Lattice Beam dynamics study and loss estimation for SARAF/ EURISOL driver 40/60 MeV 4mA d/p superconducting Linac

J. Rodnizki

SARAF, Soreq NRC

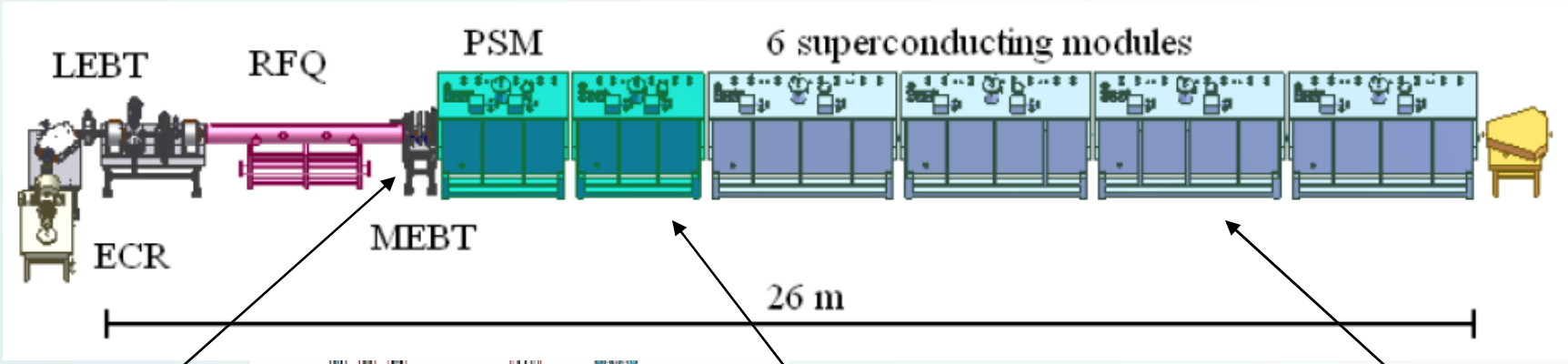
HB2008,
August, 2008
Nashville TN

Content of talk

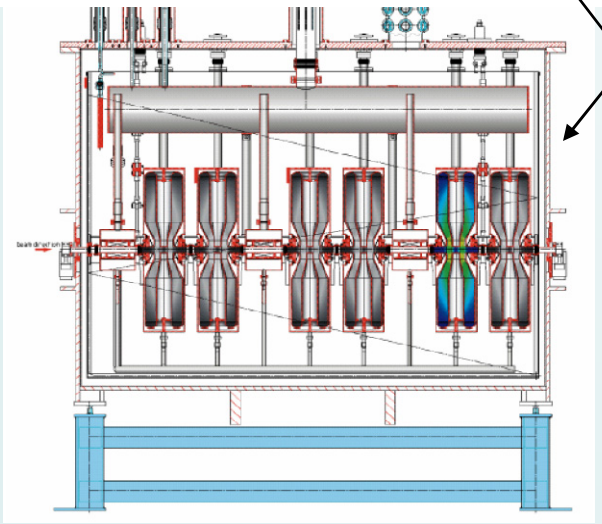
1. Introduction- Acceleration at low β with β mismatch
2. The tune method
3. The lattice variations
4. Loss estimation using tail emphasis method

Acceleration at low β with β mismatch

The SARAF is SC linac design for 4 mA p/d acceleration up to 40 MeV



Inlet energy
1.5 MeV/u
(β = 0.0567)



6*HWR module
(geometric
β = 0.09)

8*HWR module
(geometric
β = 0.15)

* with the TRACK code, P. Ostroumov, ANL
and benchmarked with GPT, www.pulsar.nl/gpt

Acceleration at low β with β mismatch

- The SARAF SC linac inlet energy is 1.5 MeV/u, β=0.0567 while the HWR start at β=0.09
- At low energy for light ions the acceleration is limited by the induced strong longitudinal focusing force accompanied by transverse defocusing due to the induced space charge
- High accelerating gradient could introduce high longitudinal phase advance resulting in beam losses
- Our study* is relevant for other linacs that start with SC cavities right after the RFQ, such as SPIRAL2, and maybe IFMIF too, which start with similar β mismatch at the low β range

* with the TRACK code, P. Ostroumov, ANL and benchmarked with GPT,www.pulsar.nl/gpt

Beam tuning method

- For multi gap cavities, the problematic region for the tune is the low β section
- In this area the acceleration in each gap is quite large in comparison to the particles initial velocity at the cavity entrance
- The particle deviation from the reference particle at the second gap of the cavity depends on the velocity gain of the particle at the first gap

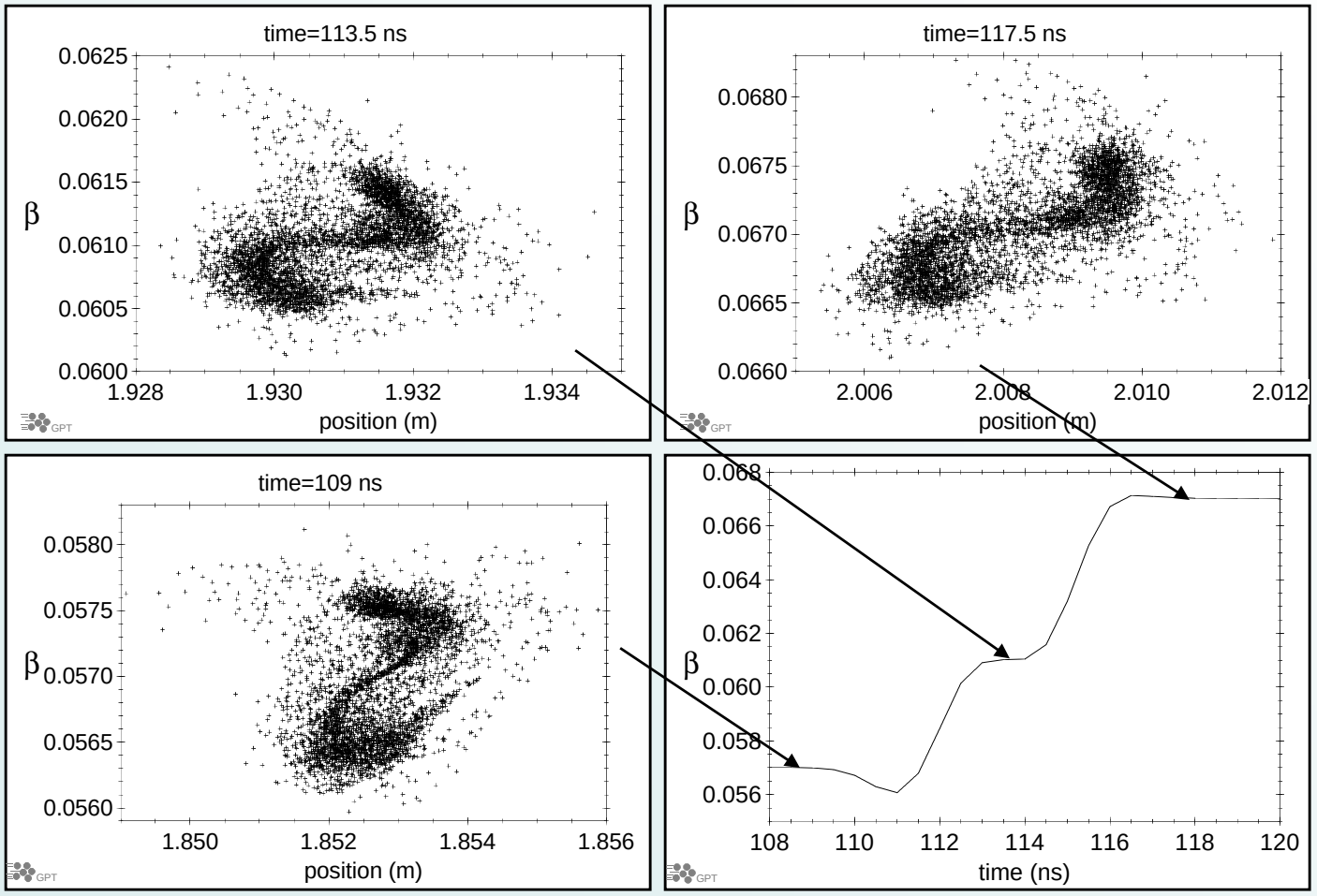
Beam tuning method cont.

