



聚变堆主机关键系统综合研究设施  
Comprehensive Research Facility for Fusion Technology

# Long-lived high-power negative ion beam accelerations update from CRAFT NNBI test facility

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# R&D Roadmap of Fusion Energy in Hefei

**CRAFT** | First fusion technology R&D cluster



**CFEDR** | Chinese fusion DEMO



**EAST** | First full superconducting tokamak



**BEST** | First fusion to electricity demonstration





# CRAFT--Fusion Technology R&D Cluster

- **CRAFT** (Comprehensive Research Facility for Fusion Technology): **19 test facilities or prototypes**
- To develop key **materials/components/systems/methods** for **BEST, CFETR, PFPP**

## Superconductor R&D System

- SC Material Testing Facility
- SC Conductor Testing Facility
- SC Magnets Testing Facility
- CFETR CSMC & Testing Facility
- CFETR HTc Coil & Testing Facility
- CFETR TF & Testing Facility
- Cryogenic Testing Facility
- Power Supply Testing Facility

## CRAFT Campus

(near BEST site, 2 km to ASIPP campus )



## Divertor R&D System

- Plasma Material Interaction Facility
- CFETR Divertor Testing Facility
- CFETR Divertor Prototype
- EAST Divertor Upgrade
- VV & Installing Testing Facility
- Master Control System
- Remote Handling Testing Facility
- **NNBI Prototype System**
- ECRH Prototype System
- LHCD Prototype System
- ICRF Prototype System

**8 R&D Plants** + Transformer Substation + Fusion Museum  
+ Administration Building (Office/Meeting/Restaurant/Sport/Apartment)

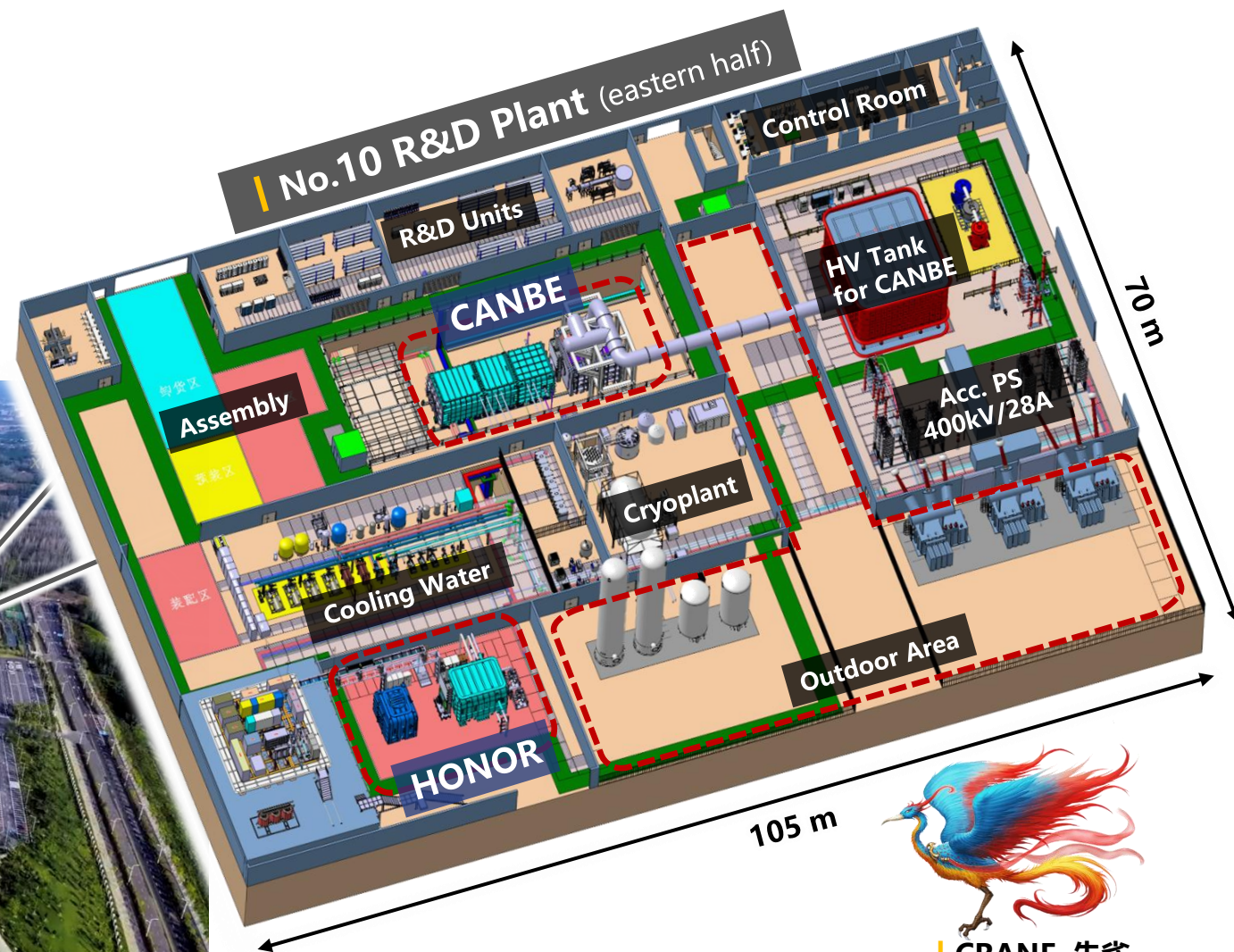


# CRAFT NNBI Test Facility (CRANE)

## Key Science & Technology of NNBI

NIBS issues

- Large-area & uniform plasma
- Production of negative ions
- Acceleration of negative ions
- Multi-beamlet optics & steering
- High-Voltage generation & transmission
- Neutralization of negative ions
- Electrical removal of residual ions
- High-vacuum pumping & holding

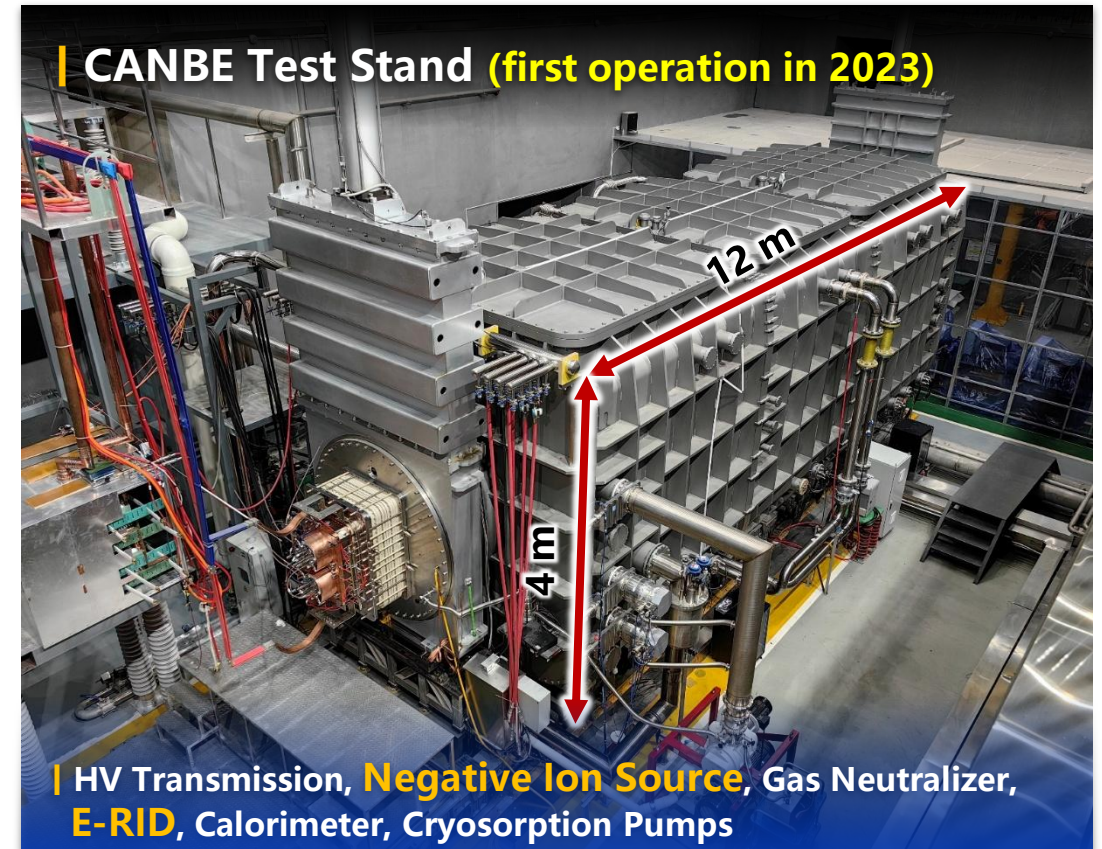
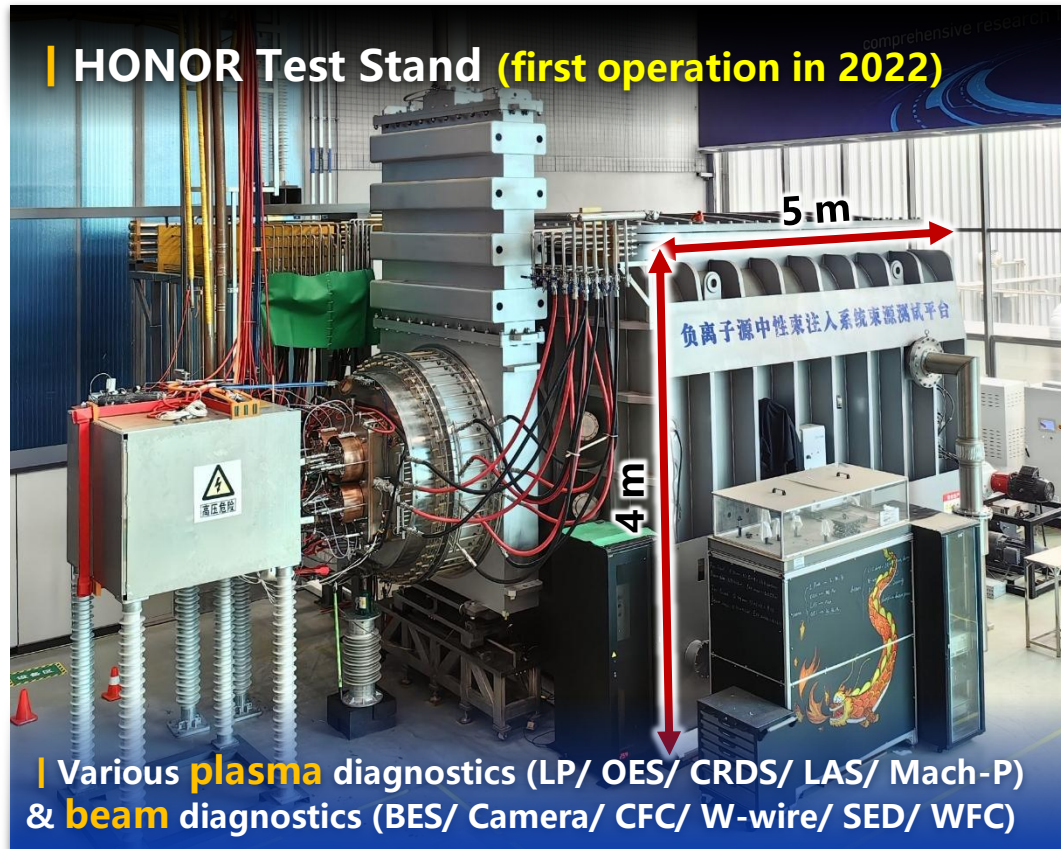


