



中国科学院合肥物质科学研究院
Hefei Institutes of Physical Science, Chinese Academy of Sciences



Study on HV Breakdown Mechanisms Based on FE and TFE under Cesium Deposition Conditions & an Experimental Plan

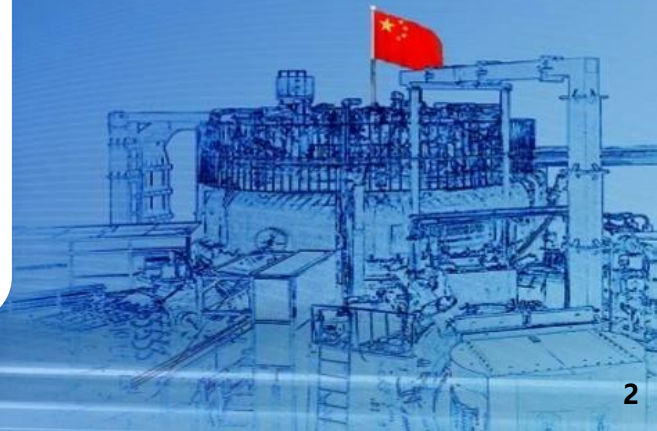
Speaker: Bo Liu

September 24, 2026



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- 01 Introduction**
- 02 Experimental Setup**
- 03 Future Plans**
- 04 Summary**



