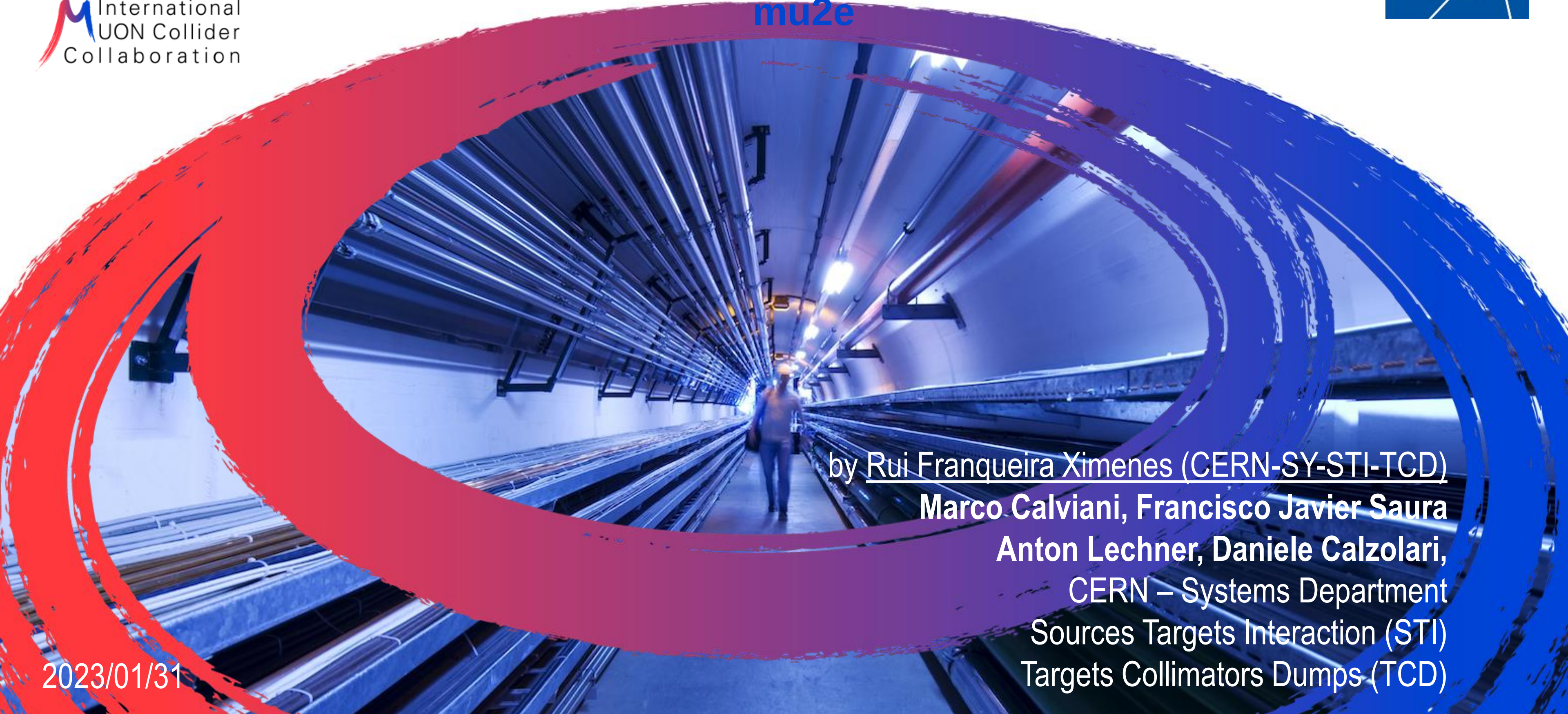
MuC Target Design Overview

Discussion of shared targetry needs between MuCol and mu2e



by Rui Franqueira Ximenes (CERN-SY-STI-TCD)

Marco Calviani, Francisco Javier Saura

Anton Lechner, Daniele Calzolari,

CERN – Systems Department

Sources Targets Interaction (STI)

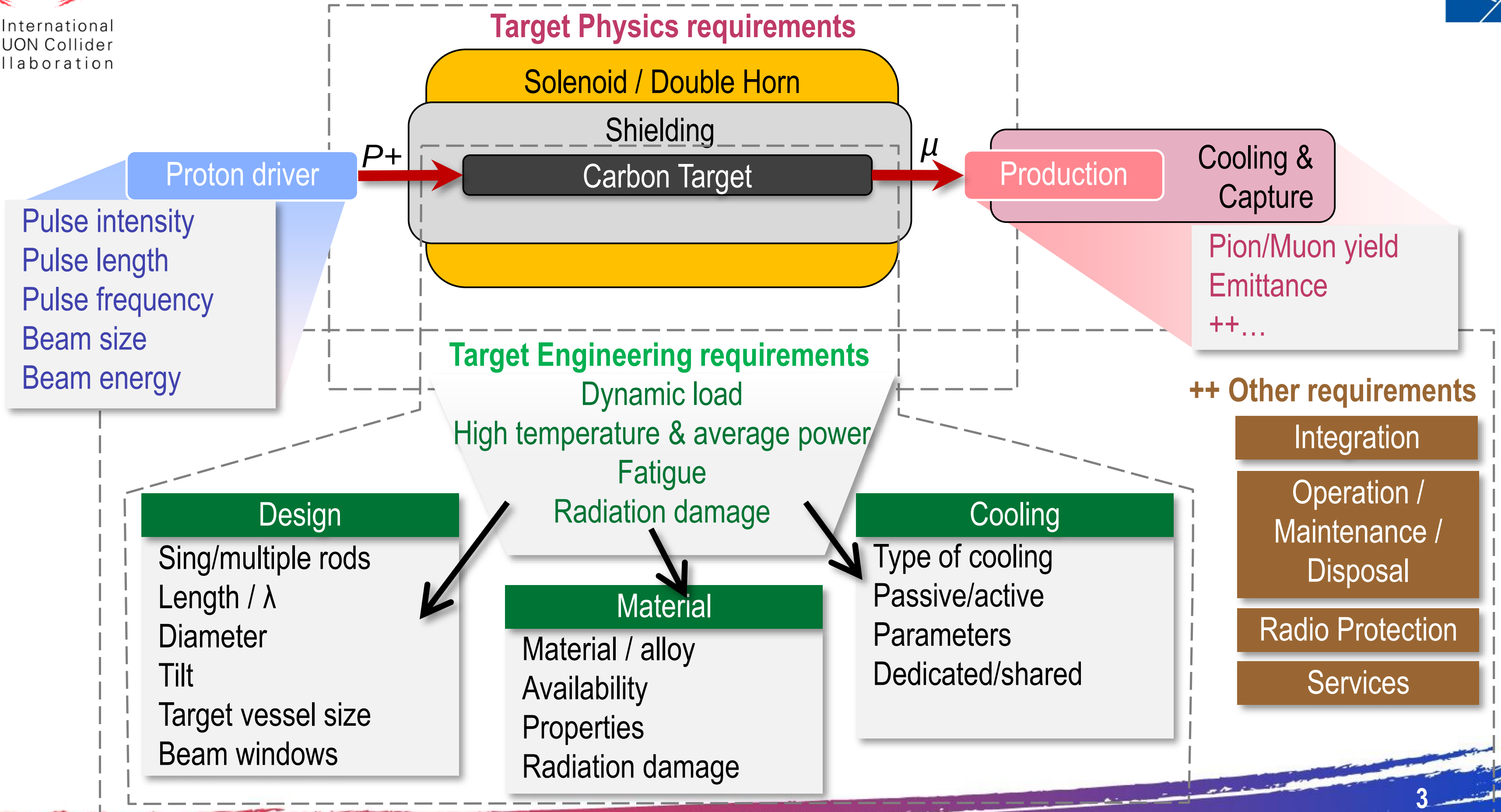
Targets Collimators Dumps (TCD)

