Linac 4 – Transfer Line

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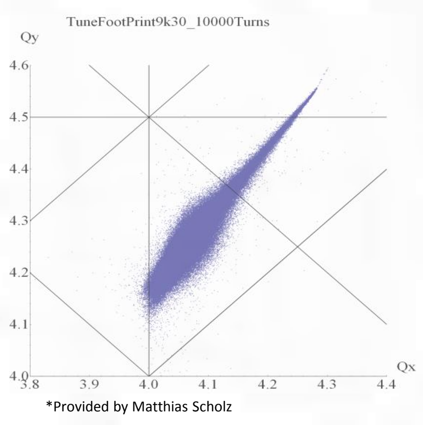
Abstract

A new H⁻-accelerator Linac4 at CERN is under construction for achieving a higher beam quality, which is required for ultimate LHC Luminosity. As the Linac4 beam is characterised by a high charge density at low energy, space charge dominated behaviour of the beam is expected. Hence, the beam control is particularly critical. Along the 80m long Linac the focusing structure has to be designed tight in transverse and longitudinal directions for reducing the space charge driven emittance growth. The design of the 177m transfer line poses an even greater challenge. The transverse focusing structure is extended and any longitudinal focusing is vanished. The beam quality is suffering uncompensated space charge effects, therefore the design of the transfer line becomes especially critical.

General Introduction

The new H⁻-accelerator Linac4 at CERN will serve as injector to the PS Booster and replaces the old proton-accelerator Linac2. It raises the PS Booster injection energy to 160MeV and so it provides the potential to double the brightness of the beam, whereby amongst others an amplification factor of 2.3 at the LHC Luminosity becomes feasible. Special features of Linac4 are the hydrogen ion (H⁻) source as well as the chopper section. The hydrogen ion source is an enhancements of the DESY (HH-Germany) hydrogen ion source for the generation of higher average beam current as well as higher peak current. In the chopper section Linac4 bunches, which would be injected into unstable regions of the PSB phase space or dumped while injection, are removed from the bunch train.

Motivation – Space Charge Tune Shift



*Provided by Matthias Scholz

$$\Delta Q \sim \frac{N}{\beta\gamma^2}$$

	Linac2	Linac4
Energy	50 MeV	160 MeV
$\beta\gamma^2$	0,3483	0,7119

$$\Delta Q = const.$$
$$N_{Linac4} = 2 \times N_{Linac2}$$ in PSB

The tune, Q, indicates the number of betatron oscillations pro circulation. Since tune resonances lead to particle losses, the tune shift, ΔQ, should be maintained as small as possible. Due to the increasing of the PSB injection energy a doubling of the bunch population becomes feasible while preserving the tune shift.

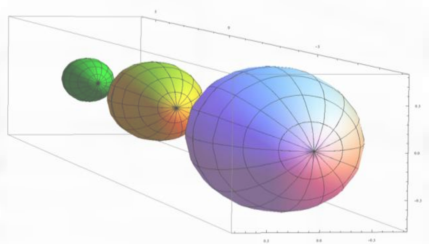
Parameters List Linac2 – Linac4

	Linac 2	Linac 4
Particle Species	Protons	H⁻ Ions
Linac Length	30 m	80 m
Output Energy	50 MeV	160 MeV ±1.2MeV[1]
Bunch Frequency	200 MHz	352.2 MHz
Linac Current	160mA	40 mA
Duty Cycle	0.01%	0.08% .. 10%

[1] *Energy Swing for long. Painting*

In contrast to Linac2 the working frequency of Linac4 is shifted to 352.2MHz. The higher frequency provides the possibility for a more compact design as well as higher accelerator field strengths. In addition an energy swing of ±1.2MeV is intended for longitudinal phase space painting in the PSB.

