Beam Dynamics for CSNS Linac

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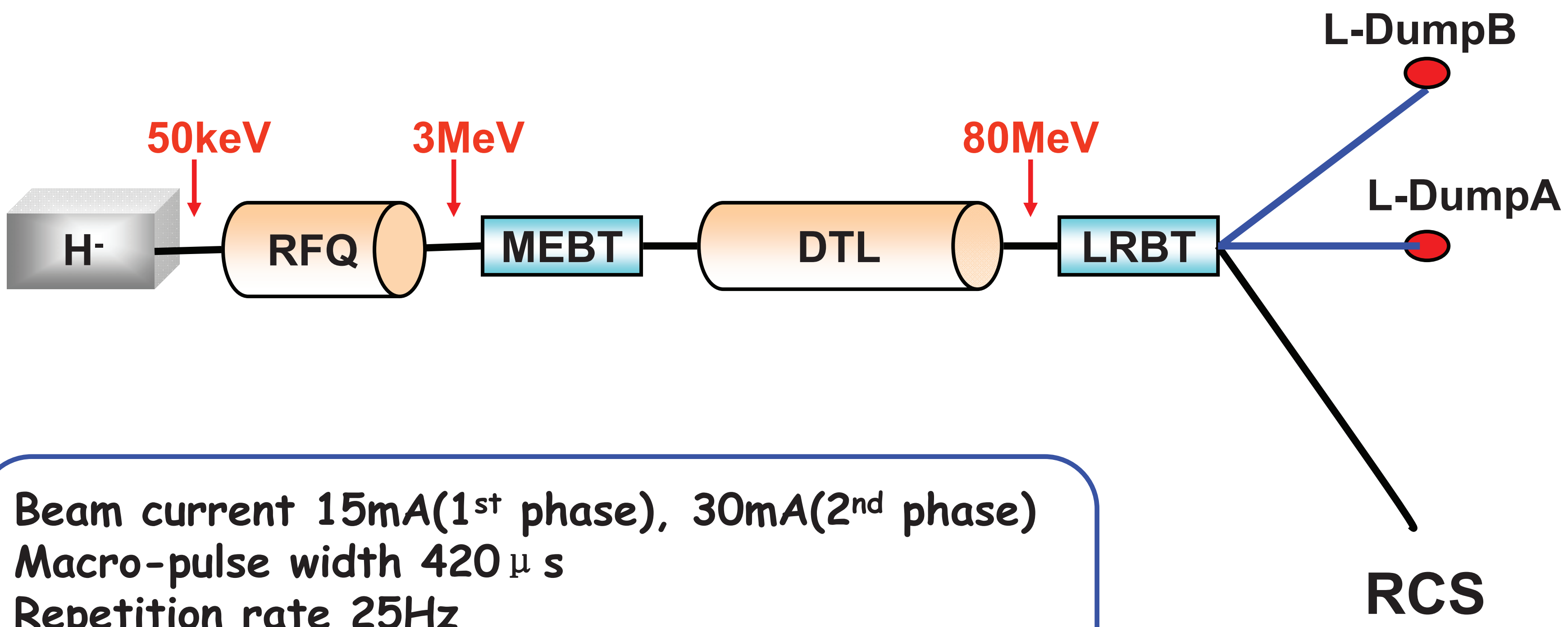
CSNS
CHINESE ACADEMY OF SCIENCES

Outline

- Beam loss study
- MEBT optimization
- DTL optimization
  - Geometry
  - Accelerating field and synchronous phase
  - Focusing scheme
- End to end simulation

Introduction



Beam current 15mA(1st phase), 30mA(2nd phase)
Macro-pulse width 420μs
Repetition rate 25Hz
Duty factor 1.05%
Chopping rate 50%

Beam loss study

- PARMILA with 2D space charge routine
- .The initial distribution at the exit of RFQ is from PARMTEQM
- The beam current is 15mA(1st phase) 30mA (2nd phase)

Error Analysis

For the quadrupoles:
- Transverse displacements ⩽ ± 0.1mm,
- Rotations ⩽ 3mrad，
- Integrated field ⩽ 1 % ,

