FCC-hh machine summary

Antoine CHANCE
on behalf of the FCC-hh machine team

CEA/DRF/IRFU/DACM

FCC week 2019
28th June 2019
### Tuesday morning

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
</tr>
</thead>
<tbody>
<tr>
<td>9:00</td>
<td>Coffee break</td>
</tr>
<tr>
<td>10:00</td>
<td>FCC-hh machine programme</td>
</tr>
<tr>
<td>10:30</td>
<td>Lattice integration</td>
</tr>
<tr>
<td>10:45</td>
<td>Dr. Antoine Chance</td>
</tr>
<tr>
<td>11:00</td>
<td>Correlation solvers</td>
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<tr>
<td>11:45</td>
<td>David Ortolani</td>
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<tr>
<td>12:00</td>
<td>Field Quality at injection for FCC-hh</td>
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<tr>
<td>12:22</td>
<td>Dr. Stefano Costi</td>
</tr>
<tr>
<td>12:45</td>
<td>FCC-hh single beam intensity limitations and scans</td>
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<tr>
<td>13:05</td>
<td>Oliver Jollet-François</td>
</tr>
<tr>
<td>14:00</td>
<td>Impact factor and stability</td>
</tr>
<tr>
<td>14:20</td>
<td>Sergey Aleshkevich</td>
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### Tuesday afternoon

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
</tr>
</thead>
<tbody>
<tr>
<td>14:00</td>
<td>Options</td>
</tr>
<tr>
<td>14:40</td>
<td>Antoine Marchi</td>
</tr>
<tr>
<td>15:00</td>
<td>Additional options</td>
</tr>
<tr>
<td>15:20</td>
<td>Johan Van Beers-Haeghe</td>
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<tr>
<td>15:40</td>
<td>Beam-beam effects</td>
</tr>
<tr>
<td>16:00</td>
<td>Dr. Stefano Costi</td>
</tr>
<tr>
<td>16:20</td>
<td>Dynamic aperture Studies</td>
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<tr>
<td>16:30</td>
<td>Eric Cottard</td>
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<tr>
<td>16:40</td>
<td>Imaging resolution in the FCC-hh RIB</td>
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<tr>
<td>17:00</td>
<td>Antoine Aleshkevich</td>
</tr>
<tr>
<td>17:20</td>
<td>Specifications; radiation background in the experimental insertion region of the FCC-hh</td>
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<tr>
<td>17:40</td>
<td>Antoine Aleshkevich</td>
</tr>
<tr>
<td>18:00</td>
<td>Fast hadron interaction region</td>
</tr>
<tr>
<td>18:20</td>
<td>Michael Vshivetskii</td>
</tr>
<tr>
<td>18:40</td>
<td>Injection design</td>
</tr>
<tr>
<td>19:00</td>
<td>Jean-Christophe Bouju</td>
</tr>
<tr>
<td>19:20</td>
<td>Injection and extraction insertion</td>
</tr>
<tr>
<td>19:40</td>
<td>Christiano Cassapese</td>
</tr>
<tr>
<td>20:00</td>
<td>Ice option for FCC-hh</td>
</tr>
<tr>
<td>20:20</td>
<td>Michaela Schillberg</td>
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<tr>
<td>20:40</td>
<td>FCC-hh heavy ion calibration</td>
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<td>21:00</td>
<td>Antoine Aleshkevich</td>
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</table>

