Update on TDIS impedance and stability studies

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TDIS review , 1-12-2016

With many thanks to:
I.lamas, Garcia, A. P. Marcone and L.Gentini for the mechanical design and technical informations
G. Arduini, the WP2 members and A. Grudiev for the useful comments and suggestions received

Outline

- TDI performance summary of 2015/2016
- TDIS design aspects relevant for impedance
- Effect on impedance of:
  - jaws segmentation
  - Lateral RF fingers
  - Heating from HOMs
  - Longitudinal RF fingers
  - Heating from resistive wall
  - Transition flanges and jaw tapers
  - Gaps between the blocks
- Impact on HL-LHC stability threshold at 450 GeV
- Conclusions and outlook

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TDI performance between 2015/2016

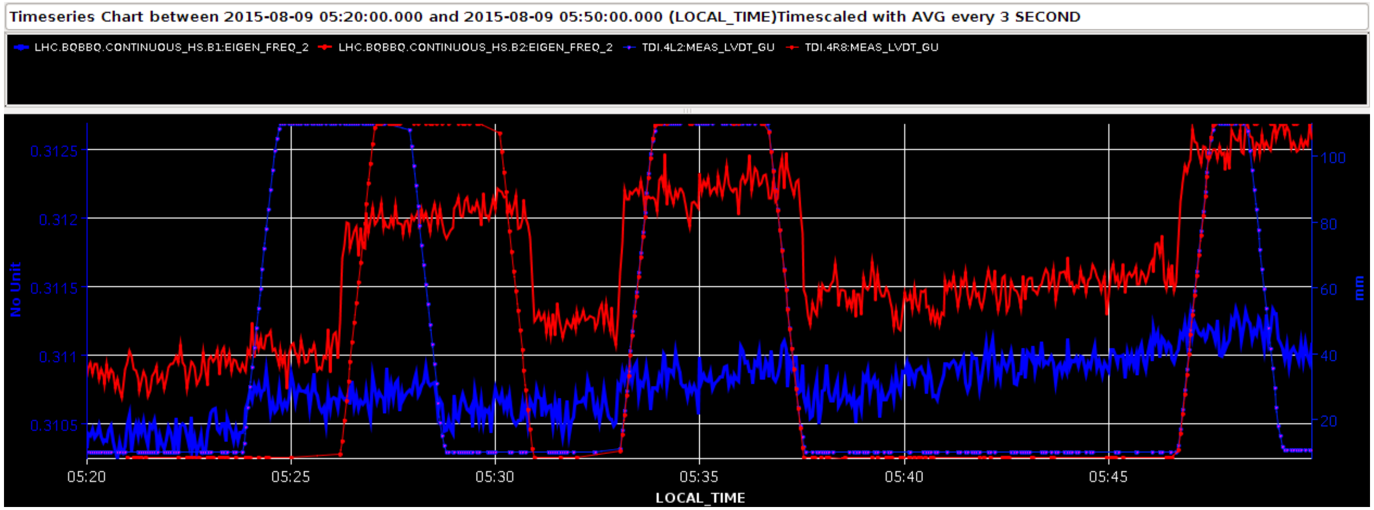
2015 performance:

- TDI jaw in **hBN coated with Ti**.
- Observed **higher transverse impedance** and **power loss** in **TDI8 w.r.t. TDI2** through **tune shifts** and **sync. phase shift** measurements.

2015
Ti + hBN jaw

B2: $\Delta Q_y \simeq 10^{-3}$

B1: $\Delta Q_y \simeq 2 \cdot 10^{-4}$

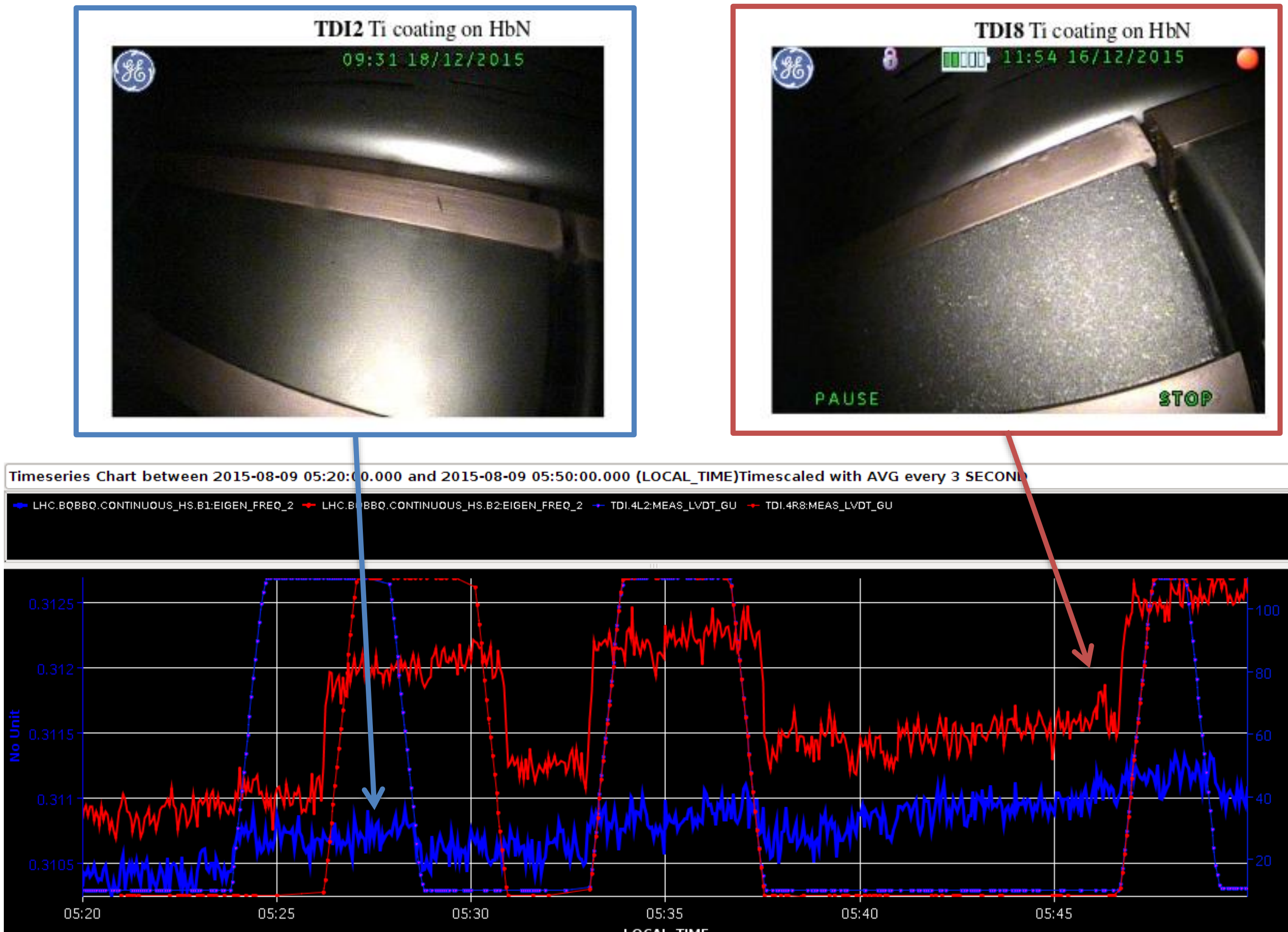


See also:
B. Salvant, Impedance meeting 10 Aug 2015
J. Uythoven in LMC 30 Sep 2015

TDI performance between 2015/2016

Measurements and inspections during the 2015/2016 YETS:

- Issue **confirmed** to be the **degraded Ti coating on hBN**



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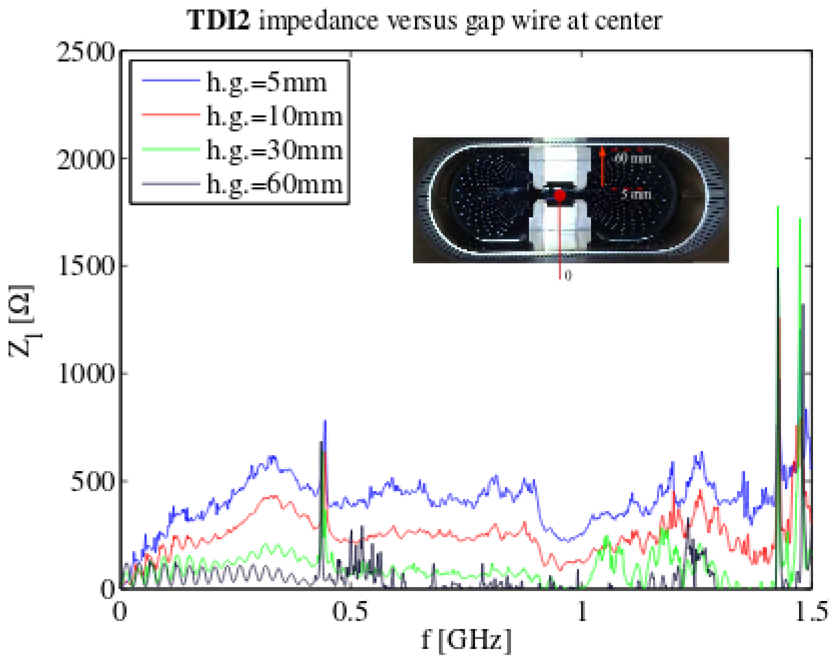
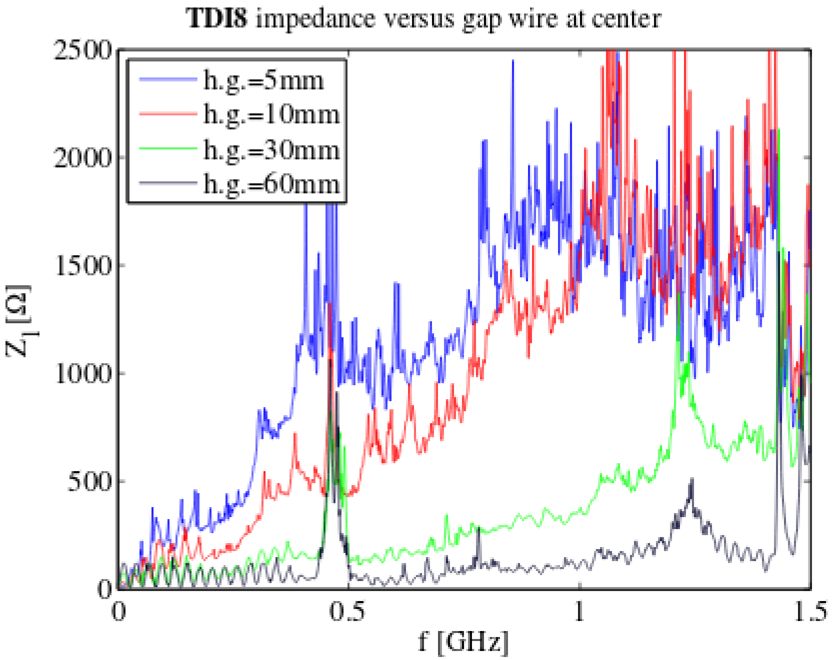
- Confirmed also through **stretched wire measurements**.



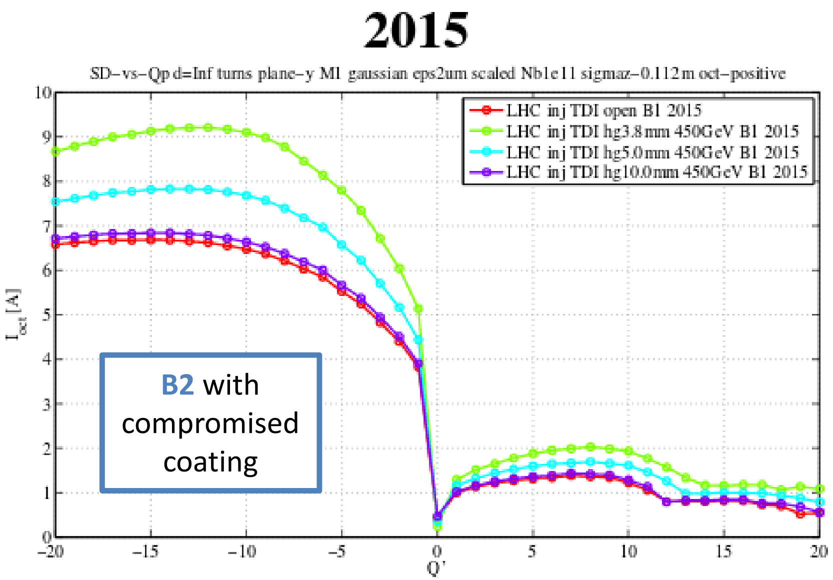


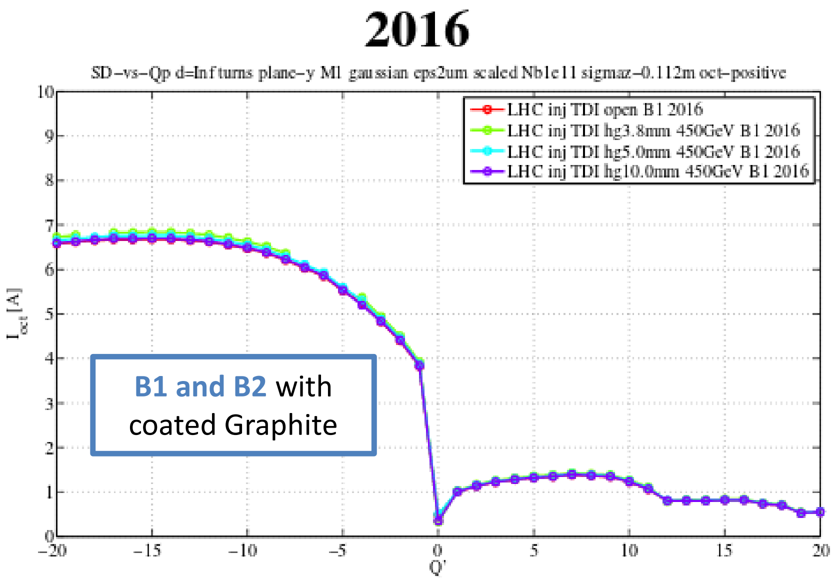
See also:
N.Biancacci, Impedance meeting 15 Feb 2016

TDI performance between 2015/2016

Measurements and inspections during the 2015/2016 YETS:

- Issue **confirmed** to be the **degraded Ti coating on hBN**
- Confirmed also through **stretched wire measurements**.
- **B2** much more critical than **B1** -> TDI **doubled the LHC impedance** at injection!





