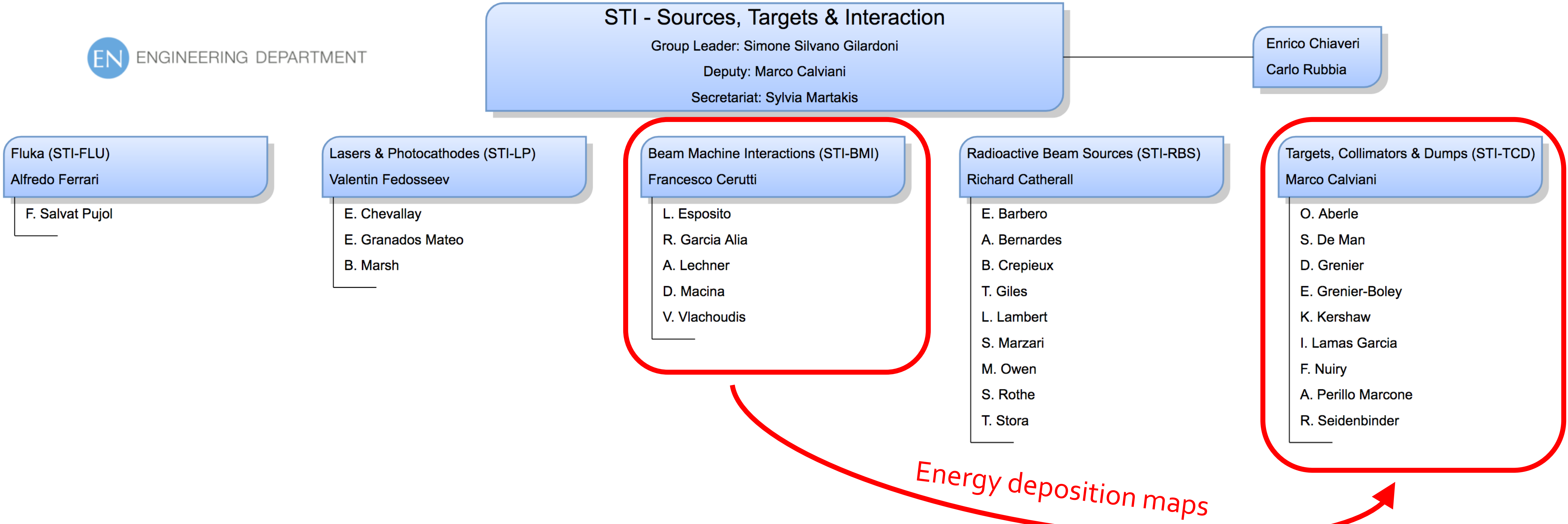
Thermo-Mechanical Simulations of Beam Intercepting Devices by EN-STI-TCD

Antonio PERILLO MARCONE

on behalf of EN-STI-TCD

CERN | EN ENGINEERING DEPARTMENT

STI Group



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Energy deposition maps

EN-STI-TCD Mandate

- Responsible for all beam-intercepting devices (BIDs)
- Conceptual studies, manufacturing, installation and maintenance of mechanical systems of BIDs
    - Thermo-mechanical studies of all BIDs
    - R&D activities
    - Continuous development of expertise in materials under extreme operation and mixed field irradiation
- Technical coordination and supervision of n_TOF and AD target areas
- Design, testing and operation of focusing magnetic horns
- Remote handling compliant design of BIDs

Beam Intercepting Devices

Safety function

- Beam stoppers
- **Beam dumps**

Beam cleaning & control

- Collimators
- Scrapers
- Strippers
- Slits

Physics

- **Particle producing targets**

Some examples of Simulations / Applications

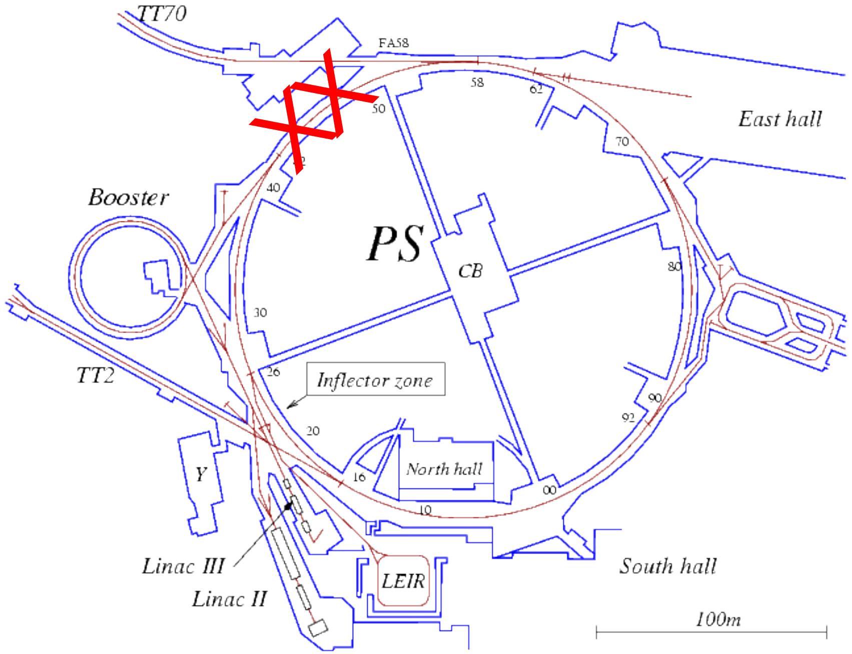
PS
(and targets)

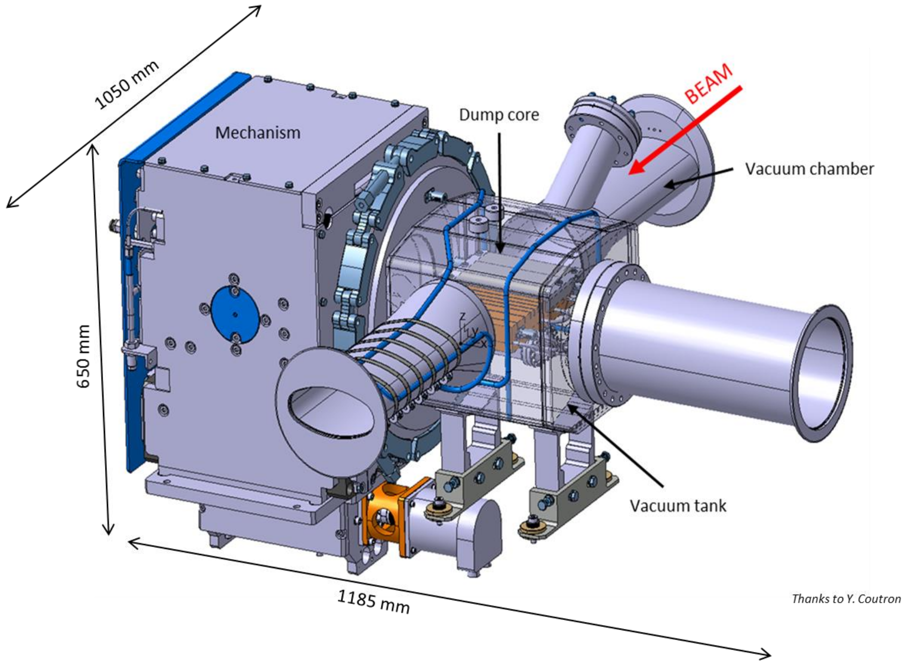
PS Internal Dump

J. Esala
F-X Nuiry
G. Romagnoli
J.A. Briz

PS DUMP

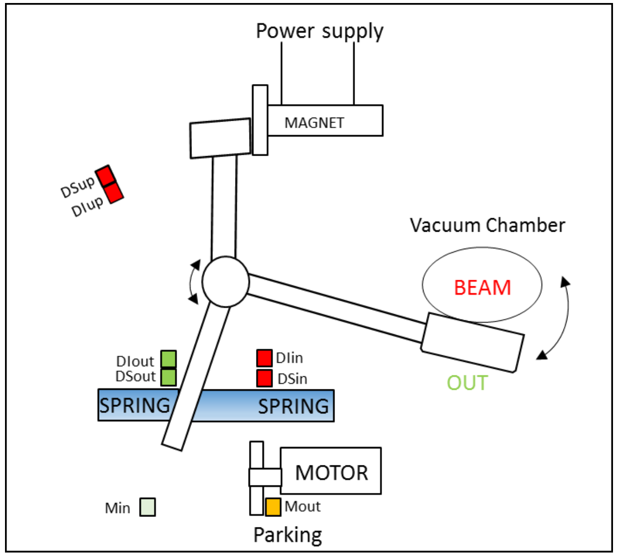
The Internal PS dumps are beam diluters, which reduce the beam intensity down to zero after several beam turns in the PS ring





~ 200 kg

Thanks to Y. Coutron



PS Internal Dump

J. Esala
F-X Nuiry
G. Romagnoli
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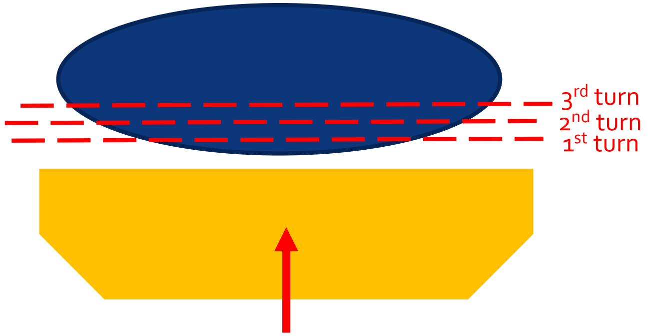
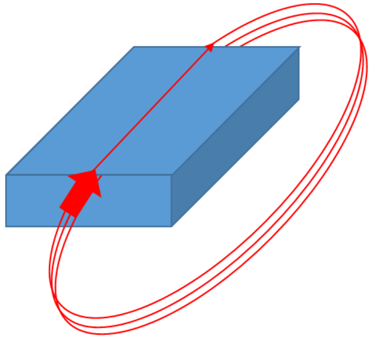
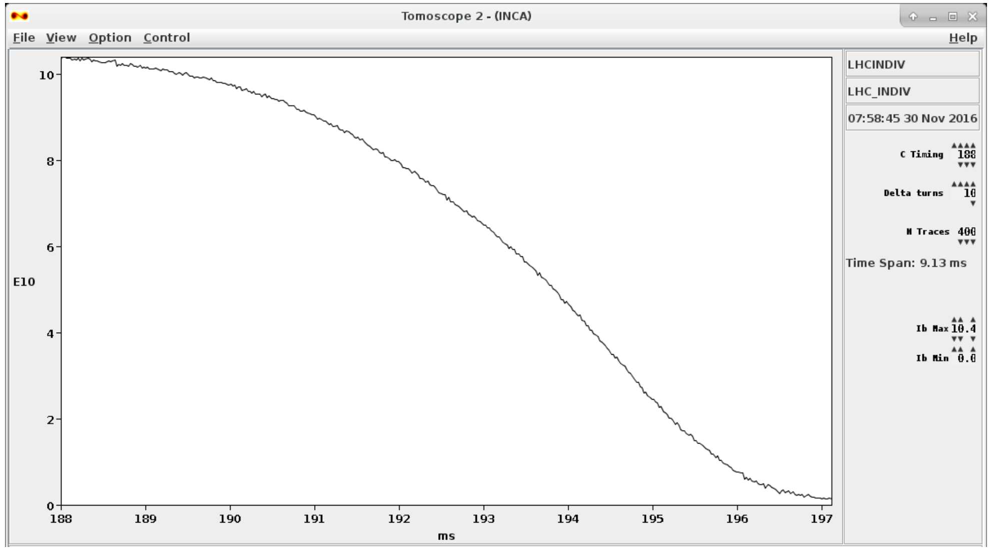


- → Beam speed = 70000 times dump speed
- → Turn after turn, the dump intercepts a small fraction of beam;
- → **Multi-turn shaving phenomenon, mainly at the dump surface**
- → The **beam betatronic motion in the machine** → some protons can be where the dump previously shaved the beam the previous turn



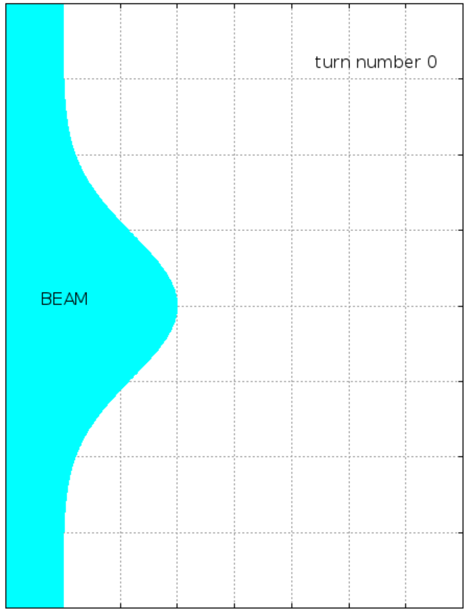


LHCINDIV
LHC_INDIV
07:58:45 30 Nov 2016
C Timing 188
Delta turns 10
N Traces 400
Time Span: 9.13 ms
Ib Max 10.4
Ib Min 0.0

Dump speed = 0.8 m/s
Considering DUMP47

For LHCINDIV beam at injection
Beam size= σ_h 5.46 mm x σ_v 3.31 mm
Intensity 13×10^{10} protons

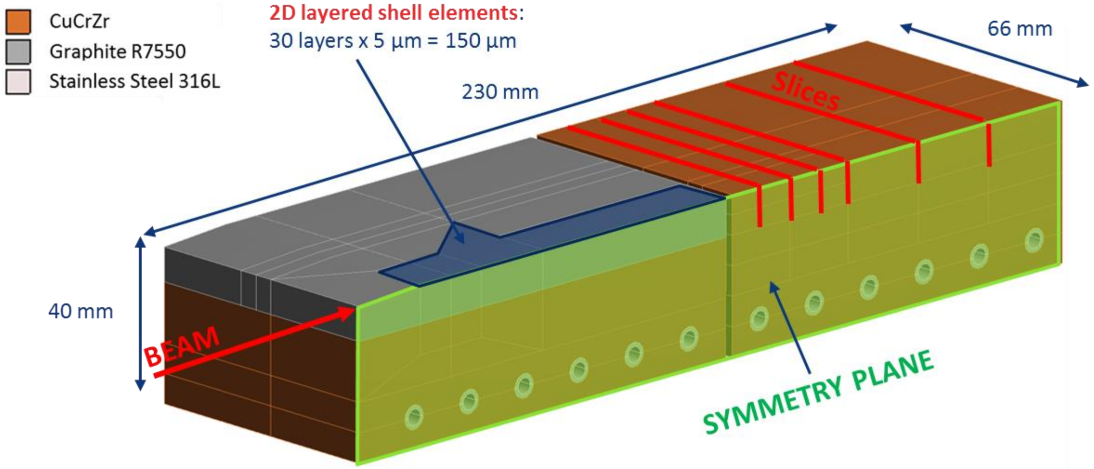
Time to STOP the beam: **9 ms**
($2\sigma=7.2$ mm) ~4300 turns

