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日本大学

NIHON UNIVERSITY

# Compact Toroid Injection into C-2U FRC

US-Japan CT2016, August 24

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Nihon University

# Collaborations



**Nihon University**

- Integral partnership
- Development of a compact toroid injector for particle refueling

- This project has been conducted in part under the MOU on the research cooperation between UCI and NU.

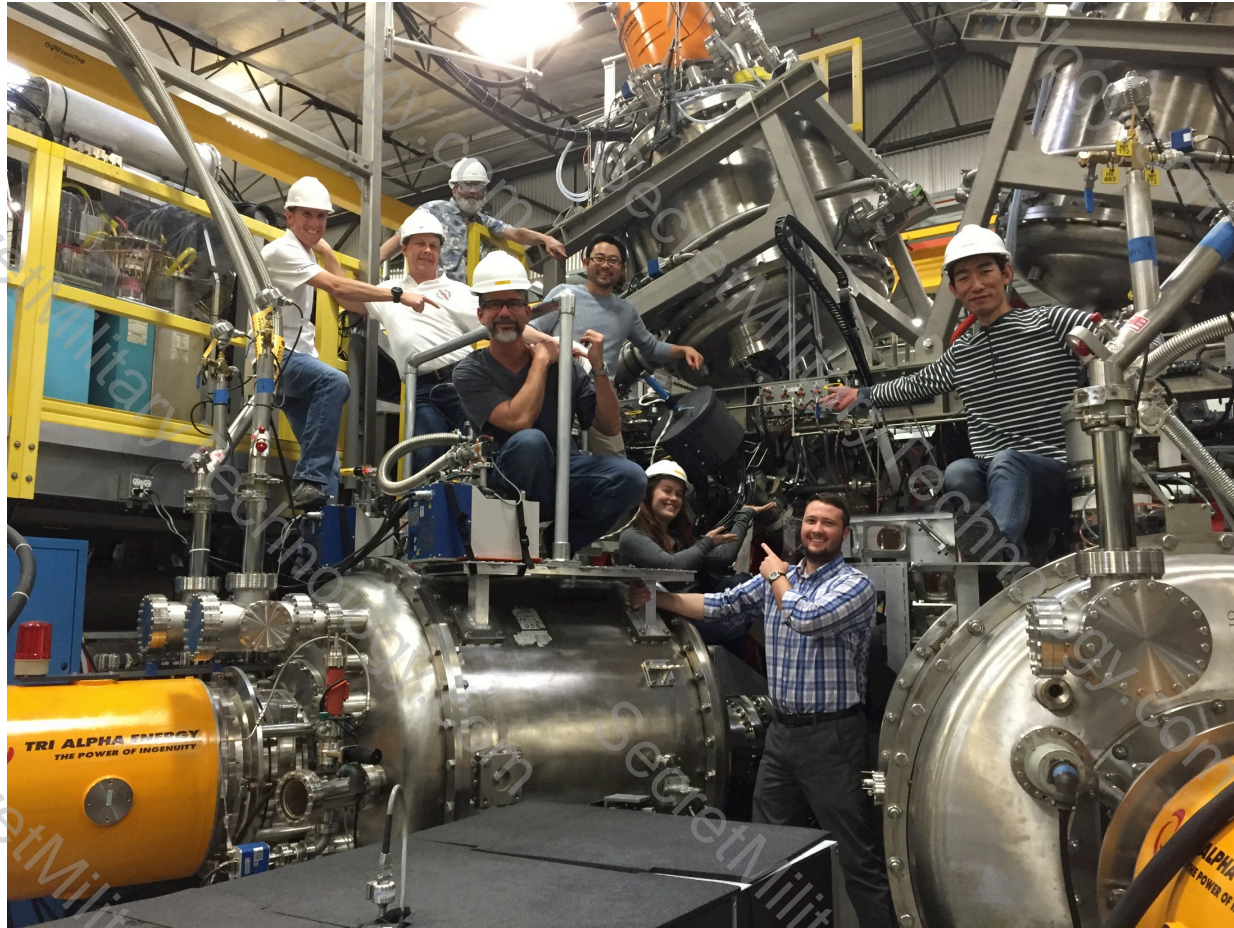


**Tri Alpha Energy**

**University of California at Irvine**



# Acknowledgements



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E. Garate      University  
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D. Sheftman  
T. Tajima\*      \*UCI

# Outline

- **Motivation**
- **CT Injector Overview**
- **CT injection into C-2U FRC**
- **Upgrade**
- **Summary**

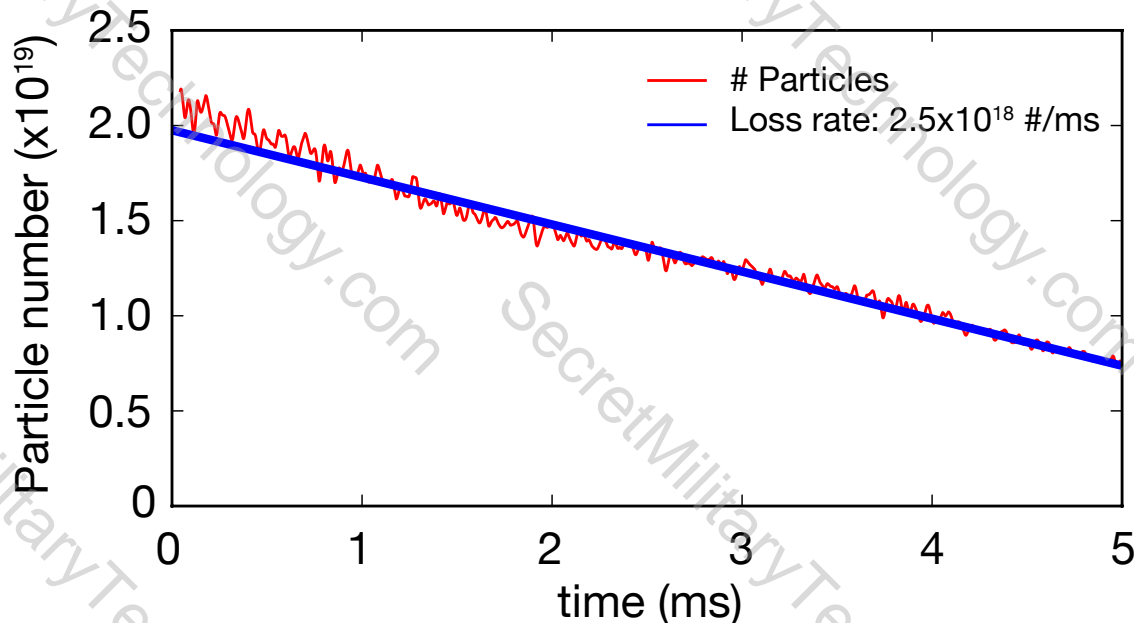
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# Motivation

## Requirement for CT Injection

- In C-2U particle loss rate was  $2.0 - 4.0 \times 10^{18} / \text{ms}$
- To penetrate the FRC, the **kinetic energy density of the CT must be higher than  $4 \text{ kJ/m}^3$** , which is magnetic field energy inside the confinement vessel, e.g., density of CT  $1 \times 10^{15} \text{ cm}^{-3}$ , velocity  $70 \text{ km/s}$
- The CT Injector is a viable refueling candidate