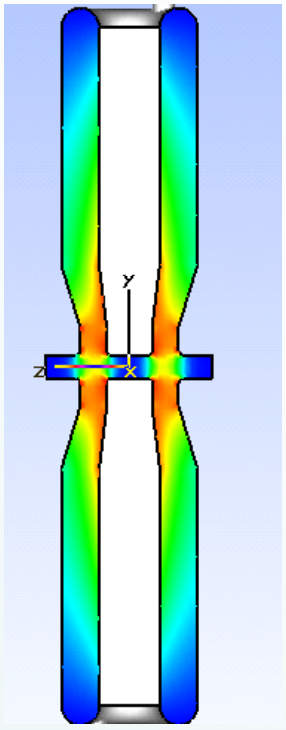
- The evaluation of the particle's trajectory, with significant velocity increase along the cavity, has to be performed at each gap separately, taking into account the particles phase deviation from the reference particle at each gap

- If the accelerating RF field along the bunch in one of the gaps, deviates from the linear range it could introduce a significant emittance growth during the acceleration

- The range of the accelerated particle's phase ϕ_i, at each gap *i* is defined by the reference particle phase and the bunch half length

Longitudinal phase space along the first accelerating two gaps HWR after the buncher, 3.5 mA p

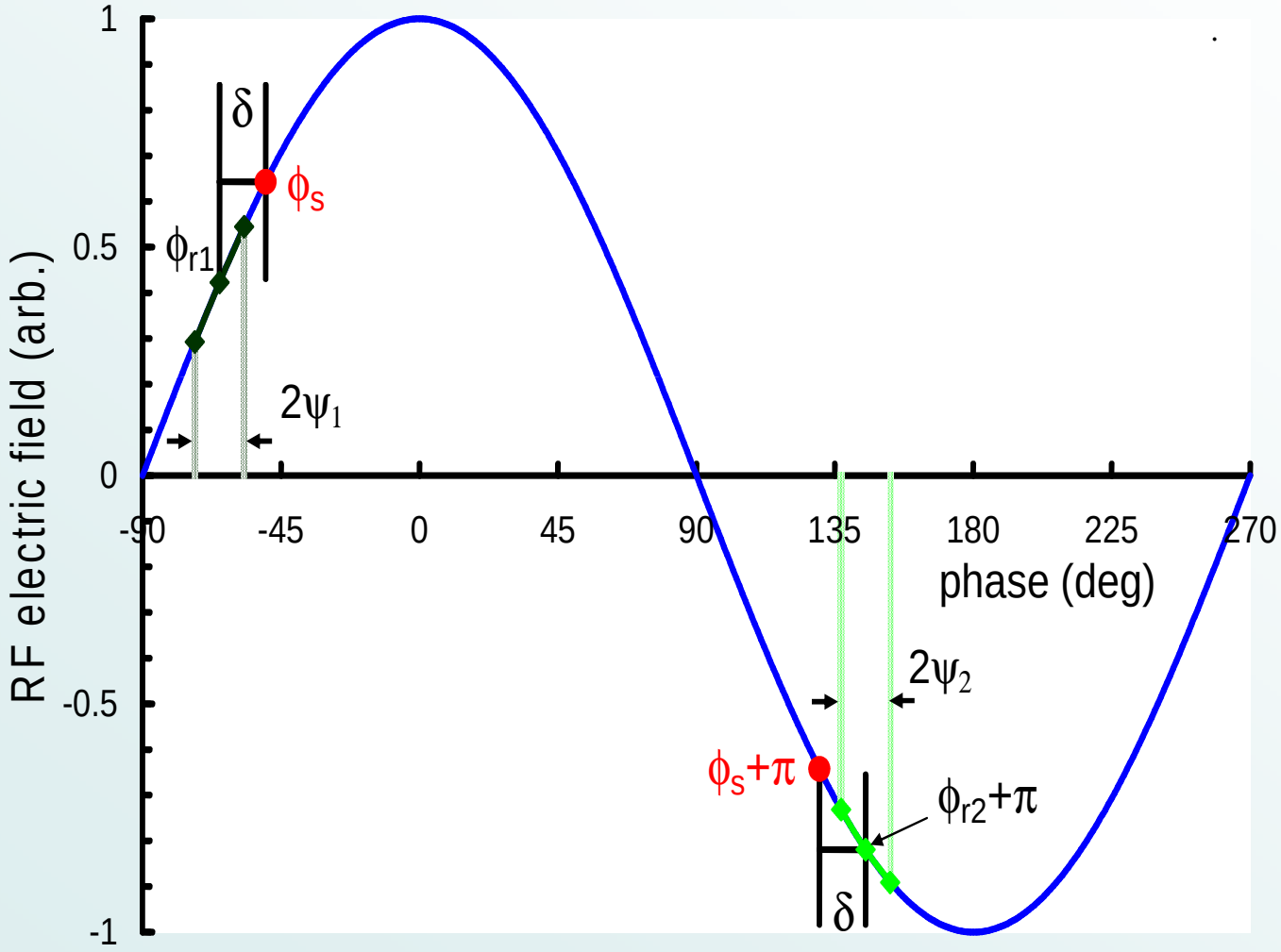




M. Pekeler HPSL 2005

The longitudinal emittance ≈ ΔE*Δt (proportional to $\gamma\beta^*$ z, $\gamma \approx 1$) is an invariant along the linac for a conservative system.

The accelerating range at each gap



The reference particle phase at each gap as function of the synchronous phase

- For a two gap cavity the reference particle phase at each gap is a function of:
  - bunch β at the first gap exit
  - the geometric β of the cavity

$$\phi_{r1} = \phi_s - \delta$$

$$\phi_{r2} = \phi_s + \delta$$

$$\delta = (\beta_0 / \beta - 1) * \pi / 2$$

The effective voltage as function of the selected synchronous phase

- The effective cavity voltage is tuned to keep the upstream phase advance:

$$\frac{d(W-W_s)}{ds} = qV_0T(\cos\Phi - \cos\phi_s)/L$$

$$\frac{d(\Phi-\phi_s)}{ds} = (W-W_s)2\pi/(mc^2\gamma_s^{\,3}\beta_s^{\,3}\lambda)$$

$$k_{l0}^{\;2} = -2\pi/(mc^2\gamma_s^{\,3}\beta_s^{\,3}\lambda)qV_0T\sin\phi_s/L$$

$$V_{02}T_2 = V_{01}T_1(\sin\phi_{s1}/\sin\phi_{s2})(\gamma_{s2}^{\,3}\beta_{s2}^{\,3}L_2)/(\gamma_{s1}^{\,3}\beta_{s1}^{\,3}L_1)$$

- The development and the notation followed T. P. Wangler, *Principles of RF Linear Accelerators*, John Wiley and Sons, Inc., 1998. p 175

The tune method steps at low β with β mismatch

- Bunch the RFQ exit beam to apply linear fields along the acceleration at each cavity gap
- Select an appropriate synchronous phase for a multi gap cavity to reach a linear accelerating field at each gap
- Find the cavity field amplitude base on the cavity synchronous phase and the upstream phase advance

The lattice variations

Lattice symmetry variations

Comparison between symmetric and asymmetric lattice extended to 60 MeV for the EURISOL driver

Symmetric – the period is composed of [cavity - solenoid - cavity]

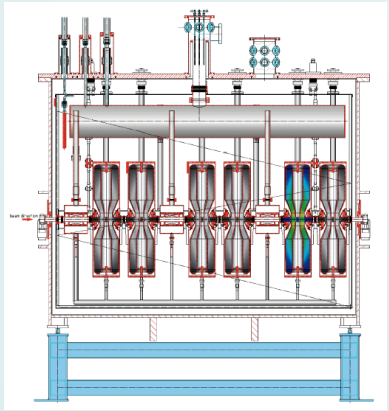


Asymmetric – the period is composed of [solenoid - cavity - cavity]



