FCC-hh impedance budget and single beam stability

SERGEY ARSENYEV

FCC WEEK 2019 IN BRUSSELS, BELGIUM

Part 1: impedance

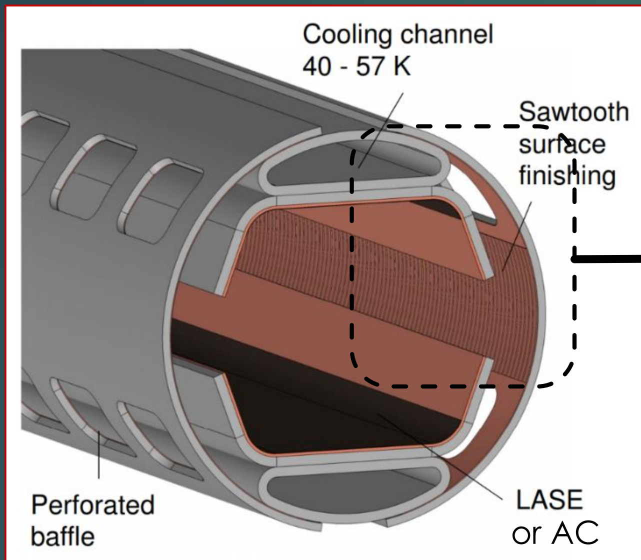
Main impedance updates since FCC week 2018

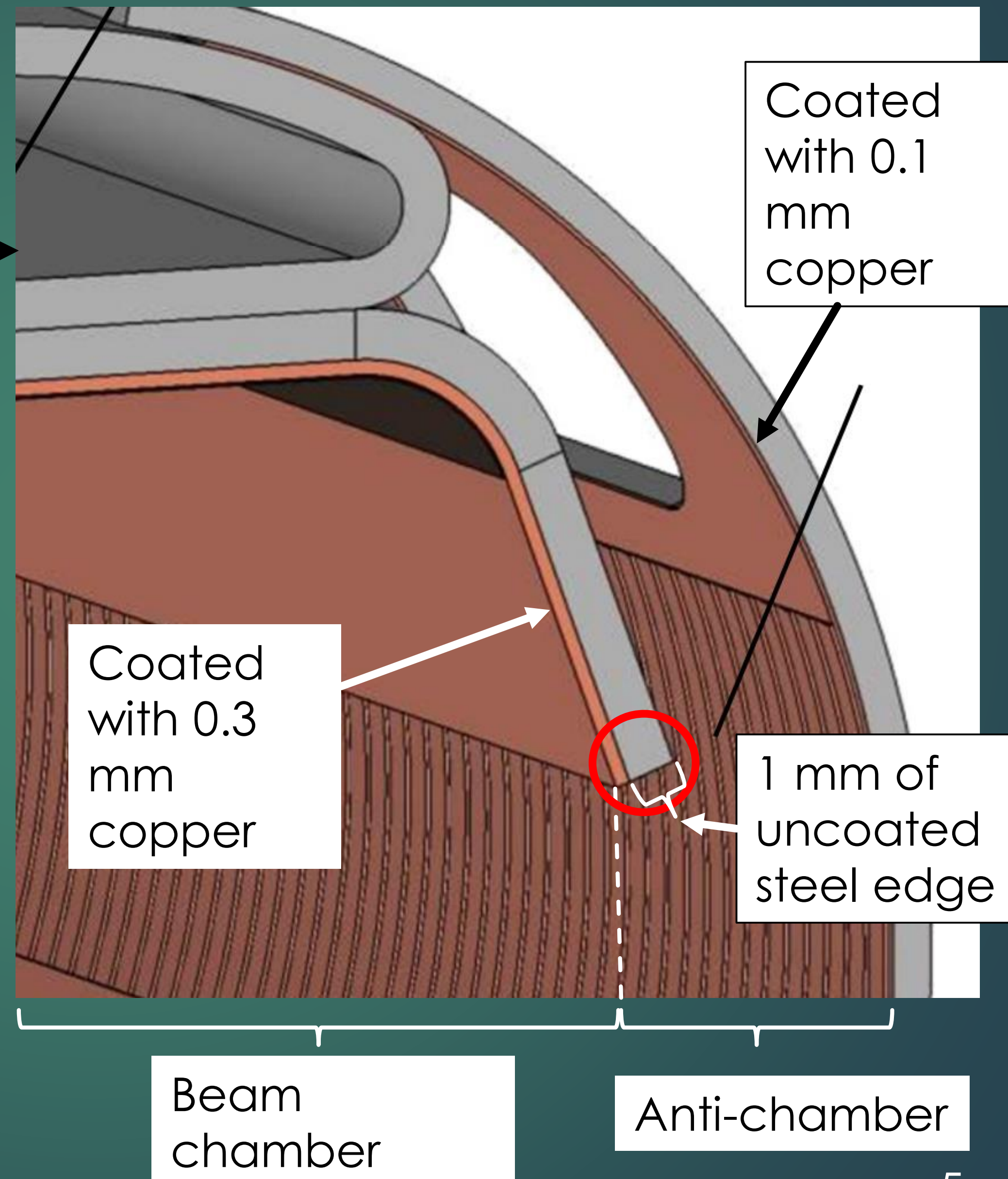
- Tighter beamscreen aperture is officially accepted
  Vertical aperture: 13.2 mm → 12.22 mm
- The "stainless steel edge" issue in the beamscreen is discovered and analyzed (D. Astapovych)
- Measurements of laser treated surface impedance are on the way (K. Brunner)
- Injection kicker magnet impedance is calculated (A. Chmielinska)
- A high-Q HOM in crab cavities is damped
  Dipolar mode at 1.276 GHz: Q-factor 23000 → 1100
- Collimator impedance is updated with the new gaps

More details in the next slides

So what is the issue with the stainless steel in the beamscreen?

Stainless steel edge (1/3)



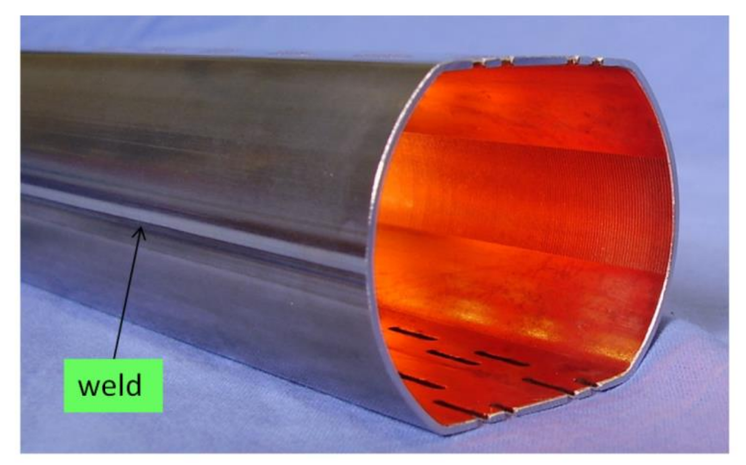


Stainless steel is ~1000 times more resistive than copper:

$$\rho_{copper}(50K, 1.06T) = 7.88 \times 10^{-10}\ \Omega m$$

$$\rho_{st.steel} = 6 \times 10^{-7}\ \Omega m$$

Stainless steel edge (2/3)



