The beam commissioning of China Accelerator for research on superheavy elements

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Outline

- Motivation & background of CAFe^2 facility
- Challenges & solutions of beam commissioning
- Beam operation performance of CAFe^2 facility
- Perspective for the future

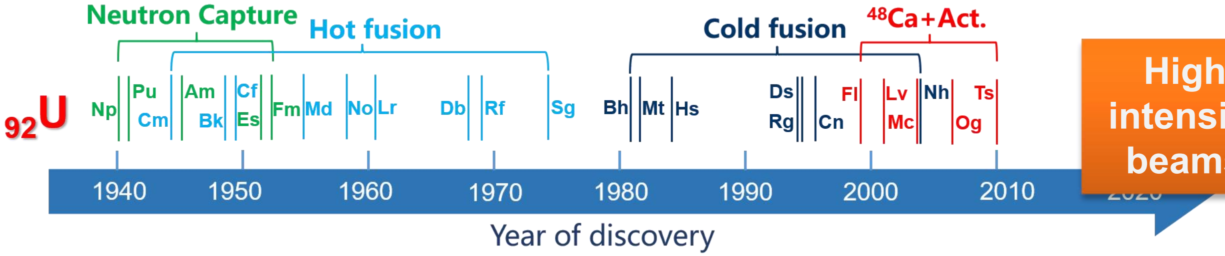
Motivation & background of CAFe² facility

SuperHeavy Elements（SHE） (Z>103)

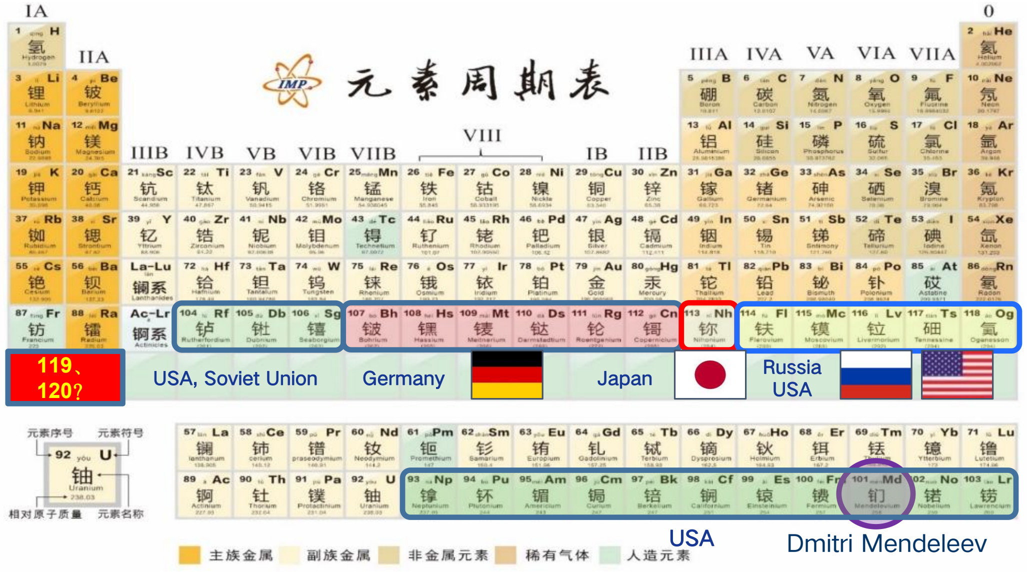
➡Evolution of the universe

Top science questions：

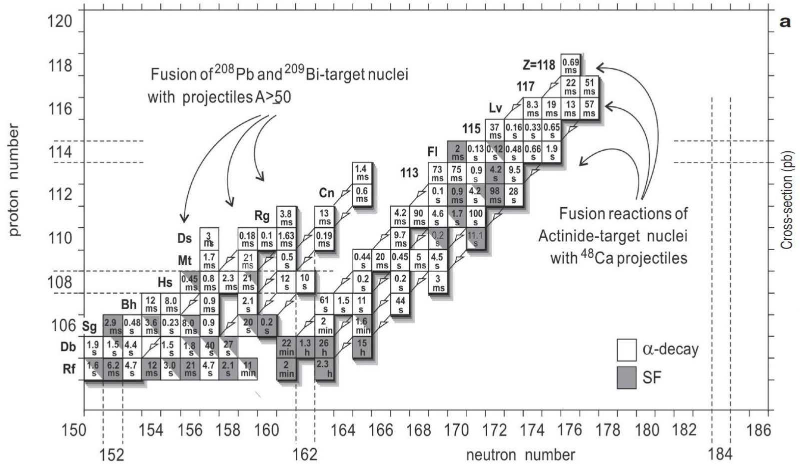
How many elements can exist on Periodic Table?
Are there stable high-atomic-number elements?
What are their chemistry properties for the heaviest elements?

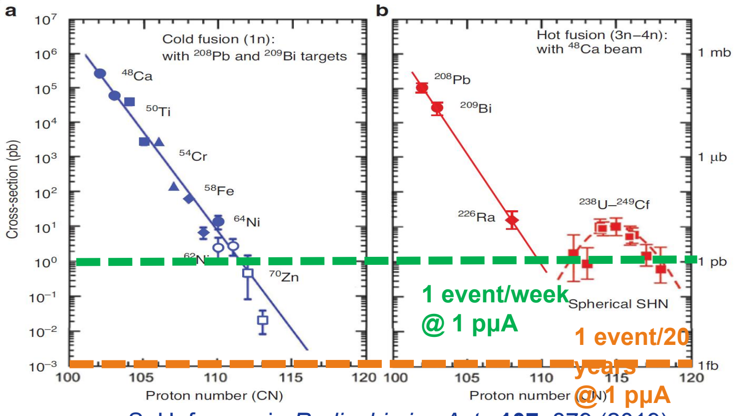


High intensity beams



More than ten artificially synthesised elements





S. Hofmann, in *Radiochimica Acta* **107**, 879 (2019).

➢ ***Challenges:***

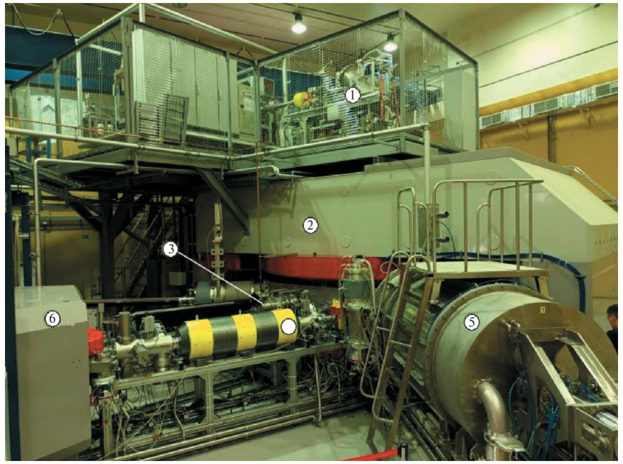
- **High beam intensity , sun as Calcium ions (5~10 pμA)**
- **Long beam time (a few months or years expt.)**
- **Rotating target withstanding high power beams**
- **High efficiency separator**

Motivation & background of CAFe^2 facility

Accelerators for SHE synthesis

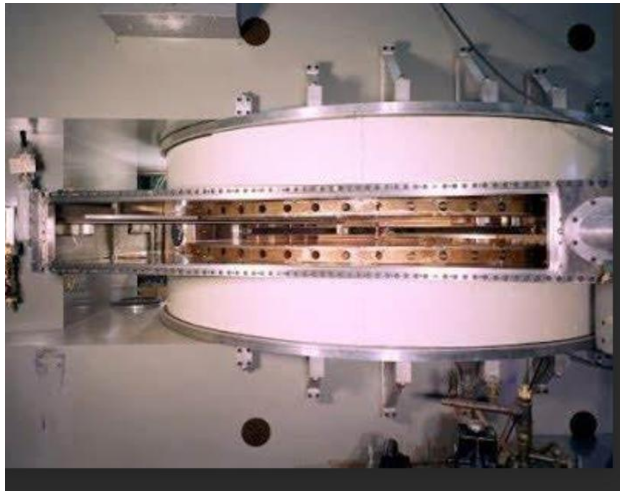
Country	Institute	Accelerator	Current/puA
Japan	RIKEN	RILAC	3
Russia	JINR	DC-280	3~6
Germany	GSI	UNILAC	1
American	LBNL	88-inch Cyclotron	1
China	**IMP**	**CAFe2**	**3~10**

RILAC



Cyclotron DC-280

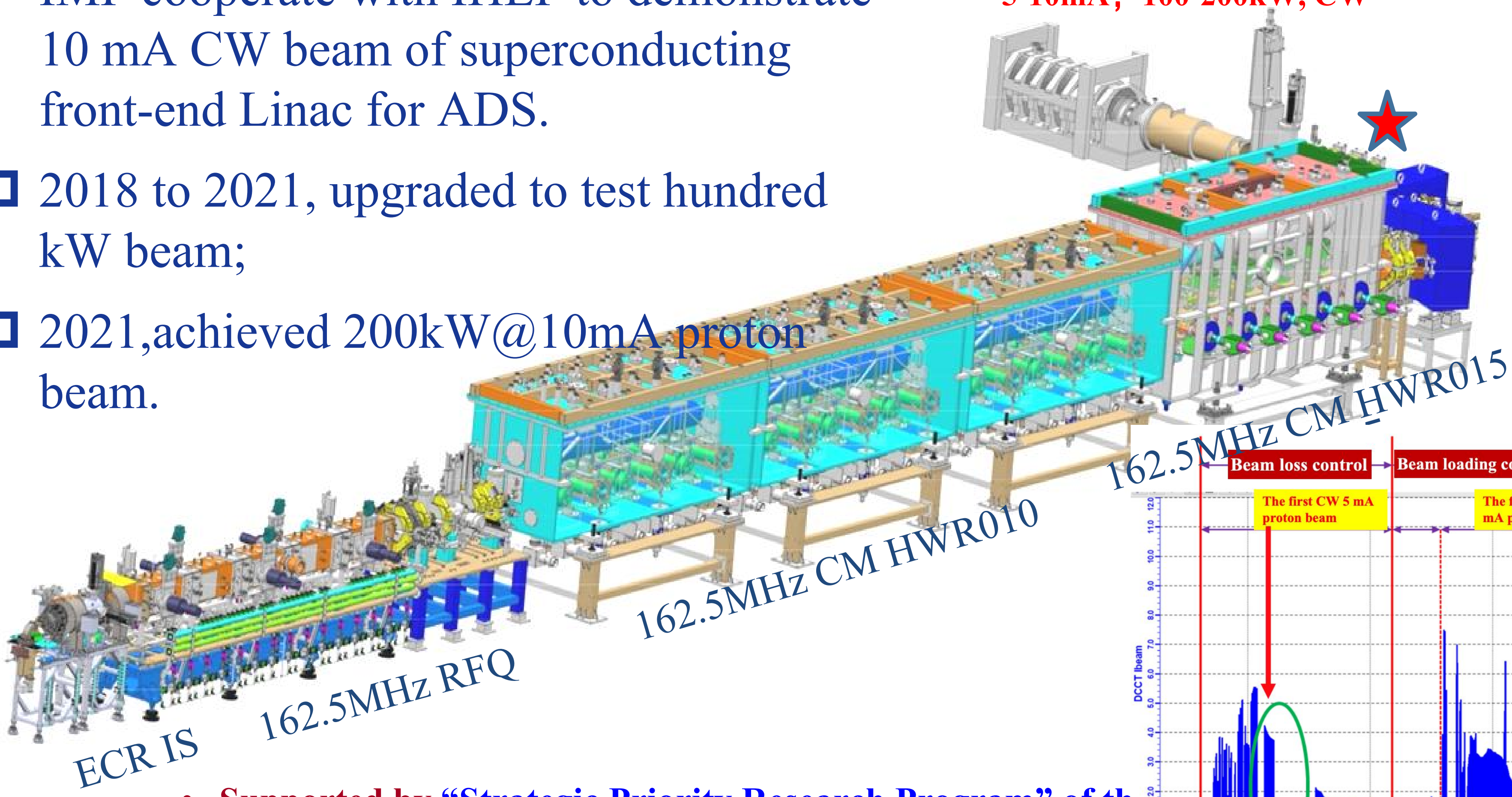
UNILAC



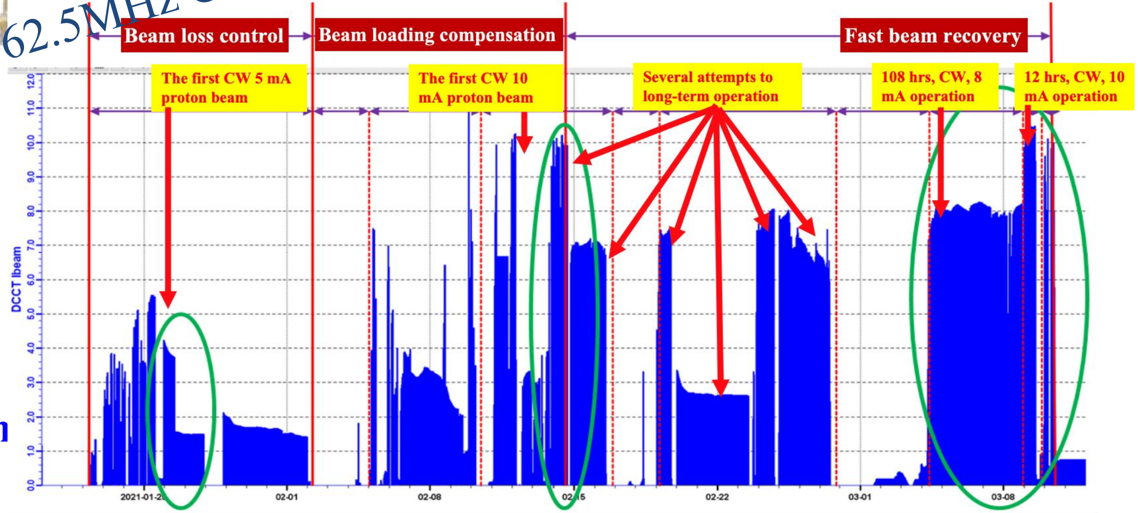
88-inch cyclotron

Motivation & background of CAFe² facility

- 2011-2017,CAFe facility constructed, IMP cooperate with IHEP to demonstrate 10 mA CW beam of superconducting front-end Linac for ADS.
- 2018 to 2021, upgraded to test hundred kW beam;
- 2021,achieved 200kW@10mA proton beam.