40 MeV

60 MeV



Pekeler linac 2006

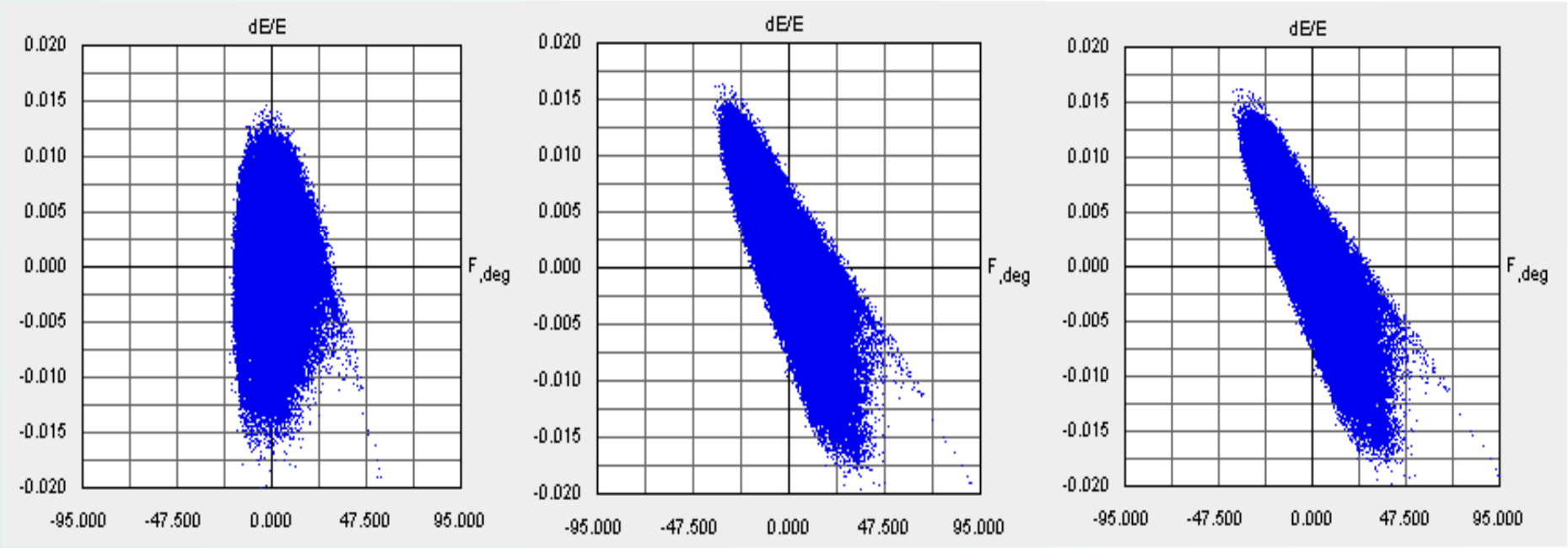
The lattice variations

- Two basic lattices were considered: a symmetric lattice and an asymmetric one.
- The internal period of a symmetric module is consisted of [HWR, solenoid, HWR], The Internal period of an asymmetric module is consisted of [solenoid, HWR, HWR].
- Both lattices consist of 3 internal periods for β_0=0.09 and 4 internal periods for β_0=0.15.
- The symmetric lattice MEBT is longer, including an extra drift between the quadrupoles to enhance the focusing since the symmetric module starts with a HWR.
- The distance to the first HWR which act like a buncher could be 16 cm shorter at the symmetric lattice.
- The asymmetric lattices have a SC solenoid which acts like a cold trap after the normal MEBT.
- The diagnostic space between the modules is 15 cm (except the first space of 10 cm at the asymmetric lattice).

Tune parameters

- The tune acceptance was fitted to the expected RFQ exit particles phase space distribution including an errors study.
- The errors are based on ACCEL designed and measured values.
- The tune was optimized for:
  - Deuterons/ Protons
  - 4 mA
  - moderated beam emmitance increase
  - moderated beam envelope

Longitudinal phase space at the RFQ exit and at the entrance to the SC linac.

