Beam dynamics studies for 10 MHz post-accelerated RIBs in Phase 3 of the HIE-ISOLDE linac upgrade

ISOLDE Workshop and Users meeting
4 – 6 December 2017

M.A. Fraser - TE-ABT-BTP, CERN
• Intro to the RFQ and concept of pre-bunching
• Beam dynamics studies:
  – Electrostatic modeling of RFQ in CST
  – PARMTEQ vs. TRACK
• Results from the feasibility study
• Integration at HIE-ISOLDE:
  – LEBT (bunching)
  – MEBT (chopper line)
• Summary
• Reference material / extra slides
Introduction

• This is intended to be only a very brief overview:
  – Studies carried out as part of Fellowship in BE-RF (2012 – 14)
  – Full details of the studies can be found in the documentation collected in the ”Reference material” section at the end of the talk (simulation tools available on request).

• No RF hardware design work carried out:
  – Only functional specification from beam dynamics studies
  – Specifications looks reasonable and comparable to systems at other labs, including CERN.

• Comment:
  – Increasing the beam energy spread from the EBIS impacts the 10 MHz bunching efficiency and influences the choice of layout.
RFQ: transverse focusing

RFQ: longitudinal focusing (bunching)

# REX-ISOLDE RFQ

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFQ type</td>
<td>4-rod $\lambda/2$ (IH type)</td>
</tr>
<tr>
<td>$f$ [MHz]</td>
<td>101.28</td>
</tr>
<tr>
<td>$L$ [m]</td>
<td>3.0</td>
</tr>
<tr>
<td>$W_{in} \rightarrow W_{out}$ [keV/u]</td>
<td>5 $\rightarrow$ 300</td>
</tr>
<tr>
<td>$\beta_{in} \rightarrow \beta_{out}$ [%]</td>
<td>0.3 $\rightarrow$ 2.5</td>
</tr>
<tr>
<td>No. of cells</td>
<td>232</td>
</tr>
<tr>
<td>$P$ [kW]</td>
<td>36.3 @ $A/q = 4.5$</td>
</tr>
<tr>
<td>$A/q_{limit}$</td>
<td>$&lt; 5.5$</td>
</tr>
<tr>
<td>Duty cycle [%]</td>
<td>$&lt; 10$</td>
</tr>
</tbody>
</table>

### REX-ISOLDE RFQ

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFQ type</td>
<td>4-rod $\lambda/2$ (IH type)</td>
</tr>
<tr>
<td>$f$ [MHz]</td>
<td>101.28</td>
</tr>
<tr>
<td>$L$ [m]</td>
<td>3.0</td>
</tr>
<tr>
<td>$W_{in} \rightarrow W_{out}$ [keV/u]</td>
<td>5 $\rightarrow$ 300</td>
</tr>
<tr>
<td>$\beta_{in} \rightarrow \beta_{out}$ [%]</td>
<td>0.3 $\rightarrow$ 2.5</td>
</tr>
<tr>
<td>No. of cells</td>
<td>232</td>
</tr>
<tr>
<td>$P$ [kW]</td>
<td>36.3 @ $A/q = 4.5$</td>
</tr>
<tr>
<td>$A/q_{limit}$</td>
<td>$&lt; 5.5$</td>
</tr>
<tr>
<td>Duty cycle [%]</td>
<td>$&lt; 10$</td>
</tr>
</tbody>
</table>

REX-ISOLDE RFQ: modulation

• Thanks to O. Kester (TRIUMF) for helping me dig out the actual CNC machine files used to mill the electrodes... a critical step in confirming what is actually installed in the REX-ISOLDE RFQ:
Beam dynamics in the REX-RFQ (1)

*** REX-RFQ final version (angepasst an rods) ***

Electrode modulation bunches, before accelerating

M.A. Fraser, TE-ABT-BTP 10 MHz RIBs at HIE-ISOLDE, ISOLDE WS and Users Meeting 2017
Beam dynamics in the REX-RFQ (2)

- Benchmarked the code *PARMTEQ* (LANL) [1]:
  - *PARMTEQ* was used to design the RFQ
  - Tracked particles in the field map using TRACK
  - Electric field map generated using finite element modelling in CST EM studio and data from CNC milling files and drawings
CST EM simulations of RFQ (1)
CST EM simulations of RFQ (2)

