Development of RFQ Accelerators for Modern Scientific and Applied Research

Chuan Zhang
Institute for Applied Physics, Goethe-University
zhang@iap.uni-frankfurt.de

Seminar at Lawrence Berkeley National Laboratory, United States, May 31, 2012
San Francisco Bay: A Cradle for Modern Accelerators

1930: Ernest O. Lawrence invented the cyclotron at University of California, Berkeley.

1947: Luis W. Alvarez built the first Drift Tube Linac for protons at University of California, Berkeley.

1949: Edward L. Ginzton developed the first disc-loaded linac for electrons at Stanford University.
Scientific and Applied Research Driven by Accelerators

Time tree by U. Amaldi & K. Bethge

Pic: lbl.gov
Modern Accelerator-Based Science Centers

RHIC 2000

SNS 2006

LHC 2008

FAIR 2016?
Modern Accelerators for Energy Development

European ADS project for nuclear waste transmutation

Pic: SCK-CEN

Ifmif: International Fusion Materials Irradiation Facility

Pic: Ifmif

© Enea, 2001

- EU: 145 reactors
- 35% of electricity
- 2500 tons of waste/year (Pu: 1%, minor actinides...)

© Enea, 2001

Spallation

Fission

Neutrons

Li flow

© Enea, 2001

spent fuel before and after transmutation

Transmutation (ADS)

uranium ore

700 years

10^6 years

Radiotoxicity (relative)

Time (years)

© Enea, 2001
"Everything is Hard at the Beginning"

0.01 \hspace{1cm} 0.1 \hspace{1cm} 0.5 \hspace{1cm} 1

\begin{align*}
\text{Low-\(\beta\)} & \downarrow \\
\text{RT} & \text{RT-SC Transition} \\
\text{Medium-\(\beta\)} & \downarrow \\
\text{RFQ} & \text{CH-DTL} \\
\lambda/4 \text{ Resonator} & \lambda/2 \text{ Resonator} \\
\text{Alvarez-type DTL} & \text{Spoke Resonator} \\
\text{Coupled-Cavity DTL} & \\
\text{High-\(\beta\)} & \downarrow \\
\text{RT} & \text{Elliptical Resonator} \\
\text{Reentrant Resonator} & \\
\end{align*}

Pic: J-PARC
Chuan Zhang

Seminar at Lawrence Berkeley National Laboratory, United States, May 31, 2012

Challenges for Realizing Modern RFQs

Beam Intensity = Peak Intensity × Duty Cycle

Space-Charge

Sparking / Cooling

Plot by K. Schindl

Low Beam Losses
(Hands-on Maintenance)

Good Beam Quality
(Downstream HoM, SC Quenching)

Short Length (Costs)
Introduction

Projects

RFQ

RF Structure

Beam Dynamics
How does an RFQ Accelerator Work

Velocity independent

\[ F = qE \]

\[ -\frac{v}{2} \sin (\omega t + \varphi) \]

\[ \frac{v}{2} \sin (\omega t + \varphi) \]

\[ \frac{1}{2} \sin (\omega t + \varphi) \]

\[ m = 1 \ldots 2.5 \]

\[ r_{\text{cell}} \]

\[ s \]

\[ \cos \]

\[ L \]

\[ \phi \]

\[ \Delta W_s = qEzT \cos \phi_s L_{\text{cell}} \]

\[ \phi_s = -90 \ldots \]

\[ \phi_s = -30 \]

\[ m = 1 \ldots \]

\[ m = 1.8 - 2.5 \]

\[ f, A/q, W, V, a (r_0, B), m, \phi_s \ldots \]
LANL Four-Section Procedure

Radial Matcher $\rightarrow$ Shaper $\rightarrow$ Gentle Buncher $\rightarrow$ Accelerator

Kapchinsky-Teplyakov Condition:
To maintain a constant beam density for an adiabatic bunching

