中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

中国科学院
CHINESE ACADEMY OF SCIENCES

Beam Dynamics Design of CW RFQ for Chinese ADS

Dou WeiPing

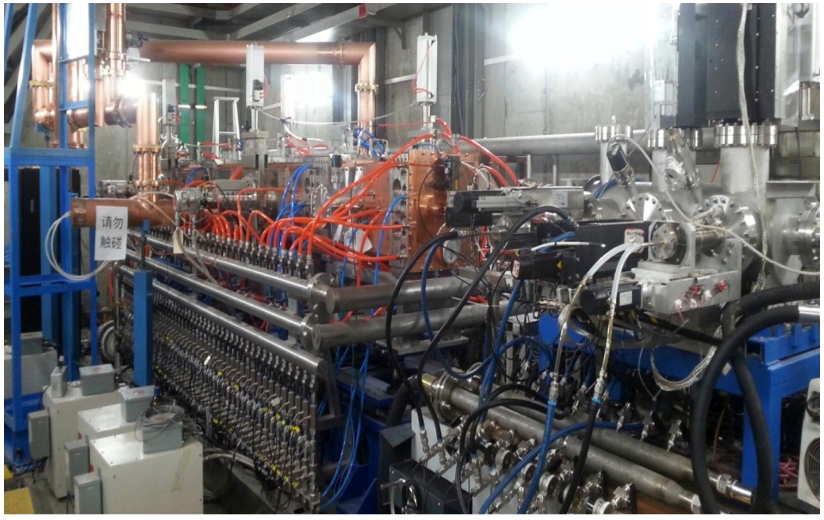
On behalf of Linac Center

Institute of Modern Physics (IMP) ,Chinese Academy of Sciences
Lanzhou, China

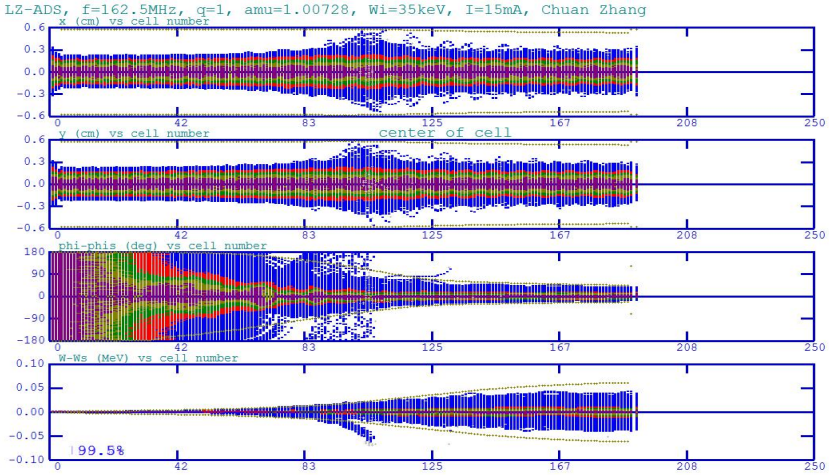
OUTLINE

- **Present RFQ for ADS injector II**
- **Why we need a new RFQ for CiADS?**
- **CiADS RFQ design**
  - CiADS RFQ design requirements
  - Beam dynamics
  1. A easy match between LEBT and RFQ
  2. A lower longitudinal emittance
  - Mismatch analysis
  - Combination simulation with SC linac
- **Summary**

Present RFQ for ADS injector II

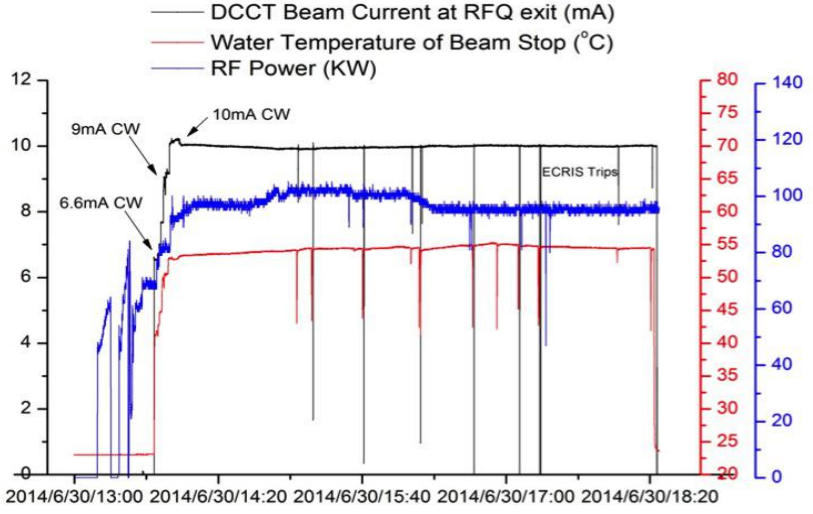


Present RFQ in tunnel , ADS injector II



Beam dynamic 10mA proton from 35keV to 2.1MeV

- '11-'13, Designed by LBNL and fabricated in IMP.
- Jun. 6 '14, conditioned to 90 kW
- Jun. 6th '14, the first pulse beam, 2.1 MeV, trans 97%
- Jun. 30th'14, 10 mA, CW, 4.5 hours
- Up to date, full power operation 5903 hours, beam time is around 3007 hours, CW beam 105 hours.



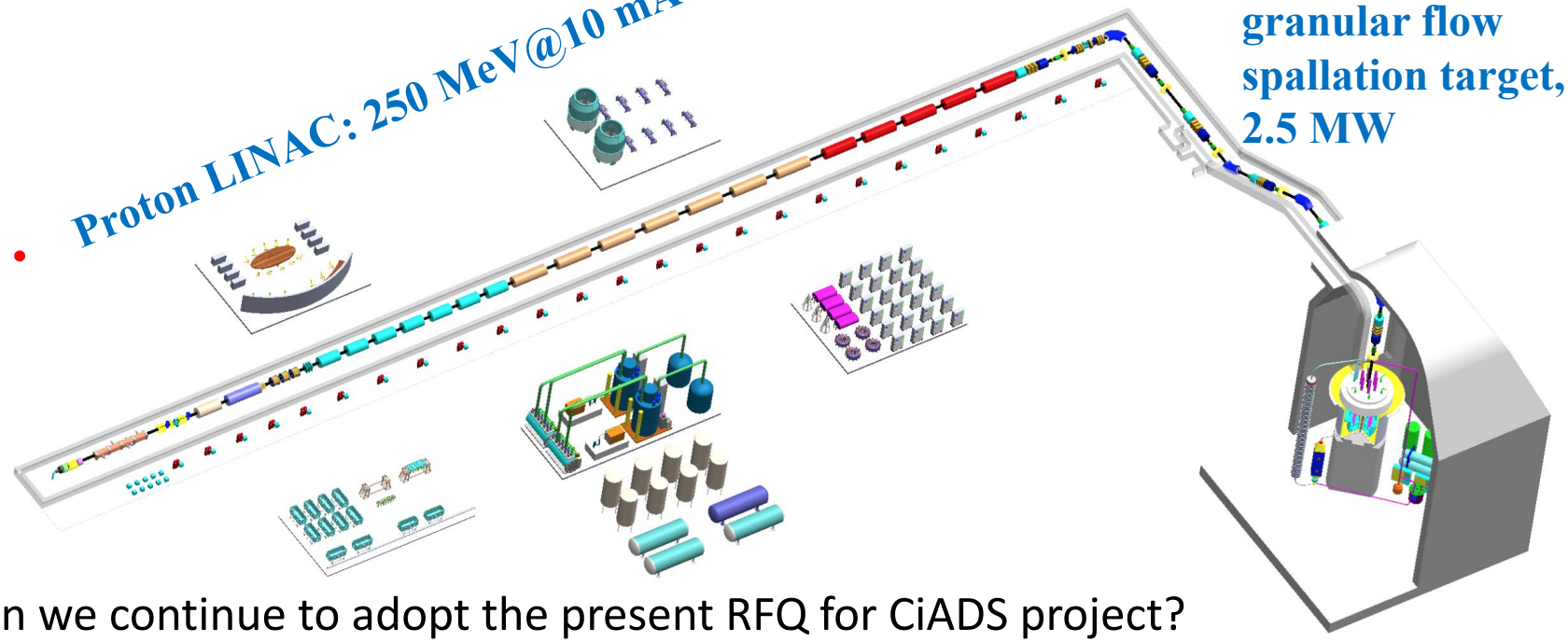
Historical record of first 10 mA CW proton beam

Why we need a new RFQ?