For the accelerating field:
- RF amplitude ⩽ 1 %
- RF phase ⩽ 1degree

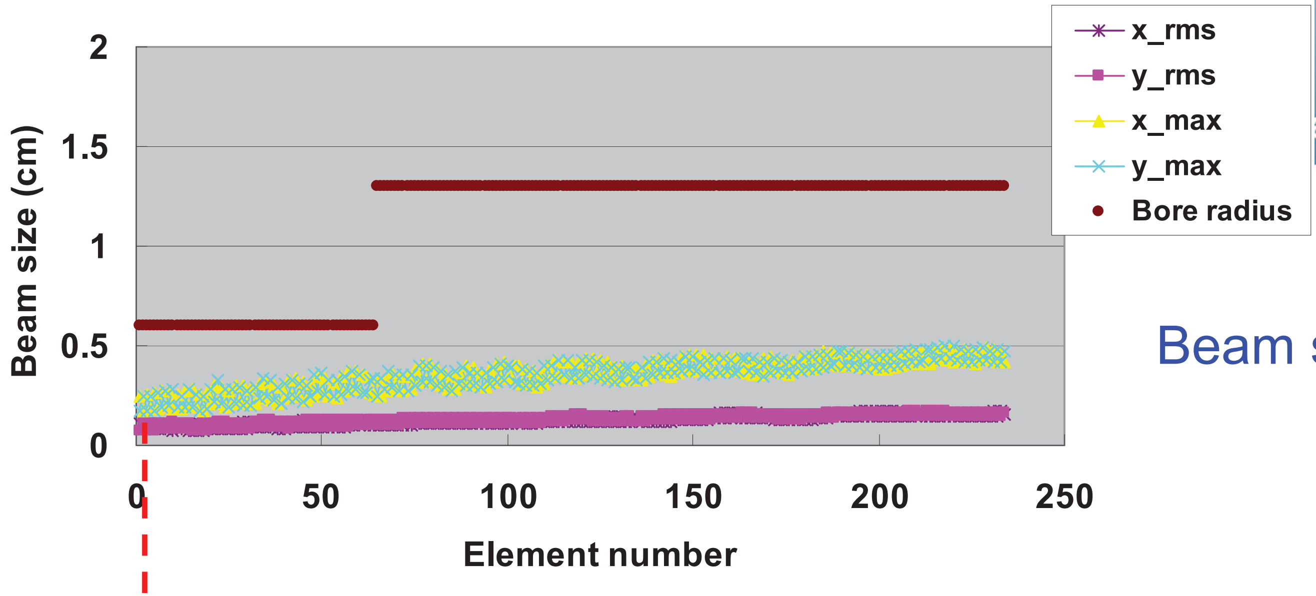
Beam loss rate-1st phase, I=15mA

	Tank1	Tank2	Tank3	Tank4
Beam loss <1W/m Probability	89%	100%	100%	100%

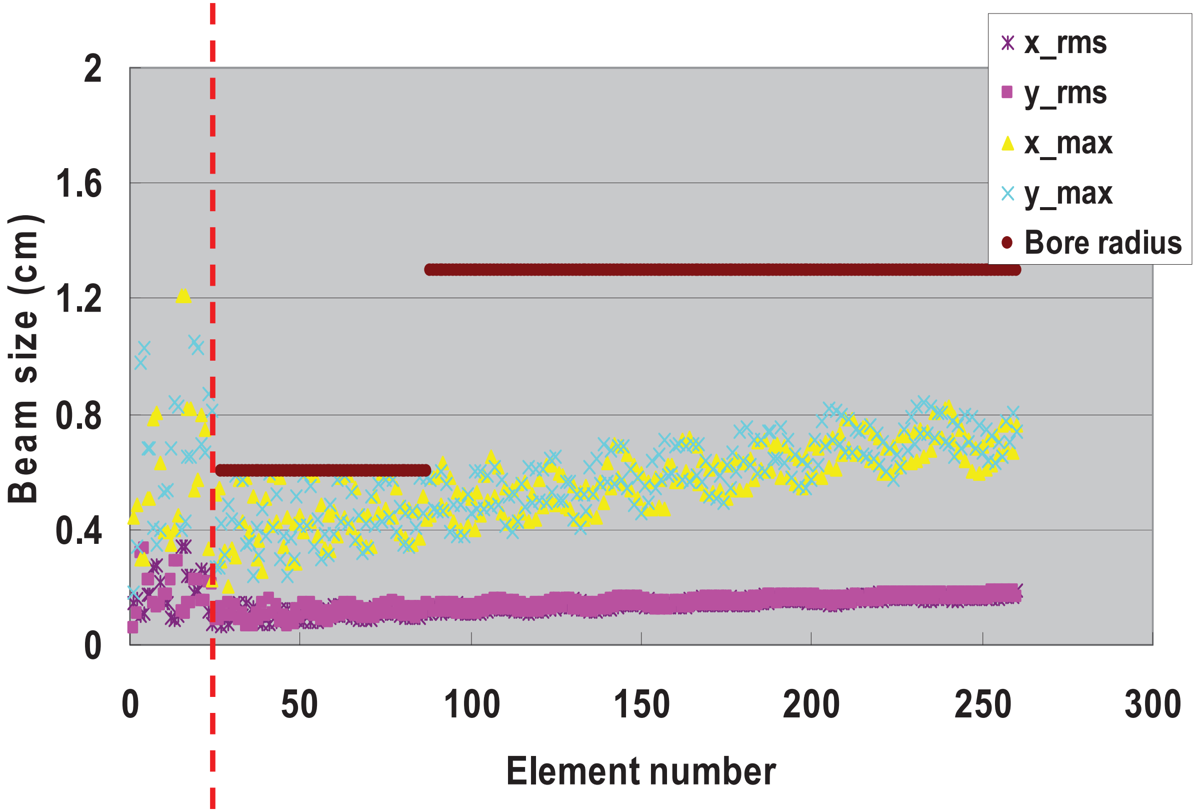
Beam loss rate-2nd phase, I=30mA

	Tank1	Tank2	Tank3	Tank4
Beam loss <1W/m Probability	39%	100%	100%	100%

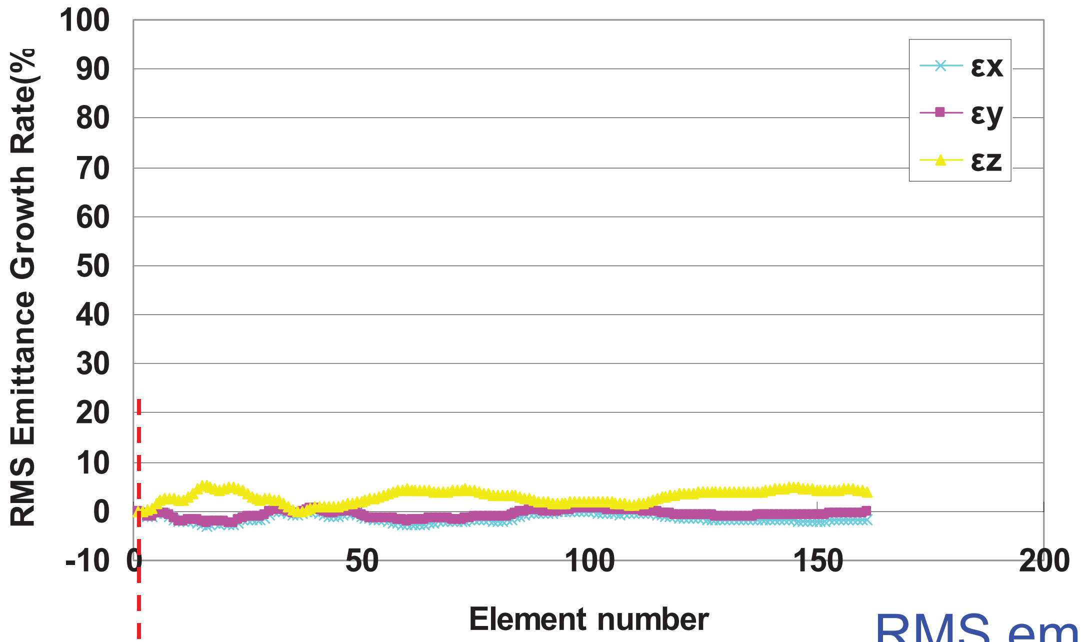
	Tank1	Tank2	Tank3	Tank4
Old design:	FD Rb=0.6cm	FD Rb=1.3cm	FD Rb=1.3cm	FD Rb=1.3cm
New design:	FFDD Rb=0.8cm	FFDD Rb=1.0cm	FFDD Rb=1.0cm	FFDD Rb=1.2cm



Beam size along the DTL



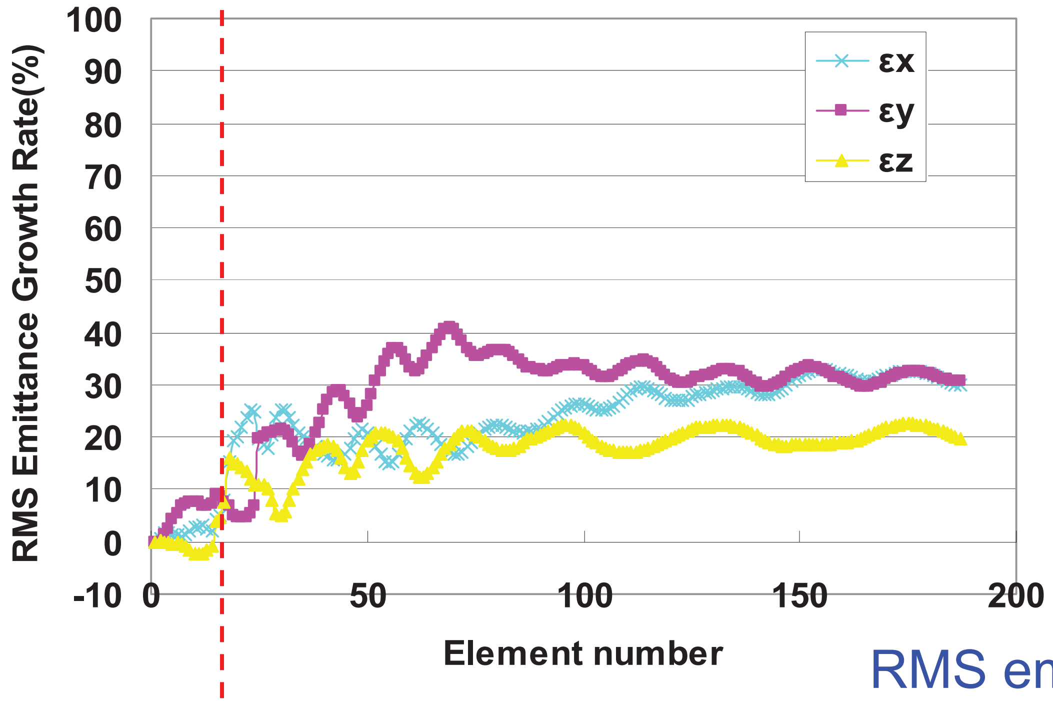
Beam size along the DTL



Don’t simulate
RFQ+MEBT+DTL together,

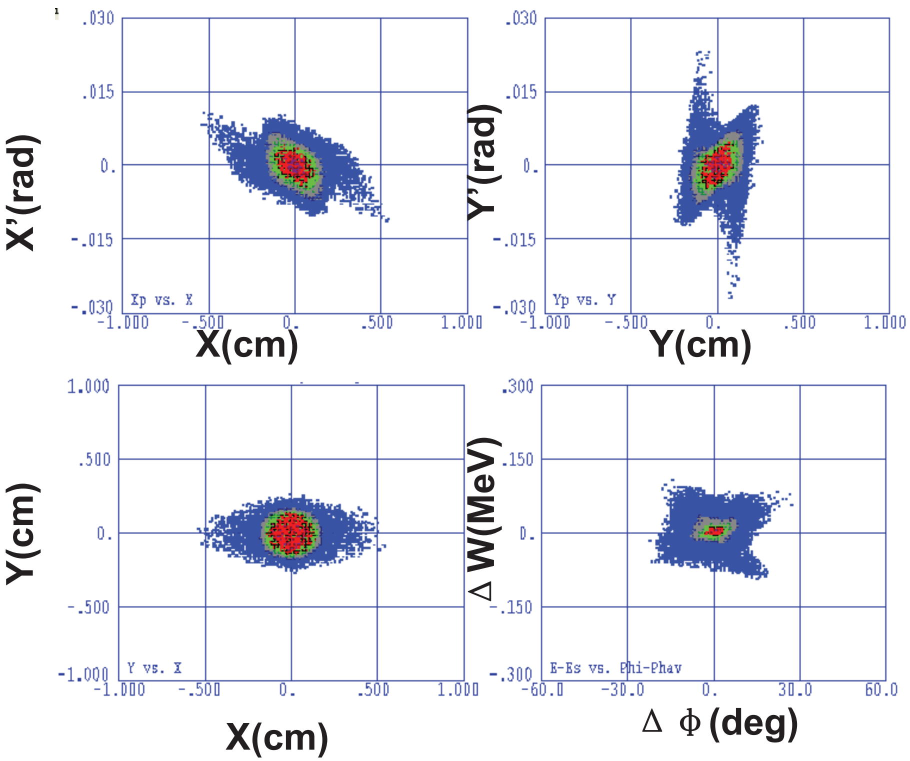
Don’t consider
beam emittance growth in
the MEBT

RMS emittance growth along the DTL

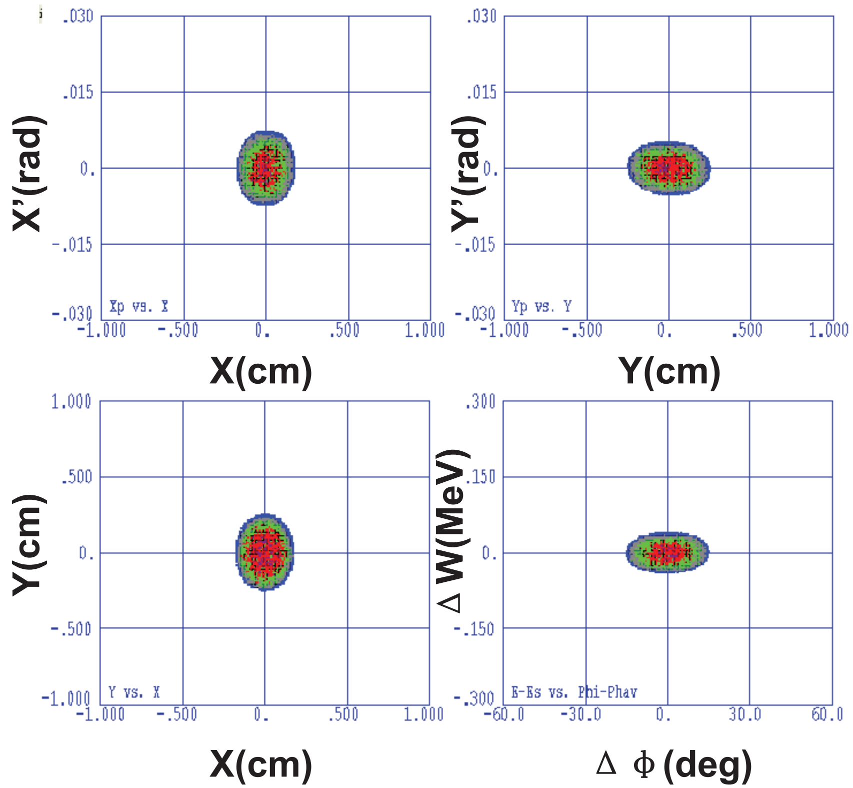


RMS emittance growth along the MEBT+DT

DTL in (from MEBT)

