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Compact Toroid Injection into C-2U FRC

US-Japan CT2016, August 24

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Collaborations

Nihon University

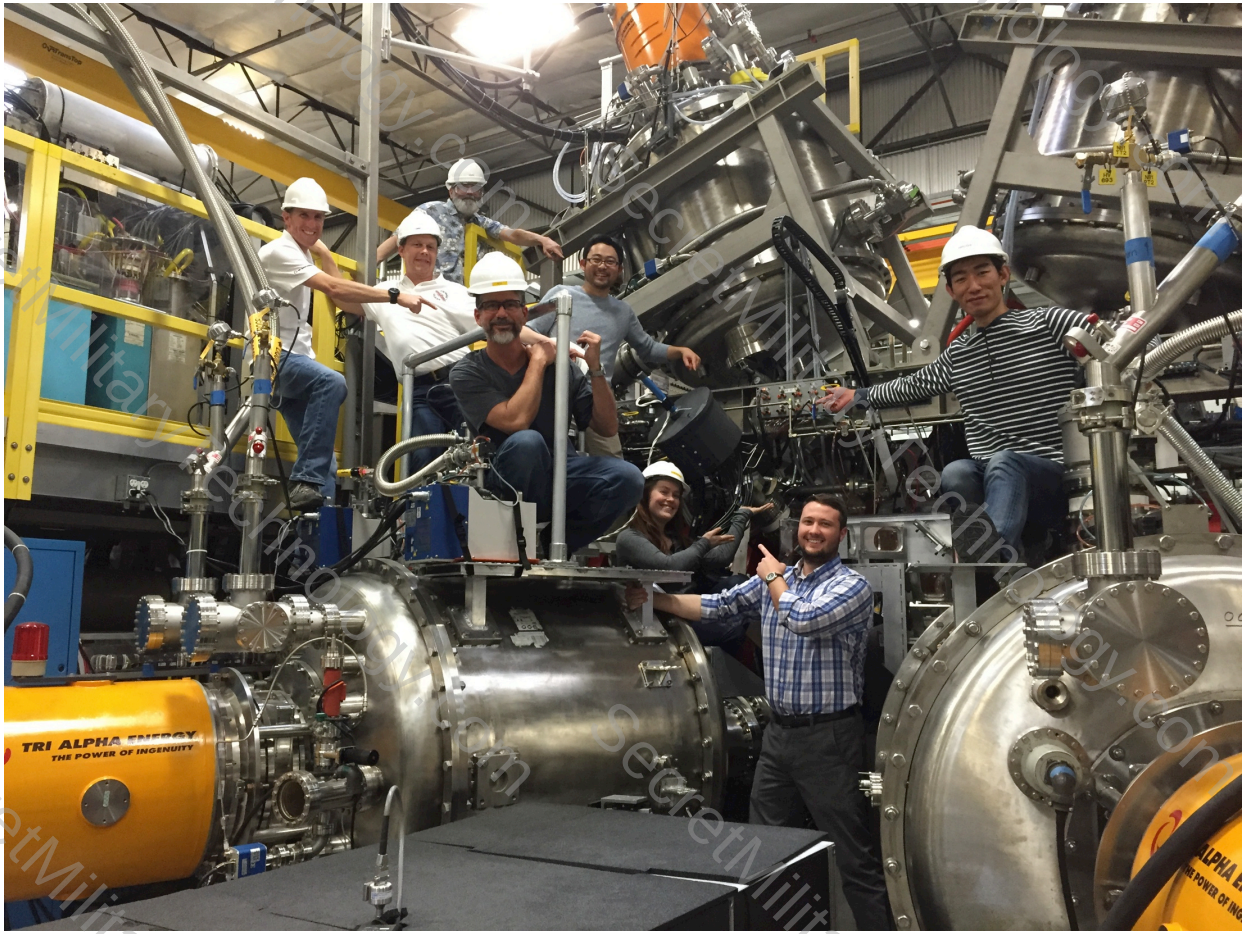
- Integral partnership
- Development of a compact toroid injector for particle refueling

- 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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Outline

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

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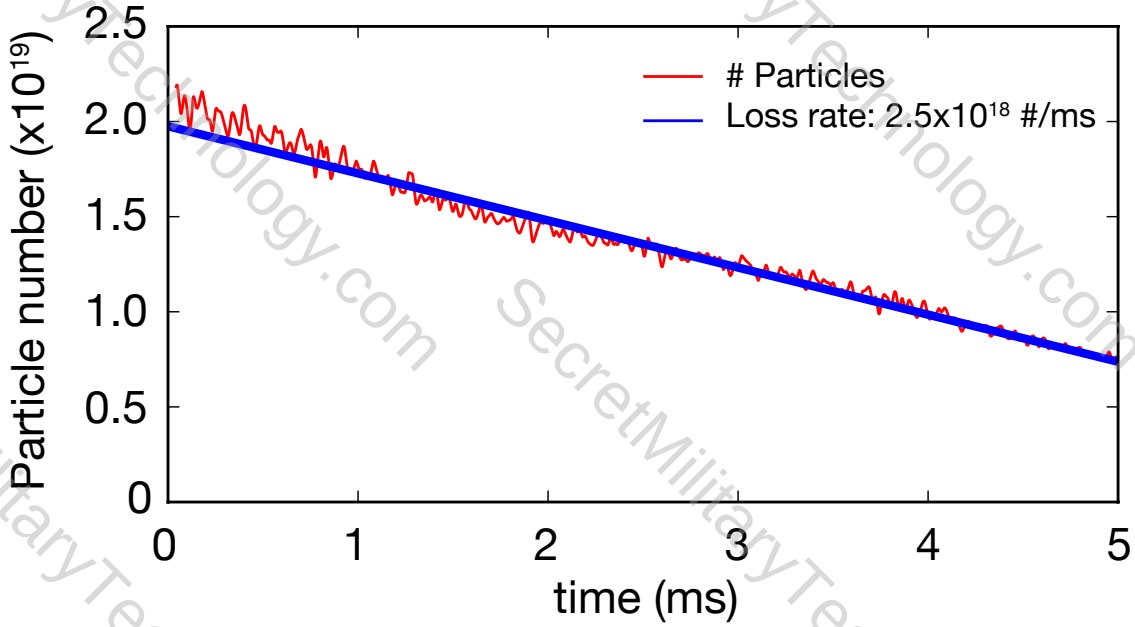
Motivation

Requirement for CT Injection

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

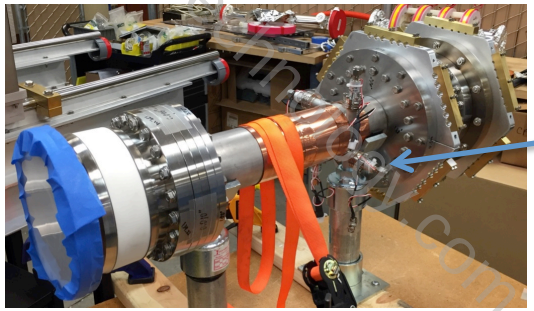


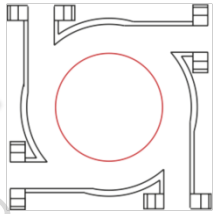
Time evolution of particle loss rate of the C-2U FRC

