FCC–hh Injection and Extraction:
An update due to recent tunnel/layout considerations

W. Bartmann, CERN


FCC Week 2021, 30th June 2021
Outline

- Recent FCC tunnel options
- Transfer line feasibility
- Impact on CDR layout regarding injection and extraction
- Summary
Various tunnel options impacting collider layout

2 families of layout: 12 or 8-sites

- 12-sites
- 8-sites

- Different symmetry constraints
- Different shapes
- Different degrees of freedom

Layout flexibility

Connection to LHC/SPS:
- LHC, SPS or both

P. Boillon, Placement review
Various tunnel options for transfer lines

<table>
<thead>
<tr>
<th>Scenario ID</th>
<th>Circumference [m]</th>
<th># CELLS ARC</th>
<th>SAFT</th>
<th>LSS PA, PD, PG, PJ</th>
<th>LSS PB, PF, PH, PL</th>
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</thead>
<tbody>
<tr>
<td>PA31-0.4</td>
<td>90932,686</td>
<td>42</td>
<td>1,000</td>
<td>1400</td>
<td>2100</td>
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<tr>
<td>PA35-0.6</td>
<td>92637,057</td>
<td>43</td>
<td>1,000</td>
<td>1400</td>
<td>2100</td>
</tr>
<tr>
<td>PA37-0.3</td>
<td>94823,477</td>
<td>44</td>
<td>1,006</td>
<td>1400</td>
<td>2100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th># CELLS S_ARC</th>
<th># CELLS L_ARC</th>
<th>LSS PA, PB, PF, PG, PH, PL</th>
<th>LSS PD, PJ</th>
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</thead>
<tbody>
<tr>
<td>PB17-0.8</td>
<td>24</td>
<td>65</td>
<td>1,000</td>
</tr>
<tr>
<td>PA38-0.1</td>
<td>24</td>
<td>59</td>
<td>1,000</td>
</tr>
</tbody>
</table>

- PB17-08 and PA38 (12P) - same what concerns beam transfer
- PA31 and PA35 (8P) - similar what concerns beam transfer, PA31 studied
- PA37 (8P) - 45 deg rotated
Transfer lines PB17 and PA38

- Crossing lines: IP8toPL could be NC with 10.8 km TL in completely separate tunnel; reduce TL tunnel to 4 km if injecting into arc tunnel, then SC
- IP1toPB, 6.2 km, SC
- Going directly from IP1 to PL needs 6.2 km, fully separate tunnel required, SC, no shortening possible; just within CE perimeter possible
- IP8toPB, 3.7 km, SC
- Vertical bending by tilting dipoles
## Transfer Line Feasibility

<table>
<thead>
<tr>
<th></th>
<th>Line/tunnel to PB [km]</th>
<th>Line/tunnel to PL [km]</th>
<th>Line/tunnel total [km]</th>
<th>Magnets</th>
<th>Feasible</th>
</tr>
</thead>
<tbody>
<tr>
<td>PB17/PA38</td>
<td>12 xing</td>
<td>10.8/10.8</td>
<td>6.2</td>
<td>17/17</td>
<td>NC + SC</td>
</tr>
<tr>
<td></td>
<td>12 arc</td>
<td>10.8/4</td>
<td>6.2</td>
<td>17/10.2</td>
<td>SC + SC</td>
</tr>
<tr>
<td></td>
<td>12 direct</td>
<td>6.2/6.2</td>
<td>3.7</td>
<td>10/10</td>
<td>SC + SC</td>
</tr>
<tr>
<td>PA31/35</td>
<td>8 xing</td>
<td>10./10</td>
<td>&gt;20/6</td>
<td>&gt;30/16</td>
<td>NC + SC</td>
</tr>
<tr>
<td></td>
<td>8 arc</td>
<td>10./4</td>
<td>&gt;20/6</td>
<td>&gt;30/10</td>
<td>SC + SC</td>
</tr>
<tr>
<td>PA37</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹exact length to be verified with full model in MADX
²feasibility of injection into arc tunnel to be studied
Transfer lines conclusions

- All options but PA37 seem feasible re beam transfer
- Total minimum tunnel length 10 - 17 km
- Total line lengths 10 - >30 km
- 12P and 8P similar for tunnel length, significantly longer TL lengths for 8P
- NC magnets for both lines only possible in case of separate tunnel under lake for 8P options, otherwise only for one of the lines possible which is likely not preferred
- All options but PA37 can also be reached from the SPS tunnel, at 1.3 TeV with NC technology and similar length as for LHC lines
Various tunnel options impacting collider layout

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<th>LSS PA, PB, PF, PG, PH, PL</th>
<th>LSS PD, PJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>PB17-0.8</td>
<td>96093,614</td>
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<td>65</td>
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<tr>
<td>PA38-0.1</td>
<td>90040,501</td>
<td>24</td>
<td>59</td>
</tr>
</tbody>
</table>

- Reduction of extended LSS length: 2.8 km → 2.1 km for dump system
- Rotated version requires combination of main experiment with injection
Injection in a Nutshell

Summary of FCC-hh transfer line and injection design.

