Study of Front-End RF Structures (RFQ and MEBT)

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Acknowledgement

• Spallation Neutron Source (Oak Ridge National Laboratory)
  ▪ Yoon Kang (Lead Engineer, RF group)
  ▪ Alexandre Vassioutchenko (Engineer, RF group)
  ▪ Mark Champion (Group leader, RF and Electrical group)
  ▪ Sang-Ho Kim (Group leader, SRF group)
  ▪ Robert Peglow (Technician, RF group)

• Microwave and Antenna Lab. (University of Tennessee)
  ▪ Aly Fathy (Professor, Electrical Engineering)

This work was supported by SNS through UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. DOE
Outline

- Research Motivation

- RFQ with different vane-end termination
- Double-gap MEBT rebuncher cavity
- Perturbation and RFQ

- Summary
Research Motivation
Radio Frequency Quadrupole (RFQ) is expensive

- RFQ fabrication cost is very expensive because of modulation, brazing, **mode stabilizer design**, ...

- Can mode stabilizer design be removed?
SNS MEBT rebuncher emits X-radiation

- Rebuncher cavity 4 of SNS MEBT emits X-radiation after maintenance

- SNS MEBT system is not in Concrete tunnel

- Can X-radiation be decreased by another cavity design?
New SNS RFQ has been installed

- **Existing vs. New RFQ (RF vs. Mechanical)**

<table>
<thead>
<tr>
<th></th>
<th>Existing RFQ</th>
<th>Spare RFQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composite</td>
<td>Copper + Glidcop shell</td>
<td>Copper</td>
</tr>
<tr>
<td>Shape</td>
<td>Rectangular</td>
<td>Octagonal</td>
</tr>
<tr>
<td>Stabilization</td>
<td>Pi-mode stabilizing loop</td>
<td>Dipole stabilizer rods</td>
</tr>
</tbody>
</table>

- **Perturbation and RF tuning?**

RFQ with different vane-end termination
(For cost effective RFQ)

RFQ cut-back

- RFQ requires vane end cut-backs to have uniform E-field
- Transverse resonance + Cut-back resonance

End-plate (electric conductor)

RFQ without cut-back

End-plate (electric conductor)  Cut-back (at vane ends)

RFQ with cut-back

Same Frequency
**Split coaxial structure for heavy-ion**

- Common RFQ has cut-backs on every four vane ends
- Split coaxial: a vane pair with short circuit condition
  
  Another vane pair with cut-back
- Interleaved (upstream ↔ downstream)

<table>
<thead>
<tr>
<th></th>
<th>Traditional</th>
<th>Split coaxial</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pro.</strong></td>
<td>Symmetric ends</td>
<td>Better mode separation with short RFQ length</td>
</tr>
<tr>
<td><strong>Con.</strong></td>
<td>-</td>
<td>Asymmetric ends (finite axial field)</td>
</tr>
</tbody>
</table>

On-axis field at RFQ ends (Split coaxial)

- Recent beam dynamics study at ATLAS states that these on-axis fields do not affect beam quality


FIG. 2. On-axis longitudinal field along the RFQ.

“The Ez component of the field at the entrance extends over about 2 RF periods. If the Ez(z) sign is the same over RF period, the average energy gain per RF period is equal to 0.”

- Asymmetric ends for light ion 4-vane RFQ?
Terminations for light ion 4-vane RFQ

- Two possible terminations were studied at Chalk River

- Test model was built with \( \approx 1\lambda \) length

- Dipole characteristics ?

- For long light ion RFQ ? (Mode separation ?)