$E_z (x = y = 0 \text{ mm})$ [MV/m]

-1.5
-1
-0.5
0
0.5
1
1.5

0 500 1000 1500 2000 2500 3000

$z$ [mm]

PARMTEQM v3.09
CST EM Studio
CST EM simulations of RFQ (2)

- Graph showing the electric field $E_x$ at $x = 1 \text{ mm}$, $y = 0 \text{ mm}$ for different models:
  - PARMTEQM v3.09
  - CST EM Studio

- 10 MHz RIBs at HIE-ISOLDE, ISOLDE WS and Users Meeting 2017
Concept of pre-bunching into RFQ

- Concept simple: velocity bunching with RF buncher
- Multiple harmonics added to linearise and approximate a saw-tooth, see [2] for optimisation:

\[ V_{\text{eff}}(\tau) = V_0 (\sin \omega_0 \tau - 0.43 \sin 2\omega_0 \tau + 0.21 \sin 3\omega_0 \tau - 0.10 \sin 4\omega_0 \tau) \]
Pre-bunching feasibility studies at REX

- Red area: uncaptured particles, not accelerated and lost
- Green particles: $A/q$ contaminants rejected in other buckets by TOF

Central grey bucket at 10 MHz: adjacent buckets are the standard 101.28 MHz buckets
Pre-bunching at other laboratories

Table 1: Comparison of the key parameters of a selection of relevant worldwide MHB-RFQ systems.

<table>
<thead>
<tr>
<th>Facility</th>
<th>ATLAS (ANL)</th>
<th>ISAC (TRIUMF)</th>
<th>PIAVE (LNL)</th>
<th>ISOLDE (CERN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFQ frequency [MHz]</td>
<td>60.625</td>
<td>35.4</td>
<td>80</td>
<td>101.28</td>
</tr>
<tr>
<td>MHB fundamental (beam) frequency [MHz] ($h = \frac{f_{RFQ}}{f_{MHB}}$)</td>
<td>12.125</td>
<td>11.8</td>
<td>40</td>
<td>10.128</td>
</tr>
<tr>
<td>($h = 5$)</td>
<td>($h = 3$)</td>
<td>($h = 2$)</td>
<td>($h = 10$)</td>
<td></td>
</tr>
<tr>
<td>No. of MHB harmonics</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>≥ 3</td>
</tr>
<tr>
<td>RFQ structure type</td>
<td>multisegment split-coaxial</td>
<td>4-rod split-ring</td>
<td>superconducting</td>
<td>4-rod ($\lambda/2$)</td>
</tr>
<tr>
<td>MHB RF structure type</td>
<td>lumped circuit (resonant)</td>
<td>transmission line (non-resonant)</td>
<td>QWR (resonant)</td>
<td>to be defined</td>
</tr>
<tr>
<td>MHB drift-tube type</td>
<td>single-gap</td>
<td>single-gap</td>
<td>2× double-gap</td>
<td>single-gap</td>
</tr>
</tbody>
</table>

- Most labs designed the RFQ with the pre-buncher (shorter structure, reduced longitudinal emittance by design)
- We propose to retrofit the existing RFQ with the pre-buncher
Pre-bunching at other laboratories

Table 1: Comparison of the key parameters of a selection of relevant worldwide MHB-RFQ systems.

<table>
<thead>
<tr>
<th>Facility</th>
<th>ATLAS (ANL)</th>
<th>ISAC (TRIUMF)</th>
<th>PIAVE (LNL)</th>
<th>ISOLDE (CERN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFQ frequency [MHz]</td>
<td>60.625</td>
<td>35.4</td>
<td>80</td>
<td>101.28</td>
</tr>
<tr>
<td>MHB fundamental (beam) frequency [MHz] ( (h = \frac{f_{RFQ}}{f_{MHB}}) )</td>
<td>12.125 ( (h = 5) )</td>
<td>11.8 ( (h = 3) )</td>
<td>40 ( (h = 2) )</td>
<td>10.128 ( (h = 10) )</td>
</tr>
<tr>
<td>No. of MHB harmonics</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>≥ 3</td>
</tr>
<tr>
<td>RFQ structure type</td>
<td>multisegment split-coaxial</td>
<td>4-rod split-ring</td>
<td>superconducting</td>
<td>4-rod ((\lambda/2))</td>
</tr>
<tr>
<td>MHB RF structure type</td>
<td>lumped circuit ((\text{resonant}))</td>
<td>transmission line ((\text{non-resonant}))</td>
<td>QWR ((\text{resonant}))</td>
<td>to be defined</td>
</tr>
<tr>
<td>MHB drift-tube type</td>
<td>single-gap</td>
<td>single-gap</td>
<td>2× double-gap</td>
<td>single-gap</td>
</tr>
</tbody>
</table>

