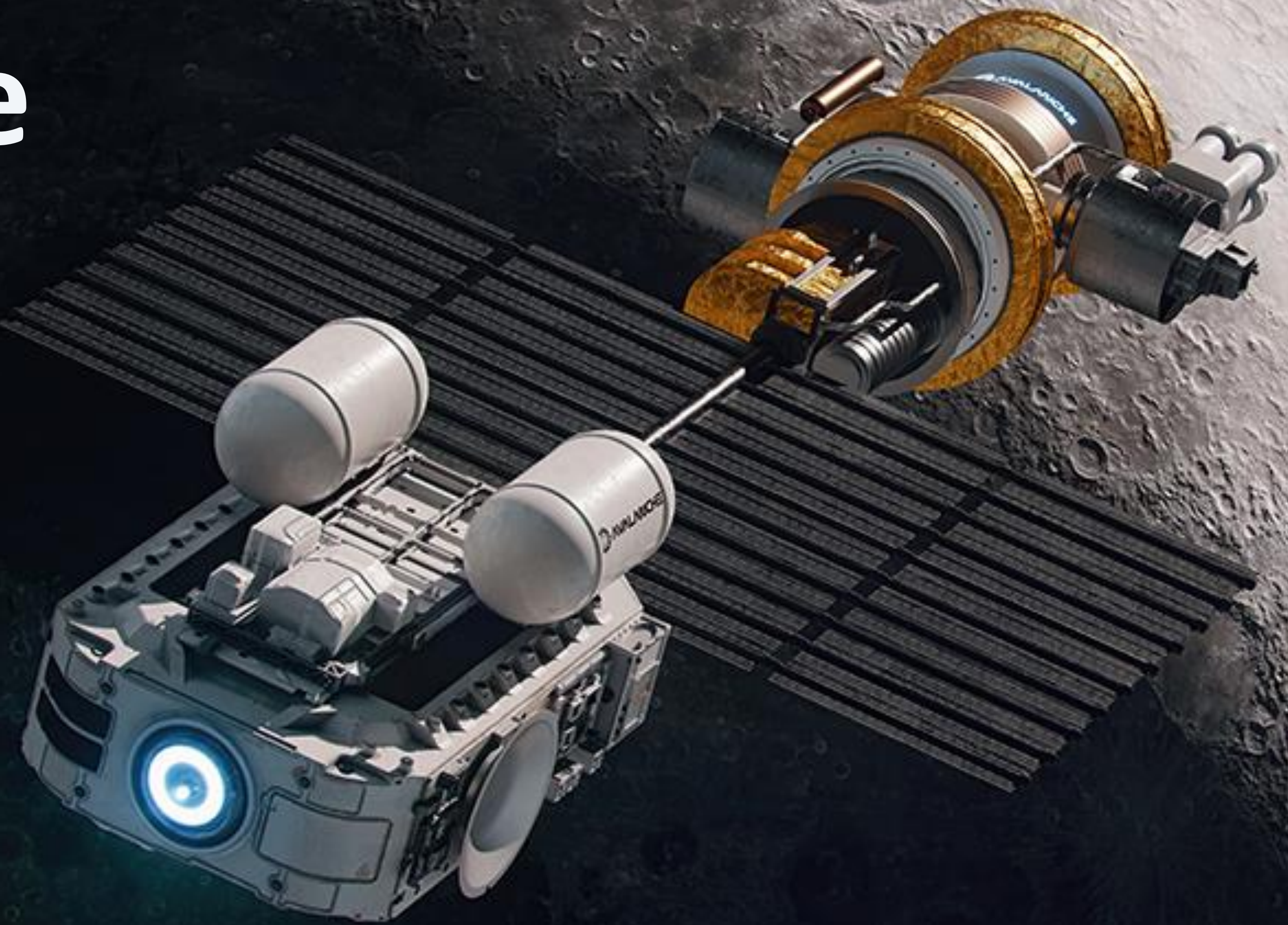
AVALANCHE

Avalanche Fusion

Nearly endless clean energy for mobility and distributed energy applications.

Imagine the applications…

CWFEST, October 2023



"What important truth do very few people agree with you on?"

— Peter Thiel, Zero to One: Notes on Startups, or How to Build the Future

Fusion Reactors do not need to be large >$1B machines

Fusion power can be small, mobile, distributed and mass produced at scale like a Tesla battery pack

How? Electrostatic fusion using very high voltages in a small compact form factor 10's of cm in diameter

What is new here? Electrons co-rotating with ions in "ExB" fields is the key to unlocking small scale fusion.

1. Electrons mitigate "space charge effects" enabling a high plasma density
2. Co-rotating electrons are like a tail wind for ions allowing them to burn longer at high fusion energies

Why we're here.

Humanity won't reach Net Zero Greenhouse Emissions by 2050 without fusion power.
Everything that is powered needs to decarbonized, from power grids to maritime transport, aviation and the military.

Most fusion companies are tackling the major opportunity that is the grid-scale electricity.

Avalanche intends to power everything else.

Fusion Reactor Size determines Capital, Headcount and Development Speed

Built in years, iterate in months, civil engineering project

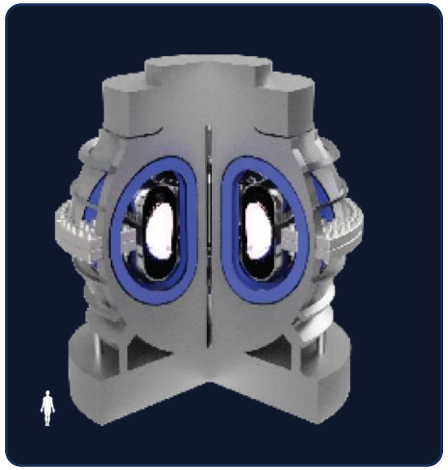
Application: Grid
Most approaches are thermonuclear.

Reactor size varies from house to warehouse scale

Capital costs to commercial operations >$1B

Headcounts 100's to 1000's of people

Estimated first commercial operations >6 years



Built in weeks, iterate in days, mass produce at factory scale

Application: Mobility and Distributed Energy
Avalanche is developing world's smallest fusion microreactor.

Capital costs to commercial operations <$1B

Headcount <200 of people

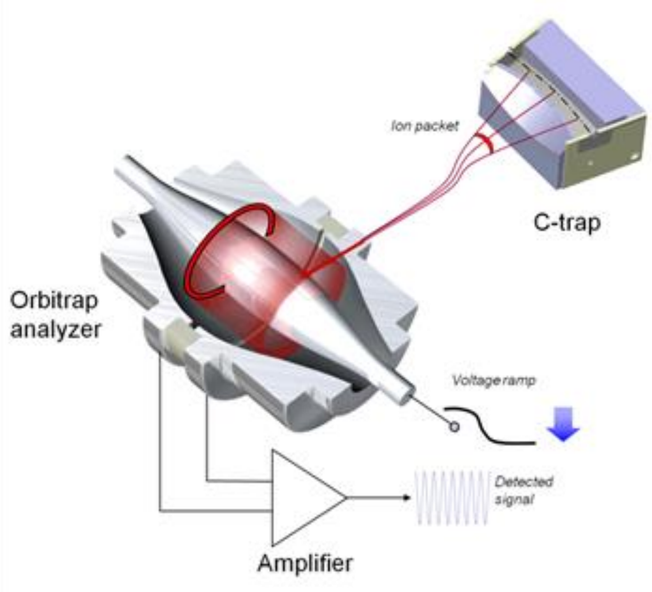
Estimated first commercial operations <6 years

1GW

10's MW

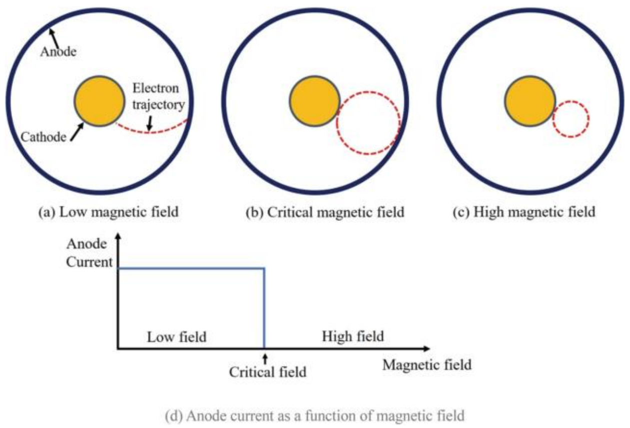
10's kW

Orbitrap



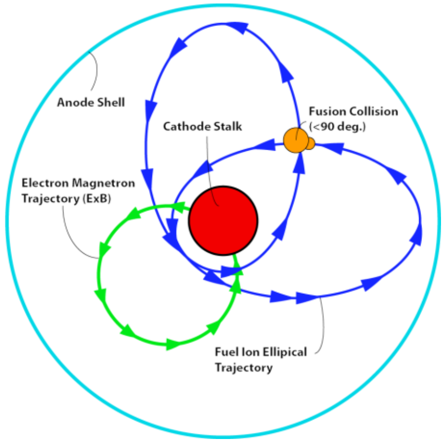
- Ion beam confined electrostatically in orbits around special shaped cathode rod and outer anode shell

