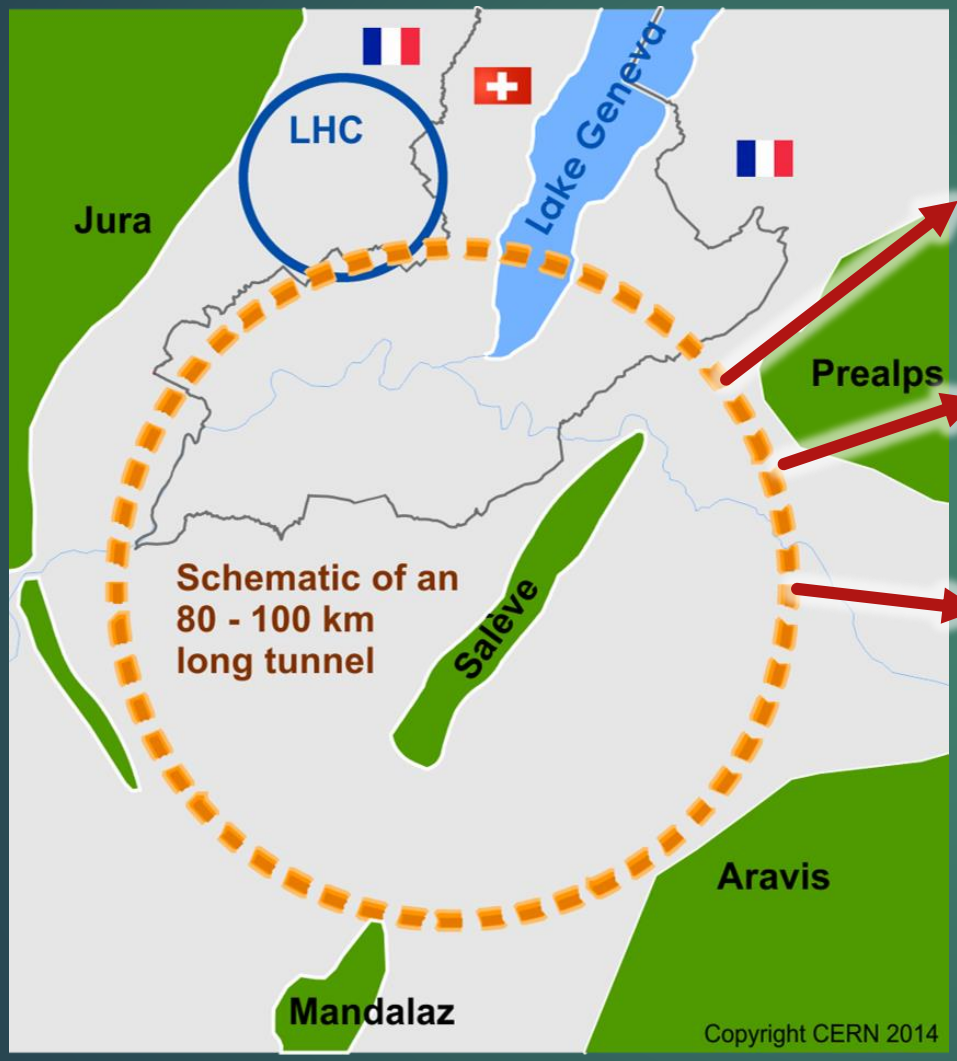
Low-impedance beam screen design for future colliders

SERGEY ARSENYEV

MINI-WORKSHOP ON MITIGATION OF COHERENT BEAM INSTABILITIES IN PARTICLE ACCELERATORS (MCBI 2019)

ZERMATT, SWITZERLAND

Future Circular Collider study



FCC-ee (electron-positron collider)

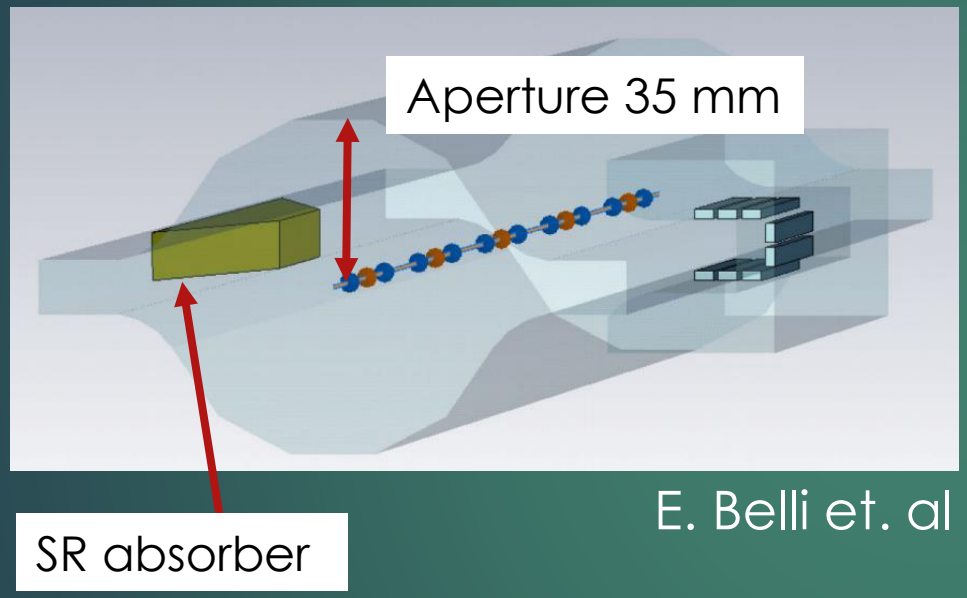
FCC-hh (hadron-hadron collider)

FCC-eh (electron-hadron collider)

Conceptual design report published in 2018: https://fcc-cdr.web.cern.ch/

Beam screens in future colliders

FCC-ee

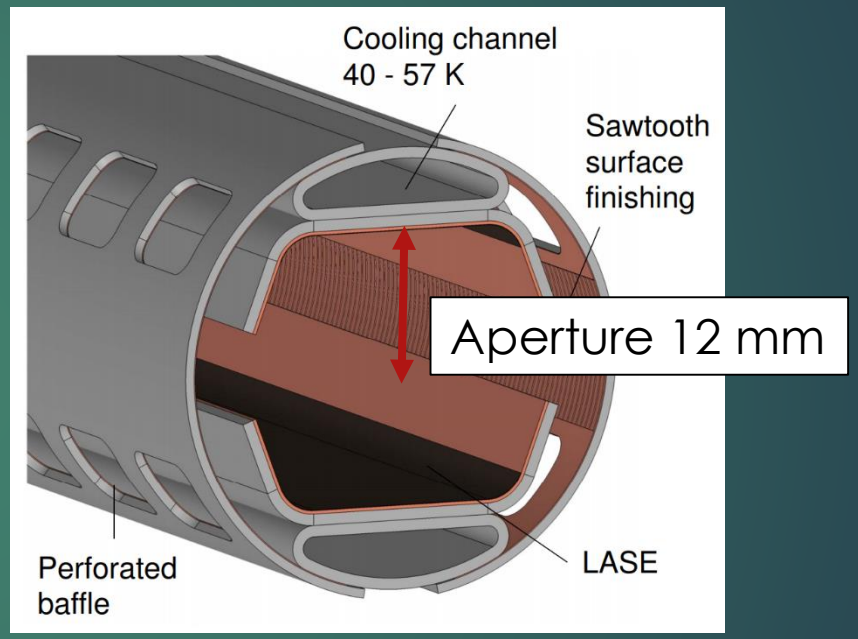


E. Belli et. al

Main impedance issues:

- Resistive wall impedance
- SR absorbers
- NEG coating

FCC-hh



Main impedance issues:

- Resistive wall impedance
- Pumping holes
- AC coating or laser treatment

FCC-hh beamscreen

Prototype tested at Karlsruhe Light Source KARA to simulate the level of SR

In comparison to the LHC, FCC-hh has:

- 7 times the LHC collision energy
- 17 times the LHC luminosity
- 20 times the LHC stored beam energy
- 200 times the LHC synchrotron radiation

Impedance estimation effort for the FCC-hh beamscreen

Daniel Schulte
Nicolas Mounet
Xavier Buffat
Sergey Arsenyev
Sergio Calatroni
Kristof Brunner

Bernard Riemann

CERN

technische universität dortmund

TECHNISCHE UNIVERSITÄT DARMSTADT

GSI

Oliver Boine-Frankenheim
Uwe Niedermayer
Patrick Krkotic
Daria Astapovych

Vladimir Kornilov

Impedance of the FCC-hh beam screen is a critical point of the design

- Low aperture to reduce magnet cost
- High surface temperature (50K) to extract the heat from SR
- Large pumping holes for high vacuum
- Surface coating (or treatment) for e-cloud suppression