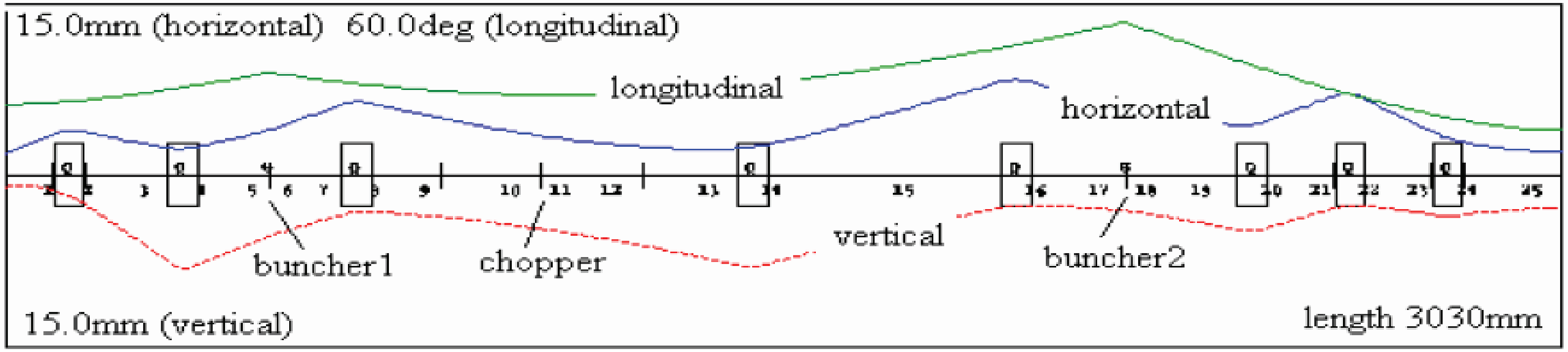


DTL in (K-V)

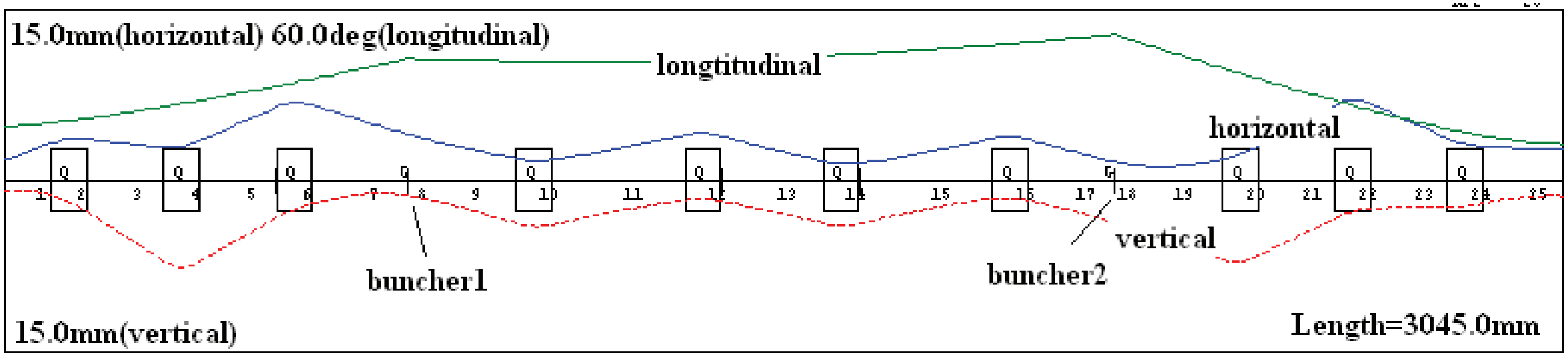


MEBT optimization

MEBT layout

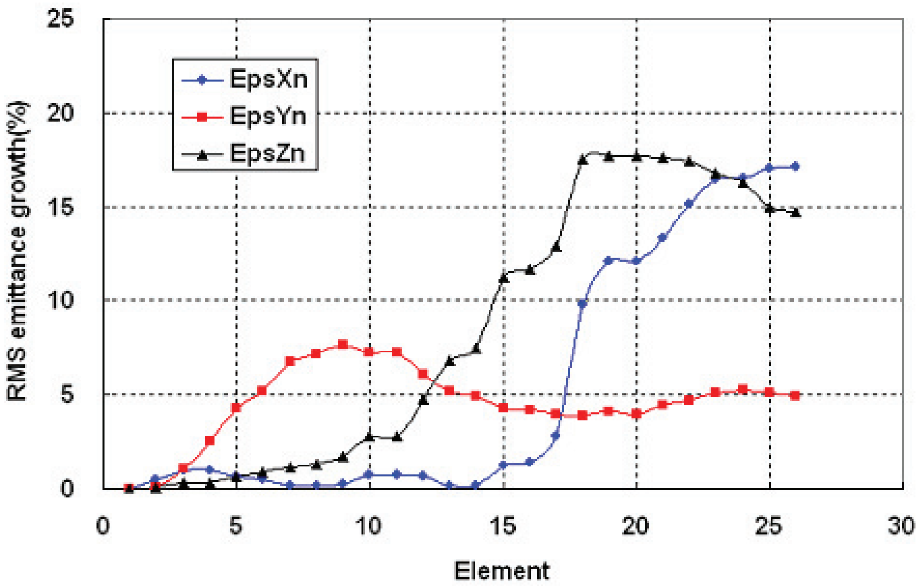


Old design: the MEBT comprises of a chopper, two 324MHzbuncher cavities and eight quadrupole magnets

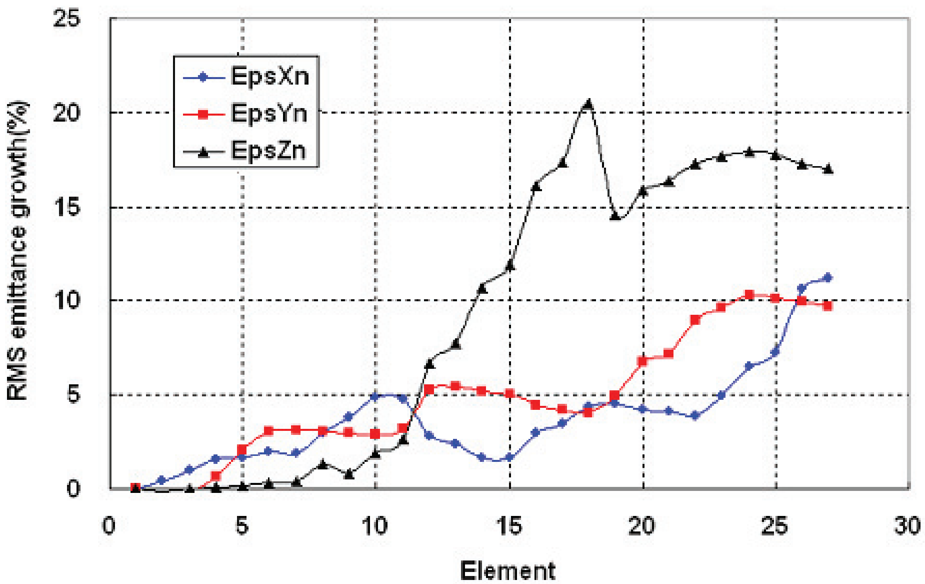


New design: the MEBT comprises of two 324MHzbuncher cavities and ten quadrupole magnets

Old design



New design



The rms emittance growth in x (dot), y (square) and z (triangle) direction versus the element obtained by code PARMILA

DTL optimization

DTL cell geometry-old design

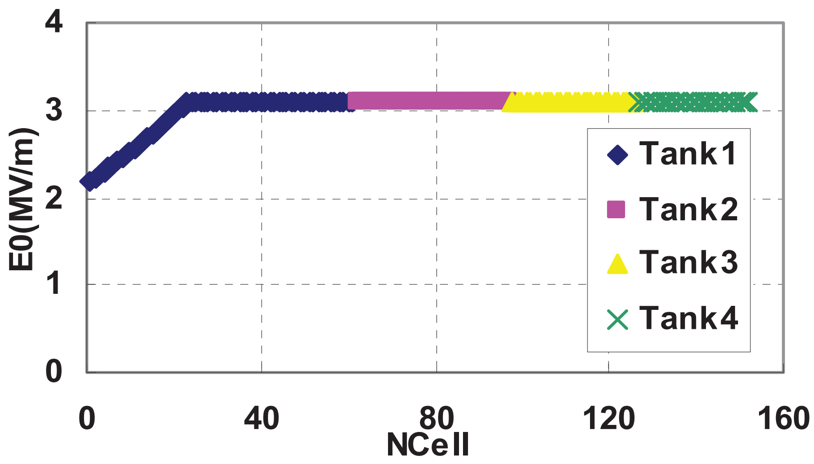
Beta	Bore Radius (cm)	Face angle (degree)	Inner nose Radius (cm)	Outer nose Radius (cm)	Corner Radius (cm)	Diamter of drift tube(cm)	Cavity Diameter (cm)	Flat length (cm)	
0.08-0.1	0.6	0	0.2	0.2	0.6	14.8	56	0	Tank1
0.1-0.13		9						0.2	
0.13-0.16		14	0.3	0.6				0.4	
0.16-0.2		20		0.8				0.5	
0.2-0.22		30		1					
0.22-0.25	1.3	35							
0.25-0.29		50							Tank2
0.29-0.32		50				14			Tank3~4
0.32-0.39		60							

