

# Divertor Ion Temperature Profile Measurements at DIII-D with RFEA and PIC-Enhanced Interpretation

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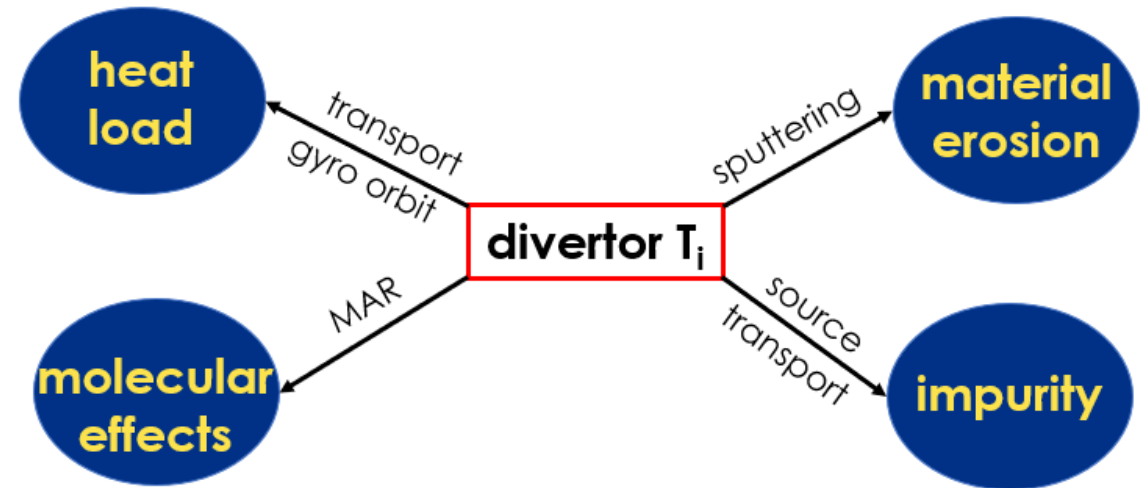
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# Motivation

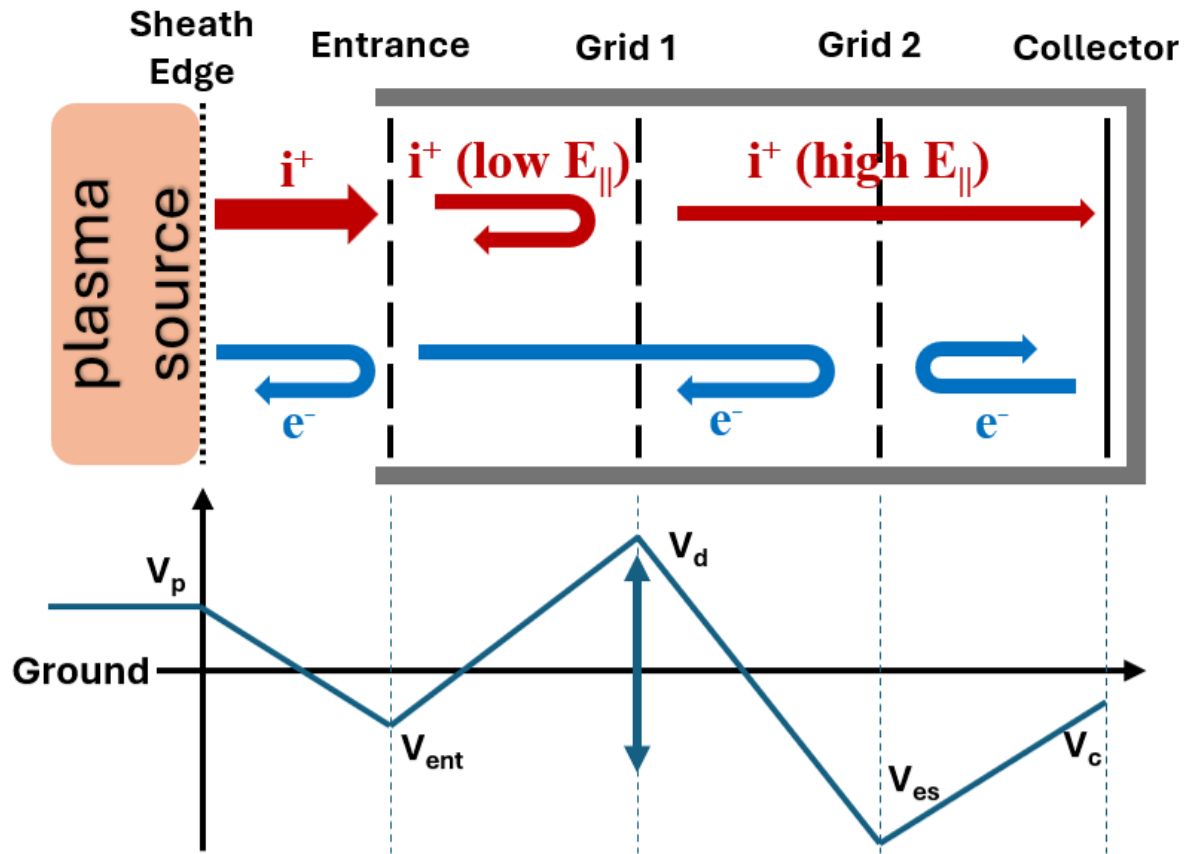
## Ion temperature ( $T_i$ ) measurements on the divertor target

- $T_i$  plays important roles in the scrape-off layer (SOL) and divertor physics. But it is often assumed  $T_i = T_e$  for modeling of plasma-surface interaction processes due to the lack of direct experimental measurements.
- A divertor Retarding Field Energy Analyzer (RFEA) has been developed at DIII-D which enabled time-resolved divertor  $T_i$  measurements for the first time.
- RFEA implementation in fusion environments is challenging due to harsh environments, most notably, high heat flux



# Background

## How does the RFEA acquire the ion temperature?



- Entrance with aperture size smaller than Debye length rejects most thermal electrons
- Scanning bias on Grid 1 repels low energy ions
- Assuming Maxwellian plasma, collected current can be interpreted as a function of the bias with  $T_i$  being the characterizing parameter:

$$I_c(V_d) = \begin{cases} I_0, & V_d < V_p \\ I_0 e^{-Z(V_d - V_p)/T_i}, & V_d \geq V_p \end{cases}$$

# Overview

- **Hardware**
  - Design overview
  - Thermal performance evaluation
- **Experimental results**
  - Divertor Ti profile
  - Ion energy distribution

