BEAM LOSS STUDIES IN THE CSNS LINAC

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On behalf of the CSNS Accelerator Team & Collaboration

Dongguan Campus, IHEP

Special thanks to: Yu-liang Zhang,, Zhi-ping Li, Xin-yuan Feng, Yan-liang Han, Xi-bao Luo, Hua-fu Ouyang

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HB 2023, October 11th , 2023

Outlines

1 Introduction

2 Accelerator status

3 Beam loss mechanisms

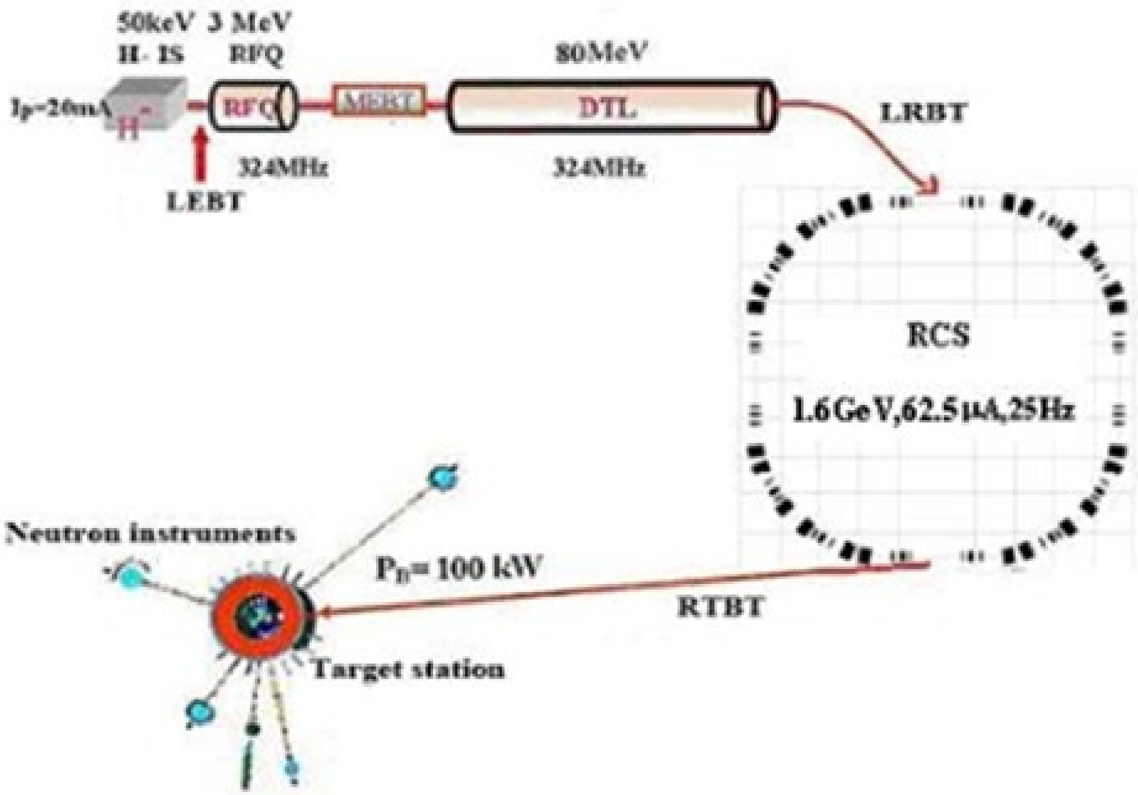
4 Comparison of FD and FFDD lattices for the DTL

5 Summary

CSNS overview

◆ **The CSNS facility consists of an 80-MeV H- linac, a 1.6GeV rapid cycling synchrotron(RCS), beam transport lines, a target station, and 3 spectrometers.**

Project Phase	**I**	**Ⅱ**
Beam Power on target [kW]	100	500
Proton energy [GeV]	1.6	1.6
Average beam current [μA]	62.5	312.5
Macropulse.ave current[mA]	15	40
Macropulse duty factor	1.05	1.7
Linac energy [MeV]	80	300
Linac type	DTL	Spoke+ Elliptical
Target	1	1
Spectrometers	3	20

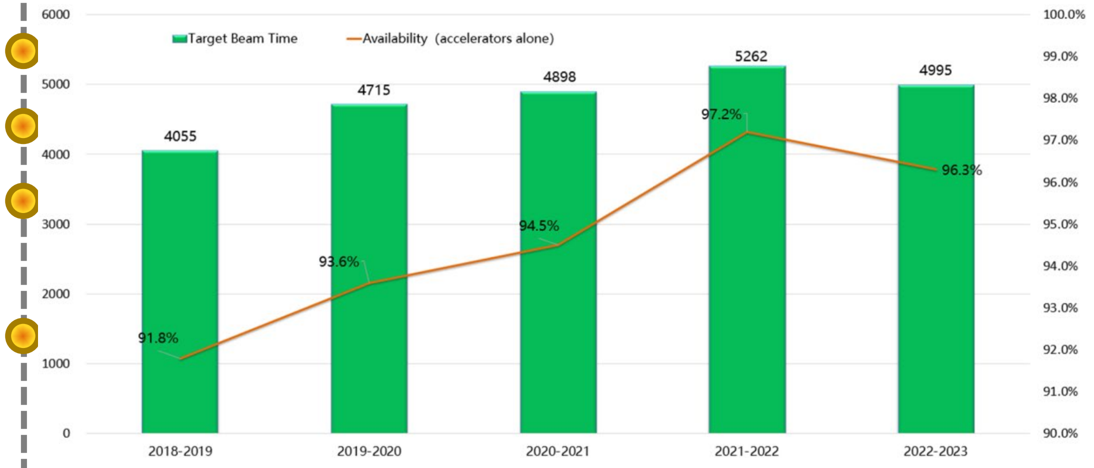


CSNS accelerator performance

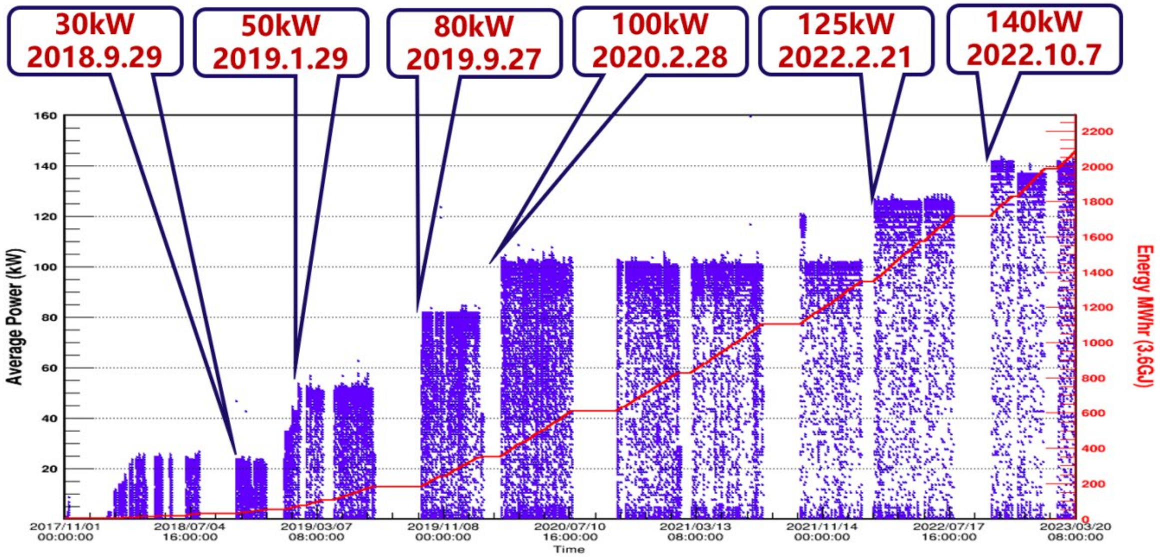
From Y.L. Zhang, private report

Key milestones(On schedule)

2015 start beam commissioning
2017 first beam on target
2018 end of beam commissioning
start operation for user program(20kW)
2020 Reach the design power(100kW)
2022 40% more than the design power



Power and Energy on Target



- ➢ The accelerator routinely operates with >90% availability in recent years
- ➢ From October 2021 to July 2022, the beam availability was improved to more than 97%.

