ESRF Experience

S. White

Acknowledgments: M. Dubrulle, M. Morati, G. Le Bec, T. Perron, P. Raimondi, L. Farvacque, S. Liuzzo, B. Roche, E. Plouviez, J-L. Revol
ESRF injection

Accelerator complex, booster extraction,
storage ring injection

Tuning and experience with top-up

Procedures, performance
operation, sequencer

Injection perturbations

Sources, mitigations

Plans for EBS

Design, new equipment

Summary and outlook
ACCELERATOR COMPLEX UPGRADE

- The whole accelerator complex is undergoing significant upgrades. Main objective:
  - Reduction of the horizontal equilibrium emittance
  - Increased brilliance and coherence

- 200 MeV linac:
  - New buncher installed
  - Refurbishment of ageing component (ongoing)

- TL2 transfer line:
  - Pulsed elements replacements
  - Improved diagnostics (ongoing)
  - Adaptation to the new Booster/Storage ring layout

- 6GeV booster:
  - New power supply system based on IGBT technology: now in operation
  - Emittance reduction campaign
  - Circumference reduction
  - Partial extraction upgrade

- 6GeV storage ring:
  - Accelerator replacement: only the straight sections are kept
  - New injection kickers

<table>
<thead>
<tr>
<th></th>
<th>ESRF</th>
<th>upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hor. Emittance [pmrad]</td>
<td>4000</td>
<td>134</td>
</tr>
<tr>
<td>Vert. Emittance [pmrad]</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Energy spread [%]</td>
<td>0.1</td>
<td>0.09</td>
</tr>
<tr>
<td>$\beta_x$[m]/$\beta_z$[m]</td>
<td>37/3</td>
<td>6.9/2.6</td>
</tr>
</tbody>
</table>
• Pulsed elements at the Booster extraction:
  • 3 bumpers B1/2/3 on separate power supplies ~7ms
  • 1 fast kicker Ke triggering the extraction ~1μs
  • 1 in-vacuum septum Se1 ~1.2ms
  • 2 active septa, 1 long Se21 and one short Se22 ~2ms
• All element except bumpers synchronized with booster revolution frequency

Same power supply

Ke ON: TL2

Ke OFF: Booster
• Pulsed elements at the end of TL2:
  • 2 active septa S1 and S2 – 2ms on the slow timing ~32μs jitter
  • 1 in-vacuum septum S3 – 66μs on the fast timing ~1μs (booster revolution)

Same power supply ~19mm

~19mm

5mm
• In-depth injection tuning and optimization is done at the beginning of each run (~2 month). Mostly done “by hand”:  
  • Phase / timing between accelerators  
  • Booster (FODO lattice) tune orbit, chromaticity, injection and extraction  
  • TL2 trajectory and extraction  
  • Vertical injection oscillations and bump closure  

• Recently installed striplines pick-ups in TL2 transfer line:  
  • Trajectory monitoring  
  • Automated correction  
  • Losses in TL2  
  • Data archived for statistics  

• Very useful during machine restart to establish trajectory or MDTs, i.e., quadrupole scans at constant trajectory
• After optimization ~70% efficiency can be achieved depending on the mode (80% max)
• Slowly degrades during the run (thermalization? Tuning done with “hot” magnets?) down to 40-50%
• Operators slightly retune pulsed elements (septa, bump amplitude) when necessary

Simulated ESRF injection efficiency

Measured injection efficiency in 16 bunch mode 20/08/17. Source of the fluctuations unknown
LIMITATION ON SINGLE BUNCH CURRENT

- ESRF is operated with $Q_x=36.44$ and $Q_y=13.39$

- As the bunch current is increased two effects appear:
  - Stabilization of horizontal instability near 0.5 resonance
  - Strong emittance blow-up near 0.5 resonance

- Injection saturated at around 8mA with gaps closed: most likely losses on the septum blade
- Top-up with closed gaps in 4x10mA not yet achieved

- Horizontal instabilities observed in 7/8+1 on the single bunch (8mA)
- Indirect observation through lifetime
EXPERIENCE WITH TOP-UP

- Top-up operation in 16x6 and 4x10 bunch modes since April 2016:
  - Refill every 20 minutes in 16 bunch, every hour in 4 bunch (need to open the gaps + cleaning in SR)
  - Last 4 bunch mode done with 8mA/bunch to allow injection with closed gaps
- Time between injections: request from users

