Design of Injector II for C-ADS

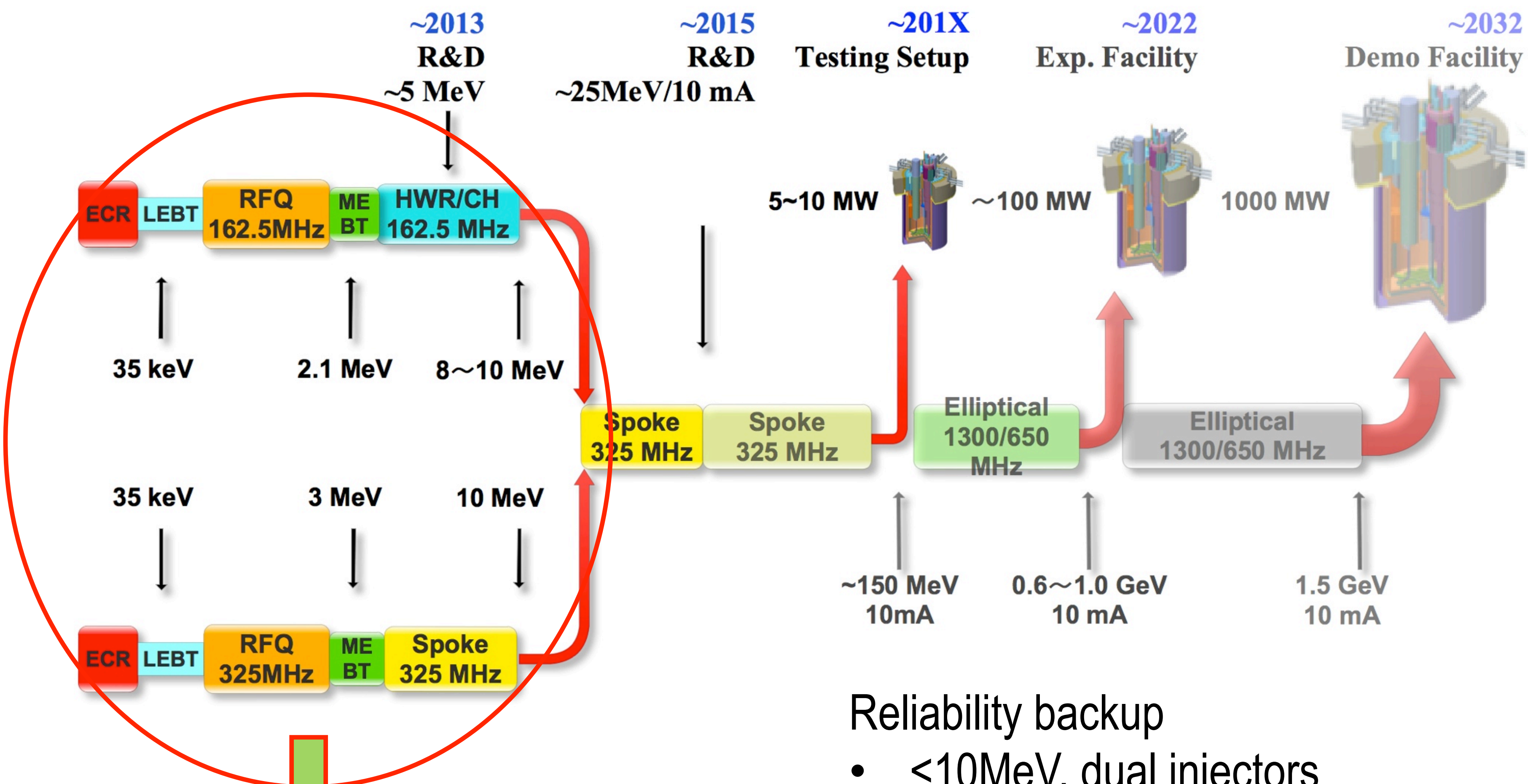
Linac Group

Institute of Modern Physics, CAS

2011-09-19

IHEP, Beijing

General design of ADS accelerator



Reliability backup

- <10MeV, dual injectors
- >10MeV, cavities

uncertainly

IHEP

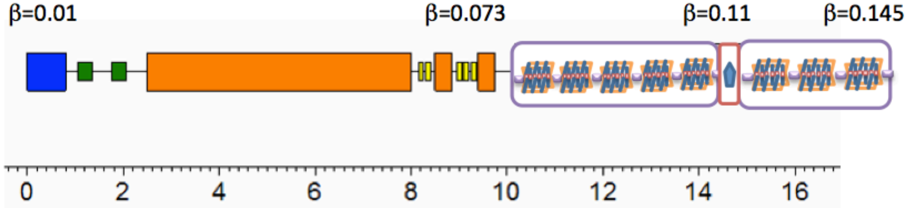
IMP

To be backup for each other

Original Schemes of Injector II

Scheme 1: RFQ + CH

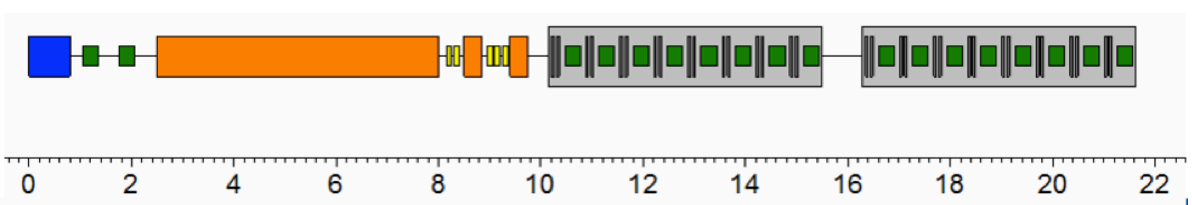
ECR	LEBT	RFQ 325MHz	MEBT	CH C.M. 4.5m	CH C.M. 3.5m
	2*Sole.	2part./sect.*3sect.	FD-B-FDF-B	5*CH+6*Sole.	3*CH+4*Sole.
	50keV		3MeV	5MeV	10MeV
	β=0.01		β=0.073	β=0.11	β=0.145



parameter	CH-linac	spoke linac
number of cavities	4	30
β	0.1-0.2	0.15
gradient at β_{opt}	3 MV/m	6.3 MV/m
gradient (cavity length)	3 MV/m	2.5 MV/m
real estate gradient	1.62 MV/m	0.33 MV/m
energy gain per cavity	3-3.5 MeV	0.16-0.42 MeV
E_p at design gradient	19.5 MV	25 MV
B_p at design gradient	22 mT	50 mT
total length (m)	8	40

Scheme 2 (Backup): RFQ + HWR009

ECR	LEBT	RFQ 5.5m	MEBT	HWR C.M. 5.5m	HWR C.M. 5.5m
	2*Sole.	2part./sect.*3sect.	FD-B-FDF-B	8*(HWR+Sole.)	8*(HWR+Sole).
	35keV		2.1MeV	5.0MeV	9.34MeV
	β=0.009		β=0.067	β=0.103	β=0.14



- CH merits
  - High real estate Vacc
  - Compact (short)
  - Lower Ep and Bp
- CH drawbacks
  - Complicated structure
  - New technology
  - Difficult beam dynamic

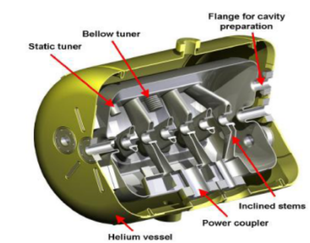
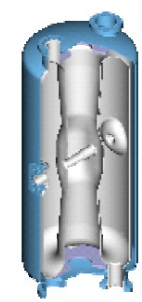


Figure 9: Layout of the superconducting 325 MHz CH-cavity with helium vessel.

CH



HWR

Options of Injector II

- For CW RFQ, structure cooling is critical, special effort should be put on how to reduce the required RF power, for instance reducing vane tip-tip voltage or beam bore. Reducing RFQ output energy to 2.1 MeV (neutron production in copper) can also be evaluated for its merits and drawbacks.
- Of the two accelerator layout proposals for the ADS Injector II from IMP to reach 10 MeV and 10 mA, with RFQ frequency of 162.5 MHz, we suggest the preferred configuration option to be the lattice using the low-beta HWR (0.093). Significant R&D will be required for the superconducting CH structures proposed in the other option. With the tight schedule required to reach the goal of Phase I for the ADS project, we feel the superconducting HWR cavity has significant lower technical risks and performance advantages. Again, extensive R&D in similar HWR cavities have been taken recently in several international laboratories and the performance of these cavities have been shown to be well above the level required by the ADS accelerator design requirements.

Comments of international review on April 27th

- Lower RFQ output energy to 2.1 MeV and injection energy is 35 keV
- Setup RFQ design current to 15 mA
- Setup baseline to HWR with 162.5 MHz
- Setup CH cavity to be backup

Frequency choice：
Half frequency 162.5 MHz to reduce average wall power density

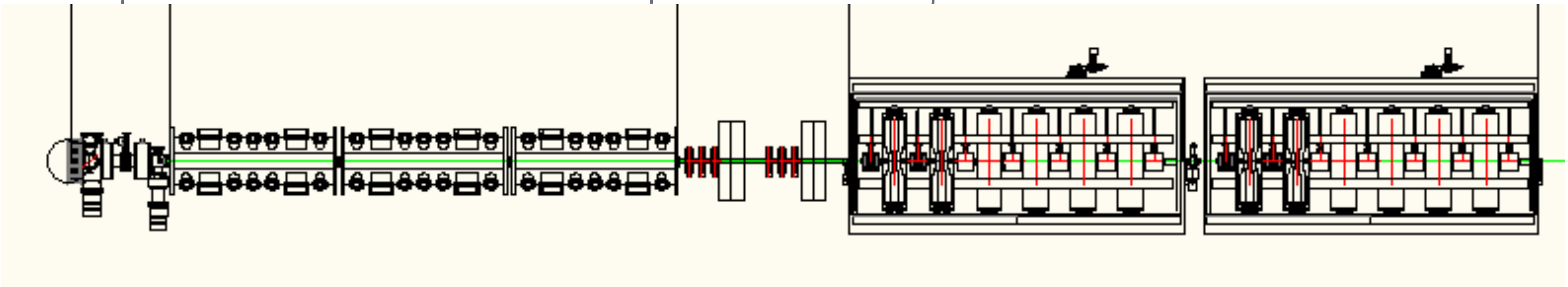
	Proj-X 162	Proj-X 325	KOMAC	
Frequency	162.5	325	350	MHz
Injection Energy	35	30	50	keV
Output Energy	2500	2500	3000	keV
Current	10	10	23	mA
Length	385	287	324	cm
Length/Lambda	2.1	3.1	3.8	
Vane-Vane Voltage	90.8	64.2	100	kV
Peak E-field	20.7	27.6	33.1	MV/m
E-field/Kilpatrick	1.52	1.55	1.8	kilpatrick
Cavity Power	155*	149*	350*/417	kW
Power/Length	40	52	108	kW/m
Avg Wall Power Density	2.1	5.2	13	W/cm^2
r_0 (transverse vane tip radius)	0.61	0.31		cm
minimum longitudinal radius	1.2	0.69		cm
Output rms Momentum Spread	0.2	0.15		percent
Output rms Longitudinal Emittance	0.050	0.046	0.246	MeV-Degree
Output Transverse Emittance	0.030	0.028	0.023	cm-mrad
Transmission	94	90		percent

*=Calculated

Base line of injector II

- Basic frequency is 162.5 MHz
- Ion source extraction voltage is 35 kV
- Extraction energy of RFQ is 2.1 MeV
- HWR is the main road to develop
- CH cavity will be R&D

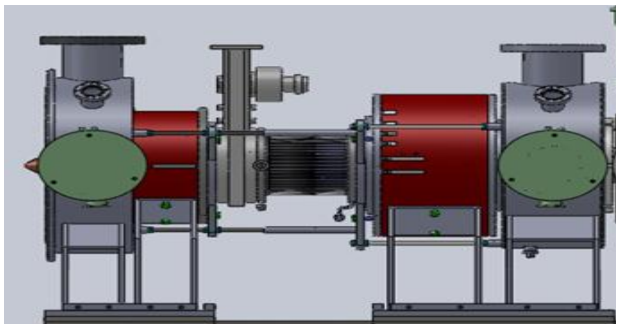
ECR | LEBT 2*Sole. 35keV β=0.087 | RFQ 4-5m 4-5parts 162.5 MHz | MEBT FDF-B-FDF-B 2.1MeV β=0.067 | SC-segment HWR C.M. 162.5 MHz 2.1-10MeV β~0.09

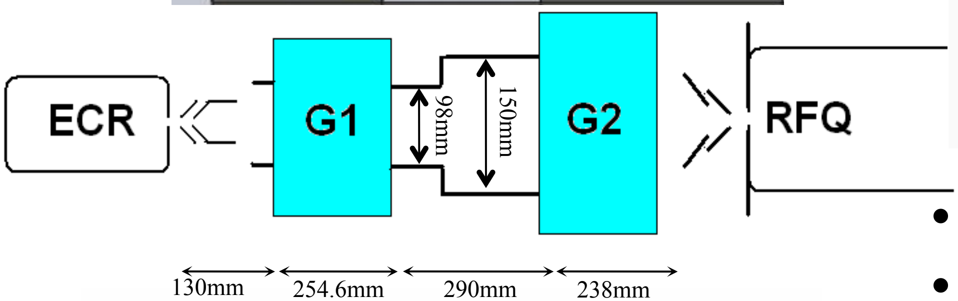


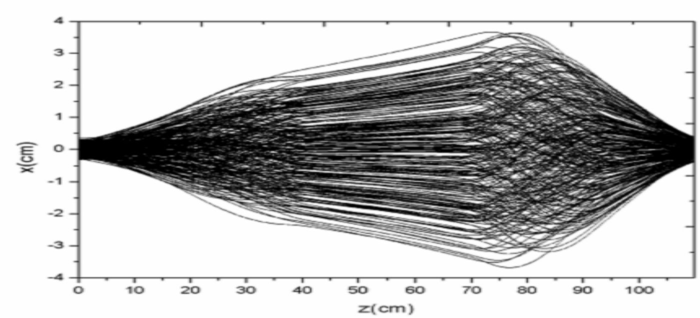
Consideration of IS and LEBT design

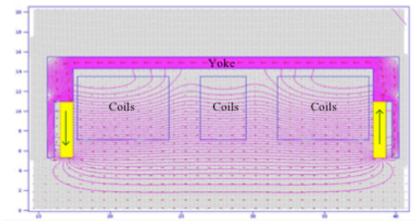
Details will be presented in another talk.

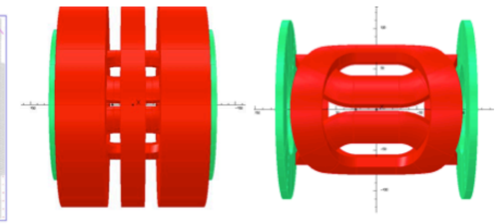
❖ LEBT design

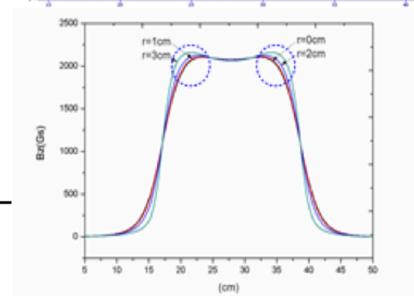


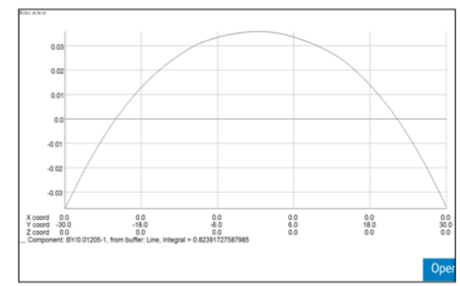












- 35 keV to reduce sparking
- To avoid aberration
  - Shorten the distance between ion source and the first solenoid to reduce the beam size
  - Shim the solenoid to get a homogeneity field in radius

Consideration of RFQ design

Details will be presented in another talk.

