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

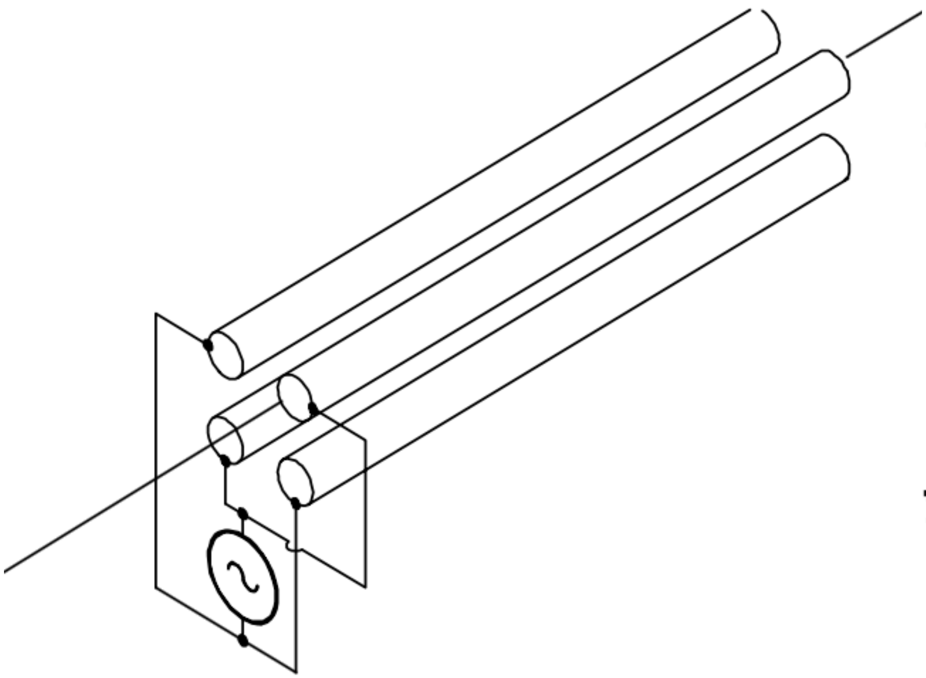
Contents

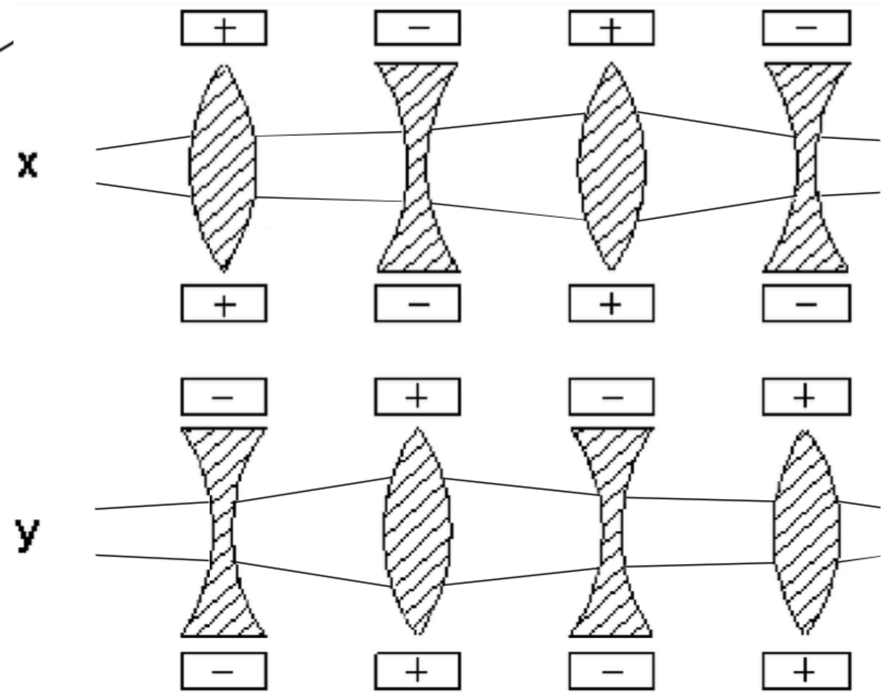
- Intro to the RFQ and concept of pre-bunching
- Beam dynamics studies:
  - Electrostatic modeling of RFQ in CST
  - PARMTEQ vs. TRACK
- Results from the feasibility study
- Integration at HIE-ISOLDE:
  - LEBT (bunching)
  - MEBT (chopper line)
- Summary
- Reference material / extra slides

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.

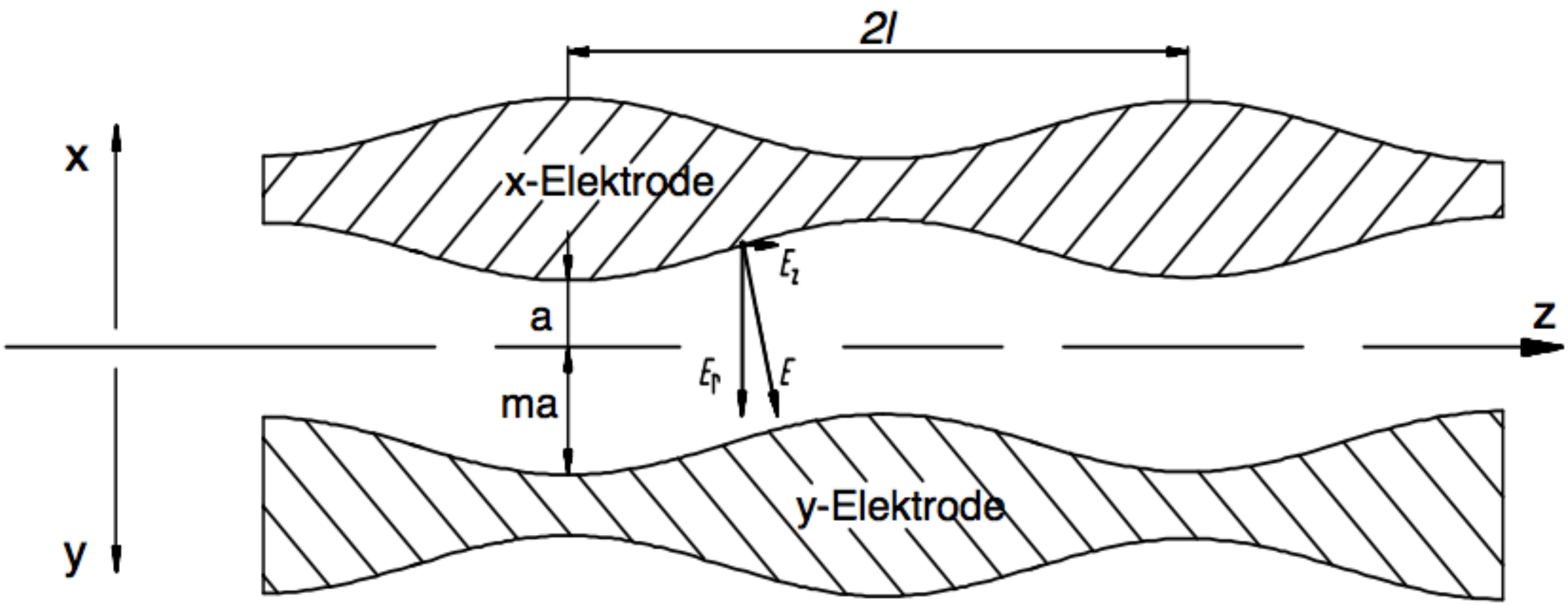
RFQ: transverse focusing





Courtesy of T. Sieber, *Entwicklung von 4-Rod- und IH- Radio- Frequenz-Quadrupol (RFQ) Beschleunigern für radioaktive Ionenstrahlen bei REX-ISOLDE und MAFF*, PhD Thesis, LMU Munchen, May 2001

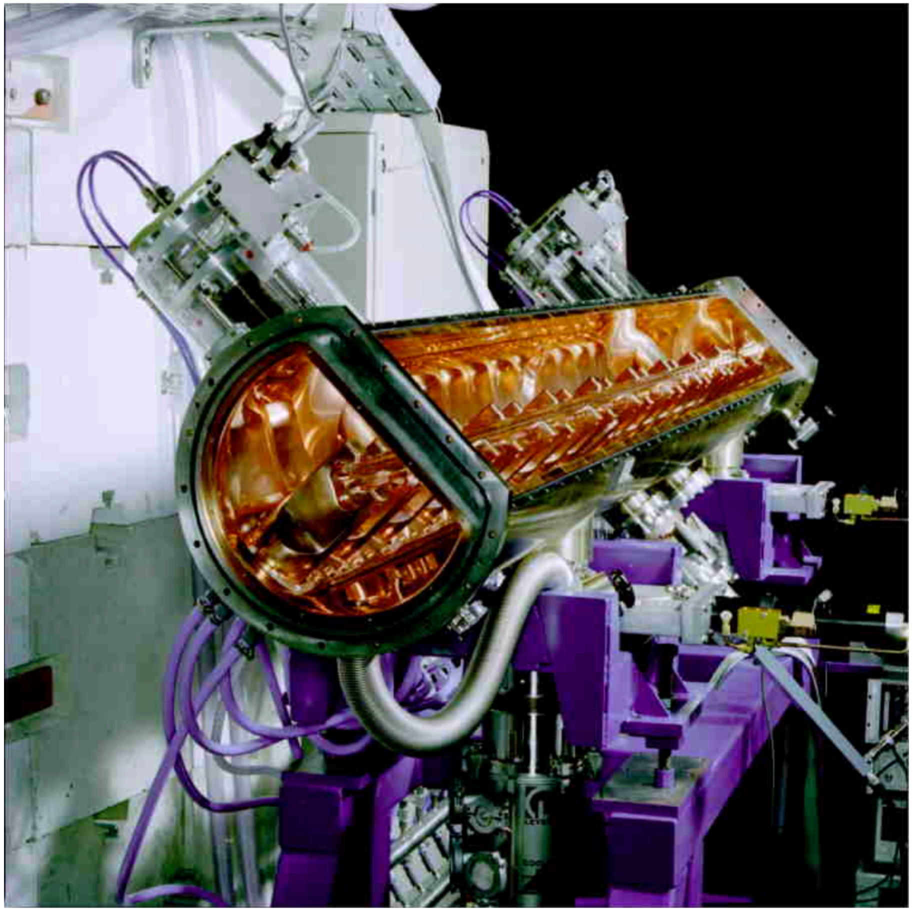
RFQ: longitudinal focusing (bunching)



Courtesy of T. Sieber, *Entwicklung von 4-Rod- und IH- Radio- Frequenz-Quadrupol (RFQ) Beschleunigern für radioaktive Ionenstrahlen bei REX-ISOLDE und MAFF*, PhD Thesis, LMU Munchen, May 2001

REX-ISOLDE RFQ

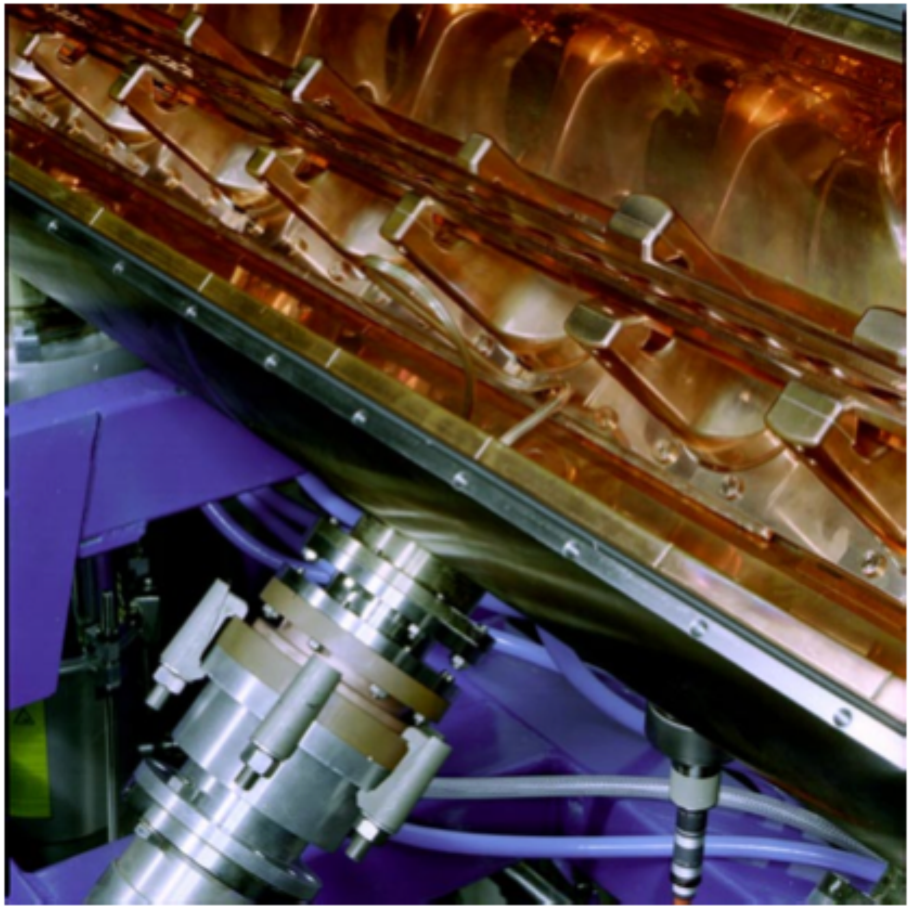
Parameter	Value
RFQ type	4-rod $\lambda/2$ (IH type)
f [MHz]	101.28
L [m]	3.0
$W_{in} \rightarrow W_{out}$ [keV/u]	$5 \rightarrow 300$
$\beta_{in} \rightarrow \beta_{out}$ [%]	$0.3 \rightarrow 2.5$
No. of cells	232
P [kW]	36.3 @ A/q = 4.5
A/q_{limit}	< 5.5
Duty cycle [%]	< 10



Courtesy of T. Sieber, *Entwicklung von 4-Rod- und IH- Radio- Frequenz-Quadrupol (RFQ) Beschleunigern für radioaktive Ionenstrahlen bei REX-ISOLDE und MAFF*, PhD Thesis, LMU Munchen, May 2001

REX-ISOLDE RFQ

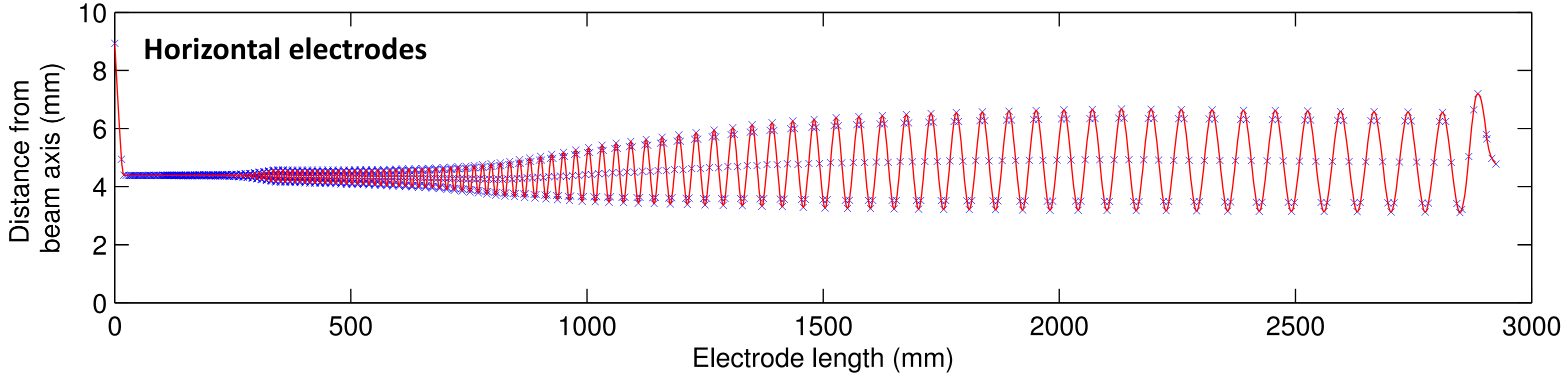
Parameter	Value
RFQ type	4-rod $\lambda/2$ (IH type)
f [MHz]	101.28
L [m]	3.0
$W_{in} \rightarrow W_{out}$ [keV/u]	$5 \rightarrow 300$
$\beta_{in} \rightarrow \beta_{out}$ [%]	$0.3 \rightarrow 2.5$
No. of cells	232
P [kW]	36.3 @ A/q = 4.5
A/q_{limit}	< 5.5
Duty cycle [%]	< 10