2023/01/31

Outline

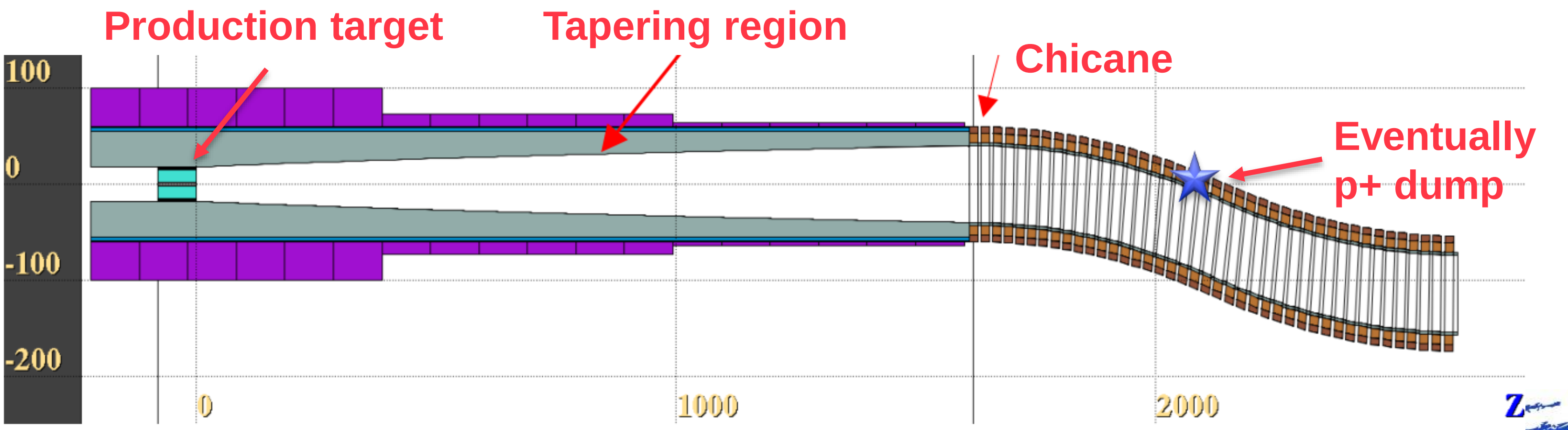
- Carbon target & target systems considerations
- Design overview
- Carbon Target & shielding feasibility studies
- HLM Target - a possibility
- Final remarks

Carbon target & target systems considerations

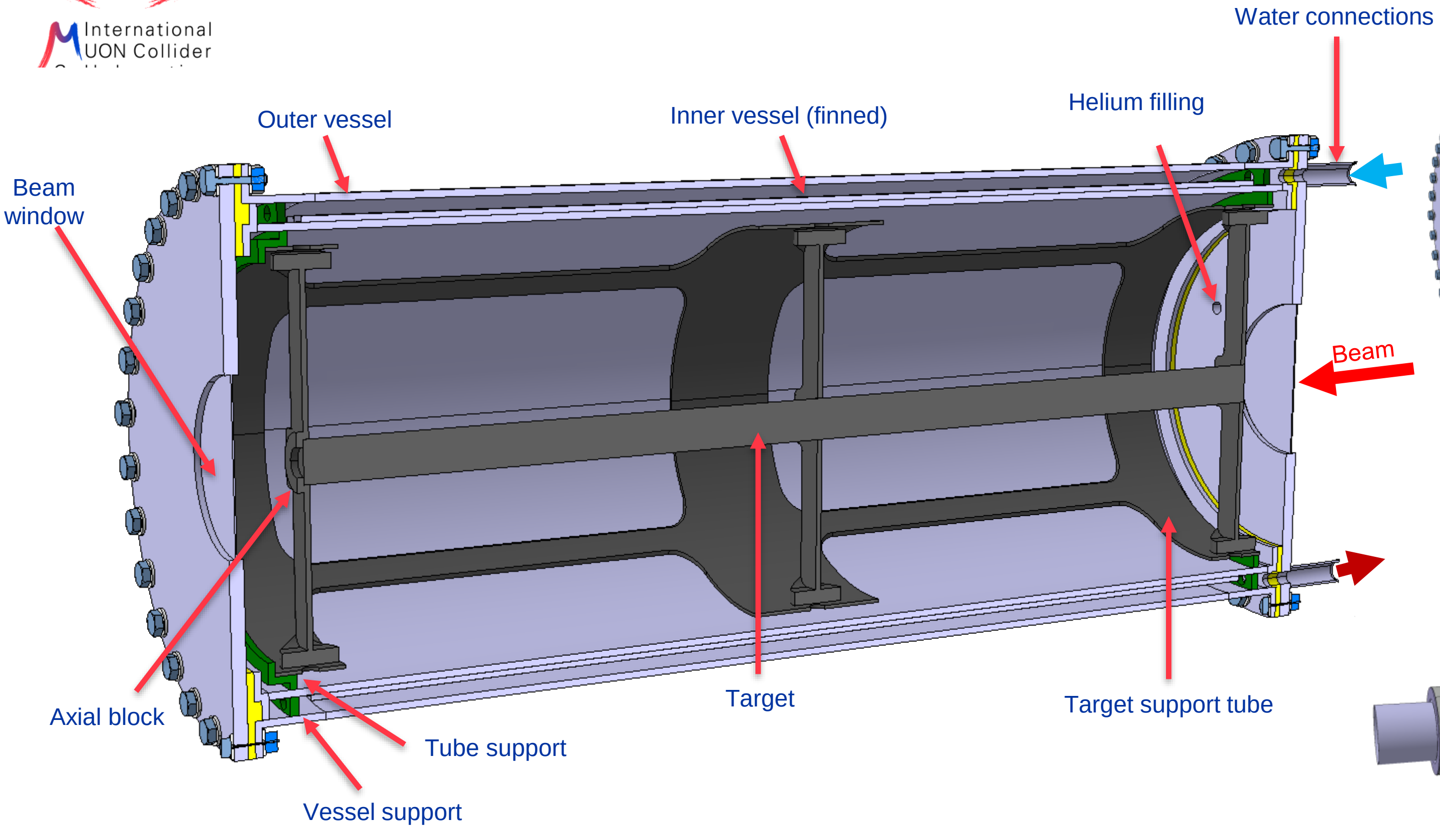


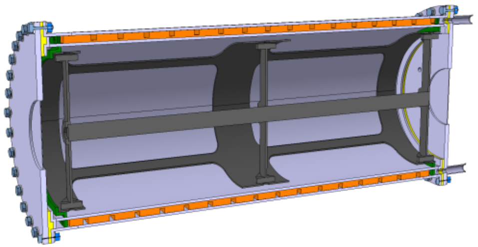
Carbon target & target systems considerations

- Energy deposition/dpa studies on the Target, windows, shielding, magnets, chicane
- Parameterization study / optimization of beam parameters
- (Conceptual) Engineering study of Target & Target Systems, shielding, p+ dump -> feasibility
- ++ iteration loops with p+ driver, magnets, cooling

