Impedance model of a machine and associated challenges

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for the CERN impedance team,

http://impedance.web.cern.ch/impedance/

with inputs from Marit Klein, Ryutaro Nagaoka (SOLEIL), Reiner Wanzenberg (DESY), Mikhail Zobov (INFN).

ICFA mini-Workshop on

Electromagnetic wake fields and impedances in particle accelerators

April 25th 2014

Erice, Sicily

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Agenda

- What is an impedance model?
- Why build an impedance model?
- Procedure for hardware installation at CERN
- How to build an impedance model?
- 2 current ongoing studies
- Summary

What is an impedance model?

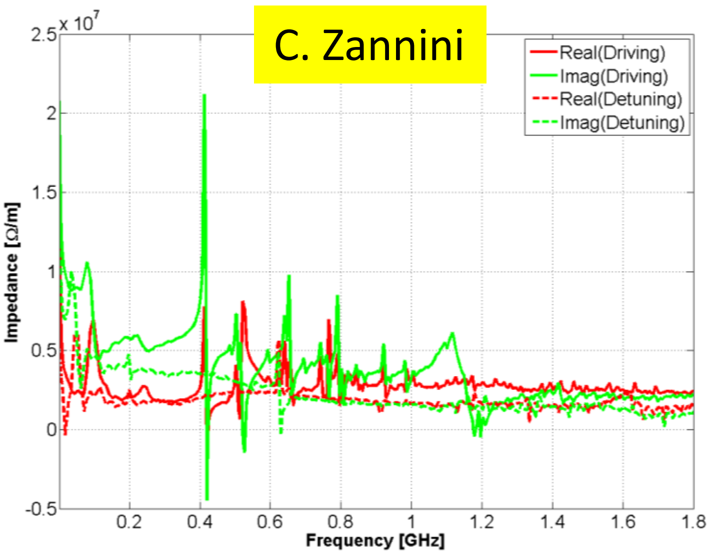
- Also called "impedance budget"

- Gives the necessary information on the **status of criticality of the impedance of a machine** with respect to beam dynamics thresholds

- Depending on the need, an impedance model can be anything between:
  - **A single number** (for instance Im(Z/n) at low frequency),
  - And an elaborated tool that is able to recompute **many impedance contributions as a function of frequency** and related thresholds with slight changes of machine configuration

element	Ref	b	$\mathrm{Im}(Z/n)$	$\mathrm{Im}(Z_\perp)$
		mm	Ω	MΩ/m
Pumping slots	[23]	18	0.017	0.5
BPM's	[24]	25	0.0021	0.3
Unshielded bellows		25	0.0046	0.06
Shielded bellows		20	0.010	0.265
Vacuum valves		40	0.005	0.035
Experimental chambers		-	0.010	-
RF Cavities (400 MHz)		150	0.010	(0.011)
RF Cavities (200 MHz)		50	0.015	(0.155)
Y-chambers (8)	[25]	-	0.001	-
BI (non-BPM instruments)		40	0.001	0.012
space charge @injection	[2]	18	-0.006	0.02
Collimators @injection optics		4.4 ÷ 8	0.0005	0.15
Collimators @squeezed optics		1.3 ÷ 3.8	0.0005	1.5
TOTAL broad-band @injection optics			0.070	1.34
TOTAL broad-band @squeezed optics			0.076	2.67

LHC design report, chap 5



SPS dipolar and quadrupolar impedance model in 2012

Agenda

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- Procedure for hardware installation at CERN
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Why build an impedance model?

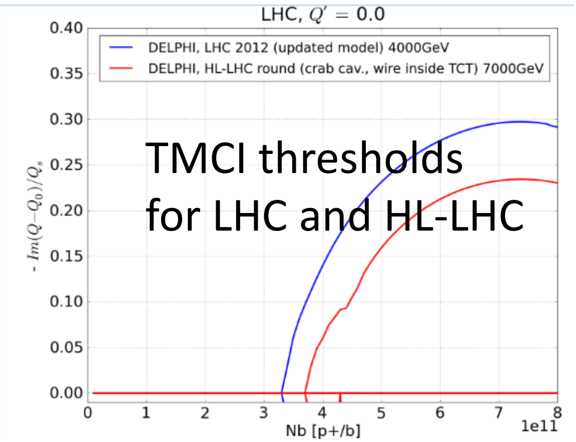
- **Estimate the intensity/brightness limits** of new projects and existing accelerators
  - With respect to single bunch and coupled bunch instability thresholds
  - All new projects ask at a very early stage for an estimate of the impedance budget
    (e.g. ZBASE for LHC, HPPS, TLEP, FCC).

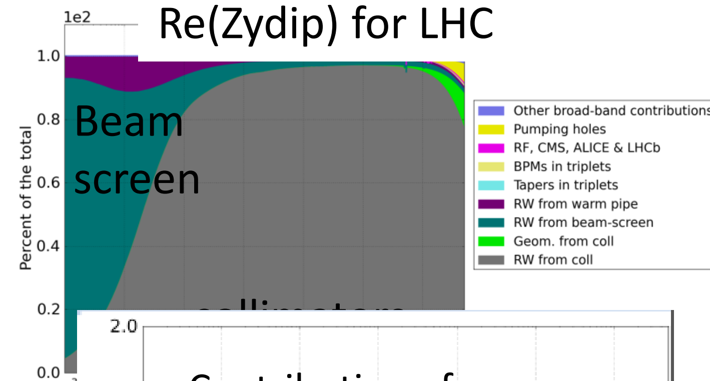
- **Identify large impedance contributors** that could be optimized to improve the performance of existing accelerators

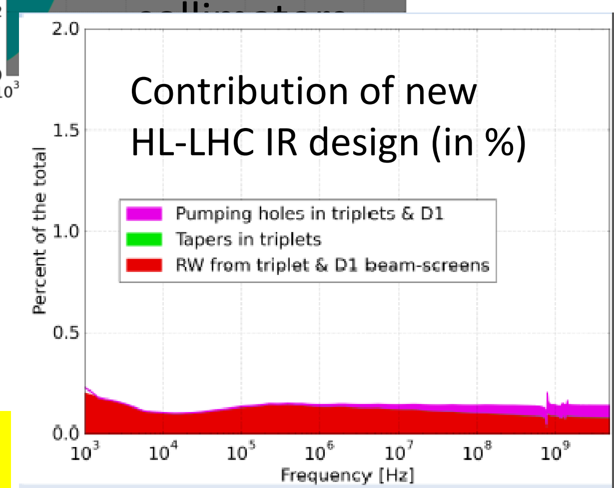
- Design standardized tools to objectively **estimate the criticality of impedance of existing and foreseen hardware**

  → help the "impedance police" make informed decisions

  → predict beam induced heating







Plots taken from N. Mounet et al

Agenda

- What is an impedance model?
- Why build an impedance model?
- Short digression:
  Procedure for hardware installation at CERN
- How to build an impedance model?
- 2 current ongoing studies
- Summary

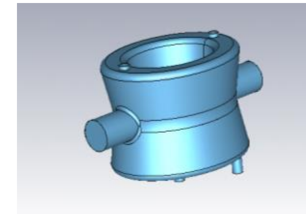
Digression:
procedure to accept/reject installation of new devices in machines at CERN

- Needs to put a request for installation for all new devices in the tunnel, that has to be signed and agreed by all parties, in particular safety, radiation protection, vacuum, aperture, and now impedance.

- Document is circulated electronically for 2 weeks, before its status is reviewed one by one by managerial committees.

- Consequences for impedance team:
  - **Need to take responsibility** for the possibility to modify the machine
  - **Need efficient tools** to be able to answer very fast on the predicted impact on the performance and protection of the machine:
    - longitudinal stability for single bunch and coupled bunch,
    - transverse stability for single bunch and coupled bunch,
    - beam induced heating to the device itself, and maybe also neighboring devices
  - **Need objective criteria to accept or reject the installation of new devices**

Digression: procedure put in place by the CERN impedance team to address these requests



- Ask for geometry (3D models, drawings) and material properties.

- Decide which code to use:
  - Analytical models for simple geometries (**ReWall** for round/flat chambers)
  - 2D models for axisymmetric geometries (**ABCI**, **ECHO**)
  - 3D models for more complex geometries (**CST**, **GdfidL**, **ACE3P**) → most of the cases unfortunately

- Obtain all impedance contributions as a function of frequency (up to XXX GHz):
  - Longitudinal
  - Horizontal (dipolar, quadrupolar)
  - Vertical (dipolar, quadrupolar)
  - Coupled terms (if needed, dipolar, quadrupolar)

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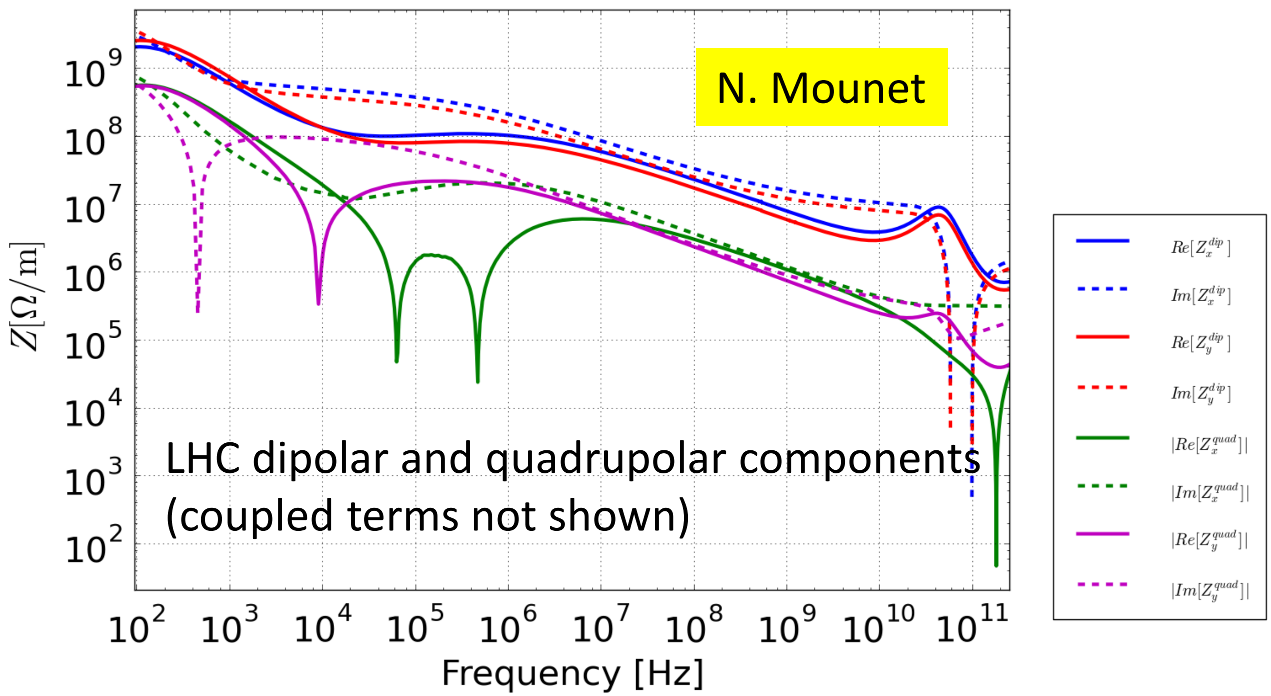

→ Lot ...
→ Requ ...
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Agenda

- What is an impedance model?
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- How to build an impedance model?