DTL cell geometry-new design

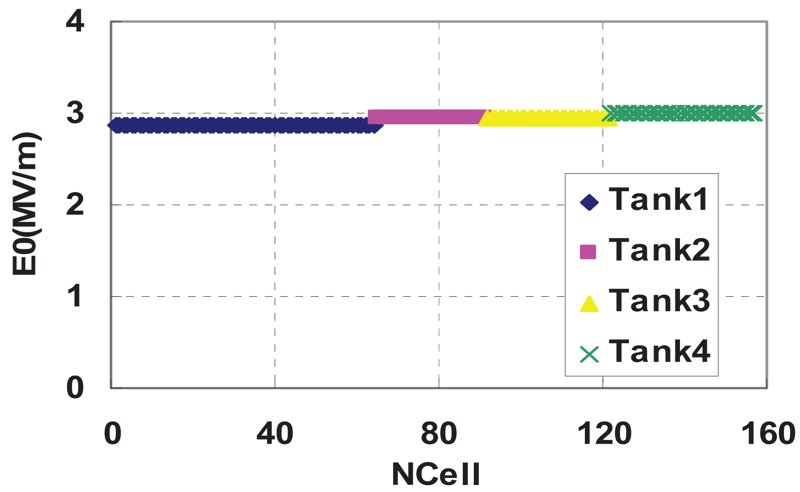
<table>
<tr><th>Beta</th><th>Bore radius (cm)</th><th>Face angle (degree)</th><th>Inner nose radius (cm)</th><th>Outer nose radius (cm)</th><th>Corner radius (cm)</th><th>Diameter of Drift tube(cm)</th><th>Cavity diameter (cm)</th><th>Flat length (cm)</th><th>Tank</th></tr>
<tr><td>0.08-0.1</td><td rowspan="5">0.8</td><td>0</td><td rowspan="2">0.2</td><td rowspan="2">0.2</td><td rowspan="9">0.6</td><td rowspan="9">14</td><td rowspan="9">56</td><td rowspan="2">0</td><td rowspan="5">Tank1</td></tr>
<tr><td>0.1-0.13</td><td>8</td></tr>
<tr><td>0.13-0.16</td><td>15</td><td rowspan="7">0.3</td><td>0.6</td><td>0.2</td></tr>
<tr><td>0.16-0.2</td><td>20</td><td>0.8</td><td>0.4</td></tr>
<tr><td>0.2-0.21</td><td>30</td><td rowspan="5">1.0</td><td rowspan="5">0.5</td></tr>
<tr><td>0.21-0.25</td><td rowspan="3">1.0</td><td>35</td><td rowspan="2">Tank2</td></tr>
<tr><td>0.25-0.29</td><td>40</td></tr>
<tr><td>0.29-0.34</td><td>50</td><td>Tank3</td></tr>
<tr><td>0.34-0.4</td><td>1.2</td><td>60</td><td>Tank4</td></tr>
</table>

Accelerating field

Old design



New design

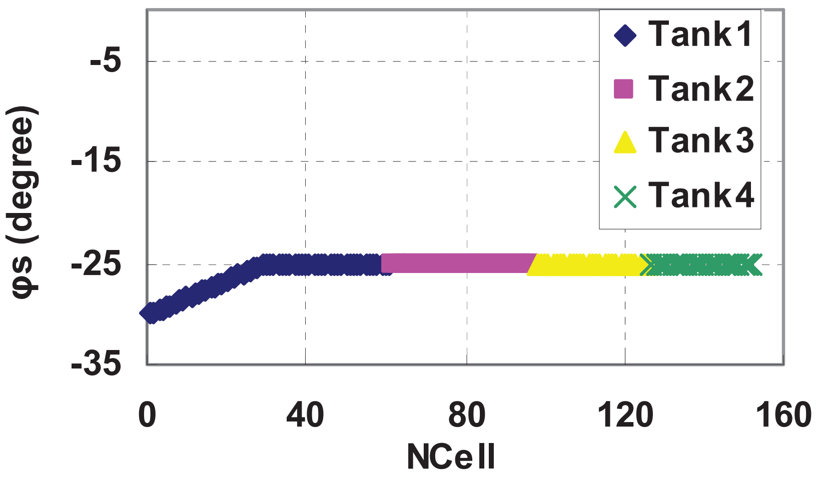


- **In the 1st tank, the E_0 is ramped from 2.2MV/m to 3.1MV/m over the first 24 cells, and then keeps constant.**
- **No field ramp in other tanks.**

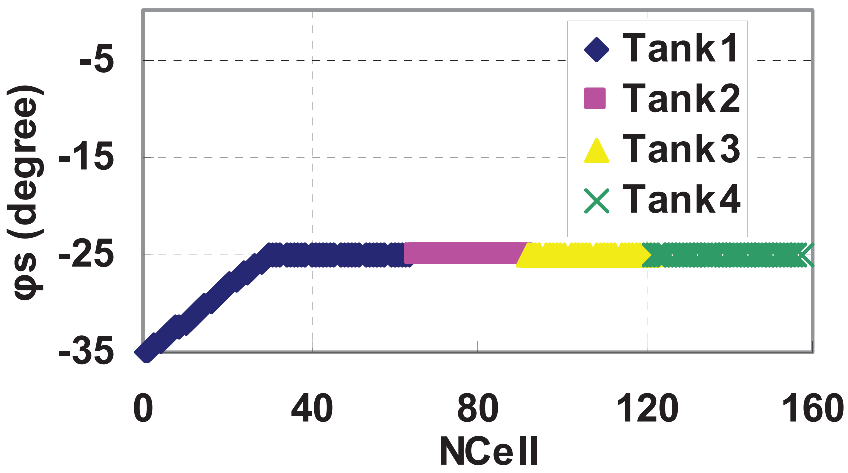
- **To simplify RF tuning and obtain high accelerating gradient, constant field E_0 of 2.86MV/m is chosen over the 1st tank.**
- **No field ramp in other tanks**

Synchronous phase

Old design



New design



Multi partIcle simulation shows that, at the exit of MEBT,
the beam RMS phase width is 5.58degree, the total phase width is 30.98degree

Old design

Tank number	1	2	3	4	total
Output energy (MeV)	21.76	41.65	61.28	80.77	80.77
Length (m)	7.99	8.34	8.5	8.85	34.45
Number of cell	61	36	29	26	152
Total RF power (MW) I=30mA	1.97	2.01	1.98	2.03	7.99

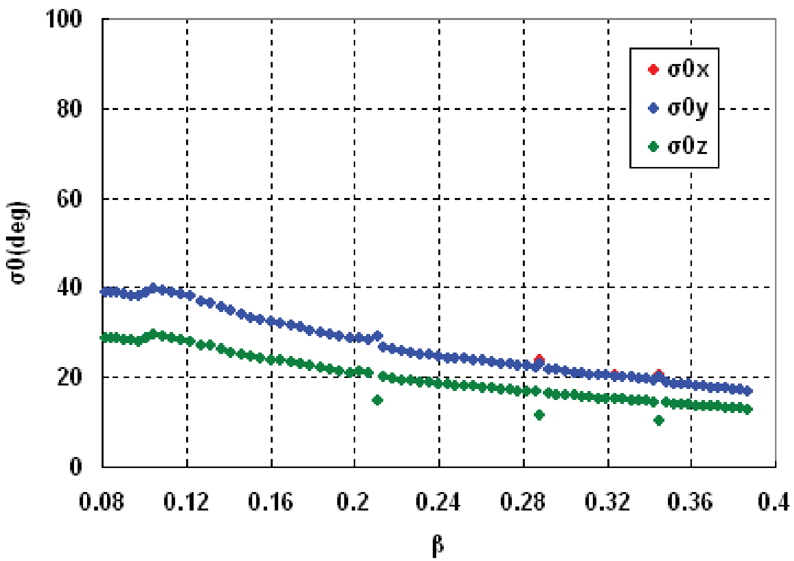
New design

Tank number	1	2	3	4	total
Output energy (MeV)	21.67	41.41	61.07	80.1	80.1
Length (m)	8.51	8.56	8.78	8.8	35.44
Number of cell	64	37	30	26	157
Total RF power (MW) I=30mA	1.91	1.92	1.92	1.93	7.68