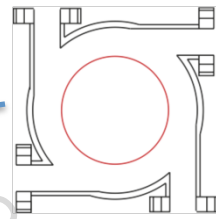
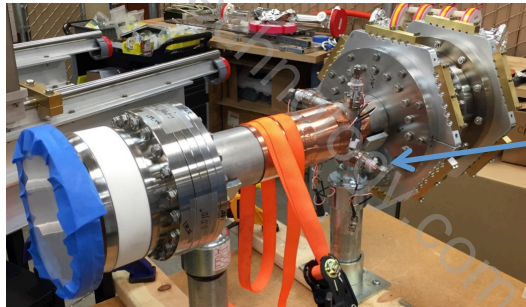


Time evolution of particle loss rate of the C-2U FRC

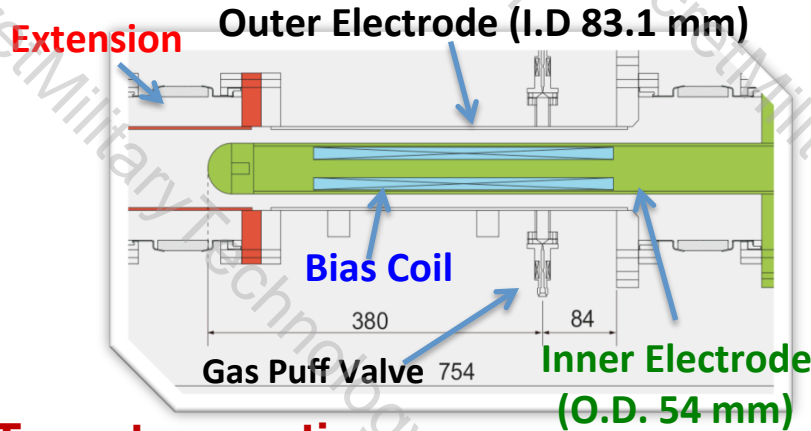
# Outline

- Motivation
- **CT Injector Overview**
  - **Developed CT injector**
  - **Test Stand**
  - **CT Parameters**
- CT injection into C-2U FRC
- Upgrade
- Summary

# Magnetized Coaxial Plasma Gun



Gas port

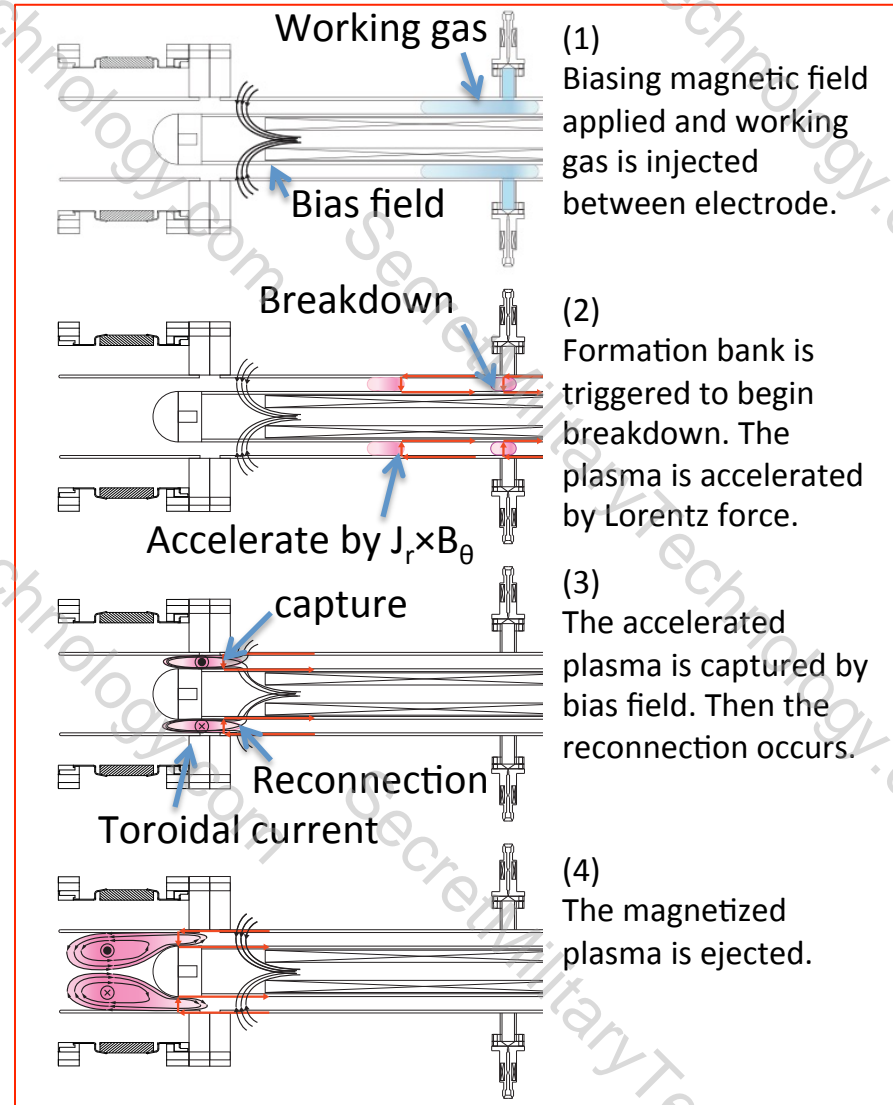


## Tungsten coating

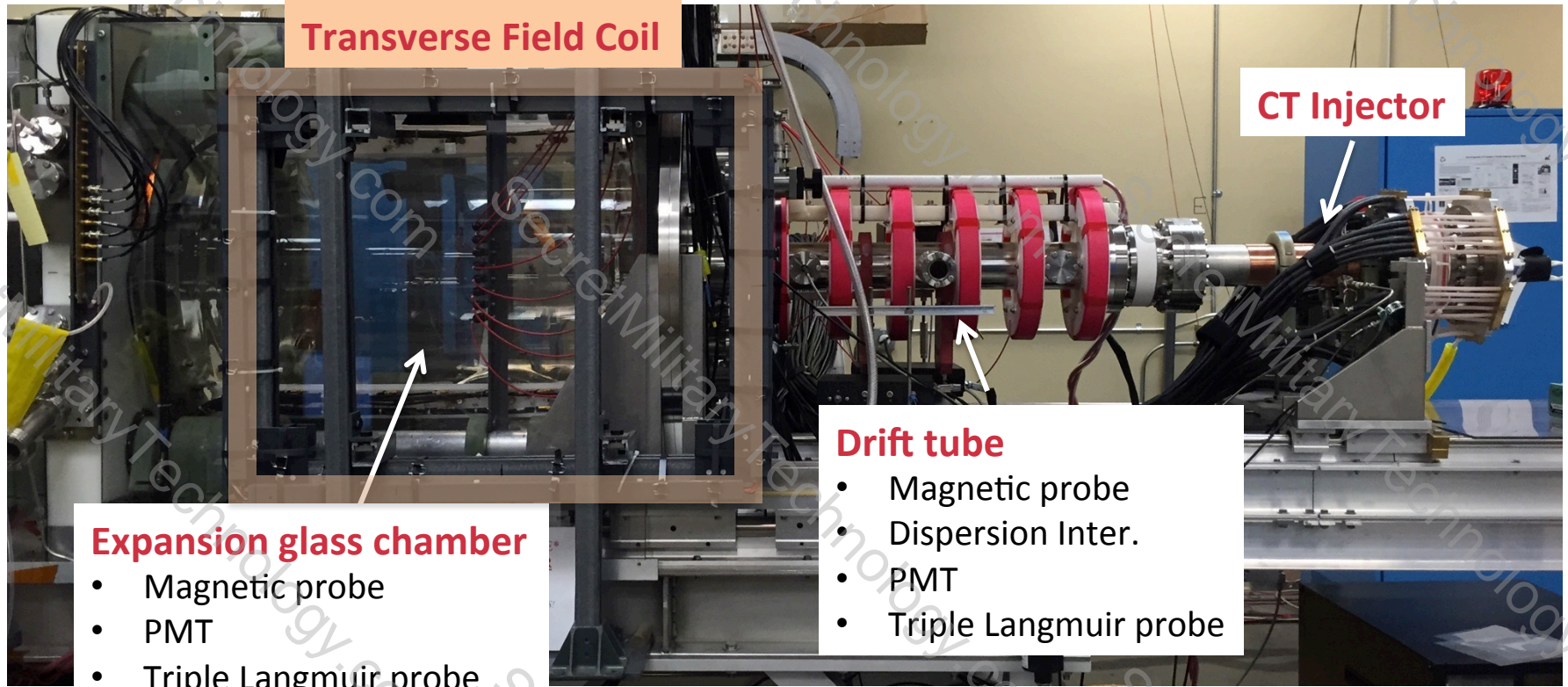
- The surface of the inner electrode is coated with tungsten by Vacuum Plasma Spraying

