Enhancement of an IEC Device with a Helicon Ion Source for Helium-3 Fusion

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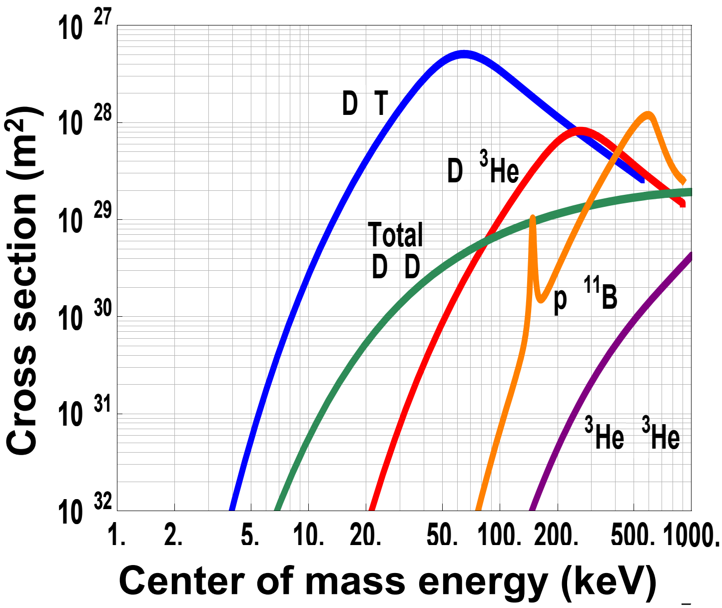
13th U.S.-Japan Workshop on Inertial Electrostatic Confinement Fusion
Sydney, New South Wales, Australia | December, 2011

Neutron production from helium-3 fusion is minimal

- High-energy neutrons:
  - induce radioactivity in the first wall;
  - do not allow for direct conversion.
- $^{3}He(^{3}He,2p)^{4}He$ advantages:
  - No direct neutron production
  - Negligible neutrons from side reactions
  - All reactants and products are stable
  - → <u>Radioactivity concerns are minimized</u>
- Challenges:
  - Low fusion cross-section, need higher ion energies
  - Fuel cost and availability

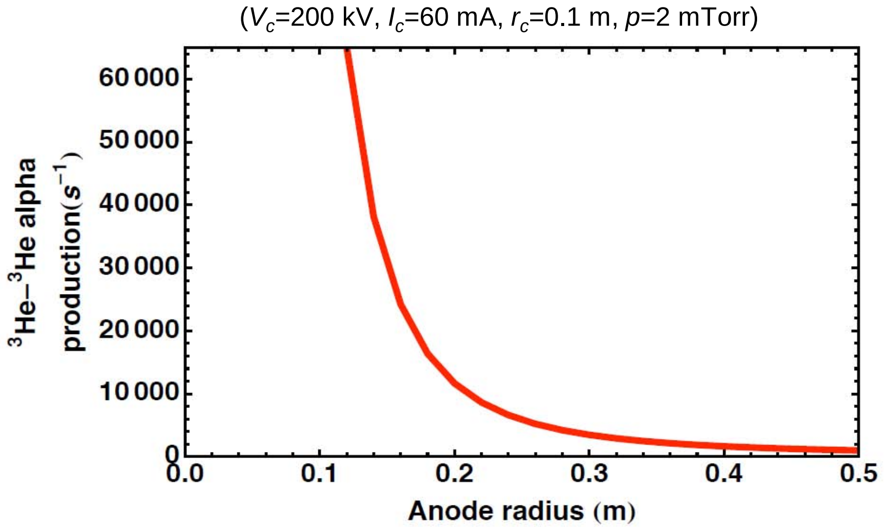
Neutron rate per watt of fusion (from fuel only)	
Reaction	**Neutrons/s (MeV)**
D-T	4×10^{11} (14.1)
D-D	9×10^{11} (2.45)
D-^{3}He	2×10^{10} (2.45)
^{3}He-^{3}He	~ 0

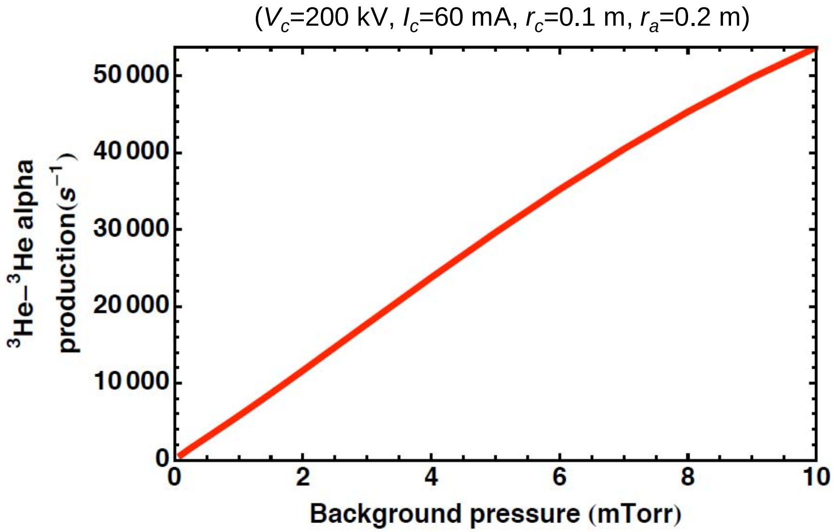


Helium-3 fusion experiments can benchmark the VICTER code

- ^{3}He fusion: no molecular ions → easier to model
- Experiments can help benchmark the VICTER code on spherically convergent ion flow, in its single-ion-species formalism*
- VICTER models beam-background fusion reactions only

