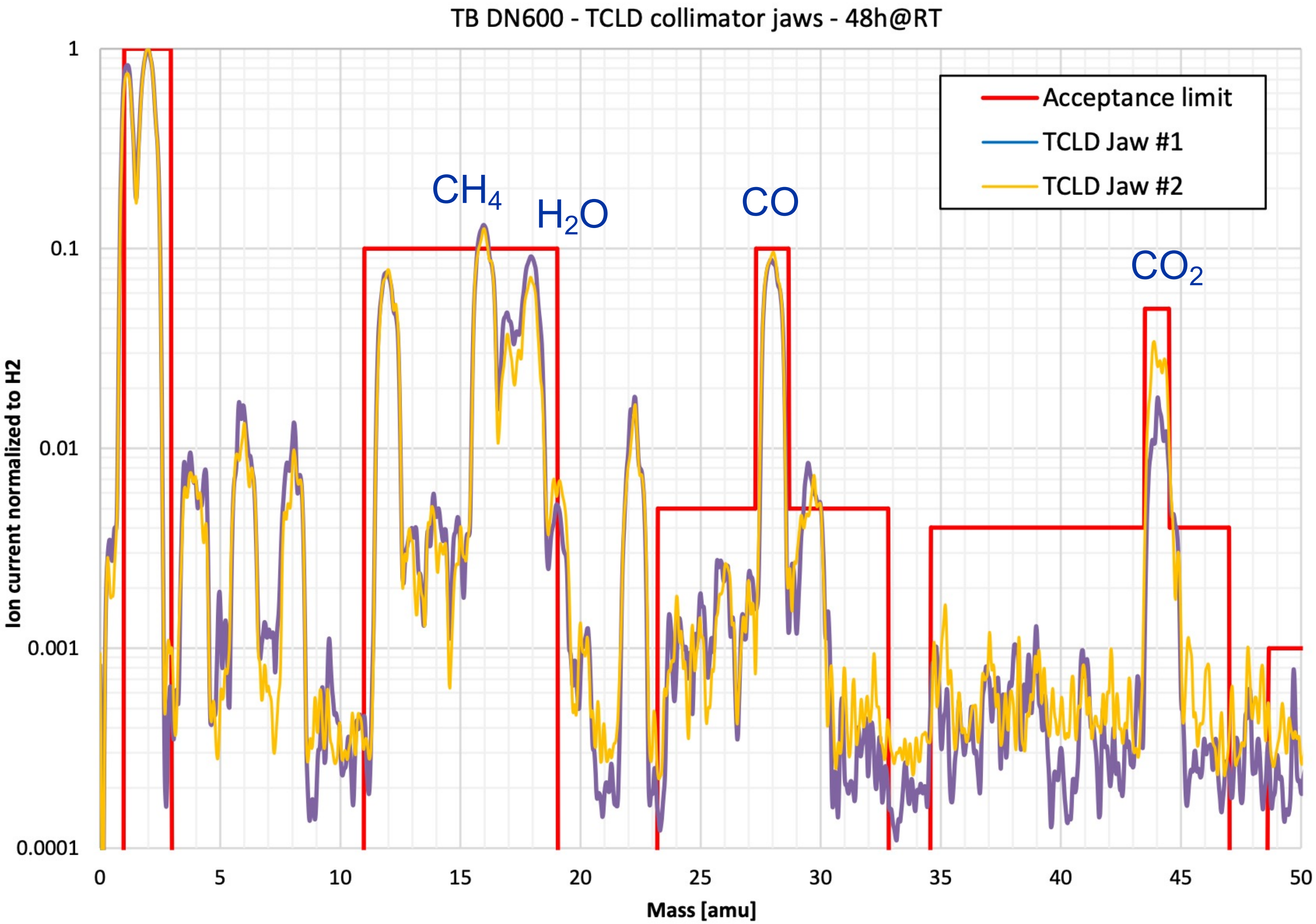
(hydrocarbons, CO/CO_2, higher Z – from cleaning or poor design)

Outgassing (from internal components)

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

Virtual leaks (e.g. trapped pockets of gas)

(< $5 \cdot 10^{-9}$ mbar·l·s^{-1})



- Residual Gas Analysis spectrum for a collimator jaw
  - 48 hours at room T after a bake-out cycle at 250°C
- Gas-rates normalized to H_2 and respective limits for different gas species

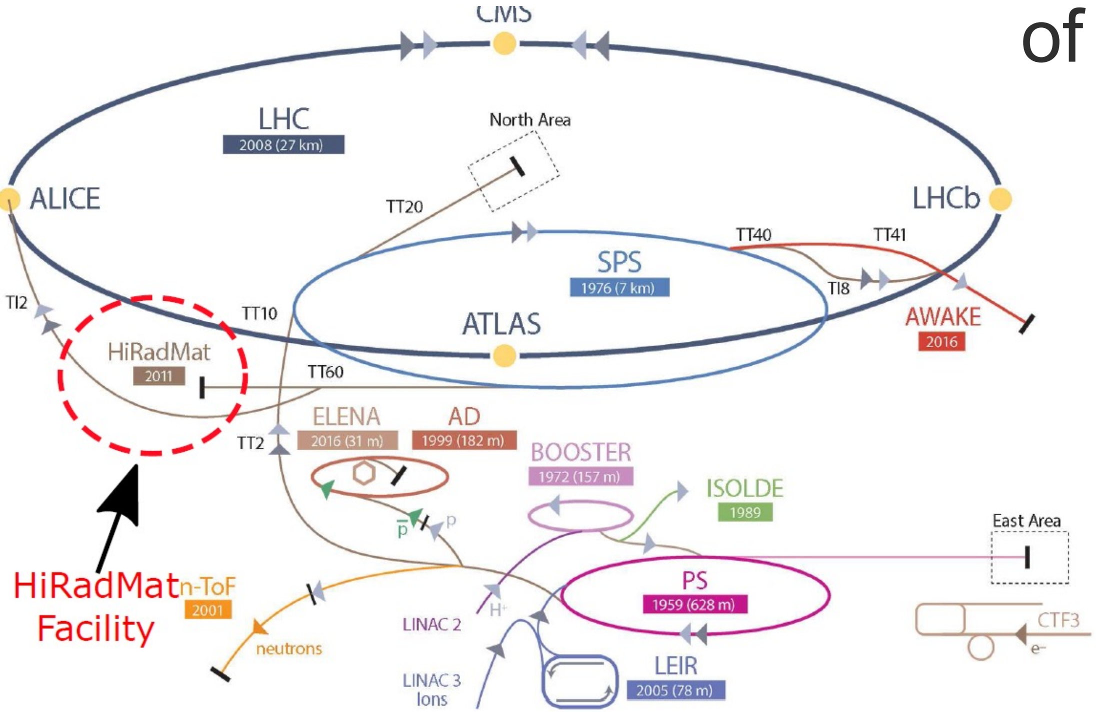
Beam impact experimental testing and validation

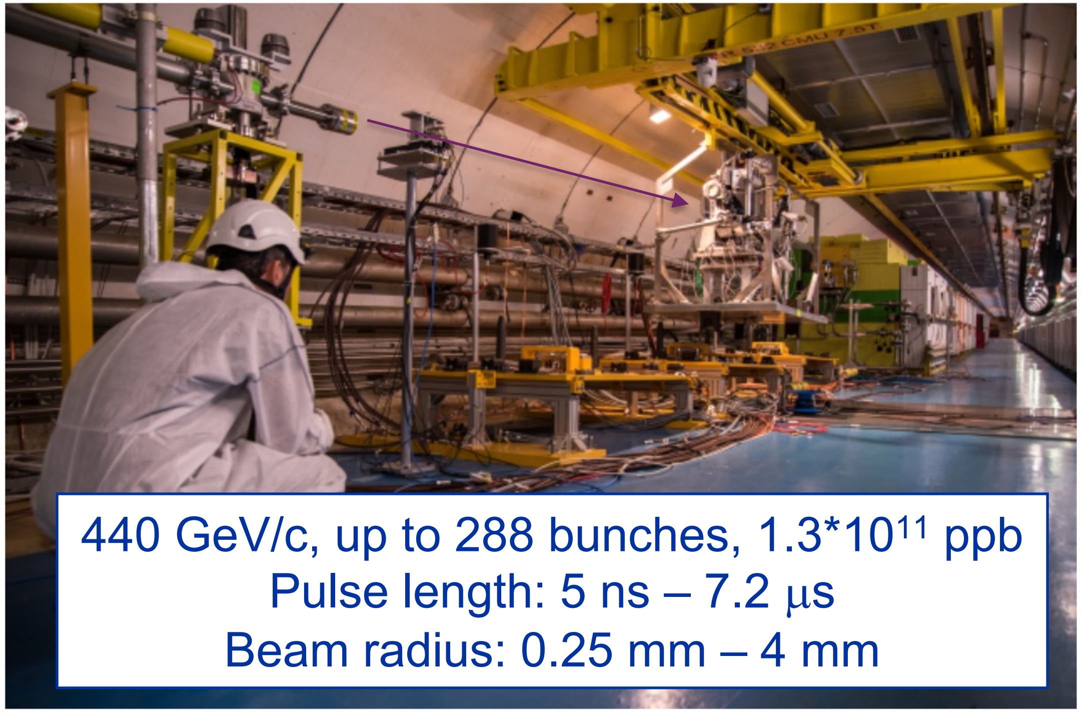
- Validation of design often include the possibility of **testing components or integral devices under beam impact**
- Sometimes devices and materials operate at the extreme – **uncharted territory of temperature and stress** (where EOS are not available)
- Existing material constitutive models at extreme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