CRANE, 朱雀

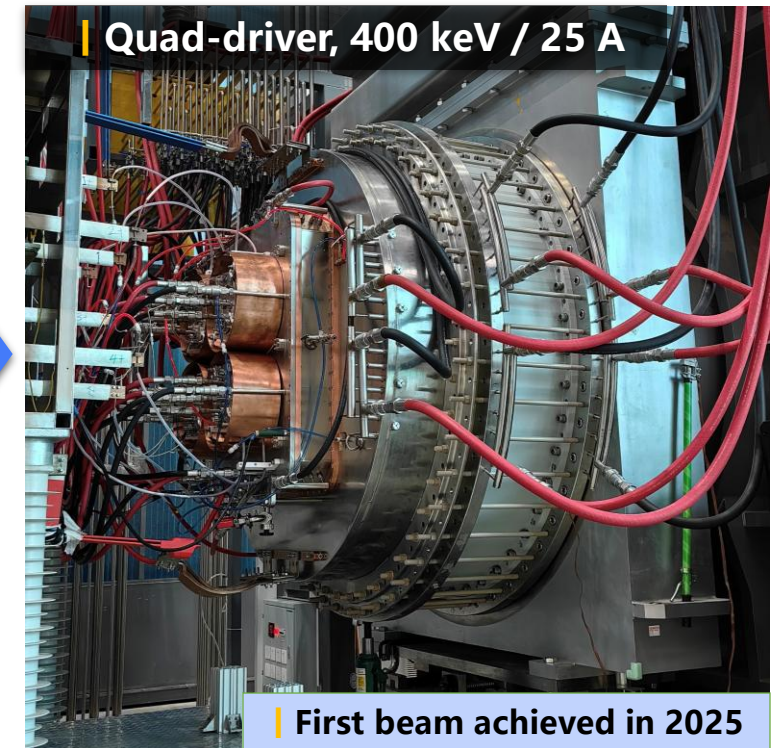
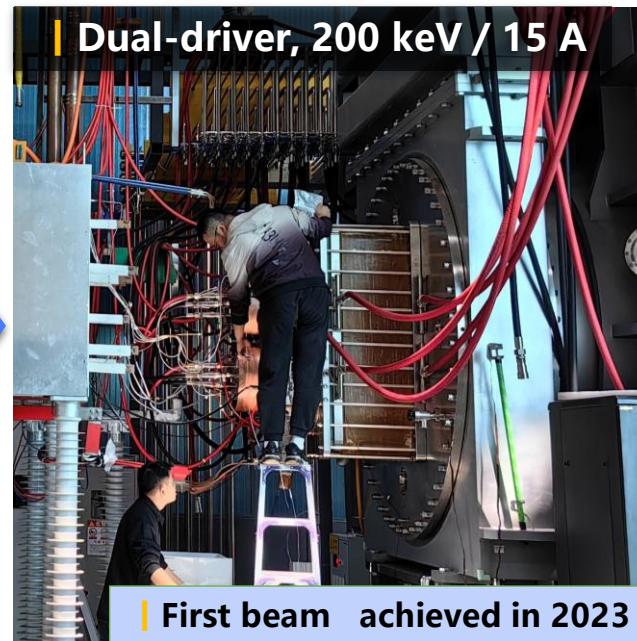
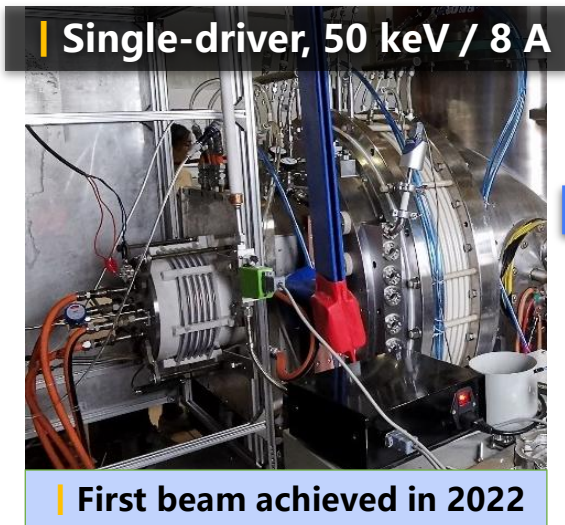


# Test Stands in CRAFT NNBI Test Facility

- **HONOR** (Hefei Open-facility for Negative-ion Source Research) → **H- production & acceleration**
- **CANBE** (CFETR Advance Neutral Beam Equipment) → **key NNBI technology** (HV, neutralization, beam focus...)



- For plasma source: **Single-driver** → **Dual-driver** → **Quad-driver**
- For accelerator: single-stage of **50 keV** → single-stage of **200 keV** → two-stage of **400 keV**

