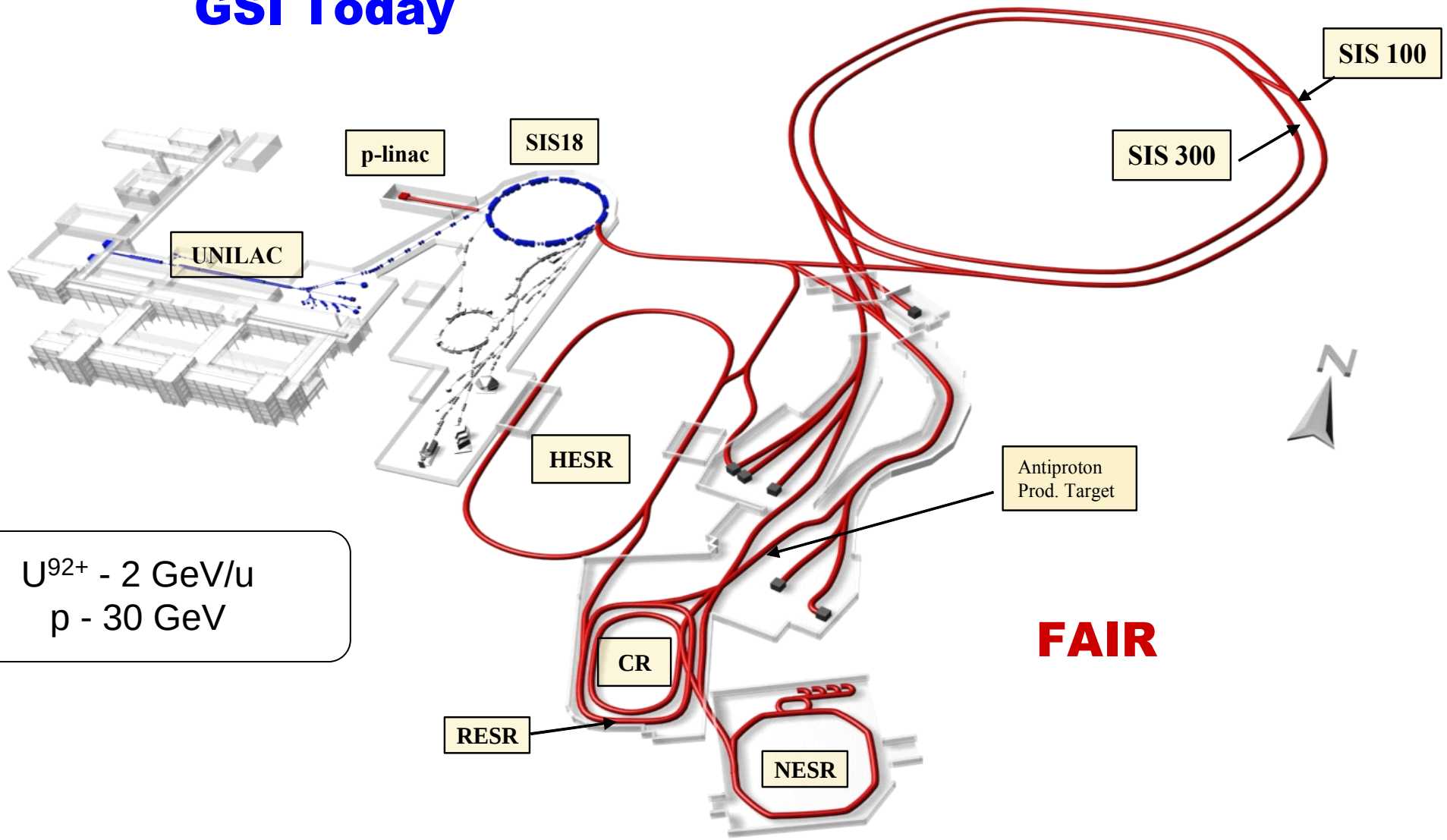
Development and application of the RFQs for FAIR and GSI Projects

Stepan Yaramyshev

GSI, Darmstadt

Facility for Antiproton and Ion Research at Darmstadt

GSI Today



U^{92+} - 2 GeV/u
p - 30 GeV

FAIR

FAIR and GSI linac Projects

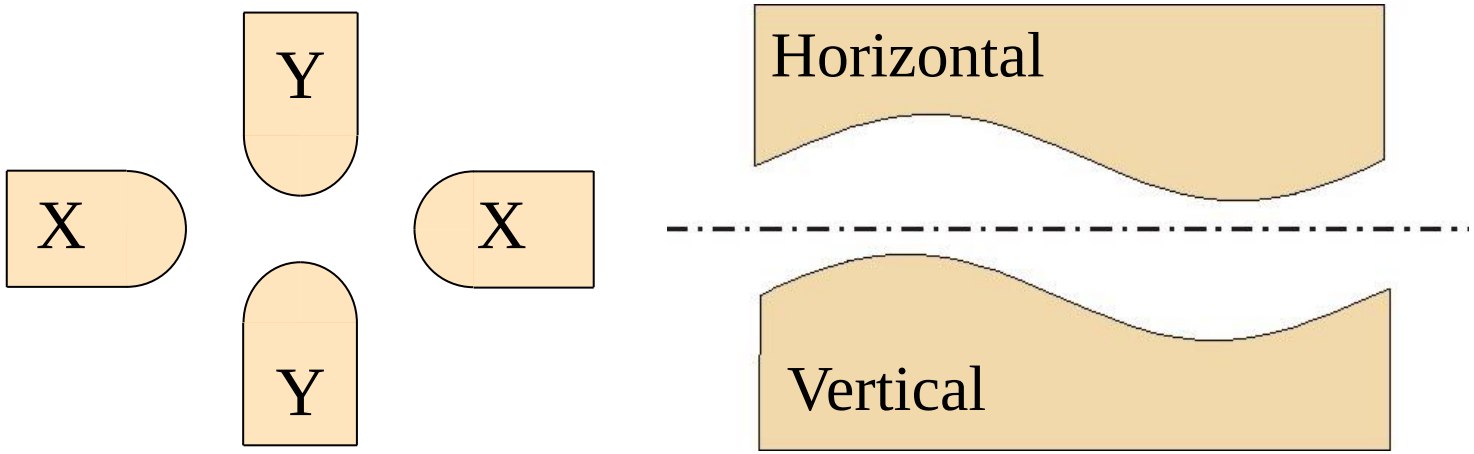
- Heavy ion high current UNILAC (in operation)
- High current proton linac (R&D stage)
- CW linac (demonstrator)
- HITRAP decelerator (commissioned in 2014)
- Therapy linac at Heidelberg (in operation)

Radio Frequency Quadrupole - RFQ

Invented in 1970 by Prof. Kapchinsky and colleagues (IHEP, Russia)

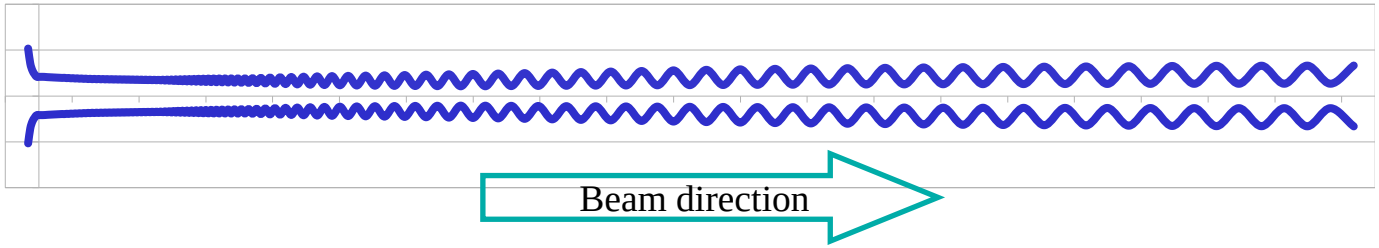
Recently RFQ is used as a front-end for almost all proton and ion linacs

