Damping Ring and Transfer Lines for the FCC-ee pre-Injector Complex

Milardi C., De Santis A., S. Spampinati (LNF-INFN, Italy)
Etisken O., (LNF-INFN, Italy and Kirikalle University, Turkey)
Ramjiawan R. L., Y. Dutheil, (CERN, Geneva, Switzerland)
FCC-ee pre-Injector Complex Layout

(P. Craievich, CO84, version 8, 02.06.23)
Damping Ring and Transfer Lines

(WP4)

Cell for Arcs
Triple Bend Achromat

Cell for Arcs
Triple Bend Achromat

Energy Chirp for Bunch compressor

Bunch dechirping

to common linac

1.54 GeV – 4.8 nC
σ_z = ... mm

σ_δ = ... %

ε_N,proj < 5.1 μm

E = 1.54 GeV
Q = 13.5 nC

Injection section
~10 m

Energy Compressor

FODO and Matching Section

Return transfer line

Damping Ring

C = 242 – 271 m
E = 1.54 GeV
Qe = 5.4 nC

Extraction section

~400 m

C. Milardi, DR and TLs for FCC-ee pre-injector,
FCC Week, Jun 5–9 2023, London, Great Britain.
## Injector Parameters (Z-mode)

**FCC Accelerator Pillar meeting #07, 01.11.22**

<table>
<thead>
<tr>
<th></th>
<th>SPS</th>
<th>HE Linac</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Injection energy</strong></td>
<td>6</td>
<td>20</td>
<td>GeV</td>
</tr>
<tr>
<td><strong>Bunch charge both species</strong></td>
<td>4.4</td>
<td>4.4</td>
<td>nC</td>
</tr>
<tr>
<td><strong>Repetition rate</strong></td>
<td>200</td>
<td>200</td>
<td>Hz</td>
</tr>
<tr>
<td><strong>Number of bunches</strong></td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td><strong>Bunch spacing</strong></td>
<td>25</td>
<td>25</td>
<td>ns</td>
</tr>
<tr>
<td><strong>Normalized emittance (x, y) (rms)</strong></td>
<td>10,10</td>
<td>10,10</td>
<td>mm mrad</td>
</tr>
<tr>
<td><strong>Bunch length (rms)</strong></td>
<td>~1</td>
<td>~1</td>
<td>mm</td>
</tr>
<tr>
<td><strong>Energy spread (rms)</strong></td>
<td>~0.1</td>
<td>~0.1</td>
<td>%</td>
</tr>
</tbody>
</table>

* Specification for the charge at the linac end. Charge to be injected into the collider rings is 3.84 nC (bunch population $2.4 \times 10^{10}$ particles).

* Target bunch length and energy spread at the LINAC end, TL from HE LINAC to booster will include energy and bunch length compression.

Other important requests:

- The bunch by bunch intensity will *arbitrarily vary in the range 0 - 100%*, depending on the beam intensity balance in the collider rings

- Bunch-by-bunch injection intensity fluctuation: 3%

- Bucket selection/filling pattern
Damping Ring
Damping Ring optics has been optimized starting from the CDR version, with special attention to: dynamic aperture evaluation, beam acceptance and injection section design.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FCC_ee DR (CDR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>241.8 m</td>
</tr>
<tr>
<td>Equilibrium emittance (x/y/z)</td>
<td>0.96 nm / -1.46 μm</td>
</tr>
<tr>
<td>Dipole length, Field</td>
<td>0.21 m / 0.66 T</td>
</tr>
<tr>
<td>Wiggler #, Length, Field</td>
<td>4, 6.64 m, 1.8 T</td>
</tr>
<tr>
<td>Cavity #, Length, Voltage</td>
<td>2, 1.5 m, 4 MV</td>
</tr>
<tr>
<td>Bunch # Stored, Charge</td>
<td>16, 3.5 nC</td>
</tr>
<tr>
<td>Damping Time $T_1/T_2/T_3$</td>
<td>10.5 / 10.9 / 5.5 ms</td>
</tr>
<tr>
<td>Store Time</td>
<td>40 ms</td>
</tr>
<tr>
<td>Kicker Rise Time @1.54 GeV</td>
<td>50 ns</td>
</tr>
<tr>
<td>Energy Loss per Turn</td>
<td>0.225 MV</td>
</tr>
<tr>
<td>SR Power Loss Wiggler</td>
<td>15.7 kW</td>
</tr>
</tbody>
</table>