Double dipole (DD)
- Not Interleaved
- Dipoles do not degenerate

Folded dipole (FD)
- Interleaved
- Similar to split-coaxial

Dipole mode in 4C / FD / DD RFQ (1)

- Traditional RFQ (4C) generate dipole in two diagonal
- FD has finite fields in other quadrants as well

Traditional RFQs

Folded Dipole
(Unbalanced Transmission Line
→ Common mode currents excited through cut-back)
→ Gives Strong effects in short RFQ with more H/E coupling ratio
Dipole mode in 4C / FD / DD RFQ (2)

- DD generate one dipole with open circuit-like end
- DD generate another dipole with short circuit-like end
- Similar frequencies with an harmonic order difference

Double Dipole (open)
(DD_open \approx \text{waveguide term.})

Do not degenerate, But related?
(By an harmonic order)

Double Dipole (short)
(DD_short \approx \text{cavity term.})

E field  H field  H field (Cut-back)
Dipole field distribution in longitudinal direction

- An example with 0.74 λ RFQ with SNS geometry
- 4C / FD / DD and 4C-DSR (Dipole stabilizer rods)

- 4C (unmatched)
- 4C + DSR (matched)
- DD_open (matched)
- DD_short (sinusoidal)

Because of axial capacitance
Higher cut-back capacitance in dipole

DD has unique dipole frequencies (similar to 4C +DSR)
RFQ mode spectrum by structure length:

- with SNS transverse geometry (1)

- DD gives wideband exactly in where 4C RFQ does not
RFQ mode spectrum by structure length with SNS transverse geometry (2)

- As expected, FD scheme is useful in short RFQs

![Graph showing RFQ mode spectrum by structure length with SNS transverse geometry.](image)
Short summary of Part I

- DD RFQ can be selectively used as well as 4C RFQ for fixed length RFQs

- FD RFQ can be useful for short RFQs

- RFQ design / tuning cost can be decreased (Stabilizer design may not be necessary)
Double-gap MEBT rebuncher study

X-radiation issue and SNS MEBT

- SNS MEBT has 4 rebuncher cavities

- Cavity 4 with the highest operating gap voltage (120kV) emitted over 50~100 mRad X-radiation
  → Space with > 5 mRad is unoccupiable (radiation area)

- SNS MEBT system is outside of Concrete tunnel

- Another cavity design with reduced gap voltage?
X-radiation, cavity gap voltage and field

- X-radiation is determined by the gap voltage and field

Radiation mostly comes from the high voltage / field gap

\[ J_X \propto i(t) \cdot V^n(t) \]

- \( J_X \): radiation intensity
- \( i(t) \): discharge current
- \( V(t) \): gap voltage
- \( n \): 1.8 ~ 3.0

\[ i(t) \approx A E(t)^{2.5} e^{-\frac{B}{E(t)}} \]

- \( E(t) \): electric field
- A, B: constant

Klystron cavity (SLAC)


- < 25% X-radiation is expected with double-gap
Double-gap design and X-radiation

- Double-gap design reduces the gap voltage as a half
- Similar gap size $\rightarrow$ decrease electric field
- TM cavity to provide similar cavity length (11.5 $\rightarrow$ 13.0cm)

\[ V_{\text{gap(tot)}} = V_{\text{gap}} \]

Single gap voltage

\[ V_{\text{gap(tot)}} = V_{\text{gap}} \]

Double gap voltage

\[ V_{\text{gap(tot)}} = \frac{V_{\text{gap}}}{2} + \frac{V_{\text{gap}}}{2} \]

