FCC-ee machine design overview

M. Boscolo (INFN-LNF) for the FCC-ee collaboration

Special Thanks to: M. Benedikt, K. Oide, F. Zimmermann
Outline

• Design challenge, key parameters and layout
• Optics design and beam dynamics
• Interaction Region and MDI
• Collective effects
• Energy calibration and polarization
• Injection system
• Vacuum system
• Conclusions

M. Boscolo, FCCWEEK18
Future Circular Collider (FCC) Study

International FCC collaboration (CERN as host lab) to study:

- **pp-collider (FCC-hh)**
  - main emphasis, defining infrastructure requirements

\[ \sim 16 \, \text{T} \Rightarrow 100 \, \text{TeV \, pp in 100 km} \]

- ~100 km tunnel infrastructure in Geneva area, site specific
- **e^+e^- collider (FCC-ee)**, as potential first step
- **HE-LHC** with **FCC-hh** technology
- **p-e (FCC-he)** option, IP integration, e^- from ERL

Copyright CERN 2014
Introduction

- Great progress has been made in the FCC-ee collider design
- FCC-ee CDR summary volume writing and editing is on schedule

FCC-ee collider is extremely challenging but feasible with great physics potential
# FCC-ee operation model

<table>
<thead>
<tr>
<th>working point</th>
<th>luminosity/IP [10^{34} cm^{-2}s^{-1}]</th>
<th>total luminosity (2 IPs)/yr</th>
<th>physics goal</th>
<th>run time [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z first 2 years</td>
<td>100</td>
<td>26 ab^{-1}/year</td>
<td>150 ab^{-1}</td>
<td>4</td>
</tr>
<tr>
<td>Z later</td>
<td>200</td>
<td>52 ab^{-1}/year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>32</td>
<td>8.3 ab^{-1}/year</td>
<td>10 ab^{-1}</td>
<td>1</td>
</tr>
<tr>
<td>H</td>
<td>7.0</td>
<td>1.8 ab^{-1}/year</td>
<td>5 ab^{-1}</td>
<td>3</td>
</tr>
</tbody>
</table>

machine modification for RF installation & rearrangement: **1 year**

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>top 1st year (350 GeV)</td>
<td>0.8</td>
<td>0.2 ab^{-1}/year</td>
<td>0.2 ab^{-1}</td>
<td>1</td>
</tr>
<tr>
<td>top later (365 GeV)</td>
<td>1.5</td>
<td>0.38 ab^{-1}/year</td>
<td>1.5 ab^{-1}</td>
<td>4</td>
</tr>
</tbody>
</table>

**total program duration: 14 years - including machine modifications**

phase 1 (Z, W, H): 8 years,  **phase 2 (top): 6 years**

M. Boscolo, FCCWEEK18
Key parameters and baseline optics design

- **Double ring** e+ e- collider ~100 km
- Follow the footprint of FCC-hh, except for around the IPs
- **2 IPs** with **crab-waist scheme**, large horizontal crossing angle of 30 mrad.
- **Flexible design, for all energies:**
  - **common lattice**, except for a small rearrangement in the RF section
  - \( L^* = 2.2 \text{ m} \) (length of the free area around the IP), \( B_{\text{detector}} = 2 \text{ T} \)
  - \( E_{\text{critical}} < 100 \text{ keV} \) (critical energy of the synchrotron radiation) of incoming beam toward IP from 450 m
- **Top-up injection** scheme to maintain the stored beam current and the luminosity at the highest level during experiment runs. It is necessary to have a booster synchrotron in the same tunnel as the collider.
- **Synchrotron radiation power 50 MW/beam** at all energies.
- "**Tapering**" of magnets along the ring to compensate the sawtooth effect
- Common RF cavities for e+ and e- at ttbar (RF frequency 400 MHz and 400+800 MHz at ttbar)

