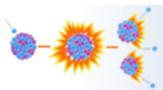


Beam Dynamic of Accelerator for CiADS & Commissioning of CAFe

Yuan He

On behalf of Joint Accelerator Team of ADS
Institute of Modern Physics, CAS

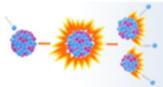


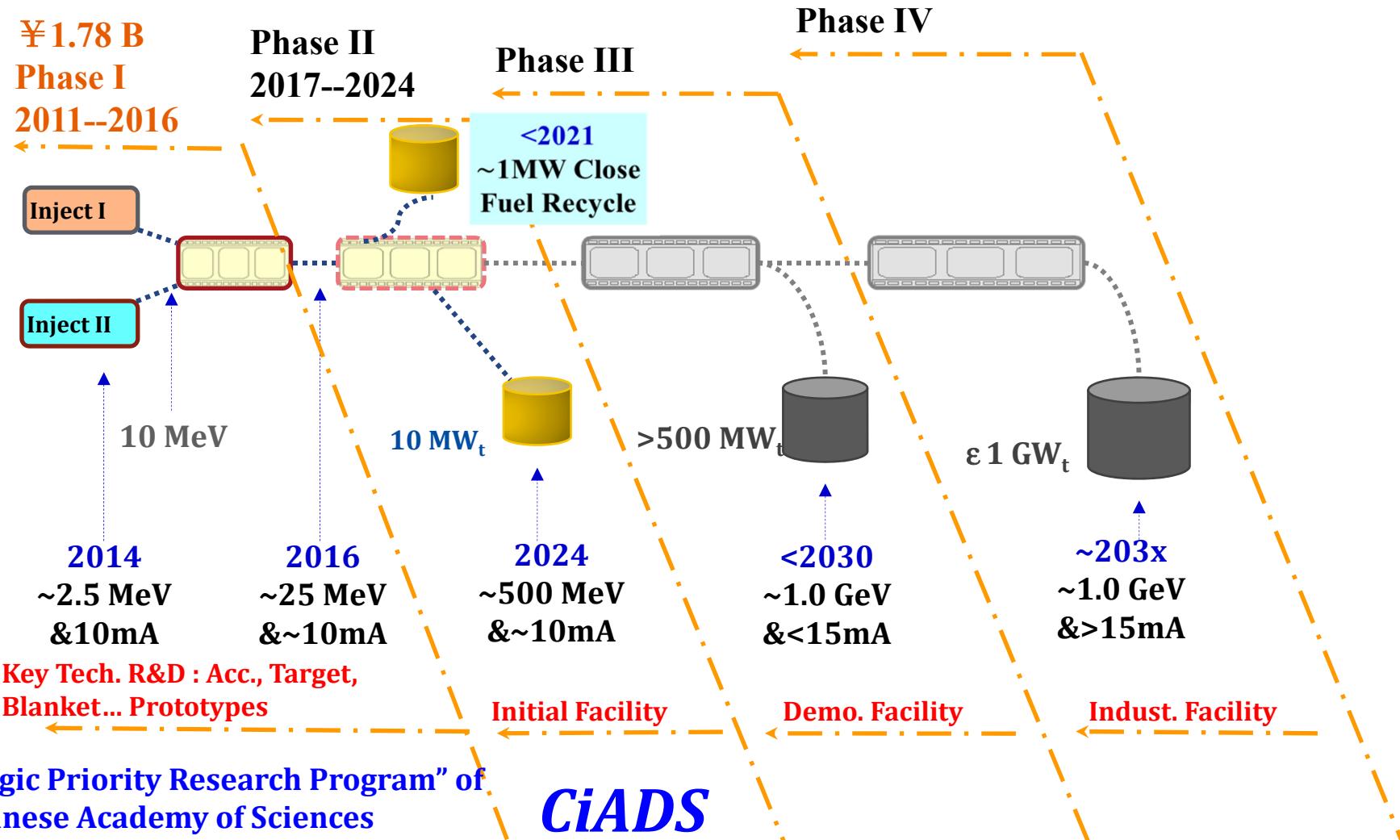


Outline



- ▶ **Introduction of CiADS**
- ▶ Design of superconducting Linac
- ▶ Beam commission of Chinese ADS
Front-end Demo Linac (CAFe)
- ▶ Summary







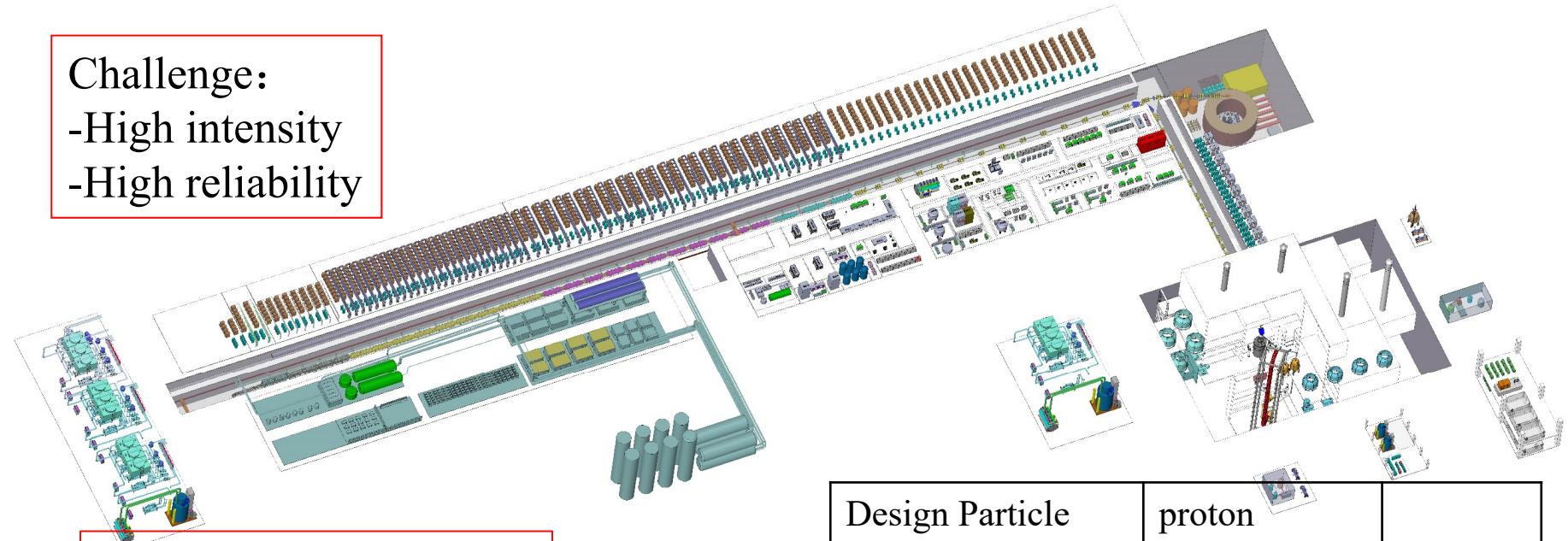
CiADS Project (2018-2024)



The first demonstration of ADS at MWs level

Challenge:

- High intensity
- High reliability

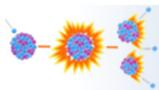


Only one injector
Non-local compensation

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	<0.1	W/m
Reactor power	7.5	MWt



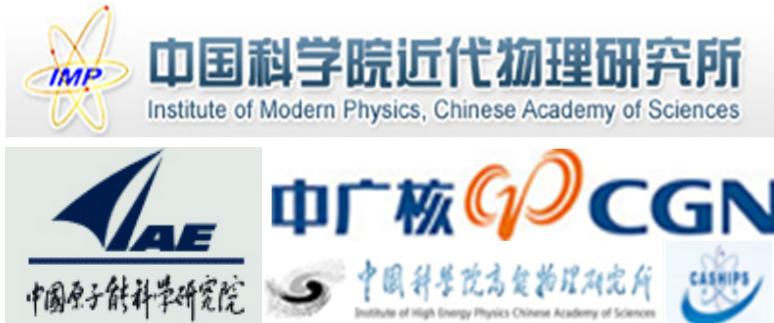


CIADS Project (2017-2024)

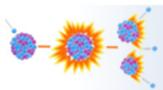


China initiative Accelerator Driven System (CiADS)

- 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.

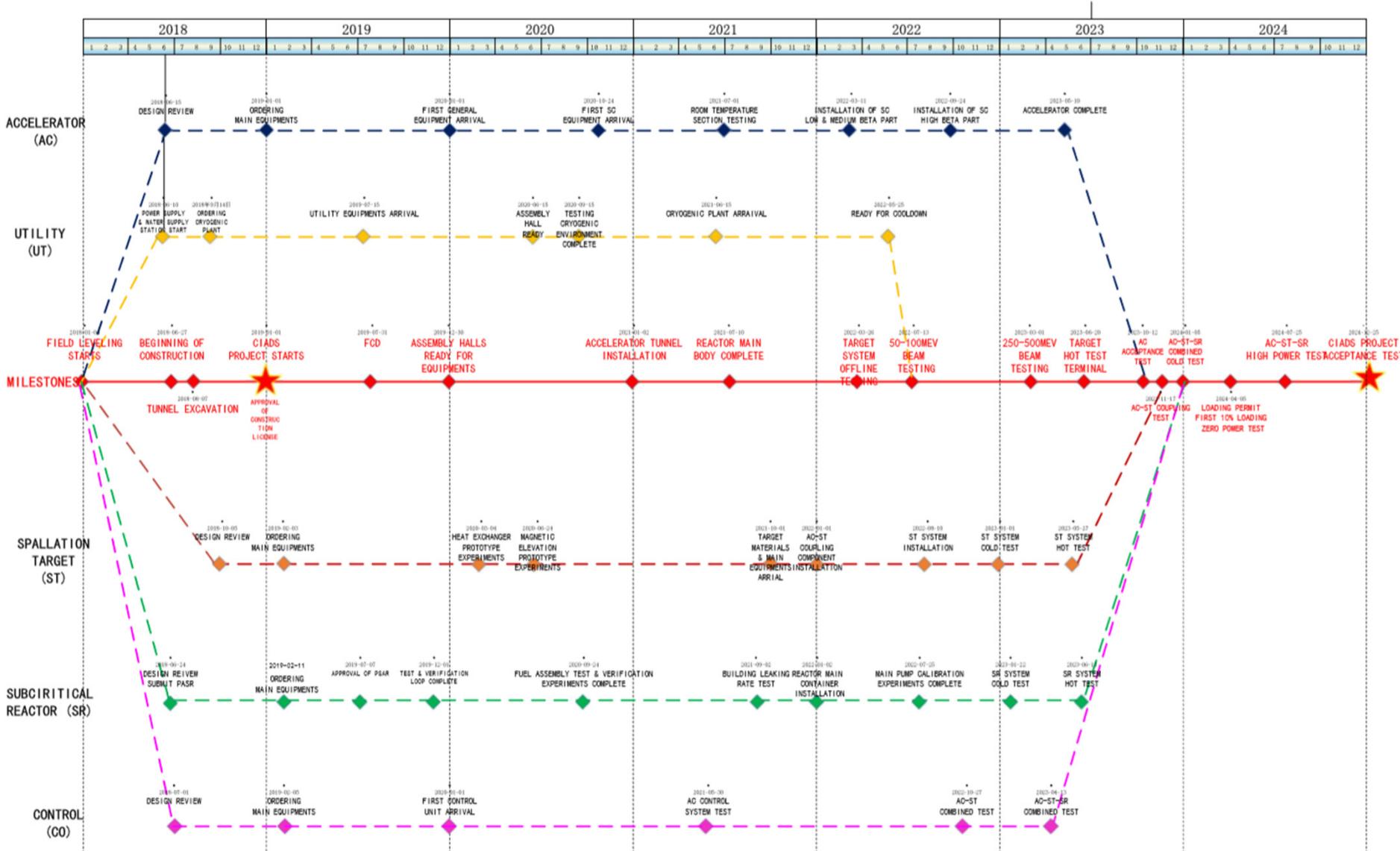


Location is in Huizhou city, Guangdong Province, 73 km away from Huizhou and 140 km away from Shenzhen. The site is on the top of hill, latitude is around 150m, facing the South See and backing on the mountain. The High Intensity Heavy Ion Accelerator Facility (HIAF) is in the same campus.



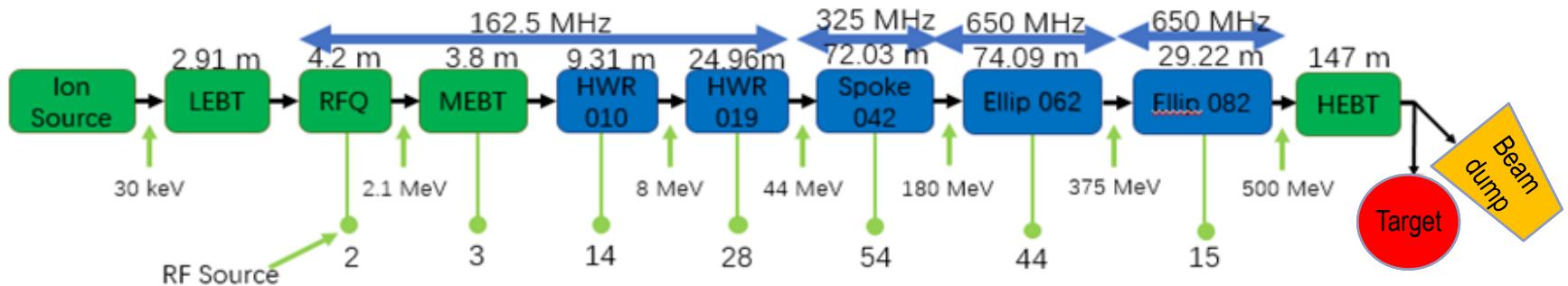


Schedule of CiADS



- ▶ Introduction of CiADS
- ▶ Design of superconducting Linac
- ▶ Beam commission of Chinese ADS
Front-end Demo Linac (CAFe)
- ▶ Summary

General configuration of CiADS Linac



The design consideration :

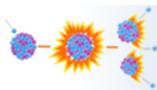
- reliability-oriented design
- The extremely beam loss control (< 0.1W/m)
- Based on the experience of beam commissioning

Specifies at sections:

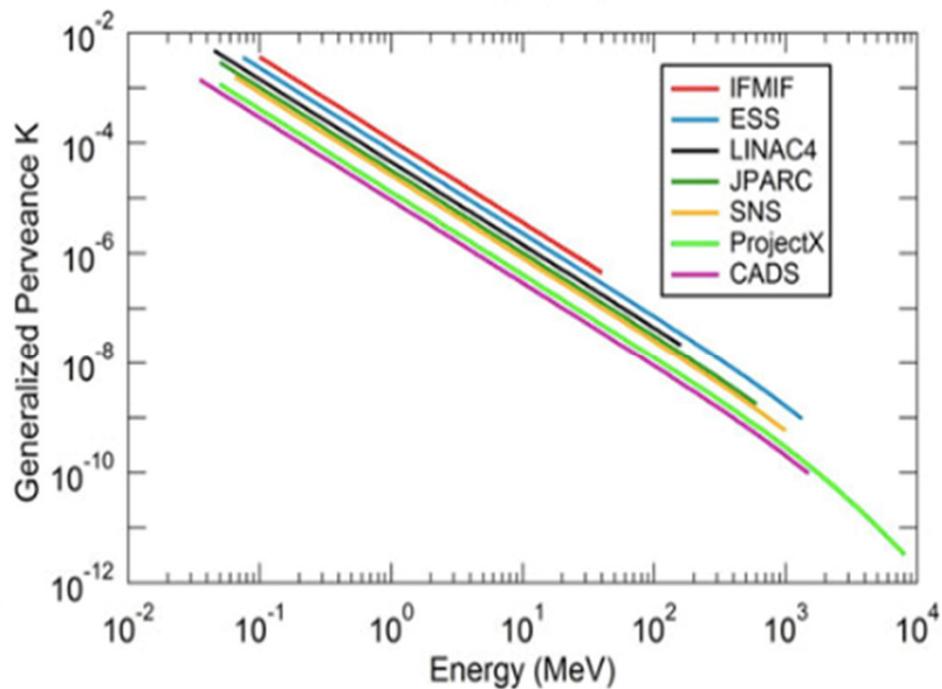
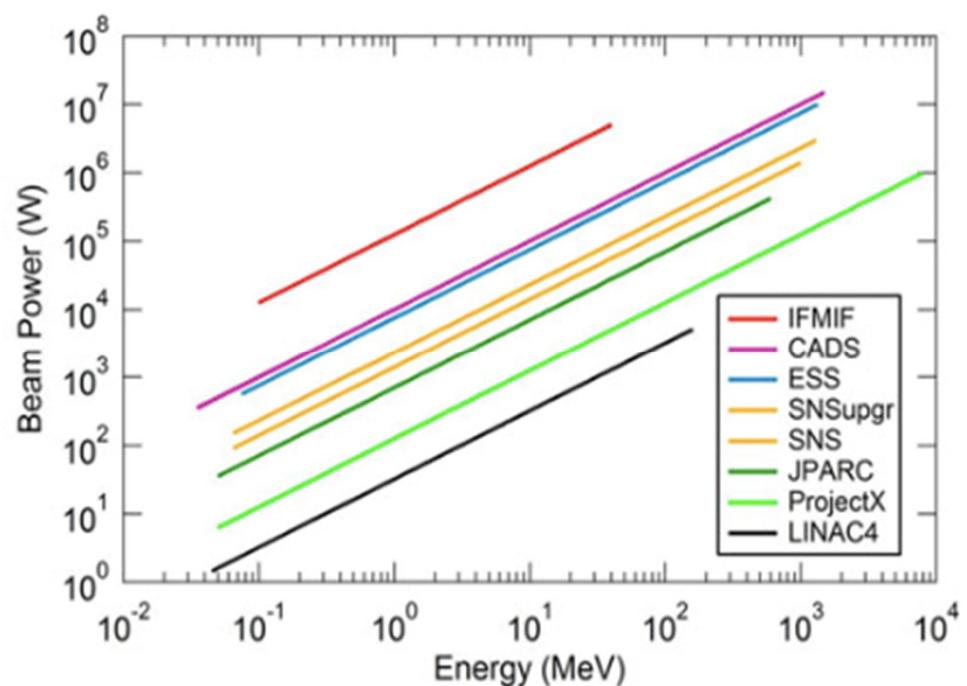
- Rt front end: beam quality control and re-built
- Sc-linac: high redundancy, compensation
- Beam on target: homogenies scanning

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	<0.1	W/m
Total length	367.5	m



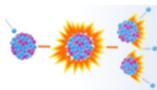
General characteristics of ADS linac



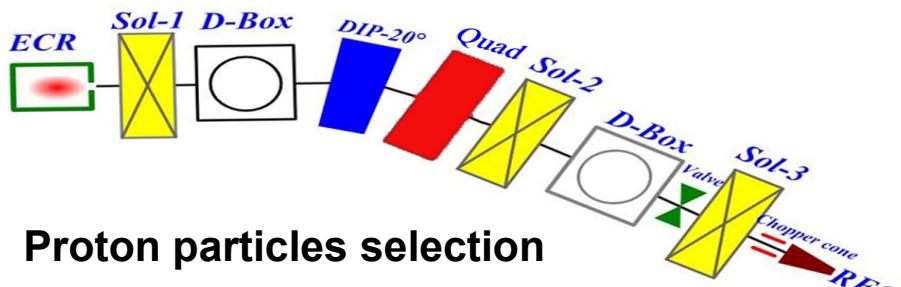
Compared with existing proton linac, ADS linac is **high average power** and **low intensity**.