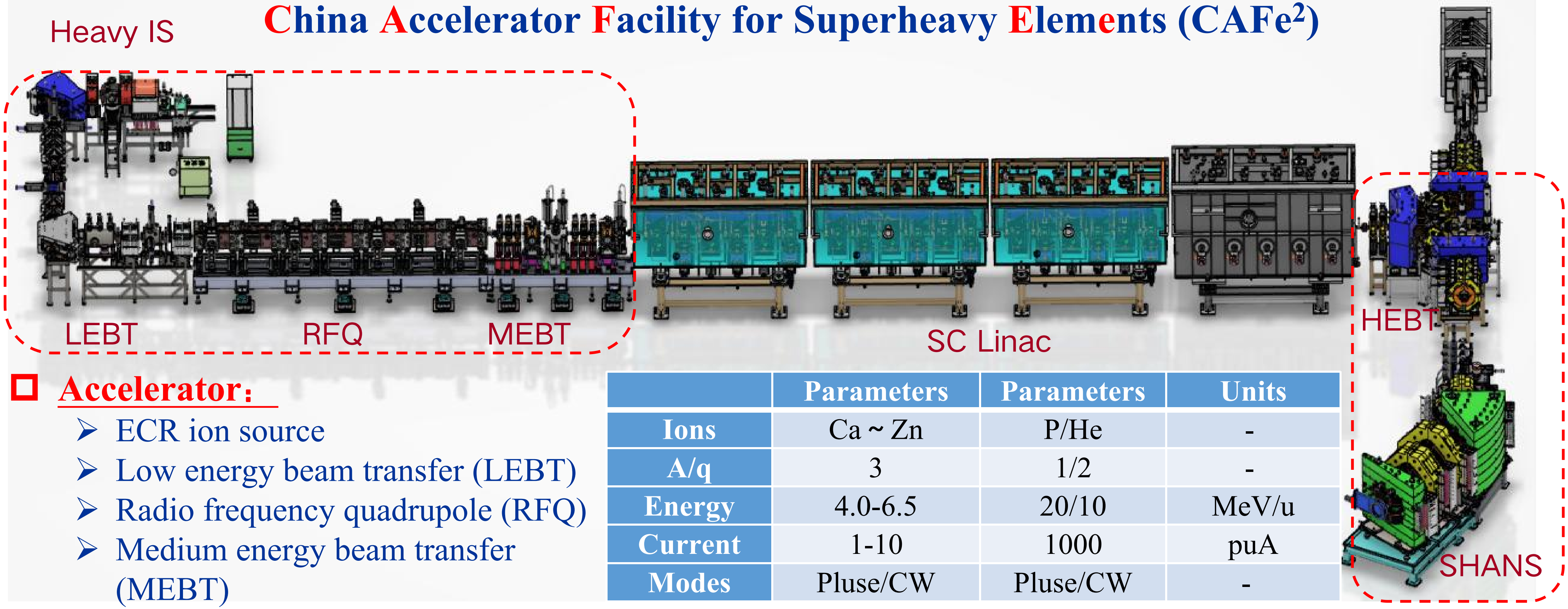
ions	P， Alpha
Frequency	162.5 MHz
Current	10 mA
E_{out}	20MeV/u
Temp.	4.5 K



- **Supported by "Strategic Priority Research Program" of th Chinese Academy of Sciences.**

Motivation & background of CAFe^2 facility

China Accelerator Facility for Superheavy Elements (CAFe^2)



- **Accelerator:**
  - ECR ion source
  - Low energy beam transfer (LEBT)
  - Radio frequency quadrupole (RFQ)
  - Medium energy beam transfer (MEBT)
  - High energy beam transfer (HEBT)
- **Terminal:**
  - Differential pumping system
  - Rotating target with actinide materia
  - Gas-filled recoil separator (SHANS2)
  - Detection system and DAQ

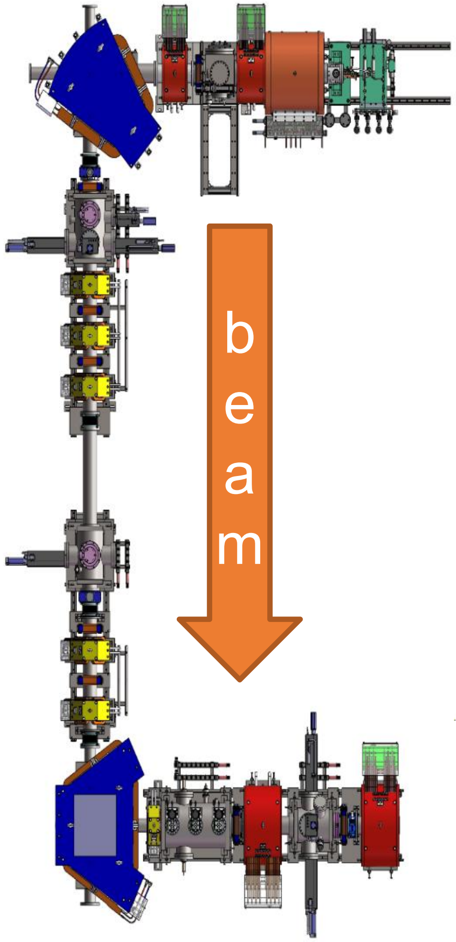
	Parameters	Parameters	Units
Ions	Ca ~ Zn	P/He	-
A/q	3	1/2	-
Energy	4.0-6.5	20/10	MeV/u
Current	1-10	1000	puA
Modes	Pluse/CW	Pluse/CW	-

Target:

- **Highest beam current accelerator for superheavy elements synthesis**
- **Engaging in research on the synthesis of the 119th and 120th element.**

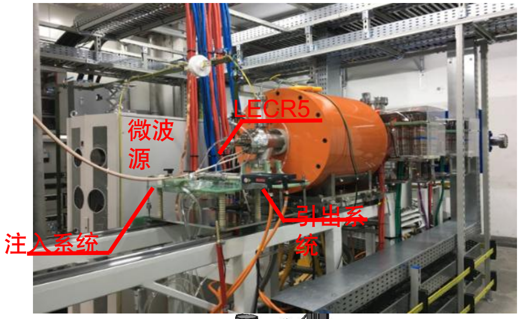
Motivation & background of CAFe² facility

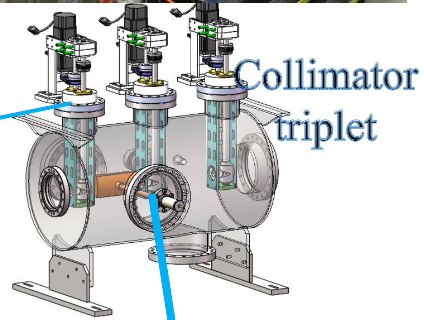
IS+LEBT

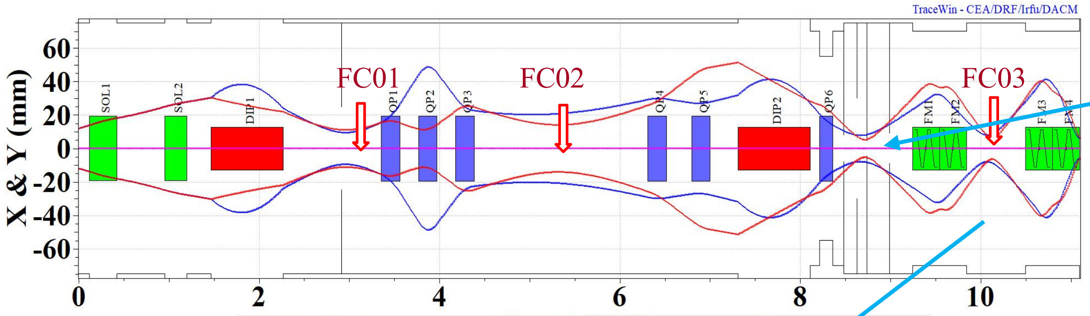


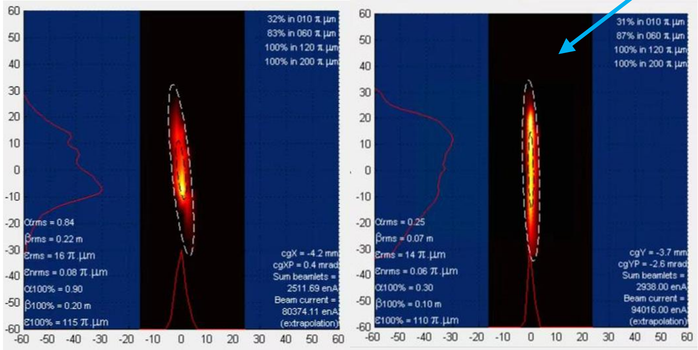
- **Ions delivered from LECR5 (2021-2022):** $^{16}O^{6+}$, $^{36}Ar^{12+}$, $^{40}Ar^{13+}$, $^{40}Ca^{13+}$, $^{55}Mn^{17+}$;
- **Beam intensity: 2-10 puA;**
- **Extraction energy: 10 keV/u;**

LECR5



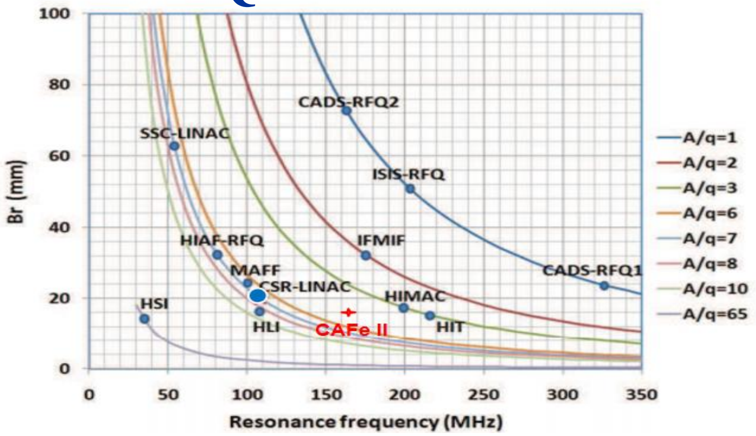




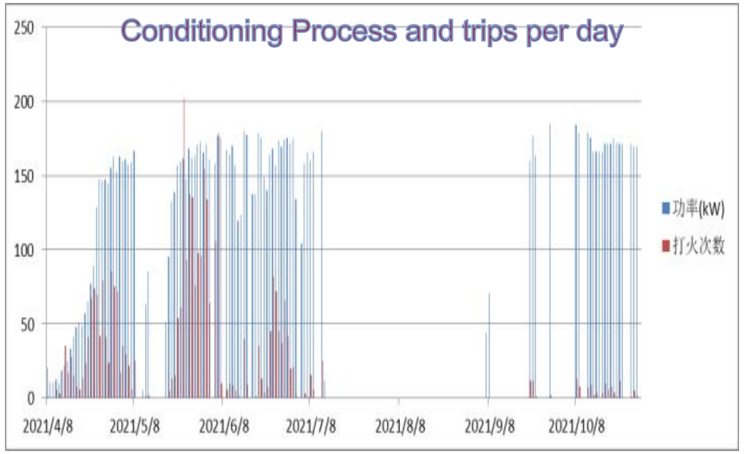


Motivation & background of CAFe² facility

RFQ



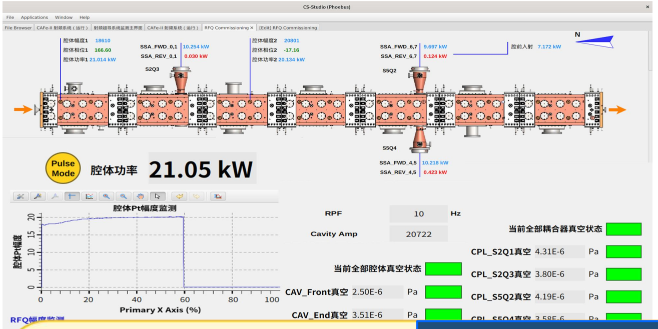
Parameter	Value
Operation Frequency	162.5 MHz
Charge-to-mass ratio	1/3≤q/A≤1
Beam current density	10 pμA
Cavity length	7047.5 mm
Input energy	10 keV/u
Output energy	1.33 MeV/u
Inter-vane Voltage	60 kV
E_{peak}（Kilpatrick factor）	21.49 MV/m (1.58)
Power loss	166 kW (@60 kV)
Q value	12745



