CERN

Building the impedance model of a real machine

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Agenda

- Impedance?
- What is an impedance model?
- Why build an impedance model?
- How to build an impedance model?
- Examples of benchmarks
- Outlook

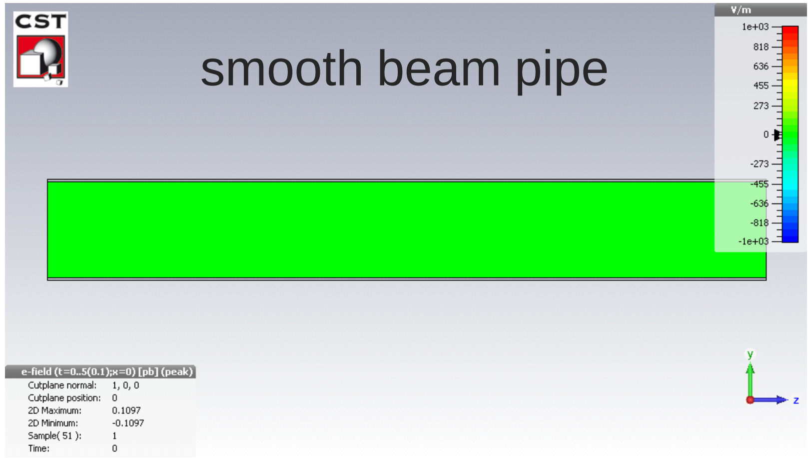
Note: strong bias towards impedance of synchrotrons in this talk

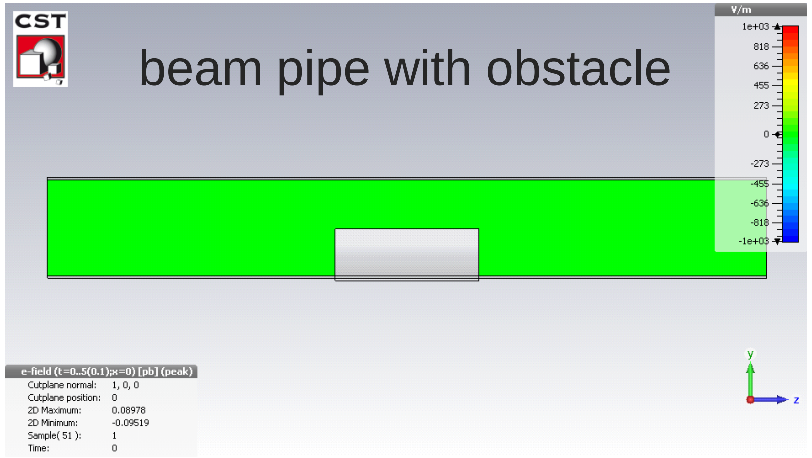
Impedance?

- When a beam of ultra-relativistic charged particles traverses a device which
  - is not a perfect conductor
  - or is not smooth

  it will produce electromagnetic wake fields that will perturb the following particles

  → wakefields (in time domain) or impedance (in frequency domain)





Impact of impedance?

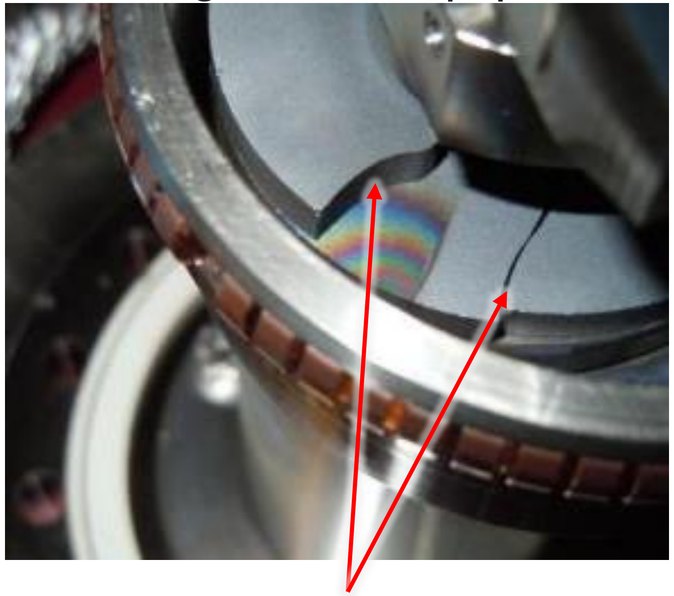
1) Energy is lost by the beam
2) Kicks to following particles (in longitudinal and transverse planes)

→ Are these impedance perturbations an issue?

Impact of impedance?

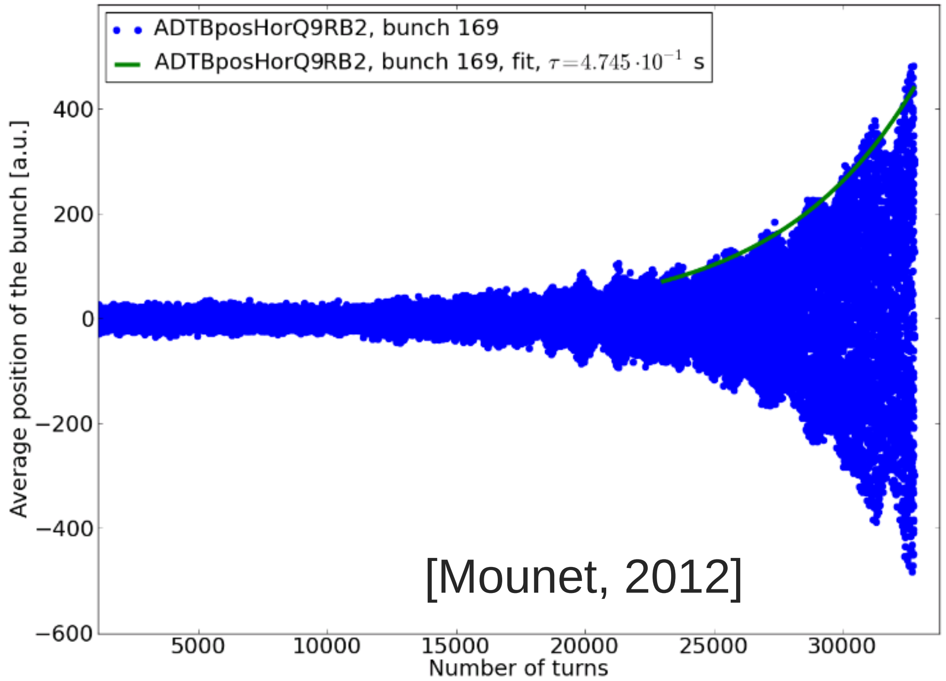
1) Energy is lost by the beam → dissipated in surrounding chambers → damage and outgassing
2) Resonant kicks to following particles → instabilities → beam loss and blow-up

Damaged LHC equipment:



Cracked ferrite ring
of synchrotron light monitor

LHC transverse instability observed in 2011



→ More beam intensity → more perturbations → more damage and beam quality issues
→ Impedance effects are limiting the performance of many accelerators
→ Requires strict follow-up, impedance minimization and support
→ mandate of the Impedance Working Group at CERN

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- Impedance?
  - Some useful definitions
  - Focus on driving and detuning impedances
  - Driving and detuning impedances and beam observables
- What is an impedance model?
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Some useful impedance definitions

- Wake potentials W(s):
  integrated force F generated by **source bunch (1)** of longitudinal distribution $\rho(s)$ on a **witness particle (2)** **following at a distance s**.

$$W_{x,y,z}(s) = \frac{1}{q_1 q_2} \int_0^L F_{x,y,z}(s,z)\, dz$$

- Wake functions G(s):
  wake potential for which the source is a point charge

$$G(s) = iFT\left(\frac{FT\big(W(s)\big)}{FT\big(\rho(s)\big)}\right)$$

- Beam impedance Z(ω)
  Fourier Transform (FT) of the wake function

$$Z(\omega) = FT\big(G(s)\big)$$

- Effective impedance Z^{eff} (Z^{eff}/n for longitudinal)
  impedance integrated over the bunch oscillation spectrum $h(\omega_k)$

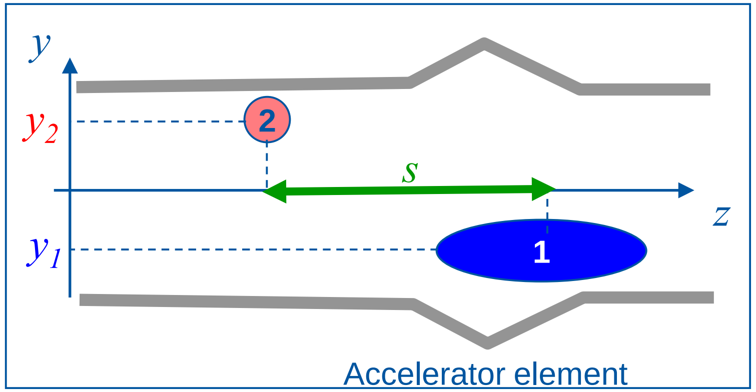
$$\frac{Z_{//}^{eff}}{n} = \frac{\sum_k Z(\omega_k)\frac{\omega_{rev}}{\omega_k} h(\omega_k)}{\sum_k h(\omega_k)}$$

$$Z_t^{eff} = \frac{\sum_k Z(\omega_k) h\left(\omega_k - \omega_\xi\right)}{\sum_k h(\omega_k)}$$

$$\omega_\xi = Q\omega_{rev}\frac{\xi}{\eta}$$ Chromatic frequency shift

$$\xi = \frac{\Delta Q/Q}{\Delta p/p}$$ Chromaticity

Q tune, number of oscillations per turn



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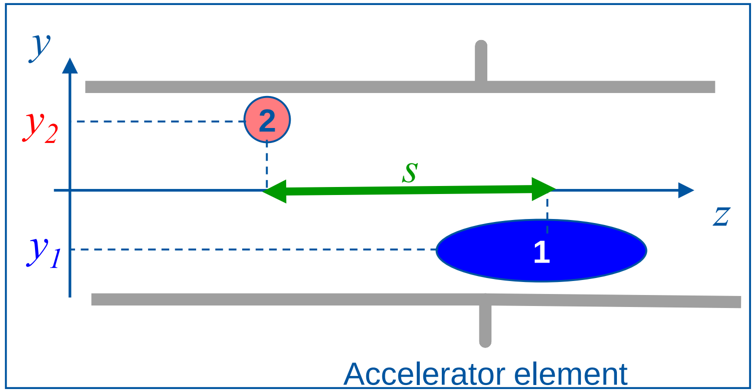
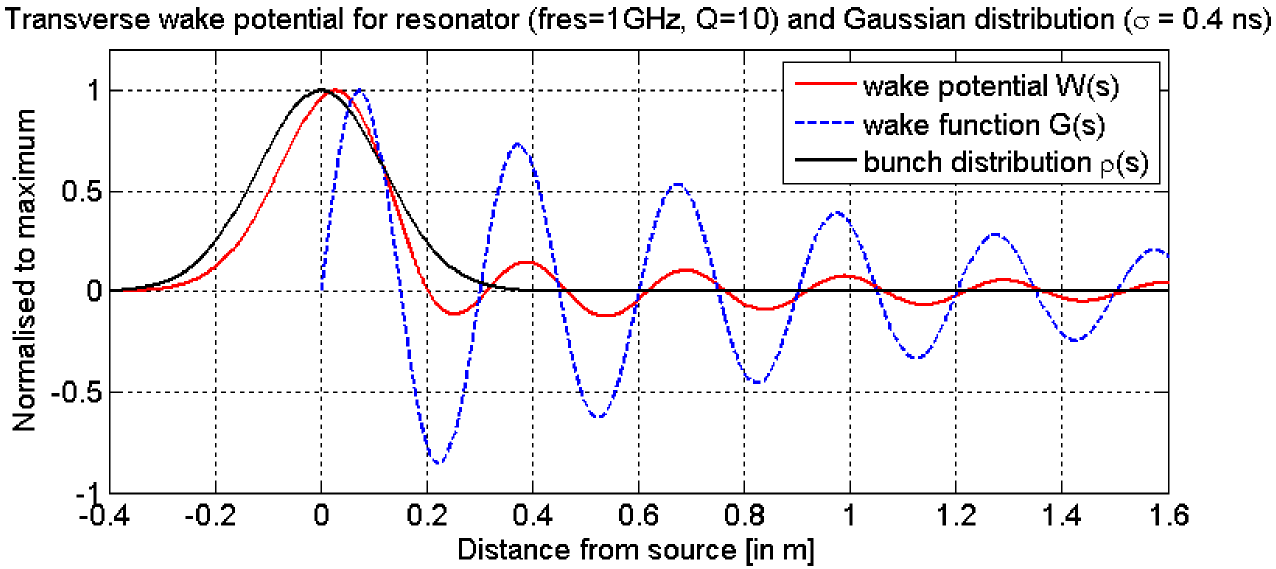
- Rigid beam approximation:
  → element **assumed infinitely thin**
  → all **interactions lumped into kicks**

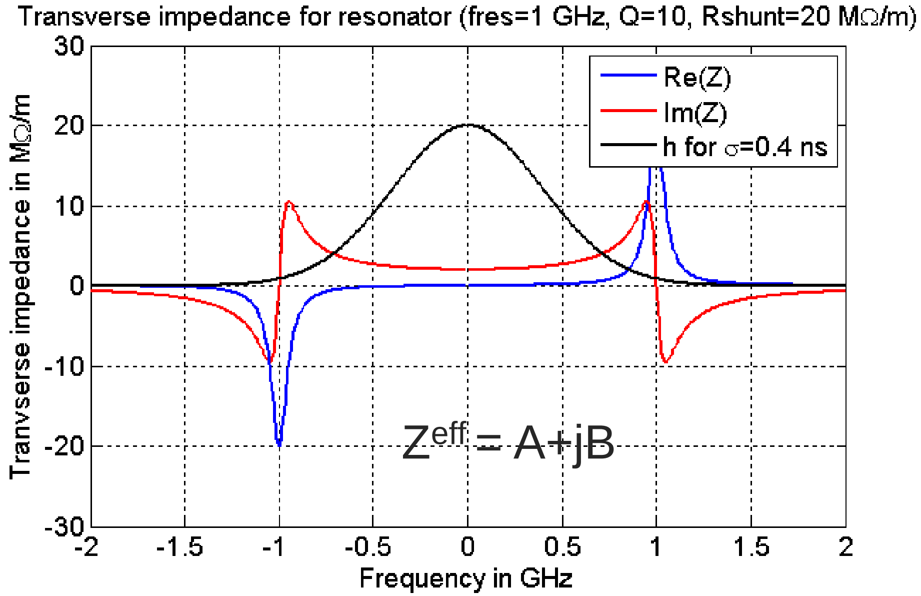


Some useful impedance definitions

- Wake potentials W(s):
  → typical output of wakefield simulations
- Wake functions G(s):
  → typical input for beam dynamics simulations
- Beam impedance Z(ω)
  → typical output from analytical impedance codes
- Effective impedance Z^{eff}
  → can be computed from measured beam observables
  – synchrotron and betatron tune shifts
  – bunch lengthening
  – Instability thresholds and growth rates



→ wake potentials ≠ wake functions



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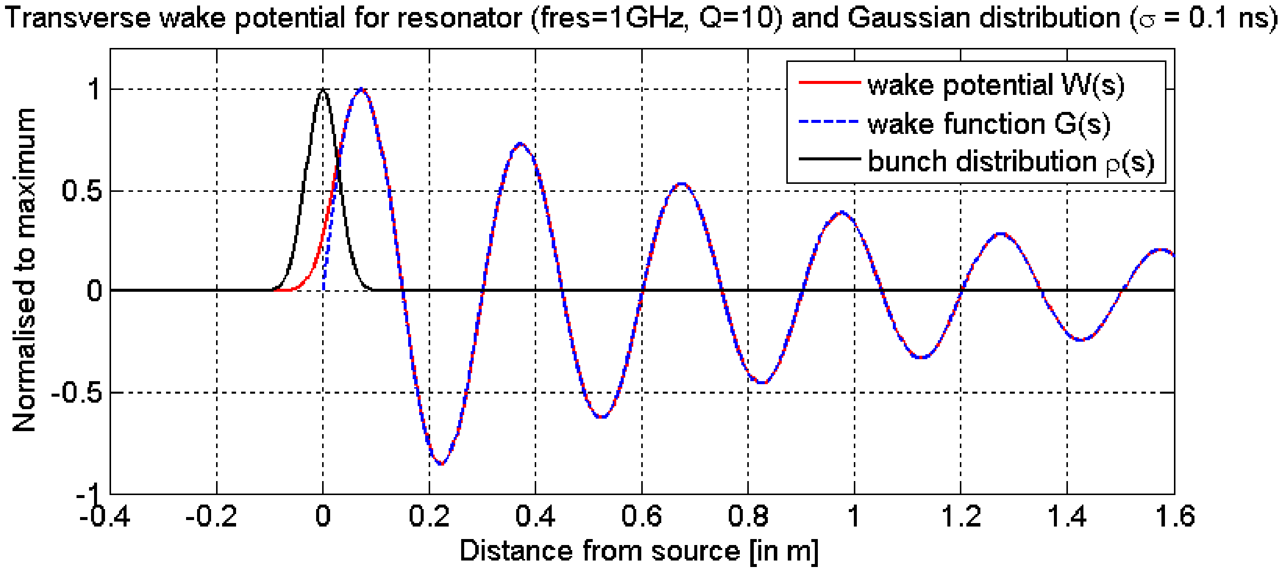
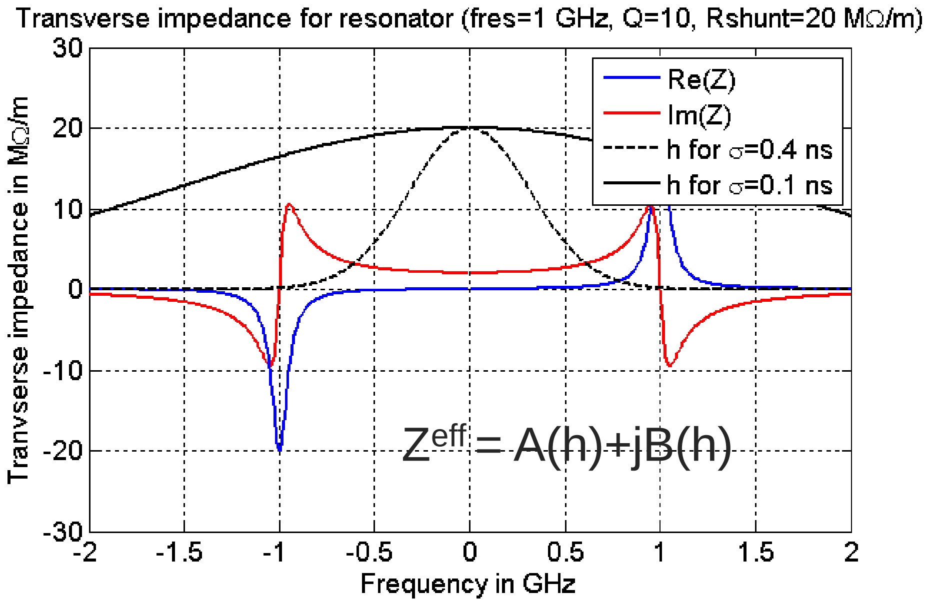


→ Wake potential close to wake function if bunch small enough



→ Z^{eff} varies with longitudinal bunch distribution

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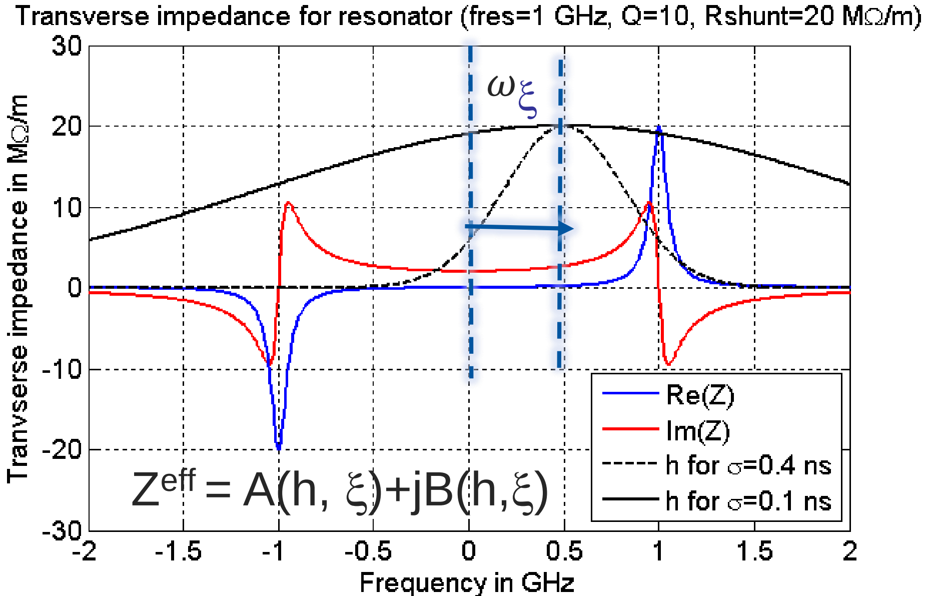