Space Charge Effects – Theory



Simple Model:
- Charge Distribution is uniform
- circular Beam Cross-section
- Bunch Length >>Bunch Cross Section

Maxwell: (Coulomb,Ampère)

$$\iint \vec{E}\cdot d\vec{A} = \iiint \frac{\rho(r)}{\epsilon_0} d^3r$$

$$\oint \vec{B}\cdot d\vec{s} = \mu_0 \iint \vec{j}\cdot d\vec{A}$$

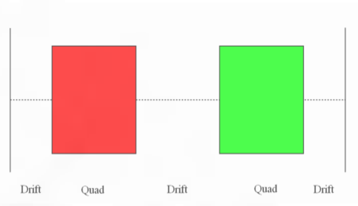
Lorentz:

$$F_x = \frac{e}{2\pi\cdot\varepsilon_0 c a^2}\frac{I}{\beta\gamma^2}\cdot x$$

$$x'' = \frac{F_x}{m_0\gamma\beta^2c^2} = k_{sc}\cdot x$$

$$\Delta K(s) = k_{sc} = \frac{2r_0 I}{e\beta^3\gamma^3 c a^2}$$

= Field Error



Tune Shift:

$$\Delta Q = \int_0^{2\pi R} \frac{\Delta K(s)\beta(s)\mathrm{d}s}{4\pi}$$

$$\Delta Q = \frac{1}{4\pi}\frac{2r_0 I}{e\beta^3\gamma^3 c}\int_0^{2\pi R}\frac{\beta(s)}{a^2}\mathrm{d}s = \frac{r_0 I R}{e\beta^3\gamma^3 c}\left\langle\frac{\beta(s)}{a^2}\right\rangle \quad = \varepsilon_t$$

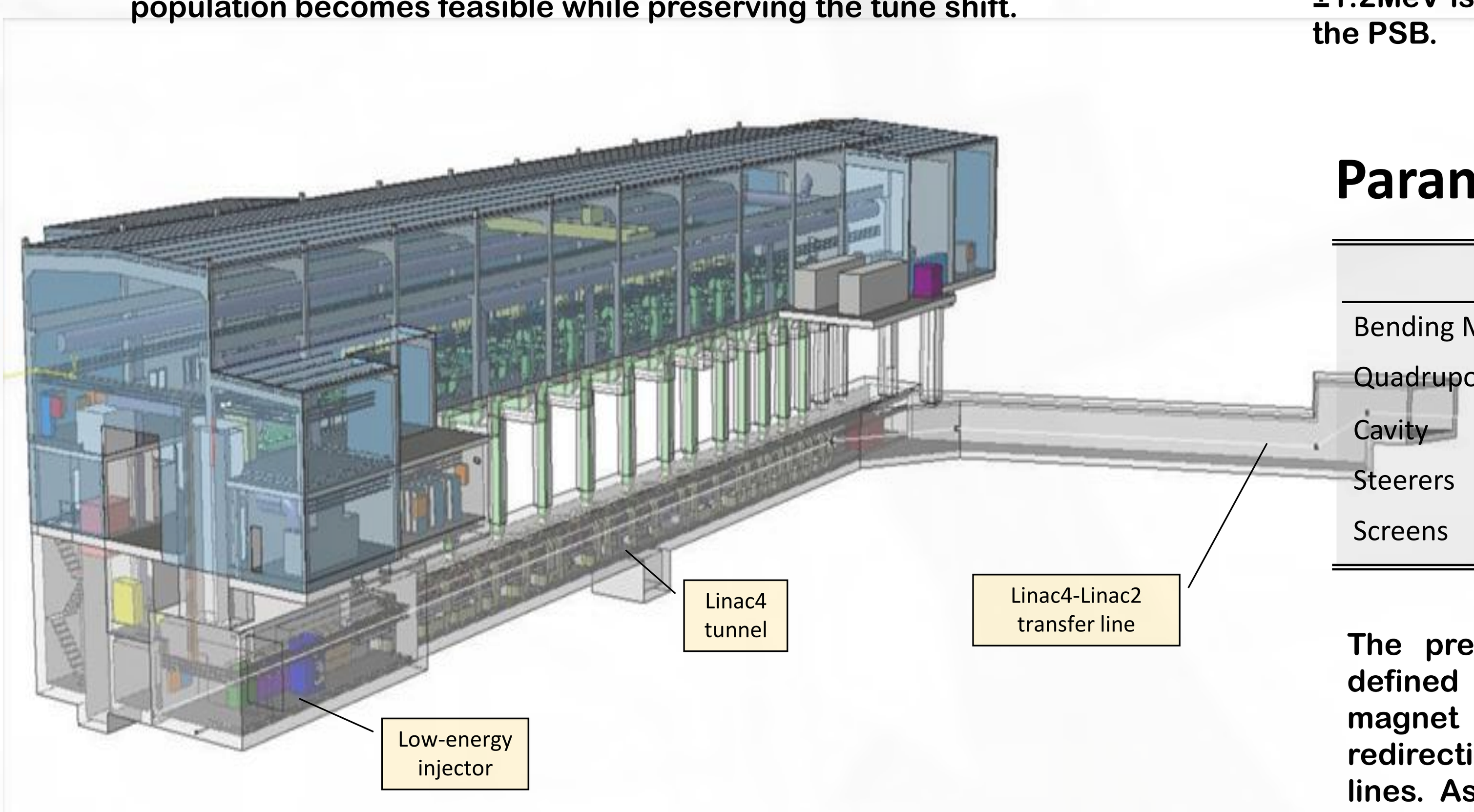
Replacing: $I = \frac{N\cdot q\beta c}{2\pi R}$, $\varepsilon_n = \varepsilon_t\beta\gamma$

