Beam-Beam Wire Compensator (BBWC)
Impedance studies

Beam-Beam Wire Compensation Review Meeting

CERN 14-15 October 2024

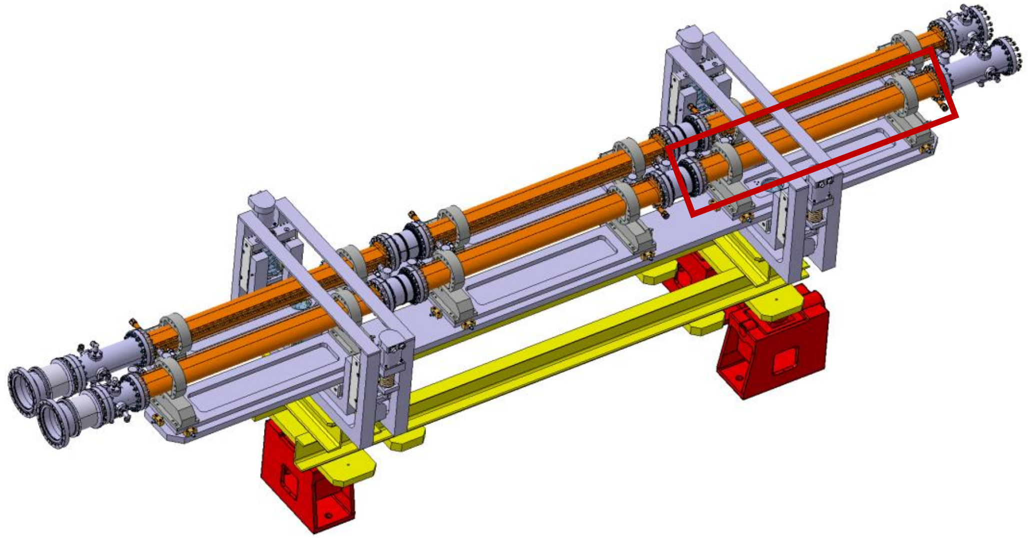
Leonardo Sito

A. Bertarelli, F. Carra, L. Gentini, L. Giacomel, B. Salvant, G. Sterbini, C. Zannini

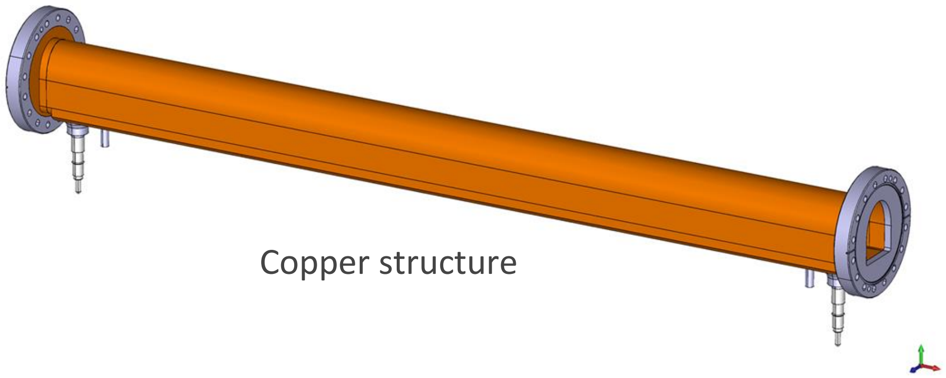
Outline

Outline

The Beam-Beam Wire Compensator:



The impedance study focuses on a **single module**:



4 BBWC **assemblies** (1 per side of IP1 and IP5)

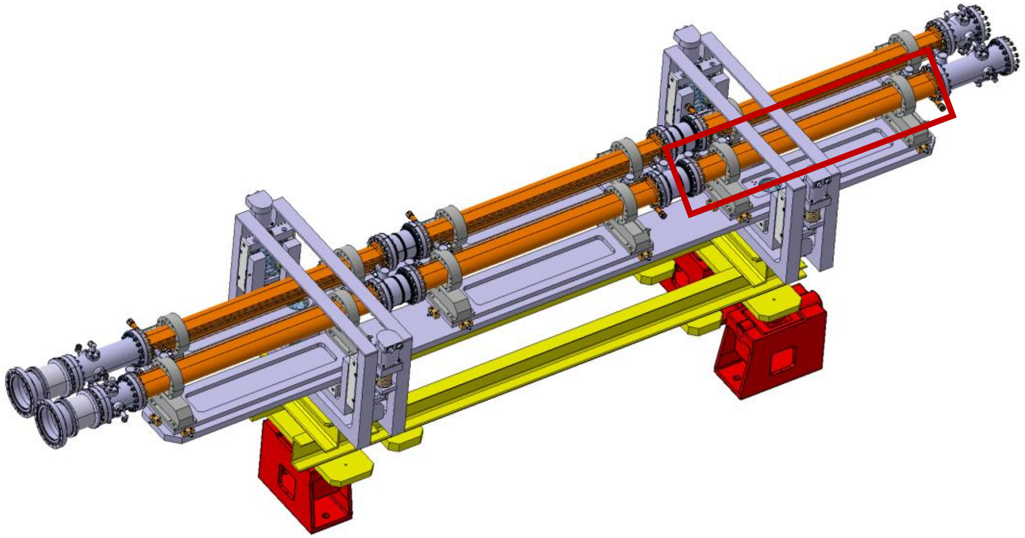
2 beam lines per assembly

3 BBWC modules per beam line

Tot: 12 BBWC modules per beam

Courtesy of A. Bertarelli

The Beam-Beam Wire Compensator:



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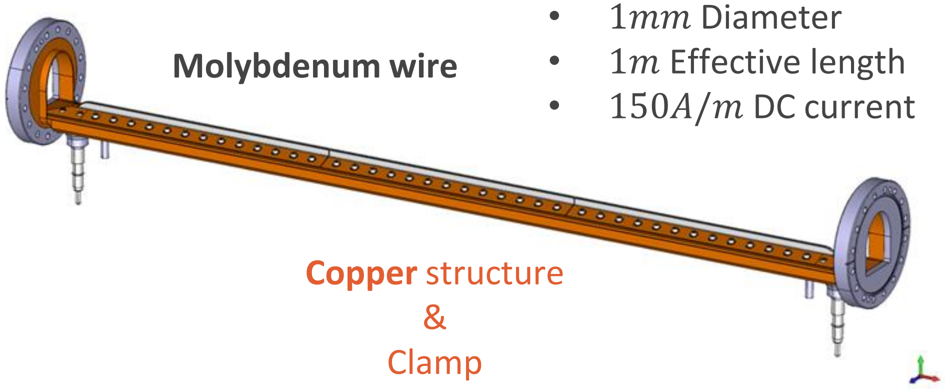


- $1mm$ Diameter
- $1m$ Effective length
- $150A/m$ DC current

Aluminum Nitride support:

- Support mechanically the wire.
- Enables better heat dissipation.