Integral and material testing at CERN

HiRadMat facility

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





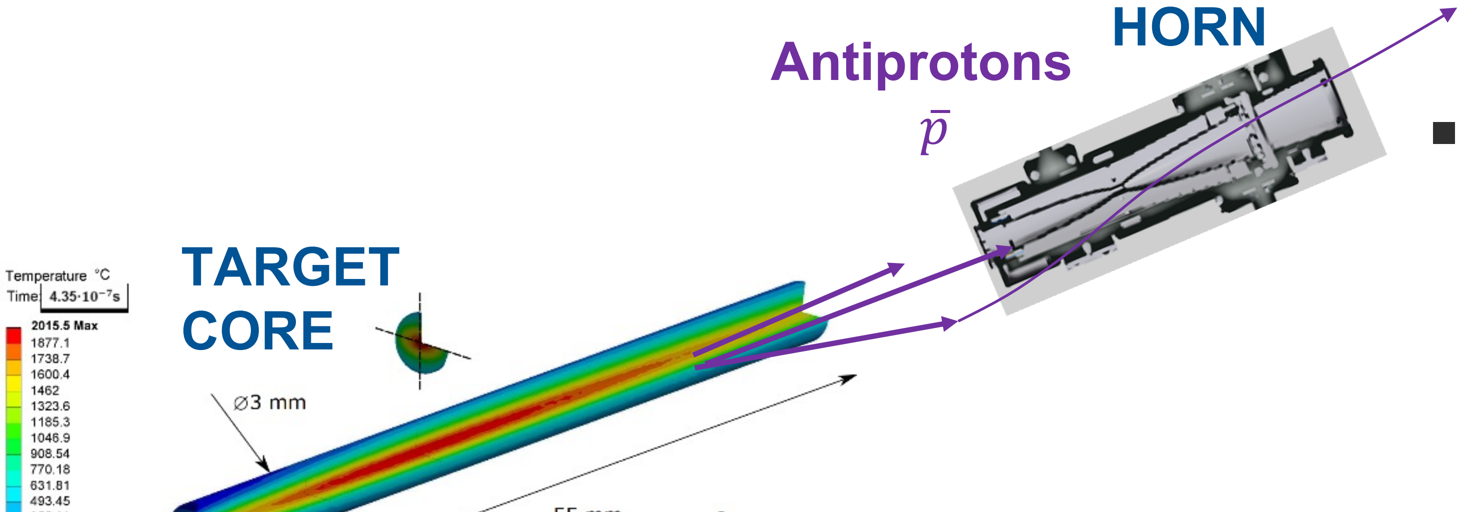
440 GeV/c, up to 288 bunches, $1.3 \cdot 10^{11}$ ppb
Pulse length: 5 ns – 7.2 μs
Beam radius: 0.25 mm – 4 mm

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

$$1.3\ {}^{\mathrm{GJ}}\!/_{\mathrm{cm}^3}$$

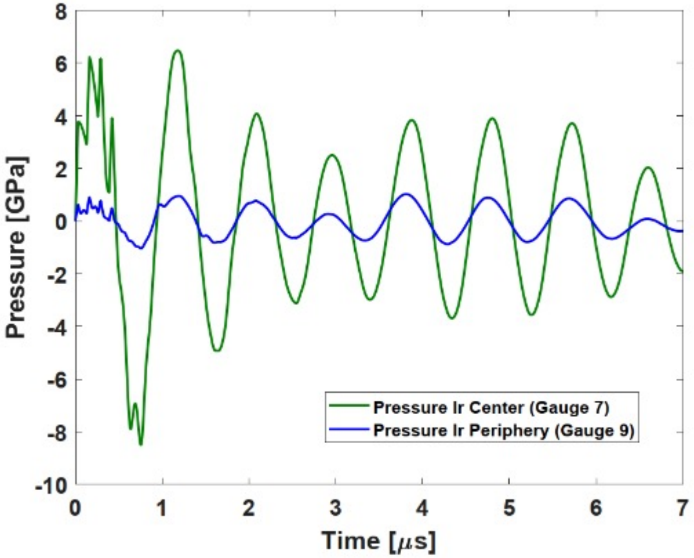
J. Phys.: Conf. Ser. 1350 012162

Application of HiRadMat to antiproton production



Proton Beam
26 GeV
$1.5\cdot10^{13}$ ppp

Extreme dynamic response!



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

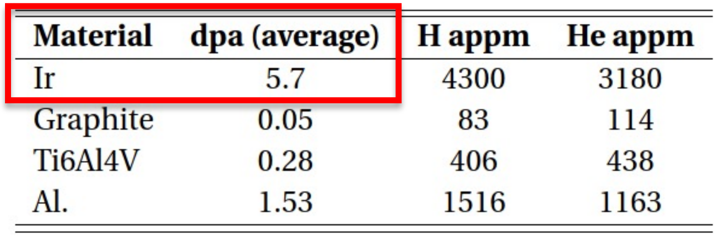
$$\dot{\varepsilon}_{max} \approx 5 \cdot 10^4\ \mathrm{s}^{-1}$$

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

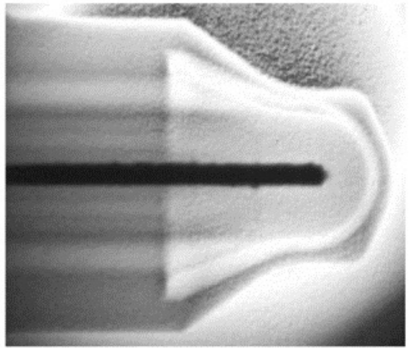
Relevance of post-irradiation examination

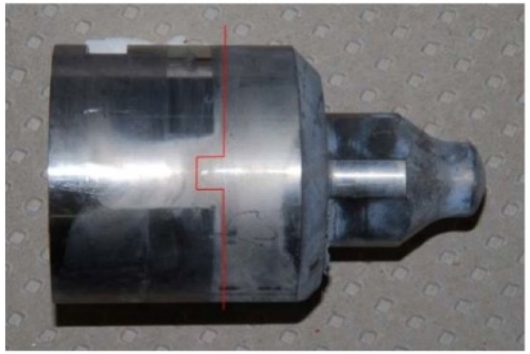
- Irradiated AD-target (2000-2008), $1.6*10^{19}$ POT

ESTIMATED DPA

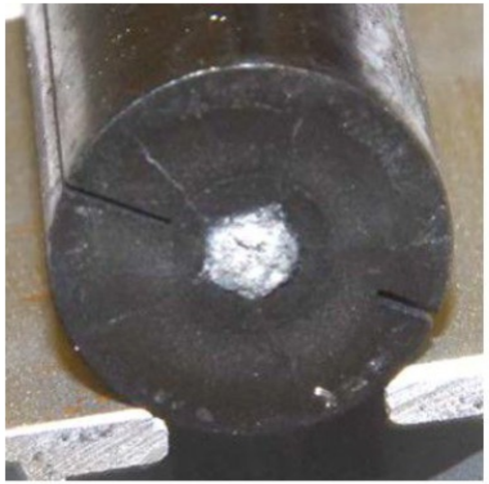


Material	dpa (average)	H appm	He appm
Ir	5.7	4300	3180
Graphite	0.05	83	114
Ti6Al4V	0.28	406	438
Al.	1.53	1516	1163