China Initiative Accelerator Driven System

ADS injector II SC linac: 25MeV

- **Proton LINAC: 250 MeV@10 mA with CW mode**



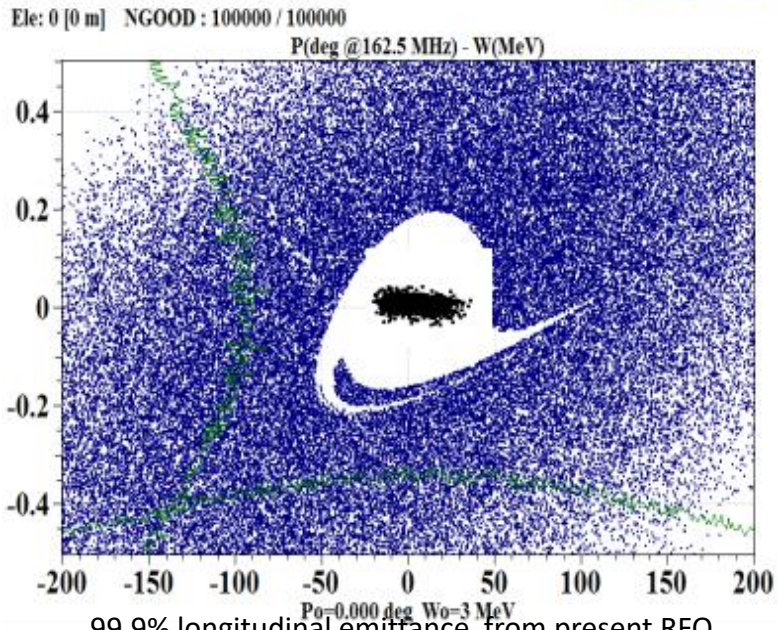
- **Spallation Target: granular flow spallation target, 2.5 MW**

Can we continue to adopt the present RFQ for CiADS project?

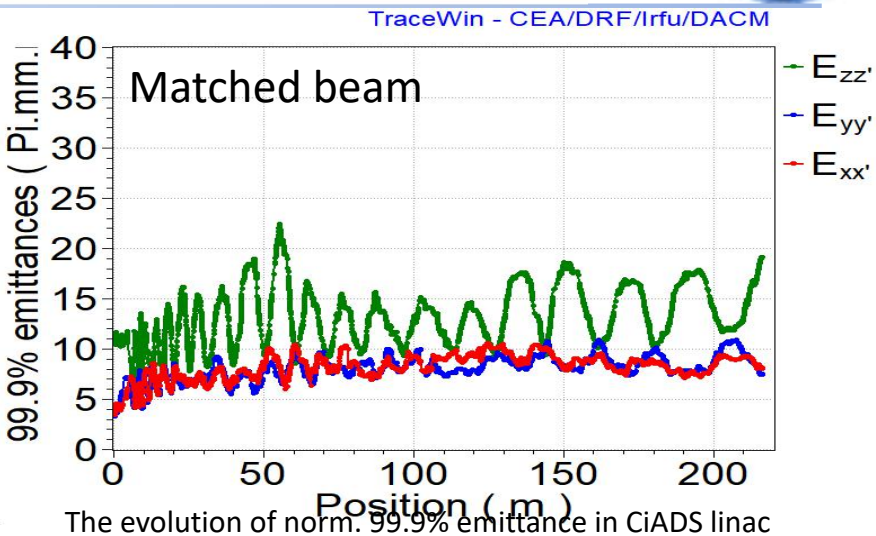
- **Sub-critical core: 10 MWt**

Why we need a new RFQ?

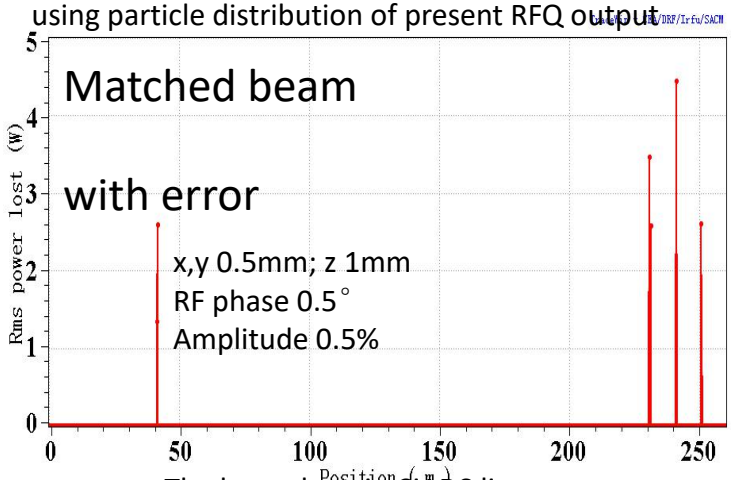
1. Do the combination simulation with SC linac of CiADS
2. The acceptance of downstream SC linac is optimized to 27 π.mm.mrad.
3. The 99.9% longitudinal emittance from present RFQ is 8.15π.mm.mrad. The ratio is only 1/3.3



99.9% longitudinal emittance from present RFQ and the acceptance of SC linac of CiADS



The evolution of norm. 99.9% emittance in CiADS linac using particle distribution of present RFQ output



The beam loss in CiADS linac, using particle distribution of present RFQ output

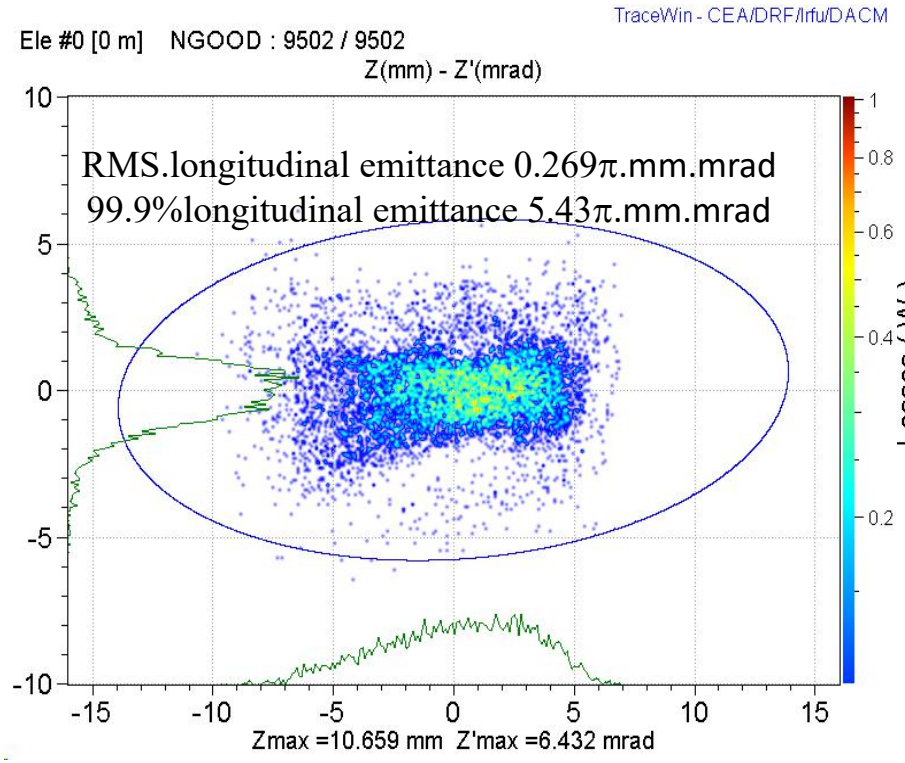
Why we need a new RFQ?