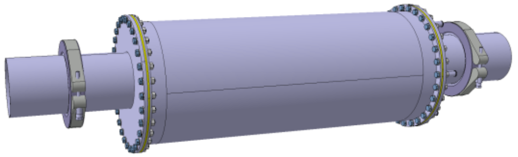


Carbon target concept



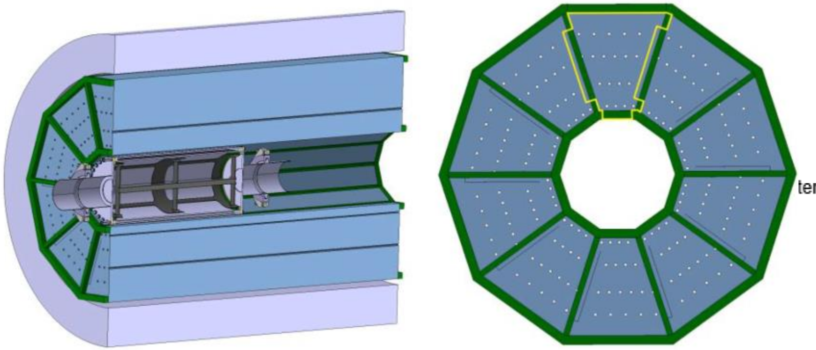


Serpentine cooling version



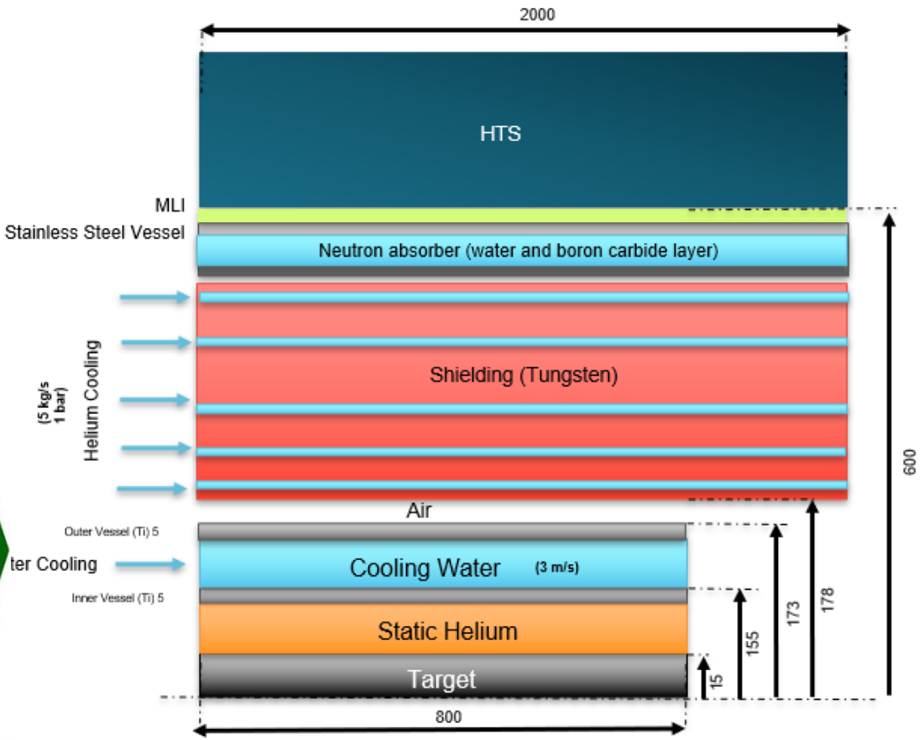
Carbon target concept

- C-Target in static helium
- Water cooled Ti vessel
- Helium (gas) cooled W shielding
- Moderator & neutron absorber at outer radius with water & Boron carbide



Conceptual shielding design

Target & shielding schematic (not at scale)



Carbon Target: engineering feasibility

International MUON Collider Collaboration

Carbon Target

Study considerations

- Simple C-rod (L800 mm, 1.79 nuclear inelastic scattering lengths)
- Beam energy (5 GeV), bunch length (2ns) and average beam power (1.5 – 3 MW)

↓

- Sensitivity study: thermal behavior as a function of beam sigma and frequency
- Studied cooling concepts:
  - Only radiation cooling
  - Natural convection + radiation cooling
  - Forced convection cooling
- Structural calculation

→ How much do we gain by playing with these beam parameters?

→ How can we cool it?

→ Does it 'survive'?

Note: Not coupled with any pion-muon physics optimization → purely thermo-mechanical feasibility assessment.

Carbon Target: engineering feasibility

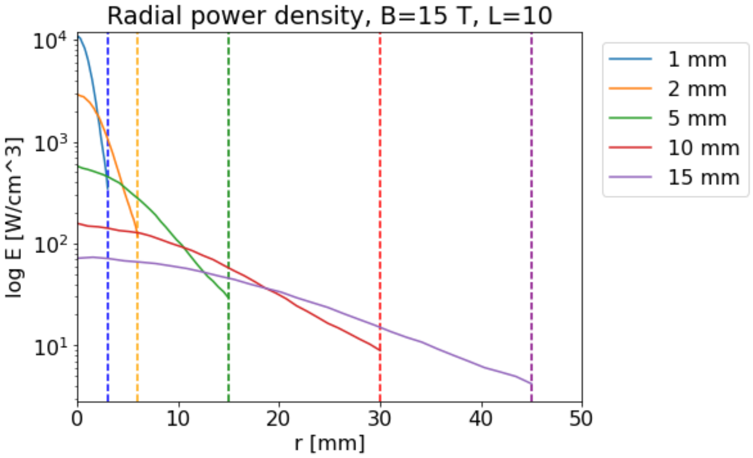
International MUON Collider Collaboration

Carbon Target

*Maximum temperature and power deposition for **1.5 MW** as function of the beam sigma.*

Considering only radiative heat dissipation

Tpeak (°C)	Transient				Steady state	Power deposited
σ_{beam} (mm)	5 Hz	10 Hz	20 Hz	50 Hz	Average	(W)
1	4301	3908	3735	3641	3583	44832
2	3318	3221	3177	3152	3135	59000
5	2740	2721	2713	2708	2704	90632
10	2305	2297	2293	2290	2288	129207
15	1947	1943	1940	1938	1938	163214



- Beam size is driving parameter of target temperature (for a given average power)
- However, larger target D increases cooling requirements (for a given Radius – beam σ ratio)
- Pulse frequency (thus pulse intensity) driving parameter for thermal gradient and consequently dynamic stress of the target.
- **Beam sizes of >5mm (1σ) recommended (on a thermal perspective. +info later)**

Carbon Target: engineering feasibility

Direct cooling considerations

Temperature (°C)	sigma 5/5Hz – 1.5MW	
Only radiation	T max	2801
	T max surf	2240
Radiation + natural convection	T max	2768
	T max surf	2207
Radiation +Forced convection (He, 20 bar, 0.1 kg/s)	T max	573
	T max surf	278

*Maximum temperature and power deposition for **1.5 MW** as function of the beam sigma.*