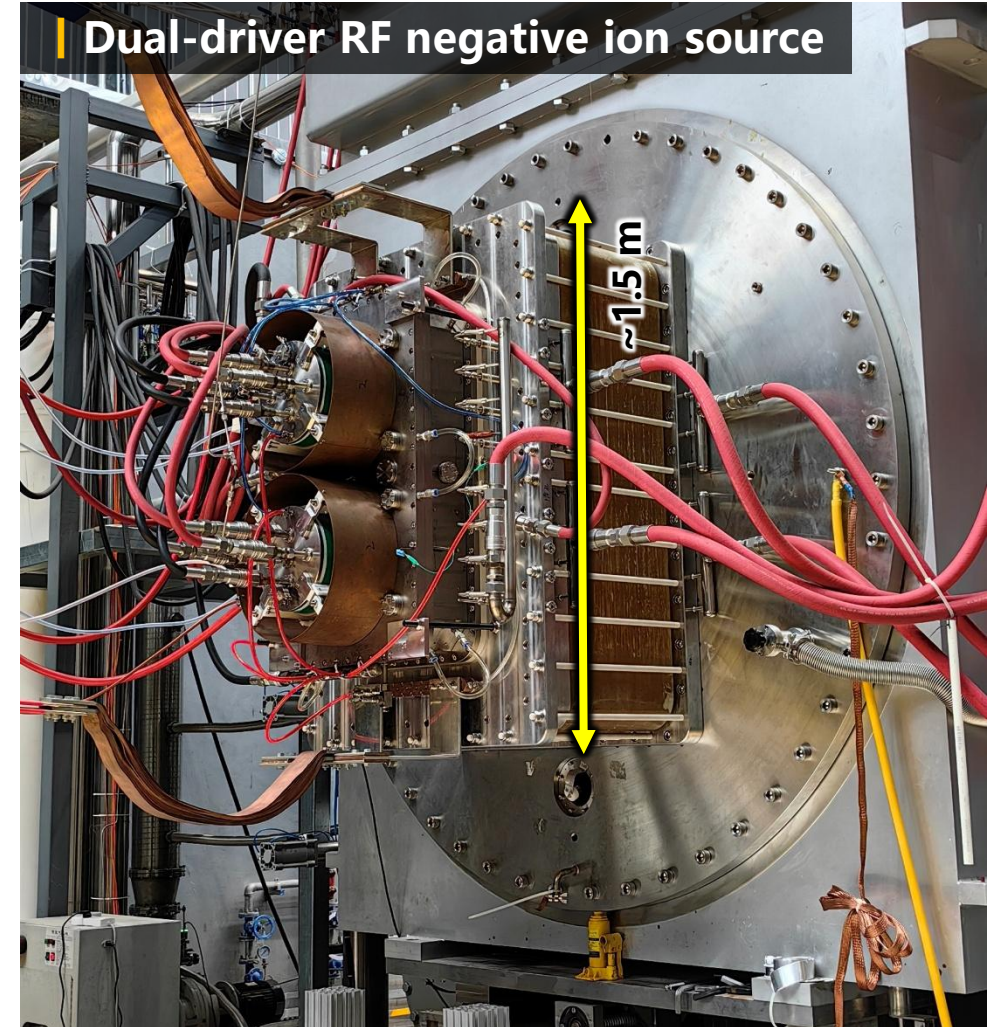


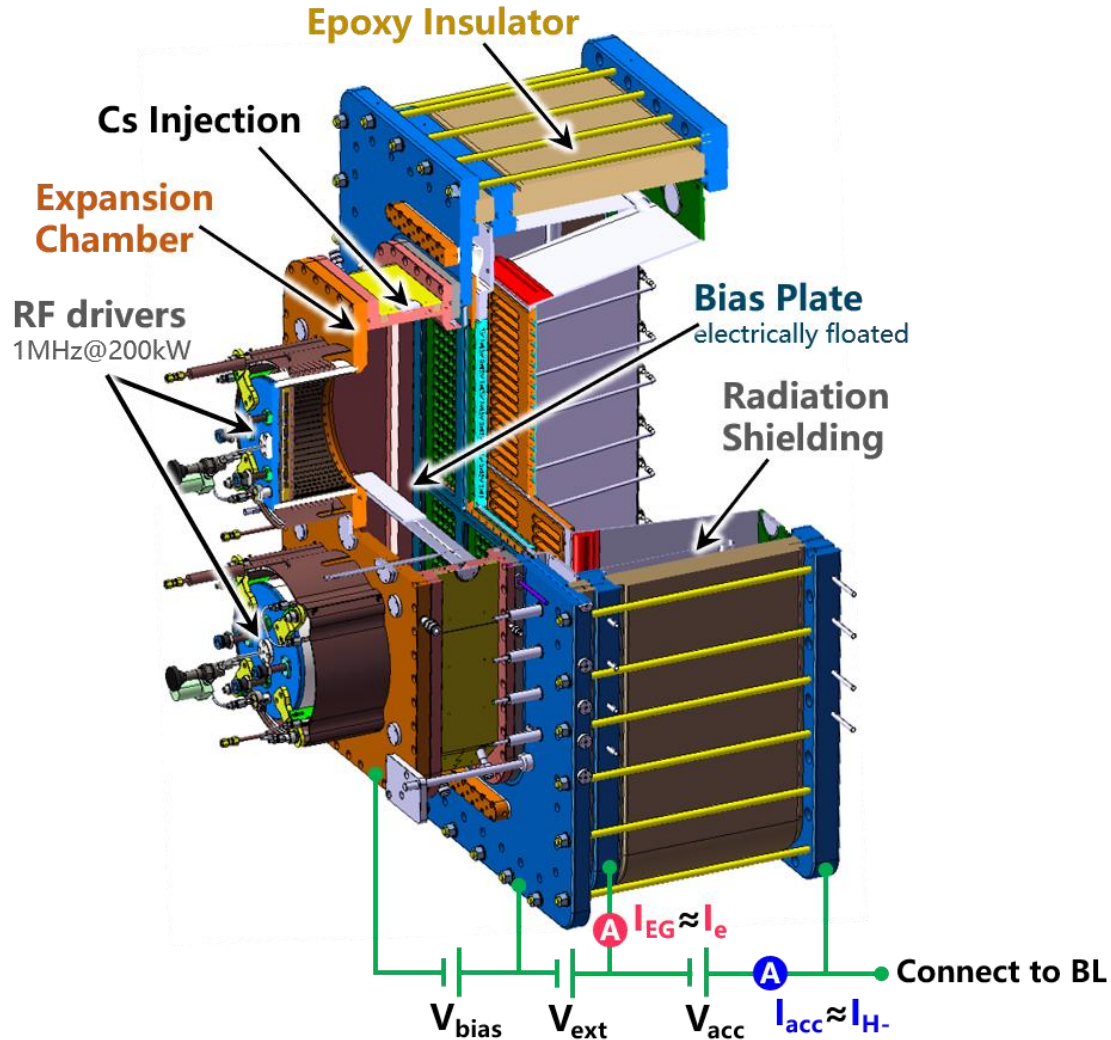
## ■ Experiment conditions

- CANBE test stand, cryopumps  $\sim 4,000,000$  L/s
- Working gas: Hydrogen
- **CRAFT dual-driver RF negative ion source**  
Target: **200kV@15A(250A/m<sup>2</sup>)@100s**
- ERID & NEU turn on in most of time

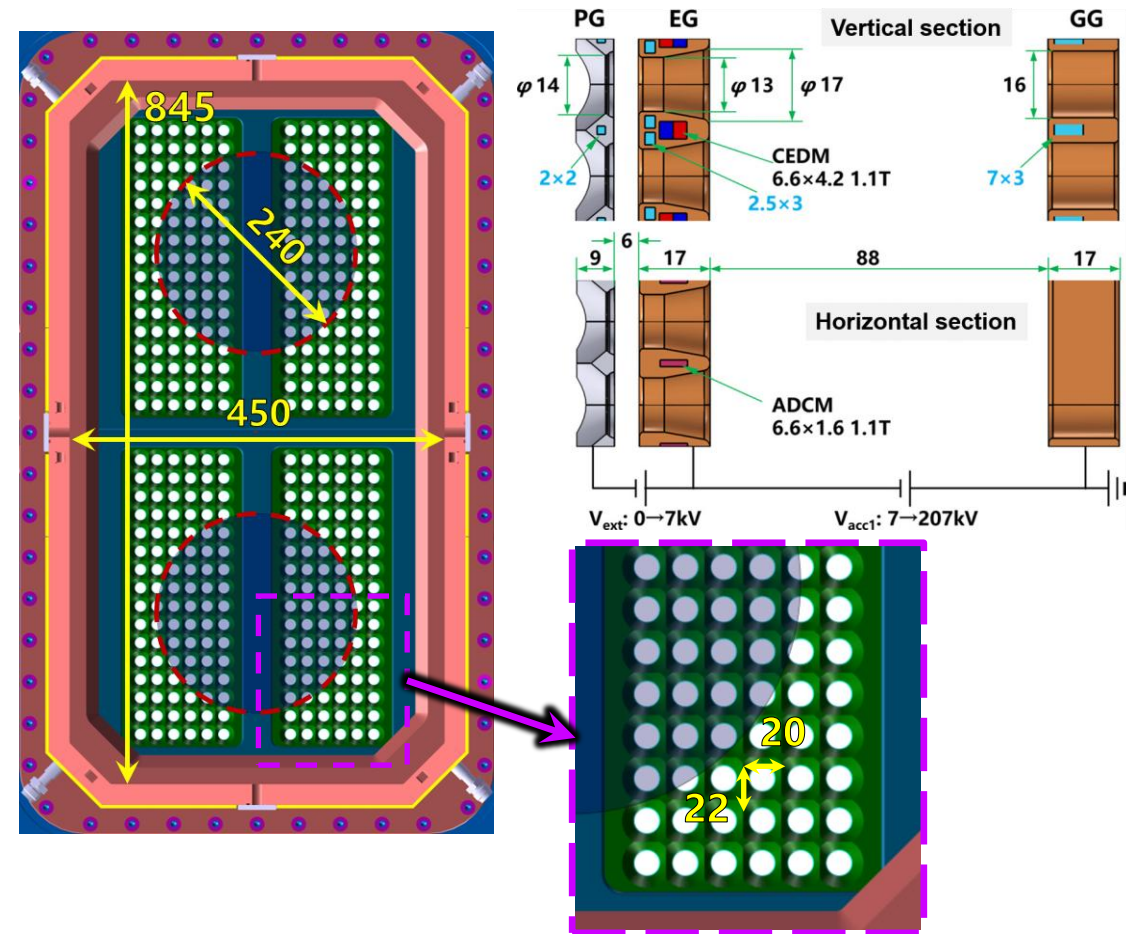
## ■ Experiment overview

- 4<sup>th</sup> annual experiment campaign of CRAFT NNBI
- 1<sup>st</sup> stage of Y2026: **from Apr. 28 to Aug. 6**  
(not so long-lived)
- **72** beam operation days, **12 h** each day,  
 **$\sim 6000$**  beam shots, **20~40 s** typical pulse
- Experiments paused now, due to debugging of ERID