Outline

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

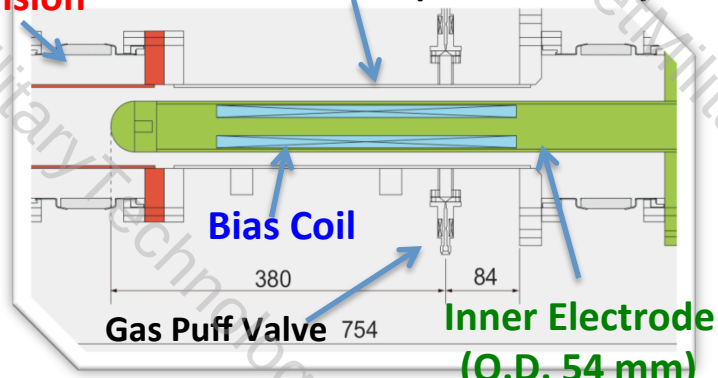
Magnetized Coaxial Plasma Gun





Gas port

Outer Electrode (I.D 83.1 mm)

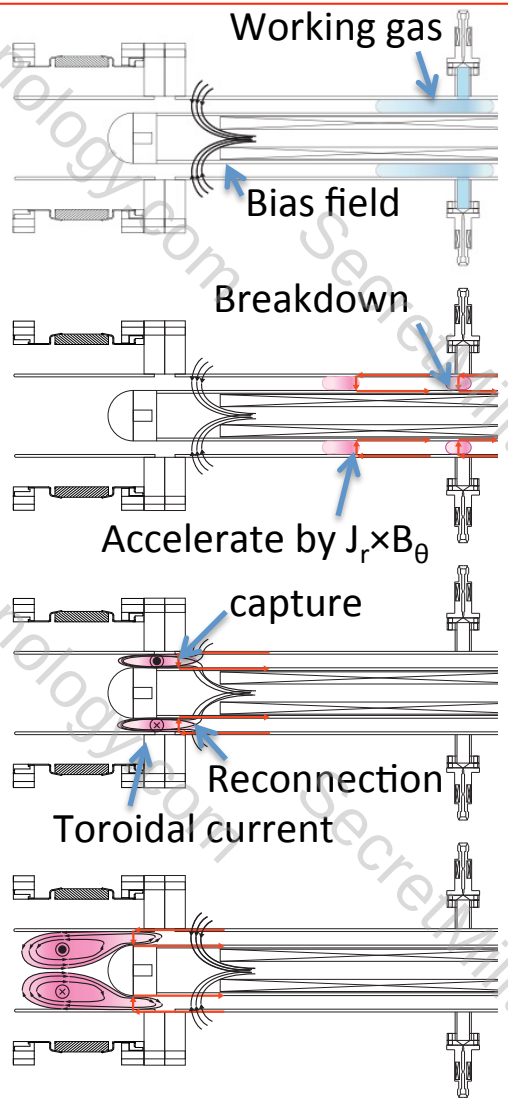


Tungsten coating

- 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.



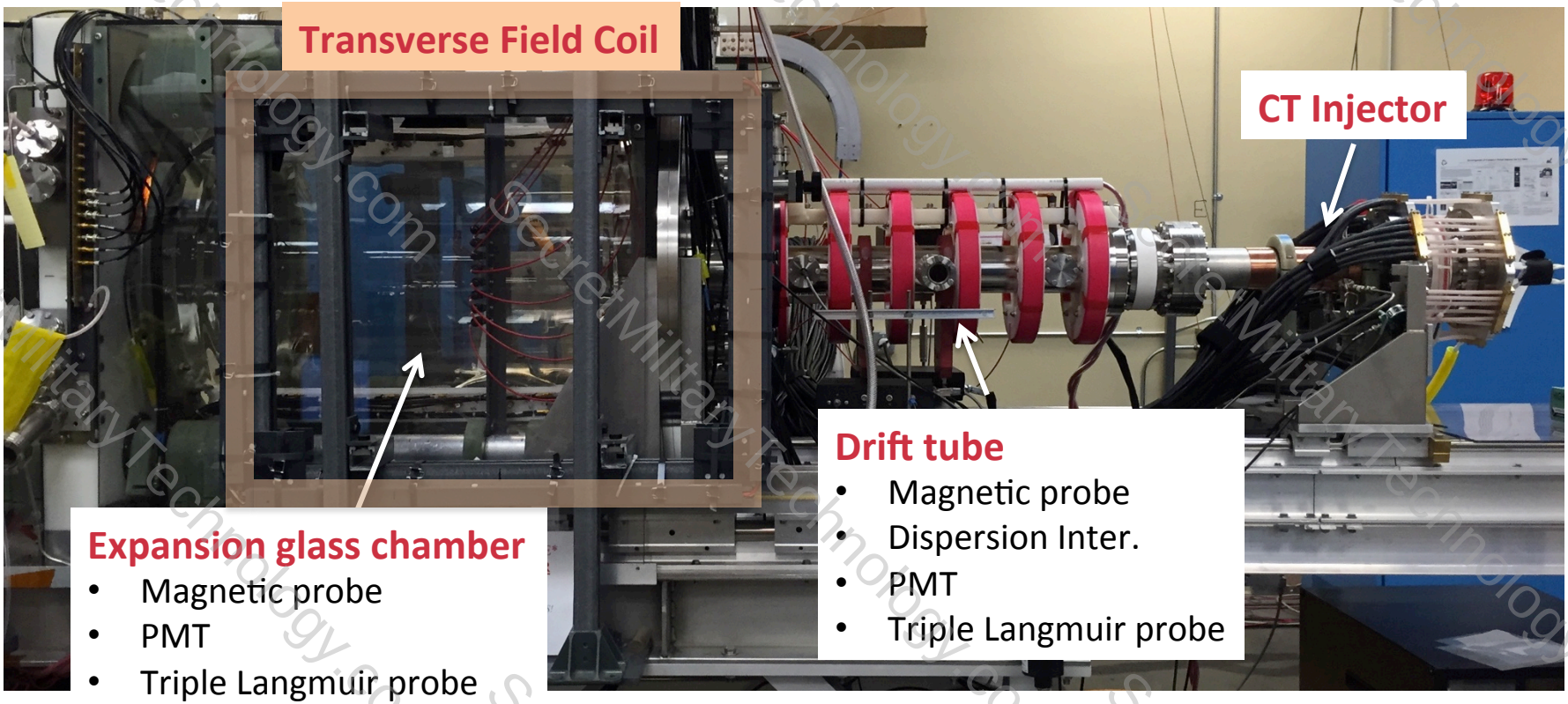
(1)
Biasing magnetic field applied and working gas is injected between electrode.

(2)
Formation bank is triggered to begin breakdown. The plasma is accelerated by Lorentz force.

(3)
The accelerated plasma is captured by bias field. Then the reconnection occurs.

(4)
The magnetized plasma is ejected.

