Beam coupling impedance of the new LHC collimators

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SIF 2015, 101^{th} National Congress
September 24th, 2015

High Luminosity LHC

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404

CAPACITIES

INFN Istituto Nazionale di Fisica Nucleare

Laboratori Nazionali di Frascati

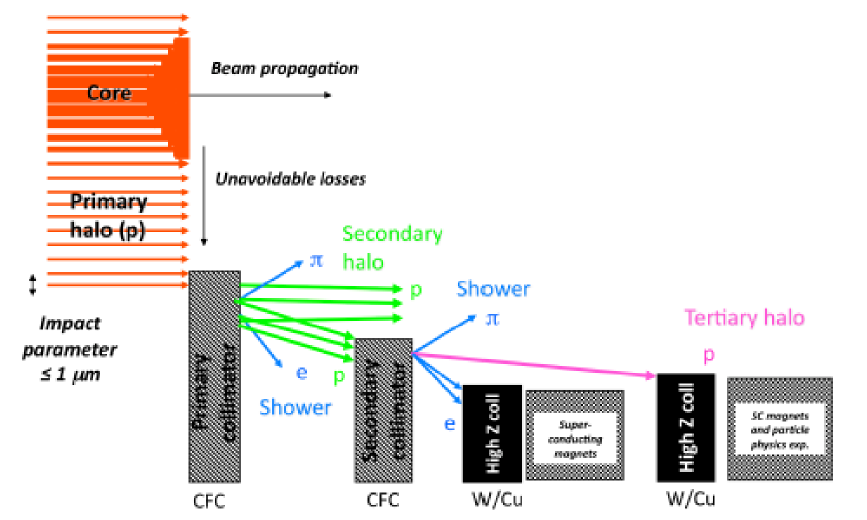
General outline

- Introduction
- LHC Run II TCS/TCT features
- Kick factors estimations
- Study of material properties for GdfidL simulations[1]
  - I Resistive wall
  - II TT2-111R dispersive properties
- LHC Run II TCS/TCT impedance study, HOMs characterization and comparison with measurements
- Conclusions

[1] Frasciello, O. and others. *Wake fields and impedances calculations with GdfidL, MMM and CST for benchmarking purposes*. Contributed talk at BE-ABP Impedance meeting, February 2nd 2014, CERN, Geneva, Switzerland. 2014. URL: https://indico.cern.ch/event/370569/.

The LHC collimators' hierarchy

A multi-stage beam cleaning system



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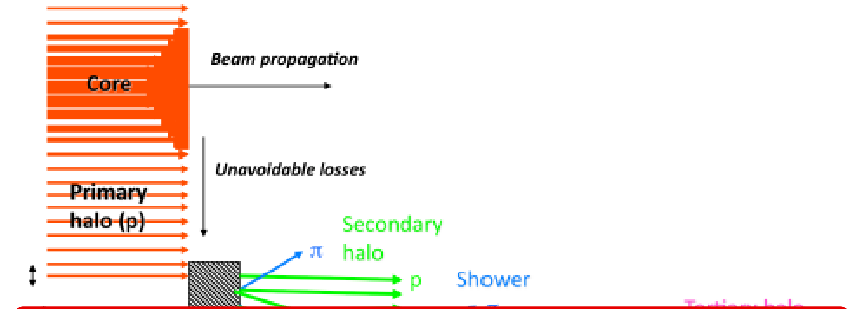


Functionalities

- Beam halo cleaning throughout the LHC beam cycle (99.998% of efficiency)
- Machine aperture passive protection against radiation (hardware)
- Halo diagnostics and tails scraping
- SC magnets protection against quenching

The importance of impedance study in beam dynamics

As a general remark

$$Z_{\parallel}(\omega) \equiv \frac{1}{c}\int_{-\infty}^{\infty} W_{\parallel}(z) e^{-i\frac{\omega}{c}z} \mathrm{d}z; \quad [\Omega] \tag{1}$$

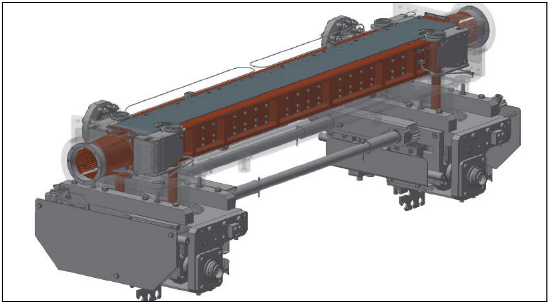
$$Z_{\perp}(\omega) \equiv \frac{i}{c}\int_{-\infty}^{\infty} W_{\perp}(z) e^{-i\frac{\omega}{c}z} \mathrm{d}z; \quad [\Omega/\mathrm{m}] \tag{2}$$

- Collective effects are *intensity dependent* $\Rightarrow$ the higher the currents the stronger the parasitic heating and the beams' instabilities $\Rightarrow$ beam lifetime and beam quality degradation
- Short range wake fields affect *single bunch* instabilities (e.g. Transverse Mode Coupling Instability); long range wakes affect *multi bunch* instabilities (e.g. Coupled Bunch Instability) $\Rightarrow$ HOMs damping in cavity structures is mandatory
- Collimators are among the main beam coupling impedance contributors!

What our work aims at..

Our goal is to simulate the complicated 3D collimator structures as close as possible to their real design

- Using CAD drawings and billions of mesh points
- Properties of real materials



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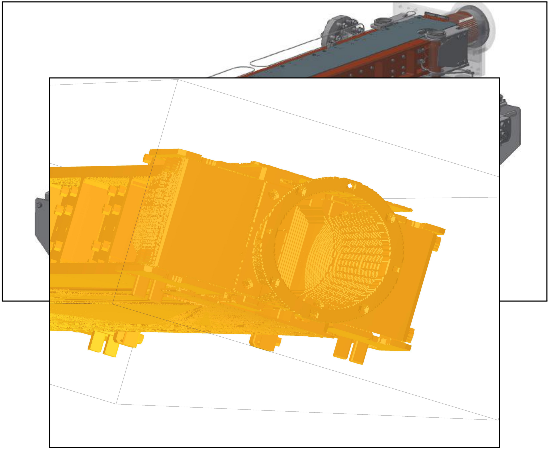

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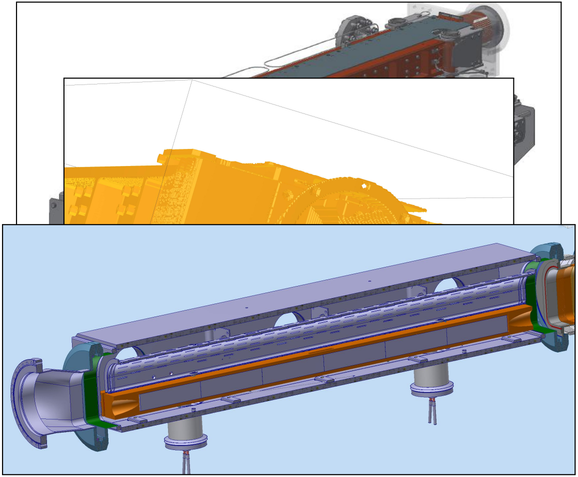