### Wednesday morning

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
</tr>
</thead>
<tbody>
<tr>
<td>9:00</td>
<td>Sleeper on the beam induced vacuum effects in the FCC-hh beam vacuum chamber</td>
</tr>
<tr>
<td>9:30</td>
<td>Ground floor</td>
</tr>
<tr>
<td>10:00</td>
<td>Material properties of reference to cryogenic vacuum systems</td>
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<tr>
<td>10:30</td>
<td>Ground floor</td>
</tr>
<tr>
<td>11:00</td>
<td>W and P from candidate materials for the FCC-hh Vacuum system</td>
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<tr>
<td>11:30</td>
<td>Ground floor</td>
</tr>
<tr>
<td>12:00</td>
<td>Photo destruction studies at the W/NN alignment on LIVF</td>
</tr>
<tr>
<td>12:30</td>
<td>Ground floor</td>
</tr>
<tr>
<td>13:00</td>
<td>Coffee break</td>
</tr>
<tr>
<td>13:30</td>
<td>Cremer Place Bureaux Le Palais</td>
</tr>
<tr>
<td>14:00</td>
<td>Evaluation of LIVNI/Galileo surface engineering of copper and stainless steel for particle acceleration</td>
</tr>
<tr>
<td>14:30</td>
<td>Paolo Soldani</td>
</tr>
<tr>
<td>15:00</td>
<td>Recent Results on NEG Coating Characterization</td>
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<tr>
<td>15:30</td>
<td>Aria Simonetti</td>
</tr>
<tr>
<td>16:00</td>
<td>Photoemission Studies on FCC-hh Beam Screen Prototypes at ANKA</td>
</tr>
<tr>
<td>16:30</td>
<td>Luis Antonio Gonzalez Contreras</td>
</tr>
<tr>
<td>17:00</td>
<td>Update of the design and thermal mechanical study of the FCC-hh beam screen</td>
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<tr>
<td>17:30</td>
<td>Antoine Aleshkevich</td>
</tr>
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</table>

30 talks.
### Beam parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>FCC-hh Initial</th>
<th>FCC-hh Nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.M. Energy [TeV]</td>
<td>14</td>
<td>100</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Injection Energy [TeV]</td>
<td>0.45</td>
<td>3.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak Luminosity [$10^{34}$ cm$^{-2}$s$^{-1}$]</td>
<td>1.0</td>
<td>5.0</td>
<td>5</td>
<td>&lt;30</td>
</tr>
<tr>
<td>Integrated Luminosity/day [fb$^{-1}$]</td>
<td>0.47</td>
<td>2.8</td>
<td>2.2</td>
<td>8</td>
</tr>
<tr>
<td>Bunch distance $\Delta t$ [ns]</td>
<td>25</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bunch charge $N$ [$10^{11}$]</td>
<td>1.15</td>
<td>2.2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Number of bunches</td>
<td>2808</td>
<td>10400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Norm. emitt. [mm]</td>
<td>3.75</td>
<td>2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max $\xi$ for 2 IPs</td>
<td>0.01</td>
<td>0.015</td>
<td>0.01 (0.02)</td>
<td>0.03</td>
</tr>
<tr>
<td>IP beta-function $\beta$ [m]</td>
<td>0.55</td>
<td>0.15</td>
<td>1.1</td>
<td>0.3</td>
</tr>
<tr>
<td>IP beam size $\sigma$ [$\mu$m]</td>
<td>~16</td>
<td>~7</td>
<td>6.8</td>
<td>3.5</td>
</tr>
<tr>
<td>RMS bunch length $\sigma_z$ [cm]</td>
<td>7.55</td>
<td></td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Assumed Turn-around time [h]</td>
<td>5</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stored Energy per beam [GJ]</td>
<td>0.392</td>
<td>0.694</td>
<td>8.3</td>
<td></td>
</tr>
<tr>
<td>SR power per ring [MW]</td>
<td>0.0036</td>
<td>0.0073</td>
<td>2.4</td>
<td></td>
</tr>
</tbody>
</table>

24/06/2019
• Sextupole and decapole corrections required to have minimum DA above the target of 12 $\sigma$
• Negligible impact of Experimental Insertion Regions (EIR) on DA
• Minimum DA ~ 8.3 $\sigma$ at injection energy of 1.3 TeV