Part 01

Introduction

R&D Background



Introduction

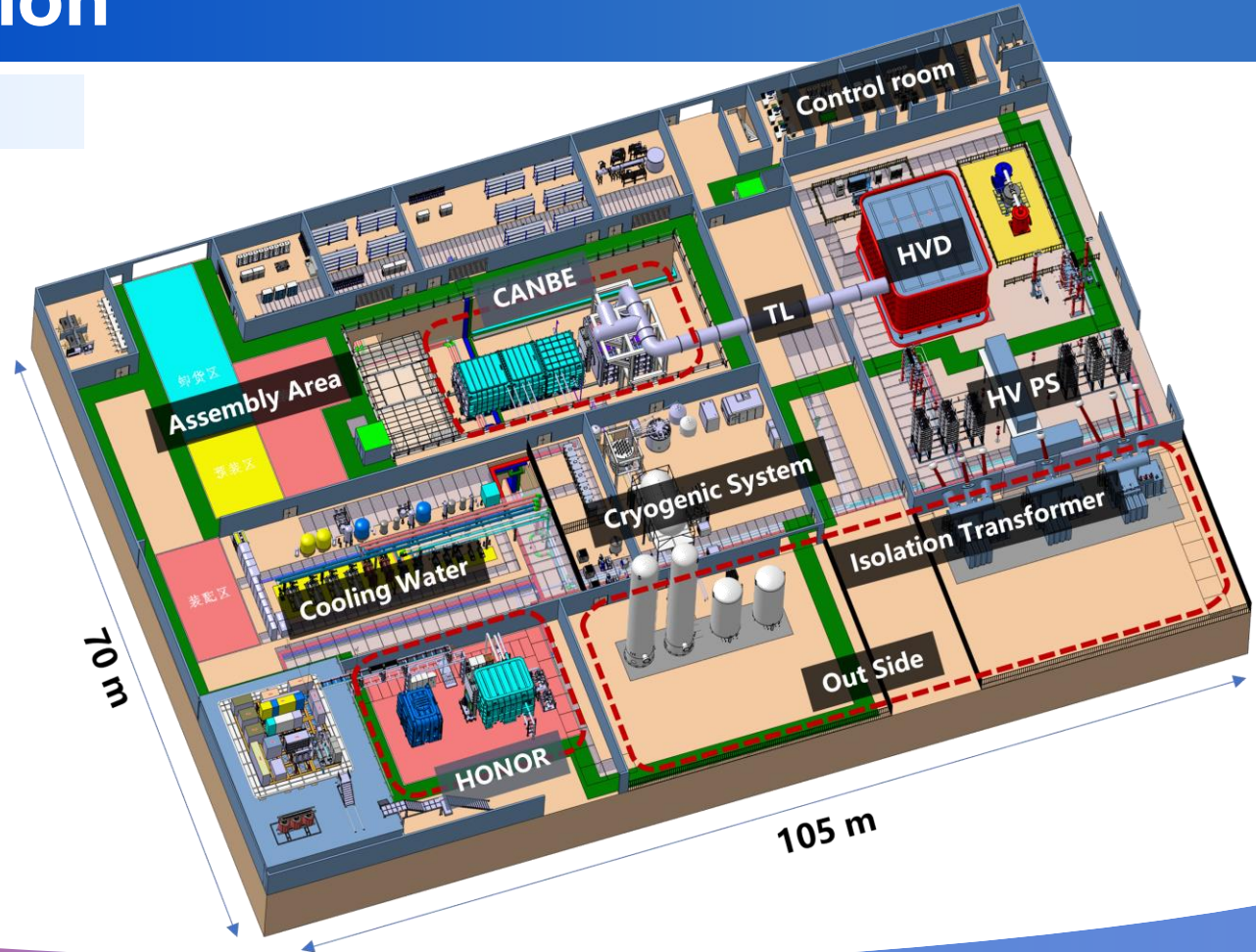
The CRAFT NNBI

- **The HONOR facility**

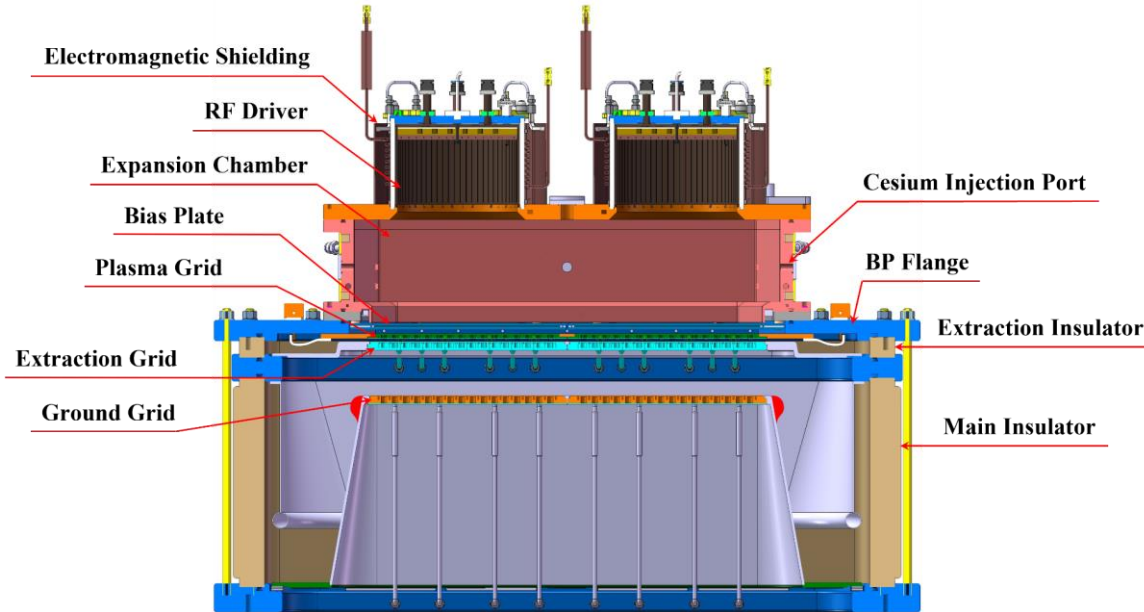
Hefei Open-facility for Negative-ion Source Research, dedicated to negative ion source experimental studies / RF ion source development

- **The CANBE facility**

CFEDR Advance Neutral Beam Equipment, serves as neutral beam injector for CFETR — a full-function NNBI beamline



The negative ion beam source



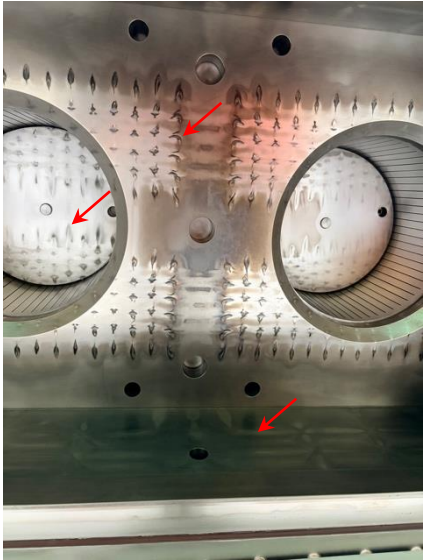
The Dual-driver Negative Ion Beam source of CRAFT NNBI

Items	Value
RF Power	140 kW
Extraction Voltage	-8 kV
Accelerator Voltage	-200 kV
Ion Current	15 A
Pulse Duration	>100 s
Cs Injection Port	2
d_{PG-EG}	7 mm
d_{EG-GG}	90 mm

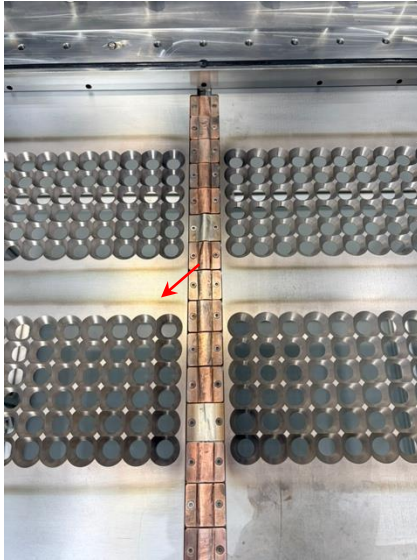
Introduction

| Where does the injected Cs go?

