ORBIT SIMULATIONS ABOUT THE PSB INJECTION WITH LINAC4

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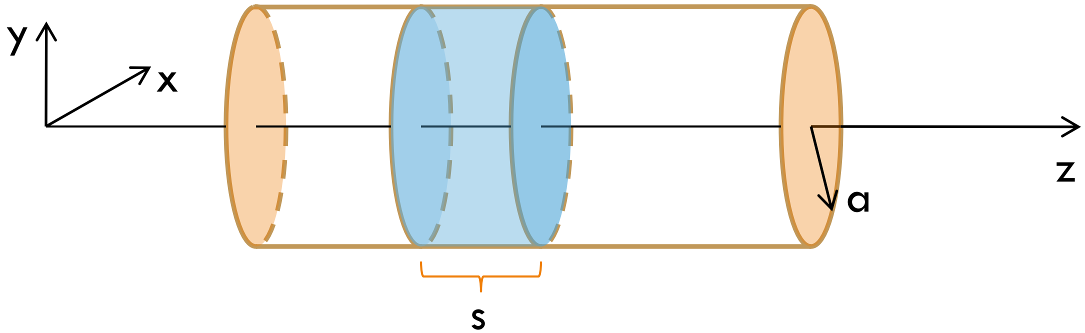
Joined DESY and University of Hamburg Seminar

Table of contents

Space charge effects



$$I = \frac{N\beta_{rel}c}{C}$$

$$\rho = \frac{I}{\pi\, a^2 \beta_{rel} c}\ ;\ \ j = \frac{I}{\pi\, a^2}$$

Gauss's Law

$$\varepsilon_0 \int_{\partial S} \vec{E}\, d\vec{S} = \int_{\partial V} \rho\, dV \quad \Leftrightarrow \quad 2\pi\, r\, s\, \varepsilon_0\, E_r = \rho\, \pi\, r^2 s \quad \Leftrightarrow \quad E_r = \frac{\rho\, r}{2\, \varepsilon_0} = \frac{I\, r}{2\pi\, \varepsilon_0\, a^2\, \beta_{rel} c}$$

Ampère's Law

$$\int_{\partial r} \vec{B}\, d\vec{r} = \mu_0 \int_{\partial S} \vec{j}\, d\vec{S} \quad \Leftrightarrow \quad 2\, s\, B_\varphi = \mu_0\, j\, r\, s \quad \Leftrightarrow \quad B_\varphi = \frac{\mu_0\, j\, r}{2} = \mu_0 \frac{I\, r}{2\pi\, a^2}$$

Lorentz force and equation of motion

The Lorentz force on a particle in a bunch: use: $B_\varphi = \frac{\beta_{rel}}{c} E_r$

$$\vec{F} = q(\vec{E} - \vec{v} \times \vec{B}) = q(E_r - \beta_{rel} \gamma B_\varphi) = q(1 - \beta_{rel}^2) E_r = \frac{qE_r}{\gamma^2}$$

Equation of motion in a drift space: use: $\frac{d^2 r}{dt^2} = \beta_{rel}^2 c^2 \frac{d^2 r}{dz^2}$

$$\gamma m \frac{d^2 r}{dt^2} = \frac{q\, E_r}{\gamma^2} \qquad \Leftrightarrow \qquad \frac{d^2 r}{dz^2} = \frac{q\, I}{2\pi\, m \varepsilon_0 a^2 \beta^3 \gamma^3 c^3} r = \frac{\kappa}{a^2} r$$

$$\kappa = \frac{q\, I}{2\pi\, m \varepsilon_0 \beta^3 \gamma^3 c^3} = \frac{2\, I}{I_0 \beta^3 \gamma^3}\, ; \quad I_0 = \frac{4\pi \varepsilon_0 m c^3}{q}$$

Generalised perveance and Alfven current

Laslett tune shift

Tune shift caused by the space charge effects.

For the calculation with the smooth approximation model take:

$$Q = Q_x = Q_y\,; \quad \varepsilon = \varepsilon_x = \varepsilon_y\,; \quad a = \sqrt{\varepsilon \beta_0}$$

$$k_x(s) = k_y(s) = k_0 \qquad k_0 = \left(\frac{2\pi\, Q_0}{\mathrm{C}}\right)$$ and $$\beta(s) = \beta_0 = \frac{1}{\sqrt{k_0}} = \frac{C}{2\pi\, Q_0}.$$

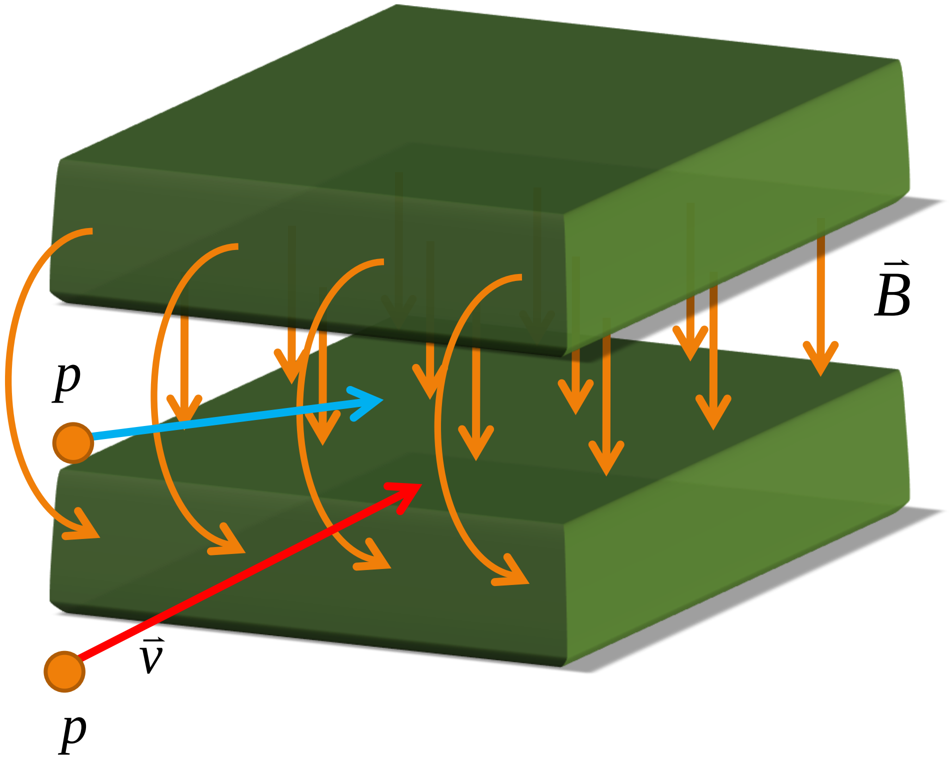
The envelope equation is given by: $k\,a - \dfrac{\varepsilon^2}{a^3} = 0$ with $k = k_0\, a - \dfrac{\kappa}{a^2}$

The effect of the SC is the same as a defocusing quadrupole with strength κ.

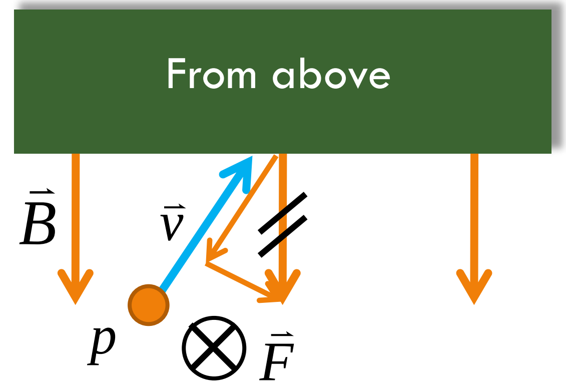
$$\Delta Q = \frac{1}{4\pi} \oint \beta(z)\, \Delta k(z)\, dz = -\frac{1}{4\pi} \oint \beta_0\, \frac{\kappa}{a^2}\, dz$$

$$= -\frac{C}{4\pi} \frac{I\, q\, \beta_0}{a^2 \beta_{rel}^3 \gamma^3 I_0} = -\frac{\mathrm{N c}}{2\pi I_0 \varepsilon^{norm} \beta_{rel} \gamma^2} \propto \frac{N}{\varepsilon^{norm} \beta_{rel}\, \gamma^2}$$

