RF Studies for FP420 at LHC

F.Roncarolo - LCU meeting 4-Jun-07

In collaboration with:
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What is FP420 ?

FP420 R&D Collaboration

Spokes : Brian Cox (Manchester, ATLAS) and Albert DeRoeck (CERN,CMS)

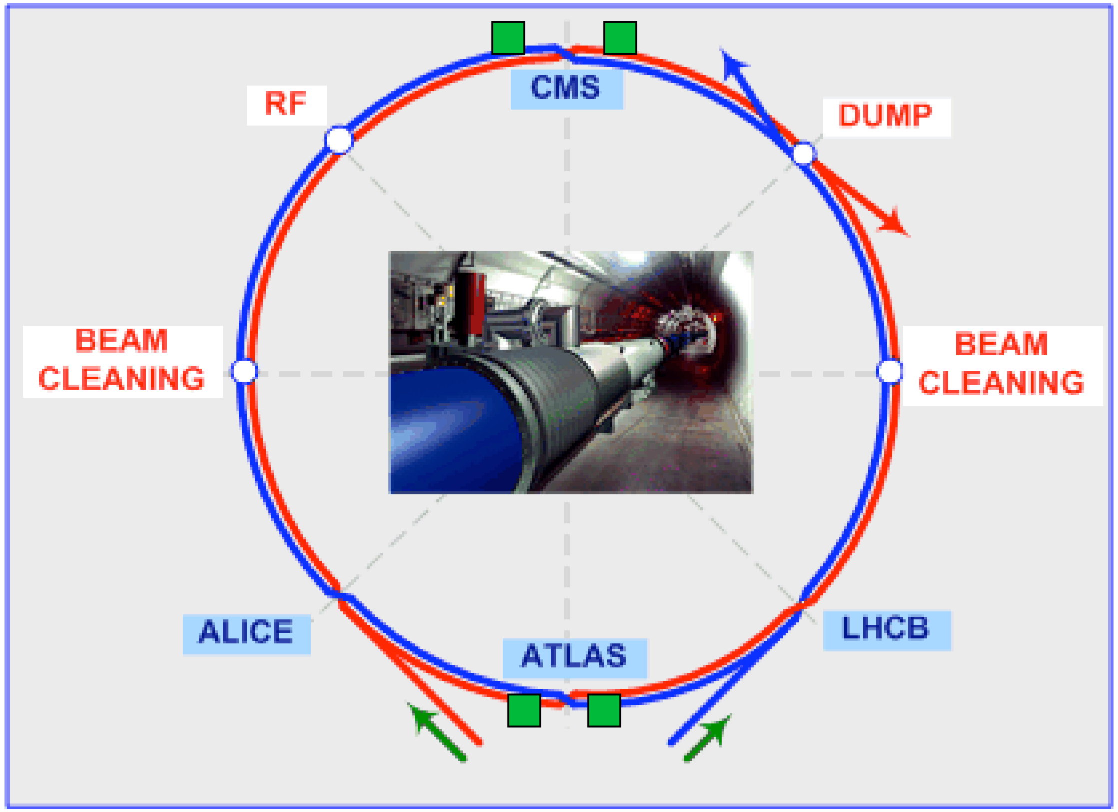
Technical Co-ordinator : Cinzia DaVia (Manchester)

Collaboration : FNAL, The University of Manchester, University of Eastern Piedmont, Novara and INFN-Turin, The Cockcroft Institute, University of Antwerpen, University of Texas at Arlington, The University of Glasgow, University of Calabria and INFN-Cosenza, CERN, Lawrence Livermore National Laboratory, University of Turin and INFN-Turin, University of Lund, Rutherford Appleton Laboratory, Molecular Biology Consortium, Institute for Particle Physics Phenomenology, Durham University, DESY, Helsinki Institute of Physics and University of Helsinki, UC Louvain, University of Hawaii, LAL Orsay, University of Alberta, Stony Brook University, Boston University, University of Nebraska, Institute of Physics, Academy of Sciences of the Czech Republic, Brookhaven National Laboratory, University College London, Cambridge University

The R&D phase has been fully financed

The final project approval by the financing **institutes** and by the concerned **LHC committees** is expected during 2007

FP420 @ LHC



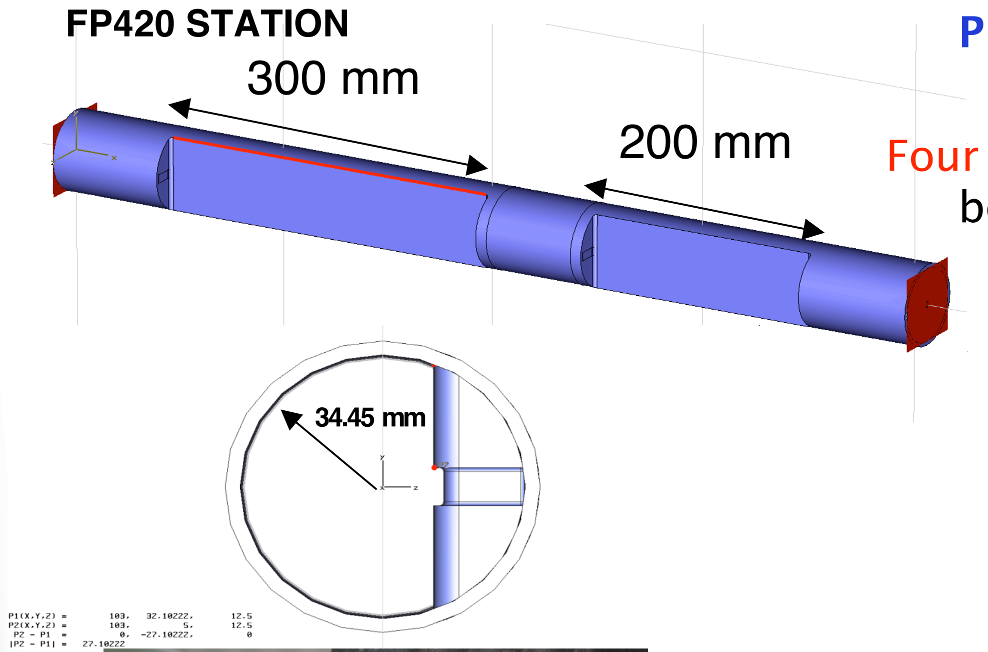
- FP420 detectors at about 420 meters around ATLAS and CMS
--> see next slide

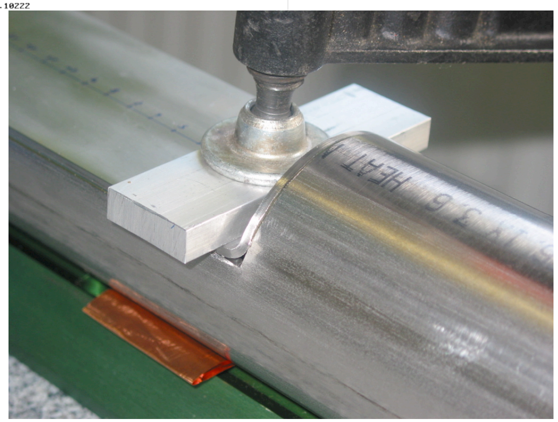
FP420 detectors

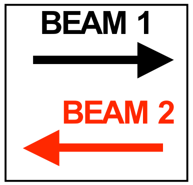
Mechanical design based on **movable "Hamburg Pipe"**

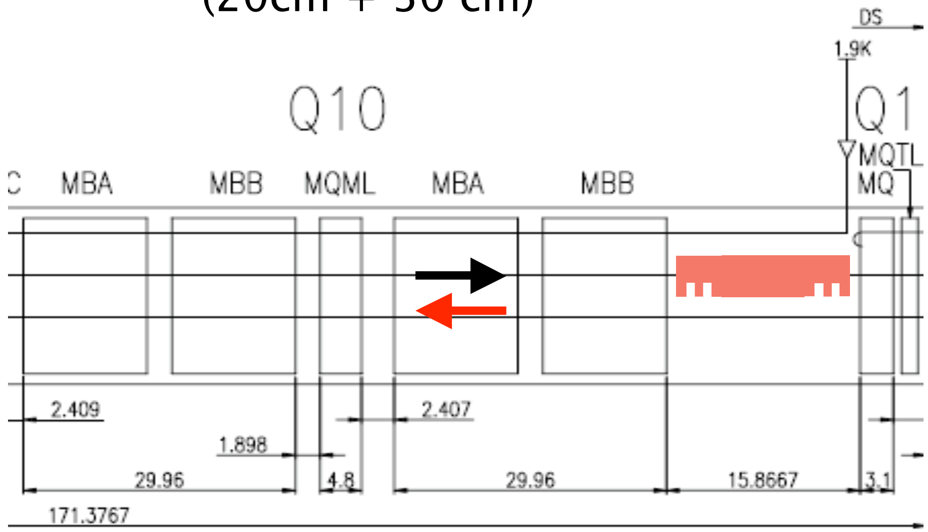
Four detectors proposed (IP1, IP5, beam1 + beam2)

- Two (or three) stations for each detector
  - Two pockets for each station with (20cm + 30 cm)









RF Studies

RF Studies – Motivations

The electromagnetic interaction between the beam and its surroundings, will be one of the phenomena limiting the ultimate performance of LHC, because can lead to single bunch and multi-bunch beam instabilities, beam emittance growth and beam losses

In addition: electromagnetic coupling can disturb the detectors operation at the electronic level

RF effects are usually expressed in terms of wake fields and beam coupling impedances

For each accelerator element, the critical aspects are:

-materials --> resistive wall effects, enhanced as the element approaches the circulating beam

-geometry --> possible trapped modes at any cross section variation of the beam line

FP420: in order to be approved by the LHC concerned committees we need to prove that we will introduce a limited contribution to the total impedance (dominated by collimators at LHC)

> Why FP420 could affect the LHC impedance:
>
> -it introduces a cross section variation
>
> -we want to go as close to the beam as $\boxed{3\,mm \approx 10 \cdot \sigma_x}$

How to measure the impedance

Stretched wire method

The wire is used to simulate the EM fields induced by the beam. The structure becomes a coaxial wave guide structure with TEM modes. The set up consists in some alignment system and a Vector Network Analyzer as RF source.

The longitudinal impedance can be inferred from scattering parameters analysis. In particular: the signal S21 transmitted through the wire along the Device Under Test (DUT) has to be compared to the one measured along a smooth reference beam pipe with the same length of the DUT.