Courtesy of A. Bertarelli

The Beam-Beam Wire Compensator:

BBWC **electromagnetic model** keeps all **significant features** of the mechanical one:

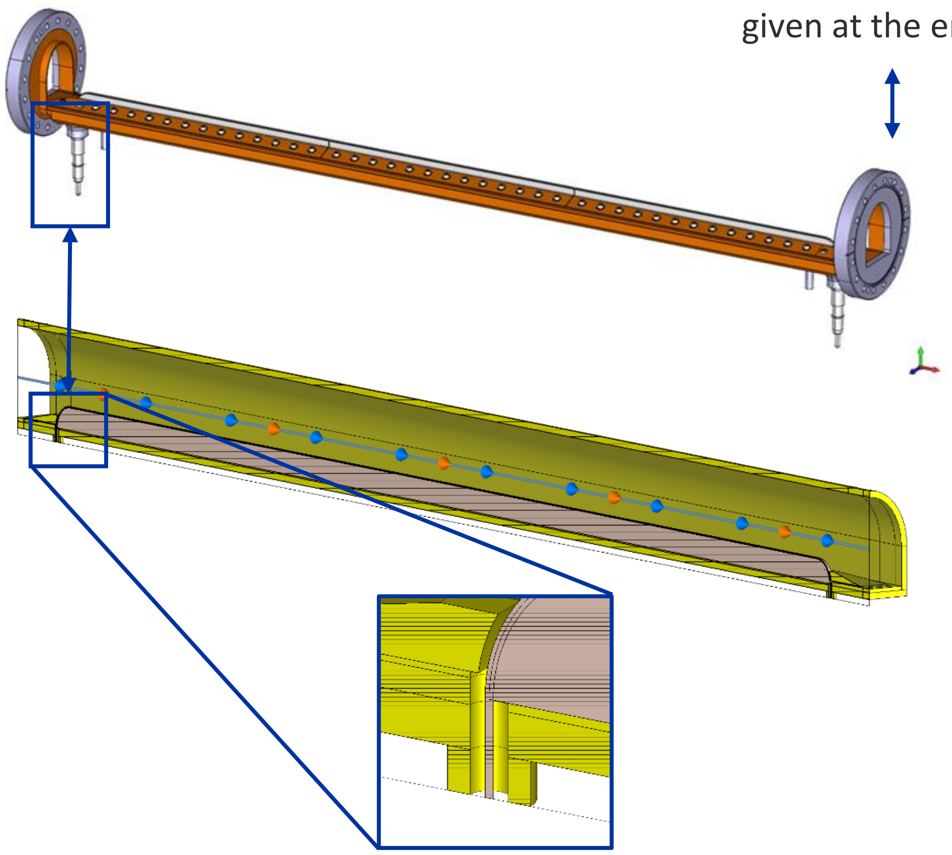
Some **considerations** on **interconnections** will be given at the end

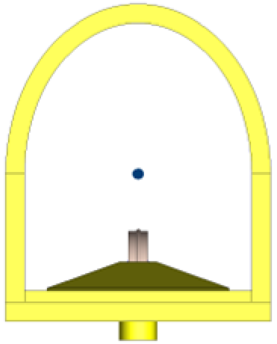
Integration with other modules:

1. No stainless-steel **flanges**.
2. No **interconnecting pipes** with other modules.

Single module:

1. No stainless-steel **bolts**.
2. Commercial Feedthrough replaced by a **coaxial structure**.

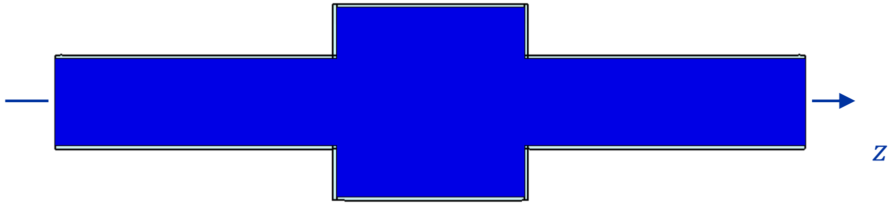




The **BBWC module** can **move** in respect beam.
(Span of movement: ±12.5 mm)

- **32.5 mm** → Fully out position
- **7.5 mm** → Operation (end of levelling)
- **5 mm** → Very conservative situation

Beam-coupling impedance study



Particle bunch travels in an accelerator device → **Electromagnetic wake fields**

- The wake fields **dissipate power** (Beam-Induced Heating).
- The wake fields can **trigger instabilities**.

To quantify the wake fields' effects → **Beam-coupling impedance**: frequency dependent complex vector ($\boldsymbol{Z}$) quantity.

Impedance → 3D computation tools (CST®)

Beam-coupling impedance study

Two figures of merit:

- **Stability** (longitudinal) ⟷ Low-frequency **effective longitudinal impedance** $\frac{Im(Z_z)}{n}$, with $n = \frac{f}{f_0}$

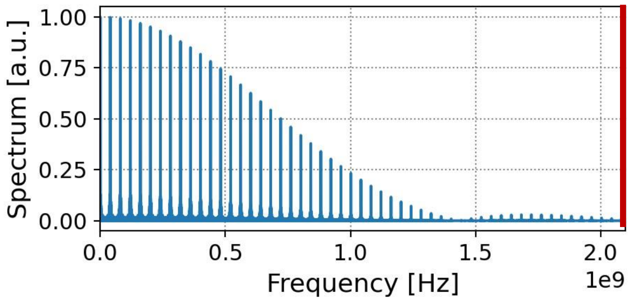
- **Power** deposition (On the **whole device**) ⟷ $\Delta W = 2(f_0 e N_{beam})^2 \sum_{p=0}^{\infty} (|\Lambda(p\omega_0)|^2 Re[Z_z(p\omega_0)])$

LHC budget: ~ **90 mΩ**

Power dissipated by the wire in DC is **2.1 kW**

Computed with **HL beam properties**:

- N_{beam} = 2748 (bunches) × 2.3e11 ppb
- Bunch shape: q-Gaussian (q=3/5) , 1 ns bunch length



Significantly decayed after 2 GHz

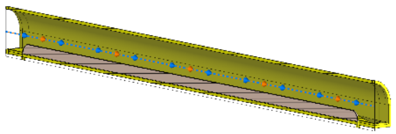
Also a **comment** on **transverse impedance** contribution will be given.

N_{beam}: number of particles in the beam
f_0: beam revolution frequency
$\Lambda(p\omega_0)$: normalized beam spectrum

Outline

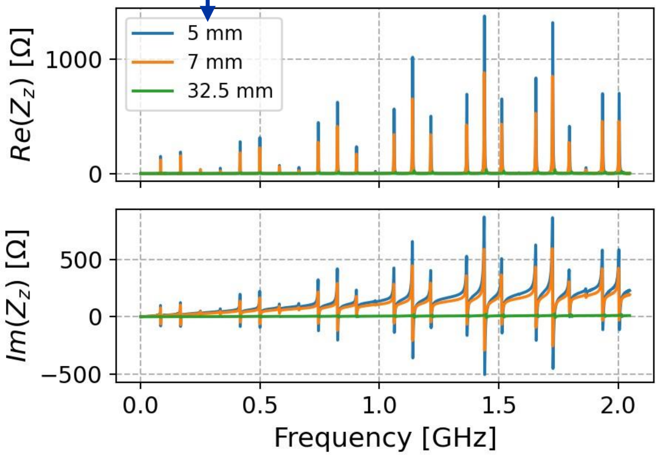
Results presented at Uppsala, 12th HL Collaboration Meeting

Unshielded BBWC module



Surface current distribution in time:

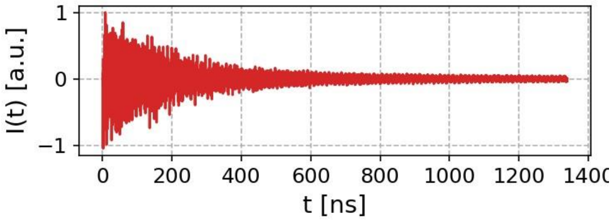
Distance wire-beam



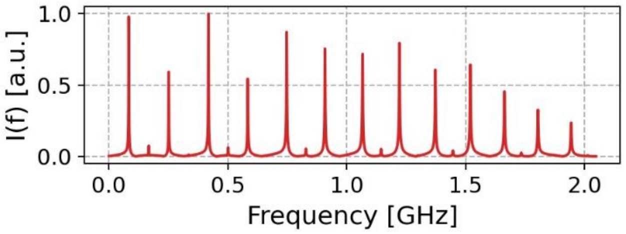
- Several **resonances** below 2 GHz
- **Slope** in the Im(Z_z)

Increasing when getting **closer** to the beam

Current in the wire in time:

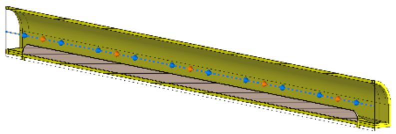


FFT

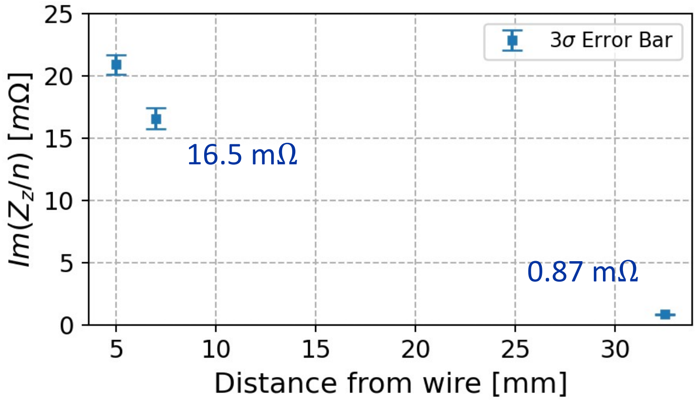


Good understanding of this behavior: resonances due to **multiple** current **reflections along the wire**

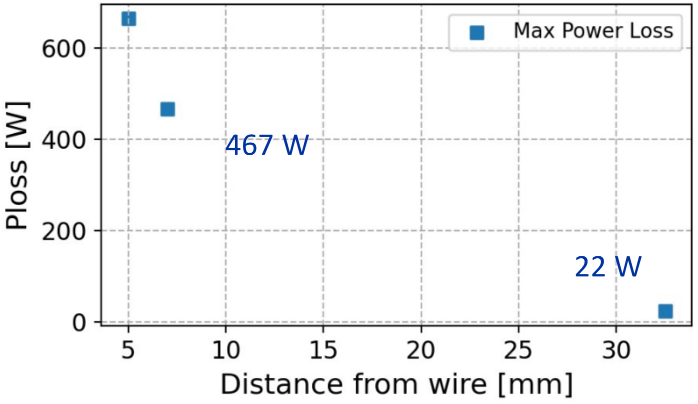
Unshielded BBWC module



Longitudinal Effective Impedance of all **12 modules** per beam



Power deposition on a **single module**



LHC budget $\frac{Im(Z_z)}{n} \sim$ **90 mΩ**

DC dissipated power: **2.1 kW**

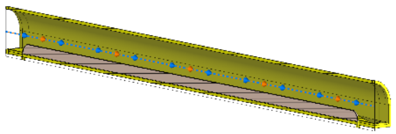
At **7.5 mm** from the beam:

- Around **20%** of the total budget of **Longitudinal Effective Impedance**
- Around **25%** of the **power dissipated in DC**

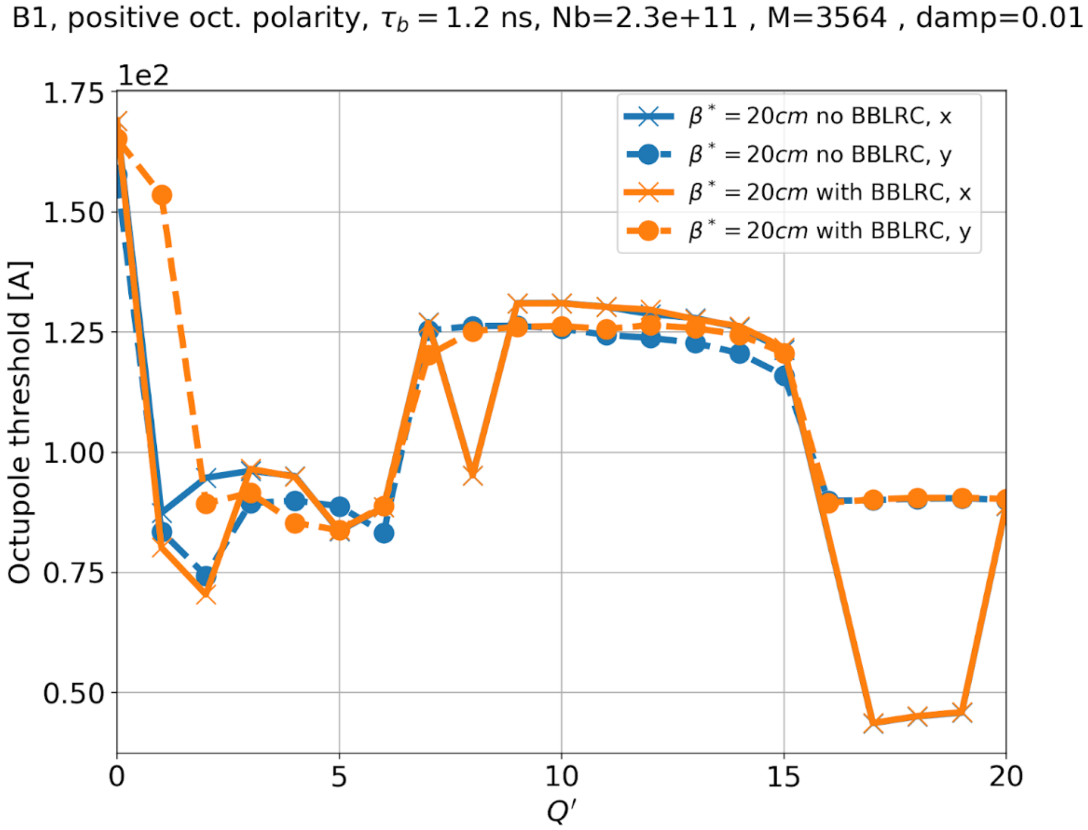
Impedance contributions are significant, but **no showstopper is identified** provided impedance minimization iterations in the design.

Results presented at Uppsala, 12th HL Collaboration Meeting

Unshielded BBWC module



We compute the **octupole threshold with BBLRC** to check **the impact of the HOMs on beam stability**



Device in parking, end of levelling.

The increase of the stability threshold is well below 10A for Q'>10.