- Most labs designed the RFQ with the pre-buncher (shorter structure, reduced longitudinal emittance by design)
- We propose to retrofit the existing RFQ with the pre-buncher
Pre-bunching feasibility studies at REX

\[ \frac{\Delta W}{W} \]

Buncher voltage fixed \((V = \text{const.})\), position scanned

\[ \Delta t \]
Pre-bunching feasibility studies at REX

Buncher location fixed (L = const.), voltage scanned
Pre-bunching feasibility studies at REX

Transmission at 10 MHz and 300 keV/u [4]:

![Graph showing transmission at 10 MHz and 300 keV/u](image-url)
Pre-bunching feasibility studies at REX

Transmission at 10 MHz and 300 keV/u [4]:

![Graph showing transmission at 10 MHz and 300 keV/u](image)
Pre-bunching feasibility studies at REX

Longitudinal emittance (rms) at 300 keV/u [4]:

![Graph showing longitudinal emittance at 300 keV/u](image)
Pre-bunching feasibility studies at REX

Longitudinal emittance (rms) at 300 keV/u [4]:

Gentle pre-bunching can significantly reduce the longitudinal emittance (energy spread)
Pre-bunching feasibility studies at REX

\[ V_{\text{eff}} = \frac{2q}{\lambda Au c^2 \beta^3 \gamma^3} \frac{1}{L + d} \]

Optimum focal point of pre-buncher is at 29 cm on the electrodes (where modulation starts)
\[ d = 29 \text{ cm} \]
Energy acceptance of REX RFQ

Measured momentum acceptance of RFQ shows very good agreement with the simulations (same with transmission vs. voltage) [5]:

\[ \frac{\Delta W}{W} \sim \pm 5\% \]
Multi-harmonic buncher (MHB)

- Detailed design studies of MHB electrode geometry found in [3]
  - 2 electrodes operated in push-pull mode (equal but opposite voltages)
Multi-harmonic buncher (MHB)

- Detailed design studies of MHB electrode geometry found in [3]
  - 2 electrodes operated in push-pull mode (equal but opposite voltages)
  - Aperture large compared to accelerating gap: strong radial dependence

![Graph showing electric field and transit time factor vs. beta times lambda]
Integration at HIE-ISOLDE (1)

- REX accelerator: $W = 3$ MeV/u

**KEY:**
- RFQ
- IHS
- 7G1,2,3
- 9GP
- $\beta_g = 6.3\%$
- $\beta_g = 10.3\%$
- LOW-\(\beta\) CRYO.
- HIGH-\(\beta\) CRYO.
Integration at HIE-ISOLDE (1)

- REX accelerator: $W = 3 \, \text{MeV/u}$

- HIE Stage 1 (2016): $W = 5.5 \, \text{MeV/u}$

**KEY:**
- RFQ
- IHS
- 7G1,2,3
- 9GP
- $\beta_g = 6.3\%$
- $\beta_g = 10.3\%$
- LOW-\(\beta\) CRYO.
- HIGH-\(\beta\) CRYO.