$$\Delta Q = -\frac{r_0}{2\pi\varepsilon_n}\frac{N}{\beta\gamma^2}$$

$r_0(e^-) = 2.818\cdot10^{-15}$ m
$r_0(p^+) = 1.5\cdot10^{-18}$ m

Space Charge Tune Shift: $$\Delta Q \sim \frac{N}{\beta\gamma^2}$$

From the Maxwell equations follows the Lorentz force, which is experienced by a test particle at position *x* with charge *e*. This force can be expressed by a defocusing strength k_{sc}. This additional defocusing strength can be treated similar to magnetic field errors ΔK(s), whose tune shift is defined by the present formula. Closing the beam current and the averaging of β-function divided by the square of beam size are replaced by the number of particles(*N*) and the transverse normalised emittance(ε_n). As a result the tune shift depends on constants, particle radius(r_0) and ε_m and the ratio of N and the relativistic variables $\beta\gamma^2$.



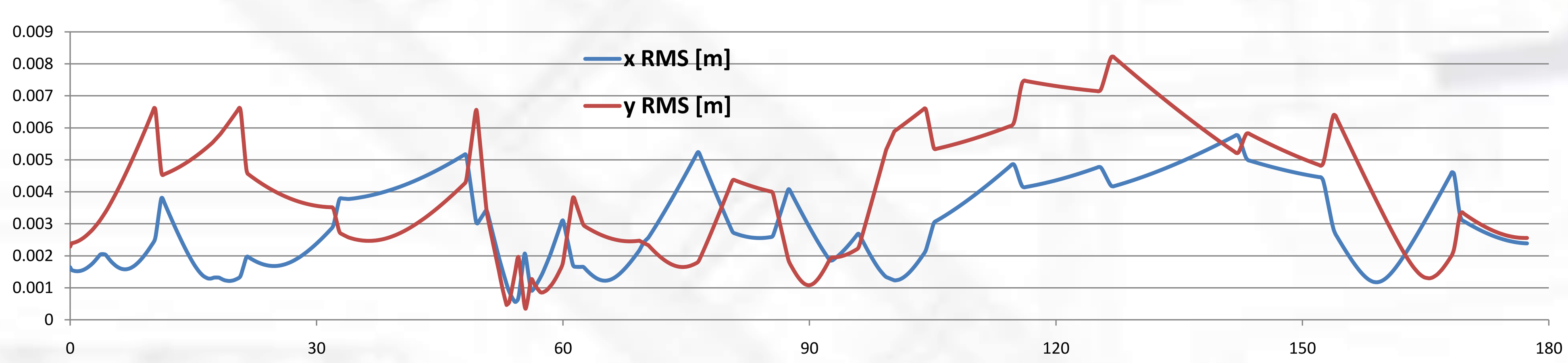
Parameters List Transfer Line

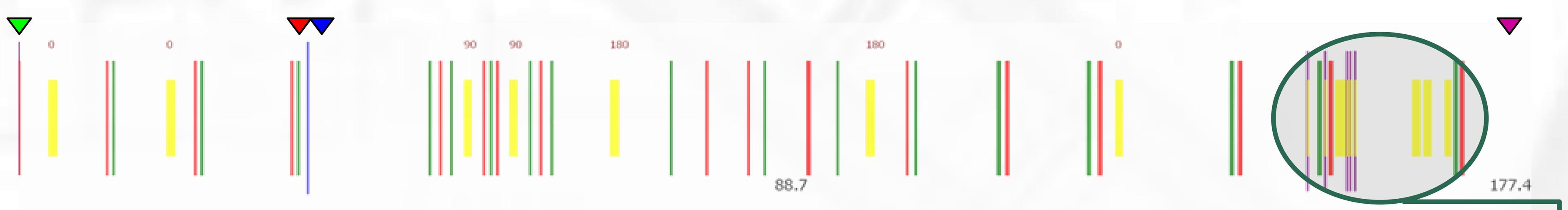
	# in new Part	# in old Part
Bending Magnets	4	3
Quadrupole	16*	18
Cavity	1	-
Steerers	12*	11
Screens	10*	10

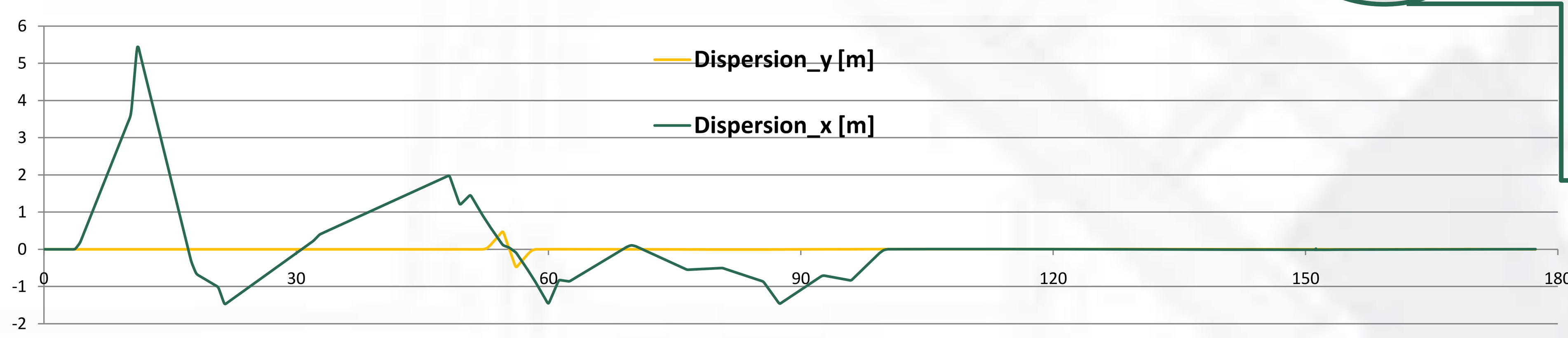
* Present Layout

The present geometrical path of the transfer line is defined by 6 of 7 bending magnets. The last bending magnet upstream the PSB injection is used for the redirection of the beam towards one of the two diagnostic lines. As the transfer line is still under investigation the total numbers of quadrupoles, steerers as well as screens are still modifiable.

