SRF for Future Circular Colliders
Rama Calaga, CERN
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Acknowledgements:
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May 2015: Record collisions at 13 TeV CM!
FCC Study Scope

FCC-hh: 50 TeV proton collider as a long term goal
FCC-ee: 45.5-175 GeV $e^+e^-$ collider as an intermediate step
FCC-he: Study integration aspects for electron-ion collisions

Main Goal
- Complete exploration of Higgs
- Direct/indirect probes beyond SM

Dedicated SC R&D programs
- 16 T dipole magnets for 100 TeV in 100 km
- SRF technologies & RF power sources
Livingston Plot

Hadron Colliders

100 TeV

FCC-hh: 0.5-3x10^{35} /cm^2s

e^+e^- Colliders

10 TeV

ILC: 2x10^{34} /cm^2s

1 TeV

FCC-ee: .7-1x10^{35} /cm^2s

100 GeV

Livingston Plot

W. Panofsky
Parameters, FCC-hh

Main goal increase the LHC energy by factor ~7
Increase ramp rate (~30 min) by factor ~18 from LHC

<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th>HL-LHC</th>
<th>FCC-hh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [TeV]</td>
<td>7</td>
<td>7</td>
<td>50</td>
</tr>
<tr>
<td>Current, DC [A]</td>
<td>0.55</td>
<td>1.1</td>
<td>0.51</td>
</tr>
<tr>
<td>Rad Loss [MeV]</td>
<td>0.007</td>
<td>0.007</td>
<td>3.9</td>
</tr>
<tr>
<td>Total Voltage [MV]</td>
<td>16</td>
<td>16</td>
<td>&gt;32</td>
</tr>
<tr>
<td># of Cavities</td>
<td>8</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>RF Power [kW]*</td>
<td>300</td>
<td>450</td>
<td>300-500</td>
</tr>
<tr>
<td>Frequency [MHz]</td>
<td></td>
<td>400</td>
<td></td>
</tr>
</tbody>
</table>

*Using $\frac{1}{2}$-detuning: $R/Q=45\Omega$ & $QL=60k$, $V=2$ MV/cavity
FCC -hh, Stability

Bunch length = 1ns
Bunch spacing = 5ns, 25 ns
Frequency = 400 MHz

Optimum filling factor (bucket losses vs. instability threshold)
Single bunch instability, loss of landau damping

For example: 16 MV ($\varepsilon_L=7.0$ eVs) $\rightarrow$ 0.2 $\Omega$ (LHC $\sim$0.1 $\Omega$)

Continuous longitudinal blow necessary due to sync radiation
2\textsuperscript{nd} harmonic system may be necessary, not considered here

Courtesy E. Shaposhnikova
FCC -hh, RF

Inject, capture & ramp 10600 bunches 3.3 – 50 TeV
Store 50 TeV beams

Keep peak power & voltage \textbf{constant}

\[
\Delta f = \frac{1}{4} I_b \frac{R/Q}{V_{RF}} f_{RF}
\]

\(\frac{1}{2}\)-detuning is -3.1 kHz @0.51A, at 2 MV
Remember that revolution freq (100 km) = 3 kHz

Will excite strong coupled bunch instabilities (feedback!)
Synchrotron freq. is 2.9 Hz! RF Noise may become an issue
FCC -hh, RF Power

Additional 4.5 MW total power to ramp the beam (+ synchrotron radiation power)

* Possibly requires variable coupler

If beam current increases, the ramp rate must proportionally increase
FCC -hh, Energy Ramp

A simple RF program during the energy ramp (30 min)
Energy ramp is the dominant factor, optimization feasible

![Graph showing RF Power vs Energy for different cavity voltages: 1.0 MV, 1.5 MV, 2.0 MV.](image)

N. of Cavities = 16
Present LHC RF System

FCC -hh: At least 2-3 times the LHC system & increased power handling capacity to ~500 kW – CW is necessary