→ Changing chromaticity shifts the sampled impedance frequencies
→ Transverse Z^{eff} varies with both bunch length and chromaticity

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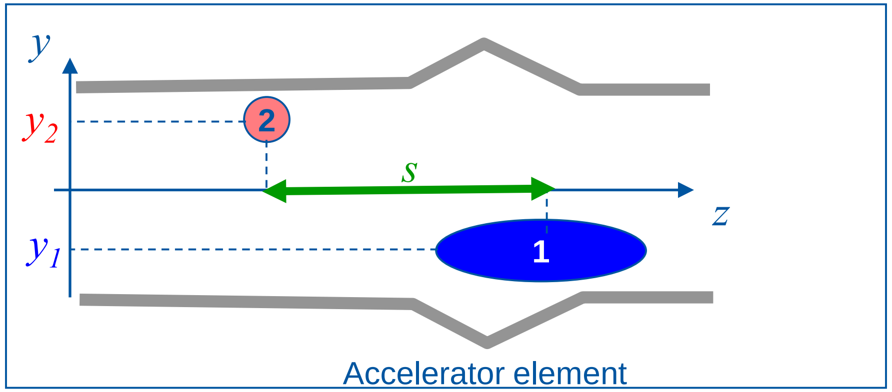
Focus on transverse impedance: driving and detuning contributions

→ linear terms of the wake with the source and witness transverse offsets



	constant		Driving		Detuning		Higher order
$W_y(y_1, y_2, s) =$	$W_y^0(s)$	+	$W_{y,driv}(s)\, y_1$	+	$W_{y,det}(s)\, y_2$	+	$o(y_1,y_2)$
$Z_y(y_1, y_2, \omega) =$	$Z_y^0(\omega)$	+	$Z_{y,driv}(\omega)\, y_1$	+	$Z_{y,det}(\omega)\, y_2$	+	$o(y_1,y_2)$
	change orbit		can modify the tunes				neglected

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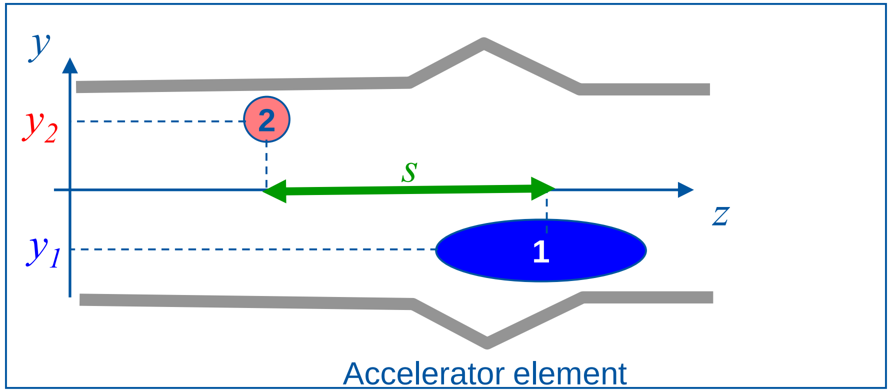

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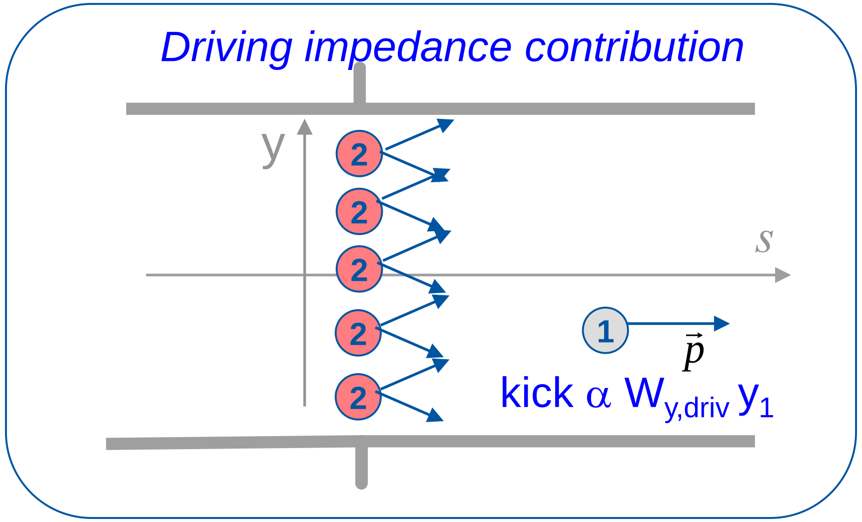
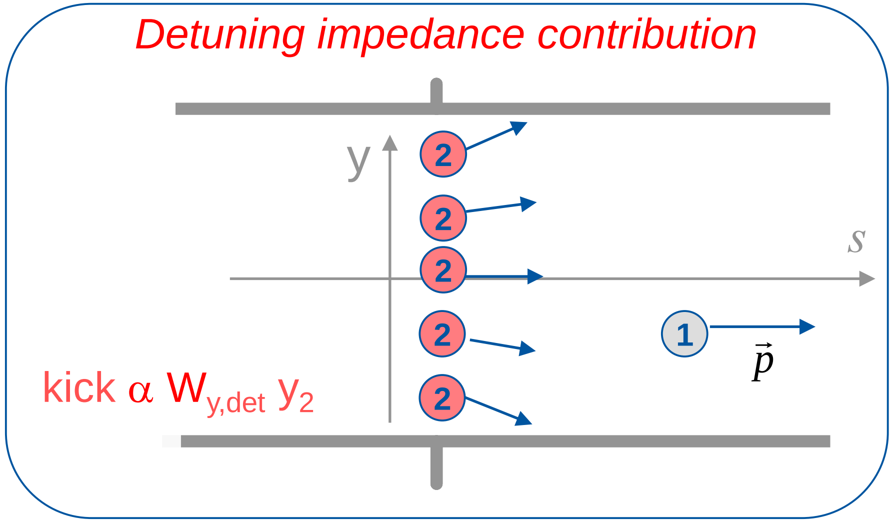
change orbit — can modify the tunes — neglected

The driving kick depends only on the source location





The detuning kick depends only on the witness location

Coherent effect → drives coherent instabilities

Incoherent effect → detunes single particles

$Z_{driving} \neq 0$ even in circular pipe

$Z_{detuning} = 0$ in circular pipe, but $Z_{detuning} \neq 0$ for flat pipe or $\beta<1$

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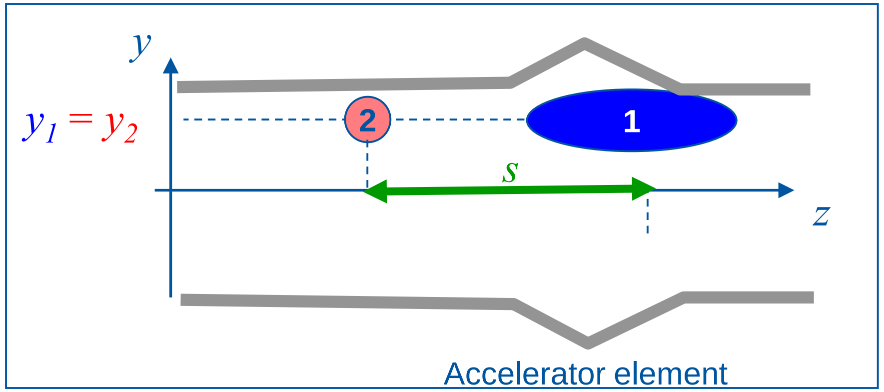
Why is it important to disentangle driving and detuning?

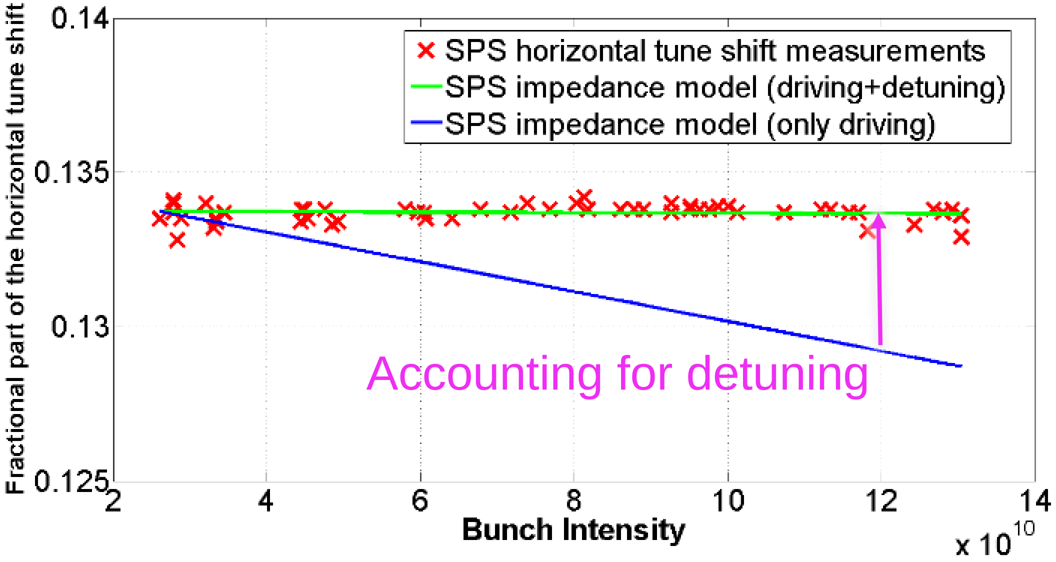
Zannini, 2015

Beam measurement of intensity dependent tune shift
→ kick the whole beam and measure betatron tune



Position of all particles after the kick forced to y1~y2

Horizontal tune shift vs intensity



→ driving and detuning contributions add up for tune shift

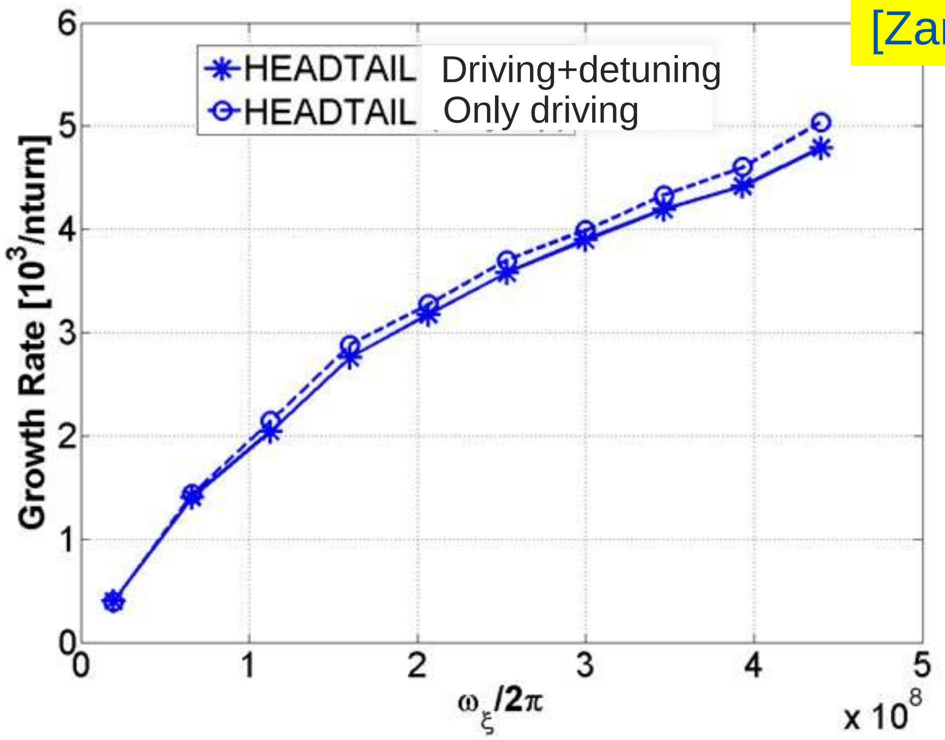
Accounting for detuning

→ Confirmed by measurements of tune shifts in SPS

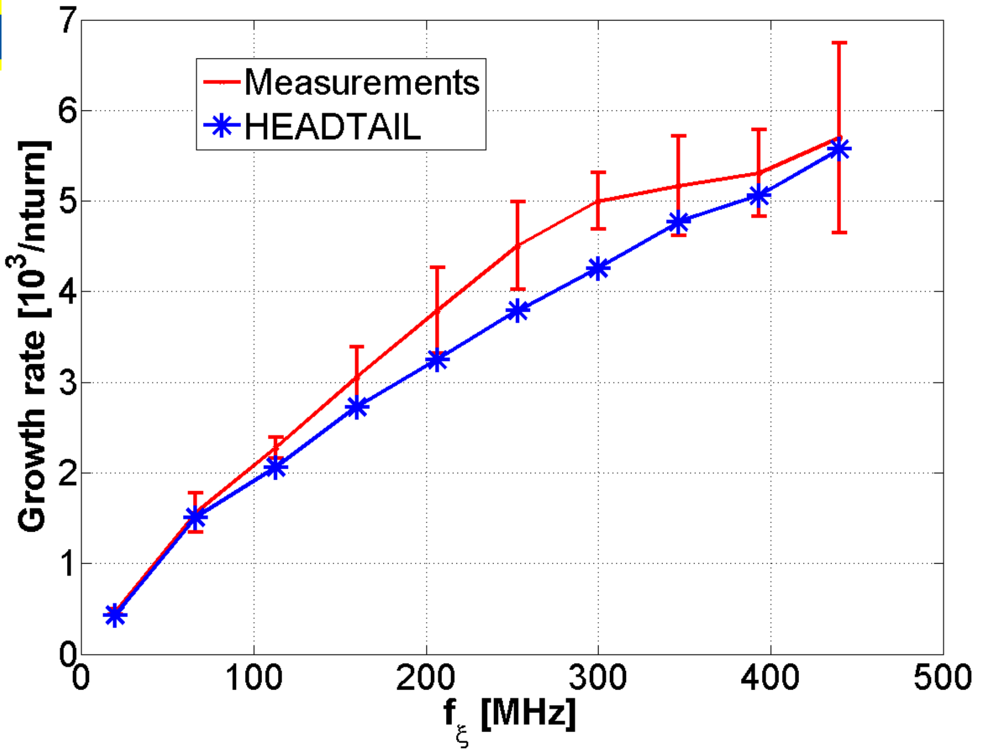
→ Cannot explain tune shift observations without detuning impedance

Why is it important to disentangle driving and detuning?

Simulation of instability growth rate vs negative chromaticity with HEADTAIL code



[Zannini, 2015]



→ Very small impact of detuning impedance on this simulated coherent instability

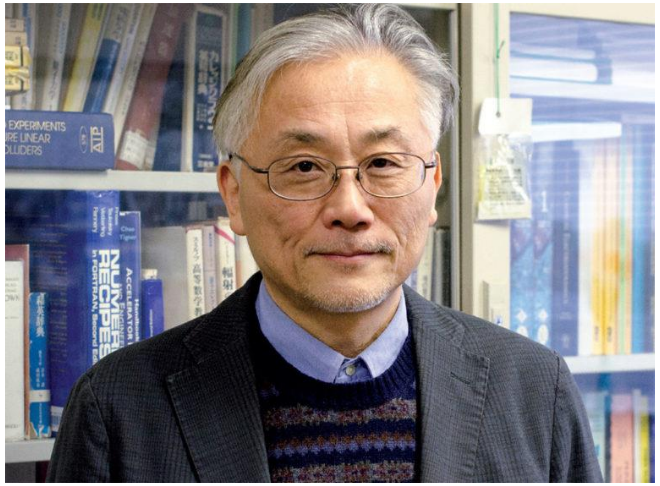
→ confirmed by comparing with measurements in SPS

→ Should not account for detuning impedance for growth rate

→ Need accurate evaluation of both driving and detuning separately to reproduce beam observables

The impedance family recently lost several distinguished members

- Andy Sessler (1928-2014)
- Bruno Zotter (1932-2015)
- Albert Hofmann (1933-2018)
- Yong Ho Chin (1958-2019)



→ So grateful to all those who have inspired us (and continue to do so)

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What is an impedance model for a machine?

→ A **global impedance representative of the whole machine**

→ Used to compute related beam dynamics effects

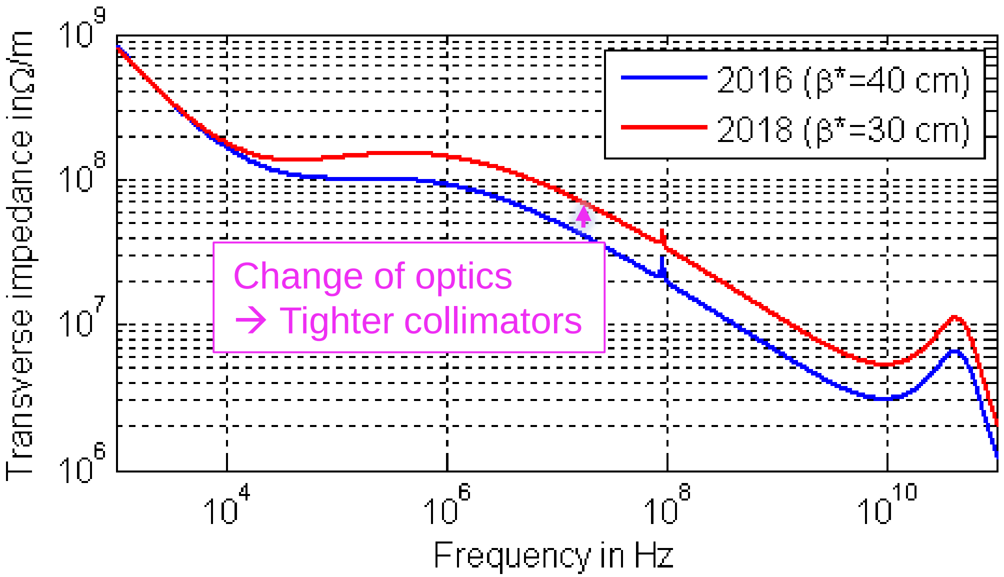
Depending on the need, an impedance model can be anything between:

- **a single number** (effective impedance)
- and an elaborated tool that is able to recompute
  - **many impedance contributions as a function of frequency** and related thresholds
  - with **changes of machine configuration** (beam energy, optics, moveable device position)

Example of effective impedance model:
Australian Synchrotron
[Dowd et al, IPAC'10]

Effective longitudinal impedance	Z/n = 0.6 Ω
Effective vertical impedance	$Im(Z_y^{eff})$=1.2 MΩ/m

LHC real horizontal driving impedance model (single bunch and multibunch)
[Amorim et al, 2019]



10 functions of frequency:

- $Re(Z_{long})$
- $Im(Z_{long})$
- $Re(Z_x^{driv})$
- $Im(Z_x^{driv})$
- $Re(Z_y^{driv})$
- $Im(Z_y^{driv})$
- $Re(Z_x^{det})$
- $Im(Z_x^{det})$
- $Re(Z_y^{det})$
- $Im(Z_y^{det})$