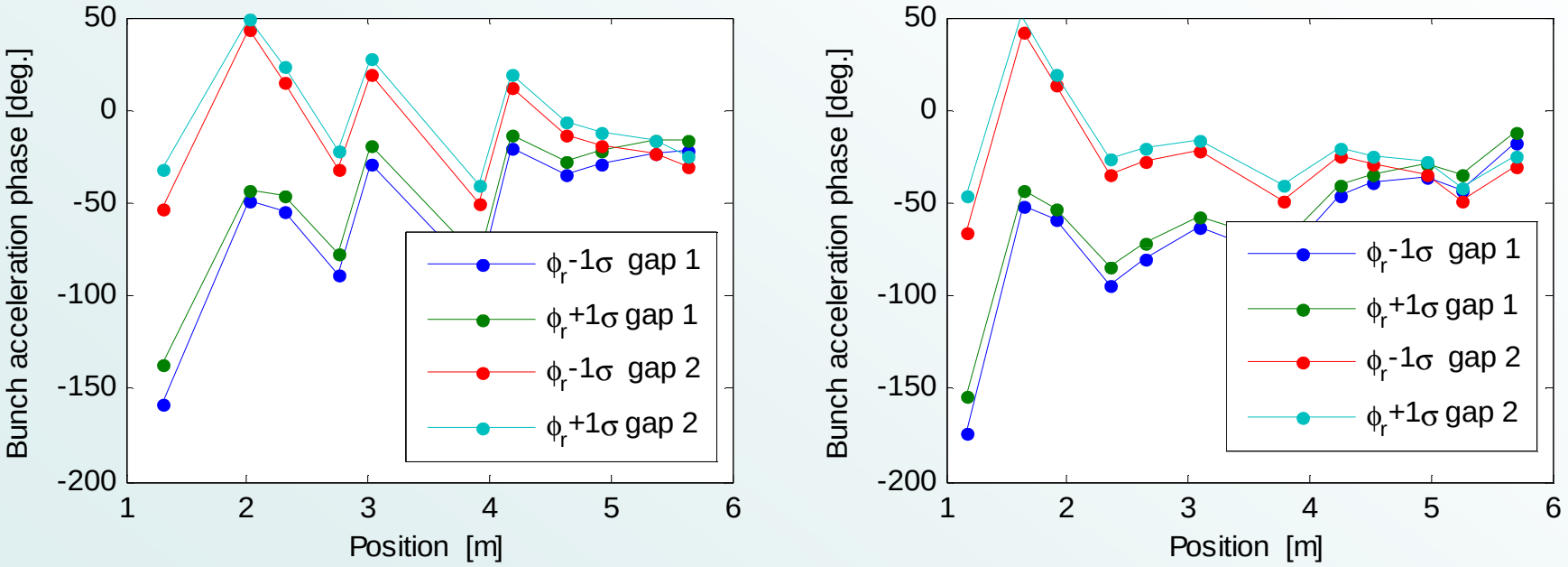


At the RFQ exit

Symmetric first gap

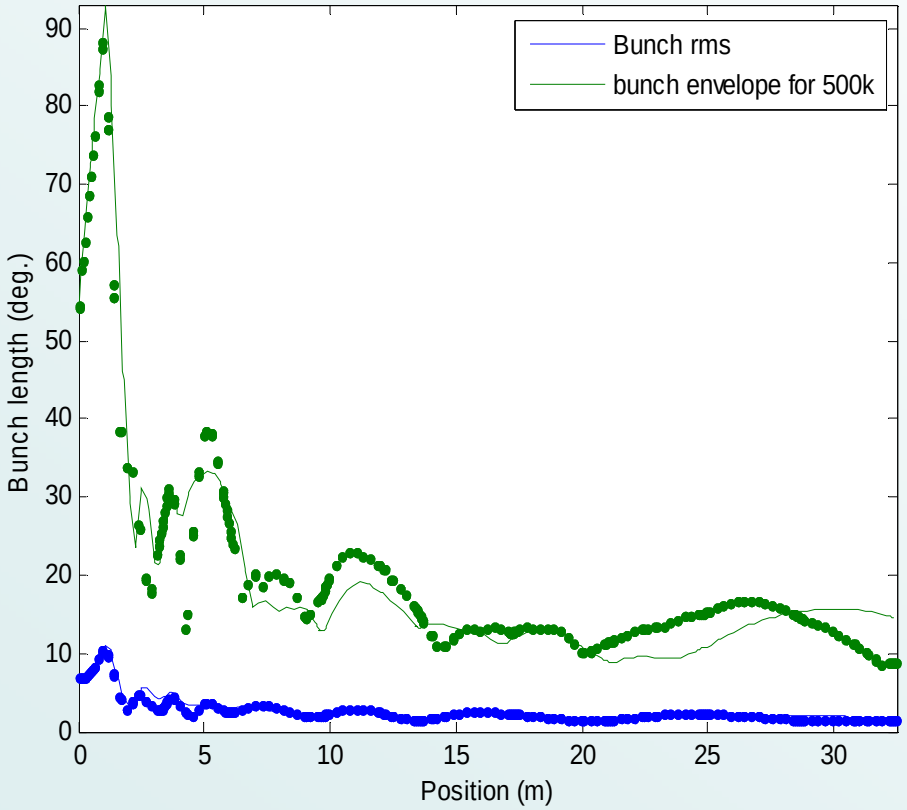
Asymmetric first gap

RF Acceleration phase at each gap along the low β SC linac section, 4mA d

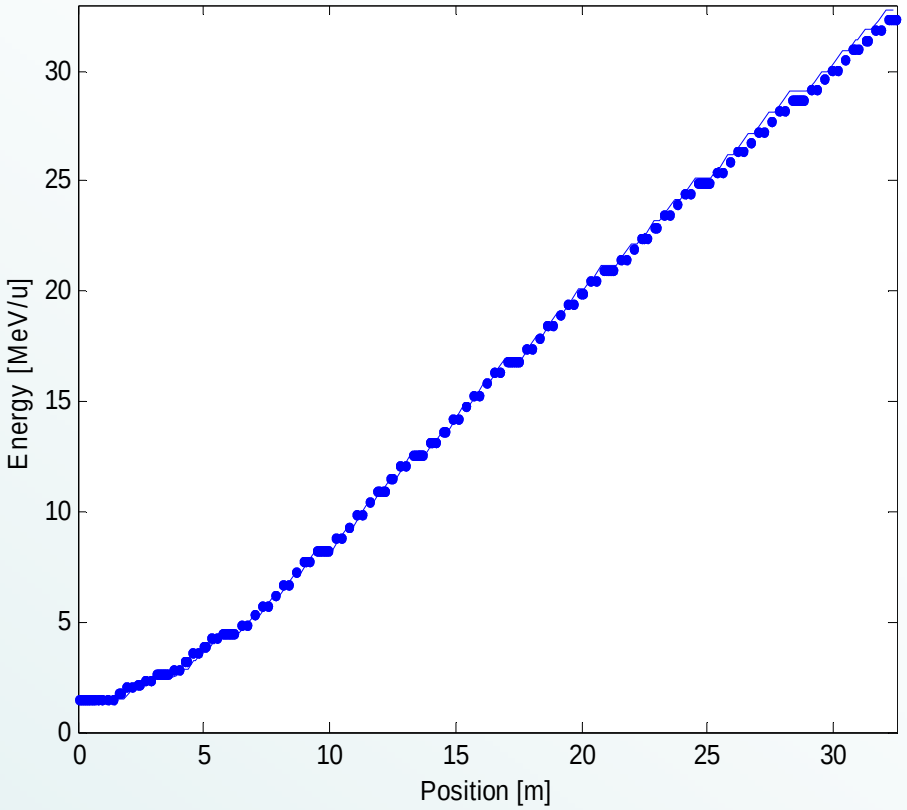


Asymmetric (left) and symmetric (right) lattice bunch acceleration phase at the first cavity gap (bottom) and the second gap (top)

Bunch energy and spread along the linac

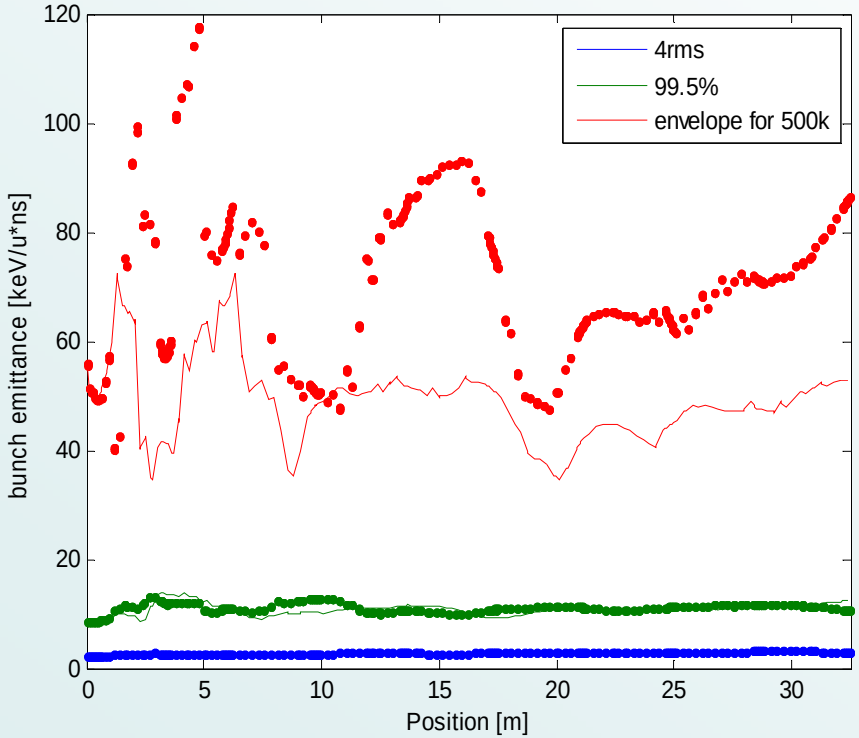


Bunch length for the symmetric (dots) and the asymmetric (solid line) lattices.

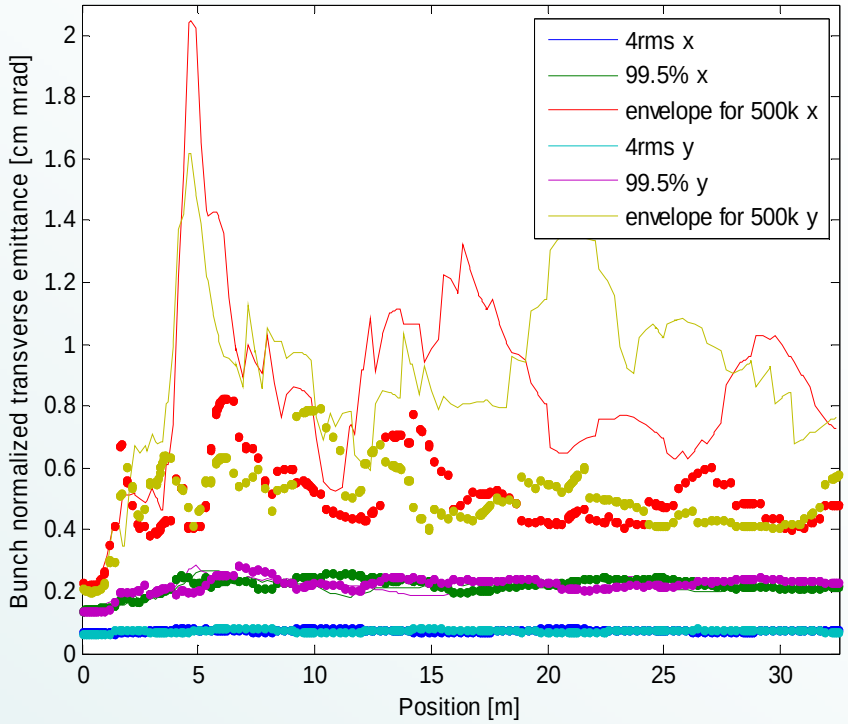


Bunch energy along the linac for the symmetric (dots) and the asymmetric (solid line) lattices.

Bunch normalized emittance along the linac

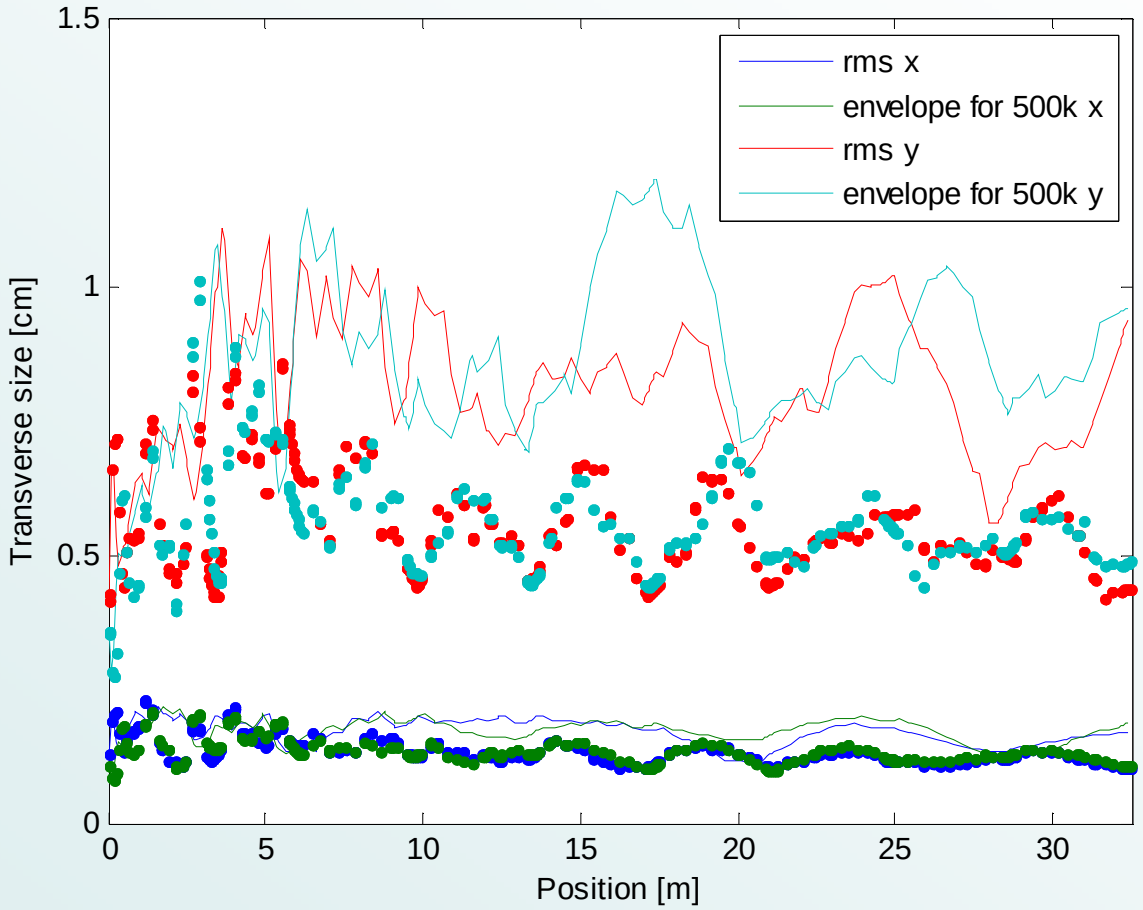


Bunch longitudinal emittance for the symmetric (dots) and the asymmetric (solid line) lattices.