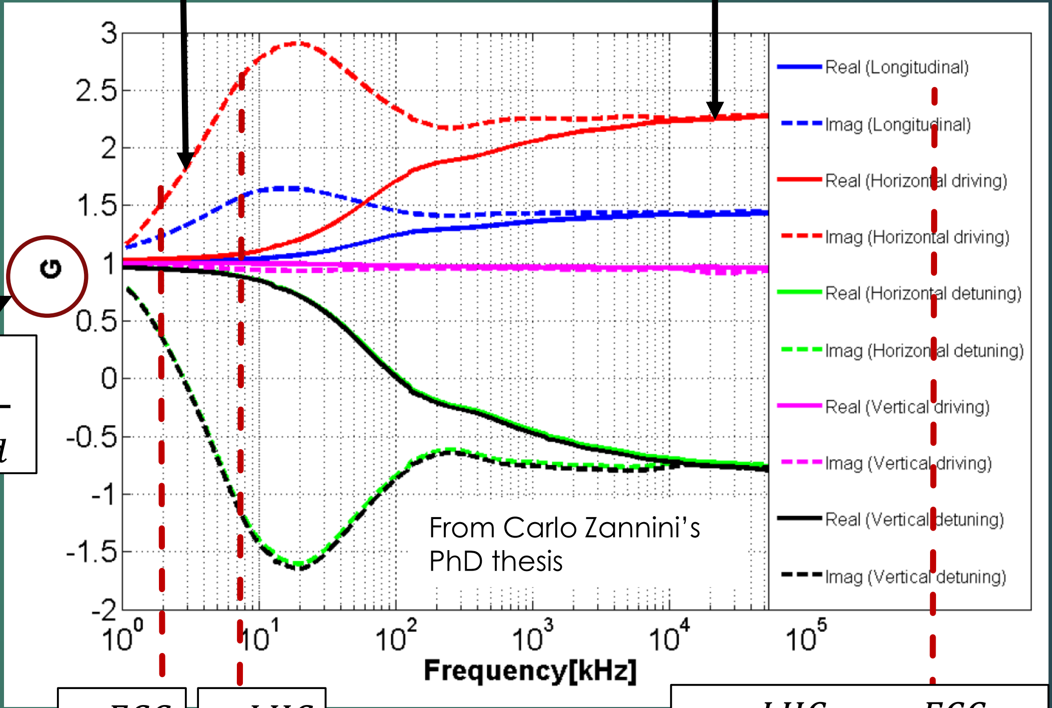
Similar issue also exists in the LHC beamscreen due to the weld

Skin depth	$f = 2.1\ kHz$	$f = 1\ GHz$
δ_{copper}	$0.3\ mm$	$0.4\ \mu m$
$\delta_{st.\ steel}$	$8.5\ mm$	$12\ \mu m$

At kHz level increase in Z_x^{dip} is purely imaginary

Factor of 2.3 increase in Z_x^{dip}

$\frac{Z_{with\ weld}}{Z_{without\ weld}}$

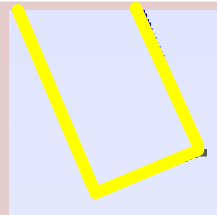
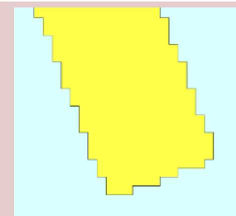
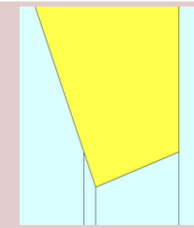
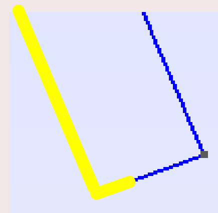
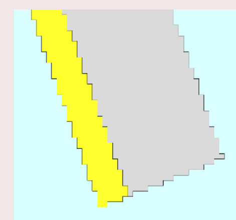
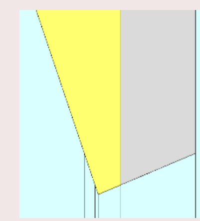
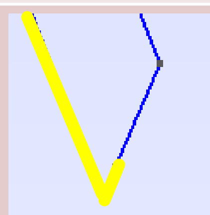
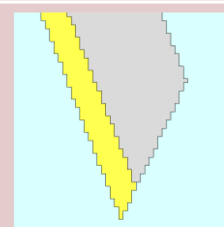
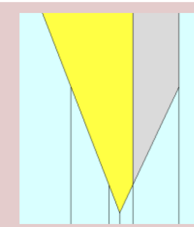


f_{CB}^{FCC} f_{CB}^{LHC} $f_{SB}^{LHC} = f_{SB}^{FCC}$

Problem: Z_x is increased at single bunch frequencies (~1 GHz)
The latest FCC-hh impedance model has similar contributions in x and y from the other elements, leaving no margin for Z_x increase

Stainless steel edge (3/3)

The value in the vertical plane is almost not affected by the issue: $Im(Z_y) = 12.2\ \Omega/m^2$ at 1 GHz. We should aim to not exceed this value for $Im(Z_x)$.

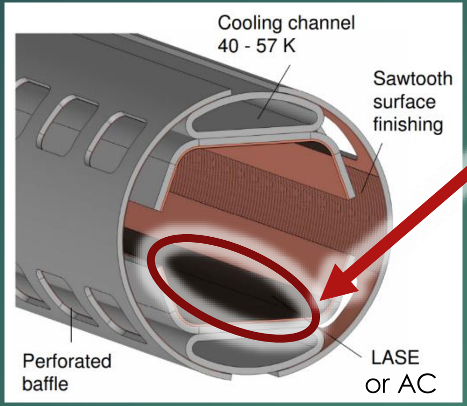
	$Im(Z_x)$ per meter $[\Omega/m^2]$ at 1 GHz, BI2D result (D. Astapovych)	$Im(Z_x)$ per meter $[\Omega/m^2]$ at 1 GHz, CST - discretized borders	$Im(Z_x)$ per meter $[\Omega/m^2]$ at 1 GHz, CST - borders on mesh diagonals
Present geometry, if everything was copper coated	10.86 	10.40 	11.55 
Present geometry with exposed steel edge	22.45 	25.0 	36.33 
Steel and copper are cut at 45 deg	18.06 	14.83 	19.01 

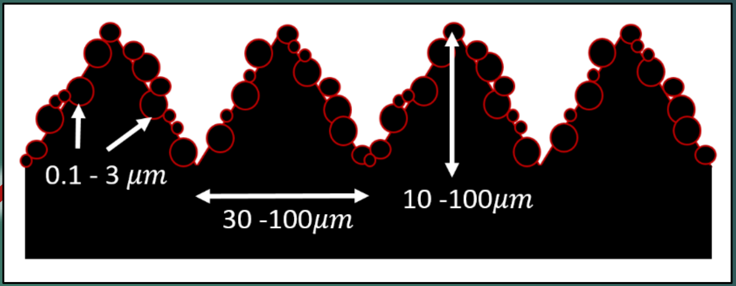
Preferred solution: coating of the edge, but other options (bending, sharp cuts) could be considered.

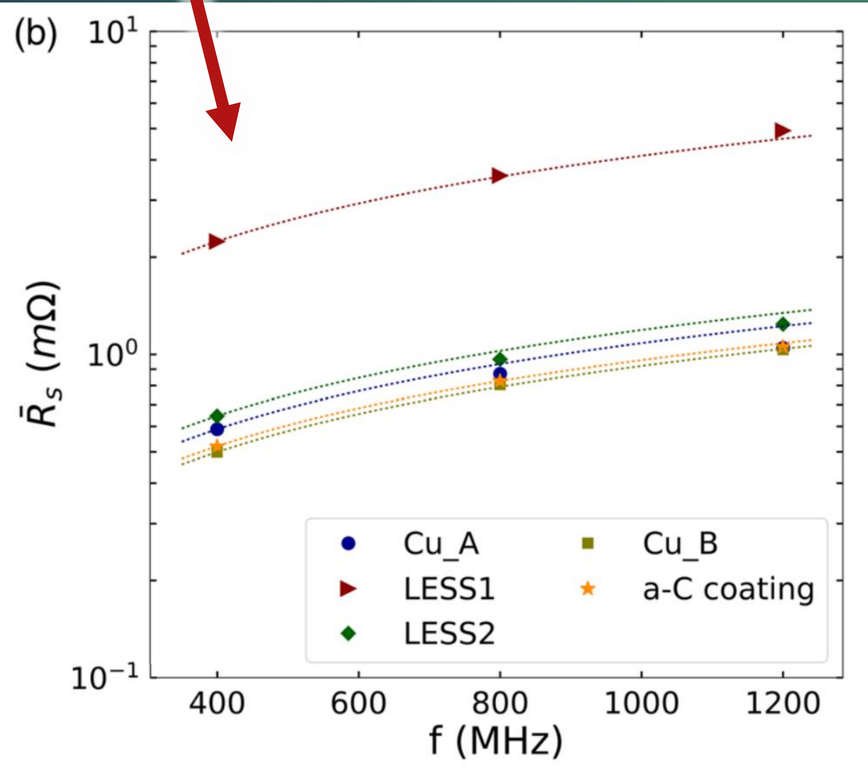
What is the progress on the impedance of a laser-treated surface?