→ Higher impedance

Consequences of beamscreen impedance

Approximate expressions for resistive-wall impedance

$$Z_{||} = (1+i)\frac{L}{2\pi b}\sqrt{\frac{\mu_0 \omega}{2\sigma}}$$

$$Z_{\perp} = (1+i)\frac{Lc}{\pi b^3}\sqrt{\frac{\mu_0}{2\sigma\omega}}$$

Cubic dependence makes transverse effects more critical

Transverse coupled-bunch instability (TCBI)

$$n_{turns}^{-1} \propto \frac{N_b \beta_{avg}}{\gamma \Delta s} \mathrm{Re}\left(Z_{\perp}(f_{\mathrm{CB}})\right)$$

Transverse head-tail instability

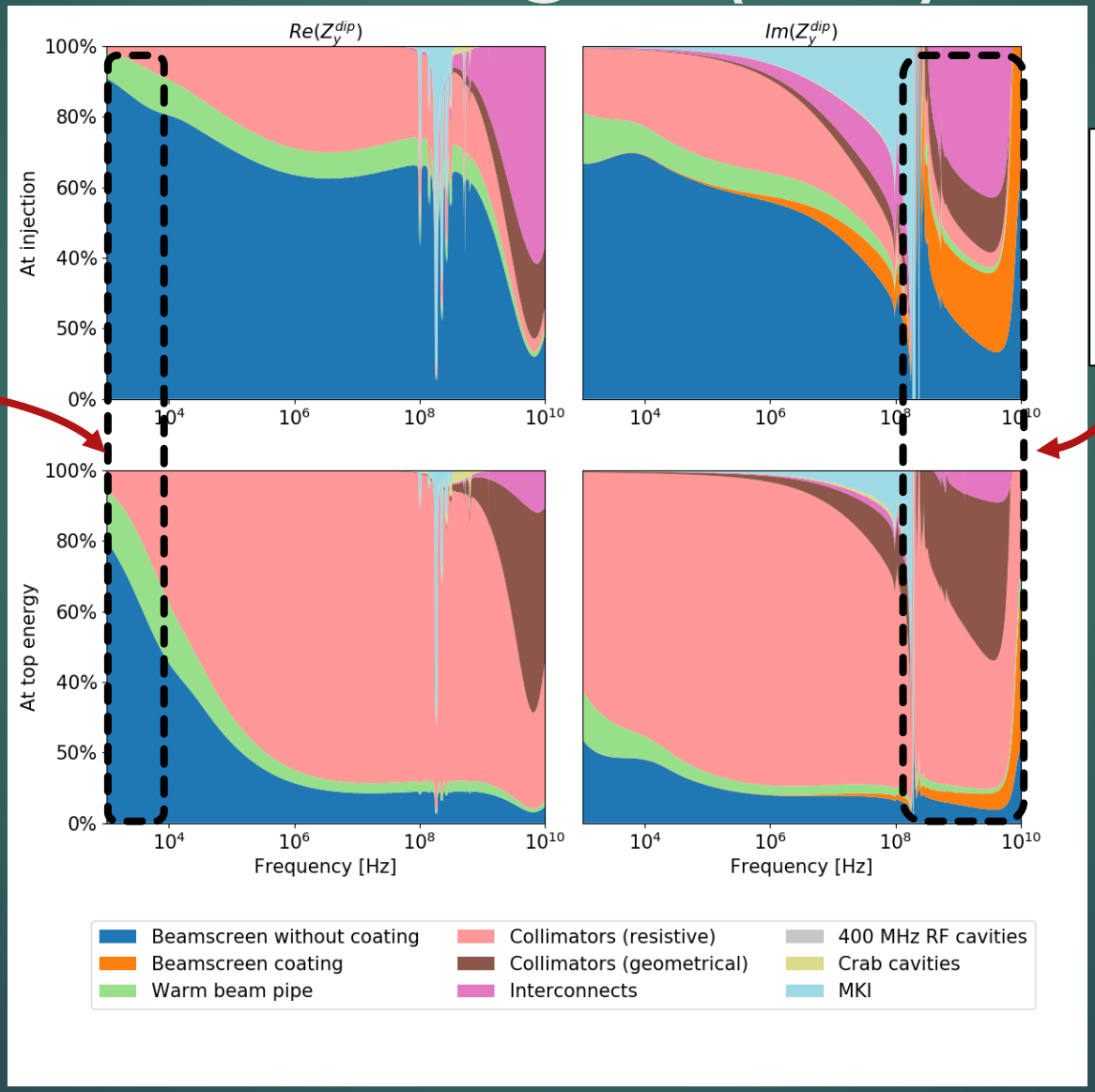
$$n_{turns}^{-1} \propto \frac{N_b \beta_{avg}}{\gamma \tau_b} \mathrm{Re}\left(Z_{\perp}(f_{\mathrm{SB}})\right)$$

Transverse mode-coupling instability

$$N_b / N_b^{th} \propto \frac{N_b \beta_{avg}}{\gamma \tau_b Q_s} \mathrm{Im}\left(Z_{\perp}(f_{\mathrm{SB}})\right)$$

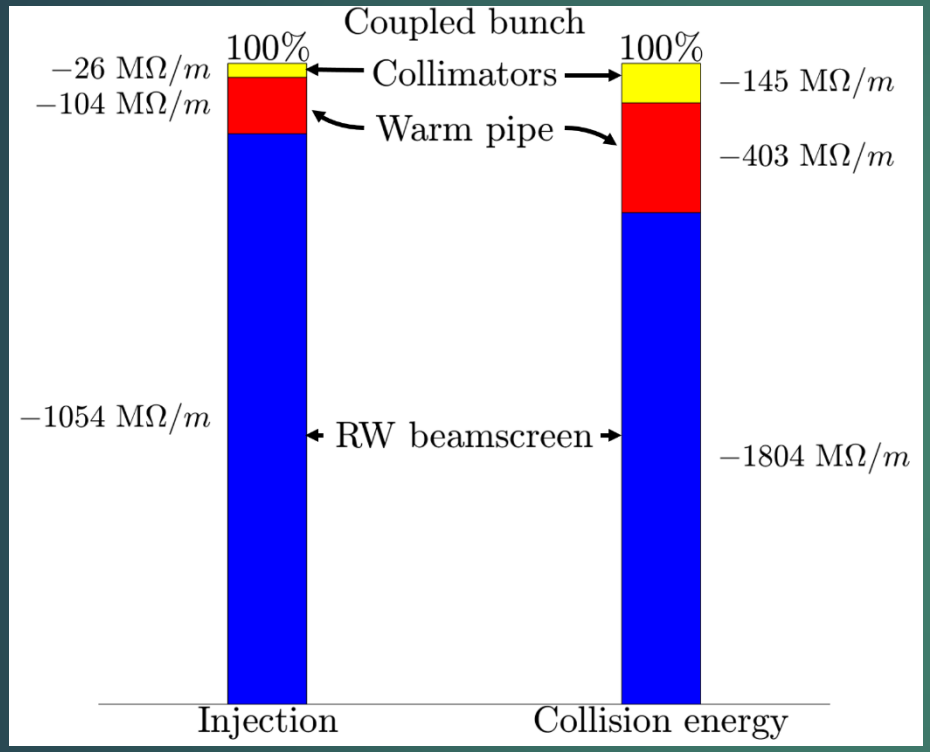
Role of the beamscreen in impedance budget (1/2)

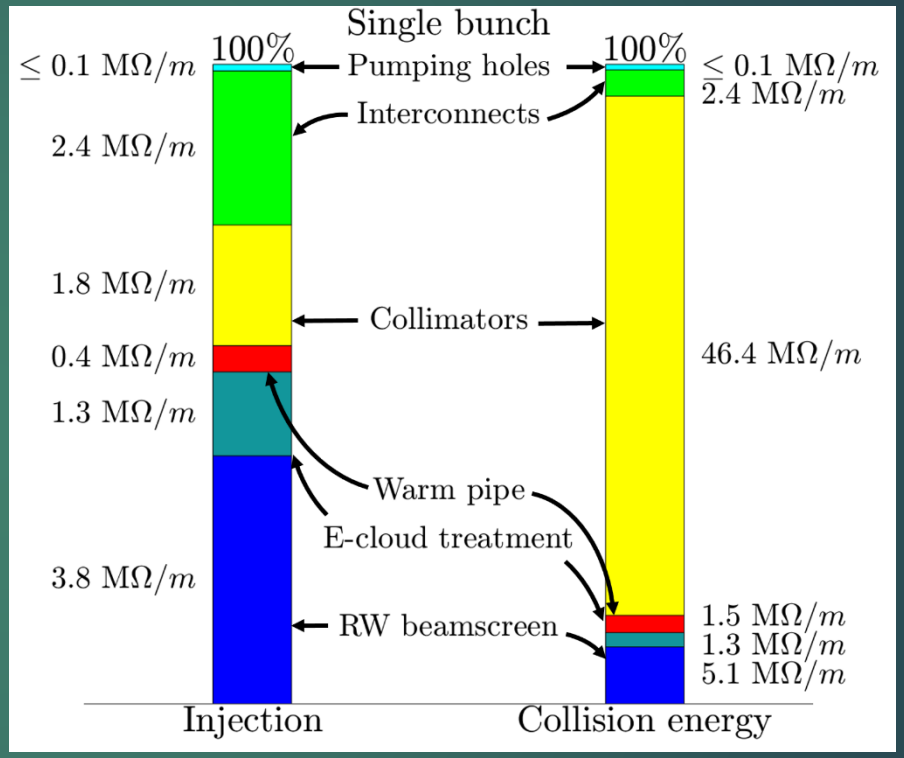
Frequencies important to coupled bunch instabilities