  → Challenges?
- 2 current ongoing studies
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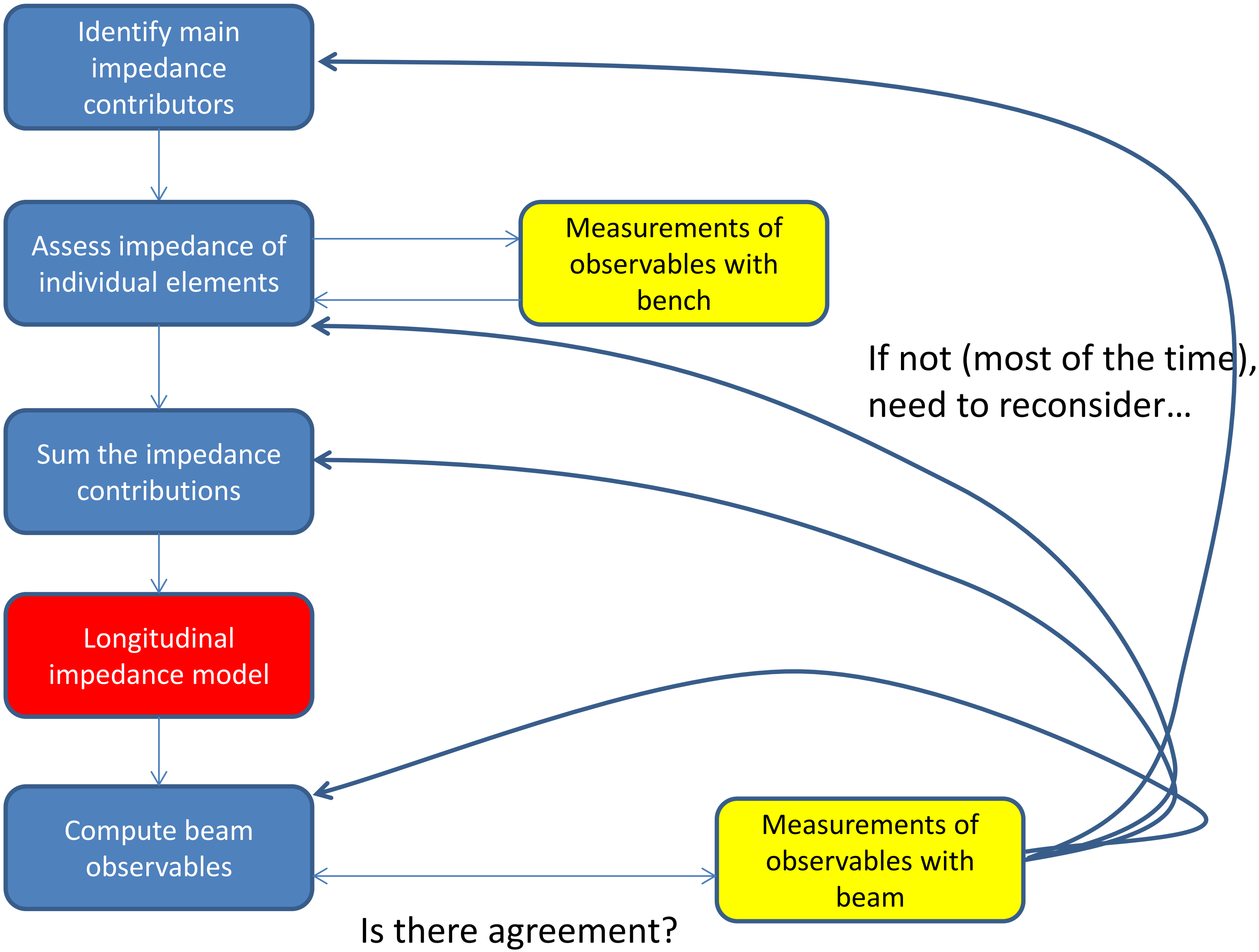
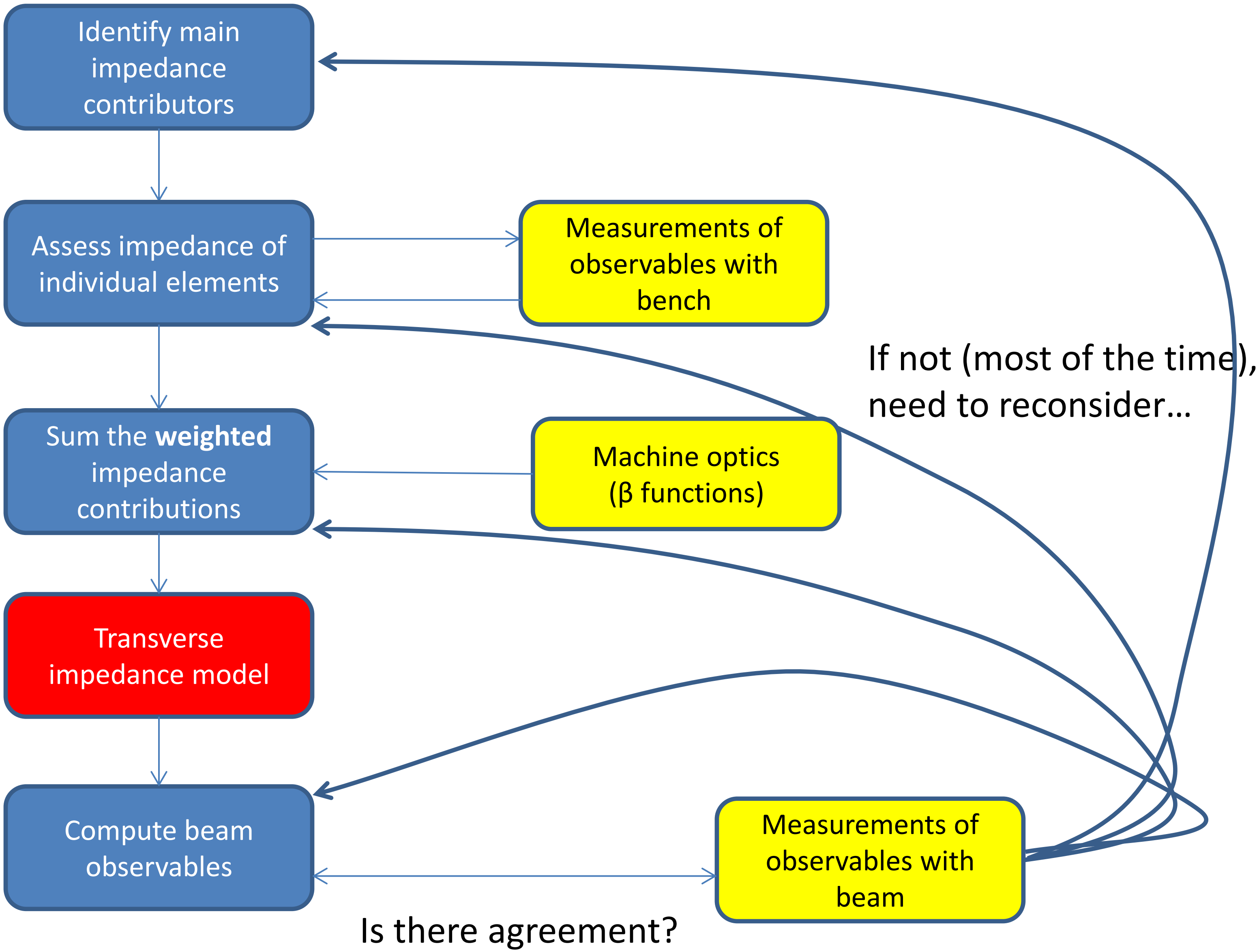
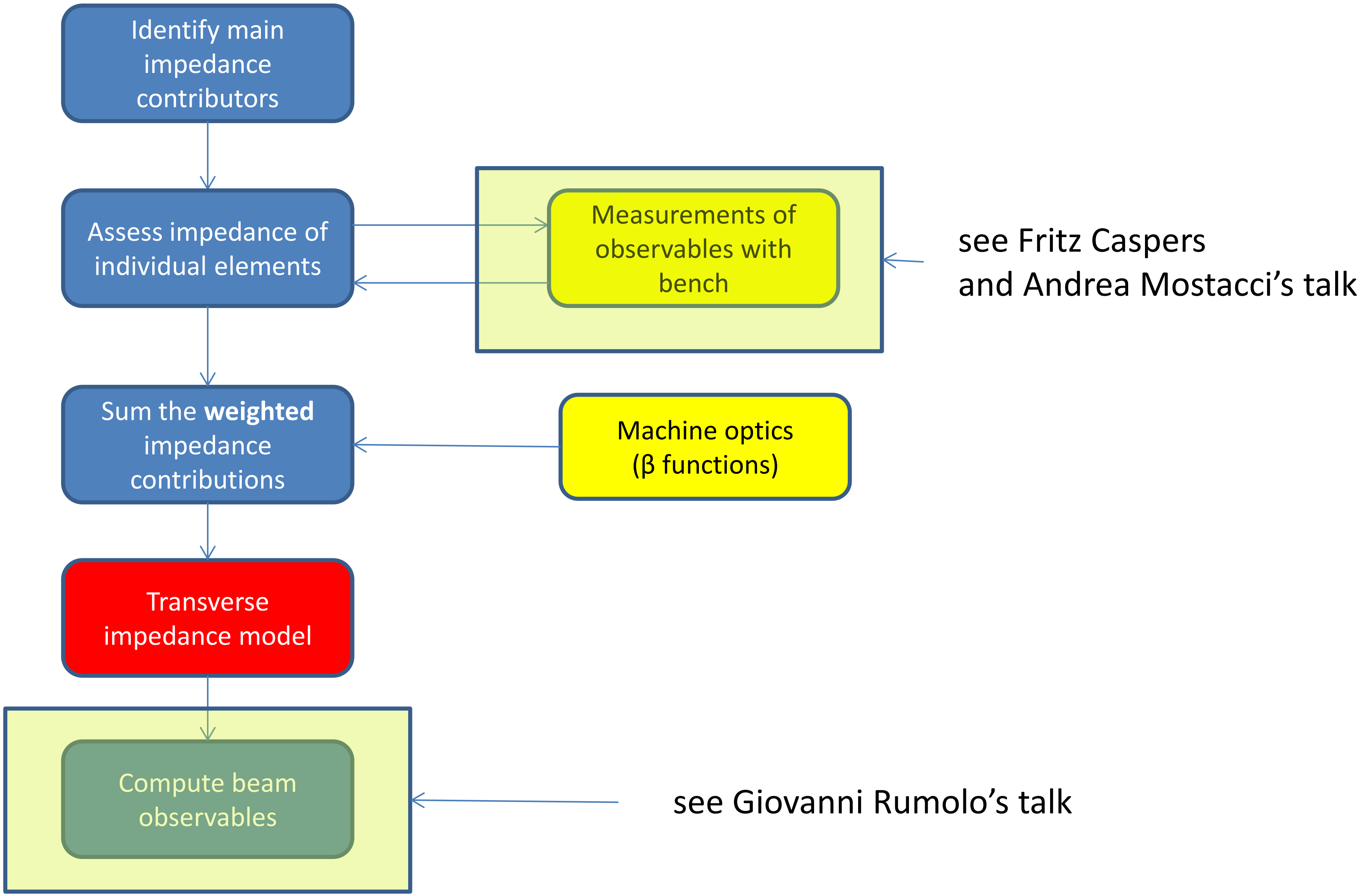
How to build a longitudinal impedance model?



How to build a transverse impedance model?



There are challenges at all levels!



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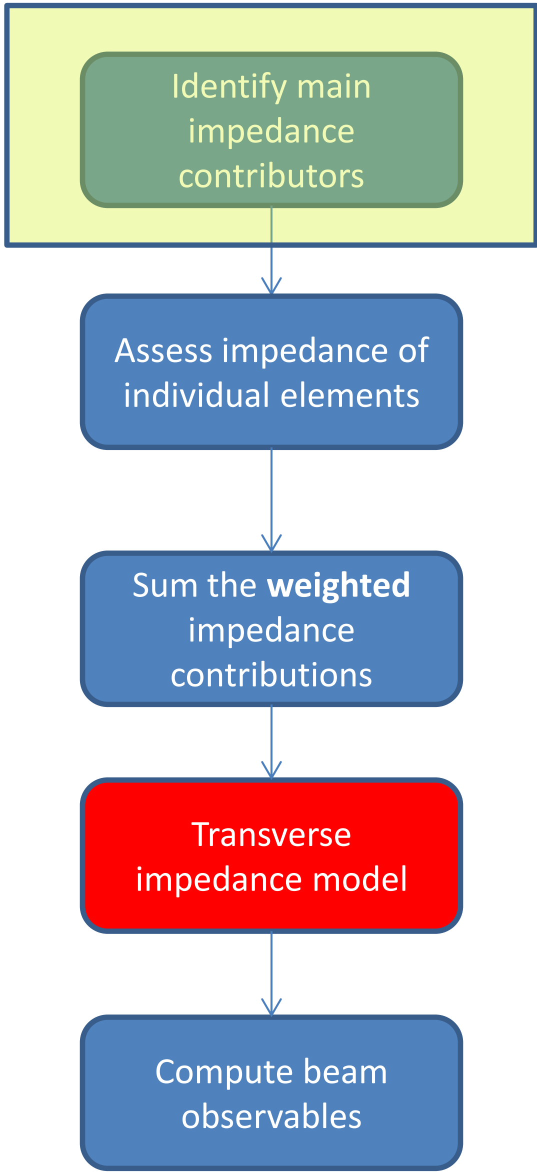
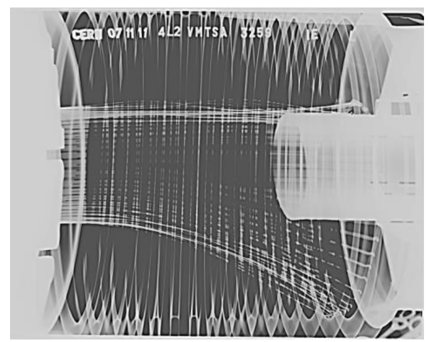


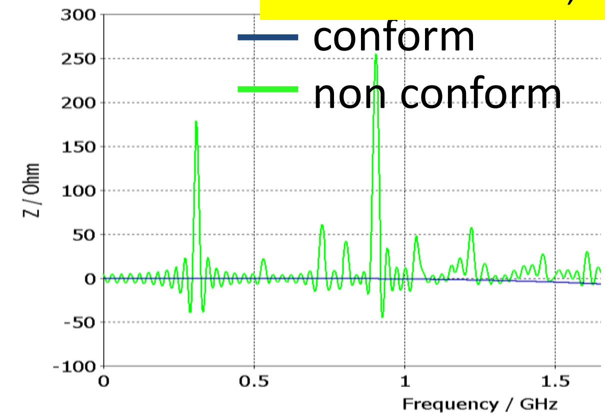
Do we know the machine well enough?

