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

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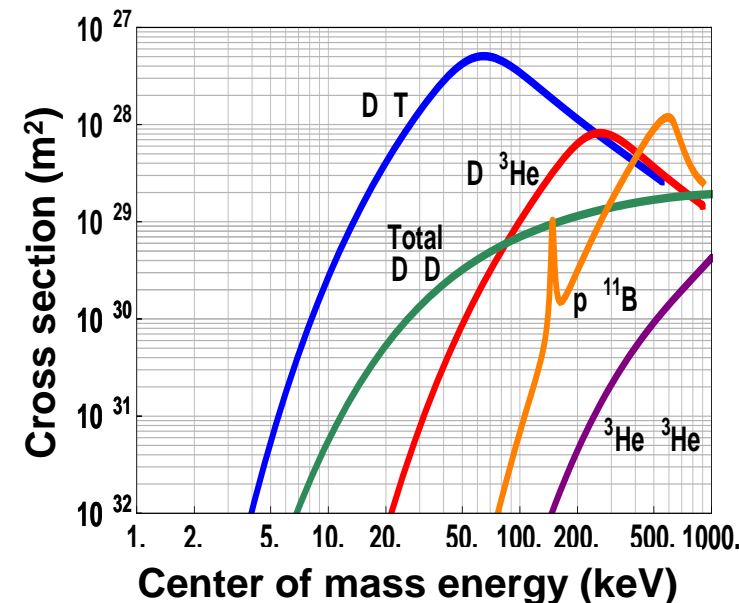


Neutron production from helium-3 fusion is minimal



- High-energy neutrons:
 - induce radioactivity in the first wall;
 - do not allow for direct conversion.
- ${}^3\text{He}({}^3\text{He}, 2p){}^4\text{He}$ advantages:
 - No direct neutron production
 - Negligible neutrons from side reactions
 - All reactants and products are stable
 - Radioactivity concerns are minimized
- 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- ${}^3\text{He}$	2×10^{10} (2.45)
${}^3\text{He}$ - ${}^3\text{He}$	~ 0





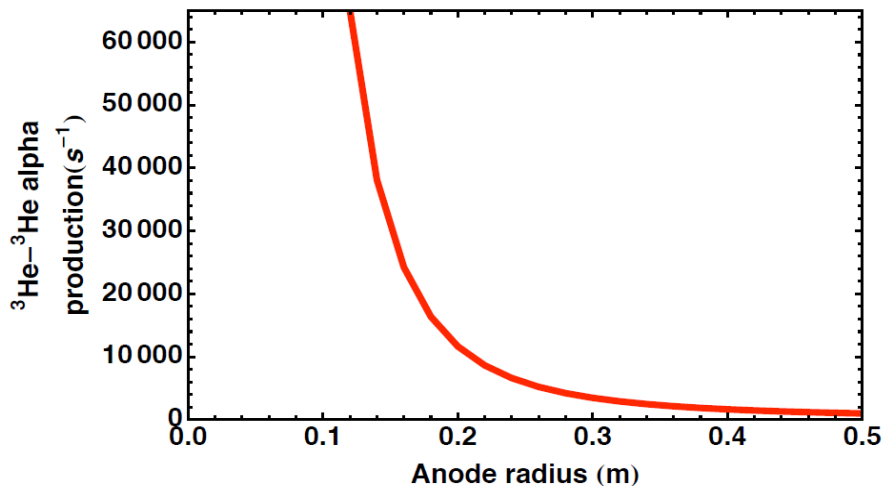
Helium-3 fusion experiments can benchmark the VICTER code



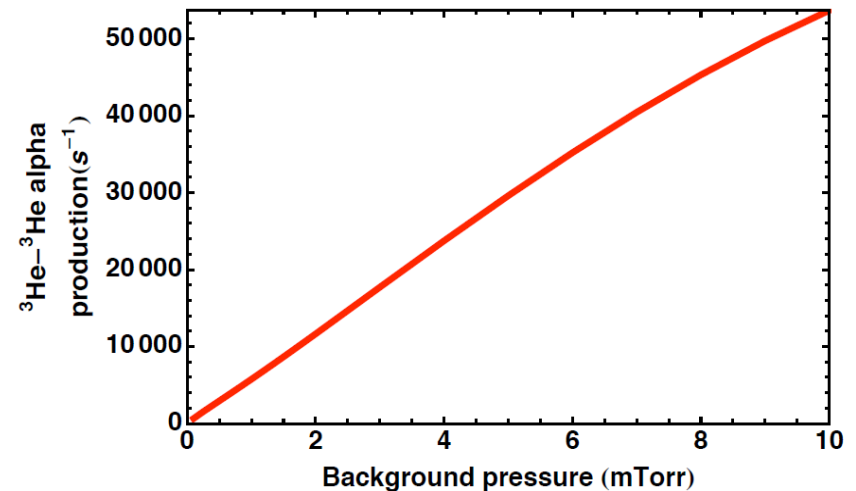
- ^3He fusion: no molecular ions \rightarrow easier to model
- Experiments can help benchmark the VICTER code on spherically convergent ion flow, in its single-ion-species formalism*
- VICTER models beam-background fusion reactions only