Laser treated surface impedance (1/2)

Calatroni et al 2019, “Cryogenic surface resistance of copper: Investigation of the impact of surface treatments for secondary electron yield reduction”







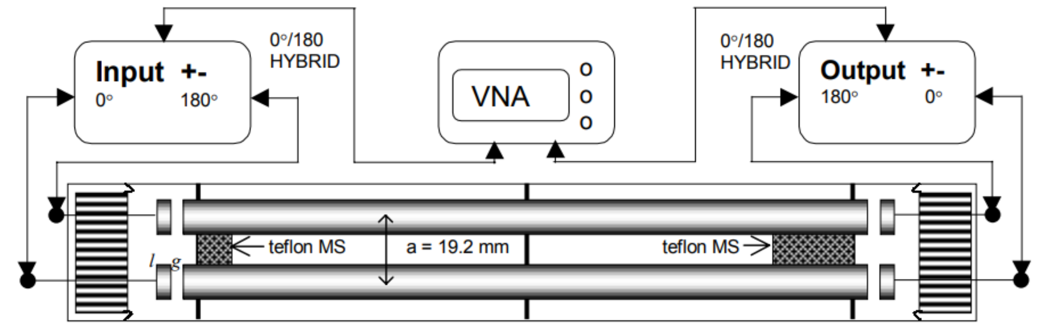
QPR measurements (cryogenic temperature, no external B-field) show a big difference in impedance depending on the current direction. With the grooves parallel to the beam the results seem OK, but we still need:

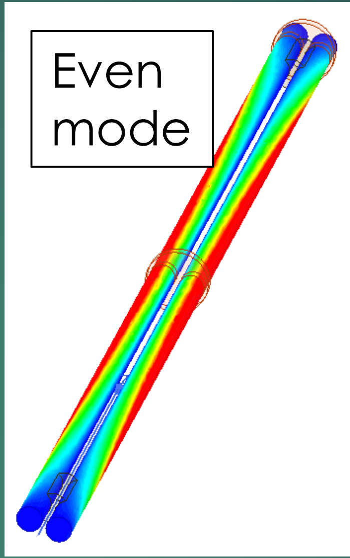
- Measurements with B-field
- Measurement of $Im(Z_{surf})$, or at least $Re(Z_{surf})$ in a wide enough frequency span to apply an analytical model.

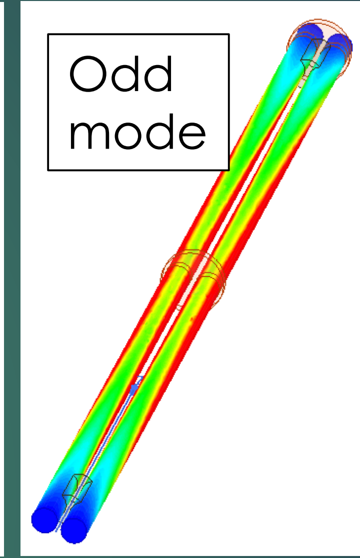
For the moment, AC coating is assumed in the impedance budget, but can be changed to laser treatment if FRESCA experiments show moderate impedance increase

Laser treated surface impedance (2/2)

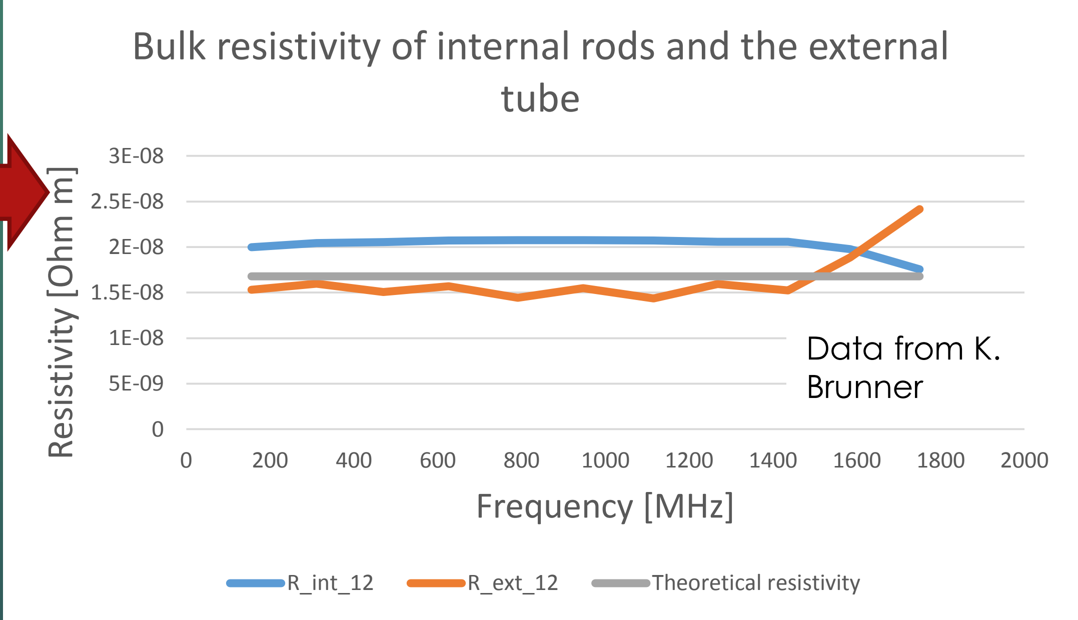
Experiment at FRESCA – preparation is ongoing with K. Brunner and S. Calatroni





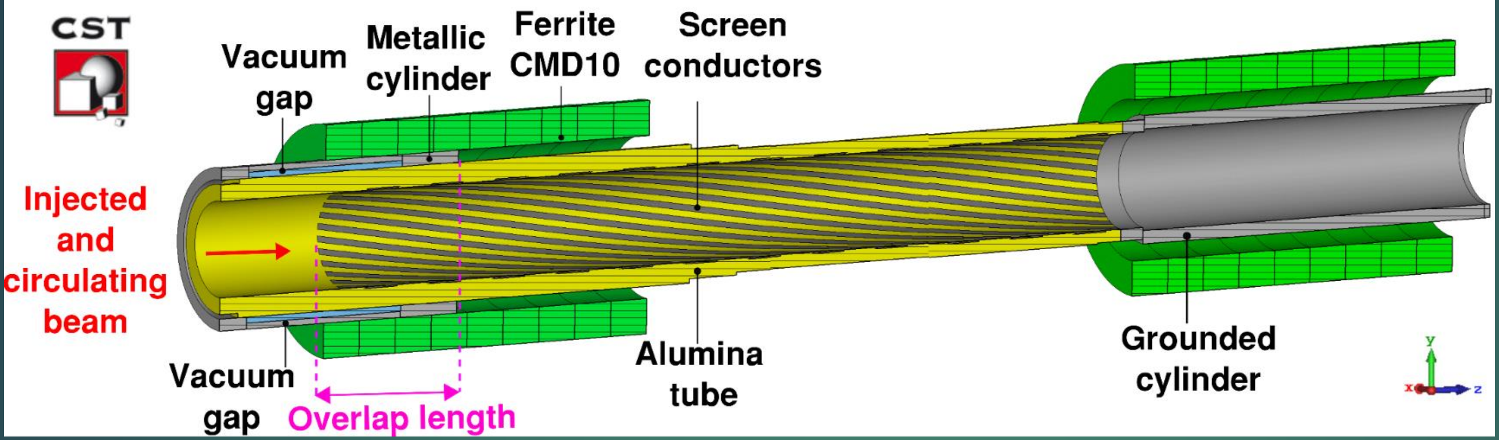


Recent results from K. Brunner: prototype test-stand allows measuring copper resistivity with 10% accuracy (room temperature, no B-field)



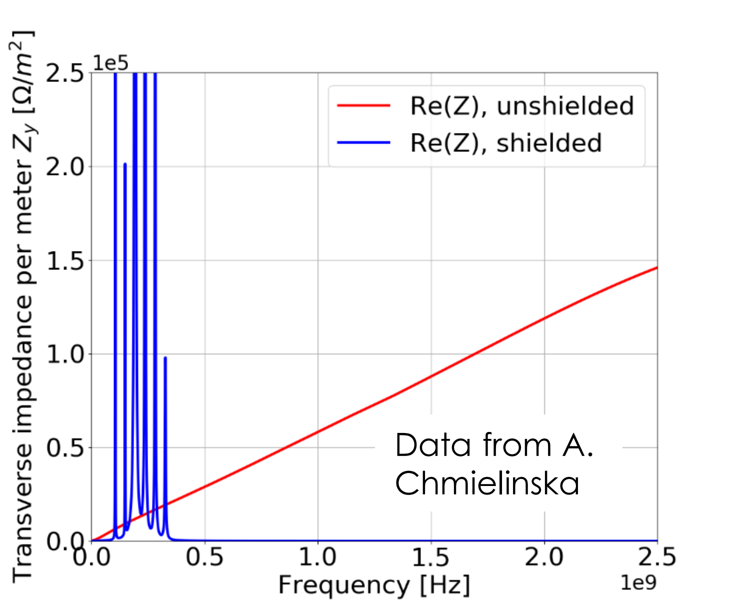
So what is the MKI impedance?