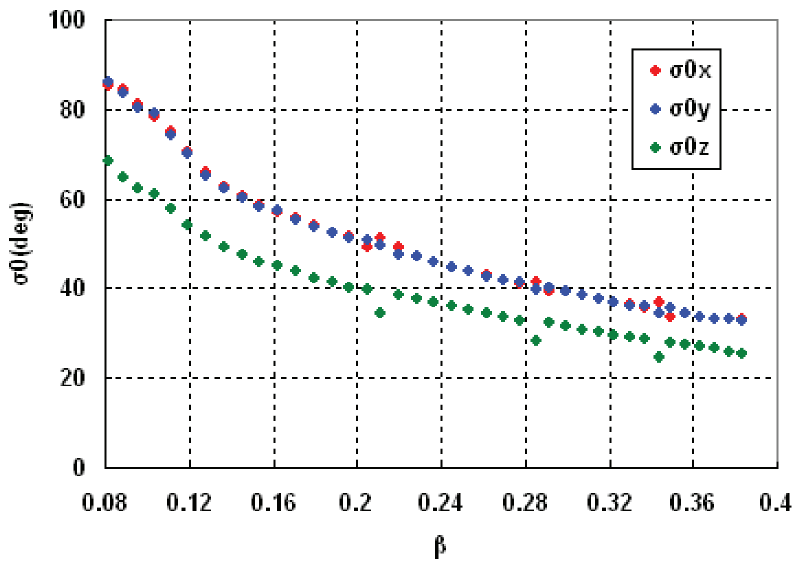
Beam stability requirements

- σ_{t0}，σ_{z0}<90°
- $\sigma_{0t} \neq n\sigma_{0l}/2$,for n=1, 3…
- Equipartitioning require:

$$\frac{k_{t0}}{k_{z0}} = \sqrt{\frac{3}{2}\frac{\varepsilon_{nz}}{\varepsilon_{nt}} - \frac{1}{2}}$$



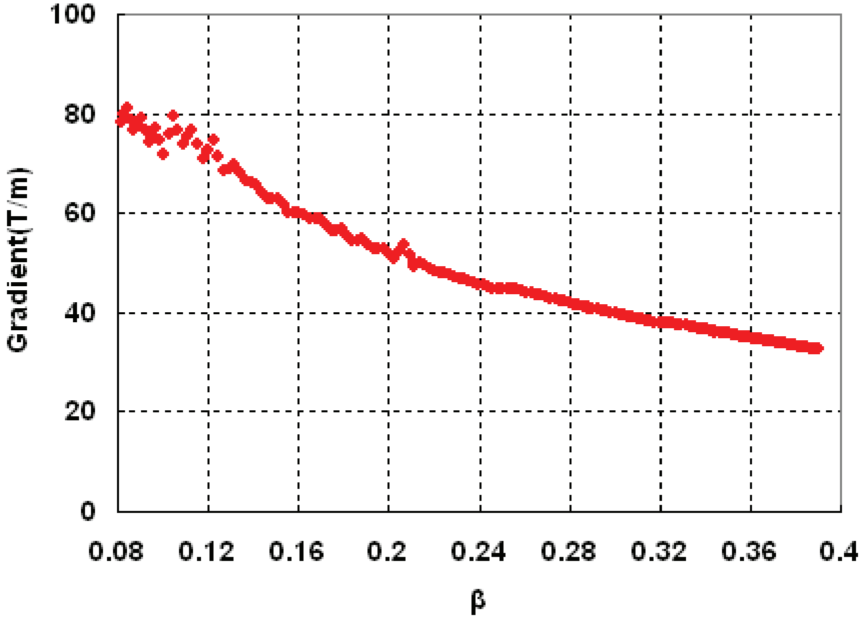
Zero-Current Phase Advance per Period for FD lattice



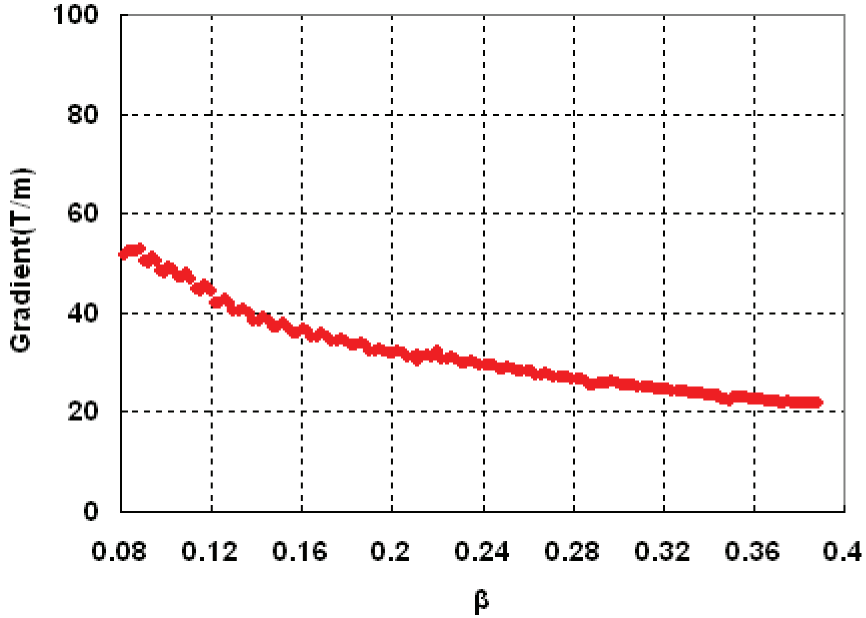
Zero-Current Phase Advance per Period for FFDD lattice

Focusing scheme FD VS FFDD

FD Lattice



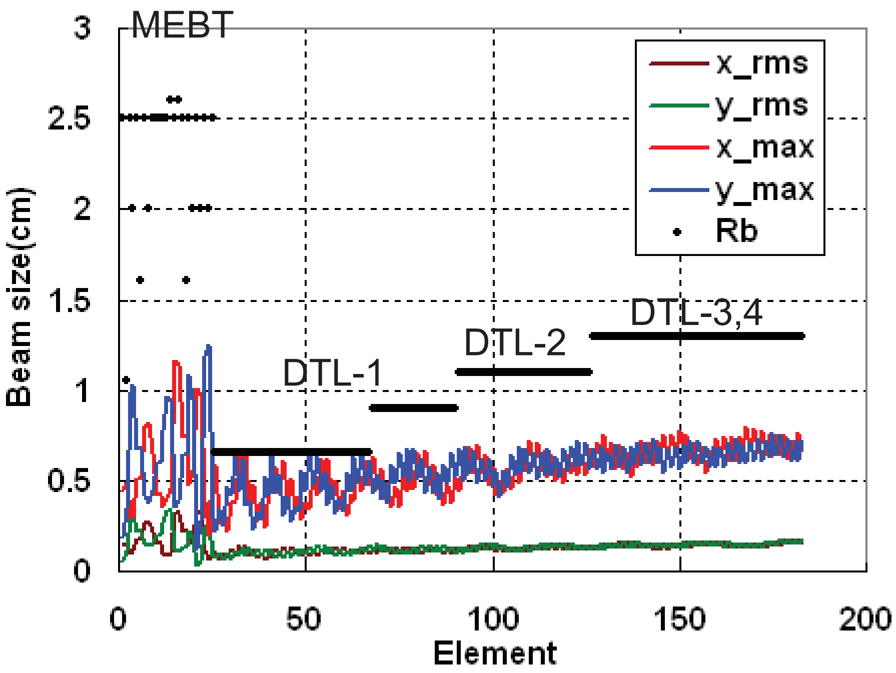
FFDD Lattice



Disadvantage: high quadrupole gradient, small beam bore radius

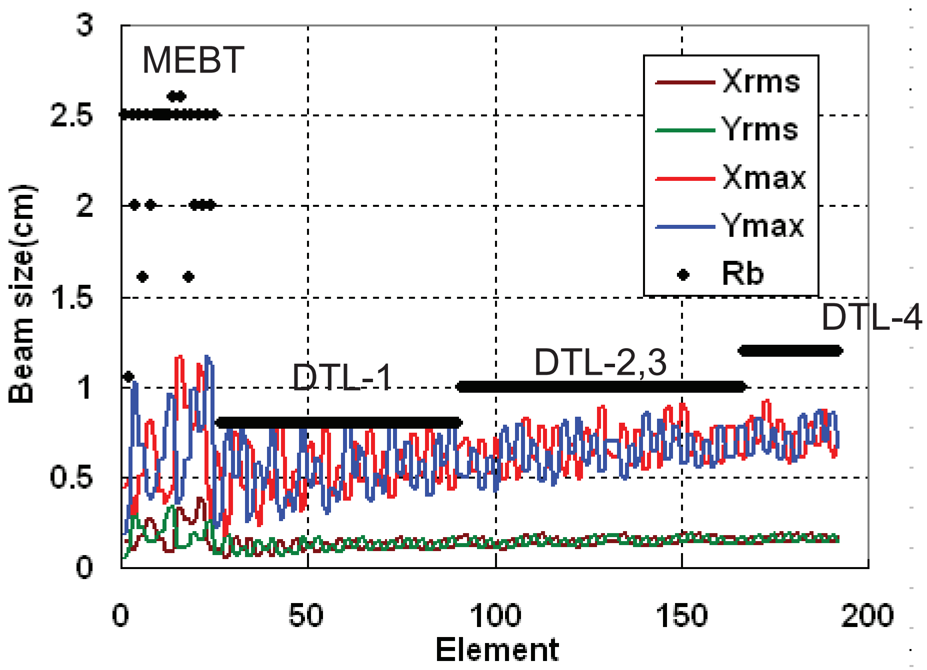
Advantage: lower quadrupole gradient, bigger beam bore radius

FD Lattice



Advantage: strong focusing,
small beam size,
small amplitude of
envelope oscillation