Courtesy of L. Giacomel

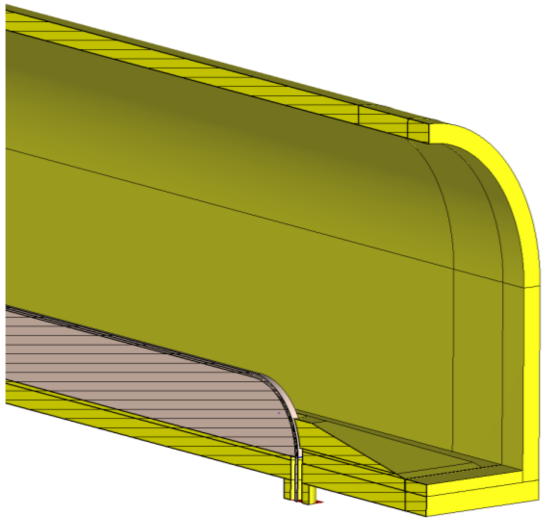
Outline

Impedance optimization options

External

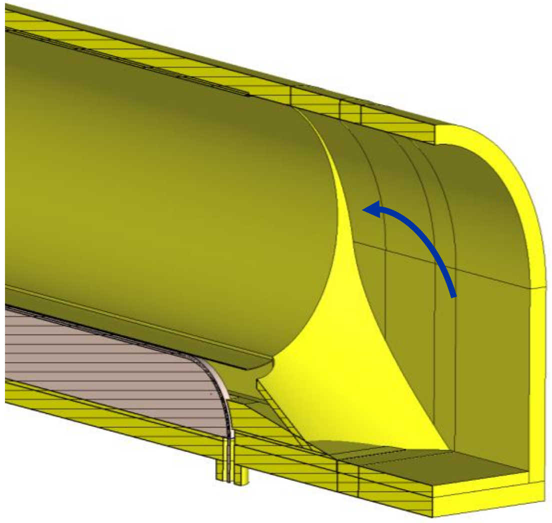
Internal shield

Option A: RF load



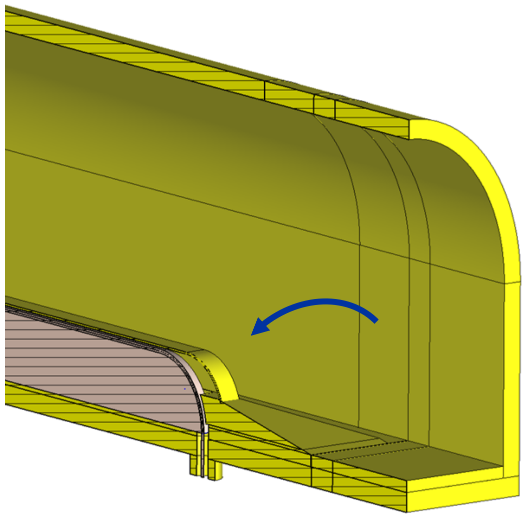
- No modification to the module
- External circuit at wires' termination

Option B: Elliptical Shield



- Elliptical pipe as shield
- Thin window
- Tapering

Option C: Box Shield



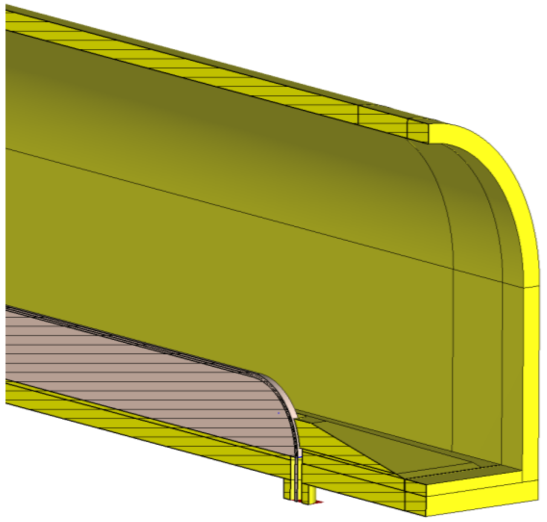
- Box on top of wire and Aluminum Nitride support

Impedance optimization options

External

Internal shield

Option A: RF load



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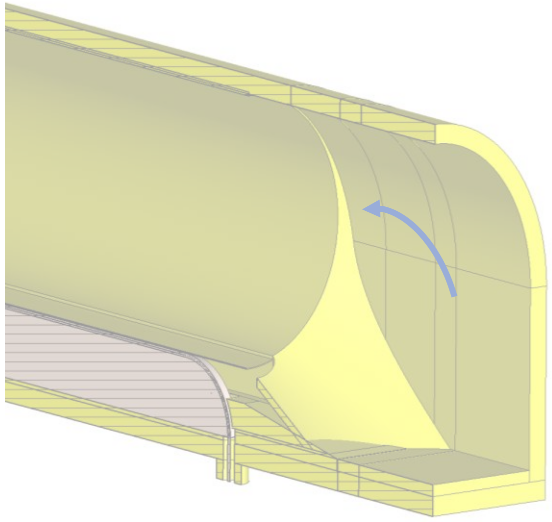
Option B: Elliptical Shield



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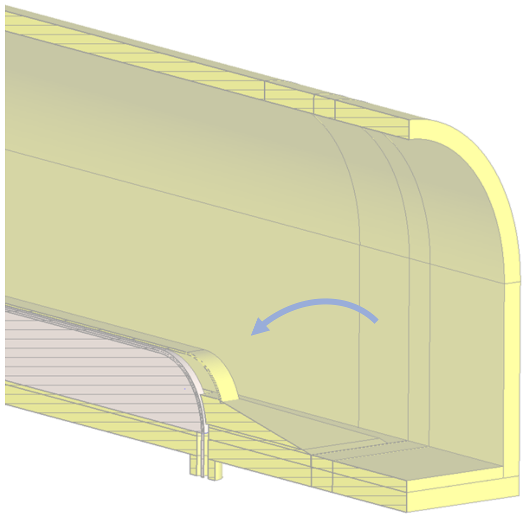
Option C: Box Shield



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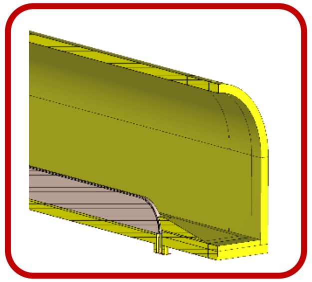
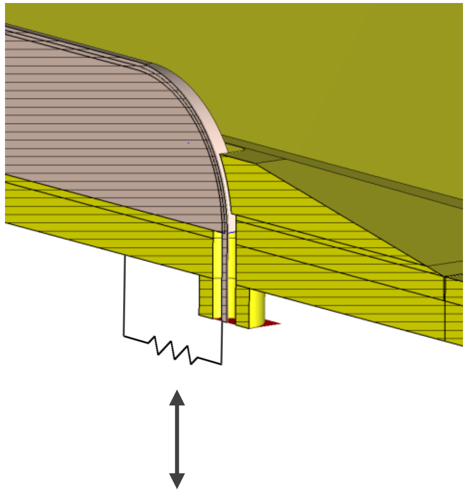
Option A: RF load



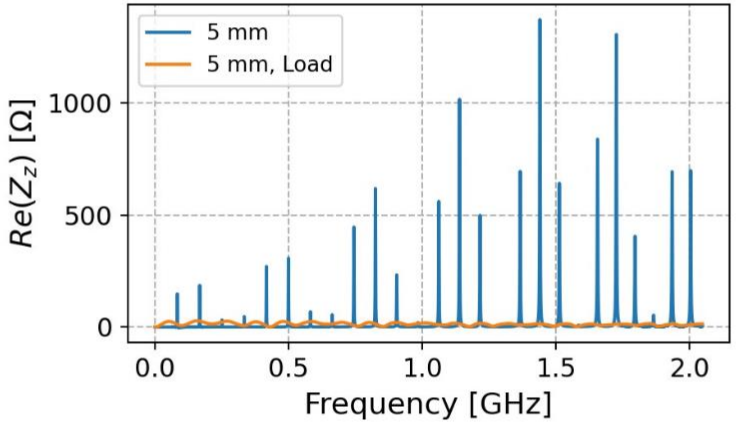
Driving away RF power from the wire to an external circuit, outside of the vacuum chamber.