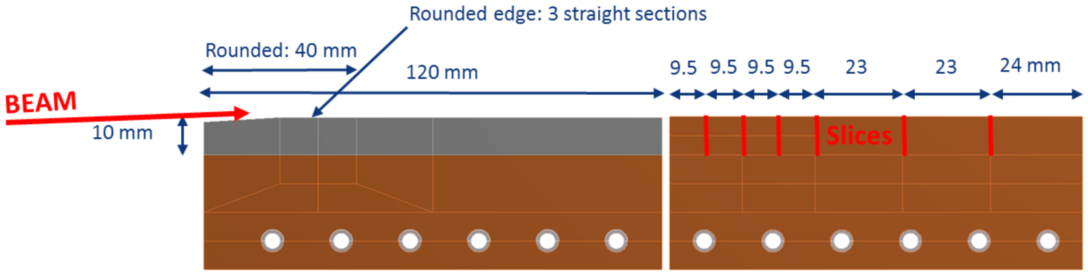


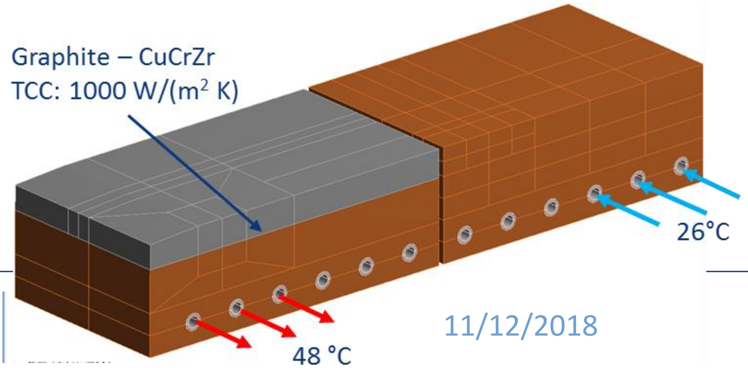
Nonlinear beam intensity drop over time: ~3-7 ms depending on beam type

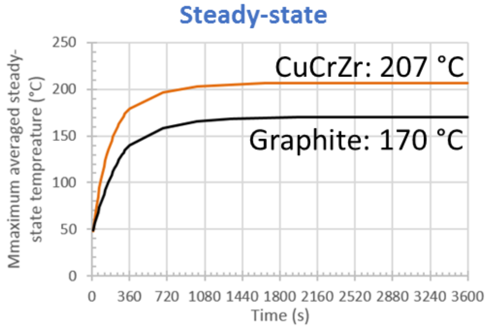
PS Internal Dump

J. Esala
F-X Nuiry
G. Romagnoli
J.A. Briz









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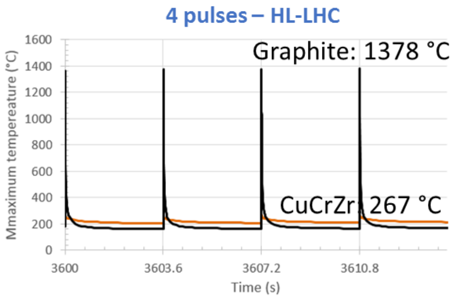


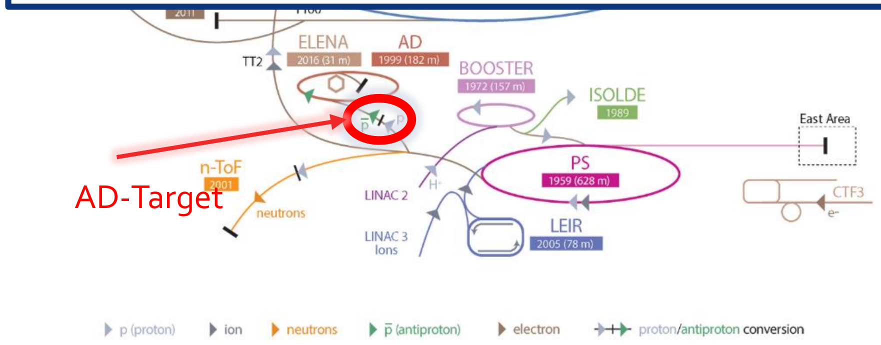
- Time stepping: 20-60 x 150 µs (from FLUKA)
  - New Energy deposition map each time step
- Vertical tune Q=6.33
- Symmetry in geometry, loading and boundary conditions
- Linear elastic temperature dependent material model
- Dump core velocity: 0.8 m/s
- Beam impact always in the same position, in the middle

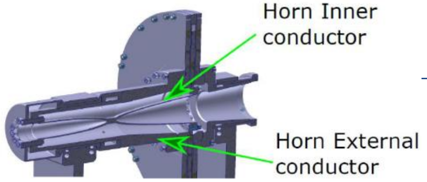
AD Target

C. Torregrosa
N. Solieri

- Antiprotons are produced by colliding a 26 GeV/c proton beam with a fixed **target**
- Collected at 3.5 GeV/c by a magnetic horn, focused and injected to the AD-ring

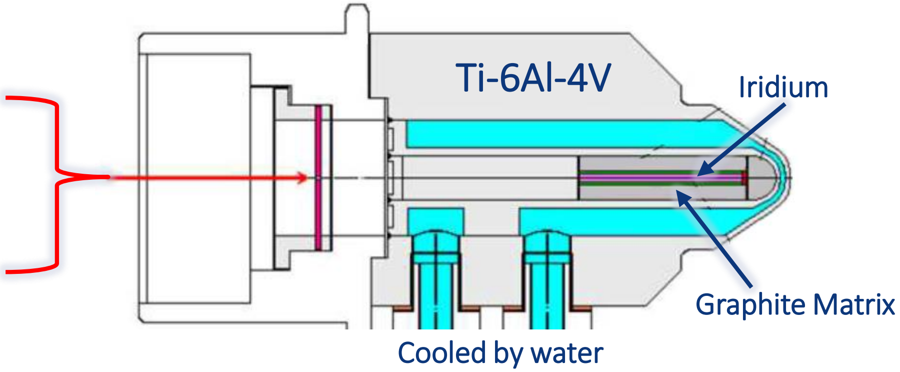
CERN's Accelerator Complex





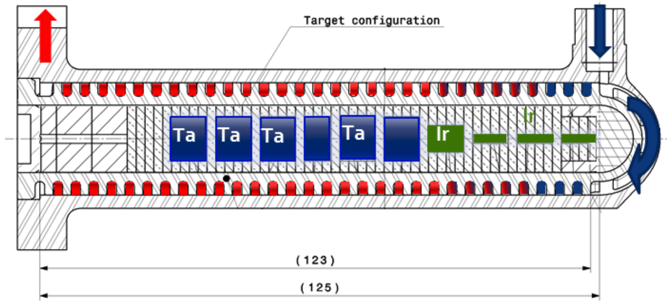
Current target

- 26 GeV/c , $1.45 \cdot 10^{13}$ ppp
- **430 ns pulse length**
- 0.5 mm x 1 mm σ



New Proposed Design (operating after LS-2)

- More compact
- Pressurized-Air-cooled (5-6 bars) double wall Ti-6Al-4V assembly, with an internal serpentine.
- New core & matrix configuration



Operating conditions

- Extremely **high instantaneous power in the core** (~11 GW)
- Dynamic stresses of several GPa, above the strength of the core material
- **Low total power** (40-260 W), but in a small volume ~2 cm^3)

Simulation Challenges AD-Target

C. Torregrosa
N. Solieri

1) Simulate **target core dynamic response** considering <u>material yielding and even fracture at high strain rates and temperatures</u>

Use of **hydrocodes** (Autodyn) with advance material models

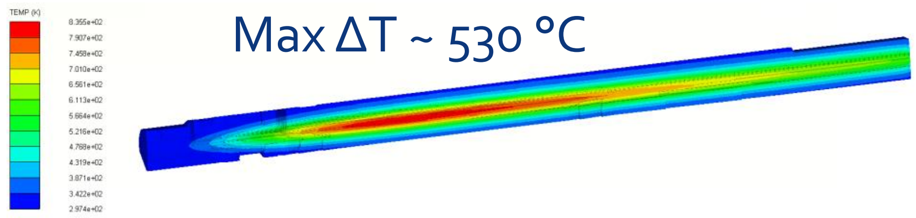
- Johnson-Cook Strength model
- Minimum Hydrostatic Pressure Failure model

2) To simulate the new pressurized air cooling system

Use of ANYS-CFX one-way coupled with FLUKA Monte Carlo Simulations

- Accurate simulation of cooling flow heat-up and pressure drop

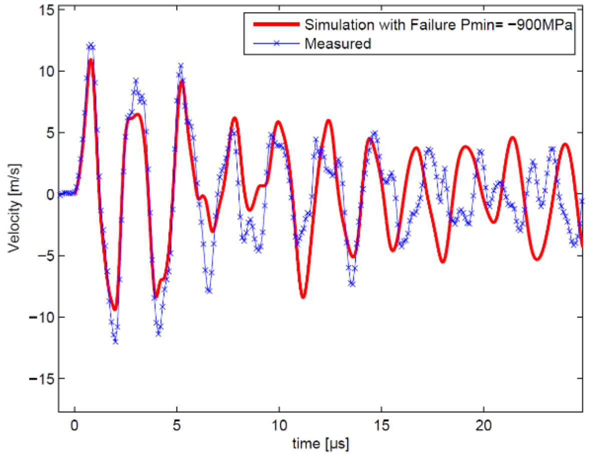
<u>Iridium rod – HiRadMat-27</u>



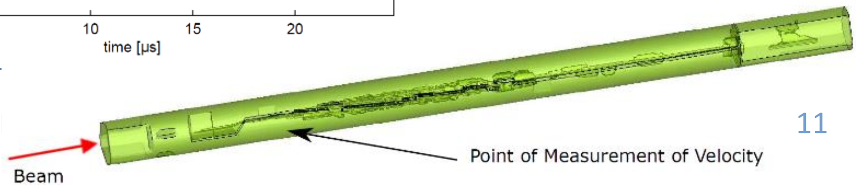
Max ΔT ~ 530 °C

<u>Simulations vs Experimental Data</u>

J-C strength model
failure model P_{min}= 900 MPa

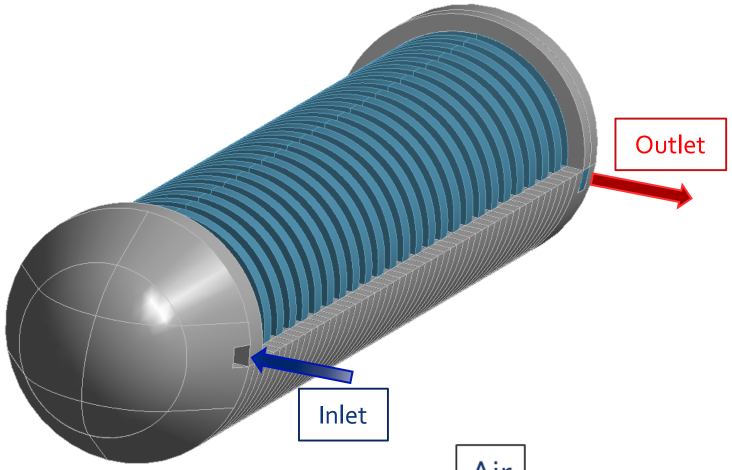


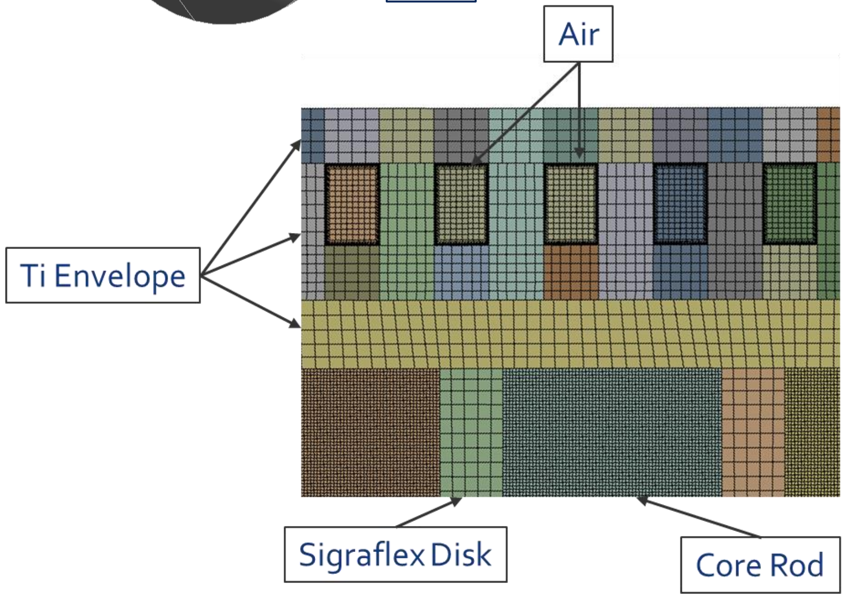
Very close agreement between simulations and experimental results