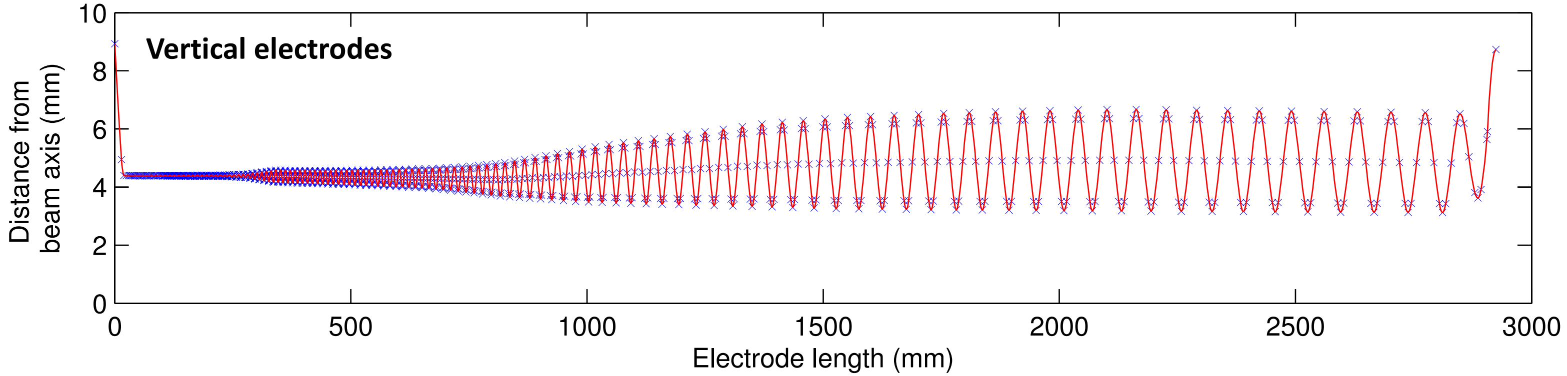


Courtesy of T. Sieber, *Entwicklung von 4-Rod- und IH- Radio- Frequenz-Quadrupol (RFQ) Beschleunigern für radioaktive Ionenstrahlen bei REX-ISOLDE und MAFF*, PhD Thesis, LMU Munchen, May 2001

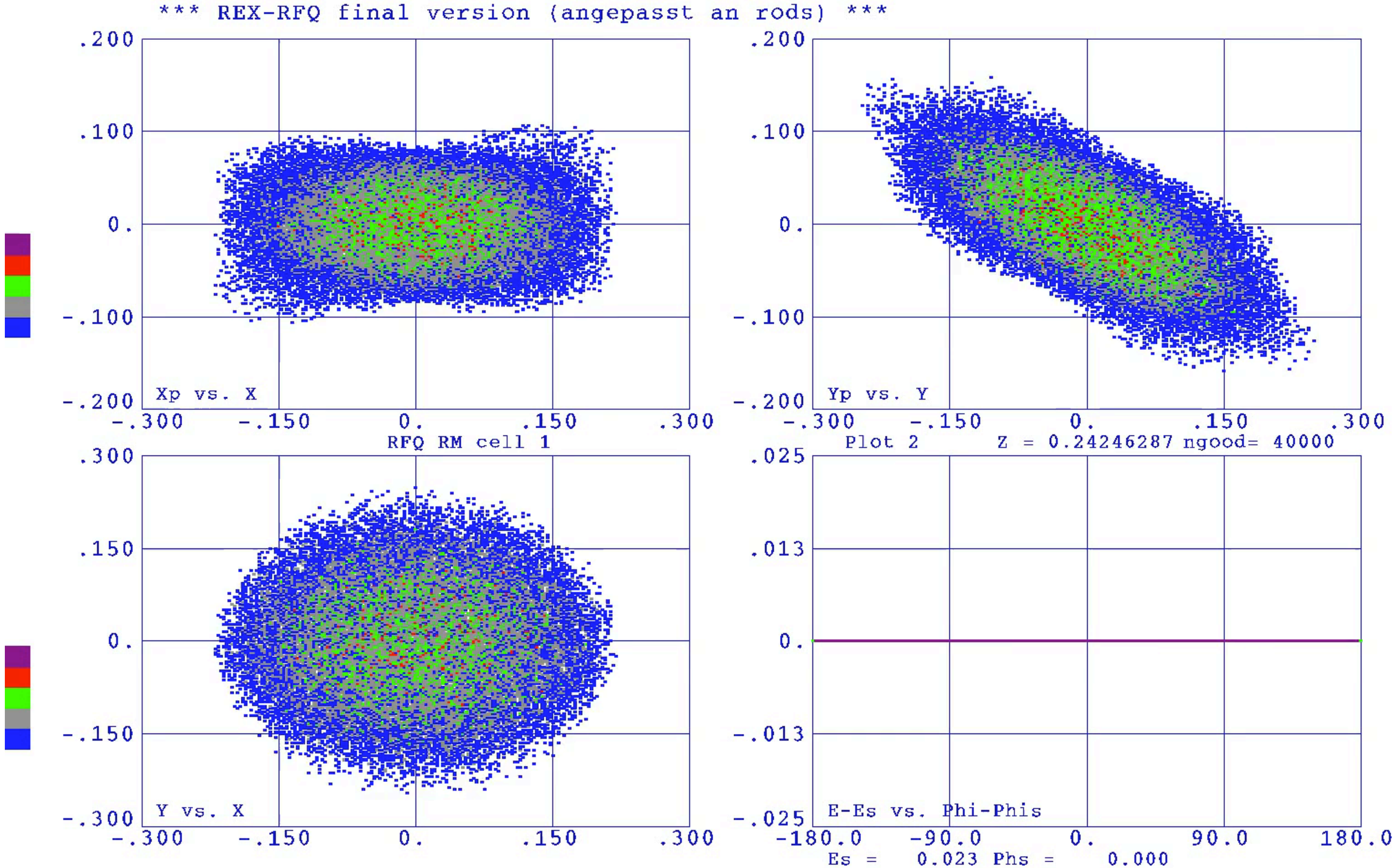
REX-ISOLDE RFQ: modulation

- 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:





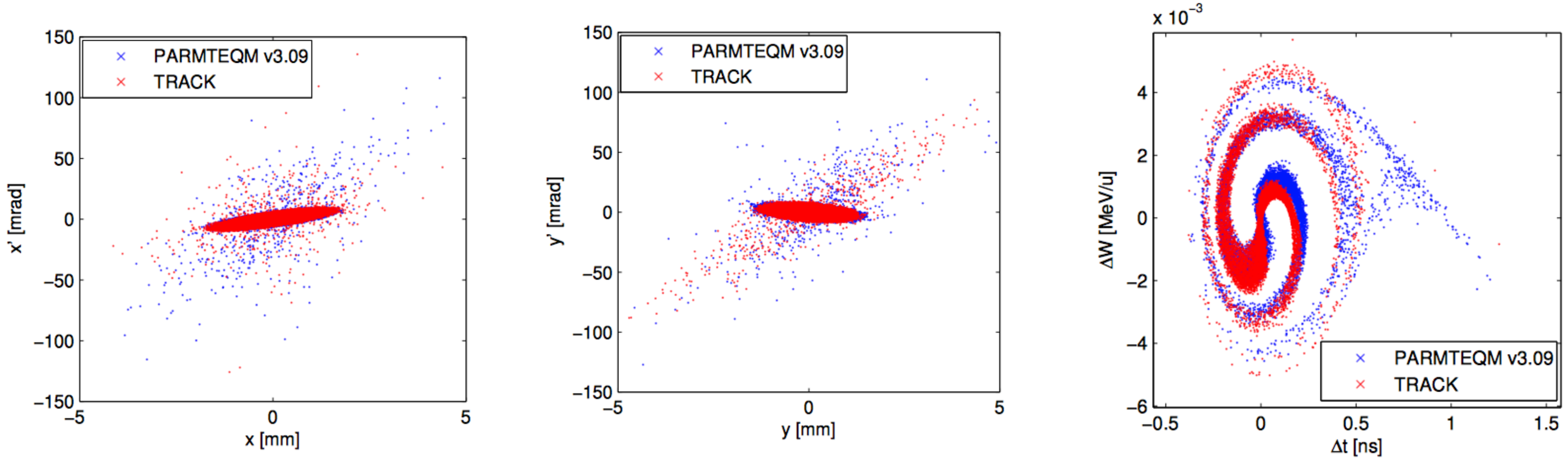
Beam dynamics in the REX-RFQ (1)



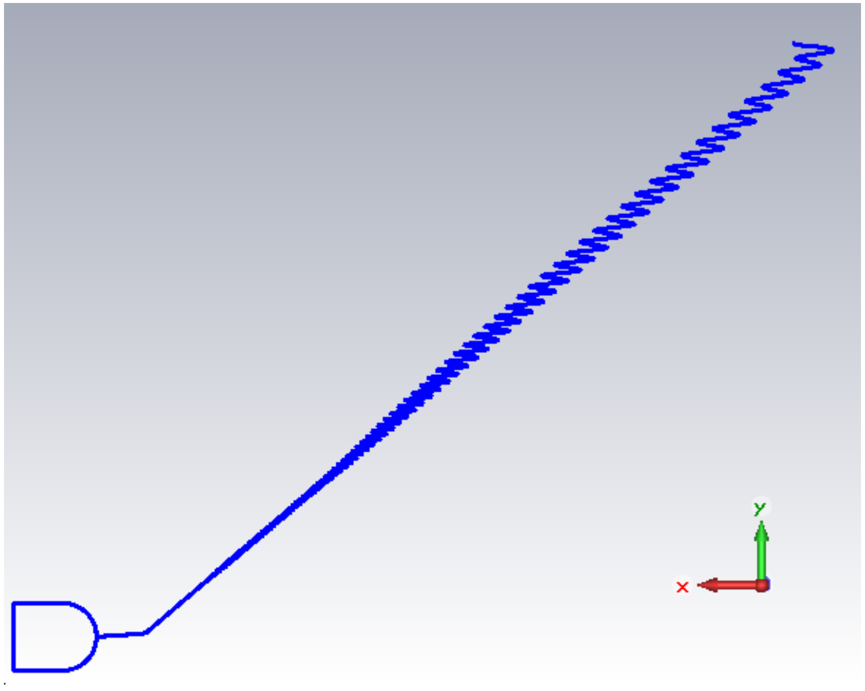
Electrode modulation bunches, before accelerating

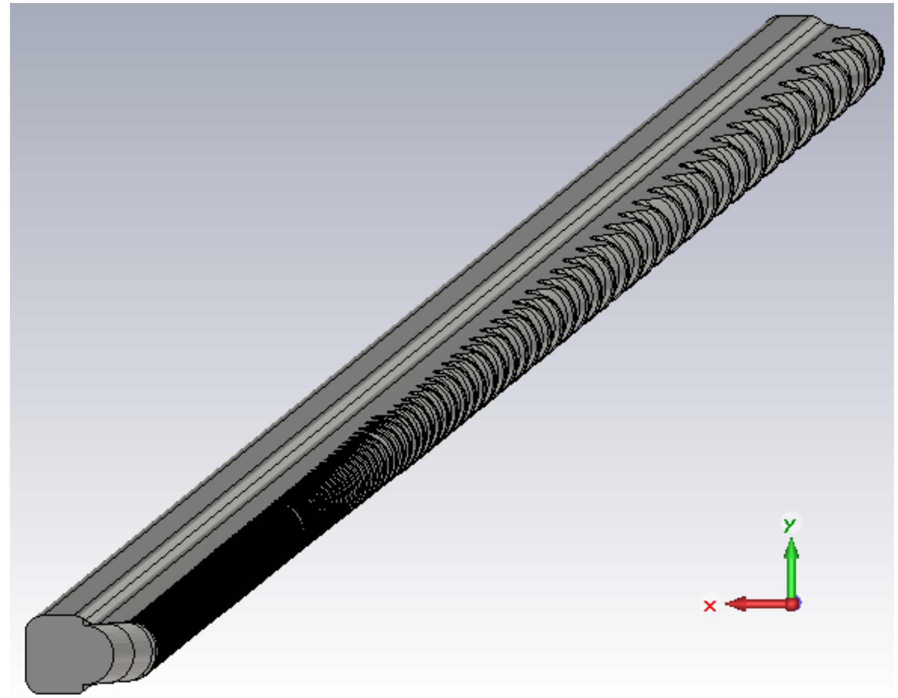
Beam dynamics in the REX-RFQ (2)

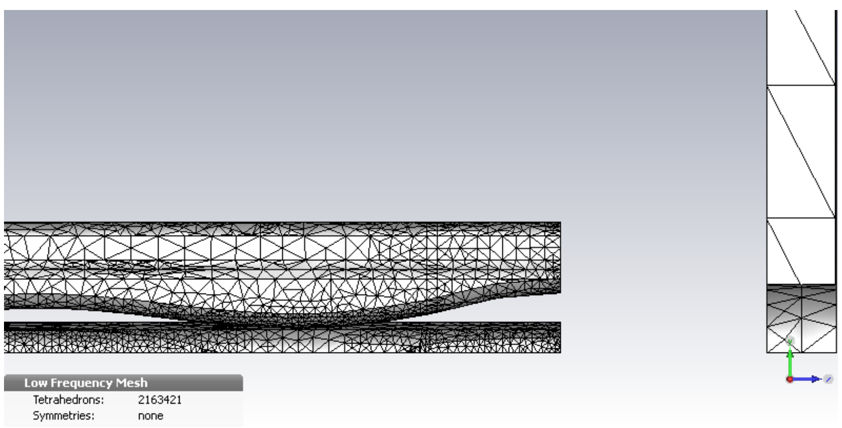
- Benchmarked the code *PARMTEQ* (LANL) [1]:
  - PARMTEQ was used to design the RFQ
  - Tracked particles in the field map using TRACK
  - Electric field map generated using finite element modelling in CST EM studio and data from CNC milling files and drawings

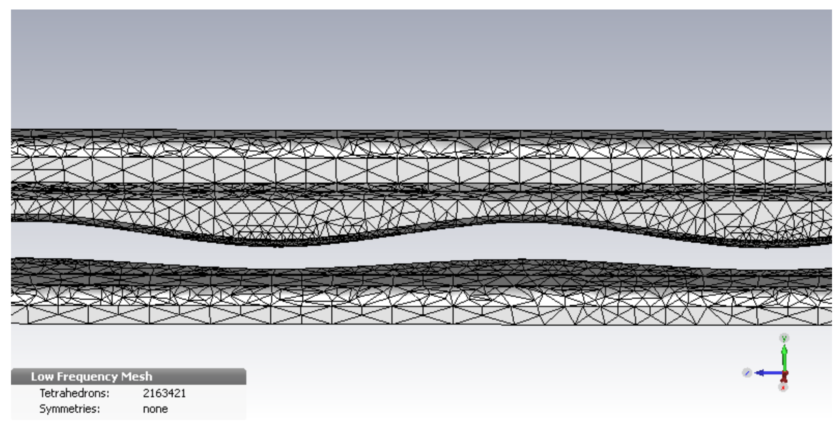


CST EM simulations of RFQ (1)

