Accelerator Physics study of ADS & Commissioning of Front-end Demo

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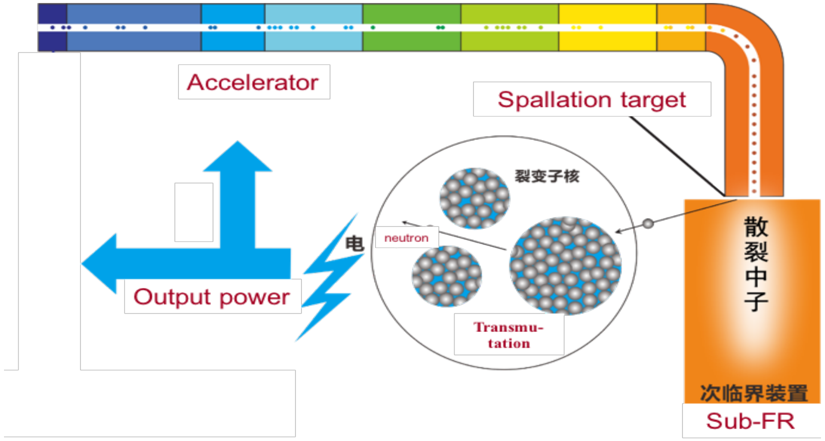
Outline

- **Background and introduction of ADS**
- Sc-Linac design study for CIADS
- Beam commission of front-end demo
- Summary

Issues for Sustainable NP and Solution

China status: ~3% now, ~7% by 2020, By 2050, 350~400GWe (~20%), comparable with the total NP capacity in the world (391GWe, 447 reactors in 2017).

- **Management and safe disposal of nuclear waste**
  - 1GWe PWR ~25 ton/year;
  - ~2200 ton/year in 2030 in China; ~10000 ton/year now in the world
  - Total capacity of Yucca Mountain ~ 70000 ton;
  - 300~500M$ budget per year; 833.4M$ in 2015; 986.2M$ in 2016



"The ADS has the advantage that it can burn pure minor actinides while avoiding a deterioration of the core safety characteristics."

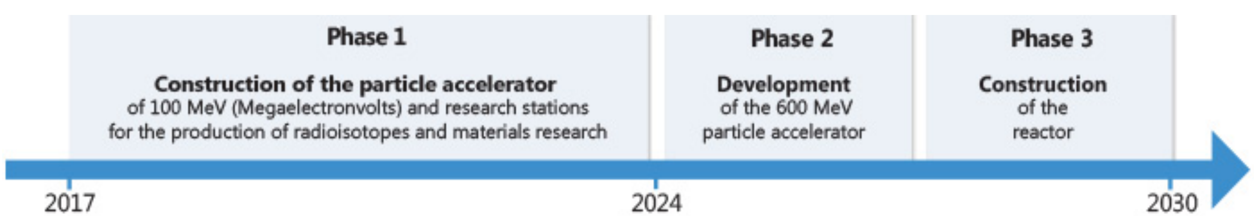
– ADS and FR in Advanced Nuclear Fuel Cycles – A Comparative Study, NEA/OECD, 2002

Status of ADS projects worldwide

Projects		Accelerator Power (MW)	Keff	Reactor Power (MW)	Coolant	Target	Fuel
China	**CiADS**	**2.5(500MeV/5mA)**	**~0.75**	**10**	**LBE**	**W granular**	**UO2**
EU	**MYRRHA**	**2.4 (600MeV/4mA)**	**0.955**	**85**	**LBE**	**LBE**	**MOX**
	AGATE	6 (600MeV/10mA)	0.96	100	Gas He	W/Gas He	MOX
	EFIT/LEAD	16 (800MeV/20mA)	~0.97	400	Lead	Lead/windowless	MA/MOX
	EFIT/GAS	16 (800MeV/20mA)	0.96	400	Gas He	W/Gas He	MA/MOX
US	ATW/LBE	100 (1GeV/100mA)	~0.92	500~1000	LBE	LBE	MA/MOX
	ATW/GAS	16 (800MeV/20mA)	0.96	600	Gas He	W/Gas He	MOX
Russa	INR	0.15 (500MeV/10mA)	0.95~0.97	5	LBE	W/Gas He	MA/MOX
Japan	JAERI-ADS	27 (1.5GeV/18mA)	0.97	800	LBE	LBE	MA/Pu/ ZrN
Korea	HYPER	15 (1GeV/10~16mA)	0.98	1000	LBE	LBE	MA/Pu

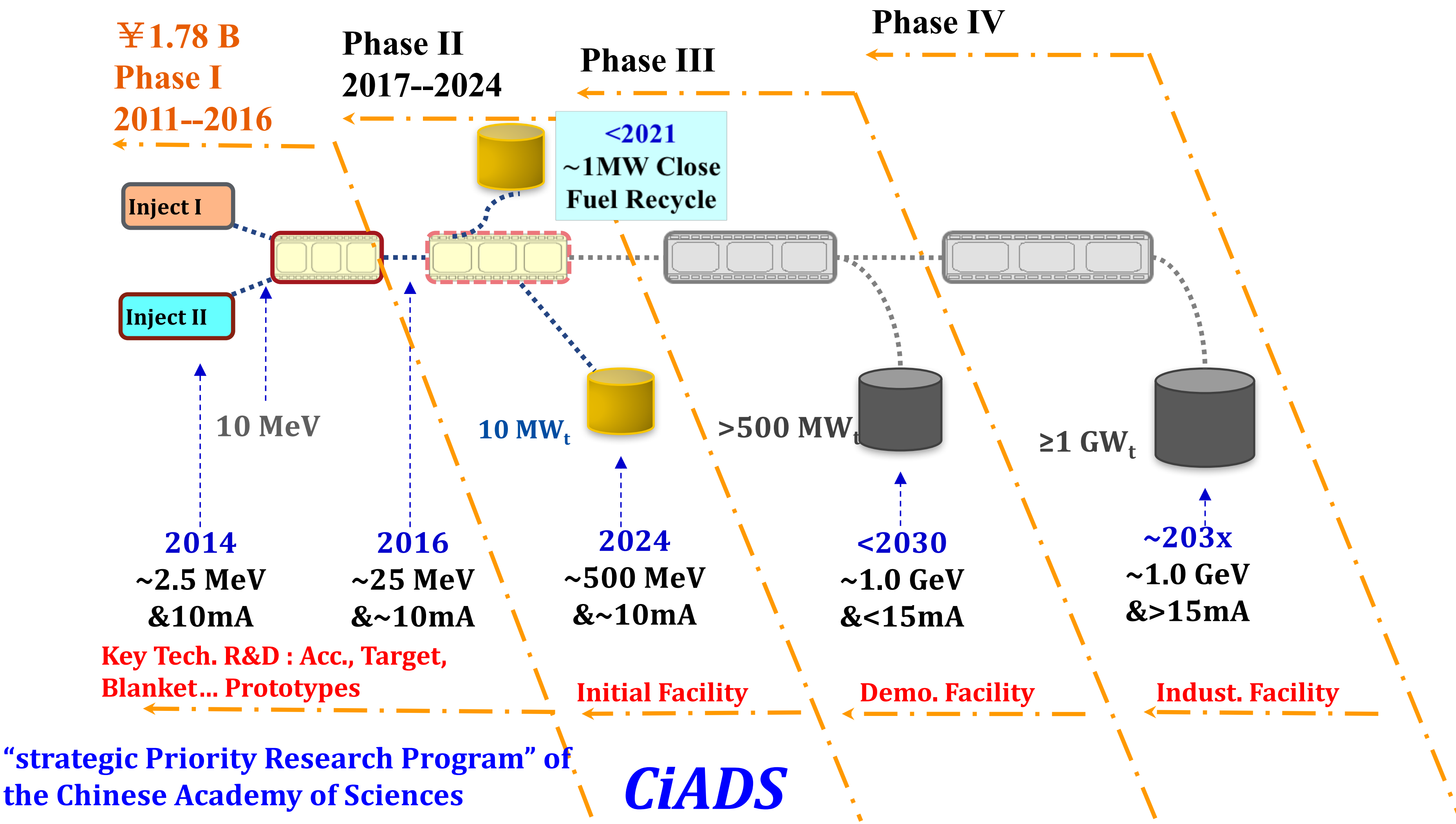
MYRRHA

(Total budget 1.6 B Euro)



Construct 100MeV accelerator   Upgrade to 600MeV   Construct reactor

ADS/ADANES Roadmap in China

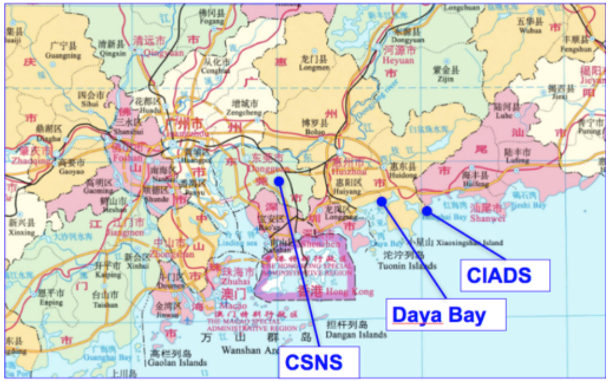


CIADS Project (2017-2024)

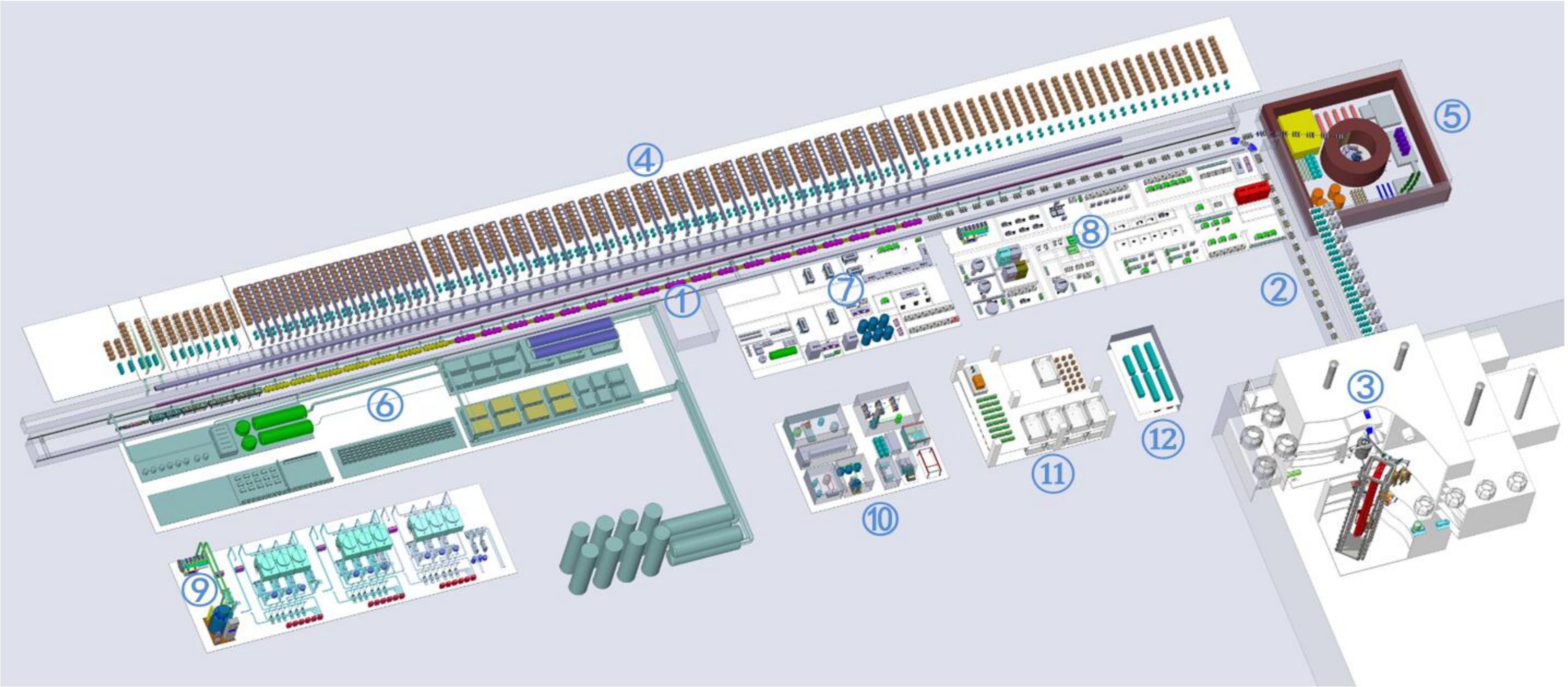
China initiative Accelerator Driven System (CiADS)

- **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.

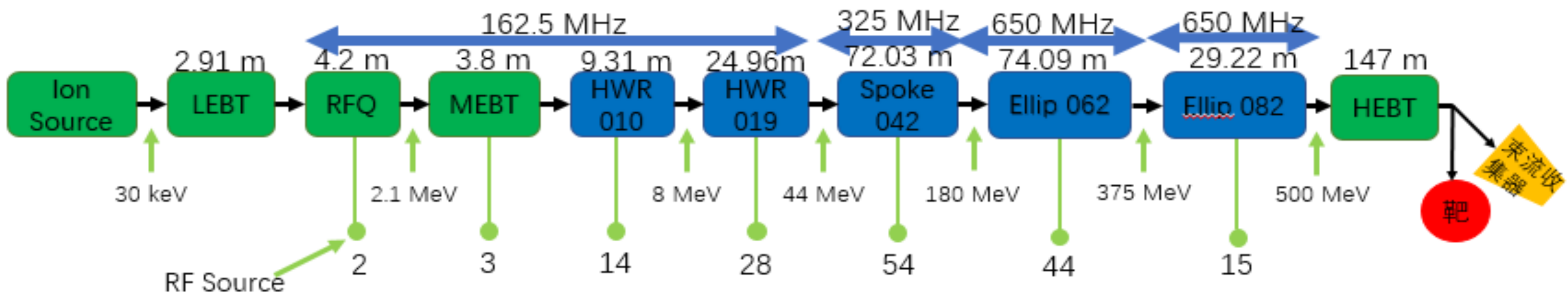


Overall Arrangement of CiADS



① SC linear accelerator
② Coupling beam line
③ Reactor Hall
④ RF High power station
⑤ Beam dump and target exp.
⑥ Cryogenic station
⑦ Accelerator assembly Hall
⑧ SC resonator conditioning hall
⑨ Cooling water station
⑩ Target assembly and exp. hall
⑪ Hot cell building
⑫ Electric transform station

General configuration of CiADS Linac



The design philosophy :

