CiADS，Next Phase and Demo Linac Commissioning Results

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Outline

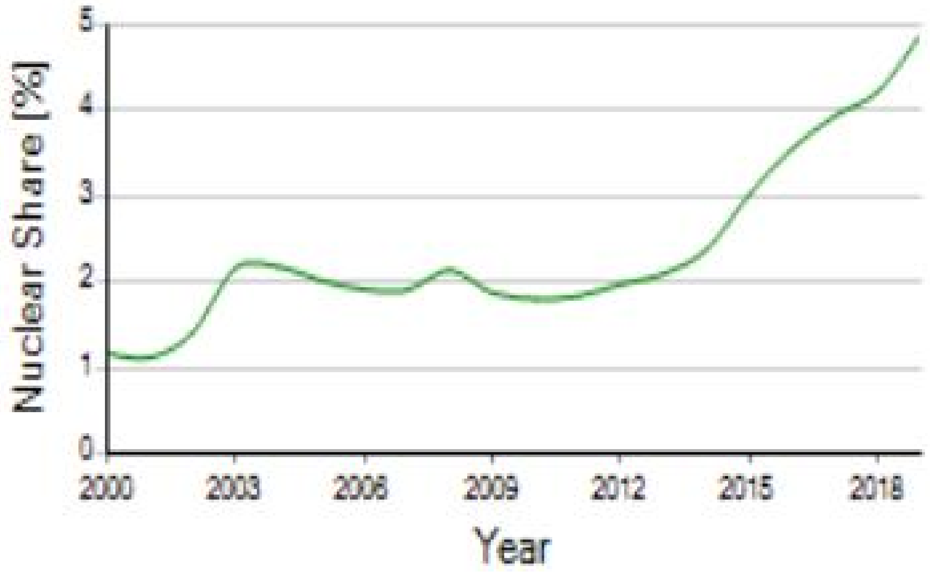
- Brief introduction of CiADS project
- The challenges and design of sc-linac CiADS
- Beam commissioning of demo linac for ADS
- Special issues for high power SC linac
- Results and summary

Motivation of CiADS

- **Current status of China (including Taiwan, China) nuclear power (by the end of 2018)**
  - 50 nuclear power reactors in operation, 47.528 GWe (3th , total 452 and 399.354 TWe in the world)
  - 14 reactors under construction, 13.175 GWe, (1st in the world)

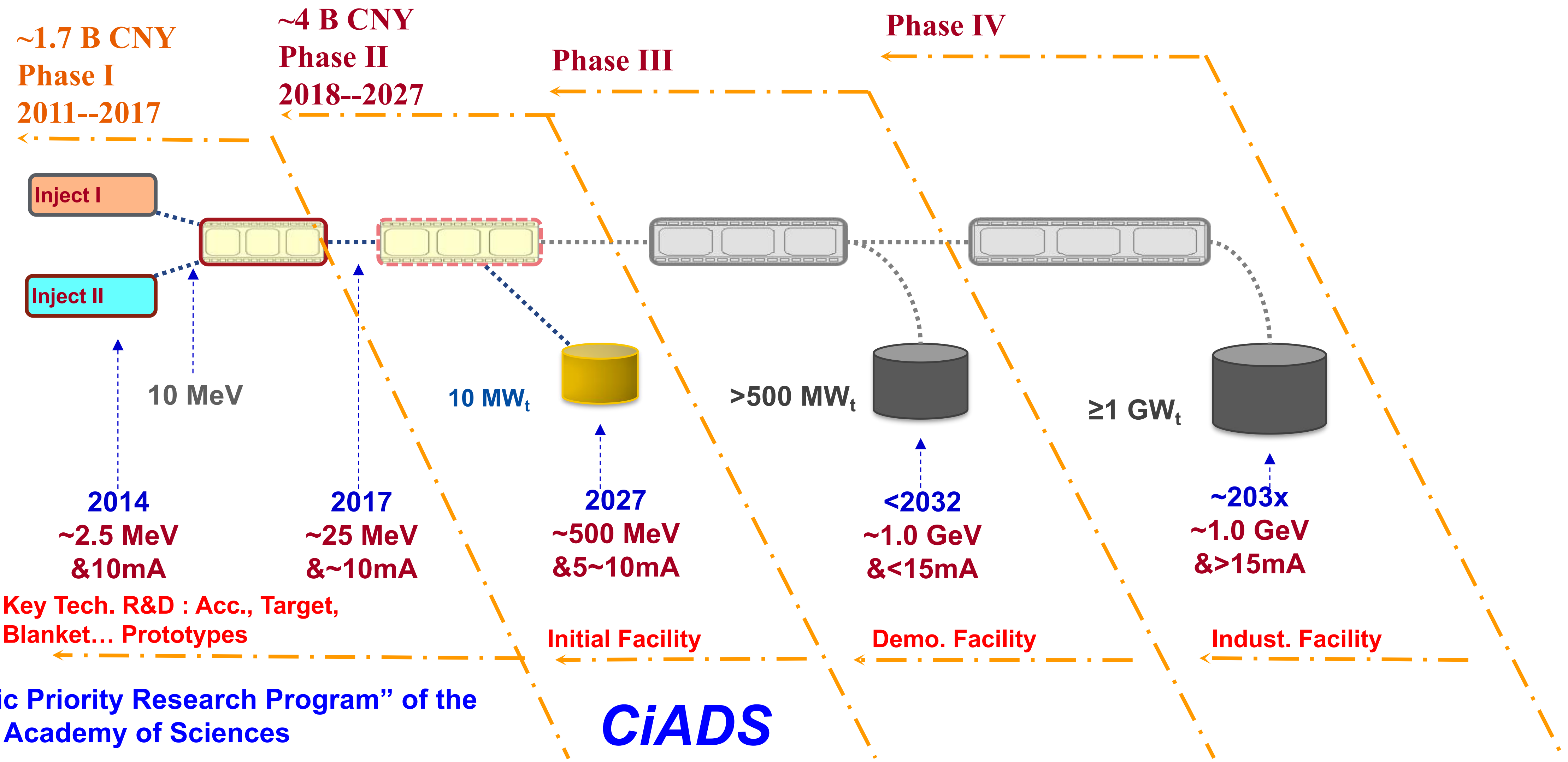
- **Nuclear energy is an inevitable strategic option to meet China energy demand in the future**
  - China has already committed to peak carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060.
  - Nuclear will be the important one in the carbon fre energies.

Data from IAEA/PRIS, update on 2021-05-13



- **Management and safe disposal of nuclear waste**
  - 1 GWe 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;

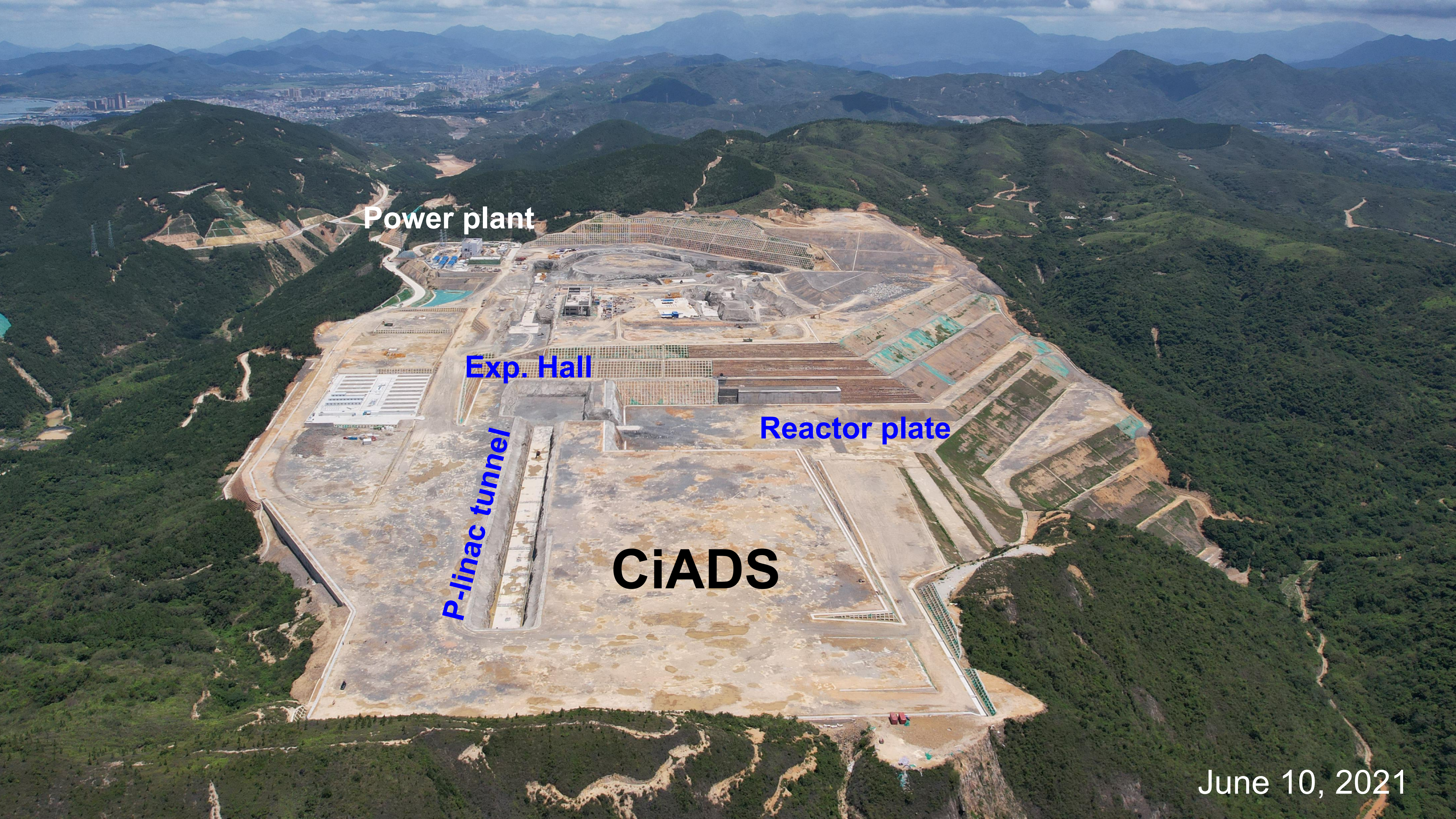
ADS/ADANES Roadmap in China



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

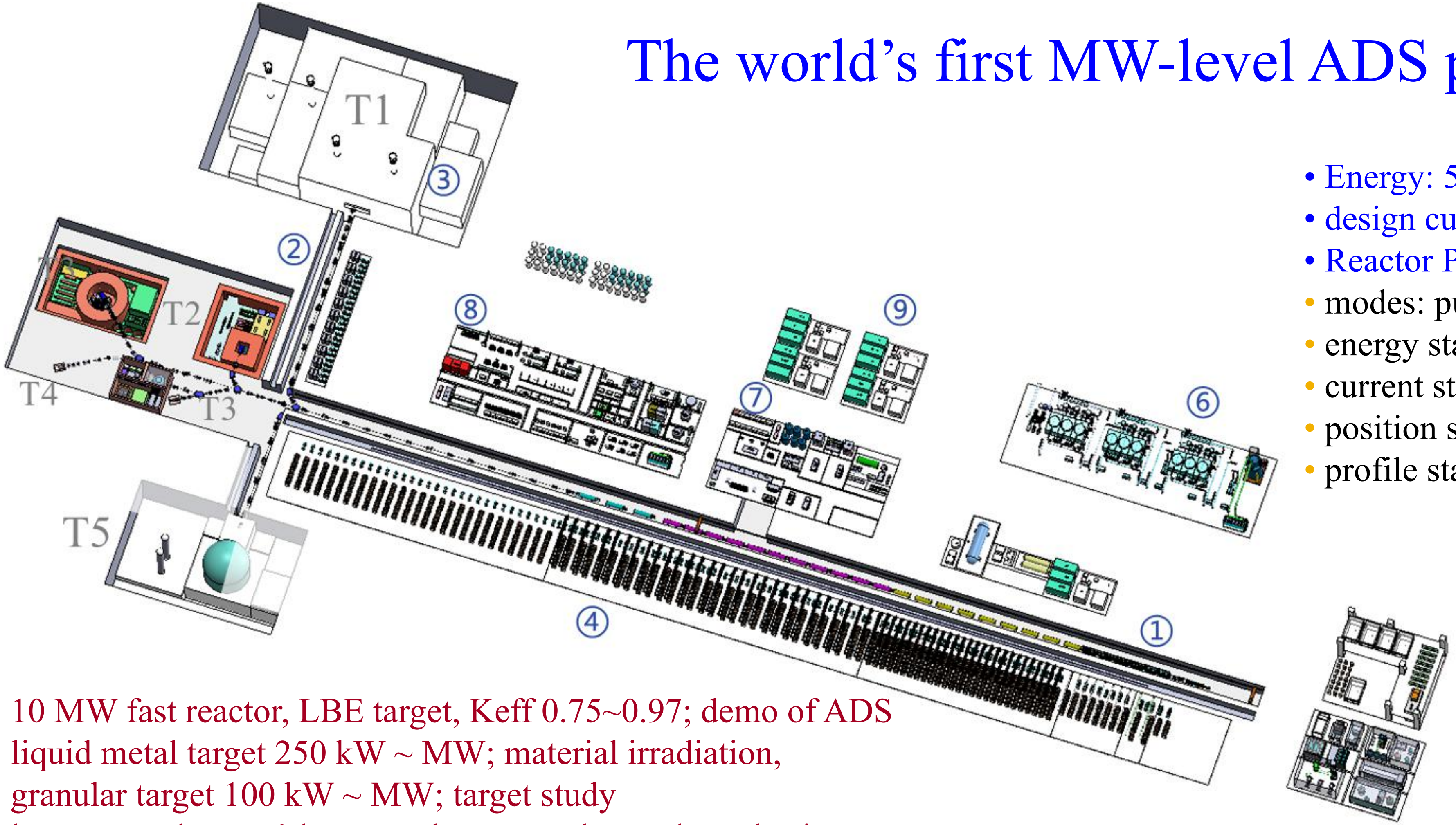
CiADS Project in Huizhou

- **Approved in Dec. 2015, Ground broke in August 2018, Officially started in July 2021**
- **Leading institute: IMP**
- **Budget: ~4 B CNY (Gov. 1.8B + CNNC 1.0 B + Local Gov. 1.2 B)**
- **Location: Huizhou, Guangdong Prov.**
- **Partners: CIAE, CGN, IHEP, etc.**


Power plant
Exp. Hall
Reactor plate
P-linac tunnel
CiADS
June 10, 2021

The Configurations of CiADS

The world’s first MW-level ADS prototype



- Energy: 500 MeV (to 1.5GeV)
- design current: 5 mA (to 10 mA)
- Reactor Power: 10 MW
- modes: pulse&CW（Hus gap for reactor）
- energy stability: ±1%@100ms
- current stability: ±2%@100ms
- position stability: ±1mm
- profile stability: ±1mm

CiADS:

- Beam-trip-duration tolerance is 10 s.
- < 10 s, rapid recovery
- 10 s ~ 5 min, <2500 /year
- > 5 min, < 50 /year

- T1: 10 MW fast reactor, LBE target, Keff 0.75~0.97; demo of ADS
- T2: liquid metal target 250 kW ~ MW; material irradiation,
- T3: granular target 100 kW ~ MW; target study
- T4: low power dump 50 kW; accelerator study; nuclear physics
- T5: upgrade ISOL target: iLinac of HIAF is post-acc, to 100 MeV/u

The devices are in fabrication, the first beam of RFQ in Dec. 500MeV beam in reactor in 2026.

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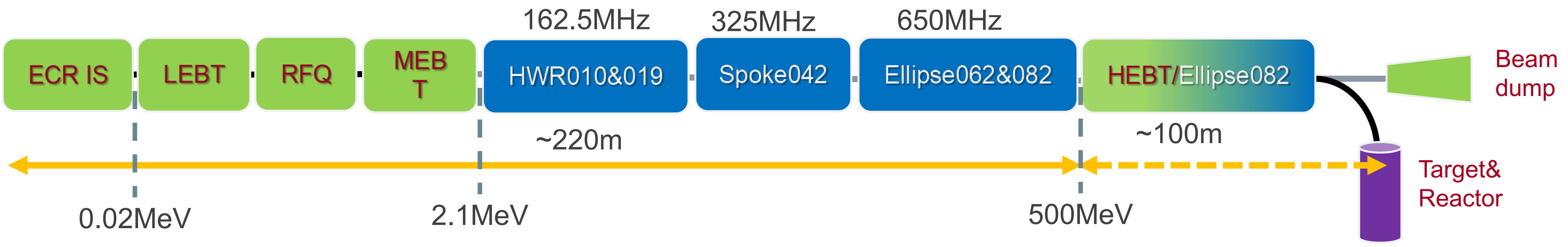
Challenge of sc-Linac for CiADS

- to control beam loss to a reasonable level
  - to make a high quality beam at the warm front end
  - to minimize beam loss at the high energy section
  - to avoid tiny unnecessary beam loss along the linac
  - to detector sudden loss happens at any position of all the linac

- to maintain both high availability and high safty
  - A physical design able to realize element failure-compensation
  - A reliable MPS to keep the high power machine safe
  - to recover beam in a few seconds
  - A reliable beam trip recovery scheme for CW machine

Physics design based on low beam loss



① **LEBT：Point scraping method，optimize transverse beam quality，reduce the beam loss of downstream accelerator——ECR ion source can provide produce tens of mA proton beam intensity**

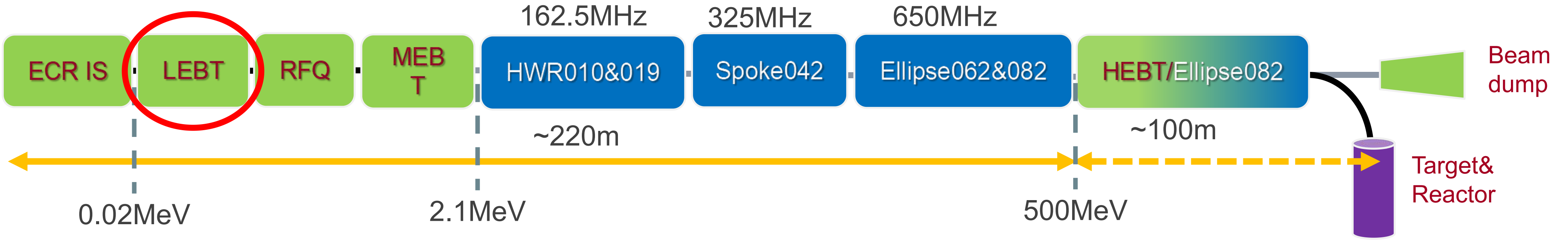
② **RFQ: Discontinuous dispersion optimization method-optimize longitudinal beam distribution，remove particles with off-center energy as much as possible**

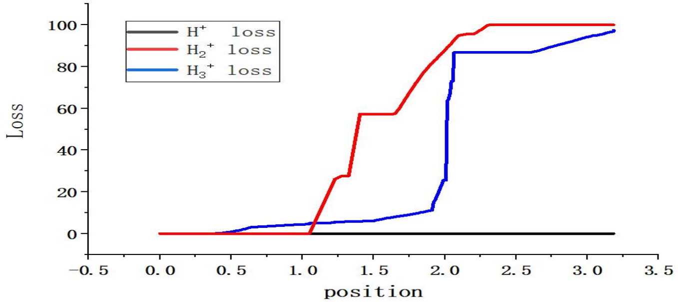
③ **MEBT：Beam scraping method based on phase advance，remove the halo particles，Reduce beam loss probability of downstream accelerator**