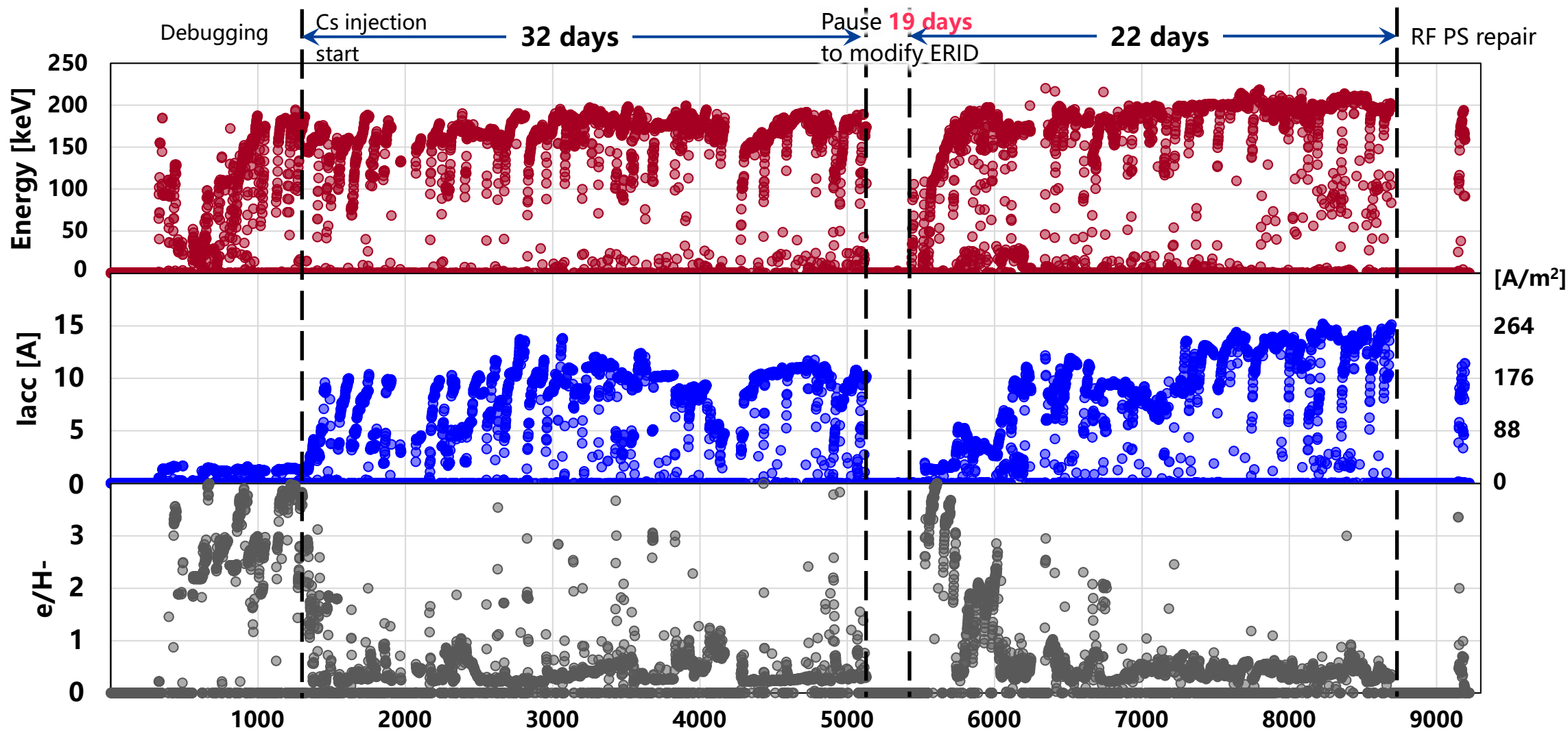




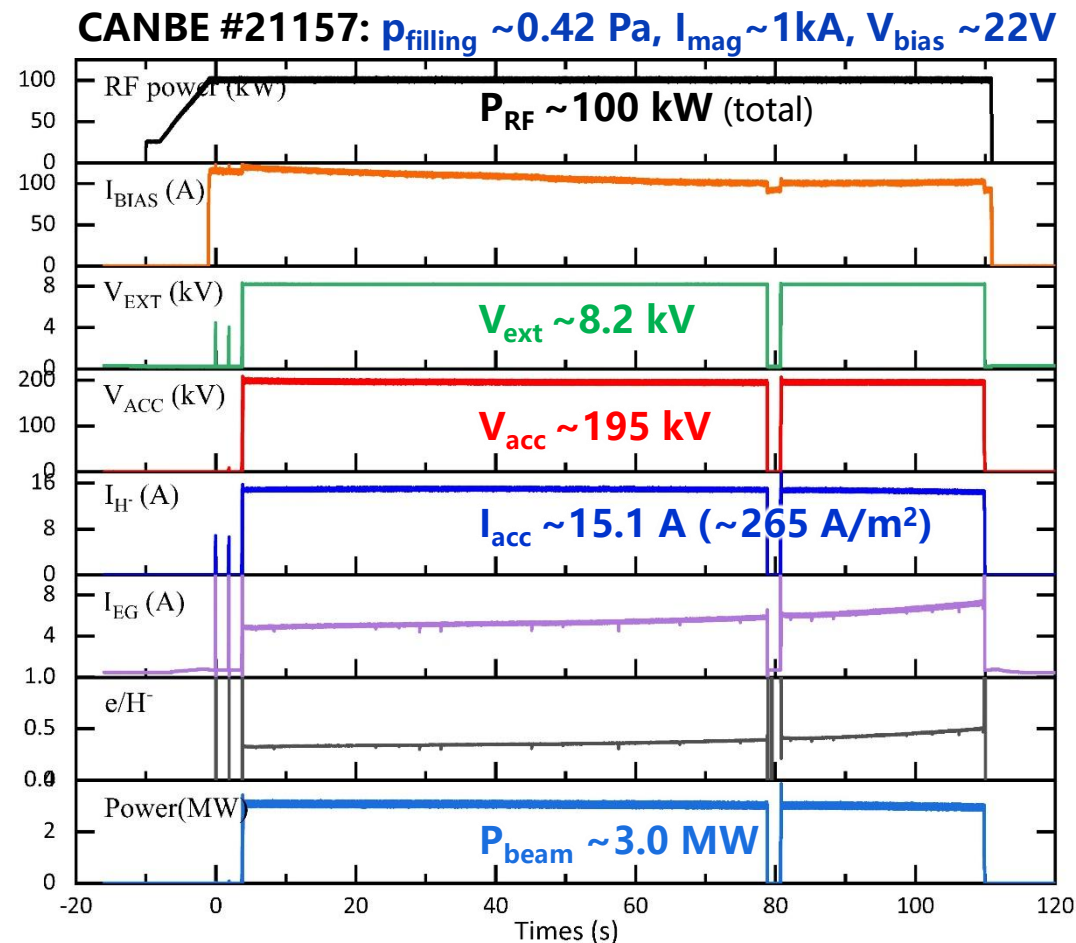
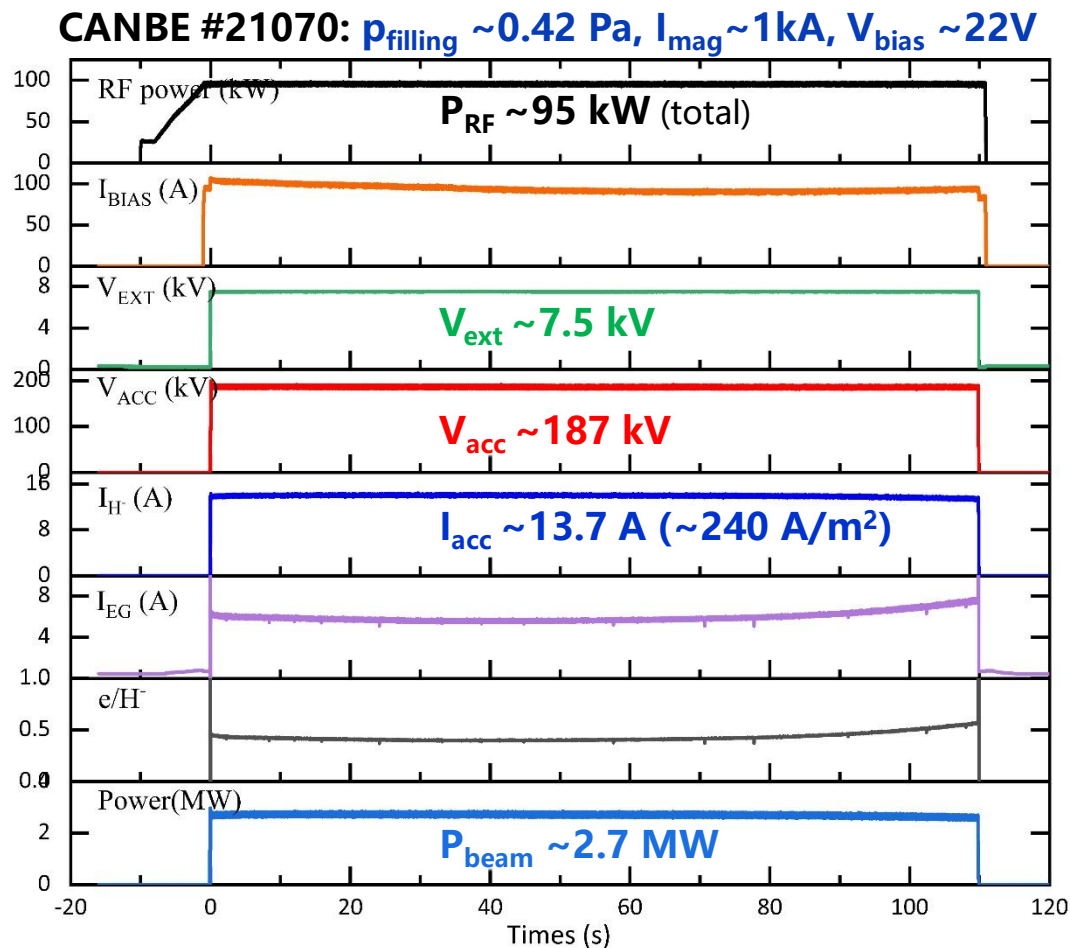
## Detailed Design of Electrode Aperture



# Variations of Key Beam Parameters



■ **Reach design objective** of CRAFT dual-driver negative ion source ( $>200\text{keV}$ ,  $>15\text{A}$ ,  $>100\text{s}$ )



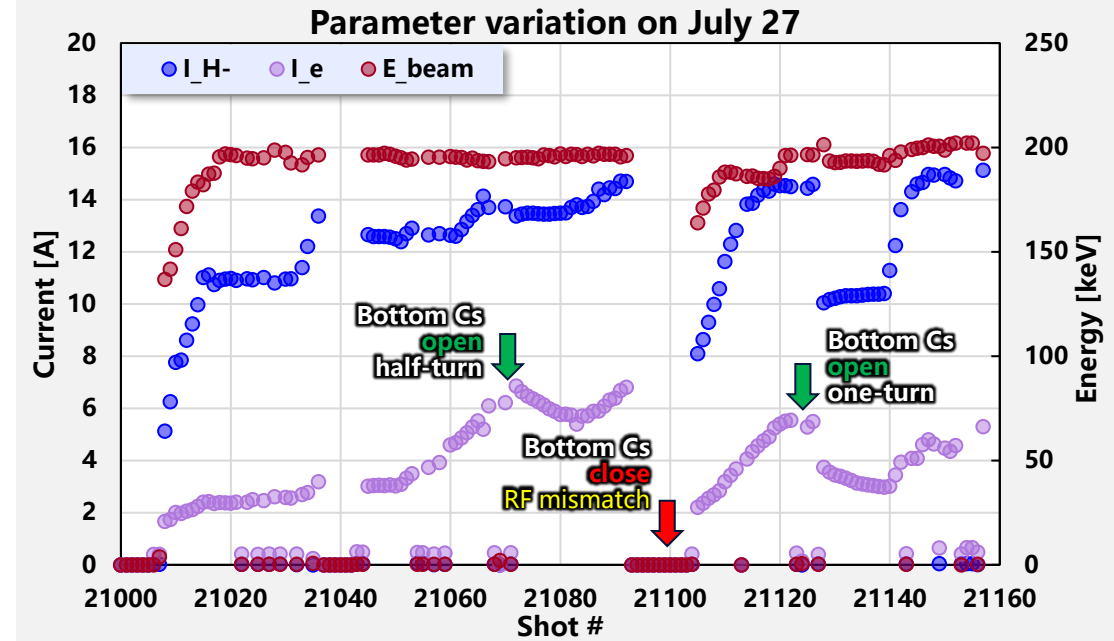
## ■ Problem

**RF sudden mismatch became frequent in 3-MW beam acceleration of Campaign 2025**

- ONLY high energy / high current, no problem (e.g., <170 keV, 15 A, 100 s & 200 keV, <13 A, 100 s)
- Increase gas pressure to 0.6 Pa, little effect
- **GUESS: Cs sputtering** by back-streaming ions

## ■ Solution

- Cs supplement is very **restrained** this campaign
- Total Cs consumption: **top oven** ~0.256 g **54**  
**bottom oven** ~0.206 g **days**
- ONLY when  $e/H^- > 0.5$ , Cs supplement turn on
- Unbalance **Cs top/bottom supplement**, to uniform heat load on **top/bottom EG segment**