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

2010 DOE white paper on ADS

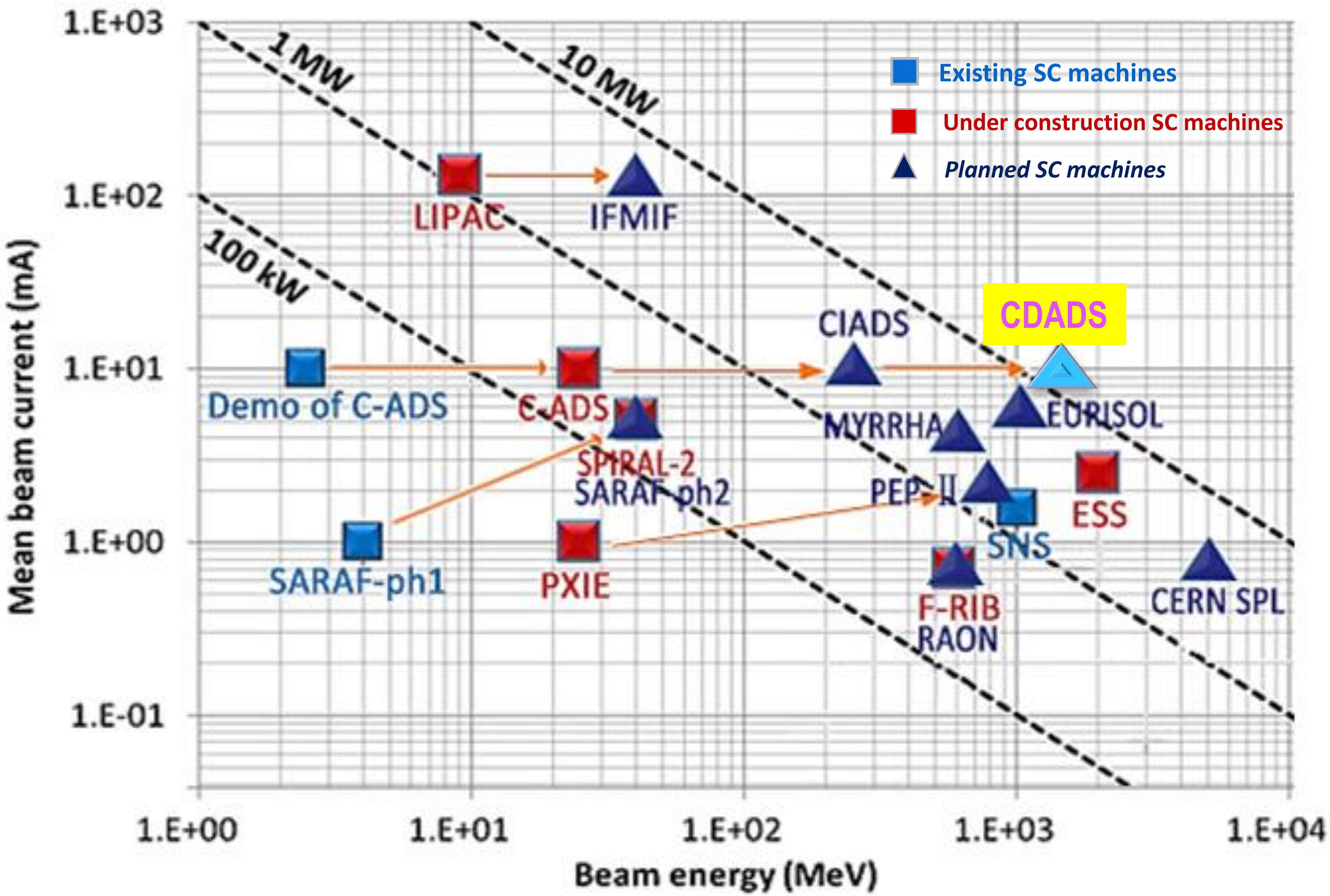
Beam trips:

1～10s, 2500/y
10s～5min, 2500/y
>5min, 300/y

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&Pluse	
Beam loss	< 0.1	W/m
Total length	367.5	m

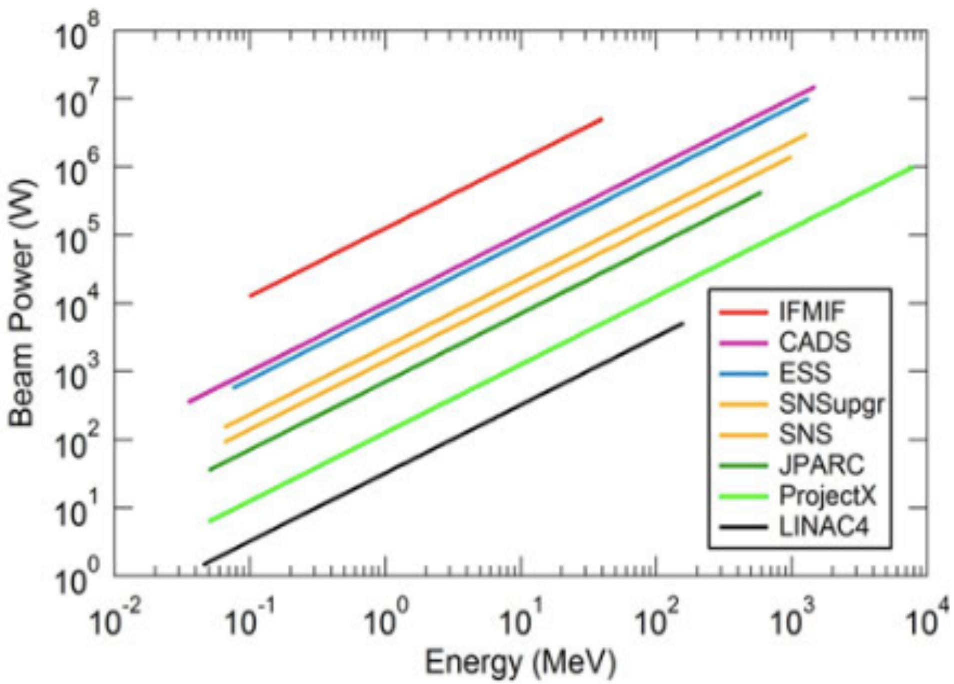
High power SRF Linacs in the world

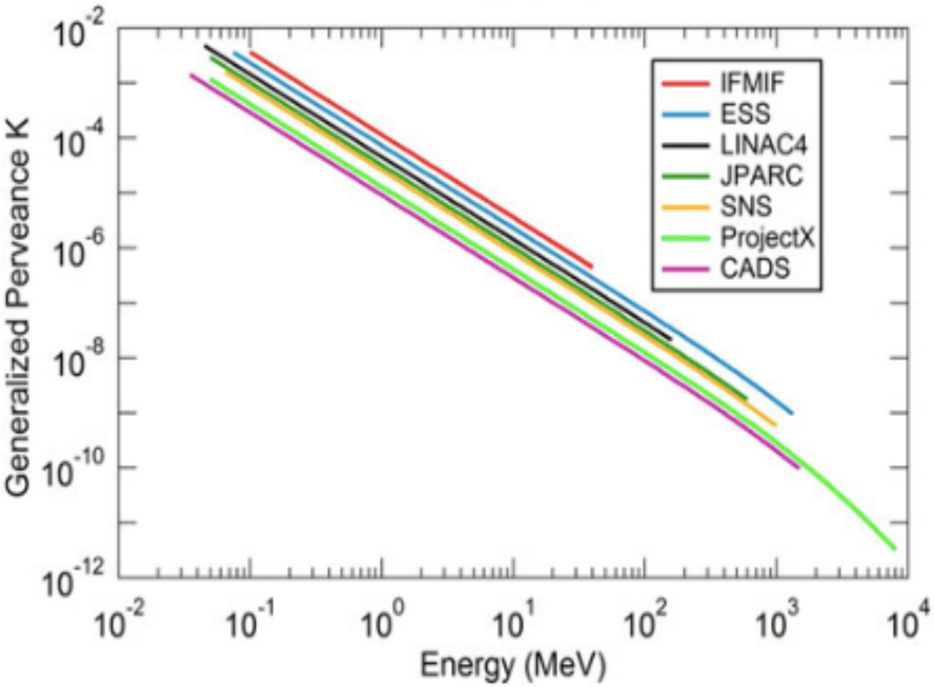


Non exhaustive plot!

Modified from J-Luc Biarrotte, SLHIPP-4, CERN, 15-16 May 2014

General introduction of China ADS project





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

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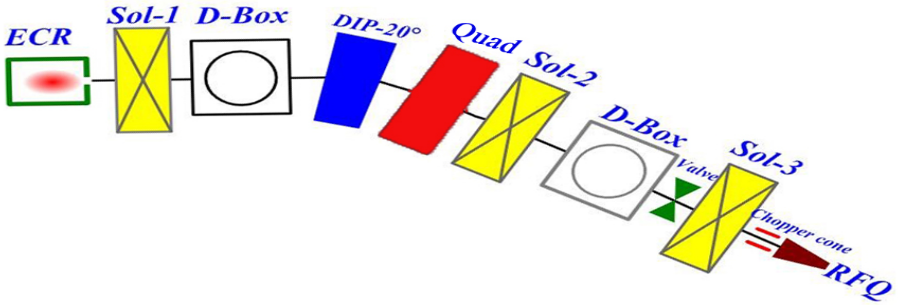
LEBT design



① Proton beam Choose for Acc.

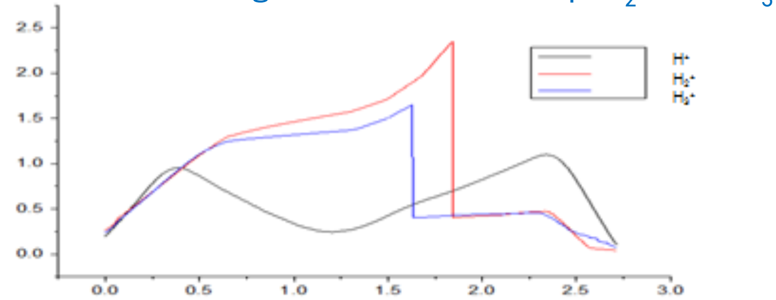
② Beam symmetrical inject to RFQ

③ Beam match with ECR and RFQ

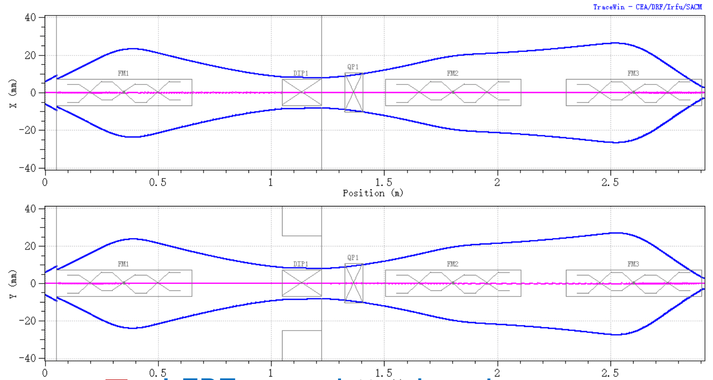
- ECR&LEBT design parameter

Inject energy (keV)	35
Beam current (mA)	20
Horizontal normal emittance (πmm•mrad)	0.1885
Energy spread	≤0.5%
Extract beam stability	＜1%
Total length (m)	2.9

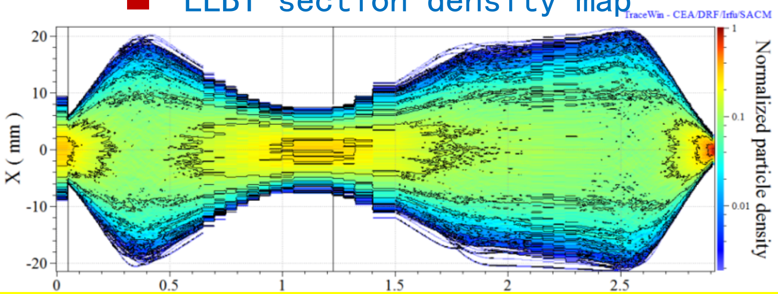
- Bending section to scrap H_2^+ and H_3^+



- LEBT section envelop



- LEBT section density map

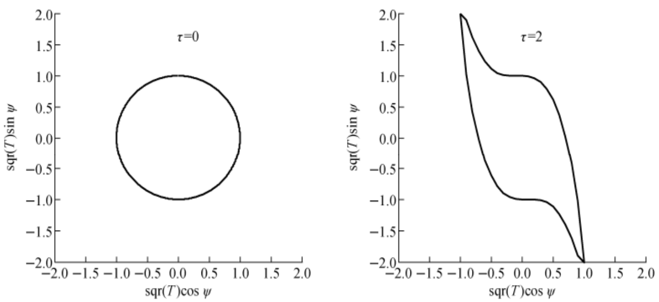


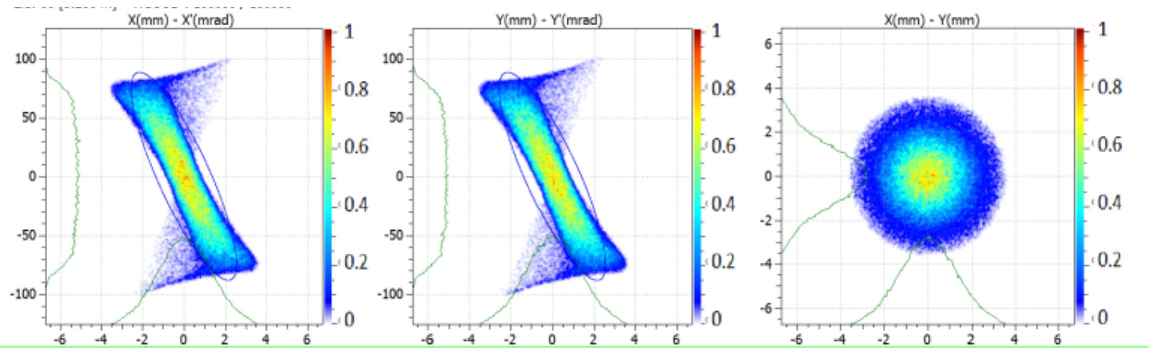
Designed 20° bending magnet +6.3° edge angle to ensure proton beam purification and also achieve both horizontal and vertical direction beam symmetrical matching.