- Integrated MCD in lattice to correct $b_5$.
- Larger intra-beam distance: 250 mm.
  - Shorter MQ (smaller $b_2$ in MB), longer and weaker MB
  - Updated arc lattice.
- Consolidated correction scheme.
- Most of residual errors acceptable.
  - $\beta$-beating and dispersion beating are too large but uncorrected.
- Alternative FODO arc cells with 60°.
The FODO cell is 213.04 m long.
- The distance inter-dipole is 1.5 m.
- The main dipole MB is 14.19 m long.
- The maximum dipole field is 15.81 T with an aperture of 50 mm.
- MCS has the same length as in LHC: 0.11 m.
- MCD has been added at every other dipole to correct $b_5$.
- MQ is shorter (6.4 m) with a quadrupole gradient of 358 T/m.
- The maximum corrector field is 4 T.

- Integrated MCD in lattice to correct $b_5$.
- Larger intra-beam distance: 250 mm.
  - Shorter MQ (smaller $b_2$ in MB), longer and weaker MB
  - Updated arc lattice.

- Consolidated correction scheme.
- Most of residual errors acceptable.
  - $\beta$-beating and dispersion beating are too large but uncorrected.
- Alternative FODO arc cells with 60°.
OVERVIEW OF THE RESULTS

<table>
<thead>
<tr>
<th>Observable</th>
<th>Injection</th>
<th>Collision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hori. orbit</td>
<td>0.80 mm</td>
<td>0.79 mm</td>
</tr>
<tr>
<td>Vert. orbit</td>
<td>0.73 mm</td>
<td>0.73 mm</td>
</tr>
<tr>
<td>Hori. angle</td>
<td>26 (\mu)rad</td>
<td>26 (\mu)rad</td>
</tr>
<tr>
<td>Vert. angle</td>
<td>25 (\mu)rad</td>
<td>27 (\mu)rad</td>
</tr>
<tr>
<td>Hori. beta-beating</td>
<td>22 %</td>
<td>34 %</td>
</tr>
<tr>
<td>Vert. beta-beating</td>
<td>24 %</td>
<td>42 %</td>
</tr>
<tr>
<td>Hori. disp. beating</td>
<td>0.023 (\frac{1}{\sqrt{m}})</td>
<td>0.036 (\frac{1}{\sqrt{m}})</td>
</tr>
<tr>
<td>Vert. disp. beating</td>
<td>0.028 (\frac{1}{\sqrt{m}})</td>
<td>0.027 (\frac{1}{\sqrt{m}})</td>
</tr>
<tr>
<td>Hori. orbit corr. str.</td>
<td>0.31 Tm</td>
<td>4.7 Tm</td>
</tr>
<tr>
<td>Vert. orbit corr. str.</td>
<td>0.28 Tm</td>
<td>4.2 Tm</td>
</tr>
<tr>
<td>Skew quad. str.</td>
<td>8.57 T/m</td>
<td>148 T/m</td>
</tr>
<tr>
<td>Trim quad. str.</td>
<td>3.68 T/m</td>
<td>140 T/m</td>
</tr>
</tbody>
</table>

- Results satisfactory except for beta-beating
- Some DIS and all insertion correctors are not included into the results
- Beta-beating and dispersion beating need further investigation

- Integrated MCD in lattice to correct \(b_5\).
- Larger intra-beam distance: 250 mm.
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- Consolidated correction scheme.
- Most of residual errors acceptable.
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  - Updated arc lattice.
- Consolidated correction scheme.
- Most of residual errors acceptable.
  - $\beta$-beating and dispersion beating are too large but uncorrected.
- Alternative FODO arc cells with 60°.
Main IR Optics: Energy deposition in triplet

- Triplet magnets are exposed to high levels of radiation from collision debris.
- Large apertures necessary to house thick shielding inside.

Thick shielding option now default:
- 35 mm of INERMET180 (Tungsten).
- Aperture large enough to accommodate $\beta^* = 0.2$ m.

Can reach $\beta^*$ beyond Ultimate / have comfortable margins.

Updated optics.
- Margins on beam-stay clear (up to $\beta^* = 0.2$ m).
- Proposal to split Q1b to reduce peak energy deposition.
- Critical deposition in Q7: collimator to optimize.