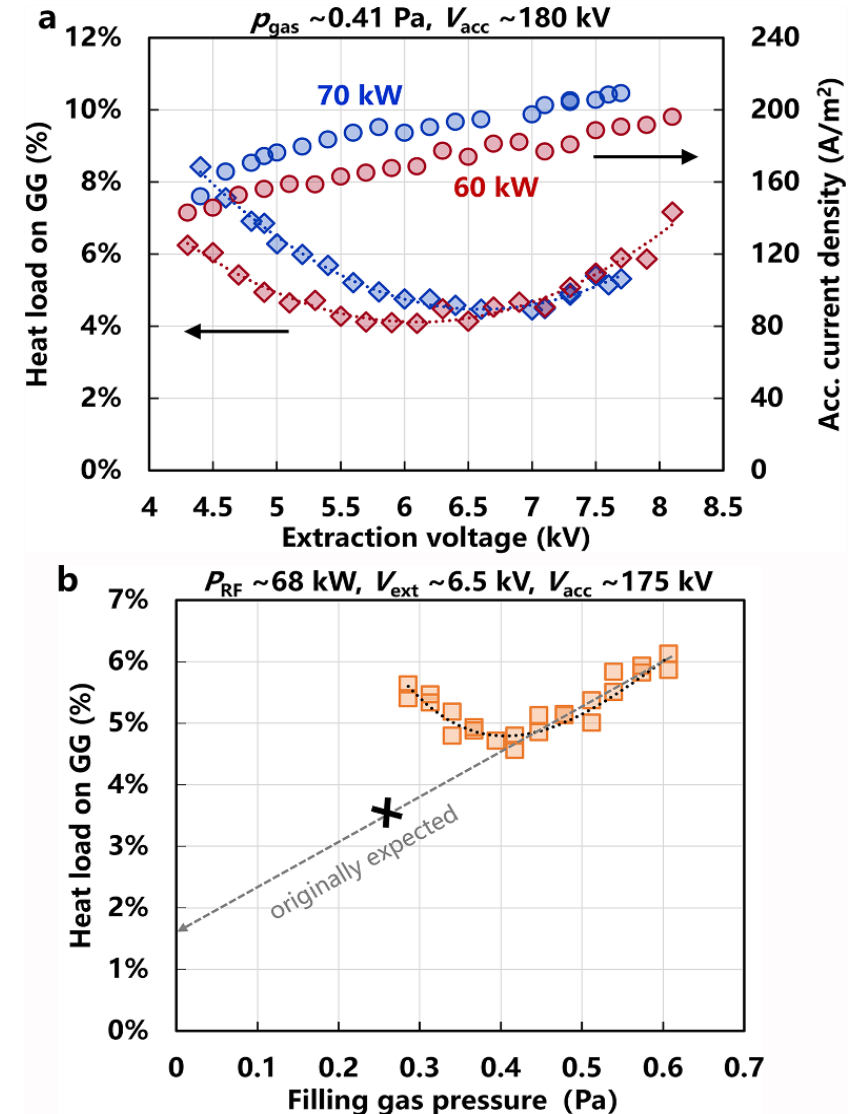
## ■ Problem

**Beam acceleration breakdown still exist in high-power operation**

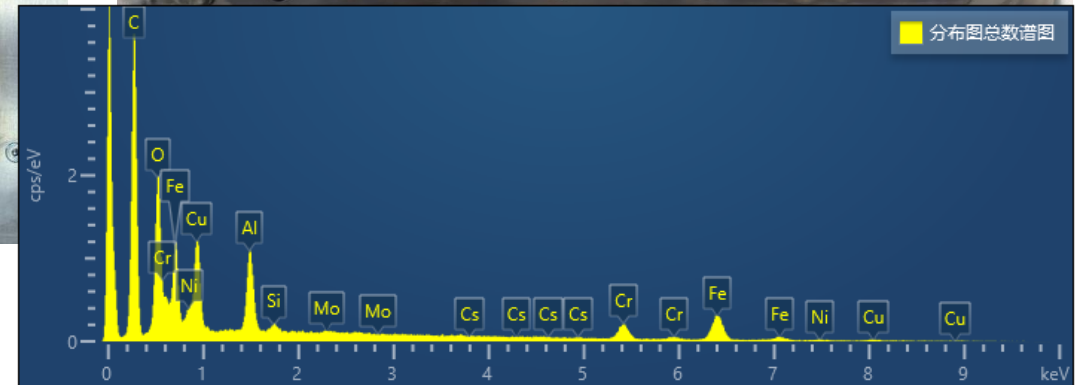
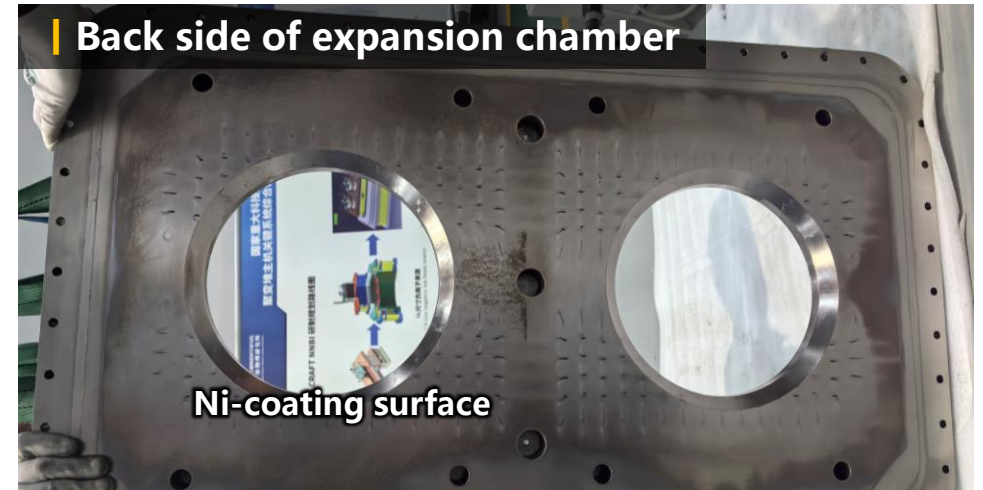
- Campaign **2024**: Acc. breakdown is **14 times** during 1.4 MW, 110 s shot
- Campaign **2025**: Acc. breakdown is **2 times** during 2.1 MW, 120 s shot

## ■ Solution

- **1** Low Cs supplement also reduce Acc. breakdown
- **2** Minimize **heat load on GG** via **parametric scan** measured by WFC (Water Flow Calorimetry)
- **3** Minimize **beam width** via **parametric scan** measured by DSS (Doppler Shifting Spectroscopy)
- For 15 A, 200 keV beam, best parameters:  
 $V_{\text{ext}} \sim 8 \text{ kV}$ ,  $p_{\text{filling}} \sim 0.4 \text{ Pa}$ ,  $V_{\text{bias}} \sim 18 \text{ V}$



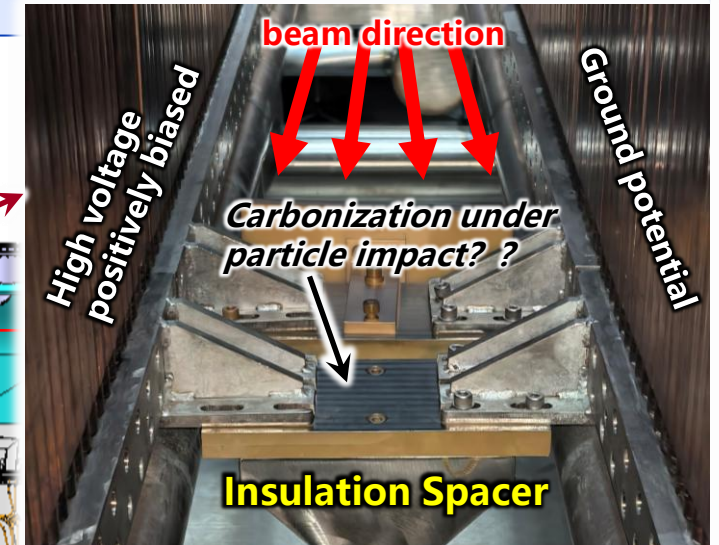
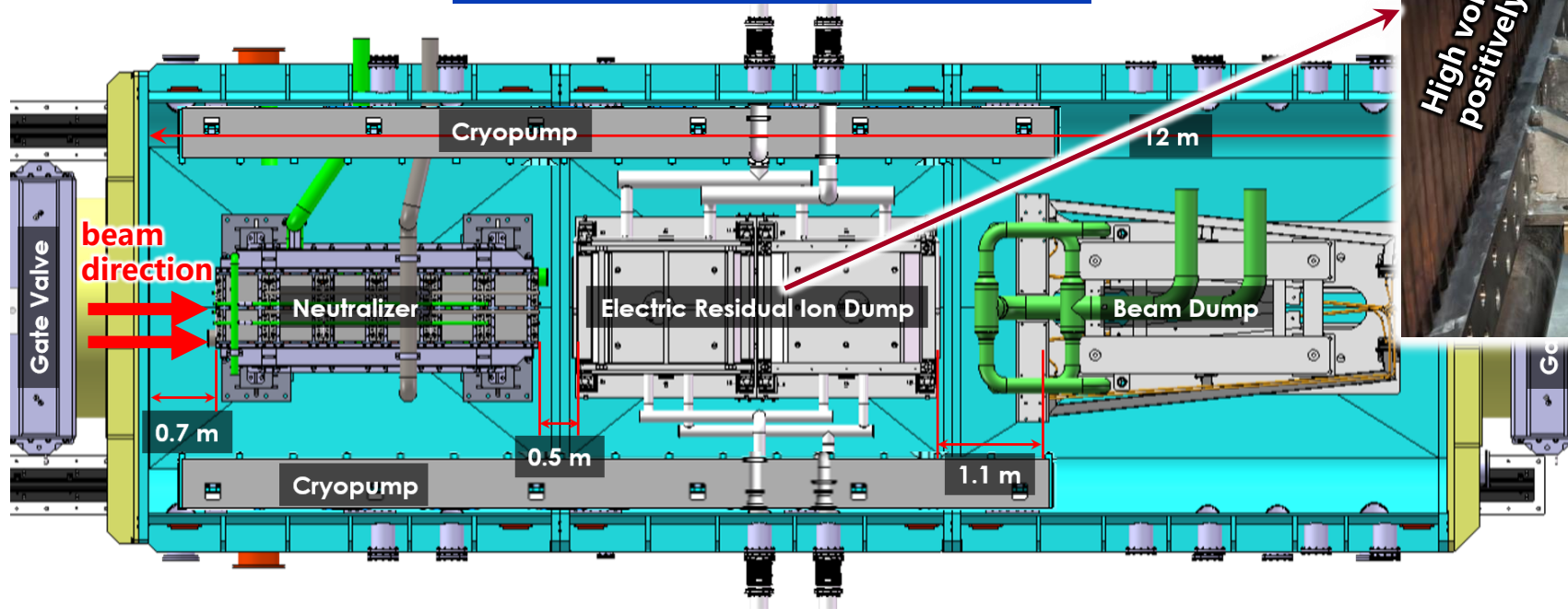
- No erosion, deformation or damage, on each component
- **But serious Cu layers**, on back side of EG, PG and source chamber (analyzed via SEM)