Difficulties of ADS-RFQ

- Beam dynamic of high intensity
- Thermal analysis and cooling
- Brazing with accuracy
- Electrodes machining

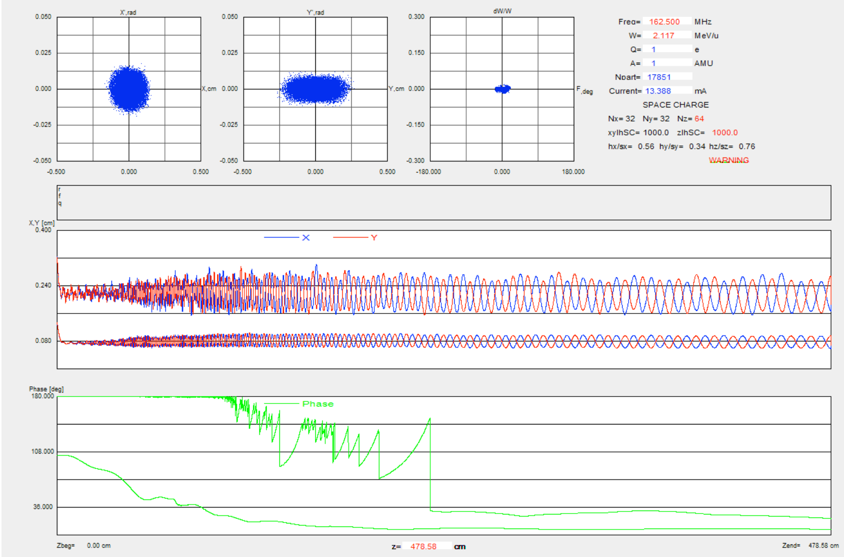
Ion	Proton
RF frequency	162.5 MHz
Duty factor	100%
Average beam current	15 mA
Output energy	2.1 MeV/u
Output beam transversal emittance, rms	$\leq 0.025\ \pi.cm.mrad$
Output beam longitudinal emittance, rms	$\leq 1\ keV.ns$
Total structure length	≤5 m
Output beam ellipse	Double waist

Challenge to IMP

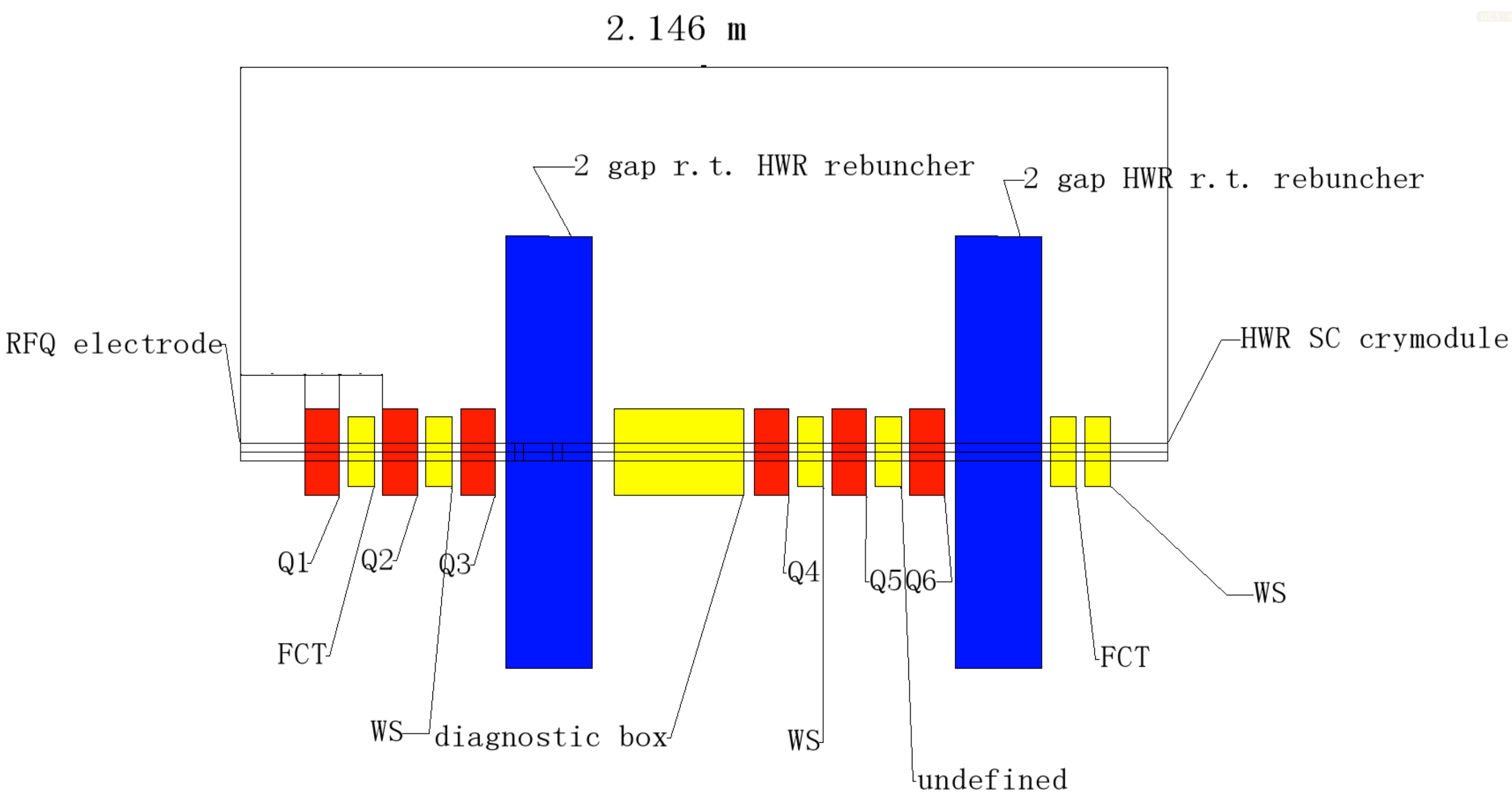
- Less experience on RFQ

Strategy of development

- Design of LBNL (experts on SNS's RFQ)
  - Crosscheck physics design
  - Depends on the vendor in China to fabricate base on the mechanical design of LBNL
  - Assembling and commissioning with LBNL
- R&D at IMP
  - To do experiments of brazing and machine
  - To fabricate a full-powered model, base on the mechanical design of IMP



Consideration of MEBT1 design

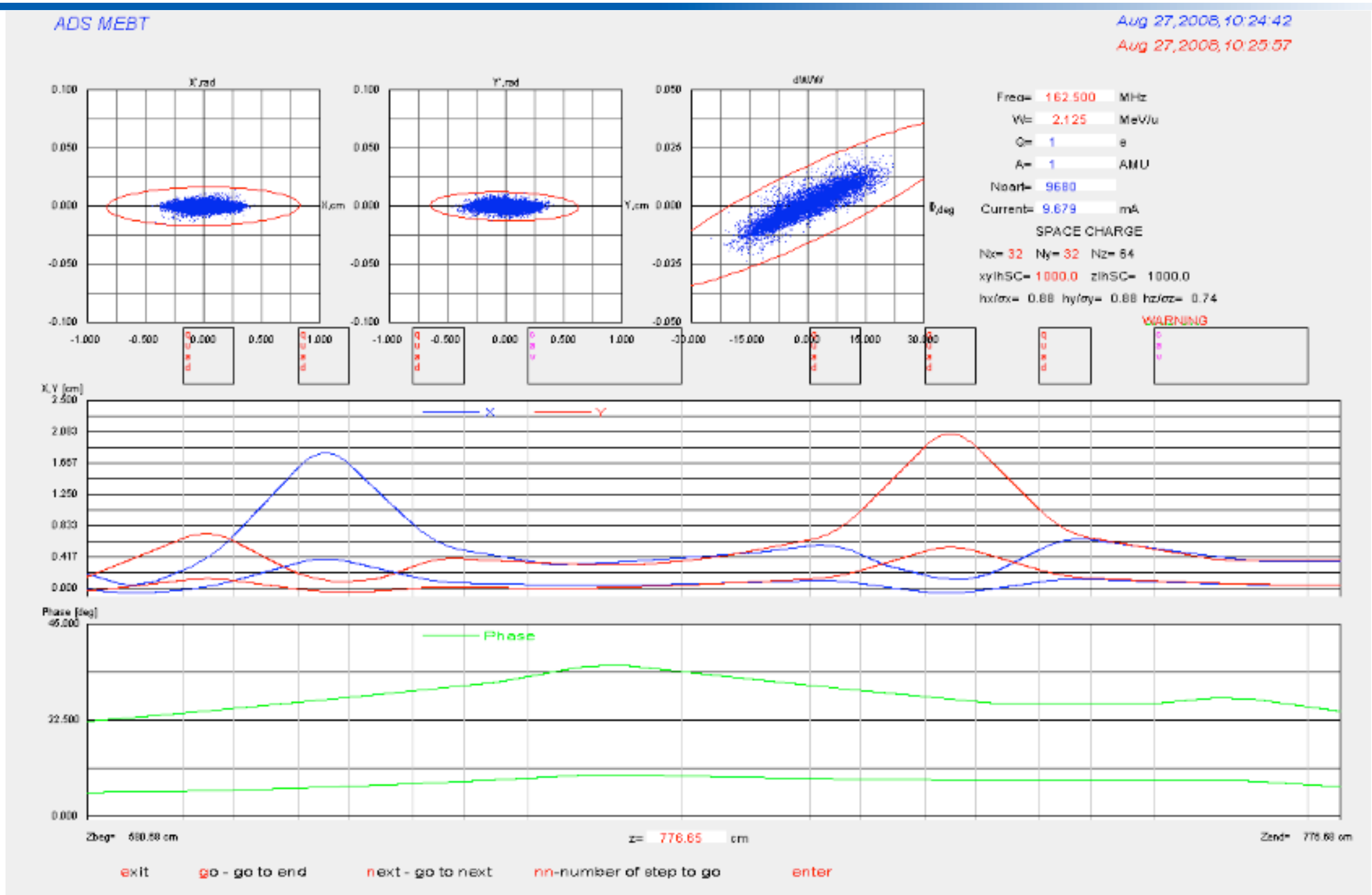


MEBT1 functions:

- matching between RFQ and HWR cavity
- diagnostics for beam parameters from upstream
- beam halo scraping (Not considered in this lattice yet)

Matching elements:	
Quadrupoles	6
Bunchers	2

Simulation of MEBT



- The output initial beam from RFQ is used to do the simulation. The lattice can realize longitudinal and transversal matching with 10 mA.
- It is a symmetric beam in transverse at the entrance of SC segment.

Design of SC segment

- Three designs base on two types of cavity
  - SARAF type (R&D by self)

    Ep=25MeV/m

    A1: SR(Main design)

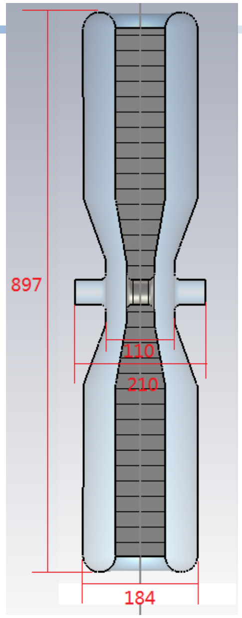
    A2: SRR
  - Taper type (collaborating with ANL)

    Ep=43MeV/m

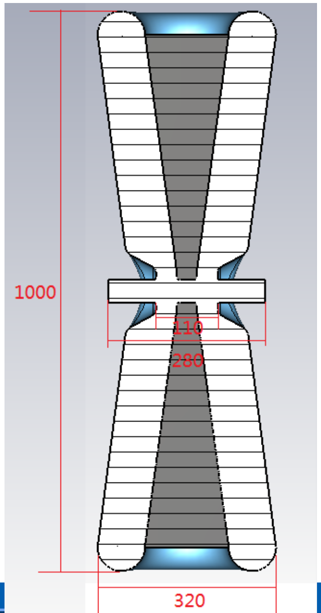
    B:SR

Performance of Cavities

Parameters	Self-developing		ANL-collaboration		Units
	Cavity A		Cavity B		
energy	1	4	1	12.6	Joule
frequency	162.5	-	162.5	-	MHz
β_G	0.09	-	0.09	-	-
β_{opt}	0.101	-	0.099	-	-
TTF_{opt}	0.824	-	0.812	-	-
E_{peak}	12.5	25	11.9	42.5	MV/m
B_{peak}	25.67	51.3	13.78	49.3	mT
U_0	0.48	-	0.52	-	MV
U_{acc}	0.395	0.79	0.42	1.5	MV
E_{acc}	2.21	4.42	2.3	8.2	MV/m
G	28	-	42	-	-
R/Q_0	153	-	177	-	-
B_{peak}/E_{acc}	11.6	-	5.17	-	mT/(MV/m)
E_{peak}/E_{acc}	5.6	-	5.74	-	mT/(MV/m)
loss	0.725	2.9	0.49	6.2	W



Cavity A

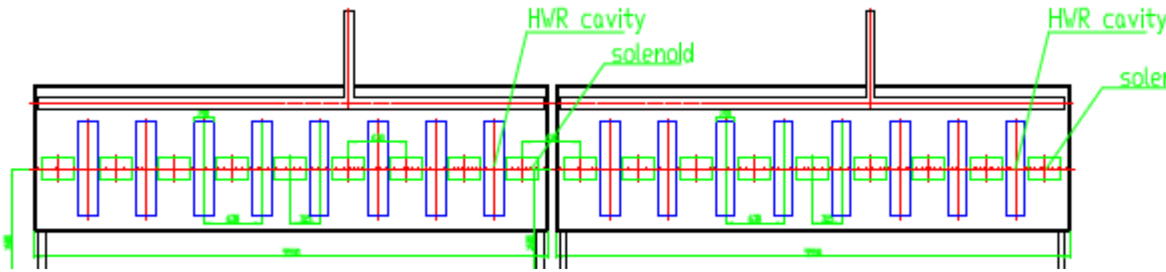


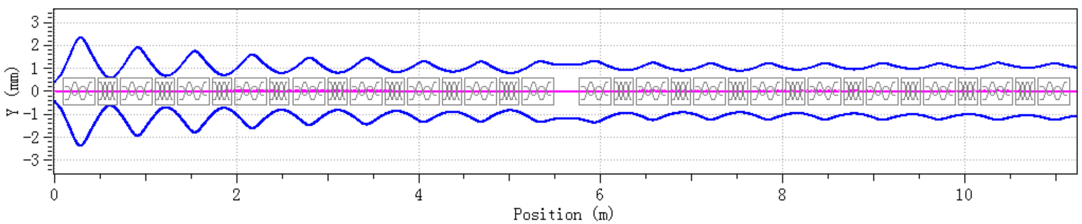
Cavity B

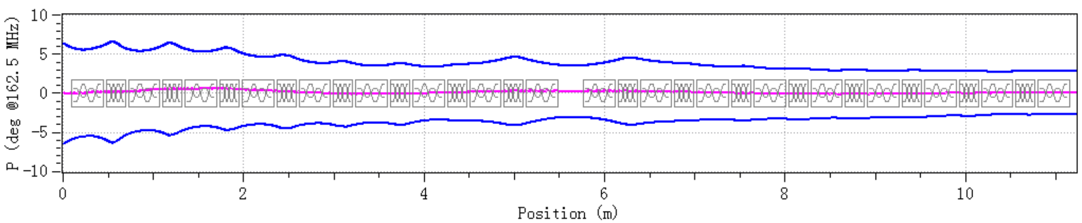
Initial conditions and tools for simulation