## Extension electrode

- The roles of the extension electrode are; protect ceramic break from the plasma, and suppress diffusion of the magnetic field.



# Test Bed with Transverse magnetic field coil



## Drift tube

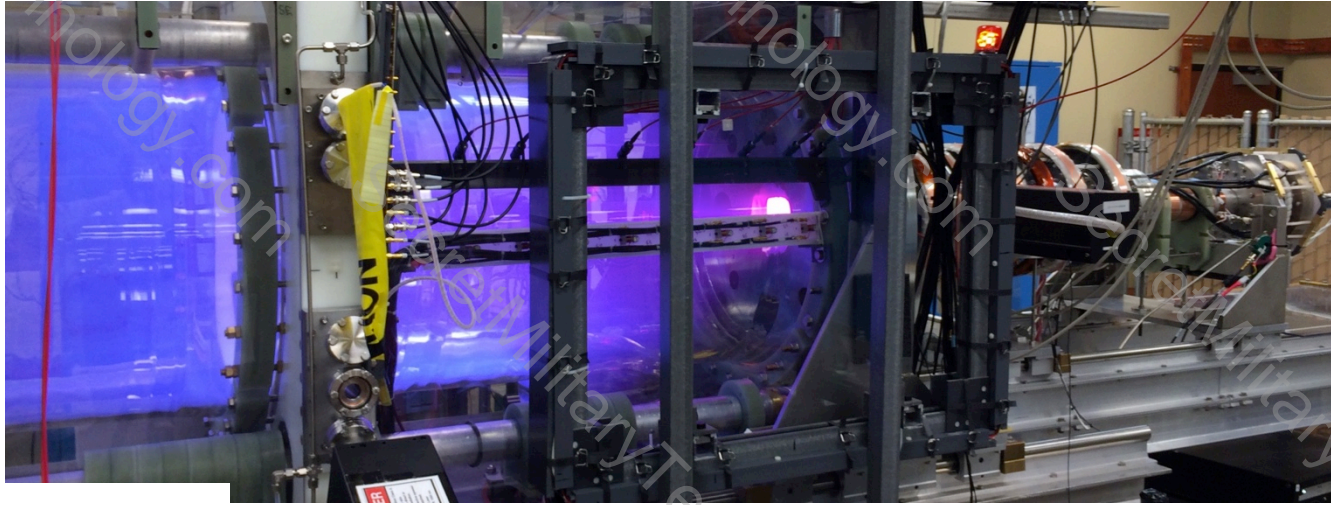
- The drift tube diagnostics measure typical CT parameters; velocity, density, and temperature.

## Glass chamber

- The transverse magnetic field coil simulates C-2U's magnetic field.

# CT was compressed by magnetic field

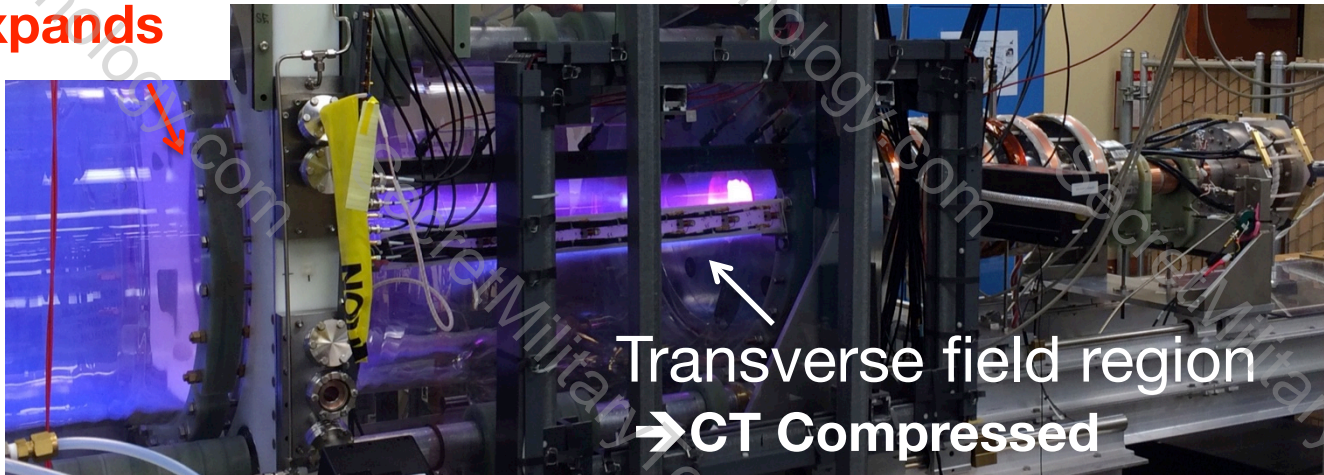
w/o Transverse field



Field-free region

→ CT Expands

w/ Transverse field



Transverse field region

→ CT Compressed

# Summary of CT Optimization

## CT Performance

- Required parameters **>70 km/s,  $1.0 \times 10^{15} \text{ cm}^{-3}$**
- Gun current up to **190 kA**
- Total energy of CT up to **0.7 kJ**
- Velocity **>100 km/s**
- Density  **$1.5 - 3.5 \times 10^{15} \text{ cm}^{-3}$**
- Electron temperature **20 - 40 eV**
- Energy Density **50 kJ/m<sup>3</sup>**

