PRE-BOOSTER RING DESIGN OF THE FCC-e⁺e⁻ INJECTOR COMPLEX

CERN - Beams Department (BE) Seminars
16th of July, 2021

Ozgur ETISKEN (IUE and CERN-BE-ABP-INC)

Thanks to: Dr. Yannis Papaphilippou, Dr. Fanouria Antoniou, Prof. Dr. Abbas Kenan Ciftci and the FCC-e⁺e⁻ injector working groups

Remotely due to Covid-19 pandemic
Outline

- Introduction
- FCC-$e^+e^-$ injector complex
- Requirements for the PBR
- Pre-booster ring design for FCC-$e^+e^-$ injector complex
  - SPS as FCC-$e^+e^-$ pre-booster ring
  - Conceptual design of an alternative pre-booster ring
- Collective effect estimations for pre-booster ring options
- Conclusion

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    ▶ SPS as FCC-e⁺e⁻ pre-booster ring
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  ○ Conclusion
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- **Provide** a unique range of particle accelerator facilities that enable research at the forefront of human knowledge.
- Perform world-class research in fundamental physics.
- **Unite people** from all over the world to push the frontiers of science and technology, for the benefit of all.
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1959 - PS
1989 - LEP
628 m
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6.9 km
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Key dates:

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- 1959 - PS
- 1976 - SPS
- 1989 - LEP

27 km
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- 1959 - PS
- 1976 - SPS
- 1989 - LEP
- 2008 - LHC

27 km
• Now, CERN is planning the future:
Introduction

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ESPPU (European Strategy for Particle Physics) 2013

"Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update" and that CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide."
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ESPPU 2020

“Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.”
• The future may be calling for the Future Circular Collider (FCC)…

Do not worry!
The oracle will tell us about the future.

Let me see…
Introduction


- 144 Institutes and 30 companies from 34 countries have been contributing to the project.

- FCC project has a 70 years plan for CERN!
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The FCC-e$^+e^-$ Project

- The FCC-e$^+e^-$ is a design project of a circular collider of around 100 km circumference.
  - Center of energies of the collider ring varies between 91.2 and 365 GeV.

- General precision machine for the investigations of the Z, W, Higgs and top particles.
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- The injector complex consists of:
  - e-gun
  - Linac
    - up to 6 GeV
    - Positron production
  - Damping ring @ 1.54 GeV
    - Bunch compressor and energy compressor
  - Pre-booster ring up to 16 GeV
    - SPS (baseline)
    - Alternative design
  - Main booster ring

---

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The existing SPS is considered as the baseline scenario for the pre-booster ring in the injector complex; however, using the SPS as pre-booster ring imposes a series of challenges:

- Machine availability
- Minimum modification constraint
- Vacuum chamber
- RF system requirements

Consequently, a "green field" alternative pre-booster ring design has also been studied.
• The FCC-e+e- is a design project of a circular collider of around 100 km circumference.
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    - SPS (baseline)
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The FCC-e+e-+e- Project
The latest proposed version of the **injector complex** consists of:

- $e^-$ source
- Linac (1) up to 1.54 GeV
- Energy compressor (EC, for $e^+$), damping ring (DR, for $e^+$/e$^-$) at 1.54 GeV and bunch compressor (BC, for $e^+$/e$^-$)
- LINAC (2) up to 6 GeV
- $e^+$ production at 6 GeV

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**C. Milardi, et. al., FCC-ee Injector Design/CHART Coordination meeting, 2021**
The pre-injector complex

The latest proposed version of the injector complex consists of:

- **e⁻ source**
- Linac (1) up to 1.54 GeV
- Energy compressor (EC, for e⁺), damping ring (DR, for e⁺/e⁻) at 1.54 GeV and bunch compressor (BC, for e⁺/e⁻)
- LINAC (2) up to 6 GeV
- e⁺ production at 6 GeV

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- **LINAC (2)** up to 6 GeV
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**Diagram:**

- **LINAC 1** up to 1.54 GeV
- **LINAC 2** up to 6 GeV
- **Target & e⁻ capture at 6 GeV**
- **BC** at 6 GeV
- **80 m** distance

**Equations:**

- LINAC 2: 240 m
- 20 ms

C. Milardi, et. al., FCC-ee Injector Design/CHART Coordination meeting, 2021

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The custom built RF gun has a normalized transverse emittance of <10 μm, and can provide up to 6.5 nC of charge at around 10 MeV.

Apart from RF gun for the low e⁻ beam, a thermionic gun will also be utilized in order to supply 10 nC of bunch charge for positron beam.

The normal conducting linac will be fed by two electron sources (the RF gun for the low emittance e⁻ beam and the thermionic gun with higher charge for positrons production).

The linac consists of S-Band structures accelerating the beam up to 6 GeV.
Damping ring

- The **purpose** of the damping ring design is to **accept** the **1.54 GeV beam** coming from the linac (1), **damp the positron/electron beams** and provide the **required beam characteristics** for injection into the linac (2).

- The DR design was done by **S. Ogur and K. Oide** and the design was taken over (early 2021) by **C. Milardi, O. Blanco, A. De Santis**.
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**Straight sections:** allocated for
- RF elements,
- Injection and extraction elements (12m between wigglers),
- Damping wiggler magnets (4x17 m, 1.8 T).
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**C= 270.65 m**