CFD Simulations AD-Target

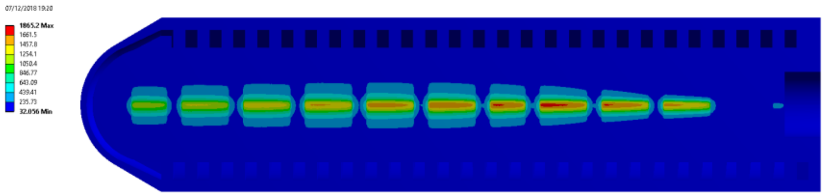
C. Torregrosa
N. Solieri



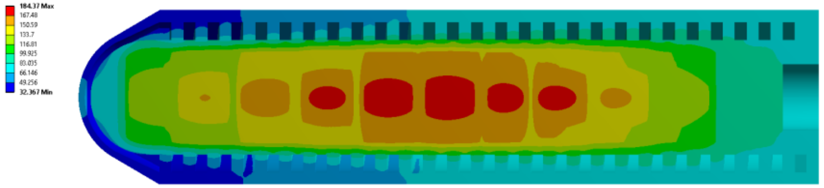


- ~1.3 kJ deposited in the core at each pulse
- Efficient cooling system needed
- Pressurized-air cooling line.
  - Internal serpentine in Ti casing:
    - 2 x 3 mm cross section
    - Total length ~2050 mm
- Simulations needed to validate cooling system effectiveness and perform sensitivity analyses (pulse rep. rate, inlet pressure, flow rate, …)
- Main simulation challenges
  - Complexity of the model (>700k elements)
  - Compressive flow, heated and expanding over the cooling channel
- Computation time ~ 12h for steady state analysis in cluster→ transient analysis very computationally expensive

t = 400 ns, end of pulse



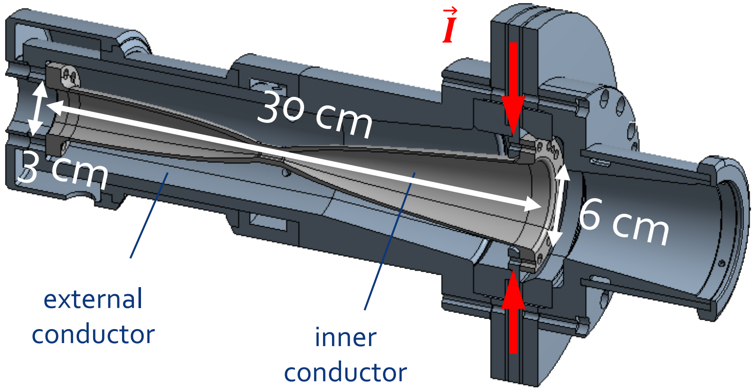
t = 1 s



t = 35 s, end of cycle

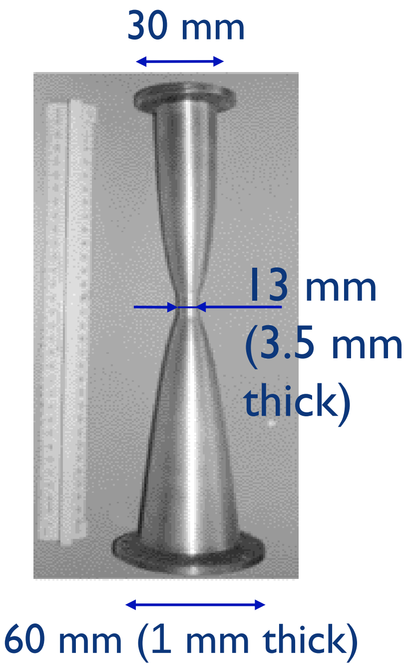
AD Magnetic Horn

E. Lopez



Two coaxial conductors:

- **Inner conductor** with bi-conical "horn" shape
- **External conductor** carrying 400 kA current pulse to and from the inner conductor



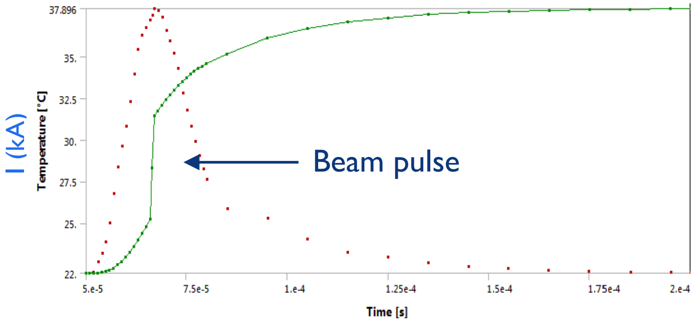
Inner conductor:

- **Optimized thickness (1 mm – 3.5 mm)**
  - small as possible to decrease antiproton reabsorption
  - without compromising the mechanical integrity.
- **Material:** Aluminium AA7075-T6
  - High tensile strength under dynamic stresses
  - Work in intense radiation fields

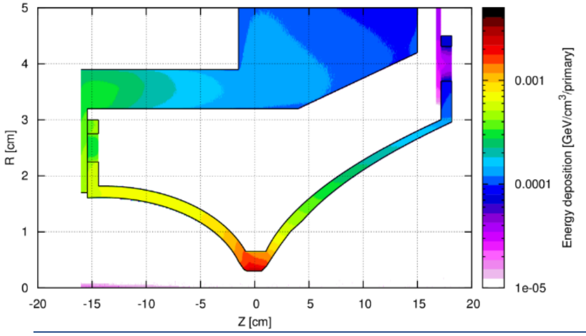
AD Horn – Thermal Calculations

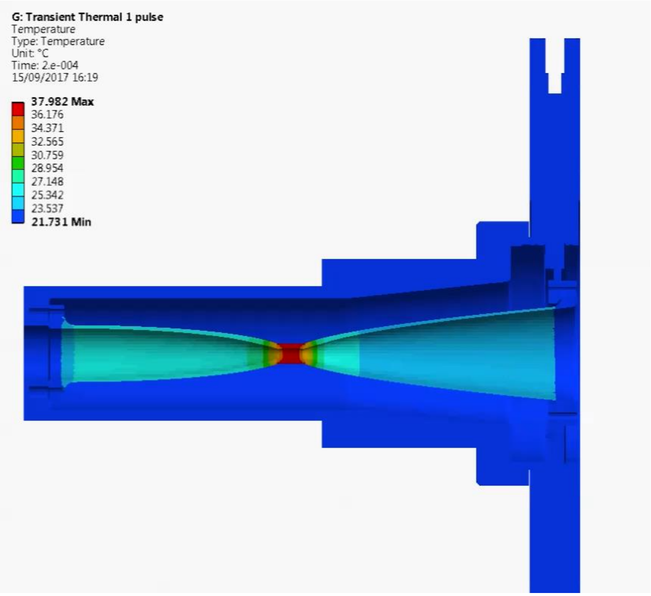
E. Lopez

- Beam pulse = 4 proton bunches coming from the PS machine **~ 500 ns pulse, 1.5×10^{13} ppp at 24 GeV**
- **Coincident with the current peak**
  → Strongest focusing magnetic field

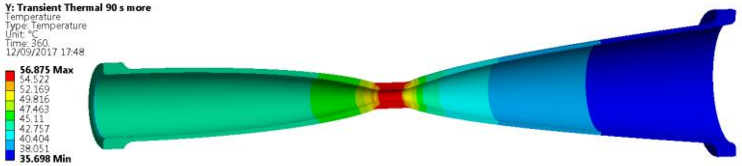


Energy deposition in the inner conductor (FLUKA)

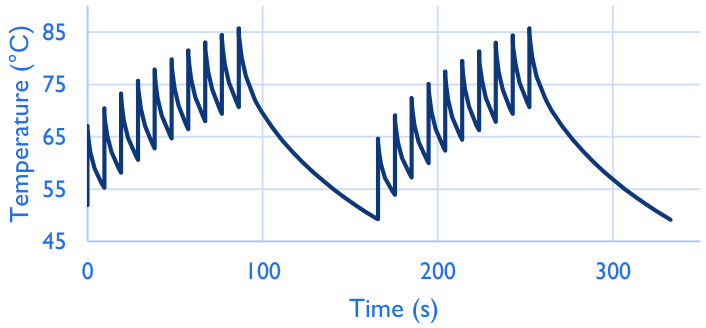


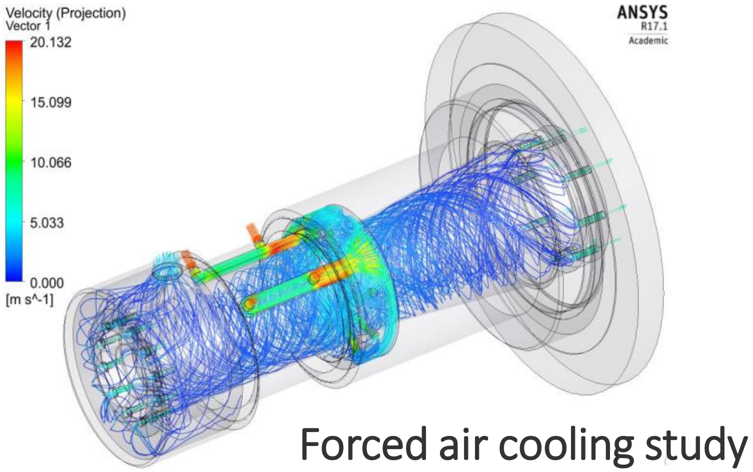


- Current operational scenario: 90s repetition rate
  Max temperature ~ 55°C ✓
  Inner conductor "neck"



- Future possible operational scenario:
  - 9.6 s repetition rate + 70 s cooling
  - **Max temperature > 85°C!**



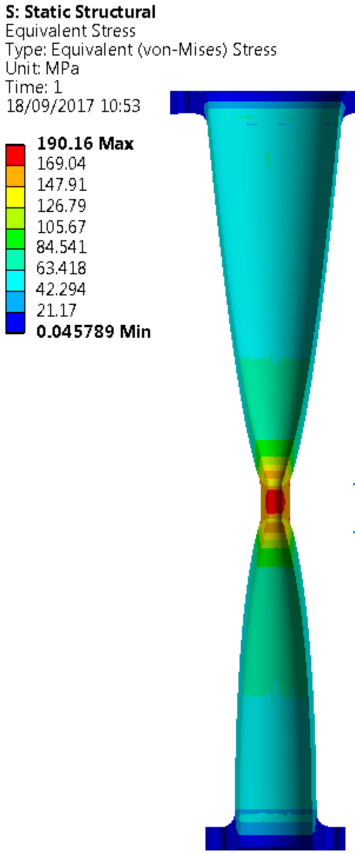


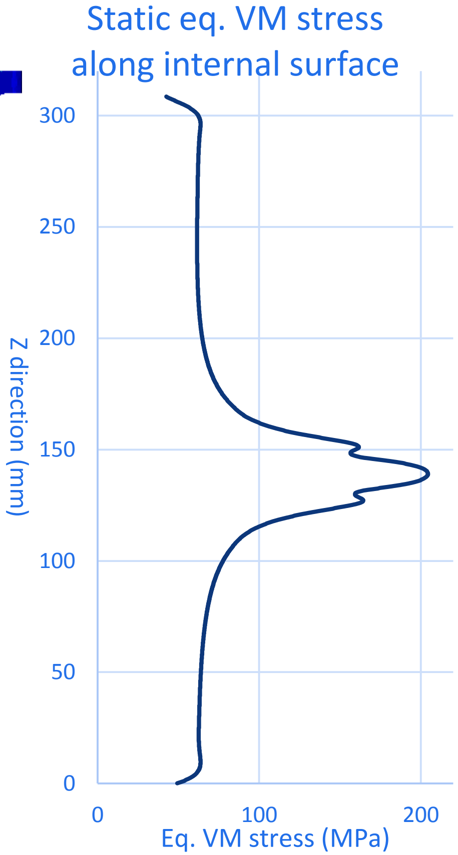
Forced air cooling study

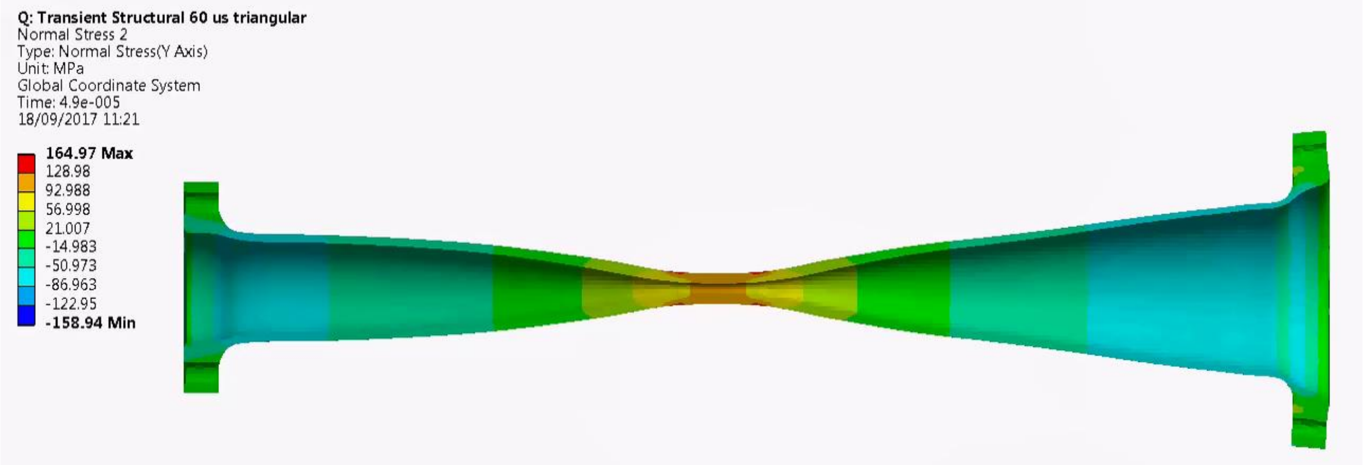
AD Horn – Structural Calculations

E. Lopez

- High-current pulse → strong electromagnetic forces
  - Compressive pressure applied to the external surface of the inner conductor




Static eq. VM stress along internal surface



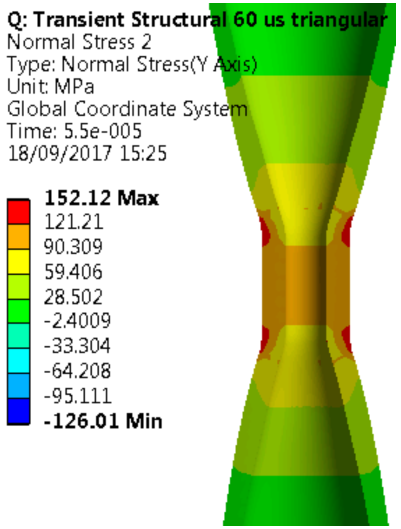
Yield strength of AA7075 at operation temperature: **430 – 450 MPa**