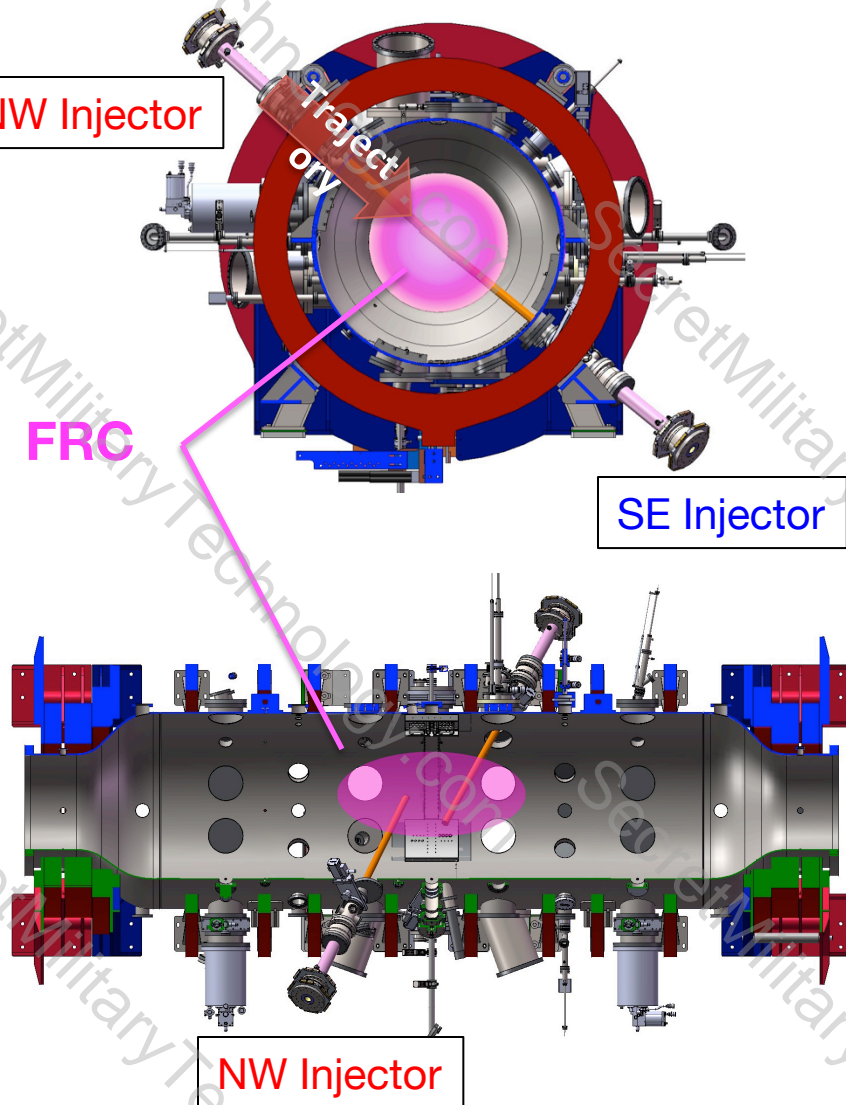
## CT Injection across transverse field

- Developed CT injector achieved the requirement
- CT will penetrate C-2U Field
- Diameter of CT in the transverse field is 5-10 cm according to probe measurements

# Outline

- Motivation
- CT Injector Overview
- **CT injection into C-2U FRC**
  - **Installation of CTI**
  - **Single CT injection** ————— **1 CT**
  - **Multi-Pulse CT injection** ————— **Up to 3 CTs**
- Upgrade
- Summary

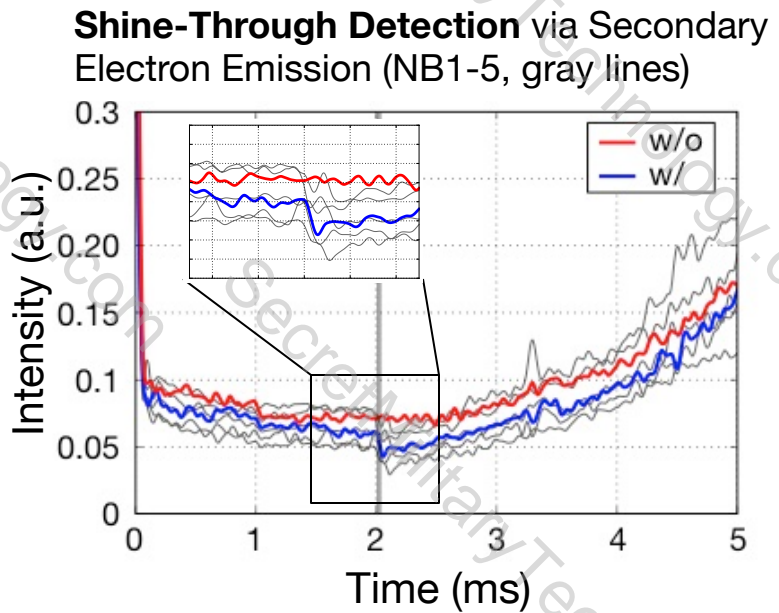
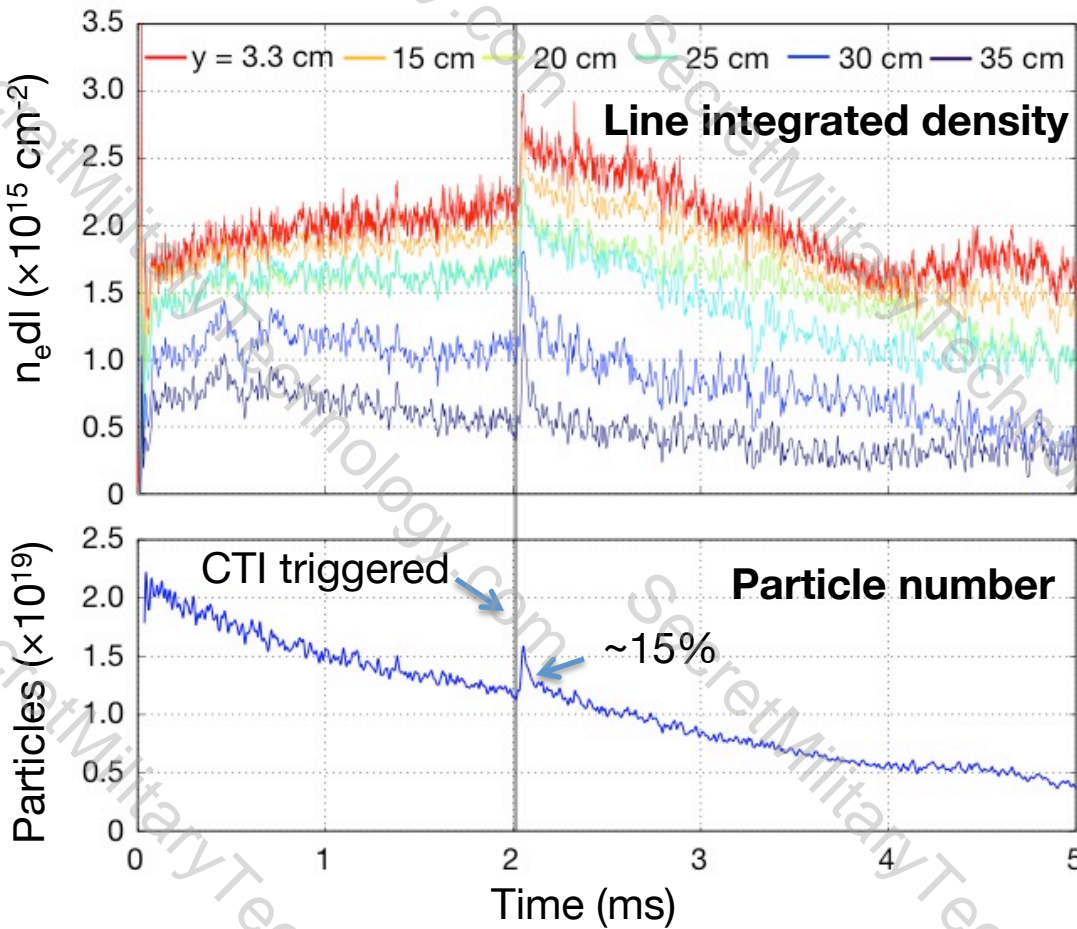
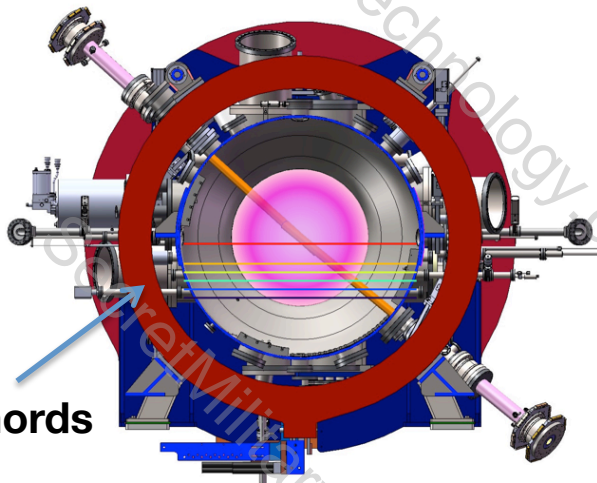
# CT injectors installed on C-2U