Transfer Line Layout







In these plots the development of the beam size as well as the dispersion from the outlet of Linac4 (left) to the injection point of the PSB(right) are presented. The schematical diagram between the two plots illustrates the sequence of beam optical elements. Bending magnets and the injection kicker magnets are marked by yellow lines. Red and green lines represent quadrupoles depending of their polarisation. The position of the debuncher cavity is labeled by the blue line. Along the transfer line four main features are arranged on after another. In the first part upstream the debuncher cavity intense space charge effects cause an inevitable degradation of the beam quality. At the saturation of the space charge effects the debuncher cavity is used for the reduction of the correlated energy spread. The third feature of the transfer line is the vertical offset chicane. Since an achromatic chicane design is demanded, this part is characterised by a high phase advance. The fourth quality of the transfer line is the distributor section, where the aperture limits of the kicker magnets require a high phase advance lattice design as well. A more detail description of the distributor section layout and distribution progress is presented ->.

Bottleneck – Debuncher Cavity

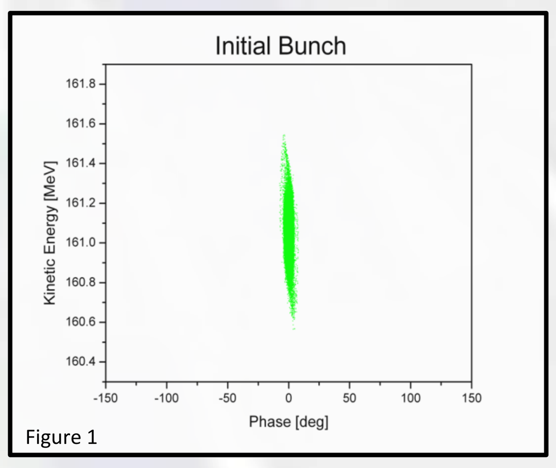


Figure 1

Due to the low energy the energy spread causes a longitudinal expension of the beam. Particles with energy above the average energy are faster and reach the debuncher cavity earlier in time, i.e. later in phase (fig.2). This leads to the generation of an energy shirp. As the synchrotron phase is set to 90 deg., this correlated energy spread can be reduced while conserving of the emittance. The energy swing of ±1.2MeV requires the readjustment of the synchrotron phase for each bunch.