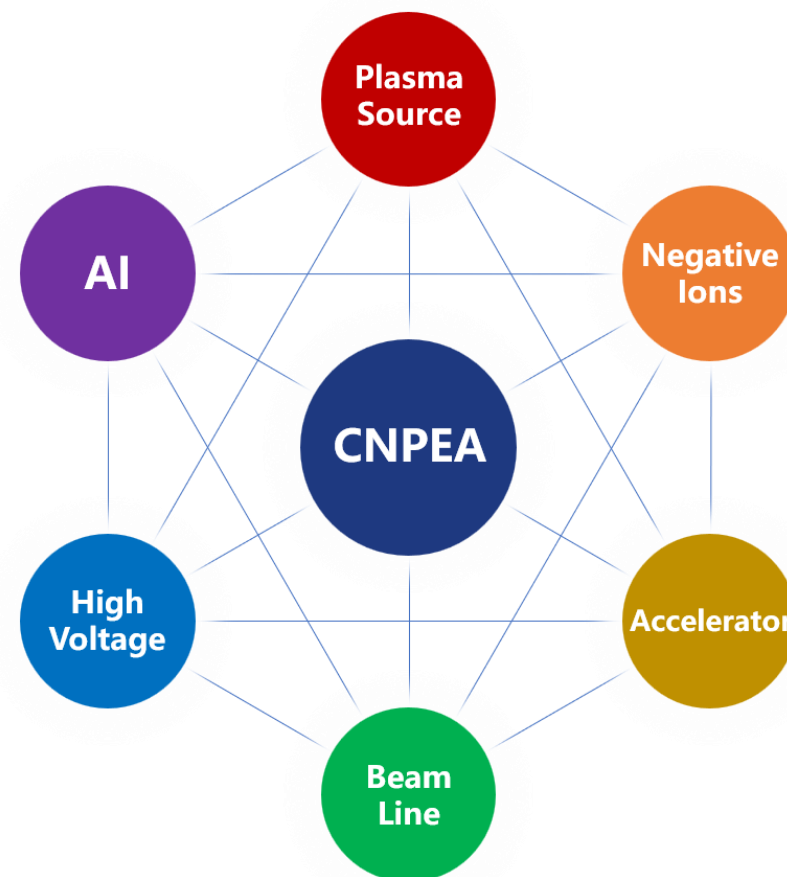
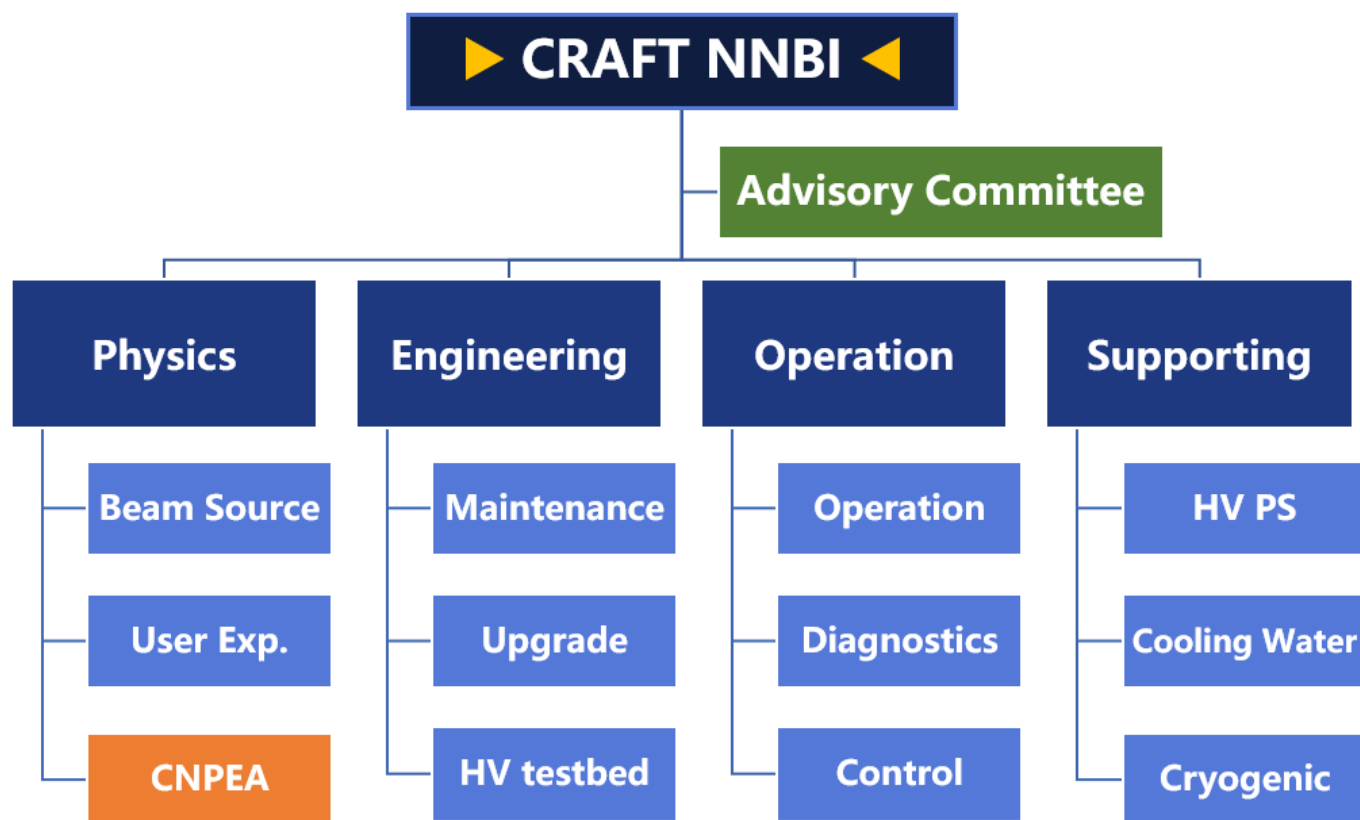
## ■ Problem: Electric breakdown between high-voltage and grounded plates

- w/o beam, 10 kV holding on ERID was OK; with beam, working pulse of ERID was 2~3 s
- with or w/o neutralizer gas, high or low potential, had little effect

### Design of CANBE Beam Line



- CRAFT NNBI project includes **four working groups** (Physics, Engineering, Operation, Supporting)
- R&D organized under **CRAFT NNBI Physics & Engineering Activity** (CNPEA)



## ■ Motivation

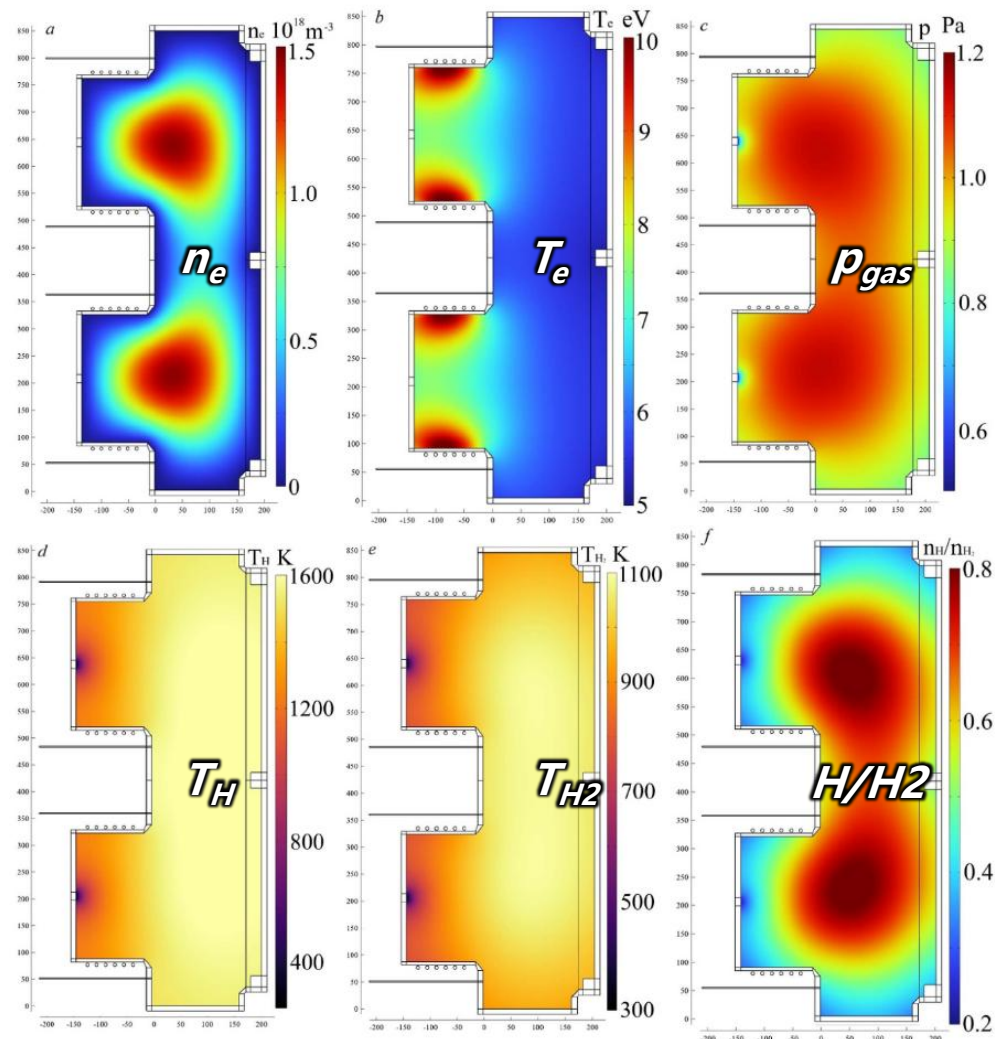
Is gas pressure 0.3 Pa for RF plasma simulation of NNBI source?