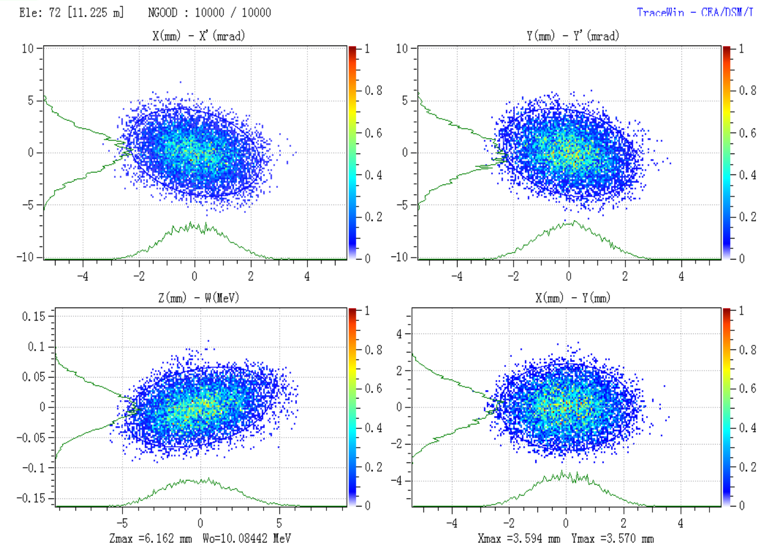
- The initial location of the simulation is from the end of MEBT
- The initial beam parameters are the output of RFQ as follows:
  - Emittance (normalized rms): $\varepsilon_x = \varepsilon_y = 0.25\pi \cdot mm \cdot mrad$ $\varepsilon_z = 0.42\pi \cdot mm \cdot mrad = 1.025\pi \cdot KeV \cdot ns = 77\pi\, KeV \cdot deg$(162.5MHz)
- The design and simulation code is TraceWin
  - The space charge is simulated by 2-D PIC subroutine in TraceWin code
  - The initial particle distribution is 3δ Gaussian distribution with 10000 particles
  - The elements cavity and solenoid are simulated with real field map got from CST and Opera3D
- End to end simulation code is Track

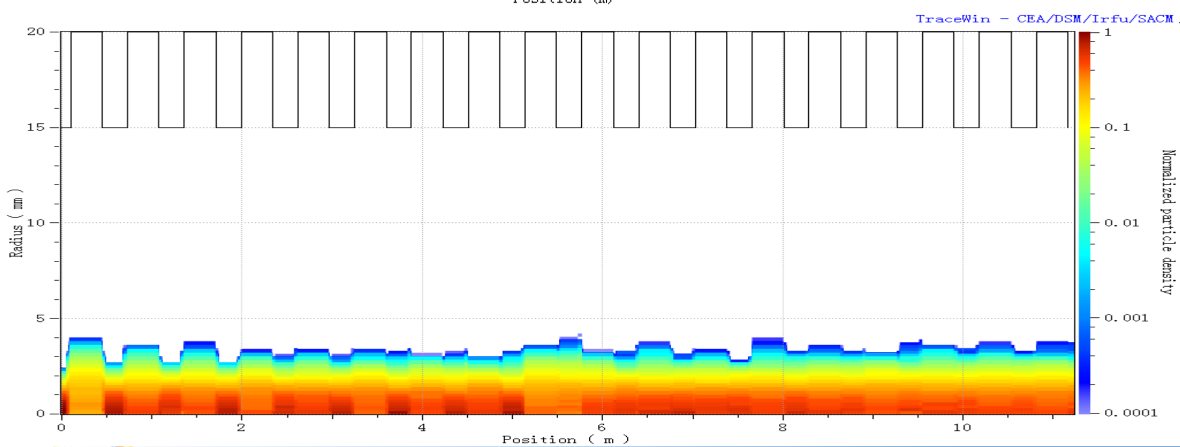
Option A1





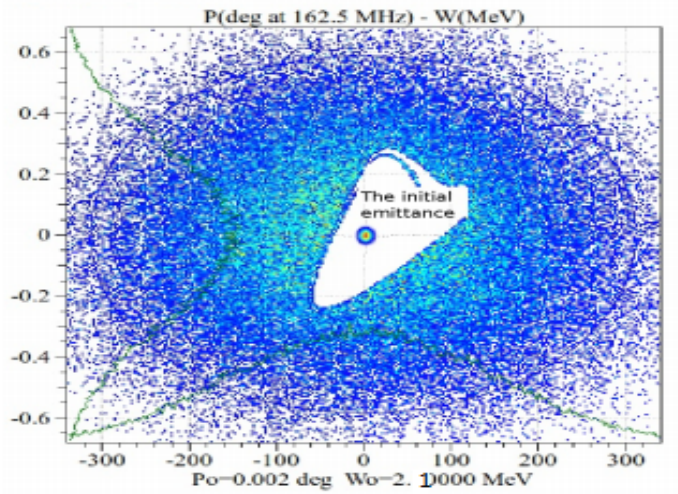




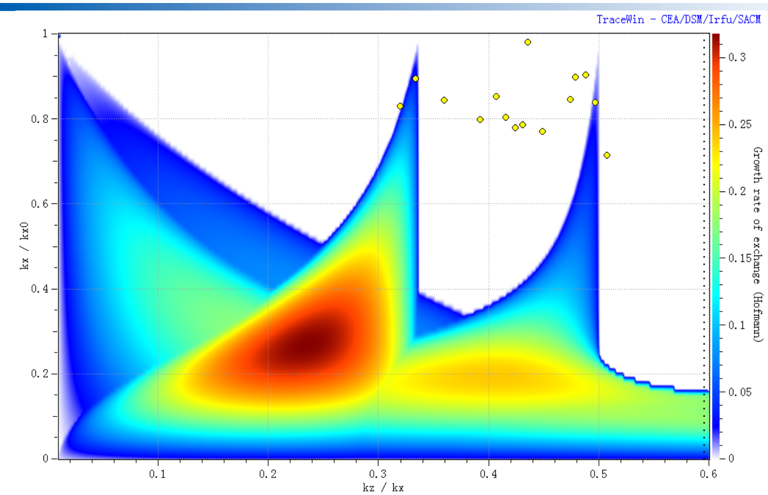


A continuous repetition lattice are used for the two CMs, a cavity is removed to separate. The neighbors of the removed cavity are used to do longitudinal matching.

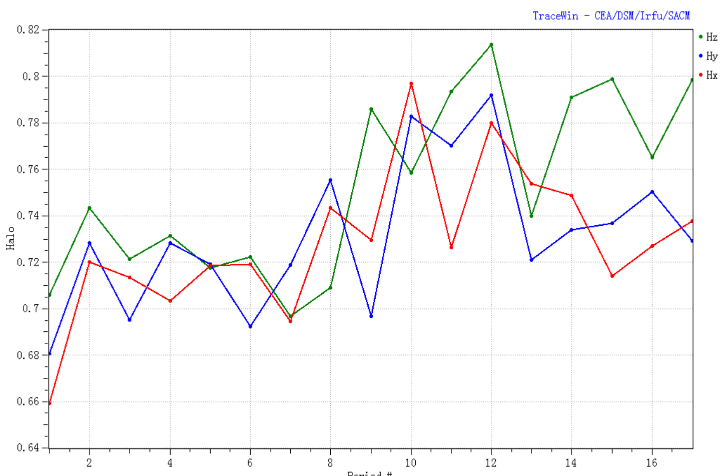
Option A1: Stability analysis



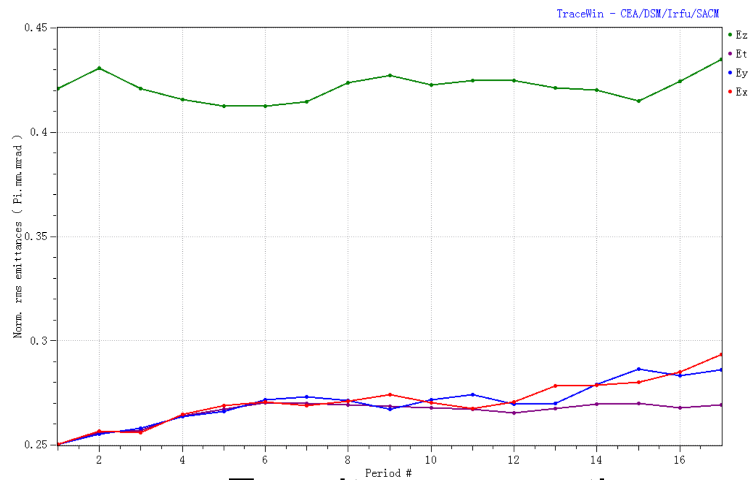
Longitudinal acceptance is 15 times of emmitance