Acceleration efficiency

Synchronous phase

Inter-vane voltage

Longitudinal small oscillation frequency

Synchronous velocity

Separatrix length in degree

Separatrix length in cm

Synchronous velocity

$\omega_i^2 = \frac{\pi^2 qAV \sin(-\varphi_s)}{M\beta_s^2 \lambda^2}$

$Z_b = \frac{\psi_b \beta_s \lambda}{2\pi}$

$\tan \varphi_s = \frac{\sin \psi_b - \psi_b}{1 - \cos \psi_b}$
An Example of the LANL Method

Transverse focusing strength $B = \text{constant}$

Mid-cell aperture $r_0 = \text{constant}$

Capacitance: position independent

$$B = \frac{qV\lambda^2}{Mc^2r_0^2}$$

Inter-vane voltage

Wavelength

Charge

Rest energy

Mid-cell aperture
The Shortcomings of the LANL Method

GB: beam bunching is not efficient (will lead to a long structure).

SH: could be an important source of unstable particles.

Constant $B$: deal with the longitudinal and transverse planes separately; and MOST IMPORTANT, it ignores the space-charge effects.

The synchronous phase $\phi_s$ is controlled by controlling the center-to-center spacing of the unit cells. Combining Eqs. (8.39) and (8.40) gives a prescription for specifying both $A(\beta_s)$, and $\phi_s(\beta_s)$ to maintain a constant bunch length. This adiabatic bunching approach is the basis of the bunching section of the RFQ, known as the gentle buncher. Although the space-charge forces have been neglected in this discussion, numerical simulation studies that include space-charge forces have shown that this procedure leads to an approximately constant bunch density and provides excellent control of space-charge-induced emittance growth. In practice, all of the bunching of an initial dc beam cannot be done adiabatically without making the RFQ too long. The prebunching is usually started in a section called the shaper using a prescription that ramps the phase and the acceleration efficiency linearly with axial distance. A schematic drawing of the pole tips of an RFQ designed for adiabatic bunching is shown in...

New Four Section Procedure

Balanced

Transverse focusing strength $B$

Transverse

C. Zhang et al., NIM-A 2008 & PRST-AB 2004

Longitudinal

Electrode modulation $m$

Accelerated

Softened

Synchronous phase $\phi_s$

NFSP

FSP

$(W_i - W_s) / W_s$

$\phi [\text{deg}]$

separatrix

$W_i / W_s$

-0.2

-0.1

0.0

0.1

0.2

-270

-180

-90

0

90

Chuan Zhang

Seminar at Lawrence Berkeley National Laboratory, United States, May 31, 2012
Main RFQ Structures

4-Vane

- TE-mode resonator
- Vanes + cavity wall => RF properties
- Even RF power density
- Easy cooling
- Large radial size at low frequencies (<200MHz)
- Error sensitive and tight tolerances
- Relatively complicated & expansive construction

4-Rod

- A chain of $\lambda/4$ resonators
- Inner structure => RF properties
- Always compact radial size
- Easy construction, tuning & repair
- RF power density is locally 2 times higher
- Dipole problem at high frequencies (>200MHz)
- CW operation is challenging at $P_c \geq 50kW/m$

Plot by LANL
Plot by A. Schempp
# LEDA vs. SARAF

**Project Parameter** | **LEDA (4-Vane)** | **SARAF (4-Rod)**
--- | --- | ---
Ion species | $H^+$ | $D^+$ ($H^+$)
$f$ [MHz] | 350 | 176
$W_{in}$ / $W_{out}$ [MeV] | 0.075 / 6.7 | 0.040 (0.020) / 3.0 (1.5)
$U$ [kV] | 66-120 | 65 (32.5)
$L$ [m] | 8 | 3.8
$\#_{\text{tank}}$ | 8 | 1
$\#_{\text{coupler}}$ | 12 | 1
$\#_{\text{tuner}}$ | 128 | 2 plungers
$E_k$ | 1.8 | 1.6 (0.8)
$P_c$ [kW/m] | 150 In oper.: 182 | 62.5 (15.6) Reached in CW: 50 *