T peak (°C)	Transient				Steady state	Power deposited
σ_{beam} (mm)	5 Hz	10 Hz	20 Hz	50 Hz	Average	(W)
1	4301	3908	3735	3641	3583	44832
2	331[illegible]	3221	3177	3152	3135	59000
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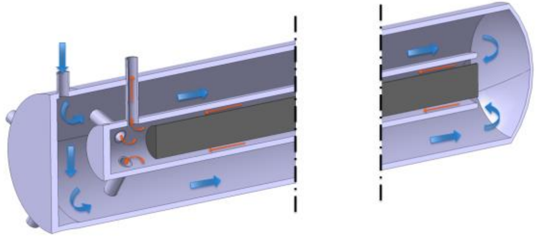
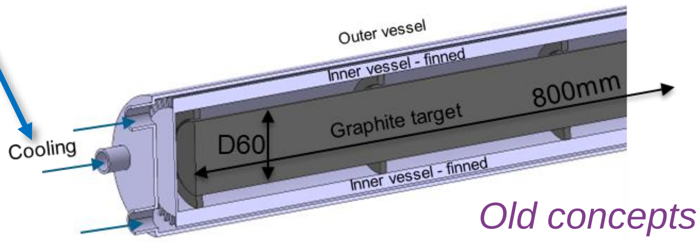


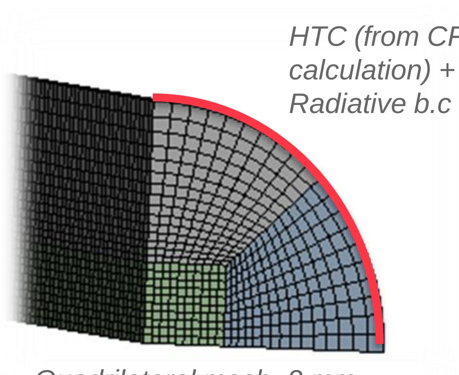


Old concepts

Target Cooling

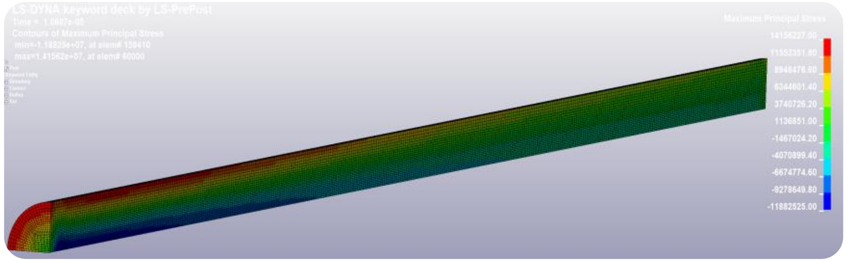
- Due to high T and sublimation of graphite, an enclosed ‘pressurized’ atmosphere is required.
- However, active cooling can be made indirectly. Heat dissipation mostly via radiation and natural convection. → target confinement / separation of cooling system is advantageous (maintenance, RP, disposal, cooling services requirements).

Carbon Target: engineering feasibility

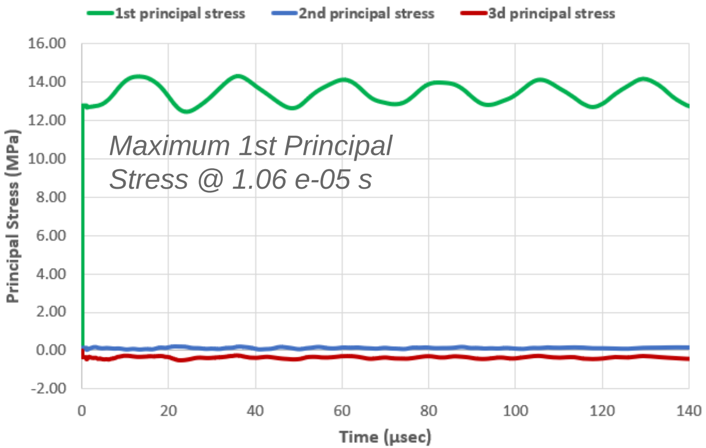


HTC (from CFD calculation) + Radiative b.c

Quadrilateral mesh, 2 mm
160.000 elements
Avg. skewness 0.08



LS Dyna explicit structural simulation with time step resolution of stress waves speed propagation in graphite



Target structural considerations

- 1 single shot @(5GeV,1σ=5mm,5Hz,1.5MW)
  - Max energy density = 95 J/g/pulse
- No showstopper in the structural point of view.
- Considered parameters results in a similar dynamic load as the CNGS target ⟶ Future dismantling/PIE to provide important data.

Carbon Target: engineering feasibility

International MUON Collider Collaboration

Carbon Target

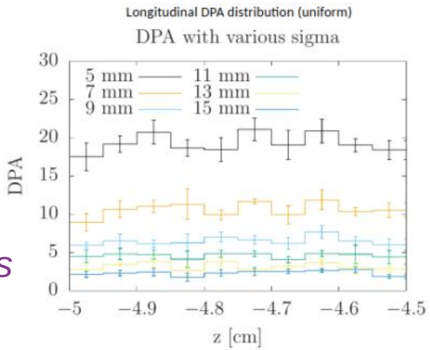
For these beam parameters, C-Target seems feasible.

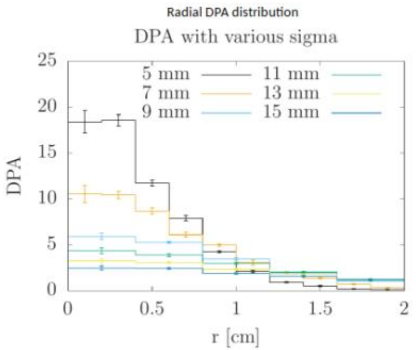
However:

- **Fatigue**: extensive load cycles to be experienced by the target (10^8 /y) at very high temperature.
- **DPA**: >1 dpa levels on the beam windows. Strategy to be defined. E.g. windowless, blown-up beam somewhere upstream, rotating window “dilution”, frequent window exchange.
- **Beam power** > 2 MW or more

stringent beam parameters

DPA on windows for 1 MW





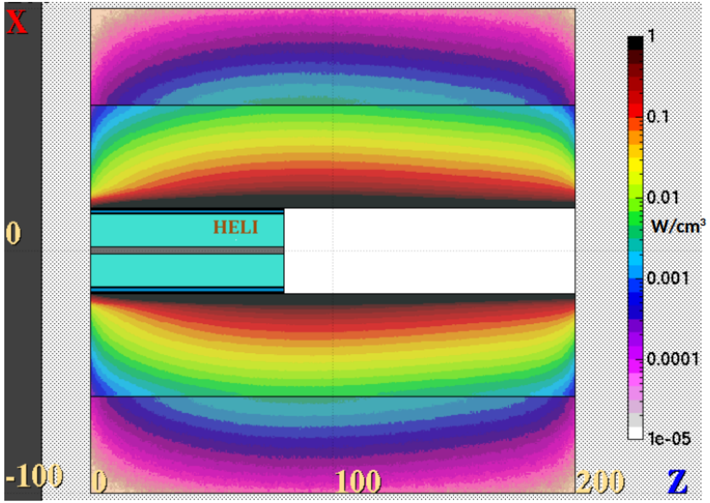
@ Daniele Calzolari / Anton Lechner

Target shielding

Energy deposition

- The energy deposited on the target is only 5.5 % (D30xL800 mm) of the total beam power
- Most of the thermal energy is deposited on the shielding (35.3 %).