LEBT design

$$r'' = -\frac{q^2}{8mE}B^2(z)r$$

$$\Delta_3 = \frac{Kr^3}{2}\int B(z)\,B''(z)dz$$

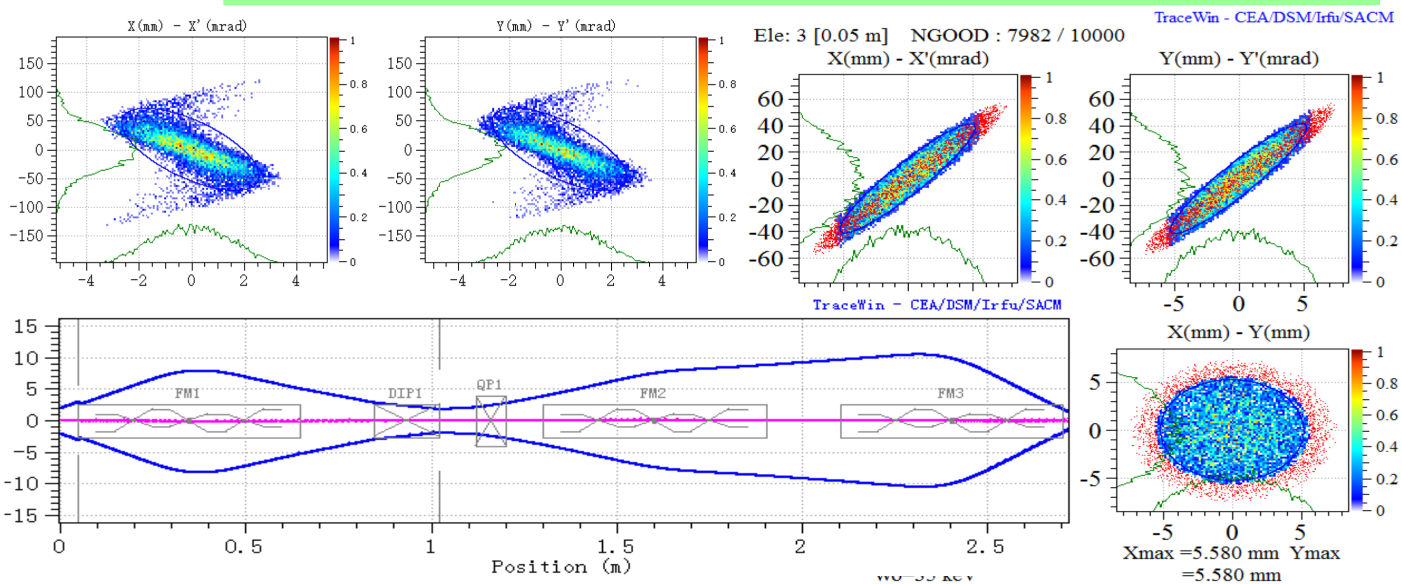




The higher order of the magnetic field is the root cause of the "aberration" of the solenoid

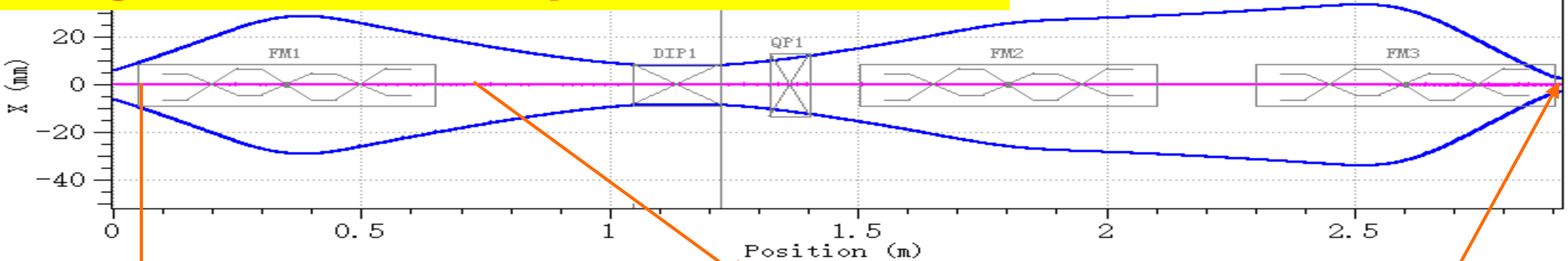
Controlling the beam envelope in the solenoid is an effective way to reduce the beam dynamics

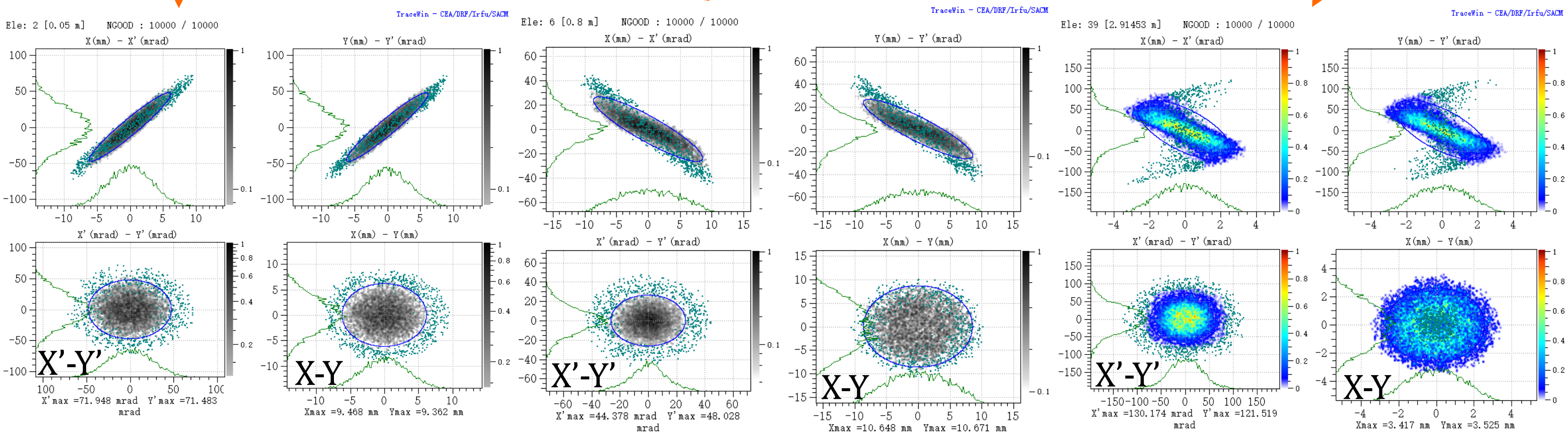
Point light source concept: Near the extraction of the ion source, the beam action is similar to the "stratosphere" state, the outer particles are the ones with larger beta and beam spread angle.



LEBT design

Point light source concept verification





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 coefficient**

③ **High acceleration efficiency and high transmission efficiency**

④ **The RFQ lattice optimization to minimize the beam loss power**

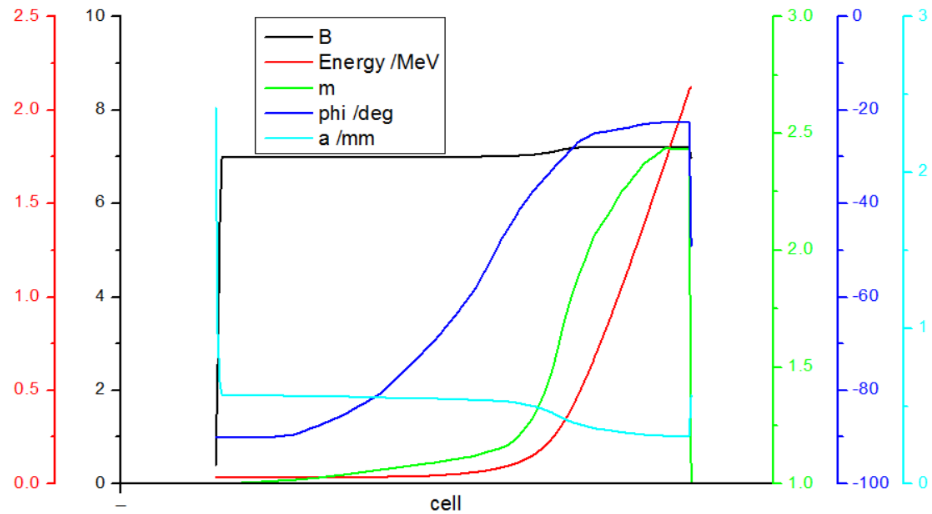
⑤ **Aim to 99.99% longitudinal emittance，to decrease the beam loss probability in high energy superconducting section.**

RFQ parameters

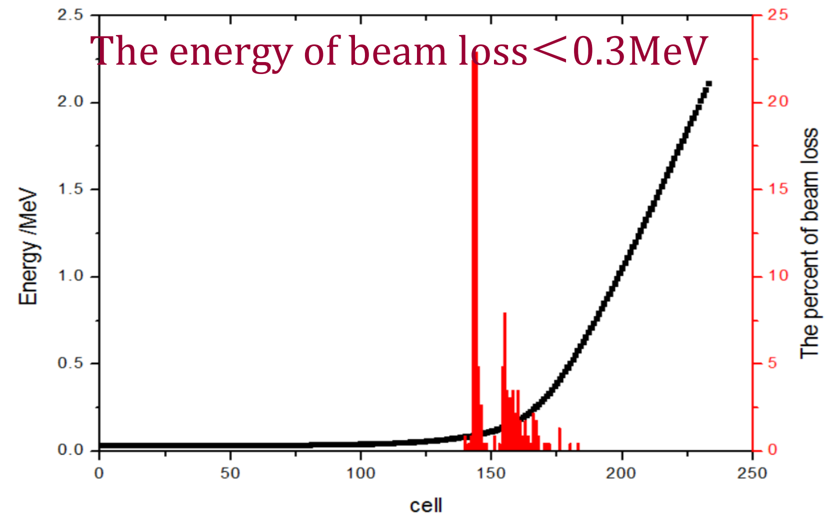
Frequency（MHz）	162.5
Beam current（mA）	15
I/O energy(MeV)	0.035 / 2.1
Vane voltage(kV)	65
Max. surface.field（MV/m）	15.88
Average aperture(mm)	5.71
Min aperture（mm）	0.31
Iuput.Nor.RMS.emit (πmm•mrad)	0.2/0.2/-
Ouput.Nor.RMS.emit (πmm•mrad)	0.21/0.21/0.25
Output.99.99% longitudinal emit (πmm•mrad)	5.5
Length (m)	4.52
Transmission efficiency@15mA (%)	95.5%

RFQ design

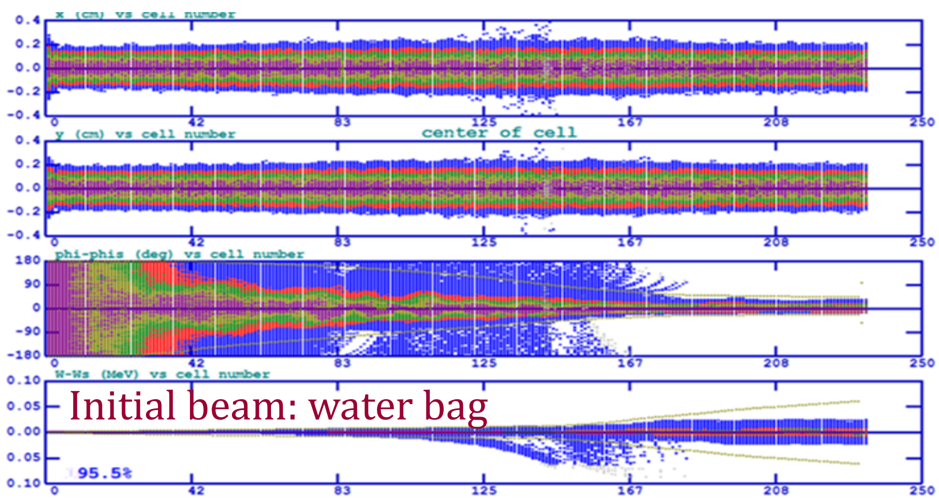
RFQ key parameters



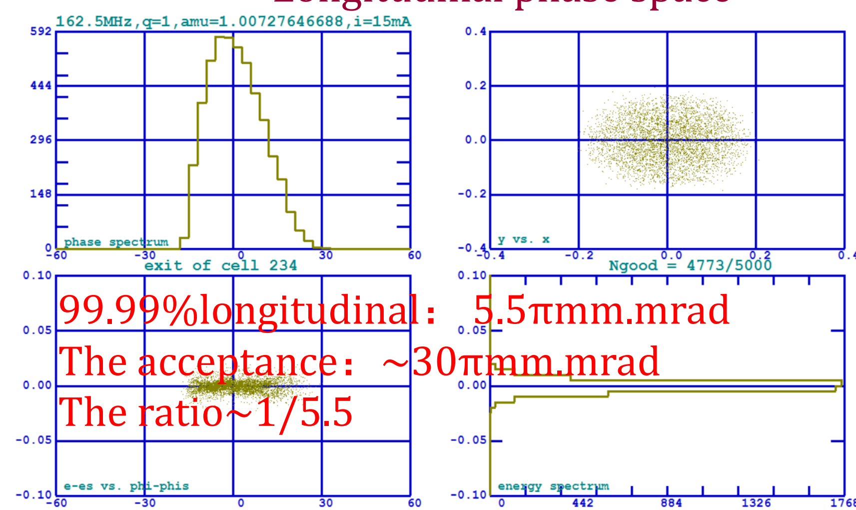
Beam loss distribution



Beam simulation



Longitudinal phase space



Superconducting section

General parameters

1、 Less SC cavity types
2、 High acceleration efficiency
3、 High power utilization

Lattice design

1、 Phase advance per meter continuous and smooth
2、 Keep envelope smooth
3、 Less than 90° of zero-current period phase advance to avoid envelope instability and resonance crossing with space charge
4、 Period phase advance of every segment begin with value near 90° to improve accelerating efficiency
5、 Optimize frequency transitions and cavity types for smooth beam matching along the linac

Multiparticle simulation

Minimize the emittance growth

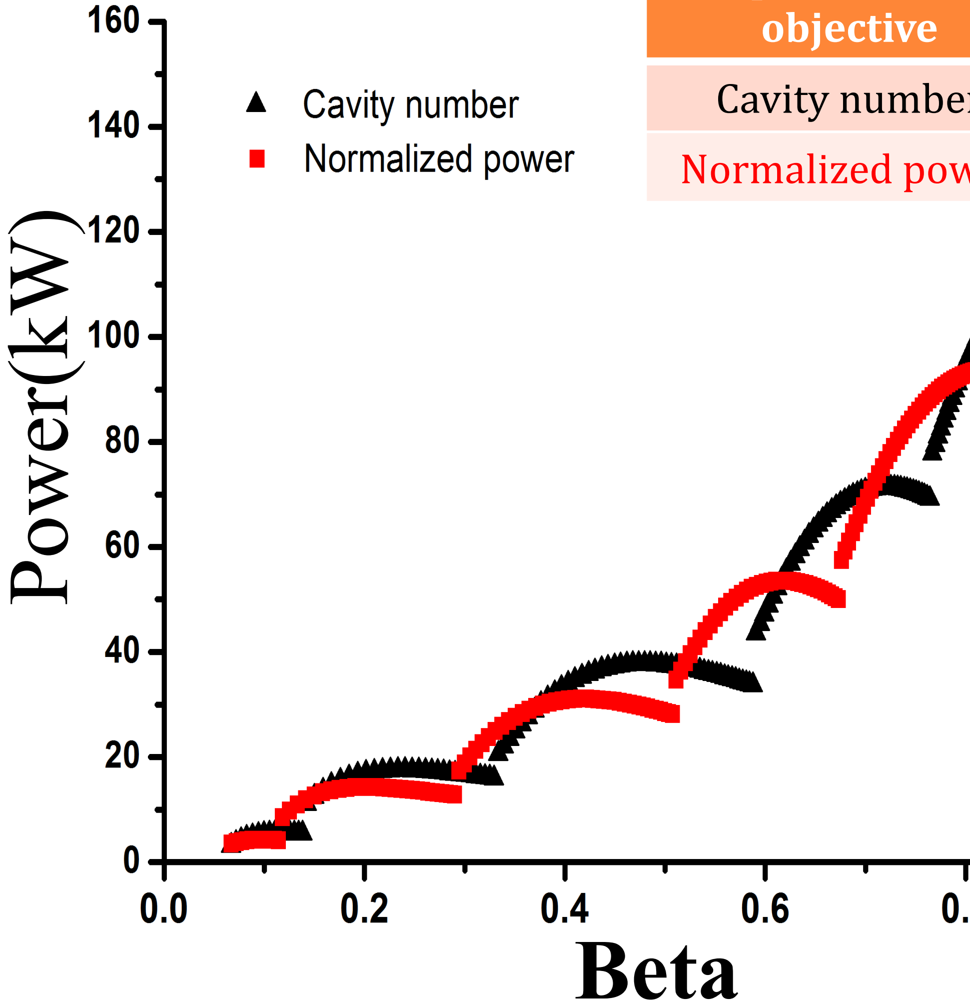
Avoid beam loss

Error analysis

Test lattice structure robustness

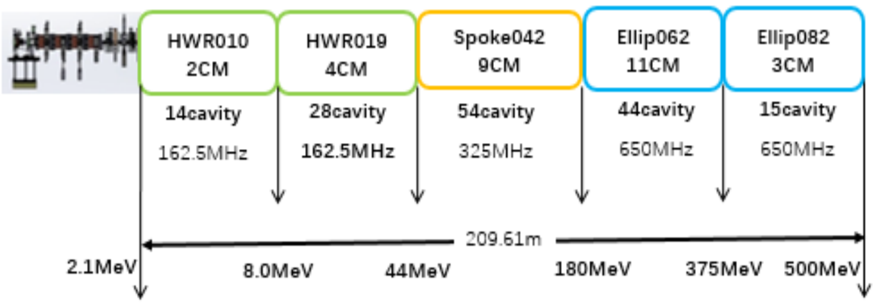
General parameters

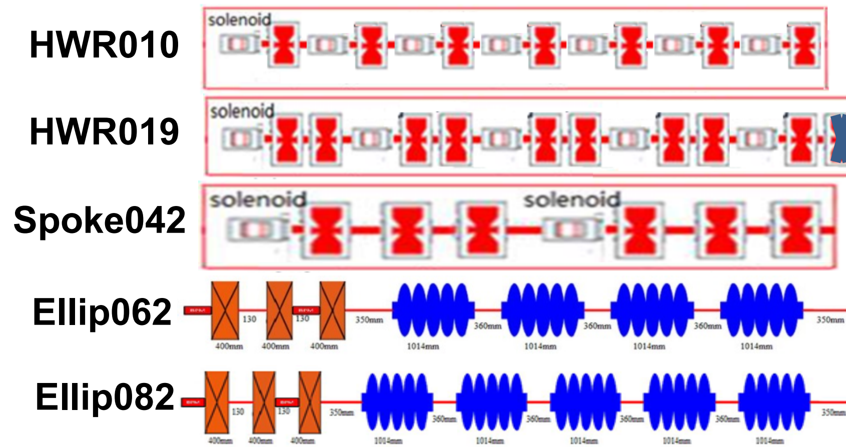
Optimization objective	Cavity number	Max power_single cavity (kW)
Cavity number	227	134
Normalized power	249	94