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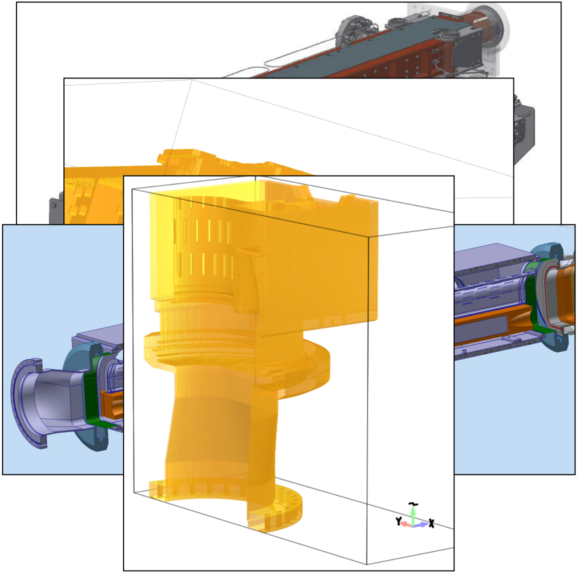
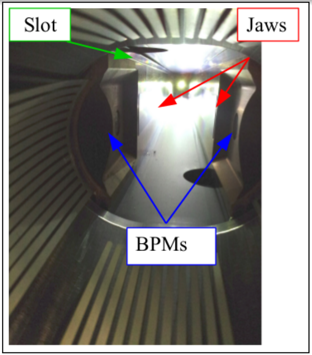
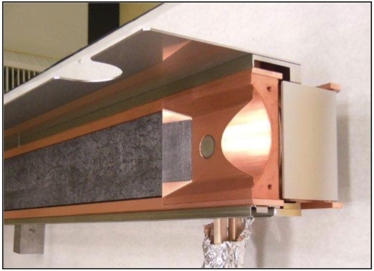


The LHC Run II BPM embedded collimator design





- RF fingers are removed from the previous LHC Run I TCS/TCT design[2]. HOMs damping provided by TT2-111R ferrite blocks
- It was already shown[3] that the transverse effective impedance was expected to increase of about 20% wrt LHC RUN I no BPM pickup button collimator design.

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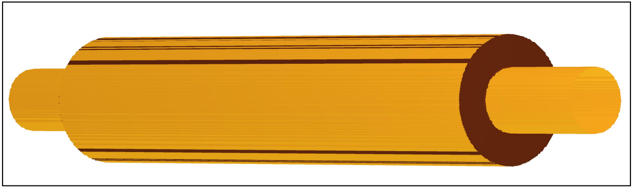
[2] O. Frasciello et al. "Geometric beam coupling impedance of LHC secondary collimators". In: *Proceedings of IPAC 2014*. (Dresden, Germany). 2014.

[3] Frasciello, O. and others. *Wake fields and impedances of LHC collimators*. Invited talk at 100th National Congress of the Italian Physical Society (SIF), 22 - 26 September 2014, Pisa, Italy. 2014.

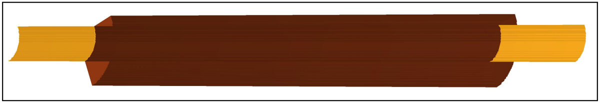
Resistive insert

GdfidL model

Whole view



One quarter view



L=30 cm, a=5 mm, b=10 mm, σ=$7.69 \cdot 10^5$ S/m

The length is chosen in order to minimize z ends contributions

Resistive insert

For Azimuthally Symmetric Thick Resistive Walls

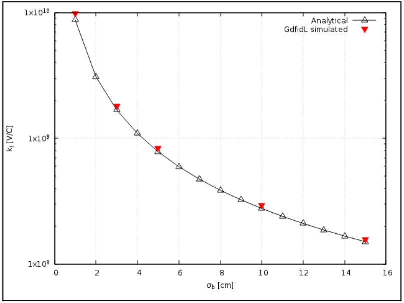
Longitudinal Loss factor

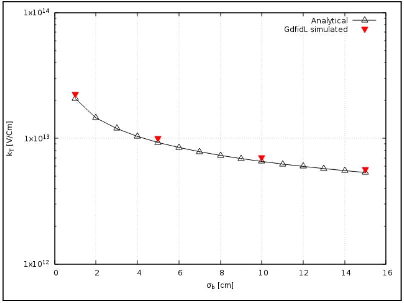
$$k_{\parallel} = \frac{cL}{4\pi b \sigma^{3/2}} \sqrt{\frac{Z_0 \rho}{2}} \Gamma\left(\frac{3}{4}\right)$$

Transverse kick factor

$$k_{\perp} = \frac{cL}{\pi^2 b^3} \sqrt{\frac{2 Z_0 \rho}{\sigma_z}} \Gamma\left(\frac{5}{4}\right)$$

Loss and Kick factors benchmark: GdfidL vs. Analytical formulas

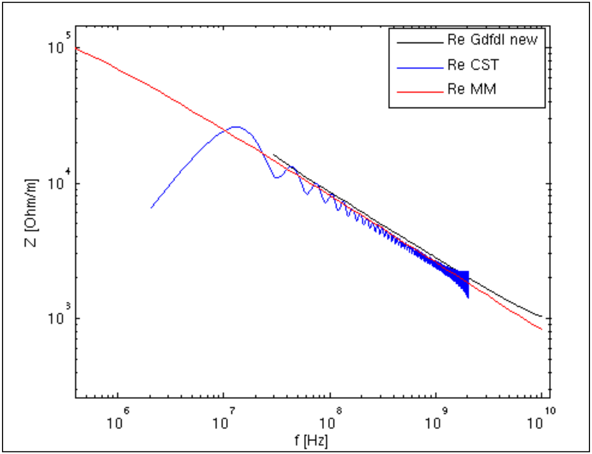




Some excess in Kicks may be due to the rough mesh

Resistive insert

Transverse impedance benchmark: GdfidL, CST, MMM

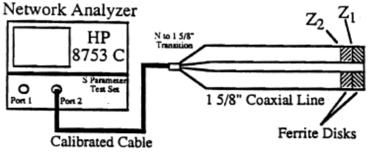


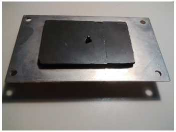
Results are shown down to $\sim$ 10 MHz because this is the frequency range of interest up to now. We also got results down to fractions of MHz (not shown here)

Simulation of S_{11} measurement setup

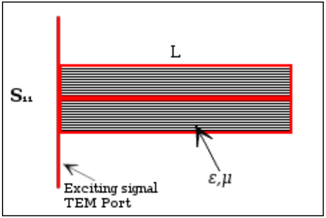
In our opinion it was a very useful method to arrange simple coaxial probe measurement simulations, in order to check for the numerically computed S-parameters to be fully in agreement with theoretical prediction.