Parameter	Thermal power	% of Beam Power
Shielding	**530 kW**	**35.3 %**
Target	**84 kW**	**5.5 %**
Al Vessel	11 kW	0.7 %
Water	8 kW	0.5 %
Helium	~0 kW	~0 %
TOTAL	~634 kW	~42 %

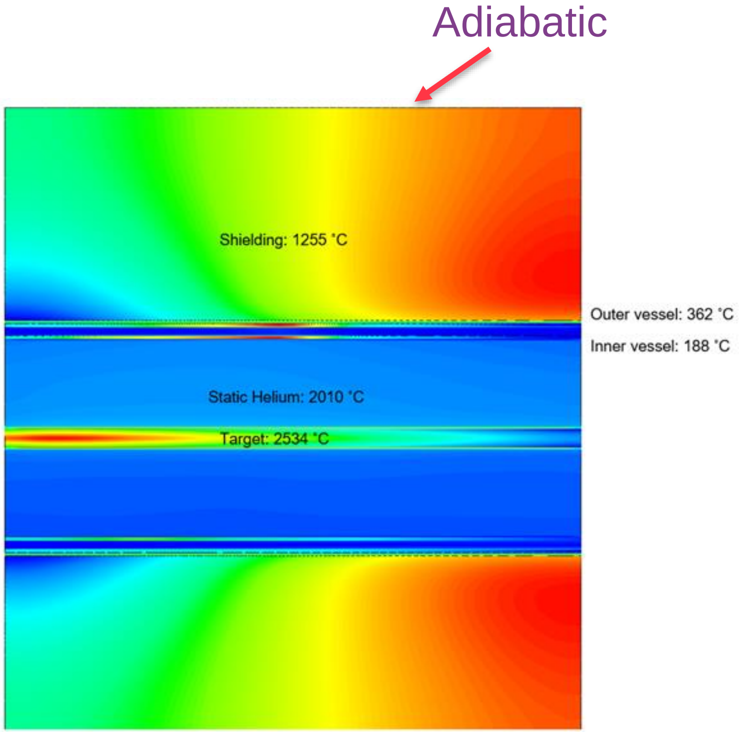


Power deposition provided by Daniele Calzolari SY-STI-BMI
https://indico.cern.ch/event/1176034/contributions/4939053

Target shielding: no cooling

Shielding not cooled

- Despite thermally possible, it would be far from conceivable with a SC Solenoid in the surroundings
- Shared shielding-target water cooling circuit would be very challenging
- Large target vessel is mostly to reduce temperature in the vessel – to be fined tune.



Target shielding: water cooled

Shielding water cooled

- **Cooling of the shielding is required but not a showstopper**

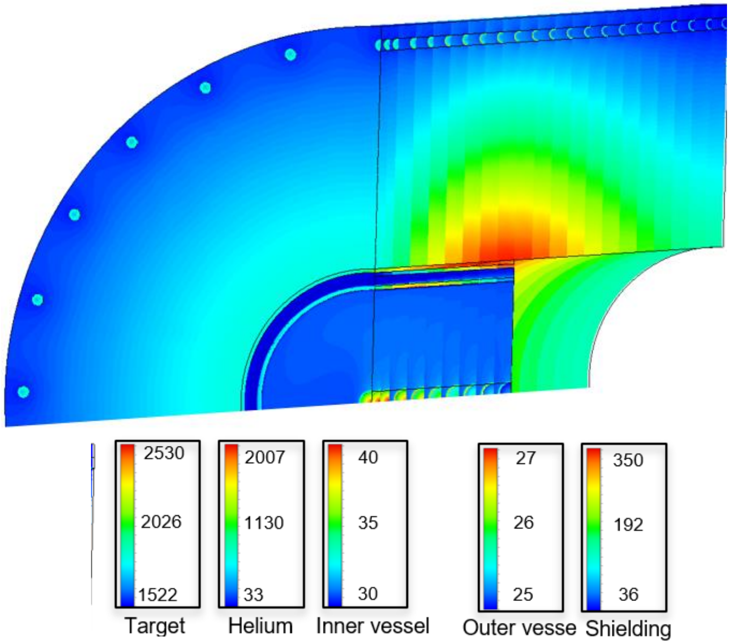
Example of reasonable parameters:

Shielding

- Cooling: 26 pipes w/ RT water @ 3m/s
- max T = 350 °C
- External max T = 80 °C

Target

- Cooling: Annular RT water @ 3m/s
- Max T = 2530 °C
- Al vessel max T: of = 40 °C
- He pressure ~1.5 bar

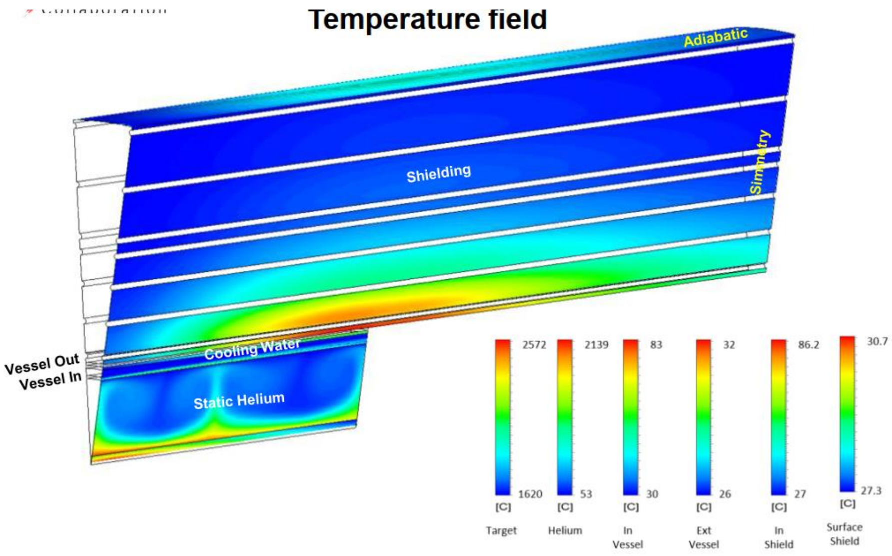


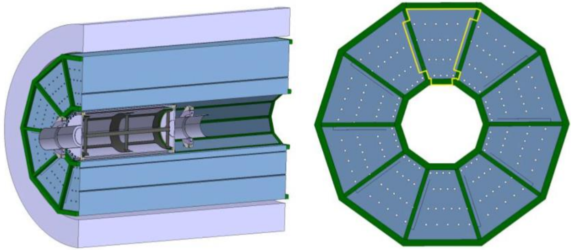
Target shielding: He cooled

Shielding He cooled

Looks feasible (for 2 MW facility):

- He (gas cooled, 5kg/s at 1 bar)
- Conceptual frame with 40 mm square SS profiles
- ➢ Temperatures below 100 °C
- ➢ First structural analysis suggest tensions around 150 Mpa (actually due to constrains from the supporting assembly). This value falls under the yield strength and fatigue limit of W

