Upgrade of the HIT Injector Linac-Frontend

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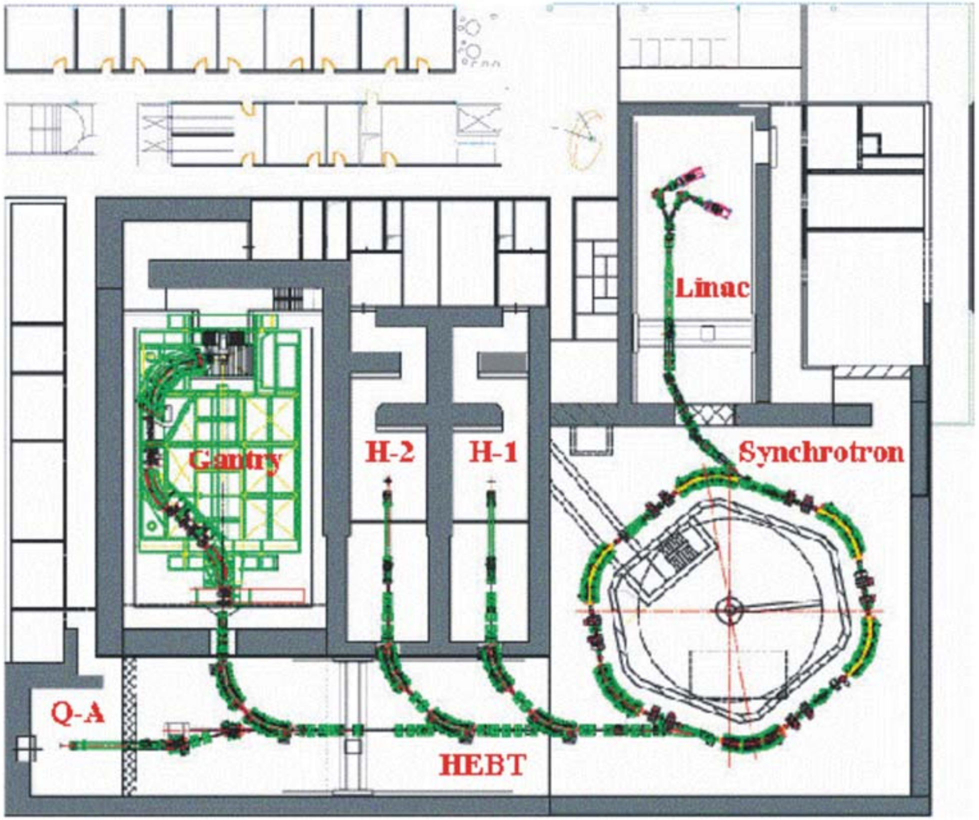
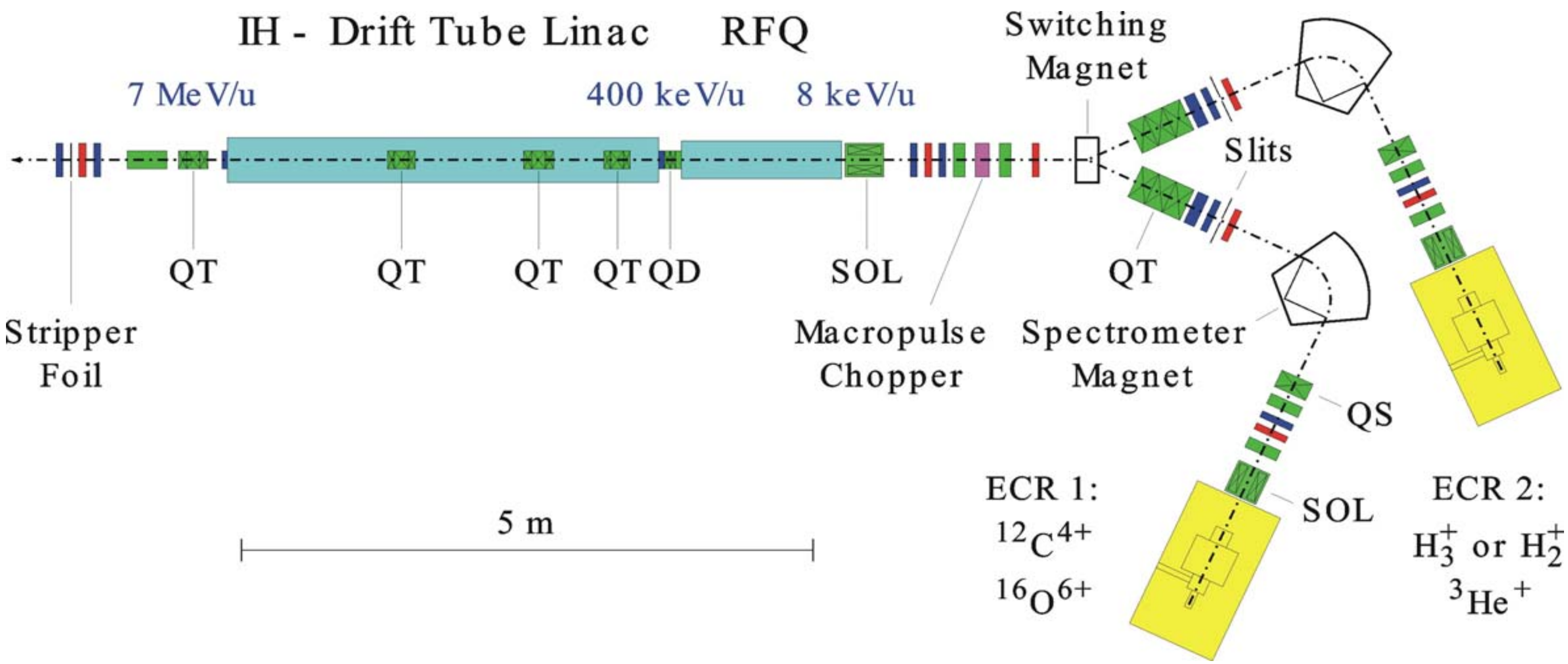
HIT - Therapy Accelerator

in Heidelberg, Germany



HIT Linac is a first one from the set of therapy projects



Introduction

HIT front-end commissioned in 2006

The carbon (C^{4+} design ion) beam transmission of the solenoid together with the RFQ is approximately 30% only

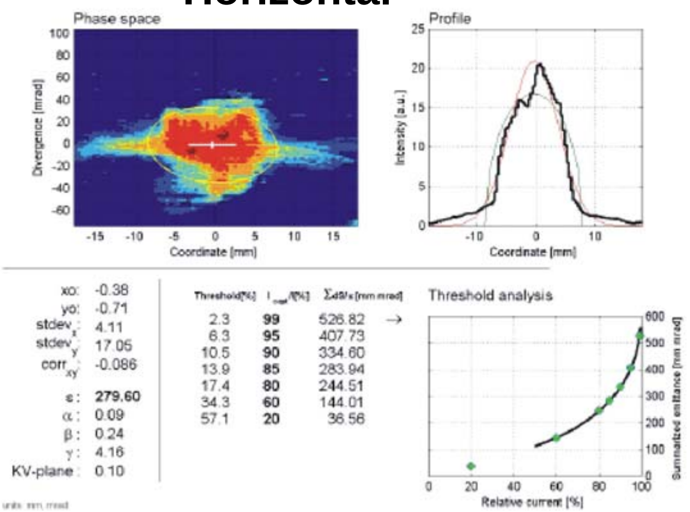
An upgrade of the HIT Linac has been started to improve the particle transmission

Possible sources of the particle losses

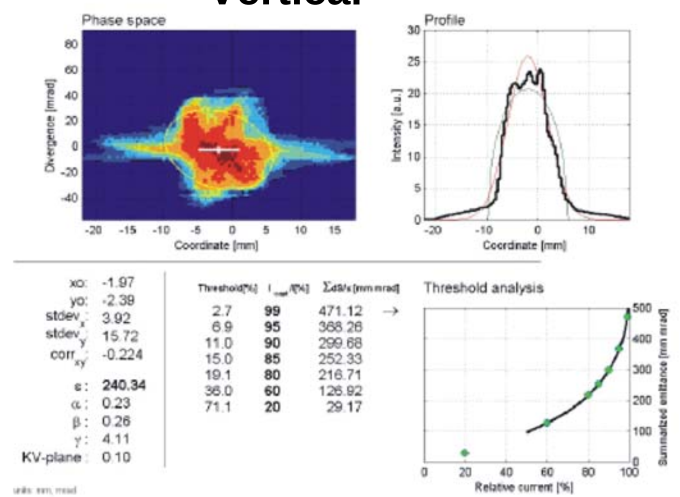
- C^{4+} beam emittance of about 300 mm*mrad (95% of intensity), twice bigger than design value (from ion source);
- non-ideal shape of the beam emittance (from ion source);
- significant dipole component of the magnetic field in the matching solenoid (old solenoid);
- misalignment of the solenoid (tilt and shift);
- misalignment of the RFQ electrodes / deformation of the tank;
- matching of the beam emittance to the RFQ acceptance;

Beam emittance measurements behind solenoid

Horizontal



Vertical



Emittance measurement device was positioned (without RFQ) about 40 cm behind RFQ entrance. Solenoid field during measurements was 45% of the design value

5000 macro-particles are generated from measured emittance data proportionally to the intensity in each bin

Dedicated procedure was developed to combine particle coordinates in the horizontal and vertical phase planes

Measured magnetic field along the solenoid

Significant dipole component !