Highlights in CAFe² RFQ cavity

- RF design for attenuation of the electrical field enhancement located in section gap and undercut
- Cooling channel design of steady-state frequency shift
- Auto-Conditioning and Auto-Loading of RF operation

RFQ UI

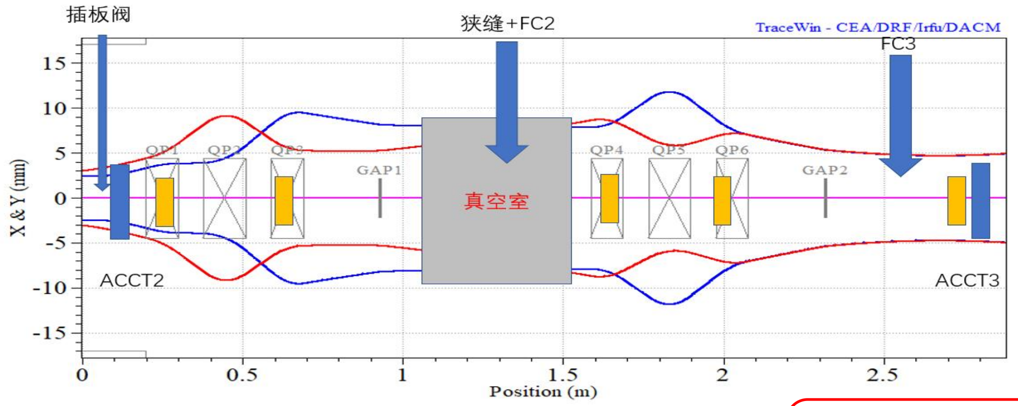


RFQ running power

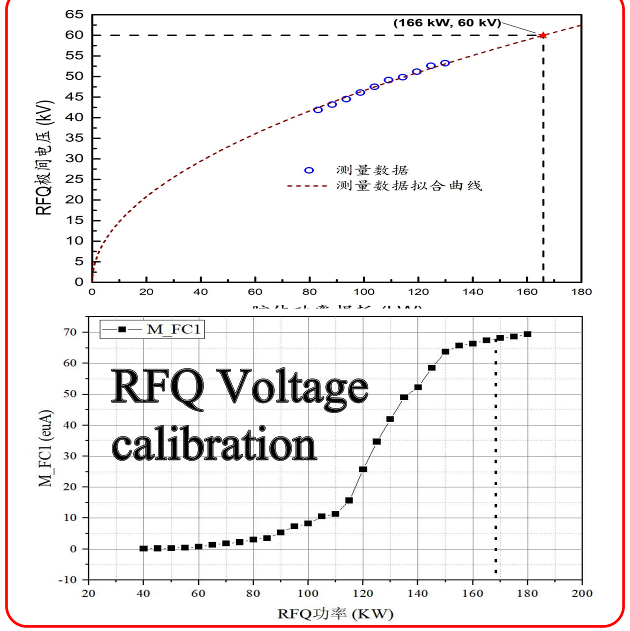
- H+: 18kW
- 40Ar13+: 165kW; 40Ca13+: 165kW
- 54Cr17+: 175kW
- 55Mn17+: 182kW

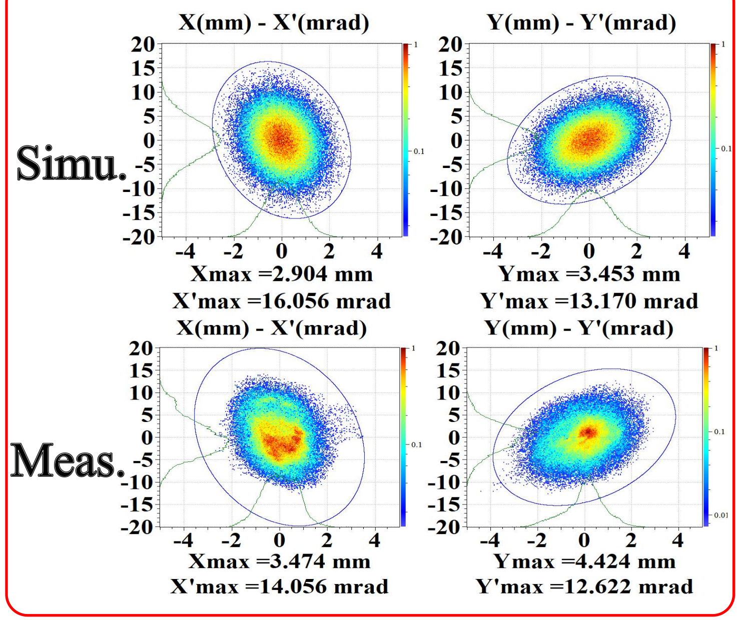
Motivation & background of CAFe^2 facility

MEBT



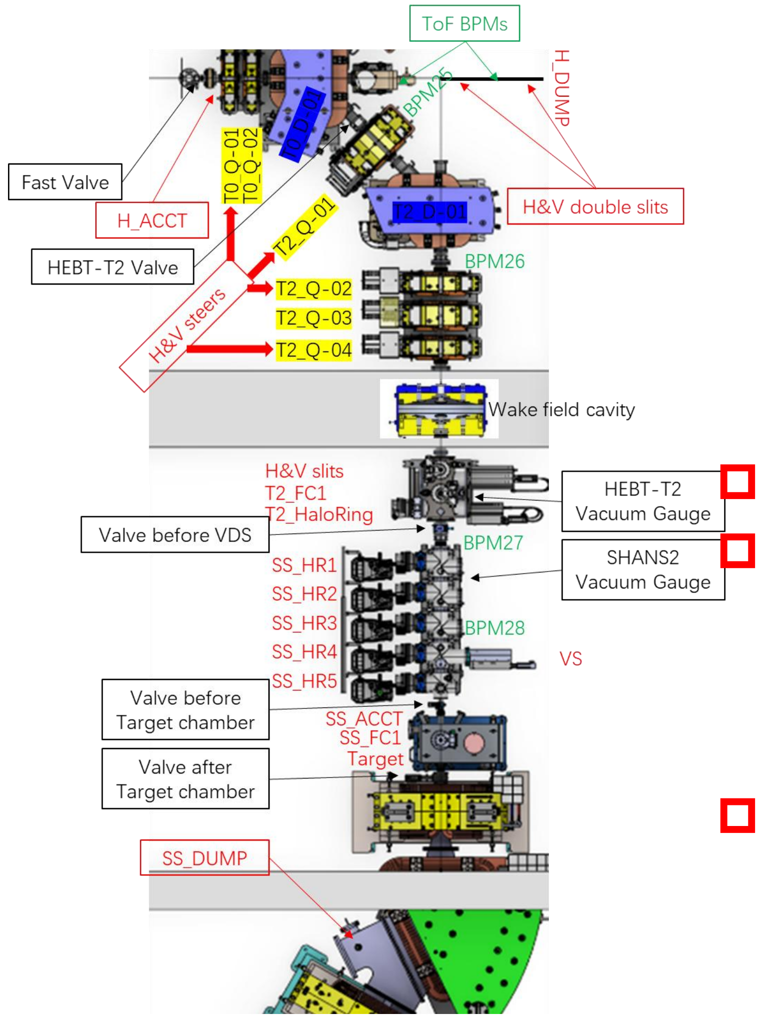
	Element	parameters
Magnet	Q120	23T/m
	Q150	27T/m
Buncher	IH-Buncher	162.5MHz/220kV
Beam dignostics	ACCT	φ40
	BPM	162.5MHz/φ40
	FC	1uA~2mA
	Emittance slit+wire	0.016pi.mm.mrad (resolution)

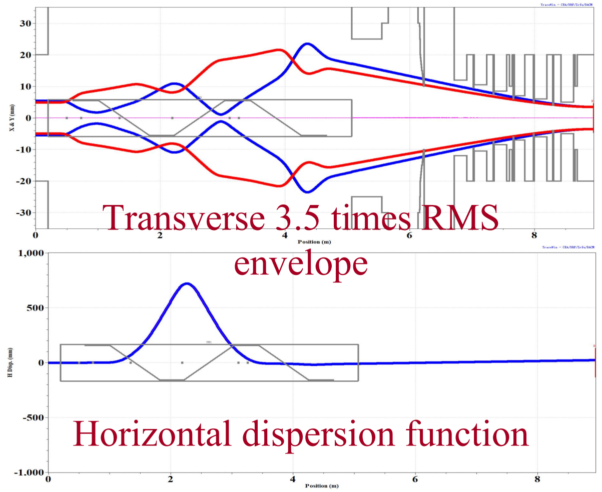




Motivation & background of CAFe^2 facility

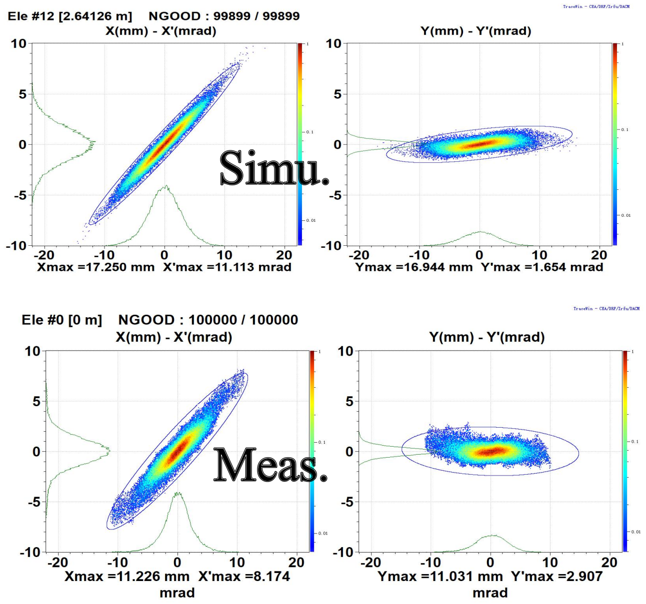
HEBT

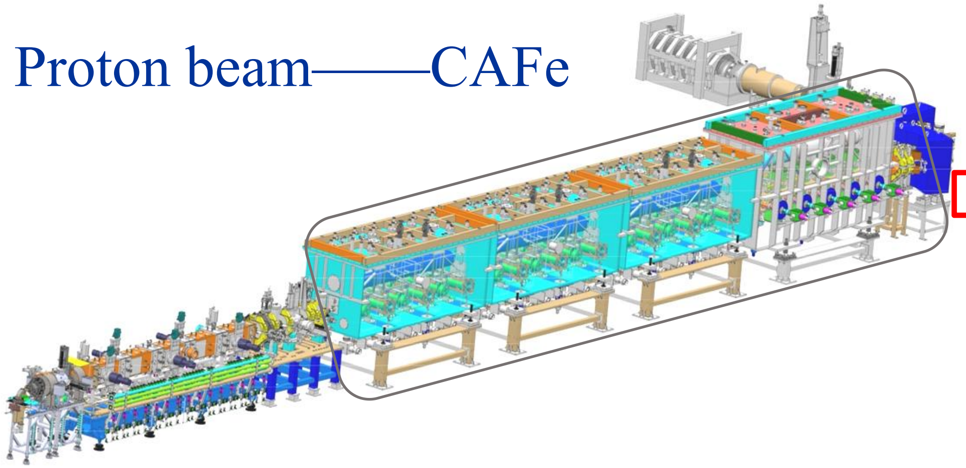


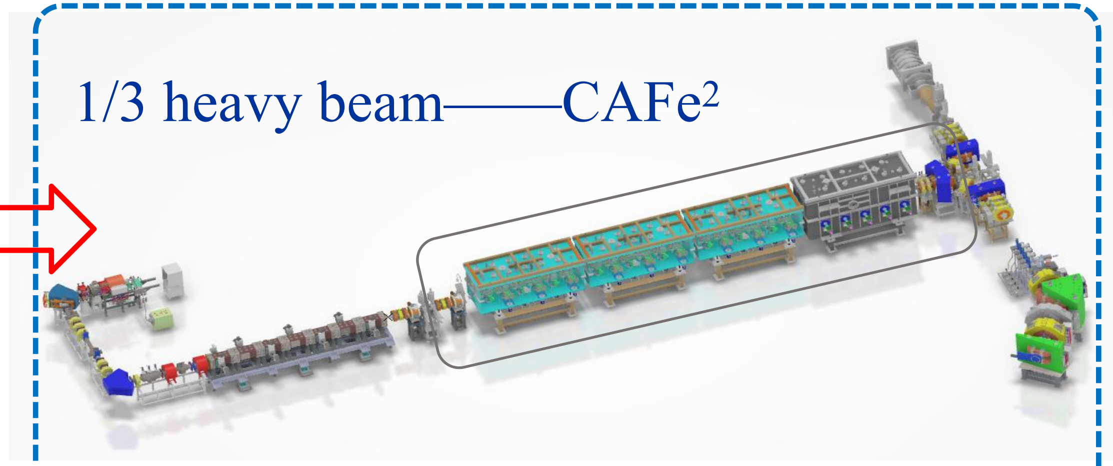


HEBT

- **Doublet focusing**
- **Symmetric achromatic bending**
  - Dipole + Quad + Dipole
  - Cancel the energy spread contribute on transverse envelope
- **Triplet focusing to form small beam size**
  - 1E2 Pa to 1E-6 Pa in vacuum differential section
  - 6 thin tubes 1.5m long







