CW commissioning of China ADS Front-end demo Linac and CIADS project

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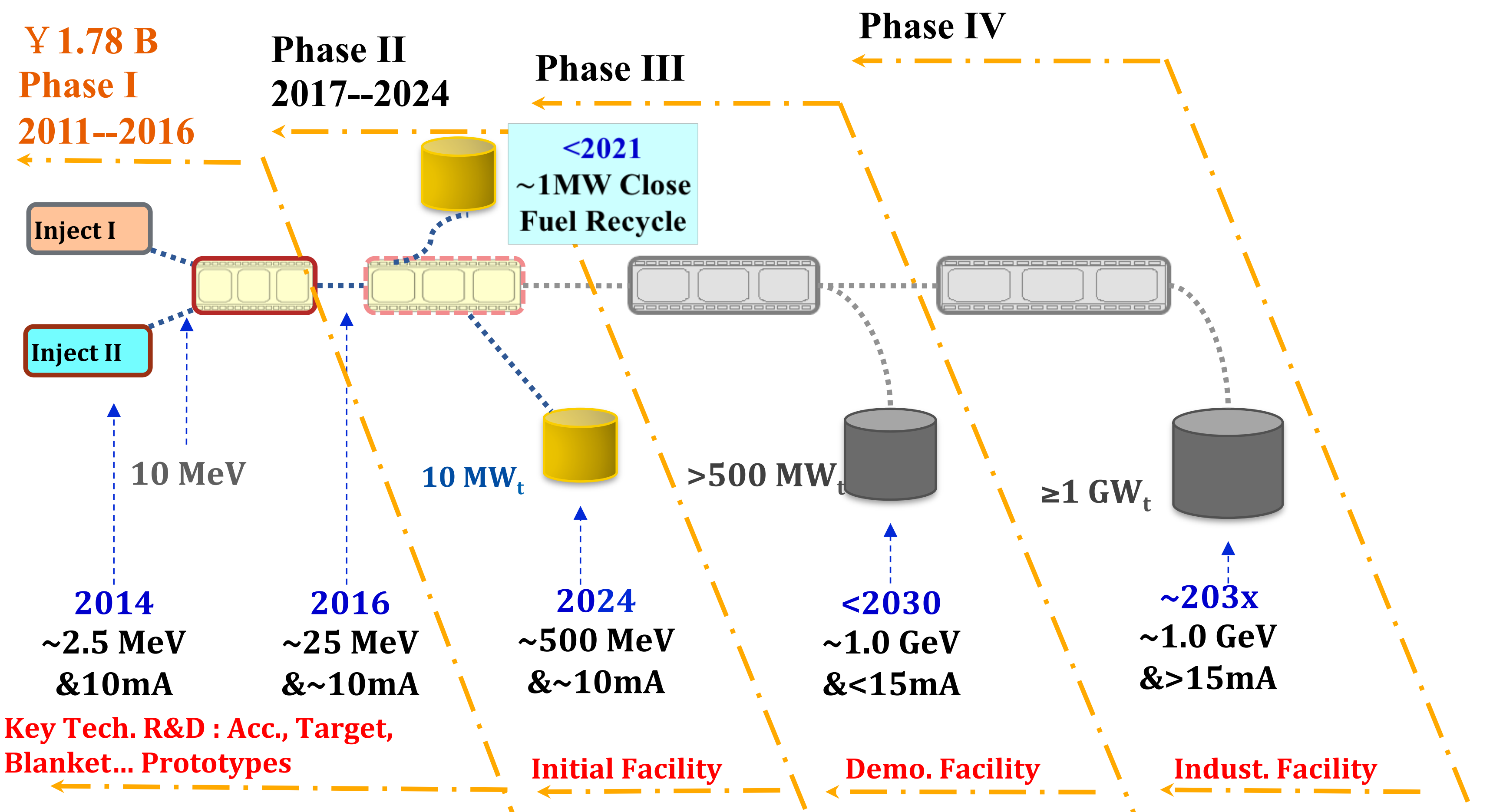
Outline

- **Introduction of China ADS driven linac**
- Beam commission of Chinese ADS Front-end Demo Linac (CAFe)
- Preliminary design of CiADS Linac
- Summary

ADS/ADANES Roadmap in China



"strategic Priority Research Program" of the Chinese Academy of Sciences

CiADS

Outline

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- **Beam commission of Chinese ADS Front-end Demo Linac (CAFe)**
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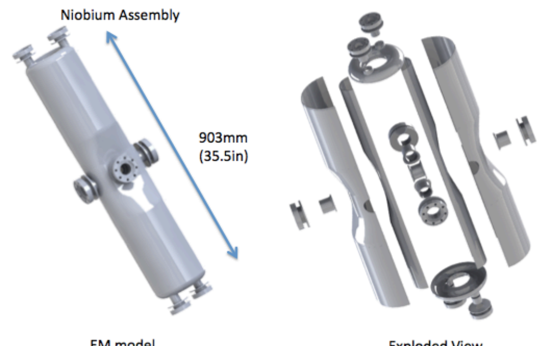
ADS Front-end Demo Linac (2011-2017)

	RFQ/IMP	CM1/IMP	CM2/IMP	CM3/IMP	CM4/IHEP
frequency	162.5 MHz	162.5 MHz	162.5 MHz	162.5 MHz	325 MHz
output energy	2.1 MeV	5 MeV	10 MeV	18.5 MeV	25 MeV
cavity type	4-vane	HWR010	HWR010	HWR015	Spoke021
cavity number	1	6	6	5	6

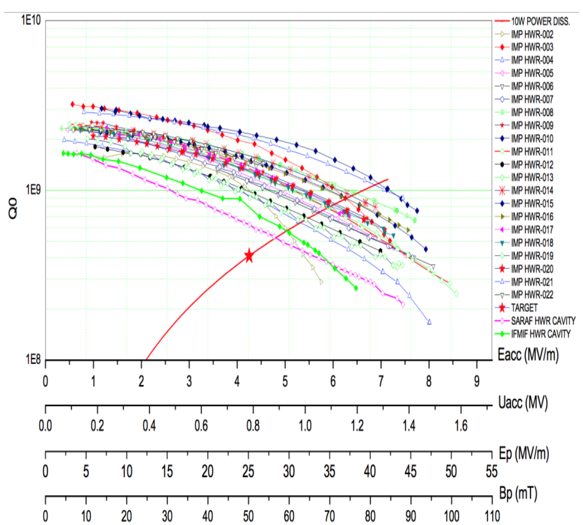
- **Design: Proton, 25 MeV, 10 mA, CW, ~ 35 m, 4.5 K operation**
- **IMP collaboration with IHEP**
- **Major target: to demonstrate the technology of 10 mA CW beam of superconducting linac at the front-end: CW RFQ, Superconducting cavities, Cryomodule**
- **Supported by "Strategic Priority Research Program" of the Chinese Academy of Sciences**

Specifications of SC-cavities

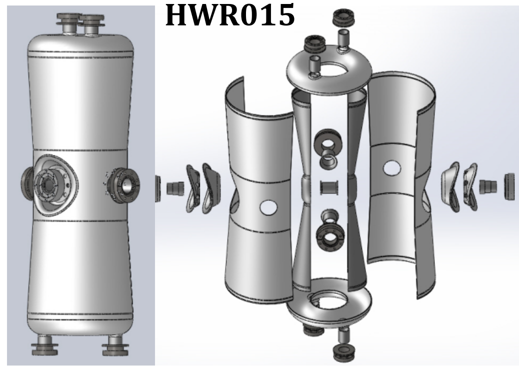
162.5 MHz Half-wave Cavity



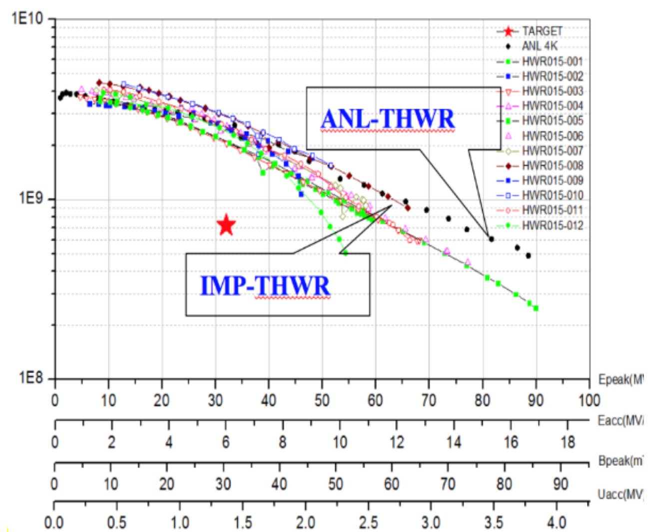
βopt	0.10
Vmax (MV)	1.06
Epeak (MV/m)	28



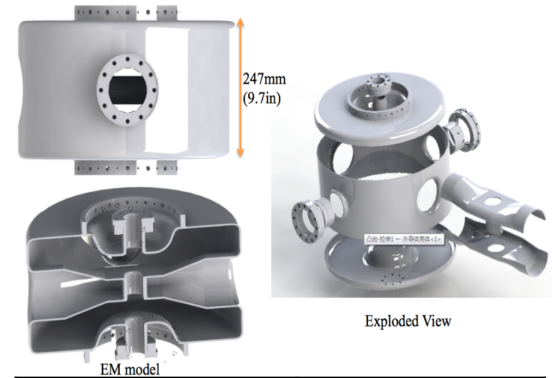
162.5 MHz Taper HWR015



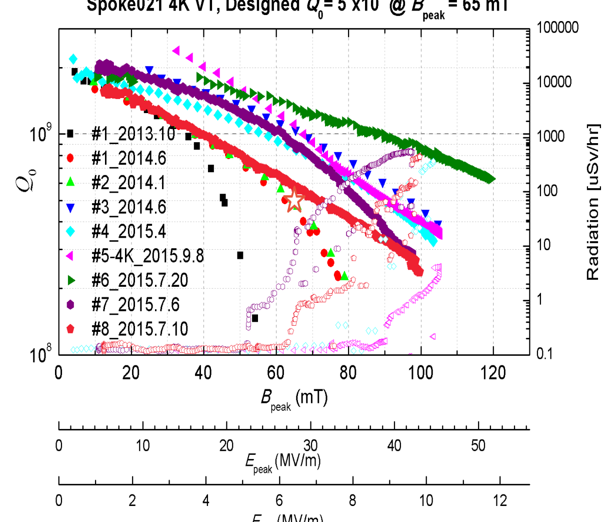
βopt	0.15
Vmax (MV)	1.8
Epeak (MV/m)	32



325 MHz Spoke cavity

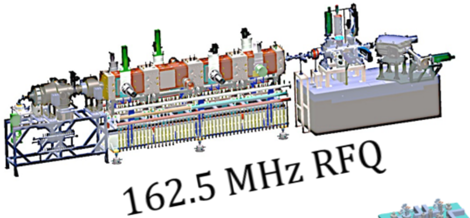


βopt	0.246
Vmax (MV)	1.75
Epeak (MV/m)	32.5



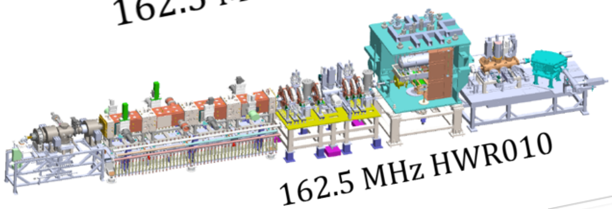
Beam Commissioning since 2014

1



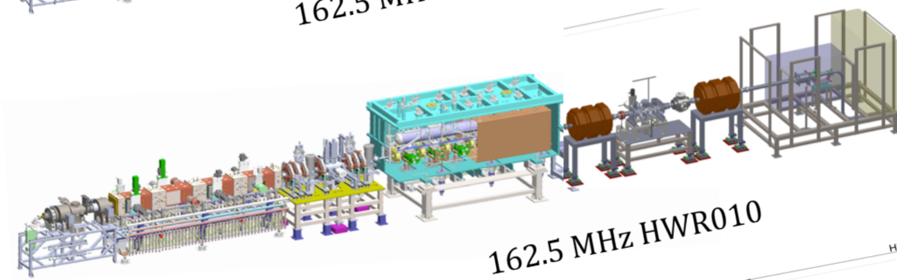
- ECRIS + RFQ
- Energy is ~2.1 MeV
- First beam Jun. 6th, 2014;
- achievement 10 mA, 2.1 MeV, 4.5 hours

2



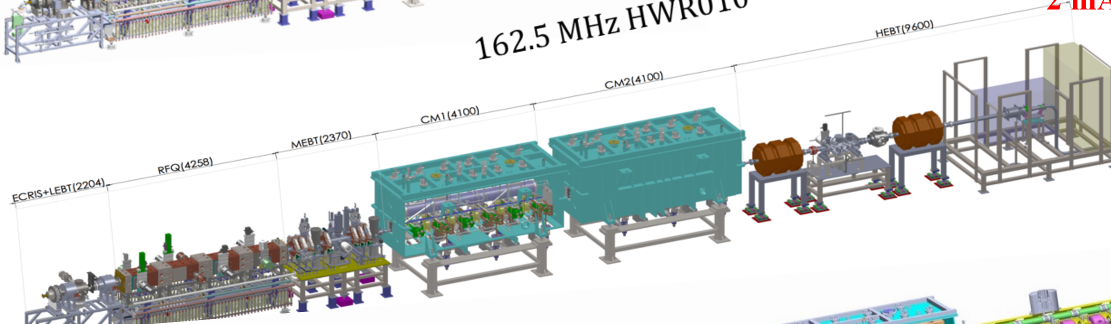
- ECRIS + RFQ + MEBT + TCM1 (single HWR)
- Energy is ~2.5 MeV
- First beam October 1st, 2014;
- achievement 11 mA, 2.55 MeV

3



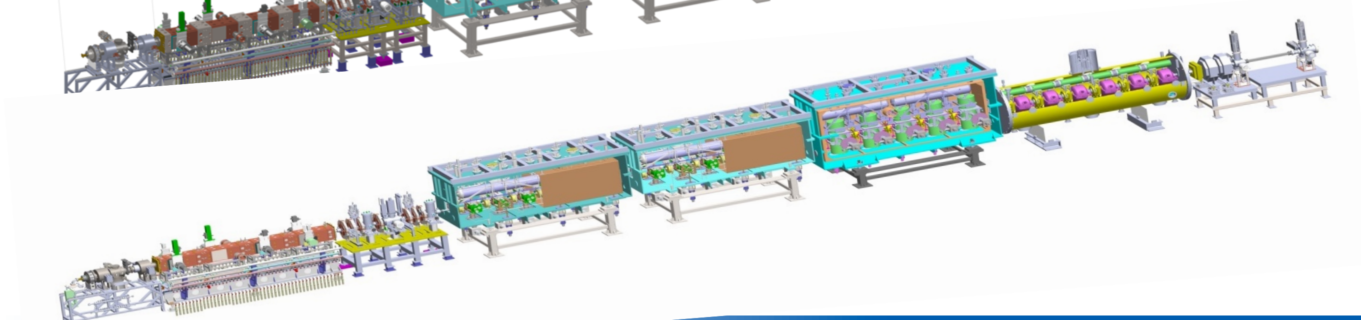
- ECRIS + RFQ + TCM6
- Energy is ~5 MeV
- First beam June 6th, 2015;
- achievement 2.7 mA, 5.3 MeV; ~7.5 hours
  2 mA 4 MeV operation