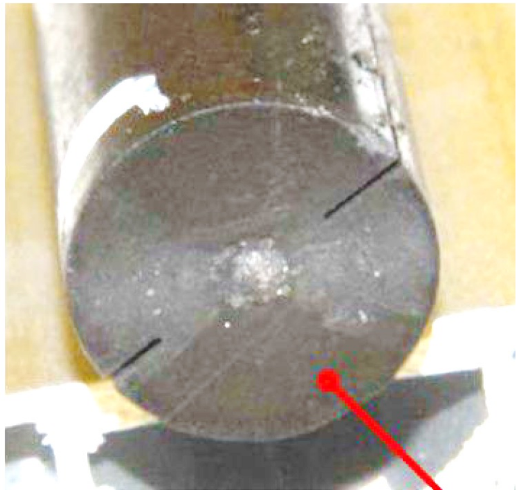


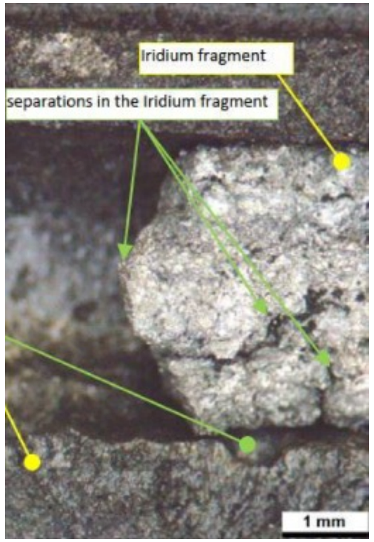


Upstream face



Mid face

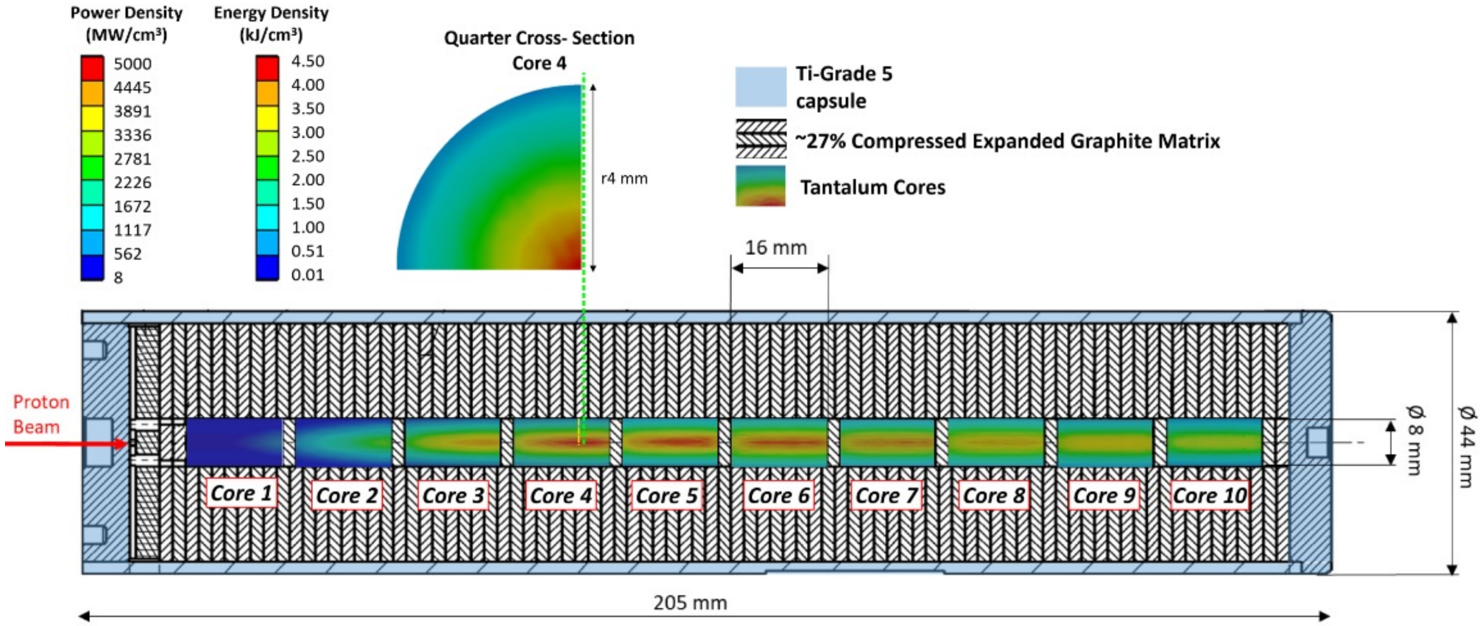


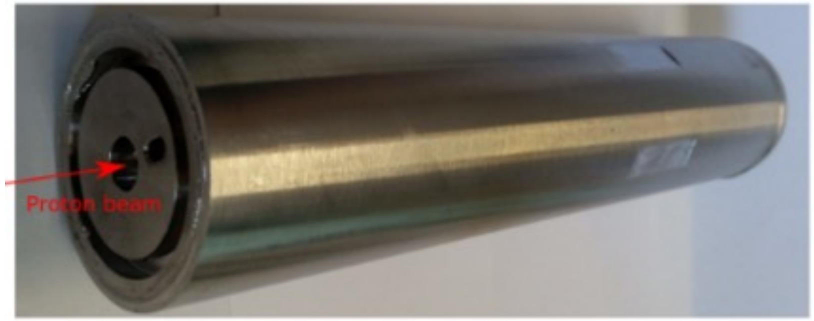


- Iridium core is an amalgam of broken, melted & re-solidified fragments
- Cracks in the graphite matrix also observed

Application of HiRadMat to antiproton production

- Target Core made of 10x Ta rods (un-annealed) 8 mm ⌀ by 16 mm in length
- Embedded in a matrix made of compressed layers of Expanded Graphite (EG)
- Encapsulated in Ti-6V-4Al e-beam welded container





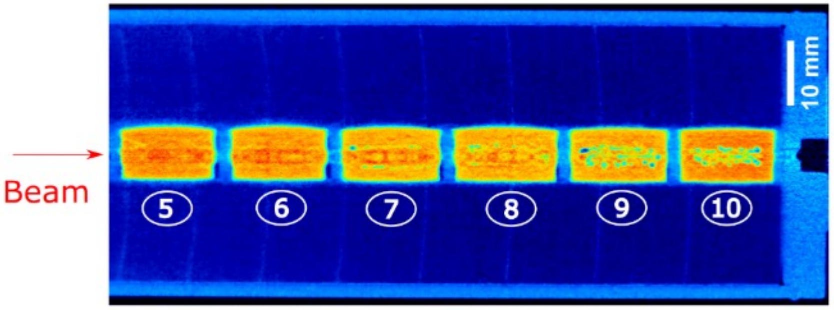
x49 pulses impacted (ΔT_{max}/pulse = 1800 ºC)

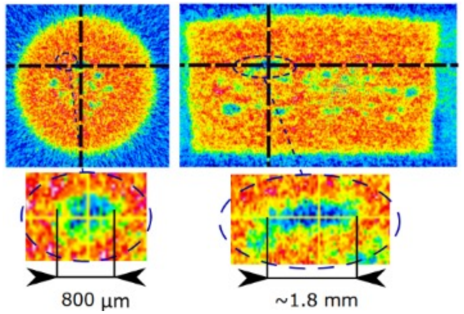
Reliance on post-irradiation examination

Phys. Rev. Accel. Beams 21, 073001 (2018)

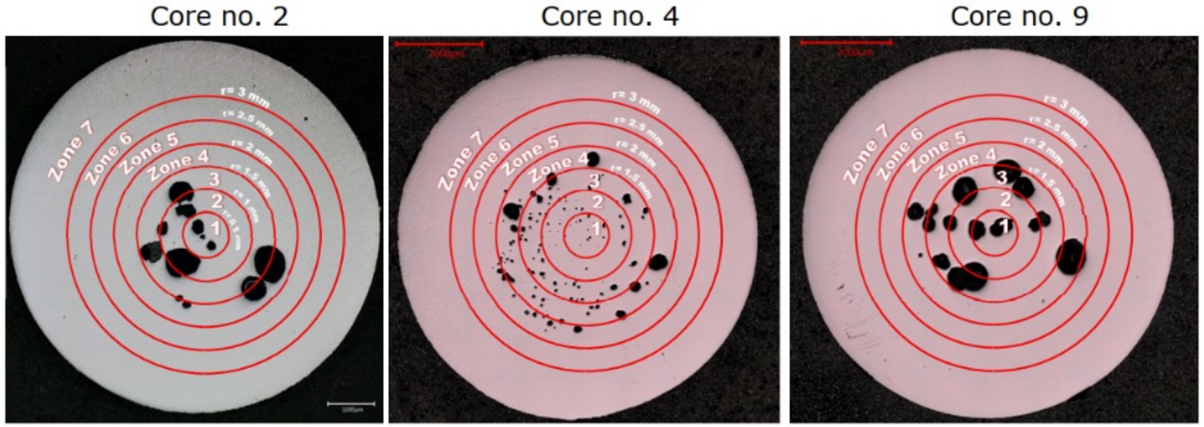
Post Irradiation Examination of Ta-irradiated sample