- Some changes sometimes not well recorded
  → Layout database not up to date
- Non conformities, damage, ageing → unexpected high impedances

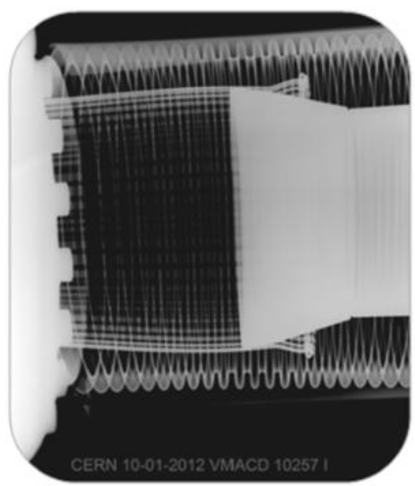
LHC RF fingers



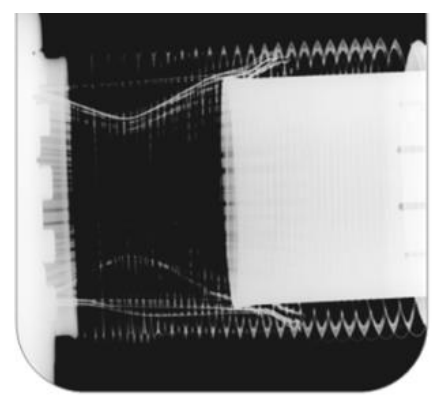
O. Kononenko et al, IPAC13



Conform



Non-conform: reduction of aperture with increase of contact resistance



Courtesy CERN TE-VSC

There are challenges at all levels!

Identify main impedance contributors

Assess impedance of individual elements

Sum the **weighted** impedance contributions

Transverse impedance model

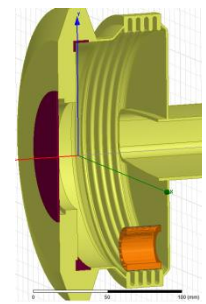
Compute beam observables

Do we know the machine well enough?

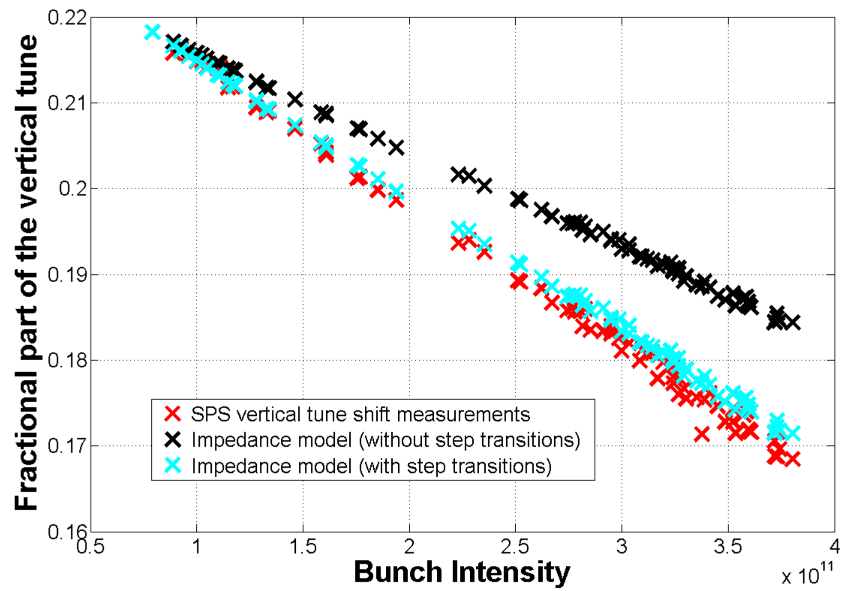
- Some changes sometimes not well recorded → Layout database not up to date
- Non conformities, damage, ageing → unexpected high impedances
- Napolitan proverb: "Many small impedances make large tune shift"
- It takes a while to cover all hardware in large machines

Example of the step transitions in SPS (C. Zannini, J. Varela et al)

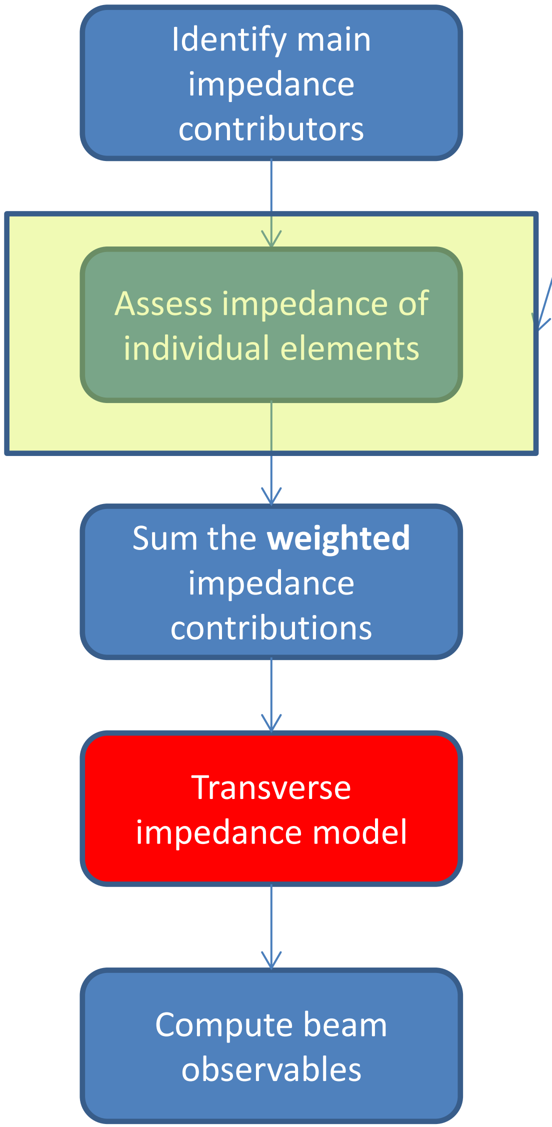
Flange Type	Num. of elements
BPV-QD	90
BPH-QF	39
QF-MBA	83
MBA-MBA	14
QF-QF	26
QD-QD	99
QF-QF	20
BPH-QF	39
QD-QD	75
QD-QD	99



Small contribution, but many steps!



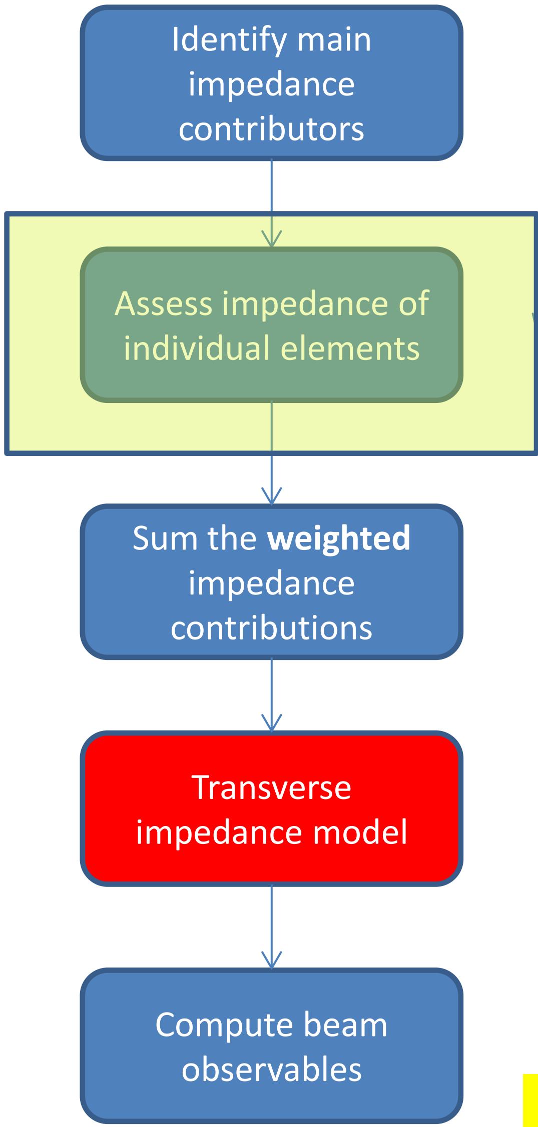
There are challenges at all levels!



Can we compute the impedance of a given device correctly?

- Non conformities, damage, ageing
- Many limitations of the calculation/simulation code

There are challenges at all levels!



Can we compute the impedance of a given device correctly?

- Non conformities, damage, ageing
- Many limitations of the calculation/simulation code

→Limitation in the number of mesh cells

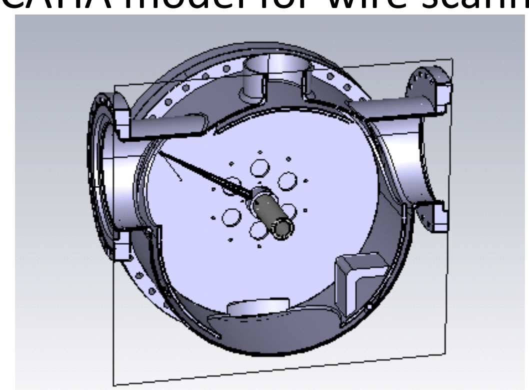
(see talks yesterday by T. Weiland, W. Bruns, Y.H. Chin, I. Zagorodnov)

→ Requirement to often drastically simplify the structure

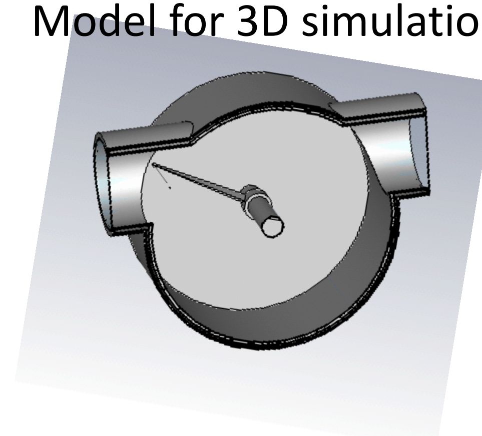
→ Decision to remove many details.

→ Ideally we should check that every removal does not change the result, but it is not always possible.