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### Parameter Table

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Damping Ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>$E$ [GeV]</td>
<td>1.54</td>
</tr>
<tr>
<td>Circumference</td>
<td>$C$ [m]</td>
<td>270.65</td>
</tr>
<tr>
<td>Eq. geo. emittance</td>
<td>$\varepsilon_x$ [nm.rad]</td>
<td>1.25</td>
</tr>
<tr>
<td>Eq. bunch length</td>
<td>$\alpha_x$ [mm]</td>
<td>3.19</td>
</tr>
<tr>
<td>Eq. momentum spread</td>
<td>$\alpha_z (x10^{-2})$</td>
<td>0.074</td>
</tr>
<tr>
<td>Damping time</td>
<td>$\tau_h$ [ms]</td>
<td>5.9</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>$h$</td>
<td>360</td>
</tr>
<tr>
<td>Momentum Compaction factor</td>
<td>$\kappa_z (x10^{-1})$</td>
<td>1.49</td>
</tr>
<tr>
<td>Tune (h/v)</td>
<td>$Q_{x,y}$</td>
<td>22.57/23.61</td>
</tr>
<tr>
<td>Tune (s)</td>
<td>$Q_s$</td>
<td>0.019</td>
</tr>
<tr>
<td>Energy loss per turn</td>
<td>$U_0$ [MeV]</td>
<td>0.47</td>
</tr>
<tr>
<td>Bunch population</td>
<td>$N_b (x10^9)$</td>
<td>2.13x$10^9$</td>
</tr>
<tr>
<td>Stored time</td>
<td>$t_s$ [ms]</td>
<td>20</td>
</tr>
<tr>
<td>Beam Current</td>
<td>$I$ [mA]</td>
<td>188</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>$\Delta T_b$ [ns]</td>
<td>18</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>$n_b$</td>
<td>50</td>
</tr>
<tr>
<td>RF frequency</td>
<td>$F_{rf}$ [MHz]</td>
<td>400</td>
</tr>
<tr>
<td>RF Voltage</td>
<td>$V_{rf}$ [MV]</td>
<td>4</td>
</tr>
<tr>
<td>Bending magnet length</td>
<td>$l_{bend}$ [m]</td>
<td>0.219</td>
</tr>
<tr>
<td>Number of bending magnets</td>
<td>$N_{bend}$</td>
<td>212</td>
</tr>
<tr>
<td>Bending radius</td>
<td>$\alpha$ [m]</td>
<td>7.38</td>
</tr>
<tr>
<td>Bending magnet field</td>
<td>$B_{dipole}$ [T]</td>
<td>0.69</td>
</tr>
<tr>
<td>Wiggler magnet length (total)/field</td>
<td>$L_w$ [m]/$B_w$ [T]</td>
<td>68/1.8</td>
</tr>
<tr>
<td>Number of wiggler magnets</td>
<td>$N_w$</td>
<td>4 (x17 m)</td>
</tr>
</tbody>
</table>
**Positron production**

- **Same linac used for positron production @ 4.46 GeV** with bunch intensity of $4.2 \times 10^{10}$ particles. Positron beam emittance are reduced in DR @ 1.54 GeV.
- After target, the capture section is composed of an AMD followed by the capture linac embedded in a DC solenoid magnetic field used to accelerate the beam until about 200 MeV.
- Presented studies show that the comparable positron yield ($\frac{N_{e^+}}{N_{e^-}}$).

---

**Beam energy, GeV**

<table>
<thead>
<tr>
<th>Number of bunches</th>
<th>2</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+$ bunch charge @200 MeV, $e^+$</td>
<td>4.2E+10</td>
<td>4.2E+10</td>
<td>4.2E+10</td>
<td>4.2E+10</td>
<td>4.2E+10</td>
<td>4.2E+10</td>
</tr>
<tr>
<td>$e^+$ yield</td>
<td>2.3</td>
<td>2.3</td>
<td>2.2</td>
<td>2.1</td>
<td>1.8</td>
<td>1.2</td>
</tr>
<tr>
<td>Bunch charge, $e^-$</td>
<td>1.8E+10</td>
<td>1.8E+10</td>
<td>1.9E+10</td>
<td>2.0E+10</td>
<td>2.4E+10</td>
<td>3.4E+10</td>
</tr>
<tr>
<td>Bunch length (rms), mm</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Bunch transv. size (rms), mm</td>
<td>0.5</td>
<td>0.65</td>
<td>0.9</td>
<td>1.15</td>
<td>1.7</td>
<td>2.5</td>
</tr>
<tr>
<td>Bunch separation (tens of ns)</td>
<td>tens of ns</td>
<td>tens of ns</td>
<td>tens of ns</td>
<td>tens of ns</td>
<td>tens of ns</td>
<td>tens of ns</td>
</tr>
<tr>
<td>Repetition rate (max), Hz</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Beam power, kW</td>
<td>3.5</td>
<td>17.3</td>
<td>27.4</td>
<td>38.4</td>
<td>69.1</td>
<td>130.8</td>
</tr>
<tr>
<td>Emittance (normalized max), mm.rad</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Energy spread, %</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
</tr>
<tr>
<td>PEDD (target), J/g</td>
<td>8.6</td>
<td>32</td>
<td>32</td>
<td>32</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>Deposited power (target), kW</td>
<td>0.6</td>
<td>3.3</td>
<td>5.1</td>
<td>7.2</td>
<td>13</td>
<td>25</td>
</tr>
</tbody>
</table>

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Bunch compressor

- FCC-e⁺e⁻ injector requires two 180° turnaround loops to transport the positron beam from the damping ring to the lower energy section of the linac.

- In addition, bunch compression is required to reduce the RMS bunch length from 5mm to 0.5 mm, prior to injection into the linac. Following the second loop, before the beam is injected back into the linac, is the location of the bunch compressor.

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<th>Value</th>
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</tr>
</thead>
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<tr>
<td>Beam energy</td>
<td>$E_0$</td>
<td>1.54</td>
<td>GeV</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>$Q$</td>
<td>4.80</td>
<td>nC</td>
</tr>
<tr>
<td>Bunch length, initial</td>
<td>$\sigma_{z,0}$</td>
<td>5.00</td>
<td>mm</td>
</tr>
<tr>
<td>Energy spread</td>
<td>$\sigma_{E/E_0}$</td>
<td>0.10</td>
<td>%</td>
</tr>
<tr>
<td>Horizontal emittance</td>
<td>$\epsilon_x$</td>
<td>1.81</td>
<td>nm rad</td>
</tr>
<tr>
<td>Vertical emittance</td>
<td>$\epsilon_y$</td>
<td>0.37</td>
<td>nm rad</td>
</tr>
</tbody>
</table>

- CSR cancellation techniques were applied to minimize the emittance growth across the compressor to 6.8%.

Ozgur Etisken, BE Seminars, 16th of July, 2021

ozgur.etisken@cern.ch
Several injection filling scheme discussions are ongoing!
2.8 GHz Linac, accelerating 1 or 2 bunces
100-200 Hz repetition rate
60 ns bunch spacing

From 50 to 595 times injection into the SPS from linac

Main booster (16 GeV - collision energy)

Pre-booster (6-16 GeV)

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400 MHz SPS,
0.125 s ramping time, 15/17.5/20 ns bunch spacing,
around 50-1190 bunch

**e⁻/e⁺**

**e⁻ (10 MeV from e⁻ gun)**

**e⁺ (10 MeV from e⁺ gun)**

**hybrid target for e⁺ production**

**50-100 ms**

**60 ns**

**Damping ring (1.54 GeV)**

**Ozgur Etisken, BE Seminars, 16th of July, 2021**

**Several injection filling scheme discussions are ongoing!**
The main booster: 400 MHz BR, 20 ns bunch spacing, around 50-16640 bunches 0.32-2 s ramping time

From 1 to 14 times injection into the main booster from SPS.