8 SC Cavities/beam (400 MHz, 2 MV)

RF Power

300 kW LHC
Variable Coupler
4-HOM Couplers

300 kW Klystron
LHC 400 MHz
Handful of sources available at low freq with high power CW
SSA in this power range (& low noise) could be expected in 2 decades (?)
FCC -ee, RF

The maximum energy (physics) $\rightarrow$ appropriate circumference (sync radiation)
Radiation loss + energy acceptance $\rightarrow$ required voltage
Available power ($\sim$50 MW) $\rightarrow$ maximum current at each energy
Parameters, FCC-ee

Main goal to provide Higgs~5-30 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} (in 2-phases)

From LEP2 → Extend energy ~factor 2 & current by several orders

<table>
<thead>
<tr>
<th></th>
<th>LEP2</th>
<th>FCC-Z</th>
<th>FCC-W</th>
<th>FCC-H</th>
<th>FCC-T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [GeV]</td>
<td>104</td>
<td>45.5</td>
<td>80</td>
<td>120</td>
<td>175</td>
</tr>
<tr>
<td>Current [A]</td>
<td>0.003</td>
<td>1.45</td>
<td>0.152</td>
<td>0.03</td>
<td>0.0066</td>
</tr>
<tr>
<td>Rad Loss [GV]</td>
<td>3.34</td>
<td>0.03</td>
<td>0.33</td>
<td>1.67</td>
<td>7.55</td>
</tr>
<tr>
<td>Total Voltage [GV]</td>
<td>3.5</td>
<td>2.5</td>
<td>4.0</td>
<td>5.5</td>
<td>11.0</td>
</tr>
<tr>
<td>Frequency [MHz]</td>
<td>352.2</td>
<td></td>
<td></td>
<td>400.79</td>
<td></td>
</tr>
<tr>
<td>Harmonic #</td>
<td>31320</td>
<td></td>
<td></td>
<td>133689</td>
<td></td>
</tr>
</tbody>
</table>

2\text{nd} harmonic is not considered but maybe needed
FCC-ee, RF & Staging

Large variation in detuning angle ($Z$-energy $> \text{factor } 4.f_{\text{rev}}$)

Extremely large HOM power for high current $\rightarrow$ limit on number of cells

Assumption:

$fr_{\text{rev}} = 3 \text{ kHz}$
Existing Cavity Options

Frequency: 350-500 MHz

352 MHz: LEP, Nb-Cu

352 MHz: Bulk Nb Variant

400 MHz: LHC, Nb-Cu

CESR-B: 500 MHz

500 MHz: CESR-B, KEK-B
LEP Experience, Nb/Cu

One of the largest SRF installation to date, the only to successfully exploit thin-film technology to record energies
LEP 2 SC-Cavity Performance

Mean value of approximately 7.2 MV/cavity → 12 MV/cavity (4-cells)
We assume same performance for a 4-cell equivalent
Cavity Options, 400 MHz

2+2 cells is assumed as a reference – study ongoing
Minimize beam loading & HOM power

<table>
<thead>
<tr>
<th></th>
<th>1-Cell</th>
<th>2-Cells</th>
<th>4-Cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$ [m], Active</td>
<td>0.374</td>
<td>0.748</td>
<td>1.5</td>
</tr>
<tr>
<td>$V$ [MV]/cav</td>
<td>3.75</td>
<td>7.5</td>
<td>15</td>
</tr>
<tr>
<td>$E_p$ /$E_a$</td>
<td>3.1</td>
<td>3.3</td>
<td>3.3</td>
</tr>
<tr>
<td>$B_p$ [mT]/$E_a$</td>
<td>4.2</td>
<td>4.7</td>
<td>4.7</td>
</tr>
<tr>
<td>$R/Q$ [$\Omega$]</td>
<td>87</td>
<td>169</td>
<td>310</td>
</tr>
<tr>
<td>$U$ [J]</td>
<td>0.54</td>
<td>1.3</td>
<td>2.7</td>
</tr>
</tbody>
</table>
FCC ee, RF Layout

Total available length: 1.2 km

10 symmetrically placed straight sections for RF
Layout Options, 4-Cell Equivalent