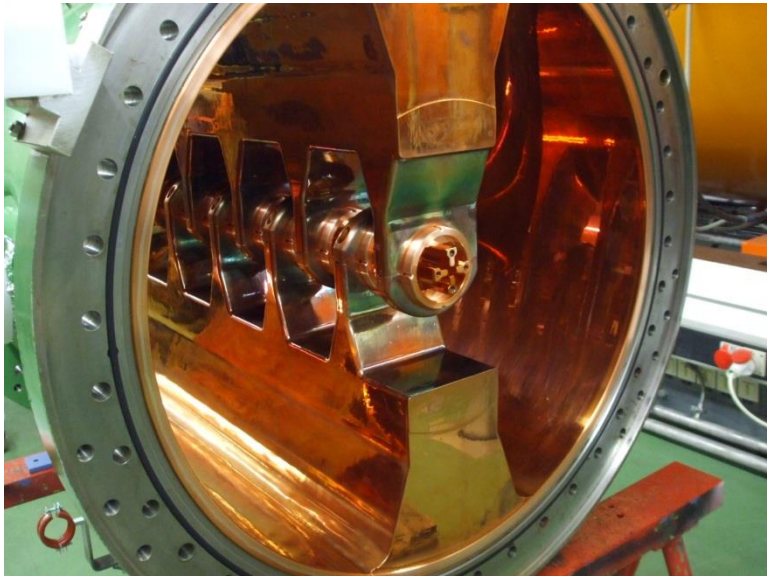
RFQ Structure



Modulated electrodes provide for simultaneous beam focusing and acceleration

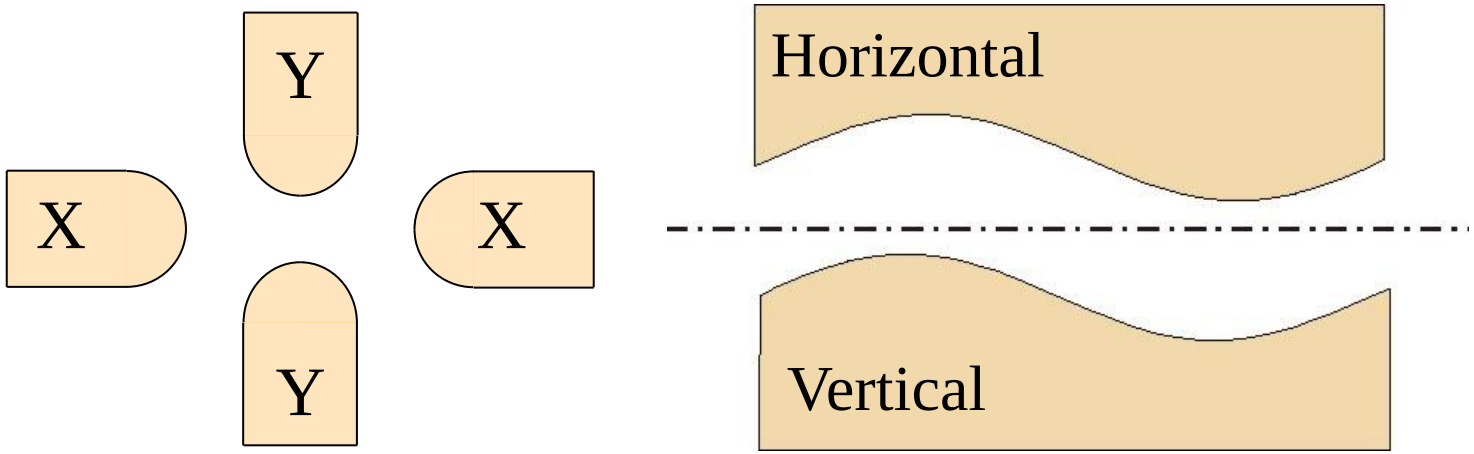
Schematic view of an RFQ electrodes





Modulation for horizontal and vertical electrodes is shifted on 180°

RFQ Structure



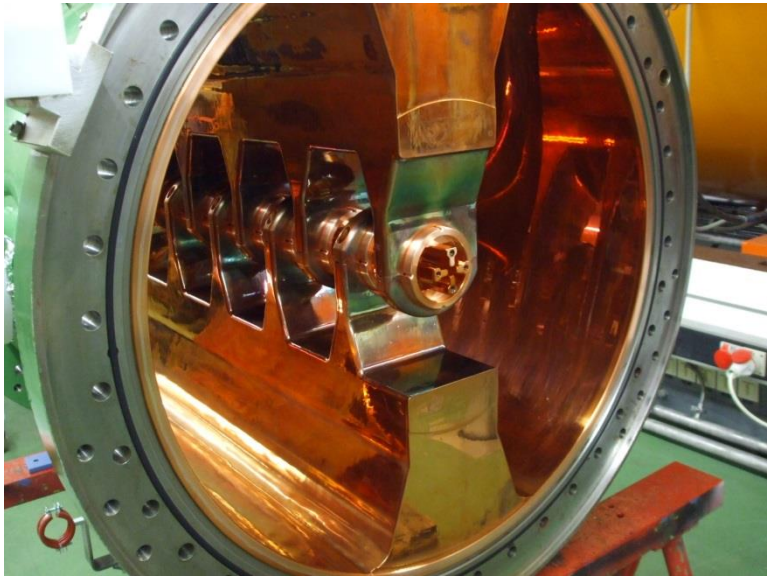
Modulated electrodes provide for simultaneous beam focusing and acceleration

Potential of an RFQ cell by ***Prof. Kapchinsky*** *(ITEP, Moscow)*

$$U(r,\psi,z) = -\frac{U_l}{2}\left[F_0(r,\psi) + \sum_{n=1}^{\infty} F_n(r,\psi)\sin(2n-1)\,kz\right]$$

$$F_0(r,\psi) = \sum_{s=0}^{\infty} A_{0s}\left(\frac{r}{R_0}\right)^{2(2s+1)}\cos\left(2(2s+1)\psi\right)$$

$$F_n(r,\psi) = \sum_{s=0}^{\infty} A_{ns}\, \mathrm{I}_{4s}\left[(2n-1)\,kr\right]\cos 4s\psi$$



z,r,ψ - cylindrical coordinates, F_n, A_{ns} - Fourier-Bessel coefficients, $k = 2\pi/\beta\lambda$, β - relative ion velocity, λ - wavelength of rf field, R_0 - average aperture of an RFQ

DESRFQ – a Code for Design of Radio Frequency Quadrupole

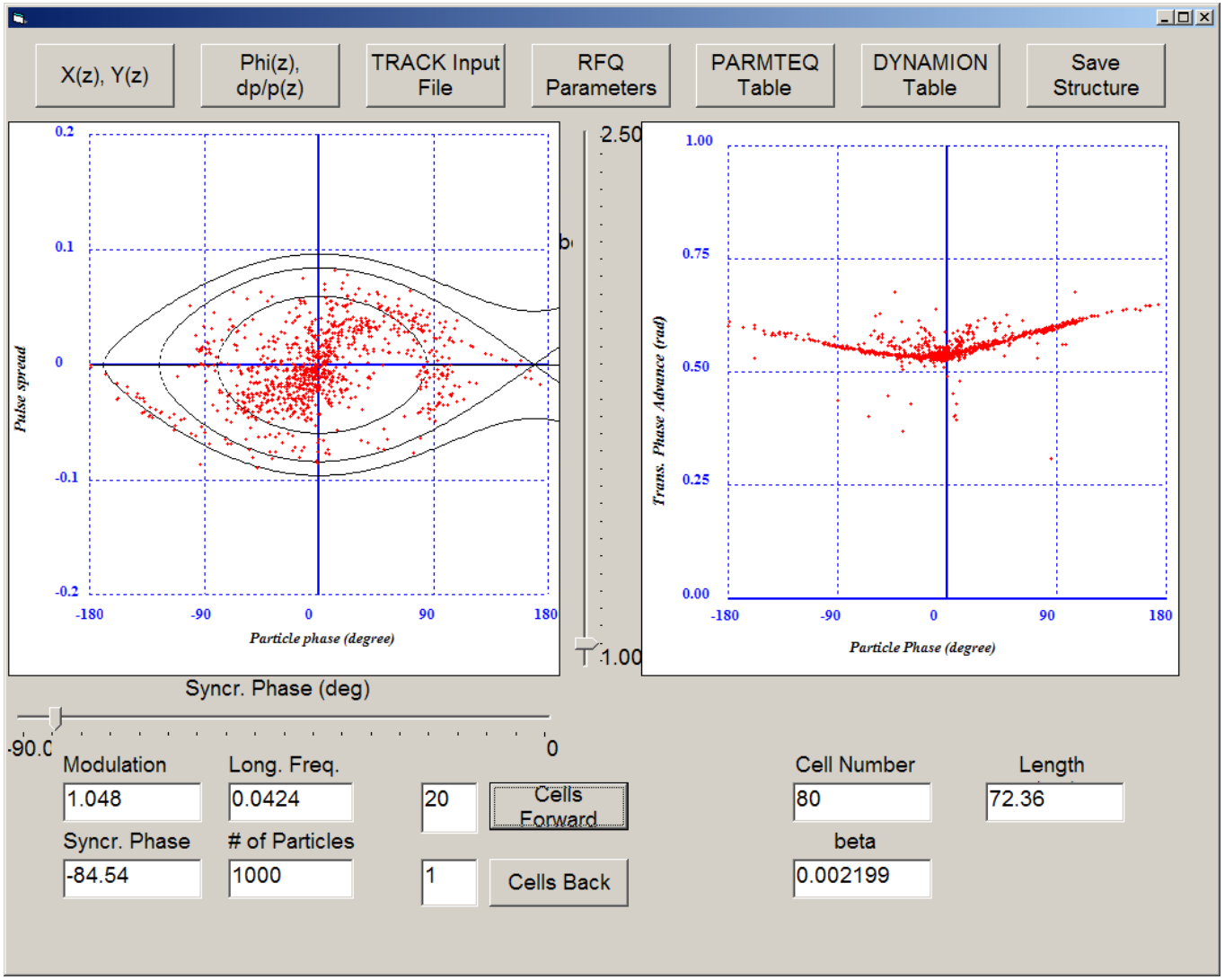
A. Kolomiets, S. Yaramyshev et al.

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

about 1997

Step III: detailed RFQ design cell-by-cell

DESRFQ window for interactive work



- advanced
- visualized
- interactive
- user friendly
- ...

Requirements for an RFQ design

Proper RFQ design:

- high particle transmission (up to 100%)

- high intensity (compensation of space charge)

- low emittance growth (dedicated modulation law)

- reliable routine operation (limited power & voltage)

Proper beam matching to RFQ

RFQ is not a separate part of linac - should be designed together with of sections in front and behind RFQ

Dedicated advanced software is required !