Measurements are done along solenoid for several transverse positions:

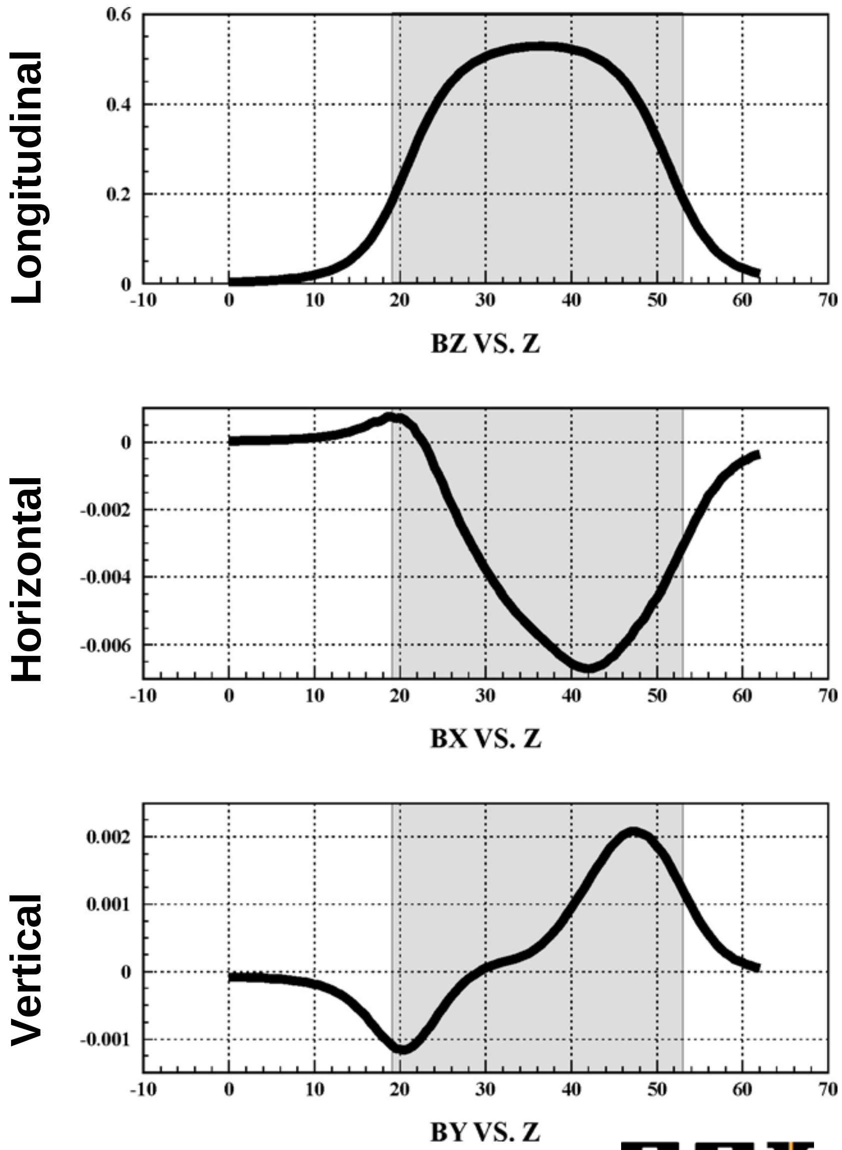
-30 mm < X < 30 mm ; Y = 0 ; dX = 10 mm

X = 0 ; -30 mm < Y < 30 mm ; dY = 10 mm

R = 30 mm; 0° < α < 360° ; dα = 10°

Aperture of the solenoid is 50 mm

Field mapping on the grid.
Relaxation scheme is realized.



Versatile multiparticle code DYNAMION

DYNAMION code

- has been written in ITEP (Moscow) for the simulations of the beam dynamics in high current linacs;

- development was strongly supported by GSI and recent improvement is going on in collaboration GSI-ITEP

DYNAMION has been implemented to the beam dynamics simulations for several projects in **ITEP** (Moscow, Russia), **INR** (Troitsk, Russia), **GSI** (Darmstadt, Germany), **CERN** (Geneva, Switzerland), **LNL-INFN** (Legnaro, Italy), **ANL** (Argonne, USA) and other leading accelerator centers.

High level of DYNAMION reliability was demonstrated by numerous comparisons of measured data and simulated results for the operating linacs in ITEP, GSI, CERN and ANL

DYNAMION code

Main features:

- time integration of **3-D equation of particle motion** in the most common form;
- **end-to-end** simulations of beam dynamics in a linac, consisting of the arbitrary sequence of the RFQs, DTLs and transport lines can be done **in one run;**
- **transport lines** may include magnetic and electrical lenses, bendings, solenoids, stripper sections, slits, steerers, ...
- electrical field in an RFQ and DTL is calculated **for the real topology**;

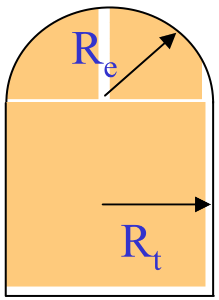
- **external** electromagnetic fields, **measured** or **simulated** by special codes;
- **multi-charged** beam;
- input particle distribution - from **measured emittance** or other calculations;
- **misalignments**.

- Detailed analysis of the results.

3-D space charge forces:

- p-p with special routine to avoid collisions;
- special treatment of continuous beam and bunching process;
- advanced solvers are recently under development in GSI and ITEP.

Description of an RFQ in DYNAMION code



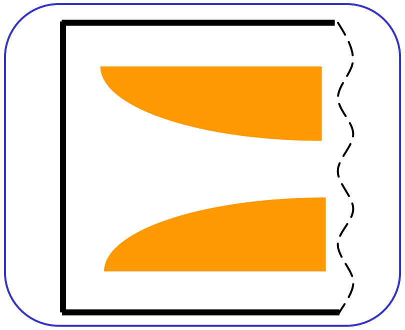
Transverse shape of an RFQ electrode

R_e - *radius of curvature*

R_t - *half-width of vane*

In the regular RFQ cell the Laplace equation for potential is solved on the grid. The area is formed by surfaces of the modulated electrodes. Field is approximated by well-known 8-term series.

Only data for machining is required for reliable beam dynamics simulations with the DYNAMION code !



RFQ Input

Radial Matcher

Laplace equation for potential is solved on the grid for real topology of the area, formed by the surfaces of electrodes/flange. Field mapping is introduced to the code.

Additional features:

- measured voltage along RFQ
- misalignments

Electric field for the integrated rebuncher section (DTL) is also calculated with an advanced algorithm (Laplace equation, real topology)

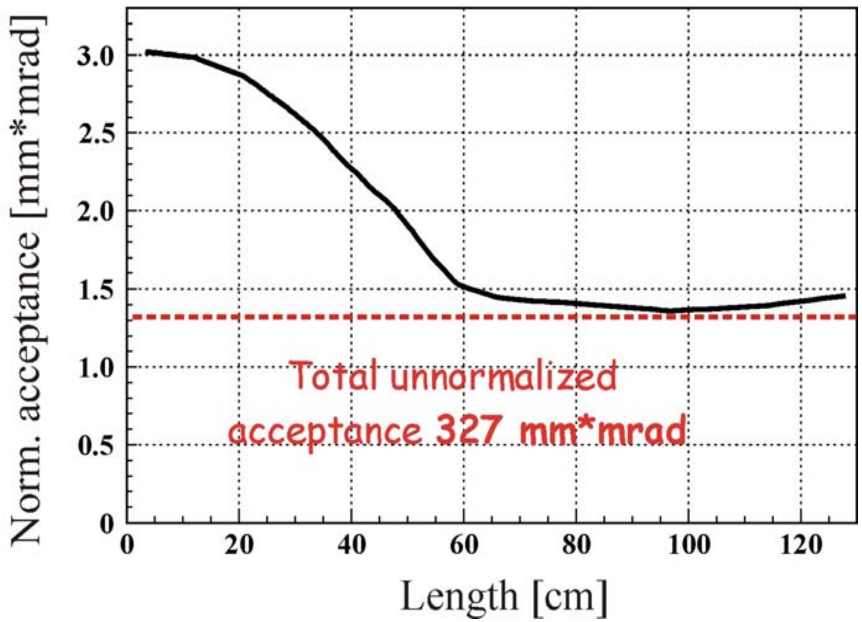
Analytical calculation of an RFQ acceptance

A normalized acceptance V_k for each RFQ cell can be calculated from the Floquet functions, which are the solution of the Mathieu-Hill equation for the particle motion:

$$V_k = \nu_f \frac{a^2}{\lambda}, \qquad \nu_f = \frac{1}{\rho^2}$$

where ρ is a module of the Floquet function, a - aperture (radius) of the cell, λ - wave length of the operating frequency; ν_f can be be treated as a minimum of the phase advance μ on the focusing period

HIT RFQ



Shape of the Input Radial Matcher ⇨ matched Twiss-parameters

Calculation of an RFQ acceptance from beam dynamics

Input particle distribution: 4D transverse "cubic"

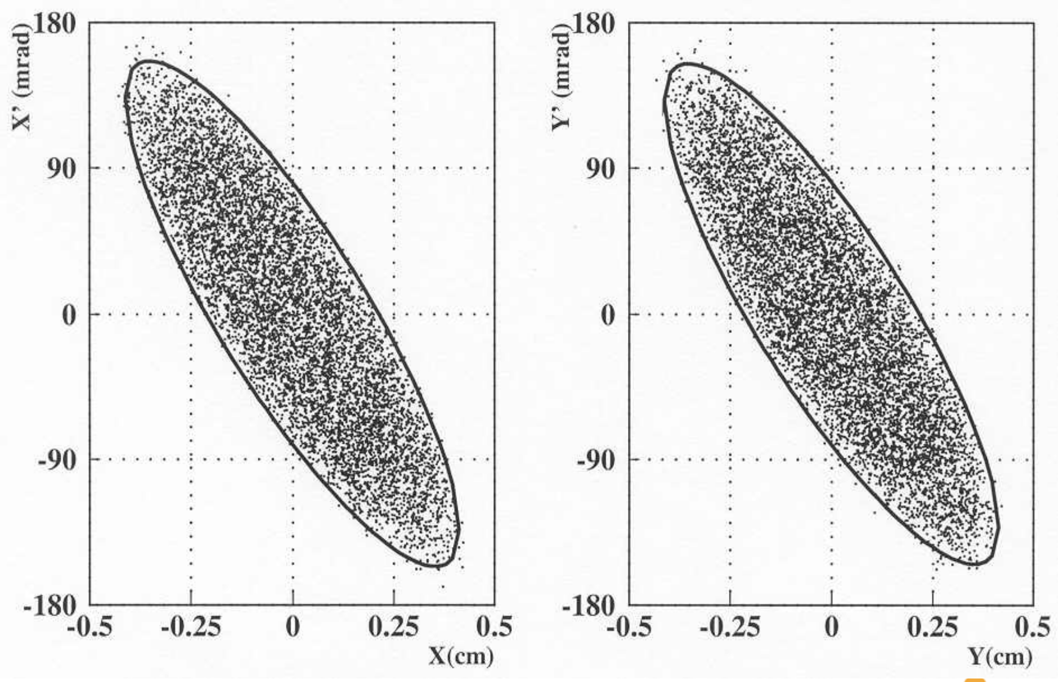
Standard way: only particles accelerated to the final RFQ energy are considered and are used for the backward beam dynamics simulations to the RFQ entrance

Smart way: in the DYNAMION code each particle has unique identification number. Particles from the input distribution are selected in accordance with the ID number of accelerated ones behind an RFQ. No backward simulations are required.

HIT RFQ

Particle coordinates at the RFQ entrance are extracted from the "cubic" distribution. All shown particles will be accelerated to the final RFQ energy.

Ellipses represent an area occupied by 99% of particles. The acceptance is 333 mm*mrad.