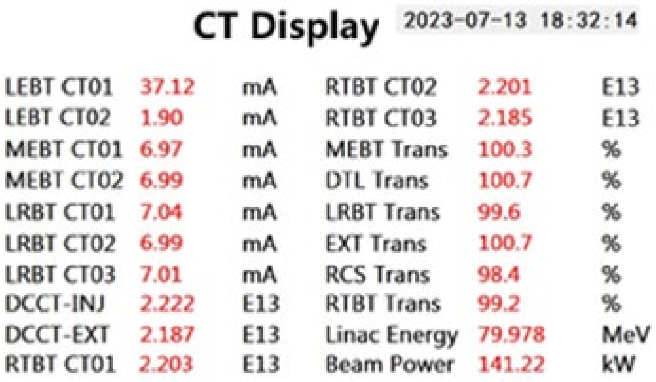
CSNS Linac: Progress and Challenges

Progress:

1、Beam pulse: 100µs ->540 µs

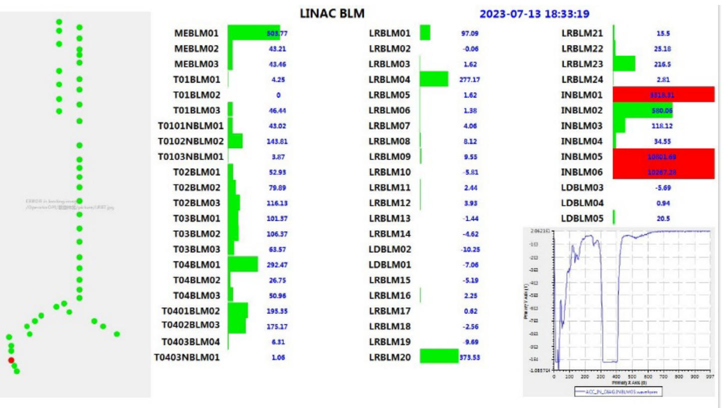
2、Beam current: 10mA ->17mA
(without chopping)

Linac beam transmission~100%, activation level<7.0mrem/hr@30cm



CT Display 2023-07-13 18:32:14

LEBT CT01	37.12	mA	RTBT CT02	2.201	E13
LEBT CT02	1.90	mA	RTBT CT03	2.185	E13
MEBT CT01	6.97	mA	MEBT Trans	100.3	%
MEBT CT02	6.99	mA	DTL Trans	100.7	%
LRBT CT01	7.04	mA	LRBT Trans	99.6	%
LRBT CT02	6.99	mA	EXT Trans	100.7	%
LRBT CT03	7.01	mA	RCS Trans	98.4	%
DCCT-INJ	2.222	E13	RTBT Trans	99.2	%
DCCT-EXT	2.187	E13	Linac Energy	79.978	MeV
RTBT CT01	2.203	E13	Beam Power	141.22	kW



LINAC BLM 2023-07-13 18:33:19

MEBLM01	503.77	LRBLM01	97.09	LRBLM21	15.5
MEBLM02	43.21	LRBLM02	-0.06	LRBLM22	25.18
MEBLM03	43.46	LRBLM03	1.62	LRBLM23	216.5
T01BLM01	4.25	LRBLM04	277.17	LRBLM24	2.81
T01BLM02	0	LRBLM05	1.62	INBLM01	8818.81
T01BLM03	46.44	LRBLM06	1.38	INBLM02	580.06
T0101NBLM01	43.02	LRBLM07	4.06	INBLM03	118.12
T0102NBLM02	143.81	LRBLM08	8.12	INBLM04	34.55
T0103NBLM01	3.87	LRBLM09	9.55	INBLM05	10801.69
T02BLM01	52.93	LRBLM10	-5.81	INBLM06	10267.28
T02BLM02	79.89	LRBLM11	2.44	LDBLM03	-5.69
T02BLM03	116.13	LRBLM12	3.93	LDBLM04	0.94
T03BLM01	101.37	LRBLM13	-1.44	LDBLM05	20.5
T03BLM02	106.37	LRBLM14	-4.62		
T03BLM03	63.57	LDBLM02	-10.25		
T04BLM01	292.47	LDBLM01	-7.06		
T04BLM02	26.75	LRBLM15	-5.19		
T04BLM03	50.96	LRBLM16	2.25		
T0401BLM02	195.35	LRBLM17	0.62		
T0402BLM03	175.17	LRBLM18	-2.56		
T0403BLM04	6.31	LRBLM19	-9.69		
T0403NBLM01	1.06	LRBLM20	373.53		

Challenges:

Beam loss <1W/m (~100mrem/hr@30cm)

Beam loss mechanism	**Transmission improved**	**Beam loss mitigation**
Beam halo/tails	2~3%	***Transverse matching:*** studying the effect of the fringe magnetic field, keeping beam equipartitioned, making phase advance smoothing, etc. ***Longitudinal matching:*** keeping the RFQ transmission>95%, optimizing buncher settings.
Ion source turn on/off transient	~0.5%	About 20µs before and after the macro beam pulse are chopped with the LEBT chopper.

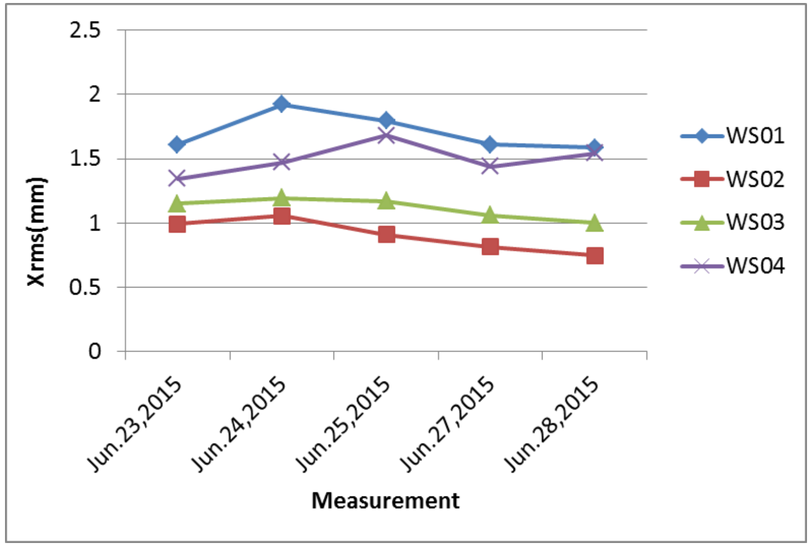
3

Beam loss mechanisms

- Ion source instability
- Quad failure in the DTL
- Effect of the fringe field
- Effect of the chopper

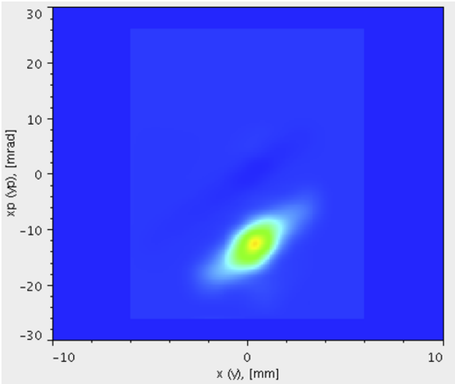
Ion Source Instability

- From 2015 to 2021, the H$^-$ Penning surface plasma source was used for the commission and operation of the CSNS accelerator. The beam transmission in the linac has about 2~4% fluctuation due to ion source instability.
- Though the beam current was stable, the beam orbit and distribution were changed.

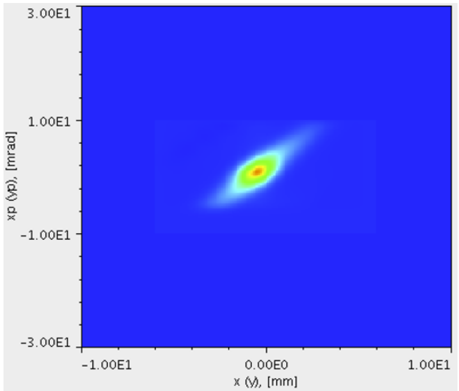


The X-direction beam sizes were obtained with wire scanners on different days. The differences between results from the same WS were about 20%.