④ **SC :Small aperture design of RT magnet in high energy section，increase the probability of beam loss in the RT element and reduce the beam loss in the SC element**

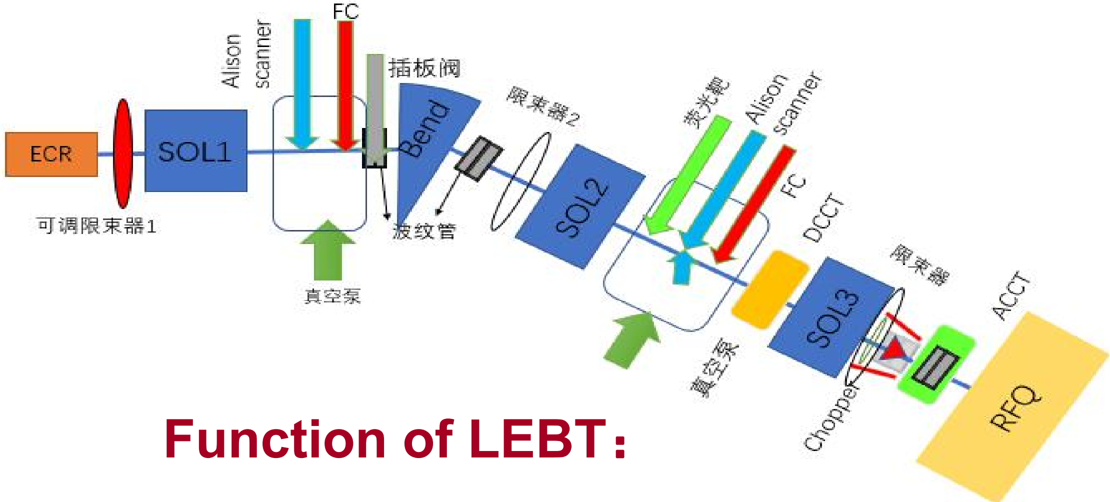
Particle	H^+	
Output energy	500	MeV
Beam current	5	mA
Beam power	2.5	MW
RF frequency	162.5/325/650	MHz
Operation mode	CW&Pulse	
Limitation of beam loss	< 1	W/m

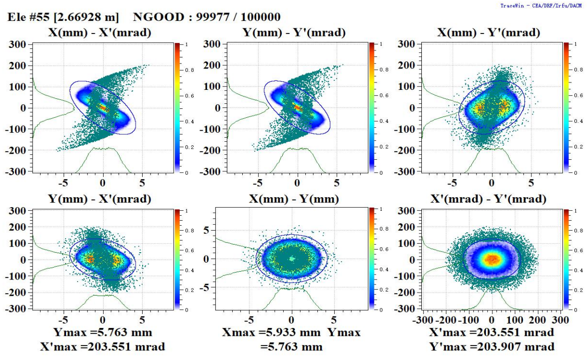
Physics design: LEBT



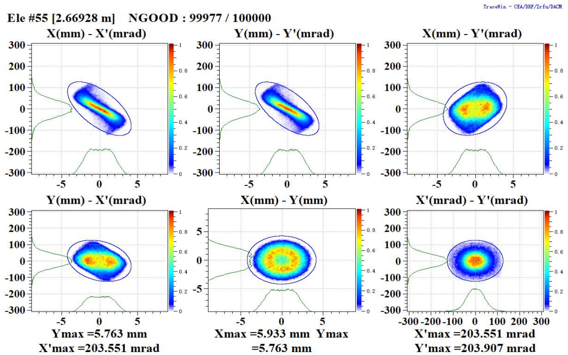


Purified proton beam-remove H^{2+},H^{3+}（100%）





Phase space distribution before beam scraping

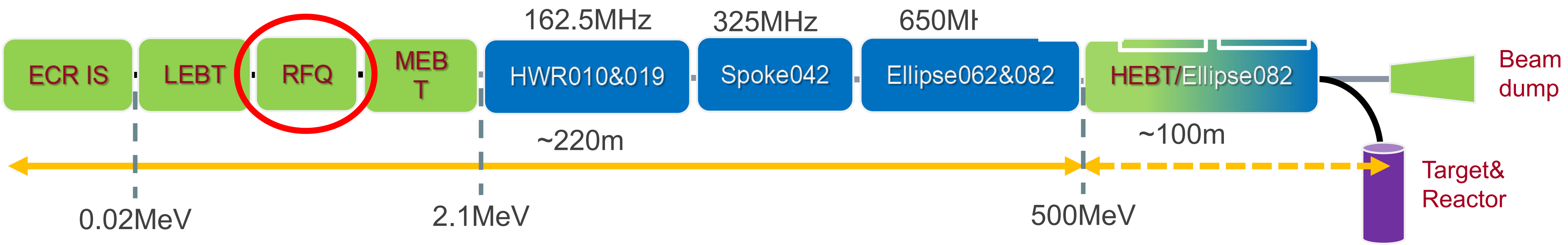


Phase space distribution after beam scraping

Function of LEBT:

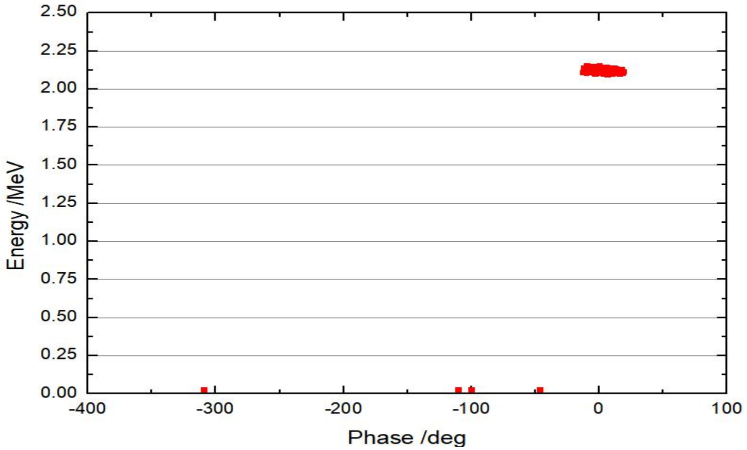
- Purified proton beam
- Transverse beam quality operation
- Beam parameters measurement
- Matching between ECRIS and RFQ

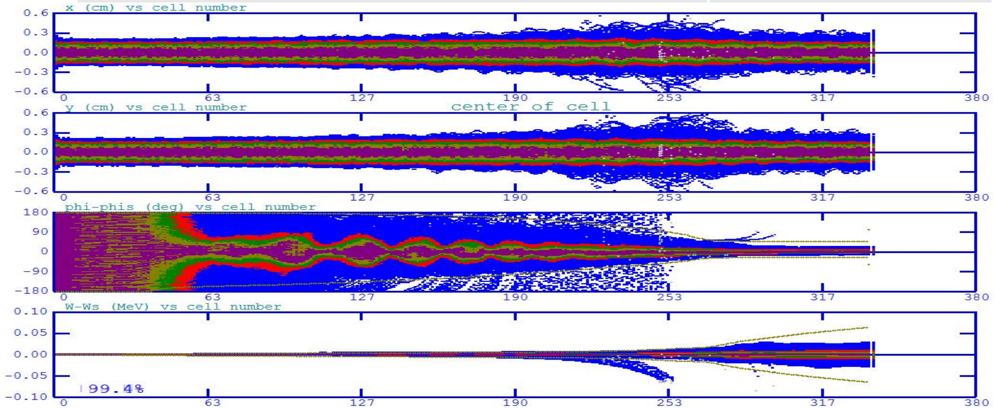
Physics design: RFQ

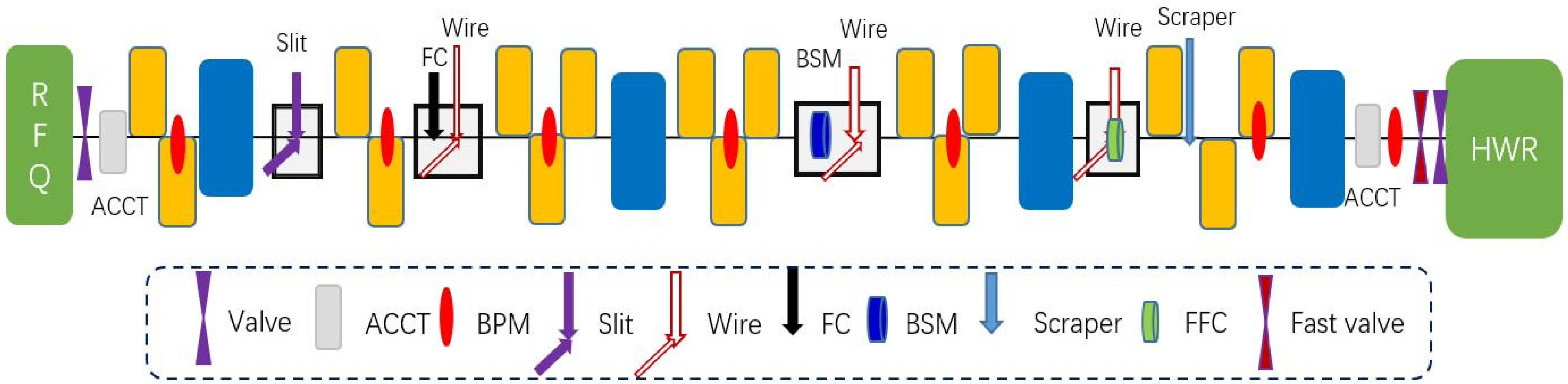


- Fine optimization to control beam quality at shaper segment
- Full particle optimization aimed at 99.99% longitudinal emittance at bunching segment
- Smooth transition to prevent emittance increase caused by parameter mutation at transition segment

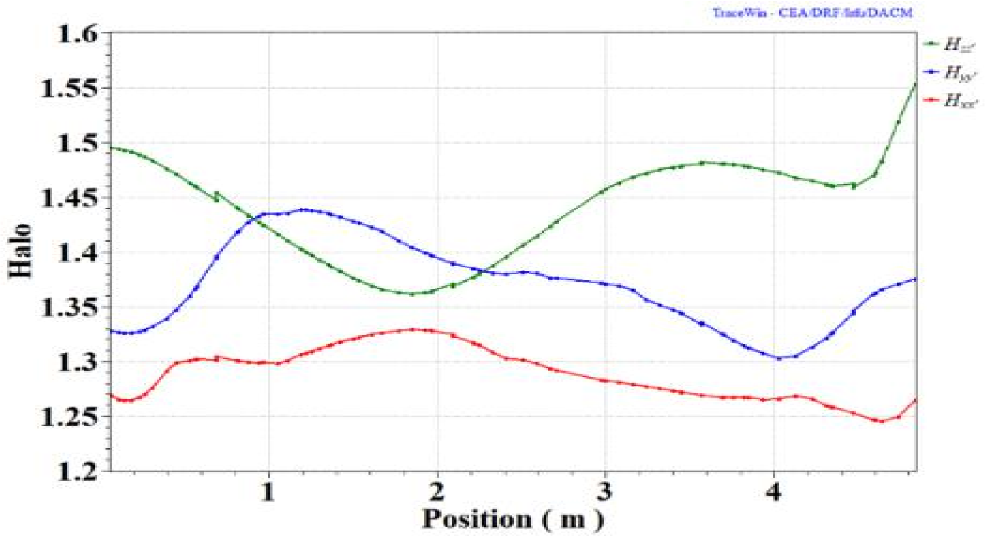
Parameters	value
Vane voltage（kV)	65
Max surface electric field（MV/m）	13.59@kp=1
Average aperture(mm)	6.79
Length (m)	4.90
transport effeciency/acceleration efficency	99.6/99.4





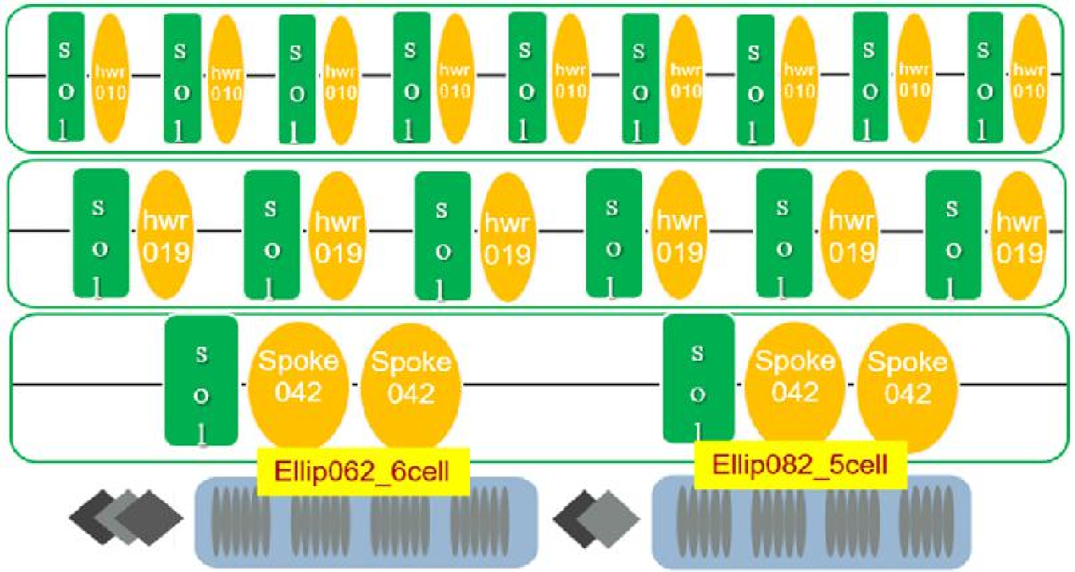


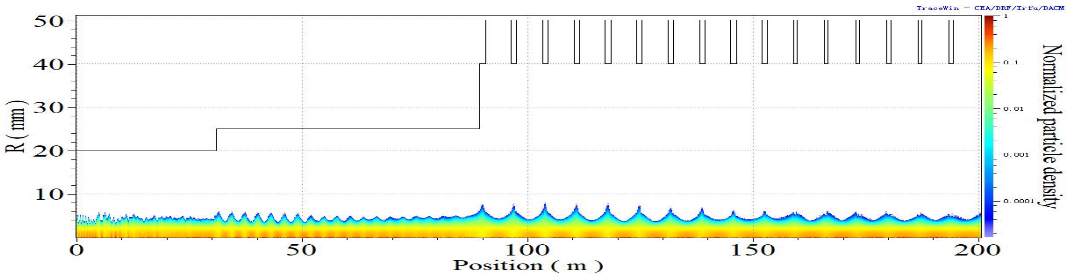
- beam diagnostics enough to do 6-D measurement or to reconstruct 6-D distribution
- internal and external focusing optimization for smooth envelope
- Full space scraping method to reduce halo particle loss in the downstream linac

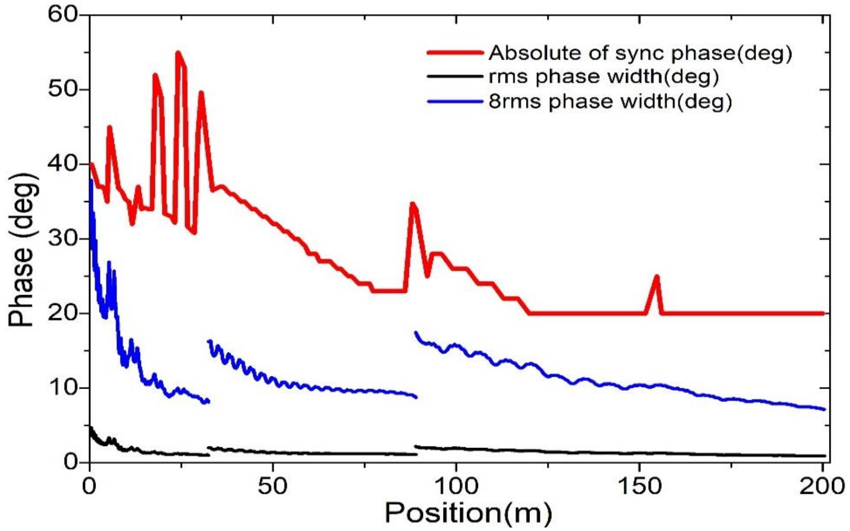


Physics design: SC section

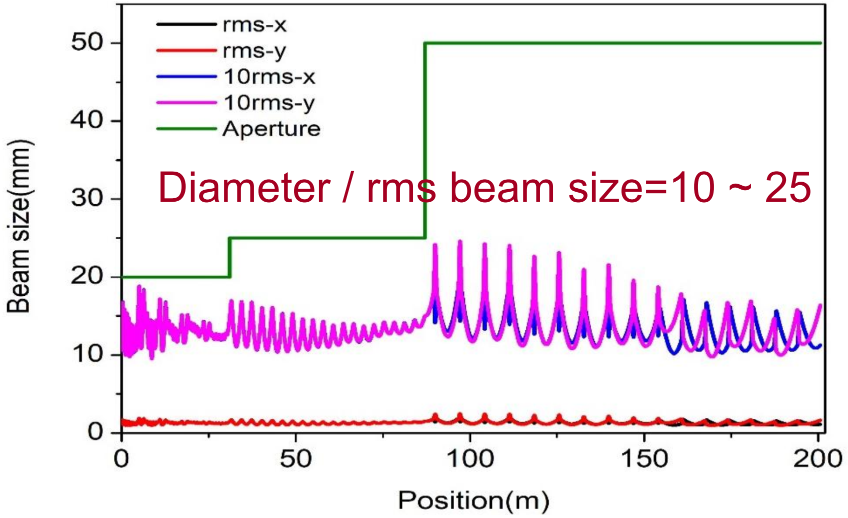
- A compact periodic structure is determined to overcome the space charge effectand increase the acceleration efficiency in the low energy section
- Full period structure is adopted to avoid mismatching effect in the high energy section
- Quadrupole with small aperture is used to scrape out halo particles to reduce the beam loss in the SC cavities in the high-energy section







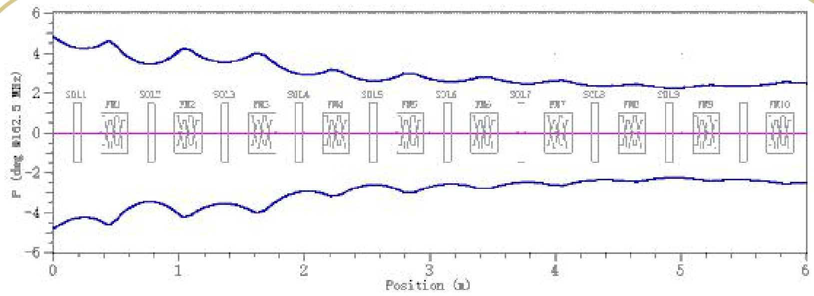
Relationship between phase width and sync phase



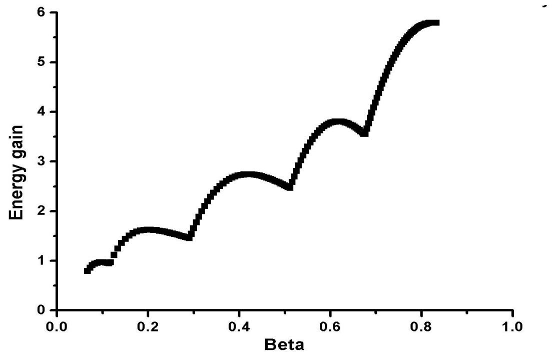
Relationship between envelope and aperture

Compensation design: mix-way

Adaptive compensation scheme based on physical characteristics



In the low energy section, the impact on the overall beam quality is more obvious, and it is easier to cause beam loss. Matching compensation is particularly critical.



