The Availability Challenge:
Targets, shortfalls and game-changing opportunities

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Acknowledgements: Lukas Felsberger, Jan Uythoven, Daniel Wollmann, Felix Rodriguez Mateos

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Availability and Integrated Luminosity

- **Integrated Luminosity:**

  Goals:

  \[
  L_{\text{int}} = ATL
  \]

  \[
  L = \text{Nominal luminosity}
  \]

  \[
  T = \text{Time for physics}
  \]

  \[
  A = \text{Availability} = \frac{\text{up time}}{\text{total time}}
  \]

  \[
  A_{\text{FCC}} \geq 80\%
  \]

<table>
<thead>
<tr>
<th>(L (10^{34}/\text{cm}^2\text{s}))</th>
<th>Run time (years)</th>
<th>(L_{\text{int}} \text{ (ab}^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Z)</td>
<td>200</td>
<td>4</td>
</tr>
<tr>
<td>(W)</td>
<td>25</td>
<td>2</td>
</tr>
<tr>
<td>(H)</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>(t\bar{t})</td>
<td>1.4</td>
<td>4</td>
</tr>
</tbody>
</table>

**FCC-ee Availability Requirement:**

- 365 days
- -120 (extended shutdowns)
- -30 (annual commissioning)
- -20 (machine development)
- -10 (technical stops)

185 days for physics

LHC Availability in Run 2 (2016-2018)

\[ A_{LHC} = 77\% \]

- Down time scales with number of components:

For example:

<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th>FCC-ee</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipoles</td>
<td>1232</td>
<td>2900 – 11600</td>
</tr>
<tr>
<td>RF cavities (accelerating)</td>
<td>16</td>
<td>140 – 1232</td>
</tr>
</tbody>
</table>

“Accelerator Fault Tracker”, [https://aft.cern.ch/](https://aft.cern.ch/)
Three-step approach

1. Targets
   To reach overall 80% availability:
   • “RF availability must be above…”
   • “Top-up booster must be above…”
   • ...

2. Shortfalls
   Based on current designs & similar systems:
   • “RF Availability will likely be…”
   • “Top-up booster will likely be…”
   • ...

3. Opportunities
   Where do we fall short?
   What can we do about this?
   • Solution 1...
   • Solution 2...
1. Targets $\hat{A}_i$

Allocate availability according to the "complexity" of assuring it.

<table>
<thead>
<tr>
<th>$i$</th>
<th>System $i$</th>
<th>Complexity (%)</th>
<th>Availability Target $\hat{A}_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Top-Up Booster Ring</td>
<td>$c_1$</td>
<td>$\hat{A}_1$</td>
</tr>
<tr>
<td>2</td>
<td>Radio Frequency</td>
<td>$c_2$</td>
<td>$\hat{A}_2$</td>
</tr>
<tr>
<td>3</td>
<td>Power Converters</td>
<td>$c_3$</td>
<td>$\hat{A}_3$</td>
</tr>
<tr>
<td>4</td>
<td>Vacuum</td>
<td>$c_4$</td>
<td>$\hat{A}_4$</td>
</tr>
<tr>
<td>5</td>
<td>Cryogenics</td>
<td>$c_5$</td>
<td>$\hat{A}_5$</td>
</tr>
<tr>
<td>6</td>
<td>Extraction &amp; Beam Dump</td>
<td>$c_6$</td>
<td>$\hat{A}_6$</td>
</tr>
<tr>
<td>7</td>
<td>Machine Protection &amp; Interlocks</td>
<td>$c_7$</td>
<td>$\hat{A}_7$</td>
</tr>
<tr>
<td>8</td>
<td>Collimation</td>
<td>$c_8$</td>
<td>$\hat{A}_8$</td>
</tr>
<tr>
<td>9</td>
<td>Beam Instrumentation</td>
<td>$c_9$</td>
<td>$\hat{A}_9$</td>
</tr>
<tr>
<td>10</td>
<td>Cooling &amp; Ventilation</td>
<td>$c_{10}$</td>
<td>$\hat{A}_{10}$</td>
</tr>
<tr>
<td>11</td>
<td>Electrical Networks</td>
<td>$c_{11}$</td>
<td>$\hat{A}_{11}$</td>
</tr>
<tr>
<td>12</td>
<td>Experiments</td>
<td>$c_{12}$</td>
<td>$\hat{A}_{12}$</td>
</tr>
<tr>
<td>$\vdots$</td>
<td>etc., etc…</td>
<td>$\vdots$</td>
<td>$\vdots$</td>
</tr>
</tbody>
</table>