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Injection filling scheme

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The bunch charge is accumulated in the collider ring

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The Super Proton Synchrotron (SPS) is the second-largest machine in CERN’s accelerator complex.

The SPS was initially used as a hadron collider and later as the injector of the lepton collider (LEP).

Currently, it operates as the injector of the large hadron collider (LHC).

It consists of 6 arcs and 6 straight sections: each super-period is composed of 18 FODO cells.

The circumference is around 6.9 km.

Naturally, considered as the baseline option for the PBR of the FCC-\(e^+e^\).
The existing machine is evaluated for the FCC-\(e^+e^−\) based on an energy scaling of the SPS and taking into account the design requirements for the PBR.

Accordingly, two main challenges were revealed:

- The extraction horizontal geometric emittance is 74 nm.rad which is much larger than the required one,

- The synchrotron radiation damping time at injection for the SPS is 1.8 s which is much longer than the 0.1 s required for the pre-booster ring and should be shorten seriously for the efficiency of the injection oscillation.
• Several methods may be applied to reduce the horizontal emittance in a circular accelerator.

• However, minimum modifications can be applied to the current machine, since it has currently been providing beams for several experiments.

• In this regard, the horizontal emittance must be reduced while keeping the existing SPS lattice design.
The horizontal emittance expressed by the second and fifth synchrotron radiation integrals is given by:

$$\epsilon_0 = c q \gamma^2 \frac{I_5}{J_x I_2}$$

$$I_2 = \oint \frac{1}{\rho^2} ds$$

$$I_5 = \oint \frac{\mathcal{H}_x}{\rho^3} ds$$

$$\mathcal{H}_x = \gamma_x \eta_x^2 + 2 \alpha_x x \eta_x \eta_{px} + \beta_x \eta_{px}^2$$
The horizontal emittance expressed by the second and fifth synchrotron radiation integrals is given by:

$$
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$$

where

$$
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$$
$$
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$$

and

$$
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Thus, it is possible to reduce the emittance seriously by means of phase advance optimization only.
• The **nominal phase advance** of the SPS is around 90 degrees per cell.

• The existing phase advance **cannot** provide the required **horizontal emittance**.

• A numerical parametrization of the equilibrium horizontal emittance with the horizontal and vertical phase advance of the FODO cell was performed.

• The optimum phase advance is around 135°, achieving an **emittance of 34 nm.rad** at extraction, which is **seven times larger** than the requirement of 5 nm.rad.
• The nominal phase advance of the SPS is around 90 degrees per cell.
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• 1.79 s damping time is much longer than needed.
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To overcome these limitations, the insertion of damping and Robinson wiggler magnets is proposed.

---

**SPS Parameters**

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<tr>
<td>Phase advance @ injection (m.rad)</td>
<td>54.8x10^{-9}</td>
<td>34</td>
</tr>
<tr>
<td>Energy Loss / turn @ injection (MeV)</td>
<td>0.134</td>
<td>0.154</td>
</tr>
<tr>
<td>Energy Loss / turn @ extraction (MeV)</td>
<td>7.8</td>
<td>7</td>
</tr>
<tr>
<td>Transverse Damping time @ injection (s)</td>
<td>1.79</td>
<td>0.1</td>
</tr>
<tr>
<td>Natural chromaticity h/v</td>
<td>-727/-40</td>
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• **Damping wiggler (DW)** magnet consists of a series of dipole magnet poles deflecting the beam periodically in opposite directions.

• They are used to enhance radiation damping and thus **impact** the energy loss per turn \(U_0\), energy spread \(\sigma_s\), transverse emittance \(\epsilon_x\), damping time \(\tau_x\).

\[
\tau_x = \frac{3E_0}{2\pi r_0 c^2} \frac{C}{\beta \gamma^2 (J_x + F_w)} \quad ; \quad F_w = \frac{L_w B_w^2}{4\pi B^2 \rho}
\]

\[
\sigma_s = \frac{B c_q (1 + F_w \frac{B_w}{B})}{B \rho (3 - J_x + 2F_w)}^{1/2}
\]

\[
\epsilon_x = \frac{c_q \gamma^2}{12(1 + F_w) J_x} \left( \frac{c_r \theta^3}{\sqrt{15}} + \frac{\beta_{xw} F_w \beta_{ww}^2 \gamma^3}{16(B\rho)^3} \right)
\]

\[
U_0 = 2\pi c_q \frac{E^4}{Nl} (1 + F_w)
\]
Damping W. magnets

- Analytical Parameterization of the horizontal emittance ($\varepsilon_x$), damping time ($\tau_x$) and energy loss per turn ($U_0$) with the wiggler peak field and total length.

- The required horizontal emittance at extraction and damping time at injection can be achieved for a total wiggler length of 23m and 3.5T peak field.

- For this choice, the energy loss per turn is however very large (>60MeV).
The Robinson wiggler (RW) is composed by a series of combined function magnets.
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It impacts the damping partition \((D = I_4/I_2)\) by modifying the 4th synchrotron radiation integral \(I_4\).

- Equilibrium horizontal emittance
  \[ \epsilon_0 = c_q r^2 \frac{I_5}{J_x I_2} \approx \frac{1}{1 - D} \]

- Equilibrium energy spread
  \[ \sigma_\delta^2 = c_q r^2 \frac{I_3}{J_z I_2} \approx \frac{1}{(2 + D)^{1/2}} \]

- Damping time
  \[ J_x \tau_x = J_y \tau_y = J_z \tau_z = \frac{2 E_0}{U_0 T_0} \approx \frac{1}{1 - D} \]

- Energy loss per turn
  \[ U_0 = \frac{c_q}{2\pi} E^4 I_2 \approx I_2 \]

Fig: Tobias Tydecks, PhD thesis, 2016
The Robinson wiggler (RW) is composed by a series of combined function magnets. It impacts the damping partition \((D = I_4/I_2)\) by modifying the 4th synchrotron radiation integral \((I_4)\). By introducing a RW (and thus modifying the damping partition number) the horizontal emittance can be significantly decreased, while the energy spread is increased.
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By introducing a RW (and thus modifying the damping partition number) the horizontal emittance can be significantly decreased, while the energy spread is increased.

There is an energy spread limit (0.3 %) coming from the acceptance of the main BR.

The required emittance at extraction can be achieved, while keeping the energy loss per turn in acceptable levels, by using a combination of damping and Robinson wiggler magnets.
• The value of the maximum momentum deviation, for which a particle may have and still undergo stable synchrotron oscillation, is called the momentum acceptance of the accelerator.

• The energy acceptance of the SPS, at the PBR injection energy, is defined by the mechanical aperture constraints and the limit is 1.0 % at injection for the chosen phase advance.