<u>Dynamic stresses</u>

Max eq. Von Mises stress = 190 MPa

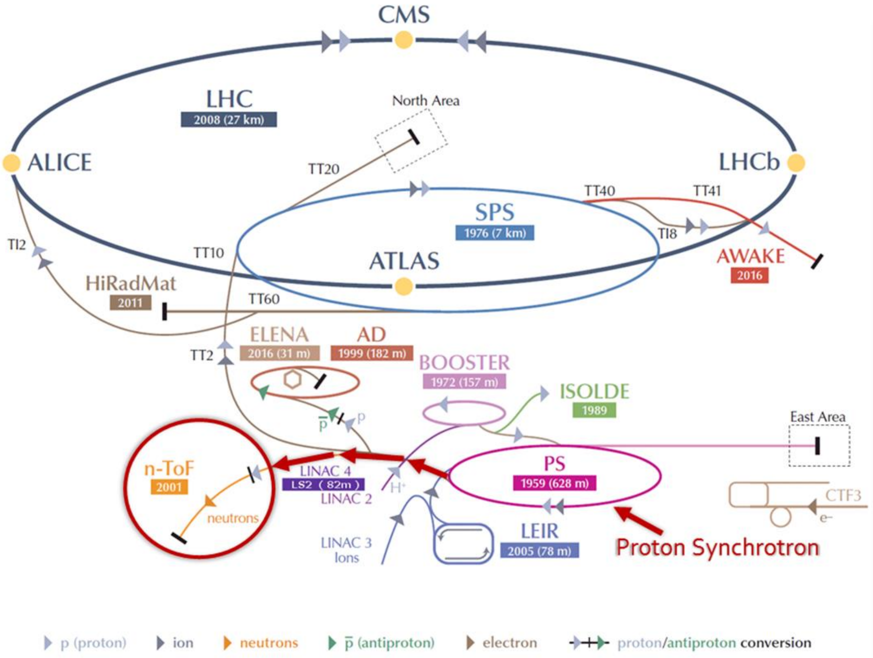
Maximum tensile stress = 150 MPa

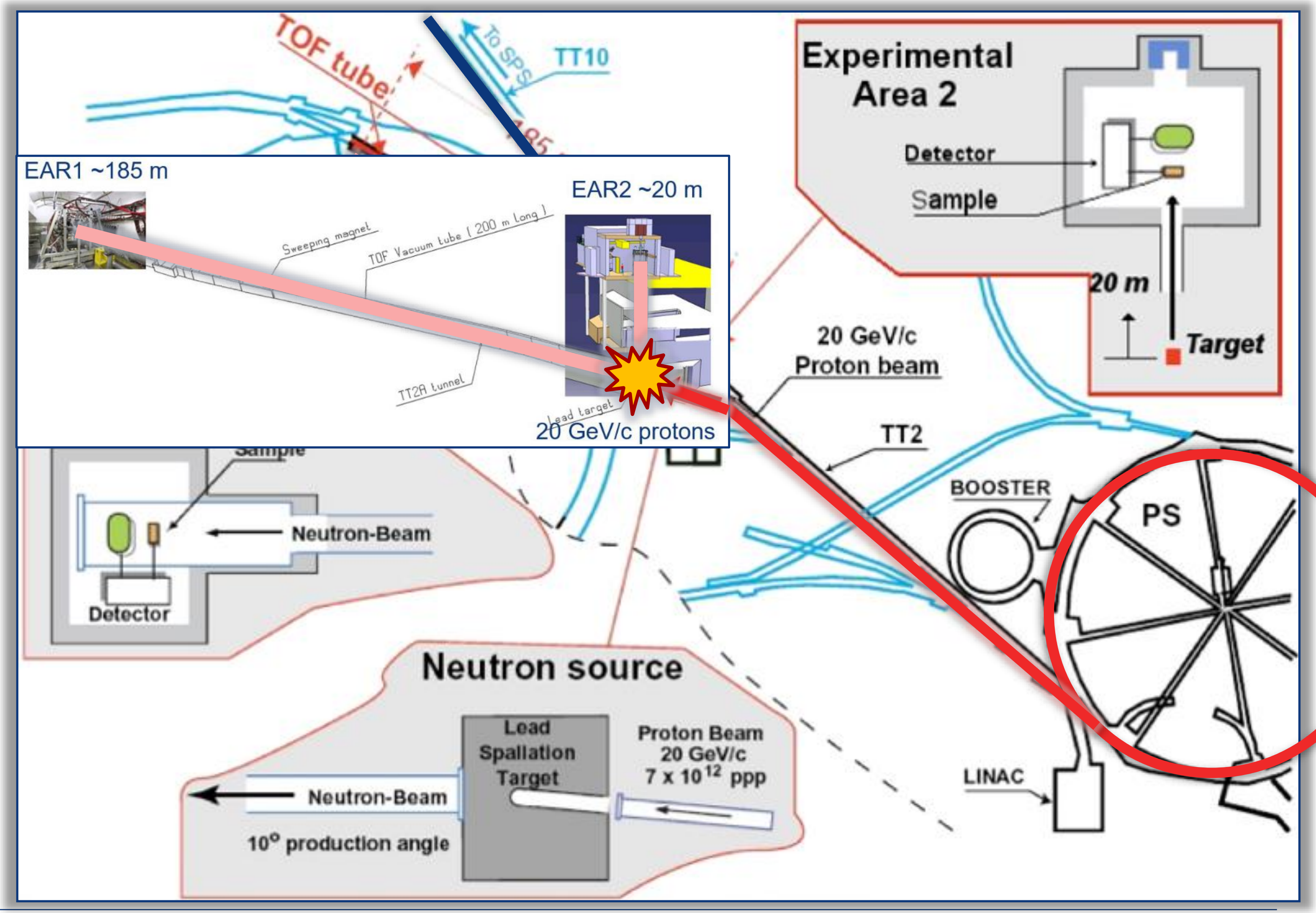
(Horn neck surface, longitudinal direction)



n_TOF Target

R. Esposito





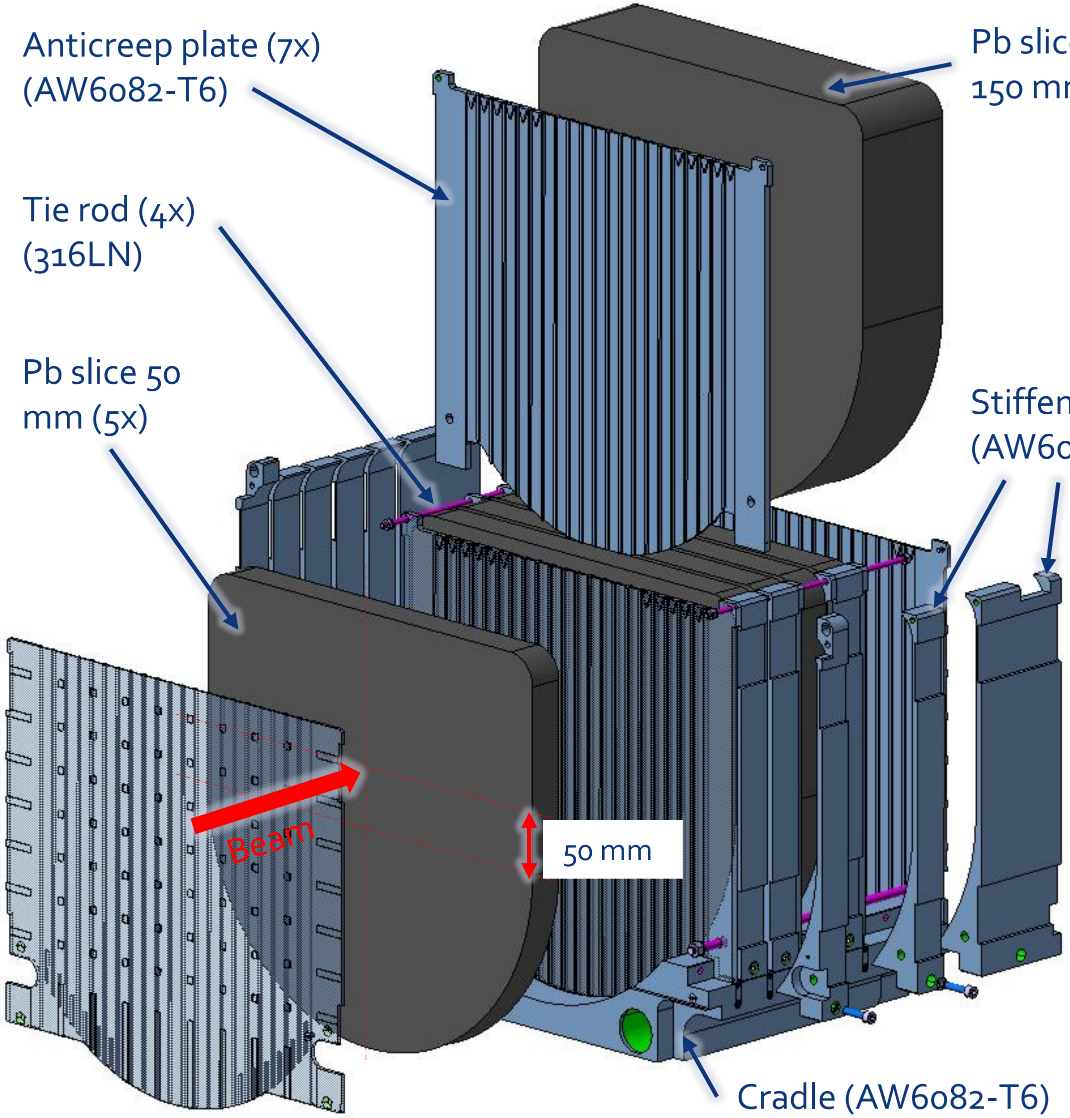
Collaboration between many universities and research institutes all over the world

Applications:

- Nuclear physics
- Astrophysics
- Nuclear technology
- Medical research

Detailed design of n_TOF Target

M. Timmins
V. Maire
R. Esposito



Anticreep plate (7x)
(AW6082-T6)

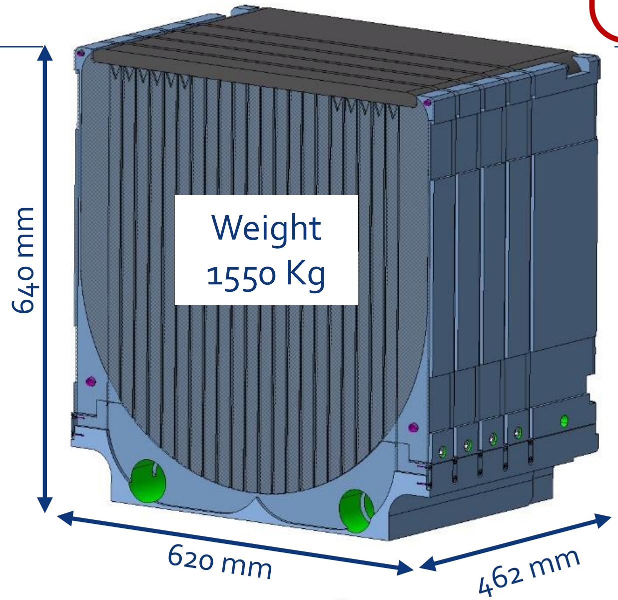
Tie rod (4x)
(316LN)

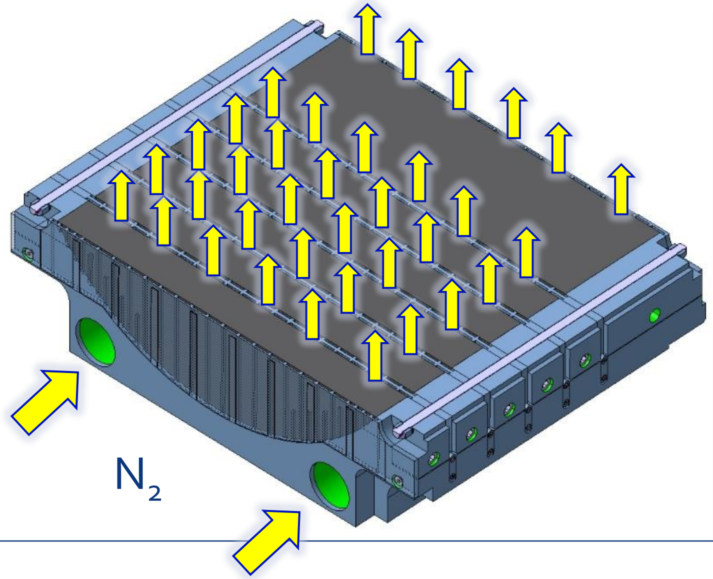
Pb slice 50
mm (5x)

Pb slice
150 mm

Stiffeners
(AW6082-T6)

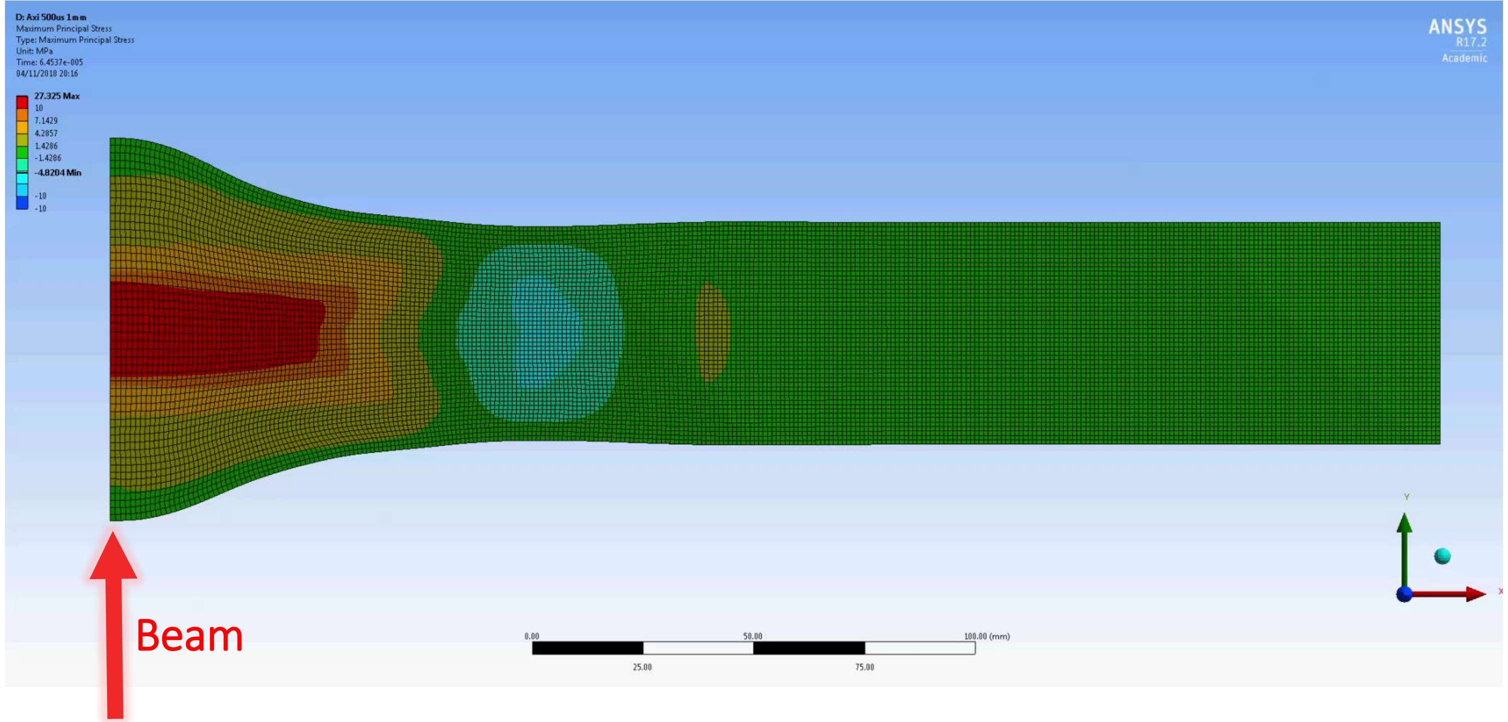
Cradle (AW6082-T6)