Plots from VICTER code calculations

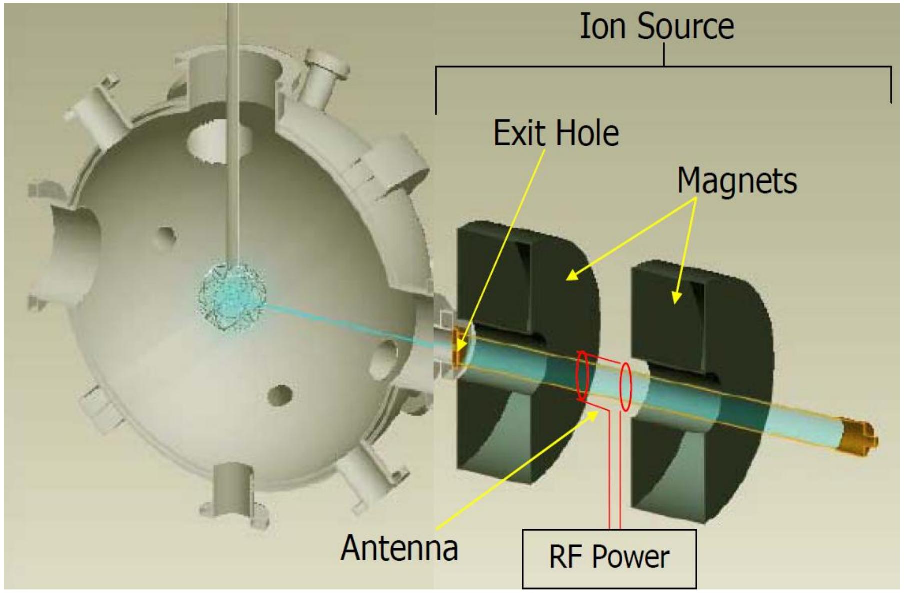


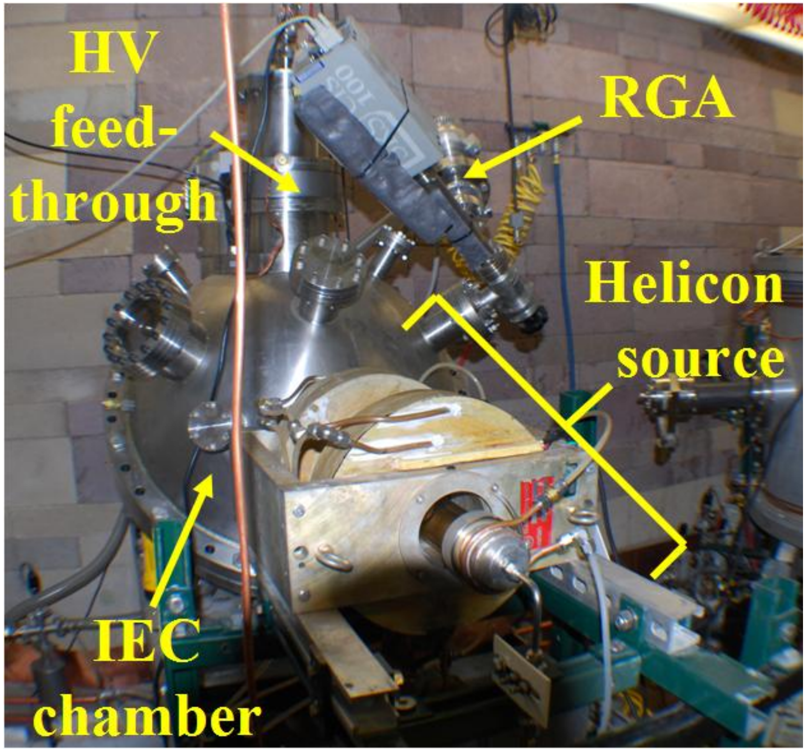


*G.A. Emmert and J.F. Santarius, *Phys. Plasmas* **17**, 013502 (2010).

The HELIOS IEC device

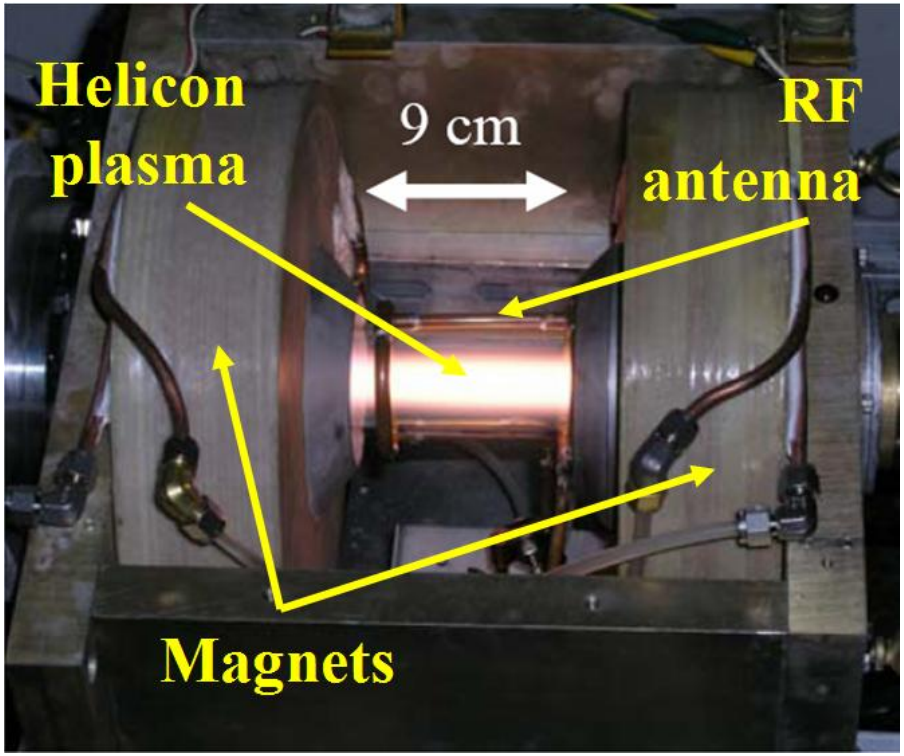
- HELIOS was designed specifically for ^{3}He fusion experiments*:
  - uses an external helicon plasma as source of ions
    - high density, allows for lower neutral pressure in chamber
  - single grid acts as cathode, chamber walls as anode

