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

Burning plasma Experimental Superconducting Tokamak

Physics and Engineering Design of the 500 keV Beam Source for BEST Neutral Beam Injector

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CONTENT

Introduction of BEST

Burning plasma Superconducting Tokamak with High-Jc superconductor

Object: **to generate electricity from fusion power** for the first time on Earth

Main design parameters of JT-60SA, ITER & BEST

Key Design	JT-60SA	ITER	BEST	
Species	DD	DD, DT	**DD, DT**	
Major Radius	3.0 m	6.2 m	**3.6 m**	
Minor Radius	1.18 m	2.0 m	**1.1 m**	
Toroidal Field	2.3 T	5.3 T	**6.1 T**	
Plasma Current	5.5 MA	15.0 MA	**2.8 MA (S.S.)**	**7.0 MA (ind.)**
Fusion Power	--	500 MW	**10 MW (S.S.)**	**160 MW (ind.)**
Energy Gain Q	--	10	**0.3 (S.S.)**	**5 (ind.)**
Pulse Length	100 s (ind.)	400 s (ind.)	**1~4 h (S.S.)**	**10 s (ind.)**

S.S.=steady-state operation, ind.=inductive operation

Higher field → Higher confinement

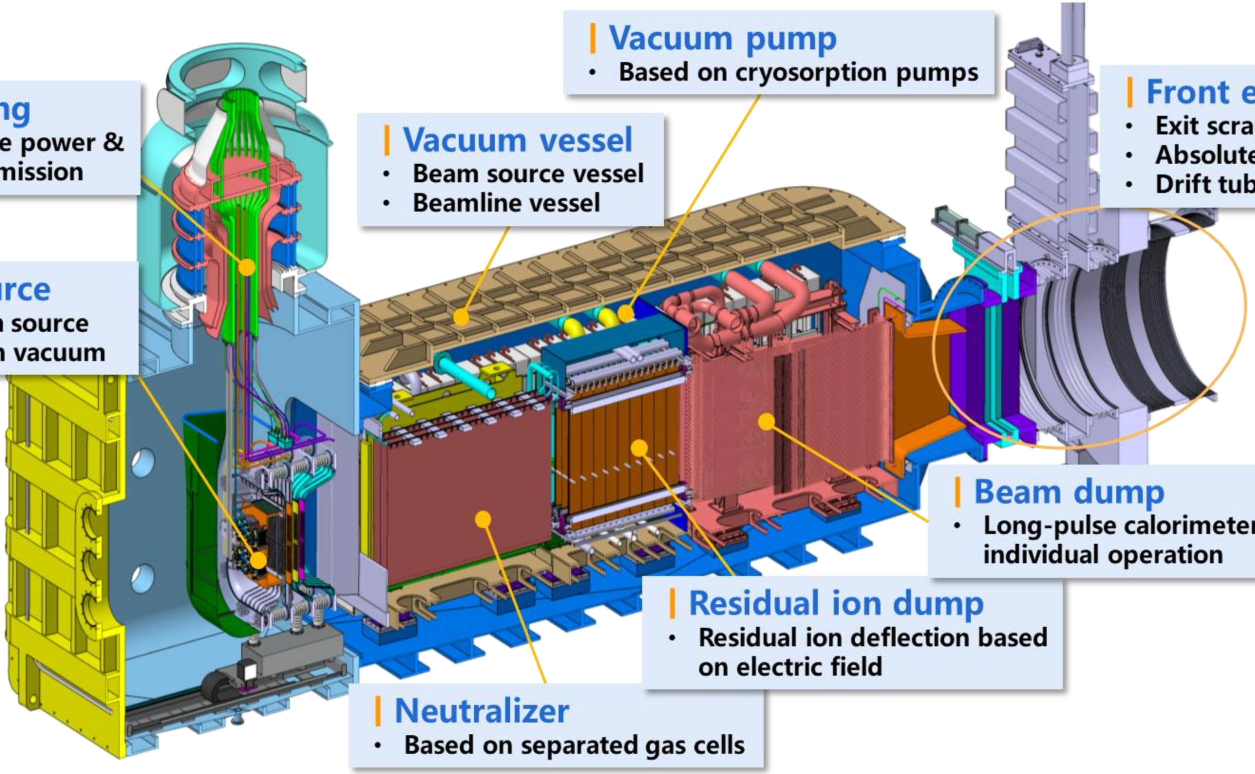
BEST Neutral Beam Injector

| For plasma heating & current drive, burning control, **essential for Q>5 scenario**

| **Negative ion source based** neutral beam injector, ITER-like structure

Basic requirements of BEST NBI

BEST NBI	Phase I	Phase II
Species	D^0	D^0
Injection Power	4 MW	10 MW
Beam Energy	500 keV	800 keV
Pulse Duration	≥1000 s	≥1000 s
Structure	One Injector with One Beam Source	
Layout	Injection Angle 31° Tangency Radius 3.12 m	



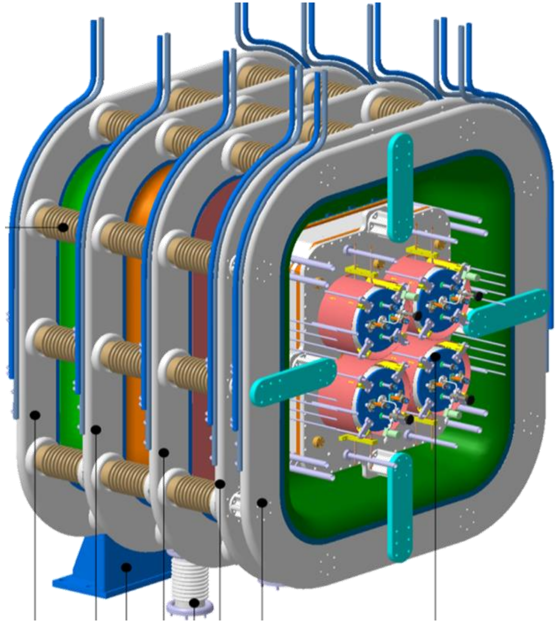
Overall Design of Beam Source

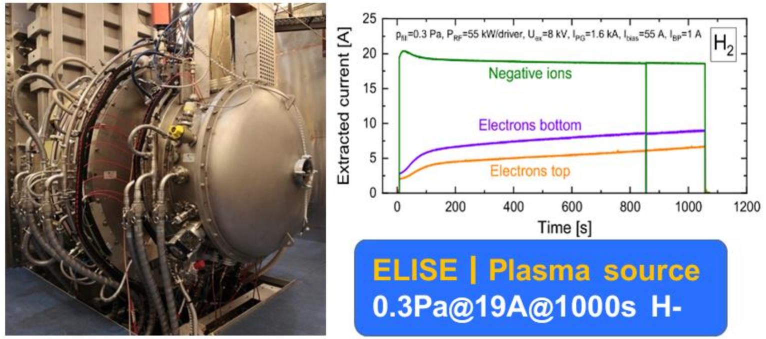
| **RF driven & Cs seeded** plasma source + **multi-aperture & multi-stage** accelerator

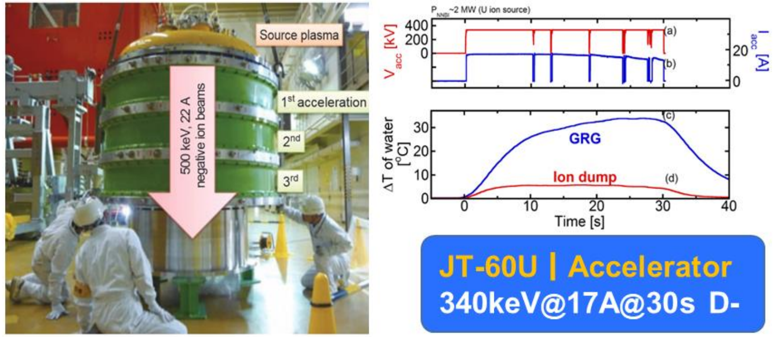
| Based on **R&D experience worldwide** and R&D activities of CRAFT NNBI project

