ERL 2011
the 50th ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs

HZB Helmholtz Zentrum Berlin

Optics design of a high current low emittance injector for B*ERL*inPro

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Design parameters of the B*ERL*inPro

MAIN PARAMETRS

Average current up to	100 mA
Max. beam energy	50 MeV
Nominal bunch charge	77 pC
Max. repetition rate	1.3 GHz

INJECTOR

Beam energy	7 MeV
Energy spread, rms	10^{-2}
Bunch length, rms	>2 ps
Peak current	<20 A

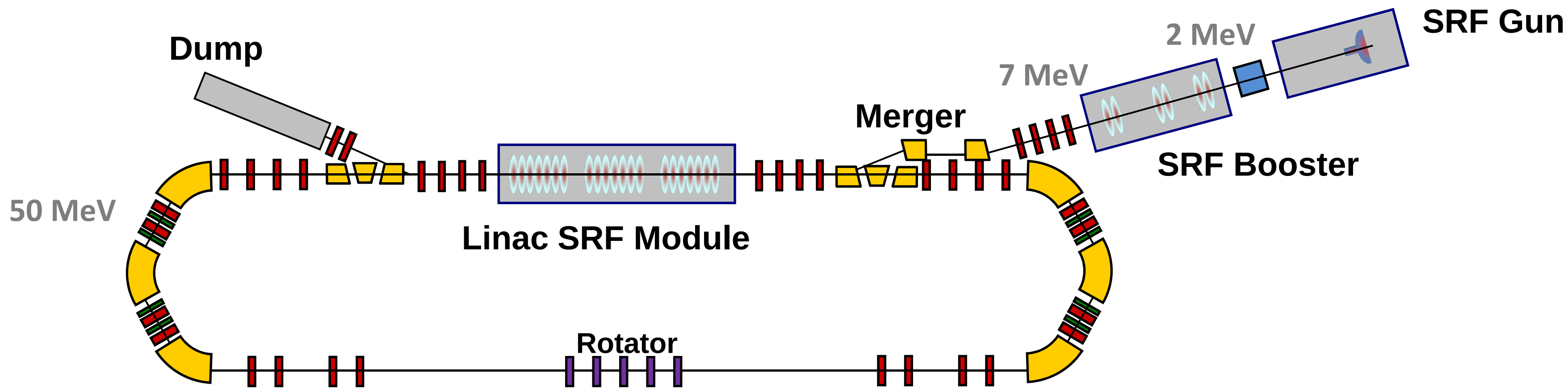
RECIRCULATOR

Low Emittance Mode

Bunch length, rms:	2 ps
Peak current:	20 A
Normalized emittance	1 mm mrad

Short Bunch Mode

Bunch length, rms:	~ 100 fs
Peak current	~ 400 A



Outline

77 pC
1 mm mrad
~ 100 fs

- low emittance ERL injector without axial symmetry
  - emittance compensation principle
  - emittance compensation for elliptical beams
  - dispersive effects
  - aberrations
  - tracking results for the B*ERL*inPro injector

- high current issues (beam halo)
  - halo formation model
  - collimation

Effects leading to the emittance growth in an RF photoinjector

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1 mm mrad
~ 100 fs

1. **Transverse space charge**

- Longitudinal inhomogeneity of space charge density
- Slice emittance growth due to transversal inhomogeneity of space charge density

2. **Energy change in dispersive section due to longitudinal space charge force ("space charge dispersion").**

- Mismatch of slice centers at the end of the dispersion section
- Slices emittance growth due to inhomogeneity of energy change in slices

3. **Aberrations**

- In solenoid
- Overbunching due to RF nonlinearity

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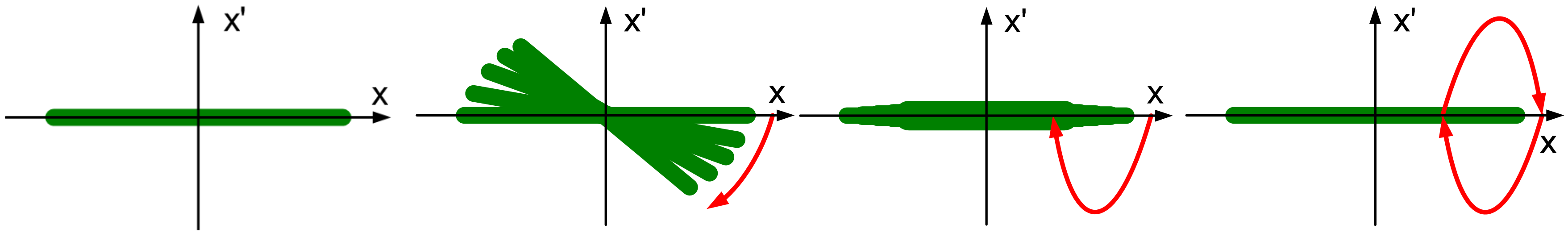

The emittance compensation is necessary to achieve our target (normalized rms emittance 1 mm·mrad). Basic idias behind 2-D emittance compensation can be found in [1].