Longitudinal impedance

$$Z_{||}(f) = -2Z_c ln \frac{S_{21}^{DUT}(f)}{S_{21}^{REF}(f)}$$

with: $Z_c =$ Line impedance

$d =$ Wire diameter

$D =$ Inner pipe diameter (or distance between plates)

Transverse impedance from longitudinal impedance variation

$$Z_{\perp}(x,\omega) \simeq \frac{c}{\omega}\frac{Z_{||}(x) - Z_{||}(x=0)}{x^2}$$

Models and simulations

Analytical models can predict

- resistive wall impedance -> very useful for FP420
- wake fields generated by effects of the structure geometry --> not easily applicable to the asymmetric geometry of FP420

There are a number of numerical codes based on finite elements meshing.

Mafia, Microwave Studio, HFFS … etc. These codes are able to simulate cavity-like and wave guide like structures fed by RF ports

- we are using them to simulate the stretched wire setup

GDFIDL is able to directly calculate wake fields induced by charged particles traveling in the structure

- it can be used to have simulations independent from the wire setup

Remarks:

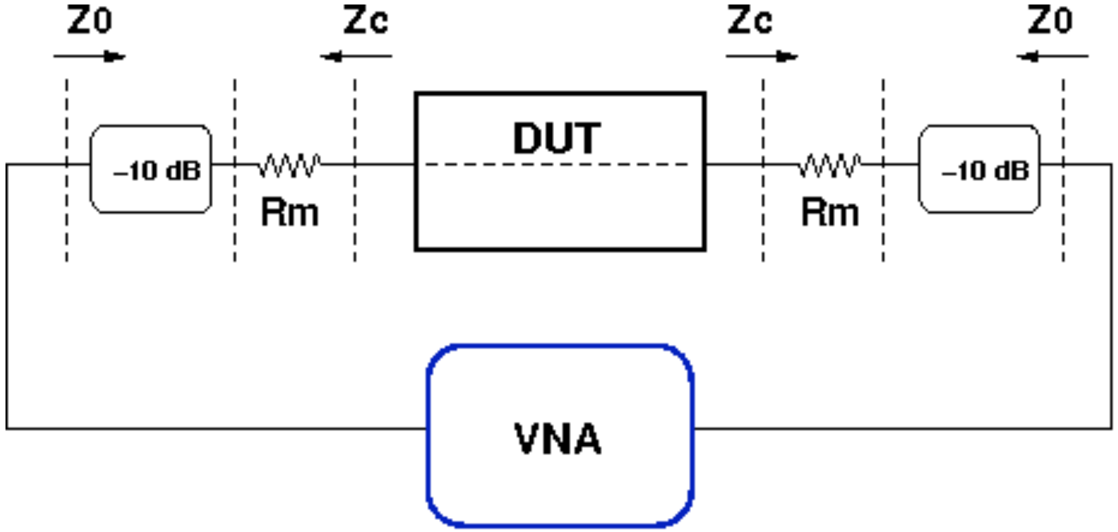
- Numerical simulations and measurements give poor accuracy at very low frequencies
- FP420 structure --> thin wall regime --> is not suitable to investigate inductive by-pass effect at low frequency

Laboratory measurements

Stretched wire measurement setup with Vector Network Analyzer

→ resistors to match the line impedance/cables

→ The residual mismatch is calibrated out (measuring only cables + resistors)



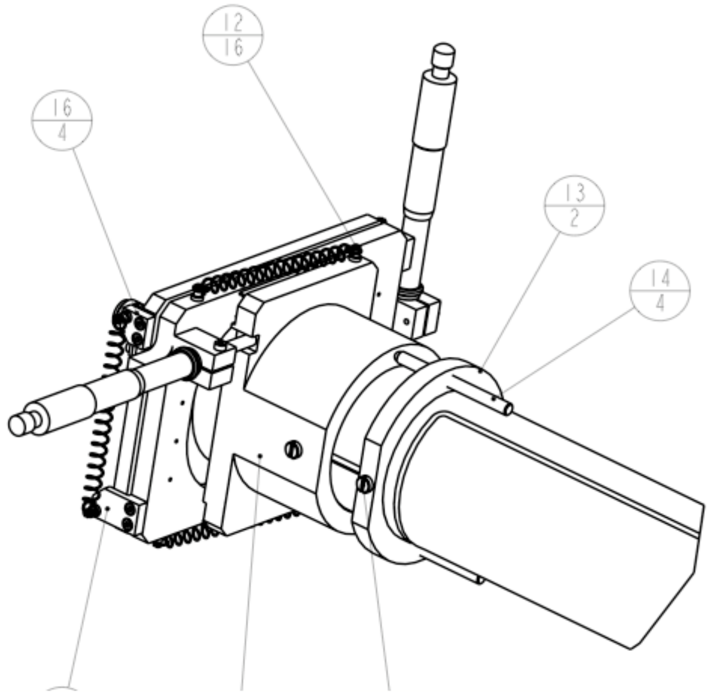
$$
\begin{aligned}
R_m &= Z_c - Z_0 \\
Z_0 &= 50\,\Omega \\
Z_c &= \text{From analytical models, i.e. } 60 \cdot ln\left(\frac{d}{D}\right) \text{ for cyl. coax} \\
& \text{Moving the wire } Z_c \text{ changes, unavoidable missmatch}
\end{aligned}
$$

Laboratory measurements

<u>Laboratory setup at Cockcroft Institute (Daresbury)</u>

- Sophisticated system to position and stretch the wire
- High precision micrometer screws to monitor the wire position
- Measurements started first week of May and are in progress
- At the moment: only “single pocket” prototype is available for measurements

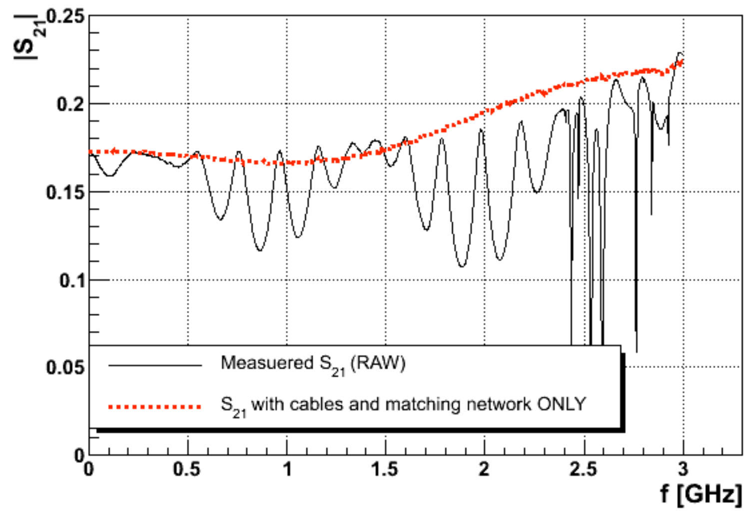
- I will show first results



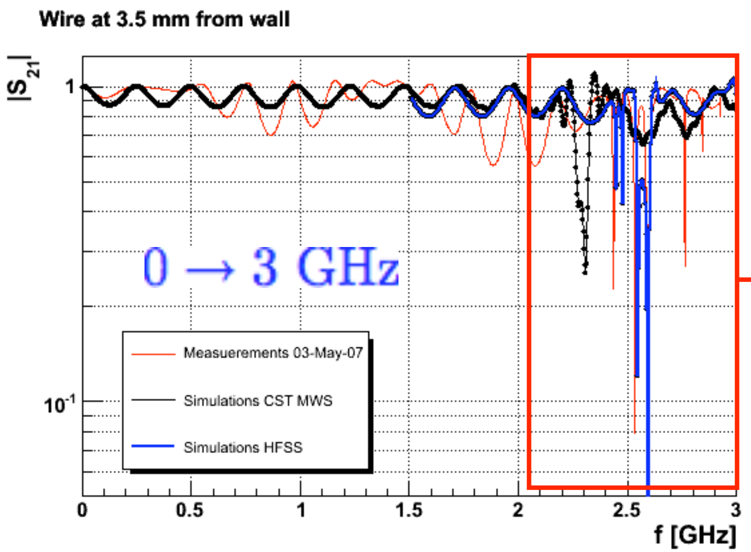
Some simulation and measurements results