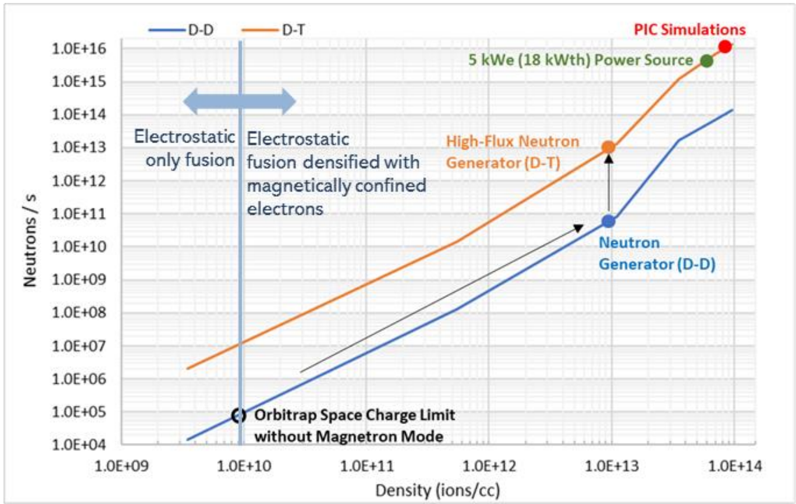
Magnetron



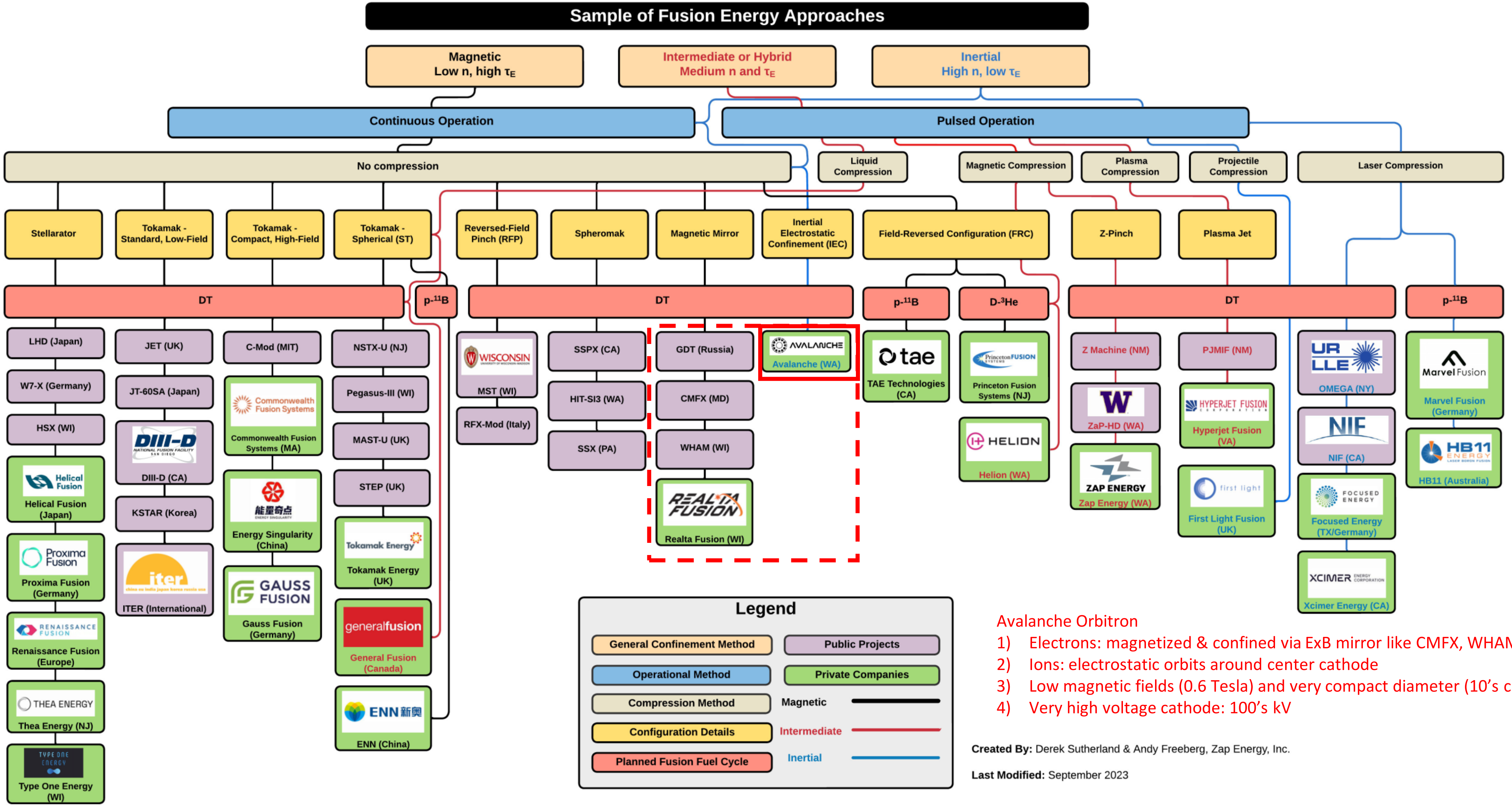
- Electrons confined in ExB field between cathode and anode
- Long electron confinement times and low current between cathode and anode

Orbitron





- Dense high energy plasmas
- Bright neutron sources via D-D and D-T fusion
- Potential for small net energy fusion devices



Avalanche Orbitron

1) Electrons: magnetized & confined via ExB mirror like CMFX, WHAM/REALTA
2) Ions: electrostatic orbits around center cathode
3) Low magnetic fields (0.6 Tesla) and very compact diameter (10's cm)
4) Very high voltage cathode: 100's kV

Created By: Derek Sutherland & Andy Freeberg, Zap Energy, Inc.

Last Modified: September 2023

Orbitron Fusion Rate Scaling

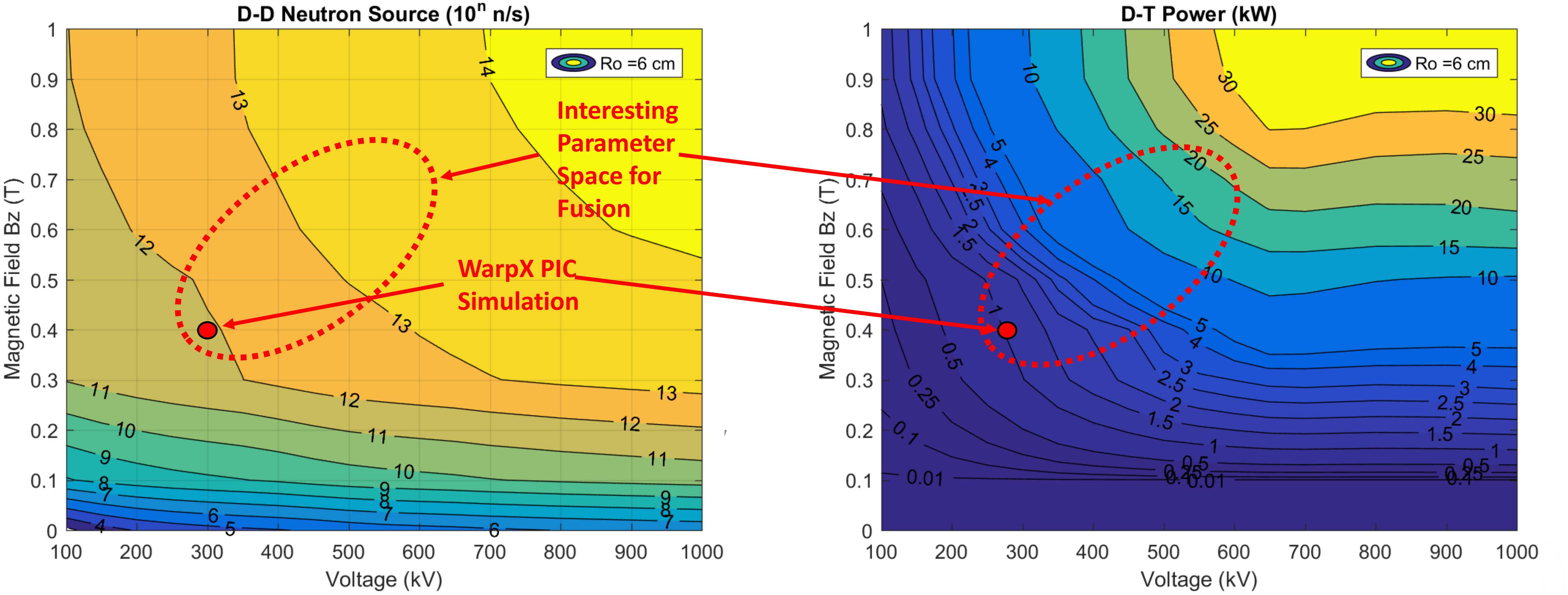
Particle-in-Cell simulation (Vsim) explored ion density and energy for 6 cm radius Orbitron

300 kV cathode, 30 keV beam, **0.4 Tesla** achieved **Density 5E19/m3** **ECoM D-T 63 keV** **Te 15 keV**

Orbitrons confine non-thermal plasmas: Ions are unmagnetized and orbiting electrostatically, electrons ExB

Orbitrons can vary ion collisional energy (voltage, beam energy) independently from average electron energy (magnetic field)