Measurement layout (From R. Boni *et al.*, LNF-93/014)





Simulated measurement

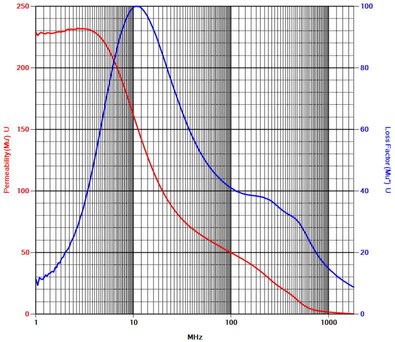


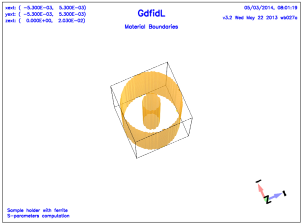
Analytical formulas

$$S_{11} = \frac{\Delta \cdot \tanh(\gamma L) - 1}{\Delta \cdot \tanh(\gamma L) + 1}; \qquad \gamma = j\omega\sqrt{\varepsilon\mu}; \qquad \Delta = \sqrt{\frac{\mu_r}{\varepsilon_r}}$$

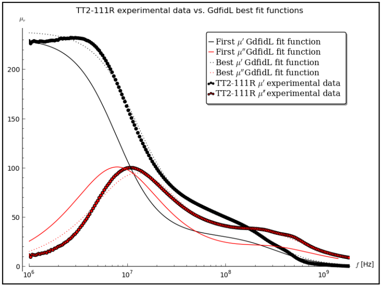
Simulation of S_{11} measurement setup

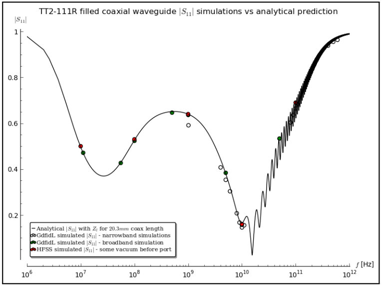
μ experimental data (Courtesy of B. Salvant) & GdfidL DUT model





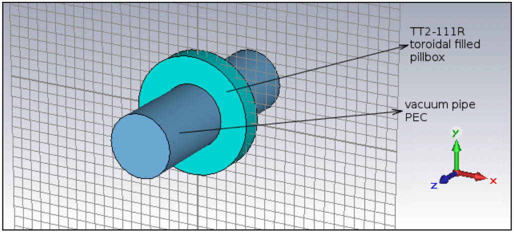
Data fits with n[th] order Lorentz function & S_{11} results comparison

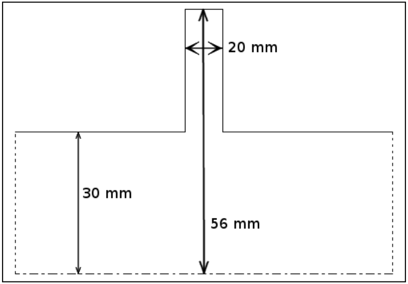




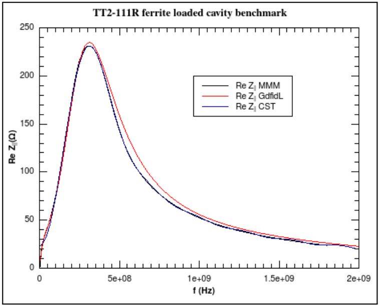
TT2-111R ferrite loaded pillbox

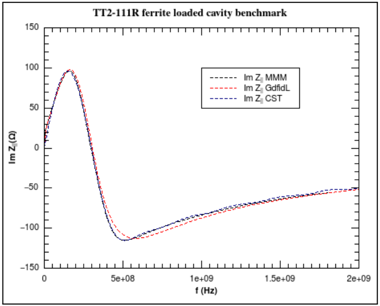
The simple pillbox geometry

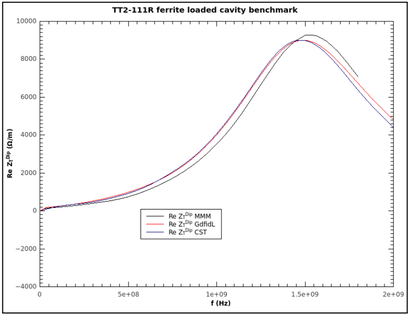


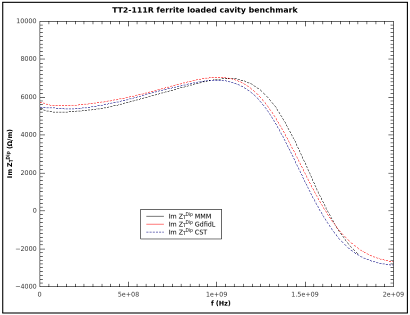


TT2-111R ferrite loaded pillbox

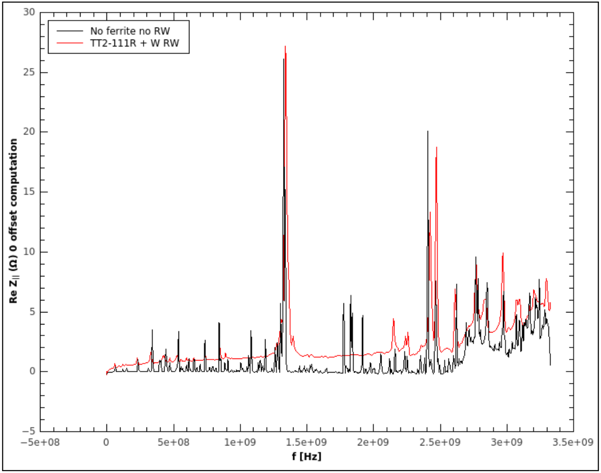






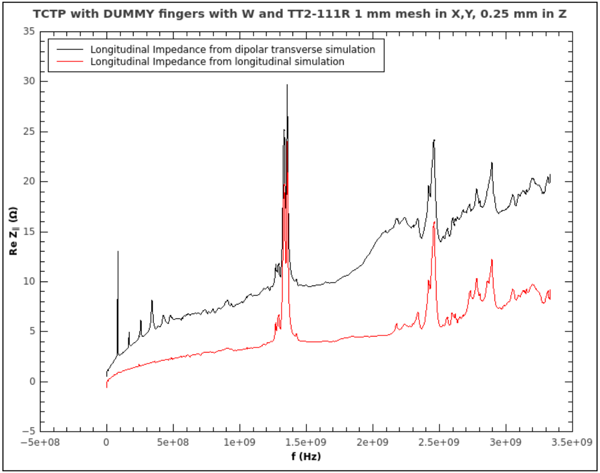


BPM TCS-TCT:$Z_{\parallel}$



- An overall damping feature is shown to be proper of the structure made by resistive Tungsten jaws plus ferrite blocks