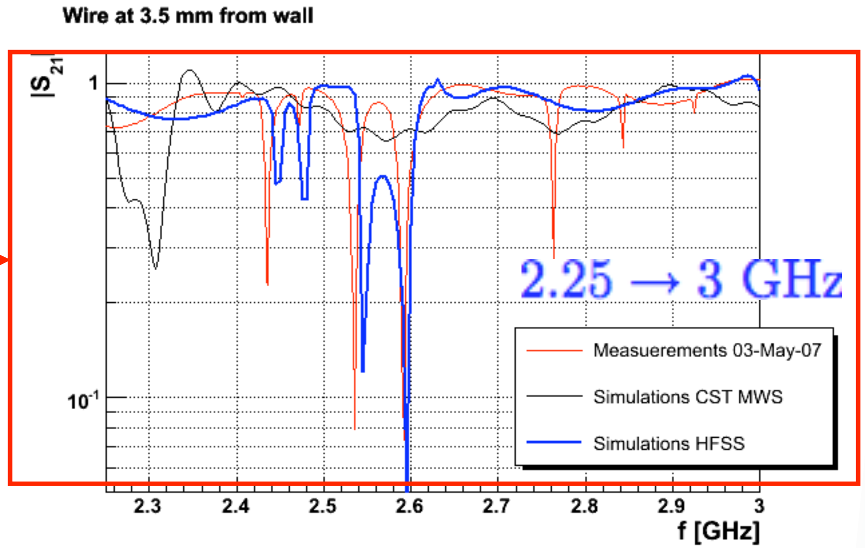
Transmission signal S21

Raw signal and “cables+matching” signals

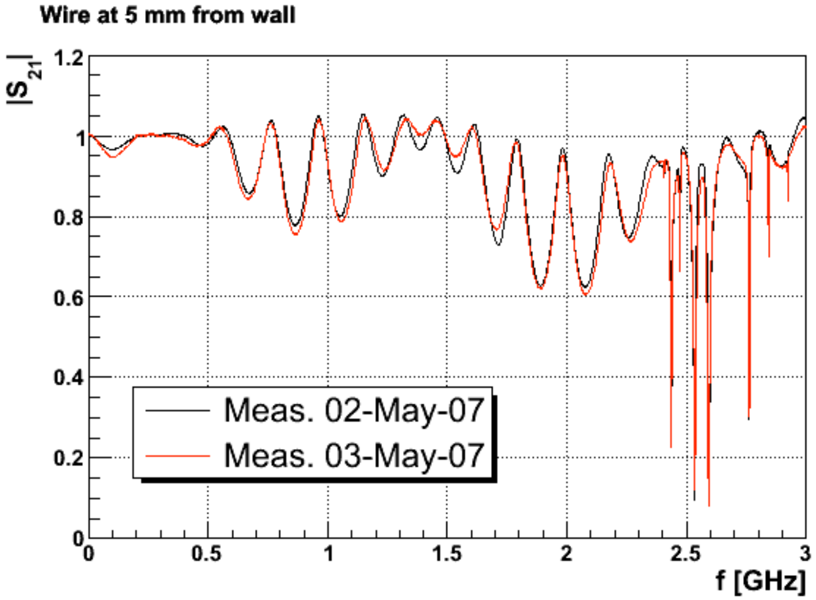


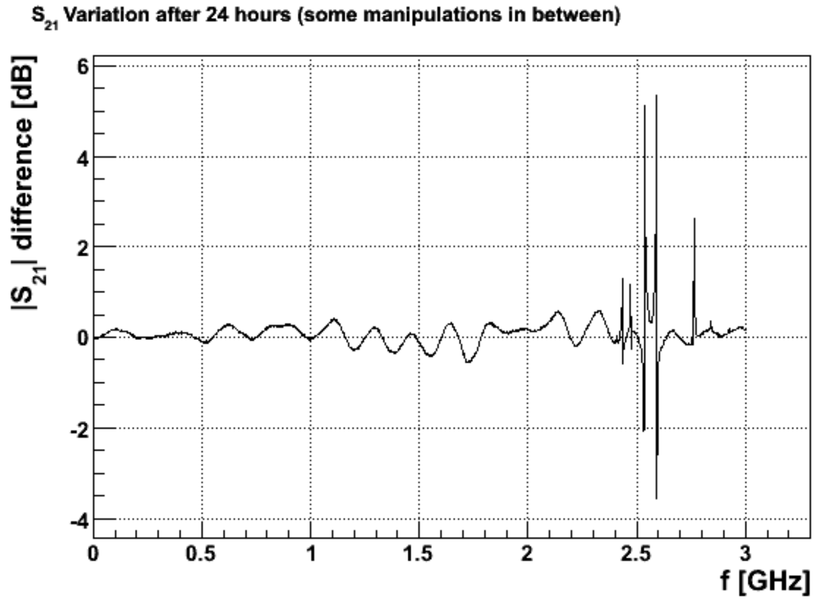
Transmission signal S21 after correction for cables+matching resistors, compared to MWS and HFFS





Measurements – Reproducibility



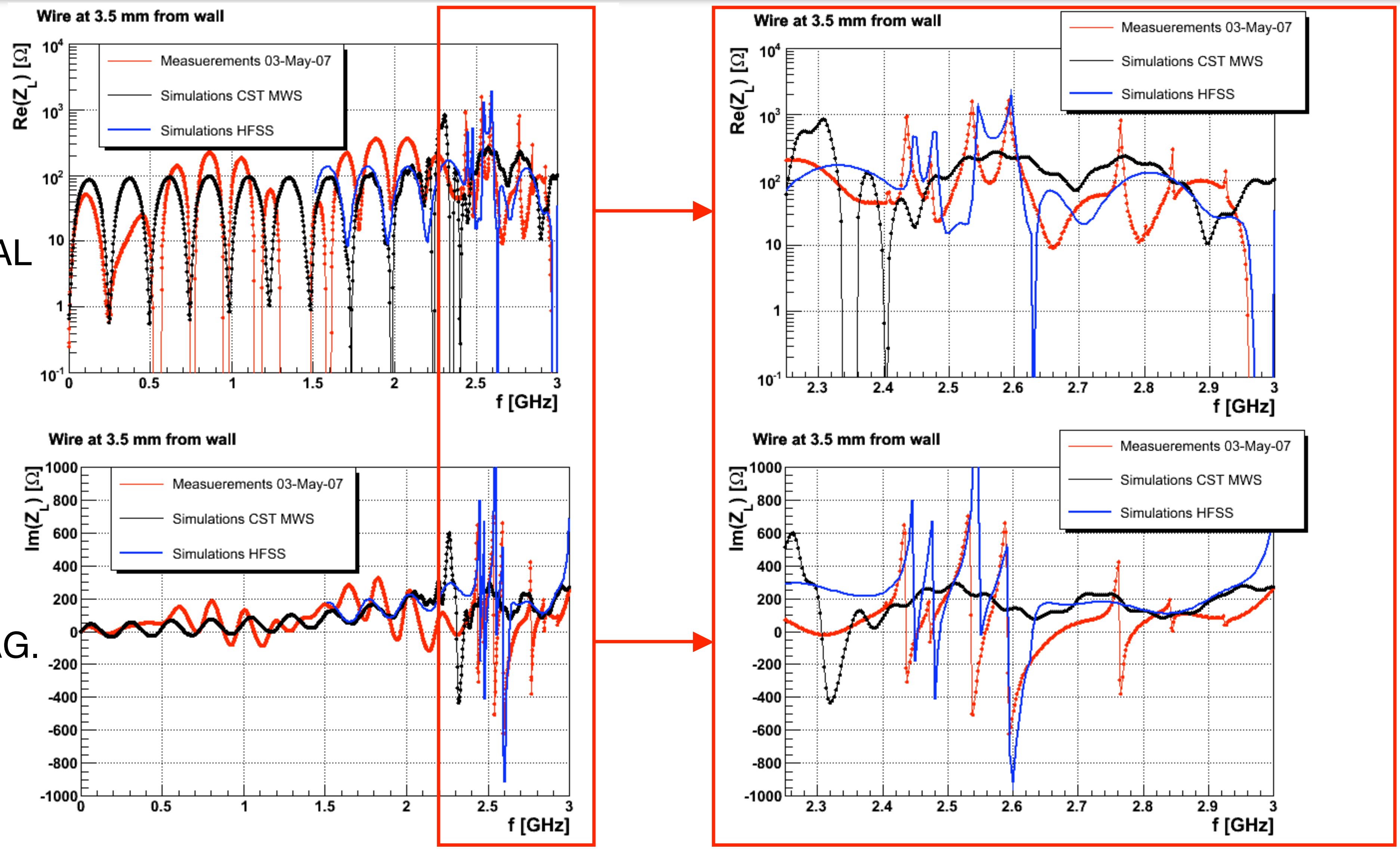


S21 measured in two different days with “manipulations” in between

Longitudinal Impedance

REAL

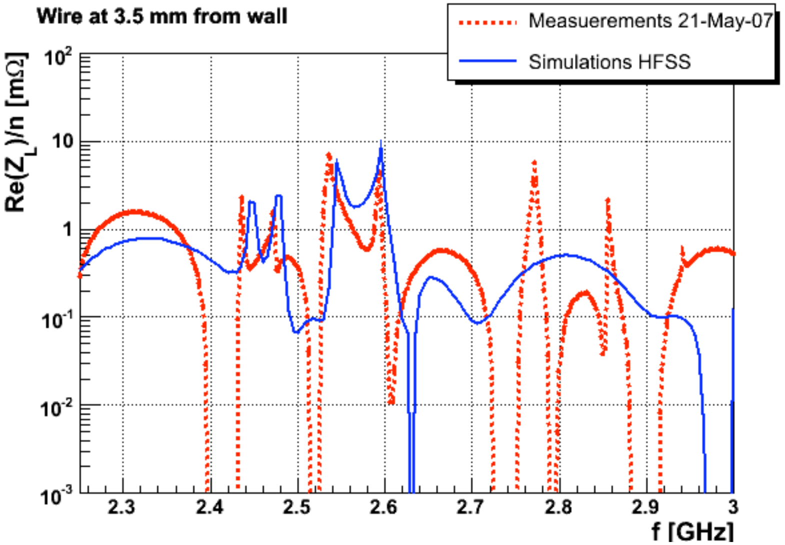
IMAG.

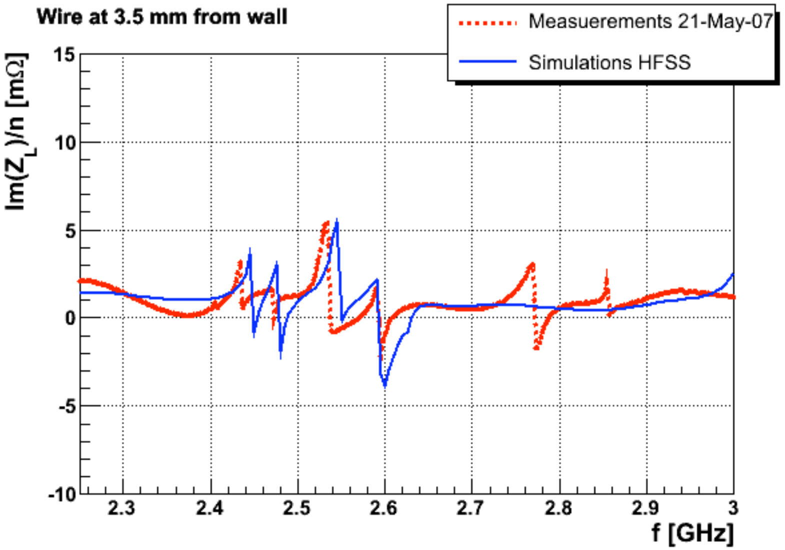


Effective Long.Impedance

$$Z_L^{eff}(f) = \frac{Z_L(f)}{n(f)}$$

$$n(f) = \frac{f}{f_{rev}}$$





This is the number quoted for a circular accelerator to quantify the longitudinal effect.