	JT-60SA	ITER	BEST-I
Species	D-	D-	**D-**
$\eta_{transport}$	45.6%	41.2%	**40%**
P_{D-} (MW)	11	40	**10**
E_{D-} (keV)	500	1000	**500**
t (s)	100	3600	**1000**
η_{strip}	--	≤0.3	**≤0.25**
J_e/J_{D-}	≤1	≤1	**≤1**
θ_{div} (mrad)	≤7	≤7	**≤7**

| Design of BS-500keV

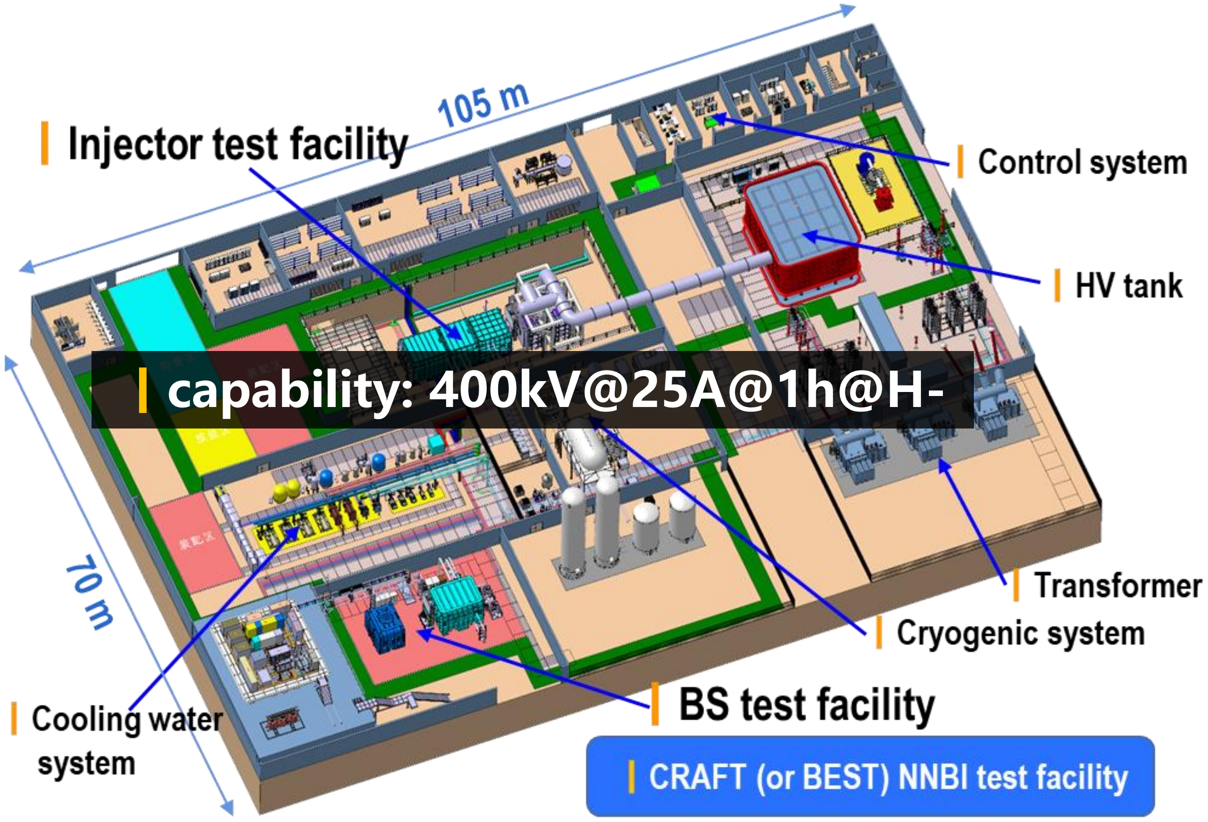




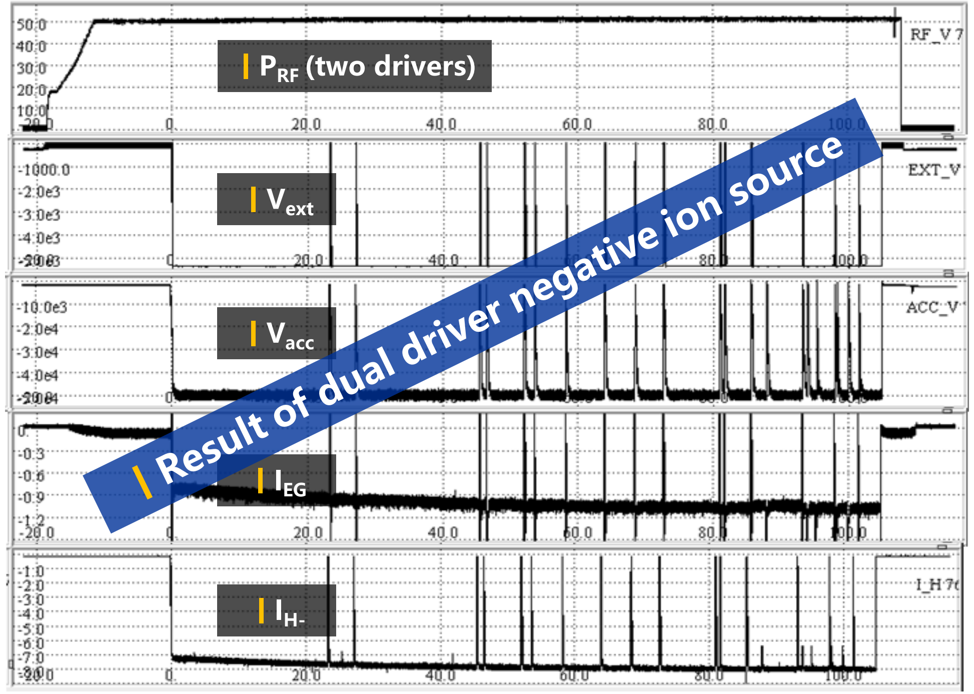


Overall Design of Beam Source

- **RF driven & Cs seeded** plasma source + **multi-aperture & multi-stage** accelerator
- Based on R&D experience worldwide and **R&D activities of CRAFT NNBI project**