- Neutron Tomography @PSI (NEUTRA)





- Target opening and slicing cores at CERN



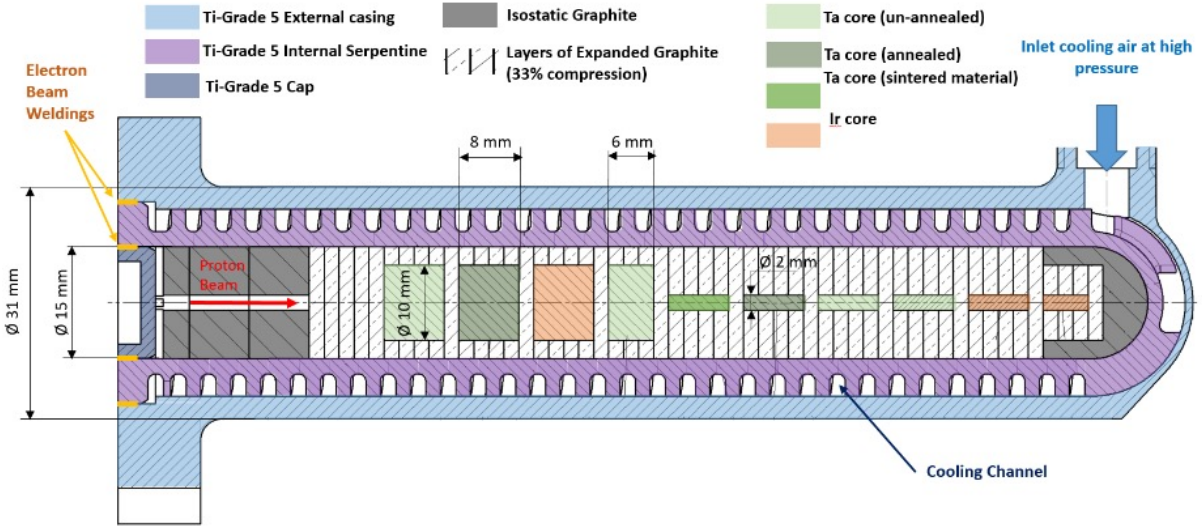
Observation of spalling voids

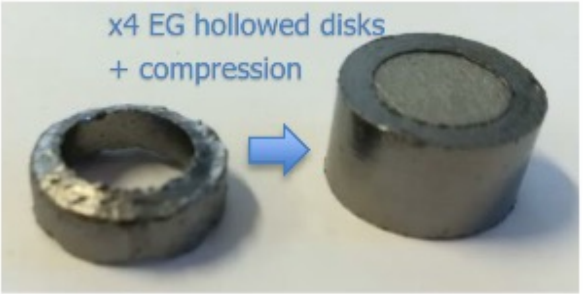
Tensile pressure shall be kept <2-3 GPa to avoid void nucleation

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

Application of HiRadMat to antiproton production

New target design



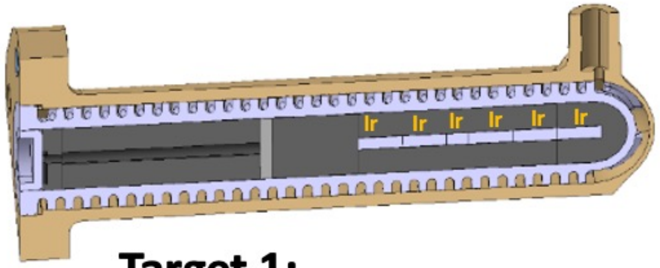


- Air cooled target
- Sliced core, with different diameter and length
- Matrix of different graphitic materials

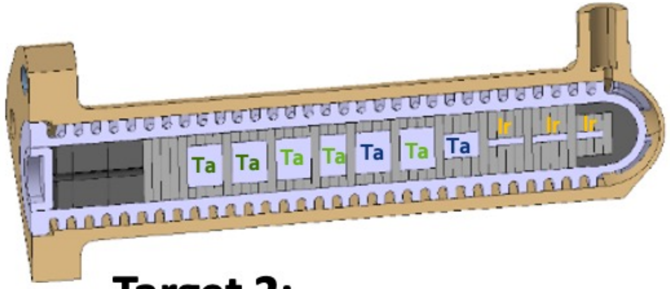
Courtesy C. Torregrosa

Application of HiRadMat to antiproton production

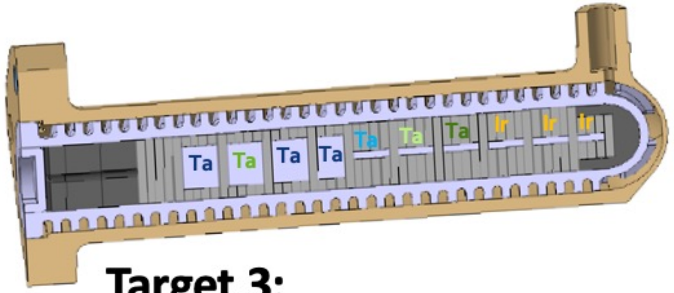
New target design – tested at HiRadMat



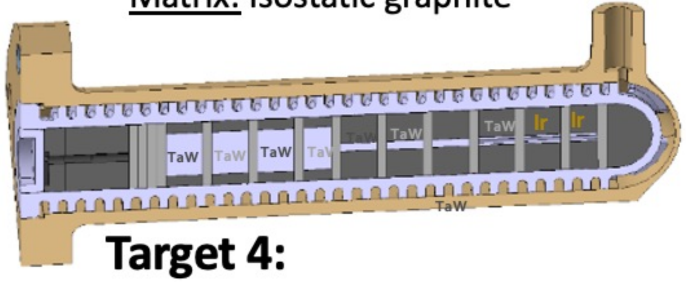
Target 1:
Core: Ø 3 mm Ir
Matrix: Isostatic graphite



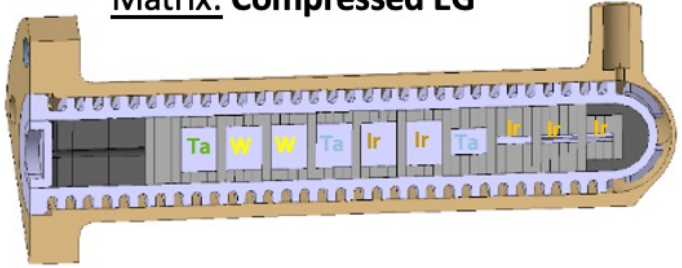
Target 2:
Core: Ø 10 mm Ta + Ø 2 mm Ir
Matrix: **Compressed EG**



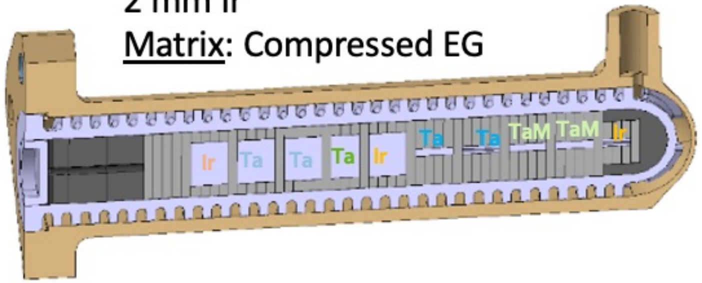
Target 3:
Core: Ø 10 mm Ta + Ø 2 mm Ta + Ø 2 mm Ir
Matrix: Compressed EG