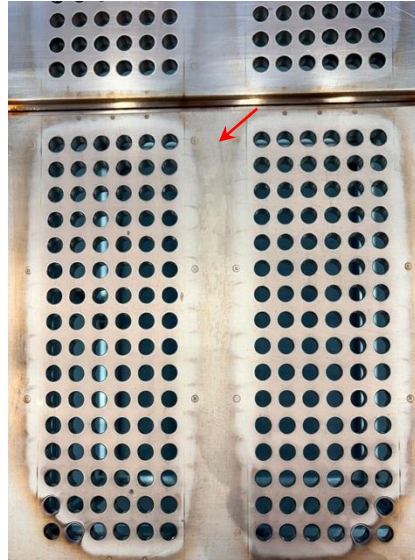
| The Expansion Chamber



| The PG



| The EG



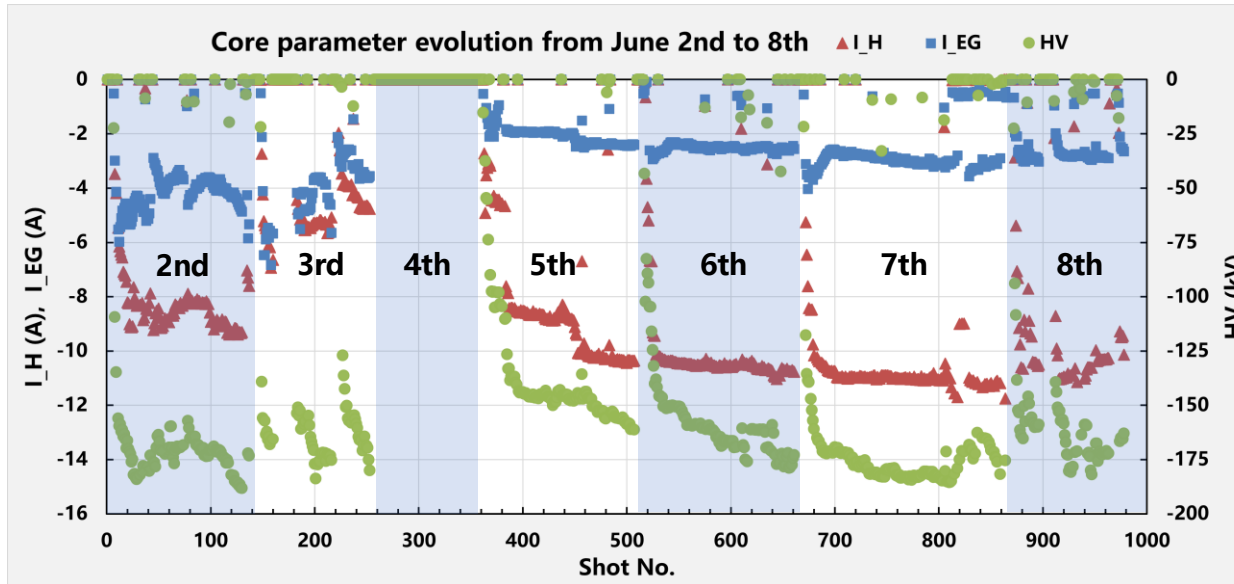
| The GG



- In the LHD-NNBI, approximately 99.5% of the cesium deposited in the plasma generator, and 0.5% deposited on the accelerator electrodes [1].

[1] K. Tsumori, et al. 2010.

What happens macroscopically?