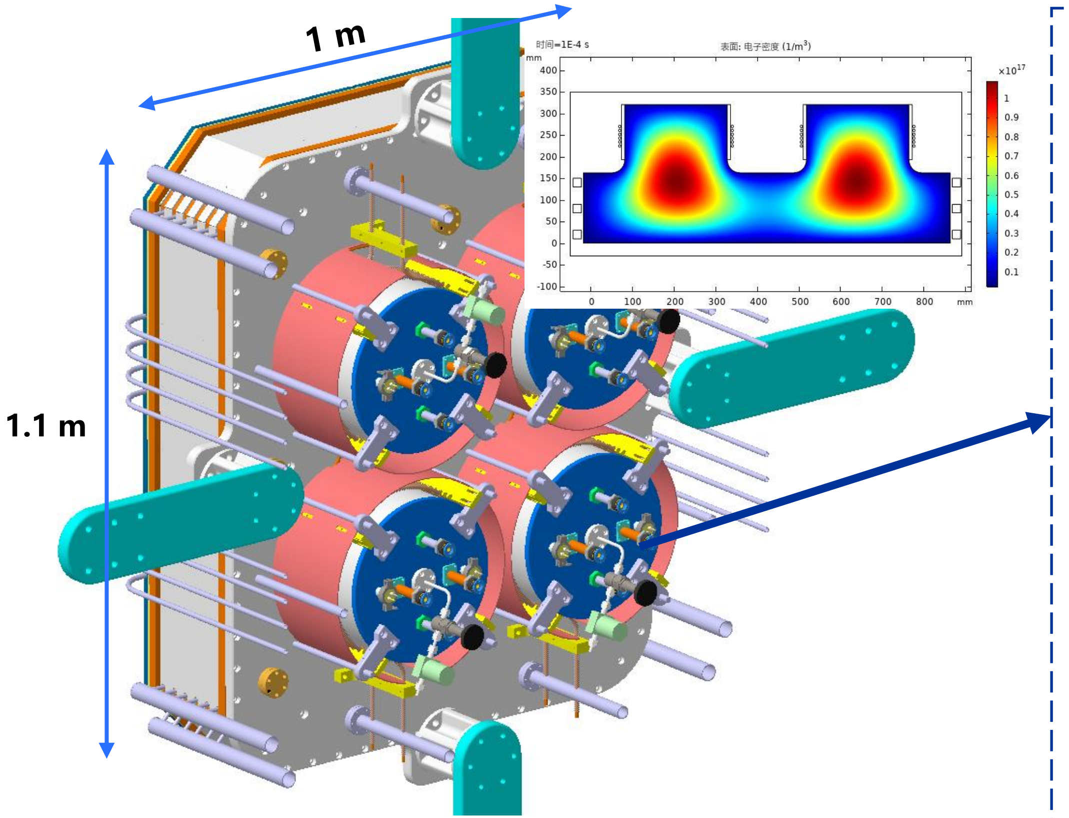


- 7.7A (130A/m²) @ 0.4Pa @ 55kV @ 105s
- 13.0A (220A/m²) @ 0.4Pa @ 51kV @ 10s

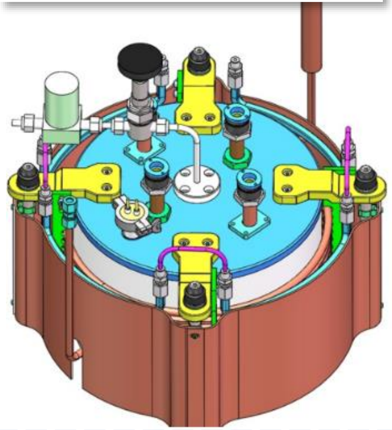


Key Design of Plasma Source

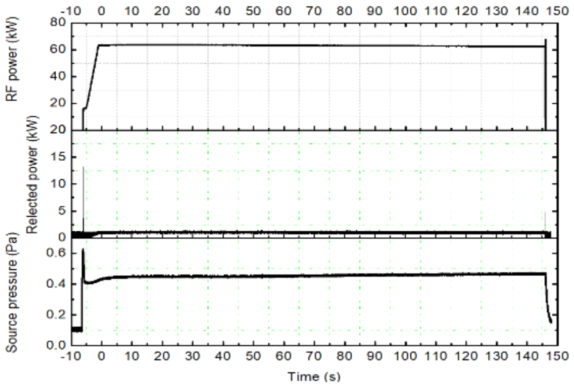
- RF driver: **1MHz@45kW/driver** → 200A/m² H-; 2MHz & longer tube will be tested
- Expansion chamber: **Larger cross section** of 1.1×1 m² (vs ELISE) for better beam uniformity

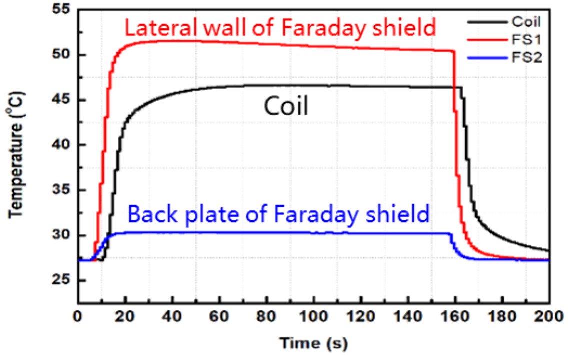


Design Parameters
1 MHz
80kW/driver
6.5 turns
ϕ270mm, h130mm



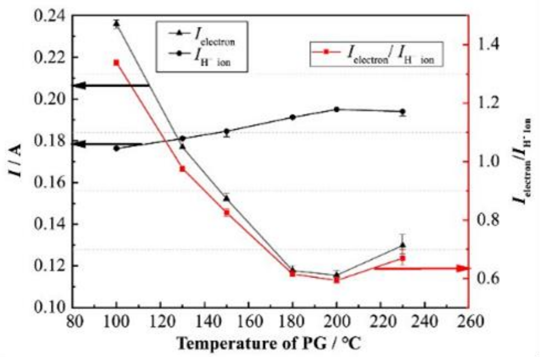
60kW@150s discharge & water Δt

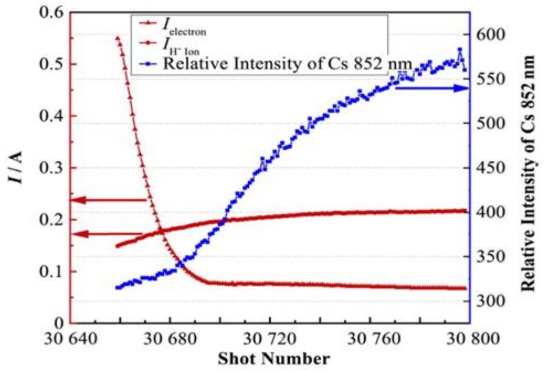




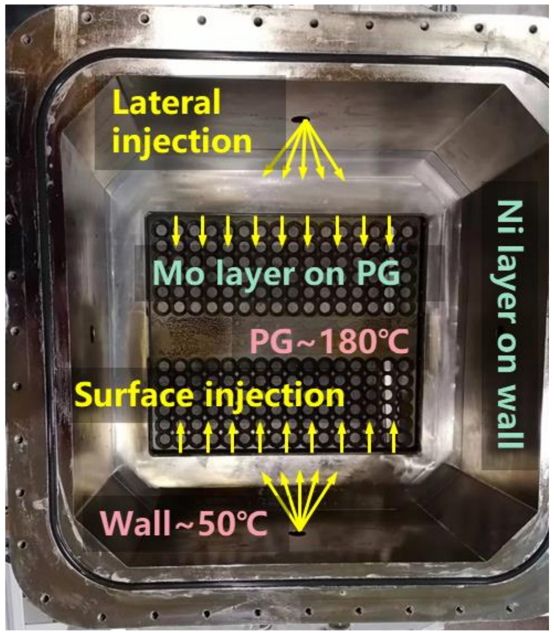
Key Design of Plasma Source

- Cs seeding: Sensitive to **T_{PG}** (optimal 180℃) and **surface injection** (but increase breakdown)
- Confinement/Filter field: **Lower e/H- with conf. field**; **I_{PG}~1000A w/o I_{return}** → 200A/m² H-

