High intensity RFQ design -- beam dynamics

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1. Bit of History

2. Computer codes for beam dynamics simulations and RFQ design

   as related to high intensity RFQ design

3. RFQs for GSI projects (HIT, p-Linac, HITRAP Decelerator, HLI)

   as related to high intensity RFQ design

4. High Current Injector (HSI) development and optimization (until 2014)

   high intensity HSI-RFQ

5. Possible optimization/upgrade of the HSI in order to reach
   high intensity heavy ion beams, required for FAIR

Since decades an RFQ is the "standard" part

of the proton or heavy ion linac front-end,

allowing for acceleration of the high intensity beams

1989: High current proton **RFQ** at ITEP, Moscow - ***in operation***
Modulation design, beam dynamics study, control of fabrication

1991: **RFQ** booster section for Moscow Meson Factory at Troitzk - ***in operation***
Modulation design, beam dynamics study

1993: HLI **RFQ** at GSI, Darmstadt - ***in operation***
Investigation of low beam transmission, proposals for optimization

1993: Study for possible substitution of heavy ion Wideroe injector at GSI, Darmstadt
Proposal for upgrade, preliminary design of high current RFQ, beam dynamics simulations

1994: Heavy ion high current **RFQ** at ITEP, Moscow - ***in operation***
Modulation design, beam dynamics study, direct injection of the multi-charged beam into the RFQ

1996: SC **RFQ** for ALPI Complex at LNL, Legnaro - ***in operation***
LEBT design and optimization, benchmarking RFQ beam dynamics simulation

1996: High Current heavy ion Injector (HSI) at GSI, Darmstadt - ***in operation***
*Benchmarking of the HSI-**RFQ** beam dynamics simulations*

1997: CW **RFQ** at ANL, Argonn - ***in operation***
Benchmarking of the RFQ beam dynamics simulations

1997: TWAC **RFQ** at ITEP, Moscow - ***in operation***
Direct injection of the LIS multi-charged beam into the RFQ

1998: Laser Ion Source **RFQ** at CERN, Geneva - ***in operation***
Benchmarking beam dynamics simulations

2000: Heavy ion high current linac at GSI, Darmstadt - ***in operation***
*HSI (LEBT+**RFQ**+Superlens+IH) + stripper section + UNILAC poststripper*
End-to-End beam dynamics simulations

2001 (until 2014): Compact LEBT with direct injection to the **RFQ**
Beam line layout, beam dynamics simulations LEBT+RFQ

2004: GSI HSI **RFQ** upgrade I - ***in operation***
to be shown below...

2004 (until 2015): GSI proton **RFQ**
to be shown below...

2006: LEBT and **RFQ** for therapy linac at HIT, Heidelberg - ***in operation***
to be shown below...

2008: HSI **RFQ** upgrade II - ***in operation***
to be shown below...

2010: HLI **RFQ** upgrade II - ***in operation***
Benchmarking of the RFQ beam dynamics simulations

2010 (until 2014): HSI injector further optimization (LEBT+**RFQ**+Superlens+IH) - ***in operation***
to be shown below...

2012: HITRAP Decelerator **RFQ** re-design - ***in operation***
to be shown below...

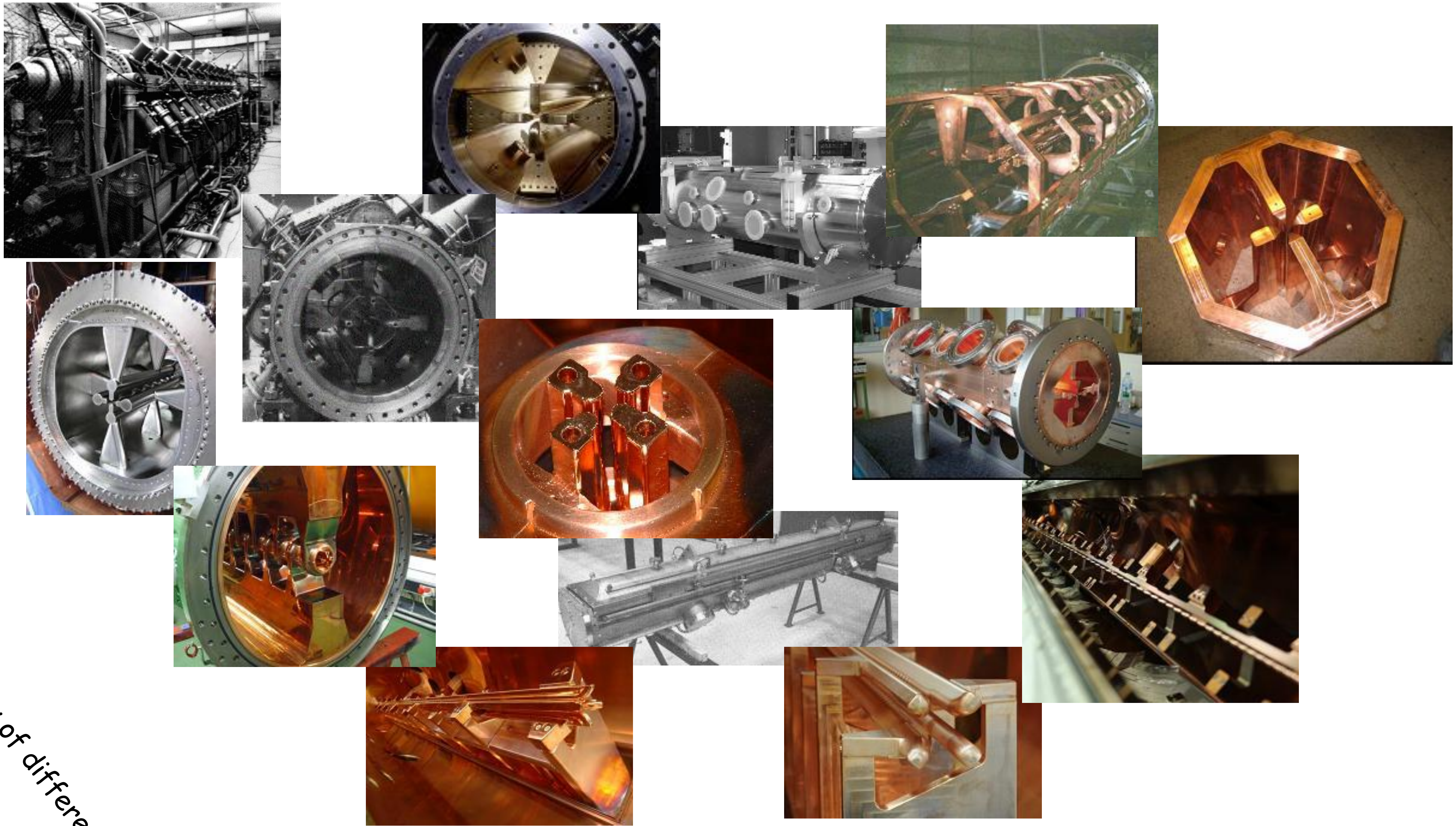
2014: LINAC4 **RFQ** at CERN, Geneva - ***in operation***
Benchmarking beam dynamics simulations

2015 until now: CW **RFQ** for HELIAC room temperature injector
Modulation design, benchmarking of the beam dynamics codes

2016: SARAF CW **RFQ** upgrade at Soreq NRC, Yavne - ***in operation***
Beam dynamics study, proposals for upgrade, benchmarking simulations

2017: Compact proton **RFQ** for medical purpose at ITEP, Moscow
Modulation design, beam dynamics simulations

15 RFQs in operation



courtesy of different authors

RFQ design requirements

- high particle transmission (up to 100%)

- high intensity (compensation of space charge)

- low emittance growth (dedicated modulation law)

- reliable routine operation (limited RF-power & RF-voltage)

Proper beam matching along the linac: RFQ is not a separate part, but should be designed together with LEBT & MEBT)

Dedicated advanced software is required !

2. Computer codes for beam dynamics simulations and RFQ design

in relation to high intensity RFQ design and beam dynamics

Multiparticle DYNAMION code

- originally written at Institute for Theoretical and Experimental Physics (ITEP, Moscow) for beam dynamics simulations in high intensity linacs (1985-1992)
- several further modifications for dedicated GSI tasks in 1993-2001
- generally revised during 2002-2005

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

S. Yaramyshev et al, "Development of the versatile multi-particle code DYNAMION", NIM A, Vol 558/1 pp 90-94, (2006)

Multiparticle DYNAMION code

Main purpose and advantage of the code is reliable **front-to-end** beam dynamics simulations for a linac, consisting of the arbitrary sequence of the beam transport lines, RFQs and DTLs.

Beam transport lines may include magnetic and electrical lenses (quadrupole, octupole, etc.), bending magnets, solenoids, slits, steerers, apertures, stripper sections, etc ...

Time integration of **3-D equation of particle motion** is used in the most common form.

External electrical field in RFQ and DTL is modeled inside the code solving the Laplace equation **for the real shape** of the elements.

Space charge effects could be calculated with different solvers.

Also could be implemented:

- **external** electromagnetic fields, **measured** or **simulated** by dedicated codes;
- **multi-charged** beam (particles with different mass to charge ratio);
- input particle distribution from **measured emittance** or other calculations;
- **misalignments** of the elements.