Multiparticle DYNAMION code

- has been written in Institute for Theoretical and Experimental Physics (ITEP, Moscow) for the simulations of the beam dynamics in high current linacs (1985)

- development since 1993 was supported by GSI

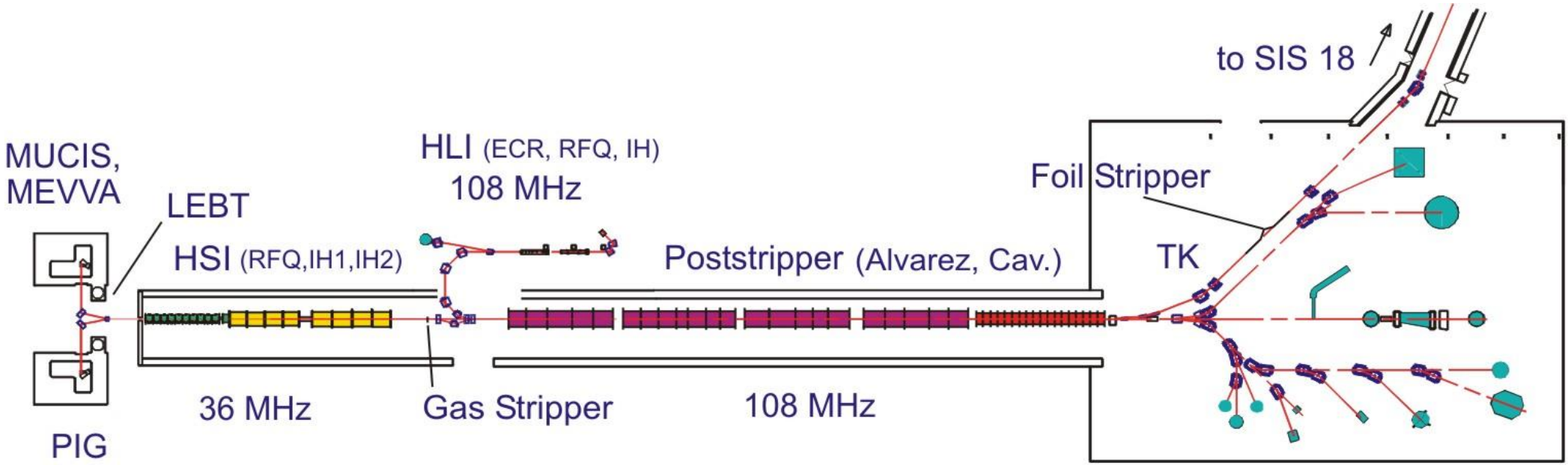
- significant further improvement was done at GSI during last decade

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

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

S. Yaramyshev et al, "Development of the versatile multi-particle code DYNAMION", Nuclear Inst. and Methods in Physics Research A, Vol 558/1 pp 90-94, (2006)

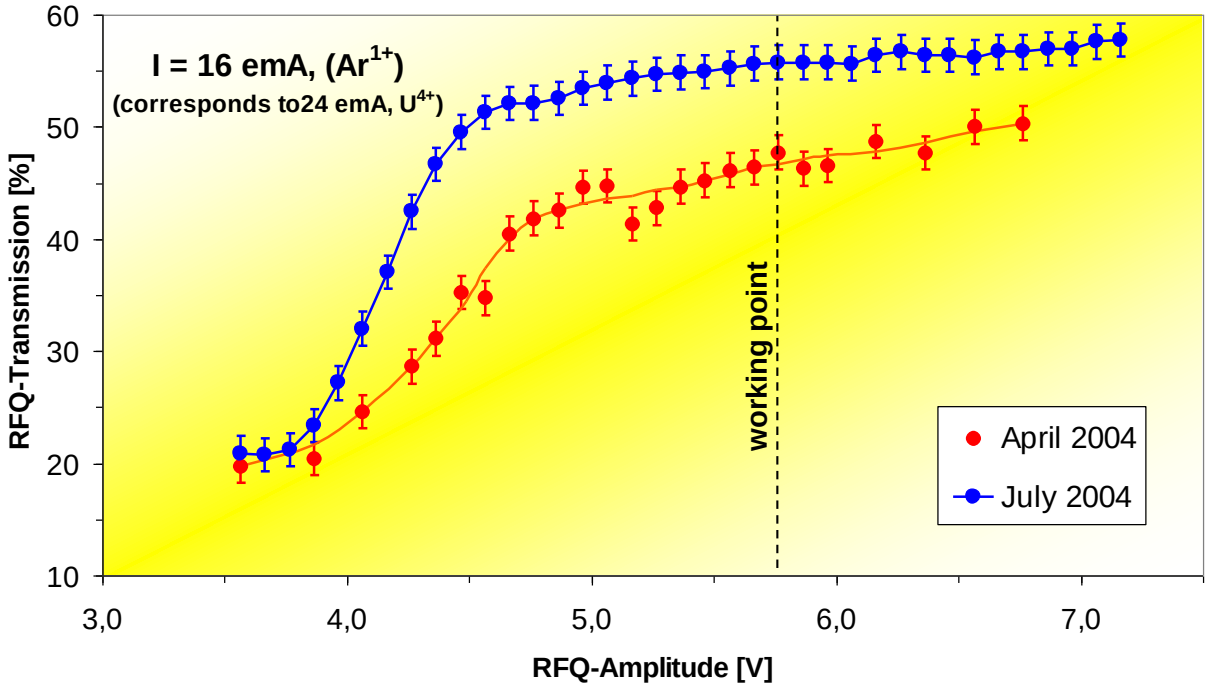
UNIversal Linear ACcelerator



Winfried Barth
Injector-upgrade for FAIR
ICST for FAIR (2014)