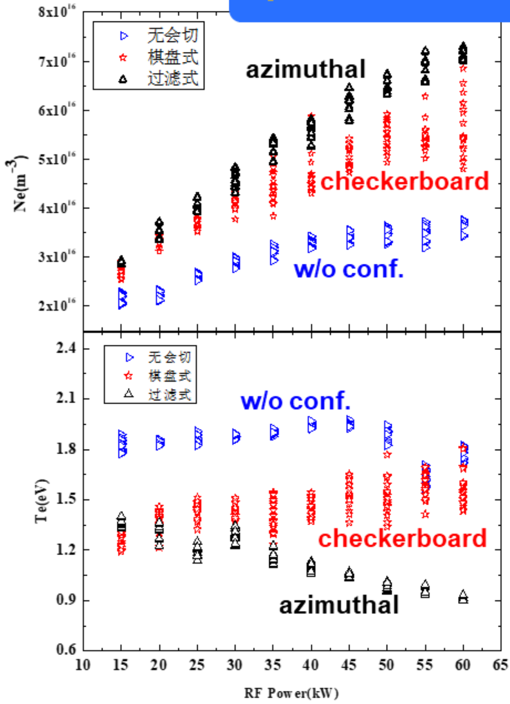


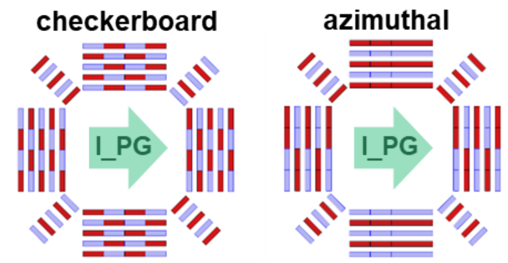


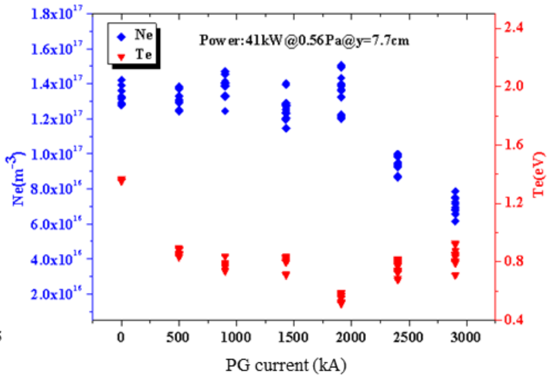
Cs relative experiments



confinement & filter field experiment



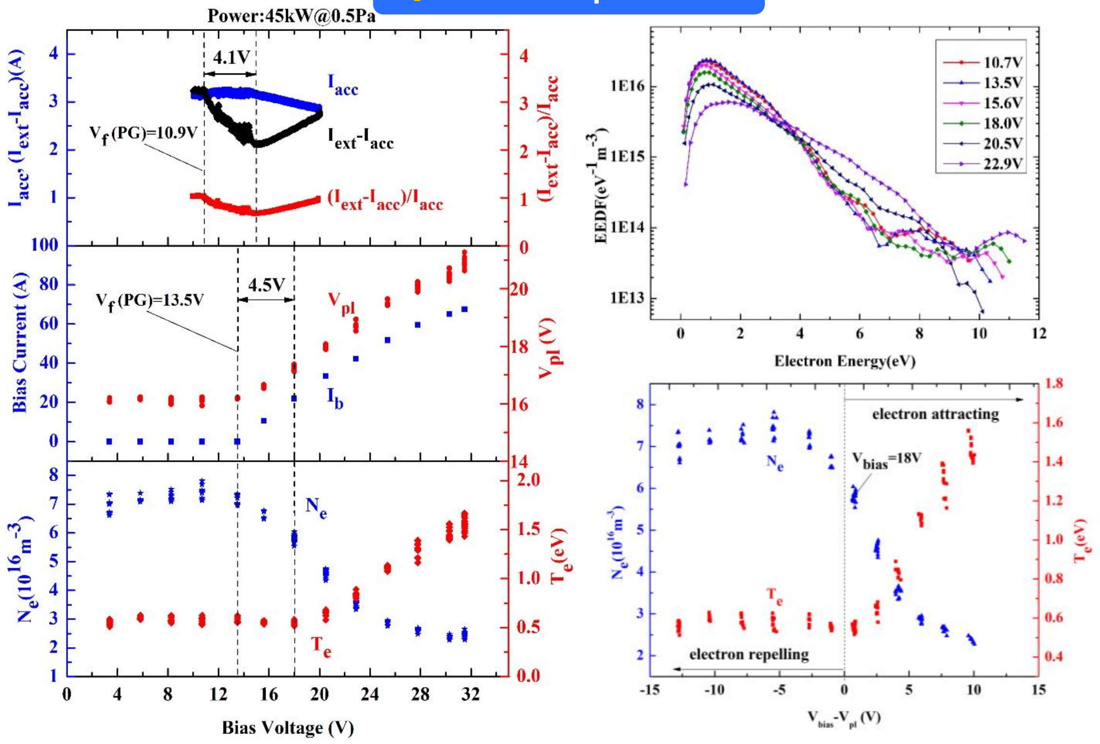




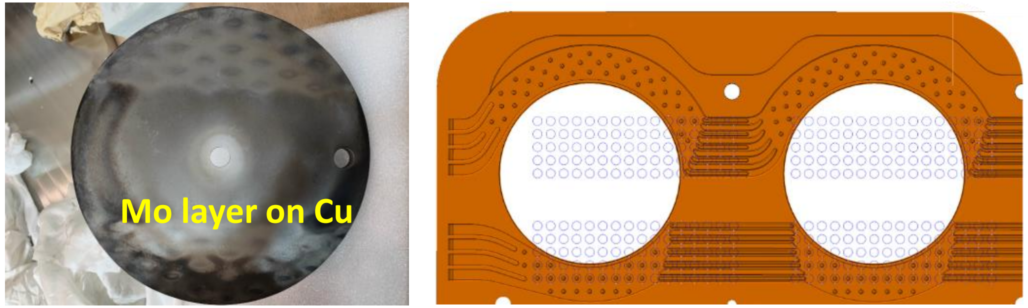
Key Design of Plasma Source

- PG Bias: **V_{bias} ~15V (BP floating)** → 200A/m² H-; Optimal V_{bias} for e/H- (repeated experiments)
- Backstream ions: Source backplate adopts **Mo-Cu composite structure** (Mo ~1mm)