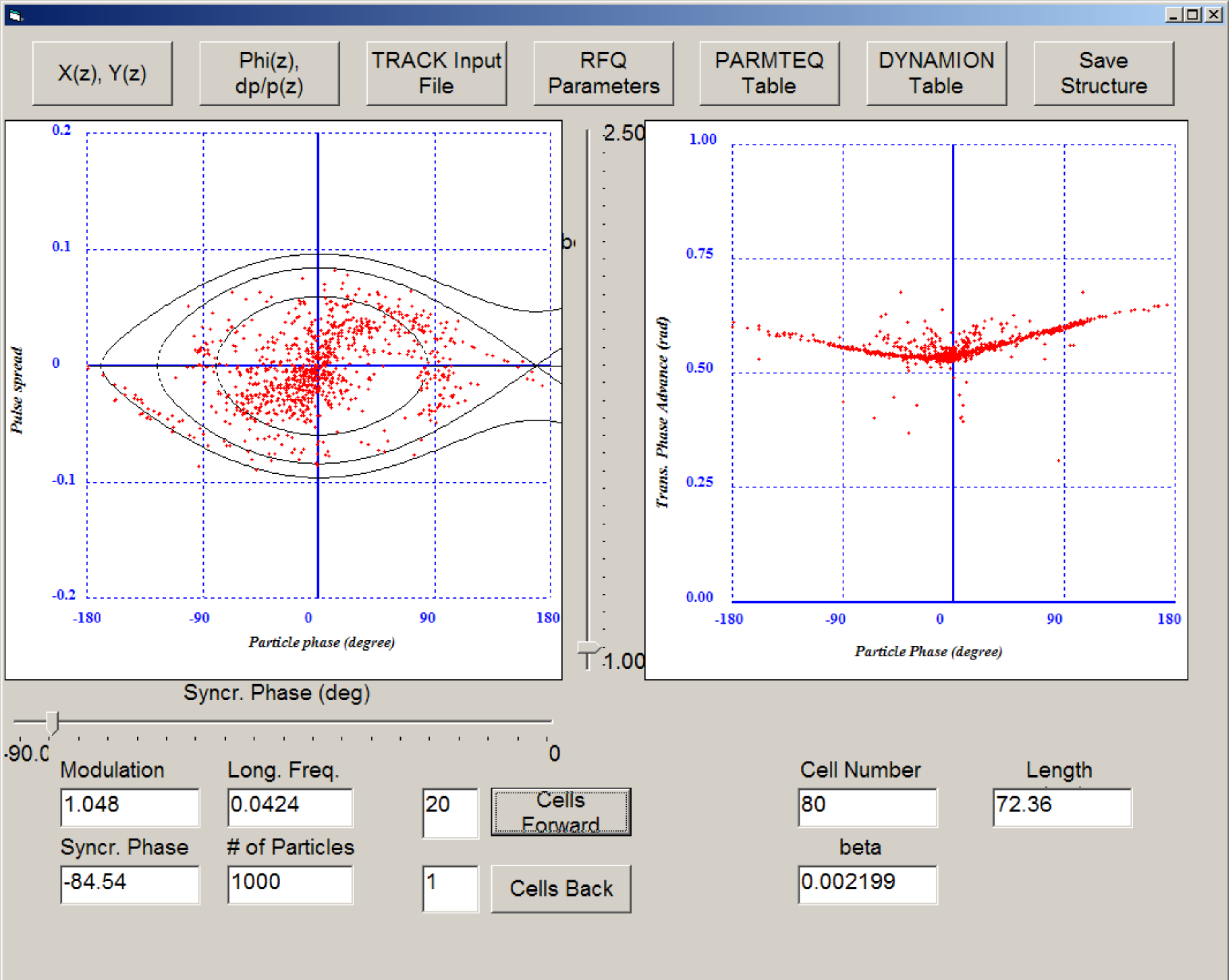
DESRFQ Code for RFQ Design

A. Kolomiets, S. Yaramyshev et al. (*1997-2000)*

Institute for Theoretical and Experimental Physics (ITEP)
Moscow, Russia

generally revised in 2004-2006

DESRFQ interactive window

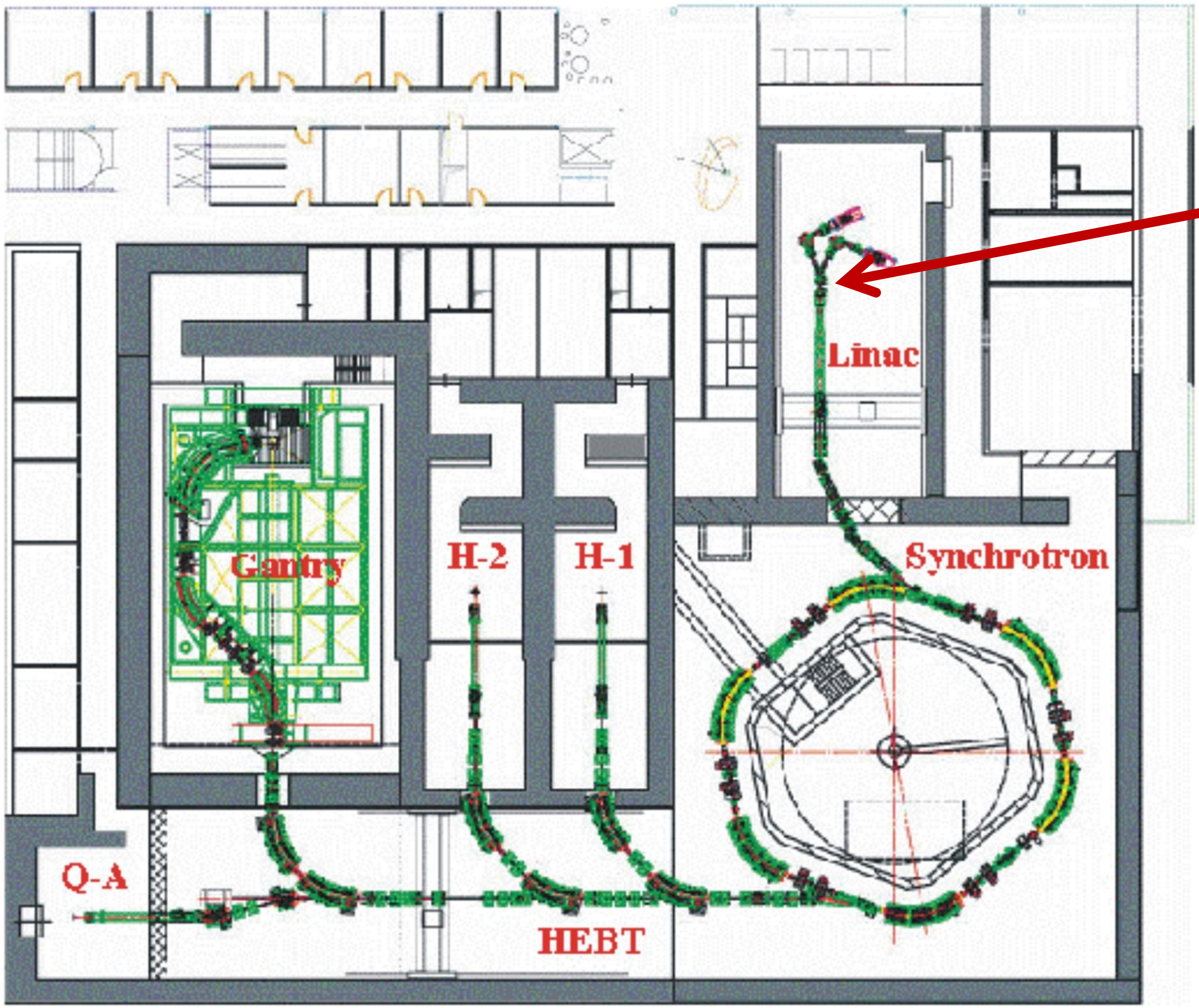


- detailed
- advanced
- visualized
- interactive
- user friendly

3. RFQs for GSI projects (HIT, p-Linac, HITRAP Decelerator, HLI)

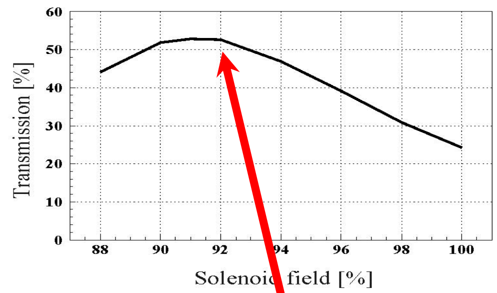
in relation to high intensity RFQ design and beam dynamics

HIT - Therapy Accelerator in Heidelberg, Germany



Beam matching to RFQ acceptance with solenoid

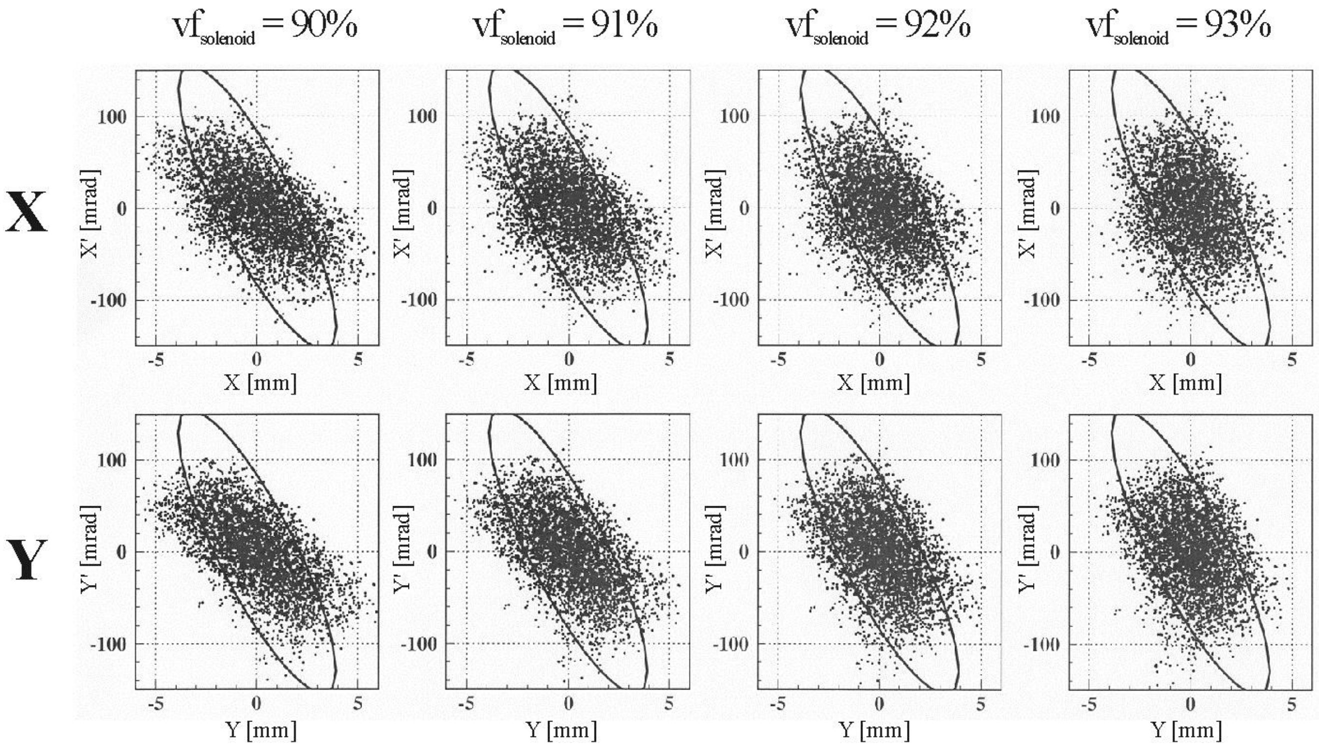
RFQ transmission

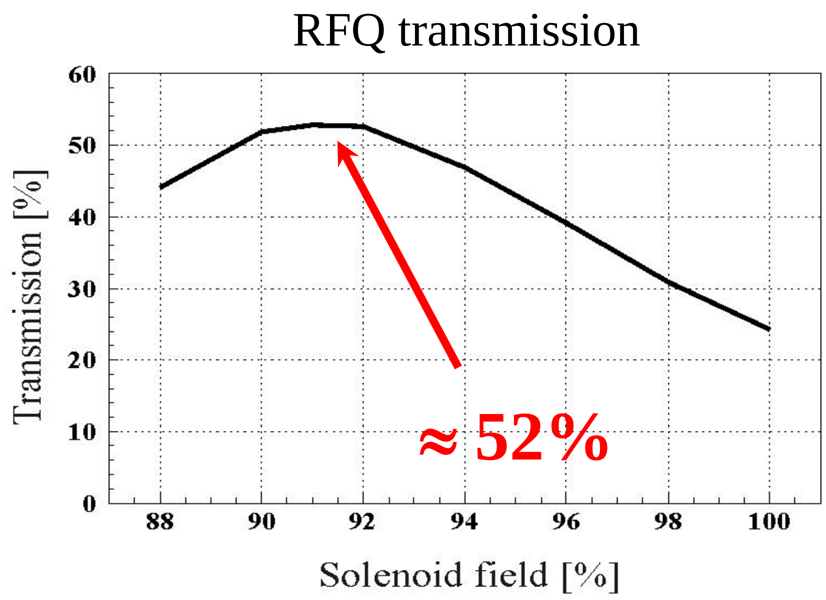


≈ 52%

Particle distribution generated from **measured emittance**
Measured magnetic field for the solenoid in front of RFQ
Beam dynamics simulations with **DYNAMION code**