BPM TCS-TCT: $Z_{\parallel}$

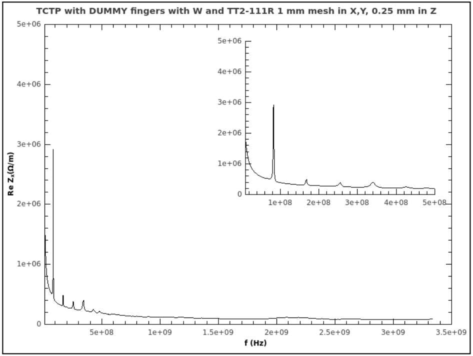


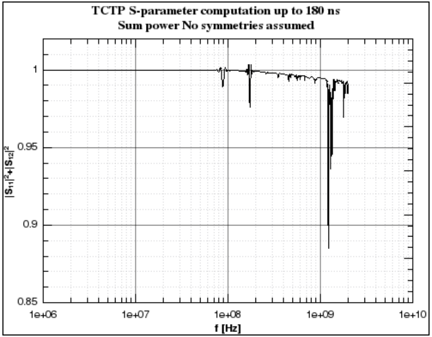
- The low frequency modes grow with the offset

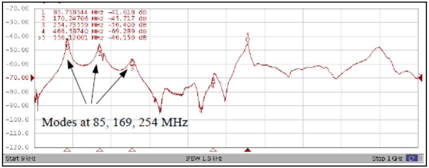
$\Downarrow$

- The low frequency peaks clearly correspond to transverse modes

BPM TCS-TCT:$Z_\perp$ simulations vs loop meas w/ ferrite





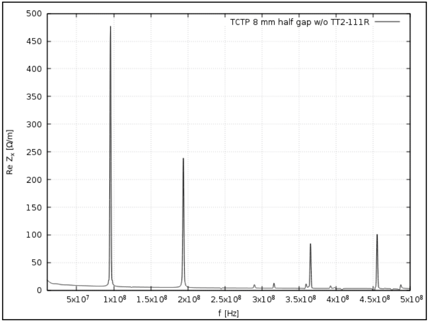


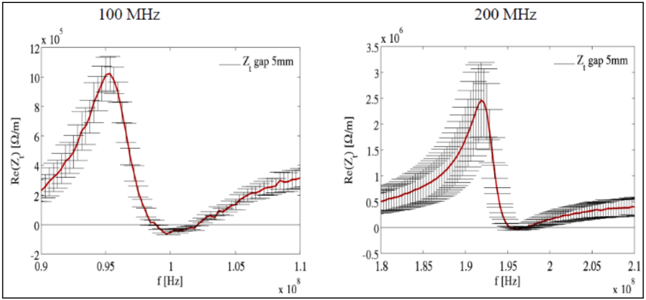
GdfidL computed modes

i	f [MHz]
1	84.0
2	169.0
3	256.0

Measurements data and plots courtesy of N. Biancacci

BPM TCS-TCT: $Z_\perp$ simulations vs wire meas w/o ferrite





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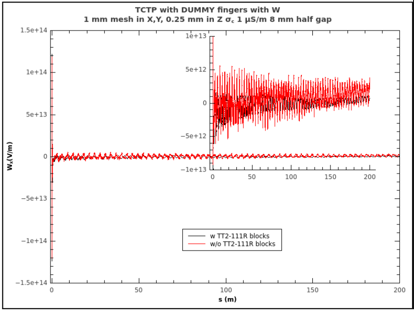
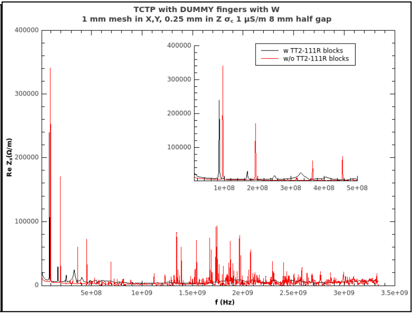
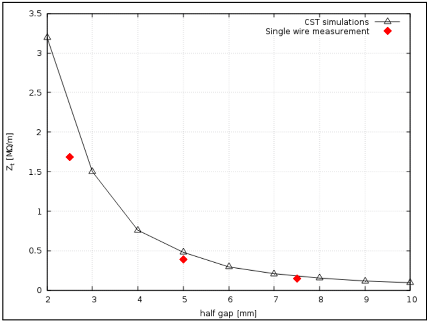






Measurements data courtesy of N. Biancacci

BPM TCS-TCT: $Z_\perp$ vs measurements

- All HOMs found to correspond to those measured with loop (w/ ferrite) and with single wire (w/o ferrite) at the same frequencies
- The R_s of the first HOM is about 2 times higher than that obtained by CST (1.5 MΩ/m) for the same half gap
- Results may depend on
  - the gap between the plate where ferrite blocks are installed (HOMs frequencies shifts of the order of tens %)
  - the gap between collimator jaw and tank (HOMs R_s)
  - mesh and computed wake length
- A strong damping feature of the ferrite is exhibited at all frequencies
- Adding ferrite blocks, HOMs' frequencies shift down and their Rs are damped; E.g. for the first HOM, the characteristic frequency shifts from $\approx$ 95 to $\approx$ 84.5 MHz, whereas the R_s is damped from $\approx$ 340 kΩ/m to $\approx$ 237 kΩ/m;
- the wake has a stronger and better convergence, within the computed range of 200 m, for the collimator with ferrite, as expected.

Conclusions

- The performed numerical tests have confirmed that GdfidL reproduces very well the properties of the lossy dispersive materials. The simulation test results for the resistive walls and the lossy ferrites are in a good agreement with available analytical formulae and the results of other numerical codes and semi-analytical models
- The numerical studies of the impedance of the new LHC collimators with incorporated BPMs have shown that:

  I The longitudinal higher order modes till 1.2 GHz are heavily damped by the TT2-111R ferrite blocks and by the resistive contribution of the jaws. This is very important for the heating reduction of the collimators in the multibunch regime (for the nominal LHC bunches 7.5 cm long);

  II The transverse modes at low frequencies are less damped, there are still residual transverse HOMs at frequencies around 100 MHz and 200 MHz with non-negligible shunt impedances. The calculated frequencies of the modes are in remarkable agreement with the loop measurements. The shunt impedances of the modes obtained numerically agrees within a factor of 2 with the experimental data of the wire measurements performed by the CERN impedance group;

  III The broad-band transverse impedance of the new double taper collimators are evaluated to be approximately by 20% higher with respect to that of the single taper secondary collimators.
- The calculated impedance of the new collimators is required for the update of the LHC impedance model used to estimate the instabilities rise times, betatron tune shift with the beam current, eventual beam power losses etc