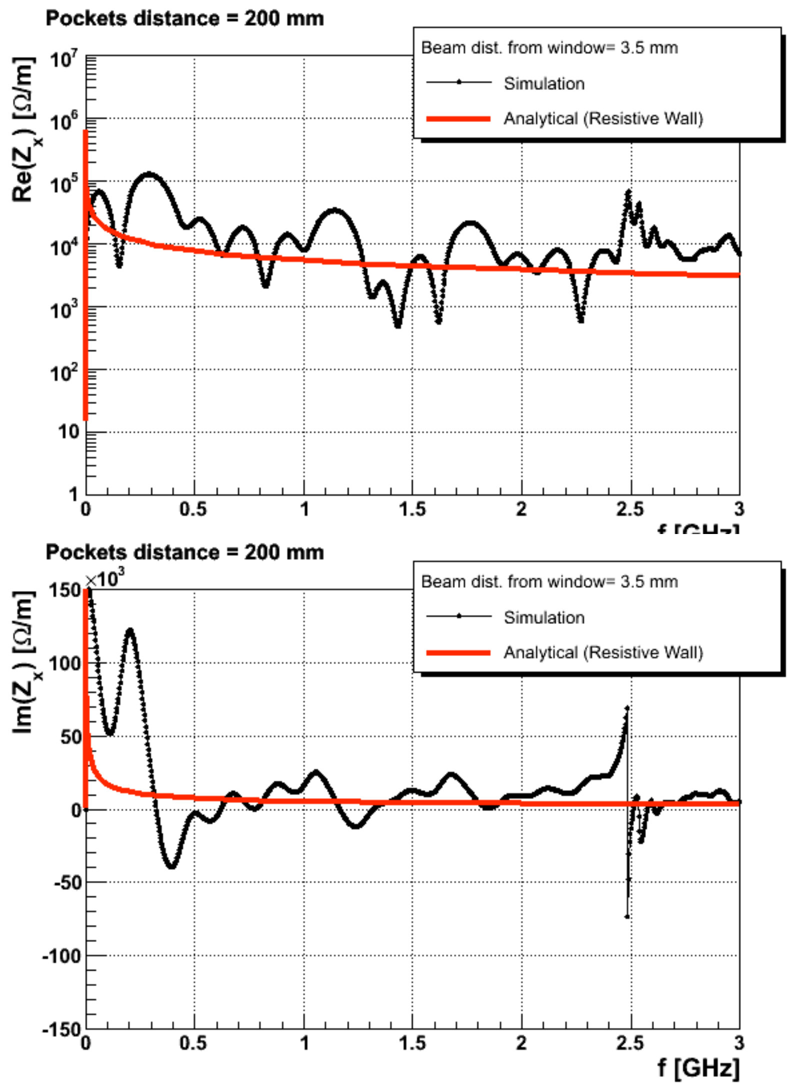
10 mOhms is not so low, but, we need to get rid of the wire effect …

(See GDFIDL simulations without wire)

Transverse Impedance

Using the stretched wire method, the **transverse impedance** can be calculated from the variation of the longitudinal impedance for different transverse positions of the beam.

This is not strict forward for our **asymmetric structure**, here is my guess compared to the analytical value from **resistive wall theory** applied to a symmetric beam pipe (E.Metral's model).

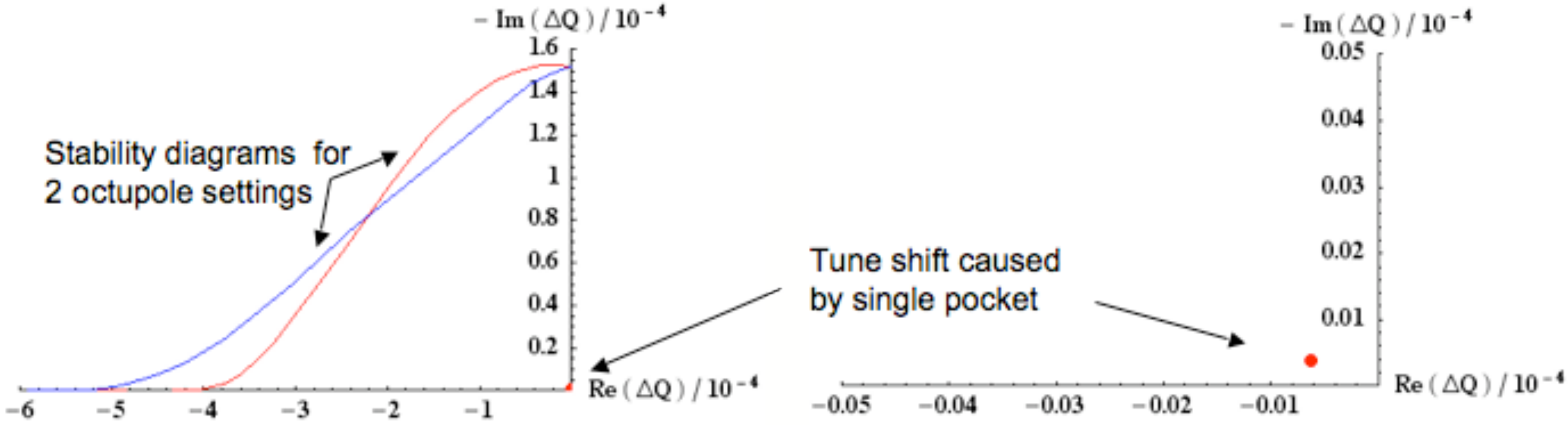


In the next slide:

effect on **beam stability** calculated from resistive wall theory

Effect of transverse impedance

The induced tune shift is well within the stability region and much below the effect of single LHC collimator



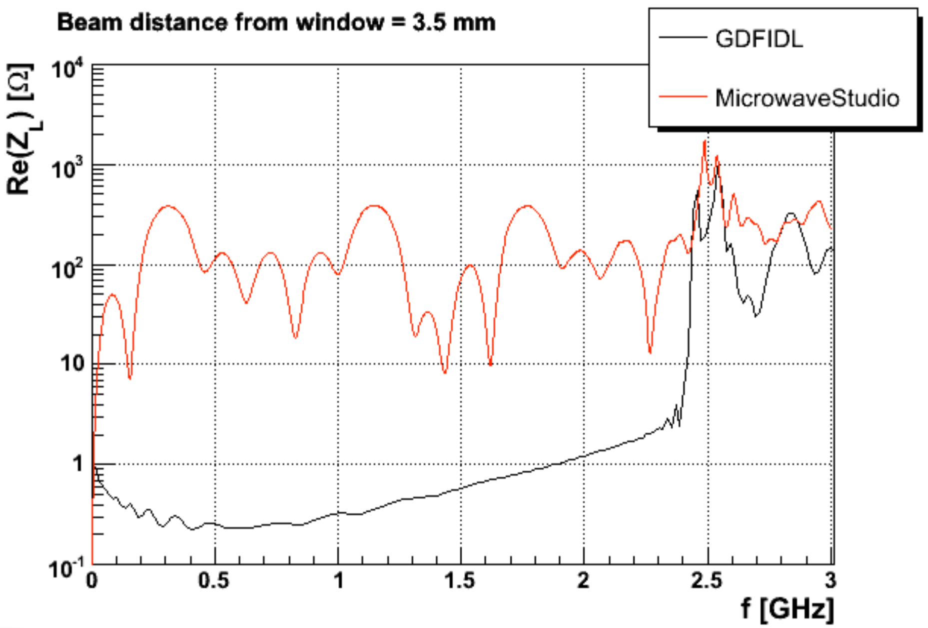
<u>Plots produced using E.Metral's model applied to one FP420 station</u>

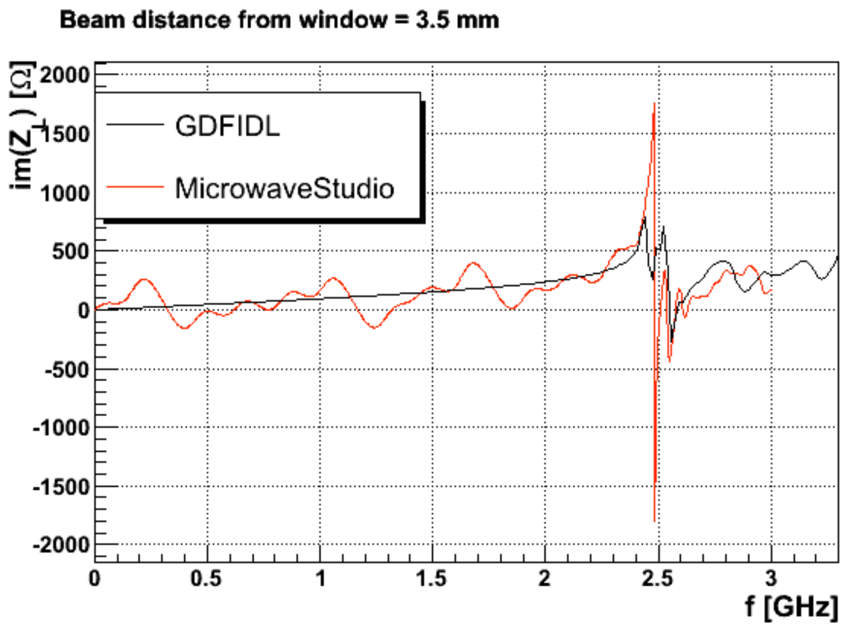
Simulations with GDFIDL (20+30cm pockets)

With GDFIDL it's possible to compute wake fields and impedances without simulating the stretched wire

I will check this results using new tool of CST Particle Studio that gives the option of shooting particle beams throughout the structure

Double pocket station (not available for measurements yet)

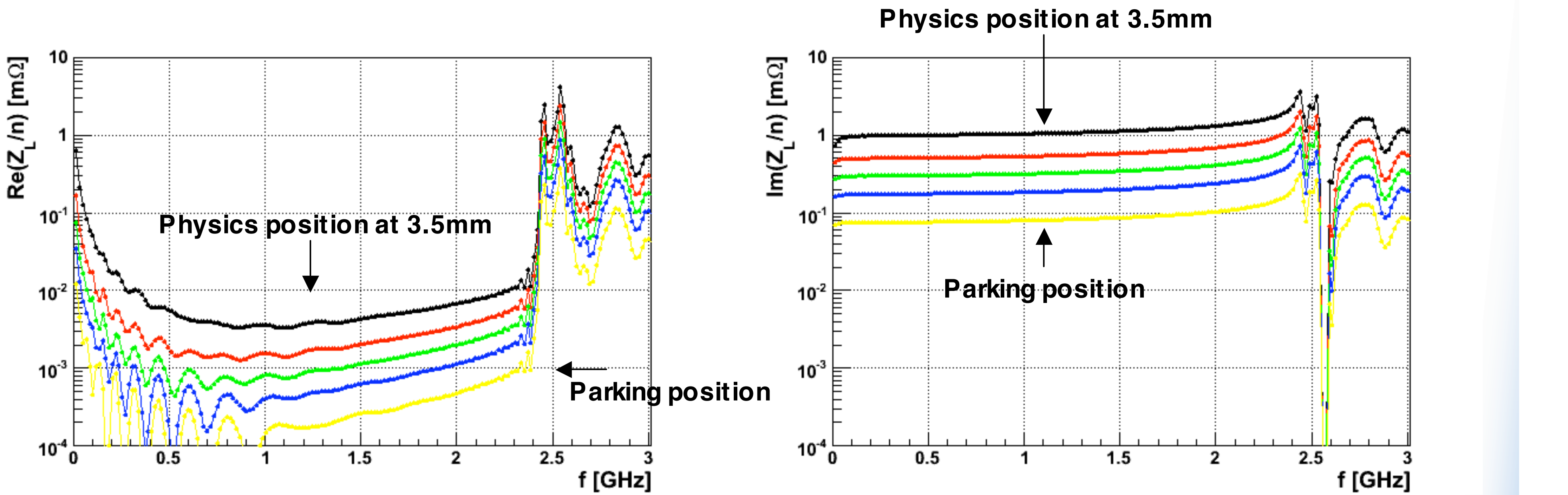




Plots of simulation done by W.Bruns (creator of GDFIDL)