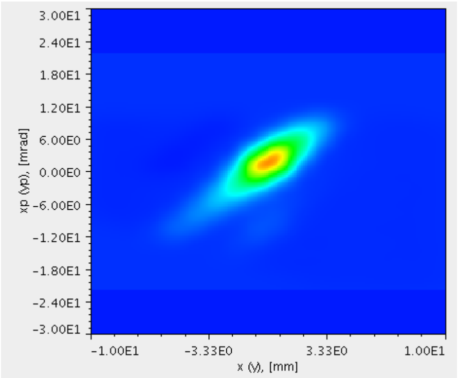
Sep. 21th,2020



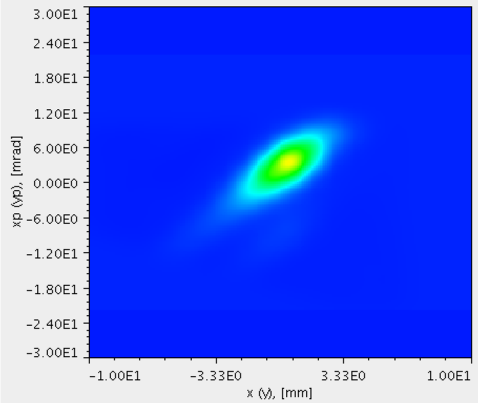
Oct. 1st, 2020



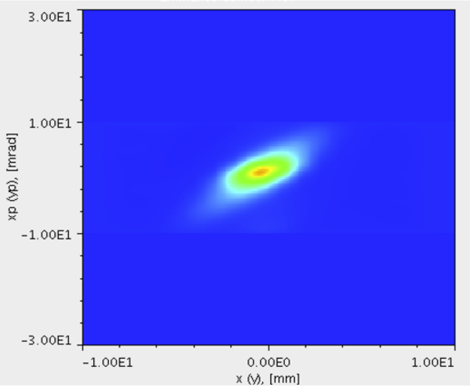
Feb.24th, 2021



Mar.31th, 2021



Apr. 27th, 2021



The beam ellipses in x-x’ phase plane were obtained with an emittance monitor on different days.

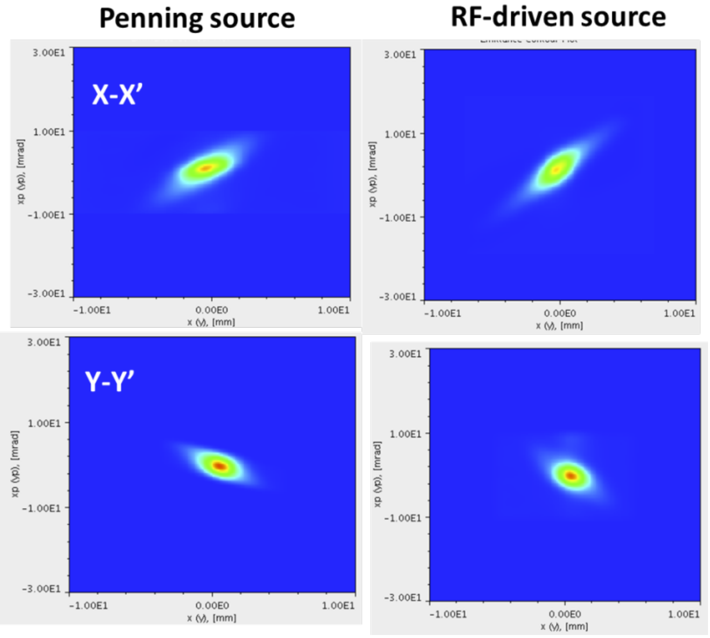
Improvements:

H.F. Ouyang et al., Proc. IPAC2019, TUPTS038

- Many improvements have been made to the ion source. The electric Penning magnet, the post-acceleration ceramic insulator, and the post-acceleration power supply were all replaced by modified ones.
- The instability could also be well controlled by strictly limiting the consumption of cesium. With these improvements, the beam transmission fluctuation could be kept within 1%.
- In the summer of 2021, the Penning ion source was replaced by the RF-driven H- ion source, to fulfill the requirements of the CSNS-II upgrade project.

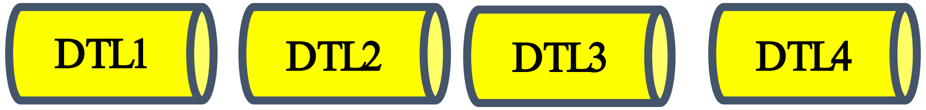
Beam distributions in phase planes are obtained with an emittance monitor in the MEBT. Two groups of the Twiss parameters in the vertical plane agree well, while those in the horizontal plane are slightly different.

X-X′	α_x	β_x	ε_x(Pi mm mrad)
Penning H^- IS	-1.59	0.79	0.243
RF-driven H^- IS	-2.86	1.12	0.202
Y-Y′	α_y	β_y	ε_y(Pi mm mrad)
Penning H^- IS	0.87	0.76	0.213
RF-driven H^- IS	0.66	0.44	0.224



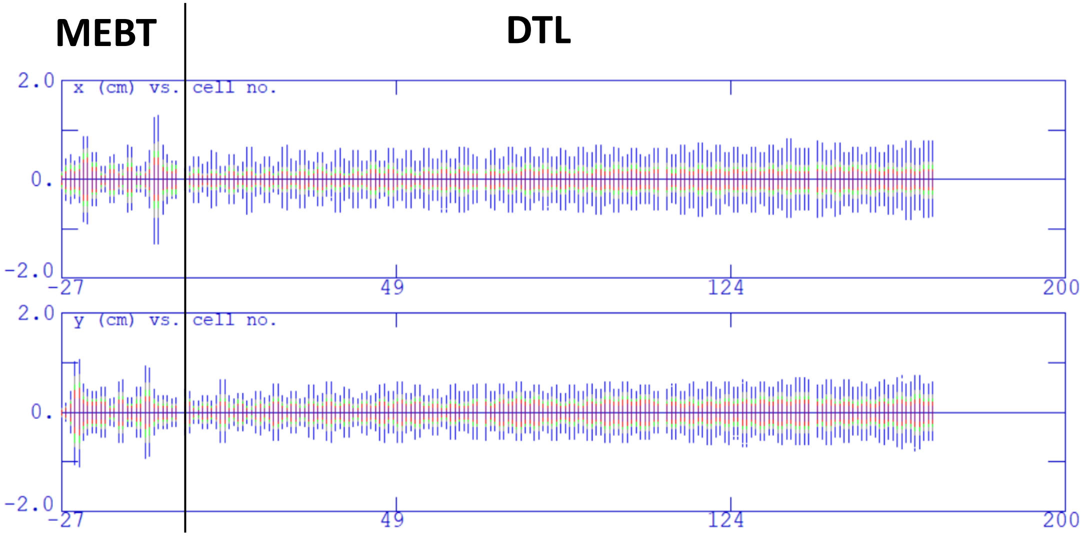
A quadrupole failure in the DTL

There are 161 EMQs in the DTL, arranged as a FFDD lattice for transverse focusing.

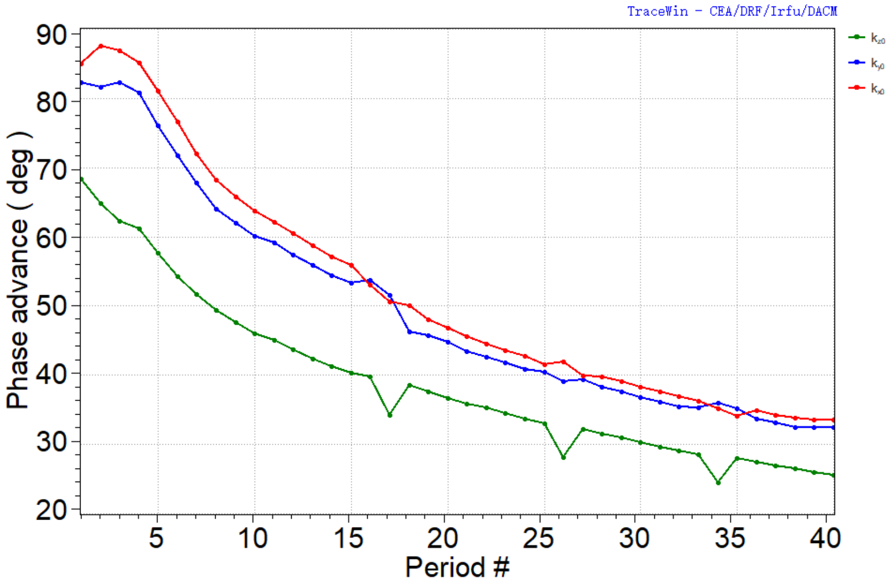


The gradients of the EMQs are calculated to make the beam equipartitioned throughout the linac :

