Low-impedance beam screen design for future colliders

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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

Aperture 35 mm

E. Belli et. al

SR absorber

Main impedance issues:
- Resistive wall impedance
- SR absorbers
- NEG coating

FCC-hh

Aperture 12 mm

Cooling channel 40 - 57 K
Sawtooth surface finishing

Main impedance issues:
- Resistive wall impedance
- Pumping holes
- AC coating or laser treatment
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

Prototype tested at Karlsruhe Light Source KARA to simulate the level of SR
Impedance estimation effort for the FCC-hh beamscreen

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

- Transverse head-tail instability
  \[ n_{\text{turns}}^{-1} \propto \frac{N_b \beta_{\text{avg}}}{\gamma \tau_b} \text{Re} \left( Z_{\perp}(f_{\text{SB}}) \right) \]

- Transverse mode-coupling instability
  \[ \frac{N_b}{N_b^{th}} \propto \frac{N_b \beta_{\text{avg}}}{\gamma \tau_b Q_s} \text{Im} \left( Z_{\perp}(f_{\text{SB}}) \right) \]
Role of the beamscreen in impedance budget (1/2)

Frequencies important to single bunch instabilities

Frequencies important to coupled bunch instabilities
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
Beam screen is increasingly more important in future colliders.

In FCC-hh, it overshadows the collimators as the main source of impedance.
Stainless steel is $\sim 1000$ times more resistive than copper:

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

$$\rho_{\text{st.steel}} = 6 \times 10^{-7} \ \Omega m$$
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: Surface Impedance Boundary Condition (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

Why is the effective impedance higher?
- Lower aperture
- Higher temperature
- Higher magnetic field (magneto-resistance)
- Lower revolution frequency

\[
Re \left( Z_{y}^{\text{dip}}(7.8 \, \text{kHz}) \right) = 4 \times 10^3 \Omega/m^2
\]

\[
Re \left( Z_{y}^{\text{dip}}(2.1 \, \text{kHz}) \right) = 1.6 \times 10^4 \Omega/m^2
\]

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.

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

Courtesy of 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.
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 actual slit width

The final result

Im(Z_\parallel f per period [\Omega/\text{GHz}]) vs Slit width w [mm]

The actual slit width

Im(Z_x f per period [\Omega/\text{m}]) vs Slit width w [mm]
Pumping holes impedance (2/3)
Pumping holes impedance (3/3)

Longitudinal impedance per period

Transverse impedance per period

Group-velocity corrections

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

Shunt impedances of synchronous waves

Paper for details:
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)

Amorphous carbon or TiN coating

- 0.2 μm Carbon
- Copper

~30% impedance increase at 1 GHz

Laser treatment

- 0.1 - 3 μm
- 30-100 μm
- 10-100 μm

Impedance increase = ?
Surface treatment for e-cloud mitigation (2/5)

Cu-LESS sample identifies as 23.11.2016
Cross sectional view prepared by FIB-EM

Pt coating was added to reduce curtaining effect due to the topography of the sample

Pt appears light grey in the AsB pictures in contrast with the Cu
Surface treatment for e-cloud mitigation (3/5)

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.

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.

<table>
<thead>
<tr>
<th></th>
<th>Sample 1</th>
<th>Sample 4</th>
<th>Sample 6</th>
<th>Untreated</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{SRT}$ [mΩ]</td>
<td>25.527</td>
<td>24.940</td>
<td>25.100</td>
<td>26.035</td>
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<tr>
<td>$R_{S77K}$ [mΩ]</td>
<td>10.792</td>
<td>9.814</td>
<td>9.697</td>
<td>10.709</td>
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</tbody>
</table>

Reza Valizadeh, FCC week 2019

3.9 GHz, with no magnetic field
Surface treatment for e-cloud mitigation (4/5)

How to estimate impedance of a rough surface?

Geometrical impedance models

- Inductive model (Stupakov, Biancacci)
- Resonator model (Bane, Novokhatsky)

Through modified surface impedance

Two-layer model

Other roughness models
- Hammerstad
- Groiss
- Snowball
Surface treatment for e-cloud mitigation (5/5)

Numerically solve a differential equation

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

This method allows to obtain both real and imaginary surface impedance

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