Hofmann chart shows the working point is away from the oscillation area

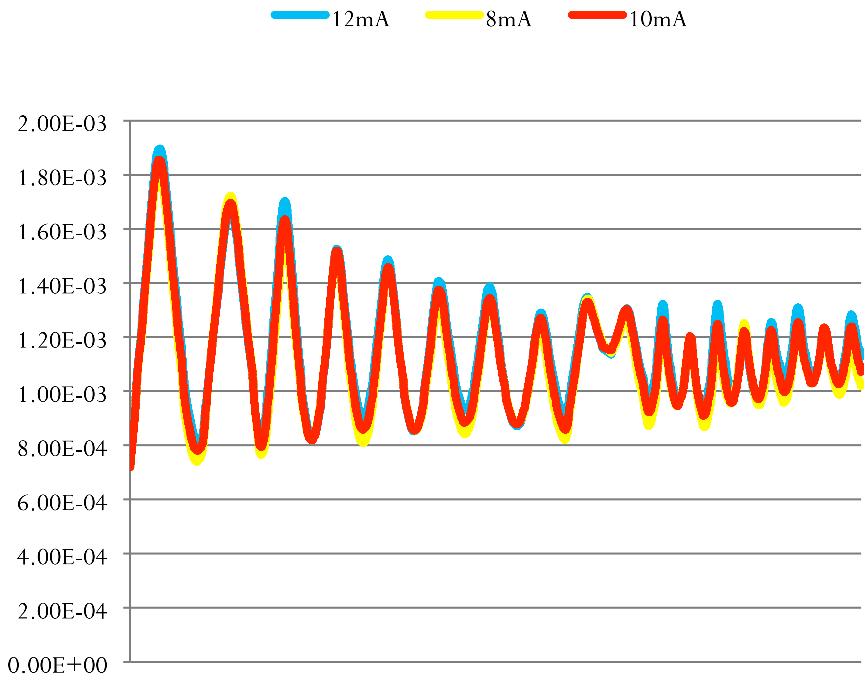


Beam halo parameter

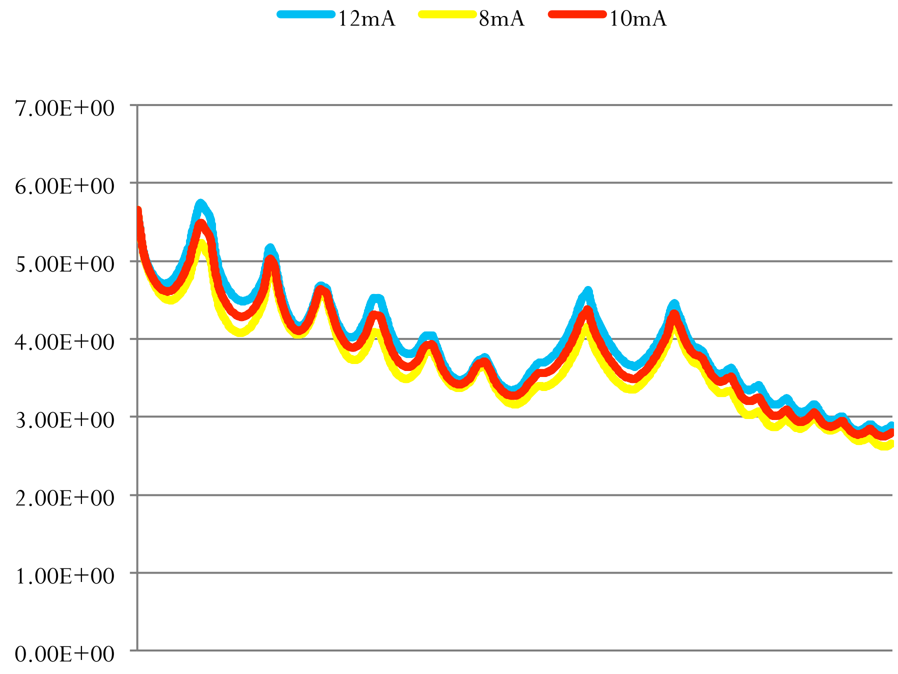


Emmitance growth

Option A1: space charge effect

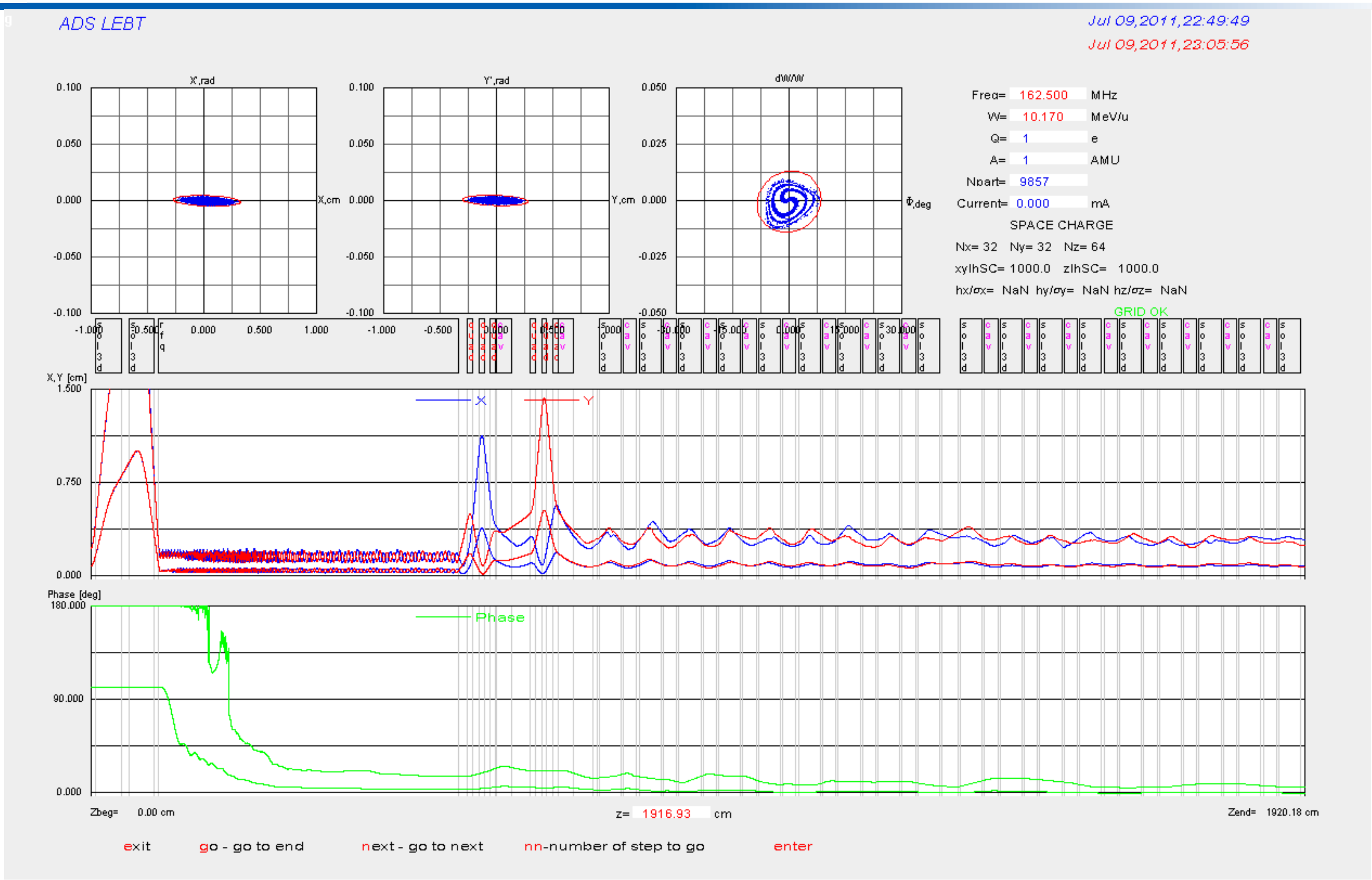


Transversal



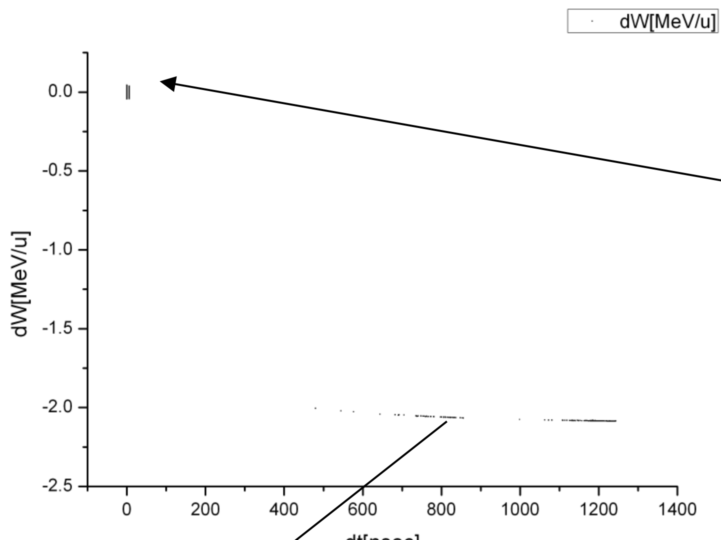
Longitudinal

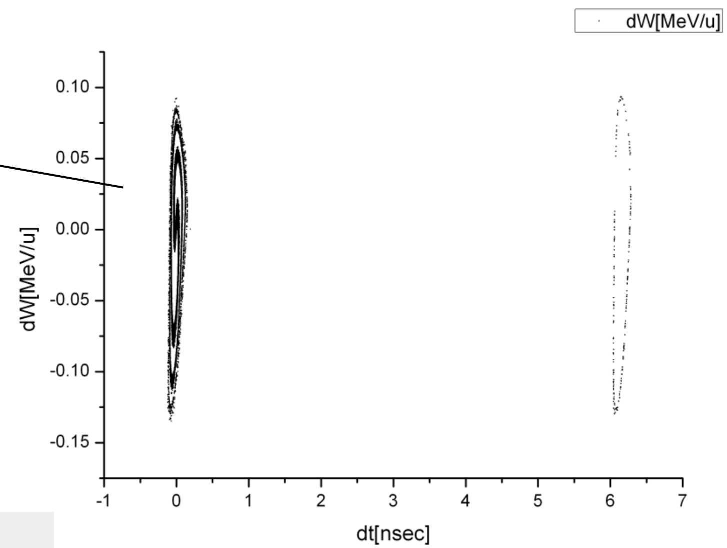
End to end simulation @ 0 mA

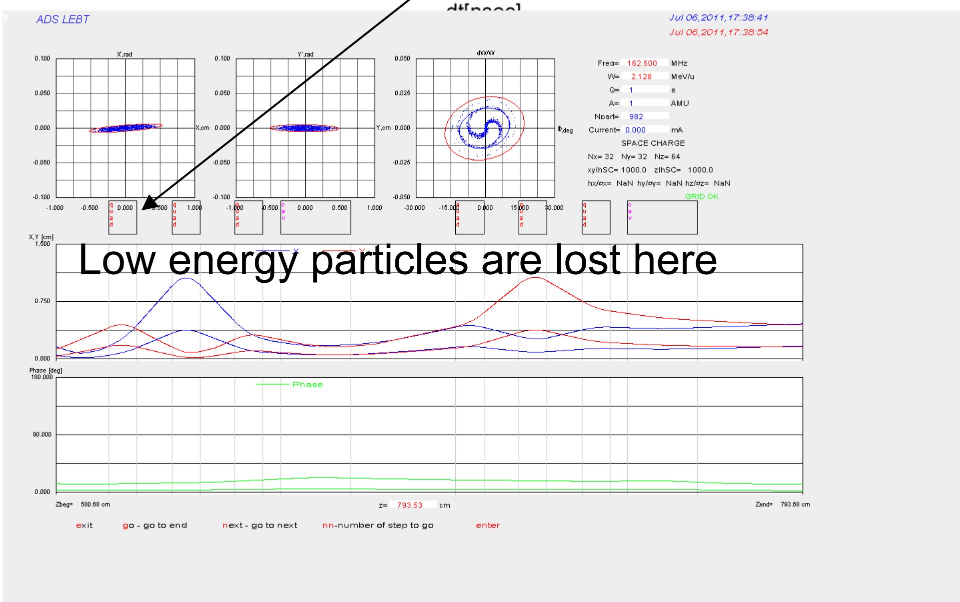


End to end simulation shows the matching between LEBT and RFQ, RFQ and SC segment are very well at 0 mA. The envelop keeps smooth and no oscillation.

MEBT transmit @ 0 mA





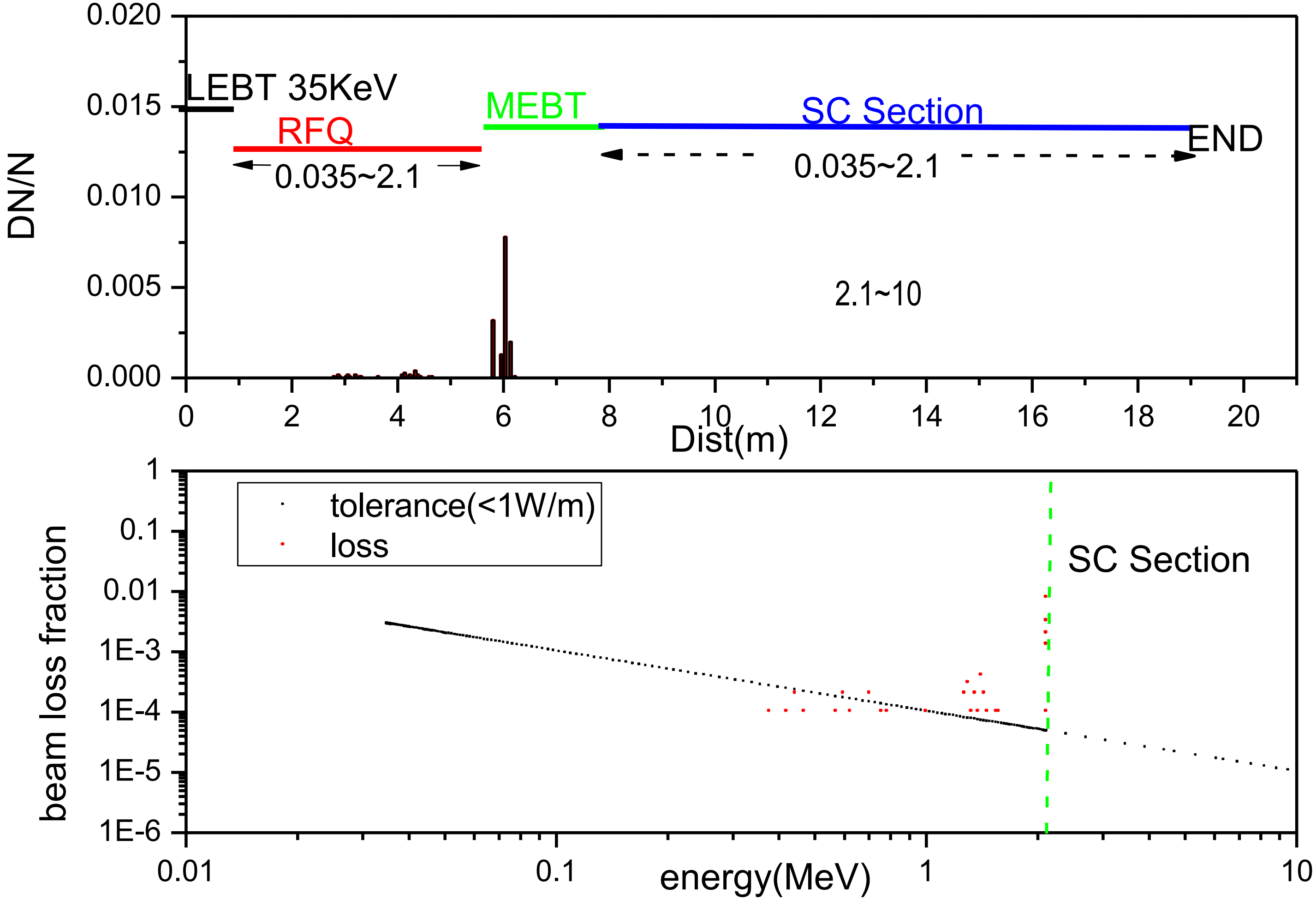


For 0-mA beam, the particle energy from RFQ is only in two regions.

The low energy particles are mostly lost at the first quadrupole.

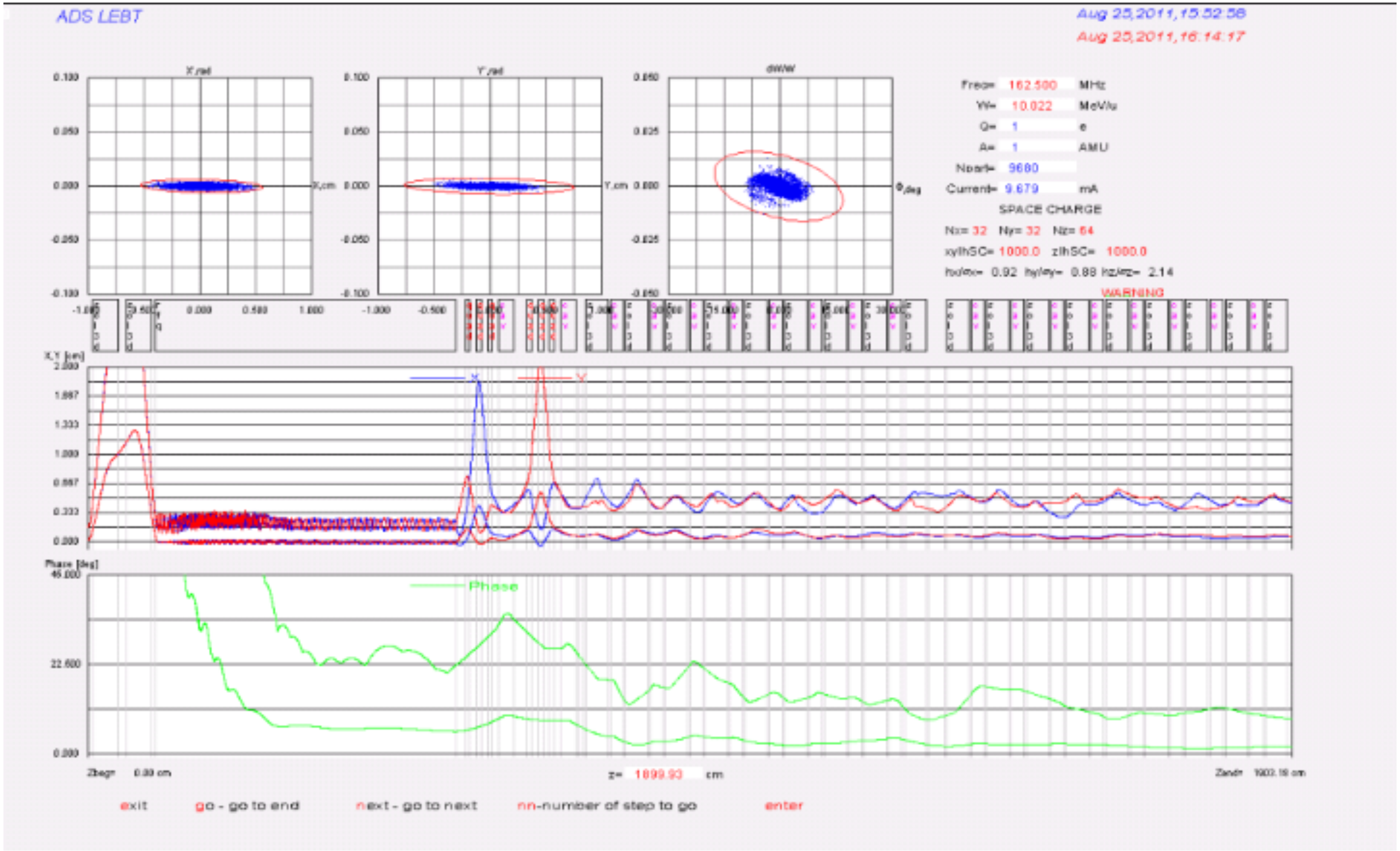
So the rest particles are fully accelerated and there will be no particle loss at the superconducting cavities up to 10MeV.

Beam loss analysis @ 0 mA



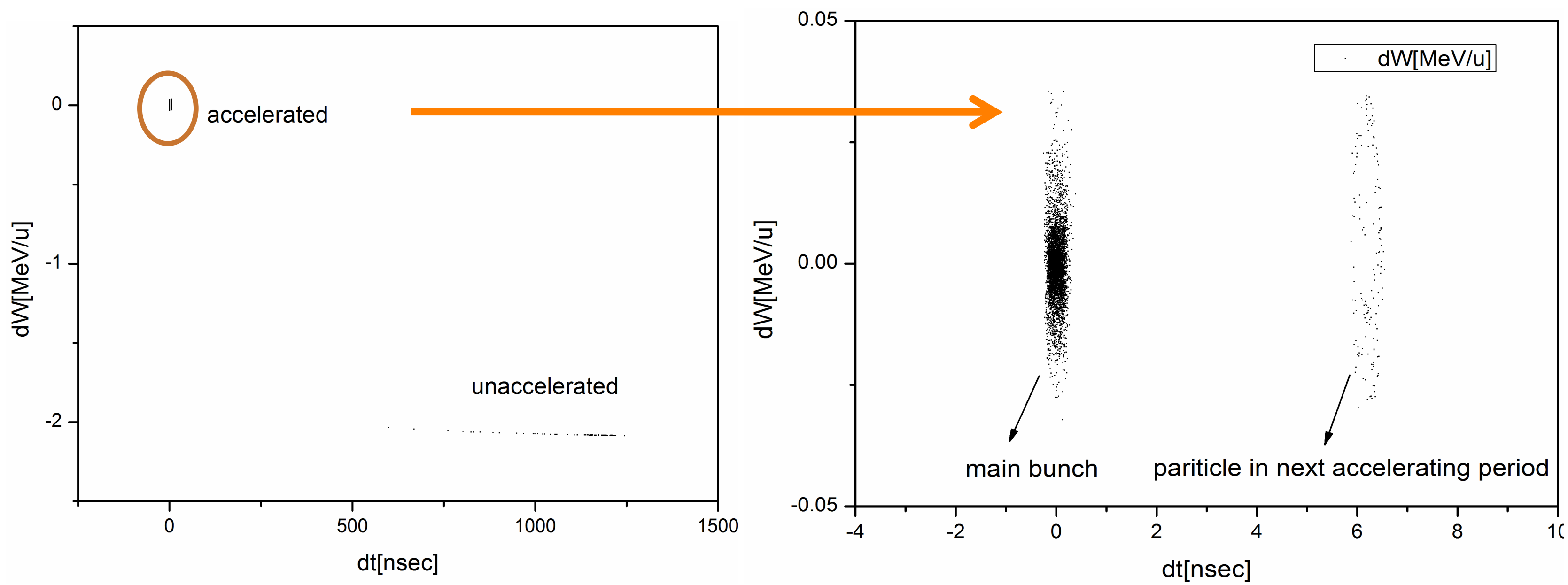
Beam loss happens in RFQ and the first quodruple of MEBT. No beam loss happens in SC segment.