Test Bed with Transverse magnetic field coil



Drift tube

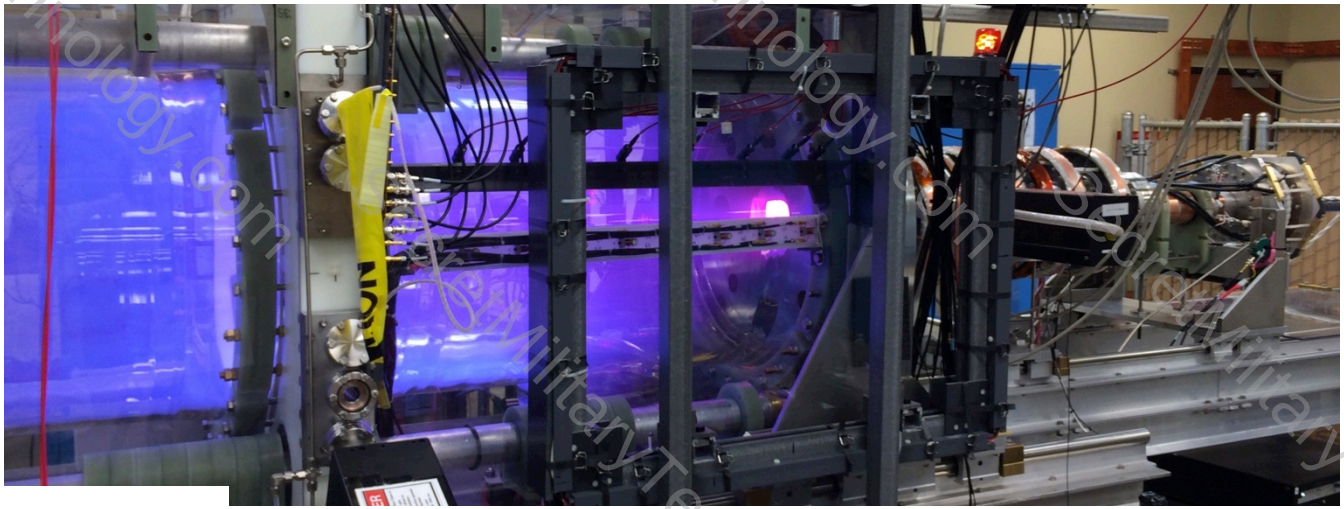
- The drift tube diagnostics measure typical CT parameters; velocity, density, and temperature.

Glass chamber

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

CT was compressed by magnetic field

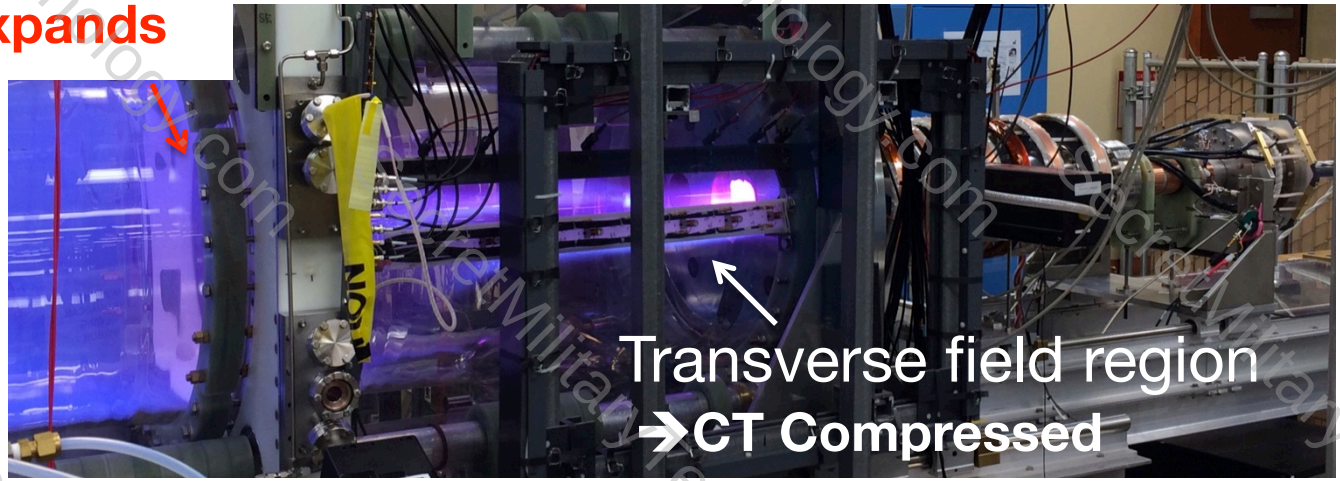
w/o Transverse field



Field-free region

➔CT Expands

w/ Transverse field



Summary of CT Optimization

CT Performance

Required parameters	>70 km/s, 1.0×10^{15} cm^{-3}
Gun current up to	190 kA
Total energy of CT up to	0.7 kJ
Velocity	>100 km/s
Density	$1.5 - 3.5\times10^{15}$ cm^{-3}
Electron temperature	20 - 40 eV
Energy Density	50 kJ/m^3