C. Milardi, DR and TLs for FCC-ee pre-injector, FCC Week, Jun 5-9 2023, London, Great Britain.
Damping Ring Optics

Straight section including two of the four wigglers.
Straight sections are designed to host RF cavities, and Injection/Extraction equipment.
Beam Dynamics Parameters

Computed by using the following DR parameters:

\[ E_s = 1.54 \text{ GeV} \]
\[ L = 239.2628817 \text{ m} \]
\[ \alpha_c = 0.001535 \]
\[ h = 319 \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>V= 8MV</th>
<th>V= 6MV</th>
<th>V= 4MV</th>
<th>V= 2MV</th>
</tr>
</thead>
<tbody>
<tr>
<td>( U_0 ) [KeV]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Delta E/E_s )</td>
<td>0.71 \times 10^{-3}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Omega_s ) [KHz]</td>
<td>25.313</td>
<td>21.918</td>
<td>17.888</td>
<td>12.618</td>
</tr>
<tr>
<td>( T_0 ) [\mu sec]</td>
<td></td>
<td></td>
<td>0.79801</td>
<td></td>
</tr>
<tr>
<td>( \omega_0 ) [s^{-1} rad]</td>
<td></td>
<td></td>
<td>7.87 \times 10^6</td>
<td></td>
</tr>
<tr>
<td>( \nu_s )</td>
<td>0.003215</td>
<td>0.00278</td>
<td>0.002272</td>
<td>0.0016</td>
</tr>
<tr>
<td>( L_{bunch} ) [m]</td>
<td>0.00207</td>
<td>0.00239</td>
<td>0.00293</td>
<td>0.00415</td>
</tr>
<tr>
<td>( \varphi_s ) [rad]</td>
<td>0.0283967</td>
<td>0.037863</td>
<td>0.0568164</td>
<td>0.113817</td>
</tr>
<tr>
<td>( E - E_s ) [GeV]</td>
<td>0.124</td>
<td>0.107</td>
<td>0.0862</td>
<td>0.058</td>
</tr>
<tr>
<td>( \Delta \varphi ) [unit of \pi]</td>
<td>1.8</td>
<td>1.7769</td>
<td>1.7269</td>
<td>1.6016</td>
</tr>
<tr>
<td>( L_{bucket} ) [m]</td>
<td>0.6788</td>
<td>0.6664</td>
<td>0.6476</td>
<td>0.6006</td>
</tr>
</tbody>
</table>

Short bunch length can be an issue for:
- lifetime,
- injection must be carefully tuned,
- impedance and bunch lengthening must be evaluated,
- beam coupling with RF system
- CSR,
- IBS,
- beam instability impact.

SC RF cavity working at 400 MHz and providing at last 4 MV is considered.
Minimum RF cavity voltage request to compensate the energy lost per turn is \( E_{LT} = 0.225 \text{ MV} \)
RF System

RF as in the CDR
- LHC type 400 MHz,
- SC cavities.
- two RF modules providing 2 MV each,
- 1.5 m long (3.5 with cryostat).