PG bias experiments



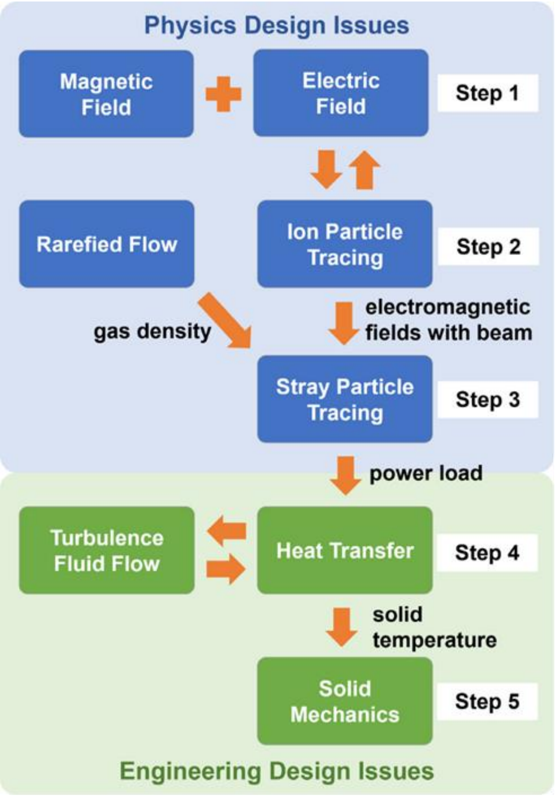
Backstream ions

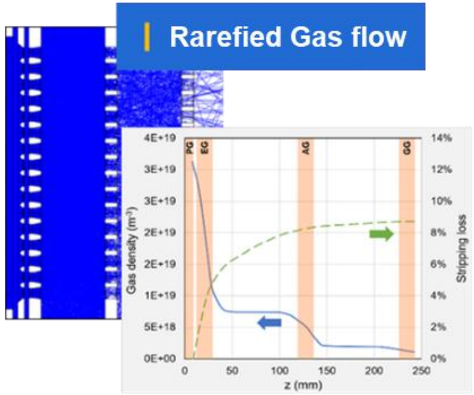


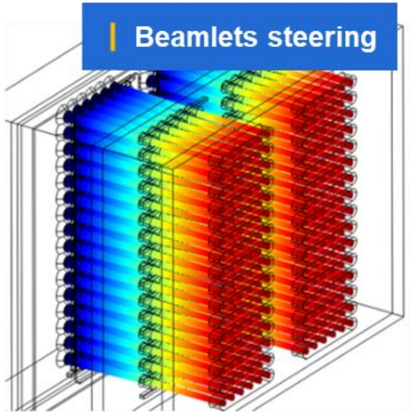
	Atomic density	Sputtering yield (300keV D_2^+)	Sputtering flux (80A/m² D_2^+)	Time for 1μm sputtering
Cu	8.4e22 m^{-3}	1e-2	1.0e15	2.3h
Mo	6.4e22 m^{-3}	2e-3	2e14	9.0h

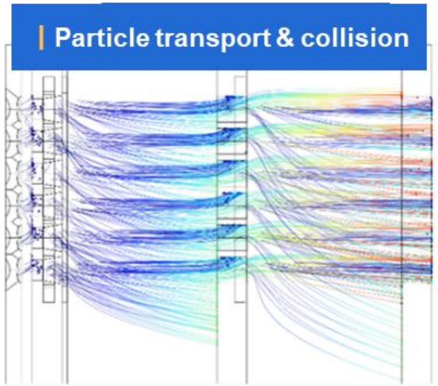
Key Design of Accelerator

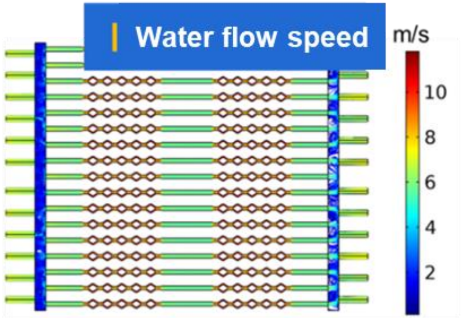
- Based on the design or experimental results of **JT-60SA/LHD/ITER**
- **Multiphysics modeling** including almost physics and engineering issues of an accelerator