- Considerable **improvement** in **2016** thanks to the **Cu coating.**

See also:
N.Biancacci, Impedance meeting 15 Feb 2016

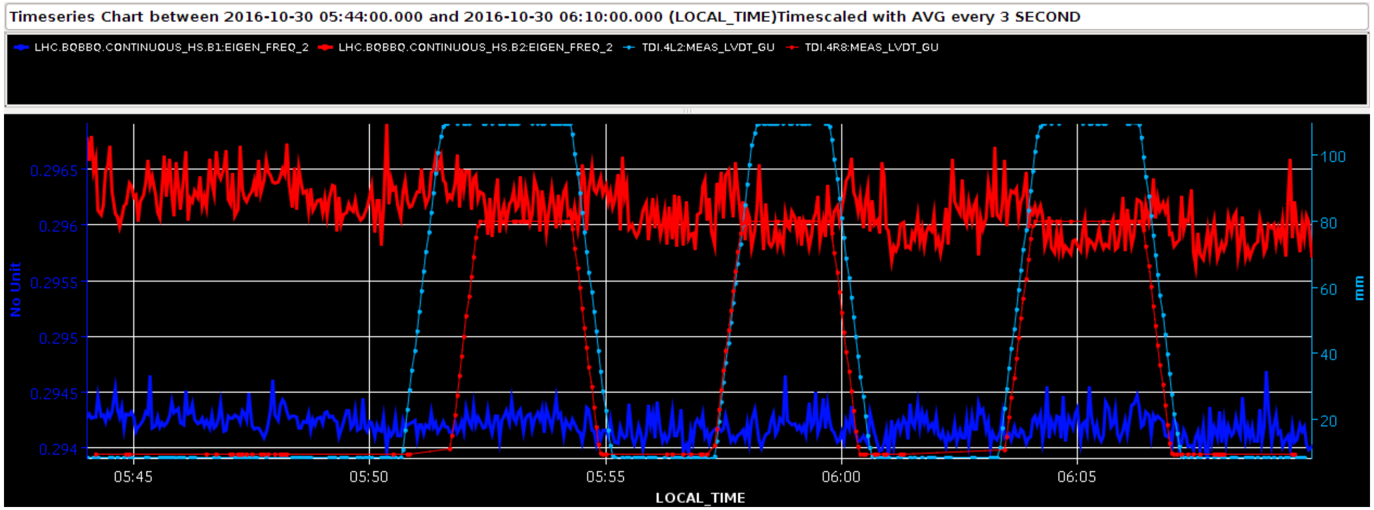
TDI performance between 2015/2016

2016 performance:

- TDI jaw in **Graphite coated with Cu + Ti**.
- Tune shift **barely measurable with BBQ system**
- **Power loss not detectable** through phase shift measurements in single bunch.

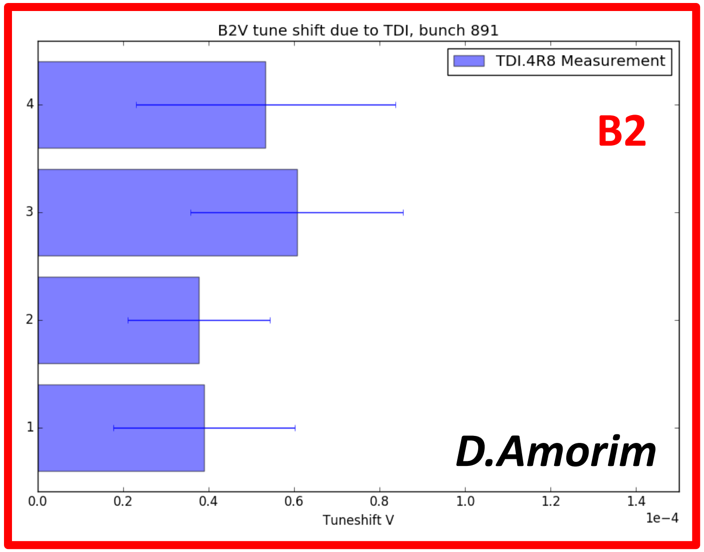
2016
Cu + Gr jaw

Barely measurable from the BBQ system.

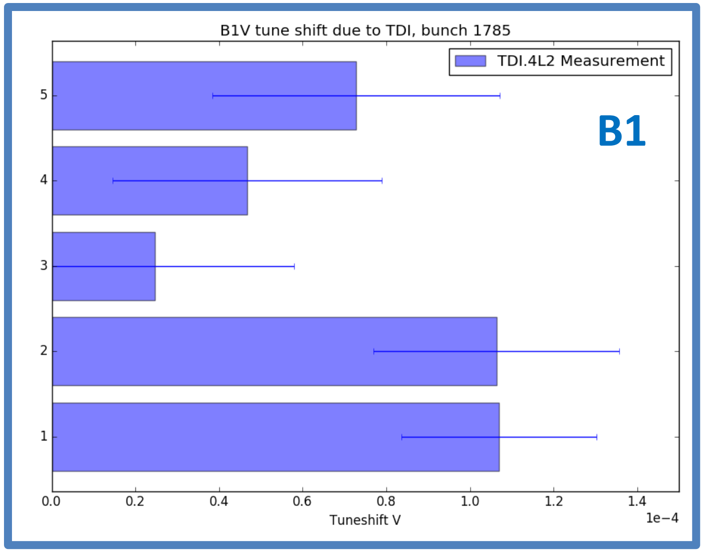


TDI performance between 2015/2016

- Single bunch **tune shift measurements** on 30-10-2016 with **MKQ kick + ADT.**



Measurement: ~4e-5
Simulations: 3e-5 (RW + Geom)



Measurement: ~6e-5
Simulations: 3e-5 (RW + Geom)

- **Reasonable good agreement** between a factor 2 on theory and measurements!
- **Compromised Cu coating** would lead to **1e-4** tune shift (**Graphite exposed**).
- **Phase shift not visible** (J.E.Muller)
- **Copper coating the jaw surface drastically reduces the TDI broadband impedance.**

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TDIS design aspects relevant for impedance

Proposed 3 tank segmentation (TDI+S) in order to:

- Improve **mechanical reliability**.
- Allow **module exchangeability.**

Aimed for collimator like design at the transitions:

- **not possible due to ALICE ZDC**: no metallic surfaces at the level where the beam could impact.

Jaw materials:

- **a) Graphite**
  - First two modules with **Graphite** (1.565mm each)
  - Last module**: 1 Al (Ti coated) + 1 CuCrZn** (with total integrated length 1.565mm)
- **b) 3D C-C**
  - First two modules with **1x 3D C-C** (570mm) + **1x Graphite** (995mm)
  - Last module **1 Al (Ti coated) + 1 CuCrZn** (with a total total integrated length 1.565mm)
- **c) Cu coating on Graphite**
  - Graphite coated as in the present TDI

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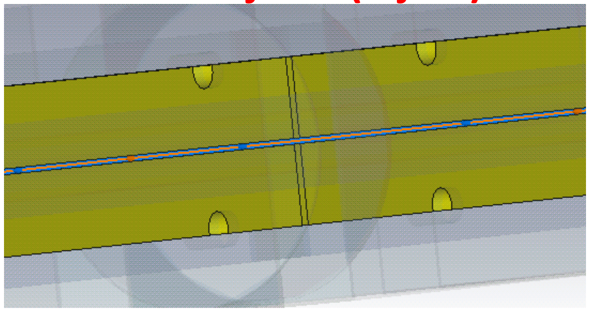
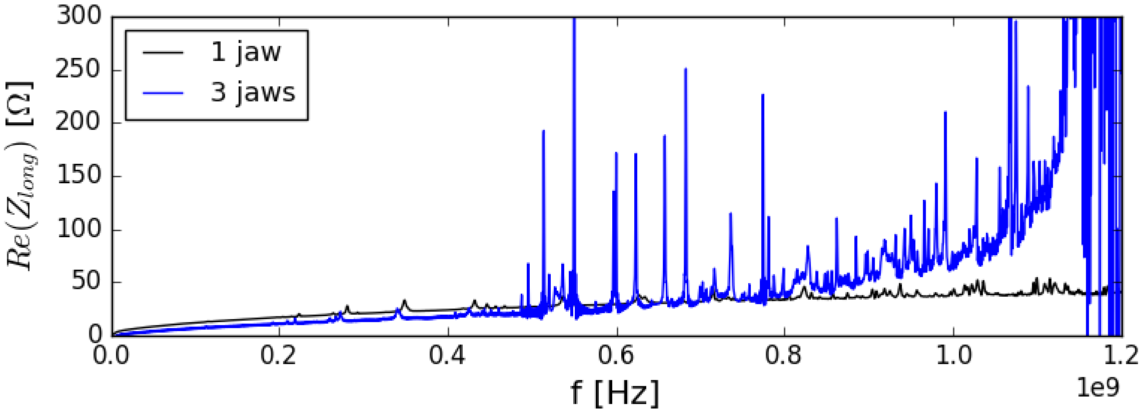
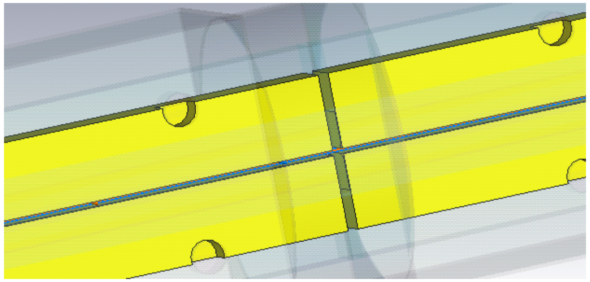
1 jaw Vs 3 jaws

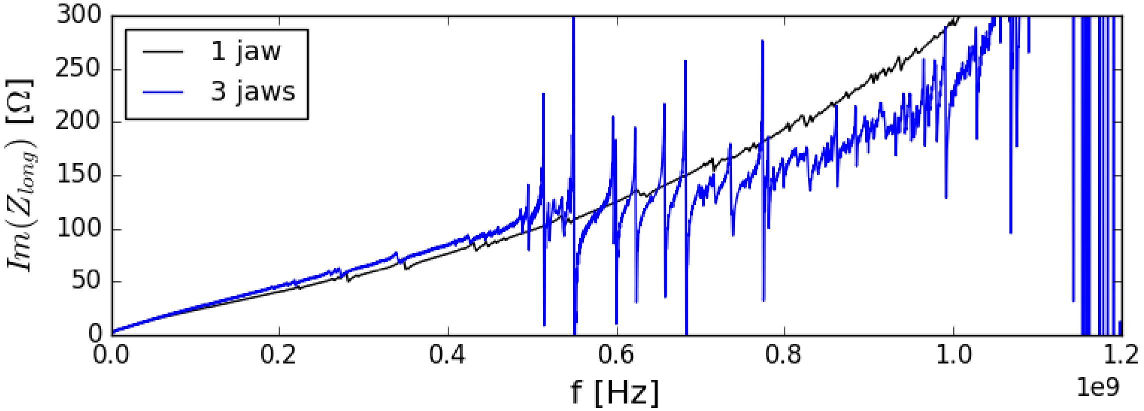
Connected jaws (1 jaw)





Segmented jaws (3 jaws)





Approximated approach: connected the segmented jaws.

- **Same mode pattern below 500 MHz**
- **Stronger modes** develop **above 500 MHz**.

Segmenting the jaws is clearly **detrimental for impedance**:

- **RF fingers**, **transitions** and **coating** are countermeasures that can **mitigate** it.