2nd: Normal operation

3rd: Over cesiated, H-/e ratio decreases

4th: RF plasma discharge cleaning @80 kW/100 s

5th: Negative ion yield returns to normal, frequent breakdowns

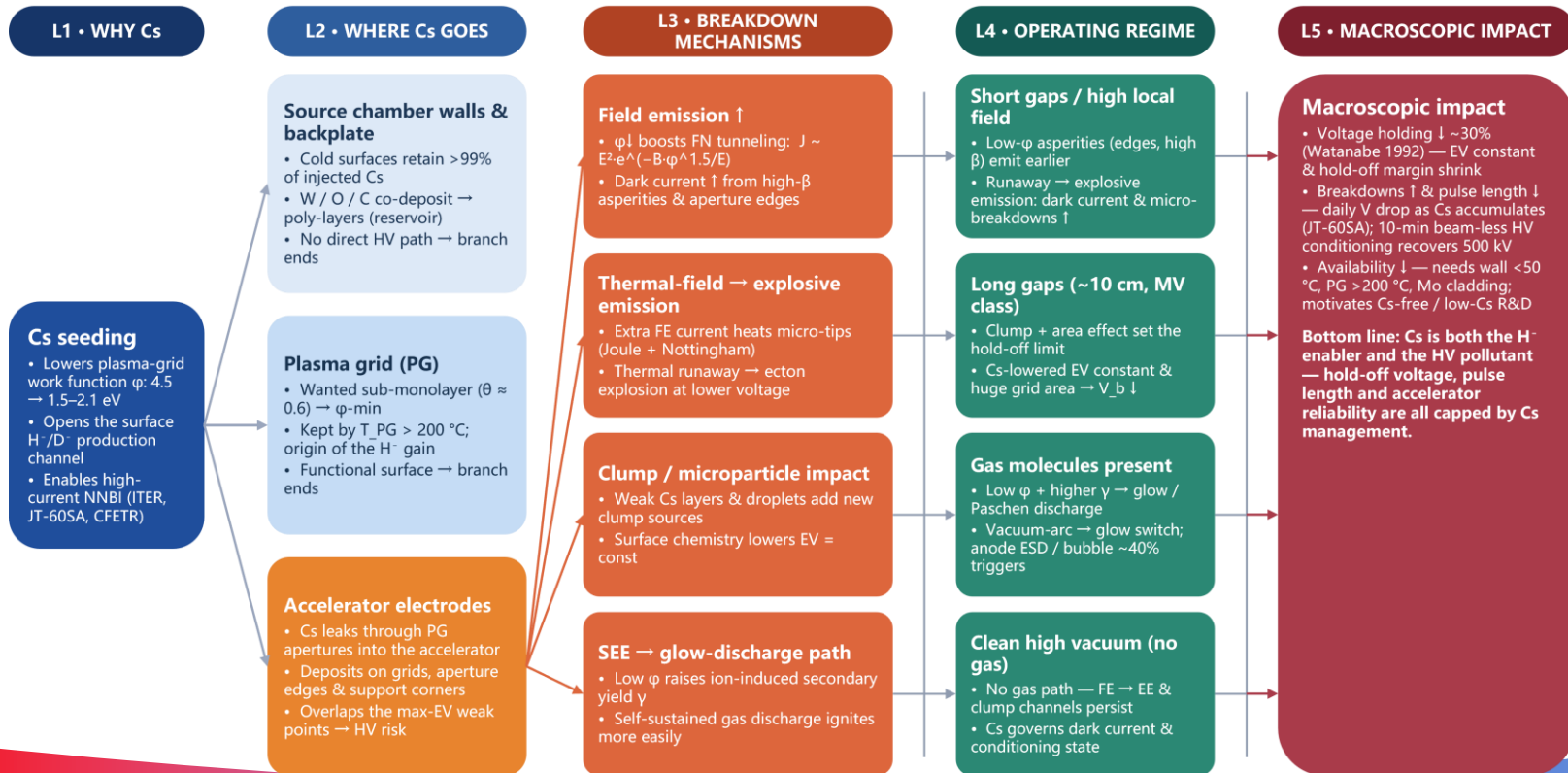
6th:Stepping up the operation voltage

7th: The acceleration voltage recovers

8th: Normal operation

Full-chain effect of cesium on vacuum insulation

NNBI • 1 MV accelerator • vacuum insulation



Part 02

Theoretical Evaluation

FE&TFE

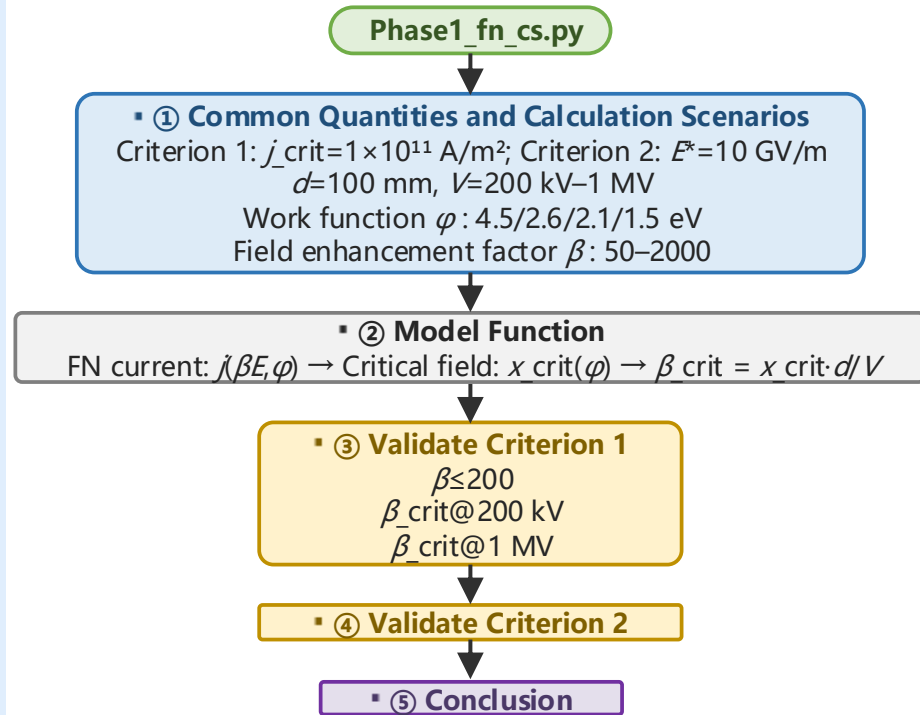


Theoretical Evaluation

Phase1: Effect of low work function of Cs on field emission

The model introduction

- Assume a vacuum gap with a spacing of 100 mm, across which a voltage of 0.2–1 MV applied.
- The work functions of a clean electrode surface, a contaminated cesium-covered surface, an ideal cesium monolayer surface, and an optimal cesium submonolayer surface are 4.5, 2.6, 2.1, and 1.5 eV, respectively.
- Starting from the two criteria of critical current density and local electric field strength, determine whether field emission can lead to microprotrusion explosion-induced breakdown.