+ coupled terms

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  - To push machine performance
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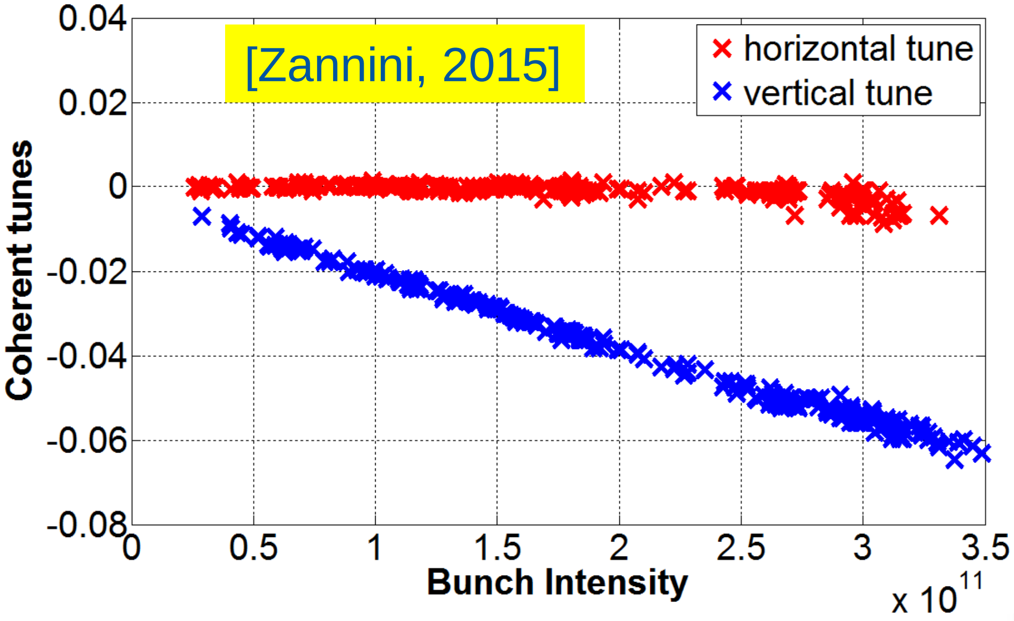
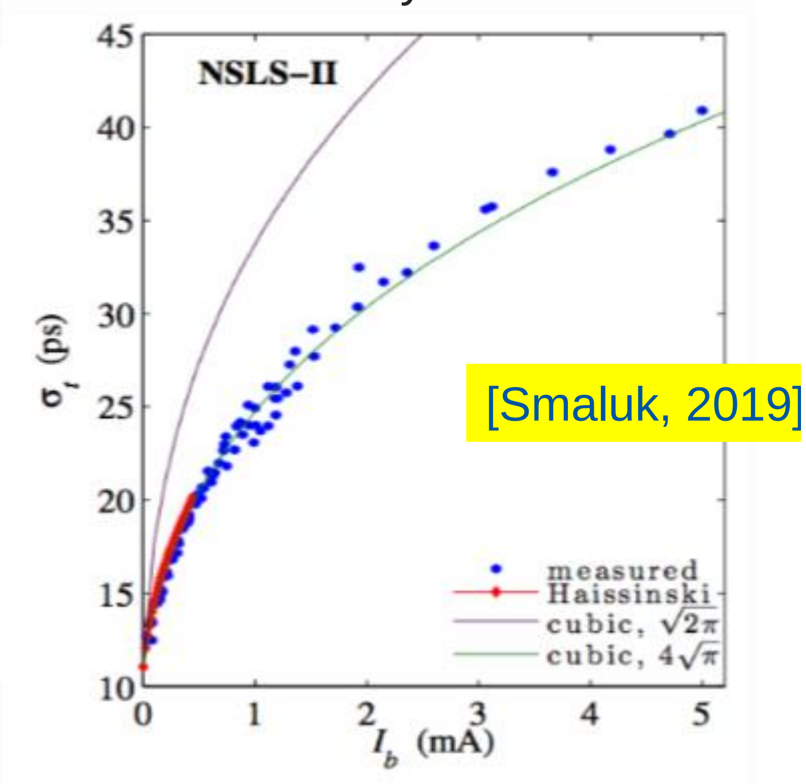
Impedance model to explain beam observables

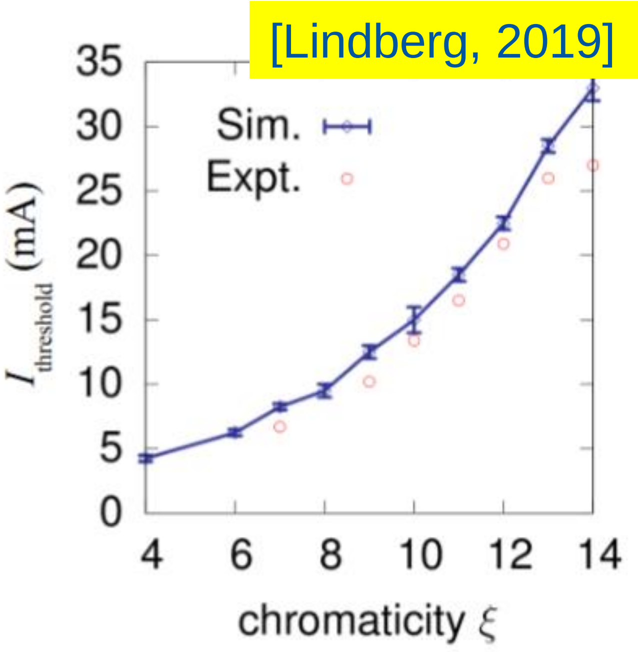
Examples: coherent betatron tune shifts asymmetry in SPS



Bunch lengthening with intensity in NSLS-II



Instability threshold with chromaticity in APS



→ Impedance models can explain these beam observations

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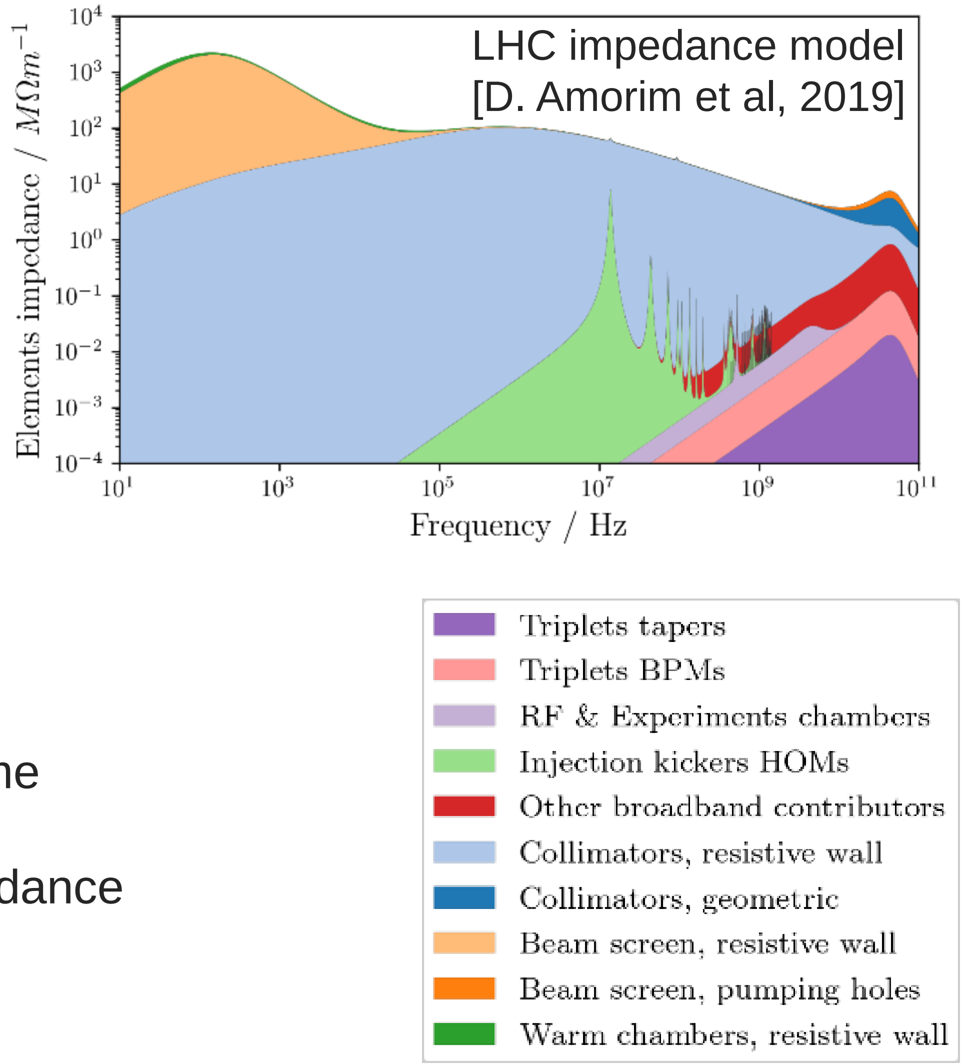
Impedance model to push performance

Example: LHC octupole current needed to mitigate transverse instabilities over the years



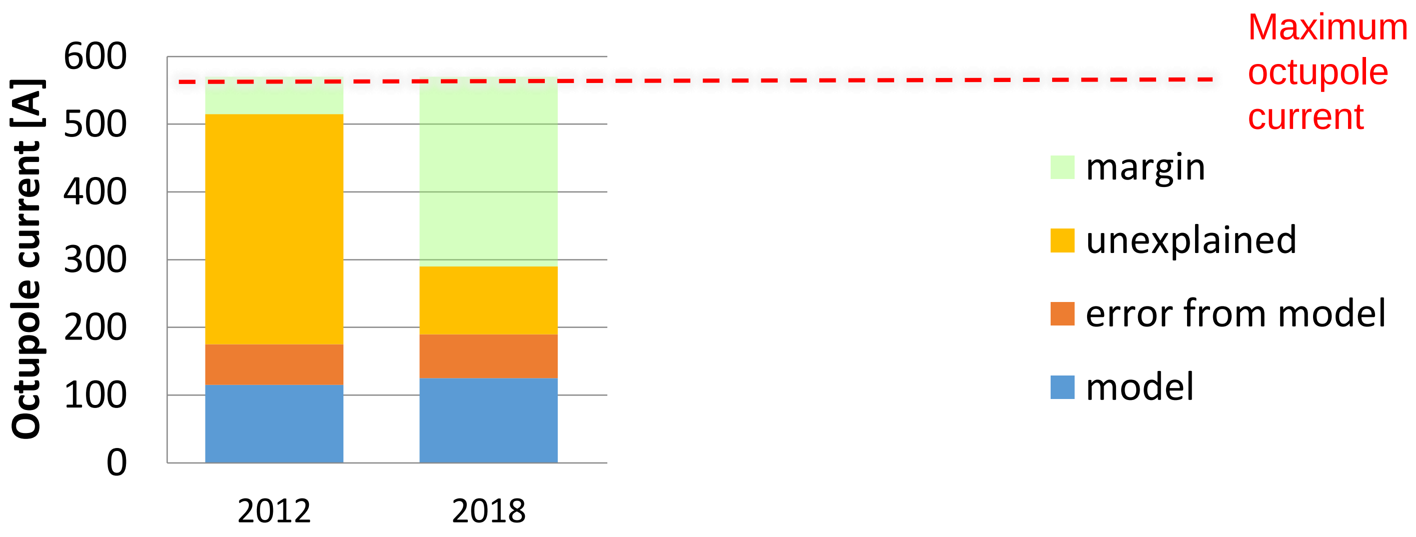
→ Required octupole current very close to maximum
- → Very little margin for operation!

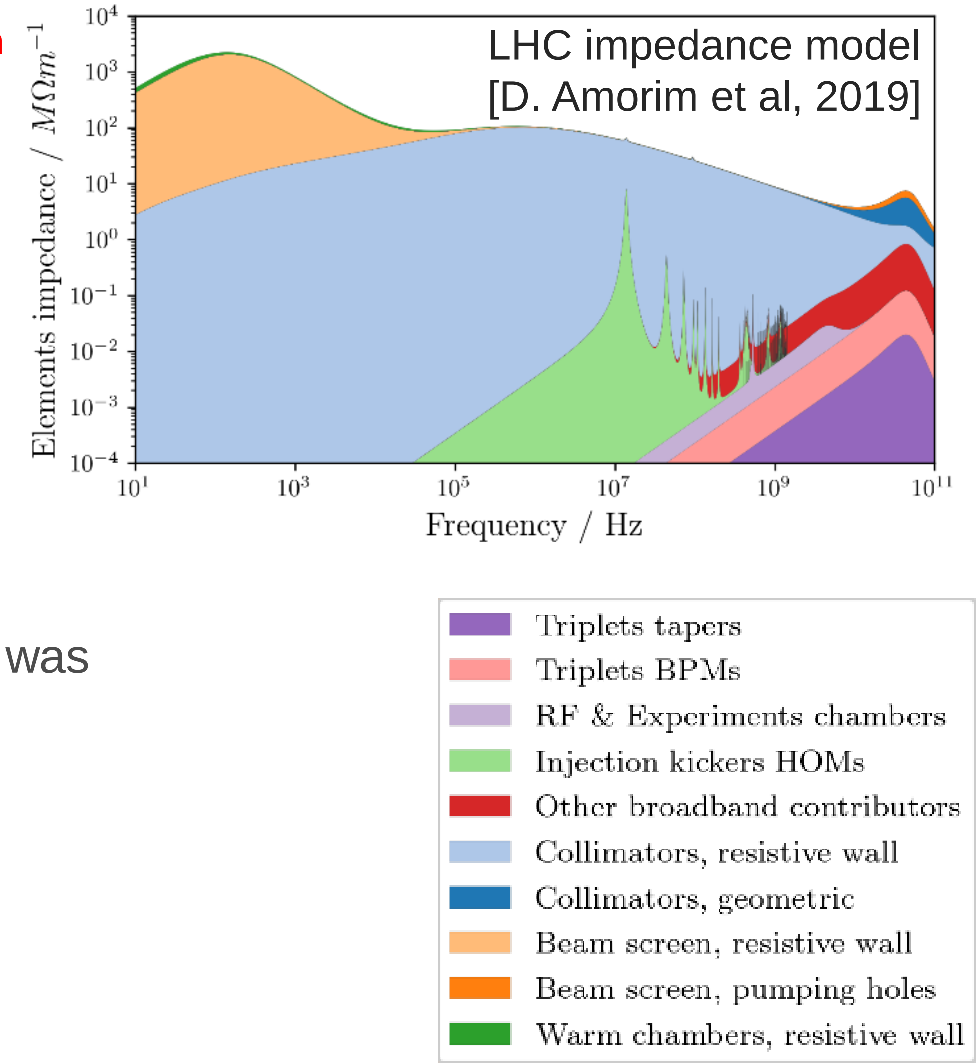
→ Frequent instabilities and beam quality degradation at that time

→ Also checked impedance models by e.g. tune shifts
- → Unlikely that the unexplained difference is linked to impedance

Impedance model to push performance

Example: LHC octupole current needed to mitigate transverse instabilities over the years

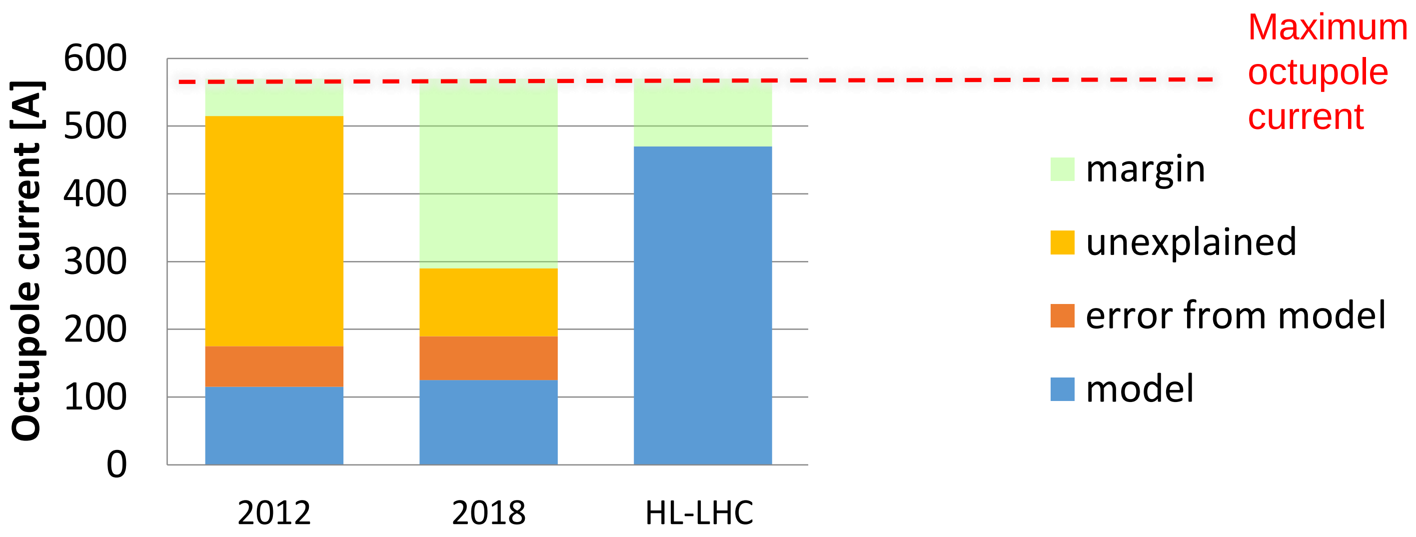


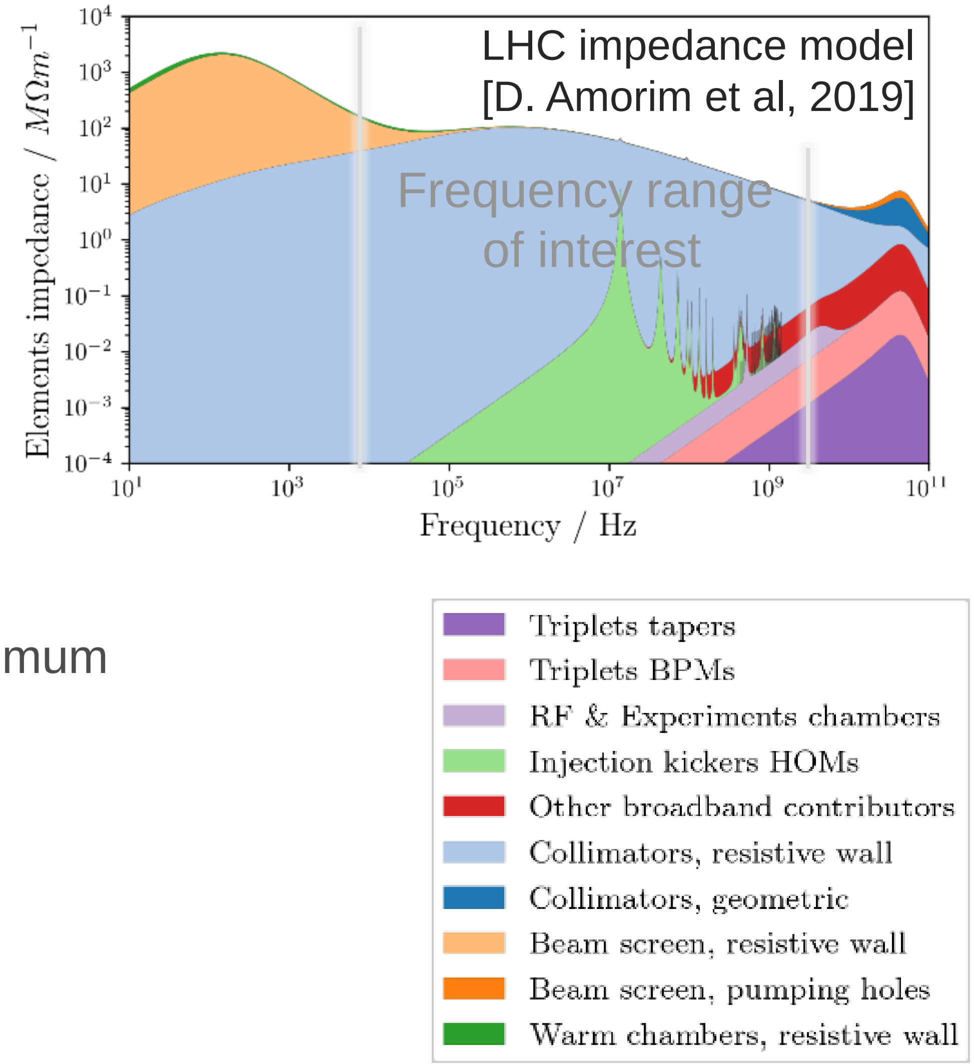


→ Understood and confirmed in 2017 that large linear coupling was destabilizing the beams [Métral/Carver 2018] → corrected
→ Much more operational margin
→ What remains unexplained is believed to come from noise

Impedance model to push performance

Example: LHC octupole current needed to mitigate transverse instabilities over the years