Frequencies important to single bunch instabilities

Role of the beamscreen in impedance budget (2/2)





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

Single bunch instabilities are dominated by

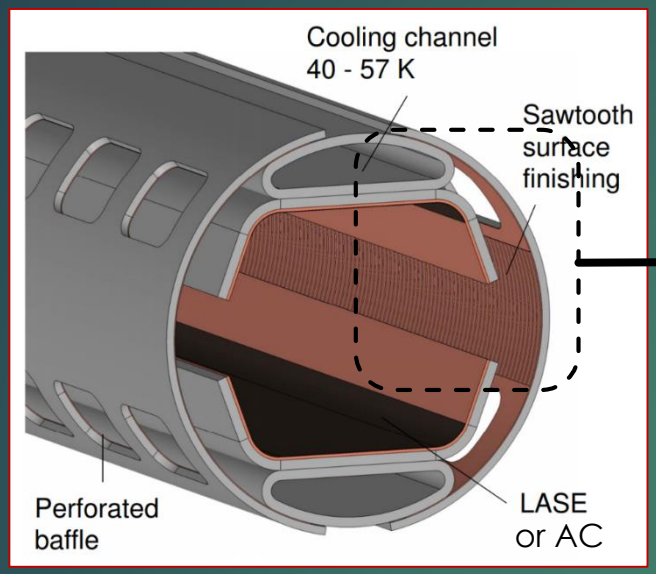
- At injection: res wall BS, BS coating, collimators, interconnects, MKI
- At top energy: Collimators

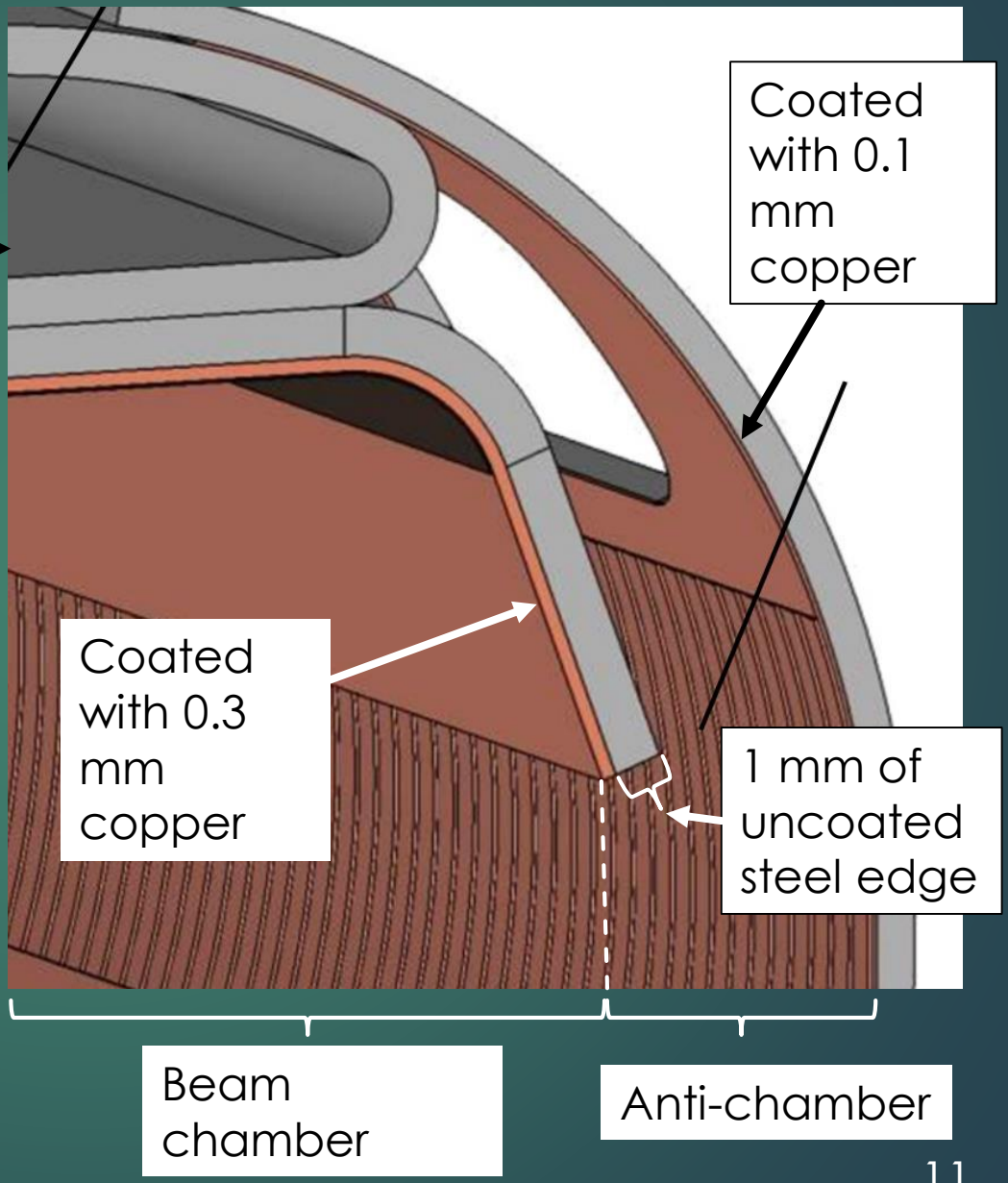
Conclusion 1

Beam screen is increasingly more important in future colliders.

In FCC-hh, it overshadows the collimators as the main source of impedance.

Resistive wall impedance (1/3)





Stainless steel is ~1000 times more resistive than copper:

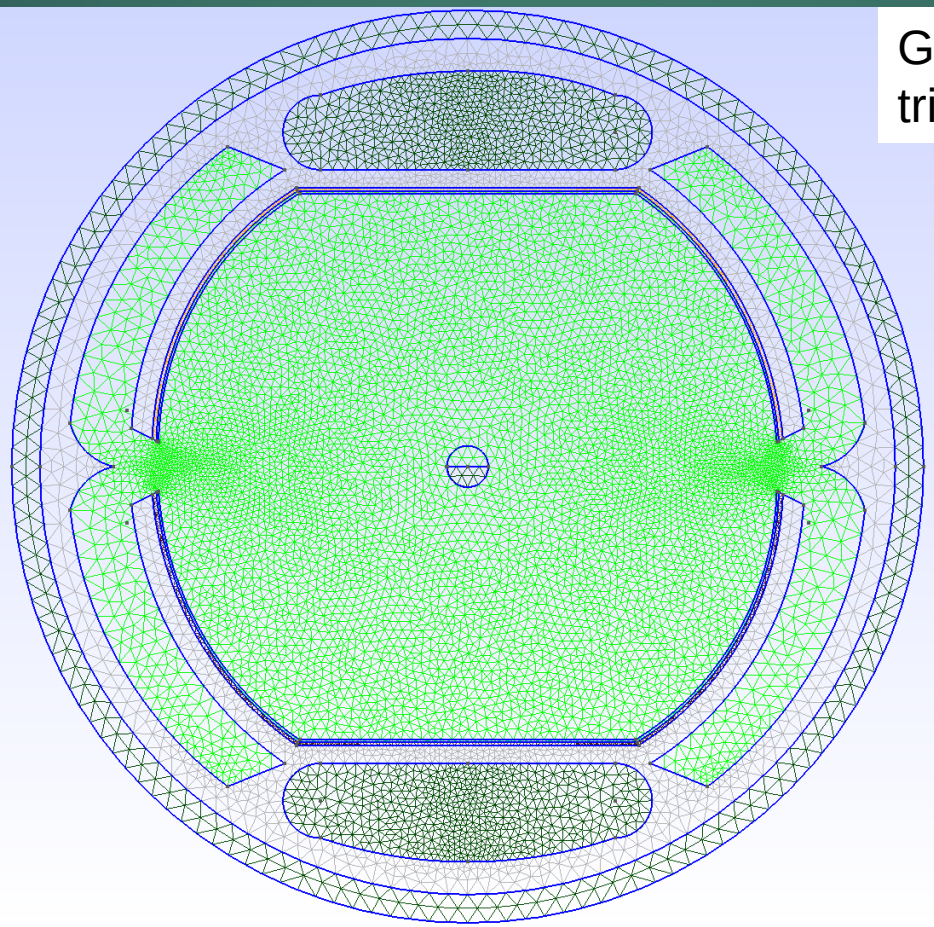
$$\rho_{copper}(50K, 1.06T) = 7.88 \times 10^{-10}\ \Omega m$$

