中国科学院
CHINESE ACADEMY OF SCIENCES

等离子体物理研究所
Institute of Plasma Physics, CAS

Modelling of beam transport and interactions with beamline components in the CFETR neutral beam test facility

Jianglong Wei, Yuanlai Xie, Lizhen Liang, Ling Tao, Yahong Xie, Yongjian Xu, Chundong Hu, and ASIPP-NBI Team

Neutral beam Injection Division，Institute of Plasma Physics, CAS

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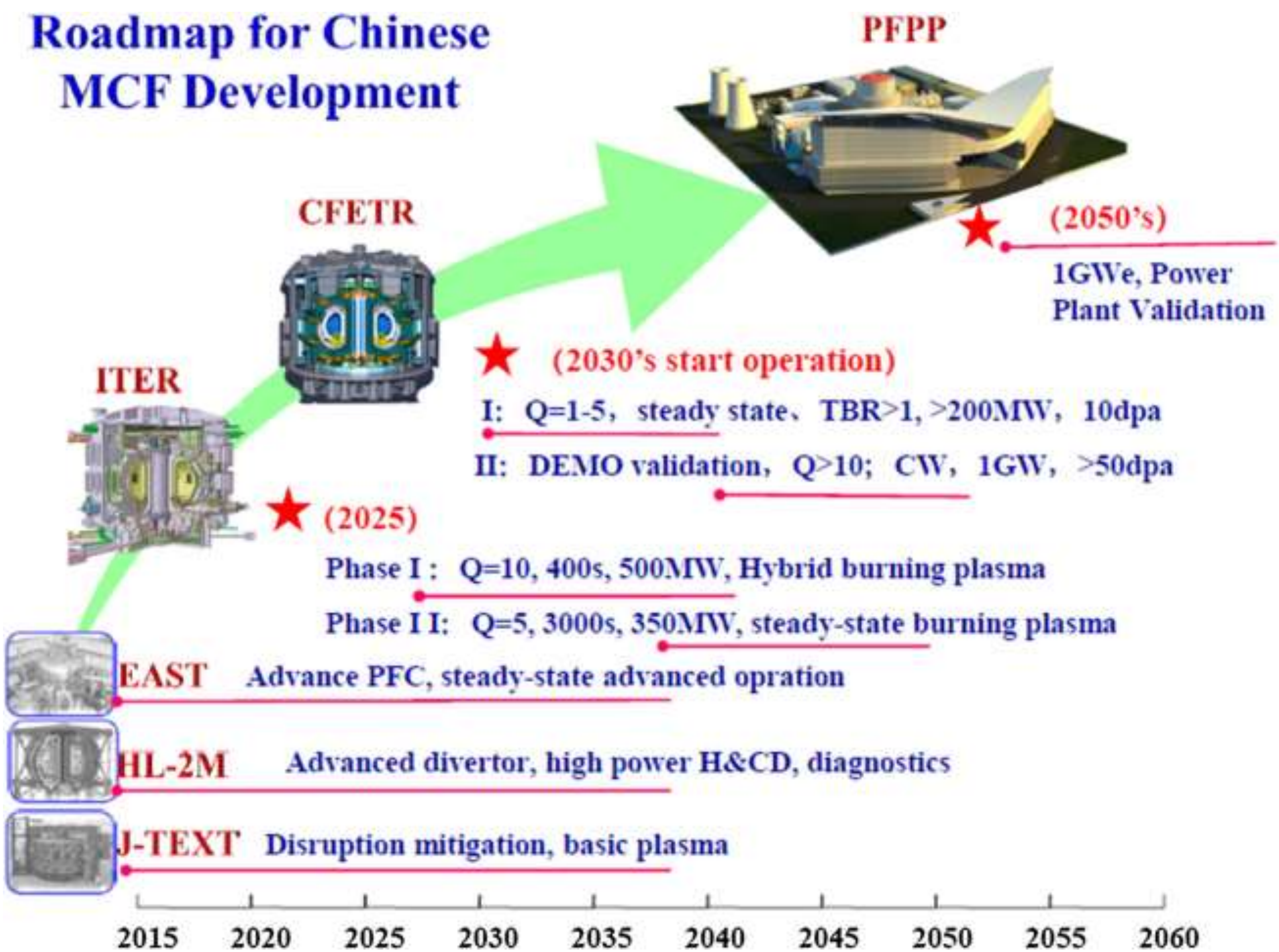
Outlines

- **CFETR neutral beam test facility**
- **Conceptual design of beamline**
  - Beam transport
  - Beam deposition
  - Thermo-mechanical analysis
- **Summary**

Chinese Magnetic Fusion Development



Chinese Fusion Engineering Test Reactor

- **Demonstration of a full cycle of fusion energy with a fusion power of 200-1000 MW**
- **Demonstration of long pulse or steady-state operation with duty cycle of 0.3–0.5**
- **Demonstration of a full fuel cycle of Tritium aiming at a tritium breeding ratio (TBR) >1.0**

	CFETR		ITER	
Major Radius(m)	7.0		6.2	
Minor Radius (m)	2.2		2.0	
Elongation	2.0		1.86/2.0	
Fusion Power (MW)	200	1000	500	350
Burning Time (sec)	Steady-state	Steady-state	≤400	≤3600
Duty Circle	0.3-0.5	0.3-0.5	0.25	0.25
Q-value	3	17	10	5
Toroidal Field (T)	6	6.5	5.3	5.18
Plasma Current (MA)	12	13	15	9
Bootstrap Fraction	0.4	0.6	--	0.5
Additional Heating (MW)	69	58	50	59

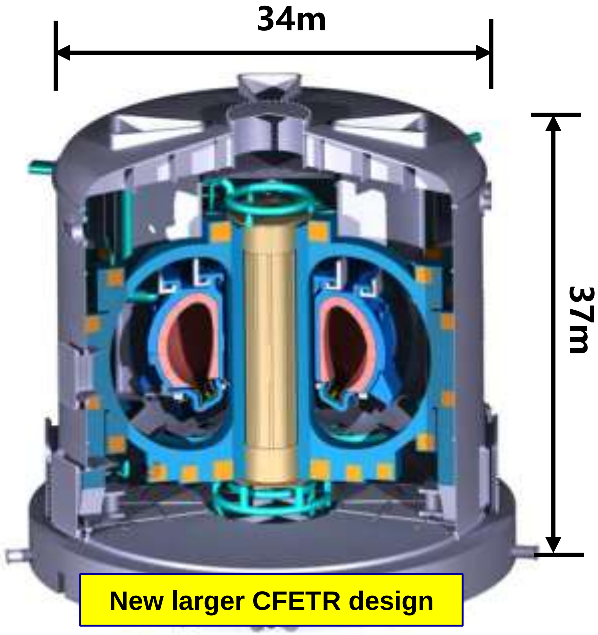
H&CD system for CFETR

- Phase I (P_{add}=69 MW): **Off-axis NBI** + Top launch ECRH (170-230GHz)
- Phase II (P_{add}=58 MW): **Off-axis NBI** + Top launch ECRH (170-230GHz) + LHCD (5-7.5GHz) at high field side
- NB energy and power is not determined for CFETR, but will be **similar to (or more demanding than) ITER-NBI requirement.**

>0.8MeV, >30MW, >1h

NB heating is required for CFETR

ITER operation scenarios	NB	RF (ICRH+ECRH)
Inductive operation (500MW@400s)	34 MW (H)	16 MW
Steady state operation (350MW@3600s)	30 MW (D)	29 MW
Initial installed	33 WM (D)	20+20 MW