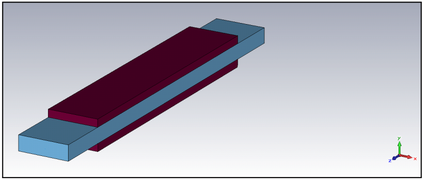
Thanks for your kind attention

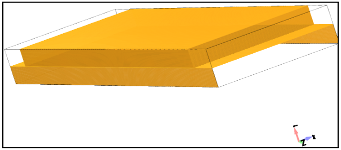
Acknowledgements: *E. Metral, B. Salvant, N. Biancacci*
W. Bruns, for his invaluable support

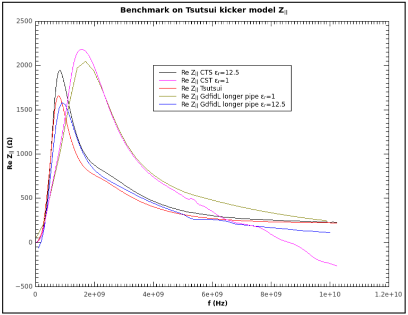
Backup slides

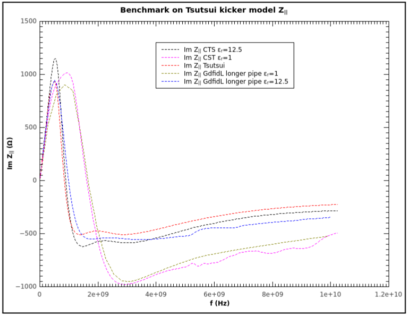
Tsutsui model for TT2-111R ferrite kicker

Kicker model in CST and GdfidL

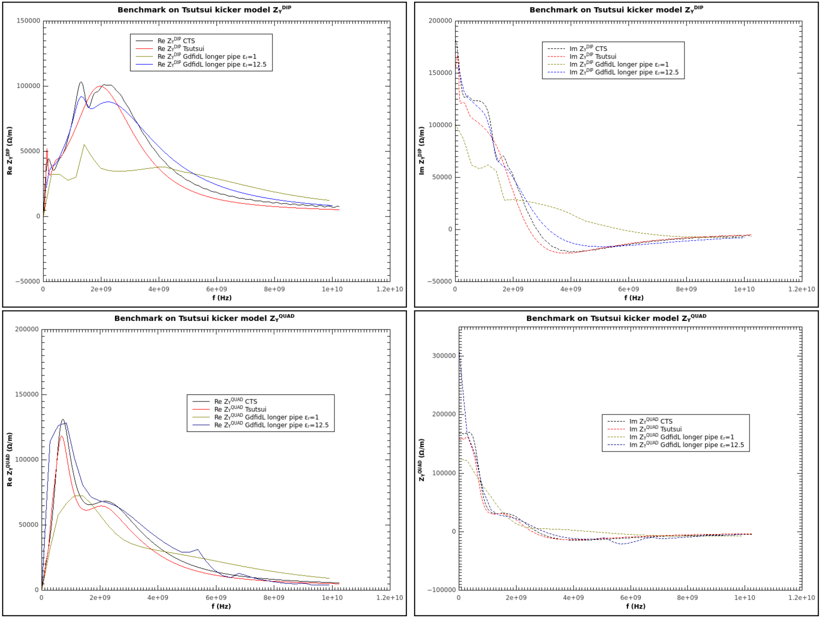








Tsutsui model for TT2-111R ferrite kicker



ε_r contribution to $Z_{\parallel}$ and $Z_{\perp}$ in Tsutsui models

For axisymmetirc model:

$$\frac{Z_{\parallel}}{L} \simeq (1-j)\frac{Z_0}{2\pi b}\sqrt{\frac{\mu_r''}{2\varepsilon_r'}}$$

For rectangular model:

$$\frac{Z_{\parallel}}{L} = \frac{j}{I_0}\sum_{n=0}^{\infty}\frac{E_{xn}^{(S)}\text{sh}+E_{yn}^{(S)}\text{ch}}{\left[\frac{k_{xn}}{k}(1+\varepsilon_r\mu_r)\text{shch}+\frac{k_{yn}}{k}(\mu_r\text{sh}^2\text{tn}-\varepsilon_r\text{ch}^2\text{ct})\right]/(\varepsilon_r\mu_r-1)-\frac{k}{k_{xn}}\text{shch}}$$

$$\frac{Z_{\perp}^X}{L} = j\frac{Z_0}{2a}\sum_{n=0}^{\infty}\frac{k_{xn}^2}{k}\left[\frac{\frac{k_{xn}}{k}(1+\varepsilon_r\mu_r)\text{shch}+\frac{k_{yn}}{k}(\mu_r\text{sh}^2\text{tn}-\varepsilon_r\text{ch}^2\text{ct})}{(\varepsilon_r\mu_r-1)}-\frac{k}{k_{xn}}\text{shch}\right]^{-1}$$

$$\frac{Z_{\perp}^Y}{L} = j\frac{Z_0}{2a}\sum_{n=0}^{\infty}\frac{k_{xn}^2}{k}\left[\frac{\frac{k_{xn}}{k}(1+\varepsilon_r\mu_r)\text{shch}+\frac{k_{yn}}{k}(\mu_r\text{ch}^2\text{tn}-\varepsilon_r\text{sh}^2\text{ct})}{(\varepsilon_r\mu_r-1)}-\frac{k}{k_{xn}}\text{shch}\right]^{-1}$$

In all above formulae:

$\text{sh} = \sinh(k_{xn}b)$; $\text{ch} = \cosh(k_{xn}b)$;

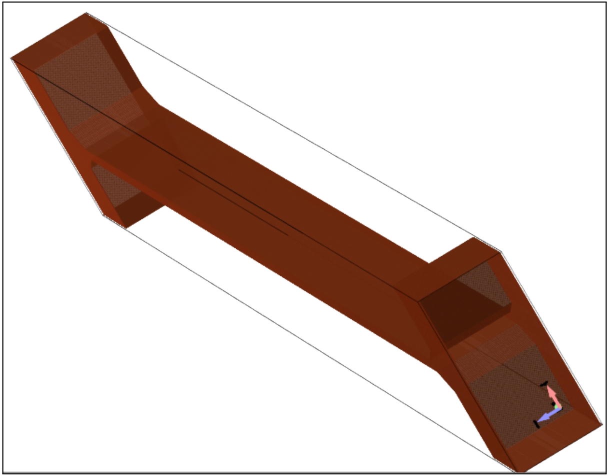
$\text{tn} = \tan(k_{yn}(b-d))$; $\text{ct} = \cot(k_{yn}(b-d))$

$\varepsilon_r = \varepsilon_r' - j\varepsilon_r'' + \frac{\sigma}{j\omega\varepsilon_0}$

$\mu_r = \mu_r' - j\mu_r''$

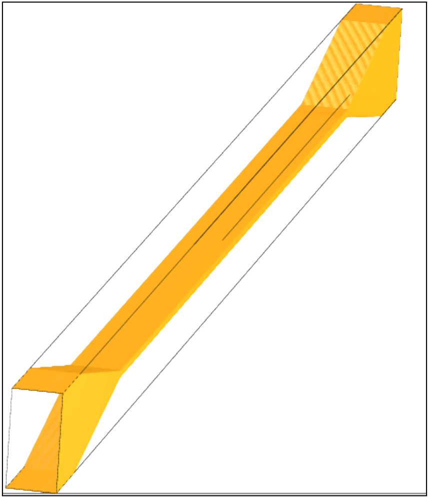
TDI designs: present one installed in LHC

Present TDI single segment geometry, one linear taper plus sharp discontinuity plus in & out 10 cm tubes, GdfidL wakefield simulations: σ_z =7.5 cm, s=75 cm.