$$\frac{\epsilon_{nx}k_x}{\epsilon_{nz}k_z} = 1$$

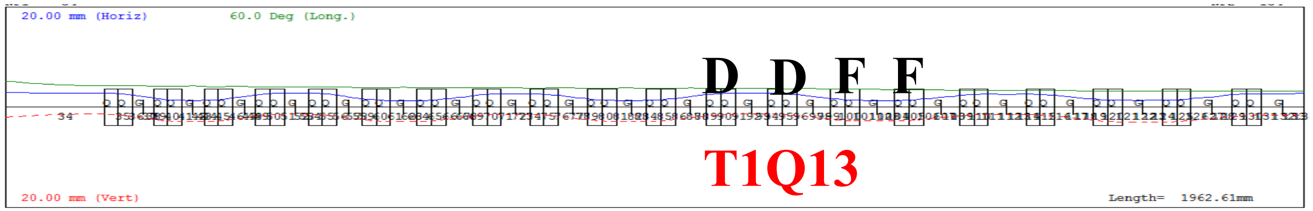


Beam envelope along the MEBT and the DTL

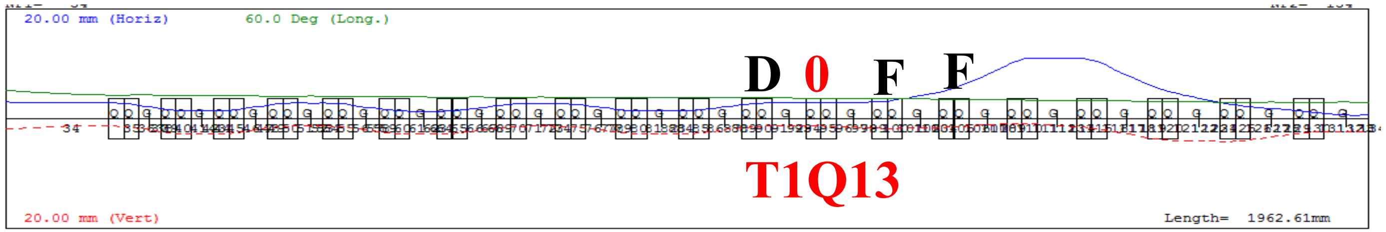


Phase advance per period

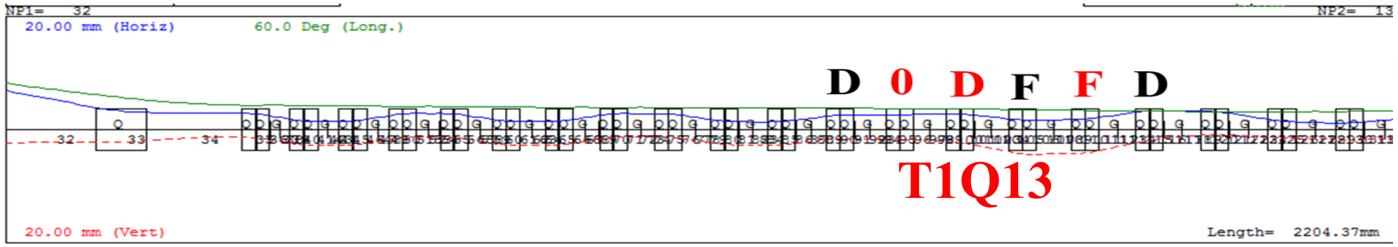
Nominal lattice



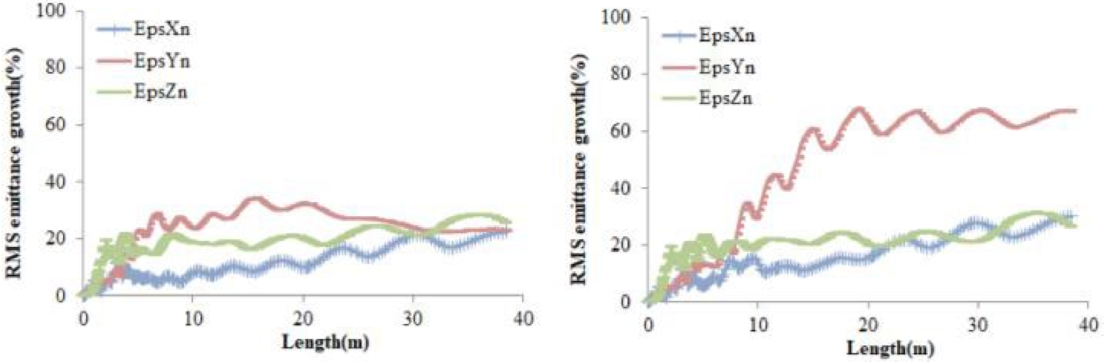
A quadrupole failure



Modified lattice



◆ A quadrupole in the 1st DTL tank was turned off due to the leaking of the cooling channels in the drift tube. We exchanged the polarities of the quadrupoles after the failure magnet and modified the settings of the adjacent quadrupoles to make the transverse phase advance smoothly. With these modifications, the beam transmission and beam loss throughout the linac were both recovered. However, since the discontinuity of the transverse focusing, the vertical emittance growth was significantly larger than that with the nominal quad settings.



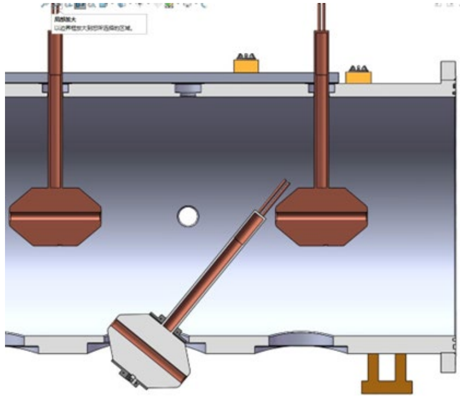
Nominal lattice *Modified lattice*

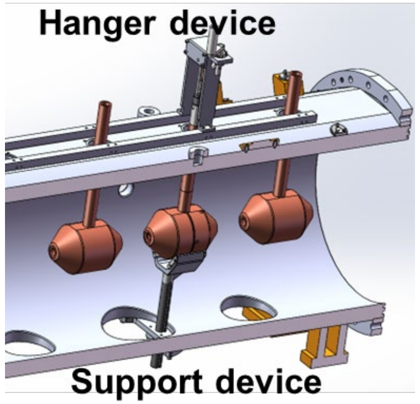
RMS emittance evolution along the DTL

Replace the faulted drift tube

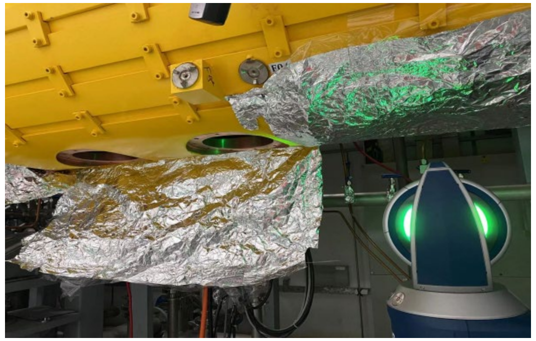
- In the summer of 2021, the faulted drift tube was replaced with a newly manufactured one. And the transverse focusing lattice was also recovered to the nominal lattice.