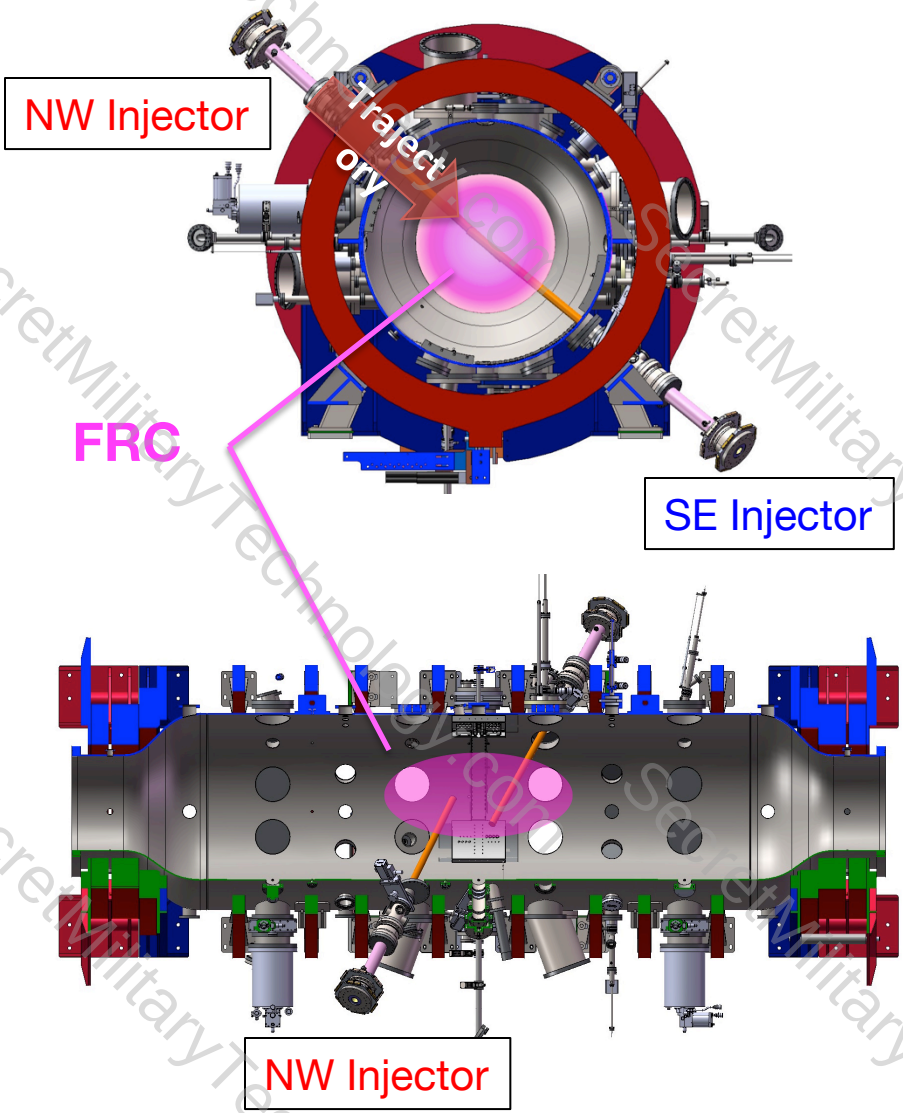
CT Injection across transverse field

- 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

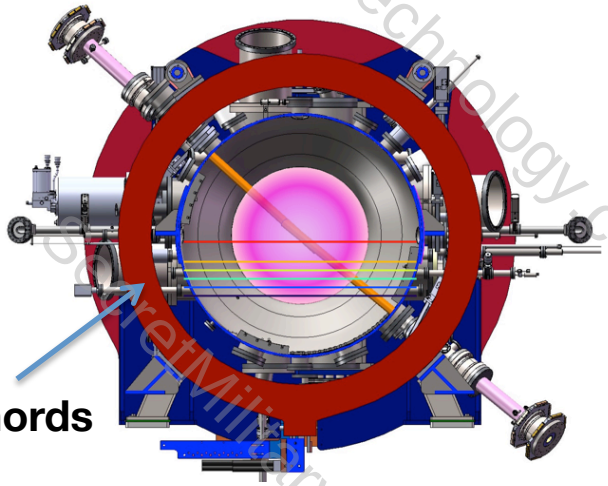
CT injectors installed on C-2U

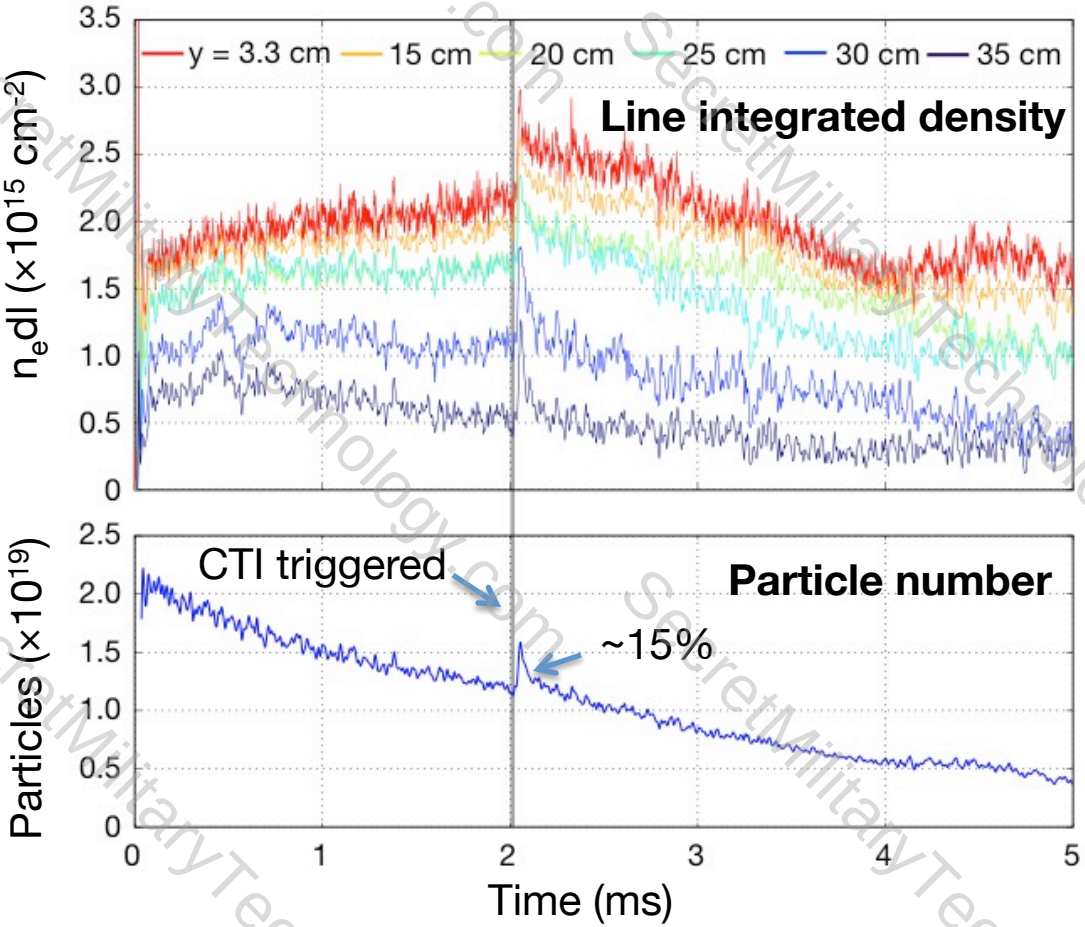


- The CT injectors were installed on the confinement vessel.
- Angles
  - NW CTI
    - From mid-plane 26.1 deg
    - From Vertical 42 deg
  - SE CTI
    - From mid-plane 29 deg
    - From Vertical 39.3 deg
- These injectors can be controlled independently.

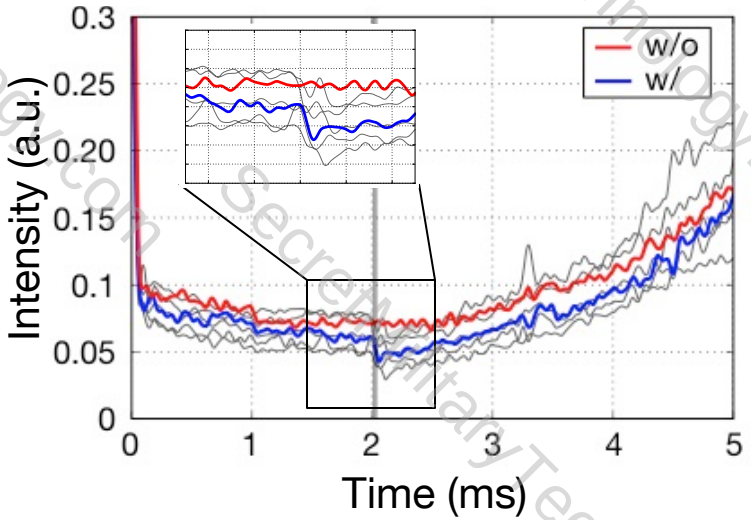
Single CT pulse increased density/particles