4



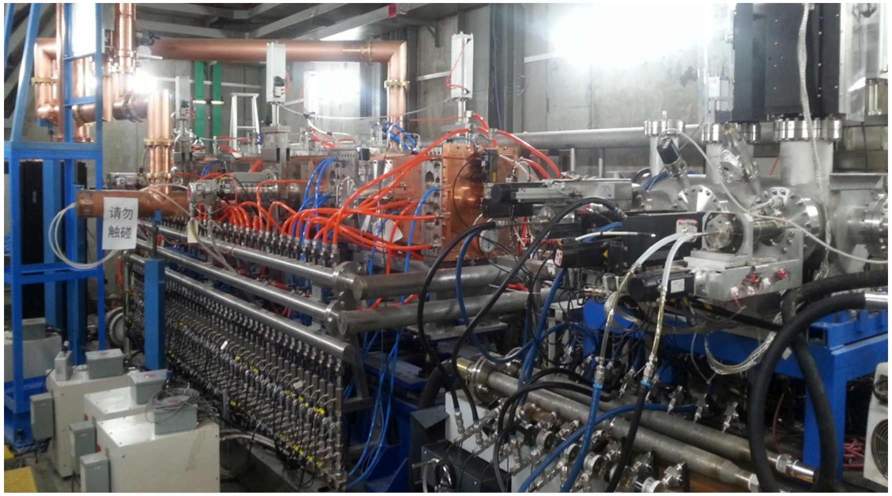
- ECRIS + RFQ + CM1 + CM2
- Energy is ~10 MeV
- First beam September 15th, 2016
- Achievement ~ 2.7 mA, 9.55 MeV

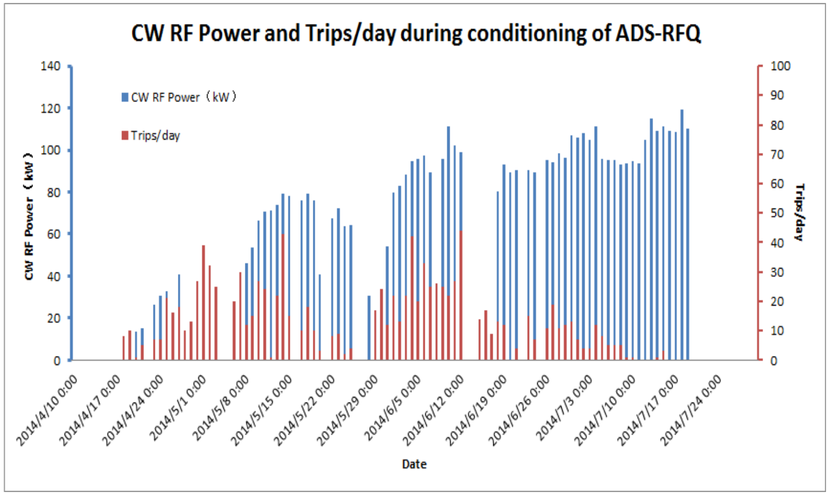
5



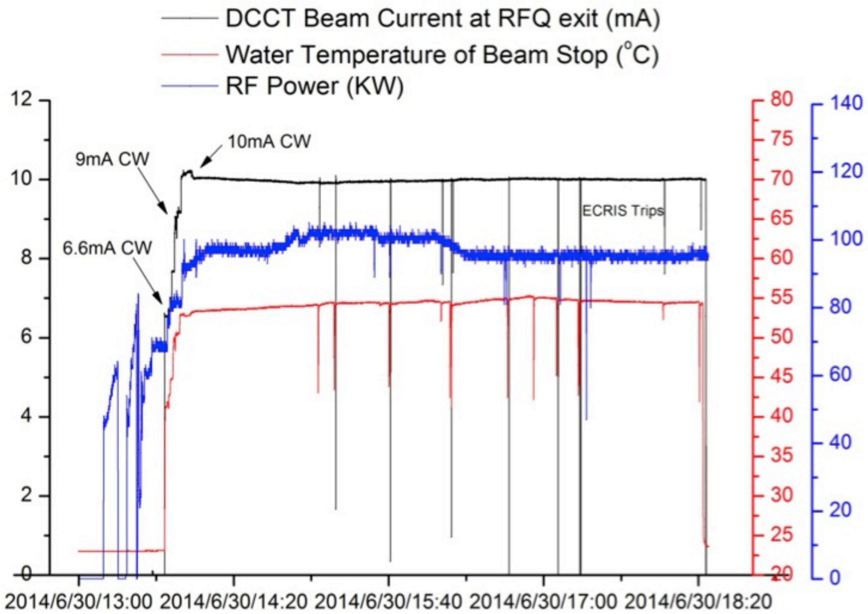
- ECRIS + RFQ + CM1 + CM2 + CM3 + CM4
- Energy is ~25 MeV
- First beam May 28th, 2017
- Achievement 0.2 mA 25 MeV

Commissioning of RFQ



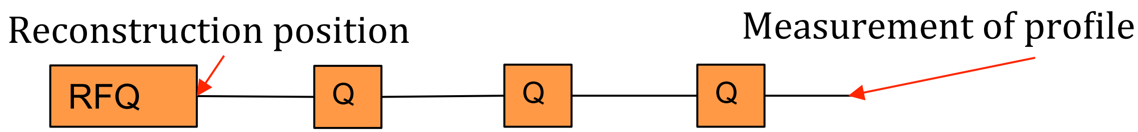


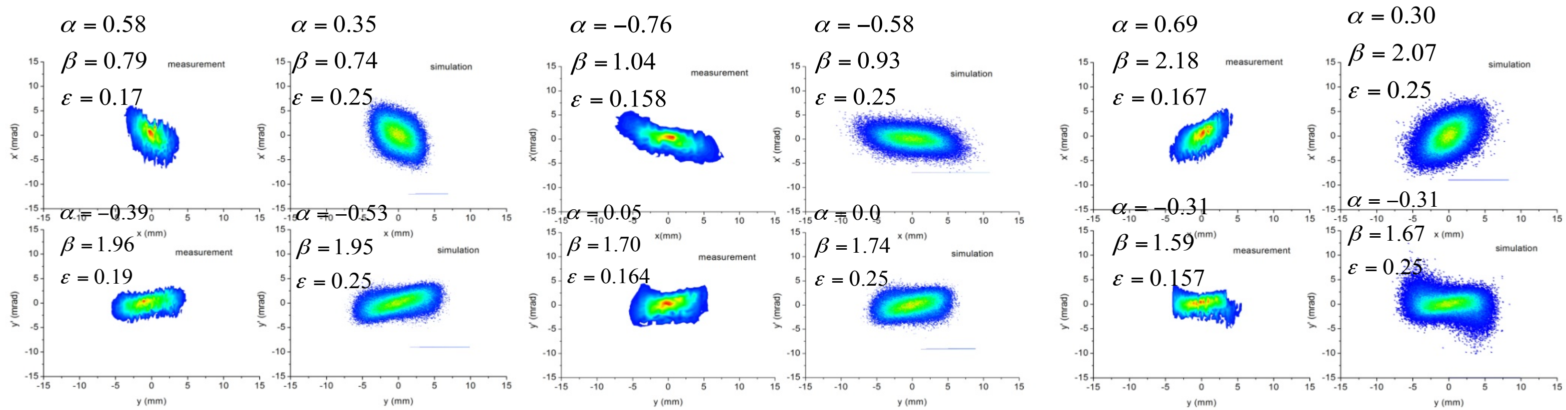
- Apr. 17 to Jun. 6 '14, conditioned to 90 kW
- **June 6th, 2014， the first beam, 2.16 MeV**
- **June 21st, the first CW beam @ 2 mA**
- **June 30th， 10 mA, CW, 21 kW, 4.5 hours, transmission >97%**
- **CW RF Operation > 6000 hours , 2000 hours with beam**



Beam re-construction in MEBT

Re-construction of beam distribution



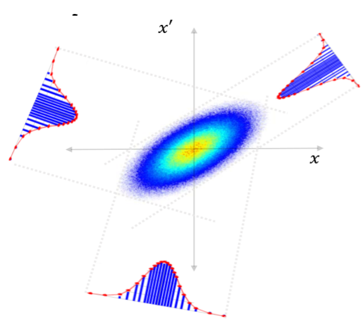


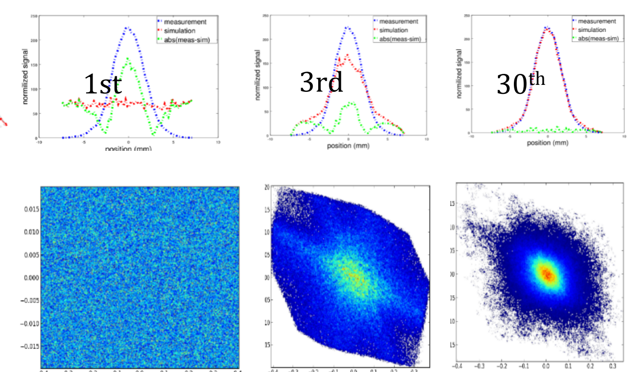
Objection：

- Reconfiguration of four dimension emittance with space charge effect

Challenge：

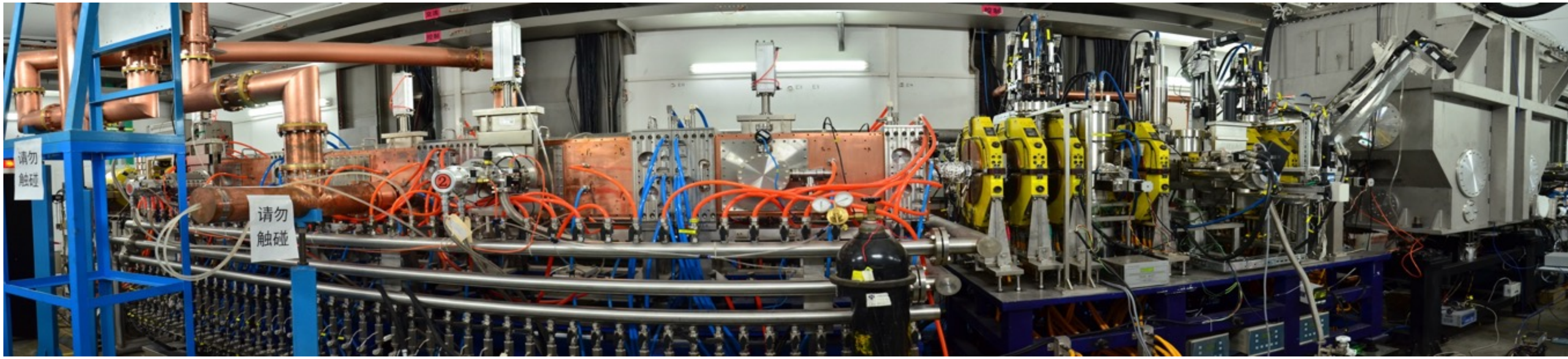
- Nonlinear space charge effect
- RF nonlinearity

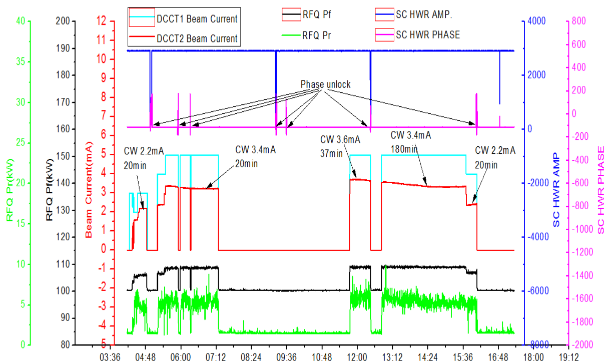


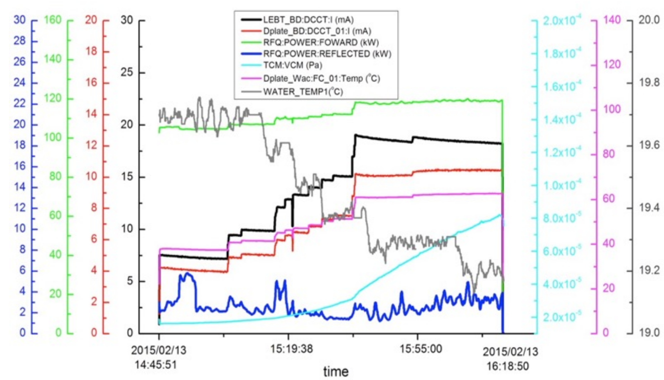


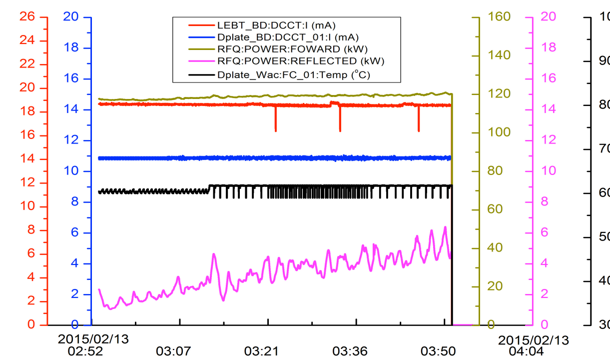
Configuration of SC linac base on the re-constructed beam

CW Beam Commission to 11 mA









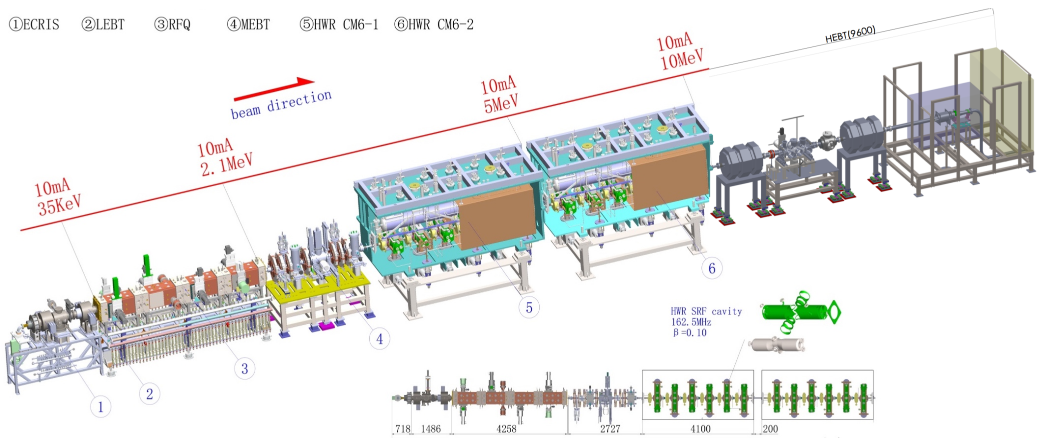
- **Nov.25th, 2014, first CW,**
- **3.4 mA, ~6 hours.**