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

Resistive wall impedance (2/3)

A 2D resistive wall solver is ideal for this problem

BI2D implementation for the FCC-hh beamscreen



GMSH (Geuzaine et al.) triangular mesh

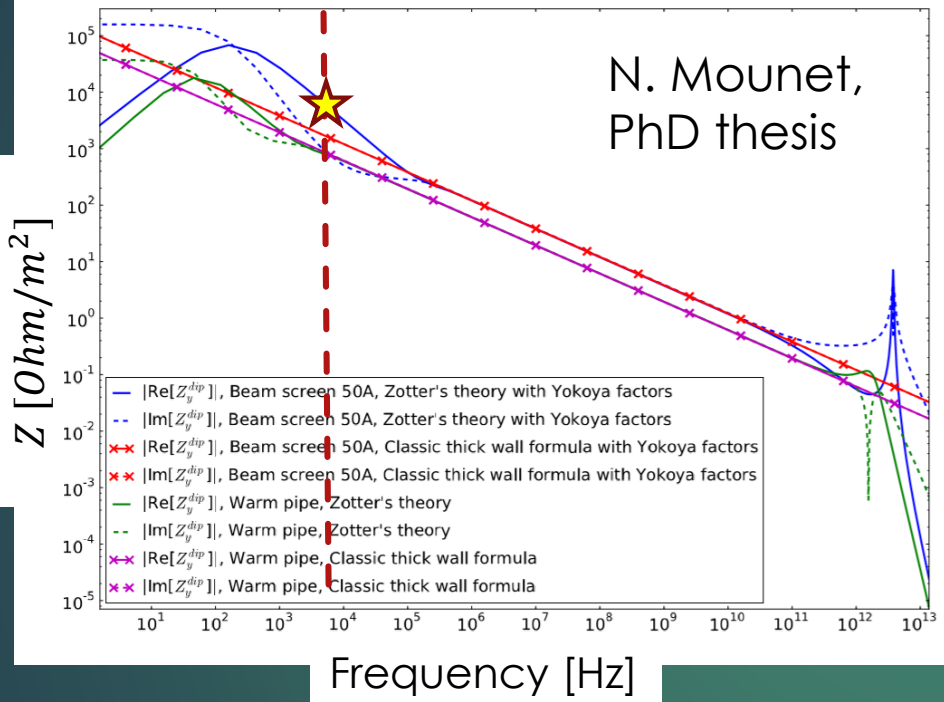
Meshing the whole structure is required only for extremely low frequency!

Otherwise: **S**urface **I**mpedance **B**oundary **C**ondition (SIBC)

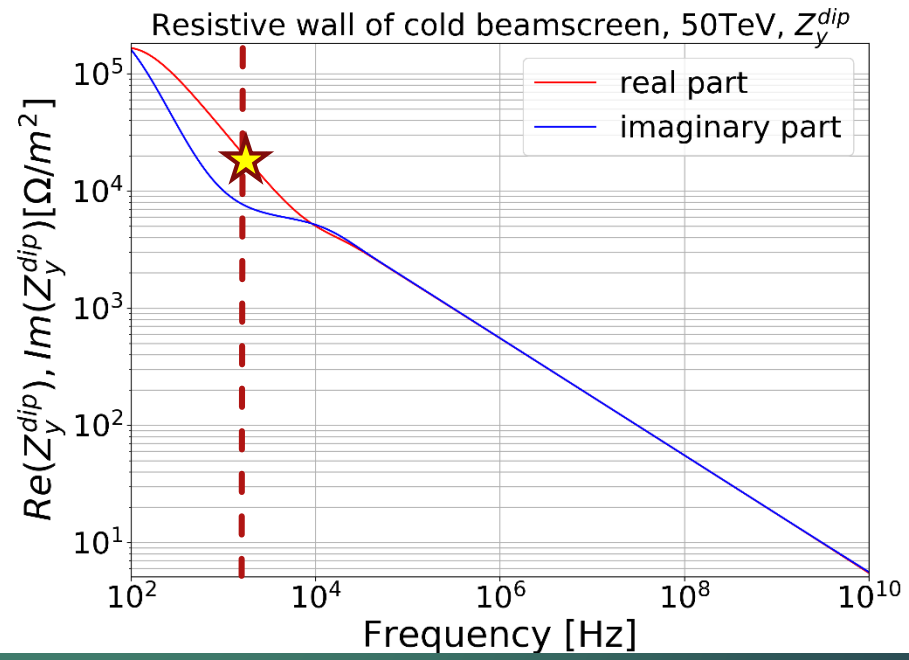
BI2D: code by Uwe Niedermayer, TU Darmstadt

Resistive wall impedance (3/3)

LHC RW impedance per unit length



FCC-hh RW impedance per unit length



$$Re\left(Z_y^{dip}(7.8\ kHz)\right) = 4 * 10^3 \Omega/m^2$$

$$Re\left(Z_y^{dip}(2.1\ kHz)\right) = 1.6 * 10^4 \Omega/m^2$$

Why is the effective impedance higher?

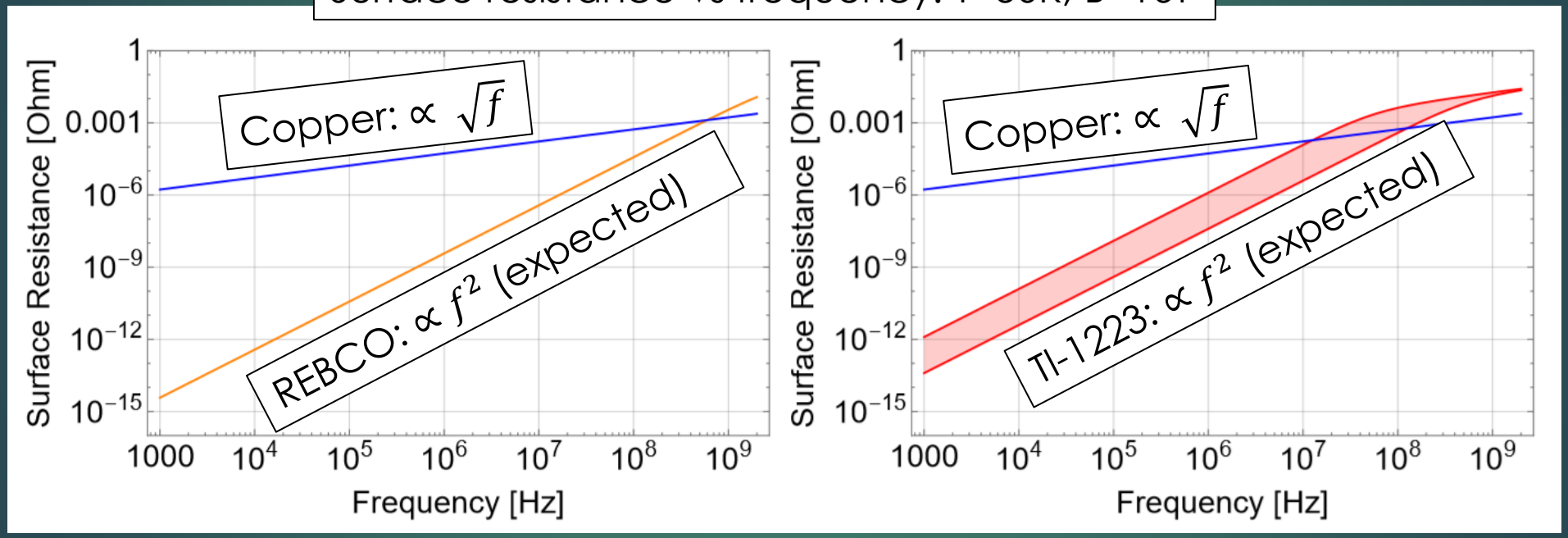
- Lower aperture
- Higher temperature
- Higher magnetic field (magnetoresistance)
- Lower revolution frequency

TCBI growth rate is expected to be 65 turns (injection) and 460 turns (top energy)

Alternative: HTS beamscreen (1/2)

The idea: coat inner beamscreen surface with a high-temperature superconductor.

