HTS Superconductor beam screen for the future collider FCC at CERN

Sergio Calatroni, CERN TE-VSC Division (project leader)

E. Bellingeri et al.

T. Puig et al.

M. Eisterer et al.
It is time to plan for a Future Circular Collider at CERN! 
Drive: pushing the energy frontier of a factor 10

FCC e-e, h-h
Future h-h Circular Collider at CERN

- FCC h-h will reach 100 TeV c.m. collision energy (50TeV+50TeV)
- Energy depends on both collider radius and curving magnetic field:
  \[ E \propto r \times B \]  
  (100TeV: \( r = 16\,\text{Km}, B = 16\,\text{T} \))
- Goal: Access to new particles (direct production) far beyond LHC reach and much-increased rates for phenomena at lower energies

The beam will be made of 12500 bunches of \( 10^{11} \) protons, 8 cm long, traveling at a distance of about 8 m each other
Overall energy: \( 10^{10} \) J!

Freccia Rossa: \( m=500\,\text{T}, v =300\,\text{km/h} \)
\[ E_k = (\frac{1}{2})mv^2 = 2 \cdot 10^9 \,\text{J} \]
Examples of Key Technology R&D for FCC: 16T Magnets

- Increase critical current density
- Obtain high quantities at required quality
Examples of Key Technology R&D for FCC: 16T Magnets

- 4700 dipole magnets, 14m long: 10,000 tons Nb
- Design optimum coil geometry to achieve the required field quality
- Mechanical design (foreseen peak stress 200MPa)
- Thermal management and quench protection
- Manufacturing and cost optimisation
The synchrotron radiation problem

Synchrotron radiation load for protons @50 TeV:

~ 25-45 W/m (@16 T)

(LHC <0.2W/m !!)
The synchrotron light does not hit directly the internal beam screen surface!!

Taking into account overall cryogenic efficiency and power consumption of the accelerator, the synchrotron radiation has to be absorbed by a copper screen held at low temperature.
Cryo-power for cooling of SR heat

Overall optimization of cryo-power and vacuum
Temperature ranges: 40K-60K, 100K-120K

Beam - screen chamber Temperature (K)
Image charges flow on the surface of the beampipe, generating “wakefields”

Wakefields have an effect on beam stability, in particular both the risetime of resistive wall transverse instabilities and the Intensity threshold of transverse mode coupling instabilities depend on the surface impedance of the material:

\[
\tau \propto \frac{1}{\Re[Z_T]} \quad ; \quad I_b \propto \frac{1}{\Im[Z_T]} \quad \text{with} \quad Z_T = \frac{2\pi R c}{\pi b^3 \omega Z_s}
\]

Copper at 50 K may not guarantee a large enough stability margin of the beam!
Frequency spectrum

Beam instantaneous image current

Time evolution at a fixed point

Frequency spectrum
High Temperature Superconductor at low fields present a Surface Impedance much lower than Copper at 50K!!!
But...the HTS film should operate in a 16T magnetic field and present $J_c \gg 2.5 \cdot 10^8$ A/m² over a 100Km long narrow tube!

HTS Surface Impedance will still be well below copper in the assumed frequency, field, temperature and current regimes???
Superconductors in high fields: Abrikosov Vortices

Gittleman and Rosenblum: - Phys Rev. Lett. 16, 734 (1966) discuss the effect of a rf applied field ($J_{\text{rf}}$). At $B_o \gg B_{c1}$ repulsion forces between fluxon lines are higher in respect to the pinning forces. The fluxon array moves rigidly and feels a periodic force of the form:

$$U(x) = \frac{1}{2} k x^2$$

$$f_p = -kx$$

$$(J_{\text{rf}} \ll J_c)$$
Equation of motion for the fluxon lattice

\[ m\ddot{x} + \eta \dot{x} + kx = J_{rf} \phi_o \]

\( m \): fluxon mass per unit length

\[ \eta = \frac{\phi_o B_{c2}}{\rho_n} \]: fluxon viscosity per unit length

\( (m \approx 0) \quad J_{rf} = J_{rfo} e^{i\omega t} \), \( \dot{x} = v = v_o e^{i\omega t} \)

\[ v_o = \frac{J_{rfo} \phi_o}{\eta} \left( \frac{\omega^2}{\omega^2 + \omega_o^2} + i \frac{\omega \omega_o}{\omega^2 + \omega_o^2} \right) \]

\[ \omega_o = \frac{k}{\eta} \quad \text{«depinning frequency»} \]
\[ \vec{J}_{rf} = (\sigma_1 - i\sigma_2)(\vec{E}_{rf} - \vec{v} \times \vec{B}_o) \quad + \text{Maxwell equations} \]