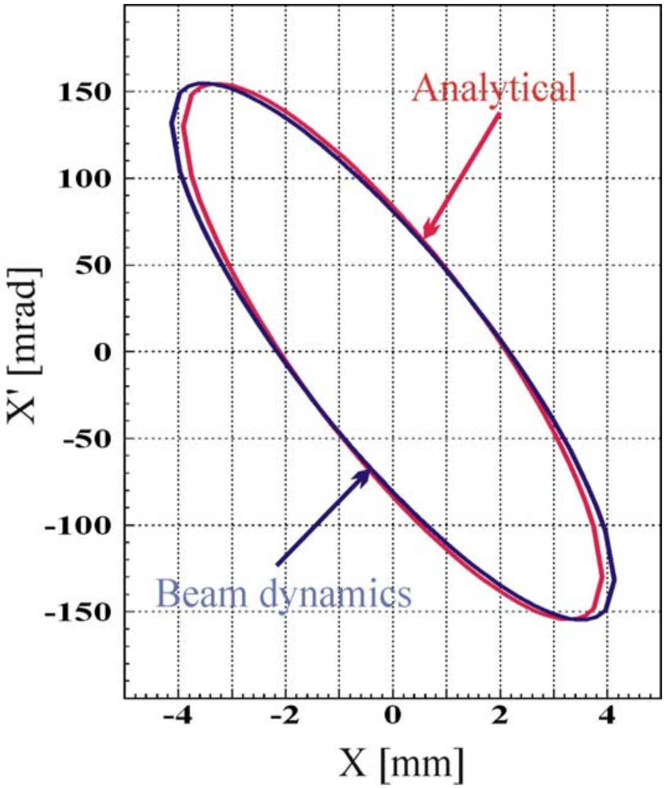
HIT RFQ acceptance

Unnormalized RFQ acceptance related to the input energy:

- 327 mm*mrad (analytical)

- 333 mm*mrad (simulated)

Perfect agreement between analytical and simulated results



RFQ itself is not a problem

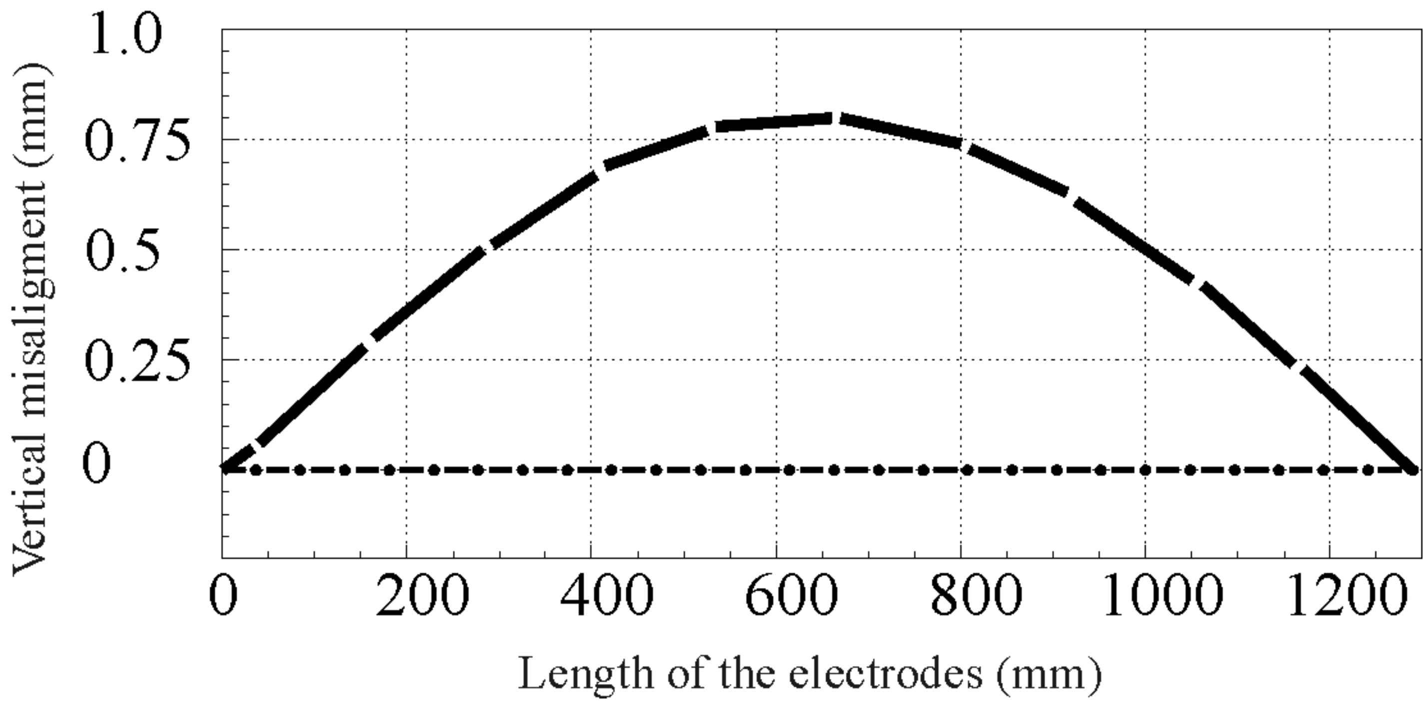
Measured emittance is about 300 mm*mrad (95% of intensity)

Why transmission is too low ? Deformation of the tank ?

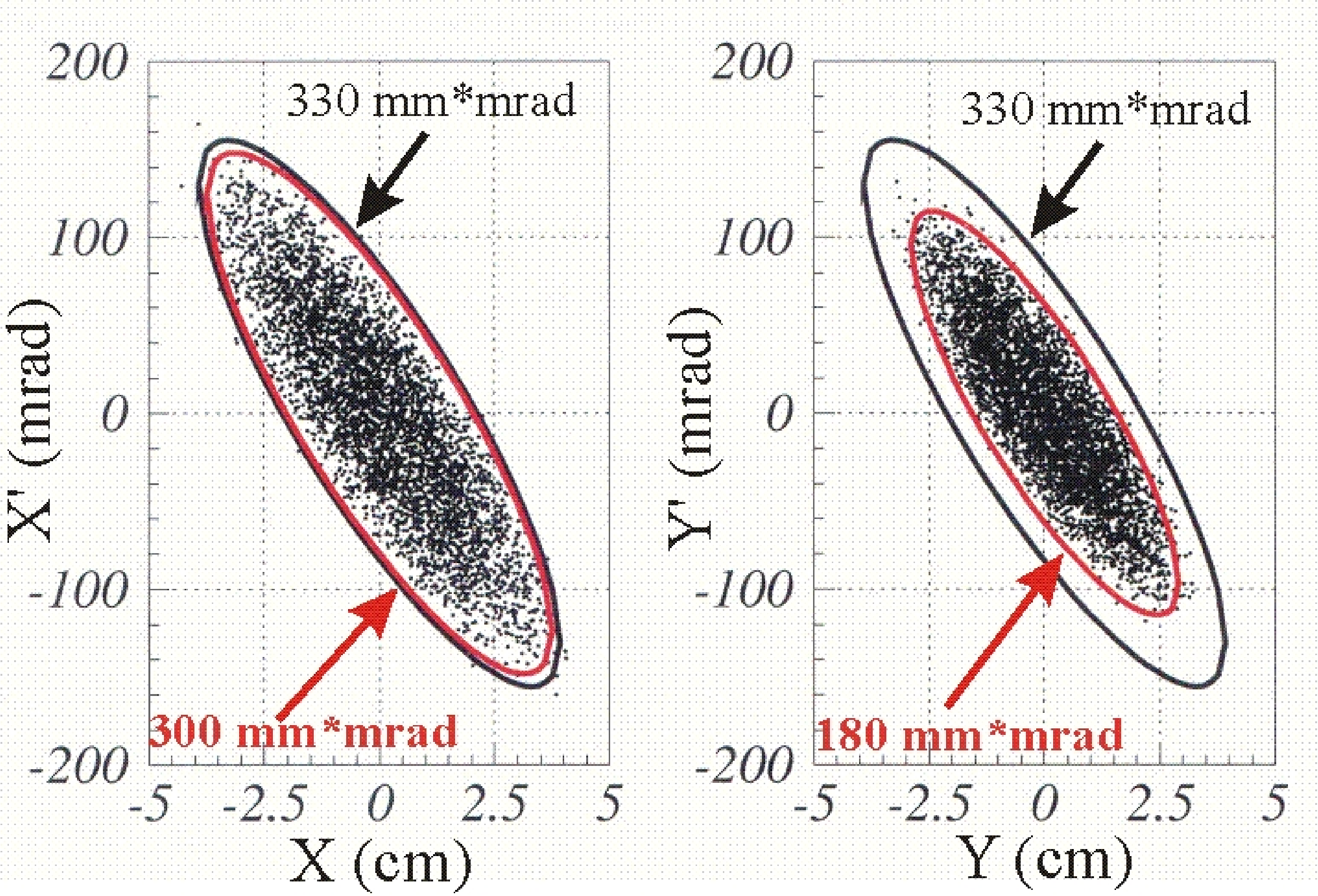
Measured deformation of the RFQ tank

$$d = 0.8\ mm * \sin(\pi z/L)$$

each part (also IRM) has its own vertical shift of the ends



Acceptance of the deformed RFQ

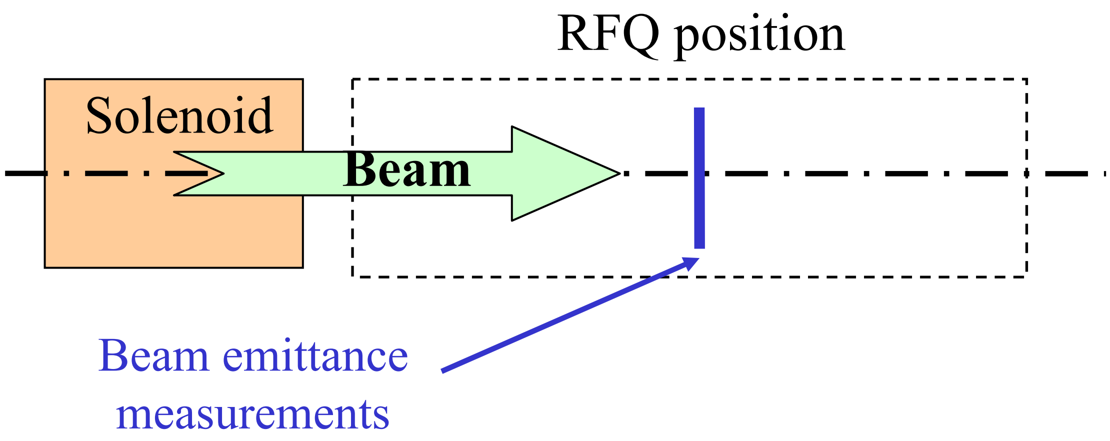


Why transmission is too low ?

Beam dynamics simulations back and forward

Measured tilt of the solenoid, included into simulations:

dx_in = -3.51 mm
dy_in = 0.65 mm
dx_out = 1.56 mm
dy_out = -0.51 mm



1) back with an amplitude of the magnetic field during emittance measurements (45% of the design value);

2) forward with design amplitude of the magnetic field;

3) simulations for the RFQ including rebuncher section;

3) small variation of the magnetic field in the solenoid for better transmission through the RFQ.

