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Low Energy Beam Transport
(LEBT)

1) Principles and transport systems

2) Space charge compensation and space charge lenses

3) Beam diagnostics

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Low **E**nergy **B**eam **T**ransport
Principles and transport systems

* Introduction

* Envelopequation

* Space charge

* Emittance growth

* Residual gas interaction

* Lens systems
  - el. static / magnetic
  - cylindersymetric / quadrupol

* Examples

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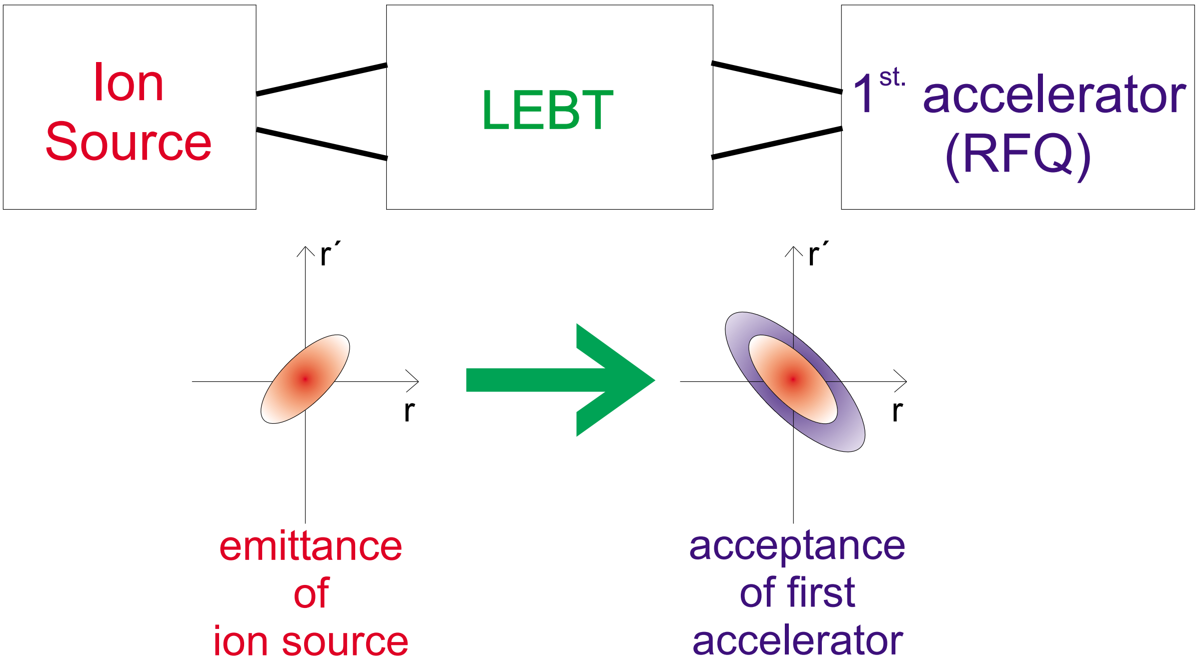
What is Low Energy Beam Transport ?



"The transformation of the emittance delivered by the ion source into the acceptance of the first accelerator structure."

Questions :

Are there particle losses ?
or
Which factors have inflcence on the transmission ?

How does the transformation influences the beam quality ?
or
What are the sources of emittance growth ?

How does Low Energy Beam Transport differ from other transport systems ?

The transmission is influenced by :

optical system (focussing force)
space charge forces
residual gas pressure

...

The emittance growth is influenced by :

optical system (lens aberrations)
space charge forces
current fluctuations
...

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How can we describe the beam transport physically ?

neglecting collisions
and
emittance growth

Envelopequation

$$\frac{d^2X}{dz^2} = \frac{\langle \varepsilon_{rms,x} \rangle^2}{X^3} + \frac{K}{2(X+Y)} - k_x^2 X$$

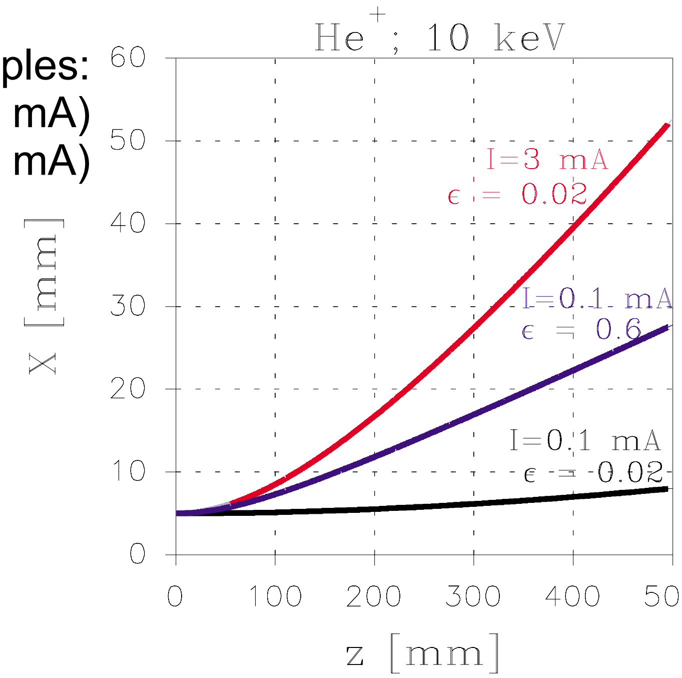
emittance

gen. perveance (space charge)

$$K = \frac{\Delta U}{U} = \left(\frac{1}{4\pi\varepsilon_0} \sqrt{\frac{Am}{2e\zeta}} \right) \frac{I}{U^{3/2}}$$

lenses

Examples:
(H / 50 kV / 70 mA)
(H / 100 kV / 200 mA)



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Space charge

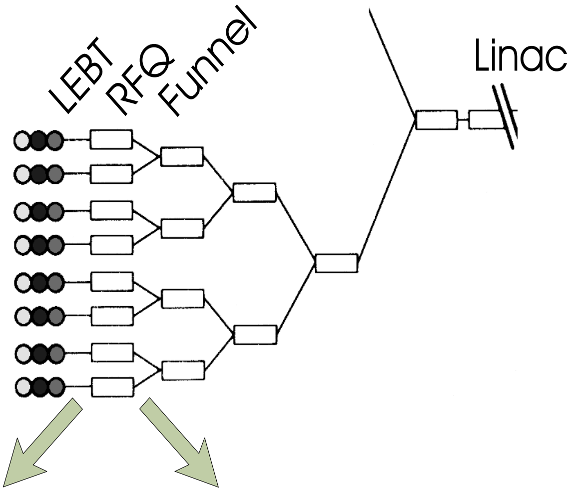
generalized perveance:

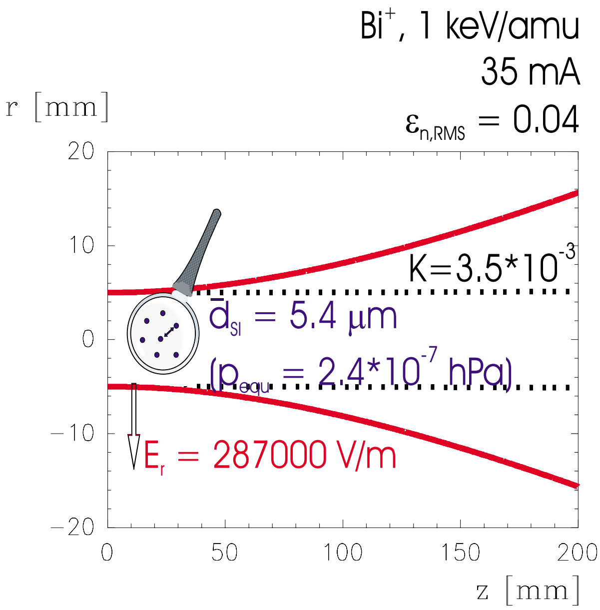
$$K=\left(\frac{1}{4\pi\varepsilon_0}\sqrt{\frac{Am}{2e\zeta}}\right)\frac{I}{U_B^{3/2}}=\frac{\Delta\Phi_{KV}}{U_B}$$

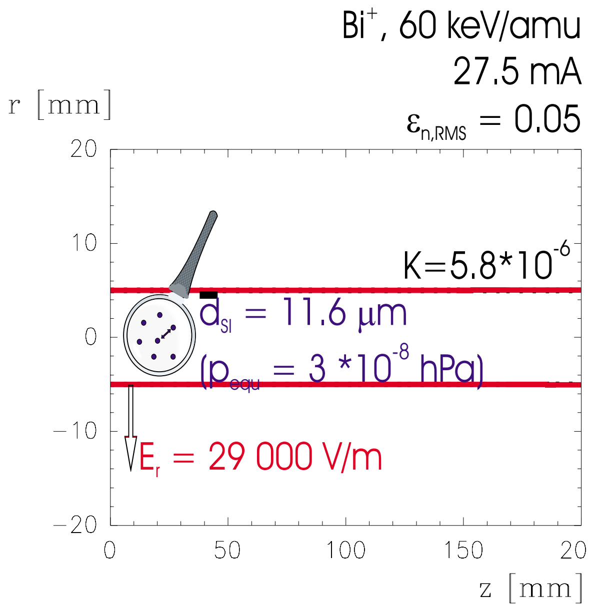
Why is space charge so dominant in the low energy section ?

Example (HIDIF) :

(~H / 50 kV / 55 mA)







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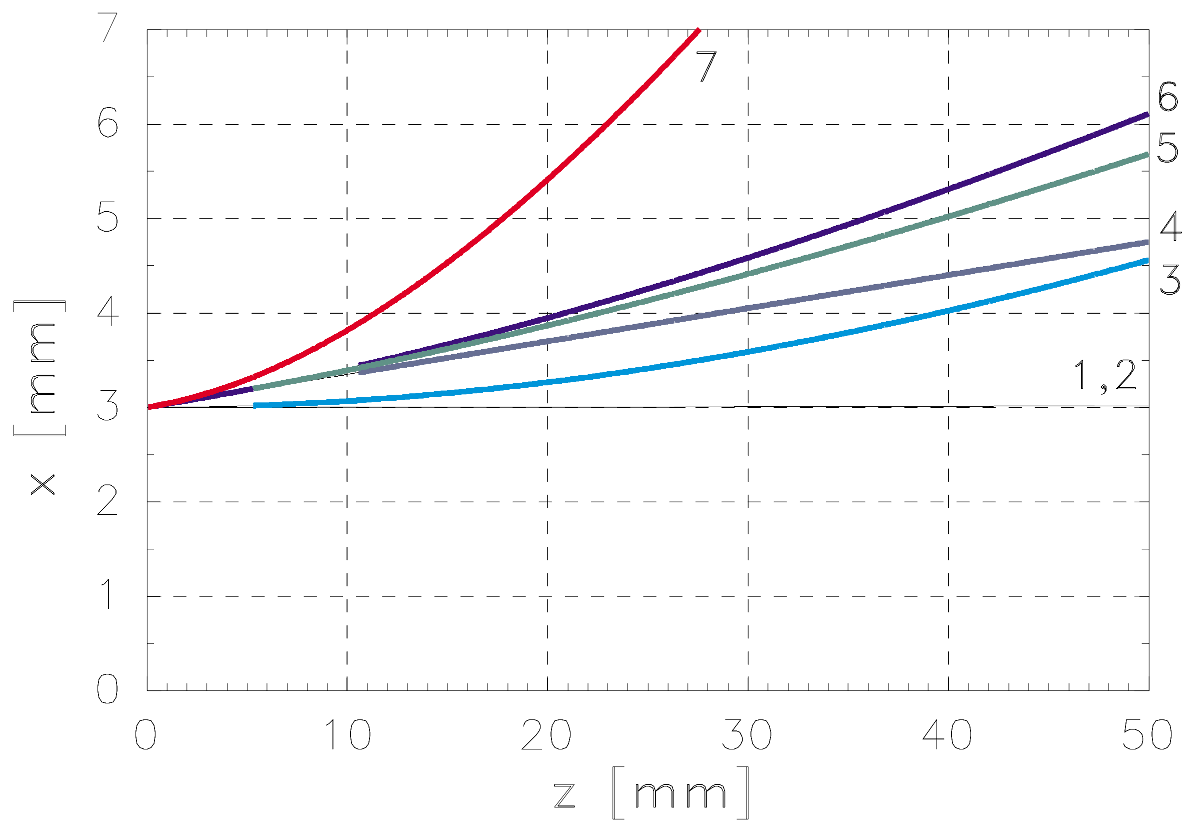
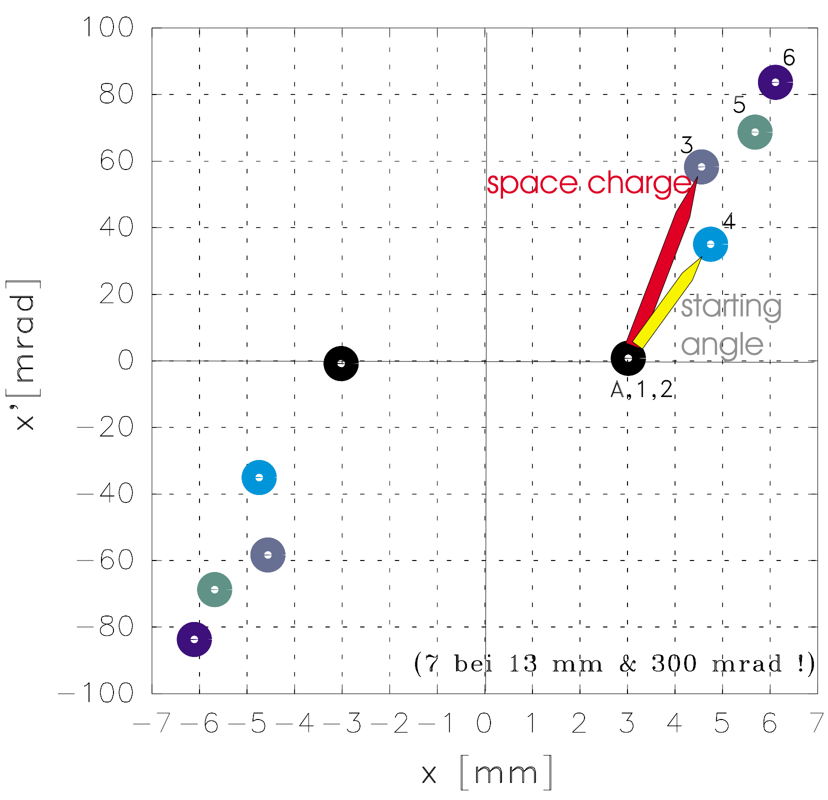
Influence of space charge on beam transport and emittance calculated for beamdrift





(1-4 & 6 IFMIF(D^+, 100 keV, 140 mA and different starting conditions) ,
5 SNS (H^-, 65 keV, 70 mA) , 7 Bi-Injektor (Bi^+, 100 keV, 100 mA)

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Emittance growth is influenced by various factors:

1) Source plasma /plasma sheeth

* plasma temperature / plasma potential

"The kinetic energy distribution of the ions is preserved in the beam extraction and defining the minimum source emittance."