New larger CFETR design

Towards CFETR NBI

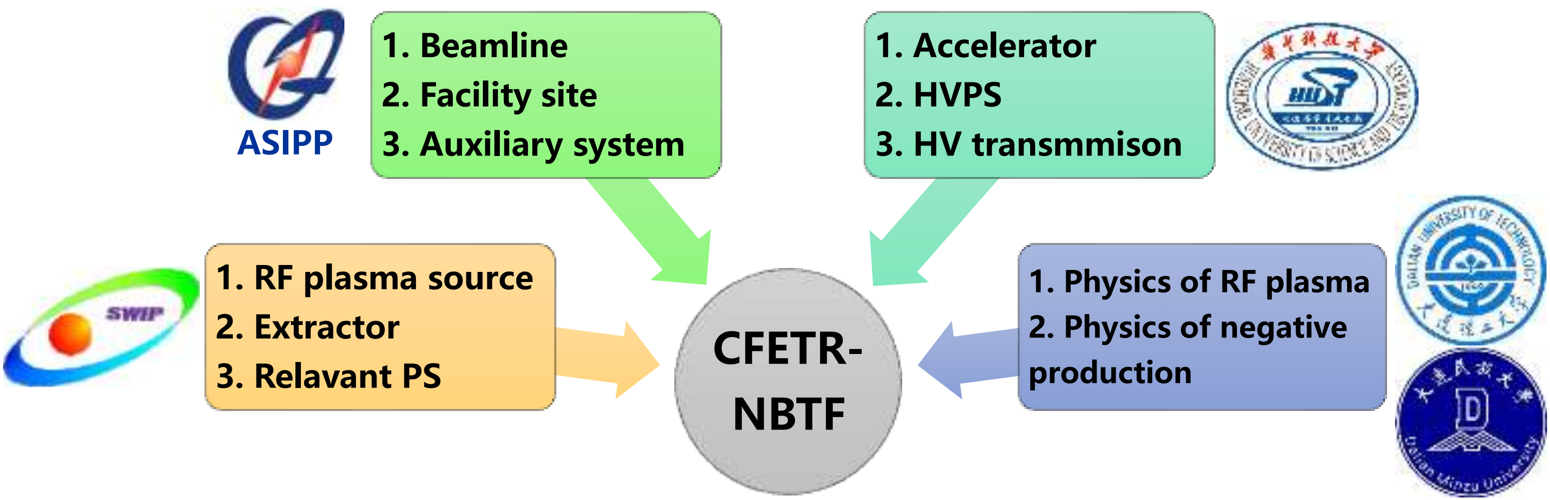
CFETR Neutral Beam Test Facility (National Key R&D Program of China)

► **Object:** 1. **Multi-RF-driver based Negative Ion Source (NIS) with single stage accelerator** for NI production & extraction, NI beam acceleration & steering

2. **Demonstration of beamline system** for NI beam transmission & neutralization, residual neg.&pos. ions separation, heat transfer enhancement, cryopump

3. **200kV HV P. S.**, HV transmission, HV holding technology

► **Goal:** **H^0 beam, 1.6×0.32m^2, 200keV, >2MW, 3600s**



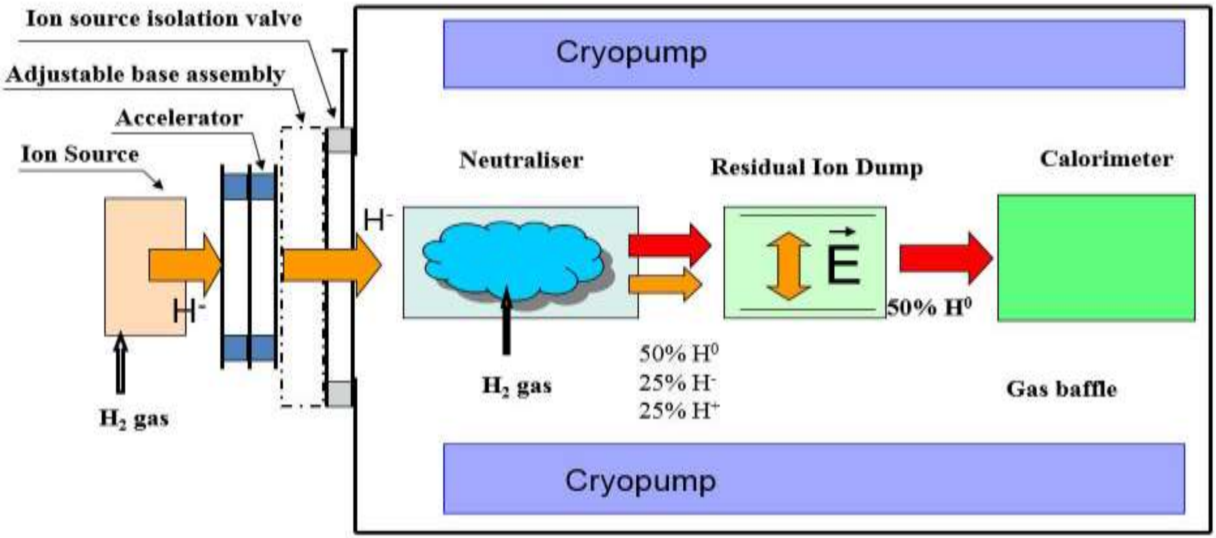
Basic designs of NBTF

Beam source (BS)

- ► Half size of ITER beam source with **1×4 RF drivers** and Cs seeding
- ► 1×200kV accelerator, not immersed in vacuum condition

Beamline (BL)

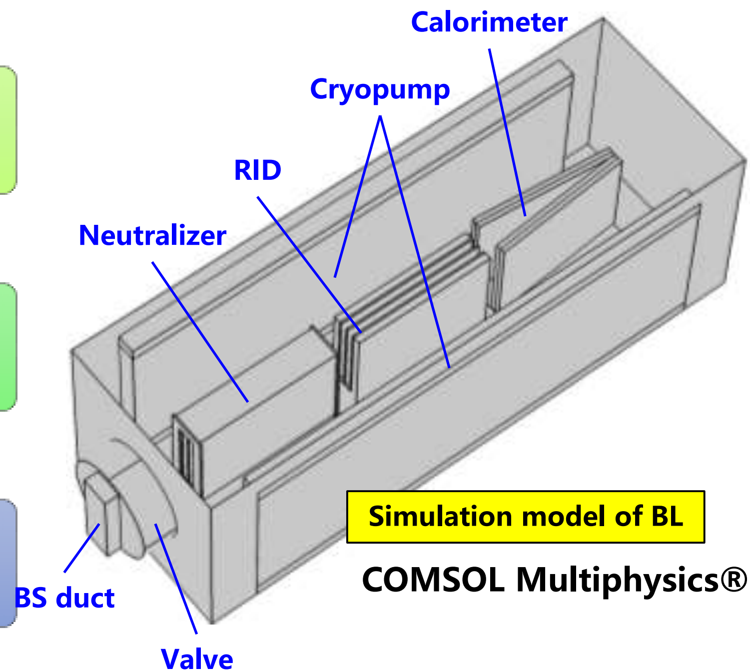
- ► Full size of ITER beamline with a longer length, **gas neutralizer, electric deflection system**
- ► But **longer residual ion dump, longer and larger cryopump**
- ► Potential capability for full-size ITER beam source with 400keV accelerator



Design process

► Optimize structure and position of inner components → **Minimize gas load on pump system and beam loss on inner components**

Components structure and position → **Profile of gas density, E and B** → **Beam transport** → **Beam-gas interation** → **Beam deposition** → **Gas load and beam loss**