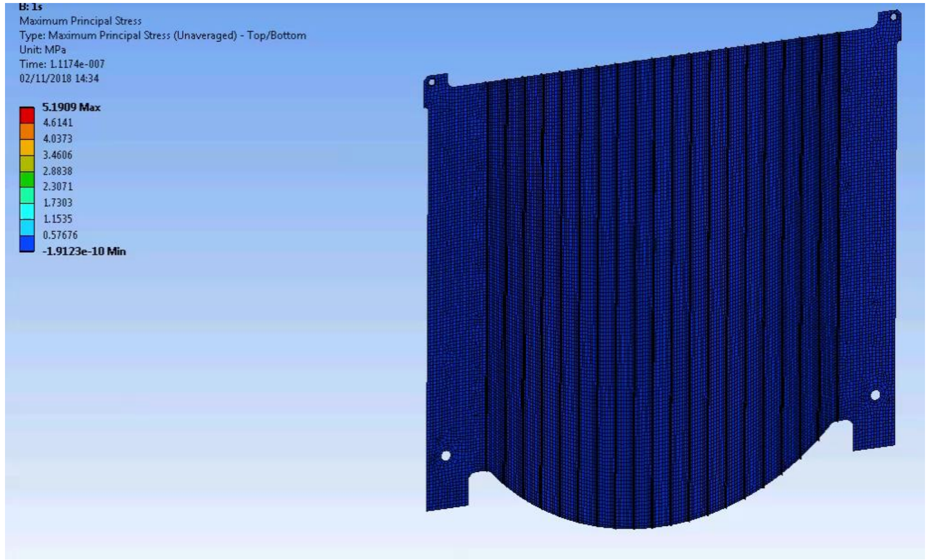
n_TOF – Thermo-mechanical simulations

Local analysis (lead)



High **hydrostatic** tensile stress due to longitudinal stress waves

Anti-creep structure



R. Esposito

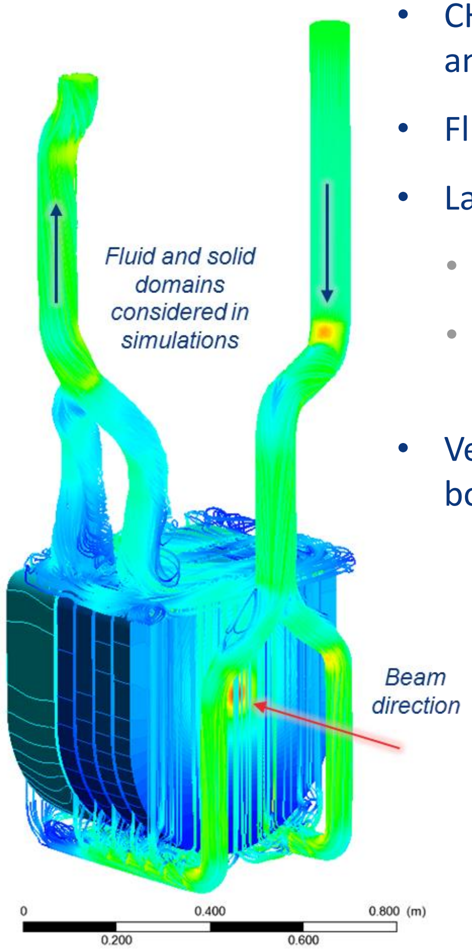
n_TOF – CFD Simulations

R. Franqueira

Combined cooling design optimization + CFD & Thermal study (CHT)

<u>Constrains & Requirements</u>:

- Cooling specs/constrains:
  - Gas cooled (**N2**), to avoid corrosion/contamination risks;
  - Supply at **20°C;,** to avoid external condensation;
  - ~Atmospheric pressure;
  - Flow **700-1000Nm³/h.**
- Integration
  - Target is confined to a very limited space/"pool".
- Key requirements
  - Average(Steady-state) temperature in the Lead below **100°C**;
  - Cooling circuit compatible with some sort of anti-creep structure;
  - Pressure Drop as low as possible.



<u>Key Simulation characteristics</u>

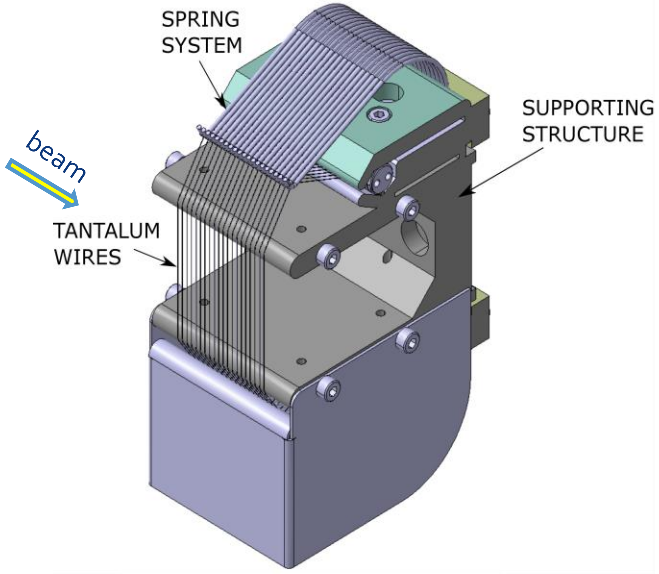
- CHT Conjugated Heat Transfer simulations (Both Fluid (CFD) and Thermal Solid parts being solved)
- Fluka energy deposition used.
- Large Domains & different scales being simulated:
  - >30M elements
  - E.g. lead blocks have 600mm side while cooling gaps are 3x20 mm
- Very fine mesh requirements to adequately resolve fluid boundary layers and consequent heat transfer & pressure drop

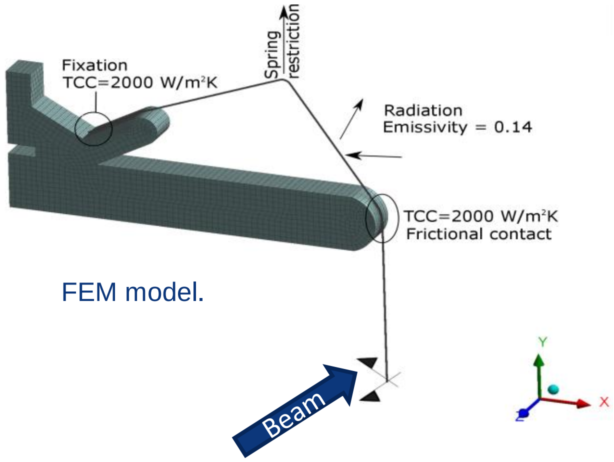
Steady state Results summary 1.66e12 p+/s	**Temperature N2 Inlets**	**20**	**C**
	Pressure N2 Outlet	7654.3	Pa
	Reference pressure	1	atm
	Volume Flow	**787**	**Nm³/h**
	Max Velocity N2	76.4	m/s
	Max Velocity N2(channels)	60.0	m/s
	Pressure Drop	**-3.9**	**kPa**
	Temperature Max lb1	**75.9**	**C**
	Temperature Max lb2	**90.1**	**C**
	Temperature Max lb3	**85.9**	**C**
	Temperature Max lb4	**77.4**	**C**
	Temperature Max lb5	**68.6**	**C**
	Temperature Max lb6	**76.2**	**C**
	Energy balance	2653	W

SPS
(and target)

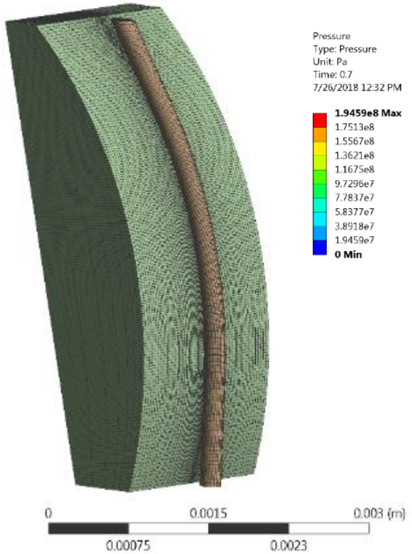
TPSWA (wire beam diffuser)

J. Maestre

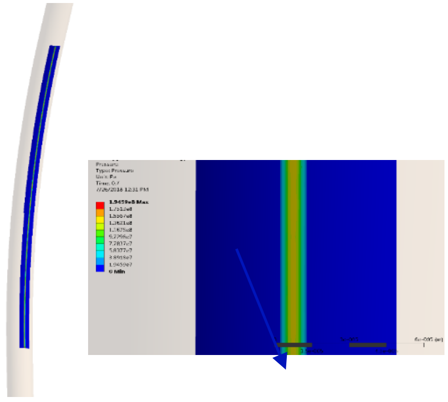




FEM model.

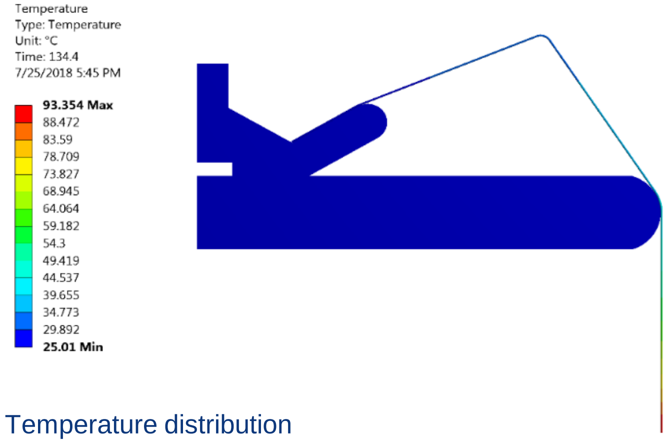


Contact model

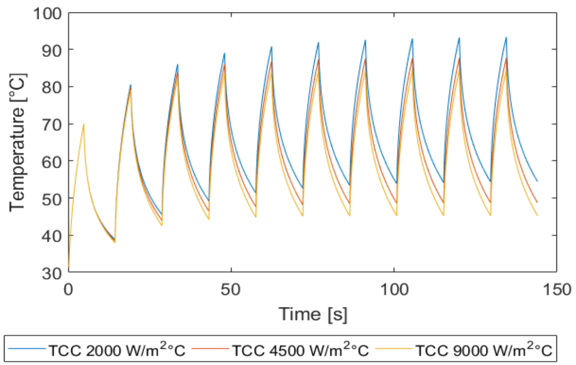


Contact pressure

- The TPSWA is a beam diffuser. In the context of the loss improvement, this device will be installed in the extraction sector of SPS complex.
- TPSWA consists in a grid of 20 tantalum wires through which the beam passes.
- The TPSWA will be exposed to high intensity levels. The structural integrity of the tantalum wires need to be analyzed under these conditions.



Temperature distribution



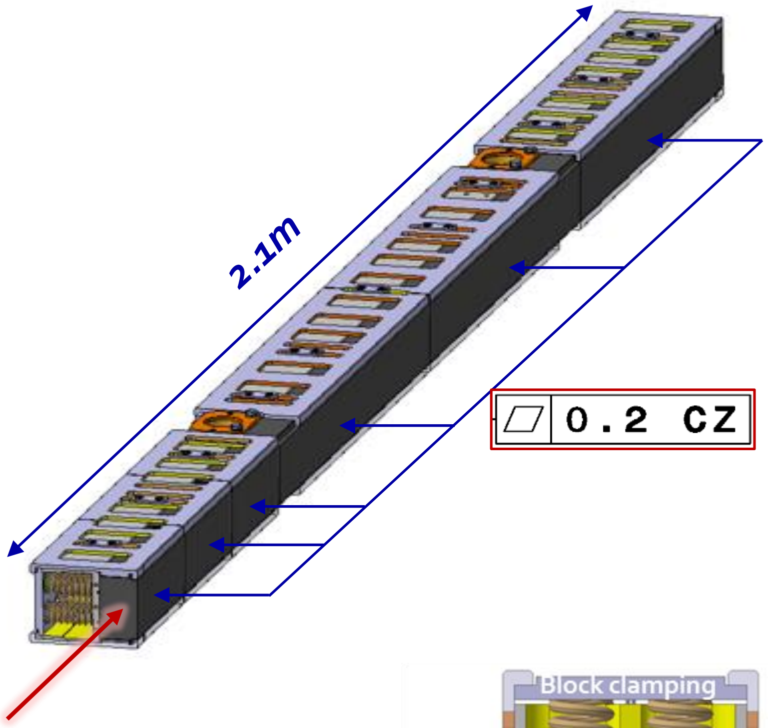
Maximum temperature evolution in the wire for three different TCC.