CATIA model for wire scanner

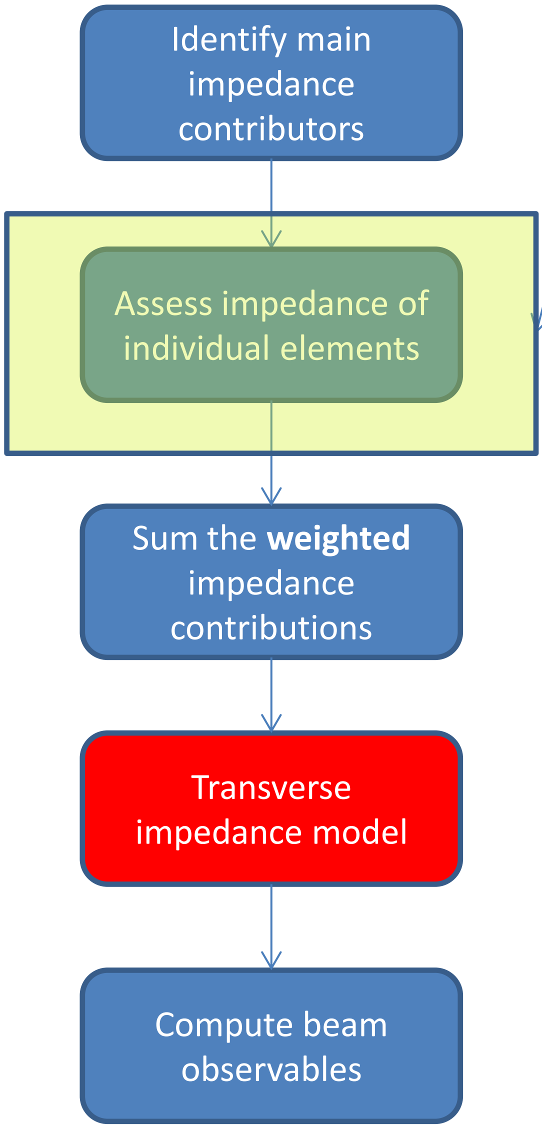


Model for 3D simulations



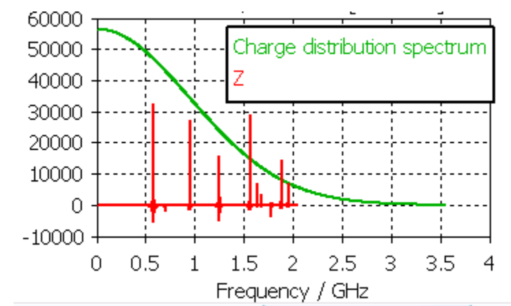
→ Very important to get validation by comparing bench measurements with simulated bench measurements (with wires and probes)

There are challenges at all levels!



Can we compute the impedance of a given device correctly?
- Non conformities, damage, ageing
- Many limitations of the calculation/simulation code

→Limitation in number of mesh cells
→Limitation in the maximum frequency



- Not an issue for analytical codes
- Severe limitation for 3D wakefield codes as minimum exciting bunch length related to mesh cell dimension

→ **Central question for an impedance model: What is the required maximum frequency?**

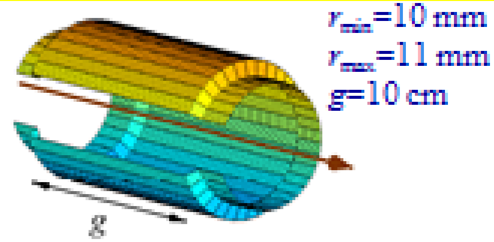
Several answers:
- Assumed to be linked to the maximum significant frequency of the longitudinal beam spectrum (1-10 fmax?)
- Choose so that the discretization that can be used in the beam dynamics code (100 to 1000 slices per bunch)
- Most of the time: the best we can do with the 3D code

Ideally, a convergence should be found for the whole chain down to the beam dynamics, but again very cumbersome to perform but also…

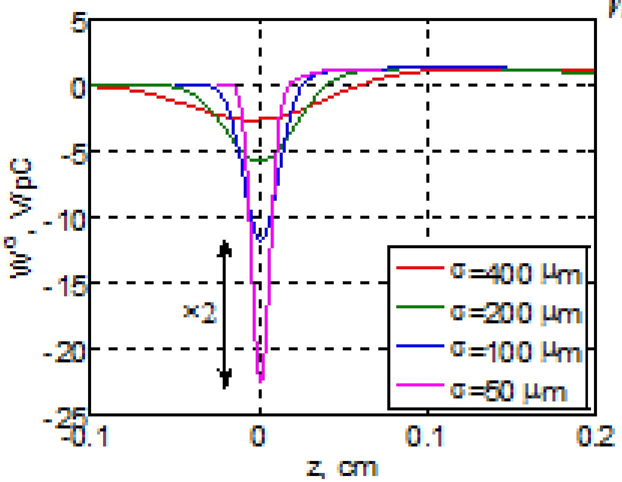
Shallow Cavity Example

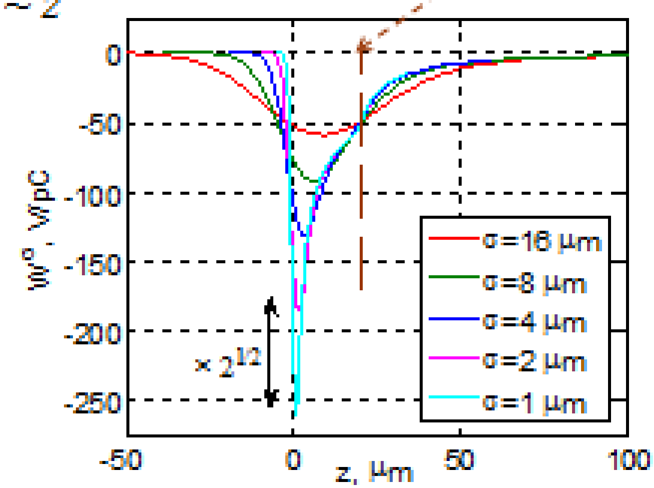
"B. Podobedov and G. Stupakov" PRSTAB 024401 (2013)

- Our method is NOT shortening the bunch until the EM solver wakes converge (this can fail!)
- For this cavity wakes are ~Gaussian; they double as σ shortens each factor of 2, suggesting
- This is totally incorrect! ~~$W^\delta(z) \sim \delta(z)$~~
- It is diffraction model instead $W^\delta(z) \sim z^{-1/2}$



$\lambda_g \approx 2(r_{max} - r_{min})^2 / g = 20\ \mu m$





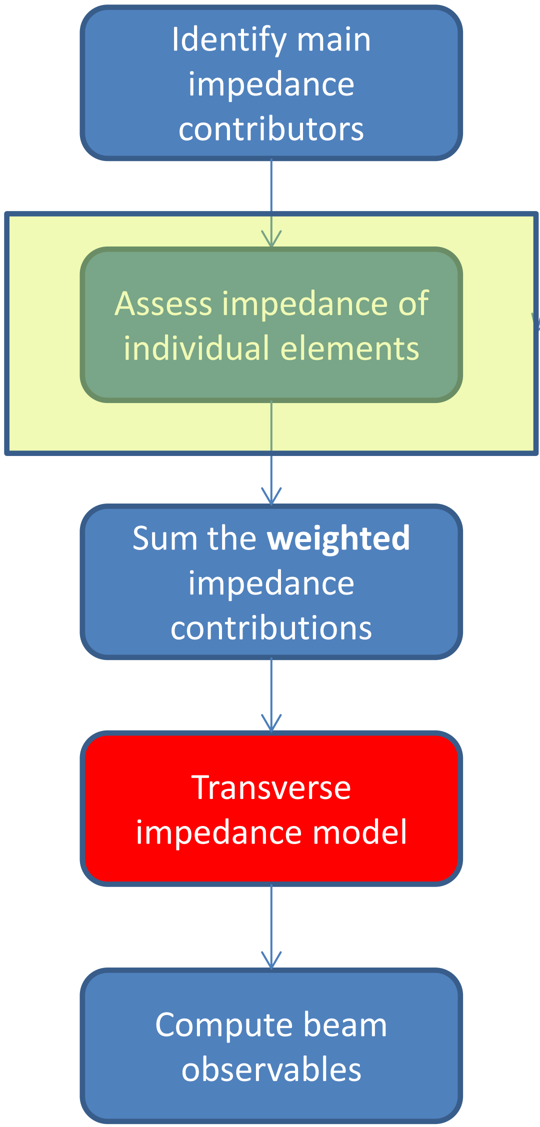
Important to Know λ_g before Running the EM Solver

dov, Jan. 16, 2014

Boris Podobedov at the TWIICE workshop in January 2014

→ Shortening the bunch until convergence does not always work
→ Recipe given to find the optimum bunch length for EM simulations
→ Can we find this optimum bunch length for all geometries/all materials? What about β<1?
→ See next talk by Gennady Stupakov

There are challenges at all levels!



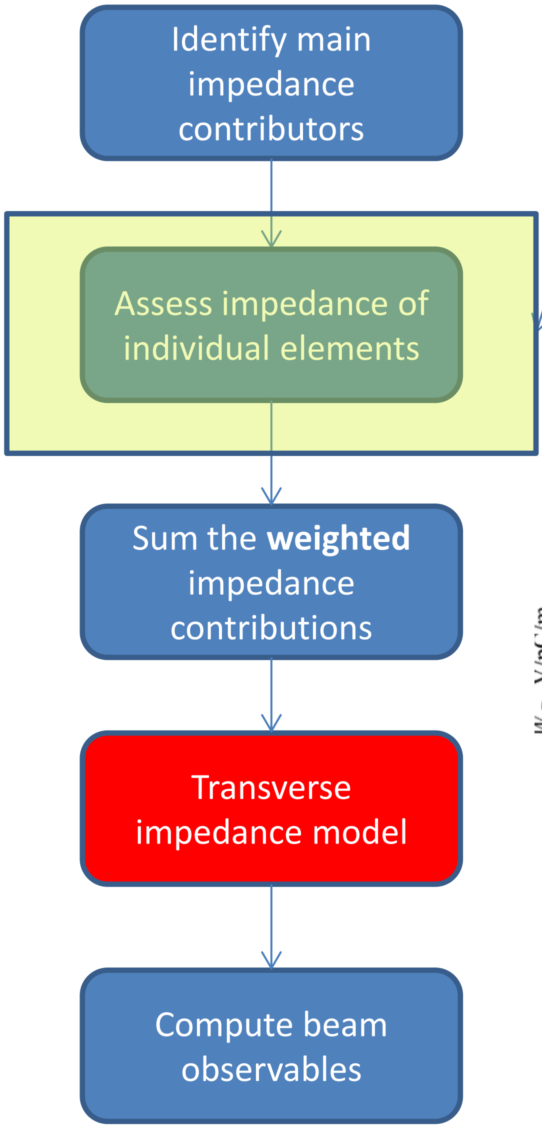
Can we compute the impedance of a given device correctly?

- Non conformities, damage, ageing
- Many limitations of the calculation/simulation code

Limitation in number of mesh cells
Limitation in the maximum frequency
Limitation in the applicability of the code

- Many codes or features **do not work when β<1**
- Many analytical formulae are **only valid in a limited range of frequencies and for simple geometries**: e.g. thick wall formula (see talk of N. Mounet), formulae for striplines, bellows, Tsutsui/Wang models for kickers, etc.
- Can we accurately **account for connection to external circuits with long cables** with 3D models? E.g. kicker and septum plates connection to power supply.
- **Need to separate the dipolar/quadrupolar impedances with the eigenmode solver** in non symmetric structures.
- Recent significant effort in treatment of dispersive materials in both wakefield and eigenmode solvers. Thanks to CST, TEMF and GdfidL!
- Difficulty to account for coatings in 3D codes.

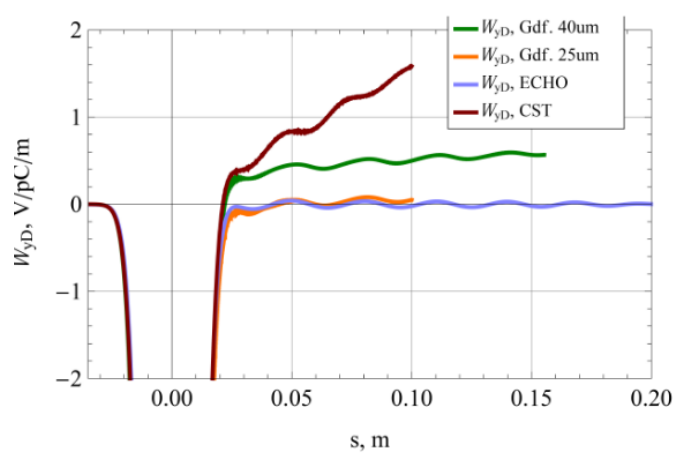
There are challenges at all levels!