- **Feb. 4th, 2015, 4.2~10.8 mA,**
- **2.5MeV, CW**

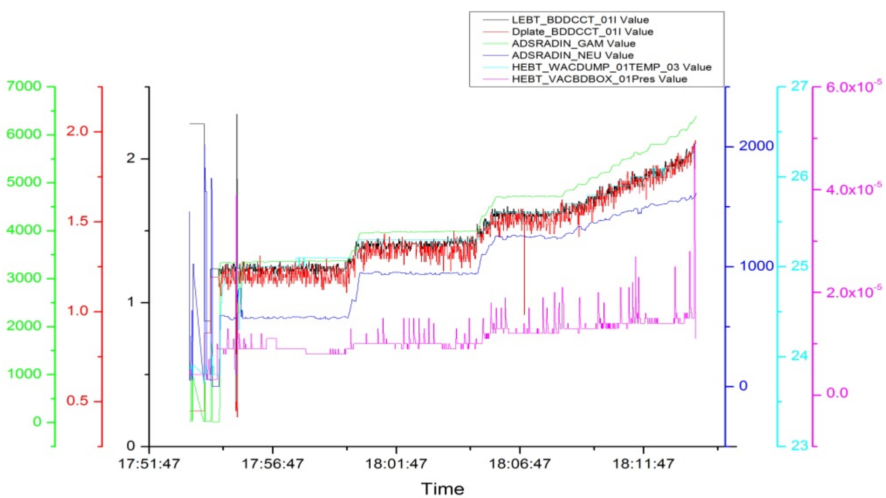
- **Feb. 23rd, 2015, achieved 2.5MeV/ ~11mA/28kW, ~1 hour**

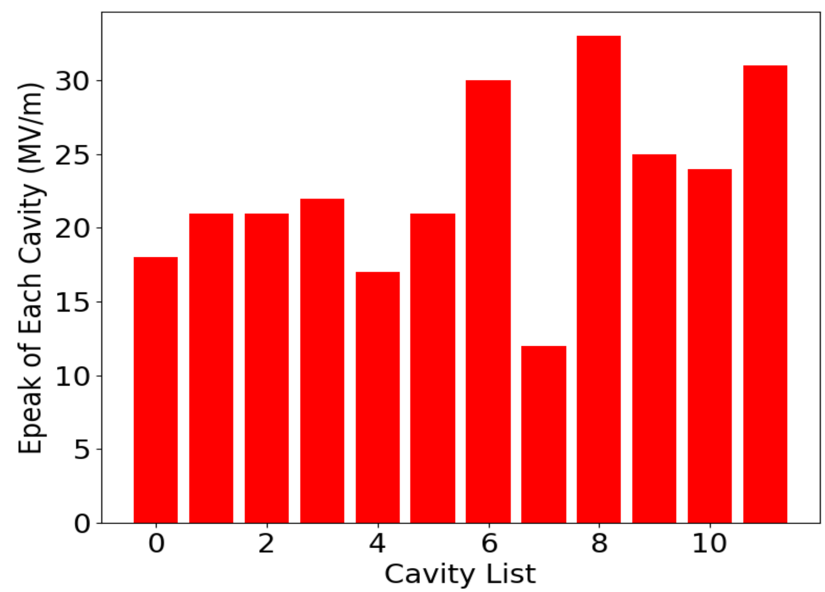
- RFQ works with two bunches and one HWR, RF frequency can not change any more like working alone.
- Due to detuning of 3 mA beam-loading, Pr is 5 kW, but it is still stable.
- 10 mA beam will cause ~8 kHz detuning of RFQ, Pr is large enough to shut down AMP.
- Frequency tuned by temp. of 0.5 C to keep Pr stable.

CW Commissioning of 10 MeV

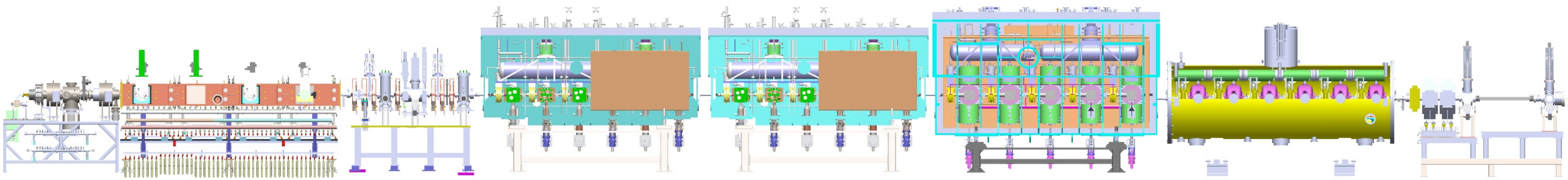


NOV 27^{th}-28^{th},20 minutes CW beam operation at 1.2 - 2.7 mA with out uncontrolled beam loss



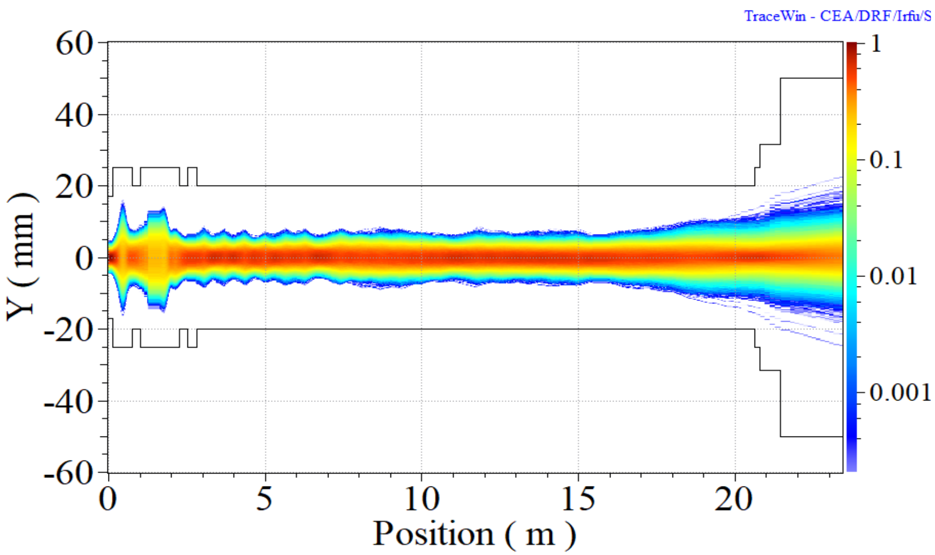


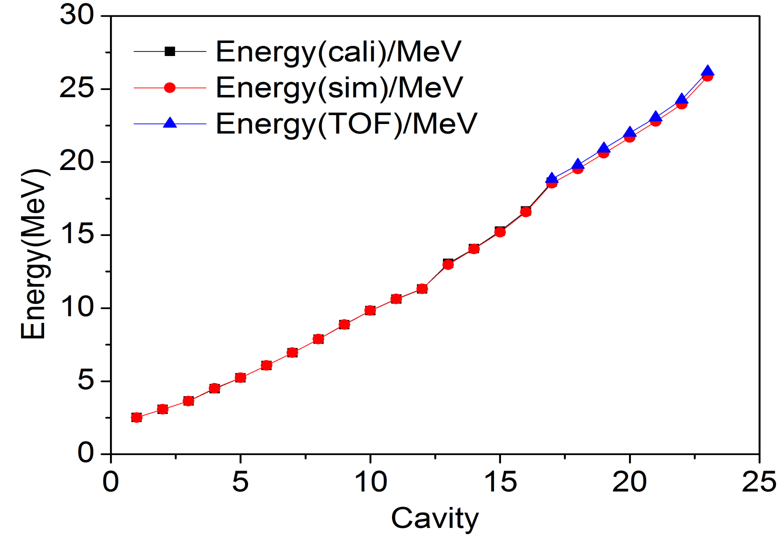
The first beam commissioning of CAFe

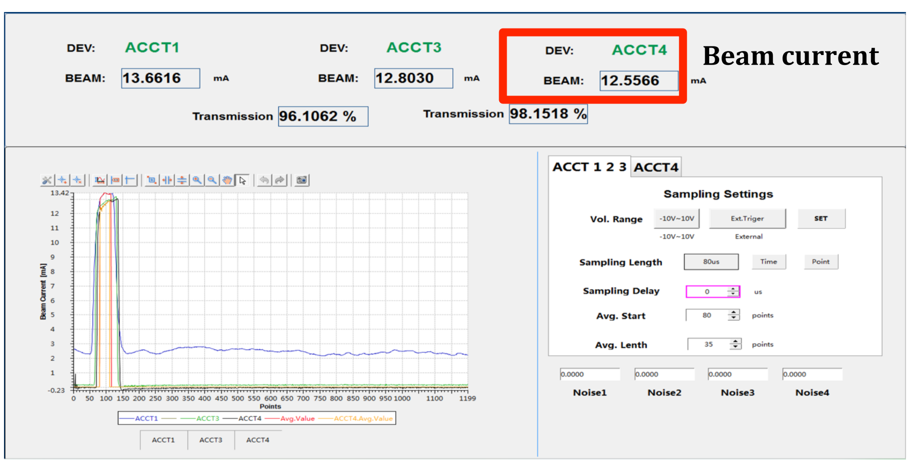


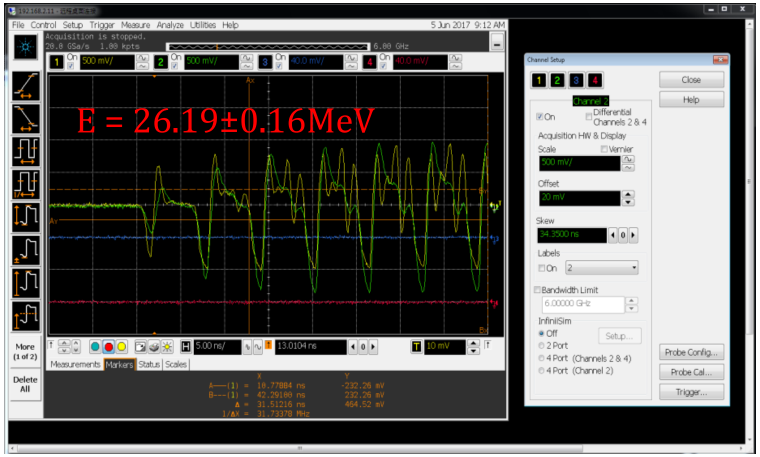
- CM1,CM2 were re-installed in Feb 2017;
- CM3 and CM4 were on line on May. 9th , 2017;
- First beam was achieved on May. 28th , 2017 ;
- The energy is up to 26.2 MeV on June. 5th , 2017;
- CW beam with energy 25MeV went through on June 6th , 2017.