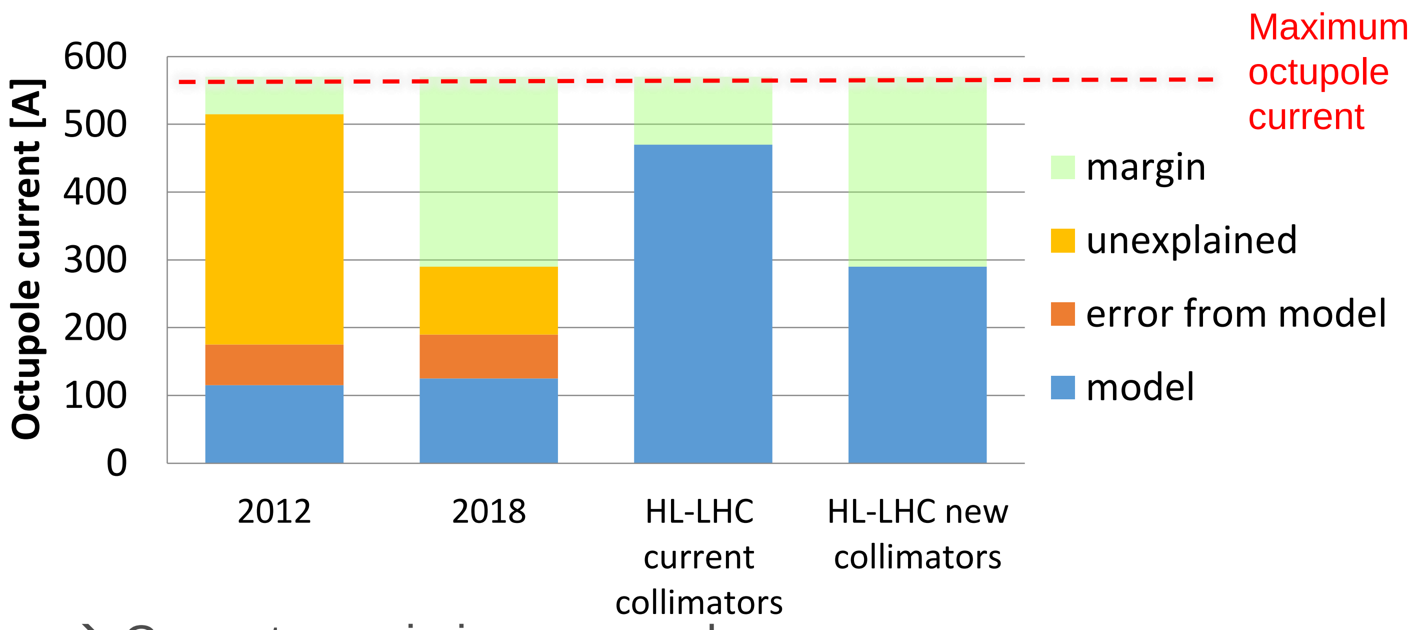
→ HL-LHC scenarios brings octupole current very close to maximum (accounting for errors)

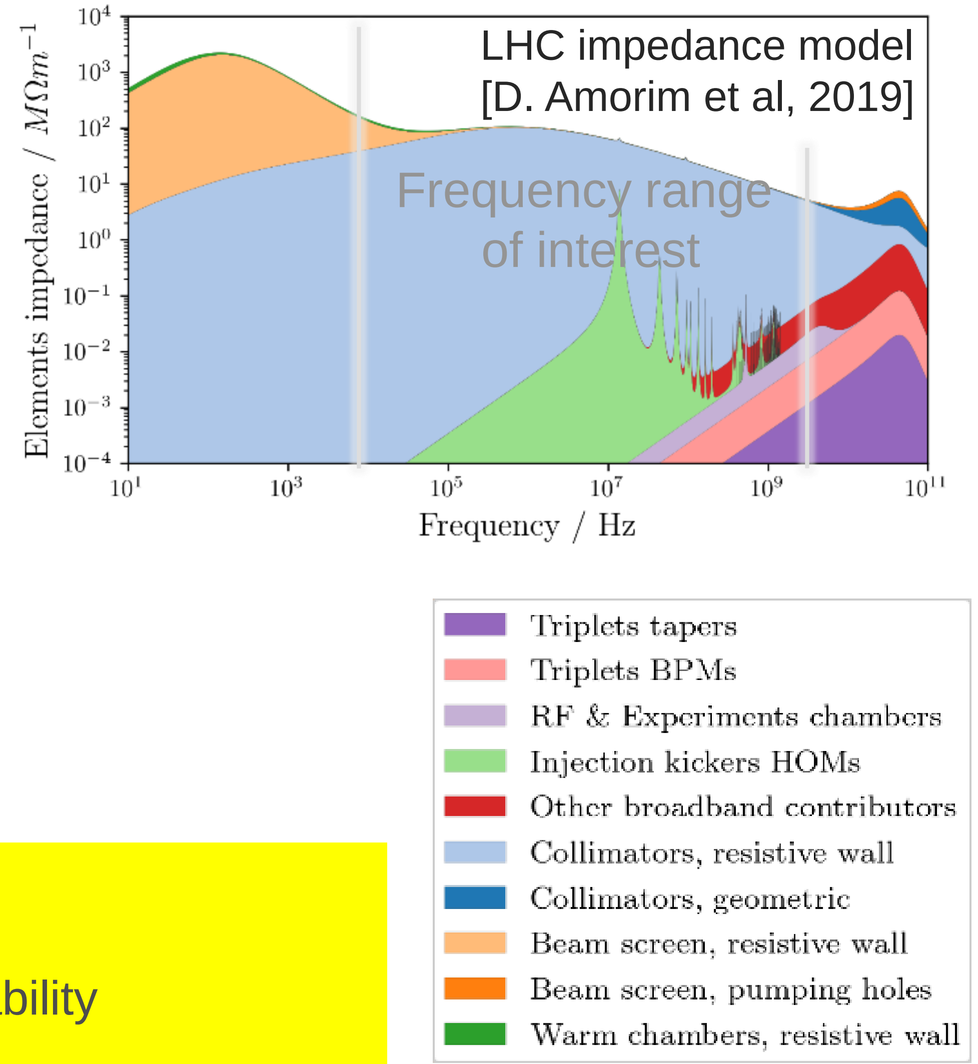
→ Need impedance reduction in frequency range of interest

→ Target: reduce impedance of collimators

Impedance model to push performance

Example: LHC octupole current needed to mitigate transverse instabilities over the years





→ Current margin is recovered

With an accurate impedance model, we can

1) assess if some ingredients are missing in understanding beam stability
2) predict operational margins in case of new machine or upgrade
3) identify targets for impedance reduction

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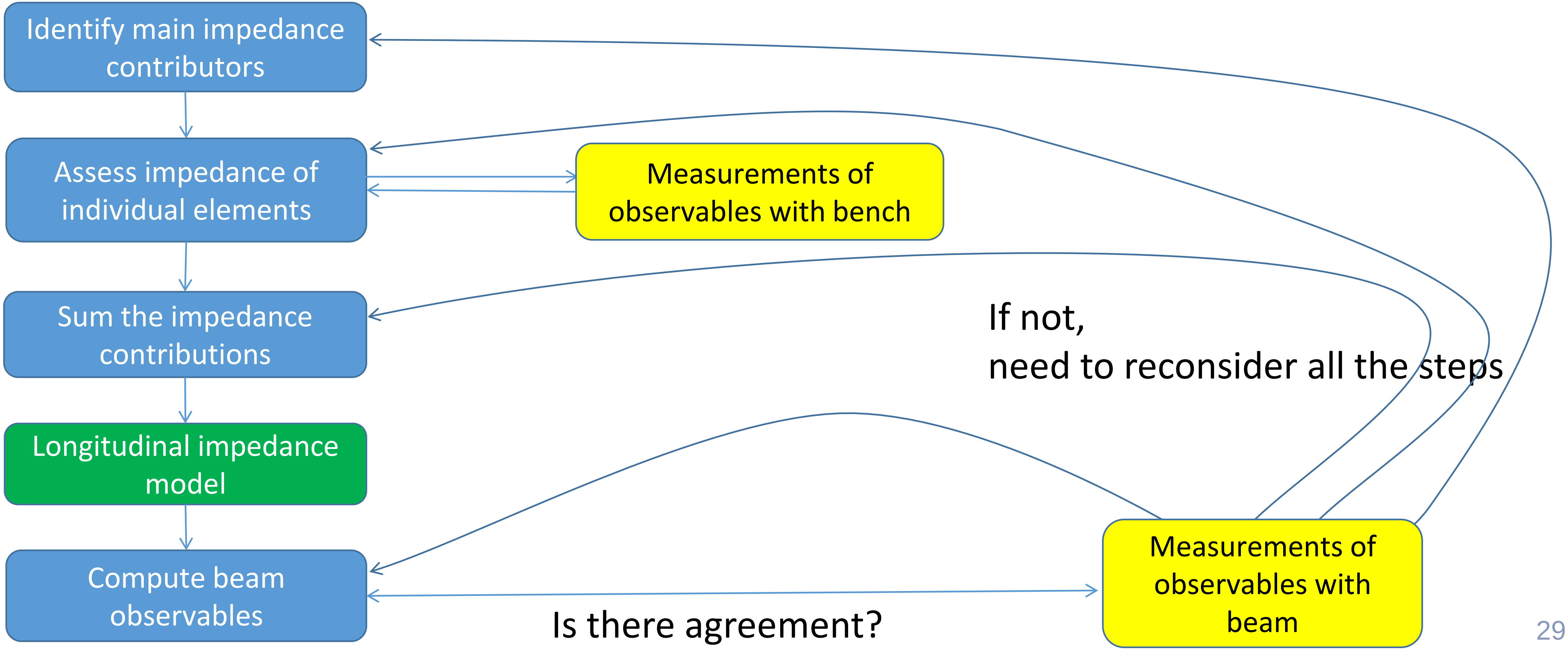
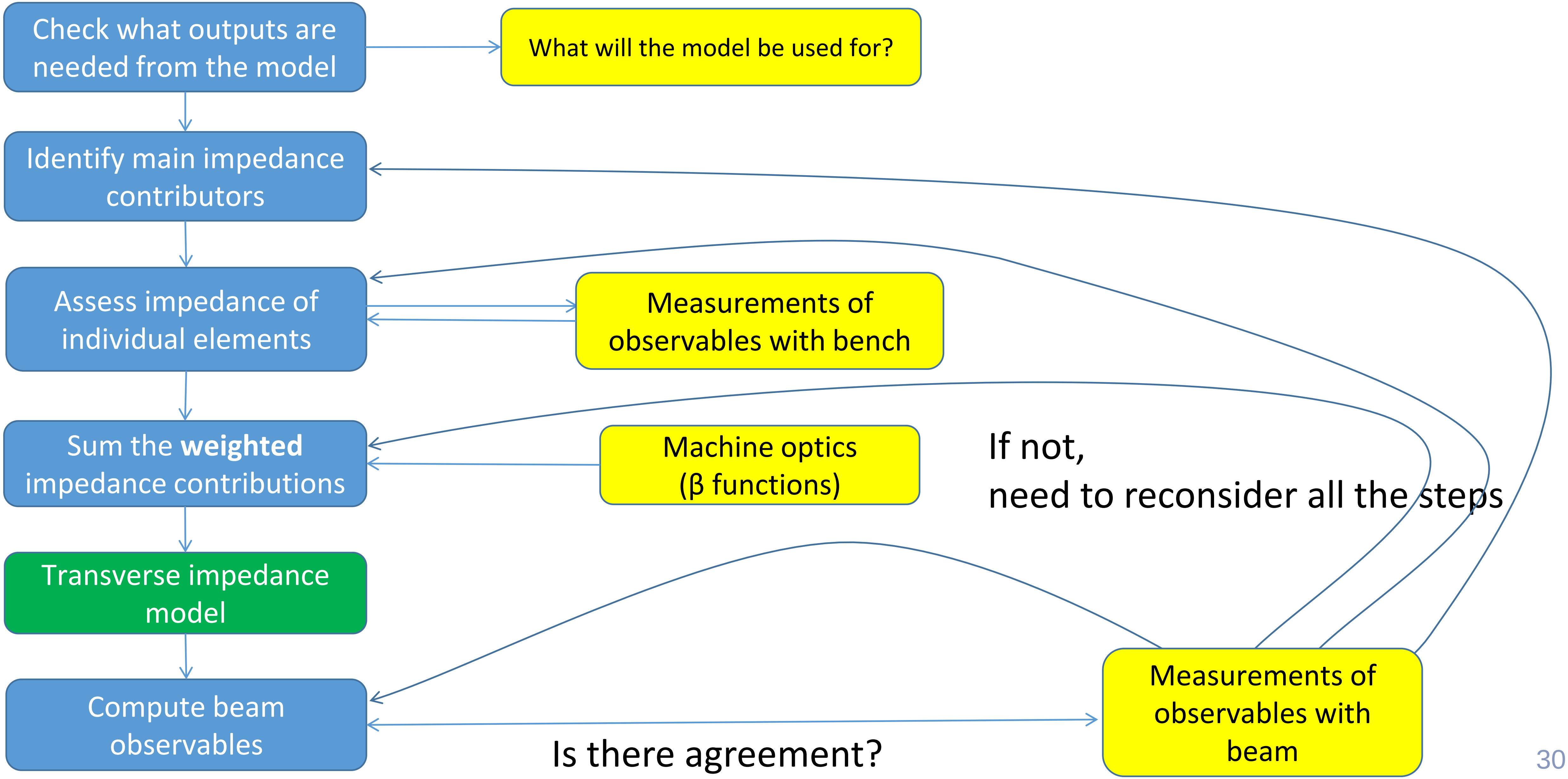
How to build an impedance model (longitudinal)



How to build an impedance model (transverse)



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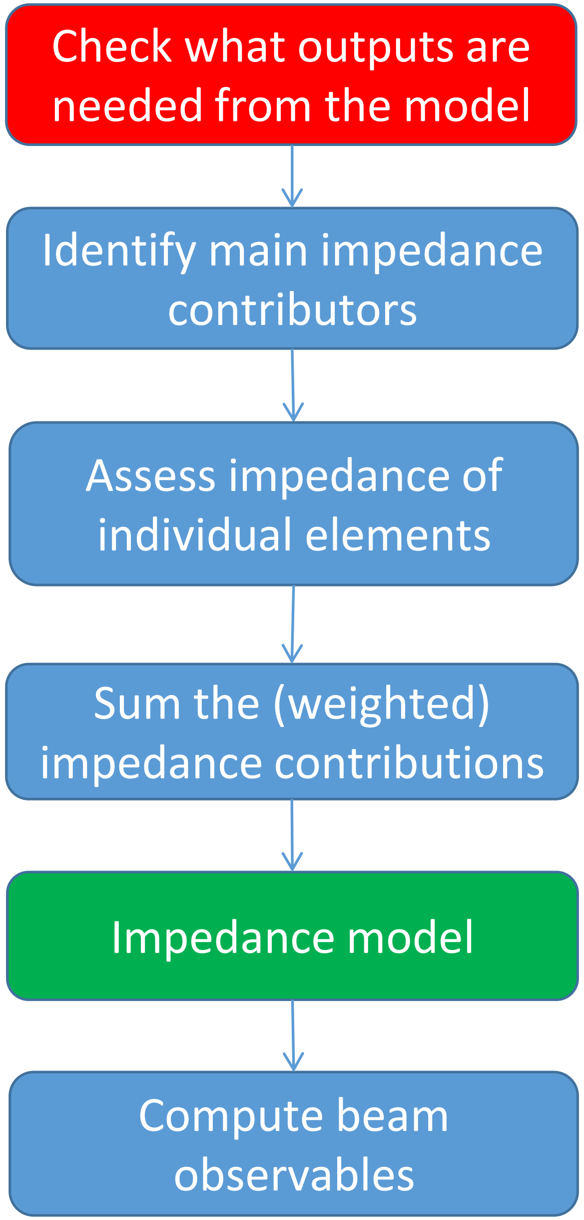
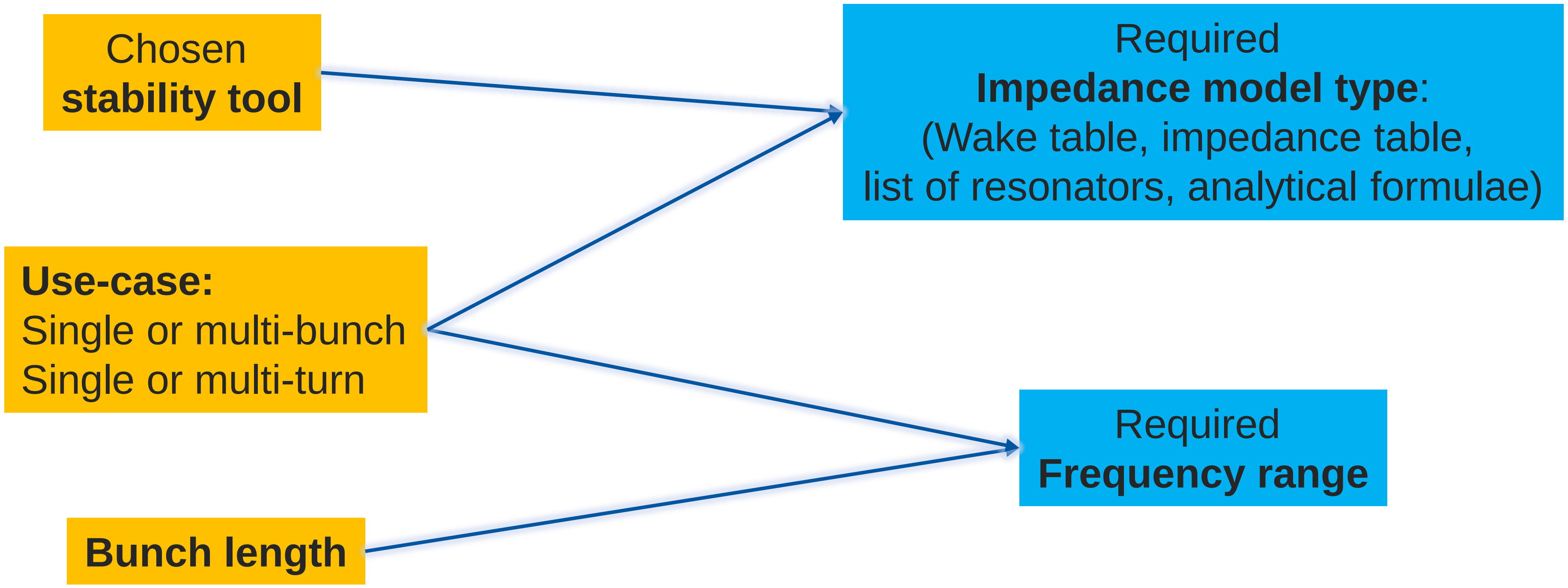


Check what outputs are needed from the impedance model

Impedance used as input of stability tools:
→ **Macroparticle simulations** (e.g. ELEGANT, PyHEADTAIL, BLonD, mbtrack, MuSic)
→ **Vlasov solvers** (e.g. BimBim, DELPHI, NHTVS, GALACTIC, GALACLIC)



→ What we do with the impedance model outputs should drive the strategy for beam impedance computations

Check what outputs are needed from the impedance model

Examples of recent advances

- Inclusion of damper in Vlasov solvers [Burov, 2014]
- Account for detuning impedance in Fokker Plank solvers [Lindberg, 2016]
- Beam dynamics codes to multibunch and low beta [Mounet 2012, Lasheen 2017]

Challenges

- Need better understanding of impact of detuning impedance on beam dynamics
- Need to include all other effects in simulations (e.g. electron cloud, IBS, SR, CSR)

Common practice

- Important to define use-case before launching the full impedance simulation campaign
- Check required frequency range, beam energy and the impedance which will be used

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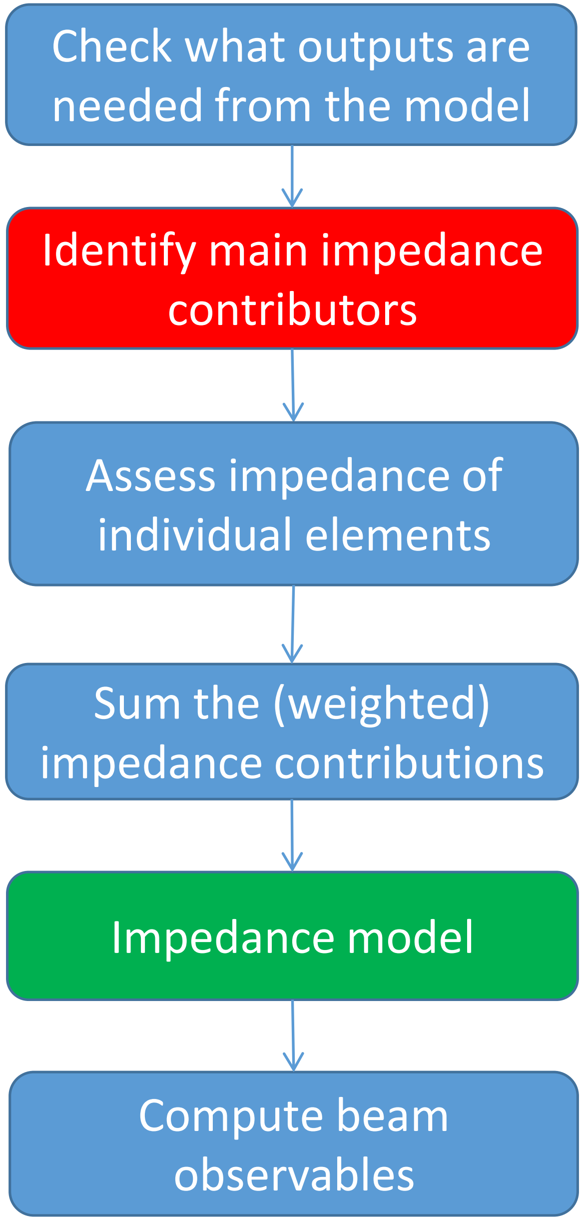