GDFIDL – Effective Impedance

This is something like **1% of the estimated total LHC** effective impedance.
However these (with GDFIDL) are preliminary results to be checked



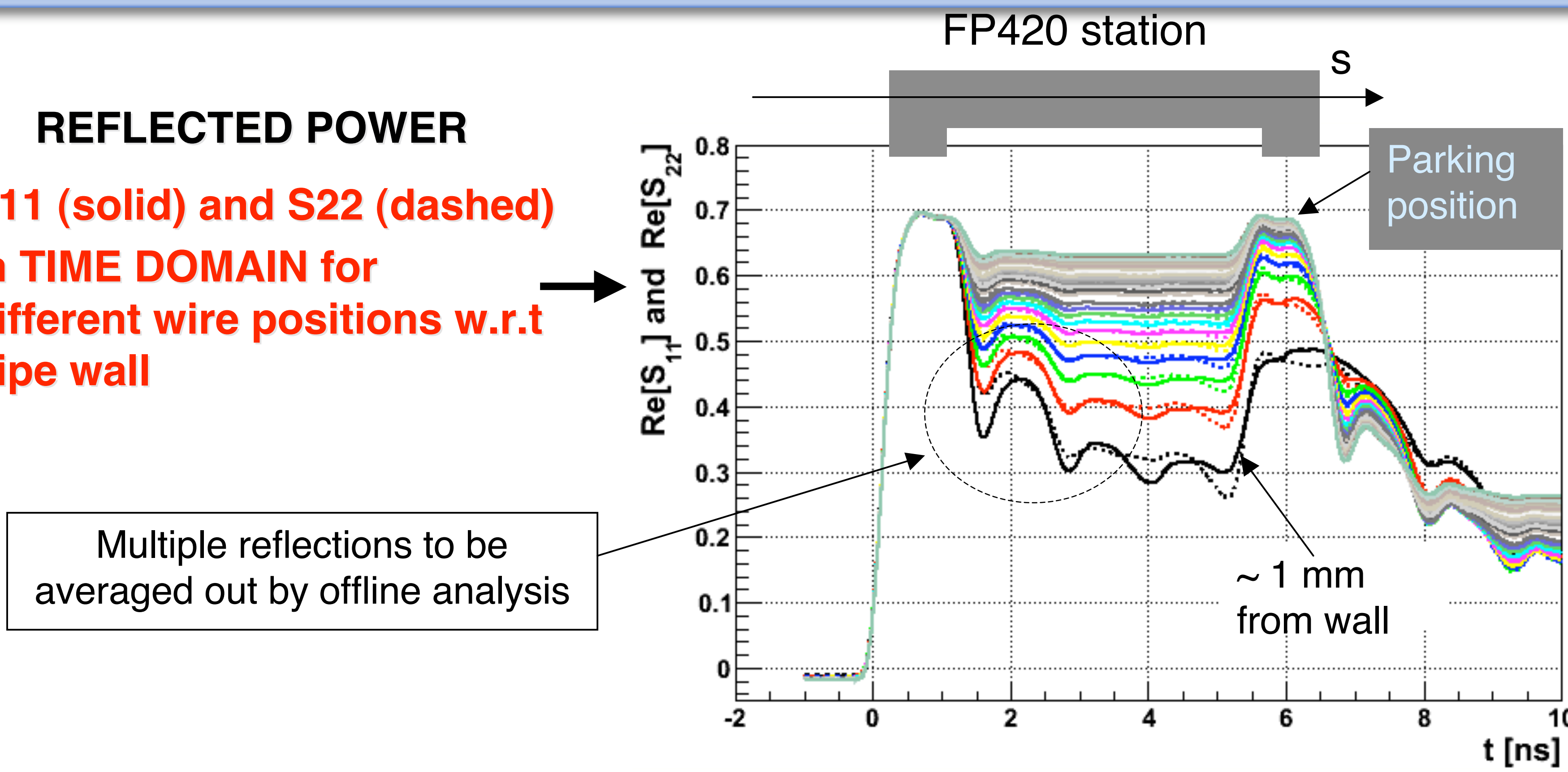
Plots of simulation done by W.Bruns

Measurements in reflection mode

REFLECTED POWER

S11 (solid) and S22 (dashed)

In TIME DOMAIN for different wire positions w.r.t pipe wall



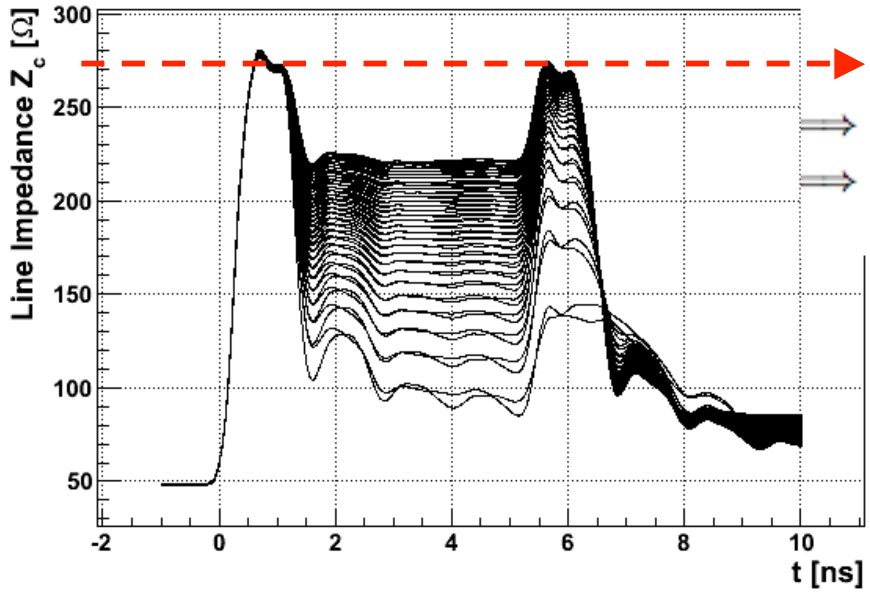
This signals can be used to estimate line impedance to be used in the "log formula"

- as function of long position
- as function of wire transverse position

RELEVANT FOR OUR ASYMMETRIC STRUCTURE

Meas. in reflection – Line impedance

$$Z_c = Z_0 \frac{1+S_{11}}{1-S_{11}}$$ line impedance from reflection signal , $Z_0 = 50\,\Omega$



Line impedance

$Z_c \approx 270\,\Omega$

$\Longrightarrow$ 10 % smaller than analytical value for symmetric structure

$\Longrightarrow$ Real part of longitudinal impedance 10 % smaller than what quoted in previous plots

Meas. in reflection – Wire position (I)

Reflected signal in time domain. We can use it to do this:

$$Z_c = Z_0 \frac{1+S_{11}}{1-S_{11}} \quad \text{line impedance from reflection signal} \quad , Z_0 = 50\,\Omega$$

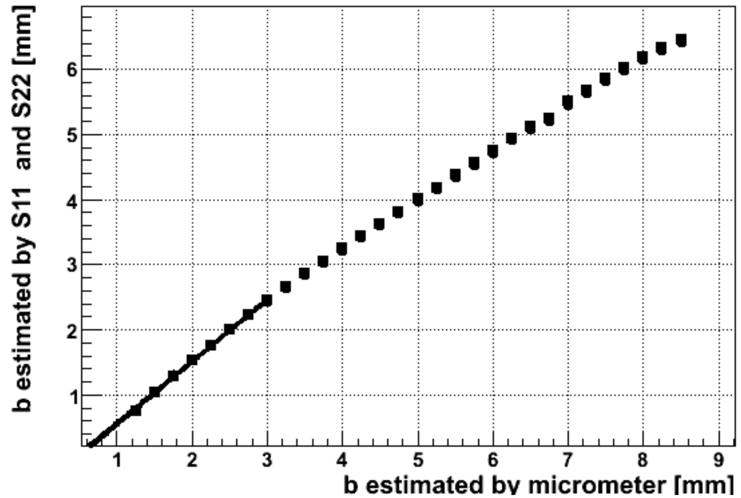
$$Z_L = 60 \cdot acosh\left(\frac{2*b}{d}\right) \quad \text{line impedance from wire close to single plate}$$

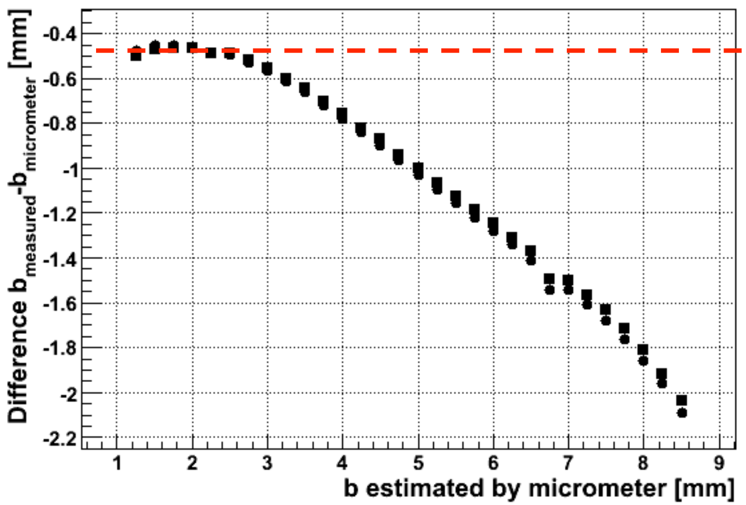
So: for different mechanical positions:

-invert this last equation using Z_c from S_{11} $\rightarrow$ get distance from windows b

-plot mechanical position (based on "touch point") .vs. this calculated b

Meas. In reflection – Wire position (II)

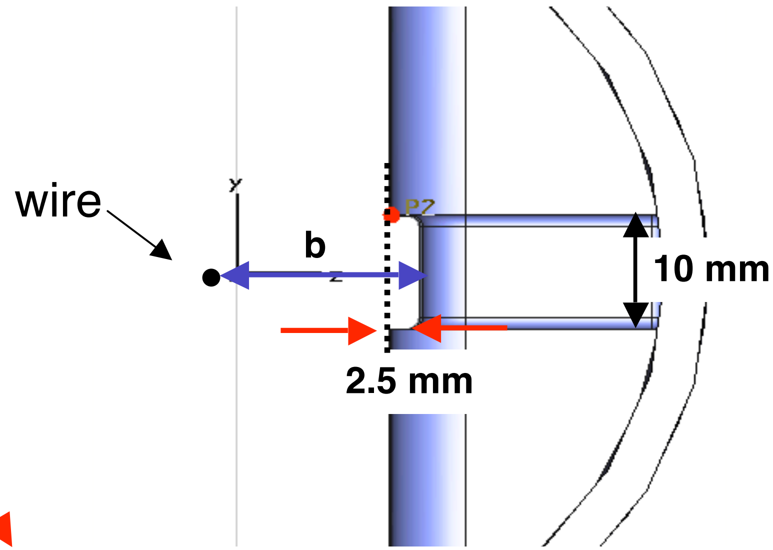




Mechanical vs measured position:

-linear only when wire is < 2 mm from wall

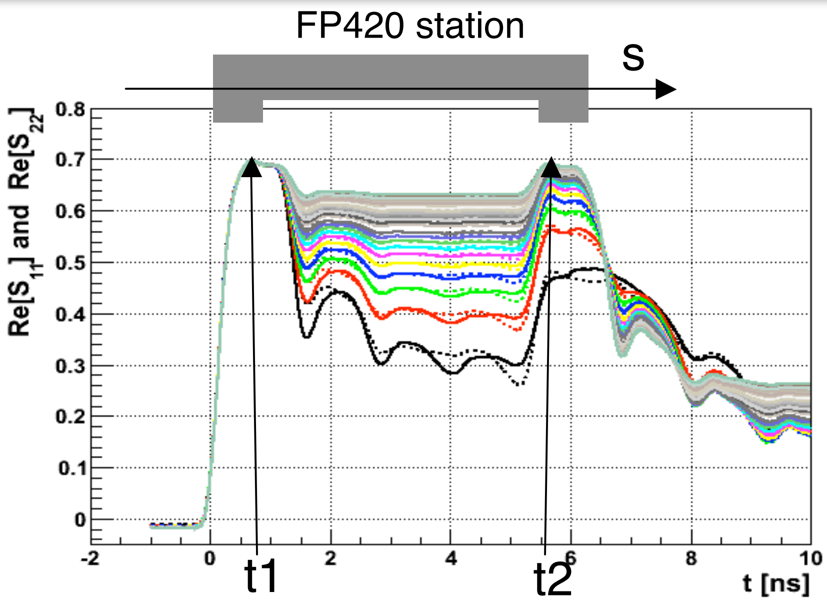
-for b > 2 mm approximation of wire close to a plate is not valid anymore



~ **0.5 mm** = correction to apply to mechanical position measurement

N.B. : we were only worried about absolute wire position not about the relative displacement

Meas. in reflection–Resistive wall (I)



The difference between the two maxima at t1 and t2 is only due to resistive wall effect integrated over the chosen frequency range.

From measurements

$$S_{11}(t_1) - S_{11}(t_2) \equiv S_{22}(t_1) - S_{22}(t_2) = \frac{S_{21}}{S_{21}^{ref}}$$

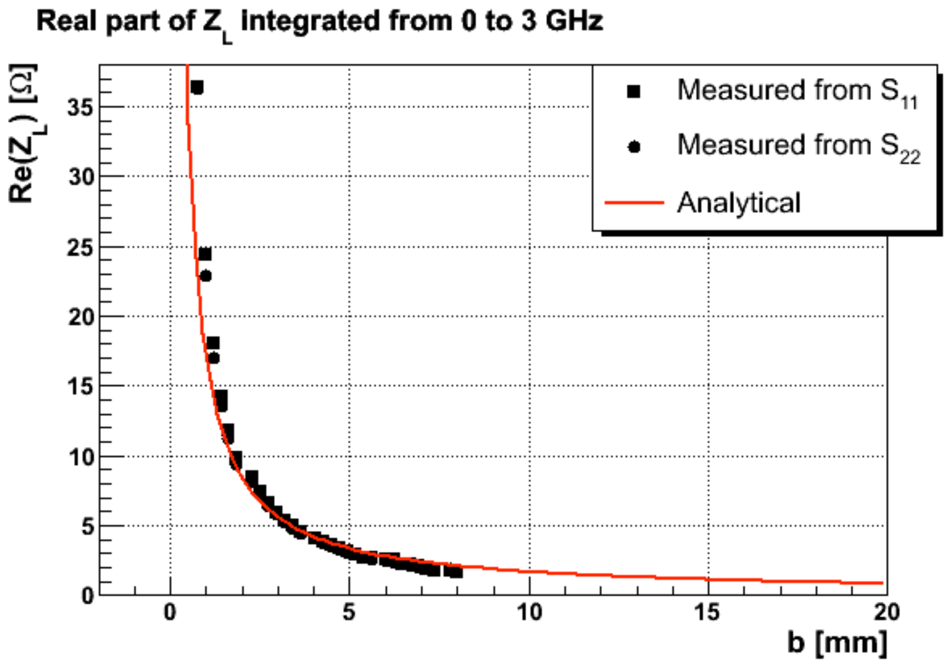
$$\int_{f_1=0}^{f_2=3\,GHz} Z_L(f)df = -2Z_C ln \frac{S_{21}}{S_{21}^{ref}}$$

Analytical prediction:

Wire close to a plate:

$$Z_L(f) = \frac{L}{2\pi b}\sqrt{\frac{\omega Z_0}{2c\sigma_c}} \cdot \frac{\pi}{12}$$

Meas. in reflection – Resistive wall (II)



Maximum discrepancy between measurement and theory:

$\Delta Z_L < 5\,\Omega$ or $\Delta x < 0.1\,mm$

To be verified:
Windowing in frequency domain of Network Analyzer not included in analytical prediction yet

Conclusions

Simulations are in good status and now crosschecked with different codes (HFSS, CST, GDFIDL). The impedance values estimation remain low.

Measurements: not completed yet, look consistent with simulations.

Items on the list:

-verify accuracy of transmission measurements for long. Impedance. Prove agreement between measurements and simulations and rely on simulations for final numbers

-estimate Q and loss factors for resonances between 2 and 3 GHz

-time domain: send pulse and measure losses in reference pipe and in DUT

--> loss factor

-transverse impedance measurements with two wires

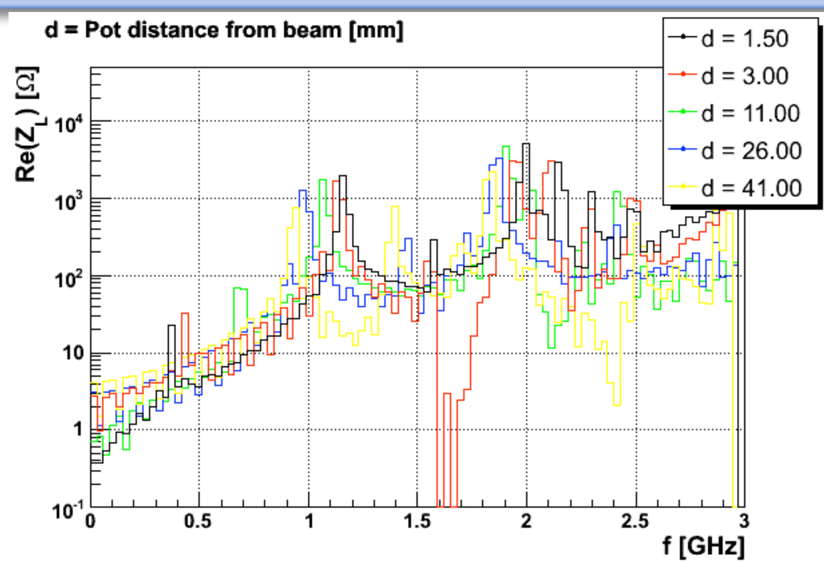
-analyze measurements in “resonator mode” already performed

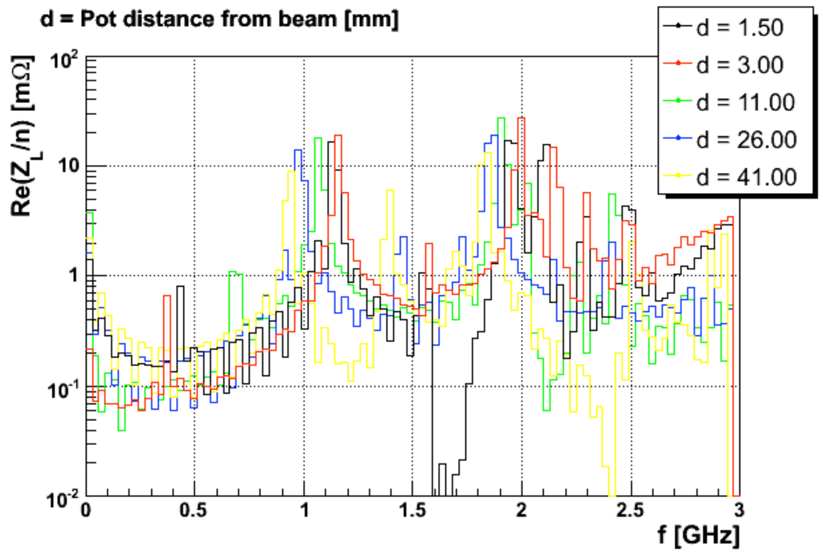
-measurement of 2 pockets station

-investigate preliminary recommendations by F.Caspers-T.Kroyer: simulate and/or measure “RF contacts” (vertically above and below the beam orbit) tapering the steps at the pipe cross-section variation

SPARE

Appendix … : ATLAS pot

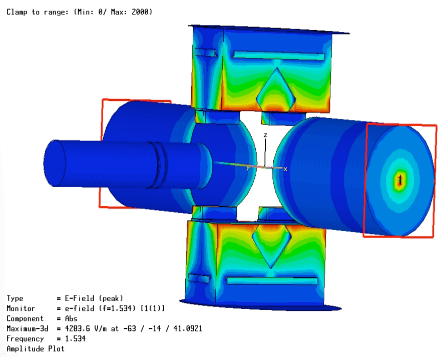


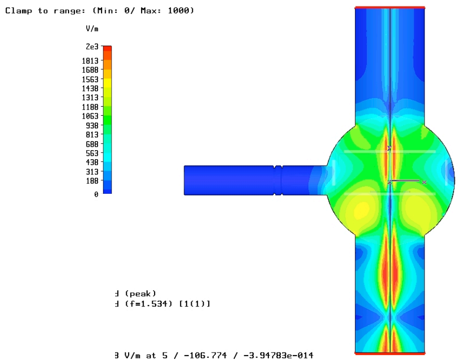


Preliminary results!