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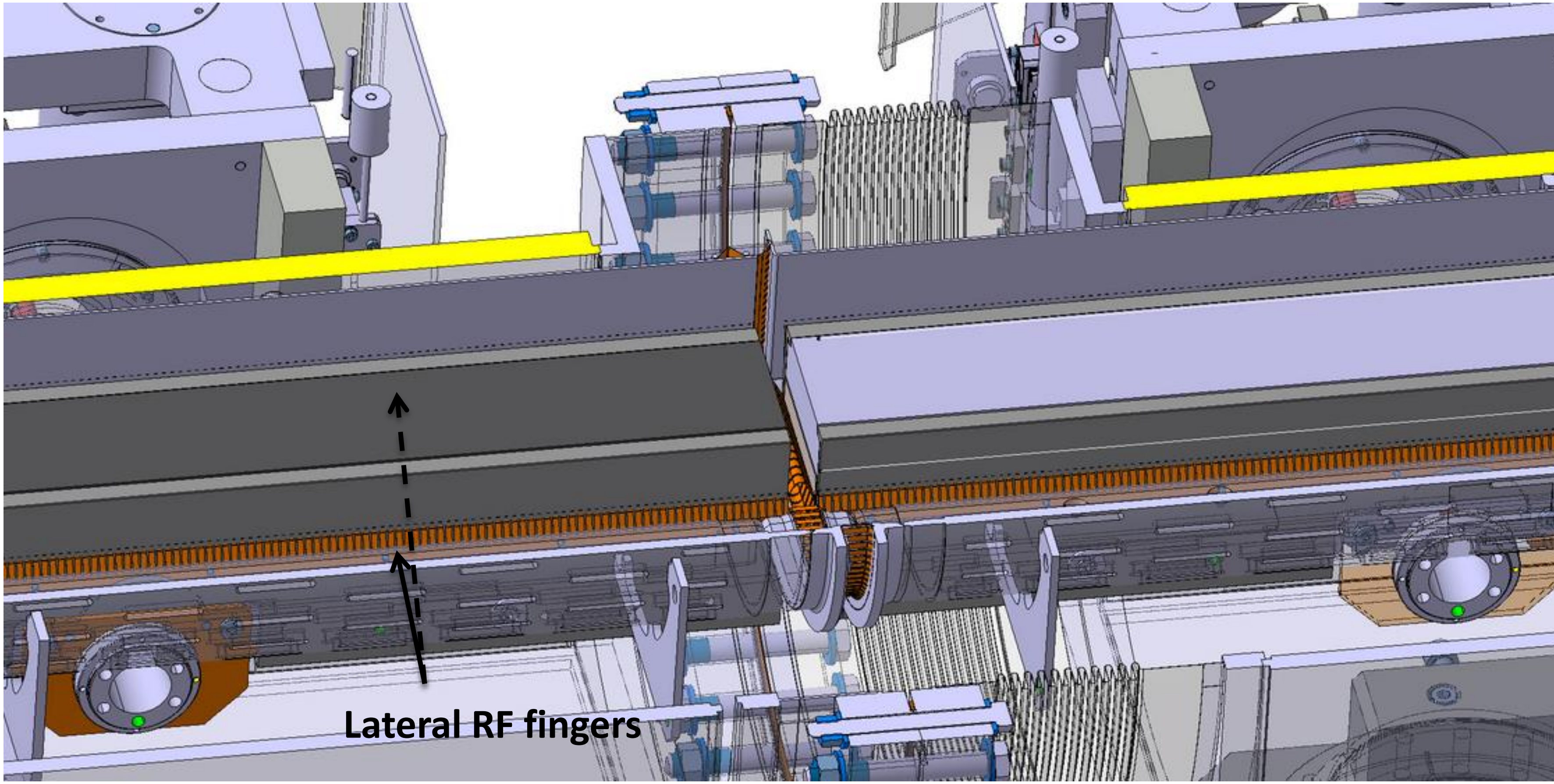
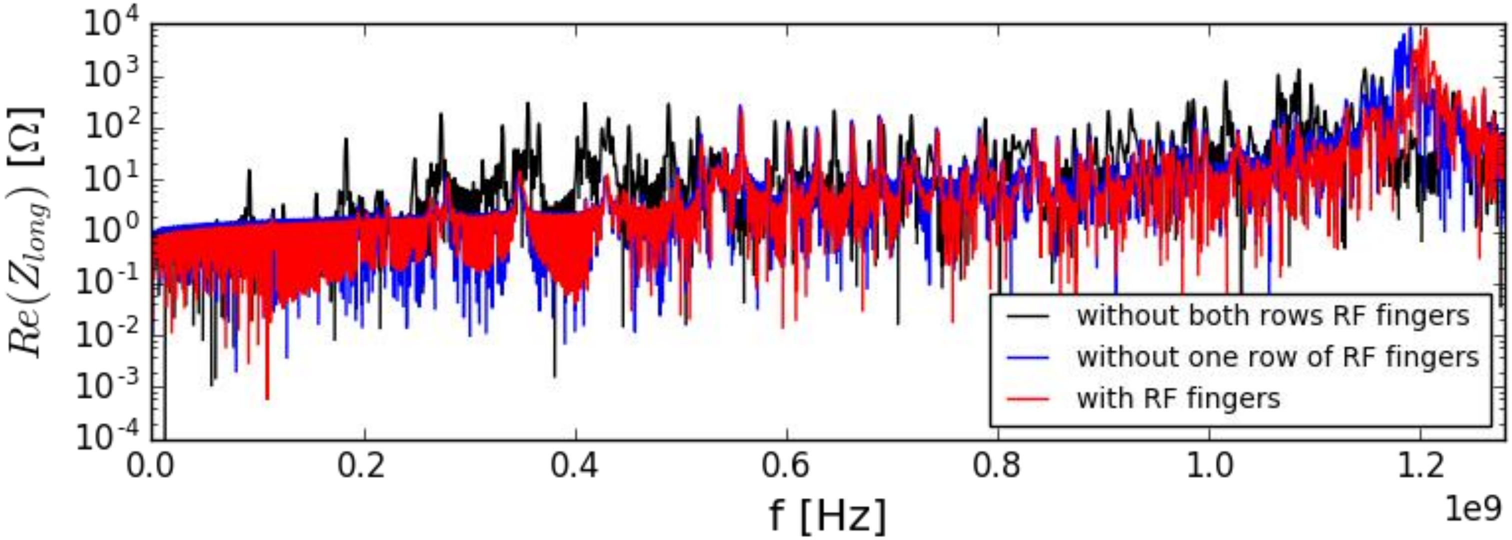
Effect of lateral RF fingers



- To study the effect of the lateral RF fingers we studied 3 cases:
  - **Presence of both lateral rails of RF fingers**
  - **Presence of only one lateral rail**
  - **Both rails removed**

Longitudinal impedance



- **Limited impact** on longitudinal impedance with 1 row of RF fingers missing.
- **Strong impact if we both are not in contact** -> more modes -> more heating.
- **We would recommend to keep both rails in order to have margin.**

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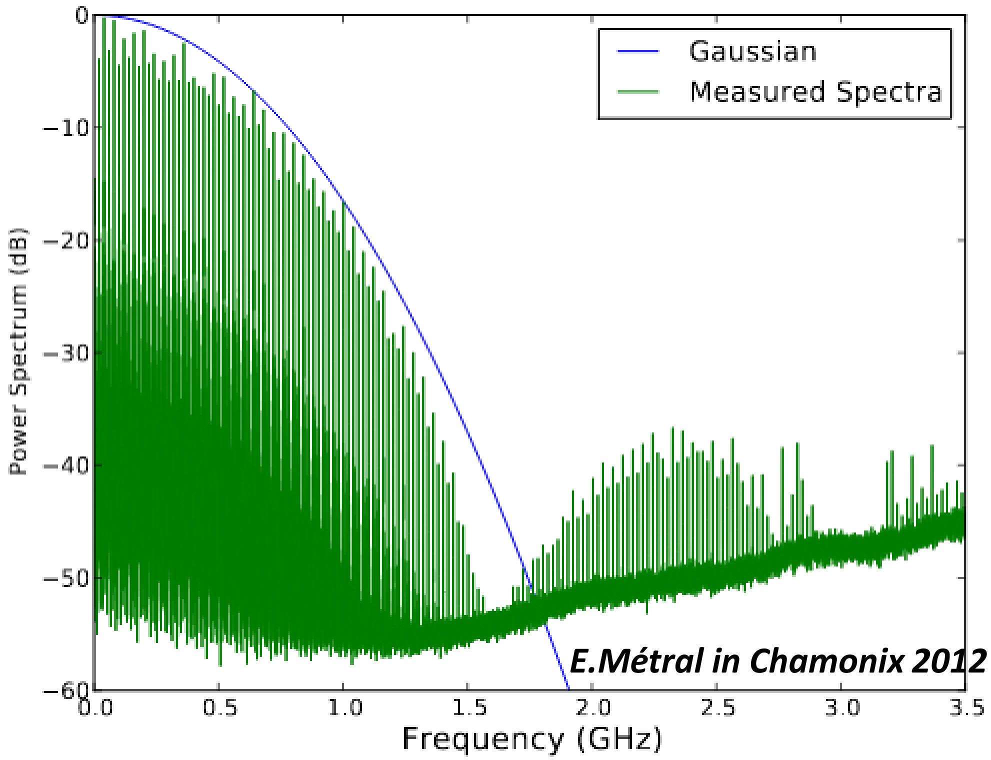
Heating from HOMs



Here we assumed a **Gaussian spectrum** corresponding to an *rms* bunch length of **8.1cm**.

NB: In the LHC the distribution is Gaussian only up **to ~1.5 GHz**. After there is still power between 2 and 2.5 GHz -> Not considered here.

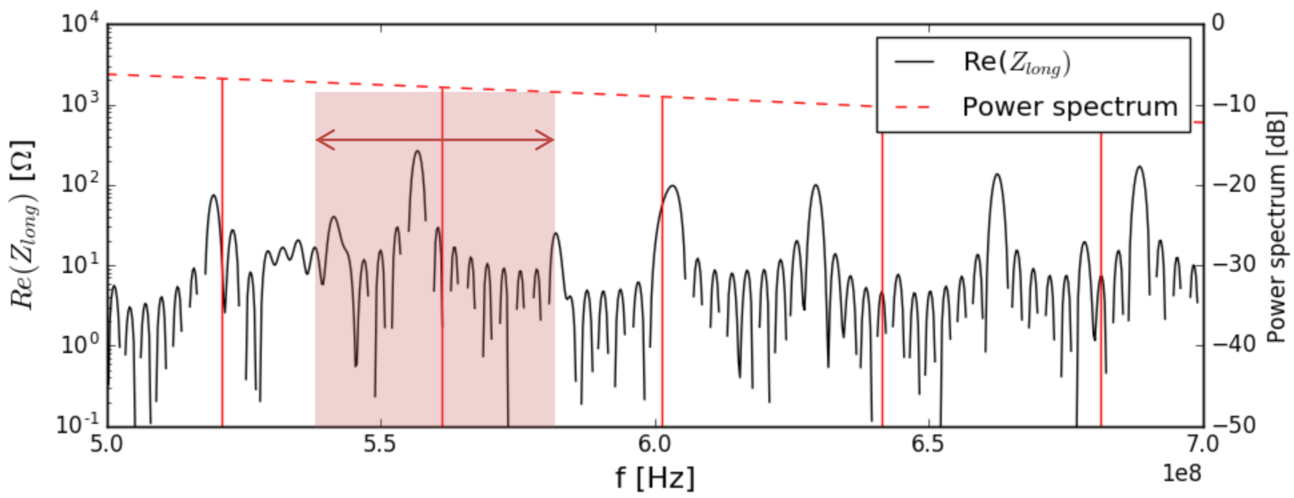
Evaluation of heating from HOMs

Since:

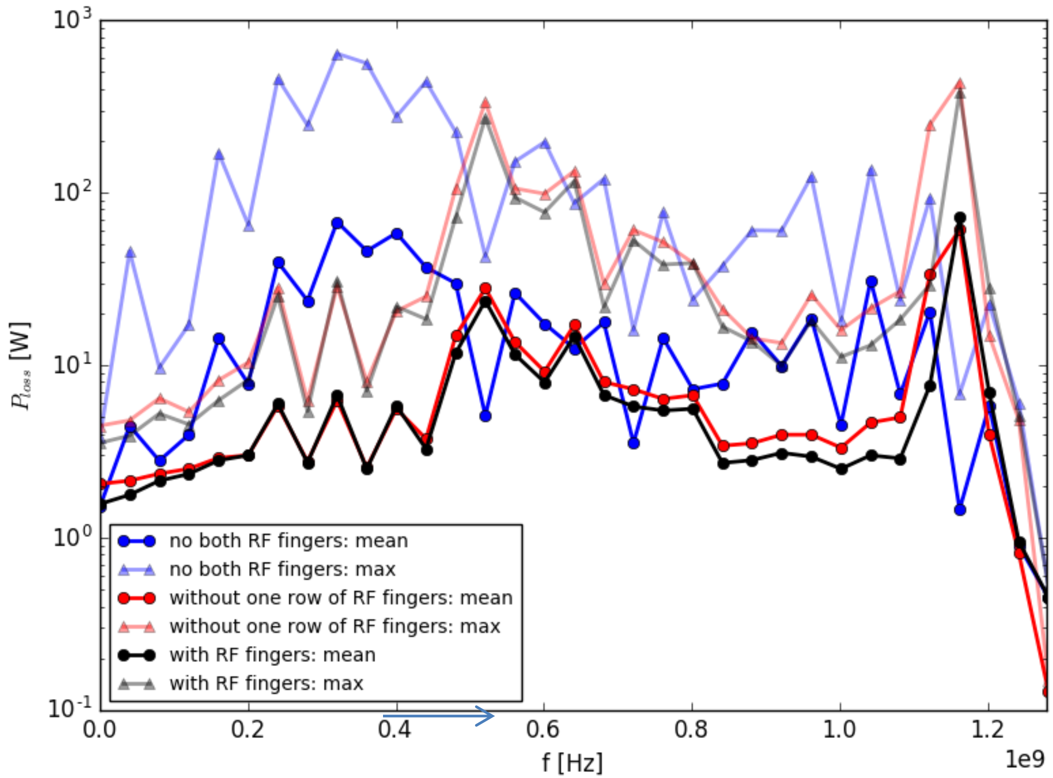
- **Spectral lines spaced by 40 MHz** for 25ns beam
- There is **uncertainty** on the HOM location due to **approximations in simulations**

We used a **statistical approach**:

- Added **uniform random noise** on each spectral line **within +/- 20 MHz** range (equivalent to apply the noise on the HOM themselves)
- Calculated the corresponding power loss.
- Deduced **mean/max** of the power loss for each spectral line.