# Design goals and challenges

- DIII-D tokamak operates under a vast range of plasma conditions, with multiple heating schemes available, so the RFEA needs to be adaptable
- Designed to survive  $q_{\parallel} = 100 \text{ MW/m}^2$  peak heat flux due to low incident angle ( $\sim 2^\circ$ ) between the field lines and divertor surface
- Maintain good signal quality under extreme noisy environment
- Space charge and selective transmissions complicate the interpretation process

## survivability

- compact design
- small exposure area

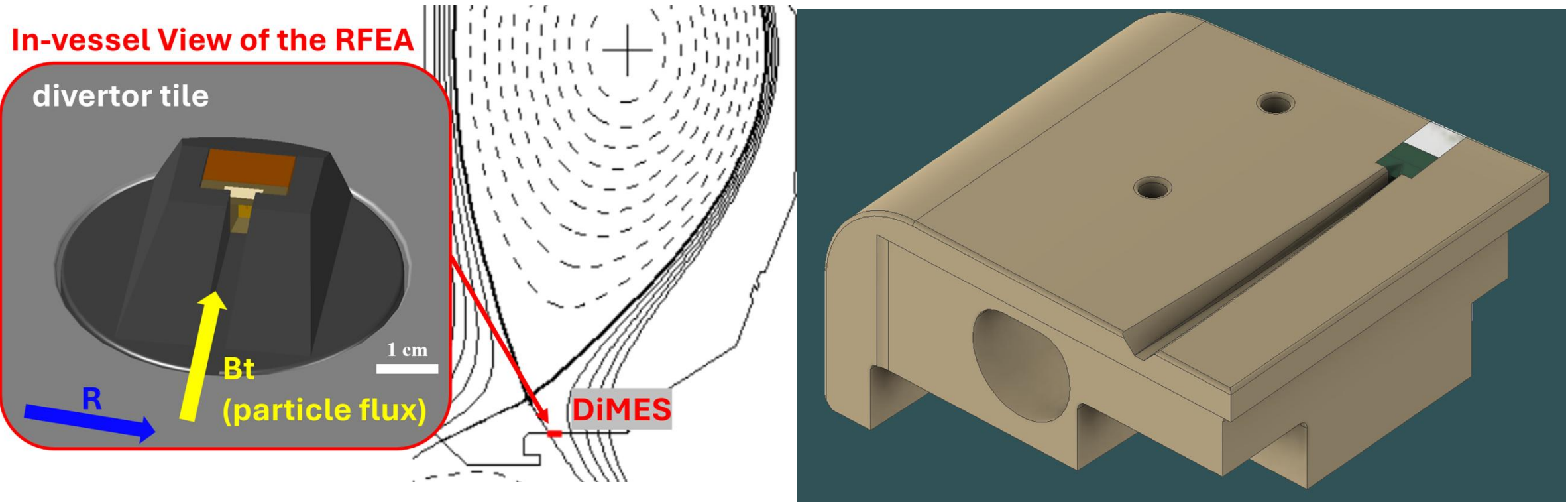


## signal quality

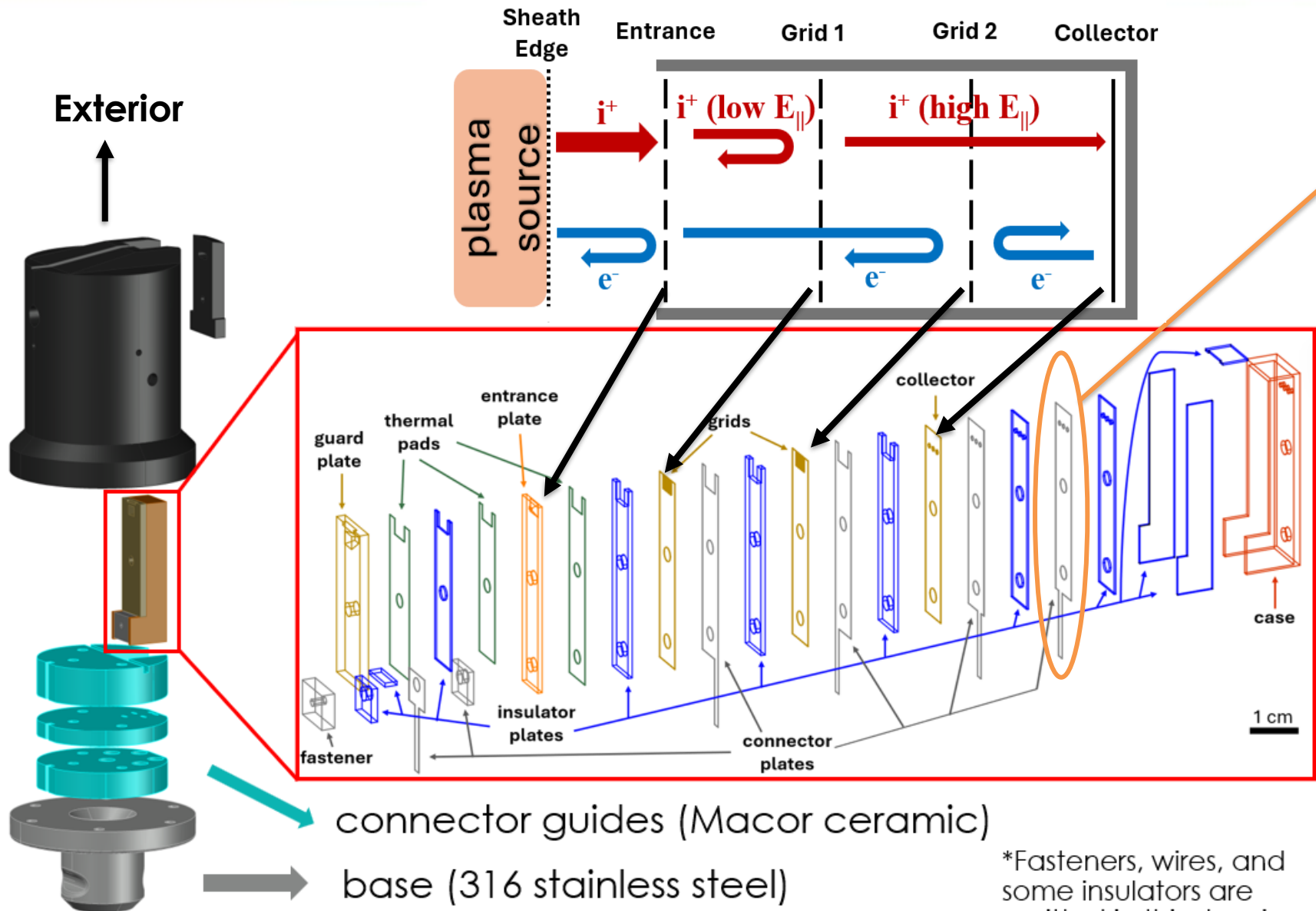
- large and open design
- large exposure area

# Two RFEAs have been implemented at DIII-D

- Utilizing the **Di**vertor **M**aterial **E**valuation **S**ystem (**DiMES**), the RFEA can be implemented without opening the vessel. Optimal for prototyping and testing.
- The Tile RFEA is design with improved thermal performance to withstand plasma exposure for a whole campaign and continuous gather data for variety of plasma conditions.