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

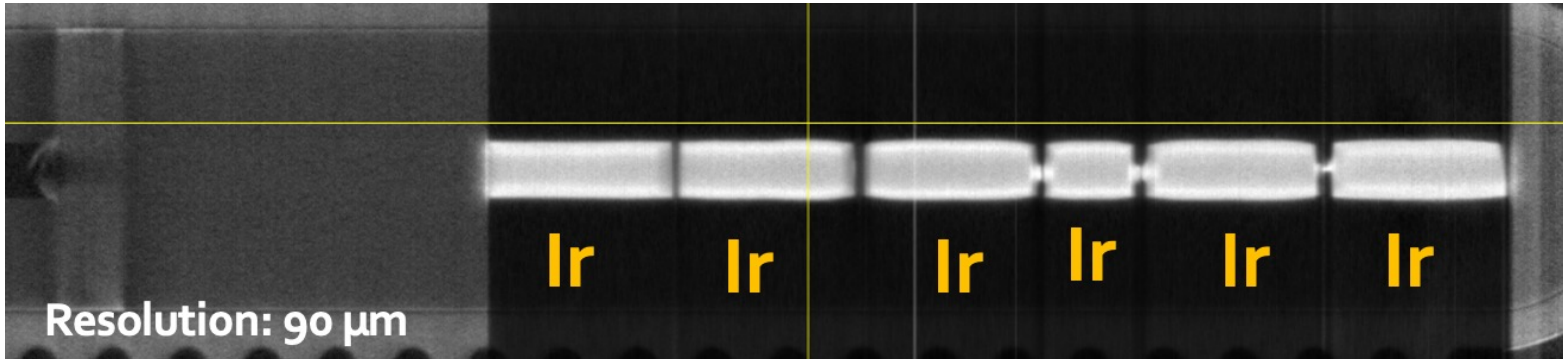


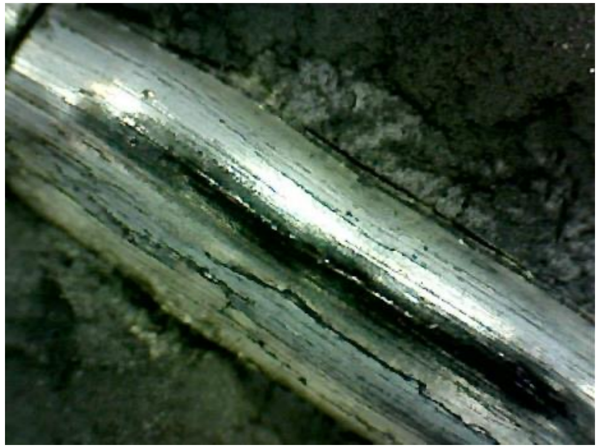
Target 6:
Core: Ø 10 mm Ir Ø 10 mm Ta +
Ø 2 mm Ta tube
Matrix: Compressed EG

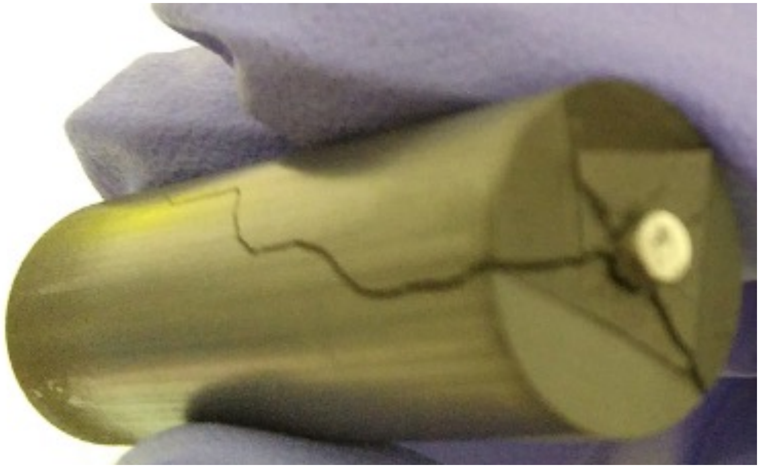
Courtesy C. Torregrosa

Application of HiRadMat to antiproton production

Some results

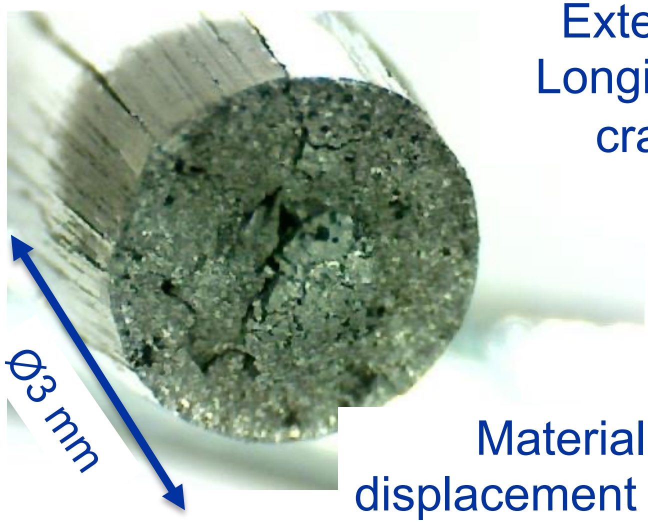






Longitudinal cracks in the isostatic-graphite matrix!

Proton beam



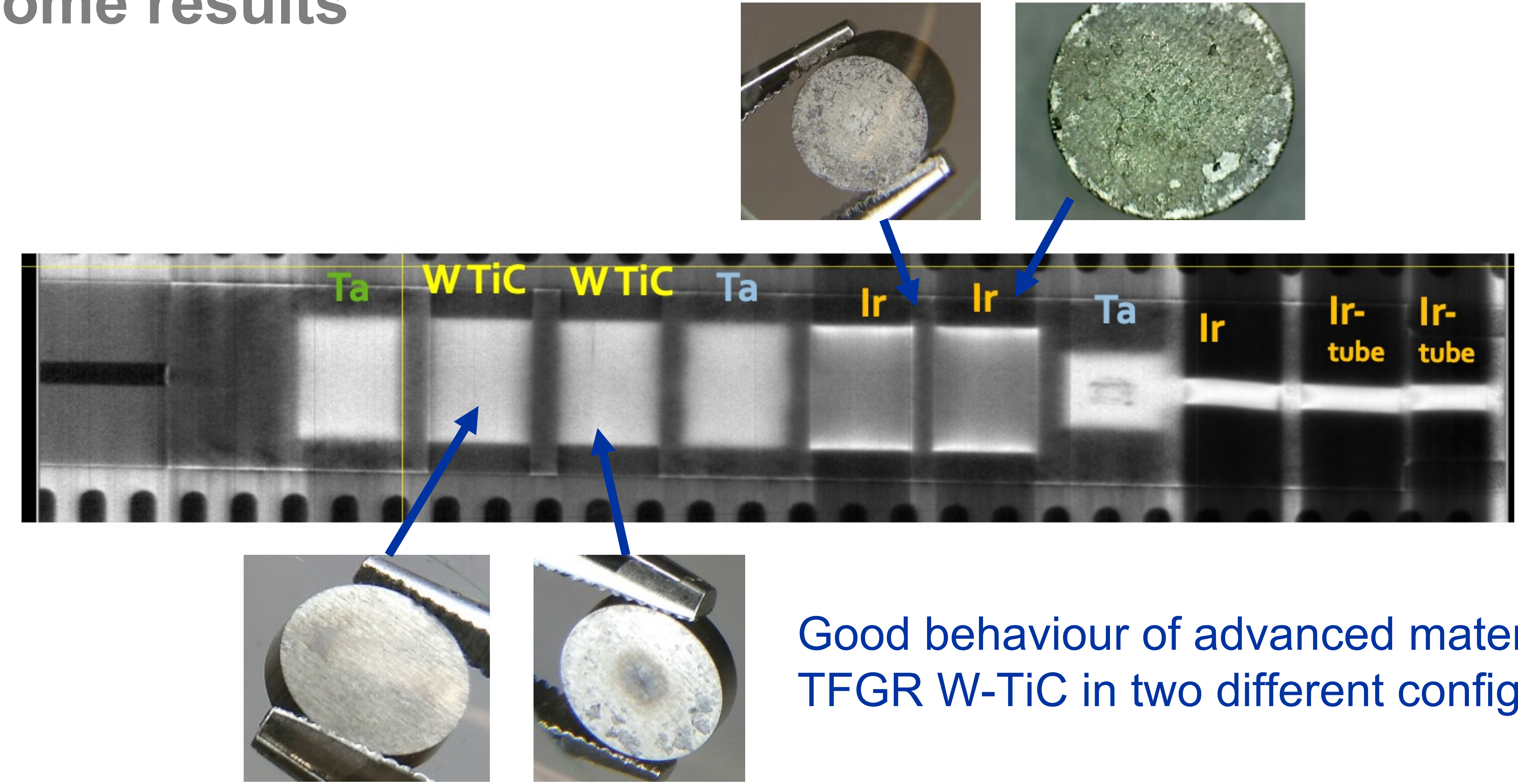
Extensive Longitudinal cracks

Material displacement along the face

Courtesy C. Torregrosa

Application of HiRadMat to antiproton production

Some results



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

Long-term radiation damage

- Irradiation of materials by particles causes **microstructural defects** (atomic displacements & transmutation products) → in turn creates macroscopic effects
- Relate
  - **Ionizi**
  - **Non-io** displacement damage)
  - **Gas production** (mostly due to protons, ^{2}H, ^{3}H, ^{3}He and alphas stopping in the target)