Pulse Beam Commissioning

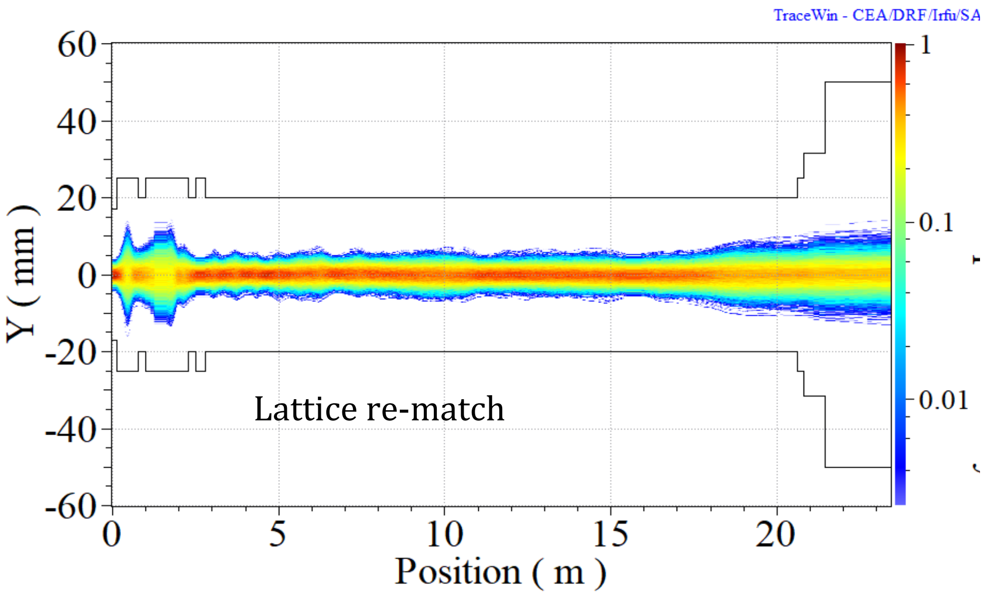


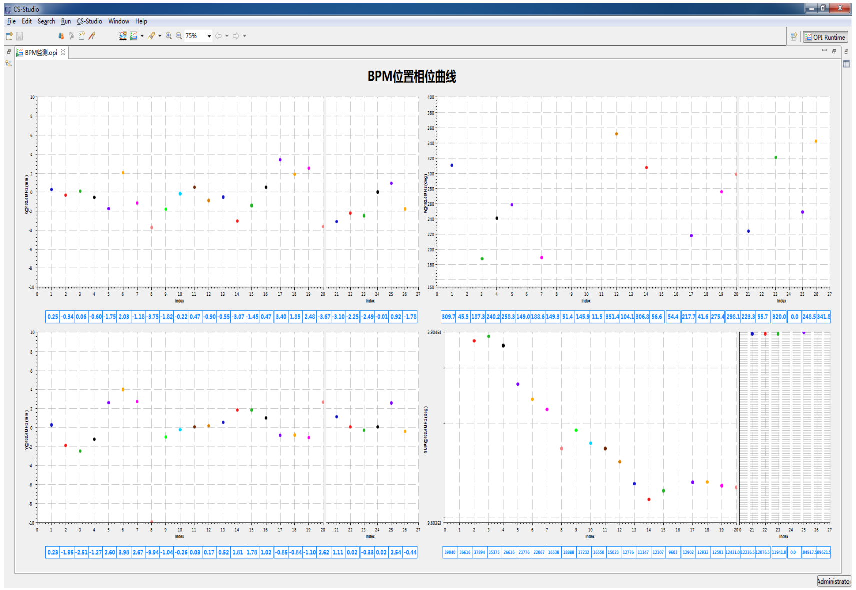




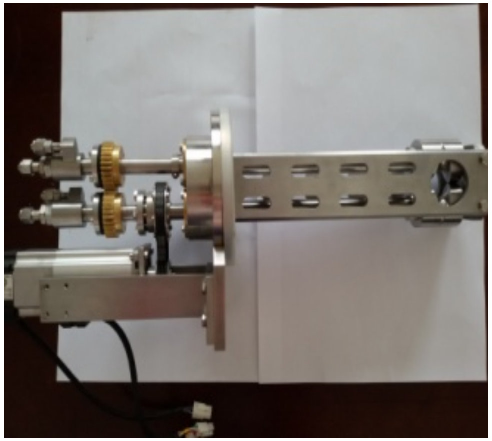


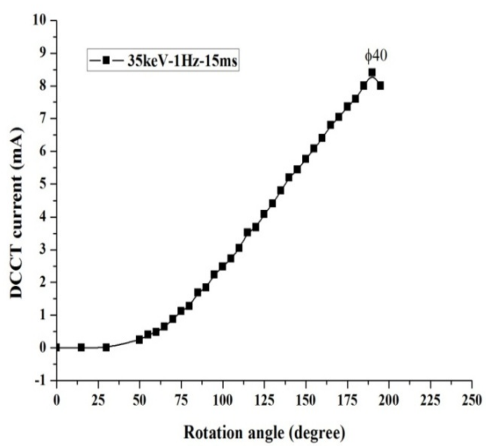
First CW Beam Tuning

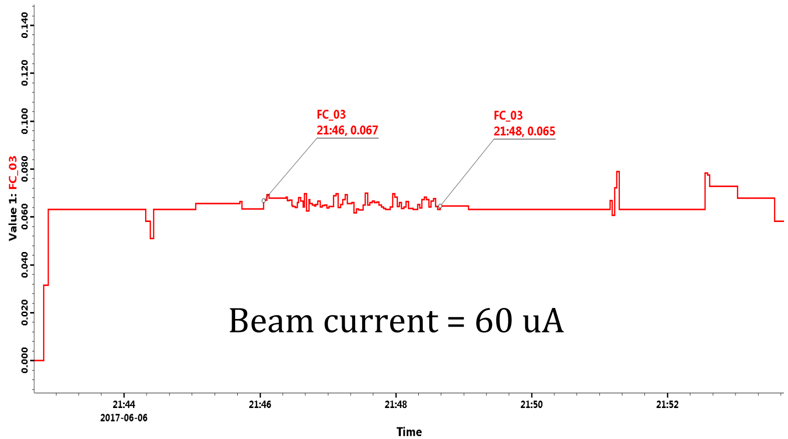




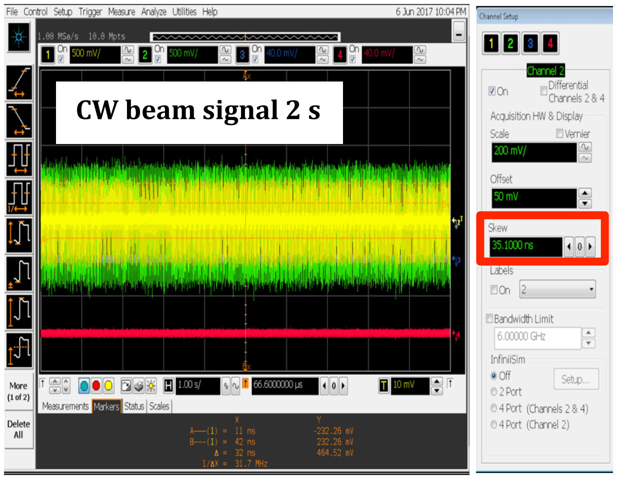
Orbit deviation < ±4 mm

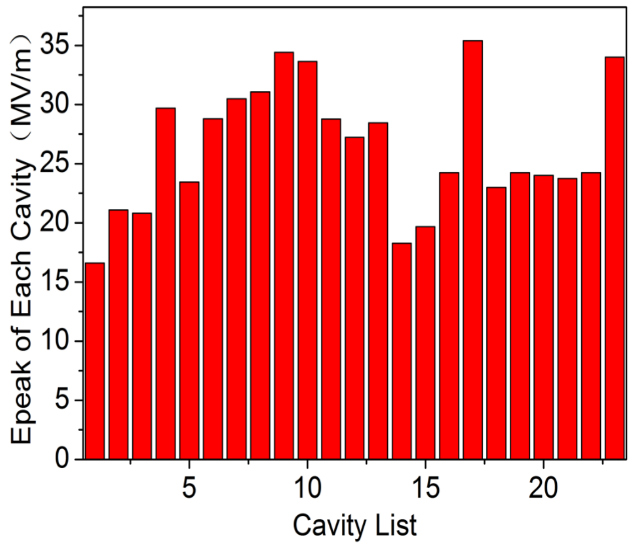


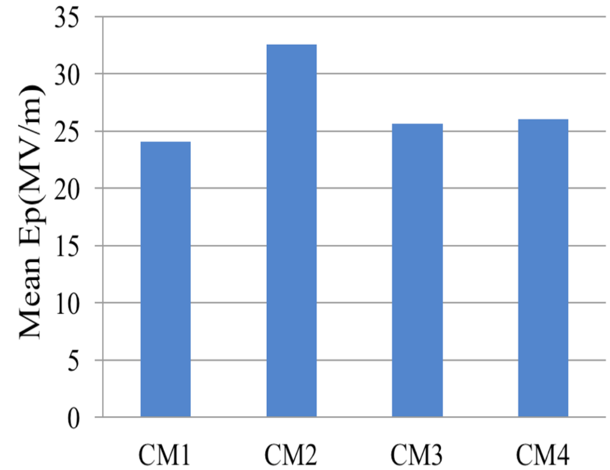


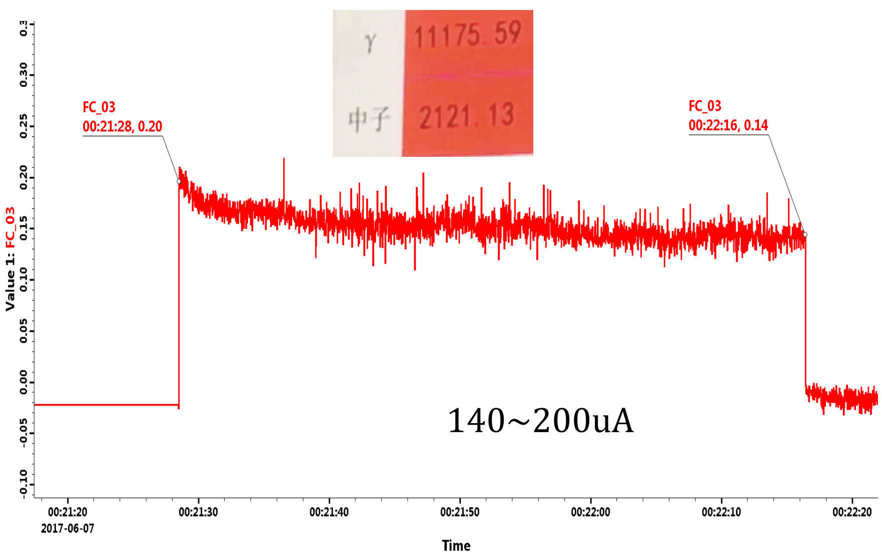


First CW Beam Commissioning





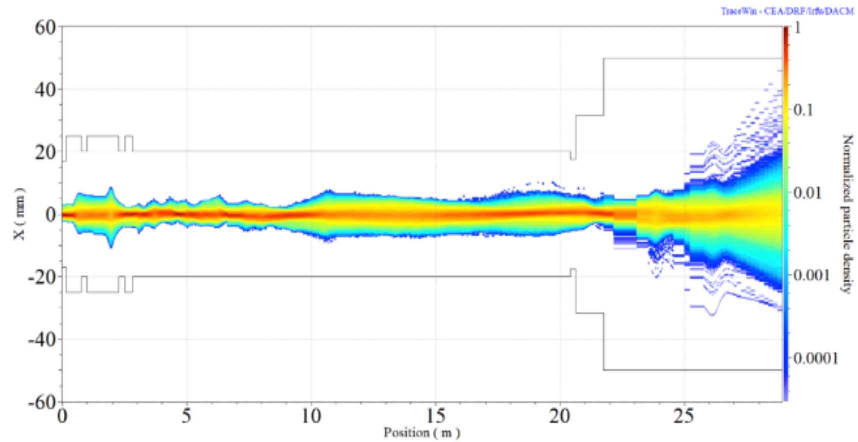


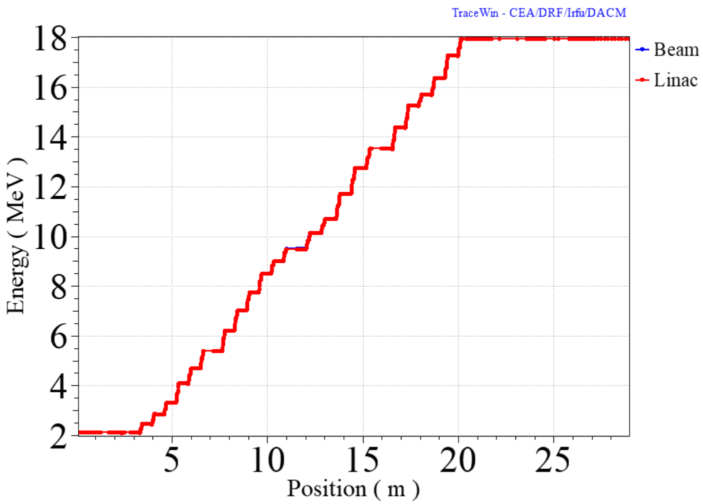


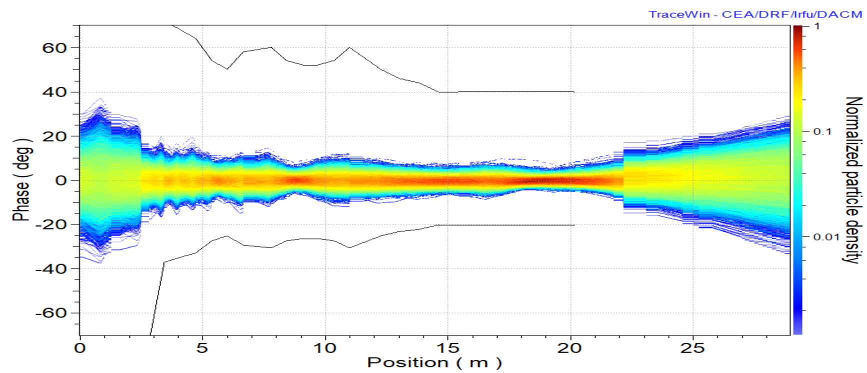
- Beam dump and radiation shielding are the limit to higher beam power and long time operation.
- No evident beam loss observed by temperature sensors

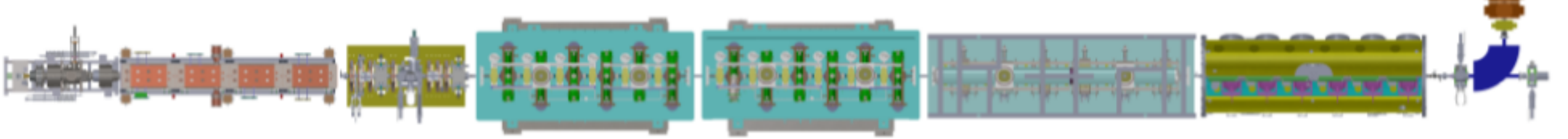
Machine Reliability Operation

- Operation in December 2017, ~18 MeV, Bending beam to the 100 kW dump
- Plan to operate pulse beam for 72 hours with 1 mA and 10 mA
- Plan to operate CW beam for 72 hours with 0.2 mA
- Current leads cooling trouble limit the transversal focus in CM3



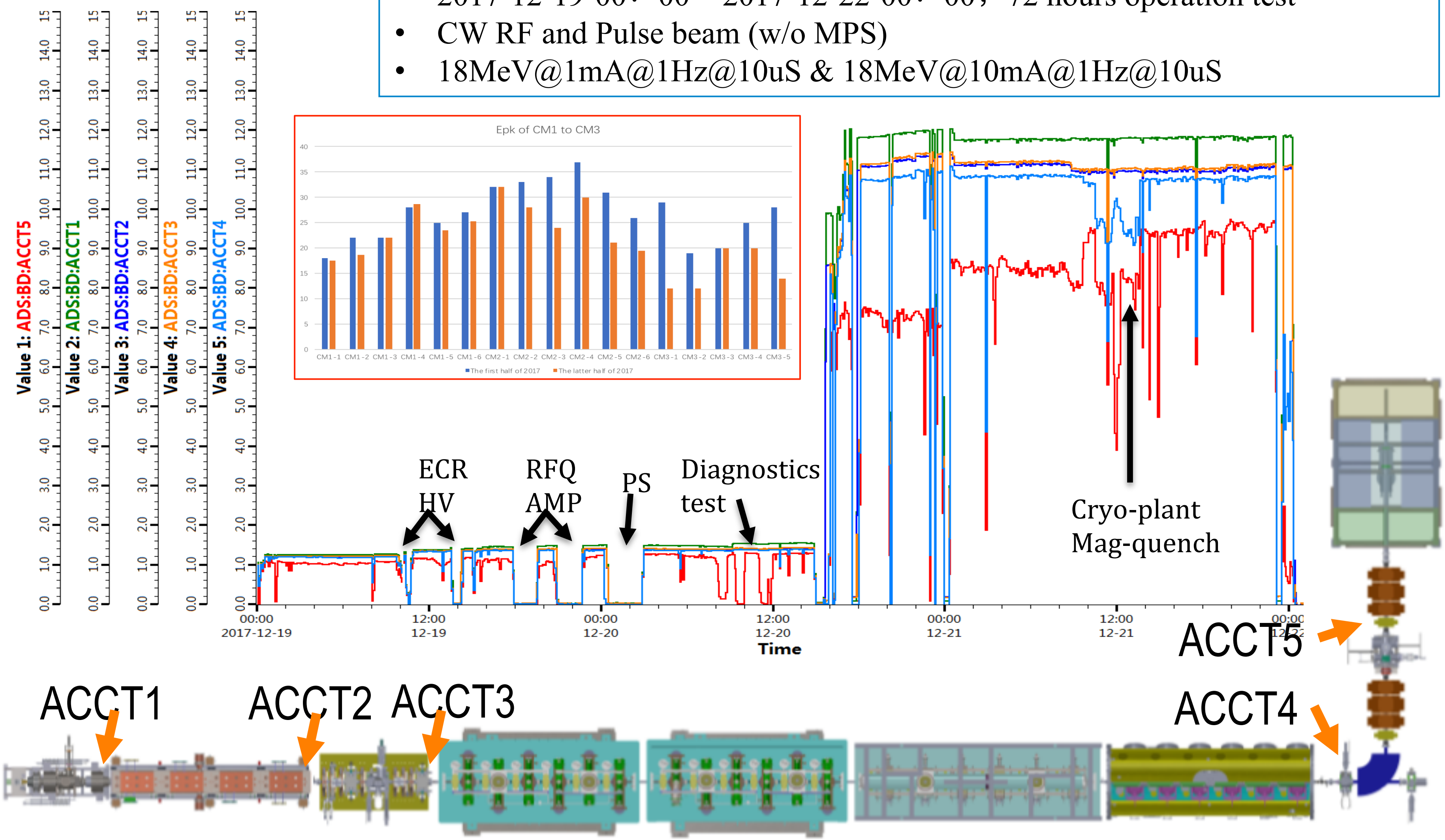






Reliability of pulse beam operation

- 2017-12-19-00：00 ~ 2017-12-22-00：00；72 hours operation test
- CW RF and Pulse beam (w/o MPS)
- 18MeV@1mA@1Hz@10uS & 18MeV@10mA@1Hz@10uS



Preliminary RAMI analysis

Beam trip required by ADS demo facility	
Beam trips（10s-5min）	2500/year
Beam trips（>5min）	300/year
Availability	80%