• The minimum RF voltage required for assuring the 1.0% energy acceptance is 15 MV at injection and increases up to 45 MV at extraction energy.

• Challenging RF system is needed.
Dynamic aperture

• Nonlinear effects are introduced by adding sextupoles magnets to the design to correct the chromaticity.

• Maximum stable oscillation amplitudes in x-y spaces due to non-linear fields generate the dynamic aperture.

• The dynamic aperture (DA) is defined as the maximum phase-space amplitude within which particles do not get lost as a consequence of single-particle effects.

• The working point of a ring is chosen to be away from resonance lines. In order to find a good working point, first, a phase advance optimization study was performed.
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• Tune working point on a resonance diagram up to 3\textsuperscript{th} order

• Systematic (red), non-systematic (blue), normal (solid) and skew (dashed) resonances

• \textbf{Black point} shows the working point and \textbf{green points} shows the tune shift with off momentum up to +/-1.0 %
Tune working point on a resonance diagram up to 3th order. Systematic (red), nonsystematic (blue), normal (solid) and skew (dashed) resonances.

Dynamic aperture for different momentum deviations (up to +/-1.0%).

- Particles with different initial conditions were tracked for 4400 turns (around one damping time),
- Sufficient dynamic aperture including off-momentum particles up to +/-1.0 % are achieved for the SPS.
Strong Synchrotron radiation (SR) may penetrate the vacuum chamber and disturb the vacuum level.

- The **SR power** is proportional to the energy loss per turn \((U_0)\), total beam current \((I_{\text{tot}})\) and inversely proportional to the circumference \((C)\):

  \[
P_{\text{sr}} \text{ [W/m]} = \frac{U_0 \text{[eV]} \cdot I_{\text{tot}} \text{[A]}}{C \text{[m]}}
  \]

- The PBR ring will operate in a strong SR regime. SR power considerations should be taken into account at this early design stage.
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The cycle length of the PBR corresponding to four different modes: $tt$ (blue), $Z$ (red), $H$ (black), $W$ (green).
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The existing vacuum chamber of the SPS cannot sustain such power loads.

A new vacuum system, using properly cooled chambers and absorbers is needed [Private communication with R. Kersevan].

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<td>SR due to dipole magnets only (W/m)</td>
<td>1.85</td>
<td>198</td>
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<td>0.024</td>
<td>8.1</td>
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<td>SR due to dipole and damping wiggler (W/m)</td>
<td>-</td>
<td>809</td>
</tr>
<tr>
<td>Average SR due to dipole and damping wiggler (W/m)</td>
<td>-</td>
<td>107</td>
</tr>
<tr>
<td>Beam current (mA)</td>
<td>0.45</td>
<td>7-160</td>
</tr>
</tbody>
</table>
Based on all the considerations summarized in this presentation, the beam parameters of the SPS ring as the FCC e+e- injector complex are summarized in the table below.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Injection</th>
<th>Extraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>$E$ [GeV]</td>
<td>6</td>
<td>16</td>
</tr>
<tr>
<td>Geo. emittance [nm.rad] (hor.)</td>
<td>$e_x$ [nm.rad]</td>
<td>0.73</td>
<td>5.6</td>
</tr>
<tr>
<td>Bunch length</td>
<td>$\sigma_z$ [mm]</td>
<td>41</td>
<td>55</td>
</tr>
<tr>
<td>Momentum spread</td>
<td>$\sigma_\delta$</td>
<td>$3 \times 10^{-2}$</td>
<td>$0.38 \times 10^{-2}$</td>
</tr>
<tr>
<td>Circumference</td>
<td>$C$ [m]</td>
<td>6911.5</td>
<td></td>
</tr>
<tr>
<td>Harmonic number</td>
<td>$h$</td>
<td>9215</td>
<td></td>
</tr>
<tr>
<td>Mom. comp. factor</td>
<td>$\alpha_c$</td>
<td>$0.98 \times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>Tunes [h/v/s]</td>
<td>$Q_{h/v}$</td>
<td>40.38/26/0.08</td>
<td>0.08/0.01/0.005</td>
</tr>
<tr>
<td>Energy loss per turn</td>
<td>$U_0$ [MeV]</td>
<td>3.4</td>
<td>31.5</td>
</tr>
<tr>
<td>Damping times [h/v/l]</td>
<td>$\tau_{h/v/l}$ [s]</td>
<td>0.03/0.03/0.15</td>
<td>0.01/0.01/0.005</td>
</tr>
<tr>
<td>RF frequency</td>
<td>$F_{rf}$ [MHz]</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>RF voltage</td>
<td>$V_{rf}$ [MV]</td>
<td>15</td>
<td>45</td>
</tr>
<tr>
<td>Bending magnet length</td>
<td>$l_{bend}$ [m]</td>
<td>6.26</td>
<td></td>
</tr>
<tr>
<td>Field of bending magnet</td>
<td>$B_{dipole}$ [T]</td>
<td>0.026</td>
<td>0.071</td>
</tr>
<tr>
<td>Nat. chromaticity</td>
<td>$\xi_{h/v}$</td>
<td>-72/-40</td>
<td></td>
</tr>
<tr>
<td>Number of bending magnets</td>
<td>$N_{bend}$</td>
<td>744</td>
<td></td>
</tr>
<tr>
<td>Number of damping wiggler</td>
<td>$N_{dw}$</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Period of damping wiggler</td>
<td>$\lambda_{dw}$ [m]</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Field of damping wiggler</td>
<td>$B_{dw}$ [T]</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>Length of damping wiggler</td>
<td>$l_{dw}$ [m]</td>
<td>12.15</td>
<td></td>
</tr>
<tr>
<td>Length of Robinson wiggler magnet (in total)</td>
<td>$l_{rw}$ [m]</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Field of Robinson wiggler magnet</td>
<td>$B_{rw}$ [T]</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Number of Robinson wiggler magnet</td>
<td>$N_{rw}$</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Energy acceptance</td>
<td>$\Delta \frac{E}{T}$ [%]</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>
Different energy discussions

- The extraction energy was planned as 20 GeV in the earlier stages of the project.

- As this option leads to a very large energy loss per turn, different extraction energy options were investigated and the results are summarized below.