Makes them very interesting devices for exploring fusion plasma parameter space



Electrostatic & Non-Thermal Fusion Plasma (1/3)

Electrostatic & Non-thermal (non-Maxwellian) fusion plasma is controversial in fusion sciences

"For all possible types of fusion reactors if major particle species are significantly non-Maxwellian or at radically different mean energies recirculating power will substantially exceed fusion power."
– Rider (MIT, 1995)

"The very large recirculating power obtained by Rider (1995) is a consequence of the assumption of particle distribution functions that simplify calculations but have no physical basis"
- Rostoker, Qerushi & Binderbauer (Tri-Alpha, 2003)

The Coulomb collision rate through 90 deg. for p-B11 is 37x faster than fusion [25x for D-T]. Colliding beam fusion is not feasible due to particle loss and energy dissipation rates orders of magnitude faster than fusion.
– Lampe & Manheimer (NRL, 1998)

Electrostatic Non-Thermal Fusion Plasma (2/3)

At a high level for D-T plasma the scientific critics can be summarized as two key points:

A) Electrostatic approaches to fusion cannot achieve high ion densities due to space charge effects

B) Electrostatic or Non-thermal (Non-Maxwellian, colliding beam) approaches to fusion cannot achieve net energy due to excessive Coulomb collision losses

Electrostatic Non-Thermal Fusion Plasma (3/3)

Much of the previous controversy stems from the modelling assumptions in the reduced order models used to assess the various fusion concepts … the real fusion and confinement physics are complicated!

We find the two high-level critics: Space Charge and Coulomb Collisions are valid

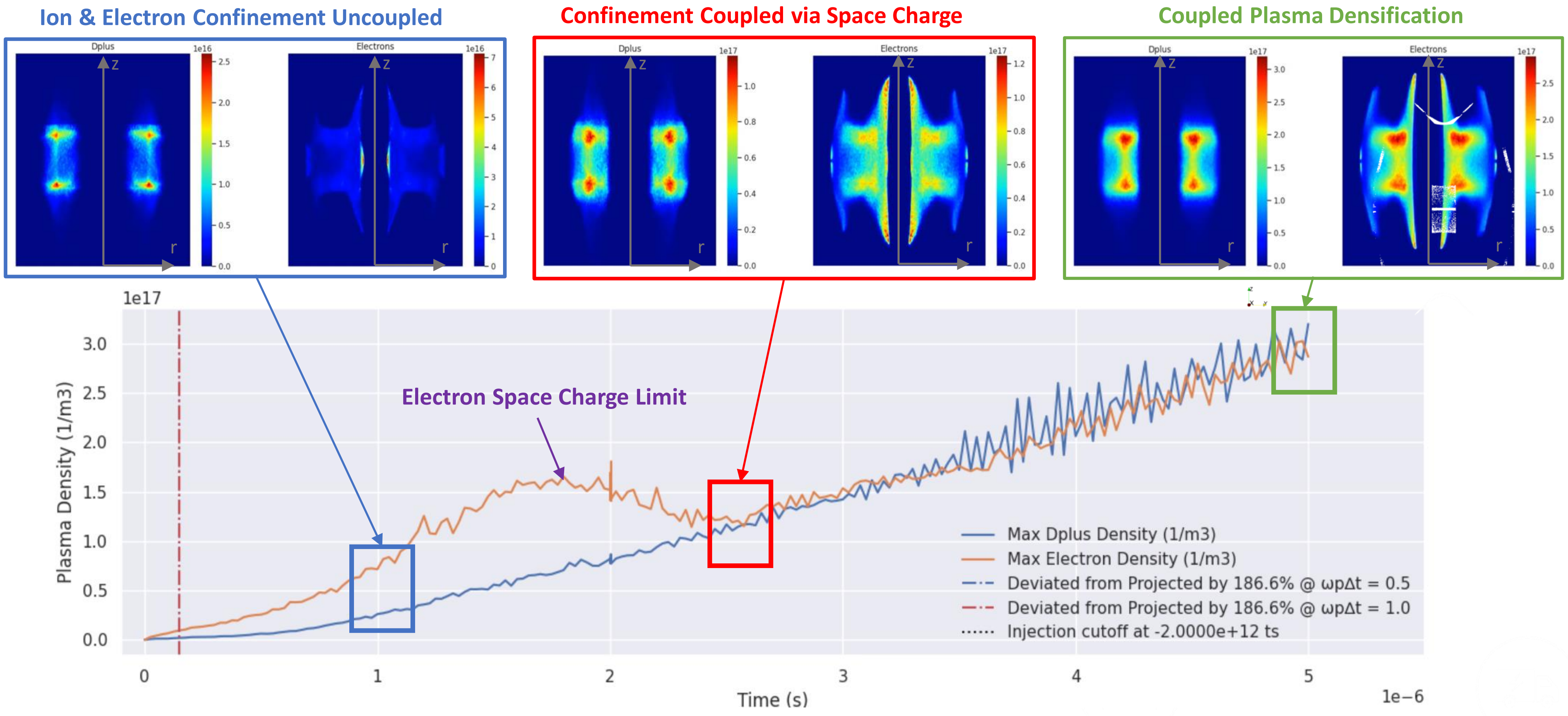
BUT the Orbitron also has some unique aspects that address both issues

First-order models to understand the high-level Orbitron physics → Particle-in-Cell simulations to incorporate the complex physics → Experimental prototypes to anchor the first-order models and simulations

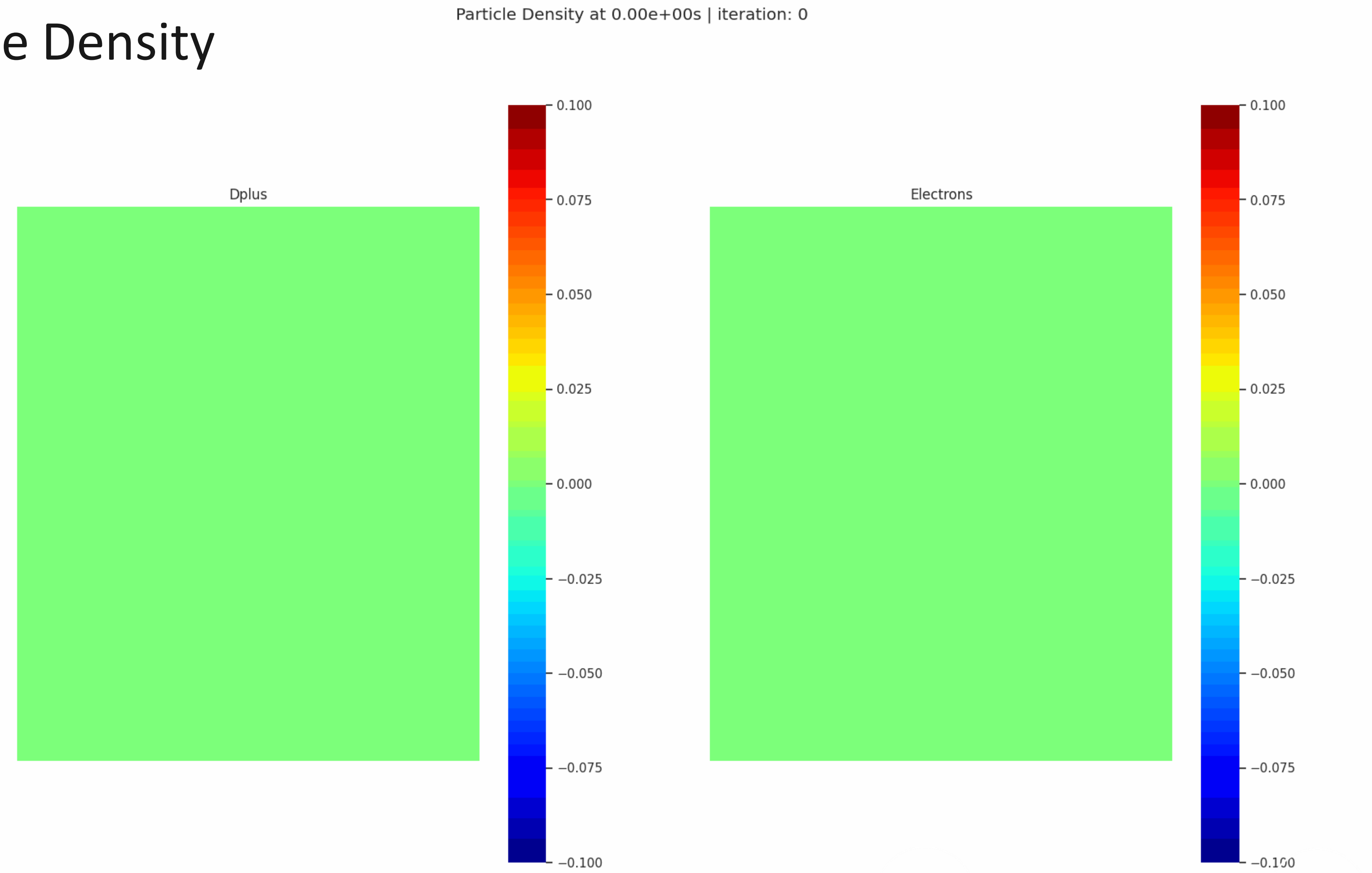
Space Charge Density

- Electrostatic fusion critic A) Cannot achieve high ion densities due to space charge
- In Orbitron electrons are introduced and confined via magnetron ExB electron scheme to overcome ion space charge density limits