M. Boscolo, FCCWEEK18
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
<th>Value 4</th>
<th>Value 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>45.6</td>
<td>80</td>
<td>120</td>
<td>175</td>
<td>182.5</td>
</tr>
<tr>
<td><strong>Luminosity / IP</strong></td>
<td>230</td>
<td>28</td>
<td>8.5</td>
<td>1.8</td>
<td>1.55</td>
</tr>
<tr>
<td>Beam current</td>
<td>1390</td>
<td>147</td>
<td>29</td>
<td>6.4</td>
<td>5.4</td>
</tr>
<tr>
<td>Bunches per beam</td>
<td>16640</td>
<td>2000</td>
<td>328</td>
<td>59</td>
<td>48</td>
</tr>
<tr>
<td>Average bunch spacing</td>
<td>19.6</td>
<td>163</td>
<td>994</td>
<td>2763</td>
<td>3396</td>
</tr>
<tr>
<td>Bunch population</td>
<td>10¹¹</td>
<td>1.7</td>
<td>1.5</td>
<td>1.8</td>
<td>2.2</td>
</tr>
<tr>
<td>Horizontal emittance εₓ</td>
<td>0.27</td>
<td>0.84</td>
<td>0.63</td>
<td>1.34</td>
<td>1.46</td>
</tr>
<tr>
<td>Vertical emittance εᵧ</td>
<td>1.0</td>
<td>1.7</td>
<td>1.3</td>
<td>2.7</td>
<td>2.9</td>
</tr>
<tr>
<td>βₓ / βᵧ</td>
<td>0.15 / 0.8</td>
<td>0.2 / 1.0</td>
<td>0.3 / 1.0</td>
<td>1.0 / 1.6</td>
<td></td>
</tr>
<tr>
<td>Beam size at IP: σₓ / σᵧ</td>
<td>6.4 / 28</td>
<td>13 / 41</td>
<td>13.7 / 36</td>
<td>36.7 / 66</td>
<td>38.2 / 68</td>
</tr>
<tr>
<td>Energy spread: SR / total (w BS)</td>
<td>0.038 / 0.132</td>
<td>0.066 / 0.131</td>
<td>0.099 / 0.165</td>
<td>0.144 / 0.196</td>
<td>0.15 / 0.192</td>
</tr>
<tr>
<td>Bunch length: SR / total</td>
<td>3.5 / 12.1</td>
<td>3 / 6.0</td>
<td>3.15 / 5.3</td>
<td>2.75 / 3.82</td>
<td>1.97 / 2.54</td>
</tr>
<tr>
<td><strong>Energy loss per turn</strong></td>
<td>0.036</td>
<td>0.34</td>
<td>1.72</td>
<td>7.8</td>
<td>9.2</td>
</tr>
<tr>
<td>RF Voltage /station</td>
<td>0.1</td>
<td>0.75</td>
<td>2.0</td>
<td>4/5.4</td>
<td>4/6.9</td>
</tr>
<tr>
<td>Longitudinal damping time</td>
<td>1273</td>
<td>236</td>
<td>70.3</td>
<td>23.1</td>
<td>20.4</td>
</tr>
<tr>
<td>Acceptance RF / energy (DA)</td>
<td>1.9 / ±1.3</td>
<td>2.3 / ±1.3</td>
<td>2.3 / ±1.7</td>
<td>3.5/ (-2.8; +2.4)</td>
<td>3.36 / (-2.8; +2.4)</td>
</tr>
<tr>
<td>Rad. Bhabha/ actual Beamstr. Lifetime</td>
<td>68 / &gt; 200</td>
<td>59 / &gt;200</td>
<td>38 / 18</td>
<td>37/ 24</td>
<td>40 / 18</td>
</tr>
<tr>
<td>Beam-beam parameter ξₓ / ξᵧ</td>
<td>0.004 / 0.133</td>
<td>0.01 / 0.141</td>
<td>0.016 / 0.118</td>
<td>0.088 / 0.148</td>
<td>0.099 / 0.126</td>
</tr>
<tr>
<td>Interaction region length</td>
<td>0.42</td>
<td>0.85</td>
<td>0.9</td>
<td>1.8</td>
<td>1.8</td>
</tr>
</tbody>
</table>
Optics design and beam dynamics

- Baseline optics was established in 2016 [PR-AB 19 (2016) no.11, 111005]

- **FCCWEEK2017:**
  - reduction $\beta_x^*$
  - 60°/60° arc cell at Z

  **Motivations** for these changes:
  - to mitigate the coherent beam-beam instability at Z
  - to adopt the twin aperture quadrupole scheme for the arc quads [PR-AB 19 (2016) no.11, 112401]
  - to fit the footprint to a new FCC-hh layout

- **FCCWEEK2018:**
  - Further reduction of $\beta^*$ at the IP at Z, $W^\pm$, ZH, ttbar($\beta_y$)
  - Increase of beam energy at ttbar (182.5 GeV)
  - Momentum acceptance at ttbar increased by “asymmetric acceptance”
  - Better packing factor of dipoles in the arcs
  - Special sections for inverse Compton spectrometer
  - Dynamic Aperture improved to maximize luminosity
  - Tolerance study on misalignments very encouraging

