Top-up injection schemes

M. Aiba, Á. Sáa Hernández, PSI
With input from B. Goddard, K. Oide, Y. Papaphillipou, D. Shwartz, F. Zimmermann

FCCee Week, Rome
Introduction

• Top-up injection is essential because of very short luminosity life time

• Booster
  – Repetition <0.1 Hz
  – Top-up injection frequency <0.05 Hz (One booster filling two rings)
  – Emittance similar to the main ring emittance (Full energy booster)
  – Negligible collective effect for low charge in Booster

• Integrated luminosity vs Number of batches:
  – Higgs mode: Luminosity life time, $\tau = 21$ min
  – Assuming top-up injection at every 25 sec

- The number of batches of 2~4 would be optimum
  - Luminosity loss
  - Booster extraction kicker rise time / flat top
  - Collider ring injection kicker rise time / flat top
- Frequent top-up injection
  $\rightarrow$ Need robust injection scheme!
Boundary condition/Criterion

- Straight section = 1.5 km
- Booster emittance ~ Collider emittance
  (This presentation is dedicated to the tt mode with $\epsilon = 1.3$ nm that is most difficult case)
- Septum thickness = 5 mm (~3 mm + mechanical tolerance)
or 200 $\mu$m with a wire septum (20~30 $\mu$m wire + mechanical tolerance)
- Clearance = 5$\sigma$ (4$\sigma$ + 1$\sigma$ tolerance)
- Assume dynamic aperture available ~15$\sigma$ / ~5$\sigma$ (on energy / 2% off energy)

Dynamic aperture in X-V plane
Courtesy of K. Oide

Dynamic aperture in X-dP/P plane
M. Benedikt et al., arXiv, “Status and Challenges for FCC-ee”
Figure 5 by P. Piminov and A. Bogomyagkov
Top-up injection schemes

- Several top-up schemes

<table>
<thead>
<tr>
<th>Scheme</th>
<th>On-energy injection</th>
<th>Off-energy injection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional scheme, on/off energy</td>
<td>Separation in transverse phase space</td>
<td>Separation in longitudinal phase space</td>
</tr>
<tr>
<td>Swap out injection</td>
<td>See backup slide</td>
<td></td>
</tr>
<tr>
<td>Longitudinal injection</td>
<td>See backup slide</td>
<td></td>
</tr>
<tr>
<td>Multipole kicker, on/off energy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kickerless injection</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Down-select from the previous study, CERN-ACC-2015-065

Down-select due to Boundary condition (not enough momentum aperture), and the scheme is applicable only for H and tt modes

Further investigation for the remaining schemes
Conventional scheme (1)

- Injection with orbit bump + septum
- Injection point
  - Light sources (Large aperture)
    - $>30\sigma \rightarrow 3\sim5$ mm septum is fine
  - FCCee (Limited aperture)
    - Maximum $\sim10\sigma$
      $\rightarrow$ Impossible with 5 mm septum (next slide)
- Off-energy injection beam $\rightarrow$ Synchrotron phase space injection* with finite dispersion at septum

*P. Collier, Proc. of PAC 1995, p.551
Conventional scheme (2)

- **On-energy, off-axis case**
  - Separation required at septum = 5$\sigma_s$ + S + 5$\sigma_i$
    - $\sigma_i$ optimum $\sim$0.5$\sigma_s$
    - Larger beta function preferred to reduce the septum thickness in terms of beam sigma
    - S = 5 mm, however, corresponds to $\sim$4.4$\sigma_s$ even for 1 km beta function ($\varepsilon = 1.3$ nm)
    - Wire septum is essential to keep the injection point <10$\sigma$
  - Bump height required = 10$\sigma_i$ + S + $\alpha$
    - Additional bump height to keep septum away from the residual betatron oscillation