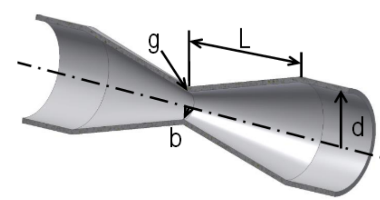


Can we compute the impedance of a given device correctly?
- Non conformities, damage, ageing
- Many limitations of the calculation/simulation code

Limitation in number of mesh cells
Limitation in the maximum frequency
Limitation in the applicability of the code
Limitation when the impedance is very small

- non-physical behaviour (in particular in transverse plane)





- Geom. Parameters: d=9.2mm, L=108mm
- Bunch Length: σ_s=7mm
- Radius b is varied from 2.5mm to 15mm

Axially Symmetric Tapered Collimator

b=2.5mm

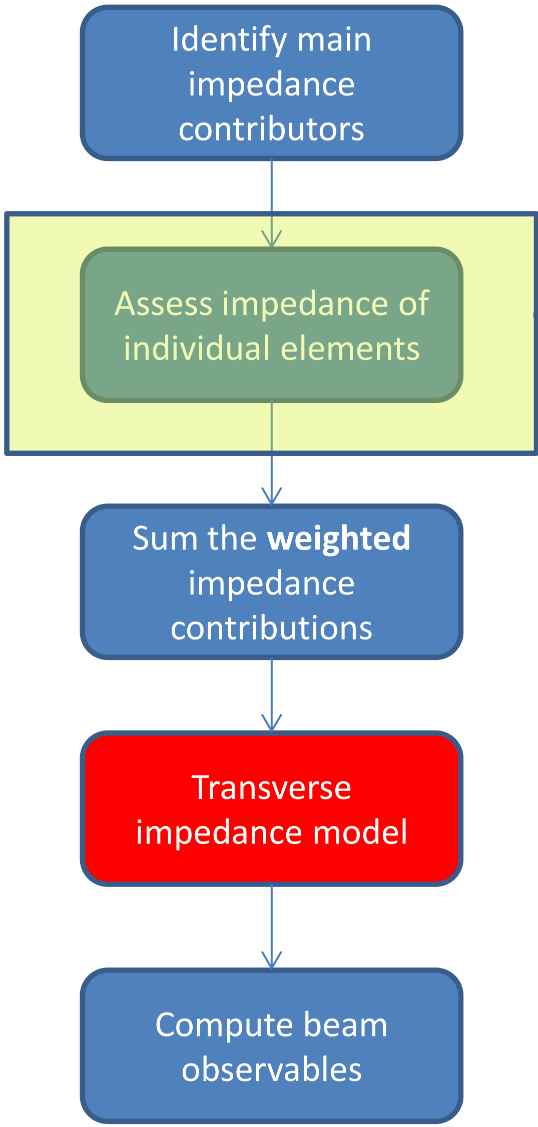
A. Blednykh, TWIICE workshop, January 2014 comparison between GdfidL, CST and ECHO for tapered collimator

→ Not a problem if there is only one device.

→ How about when there are ~1000 of these devices, or when the beta function at their location is very large?

→ What do we do when we can not use ECHO2D or reduce the mesh in GdfidL?

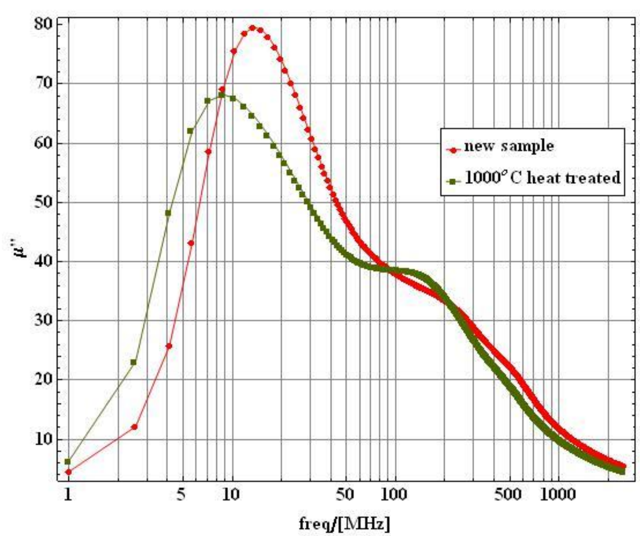
There are challenges at all levels!



Can we compute the impedance of a given device correctly?

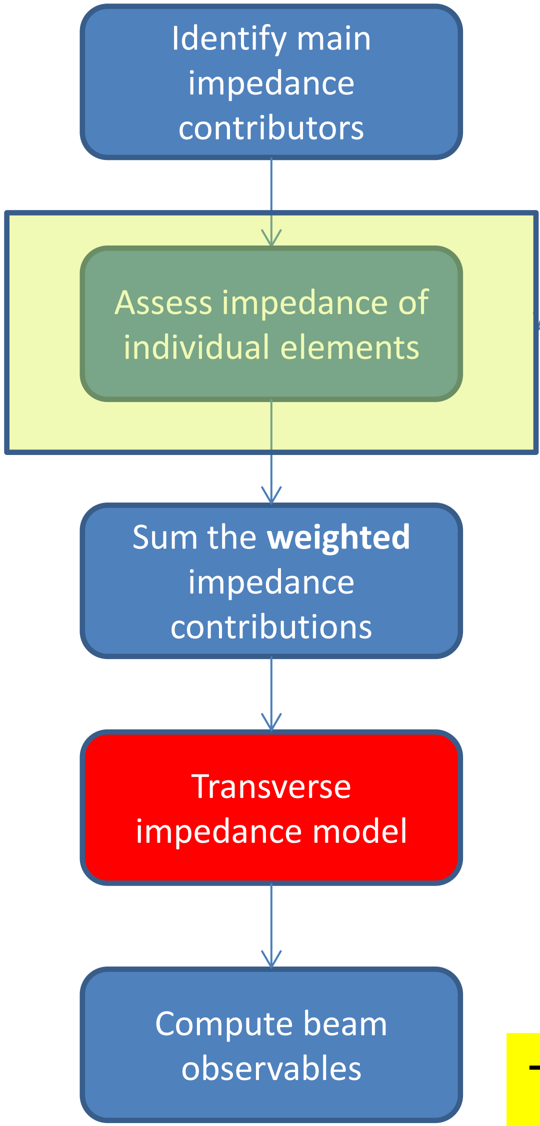
- Non conformities, damage, ageing
- Many limitations of the calculation/simulation code
- **Limitation in the knowledge of the materials and geometry**

- Electromagnetic properties of material up to several GHz are usually not a specification and may fluctuate from batch to batch.
- Problem with non isotropic materials (depends on manufacturing process).
- Thickness of thin coatings is not always well controlled.



μ'' as a function of frequency for samples of TT2-111R ferrites with and without heat treatment Courtesy Christine Vollinger (CERN)

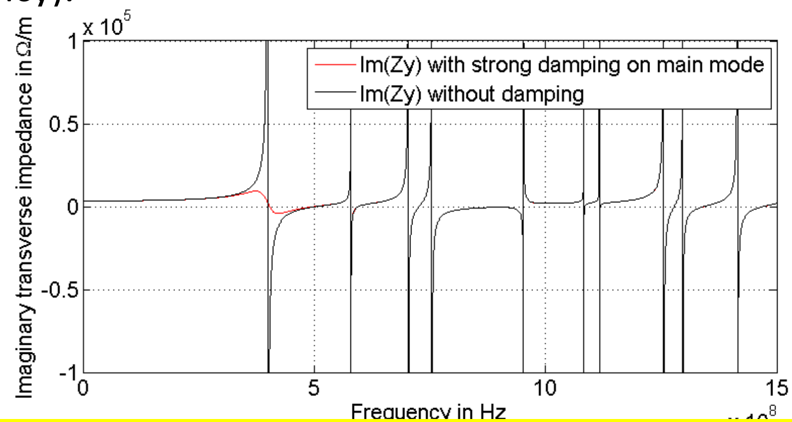
There are challenges at all levels!



Can we compute the impedance of a given device correctly?

- Non conformities, damage, ageing
- Many limitations of the calculation/simulation code
- Limitation in the knowledge of the materials
- **Impedance of active devices**

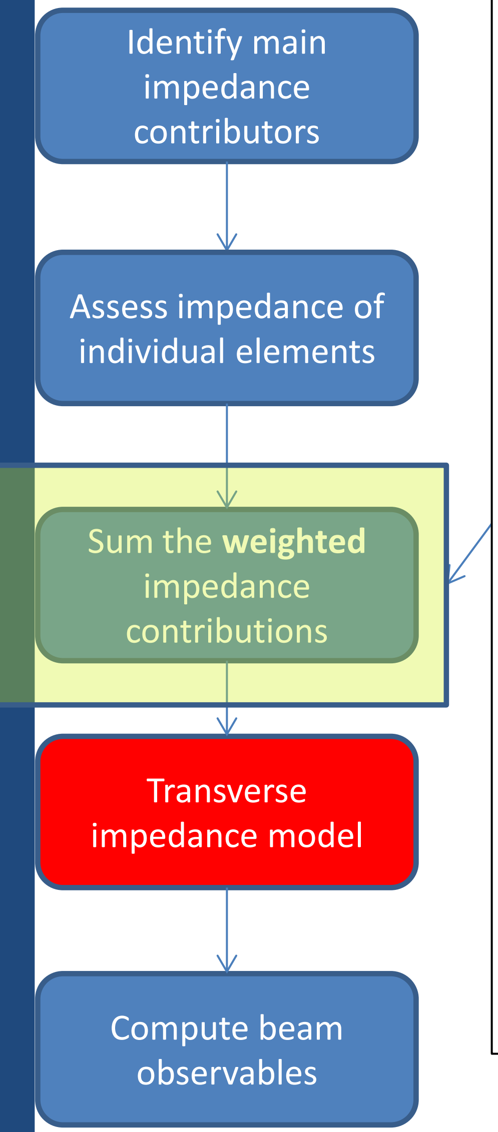
- **Question of Mikhail yesterday**: How to account for active feedback on main cavity mode?
- The active feedback acts on the fields around the main mode
- Proposal: keep the same R/Q of the mode, but strongly decrease both R and Q, as beam induced fields at the frequency of the main cavity mode should be damped very fast by the feedback (but not far from this frequency).



→ The low frequency component is mostly unchanged, and so should be the single bunch behaviour.

→ Can we assume that a damped mode still follows the resonator model?

There are challenges at all levels!



Can we aggregate the impedance contributions correctly?

- Several contributions coming from **various analytical or simulation codes**

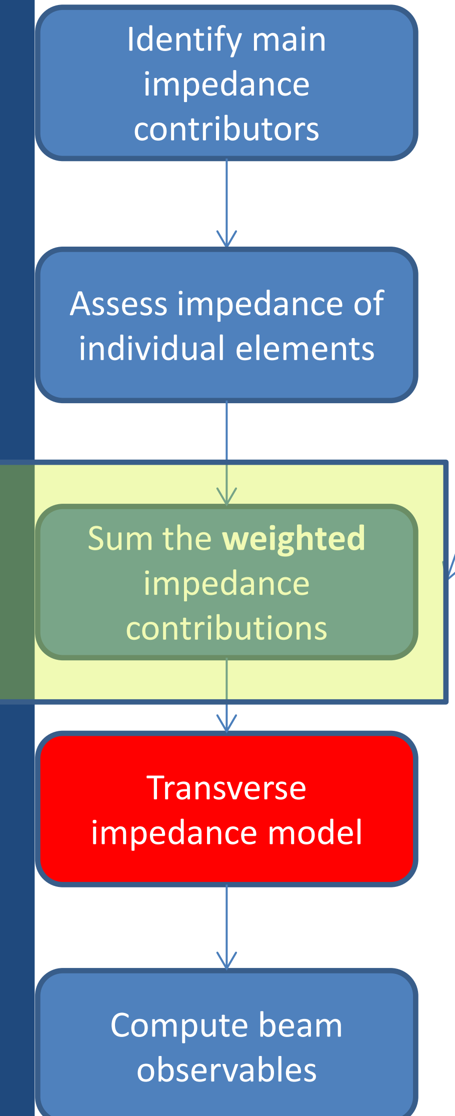
- Results can be in wake functions, "wake functions", impedances, eigenmode tables

- If beam dynamics tool requires a **single bunch wake as input**
  → short wake length is ok, but needs small bunch (HEADTAIL single bunch)
- If beam dynamics tool requires a **broadband impedance as input**
  → long bunch is ok but needs long wake length (Sacherer formula)
- If beam dynamics tool requires **both low and high frequency content**
  → need for non equidistant FFT to transform impedance into wake (see N. Mounet's PhD, EPFL 2012)
  → need both short bunch and long wake length (Headtail multibunch, DELPHI)
  → when resistive contribution is negligible, can use results of eigenmode
  → when resistive wall contribution is large, better to use wakefields

- Interpolation is required to sum contributions. If many modes and many resonances, the number of points in the wake or in the impedance can be very large ($O(10^5)$ for LHC).