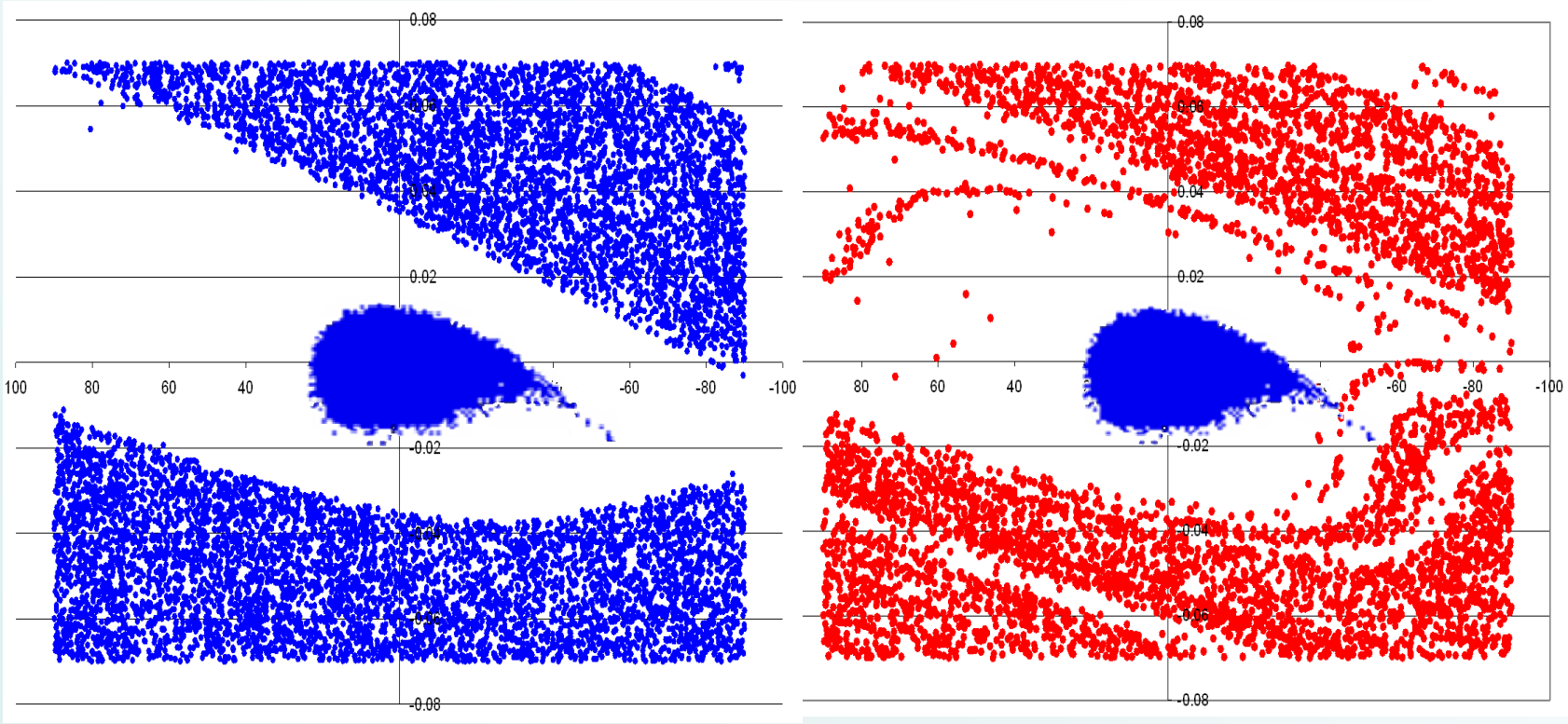
Bunch transverse normalized emittance along the linac for the symmetric (dots) and the asymmetric (solid line) lattices.

Bunch transverse envelope along the linac



Bunch transverse size along the linac for the symmetric (dots) and the asymmetric (solid line) lattices.

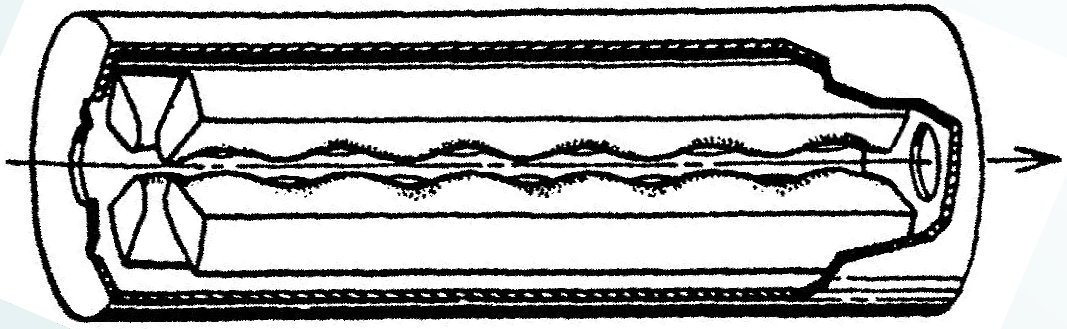
Lattice longitudinal phase space acceptance



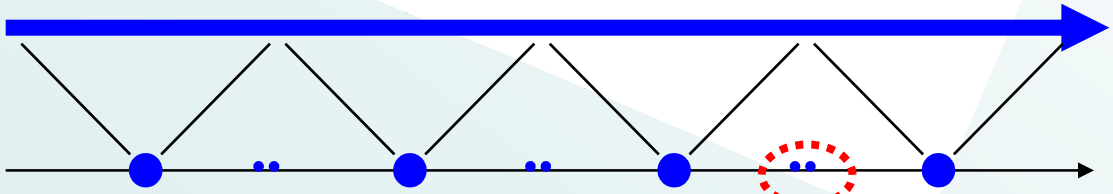
Longitudinal phase space acceptance for the symmetric (left) and the asymmetric (right) lattices vs. the bunch spread at the RFQ exit (relative energy spread vs. phase (deg)).

Loss estimation using tail emphasis method

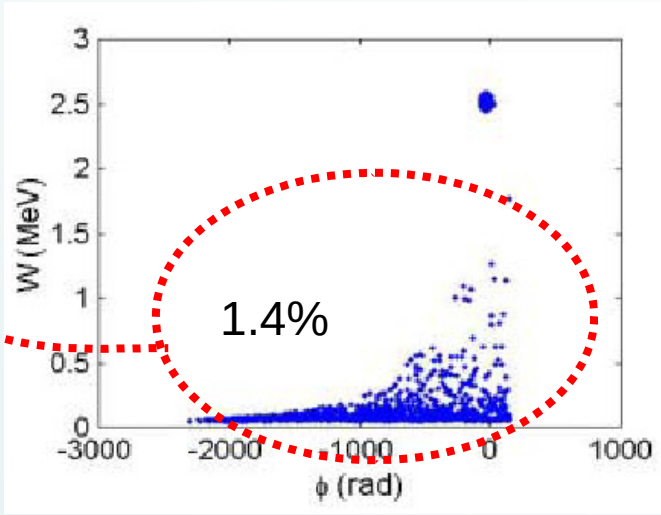
Tail formation during RFQ bunching



DC ion beam



Bunched CW ion beam



SNS Jeon linac02

Longitudinal phase space:

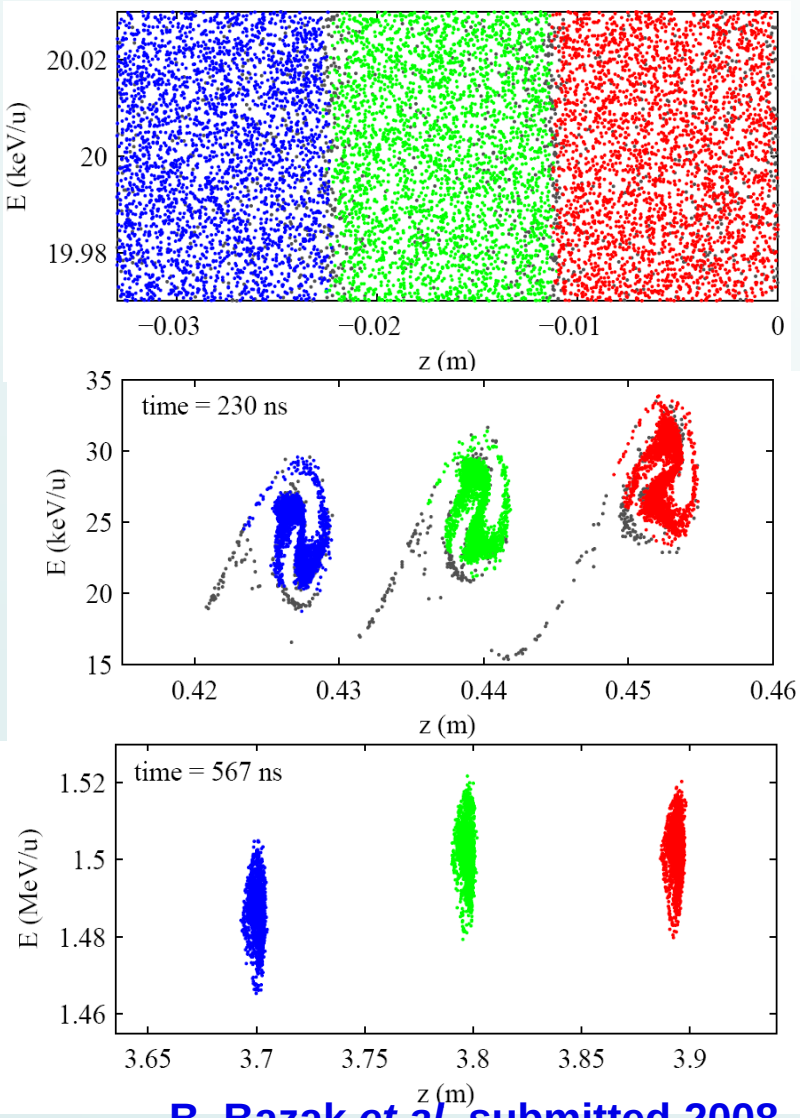
$\Delta z \Leftrightarrow \Delta\phi$

$z' \Leftrightarrow \Delta E$

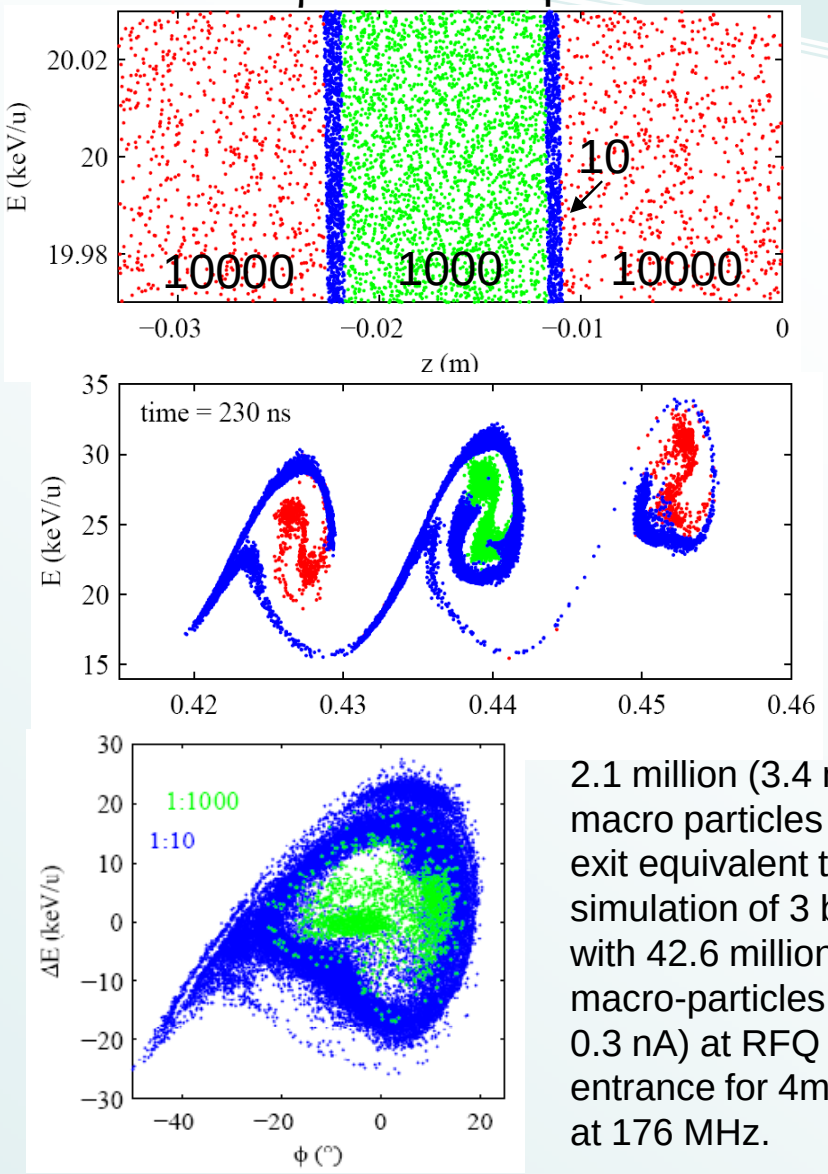
RFQ longitudinal phase space

SOREQ

3βλ - regular



3βλ – tail emphasis

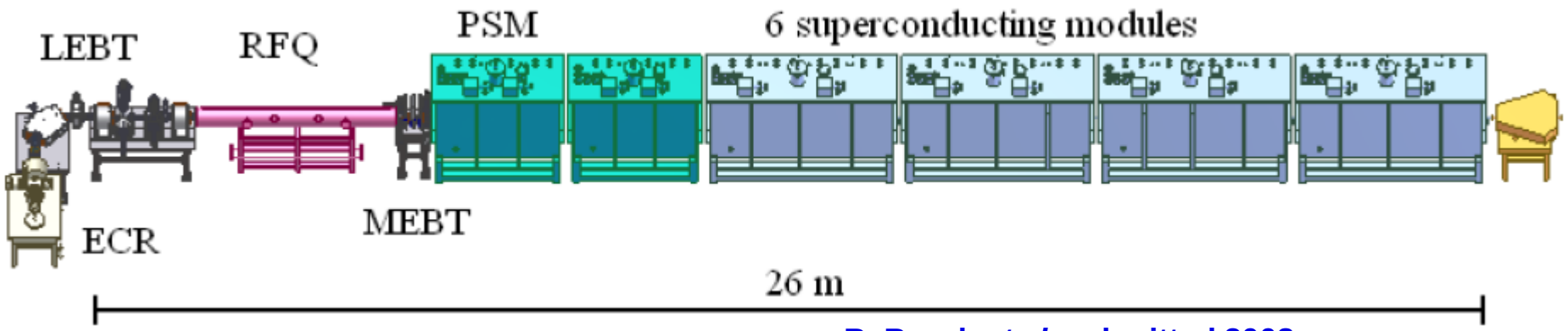


2.1 million (3.4 mA) macro particles at RFQ exit equivalent to simulation of 3 bunches with 42.6 million (1:10) macro-particles (each 0.3 nA) at RFQ entrance for 4mA CW at 176 MHz.

B. Bazak *et al.* submitted 2008

RFQ entrance norm rms $\varepsilon_{x,y}$=0.2 π mm mrad. Emittance growth <10%.

Superconducting linac simulation with error analysis



B. Bazak *et al.* submitted 2008

Simulations shown in next slides. 4 mA deuterons at RFQ entrance. Last macro-particle=1nA:

1. RFQ entrance norm rms $\varepsilon_{x,y}$=0.2 π mm mrad
2. Similar to 1 with double dynamic phase error
3. Similar to 1 with RFQ exit norm rms expanded to $\varepsilon_{x,y}$=0.3 π mm mrad