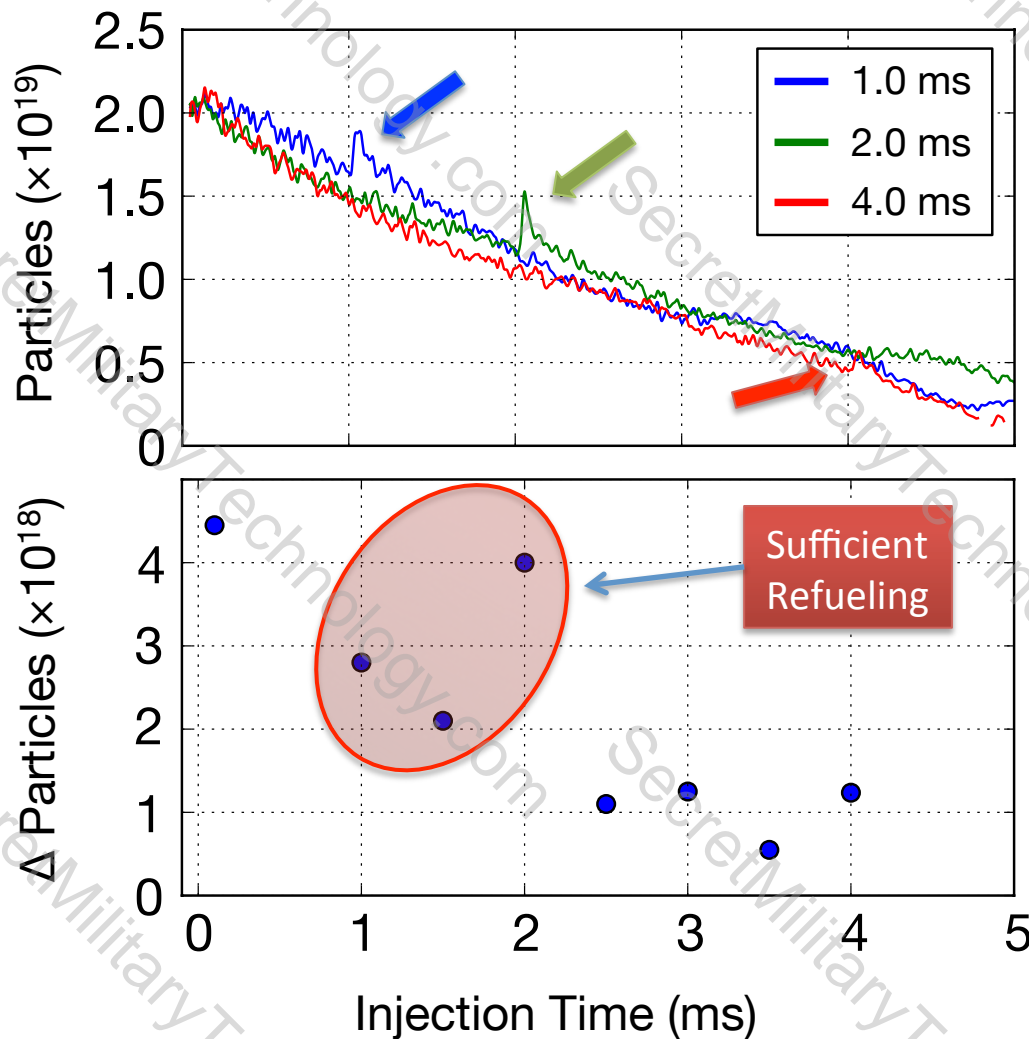
- The CT injectors were installed on the confinement vessel.
- Angles
  - **NW CTI**
    - From mid-plane 26.1 deg
    - From Vertical 42 deg
  - **SE CTI**
    - From mid-plane 29 deg
    - From Vertical 39.3 deg
- These injectors can be controlled independently.

# Single CT pulse increased density/particles

- Interferometry verifies mid-plane **density increase**
- Pressure balance confirms **particle number increases**
- Shine-through **reduced** when CT injected



# Particle number increased by CT injection



- CTs Injected at various times
- Initial rise particle inventory as high as **40%**
- Original loss rate resumes with higher offset
- Total particles added seems to depend on injection time
- Probably due to larger target
- For these conditions  **$\sim 2$ ms** was **optimal time for injection**

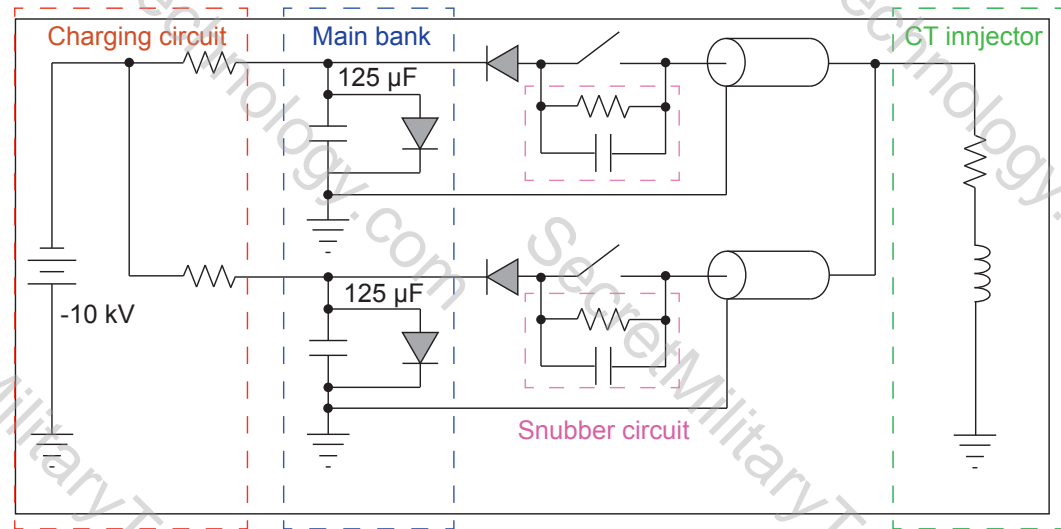
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  - Installation of CTI
  - Single CT injection                    \_\_\_\_\_                    1 CT
  - **Multi-Pulse CT injection**                    \_\_\_\_\_                    **Up to 3 CTs**
    - **Development of Multi-pulse injection system**
- Upgrade
- Conclusion

# Multi-pulse system and Fast Camera

## Multi-Pulse:

- Main Bank of 125  $\mu\text{F}$  with 10 kV
- Multi-pulse at  $\leq 1$  kHz
- Diodes as crowbar and blocking element