- **Diagram**: 
  - 200 m long cells
  - Beta at septum/kicker = 312 m
  - Phase advance = 90 deg/cell
  - With dispersion suppressor
  - Bump kicker strength = 11+$\alpha$ $\mu$rad ($0.2+$ $\alpha$ m, $\sim$0.03 T @ 175 GeV)
  - Wire septum essential

$\sigma_s$: Stored beam size
$\sigma_i$: Injection beam size
S: Septum thickness

---

$\sigma_i$: Injection beam size
$\sigma_s$: Stored beam size
S: Septum thickness
Conventional scheme (3)

- Off-energy, on-axis case
  - Separation required at septum, $5\sigma_s + S + 5\sigma_i < Dx \delta_i$
    - Requirements for dispersion and energy offset ($\delta_i$) are determined as well
    - $\sigma_i$ optimum = $\sigma_s$ (Very limited aperture for the off-energy beam)
    - $\sigma_s/i$ are increased due to the energy spread (0.19/0.14%) of the stored/injection beam
  - Bump height required = $10\sigma_i + S$

- 200 m long cells
- Beta at septum/kicker = 312 m
- Phase advance = 90 deg/cell
- Dispersion at septum = 0.8 m
  (Difficult to increase $Dx$...)
- Bump kicker strength = 44 $\mu$rad
  (0.8 m, $\sim$0.03 T @ 175 GeV)
- $\delta_i$=-2.46% to meet $5\sigma_s + S + 5\sigma_i < Dx \delta_i$
  with 5 mm septum
- $\delta_i$=-1.86% to meet $5\sigma_s + S + 5\sigma_i < Dx \delta_i$
  with a wire septum (200 $\mu$m)
- Wire septum essential
Multipole kicker injection (1)

- Injection with multipole kicker + septum *
  - Injection point
    - Light sources (Large aperture)
      - $>30\sigma \rightarrow$ Marginal kick for the store beam
    - FCCee (Limited aperture)
      - Maximum $\sim 10\sigma \rightarrow$ Some impact on the stored beam
- Nonlinear kicker**
  - Pros: Approximately dipole kick for the injected beam $\rightarrow$ Marginal mismatch from kicker
  - Cons: $\sim 1.5$ times less peak field $\rightarrow \sim 1.5$ times more kick for the stored beam

* H. Takaki et al., PR ST-AB, 13, 020705 (2010)
** T. Atkinson et al., IPAC’11
Figures from S. Leemann et al., L. O. Dallin, PAC’03

- Off-energy injection beam $\rightarrow$ On-axis injection with finite dispersion at kicker
Multipole kicker injection (2)

- On-energy, off-axis case
  - Separation required at septum = $15\sigma_s + S + 5\sigma_i$
    - The stored beam particles at $5\sigma_s$ are significantly kicked for $10\sigma$ injection point
    - Therefore, $15\sigma_s$ is to accept as much particles as in the dynamic aperture
    - At the same time, the injection point is at $10\sigma_s$, and thus $\sim 15\sigma_s$ is required anyway to accept the residual betatron oscillation of the injection beam
    - $\sigma_i$ optimum $\sim 0.5\sigma_s$

- 150 m long cells
- Beta at septum/kicker = 385 m
- Phase advance = 30 deg/cell
- With dispersion suppressor
  - Sext. kicker strength = 1.7 m$^{-2}$
    (Nonlinear kicker: 2 m, 0.012 T peak)
  - Emittance increase $\sim 15\%$
    with 5 mm septum
  - Emittance increase $\sim 6\%$
    with a wire septum (200 $\mu$m)
Multipole kicker injection (3)

- Off-energy, on-axis case
  - Separation required at septum = 15σs + S + 5σi
    - The stored beam particles at 5σs are significantly kicked
    - Therefore, 15σs is to accept as much particles as in the dynamic aperture
    - σi optimum ~σs (Very limited aperture for the off-energy beam)