- **Challenge:** transfer 550 MJ
- **Damage limit of injection dump limits** injection batch length to 80 bunches (LHC: 288, different energy and intensity)
- **Short risetime of kicker magnets (430ns)** is required to enable FCC-hh filling factor (10400 bunches)
- **Novel pulse generator technologies** (Inductive Adder or Marx Generator) for kicker to enable short risetime, fast recharging (10Hz) and have lower failure rates due to different concept
- **Normal conducting Lambertson septum:** reliable, simple, robust
- Loss studies for injection failures: protection efficiency ok, but small horizontal beam size at TDI ($\text{sig}_x = 0.15\text{mm}$) is challenging for TDI settings
Injection - Overview

- Combined with side experiments (IPB and IPL) – 1.4km, ~0.7km for injection
- Baseline: Injection from HEB (LHC) at 3.3 TeV
- 1.3 TeV option studied as well
- Double plane injection

<table>
<thead>
<tr>
<th></th>
<th>Septa (nc Lamb.)</th>
<th>Kicker</th>
</tr>
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<tbody>
<tr>
<td>System Length</td>
<td>104</td>
<td>40</td>
</tr>
<tr>
<td>Deflection [mrad/Tm]</td>
<td>9.8/92</td>
<td>0.18/2</td>
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<tr>
<td>Number of Modules</td>
<td>21</td>
<td>18</td>
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<tr>
<td>Flux Field [T]</td>
<td>0.7-1.2T</td>
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</table>
Injection

Beam size at injection dump (TDI) to stay below damage limit of the TDI in case of kicker failure

Update wrt CDR:
• Can gain ~250 m in drift space – optics for injection and physics production could be decoupled to reach more matching flexibility
• For injection proper need 450 m in lattice – to be added to LSS in 45 deg rotated tunnel option PA37
Extraction

- 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
Extraction – New Baseline

Old baseline: working backup solution

- Based on superferric Lambertson septa (1.3-1.55T / ~184m with 25 mm septum blade)
- Septa layout requires double plane extraction
- Highly segmented extraction kicker system (300 kicker)
Extraction – New Baseline

Old baseline: working backup solution

- Based on superferric Lambertson septa (1.3-1.55T / ~184m with 25 mm septum blade)
- Septa layout requires double plane extraction
- Highly segmented extraction kicker system (300 kicker)

Proposed new baseline:

- Based on novel septa: SuShi (3.2T) and Truncated CosTheta (4T). Total system length ~70m
- Septa layout requires single plane extraction (vertical)
- Reduced kicker segmentation, still highly segmented (150 kicker)
Extraction – Layout

(1) 150 Extraction Kicker (2017: 300)
   - System length 120 m
   - 1 us risetime

(2) Larger beam size at protection absorber than 2017

(3) SuShi / Cos-Theta Septa instead of superferric Lambertson
   - ~70m instead of 180m (2017)
Extraction – Septa
Extraction – Septa (MSD)

SuShi

- **3.2 T**
- Measurements on first prototype conducted
- Apparent septum blade: 25mm
  → can potentially be reduced to 20mm using NbTi for the shield (reduced kick strength)

**D. Barna**: Superconducting Shield (SuShi) septum

Truncated Cos-Theta

- **4T**
- 35mm app. septum blade
- Very flexible geometry for larger separation of circulating and extracted beam

**K. Sugita**: Status of truncated cosine-theta septum magnet study

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W. Bartmann, FCC hh Injection and Extraction

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Extraction Kicker
Extraction and Dilution Kicker Strategy

To increase availability the main idea is, that in case of a faulty kicker magnet normal operation can continue with a reduced number of kickers and repair is only required during the next scheduled technical stop.

- Septa apertures, kicker segmentations etc. are designed to allow operation with at least 10% missing dilution or/and extraction kicker.

- Furthermore, failure probabilities for and the impact of a single failing element should be reduced.