In short, elliptical beam has two coupled space charge oscillation modes (plasma oscillations). Therefore, in order to do 2-D emittance compensation, we must adjust external focusing to achieve *nπ* phase advance of these oscillations in both planes. Next 3 slides present this principle in more details.

[1] S.V. Miginsky, Emittance compensation of elliptical beams. NIM A 603 (2009), pp 32-34.

Transversal motion: Kapchinsky-Vladimirsky equation for RMS parameters

77 pC
1 mm mrad
~ 100 fs

$$x'' + k_x x - j\frac{1}{x+y} - \frac{\varepsilon_x^2}{x^3} = 0,$$

$$y'' + k_y y - j\frac{1}{x+y} - \frac{\varepsilon_y^2}{y^3} = 0, \quad j = \frac{I}{I_0(\beta\gamma)^3}$$

The space charge term overpowers the emittance term in the merger

$$\frac{\varepsilon_x^2}{x^3} << \frac{I}{I_0(\beta\gamma)^3}\frac{1}{x+y}$$

Let's divide beam into slices and look at the motion of the slices with different current densities. We neglect the slice emittance and interaction between slices.

$$x'' = -k_x x + \frac{j}{x+y}, \quad y'' = -k_y y + \frac{j}{x+y}, \quad j = \frac{I}{I_0(\beta\gamma)^3}.$$

Linearization for small "perturbations"

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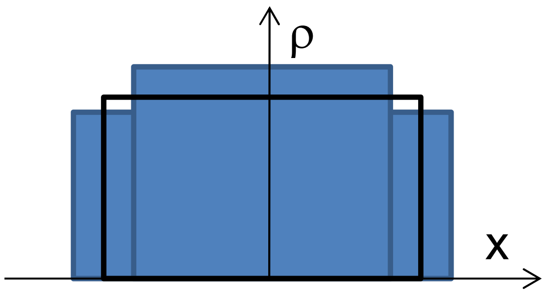
x_0, y_0 – rms size and j_0 – current of an "optimal" slice.
Let's investigate the motion of a slice with a different rms size and current.

$$\delta x = \sqrt{\frac{j}{j_0}}x_0 - x, \quad \delta y = \sqrt{\frac{j}{j_0}}y_0 - y.$$

Small deviations in the slice size or current

$$\delta x'' = -j_0 \frac{\delta x + \delta y}{(x_0 + y_0)^2} - k_x \delta x,$$
$$\delta y'' = -j_0 \frac{\delta x + \delta y}{(x_0 + y_0)^2} - k_y \delta y$$



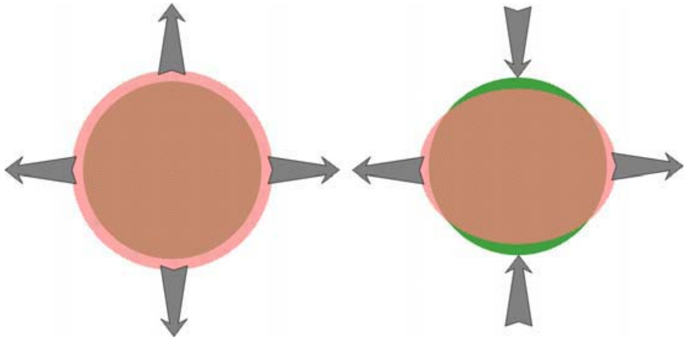
Two oscillation modes for a round beam

A solution for a homogeneous external focusing and round beam can be found analytically.

$$x_0 = y_0, \quad \frac{2j_0}{(x_0+y_0)^2} = k_x = k_y = const$$

$$\delta x_s = \delta y_s = \delta_s \exp(iz\frac{2\sqrt{j_0}}{x_0+y_0}), \qquad \omega_s = \frac{2\sqrt{j_0}}{x_0+y_0},$$

$$\delta x_{as} = -\delta y_{as} = \delta_{as} \exp(iz\frac{\sqrt{2j_0}}{x_0+y_0}), \quad \omega_{as} = \frac{\sqrt{2j_0}}{x_0+y_0},$$



Length of the charge oscillations in the B*ERL*inPro injector $\quad L_s \approx \frac{\pi}{2\omega_s} \approx \frac{\pi x_0}{2\sqrt{j_0}} \approx 1m$

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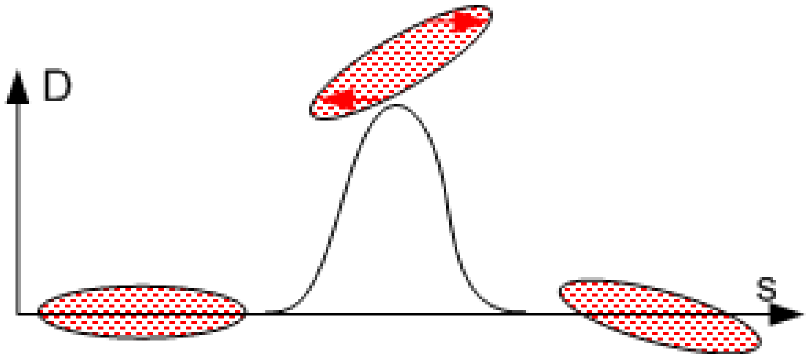
3. **Aberrations**
- In solenoid
- Overbunching due to RF nonlinearity