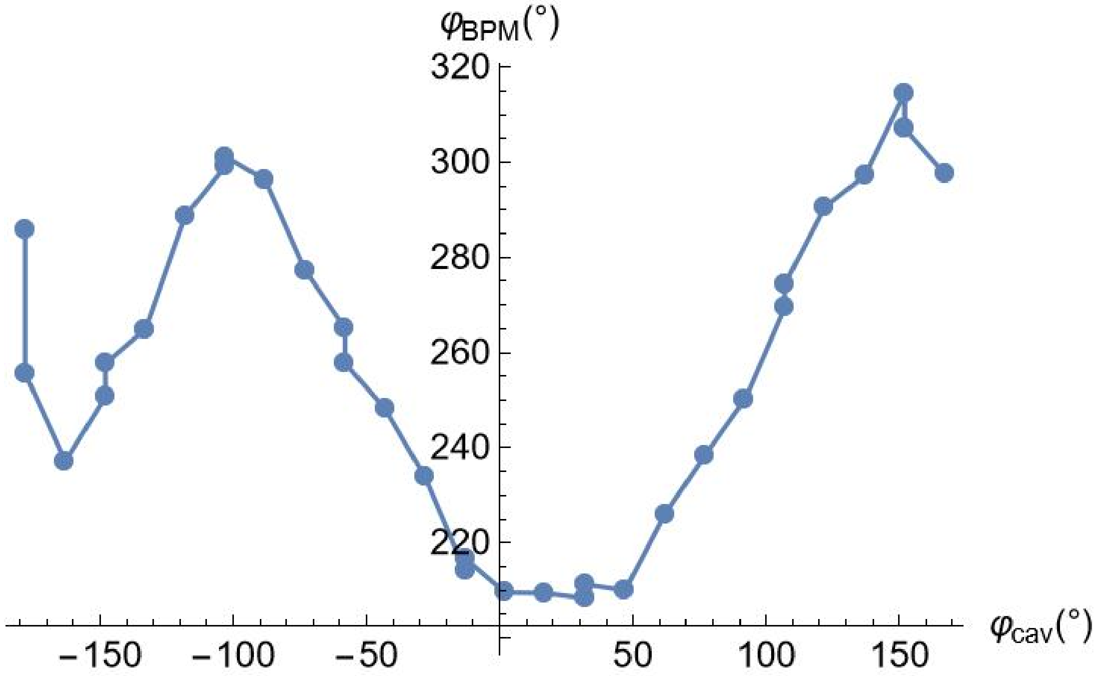
- **Low beam intensity**
  - beam current from 10 mA to 0.1 mA
- **Small acceptance of terminal**
  - from A2D to A2T which inculding Vacuum differential section
- **Undesigned hardware perfermence**
  - proton beam to 1/3 heavy ion beam
  - cavity and solenid operation parameters lower than design value

Challenges & solutions of beam commissioning

Low beam intensity

Challenges

- The BPM signal is weak and phase scanning is not as effective as it could be, It takes two or three hours.
- Frequent alteration of ions and energy



Phase scan curve of heavy ion beams

Solution

- Replacing phase scanning with phase calculating methods

Challenges & solutions of beam commissioning

Low beam intensity

-phase and distance calibration

$$\Delta W = q\int_{z_0}^{z_0+L} E(z)Cos(\omega t(z) - \varphi_{\text{abs}} + \varphi_{in})\, dz,$$

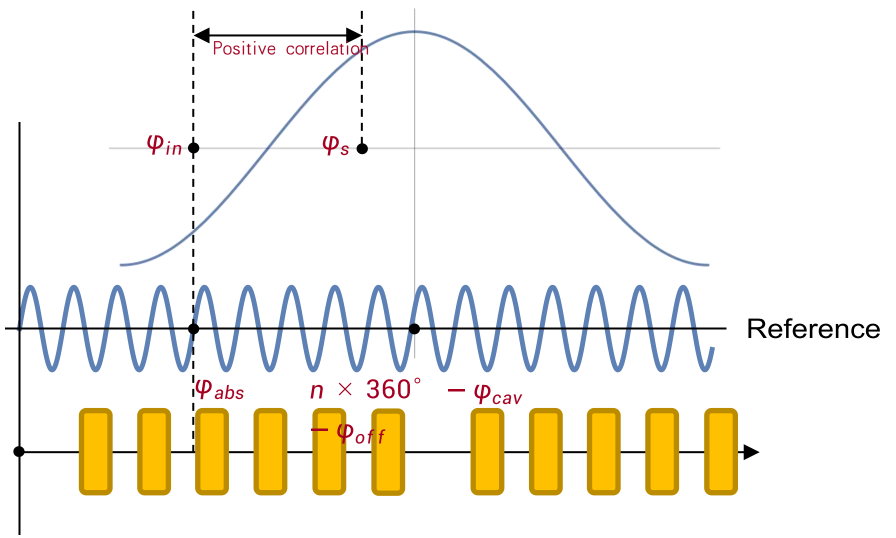
$$t(0) = 0, \omega t(z_0) = \varphi_{\text{abs}}$$

$$\varphi_{in} - \varphi_{\text{abs}} = \varphi_{cav} + \varphi_{off} - n \times 360^\circ$$

$\varphi_{\text{in}} - \varphi_{\text{abs}}$: beam phase related with energy and drift

φ_{off}: Offset with respect to the reference signal.

φ_{cav}: Cavity RF phase



- calibration experiment

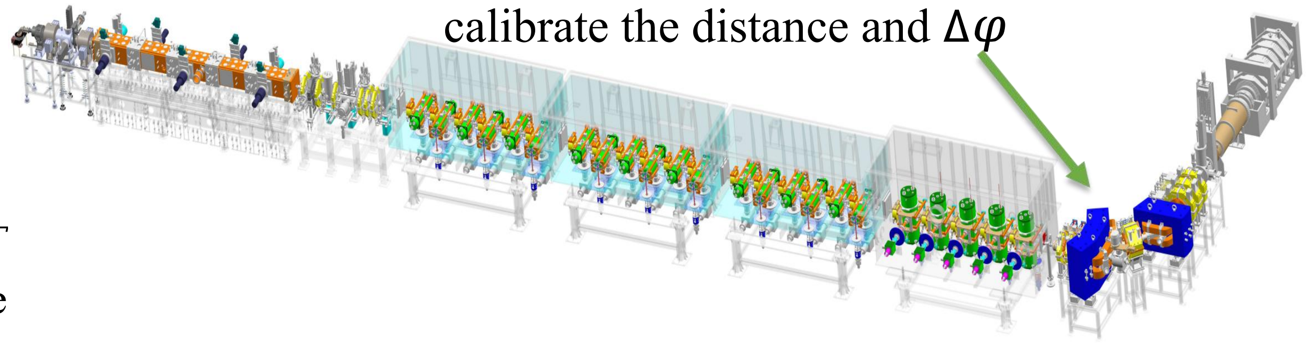
$$\Delta\varphi = \frac{l\ f \times 360^\circ}{l_{TOF}} t_{TOF} + \varphi_{02} - \varphi_{01}$$

l_{TOF} :The distance between BPMs for measuring t_T

l: The distance between the two BPMs to be calibrate

φ_{01}& φ_{02} : Phase offsets of BPMs with respect to the reference signal.

BPM25&26 located at HEBT used to calibrate the distance and $\Delta\varphi$

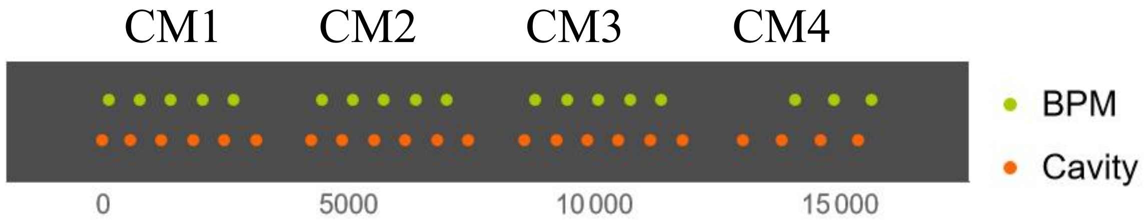


BPM6-24 in cryomodule

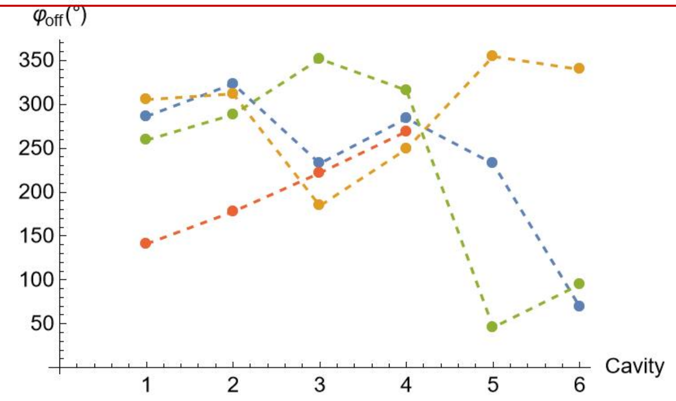
Challenges & solutions of beam commissioning

Low beam intensity

- calibration experiment



Calibration of the resulting cavity and BPM position



Calibration results of φ_{off}

- less than 10 minutes to set up the cavities
- the deviation between measured energy and designed value is less than 1%

Calibration results for cavity distribution(mm)

1-1	1-2	1-3	1-4	1-5	1-6
0(origin)	577.39	1208.78	1851.12	2490.75	3135.43
2-1	2-2	2-3	2-4	2-5	2-6
4261.70	4902.74	5534.14	6168.49	6820.66	7466.04
3-1	3-2	3-3	3-4	3-5	3-6
8606.97	9245.62	9882.59	10522.20	11164.20	11829.20
4-1	4-2	4-3	4-4		
13063.80	13838.70	14625.20	15400.50		

Effectiveness of phase design methods in different particle scenarios

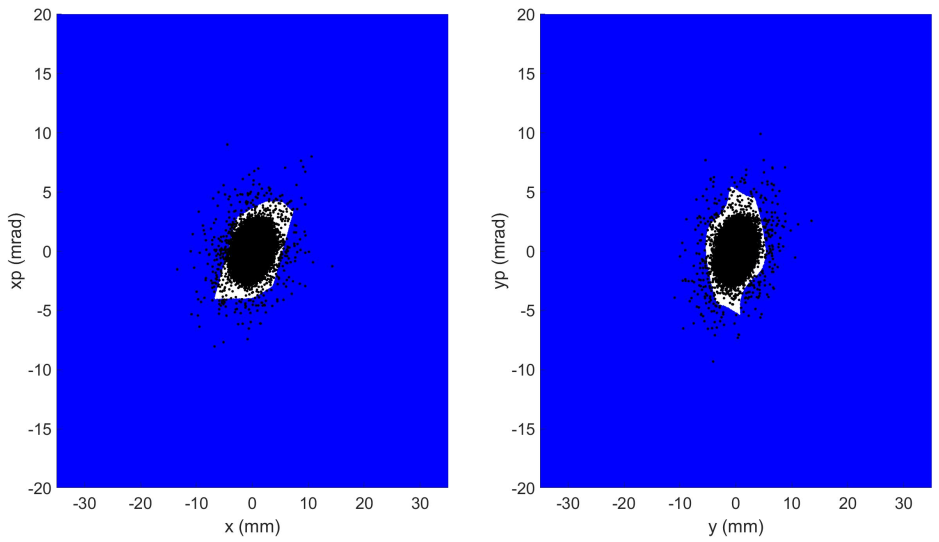
Particle	Designed(MeV)	Measured(MeV)	Deviation(%)
proton	9.289	9.285	0.04
$^{54}Cr^{17+}$	328.31	326.72	0.48
$^{48}Ca^{14+}$	262.64	261.57	0.41

Challenges & solutions of beam commissioning

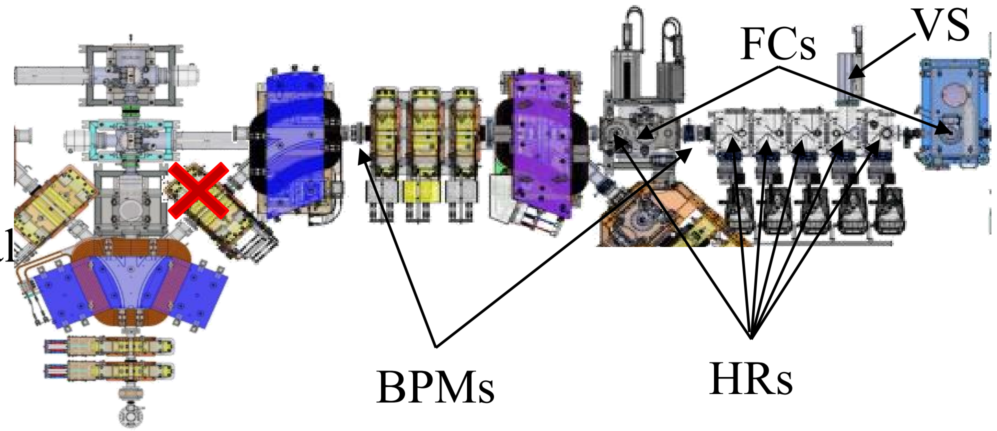
Lmall acceptance of terminal

- Difficulty in beam comissioning

- Short time window for comissioning with calcium beam (^{48}Ca)
- Low acceptance of HEBT
  - ✓ The highest transmission efficiency ~99% in simulation
- Many parameters to be adjusted for right orbit and focusing
  - ✓ Doublet+Triplet+3 couples of steers
- Different energy requirement from the terminal
  - ✓ Energy scan, several times per week
  - ✓ Cavity off, solenoid adjust, energy/distribution both different
- Inaccurate current monitors
  - ✓ The last FC in 1E2 Pa, readback much higher than real
- Time consuming in transmission efficiency optimization~1 hours by manual means, Trans~70%