Gap size
d1 $\approx$ d2
Cavity parameter

- Single gap vs. Double gap – at 28.2 kW peak power

<table>
<thead>
<tr>
<th></th>
<th>Single gap</th>
<th>Double gap (A)</th>
<th>Double gap (B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency $f_0$ (MHz)</td>
<td>401.9</td>
<td>400.3</td>
<td>400.1</td>
</tr>
<tr>
<td>Cavity length $L$ (cm)</td>
<td><strong>11.48</strong></td>
<td>13.00</td>
<td><strong>13.00</strong></td>
</tr>
<tr>
<td>Gap size $g$ (cm)</td>
<td>1.230</td>
<td>1.224</td>
<td>1.423</td>
</tr>
<tr>
<td></td>
<td>1.224</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q$ (unloaded, copper)</td>
<td>21413</td>
<td>20773</td>
<td>20903</td>
</tr>
<tr>
<td>$R/Q$</td>
<td>29.35</td>
<td>29.17</td>
<td>27.83</td>
</tr>
<tr>
<td>$R_s$ (Mohm)</td>
<td>0.629</td>
<td>0.592</td>
<td>0.581</td>
</tr>
<tr>
<td>$V_0$ (kV)</td>
<td>119.08</td>
<td>116.93</td>
<td>114.55</td>
</tr>
<tr>
<td>$T$</td>
<td>0.447</td>
<td>0.459</td>
<td>0.452</td>
</tr>
<tr>
<td>$E_0$ (MV/m)</td>
<td>2.32</td>
<td>1.94</td>
<td>1.93</td>
</tr>
<tr>
<td>$E_{pk}$ (MV/m)</td>
<td><strong>29.9</strong></td>
<td>16.75</td>
<td><strong>13.26</strong></td>
</tr>
<tr>
<td>[Kilpatrick]</td>
<td>[1.54]</td>
<td>[0.86]</td>
<td>[0.68]</td>
</tr>
<tr>
<td>$H_{pk}$ (A/m)</td>
<td><strong>6565</strong></td>
<td>9323</td>
<td><strong>8644</strong></td>
</tr>
</tbody>
</table>
Scaled model design and fabrication

- A ½ scale model is designed for low power demonstration
- RF measurements show good agreements with simulation

**Frequency**

<table>
<thead>
<tr>
<th>Mode</th>
<th>$f_S$ [MHz]</th>
<th>$f_M$ [MHz]</th>
<th>$f_M$ (Error %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM010</td>
<td>800.49</td>
<td>800.56</td>
<td>0.01</td>
</tr>
<tr>
<td>TM110</td>
<td>1427.19</td>
<td>1427.04</td>
<td>0.01</td>
</tr>
<tr>
<td>TM1110</td>
<td>1439.61</td>
<td>1439.19</td>
<td>0.03</td>
</tr>
</tbody>
</table>

**Q (unloaded, AL6061 T6 material)**

<table>
<thead>
<tr>
<th>Mode</th>
<th>$Q_S$ [MHz]</th>
<th>$Q_M$ [MHz]</th>
<th>$Q_M$ (Error %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM010</td>
<td>9286</td>
<td>8179</td>
<td>12</td>
</tr>
<tr>
<td>TM110</td>
<td>9474</td>
<td>7667</td>
<td>19</td>
</tr>
<tr>
<td>TM1110</td>
<td>10567</td>
<td>9974</td>
<td>6</td>
</tr>
</tbody>
</table>
Bead-pull measurement

- Bead-pull measurement and R/Q calculation

6.1% R/Q errors agrees well with expected errors about 3~7%

<table>
<thead>
<tr>
<th></th>
<th>Simulation</th>
<th>Measurement</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>R/Q</td>
<td>27.83</td>
<td>26.12</td>
<td>6.1%</td>
</tr>
<tr>
<td>R_s (Mohm)</td>
<td>0.258</td>
<td>0.213</td>
<td>17.4%</td>
</tr>
</tbody>
</table>
Thermal analysis

- Drift tube assembly should be made by Copper
- Steel can be used for cavity body, but thick internal Copper plate is desirable

ΔT Calculation

- CST (ΔT\textsubscript{water} = 0) → 4.8 K (Zero Gradient)
- 6.5 K (Expected)

Cooling channel in Drift tube & cavity wall

Copper plate (0.61 in) + 304 Stainless Steel (0.5 in)

Nose cone cooling is not necessary (Smaller capacitance)
Short summary of Part II

- Double-gap design would decrease X-radiation to $<< 25\%$ of single gap design

- RF power requirement remains almost the same
  - Cavity length increases from 11.5 to 13.0 cm

- Original beam performance can be maintained
  - Provides similar gap voltage and beam-line length

- Copper plate design method can prevent thermal issue
RFQ Comparison

- Same modulation / beam dynamics design (Vane voltage = 83kV, Bore radius = 3.5mm)
- Existing RFQ: better RF mode separation (33 MHz >> 4.5 MHz)
- Spare RFQ: less sensitive to deform. by vacuum (18kHz << 119kHz)
RF Mode Stabilization Methods