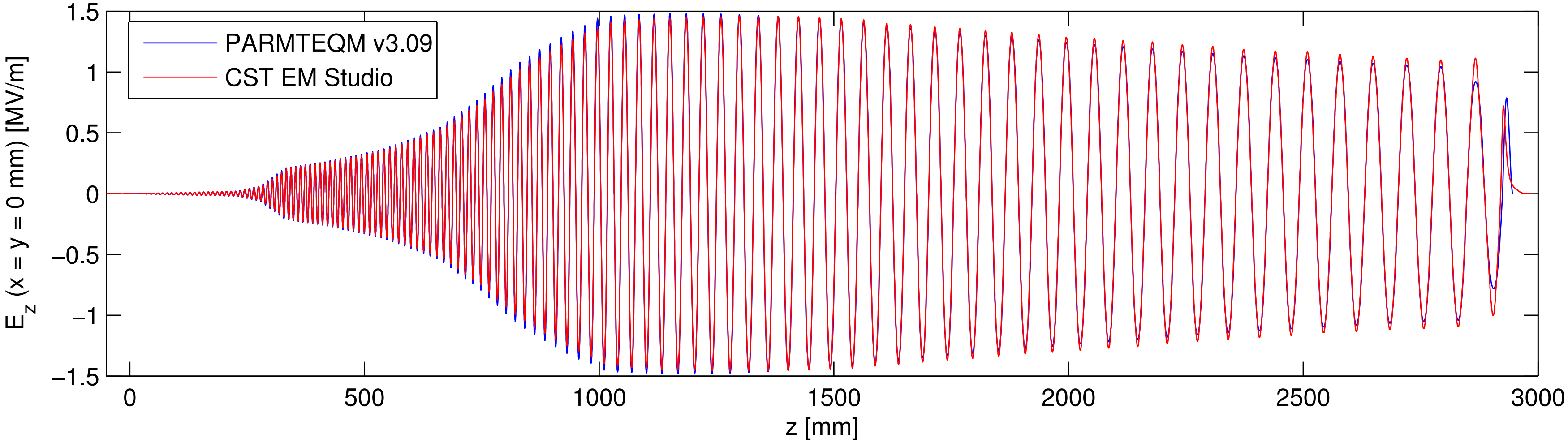


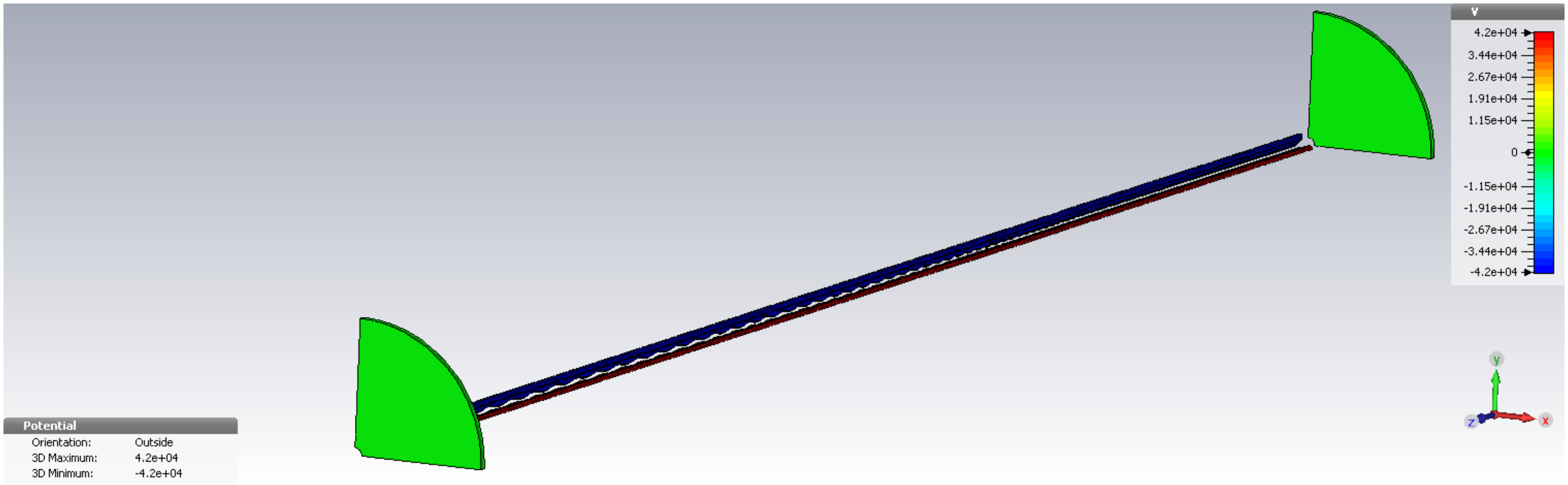




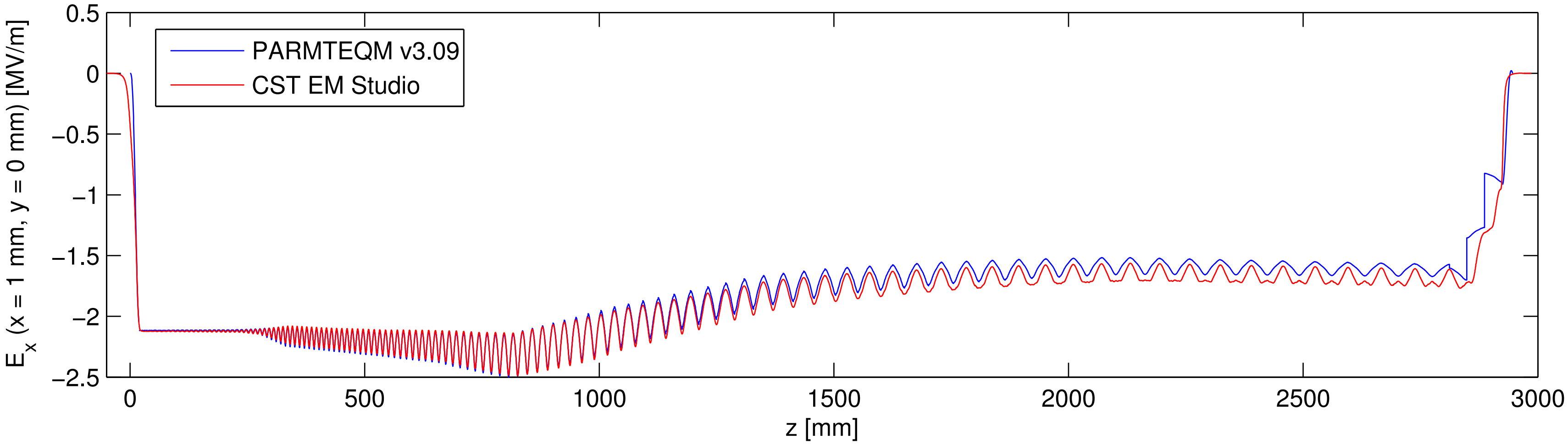


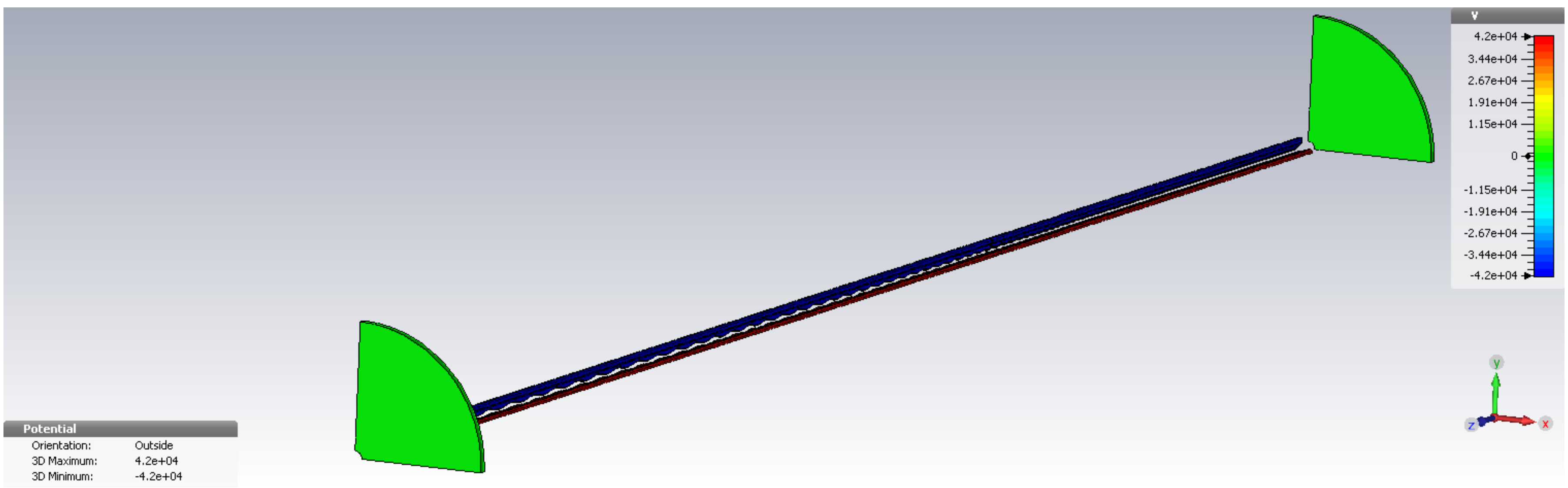
CST EM simulations of RFQ (2)



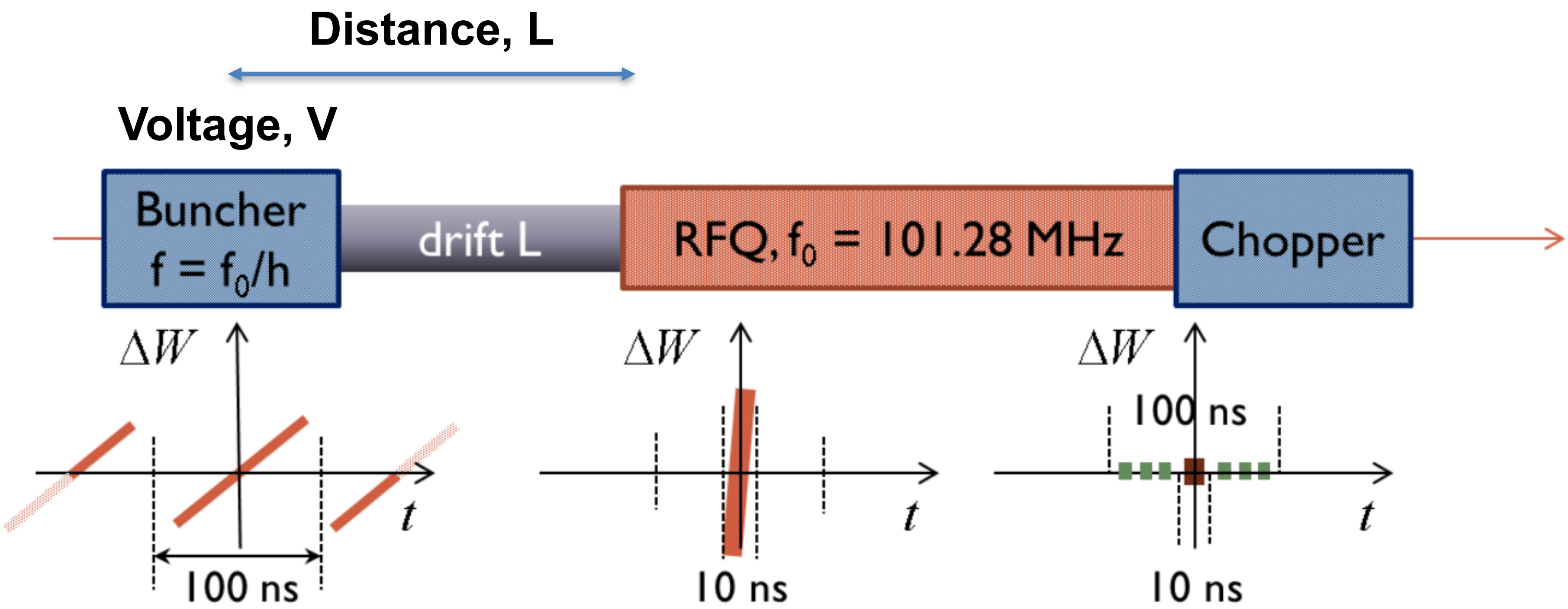


CST EM simulations of RFQ (2)





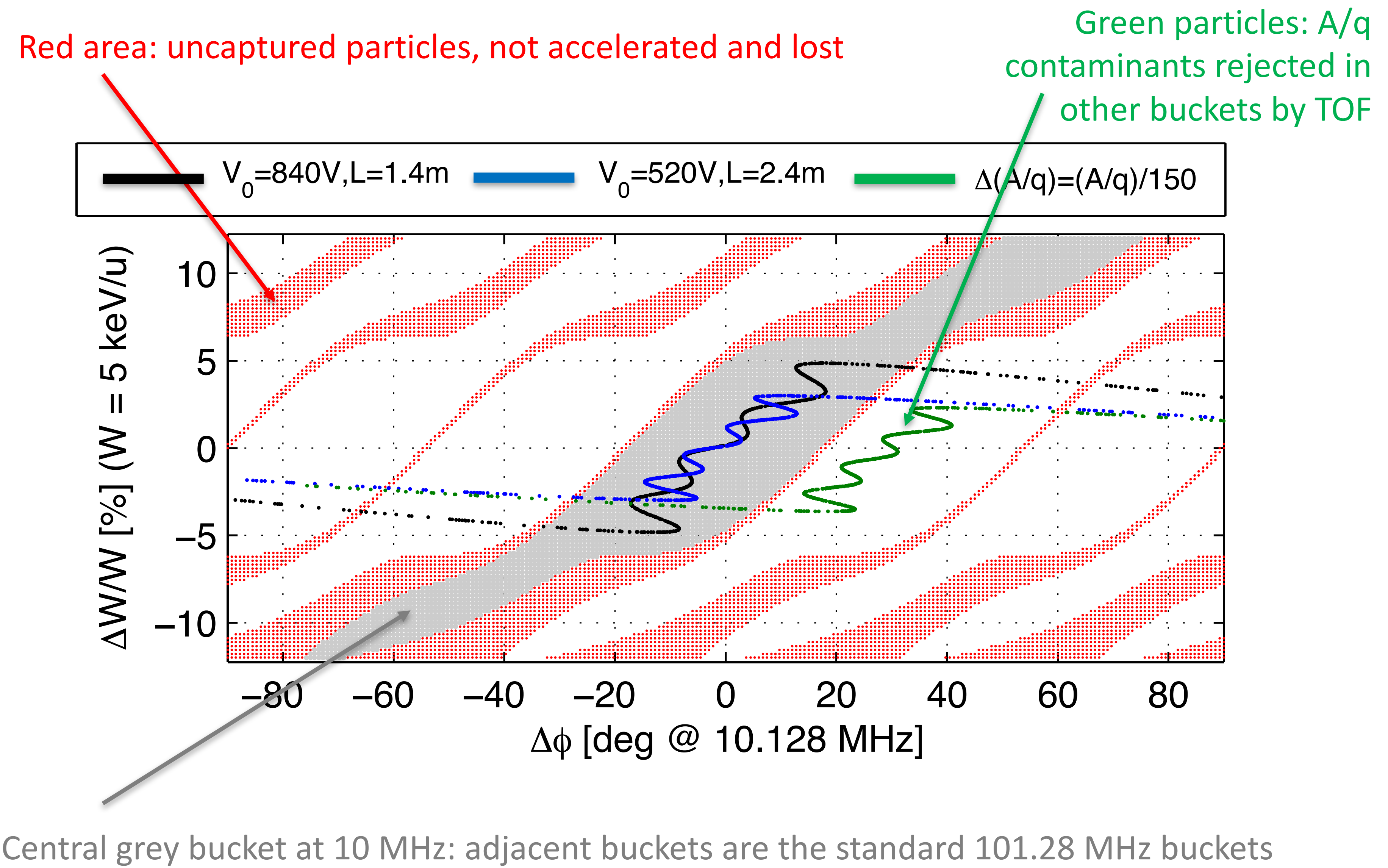
Concept of pre-bunching into RFQ



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

$$V_{\text{eff}}(\tau) = V_0 \left(\sin \omega_0 \tau - 0.43 \sin 2\omega_0 \tau + 0.21 \sin 3\omega_0 \tau - 0.10 \sin 4\omega_0 \tau \right)$$