Evaluation of heating from HOMs



- On **average** expected **< 100 W** per spectral line.
- **Max values can reach 800 W**
- **Heating** is **distributed** on different elements depending on **different field patterns**.
- **Input needed** on **max allowed power deposited per sensitive elements** in the structure.
- We can then estimate the **probability** an HOM, if present, could be **provoke deformation/damage** on these part of the TDIS.

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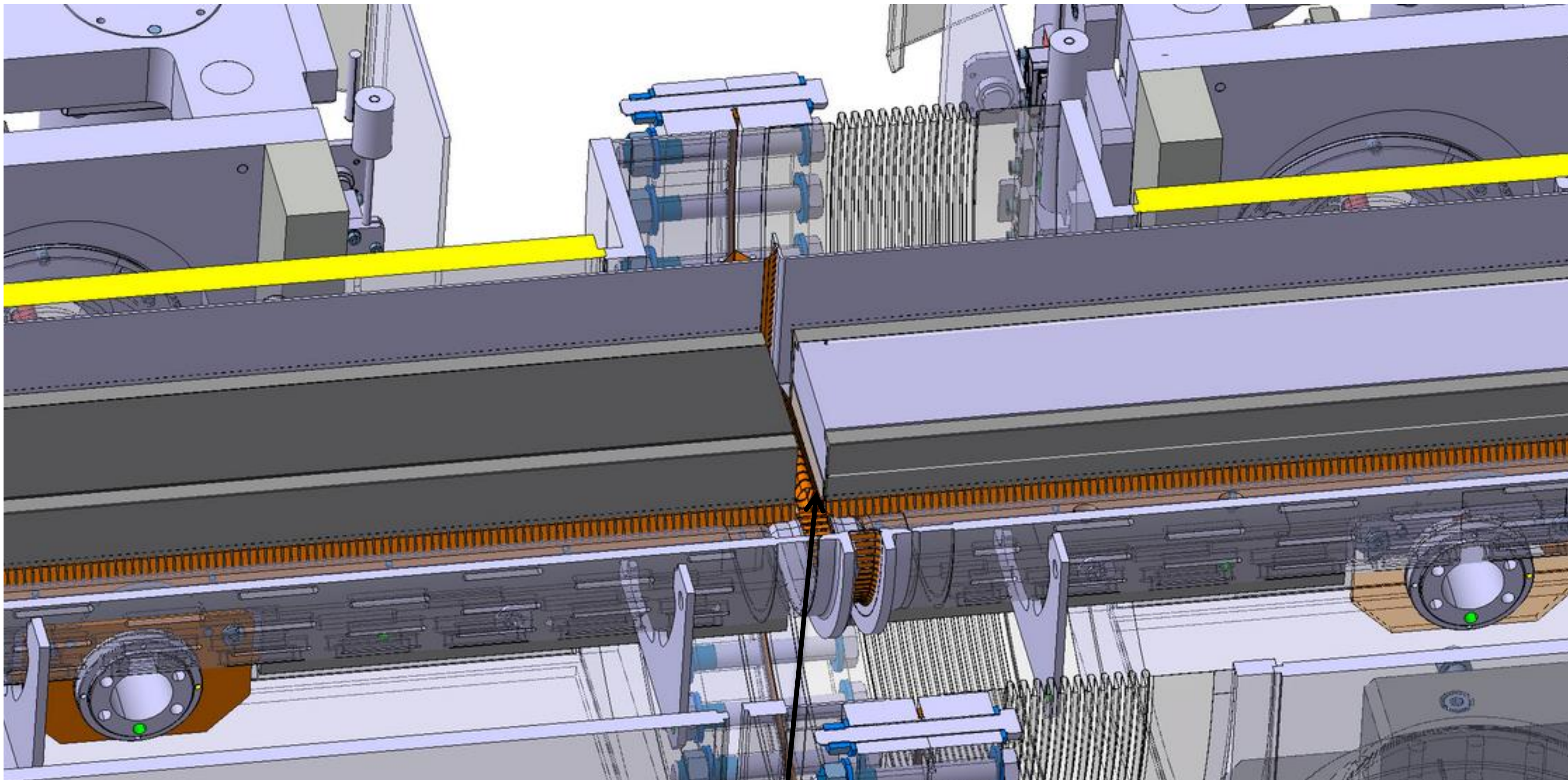
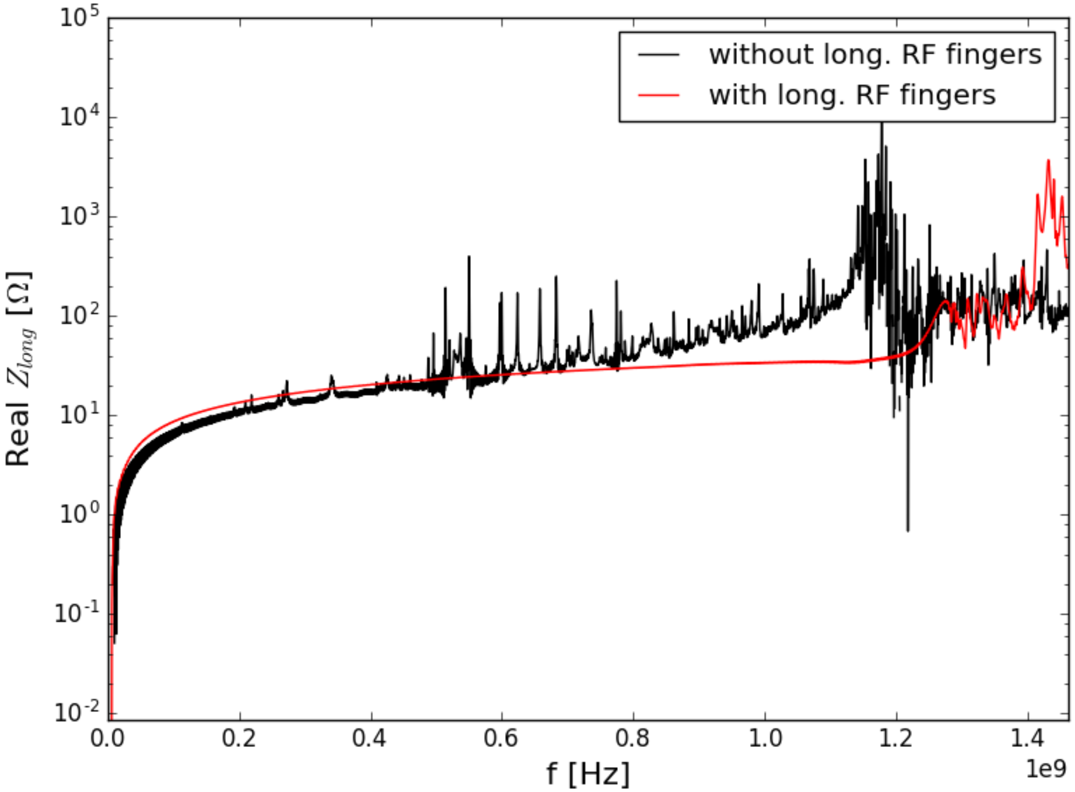
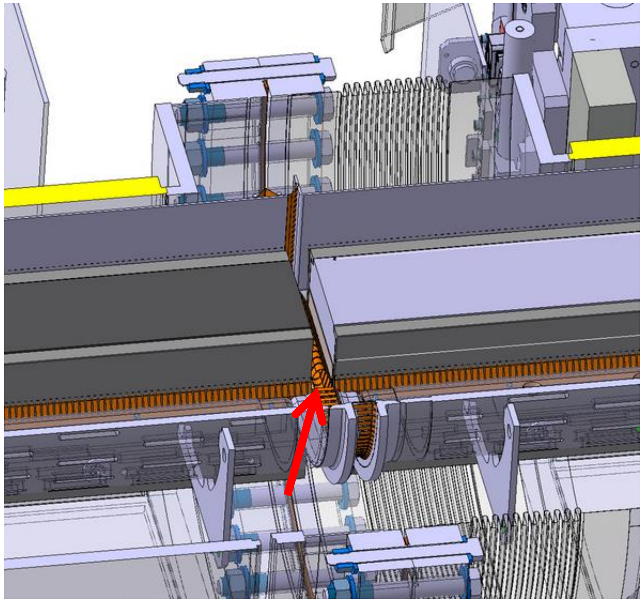
Longitudinal RF fingers



Longitudinal RF fingers

Longitudinal RF fingers





- **RF fingers location optimized** in order to **minimize the field communication with the tank volume** below the jaws (thanks Luca).
- **No visible HOMs in longitudinal impedance below 1.2 GHz** thanks to granted continuity of image current flow.
- **Need to quantify the probability of contact failure of one/some RF fingers**
- **Heat load** left is mainly due to the **resistive wall impedance of the jaw**.

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Evaluation of heating from RW

- Heating from broadband RW impedance at **injection** (3.8 mm haf gap).

$$\sigma_z = 8.1cm\ , \gamma = 479, N_b = 2.2 \cdot 10^{11} ppb, 2748\ bunches$$

Main jaw material	Resistivity [Ohm.m]	Z/n [mOhm]	Zyeff [MOhm/m]	Ploss [W]
Copper	17e-9	0.02	0.016	**55**
HL-LHC		95	3.8	-

Evaluation of heating from RW

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Main jaw material	Resistivity [Ohm.m]	Z/n [mOhm]	Zyeff [MOhm/m]	Ploss [W]
Graphite	15-6	0.4	0.2	**676**
Copper	17e-9	0.02	0.016	**55**
HL-LHC		95	3.8	-

Evaluation of heating from RW

- Heating from broadband RW impedance at **injection** (3.8 mm haf gap).

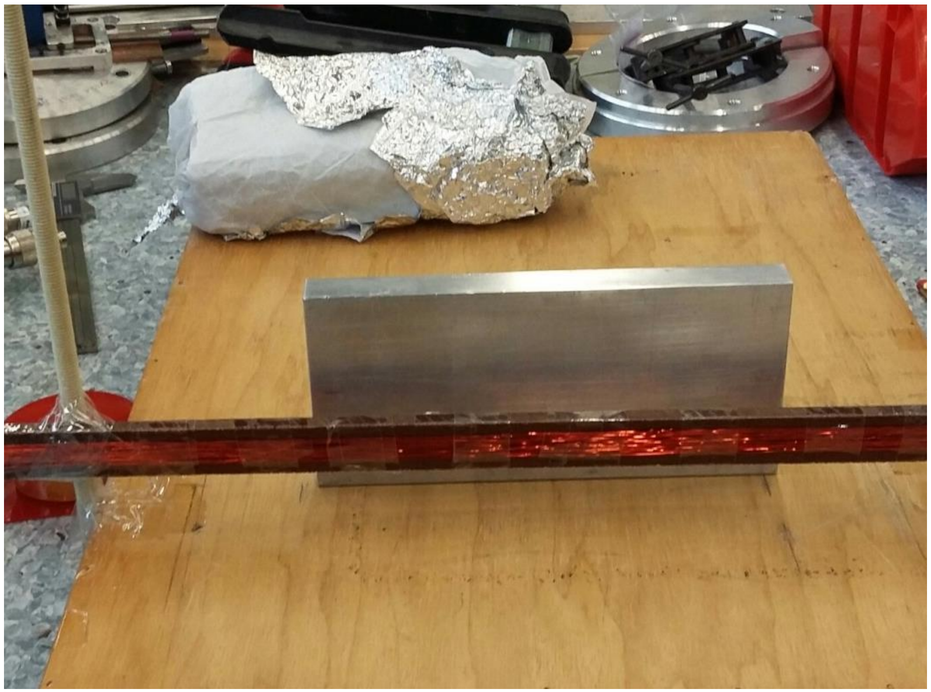
$$\sigma_z = 8.1cm\,, \gamma = 479, N_b = 2.2 \cdot 10^{11} ppb, 2748\ bunches$$

Main jaw material	Resistivity [Ohm.m]	Z/n [mOhm]	Zyeff [MOhm/m]	Ploss [W]
3D C-C	?	?	?	**?**
Graphite	15-6	0.4	0.2	**676**
Copper coating	17e-9	0.02	0.016	**55**
HL-LHC		95	3.8	-