2+2 cell structure as baseline, 1.2-1.4 km (tt)

# of cavities: 350 (+350 stage 2)

LEP like configuration

Hybrid Structure

LHC like configuration
FCC-ee, RF Power

At optimum coupling at $QL \sim 10^6 - 10^7$, Power of $\sim 100$ kW

Z-nominal is most demanding case – RF staging

Approx factor 10
FCC-ee, RF Power Options

LEP 1.3 MW Klystrons driving 8 Cavities

But, single source failure leads to large voltage drop (LEP ~100 MV)

For FCC -ee

High efficiency klystrons using core oscillation method (Lingwood et al.)
Multibeam IOT development (Morten et al., ESS)

Single source (~100 kW range), single cavity (IOT & SSA) more appropriate
Low RF noise & RF distribution system needs careful study
Loss Factor vs Bunch Length

\[ k_{\text{loss}} \propto \frac{1}{R_{\text{iris}}} \sqrt{\frac{\text{gap}}{\sigma_z}} \sqrt{N_{\text{cell}}} \]

Longer bunch lengths to be considered also for transverse impedance

*Remember: 400 → 800 MHz: approx x1.5 increase in # of cells*
### Parameters, FCC-ee

Z-nominal is most demanding case – input power & HOM power

Higher freqs. become **incompatible** with high current case

<table>
<thead>
<tr>
<th></th>
<th>FCC-Z</th>
<th>FCC-W</th>
<th>FCC-H</th>
<th>FCC-T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [GeV]</td>
<td>45.5</td>
<td>80</td>
<td>120</td>
<td>175</td>
</tr>
<tr>
<td>Beam Current [mA]</td>
<td>1450</td>
<td>152</td>
<td>30</td>
<td>6.6</td>
</tr>
<tr>
<td>Voltage [MV, 2+2 Cells]</td>
<td>3.57</td>
<td>5.71</td>
<td>7.85</td>
<td>7.85</td>
</tr>
<tr>
<td>Opt Detuning [kHz]</td>
<td>-13.6</td>
<td>-0.89</td>
<td>-0.12</td>
<td>-0.02</td>
</tr>
<tr>
<td>QL, opt</td>
<td>$0.7 \times 10^6$</td>
<td>$2.7 \times 10^6$</td>
<td>$5.3 \times 10^6$</td>
<td>$1.0 \times 10^7$</td>
</tr>
<tr>
<td>Input Power [kW]</td>
<td>100</td>
<td>72</td>
<td>72</td>
<td>36</td>
</tr>
<tr>
<td>HOM Power [kW]</td>
<td><strong>29</strong></td>
<td>1.2</td>
<td>0.15</td>
<td>0.1</td>
</tr>
</tbody>
</table>
HOM Power Extraction

Two known solutions for HOM extraction

Cornell/KEKB like ferrites, 300K
~10 kW (approx 8°C/kW temp rise)

LEP/LHC like loops, 4.5K
~1 kW maximum
Parameters, FCC -he

Goal: Luminosity $> 1 \times 10^{34}$ cm$^{-2}$ s$^{-1}$

LHeC design study is the reference baseline for FCC -he

Option 1: Use the LHeC-ERL to collide 60 GeV on 50 TeV

Option 2: Co-existing ee & hh in the FCC ring upto 200 GeV on 50 TeV

<table>
<thead>
<tr>
<th></th>
<th>LHeC-ERL (Electrons)</th>
<th>LHC (Protons)</th>
<th>FCC (Protons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [TeV]</td>
<td>0.06</td>
<td>7.0</td>
<td>50</td>
</tr>
<tr>
<td>Current, DC [A]</td>
<td>0.15 (6-passes)</td>
<td>1.1</td>
<td>0.51</td>
</tr>
<tr>
<td>Total Voltage/turn [MV]</td>
<td>2000</td>
<td>16</td>
<td>32</td>
</tr>
<tr>
<td># of Cavities</td>
<td>1069</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>RF Power [kW]*</td>
<td>~25</td>
<td>300</td>
<td>340</td>
</tr>
</tbody>
</table>