# Design overview



Dummy collector for noise subtraction is proven to be essential

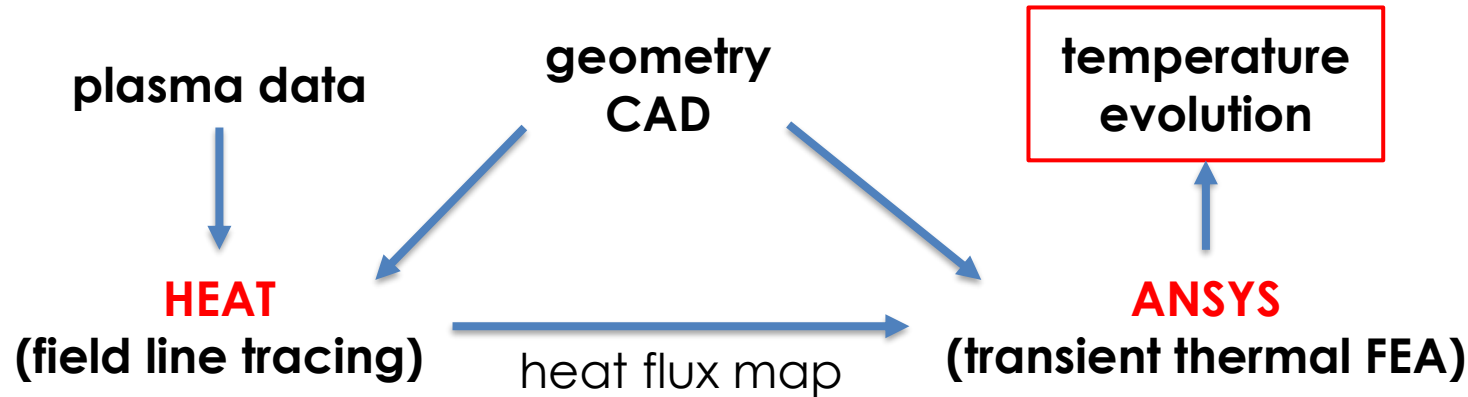
**Materials with high thermal performance:**

- laser-cut tungsten grids
- high purity alumina insulators
- tungsten guard plate
- W-Re10 entrance plate