Table 1: Design Requirements

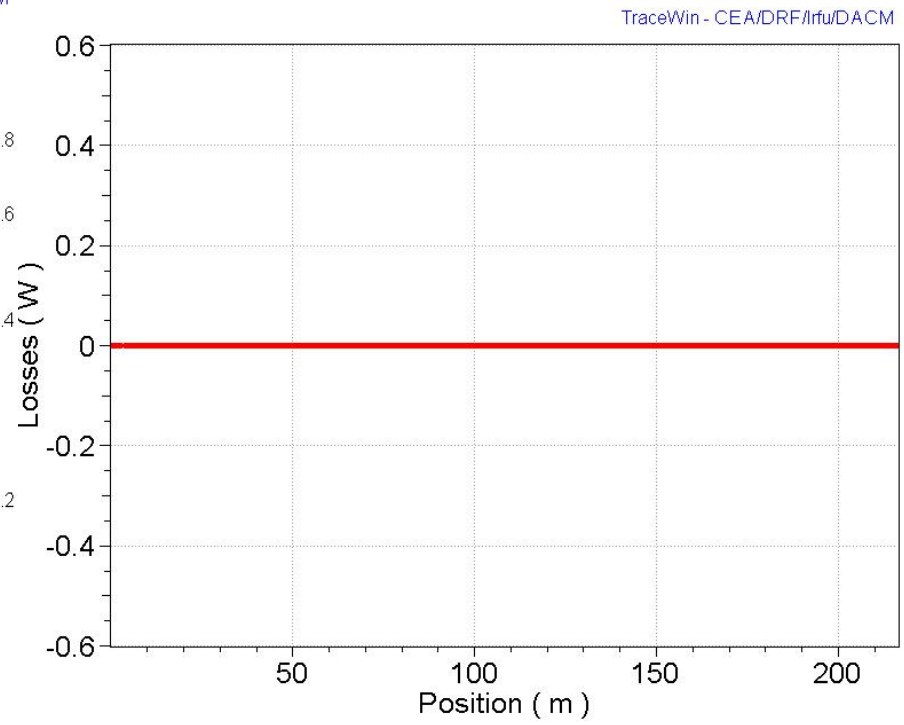
Parameters	Injector-II RFQ
Particle species	H^+
f [MHz]	162.5
W_{in} / W_{out} [MeV]	0.035 / 2.1
Duty factor [%]	100
I_{peak} [mA]	15 (up to 20)
$\varepsilon_{in}^{trans.,n.,rms}$ [π mm mrad]	0.30
$\Delta\varepsilon^{trans.}$ [%]	≤10
$\varepsilon_{out}^{longi.,n.,rms}$ [keV ns]	≤1.0
T [%]	95
Twiss α [%]	≤1.5

1. The beam quality from present RFQ can not meet requirement of CiADS SC linac.
2. The RMS longitudinal emittance of present RFQ is 0.92 keV.ns@162.5MHz. It can meet the design requirement of ADS injector II
3. The requirement of beam quality from CiADS RFQ should be more strict. The 99.9% longitudinal emittance is proposed as a key parameter in CiADS RFQ design

Why we need a new RFQ?



Iuput longitudinal phase space



The beam loss in CiADS linac

1. We study different values of the 99.9% longitudinal emittance at entrance of CiADS SC linac. When the value is reduced from 8.15 to less than 5.43 π.mm.mrad, the SC linac do not have beam loss
2. The 99.9% longitudinal emittance from CiADS RFQ should be less than 5.4 π.mm.mrad

CiADS RFQ design

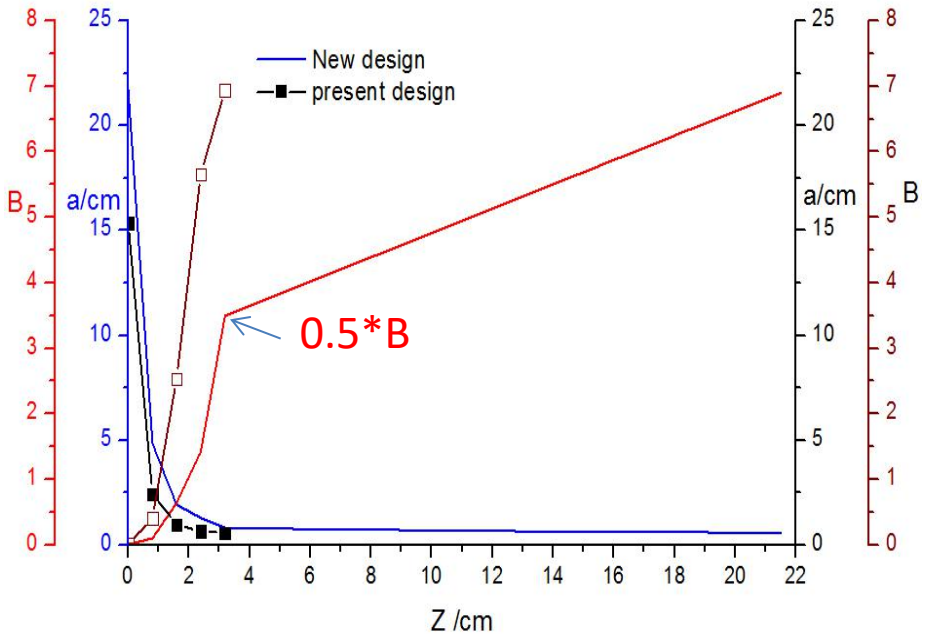
The CiADS RFQ design requirements are proposed:

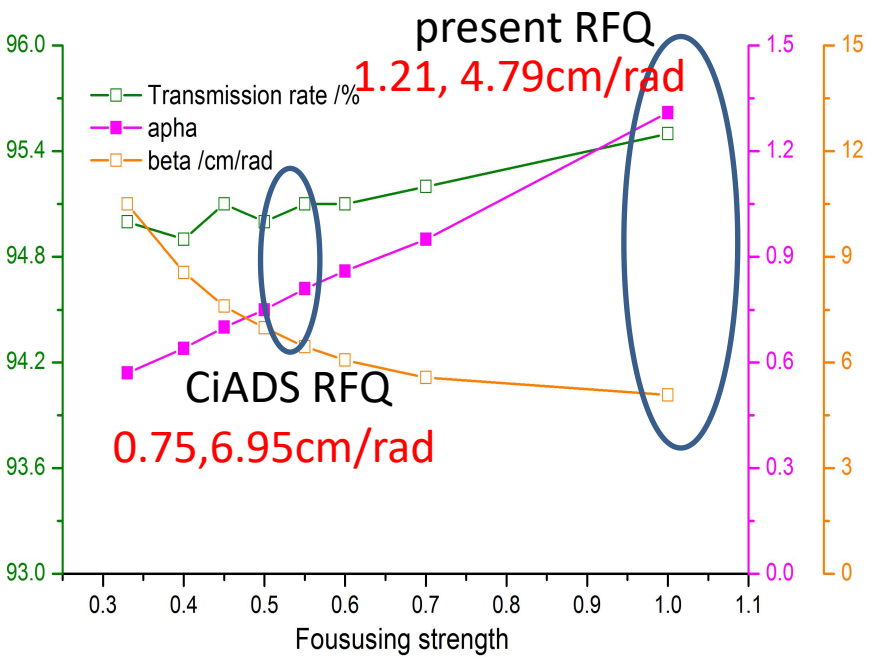
- Frequency: 162.5 MHz
- CW mode
- Injection energy: 35 keV
- Output energy: 2.1 MeV
- Beam current (nominal): 15 mA
- Input emittance [trans, rms, norm]: 0.2 π.mm.mrad
- TWISS parameters (αs): ≤ 1.0（1.5）
- Emittance growth: ≤10%
- Transmission: ≥ 95%
- RMS longitudinal emittance：≤0.25 π.mm.mrad(0.3 π.mm.mrad)
- 99.9% longitudinal emittance：≤5.4 π.mm.mrad（not mentioned）

Overview of CiADS RFQ design

- Beam dynamics design meets or exceeds the requirements in intensity, emittance growth, TWISS parameters and transmissions (rfqgen)
  - The bascic parameters are kept almost same as present RFQ (V, f, R0, Energy)
- A easy match between LEBT and RFQ
  - In radial match section of RFQ, the weaker the focusing strength , the smaller alpha and the larger beta for easy match
  - But the lower transmission efficiency
- A lower 99.9% longitudinal emittance
  - The lower output 99.9% longitudinal emittance means smaller possibility of beam loss in SC linac
  - But it is at the cost of lower transmission efficiency of RFQ