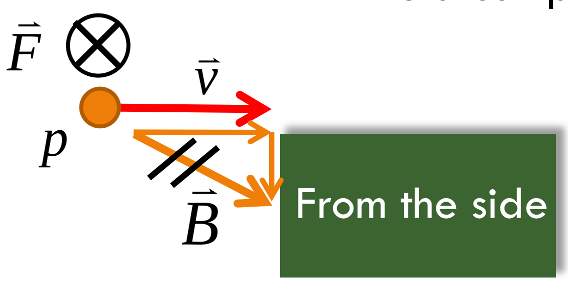
Edge focusing



Vertical focusing at horizontal field components

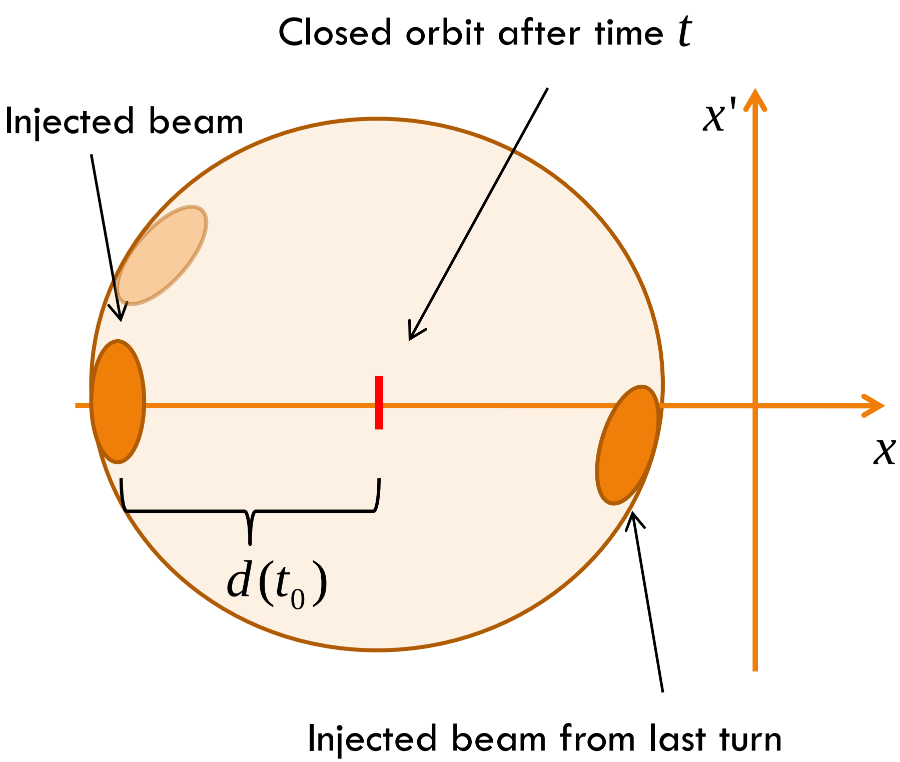


Horizontal defocusing at vertical field components

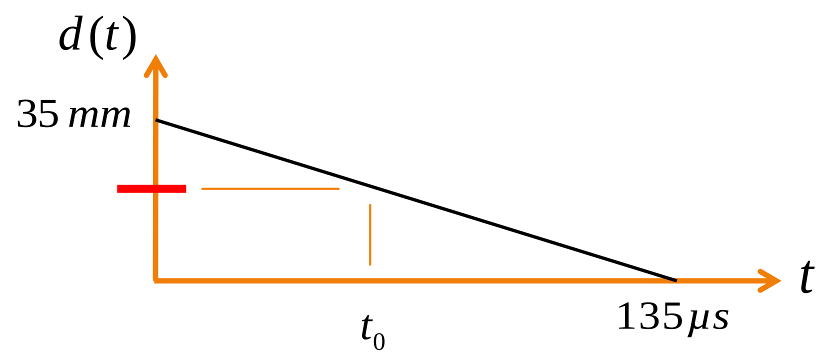


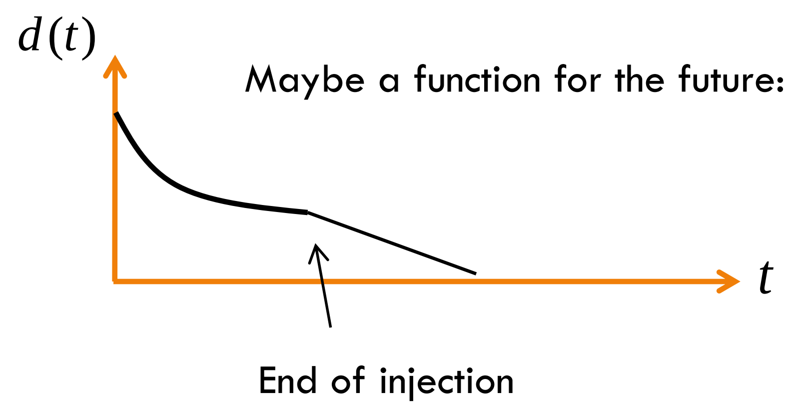
Horizontal Painting

Filling scheme for the horizontal phase space ellipse.



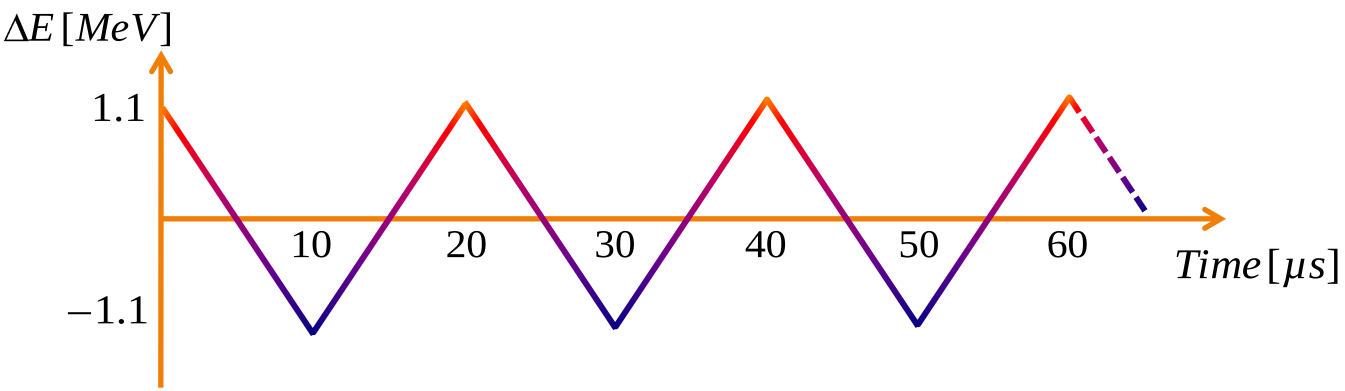
Present painting bump function for high intensity beam (active compensation).





Longitudinal Painting

Filling scheme for the bucket.