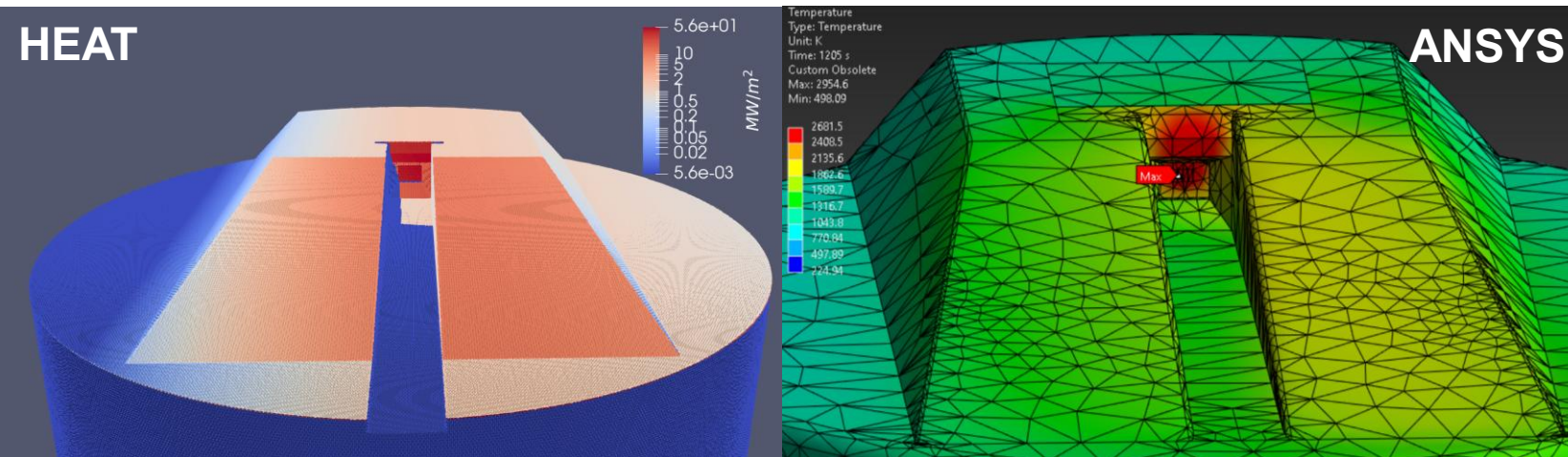
Total ion propagation length ~ 3.5 mm

\*Fasteners, wires, and some insulators are omitted in this drawing

# Exterior geometry is optimized with full CAD thermal simulations

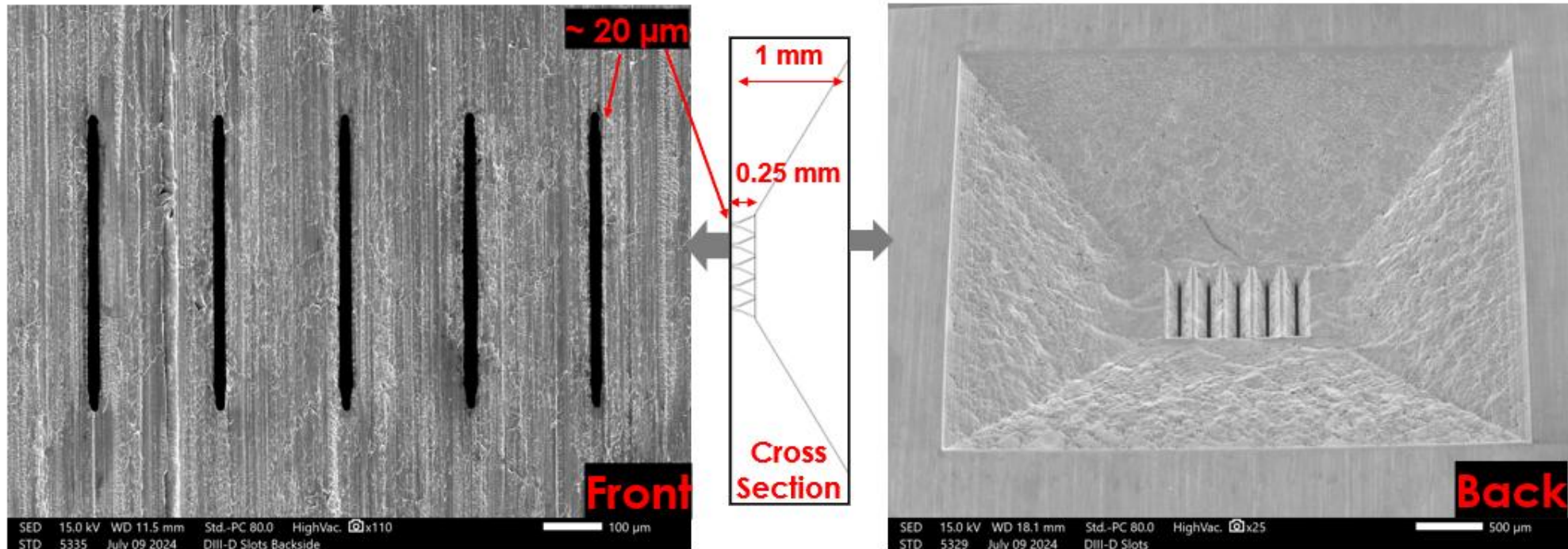


- Comprehensive thermal analysis was done to guide the design process and ensure the probes thermal performance
- **HEAT**: flux-tracing heat flux map with real DIII-D magnetic geometry
- **ANSYS**: transient thermal finite-element analysis for temperature evolution



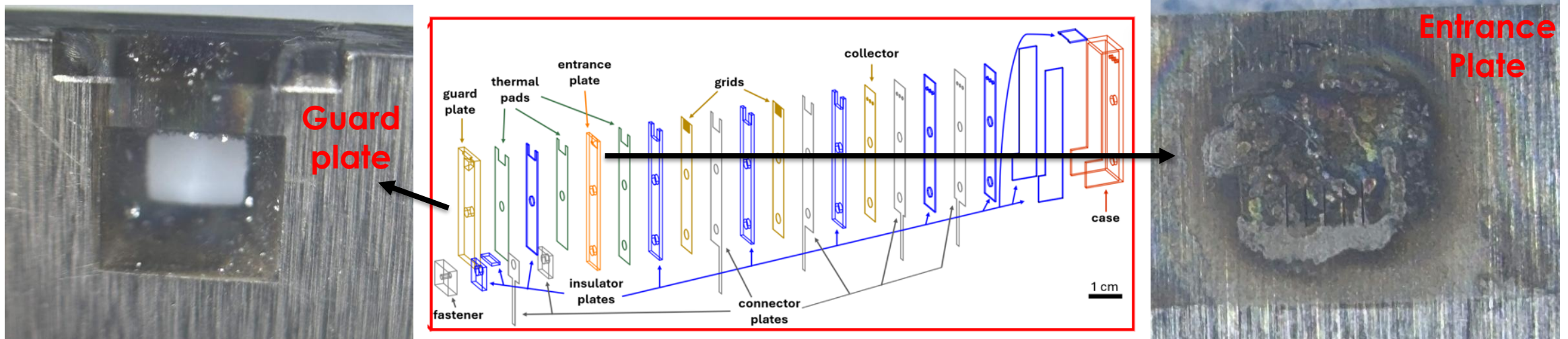
# Interior geometry is optimized with PIC simulations

- Besides thermal analysis, the entrance plate geometry is also iterated with **particle-in-cell simulations** to improve total ion throughput while limiting space charge accumulation and selective transmission
- The manufacture is accomplished by **laser micromachining** technique



# Proven survivability

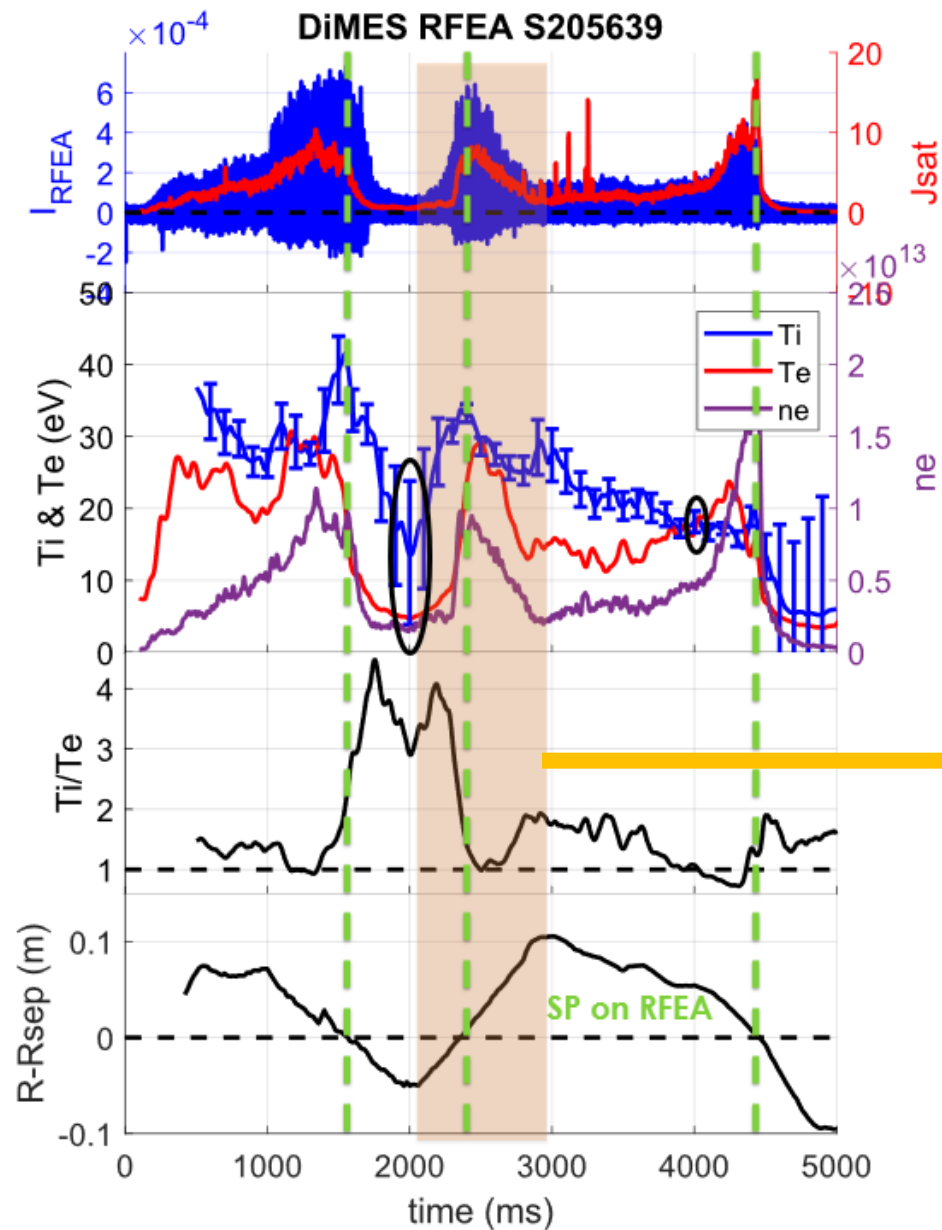
- **Survived over a hundred shots with no significant damage**
  - both L and H mode with direct strike point contact
  - fast energy-releasing events, including severe plasma disruptions, H-mode back transitions, and ELMs
- **It has been shown that this RFEA design and iteration process is very robust for extreme heat flux conditions such as the fusion environment.**