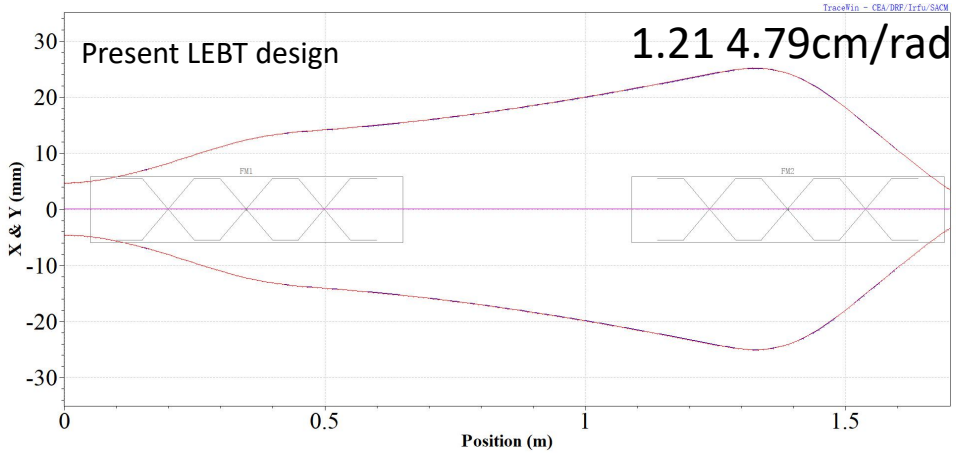
A easy match

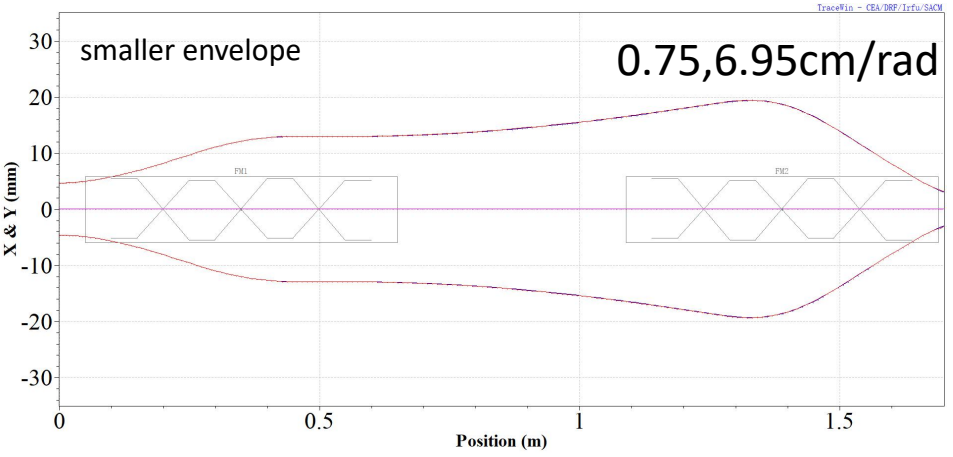


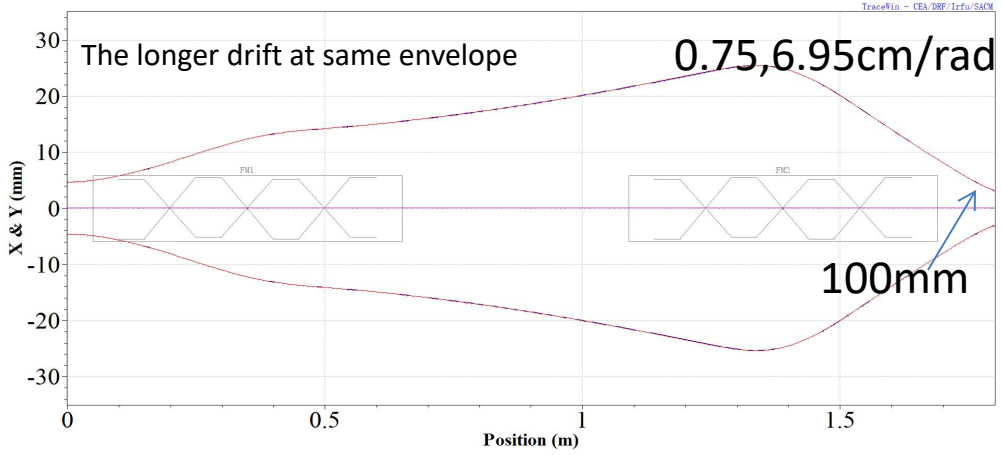


1. The 27 cells are adopted to finish the match between LEBT and RFQ. (4 cells)
2. The transverse focusing strength at the end of orgin radial match section is reduced to 0.5*B.
3. Do a combination simulation of the LEBT and RFQ to get better match and transmission(on the way)

A easy match



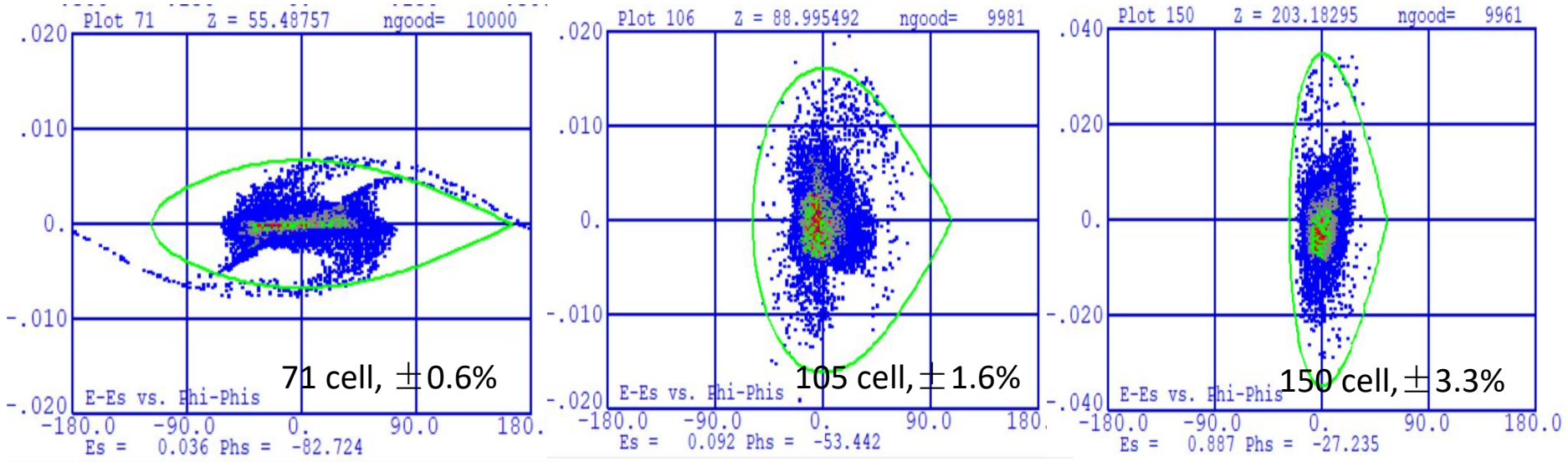




1. Smaller envelope is got with present LEBT by changing the solenoid current
2. The drift lenth in the front of RFQ may be added 100 mm at same envelope. The more beam diagnosis elements can be placed here.