- 150 m long cells
- Beta at septum/kicker = 277 m
- Phase advance = 45 deg/cell
- Dispersion at kicker = 0.6 m
  - δi = +2%
- Sext. kicker strength = 0.88 m²
  (Nonlinear kicker: 3 m, 0.012 T at peak)
- Emittance increase ~30%
  with 5mm septum
- Emittance increase ~20%
  with a wire septum (200 μm)
Wire septum (1)

• Thin septum available, e.g. SPS ZS septum*
  – 25 um wires
  – Field 100 kV/cm
  – 3 m * 5 units
  – Used for 450 GeV p-beam extraction

* Figures taken from B. Goddard and P Knaus, Proc. of EPAC 2000, p.2255
Wire septum (2)

- Specification for 175 GeV electron/positron beam
  - Amplification factor, $\sqrt{\beta_{WS} \beta_{thick\text{, septum}}} \sim 300$
  - ~12 MV integrated voltage for ~20 mm separation
    - for example <40 kV/cm, 3 m unit
- Synchrotron radiation
  - 90 degree cells in conventional injection scheme avoids the SR from the store beam 😊
  - SR mainly from the injection beam
  - SR characteristics
    - (Conventional injection, off-energy)
      - Critical/Mean photon energy = 1.3/0.4 MeV
      - SR energy of ~2 mJ into WS gap per 1% top-up (~230 keV/particle)
- SPS/LEP experience*

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>Equipment</th>
<th>Beam mode</th>
<th>HV polarity</th>
<th>Field kV/cm</th>
<th>Spark rate h⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPS</td>
<td>ZS</td>
<td>none</td>
<td>negative</td>
<td>145</td>
<td>1</td>
</tr>
<tr>
<td>SPS</td>
<td>ZS</td>
<td>p, e⁺, e⁻</td>
<td>negative</td>
<td>100</td>
<td>10</td>
</tr>
<tr>
<td>LEP</td>
<td>ZX</td>
<td>none</td>
<td>positive</td>
<td>50</td>
<td>0.2</td>
</tr>
<tr>
<td>LEP</td>
<td>ZX</td>
<td>none</td>
<td>negative</td>
<td>50</td>
<td>0.4</td>
</tr>
<tr>
<td>LEP</td>
<td>ZX</td>
<td>e⁺, e⁻</td>
<td>positive</td>
<td>15</td>
<td>0.01</td>
</tr>
<tr>
<td>LEP</td>
<td>ZX</td>
<td>e⁺, e⁻</td>
<td>negative</td>
<td>15</td>
<td>4</td>
</tr>
<tr>
<td>LEP</td>
<td>ZL</td>
<td>none</td>
<td>bipolar</td>
<td>50</td>
<td>0.2</td>
</tr>
<tr>
<td>LEP</td>
<td>ZL</td>
<td>e⁺, e⁻</td>
<td>bipolar</td>
<td>30</td>
<td>0.0004</td>
</tr>
<tr>
<td>LEP</td>
<td>ZL</td>
<td>e⁺, e⁻</td>
<td>negative</td>
<td>30</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 2: Spark rates for the HV equipment in the SPS and LEP accelerators for combinations of proton (p) and e⁺, e⁻ beams, and applied HV polarity. Normal operating conditions are in bold.

It seems encouraging to employ WS for FCCee injection

* N. Garrel, B. Goddard, W. Kalbreier and R. Keizer, CERN SL/95-18 (BT)
Experience from PF-AR, KEK*

Figure 4: Turn-by-turn stored beam profiles in the kicker, PSM, and PQM injections measured by using a fast-gated camera.

*R. Takai et al., Proc. of DIPAC 2011, p.305
Open issues

• Beam-beam effects
  – Residual betatron/synchrotron oscillation of the injection beam is problematic though the injection beam charge is a few %?
  – Preferably off-energy (on-axis) injection?
    Higher inj. efficiency and less background at LEP.
  – A few % charge difference between e- and e+ colliding over one booster cycle. Acceptable?
  – Beam disturbance in Conventional injection needs to be evaluated.
  – How much emittance growth in Multipole kicker injection is acceptable?