Simulations with CST Particle Studio

Trapped mode/peak at ~ 1GHz could be a real problem, even when in the parking position

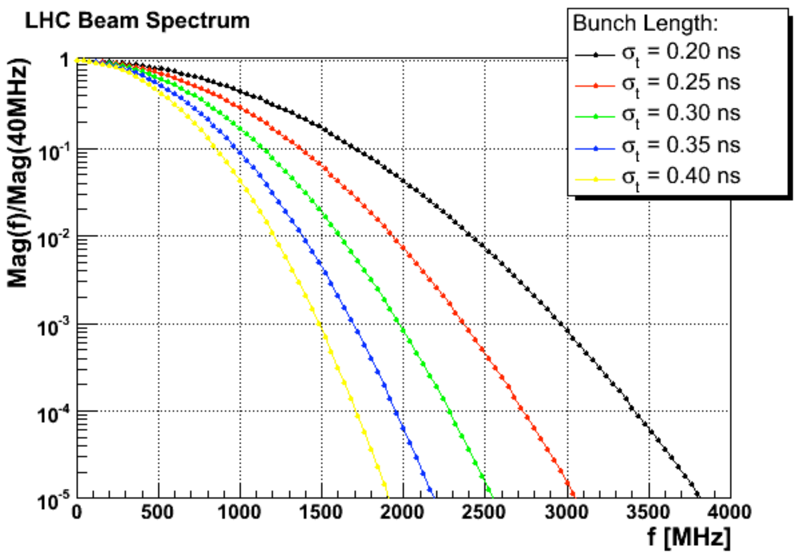




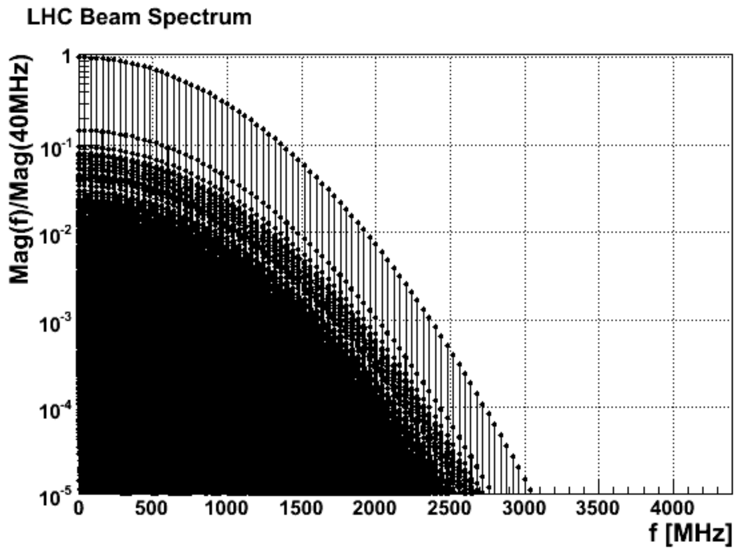
Appendix …: always to remember

LHC BEAM SPECTRUM :

at 2.5GHz less then 10e-2 of the 40MHz harmonic



Single bunch, different bunch lengths (nominal is 0.25ns)



All bunches

- **0.25ns long**
- **in sequence according to presently approved filling scheme**

Inductive by-pass at low Freq

Reminder: A new physical regime for LHC
⇒ "Inductive by-pass"

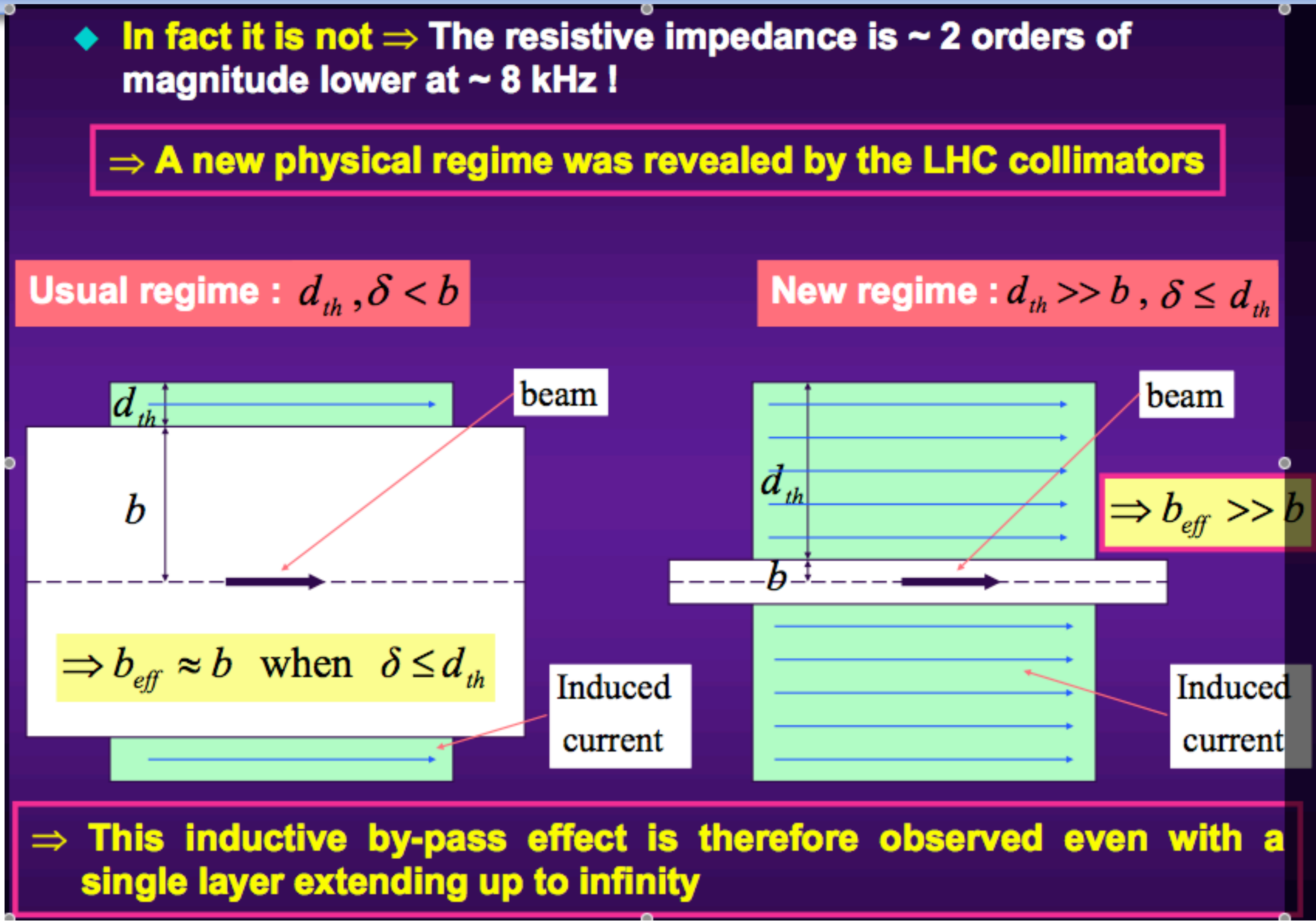
- First unstable betatron line $f_\beta^1 \approx 8\ \mathrm{kHz}$
- Skin depth for graphite (ρ = 10 μΩm) $\delta(8\ \mathrm{kHz}) = 1.8\ \mathrm{cm}$
- Collimator thickness $d_{th} = 2.5\ \mathrm{cm}$

$$\Rightarrow \quad \delta(f_\beta) = \sqrt{\frac{\rho}{\pi\,\mu\,f_\beta}} < d_{th}$$

⇒ One could think that the classical "thick-wall" formula would be about right $Z_\perp^{\mathrm{thick-wall}}(f) \propto \frac{1}{b^3\sqrt{f}}$