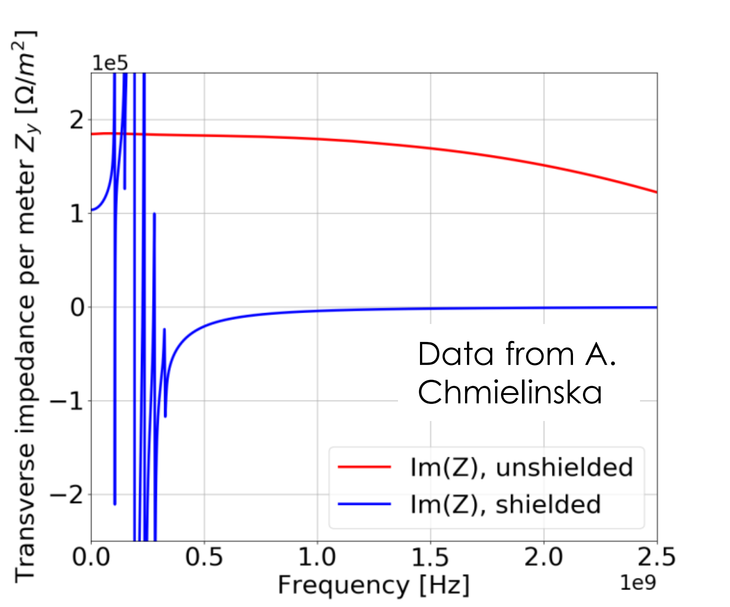
MKI impedance (1/2)



See presentation by A. Chmielinska for details

New shielded design (spiral shielding) vs old unshielded design (32 mm aperture)



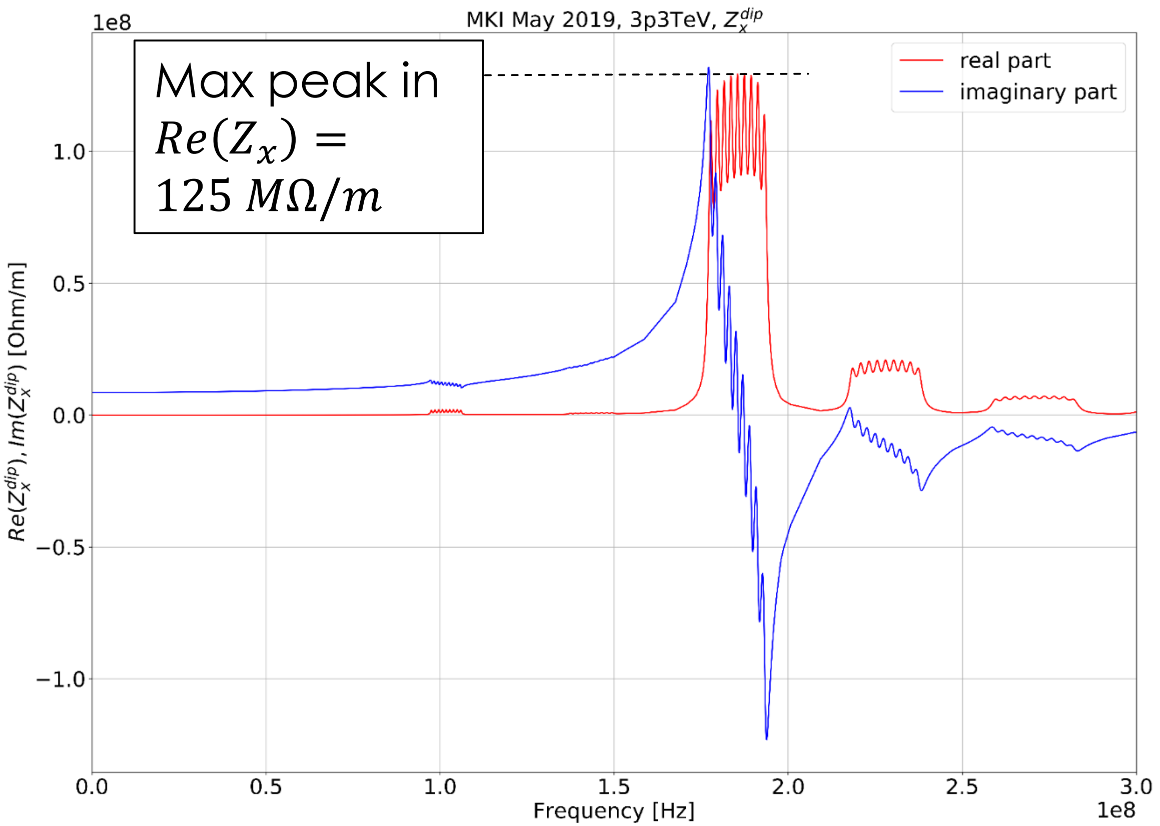


The shielding reduces the broadband impedance but introduces resonant peaks at frequencies below 500 MHz

MKI impedance (2/2)

Problem: If all 18 MKIs were resonantly adding, the CB instability driven by the resonances would be too fast.
Solution: Split 18 magnets in 9 pairs and detune each pair by 1%

Total weighted impedance of 18 MKIs:



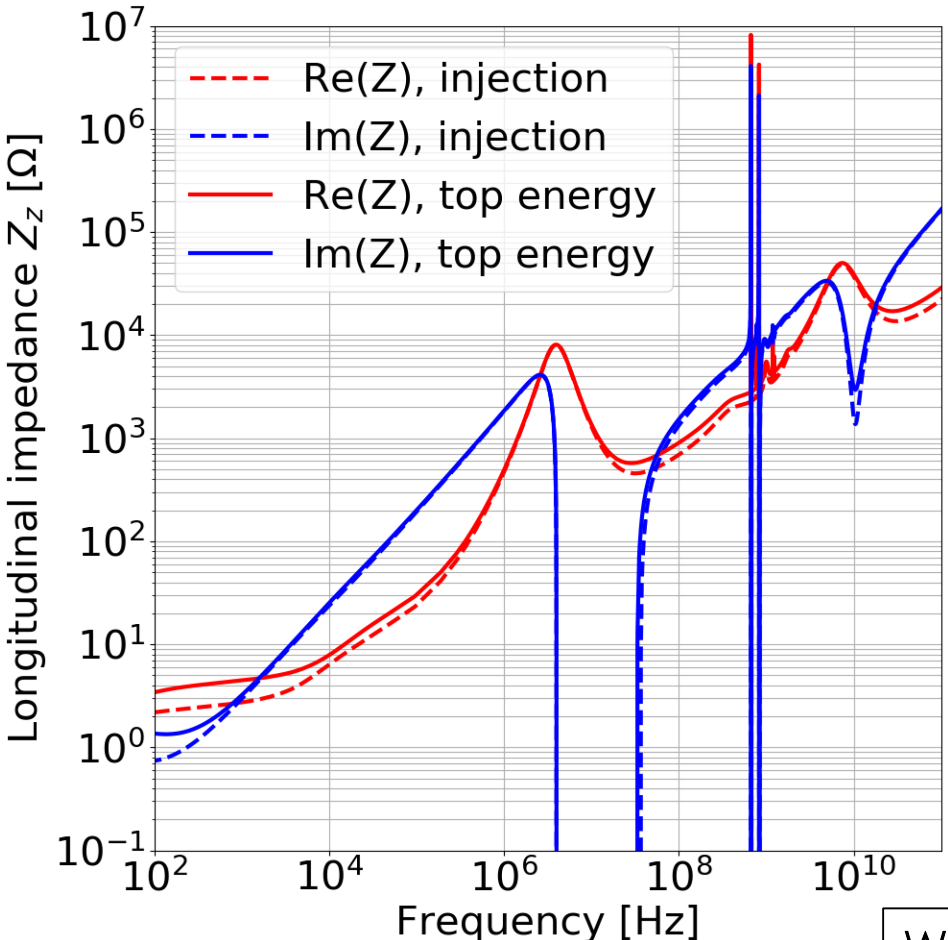
Single bunch effective impedance in the horizontal plane