- Requires accurate knowledge of the beta functions of all devices

There are challenges at all levels!



Can we aggregate the impedance contributions correctly?

- Question to the community:

Should we avoid the direct use of wake functions extracted from simulated wake potential, and fit the impedance by sum of resonators? (as done by several labs)

Advantage:

- The wake should respect causality and numerical noise can be avoided
- The number of resonators is not a limitation, but the fit itself is an issue when there are too many peaks

Disadvantage:

- What do we do when the resonator model is not applicable (dispersive materials, $\beta<1$)?
- If other contributions to low frequency impedance, how can we account for them?
- See issue of aggregated broadband model for LHC in the next slides

→ For large machines, these operations cannot be performed "by hand".
→ Need for an impedance database to store impedance results
→ Need for scripts to efficiently recompute impedances, sum them and plot them
as scan of parameters are often needed (optics, collimator aperture, addition of new device)

There are challenges at all levels!

→ Many challenges and traps before reaching an impedance model!

Identify main impedance contributors

Assess impedance of individual elements

Sum the **weighted** impedance contributions

Transverse impedance model

Compute beam observables

→ Despite these difficulties, there are many impedance models available!

KEKB low energy ring
longitudinal wake Y.H. Chin (1996)

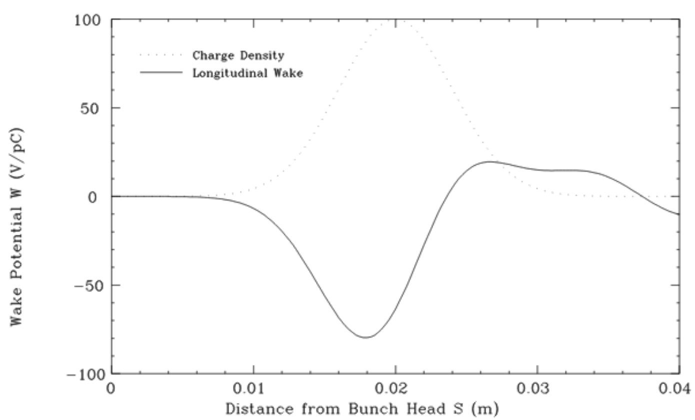


Figure. 3. Total longitudinal wake potential for the KEKB LER.

DAΦNE longitudinal impedance,
S. Bartalucci et al (1993)

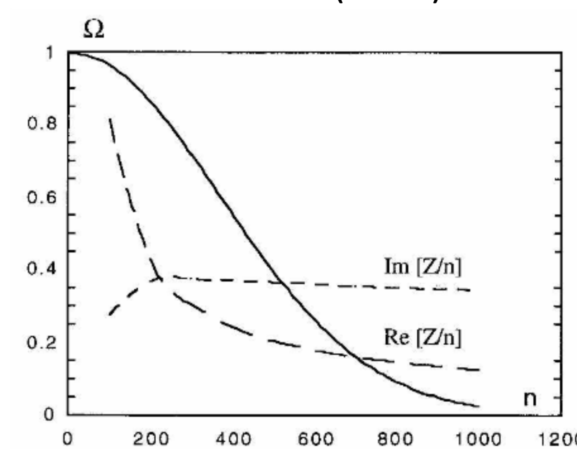
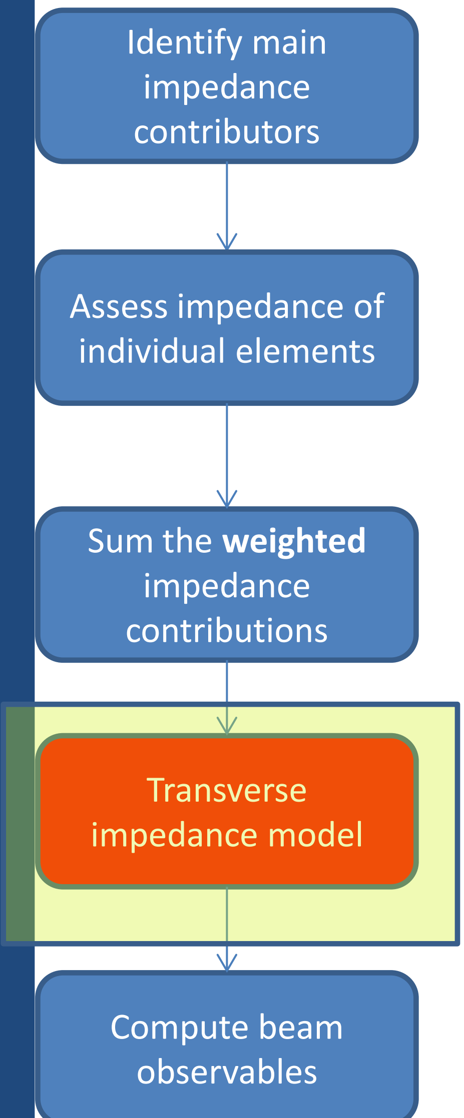


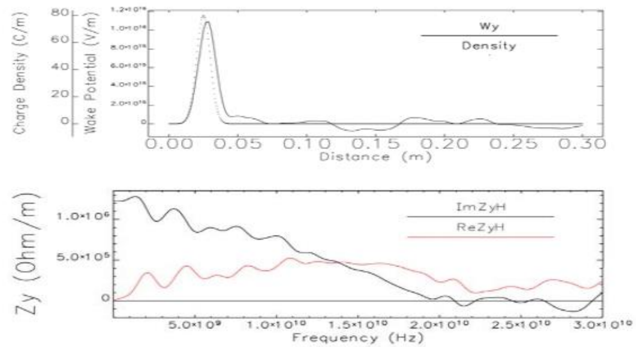
Fig. 23 - Imaginary and real part of DAΦNE main ring impedance with superimposed bunch spectrum (solid line).

There are challenges at all levels!

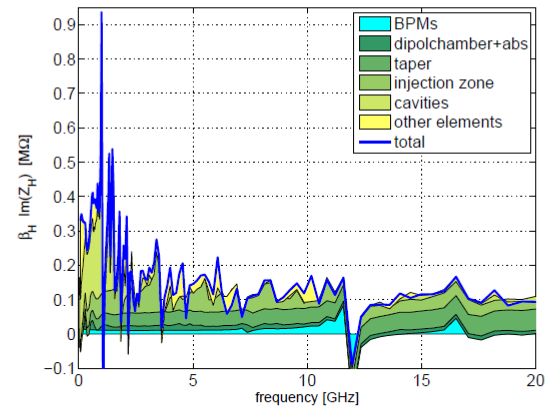


→ Many challenges and traps before reaching an impedance model!

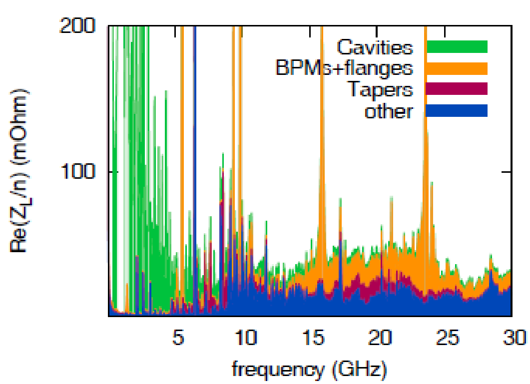
Vertical model of **APS**
Y.C. Chae (PAC07)



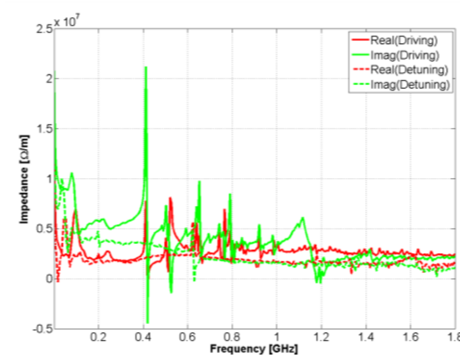
ALBA horizontal model
T,. Guenzel (ESLS 2010)



MAXIV longitudinal model
(M. Klein, R. Nagaoka et al, IPAC13)

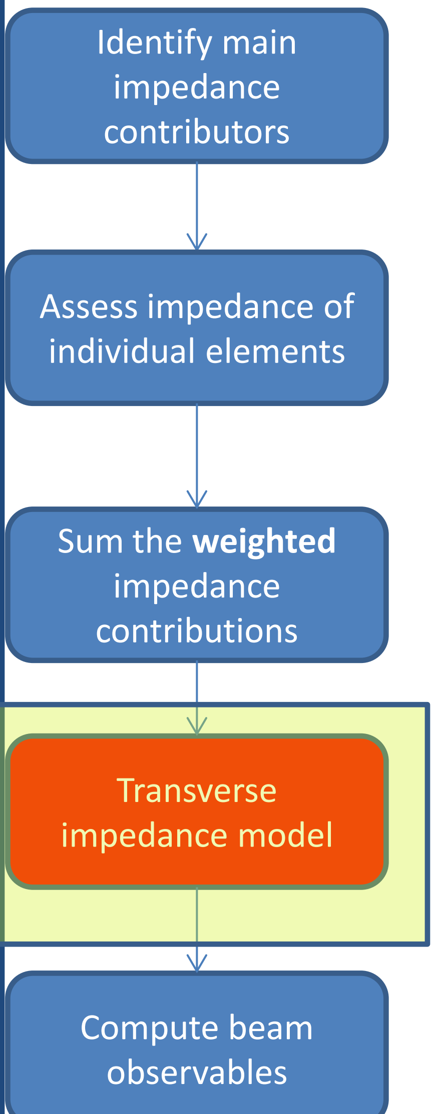


SPS vertical model
(C. Zannini et al,)

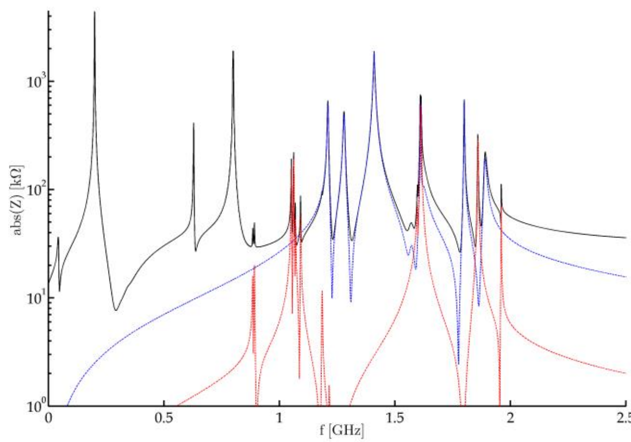


There are challenges at all levels!

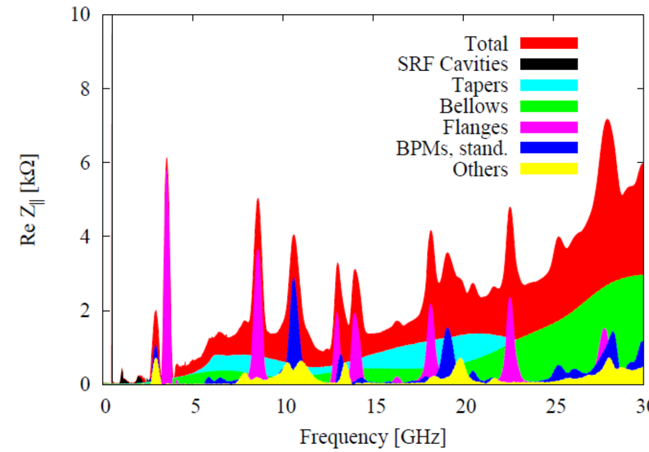
→ Many challenges and traps before reaching an impedance model!