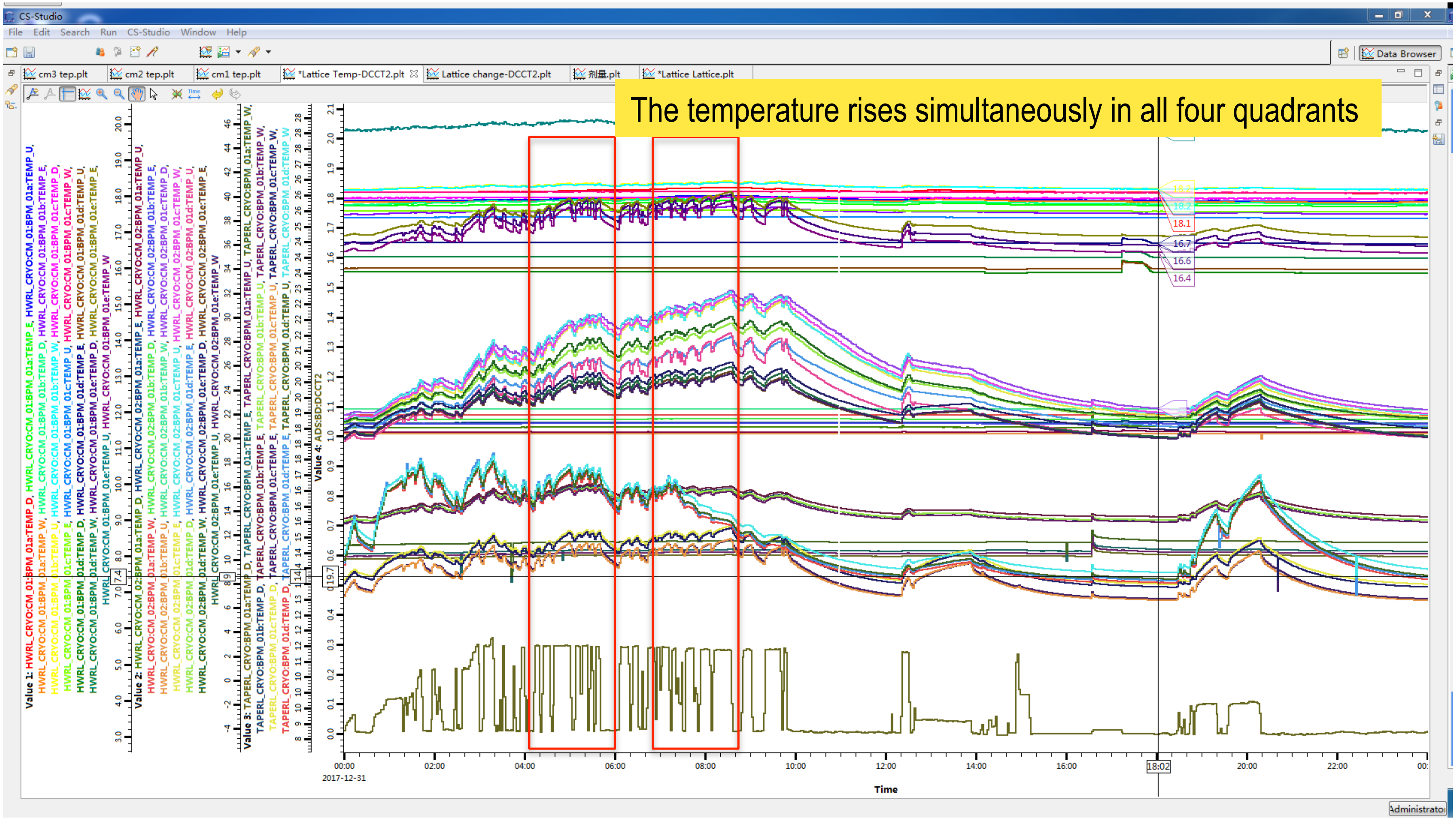
- Some long time repair failures (> 5 min), such as HV, AMP, Cryo-plant, PS, have very clear reason, can be avoided in the next stage
- 10s-5min-trip number is less than the requirement. Root cause of trips of SRF are still under investigation

Operation time	Beam time	Down time	Availability
4050 min	3566 min	484 min	0.88

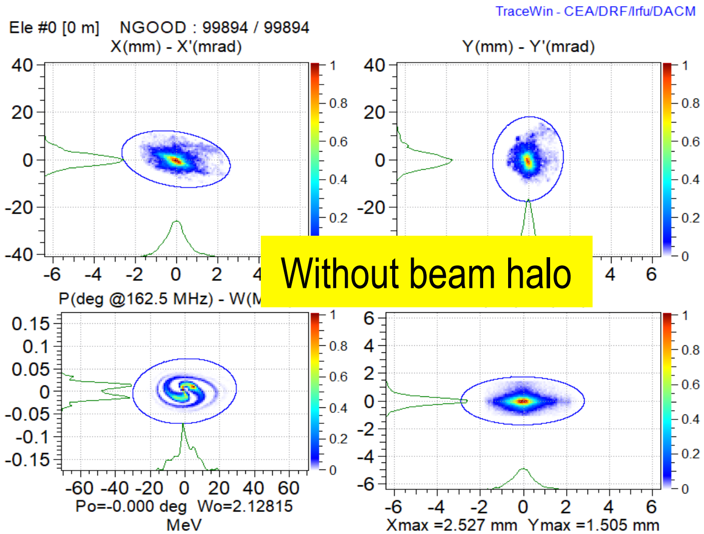
Mean time between failure MTBF (min)	Mean time to repair MTTR (min)	Beam trips (10s-5min)	Beam trips (>5min)
111.4	16.1	20	10

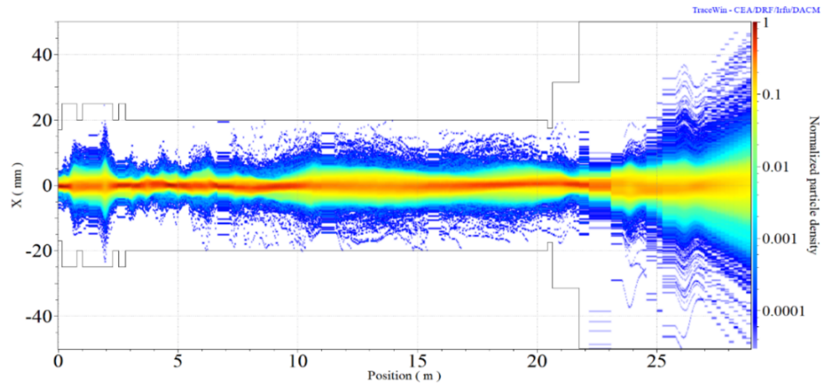
	ECR HV	RFQ AMP	SRF (incl. LLRF)	Cryo-plant	Power supply
Beam trips	6	2	21	1	1
Down time	53 min	77 min	78 min	183 min	100 min

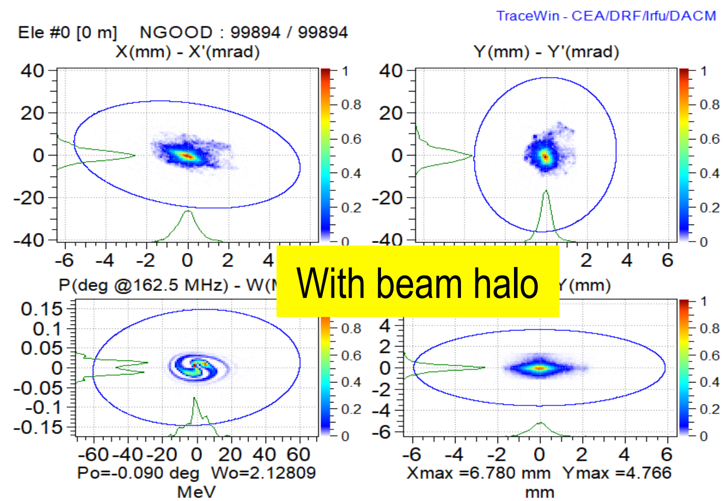
Beam loss study @ CW operation



Beam loss study @ CW operation







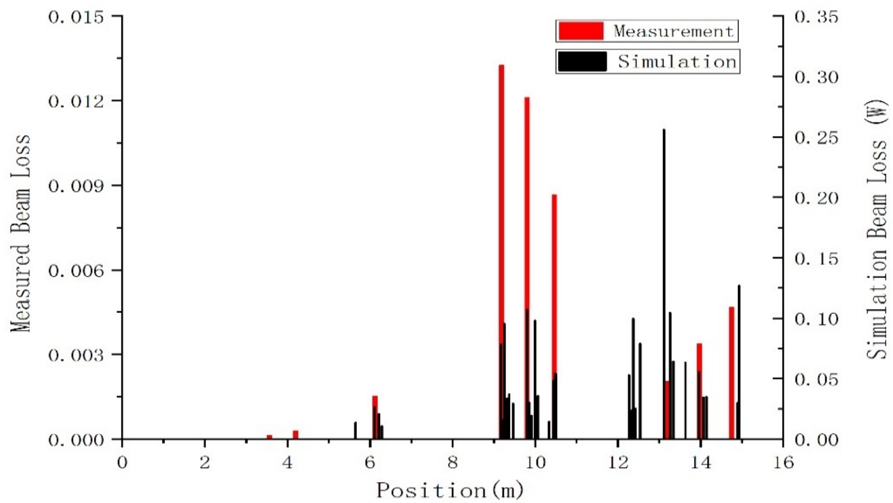
- The 6-dimensional ellipsoid gaussian is truncated at 3 RMS
- 1% of the total number of particles was defined as beam halo particles at the position of 10 times of RMS beam size in the horizontal and vertical RMS

	Alpha X/Y/Z	Beta X/Y/Z m/rad	Emit-X/Y/Z (RMS) π.mm.mrad [Norm.]	Emit-X/Y / Z(99.99%) π.mm.mrad [Norm.]
Without beam halo	0.247/-0.05/-0.076	0.226/0.096/0.611	0.112/0.097/0.094	**2.065/2.066/2.136**
With beam halo	0.247/-0.051/-0.080	0.226/0.096/0.608	0.122/0.106/0.01	**9.158/8.536/8.902**

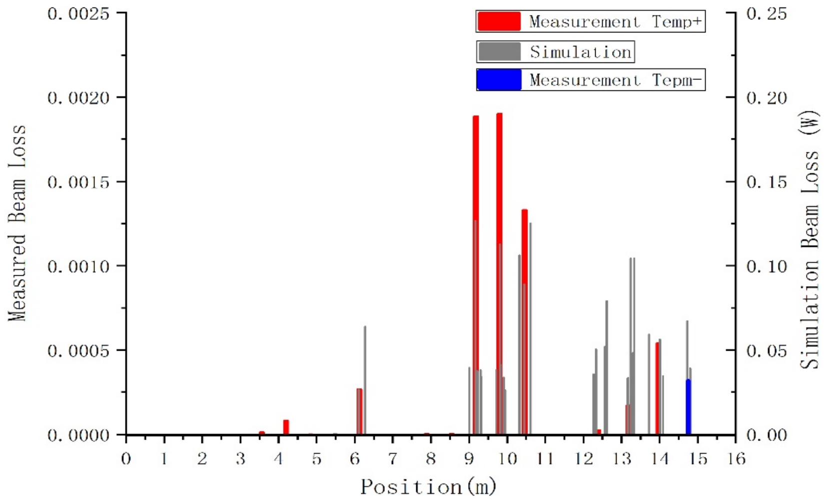
Beam loss study @ CW operation

The beam loss is defined as the sum of four quadrant temperature raising per unit time at a certain temperature probe:

Lattice 1

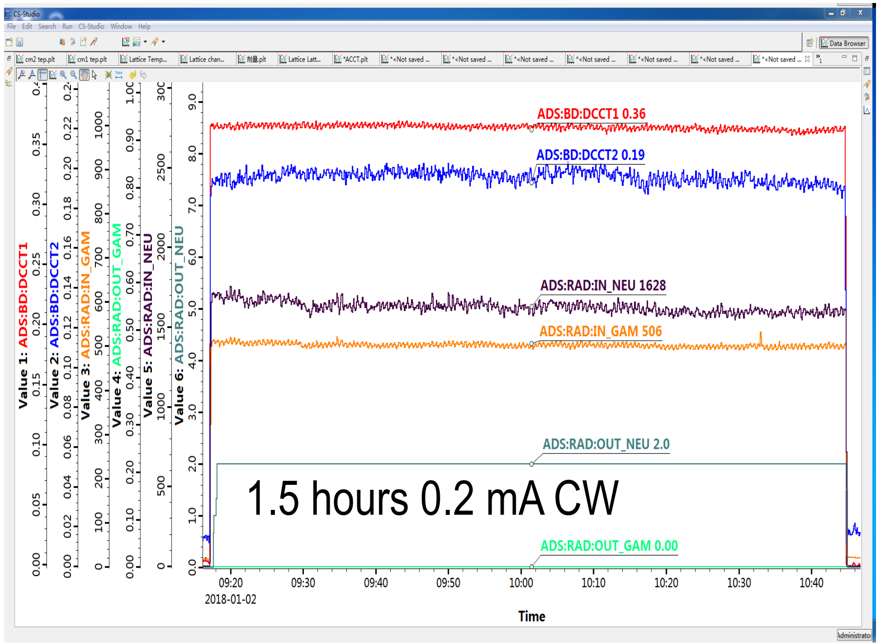


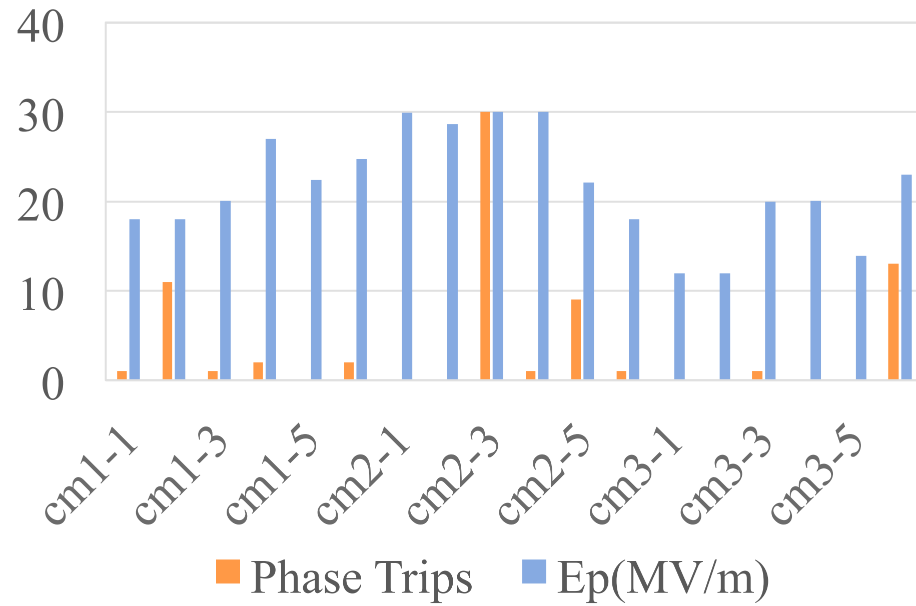
Lattice 2



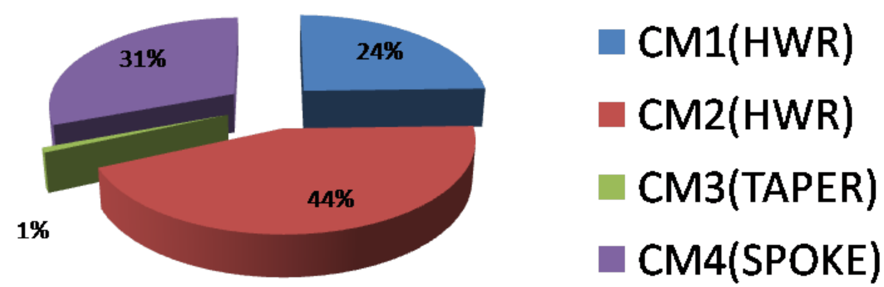
The results of simulation and experiment are consistent