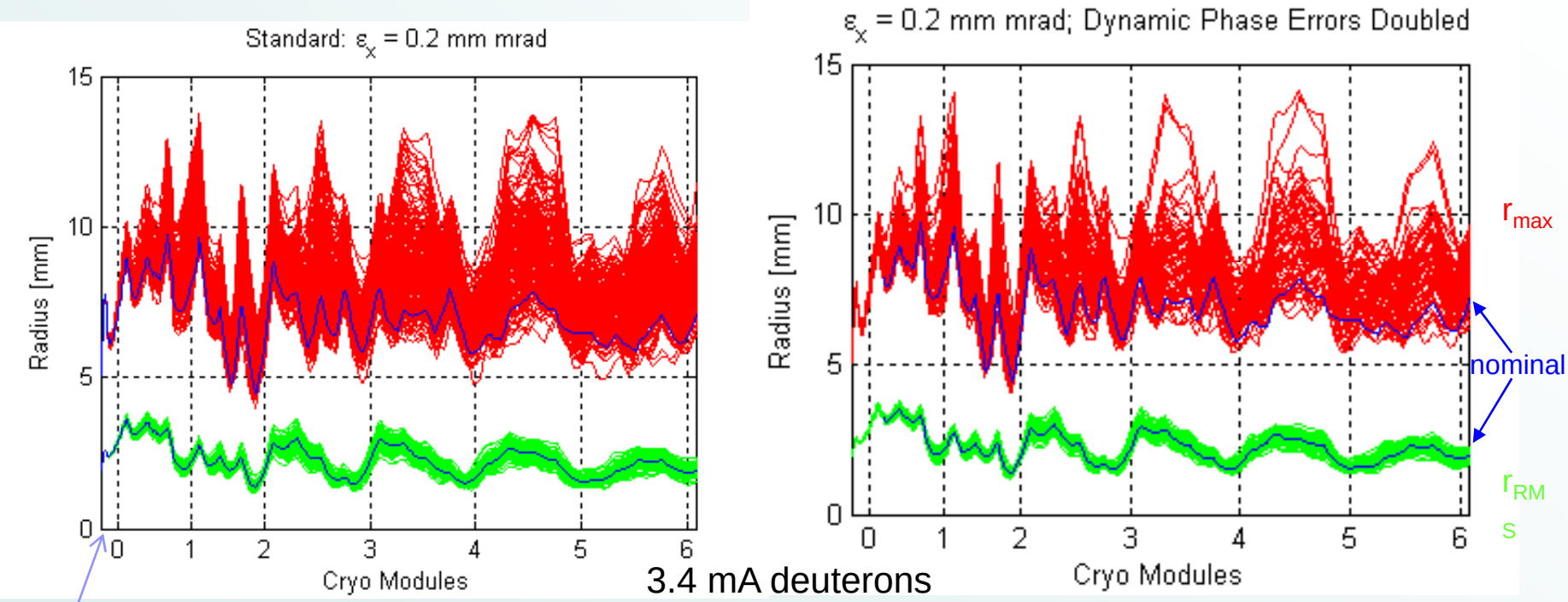
Component	Error	Static	Dyn.
Quadrupole Magnets	Misalignment x,y,z [mm]	$\pm$ 0.2	
	Rotation θ [mrad]	$\pm$ 3	
	Magnetic field [%]	$\pm$ 2	0.5
Solenoids	Misalignment x,y,z [mm]	$\pm$ 0.2	
	Magnetic field [%]	$\pm$ 2	0.5
HWR	Misalignment x,y,z [mm]	$\pm$ 0.4	
	Rotation θ [mrad]	$\pm$ 6	
	Field strength [%]	$\pm$ 2	0.5
	Phase [degree]	$\pm$ 1	0.25

Errors are double than in: J. Rodnizki *et al.* LINAC 2006, M. Pekeler HPSL 2005

d beam envelope radius along the SC linac

General Particle Tracer 2.80 2006,
Pulsar Physics S.B. van der Geer,
M.J. de Loos http://www.pulsar.nl/

Asymmetric lattice



200 realizations

3.4 mA deuterons
32k/193k particles in core/tail
Last macro-particle = 1 nA

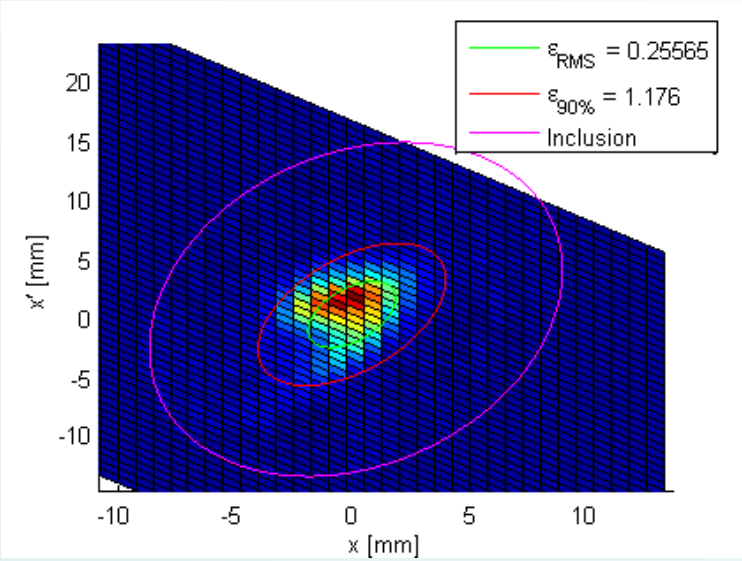
70 realizations

RFQ exit

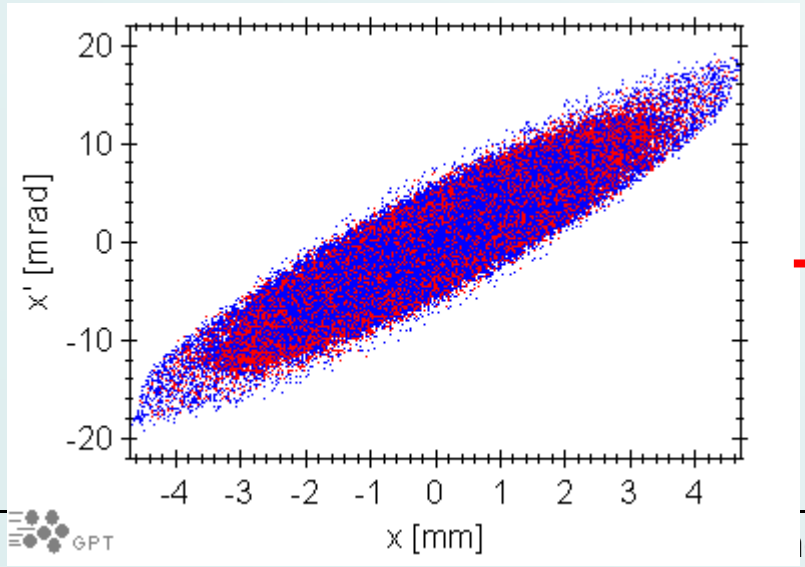
No loss observed

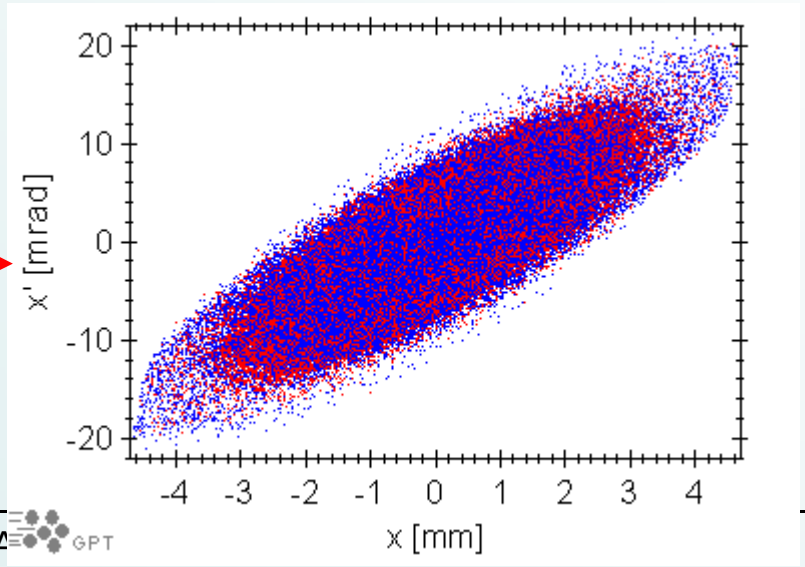
HWR bore radius = 15 mm
SC solenoids bore radius = 19 mm

Increased Emittance



- Originally we took
  ε_x = 0.2 mm mrad
- Measurements show
  ε_x = 0.3 mm mrad
- Run simulations with expanded bunch