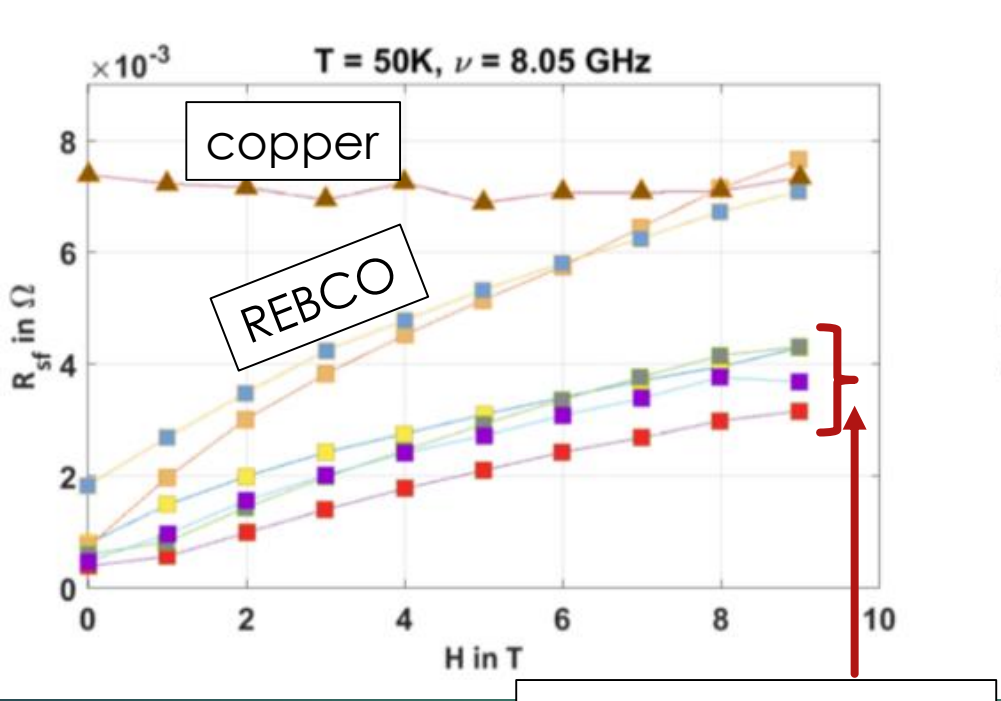
Surface resistance vs frequency: T=50K, B=16T

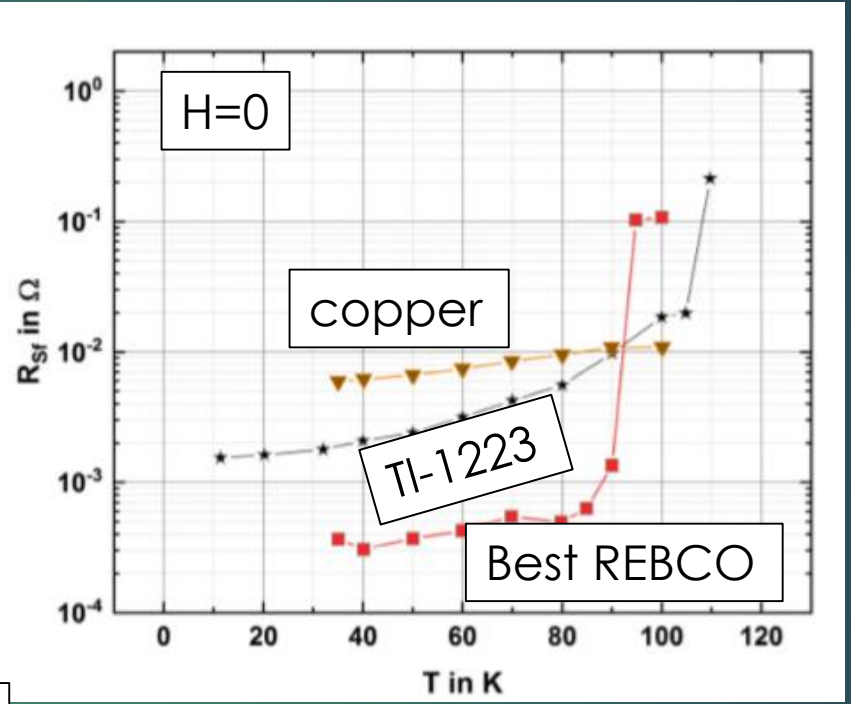


Expected dependencies of HTS surface resistance on frequency based on literature materials

Courtesy of Sergio Calatroni et. al.

Alternative: HTS beamscreen (2/2)





REBCO with artificial pinning centers

Courtesy of Patrick Krkotic, Sergio Calatroni et. al.

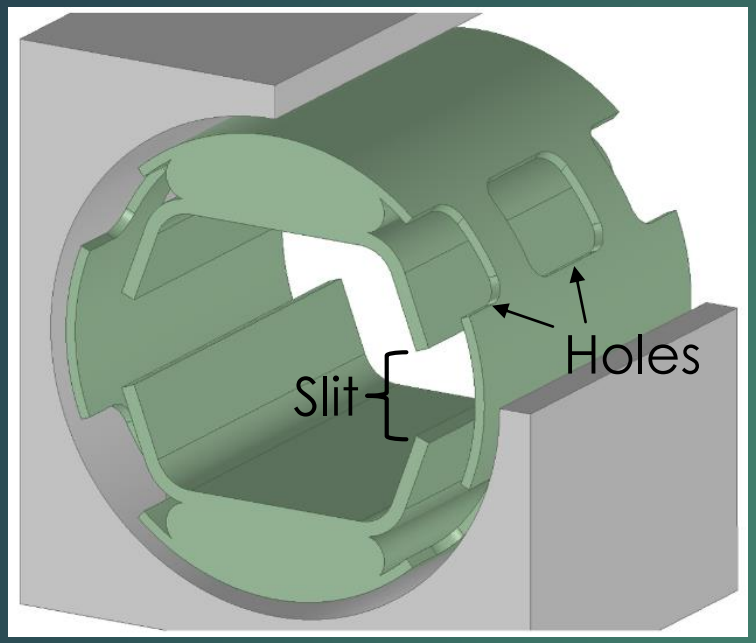
Very promising results, and further improvements are still possible.
Next steps: measurements at the needed frequency, temperature, magnetic field; mechanical analysis