Reliability of CW beam operation





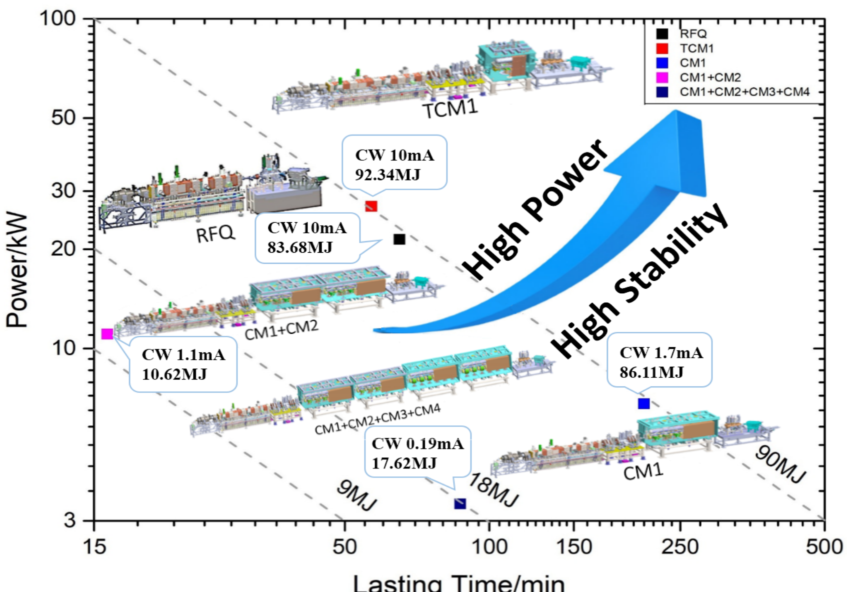
cryomodule phase trip statistics



- Beam: 0.1~0.2mA CW; Operation time: 27 h
- MPS trips while phase error $\Delta\varphi > 5\ Deg$, main reason of stopping beam
- Automatic recovery procedures need to be developed to reduce MTTR
- CM2-3 has weak coupling, 1/3 of the other bandwidth, reason 1
- Discharge in pick-up were observed, reason 2

Commissioning Summary 2014-2017

ACCELERATOR SEGMENTS	FIRST CW BEAM	MAX (MEV)	BEAM TIME (HOURS)	CW BEAM (HOURS)	CW CURRENT(MA)	CW POWER(KW)
RFQ	JUN.21, 2014	2.15	2036	90	11	23
TCM1(1HWR)	NOV.24, 2014	2.55	208	22.5	11	28
CM1(6HWRS)	JUN.24, 2015	5.3	400	20	4	21
CM1+CM2(6+6HWRS)	SEP.24, 2016	10.2	327	11	2.7	26
CM1+CM2+CM3+CM4	JUN.6, 2017	25	134.6	0.05	0.17	4.25
CM1+CM2+CM3+CM4	DEC.30, 2017	17.493	198.8	26.5	0.3	5.24



- The 25MeV SC demo facility has been built and run with proton beam successfully, including CW RFQ, high performance SC cavities, CMs .
- Tens of kilowatt CW beam achieved in the SC front-end of Chinese ADS.
- The dumper and radiation shielding is a limit for tuning higher power beam.
- Beam loss, higher power and operation stability will be the key issues to be demonstrated in the future.

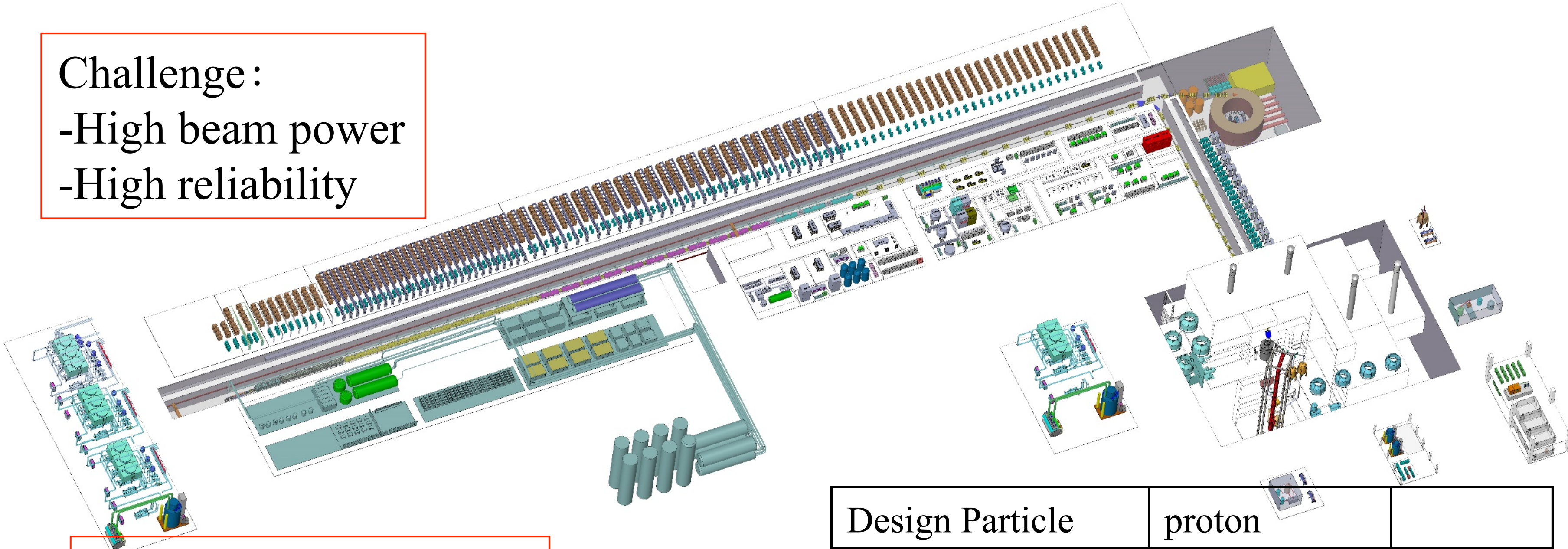
Outline

- Introduction of China ADS driven linac
- Beam commission of Chinese ADS Front-end Demo Linac (CAFe)
- **Preliminary design of CiADS Linac**
- Summary

CiADS Project (2018-2024)

The first demonstration of ADS at MWs level

Challenge:
-High beam power
-High reliability



Only one injector
Non-local compensation

Beam trips goal:

<10s,	-
10s～5min,	2500/y
>5min,	300/y

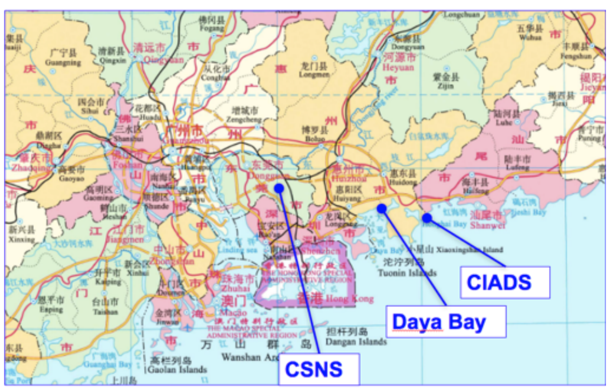
Design Particle	proton	
Energy	500 (250)	MeV
Beam current	5 (10)	mA
Beam power	2.5	MW
Operation mode	CW&Pulse	
Beam loss	＜1.0	W/m
Reactor power	7.5	MWt

CiADS Project (2017-2024)

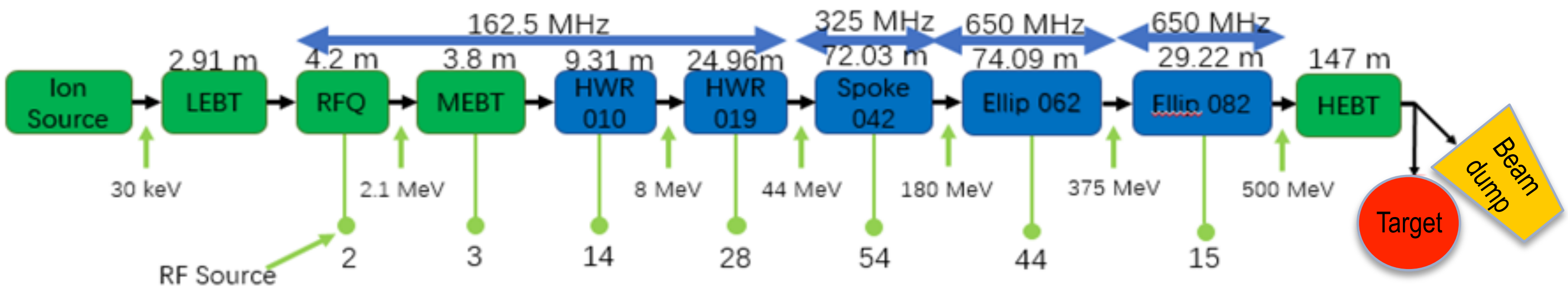
China initiative Accelerator Driven System (CiADS)

- **Approved in Dec. 2015**
- **Leading institute: IMP**
- **Budget: >1.8B CNY (Gov. and Corp.)**
- **Location: Huizhou, Guangdong Prov.**
- **Contribution Partners:**
  CIAE, CGN, IHEP, CASHIPS, etc.

Location is in Huizhou city, Guangdong Province, 73 km away from Huizhou and 140 km away from Shenzhen. The site is on the top of hill, latitude is around 150m, facing the South See and backing on the mountain. The High Intensity Heavy Ion Accelerator Facility (HIAF) is in the same campus.



General configuration of CiADS Linac



The design consideration :

- reliability-oriented design
- The extremely beam loss control(＜1W /m)
- Based on the experience of beam commissioning of CAFe

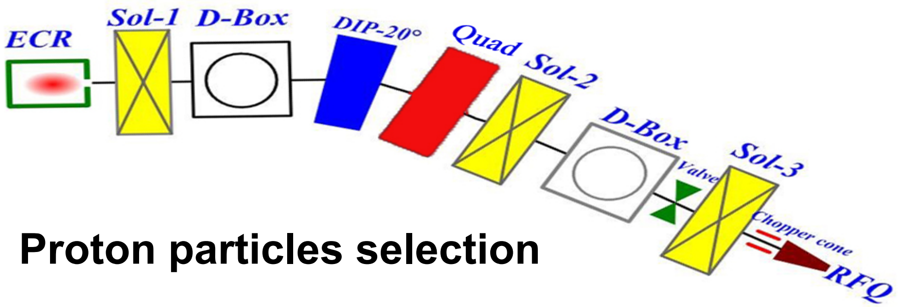
Specifies at sections:

- Rt front end: beam quality control and re -built
- Sc-linac: high redundancy, compensation
- Beam on target: homogenies scanning

General parameters

Particle	proton	
Energy	500	MeV
Beam current	5	mA
Beam power	2.5	MW
RF frequency	162.5/325/ 650	MHz
Operation mode	CW&Pulse	
Beam loss	＜1	W/m
Total length	367.5	m

LEBT design

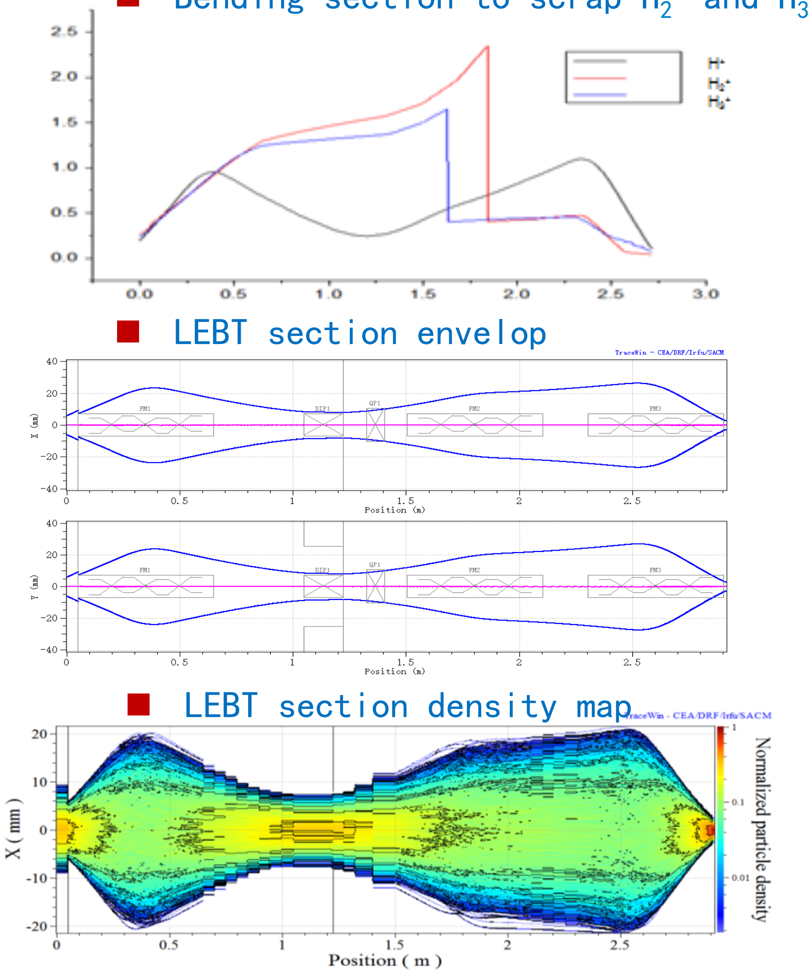


- Proton particles selection
- Collimation for beam loss control
- Beam symmetrical injection
- Match between IS and RFQ