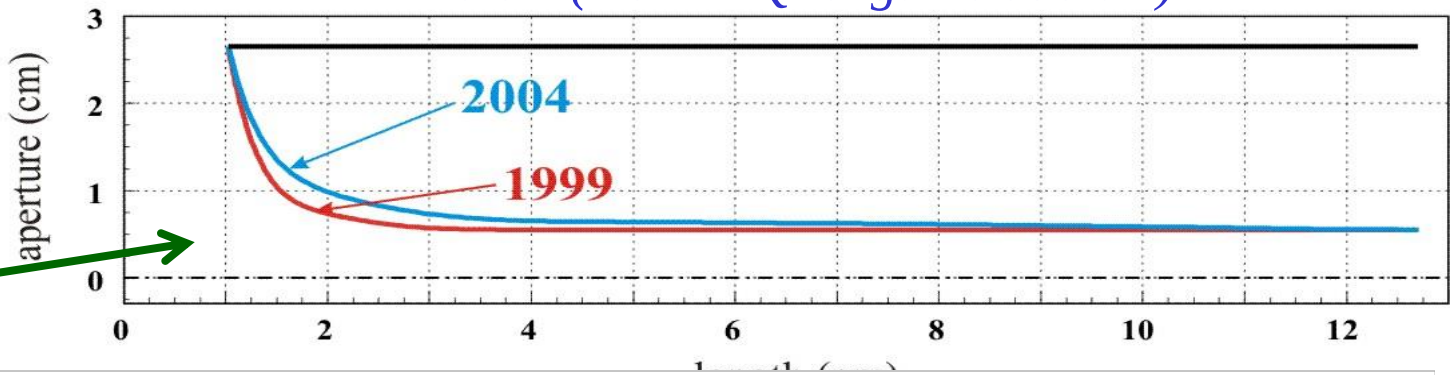
Improvement of the HSI-RFQ electrodes

Upgrade 2004



Simulated results and measurements are in a good coincidence

≈10 cm *(HSI-RFQ length is 930 cm)*

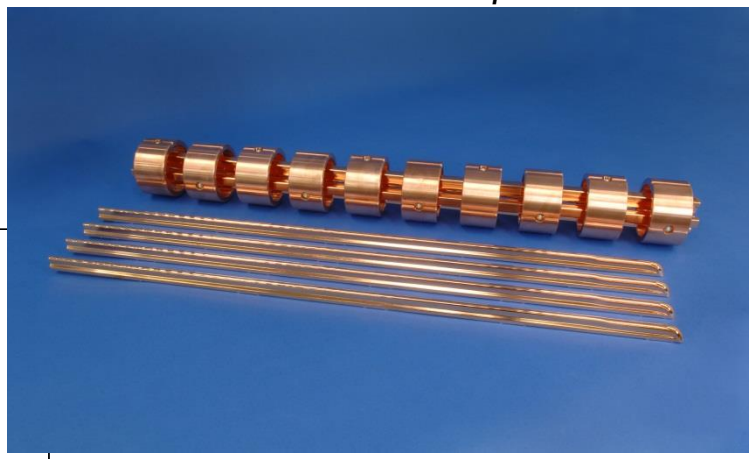


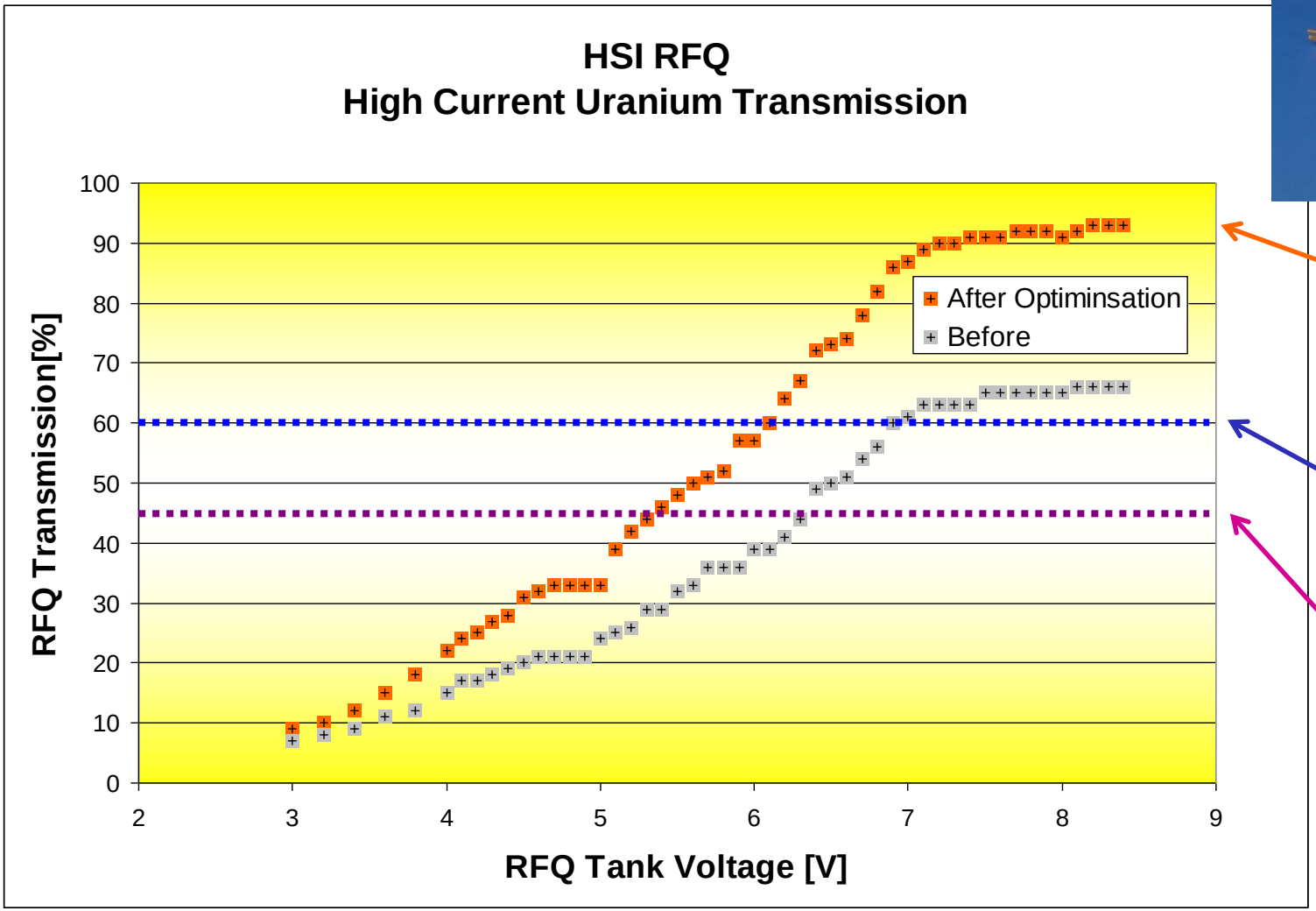
New design of the HSI-RFQ electrodes

*Upgrade **2009***

A. Kolomiets, S. Minaev *ITEP (Moscow)*

UNILAC Department & GSI Workshop





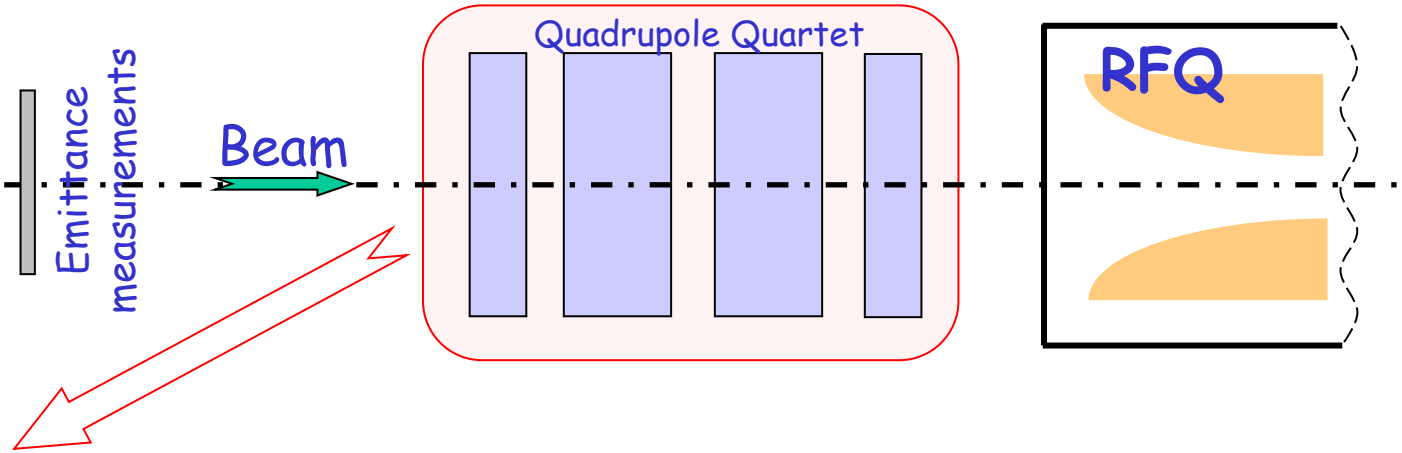
*upgrade **2009***

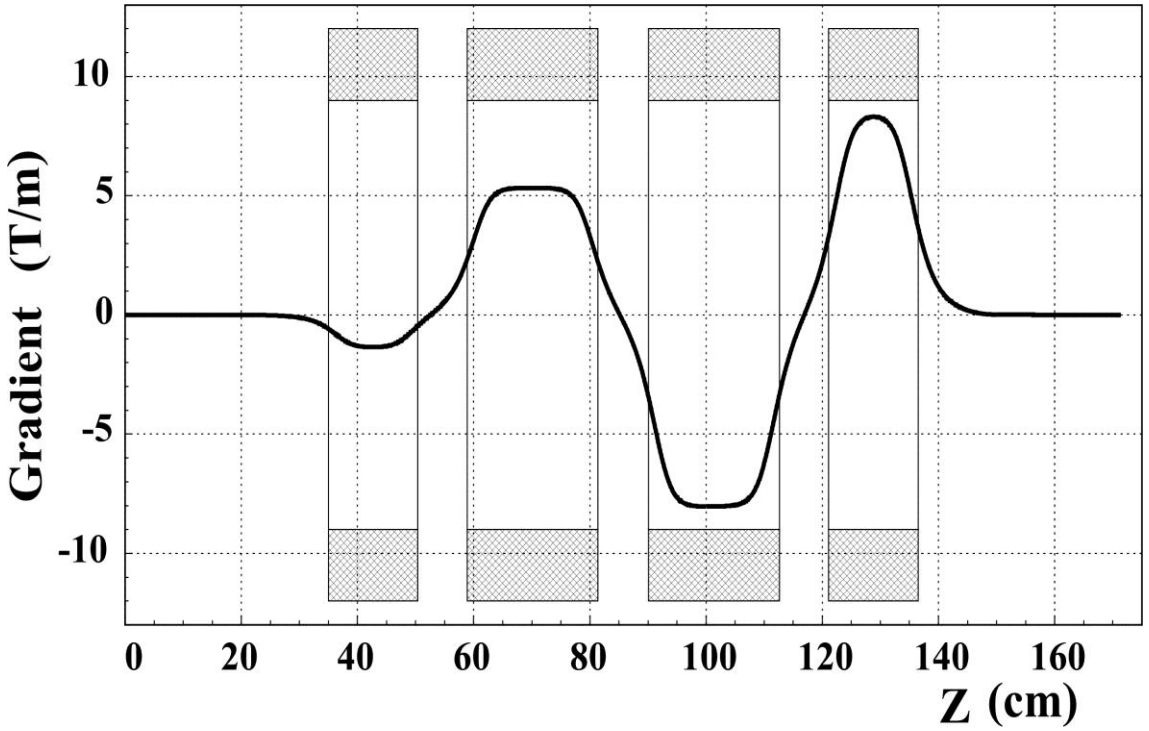
*upgrade **2004***

1999 - 2003

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).



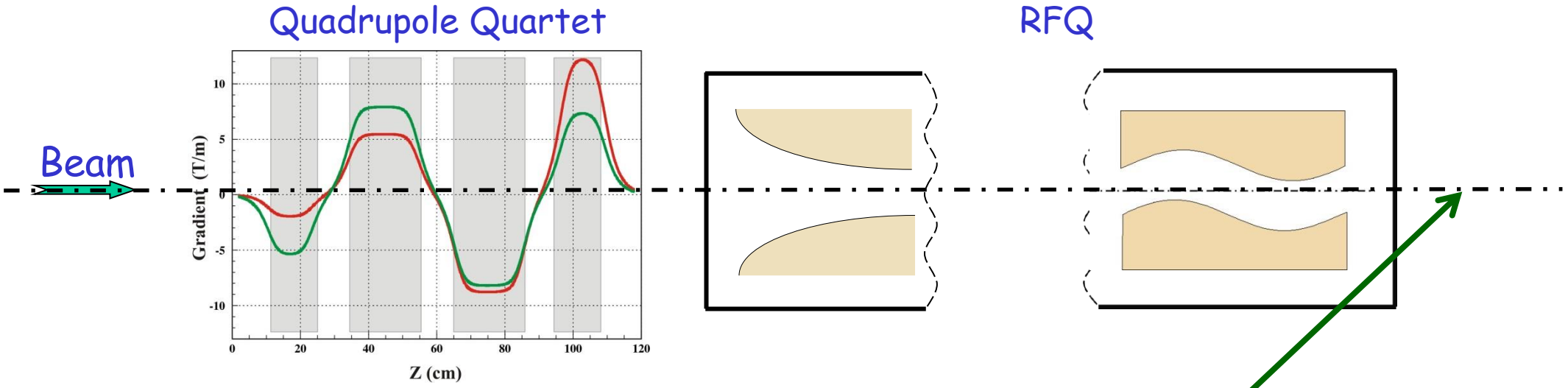


Quadrupole settings for optimum transmission have been found experimentally in 2009