* RF power for ERL linac ($\sim 20$ Hz detuning, QL=$3 \times 10^7$)
ERL Option, FCC -he

Energy: 60 GeV
Number of passes: 6
Beam current: 6.6-25.6 mA

Two 10 GeV linacs
Frequency: 801.58 MHz (h=20)
Voltage: 18.7 MV/cavity
Cryo losses: (∼ 25 MW @3x10^{10})

Basic unit: 5-cell cavity into 4-cavity module
ERL Option, FCC -he

Energy recovery after total 6 passes: 95.2 %

Sync radiation loss: 2.88 GeV (73.6 MW accumulated beam power)
Extra power for finite bandwidth of ERL cavities (~15 MW)

Note: ERL in the LHC tunnel or FCC tunnel would reduce the beam power by x3-10
Why Now?

## Future Collider

<table>
<thead>
<tr>
<th>(Estimates)</th>
<th>FCC-hh</th>
<th>FCC-ee</th>
<th>FCC-he</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [TeV]</td>
<td>50 TeV</td>
<td>45.5-175 GeV</td>
<td>50 / 0.06</td>
</tr>
<tr>
<td>RF Voltage/turn [GV]</td>
<td>0.03-0.05</td>
<td>2.5-11.0</td>
<td>20</td>
</tr>
<tr>
<td>RF Power [MW]</td>
<td>8.0</td>
<td>50</td>
<td>70</td>
</tr>
<tr>
<td>Cryo Losses [MW]</td>
<td>0.002</td>
<td>23</td>
<td>25</td>
</tr>
</tbody>
</table>
Next Steps

Proton-proton

Approximately 2-3 times the LHC RF (400 MHz, 32-50 MV, 500 kW)
Heavy R&D on RF power chain, FPC, low noise amplifiers, feedback

Electron-Positron

Most challenging! ~3 times LEP RF (2.5-11 GV, 400 MHz)
High $Q_0$ (thin films), low impedance, high power HOM coupler

Electron-Ion

60 GeV-ERL feasible, power 100+ MW (High $Q_0 \sim 10^{11}$ is essential)
“ERL” in FCC-ring will be optimum (+ top up injector)
Additional Slides: FCC -hh, RF

Assume: 16 Cavities/beam with 500 kW/cavity
Injection, 3.3 TeV (16 MV capture voltage)
Ramp rate ~30 min, ~ 9MeV/turn, Power = 4.5 MW/beam
Top energy, rad loss 3.9 MeV (32 MV total)
Transverse Loss Factor vs Bunch Length

\[ k_{\text{trans}} \propto \frac{1}{R_{\text{iris}}^3} \sqrt{\text{gap} \cdot \sigma_z N_{\text{cells}}} \]

Limiting factor for transverse instabilities. 400 MHz with large aperture is clearly beneficial.
Longitudinal Loss Factors

\[ P_{\text{ave}} = (k_{\text{loss}} Q) I_{\text{beam}} \]

1 V/pC \(\sim\) 42 kW of HOM power /cavity

4-cell cavities starts to become unfeasible
Impedance Spectrum, Longitudinal

Fundamental mode: 400.79 MHz
Impedance Spectrum, Transverse

Fundamental mode: 400.79 MHz
Assume for FCC ~25W @4.5K, 2MV (dynamic)/cavity
~45W @4.5K (static+dynamic)/cavity
Total ~1.5 kW @4.5K (32 cavities – 2 beams) – not very big
At 800 MHz, $R_{BCS} = 250 \text{ n}\Omega$

$Q_0$ increase beyond $10^9$ difficult while at 400 MHz easier

(2+2) cells @400 MHz $\sim 126$W (for 15MV total, for approx 30% more length),
ERL, Power Options

Good experience with 800 MHz IOTs (~60 kW) for the SPS 3rd harmonic system

Chain of 8 IOTs installed powering two cavities in the SPS