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

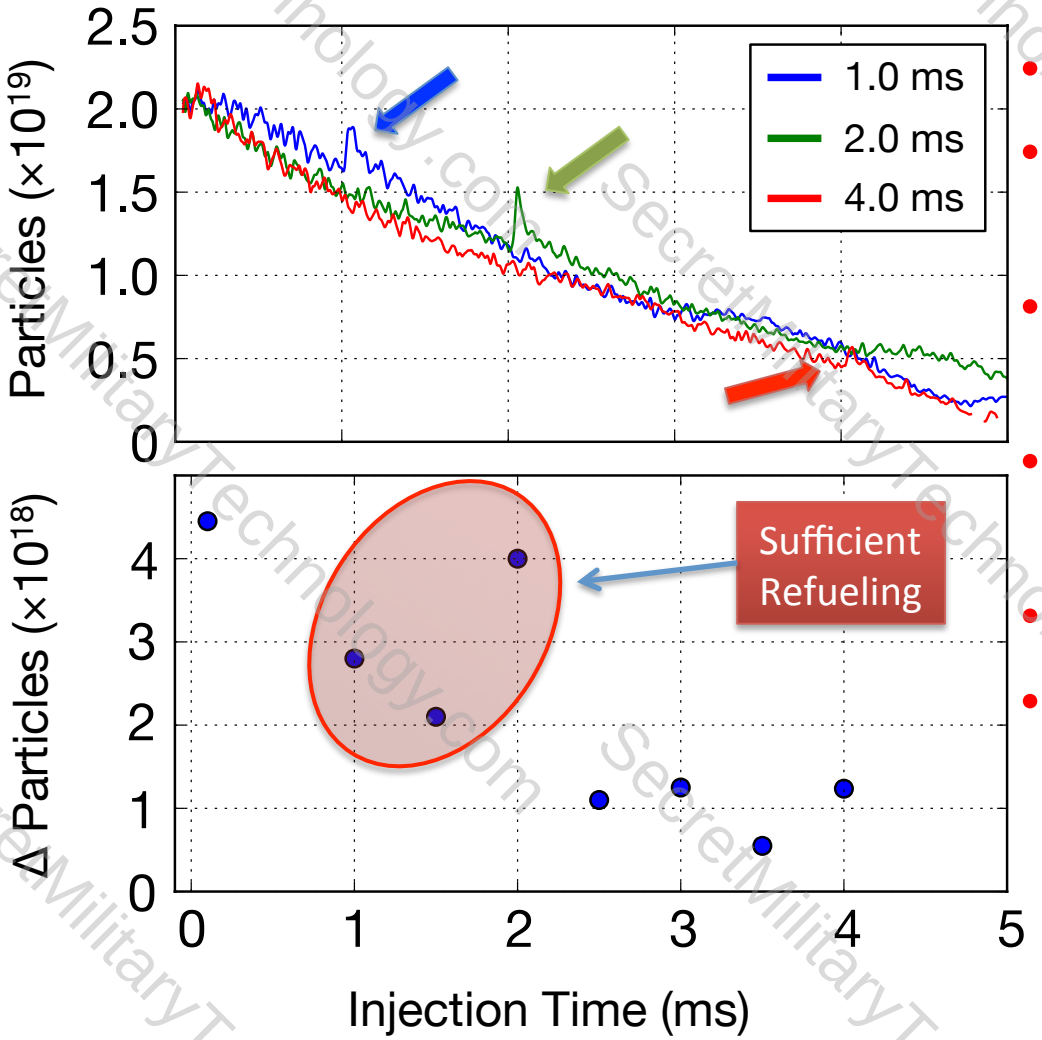




Shine-Through Detection via Secondary Electron Emission (NB1-5, gray lines)



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 **~ 2ms** was **optimal time for injection**

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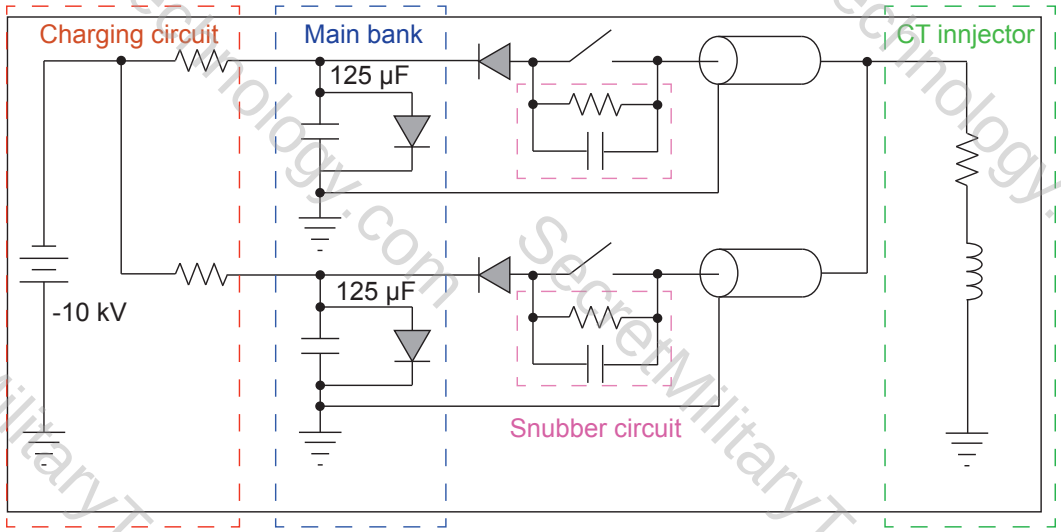
- CT Injector Overview
- **CT injection into C-2U FRC**
  - Installation of CTI
  - Single CT injection ——— 1 CT
  - **Multi-Pulse CT injection** ——— **Up to 3 CTs**
    - **Development of Multi-pulse injection system**
- Upgrade
- Conclusion

Multi-pulse system and Fast Camera

Multi-Pulse:

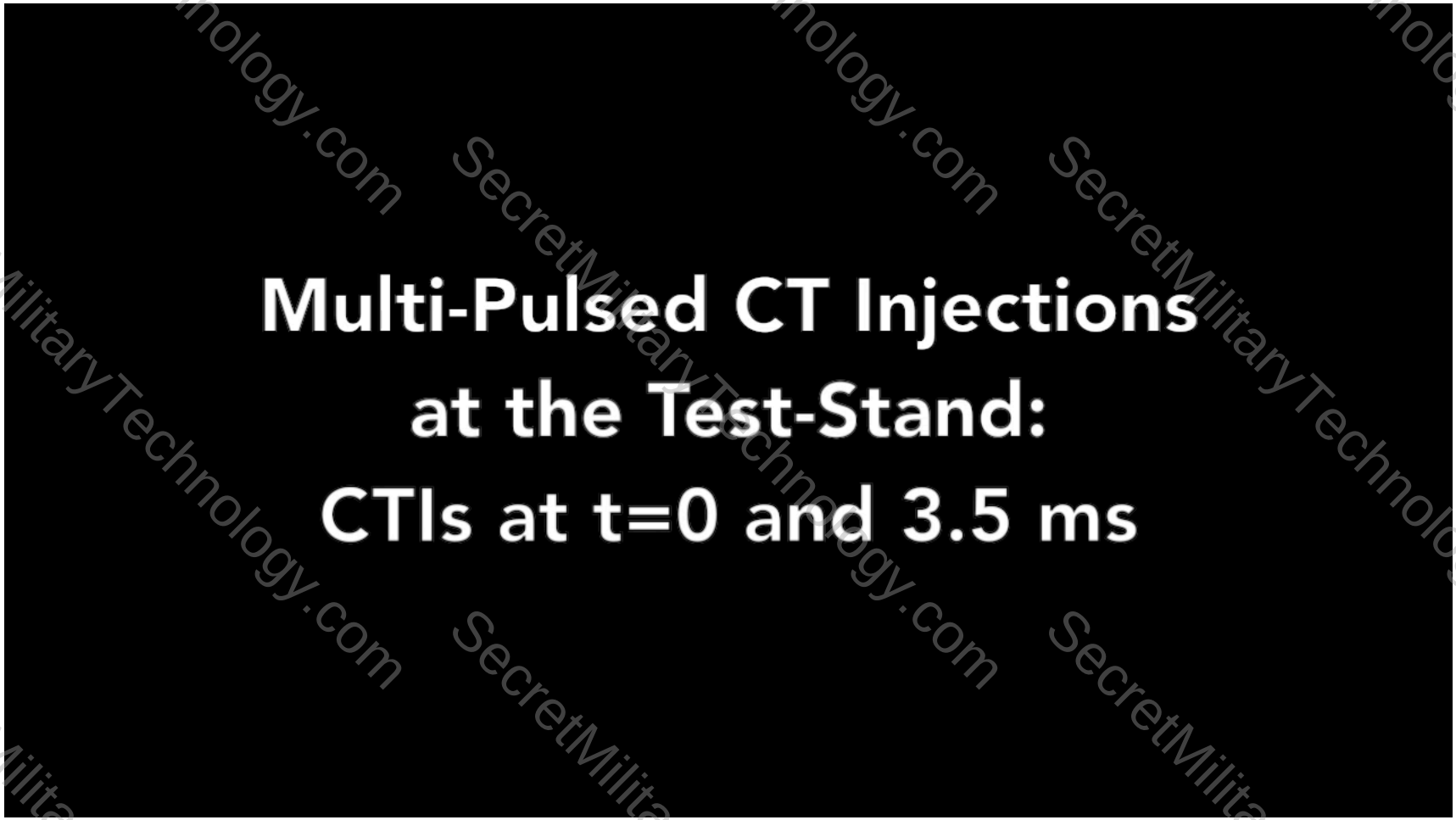
- Main Bank of 125 μF with 10 kV
- Multi-pulse at ≤ **1 kHz**
- Diodes as crowbar and blocking element