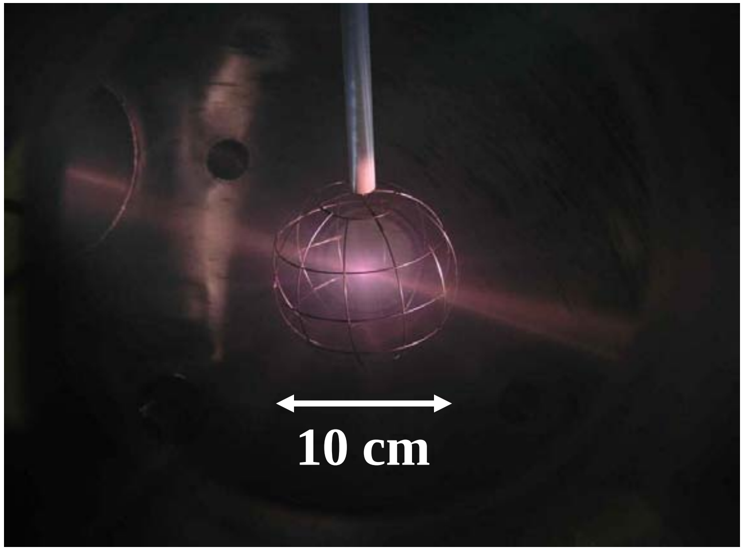




*G.R. Piefer et al., *Fusion Sci. and Technol.* **47**, 1255 (2005).

The HELIOS IEC device

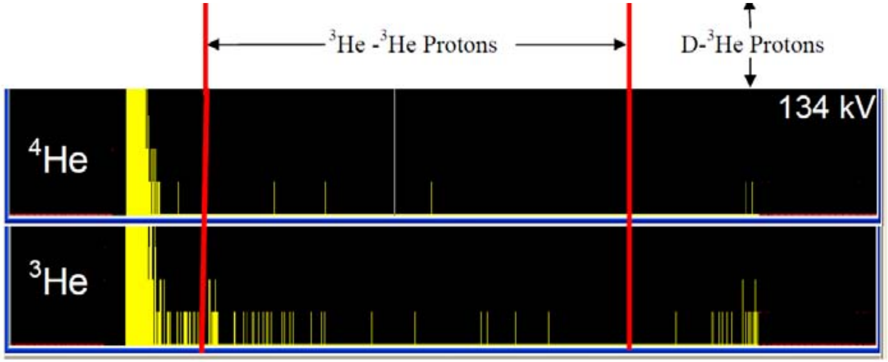




Hydrogen helicon plasma
1mTorr, 500 W, 500G

^{3}He fusion protons previously detected, higher fusion rates required

- Piefer, 2006: ^{3}He fusion protons in an IEC device first detected.

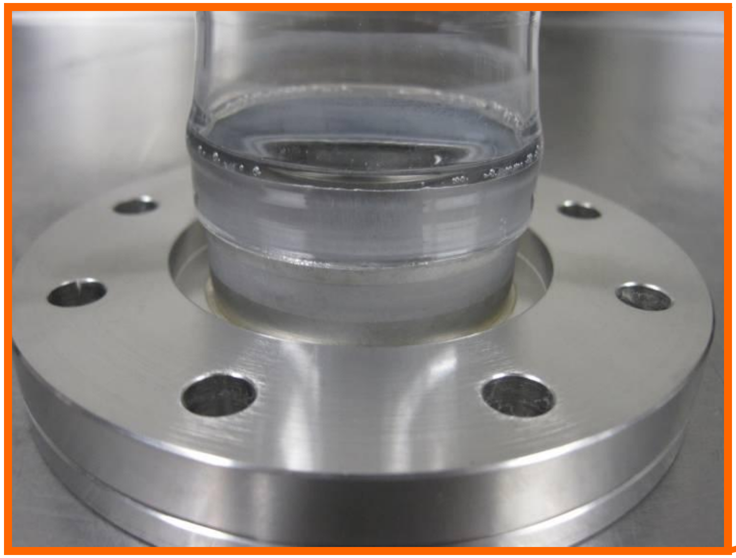


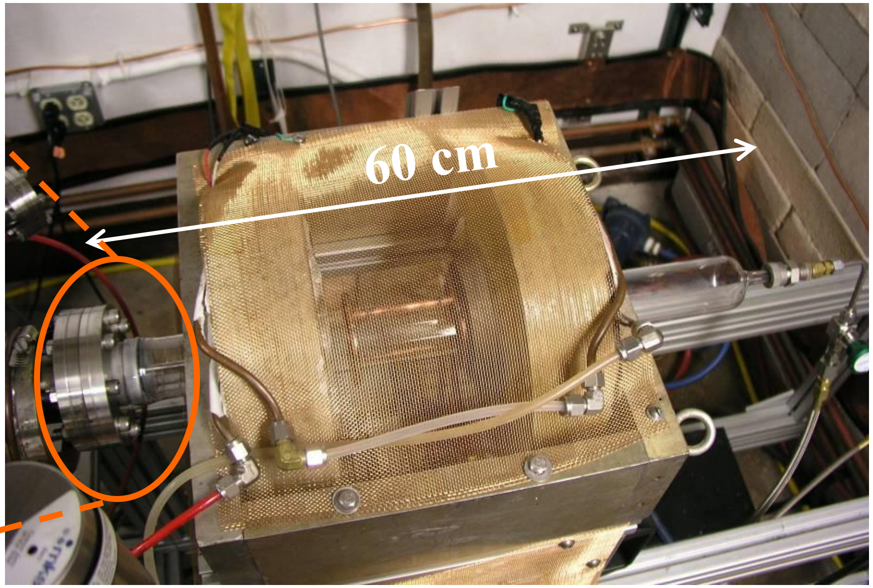
- Record rate: 1.1×10^3 reactions/s (V_c = -134 kV, I_{ion} = 7 mA)
- Too low for diagnostic investigations IEC physics with ^{3}He fuel
  - e.g. reactant energy distributions, spatial profiles of fusion events
- Campaign to increase ^{3}He fusion rates:
  - raise the ion current extracted from the helicon ion source
  - enhance the high-voltage capabilities