- Most of previous RF plasma simulations pursue a low-pressure gas discharge fixing at  $\sim 0.3$  Pa
- **Gas diffusion, depletion and heating** can change gas density, temperature and pressure

## ■ Research Activity

- Self-consistent diffusion modeling of precursor plasma and **neutral dynamics**
- With **constant gas flow rate** (corresponding to filling pressure of 0.4 Pa)
- Gas pressure increase to **1.2 Pa in the plasma center** and **0.9 Pa near the PG**
- H and H<sub>2</sub> temperature increase to  $> 1000$  K

Stepanov D S et al 2026 *Plasma Sources Sci. Technol.* **35** 085007



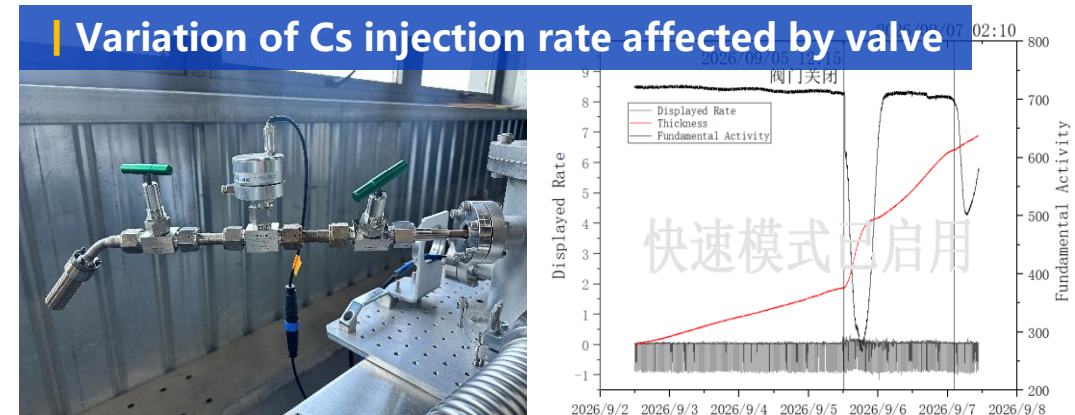
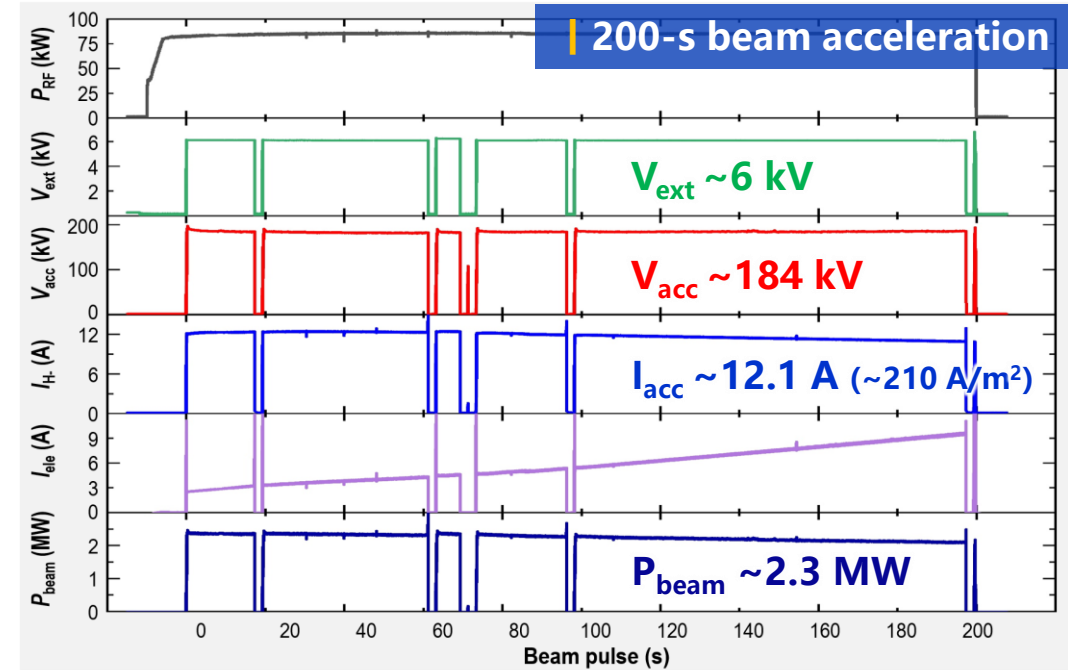
## ■ Motivation

Extraction of H- and e current is not stable during long-pulse operation

- 190 kV, 12 A (210 A/m<sup>2</sup>), 200 s beam acceleration
- H- current **slightly decrease** after 100 s
- **e current always increase from 3 A to 9 A**

## ■ Research Activity

- Propose to **supplement Cs** via more injection ports during beam acceleration
- Based on film thickness gauge, to test **turn on & off** process of
  - 1 pneumatic valve
  - 2 extra rotating mechanism



## ■ Motivation

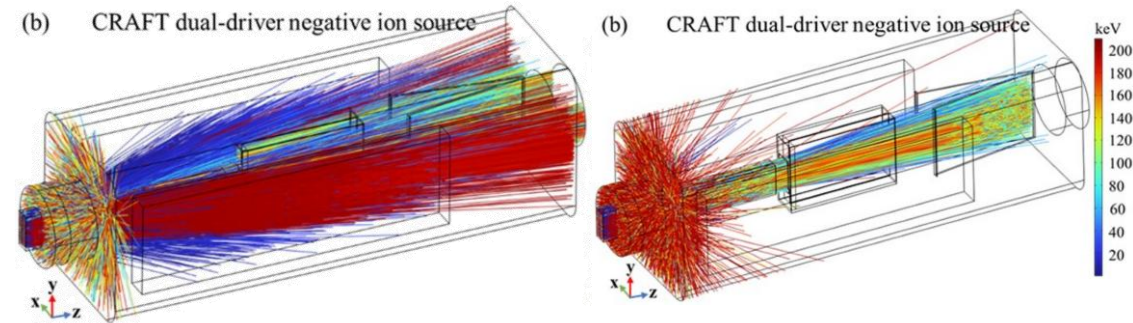
Stray particles become key factor in high-power long-pulse beam acceleration

- Grid supporting frames made by stainless steel, tend to **deformation & erosion w/o cooling**
- Cryopump temperature slightly increase during beam acceleration

## ■ Research Activity

- Simulation of stray particle trajectory to **assess heat loads inside or outside accelerator**
- Optimize thermal management including stray particles
- Measured heat load on ED of accelerator **~4%** **ratio to beam power**
- Measured heat load on ED of beam line **~5%** **ratio to beam power**
- **Heat load on EDs can reflect beam quality**

## | Stray electron outside accelerator



## | Stray electron dump of accelerator & beam line



## ■ Motivation

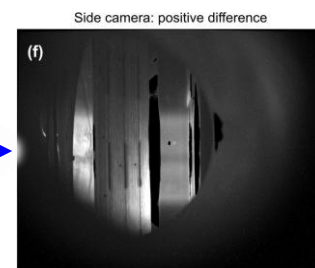
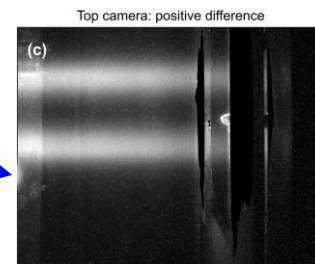
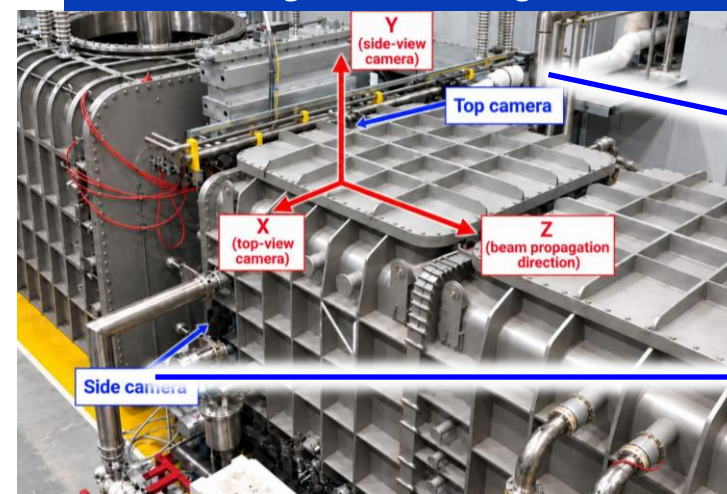
What dose beam profile & quality change during long-pulse beam acceleration?