In the high-energy section, the energy compensation is easier and more economical.

HWR010	HWR019	Spoke042	Ellip062	Ellip082

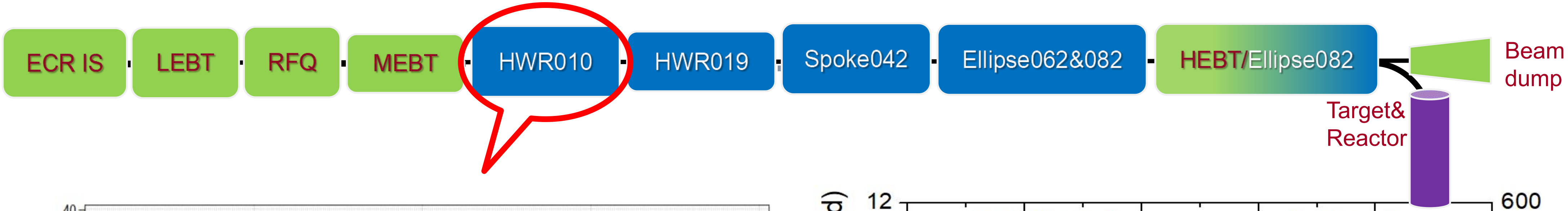
Energy compensation for velocity acceptance
Twiss parameter matching

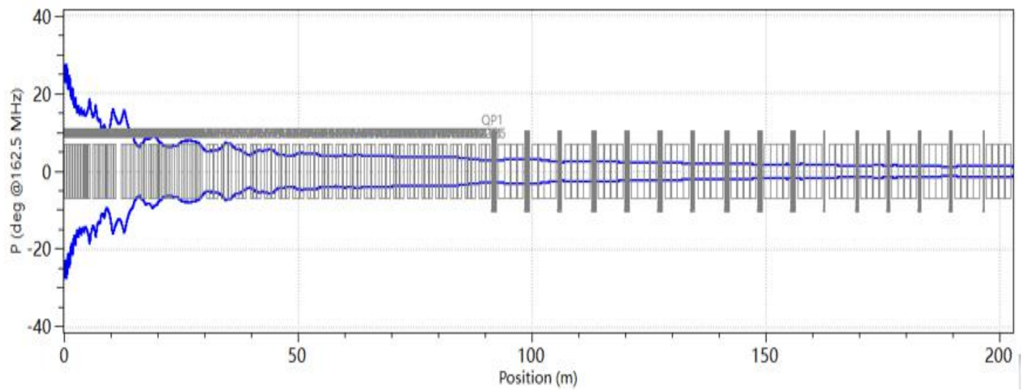
Energy compensation

Based on the intrinsic characteristics of the energy segmentation of the superconducting linac, the matching compensation and energy compensation functions are considered separately. This method has the characteristics of low redundancy and feasibility.

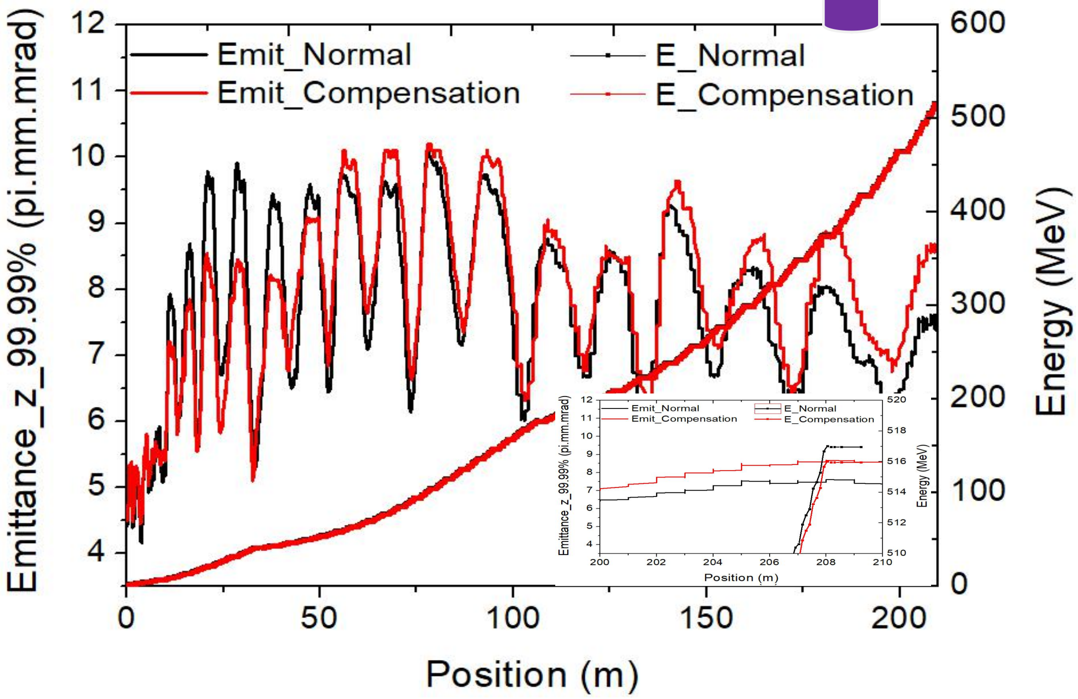
Compensation design: Example

Take single cavity failure of HWR segment as an example





Longitudinal envelope after compensation



Beam emittance and energy evolution after compensation

Compared with the normal condition:

- RMS emittance growth < 15%
- Output energy stability < 0.2%

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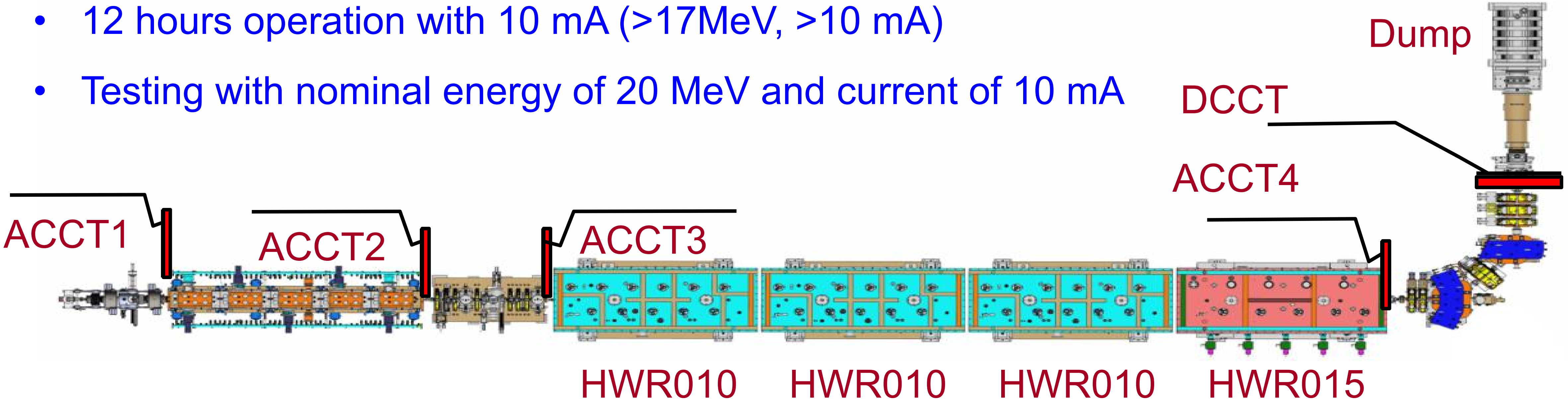
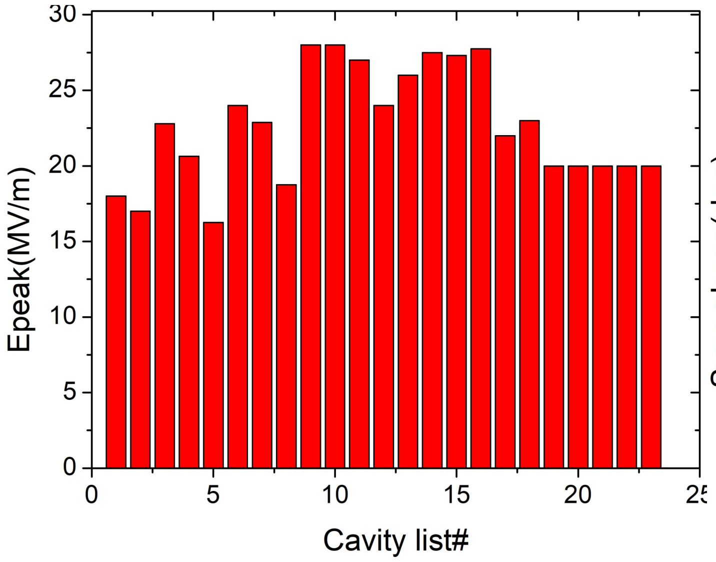
Goal of High Power Commissioning Campaign

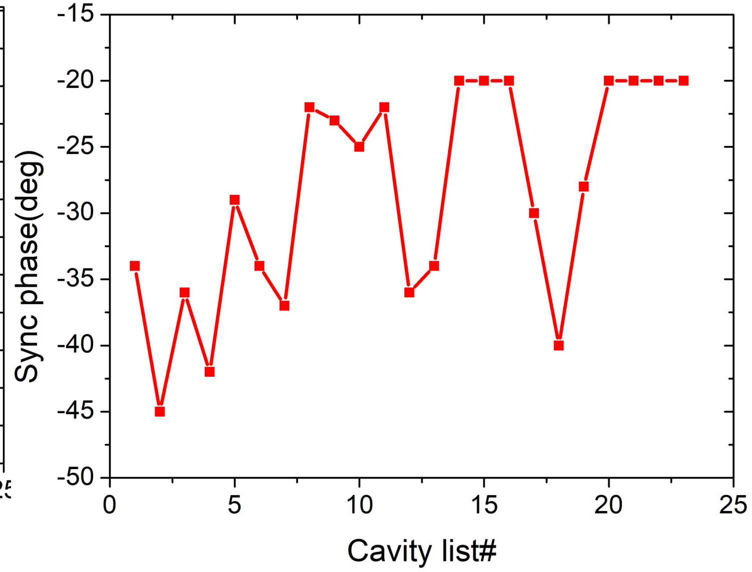
- 100 hours operation with more than 100 kW (>17MeV, >5mA) beam power
- 12 hours operation with 10 mA (>17MeV, >10 mA)
- Testing with nominal energy of 20 MeV and current of 10 mA