Modulation of the particle energy

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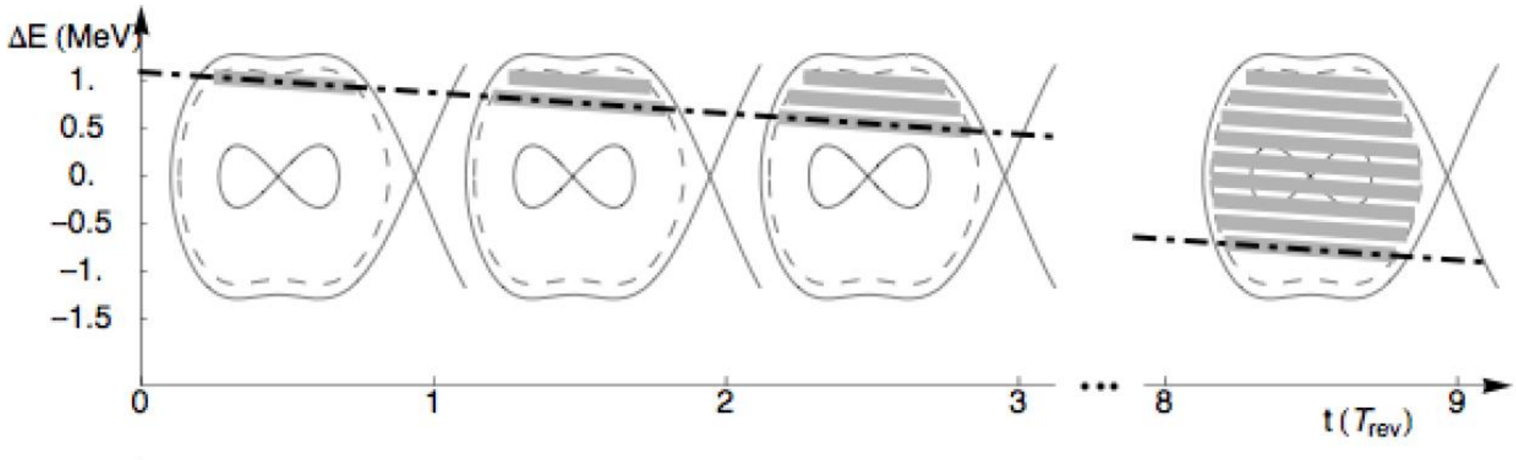
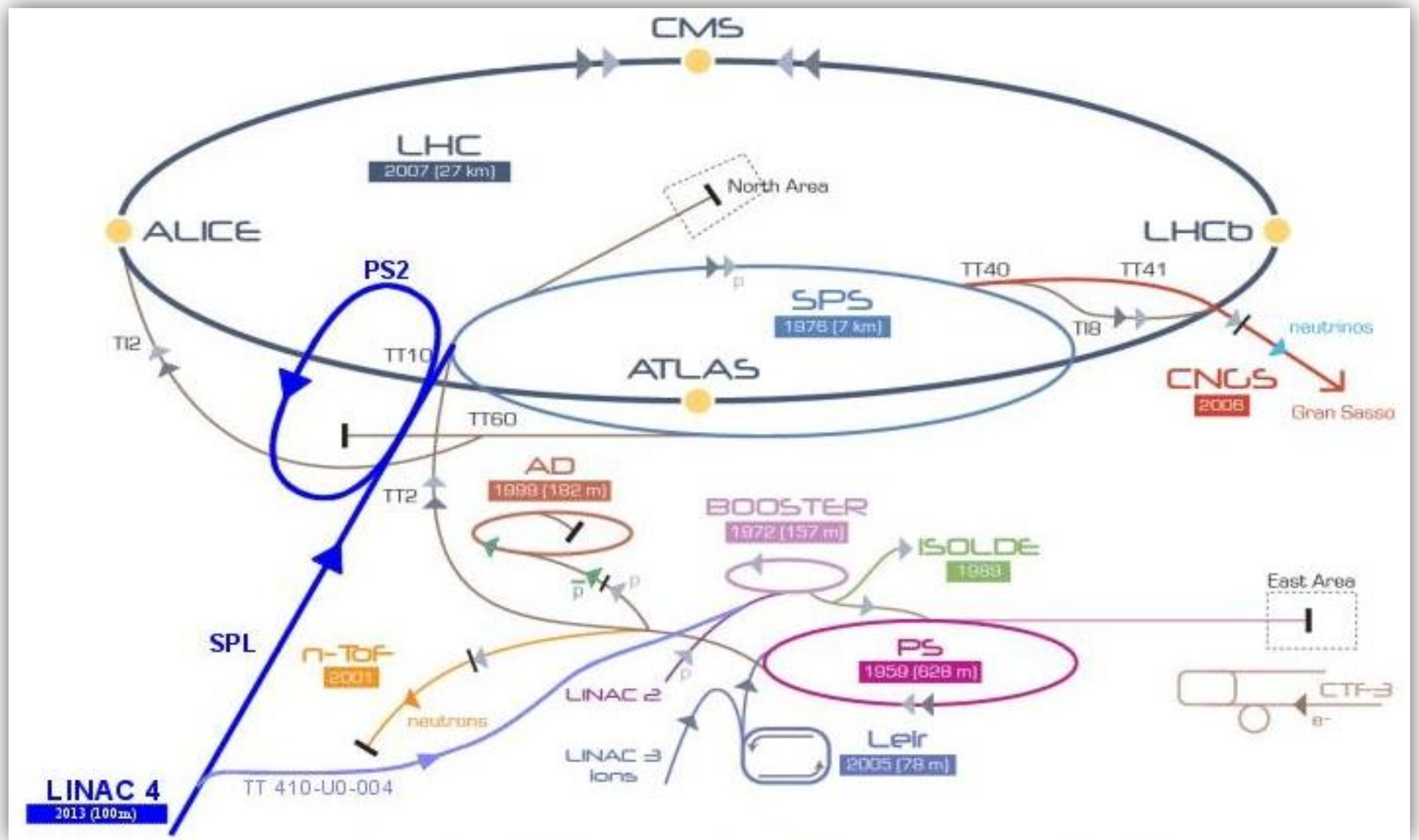
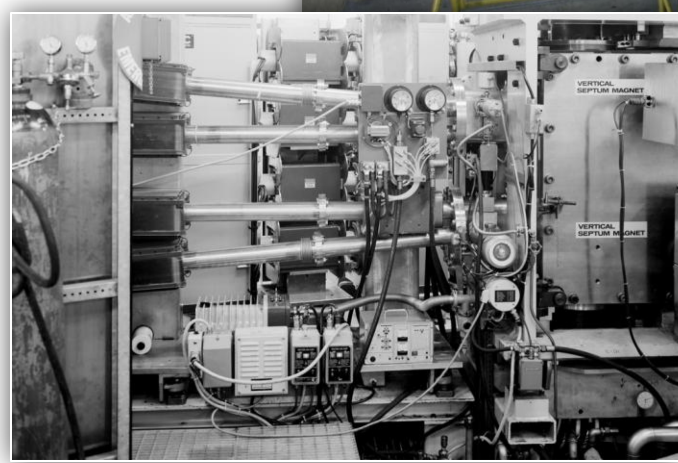


Accelerators overview

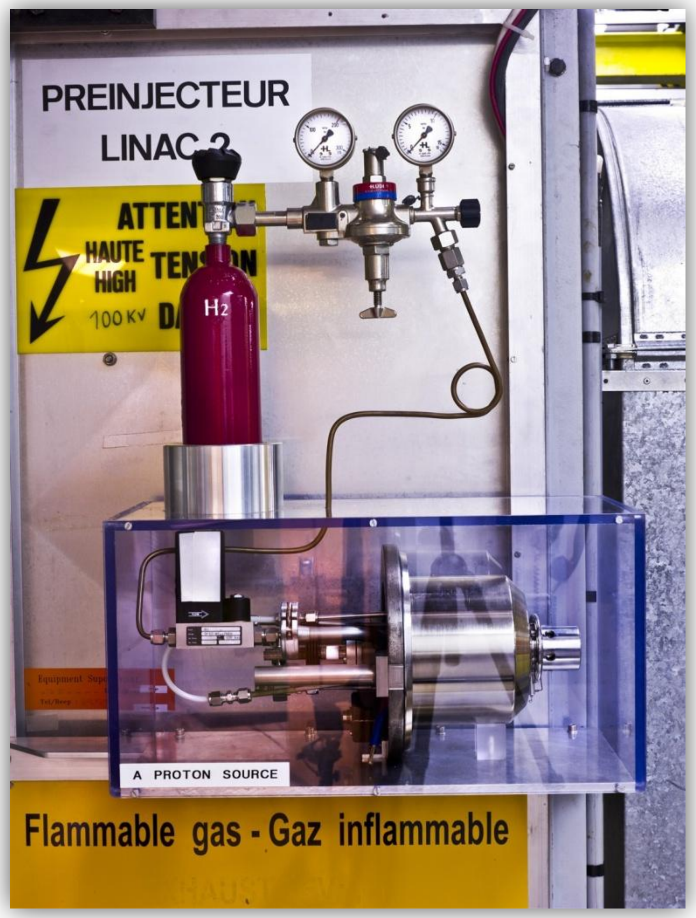


Proton synchrotron booster



- The first synchrotron in the LHC complex.
- The PSB is 157 m long and subdivided in 16 periods.
- Protons get accelerated up to 1.4 GeV.
- 4 Rings one upon the other.

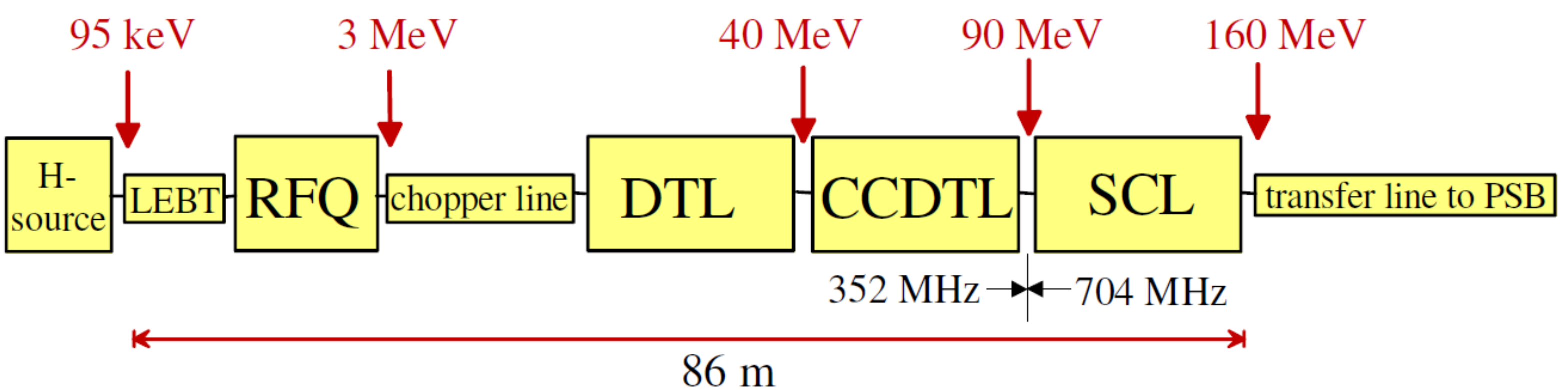
Linac2



- Alvarez structure.
- Accelerates protons up to 50 MeV.
- Protons from a H_2 source.
- Since 1978.

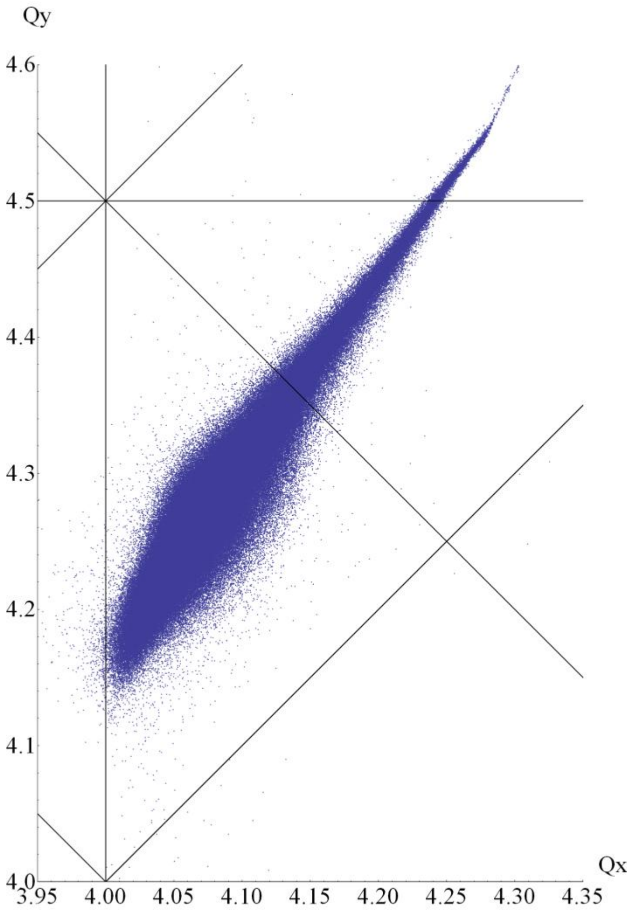
Linac4

- Linac4 will start in 2014 and replace then the old Linac2.
- H^--ions will get accelerated up to 160 MeV.
- There will be a chopper which can interrupt the beam.
- The H^--ions will be injected via a charge exchange injection.
- Horizontal and longitudinal painting can be used with Linac4.