- 3.0% skipped injections on average over year 2016:
  - Mostly BPSS faults
  - RIPS should be more robust: operation started this run
- No top-up in multi-bunch mode: perturbations
- Full sequence takes 140s, mostly starting / warming-up equipment:
  - Fully automated sequencer
  - Countdown signal sent to the beam lines
  - Perturbation observed during SRinjOn (septa, kickers)
  - Injection lasts ~15s

- CheckBooster:
  - Current in Booster < $I_{\text{ref}}$ : injection skipped
  - Test of cleaning in the Booster: fails -> cleaning in the SR, strong perturbation ~45s

- Septa started ~5s before injection: warming-up
- Kickers started at the last moment
INJECTION PERTURBATIONS

• Injection pulsed magnets:
  • Septa: fringe fields, depends on field strength and distance to the stored beam dominated by S1/2. Unshielded current leads
  • Kickers: bump non-closure, 4 identical kickers pulse shape (timing, pulse shape,…)

• Storage ring:
  • Sextupoles inside the bump: non closure, envelop oscillations

• Vertical perturbations also observed:
  • Coupling, misaligned elements,…

• Now running in top-up mode: significant effort ongoing to reduce these perturbations

• Typical rms orbit perturbation:
  • Slow perturbation from septa fringe fields
  • Fast oscillation from kickers, ramp-up and ramp-down much larger because of sextupoles, small non-closure
  • Vanishing with same time constant as radiation damping time
The perturbation is well reproducible but the Fast Orbit Feedback (FOFB) system is too slow:

- Feed-forward correction send to the FOFB
- Allows to use correctors spread over 2 cells (injection+RF) to compensate the perturbation locally
- Perturbation reduced to a few microns in both planes
- This system will be operational for the new machine
• Sextupoles are located inside the injection bump:
  • $B_y(x)$ evolves quadratically
  • Amplitude (time) dependent orbit distortion
  • Amplitude (time) dependent $\beta$-beat
→ Both resulting in apparent emittance increase
→ Presently dominating effect

• Orbit distortion:
  • Matched on the flat top
  • Maximum reached during ramp up/down
  • In horizontal plane only (no coupling)
• $\beta$-beating:
  • Follows amplitude
  • In both planes
PASSIVE COMPENSATION

- **Idea:** add copper shims inside the kickers ferrite gap to generate a non-linear field

- Shape this field with the shims dimension in order to cancel the sextupole field: reduction of both beta-beat and orbit distortions

- Creates vertical field gradient: alignment is now critical

- 40mm Copper plates top and bottom of the 4 kickers

- This shut-down: stronger c-shaped shims installed
• The injection straight section features the same vertical b-function as ID straights
• We need to top-up with closed gap, i.e. through a 6mm vertical aperture
  ➢ Use this principle to design a low gap in-vacuum non-linear kicker/bladeless septum

• The injection straight section features the same vertical b-function as ID straights
• We need to top-up with closed gap, i.e. through a 6mm vertical aperture

• Use this principle to design a low gap in-vacuum non-linear kicker/bladeless septum

  - Width of copper plates determines:
    - Central gradient
    - Distance to achieve maximum field

• 2 c-shape kickers separated by copper plates:
  - Zero dipole on axis, small quadrupole
  - Injected beam sees almost no gradient (interesting in case of large injected emittance)
  - Low gap: very high field achievable

• Additional coil can be used to cancel the remaining gradient
In parallel an active feed-forward system is under development:

- Latest results show significant improvement (problem with non-closure?)
- Presently limited by maximum current in kicker power supplies and limited power in shaker amplifier

- Corrects only dipolar oscillation, shims both dipolar and envelop: beam lines still observe significant perturbations, stronger shims should help, diagnostics needed

- Fortunately the new design is not impacted by sextupoles inside the bump with large amplitude variations: diagnostics developed are very useful and will be kept
• Vertical perturbation dominated by non-linear kicker vertical offsets and roll angles:

• Use a pair of skew quadrupoles to correct locally the vertical perturbations

• For the new machine only roll angles are an issue, method can still be applied
SEEN FROM THE USERS

- Dedicated experiments conducted with beam lines:
  - Probed the various sources of perturbations: kickers, septa, booster, tune monitor, energy modulation
  - Most experiment can take out / normalize the perturbed data: only a few cannot operate -> constrains time between injections

- Data from ID24: one of the most sensitive beam line, clearly dominated by the kickers, plans to sent fast trigger signal

- Not only the amplitude but also the duration matters: large perturbation < 1ms acceptable
Design constraint: minimize changes