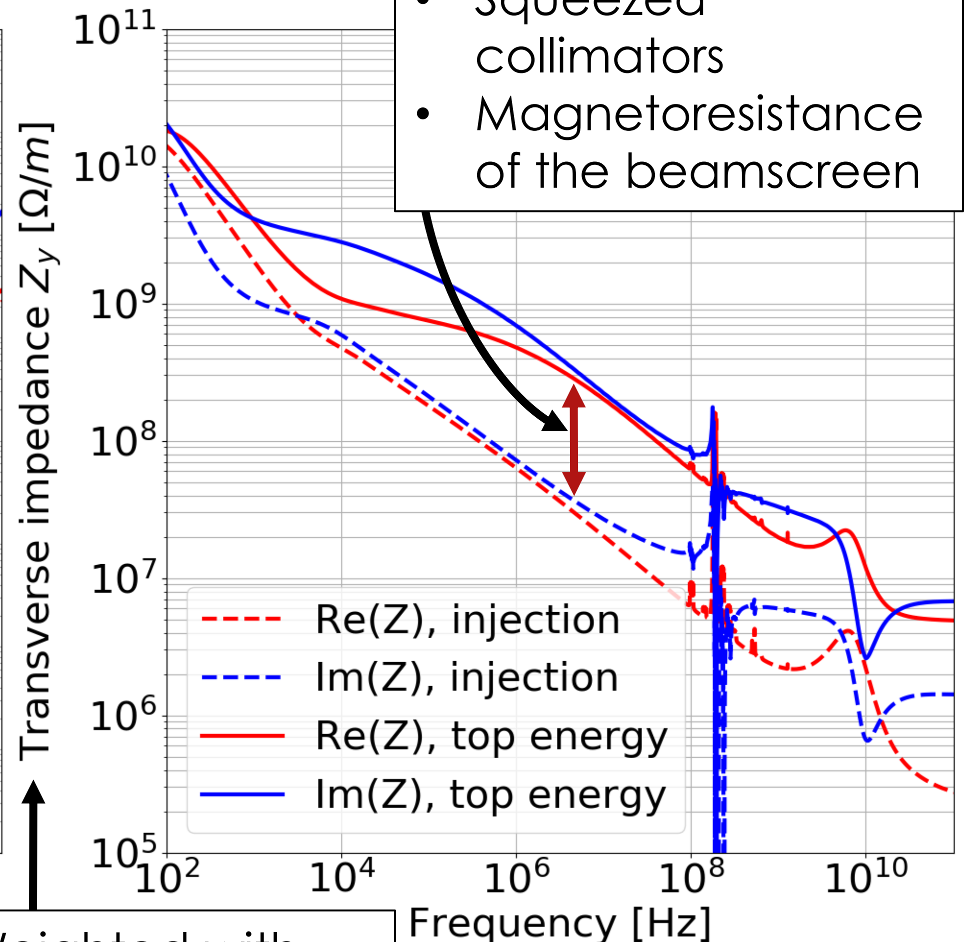
$$Im\left(Z_{SB}^{eff}\right) = 1.6\ M\Omega/m$$

What is the present state of the impedance model?

Total FCC-hh impedance as of June 2019

Impedance is higher at top energy due to
- Squeezed collimators
- Magnetoresistance of the beamscreen





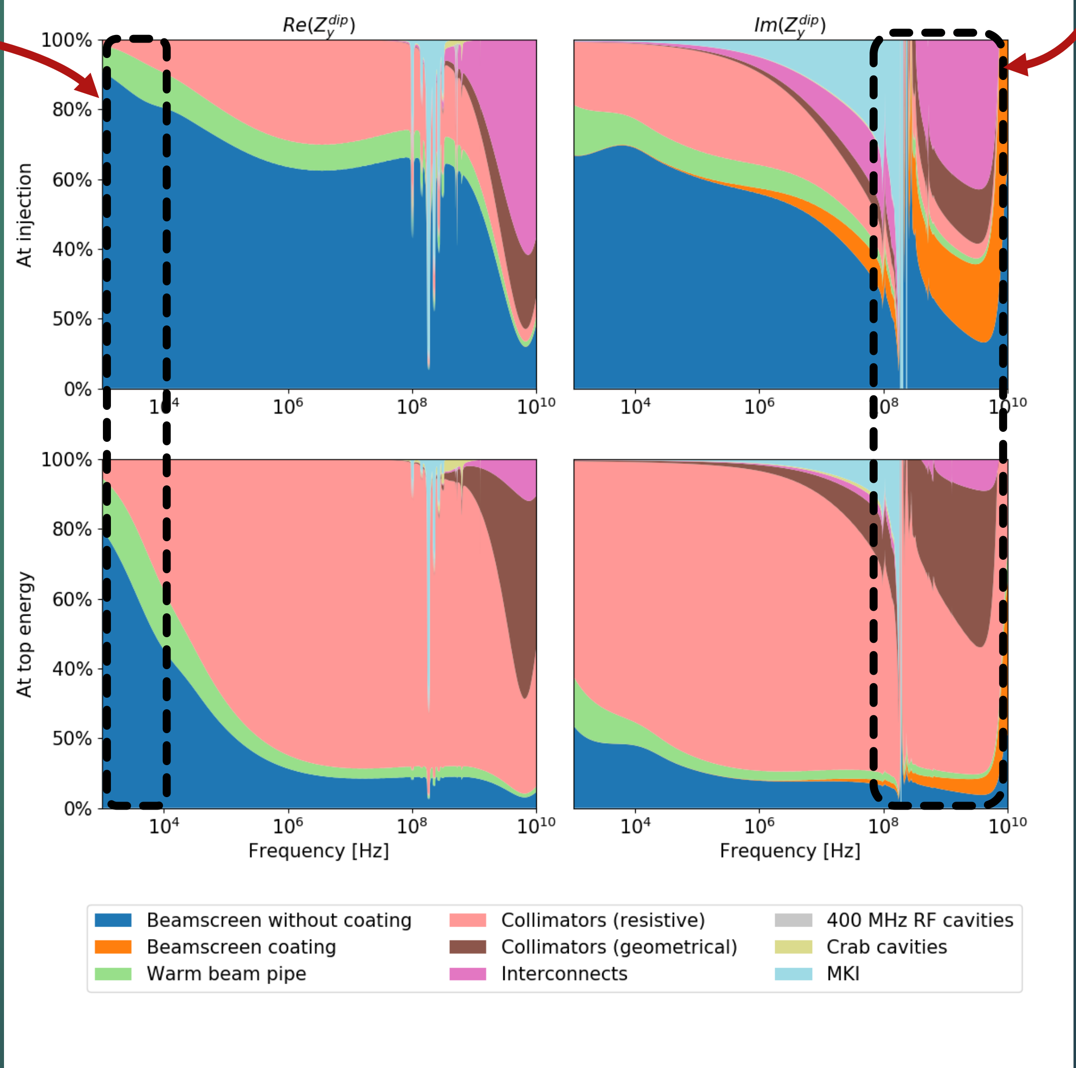
Weighted with the local β-function

Last update: May 2019

Distribution of dipolar impedance by elements

Frequencies important to single bunch instabilities

Frequencies important to coupled bunch instabilities



Coupled bunch instability is always dominated by the resistive wall impedance of the beamscreen

Single bunch instabilities are dominated by

- At injection: res wall BS, BS coating, collimators, interconnects, MKI
- At top energy: Collimators