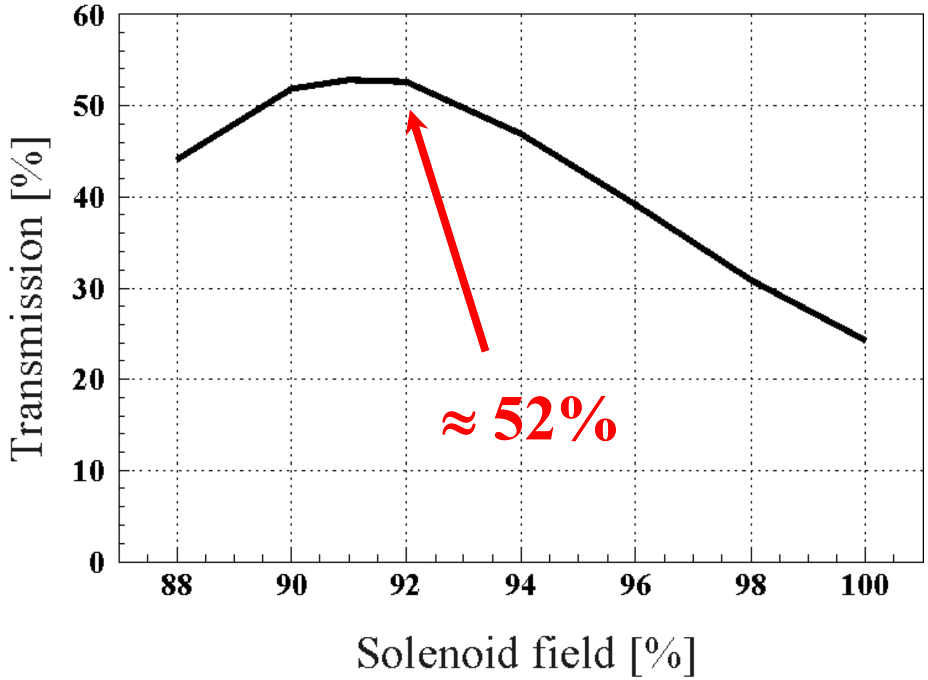
Calculated front-end transmission (I)

Realistic particle distribution based on the measurements

Measured field and tilt of the solenoid

Realistic description of the RFQ (without misalignment)

Transmission through the front-end as a function of the solenoidal field.



Transmission during design stage was expected up to 90%

May be a problem with transmission comes from the deformed field of the solenoid ?

Calculated front-end transmission (II)

Real solenoid	Ideal solenoid
Measured field distribution	Simulated with EM-Studio
Dipole component, etc ...	ideal axi-symmetrical field

Real and **tilted** solenoid + ideal RFQ
Particle transmission ≈ **52%**

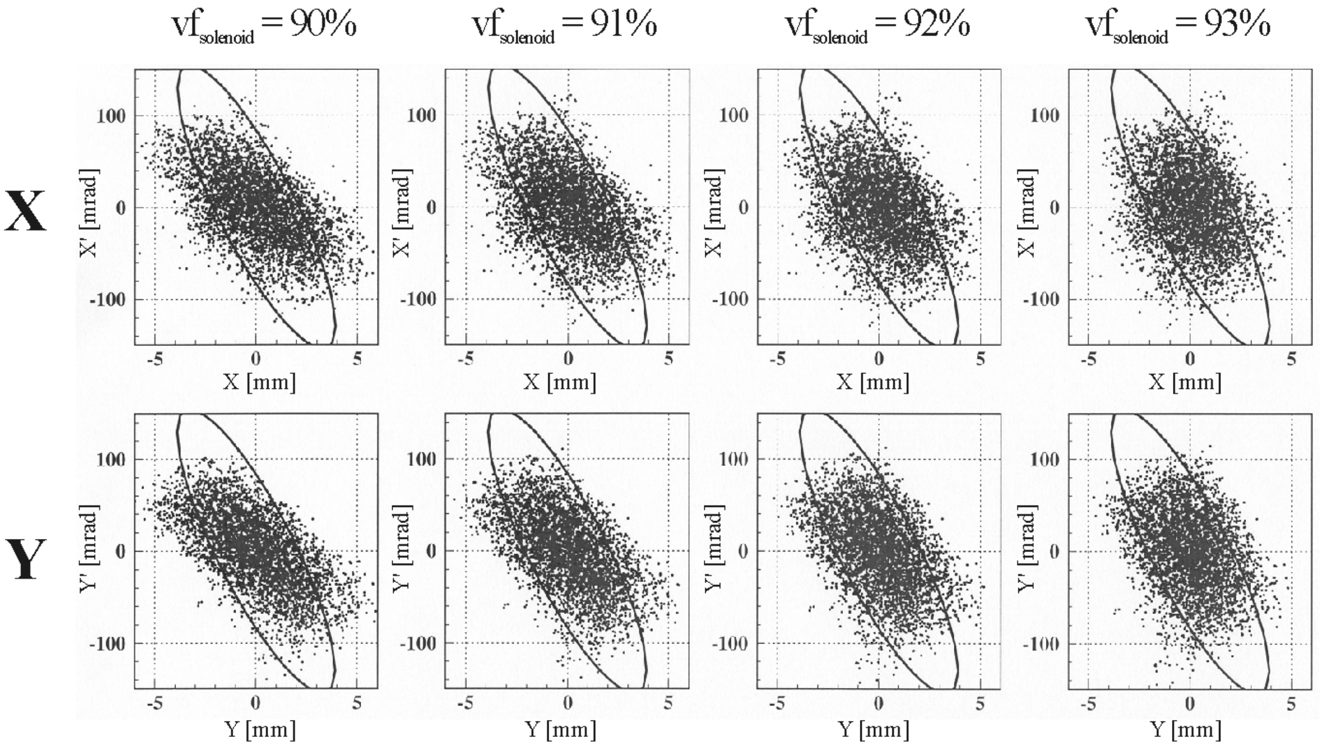
Ideal solenoid + ideal RFQ
Particle transmission ≈ **55%**

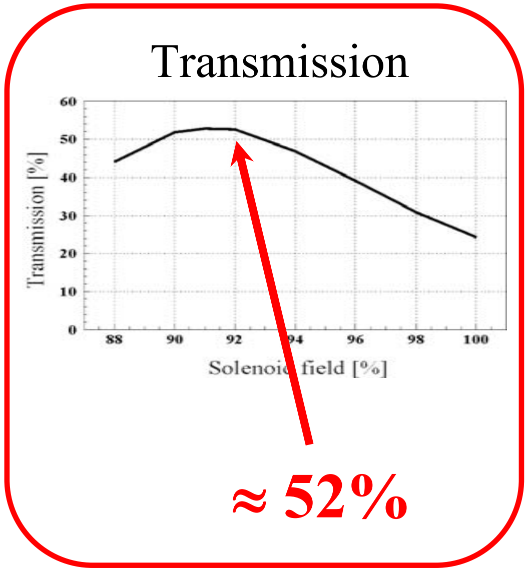
Minor difference between ideal and real tilted (!) solenoid

May be a problem with transmission comes
from the beam matching to the RFQ ?

Beam matching to the RFQ

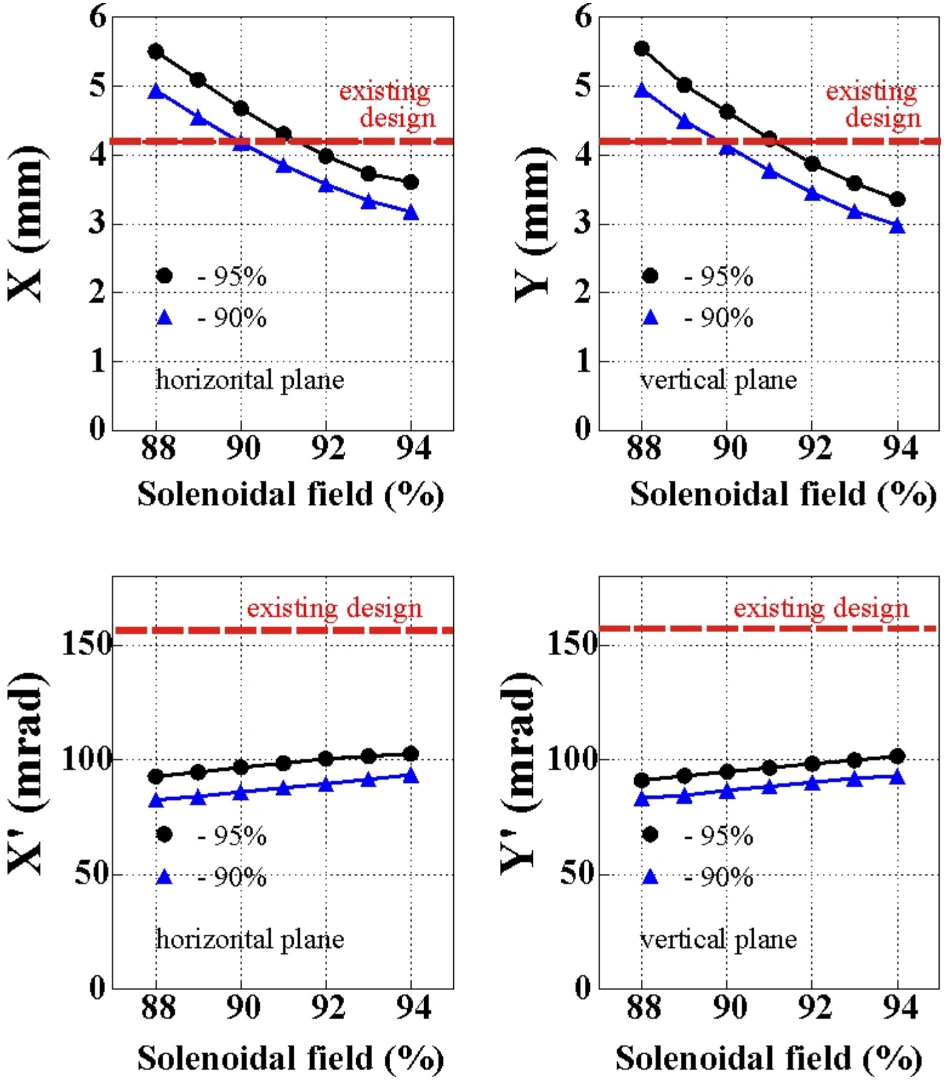
Particle distributions in horizontal and vertical phase planes at the RFQ entrance obtained with different values of the solenoidal field; ellipses represent RFQ acceptance.





Beam size and/or angle do not match to the RFQ acceptance!

Beam size and convergence at the RFQ entrance



Required matched beam size and convergence are defined by the shape of the Input Radial Matcher

Required size of the beam can be reached

Required convergence is far from the available beam parameters

In theory, the beam can be matched to the RFQ with significantly higher solenoidal field and simultaneously shorter distance Solenoid - RFQ

In reality it is not possible due to the technical reasons: field is already high; distance is already short !