$\hat{A}_{FCC} \geq 80\%$

$\prod \hat{A}_i = \hat{A}_{FCC} = 0.8$

$\hat{A}_i = 0.8^{c_i}$

Higher complexity $\implies$ Lower target

$c_1 > c_2 > \cdots > c_N \implies \hat{A}_1 < \hat{A}_2 < \cdots < \hat{A}_N$
1. Targets $\widehat{A}_i$

Seven scores define complexity $c_i$

System $i$:

- Repair Time
- Criticality
- Intricacy
- Liability
- Technical Maturity
- Performance Time
- Environment

Complexity $c_i$:

Input from 20 accelerator experts:

- “Generalist” profile
- Diverse backgrounds

$\widehat{A}_i = 0.8^{c_i}$

References:

1. Targets $\hat{A}_i$

FCC-ee (targets)

LHC (achieved)
Three-step approach

1. Targets

To reach overall 80% availability:
• “RF availability must be above 97.7%”
• “Top-up booster must be above 97.5%”
• ...

2. Shortfalls

Based on current designs & similar systems:
• “RF Availability will likely be…”
• “Top-up booster will likely be…”
• ...

3. Opportunities

Where do we fall short?
What can we do about this?
• Solution 1...
• Solution 2...
2. Shortfalls

Radio Frequency (RF)

<table>
<thead>
<tr>
<th>Energy Mode</th>
<th>Z 45.6 GeV</th>
<th>W 80 GeV</th>
<th>H 120 GeV</th>
<th>tt̅ 182.5 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (MV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gradient (MV/m)</td>
<td>5.72</td>
<td>5.34</td>
<td>10.95</td>
<td>21.55</td>
</tr>
<tr>
<td>Cavity voltage (MV)</td>
<td>2.14</td>
<td>5.00</td>
<td>8.20</td>
<td>20.19</td>
</tr>
<tr>
<td>Beam current (mA)</td>
<td>1400</td>
<td>140</td>
<td>135</td>
<td>13.5</td>
</tr>
<tr>
<td># Cells / cavity</td>
<td>1</td>
<td>5</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td># Cavities</td>
<td>56</td>
<td>28</td>
<td>128</td>
<td>52</td>
</tr>
</tbody>
</table>

*Table 1: RF configurations in FCC-ee [12]*

*Per beam; †Both beams; ‡Includes cavities from H mode

Z, W
- High current, low voltage
- 140-308 cavities
- RF trip = beam loss

H, tt̅
- Low current, high voltage
- 360-1232 cavities
- 10% voltage redundancy
2. Shortfalls

Monte Carlo Simulation:

Phase Transitions:
- Default
- Repair complete
- Main RF failure
- Booster RF failure

States:
- Available, no luminosity
- Available, luminosity
- Unavailable

- Set Up: 10 min
- Fill: 5 min
- Adjust: 10 min
- Physics + Top-Up: Until Failure
- Burn Off: 60 min (or until Repair)

Down for Repair: Until Repair

https://gitlab.cern.ch/availsim4/
2. Shortfalls

94 RF Faults in LHC Run 2

Repair

< 1h

> 1h

Short Faults

- Repair achieved without human intervention
- E.g. by remote reset
- Achievable while beam is running

Long Faults

- Requires human intervention
- Add a 45 minute drive time for FCC-ee
- Must wait until system is “down for repair”
2. Shortfalls

FCC-ee
RF only

Requirement = 97.7%

- $N_{cav} = 140$, RF Availability = 89.40%
- $N_{cav} = 308$, RF Availability = 79.34%
- $N_{cav} = 360$, RF Availability = 98.37%
- $N_{cav} = 1232$, RF Availability = 98.20%

No redundancy
10% redundancy
2. Shortfalls

### KEK-B:
- Gradient (MV/m): 6
- Beam Current (mA): 1400

KEK-B RF is more similar to FCC-ee in Z,W modes.