The longitudinal electrical field can be estimated as

$$E_z \approx \frac{Q}{\gamma 2\pi\varepsilon_0 rl}$$

In our case E_z is a few *kV/m.*

The main impact of the longitudinal space charge field on the beam dynamics is the varying slice energy.

$$\delta_{sc} \approx \frac{E_z \cdot L}{E_0}$$

The particle offset at the end of a merger is about $\delta x \approx \delta_{sc} \cdot D$

An estimation of the emittance degradation in dispersive section is:

$$\frac{\Delta\varepsilon}{\varepsilon} \approx \frac{\delta x}{x_{rms}} \approx \frac{E_z}{E_0}\frac{L \cdot D}{x_{rms}}$$

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Longitudinal motion: overbunching due to RF nonlinearity

- don't compress the bunch unless it is necessary
- overbunching is not compatible with emittance compensation techniques
- it leads to significant increasing of current in overbunched slices

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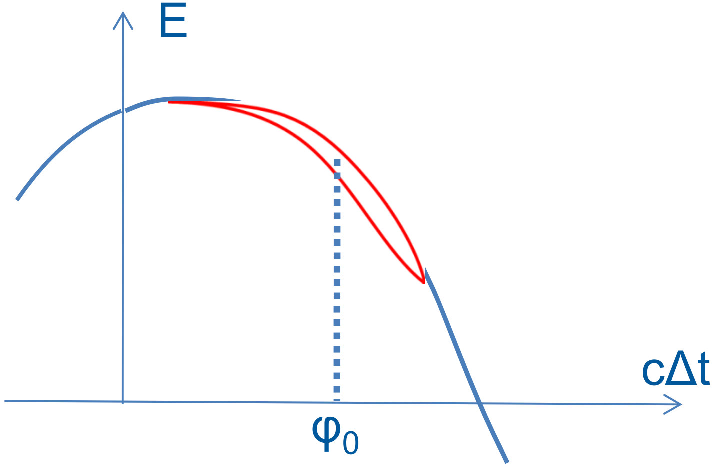
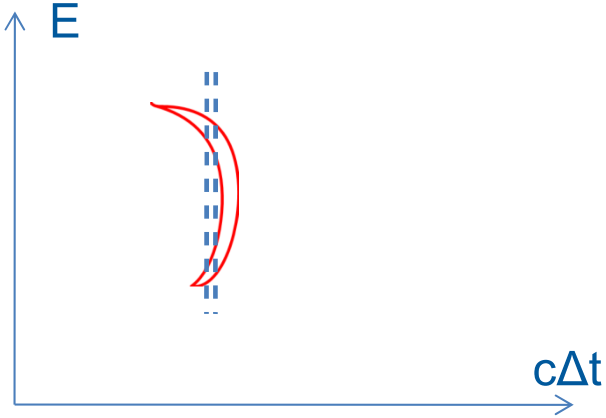
~ 100 fs



Energy gain in the booster



Overcompression

To compress without overbunching, we need a high energy spread (RF phase) and a low R_{56}. The chromatic aberration limits the rms energy spread to about 10^{-2}. The optimal R_{56} is 11 cm and maximal bunching level is 5.

1. **Transverse space charge: 2-D emittance compensation scheme**

- Longitudinal inhomogeneity of space charge density
- Slice emittance growth due to transversal inhomogeneity of space charge density **Laser beam shaping / flat QE at the cathode**

2. **Energy change in dispersive section due to longitudinal space charge ("space charge dispersion").**

- Mismatch of slice centers at the end of dispersion section: adjustable dispersion at the end of dispersive section
- Slices emittance growth due to inhomogeneity of energy change in slices: minimal length of dispersive section

3. **Aberrations**

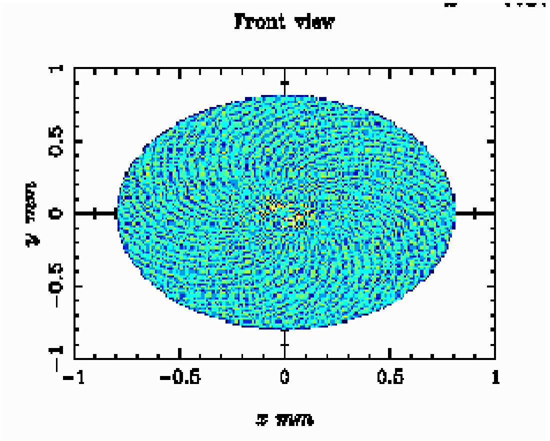
- In solenoid: Long solenoid and small bunch size in solenoid
- Overbunching due to RF nonlinearity: Small R_{56} is preferable to avoid overbunching