*plasma uniformity / plasma sheeth

"Variations of the real plasma sheeth from the ideal form due to radial or azithudinal devitaions of plasma density will lead to additional emittance growth."

2) Lens aberrations / non linear external fields

"Deviations of the external fields from linear behavior will increase beam emittance."

3) Space charge forces

* non linear internal field energy is transfered into emittance

"Deviations of the internal fields from linear behavior (non homogenious net charge density distribution) will increase beam emittance."

*current fluctuations

"Temporal variations of the space charge forces will increase the time integrated beam emittance."

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Emittance growth

1. Source plasma / plasma sheeth

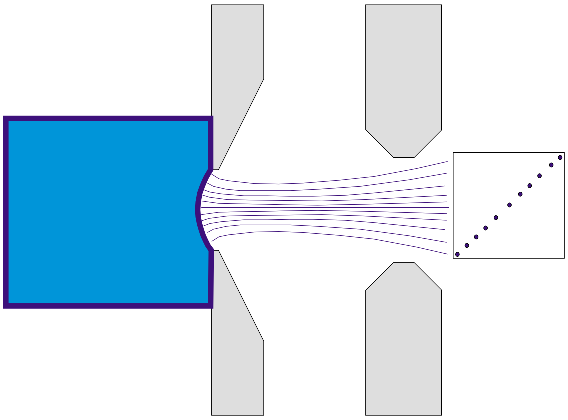
* plasma temperature / plasma potential

$$f(v_{ion}(r_{ex.},z_{ex.}))dv = \left(k \cdot \left(\frac{m}{kT}\right)^{3/2} \cdot v^2 \cdot e^{-\left(\frac{mv^2}{2kT}\right)} \right) + \left(\sqrt{\frac{2 \cdot (\phi(r_{pro.},z_{pro.}) - \phi(r_{ex.},z_{ex.}))}{m}} \right)$$

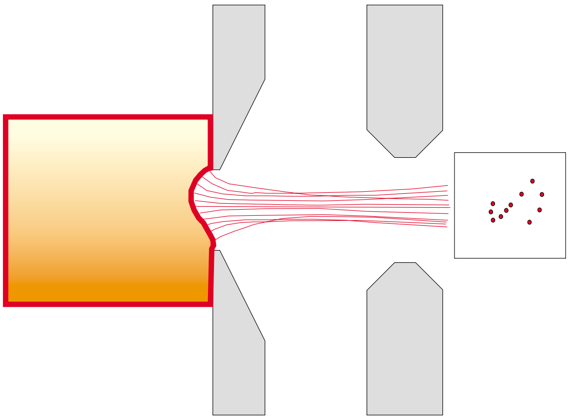
thermal term — potential term

The kinetic energy distribution of the ions in the plasma is preserved in the beam extraction system and defining the minimum "source emittance"

*plasma uniformity / plasma sheeth



homogenious



non homogenious

Spatial variations of the plasma density (external or internal fields, wall effects, geometric reasons,...) will lead to emittance growth.

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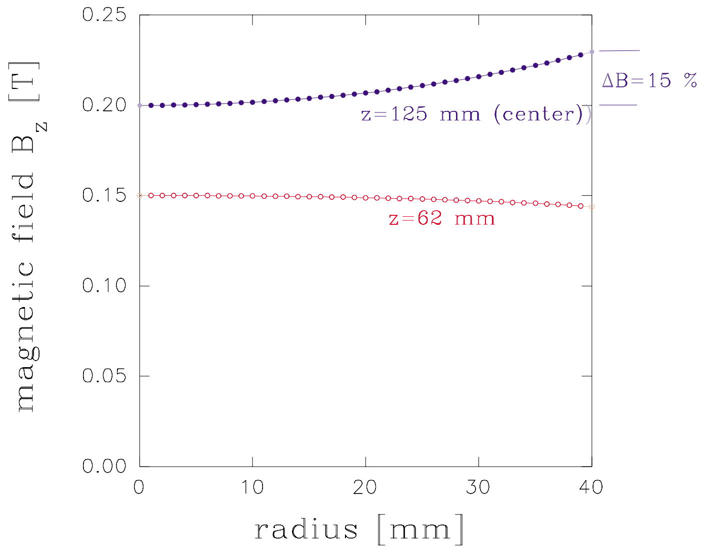
2. Lens aberrations

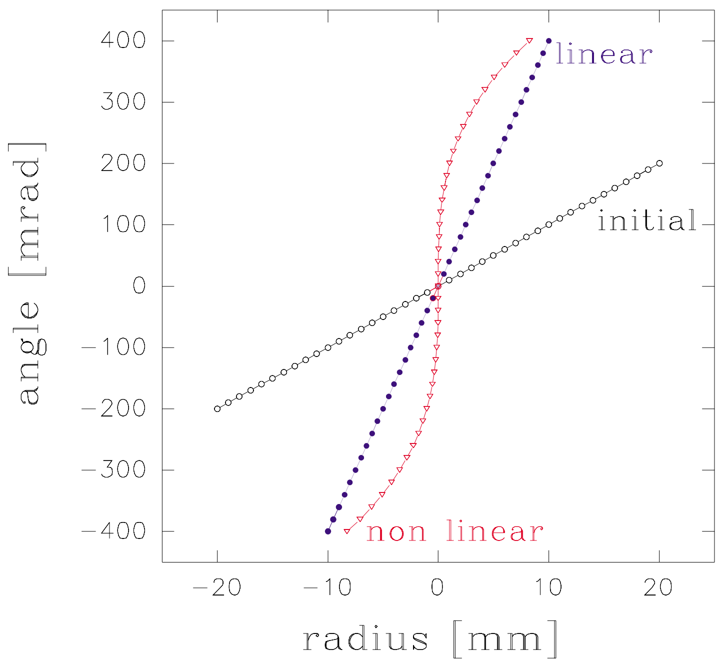
Deviations of the external fields
from linear behavior

$$F(r) \neq const.\cdot r$$

Frankfurt LEBT Solenoids



will increase beam emittance
by redistribution of the beam ions



3. Space charge forces

non linear internal field energy
defined by

$$W = \frac{\varepsilon_0}{2} \iint \vec{E}^2 dx dy$$

is transfered into emittance

$$\frac{\varepsilon_f}{\varepsilon_i} = \sqrt{1 + \frac{<x^2> K \Delta W_{nl}}{8\varepsilon_i^2}}$$

where the gen. perveance is

$$K = \frac{I}{U^{3/2}} \sqrt{\frac{A}{\zeta}} \left(\frac{1}{4\sqrt{2}\pi\varepsilon_0} \sqrt{\frac{m}{e}} \right) \qquad K = \frac{\Delta\Phi_{KV}}{U}$$

and the redistribution factor

nach von	KV	WB	PA	CO
WB	0.02240	0		
PA	0.04704	0.02640	0	
CO	0.05632	0.03392	0.00928	0
GA	0.15444	0.13204	0.10740	0.09808

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Example for ε-growth by redistributions: Numerical simulation of a 300 mm drift (H / 10 keV / 8 mA)

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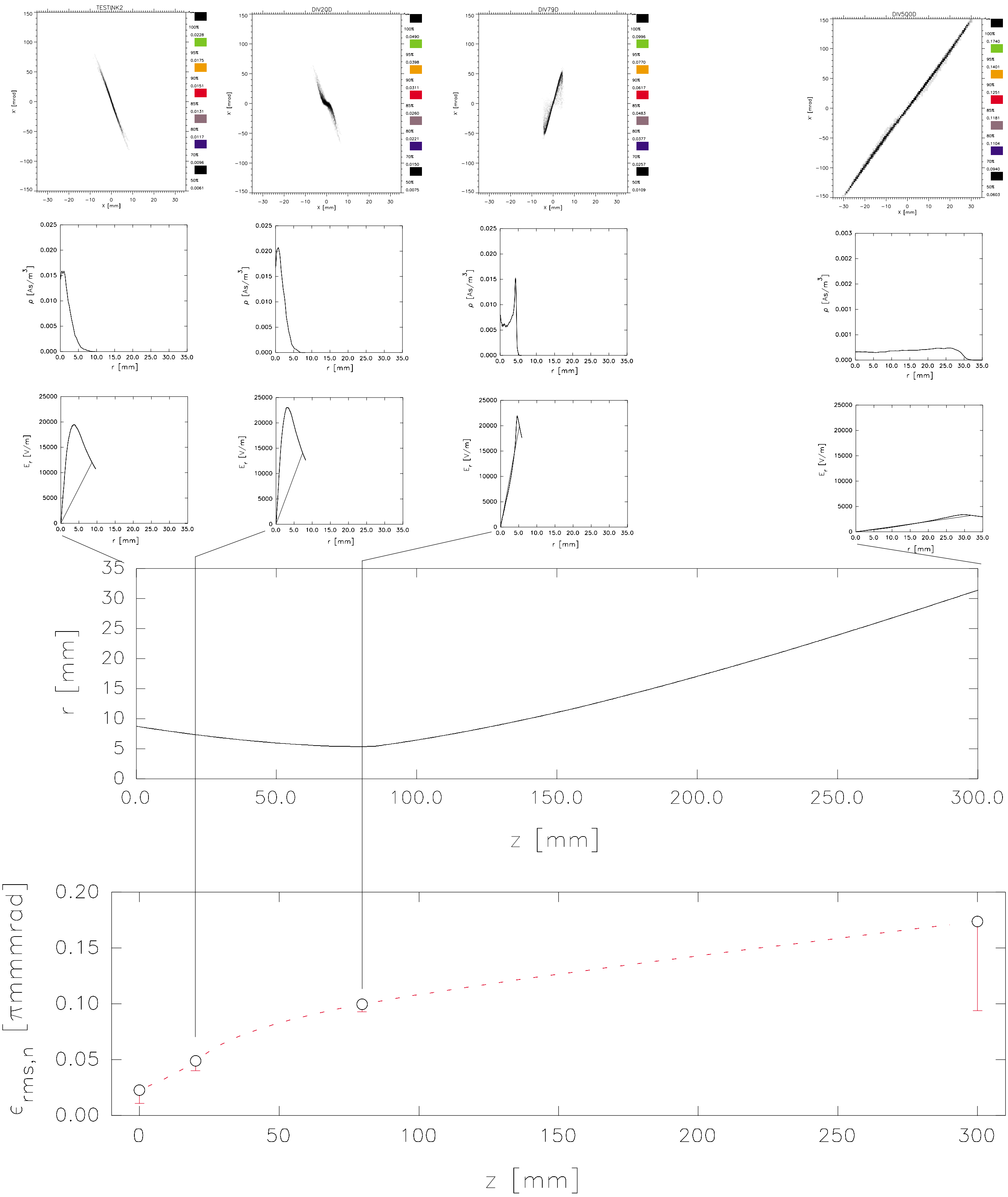

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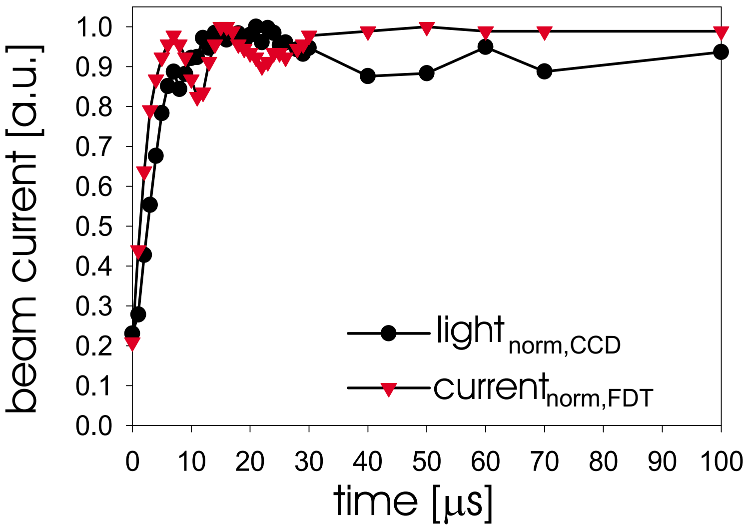
Emittance growth by space charge fluctuations

current fluctuations (e.g. source noise, rise time of ion source, rise time of space charge compensation)



