Impedance driven instabilities and coherent beam-beam effects in the early stage of the FCChh design studies

X. Buffat, O. Boine-Frankenheim, U. Niedermayer, F. Petrov, B. Salvant, D. Schulte
The Future Circular Hadron-Hadron Collider

Impedance driven instabilities
- Design strategy
- Impedance model
- Instability model

Coherent beam-beam effects
- Orbit
- Dynamic $\beta$

Conclusion
The FCChh
The FCChh
FCChh parameters and challenges

- Tighter collimation constraints than the LHC

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- Tighter collimation constraints than the LHC
- Beam screen design which allows to evacuate >20 W/m

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- LHC-like longitudinal parameters

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Beam screen design which allows to evacuate >20 W/m

Large circumference → low frequency

LHC-like longitudinal parameters

Twice larger average $\beta$

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Tentative strategy concerning coherent stability

- Estimate the impedance of the main contributors and define tolerances
- Make early design choices based on TMCI and coupled bunch instability
- Extend results with detailed model (i.e. including transverse feedback, non-zero chromaticity, Landau damping)
  - Stabilization of high order head-tail mode with Landau damping?
  - e-cloud?
- Study other mitigation techniques
Resistive wall impedance of the beam screen (N. Mounet)

- Most critical at injection
- Assumed round pipe made of copper at 50K (0.3 mm coating required)
  - The current design (15 mm) is at the edge of stability with a 50 turns transverse feedback
  - Initial design with 12 mm seemed out of reach

https://indico.cern.ch/event/289331/contribution/2/material/slides/0.pdf
Pumping holes

- Broadband impedance with $f_c = f_{\text{pipe}}$ and:

$$\frac{R}{Q} = 2 Z_0 \eta \left(\frac{\alpha_e + \alpha_m}{\pi A b^3}\right) \propto \frac{1}{b^4}$$

- Discrepancies between Kurenoy's theory and simulations (factor $\sim 4$) is being investigated**

- Due to the lower revolution frequency and to the smaller gap, the effect on the TMCI is $\sim 8$ times stronger than in the LHC

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*S. Kurenoy, Impedance issues for the LHC beam screen, Part. Acc. 50, 167-175, 1995

**F. Riminucci@HSC meeting 14-9-15
Pumping holes

- Broadband impedance with $f_c = f_{pipe}$ and:
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  \frac{R}{Q} = 2 Z_0 \eta \left( \frac{\alpha_e + \alpha_m}{\pi Ab^3} \right) \propto \frac{1}{b^4}
  \]

- Discrepancies between Kurenoy's theory and simulations (factor ~4) is being investigated

- Due to the lower revolution frequency and to the smaller gap, the effect on the TMCI is ~8 times stronger than in the LHC.
  
  → A beam screen design without holes (or at least fewer holes) would be beneficial.

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Beam screen design
(R. Kersevan)

- Longitudinal slit with anti-chamber to extract synchrotron power
Beam screen design
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- Longitudinal slit with anti-chamber to extract synchrotron power
  - Avoids outgassing in the beam chamber
    → Fewer pumping holes required
Beam screen design
(R. Kersevan)

- Longitudinal slit with anti-chamber to extract synchrotron power
  - Avoids outgassing in the beam chamber
    → Fewer pumping holes required
- Symmetrizing the design allows to shield the pumping holes

https://indico.cern.ch/event/380420/contribution/2/material/slides/0.pptx
2D simulations show a negligible effect of the anti-chambers

3D simulations are at the edge of computing capabilities

→ More studies required with CST as well as other codes (GdfidL, ACE3P, ECHO3D)
- **Scaled LHC design**:
  - Identical collimator length, material and physical gaps
  - Adiabatic damping is compensated with larger $\beta$ functions to obtain identical normalized gaps
  - The impedance is identical as the LHC, but the effect on the beam is smaller due to the $\beta$ functions
Summary

- Current impedance model of the FCChh includes:
  - The beam screen (Effect of pumping holes / slit to be fully understood → numerical challenges)
  - The collimators (Similar to the LHC's → follow up of new collimator designs / material)

- Missing components:
  - Interconnects (photon absorbers ?)
  - Injection, extraction kickers and protection devices
  - RF / crab cavities
  - Beam instrumentation
  - ...
Effective impedance of the beam screen