Cavity type	β	Freq (MHz)	Epeak (MV/m)	Epeak_Operation (MV/m)	NO. cavity
HWR	0.10	162.5	25	**18.75**	14
	0.19	162.5	32	**24**	28
Spoke	0.42	325	32	**24**	54
elliptical	0.62	650	35	**26.25**	44
	0.82	650	35	**26.25**	15

Lattice design





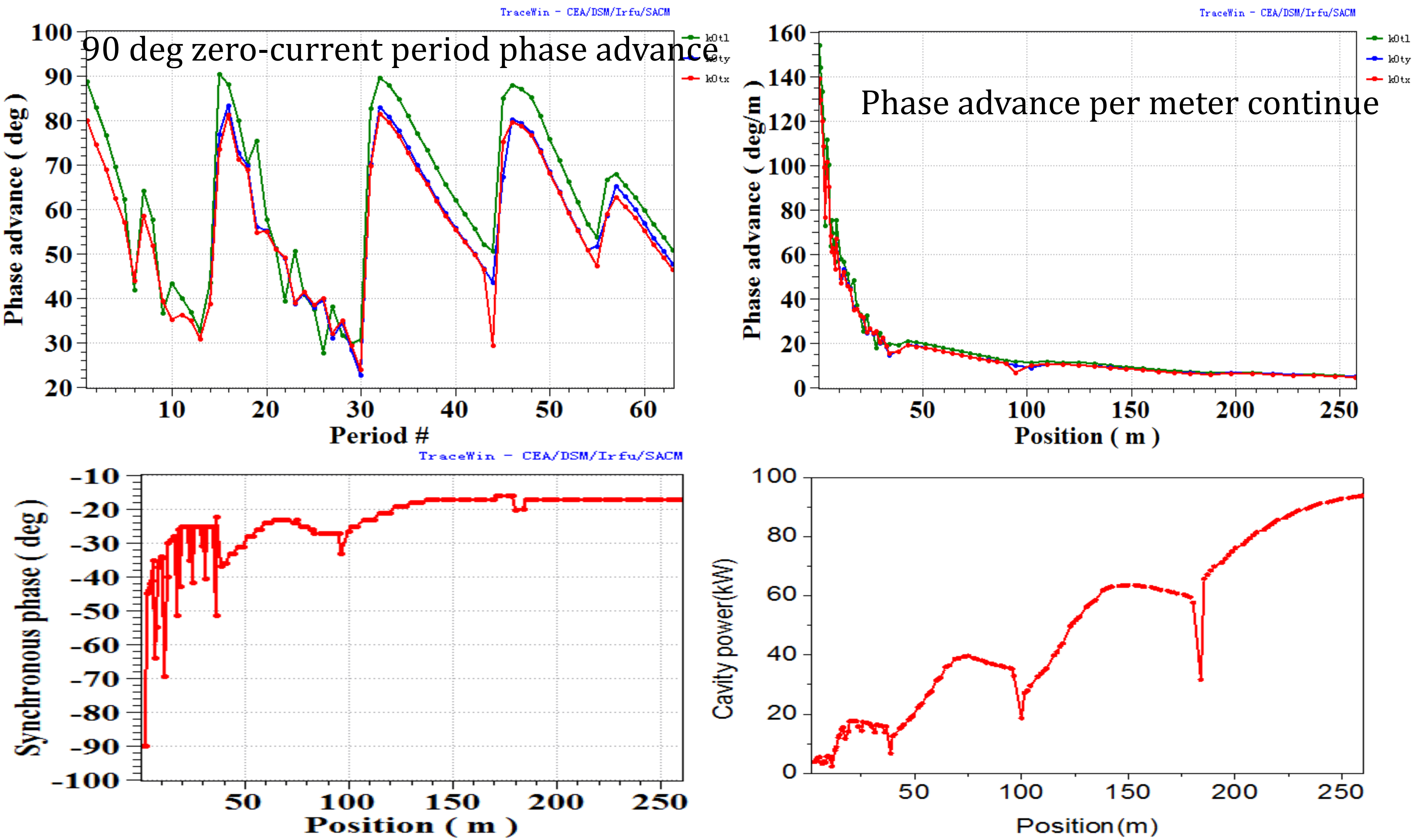
■ **Parameters of SC section**

inject / extrat energy (MeV)	2.1 / 500
Beam current (mA)	5
Frequency （MHz）	162.5
Cavity number	155
Cryomodule number	29
aperture / RMS transverse beam size	>10
Synchronous phase / RMS beam length	>9
Entrance normal RMS emittance(mmmrad)	0.216/0.216 /0.25
Total lenth(m)	209.61

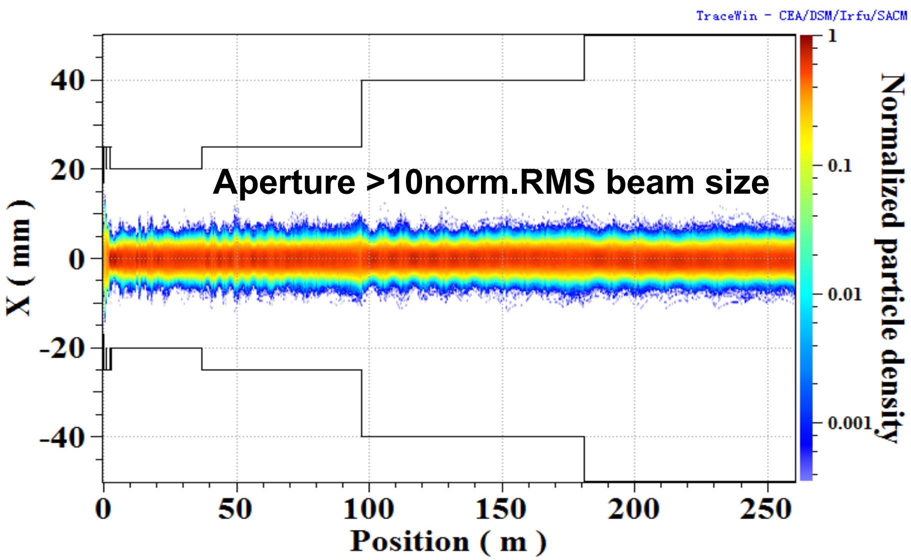
Design philosophy:

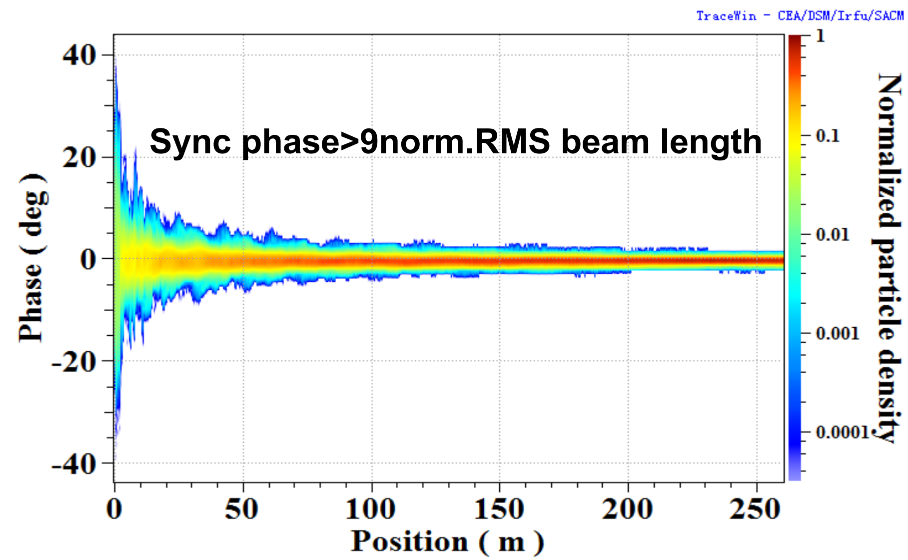
- Compact structure at low energy section to get large longitudinal acceptance and to weaken the effect from space charge
- Full period lattice structure at high energy section to benefit good matching
- Optimization between different structure and different frequency for good matching