Beam loss & beam loading dominated accelerator !

P.A.P. NGHIEM, et al , Advanced concepts and methods for very high intensity accelerators

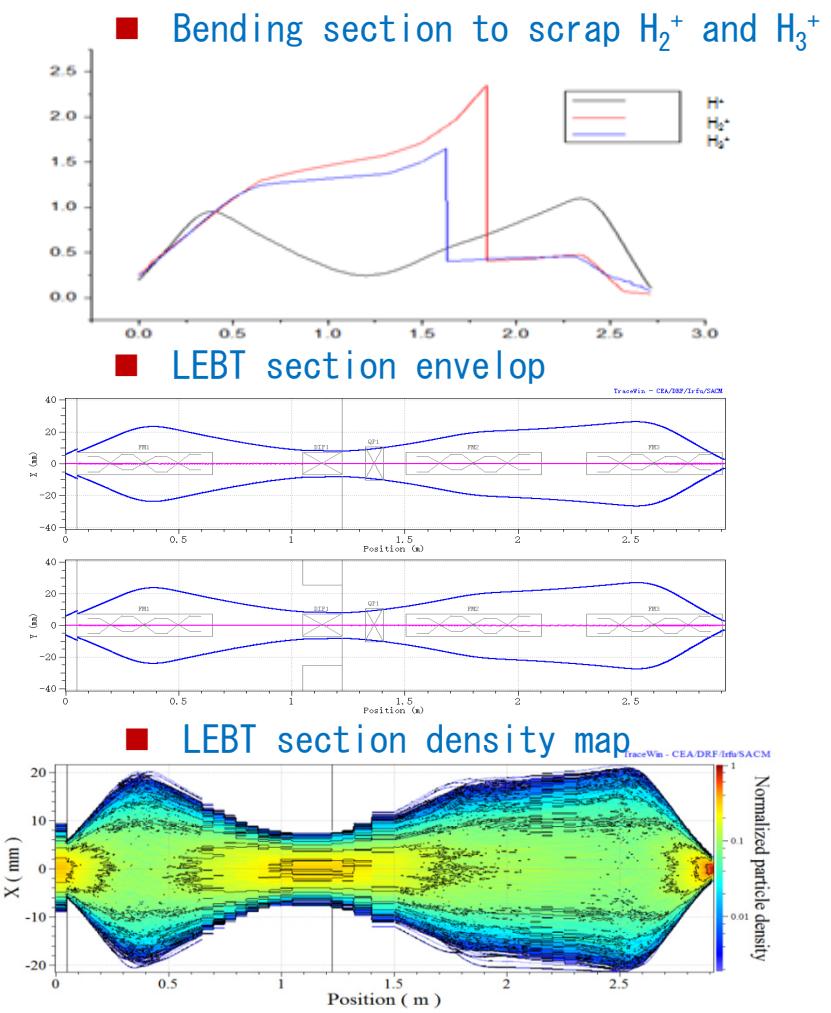


LEBT design

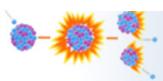


- Proton particles selection
- Collimation for beam loss control
- Beam symmetrical injection
- Match between IS and RFQ
 - IS&LEBT design parameter

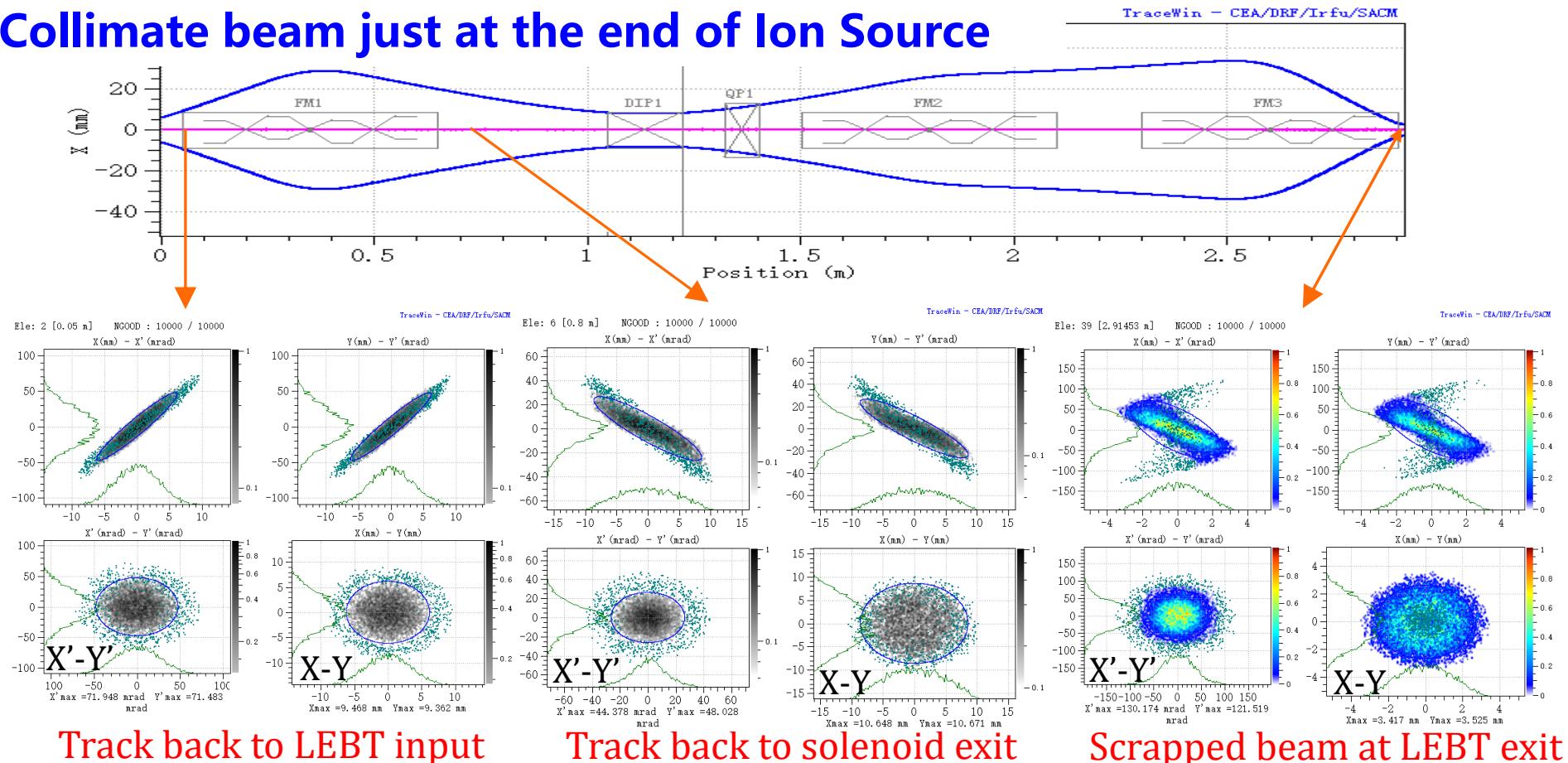
Inject energy (keV)	35
Beam current (mA)	20
Horizontal normal emittance ($\pi\text{mm}\cdot\text{mrad}$)	0.19
Energy spread	$\leq 0.5\%$
Extract beam stability	$< 1\%$
Total length (m)	2.9



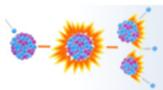
Designed 20° bending magnet + 6.3° edge angle to ensure proton beam purification and also achieve both horizontal and vertical direction beam symmetrical matching.



Collimate beam just at the end of Ion Source



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.





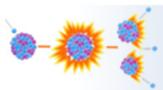
RFQ design

WG-B, 17:30, W. Dou

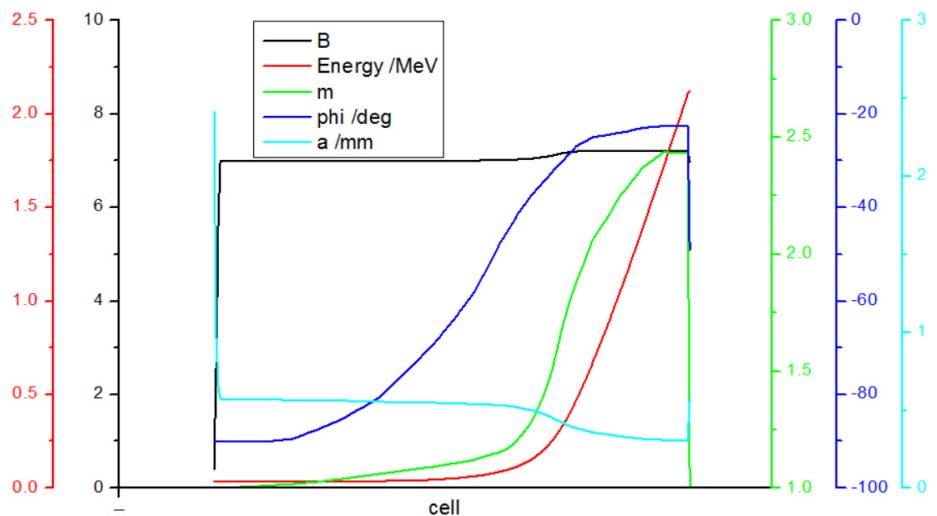


- ① Low frequency and low RF power to improve the long-term operational stability
- ② Low Kilpatrick coefficient
- ③ High acceleration efficiency and high transmission efficiency
- ④ The RFQ lattice optimization to minimize the beam loss power
- ⑤ Aim to 99.99% longitudinal emittance, to decrease the beam loss probability in high energy superconducting section.

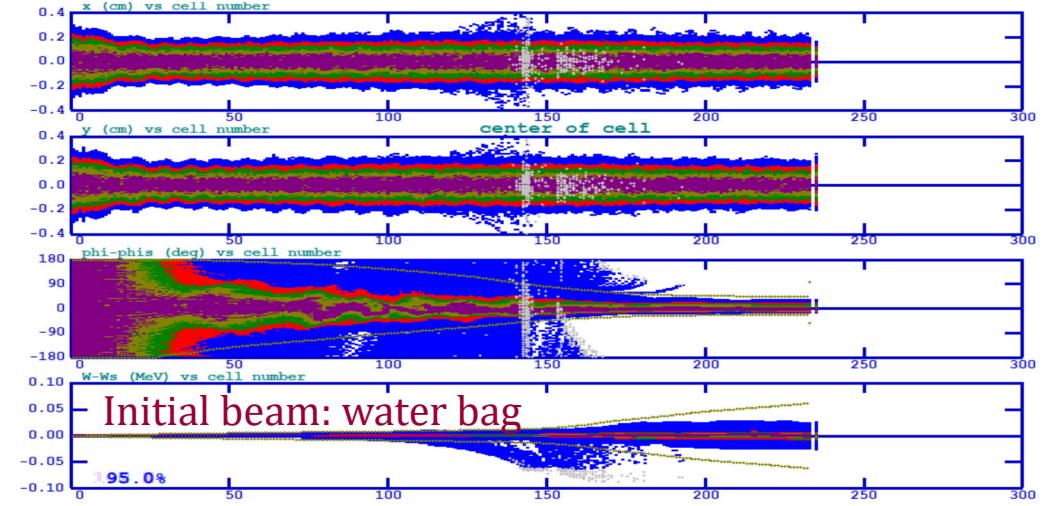
Frequency (MHz)	162.5
Beam current (mA)	15
I/O energy(MeV)	0.035 / 2.1
Vane voltage(kV)	65
Max. surface.field (MV/m)	15.88
Average aperture(mm)	5.71
Min aperture (mm)	0.308
Iinput.Nor.RMS.emit ($\pi\text{mm}\cdot\text{mrad}$)	0.2/0.2/-
Ouput.Nor.RMS.emit ($\pi\text{mm}\cdot\text{mrad}$)	0.21/0.21/0.25
Output.99.9% longitudinal emit ($\pi\text{mm}\cdot\text{mrad}$)	4.98
Length (m)	4.57
Transmission efficiency@15mA (%)	95.0%



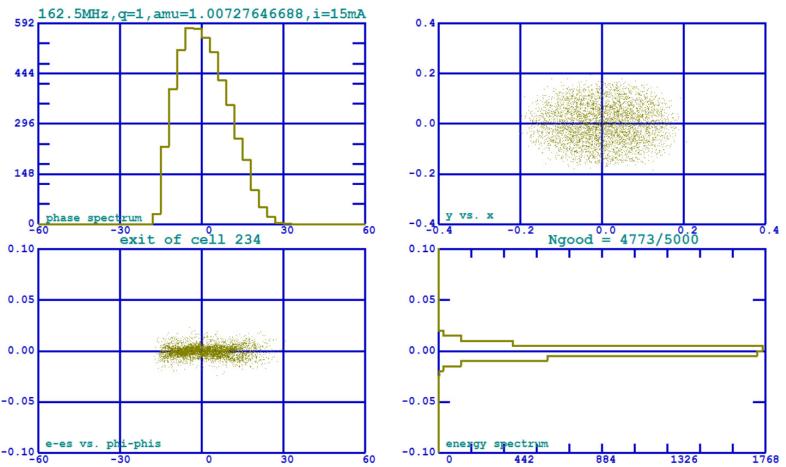
RFQ key parameters



Beam simulation



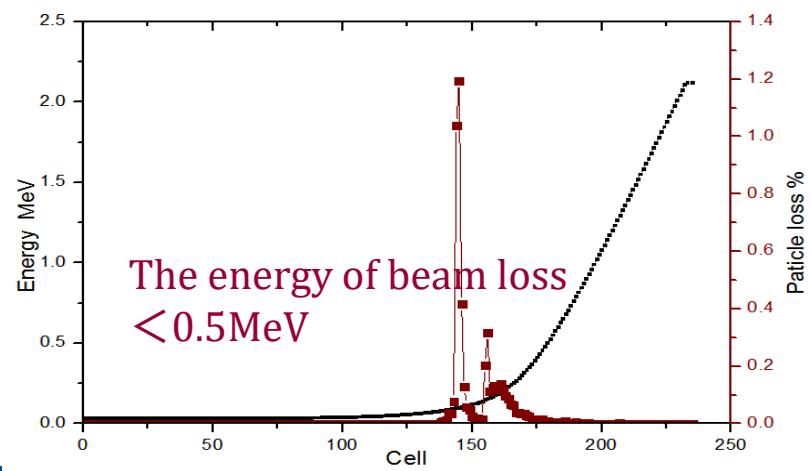
Longitudinal phase space

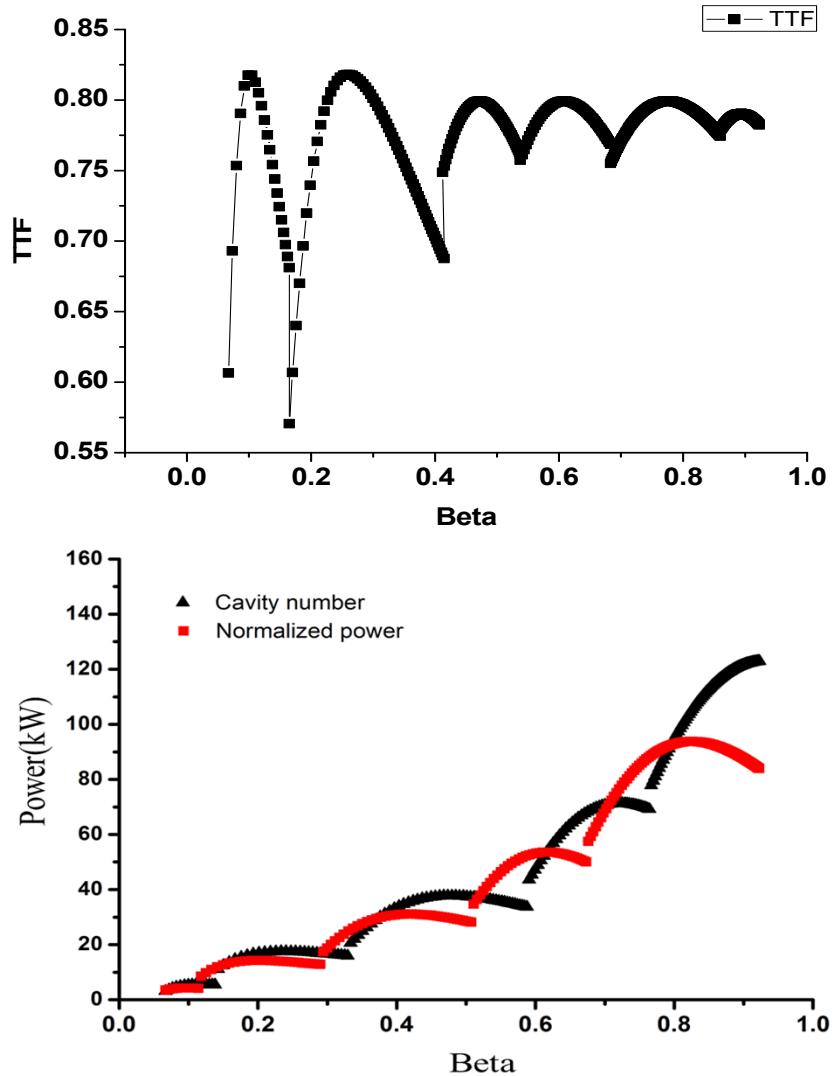


99.99%longitudinal : $4.98 \pi \text{mm.mrad}$

The acceptance : $\sim 27 \pi \text{mm.mrad}$

The ratio: $\sim 1/5.4$

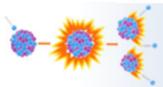




- Consideration :