Total RF Power Requirement

\[ P_b = I_b \frac{\Delta U_0}{e} \quad P_l = \frac{V_{RF}^2}{2 n_{RF} R_{shunt}} \]

\[ P_{RF} = P_b + P_l \]

<table>
<thead>
<tr>
<th>Positron charge from LINAC</th>
<th>I_b [mA]</th>
<th>I [mA] ( n_b = 2 \div 18 )</th>
<th>P_b [KW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5 [nC]</td>
<td>5.638</td>
<td>11.3 ( \div 101.5 )</td>
<td>2.6 ( \div 23 )</td>
</tr>
<tr>
<td>0.5 [nC]</td>
<td>0.6</td>
<td>1.3 ( \div 11.3 )</td>
<td>0.285 ( \div 2.56 )</td>
</tr>
</tbody>
</table>

C. Milardi, DR and TLs for FCC-ee pre-injector, FCC Week, Jun 5-9 2023, London, Great Britain.
The stability region in the transverse plane have been evaluated for different energy deviation, in the range between ±2%. Contours represents regions where at least 90% of the initial conditions leads to a successful tracking. A probability definition is needed in order to get the average value over the surface.

2000 turns have been tracked (~15% damping time). The estimated loss of accuracy is below 1% at the nominal energy.

The phase space have been sampled up to $3 \times 3 \text{ cm}^2$ in the transverse plane. Only on-axis particles have been simulated ($x'/y'=0$).

Radiation damping has been neglected allowing a much faster tracking of the DR.
DR acceptance probability has been evaluated starting with nominal beam parameters at the injection: Gaussian profile with nominal width at the injections ($\sigma \sim 2\text{mm}$ in both planes). The energy distribution has been assumed Gaussian with 5% resolution.

$10\,\text{kTurn}$ and radiation ON.

The color map represent the projection of the survival probability associated to the different position in space: horizontal and vertical, respectively.

A full matrix in phase space will be delivered to reshape particle distribution at the positron source.
Damping Ring Acceptance, and Energy bunch compressor
Transverse emittance @ pLINAC (Jan23)

\[ \Sigma_x = \begin{pmatrix} 3.26^2 & -0.35 \\ -0.35 & 0.88^2 \end{pmatrix} \]

\[ \epsilon_x = \sqrt{\text{det} \Sigma} = 2.83 \text{ mm mrad} \]

\[ \rho_x = -0.123 \]

\[ \Sigma_y = \begin{pmatrix} 8.06^2 & 0.60 \\ 0.60 & 0.82^2 \end{pmatrix} \]

\[ \epsilon_y = \sqrt{\text{det} \Sigma_y} = 2.69 \text{ mm mrad} \]

\[ \rho_y = 0.091 \]
Analytical Energy Compressor optimization

\[ \delta t = t_0 - t_{ref} \]
\[ \delta p_z = p_z^0 - p_z^{ref} \]

**R_{56} + zero-crossing cavity transform:**

\[ t_{56} = \delta t + R_{56} \frac{\delta p_z}{p_T} \]
\[ p_z^{EC} = V_{RF} \sin(2\pi f_{RF} t_{56}) \]

\[ p_z = p_z^0 + p_z^{EC} \]

Results with Elegant simulation slightly different.

V_{RF} and R_{56} parameter scan to maximize the fraction of particle within 2\% of the central energy.

Result (only analytical):

\[ V_{RF} = 100 \text{ MV} \]
\[ R_{56} = -0.35 \text{ m} \]
In a four bending C-shape chicane dispersion and second order dispersion are intrinsically closed.
Two cavities of the type used for the positron LINAC (PSI design. LINAC THPOJO08 LINAC 2022)
The beam exit ECS on the same LINAC axis, thus same diagnostics can be used for LINAC and ECS tuning.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole Bending angle</td>
<td>0.2256 (12.9)</td>
<td>rad (deg)</td>
</tr>
<tr>
<td>Dipole Magnetic length</td>
<td>1.395</td>
<td>m</td>
</tr>
<tr>
<td>Distance between dipoles</td>
<td>1</td>
<td>m</td>
</tr>
<tr>
<td>R56</td>
<td>0.205</td>
<td>m</td>
</tr>
<tr>
<td>Max dispersion</td>
<td>0.56</td>
<td>m</td>
</tr>
<tr>
<td>Number of Cavities</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>RF frequency</td>
<td>2</td>
<td>GHz</td>
</tr>
<tr>
<td>Accelerating Gradient</td>
<td>20</td>
<td>MV/m</td>
</tr>
<tr>
<td>Accelerating Voltage</td>
<td>99</td>
<td>MV</td>
</tr>
</tbody>
</table>
Results of tracking by Elegant

- Energy Compressor (ECS) reduces the width of the energy distribution and increases the number of particles accepted by the DR.
- Elegant tracking of the distribution from pLINAC.
- Tracking includes 1D CSR model.