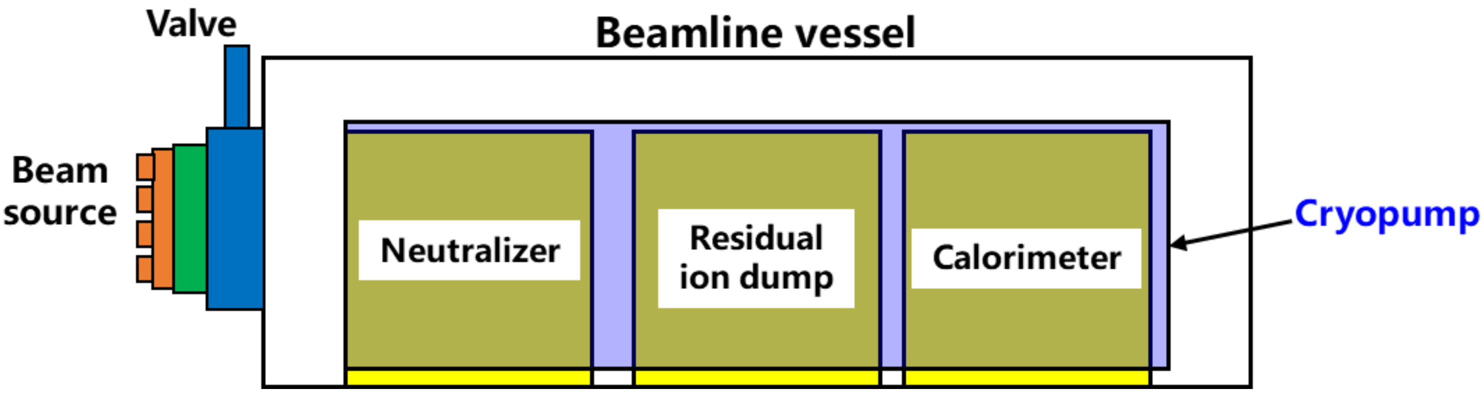
Simulation model of BL

COMSOL Multiphysics®

Conceptual design of beamline

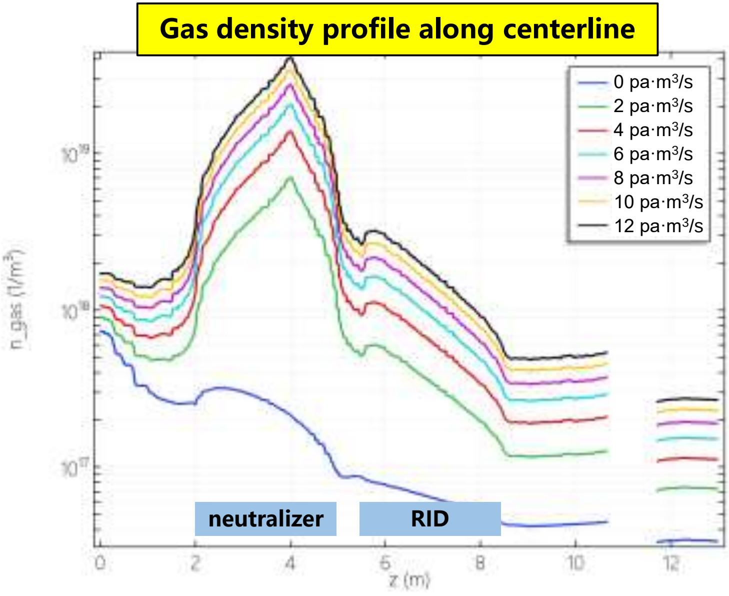
Components structure and position (Version 1.0)

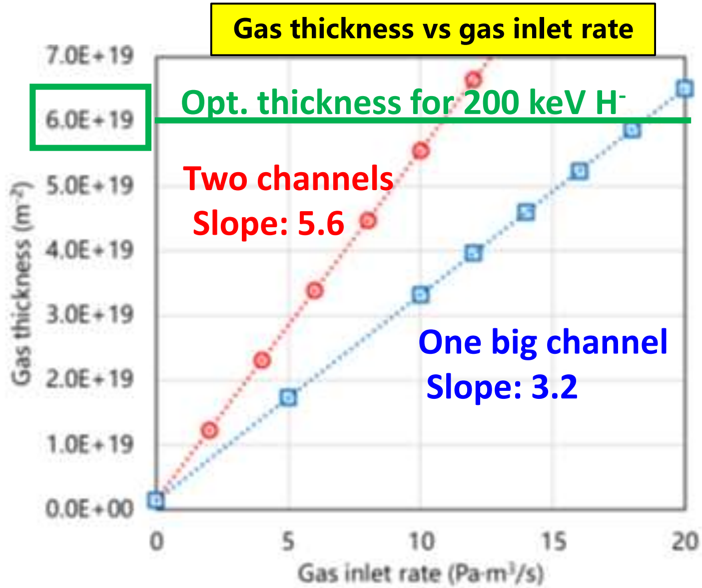
- ▶ **Beamline vessel (BLV):** rectangle, 12m long, 4m high, 4m wide
- ▶ **Neutralizer (NEU):** rectangle, 3m long, 1.7m high, 0.32m wide, 2 channels; Entrance is located 1m downstream of BLV front plate, exit is 0.5m upstream of RID
- ▶ **Residual ion dump (RID):** rectangle, 3m long, 1.7m high, 0.32 wide, 2 channels
- ▶ **Calorimeter (CAL):** V-shape, 5°opening, 3m long, 2m high, 0.2m downstream of RID exit
- ▶ **Cryopump:** two cryopumps; 10m long, 3m high, 0.45m deep; pumping surface 10m×2.5m



Gas density profile

- Neutralizer is divided into **2 adjacent vertical channels** with central panel (**40mm wide**), to minimize gas inlet rate
- Residual gas (~1000K) from beam source is 2Pa·m³/s, capture factor is 0.3 for each cryopumps surface

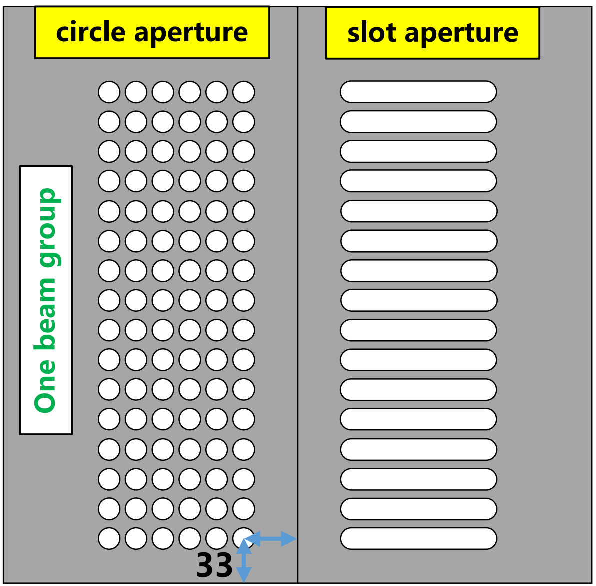


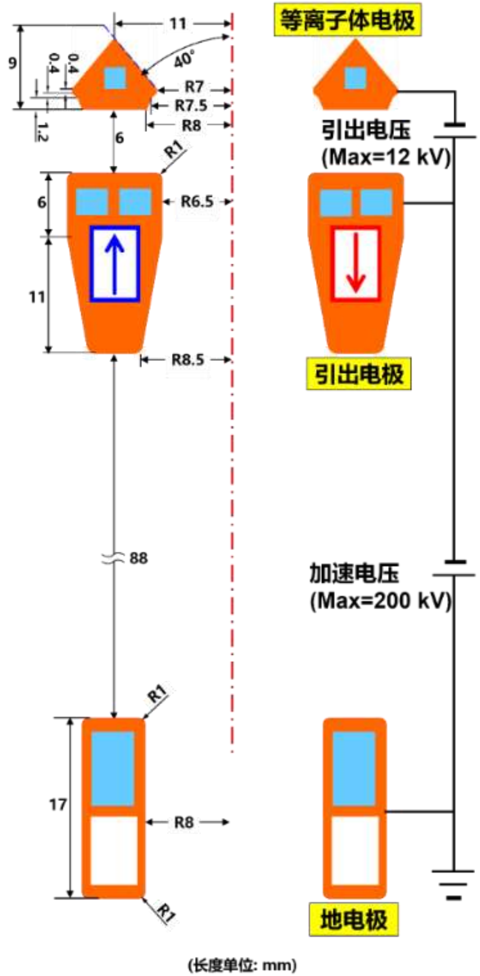


Beam transport

Ion beam emission from BS

- Apply the **ion beam simulation results** in accelerator, except a gaussian assumption
- Based on ITER-NBI accelerator: **2×4 beam groups, each 6×16 apertures, aperture spacing 22mm and 20mm**
- **Two GG designs:** (1) circle aperture, (2) slot aperture for less stripping loss