Fast-framing Camera (NAC Image Technology):

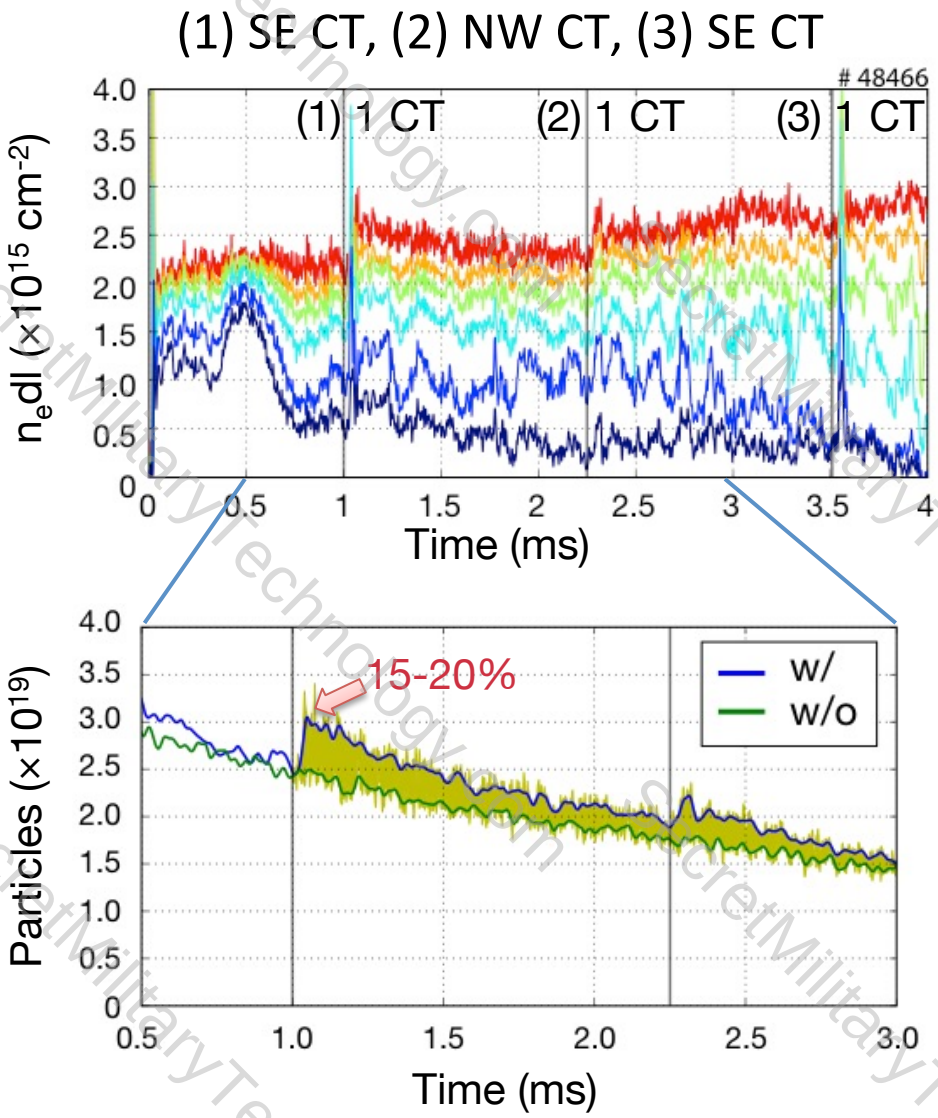
- Up to **1.25 MILLION** frames/sec for 120 frames
- 100 ns minimum exposure time
- 360×410 pixel color sensor
- 10-bit, 58 μm pixels
- Nikon lens mount

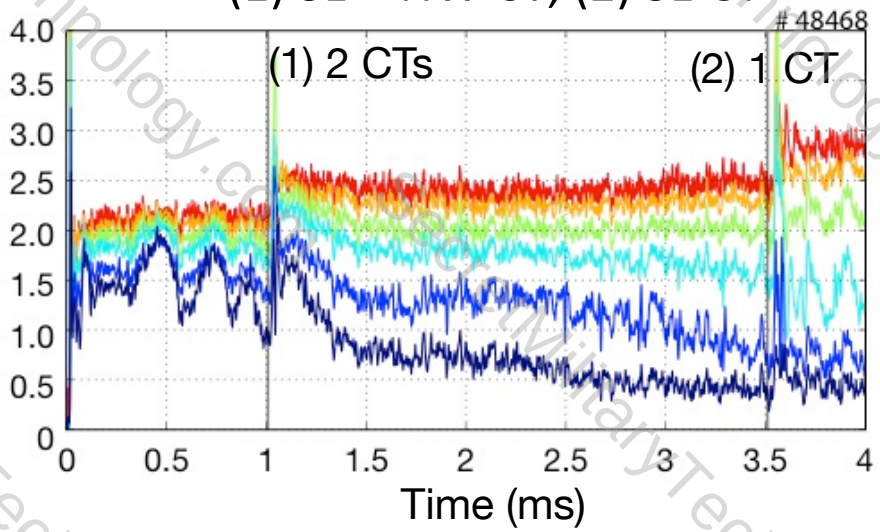
High speed imaging of 2 CTs at the Test-Stand



1st Awesome Video on the C-2U

CTs add a lot of particles



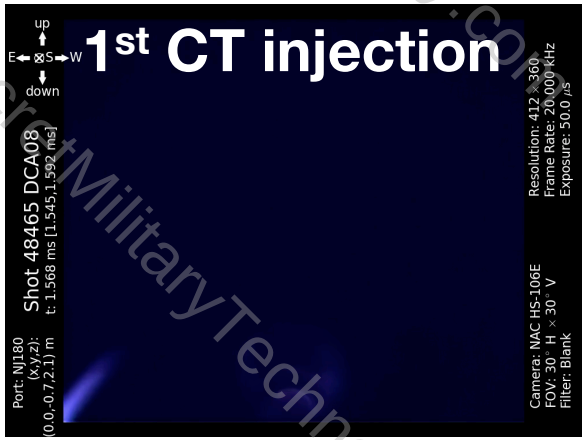


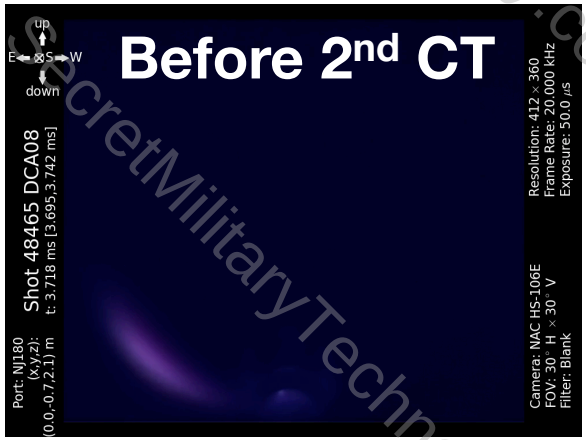
- First 2 CTs increase particle inventory
- The increased density was 10-20%
- 3rd CT alters/kills FRC
- Particle loss rate reduced by first CT
- FRC begins to decline after 2nd CT