End to end simulation @ 10 mA



When the beam is 10 mA, mismatch between LEBT and RFQ exists. Oscillation is observed in gentle bunch section. Non-symmetric beam out from RFQ causes coupling in SC segment.

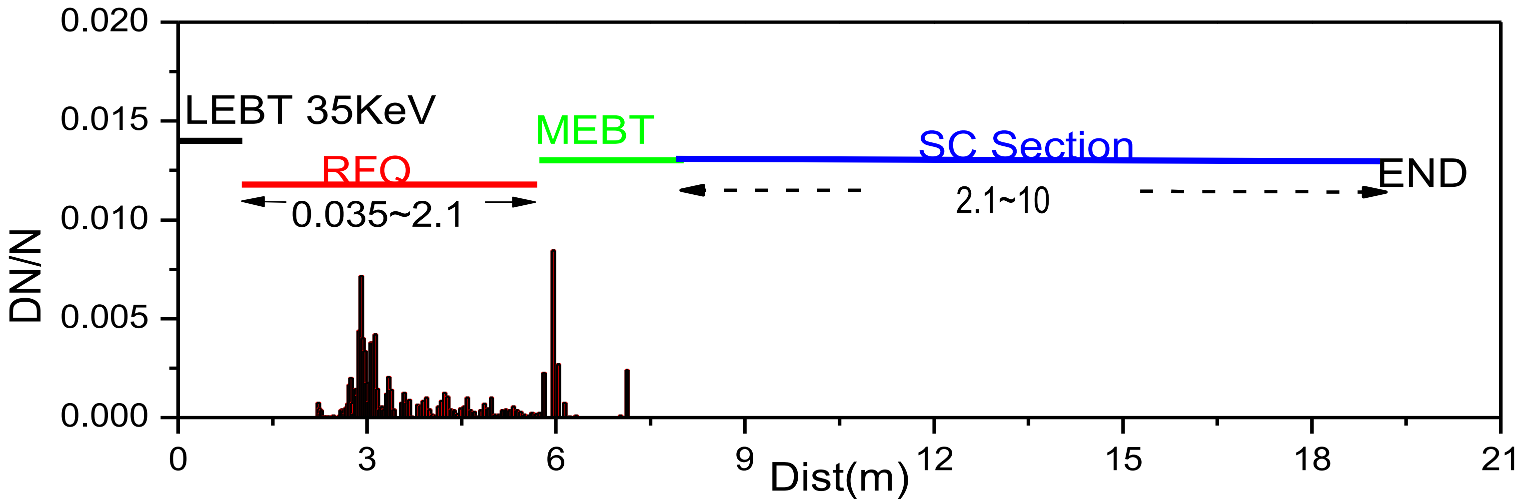
MEBT transmit @10mA

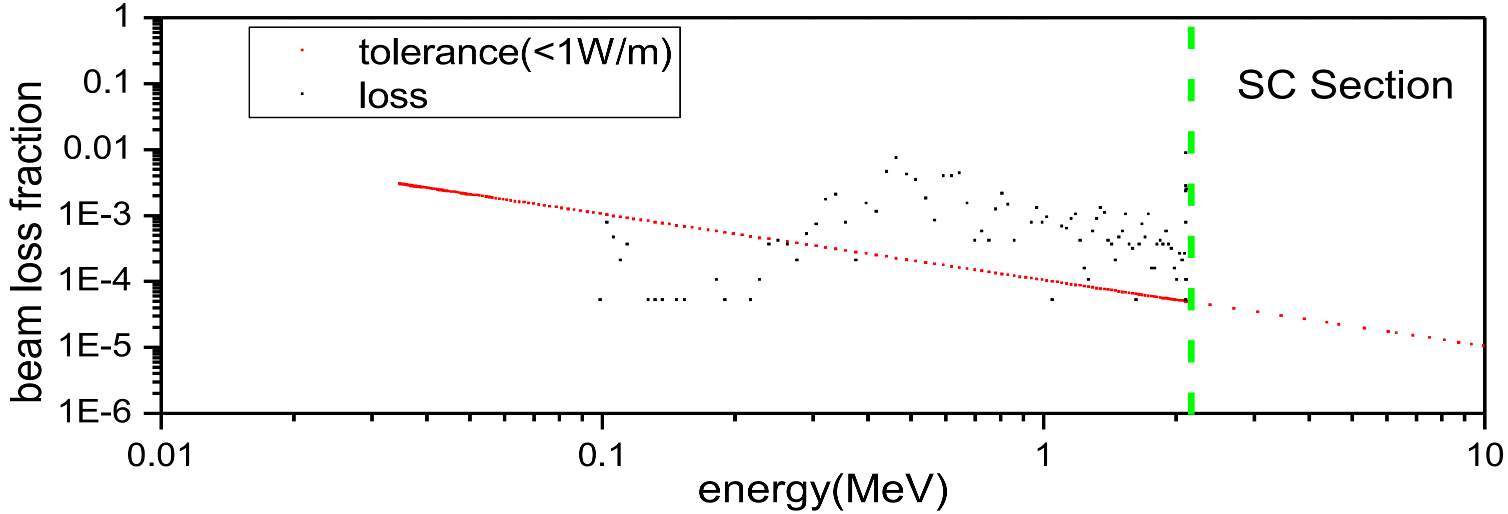


Alphax	Betax(cm/rad)	Alphay	betay(cm/rad)
1.74532	17.76	-1.2725	11.09

Particles which are not accelerated lose in RFQ, the energy of these particles is about 50~100KeV, The transmission of the whole line is 92.6%.

Beam loss analysis @ 10 mA



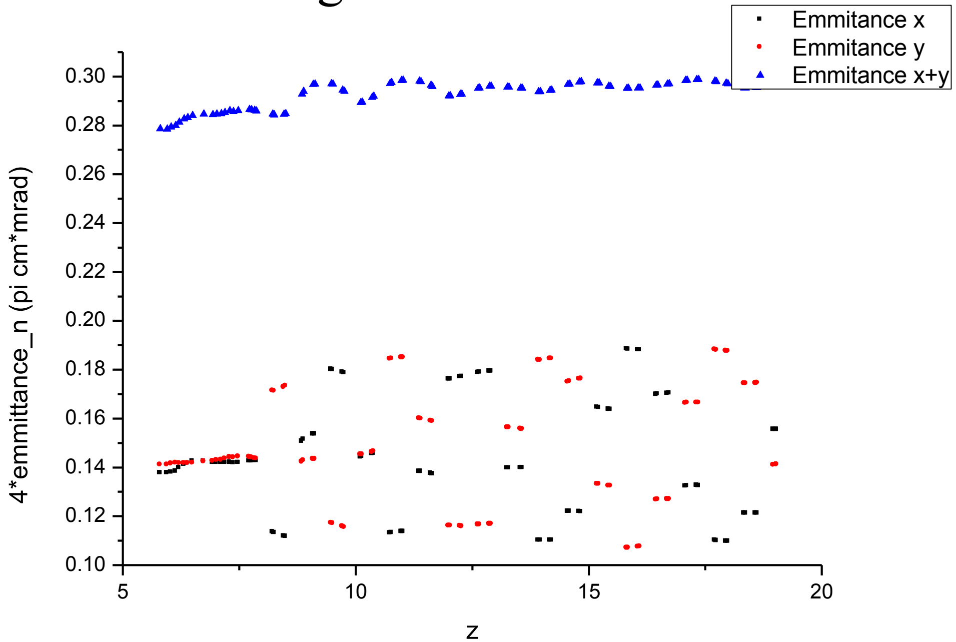


Beam loss happens in RFQ and the first quodruple of MEBT. No beam loss happens in SC segment.

Emittance growth from end to end

Emmittance exchanges between X and Y plane in solenoids

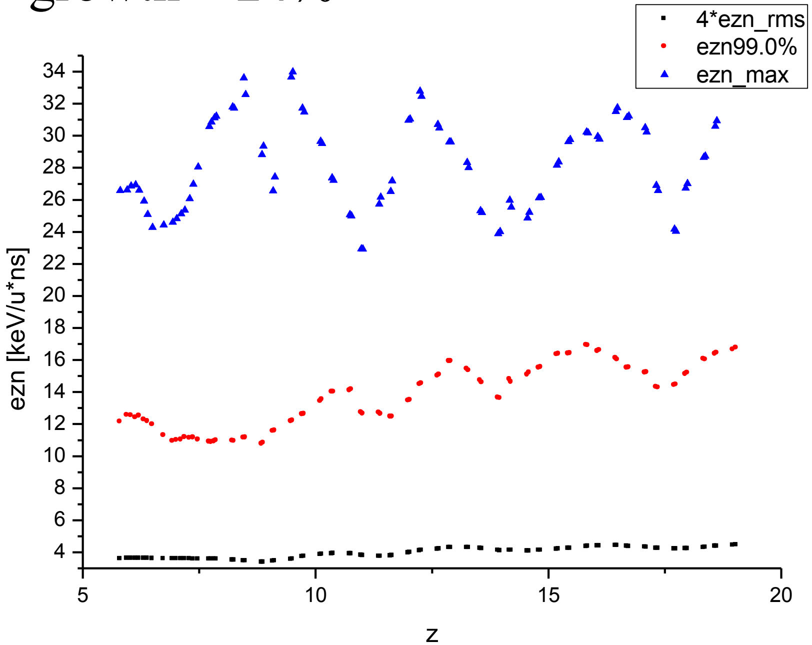
transverse (x+y) normalized rms emmittance growth = 6.5%



The emittance in X and Y direction along RFQ +MEBT1+SC section

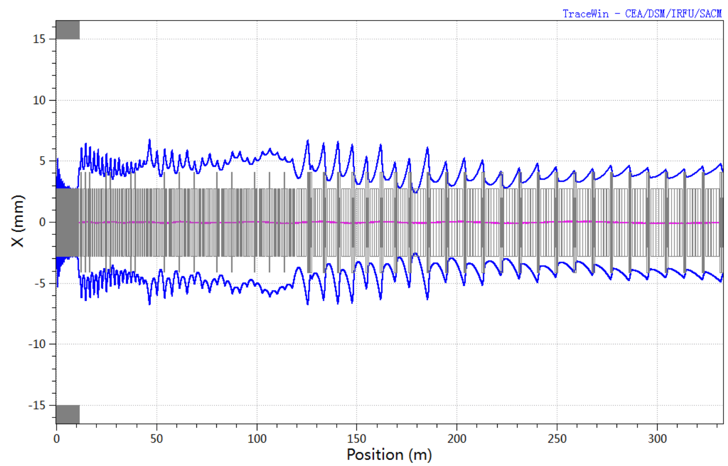
Longitudinal Emmittance growth due to filamentation, (large longitudinal emmitance from RFQ)

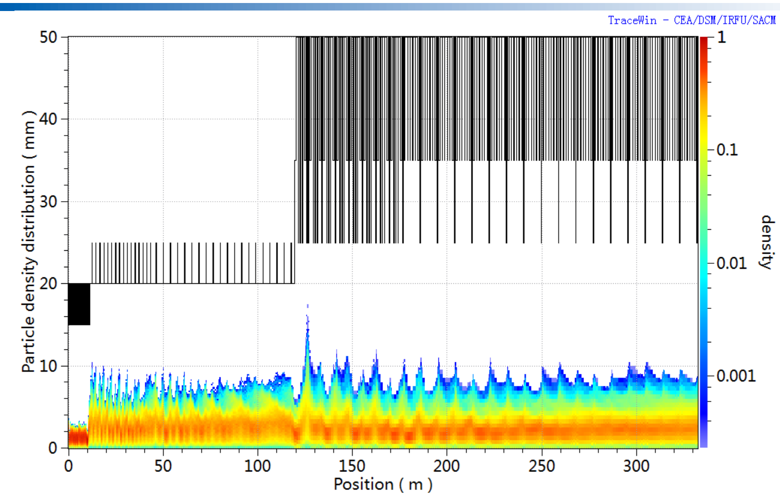
Logitidunal (z) rms emmittance growth = 24%

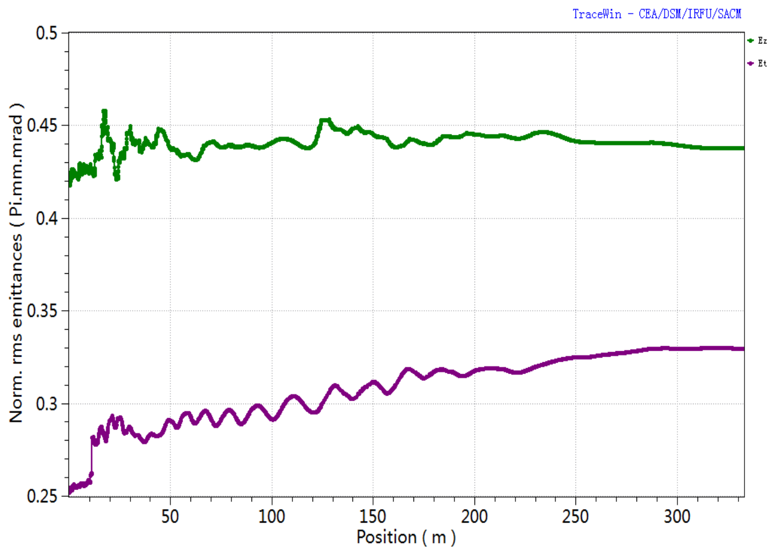


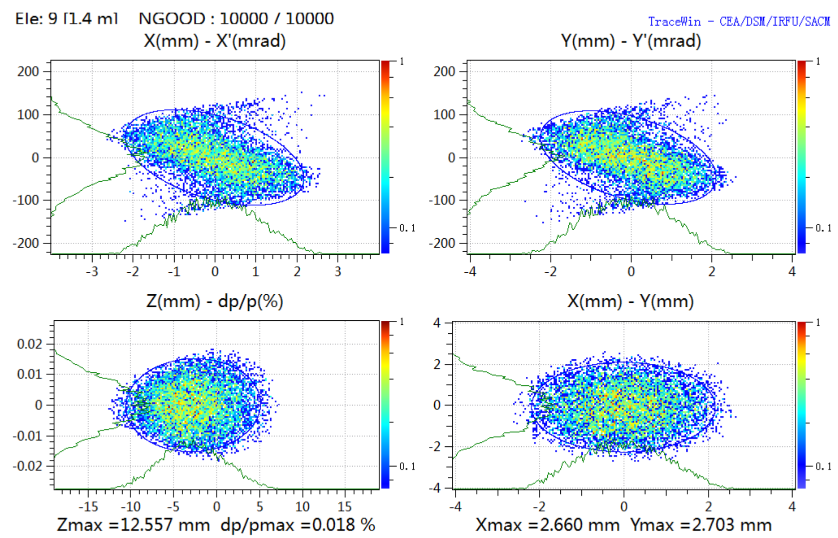
The emittance in Longitudinal along RFQ +MEBT1+SC section