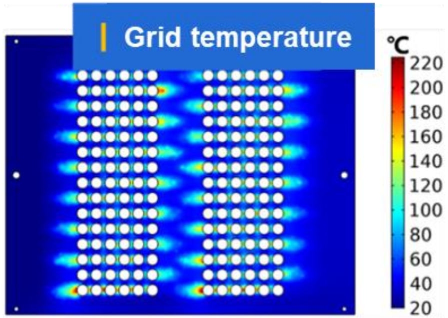


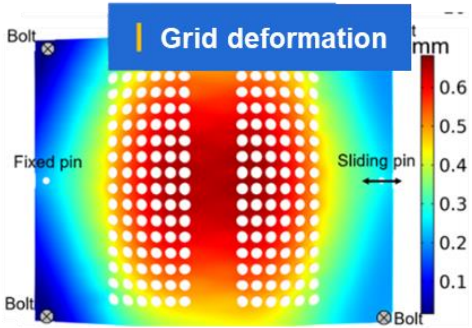






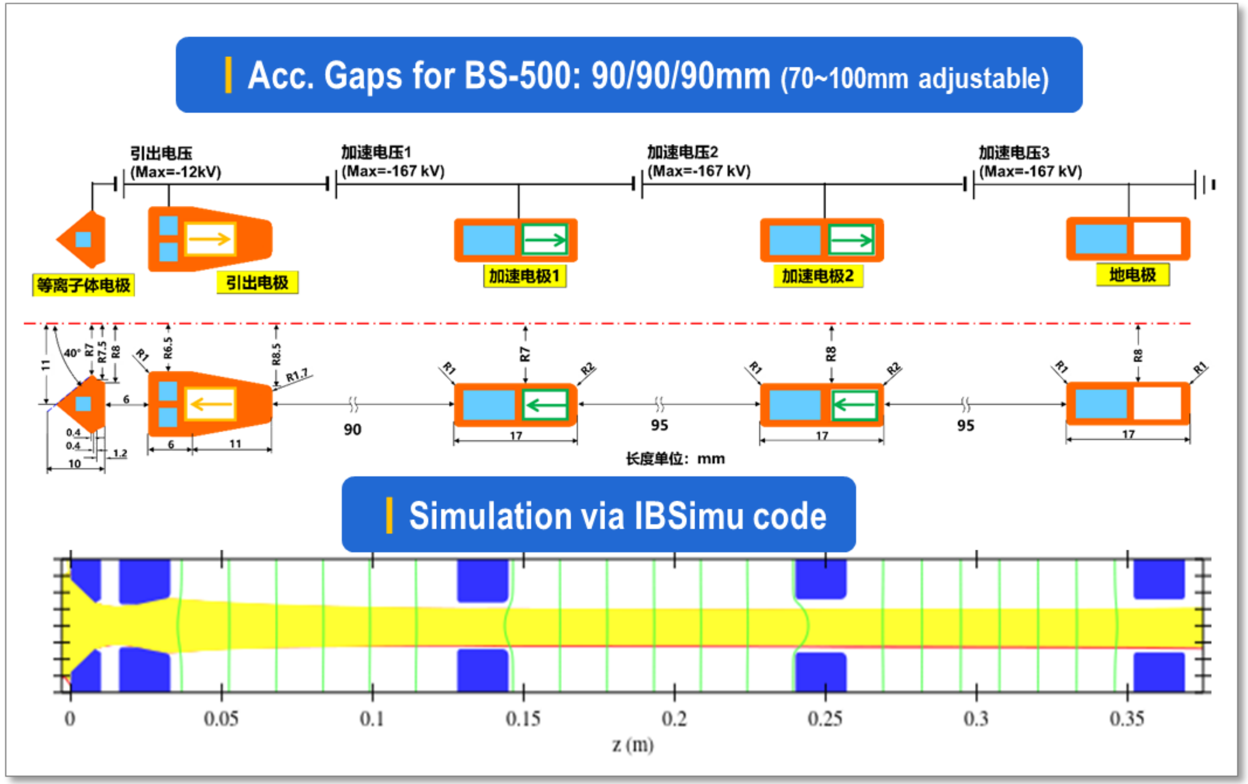


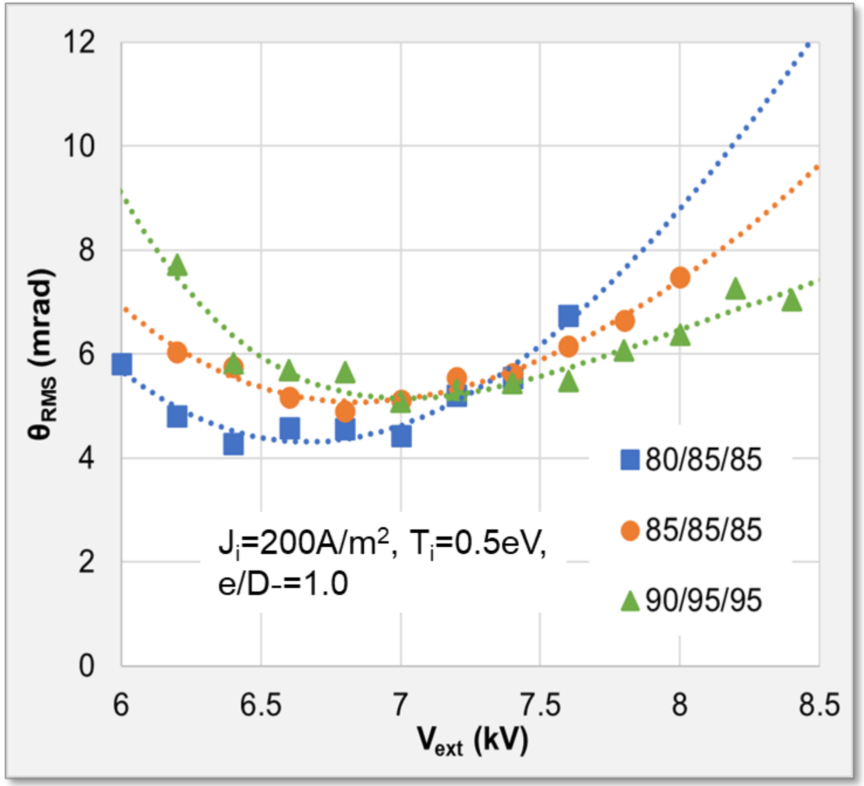




Key Design of Accelerator

- **Electrode structure**: PG/EG/AG1/AG2/GG aperture~14/13/14/16/16mm
- Single beamlet optics: **Acc. gap~90/95/95mm** for 200A/m² D- (for better HV holding)



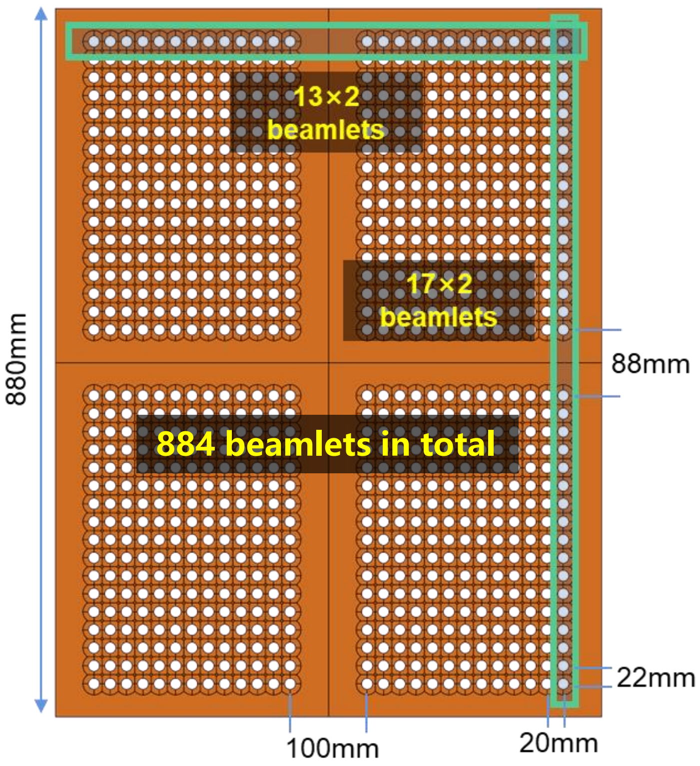


Key Design of Accelerator

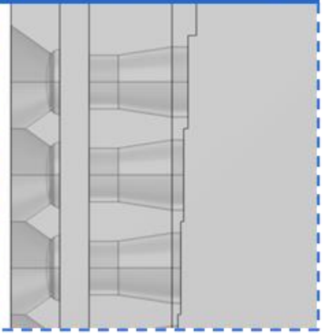
| Multi-beamlet focusing: **Multi-step of E field shaping** to steer all beamlets to a point

| Deflection compensation: **Crisscross magnets** to compensate magnetic deflection