  **Motivations** for these changes:
  - to mitigate the coherent beam-beam instability also at $W^\pm$, ZH
  - to mitigate 3D flip-flop

More details in talk by K. Oide
Asymmetric Interaction Region optics

• Asymmetric optics suppresses SR toward the IP, $E_{\text{critical}} < 100$ keV from 450 m from the IP
• Local chromaticity correction scheme for $\gamma$-plane (a-d), incorporated with crab sextupoles (a,d), needed for energy acceptance requirement (up to 2.8%)

M. Boscolo, FCCWEK18
Final Focus optics

- Flexible optics design: final focus quadrupoles are longitudinally split into three slices.
  - At the Z chromaticity is reduced for the smaller $\beta^*$, smaller beam size.

**Only 1st slice of QC1 is defocusing horizontally**

**All 3 slices of QC1 are defocusing horizontally**
Mitigation of coherent beam-beam instability

A new coherent instability in x-z plane was first predicted by K. Ohmi with a strong-strong beam-beam simulation (FCCWEEK16) [PRL 119 (2017) 13, 134801, PR-AB (2018) 21 031002]

D. Shatilov confirmed the phenomenon with an independent simulation (turn-by-turn alternating quasi-strong-strong method), very good agreement

More details in: ‘IP beam parameter otimization’ by D. Shatilov

A semi-analytic scaling of the bunch intensity threshold has been derived (K. Ohmi):

\[ N_{th} \propto \frac{\alpha_p \sigma_\delta \sigma_z}{\beta_x^*} \]

\( \beta_x^* \) has been reduced to \( \sim 1/3 \)
\( \alpha_p \) was increased by a factor of 2 (by changing the phase advance of the arc at Z) compared to the baseline 2016

M. Boscolo, FCCWEEK18
With the nominal bunch population required for high luminosity, $\sigma_z$ increases ~3.5 times because of beamstrahlung.

If we bring into collision so large currents with the “initial” $\sigma_z$ (energy spread created only by SR), the beam-beam parameters will be far above the limits.

The beams will be blown up and killed on the transverse aperture, before they are stabilized by the beamstrahlung.

To avoid this, we must gradually increase the bunch population during collision, so we come to *bootstrapping*. 

**Graphs:**
- $\sigma_z / \sigma_{z0}$
- $\varepsilon_z / \varepsilon_{z0}$
- $N_p = 4.0 \times 10^{10}$
- $N_p = 4.0 \times 10^{10}$
- $N_p = 4.5 \times 10^{10}$
- $N_p = 4.5 \times 10^{10}$
- $N_p = 5.0 \times 10^{10}$
- $N_p = 5.0 \times 10^{10}$
- $N_p = 5.5 \times 10^{10}$
- $N_p = 5.5 \times 10^{10}$
- $N_p = 6.0 \times 10^{10}$
- $N_p = 6.0 \times 10^{10}$

**Equations:**
$$N_p = 4.0 \times 10^{10}$$
$$N_p = 4.0 \times 10^{10}$$
$$N_p = 4.5 \times 10^{10}$$
$$N_p = 4.5 \times 10^{10}$$
$$N_p = 5.0 \times 10^{10}$$
$$N_p = 5.0 \times 10^{10}$$
$$N_p = 5.5 \times 10^{10}$$
$$N_p = 5.5 \times 10^{10}$$
$$N_p = 6.0 \times 10^{10}$$
$$N_p = 6.0 \times 10^{10}$$
Dynamic Aperture

- DA estimated with SAD, 2 longitudinal damping times
- Effects included in the simulation: SR, tapering, radiation loss in dipoles, quads, sextupoles, crab-waist, Maxwellian fringes, kinematic terms
- DA satisfies requirements without errors and misalignments

M. Boscolo, FCCWEEK18
Dynamic aperture, ideal and with errors for FCC-ee

- Coarse scan of 4D dynamic aperture (no radiation) (1)
- Frequency map analysis (2, 3)
- Momentum aperture with (black) and without (green) misalignment errors with considerable left over beta beat (80 %)

Studies are ongoing to correct for beta beat at 175 GeV incl. radiation.