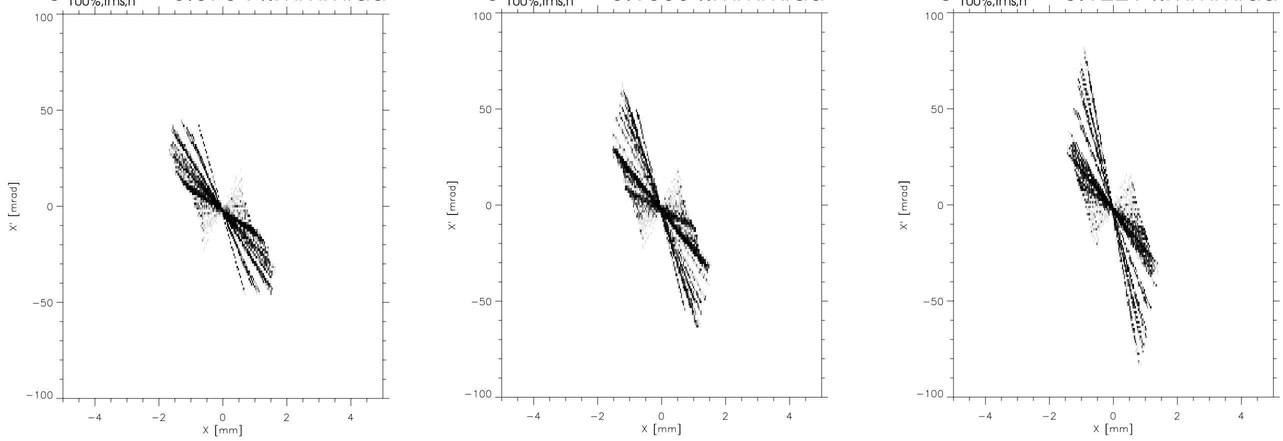
leads to varying space charge forces as a function of time and therefrom to a temporal rotation of the emittance in phase space.

Example : IFMIF D^+, 100 keV

I=137.2 mA $\varepsilon_{100\%,rms,n}$ = 0.0734 πmmmrad

I=140 mA $\varepsilon_{100\%,rms,n}$ = 0.1003 πmmmrad

I=142.8 mA $\varepsilon_{100\%,rms,n}$ = 0.1221 πmmmrad



The time integrated emittance is growing.

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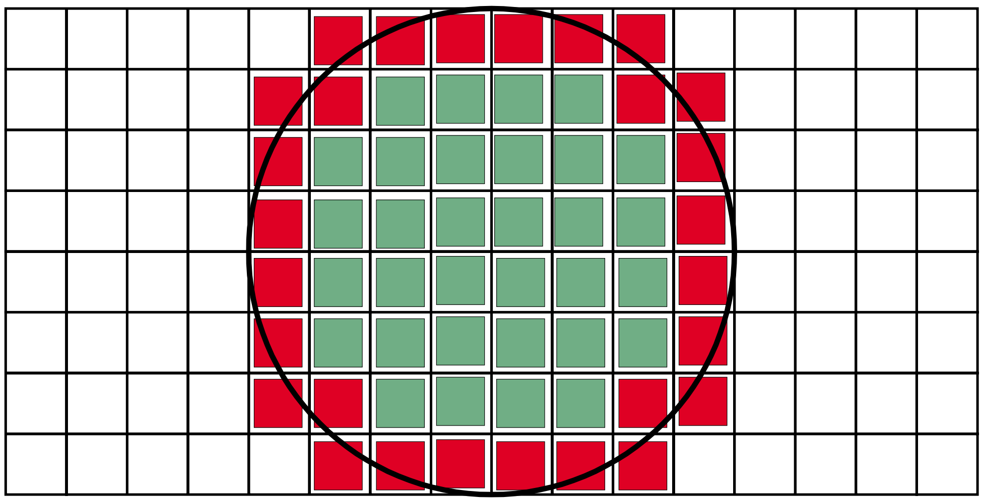
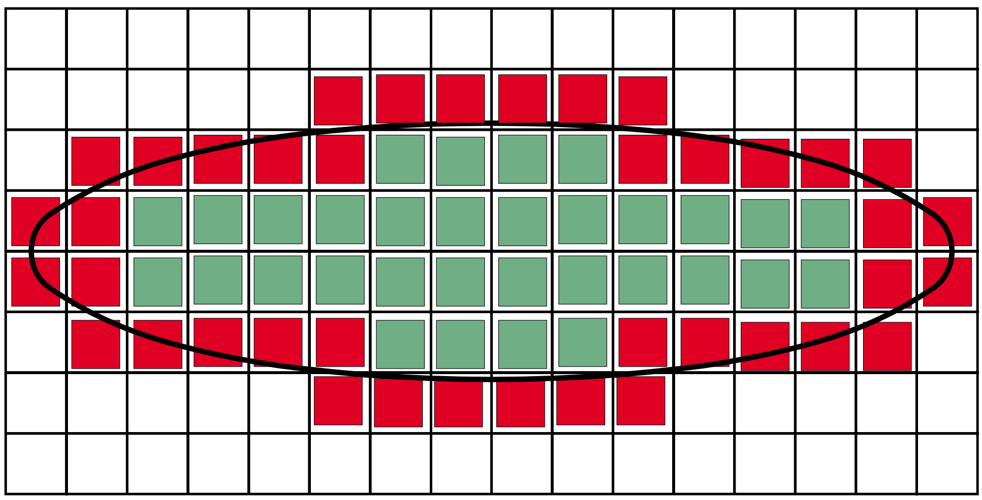
Artifical emittance growth due to discretisation



$$F_{ges} = \Delta F\,[32 + 28] = 60\Delta F$$



$$F_{ges} = \Delta F\,[32 + 40] = 72\Delta F$$

Interactions between beam ions and residual gas

$$Beam\ \ losses \propto n_{RGA} \cdot \sigma_{WW}$$

cross sections for hydrogen ions (100 kV)
on hydrogen residual gas

- residual gas ionisation by beamions
$2.26 \cdot 10^{-20}$ m^2

- charge exchange
$0.29 \cdot 10^{-20}$ m^2

- residual gas ionisation by neutrals
$0.29 \cdot 10^{-20}$ m^2

and additional interactions
(electron capture, scattering, ...).

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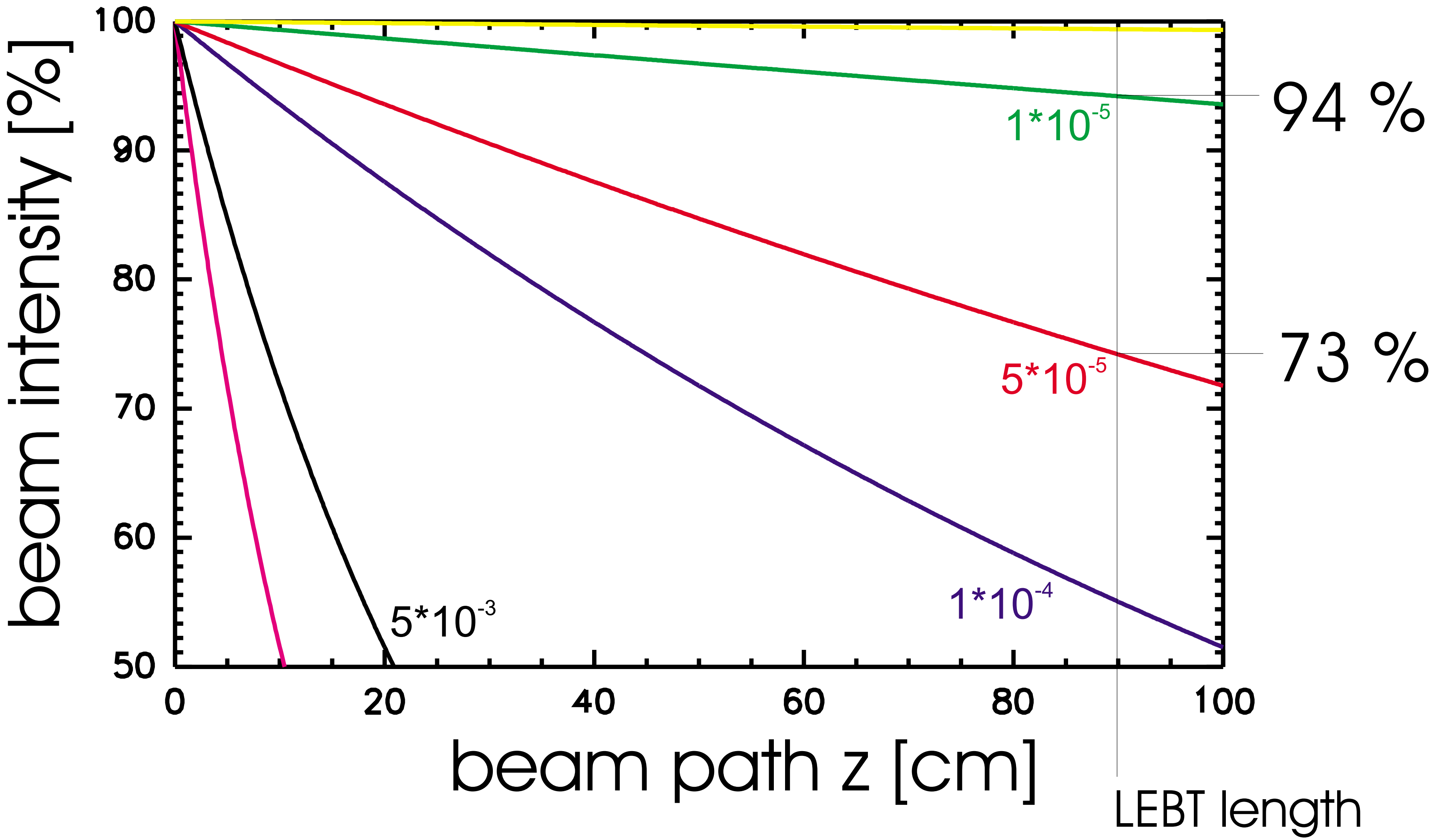
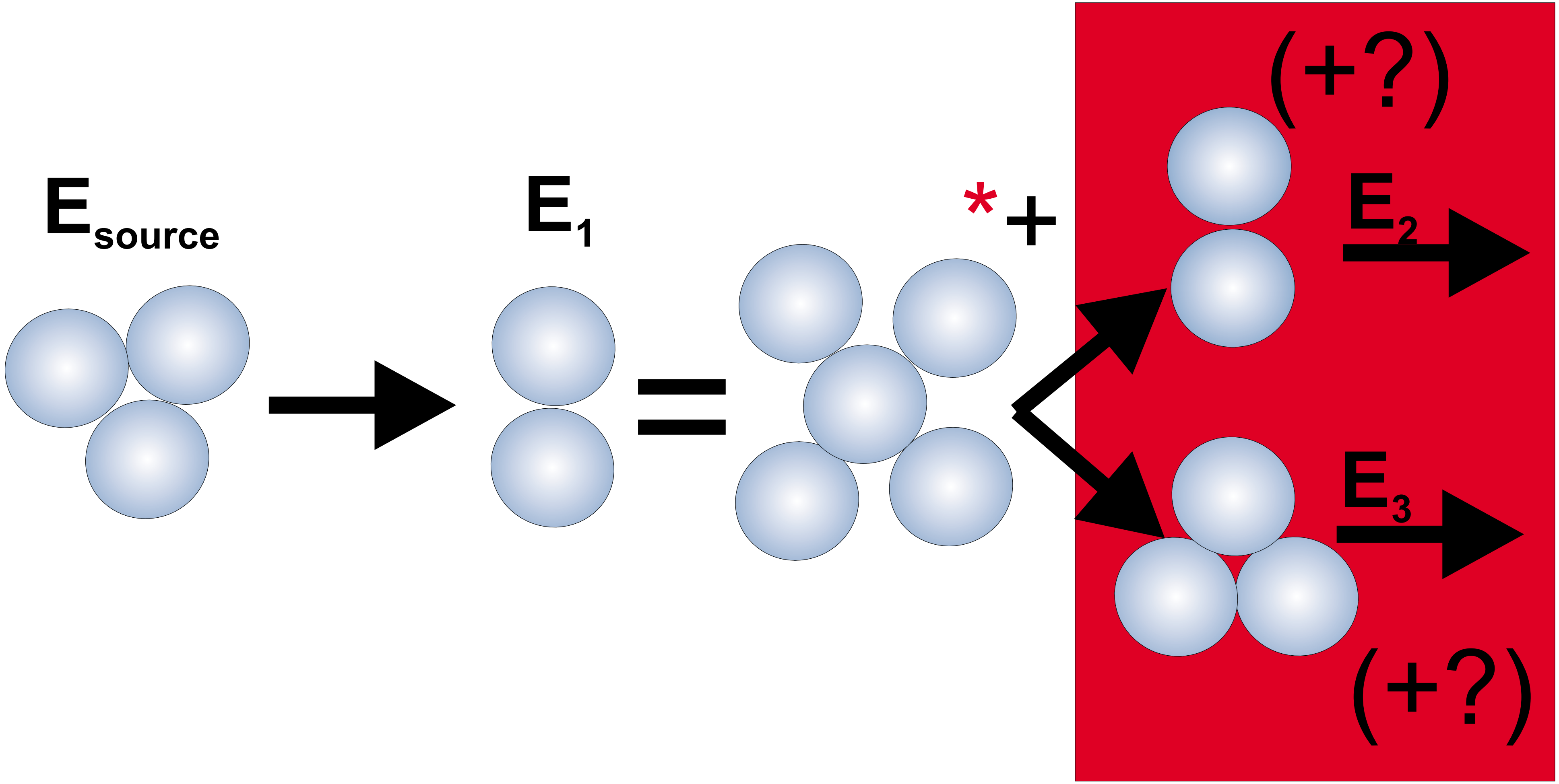
The transmission in the LEBT is due to the high gas pressure strongly influenced by interaction between residual gas and beam ions.