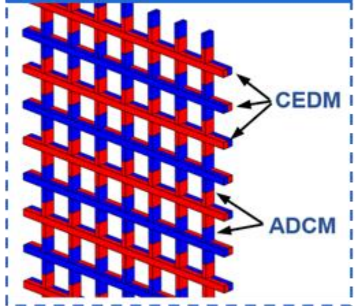
| 4 beamlet groups & 4 segments

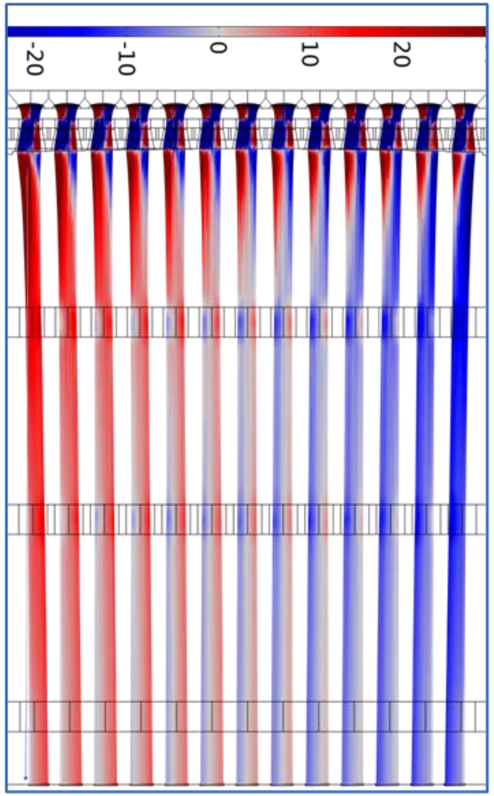


| Electric field shape



| Compensation magnet





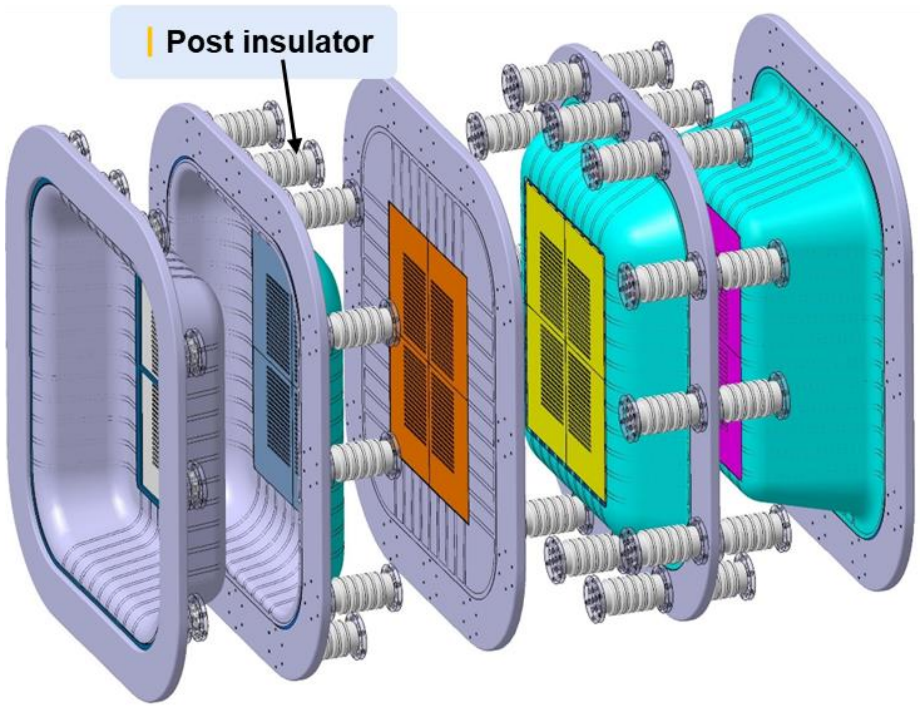
| Steering results

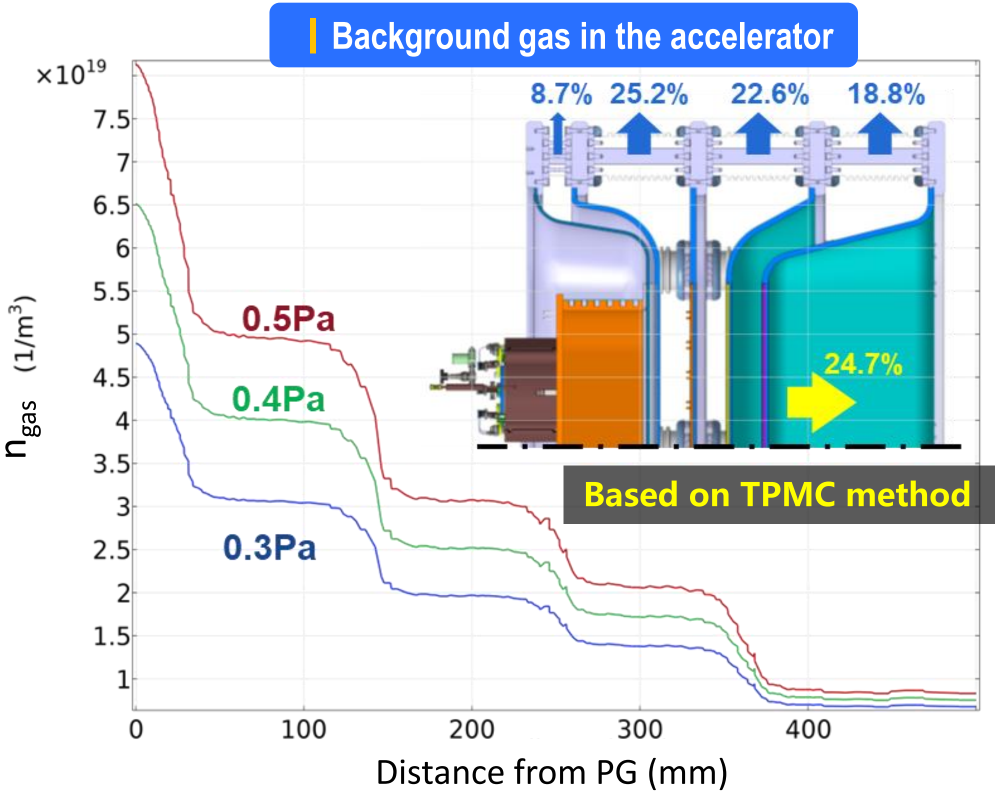
Required mrad	Design mrad	Deviation mrad
6.0	6.05	0.05
5.0	5.26	0.26
4.0	4.05	0.05
3.0	3.43	0.43
2.0	2.28	0.28
1.0	1.09	0.09
0.0	0.11	0.11
-1.0	-0.93	0.07
-2.0	-1.76	0.24
-3.0	-2.69	0.31
-4.0	-3.93	0.07
-5.0	-4.78	0.22
-6.0	-5.89	0.11

Key Design of Accelerator

| High voltage holding: **Source immersed in vacuum** for better insulation

| Stripping loss (~22% at 0.3Pa): **Lateral gas pumping (~75%)** by using post insulators



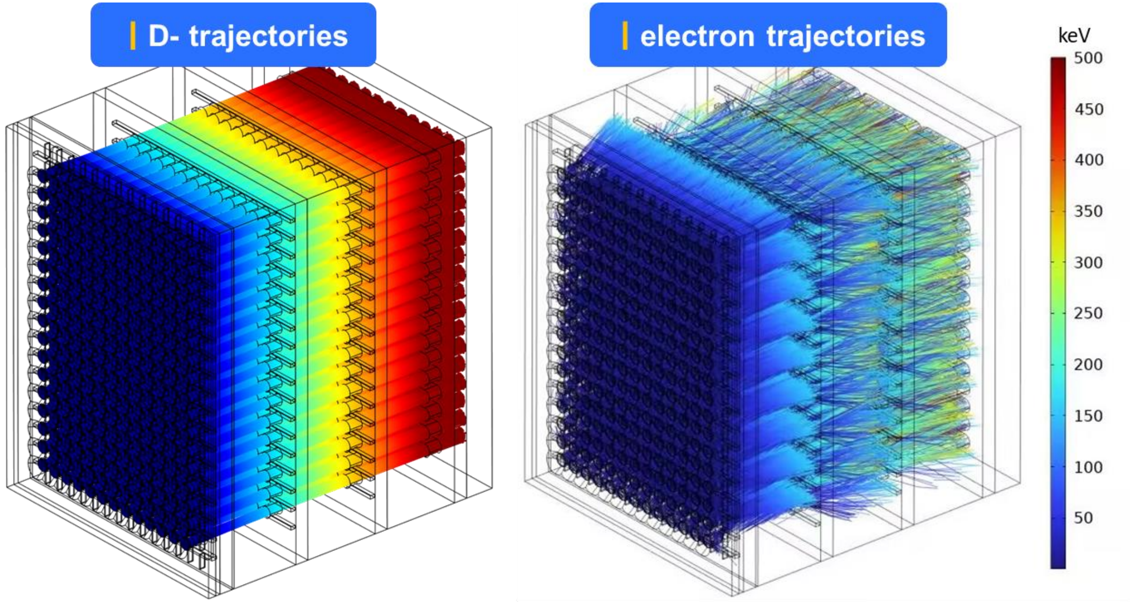


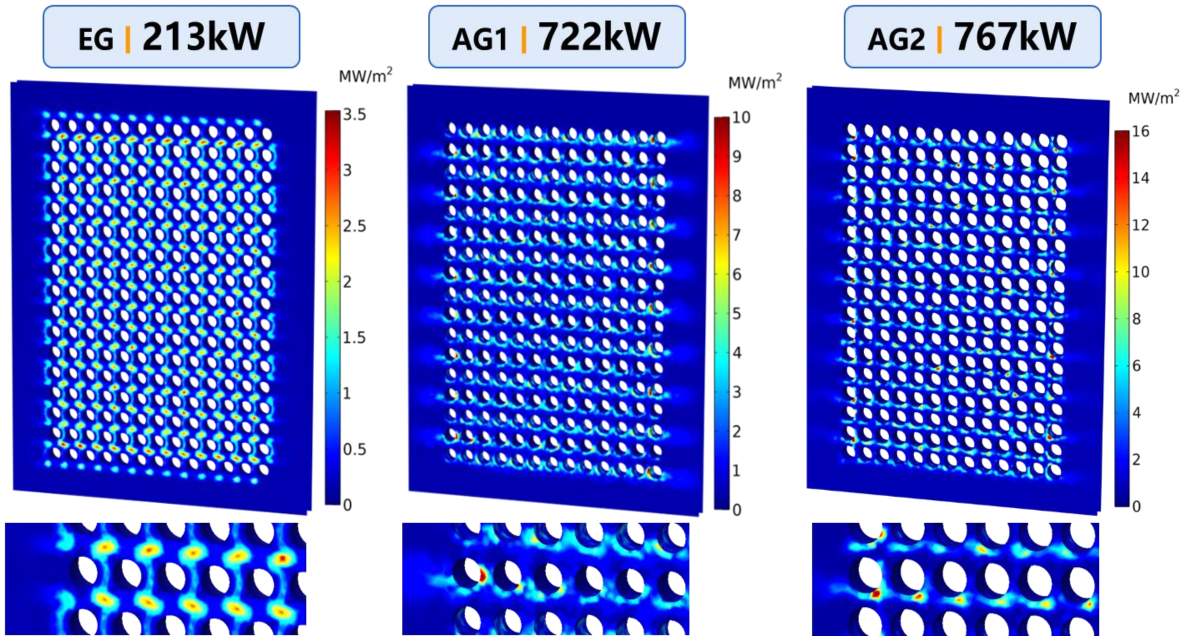
Key Design of Accelerator

| Stray particles: by simulation of **Particle-gas** & **Particle-electrode** during particle transport

| Most of power deposition on electrode is from **stray electron** by **deflection magnets**