FFDD Lattice



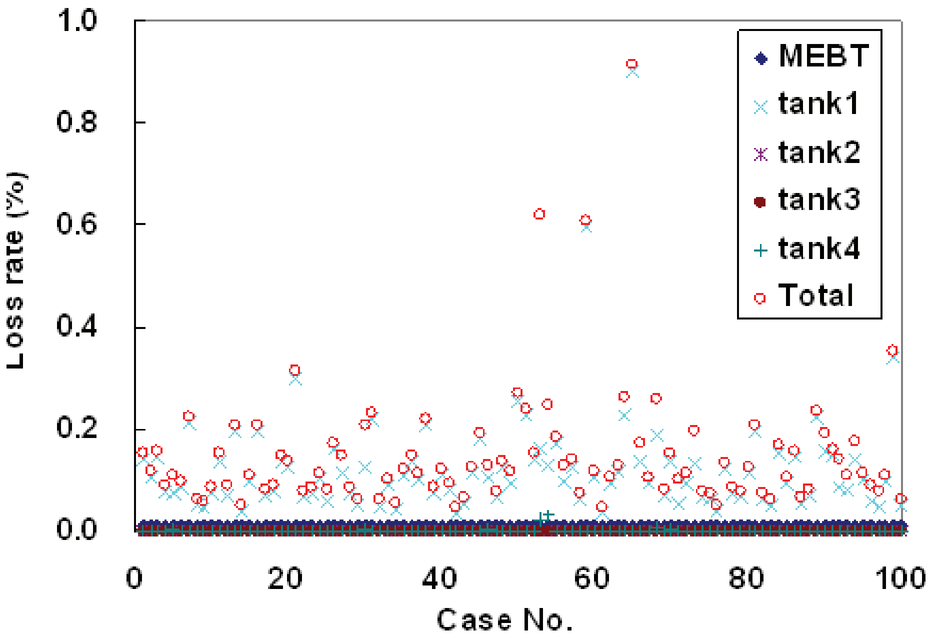
Disadvantage: weaker focusing,
bigger beam size,
bigger amplitude of
envelope oscillation

Error Analysis

For the quadrupoles:
- Transverse displacements ⩽ ±0.1mm,
- Rotations ⩽ 3mrad,
- Integrated field ⩽ 1 %,

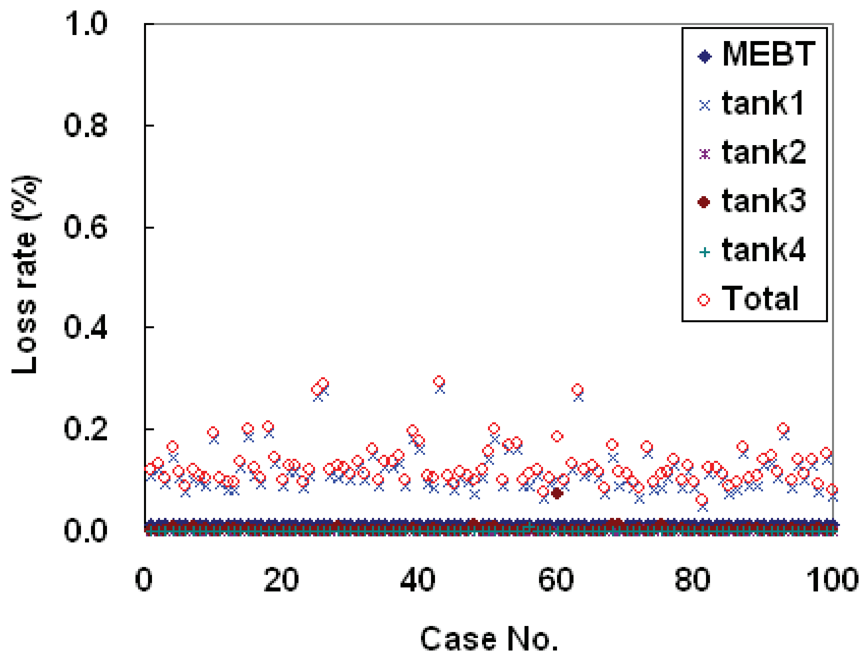
For the accelerating field:
- RF amplitude ⩽ 1 %
- RF phase ⩽ 1degree

FD Lattice



Disadvantage: In DTL-1, 89% probability beam loss <1W/m.

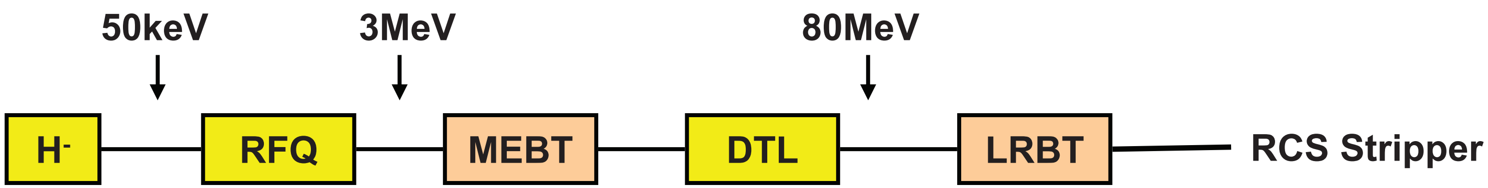
FFDD Lattice



Advantage: In DTL-1, 98.1% probability beam loss <1W/m.
In DTL-3, 99.5% probability beam loss<1W/m

End to end simulation

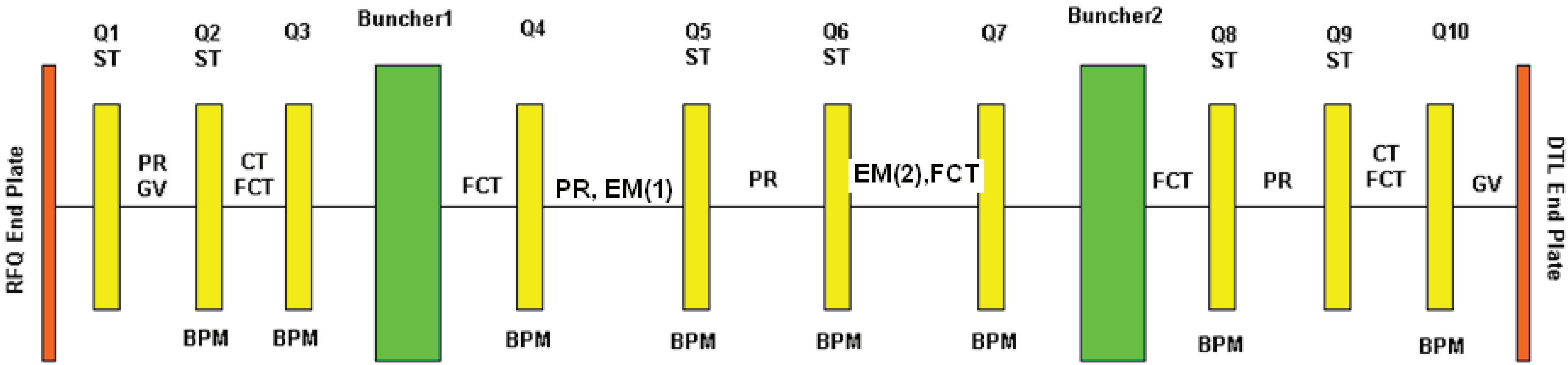
End to End Simulation

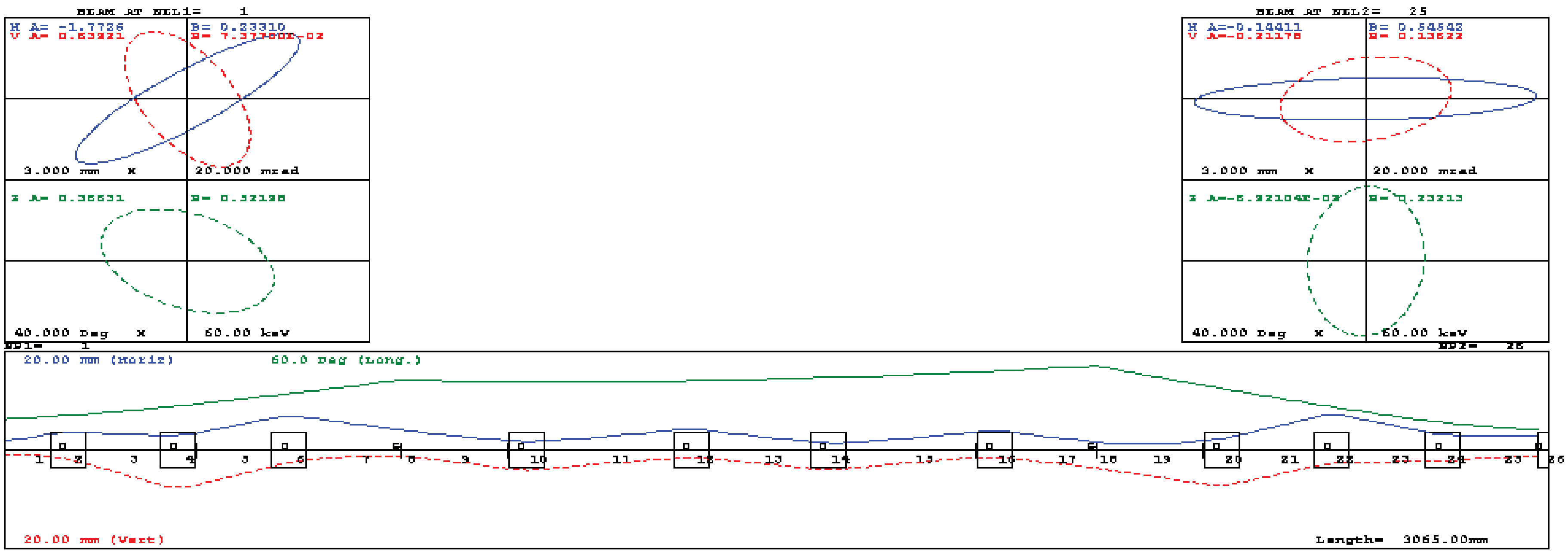


The simulation is performed from the RFQ exit to the RCS injection:

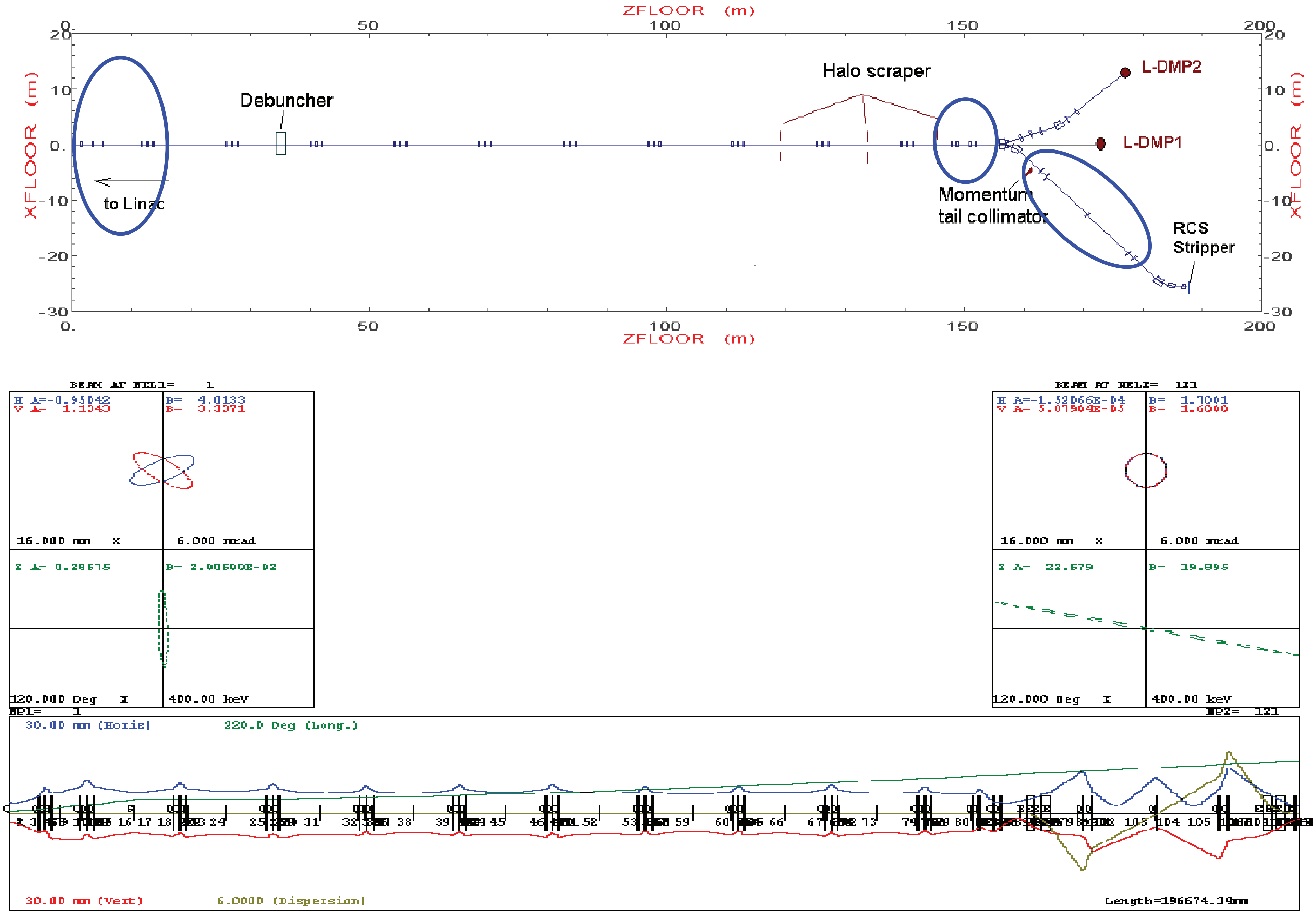
- Simulation code: PARMILA with 2D space-charge routine
- Number of particles: 50448
- Peak current: 15mA
- Initial distribution: PARMTEQM output

MEBT match


RFQ End Plate
Q1
ST
PR
GV
Q2
ST
CT
FCT
Q3
Buncher1
FCT
Q4
PR, EM(1)
Q5
ST
PR
Q6
ST
EM(2),FCT
Q7
Buncher2
FCT
Q8
ST
PR
Q9
ST
CT
FCT
Q10
GV
DTL End Plate
BPM
BPM
BPM
BPM
BPM
BPM
BPM
BPM