Beam fraction in E0 ± 2%
Tracking DR input distribution

To increase statistics distributions from ECS have been resampled. The central energy and time are assumed to be “free to be adjusted”.

Cut on the tails have been applied (8% loss)

Comparison between ECS (analytical) and ECS (Elegant) shows some difference

Simulations with EC(Elegant) distributions are on-going (no major difference expected)
DR Acceptance

\[ \sigma_x = 4.2 \text{ mm} \]
\[ \sigma_x = 1.8 \text{ mm} \]

\[ \sigma_y = 4.0 \text{ mm} \]
\[ \sigma_y = 1.8 \text{ mm} \]

Time evolution:

This box is the aperture limit.
Initial distributions are strongly asymmetric

\[ \sigma_E = 1.1\% \]
\[ \sigma_E = 0.2\% \]

\[ \text{RMS}_z = 3.2\text{ cm} \]
\[ \sigma_z = 0.8\text{ cm} \]

Damping Ring acceptance

Time evolution:

\[ f_{\text{acc}} = \frac{91.6k}{100k} \]
At large energy deviation most of the losses are concentrated in the tail of the distribution as expected. Global DR acceptance:

\[ f_{\text{ACC}} = 0.939 \times 0.917 = 86.1\% \]

Recently the emittance of the beam provided by the pLINAC has been optimized -> an even larger DR acceptance is expected. New DR acceptance is being evaluated.
Transfer Lines, and Bunch Length Compressor
pLINAC to DR TL
TL Injection Section

- flexible
- achromatic

<table>
<thead>
<tr>
<th></th>
<th>Angle [degree]</th>
<th>Length [m]</th>
<th>Field [T]</th>
<th>Thickness [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>4.2</td>
<td>0.47</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>-3.4</td>
<td>0.47</td>
<td>-0.65</td>
<td></td>
</tr>
<tr>
<td>SPT1</td>
<td>-2</td>
<td>0.8</td>
<td>-0.044</td>
<td>7</td>
</tr>
<tr>
<td>SPT2</td>
<td>-1.2</td>
<td>0.8</td>
<td>-0.026</td>
<td>2 - 4</td>
</tr>
</tbody>
</table>

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Transvers Distribution Evolution from pLINAC to DR

Transvers emittance is preserved

\[ \varepsilon_x = 2.86 \text{ mm-mrad} \]
\[ \varepsilon_y = 3 \text{ mm-mrad} \]
### TBA Cell with R56 for Arcs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_b$ total [rad]</td>
<td>$\pi/2$</td>
</tr>
<tr>
<td>$L_b$ [m]</td>
<td>1.0/0.5767</td>
</tr>
<tr>
<td>$\rho$ [m]</td>
<td>5.736/3.304</td>
</tr>
<tr>
<td>B [T]</td>
<td>0.5366/0.9315</td>
</tr>
<tr>
<td>nQUADS</td>
<td>10</td>
</tr>
<tr>
<td>$L_{QUA}$ [m]</td>
<td>0.2</td>
</tr>
<tr>
<td>$L_{cell}$ [m]</td>
<td>10.0</td>
</tr>
</tbody>
</table>

#### Quadrupole gradient m$^2$
- $K_{1qf}$: 3.47714
- $K_{1qd}$: -4.47514
- $K_{1qfe}$: 1.1759
- $K_{1qde}$: -2.84811

#### Sextupole gradient m$^3$
- $K_{2sf}$: 1.7
- $K_{2sd}$: -2.8

- $\beta_x < 16$ m
- low $\eta_x$
- $\alpha_{xy} = 0$ both ends
- achromatic
- low invariant
- $R56 \sim 0.07$ m
DR to common LINAC TL