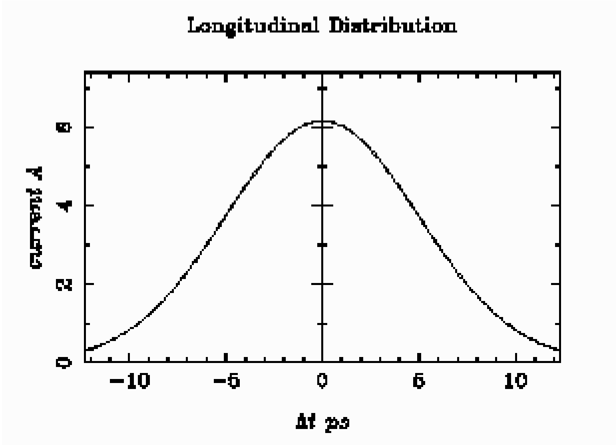
Modeling

• ASTRA is used for tracking

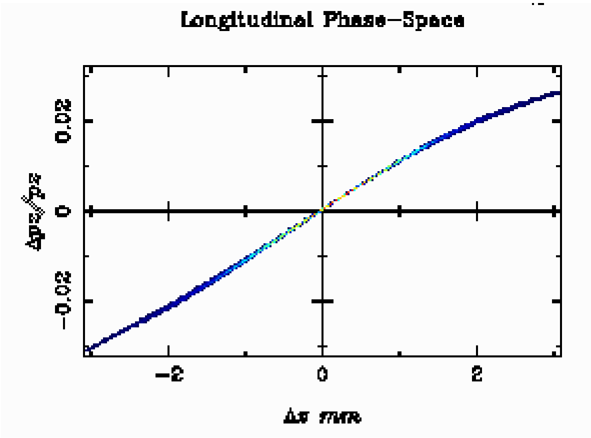
• field distributions in RF cavities is taken from Microwave Studio/CLANS

• duadrupole are optimised in linear approximation (solving the KV-system in linear approximation, code - courtesy of A.Bondarenko)





At the cathode



From the gun

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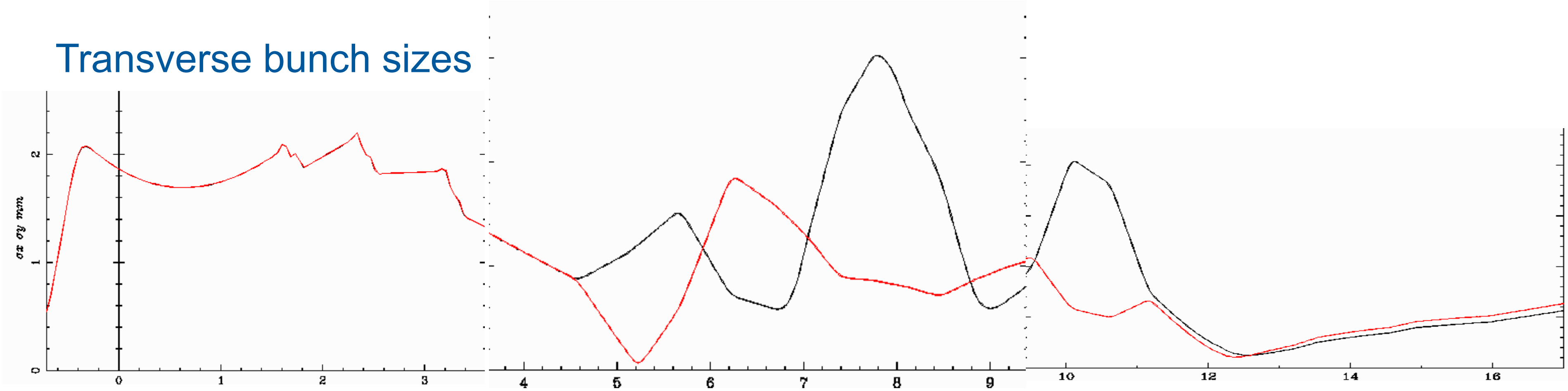
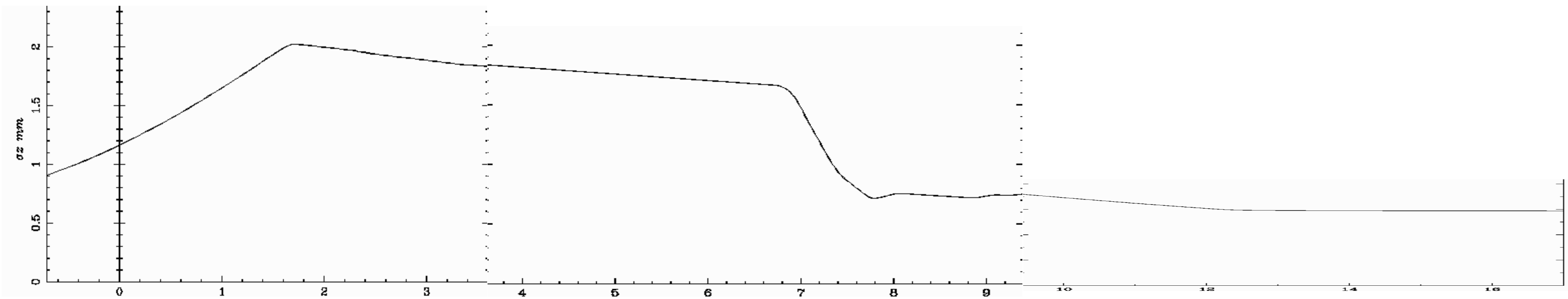
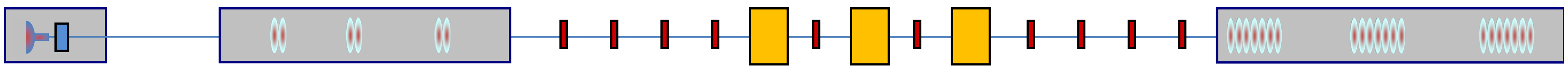
Transverse bunch sizes