Online replacing

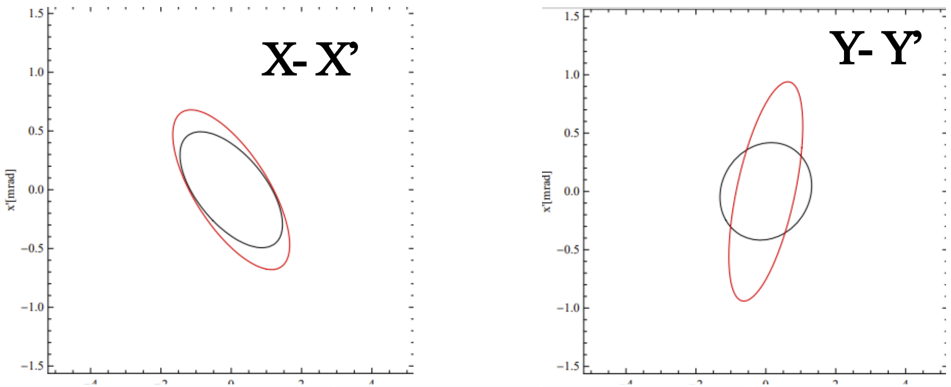




Online aligning



The Twiss parameters of the beam output from the DTL

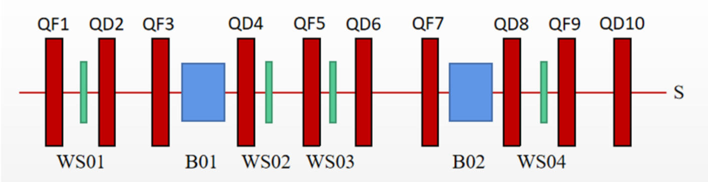


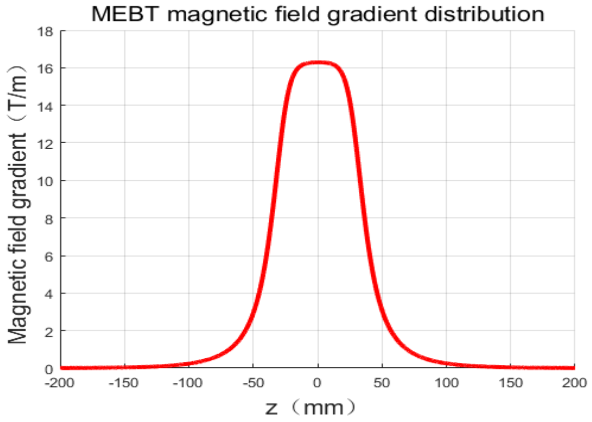
X-X′	α_x	β_x	ε_x(Pi mm mrad)
Simulation	0.75	3.69	0.243
Measurement	0.95	3.37	0.346
Y-Y′	**α_y**	**β_y**	**ε_y(Pi mm mrad)**
Simulation	-0.12	3.16	0.23
Measurement	-0.74	1.4	0.337

Effect of the fridge field

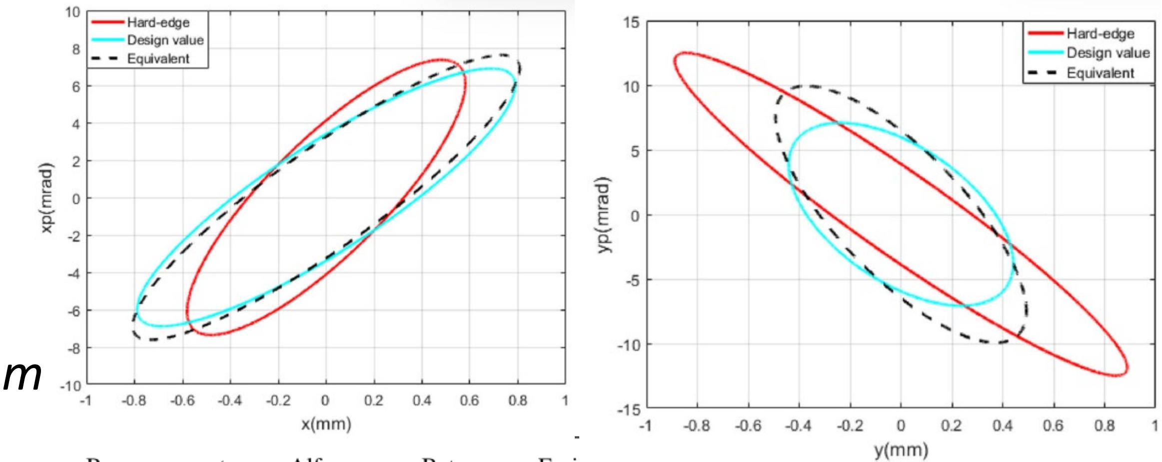
X.B. Luo et al., doi:10.1007/s41605-022-00359-9

- In the MEBT, the aspect ratio of the quadrupole is 1.67, where the fringing field effect can't be negligible. The simplified hard-edge model was unsuitable any more. A refined model called the equivalent hard-edge model was adopted. It was based on using the slicing method, to make the transfer matrix of the equivalent model equal to the transfer matrix of the slicing model.
- At the exit of the RFQ, the measured beam Twiss parameters obtained with the equivalent model are closer to the design value.




MEBT magnetic field gradient distribution

The Twiss parameters of the beam output from the RFQ based on different magnet models

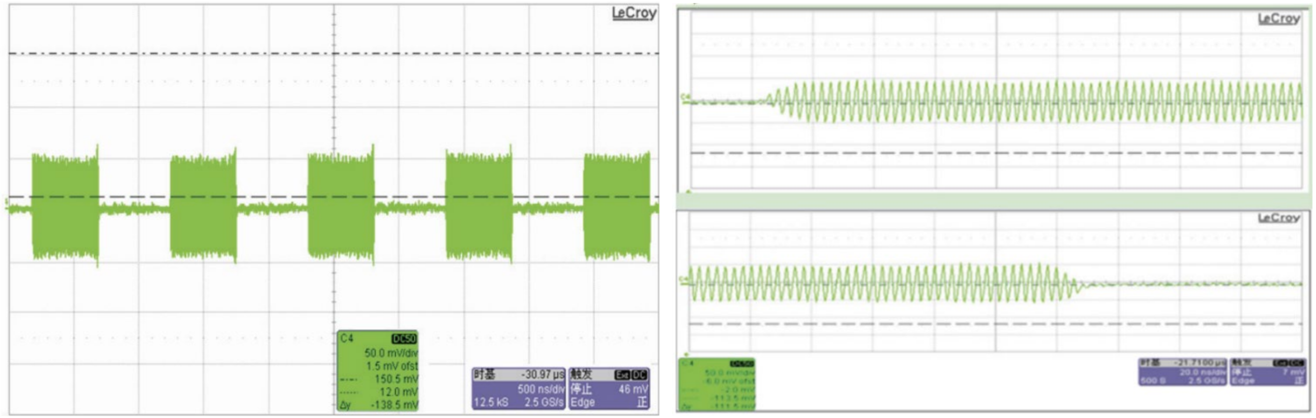


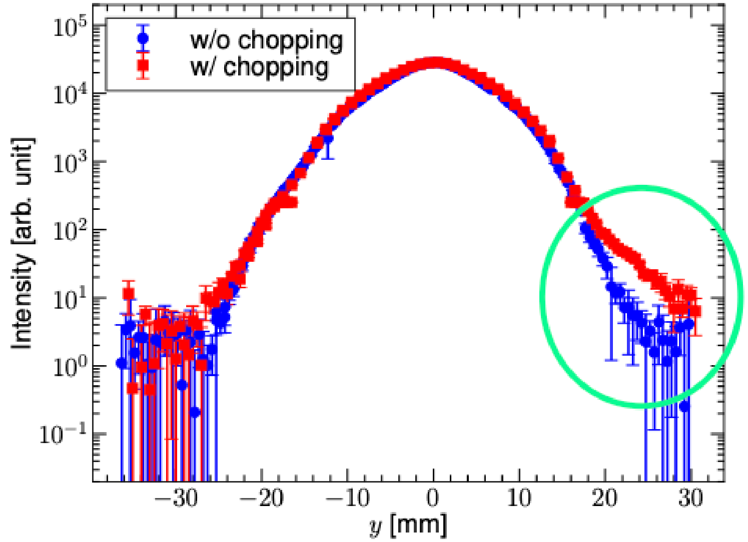
Beam parameters	Alfax	Betax (m)	Emitx (π.mm.mrad)	Alfay	Betay (m)	Emity (π.mm.mrad)
Design value of RFQ	− 1.773	0.233	2.671	0.639	0.074	2.63
Traditional hard-edge model	− 1.481	0.141	2.389	3.042	0.228	3.466
The equivalent transfer matrix	− 2.123	0.273	2.871	1.159	0.07	2.95

Effect of the chopper

H.C. liu et al., Proc. IPAC2013, THPFI025
R.J. Yang, private talk

- An electric chopper is located in the LEBT just before the entrance of RFQ to chop the beam to the required structure for RCS.
- To reduce the beam loss caused by the ion source turn on/off transient, about a rise time of 4.5μs and a fall all time of 14us of the macro-beam pulse are chopped with the LEBT chopper.
- The rise and fall time of the chopped pulse has caused a mismatch and beam halo.