Identify main impedance contributors

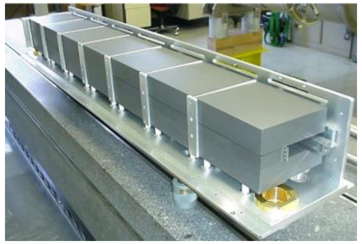
- Too many devices to compute all impedances of the machine

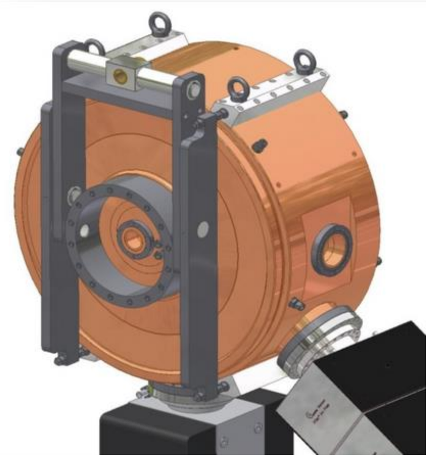
→ Need to identify the usual suspects that give large impedance contribution

  - Beam pipe
  - Material with large losses (kickers)
  - Cavities (RF cavities, crab cavities, instrumentation),
  - Low aperture devices (collimators, insertion devices),

SOLEIL chamber

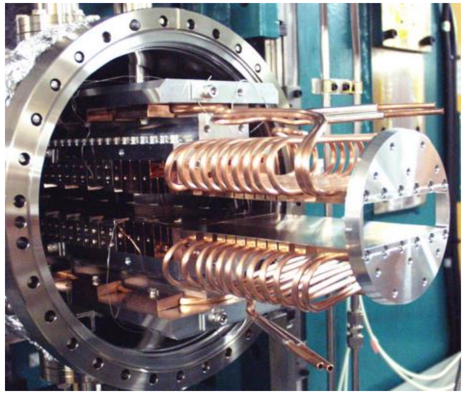
SPS extraction kicker





MAX-IV cavity

ALS in vacuum undulators



Identify main impedance contributors

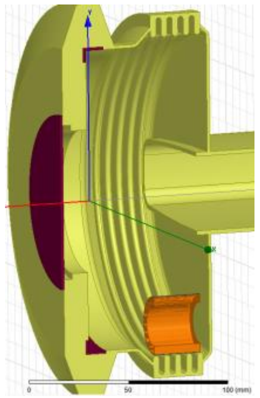
- Too many devices to compute all impedances of the machine

→ Need to identify the usual suspects that give large impedance contribution
  - Beam pipe
  - Material with large losses (kickers)
  - Cavities (RF cavities, crab cavities, instrumentation),
  - Low aperture devices (collimators, insertion devices),

→ But also very small impedances in very large numbers

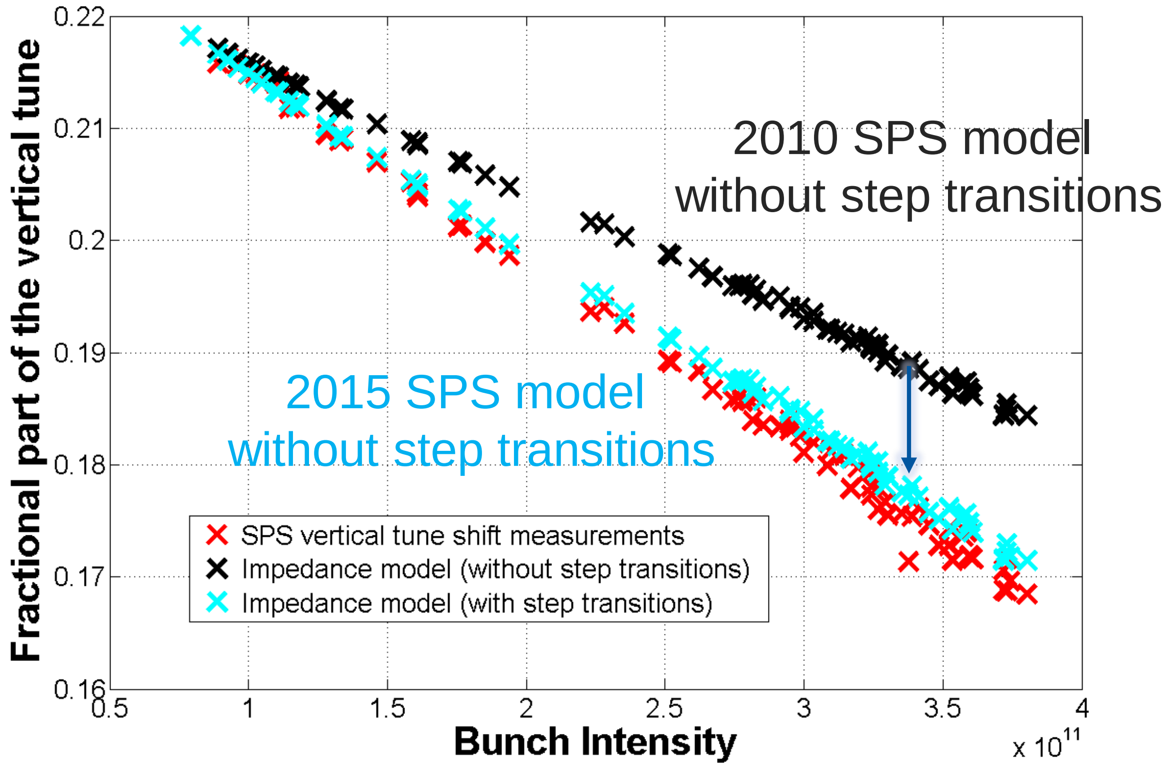
Example: step transitions in SPS

Small individual contribution, but many steps!



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

[Zannini, Varela et al, 2014]



→ Large impact on tune shift

→ Important to account for these elements to explain beam observables

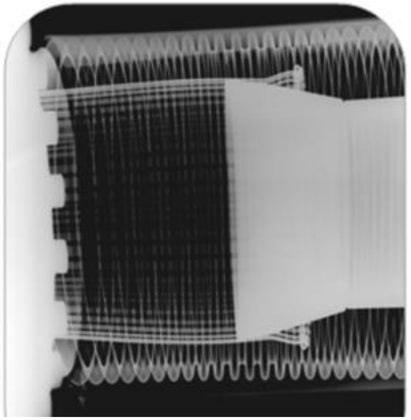
Identify main impedance contributors

- There are the impedance sources we know… and the impedance sources we don't know

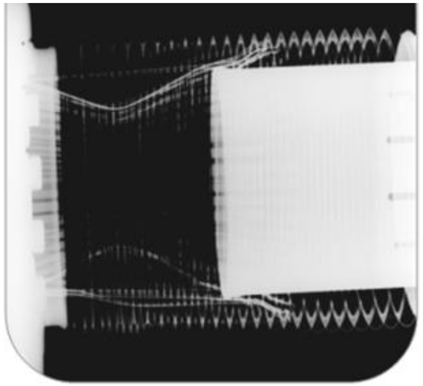
→ Non conformities, damage, ageing, wrong termination can lead to large unexpected impedances

Example: LHC RF fingers

Conform

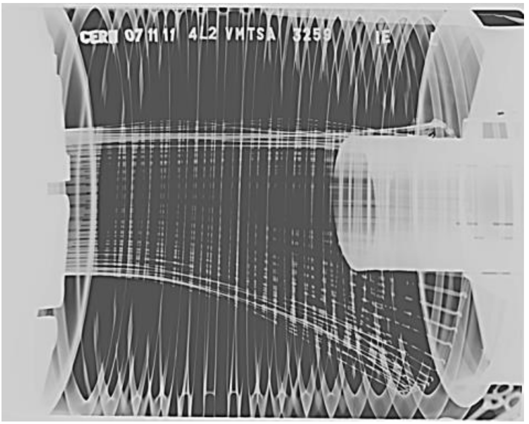


Non-conform

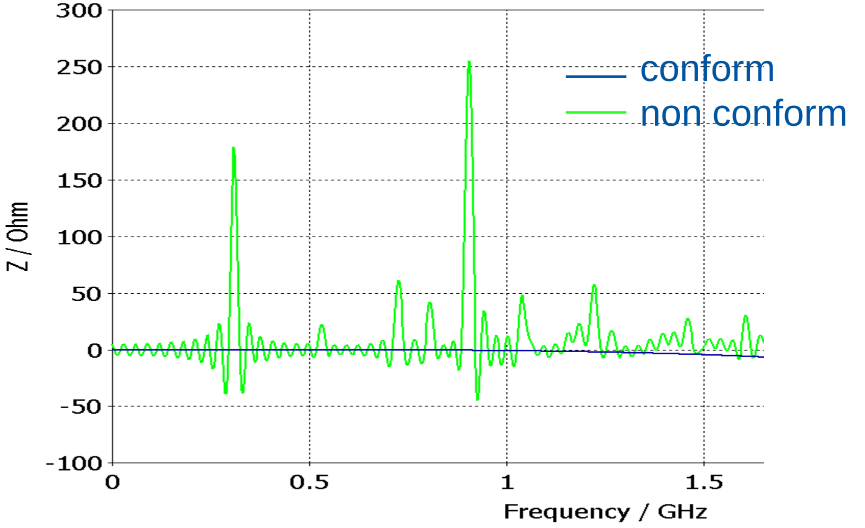


Courtesy CERN TE-VSC

Non-conform: damaged by RF heating from beam



[Kononenko et al, IPAC'13]



→ Needs very good knowledge of layout
→ Needs close follow up with equipment and integration teams
→ Look out for abnormal signs (outgassing, heating) → could be sign of degradation

Identify main impedance contributors

Example of
recent advances

- Identification of single element with bad termination driving transverse instabilities in CERN LEIR and PSB [Koukovini et al, 2018]

Challenges

The real machine is not always what it should be

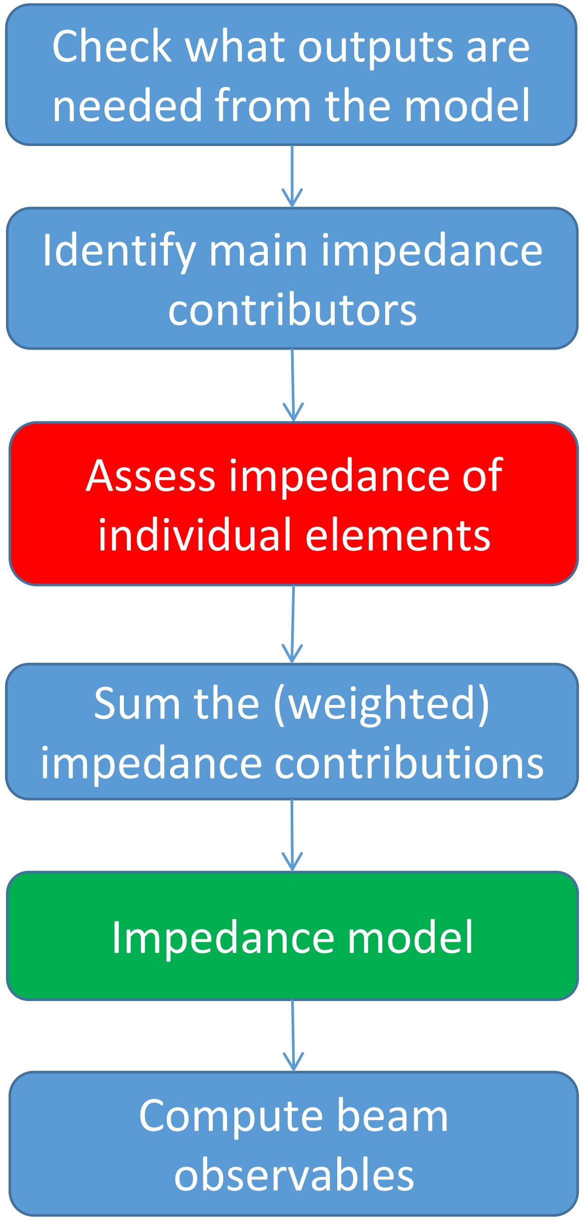
- Incorrect models in layout database
- Modifications not always recorded
- Non-conformities, damage, ageing

Common practice

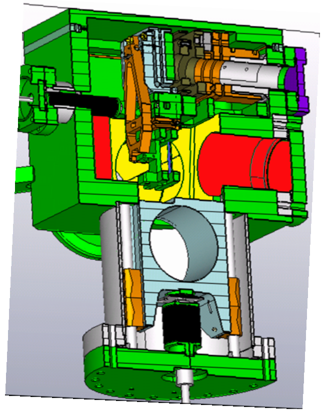
- Start with beam pipe and known large impedance sources
- Check equipment in large numbers (flanges, BPMs, bellows) and those at large β functions
- Look out for signs of non-conformities

Agenda

- Impedance?
- What is an impedance model?
- Why build an impedance model?
- How to build an impedance model?
- Examples of benchmarks
- Outlook



Assess impedance of individual elements

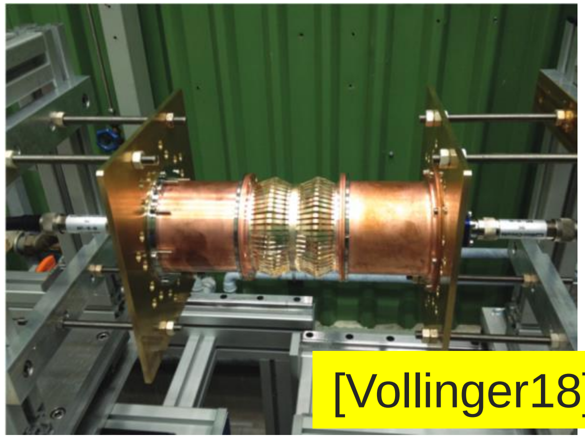


Many tools at our disposal!
→ Analytical tools for ideal simple geometries
→ Dedicated 3D simulations tools for everything else
- commercial codes (CST, GdfidL)
- university and lab-based codes (ABCI, ACE3P, ECHO3D, TBCI)

Huge improvements over past 15 years, but still many constraints and challenges

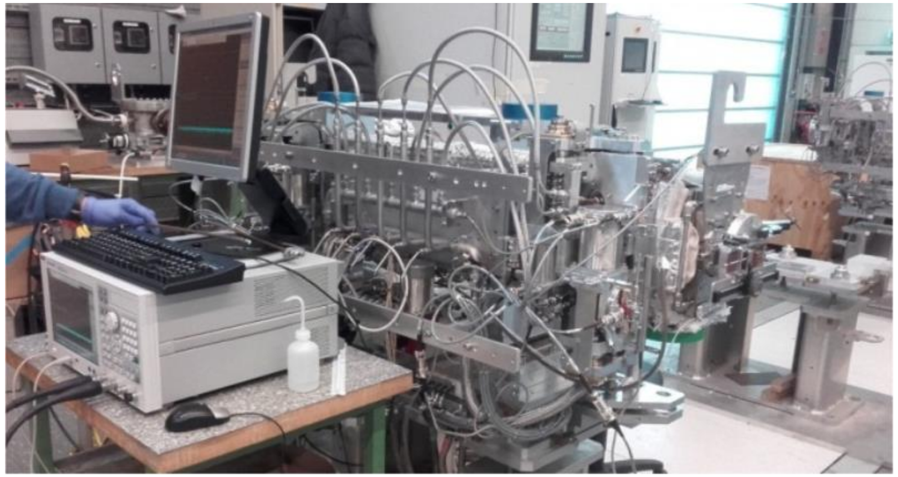
→ Bench measurements (with wire, two wires, probes and bead)

LHC deformable RF fingers



[Vollinger18]

LHC collimator



Assess impedance of individual elements

Examples of recent advances

Analytical computations
- Efficient computation of impedance of multilayer beam pipes [Mounet, 2012]
- Impedance scaling for small angle transitions [Stupakov, 2011]
- Extension of analytical theories to more realistic geometries (flat, finite length, elliptic) [Mounet 2012, Biancacci 2012, Migliorati 2019]

Simulations
- Wake functions from wake potentials [Podobedov, Stupakov, 2013]
- Simulations with low beta [Niedermayer, Zannini, 2014]
- Travelling wave method for simulating low impedance [Grudiev, Arsenyev 2019]
- Disentangling driving and detuning impedance with Eigenmode solver [Arsenyev, 2019]

RF measurements
- EM properties of coatings for ~100 GHz [Koukovini-Platia, 2015]

→ Many advances! Very active field!

Assess impedance of individual elements

Challenges

- Assess electromagnetic properties of materials at high frequency
- Account for external circuits
- Usual limitations of **3D simulation codes**:
  - Numerical noise for very low impedance
  - Number of mesh cells
    - → geometries with large aspect ratio (coatings, wires)
    - → excitation with small bunch length
- Bunch excitation beyond beam-pipe cut-off → devices no longer independent
- **RF measurements**
    - → perturbed by the probes and wires → no direct access to impedance
    - → not always possible

Common practice

- Disentangle **driving and detuning** contributions
    - → possible for wakefield, eigenmode and wire measurements
- Account for **low beta**
- **Benchmark** simulation results in-between codes
- Benchmark **bench measurements** with **simulated bench measurements**
- When possible:
  - Prefer analytical models to 3D simulations
  - Avoid deconvolution to get wake function

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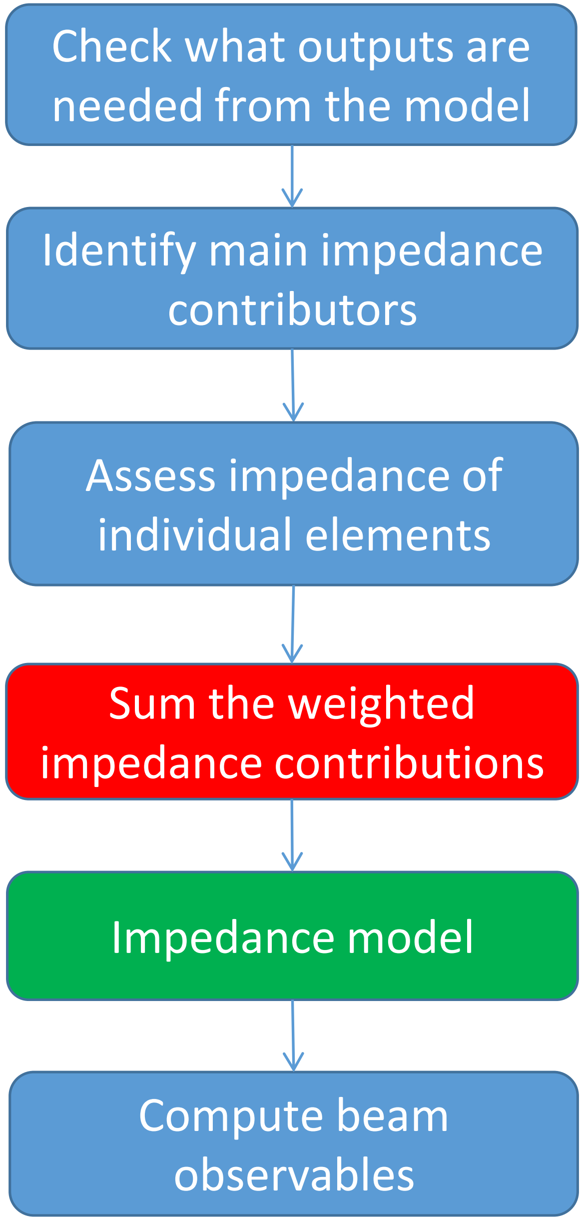

Sum the weighted impedance contributions

→ Prepare all available impedance contributions (FFT, iFFT, interpolation)
→ *Weighted with beta function at each device location (for transverse)*
→ Sum into impedance model

Assumption:
→ Can lump all impedances into one impedance model if related beam dynamics effects are much slower than revolution time.