A highly segmented system is envisaged:
- 150* extraction kicker per beam (LHC: 15)
- 30 horizontal + 55 vertical dilution kicker per beam (LHC: 10)

*2017: 300 kicker. 2018: Number of segments reduced, see next slide.
Extraction Kicker

- Highly segmented system: 150 kicker compared to 15 in LHC (l = 0.6m)*
- Main design restriction: 1 us risetime required to survive asynch. dump
- 3.3 kA / ~6kV per kicker (LHC: 30kA / 27kV)

Relaxed hardware parameters / simpler systems than LHC:
- 1 generator per kicker (LHC: 2)
- 1-2 switches per generator (LHC: 10)**

Overall complexity regarding failure/availability comparable to LHC

*2017: 300 kicker. 2018: Number of segments reduced, while still allowing for '1. sigma oscillation'(slide 17) in case of erratic, keeping hardware requirement reasonable and enable operation with reduced number of modules

**: 2 switches with current technology. R&D necessary to enable generator with 1 switch.

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Extraction – Dilution Kicker and Dumpline

2.5 km

Extraction Kicker QF MSD QD

V

H

Dilution Kicker + Triplet

TCDS

TCDQ

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Extraction – Dilution Kicker and Dumpline

2017: Dilution system envisaged kickers with modulated frequency to minimize size of dumpcore (max. 50kHz)
- Sweeppattern r=45 cm
- Very challenging for kicker system
- Problematic for survival of asynchronous beam dump

2018: Constant frequency of the dilution system (50kHz)
- Sweeppattern r=55 cm
- Energy deposition in case of asynch. dump acceptable
- Large deflection by dilution kicker necessary
  ▶ Either increase tunnel length to 3km or increase BdL of MKBs
  ▶ Focusing triplet in the dumpline helps to reduce the aperture in the dilution kickers and hence relax the hardware requirements.
Dilution Kicker (MKB)

- 30 horiz. / 55 vertical magnets to keep hardware requ. acceptable
- Hardware relaxed by triplet in dumpline
  - reduced gap height and width in vertical dilution kicker
  - reduced horizontal kick strength
- 10% less horizontal / vertical dilution acceptable

**Complex system, e.g.:**
- max. frequency mismatch of ~0.2-0.5% allowed
- time dependent damping constant, ...

<table>
<thead>
<tr>
<th></th>
<th>triplet</th>
<th>w.o triplet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MKBH</td>
<td>MKBV</td>
</tr>
<tr>
<td>frequency [kHz]</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>risetime [us]</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Installed L [m]</td>
<td>60</td>
<td>110</td>
</tr>
<tr>
<td>Gap field [T]</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Modules</td>
<td>30</td>
<td>55</td>
</tr>
<tr>
<td>BdL [Tm]</td>
<td>22</td>
<td>42</td>
</tr>
<tr>
<td>gap height [m]</td>
<td>0.03</td>
<td>0.046</td>
</tr>
<tr>
<td>gap width [m]</td>
<td>0.03</td>
<td>0.04</td>
</tr>
<tr>
<td>Current [kA]</td>
<td>12</td>
<td>16</td>
</tr>
<tr>
<td>Voltage [kV]</td>
<td>8</td>
<td>12</td>
</tr>
</tbody>
</table>

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Dilution Kicker – Frequency Mismatch

Mismatch between single generators

\[ \Delta f_{\text{mod.}} = 0 \text{, } 1\% \]

acceptable

Mismatch between horizontal and vertical system

\[ \Delta f_{H/V} = 0 \text{, } 1\% \]

acceptable

Mismatch between single generators

\[ \Delta f_{\text{mod.}} = 1\% \]

Not acceptable

Mismatch between horizontal and vertical system

\[ \Delta f_{H/V} = 1\% \]

Not acceptable

To be studied beyond the CDR – avoid impact on availability due to strict interlocking.