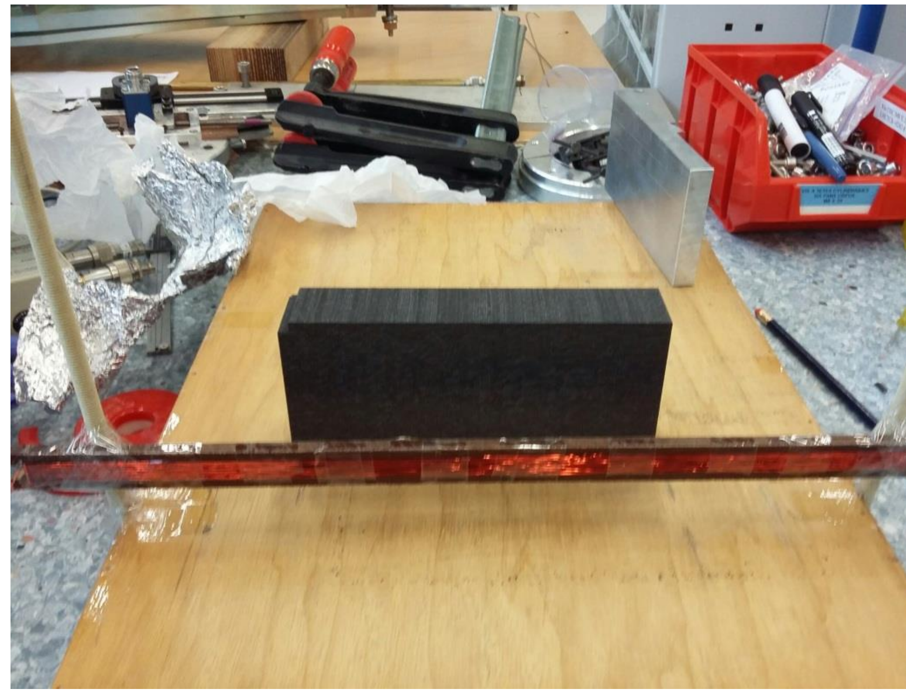
-> Performed a first measurement of 3D C-C resistivity

3D C-C resistivity measurement

Alu reference block



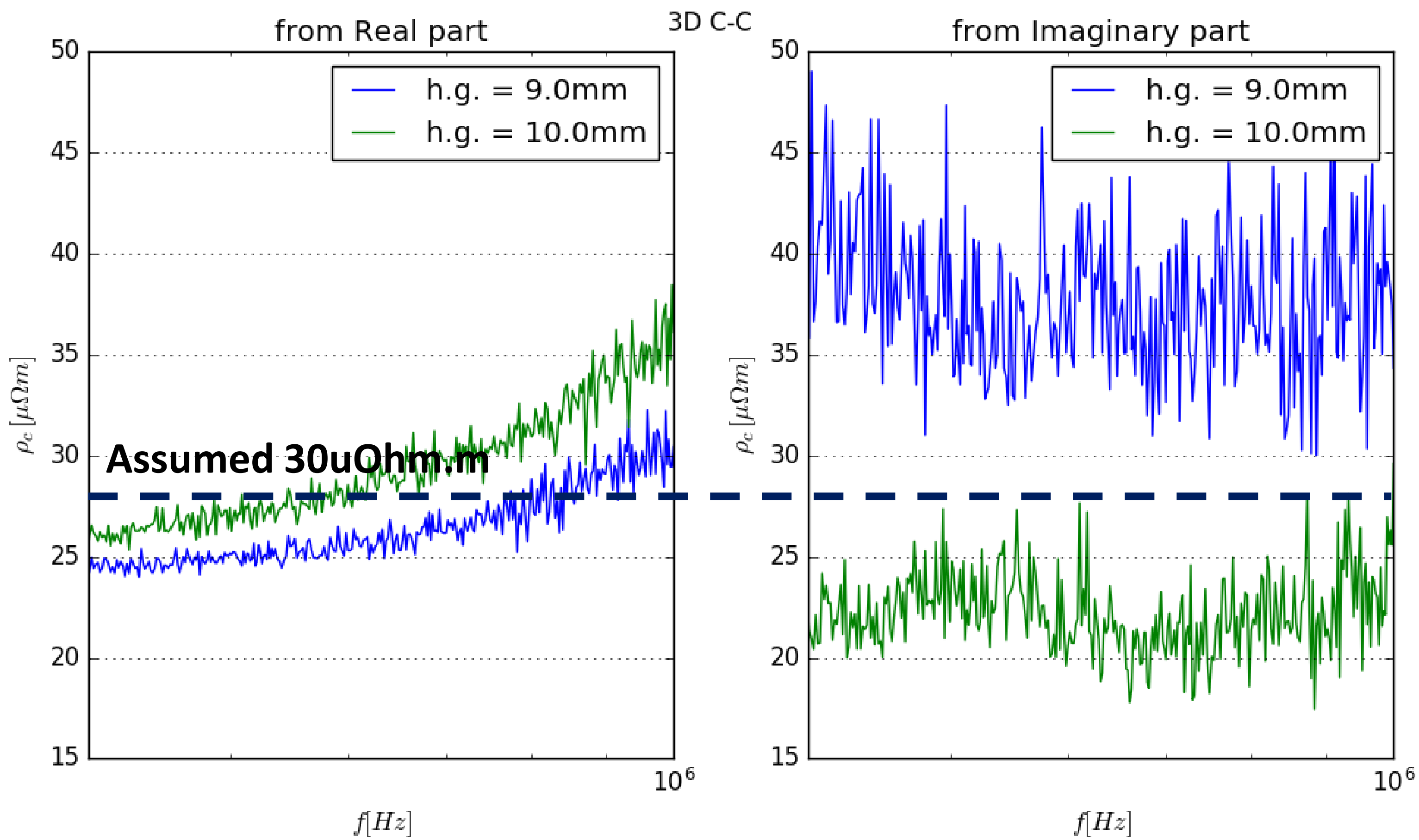
3D C-C block



- Measured the RF loop **impedance change*** between a **reference Alu block** and the **3D C-C block** provided by Inigo (thanks!)

* For details on the method and references: N.Biancacci in Impedance meeting, 2nd March 2015

3D C-C resistivity measurement



- **Resistivity ~= 30uOhm.m** within alignment uncertainties.
- **Being cross-checked** with **alternative DC resistivity measurements**.

Evaluation of heating from RW

- Heating from broadband RW impedance at **injection** (3.8 mm haf gap).

$$\sigma_z = 8.1cm\,, \gamma = 479, N_b = 2.2 \cdot 10^{11} ppb, 2748\ bunches$$

Main jaw material	Resistivity [Ohm.m]	Z/n [mOhm]	Zyeff [MOhm/m]	Ploss [W]
3D C-C	30e-6	0.6	0.3	**775**
Graphite	15-6	0.4	0.2	**676**
Copper coating	17e-9	0.02	0.016	**55**
HL-LHC		95	3.8	-

- **If cooling capacity is an issue Cu coating is highly recommended** to reduce the longitudinal broad band impedance and relative heating.

Evaluation of heating from RW

- Heating from broadband RW impedance at **flat top** (55mm haf gap).

$$\sigma_z = 8.1cm\ ,\gamma = 7460, N_b = 2.2 \cdot 10^{11} ppb, 2748\ bunches$$

Main jaw material	Resistivity [Ohm.m]	Z/n [mOhm]	Zyeff [kOhm/m]	Ploss [W]
3D C-C	30e-6	0.04	<1	**57**
Graphite	15-6	0.03	<1	**47**
Copper	17e-9	0.001	<1	**1.7**
HL-LHC		82	15000	-

- For all cases **< 60 W** expected from RW

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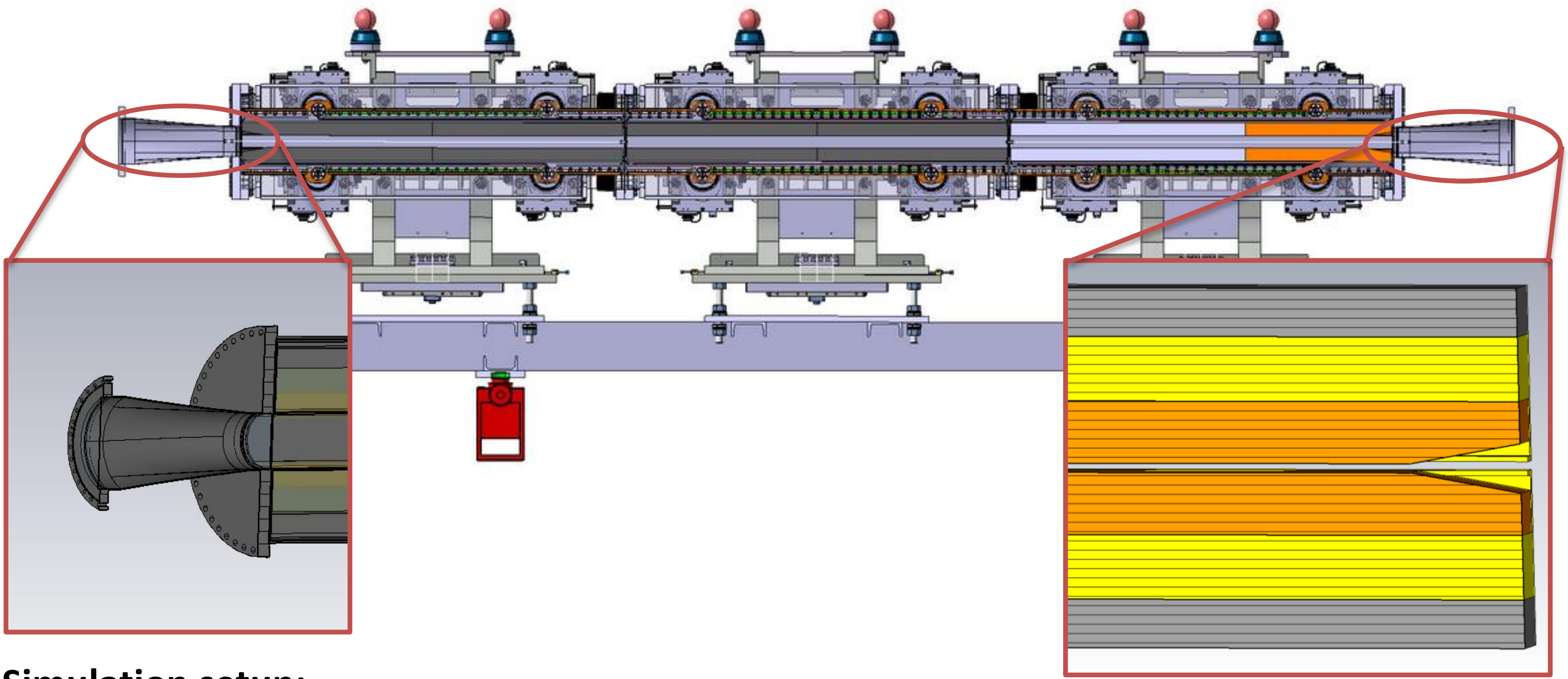
Effect of taper and conical transition

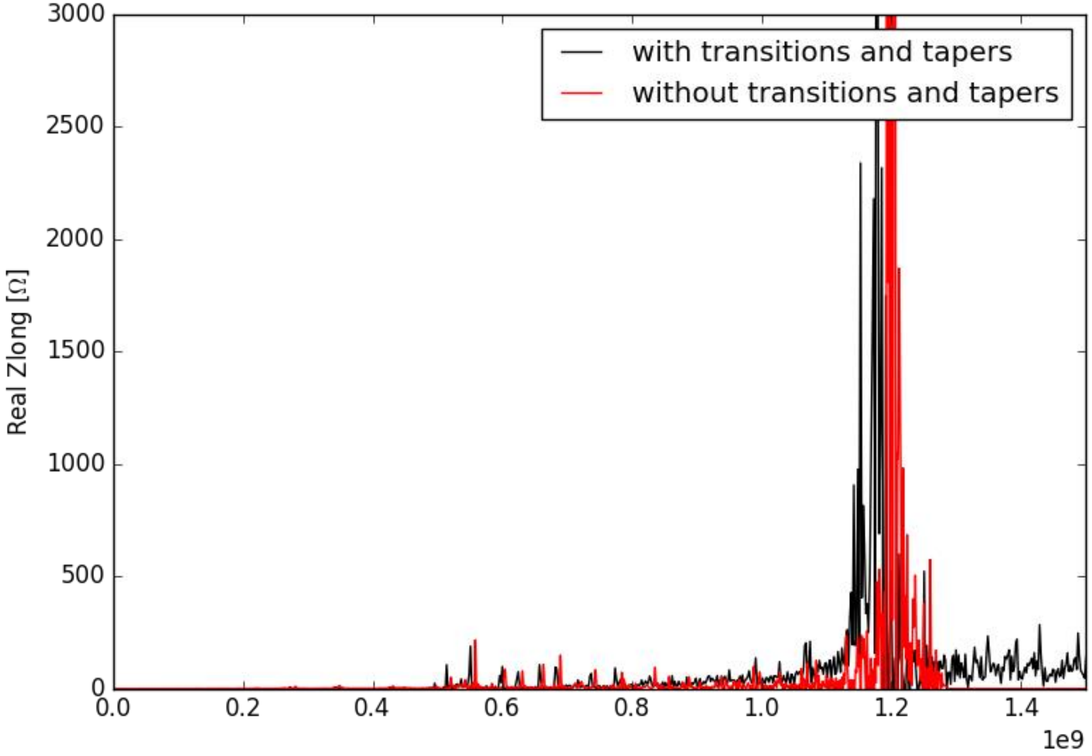


Simulation setup:

- Added **jaw tapers:** **L=100mm with 10° angle**.
- Added conical **jaw transitions.**
- **Considered Cu and Graphite jaws**.