*Provided by A. Bechtold*

---

**Figure 1:**
- **8-Hour CW (150kW) @ SARAF**: 2 Beam Trips (ms)
- **9-Hour CW Operation @ LEDA**

---

**Graphs:**
- Number of Beam Trips vs. Trip Duration (sec)
# CW 4-Rod RFQs Made at IAP

![New HLI RFQ @ GSI](image1.png)  ![ReA3 RFQ @ MSU](image2.png)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Project</th>
<th>New HLI @ GSI</th>
<th>ReA3 @ MSU</th>
<th>FRANZ @ IAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/q</td>
<td></td>
<td>6</td>
<td>≤5</td>
<td>1</td>
</tr>
<tr>
<td>$f$ [MHz]</td>
<td></td>
<td>108.48</td>
<td>80</td>
<td>175</td>
</tr>
<tr>
<td>$W_{in} / W_{out}$ [MeV/u]</td>
<td></td>
<td>0.004 / 0.3</td>
<td>0.012 / 0.6</td>
<td>0.120 / 0.7</td>
</tr>
<tr>
<td>$U$ [kV]</td>
<td></td>
<td>55</td>
<td>87</td>
<td>75</td>
</tr>
<tr>
<td>$L$ [m]</td>
<td></td>
<td>2.0</td>
<td>3.4</td>
<td>1.8</td>
</tr>
<tr>
<td>$E_k$</td>
<td></td>
<td>2.0</td>
<td>1.6</td>
<td>1.5</td>
</tr>
<tr>
<td>$P_c$ [kW/m]</td>
<td></td>
<td>28</td>
<td>35</td>
<td>65</td>
</tr>
</tbody>
</table>

Mardoron, SARAF Workshop 2009
FRANZ: Frankfurt Neutron Source at the Stern-Gerlach-Zentrum

<table>
<thead>
<tr>
<th></th>
<th>$I_{\text{peak}}$ [mA]</th>
<th>Ion</th>
<th>$f$ [MHz]</th>
<th>$W_{\text{in}} / W_{\text{out}}$ [MeV]</th>
<th>$L$ [m]</th>
<th>$U$ [kV]</th>
<th>$E_{s,\text{max}}$</th>
<th>Duty cycle</th>
<th>Transmission [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CERN RFQ2</td>
<td>200</td>
<td>H$^+$</td>
<td>202.56</td>
<td>0.090/0.750</td>
<td>1.8</td>
<td>178</td>
<td>$2.5E_k$</td>
<td>&lt;1%</td>
<td>~90</td>
</tr>
<tr>
<td>FRANZ</td>
<td>200</td>
<td>H$^+$</td>
<td>175</td>
<td>0.120/0.700</td>
<td>2.0</td>
<td>85</td>
<td>$1.6E_k$</td>
<td>CW</td>
<td>98.3</td>
</tr>
</tbody>
</table>

$W_b = 120$ keV, $I_s \leq 200$ mA

$W_b = 700$ keV, $I_b = 1.9$ mA

$W_b = 2.03\pm0.2$ MeV, $I_t = 7.7$ A

Chopper $f_c = 250$ kHz, $\tau_p = 50$-100 ns

Kicker $f = 5.1$ MHz

Multiaperture Rebuncher

Target for (p,$\gamma$)

Target for Compressor Mode

CERN RFQ2

FRANZ

~1/2 of inter-vane voltage

Courtesy D. Noll

C. Zhang, A. Schempp, NIM-A 2008
Design Parameters of the FRANZ RFQ

C. Zhang, A. Schempp, NIM-A 2008
Stability Tests of the FRANZ RFQ Design

Notes:
1. every parameter is increased along the x axis for 10 steps
2. all test ranges are much larger than the typical error ranges
3. dots are marking the design values

\( \Delta U: -5 - +5\% \)
\( \delta x: 0.1 - 1\text{mm} \)
\( \alpha: 1.15 - 2.25 \)
\( \varepsilon: 90 - 290 \pi\text{mm-mrad} \)
\( \delta W: \pm 1 - \pm 10\% \)
\( I: 50 - 300\text{mA} \)

\( \beta: 9.74 - 19.74\text{cm/rad} \)