Bunch length





Transversal and longitudinal distribution behind the linac

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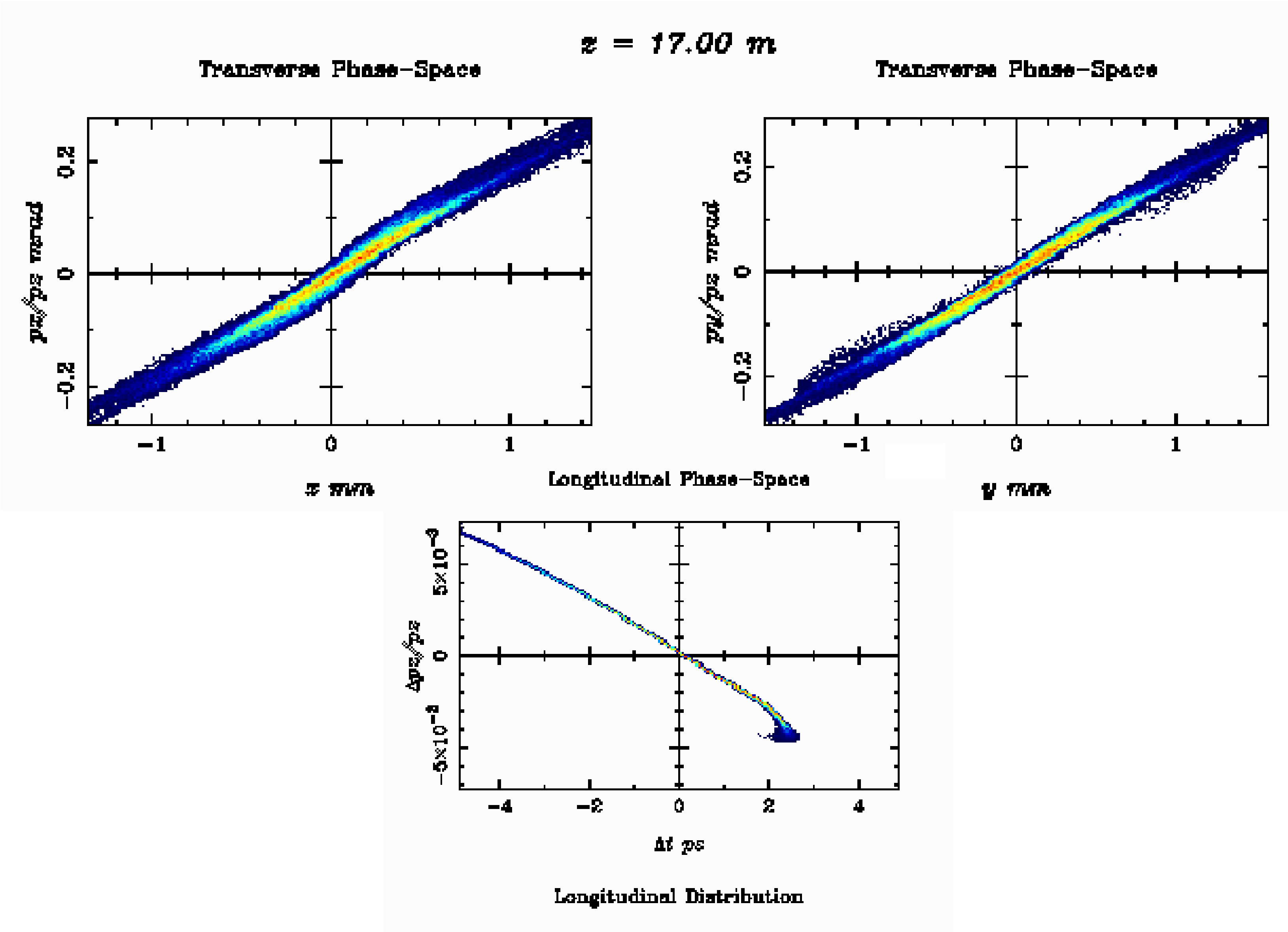
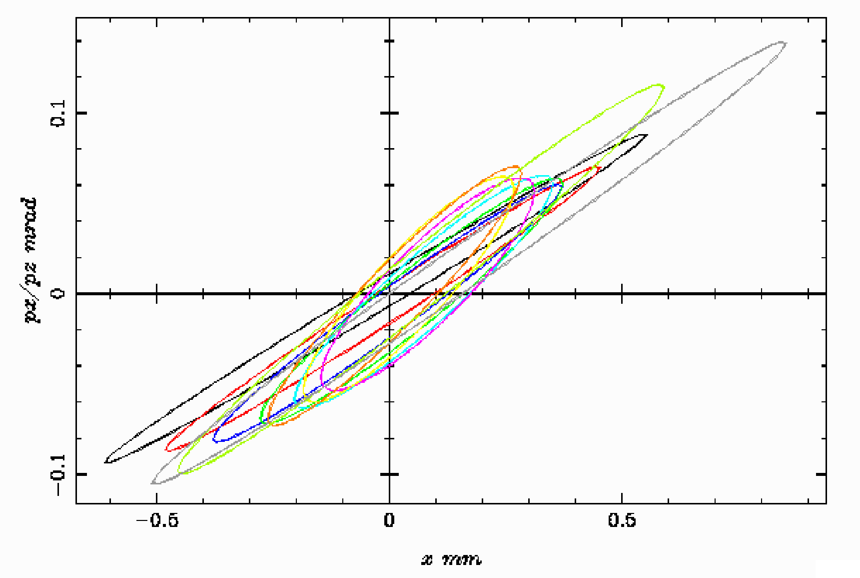
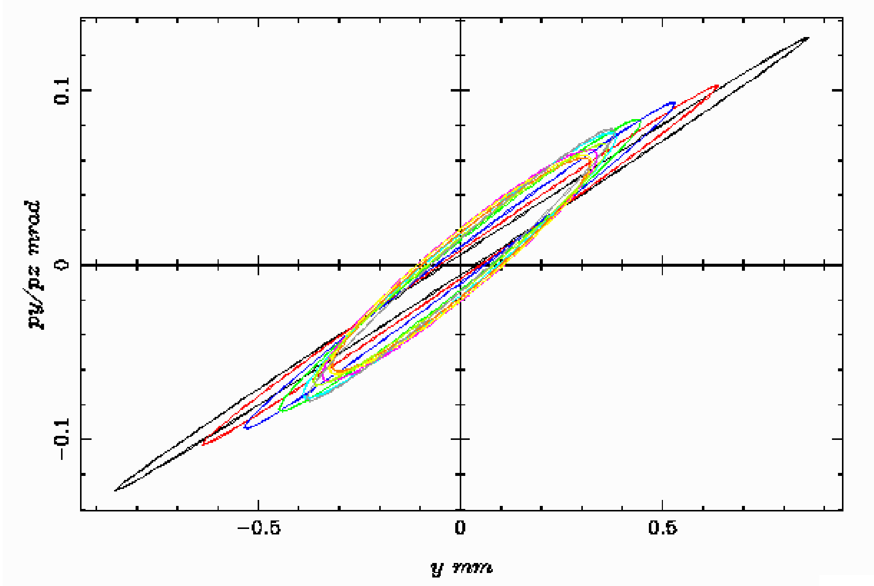