Low Energy Beam Transfer, Radio Frequency Quadrupole, Chopper Line, Drift Tube Linac, Cell-Coupled Drift Tube Linac, Side Coupled Linac.

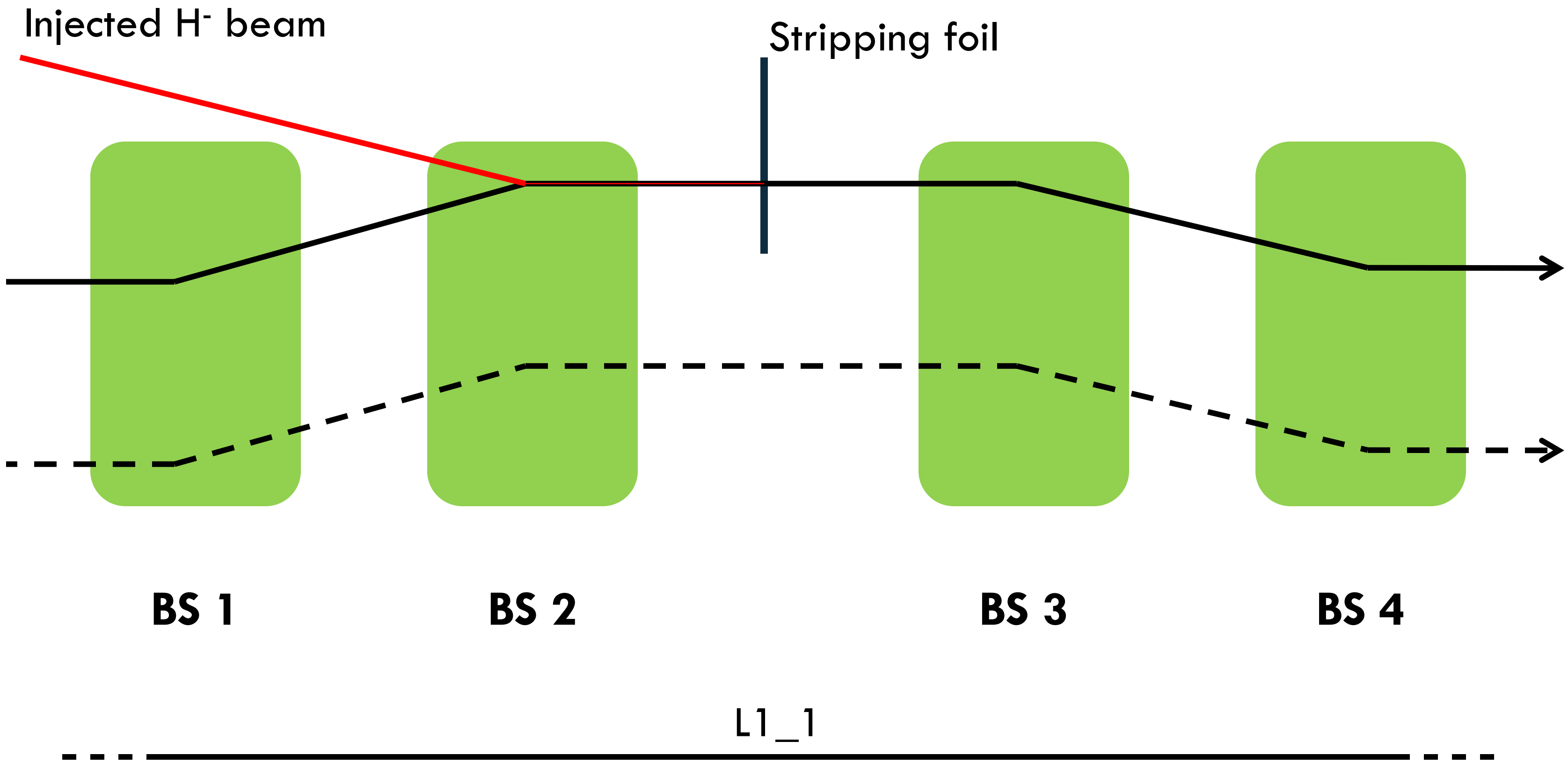
Motivation for higher injection energy



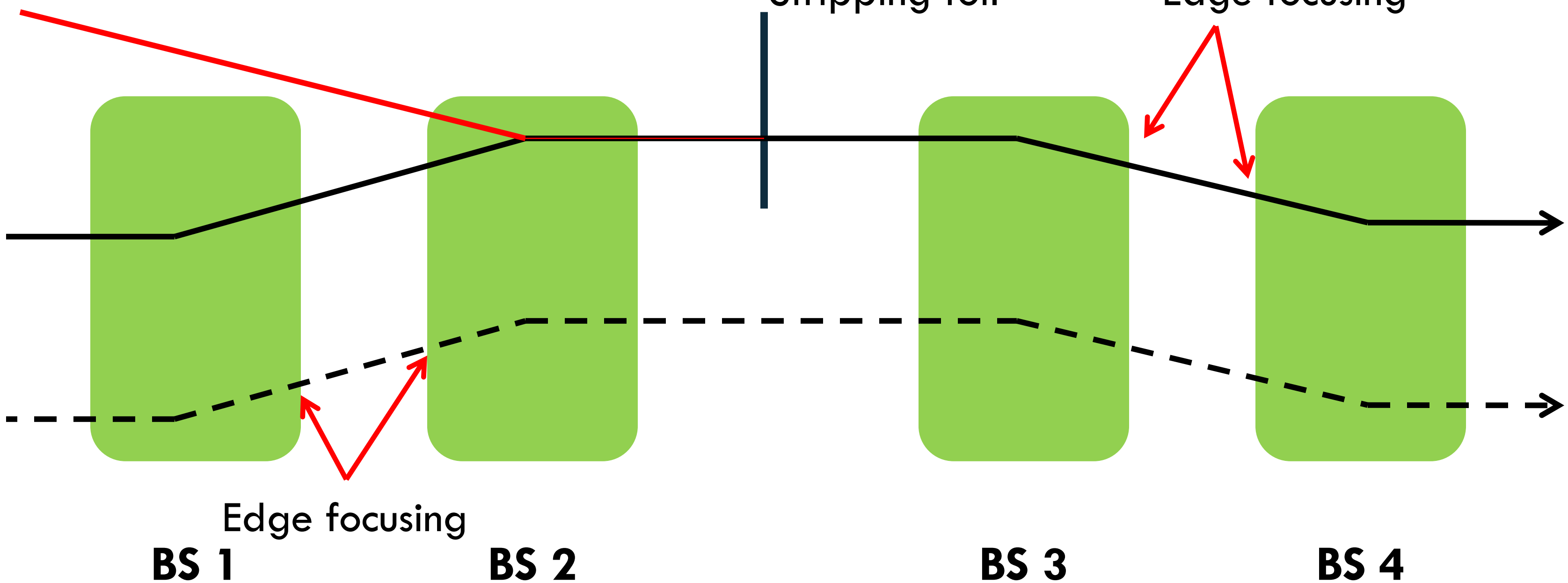
- PS Booster main limitation: direct space charge detuning.
- Mitigation of direct space charge effects improve performance.
  - Double harmonic RF to flatten bunches dynamic.
  - Dynamic working point (vertical tune at injection above half-integer resonance $2Q_V = 9$).
  - Resonance compensation ($2Q_V=9$ and 3rd order resonances).
  - The injection energy will be increased from 50 MeV to 160 MeV.

$$\frac{(\beta\gamma^2)_{160MeV\ \text{Protons}}}{(\beta\gamma^2)_{50MeV\ \text{Protons}}} = 2 \qquad \Delta Q \propto \frac{N}{\varepsilon^{norm}\beta_{rel}\,\gamma^2}$$

Motivation for H^-charge exchange injection



Motivation for H⁻charge exchange injection



- Additional vertical focusing with rectangular magnets 45 mm high and generated by 4 dipoles.
  - as long as possible chicane magnets to reduce the effect
  - Induces strong vertical beta-beating due to tune in the vicinity of half-integer resonance
  - feasibility to keep vertical injection tune above 2Qv=9 resonance with compensation?

Chicane and painting bump

There are two different bumps in the simulations, the chicane for the H^- injection and a bump for the horizontal painting.