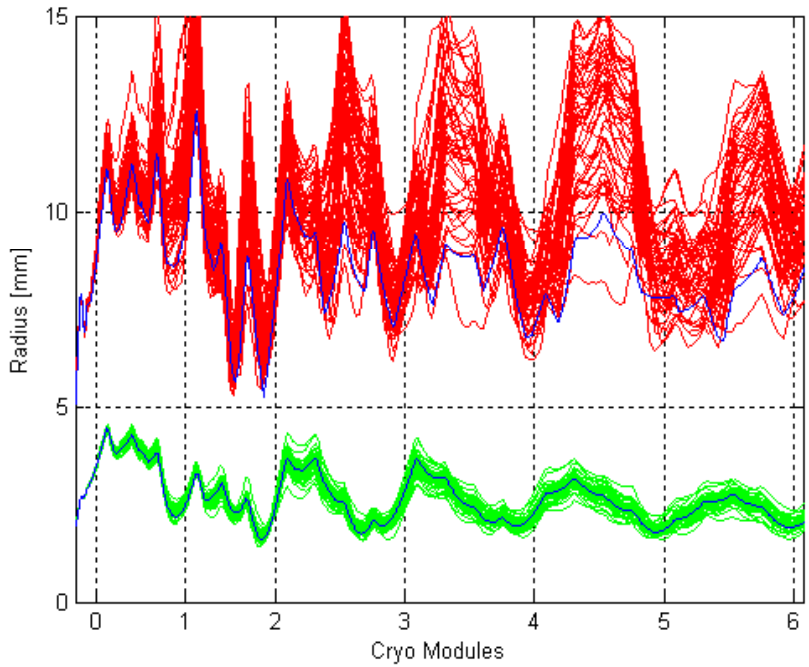


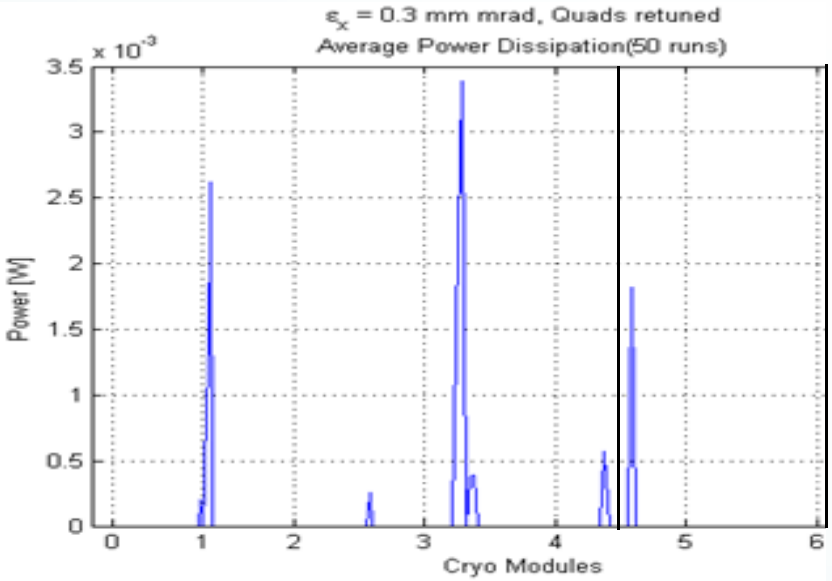


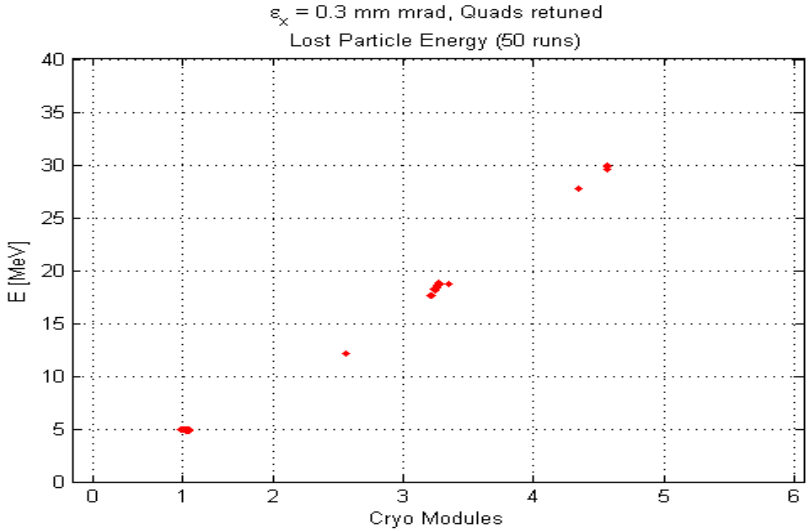
beam envelope along the linac - entrance

distribution expanded to the specified value

Simulation for 50 realizations
3.4 mA deuterons
32k/193k particles in core/tail
Last macro-particle = 1 nA







Total 78 particles (=nA) lost over 50 runs.
At 48/50 runs the lost are 0-1nA
At 2/50 runs the lost are 31 and 40 nA

Still to do

- Updated lattice:
  - As made MEBT and PSM
  - Initial deuteron distribution as measured
  - Expanded distance between module for diagnostics from 100 to 156 mm
- Check options:
  - Robustness (one or some elements are malfunctioning)
  - Replace second HWR with solenoid (semi Eurisol improvement)
  - Operation ability (related to the available beam diagnostics)

Summary

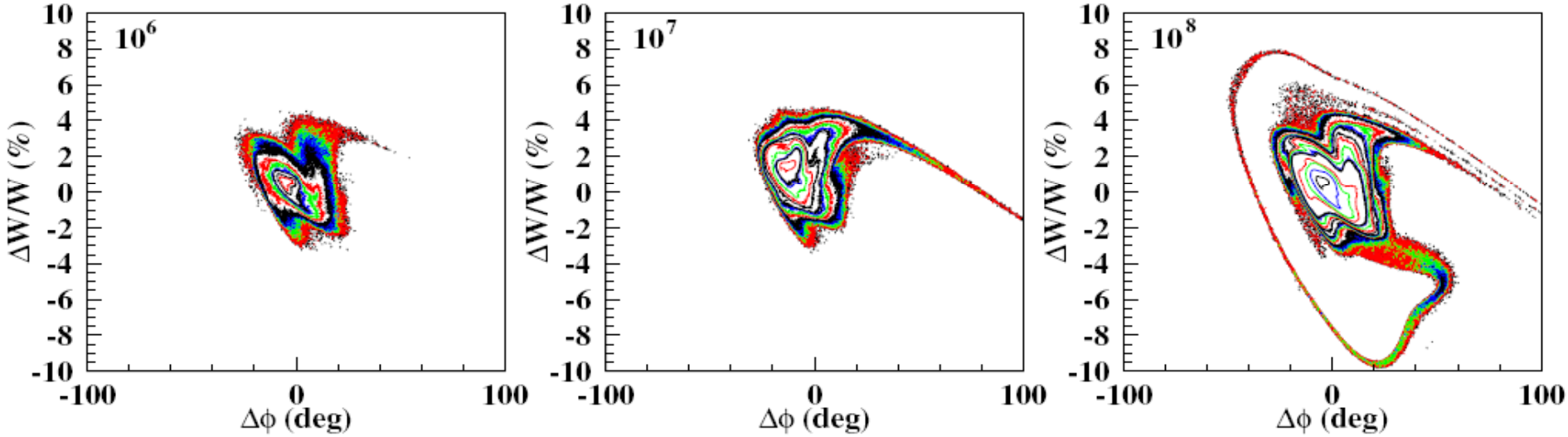
- A lattice consist of a SC linac at the RFQ exit designed for light ions that have variable mass to charge ratio probably will need a dedicated tune method to allow acceleration at low β with a β mismatch
- In the presented study a method to accelerate efficiently at the low β range was derived.
- The method was applied for two basic lattices symmetric and asymmetric lattice.
- The symmetric lattice seemed to be the favor lattice since it has a better acceptance and since its transverse envelope seemed to be easier to control.
- Improved transverse tune for the GPT simulation (not verified yet with the TRACK simulation) seemed to reduce the losses at the asymmetric lattice.
- The tail emphasis enable us to increase the resolution to the required safety level. It assumes that the losses originated at the longitudinal phase space.

END

- Collaboration
  - **B. Bazak (Soreq)**
  - **D. Berkovits (Soreq)**
  - **A. Facco (LNL)**
  - **G. Feinberg (Soreq)**
  - **P. Ostroumov (ANL)**
  - **A. Shor (Soreq)**
  - **Y. Yanay (Soreq)**

Parallelization of a beam dynamic code is adopted for large scale RFQ simulation

TRACK @ BlueGene



J. Xu, B. Mustapha, V. N. Aseev, and P. N. Ostroumov, "**Parallelization of a beam dynamics code and first large scale radio frequency quadrupole simulations",** Phys. Rev. ST Accel. Beams **10,** 014201 (2007)

The ANL LCRC Computing Cluster: JAZZ



350 computing nodes:

2.4 GHz Pentium IV
50% w/ 2 GB RAM
50% w/ 1 GB RAM
80 GB local scratch disk
Linux

10 TB global working disk:

8 dual 2.4 GHz Pentium IV servers
10 TB SCSI JBOD disks
PVFS file system

10 TB home disk:

8 dual 2.4 GHz Pentium IV servers
10 TB Fiber Channel disks
GFS between servers
NFS to the nodes

Network:

Myrinet 2000 to all systems
Fast Ethernet to the nodes
GigE aggregation

Support:

4 front end nodes: 2x 2.4 GHz PIV
8 management systems