Plots from VICTER code calculations

($V_c=200$ kV, $I_c=60$ mA, $r_c=0.1$ m, $p=2$ mTorr)



($V_c=200$ kV, $I_c=60$ mA, $r_c=0.1$ m, $r_a=0.2$ m)



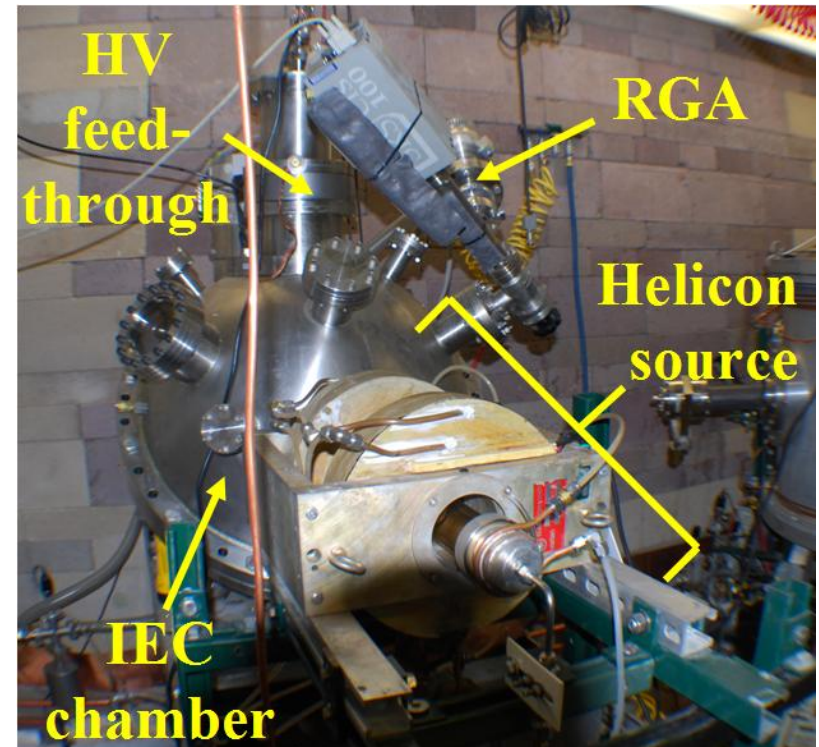
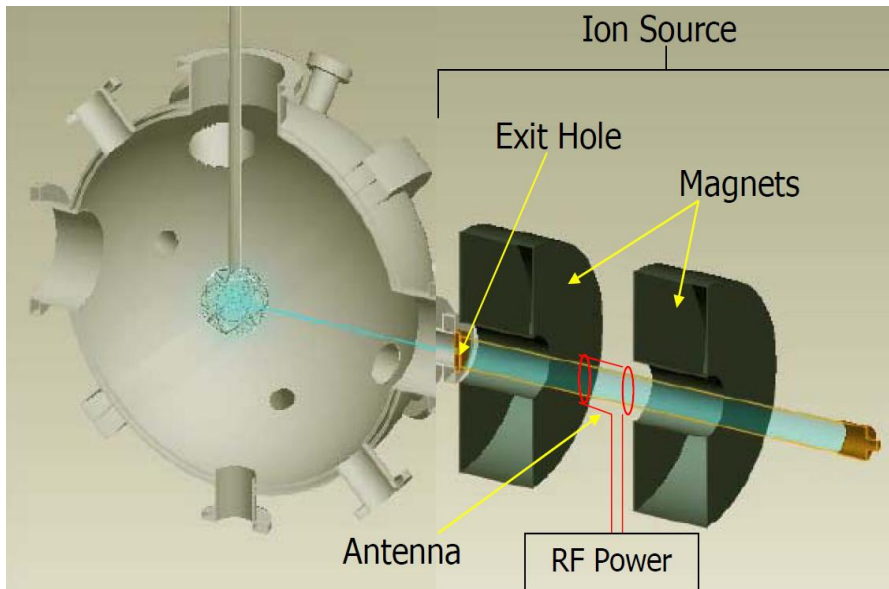
*G.A. Emmert and J.F. Santarius, *Phys. Plasmas* **17**, 013502 (2010).