TCDIL

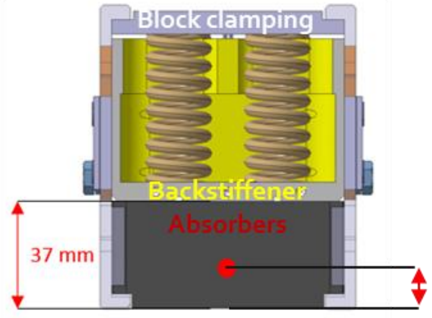
M. Bergeret
F.-X. Nuiry

- The TCDIL-Collimators form the passive protection systems of the transfer lines SPS-to-LHC, TI2 and TI8:
  - **LIU-project:** Installation during LS2
  - **Beam halo cleaner** (Nominal operation)
  - **Beam diluters** (Accidental operation)

Beam Parameters	HiRadMat Beam	Standard LIU Beam
Beam Energy [GeV]	440	450
Bunch Intensity [protons]	$1.2.10^{11}$	$2.3.10^{11}$
Number of Bunches	216 or 288	288
Pulse Length [µs]	7.2	7.8
Beam Size H×V [mm^2]	0.3×0.3 at Focal Point	0.405×0.647



- The functionalities are insured by a couple of 2.1m-long jaw, TCDIL-jaw, precisely positioned around the beams:
  - Low-Z absorbers: 3D Carbon/Carbon and Isostatic Graphite
  - Stiffener: 2.1m-long 316L stainless steel backstiffener
  - Clamps: 304L stainless steel parts and springs



Beam impact parameter
Worst case scenario: 6.9mm

TCDIL-jaw

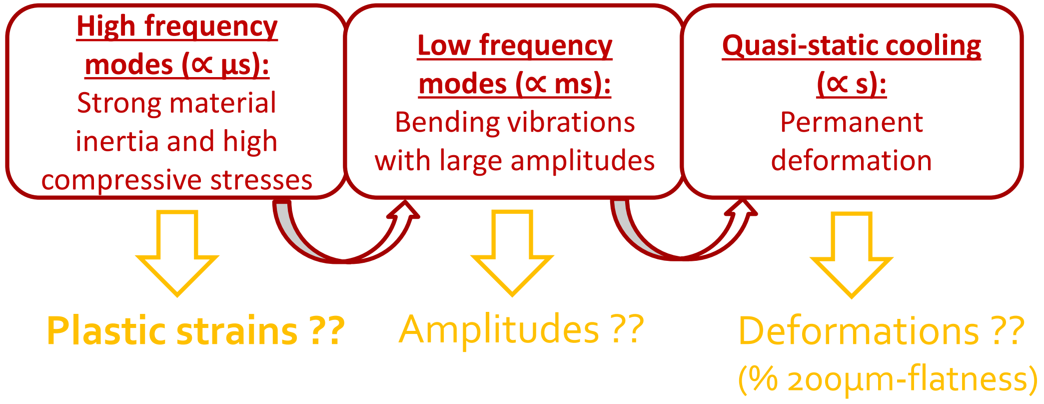
TCDIL

M. Bergeret
F.-X. Nuiry

In case of direct proton beam impact (accidental scenario):
<u>Absorbers</u>: Interactions with the beam protons (related to HRMT28)
<u>Assembly</u>: Interaction with secondary particles

Challenge 1:

- **Extreme thermal loads in few microseconds and multi-scale dynamic responses**



<u>High frequency modes (∝ µs):</u> Strong material inertia and high compressive stresses

<u>Low frequency modes (∝ ms):</u> Bending vibrations with large amplitudes

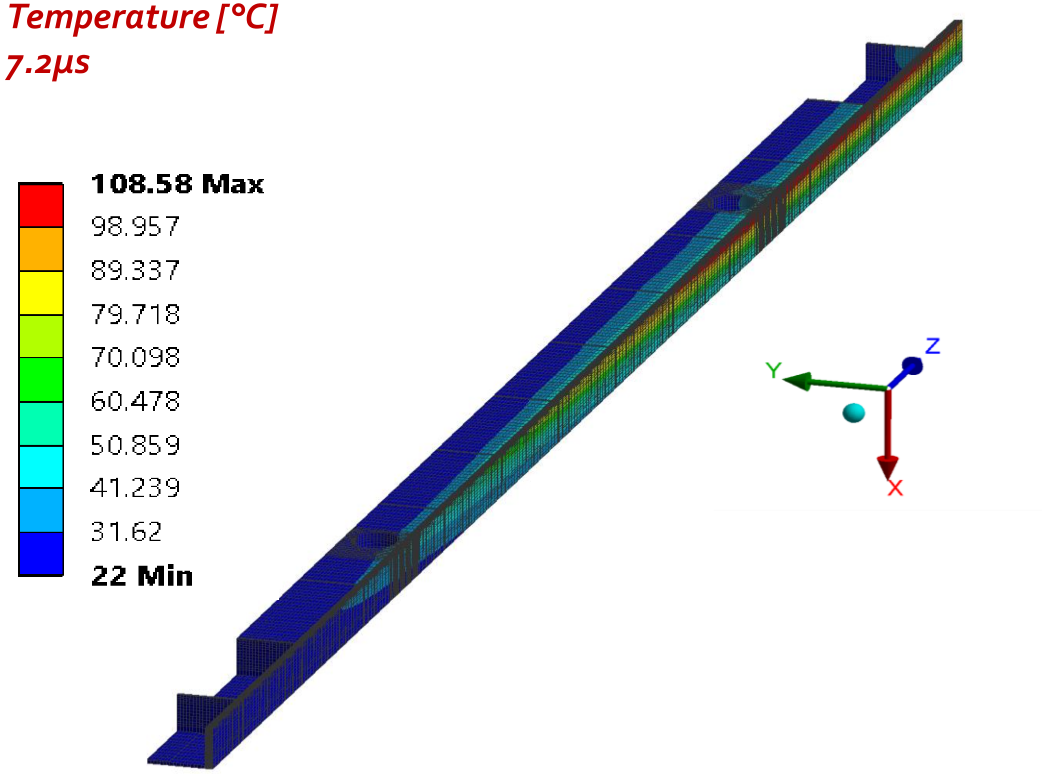
<u>Quasi-static cooling (∝ s):</u> Permanent deformation

Plastic strains ??

Amplitudes ??

Deformations ??
(% 200µm-flatness)

Temperature [°C]
7.2µs



From LIU beam impacting at 6.9mm beam impact parameter

Challenge 2:

- **Coupled Numerical/Experimental approach**

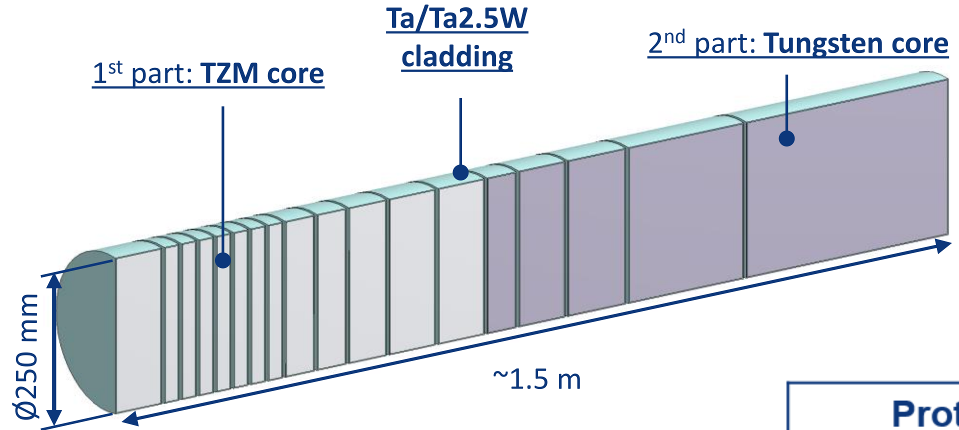
The HRMT44-Experiment to impact a scale one TCDIL-Jaw with representative high-intensity beams and verify that the equipment remains functional

Beam Dump Facility (BDF) target

E. Lopez

Beam Dump Facility: proposed fixed target facility in the **SPS North Area**

BDF Target: Full SPS 400 GeV/c beam absorption → **Target/dump**

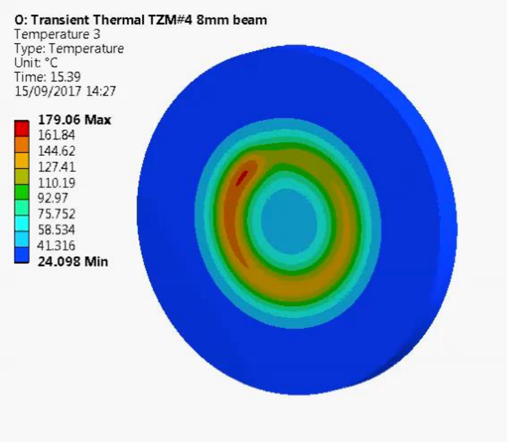


- High power deposition

→ forced water cooling required

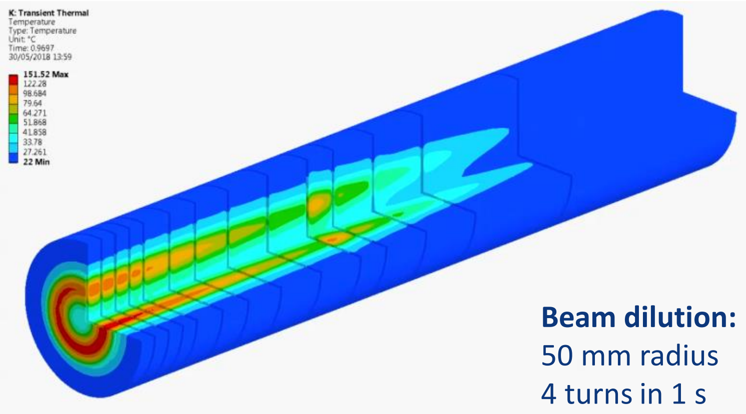
→ 5 mm gap between the blocks

→ **Ta cladding by HIP** to avoid corrosion/erosion effects

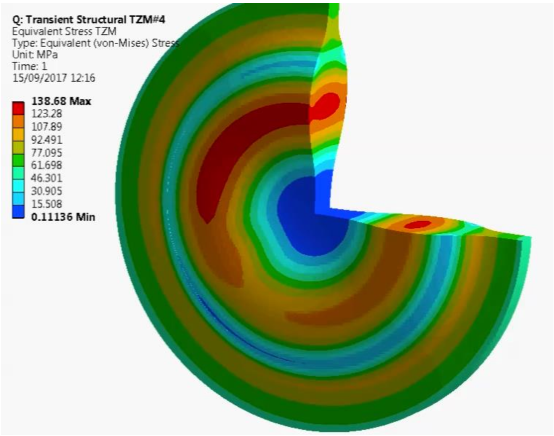


Temperature TZM core

Proton momentum	**400 GeV/c**
Beam intensity	$4.0 \cdot 10^{13}$ p+/cycle
Cycle length	7.2 s
Spill duration **(slow extraction)**	1.0 s
Average beam power deposited on target	**320 kW**
Average beam power on target during spill	2.3 MJ



Beam dilution:
50 mm radius
4 turns in 1 s

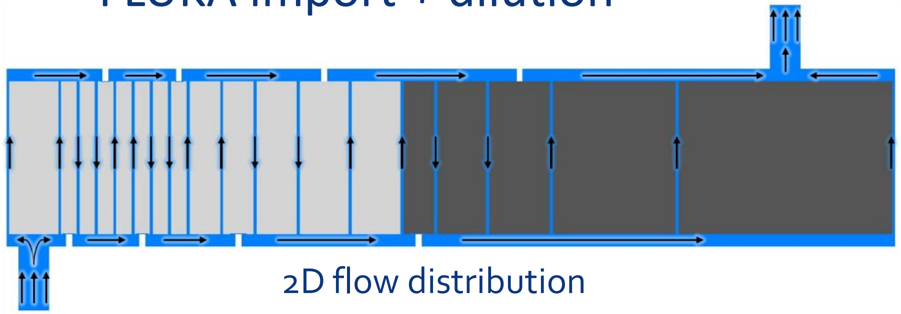


Stress TZM core

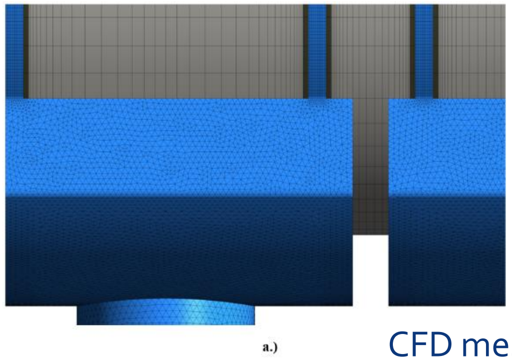
Beam Dump Facility (BDF) target

E. Lopez
M. Pandey

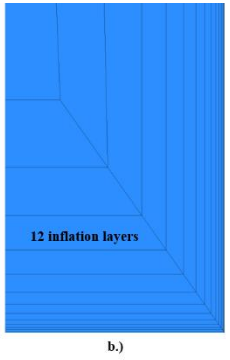
- Accurate modelling of the target cooling system
  - Complex flow distribution (serpentine with 2 parallel channels)
  - Heavy mesh (18M elements)
  - FLUKA import + dilution