White: acceptance
Black: beam distribution in simulation



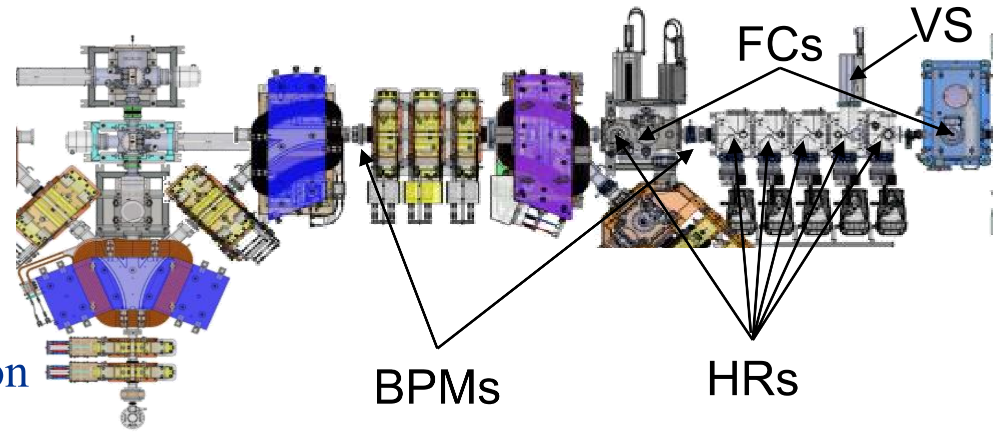
Challenges & solutions of beam commissioning

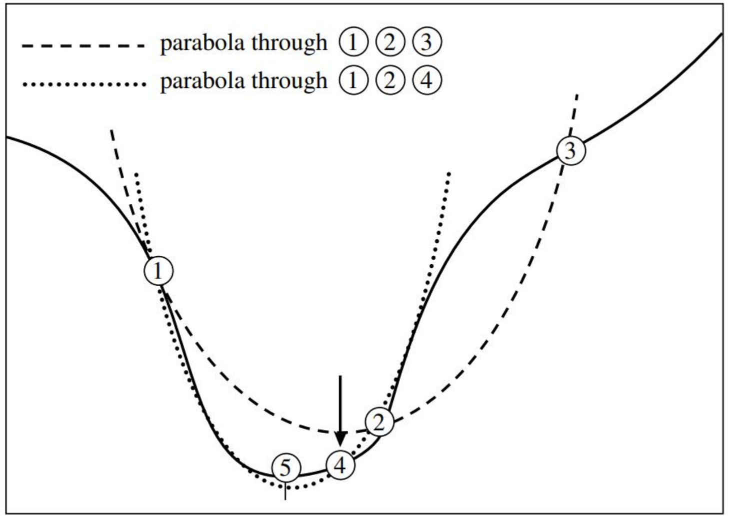
☐ Small acceptance of terminal

-PSO / Brent Optimizer

- ➢ **Transmission efficiency optimization**
  - ✓ **Orbit:** Steers with BPMs, 1D scan
  - ✓ **Focusing:** Triplet with FCs+HRs
    - D↑F↓D, 1D scan, X/Y beam waist at same location
    - D↑F↑D, 1D scan, beam waist shift to the last HR
  - ✓ **Orbit:** Steers with FCs, 1D scan
- ➢ **Brent method**
  - ✓ Fast convergence speed
  - ✓ Adaptive step-size adjust
- ➢ **Local optimization, sensitive dependence on initial values**

- ➢ **20~30 minutes by online program, Trans~70%**



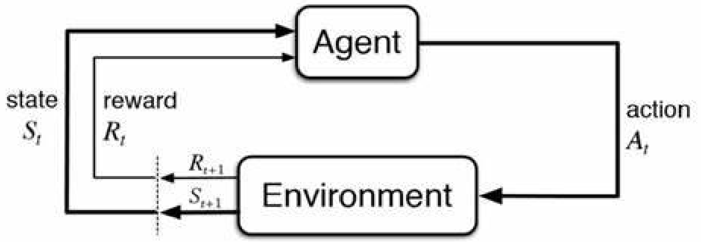


Brent method: ①②③→④, ①④③→⑤

Small acceptance of terminal

- Problems still need to be solved.
  - ✓ Higher transmission efficiency
  - ✓ Shorter tuning time
  - ✓ Multi-task coupling increases task difficulty

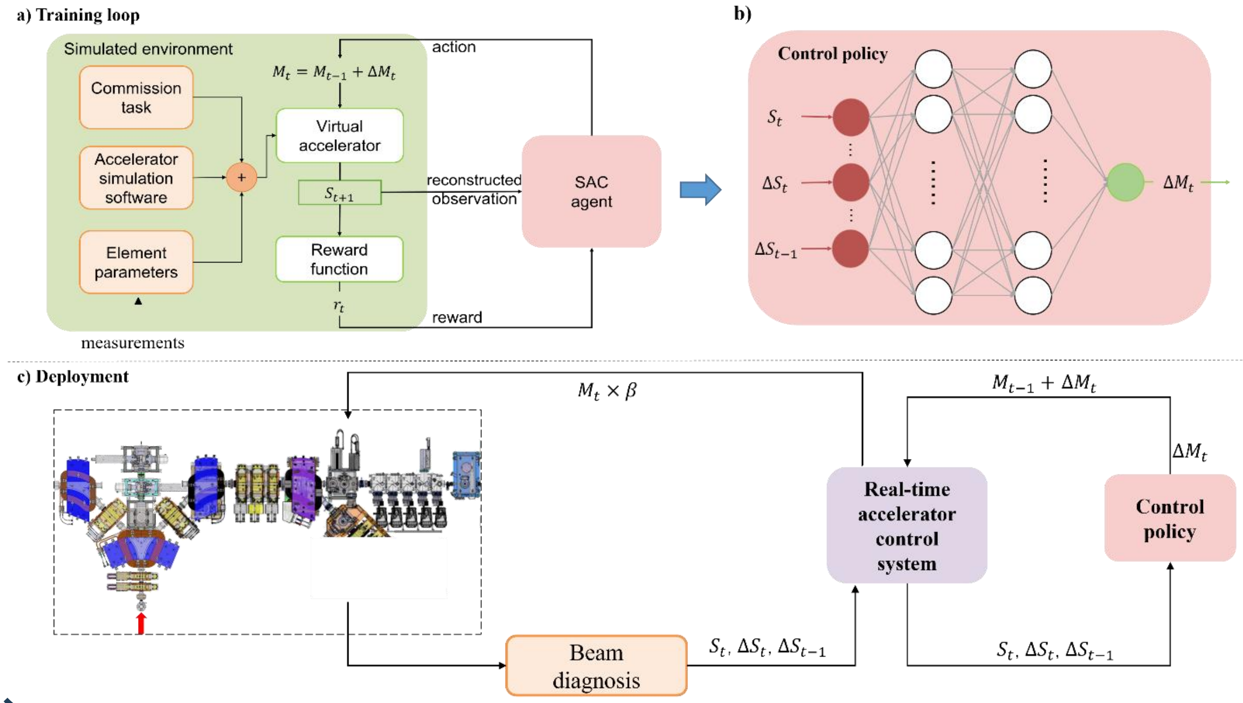
Recently, reinfocement learning(RL) is widely used in accelerator control.



- Challenges to apply RL in HEBT:
  - ✓ Highly nonlinearity complex system
  - ✓ Highly noise data from beam dignostic devices

- Soft actor critic algorithm (SAC) is selected as our optimizer.
  - ✓ Enhancing environment exploration
  - ✓ Robust noise handling

Our plan: Trained an RL controller in simulation environment and apply to real accelerator directly.



Challenges & solutions of beam commissioning

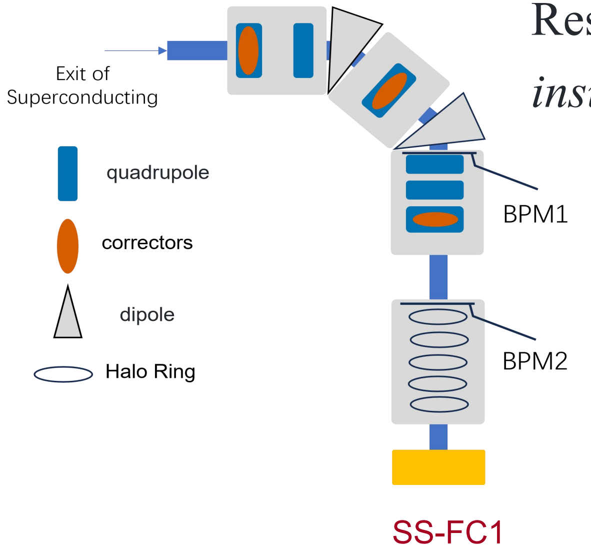
Goal: Maximize the transmission efficiency of the HEBT.

Observation: *10 dimensions.*

2 groups of BPMs, 5 HaloRings to beam loss measurement and the current of SS-FC1.

Adjustable variables: *12 degrees of freedom.*

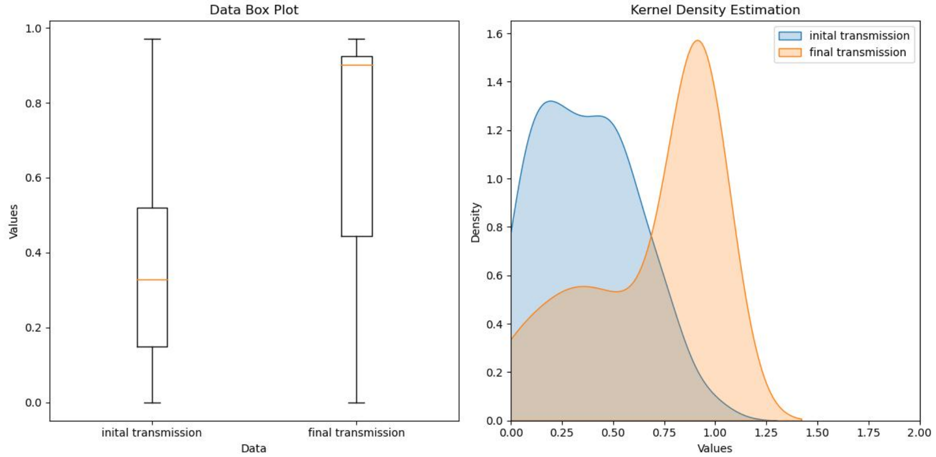
6 quadrupole magnets and 3 groups correctors.



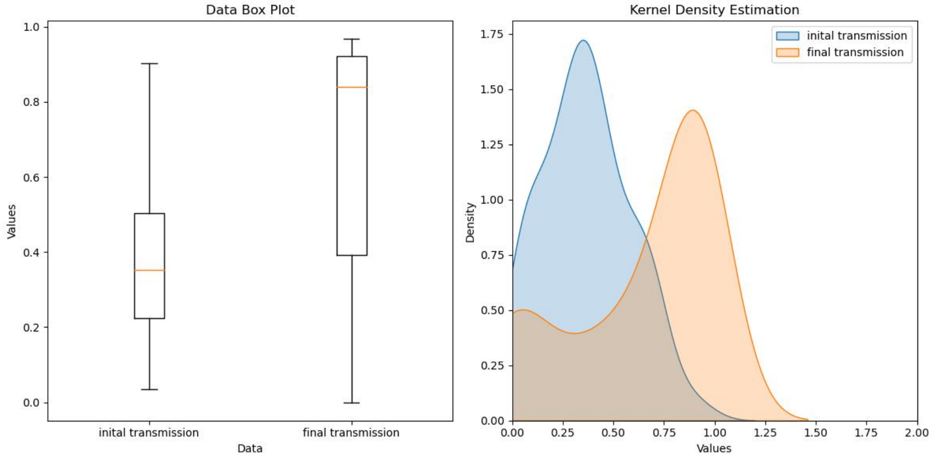
Results in simulation (*with an insufficient trained model*):

- Without incident beam errors: 28 out of 50 groups achieve 90% or higher
- With incident beam errors: 25 out of 50 groups achieve 90% or higher

Without incident beam errors

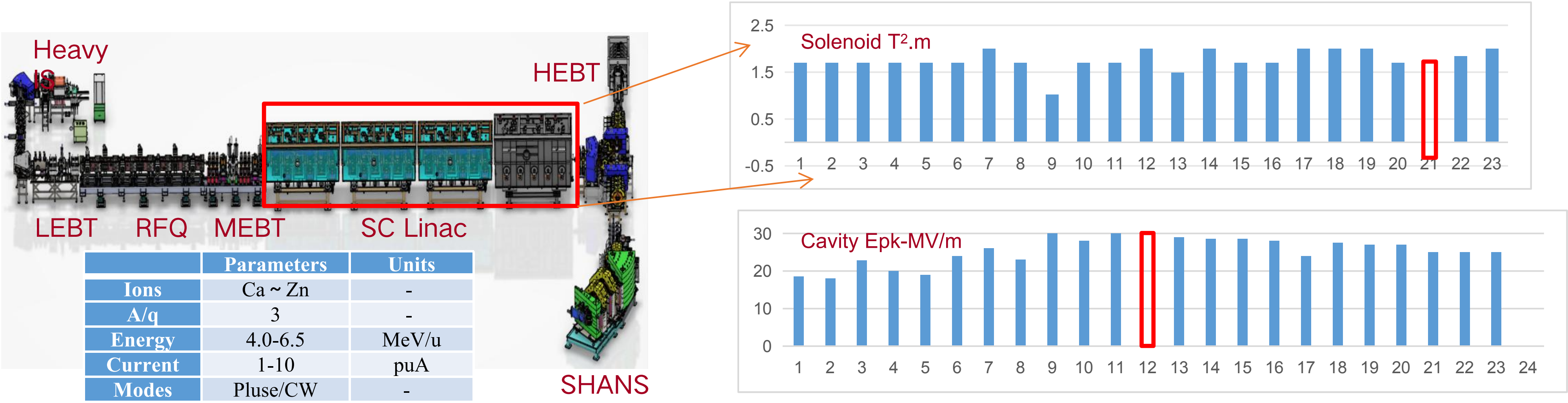


With incident beam errors ± 0.5 mm.mrad



Preliminary results indicate the feasibility of our approach in this highly nonlinear optimization problem.