Pre-bunching feasibility studies at REX



Pre-bunching at other laboratories

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

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

- 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

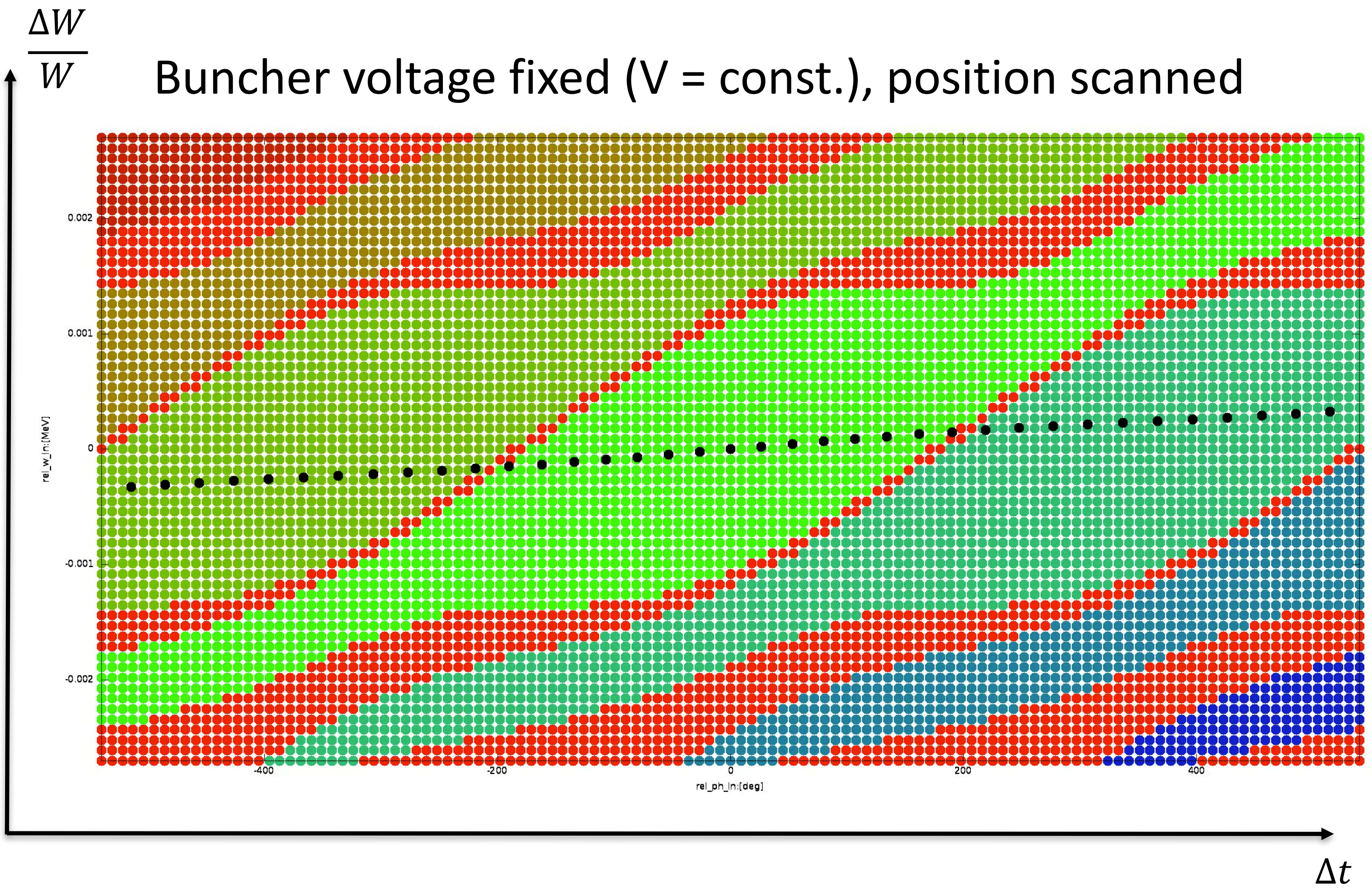
Table 1: Comparison of the key parameters of a selection of relevant worldwide MHB-RFQ systems.