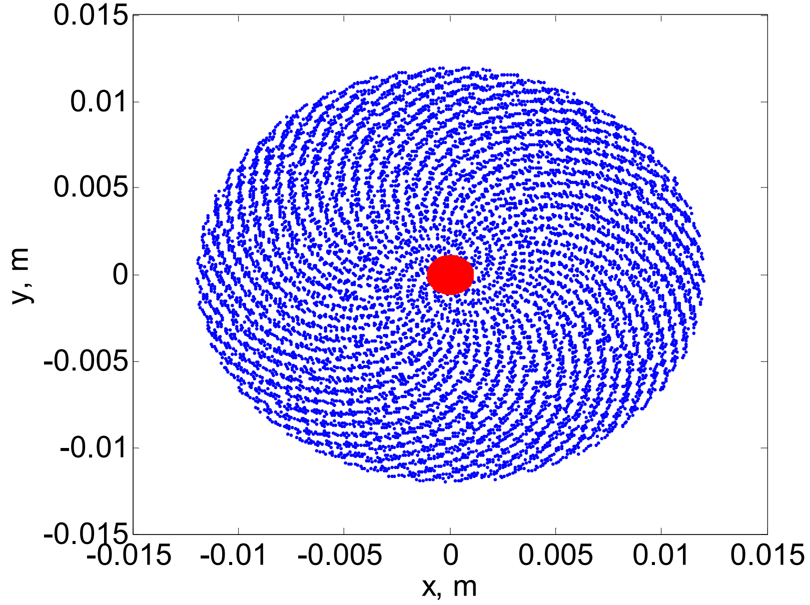
Beam parameters behind the linac:

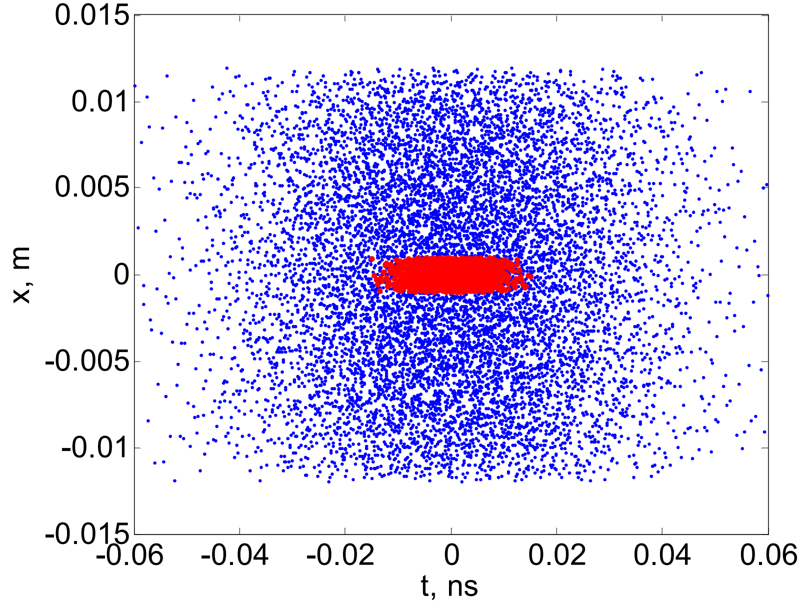
ε_{slice} ~ 0.5 – 0.7 mm·mrad (ε_{slice} ~ 0.4 mm·mrad at the cathode)

$\varepsilon_{x,\ proj}$ = 0.9 mm·mrad $\varepsilon_{y,\ proj}$ = 0.75 mm·mrad

σ_z= 0.6mm = 2ps ε_z = 5 keV·deg

Beam halo model

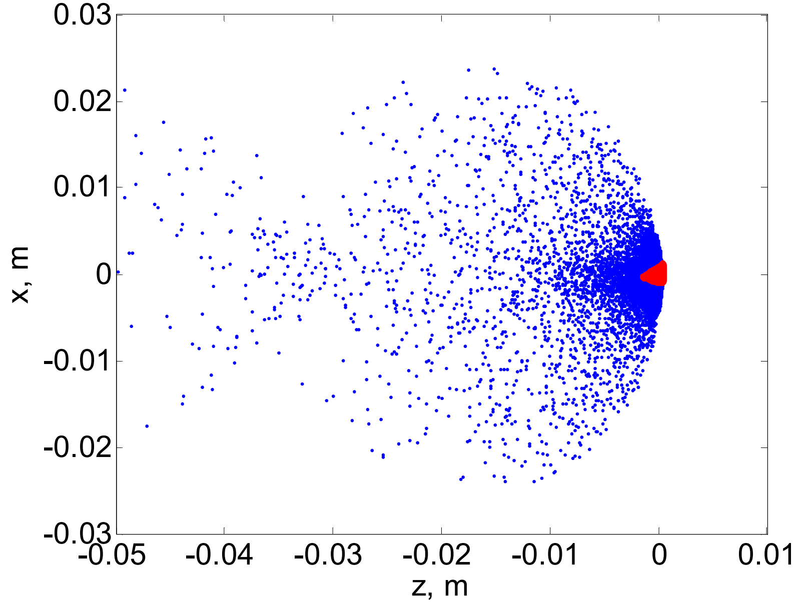


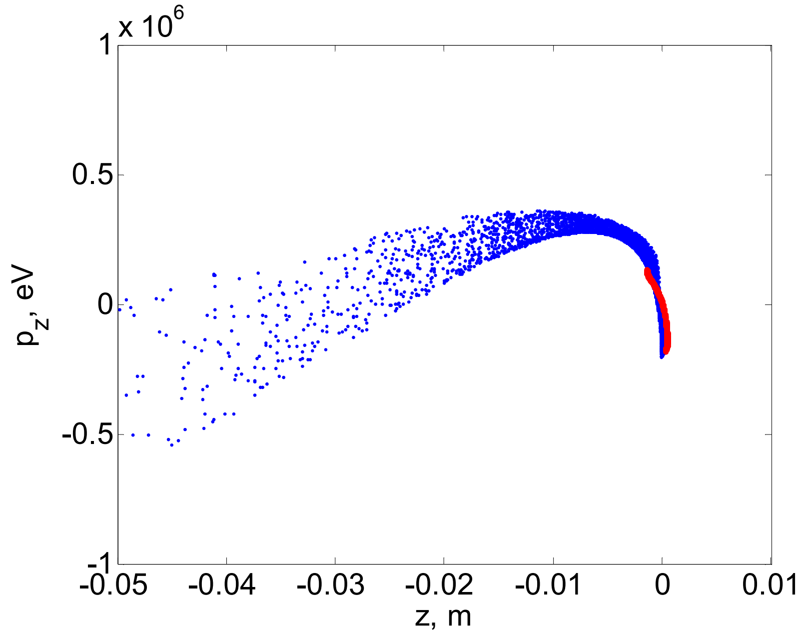


An example is shown on the next slides. Tracking is done with ASTRA from the cathode to the end of the LINAC.

Particle distribution at the cathode. Red – actual beam. Blue – passive halo particles.