**2x cryomodules**

**10x QWRs**

**2x solenoids**

Cryo-line “jumper” positions
Integration at HIE-ISOLDE (1)

- REX accelerator: $W = 3$ MeV/u
  - 4 cryomodules
  - 20x QWRs
  - 4x solenoids

- HIE Stage 1 (2016): $W = 5.5$ MeV/u
  - Cryo-line “jumper” positions

  - Cryo-line “jumper” positions

**KEY:**
- RFQ
- IHS
- 7G1,2,3
- 9GP
- LOW-β CRYO. ($\beta_g = 6.3\%$)
- HIGH-β CRYO. ($\beta_g = 10.3\%$)
Integration at HIE-ISOLDE (1)

- **REX accelerator:** $W = 3\text{ MeV/u}$
- **HIE Stage 1 (2016):** $W = 5.5\text{ MeV/u}$
- **HIE Stage 2 (2018):** $W = 10\text{ MeV/u}$
- **HIE Stage 3 (?)**: $10\text{ MeV/u}$

**KEY:**
- **RFQ**
- **IHS**
- **7G1,2,3**
- **9GP**
- **LOW-β CRYO.**
- **HIGH-β CRYO.**
- $\beta_g = 6.3\%$
- $\beta_g = 10.3\%$

**6x cryomodules**
- **32x QWRs**
- **8x solenoids**
Integration at HIE-ISOLDE (2)

• Efficient bunching is still possible without extension provided by installation of Stage 3...
  – Possible layout options and their performance explored in [3]
  – Ideal for testing a prototype MHB structure, or possibly experiments: however, request is <1% in satellite bunches
  – Chopping before RFQ is possible but not efficient and not recommended: small $\beta\gamma$, gridded chopper would cause transmission losses
Integration at HIE-ISOLDE (2)

EXISTING LAYOUT:
- E-static Quadrupoles
- Triplet Magnet
- Re-buncher @ 101.28 MHz

W = 5 keV/u (β=0.00328)
W = 300 keV/u (β=0.0254)

1.4 m
1 m
2.62 m

UPGRADE LAYOUT:
- Doublet Magnet
- Chopper
- Chopper Slits

MHB @ n-harmonics of 10.128 MHz
LEBT W = 5 keV/u
Solenoid

RFQ @ 101.28 MHz

IH-DTL @ 101.28 MHz

2.4 m
3.4 m

M.A. Fraser, TE-ABT-BTP
LEBT Design Challenges

• Non-isochronous effects [3]:
  – bunching path length depends on the transverse position, i.e. optics and emittance:

• Non-linearities: chromatic and non-linear aberrations in quadrupoles [3]:
  – solenoids preferred as beam size kept small in both planes
Baseline design with linac extension

TRACK results [3]:

Particle tracking in field maps:
Option B: integrate MHB close to EBIS

TRACK results [3]:

Particle tracking in field maps:
Option C: MHB close to RFQ

TRACK results [3]:

Particle tracking in field maps:
Bunch time structure

- Expect > 80% bunching efficiency with ~15% populated in adjacent 100 MHz satellite bunches [6]:
  - Requires a chopper for experimental request of <1% in satellite bunches
MEBT & chopper

- Classic chopper line design between RFQ and IHS:
  - 1.2 kV of chopping voltage over 0.5 m for 4 mrad kick on A/q = 4.5
  - Additional RF buncher will need procurement
  - Doublet magnets can be recovered from REX
- Emittance growth studies indicate a travelling wave structure is suited (not resonant type as used at TRIUMF) [7]:
  - HIE-ISOLDE specification is similar to the specification of the meander strip-line chopper developed at CERN for Linac4

![Diagram of chopper line design between RFQ and IHS](slide29.png)
# Beam dynamics performance summary