Dedicated beam dynamics simulations with:
- input particle distribution generated from measured beam emittance
- measured magnetic field in lenses
- realistic RFQ description

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
experimental data

Old settings ≈ 50%
New settings ≈ 75%

Beam brilliance (*current / emittance*) improvement
beam dynamics simulations

horizontal & vertical - about factor of 2
longitudinal - about 60%

Proton RFQ for FAIR

General goals of the RFQ design:

- reliable long-term routine operation

- high particle transmission

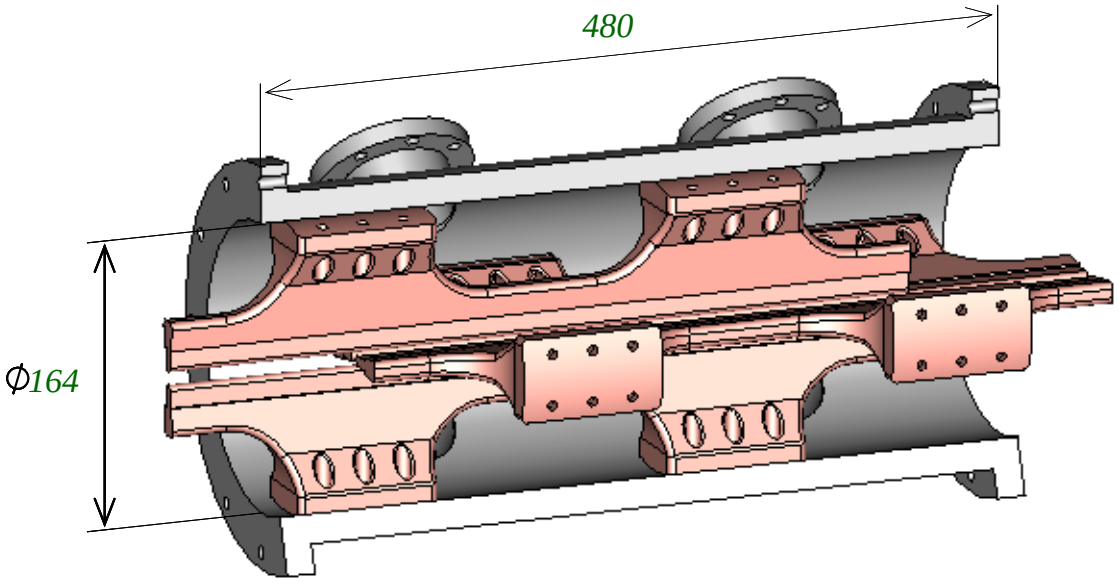
- beam quality behind RFQ

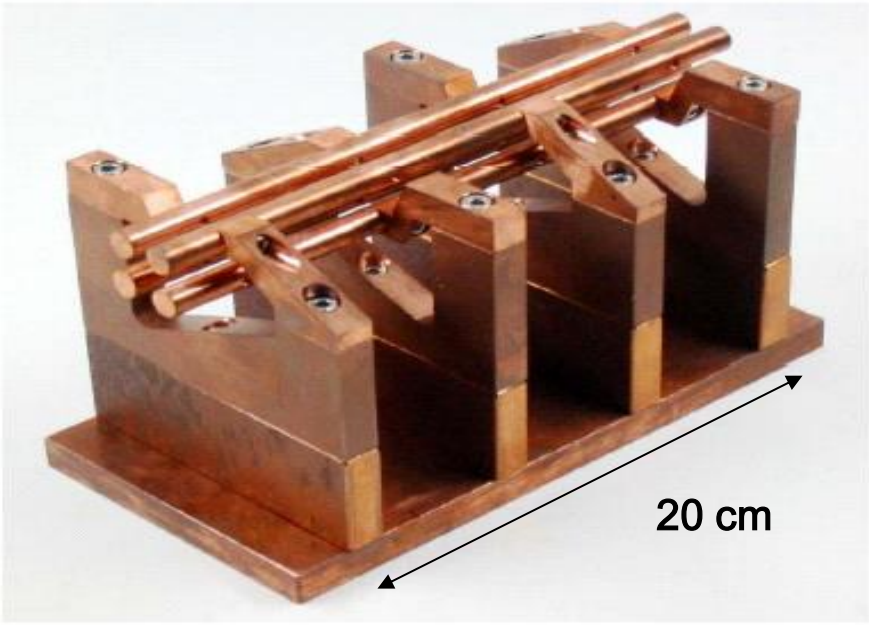
Frequency	324.224 MHz
Input energy	95 keV
Output energy	3.0 Mev
Voltage	80 kV
Max. field strength	≤ 2.0 Kp
Length	< 330 cm
Input emittance (total, unnorm.)	105 mm*mrad
Input beam current	70 mA

p-RFQ for FAIR

ITEP (Moscow) S. Minaev, A. Kolomiets et al.
4-vane (windows)

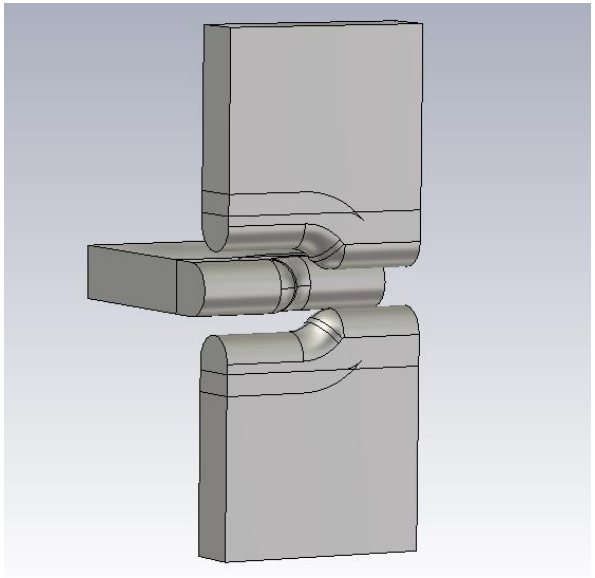
IAP (Frankfurt) A. Schempp et al.
4-rod

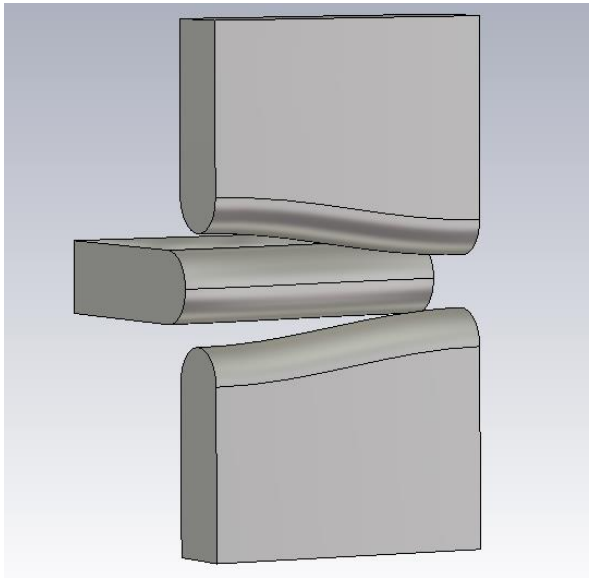




GSI design activity for p-RFQ for FAIR

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

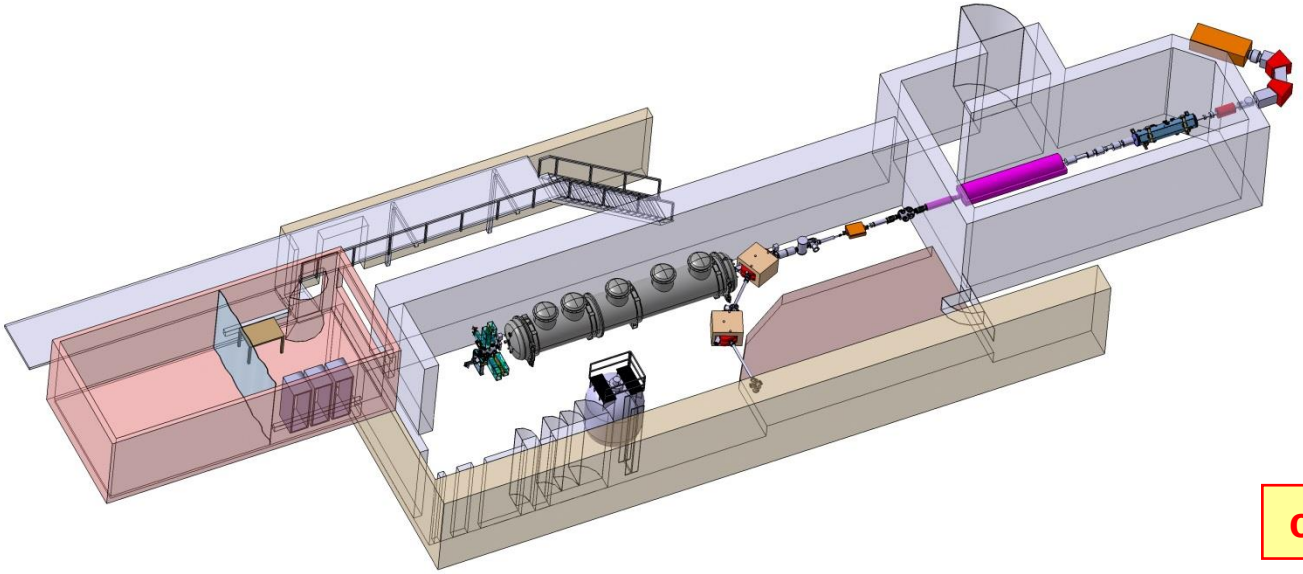




- Cross-check of software based on CERN p-RFQ (commissioned in 2013)