- Calorimetry or Thermal Radiation based diagnostics may **become invalid due to heat accumulation**
- Cs re-distribution strongly affect beam parameters

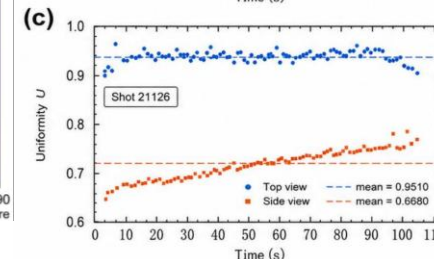
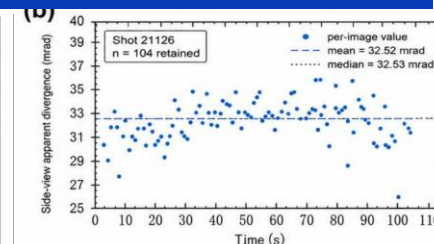
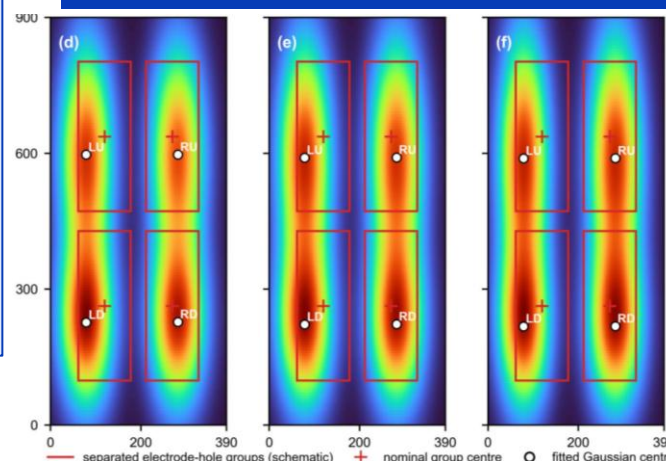
## ■ Research Activity

- By using **multiple line-of-sight DSS** to analyze distribution of beam in & beamlet divergence
- By using **array of secondary electron collectors** on beam dump to reconstruct beam profile
- By using **beam monitors** to reconstruct beam profile
  - Two orthogonal cameras (non-custom)
  - Based on Simultaneous Algebraic Reconstruction Technique (**SART**)

### | Two orthogonal visible light cameras



### | Reconstruction of beam profile & Variation of beam quality



## ■ Motivation

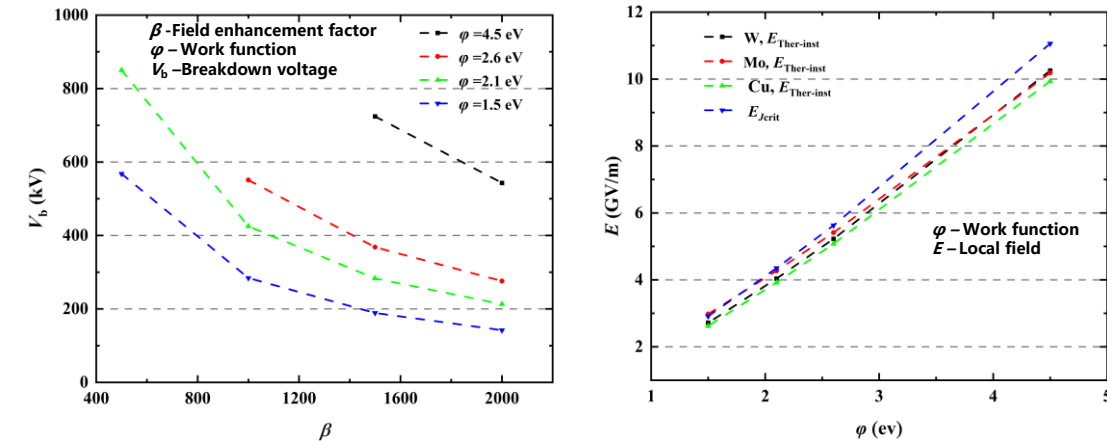
### How does Cs on the electrodes affect the insulation performance?

- Degradation of insulation performance caused by Cs deposition in the accelerator has already been observed during experiments.
- Scaling and methodology of Cs injection under safe insulation conditions need to be determined.

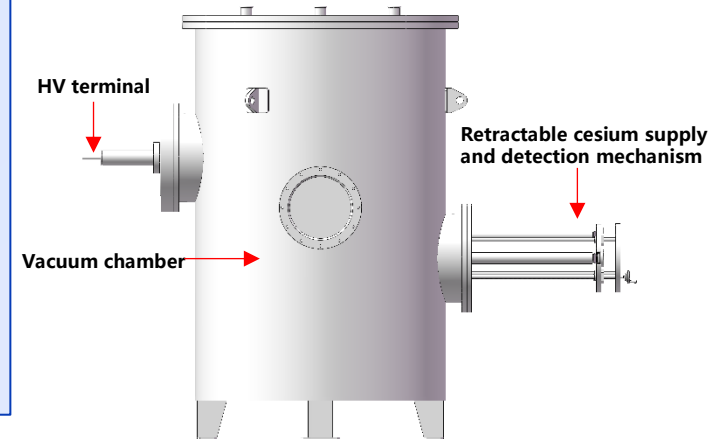
## ■ Research Activity

- By correlating the calculation models of field emission, thermal-field emission, and area effect with Cs-related parameters, a theoretical evaluation of the accelerator insulation performance with and without cesium deposition can be achieved.
- Experimental study on voltage withstand capability under varying parameters include Cs deposition amount, gas pressure, and substrate material.

### | $V_b$ - $\beta$ - $\phi$ & $E$ - $\phi$



### | Experiment setup



### ● Experimental Content

1. Cs deposition amount
  2.  $H_2$  pressure
  3. Substrate material
  4. Micro gap & long gap
  5. Thermal redistribution of Cs
- .....

## ■ Motivation

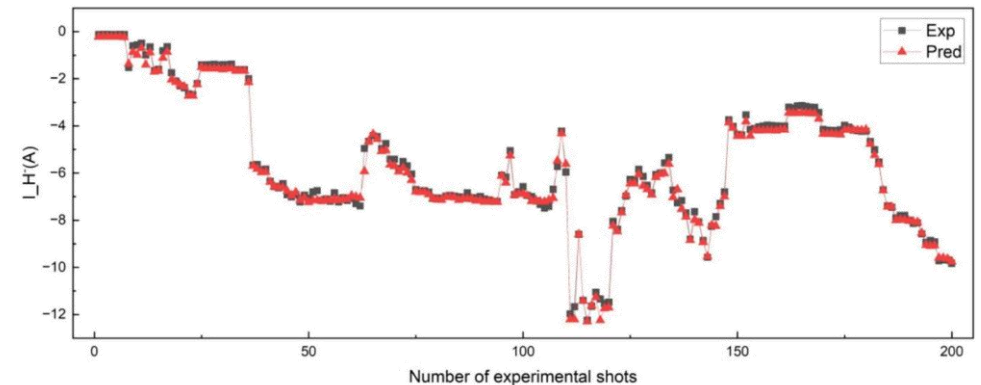
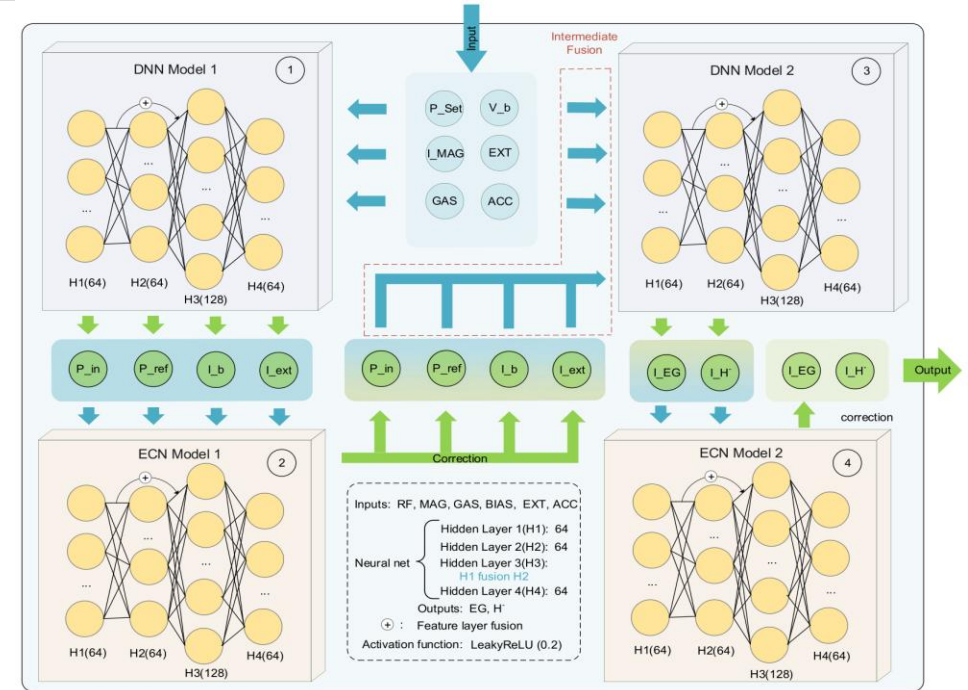
### What can we do in the Era of AI?

- AI can operate the conditioning of ion source
- AI can expedite on-line diagnostics for feedback control of beam parameter

## ■ Research Activity

- Performance prediction of the dual-driver RF negative ion source
- Data of whole year 2025, with Cs seeding
- **Prediction error ~8.2% for H- current**  
**~7.6% for e current**
- Assess Cs condition during long-term operation or **when should we supplement Cs?** (ongoing)

Gu Y et al 2025 *Nucl. Fusion* **65** 096011



- Requirements of NNBI are **500 keV, 4 MW for BEST** and **1000 keV, 35 MW for CFEDR in China**, which promote the construction of CRAFT NNBI test facility
- In first stage of 2026 experimental campaign, there are **72 beam operation days** (12 h each day), **~6,000 beam shots** (typical pulse of 20~40 s)
- **203.2 keV, 15.1 A (265 A/m<sup>2</sup>), 104 s** negative hydrogen beam acceleration has been achieved by using CRAFT dual-driver RF negative ion source (reach design target)
- Main modifications include **low-dose & intermittent Cs injection** into source (~0.46 g for 54 days) and **heat-load control** on grid electrodes
- No obvious damage was found inside ion source after long-pulse and high-power operation, except **Cu sputtering** from electrodes
- R&D on NNBI technology were carried out under **CRAFT NNBI Physics & Engineering Activity**, contain plasma source, negative ions, accelerator, beam line, high voltage, artificial intelligence



**2026 | 200 keV, 1 MW, 100 s,  $H^0$**



**2026 | 300 keV, 2 MW, 100 s,  $H^0$**



**2028 | 500 keV, 4 MW, 1000 s,  $H^0$**

## ■ Acknowledgements

Most of our designs, manufactures and operations are learned from the open publications,  
Thank all NIBS colleagues worldwide, for sharing your knowledge.



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Comprehensive Research Facility for Fusion Technology

# Thank you

## Questions & Discussions

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## ■ World-class large scientific infrastructures cluster