The needle's eye and the camel

Recently

we can't adjust

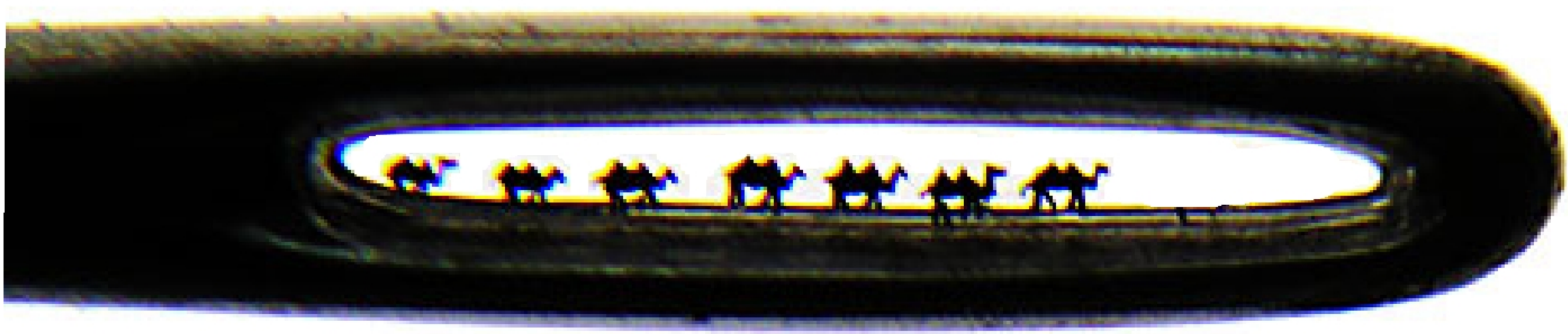
the beam emittance

to the RFQ acceptance

But we can adjust

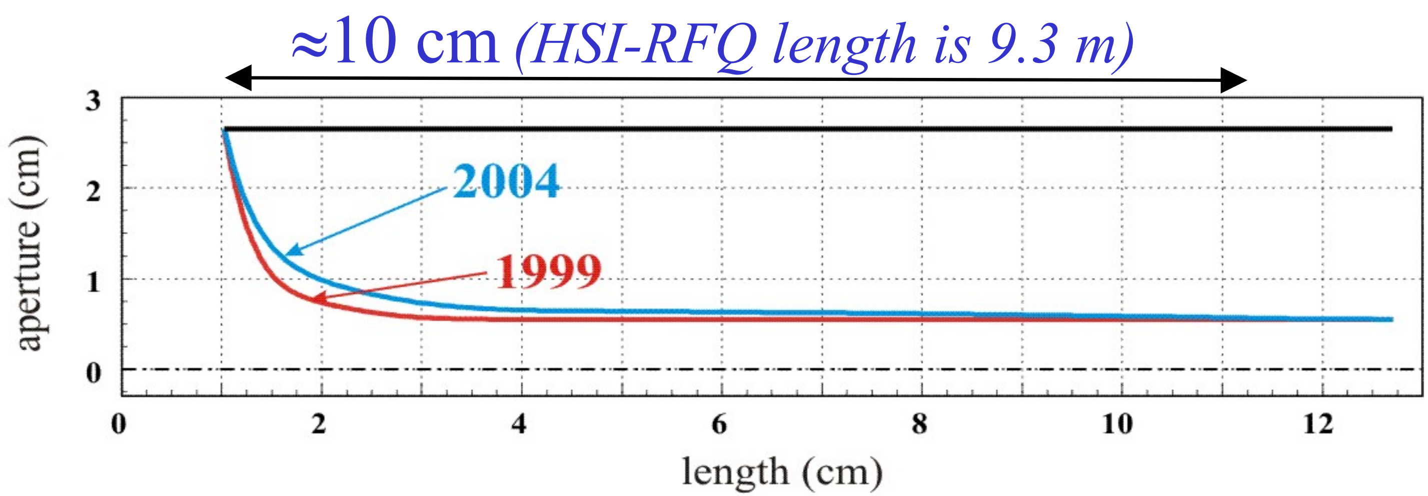
RFQ acceptance

to the beam emittance !



GSI-HSI-RFQ: the new Input Radial Matcher

Simulated results and measurements after upgrade are in a good coincidence

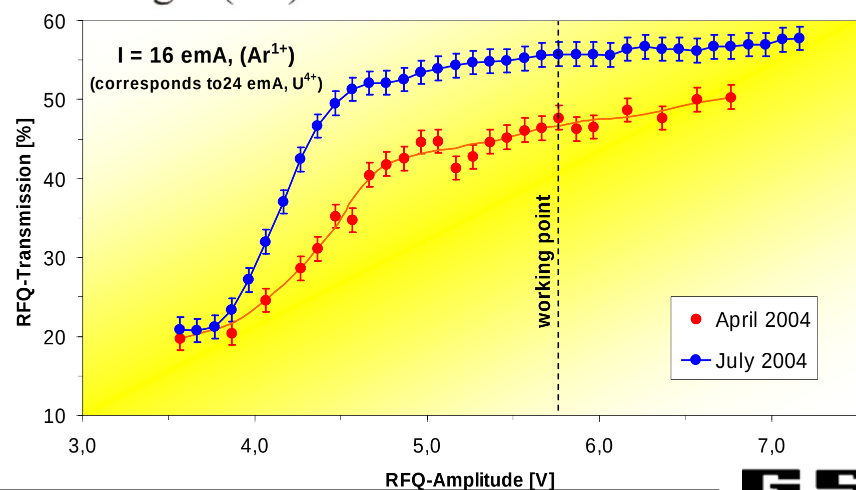


Heavy Ion

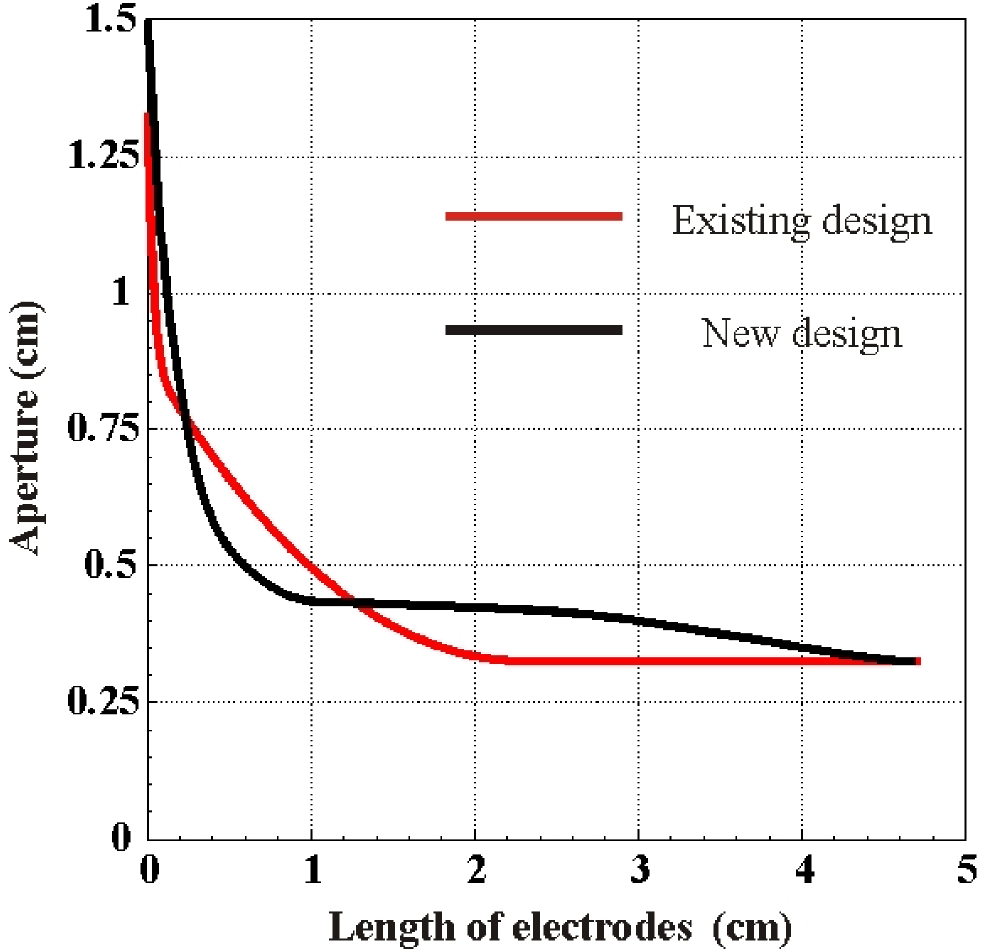
High Current

GSI-HSI-RFQ

Upgrade 2004



New shape of the HIT RFQ Input Radial Matcher (I)



- aperture was changed only at the beginning of the electrodes
(4 cm of 128 cm full length)

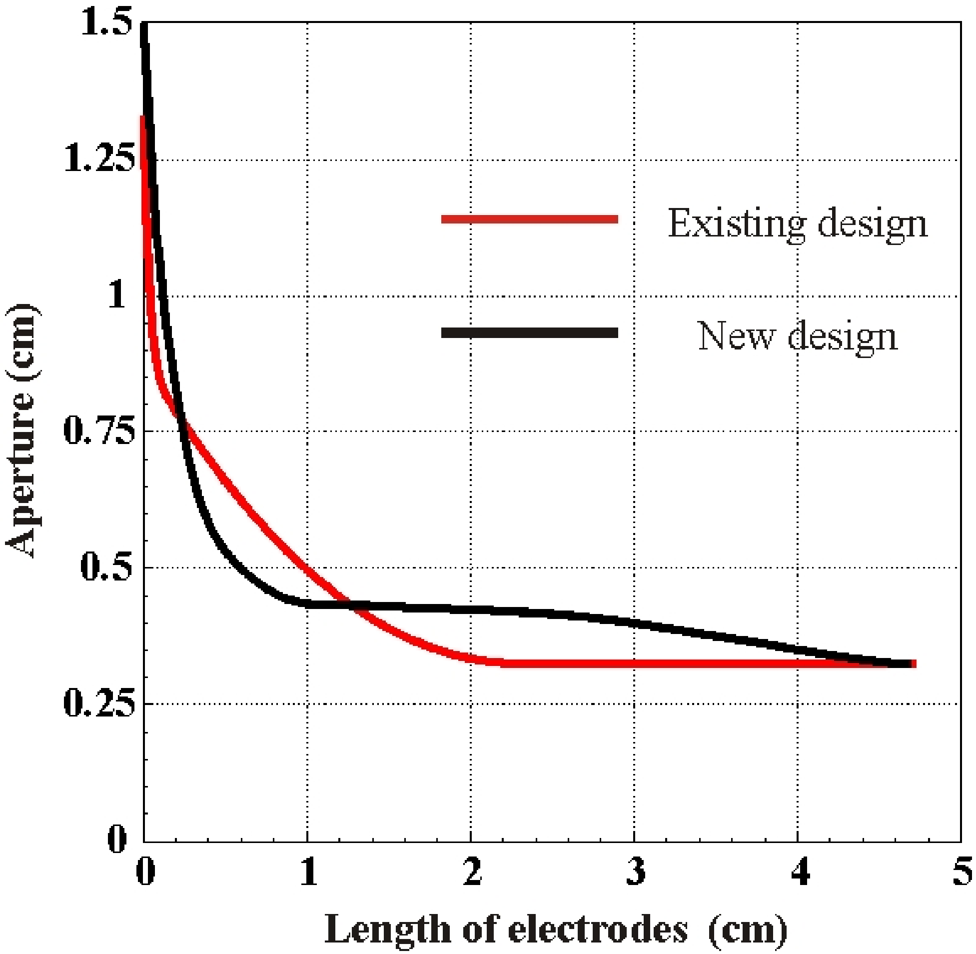
- length of the IRM is 8 cells for the recent design and 16 cells for the new one

- cells 9 ÷ 16 have modulation less than ± 2 μm

Accuracy of fabrication is several μm (or even more ?)