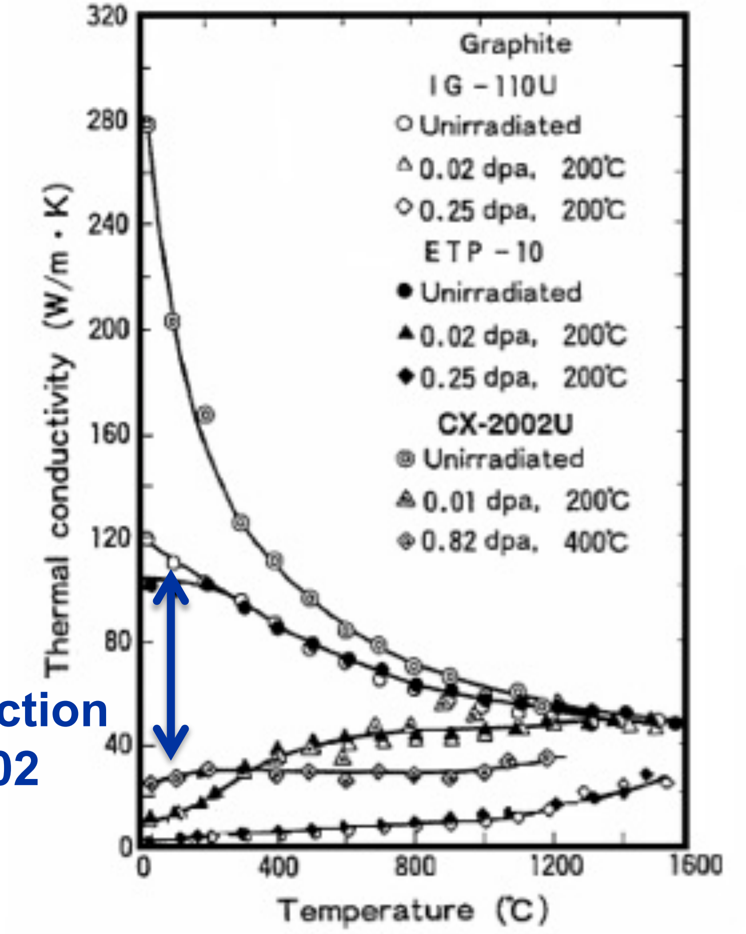
Additional variable to consider in the design of beam intercepting devices, especially targets and beam windows

Long-term radiation damage

Thermo-physical effects

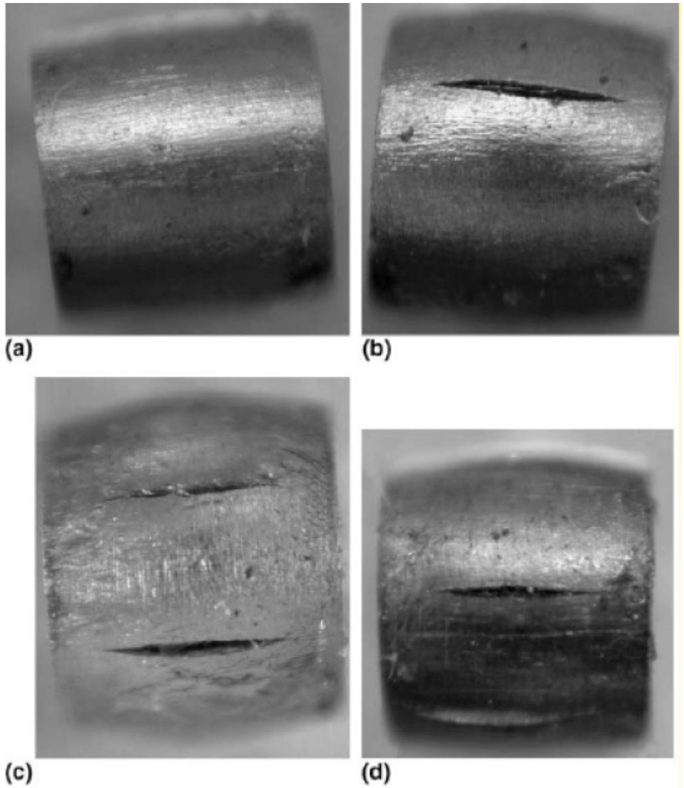
- Embrittlement, creep, **sweeling**, fracture toughness reduction, **thermal** and electrical **resistivity reduction**, CTE, young’s modulus, transmutation products, etc.

- Dependent on particle type, energy and rate of irradiation



10x reduction at 0.02 DPA

N. Maruyama and M. Harayama, “Neutron irradiation effect on … graphite materials,” Journal of Nuclear Materials, 195, 44-50 (1992)



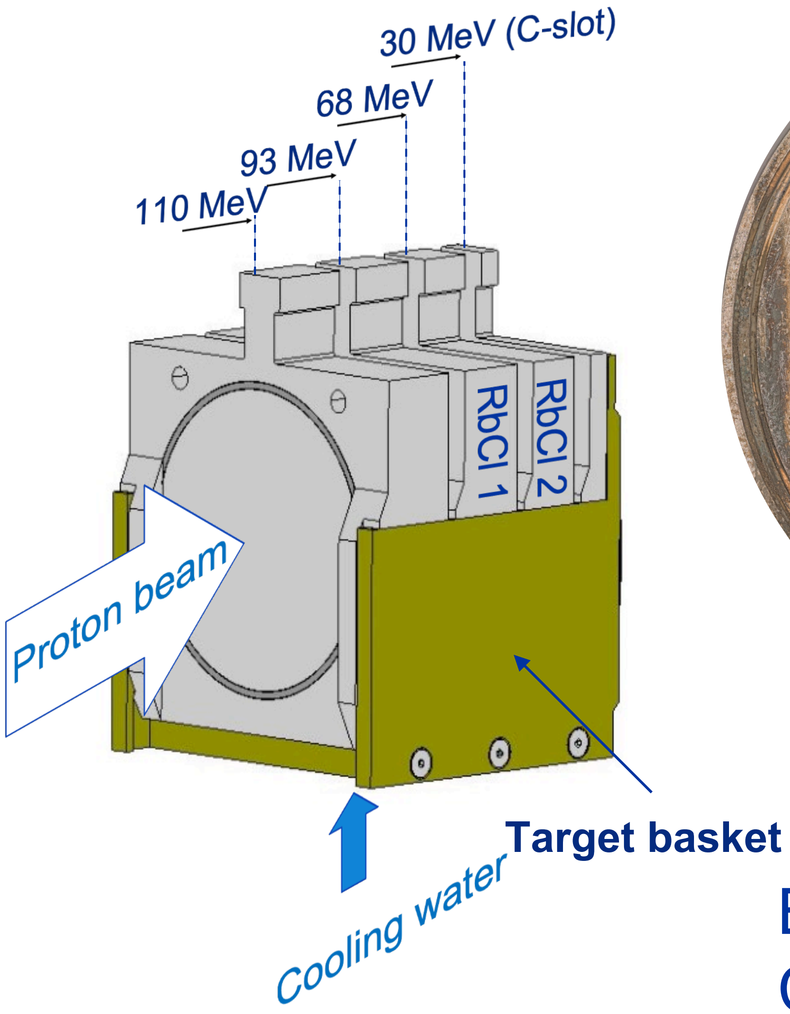
S. A. Malloy, et al., Journal of Nuclear Material, 2005. (LANSCE irradiations)