Varied solenoidal field; ellipses represent RFQ acceptance





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

The needle's eye and the camel

Recently

we can't adjust

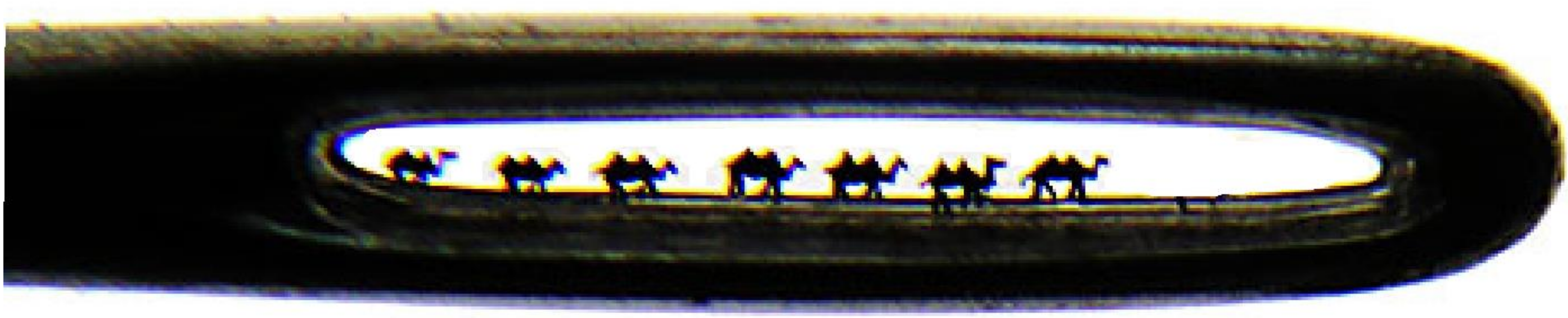
this beam emittance

to this RFQ acceptance

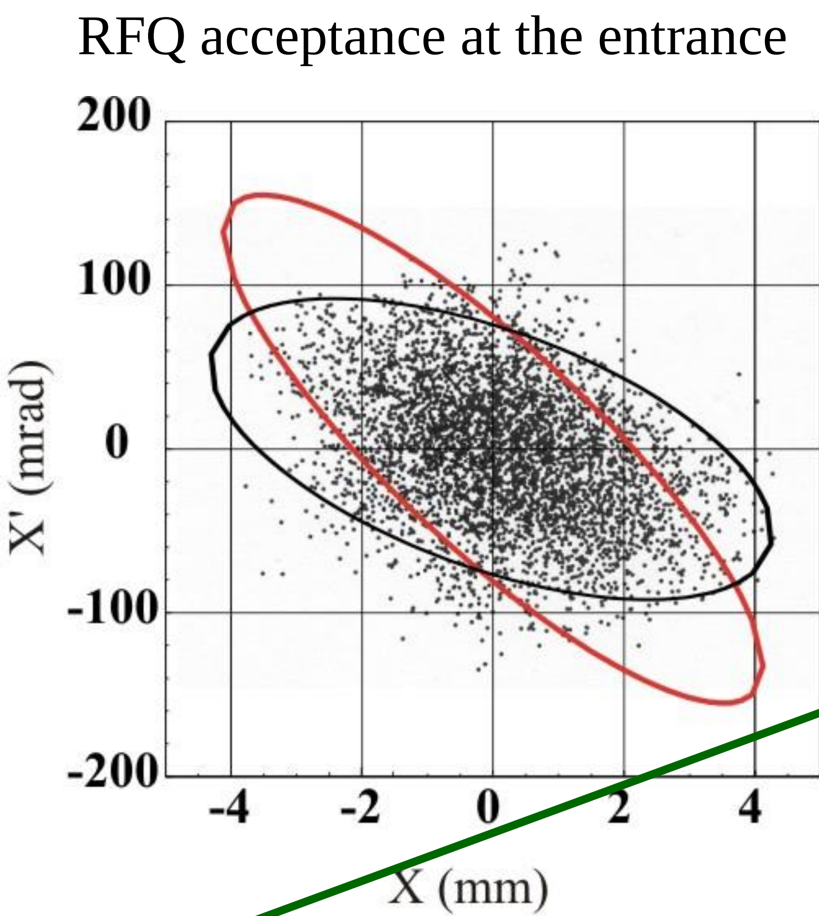
But we can adjust

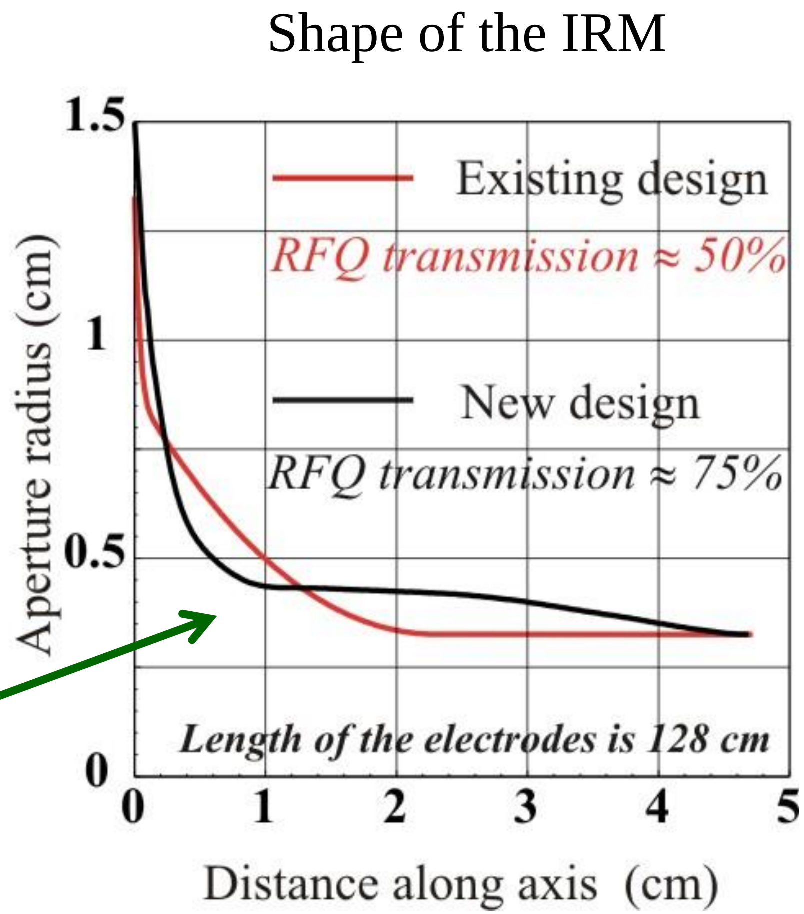
RFQ acceptance

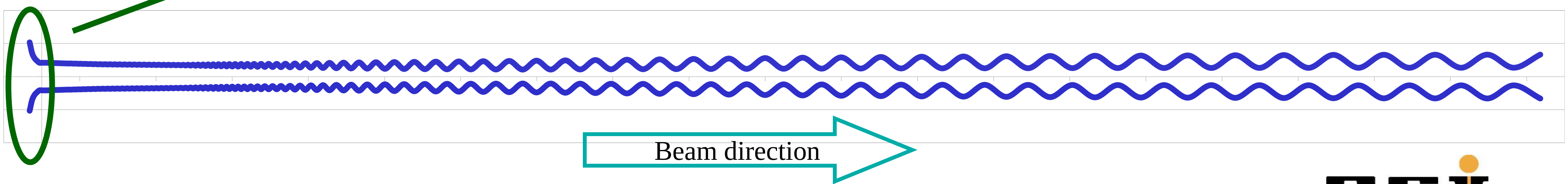
to the beam emittance !



New shape of HIT-RFQ Input Radial Matcher (2007)



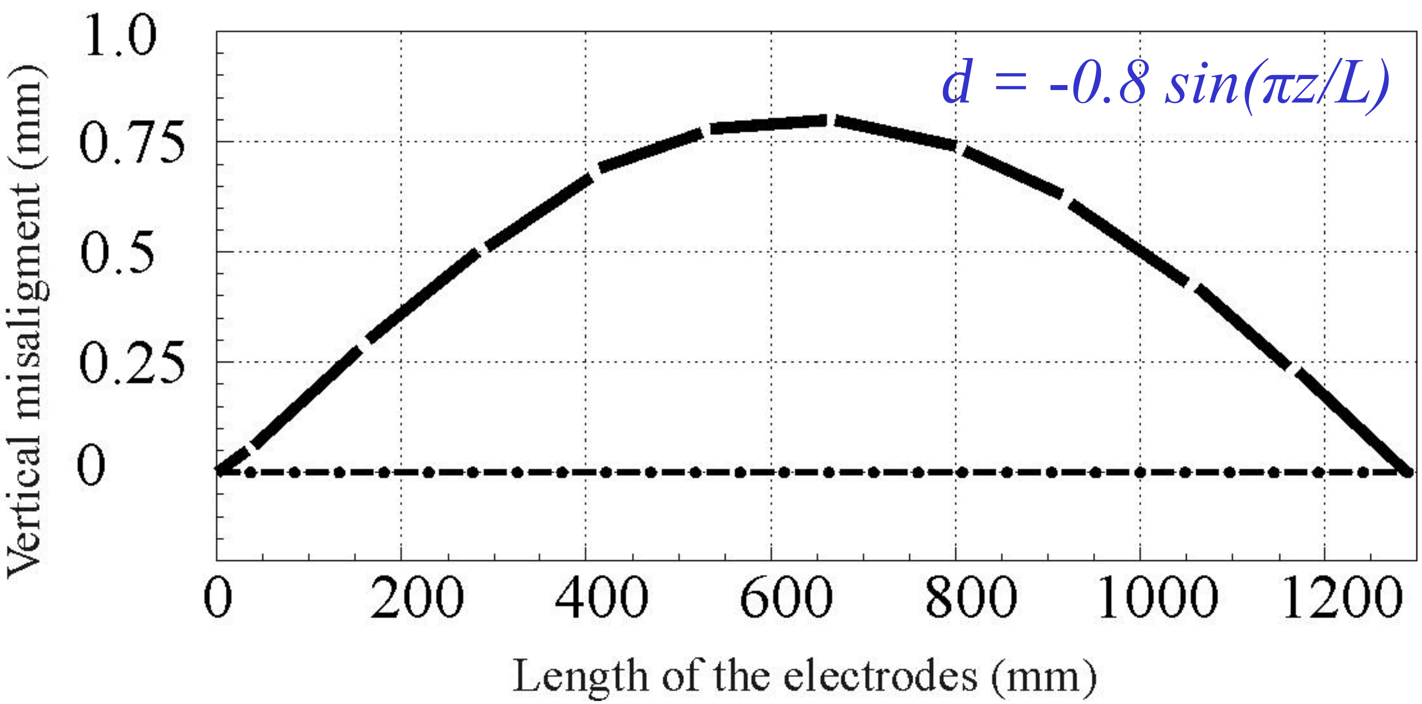




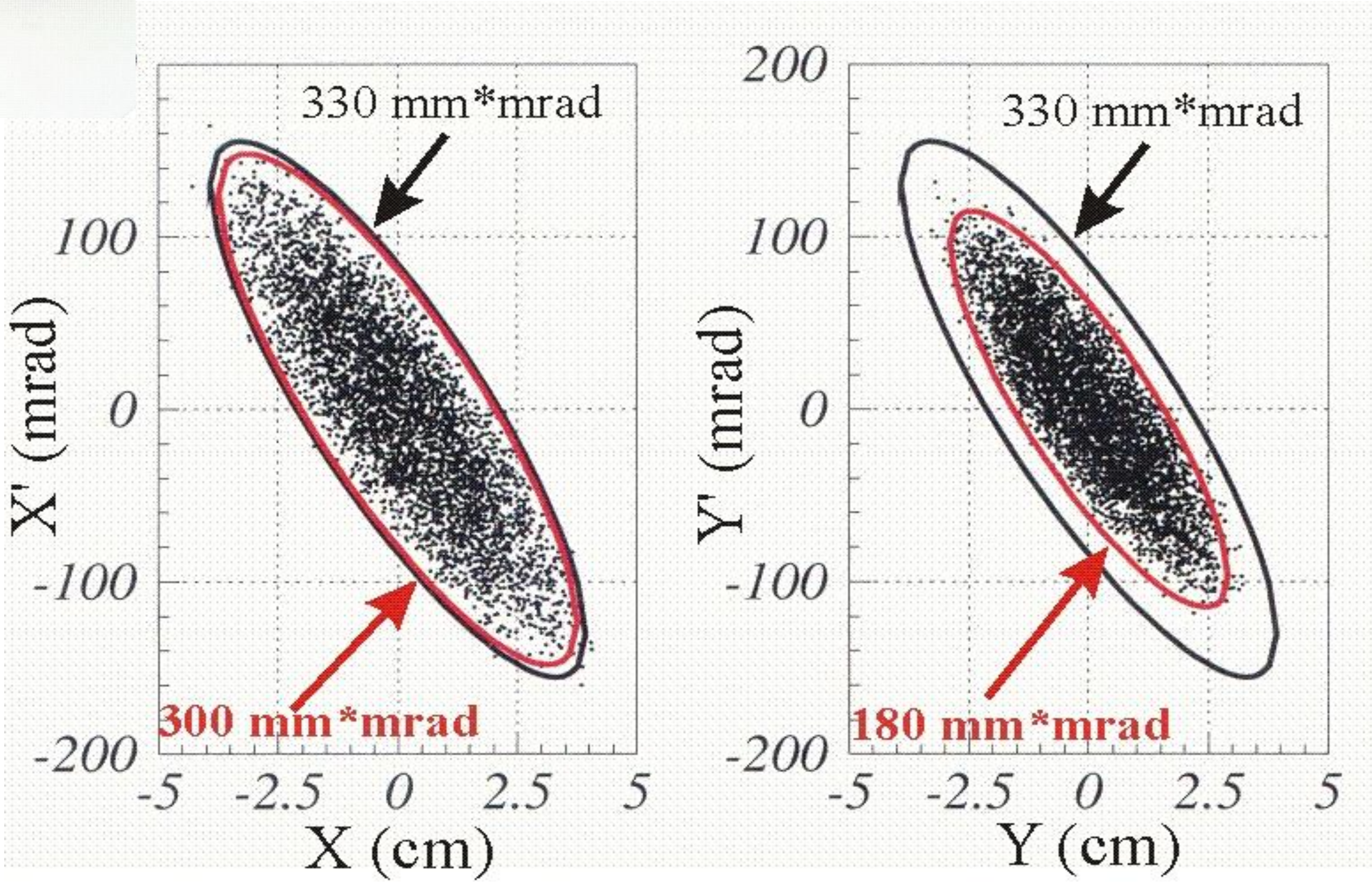
Deformation of the RFQ tank

"Banana" - shape of the RFQ

measured vertical misalignment for CNAO RFQ

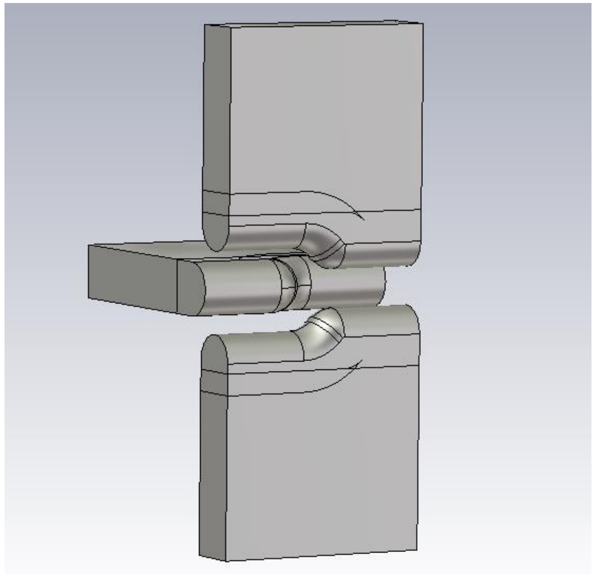


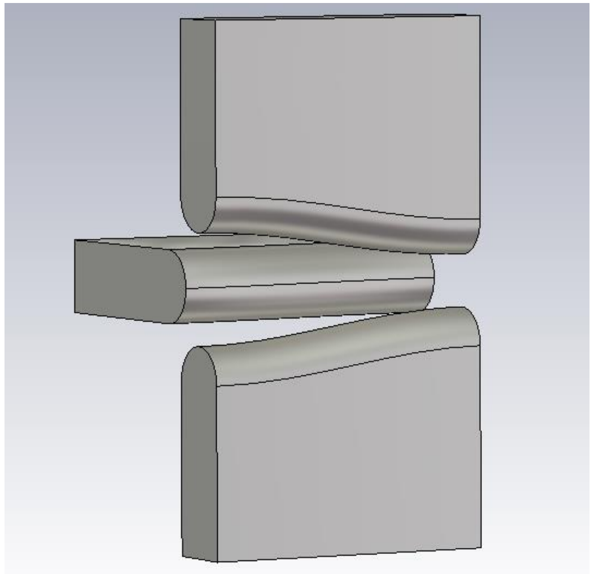
Acceptance of "banana"-RFQ



GSI design activity for p-RFQ for FAIR (2015)