Is transmission higher now ?

New shape of the Input Radial Matcher (II)



The same

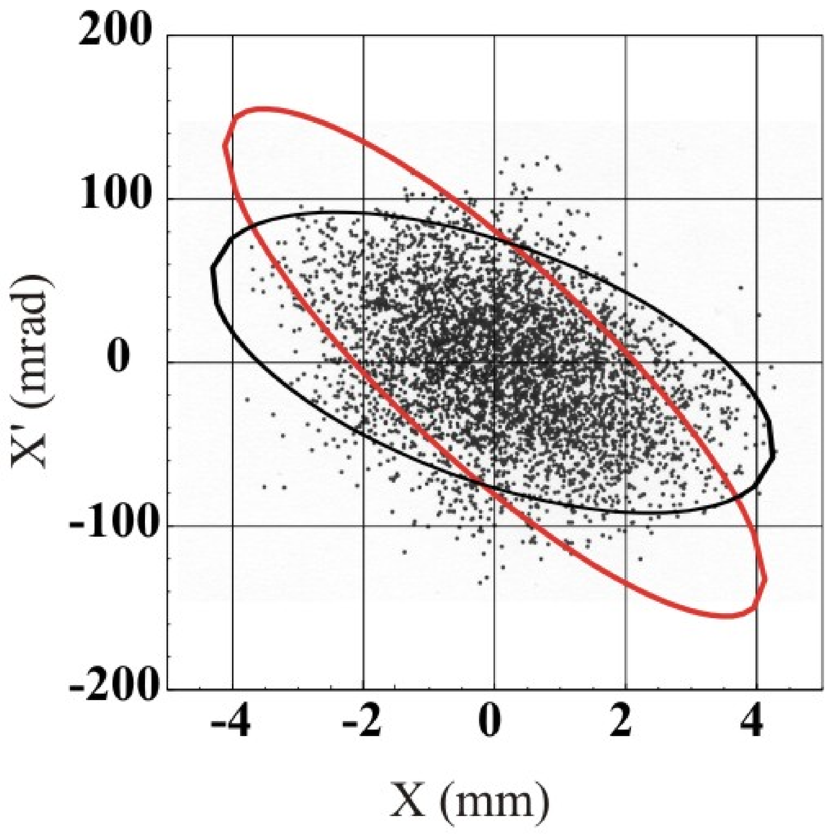
input particle distribution !

Transmission:

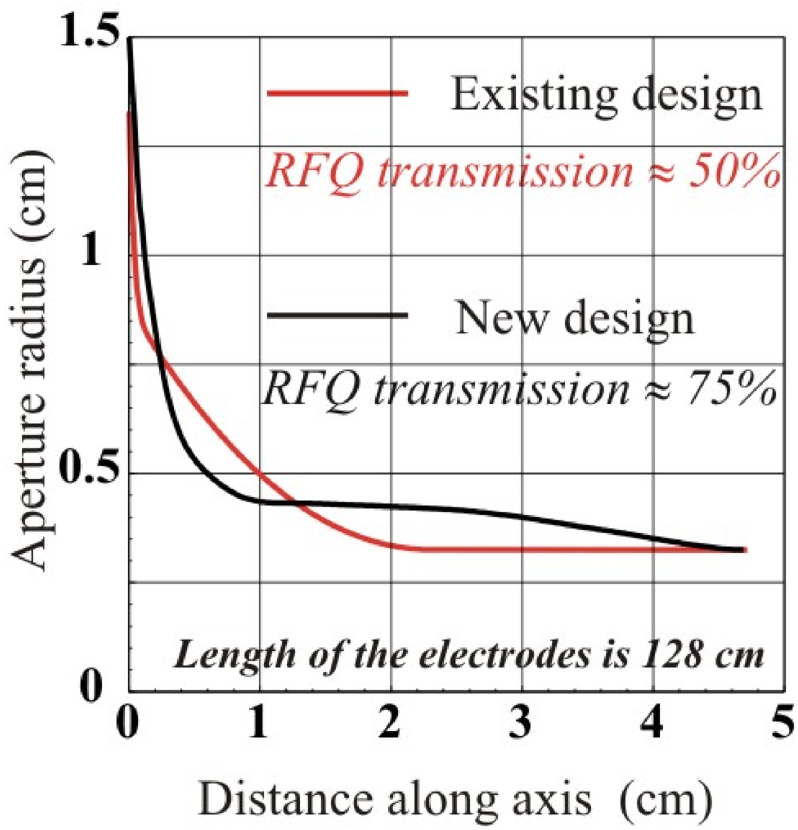
Existing design	**52%**
New design	**75%**

New shape of the Input Radial Matcher (III)

RFQ acceptance at the entrance



Shapes of the IRM



Conclusion

New shape of the RFQ Input Radial Matcher

Decreasing of the solenoidal field (≈10%)

Shift of the solenoid backwards (≈2 cm)

Calculated particle transmission
for original frontend design is 50%

Measured is 30%

Calculated for new IRM is 75%

This result may be treated as the highest possible transmission with recently available data of the emittance- and field -measurements

Recent status

Facility	IRM design	Status
HIT (old RFQ) Heidelberg, Germany	old	in operation
HIT (new RFQ)	new	under realignment and tests
Italian Hadrontherapy Center CNAO	old	under commissioning
Marburg Therapy Center Germany	new	under commissioning

Piero Antonio Posocco

next presentation

(different performance of the ion source)

New advanced design of the Input Radial Matcher is realized for the second generation of the RFQs

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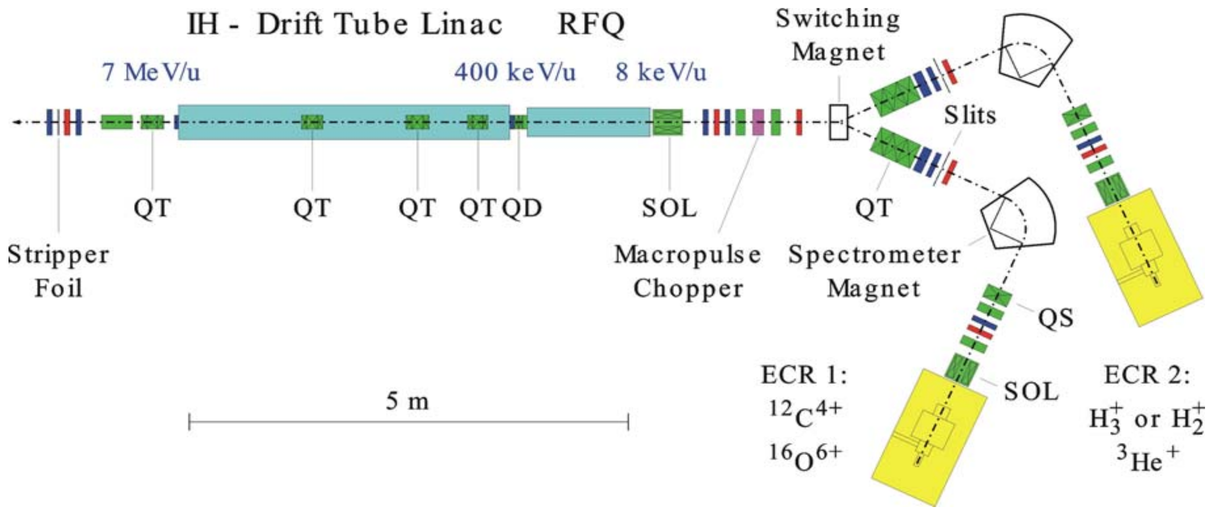
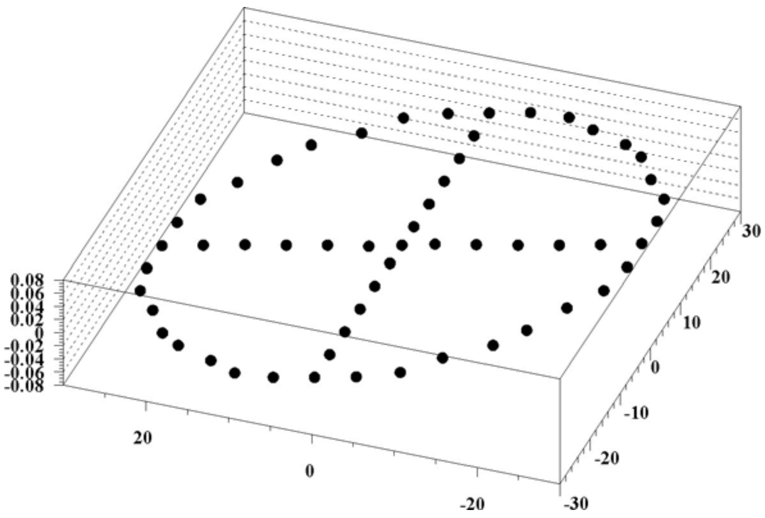
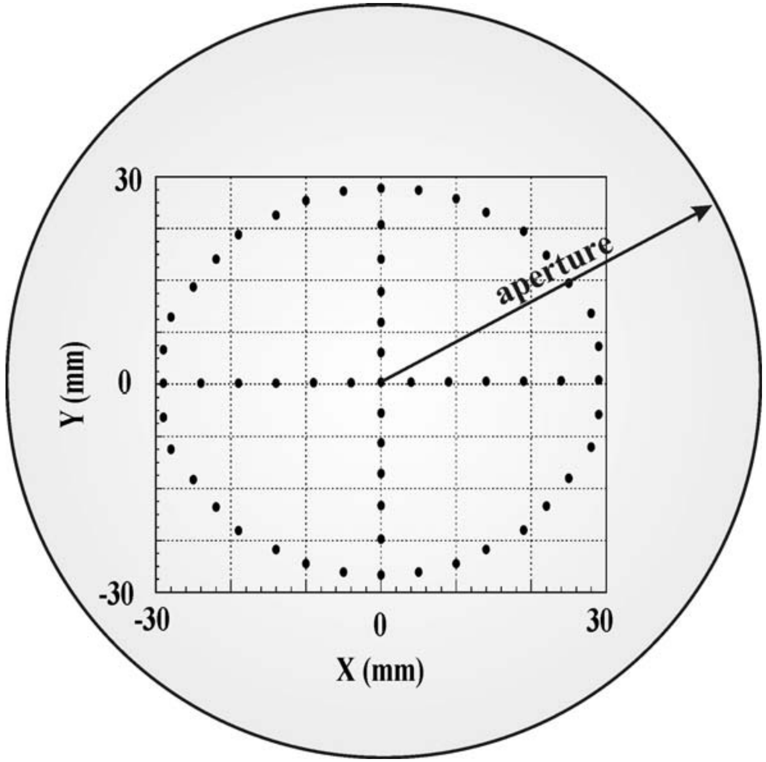