Undesigned hardware performance



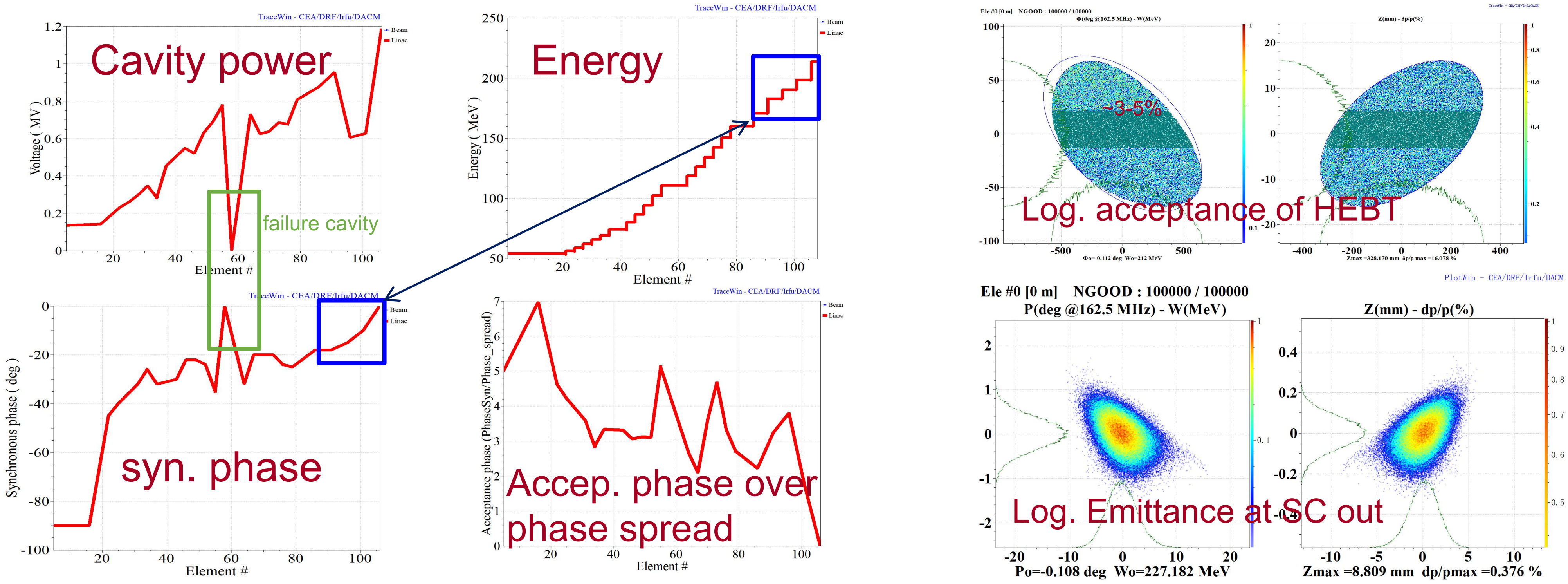
	Parameters	Units
Ions	Ca ~ Zn	-
A/q	3	-
Energy	4.0-6.5	MeV/u
Current	1-10	puA
Modes	Pluse/CW	-

Problems：

- 1/3 A/q particle beams with higher magnetic rigidity Vs. solenoids designed for proton beam
- with some superconducting cavities solenoid performance degradation

Challenges & solutions of beam commissioning

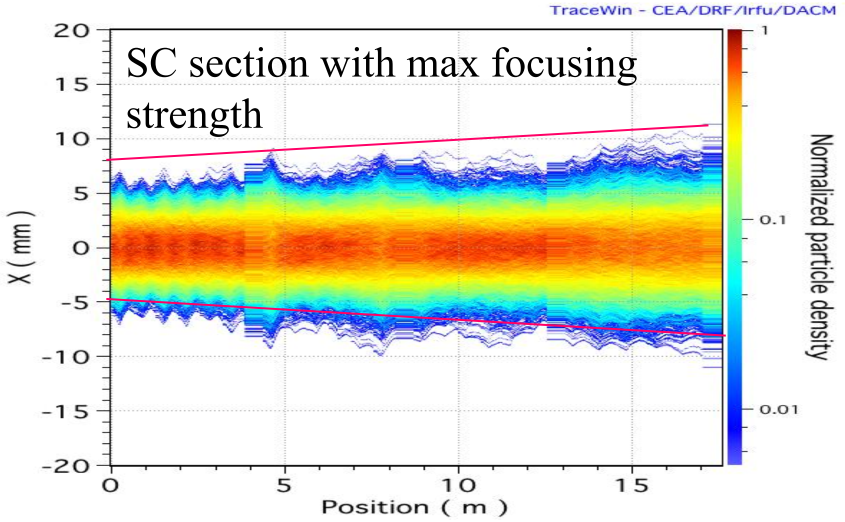
Undesigned hardware performance-longitudinal

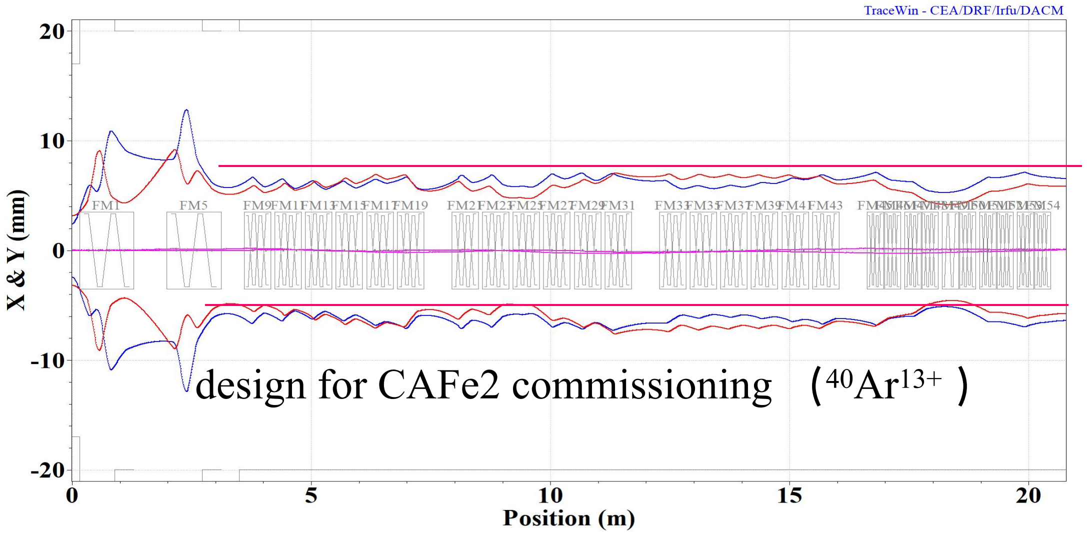


- ➢ The beam energy requirement is the priority objective
- ➢ The synchronous phase slowly changes to 0deg to reduce RF defocusing
- ➢ Ensure longitudinal emittance out of SC. section within acceptance of HEBT

Challenges & solutions of beam commissioning

Undesigned hardware performance-transverse

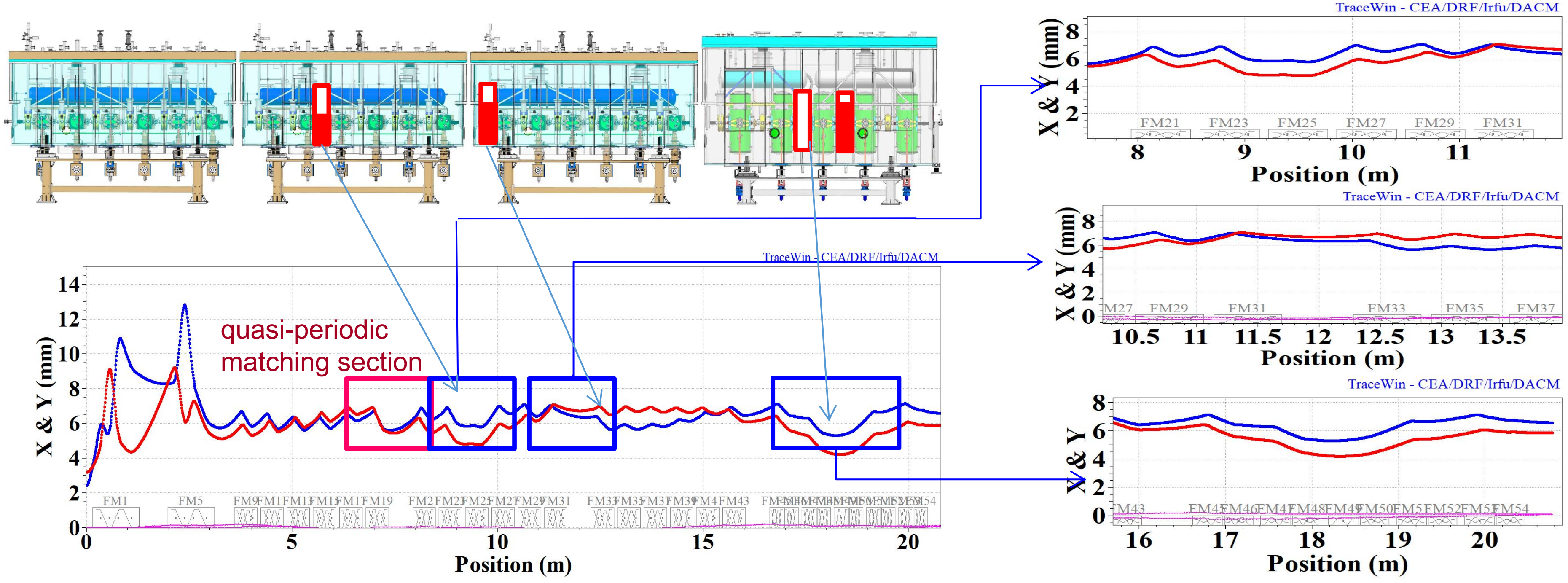




- Enlarge the overall beam envelop in the superconducting section to accomodate the insufficient foucsing strength of solenoid
- Horizontal failure compensation is designed based on the principle of smoothing the overall envelope instead of local smoothing