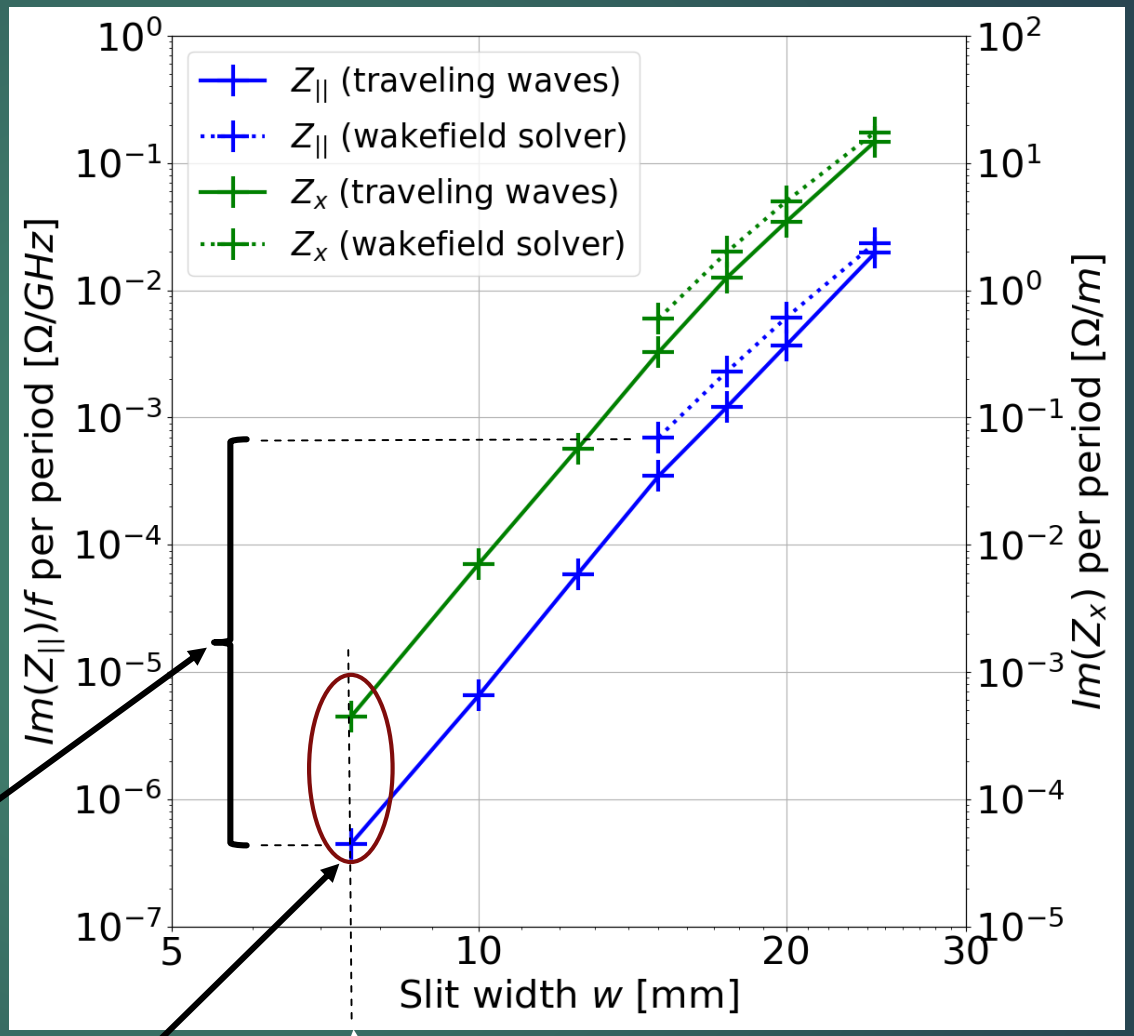
Conclusion 2

Resistive wall impedance of the beamscreen calls for faster transverse feedback.

Ideal-world solution: HTS beamscreen.

Pumping holes impedance (1/3)



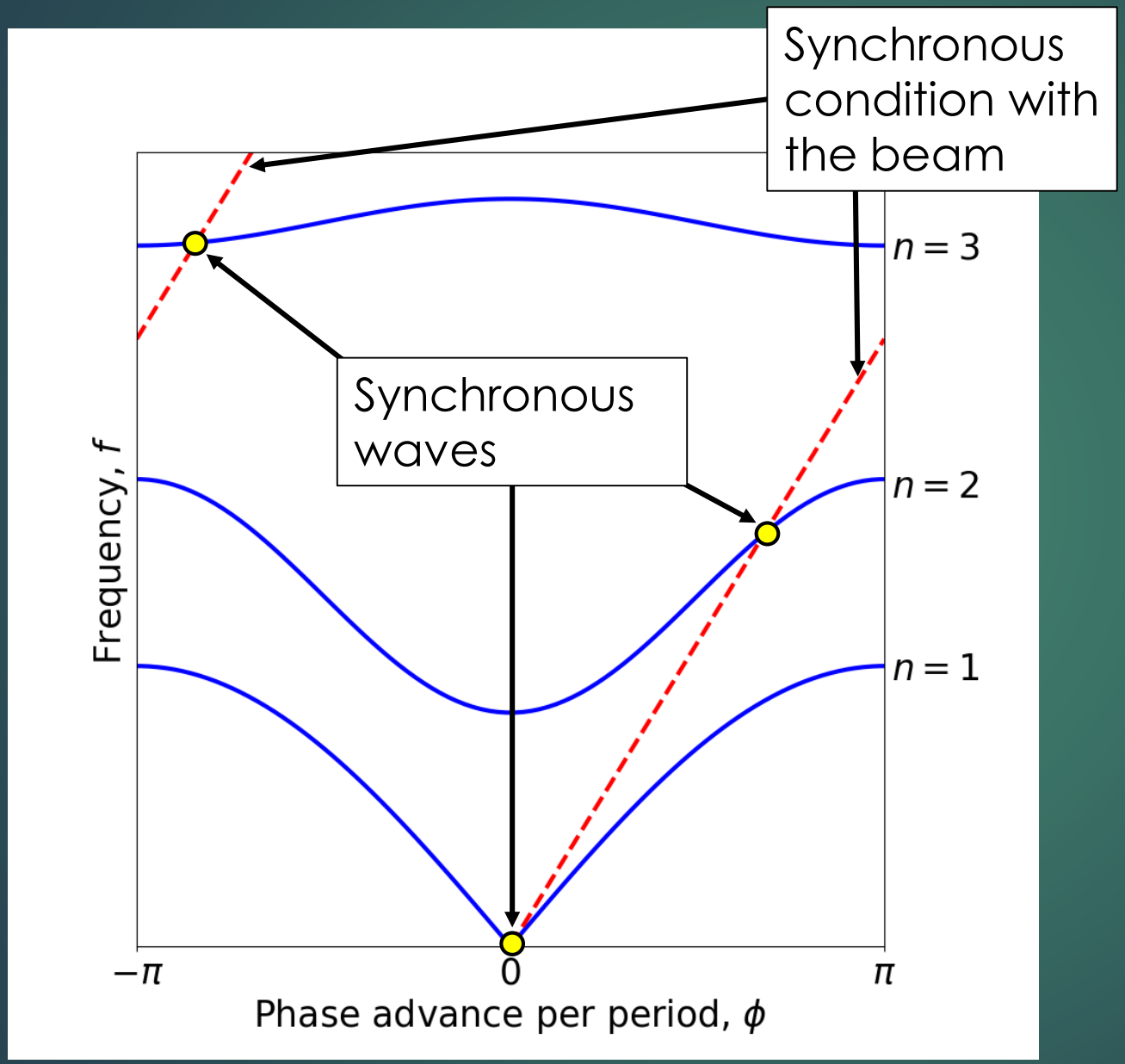


Three orders of magnitude better resolution

The final result

The actual slit width

Pumping holes impedance (2/3)



Pumping holes impedance (3/3)

Longitudinal impedance per period

Transverse impedance per period

$$\frac{Z_{||}(\omega)}{N} = i\omega \sum_n \alpha_n \frac{1}{\omega_n^{syn}} \left(\frac{R}{Q}\right)^{||}_{syn_n} + O(\omega^2)$$

$$\frac{Z_{\perp}(\omega)}{N} = i \sum_n \alpha_n \frac{\omega_n^{syn}}{c} \left(\frac{R}{Q}\right)^{\perp}_{syn_n} + O(\omega)$$

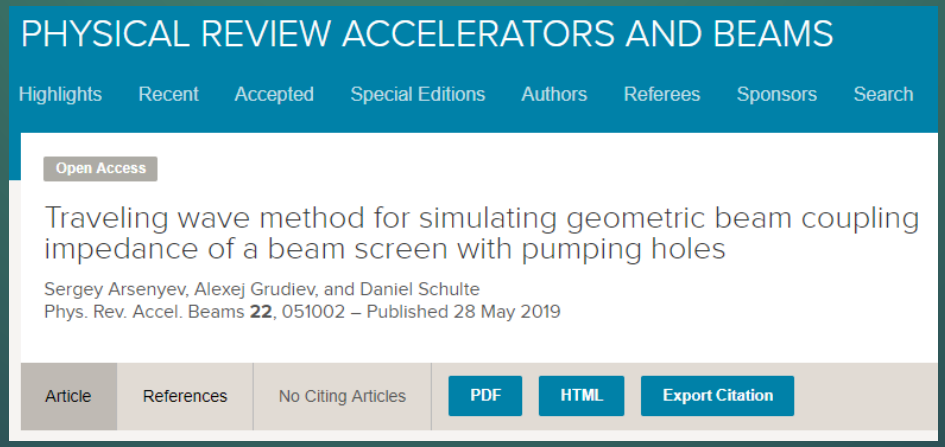
Shunt impedances of synchronous waves

The non-trivial part

Group-velocity corrections

$$\alpha(v_g) = \begin{cases} (1 - v_g/c)^{-1}, & \text{if } \omega_{syn} \neq 0 \\ (1 - v_g^2/c^2)^{-1}, & \text{if } \omega_{syn} = 0 \end{cases}$$

Paper for details:

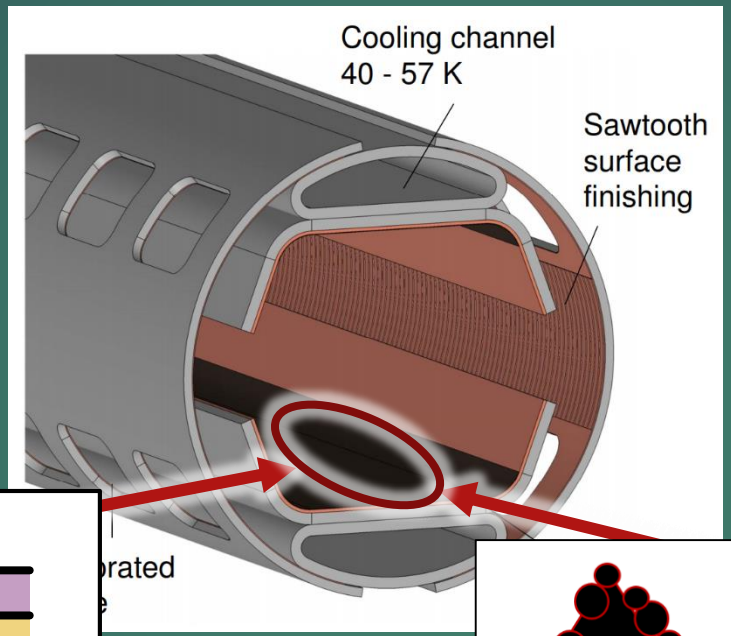


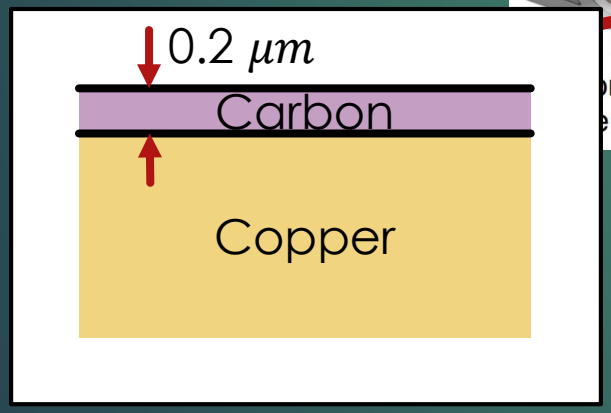
Conclusion 3

Pumping holes screening is very effective at reducing their impedance.