<table>
<thead>
<tr>
<th>20 GeV option</th>
<th>@ injection</th>
<th>@ extraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>w/ wiggler</td>
<td>w/ out wiggler</td>
</tr>
<tr>
<td>Emittance (nm.rad)</td>
<td>1.03</td>
<td>4.88</td>
</tr>
<tr>
<td>Energy loss per turn (MeV)</td>
<td>9.96</td>
<td>0.15</td>
</tr>
<tr>
<td>Damping time (s)</td>
<td>0.012</td>
<td>1.79</td>
</tr>
<tr>
<td>Energy spread (%)</td>
<td>%0.3</td>
<td>%0.01</td>
</tr>
<tr>
<td>RF Voltage (MV)</td>
<td>35</td>
<td>160</td>
</tr>
<tr>
<td>Damping wiggler B[T] / L [m]</td>
<td>6 / 12.15</td>
<td></td>
</tr>
<tr>
<td>Robinson wiggler B[T] / L [m]</td>
<td>0.5 / 12</td>
<td></td>
</tr>
</tbody>
</table>
• The extraction energy was planned as 20 GeV in the earlier stages of the project.

• As this option leads to a very large energy loss per turn, different extraction energy options were investigated and the results are summarized below.

<table>
<thead>
<tr>
<th></th>
<th>20 GeV option</th>
<th>18 GeV option</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>@ injection</td>
<td>@ extraction</td>
</tr>
<tr>
<td></td>
<td>w/ wiggler</td>
<td>w/ out wiggler</td>
</tr>
<tr>
<td>Emittance (nm.rad)</td>
<td>1.03</td>
<td>4.88</td>
</tr>
<tr>
<td>Energy loss per turn (MeV)</td>
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<td>0.15</td>
</tr>
<tr>
<td>Damping time (s)</td>
<td>0.012</td>
<td>1.79</td>
</tr>
<tr>
<td>Energy spread (%)</td>
<td>%0.3</td>
<td>%0.01</td>
</tr>
<tr>
<td>RF Voltage (MV)</td>
<td>35</td>
<td>160</td>
</tr>
<tr>
<td>Damping wiggler B[T] / L [m]</td>
<td>6 / 12.15</td>
<td></td>
</tr>
<tr>
<td>Robinson wiggler B[T] / L [m]</td>
<td>0.5 / 12</td>
<td></td>
</tr>
</tbody>
</table>
The extraction energy was planned as 20 GeV in the earlier stages of the project.

As this option leads to a very large energy loss per turn, different extraction energy options were investigated and the results are summarized below.

|                  | 20 GeV option | 18 GeV option | 16 GeV option |
|------------------|---------------|---------------|
|                  | @ injection   | @ extraction  | @ injection   | @ extraction  | @ injection   | @ extraction  |
|                  | w/ wiggler    | w/ out wiggler| w/ wiggler    | w/ out wiggler| w/ wiggler    | w/ out wiggler|
| Emittance (nm.rad) | 1.03      | 4.88    | 5.92      | 54.25    | 0.95    | 4.88    | 5.60      | 43.9    | 0.73    | 4.88    | 5.64    | 34.7 |
| Energy loss per turn (MeV) | 9.96 | 0.15 | 128.0 | 19.09 | 6.97 | 0.15 | 73.9 | 12.5 | 3.49 | 0.15 | 31.5 | 7.82 |
| Damping time (s) | 0.012 | 1.79 | 0.003 | 0.048 | 0.01 | 1.79 | 0.005 | 0.06 | 0.03 | 1.79 | 0.01 | 0.09 |
| Energy spread (%) | %0.3 | %0.01 | %0.60 | %0.06 | %0.35 | %0.01 | %0.5 | %0.05 | %0.3 | %0.01 | %0.38 | %0.05 |
| RF Voltage (MV) | 35 | 160 | 30 | 90 | 25 | 40 |
| Damping wiggler B[T] / L [m] | 6 / 12.15 | 5 / 12.15 | 3.5 / 12.15 |
| Robinson wiggler B[T] / L [m] | 0.5 / 12 | 0.5 / 12 | 0.5 / 6 |

It becomes clear that the 16 GeV option provides a reasonable energy spread, energy loss per turn and emittance at the same time.
Outline

- Introduction
- FCC-$e^+e^-$ injector complex
- Requirements for the PBR
- Pre-booster ring design for FCC-$e^+e^-$ injector complex
  - SPS as FCC-$e^+e^-$ pre-booster ring
    - Conceptual design of an alternative pre-booster ring
- Collective effect estimations for pre-booster ring options
- Conclusion
Parameter Scaling

- The extraction energy of the PBR is defined by the main BR.

\[ B = \frac{2\pi E}{FCc} \quad ; \quad F = \frac{N \cdot l}{C} \]

- A lowest limit of 50 Gauss was considered for the dipole magnet field (B) of the main BR.

- Based on the above considerations, the extraction energy of the PBR was set to 16 GeV (18 GeV and 20 GeV options were also studied).
The extraction energy of the PBR is defined by the main BR.

\[ B = \frac{2\pi E}{Fc} \; ; \; \quad F = \frac{N \cdot l}{C} \]

A lowest limit of 50 Gauss was considered for the dipole magnet field (B) of the main BR.

Based on the above considerations, the extraction energy of the PBR was set to 16 GeV (18 GeV and 20 GeV options were also studied).

For an energy loss per turn (\(U_0\)) of 30 MeV and an extraction energy of 16 GeV, the required machine circumference (C) of the alternative PBR design was estimated around 2 km.

\[ U_0 = \frac{2\pi C \cdot E^4}{FC} \]
A FODO type cell is chosen.

The cell consists of two 4.1 m-long dipoles sandwiched between quadrupoles with 30 cm length.

The natural chromaticity is compensated by two families of 20 cm long sextupoles in the arcs of the ring.

Zero-dispersion straight sections (designed with identical bending-free cells) in order to accommodate the RF system, injection and extraction.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of bending magnets</td>
<td>304</td>
</tr>
<tr>
<td>Magnet length [m]</td>
<td>4.1</td>
</tr>
<tr>
<td>Bending angle [degree]</td>
<td>1.18</td>
</tr>
<tr>
<td>Max. magnetic field [T]</td>
<td>0.27</td>
</tr>
<tr>
<td>Min. magnetic field [T]</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Main cells in the lattice

- **FODO cell:** sequence of focusing and defocusing quadrupoles which are separated by drift or dipole magnets

- One arc of the alternative PBR consists of 32 FODO cells

- **Straight sections (5 cells)** allocated for
  - RF elements
  - Injection and extraction elements
  - Possible insertion devices if needed

- **Matching section:**
  - For betatron and dispersion functions matching between the arc and straight section
• **h/v emittance** is mainly determined by the dipoles in the arcs of the ring.
• A numerical parametrization of the equilibrium horizontal emittance with the horizontal and vertical phase advances of the arc FODO cell was performed.

- The **minimum emittance** can be achieved for a horizontal phase advance of \(~0.383\).
- Minimal dependence on the vertical phase advance.
The design of the PBR composes of 4 arcs and 4 straight sections.