■ Bending section to scrap H_2^+ and H_3^+

■ LEBT section envelop

■ LEBT section density map



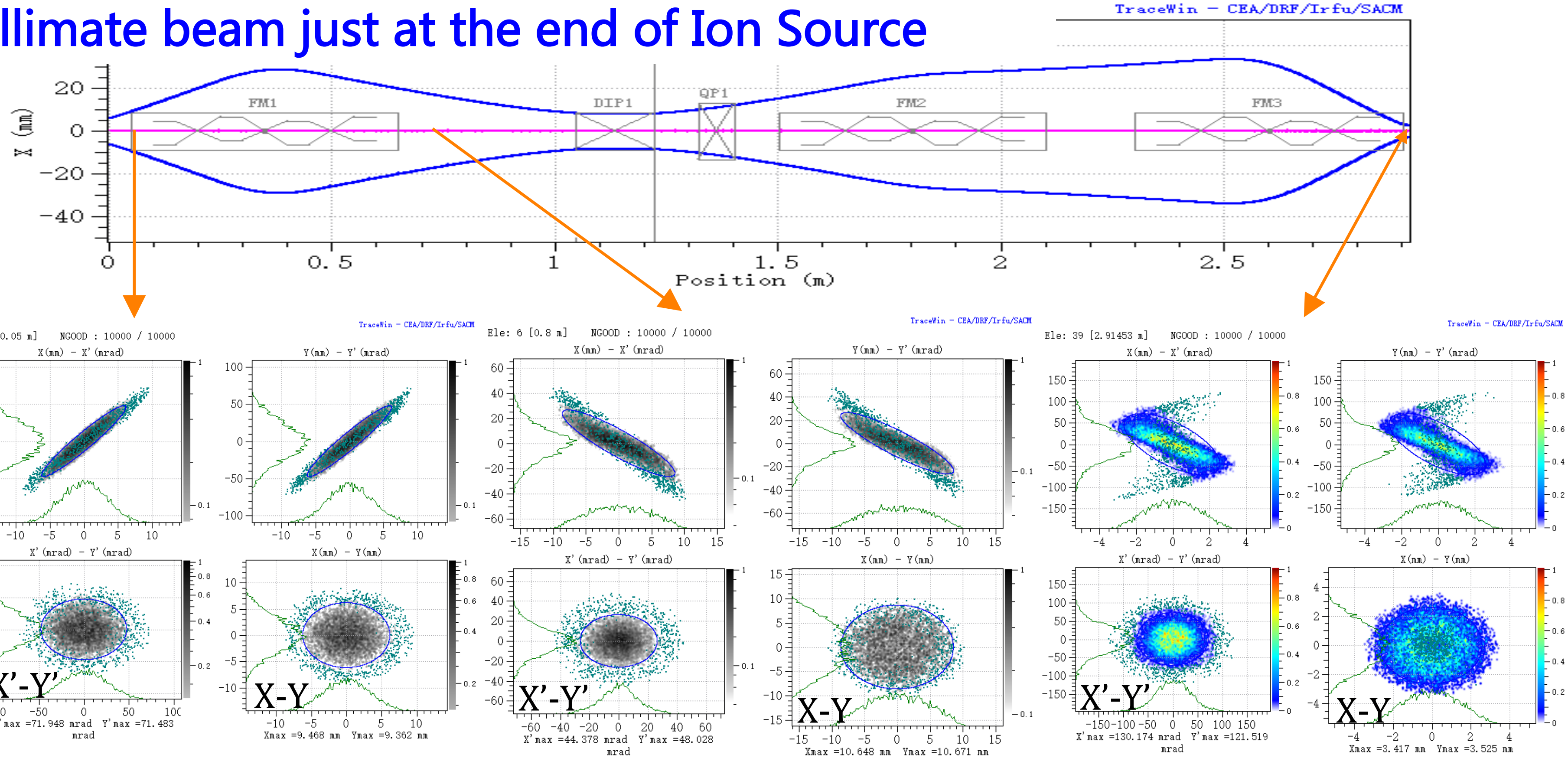
■ IS&LEBT design parameter

Inject energy (keV)	35
Beam current (mA)	20
Horizontal normal emittance (πmm•mrad)	0.19
Energy spread	≤0.5%
Extract beam stability	<1%
Total length (m)	2.9

Designed 20°bending magnet +6.3°edge angle to ensure proton beam purification and also achieve both horizontal and vertical direction beam symmetrical matching.

LEBT design

Collimate beam just at the end of Ion Source



Track back to LEBT input   Track back to solenoid exit   Scrapped beam at LEBT exit

Marking the target scrapped beam particles at LEBT exit and tracking back these particles to the entrance of the LEBT and the first solenoid exit, it will find that these "tail" particles exactly the ones outside of the beam aperture at the LEBT entrance, and it can not be scrapped at other section of the LEBT.

RFQ design

① Low frequency and low RF power to improve the long-term operational stability

② Low Kilpatrick facter

③ High acceleration efficiency and high transmission efficiency

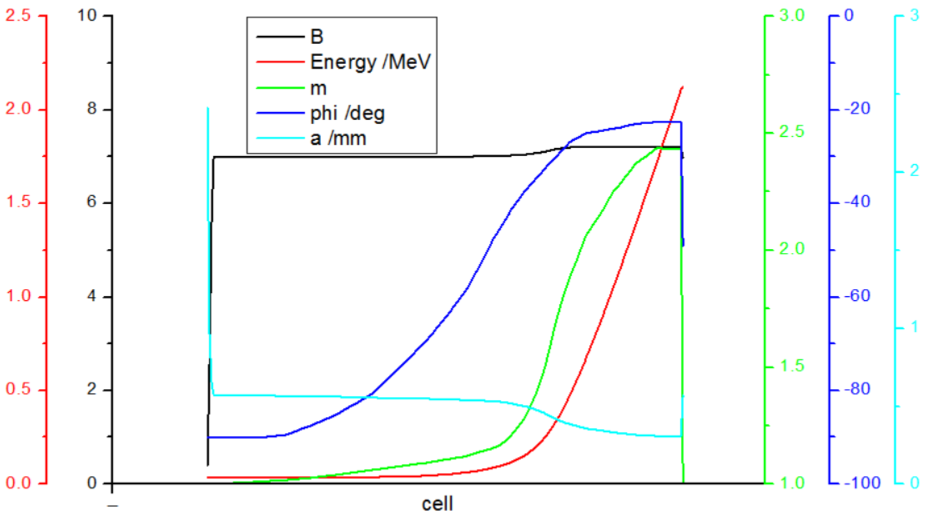
④ The RFQ lattice optimization to minimize the beam loss power

⑤ Aim to optimize 99.99% longitudinal emittance, to decrease the beam loss probability in high energy superconducting section.

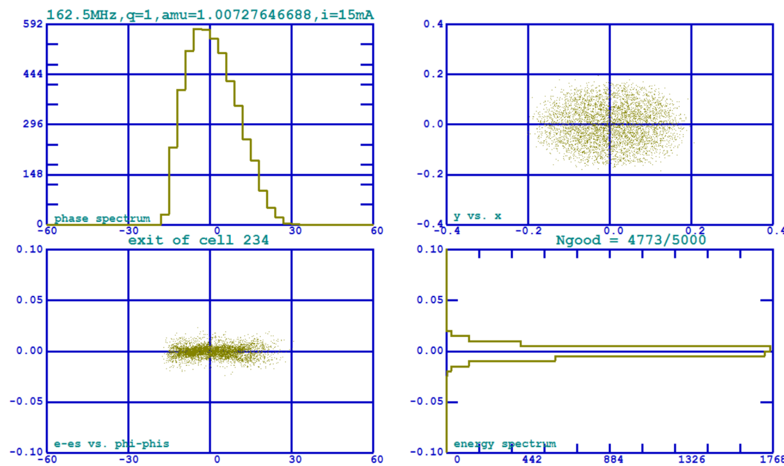
Frequency（MHz）	162.5
Beam current（mA）	15
I/O energy(MeV)	0.035 / 2.1
Vane voltage(kV)	65
Max. surface.field（MV/m）	15.88
Average aperture(mm)	5.71
Min aperture（mm）	0.308
Iuput.Nor.RMS.emit (πmm•mrad)	0.2/0.2/-
Ouput.Nor.RMS.emit (πmm•mrad)	0. 21/0. 21/ 0.25
Output.99.9% longitudinal emit (πmm•mrad)	4.98
Length (m)	4.57
Transmission efficiency@15mA (%)	95.0%