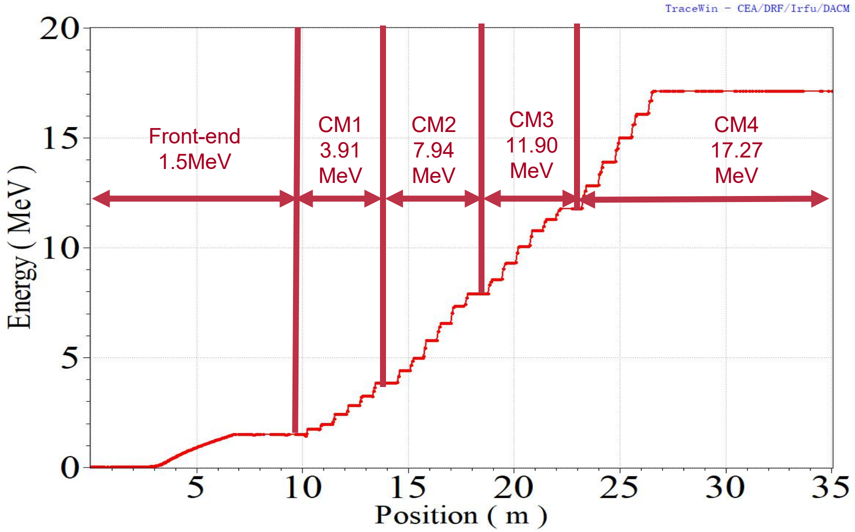
Commissioning: Lattice of CAFe



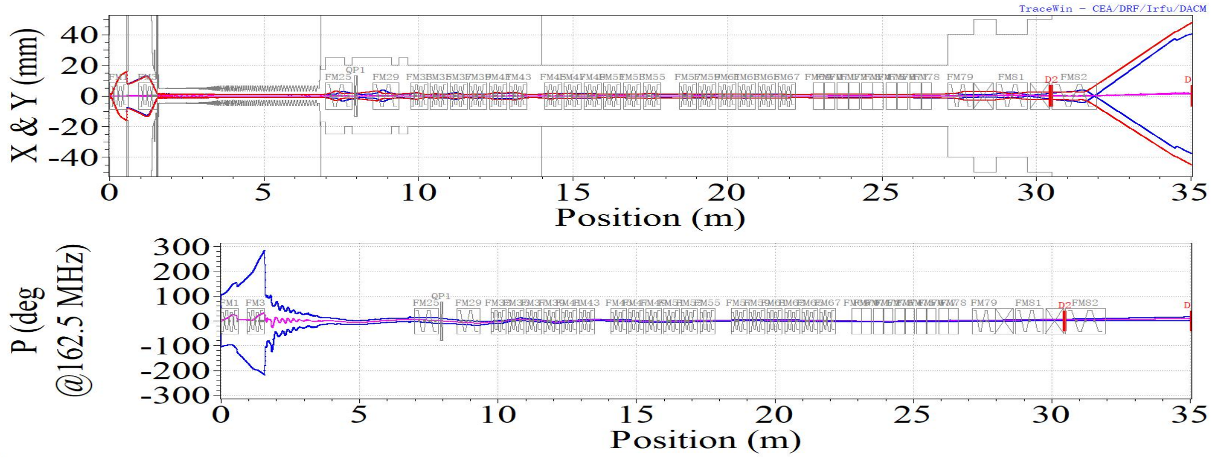
the acceleration gradient Epk



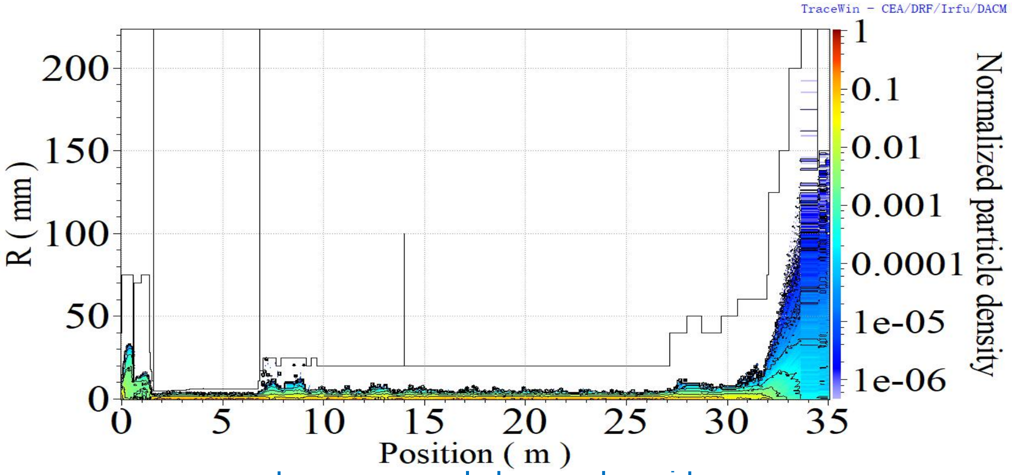
The syschnous phase



The energy along the linac

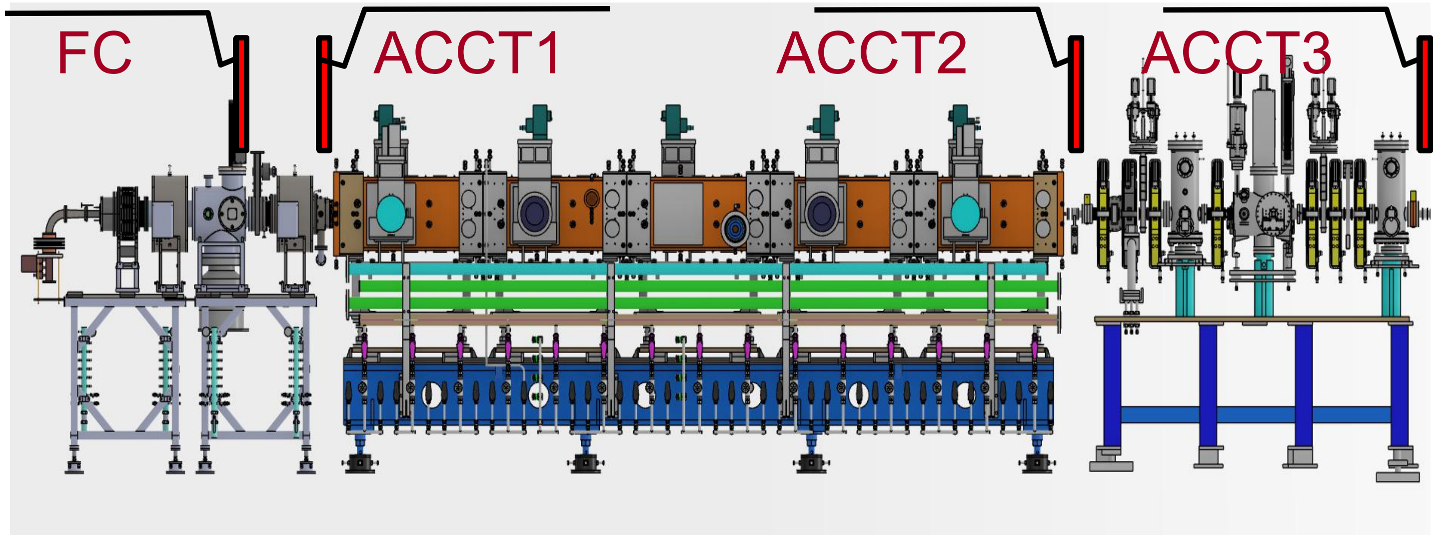


envelope along the linac



transversal beam density

Commissioning: Tuning at frontend



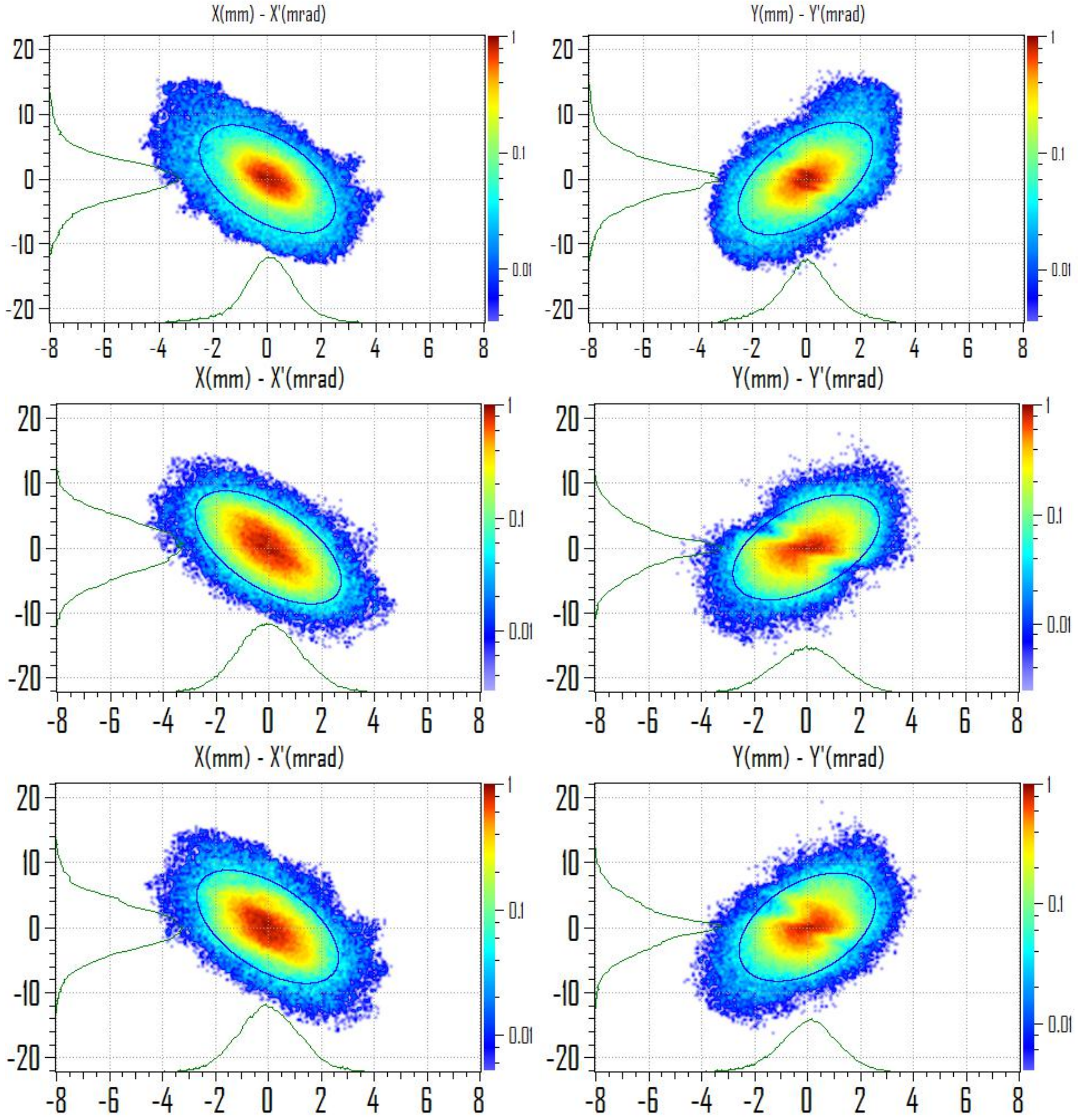
1. LEBT solenoid configuration ➡ the maximum transmission of RFQ
2. MEBT orbit correction ➡ p/m 0.5mm
3. Bucher configuration ➡ phase scanning
4. Emittance measurement study @ beam current ➡ to find a way to ramp beam power
5. Initilize beam at exit of RFQ

Commissioning: Reconstruct at MEBT

2.9mA

6.0mA

8.5mA



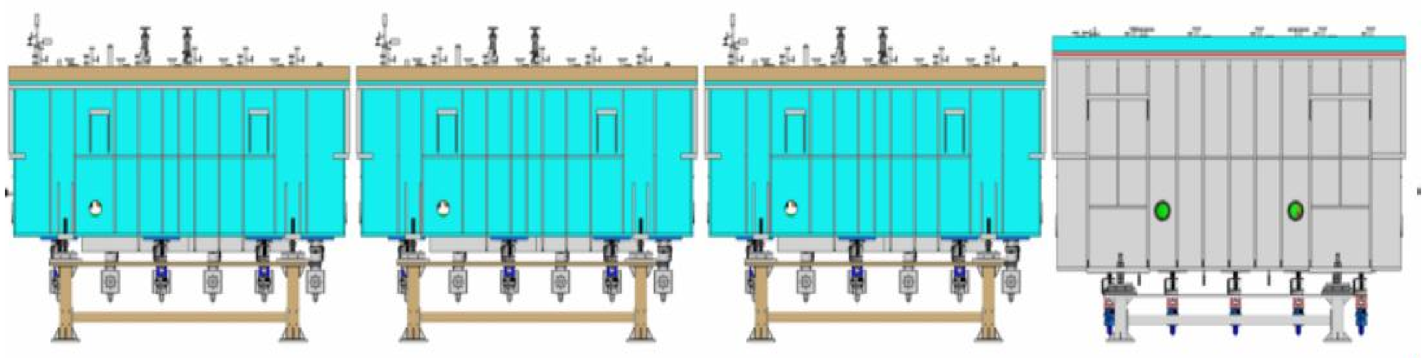
Q1=123A, Q2=105A, Q3=117A

EmitX [rms] = 0.2033 π.mm.mrad [Norm.]
BetaX = 0.3534 mm/π.mrad
AlphaX = 0.6155
EmitY [rms] = 0.2071 π.mm.mrad [Norm.]
BetaY = 0.3399 mm/π.mrad
AlphaY = -0.6389

EmitX [rms] = 0.2187 π.mm.mrad [Norm.]
BetaX = 0.4051 mm/π.mrad
AlphaX = 0.7788
EmitY [rms] = 0.2204 π.mm.mrad [Norm.]
BetaY = 0.3854 mm/π.mrad
AlphaY = -0.4866

EmitX [rms] = 0.2222 π.mm.mrad [Norm.]
BetaX = 0.3686 mm/π.mrad
AlphaX = 0.6554
EmitY [rms] = 0.2195 π.mm.mrad [Norm.]
BetaY = 0.3439 mm/π.mrad
AlphaY = -0.4827

Commissioning: Tuning at SC section



HWR010 HWR015

1. Initial beam is reconstructed at the MEBT for lattice setting
2. Probe beam to configure SC cavities, energy measured by two BPMs
3. Probe beam to correct the orbit within ± 1mm
4. Extend beam pulse length to minimize the beam halo（loss） by the temprature detectors on the flanges of BPMs

射频系统监测界面 2021-01-23 22:07:35

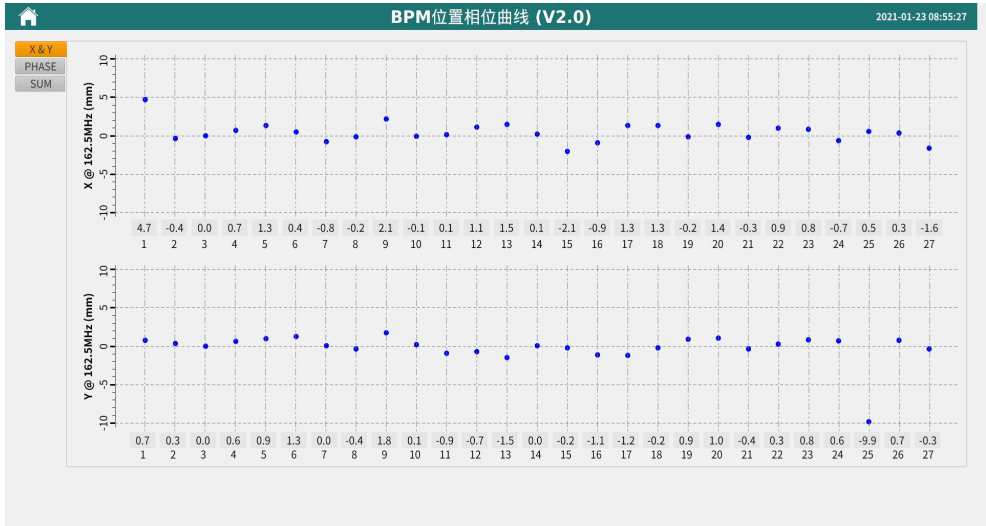
Cavity	闭环状态	Epk(MV/m)	LLRF相位	腔体幅度误差	腔体相位误差	Monitor相位°
CM1-1		18.1	-21.6	0	1	-156.5
CM1-2		17.0	-146.0	0	0	102.6
CM1-3		22.7	12.3	0	1	-129.6
CM1-4		20.7	-145.7	0	1	170.1
CM1-5		18.0	-48.9	0	0	-37.3
CM1-6		24.1	44.1	0	0	7.9
CM2-1		24.9	-40.5	0	0	93.0
CM2-2		22.0	68.4	0	1	-109.9
CM2-3		30.3	-177.3	0	1	162.7
CM2-4		27.2	88.7	0	0	118.8
CM2-5		29.1	145.1	0	0	-30.6
CM2-6		27.5	-30.6	0	0	36.2
CM3-1		28.0	0.5	0	0	159.2
CM3-2		27.5	41.2	0	0	-58.3
CM3-3		27.3	-5.5	0	0	72.7
CM3-4		27.6	120.8	0	1	-139.6
CM3-5		23.2	67.4	0	0	-31.1
CM3-6		28.5	-54.3	0	0	178.1
CM4-1		25.9	-82.3	0.0	0.3	-84.7
CM4-2		28.1	4.3	0.0	0.2	79.6
CM4-3		25.0	-32.4	0.0	0.3	49.9
CM4-4		23.7	80.6	0.0	0.3	-19.4
CM4-5		26.5	135.8	0.0	0.4	27.8

RFQ: READY; Cav_Pow 36.98; PHASE 9.97

Buncher1: READY; AMP 11865.00; VACC 78.22; PHASE 18.56

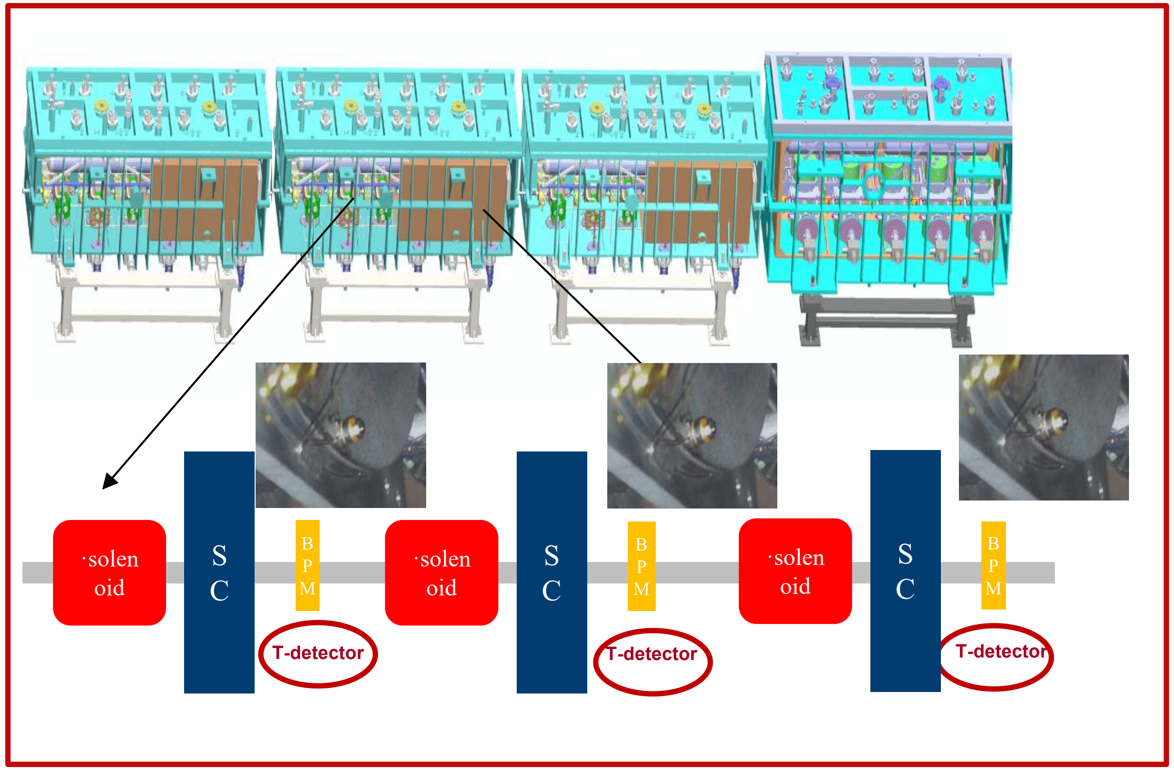
Buncher2: READY; AMP 9268.00; VACC 107.76; PHASE -146.20

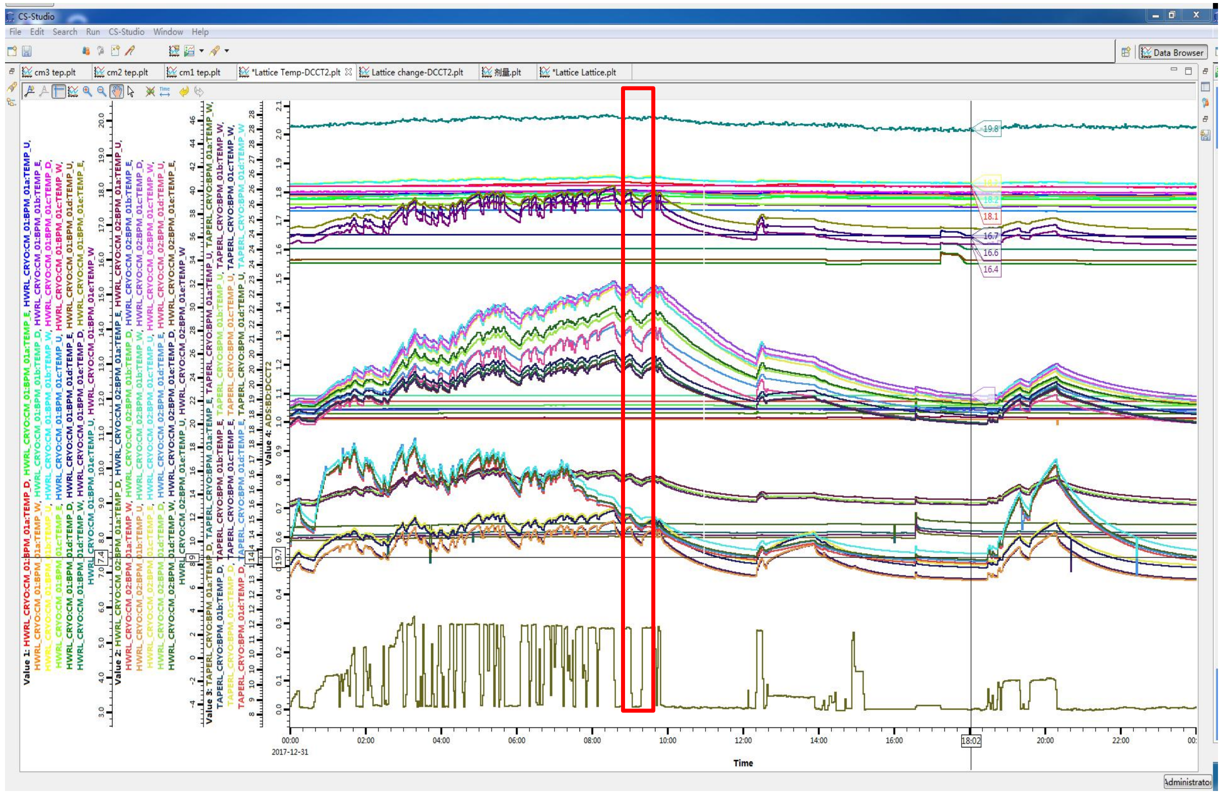
SC cavities configuration



Orbit correction

Commissioning: Tuning at SC section



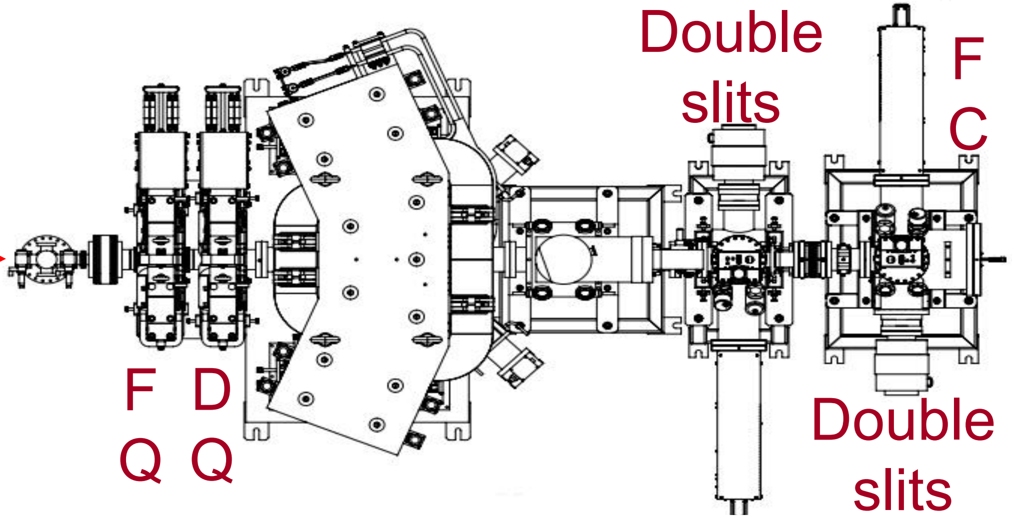


Four T-detectors located on the flange of cold BPMs to detect slow beam loss due to beam halo or off center

The T-detectors effectively indicate the loss during high beam power commissioning

Commissioning: Reconstruct at HEBT

- **HEBT transverse emittance and twiss parameters are measured with two double silts and an FC.**
- **Simulation with beam emittance from MEBT agreed with emittance measured by HEBT, verifing lattice of MEBT, SC section and HEBT.**



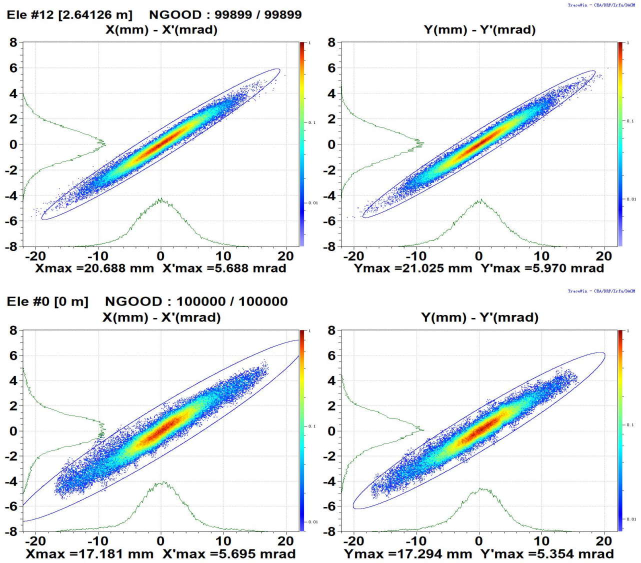
Proton energy		MeV	19.7	19.7	19.7	19.7	19.77	19.77
Beam current		mA	3	3	3	3	5.14	5.14
FQ/DQ		A	0/0	100/95	250/185	318/333.9	0/0	100/95
Simulation	$\varepsilon_{x/y}$	π·mm·mrad	0.218/0.216	0.218/0.217	0.215/0.222	0.217/0.216	0.259/0.252	0.256/0.254
	$\alpha_{x/y}$	---	-4.876/-4.940	-3.986/-2.394	-5.067/-0.684	-6.356/-8.720	-4.985/-5.074	-4.237/-2.662
	$\beta_{x/y}$	mm/(π·mrad)	16.037/16.257	11.715/11.865	8.132/10.331	10.630/7.833	15.369/15.546	11.520/11.406
Measurement	$\varepsilon_{x/y}$	π·mm·mrad	0.418/0.348	0.377/0.328	0.317/0.299	0.358/0.366	0.409/0.402	0.393/0.357
	$\alpha_{x/y}$	---	-3.316/-3.430	-3.307/-1.392	-2.754/0.097	-2.982/-6.396	-3.086/-3.388	-3.403/-1.510
	$\beta_{x/y}$	mm/(π·mrad)	11.111/11.559	9.728/8.107	4.450/6.153	5.176/6.345	9.159/10.364	8.635/6.793
$\varepsilon_{x/y}$ error		%	92/61	73/51	48/35	65/69	58/60	54/41
$MF_{x/y}$		---	0.21/0.19	0.10/0.27	0.35/0.50	0.45/0.46	0.31/0.23	0.21/0.30