- \( I \): Input beam current
- \( \varepsilon \): Input emittance (trans., unnorm., real)
- \( \alpha \): Input Twiss parameter
- \( \beta \): Input Twiss parameter
- \( \delta W \): Input energy spread
- \( \delta x \): Beam injection displacement
- \( \Delta U \): Inter-vane voltage vibration

\( T > 93\% \)
FAIR: Facility for Antiproton and Ion Research

GSI Today

FAIR p-linac

UNILAC

p-linac

L=216 m

SIS-18

L=1080 m

SIS-100/300

Radioactive Ion Production Target

Anti-Proton Production Target

FAIR

95 keV  3.0 MeV  70 MeV
## SNS RFQ vs. FAIR Proton RFQ

<table>
<thead>
<tr>
<th>Parameters</th>
<th>SNS</th>
<th>FAIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion</td>
<td>H⁻</td>
<td>H⁺</td>
</tr>
<tr>
<td>Duty cycle [%]</td>
<td>6.2</td>
<td>0.0144</td>
</tr>
<tr>
<td>$I_{\text{peak}}$ [mA]</td>
<td>~60 (35)</td>
<td>45</td>
</tr>
<tr>
<td>$f$ [MHz]</td>
<td>402.5</td>
<td>325.44</td>
</tr>
<tr>
<td>$W_{\text{in}}$ [MeV]</td>
<td>0.065</td>
<td>0.095</td>
</tr>
<tr>
<td>$W_{\text{out}}$ [MeV]</td>
<td>2.5</td>
<td>3</td>
</tr>
<tr>
<td>$U$ [kV]</td>
<td>83</td>
<td>80</td>
</tr>
<tr>
<td>$\varepsilon_{\text{in, trans., norm. rms}}$ [$\pi$ mm mrad]</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>$\varepsilon_{\text{out, trans., norm. rms}}$ [$\pi$ mm mrad]</td>
<td>0.21 0.21</td>
<td>0.30 0.30 0.30 0.31</td>
</tr>
<tr>
<td>$\varepsilon_{\text{out, longi., rms}}$ [$\pi$ MeV deg]</td>
<td>0.103 0.163 0.153 0.152</td>
<td></td>
</tr>
<tr>
<td>$L$ [m]</td>
<td>3.7</td>
<td>3.2</td>
</tr>
<tr>
<td>Transmission [%]</td>
<td>~90</td>
<td>98.7 97.2 95.3</td>
</tr>
</tbody>
</table>

C. Zhang, A. Schempp, NIM-A 2009

For accelerated particles only
Design Results of the FAIR Proton RFQ

C. Zhang, A. Schempp, NIM-A 2009
RHIC: Relativistic Heavy Ion Collider

New EBIS Preinjector

EBIS: 17 keV/u
RFQ: 300 keV/u
IH Linac: 2.0 MeV/u

External ion sources

LEBT
TOF
### Design of the New EBIS RFQ for RHIC, BNL

#### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CZ Design 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/q</td>
<td>6.25 / 1</td>
</tr>
<tr>
<td></td>
<td>2 / 1</td>
</tr>
<tr>
<td>Input Energy [MeV/u]</td>
<td>0.017</td>
</tr>
<tr>
<td>Output Energy [MeV/u]</td>
<td>0.300</td>
</tr>
<tr>
<td>Frequency [MHz]</td>
<td>100.625</td>
</tr>
<tr>
<td>Inter-Electrode Voltage [kV]</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>22.4</td>
</tr>
<tr>
<td>Design Beam Current [mA]</td>
<td>10</td>
</tr>
<tr>
<td>Max. Beam Current [mA]</td>
<td>20</td>
</tr>
<tr>
<td>$\varepsilon_{\text{in,trans.,norm.,rms}}$ [(\pi) mm mrad]</td>
<td>0.058</td>
</tr>
<tr>
<td>Kilpatrick Factor</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
</tr>
<tr>
<td>Electrode Length [m]</td>
<td>3.1</td>
</tr>
<tr>
<td>T [%]</td>
<td>&gt; 98</td>
</tr>
</tbody>
</table>

Cu$^{10+}$, He$^{2+}$, He$^+$, Ne$^{5+}$, Au$^{32+}$, and Fe$^{20+}$ have been successfully tested...