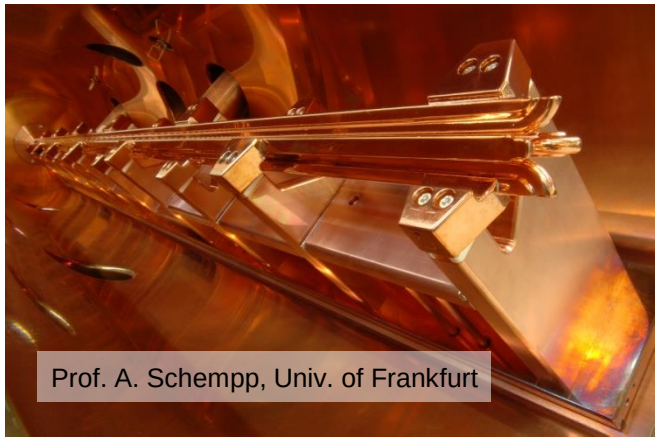
GSI / HIM superconducting CW-linac

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



High Charge State (HLI) injector for UNILAC

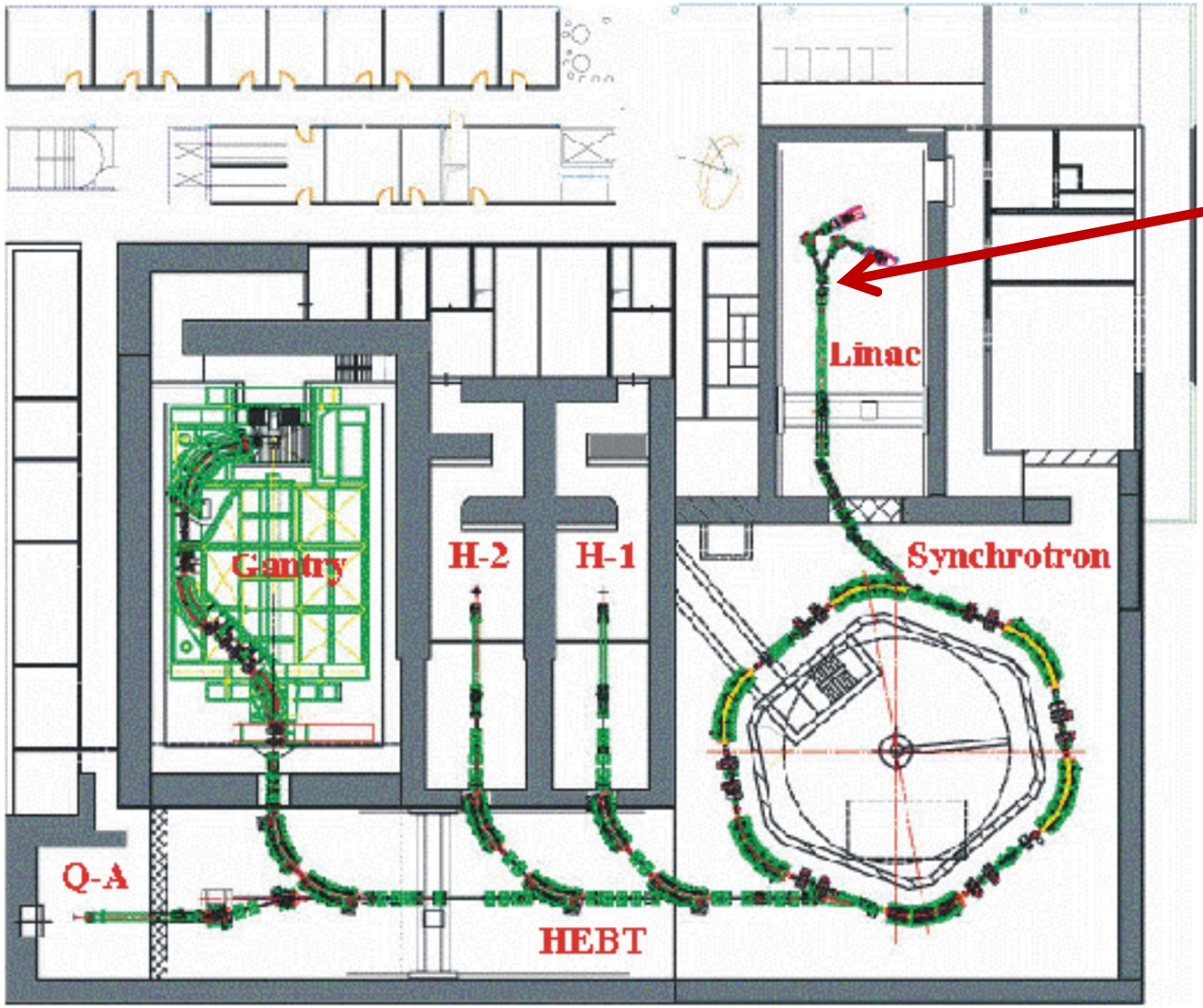
cw-RFQ-commissioning (2010)



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

Upgrade of the HIT Injector Linac-Frontend

HIT - Therapy Accelerator in Heidelberg, Germany

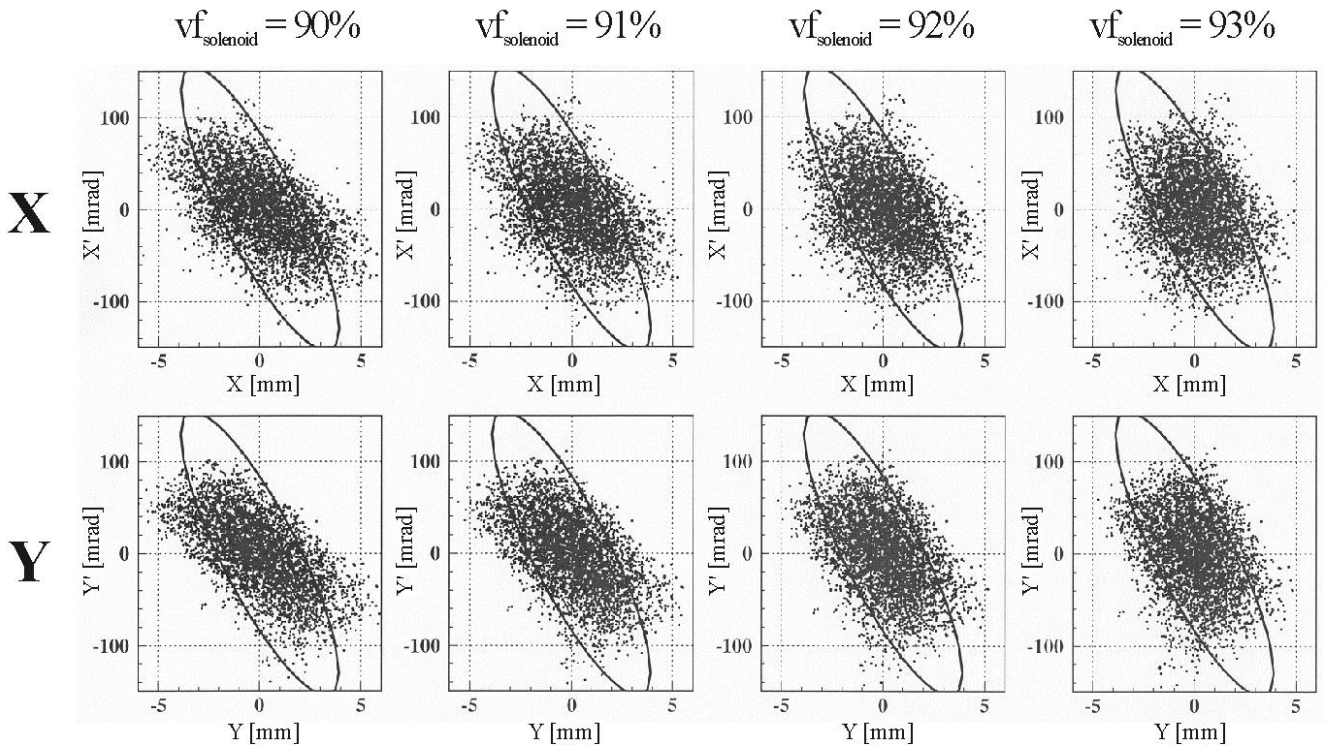


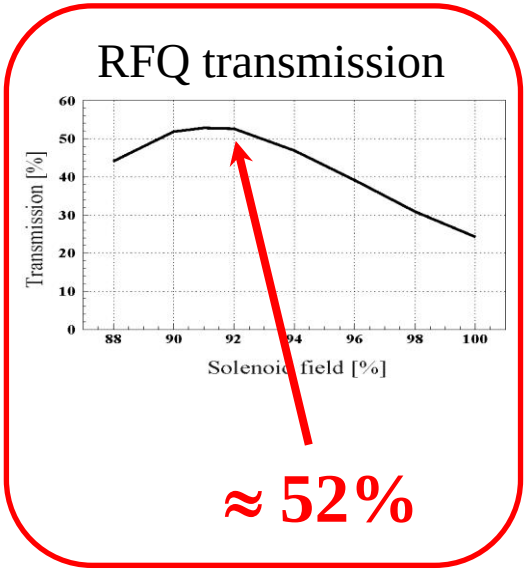
Beam matching to RFQ acceptance with solenoid