The HELIOS IEC device



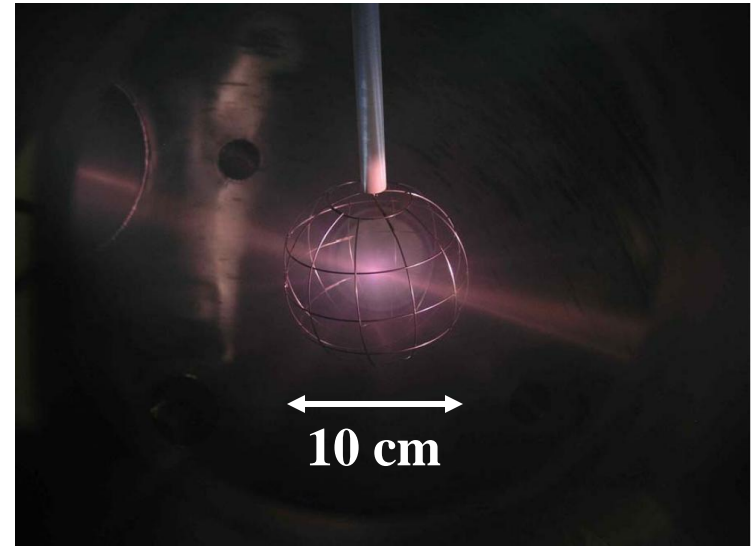
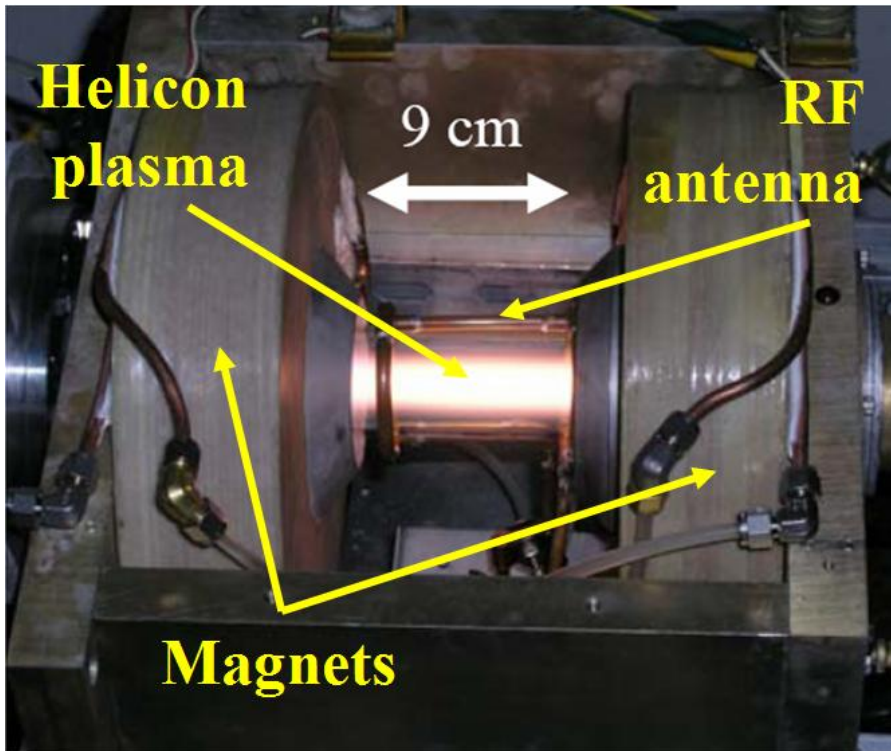
- HELIOS was designed specifically for ^3He fusion experiments*:
 - uses an external helicon plasma as source of ions
 - high density, allows for lower neutral pressure in chamber
 - single grid acts as cathode, chamber walls as anode



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



The HELIOS IEC device



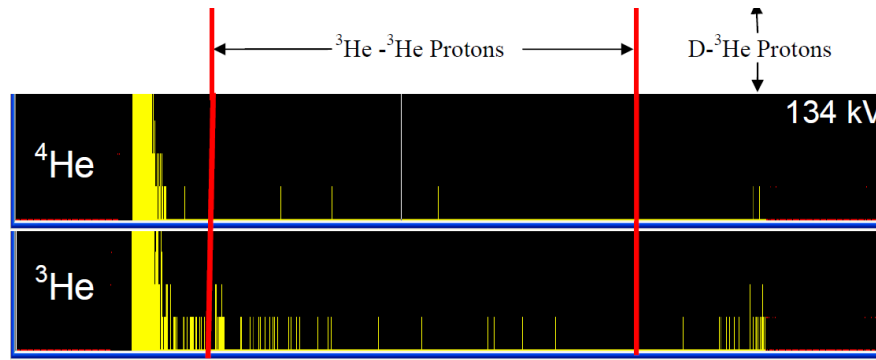
Hydrogen helicon plasma
1mTorr, 500 W, 500G