See talk by B. Humann, this session.

SR radiation is negligible.
- Linear correction scheme updated.
- Non linear correctors are mandatory for DA.
- Alternative triplet exists (same Qpoles).
- Flat optics (no crab cavities).
Dose & DPA Q1b split:

- Slightly higher dose in Q1a, but much lower dose in Q1b and Q1c
- Q1b and Q1c hardly exceed the limit of 30MGy
- Higher DPA in Q1a but reduction of DPA in area of former Q1b
- Peak on front face in Q1b in old layout is cured

Note: vertical crossing

- Updated optics.
- Margins on beam-stay clear (up to $\beta^* = 0.2$ m).
- Proposal to split Q1b to reduce peak energy deposition.
- Critical deposition in Q7: collimator to optimize.
- SR radiation is negligible.
- Linear correction scheme updated.
- Non linear correctors are mandatory for DA.
- Alternative triplet exists (same Qpoles).
- Flat optics (no crab cavities).
Peak Power Density & Integrated Dose

- Peak power density mostly below 5mW/cm$^3$, except in Q7a (not higher than 8mW/cm$^3$)
- Peak always at front face of the magnets
- Limit of 30MGy always exceeded
- Shift of critical value, due to change of insulator material?
- Further split of Q7 to reduce integrated dose? Shielding in Q7?

Critical situation in Q7: change half gap or position of collimator

- Updated optics.
- Margins on beam-stay clear (up to $\beta^* = 0.2$ m).
- Proposal to split Q1b to reduce peak energy deposition.
- Critical deposition in Q7: collimator to optimize.
- SR radiation is negligible.
- Linear correction scheme updated.
- Non linear correctors are mandatory for DA.
- Alternative triplet exists (same Qpoles).
- Flat optics (no crab cavities).
SR that reaches the experimental area

- MDISim used to produce geometry and magnetic field description
- SR simulation with GEANT4 from -700 m from IP, Gaussian proton beam

<table>
<thead>
<tr>
<th>Lattice v9</th>
<th>half crossing angle</th>
<th>Power (TAS) [W]</th>
<th>Power(Be) [W]</th>
<th>Nγ(Be) [10^3]</th>
<th>Eγ(Be) [keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>No</td>
<td>9</td>
<td>1</td>
<td>1</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>yes, 52µrad</td>
<td>27</td>
<td>1.2</td>
<td>2</td>
<td>0.2</td>
</tr>
<tr>
<td>Nominal</td>
<td>No</td>
<td>9</td>
<td>1</td>
<td>1</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>yes, 100µrad</td>
<td>47</td>
<td>13</td>
<td>16</td>
<td>0.2</td>
</tr>
</tbody>
</table>

- Slight increase of SR with the nominal crossing angle, due to the magnets that are switched on to produce it.

- Updated optics.
- Margins on beam-stay clear (up to $\beta^* = 0.2$ m).
- Proposal to split Q1b to reduce peak energy deposition.
- Critical deposition in Q7: collimator to optimize.

- SR radiation is negligible.
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- Flat optics (no crab cavities).
**Injection optics**

- For optimal machine protection, some constraints on injection optics apply:
  - Phase advance between kicker and TDI close to 90 degree, such that miskick translates into additional orbit offset at TDI.
  - Small dispersion to reduce kicker aperture and ease of protection device setup.
  - Large beam size at the TDI to limit peak energy density on the absorber [1].
- Currently very flat beam at TDI ($\beta_x = 37 \text{ m}, \beta_y = 932 \text{ m}$).
- Possible issues with collimator alignment [2].
- Alternative concepts to be looked into in the future.

---

**Updated optics.**

- Energy depositions is handled (500 fb$^{-1}$).
- New shielding design of MKI to reduce impedance.
  - Some solutions to mitigate impedance.
- New generator technologies required and studied.
- Loss studies for injection failures are ongoing.