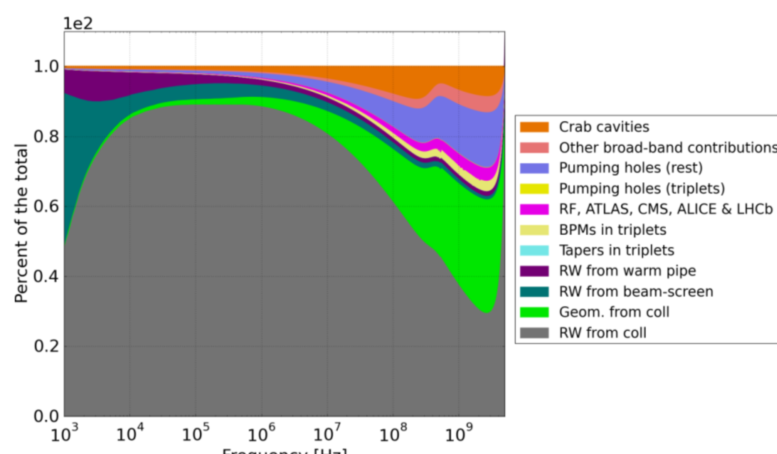
SPS longitudinal model
N. Mounet et al (2014)



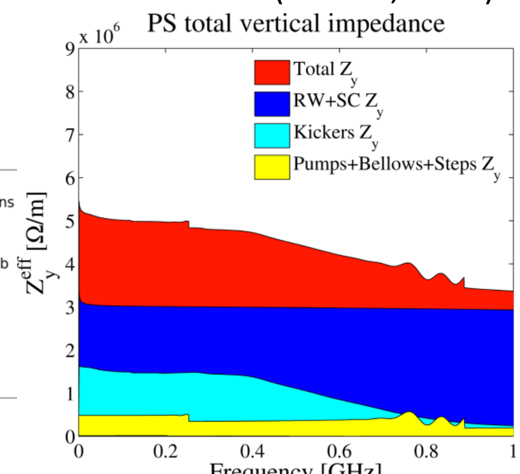
Longitudinal model of **TPS** project
A. Rusanov, EPAC08



HL-LHC horizontal model
N. Mounet et al (2014)



PS vertical model
S. Persichelli et al (TDR PS, 2014)



Agenda

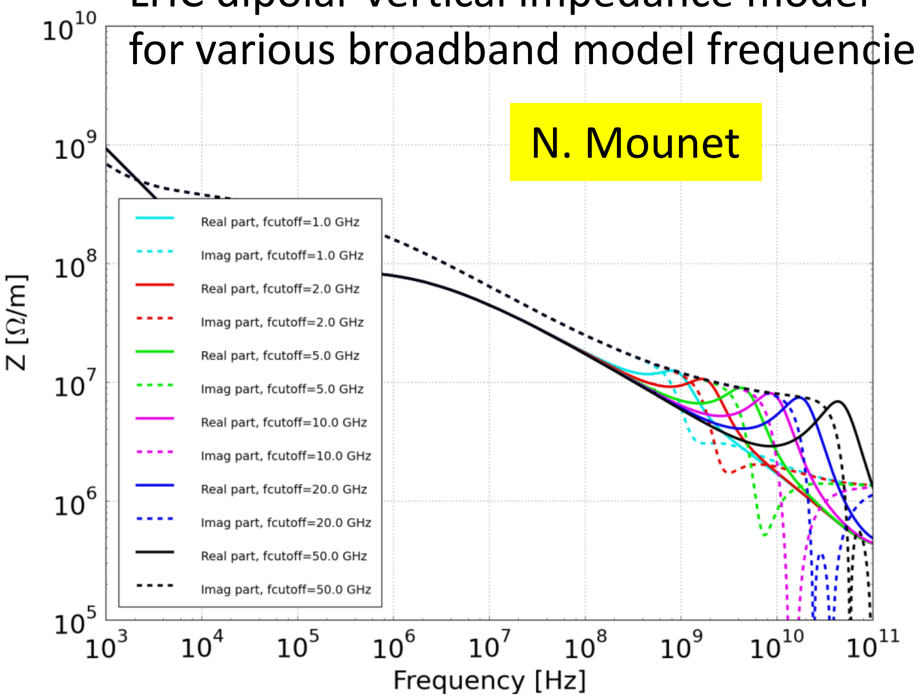
- What is an impedance model?
- Why build an impedance model?
- Procedure for hardware installation at CERN
- How to build an impedance model?
- 2 current ongoing studies
  - Impact of using resonator broadband model for instability assessment
  - Impact of new crab cavities on HL-LHC impedance model
- Summary

Impact of using broadband resonator model

- What frequency should we choose for the broadband model?
  → In general chosen to be around the cutoff of the machine pipe as steps, bellows and transitions dominate in most machines.
  → LHC situation is different as there are very few steps, impedance was very well contained. **What cutoff frequency should be used?**

element	Ref	b	$\mathrm{Im}(Z/n)$	$\mathrm{Im}(Z_\perp)$
		mm	Ω	$\mathrm{M}\Omega/\mathrm{m}$
Pumping slots	[23]	18	0.017	0.5
BPM's	[24]	25	0.0021	0.3
Unshielded bellows		25	0.0046	0.06
Shielded bellows		20	0.010	0.265
Vacuum valves		40	0.005	0.035
Experimental chambers		-	0.010	-
RF Cavities (400 MHz)		150	0.010	(0.011)
RF Cavities (200 MHz)		50	0.015	(0.155)
Y-chambers (8)	[25]	-	0.001	-
BI (non-BPM instruments)		40	0.001	0.012
space charge @injection	[2]	18	-0.006	0.02
Collimators @injection optics		$4.4 \div 8$	0.0005	0.15
Collimators @squeezed optics		$1.3 \div 3.8$	0.0005	1.5
TOTAL broad-band @injection optics			0.070	1.34
TOTAL broad-band @squeezed optics			0.076	2.67

LHC dipolar vertical impedance model for various broadband model frequencies

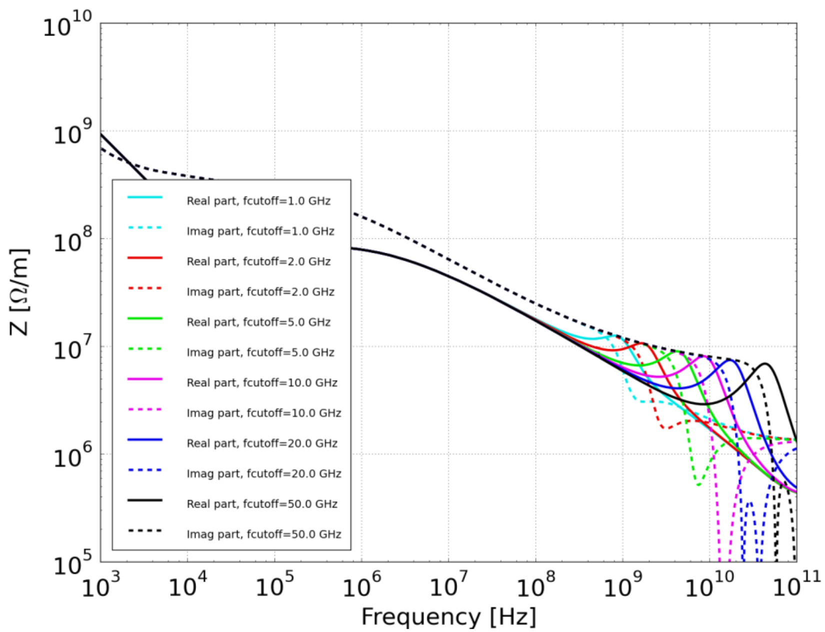


→ Clearly not a marginal impact between 100 MHz and 10 GHz!

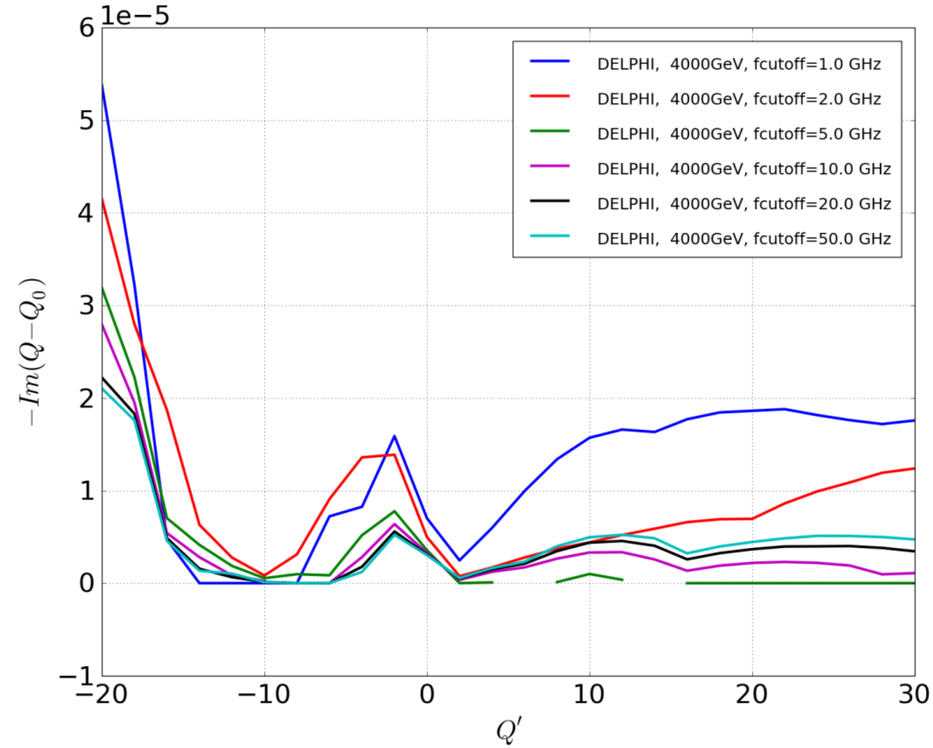
Impact of using broadband resonator model

N. Mounet

LHC dipolar vertical impedance model for various broadband model frequencies



Growth rate as a function of chromaticity for various broadband model cutoff



→ Bunch stable for positive chromaticities for initially chosen5 GHz broadband resonant frequency, but not for higher frequencies.

→ Is this a real effect? Could we count on this? Probably not.

→ Much safer to simulate/model every component separately, than use a generic impedance model as we lose the physics

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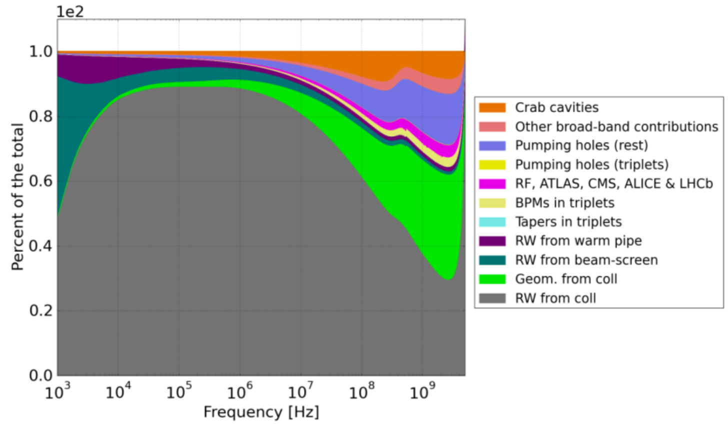
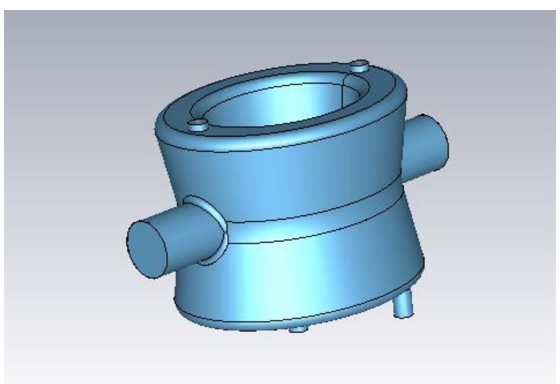
Example of ongoing work:

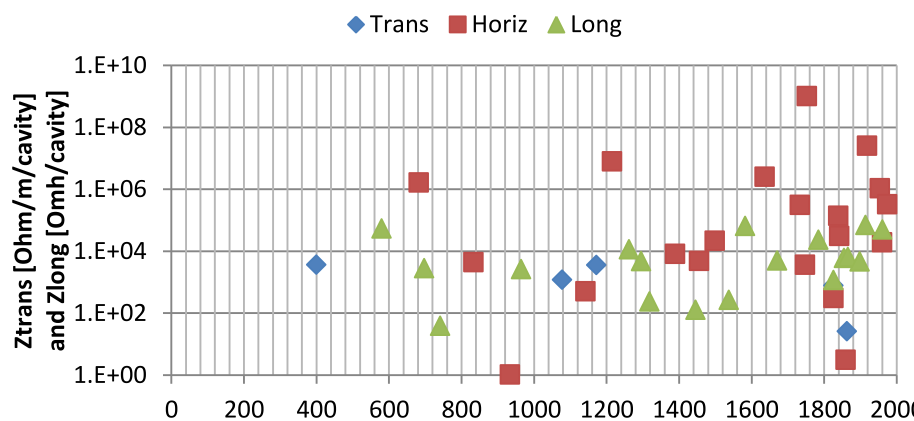
impact of Crab cavities on HL-LHC impedance model

- HL-LHC upgrade model computed by N. Mounet et al (CERN, DESY and INFN Frascati)



- Crab cavity modes from BNL design (Silvia Verdu Andres et al)





→The study on our side is far from complete, and the results are irrelevant (to this talk)
→Example of tools challenges and traps that may occur while building a model

First LHC & HL-LHC impedance models

N. Mounet et al

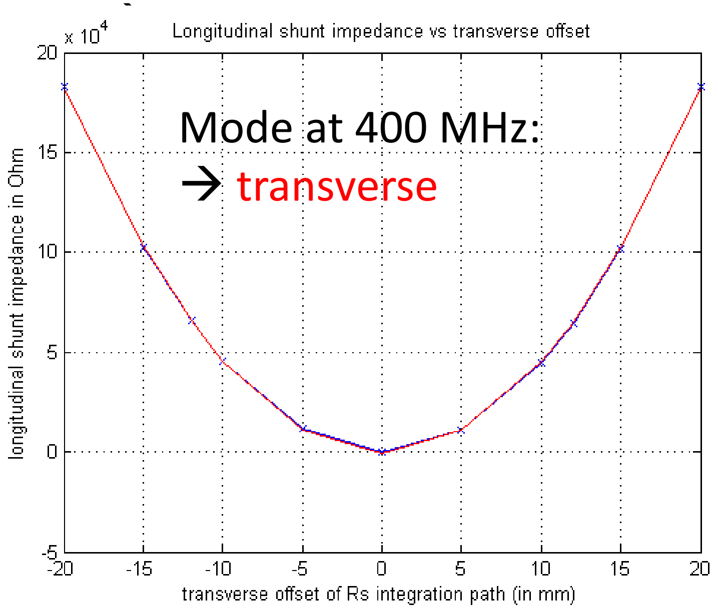
- HL-LHC first model: very similar LHC new model
  - resistive-wall impedance of collimators (settings from R. Bruce),
  - geometric impedance of collimators re-evaluated from Stupakov formula (a priori pessimistic), with double taper (for BPM cavity) – thanks to M. Zobov
  - resistive-wall impedance of beam screens and warm vacuum pipe, including NEG for the latter, effect of weld for the former (C. Zannini), and amorphous carbon coating inside the triplets,
  - Pumping holes impedance re-evaluated thanks to S. Kurennoy formula & A. Mostacci,
  - Details of the triplet region (tapers – Yokoya formula, BPMs from B. Salvant),
  - still some broad-band estimates from design report (take out collimators & pumping holes).

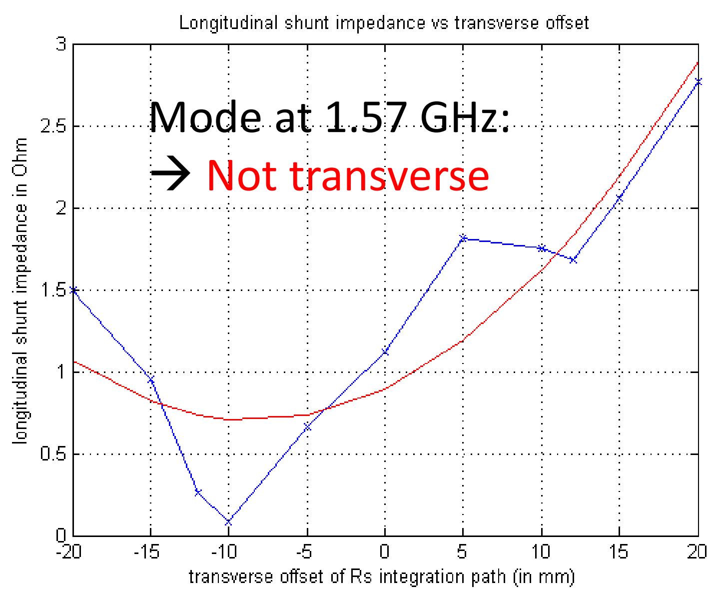
Again, all weighted by local beta functions (0.1m squeeze in IP1 & 5, from S. Fartoukh, June 2013 → pessimistic for impedance, but might be optimistic for β functions in octupoles).

Crab cavity impedance

- Trivial yet important point when working with resonant modes : always indicate clearly **which shunt impedance convention is used** (for longitudinal Ohm or LinacOhm, and for transverse Ohm, Ohm/m, LinacOhm or LinacOhm/m).

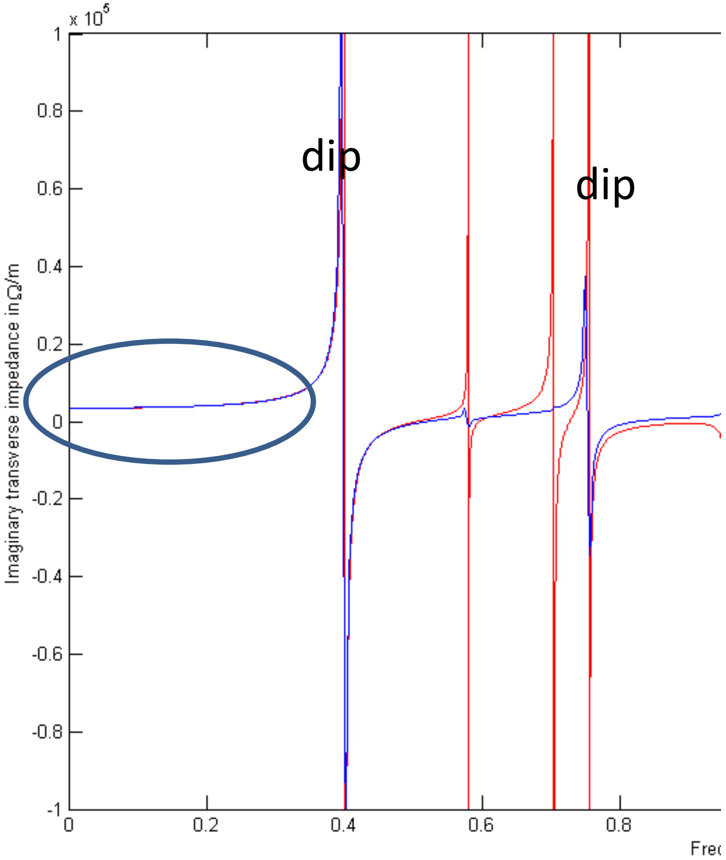
- Since the transverse impedance is the gradient of the longitudinal impedance with respect to transverse displacement, **numerical noise on top of a large longitudinal mode can appear like a transverse mode** if one does not check that it is indeed a transverse mode (leading to either dipolar impedance or transverse impedance).
  → **feature of a transverse mode**: $R_{trans}(x)$ in Ohm/m is constant with x or $R_{long}(x)$ in Ohm is quadratic with x (see for instance E. Métral, EPAC06, THPCH059)



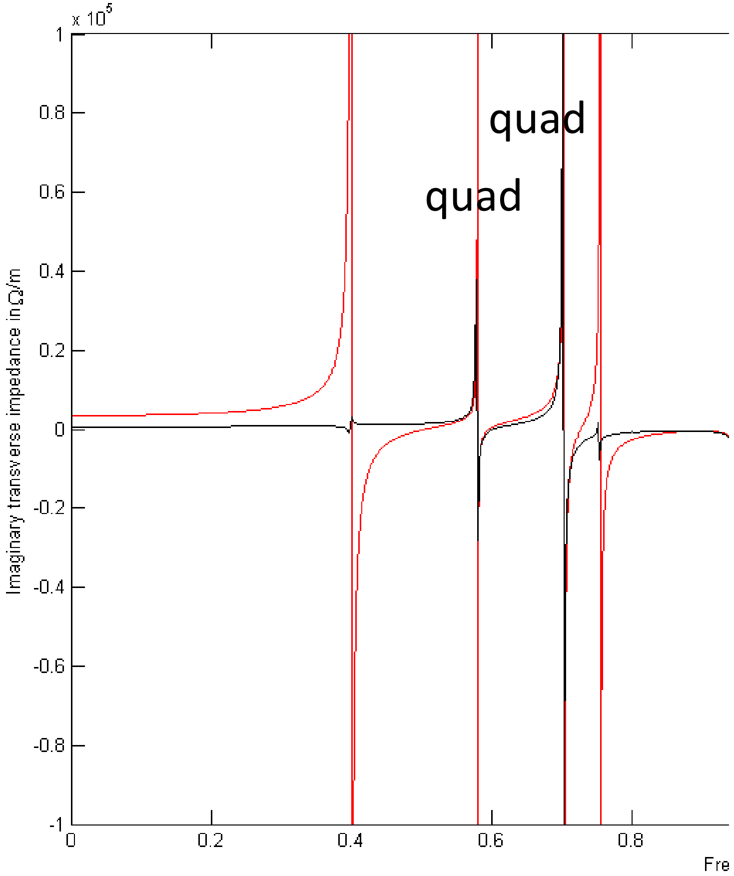


Which resonant mode is a dipolar impedance mode and which is a quadrupolar impedance mode?

Comparison between **dipolar impedance** and **transverse modes modeled as resonators**



Comparison between **quadrupolar impedance** and **transverse modes modeled as resonators**



→ With the help of wakefields, one can **identify dipolar and quadrupolar modes**

→ In addition, the low frequency component due to the resonator models for the 40 first modes (ΣR/Q) is close to the low frequency impedance computed by wakefield solver (~3 kOhm/m below 400 MHz)

Would crab cavities be an issue for the impedance?

- 3 kOhm/m is a small contribution for the LHC
(2.5 MOhm/m at injection and 25 MOhm/m at collision).

- However, there are 16 cavities per beam and the beta function at this location can reach 4km, compared to 70 m for the average of the machine
  → magnifying factor of 1000 !

- 3kOm/m*16*(4000/70)=2.7 MOhm/m
  → increase by ~10% of the total effective LHC impedance in collision
  → clearly not negligible
  → R/Q should not change with the active feedback on the cavity

→ Impact on stability? Clear need for follow up and more detailed studies.

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Outlook

- An **accurate impedance model is the key** to find ways to **improve performance with respect to related instabilities**

- Fundamental to **obtain all relevant wake or impedance contributions as a function of frequency**
  - Longitudinal, dipolar, quadrupolar, coupled terms.

- Many challenges are experienced in all phases of building an impedance model, in particular:
  - difficult to know **what is really in the machine** (device, material, geometry, non conformities)
  - Issues with **modelling/simulating accurately a device in the full frequency range** (in particular for $\beta<1$)
  - Issues in **preparing the model for beam dynamics codes**

- So many challenges that it is fundamental to compare observables with bench measurements and beam measurements.

- **Many crucial open questions**, among which:
  - Should we fit all impedances with resonators?
  - Up to what frequency should we assess the impedance?
  - Can we model accurately the impact of external circuits?

The CERN impedance and collective effects team is very grateful for the help from its colleagues from around the world

- **GSI/ TU Darmstadt**, Germany (O. Boine-Frankenheim, U. Niedermayer)
- **IHEP Beijing**, China (N. Wang)
- **LARP program** with US labs (A. Burov, S. White)
- **University of Naples** and **INFN** (V. Vaccaro)
- **University of Rome**, La Sapienza and **INFN**, Italy (O. Frasciello, M. Migliorati, A. Mostacci, B. Spataro, M. Zobov)
- **SOLEIL** (R. Nagaoka, M. Klein)

- And hopefully more after this workshop!

Many thanks for your attention!

In Geneva, we also have good food (even canoli)!