<table>
<thead>
<tr>
<th>Upgrade Stage</th>
<th>Option</th>
<th>MHB Status</th>
<th>$V_0$ [V]</th>
<th>$L$ [m]</th>
<th>$\Delta \phi^a$ [deg]</th>
<th>$\Delta W_{source}$ [%]</th>
<th>$T_{total}$ [%]</th>
<th>$T_{10 \text{ MHz}}$ [%]</th>
<th>$T_{sat}$ [%]</th>
<th>$\epsilon_{x,rms}$ [mm mrad]</th>
<th>$\epsilon_{y,rms}$ [mm mrad]</th>
<th>$\epsilon_{z,rms}$ [ns keV/u]</th>
</tr>
</thead>
<tbody>
<tr>
<td>REX (today)</td>
<td>-</td>
<td>OFF</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>0.1</td>
<td>93.9</td>
<td>-</td>
<td>-</td>
<td>0.64</td>
<td>1.36</td>
<td>0.28</td>
</tr>
<tr>
<td>REX (modified)</td>
<td>-</td>
<td>OFF</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>0.1</td>
<td>93.7</td>
<td>-</td>
<td>-</td>
<td>0.62</td>
<td>0.64</td>
<td>0.27</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>ON</td>
<td>465</td>
<td>2.32</td>
<td>-30</td>
<td>0.1</td>
<td>98.6</td>
<td>82.4</td>
<td>16.2</td>
<td>0.93</td>
<td>0.72</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OFF</td>
<td>0</td>
<td>2.32</td>
<td>-</td>
<td>0.1</td>
<td>94.3</td>
<td>-</td>
<td>-</td>
<td>0.95</td>
<td>0.74</td>
<td>0.26</td>
</tr>
<tr>
<td>3</td>
<td>B</td>
<td>ON</td>
<td>175</td>
<td>9.49</td>
<td>-70</td>
<td>0.1</td>
<td>98.5</td>
<td>83.2</td>
<td>15.3</td>
<td>0.70</td>
<td>0.79</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OFF</td>
<td>0</td>
<td>9.49</td>
<td>-</td>
<td>0.1</td>
<td>93.9</td>
<td>-</td>
<td>-</td>
<td>0.60</td>
<td>0.63</td>
<td>0.27</td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>ON</td>
<td>1150</td>
<td>0.87</td>
<td>-30</td>
<td>1.0</td>
<td>76.9</td>
<td>54.2</td>
<td>22.7</td>
<td>0.74</td>
<td>0.76</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OFF</td>
<td>0</td>
<td>0.87</td>
<td>-</td>
<td>1.0</td>
<td>93.4</td>
<td>-</td>
<td>-</td>
<td>0.72</td>
<td>0.78</td>
<td>0.27</td>
</tr>
</tbody>
</table>

* Phase shift of synchronous particle (shift of RFQ phase relative to MHB) to compensate for the phase lagging of non-isochronous particles.
Summary

• A pre-buncher operating at a sub-harmonic frequency of 10.128 MHz can deliver transmissions > 80% at HIE-ISOLDE:
  – A chopper will be required to remove ~15% beam trapped in satellite bunches
  – Pre-bunching offers a significant reduction in the longitudinal beam emittance delivered by the RFQ:
    • Factor 3 reduction in longitudinal emittance is feasible in certain scenarios

• Similar performance in bunching could be possible without Stage 3 and linac extension:
  – Experiments must accept satellite bunches
Reference material


Extra slides
Options without Linac Extension

(a) A: baseline, no modifications

(b) B: triplet and solenoids installed

(c) C: MHB installed before separator

(d) D: MHB before separator, triplet and solenoid installed
Options with Linac Extension

(a) A: triplet and solenoids

(b) B: MHB before separator, triplet and solenoid installed

(MHB close to RFQ if EBIS energy spread increased)

(c) C: MHB close to RFQ, triplet and solenoid installed
# Summary of beam dynamics performance