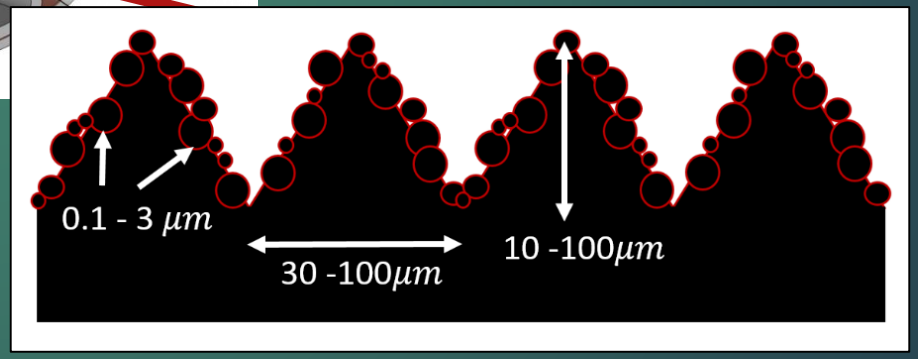
Proving that requires new methods in impedance calculation.

Surface treatment for e-cloud mitigation (1/5)





or



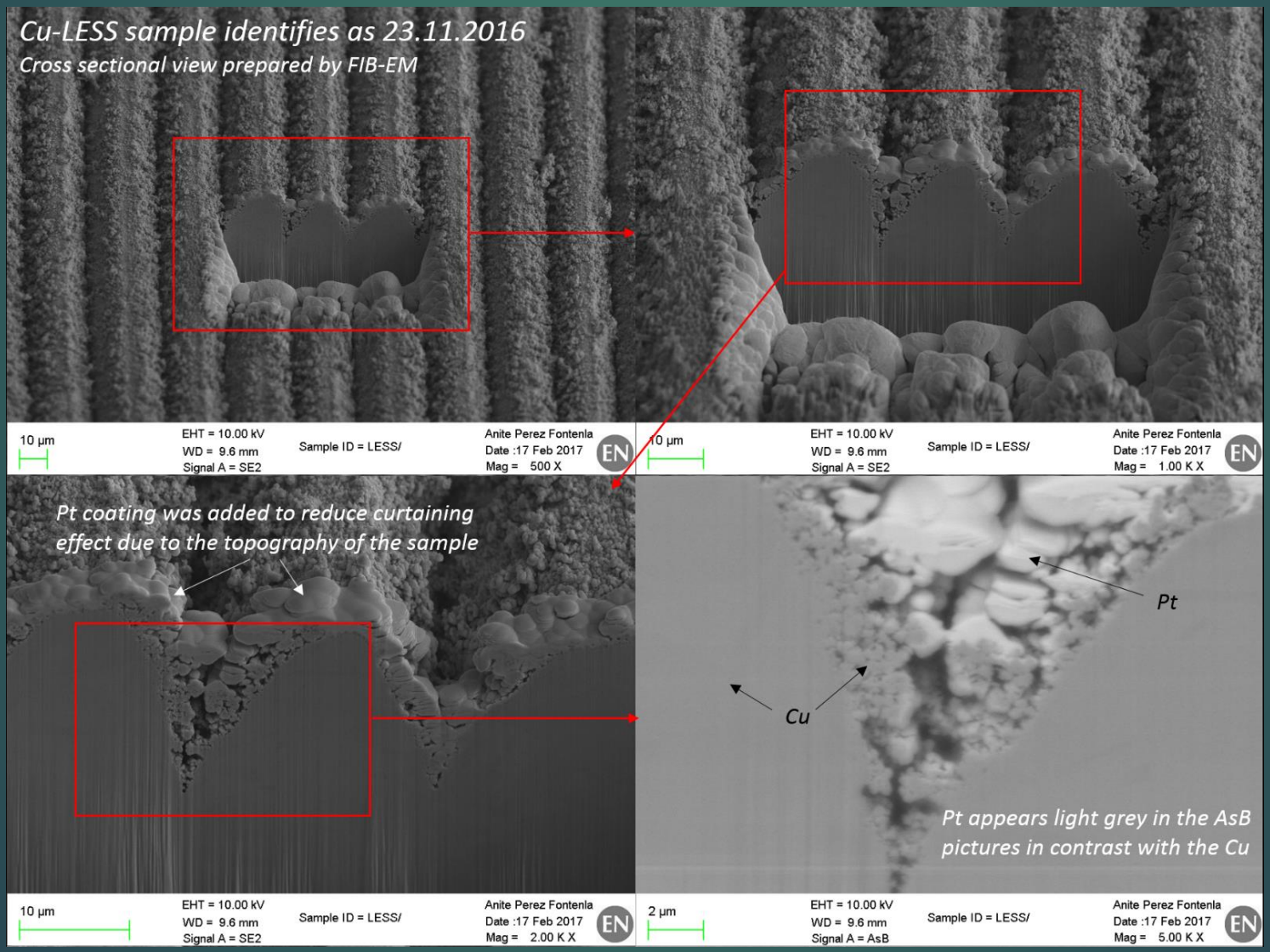
Amorphous carbon or TiN coating

~30% impedance increase at 1 GHz

Laser treatment

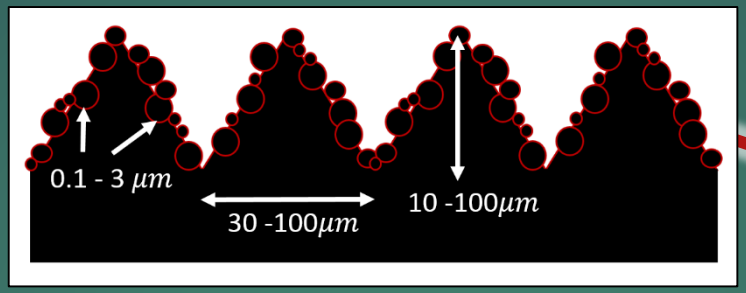
Impedance increase = ?

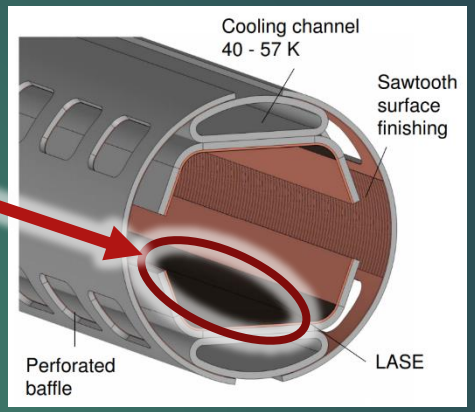
Surface treatment for e-cloud mitigation (2/5)