Partial upgrade of the SR injection:
- S2 rebuilt with new power supply
- S1 replaced with permanent magnet
- S3 kept with new power supply
- New Kickers with present power supplies

Partial upgrade of the Booster extraction:
- Se21 Septum rebuilt with new power supply
- Se22 replaced by permanent magnet
- Modification of TL2 layout up to the 1st dipole

Dipole 5 shifted towards storage ring
STORAGE RING INJECTION CELLS

- Dedicated injection cells:
  - Increased $\beta_x$ at injection point
  - Identical to standard cell up to QF4, sextupole optics function and phase advance unchanged

- Minimize symmetry breaking: optimized dynamic aperture

- No sextupole at large bump amplitude
**PERMANENT MAGNET AND KICKERS DESIGN**

- Design finished within specifications

- Longer terms plans:
  - S2 and Se21 as PM
  - Requires novel very compact design
  - R&D to start after commissioning

---

**Integrated field vs transverse position** (Radia simulations)

- Nominal field achieved for 2kA
- EM septa S2 and Se21 design done by Sigmaphi
- Facing issues with eddy current in the thin stainless steel chamber:
  - Degradation of the good field region
  - Field flatness over the pulse flat-top
- Still within specifications
- Started prospecting about ceramic chamber:
  - Positive answer from constructor
  - Acceptable reduction of vertical aperture
  - R&D to start as soon as possible
CERN MegaDiscap

• S2 and Se21 to be equipped with CERN Megadiscap power supplies
• Dynamic and precise current control for Se2/1 and S2 magnets

• In house development power supply for S3 magnet (½ sinus current waveform)
• Expected to be the main source of perturbation for the future machine:
  • Time averaged pulse shape needs to be identical for the 4 kickers: new monitoring diagnostic developed
  • Power supply fluctuations are not negligible with the present system - random fast process: very difficult to correct, no feed-forward possible

• Latest measurements: 0.29% (at 1500A) amplitude jitter

<table>
<thead>
<tr>
<th></th>
<th>ESRF</th>
<th>ESRF-EBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_x$ [pm]</td>
<td>4000</td>
<td>132</td>
</tr>
<tr>
<td>$&lt;\beta_x&gt;$ [m]</td>
<td>5.0</td>
<td>6.5</td>
</tr>
<tr>
<td>$&lt;\delta x'&gt;$ [rad]</td>
<td>1.5e-3</td>
<td>2.3e-3</td>
</tr>
<tr>
<td>$\sqrt{\varepsilon/\beta}$</td>
<td>2.8e-5</td>
<td>4.5e-6</td>
</tr>
<tr>
<td>$\delta x &lt; 0.1\sigma$ [%]</td>
<td>0.2</td>
<td>0.02</td>
</tr>
</tbody>
</table>

• Present machine almost good, future machine needs factor 10 improvement:
  • power supply upgrade?
  • Feedback system?
R&D to start as soon as possible on new kicker power supplies:
- In-house design and validation
- Use solid state technology
- Considering slow rise time: simpler design and operation, could reduce perturbations

- Principle design done:
  - Rise time: 100mus
  - Fall time: < 1mus

- Arbitrary parameters: to be defined/optimized

- Low charger voltage: few 100V required

- Fall time: fast switch opening + energy absorption in passive components (R+C)

- Low current prototype planned for testing
SUMMARY

• ESRF features a standard 4-kickers + in-vacuum septum injection scheme:
  • Tuning is done at each restart: ~2 month providing injection efficiency drifting down to 50% in USM
  • Automated tools recently developed: very useful

• Top-up operation started in April 2016 for 16 and 4 bunch modes:
  • Procedure well established, sequencer fully operational
  • Single bunch current limited to 8mA due to injection saturation with closed gaps: alternate working point?
  • No top-up operation in multi-bunch modes due to perturbation

• Strong injection perturbation observed:
  • Septa: active compensation operational, significant improvement
  • Kickers: dominated by sextupoles in the bump, tried passive and active compensation with visible improvements
  • Overall the perturbation is still too large for continuous operation of some beam lines: considering fast triggers

• ESRF-EBS:
  • Design constraint: minimize changes -> 4-kicker scheme kept, no sextupole at large amplitude
  • Improvements: new power supplies and permanent magnets
  • Users are extremely sensitive (20 years of operation with 2 injections/day…): fully transparent injection looks out of reach
  • Longer term: we will be looking for alternative schemes once the commissioning is behind us