RFQ design

RFQ key parameters



Longitudinal phase space

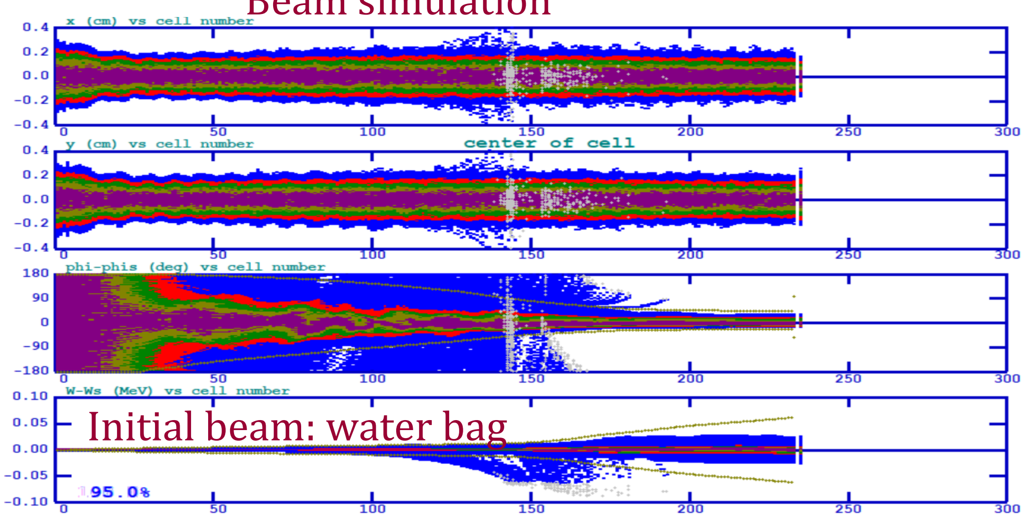


99.99%longitudinal： 4.98 πmm.mrad

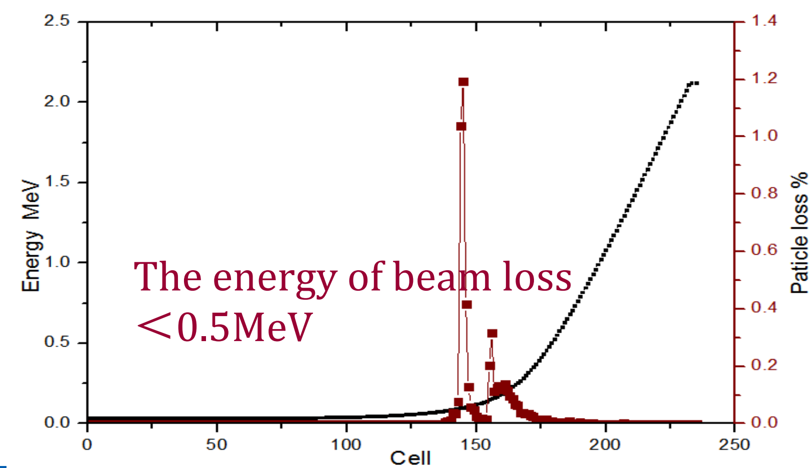
The acceptance of SC： ~27 πmm.mrad

The ratio: <1/5

Beam simulation

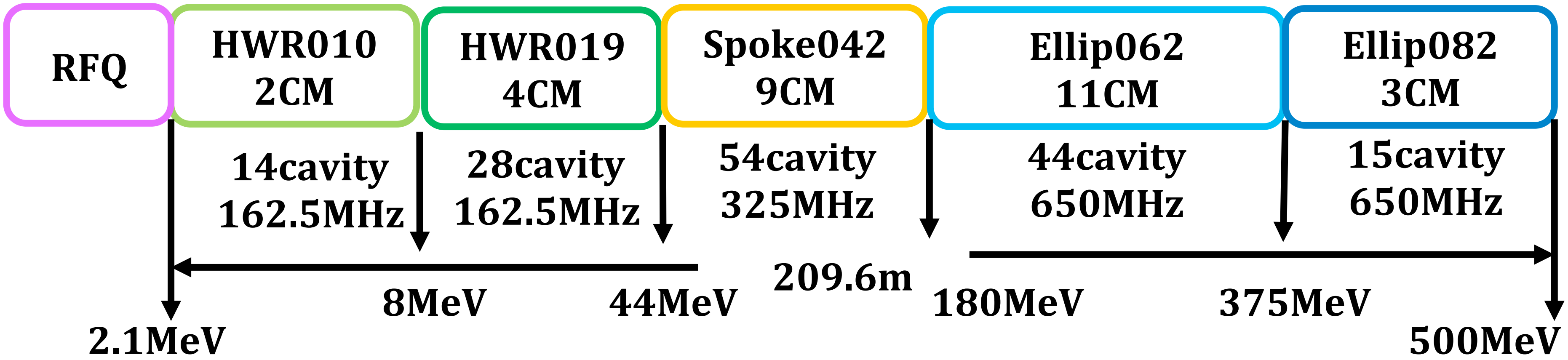


Initial beam: water bag



The energy of beam loss <0.5MeV

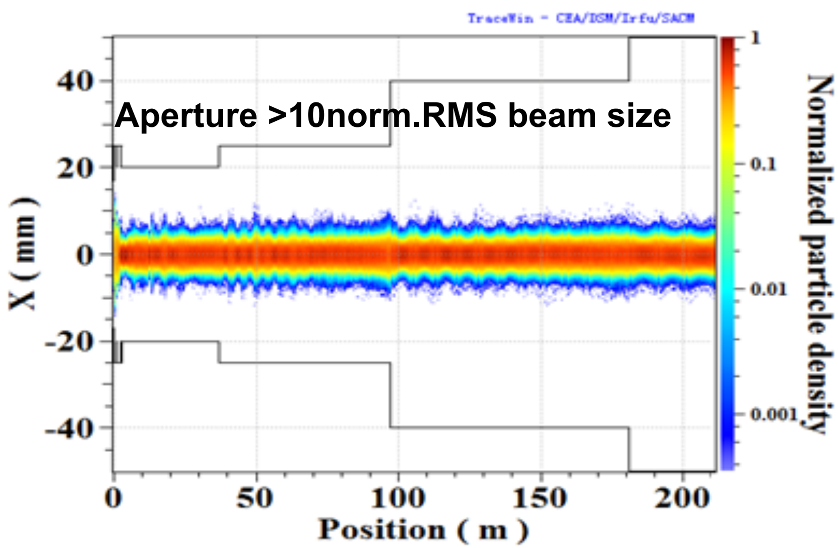
SC section design

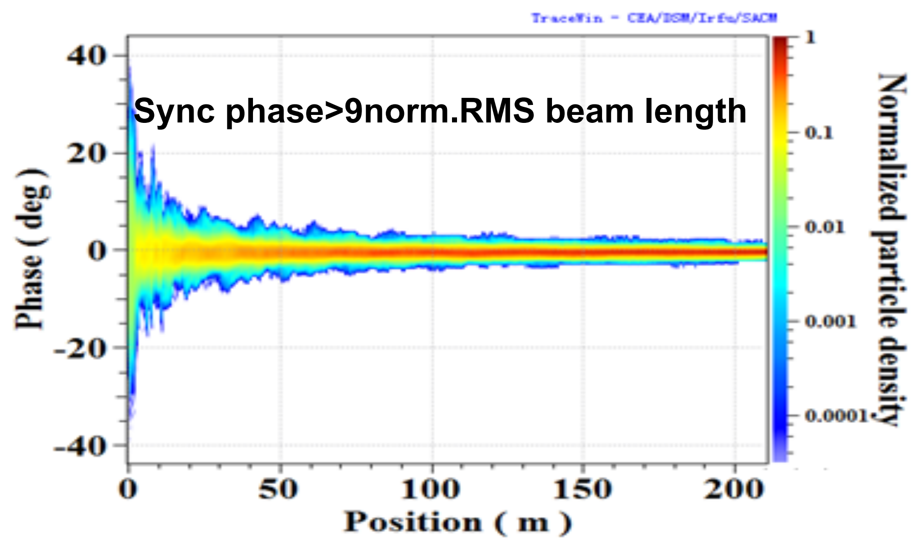


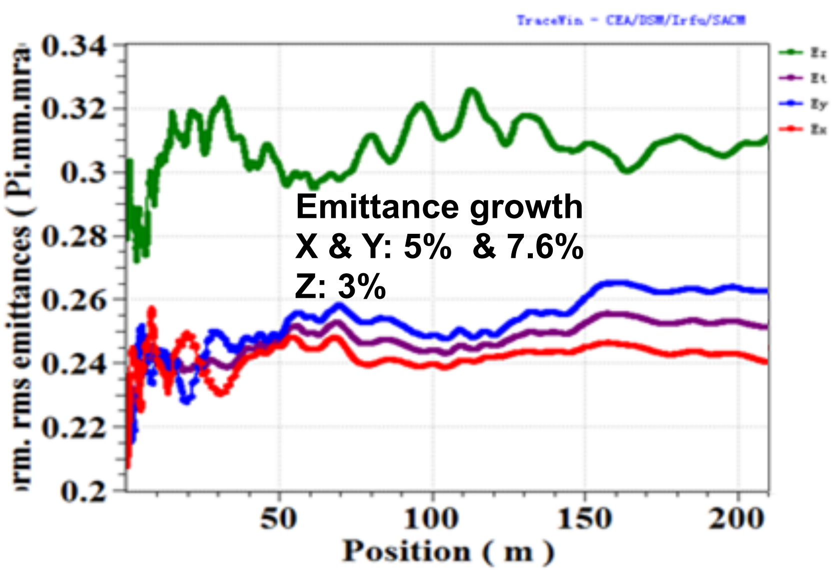
	Unit	HWR010	HWR019	SPOKE042	Ellip062	Ellip082
f	MHz	162.5	162.5	325	650	650
type		Sqreezed	Taper	Double	5 cells	5 cells
Vmax	MV	1.0	2.5	6.5	13	20
Ep	MV/m	28/20	32/25	35/28	35/28	35/28
S or Q/C	per CM	7/7	4/7	2/6	1/4	1/5

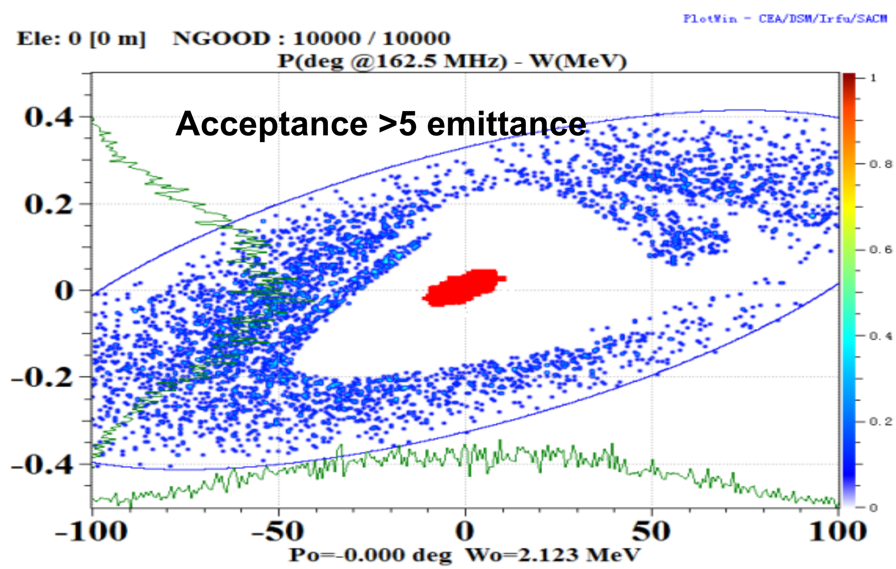
- Compact structure at low energy section to get large longitudinal acceptance and to weaken the effect from space charge
- Full period lattice structure at high energy section to reduce mismatch
- Optimization at the location of structure transition and frequency jump to immigrate the longitudinal beam loss

SC section design



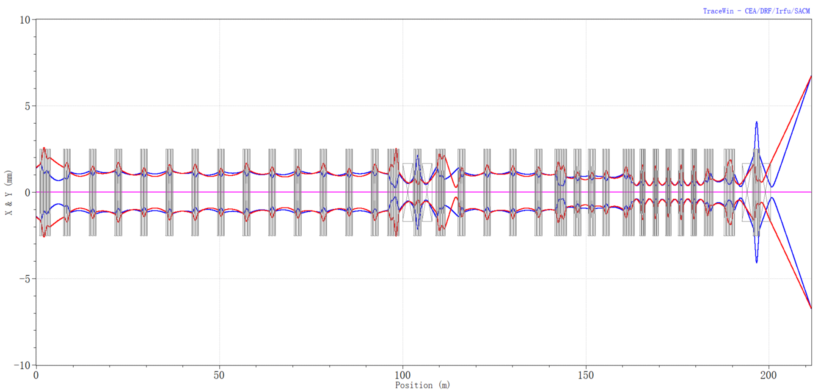


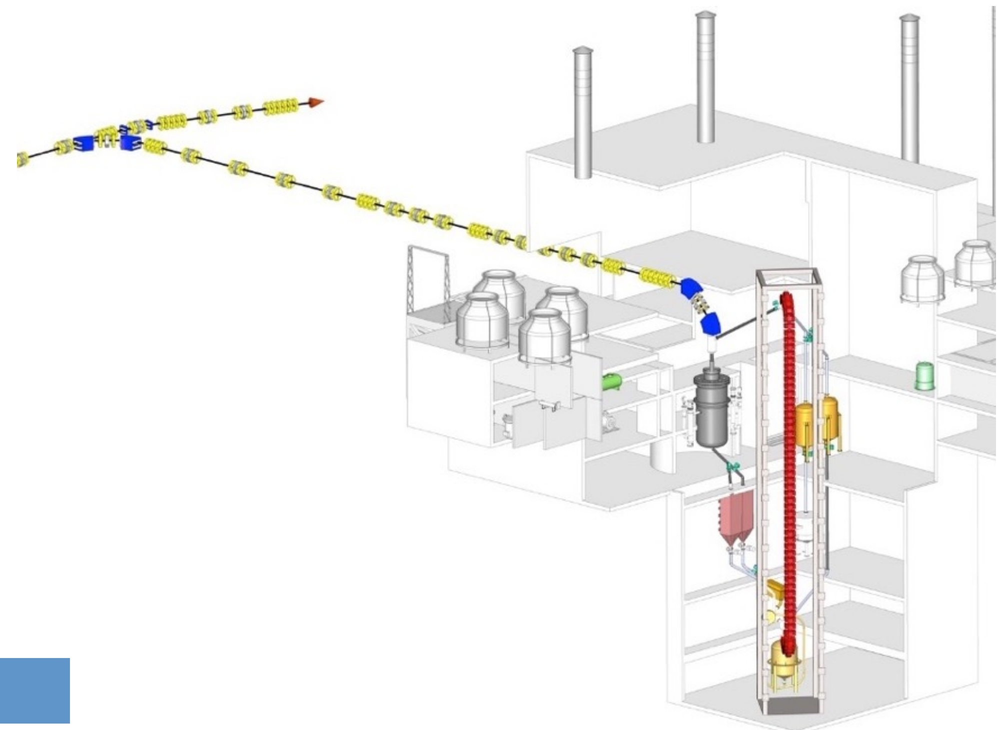




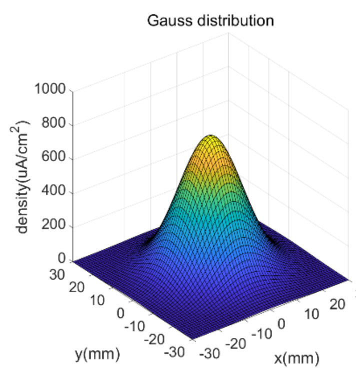
Design of A. to T.

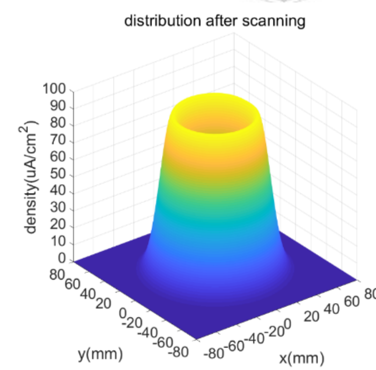
Reserved space for Energy upgrading | Collimation section | scanning section | PBW



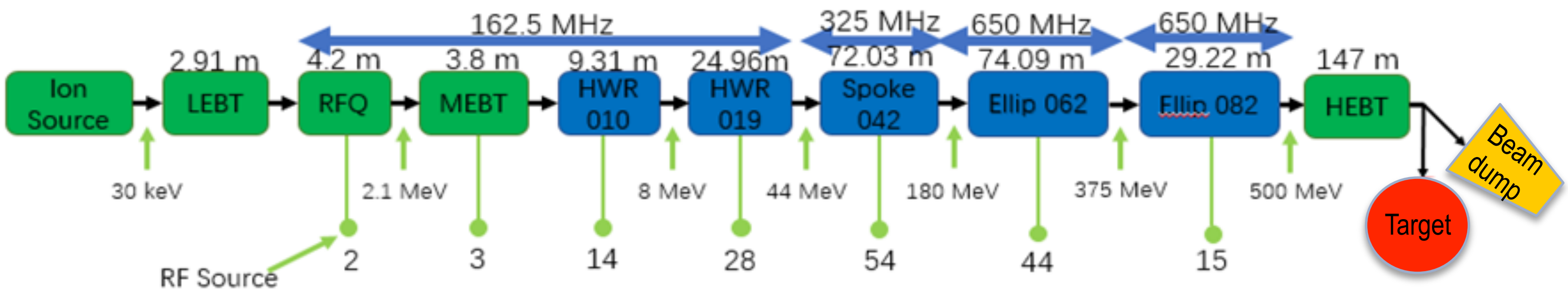


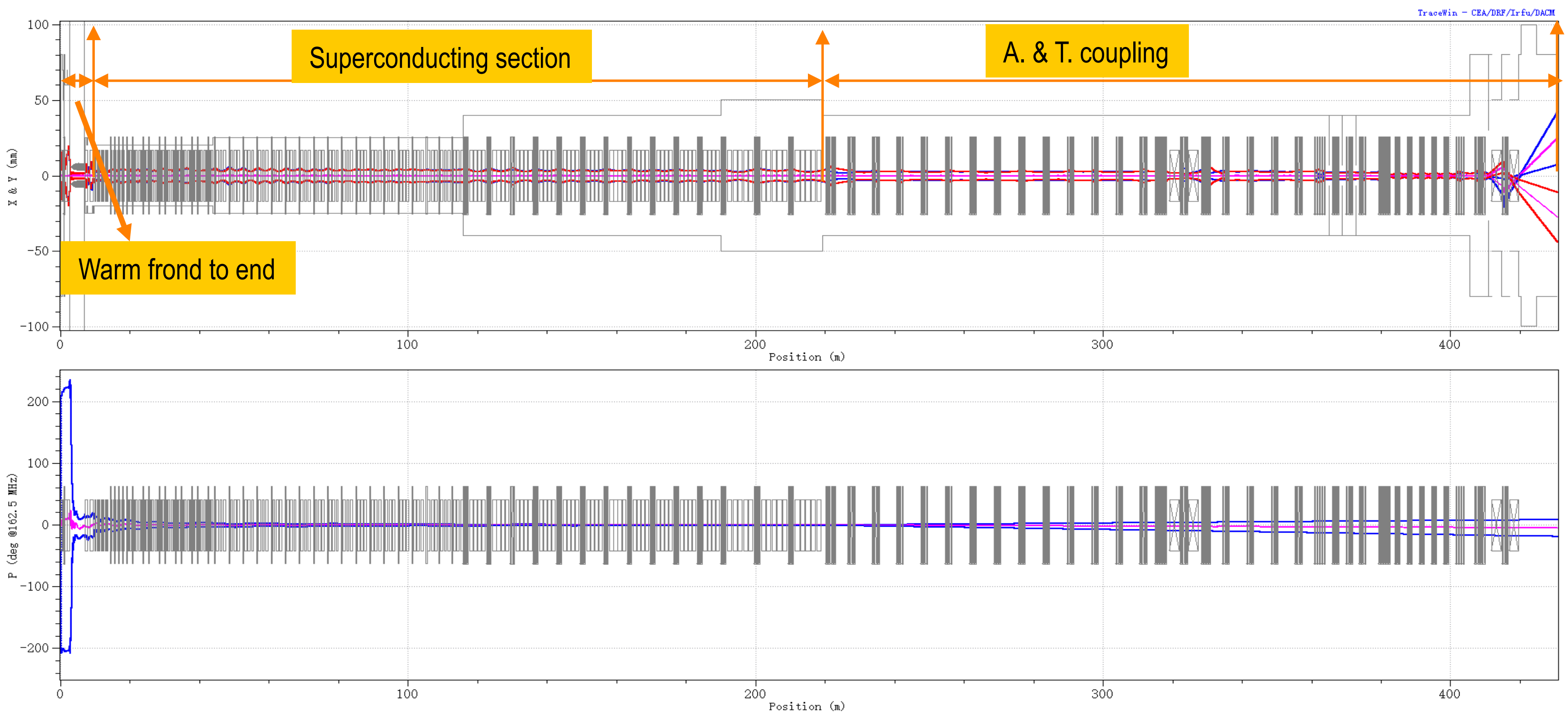
	value	unit
Emit. RMS norm. (x/y/z)	0.23/0.23/0.26	π mm.mrad
Entrance αx/αy/αz	-1.4/-1.4/0.0	——
Entrance βx/βy/βz	10.5/10.5/10.2	mm/π.mrad
Beam profile on target	Round&Hollow	
Peak current density	< 100	uA/cm^2
99.99% beam diameter	<160	mm





End to end simulation





Outline

- Introduction of China ADS driven linac
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- Preliminary design of CiADS Linac
- **Summary**

Summary

- **The China ADS Front-end demo linac (CAFe) have been constructed, and the CW beam and reliability operation have been done**
  - 4-D beam re-construction at MEBT to initialize beam
  - Orbit alignment and phase calibration
  - Effective beam loss detection at low energy section
  - Sufficient and Efficient MPS, fault recovery strategy is under developing to improve reliability
- **CiADS will be launched by the end of the year, baseline beam physics of 500 MeV, 5 mA has been done**
- **Upgrading of CAFe for He beam has been finished and will be commissioned soon.**

Thanks for your attention
Welcome collaboration

Thanks for the helps

from IHEP, LBNL, TRIUMF, SINAP, PKU, JLab, ANL, SNS, THU, MSU, ……