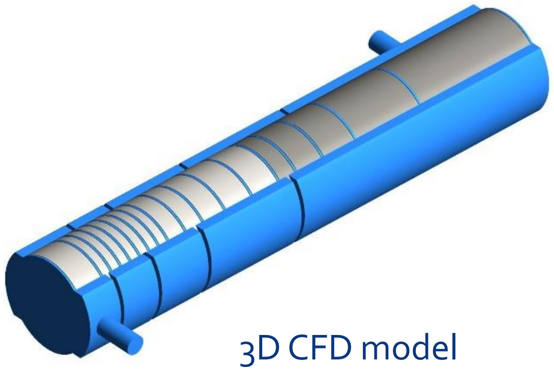


2D flow distribution

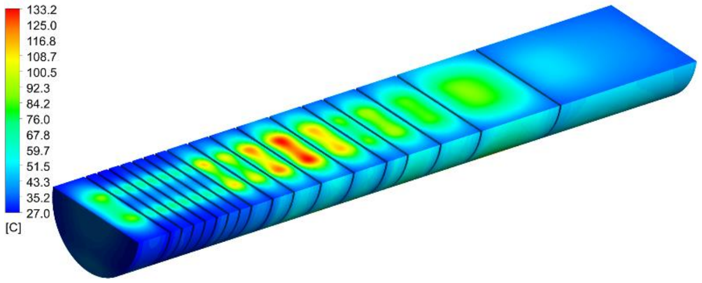


CFD mesh

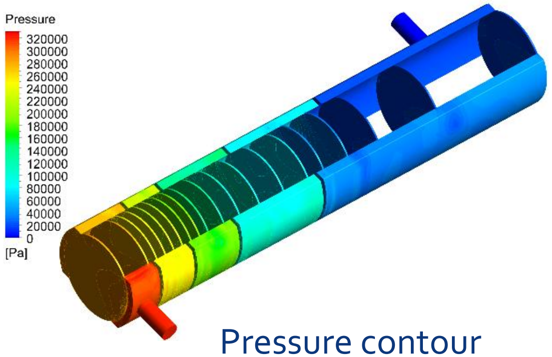




3D CFD model



Temperature distribution



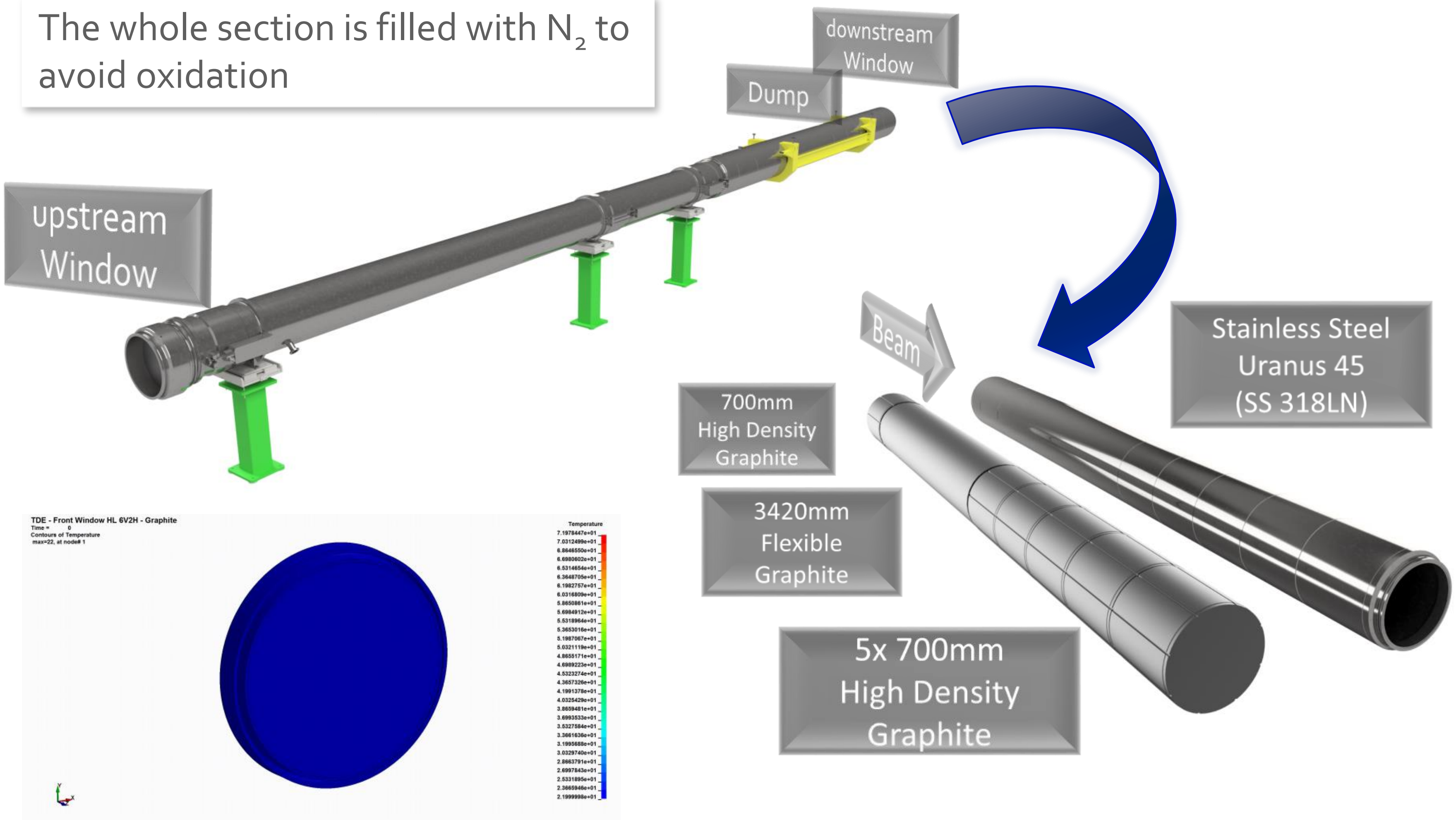
Pressure contour

LHC

TDE (LHC Dump)

T. Polzin

The whole section is filled with N_2 to avoid oxidation



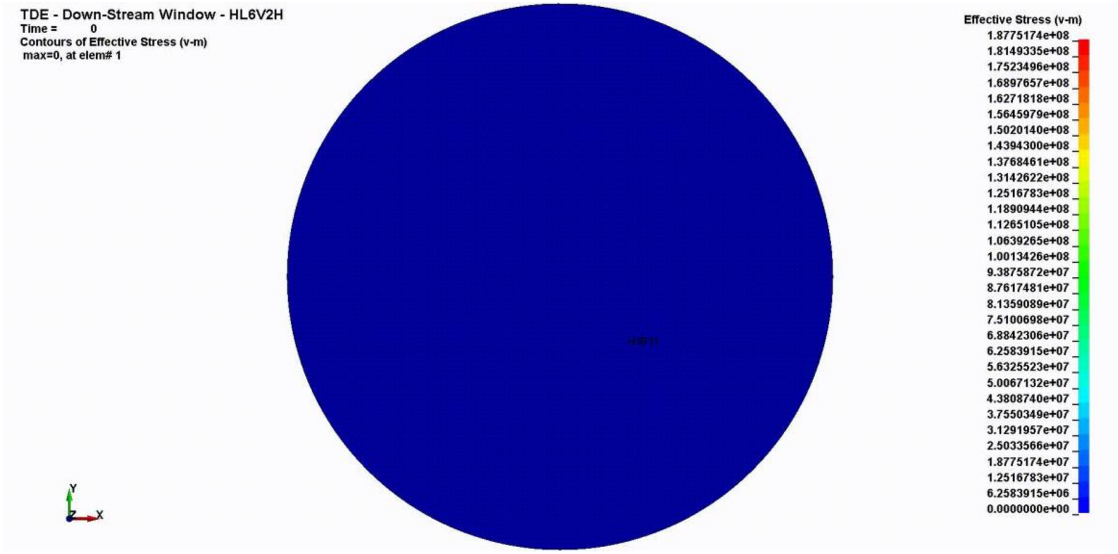
Simulated Temperature in the upstream window

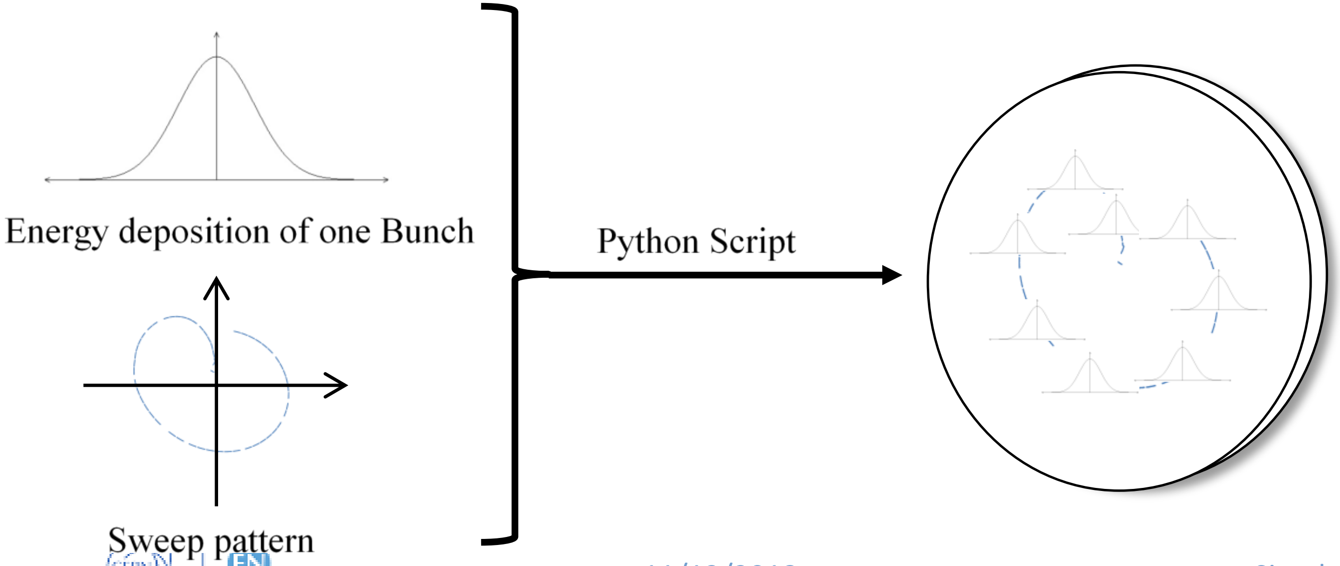
TDE – Downstream Window

T. Polzin

- Window keeps Nitrogen inside
- Material: Titanium Grade 2 with plan to upgrade it to Titanium Grade 5
- It separates the dump core from the **external** environment
- **Beam total intensity** dominates stress generation, due to showers caused by the dump core

- FLUKA simulation for one single bunch
- The FLUKA result is then interpolated on the finite element mesh (python3 with numpy), based on the changing impact location over time (processing of approx. 1E10 data points for around 2800 impact locations in approx. 80E-6s)

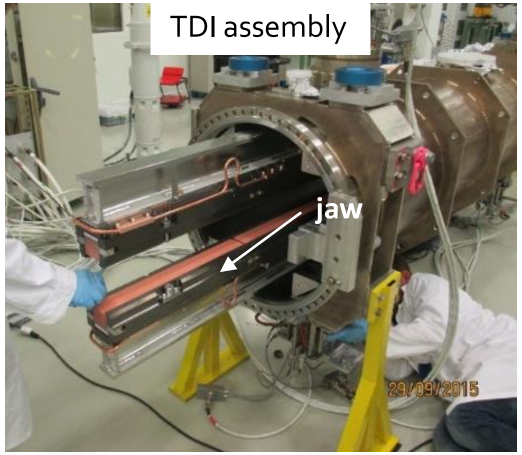




Maximum v. Mises stress	187.8 MPa
Temperature in the peak	145°C
Yield strength at 200°C	140 MPa
Safety factor against yielding	0.74

HRMT-35 (TDI - Coating on Graphite)

J. Maestre
I. Lamas

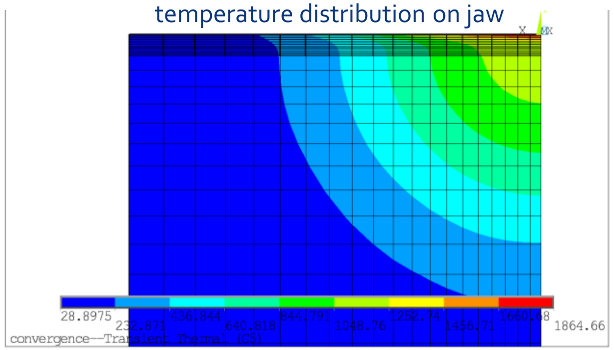


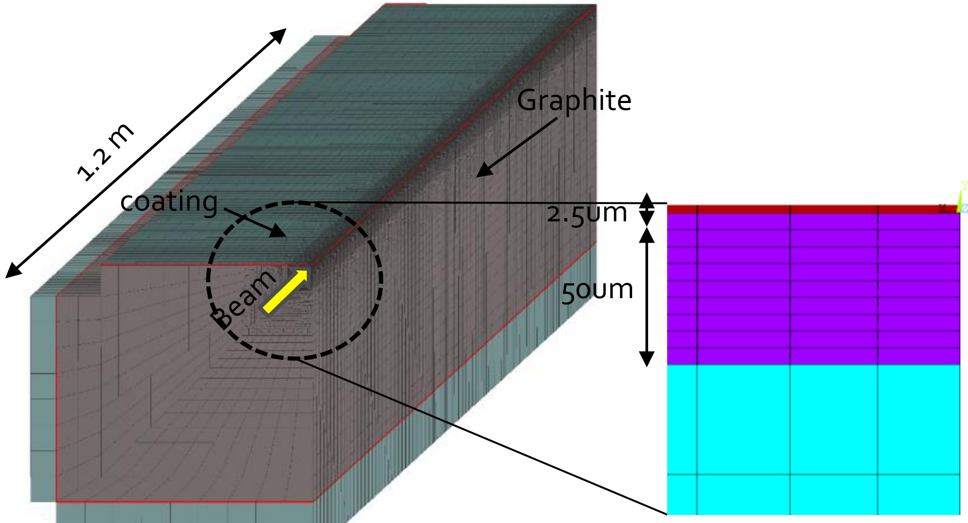
Experimental test on Cu-coated R7550 (SGL) graphite

- The FEM model is divided in several regions: element size is 1/10 σ
- Two different element types : Layered shell for the coating - Solid for the substrate

The LHC Machine Committee (LMC#256) requested to test and validate the performance of the Cu coating under different impact conditions:

- "Deep" impact (stripe 1)
- Grazing impact at 0 σ_y (stripe 2)
- Grazing impact at 0 σ_y with tilted jaw (stripe 3)

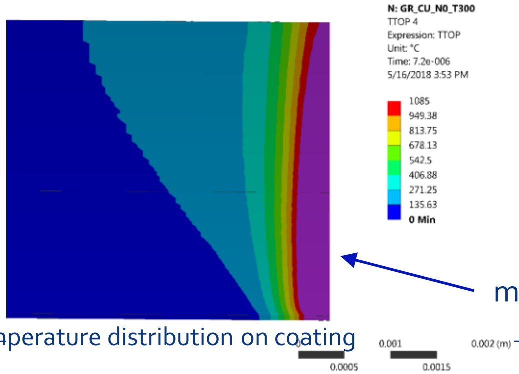




Numerical model

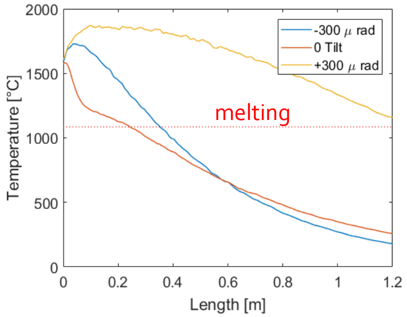
Detail of coating

Number of bunches	288
Bunch time	25 ns
Energy	440 GeV
Intensity	1.20E+11 ppb
Beam distribution	Gaussian
Beam size	$\sigma_x = \sigma_y = 300\ \mu m$



melting

temperature distribution on coating



Longitudinal temperature distribution on coating

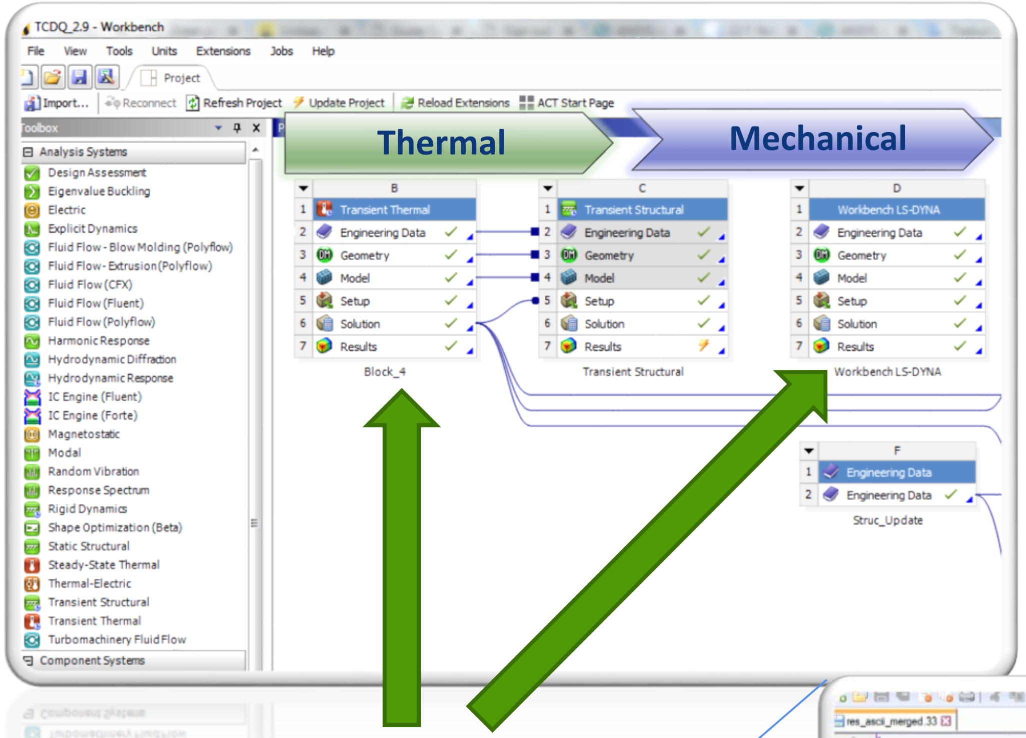
Cross-check with HiRadMat experiments

Overview of HRMT experiments

- **Unknown (non-measured) response of target materials impacted by high intensity & energy proton beams**
  - **HRMT42/48** for antiproton target materials (Ta, Ir, etc.)
  - **HRMT46** for n_TOF spallation target (pure Pb)
  - **HRMT49** for TIDVG5 (polycrystalline Si block)
- **Response to project requirements for uncharted beam intensities (LIU & HL-LHC requirements)**
  - **HRMT28/44** for LIU SPS-to-LHC transfer line collimators (3D CC)
  - **HRMT35** for coated collimators materials (operational-driven)
  - **HRMT45** for HL-LHC injection dump (TDIS)
  - **HRMT18** for crystal collimation
- **Irradiated material R&D**
  - **HRMT24/43** in collaboration with international partners