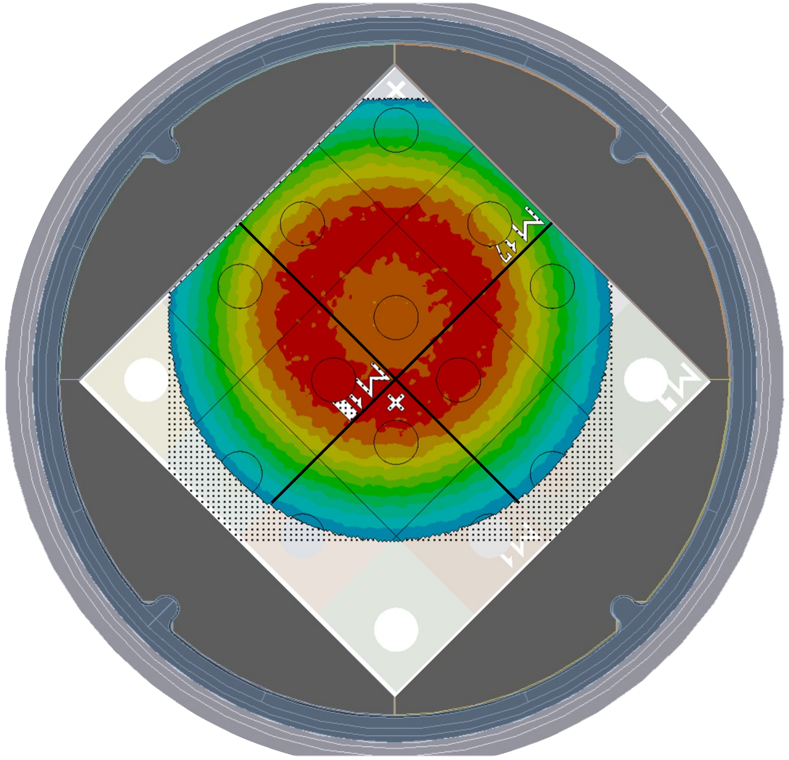
Displacement per Atom

- Is a measure of the amount of radiation damage in irradiated materials
  - For example, 3 DPA means each atom in the material has been displaced from its site within the structural lattice of the material an average of 3 times
- Displacement damage can be induced by all particles produced in the hadronic cascade, including high energy photons, albeit on a smaller scale → **directly related to energy transfers to atomic nuclei**
- Does not account for thermal annealing after the initial cascade and subsequent recombination
- NB: it cannot be measured, only estimated via Monte Carlo codes (FLUKA, MARS, PHITS, etc.)

How can we test materials?

RaDIATE





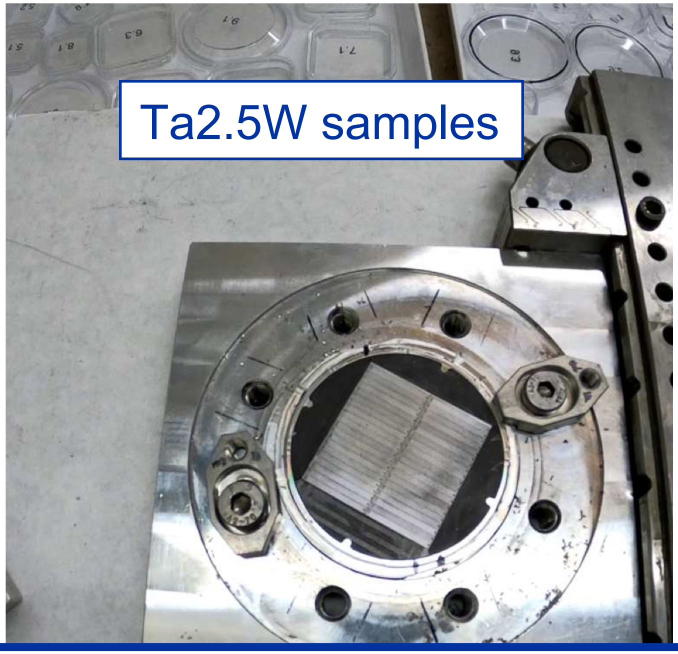
BLIP irradiation @Brookhaven National Laboratory

Capsules containing graphitic materials irradiated at **0.1 DPA**

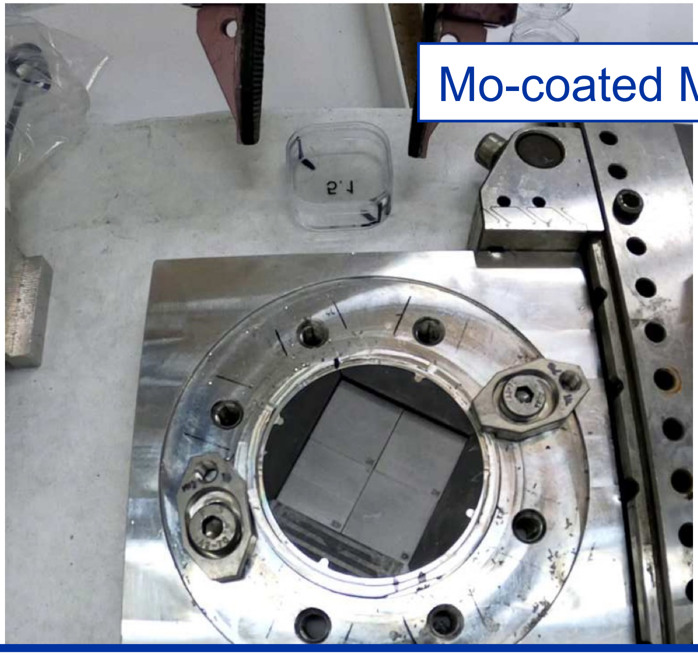
Courtesy K. Doyhun (BNL) & N. Solieri (CERN)

Challenges of post-irradiation examination

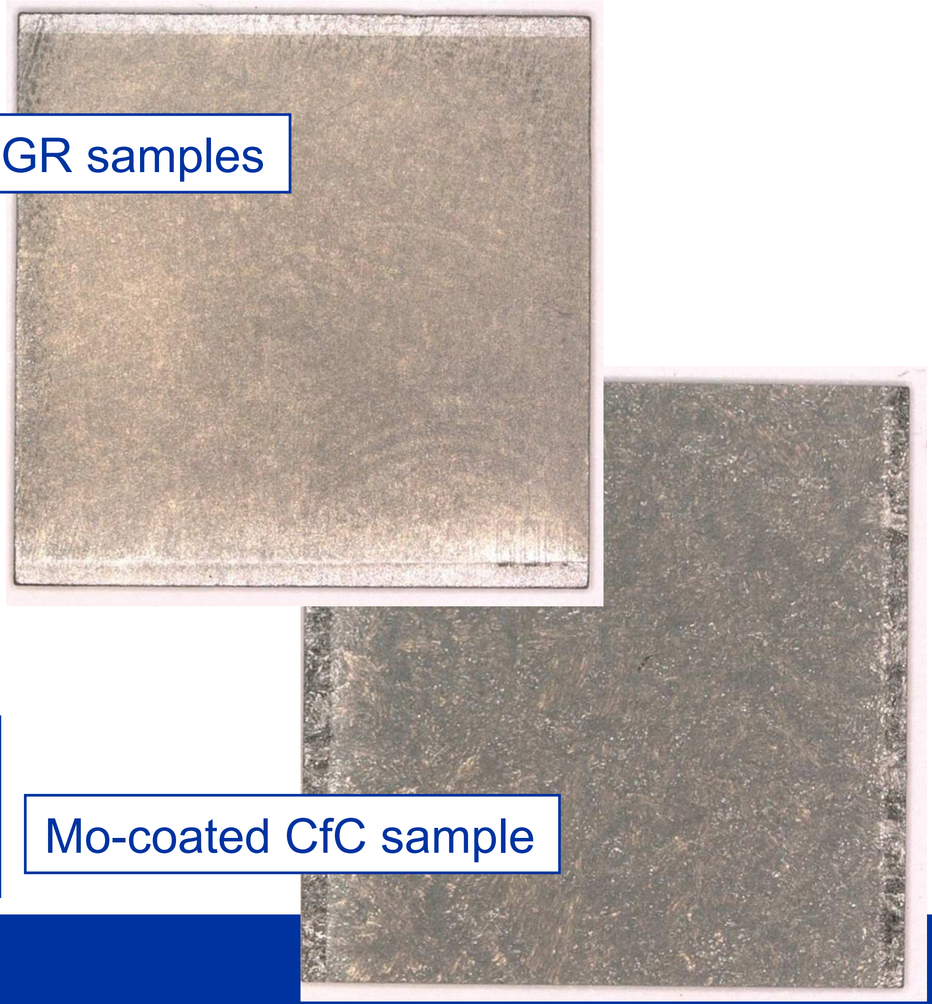
- Irradiation capsule are extremely radioactive, need a dedicated hot-cell and expertise to handle the samples