# Overview

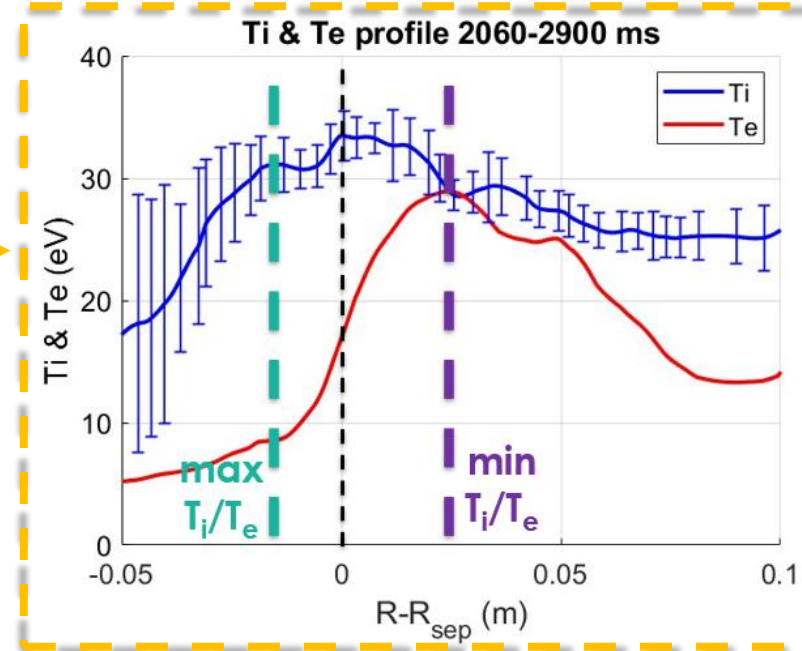
- Hardware info
  - Design
  - Thermal performance evaluation
- **Experimental results**
  - Divertor Ti profile
  - Ion energy distribution

# Ti profile from L-mode discharge



## First ever divertor Ti measurement at DIII-D

- Overall signal level shows good correlation with  $J_{sat}$  measured by the Langmuir probe in the similar radial position
- Both RFEA current and derived  $T_i$  (with conventional interpretation method) shows good correlation with strike point location
- $T_i/T_e \sim 1-2$  except for the private flux region

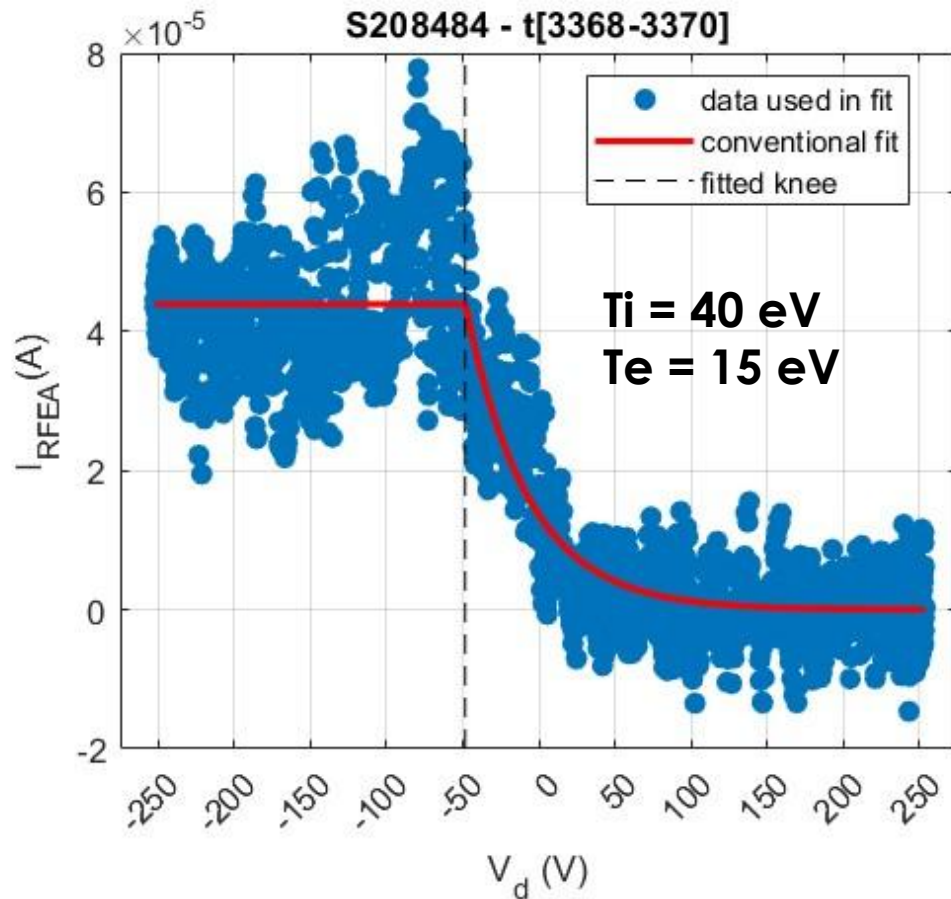


\*L-mode,  
ECH only:  
 $P_{total} = 1$  MW,  
 $I_p = 1$  MA,  
 $B_t = 1.7$  T