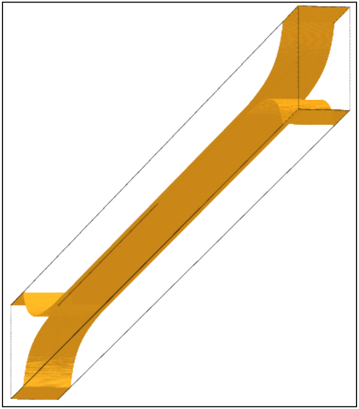
TDI designs: new one proposed by LHC collimation team

New proposed TDI single segment geometry, one linear taper plus in & out 10 cm tubes, GdfidL wakefield simulations: σ_z =7.5 cm, s=75 cm.



TDI designs: new one studied and suggested by INFN-LNF

New suggested TDI single segment geometry, plus in & out 10 cm tubes, GdfidL wakefield simulations: σ_z =7.5 cm, s=75 cm.



A non linear taper is described by a function of the type [4]: $h(z) = \frac{h_{min}}{[1+zL(\beta^{-\frac{1}{2}}-1)]^2}$,

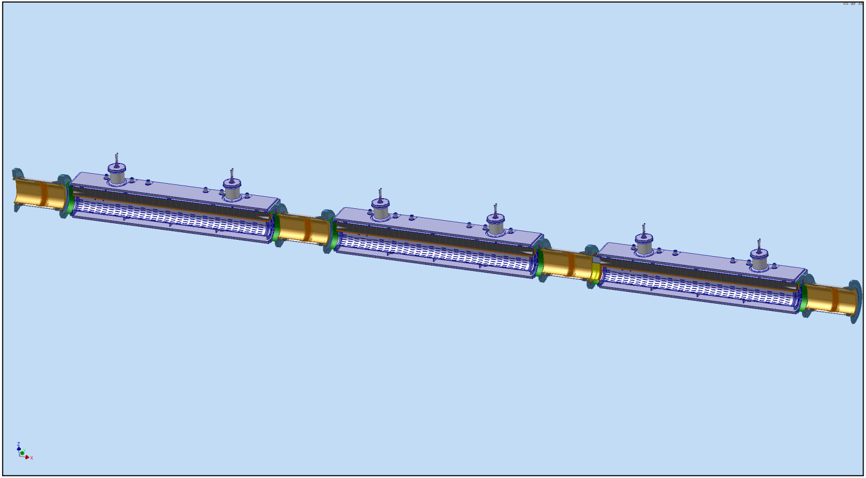
where $\beta \equiv \frac{h_{max}}{h_{min}}$

[4]B.Podobedov and I.Zagorodnov, PAC2007, p. 2006

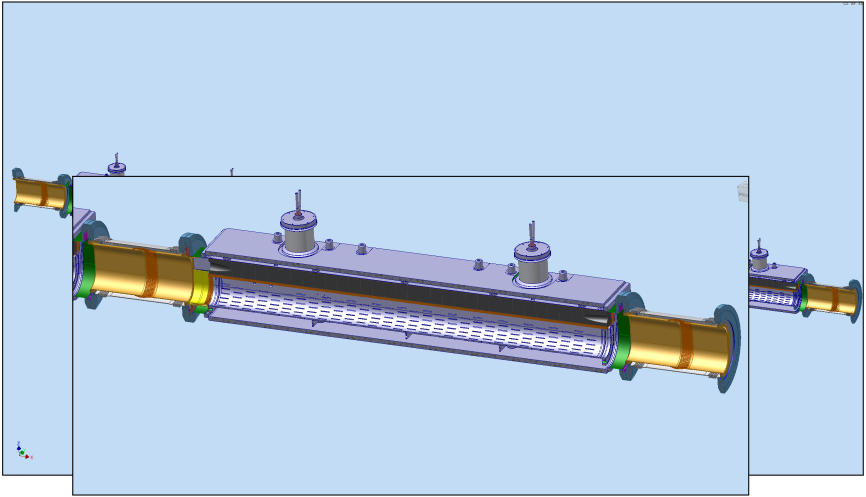
Resulting parameters from GdfidL simulations

	PEC	R4550 graphite ($\sigma_\infty = 7.64 \cdot 10^4$ S/m)
PRESENT geometry (linear flat taper + sharp discontinuity)		
$k_\parallel$ [V/C]	$1.73 \cdot 10^9$	$2.59 \cdot 10^9$
$Z_\perp(0)$ [kΩ/m]	49.4	123.1
$k_\perp$ [V/Cm]	$5.32 \cdot 10^{13}$	$1.37 \cdot 10^{14}$
NEW geometry (only longer and higher linear flat taper)		
	PEC	R4550 graphite ($\sigma_\infty = 7.64 \cdot 10^4$ S/m)
$k_\parallel$ [V/C]	$1.59 \cdot 10^9$	$2.69 \cdot 10^9$
$Z_\perp(0)$ [kΩ/m]	31.9	109.6
$k_\perp$ [V/Cm]	$3.46 \cdot 10^{13}$	$1.21 \cdot 10^{14}$
Alternative geometry (non linear taper)		
	PEC	R4550 graphite ($\sigma_\infty = 7.64 \cdot 10^4$ S/m)
$k_\parallel$ [V/C]	$1.61 \cdot 10^9$	$2.82 \cdot 10^9$
$Z_\perp(0)$ [kΩ/m]	19.98	102
$k_\perp$ [V/Cm]	$2.09 \cdot 10^{13}$	$1.11 \cdot 10^{14}$