Ta2.5W samples



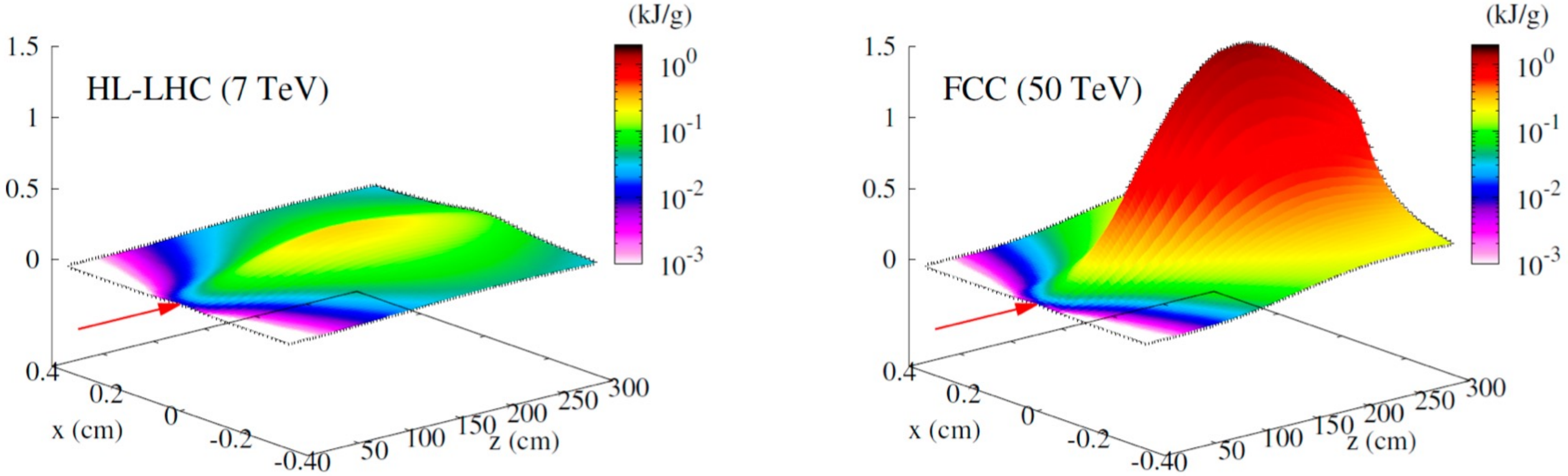
Mo-coated MoGR samples



Mo-coated CfC sample

Preliminary results indicate good adhesion of Mo-coating on graphitic materials, with hardening of bulk

Challenges for the future



Figures: Energy density in 3 m-long Graphite (1.83 g/cm^3) for one nominal proton bunch (σ=400μm), comparing HL-LHC (top) and FCC (bottom).

Conclusions

- Beam Intercepting Devices are a multi-physics, multi-expertise and cross-cultural systems
- Reliable construction relies on a delicate balance of different requirements and constraints
- Operational experience is a key aspect in the feedback loop – example of CERN’s devices in Lecture 2

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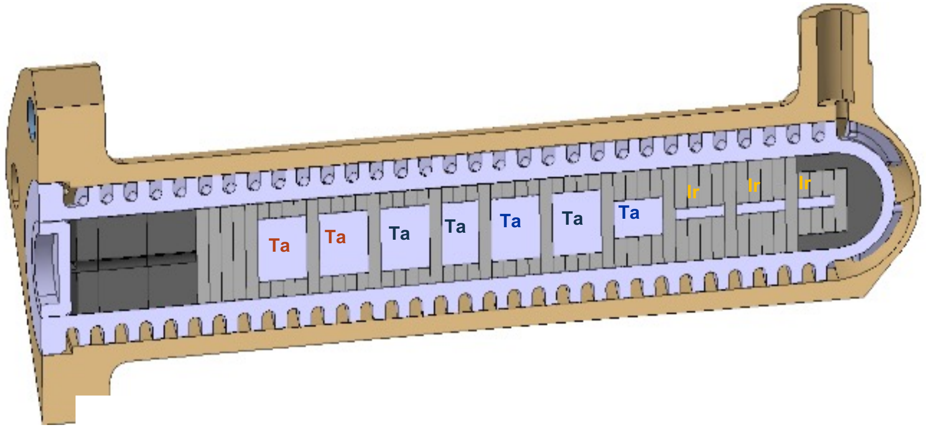
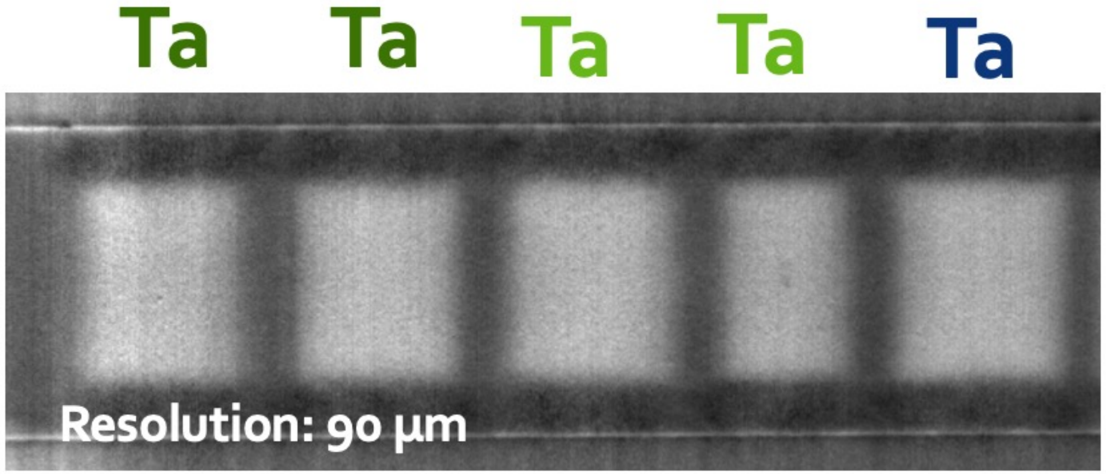
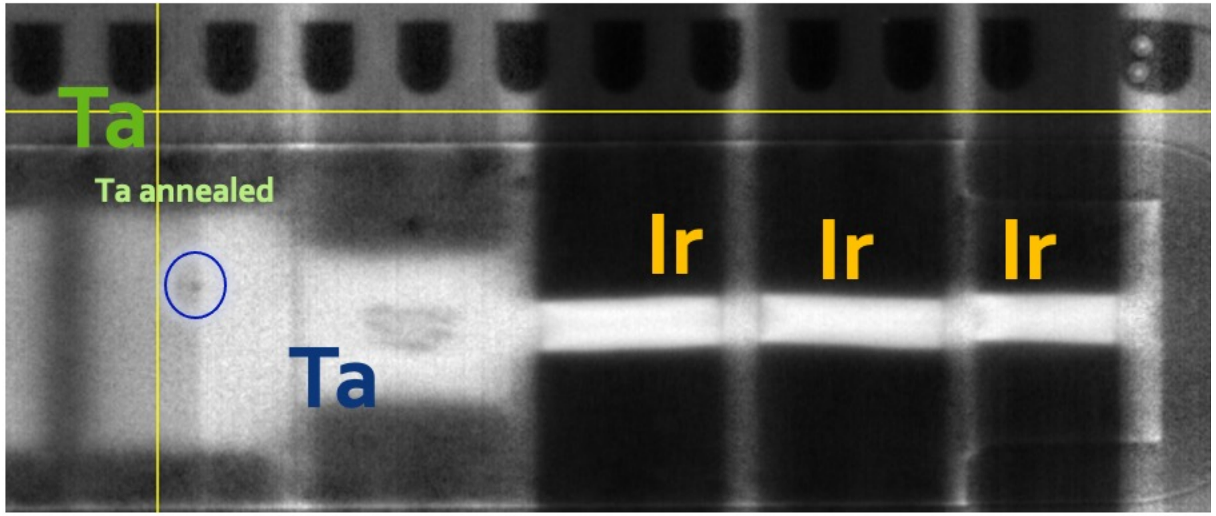
Application of HiRadMat to antiproton production

Some results







Courtesy C. Torregrosa