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Bunch Compressor Design

Beam parameters after Damping Ring
- Equilibrium (zero current) bunch length 2.9 mm assuming $V_{RF} = 4$ MV
- **Expected bunch length** < 5 mm
- Equilibrium zero current bunch energy spread 0.07%
- **Expected Bunch energy spread** ≈ 0.1%
- Equilibrium emittance 0.96 nm (normalized emittance 2.9 mm*mradi)

Beam parameters at the common LINAC entrance
- Bunch length ≈1 mm
- Relative bunch energy spread $\sigma_\gamma < 0.65\%$ at 1.54 GeV
- Normalized transverse emittance 3.4 mm*mradi

Bunch Compressor requirements
- Compressor factor 1-5 variable
- Final relative energy spread after BCS $\sigma_\gamma < 0.65\%$
- **Preserve transverse emittance.**
• In order to achieve $\sigma_y < 0.65\%$ after BCS

$$h = \frac{\sigma_y}{\sigma_z} < 1.3 \text{ m}^{-1} \quad \text{Max } C = \frac{1}{1 - R56 \cdot h} = 5 \quad |R56| > 0.62\text{ m}$$

• R56 high for a single chicane

A de-chirper after the dispersive section can reduce $|R56|$:

$$h = \frac{\sigma_y}{\sigma_z} < 2.2 \text{ m}^{-1} \quad \text{Max } C = \frac{1}{1 - R56 \cdot h} = 5 \quad |R56| > 0.4\text{ m}$$

Cavity parameters (PSI design of the common LINAC THPOJO08 LINAC 2022)

• frequency 2.80 GHz
• 84 cells for 3m structure
• One structures operating at a gradient of 20MV/m (60MV total) to chirp the beam
• Two structures operating at a gradient of 25MV/m (75MV total) to de-chirp the beam

Tunable $|R56| > 0.42 \text{ m}$ is provided by the arc cells of the TL connecting DR to common LINAC
DR and TLs Layout

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FCC Week, Jun 5-9 2023, London, Great Britain.
Motivations to review the DR design:

- Minimize cell number in the arcs,
- Reduce or even eliminate the use of wigglers magnets to achieve the required parameters ($\varepsilon$ and $\tau_d$),
- Improve Dynamic Aperture and ring acceptance,
- Optimize injection extraction sections.

Present DR design:

- The CDR DR includes a very large number of elements
- **232 short dipole magnets** were used: which requires high number of components such as: quadrupoles, sextupoles, octupoles, steering magnets, and beam diagnostics high realization costs, complicate installation and alignment procedures.
- Magnetic field in the dipoles are rather low 0.66 T
- **Long damping wiggler** (26.56 m) are necessary to achieve required parameters
- Only 2 straight sections to host injection/extraction, Rf cavity and damping wigglers. This is not the best as far as NLD is concerned
- Not optimum phase advance were chosen for the beam emittance damping.
Some of the new DR Layout