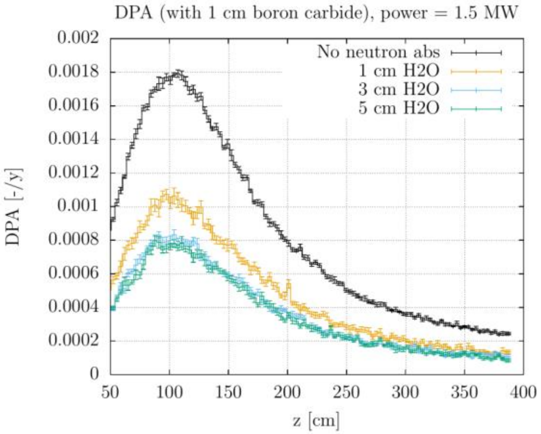


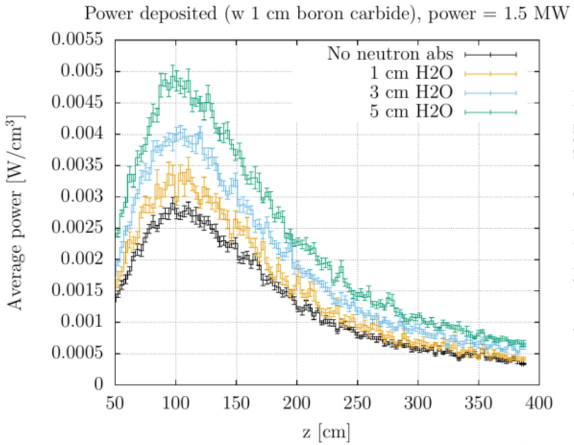


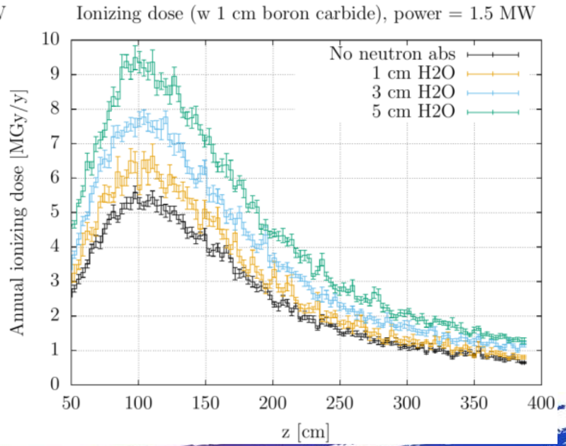
Target shielding: dpa optimization

Possible optimization to reduce radiation damage in HTS coils:

- With neutron absorber, DPA reaches values of 8×10^{-4} DPA after 1 year
- However, due to less W the Ionizing dose increases: >70 MGy after 10 years (3 cm H2O)







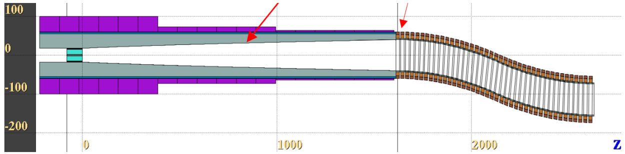
Carbon Target: pion/muon yield parameterization & energy deposition studies

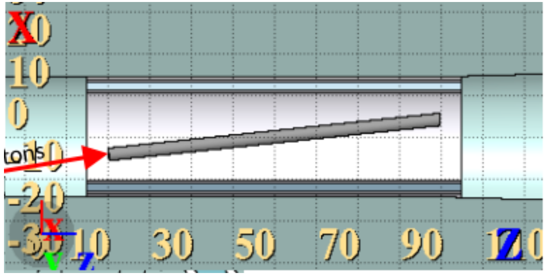
- Energy deposition/ dpa studies until the chicane
- Pion/Muon yield parameterization study as a function of:
  - **Proton energy (3 – 10 GeV)**
  - **Proton beam size (0.5 – 1.4 cm)**
  - **Target diameter (1 – 9 beam sizes)**
  - **Target length (50 – 150cm)**
  - **Target angle with the solenoid axis (0 – 6deg)**
  - **Shielding aperture (r 7 – 19 cm)**

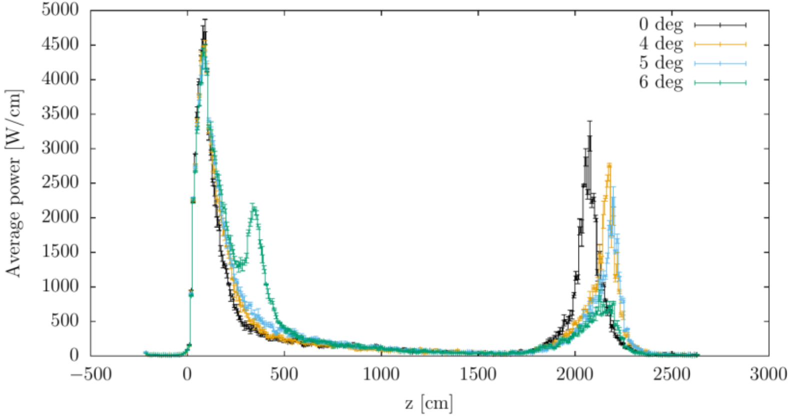
by Daniele Calzolari and Anton Lechner
https://indico.cern.ch/event/1237101/contributions/5204412/attachments/2575066/4440149/angle_dpa_updateJan23.pdf

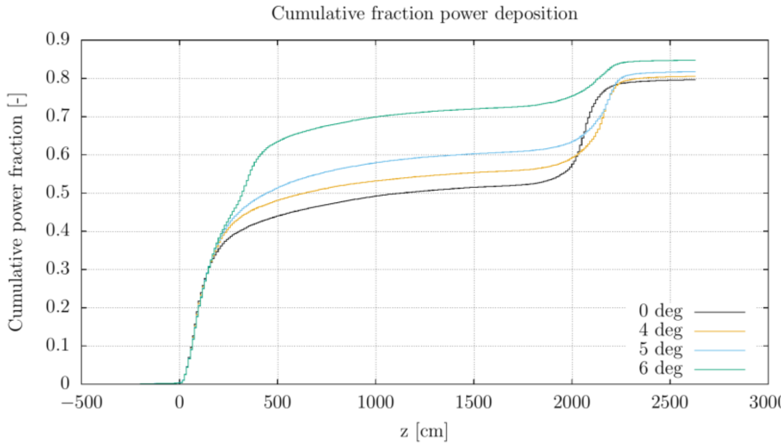
Carbon Target: pion/muon yield parameterization & energy deposition studies

- Energy deposition/ dpa studies





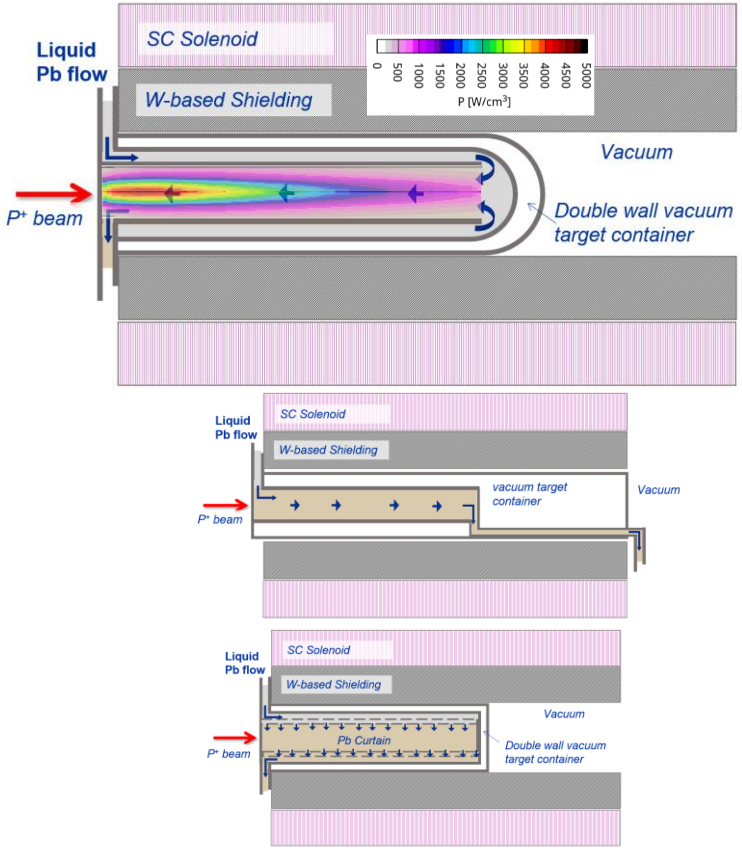




HLM Target - a possibility

Heavy liquid metal target (e.g. Liquid Pb or PbBi):