Zero-dispersion section cells with close to 90° phase advance
Dispersion suppressor and beta matching area

Arc: 32 FODO cells with optimum phase advance for low emittance

Straight sections:
- 5 cells,
- Allocated for
  - RF elements,
  - Injection and extraction elements,
  - Possible insertion devices if needed.
Energy Acceptance

- The value of the **maximum momentum deviation**, for which a particle may have and still undergo **stable synchrotron oscillation**, is called the **momentum acceptance** of the accelerator.

- Considering the maximum energy spread of the beam extracted from the linac, the energy acceptance is aimed to be **1.5%** for the PBR design at the injection energy to be able to accept the incoming beam safely.

\[
\left( \frac{\delta E}{E} \right)^2 = \left[ \frac{qV}{\pi h \alpha c E_o} \left( 2 \cos \phi_s + (2 \phi_s - \pi) \sin \phi_s \right) \right]
\]

\[\phi_s = \arcsin \left( \frac{U_0}{V_0} \right)\]

- Therefore, the minimum RF voltage is calculated as **2.5 MV** to assure **1.5%** energy acceptance at injection and it increases up to **37 MV** at extraction energy.
• Machine imperfections can have an important impact on the beam dynamics.

• Realistic alignment and main field and multipole field errors were applied.

<table>
<thead>
<tr>
<th>Magnets</th>
<th>dx (µm)</th>
<th>dy (µm)</th>
<th>dz (µm)</th>
<th>dphi (µrad)</th>
<th>dtheta (µrad)</th>
<th>dpsi (µrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Quadrupole</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Sextupole</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Magnets</th>
<th>Main field errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole</td>
<td>10^{-3}</td>
</tr>
<tr>
<td>Quadrupole</td>
<td>10^{-3}</td>
</tr>
<tr>
<td>Sextupole</td>
<td>10^{-3}</td>
</tr>
</tbody>
</table>

• Impact of different magnet errors (dipole, quadrupole, sextupole) on the orbit, optics and tune.

• The orbit and beta distortion is dominated by the quadrupole alignment errors.

• Quadrupole alignment and field errors are the main source of optics and tune distortions.
The beam optics, matching sections between the arcs and the straight section, chromaticity and tune are changed with imperfections.

They are needed to be re-matched, even though the distorted orbit is corrected, to keep the periodicity of the ring.

The re-matching processes in terms of optics functions for the **perfect lattice (up-left)**, with applied errors (up-right), with closed orbit corrections (down left and) and after re-matching (down-right).
• The beam optics, matching sections between the arcs and the straight section, chromaticity and tune are changed with imperfections.

• They are needed to be re-matched, even though the distorted orbit is corrected, to keep the periodicity of the ring.

• The re-matching processes in terms of optics functions for the perfect lattice (up-left), with **applied errors** (up-right), with closed orbit corrections (down left and) and after re-matching (down-right).
Optics functions

- The beam optics, matching sections between the arcs and the straight section, chromaticity and tune are changed with imperfections.

- They are needed to be re-matched, even though the distorted orbit is corrected, to keep the periodicity of the ring.

- The re-matching processes in terms of optics functions for the perfect lattice (up-left), with applied errors (up-right), with closed orbit corrections (down left and) and after re-matching (down-right).
The beam optics, matching sections between the arcs and the straight section, chromaticity and tune are changed with imperfections.

They are needed to be re-matched, even though the distorted orbit is corrected, to keep the periodicity of the ring.

The re-matching processes in terms of optics functions for the perfect lattice (up-left), with applied errors (up-right), with closed orbit corrections (down left and) and after re-matching (down-right).
The **dynamic aperture** (DA) is defined as the maximum phase-space amplitude within which particles do not get lost as a consequence of single-particle effects.

- **Tune working point** on a resonance diagram up to 3\(^\text{rd}\) order
- Systematic (red), non-systematic (blue), normal (solid) and skew (dashed) resonances
- **Black point** shows the working point and **green points** shows the tune shift with off momentum up to +/-1.5 %
The **dynamic aperture** (DA) is defined as the maximum phase-space amplitude within which particles do not get lost as a consequence of single-particle effects.

Particles with different initial conditions were tracked for **26000 turns** (around 1 damping time).
The **dynamic aperture** (DA) is defined as the maximum phase-space amplitude within which particles do not get lost as a consequence of single-particle effects.

- Particles with different initial conditions were tracked for **26000 turns** (around 1 damping time) including errors.
- The DA of the alternative PBR including machine and magnet imperfections is adequate for off-axis injection.
Frequency Map Analysis

- $dp/p = +1.5\%$
- On-momentum
- $dp/p = -1.5\%$
Based on all the considerations summarized in this presentation, the beam parameters of the alternative pre-booster ring of the FCC e+e- injector complex are summarized in the table below.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Injection</th>
<th>Extraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>$E$ [GeV]</td>
<td>6</td>
<td>16</td>
</tr>
<tr>
<td>Geo. emittance [nm.rad] (hor.)</td>
<td>$\varepsilon_x$ [nm . rad]</td>
<td>0.66</td>
<td>4.74</td>
</tr>
<tr>
<td>Bunch length</td>
<td>$\sigma_z$[mm]</td>
<td>5.9</td>
<td>7.2</td>
</tr>
<tr>
<td>Momentum spread</td>
<td>$\sigma_\delta$</td>
<td>$0.3 \times 10^{-3}$</td>
<td>0.97 $\times 10^{-3}$</td>
</tr>
<tr>
<td>Circumference</td>
<td>$C$ [m]</td>
<td>2030.4</td>
<td></td>
</tr>
<tr>
<td>Harmonic number</td>
<td>$h$</td>
<td>2706</td>
<td></td>
</tr>
<tr>
<td>Mom. comp. factor</td>
<td>$\alpha_c$</td>
<td>0.32 $\times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>Tunes [h/v]</td>
<td>$Q_{h/v}$</td>
<td>63.687/27.199</td>
<td></td>
</tr>
<tr>
<td>Energy loss per turn</td>
<td>$U_0$ [MeV]</td>
<td>0.57</td>
<td>29.22</td>
</tr>
<tr>
<td>Damping times [h/v/l]</td>
<td>$\tau_{h/v/l}$ [s]</td>
<td>0.18/0.18/0.09</td>
<td>0.01/0.01/0.005</td>
</tr>
<tr>
<td>RF frequency</td>
<td>$F_{rf}$ [MHz]</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>RF voltage</td>
<td>$V_{rf}$ [MV]</td>
<td>2.5</td>
<td>37</td>
</tr>
<tr>
<td>Bending magnet length</td>
<td>$l_{bend}$ [m]</td>
<td>4.1</td>
<td></td>
</tr>
<tr>
<td>Field of bending magnet</td>
<td>$B_{dipole}$ [T]</td>
<td>0.1</td>
<td>0.27</td>
</tr>
<tr>
<td>Nat. chromaticity</td>
<td>$\xi$</td>
<td>-99/-59</td>
<td></td>
</tr>
<tr>
<td>Number of bending magnets</td>
<td>$N_{bend}$</td>
<td>304</td>
<td></td>
</tr>
<tr>
<td>Dynamic aperture (h/v)</td>
<td>$DA$ [mm]</td>
<td>6.3/3.8</td>
<td>-</td>
</tr>
<tr>
<td>Energy acceptance</td>
<td>$\epsilon_x$ [%]</td>
<td>1.5</td>
<td>-</td>
</tr>
</tbody>
</table>
Different energy discussions