$H^- \rightarrow H_2$ (ESS)



Collisions between beam ions and residual gas atoms (moleculs)



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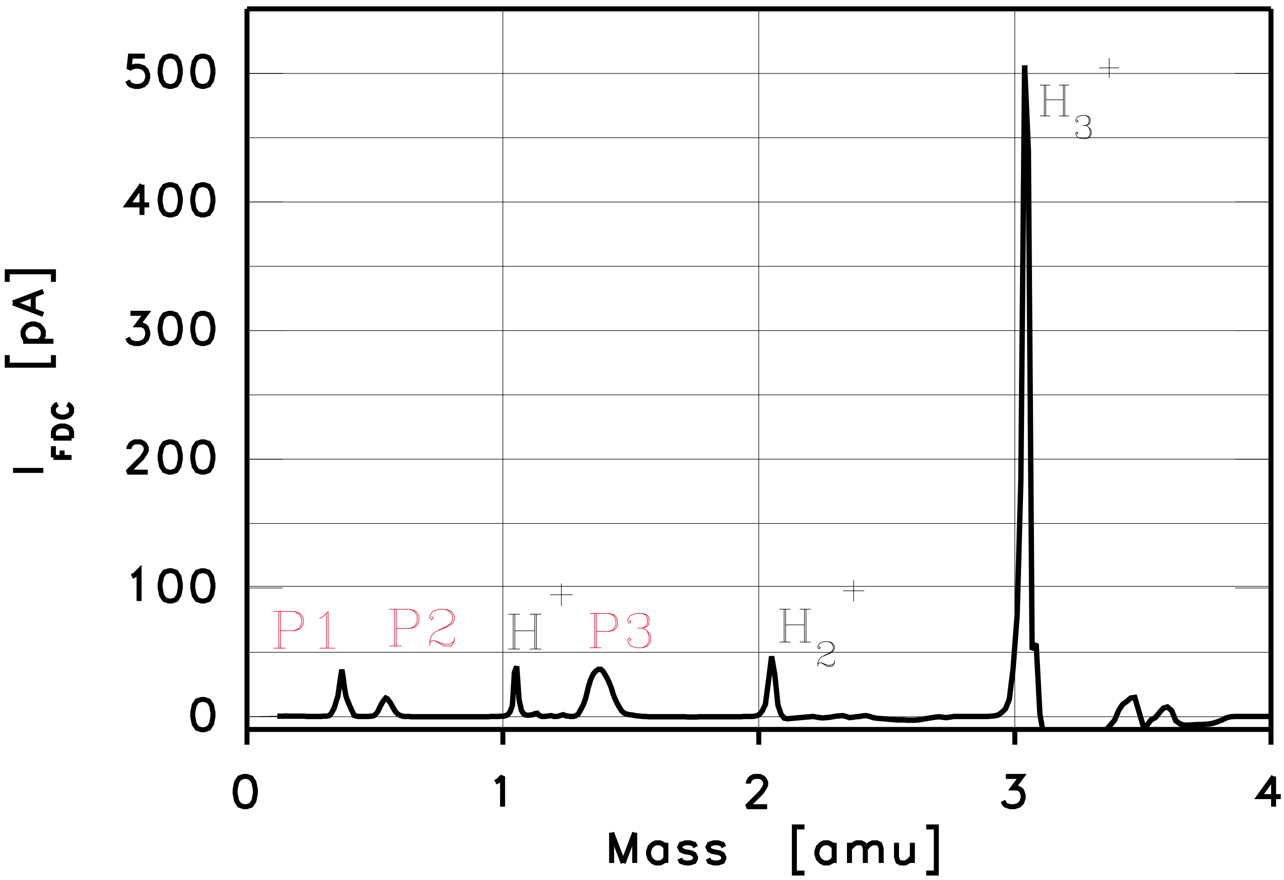
Production of ions by interaction between residual gas atoms and beam ions

Measurement of the interaction between a beam of hydrogen ions (6 keV) and hydrogen residual gas atoms (longitudinal energy and cross section)



beam ions

$H^+ - 6050\ eV$

$H_2^+ - 6047\ eV$

$H_3^+ - 6085\ eV$

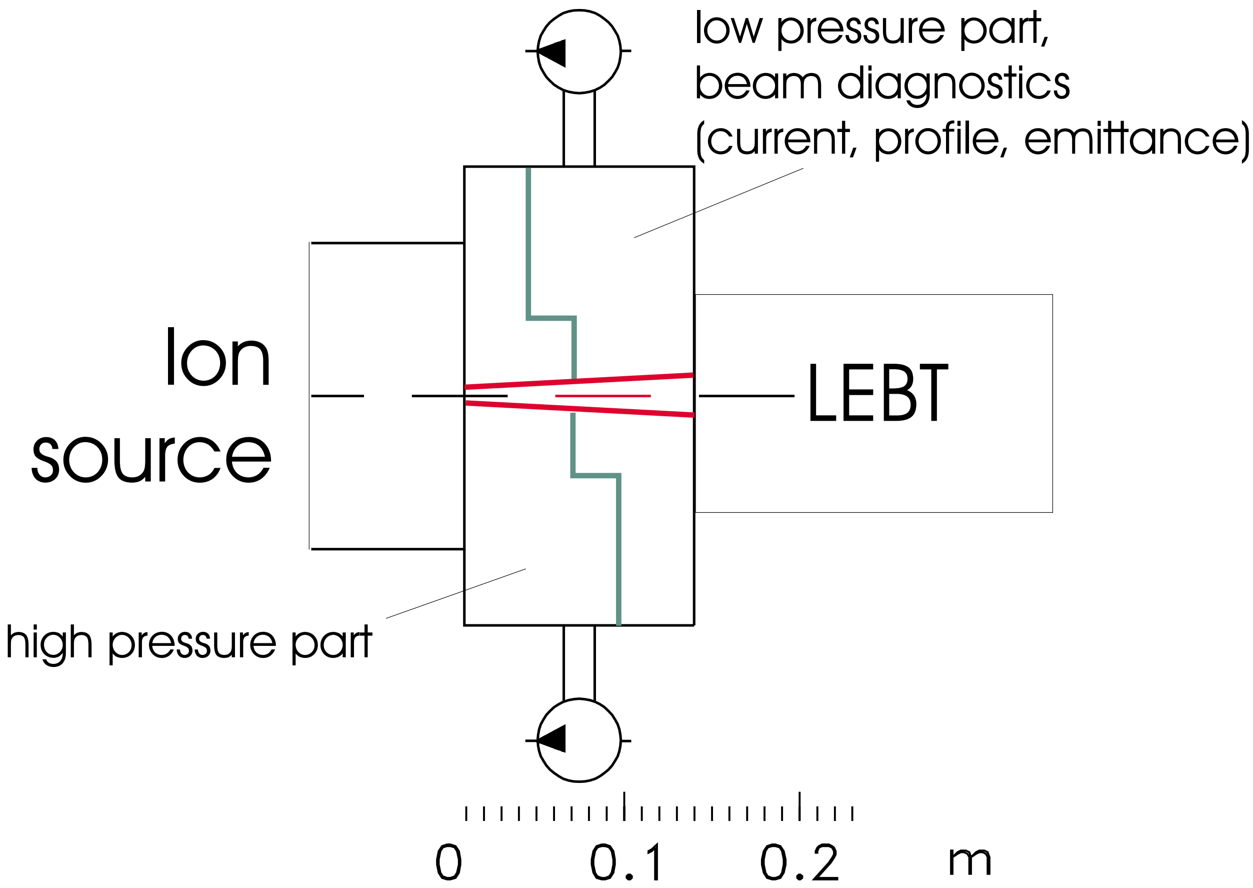
secondary ions

$P1 = H^+ - 2100\ eV$

$P2 = H^+ - 3070\ eV$

$P3 = H_2^+ - 4030\ eV$

To reduce particle losses due to interactions between residual gas and beam ions and to prevent high voltage breakdown due to high gas load (electrostatic LEBT or RFQ) the first diagnostic tank behind the source should include a differential pumping system.



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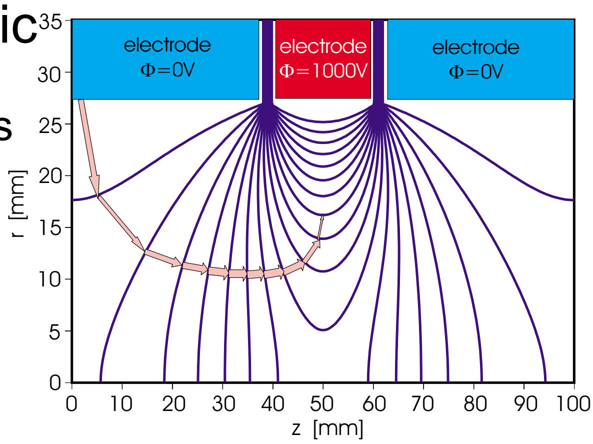
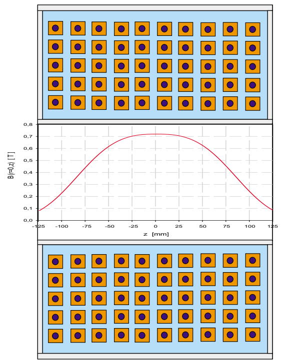
Lenssystems

* electrostatic cylindersymetric



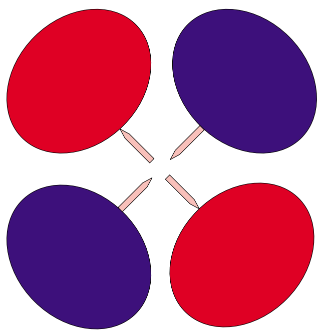
- weak cylindersymetric focussing
- deceleration / acceleration systems
- mass independent
- transportsystem is numerical accessible
- no space charge compensation
- medium investment costs
- HV-breakdown limit & availability

* solenoids



- weak cylindersymetric focussing
- mass (velocity) dependency
- space charge compensation
- limited numerical access
- higher investment costs
- no HV-breakdowns (MTBF)

* electrostatic & magnetic quadrupols



- strong focussing in one plane (defocussing in the other)
  => weak net focussing in triplett
  but reduced fields compared
  with einzellenses & solenoids
- break of cylinder symetry (space charge) can cause redistributions & emittancegrowth
- no consistent model of space charge compensation