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

- 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

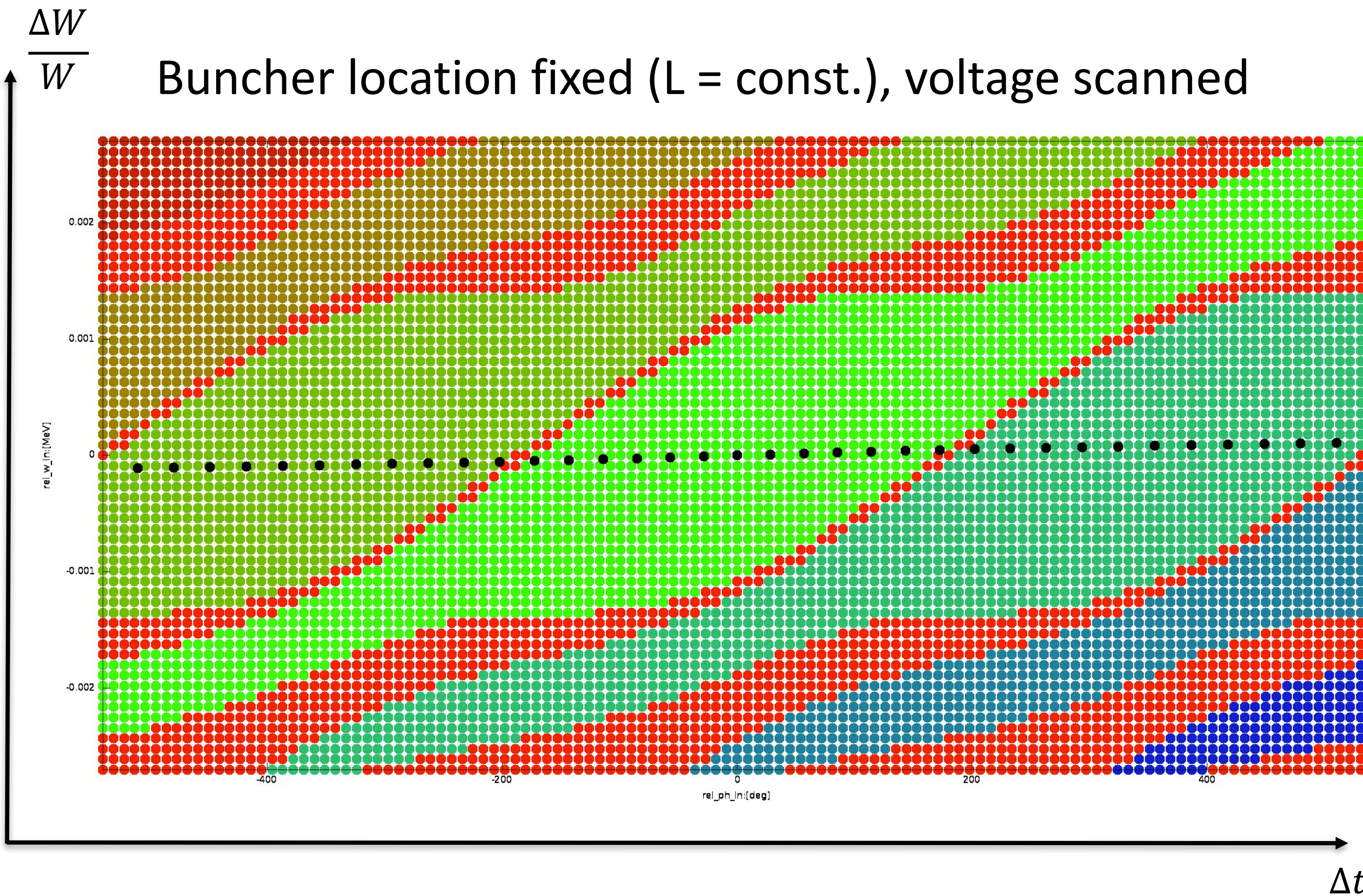
Pre-bunching feasibility studies at REX

Buncher voltage fixed (V = const.), position scanned



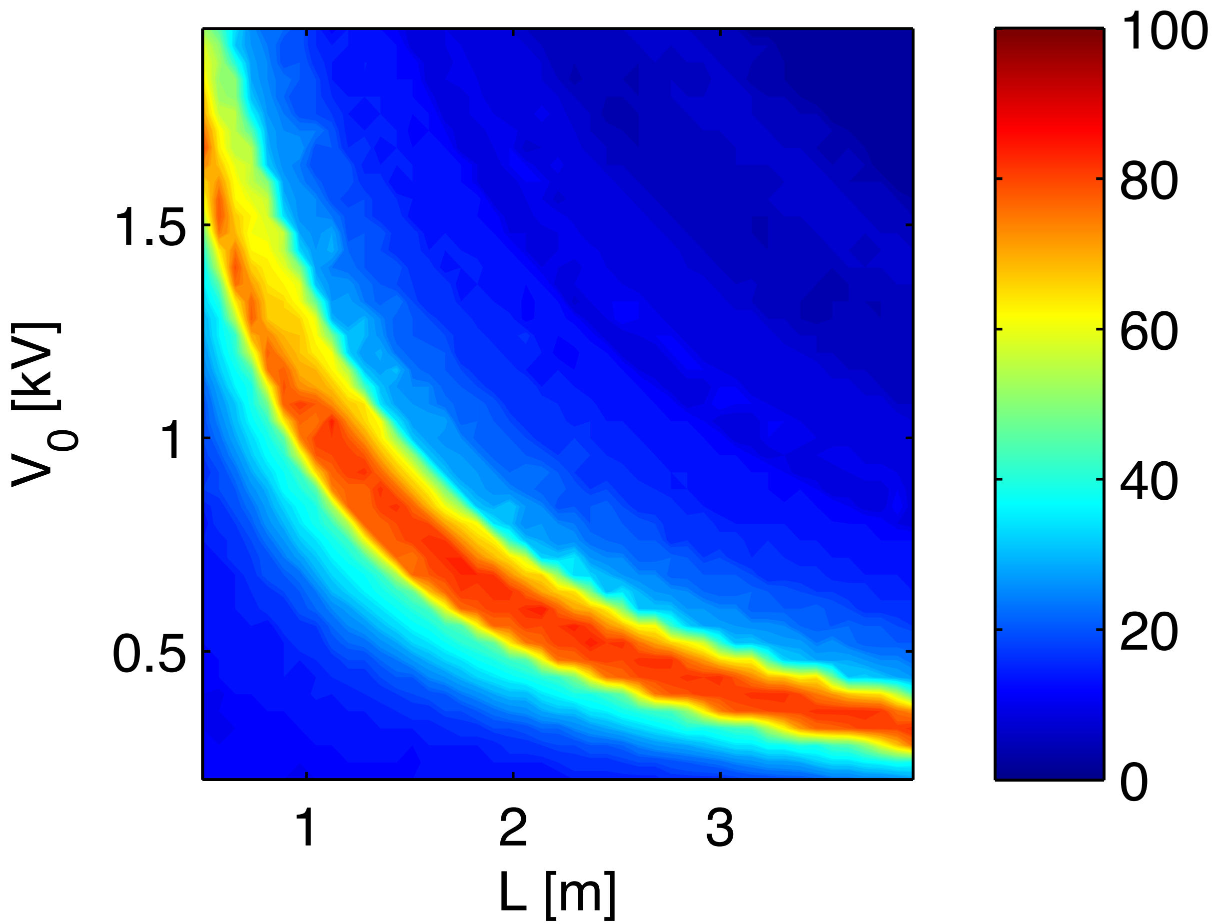
Pre-bunching feasibility studies at REX

Buncher location fixed (L = const.), voltage scanned



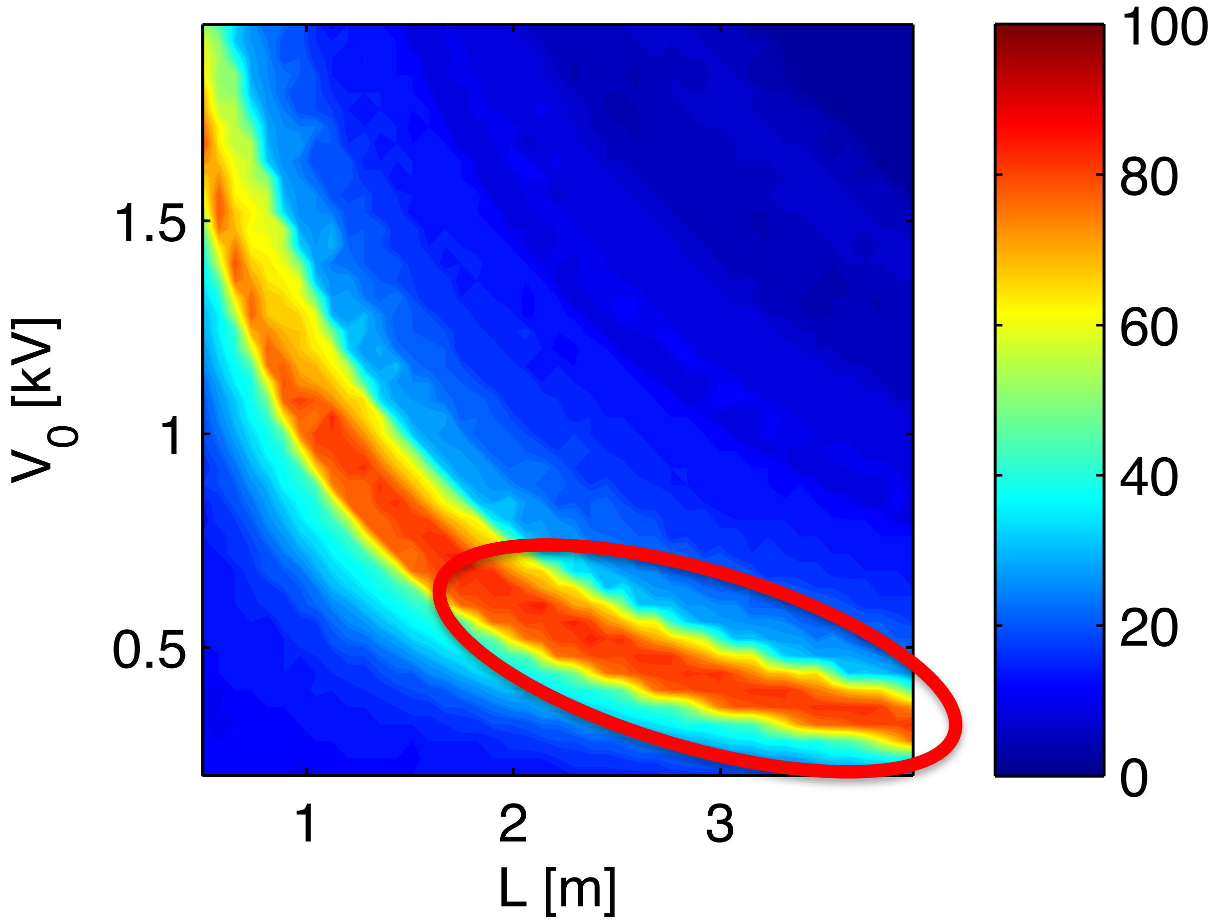
Pre-bunching feasibility studies at REX

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



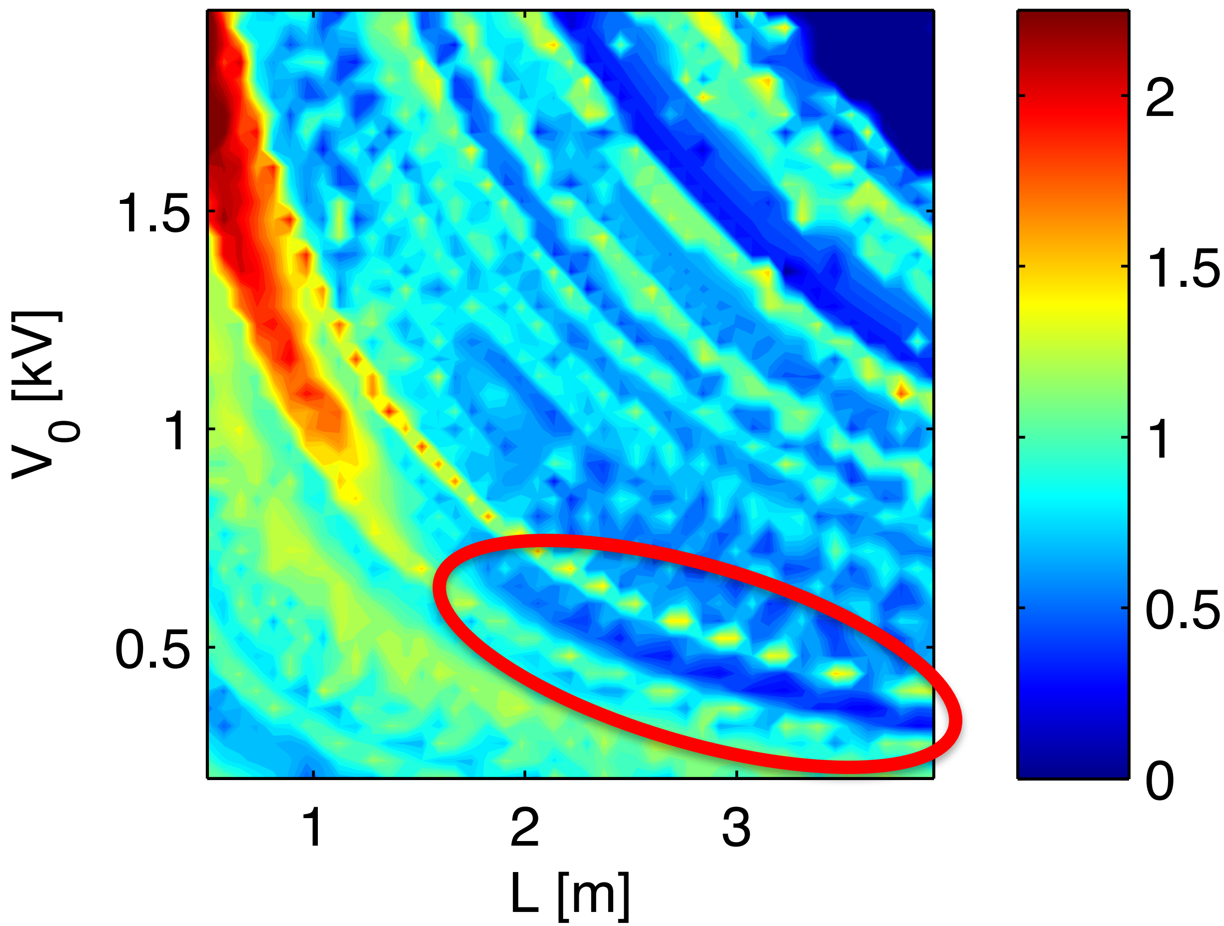
Pre-bunching feasibility studies at REX

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



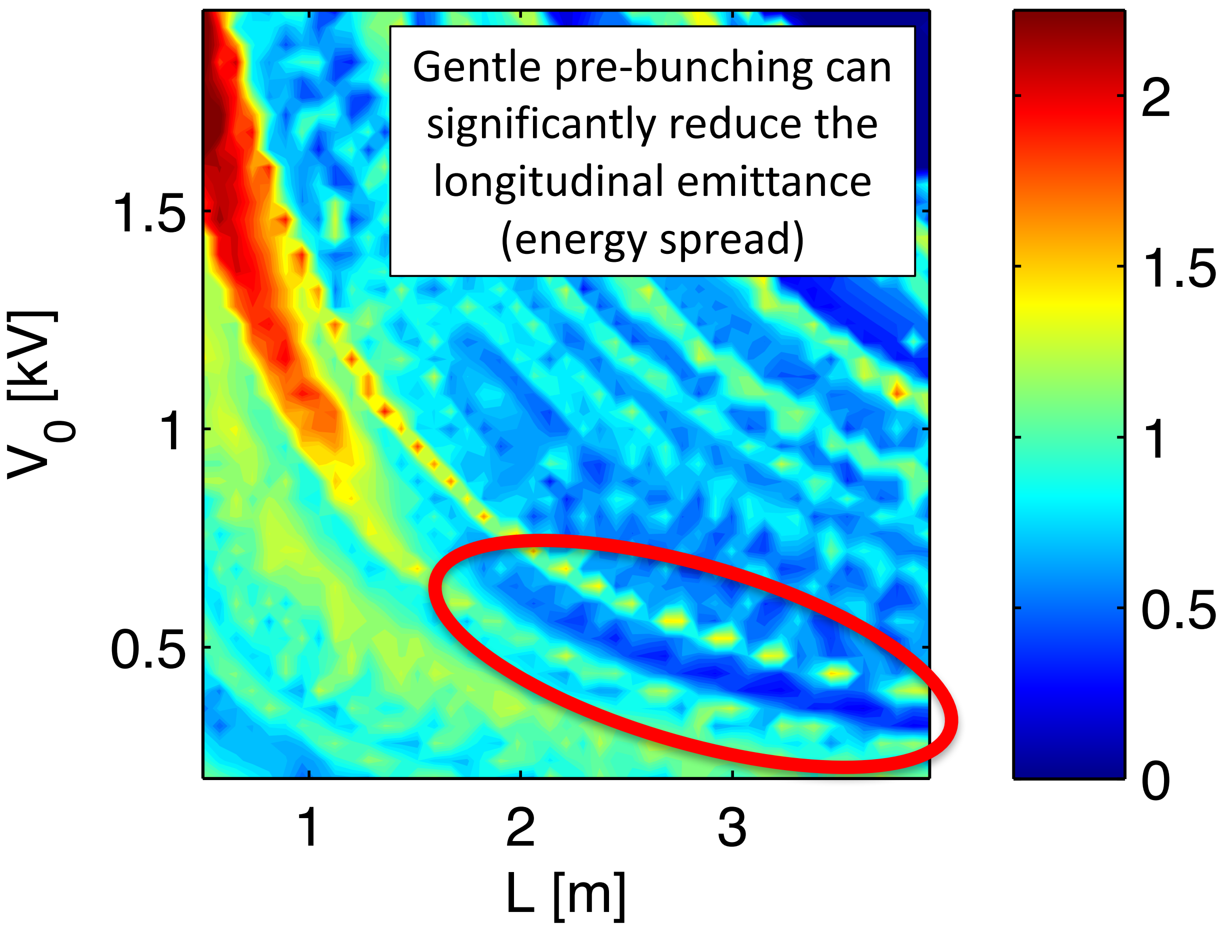
Pre-bunching feasibility studies at REX

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



Pre-bunching feasibility studies at REX

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



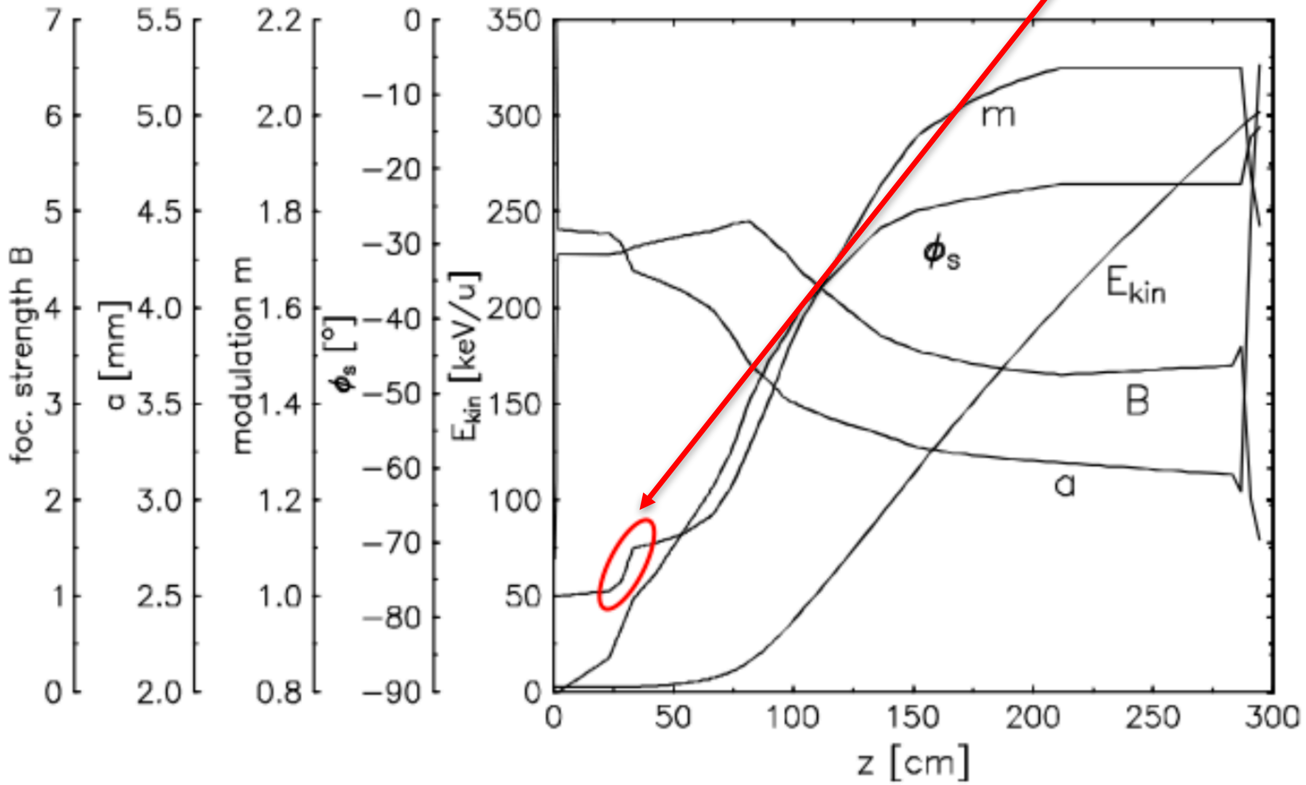
Pre-bunching feasibility studies at REX

$$V_{\mathrm{eff}} = \frac{2q}{\lambda A u c^2 \beta^3 \gamma^3} \frac{1}{L+d}$$

Optimum focal point of pre-buncher is at 29 cm on the electrodes (where modulation starts)

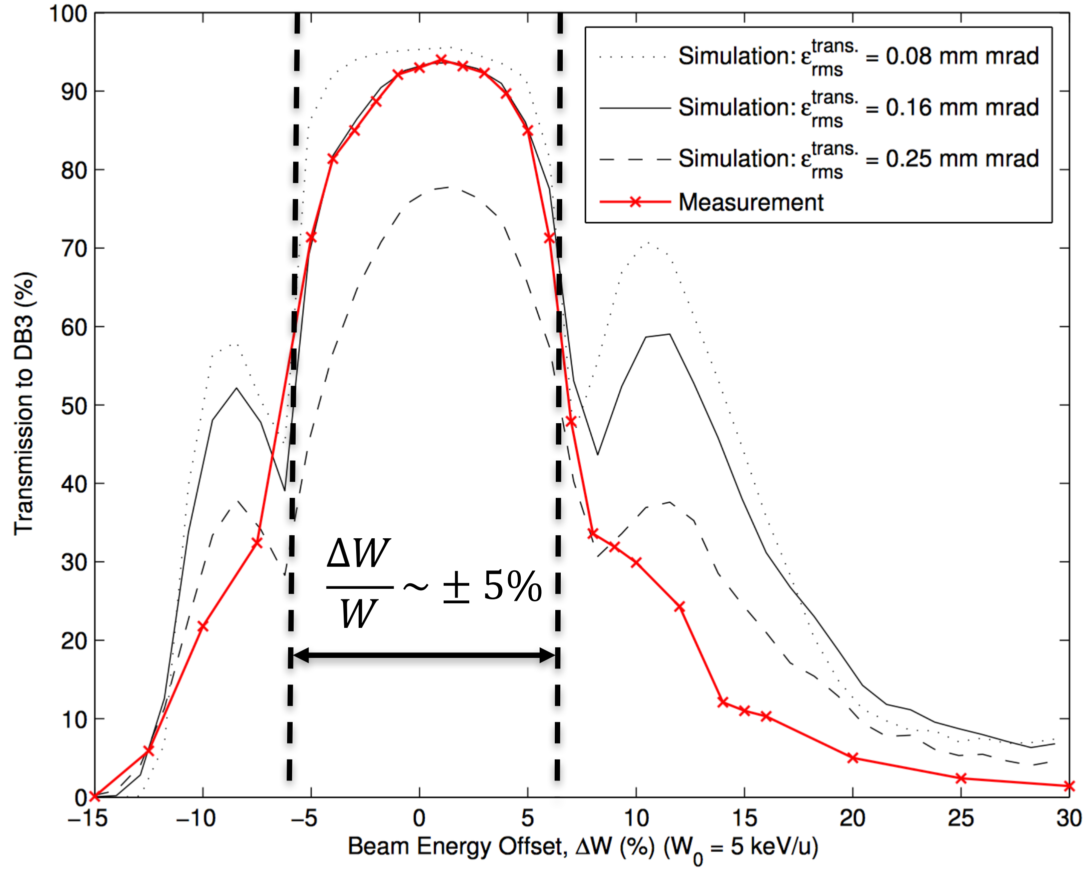
$d = 29$ cm

REX-ISOLDE electrode design parameters



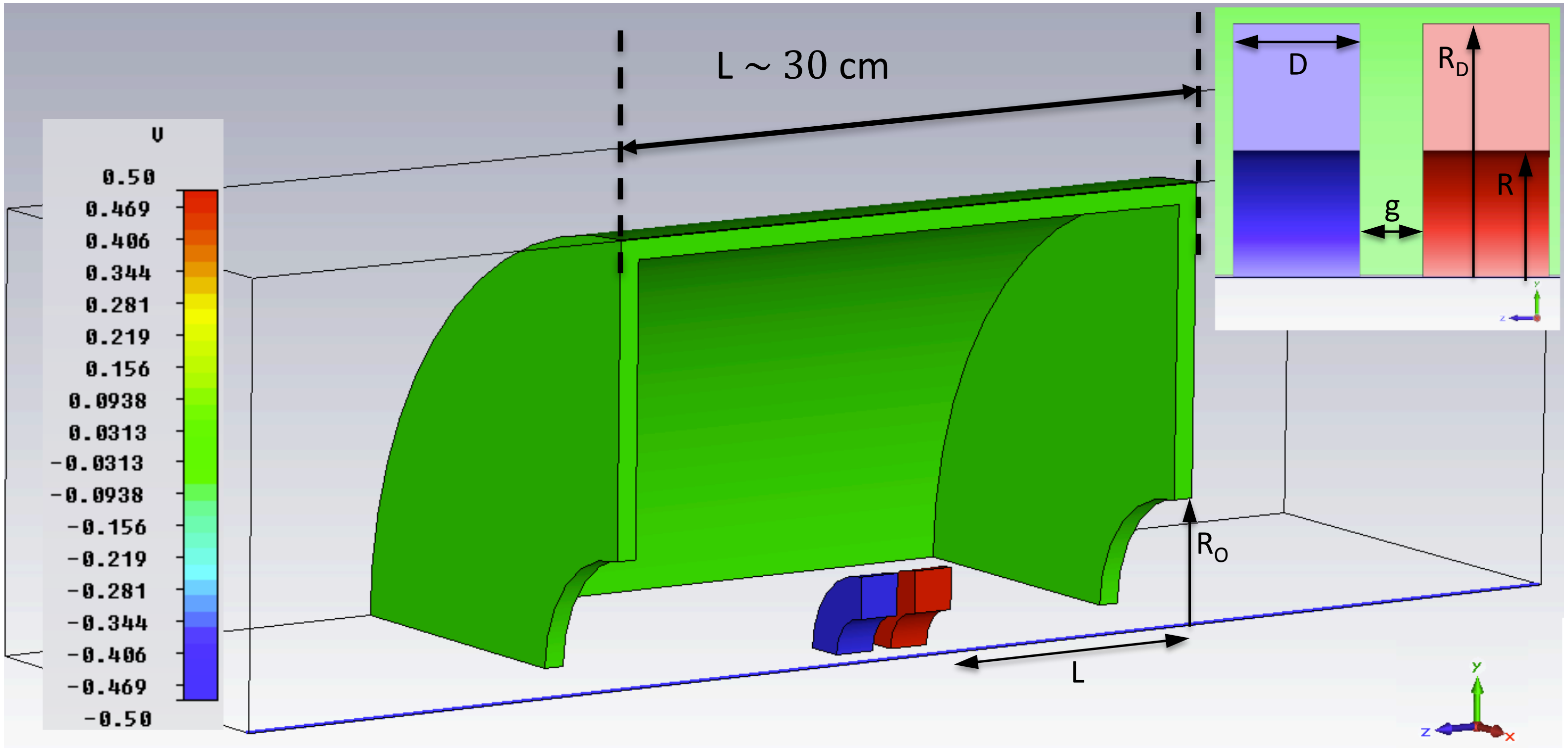
Energy acceptance of REX RFQ

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



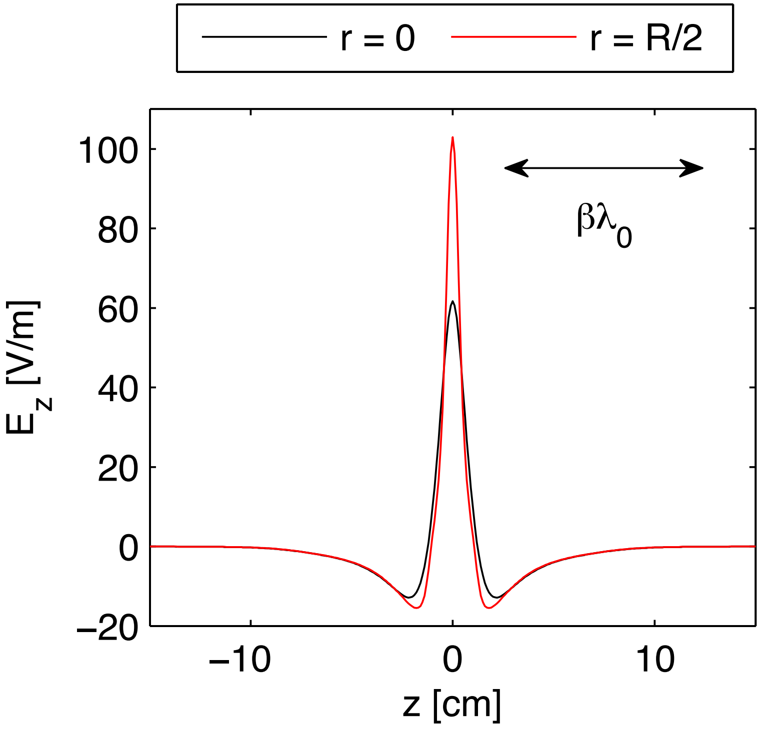
Multi-harmonic buncher (MHB)