Commissioning: Reconstruct at HEBT

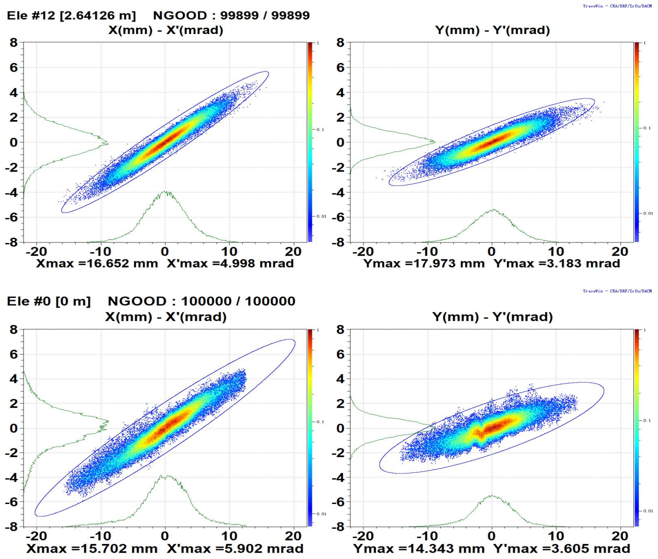
Simulation

Measurement

E=19.7 MeV,
I=3 mA,
FQ=0,
DQ=0

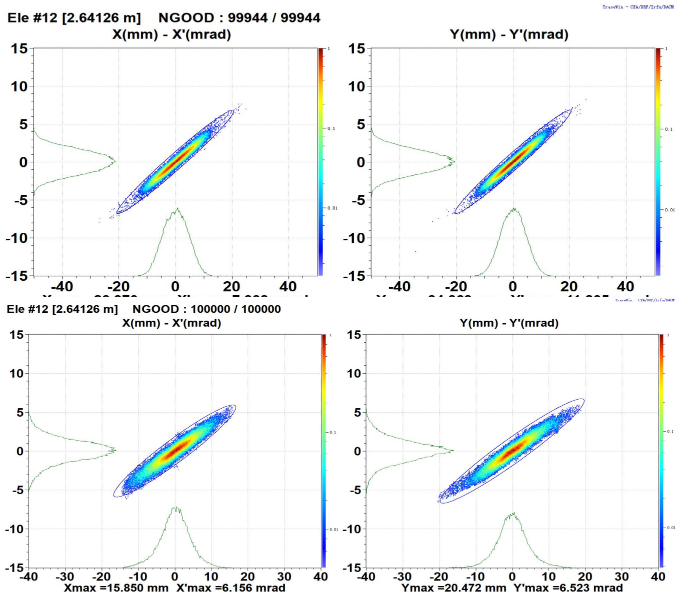


E=19.7 MeV
I=3 mA
FQ=100 A
DQ=95 A

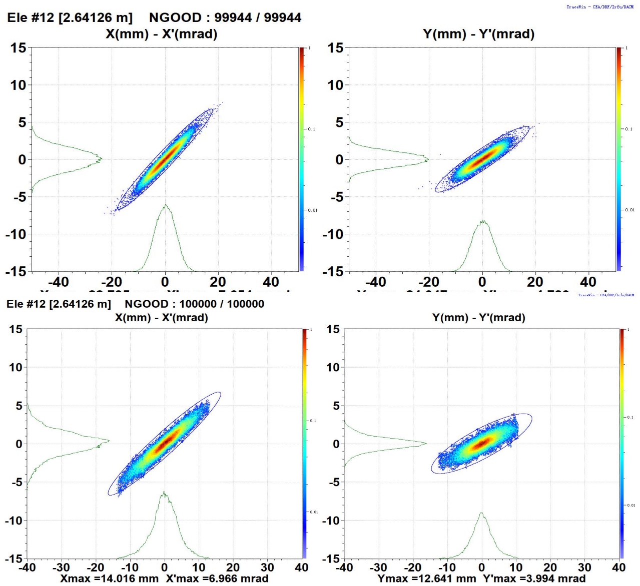


Simulation

Measurement



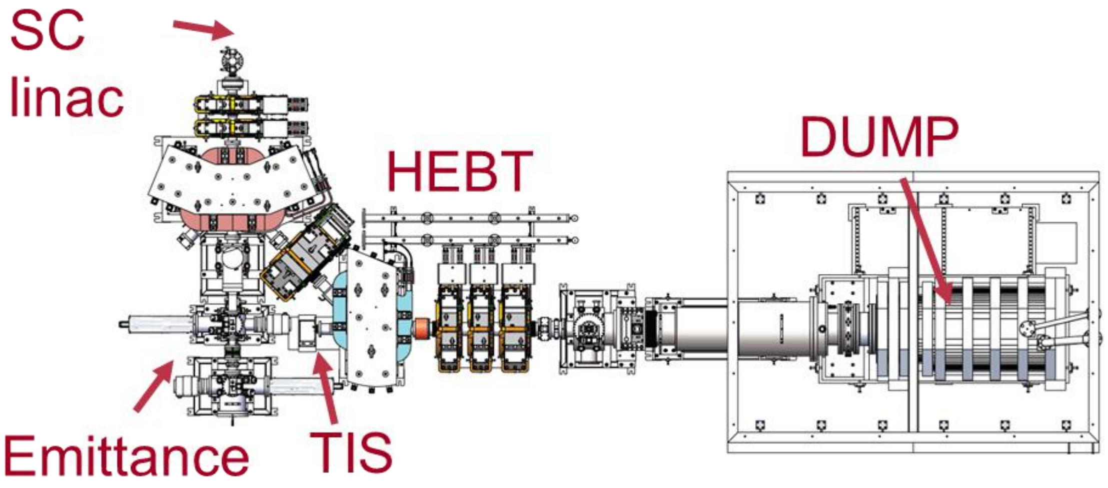
E=19.77 MeV
I=5.14 mA
FQ=0
DQ=0



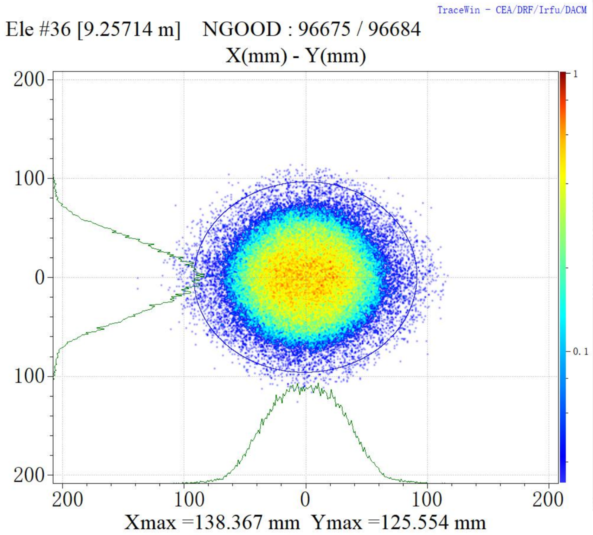
E=19.77 MeV
I=5.14 mA
FQ=100 A
DQ=95 A

Commissioning: Tuning at HEBT

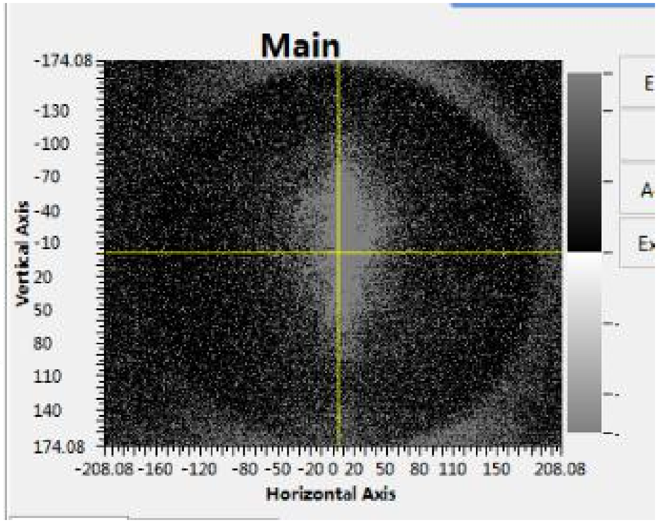
- Larger beam spot and cone dimension to limit power density at ~200 W/cm^2.
- Al6063 and pre-shielding of dump with Pb for lower residual dose.
- BLMs,TIS, DCCT, Collimator for CW beam real-time monitoring and interlock protection.



1. Inital beam from reconstructed at HEBT emmitance measurement with is more accurate than simulation
2. Correct the orbit within ± 1mm at BPMs and at the center of collimator and TIS
3. Extend beam pulse length while minimizing the beam loss on the collimator by the current of the collimator



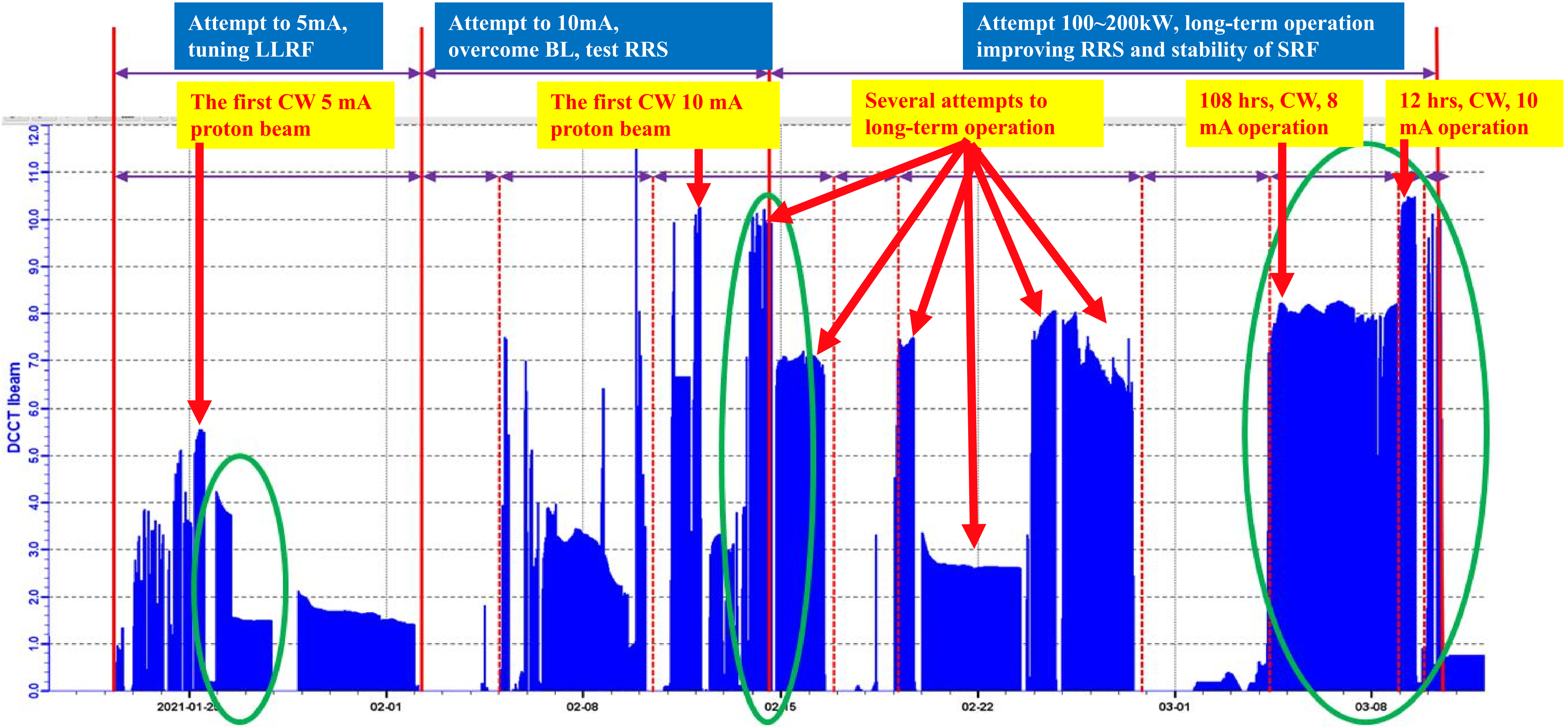
simulation



TIS

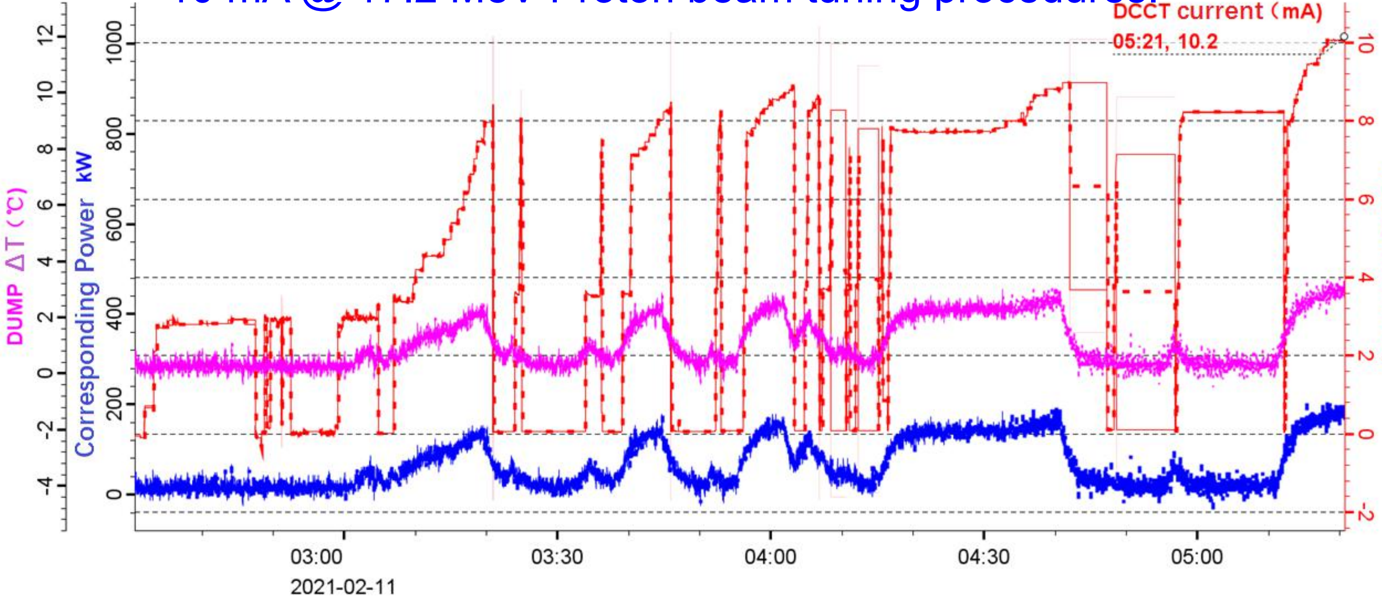
Commissioning: Operation history

- **Operation from Jan. 20 to Mar. 10, 2021**

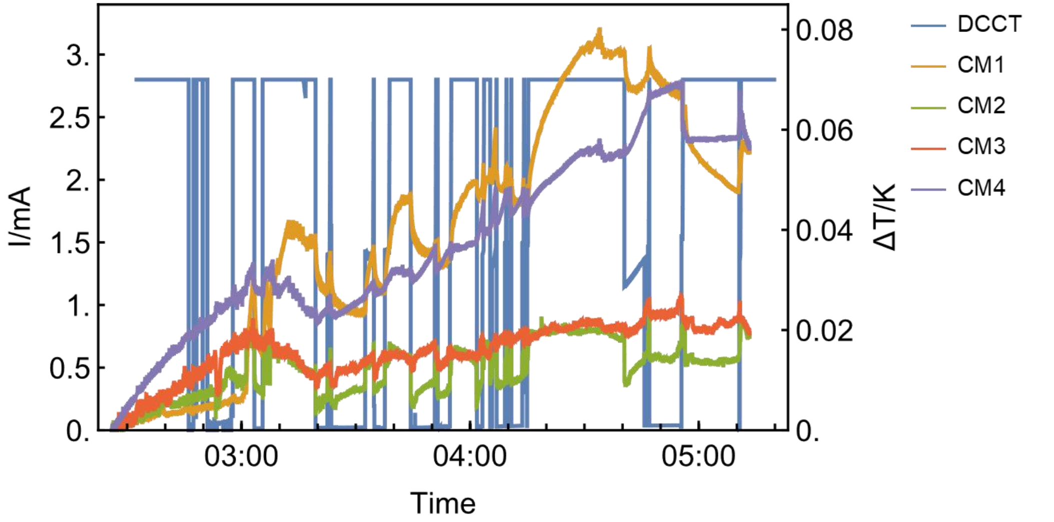


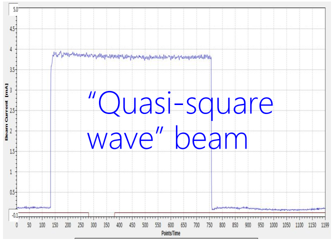
Commissioning: Tuning to 10 mA

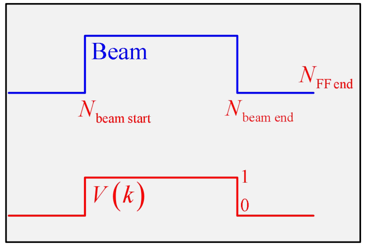
10 mA @ 17.2 MeV Proton beam tuning procedures.



BPMs' temp. rising in 4 CMs along with the normalized by beam current during tuning to 10 mA.