* higher order fields (sextupols / octupols)
* Gabor lenses
* z- pinch lenses

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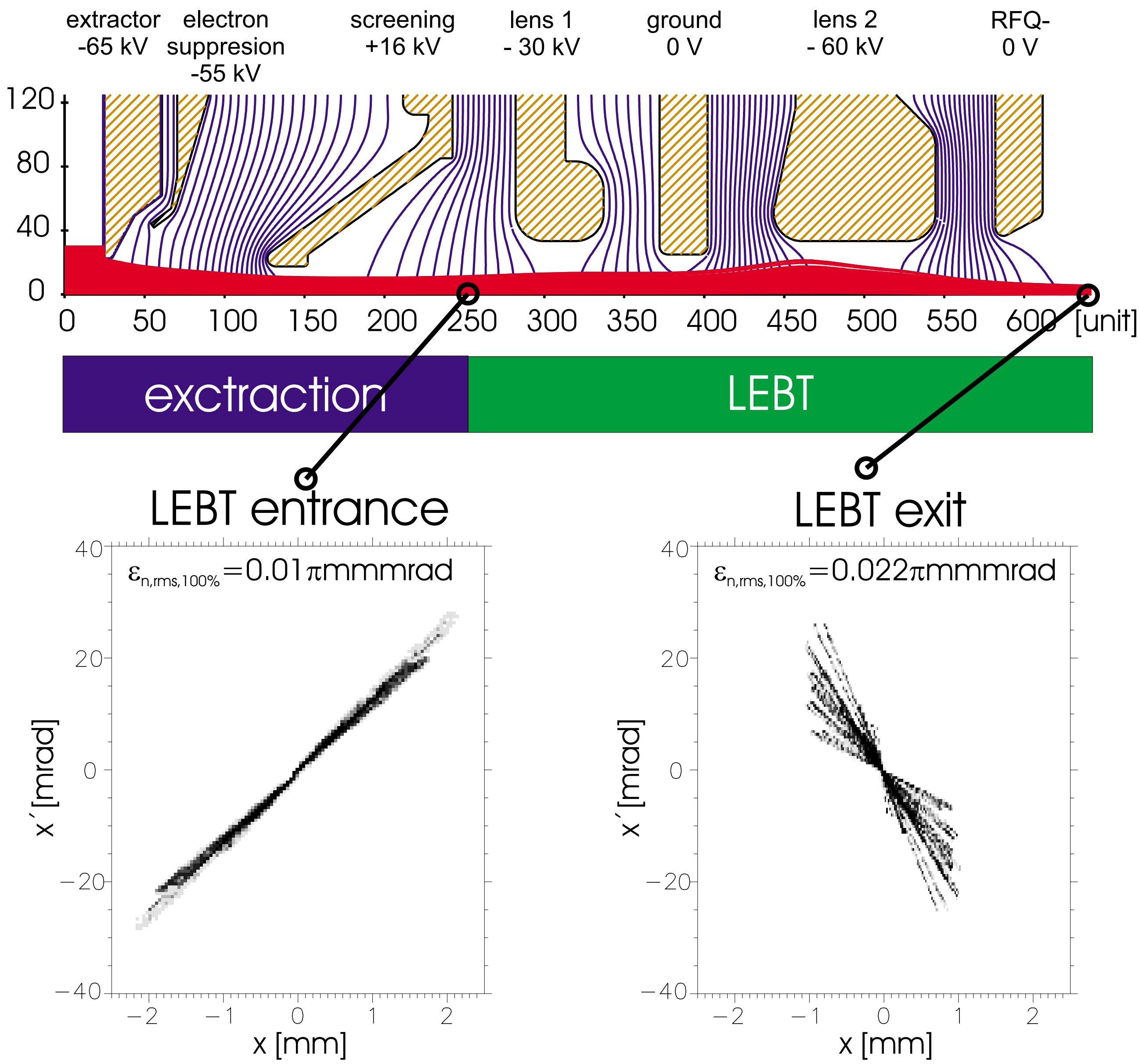
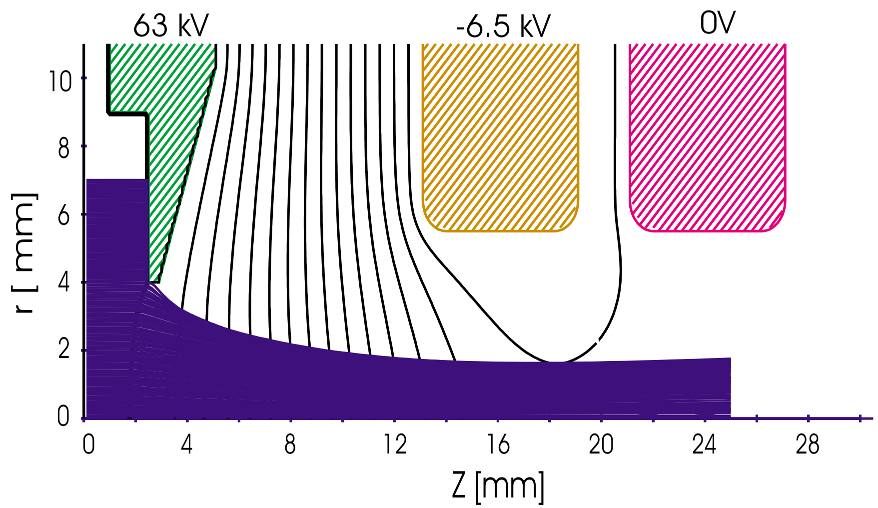
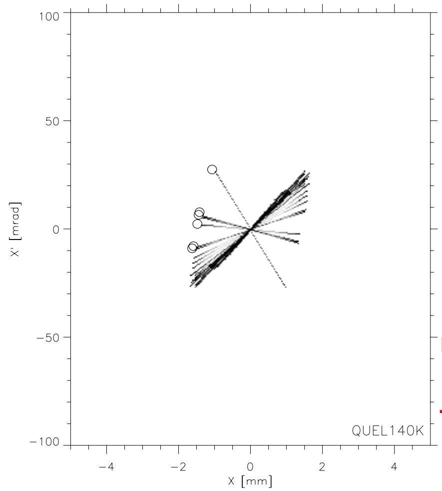
Transport calculations for current upgrade of the SNS-LEBT H⁻, 70 mA , 65 keV

(compound system including extraction, electron dumping, LEBT and steering)



Design of beam extraction and influence of space charge

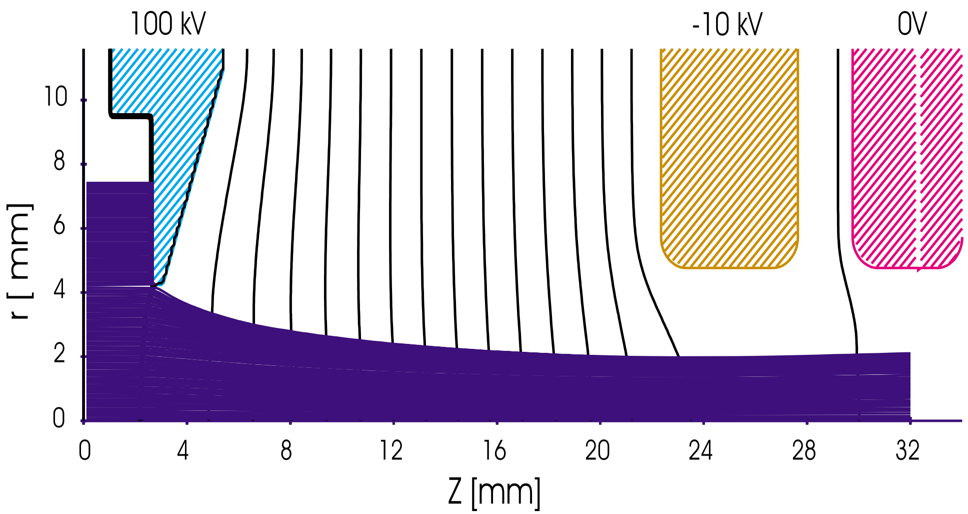


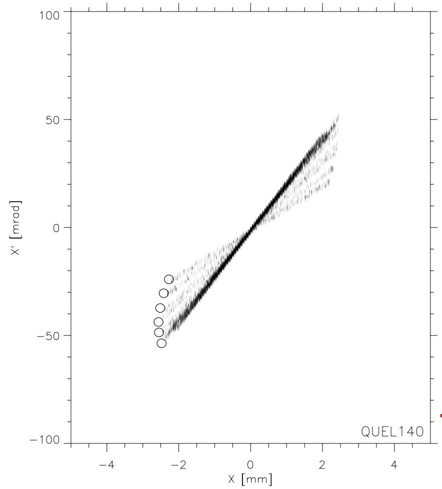


D^+,63 keV, 140 mA

r_{pl} = 4 mm, $E_{z,max}$ = 8.7kV/m

"external and internal fields unbalanced"





D^+,100 keV, 140 mA

r_{pl} = 4 mm, $E_{z,max}$ = 6.9 kV/m

"external and internal fields balanced"

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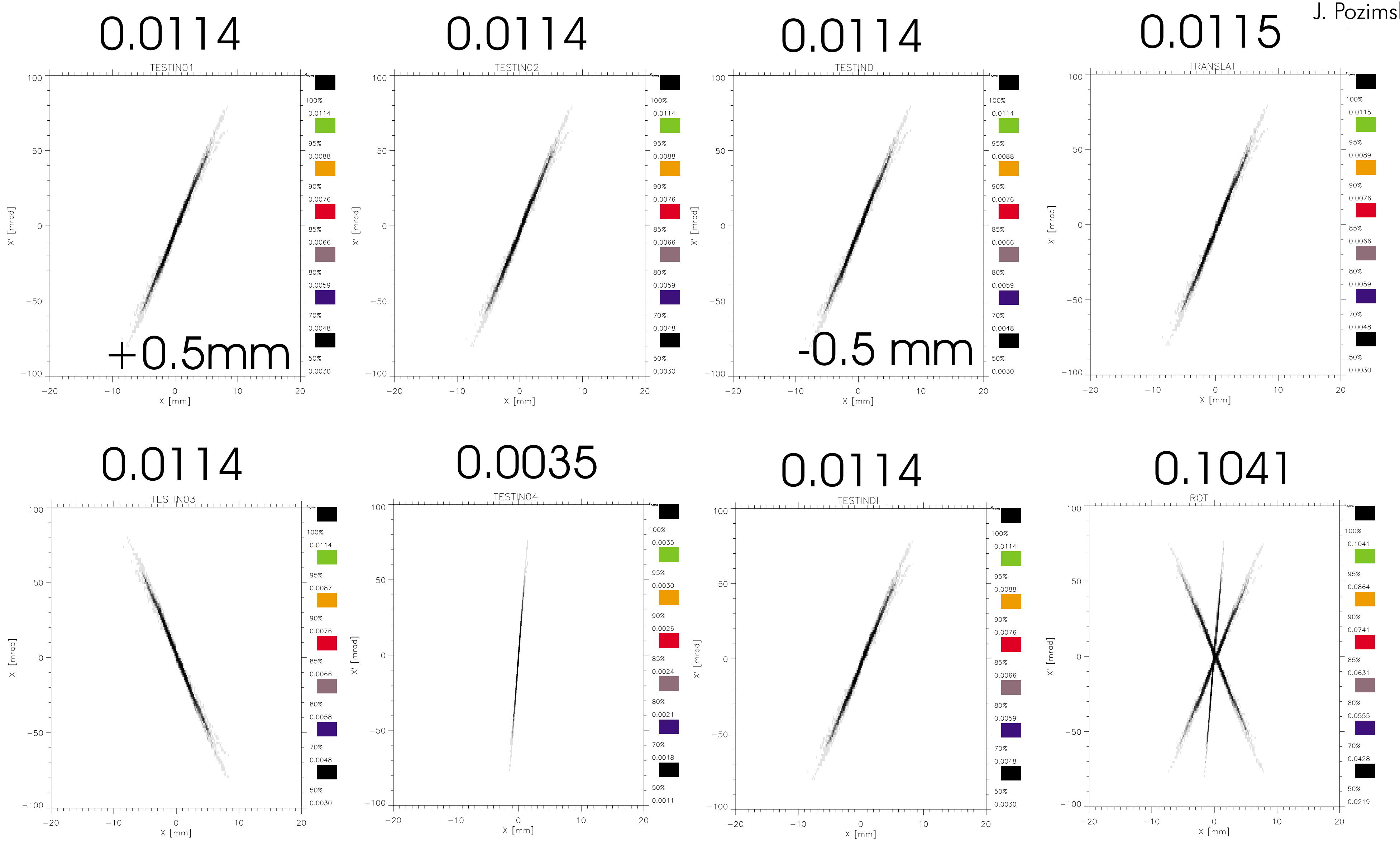
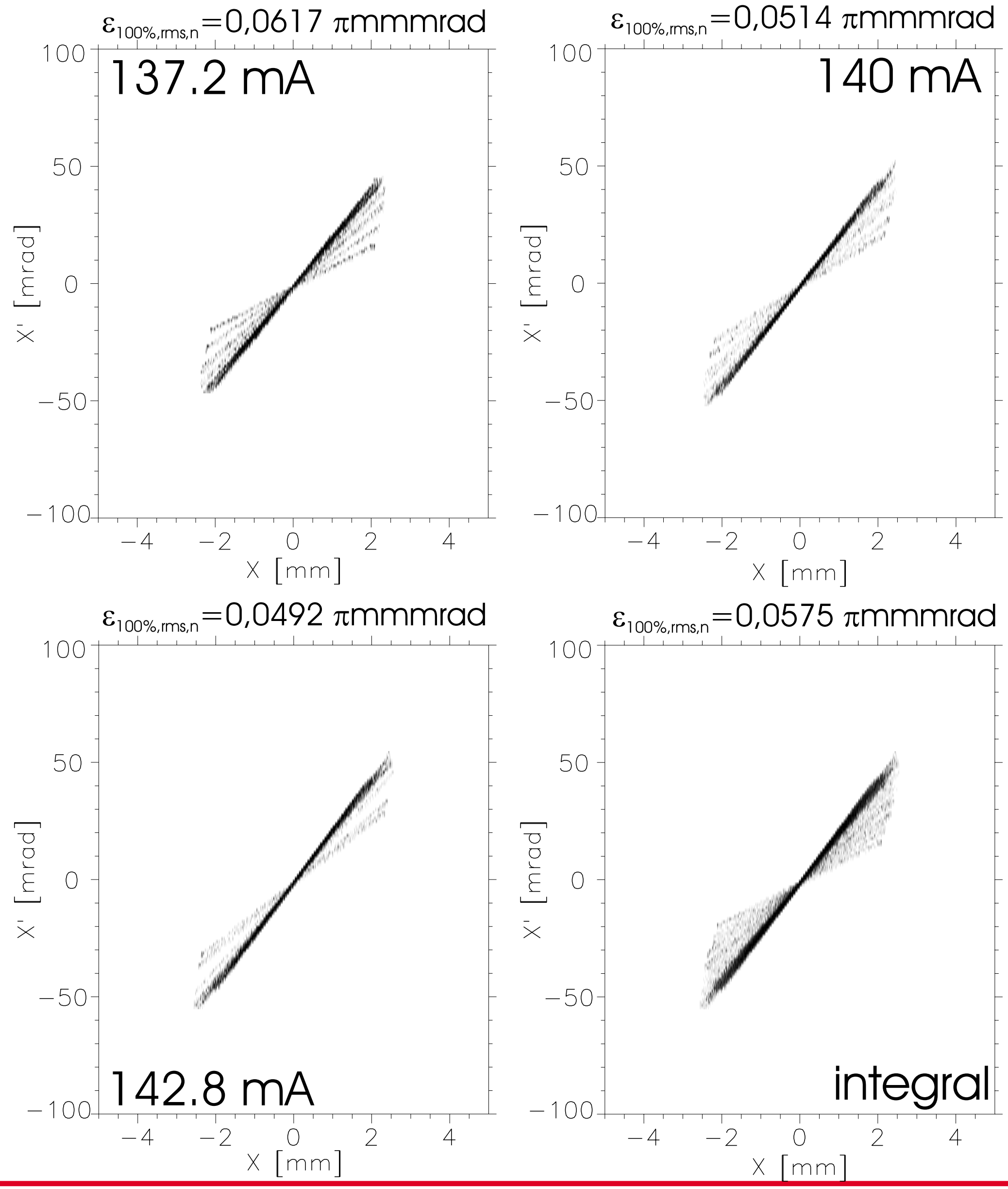
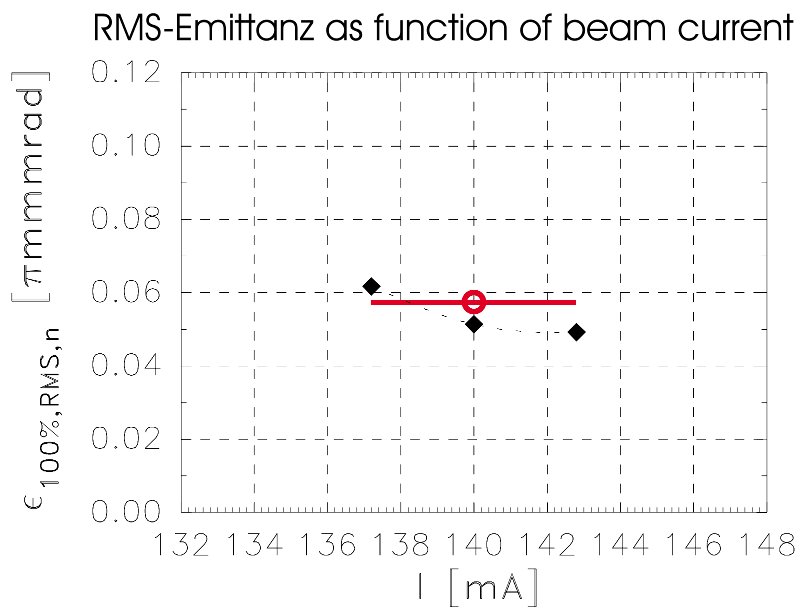
Calculation of the influence of current fluctuations by superposition of individual particle distributions