• As it was discussed and explained, the limit for the extraction energy comes from the magnetic field of the main booster ring.

• Since the main booster ring has a very large circumference (~98 km), the field of the dipole magnets become low at its injection energy.

• The extraction energy is planned 16 GeV as a baseline for the alternative PBR; however, different options such as 18 GeV and 20 GeV have been also considered and discussed.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Option 1</th>
<th>Option 2</th>
<th>Option 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extraction energy [GeV]</td>
<td>16</td>
<td>18</td>
<td>20</td>
</tr>
<tr>
<td>Circumference [m]</td>
<td>2030</td>
<td>2240</td>
<td>2644</td>
</tr>
<tr>
<td>Injection energy [GeV]</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Geo. emittance [nm.rad] (hor.) @extraction</td>
<td>4.74</td>
<td>4.63</td>
<td>5.01</td>
</tr>
<tr>
<td>Energy loss per turn [MeV] @extraction</td>
<td>29.22</td>
<td>41.36</td>
<td>57.8</td>
</tr>
<tr>
<td>Damping time (hor.) [s] @injection</td>
<td>0.18</td>
<td>0.21</td>
<td>0.1</td>
</tr>
<tr>
<td>Energy spread [%] (rms.) @extraction</td>
<td>0.097</td>
<td>0.1</td>
<td>0.12</td>
</tr>
<tr>
<td>RF voltage [MV] @extraction</td>
<td>37</td>
<td>50</td>
<td>67</td>
</tr>
<tr>
<td>Damping wiggler field [T]</td>
<td>-</td>
<td>-</td>
<td>1.3</td>
</tr>
<tr>
<td>Damping wiggler length (total) [m]</td>
<td>-</td>
<td>-</td>
<td>16.2</td>
</tr>
</tbody>
</table>
Outline

○ Introduction

○ FCC-\(e^+e^-\) injector complex

○ Requirements for the PBR

○ Pre-booster ring design for FCC-\(e^+e^-\) injector complex
  ▶ SPS as FCC-\(e^+e^-\) pre-booster ring
  ▶ Conceptual design of an alternative pre-booster ring

○ Collective effect estimations for pre-booster ring options

○ Conclusion
Collective effect estimates

Collective effects can limit the ultimate performance of any accelerator. In this respect, an analytical estimation of intensity thresholds have been performed both for the SPS and the alternative PBR designs.

Based on the analytical estimations, no major limitations are expected from space charge, longitudinal micro-wave inst. and e-cloud.

Concerning the TMCI, the transverse impedance exceeds the instability threshold for the SPS at the equilibrium state at injection energy and extraction energy. Detailed simulations should follow addressing this subject.

Fast rise times were computed for the fast ion instability rise times: 134 and 61 for the SPS and alternative PBR, respectively. These rising times can be compensated with a feedback system, provided that $10^{-11}$ mbarr SPS vacuum pressures and $10^{-10}$ mbarr alternative ring vacuum chamber are achieved.

Therefore, the current vacuum pressure of the SPS needs to be considerably improved.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Alternative PBR</th>
<th>SPS as PBR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta Q_y$ @inj.</td>
<td>0.0032</td>
<td>0.0005</td>
</tr>
<tr>
<td>$\Delta Q_y$ @eq.</td>
<td>0.028</td>
<td>0.018</td>
</tr>
<tr>
<td>$\Delta Q_y$ @ext.</td>
<td>$1.6 \times 10^{-4}$</td>
<td>$1.6 \times 10^{-3}$</td>
</tr>
<tr>
<td>Emit. growth by IBS at inj. (%)</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>$Z_{01}$ [Ω]</td>
<td>1</td>
<td>6.4</td>
</tr>
<tr>
<td>$(Z_{01}/n)_{th}$ [Ω] - @inj.</td>
<td>57.92</td>
<td>1167</td>
</tr>
<tr>
<td>$(Z_{01}/n)_{th}$ [Ω] - @eq.</td>
<td>1.44</td>
<td>31.14</td>
</tr>
<tr>
<td>$(Z_{01}/n)_{th}$ [Ω] - @ext.</td>
<td>10.11</td>
<td>100</td>
</tr>
<tr>
<td>$Z_{01}$ [Ω]</td>
<td>1</td>
<td>6.4</td>
</tr>
<tr>
<td>$Z_{\perp}$ [MΩ/m]</td>
<td>0.79</td>
<td>9.77</td>
</tr>
<tr>
<td>$Z_{th}$ [MΩ/m] @inj.</td>
<td>5.28</td>
<td>29.6</td>
</tr>
<tr>
<td>$Z_{th}$ [MΩ/m] @eq.</td>
<td>8.95</td>
<td>7.10</td>
</tr>
<tr>
<td>$Z_{th}$ [MΩ/m] @ext.</td>
<td>37</td>
<td>8.97</td>
</tr>
<tr>
<td>$\Delta Q_{\text{ion}}$</td>
<td>0.002</td>
<td>0.009</td>
</tr>
<tr>
<td>$\tau_{\text{inst}}$ [t rev]</td>
<td>134</td>
<td>61</td>
</tr>
<tr>
<td>$\rho_{\text{neut}} [10^{11}/m^2]$</td>
<td>12.55</td>
<td>7.06</td>
</tr>
<tr>
<td>$\rho_{th} [10^{11}/m^2]$ @inj.</td>
<td>2.84</td>
<td>11.30</td>
</tr>
<tr>
<td>$\rho_{th} [10^{11}/m^2]$ @eq.</td>
<td>1.62</td>
<td>1.43</td>
</tr>
<tr>
<td>$\rho_{th} [10^{11}/m^2]$ @ext.</td>
<td>1.68</td>
<td>3.67</td>
</tr>
<tr>
<td>$\Delta Q_x$ @neut. (Inj)/Eq.</td>
<td>0.003</td>
<td>0.035</td>
</tr>
<tr>
<td>$\Delta Q_y$ @neut. (Inj)/Eq.</td>
<td>0.005</td>
<td>0.035</td>
</tr>
<tr>
<td>$\Delta Q_x$ @neut. (Ext.)</td>
<td>0.001</td>
<td>0.01</td>
</tr>
<tr>
<td>$\Delta Q_y$ @neut. (Ext.)</td>
<td>0.002</td>
<td>0.01</td>
</tr>
<tr>
<td>Stupakov parameter</td>
<td>568</td>
<td>3.78</td>
</tr>
<tr>
<td>$\sigma_z$ [cm]</td>
<td>0.59</td>
<td>4.1</td>
</tr>
<tr>
<td>Condition 1 [cm]</td>
<td>0.015</td>
<td>5000</td>
</tr>
<tr>
<td>Condition 2</td>
<td>6433</td>
<td>18525</td>
</tr>
</tbody>
</table>
More options have been under consideration for the injector complex since the early studies before CDR.

