Development and application of the RFQs for FAIR and GSI Projects

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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)

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

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

\[
F_n(r,\psi) = \sum_{s=0}^{\infty} A_{ns} I_{4s}[(2n-1)kr] \cos 4s\psi
\]

\( z, r, \psi \) - cylindrical coordinates, \( F_n, A_{ns} \) - Fourier-Bessel coefficients, 
\( k = \frac{2\pi}{\lambda}, \beta \) - relative ion velocity, \( \lambda \) - wavelength of rf field, \( R_0 \) - average aperture of an RFQ.


ICST for FAIR, 15 October 2014

Development and application of the RFQs ...

S. Yaramyshev
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

Development and application of the RFQs...

S. Yaramyshev

ICST for FAIR (2014)

Winfried Barth

Injector-upgrade for FAIR

GSI
Improvement of the HSI-RFQ electrodes

Simulated results and measurements are in a good coincidence

$I = 16 \text{ emA, (Ar}^{1+})$
(corresponds to $24 \text{ emA, U}^{4+}$)

$I = 16 \text{ emA, (Ar}^{1+})$
(corresponds to $24 \text{ emA, U}^{4+}$)

Beam direction

$\approx 10 \text{ cm (HSI-RFQ length is 930 cm)}$

Upgrade 2004

Development and application of the RFQs...

S. Yaramyshev
New design of the HSI-RFQ electrodes

A. Kolomiets, S. Minaev *ITEP (Moscow)*
UNILAC Department & GSI Workshop

**HSI RFQ**
High Current Uranium Transmission

<table>
<thead>
<tr>
<th>RFQ Tank Voltage [V]</th>
<th>RFQ Transmission [%]</th>
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<tr>
<td>2</td>
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<td>8</td>
<td>60</td>
</tr>
<tr>
<td>9</td>
<td>70</td>
</tr>
</tbody>
</table>

- **Before**
- **After Optimisation**

Upgrade 2009

Section 1 of 10
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

Beam brilliance (current / emittance) improvement beam dynamics simulations

Old settings $\approx 50\%$  
New settings $\approx 75\%$

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)
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!

\[ \approx 52\% \]
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

Existing design

RFQ transmission ≈ 50%

New design

RFQ transmission ≈ 75%

Length of the electrodes is 128 cm

Beam direction
HITRAP decelerator at GSI

Linear Decelerator
- Ions - A/q < 3 (U⁹²⁺ ...)
- Input energy - 4 MeV/u
- Output energy - 6 keV/u

Deceleration:
- with IH from 4 MeV/u to 500 keV/u
- with RFQ from 500 keV to 6 keV/u
HITRAP RFQ decelerator

- 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 assembled 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

- $6 \pm 1$ keV/u
- $500 \pm 10$ 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 an important part of almost all recent linacs. Several linac projects have been realised at GSI during the 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!