E.Metral - CERN-AB/ABP

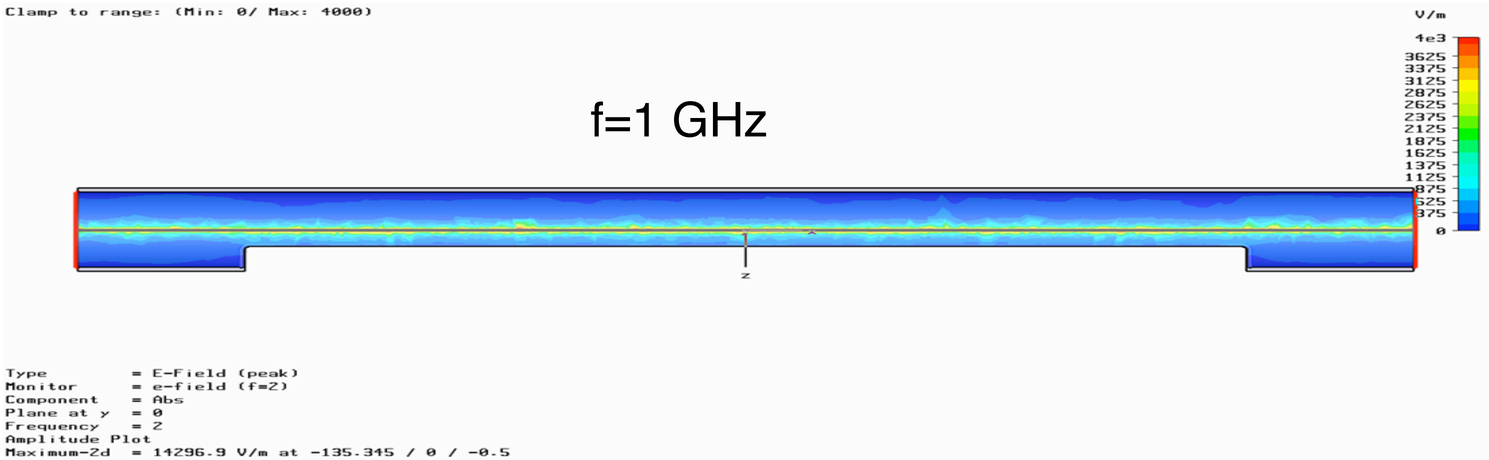
Inductive by-pass at low Freq

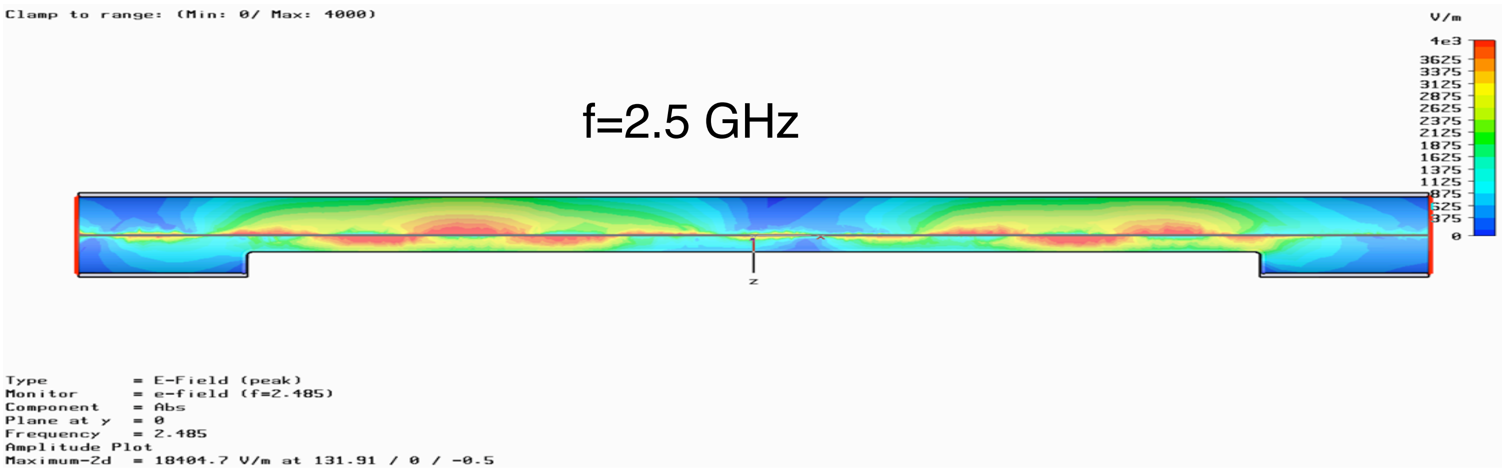


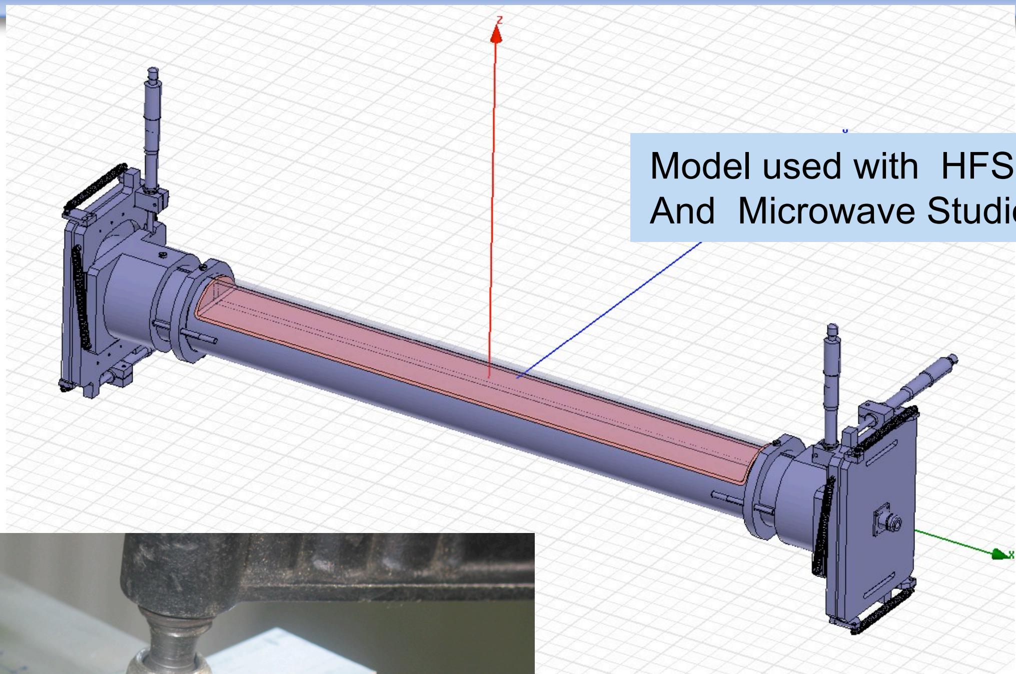
E.Metral - CERN-AB/ABP

Example of E field calculation

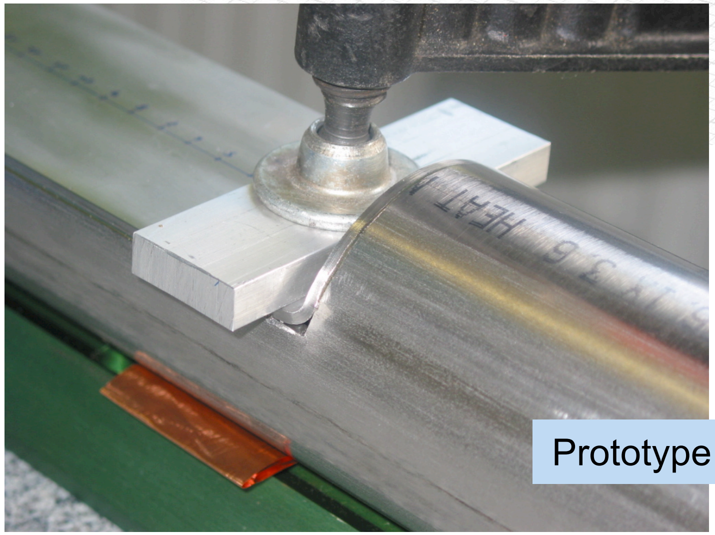
Using CST Microwave Studio, old design with single pocket per station





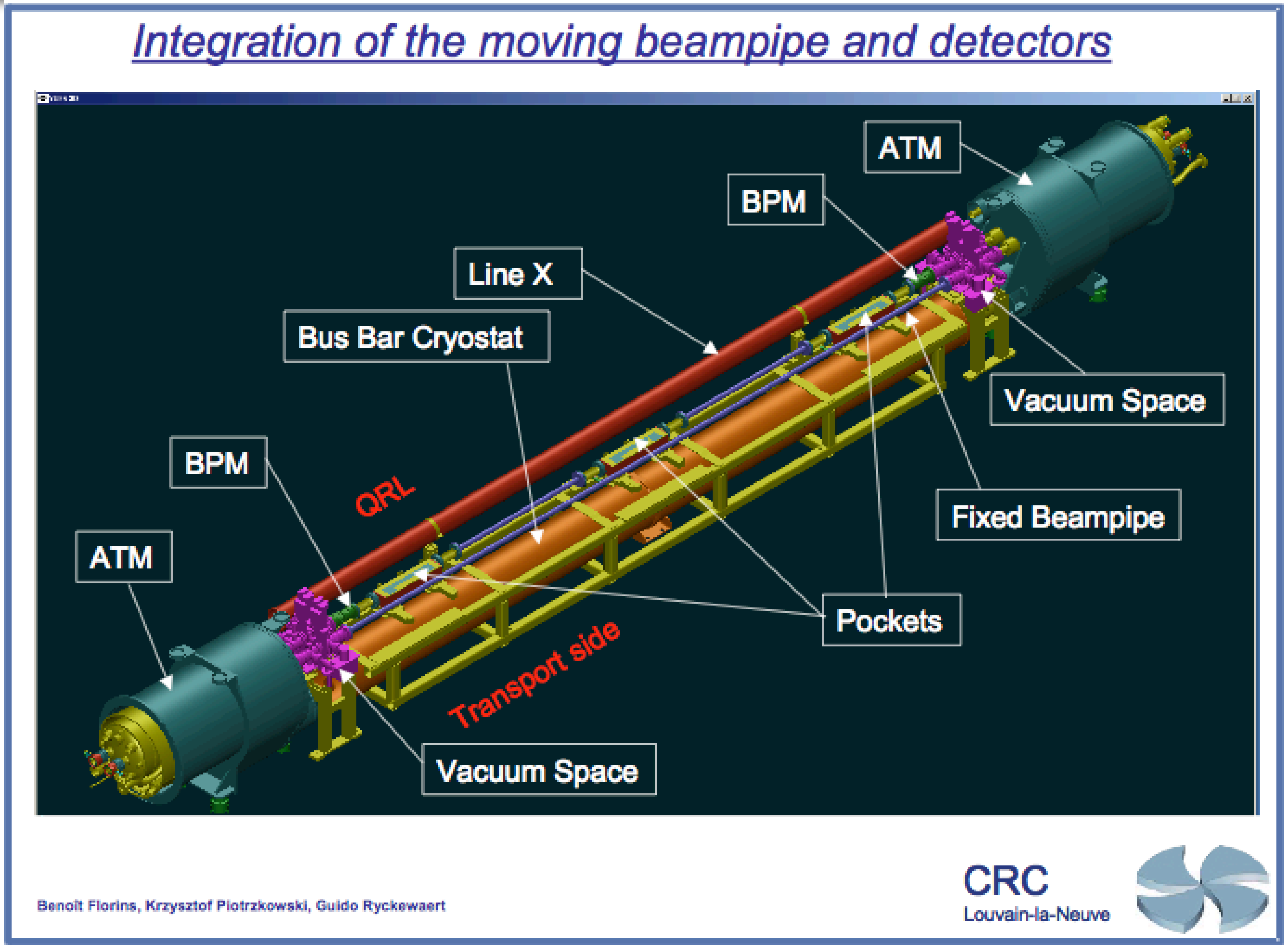


Model used with HFSS
And Microwave Studio



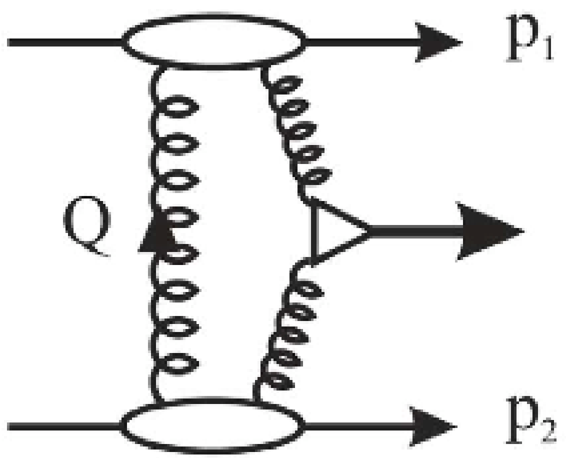
Prototype shipped to Manchester

FP420 integration



A minimal system for commissioning/calibration runs is foreseen to be ready for installation in fall 2008

FP420 Physics



Motivation from KMR calculations (e.g. hep-ph 0111078)

- Selection rules mean that central system is (to a good approx) 0^{++}
- If you see a new particle produced exclusively with proton tags you know its quantum numbers
- Proton tagging may be the discovery channel in certain regions of the MSSM
- Tagging the protons means excellent mass resolution (~ GeV) irrespective of the decay products of the central system

"The panel believed that this offers a unique opportunity to extend the potential of the LHC and has the potential to give a high scientific return." - UK PPRP (PPARC)

"By detecting protons that have lost less than 1% of their longitudinal momentum, a rich QCD, electroweak, Higgs and BSM program becomes accessible, with the potential to make measurements which are unique at LHC, and difficult even at a future linear collider."

(Taken from various FP420 presentations)