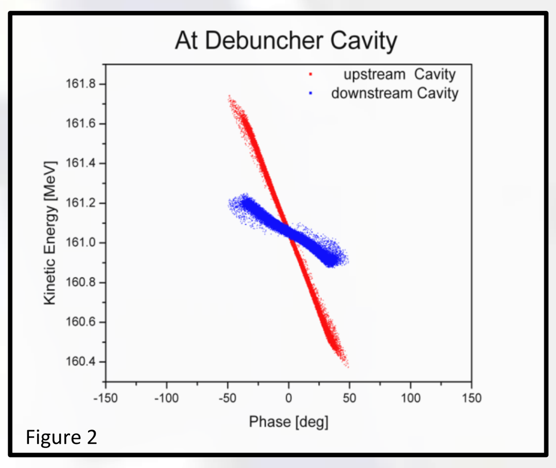


Figure 2

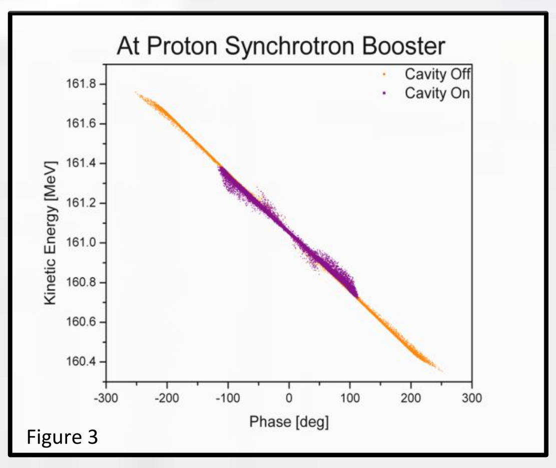
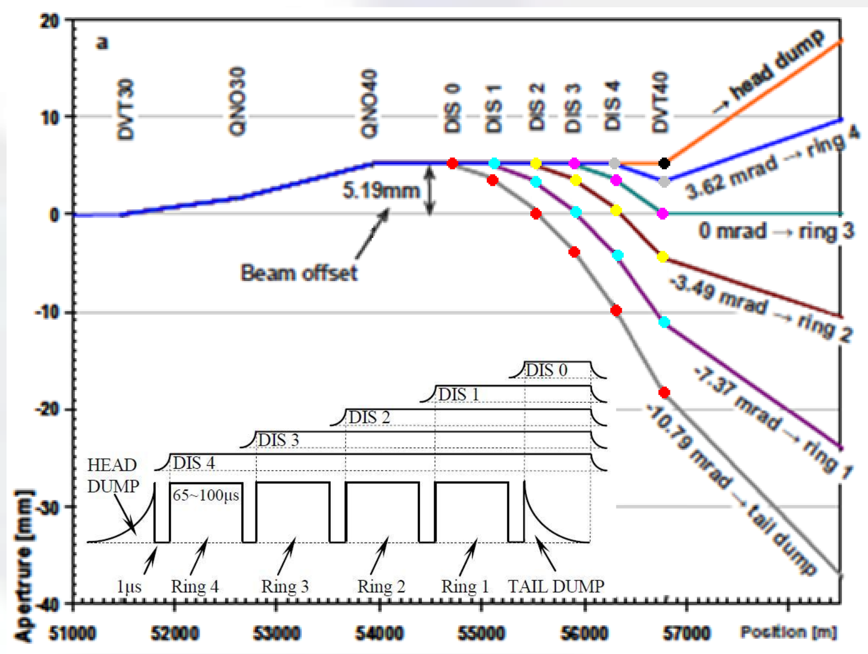
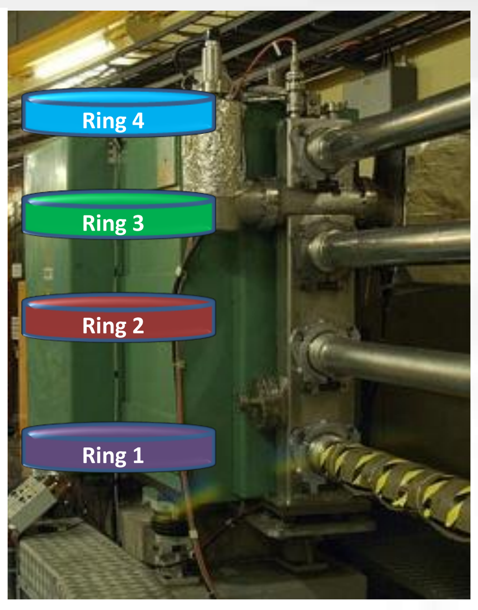


Figure 3

Proton Synchrotron Booster Injection





Since the PSBooster consists of 4 Rings the bunch sequences from Linac4 has to be separated into the 4 rings. This is performed by an ensemble of 5 fast ramping kicker magnets. For the reduction of the particle losses during ramping defined chains of bunches are generated by the chopper section of Linac4.

Conclusion

The layout of Linac4 as well as transfer line Linac4-PSB are confirmed and their reliability are proven. Furthermore, Linac4 is already integrated in the future accelerator chain, where it is the fundamental of future upgrades. Thus beam loss control systems and emittance growth control systems are implemented for higher performances. As results of the Linac4 project particle beam characterised by higher beam brightness become feasible, which leads to higher luminosity at experiments like CMS, Atlas or Isolde.

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