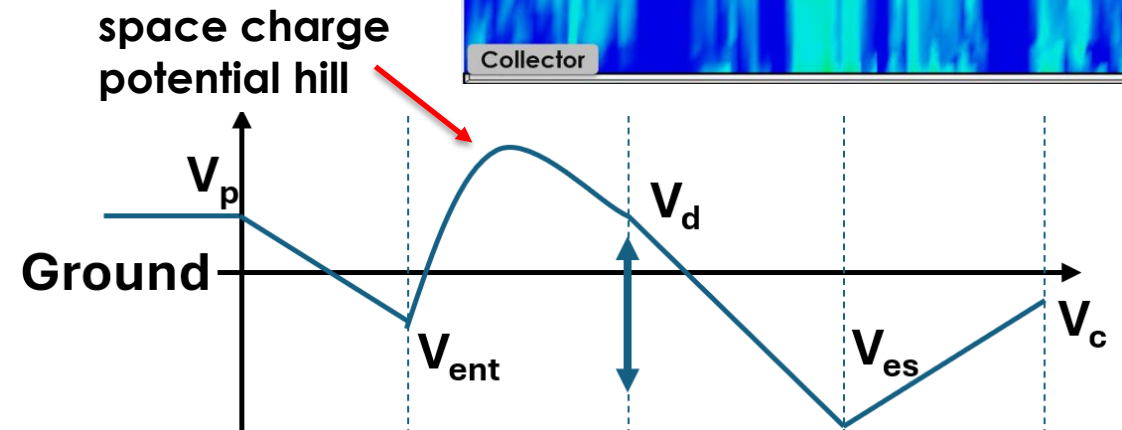
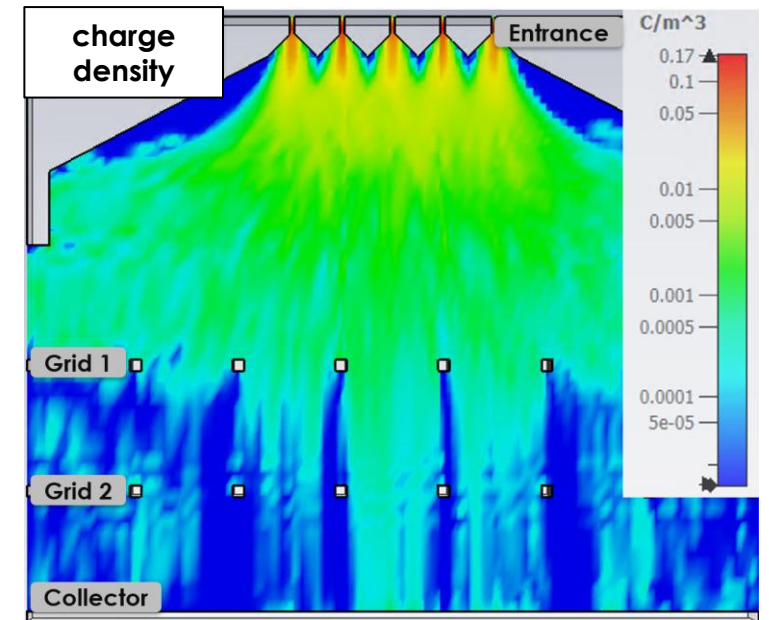
# Signal distortion potentially causing overestimated $T_i$

- The signal can be heavily distorted, causing divergence from the ideal model, as **at SOL**  $V_p < 0$  is not physical

$$I_c(V_d) = \begin{cases} I_0, & V_d < V_p \\ I_0 e^{-Z(V_d - V_p)/T_i}, & V_d \geq V_p \end{cases}$$



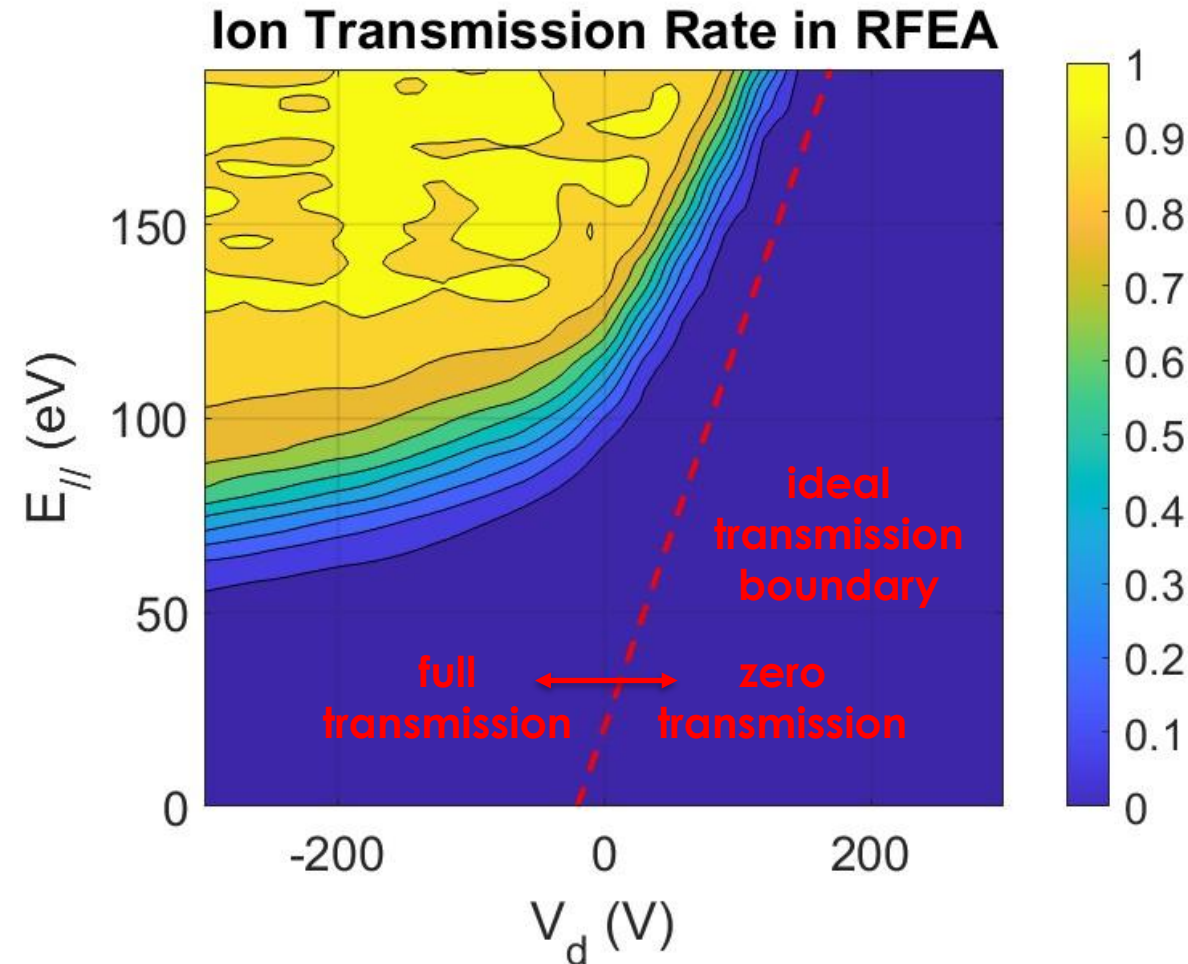
PIC simulations reveals actual ion propagation process in RFEA cavity:



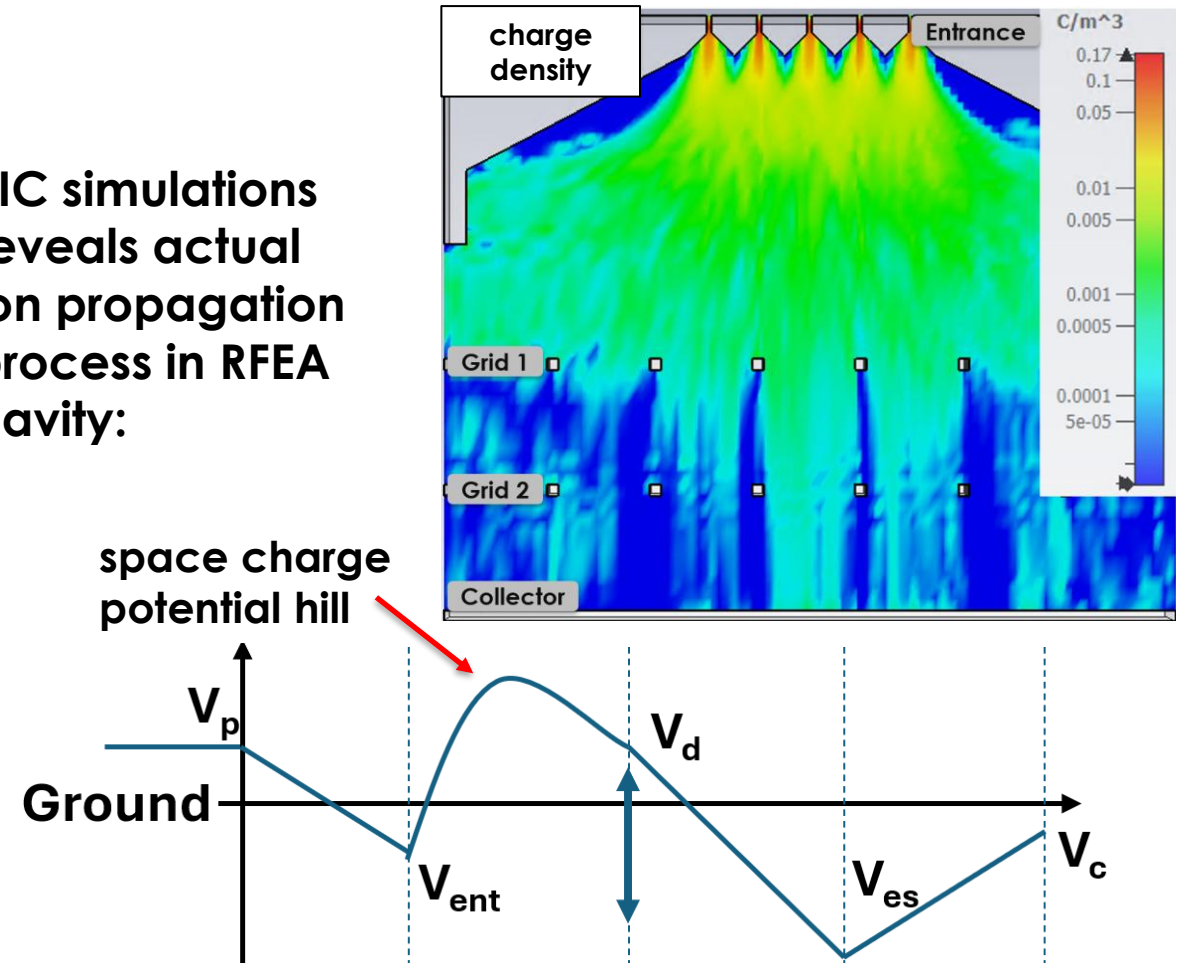
# Signal distortion potentially causing overestimated $T_i$

- **Energy-dependent transmission rate** can be calculated with PIC simulations

$$I_c(V_d) = \begin{cases} I_0, & V_d < V_p \\ I_0 e^{-Z(V_d - V_p)/T_i}, & V_d \geq V_p \end{cases}$$



PIC simulations reveals actual ion propagation process in RFEA cavity:



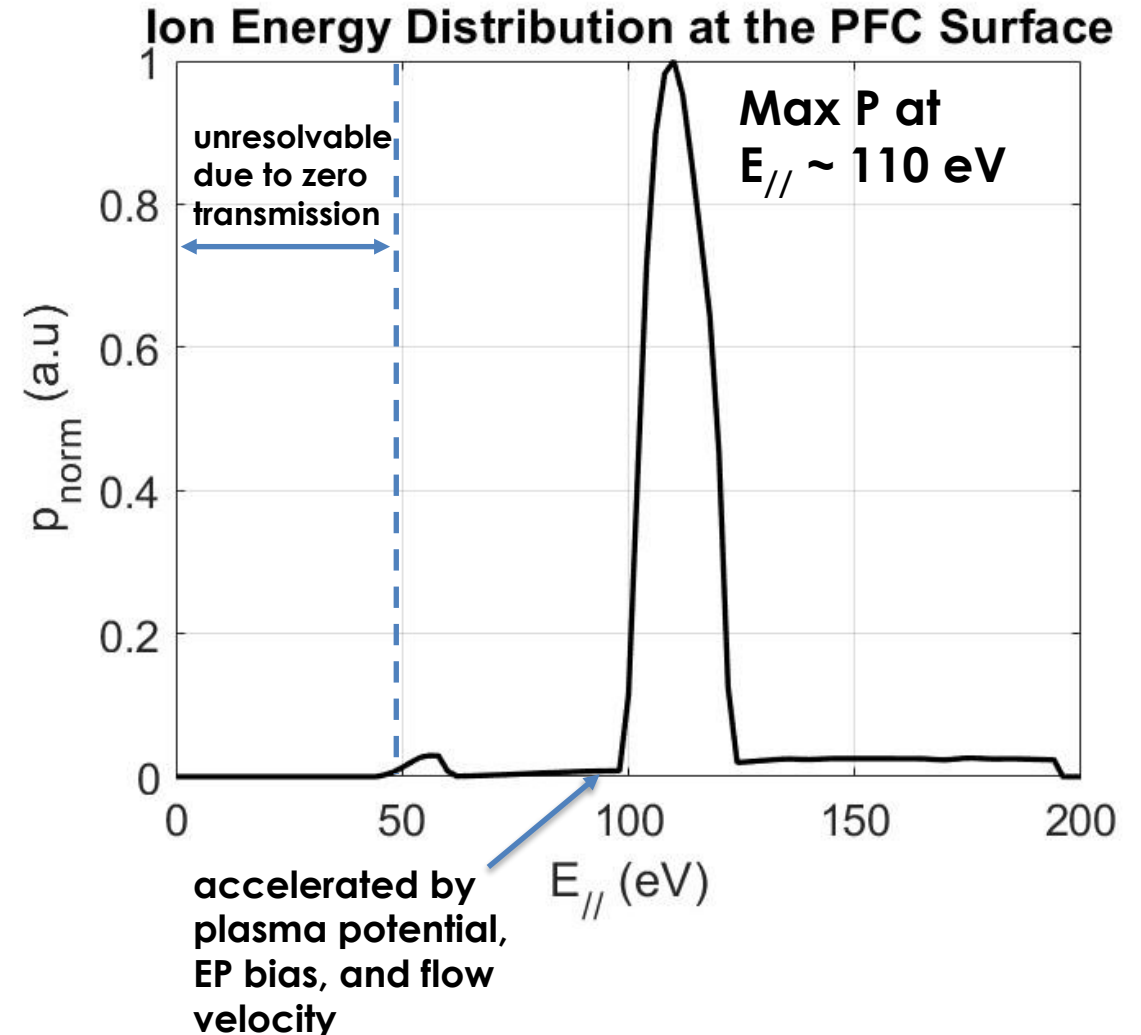
# The ion energy distribution is derived