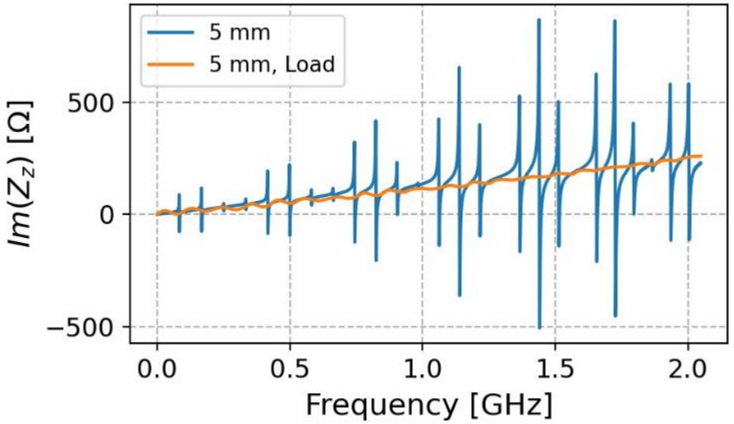


Idea tested in simulations with a **perfect load**

=

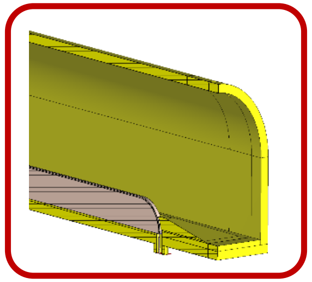
- **Total absorption** of input RF power
- **Minimized reflections** at the termination of the wire

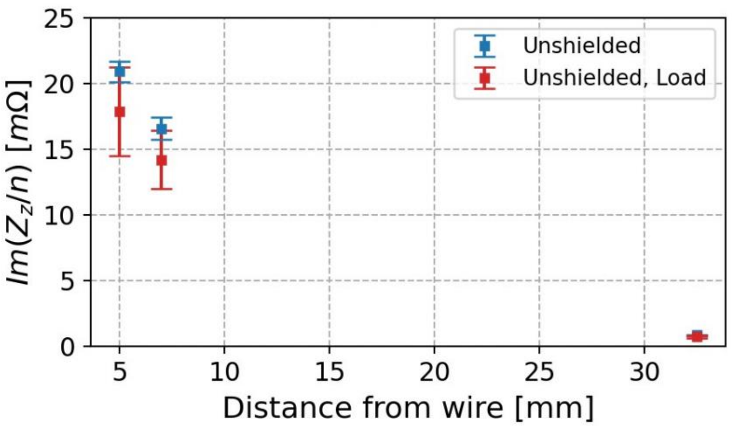


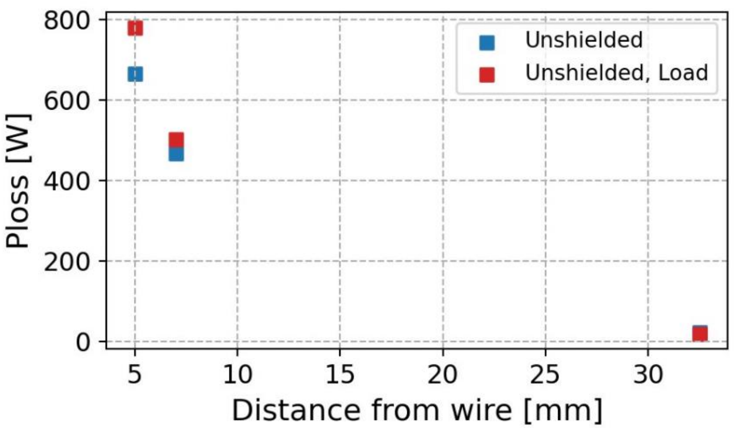


Strong **attenuation of all resonances**

Option A: RF load







- **No** significant **impact** in terms of **effective impedance**
- **Worse** in terms of **power loss**

> ➢ **Not a feasible solution** in terms of minimization of **impedance** contributions.

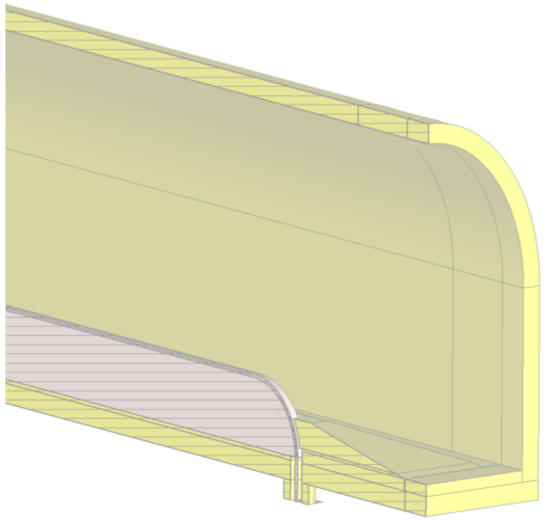
➢ **RF load** at the termination of the wire should be considered for **protection of the power converters** driving the DC current in the wires.

Impedance optimization options

External

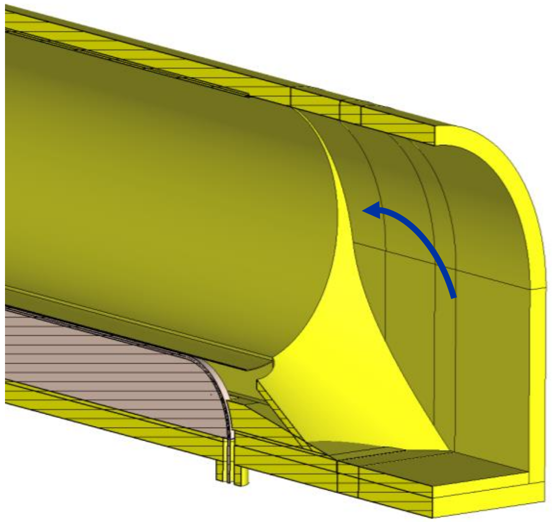
Internal shield

Option A: RF load



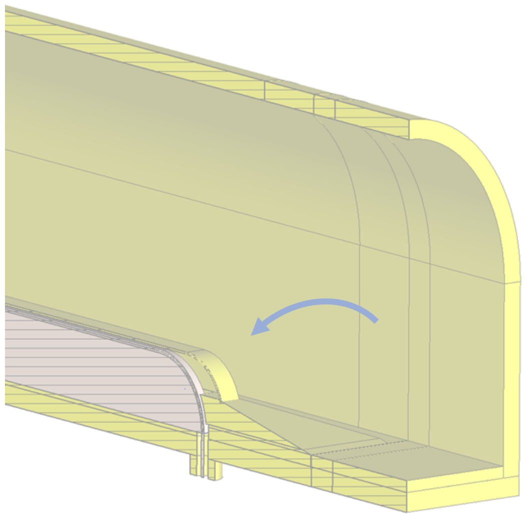
- No modification to the module
- External circuit at wires' termination