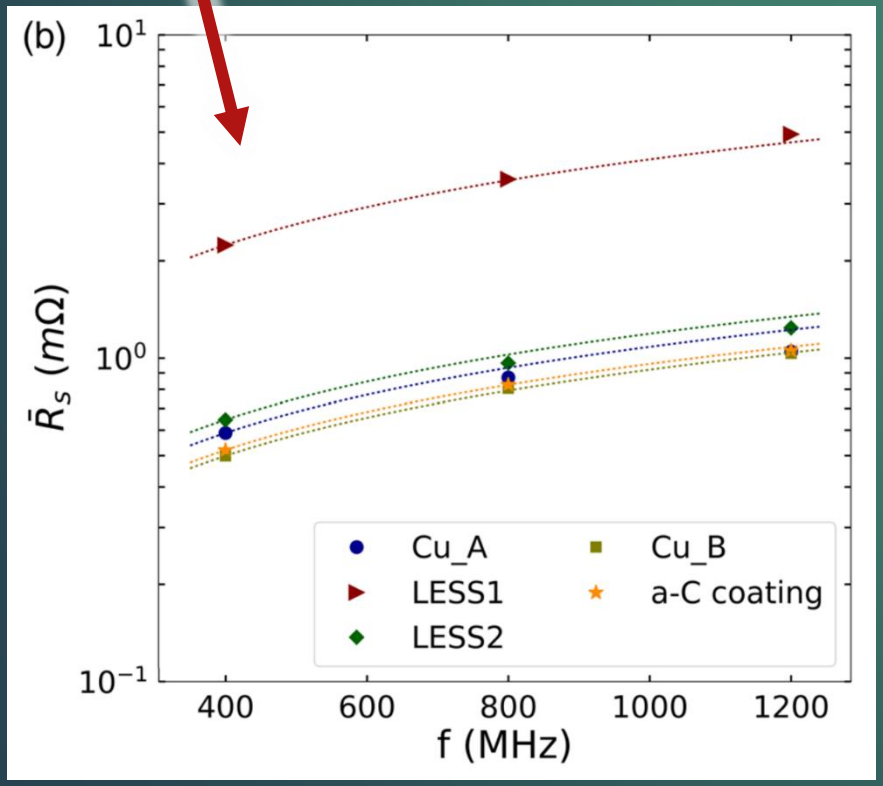


Surface treatment for e-cloud mitigation (3/5)

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

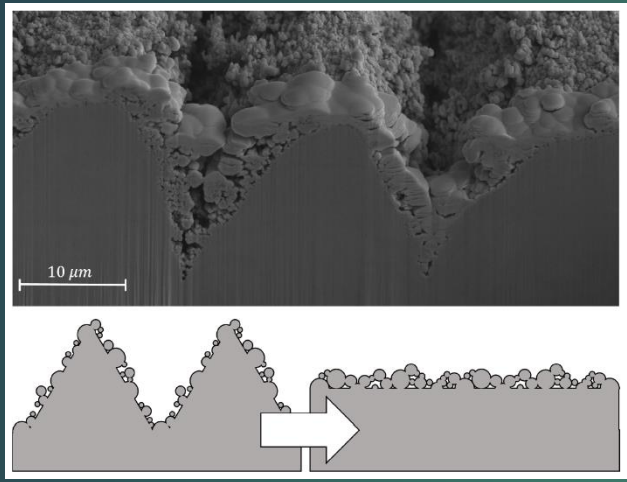


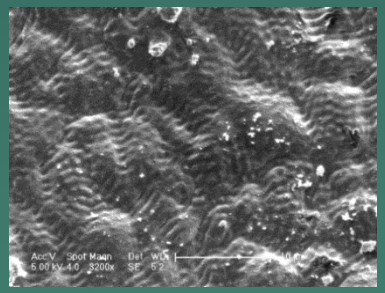


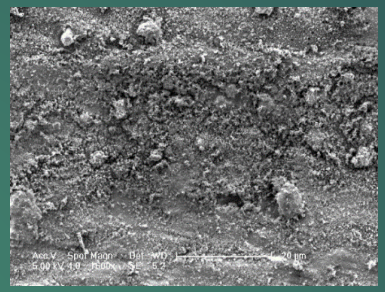


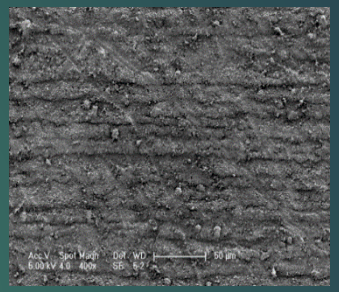
QPR measurements (cryogenic temperature, no external B-field) show a big difference in impedance depending on the current direction. With the grooves parallel to the beam the results seem OK.

Surface treatment for e-cloud mitigation (3/5)









	Sample 1	Sample 4	Sample 6	Untreated
R_{SRT} [mΩ]	25.527	24.940	25.100	26.035
R_{S77K} [mΩ]	10.792	9.814	9.697	10.709

3.9 GHz, with no magnetic field

The results are promising, but we still need:

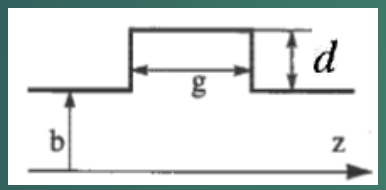
- Measurements with B-field
- Measurement of $Im(Z_{surf})$, or at least $Re(Z_{surf})$ in a wide enough frequency span to apply an analytical model.

Reza Valizadeh, FCC week 2019

Surface treatment for e-cloud mitigation (4/5)

How to estimate impedance of a rough surface?

Geometrical impedance models

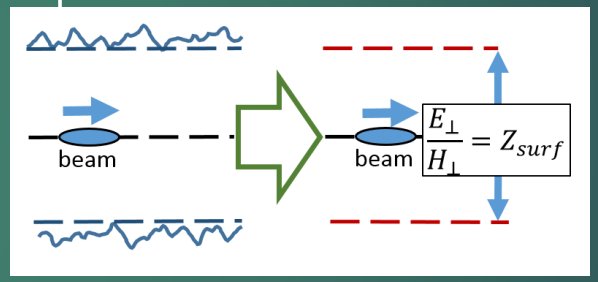


Inductive model (Stupakov, Biancacci)

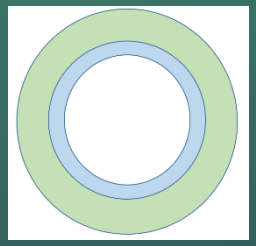
$$Z(\omega) = -i\omega\mathcal{L} = -i\omega\alpha f \frac{Z_0 \Delta L}{2\pi c a}$$

Resonator model (Bane, Novokhatsky)

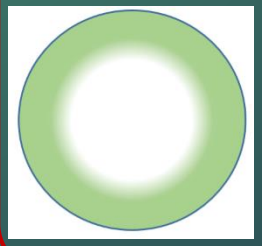
Through modified surface impedance



Two-layer model



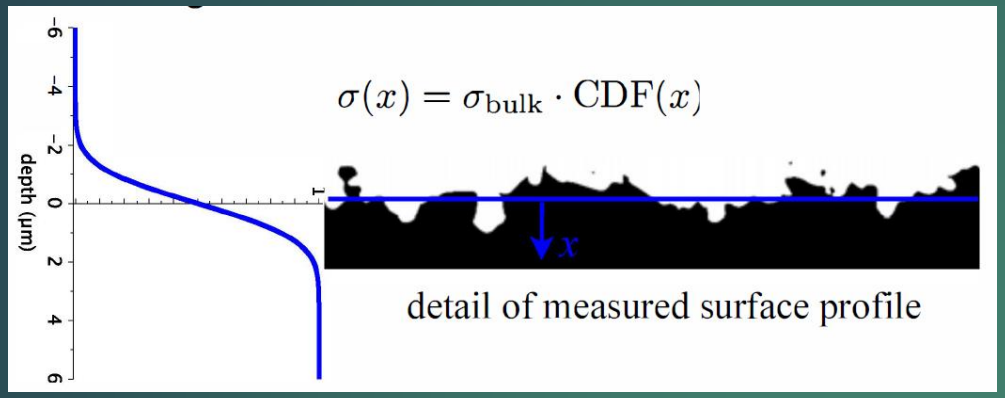
Gradient model



Other roughness models

- Hammerstad
- Groiss
- Snowball

Surface treatment for e-cloud mitigation (5/5)



G. Gold, K. Helmreich - Surface Impedance Concept for Modeling Conductor Roughness

Numerically solve a differential equation

$$\frac{\partial^2 B_y}{\partial x^2} + j\omega\mu_0\sigma B_y - \frac{\partial}{\partial x}\ln\sigma \cdot \frac{\partial B_y}{\partial x} = 0$$

$$B_y(x), J_z(x)$$

This method allows to obtain both real and imaginary surface impedance

$$Z_{surf}^{rough} = \frac{1}{\sigma_{eff}\delta(\sigma_{eff})} + i\frac{1}{\sigma_{bulk}\delta(\mu_{r,eff})}$$

Conclusion 4

Laser surface engineering is a very promising solution to mitigate e-cloud build-up.

But proper impedance measurements are necessary.

Conclusions

1) Beam screen is increasingly more important in future colliders.

In FCC-hh, it overshadows the collimators as the main source of impedance.

2) Resistive wall impedance of the beamscreen calls for faster transverse feedback.

Ideal-world solution: HTS beamscreen.

3) Pumping holes screening is very effective at reducing their impedance.

Proving that requires new methods in impedance calculation.

4) Laser surface engineering is a very promising solution to mitigate e-cloud build-up.

But proper impedance measurements are necessary.