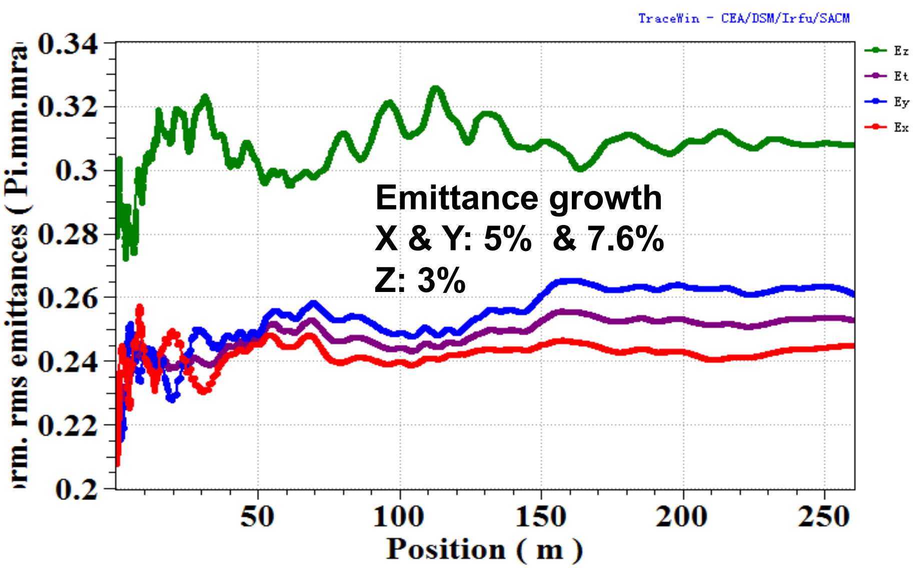
Lattice design

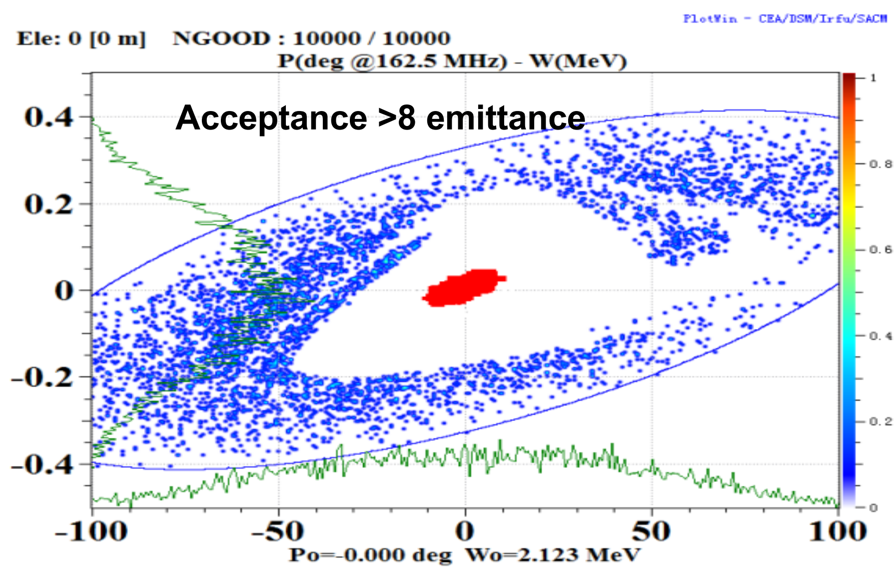


Multiparticle simulation







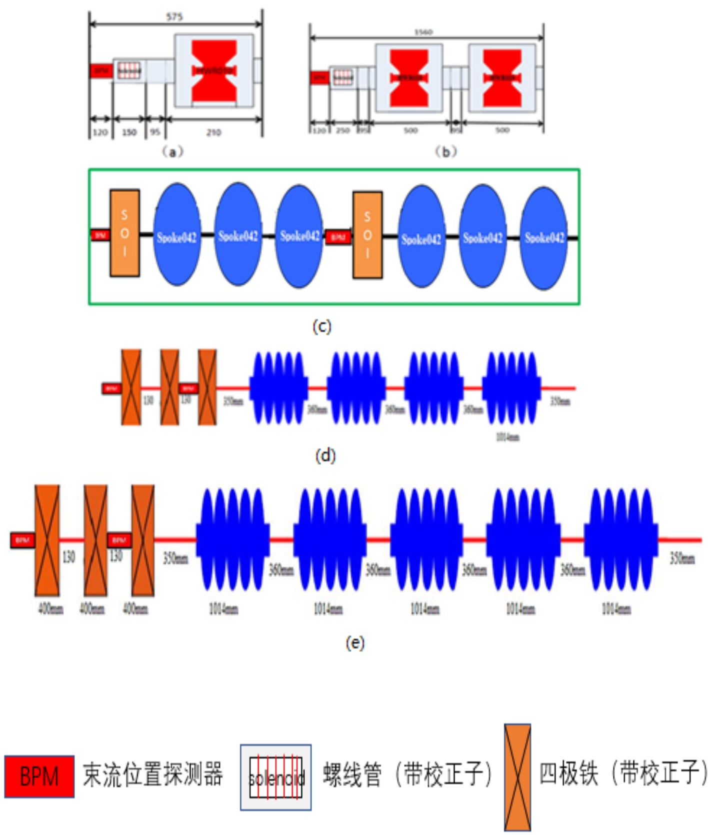


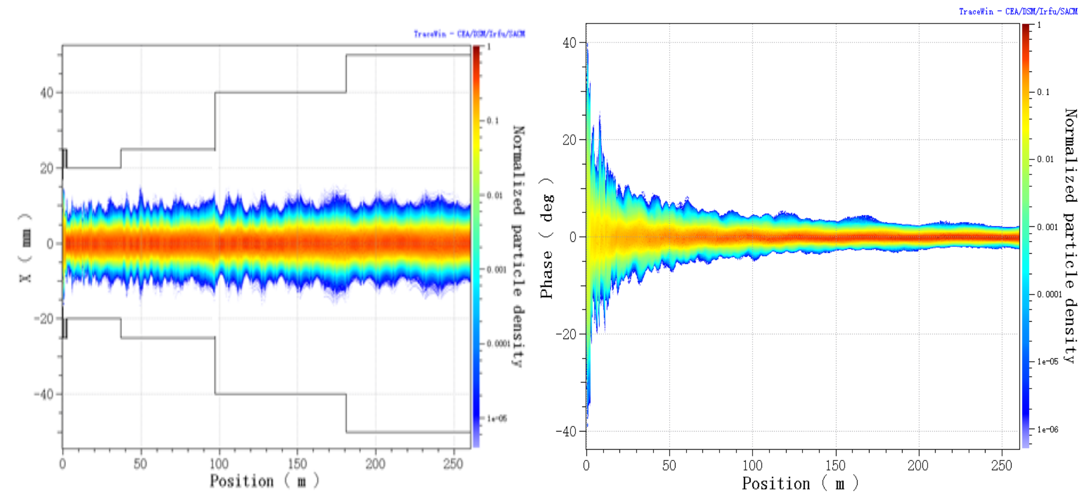
Error analysis

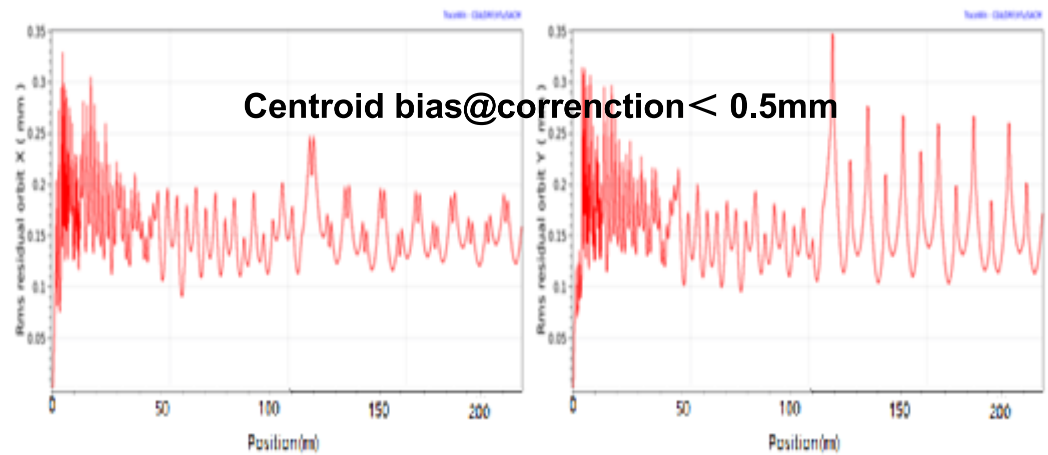
- TraceWin code is used for error analysis;
- End to end simulation including MEBT and SC section using RFQ simulated output distribution;
- 3d cavity fields are used in the multi-particle simulations;
- 100 seeds are generated randomly for the error analysis

Error type	Static (buncher/cavity)	Dynamic (buncher/cavity)	Static (Q/solenoid)	Dynamic (Q/solenoid)
δx (mm)	0.1/1	0.002/0.01	0.1/1	0.002/0.01
δy (mm)	0.1/1	0.002/0.01	0.1/1	0.002/0.01
Rx (mrad)	2	0.02	2	0.02
Ry (mrad)	2	0.02	2	0.02
Rz (mrad)	×	×	2	0.02
δg (%)		0.5	0.5	0.05
δφ (°)		0.5	×	×
δz (mm)	1/2	0	1/2	0

Error analysis



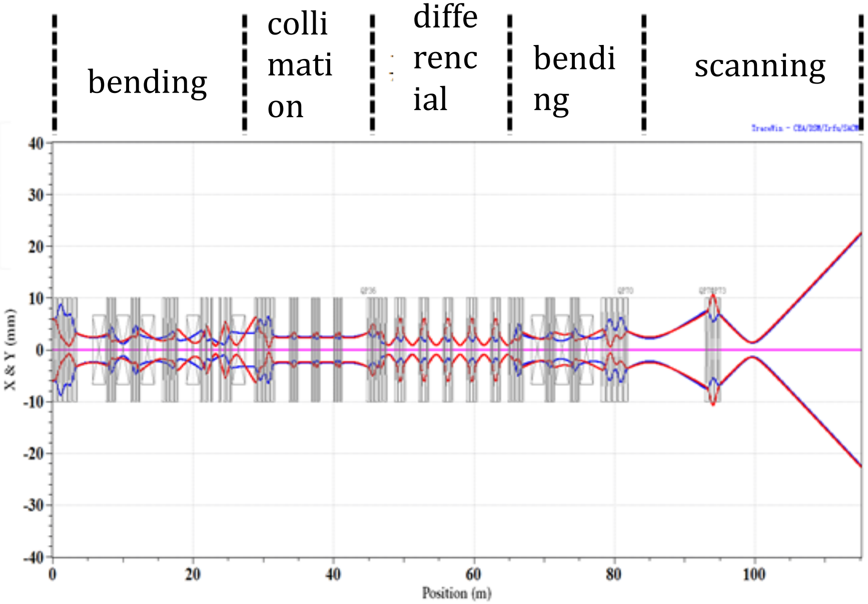


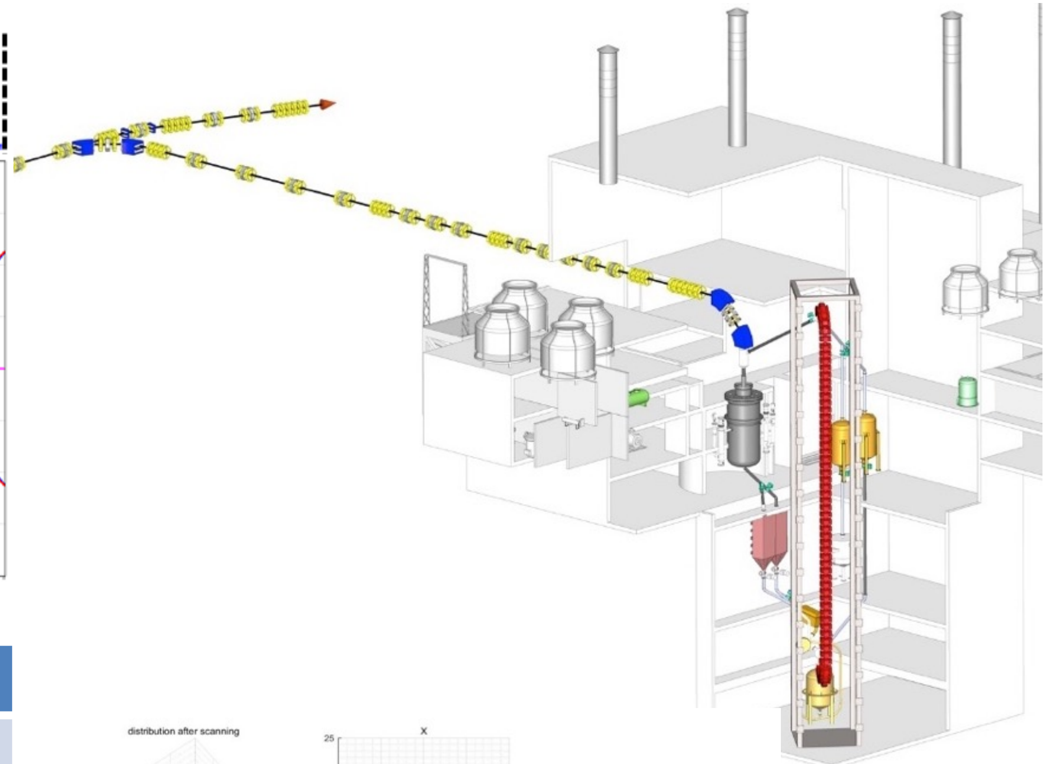


Centroid bias@correnction＜ 0.5mm

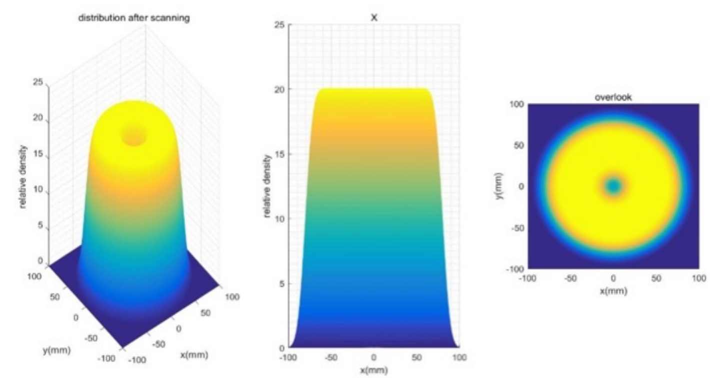
Error verifying, optimizing the orbit correction scheme to ensure high reliability and to strict control beam loss

Design of A. & T. coupling





	value	unit
Emit. RMS norm. (x/y/z)	0.28/0.28/0.33	π mm.mrad
Entrance αx/αy/αz	1/1/-1	——
Entrance βx/βy/βz	20/20/20	mm/π.mrad
Beam profile on target	round	
homogenity	±10	%
99.99% beam diameter	<110	mm



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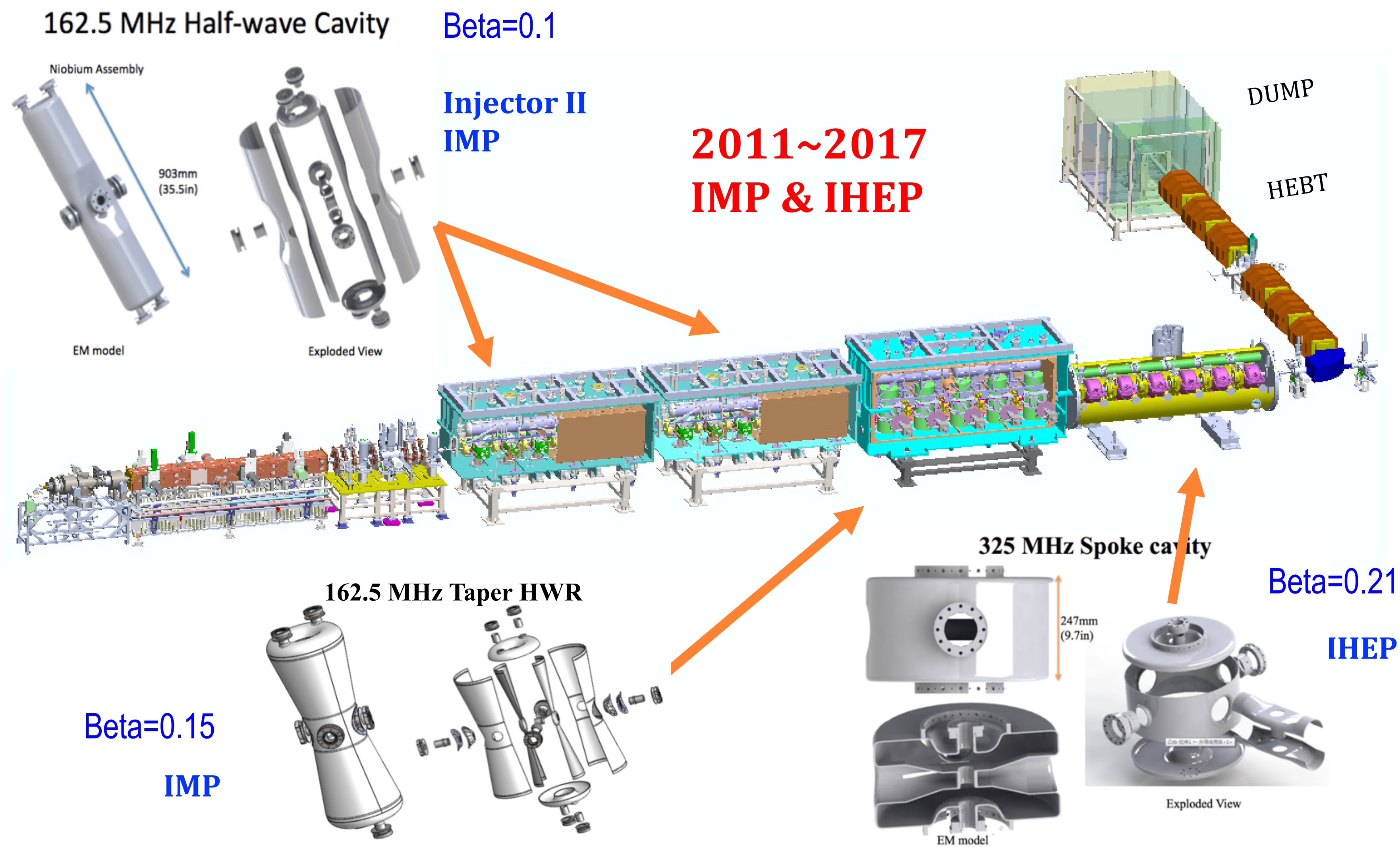
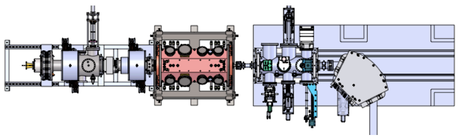
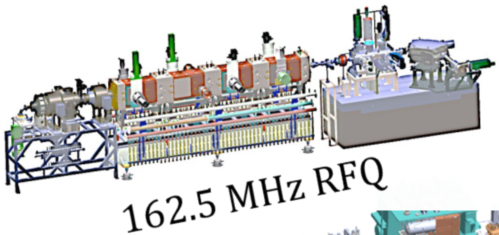
Chinese ADS Front-end Demo Linac



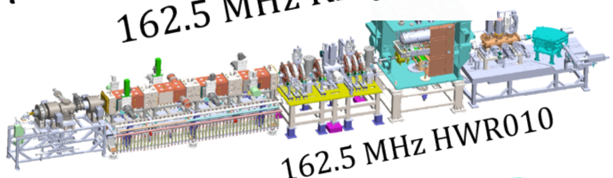
Commissioning since 2013

0


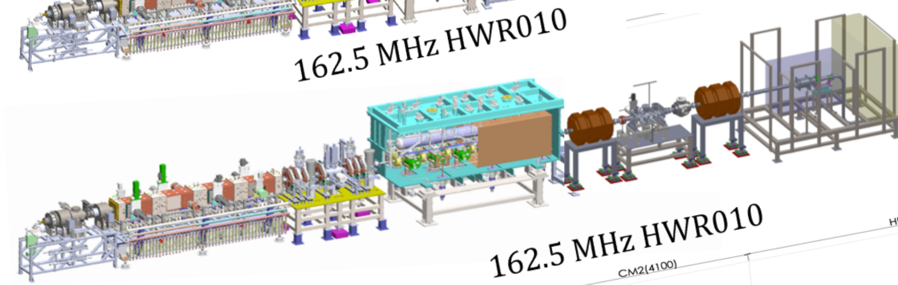
- ECRIS + LEBT + demo RFQ
- Energy is 0.56 MeV
- First beam Aug. 2013