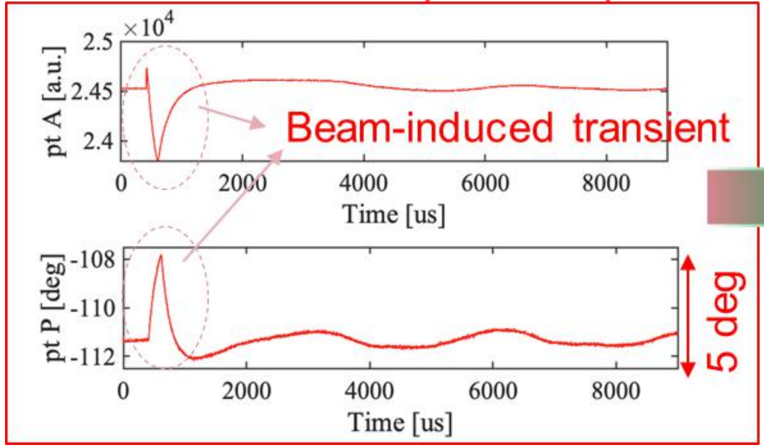




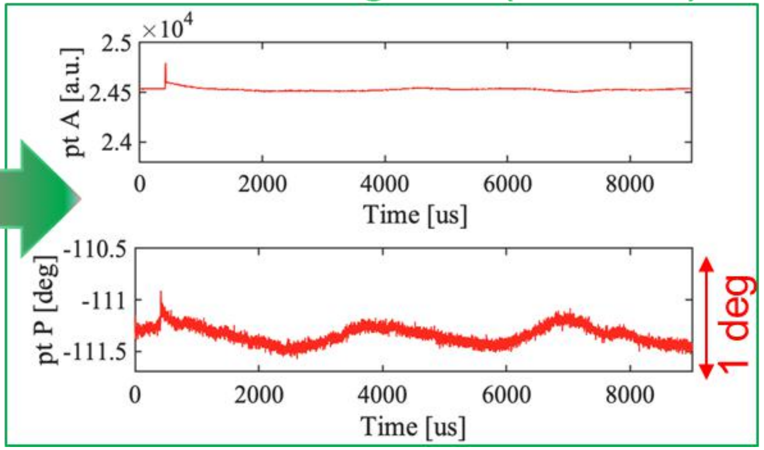


- High Beam-loading issue is one of the main challenge
- A simplified iterative learning control method (with square shape FF) was successfully applied to compensate for the beam-loading effects.

w/o FF (10 mA)



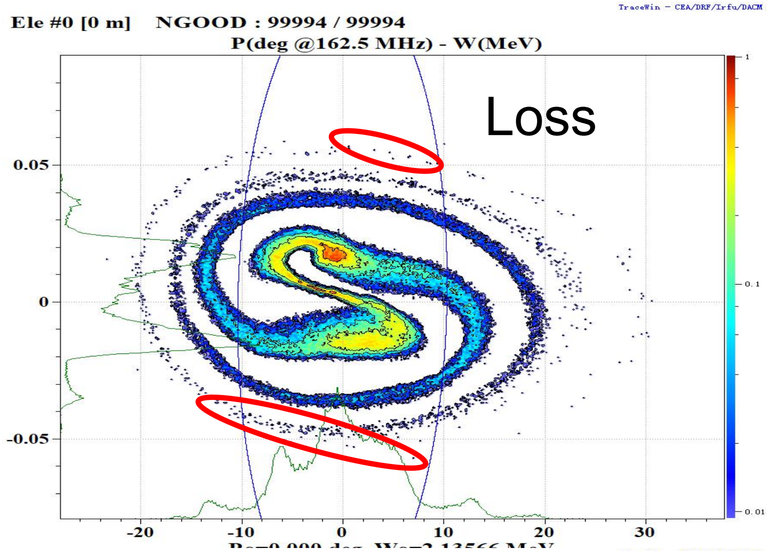
with learning FF (10 mA)

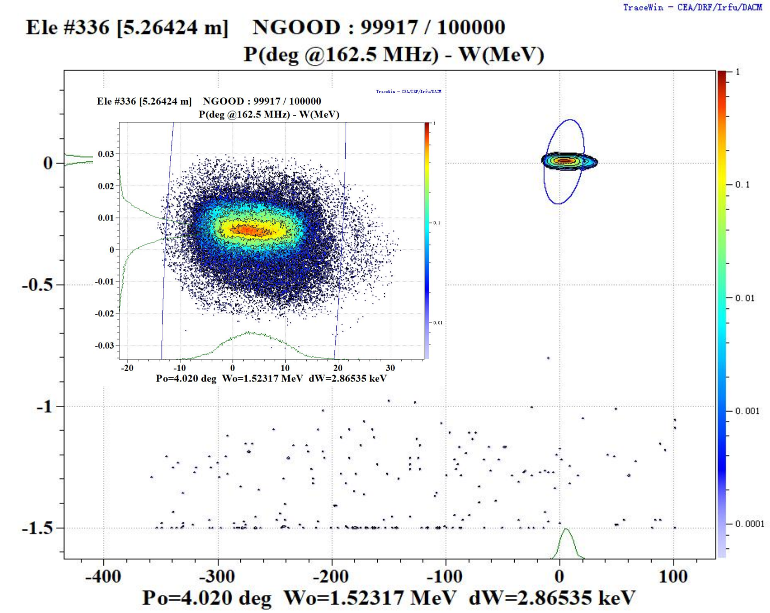


Outline

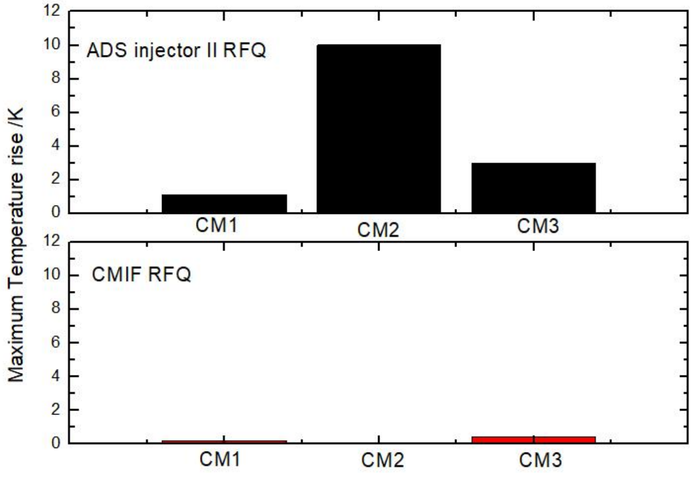
- Brief introduction of CiADS project
- The challenges and design of sc-linac CiADS
- Beam commissioning of demo linac for ADS
- Special issues for high power SC linac
- Results and summary

Beam loss: Longitudinal of RFQ

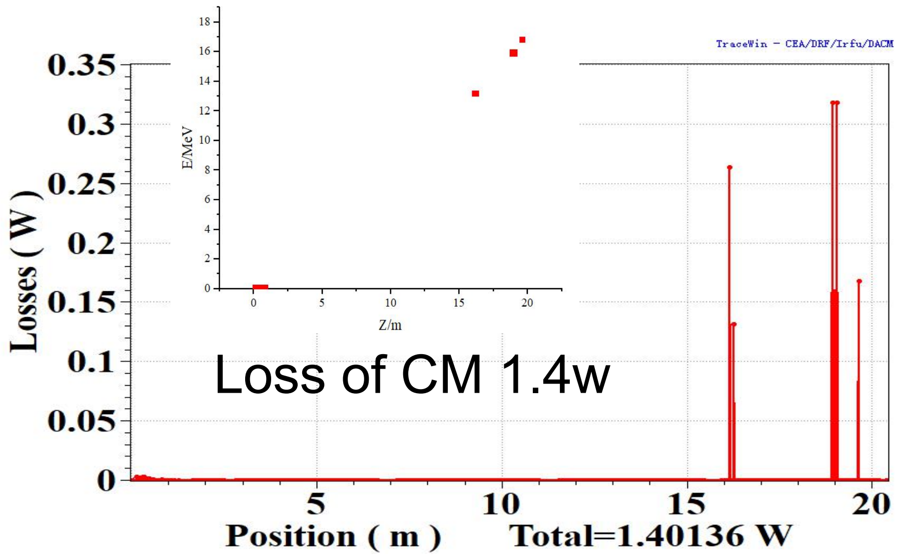


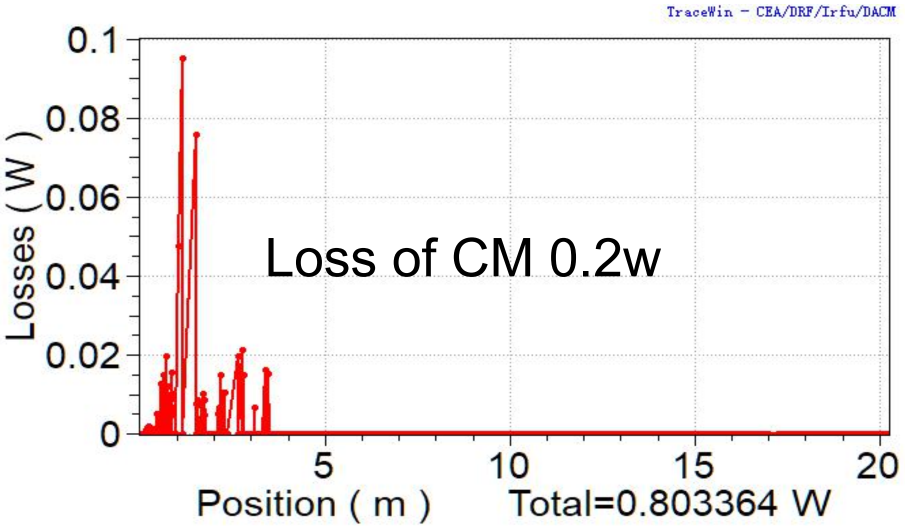


ADS Inj. II RFQ@ 1 mA
Design current 15mA
CMIF RFQ@ 2 mA
Design current 5mA



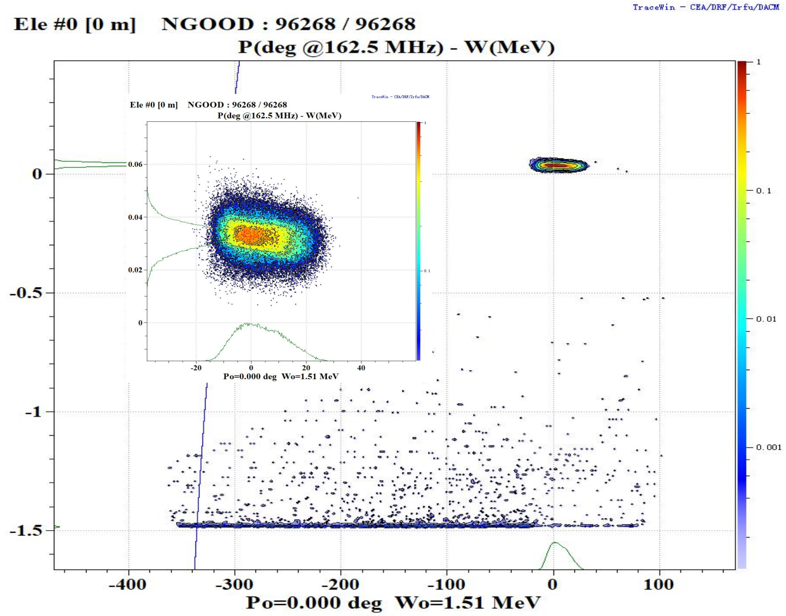
The maxinum temperature rise of CM with ADS injectorII RFQ is 25 times than one with CMIF RFQ

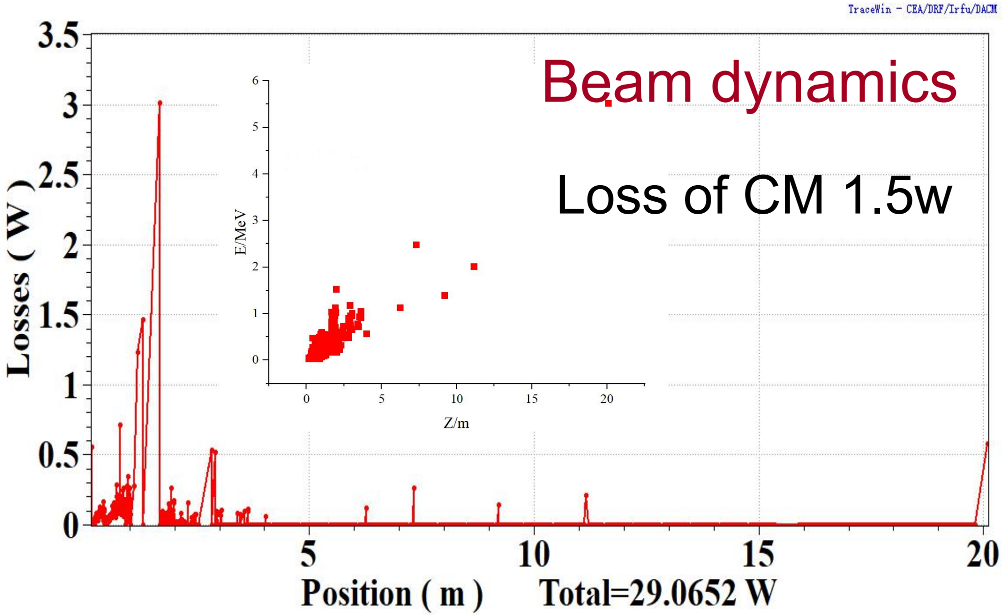


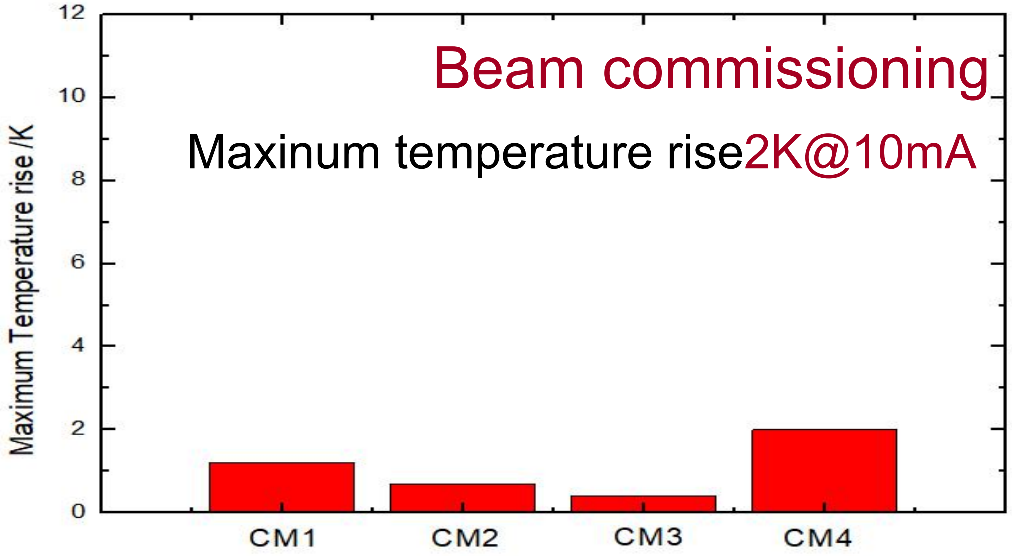


Beam loss: Longitudinal of RFQ

CMIF RFQ@ 10 mA





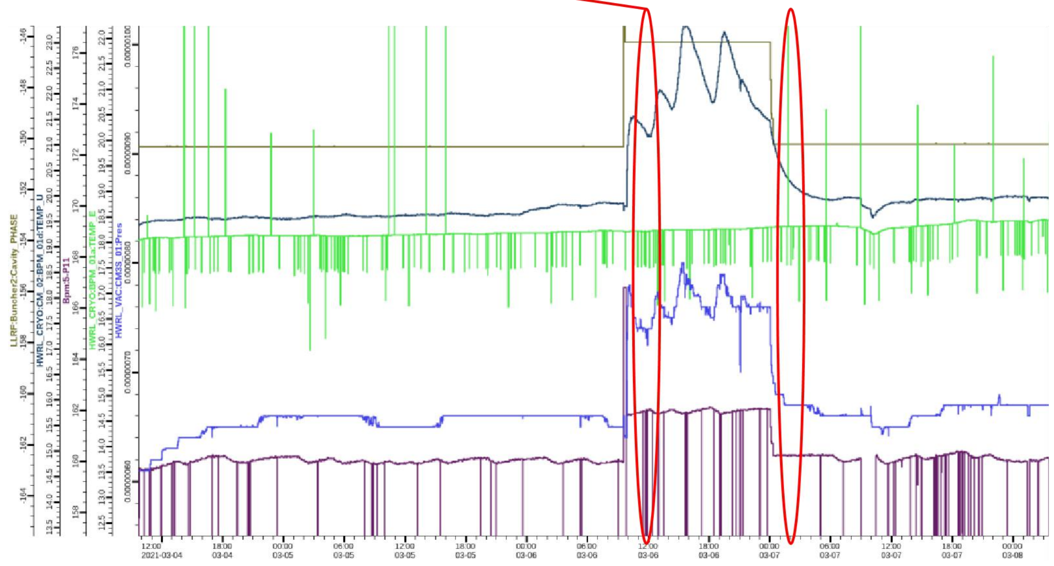


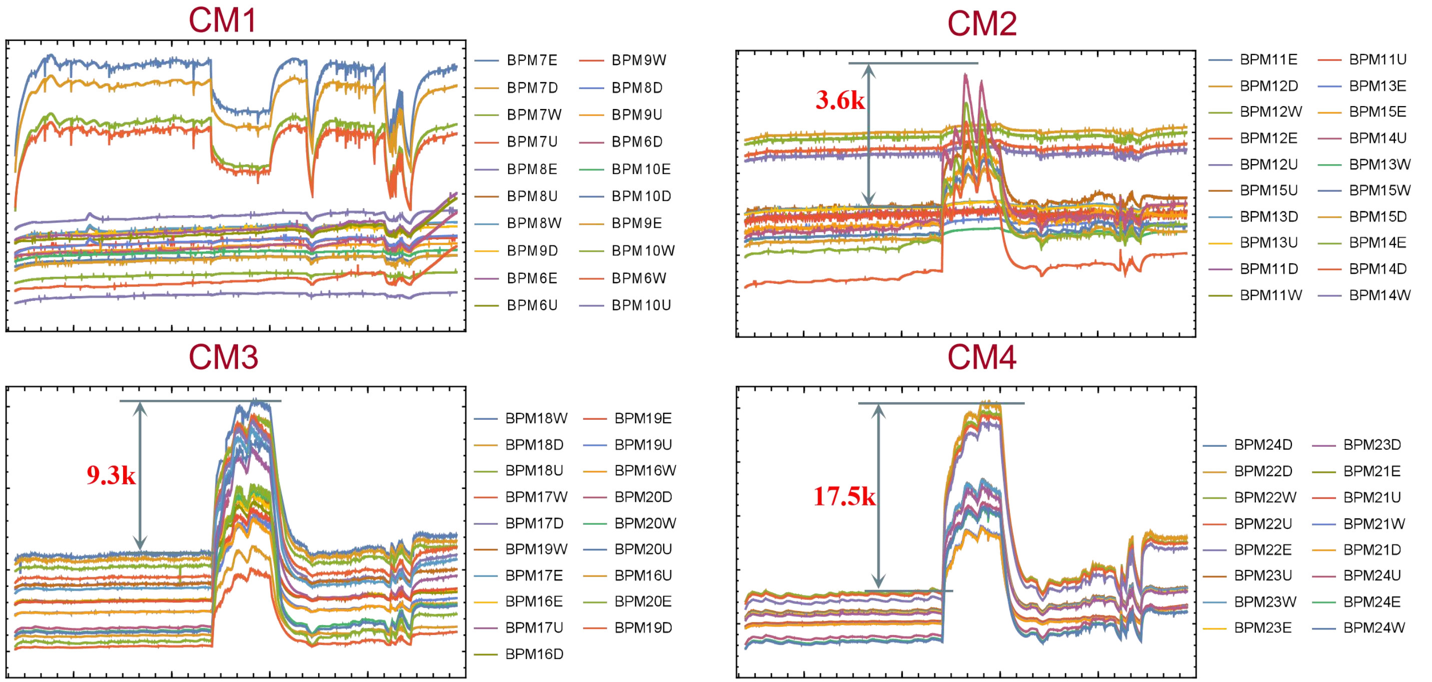
	Acc. eff. （%）	99.99% ez（πmm.mrad）
ADS Inj. II	99.5	10.48
CMIF	94.7	5.45