General expression for the surface impedance of a superconductor in presence of a rigid vortex array, with the rf current perpendicular to the magnetic field

\[ R_{sf} = R_n \sqrt{\sqrt{A^2 + B^2} - B} \]

\[ X_{sf} = R_n \sqrt{\sqrt{A^2 + B^2} + B} \]

\[ A = \frac{\sigma_1/\sigma_n}{(\sigma_2/\sigma_n)^2 + \frac{B_o}{B_{c2}}} \alpha(\omega) \]

\[ B = \frac{1}{\sigma_2/\sigma_n} + \frac{B_o}{B_{c2}} \beta(\omega) \]

\[ \alpha(\omega) = \frac{\omega^2}{\omega^2 + \omega_o^2} \]

\[ \beta(\omega) = \frac{\omega \omega_o}{\omega^2 + \omega_o^2} \]

\[ \frac{X_{sf}}{R_{sf}} = \frac{\sqrt{A^2 + B^2} + B}{A} \]
Surface Impedance in the Large Field, Low Frequency limit

FROM THE LITERATURE, FOR HIGH QUALITY HTS:

\[ f_o = \frac{\omega_o}{2\pi} \approx 10 - 20\text{GHz} \]

Large \( B_o, \ \omega \leq \omega_o \Rightarrow A \approx \frac{B_o}{B_{c2}} \frac{\omega^2}{\omega_o^2}; \quad B \approx \frac{B_o}{B_{c2}} \frac{\omega}{\omega_o} \]

\[ R_{sf} (\omega, B_o) \approx \frac{R_n}{\sqrt{2}} \sqrt{\frac{B_o}{B_{c2}}} \left( \frac{\omega}{\omega_o} \right)^{3/2} \]

\[ \frac{X_{sf}}{R_{sf}} \approx 2 \frac{\omega_o}{\omega} \]

\[ X_{sf} (\omega, B_o) \approx X_n \sqrt{2} \sqrt{\frac{B_o}{B_{c2}}} \left( \frac{\omega}{\omega_o} \right)^{1/2} \]

\[ \lambda_{sf} = \frac{X_{sf}}{\mu_o \omega} \approx \delta_n \sqrt{\frac{B_o}{B_{c2}}} \sqrt{\frac{\omega}{\omega_o}} \]
Average value of $R_{sf}$ over the FCC frequency spectrum

$$\bar{R}_{sf}(T) = \int_{0}^{\infty} S(f) R_{sf}(\omega, T) d\omega$$

$\bar{f} = 1.2\text{GHz}$

Approximating the real spectrum to a step function, we get:

$$\bar{R}_{sf}(T) = R_{sf}(\omega^*, T) ; \frac{\omega^*}{2\pi} = 0.65\text{GHz}$$
Calculations performed using high quality HTS (YBCO) parameters show a large $R_{sf}$ reduction in respect to Copper

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_c$</td>
<td>92K</td>
</tr>
<tr>
<td>$T$</td>
<td>50K</td>
</tr>
<tr>
<td>$B_o$</td>
<td>16T</td>
</tr>
<tr>
<td>$J_c (50,16)$</td>
<td>$7.5 \times 10^9$/m$^2$</td>
</tr>
<tr>
<td>$B_{c2} (50)$</td>
<td>40T</td>
</tr>
<tr>
<td>$\rho_n$</td>
<td>60$\mu\Omega$ cm</td>
</tr>
<tr>
<td>$f_o$</td>
<td>$\omega_o/2\pi=20$Ghz</td>
</tr>
</tbody>
</table>

**Graph:**

- **$R_{sf} (m\Omega)$** as a function of $f$ (GHz)
- Comparison between HTS and Copper

**Equation:**

$$f_o = \frac{\omega_o}{2\pi} = 20 \text{Ghz}$$
Possible HTS materials:

<table>
<thead>
<tr>
<th>HTS</th>
<th>$T_c$</th>
<th>$B_{c2}(50K)$</th>
<th>Anisotropy</th>
<th>Substrate requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>YBCO</td>
<td>92 K</td>
<td>40T</td>
<td>$\sim 7$</td>
<td>High quality, biaxial texture</td>
</tr>
<tr>
<td>Bi-2212</td>
<td>85 K</td>
<td>70T ($\text{very low } B_{\text{irr}}$)</td>
<td>$&gt;20$</td>
<td>No special texture requirements</td>
</tr>
<tr>
<td>TI-1223</td>
<td>125 K</td>
<td>80T</td>
<td>$\sim 8$</td>
<td>No special texture requirements</td>
</tr>
</tbody>
</table>

The YBCO solution is developed by the ICMAB group

The TI-1223 solution is developed by the CNR-SPIN group
Solution 1: YBCO tapes glued on the beam screen

YBCO deposition on Ni–W alloy rolling-assisted biaxially textured tapes (RABiTS)
Segmentation should also reduce potential problems due to persistent currents generated during field ramping.
Preliminary measurements performed on small samples from 5 different providers, show very good agreement with the theory and extremely encouraging results!

\[ T = 50K \quad f = 8.05GHz \]

\[ R_{sf} (f, T) = \frac{R_n}{\sqrt{2}} \sqrt{\frac{B_o}{B_{c2}}} \left( \frac{f}{f_0} \right)^{3/2} \]
A possible problem for YBCO tapes: thermal runaway

One dimensional thermal model: \( R_T = \frac{d_1}{k_1} + \frac{d_2}{k_2} + \frac{d_3}{k_3} + \frac{d_4}{k_4} + \frac{d_5}{k_5} \) + Kapitza interface terms

\[
\begin{cases}
T = T_1 + \Delta T \\
\Delta T = R_T P_{rf}(T) \\
P_{rf}(T) = a\bar{R}_{sf}(T)
\end{cases}
\]

\( a = 10^{-3} \text{ W/}\Omega \text{m}^2 \)

(FCC calculations)

An increase in \( T \) due to the \( rf \) power increases the superconductor surface resistance \( R_{sf}(T) \) that produces a further increase in \( T \). The process leads to a surface equilibrium temperature \( T > T_1 \), or can lead to a thermal runaway!
Assuming:

- $T_1 = 50K$
- $P_{rfCu} = 1W/m^2$
- $R_{nCu}(f^*) = 1m\Omega$

\[
\bar{R}_{sf}(T) = \frac{T - T_1}{R_T} \frac{R_{nCu}}{P_{rfCu}}
\]
Solution 2: Tl 1223 directly grown on the Copper beam screen (with a Silver buffer layer)

Preparation of Highly Textured Tl(1223)/Ag Superconducting Tapes

Emilio Bellingeri, Roman E. Gladyshevskii, Frank Marti and René Flükiger
Département de Physique de la Matière Condensée. Université de Genève, 24 Quai Ernest Ansermet, CH-1211 Genève 4, Switzerland

SEM images of a Tl,Pb, Bi(1223) powder melted at 1020°C (a), 1080°C (b) (0.5 h) after a second reaction at 930°C (3 h).
New Labs for safe Tl manipulation have been set up at SPIN-Ge
«as deposited» precursor  after thermal treatment
A further problem: effect of nonlinear pinning forces

\[ U(x) = \frac{1}{2} k x^2 + f_p = -k x \]

Nonlinear Gittleman and Rosenblum equation:

\[ \eta \ddot{x} + k x = J_{rf} \phi_0 - \gamma x^2 \]

The equation can be solved by perturbation methods. The red curve represents the calculated first order perturbation term of the wakefield, for \( J_{rf} = 0.25 J_c \) and \( f = f_o \), showing a significative third harmonic component (black curve).
Conclusions: Future directions and other facts....

• Measurements of the nonlinear component of the HTS rf surface impedance and comparison with calculations.

• Measurements of secondary electron emission from the HTS surface and effect of protective coatings on the surface impedance.

• Testing of the surface impedance at 1Ghz and 16T of a short (50cm) tube simulating the real beam screen.

• Our idea has been adopted for the design of the Chinese Super collider.

• Other accelerator physics & technology teams are following closely our research (Daresbury, Darmstadt......)

• Spin-offs may come out from this activity (axion detection, capture cavities for muon colliders)