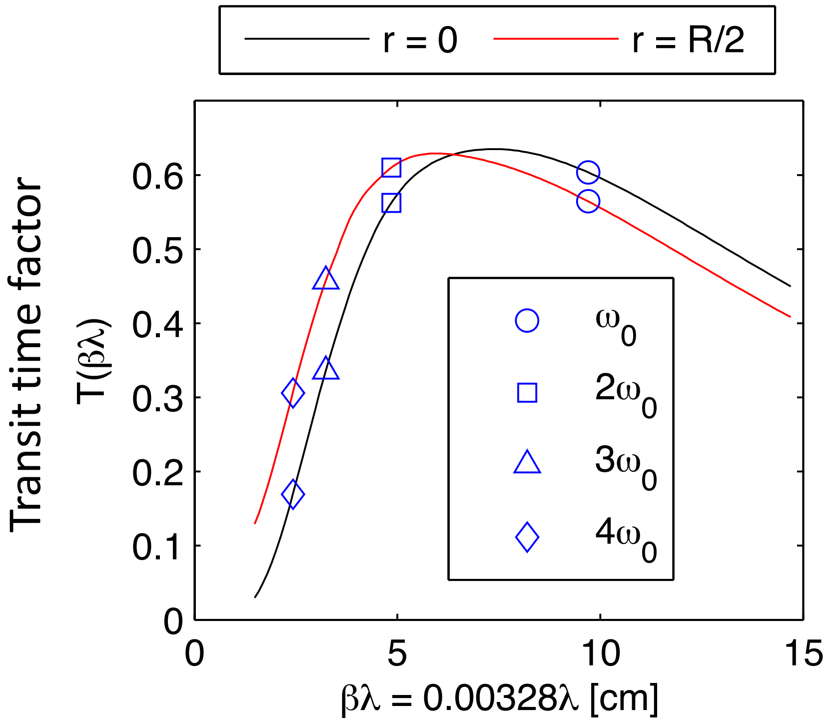
- Detailed design studies of MHB electrode geometry found in [3]
  - 2 electrodes operated in push-pull mode (equal but opposite voltages)



Multi-harmonic buncher (MHB)

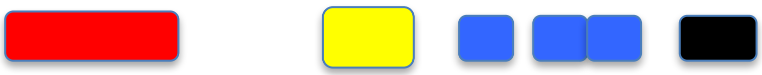
- Detailed design studies of MHB electrode geometry found in [3]
  - 2 electrodes operated in push-pull mode (equal but opposite voltages)
  - Aperture large compared to accelerating gap: strong radial dependence

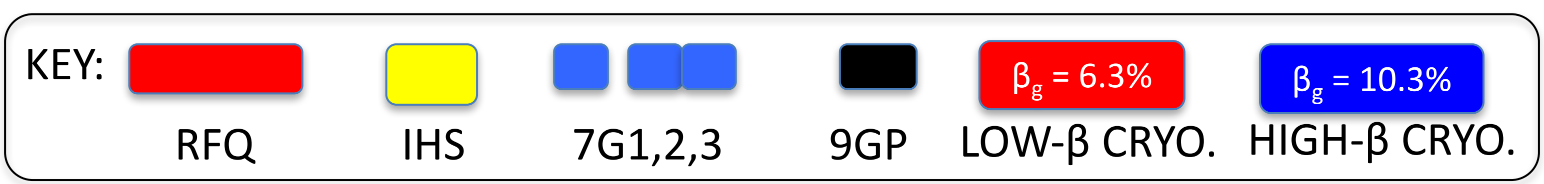




Integration at HIE-ISOLDE (1)

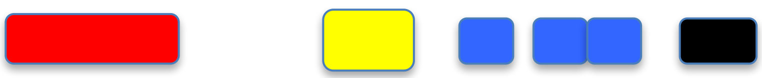
- REX accelerator: W = 3 MeV/u





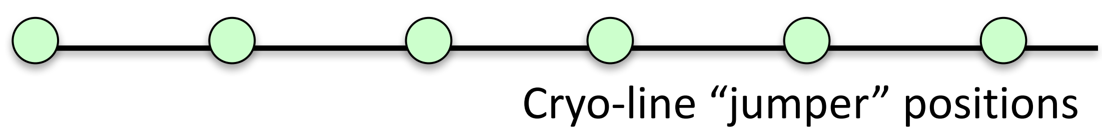
Integration at HIE-ISOLDE (1)

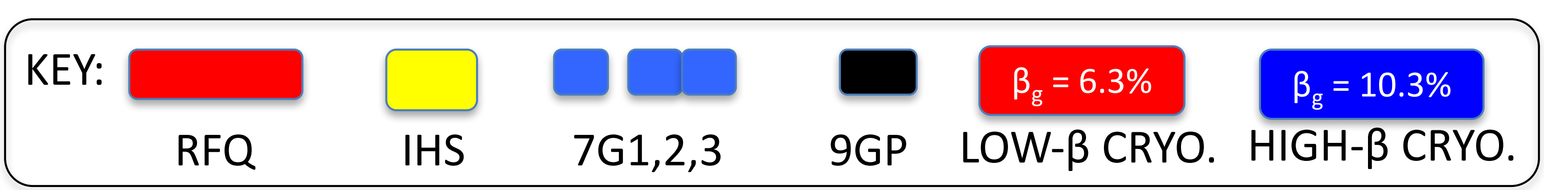
- REX accelerator: W = 3 MeV/u



- HIE Stage 1 (2016): W = 5.5 MeV/u

2x cryomodules
10x QWRs
2x solenoids

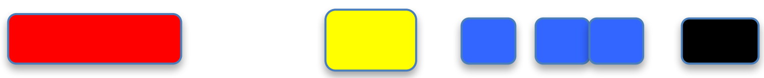




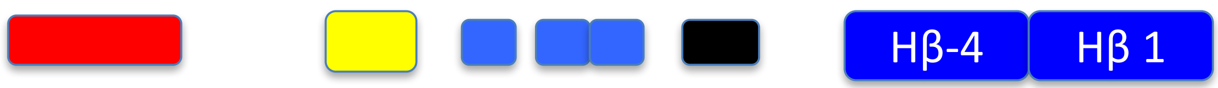
Integration at HIE-ISOLDE (1)

4x cryomodules
20x QWRs
4x solenoids

- REX accelerator: W = 3 MeV/u

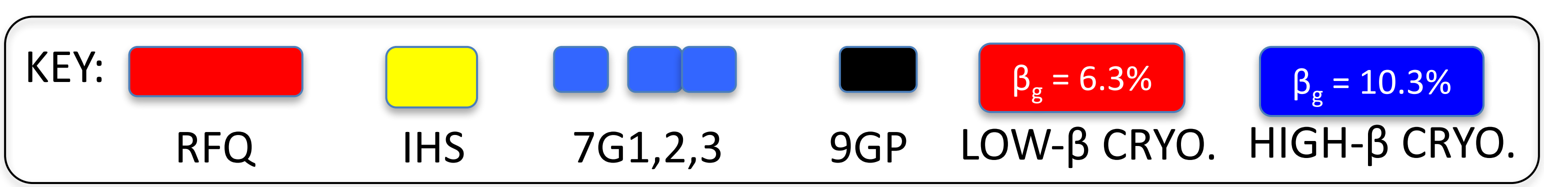


- HIE Stage 1 (2016): W = 5.5 MeV/u



- HIE Stage 2 (2018): W = 10 MeV/u

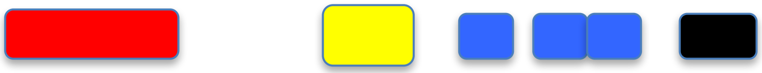
Cryo-line “jumper” positions



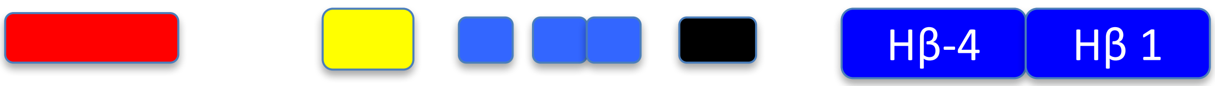
Integration at HIE-ISOLDE (1)

6x cryomodules
32x QWRs
8x solenoids

- REX accelerator: W = 3 MeV/u

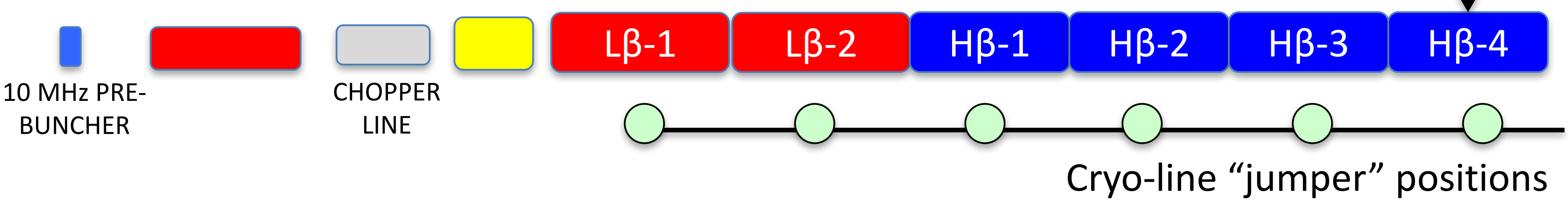


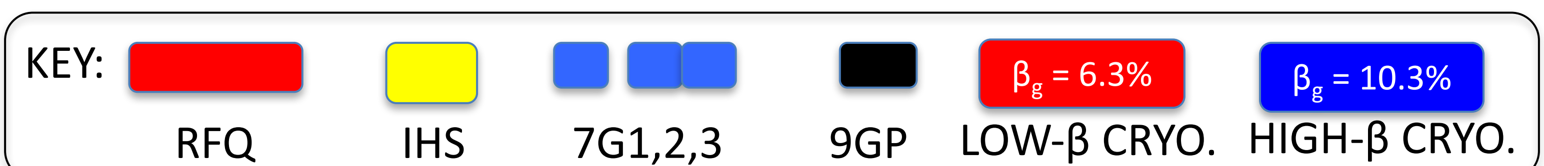
- HIE Stage 1 (2016): W = 5.5 MeV/u



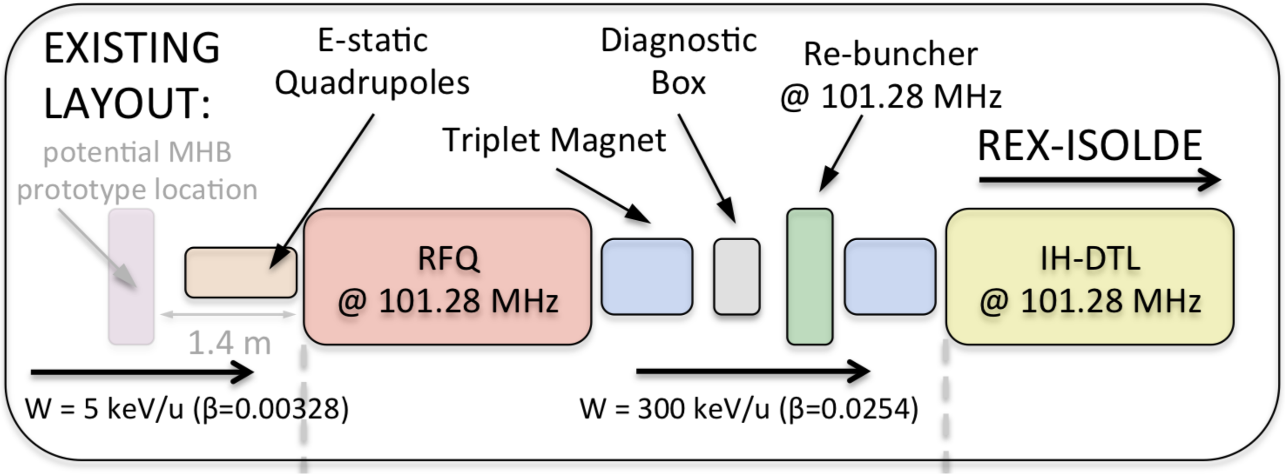
- HIE Stage 2 (2018): W = 10 MeV/u

- HIE Stage 3 (?): 10 MeV/u



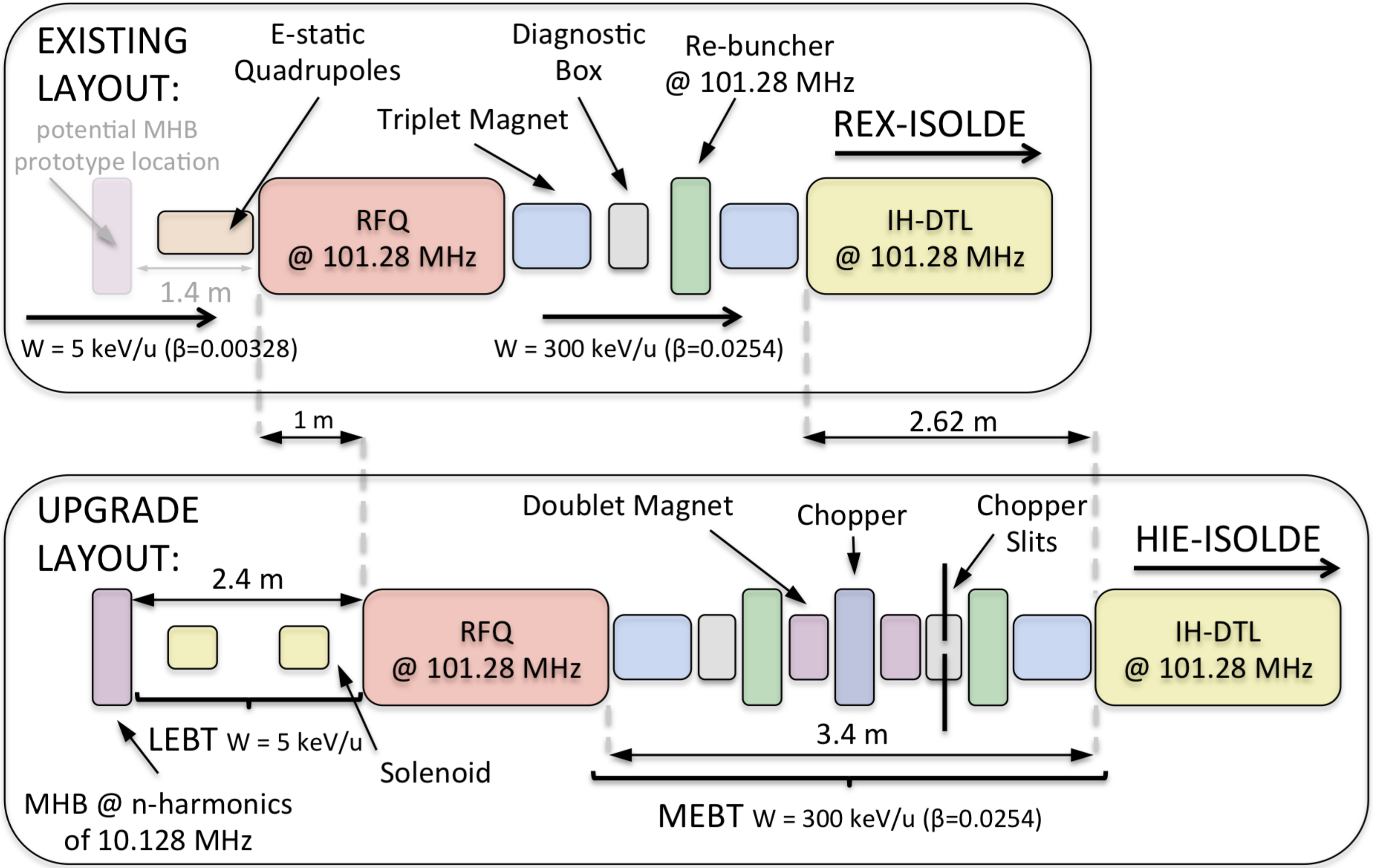


Integration at HIE-ISOLDE (2)