A lower longitudinal emittance

Present RFQ for ADS injector II—higher transmission efficiency

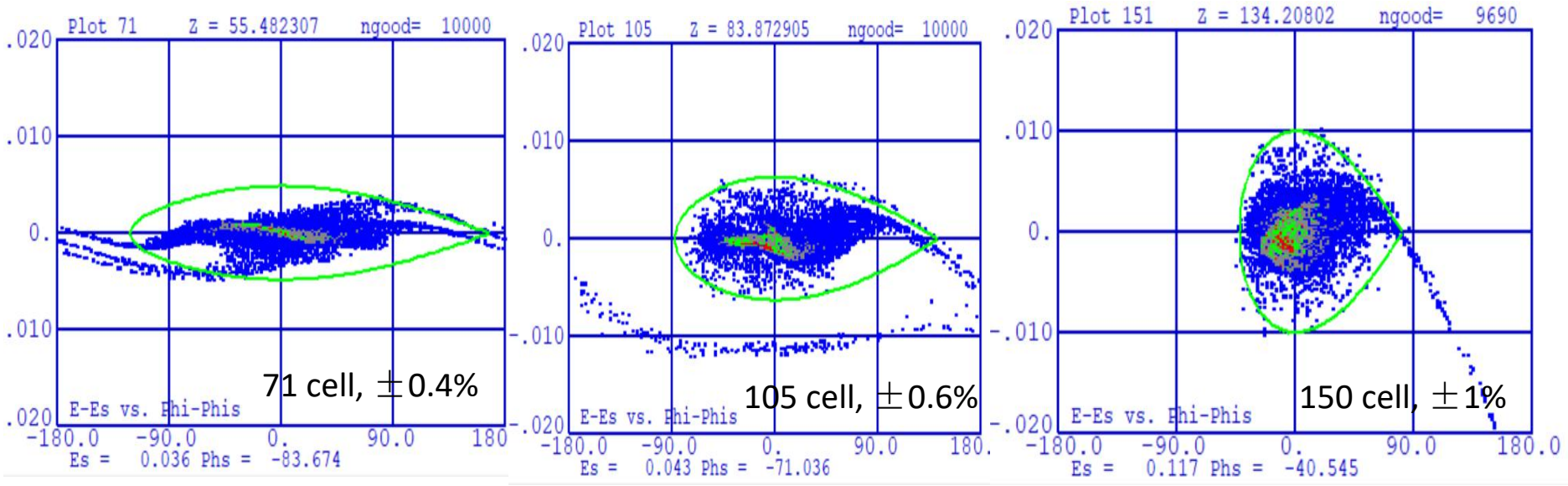


The evolution of beam longitudinal phase space and acceptance of the present RFQ

1. The goals of present RFQ design for ADS injector II are mainly higher beam transmission efficiency and shorter length.
2. The energy acceptance inside RFQ increase quickly to high transmission efficiency
3. It is difficult to get lower 99.9% longitudinal emittance in short length with high transmission efficiency up to 99.6%.

A lower longitudinal emittance

CiADS RFQ —smaller energy acceptance

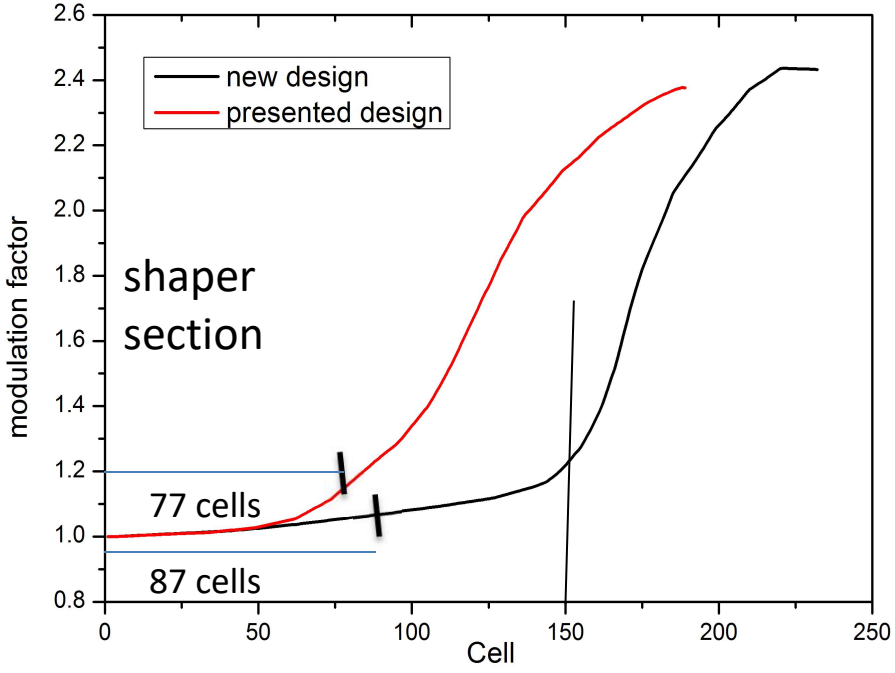


The evolution of beam longitudinal phase space and acceptance of CiADS RFQ

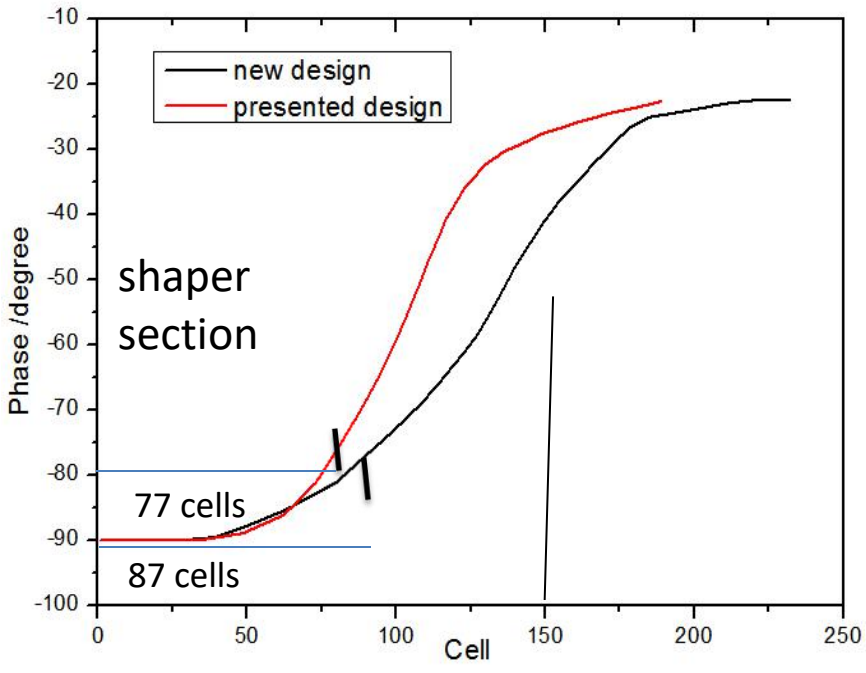
1. The 99.9% longitudinal emittance is optimized at the cost of lower transmission efficiency
2. Smaller energy acceptance inside RFQ is adopted to make particles loss in low energy section. until 150 cells, the energy acceptance is only ±1%.
3. The acceleration efficiency of CiADS RFQ is 95%, the beam loss in transverse is 3% because of transverse mismatch , and beam loss in longitudinal is 2% because of energy limit.

A lower longitudinal emittance

CiADS RFQ—longer shaper section



The evolution of modulation factor



The evolution of synchronous phase

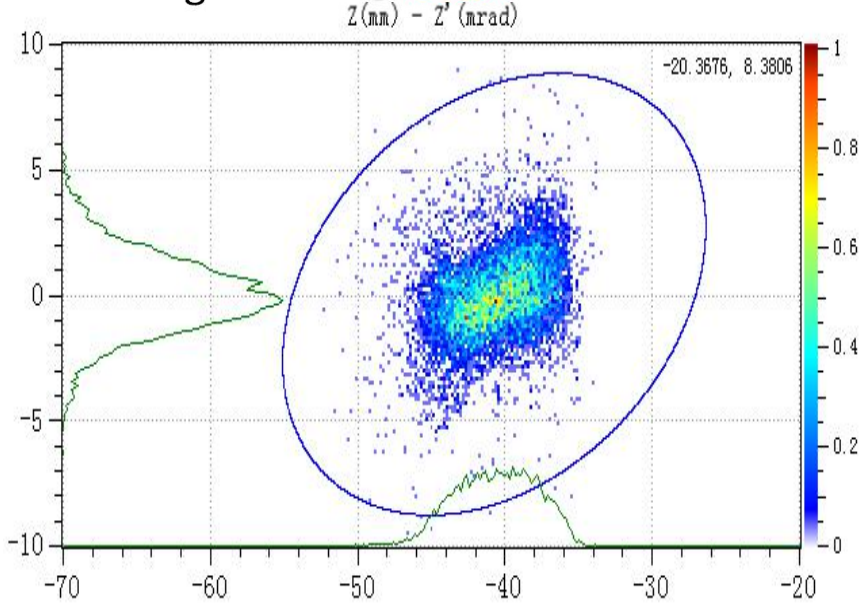
1. Longer shaper section is in order to form smaller longitudinal emittance bunch, the RMS longitudinal emittance after shaper section in CiADS RFQ decreases 6 percent.
2. Until 150 cells, smaller energy acceptance is formed by smaller modulation factor