---

Integrated Dose

- With current baseline radiation limits of 30 MGy, 500 $fb^{-1}$ seem feasible
- Options could be explored to increase triplet lifetime
  - Switch in crossing plane
  - Swap of triplet magnet in a long shutdown

- Updated optics.
- Energy depositions is handled (500 $fb^{-1}$).
- New shielding design of MKI to reduce impedance.
  - Some solutions to mitigate impedance.
- New generator technologies required and studied
- Loss studies for injection failures are ongoing.
Low $L$ + injection insertion

- Updated optics.
- Energy depositions is handled (500 fb\(^{-1}\)).
- New shielding design of MKI to reduce impedance.
  - Some solutions to mitigate impedance.

- New generator technologies required and studied
- Loss studies for injection failures are ongoing.

MKI impedance (1/2)

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

See presentation by A. Chmielinska for details.

Data from A. Chmielinska

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Courtesy: Arsenyev

Updated optics.
Energy depositions is handled (500 fb\(^{-1}\)).
New shielding design of MKI to reduce impedance.
- Some solutions to mitigate impedance.

New generator technologies required and studied
Loss studies for injection failures are ongoing.
Extraction

**New Baseline:**

- IPD, 2.8 km for extraction of beam 1 and 2
- 2.5 km dumpline with dilution kicker system to create sweep pattern at graphite beam dump
- Design mainly driven by machine protection
  - Safely extract 8.5 GJ beam
  - Reduce failure probabilities
  - Avoid downtime in case of failure

- New proposed baseline.
  - Reduced system length, pot. less kick strength required
  - Highly segmented extraction kicker system (150 modules).
  - Up to 4 kickers can safely pre-fire without damage to the machine.

- Impact of 1.5 sigma oscillation in case of single erratic acceptable.
- System designed to run with min. 10% less dilution/kick strength
- 4 abort gaps with 1.5 us proposed to reduce machine impact in case of failure
New proposed baseline.
- reduced system length, pot. less kick strength required

Highly segmented extraction kicker system (150 modules).

Up to 4 kickers can safely pre-fire without damage to the machine.

Impact of 1.5 sigma oscillation in case of single erratic acceptable.

System designed to run with min. 10% less dilution/kick strength

4 abort gaps with 1.5 us proposed to reduce machine impact in case of failure
Survival of Asynchronous Dump

**Extraction kicker:**
1 us risetime of extraction kicker to guarantee bunch spacing of ~1.8mm at septum protection

**Dilution kicker:**
Increased energy deposition at the beginning of the asynchronous dilution pattern

OK with new dilution pattern, but larger dump core (r ~70-80cm)

- New proposed baseline.
  - reduced system length, pot. less kick strength required
- Highly segmented extraction kicker system (150 modules).
- Up to 4 kickers can safely pre-fire without damage to the machine.

- Impact of 1.5 sigma oscillation in case of single erratic acceptable.
- System designed to run with min. 10% less dilution/kick strength
- 4 abort gaps with 1.5 us proposed to reduce machine impact in case of failure

Courtesy: Chmielinska
Collimation

Present baseline collimation system

- Most loaded collimators (primaries and first secondary) in CFC (carbon-fibre composite) for robustness, other secondaries in molybdenum-graphite with Mo coating for better impedance (taking over the HL-LHC design)