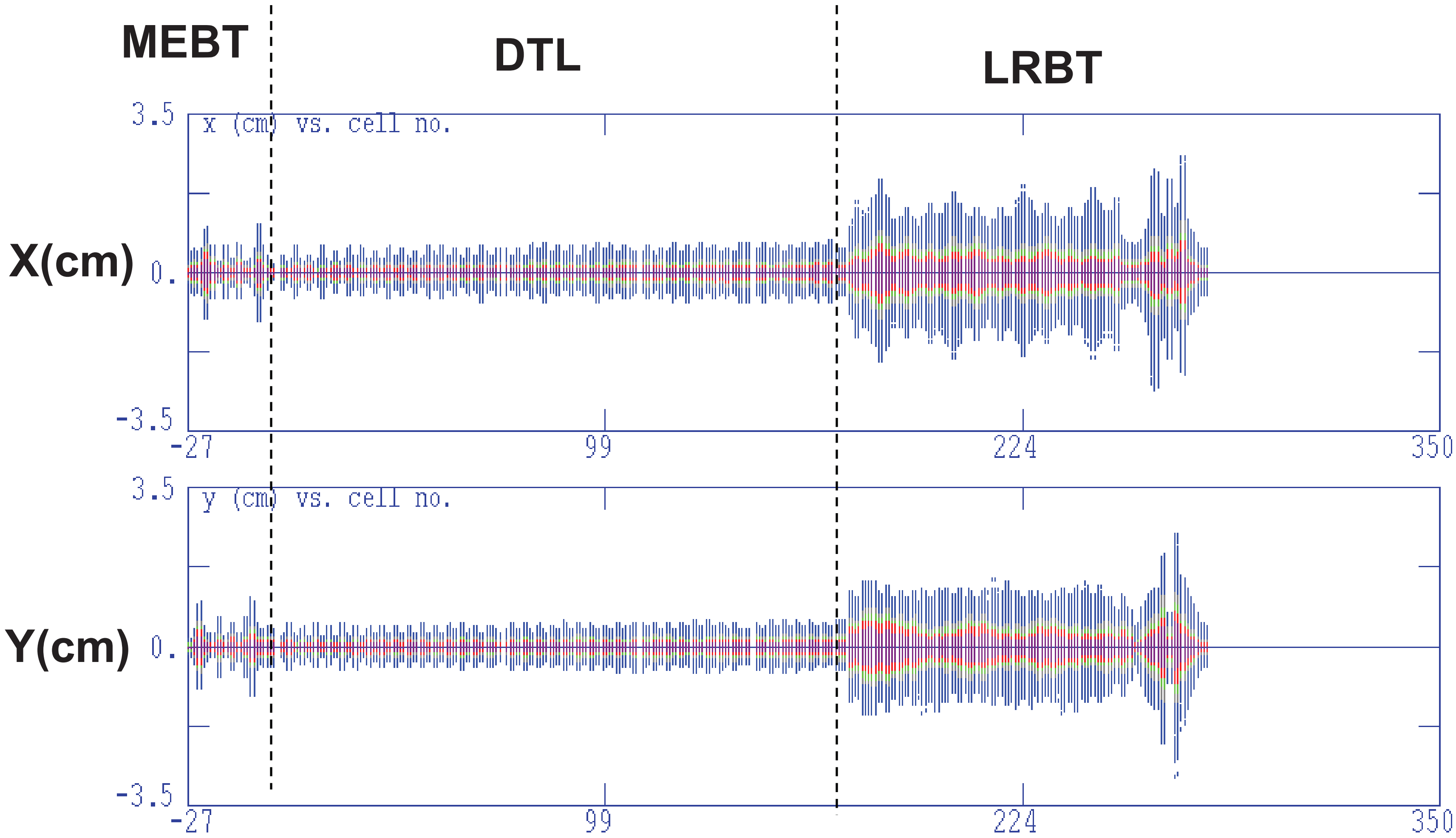

20.00 mm (Horiz)
60.0 Deg (Long.)
20.00 mm (Vert)
Length= 3065.00mm

LRBT match



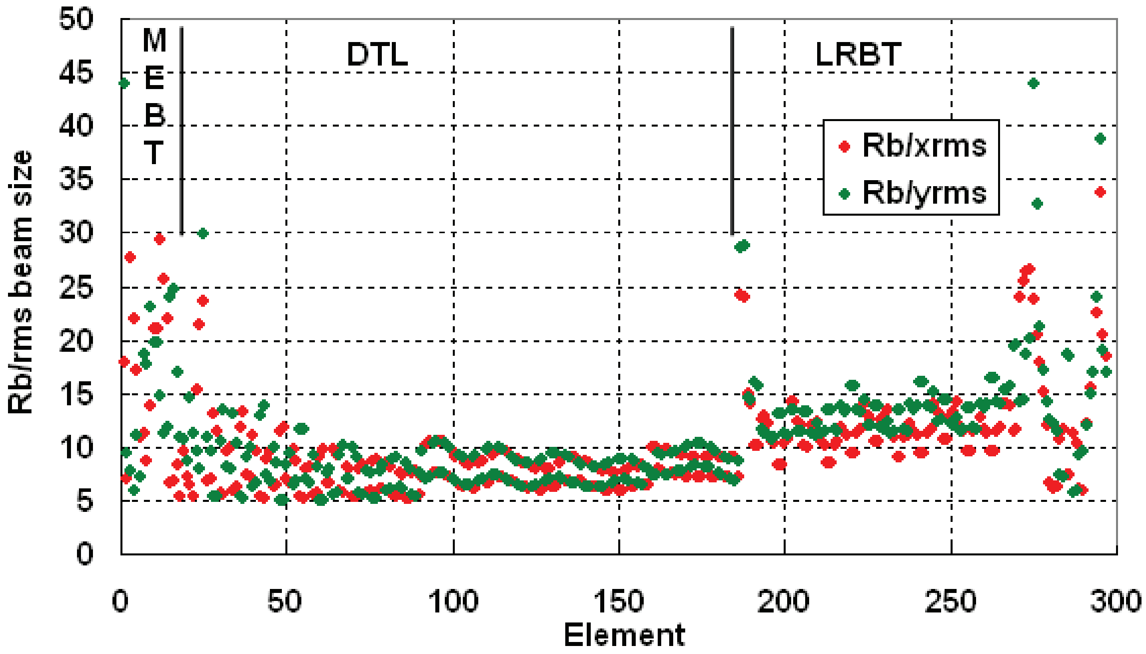
ZFLOOR (m)
XFLOOR (m)
Debuncher
Halo scraper
L-DMP2
L-DMP1
to Linac
Momentum tail collimator
RCS Stripper
BEAM AT NEL1= 1
BEAM AT NEL2= 121
30.00 mm (Horiz)
220.0 Deg (Long.)
30.00 mm (Vert)
6.0000 (Dispersion)
Length=196674.19mm

End to End Simulation (Phase Ⅰ)



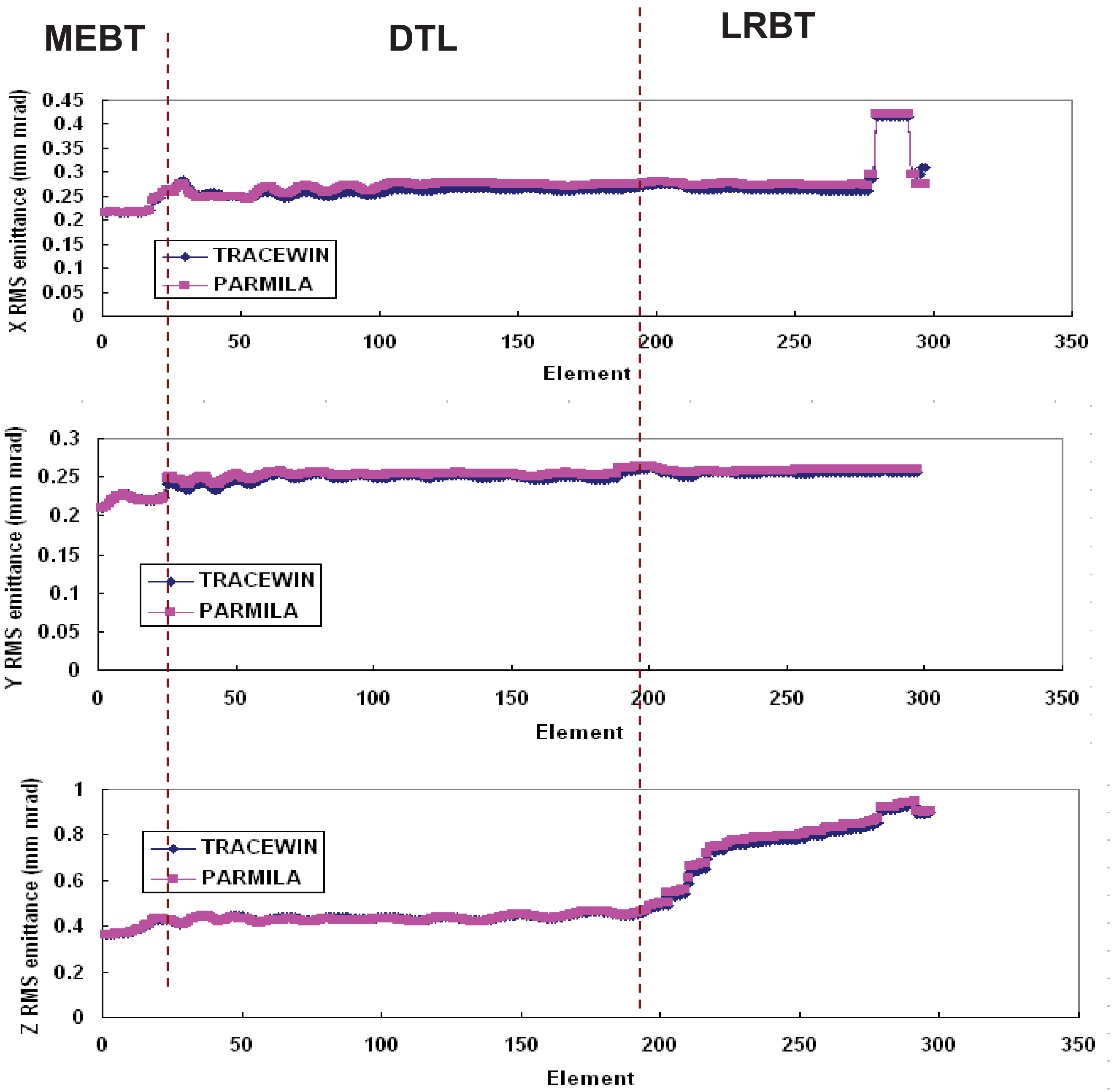
Beam envelope

Beam bore radius/rms beam size

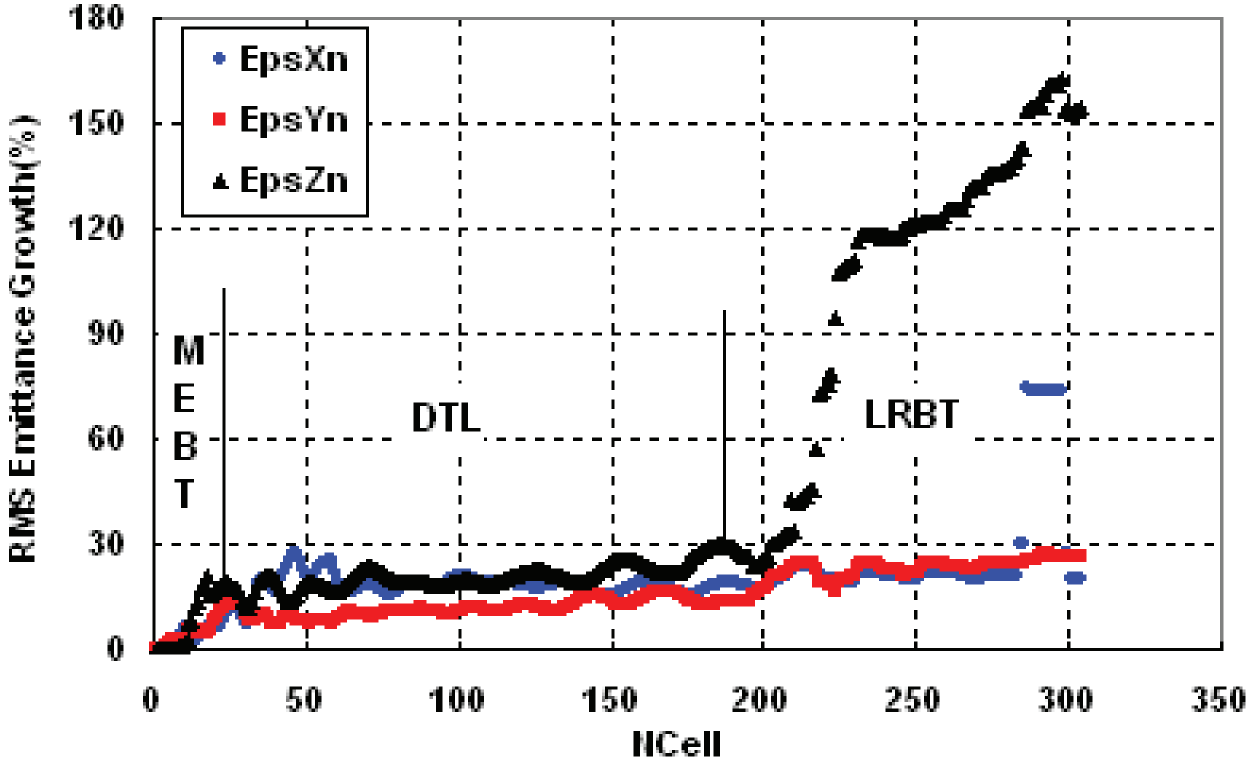


MEBT	DTL	LRBT
ratio>5.2	DTL-1: ratio>5 DTL-2,3,4: ratio>5.8	Ratio>5.7

RMS emittance along Linac



RMS emittance growth along Linac



Summary

- In the old design, the beam loss in the 1^{st} DTL tank was found serious while all errors applied. The reason to this problem was that we don't consider halo formation and emittance growth in the MEBT while optimizating DTL geometric parameters. So end-to-end simulation must be conducted before reaching a final design.
- Two transverse focusing lattices have been compared, namely FD and FFDD focusing lattice. FFDD lattice was finally chosen for its lower quadrupole gradient and smaller beam loss rate compared with FD one.
- End to end simulation has shown that the beam loss, emittance growth rate and the ratio of bore radius to rms beam size were acceptable along the linac, and now we reached a final design.

Thank you!