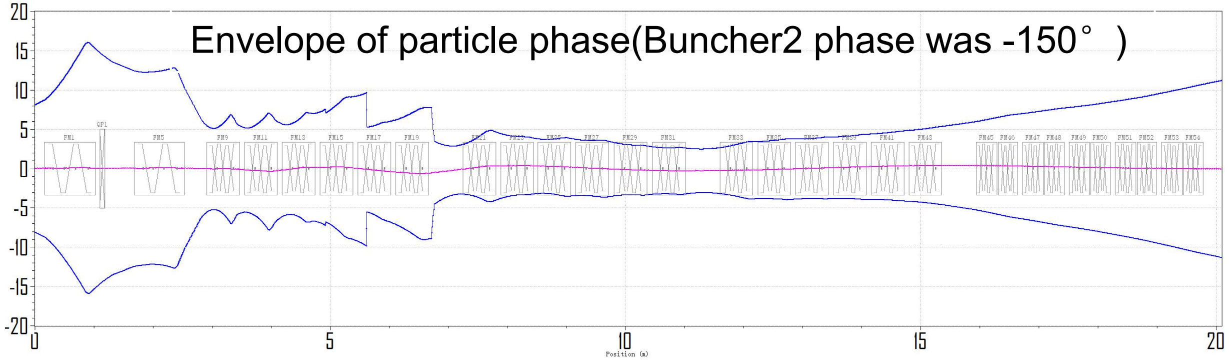
Beam loss: Influence of buncher

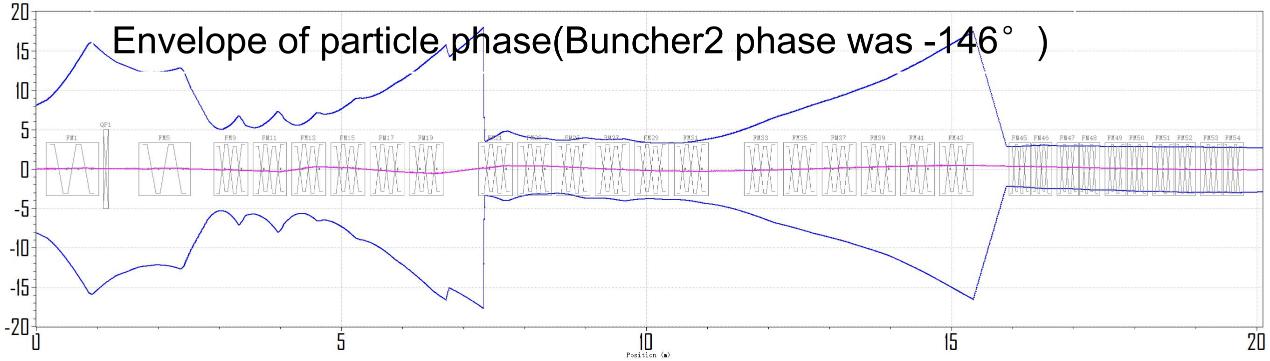
3.6 9:40, buncher2's phase turned to -146° from -150°

3.7 0:18, buncher2's phase turned back to -150° .





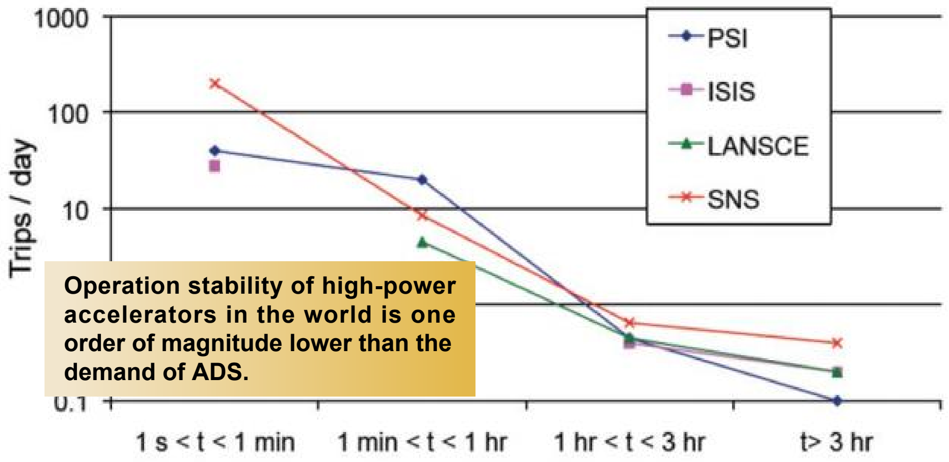




When buncher2's phase changed 4 deg, obviously temp. rising happened. The simulation shows a phase envelope before and after change. It only ~0.01% beam loss..

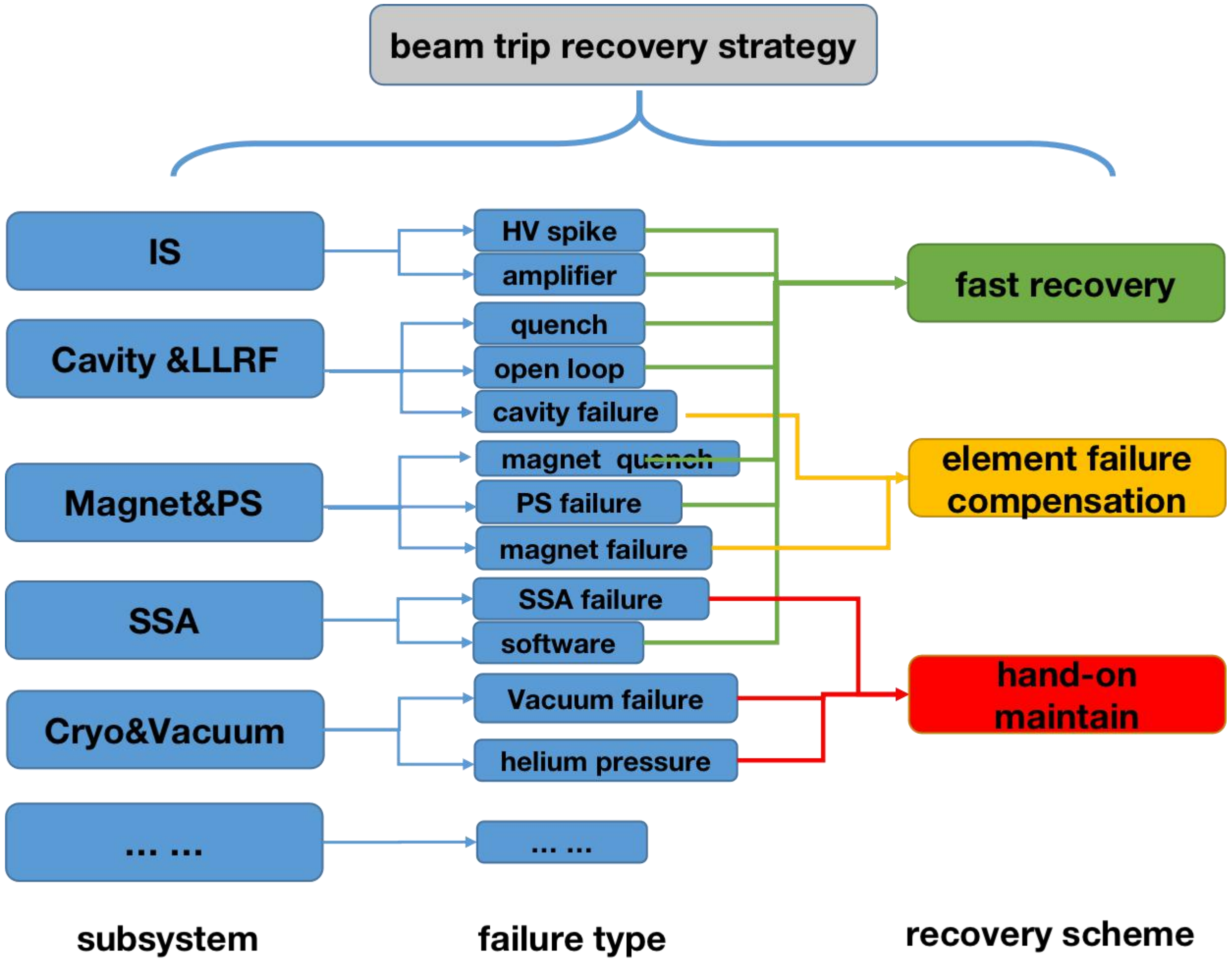
Fast Auto Recovery: Scheme

Beam trip caused by hardware failure is inevitable, Fast Beam Auto Recovery scheme is the key to maintain both high availability and high safty.



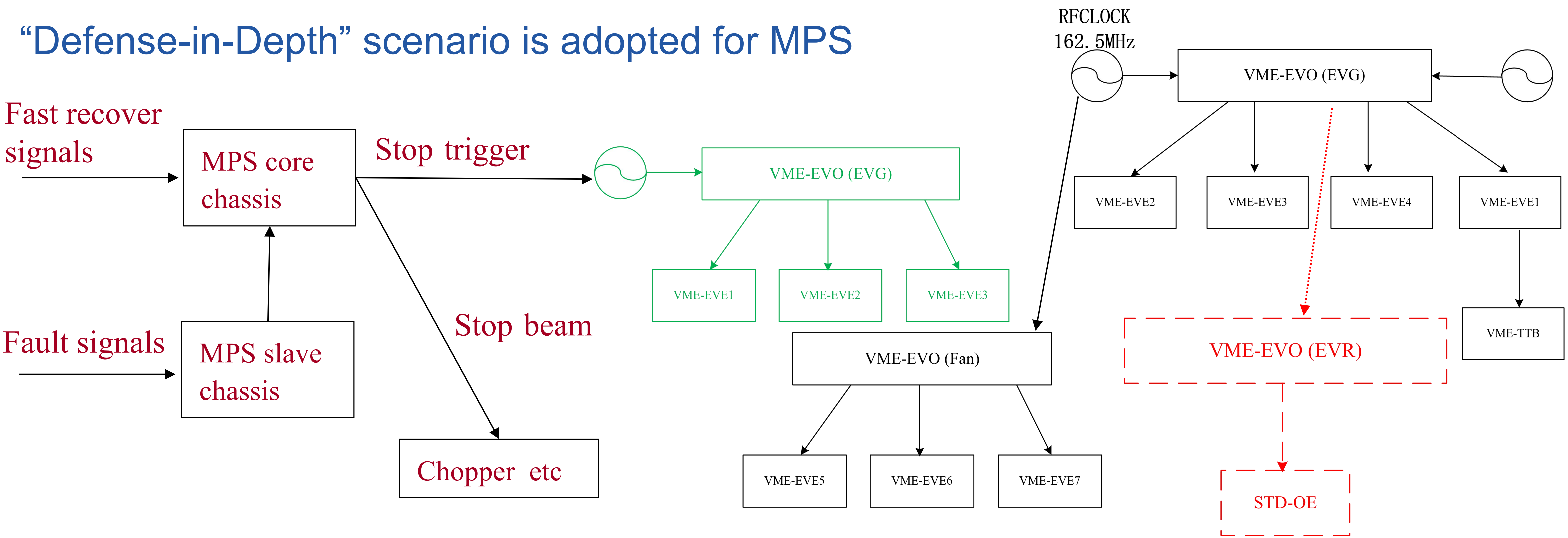
Beam Trip requirements of CiADS based on target and reactor requirements

Trip time	Trip frequency
<10s	-
10s-5min	2500/year
>5min	300/year
Availability	80%



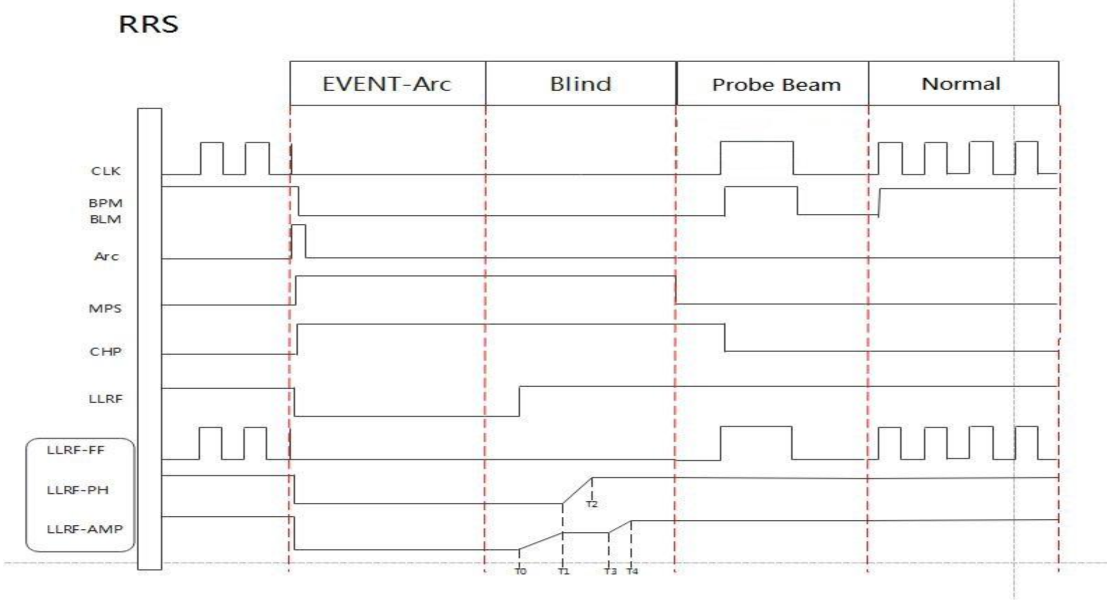
Fast Auto Recovery: MPS and Timing

"Defense-in-Depth" scenario is adopted for MPS



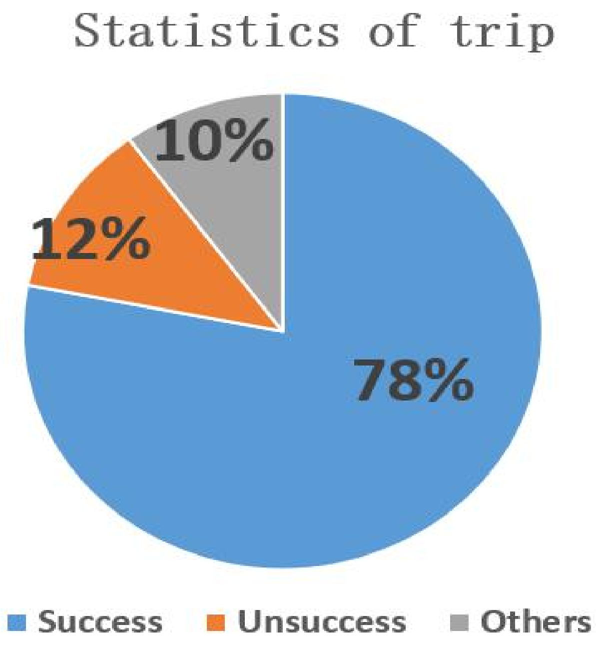
1. If Fault is a "Fast Recovered", only the trigger signals of chopper and FF are stopped and auto recovered.
2. If Fault is a "Failure", Both the trigger signals and chopper are stopped, and wait for 5 second for next beam shot.
3. If Fault is an "Emergency", the trigger signals, LEBT FC, chopper are stopped.

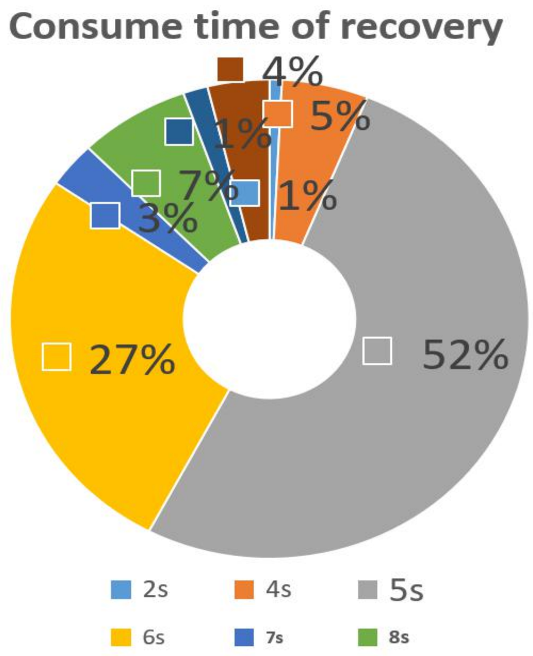
Fast Auto Recovery: Results



Timing analysis (take ARC as an example)

Year	Beam Power	time of duration	Usability
2018	12kW	70 hours	57%
2019	34kW	110 hours	89%
2021	126kW	108 hours	93.5%





Before system upgrade

- **False alarm rate： 7 times/day**
- **Everytime equipment was damaged**

•After system upgrade

- **False alarm rate: 2 times/month**
- **Safe run**

Outline

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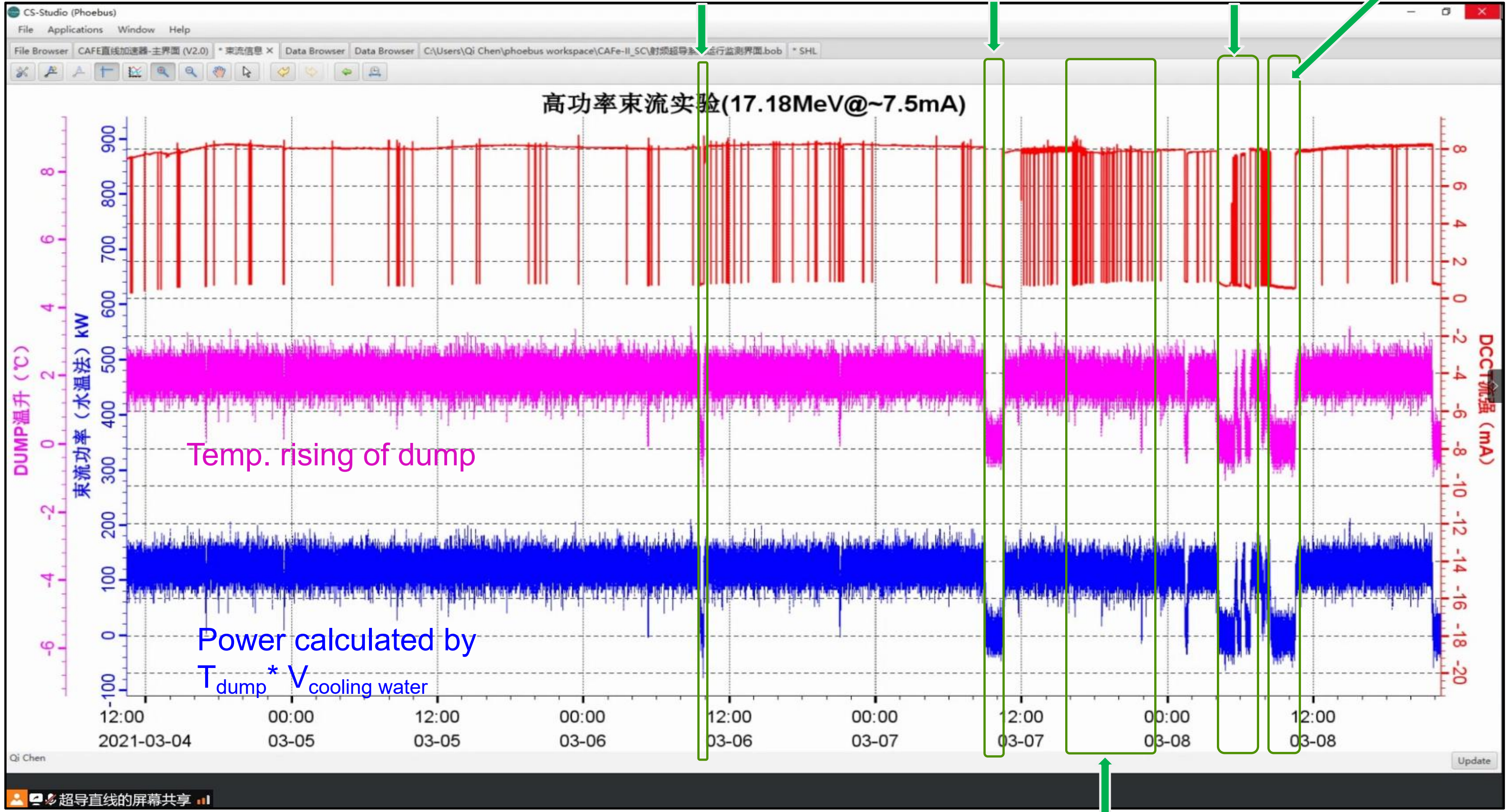
Results: 108-hrs, 120-kW operation