→ likely why the concept of impedance models is not much used in Linacs.

Sum the weighted impedance contributions

Recently Solved Challenges

- Non-equidistant Fourier Transform [Mounet, 2012]

Challenges

- not to lose information during interpolation and FFTs
- Maintaining impedance models on the long term

Common practice

- Design an impedance database to store:
  - input parameters and 3D models
  - computed impedance/wake data
  - beta functions for various machine configurations
  - With scripts to recompute automatically the impedance model
- Perform updates of model every year to follow up machine and configuration changes

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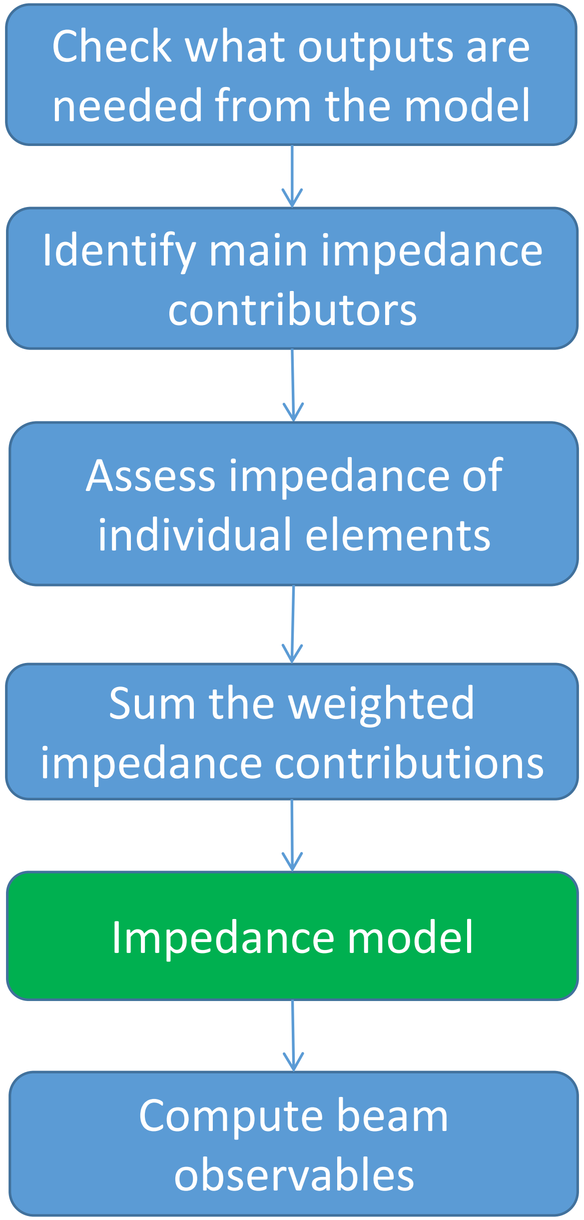
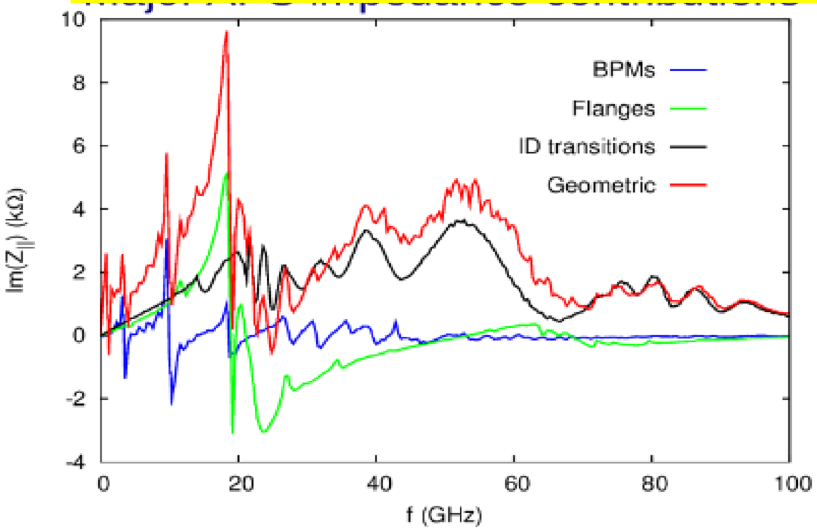
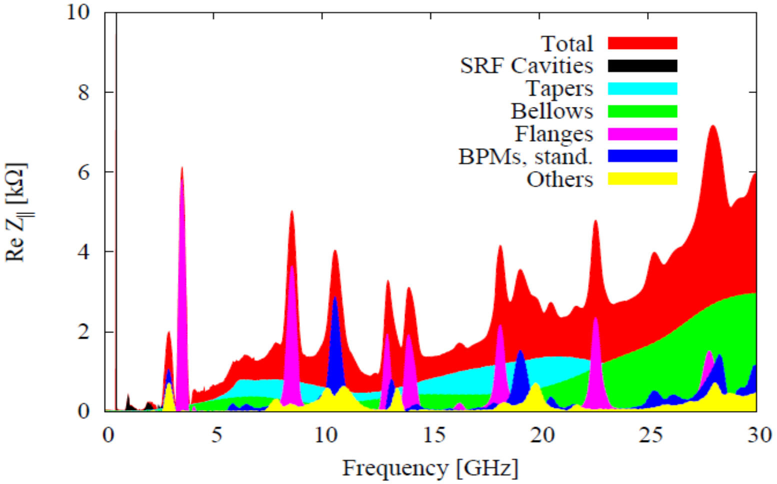


Examples of longitudinal impedance/wake models

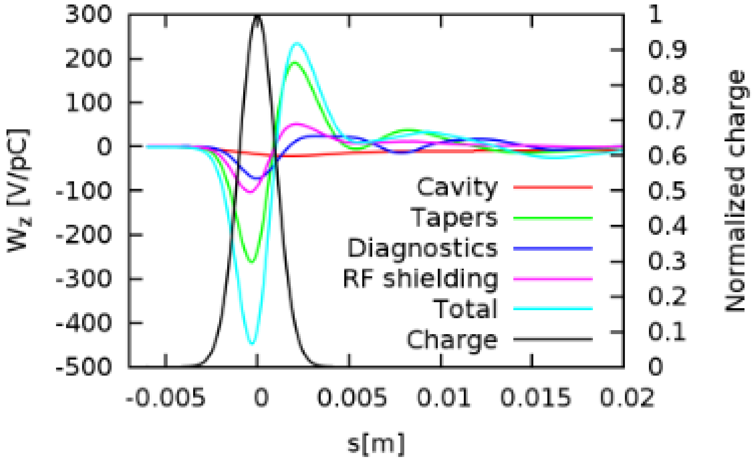
APS model [Lindberg, BTCLER’19]



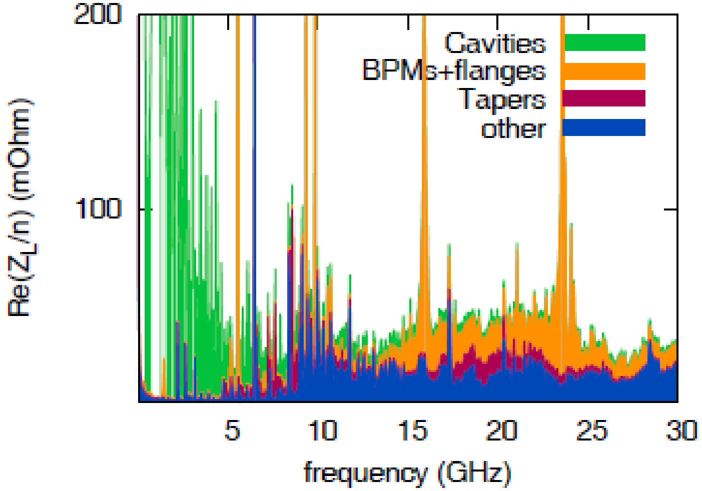
TPS model [Rusanov, EPAC08]



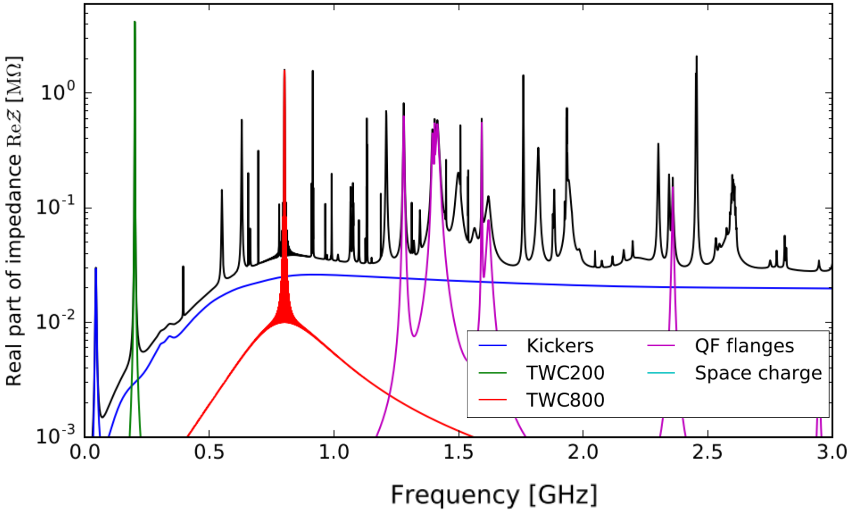
ESRF model [White, IPAC’17]



MAXIV model [Klein, IPAC13]



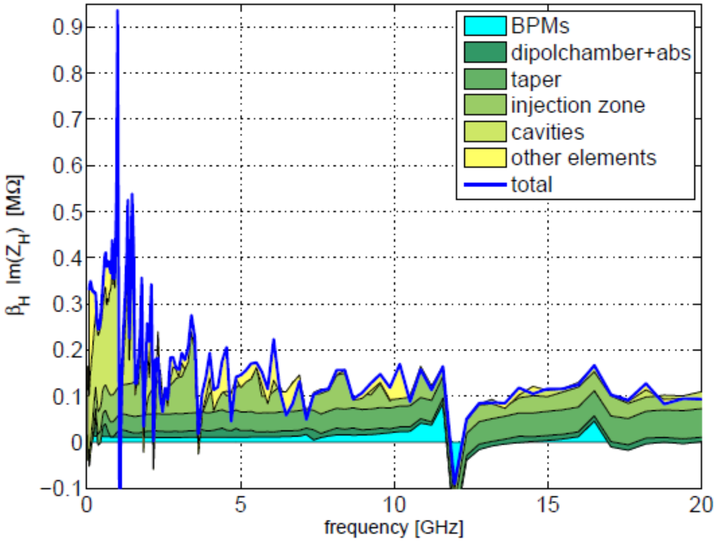
CERN SPS model [Lasheen, MD days 2017]



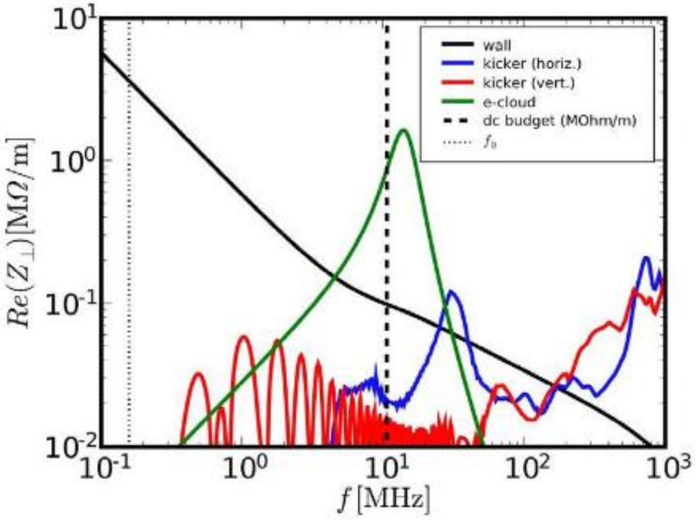
→ Many detailed longitudinal impedance models for machines around the world

Examples of transverse impedance/wake models

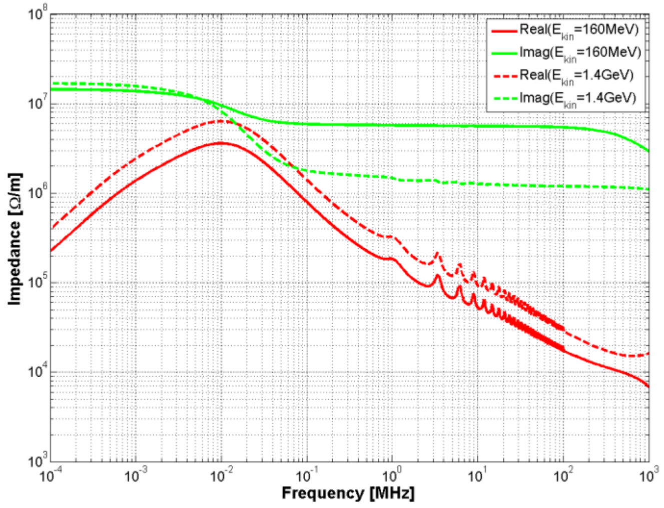
ALBA model [Guenzel, ESLS'10]



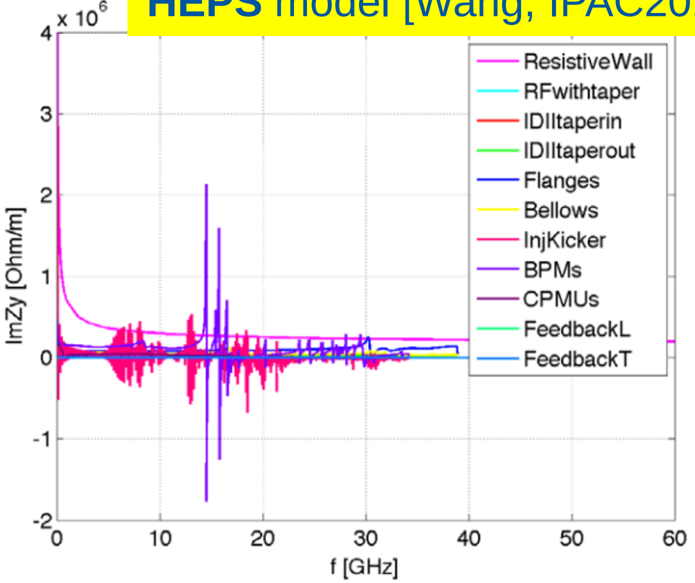
SIS18 model [Niedermayer, 2011]



PSB model [Zannini, 2019]



HEPS model [Wang, IPAC2017]



→ Many detailed transverse impedance models for machines around the world

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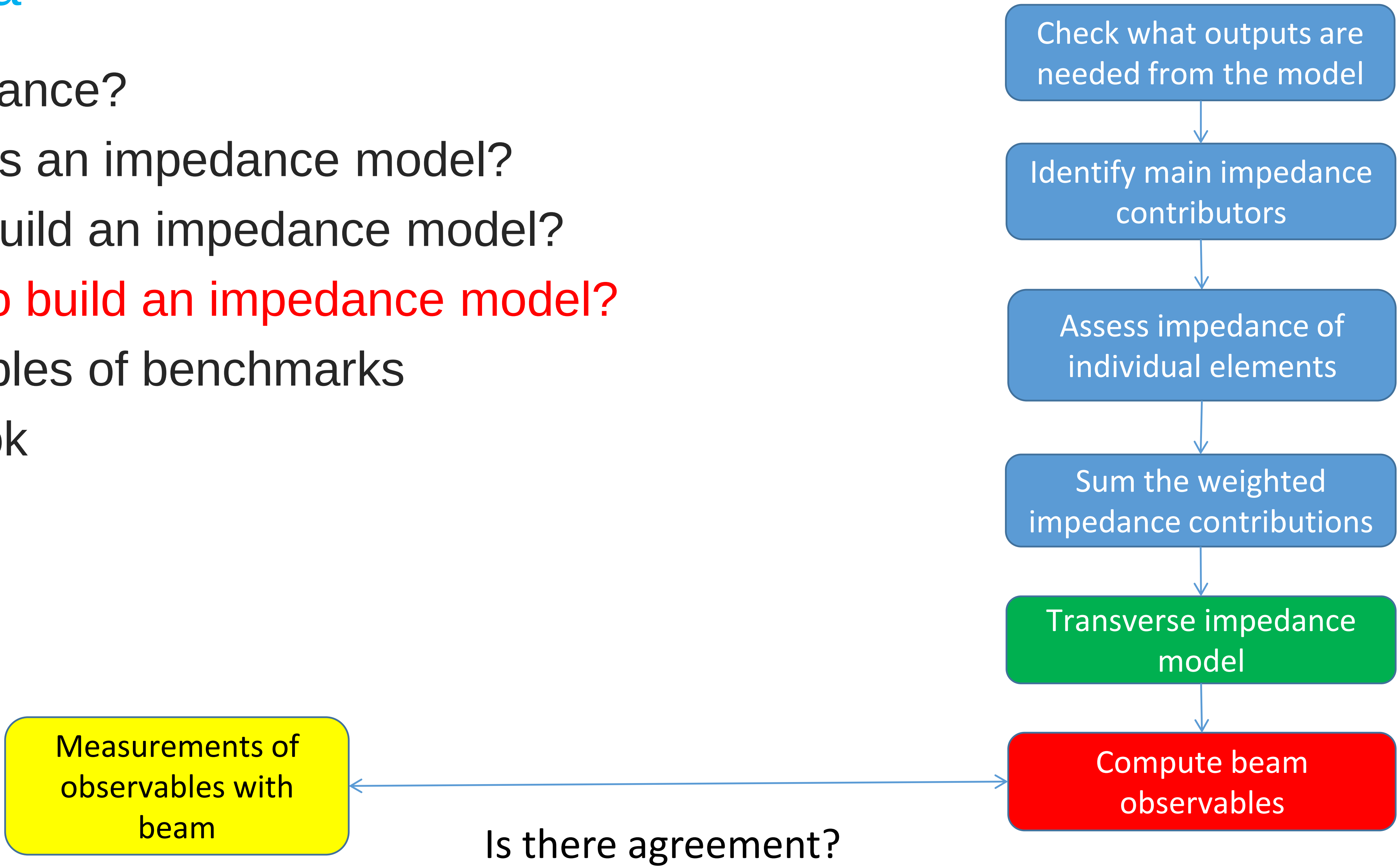

Available beam-based measurement techniques (transverse)

observable	Vs
Betatron tune shift	Intensity, chromaticity
phase advance shift (localization)	Intensity, chromaticity
orbit deviation	Orbit bump, intensity
Growth rate	Intensity, chromaticity
Damping	Intensity, chromaticity
Grow-damp	Excited frequency
Bunch by bunch and multibunch tune shift	Intensity, number of bunches
Growth rate of coasting beam spectral lines	Intensity, chromaticity

→ Many techniques available to assess and disentangle various contributions of transverse impedance
→ Possibility to sweep the sampled frequency of the impedance with chromaticity and bunch length

Available beam-based measurement techniques (longitudinal)

[Shaposhnikova 2017]

observable	Vs	Access to			Global/local	Stable beam?	Machine	Constraints
		Re/Im	Effective?	Mode				
Bunch lengthening, energy spread increase	intensity	Im(Z///n)	Effective	0	Global	Stable	All !	Assumes constant longitudinal emittance vs intensity
Incoherent quadrupole frequency shift	Intensity	$Im(Z_{//}/n)$	Effective	2	Global	Stable	RHIC, PS, LHC, PS,	Need Schottky monitor, can be made coherent
Incoherent dipole frequency shift	Intensity	$Im(Z_{//}/n)$	Effective	1	Global	Stable		
Microwave instability threshold	Intensity	$\|Z_{//}\|/n$	Effective or sampled	Mix	Global	Unstable	Most	Should fold in all the other damping/exciting mechanisms
Heat load	intensity	$Re(Z_{//})$	Effective	0	Local	Stable	LHC, SPS	Need temperature probes and an accurate modelling of thermal effects
loss of Landau damping (threshold, growth rates)	Intensity bunch length	$\|Z_{//}\|/n$	Effective or sampled	Mix	Global	Unstable	SPS	Should fold in all the other damping/exciting mechanisms
Debunching bunch	Intensity	$Re(Z_{//}/n)$	sampled	Mix	Global	Stable	SPS, LEIR	
Synchrotron phase shift	Intensity/device position	$Re(Z_{//})$	Effective	0	Global/ local	Stable	LHC, AS, PS	Other sources energy loss to be subtracted (e-cloud, SR)

→ No equivalent of chromaticity to sweep frequency dependence
→ Should compare bunch length and distribution dependence with macroparticle simulations