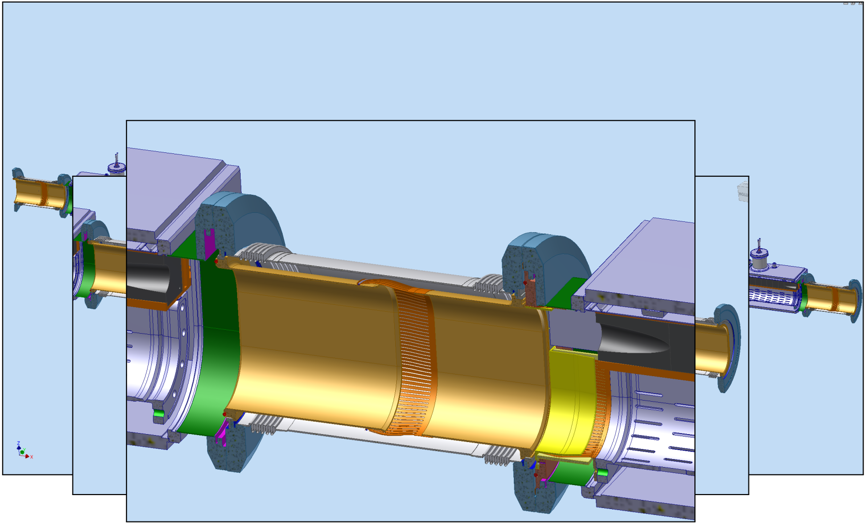
TDI new model first follow-up



TDI new model first follow-up



TDI new model first follow-up



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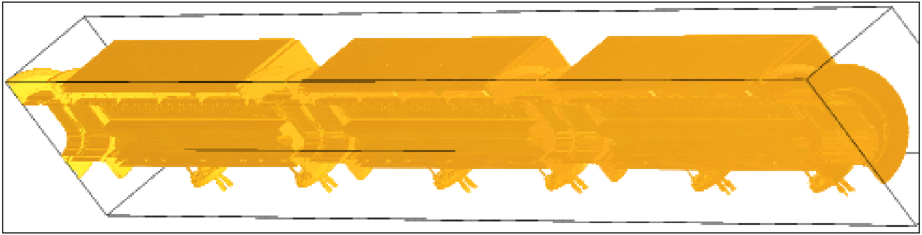

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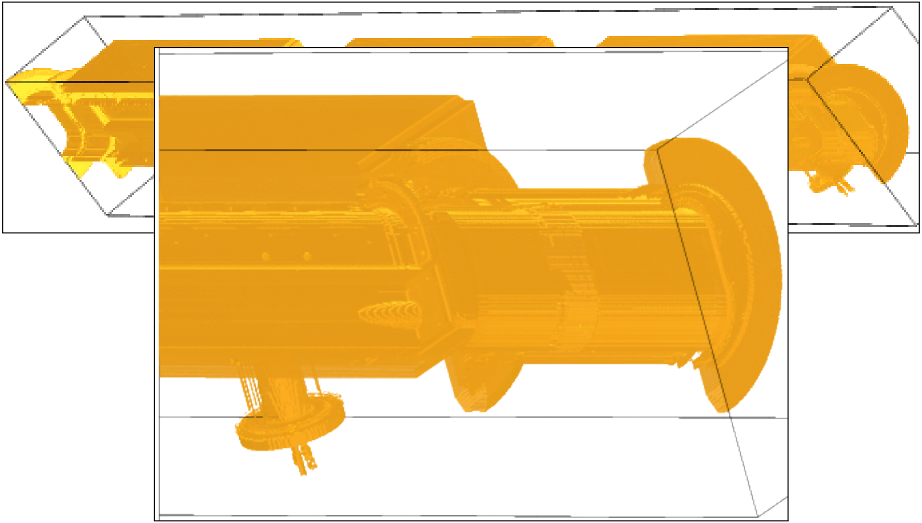
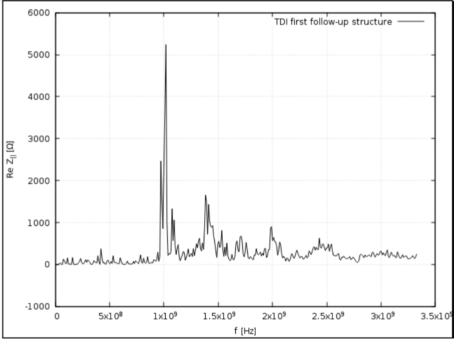
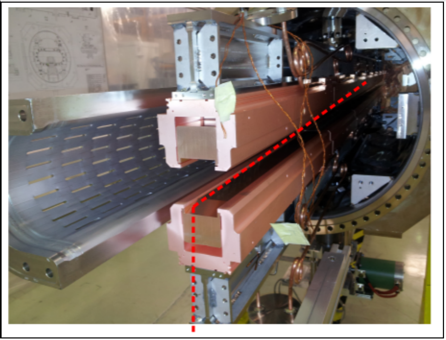
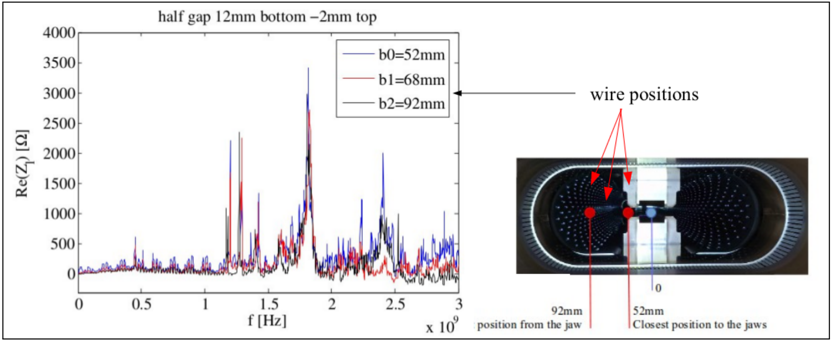


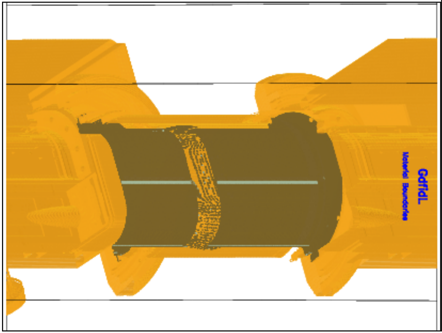


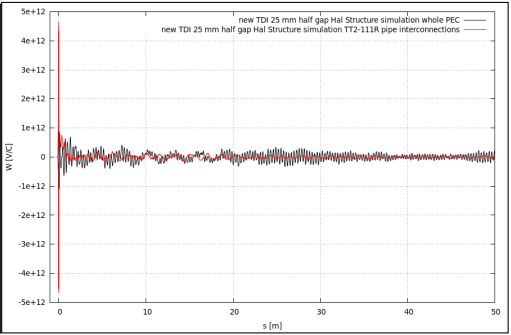
TDI first follow-up structure
Re $Z_{||}$ [Ω]
f [Hz]
6000
5000
4000
3000
2000
1000
0
-1000
0
5x10⁸
1x10⁹
1.5x10⁹
2x10⁹
2.5x10⁹
3x10⁹
3.5x10⁹