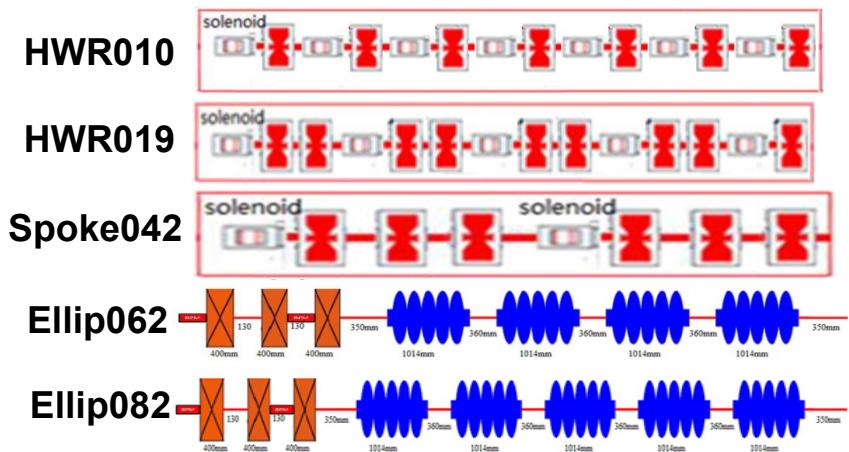
 1. limit the TTF value, $TTF > 0.6$
 2. Make TTF value of each equal as far as possible
 3. PSO was employed to optimize the cavity family and beta
 4. Limit the max RF power for single cavity

$$\sum_{i=1}^l \frac{P_i}{l * P_{\max}} + \sum_{i=1}^m \frac{P_i}{m * P_{\max}} + \dots + \sum_{i=1}^n \frac{P_i}{n * P_{\max}}$$

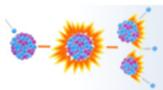


SC section design

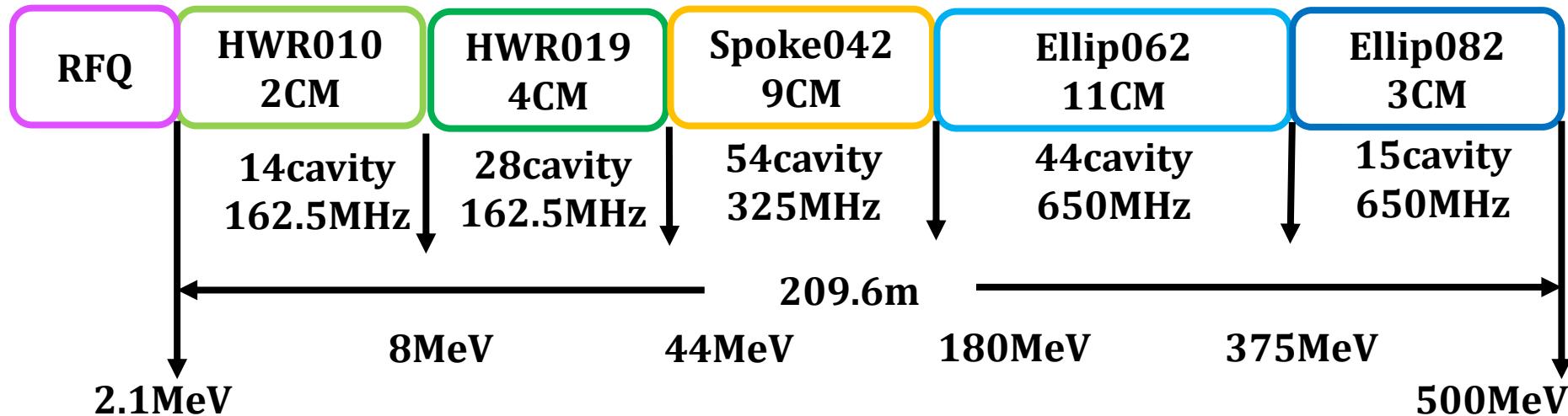
inject / extract energy (MeV)	2.1 / 500
Beam current (mA)	5
Frequency (MHz)	162.5
aperture / RMS transverse beam size	>10
Synchronous phase / RMS beam length	>9
Entrance normal RMS emittance(mmmrad)	0.216/0.216 /0.25



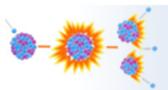
- ◆ Compact structure **at low energy section** to get large longitudinal acceptance and to weaken the effect from space charge
- ◆ Full period lattice structure **at high energy section** for good matching
- ◆ Optimization at the location of **structure transition** and **frequency jump** for good matching



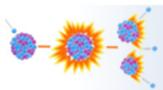
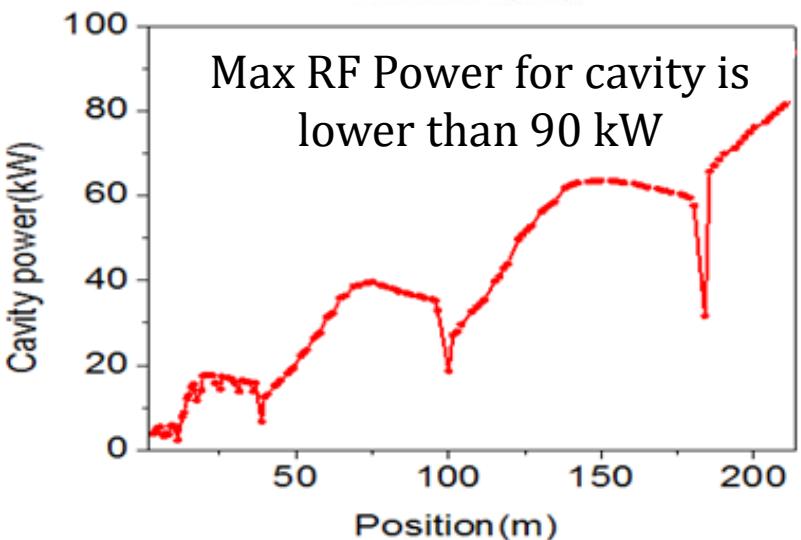
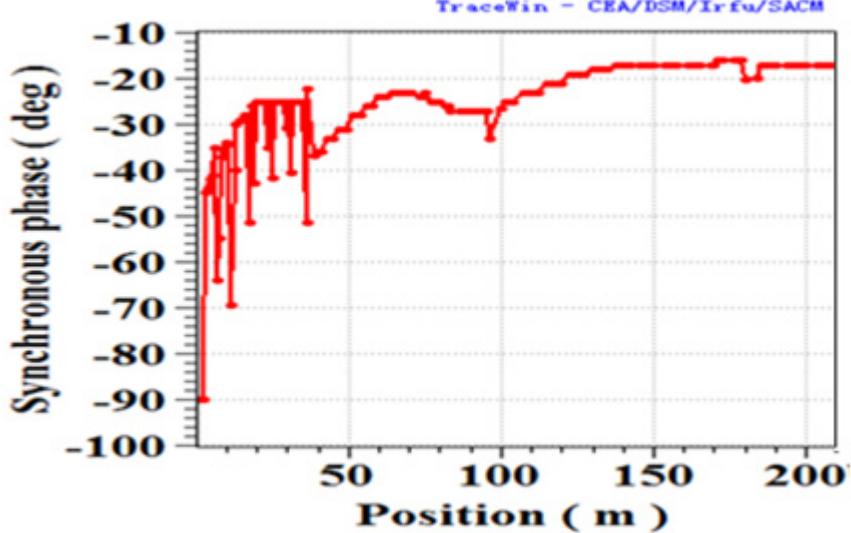
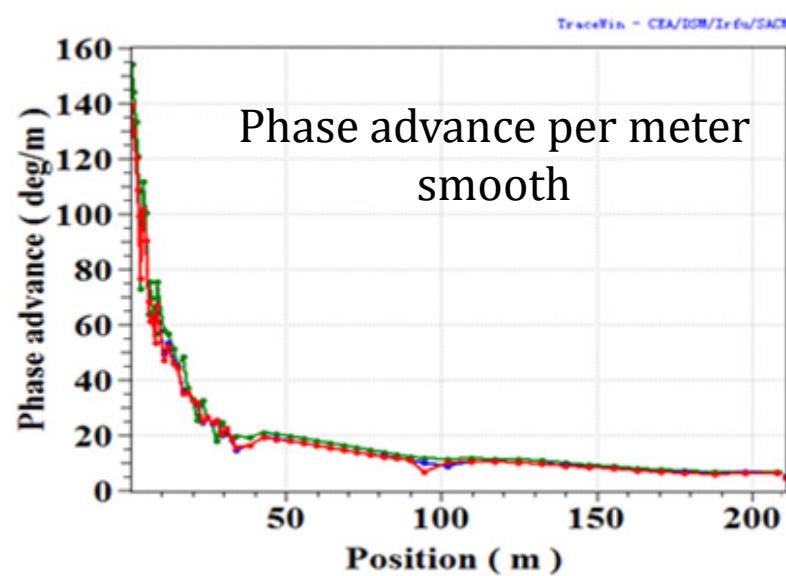
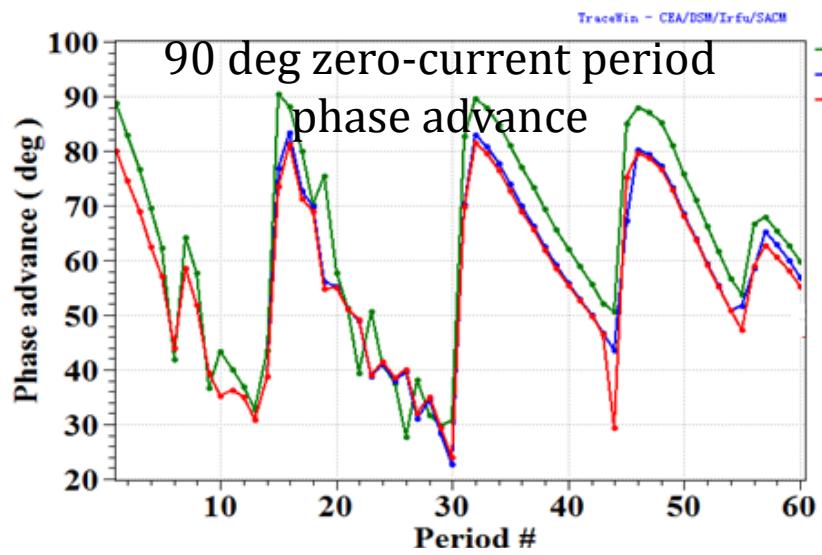
SC section design



	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
Q0	E09	5.00	5.00	6.00	10.0	10.0
S or Q/C	per CM	7/7	4/7	2/6	1/4	1/5
CMs	m/Num.	5.5/2	7.3/4	8.2/9	6.5/11	8.1/3

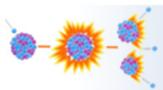
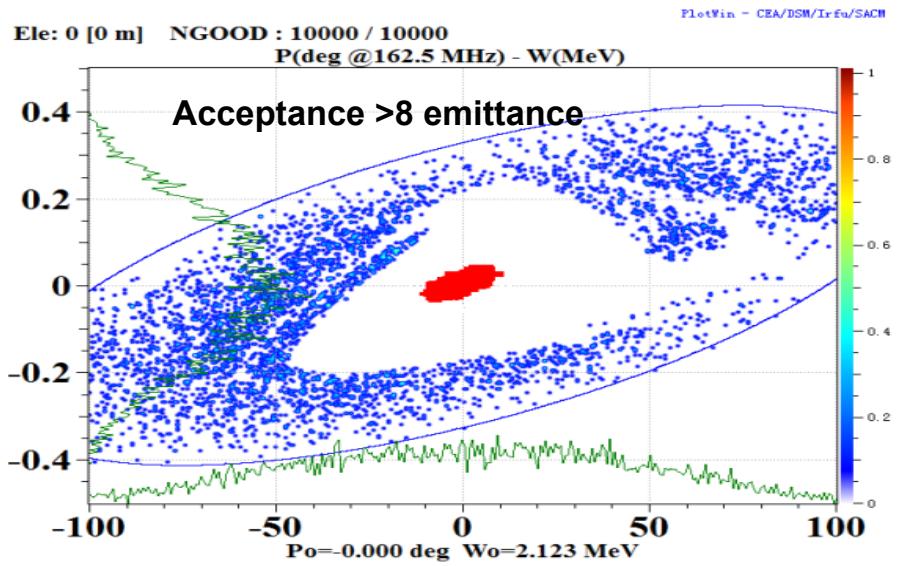
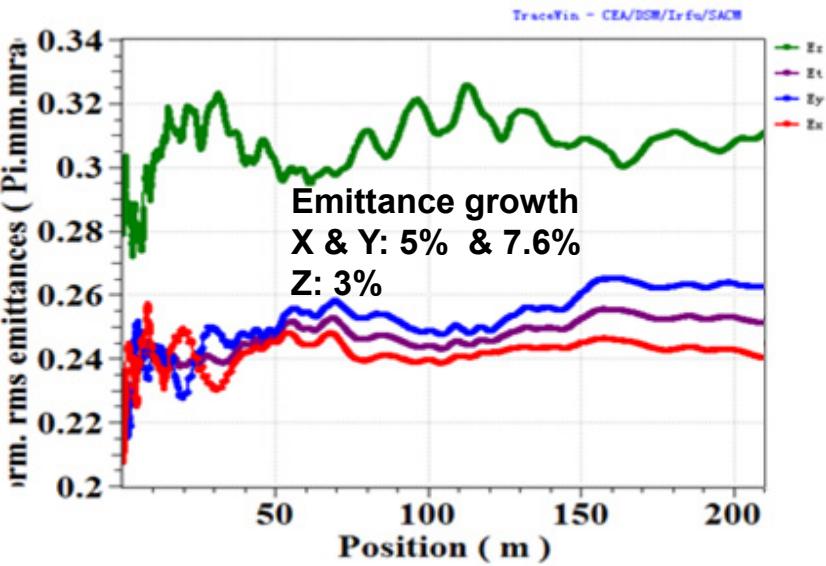
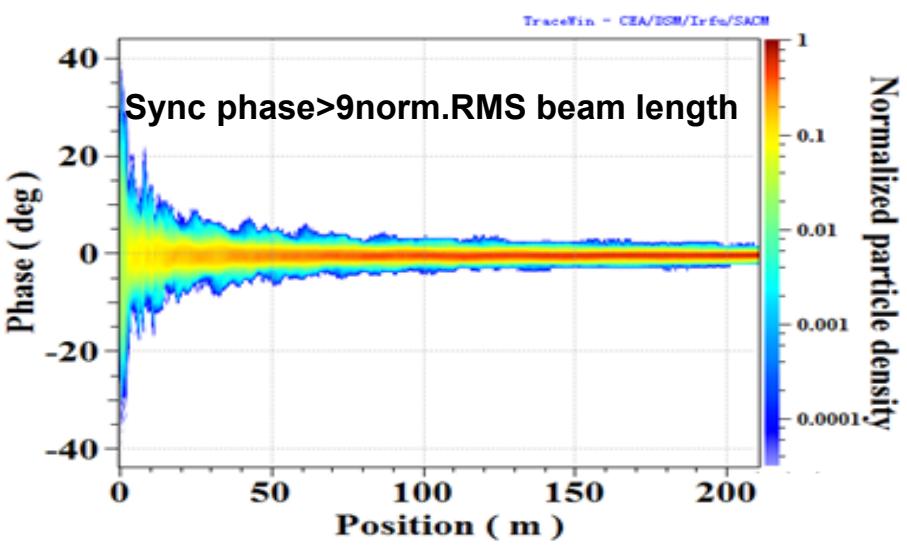
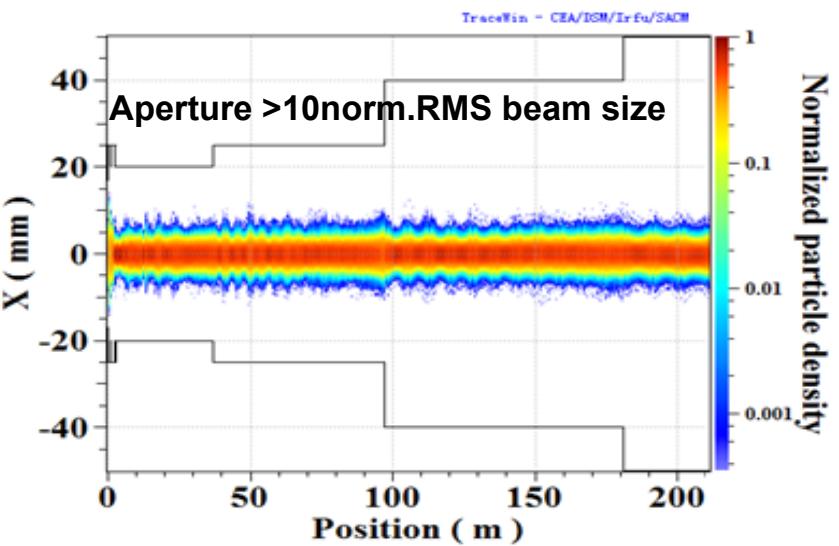


SC section design





SC section design

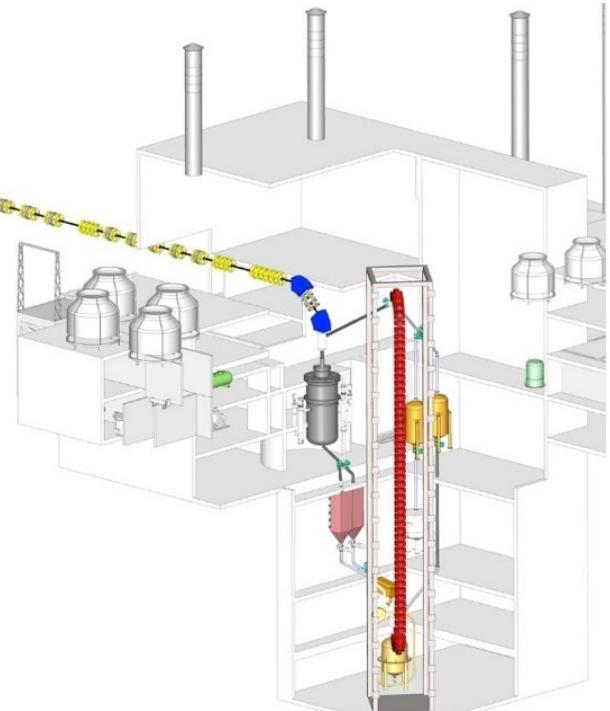
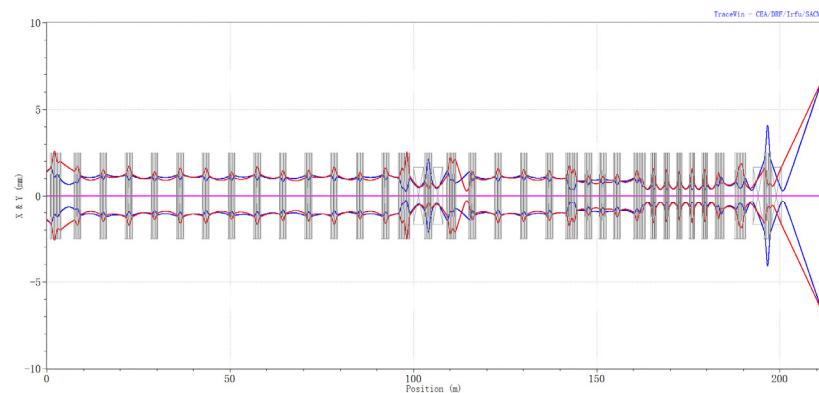


Design of A. to T.