## Knowing

$$I_{\text{RFEA}}(E_{//}, V_d) = I_0 \cdot P(E_{//}) \cdot R(E_{//}, V_d)$$

the ion energy distribution can be derived

- This analysis does **NOT** need any assumptions about the distribution function or sheath condition
- Note that the distribution **at the PFC surface** is demonstrated instead of at the sheath edge
- If assuming a drifting Maxwellian at the sheath edge, this distribution will return **Ti ~ 20 eV**



# Conclusion

- With the comprehensive simulation-guided process, the divertor RFEA design at DIII-D has been proven robust for various divertor tokamak conditions.
- We successfully measured  $T_i$  and interpreted energy distribution on the divertor surface at DIII-D for the first time.
- The PIC-based interpretation method improves our understanding of the experimental data and allows for more accurate  $T_i$  interpretation and ion distribution calculation without strict Maxwellian assumptions, which could greatly improve SOL and divertor simulation fidelity.
- Future work: with survivability and interpretability demonstrated, permanent RFEA tile with motorized shutter is in consideration



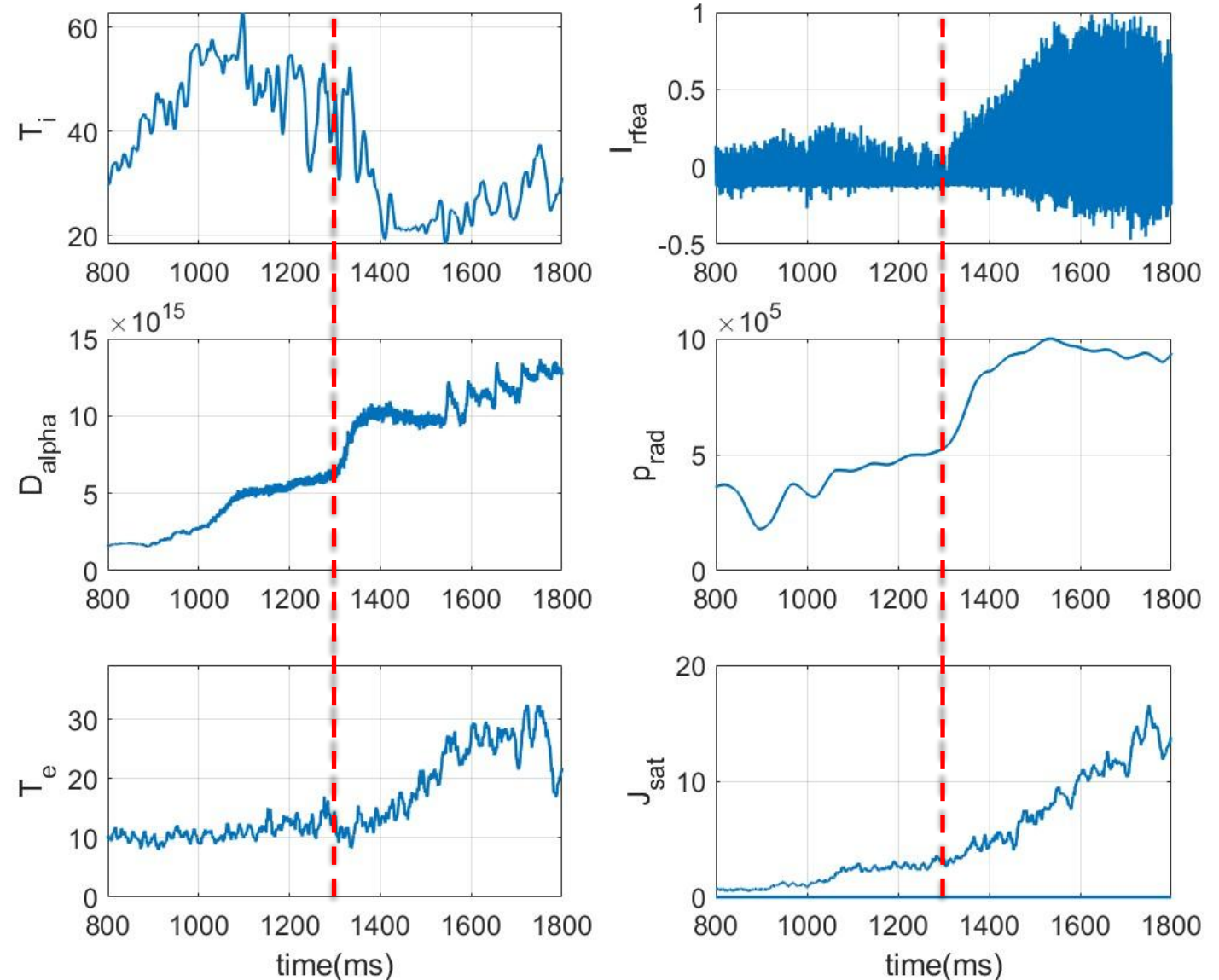
**Thanks for your attention!**



# back up: Counterintuitive Response to NBI

Within 100 ms after NBI turn-on:

- $T_i$  drops over ~40%
- D-alpha rises over 60%
- radiated power from divertor rises over 60%
- RFEA ion current rises ~ 400%
- small change on  $T_e$
- $J_{sat}$  rises ~ 50%



# back up