Misalignments used:

<table>
<thead>
<tr>
<th>Misalignments introduced and corrected</th>
<th>I procedure for correction established by S. Aumon</th>
</tr>
</thead>
<tbody>
<tr>
<td>I misalignment assigned to quadrupoles / sextupoles with Gaussian random number generator truncated at 2.5</td>
<td></td>
</tr>
<tr>
<td>I corrections performed at 1 GeV after corrections are applied, energy is increased to 175 GeV and tapering applied</td>
<td></td>
</tr>
<tr>
<td>I emittance determined using EMIT module in MAD-X</td>
<td></td>
</tr>
</tbody>
</table>

More details in talk by T. Tydecks

- arc quadrupoles: 100 µm 100 µm 100 µrad
- IP quadrupoles: 50 µm 50 µm 50 µrad
- sextupoles: 100 µm 100 µm
Interaction Region Layout

Unique and flexible design at all energies

Last year in 1st MDI workshop baseline design layout was reviewed and discussed:

- L*, opening angle acceptance, solenoid compensation scheme, LumiCal space, IR HOM and trapped modes analysis, vacuum chamber

This year we added important elements to the MDI design discussion and new topics addressed:

- Mechanical design and assembly concept, HOM absorber design, cryostat, water cooling system, remote vacuum connection, flanges, bellows, vacuum pump, vibration studies, orbit correction, fast luminosity monitor for machine tuning, BPMs

**BEAM PIPE:**

- Be in central region for LumiCal window, then Cu
- 15 mm in the central region and up through QC1, 20 mm through QC2, 35 mm in the arcs
- SR masks at FF quads before/after QC2 and after QC1
- warm beam pipe, liquid cooled (similarly to SuperKEKB) to cope with SR and HOM heating

2018 updates on:

- LumiCal and shielding (W)
- QC1
- Compensating solenoid
- Lumical
- Lumical electronics
- Lumical cables
- HOM absorbers
- W shielding

M. Boscolo, FCCWEEK18
## SR photon rates

<table>
<thead>
<tr>
<th></th>
<th>Energy (GeV)</th>
<th>Critical energy (keV)</th>
<th>number of bunches</th>
<th>Current (mA)</th>
<th>Incident $\gamma$/xing (500$\mu$m from tip)</th>
<th>Incoming on central pipe/xing</th>
<th>$\gamma$ rate on central pipe (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>tt+</td>
<td>182.5</td>
<td>113.4</td>
<td>33</td>
<td>5.41</td>
<td>3.32E+09</td>
<td>1195</td>
<td>1.18E+08</td>
</tr>
<tr>
<td>tt</td>
<td>175</td>
<td>100</td>
<td>40</td>
<td>6.4</td>
<td>3.06E+09</td>
<td>1040</td>
<td>1.25E+08</td>
</tr>
<tr>
<td>h</td>
<td>125</td>
<td>36.4</td>
<td>328</td>
<td>29</td>
<td>1.05E+09</td>
<td>10.3</td>
<td>1.01E+07</td>
</tr>
<tr>
<td>W</td>
<td>80</td>
<td>9.56</td>
<td>1300</td>
<td>147</td>
<td>6.11E+08</td>
<td>0.18</td>
<td>7.02E+05</td>
</tr>
<tr>
<td>Z</td>
<td>45.6</td>
<td>1.77</td>
<td>16640</td>
<td>1390</td>
<td>9.62E+07</td>
<td>1.92E-04</td>
<td>9.58E+03</td>
</tr>
</tbody>
</table>

- No SR from dipoles or from quads hits directly the central beam pipe (cylinder +/- 12.5 cm in Z with a 1.5 cm radius)
- Non-Gaussian beam tails, considered out to +/-20 $\sigma_x$ and +/-60$\sigma_y$
- On-axis beam
- Quadrupole radiation that may strike mask surfaces included
- G4 full simulation of interaction region (M. Lückhof, poster) and CLD detector shows low occupancy (with W shielding) (A. Kolano talk, for details)
Baseline for Solenoid Compensation Scheme

• **screening solenoid** that shields the detector field inside the quads (in the FF quad net solenoidal field=0)

• **compensating solenoid** in front of the first quad, as close as possible, to reduce the \( \varepsilon_y \) blow-up (integral BL~0)

**detector solenoid** dimensions 3.76m (inner radius) (outer radius 3.818m) × 4m (half-length) (CLD)

**drift chamber** at \( z=2m \) with 150 mrad opening angle (IDEA design)

0.34 pm is the overall \( \varepsilon_y \) blow-up for 2IPs @Z
FCC ee IR beam pipe with water-cooled HOM absorbers