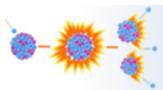
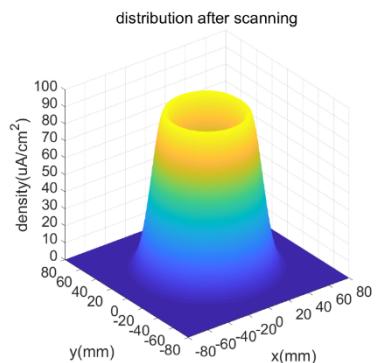
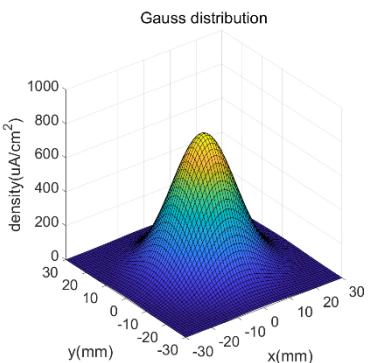
Reserved space for Energy upgrading

Collimation section

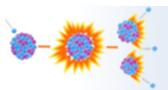
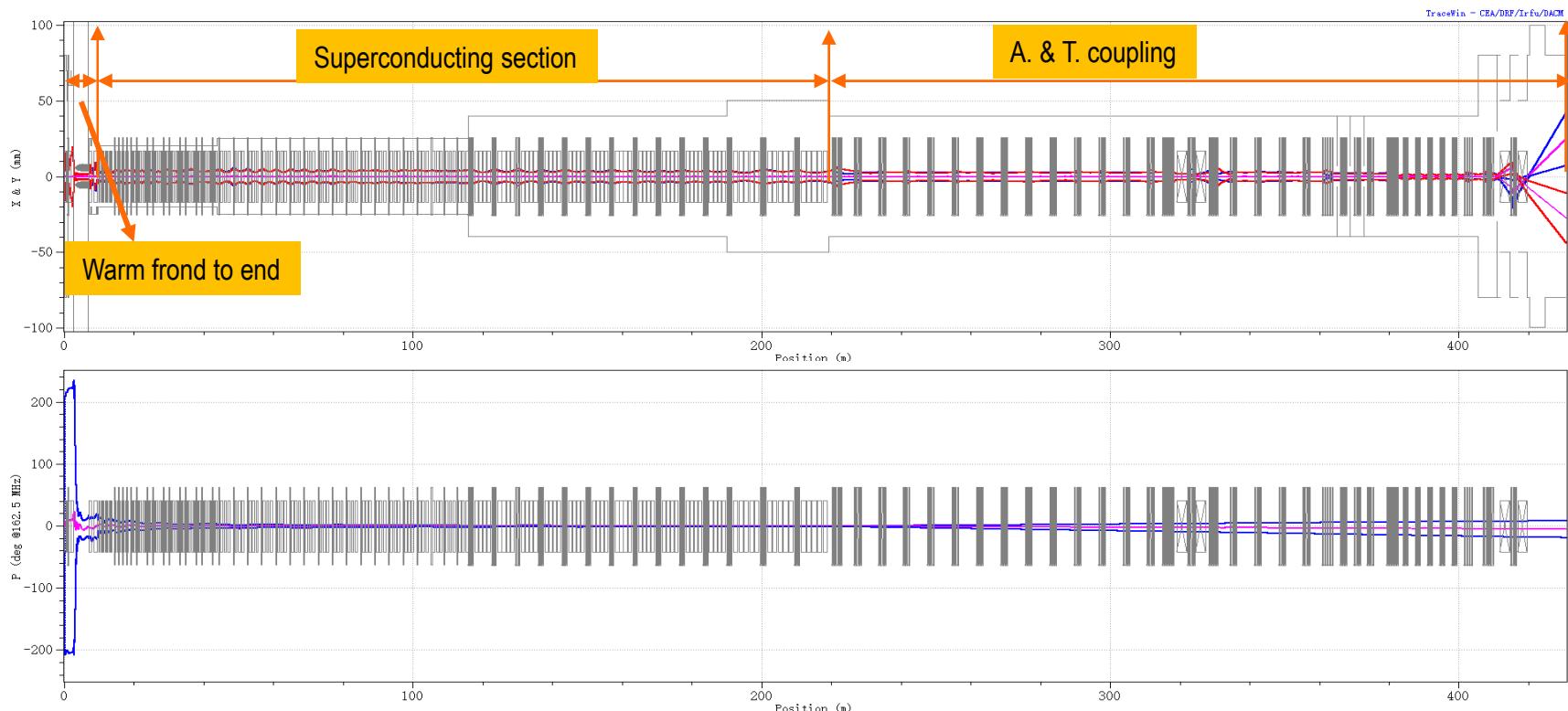
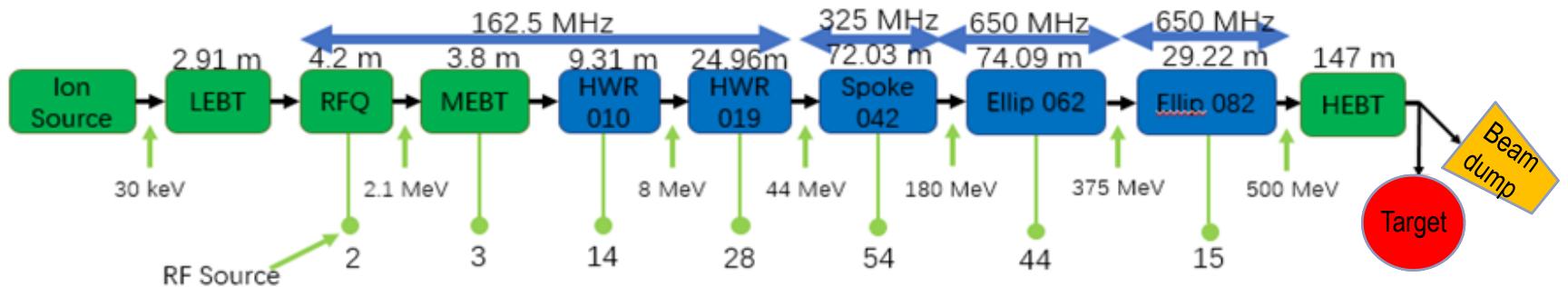
scanning section PBW



	value	unit
Emit. RMS norm. (x/y/z)	0.23/0.23/0.26	$\pi \text{ mm.mrad}$
Entrance $\alpha_x/\alpha_y/\alpha_z$	-1.4/-1.4/0.0	—
Entrance $\beta_x/\beta_y/\beta_z$	10.5/10.5/10.2	$\text{mm}/\pi.\text{mrad}$
Beam profile on target	Round&Hollow	
Peak current density	< 100	$\mu\text{A}/\text{cm}^2$
99.99% beam diameter	<160	mm



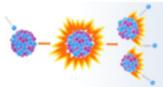
End to end simulation



- ▶ Introduction of CiADS
- ▶ Design of superconducting Linac
- ▶ Beam commission of Chinese ADS

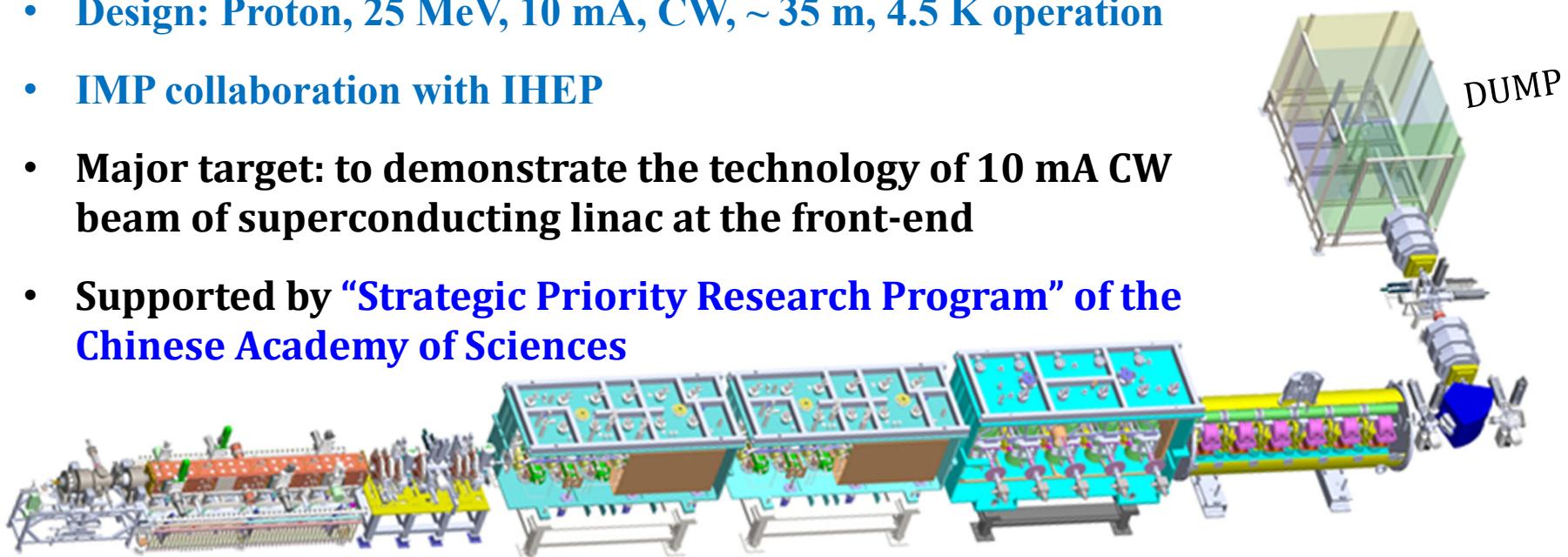
Front-end Demo Linac (CAFé)

- ▶ Summary



	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

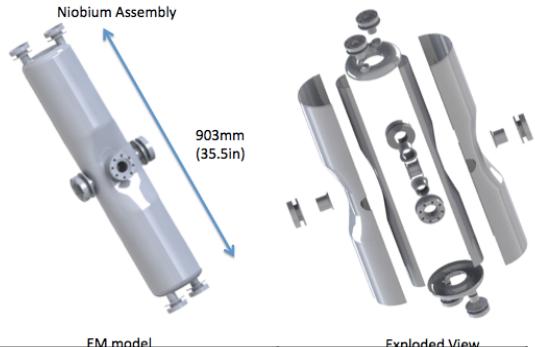
- Design: Proton, 25 MeV, 10 mA, CW, ~ 35 m, 4.5 K operation
- IMP collaboration with IHEP
- Major target: to demonstrate the technology of 10 mA CW beam of superconducting linac at the front-end
- Supported by “Strategic Priority Research Program” of the Chinese Academy of Sciences



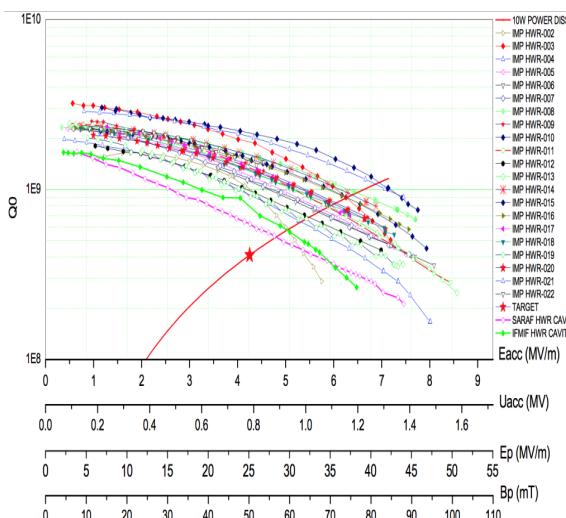
Specifications of SC-cavities



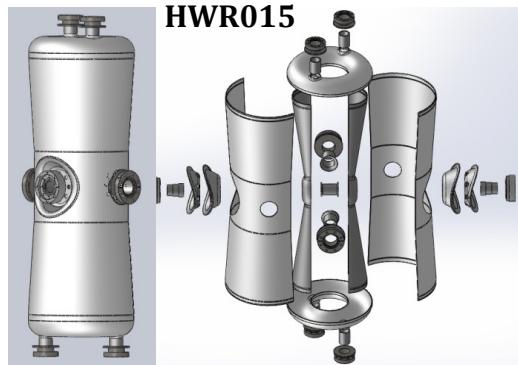
162.5 MHz Half-wave Cavity



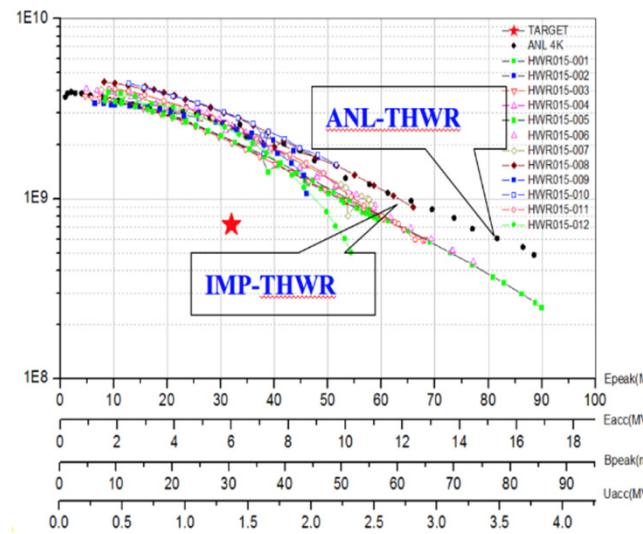
	EM model	Exploded View
β_{opt}	0.10	
Vmax (MV)	1.06	
Epeak (MV/m)	28	



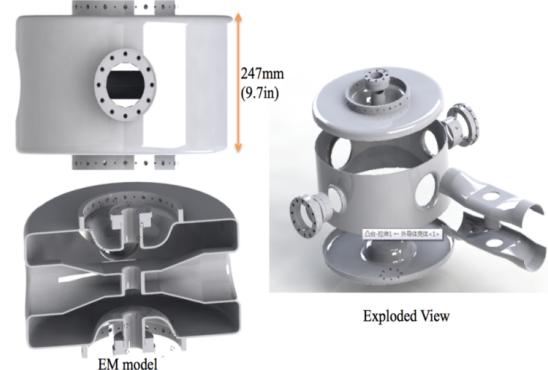
162.5 MHz Taper
HWR015



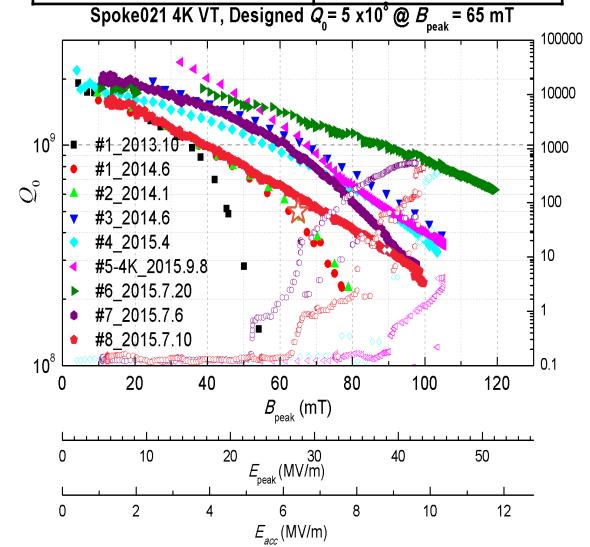
	EM model	Exploded View
β_{opt}	0.15	
Vmax (MV)	1.8	
Epeak (MV/m)	32	



325 MHz Spoke cavity

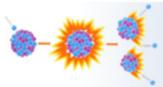


	EM model	Exploded View
β_{opt}	0.246	
Vmax (MV)	1.75	
Epeak (MV/m)	32.5	



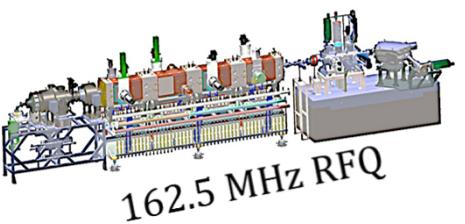


Beam Commissioning since 2014



Beam Commissioning since 2014

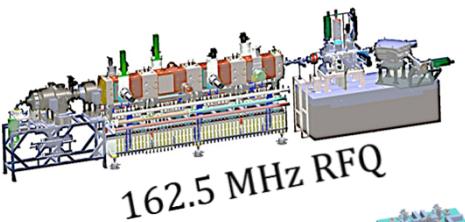
1



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

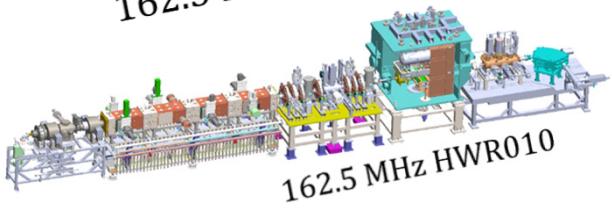
Beam Commissioning since 2014

1



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

2

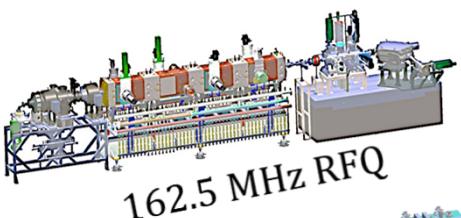


- ECRIS + RFQ + MEBT + TCM1 (single HWR)
- Energy is ~**2.5 MeV**
- First beam **October 1st, 2014**;
- **achievement 11 mA, 2.55 MeV**