- Likely allows higher beam power (> 2-3 MW)
- Eventually advantageous in terms of waste disposal (e.g. can be poured into container)
- Low radiation damage
- No need for target cooling services
- Challenging integration & remote handling
- Risk of lead vaporization and/or pressure wave
- Influence in the magnetic field
- Beam windows design challenging (depending on concept (Pb curtain, jet, tubular flow).
- **Ongoing collaboration and assessments between CERN and ENEA (see Carlo Carrelli talk)**



Possible HLM Target concepts

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Collaboration

HLM Target - a possibility

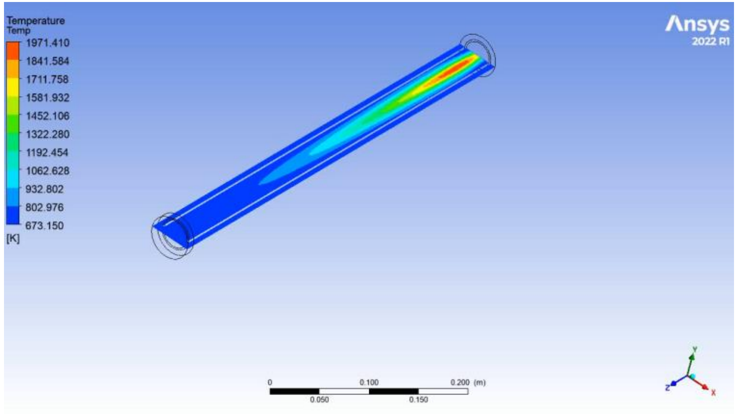
Heavy liquid metal target (e.g. Liquid Pb or PbBi):

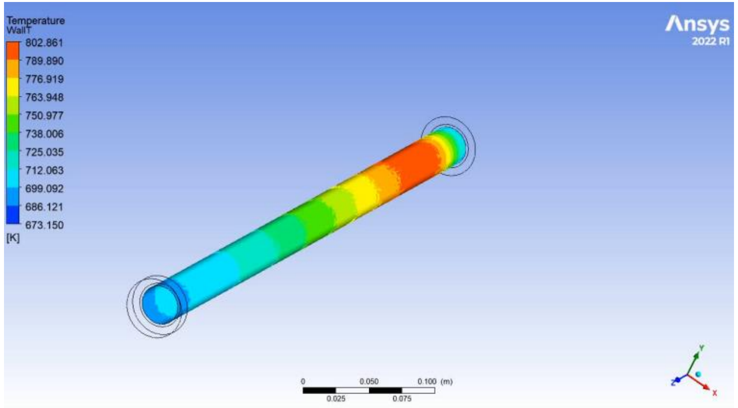
- 2ns every 0.2s, 2 MW beam power
- Target volume: D30 x L509 mm (identical interaction length as C-Target)

<u>First assessment:</u>

- Around 2000K reached in pulse (near boiling T).
- Vessel subjected to intense temperature gradient and values
- Worrying pressure waves and vibrations due to quick lead thermal expansion.
- Beam window gets too hot for common vessel materials

➢ **Different design concept under discussion**





Conclusions

- Interaction between different groups (proton driver, magnets, target, muon cooling, service groups) is key for efficient feasibility studies and optimization.
- Possible to select range of beam parameters compatible with C-Target (both thermally and structurally) but coupling with physics performance is required.
- Fatigue and radiation damage will be a major challenge of a solid target and of the beam windows. Topic to be discussed in the framework of the RaDIATE Collaboration
- Operational experience and lessons learnt from CNGS PIE should strongly support the Muon Collider studies.
- Shielding design highly coupled with Target/solenoid design and with (O)600kW cooling needs. P+ dump to be foreseen and integrated.
- Feasibility of liquid lead target to be further studied (ongoing collaboration between CERN-STI & ENEA) but likely to by an alternative for > 2MW range operation

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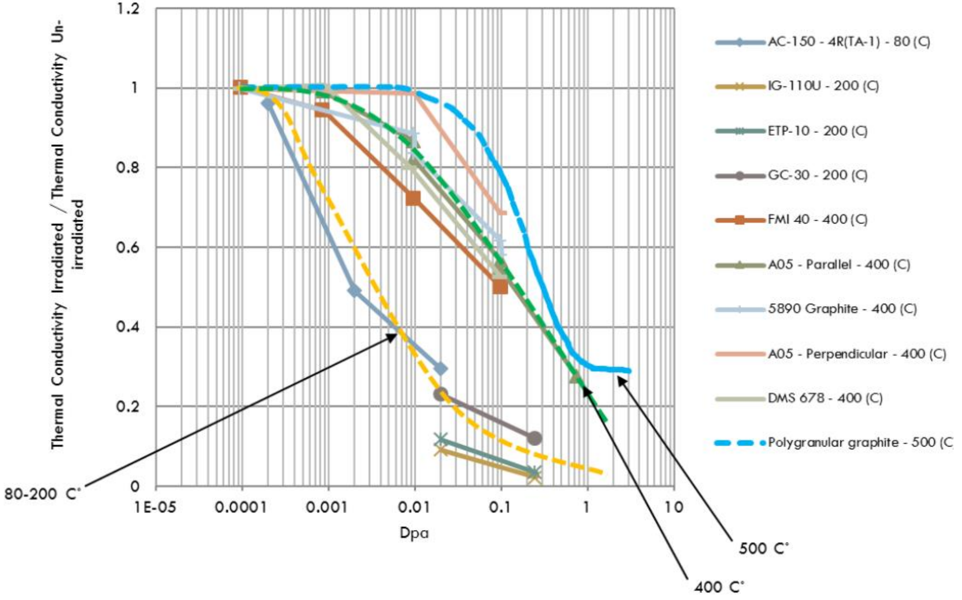
Thank you very much for your attention

T peak (°C)	Transient				Steady state	Power deposited
σ_{beam} (mm)	5 Hz	10 Hz	20 Hz	50 Hz	Average	(W)
1	4301	3908	3735	3641	3583	44832
2	3318	3221	3177	3152	3135	59000
5	2740	2721	2713	2708	2704	90632
10	2305	2297	2293	2290	2288	129207
15	1947	1943	1940	1938	1938	163214

	Max. E. Density				
	Transient (J/cm^3/pulse)				Steady state ($J/cm^3 \cdot s$)
σ_{beam} (mm)	5 Hz	10 Hz	20 Hz	50 Hz	Average
1	3464.36	1732.18	866	346.44	17288
2	933.44	466.72	233.36	93.34	4668
5	173.18	86.59	43.3	17.32	864
10	72.15	36.08	18.04	7.22	361
15	38.19	19.1	9.55	3.82	191