Fig 4. PIC Simulations showing ion and electron loading into the Orbitron, exceeding space charge limit and ultimately densified plasma



Space Charge Density



Coulomb Collisions: First-Order Model

Electrostatic fusion critic B) Non-thermal (Non-Maxwellian, colliding beam) approaches to fusion cannot achieve net energy due to excessive Coulomb collision losses

First-Order Model for Orbitron Q_{plasma}

For ions orbiting in a potential well:

Losing total energy (potential + kinetic) result in orbits that **spiral down towards the cathode**

Gaining total energy will result in orbit that **spirals up to the anode**

For electrons in an ExB

Losing total energy due to collisions with slower ions always results in **upscattering toward the anode**

Collision frequencies converted to currents (mA) and summed for net effect (upscattering vs downscattering)

$$I_{vu} = v_{TD} N_D / C$$

Power loss is determined by particle energy (keV) x net particle current (mA)

$$P_u = V_i I_{vu}$$

Plasma Q (Fusion power / Loss Power)

$$Q_{Plasma} = \frac{P_{fus}}{\underbrace{(V_i - V_c)\sum_{v_d} I_{v_d}}_{\text{Downscatter to cathode}} + \underbrace{V_i \sum_{v_u} I_{v_u}}_{\text{Upscatter to anode}} + \underbrace{P_{brem}}_{\text{Bremsstrahlung}}}$$

Collision Frequencies from NRL Plasma Formulary

Electron–ion

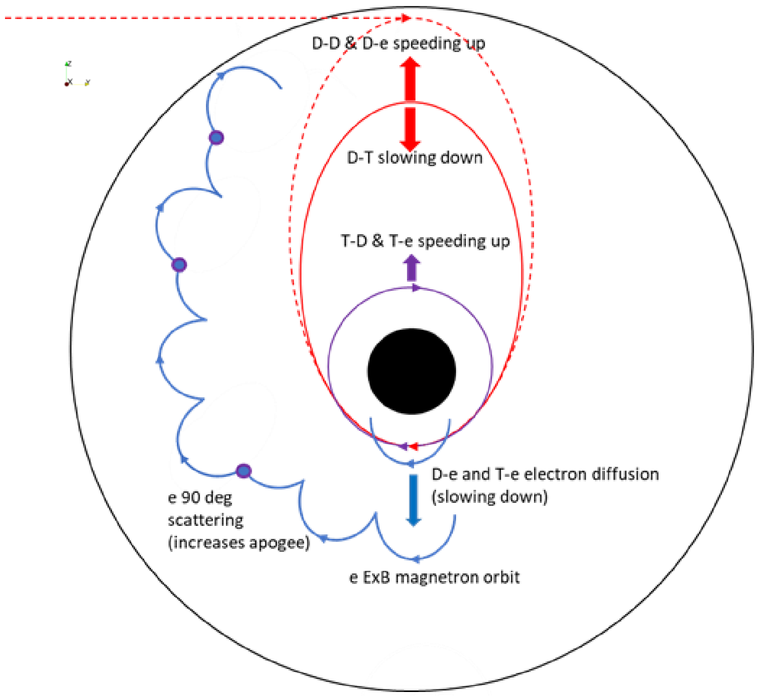
$$\nu_S^{e|i} / n_i Z^2 \lambda_{ei} \approx 3.9 \times 10^{-6} \epsilon^{-3/2}$$

Ion–electron

$$\nu_S^{i|e} / n_e Z^2 \lambda_{ie} \approx 1.7 \times 10^{-4} \mu^{1/2} \epsilon^{-3/2}$$

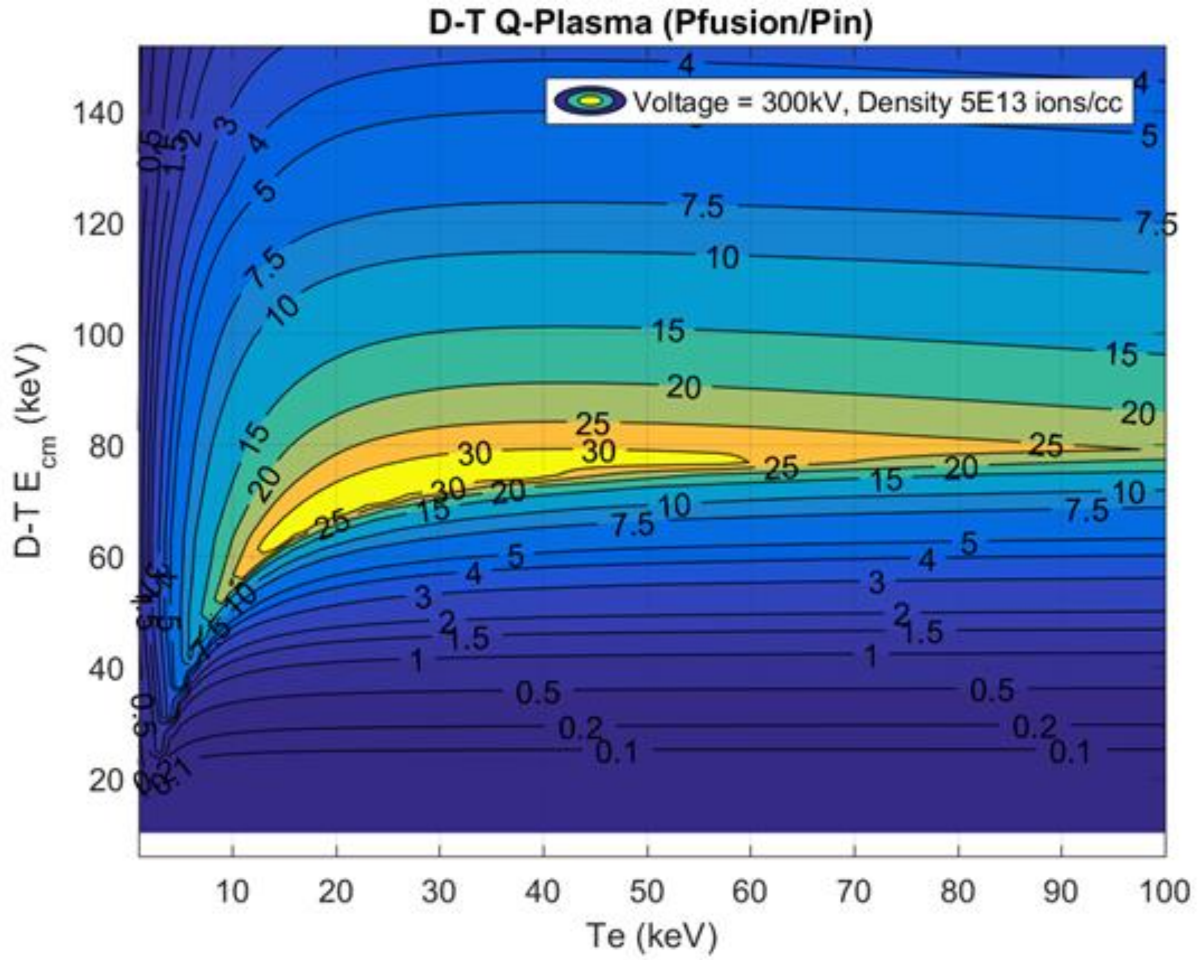
Ion–ion

$$\frac{\nu_S^{i|i'}}{n_{i'} Z^2 Z'^2 \lambda_{ii'}} \approx 9.0 \times 10^{-8} \left(\frac{1}{\mu} + \frac{1}{\mu'} \right) \frac{\mu^{1/2}}{\epsilon^{3/2}}$$