- Sacherer sum for the effective impedance

\[ Z_0 = \frac{\sum_{p=-\infty}^{\infty} H_0(\omega_p) Z(\omega_p)}{\sum_{p=-\infty}^{\infty} H_0(\omega_p)} \approx \frac{\int_{-\infty}^{\infty} H_0(\omega_p) Z(\omega_p) \, dp}{\int_{-\infty}^{\infty} H_0(\omega_p) \, dp} \]

- Approx. with integrals
  (→ assumes that there are no trapped modes)

\[ \omega_p = \omega_{rev} (Q_\beta + p) \]
Effective impedance of the beam screen

- Sacherer sum for the effective impedance
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\[ \omega_p = \omega_{rev}(Q_\beta + p) \]

\[ Z_{TW} = (\text{sign}(\omega) + i) \frac{LZ_0}{2\pi b^3} \sqrt{\frac{2}{\mu_0 \sigma_{DC}\omega}} \]

\[ \varepsilon_r = \mu_r = 1 \]
Effective impedance of the beam screen

- Sacherer sum for the effective impedance
  - Approx. with integrals (→ assumes that there are no trapped modes)
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  - Approx. mode 0 power spectrum

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\[ Z_{TW,0} \approx i \frac{4LZ_0}{2\pi b^3} \sqrt{\frac{8\sigma_z}{3\pi c \mu_0 \sigma_{DC}}} \]

**\( \epsilon_r = \mu_r = 1 \)**
\[ \Delta Q_{TW,0} = -\frac{e^2 N}{16\pi m_p \gamma Q_x \omega_{rev} \sigma_z} Z_{TW,0} \]

\[ Q_s = \sqrt{\frac{\eta hV}{2\pi E}} \approx \frac{1}{Q_x} \sqrt{\frac{hV}{2\pi E}} \]
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- Assume TMCI due to mode 0 reaching \(-Q_s\)

\[ N_{TMCI} \approx 1.1 \cdot 10^{12} \]
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- Assume TMCI due to mode 0 reaching \(-Q_s\)

\[ N_{TMCI} \sim 1.1 \cdot 10^{12} \]

- Agreement within 20% with tracking simulation (COMBI)

- Positive shift of mode 1
Coupled bunch instability

Beam screen

\[ \text{Re}(Z_{TW,0,n_{CB}}) = \text{Re} \left( \sum_{p=-\infty}^{\infty} \frac{H_0(\omega_p) Z_{TW}(\omega_p)}{\sum_{p=-\infty}^{\infty} H_0(\omega_p)} \right) \approx \frac{n_b L Z_0}{2\pi \omega_L b^3} \sqrt{\frac{2\omega_{rev}}{\mu_0 \sigma_{DC}(Q_\beta + n_{CB})}} \]

\[ \frac{1}{\tau_{CB}} = \frac{e^2 Z_0}{6\pi m_p} \sqrt{\frac{2}{\mu_0 \gamma b^3}} \sqrt{\frac{1}{\sigma_{DC} \omega_0 Q_\beta}} \]
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\[ \rightarrow \text{100 turns rise time in current design at 3.3 TeV} \]

- Study case (not nominal FCChh) to compare the formula with tracking simulation \( \rightarrow \) about 15\% difference

\[ \text{Rise time : 2426 turn} \]

![Graph showing vertical amplitude vs bunch number and turn number.](image)
Summary

\[ \frac{1}{N_{TMCI}} = \sum \frac{1}{N_{TMCI,i}} \]

Beam screen:
\[ N_{TMCI} = \frac{4\pi^3 c m_p \sqrt{3c \mu_0 b^3 \gamma}}{Z_0 e^2 L^2} \sqrt{\frac{\sigma_{DC} h V \sigma_z}{E}} \]

Each collimator:
\[ N_{TMCI} = \frac{4m_p \sqrt{3c}}{Y e^2} \sqrt{\frac{2\mu_0 \gamma b^3}{Q_x \beta_c L_c}} \sqrt{\frac{\sigma_z h V \sigma_{DC}}{E}} \]

Broad band:
\[ N_{TMCI} = \frac{16\pi m_p}{\sqrt{2\pi e^2}} \frac{\gamma \omega_{rev} \sigma_z}{R} \sqrt{\frac{h V}{2E}} \]