- Single stripping: $D^- + D_2 \rightarrow D^0 + D_2 + e$
- Double stripping: $D^- + D_2 \rightarrow D^+ + D_2 + 2e$
- Electron loss: $D^0 + D_2 \rightarrow D^+ + D_2 + e$
- Gas ionization: $D^-/D^0/D^+ + D_2 \rightarrow D^-/D^0/D^+ + D_2^+ + e$
- Secondary electron: $D^-/D^0/D^+/e + D_2 \rightarrow e$



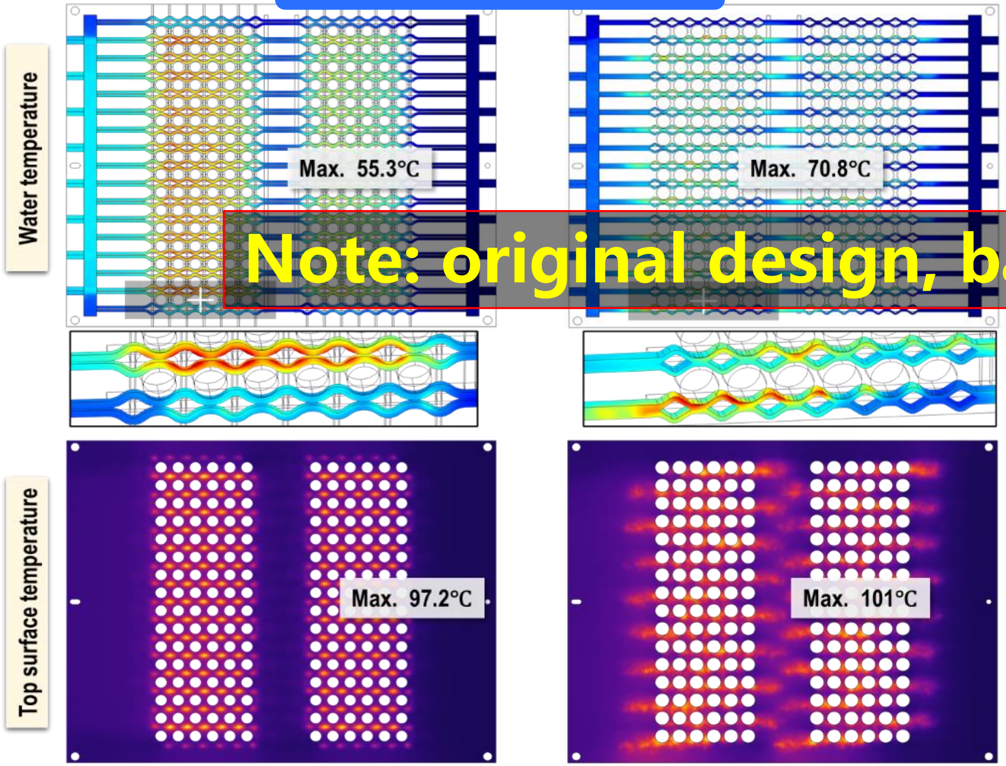


Key Design of Accelerator

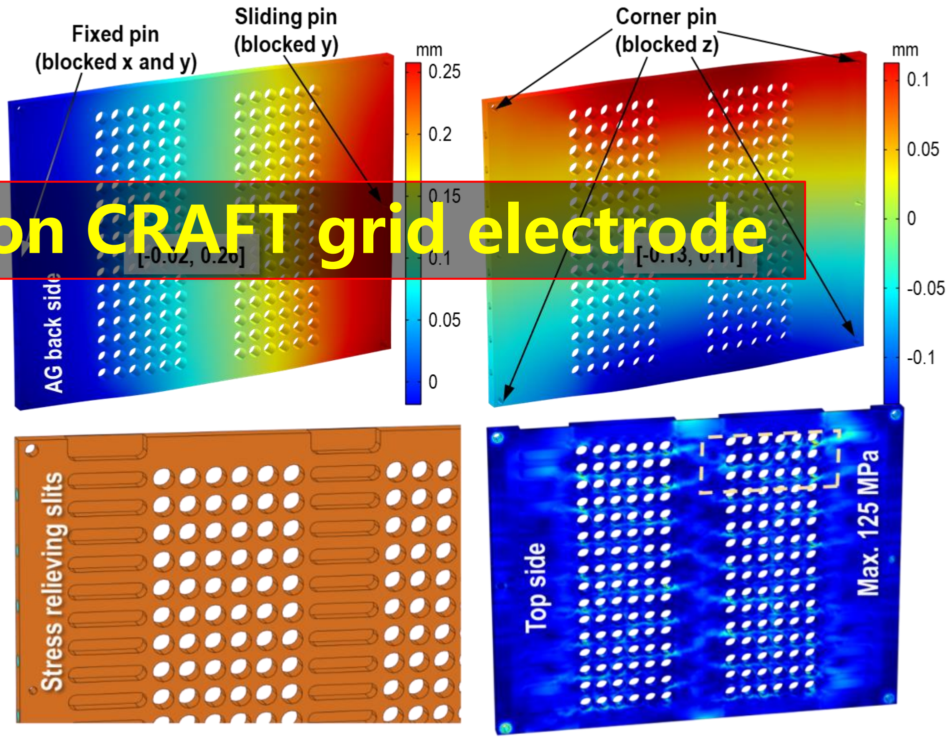
| Cooling design for electrode : **Narrow channels** (for high water speed) **close to** hot spots

| Assembly design for electrode : **Synergy the thermal deformation** among different electrodes

| Thermo-hydraulic design



| Thermo-structural design



Note: original design, based on CRAFT grid electrode

Summary & Future Plans

For 500keV BS	Contents
Conceptual/ Parametric	• Identify overall design requirements and parameters • Identify **RF-driven plasma source** and **MAMuG accelerator**
Plasma Source	• **Take ELISE plasma source as reference** • **Base on results of single/dual driver negative ion source of CRAFT** • Include RF driver, expanding chamber, Cs injection & recycle, magnetic field, electron suppression, backstream ion protection
Accelerator	• **Take JT-60/ITER accelerator as reference** • **Base on multi-physics design model** • Include single beamlet optics, multi-beamlet steering, high voltage holding, stripping loss, stray particles, thermo-mechanics

Summary & Future Plans

Milestones of R&D on 500keV BS

2023.09
Half-size BS
50kV@10A@100s H-

2023.12
Half-size BS
125kV@10A@100s H-

2024.07
BS with 2-stage acc.
CRAFT acceptance test
334kV@15A@100s

2024.12
BS with 2-stage acc.
CRAFT acceptance test
2MW@100s H^0

2025.07
BS with 3-stage acc.
High energy test
400kV@15A@100s

2025.12
BS with 3-stage acc.
Long pulse test
400kV@15A@400s

2026.07
BS with 3-stage acc.
Long pulse test
400kV@15A@1000s

2026.12
BS with 3-stage acc.
High power test
400kV@20A@1000s

Summary & Future Plans

Thanks !

Q&A

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