M. Okamura et. al., LINAC 2010

M. Okamura et. al., PAC 2009
European ADS Projects

Source

RFQ rt CH

0.05 MeV 2.0 MeV 5.0 MeV
0.03 MeV 1.5 MeV 3.5 MeV

RFQ rt CH

352 MHz (EUROTRANS)

176 MHz (MAX)

Linac Front End

17 MeV

Independently Phased Superconducting Section

2-Gap Spoke 352 MHz

5-Cell Elliptical 704 MHz

β=0.35

β=0.47

β=0.65

100 MeV

200 MeV

Spallation Target Sub-Critical Core

600 MeV 2.5–4 mA

800 MeV 20 mA

MAX EUROTRANS XT-ADS

EUROTRANS EFIT

EUROTRANS

(2005 – 2010)

EUROTRANS

(2011 – 2014)

Chuan Zhang

Seminar at Lawrence Berkeley National Laboratory, United States, May 31, 2012
# Proton Beam Specifications

## High power (radiation, cooling, sparking ...)  
Easy upgradeability

<table>
<thead>
<tr>
<th>Parameter</th>
<th>XT-ADS {MAX}</th>
<th>EFIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation (Design) intensity [mA]</td>
<td>2.5 – 4 (5)</td>
<td>20 (30)</td>
</tr>
<tr>
<td>Output energy [MeV]</td>
<td>600</td>
<td>800</td>
</tr>
<tr>
<td>Beam trip number (&gt;1s) {&gt;3s}</td>
<td>&lt; 5 {&lt;10} per 3-month operation cycle</td>
<td>&lt;3 per year</td>
</tr>
<tr>
<td>Beam stability (on target)</td>
<td>Energy: 1 %, Intensity: 2 %, Beam Size: 10 %</td>
<td></td>
</tr>
<tr>
<td>Beam time structure</td>
<td>CW, with 200μs zero-current holes</td>
<td></td>
</tr>
</tbody>
</table>

### Extreme high reliability

trips. The above requirement is still very aggressive. The number of beam trips on actual machines is at least two orders of magnitude higher (a couple per hour).

However, a distinction should be made between the availability, which is the relevant parameter for physics...  

N. Pichoff, EPAC 2001
Design Results of the EUROTRANS RFQ

$E_{th} = 2.16\text{MeV for } ^{65}\text{Cu}(p, n)^{65}\text{Zn}$

Total losses: 0.106%
EUROTRANS: a Toy! MAX: a Real Boy!

- EUROTRANS, Copper Power [kW]
- MAX, Copper Power [kW]
- EUROTRANS, Copper Power Density [kW/m]
- MAX, Copper Power Density [kW/m]

RFQ | RT-1 | RT-2 | Total
---|---|---|---
EUROTRANS| MAX| EUROTRANS| MAX

Illustration: Antje Fstood
Text: Martin Korau
From EUROTHERENS to MAX

C. Zhang, H. Klein, H. Podlech et al., IPAC 2011, WEPS043

Rp plot: the data marked in black is from A. Schempp; the data marked in blue was added by T. Sieber; the data marked in green are newly added, where the value for the IFMIF-EVEDA RFQ was kindly provided by Dr. A. Pisent.

\[ f \text{ [MHz]} : \quad 352 \text{ to } 176 \]

RFQ: 4-Vane to 4-Rod

\[ W_{RFQ,\text{in}} \text{ [MeV]} : \quad 0.05 \text{ to } 0.03 \]

\[ W_{RFQ,\text{out}} \text{ [MeV]} : \quad 3 \text{ to } 1.5 \]

\[ W_{RT,\text{out}} \text{ [MeV]} : \quad 5 \text{ to } 3.5 \]

\[ I \text{ [mA]} : \quad 5/30 \text{ to } 5 \]