Beam Commissioning since 2014

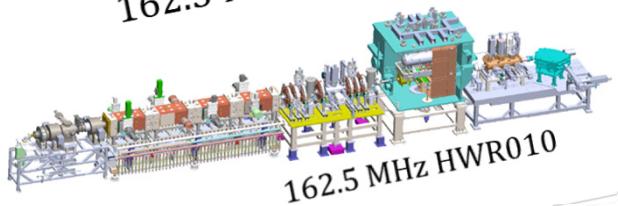


1



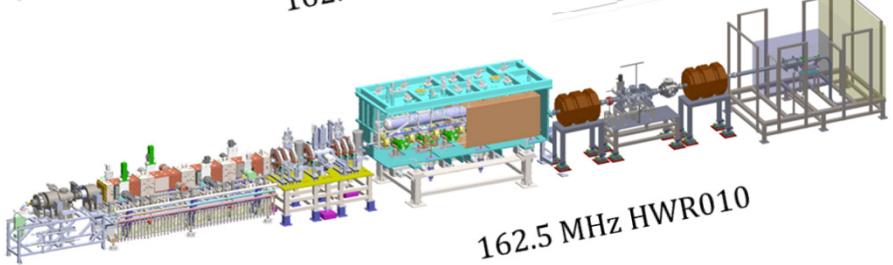
- ECRIS + RFQ
- Energy is ~2.1 MeV
- First beam Jun. 6th, 2014;
- achievement 10 mA, 2.1 MeV, 4.5 hours

2



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

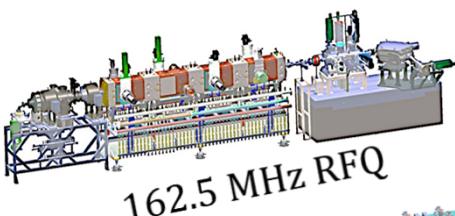
3



- 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

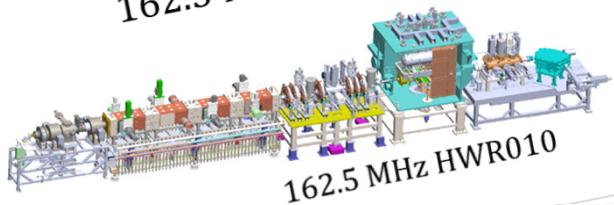
Beam Commissioning since 2014

1



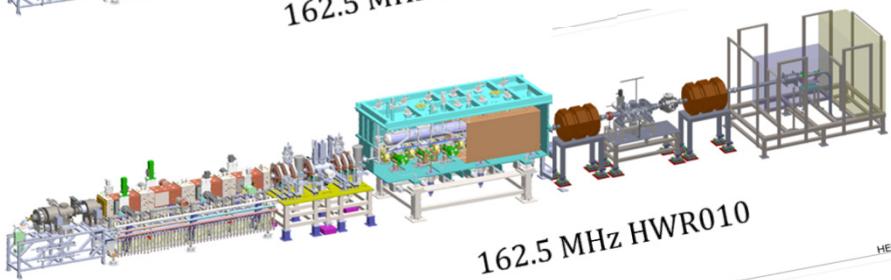
- ECRIS + RFQ
- Energy is ~2.1 MeV
- First beam Jun. 6th, 2014;
- achievement 10 mA, 2.1 MeV, 4.5 hours

2



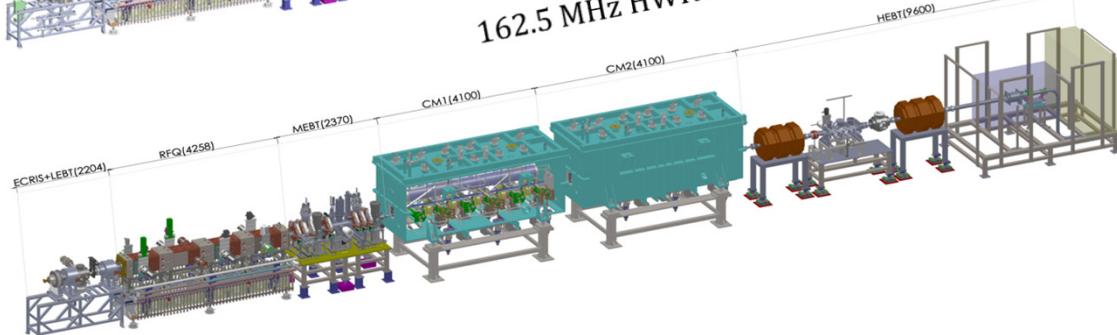
- ECRIS + RFQ + MEBT + TCM1 (single HWR)
- Energy is ~2.5 MeV
- First beam October 1st, 2014;
- achievement 11 mA, 2.55 MeV

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

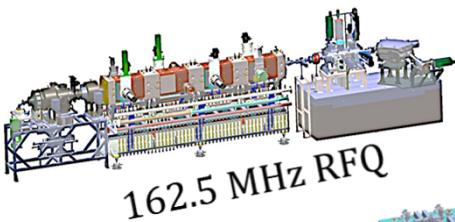


- ECRIS + RFQ + CM1 + CM2
- Energy is ~10 MeV
- First beam September 15th, 2016
- Achievement ~ 2.7 mA, 9.55 MeV

Beam Commissioning since 2014

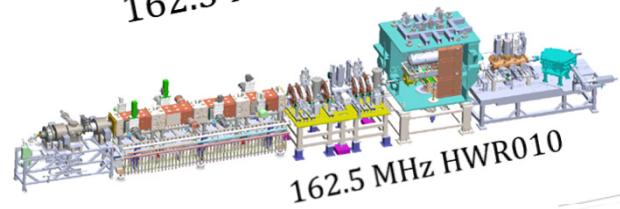


1



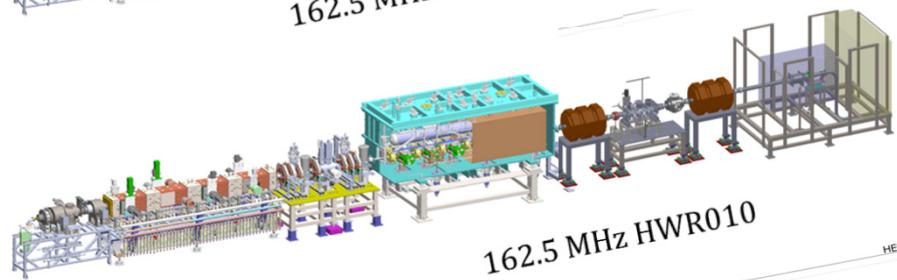
- ECRIS + RFQ
- Energy is ~2.1 MeV
- First beam Jun. 6th, 2014;
- achievement 10 mA, 2.1 MeV, 4.5 hours

2



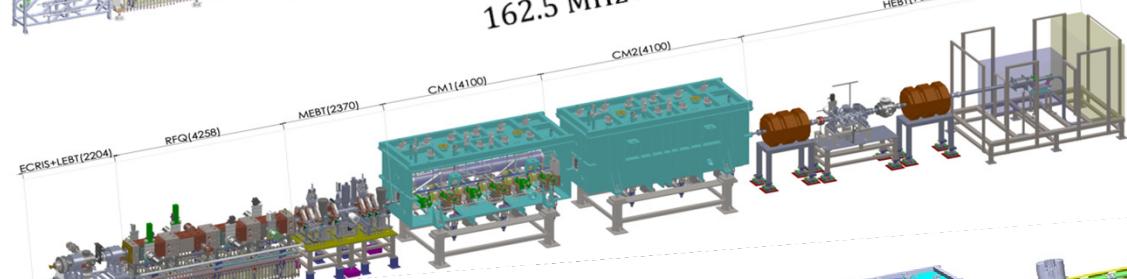
- ECRIS + RFQ + MEBT + TCM1 (single HWR)
- Energy is ~2.5 MeV
- First beam October 1st, 2014;
- achievement 11 mA, 2.55 MeV

3



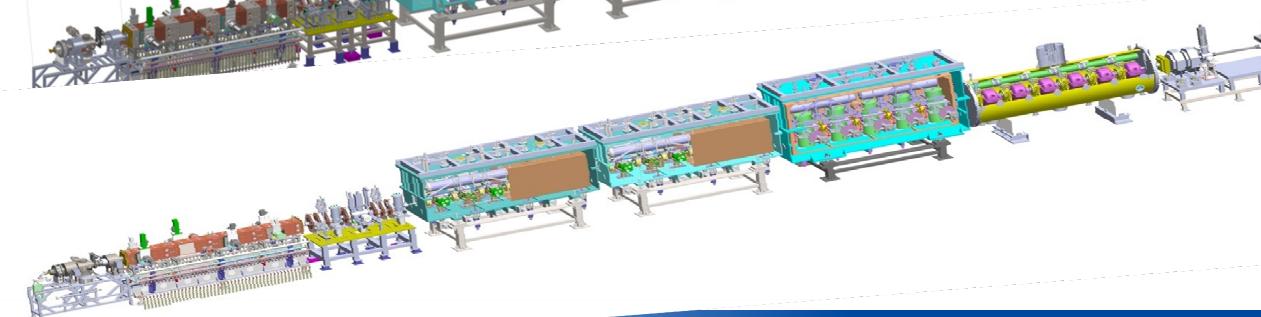
- ECRIS + RFQ + TCM6
- Energy is ~5 MeV
- First beam June 6th, 2015;
- achievement 2.7 mA, 5.3 MeV; ~7.5 hours 2 mA 4 MeV operation

4



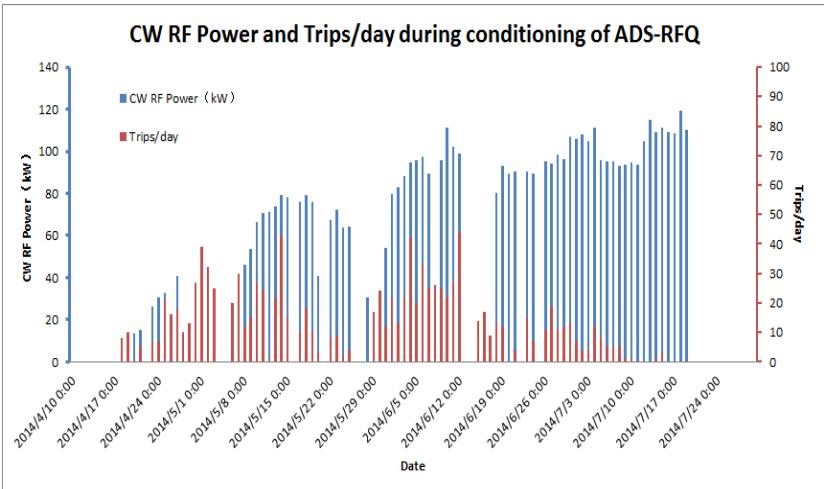
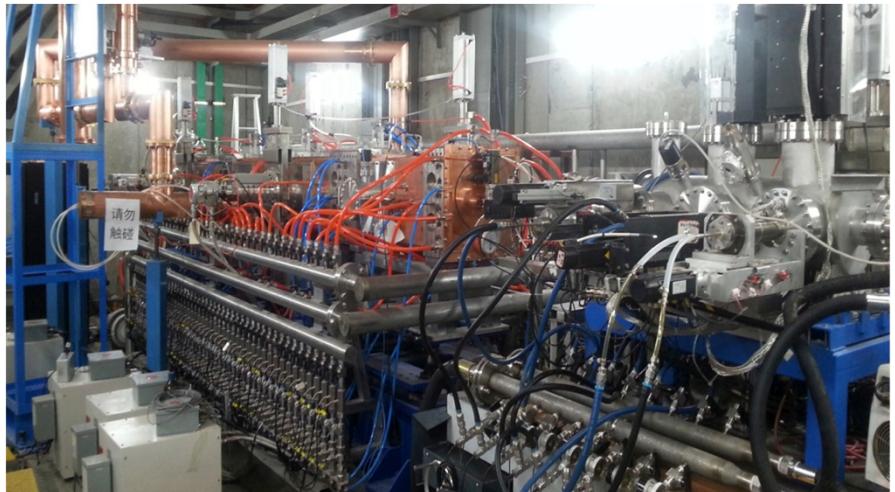
- ECRIS + RFQ + CM1 + CM2
- Energy is ~10 MeV
- First beam September 15th, 2016
- Achievement ~ 2.7 mA, 9.55 MeV

5

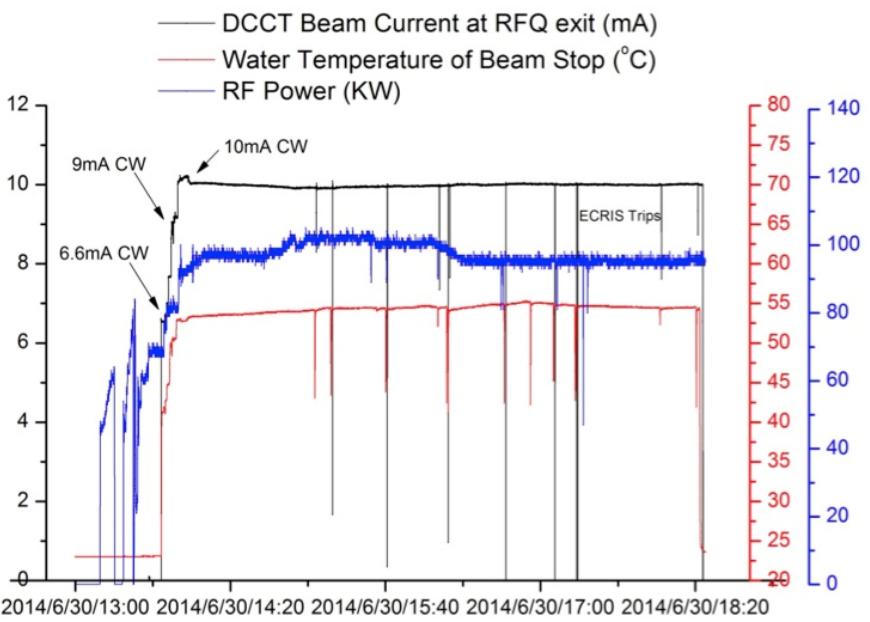


- ECRIS + RFQ + CM1 + CM2 + CM3 + CM4
- Energy is ~25 MeV
- First beam May 28th, 2017
- Achievement 0.2 mA 25 MeV

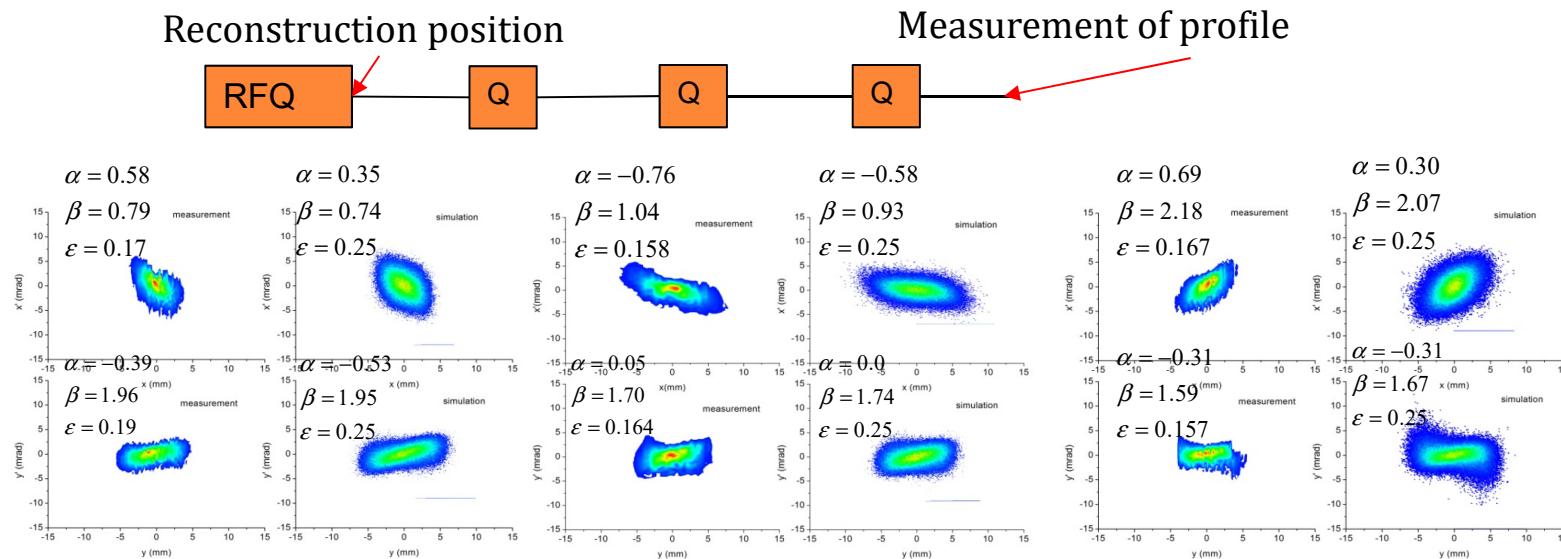
Commissioning of RFQ



- 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**



Re-construction of beam distribution

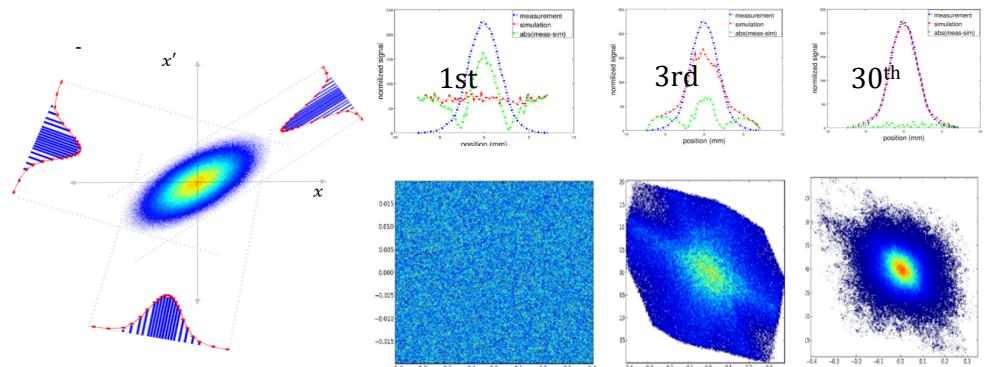


Objection :