<table>
<thead>
<tr>
<th>Collimator</th>
<th>Material</th>
<th>Number</th>
<th>Injection ($\sigma$)</th>
<th>Collision ($\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>primary TCP</td>
<td>CFC</td>
<td>2</td>
<td>7.6</td>
<td>7.6</td>
</tr>
<tr>
<td>secondary TCSG</td>
<td>CFC/MoGr</td>
<td>11</td>
<td>8.8</td>
<td>8.8</td>
</tr>
<tr>
<td>absorption TCP</td>
<td>W</td>
<td>5</td>
<td>12.6</td>
<td>12.6</td>
</tr>
<tr>
<td>absorption TCLA</td>
<td>W</td>
<td>3</td>
<td>21.0</td>
<td>35.1</td>
</tr>
<tr>
<td>dispersion TCP</td>
<td>CFC</td>
<td>1</td>
<td>10.8</td>
<td>18.7</td>
</tr>
<tr>
<td>dispersion TCSG</td>
<td>MoGr</td>
<td>4</td>
<td>13.0</td>
<td>21.7</td>
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<td>dispersion TCLA</td>
<td>W</td>
<td>5</td>
<td>14.4</td>
<td>24.1</td>
</tr>
<tr>
<td>dispersion TCLD</td>
<td>W</td>
<td>4</td>
<td>21.0</td>
<td>35.1</td>
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<tr>
<td>tertiary TCP</td>
<td>W</td>
<td>12</td>
<td>14.0</td>
<td>10.5</td>
</tr>
<tr>
<td>dispersion TCT</td>
<td>W</td>
<td>8</td>
<td>21.0</td>
<td>35.1</td>
</tr>
<tr>
<td>dispersion TCDQ</td>
<td>CFC</td>
<td>1</td>
<td>9.8</td>
<td>9.8</td>
</tr>
<tr>
<td>dispersion TCLA</td>
<td>W</td>
<td>2</td>
<td>11.8</td>
<td>11.8</td>
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<tr>
<td>dispersion TCLD</td>
<td>W</td>
<td>1</td>
<td>21.0</td>
<td>35.1</td>
</tr>
</tbody>
</table>

Still to be added in lattice: active physics debris absorbers

For 2.2 µm emittance

- Updated optics of momentum collimation insertion (larger dispersion) and DIS (reduction of peaks).
- Updated collimator lists.
- Cleaning at injection is acceptable (also in energy collimation section).
- May need skew collimator.

Betatron cleaning
- Momentum cleaning
- Experiments
- Extraction

Outgassing from collimators, power loads on warm magnets, passive absorbers, material of cooling pipes.
Updated optics of momentum collimation insertion (larger dispersion) and DIS (reduction of peaks).

Updated collimator lists.

Cleaning at injection is acceptable (also in energy collimation section).

May need skew collimator.
Collimation

Induced power density in the most exposed dipole

- Updated optics of momentum collimation insertion (larger dispersion) and DIS (reduction of peaks).
- Updated collimator lists.
- Cleaning at injection is acceptable (also in energy collimation section).
- May need skew collimator.

- Extended studies in cold parts.
  - TCLD is a must do have in DIS.

- Extended thermo-mechanical studies.
  - Collimation system survives.
  - Outgassing from collimators, power loads on warm magnets, passive absorbers, material of cooling pipes.

Maximum power density deposited in FCC-hh main dipole is 80 mW/cc

r-φ-z resolution: 1.86cm, 2°, 10cm (three radial bins of 1.86cm)

By increasing the energy, the peak power density increases as $E^{(1.15)}$ for low radial resolution and as $E^{(1.36)}$ for 3mm radial bins...corrected by the respective loss density ratio...
Collimation

Results - CFC absorber

- No failure demonstrated experimentally
- Numerical model overestimates stresses

The HRMT-23 case: max simulated T on CFC jaw: 685 °C (288b, 3.79E13p, σ = 0.35 mm)

The HRMT-36 case: >1500 °C (grazing shot at 288b, 3.72E13p, σ = 0.25 mm) → No failure observed experimentally

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- Updated collimator lists.
- Cleaning at injection is acceptable (also in energy collimation section).
- May need skew collimator.

- Extended studies in cold parts.
  - TCLD is a must do have in DIS.
- Extended thermo-mechanical studies.
  - Collimation system survives.
  - Outgassing from collimators, power loads on warm magnets, passive absorbers, material of cooling pipes.
Updated optics.