PS failure
EMC

LLRF failure
PS Chassis

Pump failure
Near dump

Timing system PC
failure, unknown reason



IS arcs, maybe mistake of MPS and RRS Logic

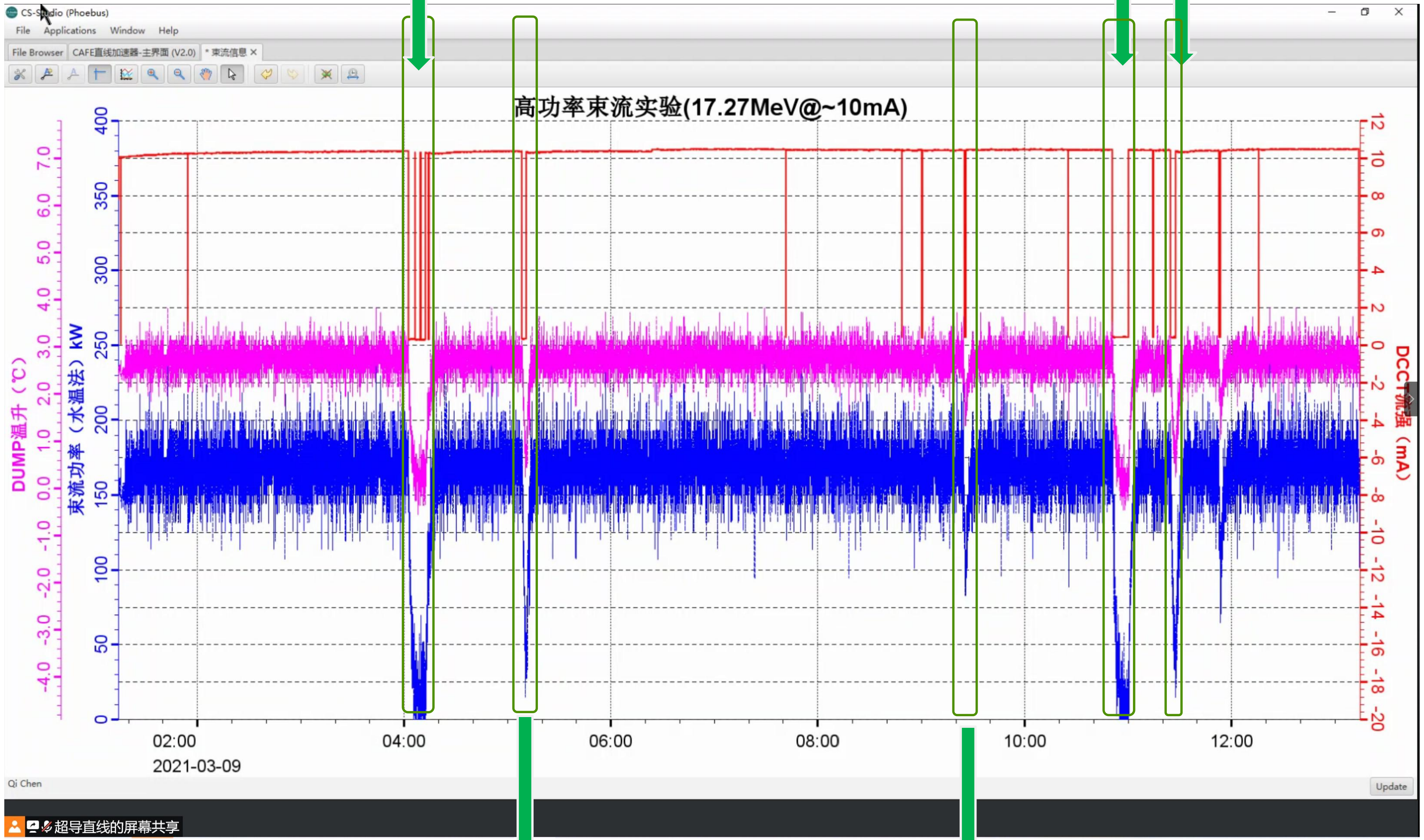
Energy	17.27±0.03MeV
Current	7.30±0.02mA
Beam power	126.0kW
Pre-set operation time	108 hours
Availability	93.5%
Availability of SRF	98.0%

Results: 12-hrs 10-mA operation

RFQ waveguide temp. alarm

PS

Arc, R manually

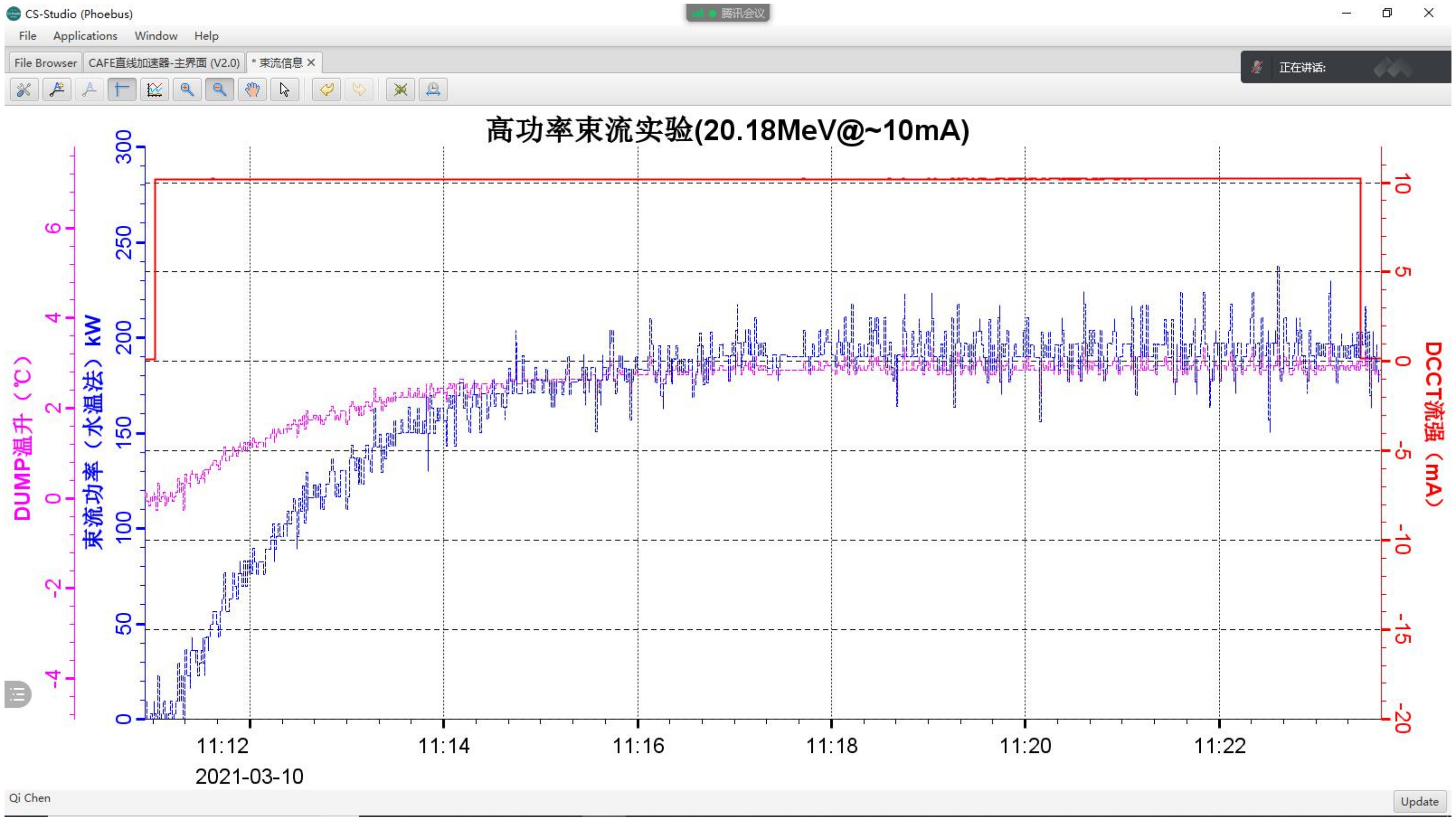


CM2-1 coupler Vac.

IS arc, R manually.

Energy	17.27±0.03 MeV
Current	10.08±0.00 mA
Beam power	174.0 kW
Pre-set operation time	12 hours
Availability of SRF	99.6%
Availability of whole system	96.2%

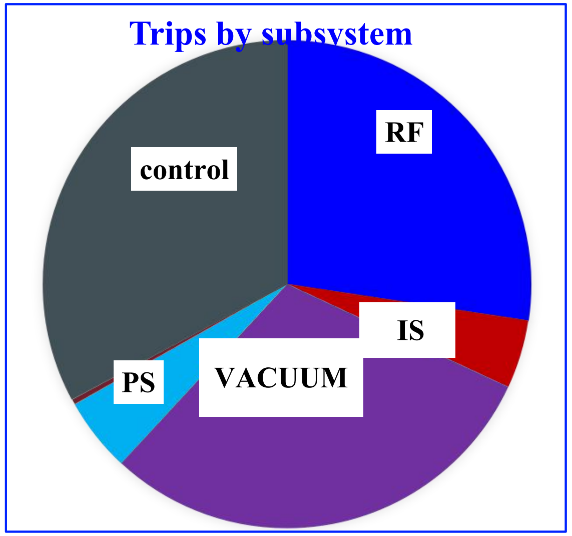
Results: Nominal current & energy attempt

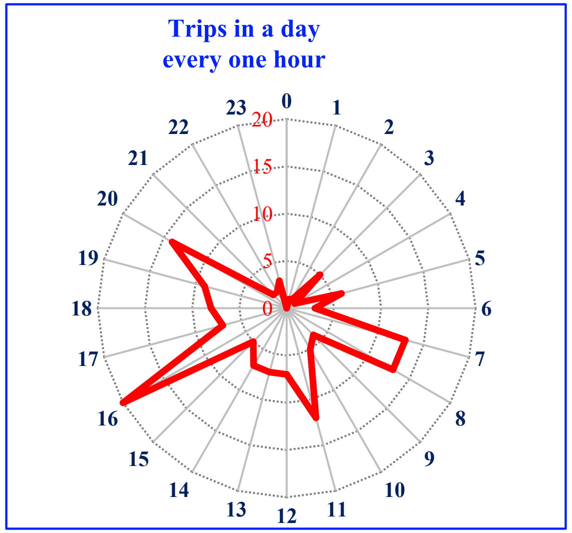


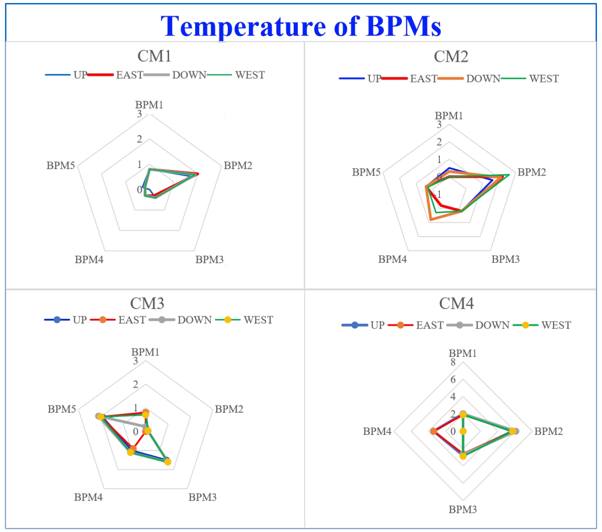
Item	Parameter
Beam E	20.18 MeV
Ave. Beam	10.2mA
Max. Beam Power	205.5kW
Total Time	12 mins

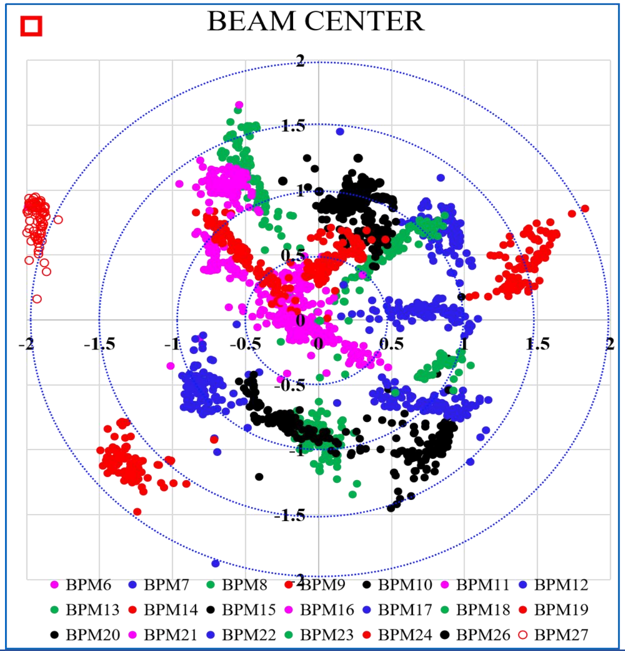
Results: Some data stastics in 108 hrs

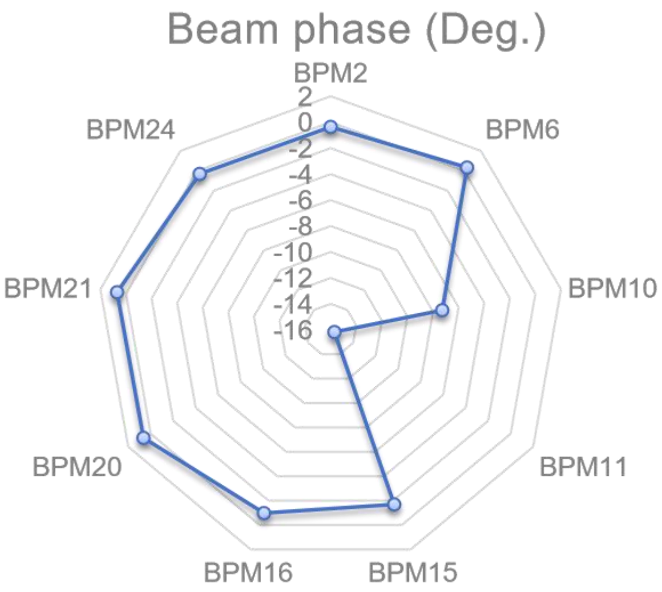
- All beam positions are within ±2 mm, and each one is within ~1mm.
- only two BPMs had big phase shift.
- Amp. is less than 1% and phase is less than 1 deg.
- most trips were in day time

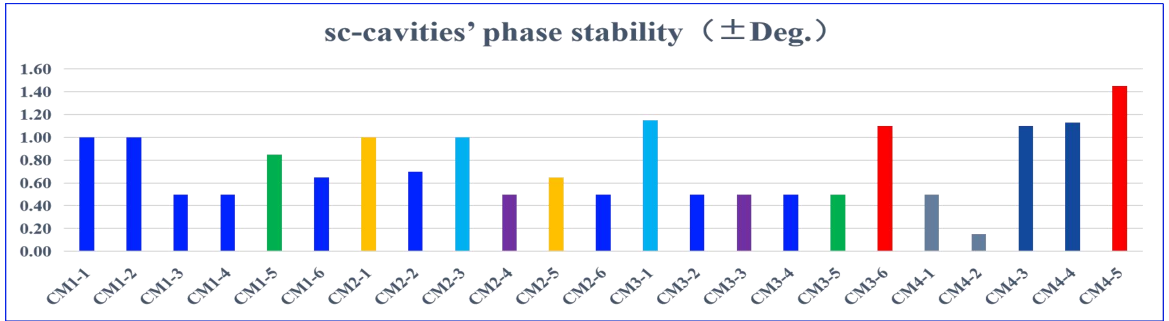


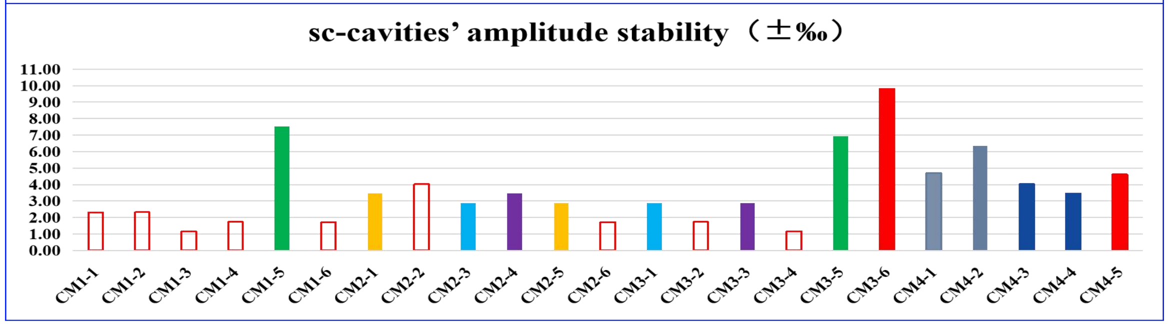












Summary

- The CiADS started in July formally. It is expected to have the first 500 MeV beam acceleration in 2025 and to inject the beam into the fast reactor in 2026.

- The CAFe a demo linac for ADS has a succesful high-power commissioning campaign at the beginning of 2021. The CW beam current of 10 mA has been demonstrated for a long-term operation. 10 mA is the basic requirement of industrial ADS.

- Fast auto recovery scheme was carried out to improve the availability of operation. It efficientlly increased the availability up to 93.5% during 108-hour opearation.

- The new design of sc-linac for CiADS has been done according to understanding of the high-power CW beam commissioning in the past three years.

Thanks for your attention

The team would like to thank all the friends for the help in the past!