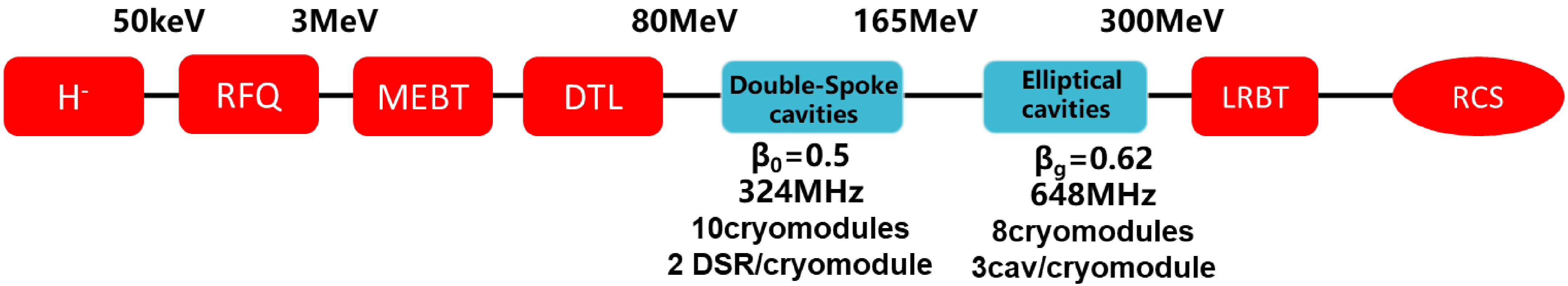
- BPM signal after chopping at the exit of the RFQ. The rise/fall time is about 10ns (1 RF period T=3.086ns).

- Signals are from the first wire scanners located at the exit of the DTL. In the vertical direction, a more significant halo(red) can be observed in the chopped beam.

4

Comparison of two lattice options for the DTL (FD vs. FFDD)

CSNS-Ⅱ □ Superconducting Linac

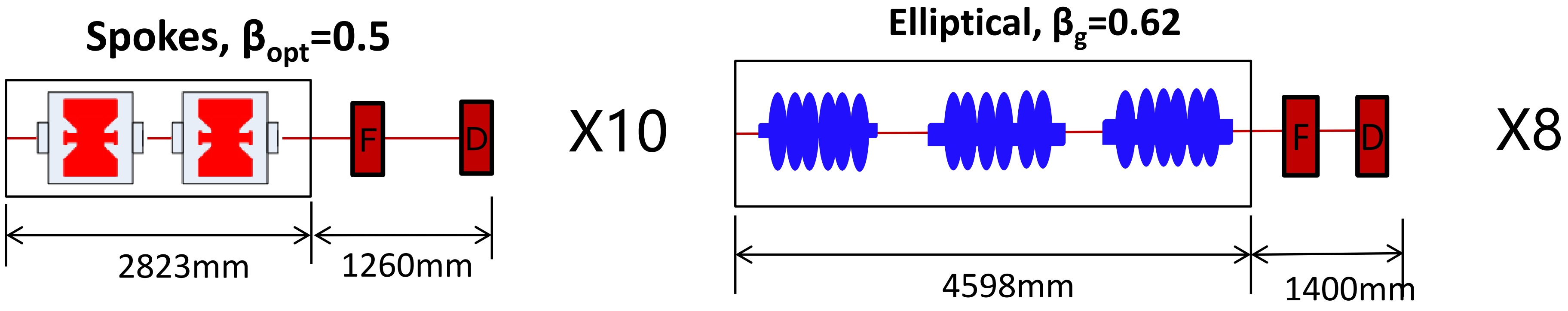


50keV 3MeV 80MeV 165MeV 300MeV

H⁻ RFQ MEBT DTL Double-Spoke cavities Elliptical cavities LRBT RCS

β_0=0.5
324MHz
10cryomodules
2 DSR/cryomodule

β_g=0.62
648MHz
8cryomodules
3cav/cryomodule



Spokes, β_{opt}=0.5

2823mm 1260mm

X10

Elliptical, β_g=0.62

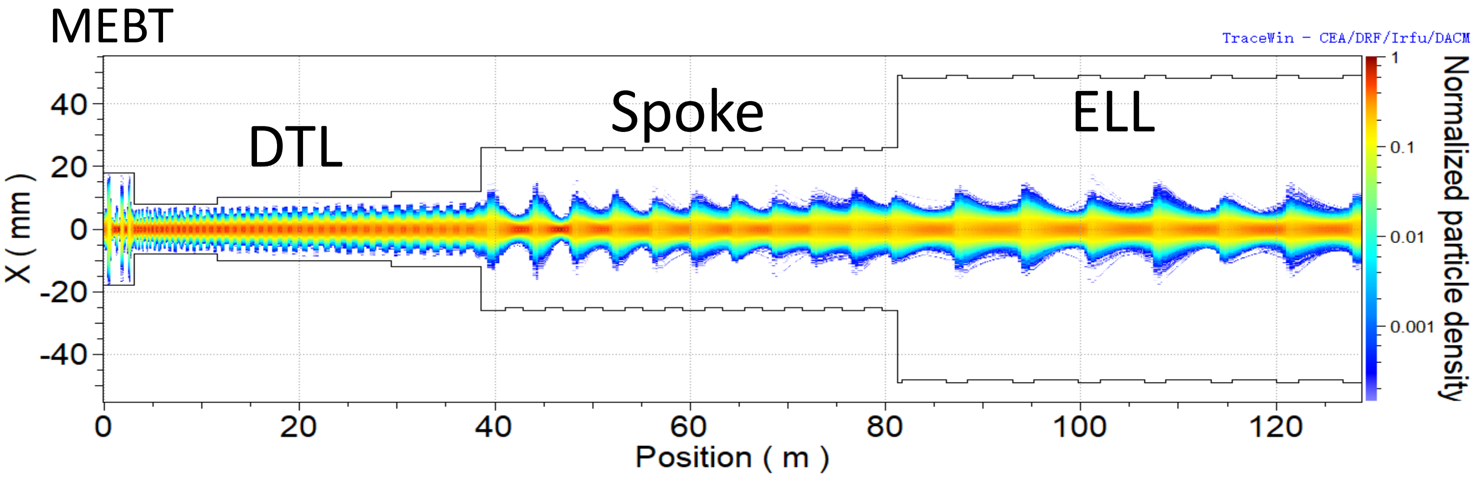
4598mm 1400mm

X8

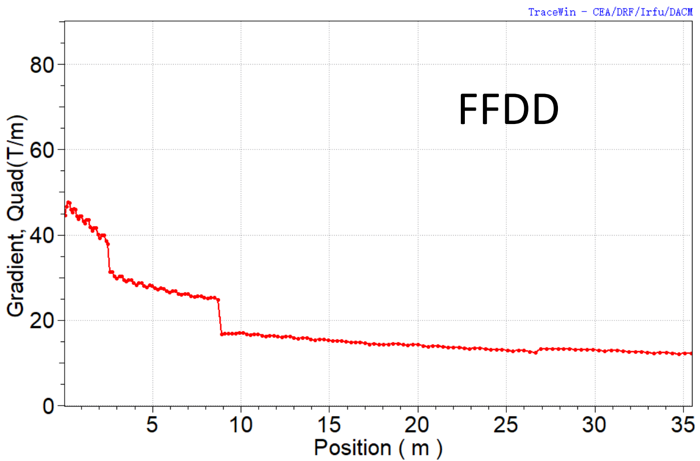
◆ To achieve the new beam power of 500kW, the beam energy output from linac will be increased from 80MeV to 300MeV by adding a superconducting linac. Moreover, the beam current throughout the linac must be improved from 10mA to 40mA and even higher.

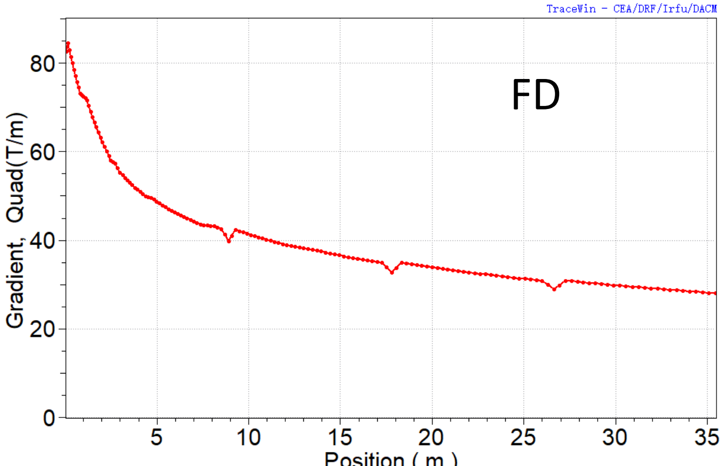
Two lattice options for the DTL (FD vs. FFDD)

◆ The bore radius of the DTL was first designed for a beam current of 30mA. To achieve a higher current, we studied a scheme to replace the existing FFDD lattice in the DTL with an FD lattice.