- Pi mode stabilizing loop (PISL) / Dipole stabilizer rods (DSR)

<table>
<thead>
<tr>
<th></th>
<th>PISL (High Q Rect. Cavity + PISL)</th>
<th>DSR (Medium Q Oct. Cavity + DSR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>freq. (D)</td>
<td>Electrical short circuit to dipole modes (raises frequency)</td>
<td>Extra loading to dipole modes</td>
</tr>
<tr>
<td>freq. (Q)</td>
<td>Decreases (loading)</td>
<td>Ideally not affected</td>
</tr>
<tr>
<td>Power</td>
<td>6 ~ 8 % RF power</td>
<td>~ 1 % RF power</td>
</tr>
</tbody>
</table>

RF tuning ?
RF tuning of PISL RFQ vs. DSR RFQ

- PISL RFQ is less sensitive to perturbation
- PISL RFQ is easier to tune

Simulation model (Perturbation on section 3)

PISL RFQ

DSR RFQ

Need more mechanical integrity
Special care for Installation

Different ratio (Source of perturbation ?)
Source of RFQ frequency detuning (1)

- Delamination

Composite shell structure (200~400 kHz huge shift)

- Sectional misalignment (Vertical > Horizontal)

- Vane tip fabrication error

Mechanical Imperfection
A mechanical imperfection example (1)

- Assume section 3 vane is vertically delaminated (75 um)
- Existing RFQ (delamination / misalignment)
- Spare RFQ (misalignment)

Simulation model (4 sections RFQ)

RF field (Measuring position)

RF field (Beam-axis position)

Perturbed field

Retuned field

Local mismatch
A mechanical imperfection example (2)

- Local field mismatch affects quadrupole gradient
- Quadrupole gradient determines RFQ focusing
- Quadrupole gradient \( \sim f \) (Gap voltage \( V_0 \), Bore radius \( a \))

\[
E_x = - \frac{XV_0}{a^2} x - \frac{kAV_0}{2} I_1(kr) \frac{x}{r} \cos(kz)
\]
\[
E_y = \frac{XV_0}{a^2} y - \frac{kAV_0}{2} I_1(kr) \frac{y}{r} \cos(kz)
\]
\[
E_z = \frac{kAV_0}{2} I_0(kr) \sin(kz)
\]

\[
A_0 = - \frac{\partial E_x}{2\partial x} = \frac{\partial E_y}{2\partial y} = \frac{V_0}{2a^2}
\]

- RF Tuning can restore the gap voltage \( V_0 \)
- But, bore radius \( a \) is changed \( \rightarrow A_0 \) detuned

[Simulation, < 5% [150\( \mu \)m], > 10% [>200\( \mu \)m]

Good RF tuning does not always promise good on-axis field

Existing / Spare RFQ Tolerance requirement can be similar
Source of RFQ frequency detuning (2)

- Chemical deposition (Hydrogen, Cesium)

Causes freq. detuning at high duty beam

Arcing sometimes

Vane picture at RFQ upstream (by R. Welton)
Ongoing project: Frequency detuning by Chemical deposition

- Q1) How chemical deposition causes frequency shift
  → Need more clear answer (Electrical model ? )

- Q2) Similar detuning effect for Spare RFQ ??
  → Cut-back resonance + Transverse resonance ?
Summary

- Folded / Double dipole RFQ design can be selectively utilized in future cost effective 4-vane RFQ design

- The proposed Double-gap MEBT rebuncher design is expected to relieve X-radiation issue

- New SNS RFQ installation is expected in near future

- Frequency detuning by mechanical imperfection is studied with 3D simulations

- Frequency detuning by chemical deposition will be investigated in future study with operation experiences
For more detail...

- Our work has been published in IEEE Transactions on Nuclear Science


- Printed copies are ready for you
Questions?
Selected Publications - RFQ


Selected Publications - MEBT


Selected Publications – RF System


Selected Publications - SRF


Career Objective in Fermilab

Be part of the Fermilab taskforce of PIP and LCLS putting my solid electromagnetic, RF and accelerator technology background and experience to serve in

The Great Fermilab Engineering Team