Theoretical Evaluation

Phase1: Effect of low work function of Cs on field emission

The modeling principles

MODEL FUNCTION A • $J_{FN}(\beta E, \varphi)$

Fowler–Nordheim emission engine

- (1) local field: $\beta E = \beta \cdot V / d$ ^[2]
applied field V/d , amplified by the site's factor β
- (2) Fowler–Nordheim current density ^[3]
 $J = A_{FN} \cdot (\beta E)^2 / \varphi \cdot \exp(-B_{FN} \cdot \varphi^{1.5} / \beta E)$
- (3) constants ^[3]
 $A_{FN} = 1.541434e-6 \text{ A-eV} \cdot V^{-2}$
 $B_{FN} = 6.830890e9 \text{ V/(m-eV}^{1.5})$
- (4) work-function inputs ^[4]
 $\varphi = 4.5 \text{ eV clean; } 2.6 / 2.1 / 1.5 \text{ eV Cs-conditioned}$
- (5) guard: $\beta E \leq 0 \rightarrow J = 0$

→ J [A/m²]

MODEL FUNCTION B • $x_{crit_local}(\varphi)$

Log-space root-find of criterion 1 → the trigger local field

- (6) criterion 1: $J = J_{crit} = 1 \times 10^{11} \text{ A/m}^2$ ^[2]
Fursey 1985 explosive-emission threshold, taken at the LOW end
 - (7) root find: $J(x_{crit}, \varphi) = J_{crit}$
geometric bisection on [1e8, 1e13] V/m, 200 steps
 - (8) shortcut: $x_{crit} \approx B_{FN} \cdot \varphi^{1.5} / L$
 $L \equiv 2 \cdot \ln x - \ln \varphi - \ln(J_{crit}/A_{FN})$; contraction $2/L \approx 0.39$
Cross-check: Ding 10±0.5, Barengolts 10.8, Ishida 13 GV/m ^{[5][6]}
- x_{crit} [GV/m]

MODEL FUNCTION C • $V_b(\varphi, \beta)$ and $\beta_{crit}(\varphi, V)$

Two voltage-side readings — criterion 1 and criterion 2

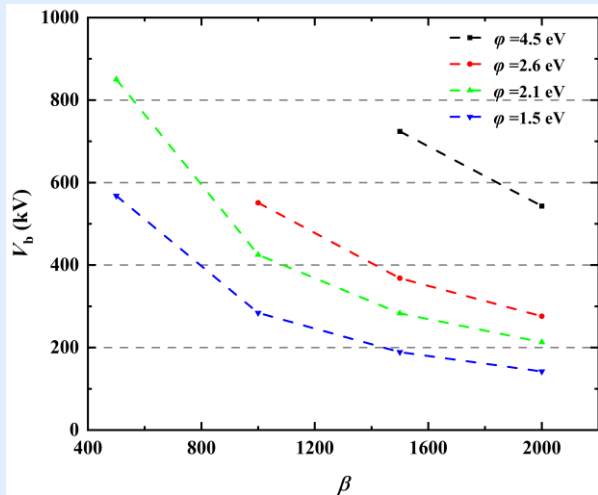
- (9) emission trigger: solve $J(\beta V_b/d, \varphi) = J_{crit}$ ^[2]
bracket [1e3, 1e6] V, 120 bisections
 - (10) Critical field factor: $\beta_{crit} = x_{crit} \cdot d / V$ ^[2]
@200 kV & @1 MV
 - (11) Criterion 2: constant local field $E_{local,crit} \approx 10 \text{ GV/m}$ ^[5]
 φ -independent: $V_b = E_{local,crit} \cdot d / \beta$
 - (12) Drop & gain: $\Delta = 1 - x_{crit}(Cs) / x_{crit}(clean)$ ^[5]
 β cancels (49.3% at $\beta = 1500$ and 2000);
- V_b [kV] & β_{crit}

Theoretical Evaluation

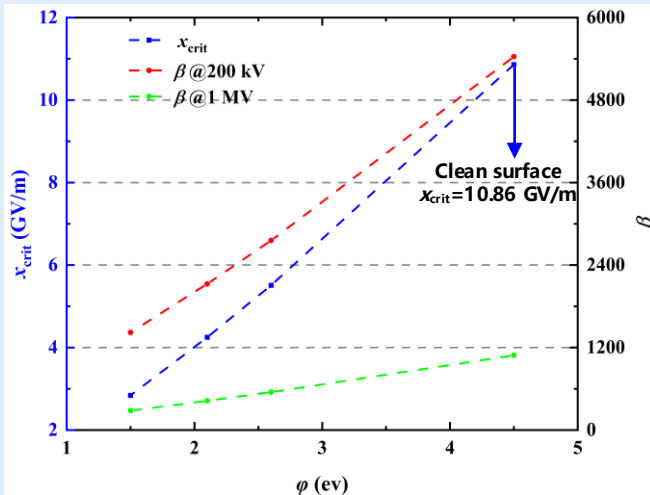
Phase1: Effect of low work function of Cs on field emission