- Prediction with the test case (Beam screen + rough collimator model + holes): \( N_{TMCI} \sim 3 \cdot 10^{11} \)
\[ \frac{1}{N_{TMCI}} = \sum \frac{1}{N_{TMCI,i}} \]

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- Prediction with the test case (Beam screen + rough collimator model + holes): \( N_{TMCI} \sim 3 \cdot 10^{11} \)

- \( N_{TMCI} \sim 10^{12} \) without holes

- The most unstable coupled bunch mode is the slowest, driven by the beam screen impedance:

\[ \frac{1}{\tau_{CB}} = \frac{e^2 Z_0}{6\pi m_p} \sqrt{\frac{2}{\mu_0 \gamma b^3}} n_b N \beta_{avg} \sqrt{\frac{1}{\sigma_{DC} \omega_0 Q_\beta}} \]

- The feedback bandwidth needs to be set according to the stability of higher frequency coupled bunch mode driven by both the beam screen and the collimators' impedances
Orbit effect

- ~3 times more long range per IP than in the LHC
- The normalized separation is increased to keep a similar dynamic aperture (~d⁻² – d⁻⁴)

→ Orbit effect is enhanced

\[
\text{orbit spread} \propto \frac{N_{LR}N_{r0}}{\epsilon d} \frac{1}{\sin(\pi Q_0)}
\]
Dynamic $\beta$

$$\max \left( \frac{\Delta \beta}{\beta} \right) = \frac{2\pi \xi}{\sin(2\pi Q_0)}$$

- Exploring high head-on beam-beam tune shift
- Effect on collimation / machine protection?
- The effects of multiple IPs do not add linearly
  → Effect of the phase advance between IPs (P.G. Jorge)
  → Local compensation (L. Medrano)

HL-LHC synergetic...
- The turn-by-turn orbit jitter at the IP close to the betatron frequencies results in emittance growth through decoherence.

- It should be roughly $\sim 10^{-4} \sigma$ to keep the emittance growth $< 10\%$/h.

- Rough estimations of the main contributors (field ripple, ground motion) seem at the edge with nowadays technology → Detailed studies required.

- Single particle diffusion mechanisms were not considered.

### TBC

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<tr>
<th>Circuit</th>
<th>$\Delta [10^{-5}]$</th>
<th>$\epsilon_{init}$</th>
<th>$\epsilon_{equ}$</th>
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<tr>
<td>Main dip.</td>
<td>1</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Separation dip.</td>
<td>1</td>
<td>8 (16)</td>
<td></td>
</tr>
<tr>
<td>Main quad.</td>
<td>0.2</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Triplet</td>
<td>0.2</td>
<td>1.5 (3)</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.4</strong></td>
<td><strong>11 (18)</strong></td>
<td></td>
</tr>
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$\beta^*=1.1 \ (\beta^*=0.3)$
The impedance model of the FCChh is under development

- The details of the impedance of some components (holes, slit, …) are critical and their evaluation is at the edge of the computing capabilities (Use other models ?)
- The impedance of several elements need to be evaluated

Simple models show that the beam stability is a limiting factor at injection

- Need detailed studies including the chromaticity, the transverse feedback and Landau damping
- An octupole scheme is being designed (V. Kornilov)

- Orbit effects and dynamic optics distortion due to beam-beam interactions are more important than in the LHC
- Noise sources have to be studied in details, they should not compromise effect of the synchrotron damping
### Parameter Table

Table 1: FCC-hh baseline parameters compared to LHC, HE-LHC and HL-LHC parameters.

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<tr>
<th>Main parameters and geometrical aspects</th>
<th>LHC (Design)</th>
<th>HL-LHC</th>
<th>FCC-hh baseline</th>
<th>FCC-hh ultimate</th>
</tr>
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<tr>
<td>c.m. Energy [TeV]</td>
<td>14</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circumference C [km]</td>
<td>26.7</td>
<td>100</td>
<td></td>
<td></td>
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<tr>
<td>Dipole field [T]</td>
<td>8.33</td>
<td>16</td>
<td></td>
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<tr>
<td>Arc filling factor</td>
<td>0.79</td>
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<tr>
<td>Straight sections</td>
<td>8 x 528 m</td>
<td>6 x 1400 m + 2 x 4200 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of IPs</td>
<td>2 + 2</td>
<td>2 + 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injection energy [TeV]</td>
<td>0.45</td>
<td>3.3</td>
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**Physics performance and beam parameters**