Effective Sacherer impedances

	Current value at injection	Max allowed at injection	Current value at top energy	Max allowed at top energy
$\left[\frac{ImZ_{\|\|}}{n}\right]^{eff}_{Landau}$	29.3 mΩ	200 mΩ	31.3 mΩ	200 mΩ
$[ReZ_{\perp}]^{eff}_{CB}$	−1080 MΩ	−1360 MΩ	−2290 MΩ	−2740 MΩ
$[ImZ_{\perp}]^{eff}_{SB}$	9.9 MΩ	11.6 MΩ	65.4 MΩ	74.0 MΩ

See presentation by I. Karpov → $\left[\frac{ImZ_{\|\|}}{n}\right]^{eff}_{Landau}$

Definition for the max allowed values:

CB instability growth rate →

$$n_{turns} = -\frac{8\sqrt{\pi}EQ}{e^2 N_b Mc \times Re(Z^{eff}_{CB})} = \begin{cases} 3 \times 20\ turns\ at\ injection \\ 3 \times 150\ turns\ at\ top\ energy \end{cases}$$

TMCI threshold →

$$N_b^{th} = \alpha \frac{4\pi E \tau_b Q_s Q}{e^2 c \times Im(Z^{eff}_{SB})} = 3 \times 10^{11}$$

Safety factor (→ the factors 3)

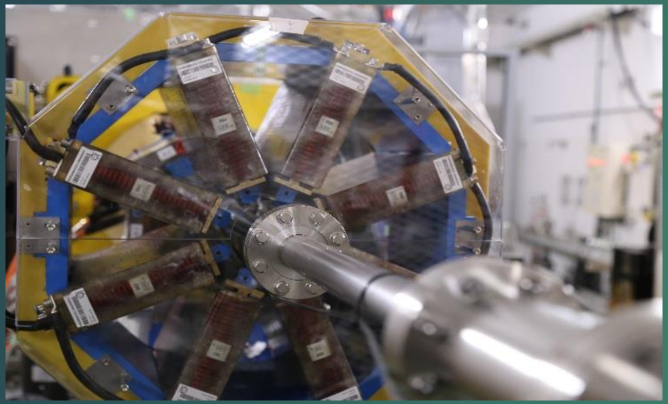
Part 2: single beam stability*

Done with the previous version of the impedance model, although the difference is marginal (MKI and new collimator gaps)

* For stability with the beam-beam effects, see the talk by Tatiana Pieloni

Simulated stabilization scheme

Landau octupoles

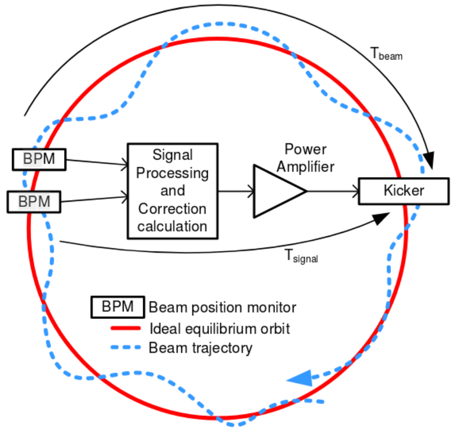


Parameter	LHC top energy	FCC injection/top energy
Gradient O_3 / (T/m^{-3})	63100	200 000
Length L_{oct} / (m)	0.32	0.5
Numb. of oct. N_{oct}	168	480
β_{yD} / (m)	175.5	352
β_{yF} / (m)	30.1	64
Emittance ϵ_{norm} / (m)	3.75	2.2
Max. current I_{max} / (A)	550	720
Nominal current I / (A)	500	15 / 720

Stabilizing effect:

$$max(Im(\Delta Q_y)_{stable}) \propto \underbrace{(\beta_{yF}^2 + \beta_{yD}^2)\frac{\epsilon_{norm}}{\gamma^2}}_{\text{Effectiveness}} \cdot \underbrace{O_3 \frac{I}{I_{max}} L_{oct} N_{oct}}_{\text{Strength}}$$

Transverse feedback (damper)



Damper type:

- Bunch by bunch (gain independent of CB number)
- Not high-bandwidth (equal kick to all particles in a bunch)

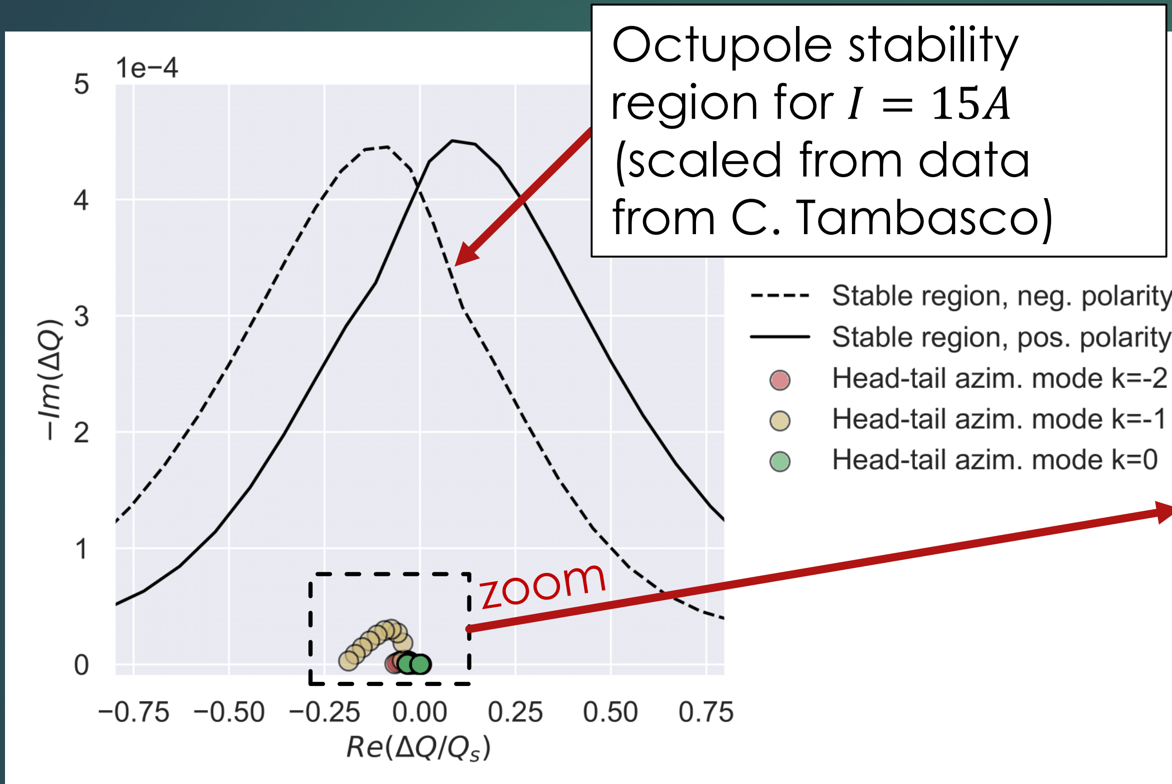
Phase: resistive

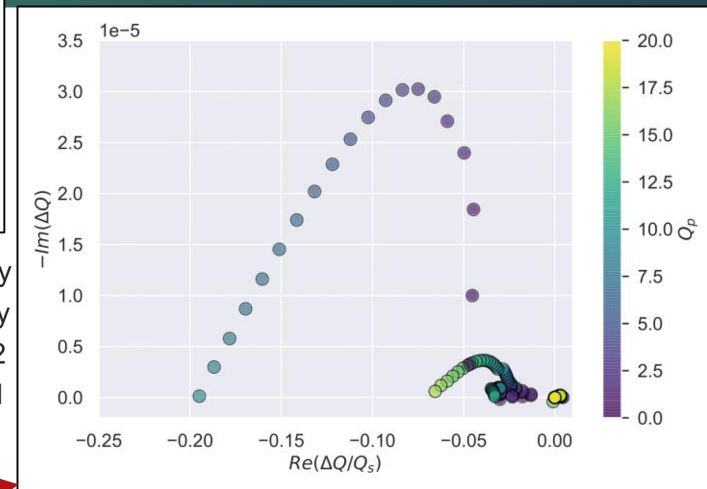
Damping rate at injection:
65 turns ≈ 3 × 20 turns