Systems need to be set up accurately but no showstopper
Summary and Next Steps

Transfer lines

- All options look feasible but the 45 deg rotated one – here we would need to extend the LSS by ~ 450 m
- 8 point options will require significantly more TL magnets
- Joining the collider tunnel as early as possible is considered – this requires a careful consideration of integration and cross-talk in terms of future availability

Injection

- Optics updated to fulfill machine protection requirements
- New generator technologies required and studied
- Failure scenarios analyzed
- Update wrt CDR: Can reduce system length to 450 m for injection equipment – might not allow for direct LSS length reduction – depending on optics matching for low beta optics
Summary and Next Steps

Extraction:

- **Vertical single plane extraction** based on SuShi and Truncated Cos-Theta Septa \(\rightarrow\) reduced system length wrt NC septa solution
- Highly segmented extraction kicker system (150 modules)
  - Impact of 1.5 sigma oscillation in case of single erratic was found acceptable (extraction at next abort gap arrival)
  - Hot spare approach \(\rightarrow\) continue operation in case of faulty generator until next stop

\(\Rightarrow\) Challenges: Trigger / Re-trigger system; Dilution system

\(\Rightarrow\) Reduction in length from 2.8 km to 2.1 km \(\rightarrow\) likely possible to find a challenging yet feasible concept; additional challenge put on the HW systems with risk of reduced reliability/availability \(\rightarrow\) given the project’s timescale, bet on sufficient technology advancement

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Thank you!
Extraction – Machine Protection Strategy

Machine protection requirements to be considered for the design are ...

1. Safely extract the beam – always guarantee kicker triggering [See appendix]

2. Survive asynchronous dump

3. Avoid asynchronous dumps

4. Avoid other failures with damage potential [See appendix]

5. Avoid failure impacting availability / avoid necessity for immediate repair
Survival of Asynchronous Dump

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

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

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

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Avoid Asynch. Dump/ ‘1.5 Sig Oscillation’

LHC: Main cause for asynch. dumps are erratic extraction kicker
**Avoid Asynch. Dump/ ‘1.5 Sig Oscillation’**

**LHC:** Main cause for asynch. dumps are erratic extraction kicker

**FCC:** 150 MKDs, 1 MKD: ~1.5 sigma (worst case MKD1)

Idea: Do not re-trigger immediately in case of an erratic kicker, but **wait until the next abort gap and dump beam synchronously.**

→ Part of beam oscillates **1 turn with ~1.5 sigma 1 turn before being extracted.**
Avoid Asynch. Dump/ ‘1.5 Sig Oscillation’

**FCC:** 150 MKDs, 1 MKD: ~1.5 sigma (worst case MKD1)

- Tracking studies conducted: up to ~2.7 sig oscill. OK for losses in collider
- 1.5 sig oscillation leaves margin for correction factors (need to be quantified more precisely)
  - e.g.
    - beta beating 20%
    - horizont. offset in Crab Cavities / phase offset in CC
    - ...
- ~Same deflection as failure of sep. dipole (1.5sig in 2ms)

**LHC:** Main cause for asynch. dumps are erratic extraction kicker

**Idea:** Do not re-trigger immediately in case of an erratic kicker, but **wait until the next abort gap and dump beam synchronously.**

- Part of beam oscillates **1 turn with ~1.5 sigma 1 turn before being extracted.**
Abort gaps need to be equally distributed
Simple for abort gap synchronization
Abort gap ~1.5us, injection gap: 0.43us. → Abort gap = 3x injection gap (advantage for RF cavities?)
Extraction: Challenges for the Re-Triggering System

Inherently different to LHC, FCC-hh requires...

- ... an active system:
  distinguish single erratics (no re-trigger) and multi-erratics (re-trigger)

- ... a fast system
  despite long system length (120m, signal propagation)

- ... exclusion of partial pre-triggering (3-67%) due to failure in output of trigger distribution.

Impact of pre-triggering of X% of all extraction kickers with subsequent re-trigger of remaining modules after re-trigger time. → not problematic in LHC

N. Magnin, Laser triggering of thyristor switches, Wed. 1050

MKD150

MKD1

Trigger
Synchronization

multiple MKDs at 1 TSU output?
Spare: Injection Deadlock

![Graph showing the relative MKD kick over time for nominal extraction and deadlock batch.]

- **Nominal Extraction**: [326us]
- **Deadlock Batch**: [max. 415us]
- **Tolerance**: Extraction Channel [90-110%]

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Spare: Transfer lines

<table>
<thead>
<tr>
<th>Name</th>
<th>Length</th>
<th>Dipole Field / Length</th>
<th>Straight Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC1 – FCCB</td>
<td>4.2</td>
<td>SC: 7.2T / 3.9km</td>
<td>0.3 (challenging TL collimation!)</td>
</tr>
<tr>
<td>LHC8–FCCL</td>
<td>8</td>
<td>SC: 7.2T / 1.5km</td>
<td>6.5</td>
</tr>
<tr>
<td>SPS3 – FCCB</td>
<td>3.3</td>
<td>NC: 1.8T / 1.9km</td>
<td>2.4</td>
</tr>
<tr>
<td>SPS5 – FCCL</td>
<td>5.8</td>
<td>NC: 1.8T / 4.4km</td>
<td>1.4</td>
</tr>
</tbody>
</table>
Spare: Dilution Kicker – Time Dependent Damping

\[ \gamma(t) = -\frac{1}{\tau} \cdot \ln \left( 1 - \frac{\Delta b}{A(t)} \right) \]