- **Trapezoidal modulation** instead of sinusoidal is proposed:
  - lower RF-voltage (RF-power)
  - higher acceleration efficiency



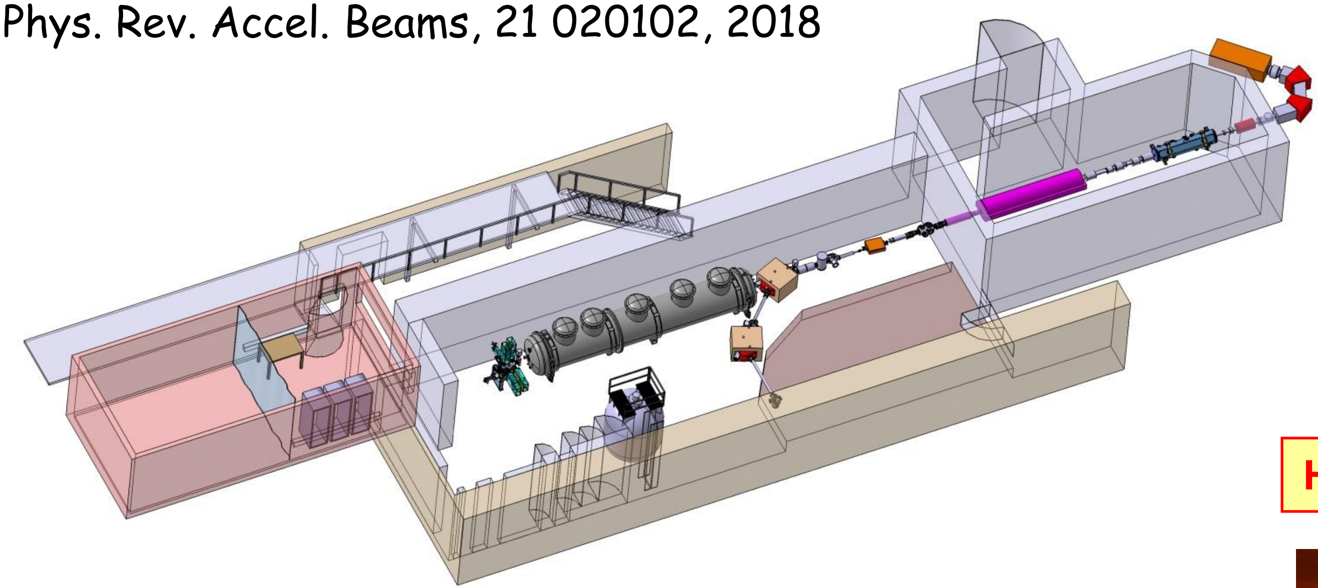


M. Vossberg, R. Brodhage, M. Kaiser, F. Maimone, W. Vinzenz, S. Yaramyshev,
GSI, Darmstadt, Germany,
DESIGN STUDIES FOR THE PROTON-LINAC RFQ FOR FAIR, IPAC'15 (2015)

GSI / HIM superconducting CW-Linac

Super Heavy community → High duty factor, 7.5 MeV/u, variable beam energy, heavy ion linac

W. Barth et al., "First heavy ion beam tests with a superconducting multi-gap CH cavity", Phys. Rev. Accel. Beams, 21 020102, 2018

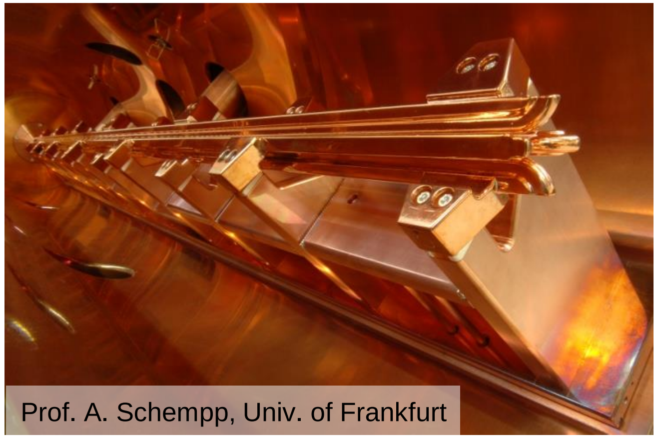


High Charge State (HLI) injector for UNILAC

and

superconducting CW Demonstrator at GSI

HLI-RFQ-commissioning (2010)



Prof. A. Schempp, Univ. of Frankfurt

- foreseen for 100% duty-cycle
- recently is about 25% only
- HLI-RFQ should be redesigned

Recent international activity in frame of CW-Linac development

Room temperature heavy ion CW injector for HIM/GSI superconducting CW-Linac

is already under development:

ECR ion source and RFQ front-end with the output energy of about 300 keV/u,

followed by IH-DTL section up to an energy of 1.4 MeV/u

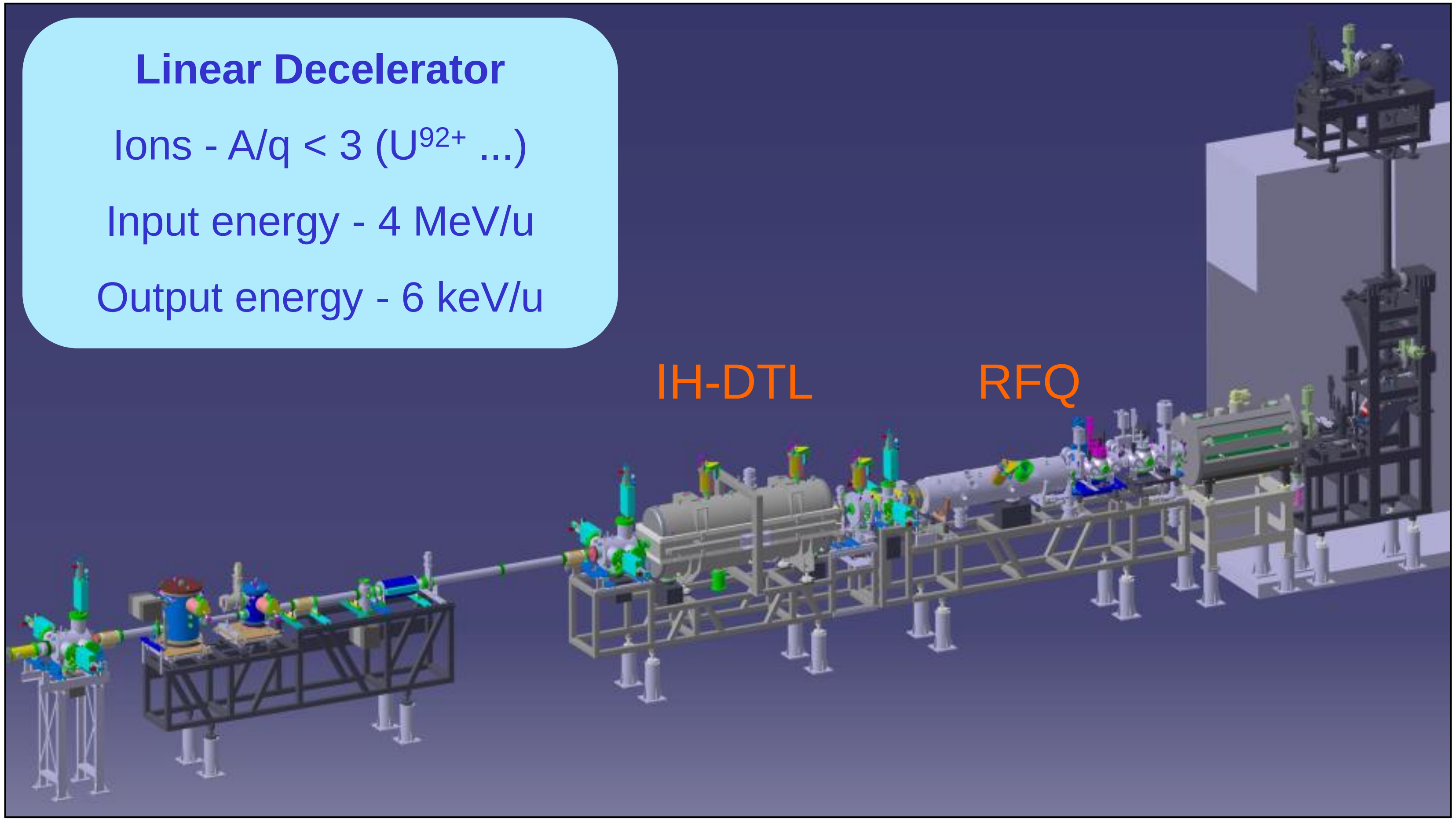
CW RFQ development in a collaboration with ITEP and MEPhI

Sergey Polozov, Winfried Barth, Florian Dziuba, Timur Kulevoy, Stepan Yaramyshev, Yury Lozeev, "Beam Dynamics Study for the New CW RFQ", RuPAC'16 (2016)

Sergey Polozov, Winfried Barth, Timur Kulevoy, Stepan Yaramyshev*, "Beam Dynamics Simulations and Code Comparison for a New CW RFQ Design", HB'16 (2016)

M. Schwarz, S. Yaramyshev and K. Aulenbacher, W. Barth, M. Basten, M. Busch, T. Conrad, V. Gettmann, M. Gusarova, M. Heilmann, E. Khabibullina, K. Taletskiy, T. Kulevoy, T. Kuerzeder, M. Miski-Oglu, H. Podlech, S. Polozov, A. Rubin, A. Ziiatdinova, "Reference Beam Dynamics Layout for SC CW Heavy Ion HELIAC at GSI", (to be published)

HITRAP Decelerator at GSI



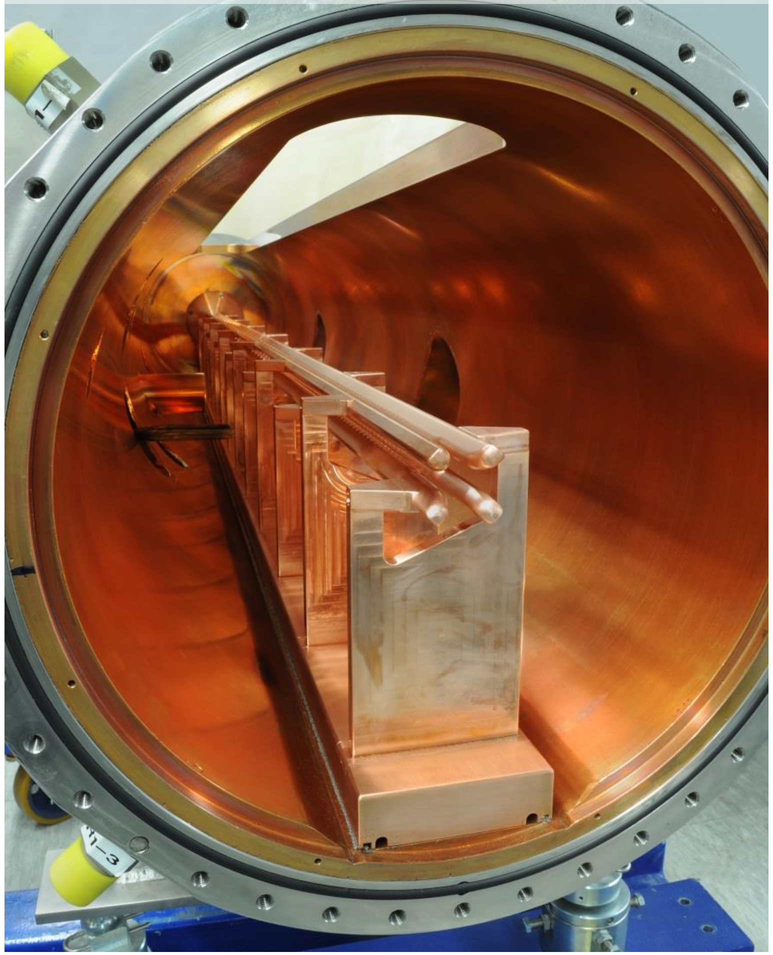
Deceleration (*status until 2012*):

with IH-DTL from 4 MeV/u to 500 keV/u

with RFQ from 500 keV to 6 keV/u

HITRAP RFQ Decelerator

Prof. A. Schempp, Univ. of Frankfurt



- almost 100% transmission of the **non-decelerated** 500 keV/u beam

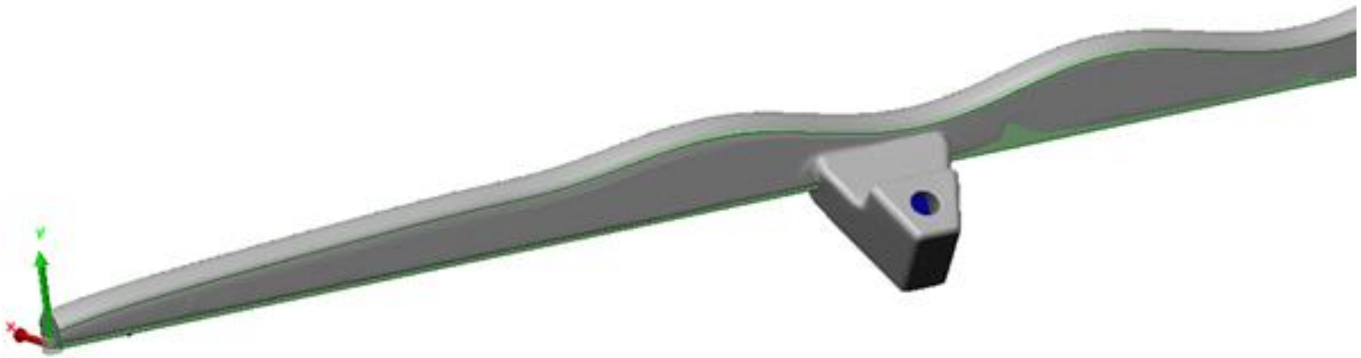
- deceleration efficiency is expected around 80% according to PARMTEQM simulation

No deceleration with RFQ

was observed at HITRAP facility

HITRAP RFQ decelerator

Fabrication data were not available => photometric measurements for the electrodes



Investigation with DYNAMION package:

HITRAP-RFQ can decelerate ions with an energy of **525**±10 keV/u (***design is 500 keV/u***)
IH-DTL can be tuned to provide beam energy in frame of **475-515** keV/u

No overlapping of longitudinal beam emittance and longitudinal RFQ acceptance !