Helicon ion source has been upgraded with a quartz-to-metal seal

- New ion source discharge chamber:
  - custom-made assembly with a quartz-to-molybdenum seal
  - rated for up to 350 ºC, higher than the previous O-ring seal
  - removes need for a castable alumina heat shield

    → fewer impurities, crucial for helium plasmas





Characterization of the helicon plasma is needed for understanding how to optimize it

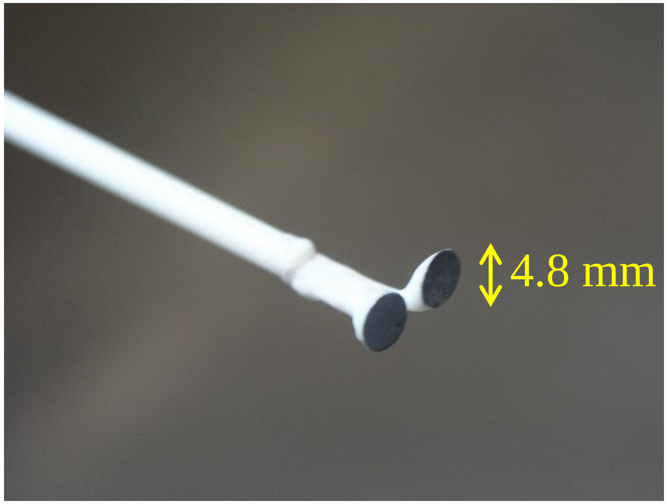
- Proper measurements of n_0 and T_e needed for:
  - confirming any progress in increasing these parameters
  - information for designing a new extraction system, currently a single grounded electrode with an aperture.

- Previous attempts at characterizing this source:
  - a Langmuir probe, which melted at high rf power levels*;
  - a "witness plate" technique to determine the extracted ion current*;
  - a spectroscopic study based on a collisional-radiative model†, valid for hydrogen only:
    - $n_0 \sim 3{-}7 \times 10^{11}$ cm^{-3} and $T_e \sim 4{-}6$ eV for up to 1.5 kW rf power and 1.2 kG magnetic field.

*G. Piefer, Ph.D. thesis (2006). †E. Alderson, M.S. thesis (2008).

Characterization of the helicon plasma: double probe in extraction region

• A double Langmuir probe and its associated circuit have been constructed to measure the plasma density and electron temperature of the helicon ion source.