The results of phase 1

The breakdown voltage under criterion 1



Critical local field under different ϕ & critical β under different voltages



The breakdown voltage under criterion 2 (ϕ independent)

β	50	200	500	1000	2000
V_b (kV)	2e4	5000	2000	1000	500

FE current at fixed local field $\beta E = 5$ GV/m

ϕ (eV)	2.6	2.1	1.5
J_{FN} (A/m ²)	4.825e10	2.871e11	2.088e12
Amplification vs $\phi=4.5$ eV	2.6e3	1.5e4	1.1e5

- According to Criterion 1, a decrease in ϕ leads to a significant reduction in the field-emission-induced breakdown voltage.
- Under the typical field enhancement factors ($\beta < 500$) of negative ion accelerators, breakdown caused purely by field emission is unlikely to occur.

Theoretical Evaluation

Phase2: Thermal instability of microprotrusion

The model introduction

- This model introduces a temperature term into the field emission current, from TFE spectral emission engine. It is validated using the Fowler-Nordheim equation.
- Using 0-D and 2-D models with TFE to calculate the local field strength required for thermal instability.

phase2_site_instability.py

① Inputs & Criterion

Criterion: $j_{crit} = 1 \times 10^{11} \text{ A/m}^2$ (low end of Fursey explosive emission)
 Materials W / Mo / Cu (T_{melt} 3695 / 2896 / 1358 K)
 Microprotrusion $\bar{R} = 1 \text{ } \mu\text{m}$, $H = 10 \text{ } \mu\text{m}$

② Model Function A • TFE spectral emission engine

$J(F, T, \varphi)$ = free-electron supply function $\times$ JWKB triangular-barrier transmission (numerical energy-grid integration)
 Also returns the mean emission energy $\langle u \rangle$ (Nottingham term, including the reversal temperature T_N)

③ Model Function B / C • Lumped thermal model + 2D FEM

B: $q_{gen} \text{ (Joule + Nottingham)} = q_{cool} \text{ at onset} \rightarrow E_b$
 C: 2D axisymmetric electro-thermal FEM

④ Output • Site-level breakdown field $E_b(\varphi)$

⑤ Conclusion

Theoretical Evaluation

Phase2: Thermal instability of microprotrusion

The modeling function

MODEL FUNCTION A • TFE (E , T , φ)

TFE spectral emission engine

- (1) free-electron supply function ^[7]
Sommerfeld free-electron gas, Fermi–Dirac
- (2) JWKB transmission coefficient ^{[3][7]}
triangular Fowler–Nordheim barrier, no image force
- (3) TFE current density — 0th moment ^[7-9]
Murphy–Good integral, $c_T(T)$ prefactor
- (4) Nottingham energy $\langle u \rangle$ — 1st moment ^[10-12]
sign of $\langle u \rangle$ sets Nottingham heating / cooling
- (5) Fowler–Nordheim equation — 0 K check ^[3]

→ J [A/m²] & $\langle u \rangle$ [eV]

MODEL FUNCTION B • 0-D lumped thermal runaway

Balance_0d() → $q_{\text{gen}} - q_{\text{cool}}$ stable $T() \rightarrow T_{\text{stab}}$, $E_{\text{b, 0D}}$

- (7) Nottingham heat flux ^{[3][11, 12]}
- (8) Joule heating, lumped ^{[3][6]}
- (9) Fourier conduction cooling ^[3]
- (10) Empirical $k(T)$, $\rho_e(T)$ laws
- (11) Thermal instability — saddle-node bifurcation → $E_{\text{b, 0D}}$ ^{[3][10][13]}
- (12) Explosive-emission criterion, $J_{\text{crit}} \approx 10^{11}$ A/m² ^[4]
- (13) Adiabatic melting time ($J^2 t_{\text{action}}$) ^{[3][6]}

→ $E_{\text{b, 0D}}$ [GV/m] & T_{stab} [K] & E_{jcrit} , t_{melt}

MODEL FUNCTION C • 2-D axisymmetric FVM

Solve_2d_axisym() → $T(r, z)$ $E_{\text{b, 2d_sweep}}() \rightarrow E_{\text{b, 2D}}$ + hot spot

- (14) Axisymmetric steady heat conduction ^[10]
- (15) Volumetric Joule source, patch-current spreading ^{[6][10]}
- (16) BCs: Neumann top/ Dirichlet base / adiabatic side ^{[3][10]}
- (17) Finite-volume discretisation → thermal-resistance network ^[10]
- Picard + sparse solve; continuation sweep in $E \rightarrow E_{\text{b, 2D}}$
- (18) 1-D analytic thermal-resistance benchmark → ratio 0.9938 ✓