End to end simulation 2.1MeV - 1.5GeV



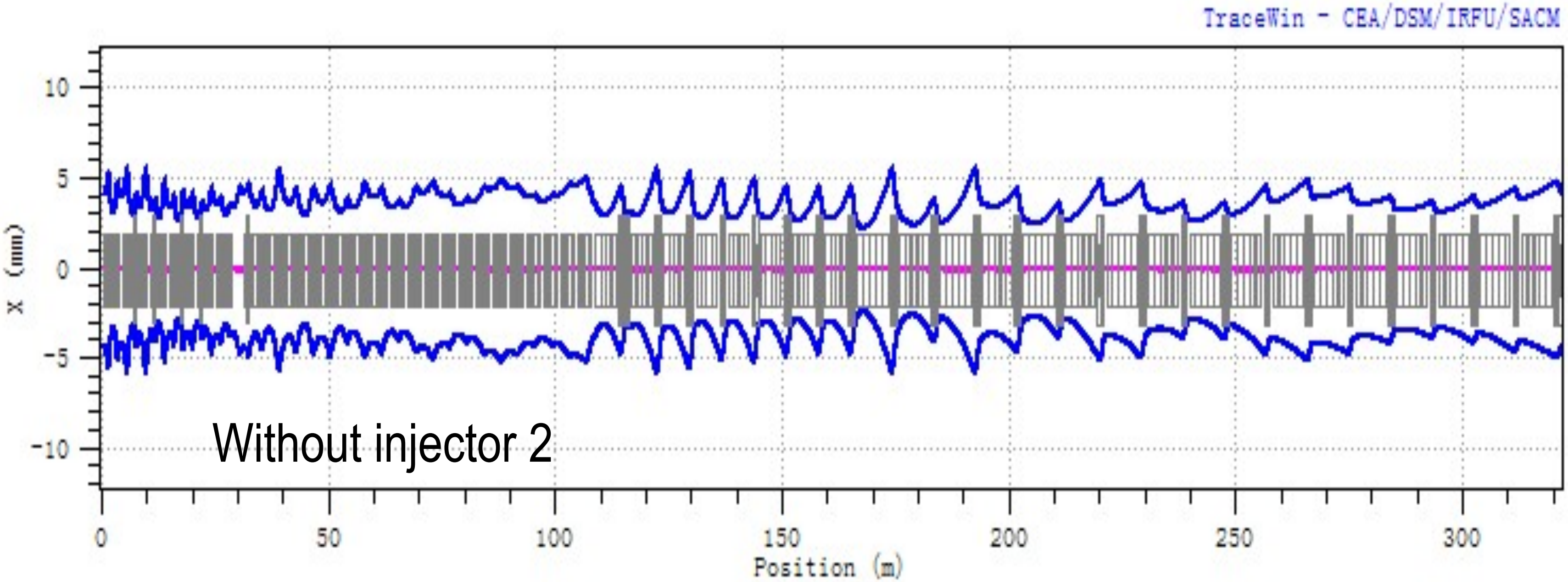


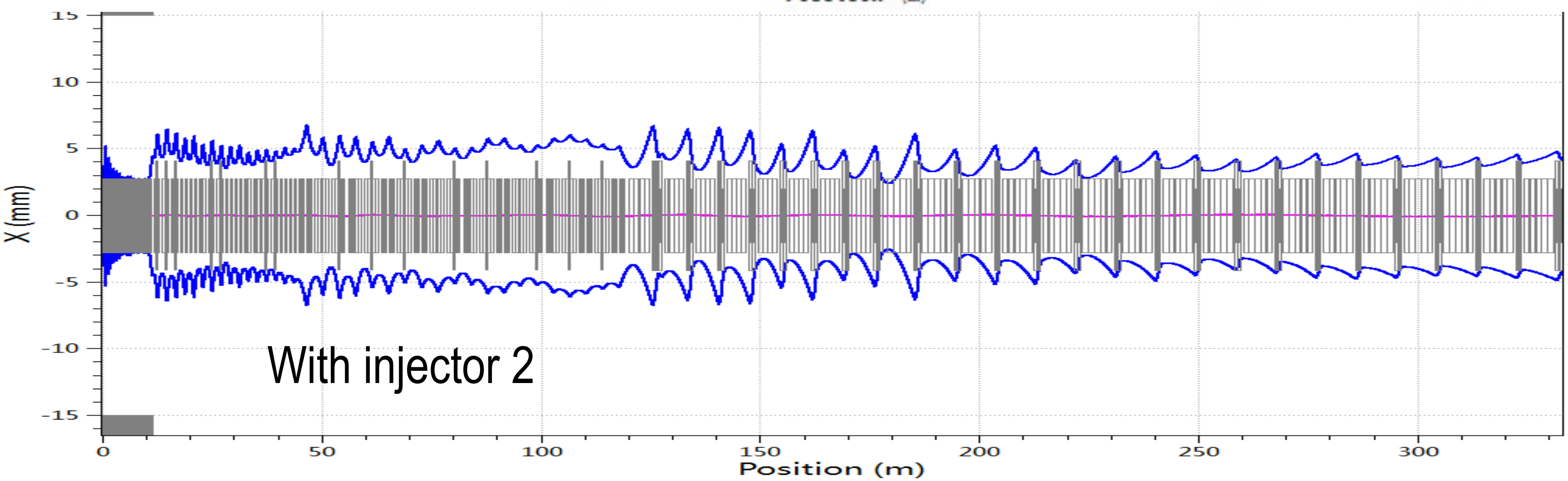




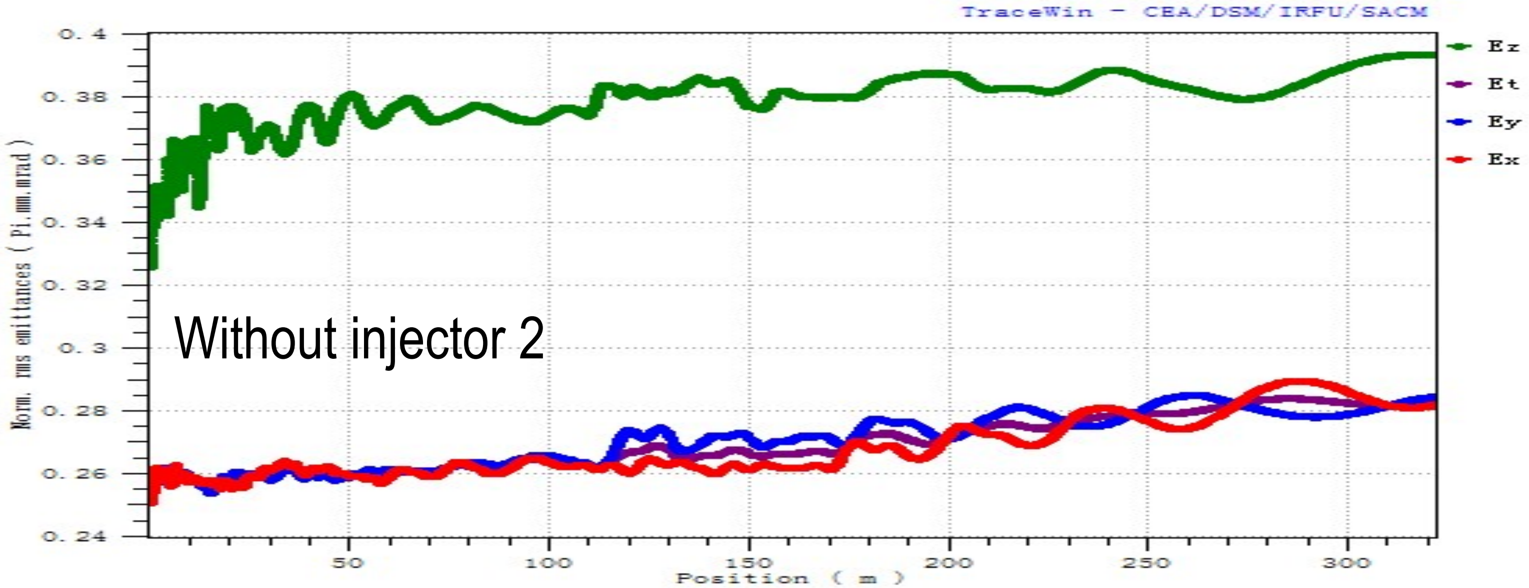
MEBT2 is not including in the simulation model. The goal is to investigate if the frequency jump cause no matching.

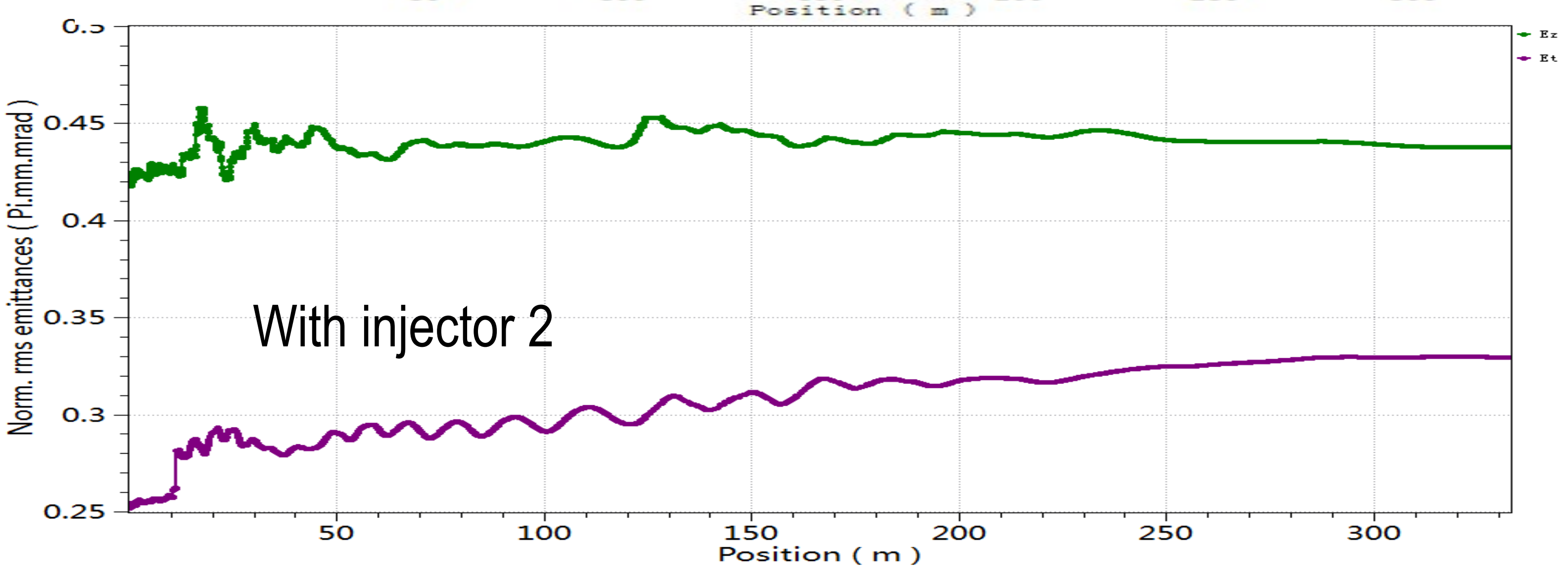
Envelop comparison



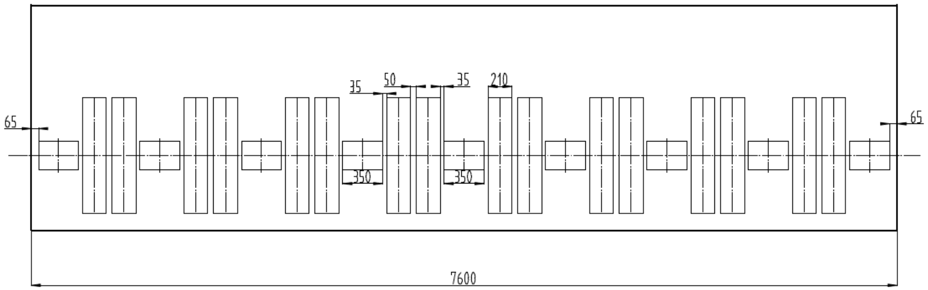


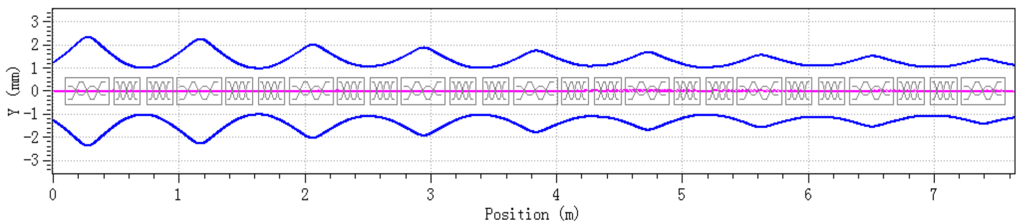
Emittance growth comparison

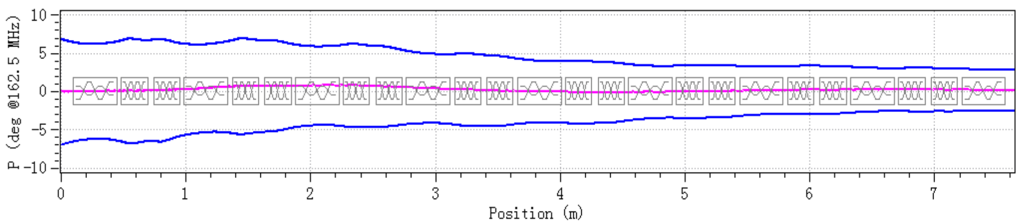


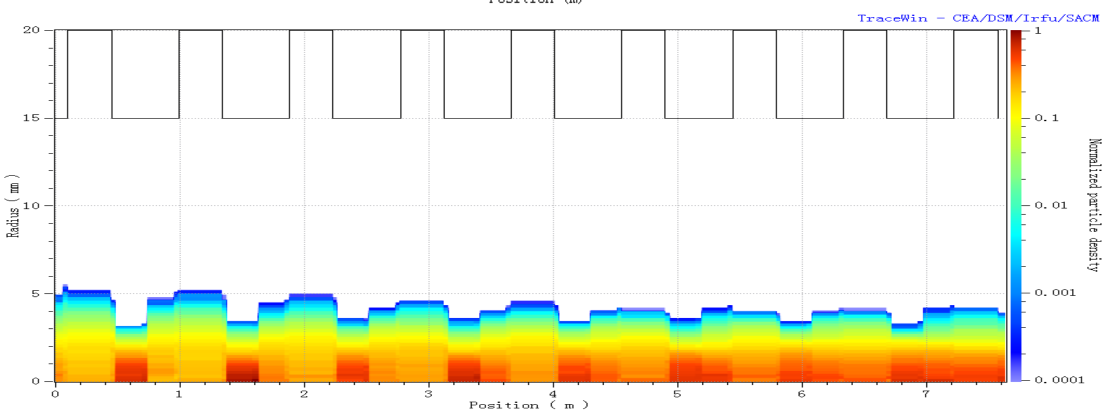


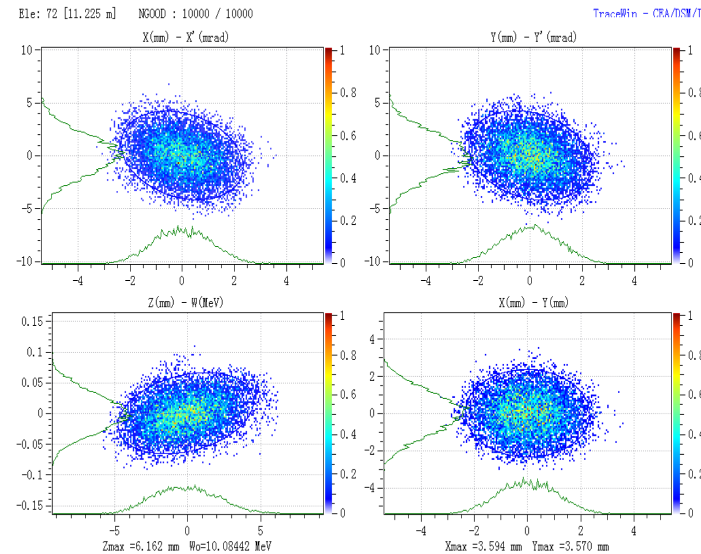
Option A2











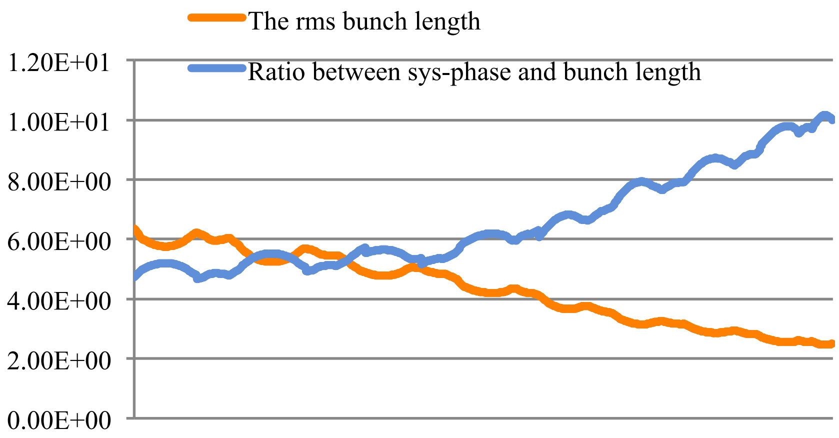
For the low frequency adopted, there is less RF defocusing force in transverse. So the SRR design as an alternative design has been done.