Influence of source noise on beamextraction($I_N \pm 2\%$)





For the given geometry and an estimated current fluctuation of+- 2% a variation of the RMS-emittance of 25 % was calculated The time integrated emittance is 11 % larger than the design value

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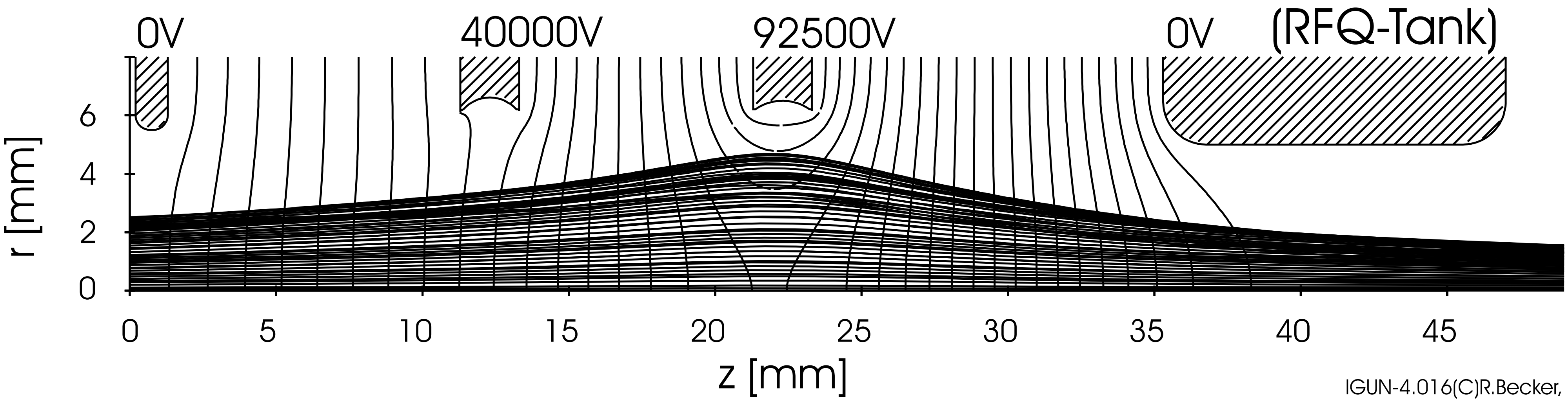
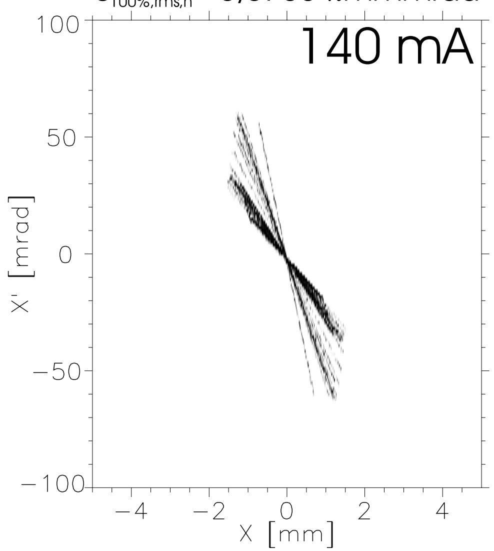
Electrostatic transport system for IFMIF (D^+ / 100 keV / 140 mA)





Design considerations
- due to space charge as short as possible (35mm)
- to prevent HV-breakdown $E_{z,max}$ <7.7 kV/mm
- beam radius at injection : 1.5 mm
- beam convergence at injection : 60 mrad
- emittance growth app. 50 %

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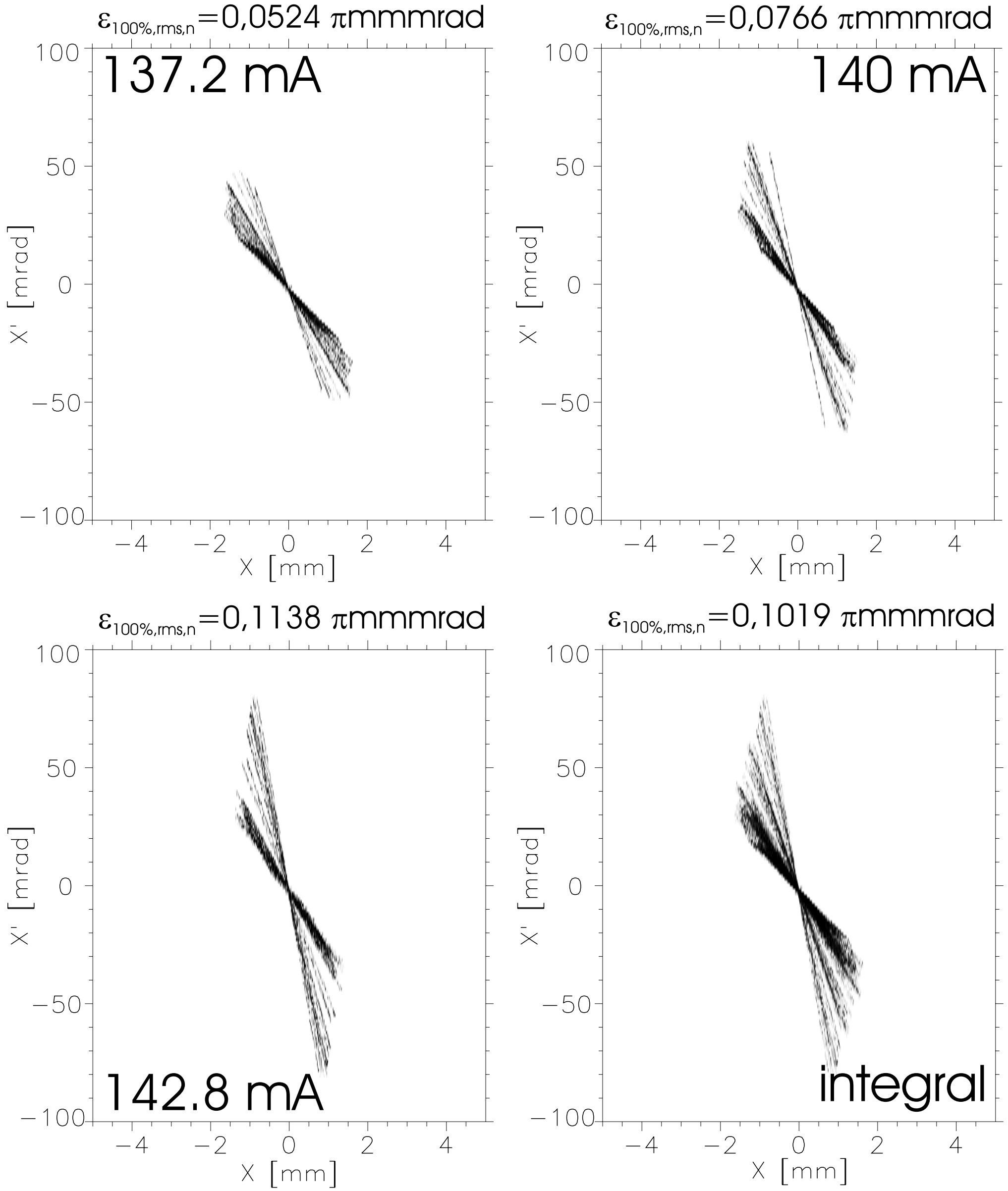
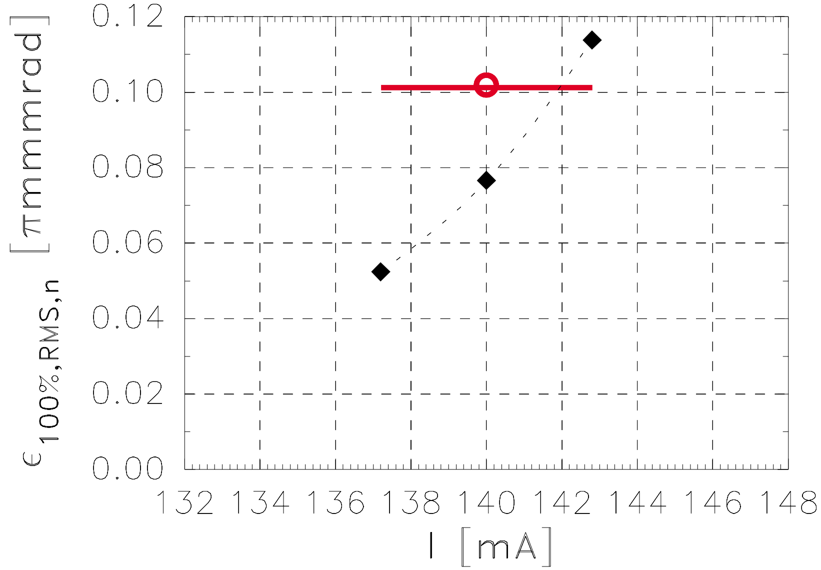
Electrostatic transport including beam current fluctuations($I_N \pm 2\%$)





For a given geometry and an estimated current fluctuation of+- 2% a variation of the RMS-emittance of 94 % was calculated (low current prefered). The time integrated emittance is 33 % larger than the design value.