<table>
<thead>
<tr>
<th>Parameters</th>
<th>CDR</th>
<th>Option - 1</th>
<th>Option - 2</th>
<th>Option-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [GeV]</td>
<td>1.54</td>
<td>1.54</td>
<td>1.54</td>
<td>2.86</td>
</tr>
<tr>
<td>Lattice type</td>
<td>FODO</td>
<td>FODO</td>
<td>FODO with DQ</td>
<td>FODO</td>
</tr>
<tr>
<td>Layout</td>
<td>Racetrack</td>
<td>3 arcs and 3 SS</td>
<td>Racetrack</td>
<td>3 arcs and 3 SS</td>
</tr>
<tr>
<td>Bending magnet quantity</td>
<td>232</td>
<td>78</td>
<td>30 DQ / 12 D</td>
<td>144</td>
</tr>
<tr>
<td>Dipole magnet length [m]</td>
<td>0.21</td>
<td>0.4</td>
<td>0.55 / 0.4</td>
<td>0.65</td>
</tr>
<tr>
<td>Bending angle [degree]</td>
<td>1.55</td>
<td>4.61</td>
<td>10 / 5</td>
<td>2.5</td>
</tr>
<tr>
<td>Dipole magnetic field [T]</td>
<td>0.66</td>
<td>1.03</td>
<td>1.62 / 0.81</td>
<td>0.94</td>
</tr>
<tr>
<td>Filling factor</td>
<td>0.2</td>
<td>0.15</td>
<td>0.11</td>
<td>0.24</td>
</tr>
<tr>
<td>Damping wiggler magnet</td>
<td>26.5 m / 1.8 T</td>
<td>36.45 m / 2 T</td>
<td>- / -</td>
<td>36.45 m / 2 T</td>
</tr>
<tr>
<td>Robinson wiggler magnet</td>
<td>- / -</td>
<td>- / -</td>
<td>- / -</td>
<td>- / -</td>
</tr>
<tr>
<td>Circumference</td>
<td>242 m</td>
<td>248.19 m</td>
<td>181.74 m</td>
<td>384.87 m</td>
</tr>
<tr>
<td>Emittance</td>
<td>2 nm.rad</td>
<td>2.1 nm.rad</td>
<td>2.25 nm.rad</td>
<td>1.20 nm.rad</td>
</tr>
<tr>
<td>Damping time</td>
<td>10.5 ms</td>
<td>8.1 s</td>
<td>9.1</td>
<td>6.4 ms</td>
</tr>
<tr>
<td>Energy loss per turn</td>
<td>0.255 MeV</td>
<td>0.31 MeV</td>
<td>0.14 MeV</td>
<td>1.13 MeV</td>
</tr>
</tbody>
</table>
New DR Layout studies

- Different options are being evaluated including different type of cell and magnet.
- In all the options, the number of elements was considerably reduced.
- In a preliminary configuration (Option-2) beam parameters were achieved even without damping wiggler insertions which helps in simplifying vacuum chamber design impedance budget and realization costs. Option-2 also minimize curly H function which is important to avoid emittance dilution effects due to CSR.
**Conclusions**

DR and TLs design has been completed.

A DR acceptance larger than 86% can be achieved with the help of an ECS installed between the pLINAC and the DR injection line. ECS reduces energy spread to ~ 2%

A BCS has been included in the return line from the DR to Common LINAC. BCS can provide maximum compression factor C ~ 5.

A breakdown schedule of the the components used for the different parts has been prepared costs are being evaluated.

Alternative DR designs are being considered.
Many thanks to all the Colleagues of the FCC-ee pre-Injector Collaboration

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Spare Slides
WP4 WBS

ECS
- 232 DIPOLEs (21 cm each) in the arcs
- 258 QUADRUPOLEs (L = 0.20 m each mostly in the arcs)
- 232 SEXTUPOLEs (L = 0.08 m each mostly in the arcs)
- 4 WIGGLERs (L = 6.7 m each: 44 poles 5 cm long)
- 258 BPMs
- 258 CHVs
- 1 SLM
- 1 DCCT
- 4 Strip line at injection extraction septa
- 2 Fluorescent screen + trigger camera
- Streak camera
- White noise generator and spectrum analyzer
- 2 Straight section hosting RF Cavity and Injection/Extraction equipment
- 4 injection/extraction kickers (Yann)
- RF (need info from CERN expert)

EBS
WP4 WBS

Damping Ring

- 232 DIPOLEs (21 cm each) in the arcs
- 258 QUADRUPOLEs (L = 0.20 m each mostly in the arcs)
- 232 SEXTUPOLEs (L = 0.08 m each mostly in the arcs)
- 4 WIGGLERs (L= 6.7 m each: 44 poles 5 cm long)
- 258 BPMs
- 258 CHVs
- 1 SLM
- 1 DCCT
- 4 Strip line at injection extraction septa
- 2 Fluorescent screen + trigger camera
- Streak camera
- White noise generator and spectrum analyzer
- 2 Straight section hosting RF Cavity and Injection/Extraction equipment
- 4 injection/extraction kickers (Yann)
- RF (cost evaluated by CERN expert)