Challenges & solutions of beam commissioning

Undesigned hardware performance

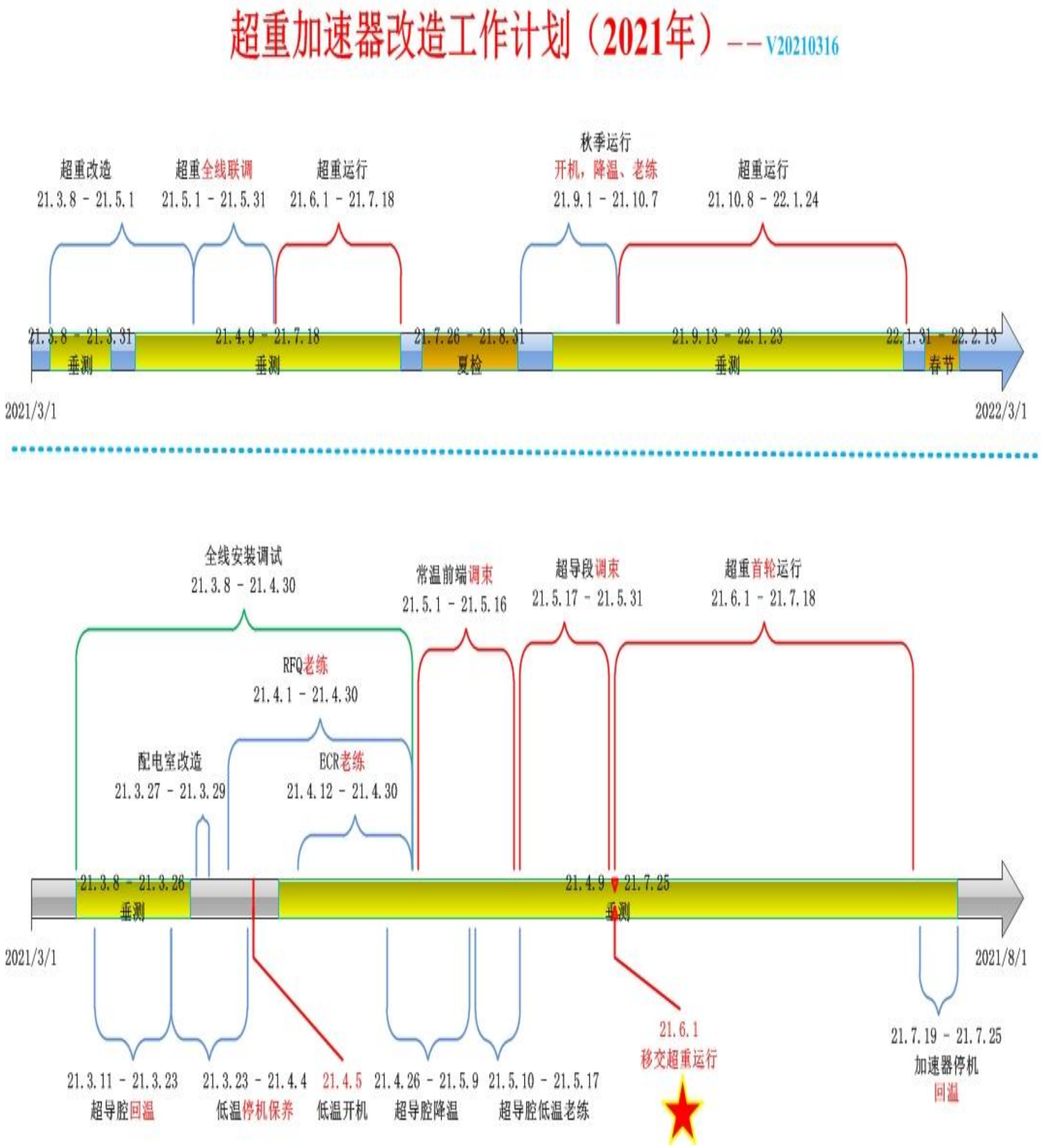


- The "peak-to-peak" matching principle is applicated both for the local failure compensation section and quasi-periodic matching section to reduce the beam halo formation

Beam operation performance of CAFe² facility

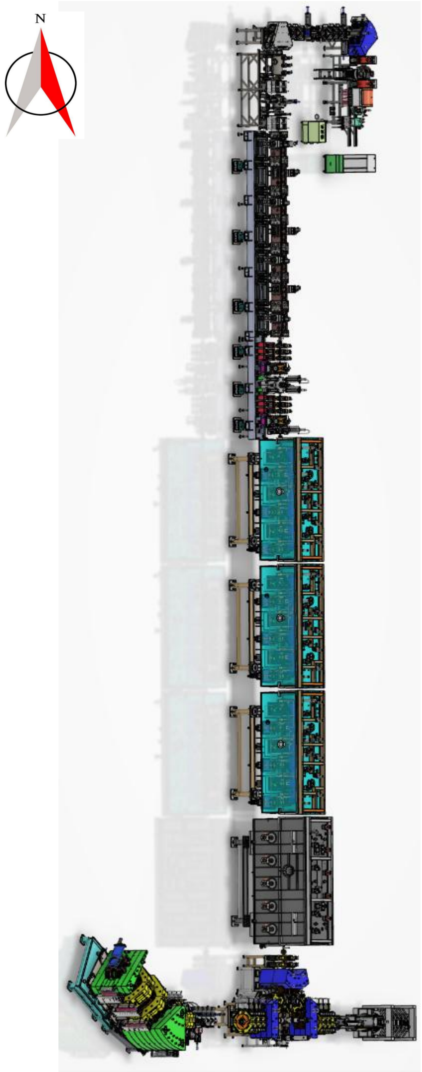
CAFe² facility roadmap：

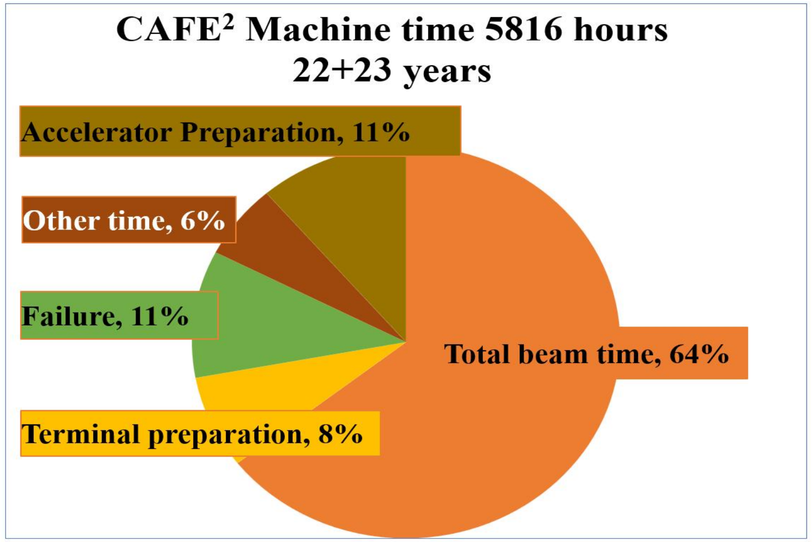
- 2021yrs： upgrading
  - 03.16： ion source first beam extraction
  - 05.01： linac commissioning
  - 06.01： A&T commissioning
- 2022.02-06：
  - Nuclide synthesis experiment （first time）
- 2022yrs second half
  - Covid-19， Work at Home , intermittent Maintenance
- 2023.02-07：
  - Officially continuous and stable operation

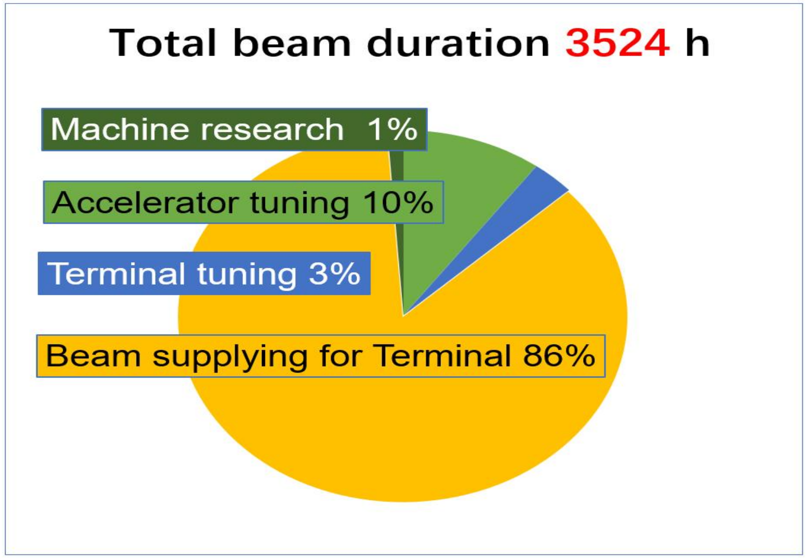


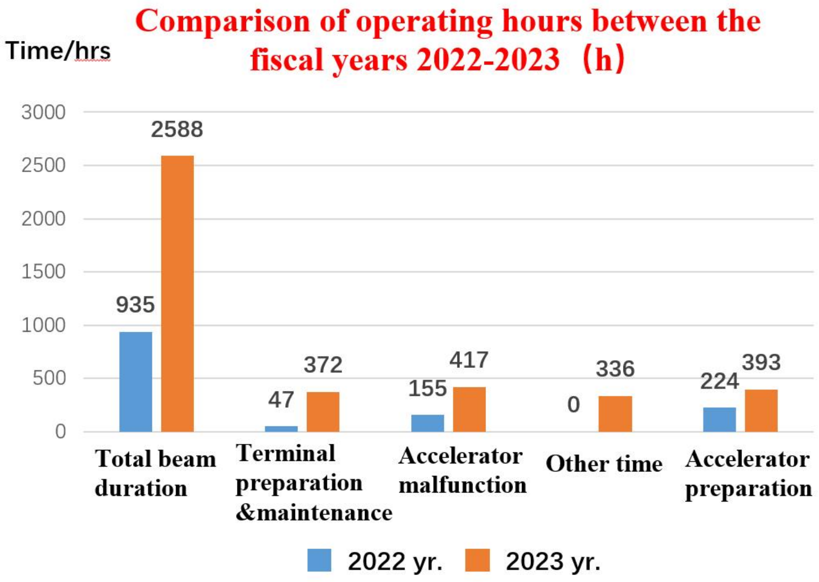
Beam operation performance of CAFe² facility