1


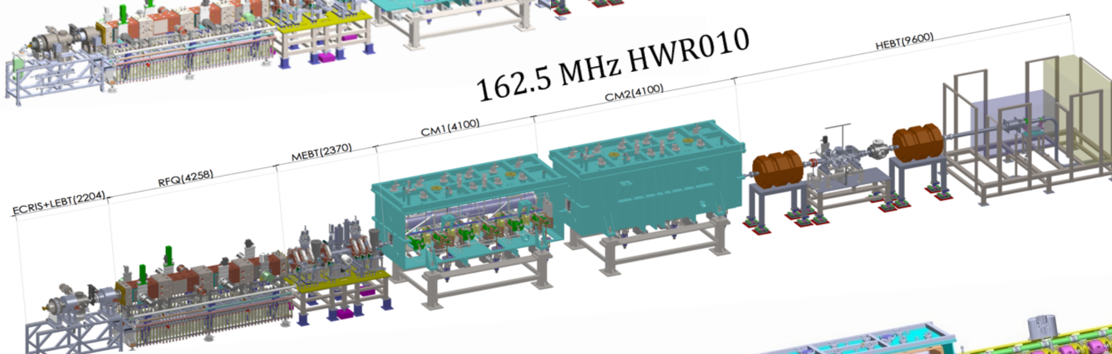
- ECRIS + RFQ
- Energy is ~2.1 MeV
- First beam Jun. 6th, 2014

2


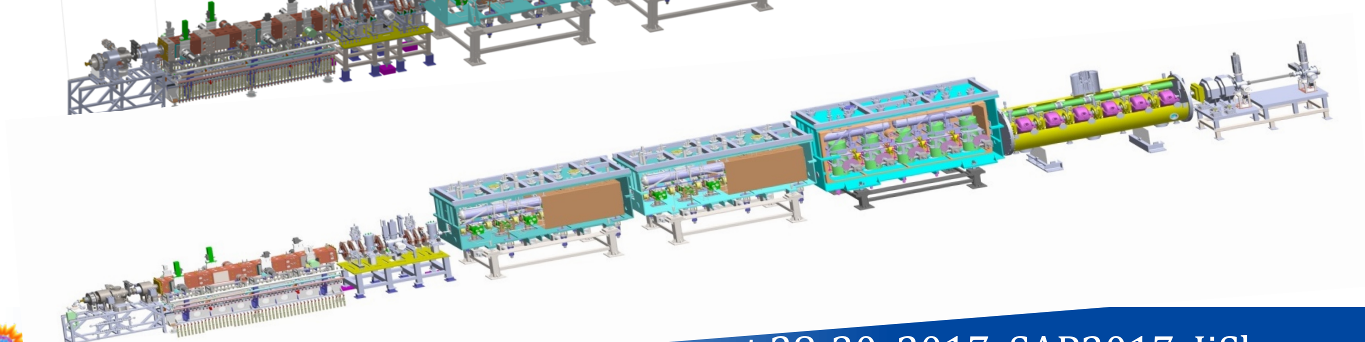
- ECRIS + RFQ + MEBT + TCM1 (single HWR)
- Energy is ~2.5 MeV
- First beam October 1st, 2014

3


- ECRIS + RFQ + TCM6
- Energy is ~5 MeV
- First beam June 6th, 2015

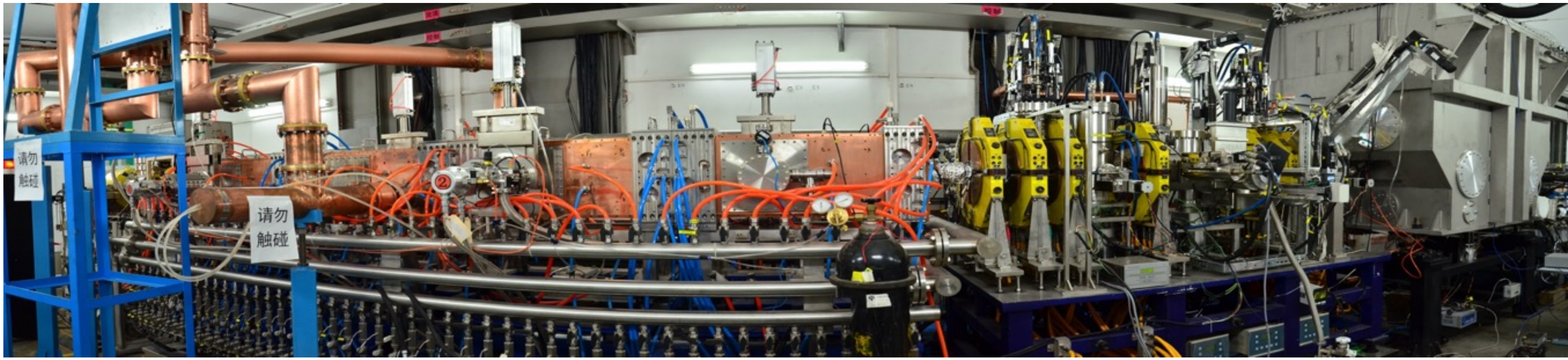
4


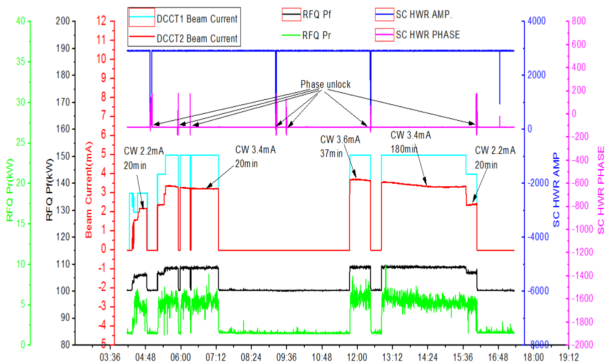
- ECRIS + RFQ + CM1 + CM2
- Energy is ~10 MeV
- First beam September 15th, 2016

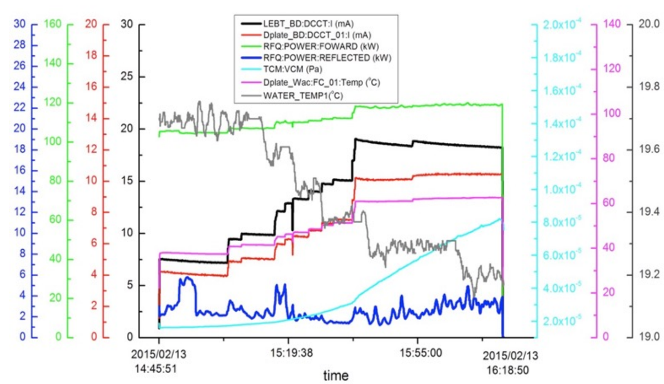
5


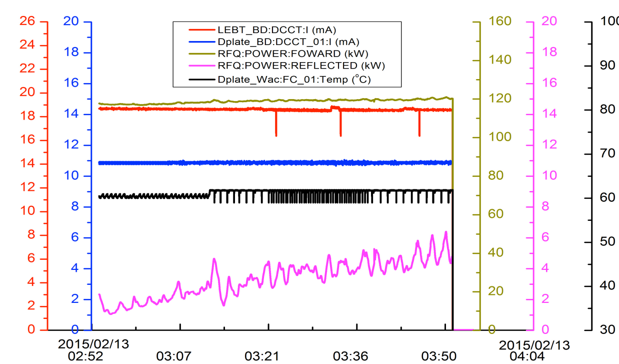
- ECRIS + RFQ + CM1 + CM2 + CM3 + CM4
- Energy is ~25 MeV
- First beam May 28th, 2017

CW Beam Commission to 10 mA









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

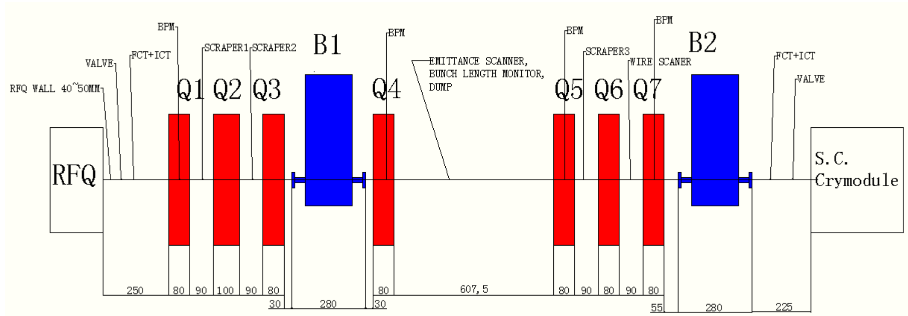
- **Feb. 4th, 2015, 4.2~10.83 mA,**
- **2.5MeV, CW**

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

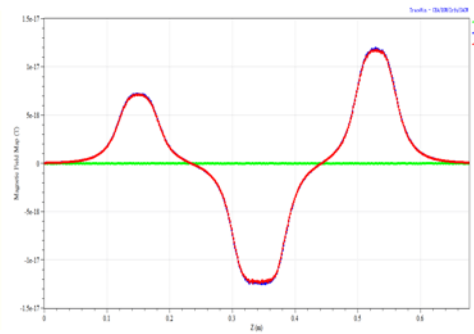
- RFQ works with two bunches and one HWR, RF frequency can not change any more like working alone.
- Due to detuning of 3 mA beam-loading, Pr is 5 kW, but it is still stable.
- 10 mA beam will cause ~8 kHz detuning of RFQ, Pr is large enough to shut down AMP.
- Frequency tuned by temp. of 0.5 C to keep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

Initial Beam Re-built at MEBT

- Scan Q1-3 for several measurements
- Trace back to get the exit twiss parameter of RFQ which agrees with the design of ParmteqM

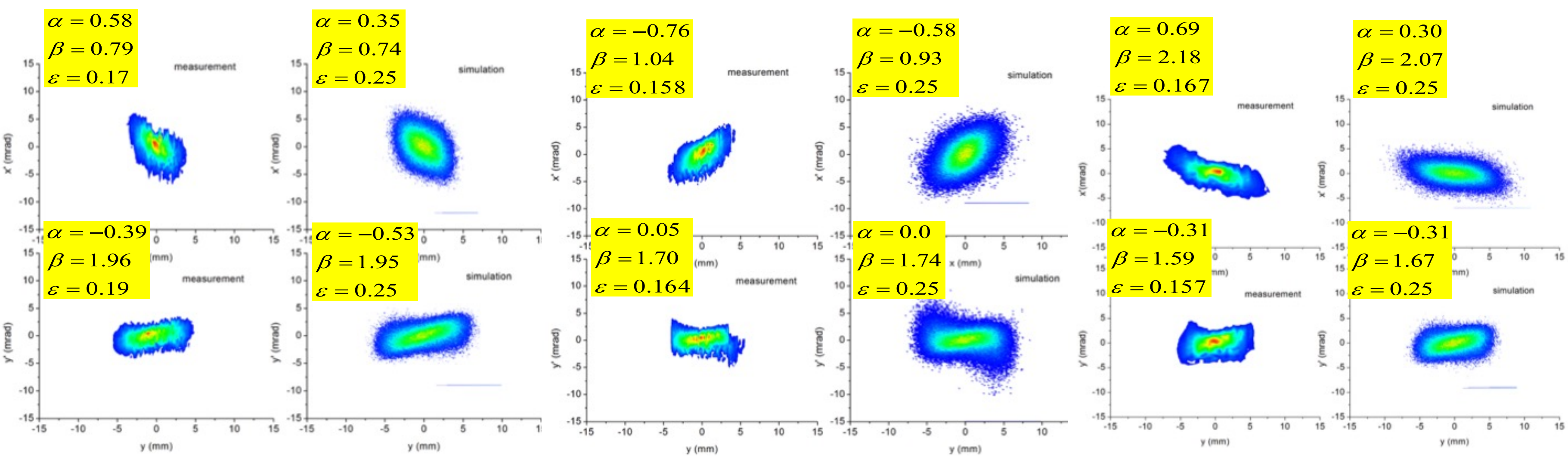


Structure of MEBT



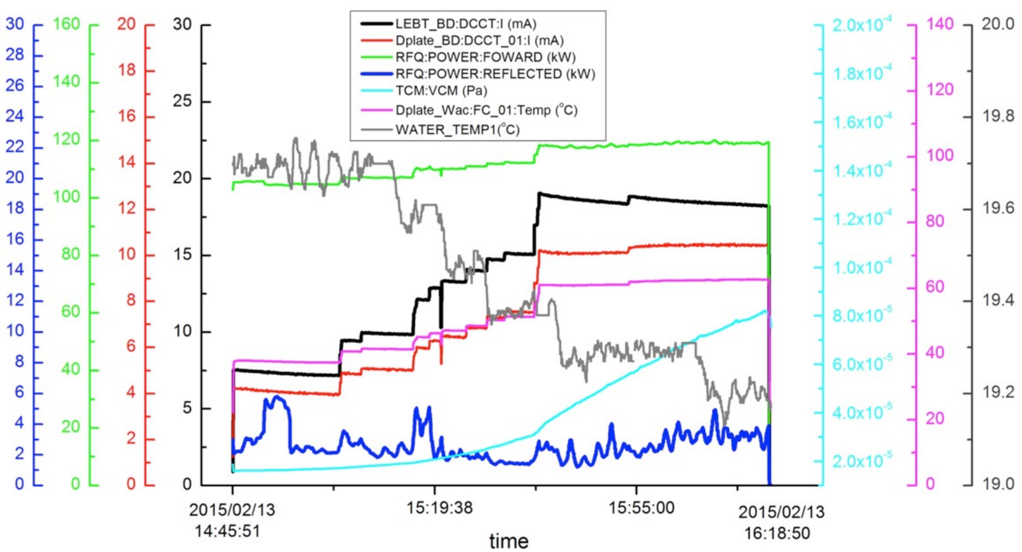
Overlap model of Q1-3

	α_x	β_x (m/rad)	α_y	β_y (m/rad)	Mismatch factor H/V
Rebuilt by Measurement	0.3	0.25	-0.11	0.12	0.078/0.005
Parmteq simul (design)	0.46	0.27	-0.10	0.12	reference



Experimental Phenomenon

- Beam experiment on the RFQ of the demo Injector II of the CIADS @10 mA CW beam
  - Large power reflection for cavity with 10 mA CW beam
  - Reflected power can be reduced by changing the temperature of the cooling water
    - Corresponding to the variation of the eign-frequency of RFQ
  - Minimum reflection power corresponding to 0.5 ° C variation in the cooling water of the RFQ vane
    - the optimum detuning of the RFQ under 10 mA CW beam is 8 kHz