A lower longitudinal emittance

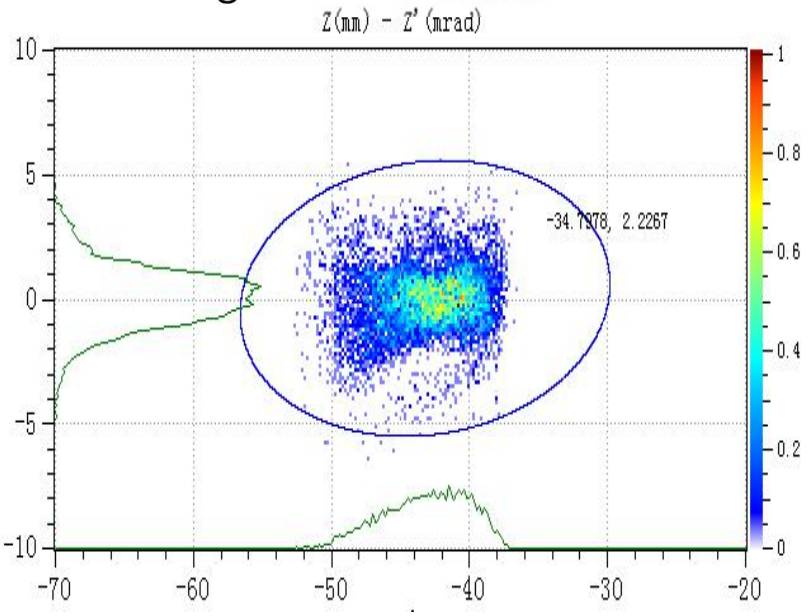
Present RFQ for injector II:
Acceleration efficiency : 99.6%
99.9% longitudinal ε: 8.15π.mm.mrad
RMS longitudinal ε: 0.297π.mm.mrad

code: rfqgen

CiADS RFQ :
Acceleration efficiency : 95%
99.9% longitudinal ε: 4.98π.mm.mrad
RMS longitudinal ε: 0.259π.mm.mrad



The longitudinal phase space at exit of present RFQ



The longitudinal phase space at exit of CiADS RFQ

The 99.9% longitudinal emittance in CiADS RFQ reduce 39 percent, smaller than requirement value of 5.4 π.mm.mrad.

Beam dynamics results

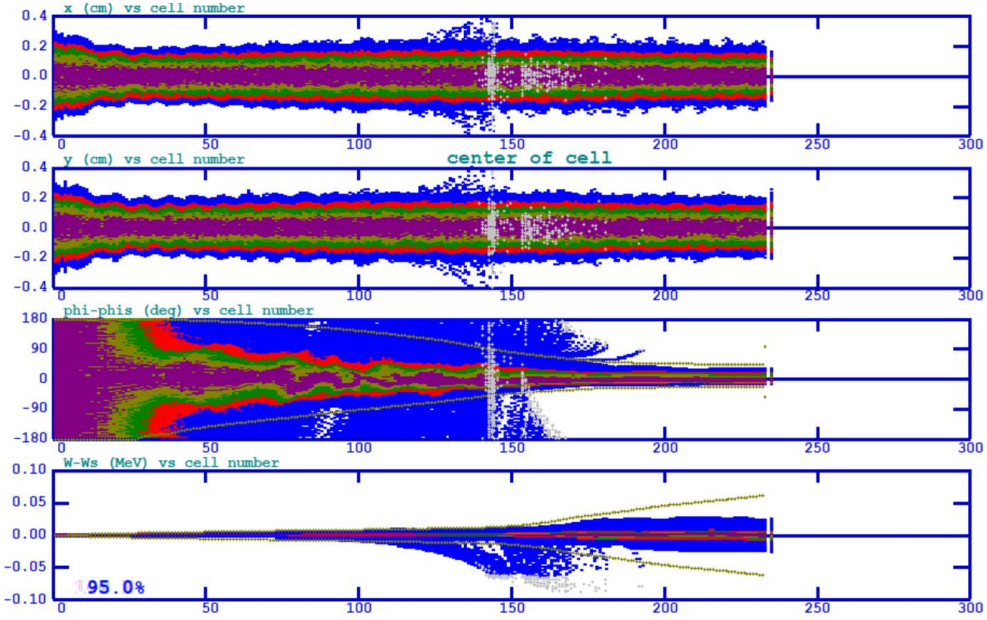
Parameters	Injector II	CiADS	Unit
Frequency	162.5	16.5	MHz
Energy	0.35/2.1	0.35/2.1	KeV
Beam current (CW)	15	15	mA
Vane Tip Voltage	65	65	kV
Minimum aperture	0.317	0.308	mm
Max. surface.field	15.77	15.88	MV/m
RFQ Length	4.2	4.57	meters
Acceleration efficiency	99.6	95	%
99.9% longitudinal ε	8.15	4.98	π.mm.mrad
TWISS, α_x, β_y	1.21, 4.79	0.75, 6.95	cm/rad
Modulation m_{max}	2.35	2.43	
ρ/r_0	0.75	0.75	

Beam dynamics results

Number: 10000

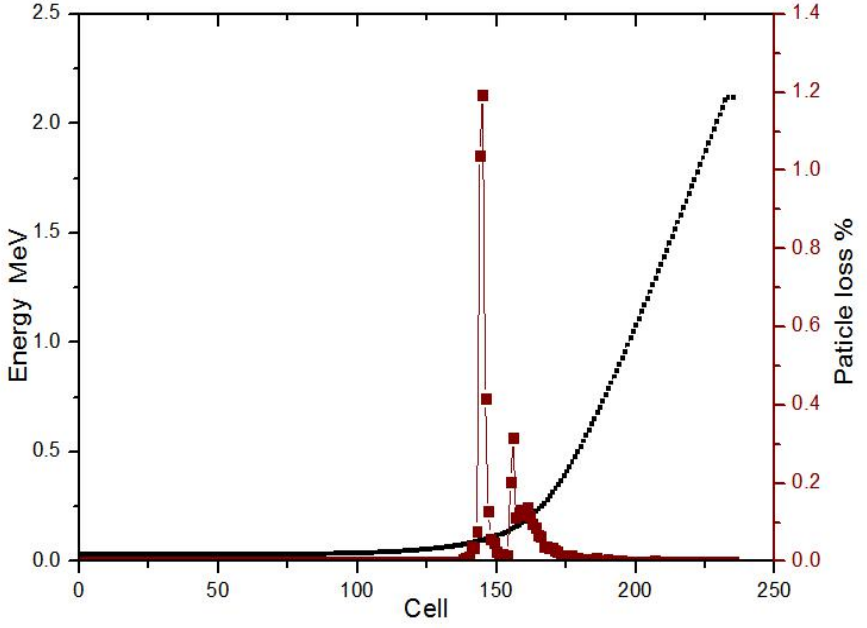
Distribution: WATERBAG

	alpha	beta (cm/rad)	Emit,n,rms (cm-mrad)
x:	0.75	6.95	0.02
y:	0.75	6.95	0.02



Beam transmission of CiADS RFQ, using RFQgen code

The ratio of loss particles with the energy higher than 0.5 MeV is smaller than one over ten thousand