Solenoid: field measurements and 3D mapping

Transverse component of the magnetic field B_x in the given crossection



Positions of the field measurements for the given crossection



Field mapping on the grid (1 mm x 1 mm)
Relaxation scheme is realized

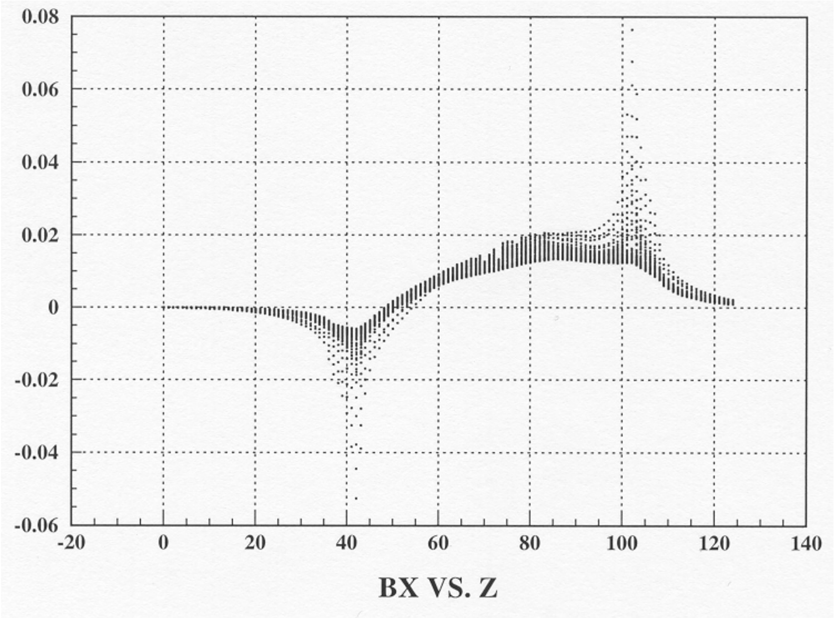
Measured only up to radius of 3 cm

Aperture radius is 5 cm

3D field mapping of the solenoid

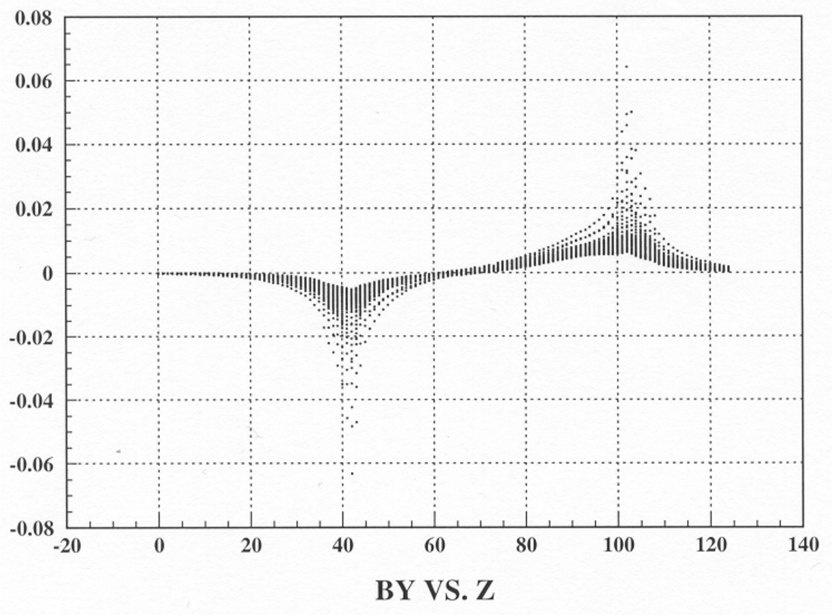
Horizontal component of the magnetic field B_x along solenoid

X = 0
-50 mm < Y < 50 mm



Vertical component of the magnetic field B_y along solenoid

Y = 0
-50 mm < X < 50 mm



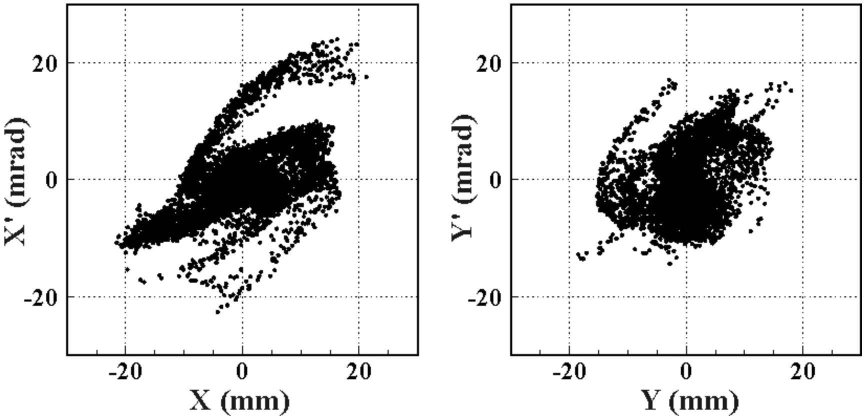
For ideal field distribution $B_{x\ (x=0)}$ and $B_{y\ (y=0)}$ have to be zero !

Status of emittance measurements before and behind solenoid

2006 - 2007

EMITTANCE MEASUREMENTS

only beam current 100 mkA !



The particle distribution generated from the emittance measurements before the solenoid in the HIT linac LEBT

NEW

S O L E N O I D

OLD

EMITTANCE MEASUREMENTS

carbon beam current

→ 100 mkA

→ 150 mkA

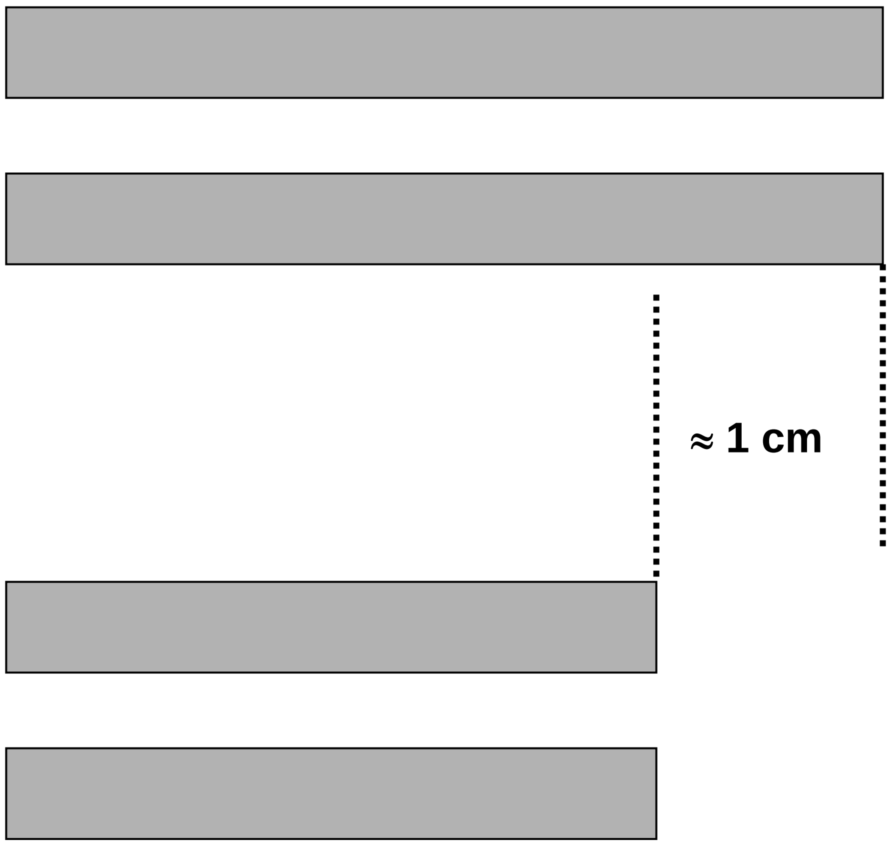
→ 200 mkA

Conclusion

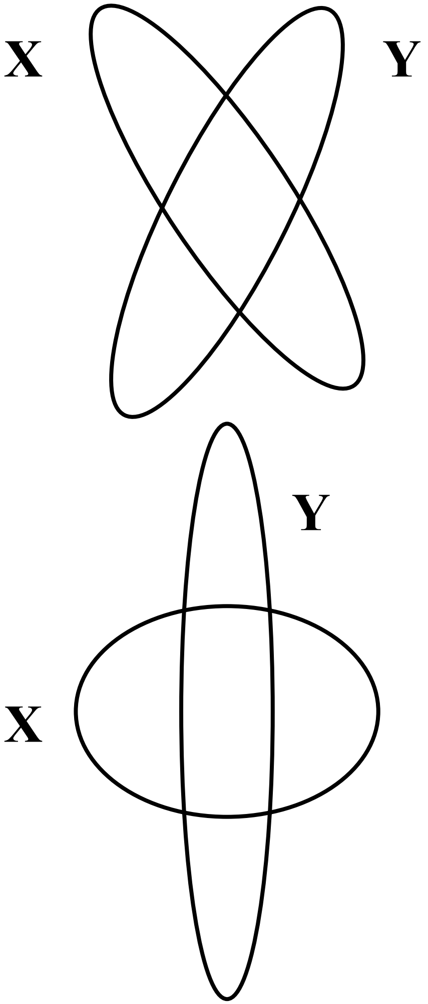
**Unfortunately,
the available now measured data can't be used for the final and reliable optimization of the IRM and, therefore, significant improvement of the performance of the whole HIT linac.**