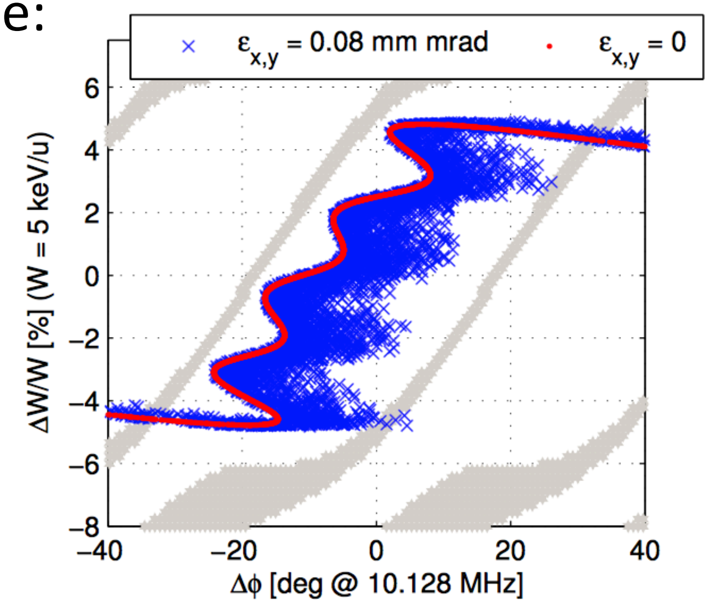
- Efficient bunching is still possible without extension provided by installation of Stage 3…
  - Possible layout options and their performance explored in [3]
  - Ideal for testing a prototype MHB structure, or possibly experiments: however, request is <1% in satellite bunches
  - Chopping before RFQ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

Integration at HIE-ISOLDE (2)



LEBT Design Challenges

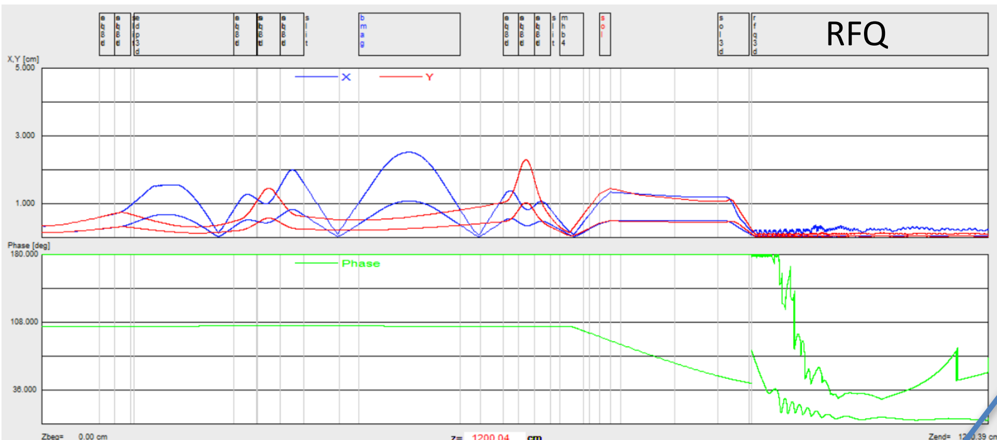
- Non-isochronous effects [3]:
  - bunching path length depends on the transverse position, i.e. optics and emittance:



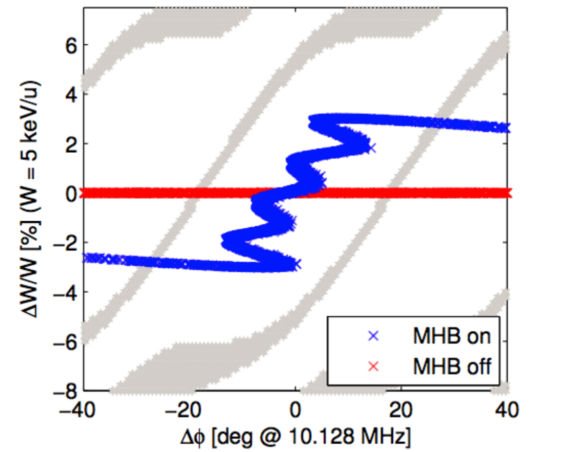
- Non-linearities: chromatic and non-linear abberations in quadrupoles [3]:
  - solenoids preferred as beam size kept small in both planes

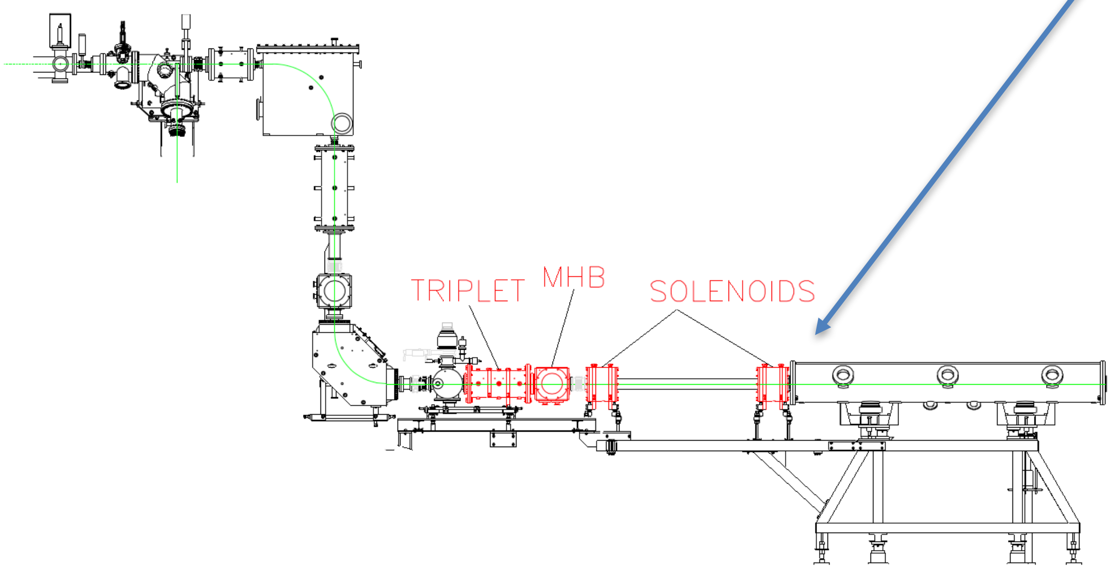
Baseline design with linac extension

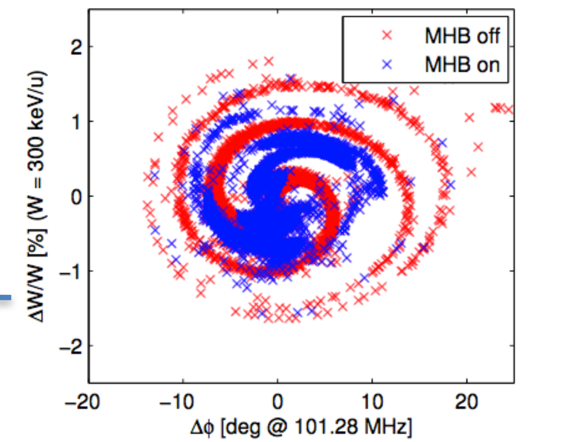
TRACK results [3]:



Particle tracking in field maps:

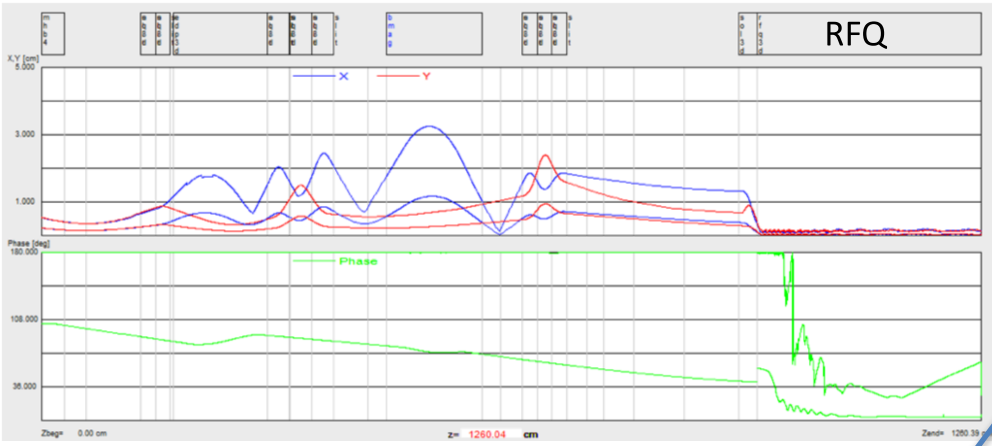


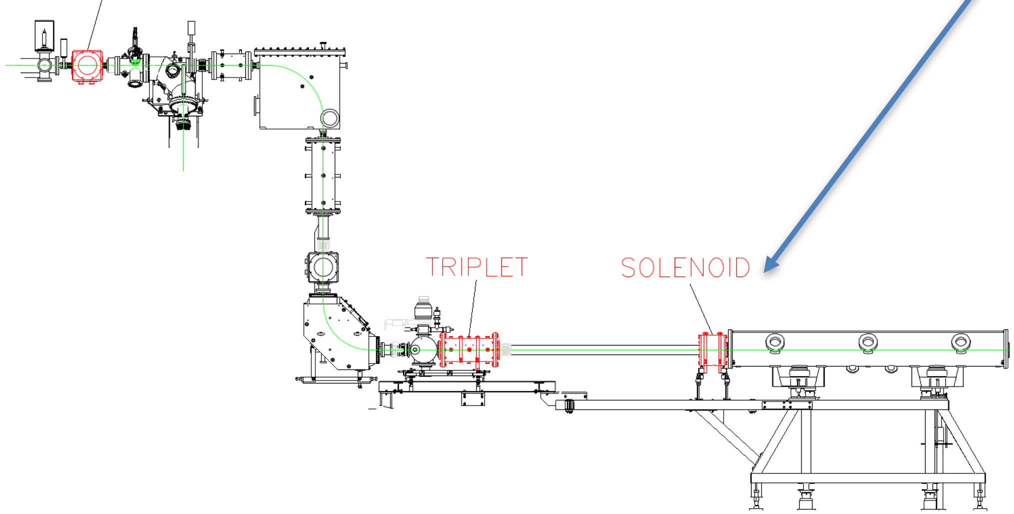




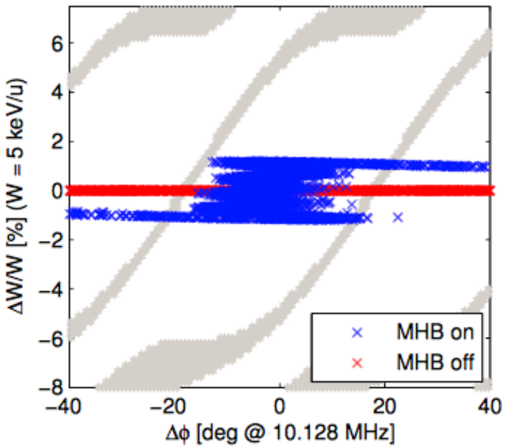
Option B: integrate MHB close to EBIS

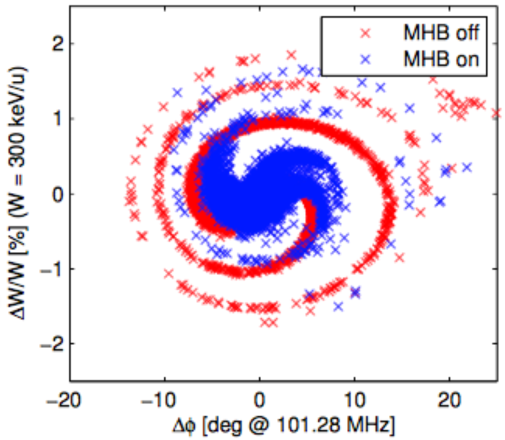
TRACK results [3]:





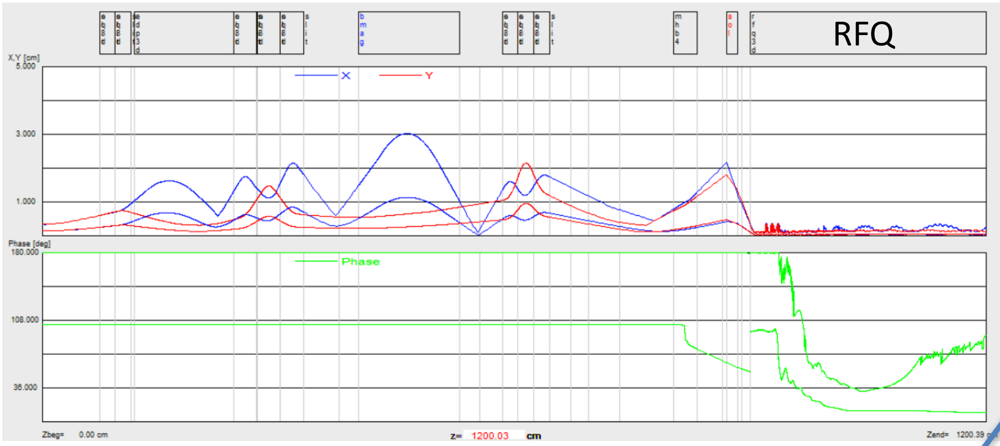
Particle tracking in field maps:



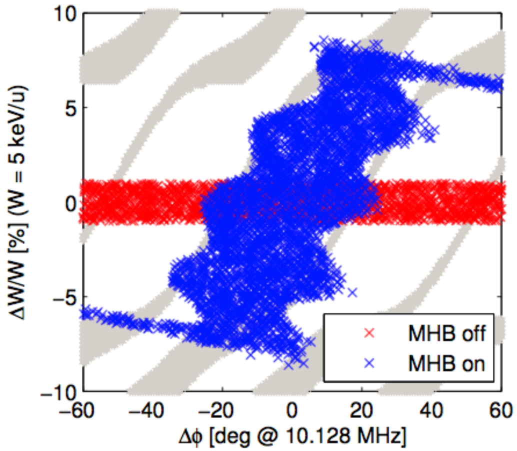


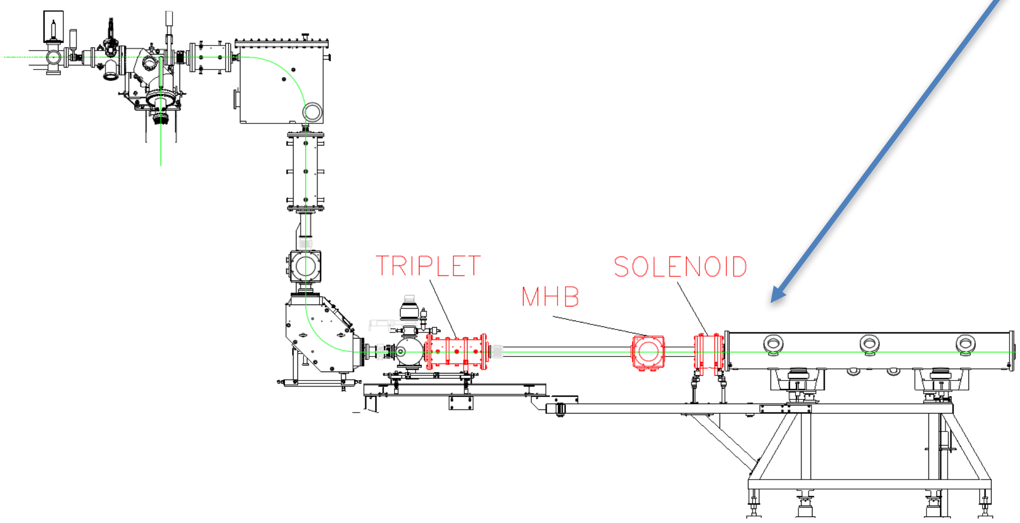
Option C: MHB close to RFQ

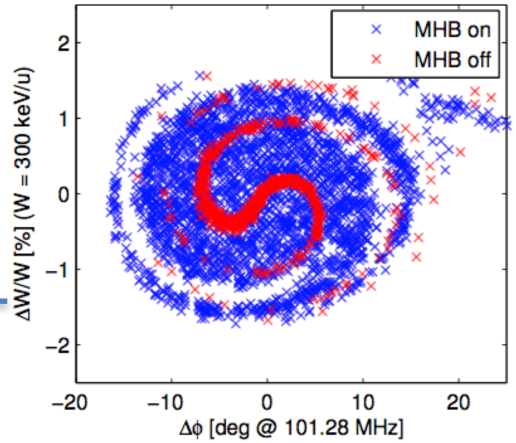
TRACK results [3]:



Particle tracking in field maps:

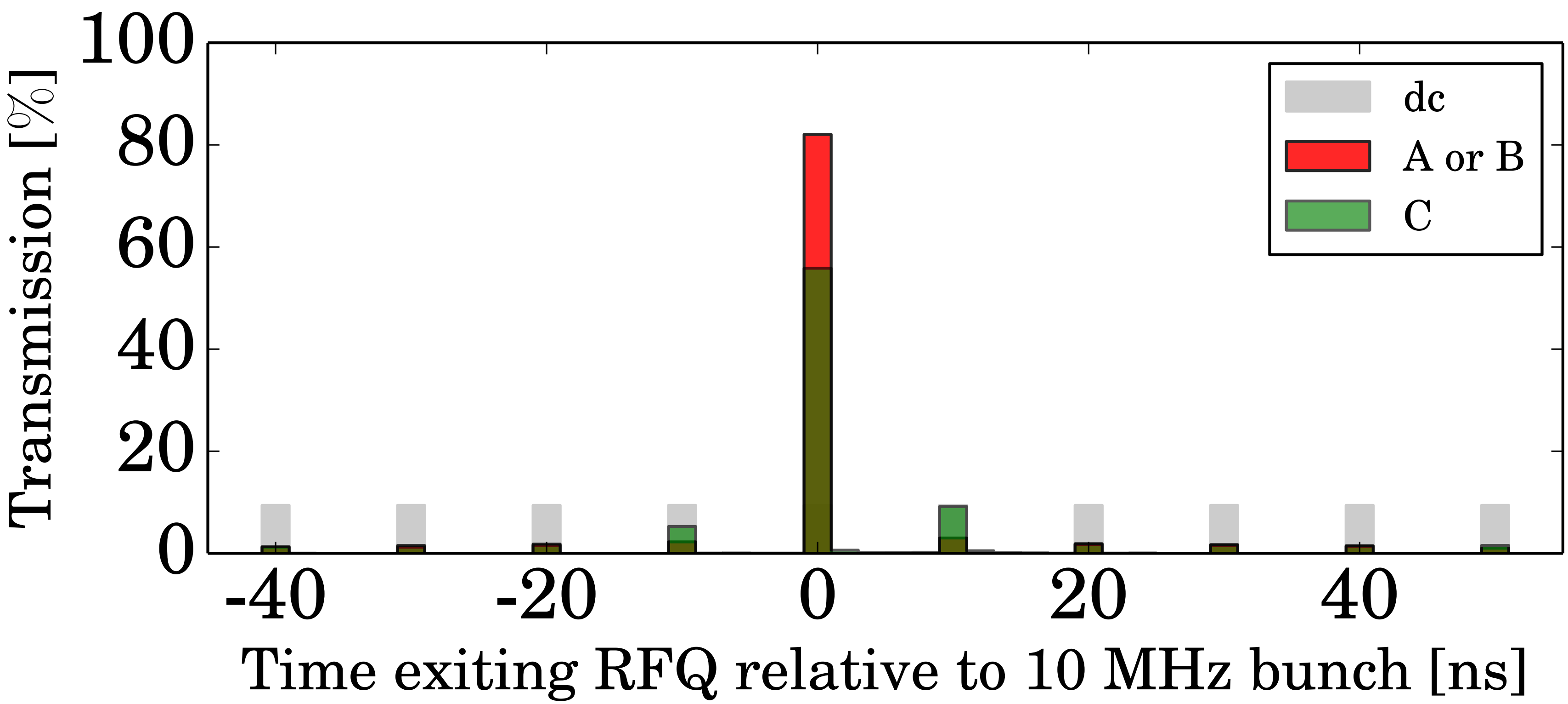






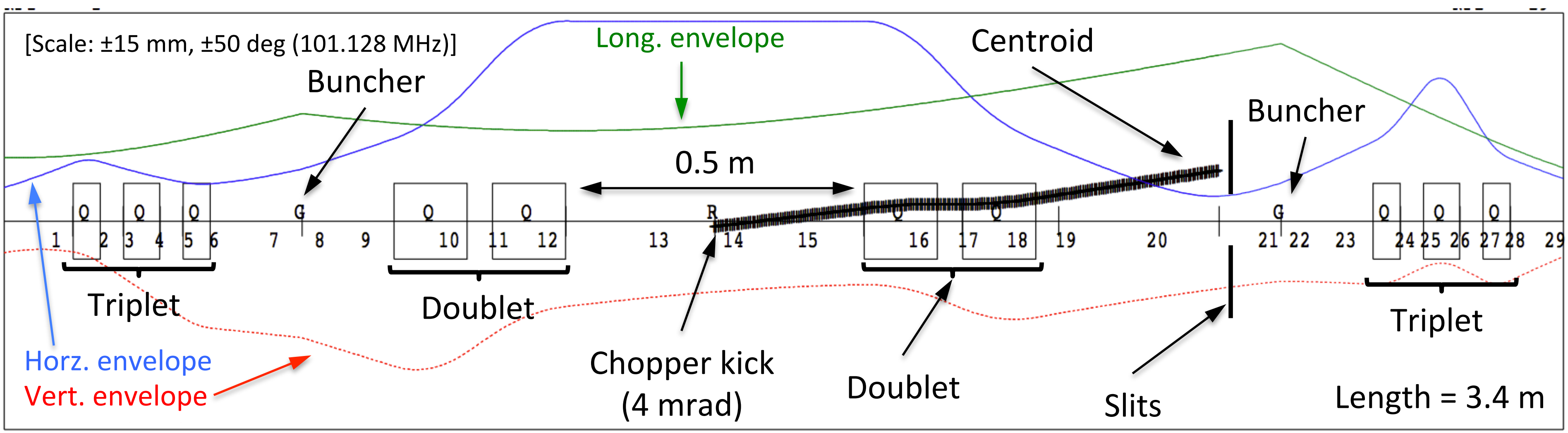
Bunch time structure

- 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 4mrad 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



Beam dynamics performance summary

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

[a] 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

[1] M.A. Fraser & R. Calaga, REX-ISOLDE RFQ Beam Dynamics Studies using CST EM Studio, **CERN-ACC-NOTE-2014-0015**, CERN, Geneva, Switzerland, June 2013

[2] I.B. Magdau & M.A. Fraser, Beam Dynamics Feasibility Study for an RFQ Sub-harmonic Pre-buncher at REX-ISOLDE, **CERN-HIE-ISOLDE-PROJECT-Note-0015**, CERN, Geneva, Switzerland October 2012

[3] M.A. Fraser, Beam Dynamics Studies of a Multi-harmonic Buncher for 10 MHz Post-accelerated RIBs at HIE-ISOLDE, **CERN-ACC-NOTE-2014-0098**, CERN, Geneva, Switzerland, October 2014

[4] M.A. Fraser et al., Design Study For 10 MHz Beam Frequency of Post-accelerated RIBs at HIE-ISOLDE, Proceedings of IPAC2013, Shanghai, China, May 2013, paper THPWO076.

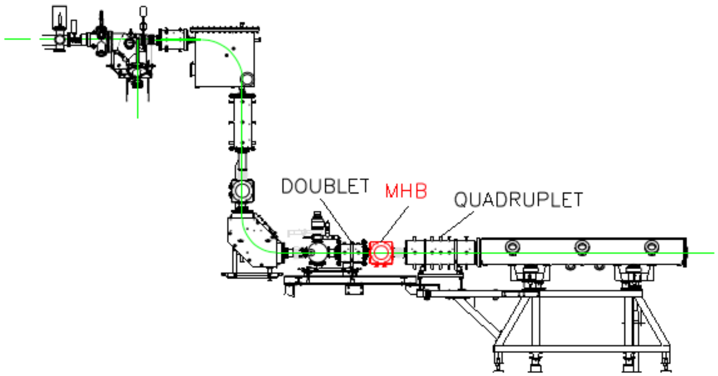
[5] M.A. Fraser & F. Wenander, Study of Effect of Ion Source Energy Spread on RFQ Beam Dynamics at REX-ISOLDE, **CERN-HIE-ISOLDE-PROJECT-Note-0018**, CERN, Geneva Switzerland, May 2013

[6] M.A. Fraser et al., Status of the Design Study for 10 MHz Post-accelerated Radioactive Ion Beams at HIE-ISOLDE, Proceedings of LINAC2014, Geneva, Switzerland, September 2014, paper THPP030.

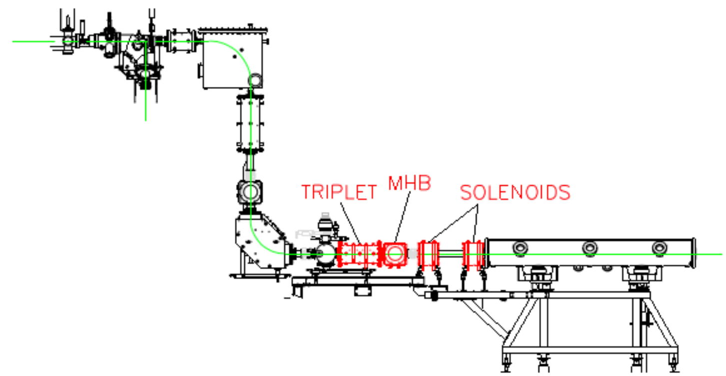
[7] A. Mukhopadhyay & M.A. Fraser, Investigating the Feasibility of a Travelling-wave Chopper for the Clean Separation of 10 MHz Bunches at HIE-ISOLDE, **CERN-ACC-NOTE-2014-0016**, CERN, Geneva, Switzerland, July 2013

Extra slides

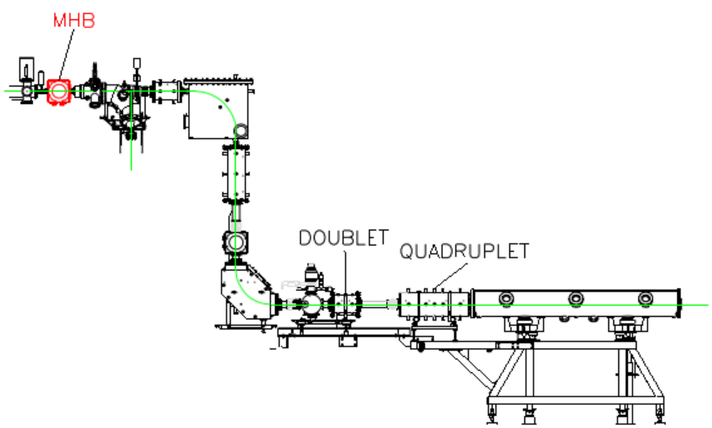
Options without Linac Extension



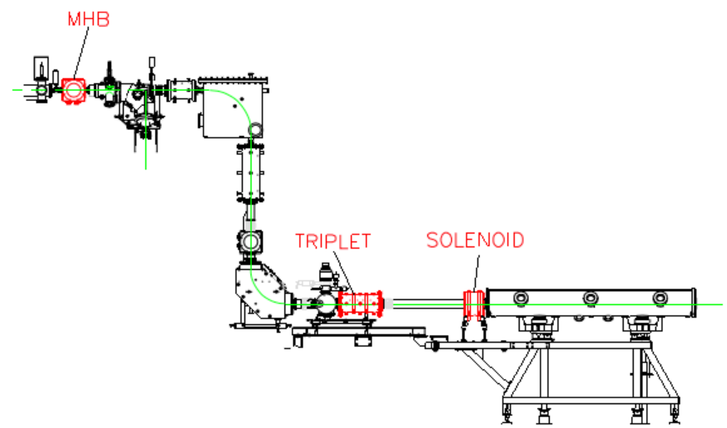
(a) A: baseline, no modifications



(b) B: triplet and solenoids installed

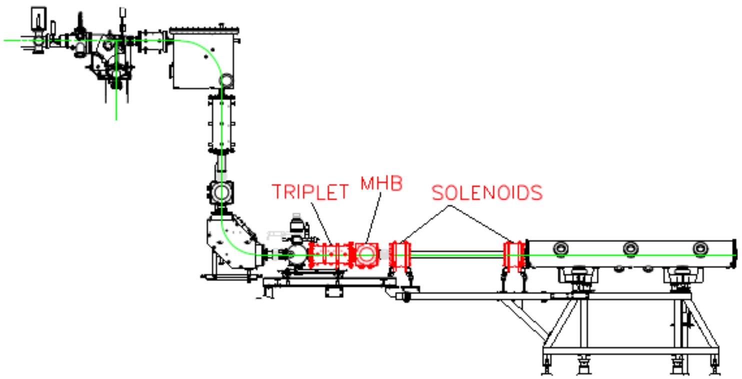


(c) C: MHB installed before separator

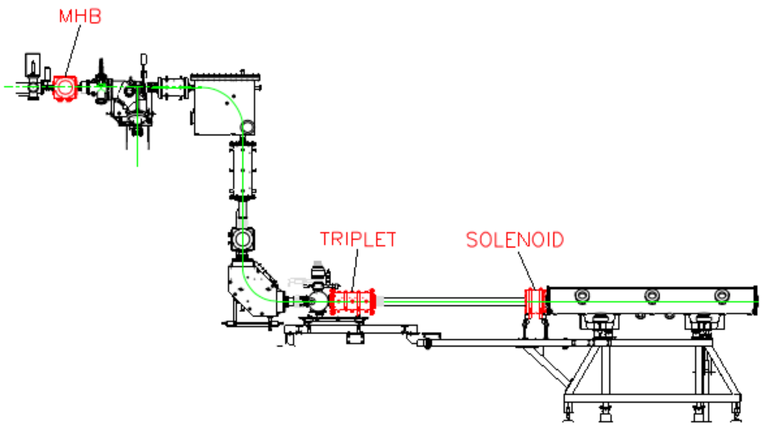


(d) D: MHB before separator, triplet and solenoid installed

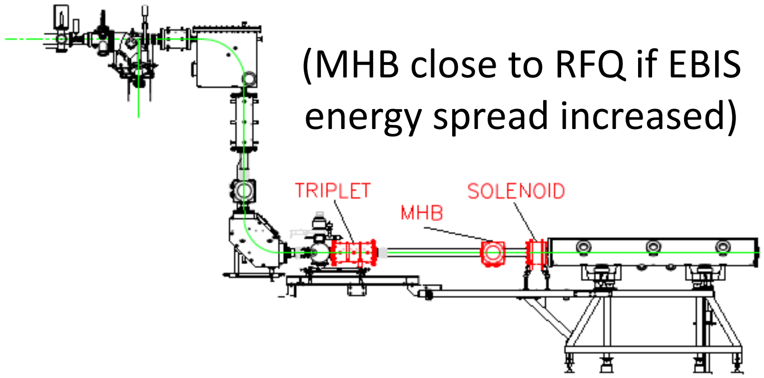
Options with Linac Extension



(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

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

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