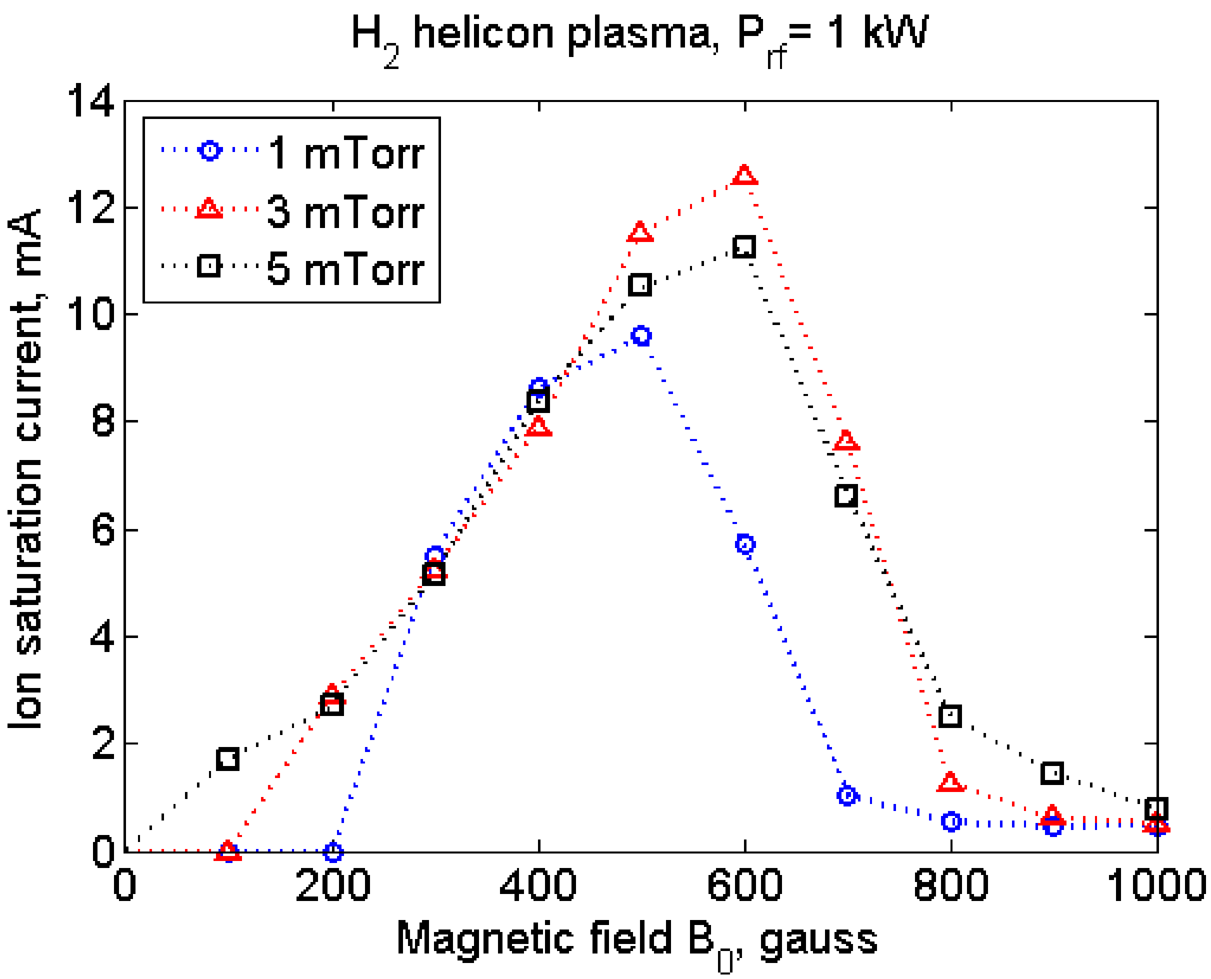


• Currents limited to the ion saturation current << electron saturation current, mitigating the heat load

• Probe is electrically isolated, floats with the rf variation, intrinsically compensating for helicon plasma oscillations.

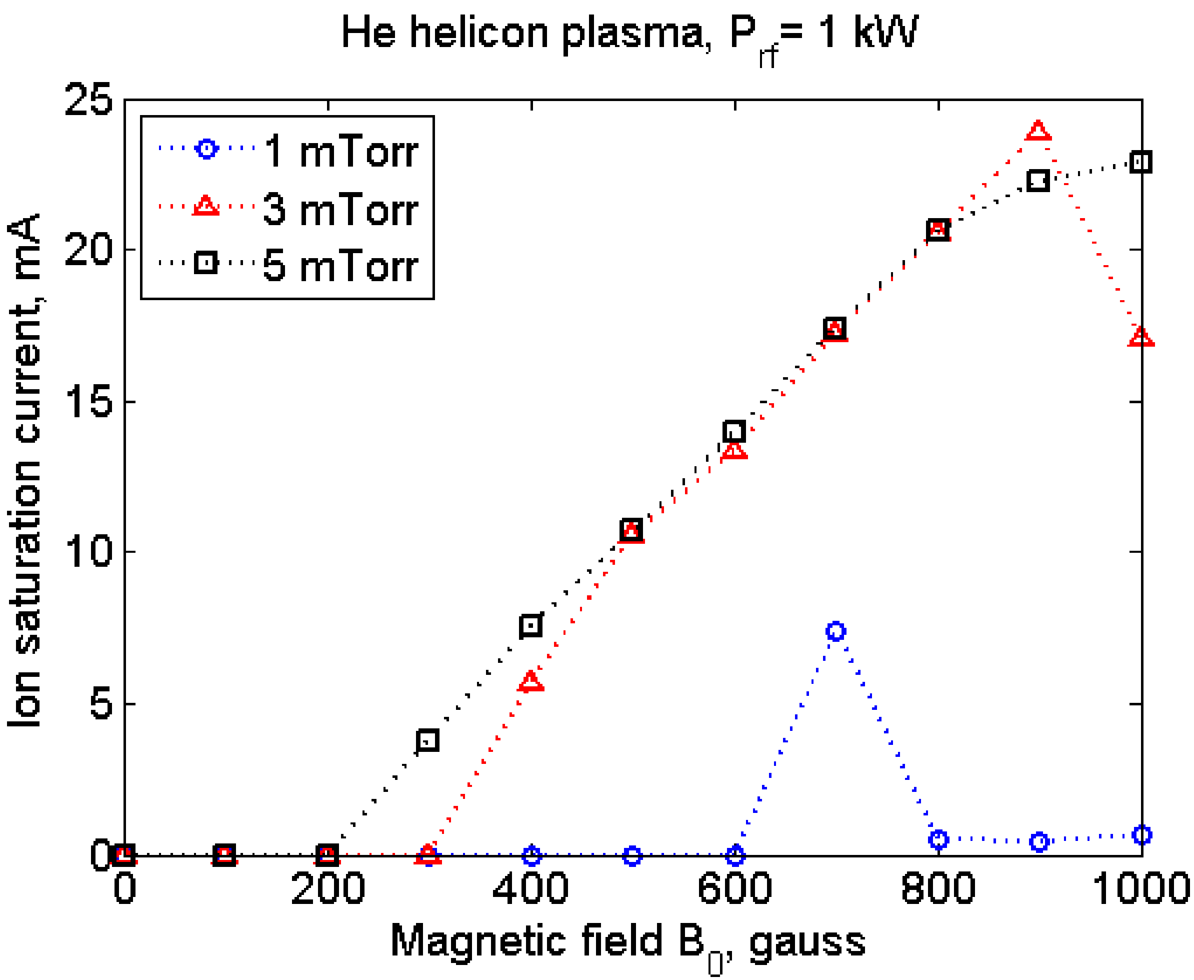
• Probe electrodes: planar tantalum discs placed in the extraction region, near the helicon source aperture.