- Chicane
  - 45 mm high and generated by 4 dipole magnets.
  - The chicane fall time is about 5 ms for the active and 0.5 ms for the passive compensation.
  - Implemented to the simulation as a part of the lattice.
  - The edge focusing at the chicane magnets has to be compensated.

- Painting bump
  - Generated by kicker magnets.
  - Implemented to the simulation using the ORBIT bump routine.
  - The height and the fall time are depending on the beam and on the compensation scheme. For the high intensity beam the height is 35 mm and the bump decreases within 0.135 ms.

Active compensation scheme

There are two different compensation schemes for the edge focusing: The active and the passive compensation.

For the active compensation scheme there have to be additional quadrupolar components by trims on lattice (QD) quadrupoles.

Focusing errors can be corrected at each ±90° of the betatron phase advance:

Period	βx [m]	βy [m]	μx [2π]	μy [2π]
3	3.709	16.574	0.668	0.720
14	3.708	16.584	-0.668	-0.720

The trims will be in the periods 3 and 14.

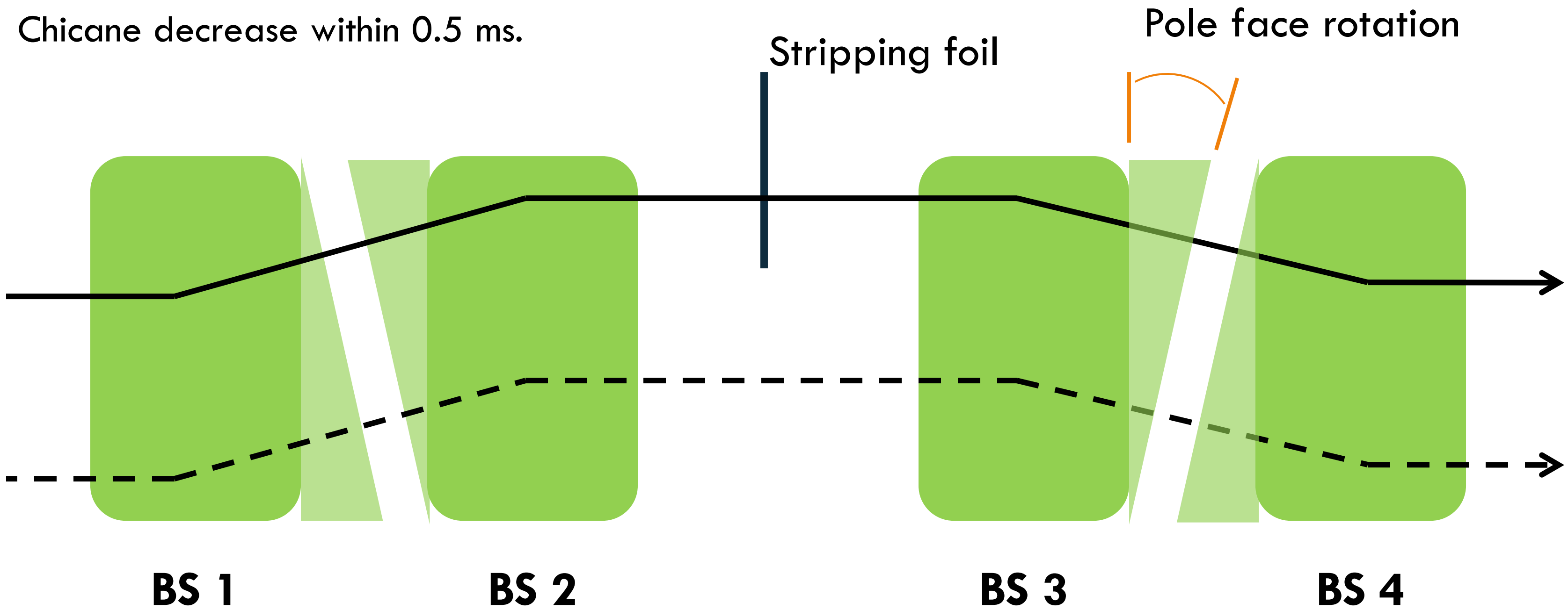
Effective compensation in vertical plane with large beta-function, little perturbation in horizontal plane due to small beta-function (QD).

$0.720 \;\; 2\;\pi = 1.44\,\pi \approx 1.5\,\pi$

$0.668 \;\; 2\;\pi = 1.34\,\pi \approx 1.5\,\pi$

Chicane decrease within 5 ms.

Passive compensation scheme



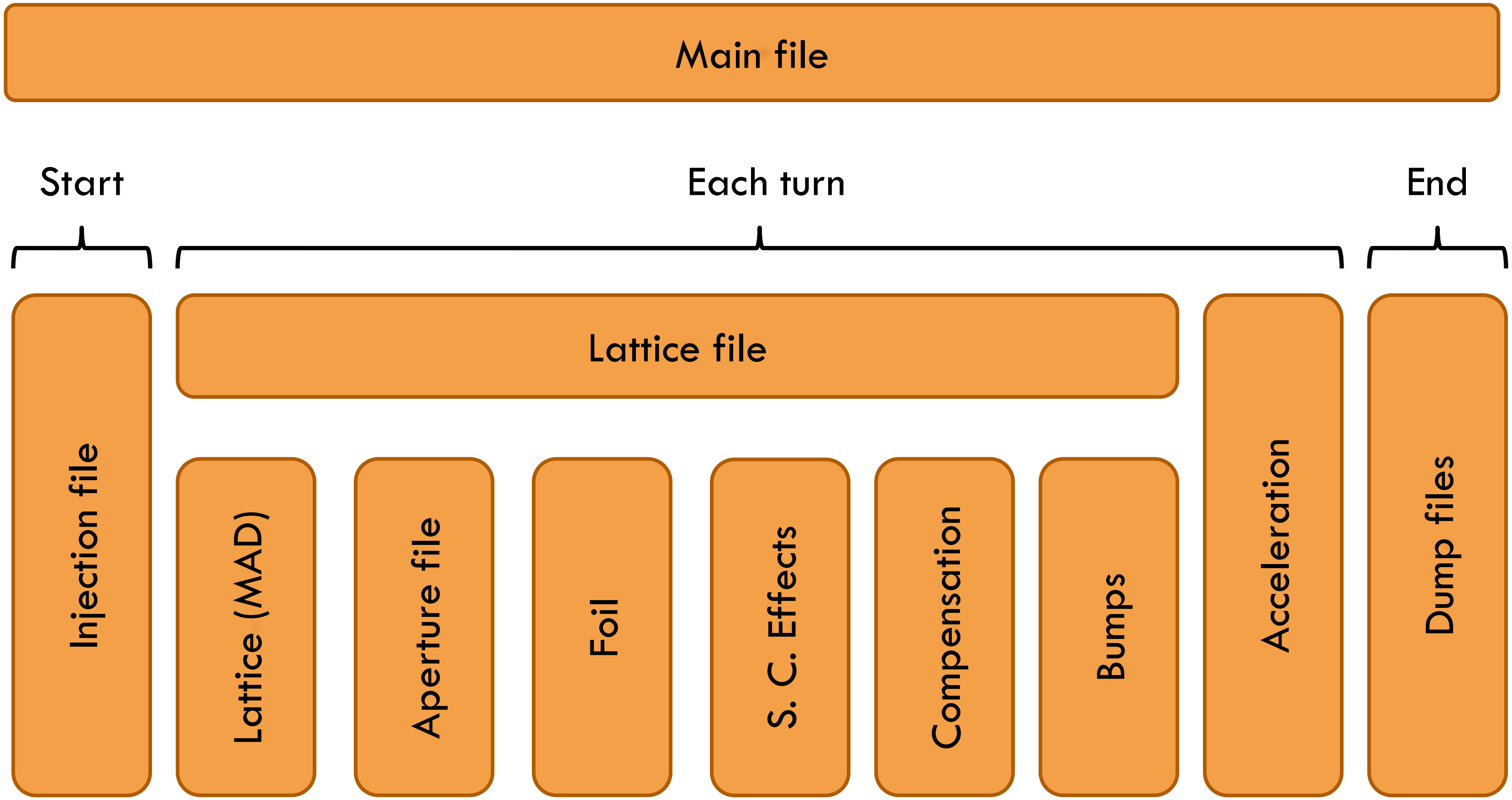
- As long as possible chicane magnets to reduce the effect.
- No perfect compensation during the whole duration of the chicane fall.

About the simulations

- Simulations
  - The lattice for the simulations was created with MAD8.
  - All simulations were done with ORBIT using multiple processing.
  - Space charge effects, apertures, foil and acceleration were included.
  - All simulations which will be presented, were run with a vertical tune of 4.55 at injection and for the high intensity beam (1.6E13 protons per bunch).
  - The particles were represented in the simulation by 500 000 macro particles.
  - The distribution of the injected particles were created using a Mathematica notebook.

- Data Analysis
  - To analyse the data from the simulation Wolfram Mathematica was used.