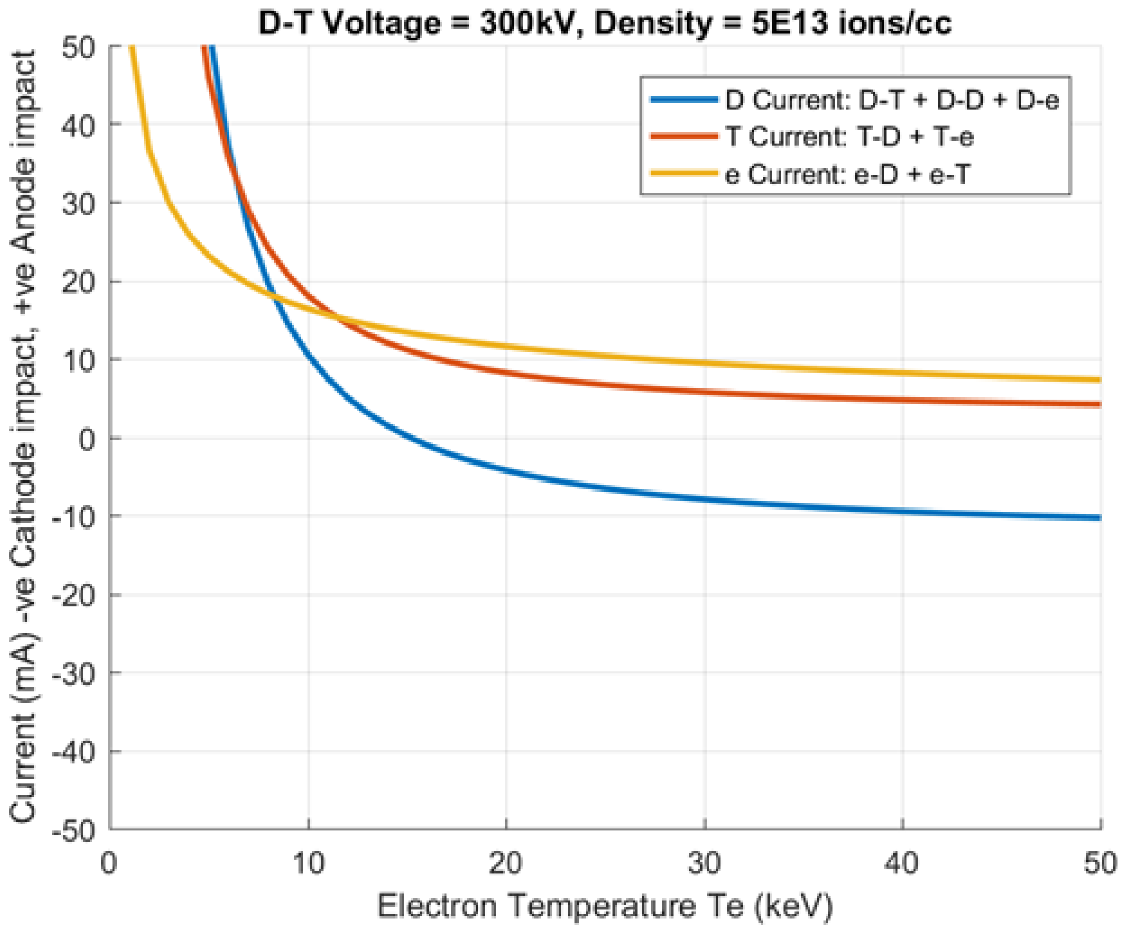


Coulomb Collisions: First-Order Model

Orbitron Q_{plasma} (Fusion Power/Plasma Losses) due to electron temperature (Te) and deuterium-tritium center-of-mass energy (E_{cm})



Net loss current (mA) for deuterium (D), tritium (T) and electrons (e) (+ve is a loss to the anode and -ve is a loss to the cathode)



Coulomb Scattering Collisions: 2.5D PIC Simulation

Using PIC Simulation with LBNL's WarpX code to anchor and validate conclusions from first-order model

WarpX includes state-of-art relativistic Coulomb collision models and fusion reactions

Some Caveats:

Time step is set by electrons at 5E-13 s

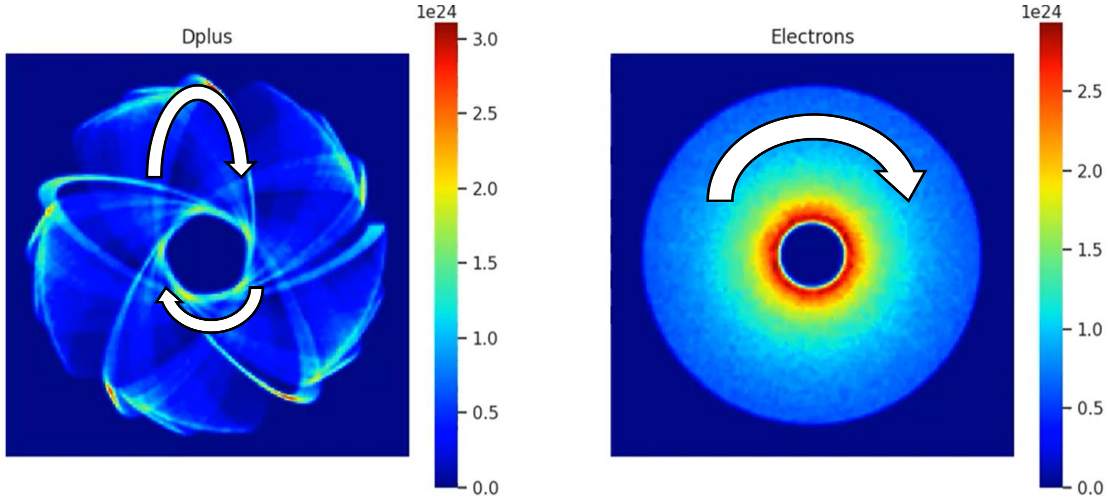
At a target Orbitron density of 5E19/m^3 estimated complete thermalization time from Lampe & Manheimer for D-T plasma is 0.05 seconds

To make computationally tractable simulation is run at densities from 1E25/m^3 - 5E23/m^3

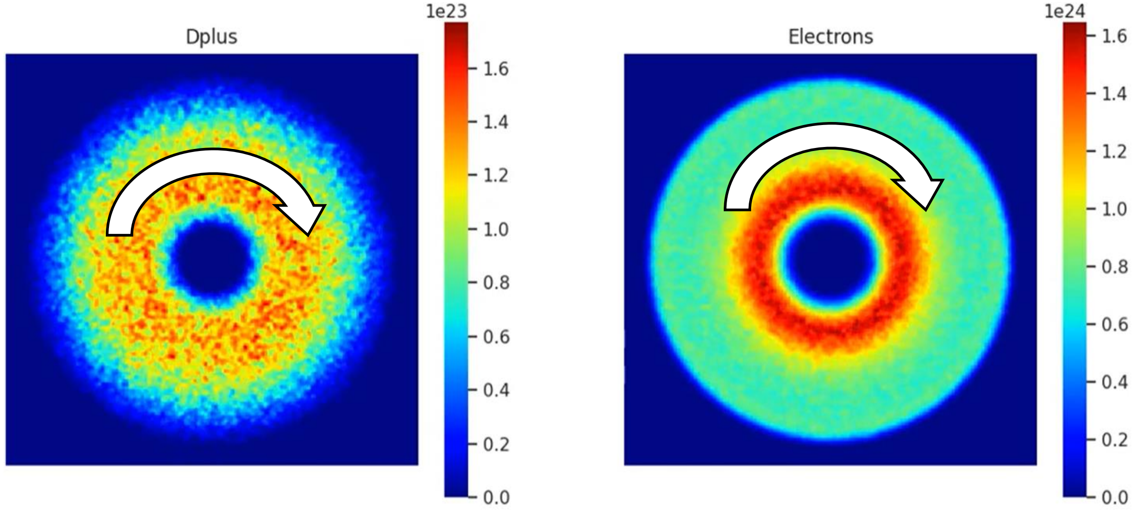
Not possible to resolve plasma frequency or space charge at these densities simulation is purely a Monte-Carlo Coulomb scattering test case