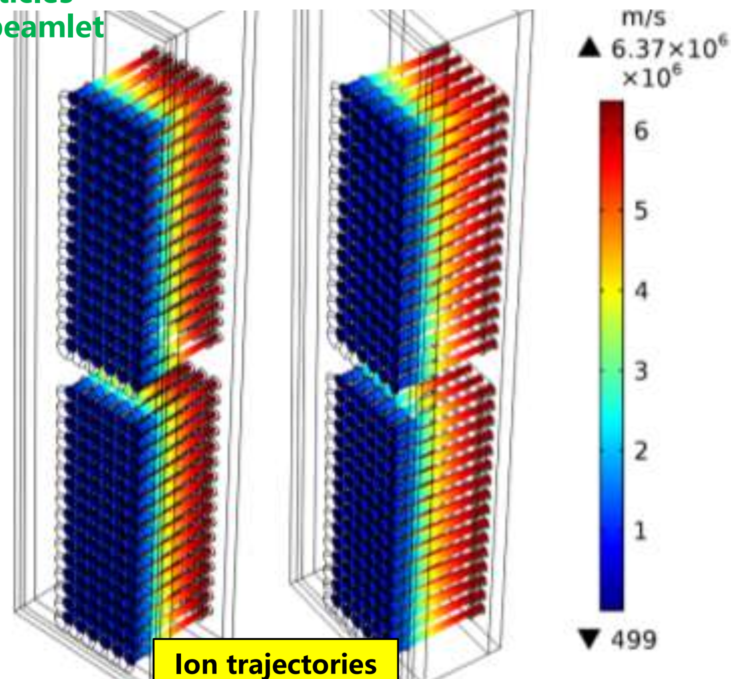


Beam transport

Ion beam emission from BS

- 1/4 grids model for calculating ion trajectories
- E_{ext}=9kV/7mm, E_{acc}=200kV/80mm, j_{ext}=300A/m^2
- **No magnetic field, no beam steering and focusing**

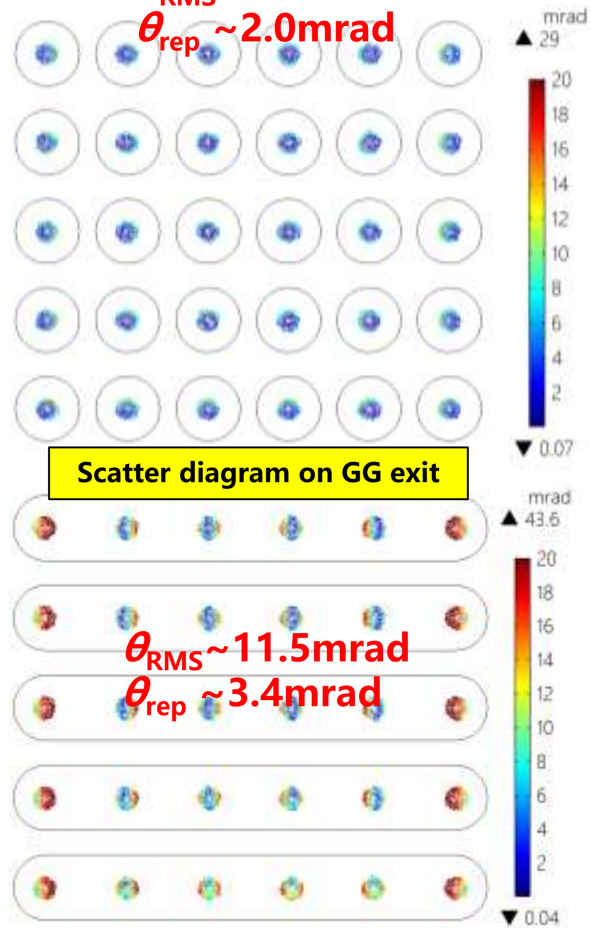
1000 particles for one beamlet



Ion trajectories

θ_{RMS}~6.3mrad
θ_{rep} ~2.0mrad

θ_{RMS}~11.5mrad
θ_{rep} ~3.4mrad

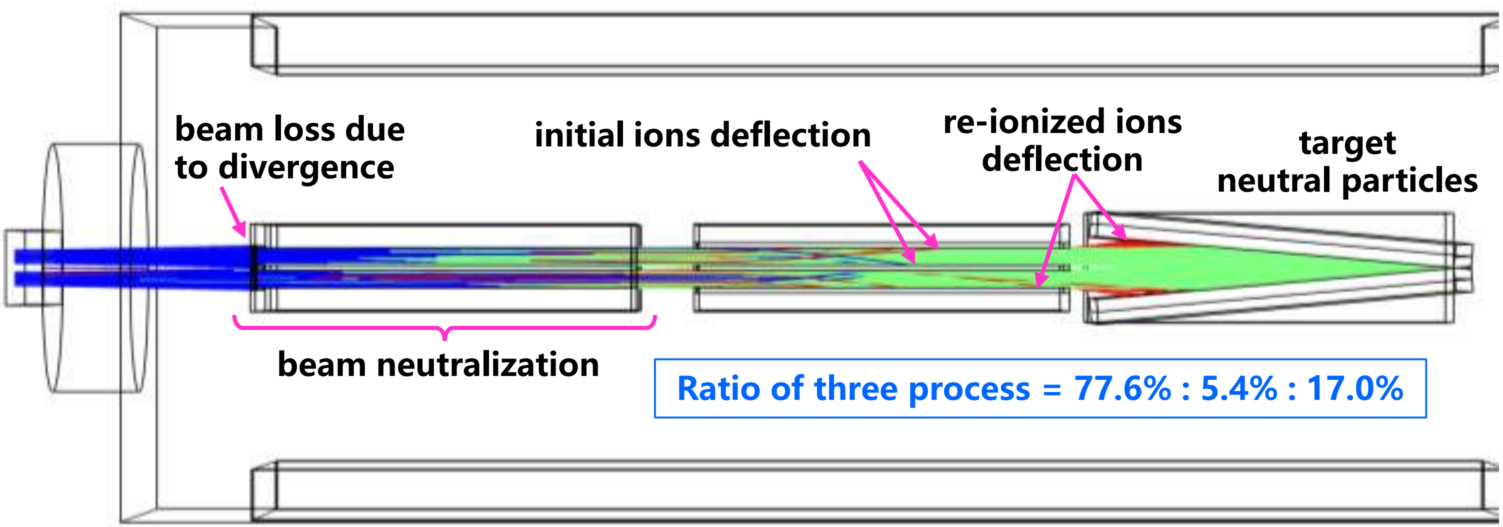


Scatter diagram on GG exit

Beam transprot along BL

- 12 middle beamlets **from circle GG apertures** are used to display beam transmission
- **Step length is ~5cm** for judgement of once beam-gas collision
- Blue—negative ions, Green—neutral particle, Red—positive ions

	beam-gas process	cross-section (200keV H)
1.	$H^- + H_2 \rightarrow H^0 + e + H_2$	2.51E-20
2.	$H^- + H_2 \rightarrow H^+ + 2e + H_2$	1.76E-21
3.	$H^0 + H_2 \rightarrow H^+ + e + H_2$	7.04E-21