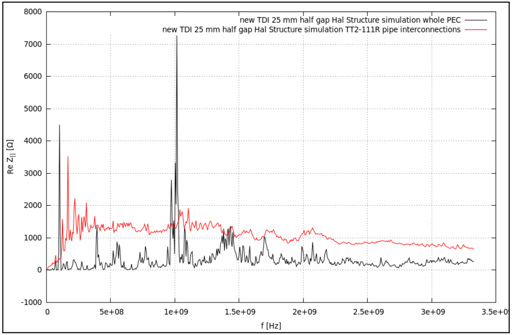




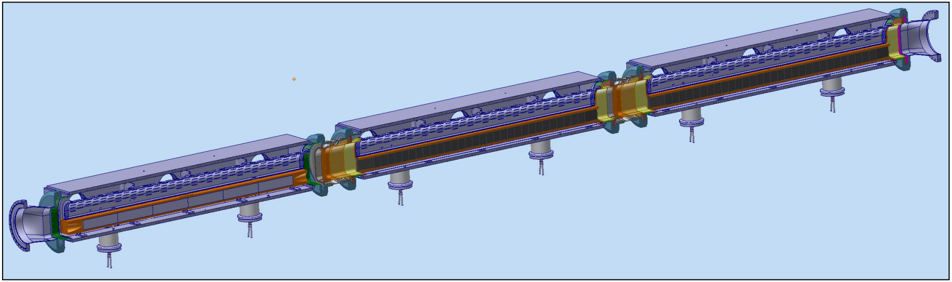
half gap 12mm bottom –2mm top
b0=52mm
b1=68mm
b2=92mm
$\mathrm{Re}(Z_l)$ [Ω]
f [Hz]
x 10^9
4000
3500
3000
2500
2000
1500
1000
500
0
0
0.5
1
1.5
2
2.5
3
wire positions
0
92mm
position from the jaw
52mm
Closest position to the jaws


GdfidL
Material Boundaries

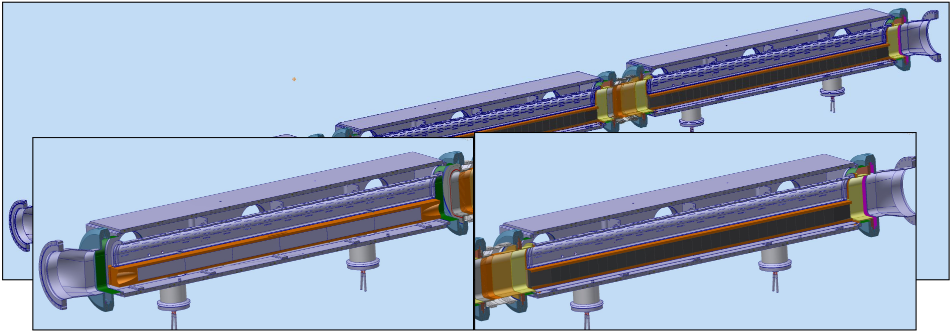

new TDI 25 mm half gap Hal Structure simulation whole PEC
new TDI 25 mm half gap Hal Structure simulation TT2-111R pipe interconnections
W [V/C]
s [m]
5e+12
4e+12
3e+12
2e+12
1e+12
0
-1e+12
-2e+12
-3e+12
-4e+12
-5e+12
0
10
20
30
40
50


new TDI 25 mm half gap Hal Structure simulation whole PEC
new TDI 25 mm half gap Hal Structure simulation TT2-111R pipe interconnections
Re Z|| [Ω]
f [Hz]
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
0
5e+08
1e+09
1.5e+09
2e+09
2.5e+09
3e+09
3.5e+0

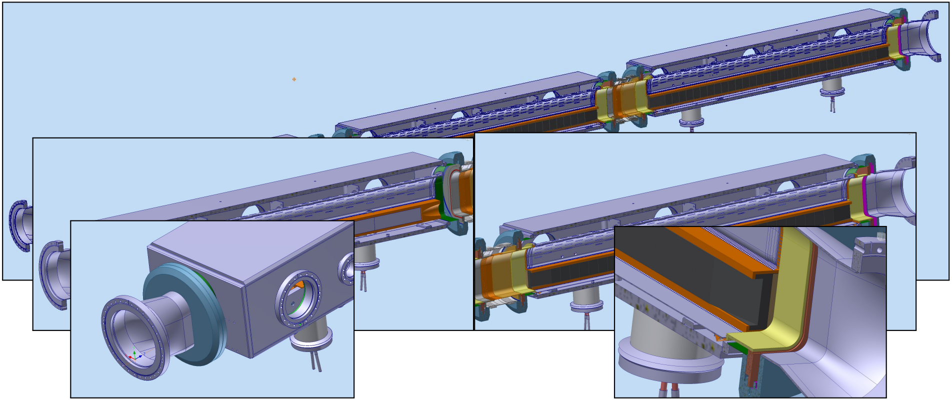
TDI new model second follow-up

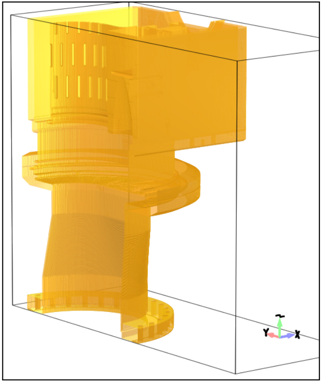


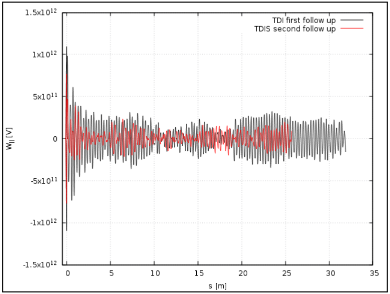
TDI new model second follow-up

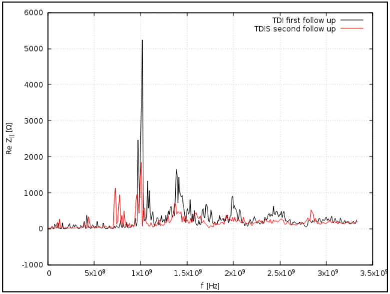


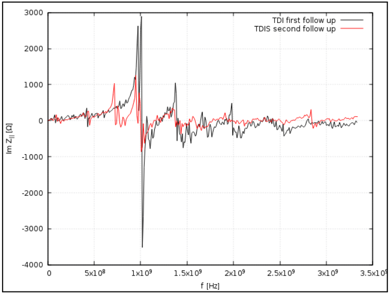
TDI new model second follow-up




Y
X
Z


TDI first follow up
TDIS second follow up
$W_{||}$ [V]
s [m]


TDI first follow up
TDIS second follow up
Re $Z_{||}$ [Ω]
f [Hz]


TDI first follow up
TDIS second follow up
Im $Z_{||}$ [Ω]
f [Hz]