Results are density scaled back to Orbitron densities of 5E19/m^3

PIC Simulations initial ion and electron density distribution axial view

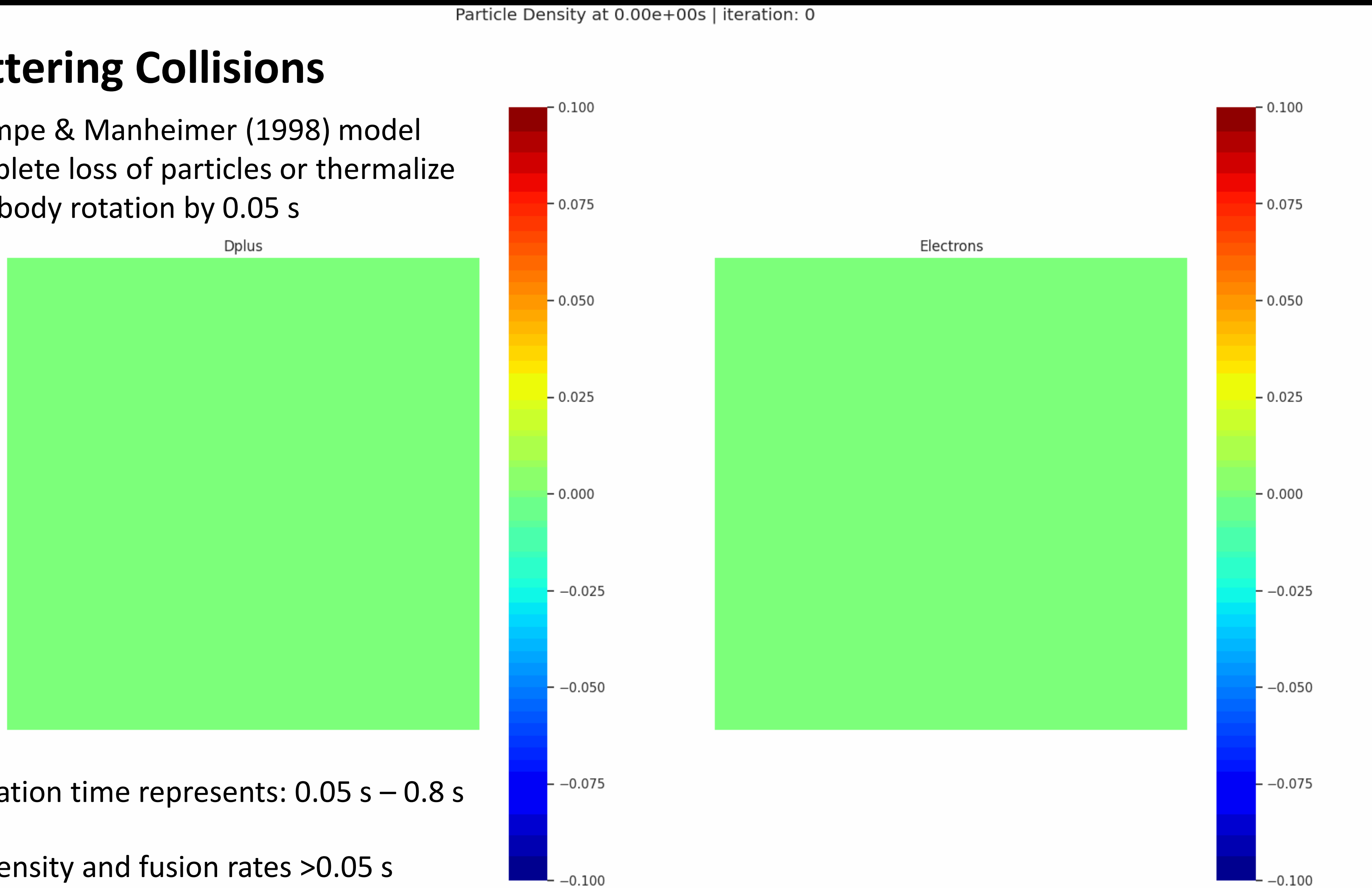


PIC Simulations thermalized ion and electron density distribution axial view



Coulomb Scattering Collisions

Per Rider (1995), Lampe & Manheimer (1998) model should observe complete loss of particles or thermalize to collisionless solid body rotation by 0.05 s



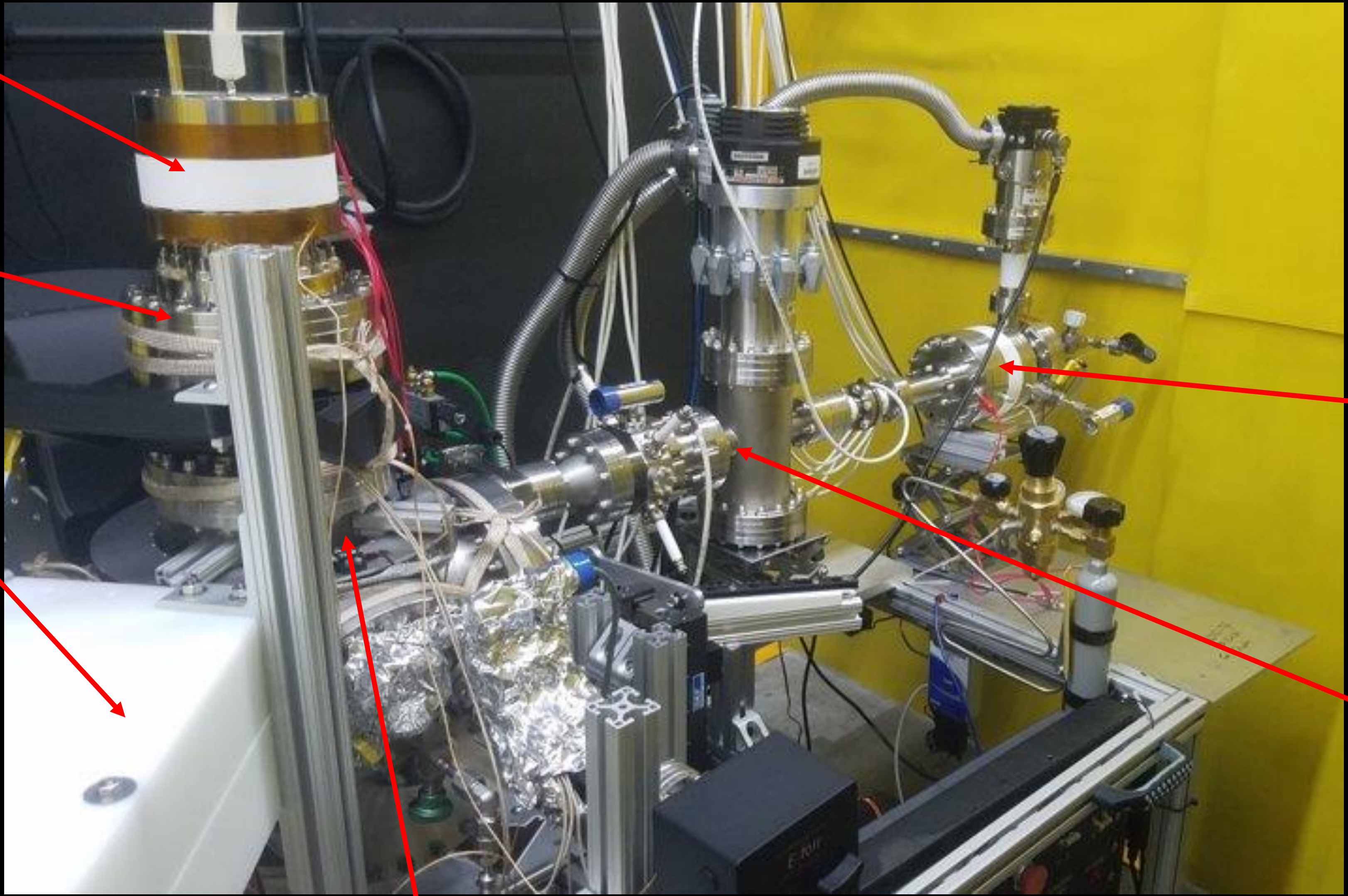
Density scaled simulation time represents: 0.05 s – 0.8 s

Significant particle density and fusion rates >0.05 s

Starting to explore plasma parameter space for beam energy, Te and Q_{plasma} via these PIC simulations

Seattle, WA Based Lab - ~15,000 sqft

Prototype 1: “Neo” 100kV, 0.07T



High Voltage Feedthrough

Permanent Ring Magnet

Diagnostics

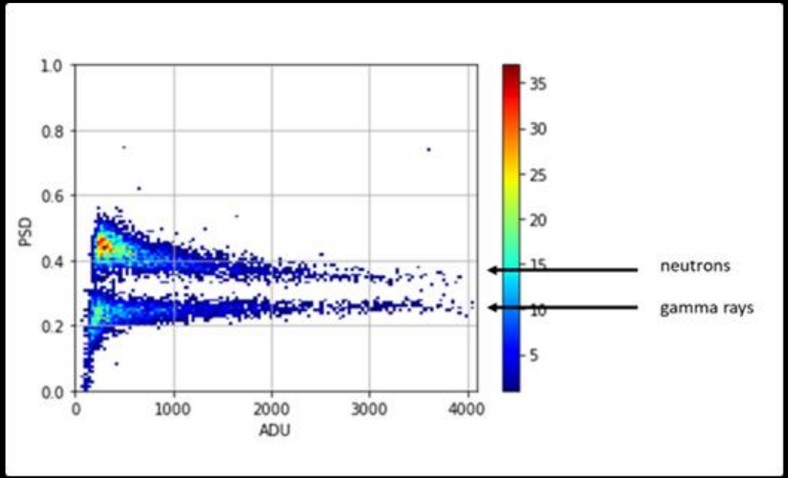
Orbitron

Ion Gun

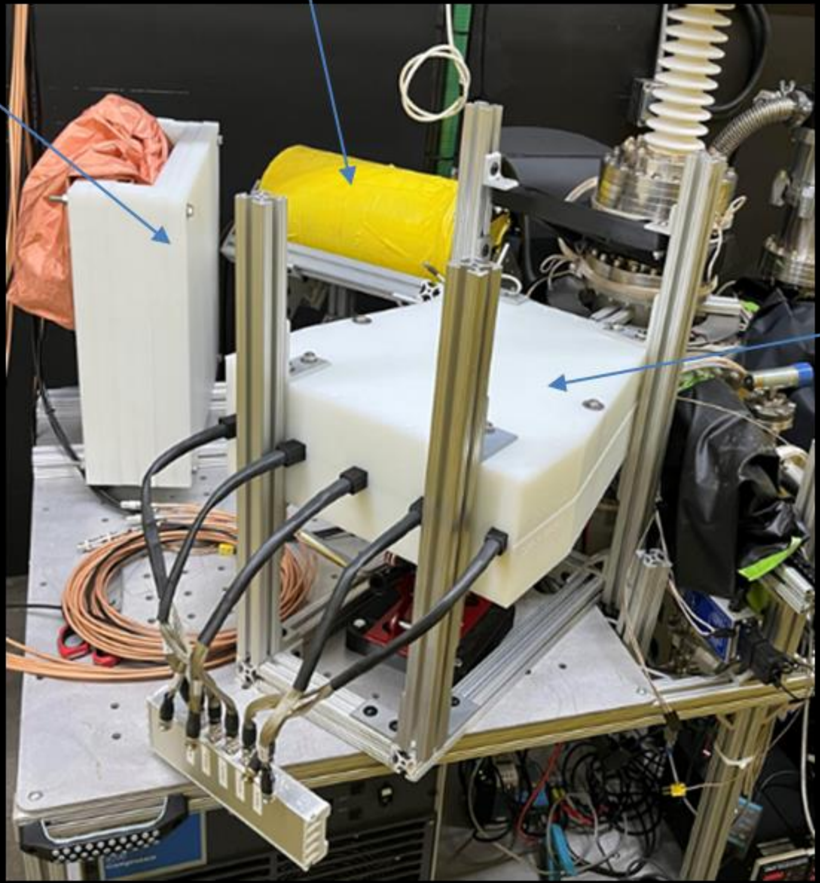
Einzel Lens (Focus and Beam Steering)