Structure of the simulations

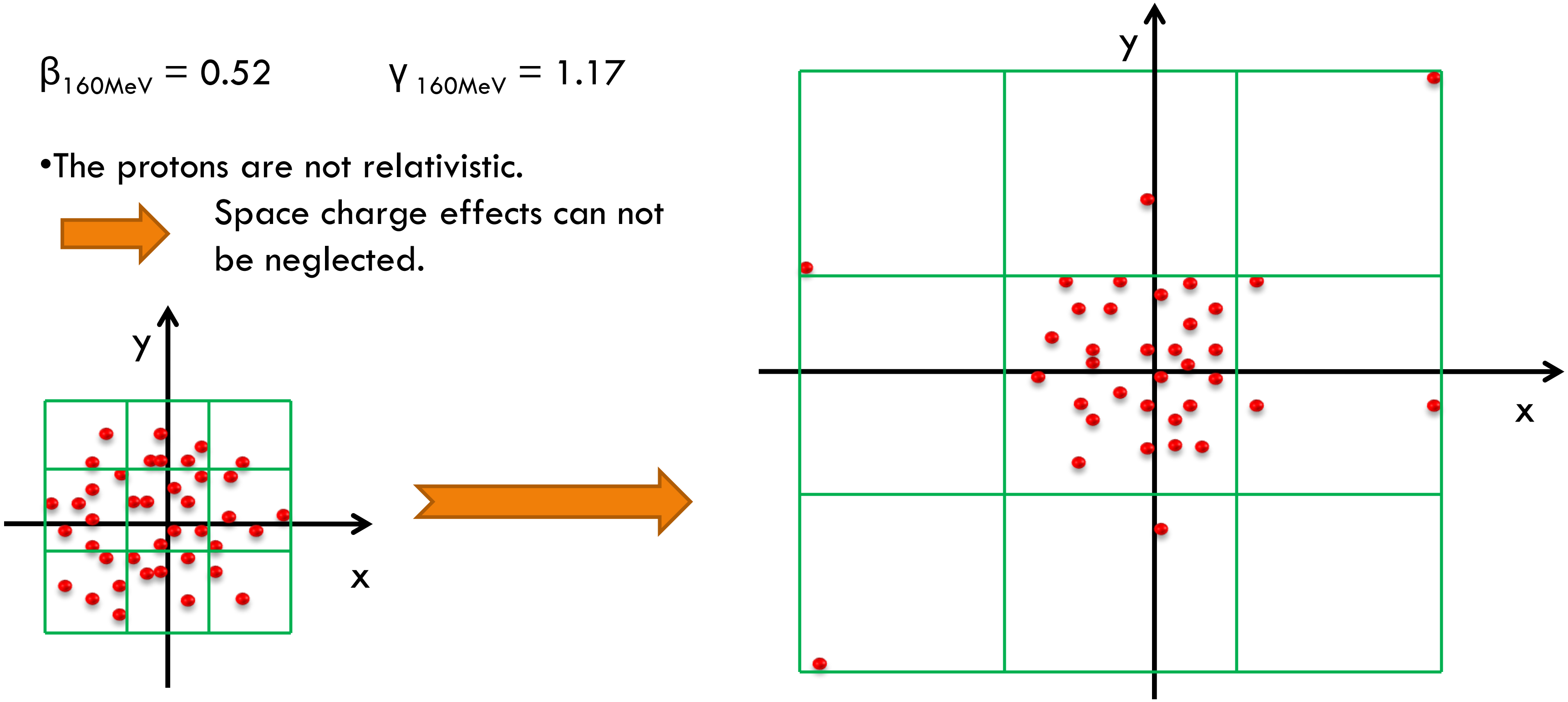


Space charge simulation

$\beta_{160MeV} = 0.52$ $\gamma_{160MeV} = 1.17$

•The protons are not relativistic.

→ Space charge effects can not be neglected.

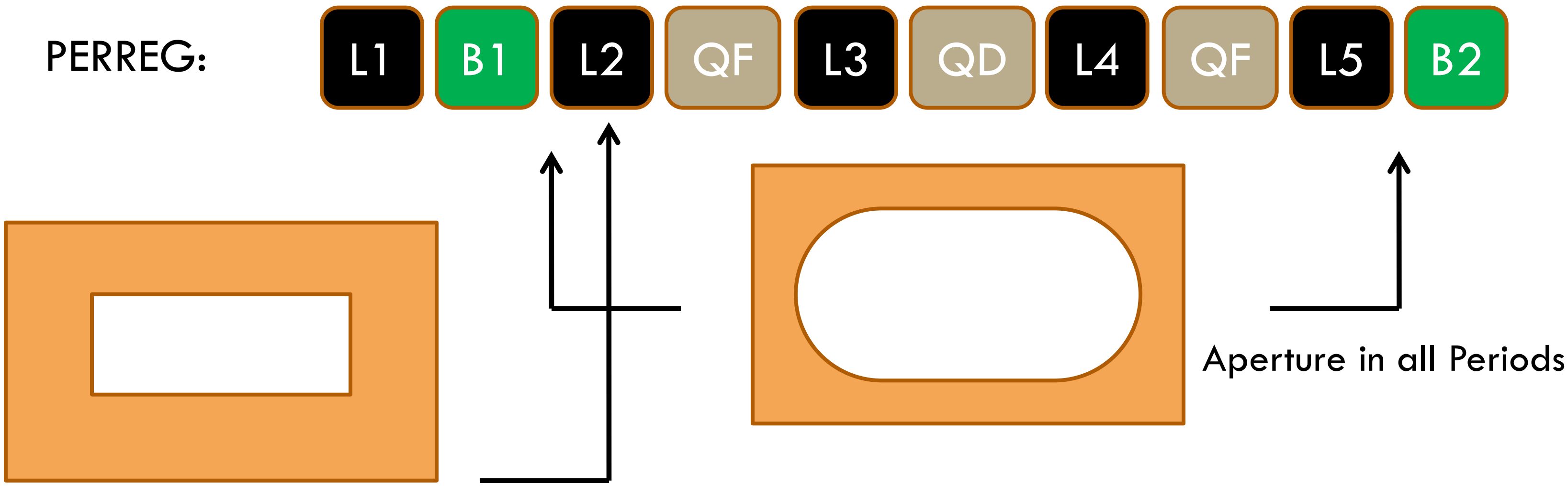


•The self adjusting grid for SC calculations depends on the particles with the biggest amplitude.

•If the lattice spacing becomes too big, the results are not useful anymore.

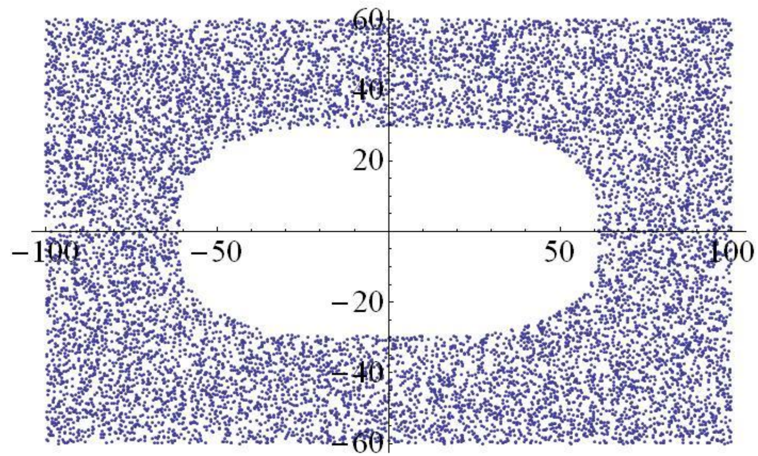
→ The particles with too big amplitudes have to be captured by apertures.

Apertures



Beam scope window

In Period 8 Drift L2

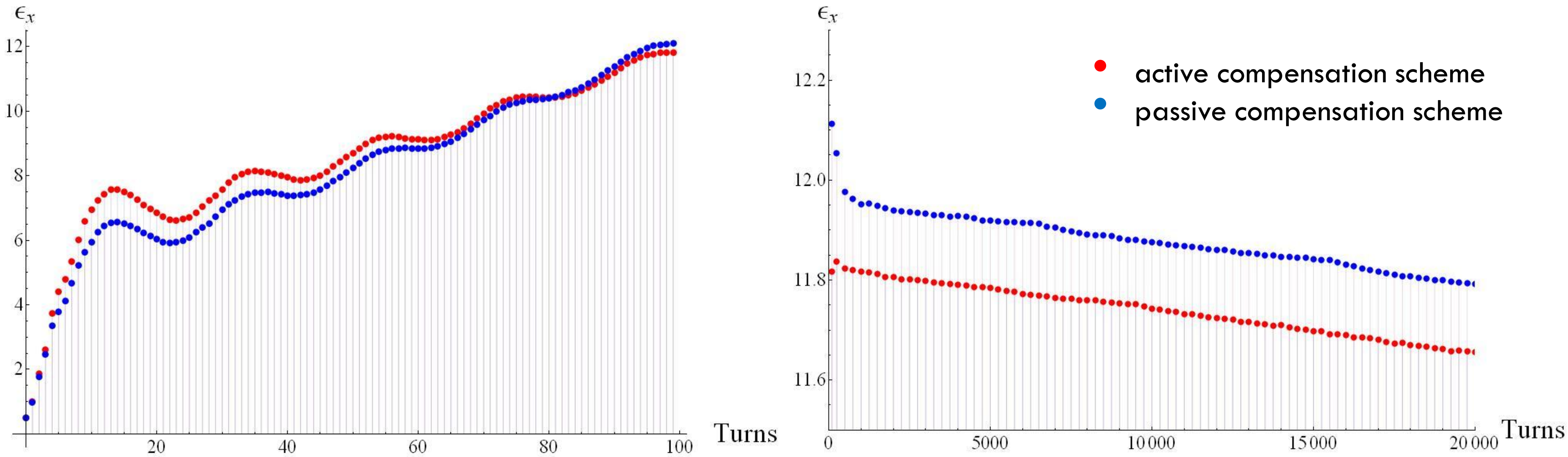


BSW: x = ± 36.8 mm, y = ± 21.7 mm

Aperture: x = ± 61 mm, y = ± 29.5 mm

Normalised emittance in x plane

The normalised emittance evolution during the simulations. The first line shows the horizontal and the second the vertical plane. On the left you can find the injection and on the right the first 20000 turns.