HOM absorber design for 10 kW power

Efficiency of Damping Trapped and Propagating Modes

- no absorber
- with HOM absorber
- bunch spacing 19.5 ns

A. Novokhatski 3/26/18
Longitudinal impedance model

Component | Number | $k_{loss}[V/pC]$ | $P_{loss}[MW]$  
--- | --- | --- | ---  
Resistive Wall (100nm) | 97.75 km | 210 | 7.95  
Collimators | 20 | 18.69 | 0.7  
RF cavities | 52 | 17.14 | 0.65  
RF double tapers | 13 | 24.71 | 0.93  
BPMs | 4000 | 40.11 | 1.5  
Bellows | 8000 | 49.01 | 1.85  
**Total** | **359.6** | **13.6**  

3.7x smaller than 50 MW (SR).

With beamstrahlung

- MI threshold $\approx 1.5x$ larger than nominal bunch population
- Beamstrahlung allows to increase the threshold

Microwave instability

- With beamstrahlung
- No beamstrahlung

Nominal bunch intensity

More details in talk by E. Belli
FCC-ee Beam Polarization and Energy Calibration (I)

1. **Priority from Physics**: $\Delta E/E \sim O(10^{-6})$ around $Z$ pole and $WW$ threshold $\rightarrow Z,W$ mass & width

2. Exploit natural transverse beam polarization present at $Z$ and $W$ (E.Gianfelice, S.Aumon)
   
   2.1 This is a unique capability of $e^+e^-$ circular colliders
   
   2.2 Sufficient level is obtained if machine alignment is good enough for luminosity
   
   2.2 Resonant depolarization has intrinsic stat. precision of $\sim 10^{-6}$ on spin tune (I.Koop)
   
   2.3 Required hardware (polarimeter, wigglers depolarizer) is defined & integrated (K.Oide)
   
   2.4 Running mode with 1% non-colliding bunches and wigglers defined (Koratzinos)

---

**FCC-ee simulation of resonant depolarization**

I. Koop, Novosibirsk

260 seconds sweep of depolarizer frequency
FCC-ee Beam Polarization and Energy Calibration (II)

3. From spin tune measurement to center-of-mass determination

\[ v_s = \left( g - 2 \right) \frac{E_b}{m_e} = \frac{E_b}{0.4406486(1)} \]

3.1 Synchrotron Radiation energy loss (9 MeV @Z in 4 ‘arcs’) calculable to < permil accuracy

3.3. Beamstrahlung energy loss (0.62 MeV per beam at Z pole), compensated by RF (Shatilov)

3.4 layout of accelerator with IPs between two arcs well separated from RF

\[ 0.5 \left( E_{CM}^{A} + E_{CM}^{G} \right) = (E_{b}^{+} + E_{b}^{-}) \cos(\alpha_{crossing}/2) \]

3.5 \( E_{b}^{+} \) vs \( E_{b}^{-} \) asymmetries and energy spread can be measured/monitored in expt:

\[ e^+e^- \rightarrow \mu^+ \mu^- \text{ longitudinal momentum shift and spread} \] (Janot)

D. Shatilov: beam energy spectrum without/with beamstrahlung

P. Janot: 2 min @Z

\[ = 10^6 \mu^+ \mu^- / \text{expt.} \]

\[ \rightarrow 50 \text{ keV meas!} \]

4. work in progress: errors from betatron motion in non-planar orbits, transverse impedance, RF asymmetries, optimum depolarizer set-up vs \( Q_s \) at W, opp. sign vertical dispersion.

\[ \rightarrow \text{On track to match goal of 100 (300) keV errors on } E_{CM} \text{ at Z (WW) energies}. \]
FCC-ee Layout

- 6 GeV Linac
- 1.54 GeV Damping Ring
- Super Proton Synchrotron 6-20 GeV
- 98 km Top-up Booster 20 GeV - final energy
- 98 km Future Circular electron-positron Collider

not to scale!
The 1.54 GeV damping ring will be at the end of the Linac and electrons will be transferred from a branching point in the linac at 1.54 GeV (its drawing is omitted in the layout scheme). We may tilt the DR just by a small angle in order not to bend e+ beam noticeably. In this way, the BTL can share the same tunnel as the main linac.
❖ The **S-band** linac has a branching point at **1.54 GeV** for emittance cooling of electron beam in the Damping Ring. After emittance cooling they will be transferred back to the linac to reach **6 GeV**.