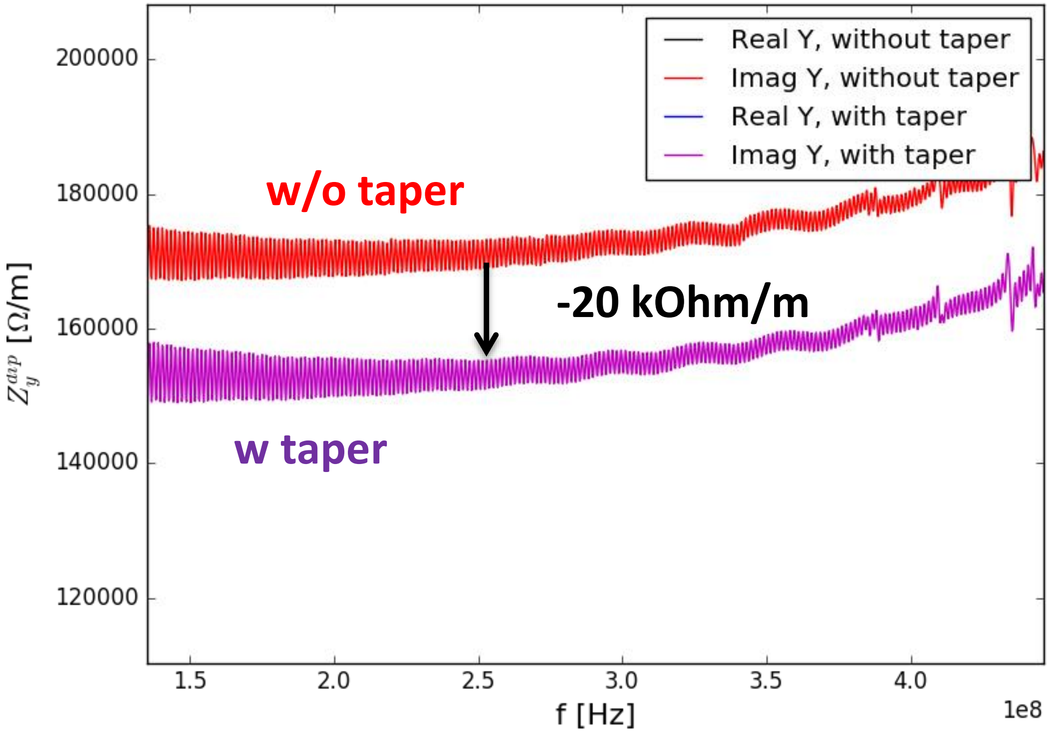
G.Mazzacano

Longitudinal impedance at injection



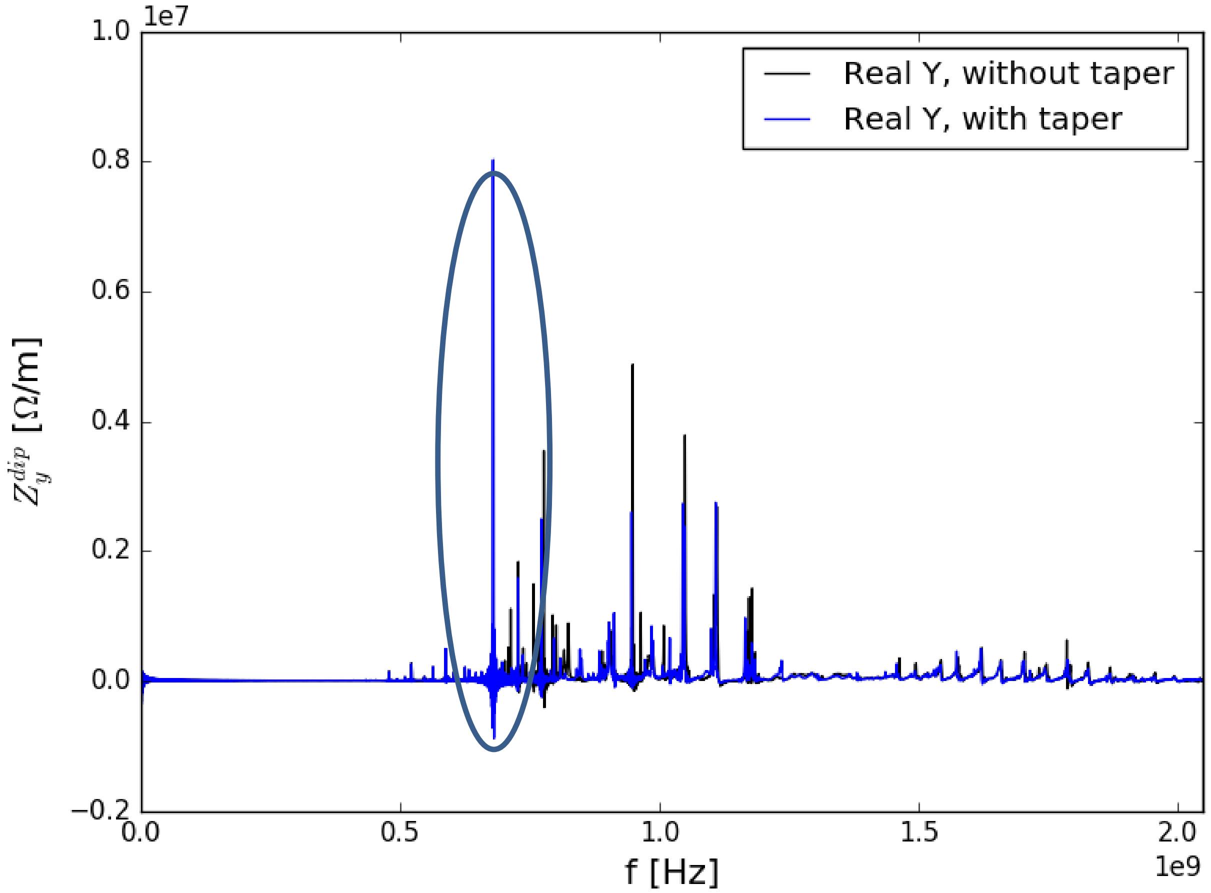
- **Slightly downshifted** the cluster the modes **around 1.2 GHz.**
- Globally, **negligible impact on mode pattern.**

Vertical impedance at injection



- **Broadband impedance reduced of 20kOhm/m** (i.e ~10 % of the transverse device impedance from RW only in case of 3D C-C)
- **Recommended to keep the taper for transverse impedance reduction.**

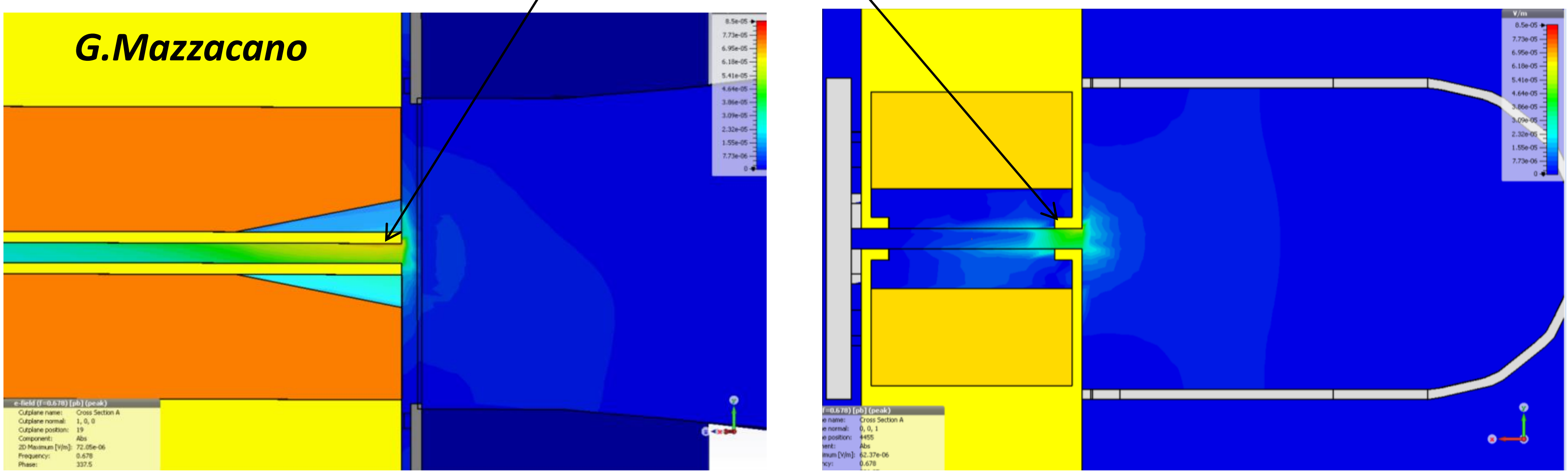
Vertical impedance at injection



- **Many HOMs present w/ and w/o taper** on the jaw peak impedance **~ 8 MOhm/m**
- **Strongest** mode **at 680 MHz**

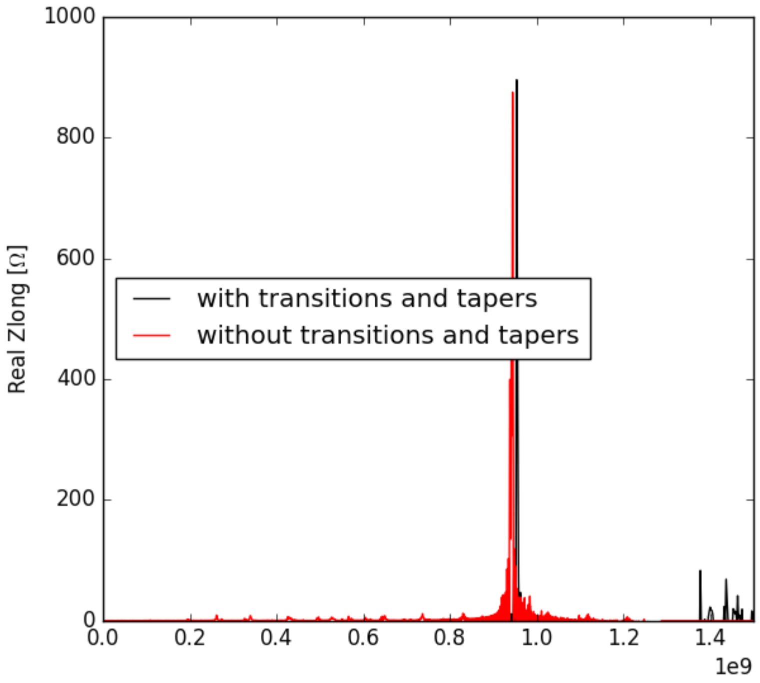
Vertical impedance at injection

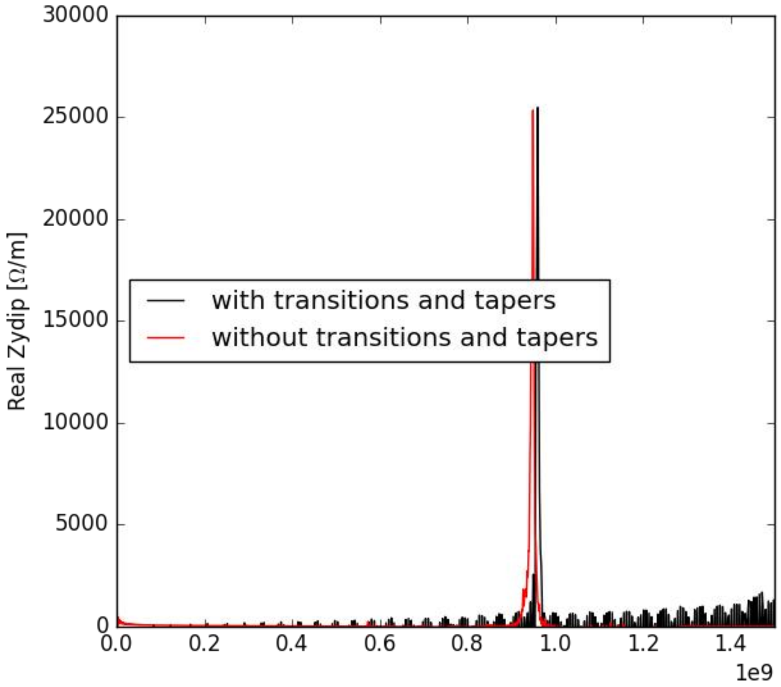
Lambda/4 mode around the not cut **edge of the envelope @ 680 MHz**



- **Strongest** mode **at 680** MHz located around the not cut edge of the envelope.
- Can be **cured tapering the envelope** as well.
- Evaluation of **HOMs impact on transverse stability requires statistical approach** as used for the longitudinal HOMs -> **Work still on progress, for the moment we evaluated the impact on stability from the impedance as it is: might be underestimated!**

Impedance at flat top





- **Small effect** of taper and transition when in parking position.
- The impedance contribution to the **heat load** budget is **negligible**.