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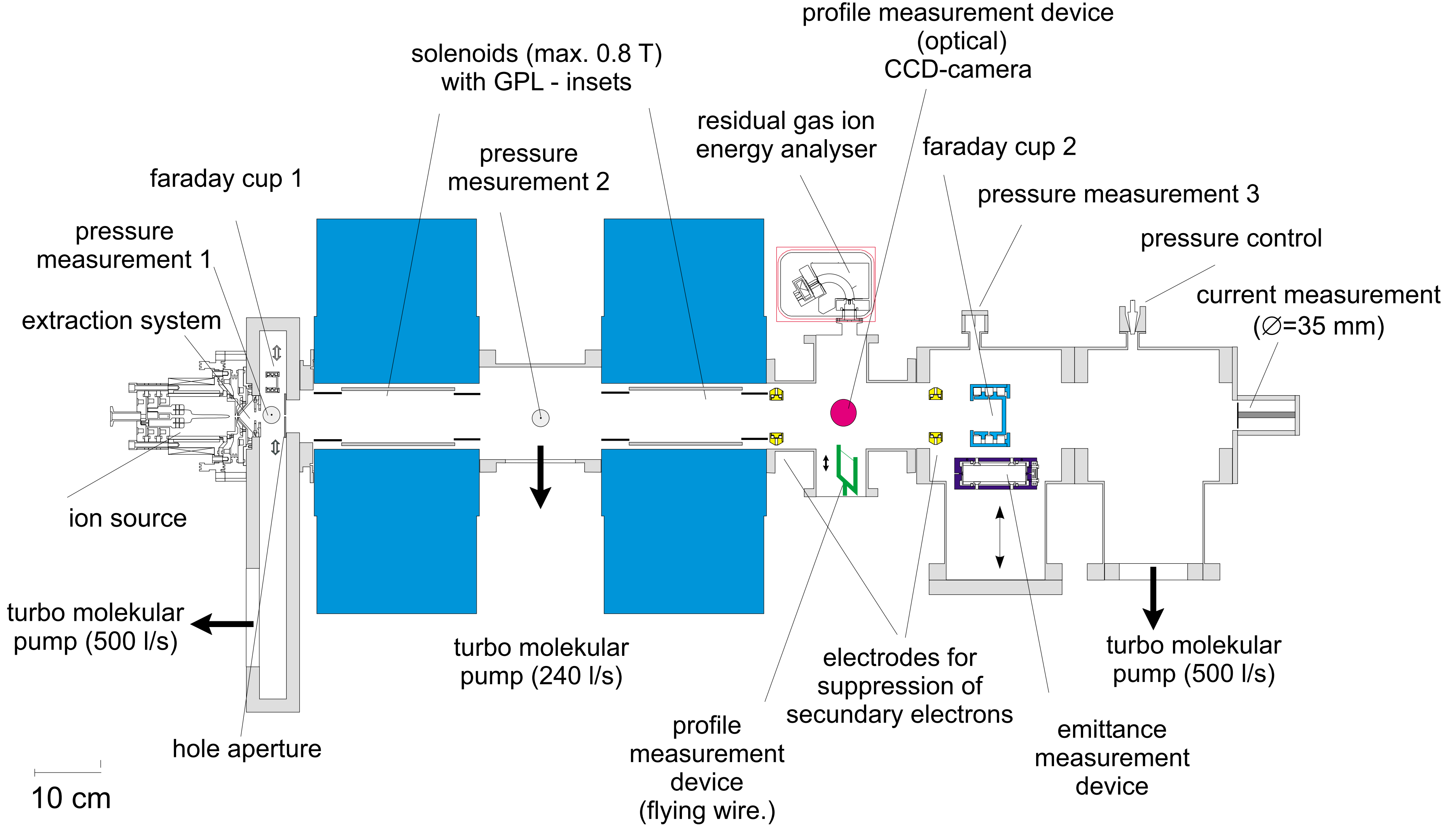
Low Energy Beam Transport (LEBT) Section Experimental set up in Frankfurt



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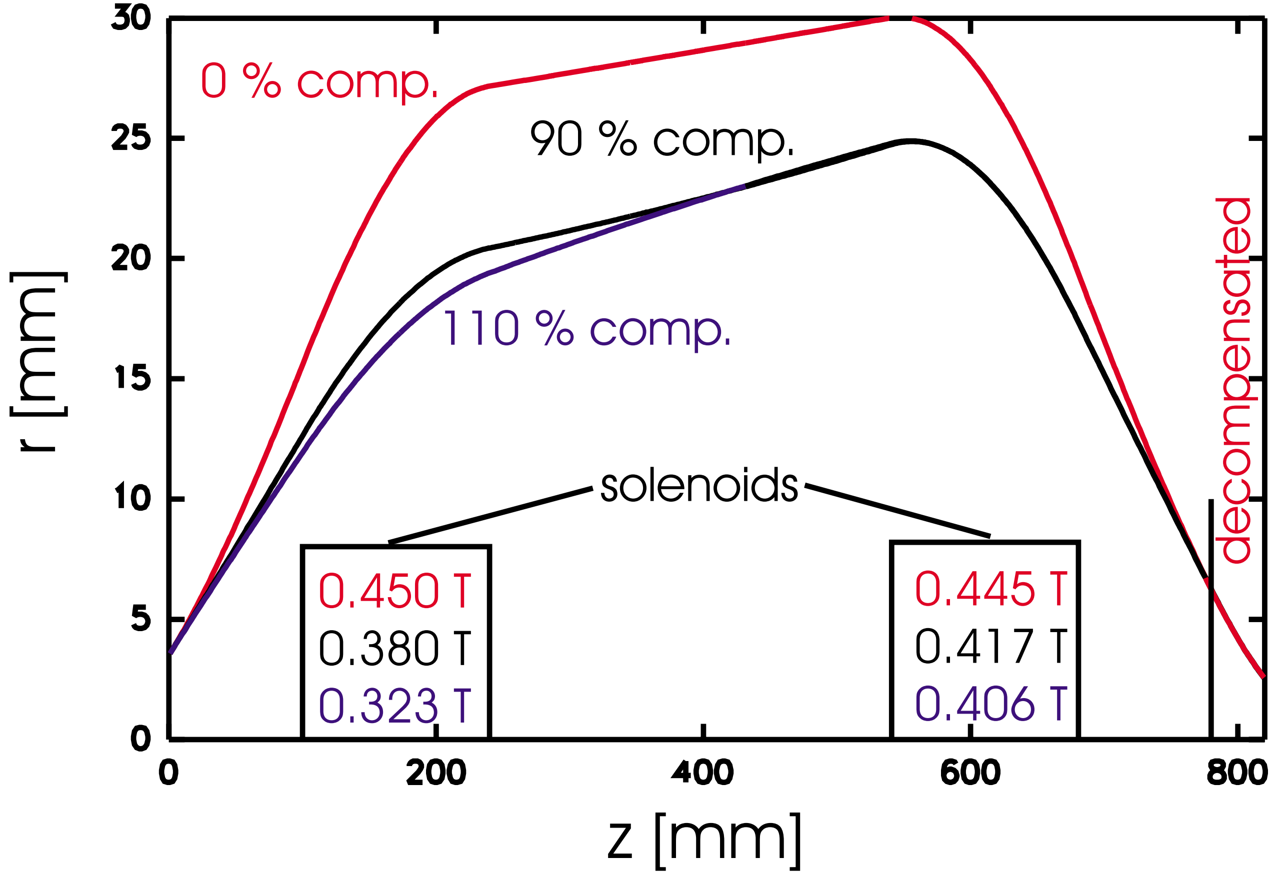
Transport calculations for the ESS LEBT
(H^-, 55 keV , 70 mA)
using the geometry of the Frankfurt set up



* even for zero space charge compensation the beam parameters for RFQ injection can be reached with only 60 % of maximum field strength and a maximum degree of lens filling (aberrations) of 60 %.

Beam transport calculation for IFMIF (D^+, 100 keV, 140 mA) using a magnetic LEBT system with two solenoids and space charge compensation for transport

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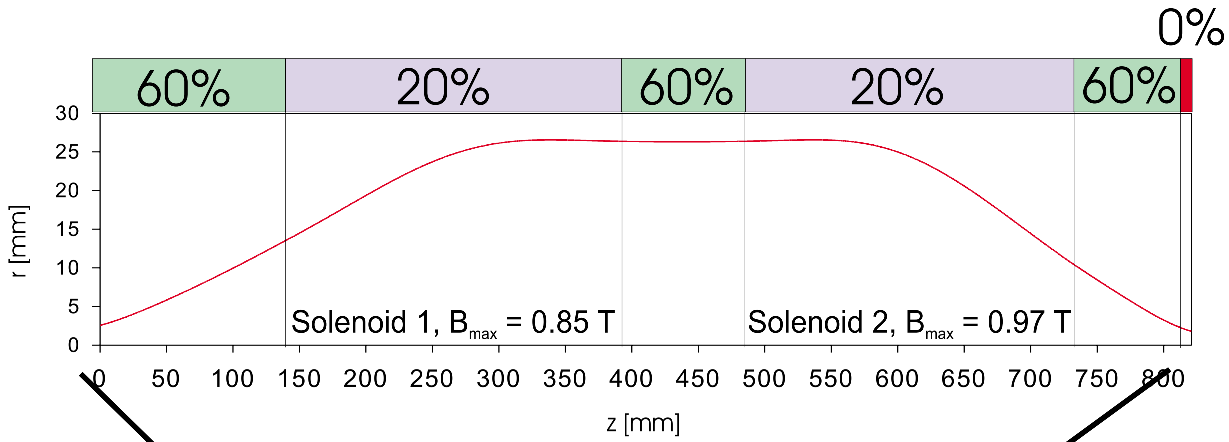
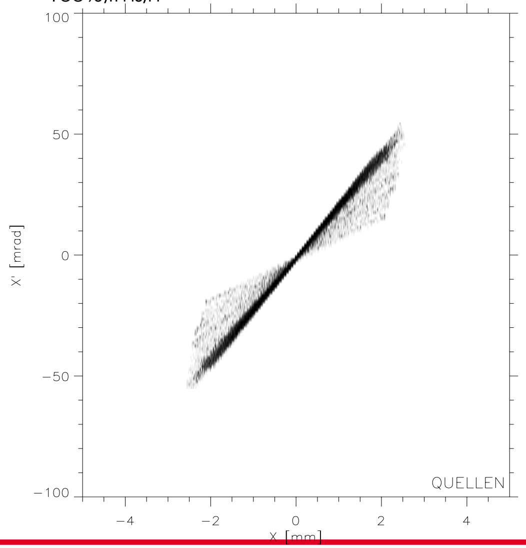


LEBT entrance

I=140 mA +/- 2%

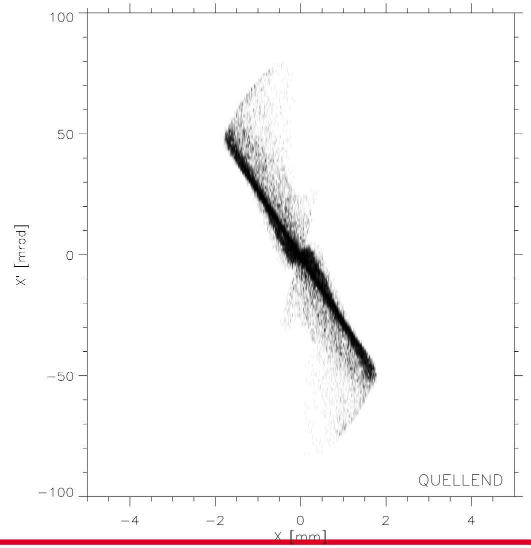
$\varepsilon_{100\%,rms,n}$=0,0575 πmmmrad



LEBT exit

I=140 mA +/- 2%

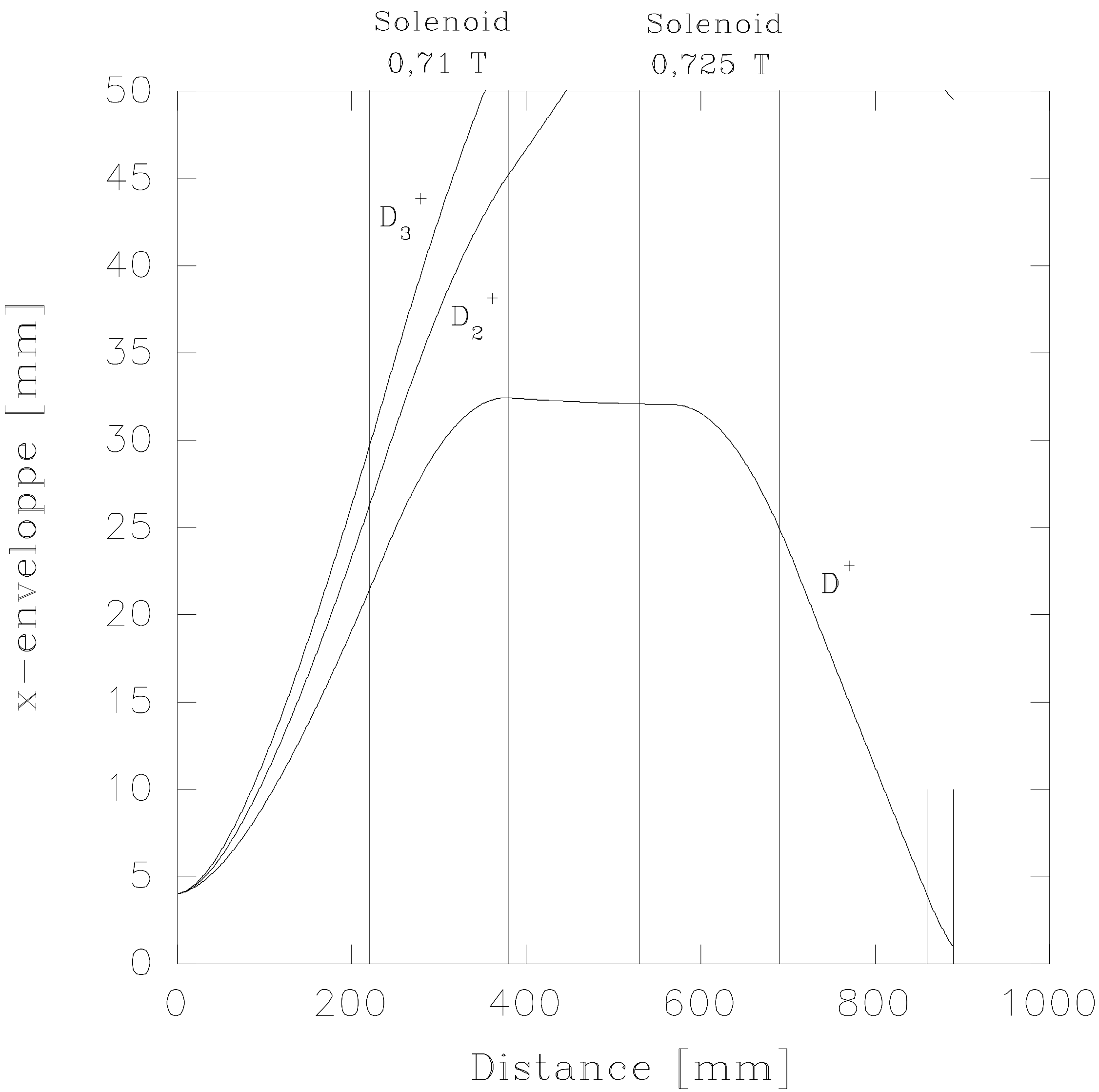
$\varepsilon_{100\%,rms,n}$=0,0817 πmmmrad



Calculations include beam current fluctuations of **+/- 2 %** at **100 kHz** and conservative estimations about the compensation degree:
In the drift sections **60 %**,
20 % inside the solenoids
and **0 %** at the RFQ entrance.
(worst case scenario!)