Change of thermal conductivity with DPA and Temperature

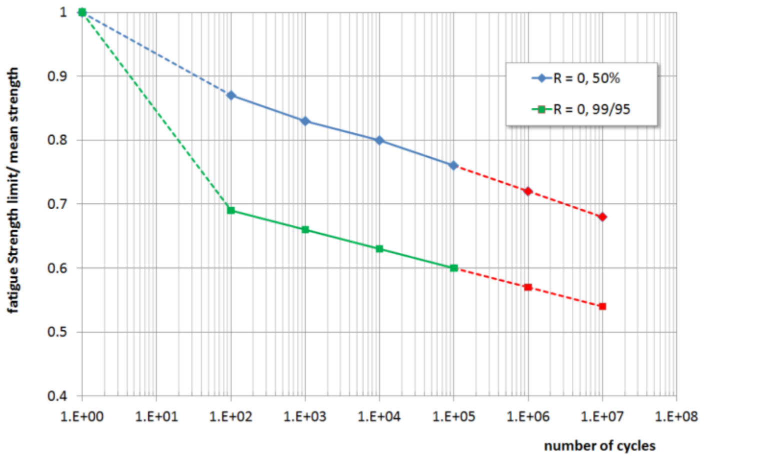
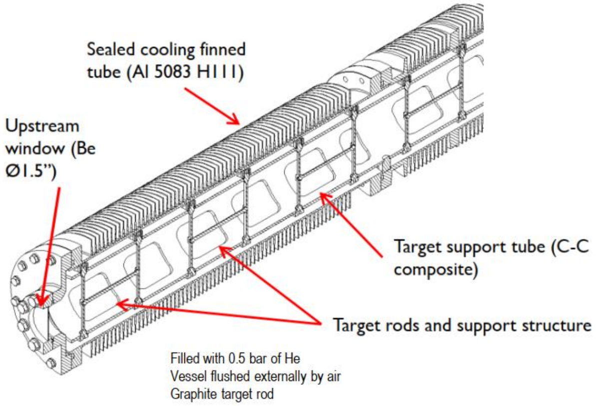


Figure 71 – Uniaxial fatigue strength limits for 2020 graphite, at $R = 0$, in air and at room temperature.

Muon Collider vs CNGS

Muon Collider vs CNGS

Parameter	CNGS Target	MuC Target
Beam energy	400 GeV/c	5 GeV/c
Beam cycle	6 s	0.2 s (5Hz)
Bunch length	2 ns (4σ)	2 ns
Batch length	10.5 us (2100, 5ns spaced bunches)	2 ns
P+/extraction	2.0, 2.4, 3.5 $\times 10^{13}$ (2 extr/cycle 50 msec apart)	3.77 $\times 10^{14}$
Beam size on target (1σ)	0.53 mm	5 mm
Average Power	520 kW (designed for 750 kW)	1.5 MW

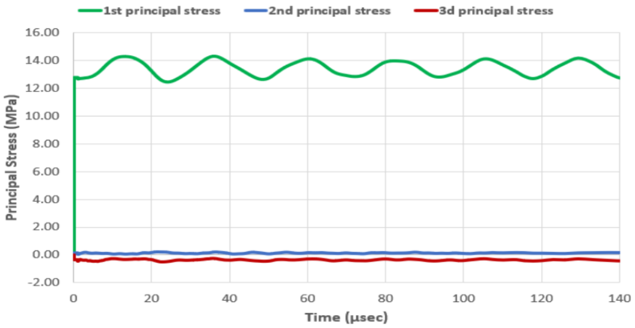


Muon Collider vs CNGS

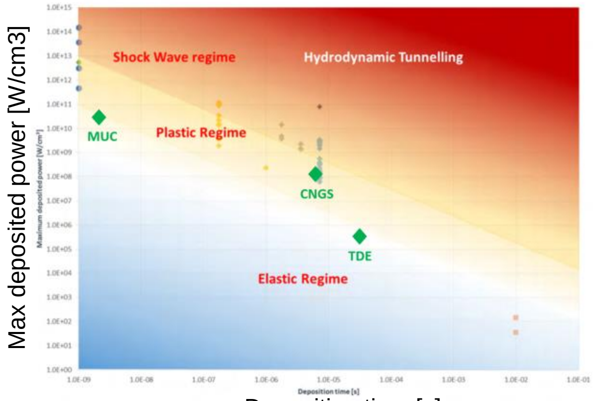
Dynamic response

- Dynamic structural calculations show that the MuC target “instantaneous survivability” seems possible.
- MuC target is likely to stay in an identical dynamic response regime as the CNGS target

- How about long-term effects?



MuC Target @ 5mm (1σ), 5 Hz, 1.5MW



Dynamic regime comparison. *Adapted from A. Bertarelli*

Carbon Target feasibility

Fatigue

- *Literature indicates possible increase in fatigue strength under neutron irradiation (1.9-3.2E20 n/cm2) at 575-650 ˚C (IG110).
- Manufacturing: considerations may play a role. E.g. Higher strength if machined along longitudinal axis.
- Different C-based materials? 3D CC composite are good to prevent crack propagation but inferior in terms of T and radiation damage

MuC Target, amplitude of stress waves is small (2 MPa)

Goodman criteria (Goodman criteria is not suitable, only indicative)

$S_{Ut} = 57\ MPa$

$S_{Uc} = 127\ MPa$

$S_f(10^8 cycles) = 0.5 * 57 MPa = 28.5\ MPa\ (99\%\ Survival)$

$$\frac{\sigma_{alt}}{S_f} + \frac{\sigma_{avg}}{S_u} = \frac{1}{\eta} \rightarrow \eta = 3.85$$

A multiaxial & non-proportional loading suited criteria would be best. → *Sines* or *Dan Van criteria* w/ data of torsional resistance of graphite for 1.0E08 cycles, high T (2500 ˚C) and irradiated can improve estimation.

*Fatigue Failure and Fracture Mechanics of Graphites for Hight Temperature Engineering Testing Reactor

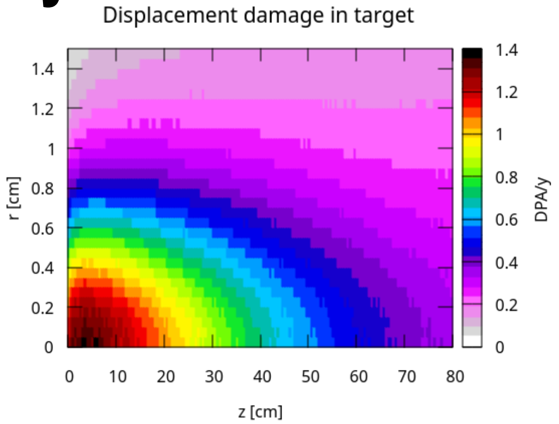
Carbon Target feasibility

Radiation damage

- Example comparing with CNGS

Parameter	CNGS	Muon Colider 1.5MW
Proton fluence [p+/cm^2]	5.77E+22	1.70E+21
PoT	1.27E+20	1.32E+21
Beam size [mm]	0.53	5
Extractions	5.29E+06	5.51E+07
Integrated Op time [days]	**183**	**128**
DPA	**1.5**	

MuC Target DPA normalized for 200days @1MW



- *Literature indicates a lifetime for graphite of 1E21-1E22 p+/cm2
- Radiation induced creep
- Radiation swelling
- Thermal conductivity loss (from 0.01 DPA, but loss is reduced with increased T)
- Thermal diffusivity loss
- Increase of stiffness and mechanical strength
- High temperature may help recovering damage
- Increase of fatigue resistance

❖ **Radiation damage may drive target life (target replacement)**

**Radiation damage study of graphite and carbon-carbon composite target materials*

Beam windows

Beam windows

- Activities discussed in the framework of RaDIATE Collaboration
- Preliminary energy deposition studies show very high DPA/y in the Muon Collider p+ beam windows.
  - + info in Daniele Calzolari's talk https://indico.cern.ch/event/1175126/contributions/5055295/
- **Will be a critical point in the design of the target**.
- Engineering studies will follow