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



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



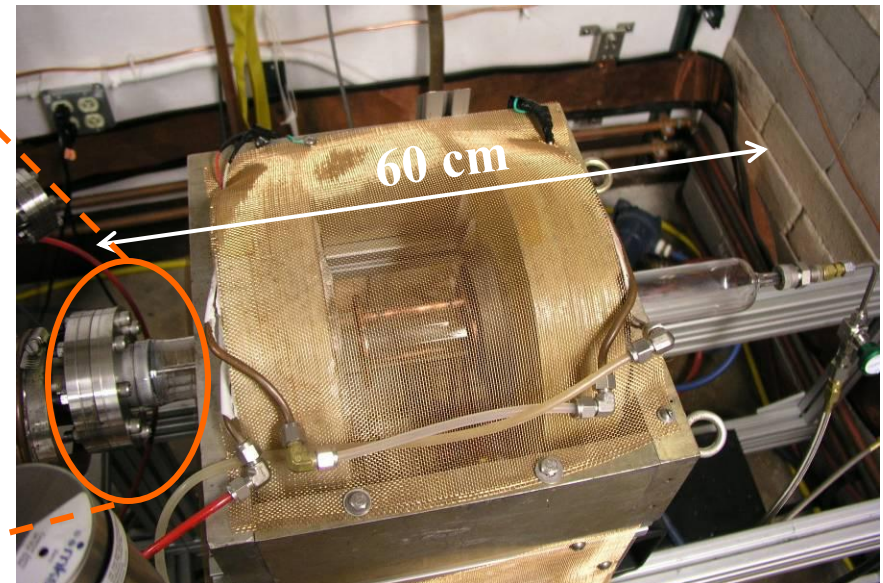
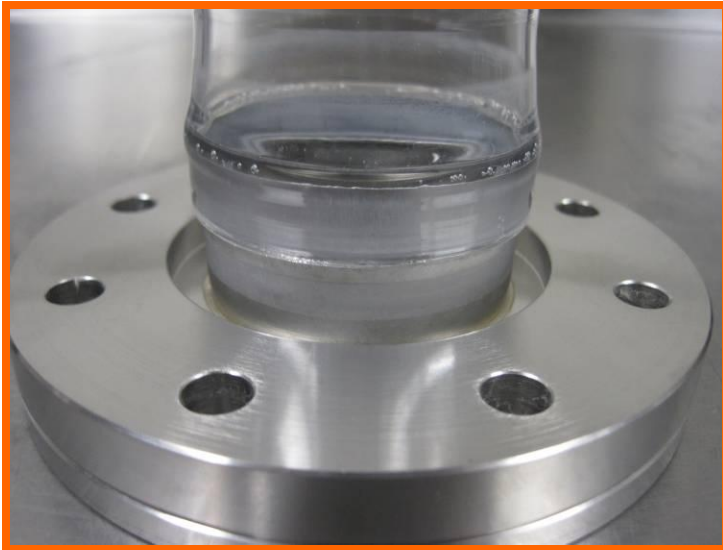
- Record rate: 1.1×10^3 reactions/s ($V_c = -134 \text{ kV}$, $I_{ion} = 7 \text{ mA}$)
- Too low for diagnostic investigations IEC physics with ^3He fuel
 - e.g. reactant energy distributions, spatial profiles of fusion events
- Campaign to increase ^3He fusion rates:
 - raise the ion current extracted 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 °C, 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:
 - $n_0 \sim 3\text{--}7 \times 10^{11} \text{ cm}^{-3}$ and $T_e \sim 4\text{--}6 \text{ eV}$ for up to 1.5 kW rf power and 1.2 kG magnetic field.

*G. Piefer, Ph.D. thesis (2006).

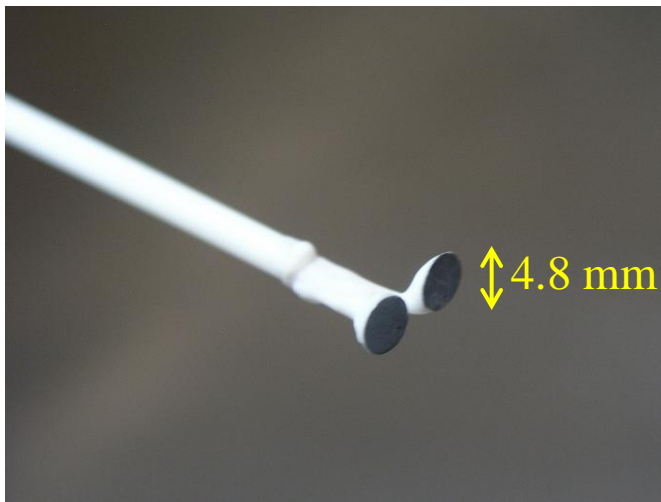
[†]E. Alderson, M.S. thesis (2008).



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.