Measured RFQ vane cooling water temperature sensitivity

$$\left(\frac{df}{dT}\right)_{\exp} \approx -16kHz / {}^{o}C$$

Temperature variation

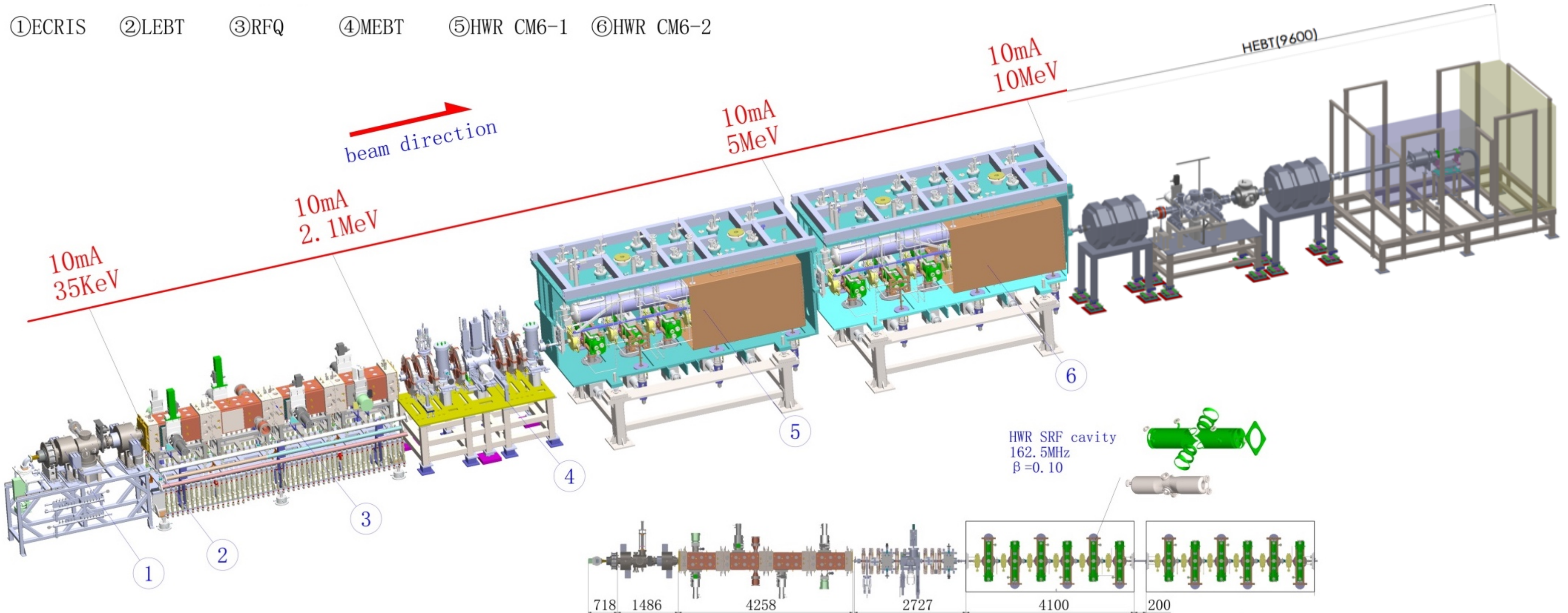
$$\Delta T \approx -0.5^{o}C$$

Tuning Amount

$$\Delta f_t \approx \left(\frac{df}{dT}\right)_{\exp} \Delta T \approx 8kHz$$

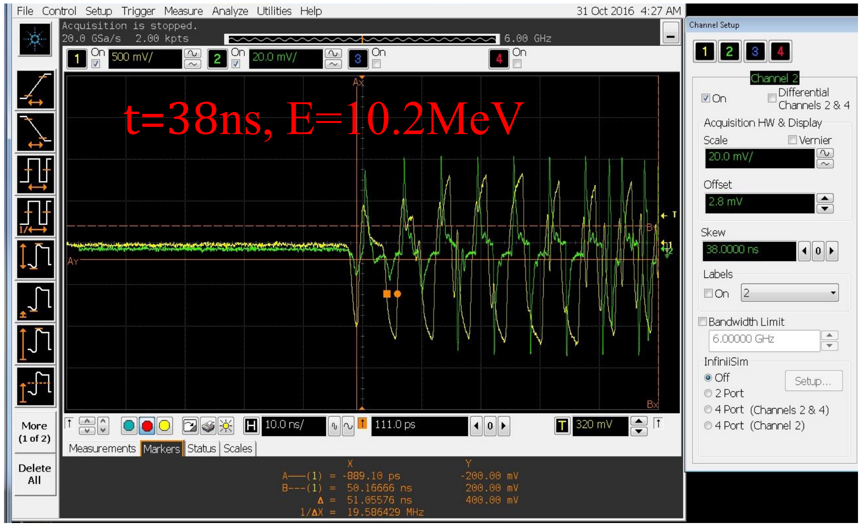
$$\Delta f_{th,0} = -\frac{P_b}{(1+\beta)P_c} \tan\phi_b \approx -7.8\text{kHz} \approx \Delta f$$

Commissioning of CM1 + CM2

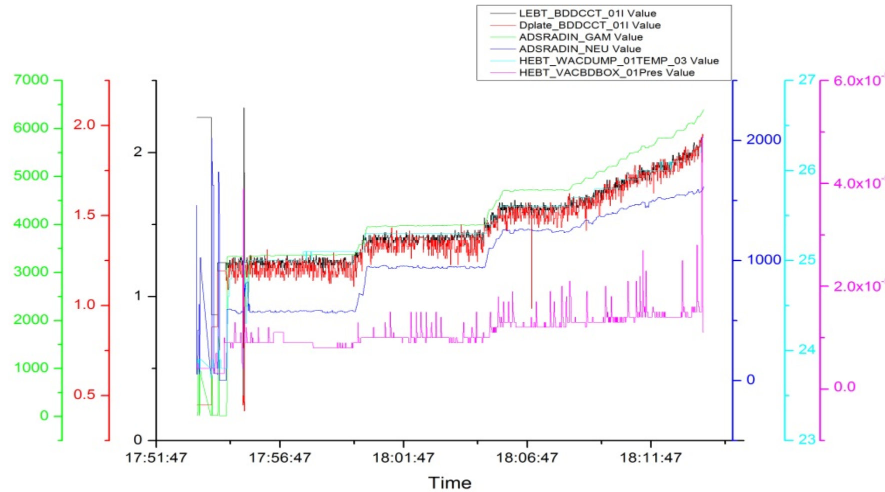


- First cooling down and conditioning of coupler on May 3rd, 2016
- 4 couplers (single-window) were broken in May
- Four broken couplers were replaced by double-window in tunnel in one week.
- Second cooling down in August. First beam was achieved on Sept. 15th, 2016.

Commissioning of CM1 + CM2

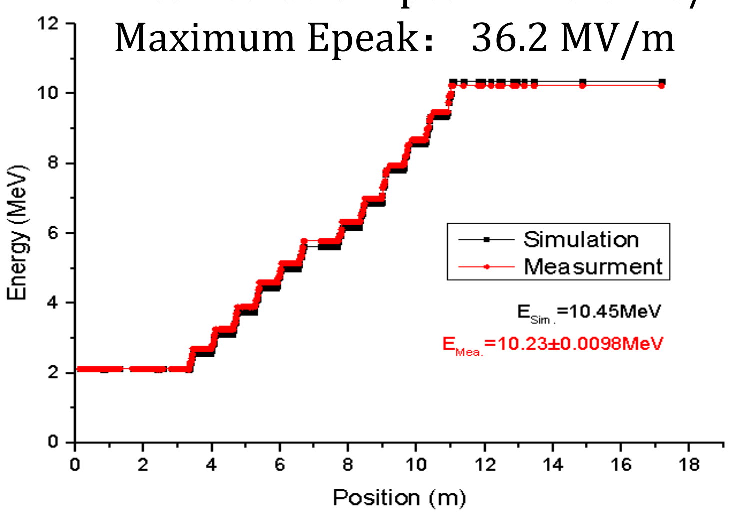


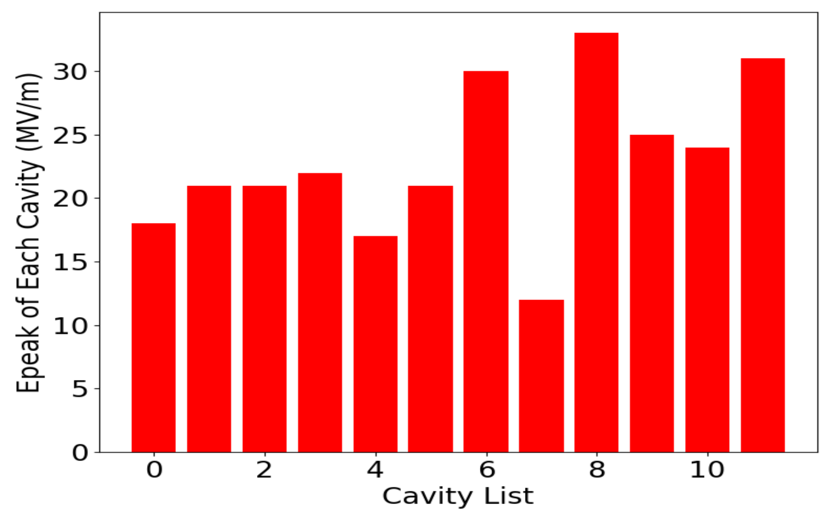
NOV 27th-28th,20 minuts CW beam operation at 1.2 - 2.7 mA with out uncontrolled beam loss



Mean value of Epeak： 23.8 MV/m

Maximum Epeak： 36.2 MV/m

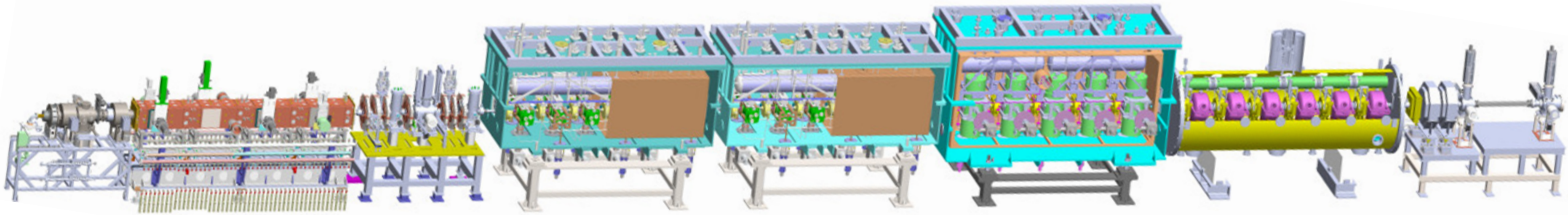




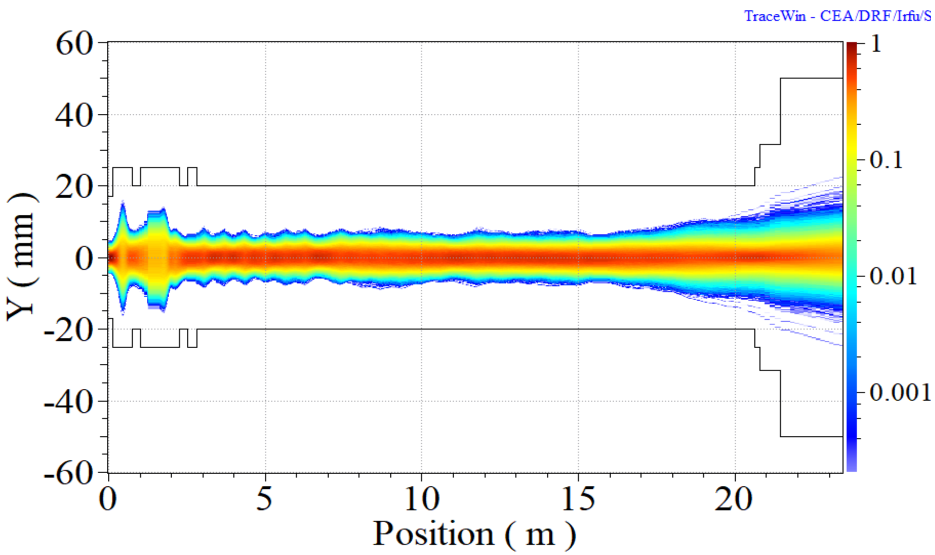
Front-end Demo of Chinese ADS

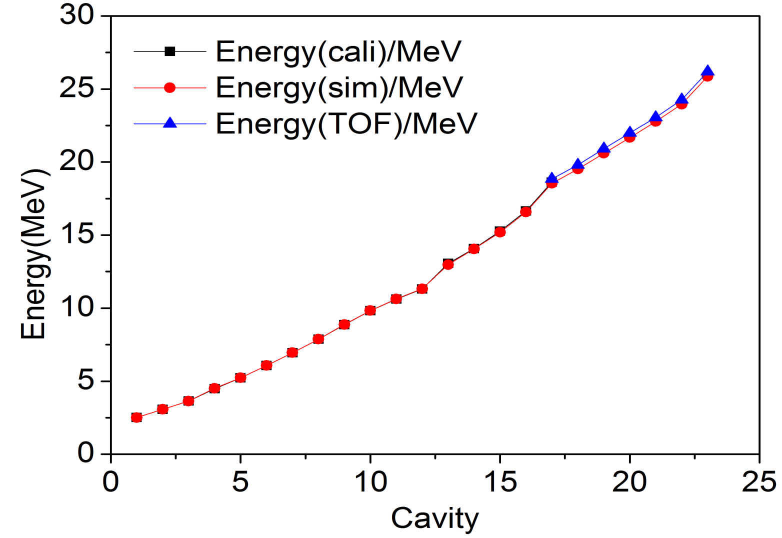
- CM1,CM2 (injector II) were re-installed in Feb 2017.
- CM3 and CM4 were on line on May. 9th;
- First beam was achieved on May. 28th ;
- The energy is up to 26.2 MeV on June. 5th;
- CW beam with energy 25MeV went through on June 6th.