There are some advantages :

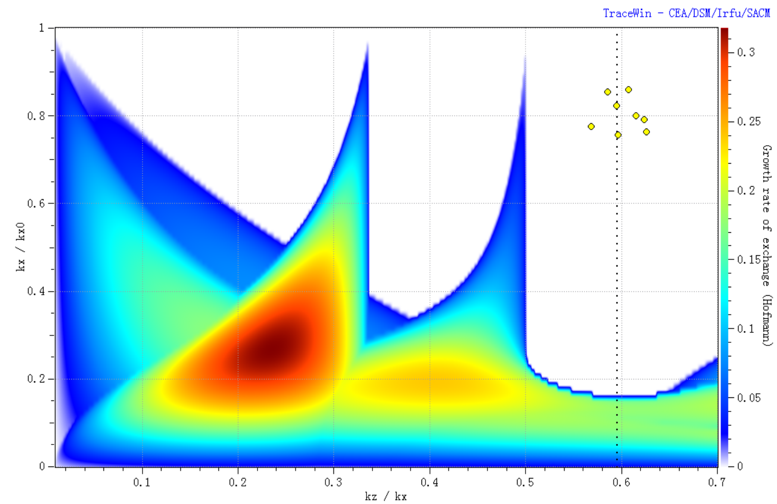
reduce the length to reduce the space charge effect;

No emittance growth from break of focusing period.

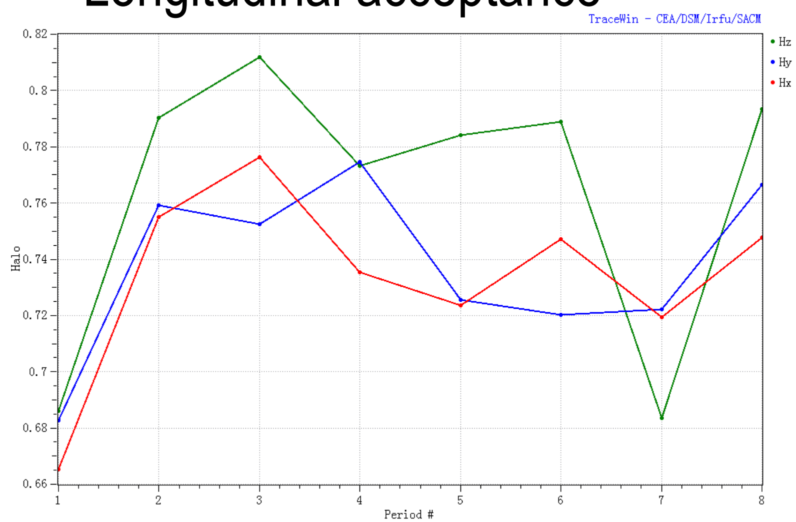
Option A2: stability analysis



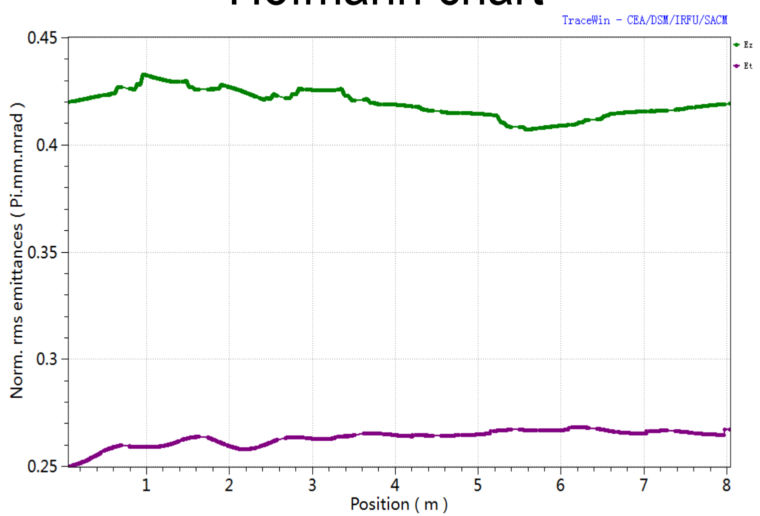
Longitudinal acceptance



Hofmann chart

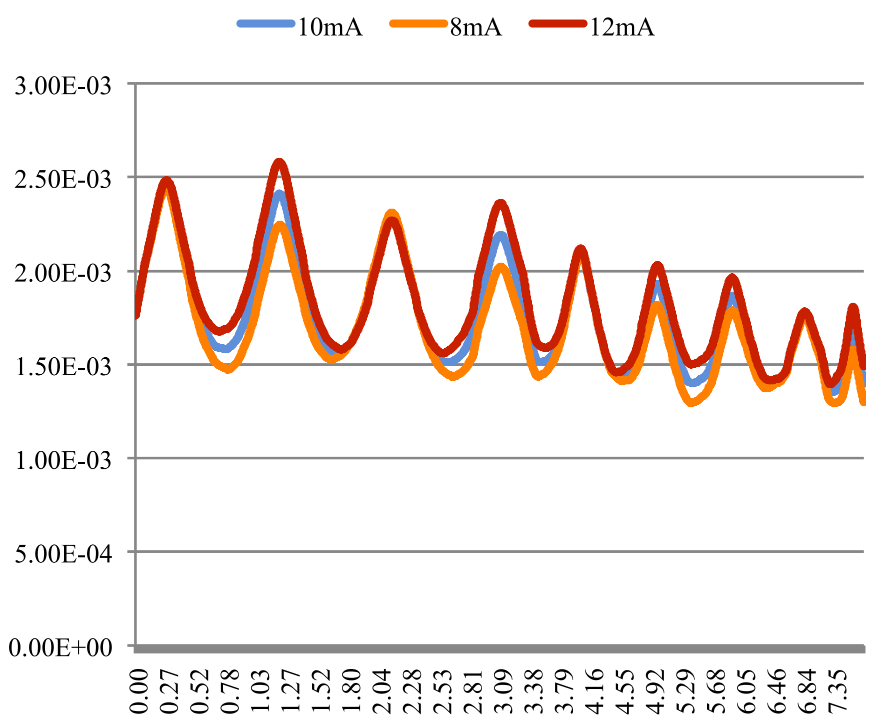


Beam halo parameter

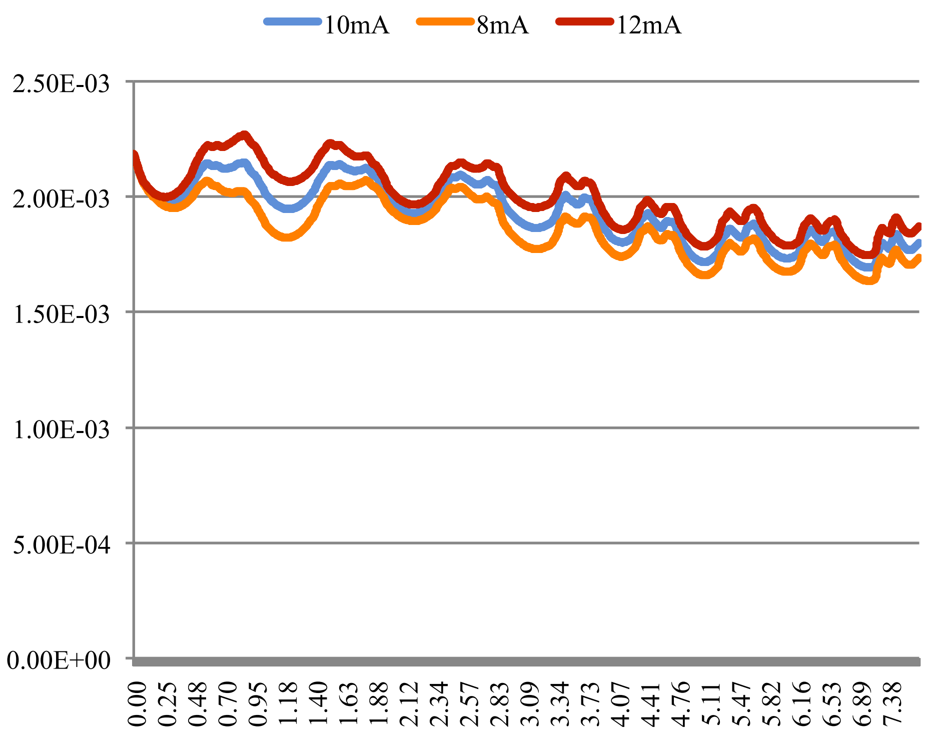


Emmitance growth

Option A2: space charge effect

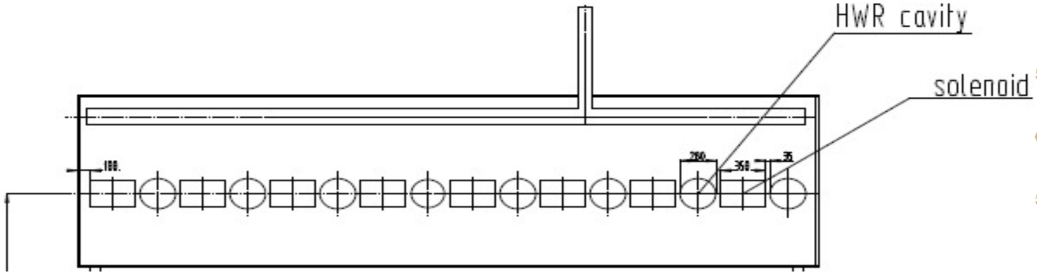


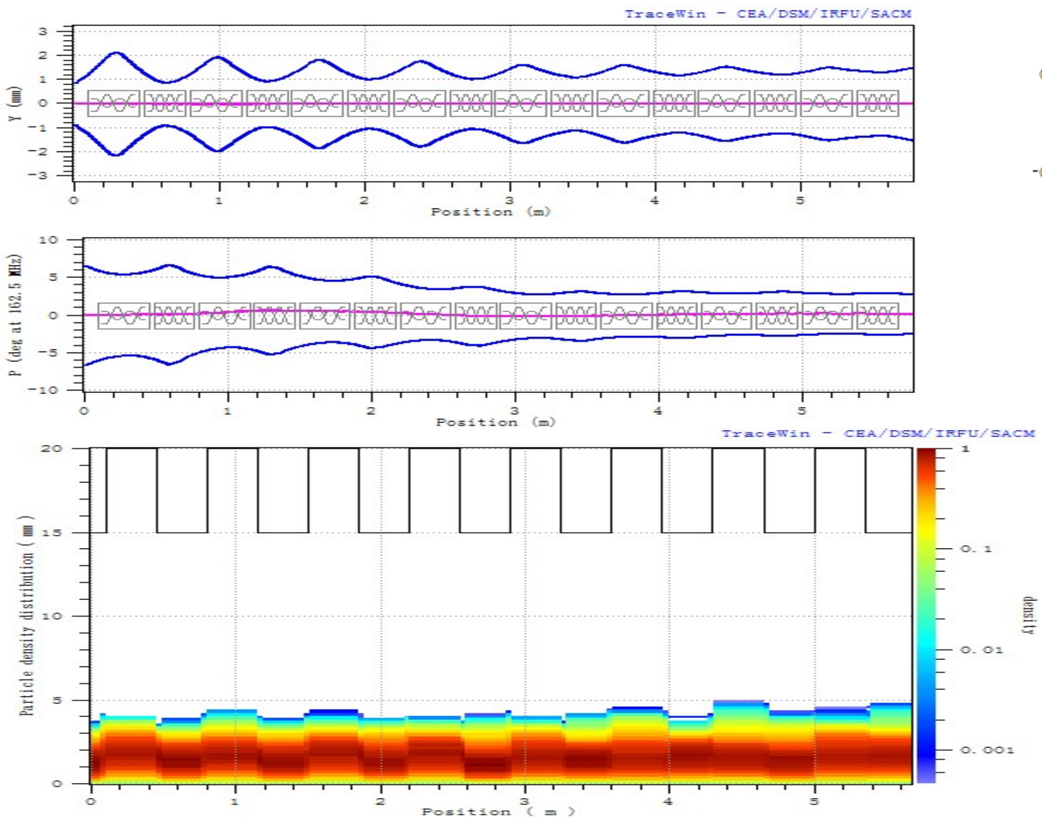
Transversal

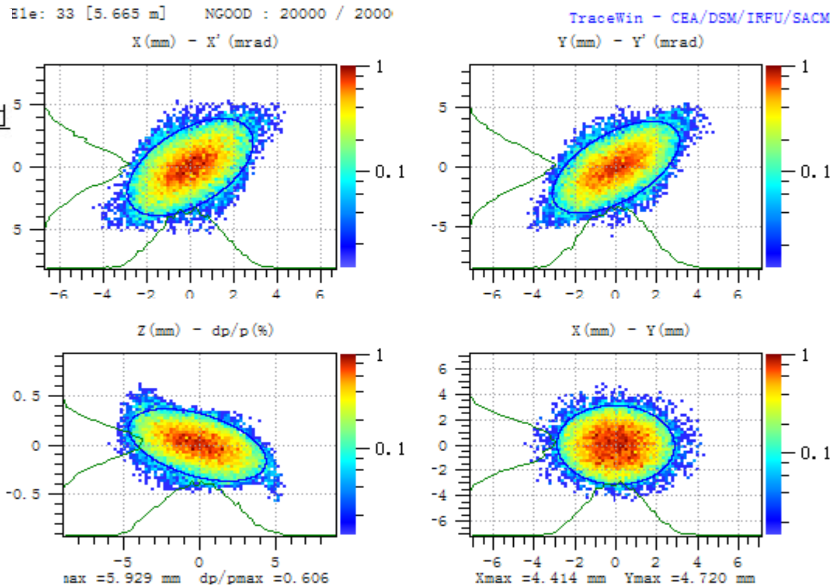


Longitudinal

Option B



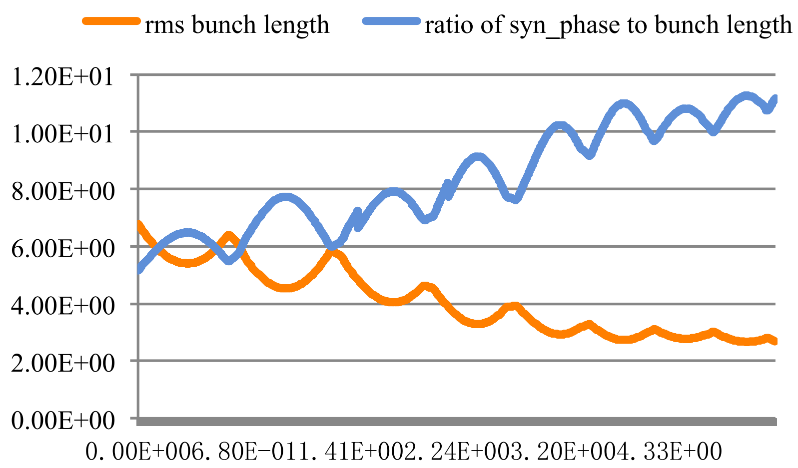




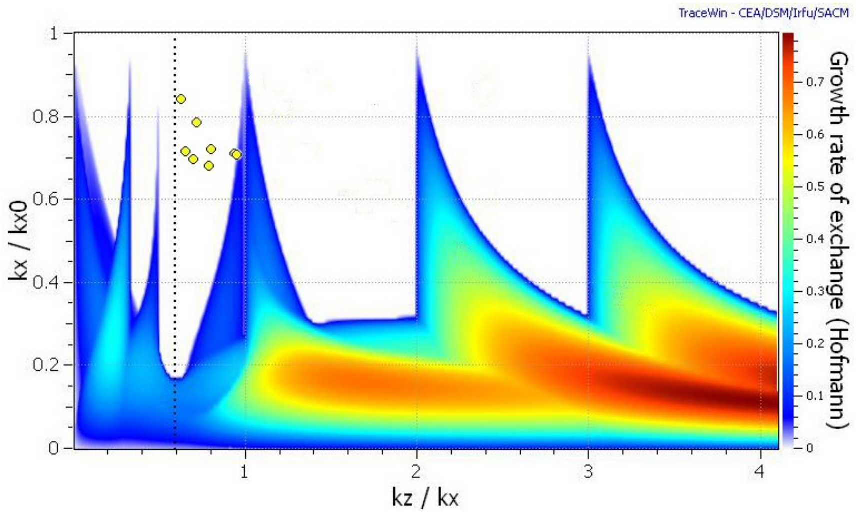
advantages :