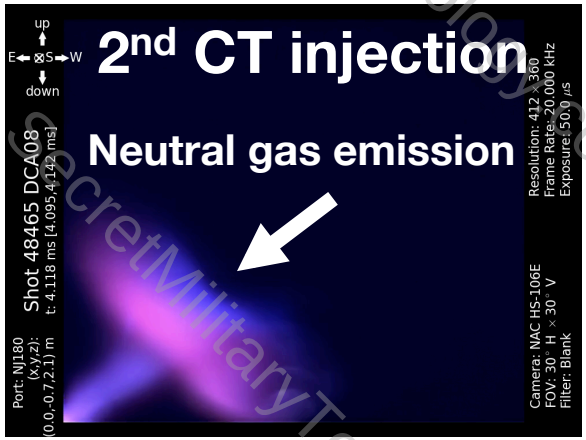
Dα emission was increased after CT injection

Fast Camera Images

- Exposure 50 μs
- Filter Blank







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

PI system is important to reduce trailing neutral gas

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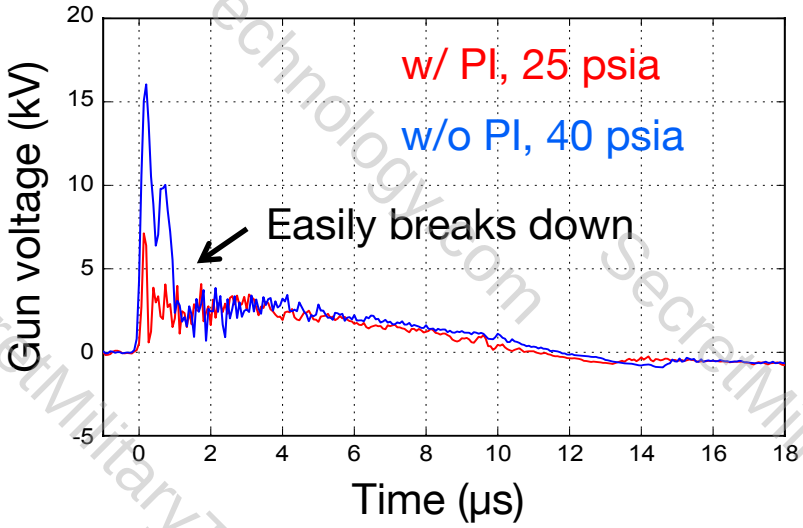
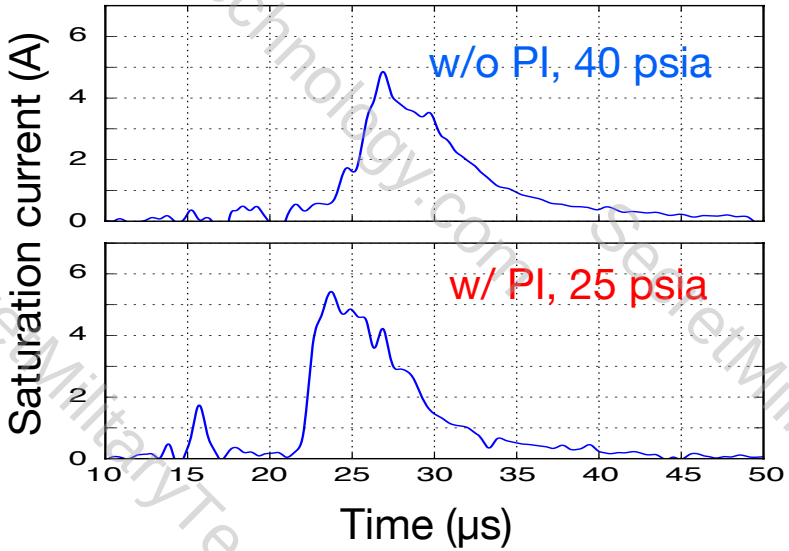
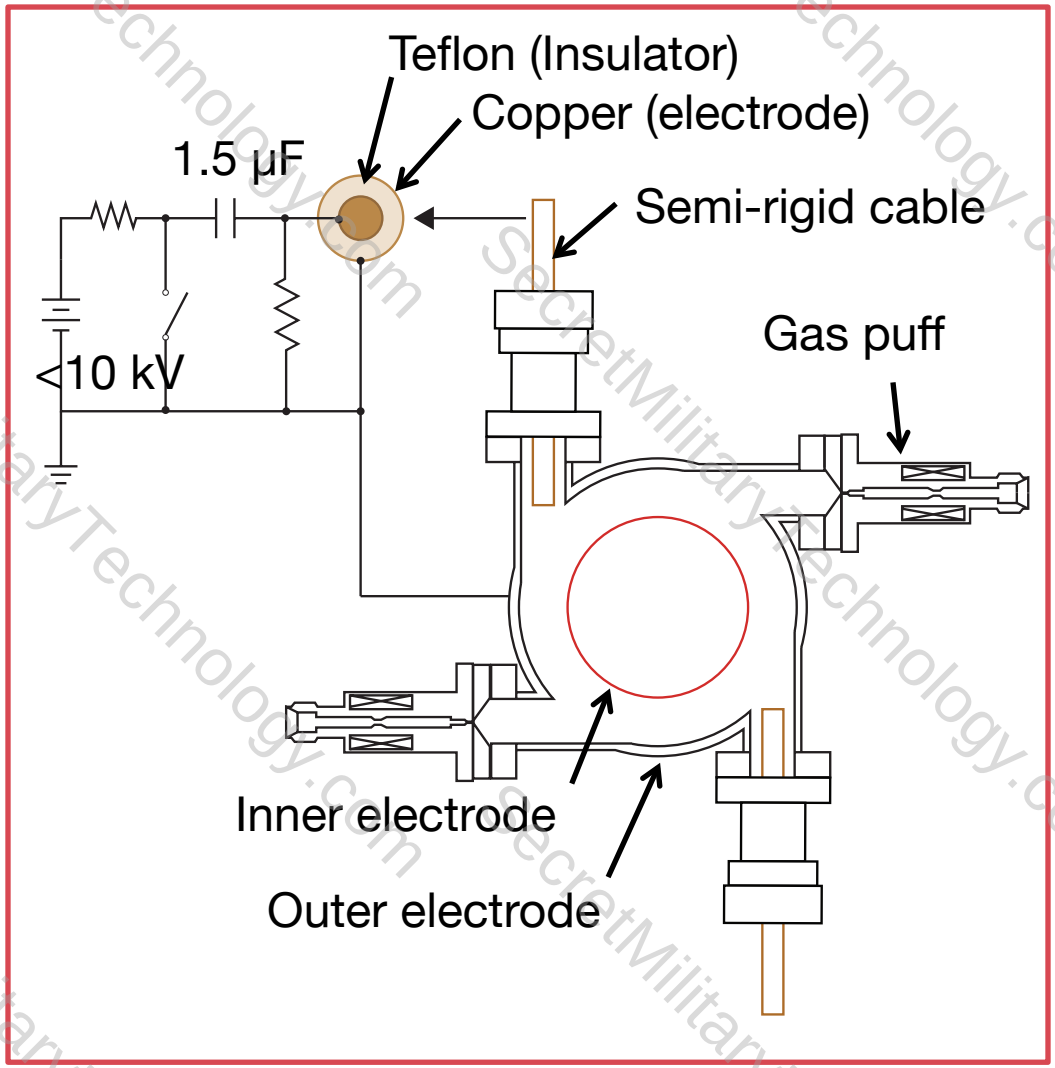
- CT injection into C-2U FRC
- **Upgrade**
  - **Development of a Pre-ionization source**
- Summary