- RF power, single-bunch stability and coupled-bunch stability gave an updated of beam and RF parameters.
  - At flat top $V_{RF} = 38$ MV.
  - At flat bottom $\tau_{4\sigma} = 1.35$ ns.
  - Long. emittance blowup $\propto \sqrt{E}$.

- RF power consumption was calculated for different transient beam loading compensation schemes.
  - Full compensation requires 600 kW peak power during acceleration (against 400 kW without compensation).
Keeping constant amplitude and phase of the cavity voltage during the FCC-hh cycle would require about 600 kW peak power (half-detuning scheme).

The full-detuning scheme requires about 25% more power compared with the case without transient beam loading compensation.

*I. Karpov, P. Baudreghien, submitted to PRAB

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Dynamic aperture + beam-beam

Global compensation of long range interactions

We choose to have Landau Octupoles powered such that they compensate the BB long-range effects:
- provides larger stability for single beam (see beam stability studies)
- allows for larger Dynamic aperture → beam lifetimes
- Full integration in the lattice design (J. Shi et al., CERN-ACC-NOTE-2017-036)

Lattice and Beam-Beam optimized together to enhance at a design stage the natural compensation between effects and allow these flexibility.

- Negative polarity for octupoles.
- Phase advance PA/PG compatible DA and beam-beam at collision.
- DA > 5σ with multipolar errors + beam-beam (Ultimate).
- Large β-beating due to beam-beam.
- Updated DA with new lattice and error table of dipoles.
- DA below target value when octupoles are used at injection.
- Still above collimation settings.
- DA reduced also by RF bucket.
• 60 seeds simulation → 60 different machines
• Minimum of DA 5σ reached → Reduction of 2σ w.r.t. the case without errors
• Challenging set-up that needs further studies and newer ways to look at DA because of the very large parameter space → Machine Learning project on-going to automatize the optimization of DA-lifetimes and feedback to design

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Dynamic aperture + beam-beam

Effect of Landau Damping

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  - Still above collimation settings.
  - DA reduced also by RF bucket.

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Certificate: Dalena

- Minimum DA below target with LO (like for LHC)
- Minimum above the collimation settings \( \Rightarrow \) is not considered a big issue
- DA is dominated by multipoles random components with sextupole and decapole correction
- DA seeds distribution is non Gaussian

17/10/2018 B. Dalena, 4th EuroCirCol meeting
Landau damping has been addressed:
- Octupoles, energy scaling and damping of "non-rigid" bunch modes
- Electron lenses and combinations.
- Beam Transfer Function simulation of stable beams and time evolution of unstable beams

Energy scaling of electron cloud induced effects: induced tune shift negligible for FCC-hh

Fully squeezed optics does not allow margins at end of squeeze.
- Initial collisions at larger $\beta^*$. 
- Collide and Squeeze.
Two beam stability: Collide & Squeeze

In order to avoid stability reduction during the squeeze, collisions at larger $\beta^*$ are foreseen (as for the HL-LHC).

Beam-beam wise we cancel long-range beam-beam effects and have only head-on $\rightarrow$ go to reduced separations when beams transverse emittances have been reduced due to damping.

- Stability reduction evaluated w.r.t. the flat top SD with negative octupole polarity (relative difference of the negative real part at the half-height).
- $\beta^* = 1.1\text{ m}$: reduction of stability of few percent $\rightarrow$ negligible effect.

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- Collide and Squeeze.
FCC beam screen: copper coating

“Optimum” thickness of the copper layer: 300 µm

D. Astapovych

- Mechanical design updated and validated by impedance team.
- Resistive wall impedance to reduce:
  - Cu coating thickness: 0.3 mm.
  - Stainless edge increases impedance.
  - Mitigation proposals: coating the edge or bending, sharp cuts.
- Reduction of SEY (Electron cloud).
- a-C coating (baseline).
- Alternatives need other treatments like LASE coating.
- Reduction of photoelectron yield.
- Saw-tooth sufficiently efficient.
- Radiation absorbers may be an issue if separation of 5 ns.
Stainless steel edge (1/3)