→ $E_{\text{b, 2D}}$ [GV/m] & hot-spot z_{max}

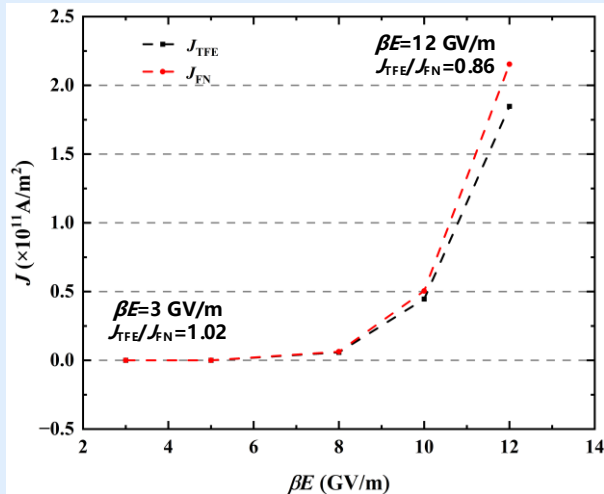
[7] Murphy E. L. et al. 1956. [8] Lin C. et al. 2024. [9] Zhao J. et al. 2024 [10] Mofakhami D. et al. 2021. [11] Nottingham W. B. et al. 1941. [12] Fleming G M. et al. 1940. [13] Dolan W. W. et al. 1953.

Theoretical Evaluation

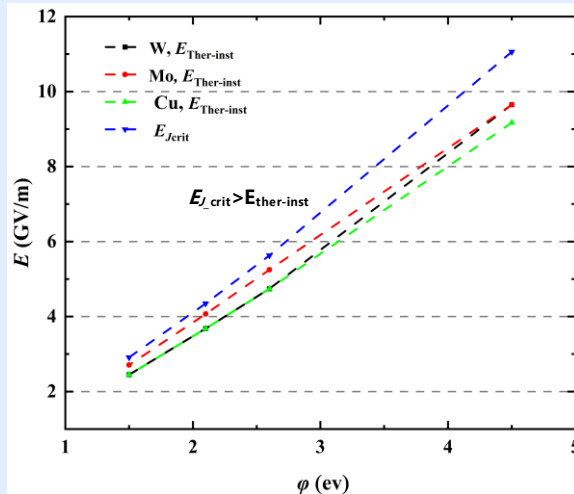
Phase2: Thermal instability of microprotrusion

The results of phase2

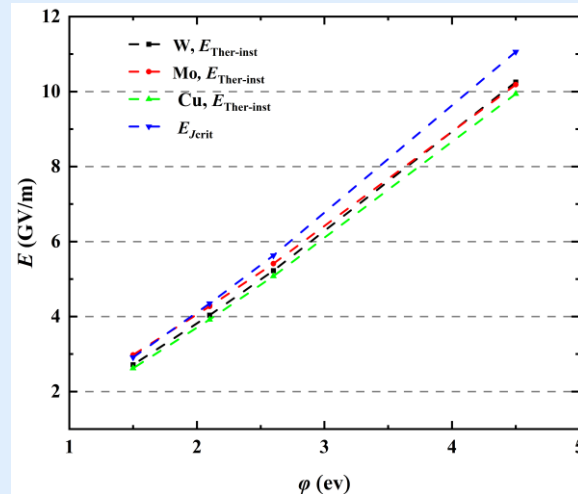
Verification of J_{TFE} calculation results, $T = 0$ K



Comparison between the thermal-instability field and the field required to reach the critical current – 0D



Comparison between the thermal-instability field and the field required to reach the critical current – 2D



- The TFE spectral emission engine agrees well with the FN equation at 0 K.
- The local field strengths for thermal instability of W, Mo, and Cu are all lower than the local critical field strengths required for pure field emission of the respective materials.

| Summary of the theoretical evaluation

- Under optimal work function conditions (1.5 eV), the field emission current density can increase by a factor of 1×10^5 compared to that of a clean metal surface.
- Breakdown caused purely by field emission requires a field enhancement factor (β) exceeding 1500, which is safe under typical negative ion accelerator processing conditions.
- Considering thermal-field emission, its breakdown voltage is lower than that of pure field emission under various material conditions.
- The model is currently limited to microscopic mechanisms. In the future, when evaluating the voltage withstand capability of the entire negative ion accelerator under cesium deposition conditions, the area effect will be further taken into account.