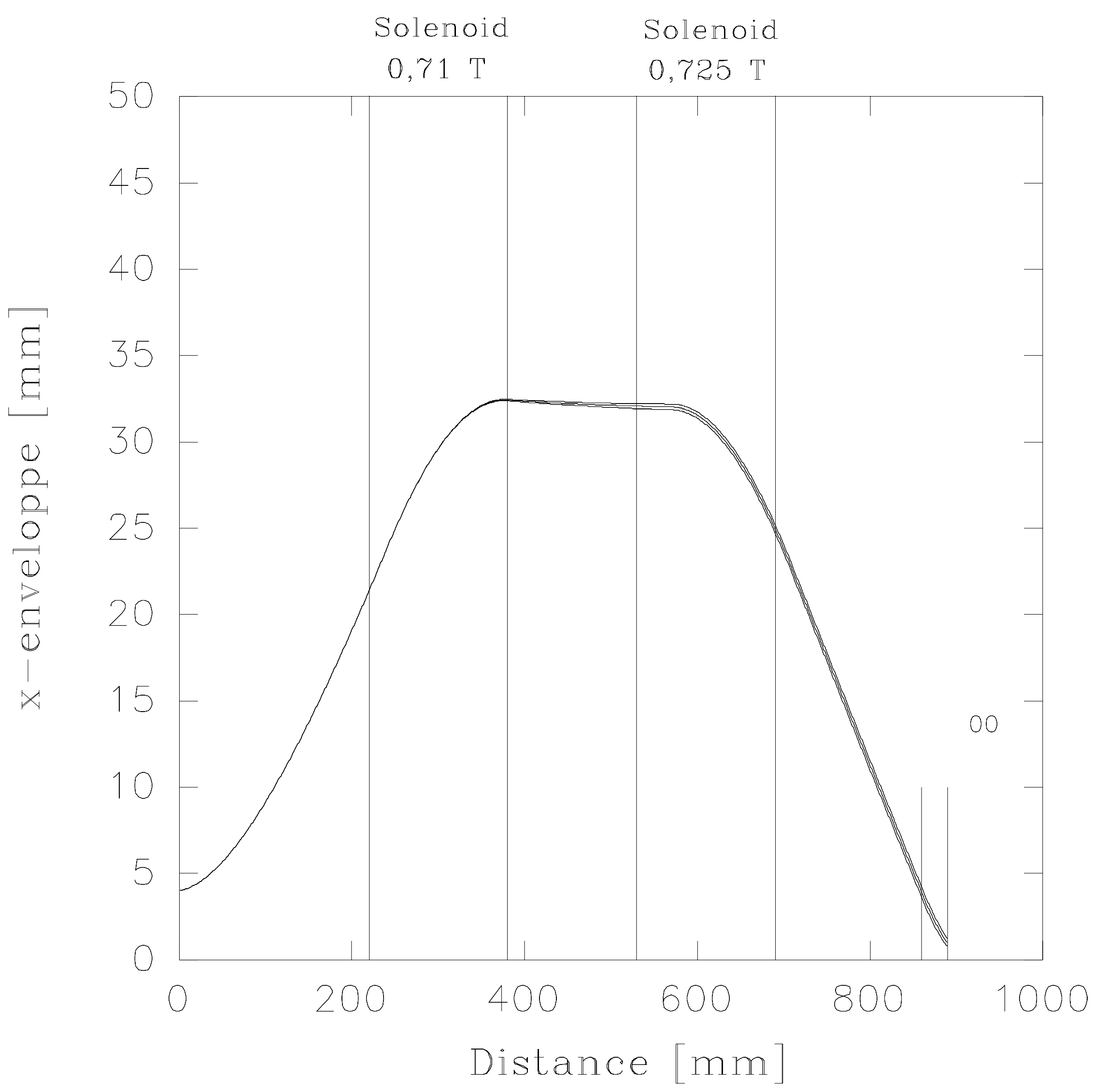
Mass seperation by use of soleniods calculated for IFMIF

Input :
$I = 140$ mA
$E = 100$ keV
$x_{in} = 4$ mm
$x'_{in} = 10$ mrad
$\varepsilon_{in} = 0.07$



Output :
D^+
$x_{out} = 1$ mm
$x'_{out} = -60$ mrad
D_2^+, D_3^+
on solenoid wall

Influence of variations of the magnetic field strength in the solenoids on injection into the RFQ (IFMIF parameters)



Output :
- -20 G
- 1.3 mm
- -67 mrad
- 0 G
- 1.0 mm
- -60 mrad
- +20 G
- 0.8 mm
- -48 mrad

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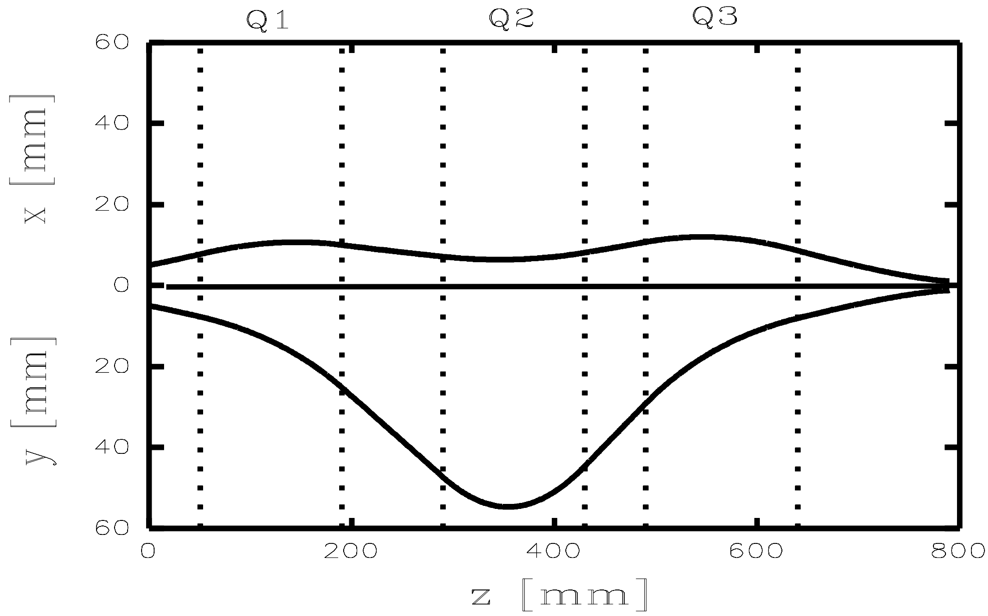
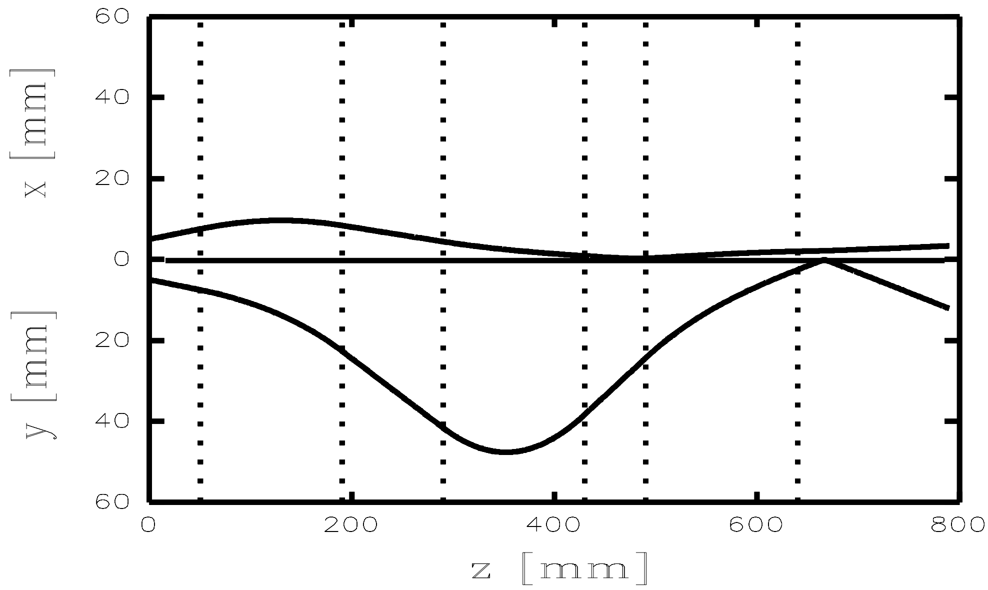
magnetic & electrostatisc LEBT consisting of quadrpol triplets for an HIDIF injector (Bi^+, 209 keV, 37 mA)

0 % space charge compensation

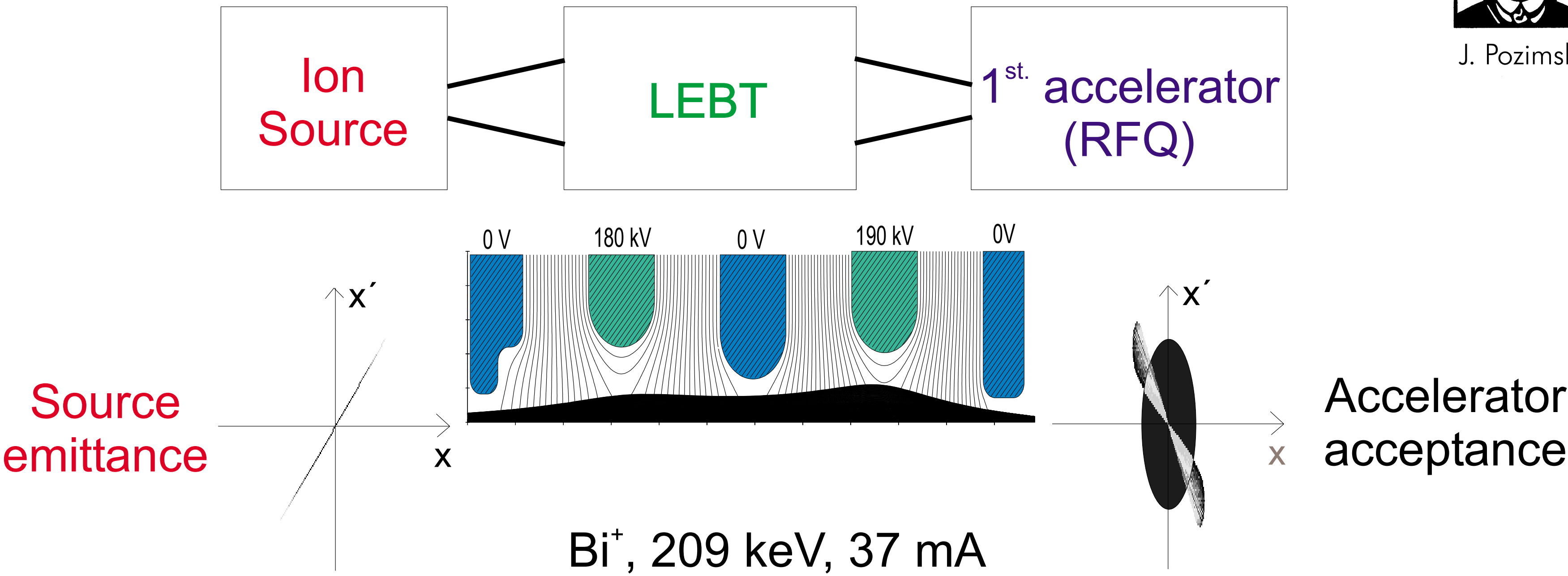
69.3	63.9	70.2	T/m
0.306	0.283	0.312	MV/m



90 % SSC (mag.)



Conclusions 1
Comparison of different LEBT sections for HIDIF



Bi^{+}, 209 keV, 37 mA

System	Number of lenses	mag. Field (T)	Electrode potential (kV)	Space charge compensation
el. einzellenses	2	----	> 190	no
el. quadrupols	3	----	> 90	no
solenoids	2	12.5	----	yes
mag. quadrupols	3	3.4	----	yes
GaborPlasma Lens	2	0.3	50	yes

Summary :

No LEBT system
(el. st. einzellenses, solenoids, quadrupols)
can fulfill simultaniously all requirements
for every beam.

my personal opinion is :

1) Electrostatic systems are in favor for
medium energy beams and
medium or low perveance
(SNS is at the borderline)

2) Solenoids are preferable for
high perveance low mass beams
(up to $A/q<20$)

3) Quadrupol LEBTS can
handle all other problems
(at higher investment costs)

4) for high masses and low charge state
other systems might be favorable
(Gabor lenses, z-pinch lenses)
for future use.