\[ R_{p, \text{RFQ}} \sim f^{-1.5} \]
EUROTRANS RFQ vs. MAX RFQ

<table>
<thead>
<tr>
<th>Parameter</th>
<th>EUROTRANS @5mA</th>
<th>MAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF Structure</td>
<td>4-Vane</td>
<td>4-Rod</td>
</tr>
<tr>
<td>$f$ [MHz]</td>
<td>352</td>
<td>176</td>
</tr>
<tr>
<td>$W_{in} / W_{out}$ [MeV]</td>
<td>0.05 / 3</td>
<td>0.03 / 1.5</td>
</tr>
<tr>
<td>$U$ [kV]</td>
<td>65</td>
<td>40</td>
</tr>
<tr>
<td>$E_k$</td>
<td>1.7</td>
<td>1</td>
</tr>
<tr>
<td>$g_{min}$ [mm]</td>
<td>2.6</td>
<td>3.6</td>
</tr>
<tr>
<td>$\varepsilon_{in}^{t, n, ms}$ [π mm-mrad]</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>$\varepsilon_{out}^{t, n, ms}$ [π mm-mrad]</td>
<td>0.21 / 0.20</td>
<td>0.22 / 0.22</td>
</tr>
<tr>
<td>$\varepsilon_{out}^{l, ms}$ [keV-deg]</td>
<td>109</td>
<td>64.6</td>
</tr>
<tr>
<td>$L$ [m]</td>
<td>4.3</td>
<td>4.0</td>
</tr>
<tr>
<td>$T$ [%]</td>
<td>~100</td>
<td>~100</td>
</tr>
</tbody>
</table>

C. Zhang, H. Klein, H. Podlech et al., IPAC 2011, WEPS043
## Design Requirements of the PXIE & China ADS RFQs

<table>
<thead>
<tr>
<th>Parameters</th>
<th>PXIE</th>
<th>China ADS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion type</td>
<td>H-</td>
<td>H+</td>
</tr>
<tr>
<td>Input energy [keV]</td>
<td>30</td>
<td>35</td>
</tr>
<tr>
<td>Output energy [MeV]</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>Duty factor [%]</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Frequency [MHz]</td>
<td>162.5</td>
<td>162.5</td>
</tr>
<tr>
<td>Beam current [mA]</td>
<td>5 (nominal); 1-10</td>
<td>15 (nominal); 1-20</td>
</tr>
<tr>
<td>Input transverse emittance [πmm-mrad]</td>
<td>0.25 (norm. rms)</td>
<td>0.3 (norm. rms)</td>
</tr>
<tr>
<td>Transverse emittance growth [%]</td>
<td>( \leq 10 )</td>
<td>( \leq 10 )</td>
</tr>
<tr>
<td>Output longitudinal emittance [keV-nsec]</td>
<td>( \leq 0.8 )</td>
<td>( \leq 1.0 )</td>
</tr>
<tr>
<td>Transmission [%]</td>
<td>95</td>
<td>95</td>
</tr>
<tr>
<td>TWISS Parameter ( \alpha ) [%]</td>
<td>( \leq 1.5 )</td>
<td>( \leq 1.5 )</td>
</tr>
</tbody>
</table>

**Constant B**
Evolutions of Main RFQ Parameters

![Graph showing the evolutions of main RFQ parameters](image-url)
Beam Transport Simulations

- Vane Length: 444.6 cm and 416.2 cm for PXIE and China ADS RFQs, respectively.
- Calculated RF Power: 100 kW and 110 kW for PXIE and China ADS RFQs, respectively.
Conclusions

• The RFQ accelerator is the standard injector.

• Characteristics of modern RFQs:
  • High beam intensity
  • High duty factor even CW
  CW operation is a different story than the pulsed operation.

• An efficient design method for modern RFQs, “New Four Section Procedure”, has been developed:
  • Applied for the designs of more than 20 RFQs:
    • Ion species: proton – uranium (A/q: 1 – 59.5)
    • Frequency [MHz]: 36.136 – 352
    • Peak beam intensity [mA]: 0 – 200 (300)
    • Duty factor [%]: 0.0144 – 100
  • Proven experimentally:
    • New EBIS RFQ for BNL
    • New HLI RFQ for GSI
Thank You 😊

Vielen Dank