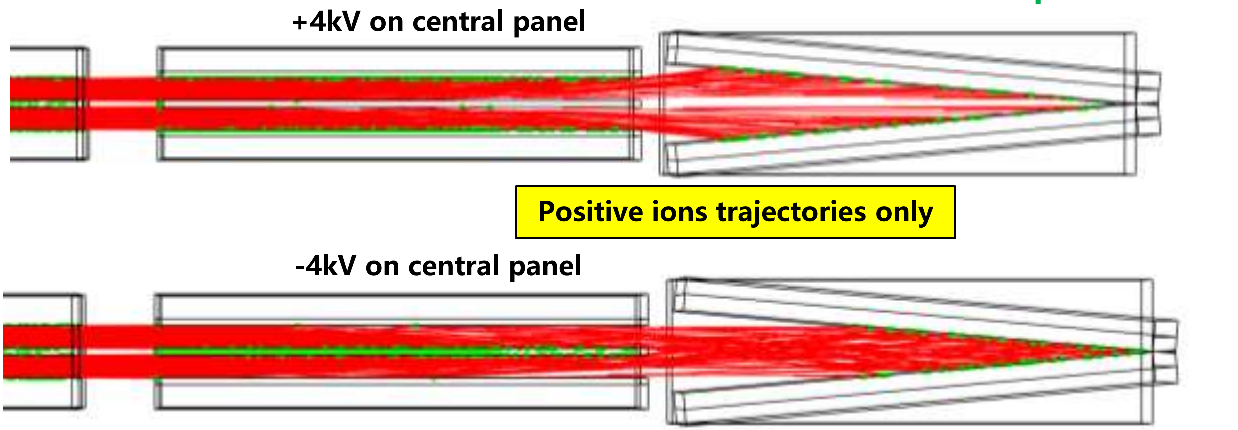


Beam particles trajectories

Beam separation

- Positive or negative voltage apply on central panel of RID (**40mm wide**)? (i.e., central panel collect negative ions or positive ions?)
- The largest difference is **the loss positions of positive ions on CAL**