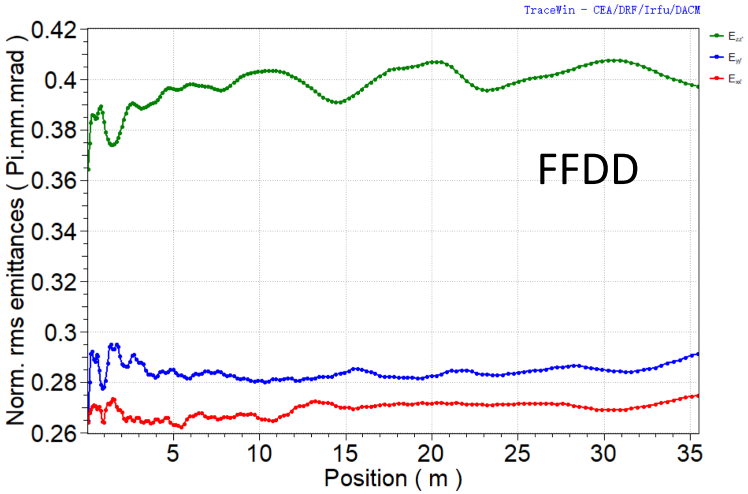
- ➢ In the 1st tank of the DTL, the ratio between the bore radius and the RMS beam size is the smallest throughout the whole linac.

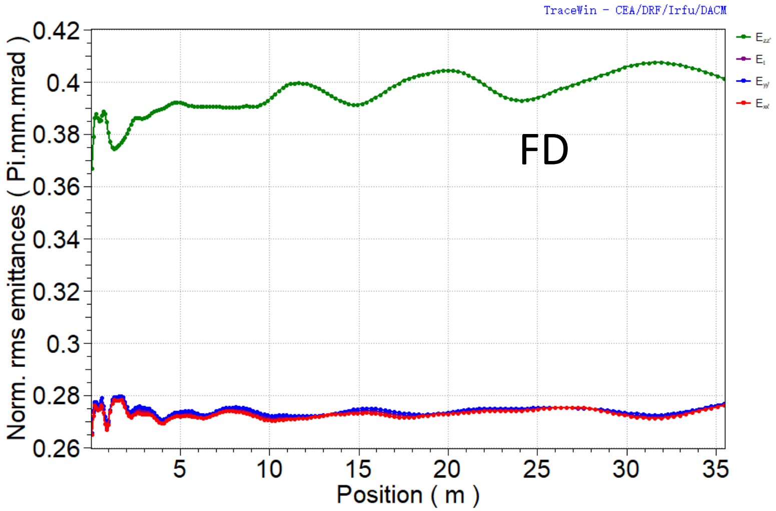




- ➢ The quadrupole gradients in the FD lattice are significantly larger than in the FFDD lattice, almost two times.

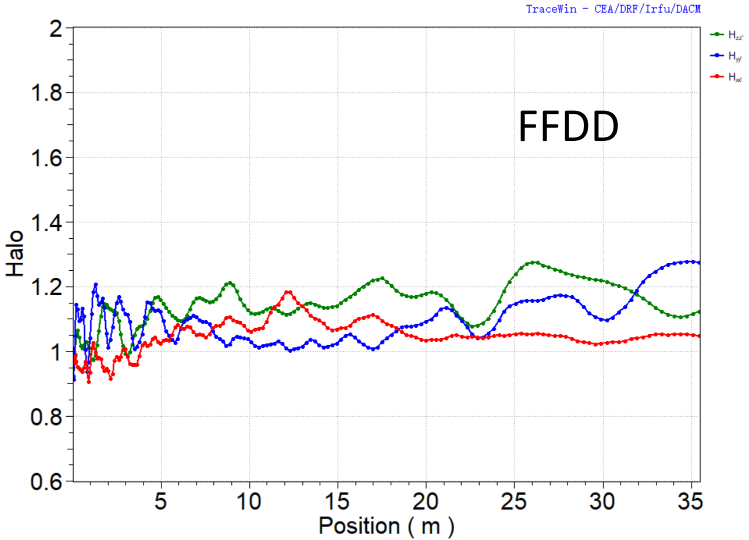
Beam dynamics in the DTL

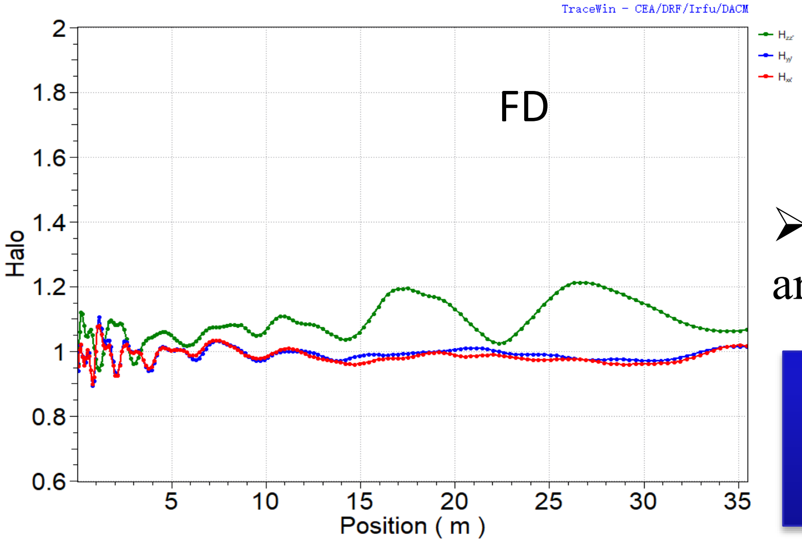




Beam emittance evolution

- ➢ For two lattice options, the RMS emittance growth are similar, .



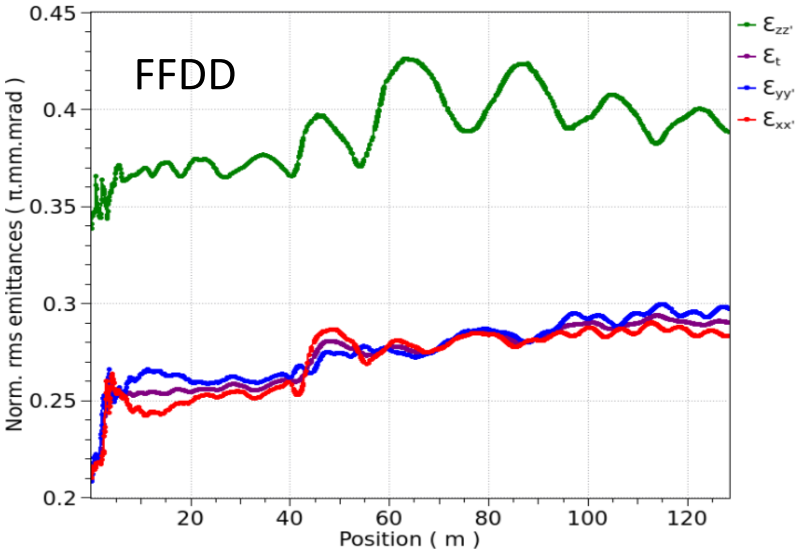


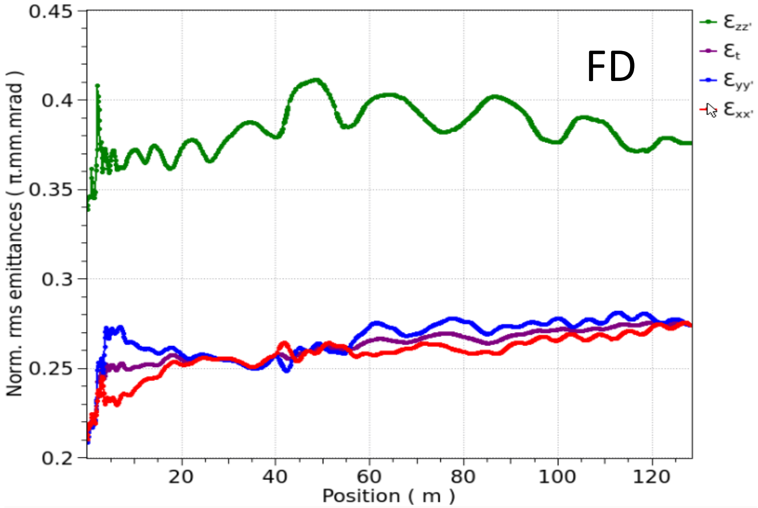
Halo parameter evolution

- ➢ For two lattice options, the halo parameters are almost the same.