Diagnostics Overview

Scintillator w/ Pulse Shape Discrimination (PSD)
- Gives total source neutron flux with high accuracy filtering out gamma rays



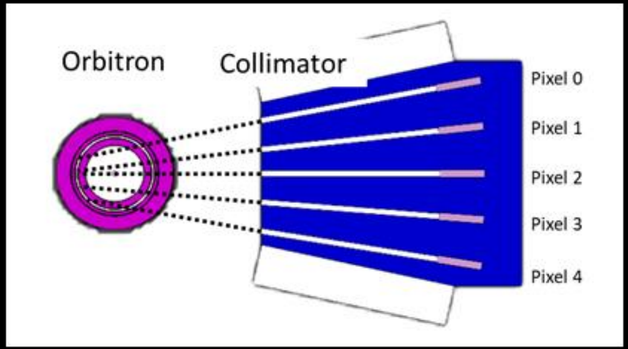
He3 Neutron counter
- Gives real time neutron flux
- Operates by thermalizing 2.5 MeV neutrons and measuring ionization pulse from He3 thermal neutron capture



Argon Spectroscopy
- Fiber optics embedded in anode looking at plasma
- Can measure number of Ar+ ions via measured brightness
- Argon spectroscopy could be alternate method to confirm plasma densification with Ar+ ion and electron confinement in Orbitron

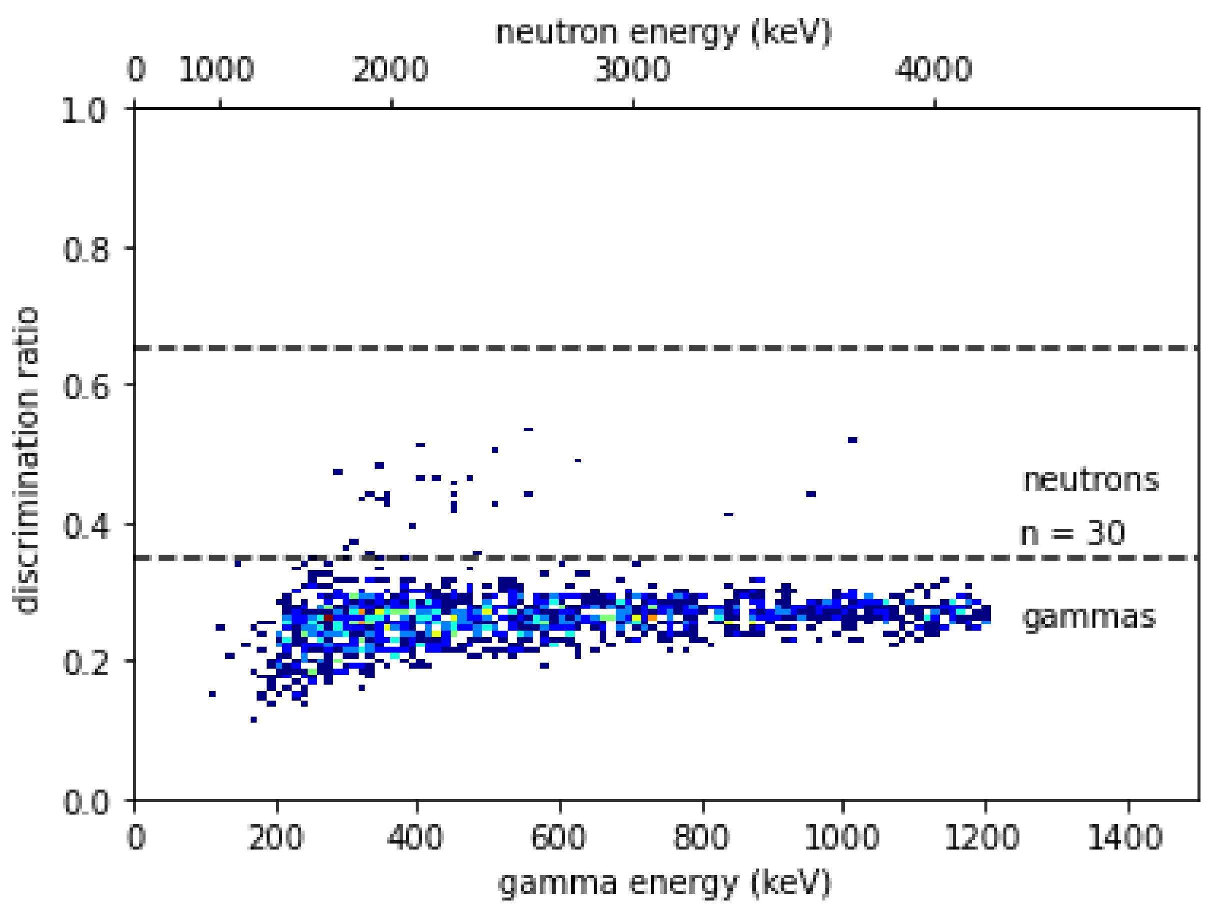
X-ray Spectroscopy
- Measuring Bremsstrahlung X-rays to determine electron energy distribution (Te) and electron density (ne) via X-ray power emitted thru Be window

Neutron Camera
- Scintillator w/ PSD collimated view to a “pixel” and locate neutron sources spatially
- Allows discrimination of beam-target fusion in cathode from beam-beam fusion in space between cathode and anode