| Peak luminosity [10^{36} cm^{-2} s^{-1}] | 1.0 | 5.0 | 5.0 | < 30.0 |
| Optimum run time [h]                    | 15.2 | 10.2 | 12.1 |
| Optimum average integrated lumi / day [fb^-1] | 0.47 | 2.8 | 2.2 |
| Assumed turnaround time [h]             | 5   | 4    |     |
| Overall operation cycle [h]             | 17.4|      |     |
| Peak no. of inelastic events / crossing at | | | | |
| - 25 ns spacing                        | 27  | 135 (lev.) | 171 | 1026 |
| - 5 ns spacing                         | 34  | 194    |     |
| Total / inelastic cross section $S_{inel}$ [mbarn] | 111 / 85 | 153 / 108 |
| Luminous region RMS length [cm]         | 5.7 | 5.7   |     |
| Init. beam lifetime due to burn off [h] | 45  | 15.4  | 19.1 | 4.75 |

**Beam parameters**

| Number of bunches $\pi$ at | 2808 | 10600 | 53000 |
| Number of $\pi$ at | 1.15 | 2.2   | 1.0   |
| - 25 ns | | | |
| - 5 ns | | | |

- 5 ns
- Nominal transverse normalized emittance [\mu m]
  - 25 ns | 3.75 | 2.5 | 2.2 |
  - 5 ns  | 2.2  | 0.44| 0.44|
- Number of IPs contributing to b-b tune shift | 3 | 2 | 2 |
- Maximum total b-b tune shift | 0.01 | 0.015 | 0.01 |
- Beam current [A] | 0.584 | 1.12 | 0.5 |
- RMS bunch length [cm] | 7.55 | 8 |
- IP beta function [m] | 0.55 | 0.15 (min) | 1.1 |
- RMS IP spot size [\mu m]
  - 25 ns | 16.7 | 7.1 (min) | 6.8 |
  - 5 ns  | 3    | 1.6    |     |
- Full crossing angle [mrad] | 285 | 590 | 91 |
- 175** | 175** |

**Other beam and machine parameters**

- Stored energy per beam [GJ] | 0.392 | 0.694 | 8.4 |
- SR power per ring [MW] | 0.0036 | 0.0073 | 2.4 |
- Arc SR heat load [W/\text{aperture}] | 0.17 | 0.33 | 28.4 |
- Energy loss per turn [MeV] | 0.0067 | 4.6 |
- Critical photon energy [keV] | 0.044 | 4.3 |
- Longitudinal emittance damping time [h] | 12.9 | 0.5 |
- Horizontal emittance damping time [h] | 25.8 | 1.0 |
- Dipole coil aperture [\text{mm}] | 36   |     |
- Beam half aperture [cm] | 2    | 1.3 |

*Depending on the operational scenario, the peak luminosity might increase to larger values during the run. **The crossing angle will be compensated using the crab crossing scheme.
Rough estimation of the effect of field ripple

- Assume that the noise arises from the power converter voltage ripple

\[
\frac{\delta B(\omega)}{B_0} = \frac{\delta I(\omega)}{B_0} = \frac{\delta V_0}{V_0} \frac{1}{\omega L_c}
\]

- Sum over main contributors (coherently for elements on the same circuit)
  - Main / separation dipole
  - Triplet with nominal Xing angle
  - Arc quad with 1mm RMS orbit

- Normalize to the beam divergence

\[
\delta_c(\omega) = \frac{\delta V_{PC}}{V_0} \frac{1}{\omega L_c} \sum_i k_{0,i}
\]

\[
\Delta(\omega) = \frac{\delta V_{PC}}{V_0} \frac{1}{\omega L_c} \sqrt{\frac{\gamma r}{\epsilon_n}} \sum_i k_{0,i} \sqrt{\beta_i}
\]

- Sum over harmonics of the revolution frequency

\[
\Delta = \Delta(\omega_{rev}) \sum_{n=0}^{\infty} \frac{1}{(n + Q_\beta)^2} \approx \Delta(\omega_{rev}) \sqrt{\frac{1}{Q_\beta} + \frac{\pi^2}{6}}
\]
Similar approach, using the ATL law to approximate the power spectrum at high frequency:

\[
\rho(f) = \frac{B}{2f^4}
\]