Damping rate at flat top:
460 turns ≈ 3 × 150 turns

Feedback capability requirement

Stability diagram at injection

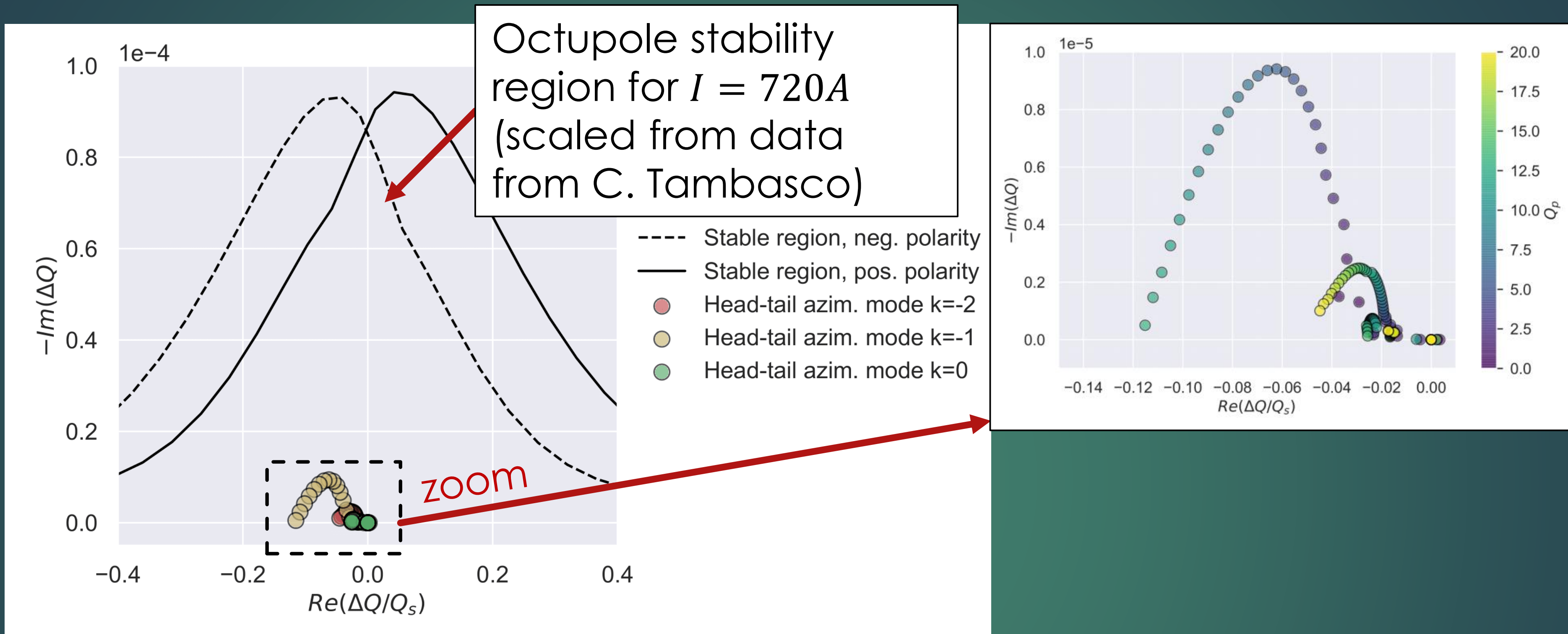




Results of multi-bunch DELPHI simulation (13068 bunches). Y-plane (most critical). Chromaticity range $0 < Q_p < 20$, 65 turns feedback gain.

Even for the weakest feedback capable of fully suppressing the rigid bunch mode (65 turns), all $|k| \geq 1$ modes lie factor of 4 below the octupoles stability curve.

Stability diagram at top energy



Results of multi-bunch DELPHI simulation (13068 bunches). Y-plane (most critical). Chromaticity range $0 < Q_p < 20$, 460 turns feedback gain.

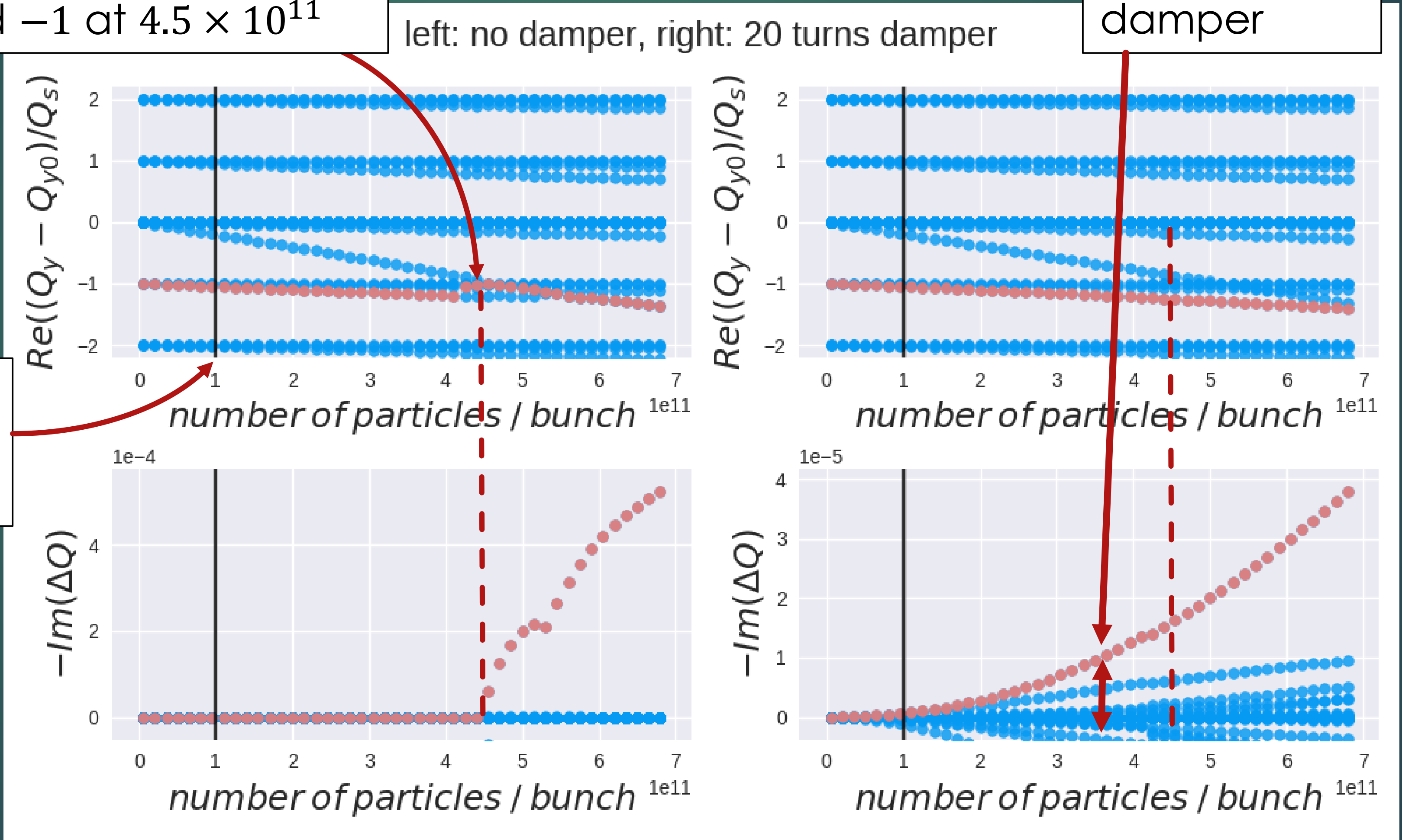
Even for the weakest feedback capable of fully suppressing the rigid bunch mode (460 turns), all $|k| \geq 1$ modes lie factor of 4 below the octupoles stability curve.