FLUKA IMPORT PLUG-IN FOR ANSYS WORKBENCH

J. Maestre

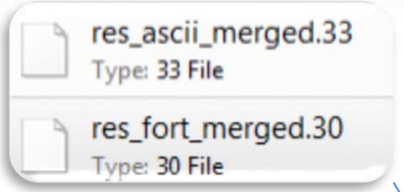


- ☐ FLUKA-ANSYS/LS-DYNA COUPLING IS NOT IMPLEMENTED IN WORKBENCH.
- ☐ APDL COMMANDS ARE REQUIRED TO IMPORT FLUKA DATA.

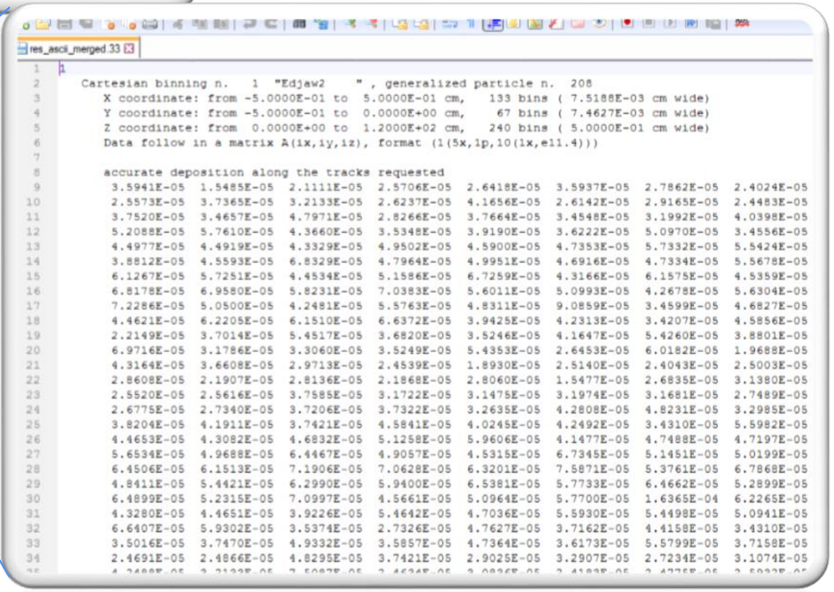
FLUKA PLUG-IN HELPS IMPORTING FLUKA DATA

- Manage the Fluka data as a standard load
- View of the energy deposition directly on your model (on the fly)
- Check the peak/total energy
- Compare the Fluka data with your model
- For steady state and transient simulation considering movable FLUKA deposition.
- ....

FLUKA files


res_ascii_merged.33
Type: 33 File
res_fort_merged.30
Type: 30 File

BINARY FILES CANNOT BE OPEN WITH A TEXT EDITOR



```
1
    Cartesian binning n.   1  "Edjaw2     " , generalized particle n.  208
      X coordinate: from -5.0000E-01 to  5.0000E-01 cm,   133 bins ( 7.5188E-03 cm wide)
      Y coordinate: from -5.0000E-01 to  0.0000E+00 cm,    67 bins ( 7.4627E-03 cm wide)
      Z coordinate: from  0.0000E+00 to  1.2000E+02 cm,   240 bins ( 5.0000E-01 cm wide)
      Data follow in a matrix A(ix,iy,iz), format (1(5x,1p,10(1x,e11.4)))

      accurate deposition along the tracks requested
       3.5941E-05  1.5485E-05  2.1111E-05  2.5706E-05  2.6418E-05  3.5937E-05  2.7862E-05  2.4024E-05
       2.5573E-05  3.7365E-05  3.2133E-05  2.6237E-05  4.1656E-05  2.6142E-05  2.9165E-05  2.4483E-05
       3.7520E-05  3.4657E-05  4.7971E-05  2.8266E-05  3.7664E-05  3.4548E-05  3.1992E-05  4.0398E-05
       5.2088E-05  5.7610E-05  4.3660E-05  3.5348E-05  3.9190E-05  3.6222E-05  5.0970E-05  3.4556E-05
       4.4977E-05  4.4919E-05  4.3329E-05  4.9502E-05  4.5900E-05  4.7353E-05  5.7332E-05  5.5424E-05
       3.8812E-05  4.5593E-05  6.8329E-05  4.7964E-05  4.9951E-05  4.6916E-05  4.7334E-05  5.5678E-05
       6.1267E-05  5.7251E-05  4.4534E-05  5.1586E-05  6.7259E-05  4.3166E-05  6.1575E-05  4.5359E-05
       6.8178E-05  6.9580E-05  5.8231E-05  7.0383E-05  5.6011E-05  5.0993E-05  4.2678E-05  5.6304E-05
       7.2286E-05  5.0500E-05  4.2481E-05  5.5763E-05  4.8311E-05  9.0859E-05  3.4599E-05  4.6827E-05
       4.4621E-05  6.2205E-05  6.1510E-05  6.6372E-05  3.9425E-05  4.2313E-05  3.4207E-05  4.5856E-05
       2.2149E-05  3.7014E-05  5.4517E-05  3.6820E-05  3.5246E-05  4.1647E-05  5.4260E-05  3.8801E-05
       6.9716E-05  3.1786E-05  3.3060E-05  3.5249E-05  5.4353E-05  2.6453E-05  6.0182E-05  1.9688E-05
       4.3164E-05  3.6608E-05  2.9713E-05  2.4539E-05  1.8930E-05  2.5140E-05  2.4043E-05  2.5003E-05
       2.8608E-05  2.1907E-05  2.8136E-05  2.1868E-05  2.8060E-05  1.5477E-05  2.6835E-05  3.1380E-05
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       2.6775E-05  2.7340E-05  3.7206E-05  3.7322E-05  3.2635E-05  4.2808E-05  4.8231E-05  3.2985E-05
       3.8204E-05  4.1911E-05  3.7421E-05  4.5841E-05  4.0245E-05  4.2492E-05  3.4310E-05  5.5982E-05
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       5.6534E-05  4.9688E-05  6.4467E-05  4.9057E-05  4.5315E-05  6.7345E-05  5.1451E-05  5.0199E-05
       6.4506E-05  6.1513E-05  7.1906E-05  7.0628E-05  6.3201E-05  7.5871E-05  5.3761E-05  6.7868E-05
       4.8411E-05  5.4421E-05  6.2990E-05  5.9400E-05  6.5381E-05  5.7733E-05  6.4662E-05  5.2899E-05
       6.4899E-05  5.2315E-05  7.0997E-05  4.5661E-05  5.0964E-05  5.7700E-05  1.6365E-04  6.2265E-05
       4.3280E-05  4.4651E-05  3.9226E-05  5.4642E-05  4.7036E-05  5.5930E-05  5.4498E-05  5.0941E-05
       6.6407E-05  5.9302E-05  3.5374E-05  2.7326E-05  4.7627E-05  3.7162E-05  4.4158E-05  3.4310E-05
       3.5016E-05  3.7470E-05  4.9332E-05  3.5857E-05  4.7364E-05  3.6173E-05  5.5799E-05  3.7158E-05
       2.4691E-05  2.4866E-05  4.8295E-05  3.7421E-05  2.9025E-05  3.2907E-05  2.7234E-05  3.1074E-05
```
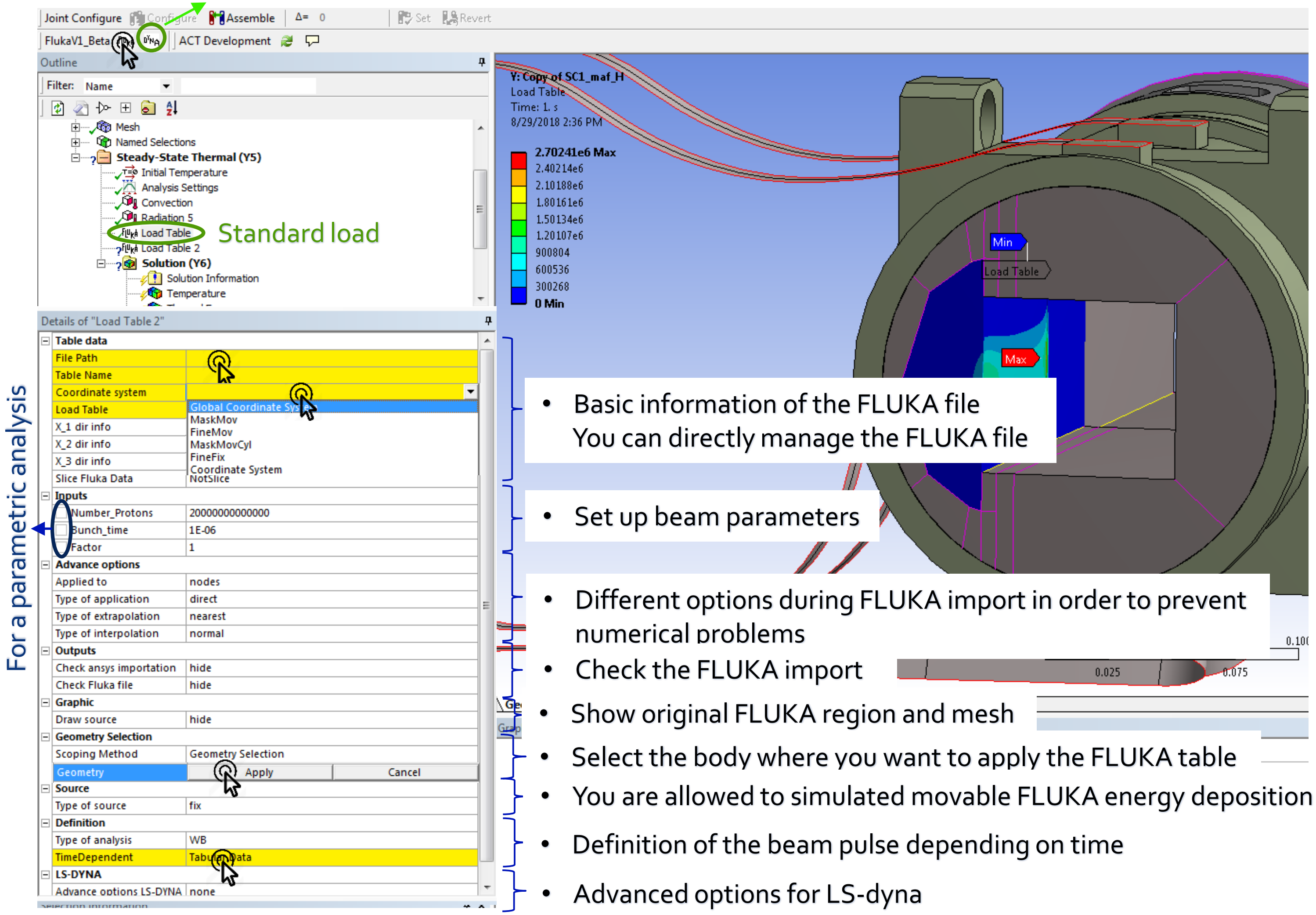

J. Maestre

HOW IT WORKS → IT IS LIKE A STANDARD LOAD…JUST CLICK ON THE BUTTON



New tool for LS-Dyna

Standard load

For a parametric analysis

Details of "Load Table 2"

Table data	
File Path	
Table Name	
Coordinate system	
Load Table	
X_1 dir info	
X_2 dir info	
X_3 dir info	
Slice Fluka Data	NotSlice
Inputs	
☐ Number_Protons	20000000000000
☐ Bunch_time	1E-06
☐ Factor	1
Advance options	
Applied to	nodes
Type of application	direct
Type of extrapolation	nearest
Type of interpolation	normal
Outputs	
Check ansys importation	hide
Check Fluka file	hide
Graphic	
Draw source	hide
Geometry Selection	
Scoping Method	Geometry Selection
Geometry	Apply Cancel
Source	
Type of source	fix
Definition	
Type of analysis	WB
TimeDependent	Tabular Data
LS-DYNA	
Advance options LS-DYNA	none

- Basic information of the FLUKA file
  You can directly manage the FLUKA file
- Set up beam parameters
- Different options during FLUKA import in order to prevent numerical problems
- Check the FLUKA import
- Show original FLUKA region and mesh
- Select the body where you want to apply the FLUKA table
- You are allowed to simulated movable FLUKA energy deposition
- Definition of the beam pulse depending on time
- Advanced options for LS-dyna

- ✓ Everything is done in an interactive way and you can see the results on fly
- ✓ The imported data is automatically checked
- ✓ The import is adapted to the FEM mesh automatically
- ✓ When you use the cluster, the FLUKA data is included in the APDL file automatically

J. Maestre

Thanks for your attention.