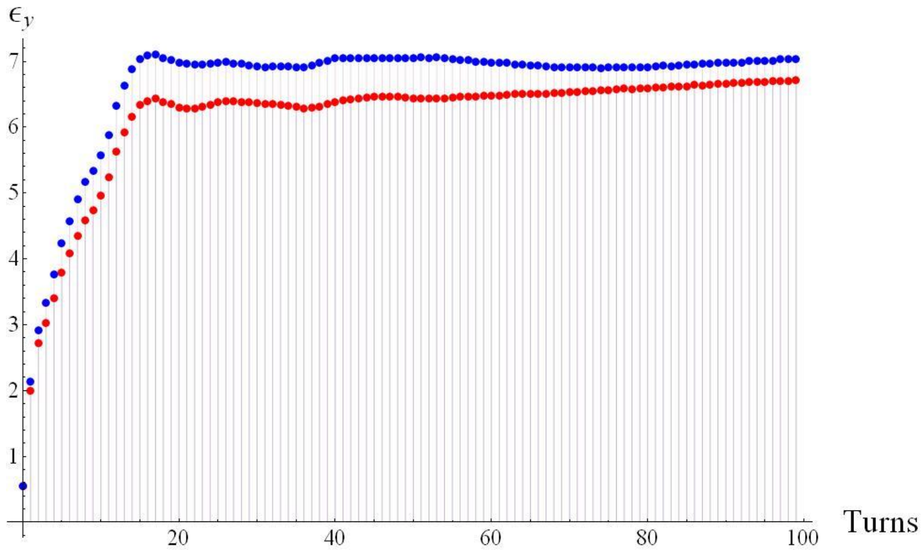


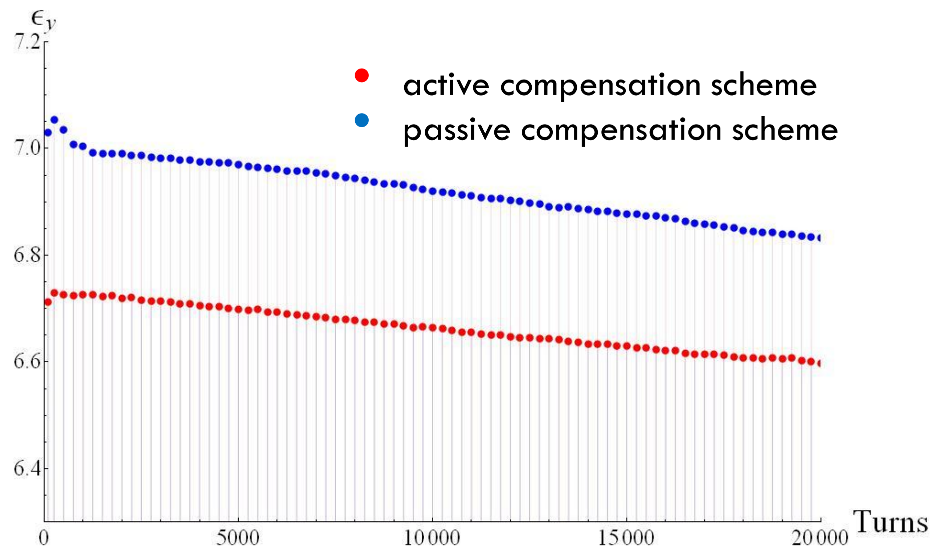
The wave form for the emittance in x plane during injection is due to the longitudinal painting and the D = 0 for the injected beam.

The slope of the normalised emittance is caused by the losses at the apertures.

Normalised emittance in y plane

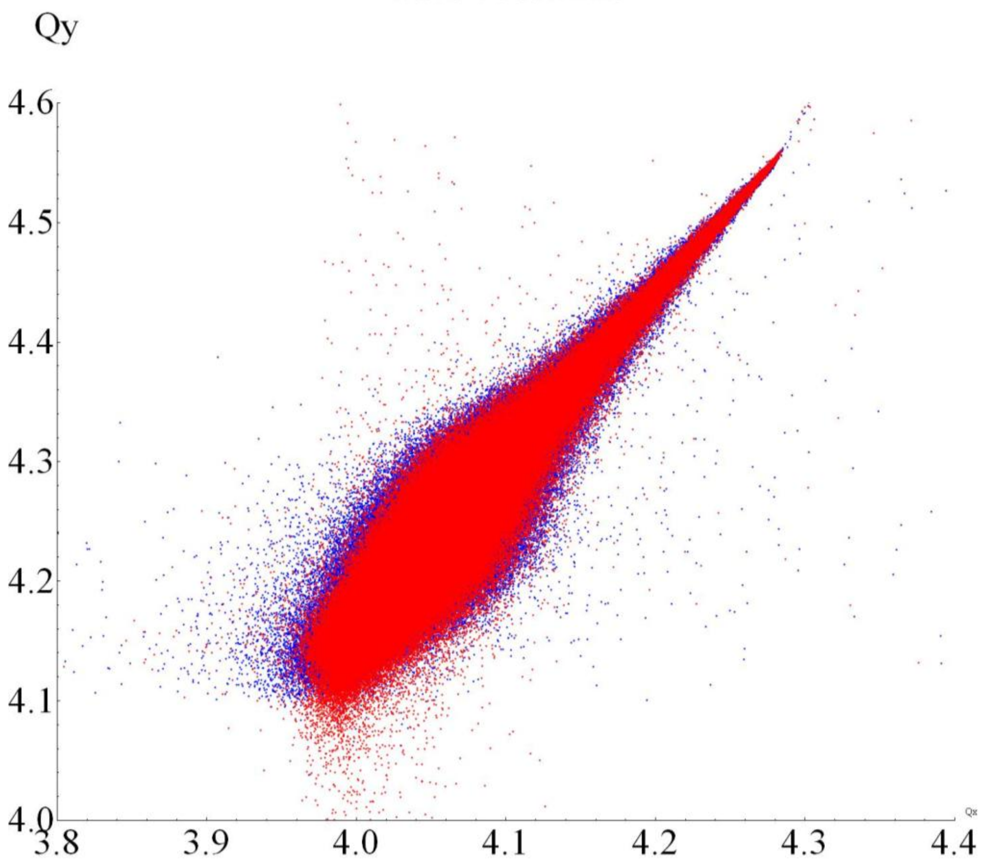
The normalised emittance evolution during the simulations. The first line shows the horizontal and the second the vertical plane. On the left you can find the injection and on the right the first 20000 turns.





No wave form in y plane because the dispersion of the injected beam as well as the dispersion of lattice at injection point are zero.