Design idea: deceleration in RFQ differs from acceleration (PARMTEQM version at IAP)
RFQ was designed to **accelerate** particles from **6 keV/u** to **525 keV/u**
Following the designer it should **decelerate** ions of **500 keV/u** (design value) to **6 keV/u**

Beam tests for original design of HITRAP RFQ Decelerator

HITRAP-RFQ (original design) has been tested

with variable energy beam at MPI-K, Heidelberg:

deceleration of ions with energy of about 525 keV/u was shown

(as in DYNAMION simulations)

Reversibility of motion has been confirmed !!!

New design for HITRAP RFQ Decelerator

- **New design** of RFQ decelerating-focusing channel has been performed at GSI with software **DESRFQ** and **DYNAMION**
- New electrodes with new modulation law have been fabricated at GSI workshop
- Mechanical stability, RF-properties and alignment accuracy were improved
- HITRAP-RFQ with newly designed electrodes has been assembled and tuned at GSI

New design for HITRAP RFQ Decelerator

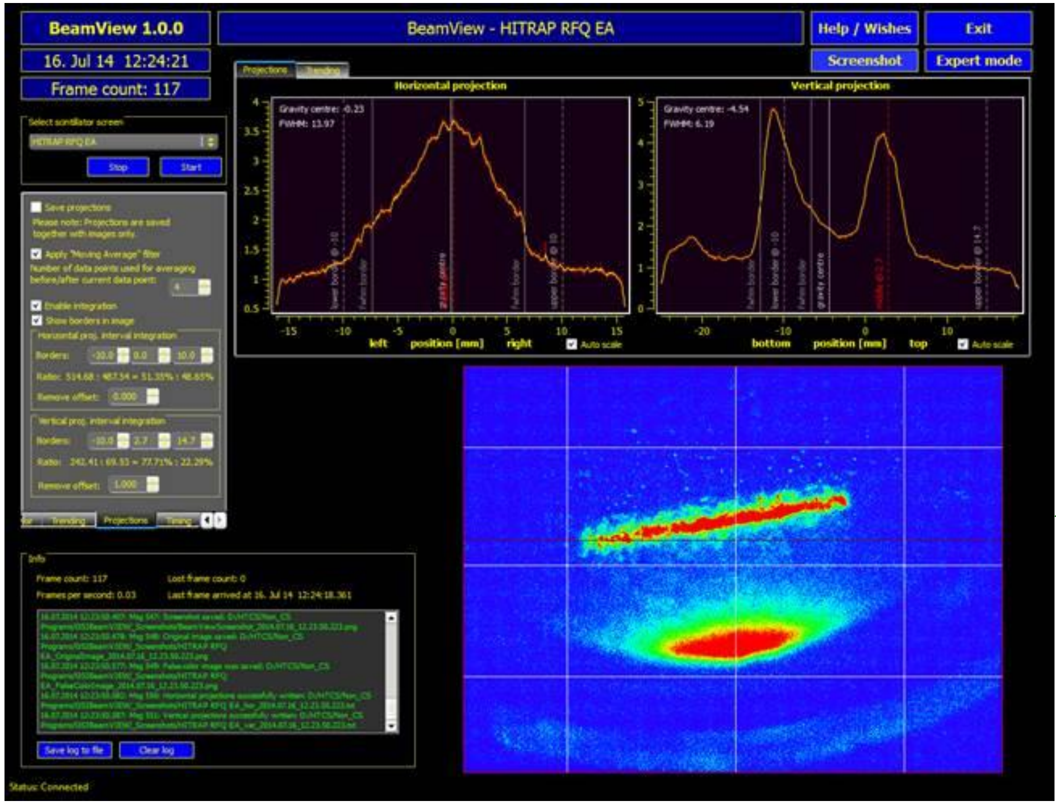
HITRAP-RFQ (new design) has been tested with variable energy beam at MPI-K, Heidelberg: deceleration of ions with required energy of about 500 keV/u was shown (as in DYNAMION simulations)

New design for HITRAP RFQ Decelerator

HITRAP-RFQ (new design) has been tested with variable energy beam at MPI-K, Heidelberg: deceleration of ions with required energy of about 500 keV/u was shown (as in DYNAMION simulations)

HITRAP-RFQ has been installed on its place at GSI HITRAP facility

Whole HITRAP linear decelerator has been successfully commissioned in July 2014

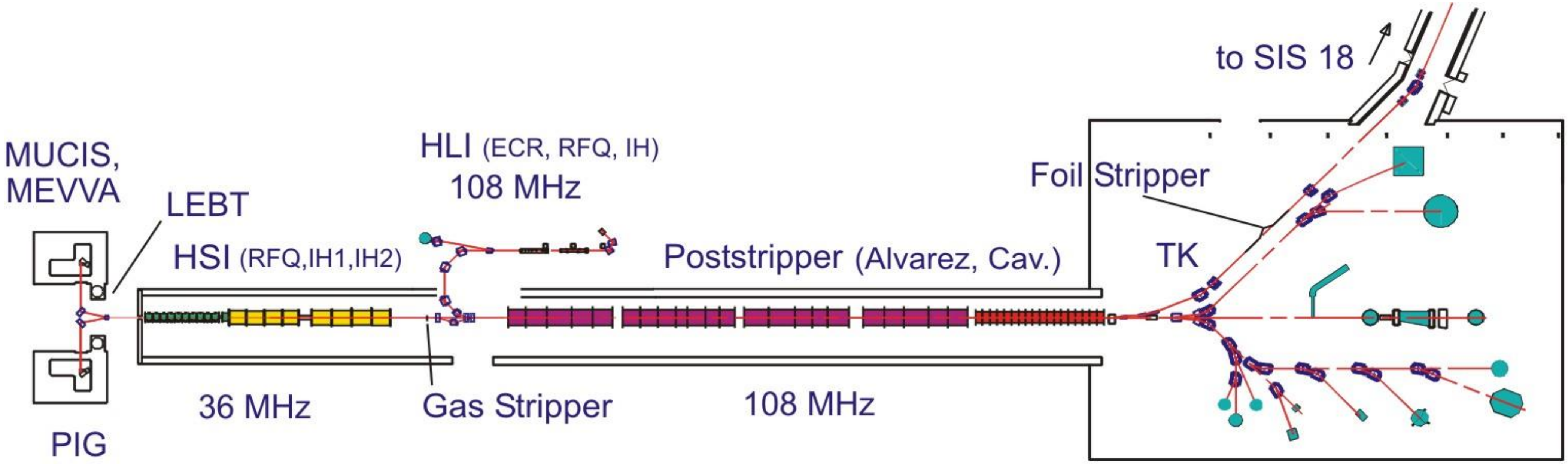


← 6 ± 1 keV/u

← 500 ± 10 keV/u

4. High Current Injector (HSI) development and optimization (until 2014)

UNIversal Linear ACcelerator

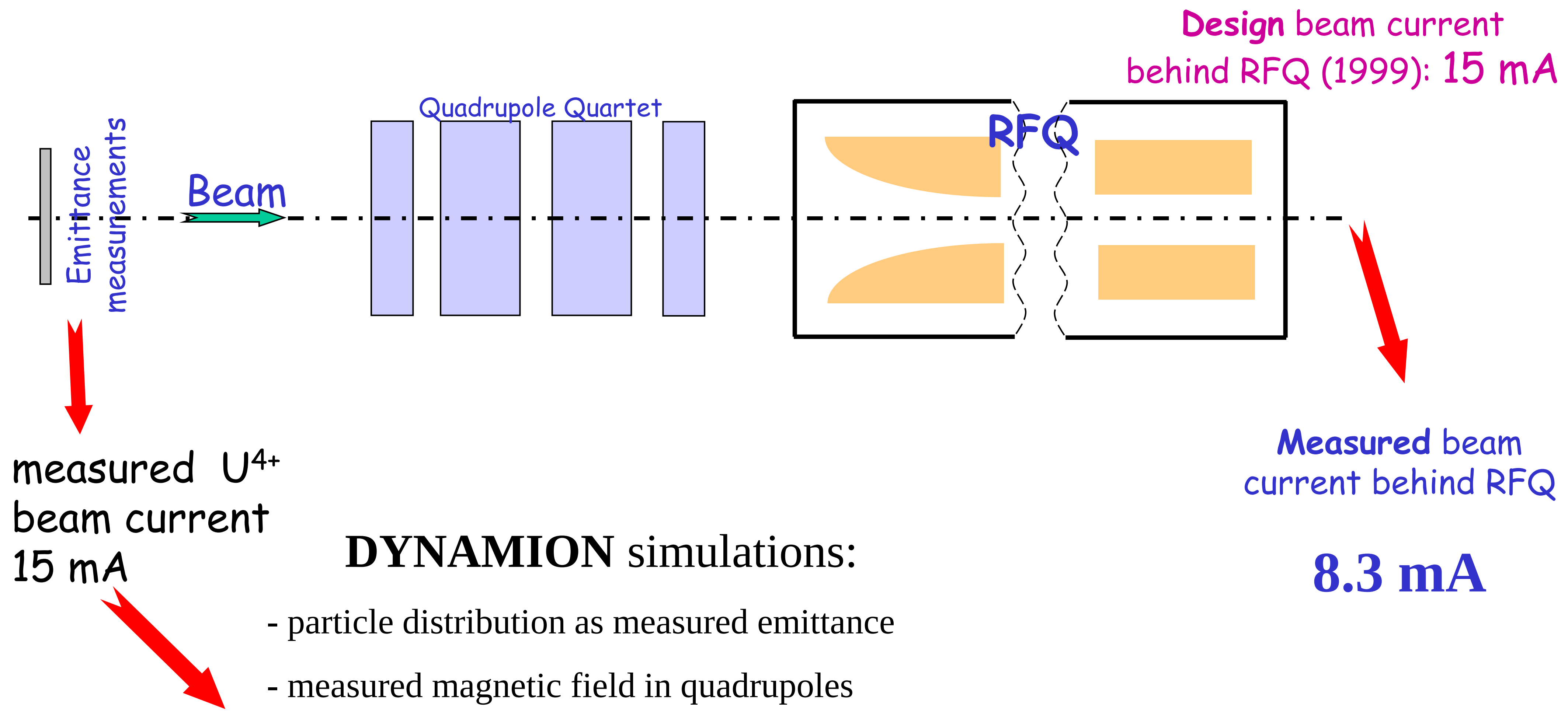


2016: world record for uranium beam intensity

11 mA U^{4+}

W. Barth et al., "High brilliance uranium beams for the GSI FAIR", Phys. Rev. STAB, 20 050101, 2017

Status of the HSI front-end before upgrade in 2004

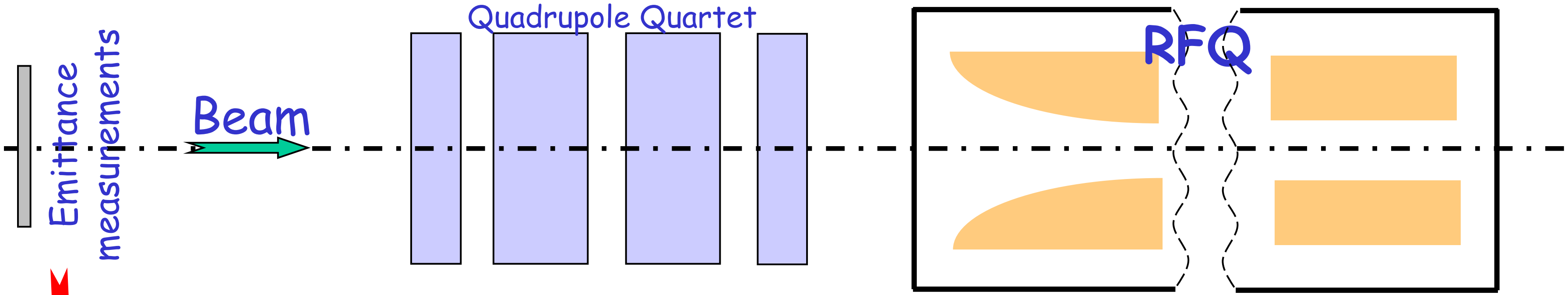


DYNAMION simulations:

- particle distribution as measured emittance
- measured magnetic field in quadrupoles
- electrical field in the RFQ for fabricated rods
- measured voltage along the RFQ
- measured RFQ tank misalignments

Status of the HSI front-end before upgrade in 2004

Design beam current behind RFQ (1999): 15 mA



measured U^{4+} beam current 15 mA

DYNAMION simulations:

- particle distribution as measured emittance
- measured magnetic field in quadrupoles
- electrical field in the RFQ for fabricated rods
- measured voltage along the RFQ
- measured RFQ tank misalignments

Measured beam current behind RFQ

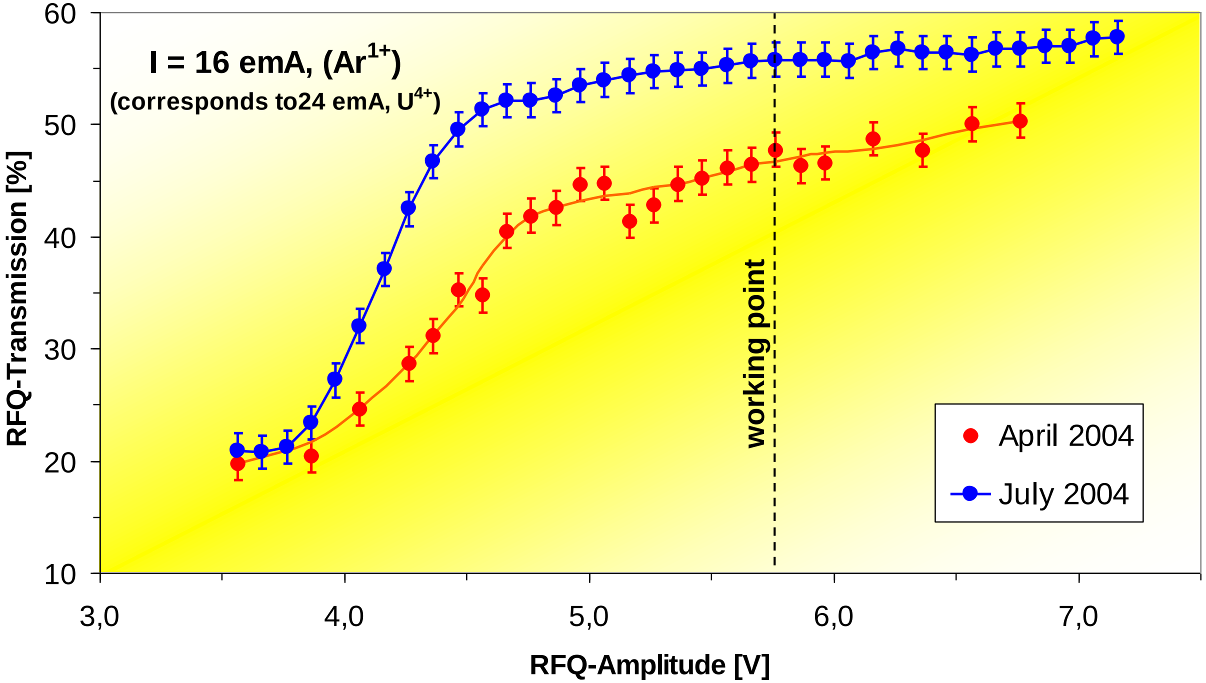
8.3 mA

Calculated beam current behind RFQ

8.7 mA

New radial matcher for the HSI-RFQ

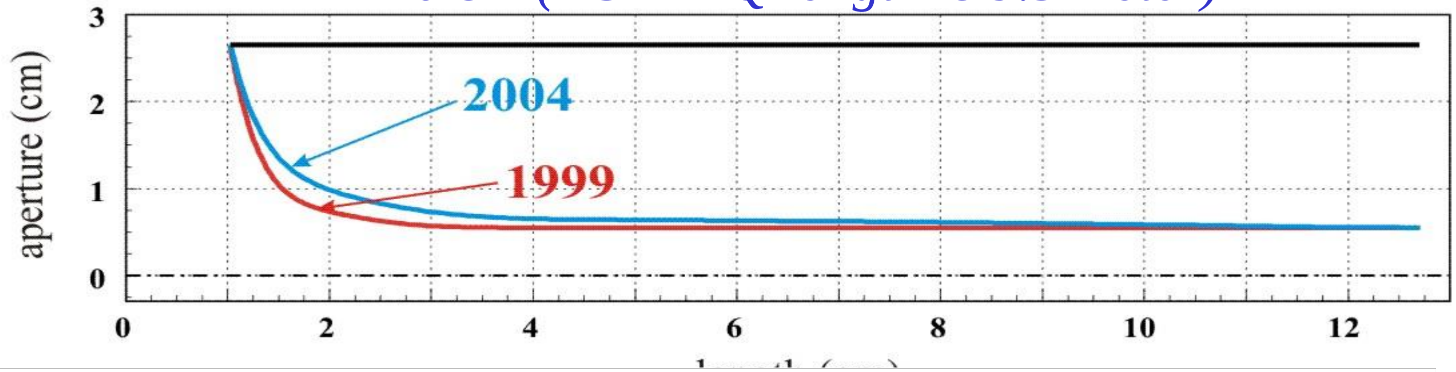
Upgrade ***2004***

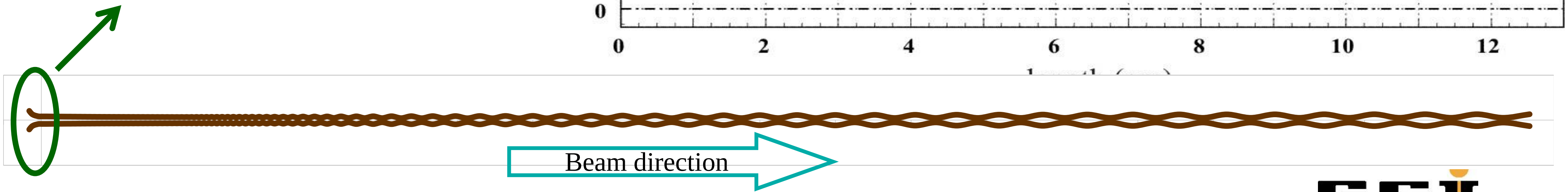


Simulated results and measurements are in a good coincidence

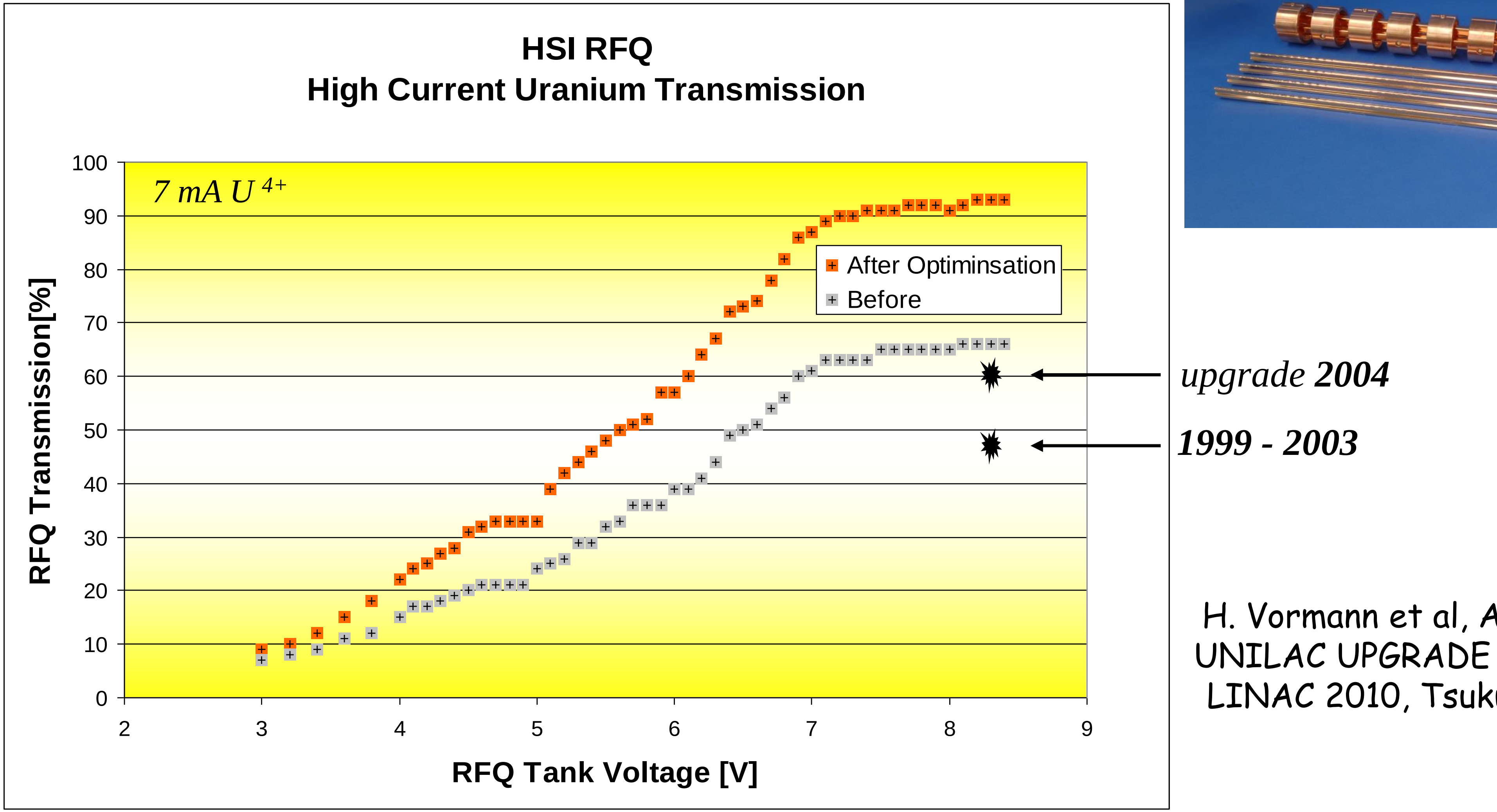
W. Barth et al., "Upgrade program of the high current heavy ion UNILAC as injector for FAIR", NIMA 577, 211, 2007