- Reconfiguration of four dimension emittance with space charge effect

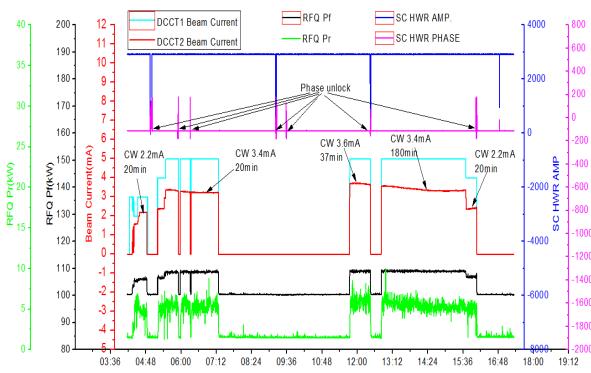
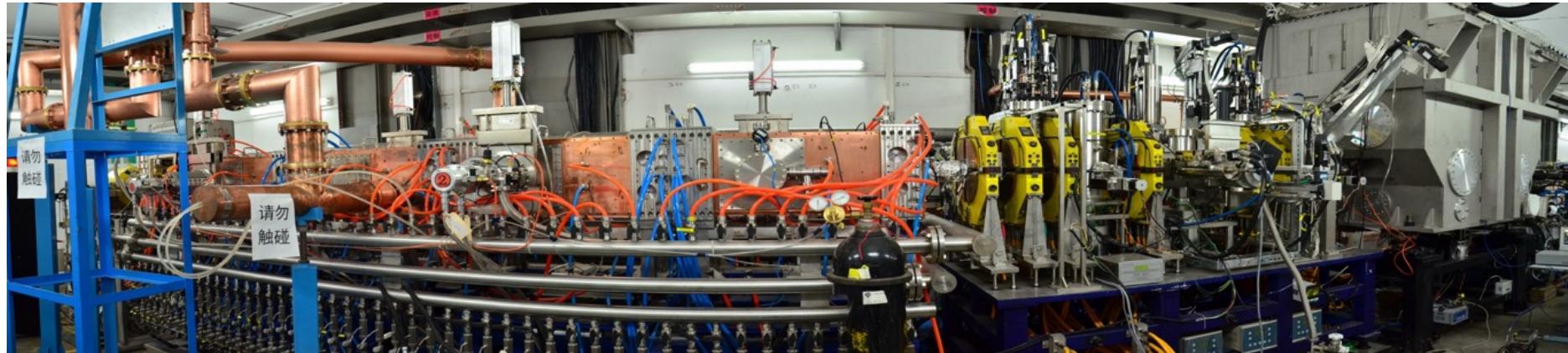
Challenge :

- Nonlinear space charge effect
- RF nonlinearity

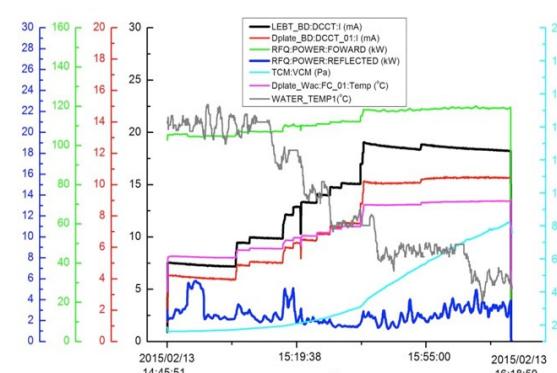


Setup of SC linac base on the re-constructed beam

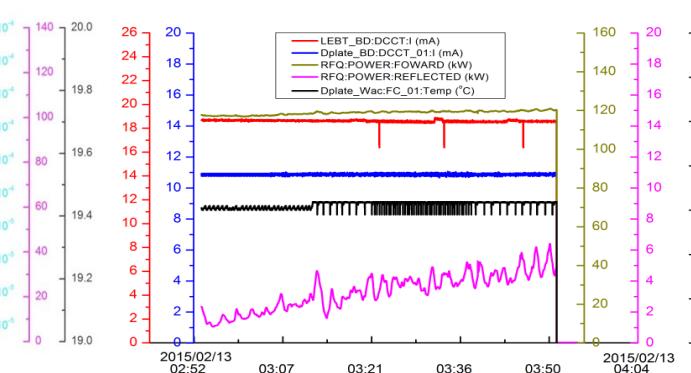
CW Beam Commission to 11 mA



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

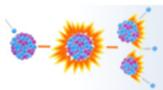


- Feb. 4th, 2015, 4.2~10.8 mA,
- 2.5MeV, CW



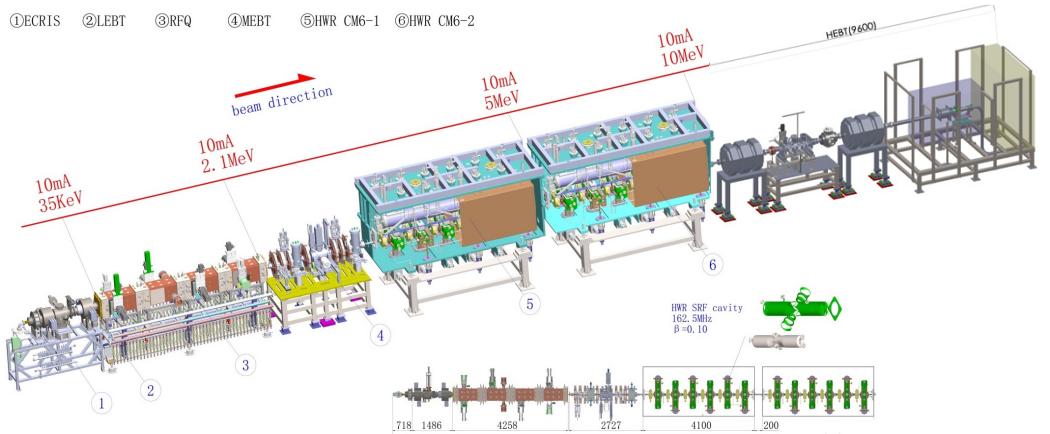
- Feb. 23rd, 2015, achieved 2.5MeV/~11mA/28kW, ~1 hour

- 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.

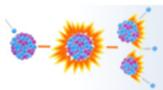
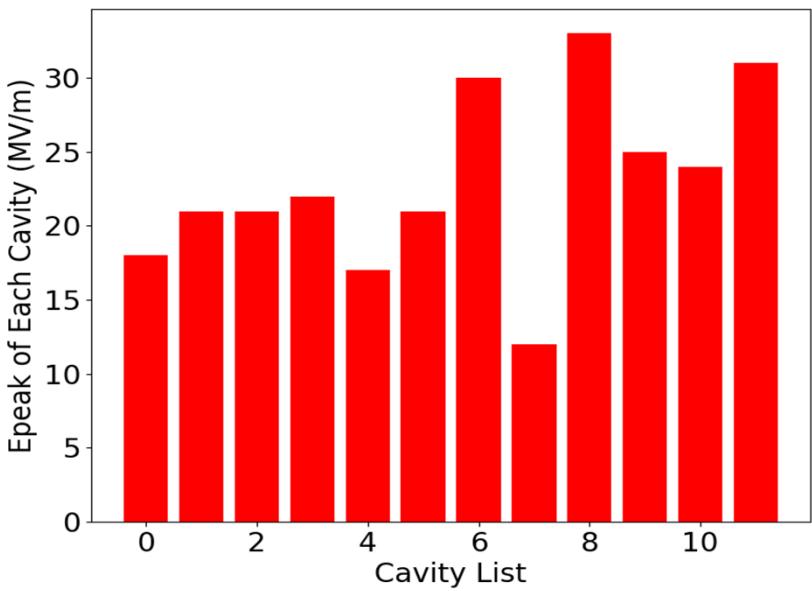
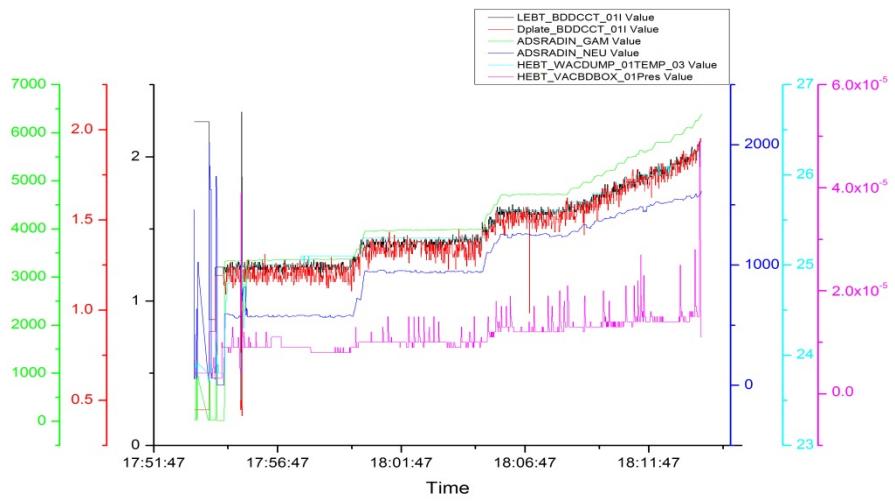


CW Commissioning of 10 MeV

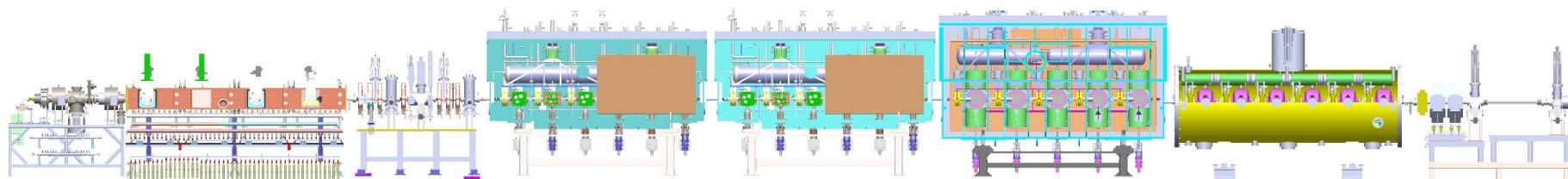
①ECRIS ②LEBT ③RPQ ④MEBT ⑤HWR CM6-1 ⑥HWR CM6-2



NOV 27th-28th, 20 minutes CW beam operation at 1.2 - 2.7 mA without uncontrolled beam loss

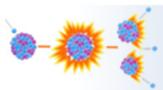
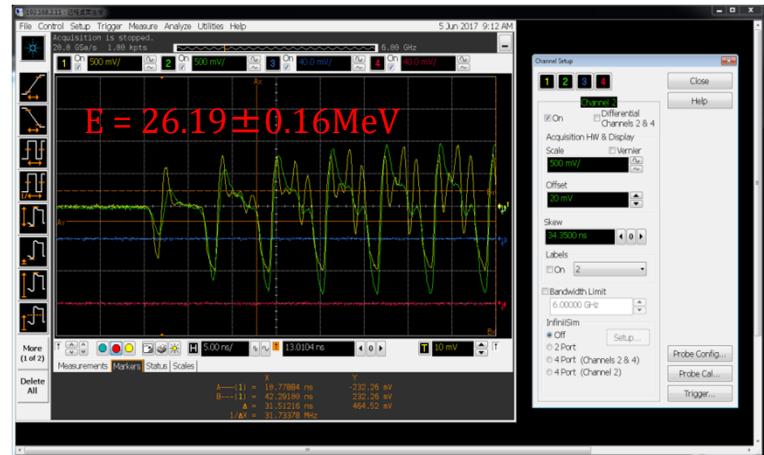
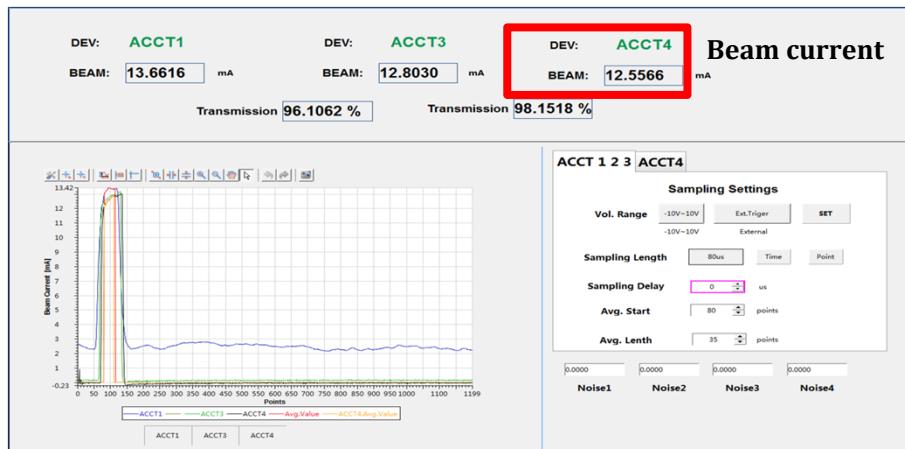
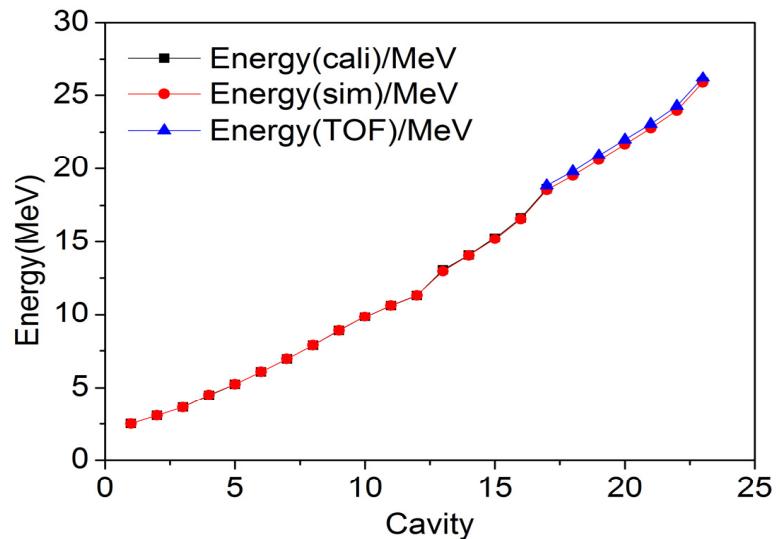
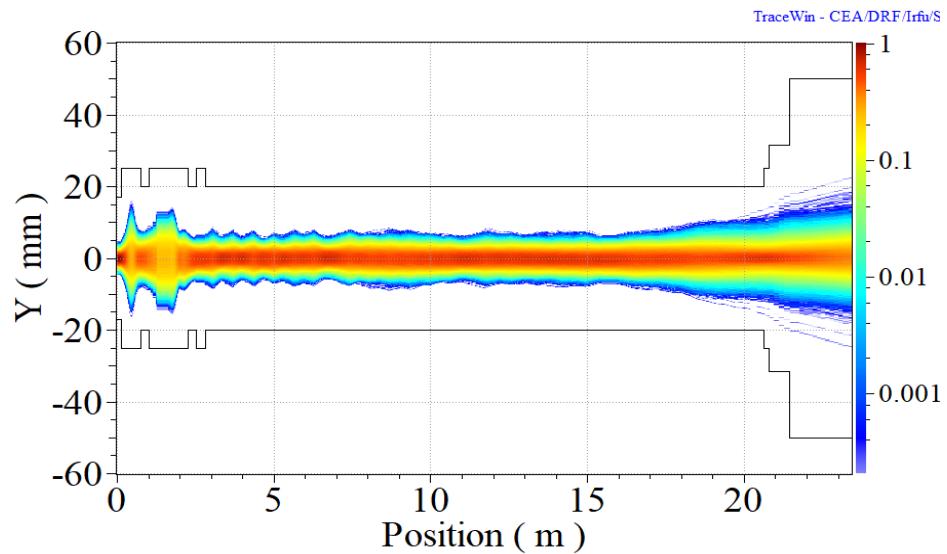