Most of re-ionized ions are quickly deflected onto the front part of CAL

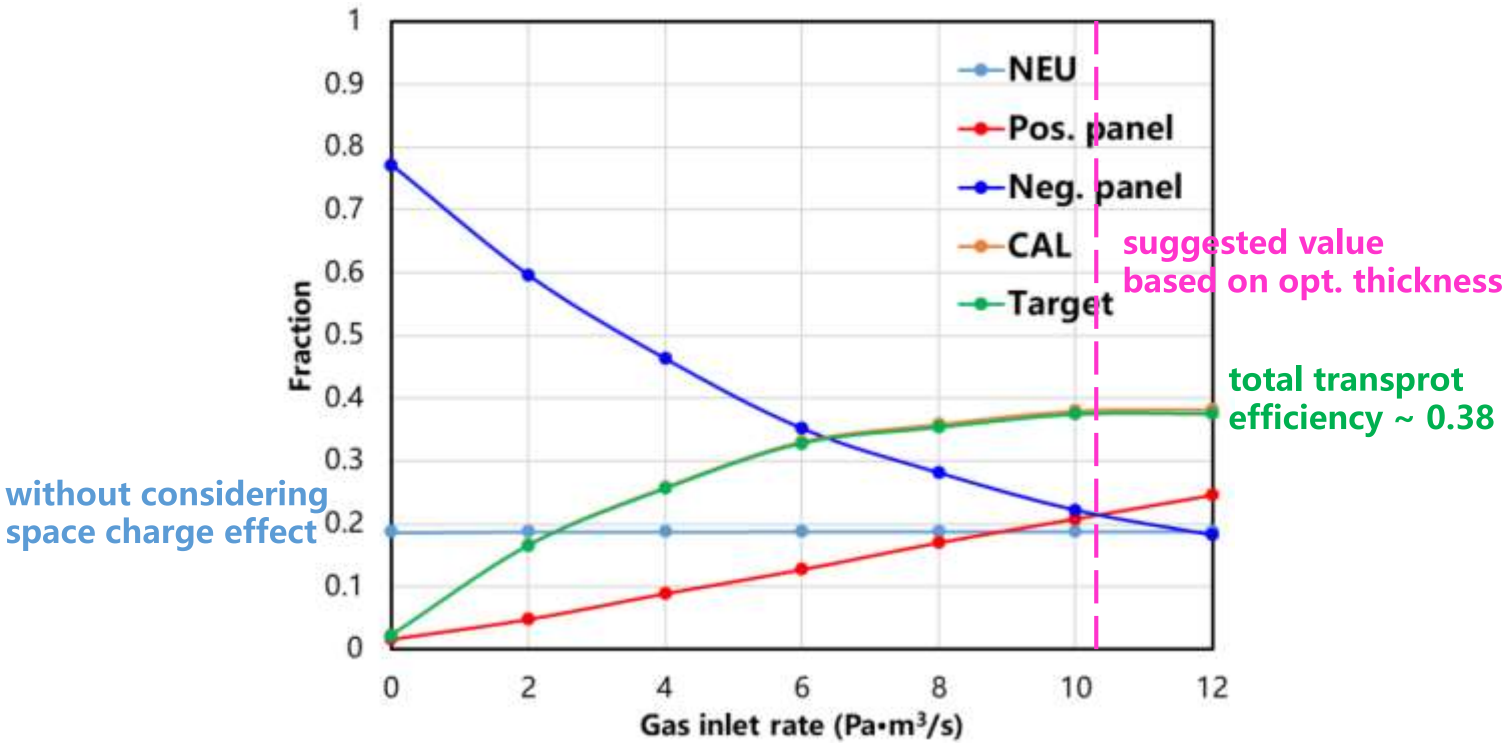


Increasing escape of positive ions in case of injection

Beam transport

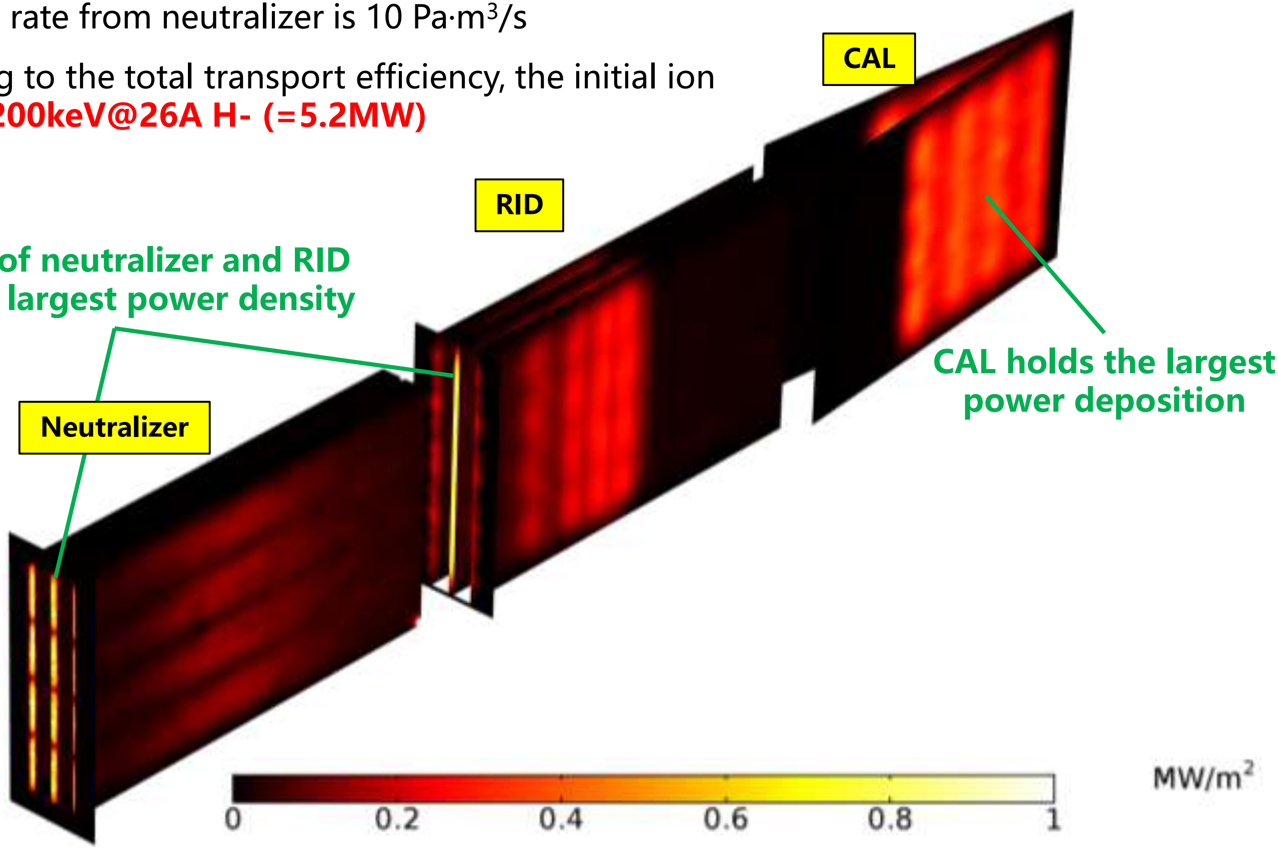
Distribution of beam deposition

- ► Due to transmission loss and re-ionization loss, target neutral particles are less than expected
- ► To attain the target neutral beam power of >2MW, **200keV@26A H- ion beam** is required



Distribution of power deposition

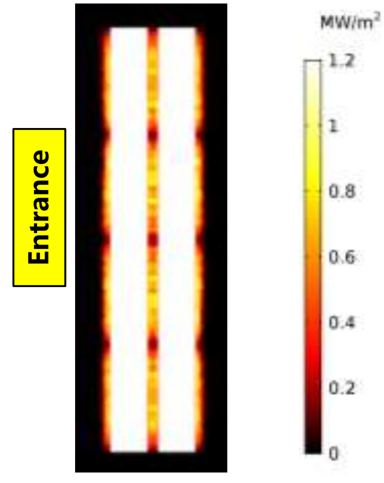
- Gas inlet rate from neutralizer is 10 Pa·m^3/s
- According to the total transport efficiency, the initial ion beam is **200keV@26A H- (=5.2MW)**



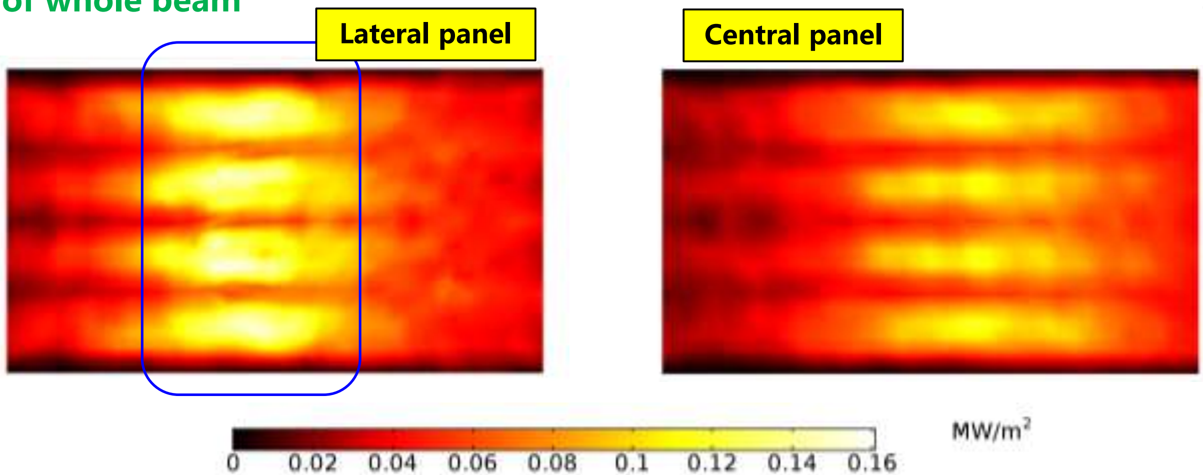
Beam deposition

Power deposition on neutralizer

- **Leading edge of panels** intercepts a high power density up to 1.2MW/m^2
- Without beam focusing, **beam loss due to replusion** accumulate in the middle section of lateral panel
- Power density on central panel is lower, but is still unacceptable

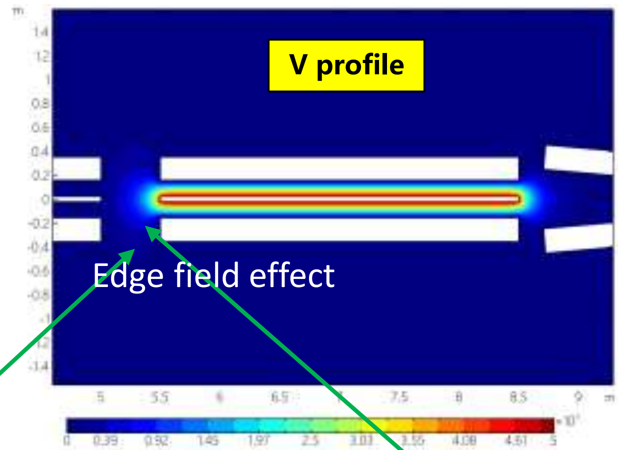


Beamlets from lateral aperture column of whole beam

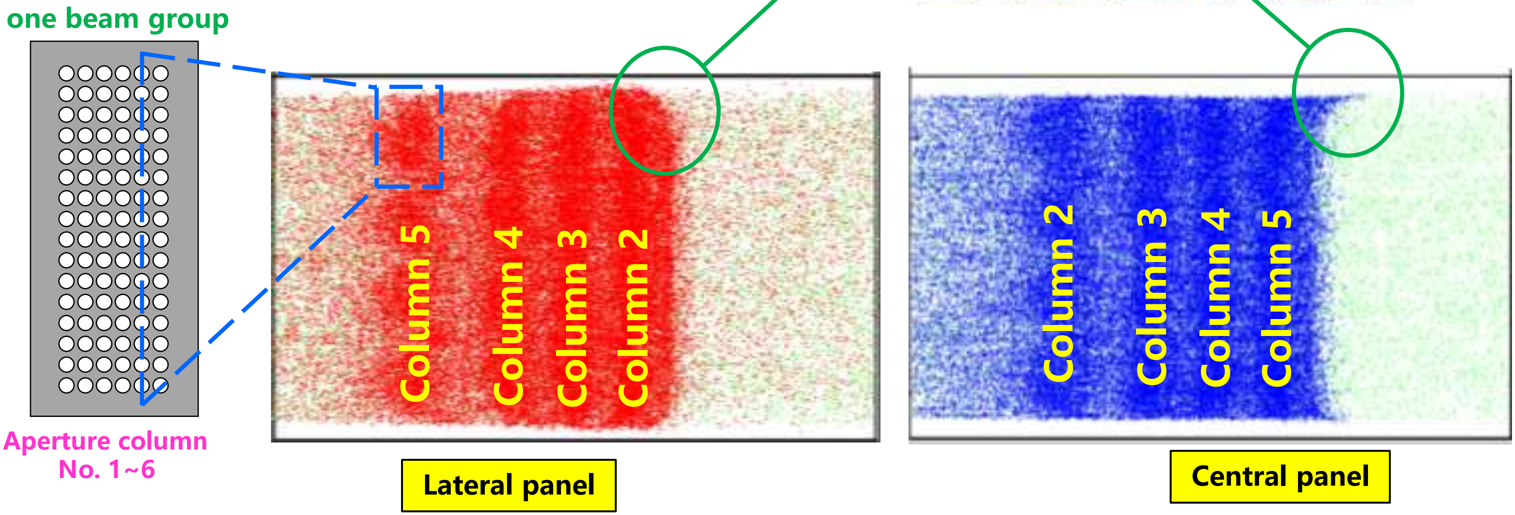


Beam deposition on RID

- **Difference of envelope** is caused by edge field effect
- Separations of footprints are relevant to beamlet groups and aperture column