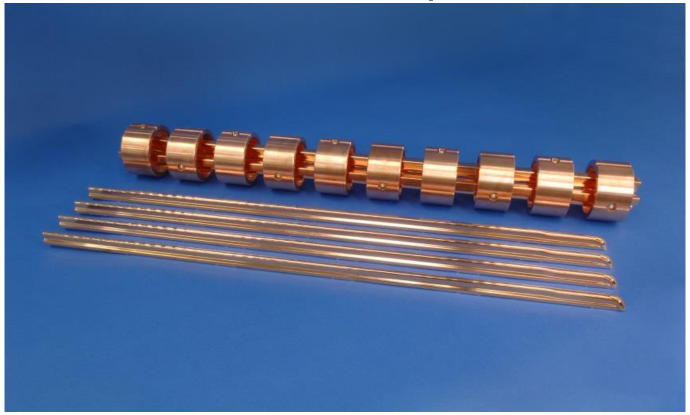
≈10 cm *(HSI-RFQ length is 9.3 meter)*





GSI Department UNILAC & ITEP (Moscow) & GSI Workshop

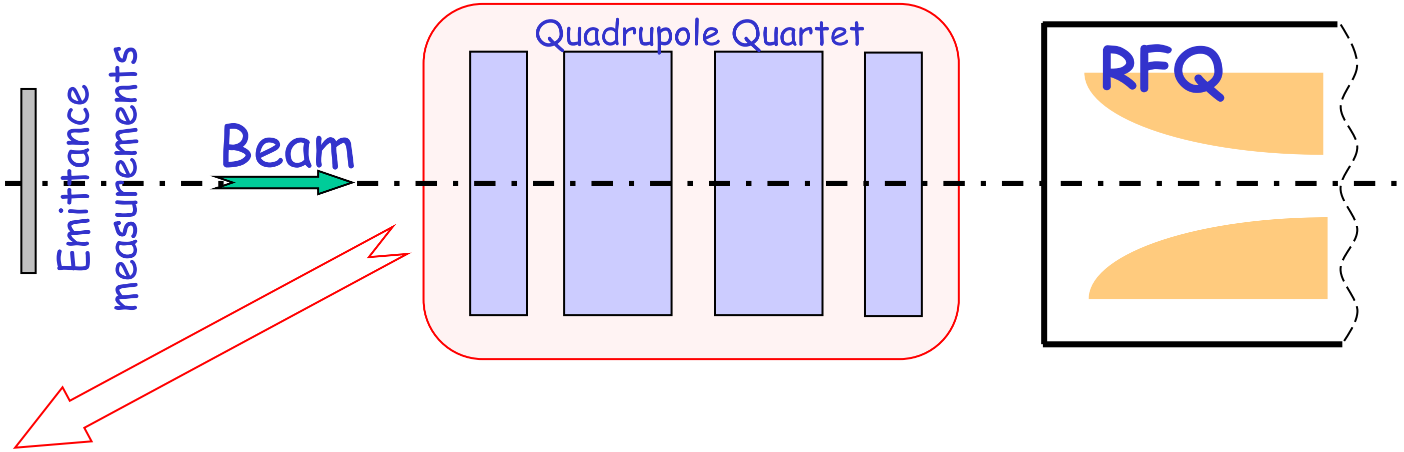


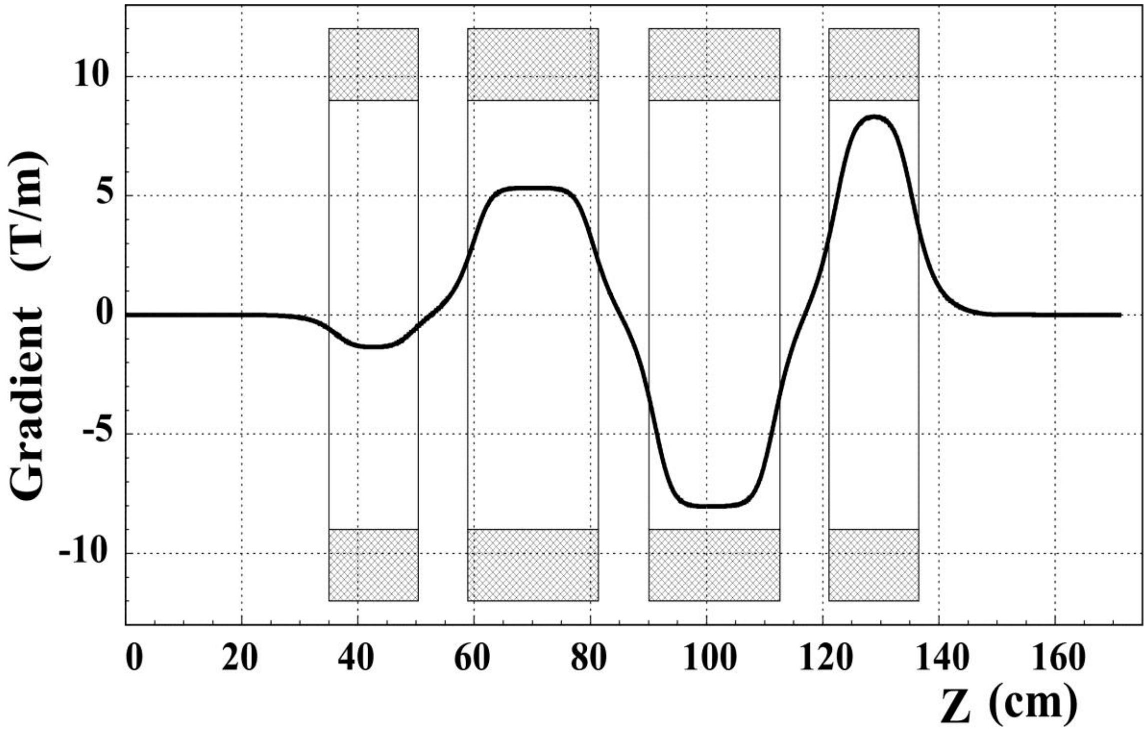


H. Vormann et al, ADVANCED UNILAC UPGRADE FOR FAIR, LINAC 2010, Tsukuba, Japan

Beam matching to the HSI-RFQ acceptance

Distribution of magnetic field, measured for each quadrupole lens, was introduced as input data (with machine settings during operation).





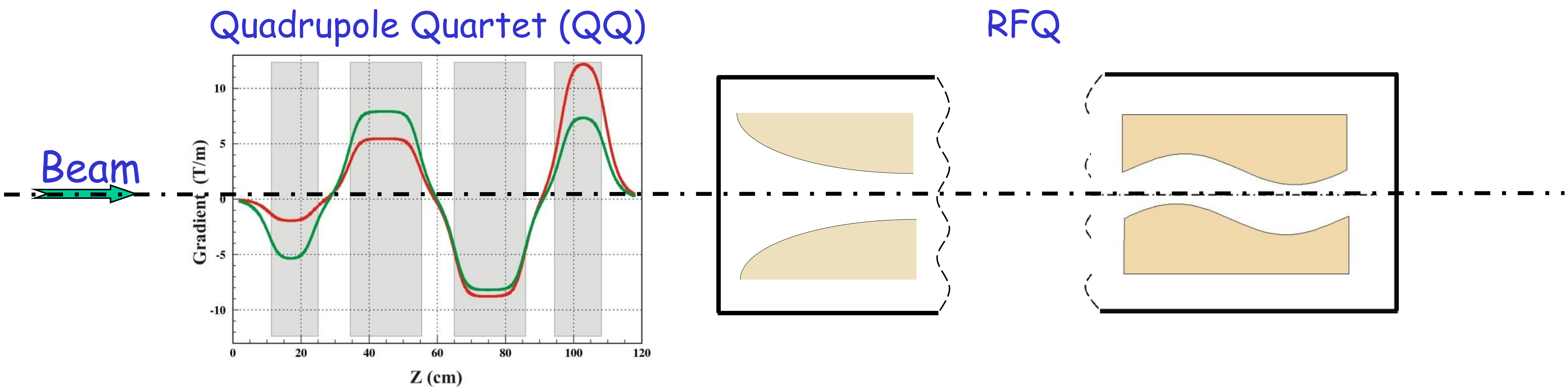
Quadrupole settings for optimum transmission have been found experimentally in 2009

Dedicated **DYNAMION** simulations with
- input particle distribution generated from measured beam emittance
- measured magnetic field in quadrupoles
- detailed RFQ representation

demonstrated **another local optimum**

Beam matching to the HSI-RFQ acceptance

The same beam (4 mA Ta^{4+}) & the same machine settings; only four quadropoles changed



Particle transmission

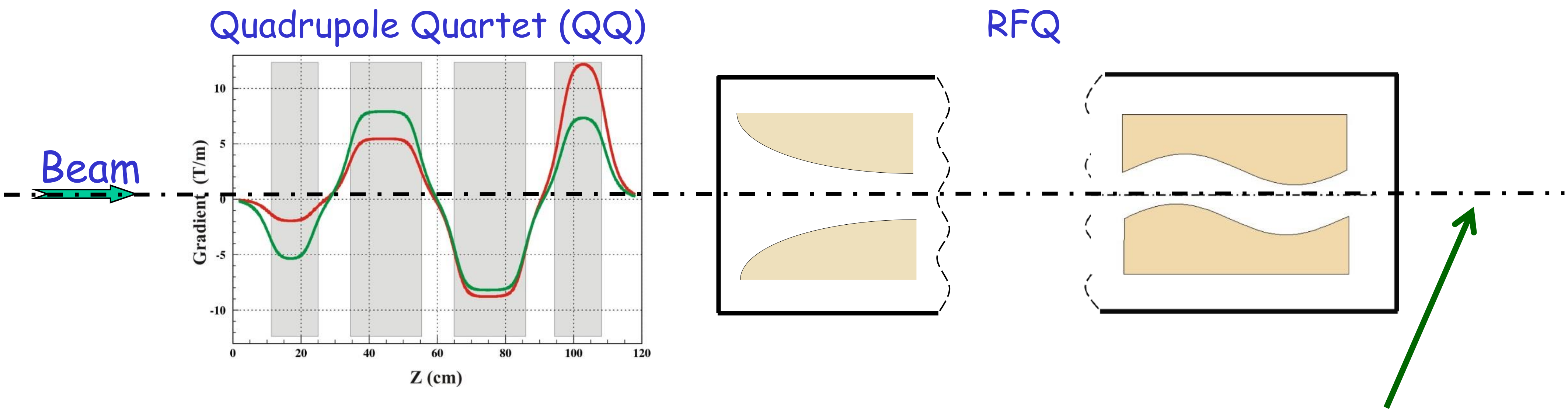
measured data (2014)

- old QQ settings ≈ 50%
  (UNILAC team / L. Groening)

- new QQ settings ≈ 75%
  (S. Yaramyshev)

Beam matching to the HSI-RFQ acceptance

The same beam (4 mA Ta^{4+}) & the same machine settings; only four quadropoles changed



Particle transmission
measured data (2014)

- old QQ settings ≈ 50%
(UNILAC team / L. Groening)

- new QQ settings ≈ 75%
(S. Yaramyshev)

DYNAMION *simulations:* particle transmission confirmed
Beam **brilliance** improvement:
- horizontal & vertical - about factor of 2
- longitudinal - about 60%

*For medium current Ar^{1+} beam **100%** transmission for the **whole HSI** is reached first time since commissioning in 1999*

S. Yaramyshev et al, ADVANCED BEAM MATCHING TO A HIGH CURRENT RFQ, LINAC 2014, Geneva, Switzerland

5. Possible optimization/upgrade of the HSI in order to reach high intensity heavy ion beams, required for FAIR

Possible upgrade for HSI at GSI

In order to

- improve performance of the GSI heavy ion UNILAC as injector for FAIR
- reach heavy ion beam intensity required for FAIR

following measures could be proposed:

1. Switching dipole at LEBT: *higher gap between poles*
2. Quadrupole doublet behind HSI-RFQ: *higher aperture and gradients*
3. Superlens: *new rods with trapezoidal modulation*
4. HSI-RFQ: *new rods with trapezoidal modulation*

Winfried Barth & Stepan Yaramyshev

Conclusion and outlook

RFQ is important part of almost all recent linacs

Several linac projects have been realized at GSI during last decade

These projects include new design or upgrade of an RFQ

GSI successfully collaborates with world-leading accelerator centers

Advanced development and fabrication
of a high intensity RFQ could be performed at GSI

GSI High Current Injector could be upgraded
to provide for heavy ion beams required for FAIR

The talk presents common work together with colleagues from

GSI (Darmstadt)
ITEP (Moscow)
IAP (Frankfurt)
HIM (Mainz)
MEPhI (Moscow)
CERN (Geneva)
HIT (Heidelberg)
MPI-K (Heidelberg)

Thank you for your attention !

Beam dynamics codes

Trace 3D — matrix

Mirko

...

$$\begin{pmatrix} x \\ v_x \end{pmatrix} = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} \begin{pmatrix} x_0 \\ v_{x0} \end{pmatrix}$$

Parmila — smooth approximation

Parmila-transport

$$v_r << v_z$$

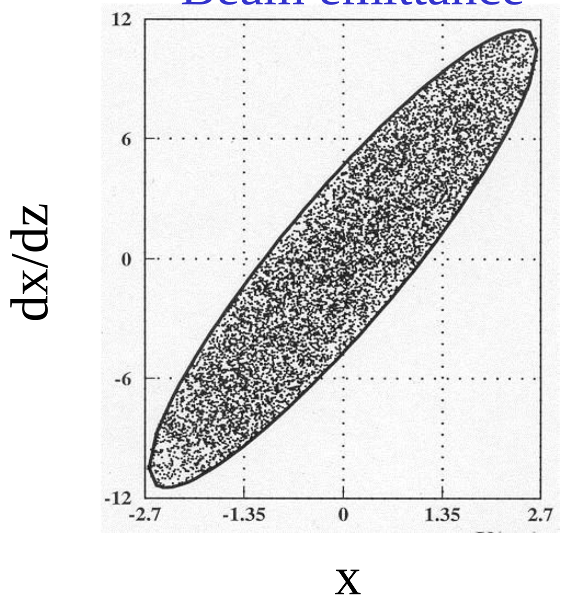
...

...

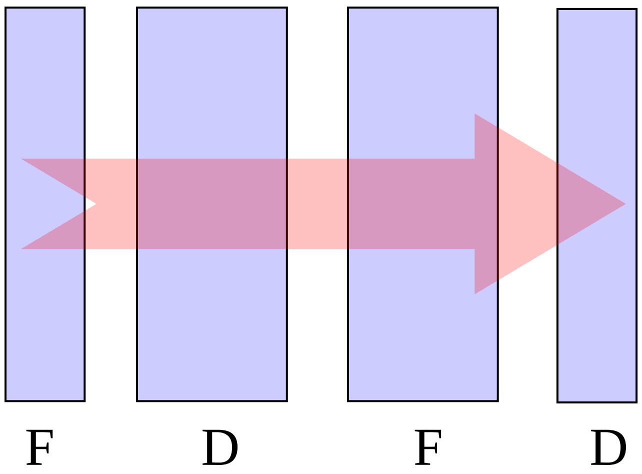
$$\frac{d\vec{p}}{dt} \Rightarrow \frac{d^2\vec{r}}{dt^2} \quad \& \quad \frac{d^2 z}{dt^2}$$

DYNAMION simulations for the Quadrupole Quartet

Beam emittance



Magnetic quadrupole lenses



an elliptical shape
of beam emittance
is expected,
isn't it ?