Hydrogen plasma density near aperture reaches a maximum at 500-600 G



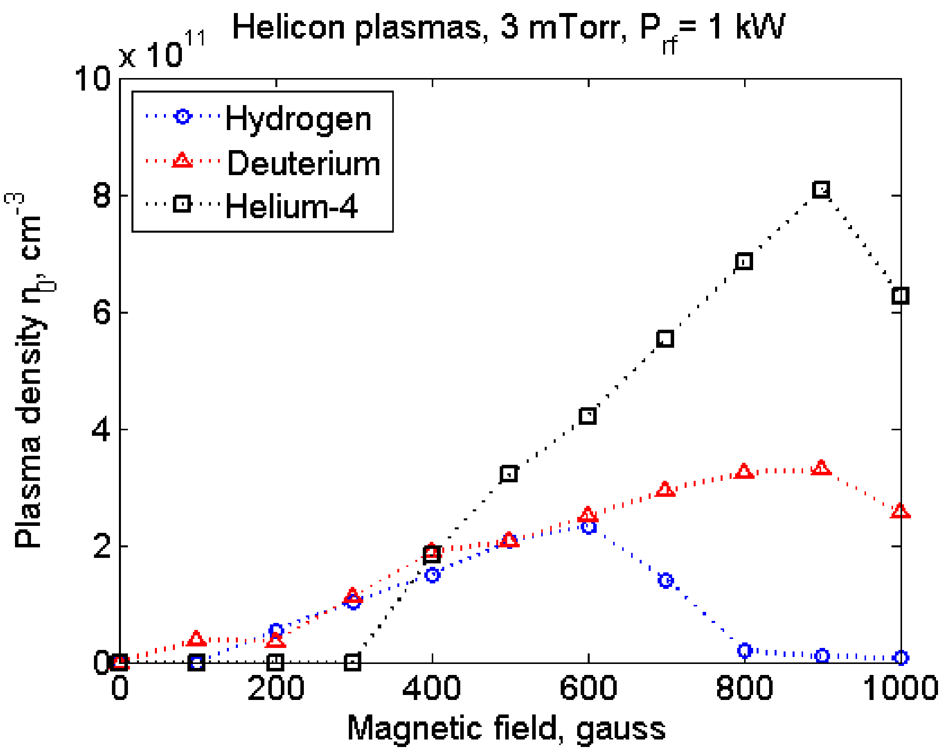
- n_0 ~1-3×10^{11} cm^{-3}
- T_e ~ 8-20 eV
- Density does not increase monotonically with magnetic field
- Maximum density achieved at intermediate pressure

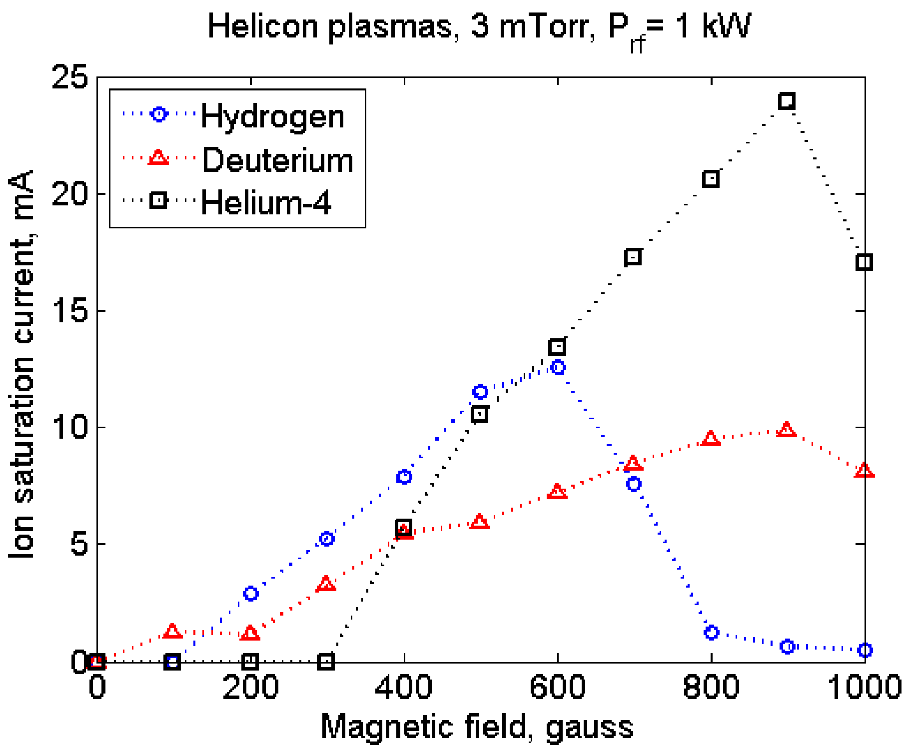
Helium-4 plasma density near aperture tend to increase with magnetic field



- n_0 ~4-8×10^{11} cm^{-3}
- T_e ~ 10-15 eV
- Difficult to obtain a dense plasma at 1 mTorr
- Density increases monotonically with magnetic field

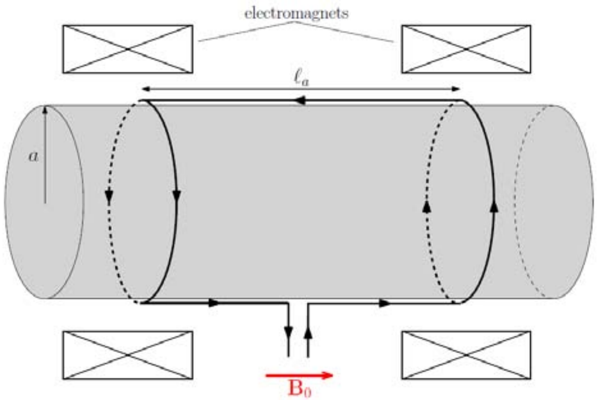
Heavier gases yield denser plasmas, but not necessarily higher currents

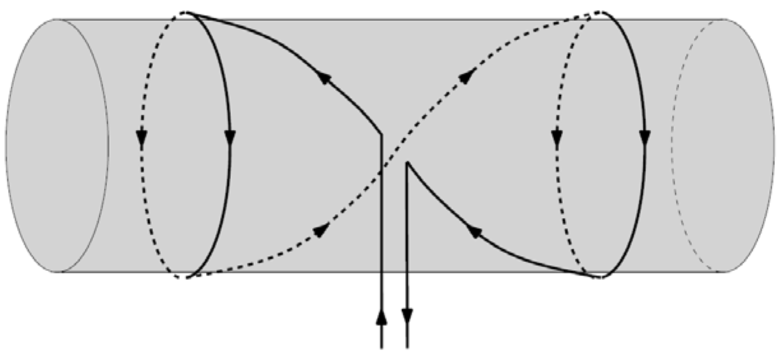




Increasing the ion current extracted from the helicon source

- Emission-limited extractable ion current: Bohm current ~ $n_0 T_e^{1/2}$.
- Approaches to increasing helicon plasma density:
  - Change of rf antenna from Nagoya type III to a twisted Nagoya geometry: ~50% increases observed*.