❖ The **positrons** will be **created** in the linac by impinging on a hybrid target at **4.46 GeV**, and the created e+ will be **accelerated up to 1.54 GeV** in the remaining part of the linac. Then they will be **injected into the DR**. After emittance cooling in the DR, they will be transferred back to the linac to reach **6 GeV**.

❖ Linac will have **200 Hz** repetition with **2 Bunches per RF pulse**. The bunch charge is **2E10** particles, but throughout e+ creation, 200 Hz with 4 Bunches per RF pulse, or simply another linac for e+ creation is needed. **Linac** is in total **301 meters** with **25 MV/m** gradient in the **2856 MHz** cavities. The **DR** is **241 m** and can host 5 trains, each train with 2 bunches. The DR has **2 superconducting 400 MHz** cavities (1.5 meter each) with **4 MV**.
**FCC-ee injector baseline scheme**

**LINAC**
- Longer pulses with 1 or 2 bunches with rep. rate 100-200 Hz, 2.8 GHz RF
- Maximum linac bunch intensity ~ $2.1 \times 10^{10}$ particles (both species).
- Twice as much needed for e+ production, i.e. $4 \times 10^{10}$ particles/bunch

**PREBOOSTER**
- Injected several times (from 50 to 1040), @ 6 GeV into of PBR (SPS or new ring) with 1 Linac bunch to 1 ring bucket (400 MHz RF system), up to 2080 bunches
- PBR ramp to 20 GeV with 0.2 s ramp rate and cycle length below 6.3 s

**BOOSTER**
- Transferred to main Booster (1 - 8 PBR cycles), with 400 MHz RF frequency, to a bunch structure required by the collider (from 50 to 16640 bunches)
- Accelerated to corresponding energy with ramp time of 0.32 - 2 s, and total cycle length up to 51.7 s

**MAIN RINGS**
- Transferred to the collider by accumulating current for the full filling or single injection for top-up
- **Interleaved** filling of e+/e- and continuous top-up (able to accommodate bootstrapping)
- Full filling below 20 min for both species, but also able to accommodate bootstrapping
- Top-up target time, based on 5 % of current drop due to corresponding lifetime, always achieved
- 80 % transfer efficiency

M. Boscolo, FCCWEEK18
FCC $e^+e^-$ Pre-Booster Ring(s) Design

Two different options are under consideration as pre-accelerator before the bunches are transferred to the high-energy booster: using the existing SPS and a completely new ring.

$C = \sim 6.9 \text{ km}$

$\mu_\chi$ is moved to $3\pi/4$.

Wiggler magnets are proposed to reduce $\varepsilon_\chi$ and $\tau$.

$C = \sim 2.3 \text{ km}$

$\varepsilon_\chi = 5 \text{ nm}.\text{rad} \text{ at 20 GeV}$

$\frac{\Delta E}{E} = \sim \pm 1.5\% \text{ at 6 GeV}$

$\tau = 0.1 \text{ s at 6 GeV}$
Booster synchrotron

Booster parameters:

<table>
<thead>
<tr>
<th>$E$ / GeV</th>
<th>45.5</th>
<th>80</th>
<th>120</th>
<th>182.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_b$</td>
<td>16640</td>
<td>2000</td>
<td>393</td>
<td>50</td>
</tr>
<tr>
<td>$n_p / 10^{10}$</td>
<td>2.13</td>
<td>1.44</td>
<td>1.13</td>
<td>2.0</td>
</tr>
<tr>
<td>$n_{cycles}$</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>$t_{cycle} / s$</td>
<td>51.74</td>
<td>13.3</td>
<td>7.53</td>
<td>5.6</td>
</tr>
<tr>
<td>$t_{fill} / s$</td>
<td>1034.8</td>
<td>288</td>
<td>150.6</td>
<td>244</td>
</tr>
</tbody>
</table>

Maximum filling time of the collider (both species): $t_{fill} \approx 17$ min

Not compatible with damping time @ 20 GeV: $\tau_x = 10.05$ s

Strong intra-beam-scattering because equilibrium emittance $\varepsilon_x = 12$ pm rad