Beam matching to HIT-RFQ

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

the beam emittance

to the RFQ acceptance

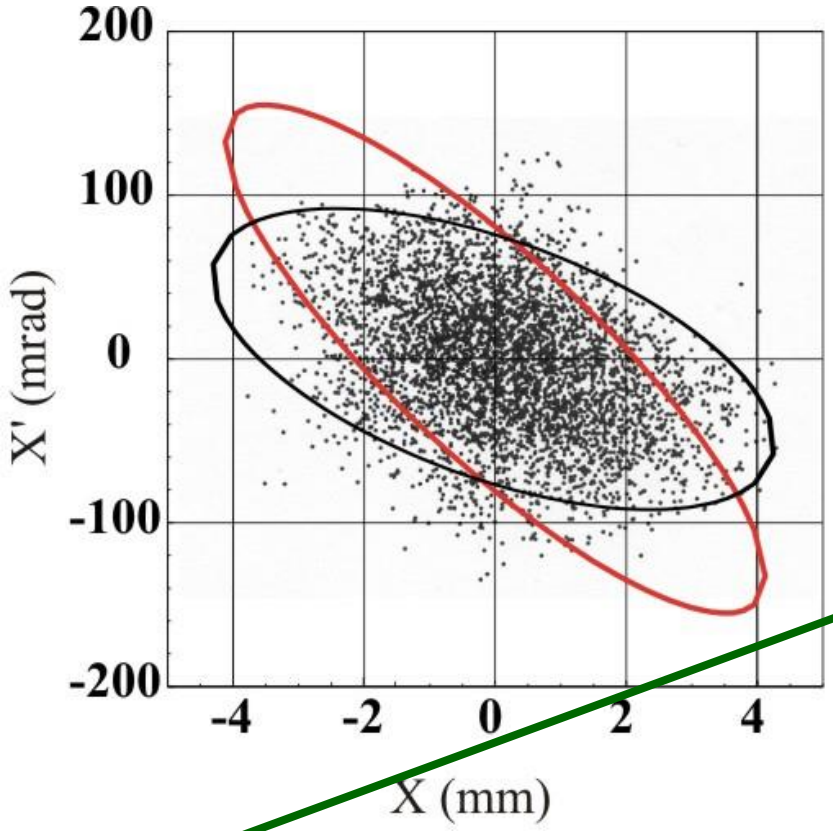
But we can adjust

the RFQ acceptance

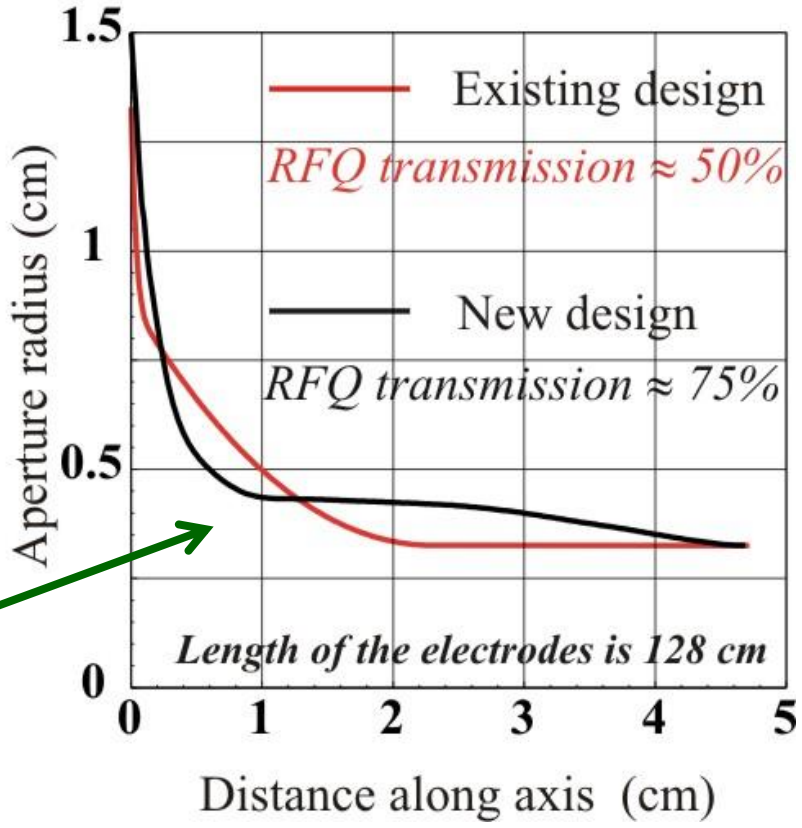
to the beam emittance !

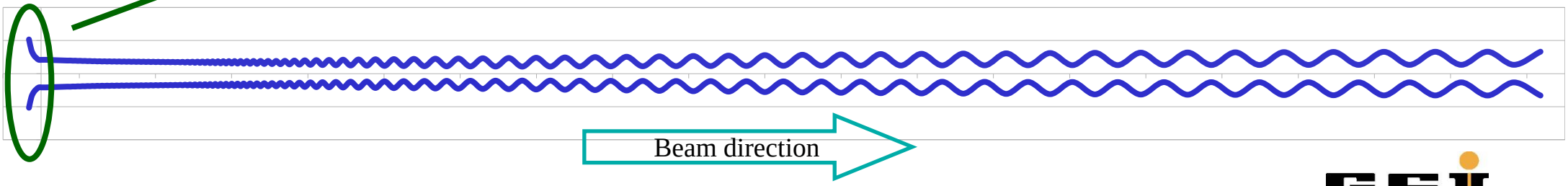
New shape of HIT-RFQ Input Radial Matcher