The first beam commissioning of CAFE

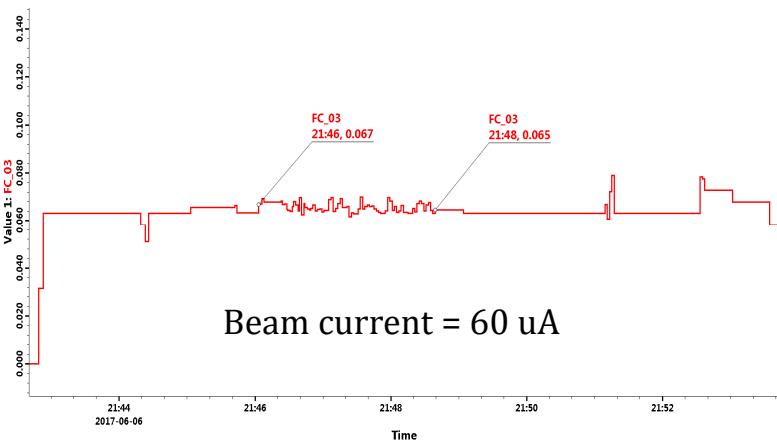
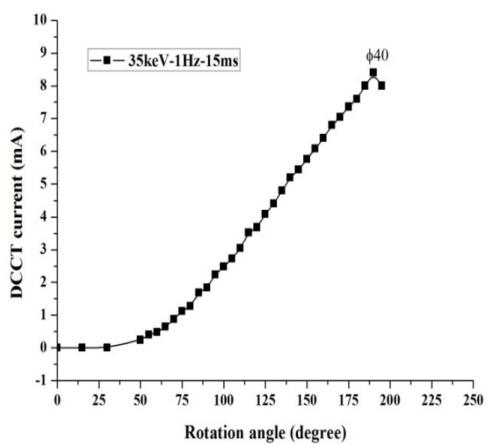
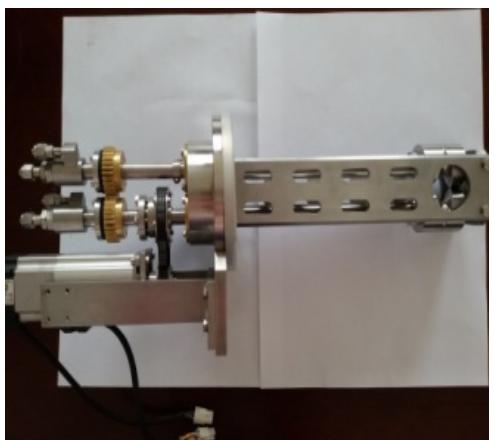
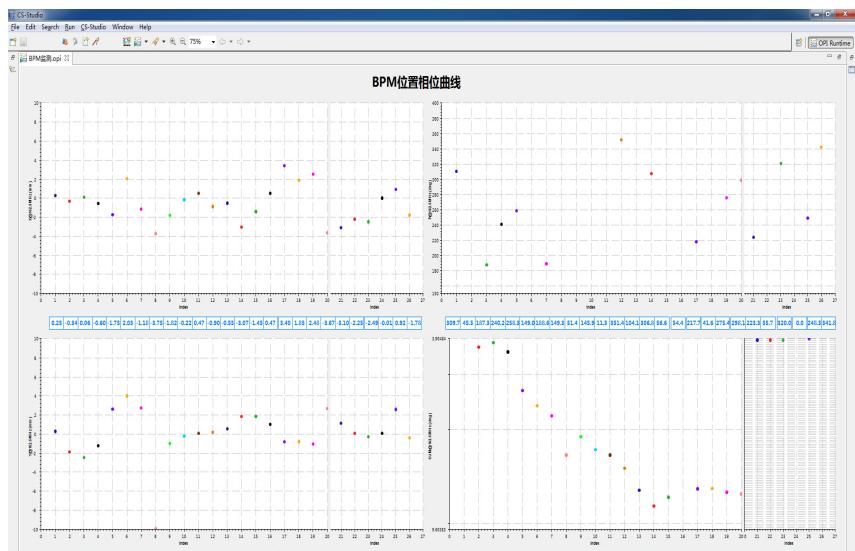
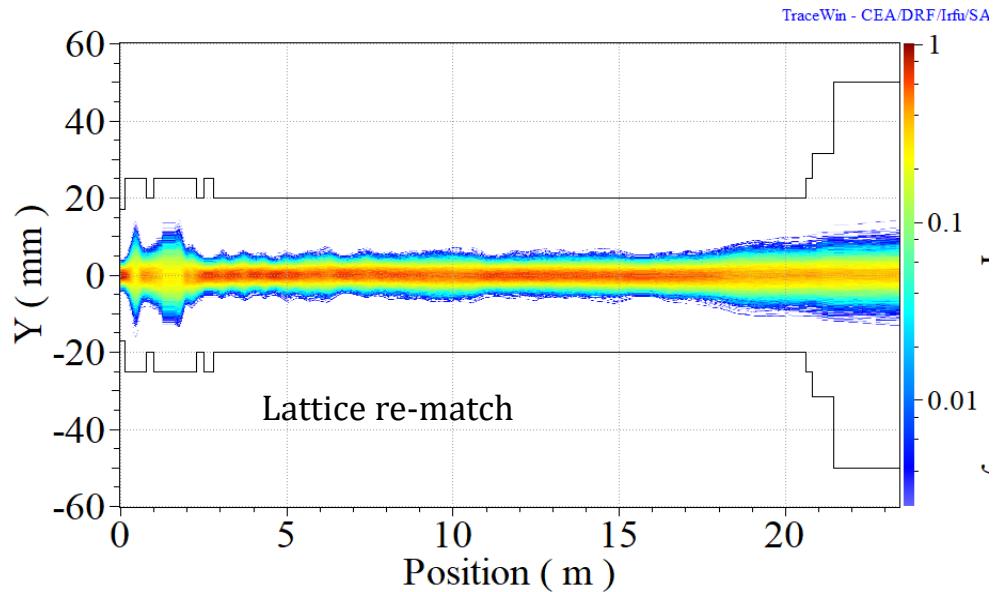


- CM1,CM2 were re-installed in Feb 2017;
- CM3 and CM4 were on line on May. 9th , 2017;
- First beam was achieved on May. 28th , 2017 ;
- The energy is up to 26.2 MeV on June. 5th , 2017;
- CW beam with energy 25MeV went through on June 6th , 2017.

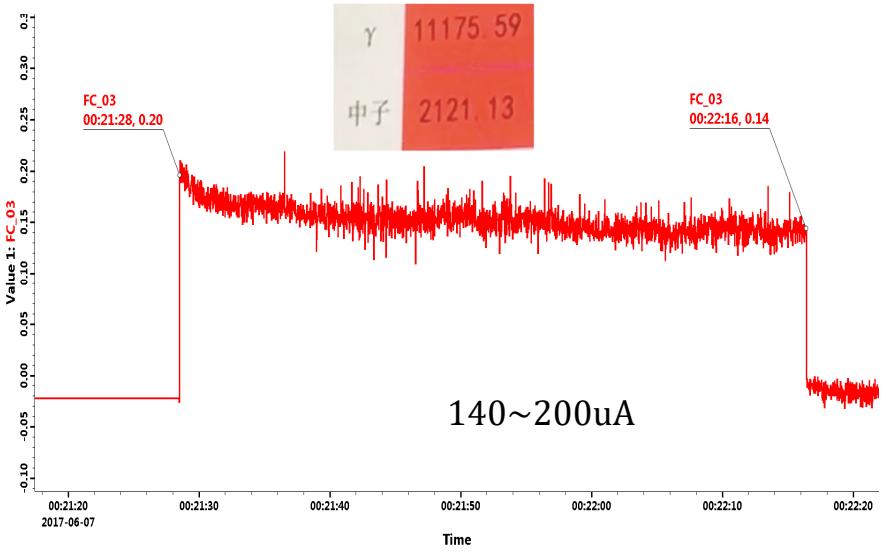
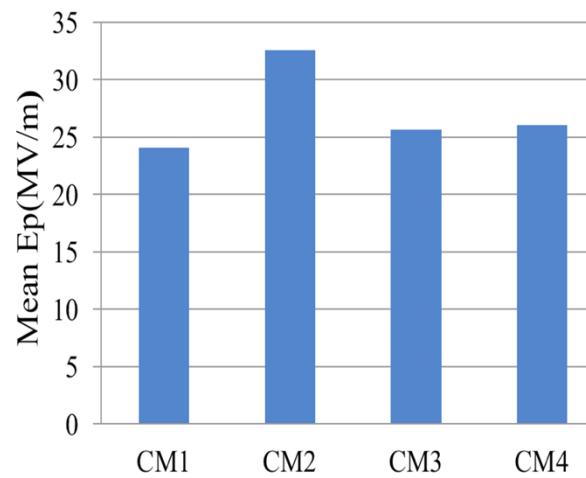
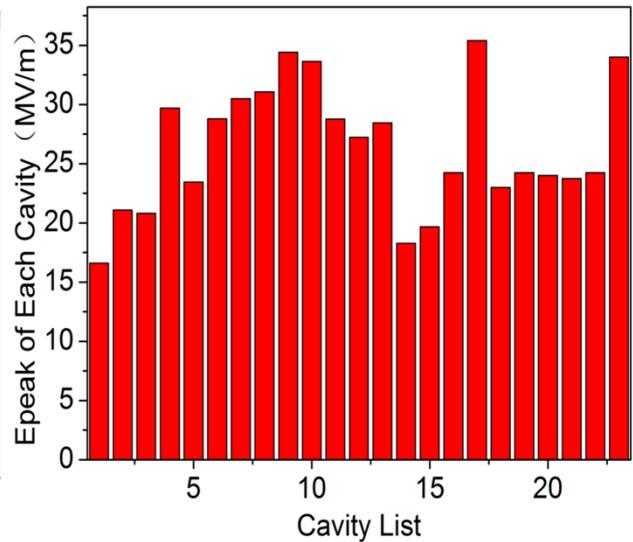
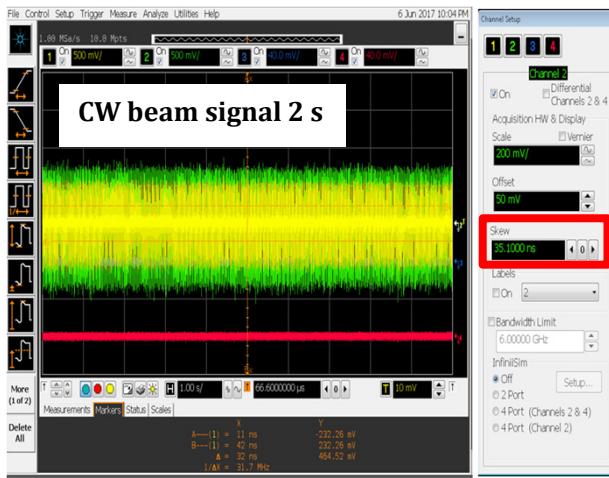
Pulse Beam Commissioning



First CW Beam Tuning



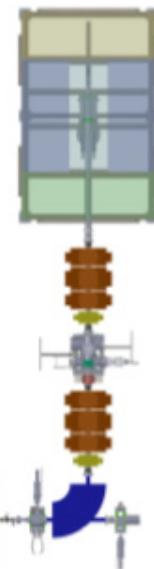
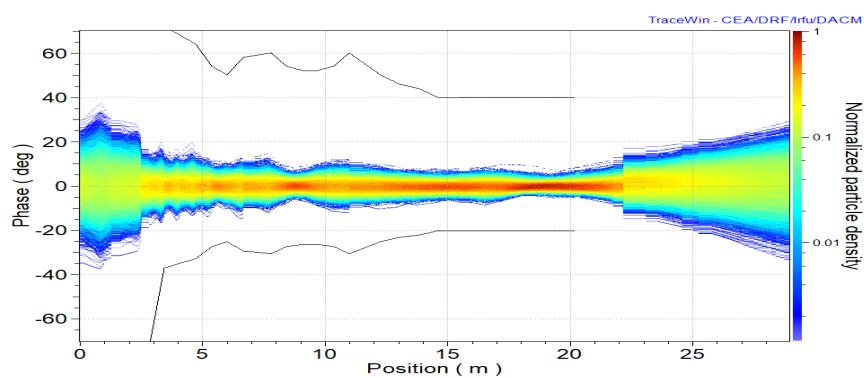
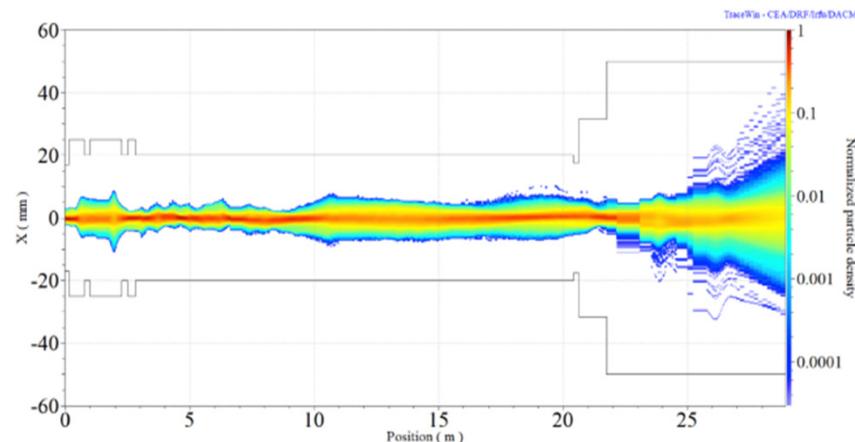
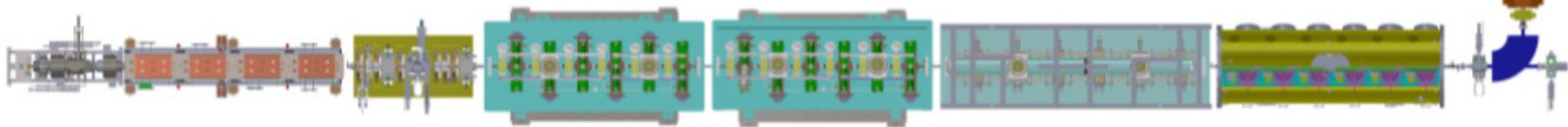
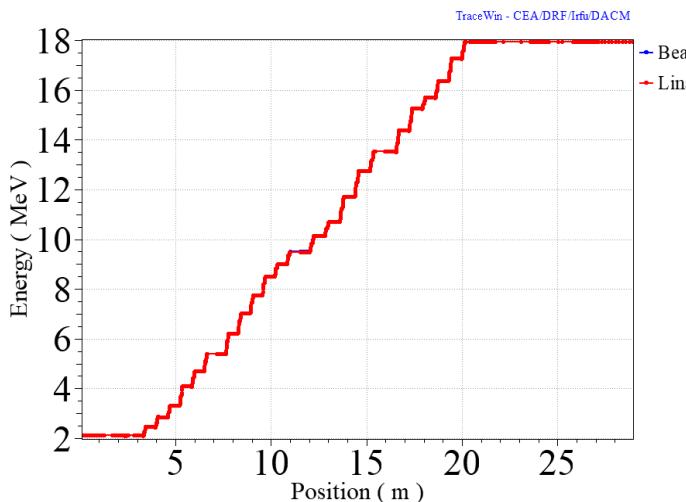
First CW Beam Commissioning



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

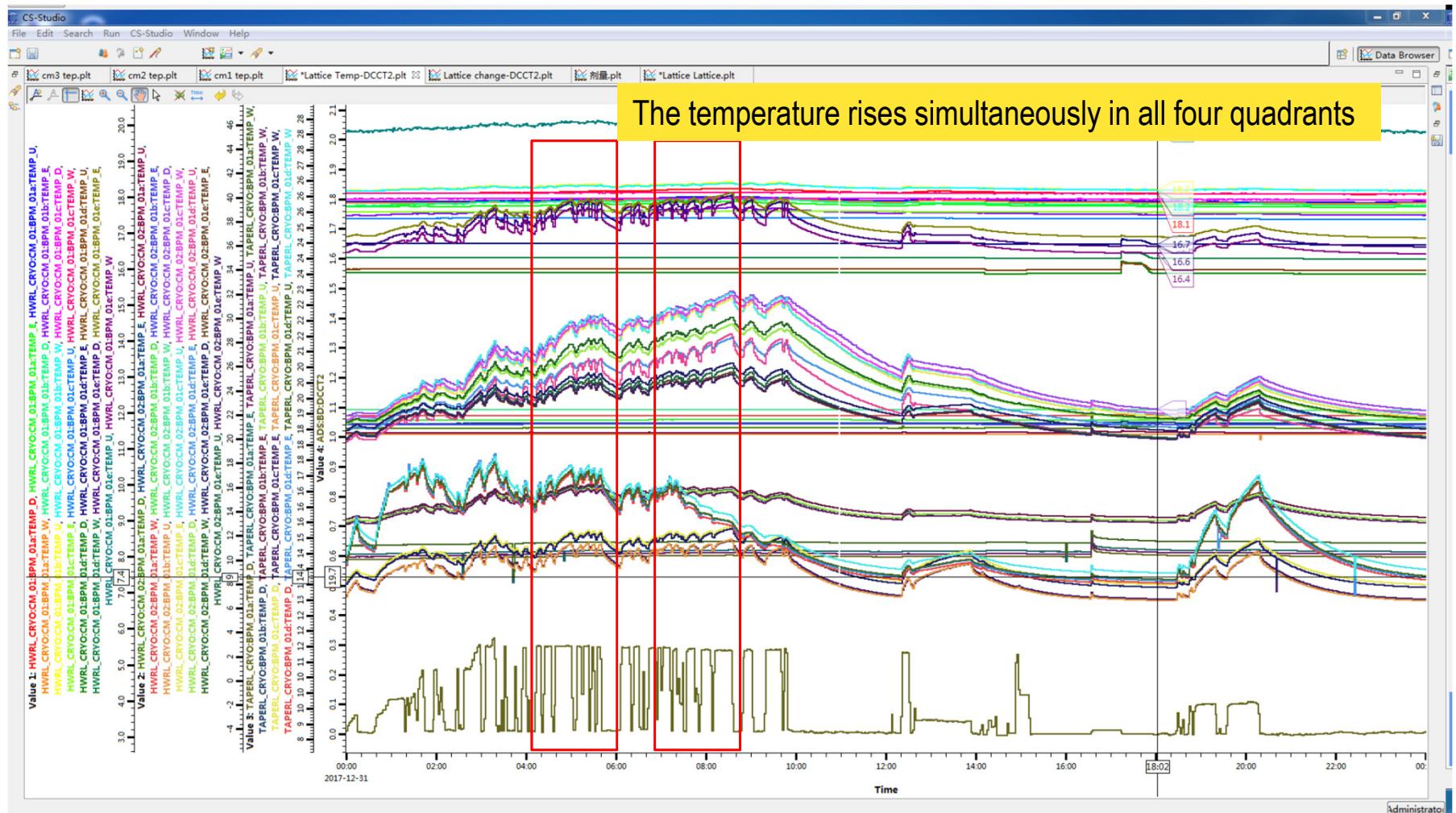
Machine Reliability Operation

- 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

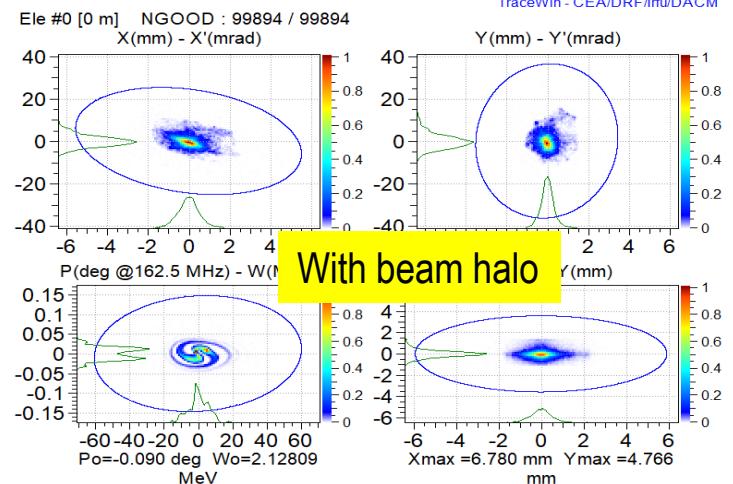
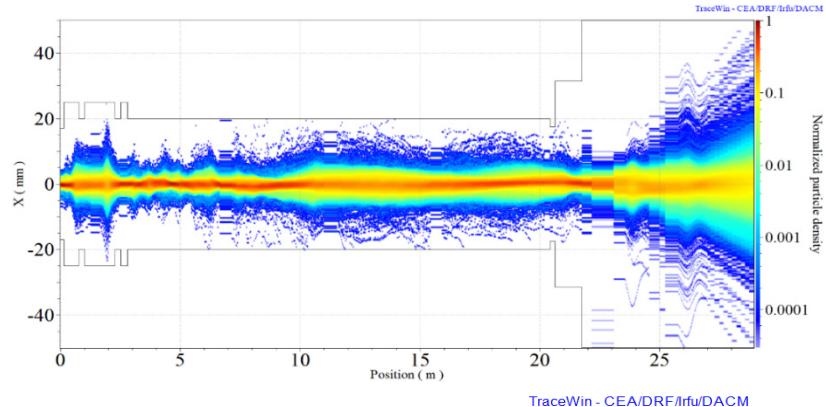
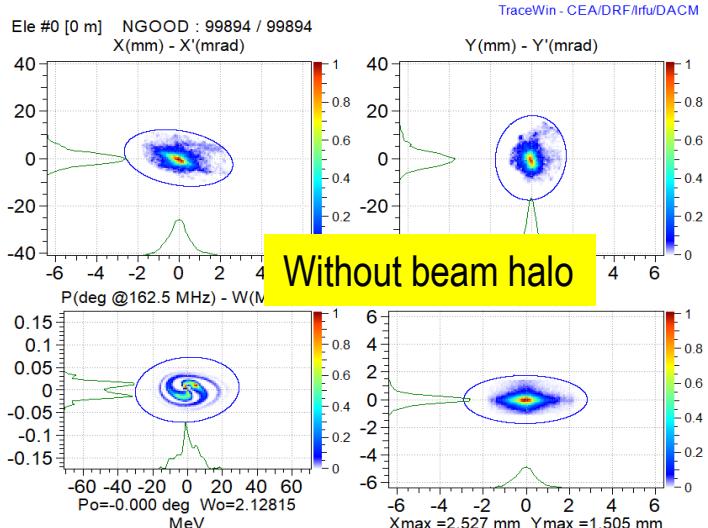