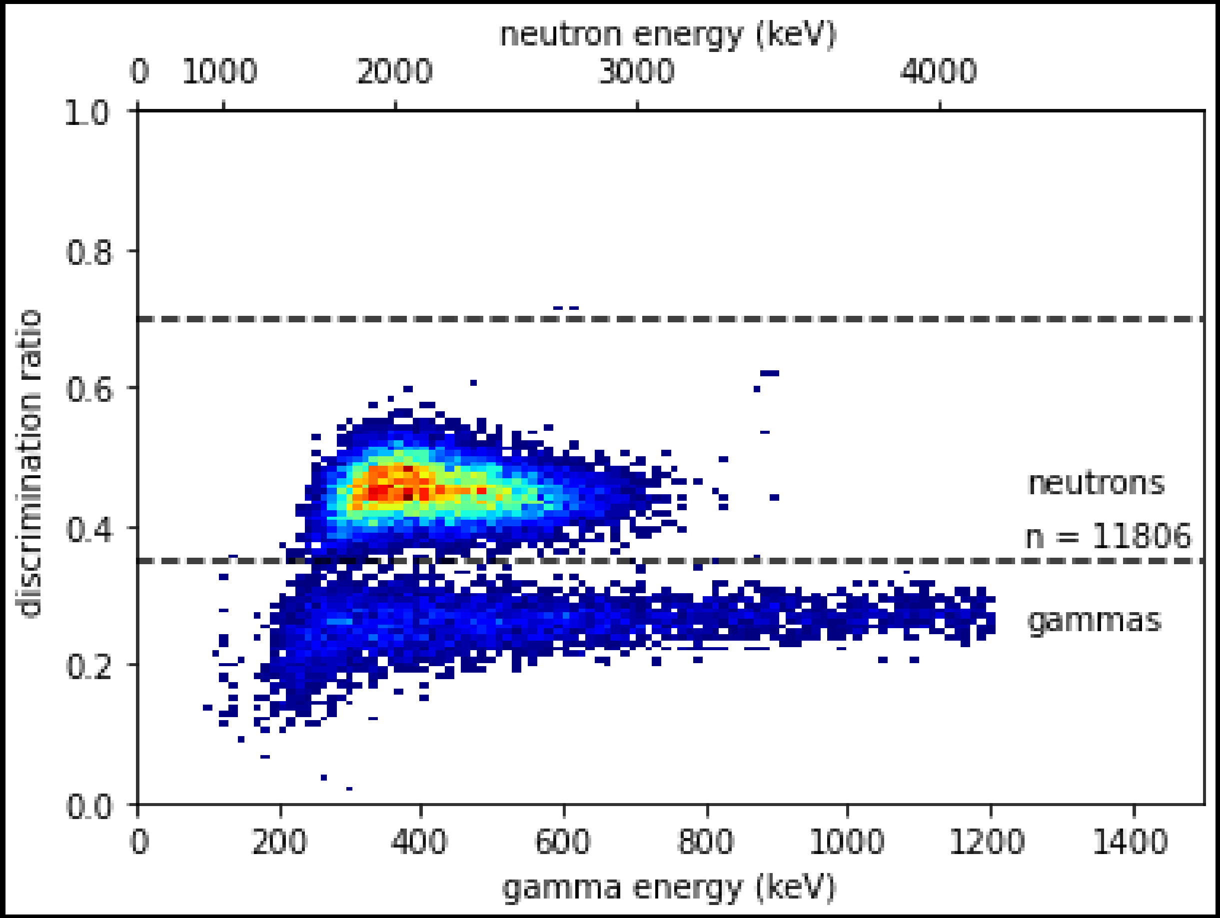


Neutron Energies with Pulse Shape Discrimination

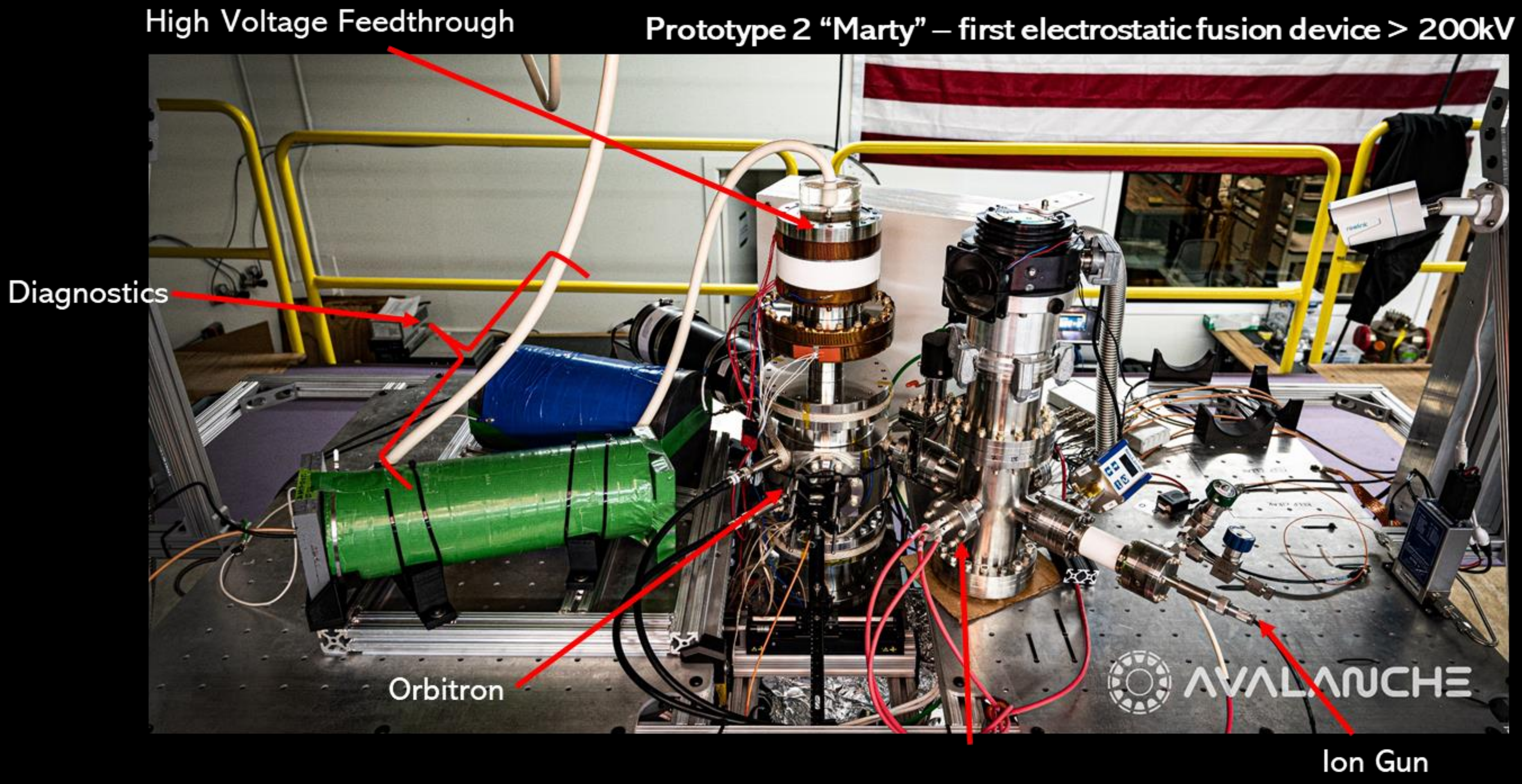
Ion Source Off (background neutrons)



Ion Source on and Orbitron Running

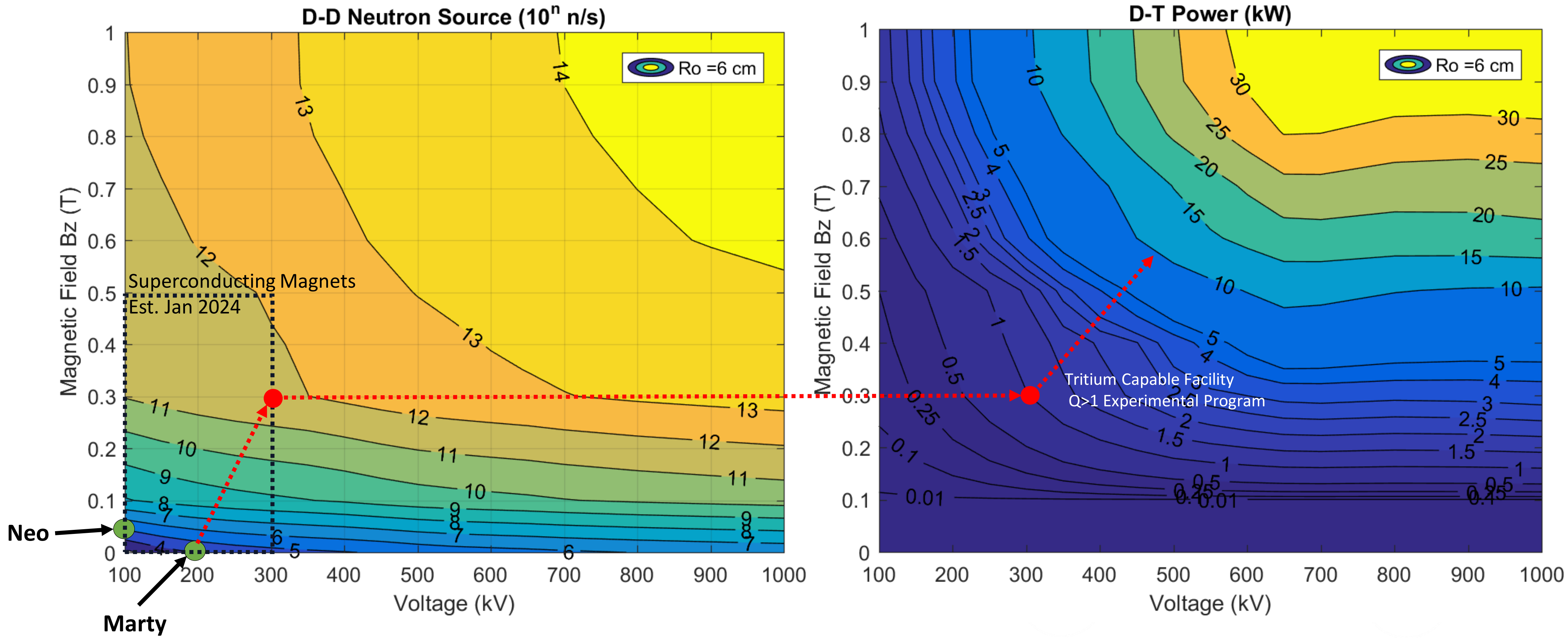


Prototype 2: “Marty” 300kV



Orbitron Experimental Program Current Status

- Prototype 1 (Neo): Measured fusion neutrons at 100 kV, 0 T (no magnets): 1E4 n/s
- Prototype 1 (Neo) : Working on Improved ion loading + magnets 100 kV, 0.05 T: ≈1E6 n/s
- Prototype 2 (Marty): Reached 200kV (no magnets) and Targeting 300 kV, 0.3 T during Series A: ≈1E11 n/s



Meet the team

Avalanche Energy is a 33-strong team including 13 PhD's with specializations in Computational & Plasma Physics, Mechanical & High Voltage Engineering on Staff. We have broad expertise from New Space, Academia, Government, Software and bring a rapid Test-Fail-Fix approach building a Micro Fusion Reactor.

BLUE ORIGIN BOEING G NASA Microsoft U.S. AIR FORCE PPPL SIEMENS

Summary

At a high level for D-T plasma the scientific critics of electrostatic fusion can be summarized as two key points:

A) Electrostatic approaches to fusion cannot achieve high ion densities due to space charge effects

We've shown via PIC simulation that electron confinement in ExB fields is key to resolving this

We are very close to demonstrating this experimentally on Neo

B) Electrostatic or Non-thermal (Non-Maxwellian, colliding beam) approaches to fusion cannot achieve net energy due to excessive Coulomb collision losses

In rotating plasmas there may be a spectrum between pure beam-beam to pure Maxwellian that is interesting for generating fusion energy as indicated by collisional PIC simulations

Demonstrating this experimentally with Deuterium-Tritium fusion is ultimately how we intend to develop a Q>1 small scale fusion reactor

Meet the Orbitron

Small scale fusion for mobility applications

Build in months, iterate in days

Small teams focus on specific problems and rapidly iterate via simulation & two prototypes in our Tukwila lab.

Inertial Electrostatic Confinement

High energy ion beams collide to create fusion plasma

Confine ions via electrostatic fields (inspired by Orbitraps)

Densify plasmas via electrons (inspired by Magnetrons)

Tackling hard to decarbonize applications

From space craft, to unmanned submersible vehicles, aviation, maritime shipping and distributed energy.

Thank you.

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