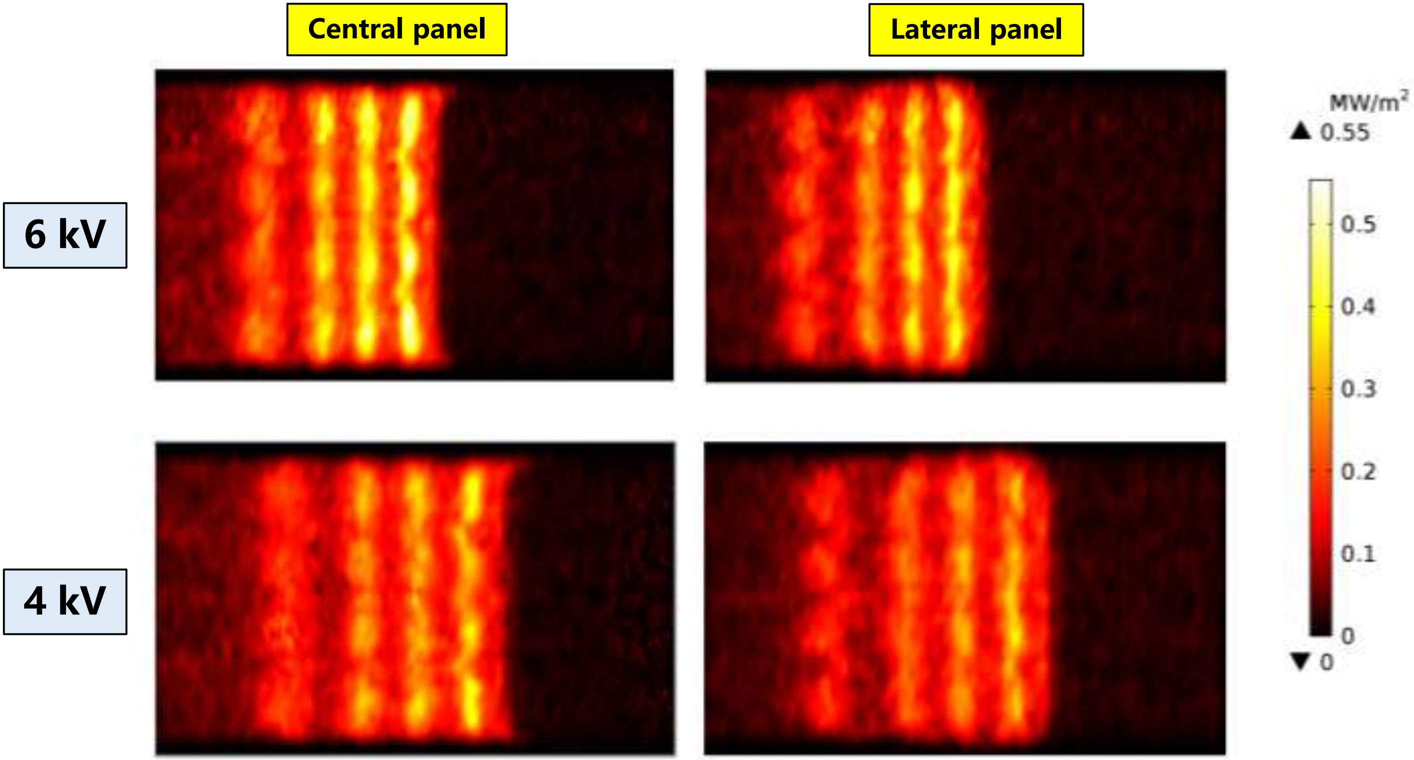
Footprints from aperture column No.1 and 6 are not clear due to interception loss



Beam deposition

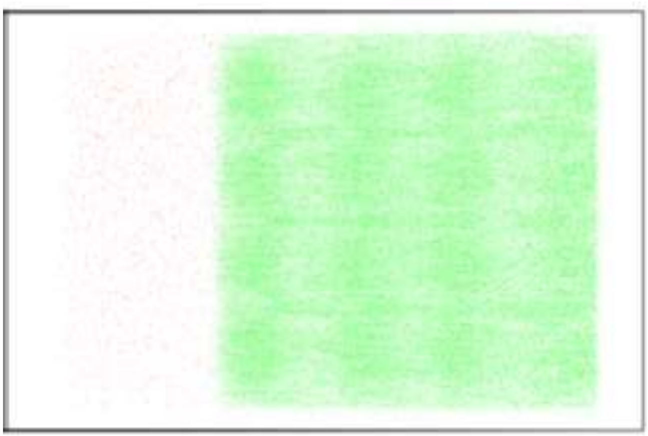
Power deposition on RID

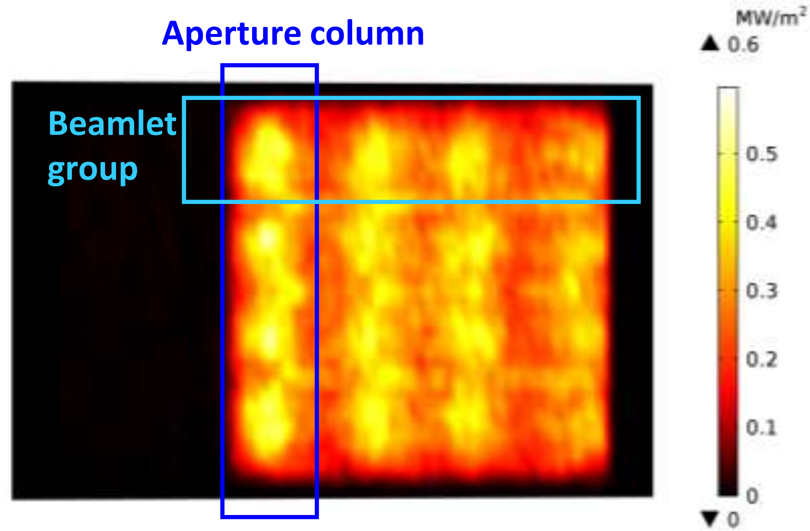
- ► Sweeping the additional voltage is to decrease the maximum average power density
- ► Larger additional voltage → closer to entrance, higher power density



Beam deposition on calorimeter

- Separations of beamlet groups in vertical direction and aperture column in horizonal direction are also clear on CAL
- Loss of beamlets form aperture column No. 1 and 6 suggests **the beam focusing is required**



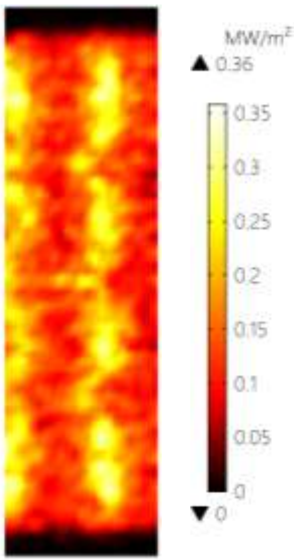


Thermo-mechanical analysis

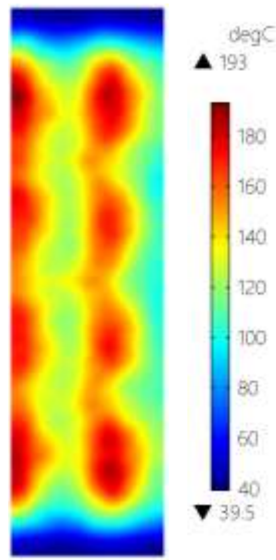
Central panel of RID **(based on results of power deposition)**