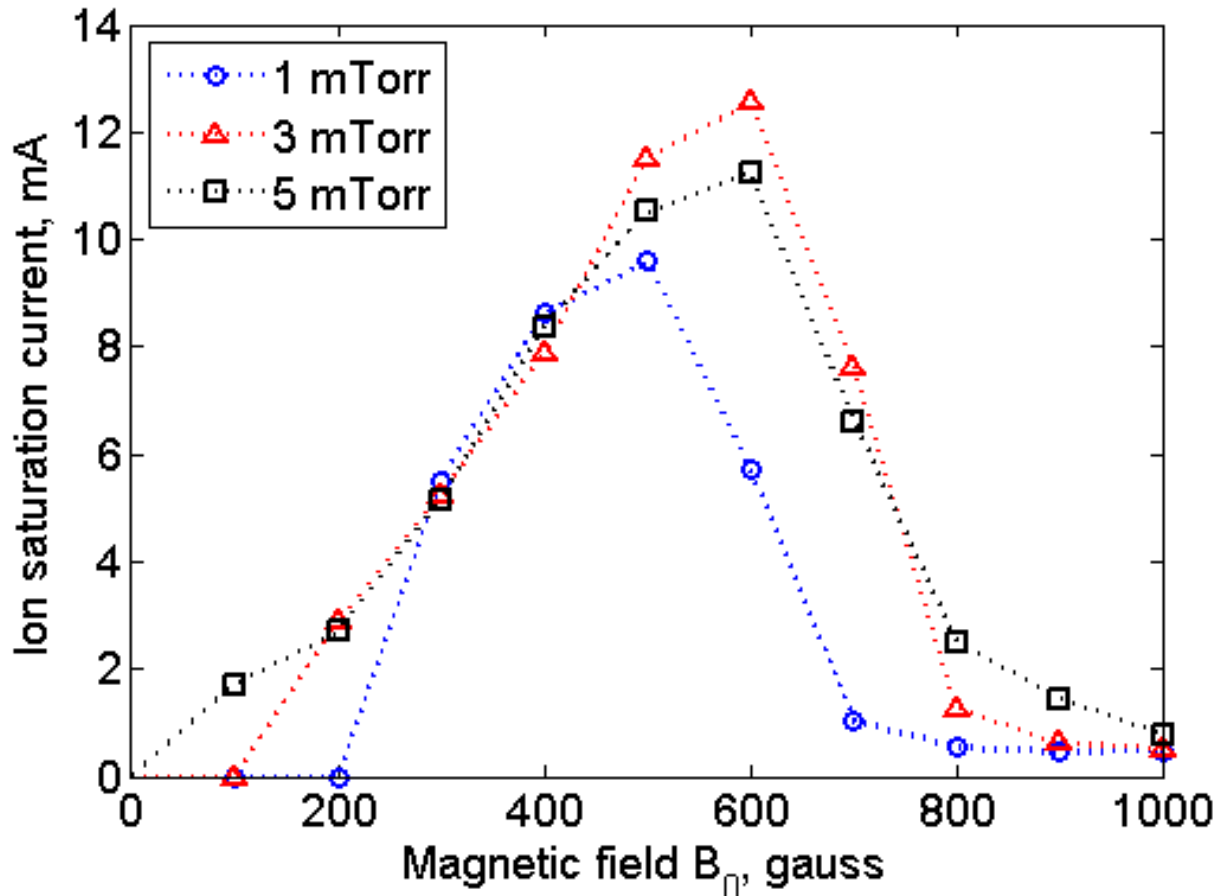
- Currents limited to the ion saturation current \ll electron saturation current, mitigating the heat load
- Probe is electrically isolated, floats with the rf variation, intrinsically compensating for helicon plasma oscillations.
- Probe electrodes: planar tantalum discs placed in the extraction region, near the helicon source aperture.



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



H₂ helicon plasma, P_{rf} = 1 kW



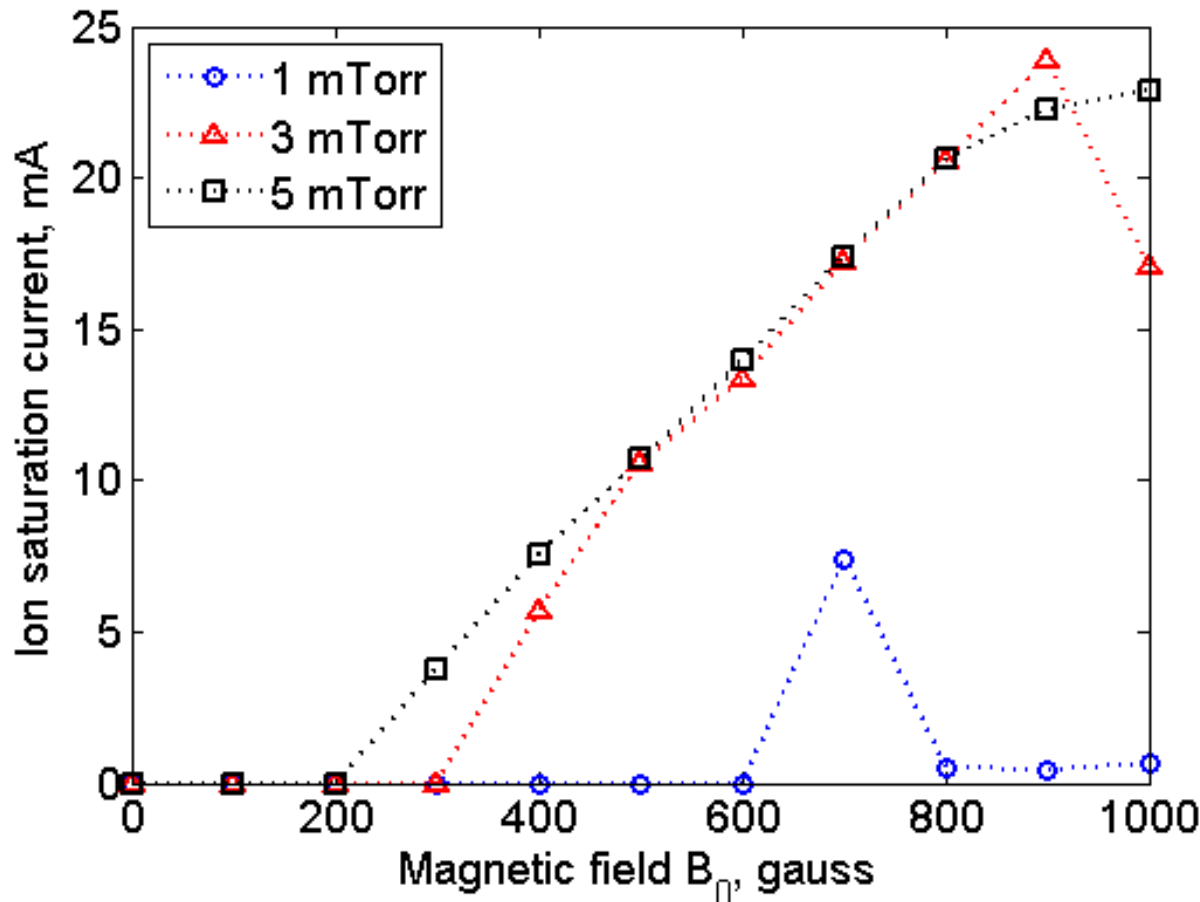
- $n_0 \sim 1-3 \times 10^{11} \text{ cm}^{-3}$
- $T_e \sim 8-20 \text{ eV}$
- Density does not increase monotonically with magnetic field
- Maximum density achieved at intermediate pressure