<table>
<thead>
<tr>
<th>Upgrade Stage</th>
<th>Option</th>
<th>MHB Status</th>
<th>$V_0$ [V]</th>
<th>$L$ [m]</th>
<th>$\Delta \phi^a$ [deg]</th>
<th>$\Delta W_{\text{source}}$ [%]</th>
<th>$T_{\text{total}}$ [%]</th>
<th>$T_{10\text{MHz}}$ [%]</th>
<th>$T_{\text{sat}}$ [%]</th>
<th>$\epsilon_{x,\text{rms}}$ [mm mrad]</th>
<th>$\epsilon_{y,\text{rms}}$ [mm mrad]</th>
<th>$\epsilon_{z,\text{rms}}$ [ns keV/\mu]</th>
</tr>
</thead>
<tbody>
<tr>
<td>REX (today)</td>
<td>-</td>
<td>OFF</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>0.1</td>
<td>93.9</td>
<td>-</td>
<td>-</td>
<td>0.64</td>
<td>1.36</td>
<td>0.28</td>
</tr>
<tr>
<td>REX (modified)</td>
<td>-</td>
<td>OFF</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>0.1</td>
<td>93.7</td>
<td>-</td>
<td>-</td>
<td>0.62</td>
<td>0.64</td>
<td>0.27</td>
</tr>
<tr>
<td>1 and 2</td>
<td>A</td>
<td>ON</td>
<td>740</td>
<td>1.40</td>
<td>-120</td>
<td>0.1</td>
<td>77.4</td>
<td>64.5</td>
<td>12.9</td>
<td>1.82</td>
<td>3.85</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OFF</td>
<td>0</td>
<td>1.40</td>
<td>-</td>
<td>0.1</td>
<td>79.7</td>
<td>-</td>
<td>-</td>
<td>1.52</td>
<td>3.07</td>
<td>0.30</td>
</tr>
<tr>
<td>1 and 2</td>
<td>B</td>
<td>ON</td>
<td>720</td>
<td>1.45</td>
<td>-80</td>
<td>0.1</td>
<td>98.2</td>
<td>83.4</td>
<td>14.8</td>
<td>0.95</td>
<td>0.90</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OFF</td>
<td>0</td>
<td>1.45</td>
<td>-</td>
<td>0.1</td>
<td>93.9</td>
<td>-</td>
<td>-</td>
<td>0.90</td>
<td>0.76</td>
<td>0.28</td>
</tr>
<tr>
<td>1 and 2</td>
<td>C</td>
<td>ON</td>
<td>205</td>
<td>8.19</td>
<td>-120</td>
<td>0.1</td>
<td>97.4</td>
<td>82.1</td>
<td>15.3</td>
<td>1.04</td>
<td>1.35</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OFF</td>
<td>0</td>
<td>8.19</td>
<td>-</td>
<td>0.1</td>
<td>94.0</td>
<td>-</td>
<td>-</td>
<td>0.62</td>
<td>1.34</td>
<td>0.26</td>
</tr>
<tr>
<td>1 and 2</td>
<td>D</td>
<td>ON</td>
<td>205</td>
<td>8.19</td>
<td>-120</td>
<td>0.1</td>
<td>98.4</td>
<td>82.8</td>
<td>15.6</td>
<td>0.72</td>
<td>0.81</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OFF</td>
<td>0</td>
<td>8.19</td>
<td>-</td>
<td>0.1</td>
<td>93.9</td>
<td>-</td>
<td>-</td>
<td>0.62</td>
<td>0.64</td>
<td>0.27</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>ON</td>
<td>465</td>
<td>2.32</td>
<td>-30</td>
<td>0.1</td>
<td>98.6</td>
<td>82.4</td>
<td>16.2</td>
<td>0.93</td>
<td>0.72</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OFF</td>
<td>0</td>
<td>2.32</td>
<td>-</td>
<td>0.1</td>
<td>94.3</td>
<td>-</td>
<td>-</td>
<td>0.95</td>
<td>0.74</td>
<td>0.26</td>
</tr>
<tr>
<td>3</td>
<td>B</td>
<td>ON</td>
<td>175</td>
<td>9.49</td>
<td>-70</td>
<td>0.1</td>
<td>98.5</td>
<td>83.2</td>
<td>15.3</td>
<td>0.70</td>
<td>0.79</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OFF</td>
<td>0</td>
<td>9.49</td>
<td>-</td>
<td>0.1</td>
<td>93.9</td>
<td>-</td>
<td>-</td>
<td>0.60</td>
<td>0.63</td>
<td>0.27</td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>ON</td>
<td>1150</td>
<td>0.87</td>
<td>-30</td>
<td>1.0</td>
<td>76.9</td>
<td>54.2</td>
<td>22.7</td>
<td>0.74</td>
<td>0.76</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OFF</td>
<td>0</td>
<td>0.87</td>
<td>-</td>
<td>1.0</td>
<td>93.4</td>
<td>-</td>
<td>-</td>
<td>0.72</td>
<td>0.78</td>
<td>0.27</td>
</tr>
</tbody>
</table>

*Phase shift of synchronous particle (shift of RFQ phase relative to MHB) to compensate for the phase lagging of non-isochronous particles.*