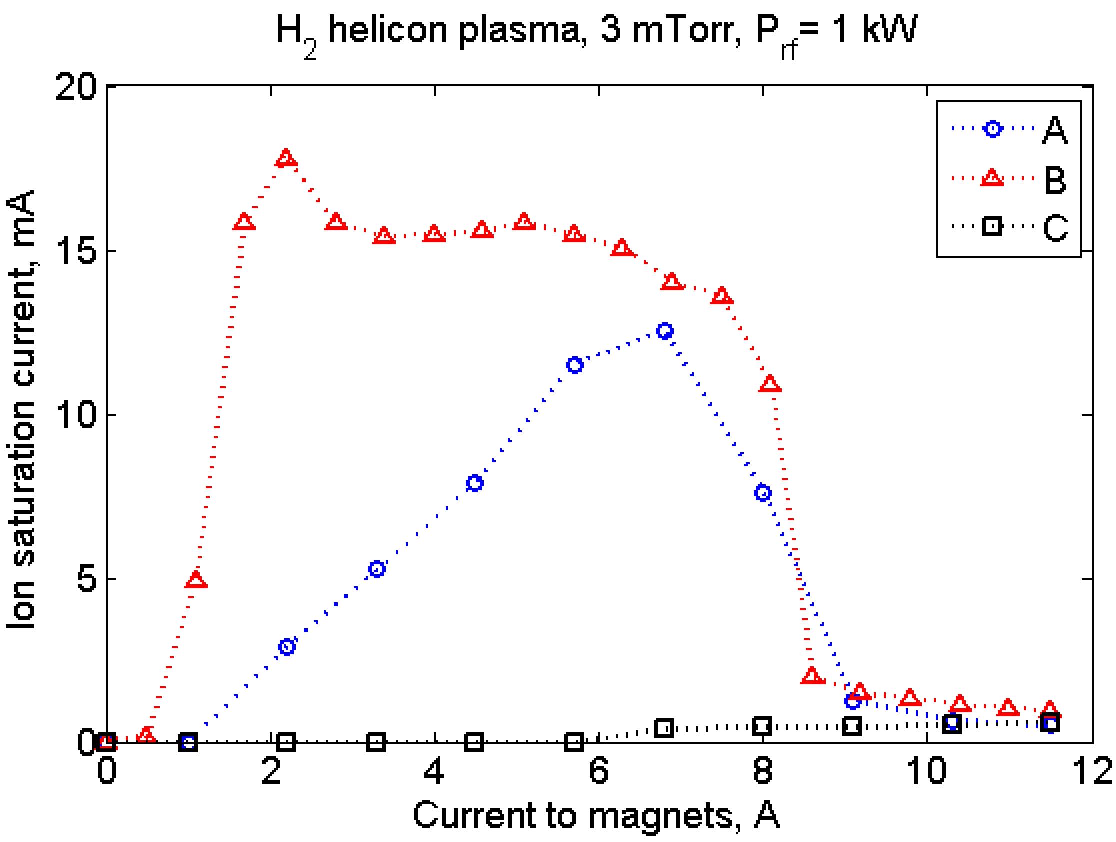


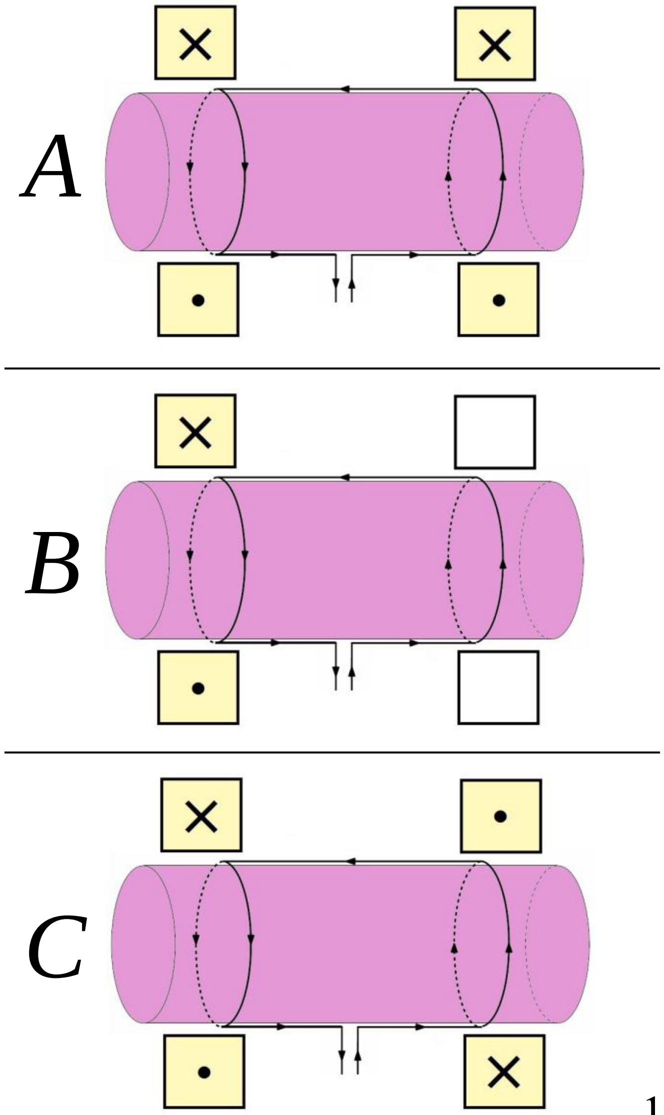
  - Change of magnetic field from uniform axial geometry to non-uniform field: increase by factor of ~3-4 observed†.