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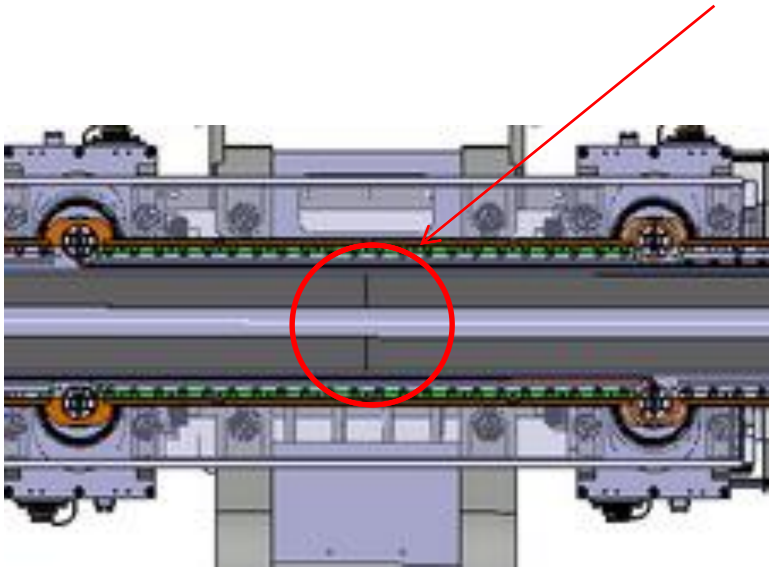
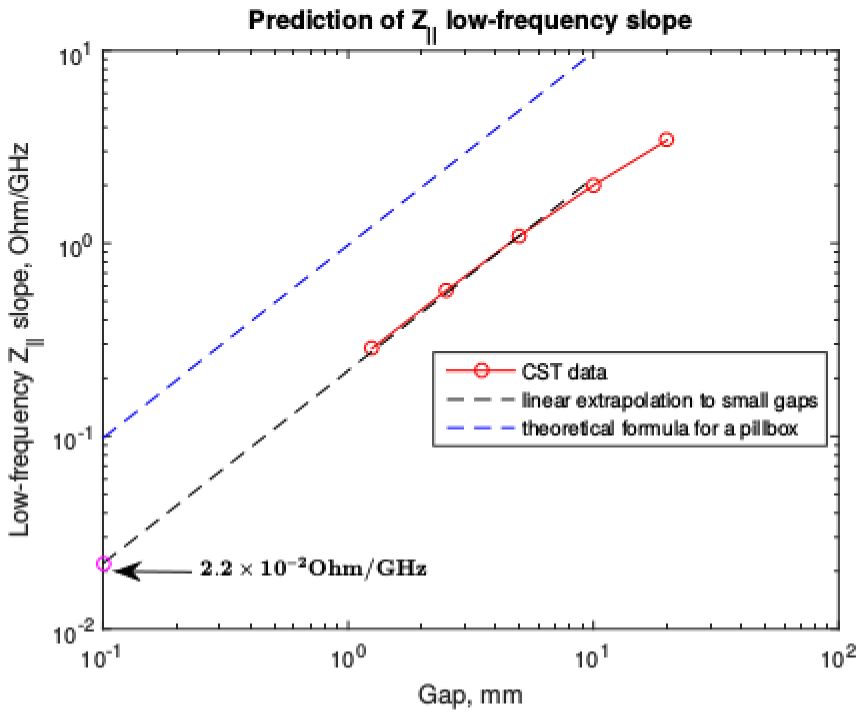
Effect of gaps between blocks

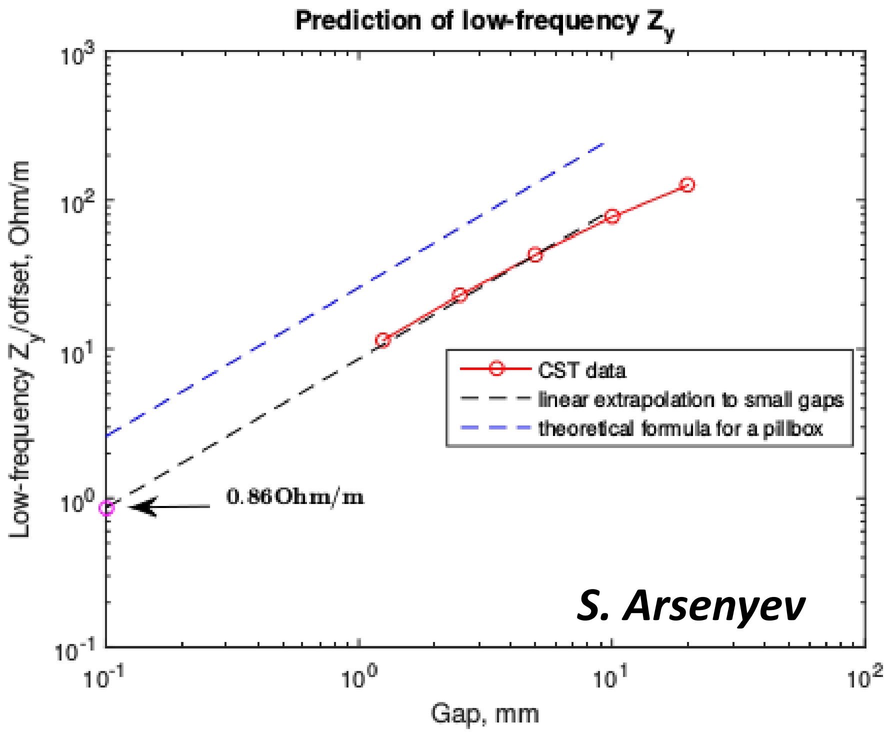


Jaw material	# gaps (upper and lower jaw)		
	1st tank	2nd tank	3rd tank
3D C-C	4	4	1
Graphite	1	1	1
Copper	1	1	1

- The jaw is made by **separated shorter blocks**.
- A **gap** might be remaining of the order of **0.1mm**
- **9 gaps** maximum when using **3D C-C**
- **Simulated within a simplified model** and extrapolated to **0.1mm gaps**.

Half gap = 55mm



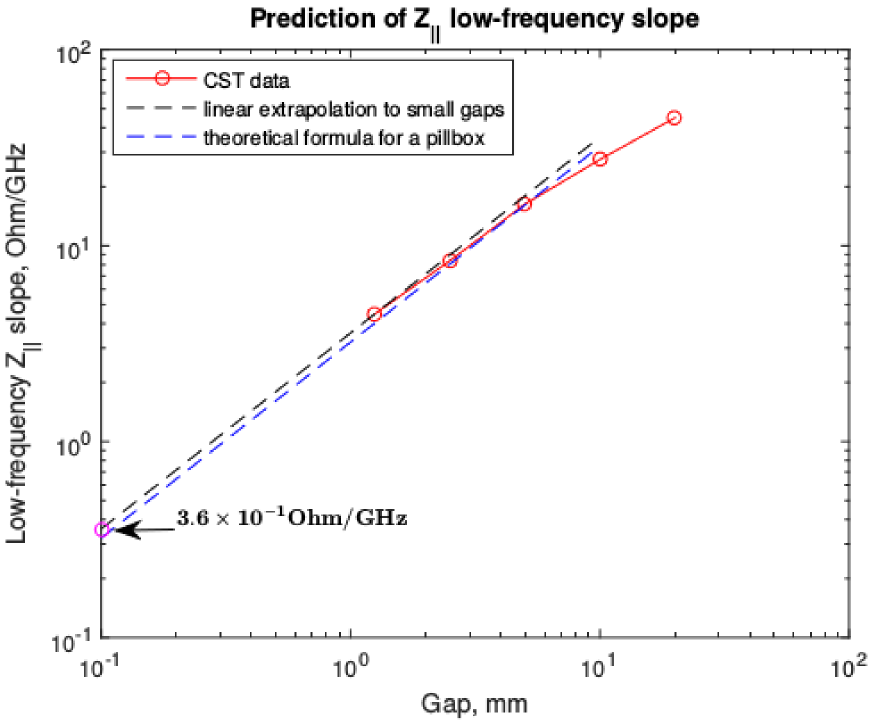


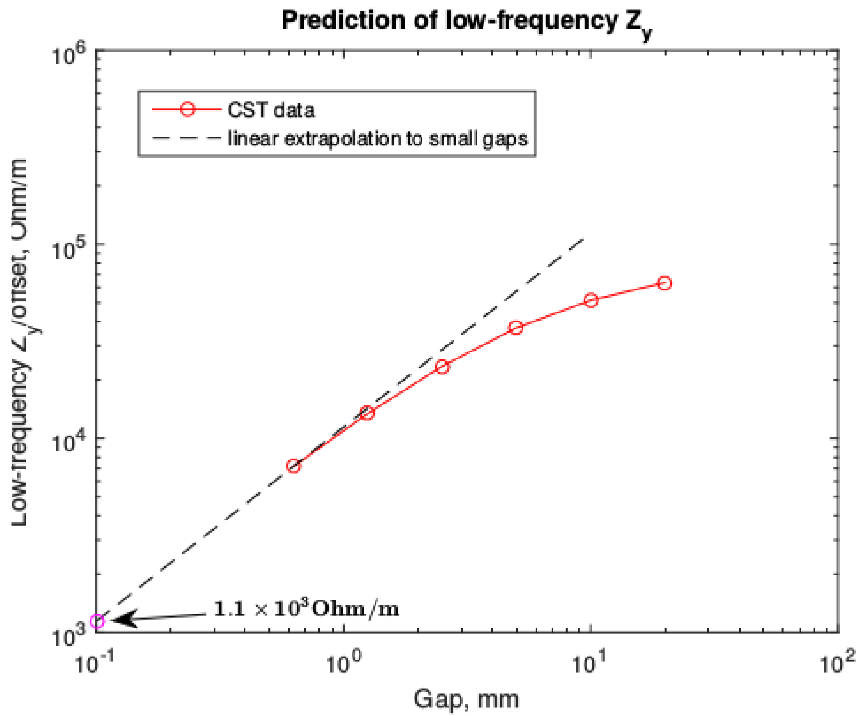
$$\frac{Z_0^{||}}{n} \approx -i \times 2.47 \times 10^{-7} \left(\frac{g}{0.1\ mm}\right) Ohm$$

$$Z_1^y \approx -i \times 8.6 \times 10^{-1} \left(\frac{g}{0.1\ mm}\right)\ Ohm/m.$$

- For **0.1mm gap** between blocks:
  - **Z/n = 0.2uOhm** -> For 9 gaps **1.8 uOhm**: **Negligible**
  - **Zy_eff = 0.5 Ohm/m** -> For 9 gaps **4.5 Ohm/m**: **Negligible**

Half gap = 4mm





$$\frac{Z_0^{||}}{n} \approx -i \times 4.1 \times 10^{-6} \left(\frac{g}{0.1\ mm}\right) Ohm$$

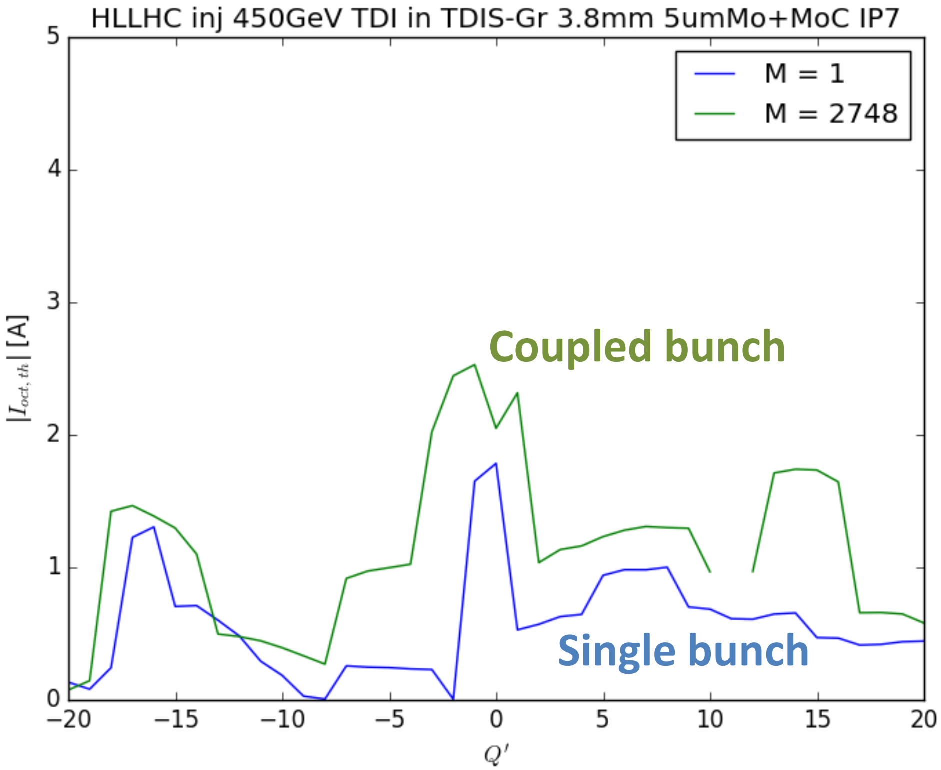
$$Z_1^y \approx -i \times 1.1 \times 10^3 \left(\frac{g}{0.1\ mm}\right)\ Ohm/m$$

- For 0.1mm gap between blocks:
  - Z/n = 4 uOhm -> For 9 gaps 36 uOhm: **Negligible**
  - **Zy_eff = 1 kOhm/m -> For 9 gaps 9 kOhm/m: ~50% tapering gain**

Outline

- TDI performance summary of 2015/2016
- TDIS design aspects relevant for impedance
- Effect on impedance of:
  - jaws segmentation
  - Lateral RF fingers
  - Heating from HOMs
  - Longitudinal RF fingers
  - Heating from resistive wall
  - Transition flanges and jaw tapers
  - Gaps between the blocks
- Impact on HL-LHC stability threshold at 450 GeV
- Conclusions and outlook

HL-LHC octupole stability threshold at 450 GeV



Parameters:

- 50 turns damper
- 8.1 cm bunch length
- Gaussian transverse profile
- $N_b = 2.2\ 10^{11}$ within $\epsilon_n = 2.5\ \mu m$
- Injection optics
- HLLHC impedance model with coated IP7 collimators
- TDIS **half gap** of **3.8 mm**
- TDIS jaw in **graphite**

- Assumed **Graphite jaw** and **transverse HOMs as-they-are: statistical simulations to be done to exploit the full impact of HOMs!**
- **10% increase in coupled bunch instability** threshold at injection **due to the HOMs**.
- **Margins for impedance but without ecloud!**
- If **Cu jaws, single bunch threshold 10% lower**, CB may be **unchanged** as it is driven by HOMs.
- **No issues** expected at **flat top** (<0.1% w.r.t. total impedance)

Conclusions (1/3)

- **Coating:**
  - **Cu coating is recommended** to keep the **device impedance low** unless **strong requirements** (10%-15% of the HLLHC budget: huge impact)
  - For **now** (**LHC**) it looks **we have margin** as i**mpedance is shadowed mainly by ecloud and coupling effects.**
  - For **HL-LHC** we **need to keep margins** to **host expected** (and **unexpected**) challenges with high brightness beams.