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



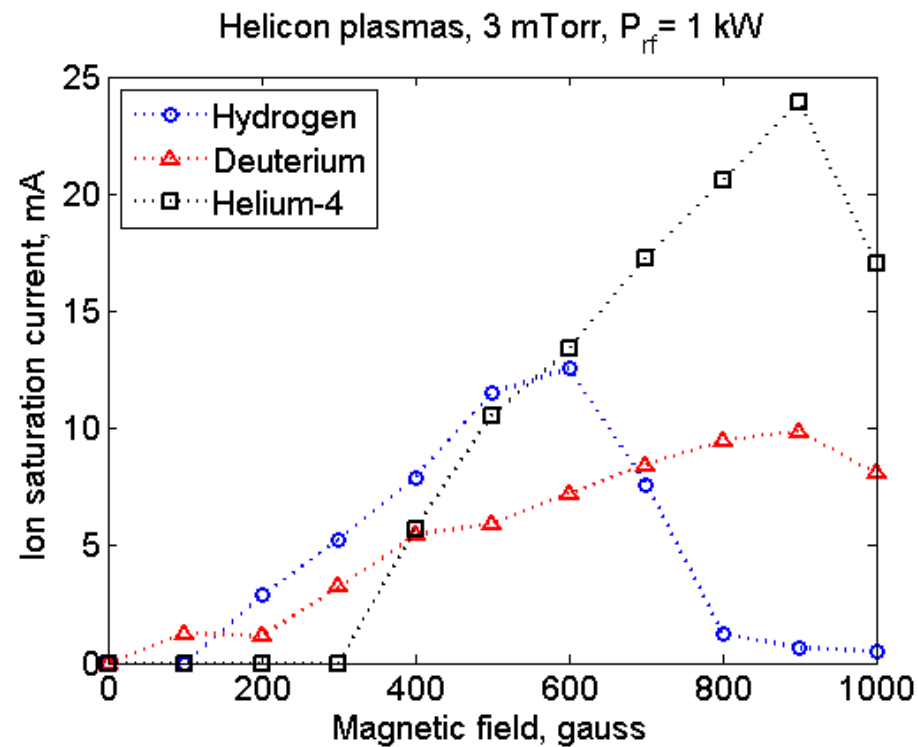
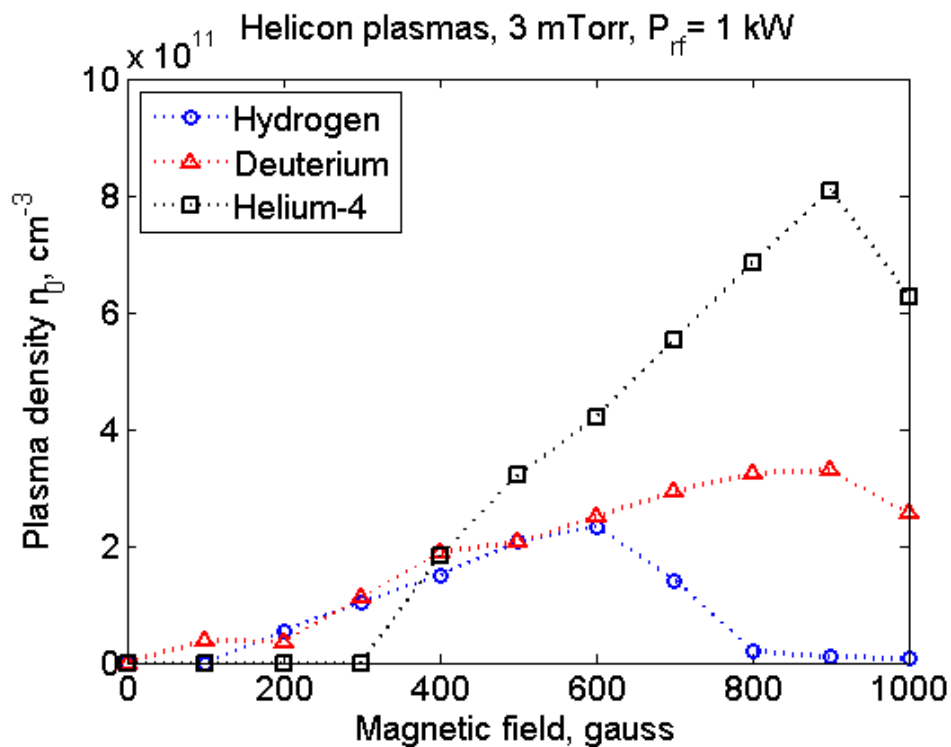
He helicon plasma, $P_{rf} = 1$ kW