1. reduce the length of the cryomodule;
2. No emittance growth led by transition section;
3. reduce number of cavities and solenoids
4. To make assembly of CM easier

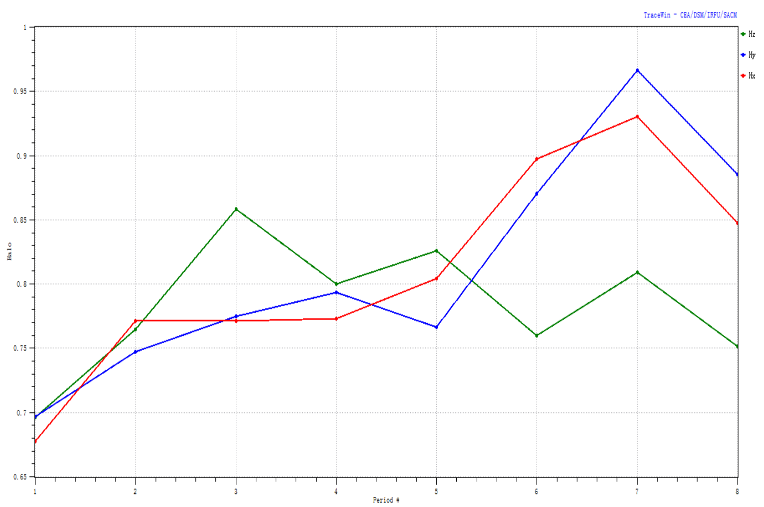
Option B: stability analysis



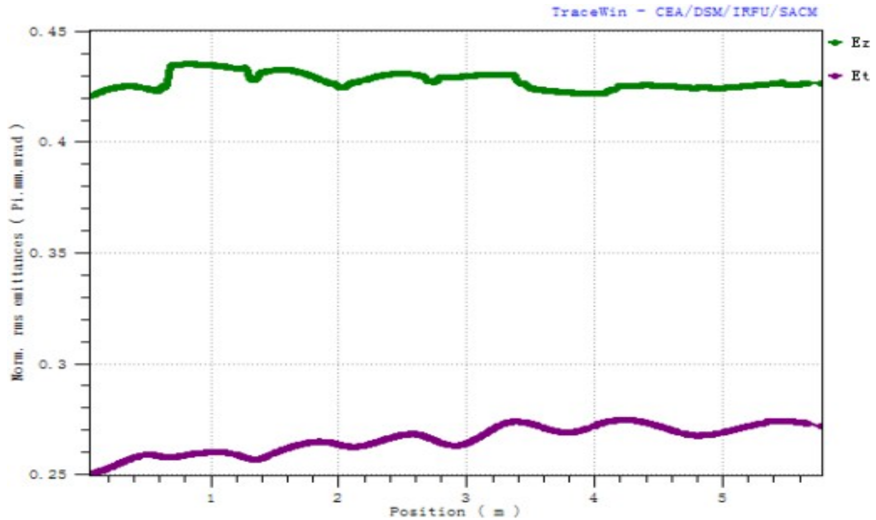
Longitudinal acceptance



Hofmann chart

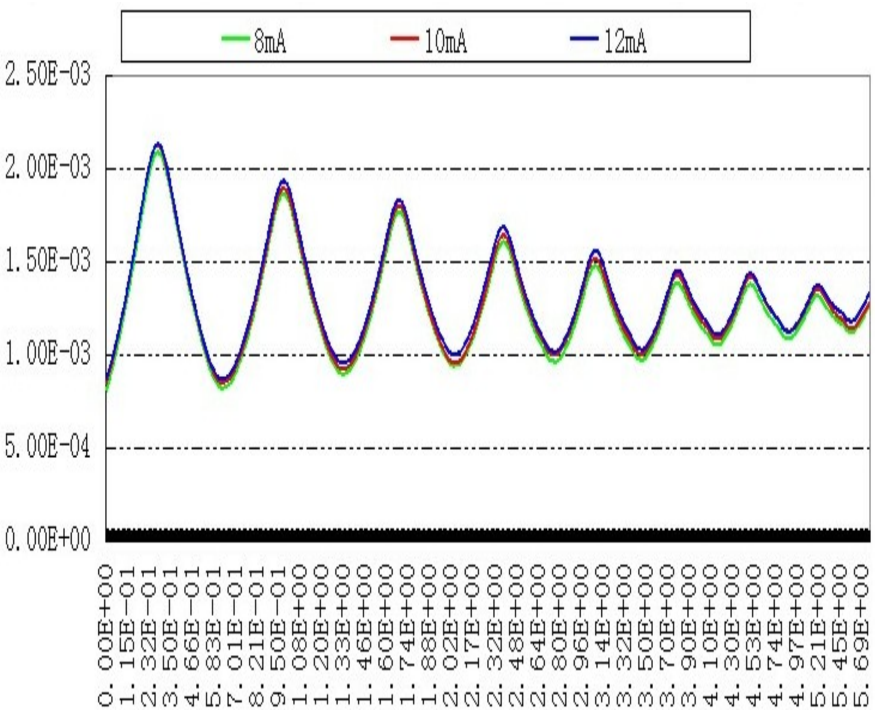


Beam halo parameter

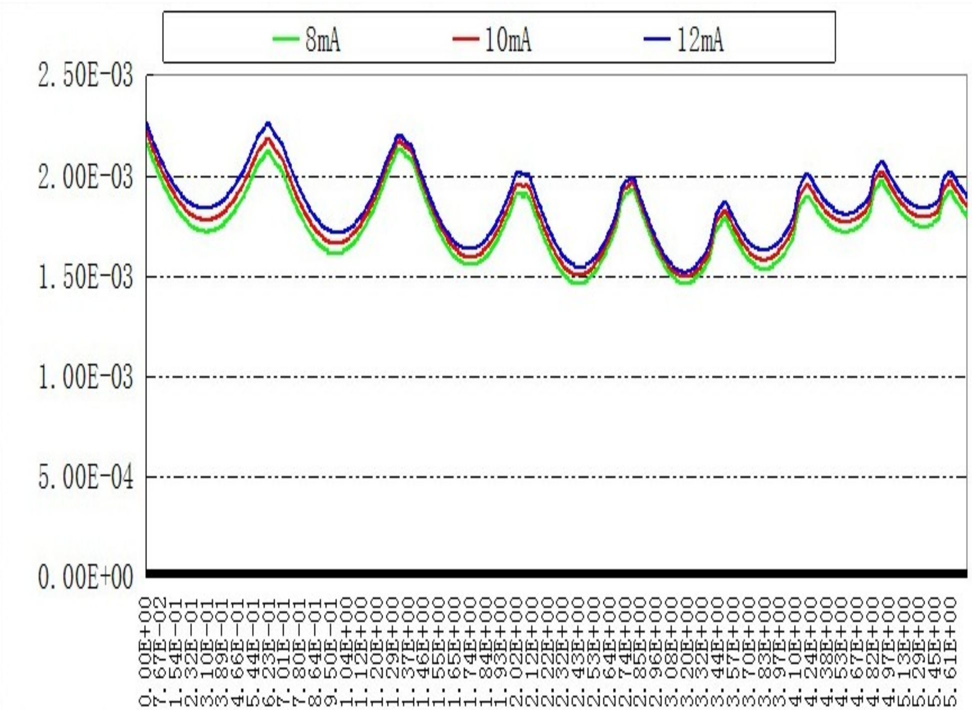


Emmitance growth

Option B: space charge effect



Transversal



Longitudinal

Options of SC segment

	Option A1	Option A2	Option B	
Length of cell	630	940	700	mm
Number of cell	16	6	8	
Number of cavities	16	16	8	
Number of solenoids	18	9	8	
Focusing period	SR	SRR	SR	
Total length	11.2	7.6	5.765	m
Cryomodules	2	1	1	
Emittance growth (rms)	3.2(t)/2.0(l)	6.0(t)/0.3(l)	9.0(t)/1.3(l)	%

Superconducting Solenoids

Number	**18**	
Max field	7	T
Leff	150	mm
L install	<280	mm
Leak field	<2.5	μT
Steering magnets	Double director	
Steering field	0.1	T
Aperture	40	mm

Power supply for sc-solenoid

Main coil		
number	18	
voltage	+/-5	V
current	205	A
stability	<0.01	%
Steering coils		
number	18*2	
voltage	+/-5	V
current	75	A
stability	<0.01	%

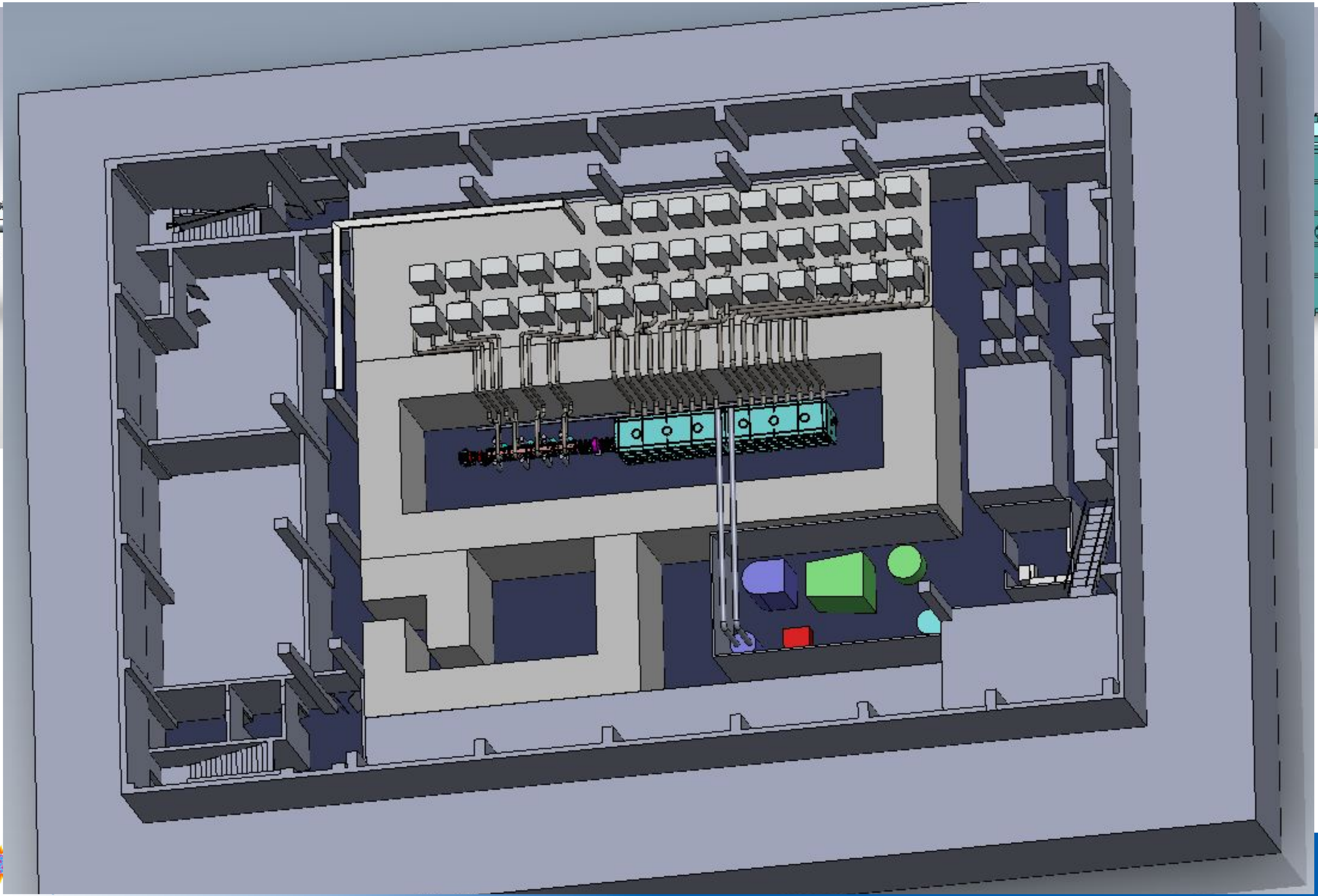
Diagnostics

	Numbers	Notes
Button BPM	18	Operation T < 4 K
Stripe line BPM	6	MEBT1 (in Quads)
Beam profile monitor	3	Wire scanner
Beam current monitor	2	MEBT 1,2 (ACCT or FCT)
Beam halo monitor	3	MEBT1 (with wire scanner)
Emmittance monitor	1	MEBT1
Beam scrapper	TBD	MEBT1
Beam stop	1	END
ACCT	1	LEBT

Vacuum

LEBT		
static	7e-5	Pa
dynamic	3e-3	Pa
MEBT		
static	5e-5	Pa
dynamic	1e-5	Pa
SC segment		
static	1e-7	Pa
dynamic	1e-7	Pa

On-site layout




Thanks for
your attention !

Emittance at entrance and exit

parameters	In / Out @ 0 mA	In / Out @ 10 mA	unit
4*exn_rms	0.0790 / 0.0888	0.0790 / 0.1555	cm*mrad
4*eyn_rms	0.0787 / 0.0818	0.0787 / 0.1411	cm*mrad
exn99.0%	0.1069 / 0.1323	0.1069 / 0.3241	cm*mrad
eyn99.0%	0.1062 / 0.1187	0.1062 / 0.3108	cm*mrad
exn_max	0.1178 / 0.2051	0.1178 / 0.6508	cm*mrad
eyn_max	0.1172 / 0.1953	0.1172 / 0.8159	cm*mrad
transmission	98.5	92.4	%
Total length	19.2	19.2	m