Stainless steel is ~1000 times more resistive than copper:
\[
\rho_{\text{copper}} (50K, 1.06T) = 7.88 \times 10^{-10} \ \Omega \text{m}
\]
\[
\rho_{\text{st.steel}} = 6 \times 10^{-7} \ \Omega \text{m}
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Mitigation scenario for alternative beams

- LASE surface treatments an option for decreasing the SEY beyond a-C
  - Within constraints imposed by the impedance
- Coating or other mitigation scheme to be considered also in drifts

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Photoelectron yield in drifts

New more detailed simulations with photoelectrons based on ray-tracing simulations as well as photoelectron yield measurements on Cu and LASE surfaces (WP4)

- Two distinct areas are considered in the interconnections

Mechanical design updated and validated by impedance team.

- Resistive wall impedance to reduce:
  - Cu coating thickness: 0.3 mm.
  - Stainless edge increases impedance.
  - Mitigation proposals: coating the edge or bending, sharp cuts.

Reduction of SEY (Electron cloud).

- a-C coating (baseline).
- Alternatives need other treatments like LASE coating.

Reduction of photoelectron yield.

- Saw-tooth sufficiently efficient.
- Radiation absorbers may be an issue if separation of 5 ns.
Beam screen: experiments

 Courtesy: Valizadeh

- LASE surface enables small SEY but impact on impedance not very well known. Needs for experiments.
  - Promising results: SEY of 1.1/0.8 with a surface resistance increase by 14%/60%.
  - To be continued.

- Photodesorptions measured at KARA.
  - Validation of saw tooth strategy.
  - LASE treatment has a dramatic effect.
  - Experiments at DAFNE very soon.

- Discrepancy between SEY models.
  - Needs for validation experiments.
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Secondary emission yield model

A comparison of two different SEY models for Cu surfaces was presented in Amsterdam.

Work by D. Astapovych, using openECLeOUD code

Significant differences in the multipacting thresholds with the two models were found.

Possible causes:
- Shape of total SEY curve for given $\delta_{\text{max}}$
- Energy spectrum of emitted electrons for rediffused component
- Numerical details e.g. representation of emitted electrons

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Discrepancy between SEY models.
- Needs for validation experiments.
- scSPS option (at 1.3 TeV) excluded because of dynamic aperture. Large energy swing may be an issue.

- Existing LHC with 5x faster ramp.
  - 3.3 TeV beam (baseline),
  - Longer filling time than desired.
  - High operating cost and complexity, availability concerns.

- 4 T, 27 km, purposed built single aperture HEB alternative:
  - Less complex machine.
  - Slightly faster filling time (39 minutes).

- Costing is needed for real comparison of both options.
Nucleon-Nucleon Luminosity Evolution

Assumptions:
- Ultimate Pb parameters
- Intensity scaling with $p=1.5$ for lighter species.
- 2 experiments

Increased luminosity lifetime, more particles available for hadronic interactions.

FCC-hh could be a very high performance heavy-ion collider.

Lead but also lighter ions are considered.
  - Operationally less challenging
  - Potential for higher performance compared to baseline Pb.

Collimation system has a good cleaning performance.

As for FCC-pp, the TCLD is a must do have.
FCC-hh could be a very high performance heavy-ion collider.

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  - Operationally less challenging
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Collimation system has a good cleaning performance.

As for FCC-pp, the TCLD is a must do have.
- A lot of different aspects have been covered: optics, collimation, dynamic aperture, collimation, machine protection, single and two beam stability, beam-beam, experimental set-up …
- All results are compiled in the long CDR.
- FCC-hh machine design is in good shape.
- Selected outlook:
  - Development of IA algorithms to predict DA.
  - To split inner triplet quadrupole to reduce peak dose.
  - New materials or system design for collimation.
  - Electron lenses or RF quads.
  - Experimental data for surface properties (SEY, impact of LASE treatment on impedance,…).
  - and many other topics.
Thank you for your attention and to all the team for the great work!