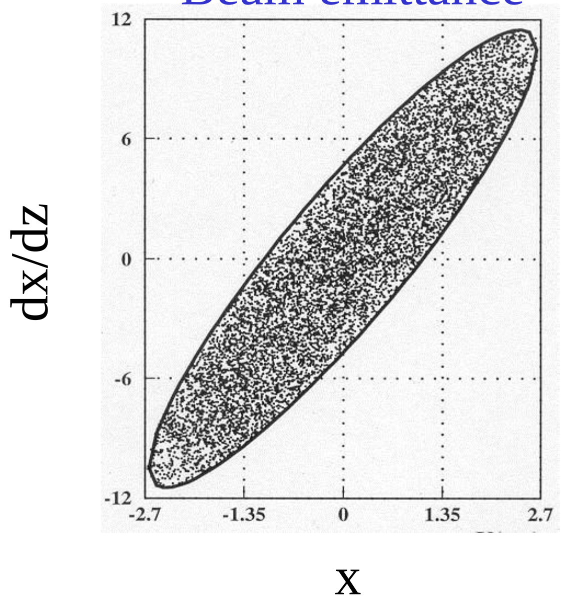
- uniform particle distribution
- no space charge
- ideal (linear) quadrupoles

$$B_x = G * y$$

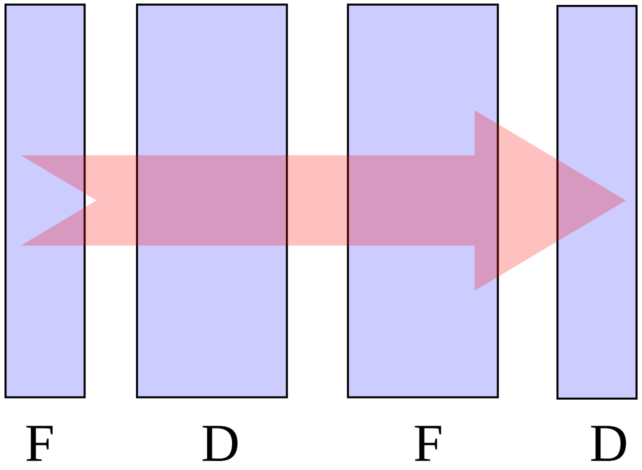
$$B_y = G * x$$

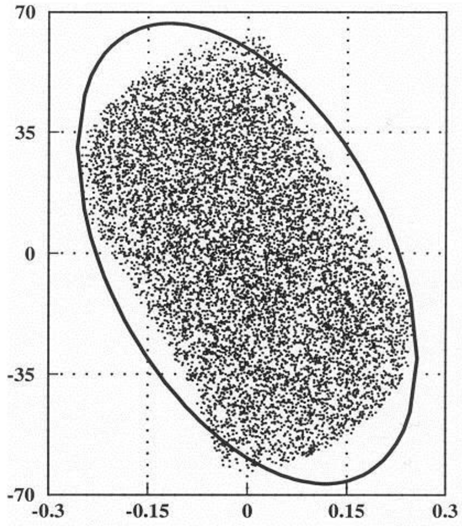
DYNAMION simulations for the Quadrupole Quartet

Beam emittance



Magnetic quadrupole lenses





- uniform particle distribution
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$$B_x = G * y$$

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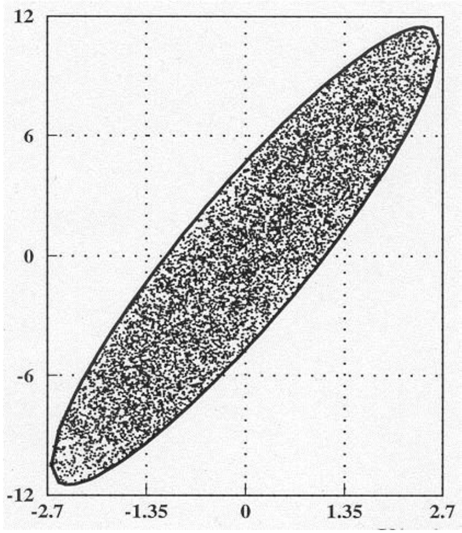
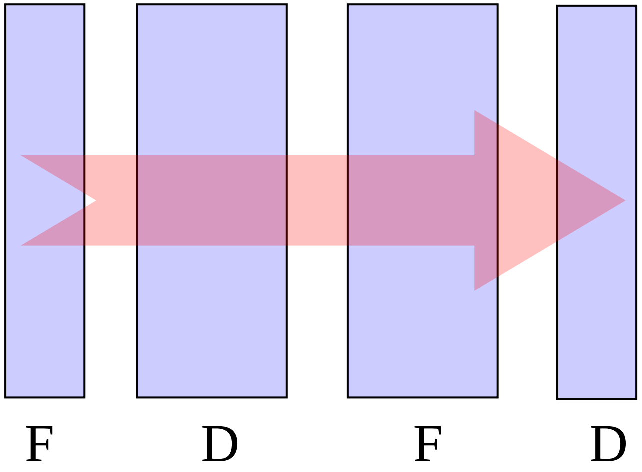
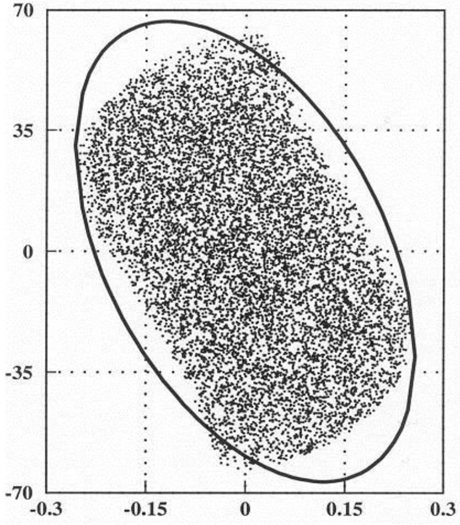
DYNAMION simulations for the Quadrupole Quartet



Magnetic quadrupole lenses





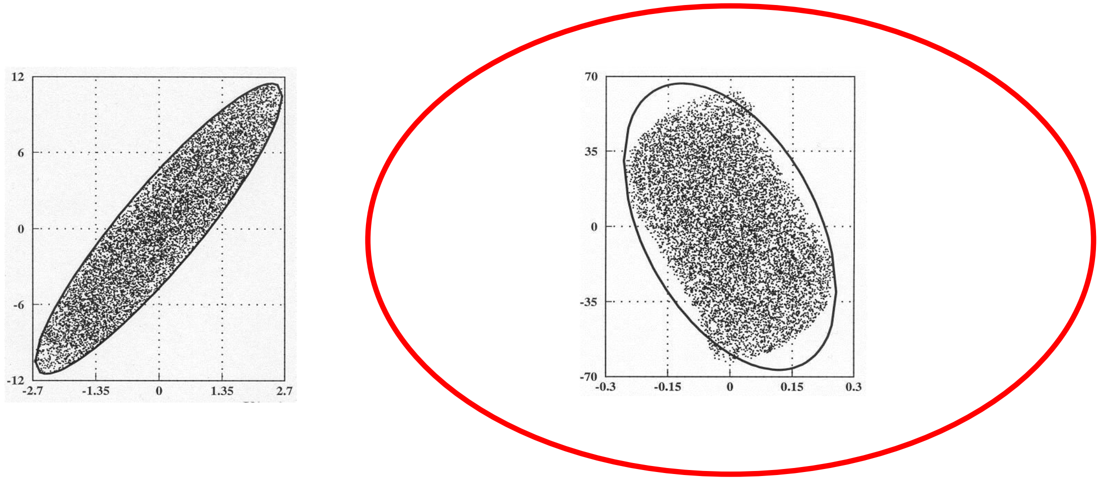
- uniform particle distribution
- no space charge
- ideal (linear) quadrupoles

In quadrupoles transversal velocity is up to 15 % of the longitudinal one.

- not only $v_z \otimes H_x$ and $v_z \otimes H_y$, but also $\mathbf{v_x \otimes H_y}$ and $\mathbf{v_y \otimes H_x}$ are important.

- high transversal component of the particle velocity - less longitudinal one.

DYNAMION simulations for the Quadrupole Quartet



Paraxial approximation doesn't work.

Full 3-D equation is required !!!

A. Lombardi et al. (HIPPI Meeting **2004**)

W. Barth, L. Dahl, S. Yaramyshev (LINAC **2002**)

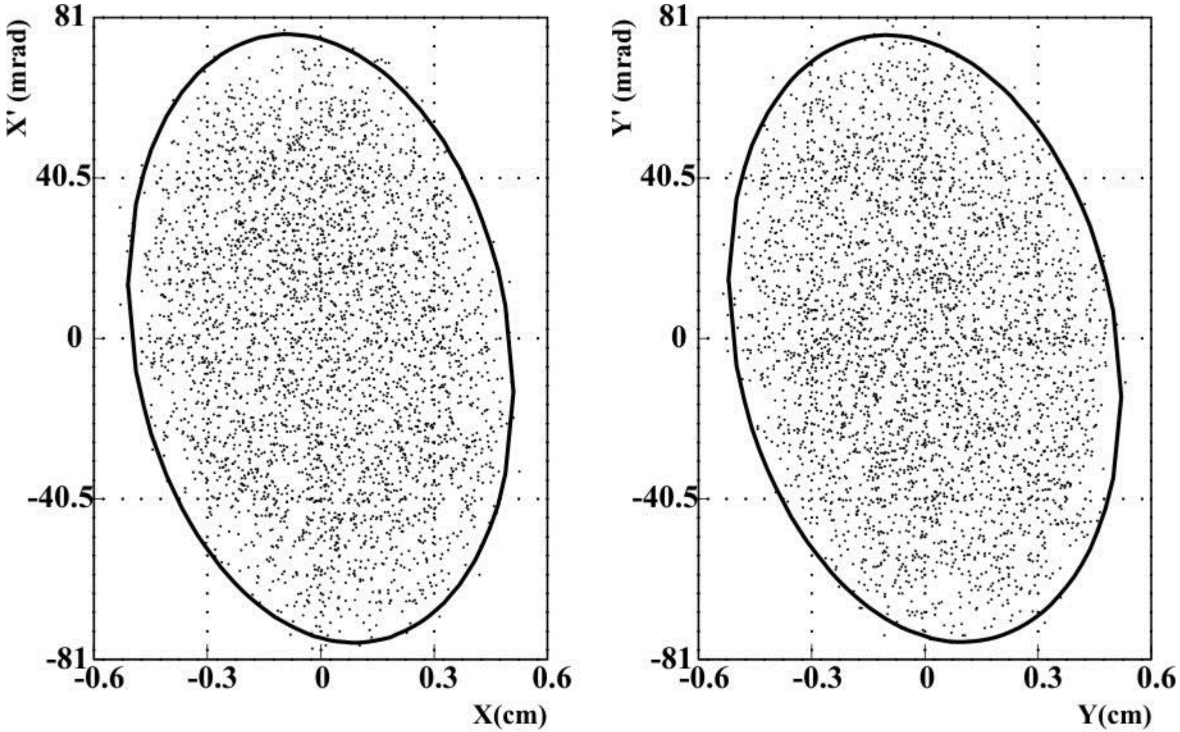
A. Kolomiets and S. Yaramyshev (EPAC **1998**)

A. Kolomiets and S. Yaramyshev (PAC **1995**)

...

HSI-RFQ acceptance / DYNAMION simulations

low beam current / without space charge



Emittance in X,X' plane

Emittance in Y,Y' plane

a_x=**0.17739**		a_y=**0.19673**	
b_x=**0.00674**	**cm/mrad**	b_y=**0.00692**	**cm/mrad**
e_x=**38.5506**	**cm*mrad**	e_y=**39.0769**	**cm*mrad**

"High current" RFQ acceptance

Assuming low beam current and smooth approximation [1], a local normalized acceptance $\boldsymbol{V_k}$ for each RFQ cell can be calculated from the Floquet functions, which are the solution of the Mathieu-Hill equation for the particle motion:

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

$$\nu_f = \frac{1}{\rho^2}$$

where $\boldsymbol{\rho}$ is a module of the Floquet function, $\boldsymbol{a}$ - aperture (radius) of the cell, $\boldsymbol{\lambda}$ - wave length of the operating frequency; $\boldsymbol{\nu_f}$ can be treated as a minimum of the phase advance $\boldsymbol{\mu}$ on the focusing period.

In case of significant beam current, the values of $\boldsymbol{\mu}$ and $\boldsymbol{\nu_f}$ decrease (tune depression). Quantitavely it can be calculated using Coulomb parameter $\boldsymbol{h}$, which combines parameters of the beam and accelerating channel:

$$h = j \cdot \frac{B\lambda}{\mu_0 \beta I_0},$$

where $j = \dfrac{I}{V_p}$ - beam brilliance, $\boldsymbol{I}$ - beam current, $\boldsymbol{V_p}$ - normalized beam emittance, $\boldsymbol{B}$ - ratio of the peak current to the pulse current, $\boldsymbol{I_0}=3.13\cdot 10^7\cdot \boldsymbol{A/Z}$ - characteristic current, $\boldsymbol{A}$, $\boldsymbol{Z}$ - mass and charge numbers, $\boldsymbol{\mu_0}$ - phase advance for "zero" current, $\boldsymbol{\beta}$ - relative velosity of particle. Phase advance and, correspondingly acceptance of the channel can be evaluated as

$$\mu = \mu_0\left(\sqrt{1+h^2} - h\right), \qquad V_k = V_{k0}\left(\sqrt{1+h^2} - h\right)$$

High current RFQ acceptance