- Each RID panel is made of several elements with the width of 0.5m, each element is embedded with 5 cooling channels

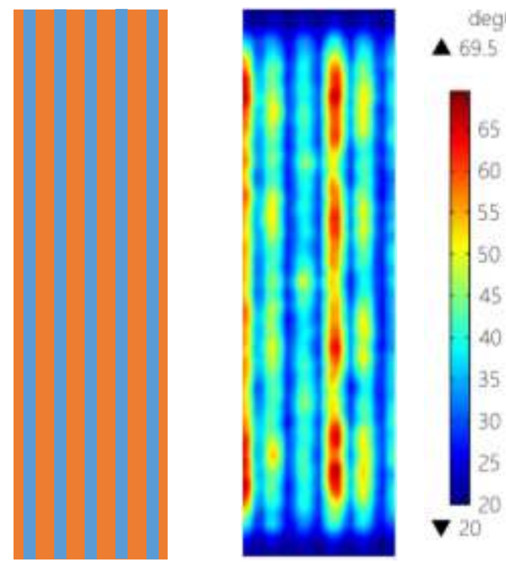
dia.=20mm
inlet pressure=0.4 MPa



Power density



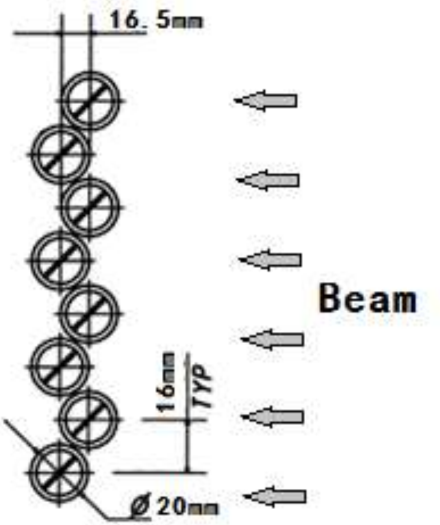
Without cooling



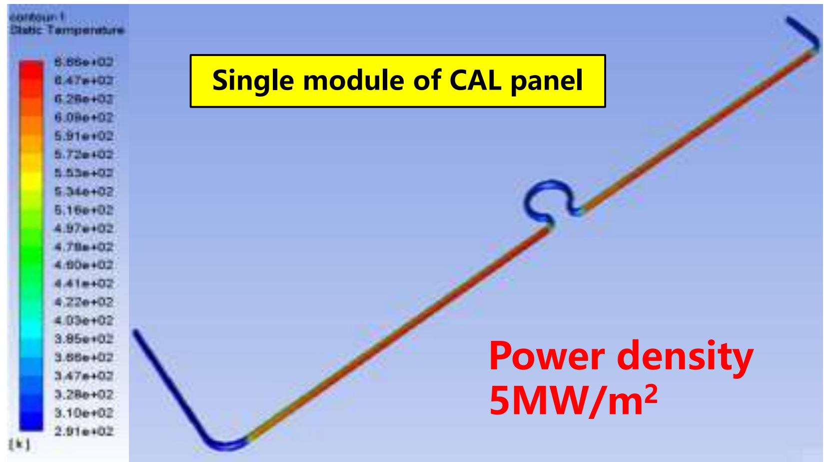
With cooling

Calorimeter panel **(helpless to complex structure)**

- ► made up of a double array of **swirl tubes**
- ► Ansys® software is used to apply the thermo-mechanical analysis



Conceptual design of swirl tubes



Single module of CAL panel

Summary

- CFETR is a transition fusion reactor between ITER and DEMO, initial requirement of **NB heating for CFETR: >0.8MeV, >30MW, >1h**
- National project of CFETR-NBTF has be started, target value: **H^0 beam 200keV, >2MW, 3600s**
- Conceptual design of beamline is ongoing, **a model of beamline has been developed to analyze beam transport and interaction with components**
- This model can give the distribution of gas density, E and B
- Beam transport is based on negative ions orbits from a real accelerator
- Beam neutralization and separation are simulated, and a total transmission efficiency of 0.38 is derived without beam steering and focusing
- Beam footprints on RID and CAL are separated by beam groups and aperture column

Next step of model

- **Update the beam optics** according to an actual design of grids system, including magnetic field, beam steering and beam focusing
- Carry out the **design of electron dump** to intercept stray particles from beam source and to protect the cryopump
- Optimize the **design of beam collimators** along the beam transport, to minimize and uniform the deposition power density
- Apply the **thermo-structural analysis to key components** based on the results of beam deposition
- Design the **thermocouple array** (position and number) based on the results of beam transport, to measure the beam profile and divergence

Future works for beamline

Development schedule

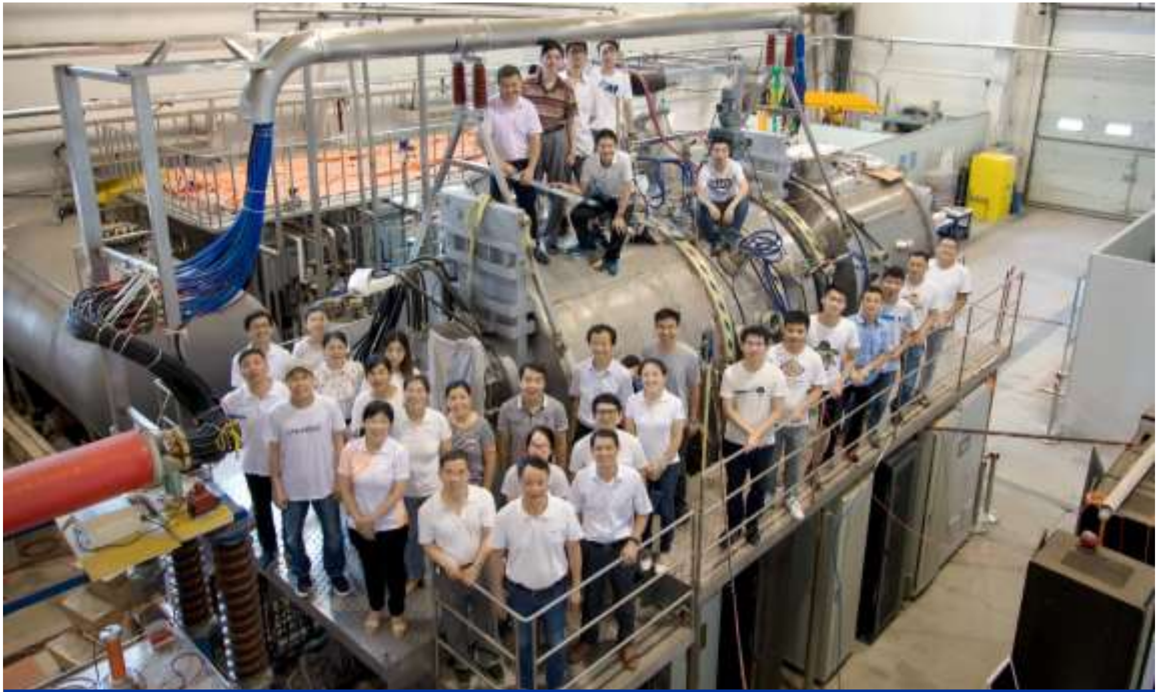
2018	2019	2020	2021-
Conceptual design	Engineering design	Manufacture and assemble	Testing and experiment

Beyond beamline development

► Research on **plasma/laser neutralizer** for negative ions, based on the RF negative ion source test equipment at ASIPP

► Research on **enhanced heat transfer technology** for high-power and steady-state beamline components, based on high heat flux test bed at ASIPP

Thanks for your attention



ASIPP-NBI team