Option B: Elliptical Shield



- Elliptical pipe as shield
- Thin window
- Tapering

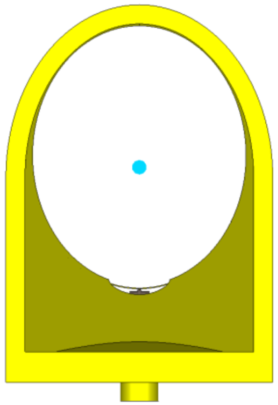
Option C: Box Shield

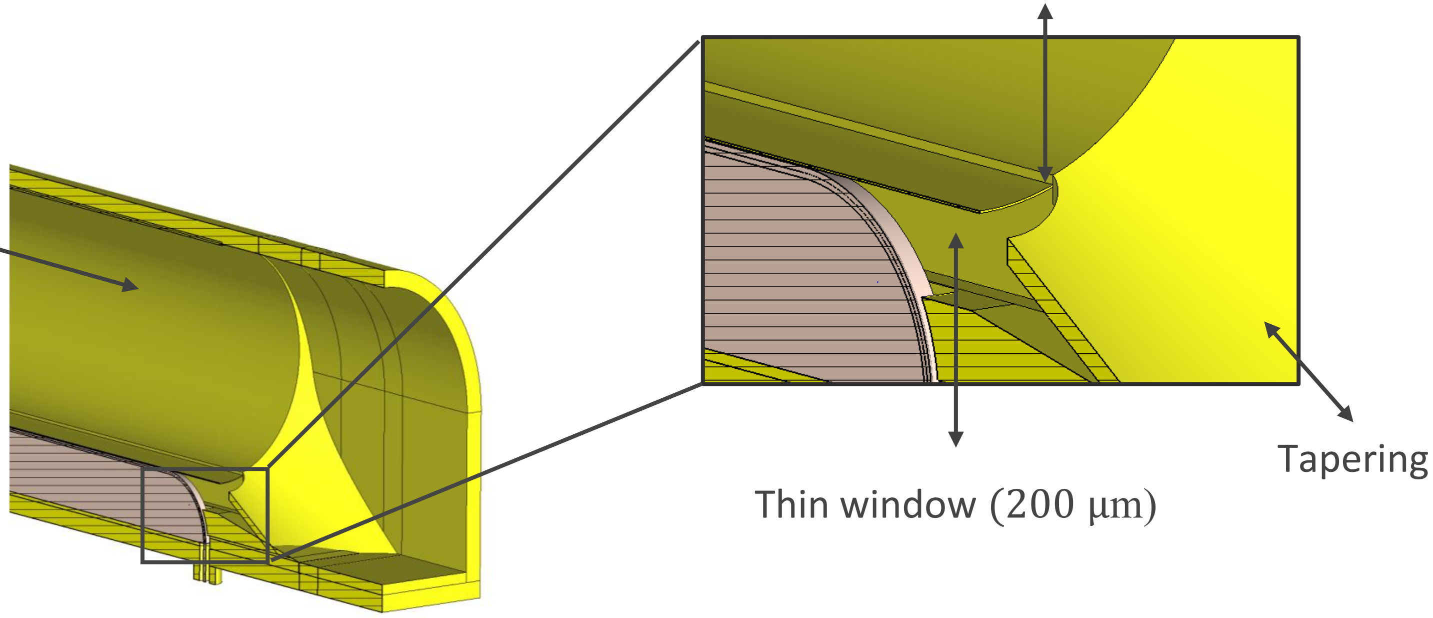


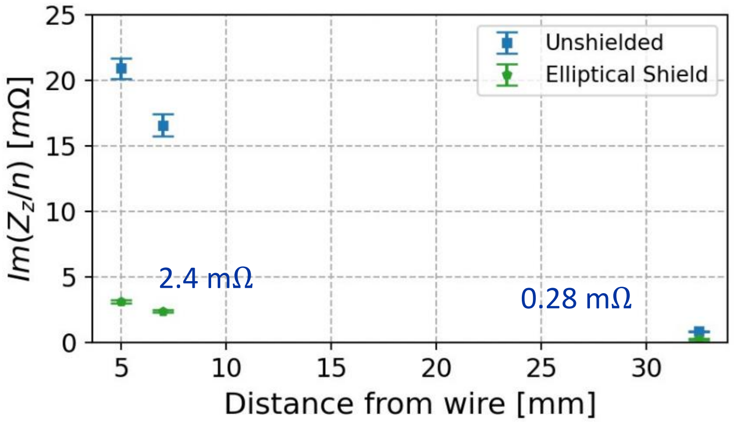
- Box on top of wire and Aluminum Nitride support

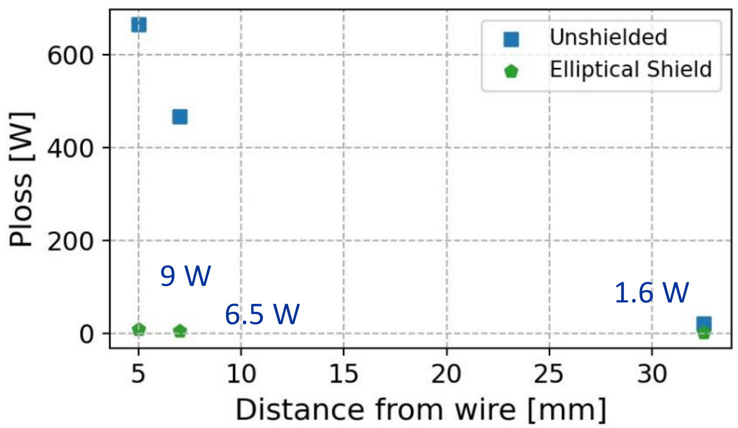
Option B: Elliptical Shield

Elliptical pipe shielding the wire from the beam









Total budget of **Longitudinal Effective Impedance**:

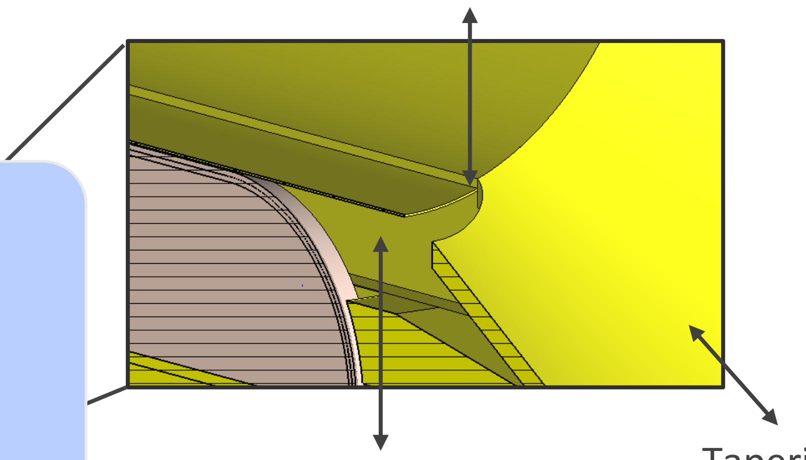
- In **Operation** ~ **2.7 %**
- **Fully out** ~ **0.3 %**

Dissipated power below **10 W**

Option B: Elliptical Shield

Elliptical pipe shielding the wire from the beam

- Impedance contribution of the **modules** is **not limiting.**
- The impedance contribution of **tapers** has to be carefully evaluated and minimized.
- This design **might pose limitations** to the **forward physics in CMS (PPS2).**



Total budget of **Longitudinal Effective Impedance**:

- In **Operation** ~ **2.7 %**
- **Fully out** ~ **0.3 %**

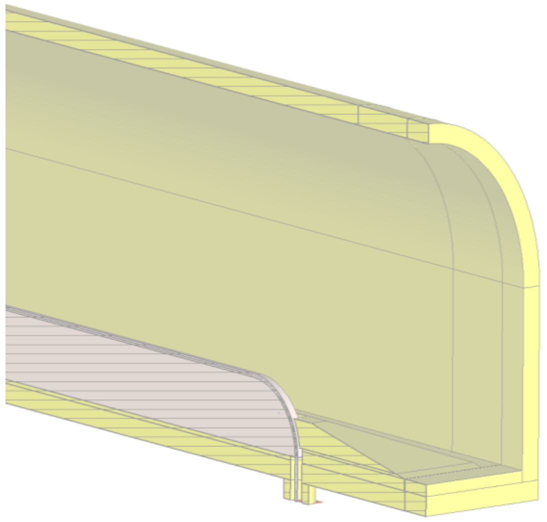
Dissipated power below **10 W (below 0.5 %)**

Impedance optimization options

External

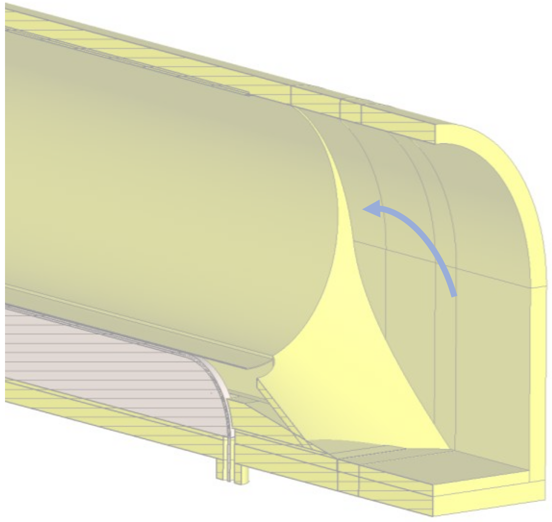
Internal shield

Option A: RF load



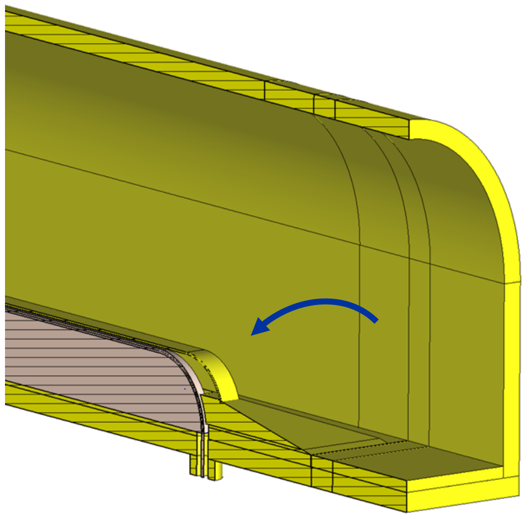
- No modification to the module
- External circuit at wires' termination

Option B: Elliptical Shield



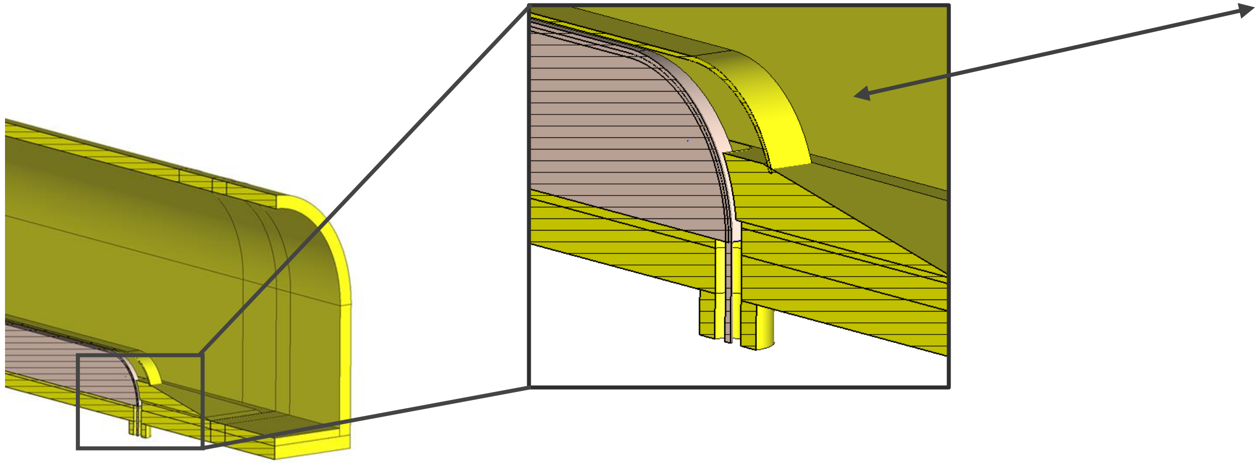
- Elliptical pipe as shield
- Thin window
- Tapering

Option C: Box Shield

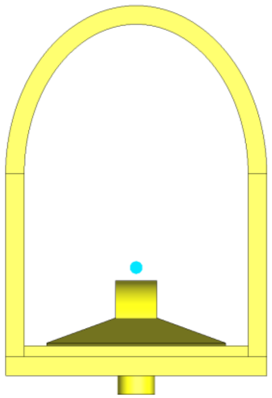


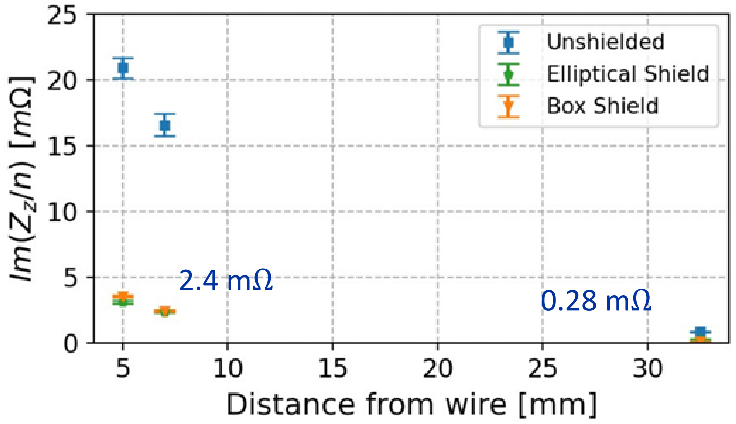
- Box on top of wire and Aluminum Nitride support