Beam loss study

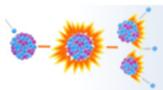


Beam loss study



- ◆ 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) $\pi \cdot \text{mm} \cdot \text{mrad}$ [Norm.]	Emit-X/Y/Z(99.99%) $\pi \cdot \text{mm} \cdot \text{mrad}$ [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

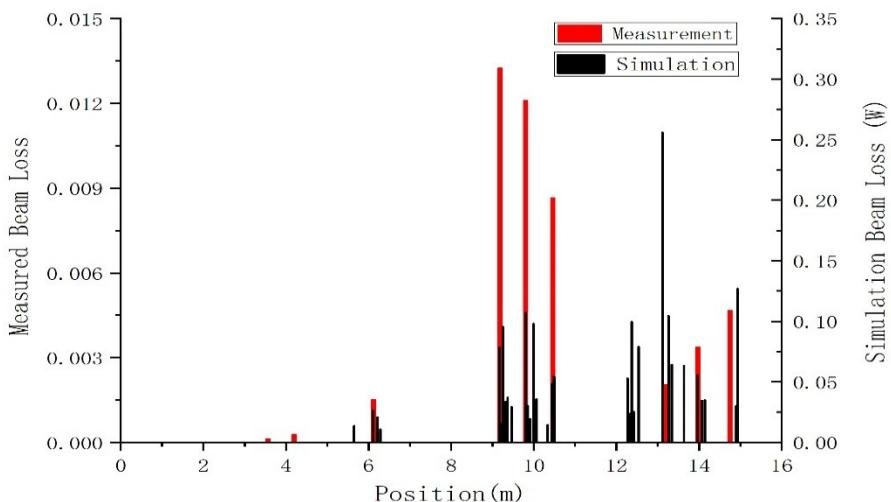


Beam loss study

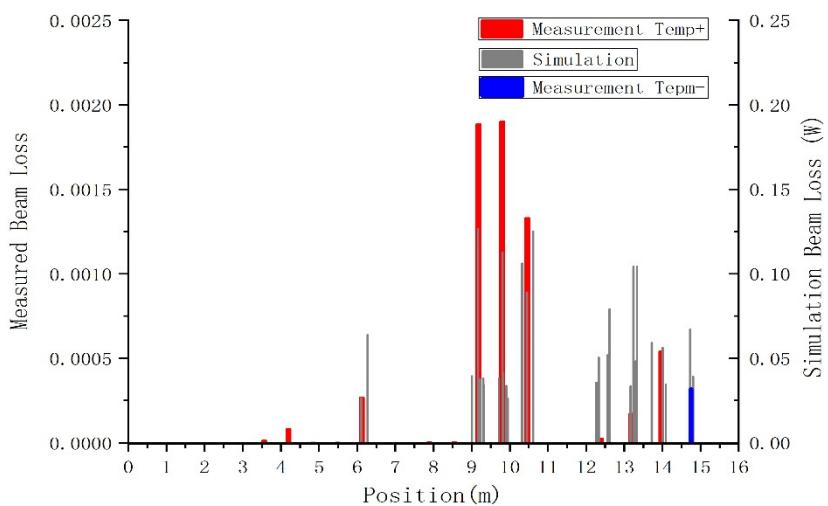
The beam loss is defined as the sum of four quadrant temperature raising per unit time at a certain temperature probe:

$$\sum_i^4 k_i = \frac{\Delta T_i}{t}$$

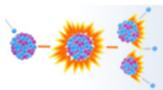
Lattice 1



Lattice 2

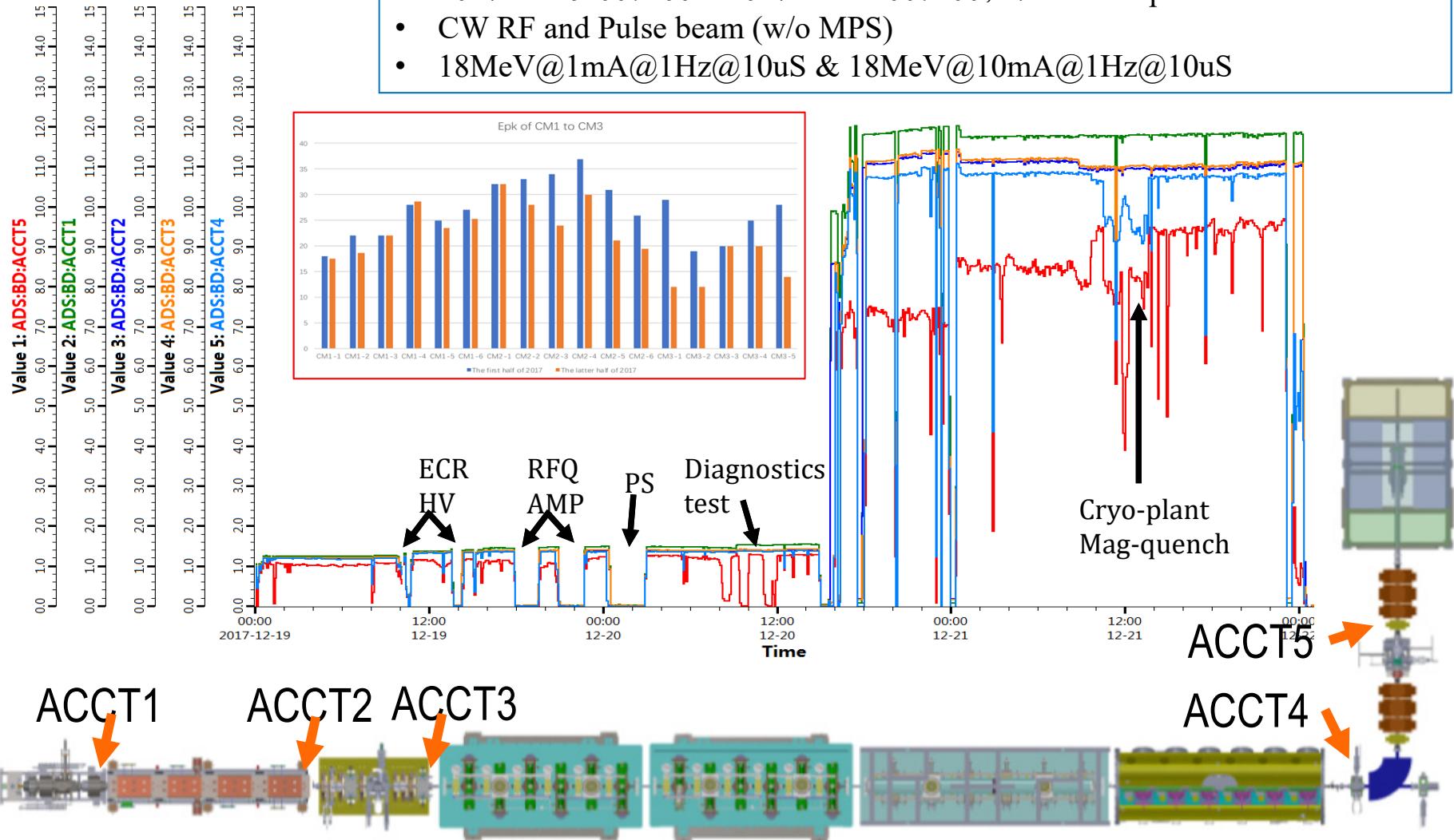


The results of simulation and experiment are consistent



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



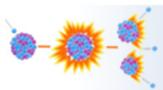
Beam trip required by ADS demo facility	
Beam trips (10s-5min)	2500/year
Beam trips (>5min)	300/year
Availability	80%

- 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

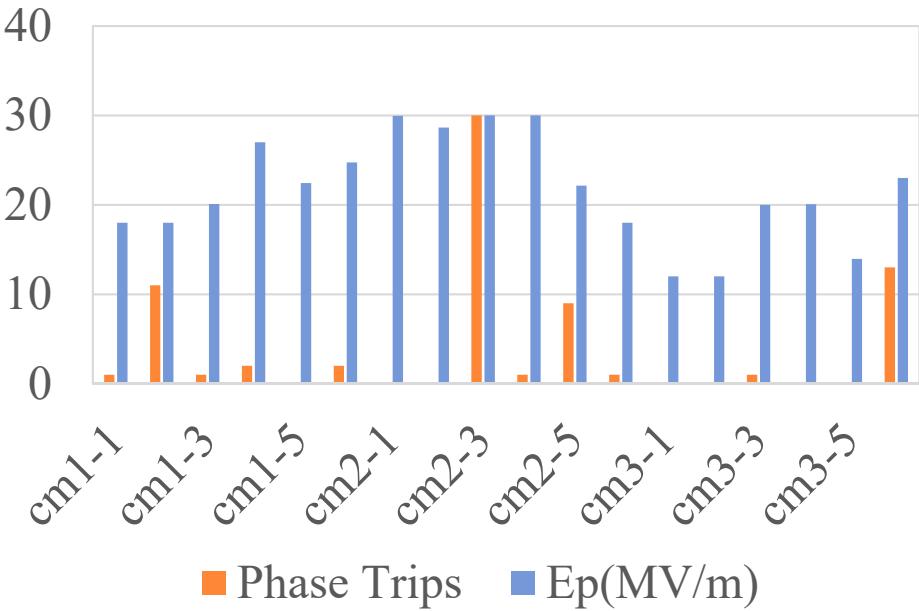
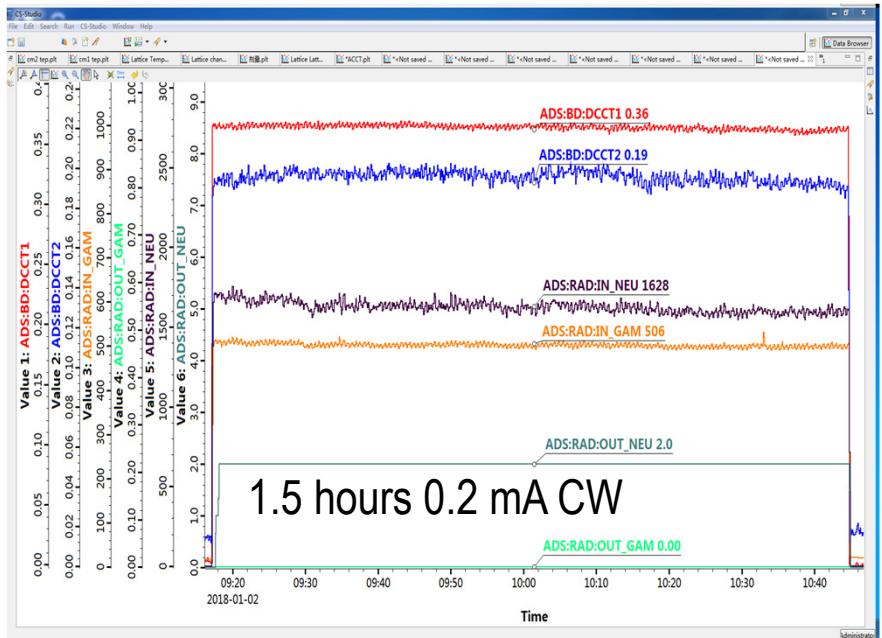
Operation time	Beam time	Down time	Availability
4050 min	3566 min	484 min	0.88

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

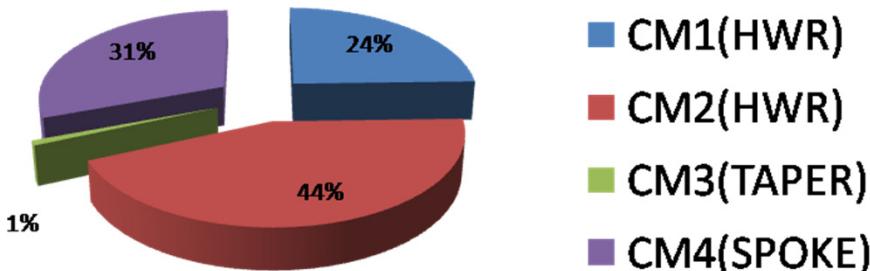


Reliability of CW beam operation



- Beam: 0.1~0.2mA CW; Operation time: 27 h
- MPS trips while phase error $\Delta\varphi > 5 \text{ Deg}$, 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

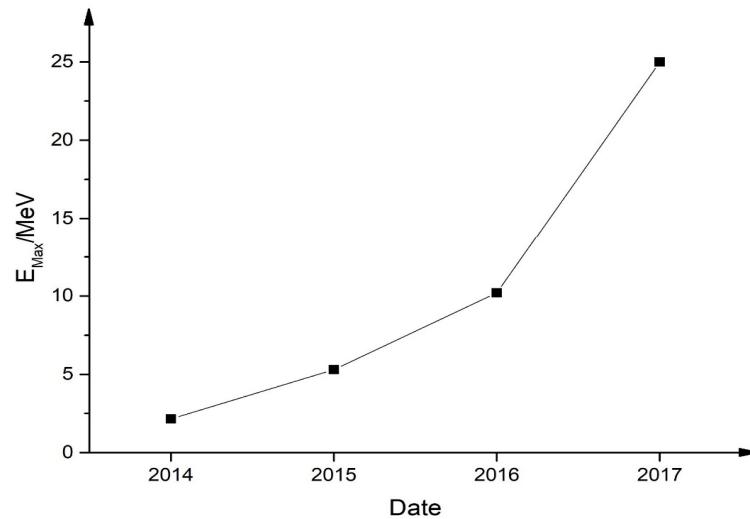
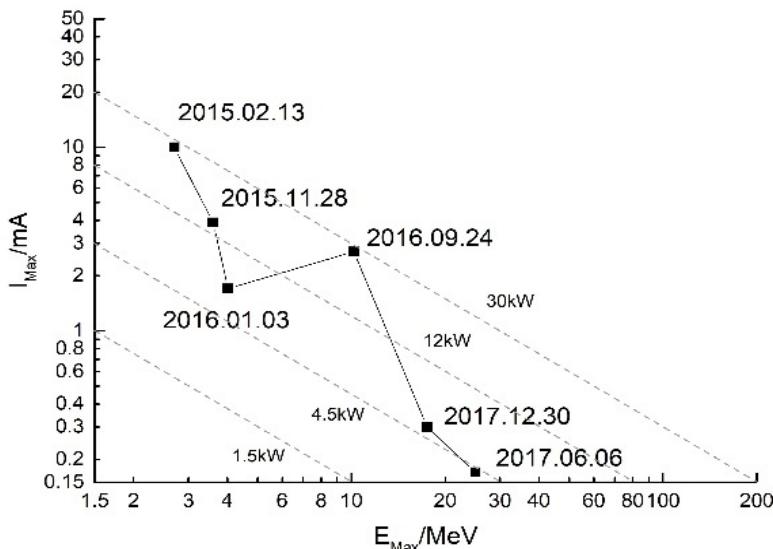
cryomodule phase trip statistics



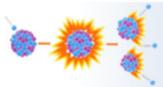
Commissioning Summary 2014-2017



Commission stage	First CW beam	Max Energy (MeV)	Beam time (hours)	CW beam time Total (hours)	CW Current Max(A)	CW Power Max(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(12HWRS)	Sep. 24, 2016	10.2	327	11	2.7	26
CM1...CM4 (17HWR+6SPOKE)	Jun. 7, 2017	26.1	334	27	0.3	5

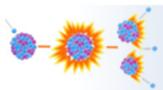


- ▶ Introduction of CiADS
 - ▶ Design of superconducting Linac
 - ▶ Beam commission of Chinese ADS
- Front-end Demo Linac (CAFe)
- ▶ Summary



Summary

- **CiADS will kick off by the end of the year, baseline beam dynamic of 500 MeV, 5 mA has been done**
- **The China ADS Front-end demo linac (CAFe) have been constructed, and the first CW beam and reliability operation have been done**
 - 4-D beam re-construction at MEBT to initialize beam
 - Orbit alignment and phase calibration
 - Machine protection under high beam power
 - Effective beam loss detection at low energy section
- **Sufficient and Efficient MPS, fault recovery strategy is under developing to improve reliability**
- **Upgrading of CAFe for He beam will be done in July, next commissioning campaign will start in September 2018.**





Thanks for your attention

Welcome collaboration

Thanks for the helps

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