Installation of 16 9-m long wiggler magnets

Both 60°/60° and 90°/90° optics provided

M. Boscolo, FCCWEEK18
Top-up injection

• Top-up injection, which keeps the beam current constant, is essential for FCC-ee collider rings
  – To maximise luminosity production efficiency despite the short beam lifetime, about 20 minutes when beamstrahlung is taken into account during collision
  – To stabilize the machine under the heat load of 100 MW synchrotron radiation

• Conceptual study has shown positive result: top-up injection is feasible with no strong technical challenge*

FCC-ee dual aperture main magnets
low power low cost design factor 2 power saving by dual aperture, combined yokes

magnetic models

prototypes

dipole

quadrupole

M. Boscolo, FCCWEEK18

A. Milanese, FCC Week 2017
Vacuum chamber geometry

- CAD model of the 1m-long common-yoke dipole and quadrupole prototypes with arc vacuum chambers (courtesy of M. Gil Costa, CERN/CIEMAT);
- The chambers feature lumped SR absorbers with NEG-pumps placed next to them;

Vacuum chamber cross section:
- 70 mm ID with "winglets" in the plane of the orbit (SUPERKEKB-like);

Need to use non-circular flanges in order to avoid interference with quad coils.

Low-loss “comb-type” bellows modules here (see next slides).
SR spectra and outgassing loads

- **Z-Pole**: very high photon flux (→ large outgassing load);
- **Z-Pole**: compliance with scheduled operation (integrated luminosity first 2 years), requires quick commissioning to $I_{\text{NOM}}=1.390$ A;
- **t-Pole (182.5)**: extremely large and penetrating radiation, critical energy 1.25 MeV;
- **t-Pole** (and also W and H): needs design which minimizes activation of tunnel and machine components;
- **W, H-Pole**: intermediate between Z and T; still $E_{\text{crit}} >$ Compton edge ($\sim 100$ keV)
FCC-ee RF staging scenario

Three sets of RF cavities to cover all options for FCC-ee & booster:

- Installation sequence comparable to LEP (≈ 30 CM/shutdown)
- High intensity (Z, FCC-hh): 400 MHz mono-cell cav, ~1 MW source
- Higher energy (W, H, t): 400 MHz four-cell cavities (4/cryomodule)
- Ttbar machine complement: 800 MHz five-cell cavities (4/cryom.)

### Parameters Table

<table>
<thead>
<tr>
<th>$E_{beam}$ (GeV)</th>
<th>$V_{tot}$ (GV)</th>
<th>$n_{bunch}$</th>
<th>$I_{beam}$ (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>45.6</td>
<td>0.1</td>
<td>16640</td>
<td>1390</td>
</tr>
<tr>
<td>80</td>
<td>0.75</td>
<td>2000</td>
<td>147</td>
</tr>
<tr>
<td>120</td>
<td>2.0</td>
<td>328</td>
<td>328</td>
</tr>
<tr>
<td>182.5</td>
<td>4.0</td>
<td>48</td>
<td>48</td>
</tr>
</tbody>
</table>

RF system needs to compensate for 100 MW SR losses → 200 MW with 50% klystron efficiency (Klystron efficiency was ~55% at LEP2)

Recent (2015) breakthroughs in klystron design promise 90% efficiency
Assume 85% will be achieved and take 10 – 20% margins
Conclusions

• FCC-ee collider is an extremely challenging but feasible with unprecedented physics potential

• Great progress has been made in the FCC-ee collider design

• CDR summary volume progressing as scheduled

• The wide energy range is challenging

  ▪ Large SR energy loss
  ▪ New instabilities from beam-beam interaction and Beamstrahlung
  ▪ Asymmetric IR optics to control SR in the IR (at all energies)
  ▪ Strong sawtooth effect (mostly at ttbar), tapering of magnet strength
  ▪ Asymmetric energy acceptance at tt (BS effect)
  ▪ Bootstrapping injection
  ▪ Proper parameters choice for stable beams at collisions ($\beta_x*$, $\alpha_c$, cell phase advance, tunes,..)
  ▪ 10% polarization ($E_b$ measurement) in 2-3 h

M. Boscolo, FCCWEEK18
Converting DAΦNE to Test Facility?

DAΦNE will shut down as a collider at the end of 2019

Proposal:

exploiting DAΦNE as an
European/International high-current beam facility

Some ideas:

- impedance, HOM effects for accelerator components
- SR effects on vacuum, SEY measurements
- positron source studies
- multi-cell SC cavities for high current CW operation, provided compatibility rf frequency