Comparing computed observables with beam based measurements

Examples of recent advances

- High accuracy tune shift measurements [Antipov2018, Podobedov2018]

Challenges

- Accuracy of instrumentation
- Machine availability for measurements
- Machine protection issues (instability and kick)
- Observables can be affected by other mechanisms
- Reproducibility of machine between measurement sessions

Common practice

- Systematic check of tune shift and bunch lengthening every year
- Assess dependence on bunch length and energy spread (for longitudinal)
- Assess dependence on chromaticity and bunch length (for transverse), and emittance (for growth rates)
- Use several measurements to test the model from different points of view

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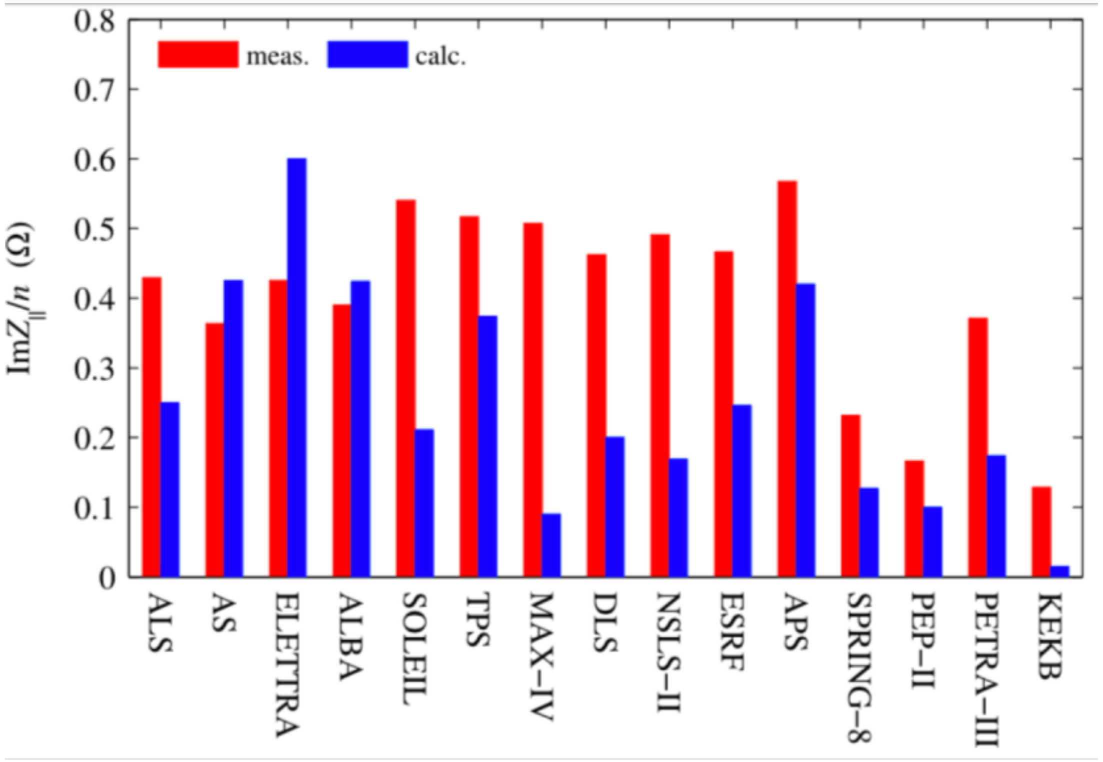
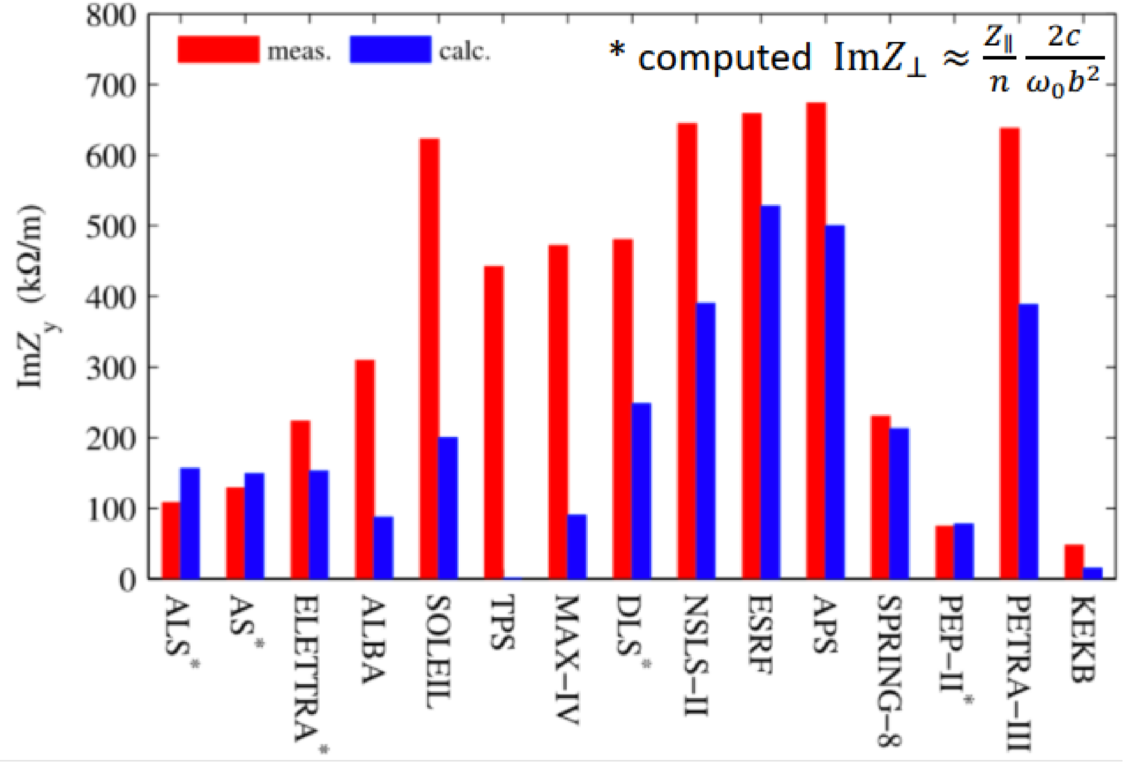
Impedance model benchmarks for lepton machines

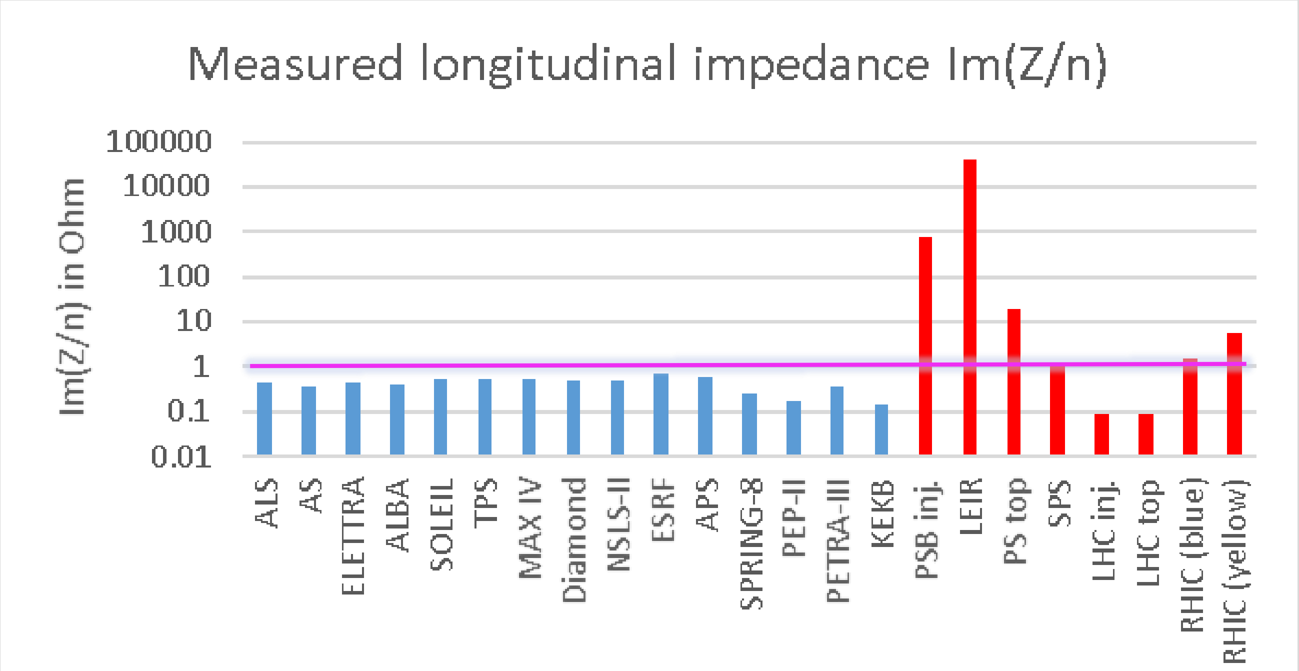
Review by V. Smaluk, 2019

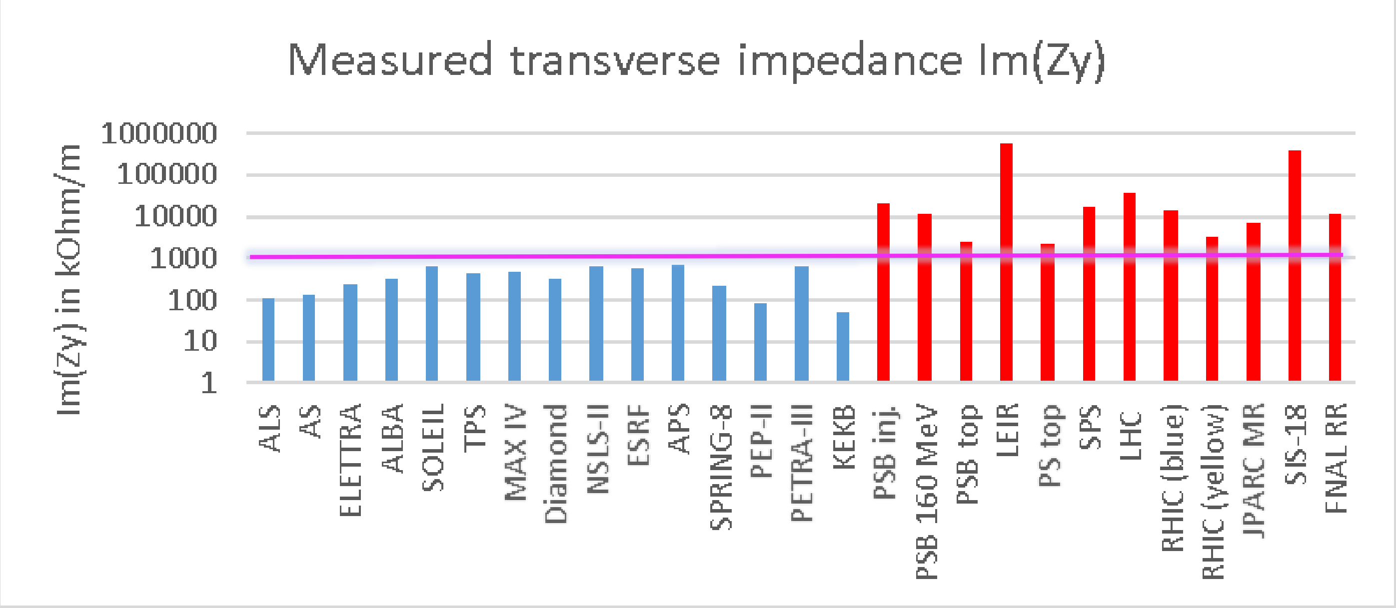




→ Quite homogeneous impedances among lepton machines

Measured impedance for all machines





→ Need logarithmic scales to display hadron and lepton machines!

Lepton machines < $\frac{1\ \Omega}{1\ M\Omega\ /m}$ < hadron machines

(except LHC)

→ Strong emphasis on minimizing LHC impedance from design stage paid off!

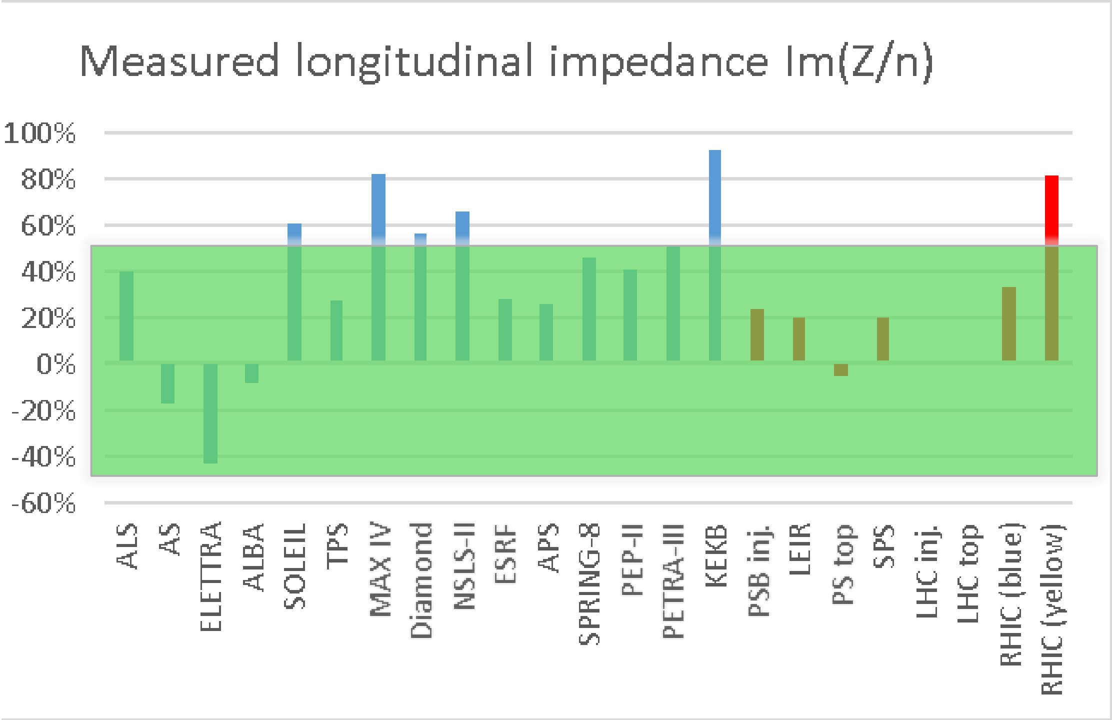
Possible reasons:

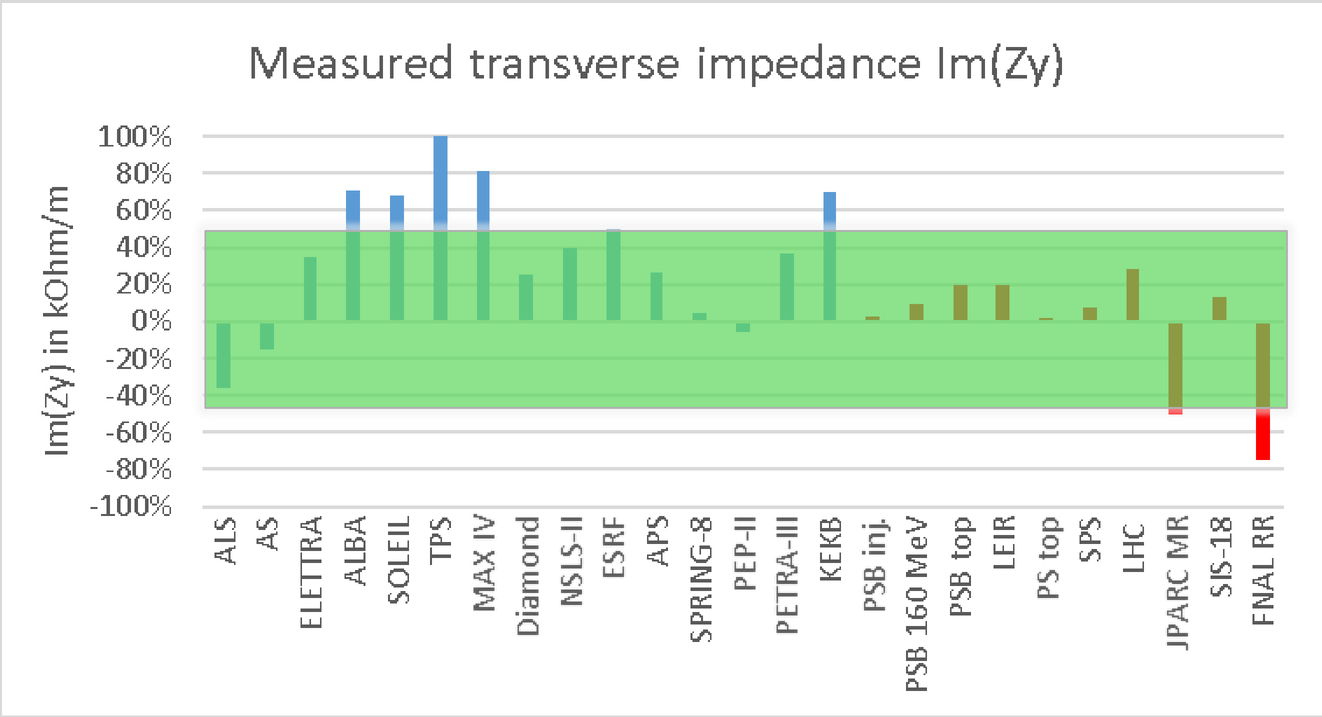
→ Beam induced heating in leptons is a strong incentive to keep low geometric longitudinal impedance

→ Strong impact of indirect space charge for low energy

→ Frequency sampling larger for smaller bunch length

Error between measurement and model





Marketing convention: $error[\%] = \frac{Z_{meas} - Z_{model}}{Z_{meas}}$

→ Most machines are within +/- 50% missing impedance from measurement
→ Reasonable target in view of the error bars accumulated along the way?