#### RF System fault statistics

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<th>t(\bar{t}) 182.5 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>main*</td>
<td>booster</td>
<td>main†</td>
<td>booster</td>
</tr>
<tr>
<td>Voltage (MV)</td>
<td>120</td>
<td>140</td>
<td>1050</td>
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<td>Cavity voltage (MV)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>260</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>696†</td>
<td>536</td>
</tr>
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*Table 1: RF configurations in FCC-ee [12]*

*Per beam; †Both beams; †Includes cavities from H mode

### FCC-ee:

If we use KEK-B fault statistics, FCC-ee availability is 5 times worse!

- **LHC**: Gradient (MV/m) 6, Beam Current (mA) 1400
- **KEK-B**: Gradient (MV/m) 6, Beam Current (mA) 1400


Three-step approach

1. Targets

To reach overall 80% availability:
- "RF availability must be above 97.7%"
- "Top-up booster must be above 97.5%"
- ...

2. Shortfalls

Based on current designs & similar systems:
- "RF Availability will likely be 89 & 79%"
- "Top-up booster will likely be..."
- ...

3. Opportunities

Where do we fall short? RF system in Z & W modes

What can we do about this?
- Solution 1...
- Solution 2...
3. Opportunities

Increase reliability

- MTBF per cavity circuit
- Hardware approach

E.g. Solid State Power Amplifiers (SSPAs) vs Klystrons

**SPS SSPA Towers**

16 towers (1280 SSPAs) = 1.6 MW


3. Opportunities

Drive time
- 45 min – 1h+

Reduce / anticipate
- Scatter teams of technicians
- Helicopter transport
- Robot Maintenance (slide 17)
- Late-stage prognostics (slide 18)
3. Opportunities

Robot Maintenance

Repair more faults while the beam is running

“Short” : “Long” fault ratio

(also eliminates drive time)

3. Opportunities

Fault Prediction

1. Identify and diagnose a deterioration in health

2. Repair / replace relevant components before the fault occurs

Also prevents child faults & collateral damage

Physical models (“white box”)
- E.g. X-ray monitoring for cavity degradation

Statistical models (“black box”)
- E.g. unsupervised anomaly detection

Applied to Long faults only.

Control Center

Health insights:
- Performance
- Efficiency
- Anomalies

Actions:
- Testing
- Maintenance
- Replace parts

Digital Twin

Sensor data

• Virtual models of system + processes
• Analysis of sensor data

Physical System

- Physical system
- Sensors

Sensor data

(Performance, health, events)

Applied to Long faults only.

FCCWEEK 2023 8th June 2023
Jack Heron | The Availability Challenge: Targets, shortfalls and game-changing opportunities
Results

Z Mode

W Mode
Results

Z Mode

W Mode
Summary

- **Targets:** Availability requirements defined at system level (for the first time!)
  - Scaled according to complexity of availability assurance

- **Shortfalls:** Projected RF availability in Z & W modes (according to LHC data) is worrying low.
  - Even worse if we look at more similar systems e.g. KEK-B

- **Opportunities:** Four solutions are analysed
  1. Increase reliability (pure hardware approach)
  2. Reduce / anticipate drive time
  3. Robot Maintenance
  4. Fault prediction
Conclusions

• The availability challenge is real.

• A seismic shift in operation & maintenance paradigm is required.

• Most compelling solutions for RF:
  • Reliability per cavity circuit
  • Fault Prediction

• Reliability per cavity circuit must improve significantly.

• Fault prediction is potentially game-changing.
Outlook

1. Targets

Top-Up Booster:
To reach overall 97.5% availability:
• "RF availability must be above..."
• "Power converters must be above..."
Also breakdown of other systems.

2. Shortfalls

Based on current designs & similar systems:
• "RF Availability will likely be 89 & 79%"
• "Top Up Booster will likely be..."
• "Injection Systems will likely be..."
• "... will likely be..."

3. Opportunities

Where do we fall short? RF system in Z & W modes
What can we do about this?
• Can we avoid losing beam on RF trips?
• Scope for reliability & fault prediction