## Fast-framing Camera (NAC Image Technology):

- Up to **1.25 MILLION** frames/sec for 120 frames
- 100 ns minimum exposure time
- 360 $\times$ 410 pixel color sensor
- 10-bit, 58  $\mu\text{m}$  pixels
- Nikon lens mount



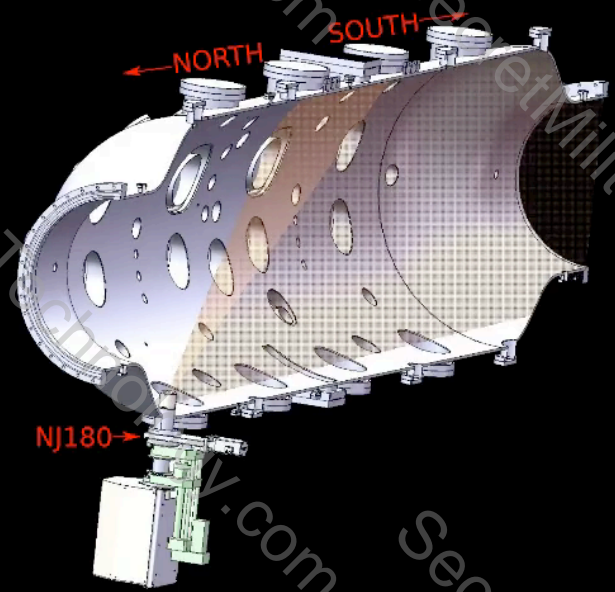
# High speed imaging of 2 CTs at the Test-Stand

**Multi-Pulsed CT Injections  
at the Test-Stand:  
CTIs at  $t=0$  and 3.5 ms**

# 1<sup>st</sup> Awesome Video on the C-2U

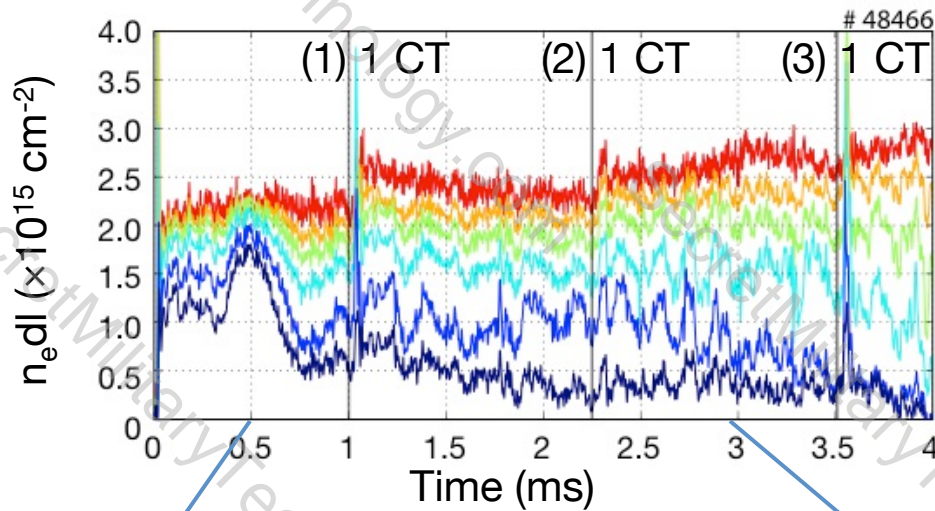
Shot 48786 DCA08

Camera: NAC HS-106E  
FOV: 30° H × 30° V  
Filter: Blank  
Resolution: 412 × 360  
Frame Rate: 500.000 kHz  
Exposure: 1.9 μs  
Port: NJ180  
(x,y,z): (0.0,-0.7,2.1) m

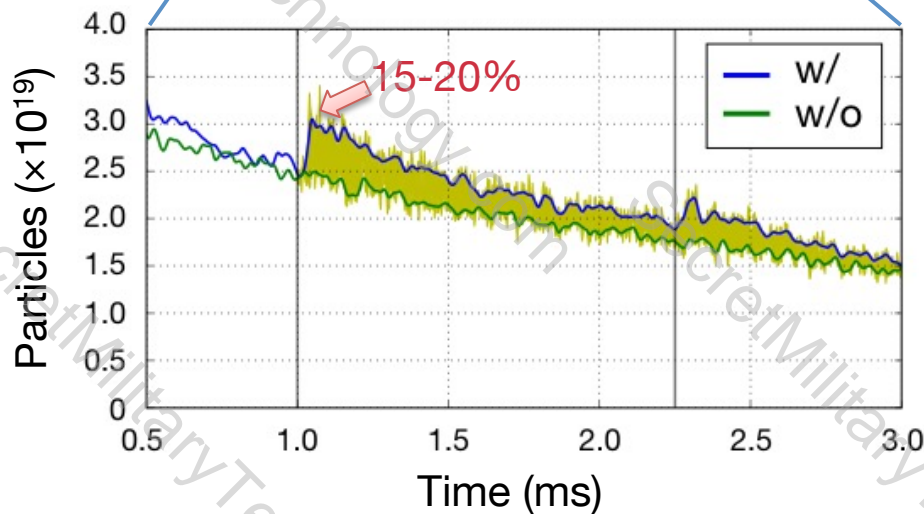
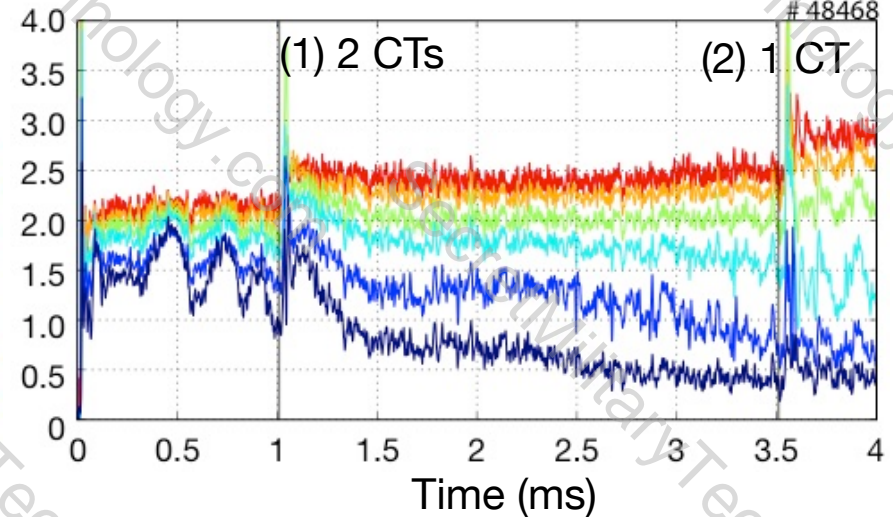