Part 03

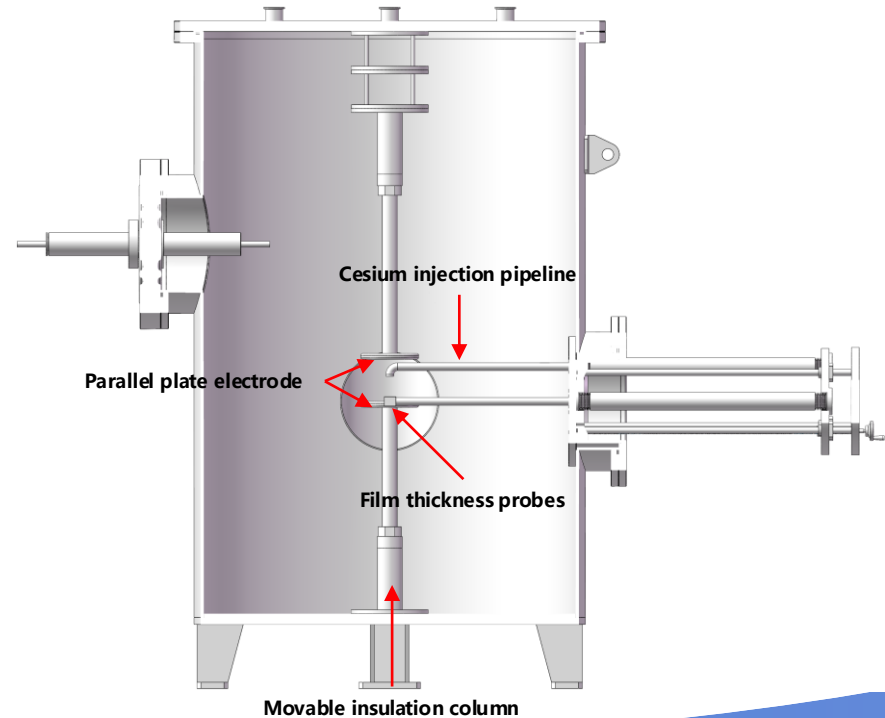
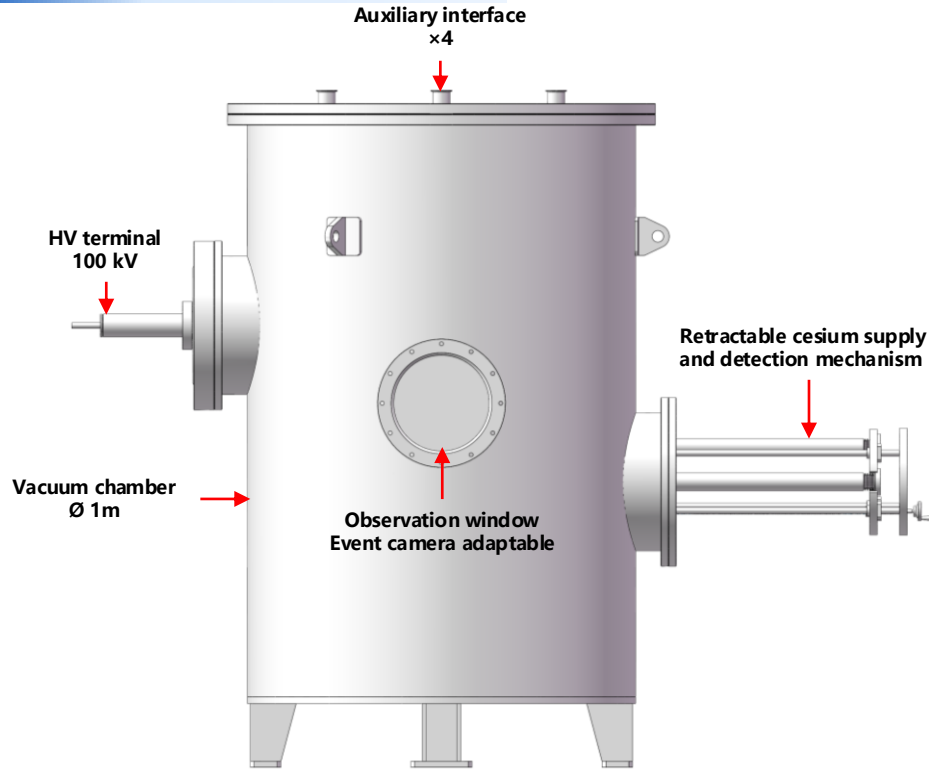
Experimental Setup

A Future Plan



Experimental Setup

Experimental facility



Experimental Setup

Experimental plans

Cs deposition
calibration

q_{cs} VS V_b

q_{cs} VS V_b ,
substrate
materials

q_{cs} VS V_b ,
 H_2 pressure

Thermal
redistribution of
Cs

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Part 04

Summary





Summary & Acknowledgments

| Summary

- Cs deposition has been observed in the negative ion accelerator of NNBI. Its impact on high-voltage insulation has been macroscopically manifested during NNBI experimental operations.
- Theoretical studies based on field emission and thermal-field emission can explain the reasons for the decline in voltage withstand capability under cesium deposition conditions, partially. However, a comprehensive and more realistic computational model for negative ion accelerators still needs to be developed.
- A cesium-related experimental facility, beyond the computational model, has been designed and is planned for operation.

| Acknowledgements

- This work has been carried out within the framework of the CRAFT NNBI Physics & Engineering Activity (CNPEA) and completed with the assistance of the CRAFT NNBI team.



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Thank you for your attention!

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