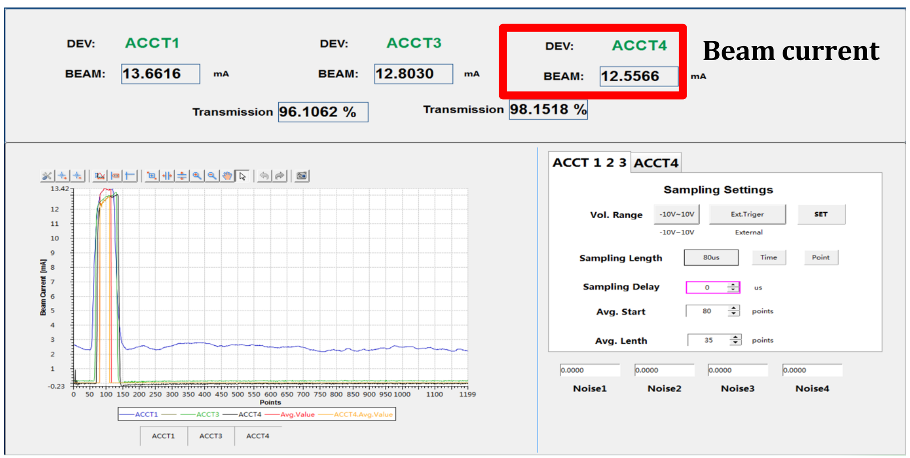
	CM1/IMP	CM2/IMP	CM3/IMP	CM4/IHEP
Frequency	162.5 MHz	162.5 MHz	162.5 MHz	325 MHz
Energy	6 MeV	11 MeV	18.6 MeV	26.2 MeV
Type	HWR010	HWR010	HWR015	Spoke021
Number	6	6	5	6

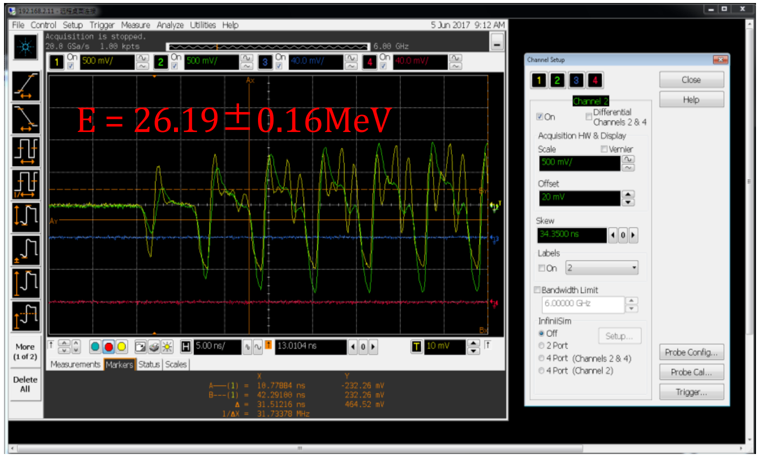


Pulse Beam Commissioning of 25 MeV

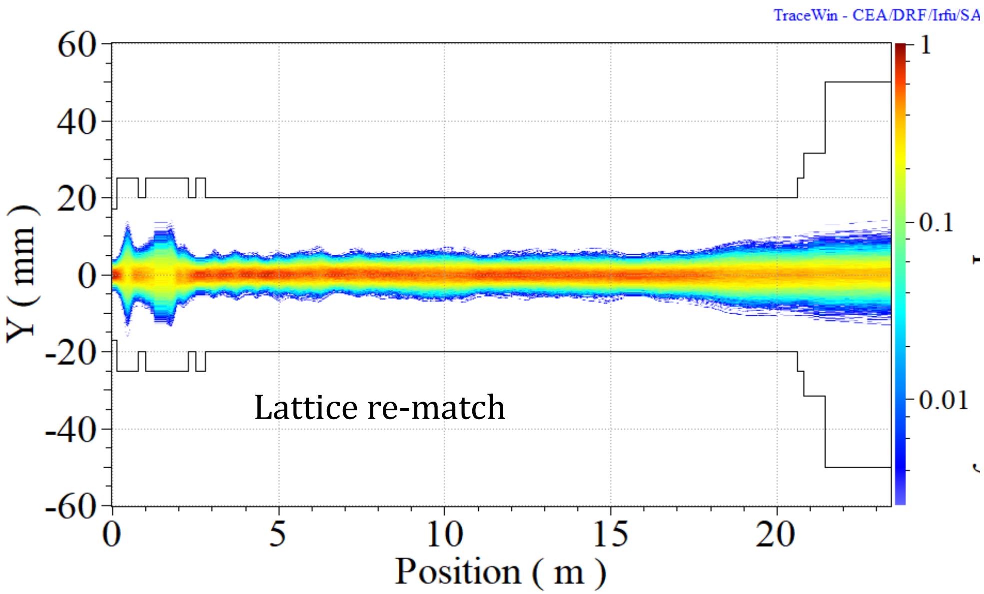


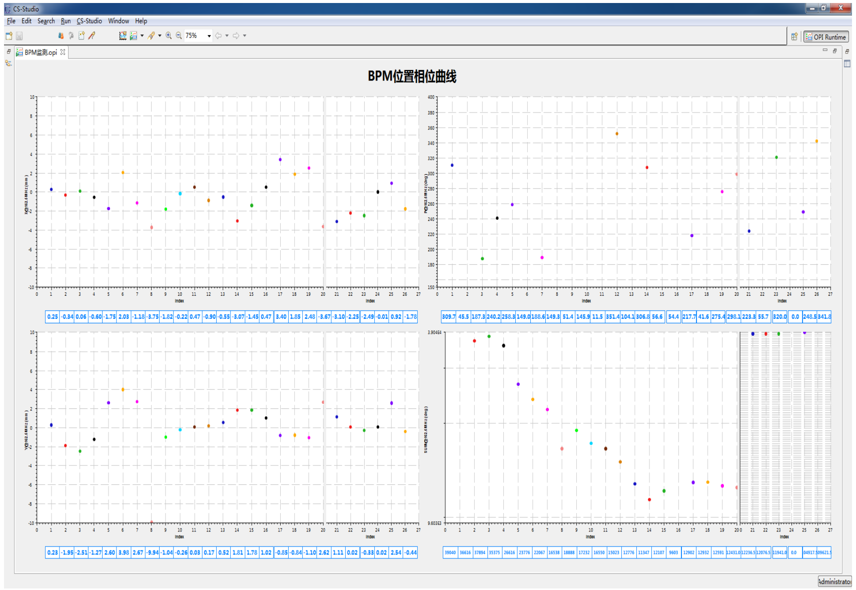




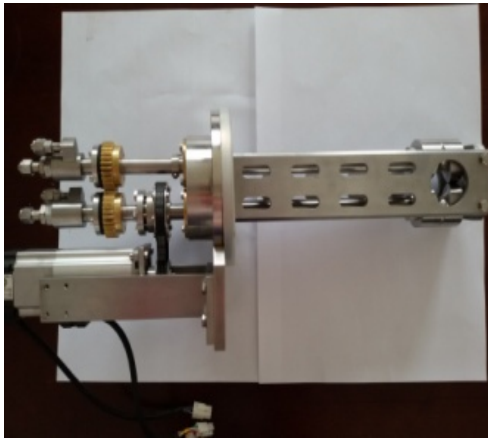


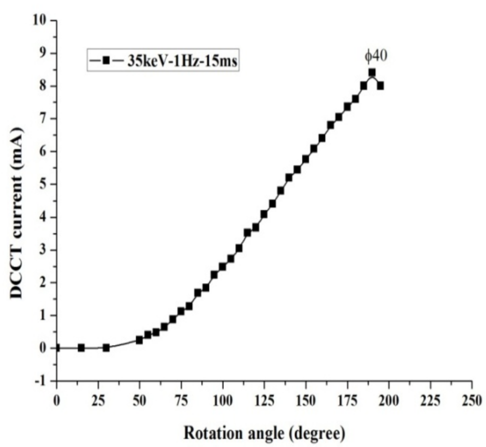
CW Beam Tuning of 25 MeV

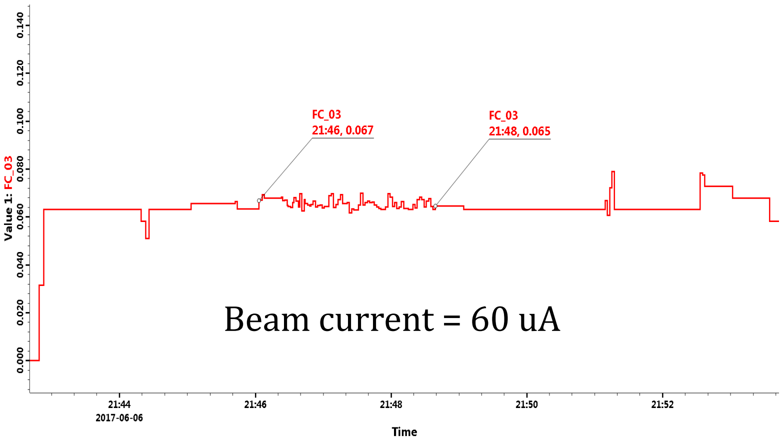




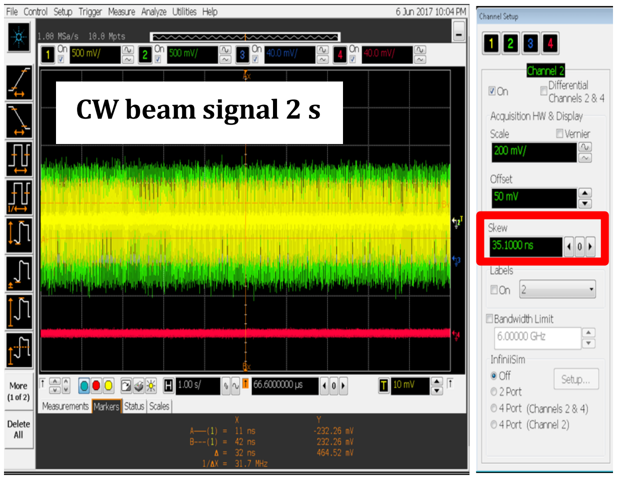
Orbit deviation < ±4 mm

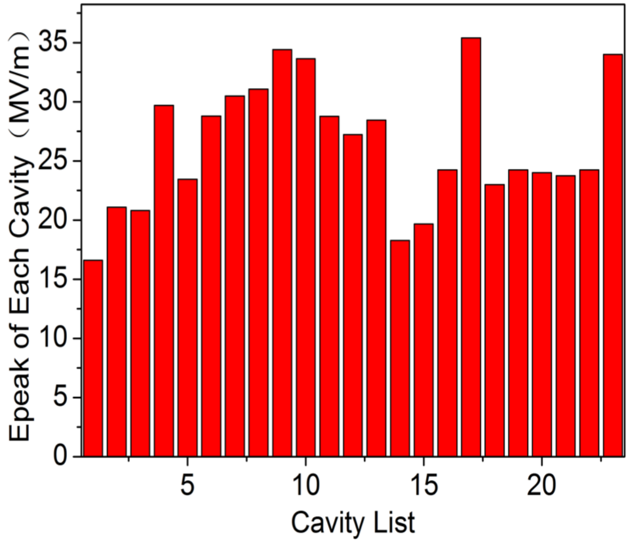


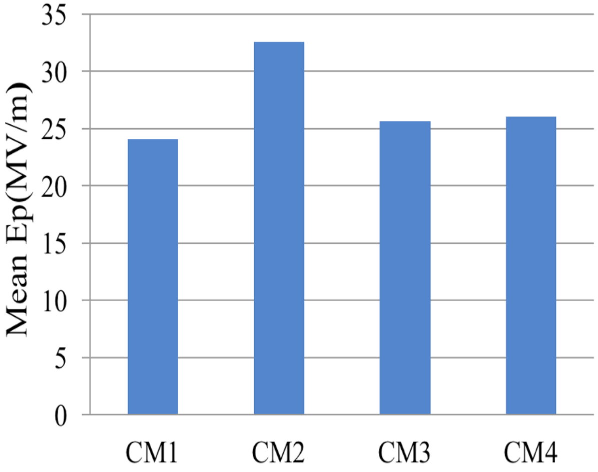


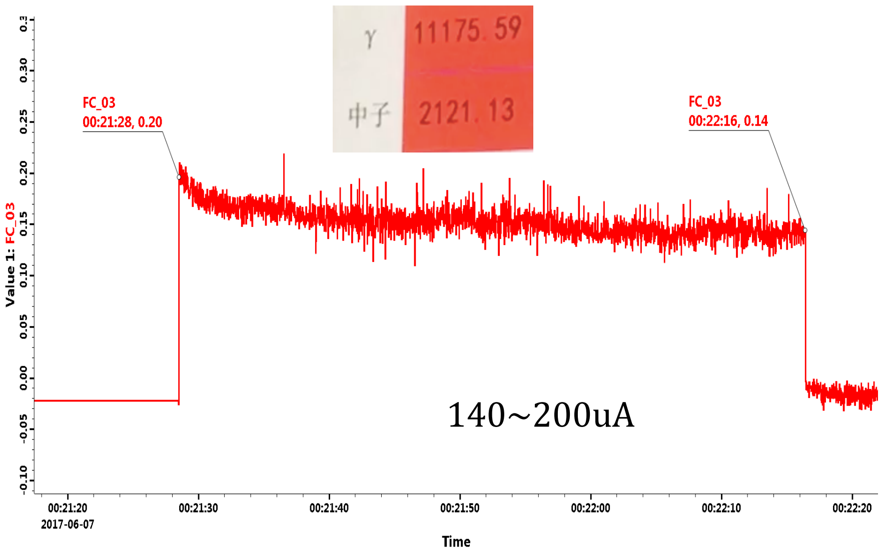


CW Beam Commissioning of 25 MeV









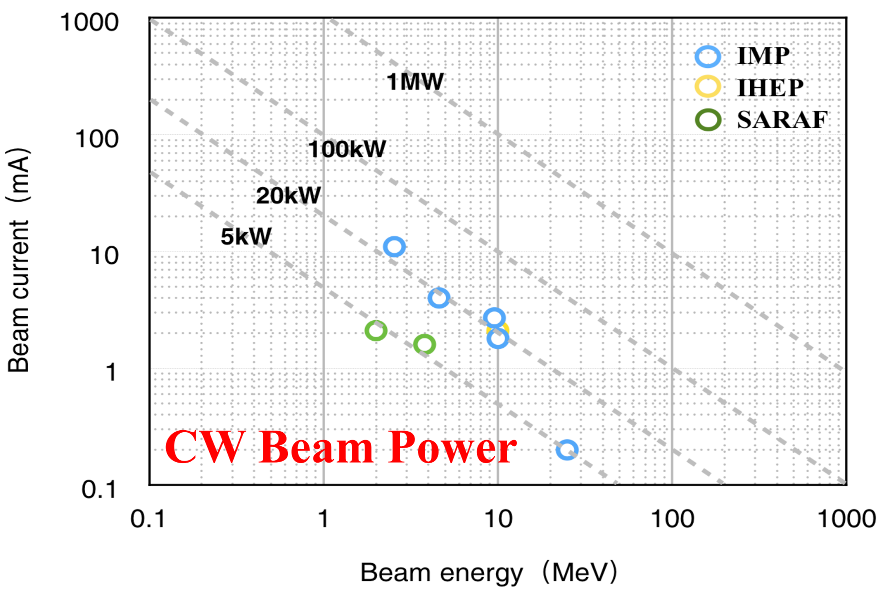
- Beam dump and radiation shielding are the limit to higher beam power and long time operation.
- The next commissioning will be in September. The goal is 2 mA CW proton beam by the end of the year.

Outline

- Background and introduction of ADS
- Sc-Linac design study for CIADS
- Beam commission of front-end demo
- **Summary**

Summary

Accelerator segments	First CW beam	E Max (MeV)	Beam time (hours)	CW beam time Total (hours)	CW Current Max (mA)	CW Power Max (kW)
RFQ	Jun. 21, 2014	2.1	2000	77	11	23
TCM1 (1 HWR)	Nov. 24, 2014	2.55	208	22.5	11	28
TCM6 (6 HWRs)	Jun. 24, 2015	5.3	400	20	4	21
Injector II (CM1+CM2)	Sept. 24, 2016	10.2	317	11	2.7	26
Demo front-end CM1+..CM4	Jun. 7, 2017	26.2	0.5	0.14	0.2	5



- **Tens of kilowatt CW beam achieved in superconducting front-end of Chinese ADS.**
- **The tuning procedures of high power CW beam has been demonstrated successfully.**
- **The dumper is a limit for tuning higher power beam.**
- **Higher power and higher stability will be demonstrated in the future.**

Summary

- **World first demonstration of the 10 mA, CW beam, at the low-energy superconducting Linac**
- **CiADS has been approved and passed CD1. It is expected to break ground in the year.**
- **Challenges of commissioning of CW sc-Linac has been demonstrated or will be attempted.**
  - Twiss parameters re-built at MEBT to initializing beam
  - Orbit alignment and phase calibration
  - Machine protection under high beam power
  - Effective beam loss detection at low energy section
  - High stability and fault recovery strategy

Thanks for your attention

Thanks for the helps

from IHEP, LBNL, Jlab, ANL, SINAP, PKU, THU, MSU, ……