- Option 1:
  - Linac 2 → Linac 1
  - 6 GeV
  - Main booster

- Option 2:
  - Linac 2 → Linac 1
  - 6 GeV
  - Linac 4
  - Option 2: positron generation at 20 GeV is still under investigation
  - Main booster

- Option 3:
  - Linac 2 → Linac 1
  - 6 GeV
  - Linac 4
  - Collider ring (45.6 GeV)

Paolo Craievich (PSI) et. al., Injector Review, 2021
LHeC-R LI as FCC-ee Injector

- LHeC (Large Hadron Electron Collider) - Recirculating Linac Injector (RLI) is also evaluated for the FCC-ee as injector.

- Based on 2 Linacs with 3 recirculating arcs (~5.3 km in total), with max. energy of ~49 GeV (60 GeV with longer version)

- Could be used for full energy top-up injector for FCCee-Z mode and pre-injector for other modes

- Small footprint PERLE-like version could be used as pre-injector to (P)BR~6-20GeV

Next steps:

- Refine parameters to include low power/energy options
- Positron production scheme (including damping ring)
- Detailed beam dynamics design
The FCC-\(e^+e^-=\) Project

- The FCC-\(e^+e^-\) is a design project of a circular collider of around 100 km circumference.
  - Center of energies of the collider ring varies between 91.2 and 365 GeV.

- General precision machine for the investigations of the Z, W, Higgs and top particles.

- The **injector complex** consists of:
  - **e-gun**
  - **Linac**
    - up to 6 GeV
    - Positron production
  - **Damping ring @ 1.54 GeV**
    - Bunch compressor
  - Pre-booster ring up to 16 GeV
    - SPS (baseline)
    - Alternative design
  - Main booster ring

**Collider**
- **Main booster (16 GeV - collision energy)**
- **Pre-booster (6-16 GeV)**

**Pre-injector design**
- Positron target at 4.46 GeV
- 1.54 GeV
- Damping ring (1.54 GeV)
- Linac

**Ozgur Etisken, BE Seminars, 16th of July, 2021**

ozgur.etisken@cern.ch
The FCC-e+e- Project

- The FCC-e+e- is a design project of a circular collider of around 100 km circumference.
  - Center of energies of the collider ring varies between 91.2 and 365 GeV.

- General precision machine for the investigations of the Z, W, Higgs and top particles.

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  - **e-gun**
  - **Linac**
    - up to 6 GeV
    - Positron production
  - **Damping ring @ 1.54 GeV**
    - Bunch compressor
  - **Pre-booster ring up to 16 GeV**
    - SPS (baseline)
    - Alternative design
  - **Main booster ring**

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The FCC-e⁺e⁻ Project

- The FCC-e⁺e⁻ is a design project of a circular collider of around 100 km circumference.
  - Center of energies of the collider ring varies between 91.2 and 365 GeV.

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  - e-gun
  - Linac
    - up to 6 GeV
    - Positron production
  - Damping ring @ 1.54 GeV
    - Bunch compressor
  - Pre-booster ring up to 16 GeV
    - SPS (baseline)
    - Alternative design
  - Main booster ring
The last stage of the FCC-e⁺e⁻ injector chain is a ~98 km full energy injector housed in the same tunnel as the collider.

The magnetic lattice is of FODO structure. Two optics are used: first, a $90^\circ/90^\circ$ optics for the operation at 120 GeV and 182.5 GeV, second, a $60^\circ/60^\circ$ optics for 45.5 and 80 GeV.

A. Chance (CEA), B. Harer (KIT) et. al.
Outline

- Introduction
- FCC-\(e^+e^\cdot\) injector complex
- Requirements for the PBR
- Pre-booster ring design for FCC-\(e^+e\cdot\) injector complex
  - SPS as FCC-\(e^+e^\cdot\) pre-booster ring
  - Conceptual design of an alternative pre-booster ring
- Collective effect estimations for pre-booster ring options
- Conclusion

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Ozgur Etisken, BE Seminars, 16th of July, 2021
• The **FCC-e⁺e⁻ injector complex** are introduced including different options

• The possibility of using the **SPS as a PBR of the FCC-e⁺e⁻** was studied

• Lattice design modifications proposed for **achieving the requirements** at injection and at extraction
  - Phase advance optimization, insertion of damping and Robinson wiggler magnets

• Main **limitations** of this option:
  - **Minimum modifications** allowed
  - Limited **machine availability**
  - **New vacuum system** with properly cooled chambers and absorbers needed
  - **Analytical collective effect estimations showed that the SPS vacuum pressure** needs to be considerably improved (10⁻¹¹ mbar)
  - **Challenging RF system** needed due to high energy loss per turn
An **alternative** study of a **green-field** pre-booster ring was studied for the injector complex of FCC-$e^+e^-$.  

A **circumference** of **2 km ring** which can achieve the requirements at injection and at extraction has been designed.  

Adequate **DA** was **achieved** including machine and magnet **imperfections**.  

An **ultra-low vacuum** ($10^{-10}$ mbar) pressure needs to be provided in order to keep the rise time of the ion instability long enough.  

**Water-cooled vacuum chamber** as well as **absorbers** needed due to high SR power.
• An alternative study of a green-field pre-booster ring was studied for the injector complex of FCC-e^+e^-.

• A circumference of 2 km ring which can achieve the requirements at injection and at extraction has been designed

• Adequate DA was achieved including machine and magnet imperfections

• An ultra-low vacuum (10^{-10} mbar) pressure needs to be provided in order to keep the rise time of the ion instability long enough

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Thank you!