Pre-Ionization system has been developed



Triple Langmuir Probe measurement



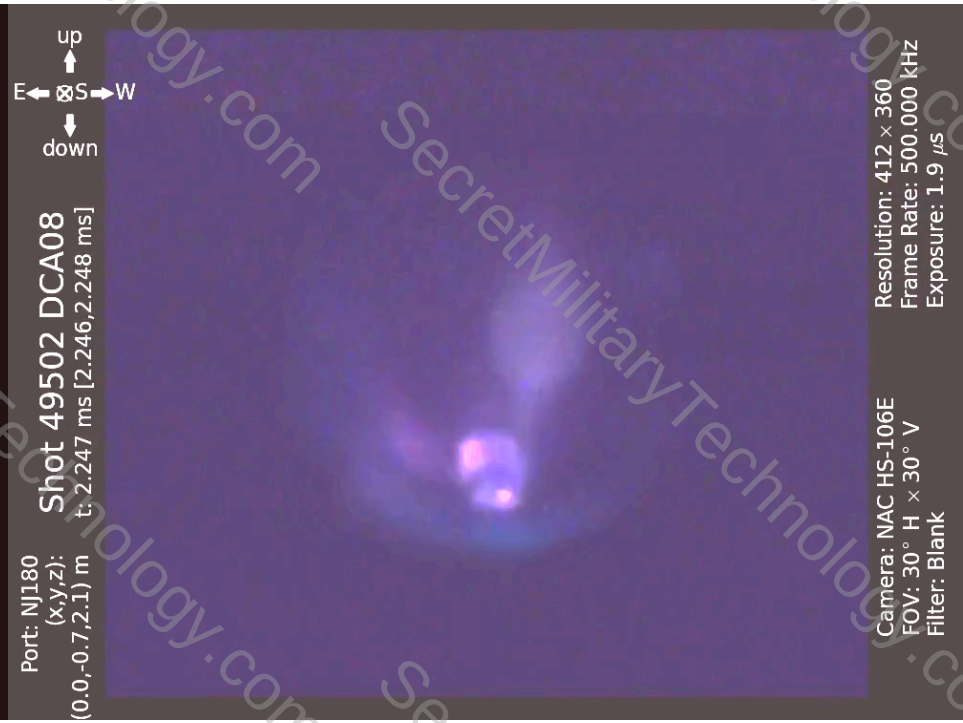


Schematic diagram of Pre-Ionization system

PI reduces trailing neutral gas

No PI

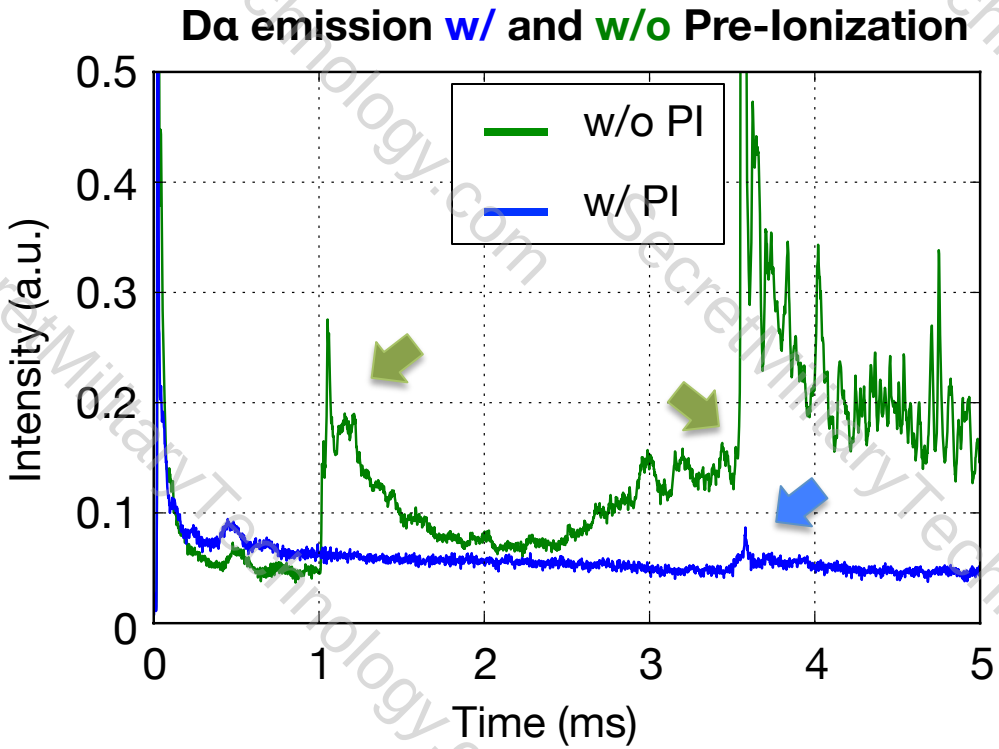
With PI

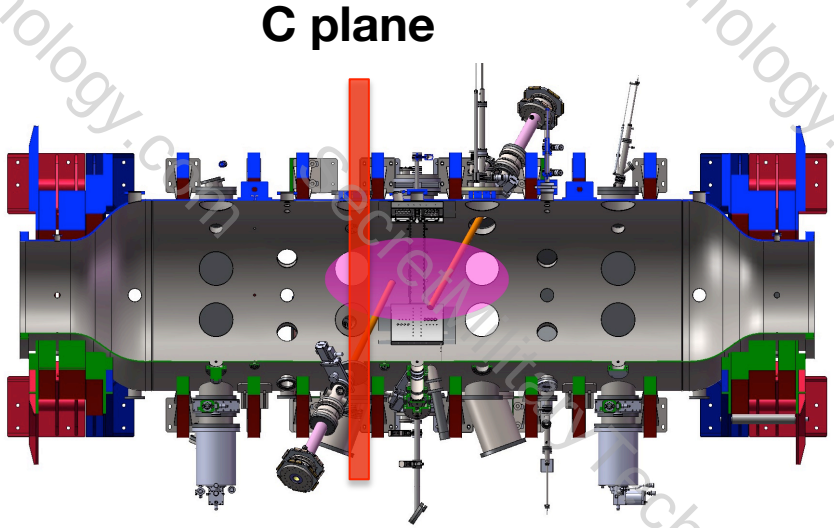


- Neutral gas follows CT
- Interacts with plasma

- PI eliminates gas trail
- Edge undisturbed

Neutral gas load removed with PI





- D_α emission at C plane minimized
- No burst of light when 2nd CT is injected
  -> Bulk of trailing neutral gas avoided

Summary

- The CTI program has advanced quickly
- Incremental addition of pulses
  - Refueling from each pulse
  - Dα 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