- **Heating**
  - **HOM heating** can be **drastically reduced** with **longitudinal and lateral RF fingers**: **recommended**
  - In case of **no or bad contacts**, **the heat load** can be as bad as **~800 W** depending on the mode.
  - **To be checked** if **sensitive equipment can sustain it** and with which **probability** it may happen.
  - **Needed input from mechanical design on the elements sensitive to power deposition.**
  - Power loss between **600 -800 W** for **Graphite** or **3D Carbon** jaws
  - Power loss between **< 100 W** for Copper coating: **recommended**

- **Longitudinal impedance budget:**
  - Contribution of **0.6mOhm** at injection, **0.04mOhm** at flat top from **RW impedance**.
  - **Loss of contacts** induces longitudinal **HOMs** -> Increase impedance up to **4 mOhm.**
  - **Within margins** but should be **considered with other equipment** (e.g. Velo when in operation).

Conclusions (2/3)

- **Transverse (vertical) impedance budget**
  - **~300 kOhm/m** at injection from RW (**~10% of the budget**)
  - **With transverse HOMs** -> Increase of ~300 kOhm/m (**~10% of the budget**)
  - **Negligible** impact at flat top

- **Transitions and jaw tapers:**
  - **Introduction of few transverse low frequency modes** at closed gap
  - Mode at **680 MHz** due to **not tapered envelope**
  - Can be **cured by envelope tapering but currently not an issue for stability**

- **Gaps between blocks:**
  - **Negligible** with **open gap**.
  - Impact with **close gap** at the order of **few %: recommend to keep the gaps minimized both in number and width.**

- **Octupole stability threshold at injection.**
  - **~1 A** necessary for stability at **Q' ~ 10** with **graphite** jaws in **single bunch**.
  - **10% less** expected going to **Copper** thanks to **RW impedance mitigation**.
  - **HOMs impact coupled bunch stability** threshold: **10% - 20% increase**.
  - **To be evaluated using statistical approach as done for heating: we might be in a lucky situation -> In case of issues HOM damping / reducing may be needed.**

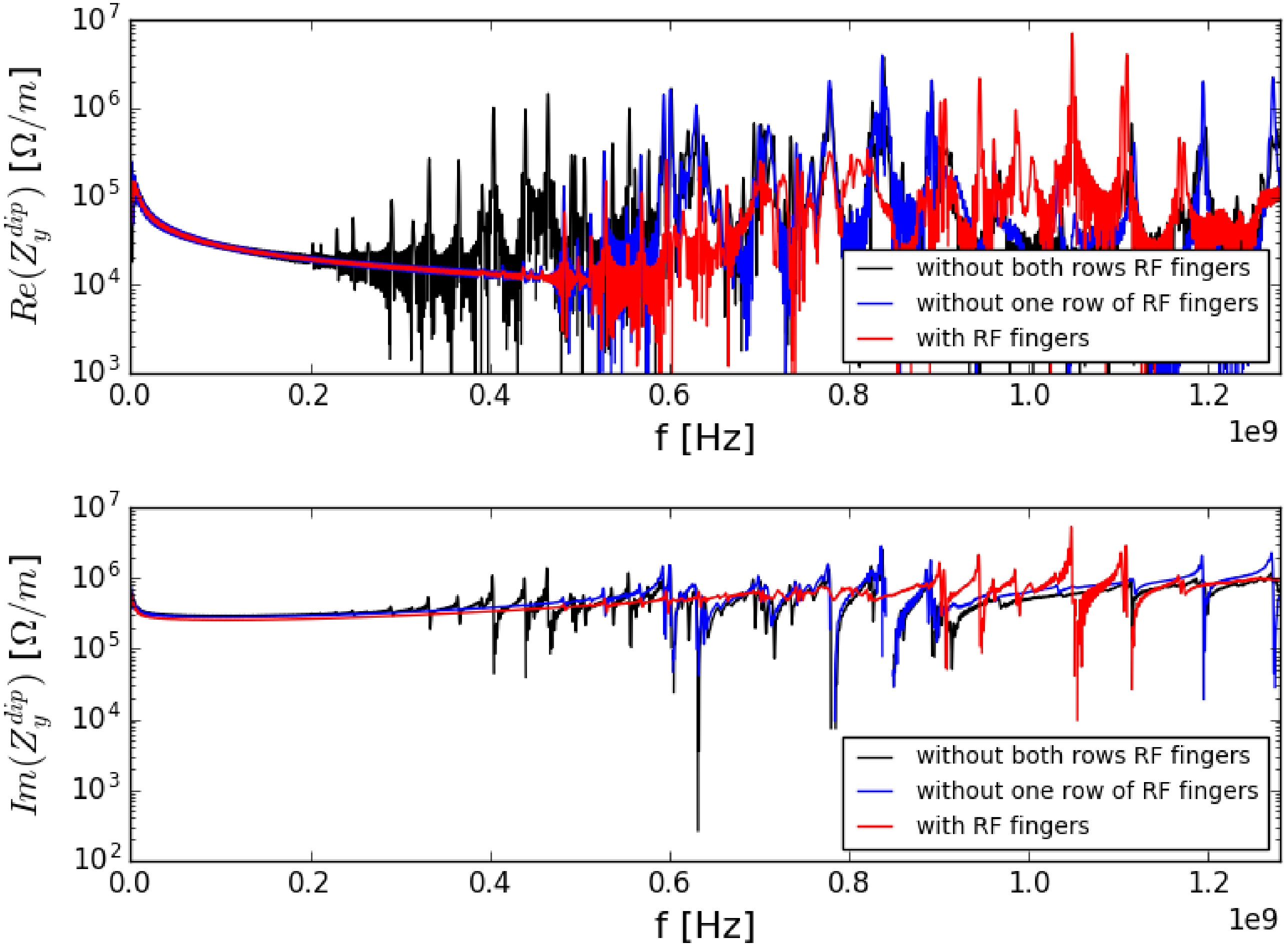
Conclusions (3/3)

- **Impedance measurements**
  - The **TDIS** should be **measured** by **the impedance team** as soon as it is available
  - The **PT100 probes** should be **shielded** in order to avoid **electromagnetic coupling** corrupting the temperature readings (current issue in present TDI)

Thanks for your attention!

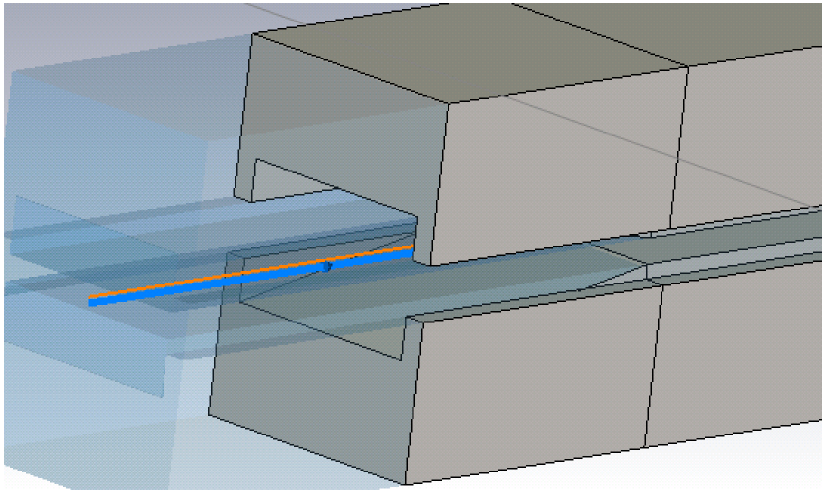
Backup

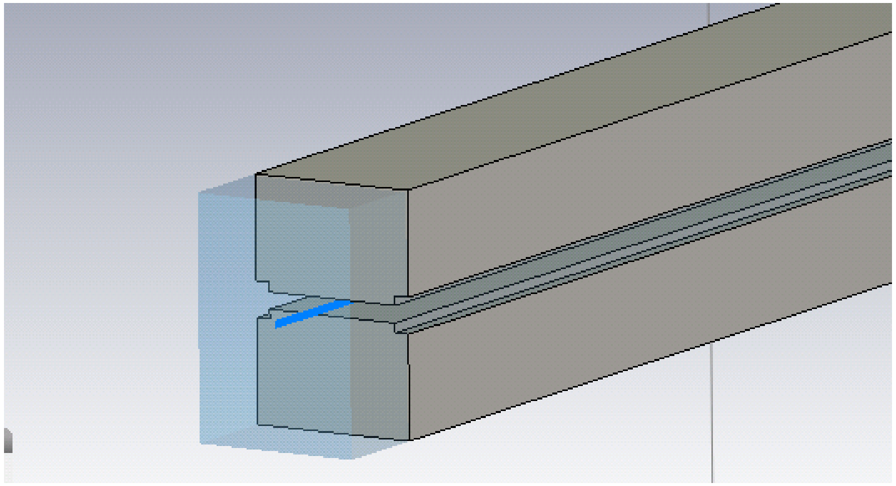
Transverse impedance (Y)



Stronger impact on **transverse impedance HOMs below 1GHz.**

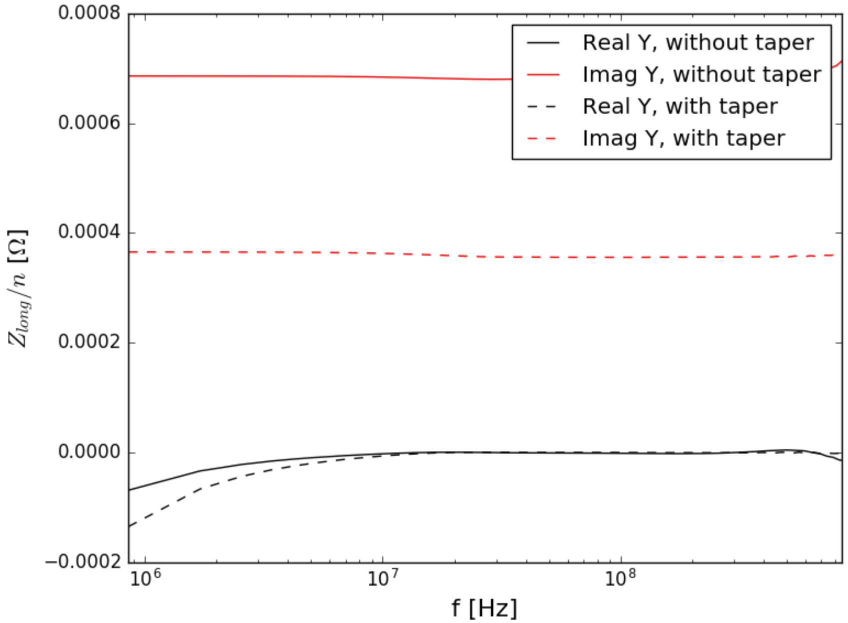
Effect of taper and conical transition

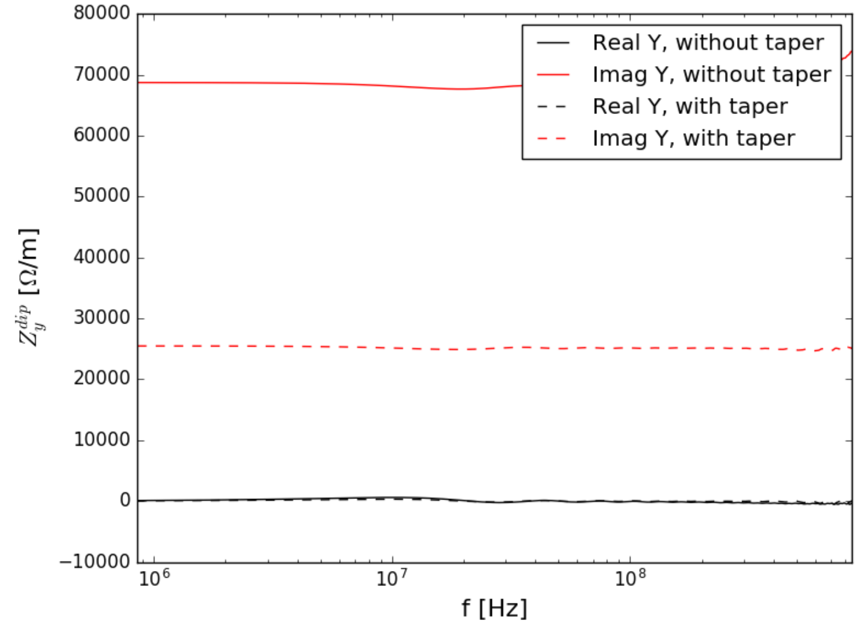




- Simplified models to study the effect of tapering:
  - Without taper: step from 55mm to 4mm half gap.
  - With taper: 10deg taper 100mm long -> ~17mm reduction in step
- Expected a reduction of the transverse impedance to 30% w.r.t. no taper

Effect of taper and conical transition





- Tapering reduces both longitudinal and transverse inductive impedance.
- ~30% gain in transverse impedance reduction (inductive).
- Almost a factor 2 in longitudinal impedance (inductive).