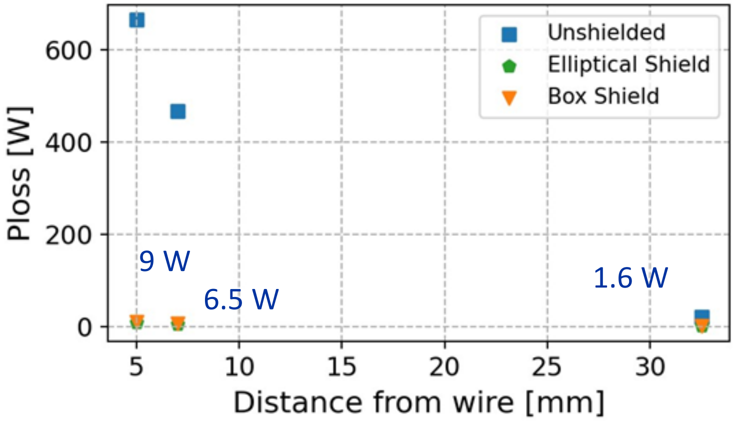
Option C: Box Shield



Box shield fully covering the wire and the aluminum nitride support





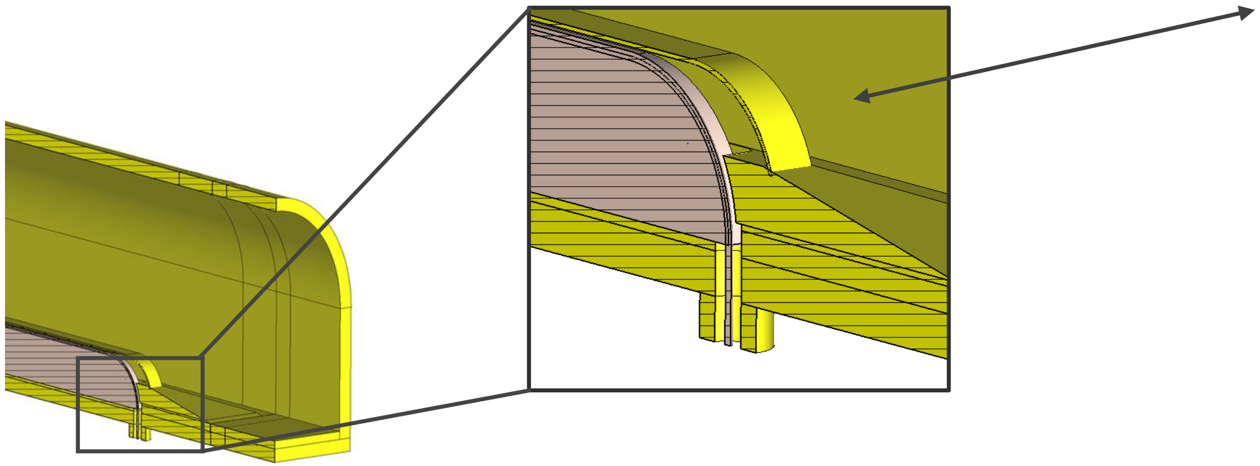


In terms of:

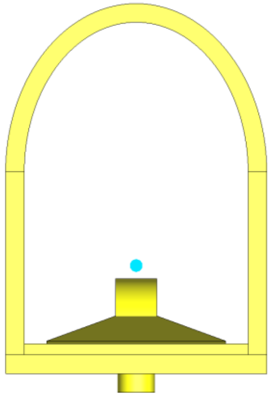
- Total budget of **Longitudinal Effective Impedance**
- Dissipated **power**

Equal to the elliptical shield option

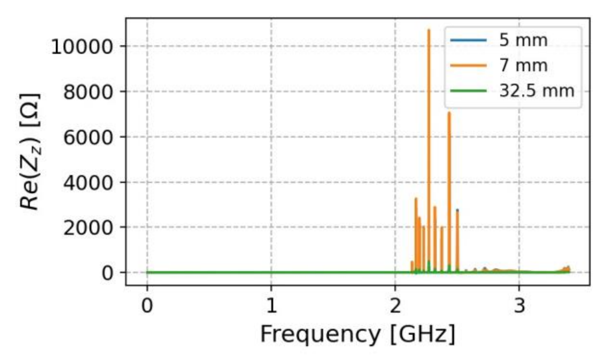
Option C: Box Shield



Box shield fully covering the wire and the aluminum nitride support



- **Resonances** above 2 GHz <u>not present in the elliptical shield option</u>



In terms of:

- Total budget of **Longitudinal Effective Impedance**
- Dissipated **power**

Equal to the elliptical shield option

Outline

The interconnections

Shielding the wire → The **major impedance contribution** could come from the **transitions and interconnections:**

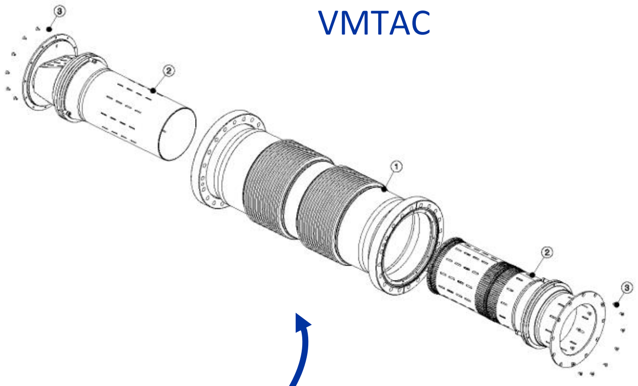
- **Bellows**

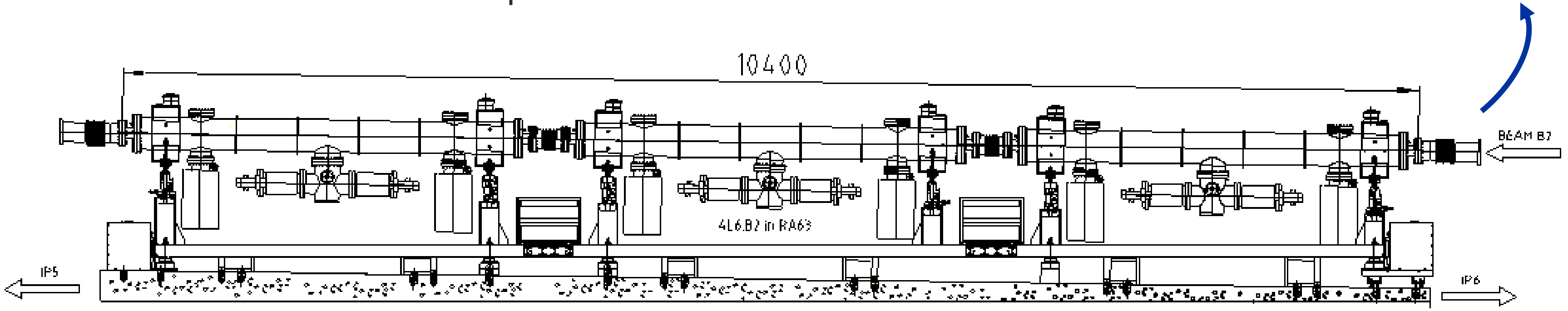
TCDQ collimator has:

1. **Cardan bellows**:
    1. Allowing a **transverse displacement of ±20 mm**
    2. With **impedance shielding**

2. Transition from elliptical to round chambers

VMTAC





This option must be discussed with vacuum team

- **Tapers:**

  Careful impedance design is needed to minimize impedance contribution.

https://edms.cern.ch/document/1167537/1.1

https://edms.cern.ch/document/1289320/AB

Outline

Conclusions

Unshielded BBWC

Behaviour in terms of impedance and power loss:

- Significant impedance contribution
- Need for a mitigation

Mitigation options

Three mitigation options presented:

- External: terminating the wire with a RF Load
  - Not a solution in terms of impedance
  - Should be considered for protection of power converters
- Internal shields:
  - Elliptical shield:
    - Best solution in terms of effective longitudinal impedance at low frequency and power loss
  - Box shield:
    - Feasible solution but several resonances above 2 GHz

Bellows and Tapers

Impedance main source after shielding

- Possibility of shielded bellows (TCDQ)
- Need for careful design of tapers

Thank you for the attention ☺

BBWC

Leonardo Sito