# CTs add a lot of particles

(1) SE CT, (2) NW CT, (3) SE CT



(1) SE + NW CT, (2) SE CT



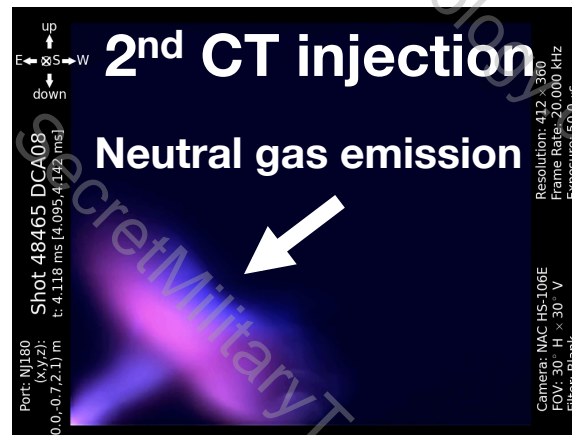
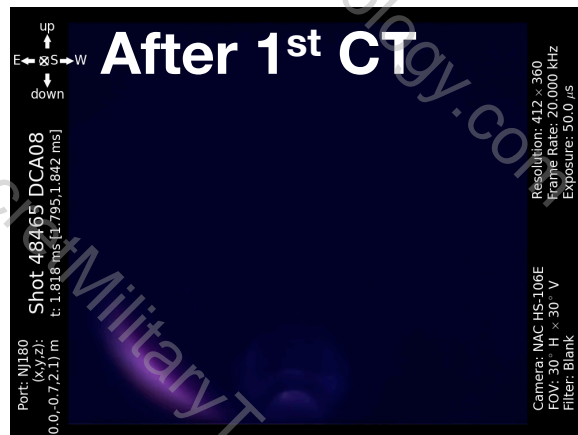
- First 2 CTs increase particle inventory
- The increased density was 10-20%
- 3<sup>rd</sup> CT alters/kills FRC
- Particle loss rate reduced by first CT
- FRC begins to decline after 2<sup>nd</sup> CT

# D $\alpha$ emission was increased after CT injection

## Fast Camera Images

- Exposure 50  $\mu$ s
- Filter Blank

- First CT leaves a trail of neutral particles
- This can be seen interacting with edge plasma
- When 2<sup>nd</sup> CT enters it collides with cloud

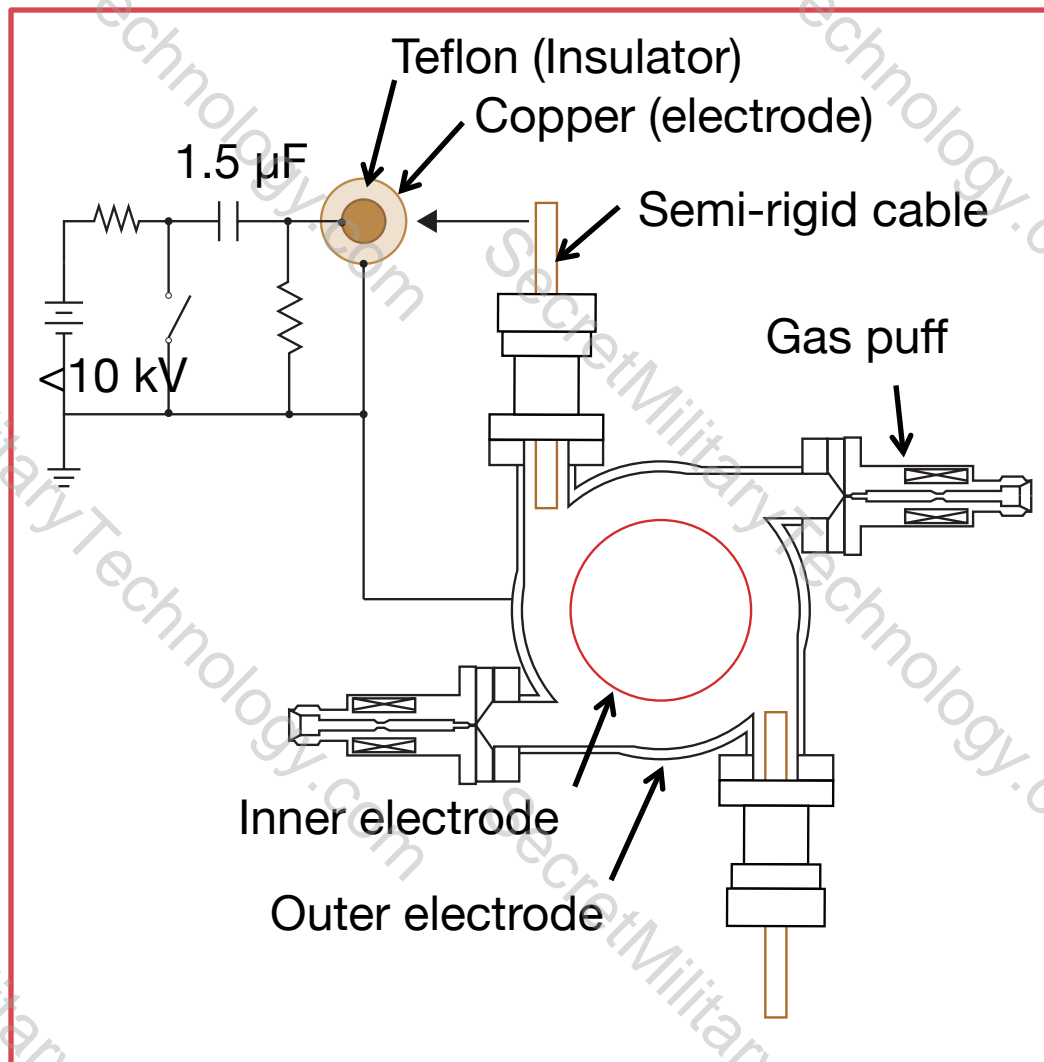
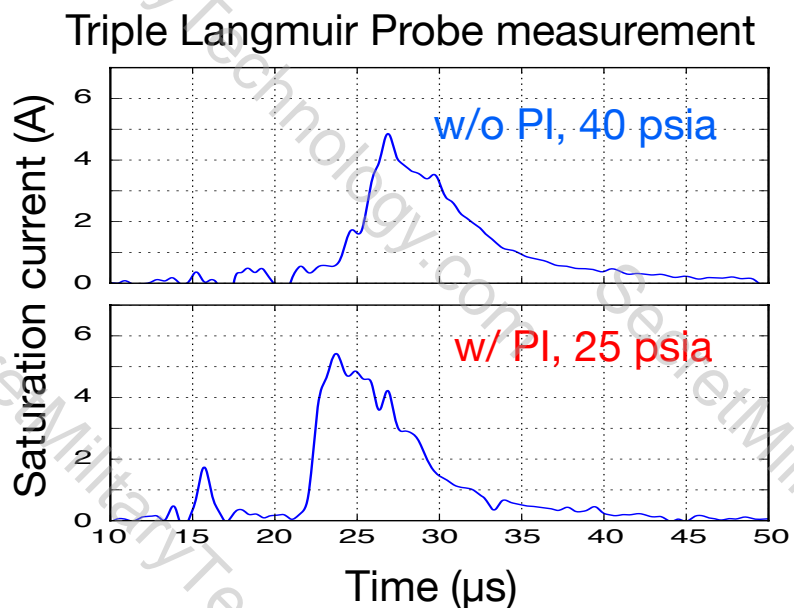
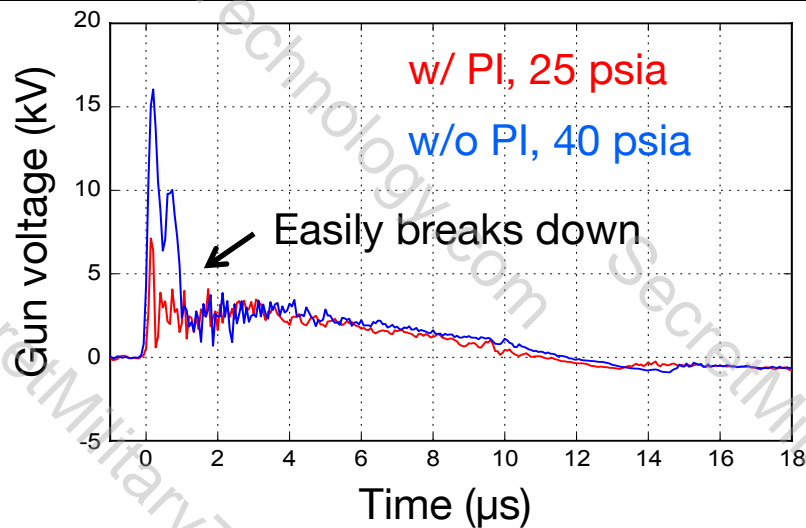