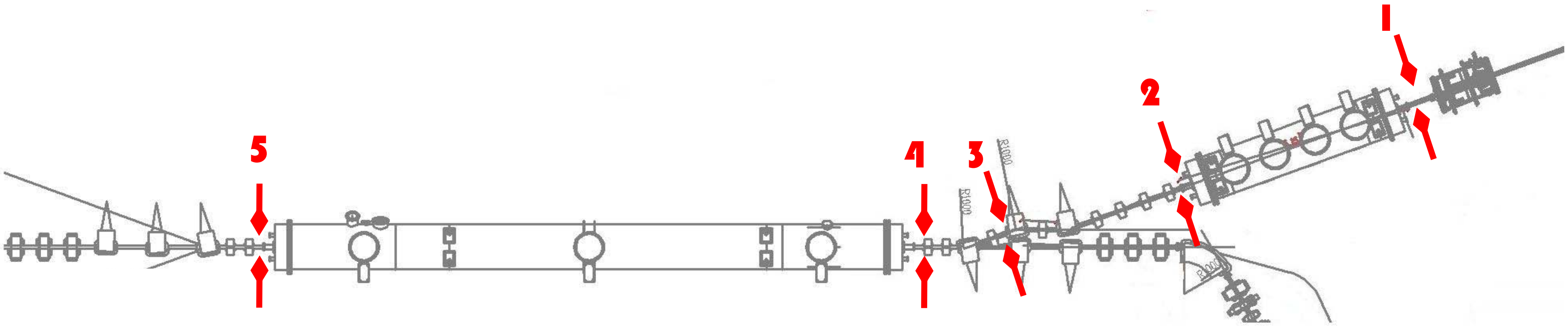
Halo particles behind the injector





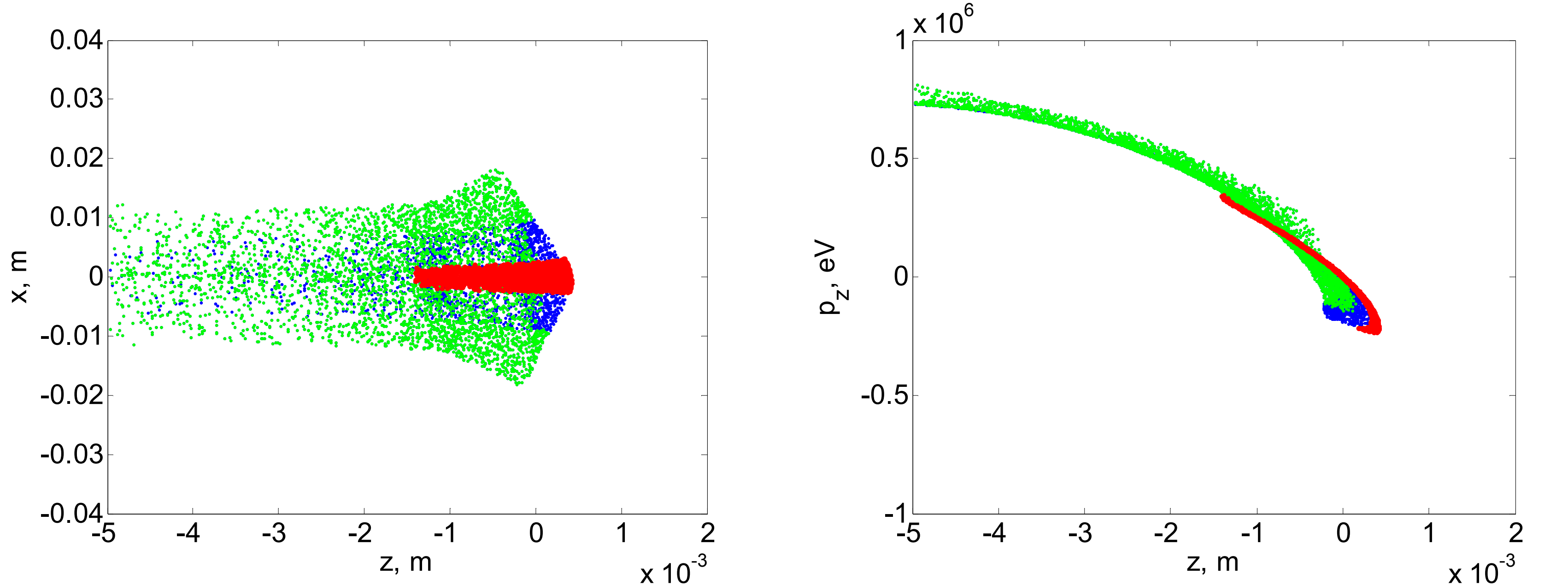
Particle distribution behind the injector. Red – actual beam. Blue – passive halo particles.

Position of collimators



- Collimators (wanted beam loss !!!)

Collimation effect on the beam



Particle distribution behind the linac. Red – actual beam. Blue – passive halo particles, green – halo particles, lost on apertures. ±10mm square apertures are assumed.

Summary

- low emittance ERL injector without axial symmetry is feasible
- emittance compensation for elliptical beams is necessary
- dispersive effects and aberrations should be taken into account

- collimation is necessary
- credible halo formation model wanted

Thank You for Your attention!