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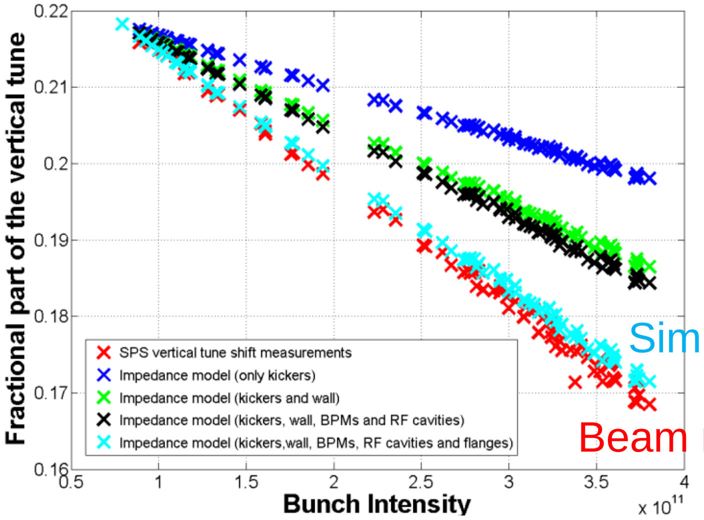
Example of the CERN SPS

Vertical headtail growth rates vs chromaticity

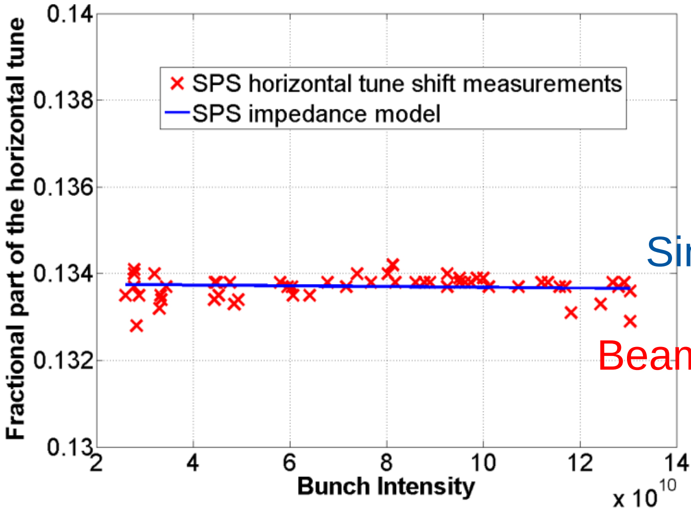
Vertical and horizontal tune shift versus intensity

Zannini, IPAC'15



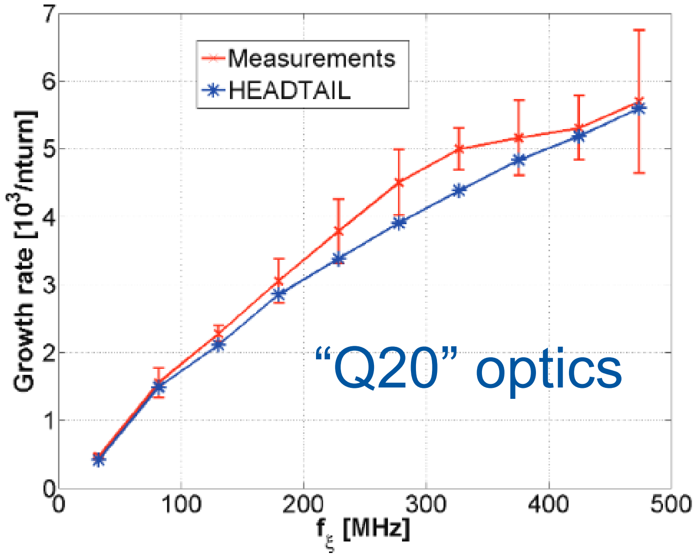
Simulation

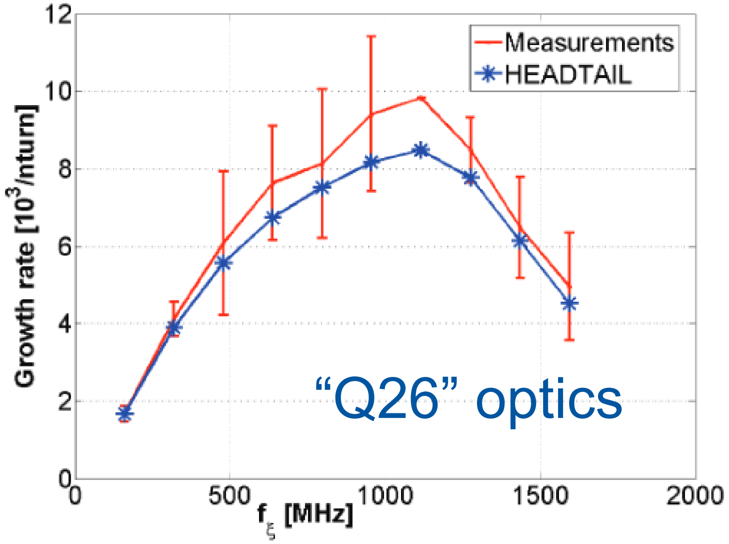
Beam measurements



Simulations

Beam measurements

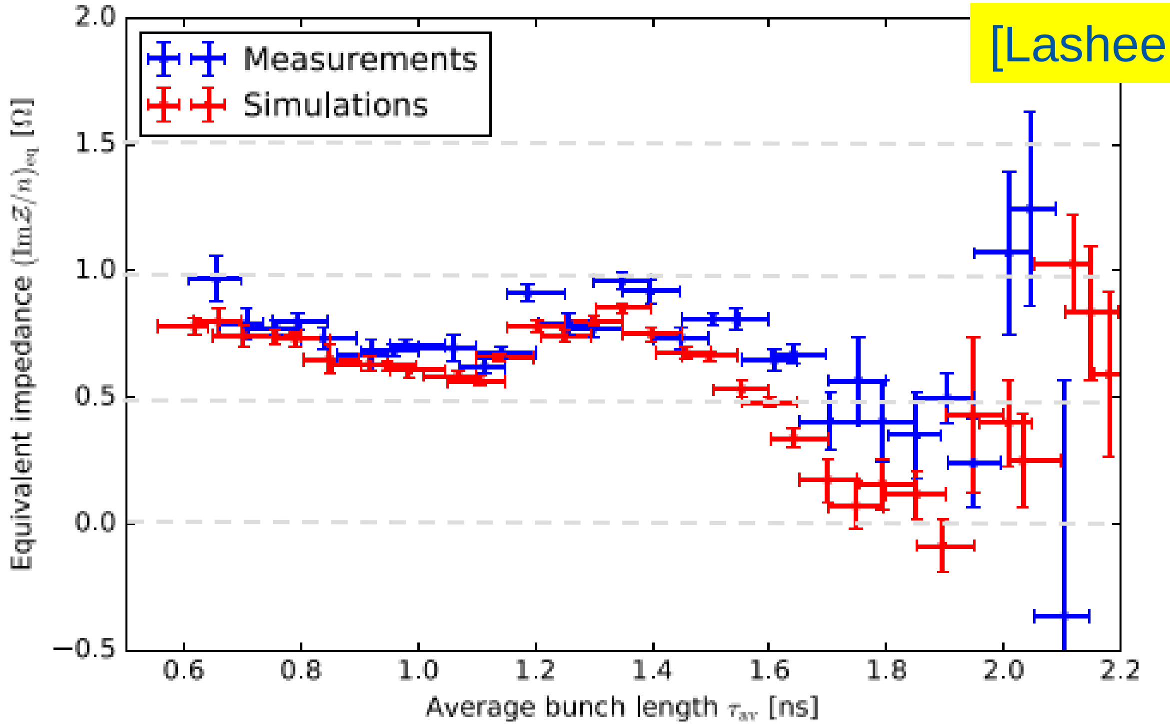




→ Model and measurements agree for several orthogonal measurements

Example of the CERN SPS

Longitudinal effective impedance vs bunch length deduced from quadrupole frequency shift



[Lasheen, 2017]

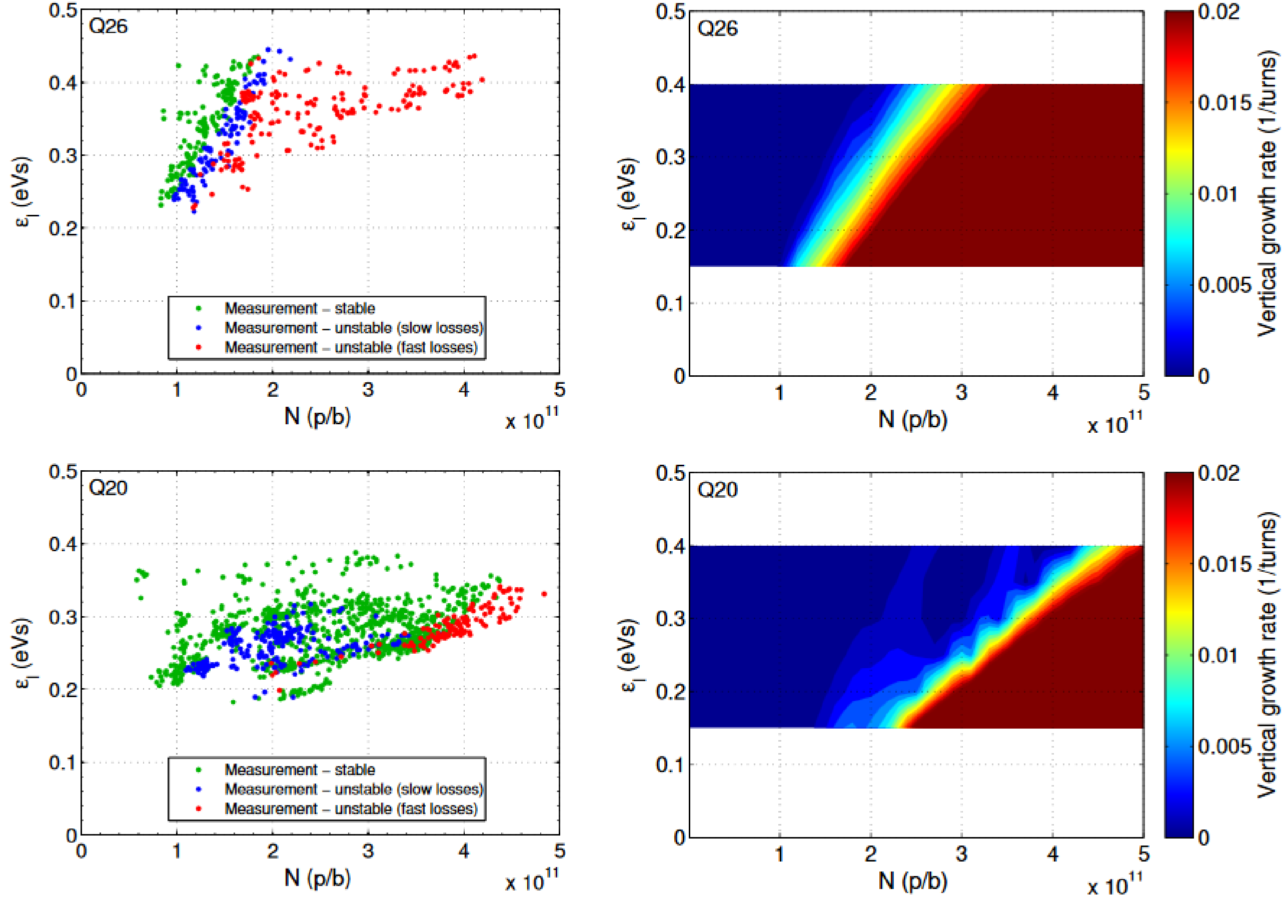
→ Model and measurements agree for several orthogonal measurements

Example of the CERN SPS

Bartosik, IPAC'14

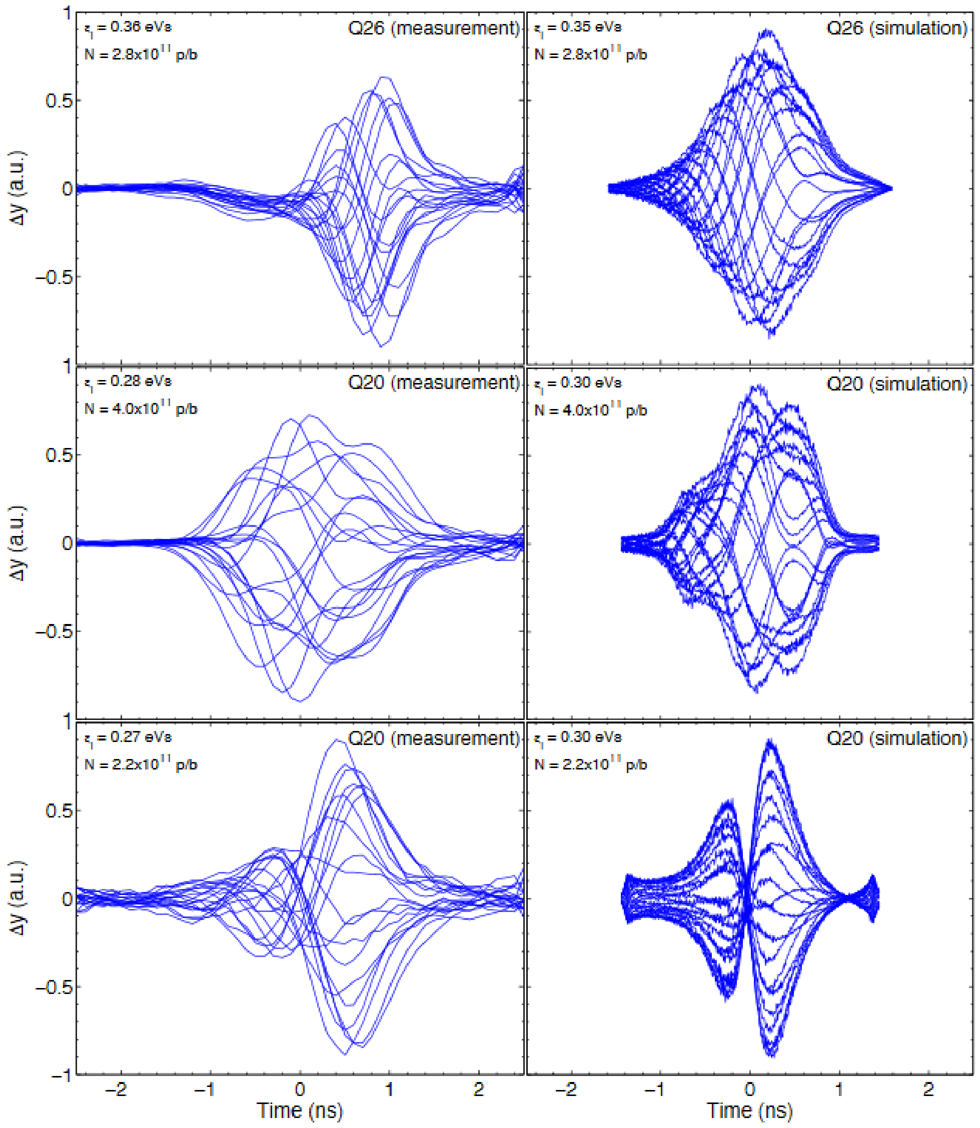
Instability threshold studies vs intensity and emittance

Beam measurements | Simulation



Intrabunch pattern during instability

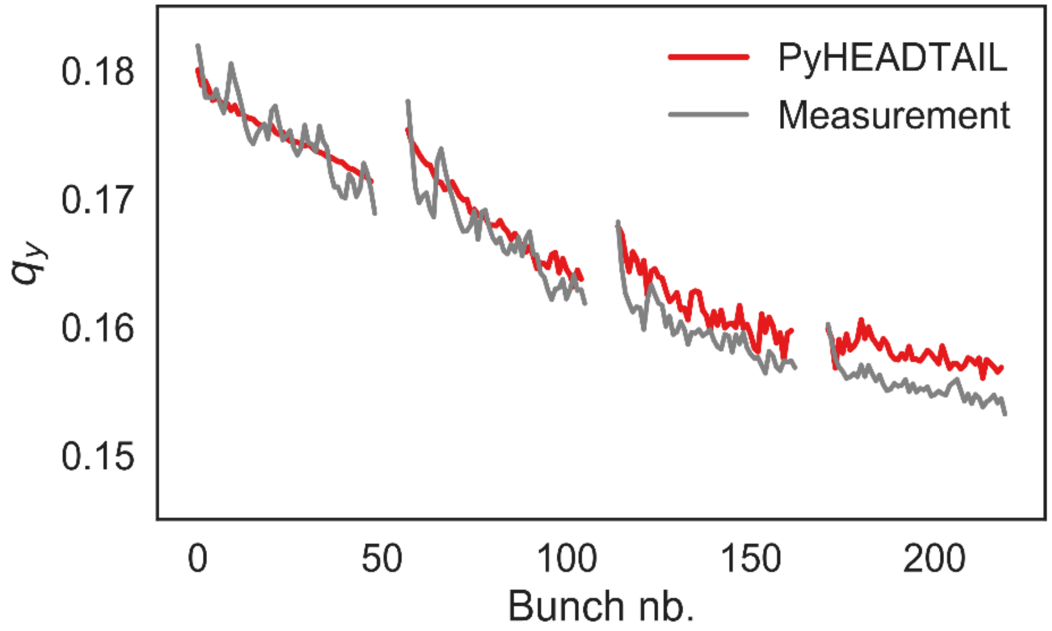
Beam measurements | Simulation



→ Model and measurements agree for several orthogonal measurements

Example of the CERN SPS

Vertical bunch by bunch tune shift
along 4 batches at injection



→ Checking parameter dependence effective impedance

- gives much more confidence in the model
- shows that effective impedance is not a single number

→ It took many years, many measurements, many models and many people to get there!

→ SPS is an ideal testbed → many possibilities to perform parallel and dedicated measurements

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Outlook: machine impedance models

- Precious tool to explain observations, stability thresholds and push the performance of a machine

- Widespread in the accelerator community

  → different levels of complexity depending on need and allocated resources

  → Building impedance models for CERN machines and benchmarking them with measurements required a critical mass of people, expertise and skills over many years in:

  - Computation of impedance (theory, simulations and measurements)
  - Beam dynamics (theory, simulations and measurements)
  - Database and scripting
  - Machine measurements (operation, instrumentation, RF, optics)

- There are heavy challenges at all levels of the making of the model, but also converging good practices and beautiful benchmarks of models with measurements

- Impedance alone cannot explain all stability observations

  → Need to include e.g. linear coupling, electron or ion cloud, space charge, IBS, beam-beam for colliders, synchrotron radiation (incoherent and coherent), damper, noise

  → Important to have an accurate impedance model to avoid propagating errors to other connex studies

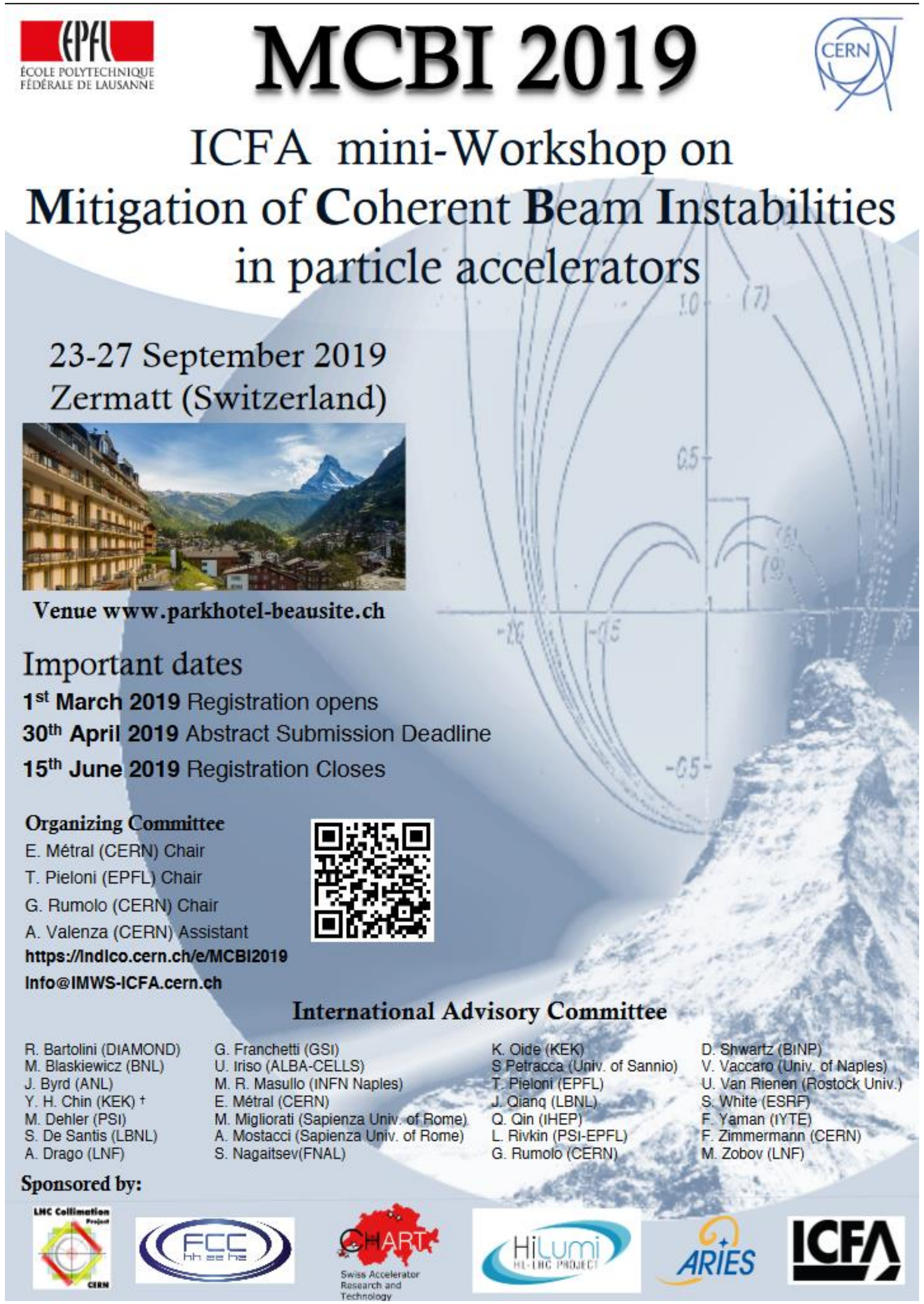
These topics will be discussed
in the upcoming Zermatt workshop

As well as at the

ALERT 2019 workshop
Advanced Low Emittance Rings Technology

July 10 – 12, 2019 | Ioannina, Greece

Dedicated to small apertures



Thank you for your attention!

… and congratulations to Vittorio, one of the fathers of the impedance concept!

Accelerator Awards

The 2019 Asian Committee for Future Accelerators (ACFA)/IPAC19 are honoure

The Xie Jialin Prize for outstanding work in the accelerator field, with no age limit.

Prof. Vittorio Giorgio VACCARO

'For his pioneering studies on instabilities in particle beam physics, the introduction of the impedance concept in storage rings and, in the course of his academic career, for disseminating knowledge in accelerator physics throughout many generations of young scientists."

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