• Filling scheme
  – Number of batches/bunches per booster cycle?
  – Timing: Ratio of Booster length to Collider length should be NB/NC with integer numbers?
  – Filling pattern feedback?
Summary

• Conventional scheme and Multipole injection are further investigated for the tt mode
  – Both schemes (and both on- and off-energy) may be feasible
  – Possible optics presented
  – Very thin septum (Wire septum)
    • Essential for the conventional scheme (on- and off-energy)
      – However, much relaxed specification w.r.t. SPS ZS septum
    • Preferable for Multipole injection scheme (on- and off-energy)
      – Injection is easier for the operation modes other than tt
• Detailed study of beam-beam effects is necessary to decide the suitable injection scheme
## Summary table

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>Multipole kicker</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Residual oscillation</strong></td>
<td>Betatron / Synchrotron (On energy / Off energy)</td>
<td>Betatron / Synchrotron (On energy / Off energy)</td>
</tr>
<tr>
<td>(Injection beam)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Disturbance</strong></td>
<td>Betatron oscillation (in practice)</td>
<td>Emittance growth (intrinsic)</td>
</tr>
<tr>
<td>(Stored beam)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Wire septum</strong></td>
<td>Essential</td>
<td>Mitigate emittance growth</td>
</tr>
<tr>
<td><strong>Kicker specification</strong></td>
<td>Feasible</td>
<td>Feasible</td>
</tr>
<tr>
<td><strong>Separation, stored beam to septum</strong></td>
<td>$\sim 15\sigma$ (5$\sigma$ at the time of injection)</td>
<td>$15\sigma$</td>
</tr>
</tbody>
</table>
Backup slides
Influence of multipole kicker

• **Mismatch**
  - Injection beam is not only kicked by the multipole kicker but also de/focused due to feed-down quad component
  - Nonlinear kicker is essential for the lattice presented since the beam size becomes too big at the septum when normal sextupole kicker is employed

• **Emittance growth**
  - Since the injection point is rather close to the stored beam, the multipole kicker increases the stored beam emittance at the moment of top-up injection
  - Using a nonlinear kicker is assumed for the evaluation of the emittance growth, i.e. $K2L$ is increased 1.5 times for the computation

**Beta function with feed-down quad (on-energy injection)**

**Particle distribution with and without sextupole kick at septum (off-energy inj.)**
Required separation
Slides from B. Goddard

Synchrotron injection: Defining bump

At moment of injection (bump at full

Next turn (bump off)

The requirement is basically the same for on-energy injection
Swap-out injection*

- Bunch-by-bunch / The entire train at one time
- Septum + Short/Long-pulse dipole-kicker
  - On-axis injection
  - Pseudo-transparent to circulating bunches
  - Without injection chicane

For FCCee, Booster may not provide an injection batch with full bunch charges...

Longitudinal injection* - principle

- Septum + Short-pulse dipole kicker
  - On-axis injection
  - Transparent to circulating bunches
  - Without injection chicane

* M. Aiba et al., PRSTAB, 18, 020701 (2015)
Longitudinal injection for FCC

- Longitudinal phase space may not be suitable (too large bucket height)
- Short pulse kicker may be too challenging...
  Fast decaying tail (~1 ns for 400 MHz RF)
  Repetition (Bunch spacing corresponds to 4 MHz)

Longitudinal 1-D tracking with H mode parameters
Kickerless injection

- Dream injection!!
- Septum only (like in cyclotrons)
  - On-axis injection
  - Transparent to circulating bunches
  - Without injection chicane

Longitudinal 1-D tracking with H-mode parameters

2nd turn ($\delta \sim -3\%$)

Injection point ($\delta = -4\%$)

Wire septum

Not enough momentum aperture, and the scheme is applicable only for H and tt modes...