Particle loss in CiADS RFQ

Benchmarking

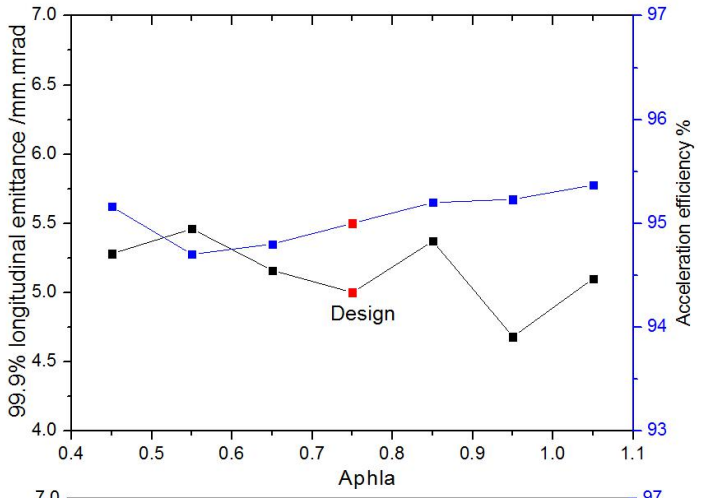
Particle: 10000 Unit: π.mm.mrad

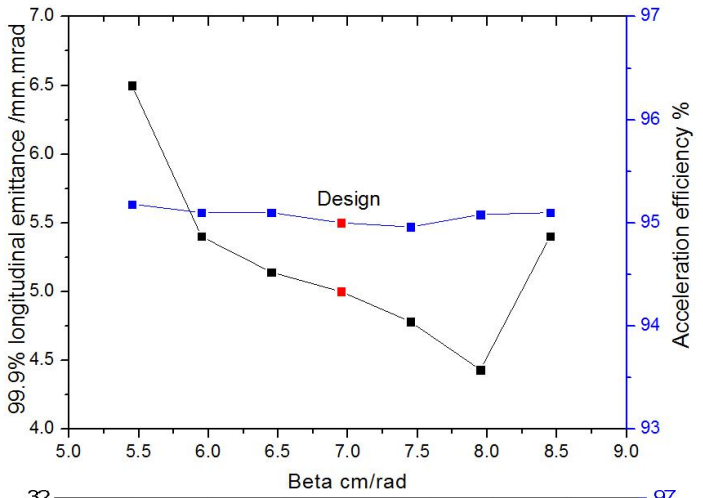
Code: Toutatis

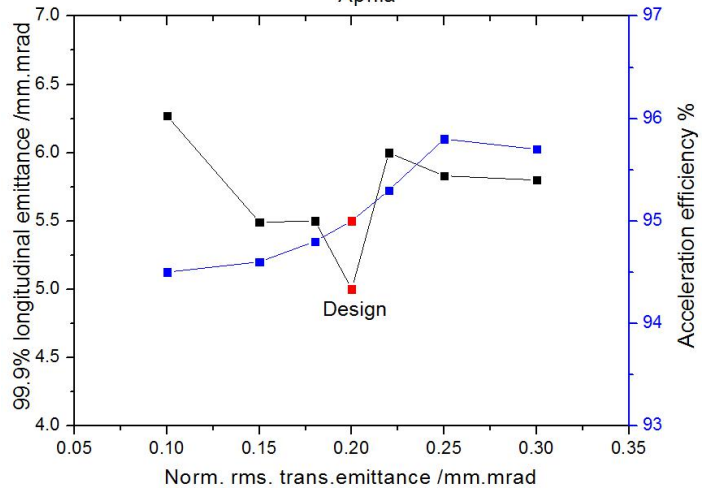
	acceleration efficiency	99.9% longitudinal emittance
In rfqgen	95%	4.98
In toutatis	96.96%	5.67

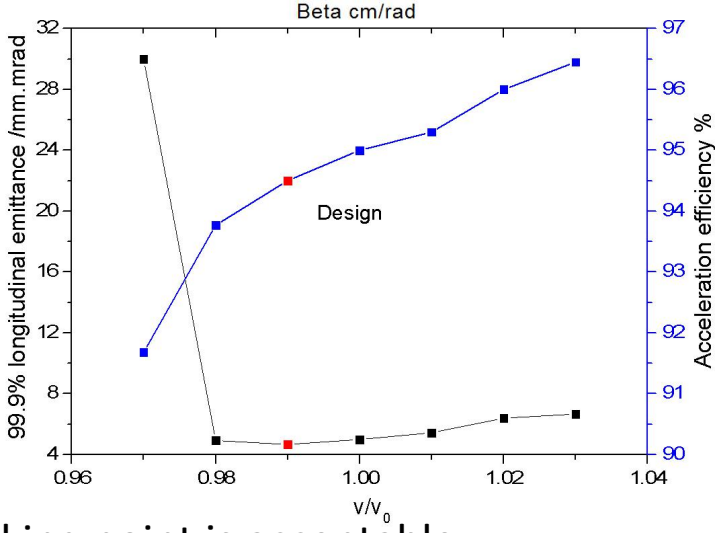
In toutatis code, the acceleration efficiency and 99.9% longitudinal emittance are slighty larger than in rfqgen code. This is due to different particle loss criteria