RFQ acceptance at the entrance

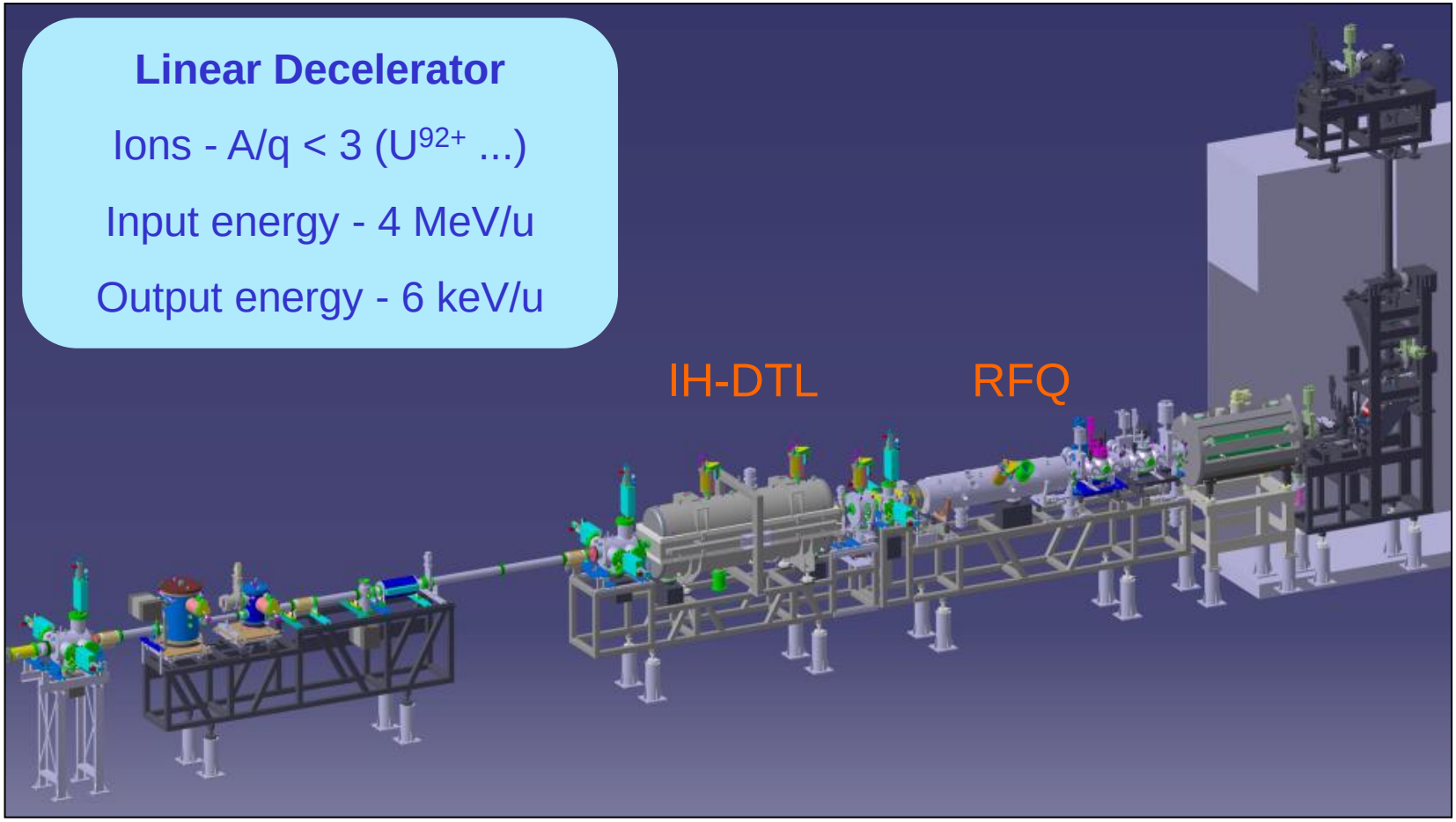


Shape of the IRM





HITRAP decelerator at GSI



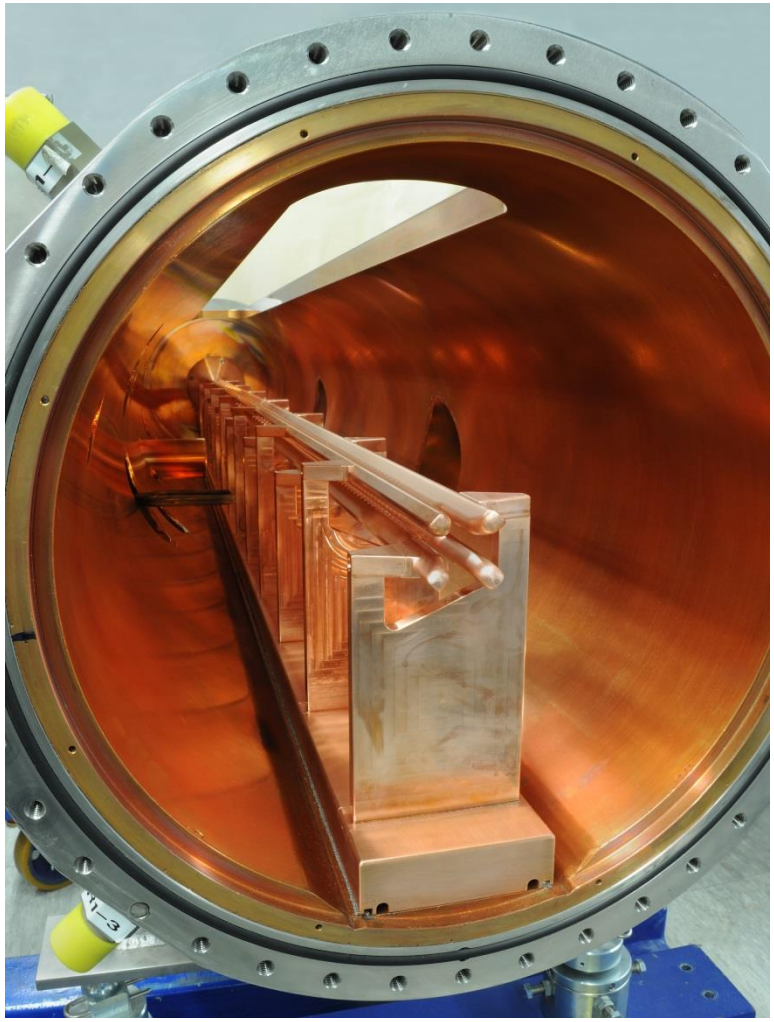
Deceleration:

with IH 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 500 keV/ beam for the RFQ in transport mode and correct quadrupole adjustment

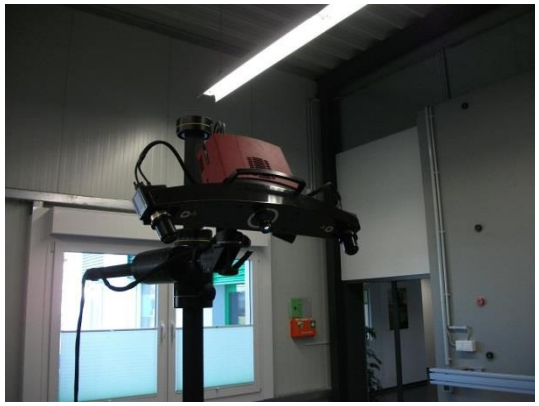
- for this setting the deceleration efficiency is expected around 80% according to PARMTEQM simulation

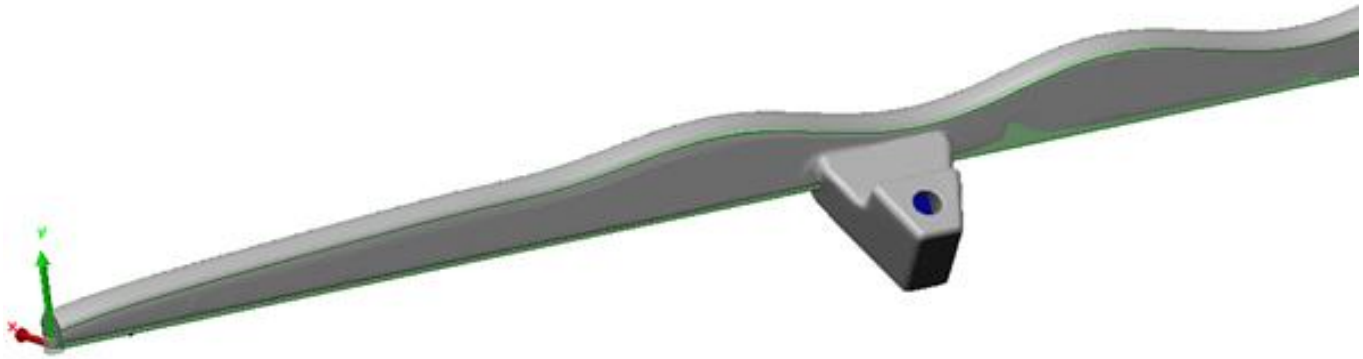
No deceleration with RFQ

was observed at HITRAP facility

HITRAP RFQ decelerator

Fabrication data not available => photometric measurements for the electrodes





Investigation with DYNAMION package:

HITRAP-RFQ can decelerate ions with an energy of 525±10 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 RFQ acceptance !

Design idea: deceleration in RFQ is differs from acceleration (PARMTEQM)
RFQ was designed to accelerate particles from **6 keV/u** to about **525 keV/u**
Then it should decelerate ions of about **500 keV/u** (design value) to **6 keV/u**

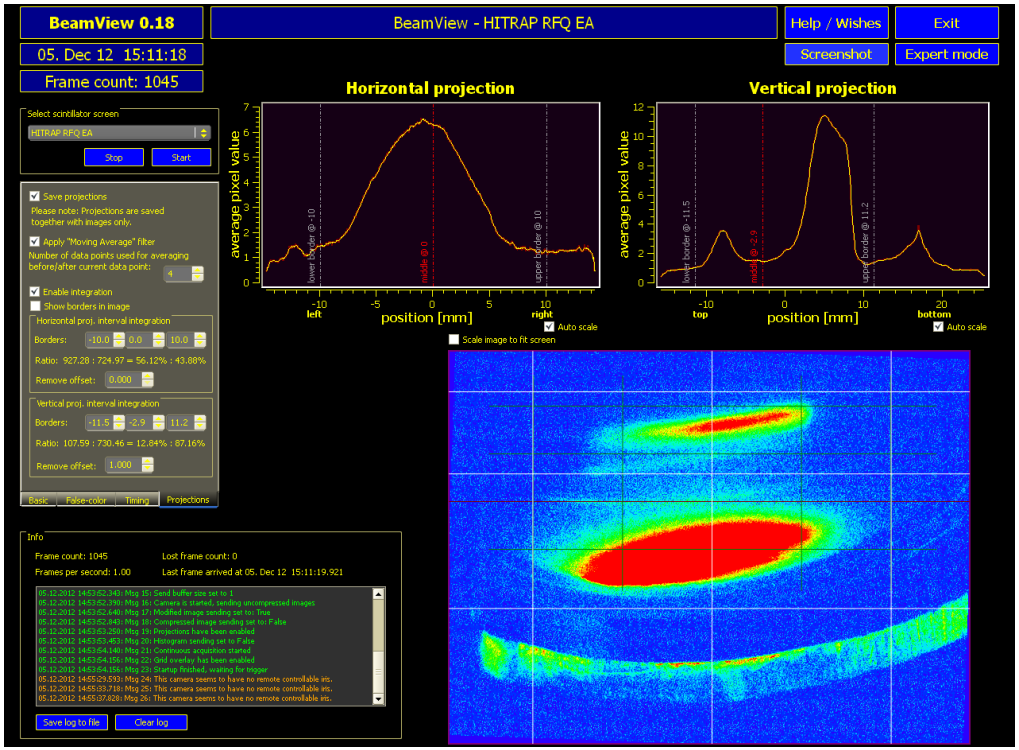
New design for HITRAP RFQ decelerator

HITRAP-RFQ (old design) has been tested using beam with variable energy at MPI-K (Heidelberg): deceleration of ions with an energy of about 525 keV/u was confirmed

- **New design** of RFQ decelerating-focusing channel has been done at GSI using dedicated 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 accembled and tuned at GSI

New design for HITRAP RFQ decelerator

HITRAP-RFQ (new design) has been tested using beam with variable energy at MPI-K (Heidelberg): deceleration of ions with required energy of about 500 keV/u was confirmed



Typical screen-shot from measurements at MPI-K

← **6 ± 1 keV/u**

← **500 ± 10 keV/u**

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

Whole HITRAP linear decelerator has been successfully commissioned in July 2014

Conclusion and outlook

An RFQ is important part of almost all recent linacs

Several linac projects have been realised at GSI during last decade

Most of these Projects include new design or upgrade of an RFQ

GSI successfully collaborates with world-leading accelerator centers

Proper development of an RFQ could be done at GSI, including:

- accelerating-focusing channel
- rf-cavity
- mechanical construction
- tuning
- commissioning

Recent GSI activity is directed to the upgrade / new design of injectors for FAIR:

- **High current heavy ion UNILAC upgrade**
- **Proton Linac for antiproton research**

Development of dedicated RFQ is a key measure for both projects

The talk presents common work
together with colleagues from

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

Thank you for your attention !