**PI system is important to reduce trailing neutral gas**

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- **Upgrade**
  - **Development of a Pre-ionization source**
- Summary

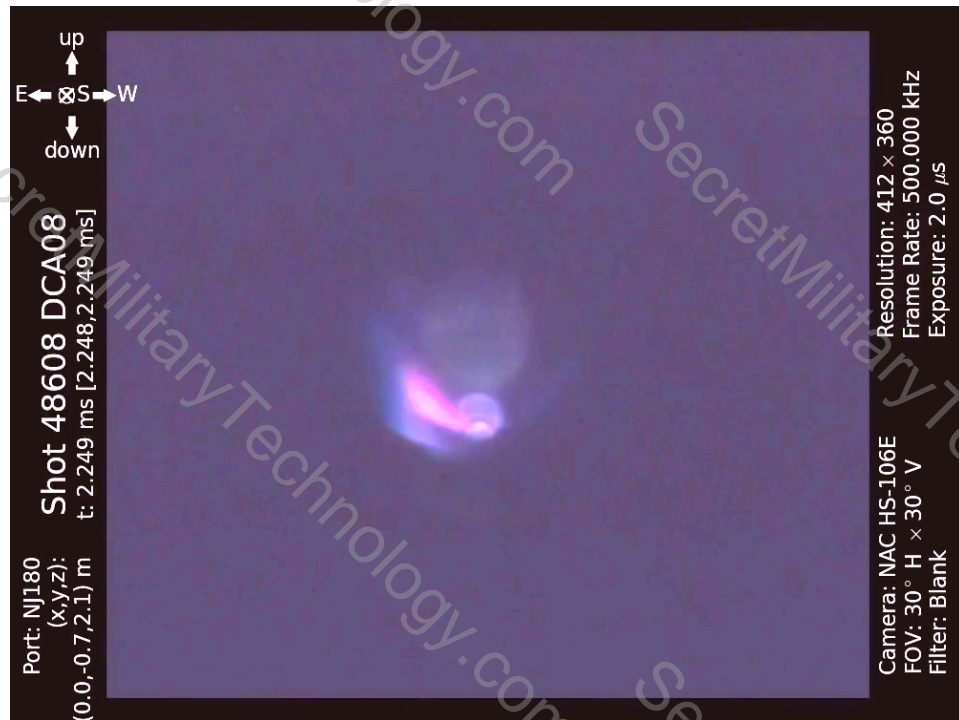
# Pre-ionization system has been developed



Schematic diagram of Pre-ionization system

# PI reduces trailing neutral gas

## No PI



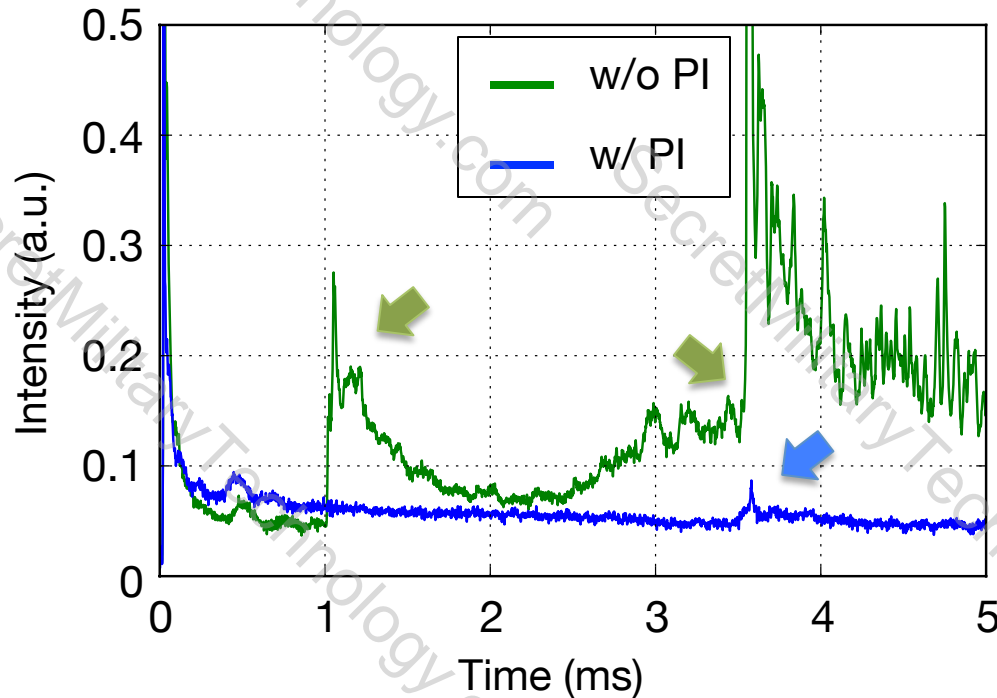
## With PI



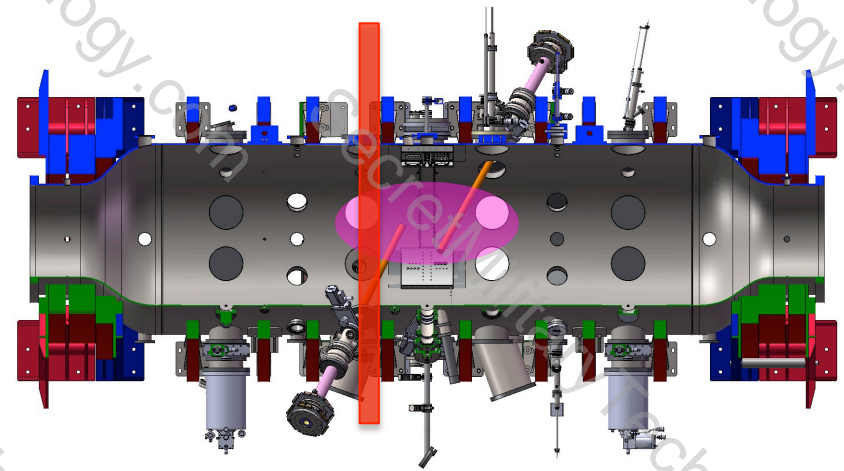
- Neutral gas follows CT
- PI eliminates gas trail
- Interacts with plasma
- Edge undisturbed

# Neutral gas load removed with PI

Da emission w/ and w/o Pre-Ionization



C plane



- $D_{\alpha}$  emission at C plane **minimized**
- No burst of light when 2<sup>nd</sup> CT is injected  
-> Bulk of **trailing neutral gas avoided**

# Summary

- The CTI program has advanced quickly
- Incremental addition of pulses
  - Refueling from each pulse
  - $D\alpha$  emission after pulse
- Several developmental cycles have led to
  - Multi-pulsed system
  - Reduction of neutral gas by Pre-ionization system
- Full refueling capabilities for C-2W currently in development