Halo parameter is defined from ref: "PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS,VOLUME5, 124202 (2002)", "Beam halo definitions based upon moments of the particle distribution (C. K. Allenand T. P.Wangler) "

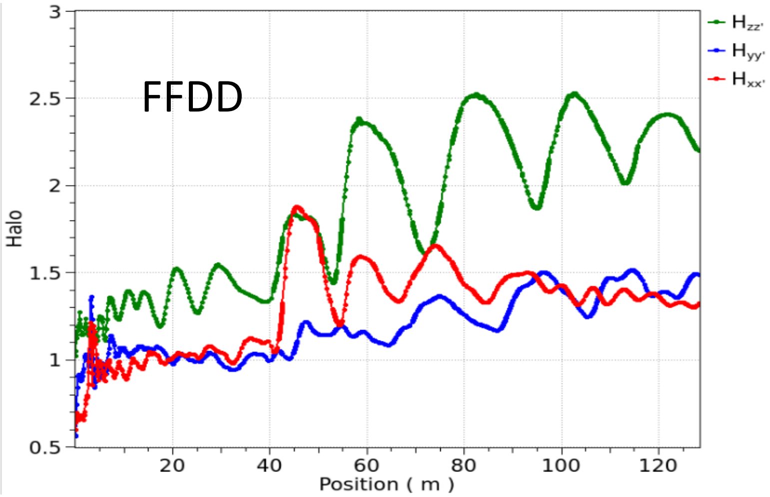
Beam dynamics in the MEBT+DTL+SC

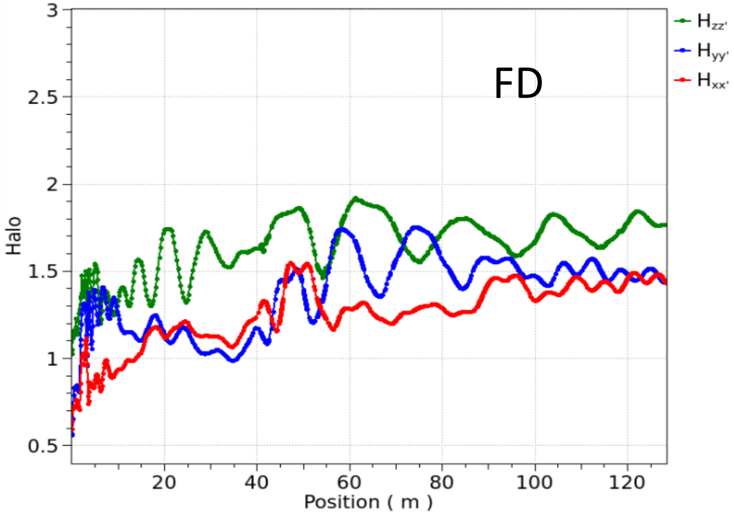




Beam emittance evolution

- ➢ The RMS emittance growth in the FD lattice is smaller than in the FFDD lattice.



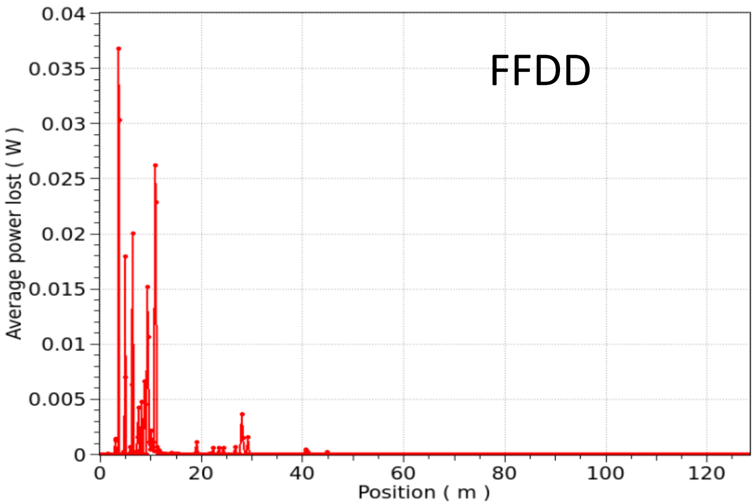


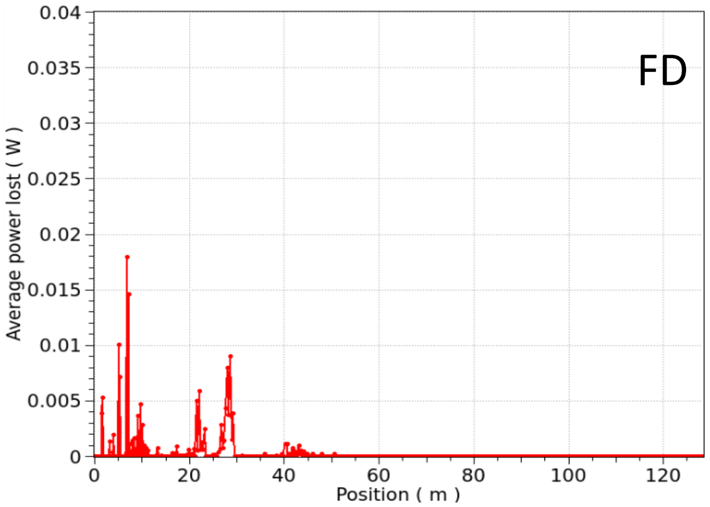
Halo parameter evolution

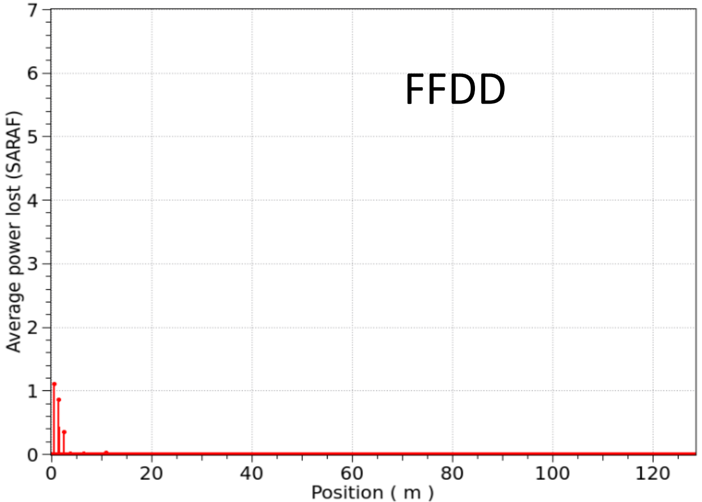
- ➢ The halo parameter in the FD lattice is smaller than in the FFDD lattice.

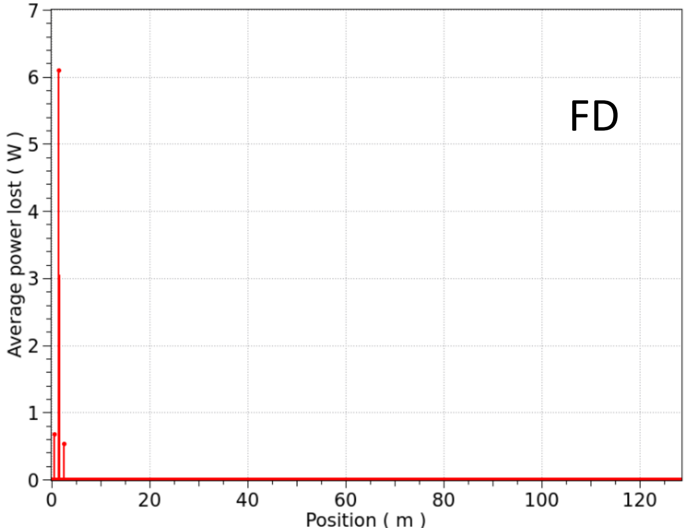
Beam loss analysis

From Y.L. Han, private report









Without using scrapers in the MEBT

- In the FFDD case, most of the beam is lost in the first tank of the DTL. In the FD case, beam loss in the DTL is smaller than that in the FFDD lattice, but more beam loss in the Spoke section is observed.

With using scrapers in the MEBT

- For two lattice options, the beam loss is concentrated in the MEBT section.

Summary

- For the CSNS linac, the primary source of beam loss is the beam halo or long tails on the beam distribution. We reviewed some issues that caused the beam mismatches during the operation. The beam transmission throughout the linac is improved by reducing these mismatches.

- To achieve the new beam power of 500kW, two lattice options for the DTL are compared. The emittance growth and halo parameter in the FD lattice are smaller than in the FFDD lattice. However, the higher gradients of quadrupoles are required in the FD lattice.

- As the beam current increases, the e-P instability will become a significant issue and cause unavoidable beam loss. We are preparing some experiments to study these mechanisms of beam loss.

Thanks For Your Attention!

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