- \( f = 50 \text{kHz} \)
- Amplitude at dump [m]
- horizontal
- vertical
- damping const. \( t = 0 \)
- damping const. \( t = 326 \text{ us} \)
- time dep. damping

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## Spare: Extraction – Machine Protection

<table>
<thead>
<tr>
<th>Category</th>
<th>Primary Failure Scenario</th>
<th>Consequence / Potential Effect</th>
<th>Comment</th>
<th>Dump Line sc DL</th>
<th>class</th>
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<tbody>
<tr>
<td>Abort gap</td>
<td>Abort gap population out of tolerance</td>
<td>Quench of MSD?</td>
<td>Define AG threshold. Sushi / superferric Lamb.</td>
<td></td>
<td>2</td>
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<tr>
<td>Abort gap</td>
<td>Synchronisation error</td>
<td>asynch. dump</td>
<td></td>
<td>Quench?</td>
<td>2</td>
</tr>
<tr>
<td>Fast kicker</td>
<td>Dilution kicker erratic (spurious) trigger</td>
<td>synch. dump, less dilution</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Fast kicker</td>
<td>&gt;10% dilution kicker magnets missing</td>
<td>TDE damage</td>
<td>self announcing</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Fast kicker</td>
<td>Extraction/injection deadlock</td>
<td>injection batch on TCDS (3.3 TeV)</td>
<td>check impact on TCDS only critical for 0.9%MKD kick</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Fast kicker</td>
<td>1 Ext. kicker erratic (spurious) trigger</td>
<td>semi-synchr. dump (next abort gap)</td>
<td>check bunch position at TDE</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Fast kicker</td>
<td>&gt;1 Ext. kicker erratic (spurious) trigger</td>
<td>re-trigger</td>
<td>active / intelligent re-trigger system</td>
<td></td>
<td>2</td>
</tr>
</tbody>
</table>
| Fast kicker | 3-10% extr. kicker magnet multierratic | collider damage | • to be excluded in re-trigger system  
• re-trigger time <0.5us | | 1 |
| Fast kicker | 7-67% extr. kicker magnet multierratic | extraction absorber damage | • to be excluded in re-trigger system  
• re-trigger time <1us  
• sacrificial absorber (new optics) | | 1-2 |
| Fast kicker | >= 10% dilution kicker magnets missing | Challenging max. energy dep. In TDE | 10% to be quantified more precisely | | 1 |
| Fast kicker | >= ~12% extraction kicker missing | Potential MSD / TCDS damage | 12% to be quantified more precisely | self announcing | 1 |
| BETS | Energy tracking error | Faulty extraction | | | 1 |
| MPS | No trigger received from BIS | No extraction | | | 1 |

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Spare: Extraction - Challenges for the Re-Triggering System

- simultaneous pre-triggering of multiple kickers due to fault at higher level in trigger system (spurious output going to multiple modules) results in a ‘step in the waveform’

- depending on re-trigger time and % of pre-firing kicker, losses in collider / at extraction absorber would not be acceptable
Spare: Extraction - Challenges for the Re-Triggering System

3-10% sim. pre-firing:
- Damaging losses in the collider
- Nearly independent of re-trigger time

10-67% sim pre-firing:
- losses ok for collider
- damage of extraction protection (TCP / TCDQ)
- sacrificial absorber
- dependency on re-trigger time

Has to be avoided

Should be avoided
- otherwise: sacrificial absorber, requires new optics layout as longer drifts are is necessary

Hardware solution seems feasible – no showstopper
Spare: Safety – Risk of Missing MKD

**Unsafety** = Probability to have less than (here) 93% of MKDs firing (equiv. to 14 out of 15) missing MKDs → no safe extraction

- Failure rates scaled from studies conducted for LHC [1]

- Above 30 modules $U << 10^{-14}$ for 1 generator branch (redundancy ≥ 2 modules)

- LHC, 2 generator branches: $U = 3 \cdot 10^{-7}$/yr
- FCC (300 MKDs), 1 branch: $U \rightarrow 0$
- ~ 30 MKDs, 1 branch: $U = 10^{-14}$/yr