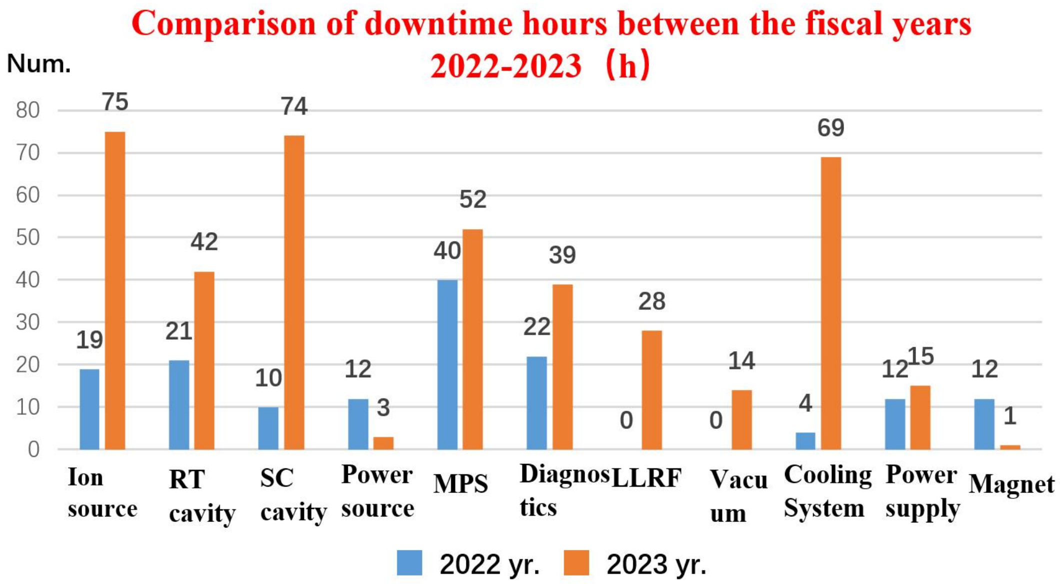
☐ Operation statistics



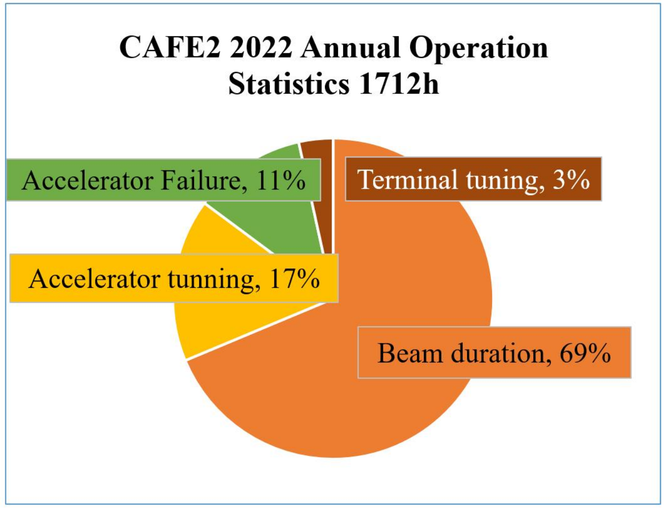


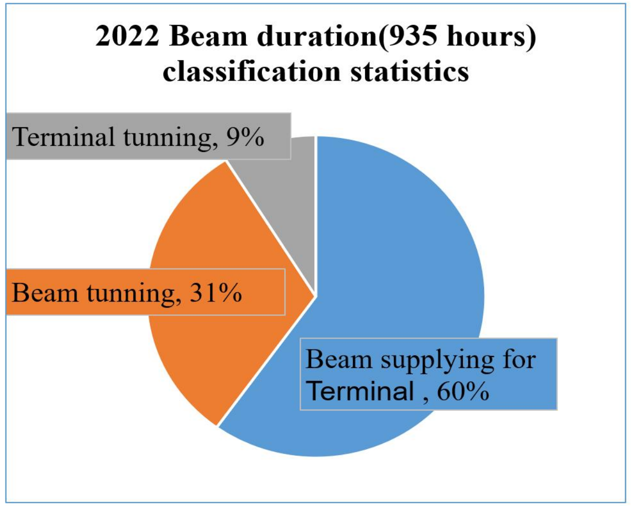


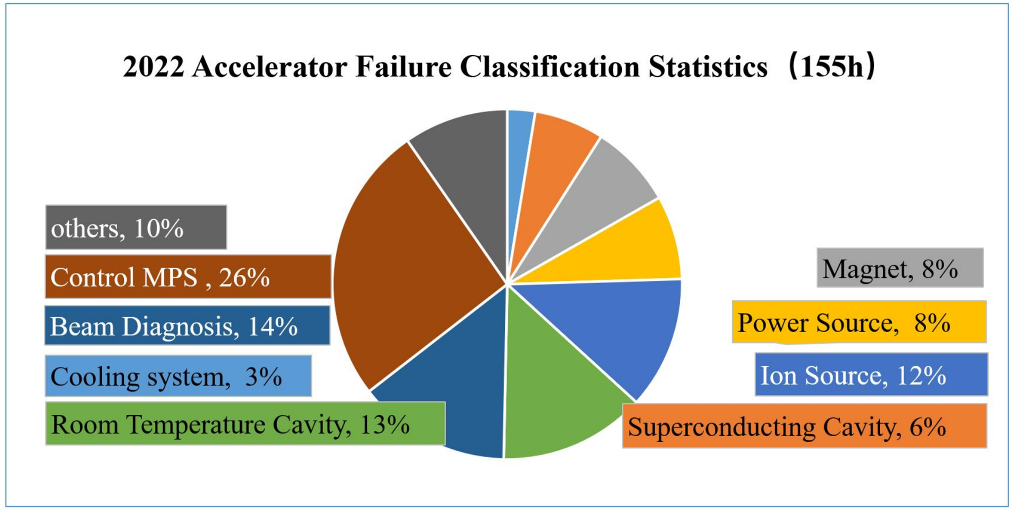


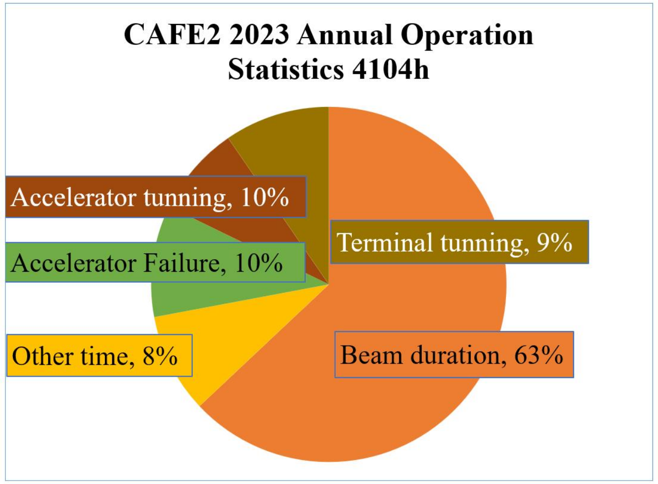


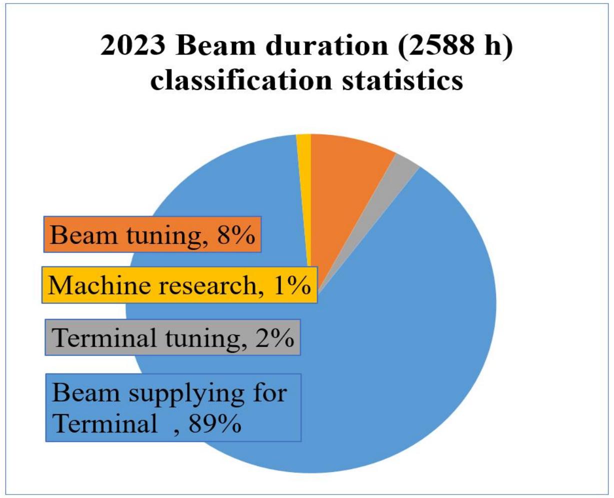
Operation statistics

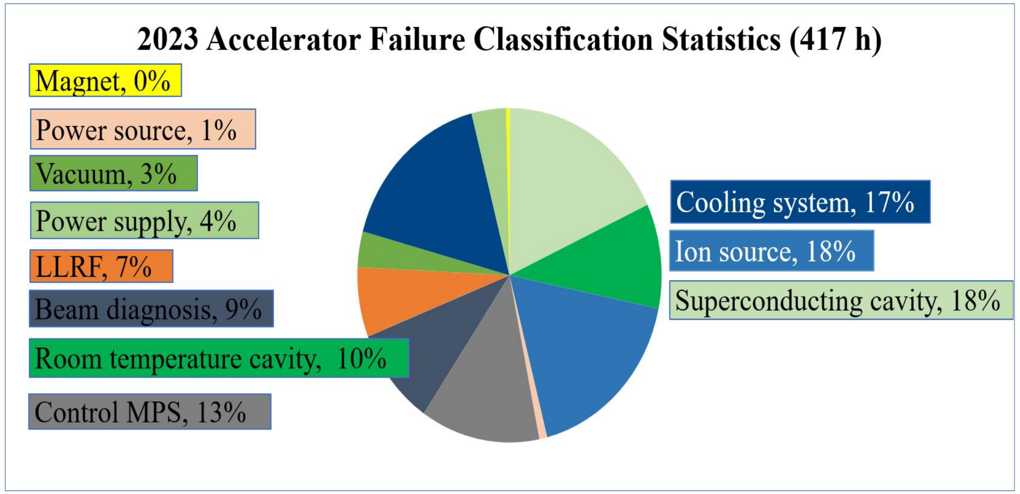










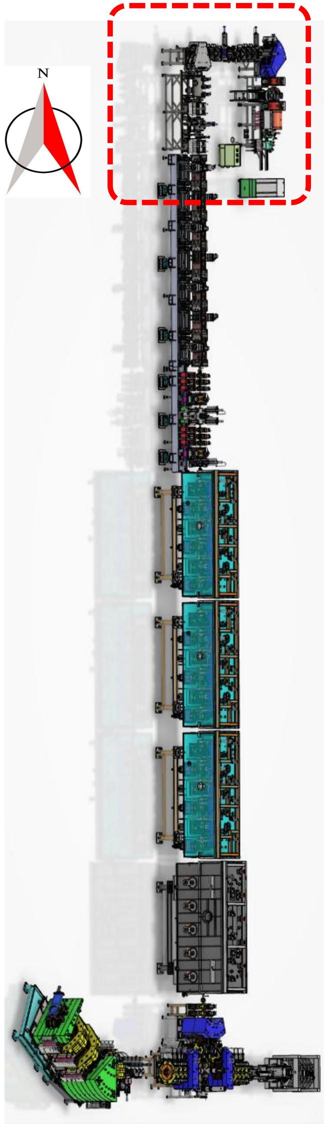


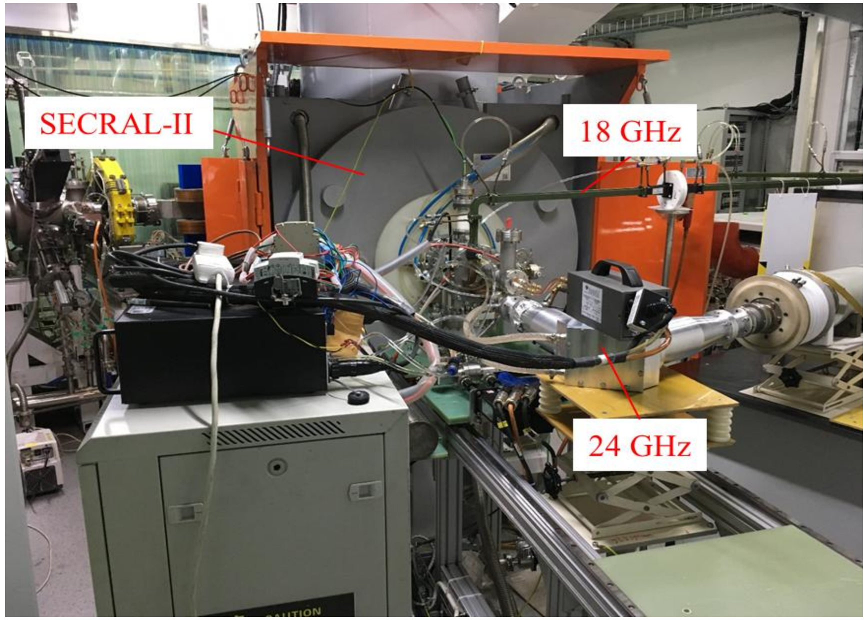
Beam operation performance of CAFe^2 facility

Years	Num.	Particles	Target (17)	Total energy (MeV) (39)	CW current(puA)
2022	1	$^{40}Ar^{13+}$	^{169}Tm	178、219	5.8
	2	$^{40}Ca^{13+}$	^{169}Tm	216、217、218、219、200、223、225、227、228	2.8
	3	$^{55}Mn^{17+}$	^{169}Tm、^{159}Tb、^{209}Bi	238、257、270	2.7
2023	1	$^{54}Cr^{17+}$	^{159}Tb、^{165}Ho、^{169}Tm、^{175}Lu、^{209}Bi、^{181}Ta、^{197}Au	213、215、223、225、229、235、237、241、245、247、250、253、256、258、259、263、264、265、270、274、276、290	1.8
	2	$^{40}Ar^{12+}$	^{197}Au、^{209}Bi、^{159}Tb、^{232}Th	170、175、176、182、187、193、198、204、211、206、215、221、234、	8.3

- A new nuclide ^{204}Ac has been published
- Other three new nuclides （^{210}Pa, ^{218}Np, ^{233}Bk） to be published

Perspective for the future





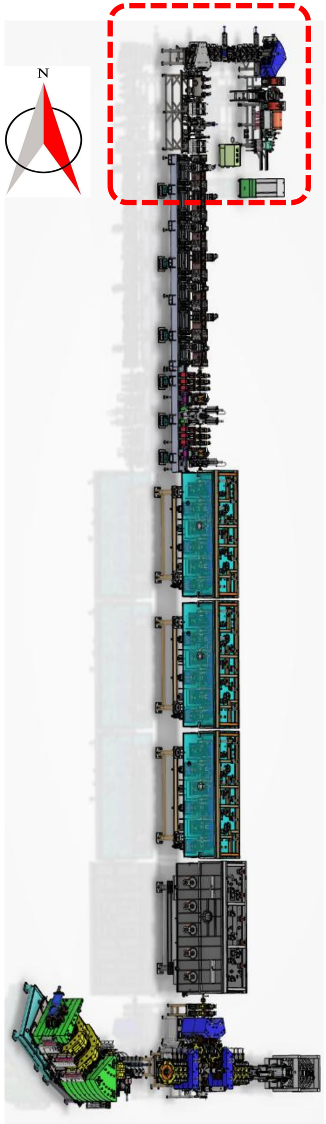
Superconducting ECR ion source- SECRAL-II

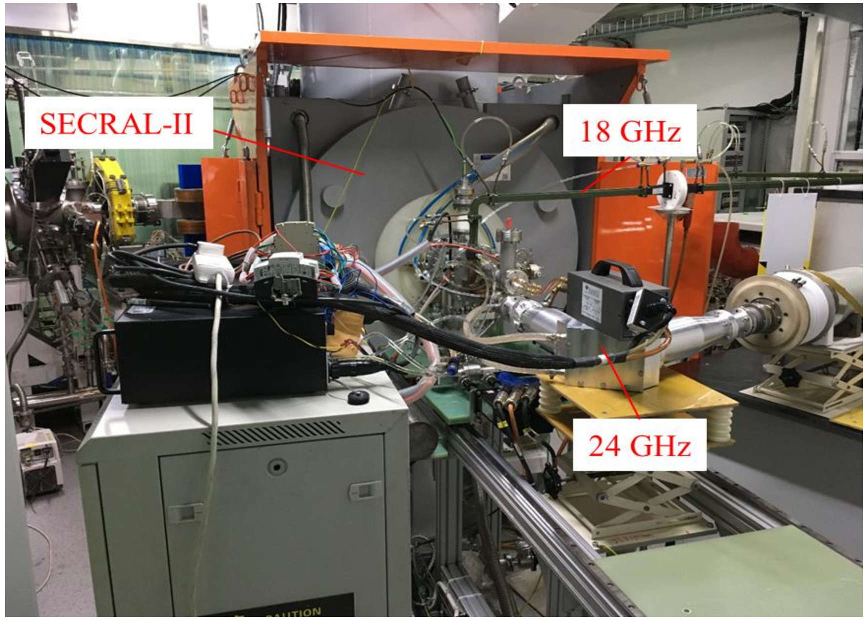
Table.2. Typical performance of superconducting ECR ion source SECRAL-II [unit: euA].

Ion species	SECRAL-II	LECR5
$^{40}Ar^{13+}$	>200	80
$^{40}Ca^{13+}$	200*	75
$^{48}Ca^{15+}$	150*	40*
$^{58}Fe^{18+}$	100	30*
$^{64}Ni^{19+}$	100*	20*
$^{70}Zn^{21+}$	100*	20*

- **A new superconducting Ion source will be installed：**
  - Beam species: Ca-Zn
  - Beam intensity: 5-15 puA
- **More effective commissioning schemes will be investigated：**
  - Machine learning assistance beam tuning
- **More detailed operation statistic**

Perspective for the future





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Thanks for your attention