- $n_0 \sim 4-8 \times 10^{11} \text{ cm}^{-3}$
- $T_e \sim 10-15 \text{ eV}$
- 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

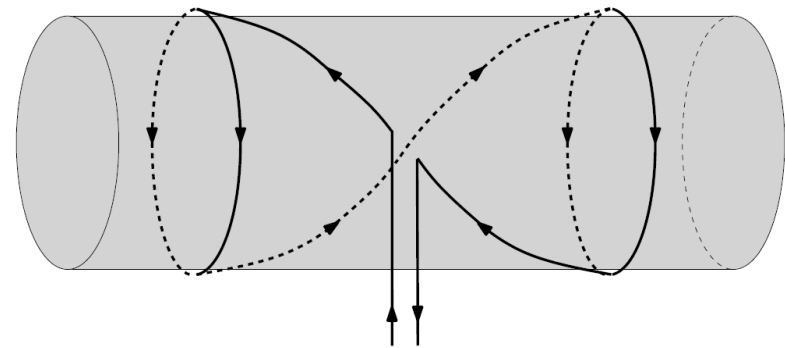
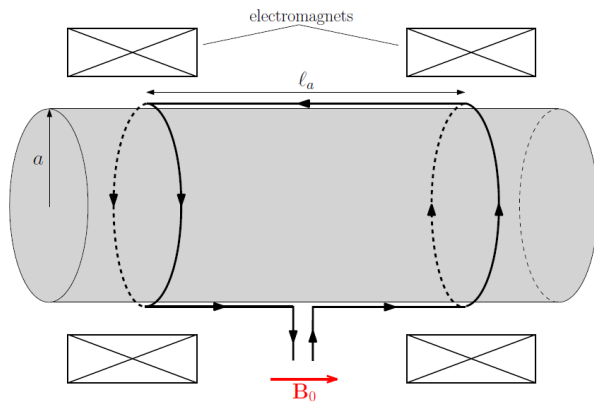