TMCI at injection

TMCI happens between modes 0 and -1 at 4.5×10^{11}

Destabilizing effect of a resistive damper

Nominal bunch intensity



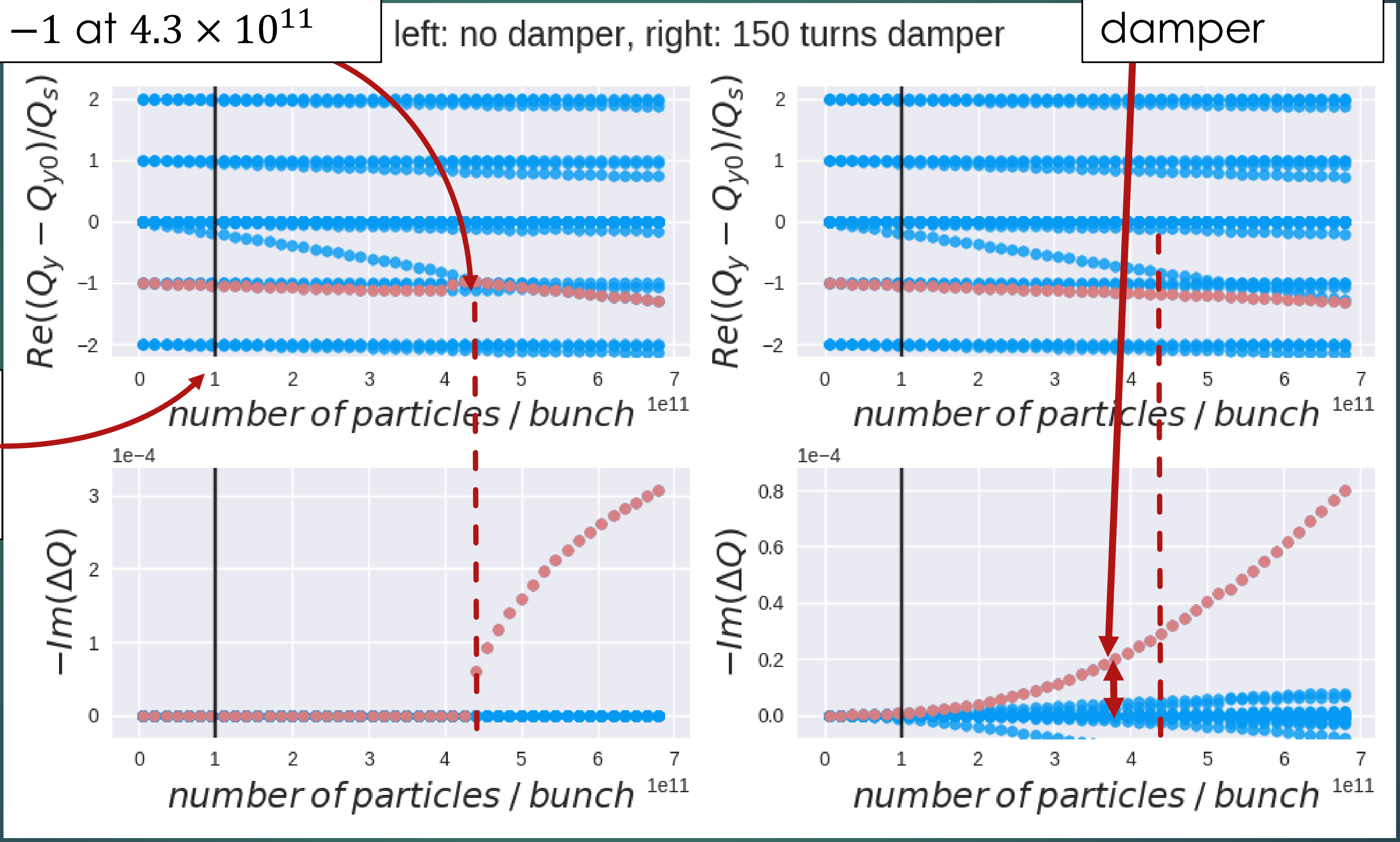
Results of DELPHI simulation (1 bunch). Y-plane (most critical). Chromaticity = 0.

TMCI at top energy

TMCI happens between modes 0 and −1 at 4.3×10^{11}

Destabilizing effect of a resistive damper

Nominal bunch intensity



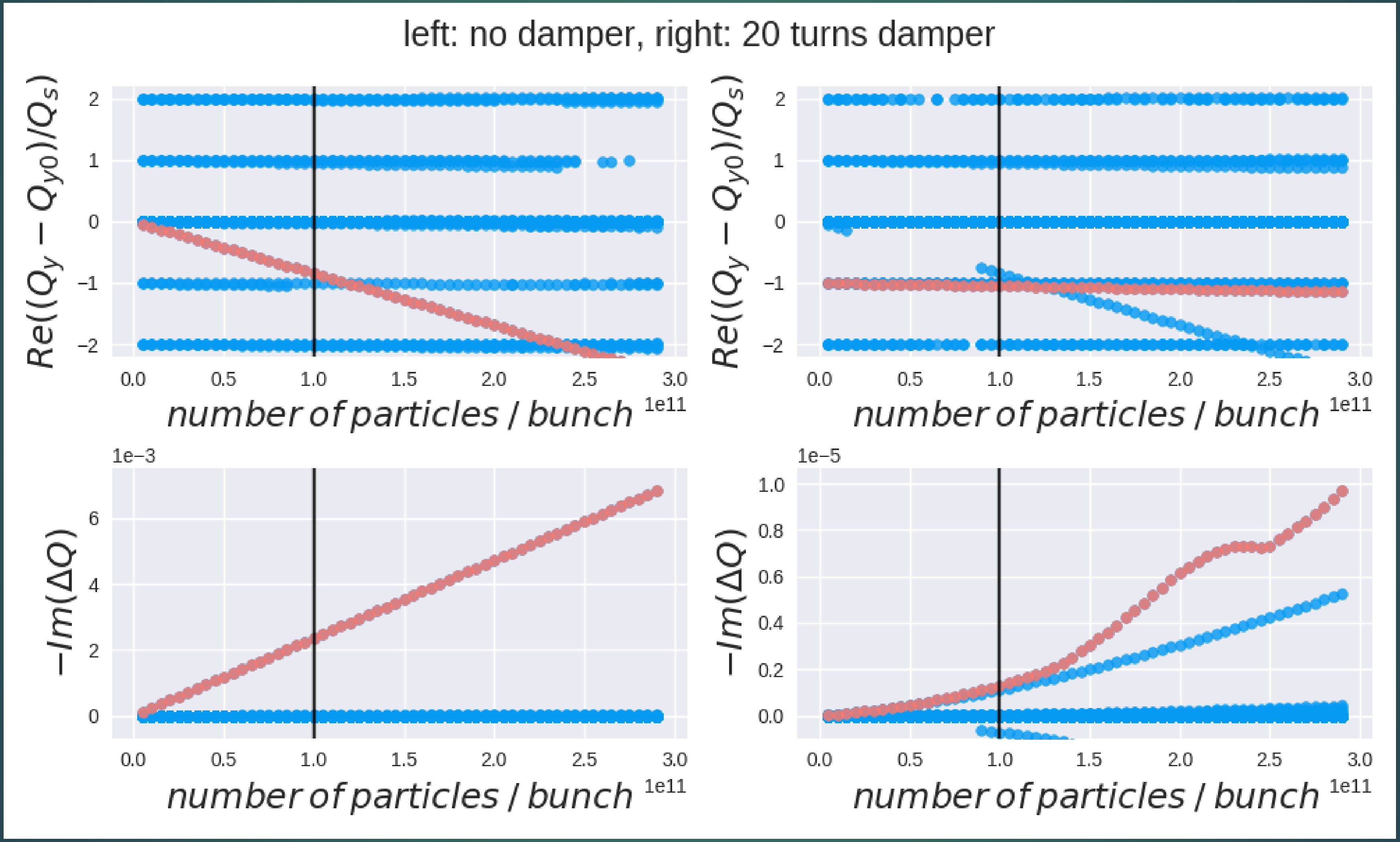
Results of DELPHI simulation (1 bunch). Y-plane (most critical). Chromaticity = 0.

Conclusions

- Increase in impedance due to 12.22 mm beamscreen aperture is accepted
- HOMs in crab cavities are better damped
- Laser treatment of beamscreen is not yet accepted due to the unknown impedance, but active research is going on
- The “stainless steel edge” issue in the beamscreen is investigated and solutions are proposed
- MKI impedance is calculated
- Laser treatment of beamscreen is not yet accepted due to the unknown impedance, but active research is going on
- Number of octupoles is sufficient with a safety margin of more than 3
- Feedback damping rate 20 turns / 150 turns is sufficient at injection / flat top with a safety factor of 3
- Single bunch mode coupling instability threshold is more than 3 times higher than the bunch intensity

Back-up slides

Multibunch TMCI (injection)



Multibunch TMCI (top energy)