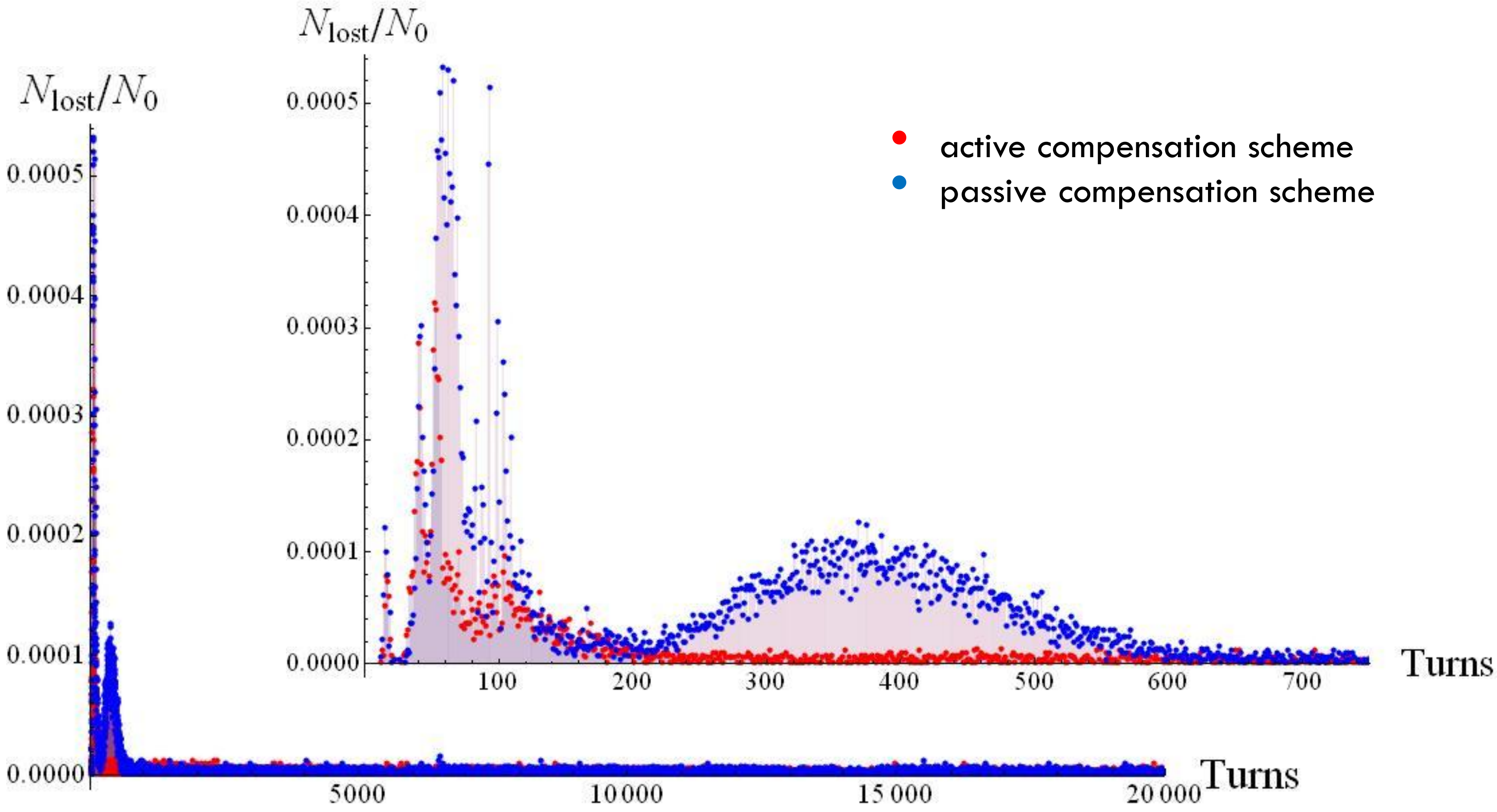
Tune foot print



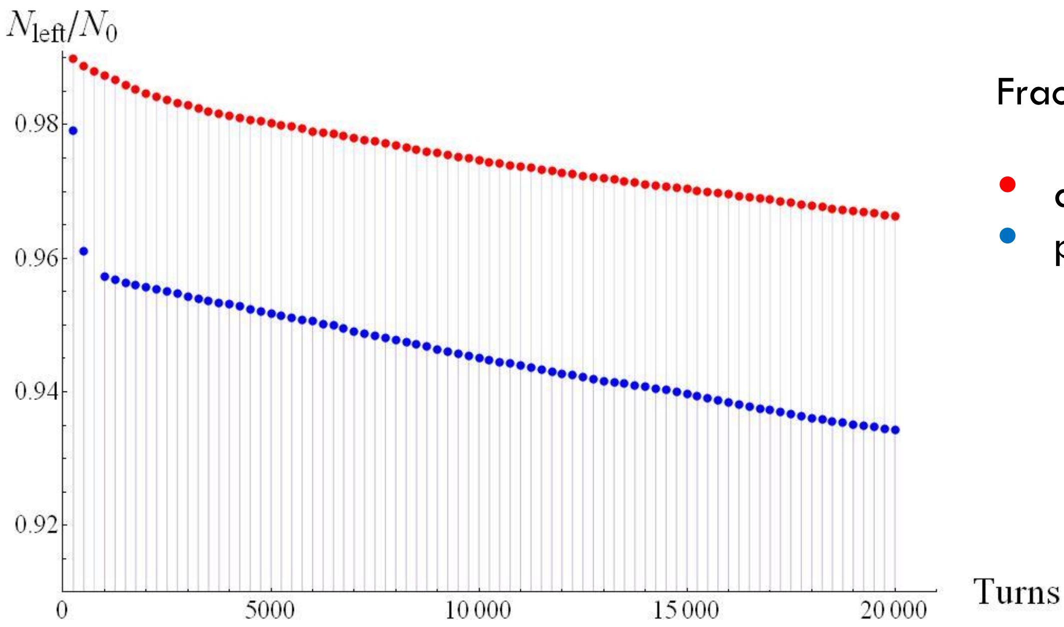
The tune foot print after 20000 turns for the active and the passive compensation scheme.

- active compensation scheme
- passive compensation scheme

Losses per turn



Losses



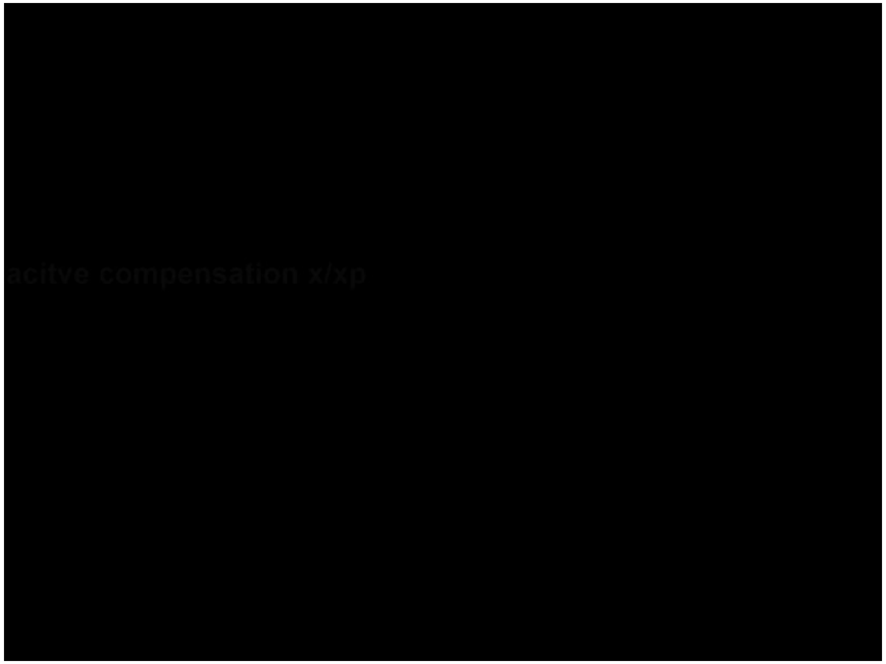
Fraction of surviving particles.

- active compensation scheme
- passive compensation scheme

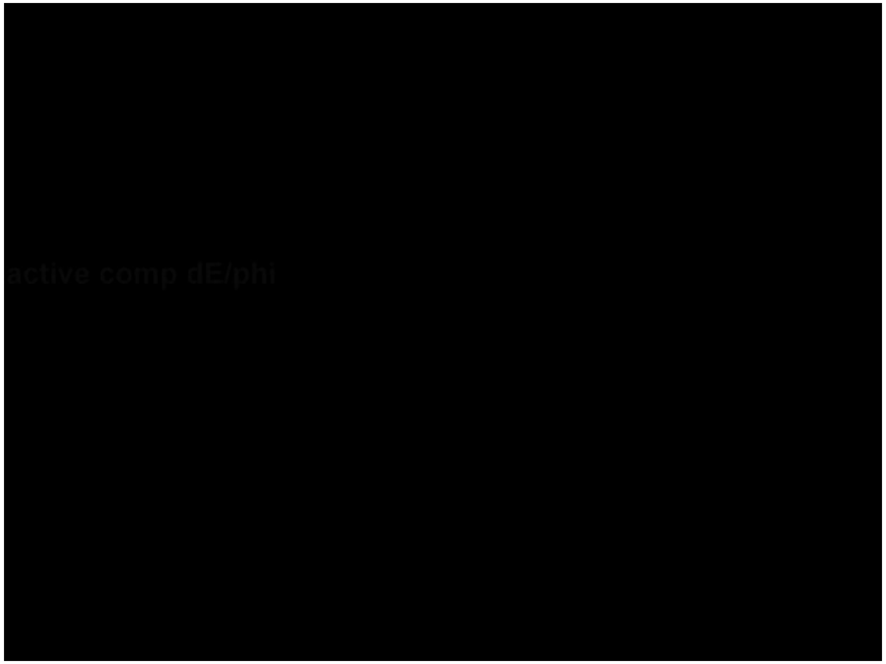
Compensation scheme	After 100 turns	After 500 turns	After 1000 turns	After 5000 turns	After 20000 turns
Active	0.69 %	1.12 %	1.27 %	1.97 %	3.37 %
Passive	1.57 %	3.89 %	4.27 %	4.83 %	6.58 %

Longitudinal and horizontal Phase space

Horizontal phase space



Longitudinal phase space



Compare the compensation schemes

- The chicane decrease time is 5 ms for the active and 0.5 ms for the passive compensation scheme.
- New power supplies would be necessary for the additional trim quadrupoles respectively a more expensive one for the fast chicane magnets.
- Possible a corrugated vacuum chamber can be used for the active compensation. Due to the fast chicane and induced currents for the passive compensation scheme, a ceramic vacuum chamber has to be installed or the chicane magnets have to be inside the vacuum.
- The passive compensation is fixed after the magnets are build. The active compensation can be modified later.
- It has to be tested if the best pole face rotation (the angle with the fewest losses) for the high intensity beam is also the best for the other beams.
- For the simulated settings, there are more losses for the passive than for the active compensation scheme.