HIT-RFQ matching out

RFQ electrodes

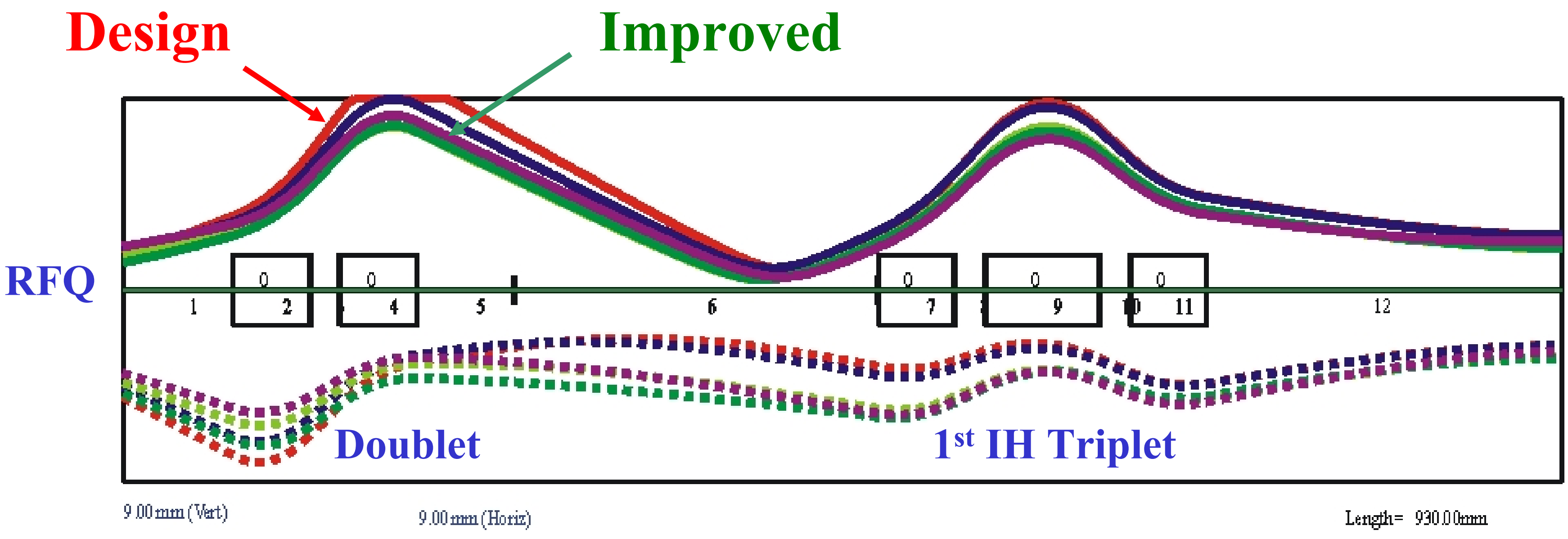


Emittance orientation



RFQ high energy end

- Shortening of the electrodes at the RFQ high energy end is possible. Position of the rebuncher is the same.
- Beam size at position of the quadrupoles is lower.
- 4 mm cut gives minimum beam size in the doublet.



- Gain in beam transmission is about 2% only.
- Output energy will be changed.

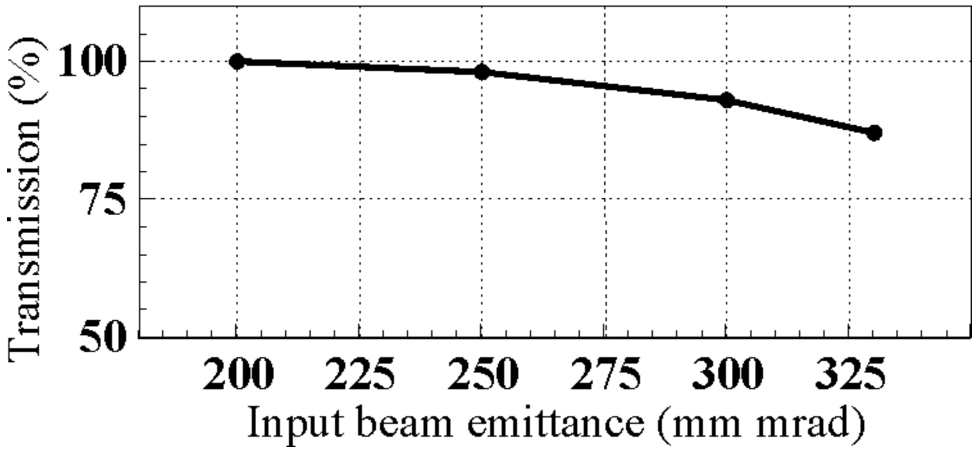
Limitations of the transmission becouse of the RFQ (I)

Calculated acceptance of the RFQ

A. Schempp, A. Bechtold : ≈ 400 mm*mrad

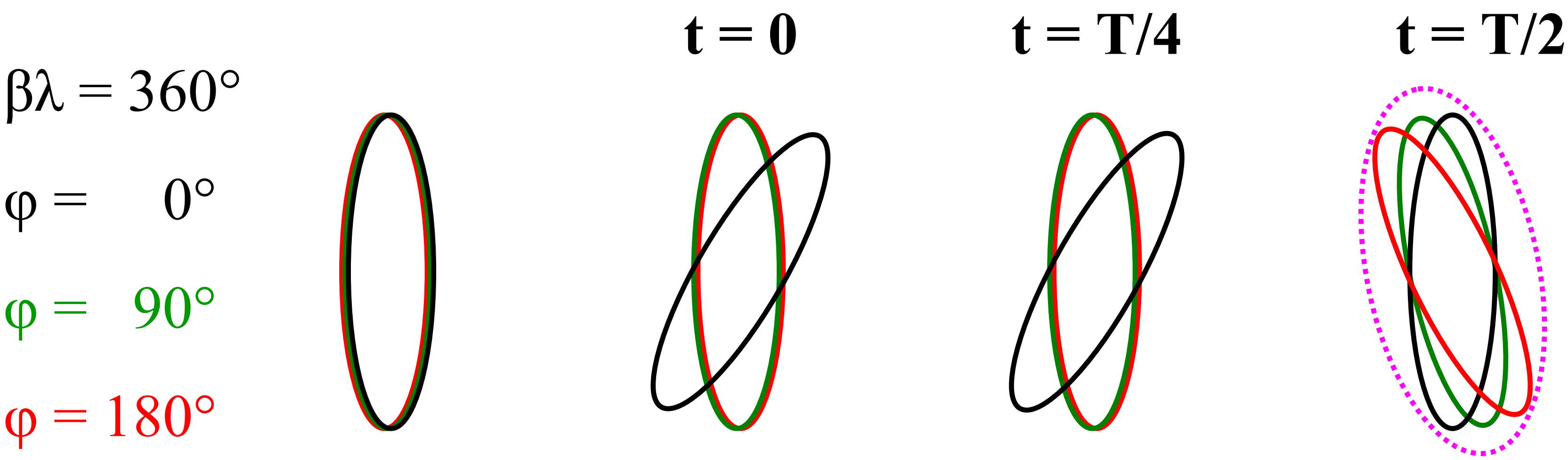
S. Yaramyshev : ≈ 330 mm*mrad

Nevertheless, for the matched to the RFQ artificial Gaussian (2σ) distribution with emittance of 330 mm*mrad, transmission is about of 90% only !

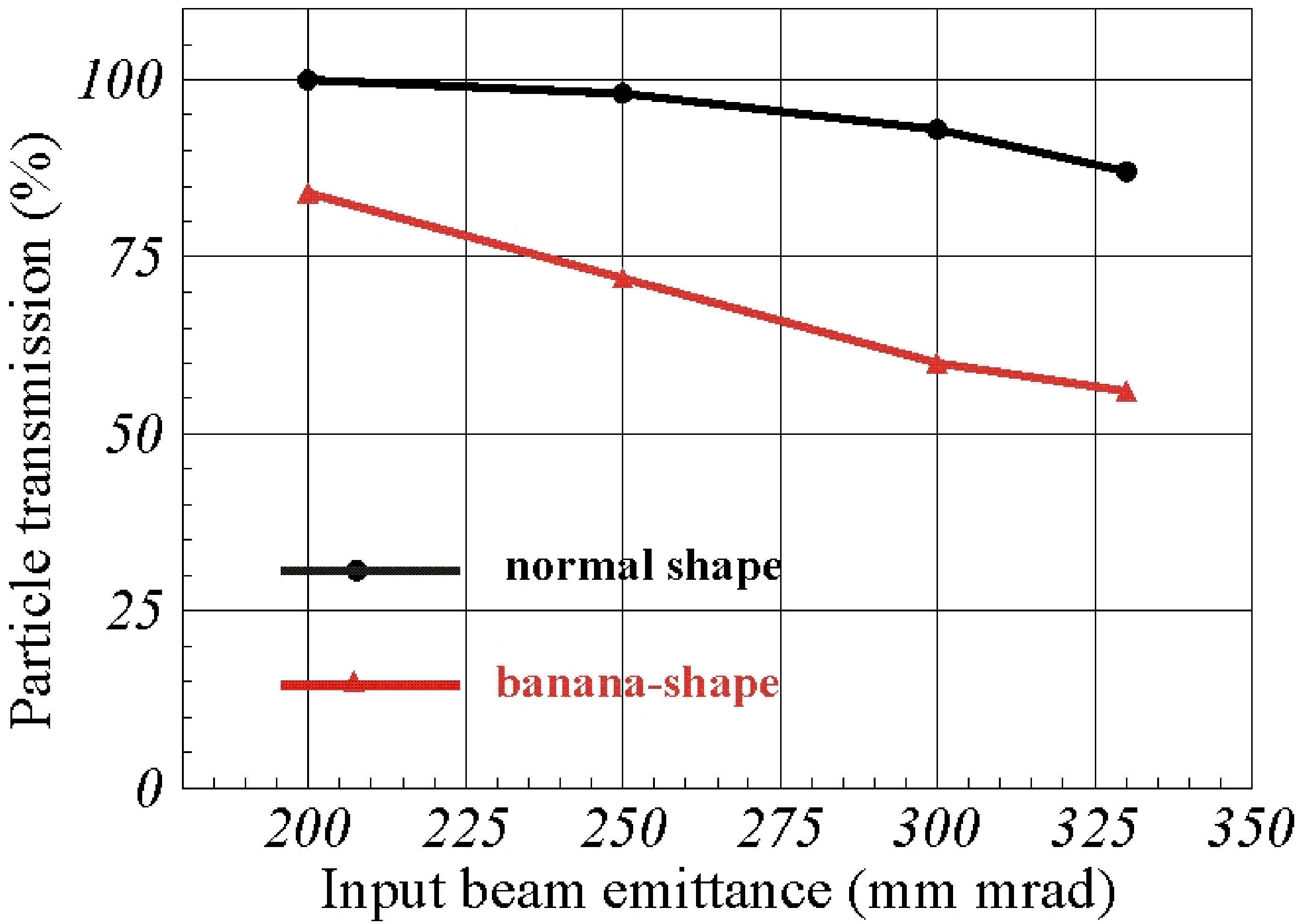


Limitations of the transmission becouse of the RFQ (II)

This effect appears due to injection of the spatially uniform beam to the time dependent focusing channel. Originally Input Radial Matcher is introduced to minimize this effect. Typical IRM design allows to reach particle transmission up to 98% even with the beam emittance, equal to the acceptance of an RFQ.



Acceptance



100
75
50
25
0
200
225
250
275
300
325
350
Particle transmission (%)
Input beam emittance (mm mrad)
normal shape
banana-shape