*D.D. Blackwell and F.F. Chen, *Plasma Sources Sci. Technol.* **6,** 569 (1997).

†H.D. Jung et al., *IEEE Trans. Plasma Sci.* **35,** 1476 (2007).

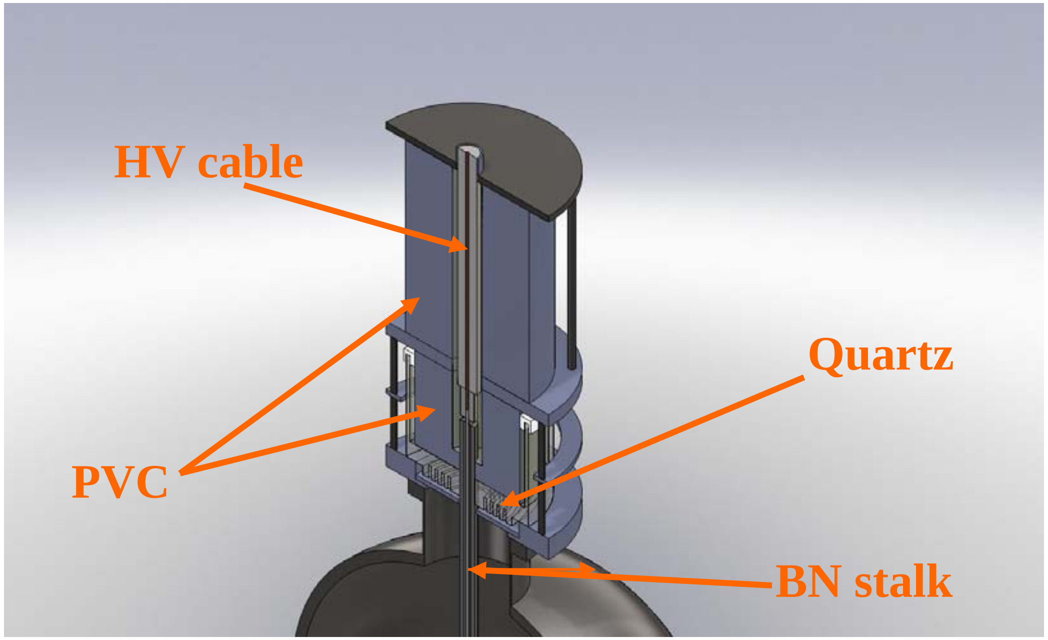
Changing B-field geometry yields denser plasma over a broad range of field strengths





High-voltage capabilities

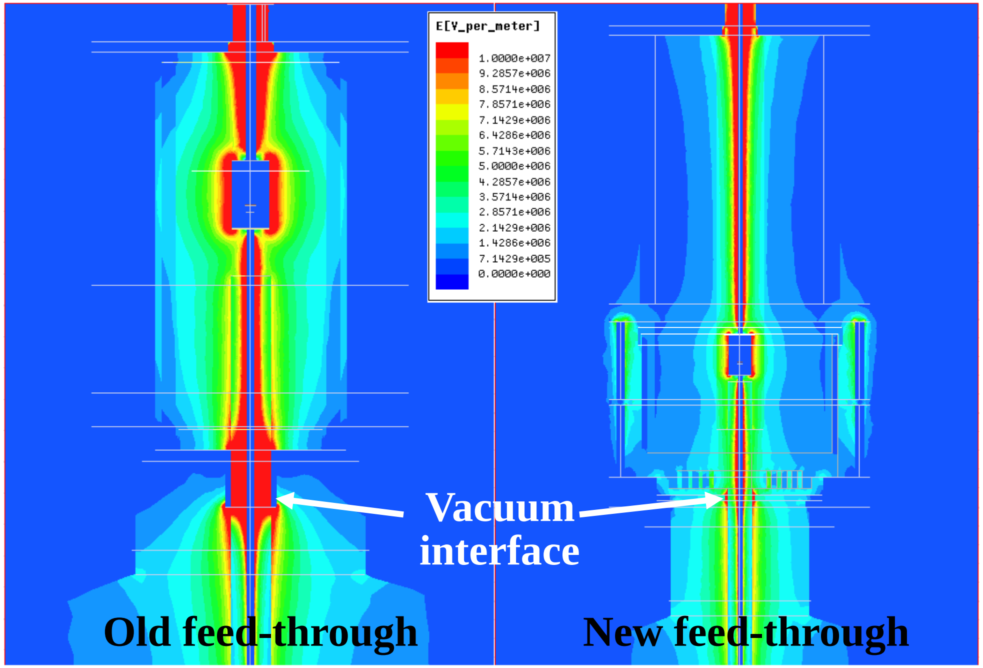
- Since 2009: 300 kV, 200 mA power supply
- New high-voltage feed-through designed and constructed, to allow for higher voltage operation:
    - Longer surface paths to ground
    - Non-conducting materials: quartz, PVC



High-voltage capabilities

• Electrostatic model: much reduced electric fields, particularly near the vacuum interface, where failures typically occur.

Ansoft Maxwell vacuum electrostatic simulations with cathode at -250 kV.



• Tests of the new HV voltage feed-through will be done once the construction of the new intermediate buffer and switching circuit is complete.

Summary and Conclusions

- HELIOS is undergoing upgrades to increase the ^{3}He-^{3}He fusion rates:
  - Enhancing the high-voltage capabilities
    - New power supply, HV feed-through, switching system
  - Increasing the extractable ion current from the helicon source
    - Characterization of helicon plasma with double probe

- Achieving higher rates will give way to:
  - Experimental studies of IEC physics with helium-3 fuel
    - Reactant ion energy distributions
    - Spatial profiles of fusion events
  - Comparison with VICTER code on spherically convergent ion flow.