Mismatch analysis



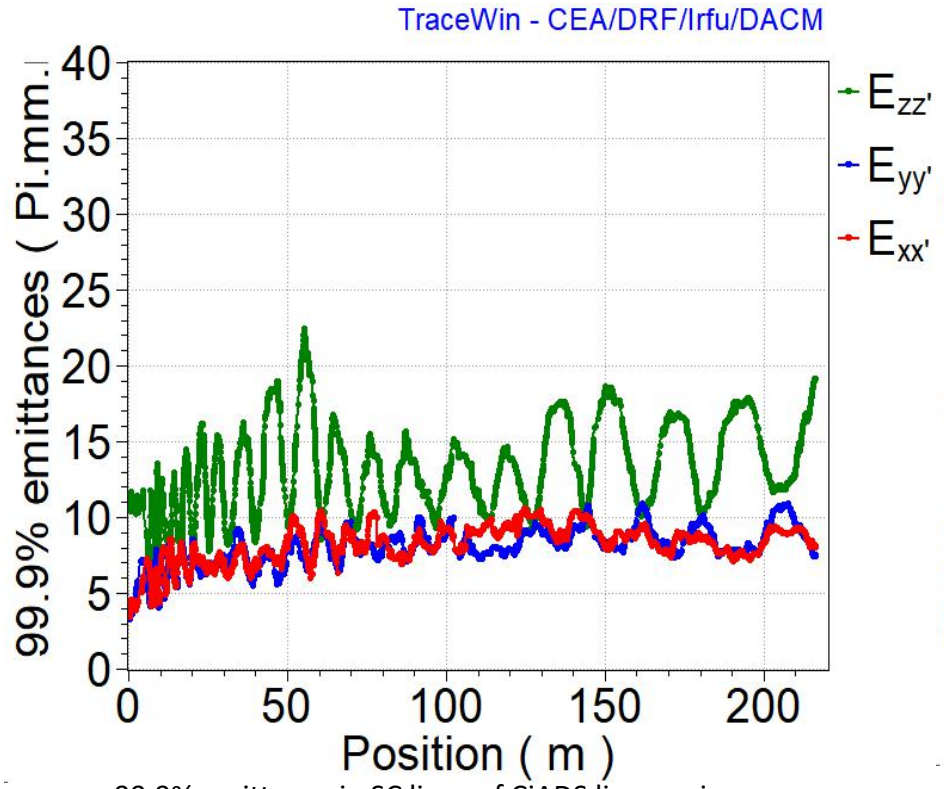




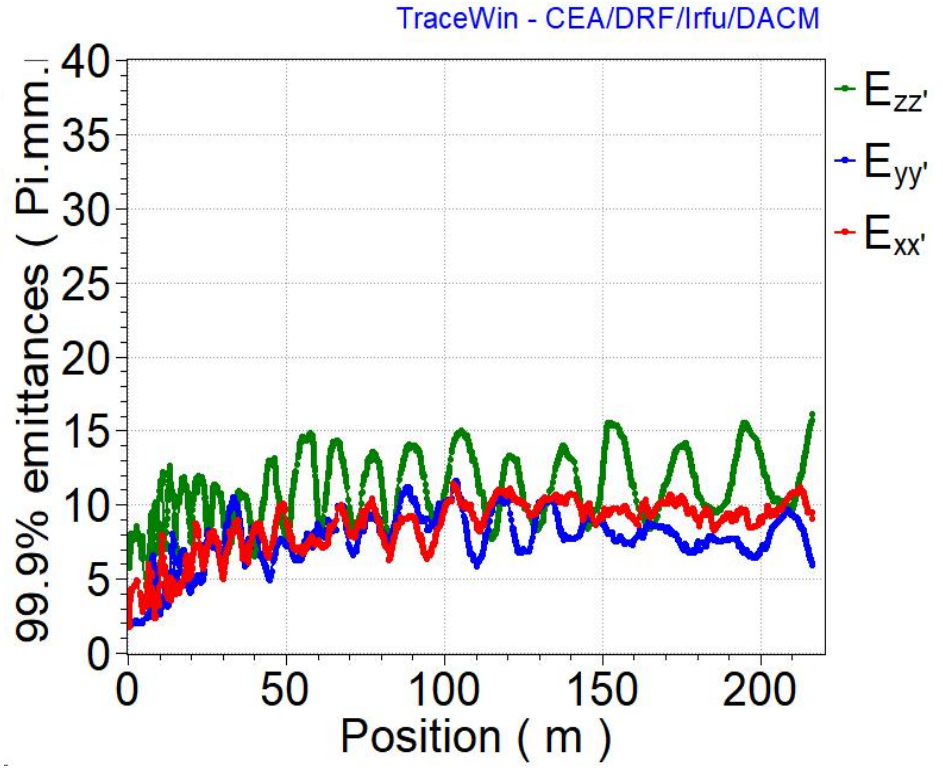


The mismatch tolerance of working point is acceptable

Combination simulation



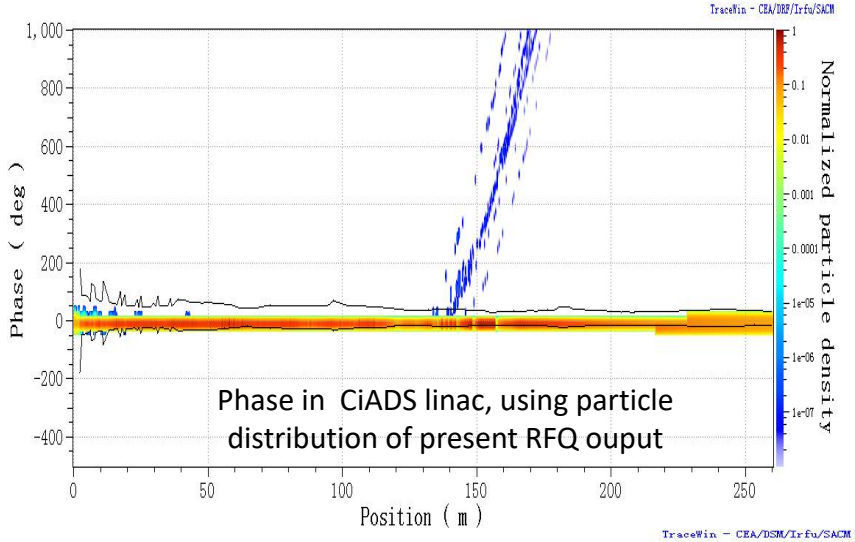
99.9% emittance in SC linac of CiADS linac, using distribution of present RFQ ouput

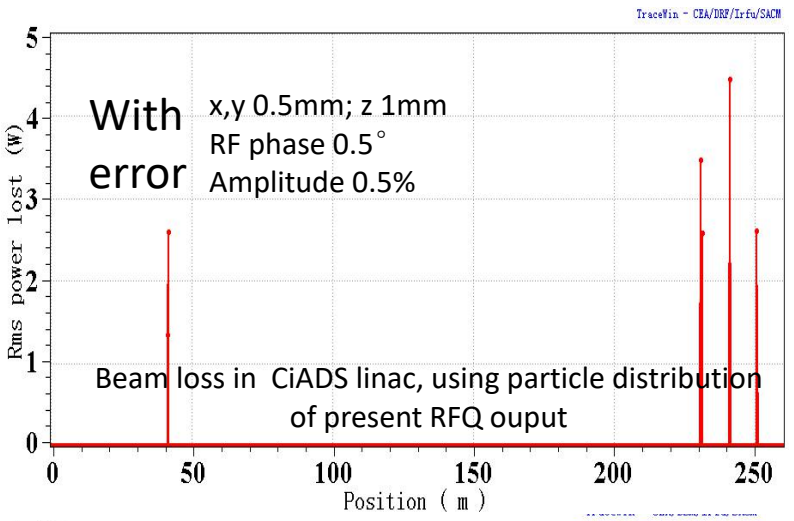


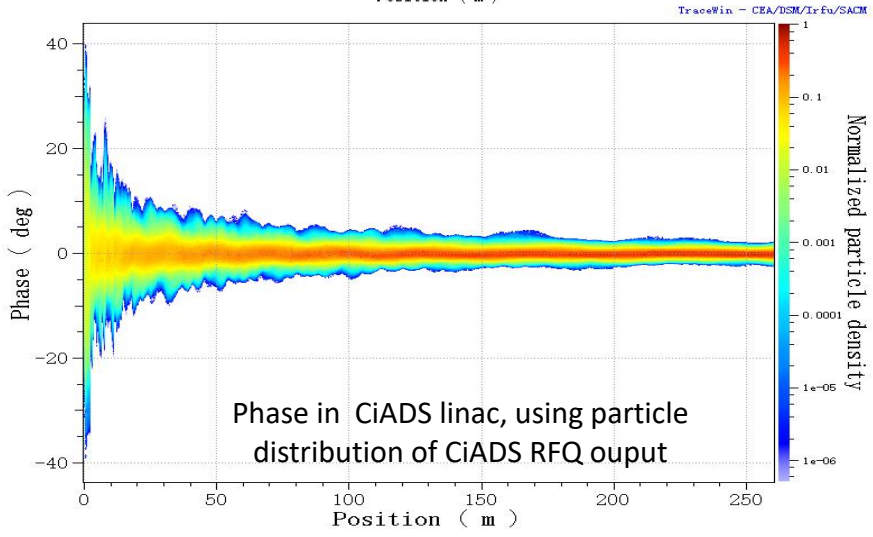
99.9% emittance in SC linac of CiADS linac, using distribution of CiADS RFQ output

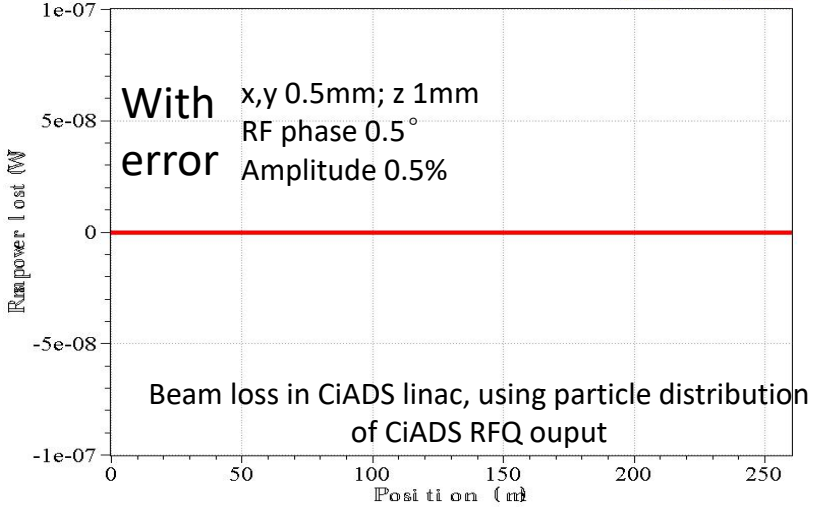
Using distribution of CiADS RFQ, the 99.9% longitudinal emittance along the CiADS SC linac reduce around 32 percent, it means smaller possibility of beam loss in SC linac

Combination simulation









Summary

1. In order to reduce possibility of beam loss in SC linac, the 99.9% longitudinal emittance is proposed as a key parameter in CiADS RFQ design
2. Small energy acceptance inside RFQ is adopted to reduce the output 99.9% longitudinal emittance
3. The acceleration efficiency of CiADS RFQ is 95%. 99.9% longitudinal emittance is reduced to 4.98 π.mm.mrad
4. When distribution of CiADS RFQ ouput is adopted, the 99.9% longitudinal emittance along the CiADS SC linac reduce around 32 percent. There is no beam loss in SC linac

Thanks for your attention !