Increasing the ion current extracted from the helicon source



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



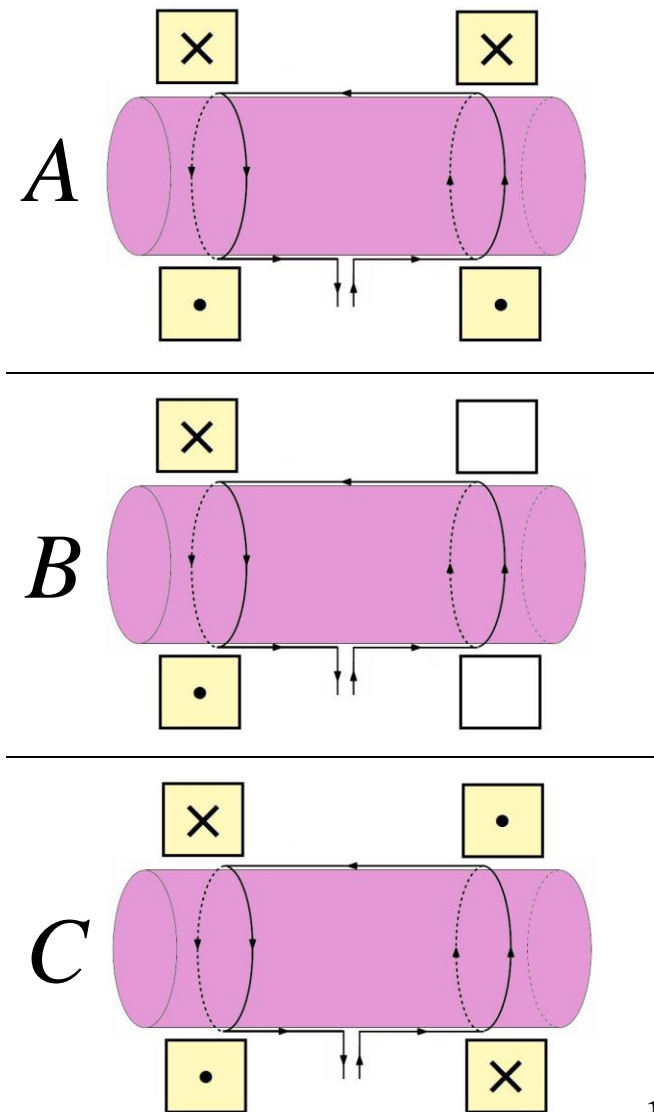
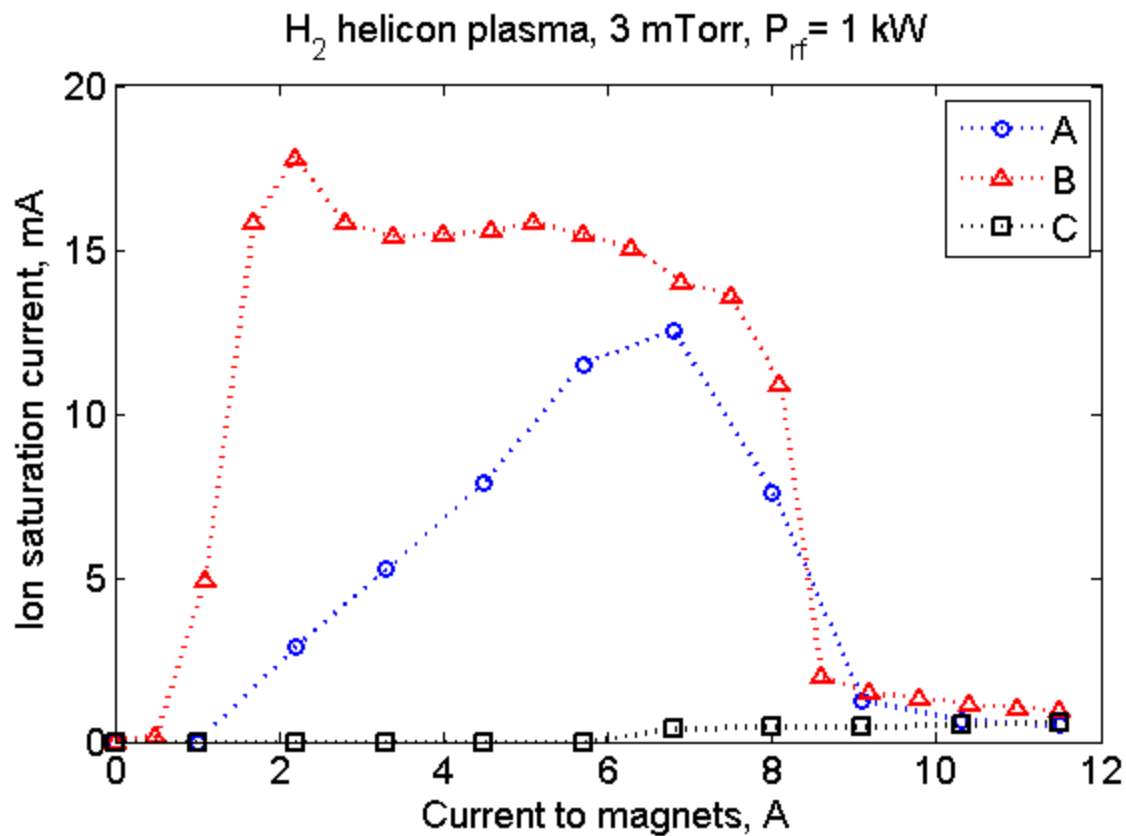
- Change of magnetic field from uniform axial geometry to non-uniform field: increase by factor of $\sim 3-4$ observed†.

*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

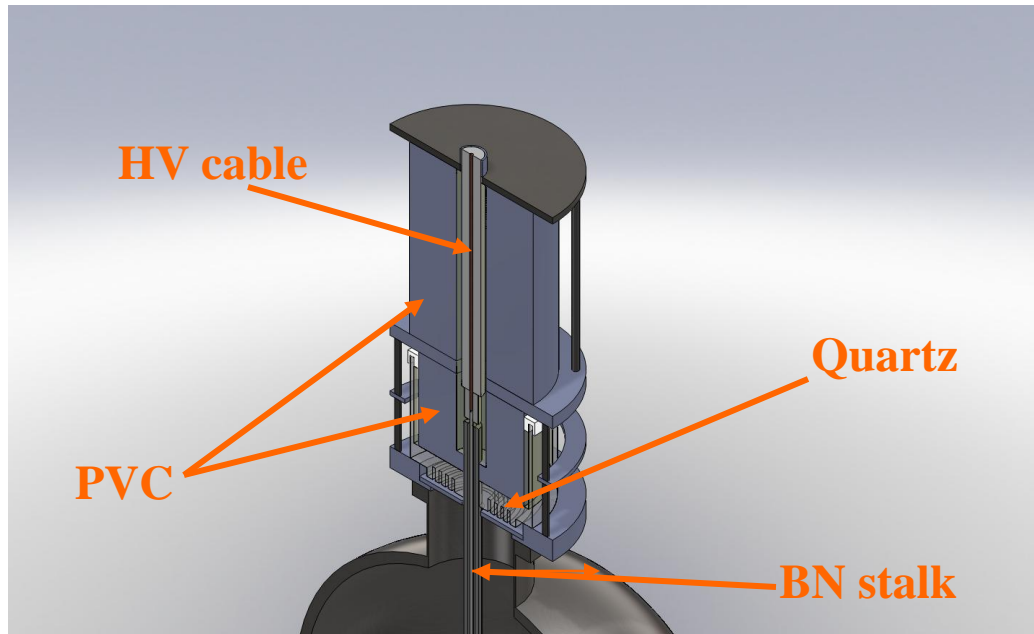




High-voltage capabilities



- 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

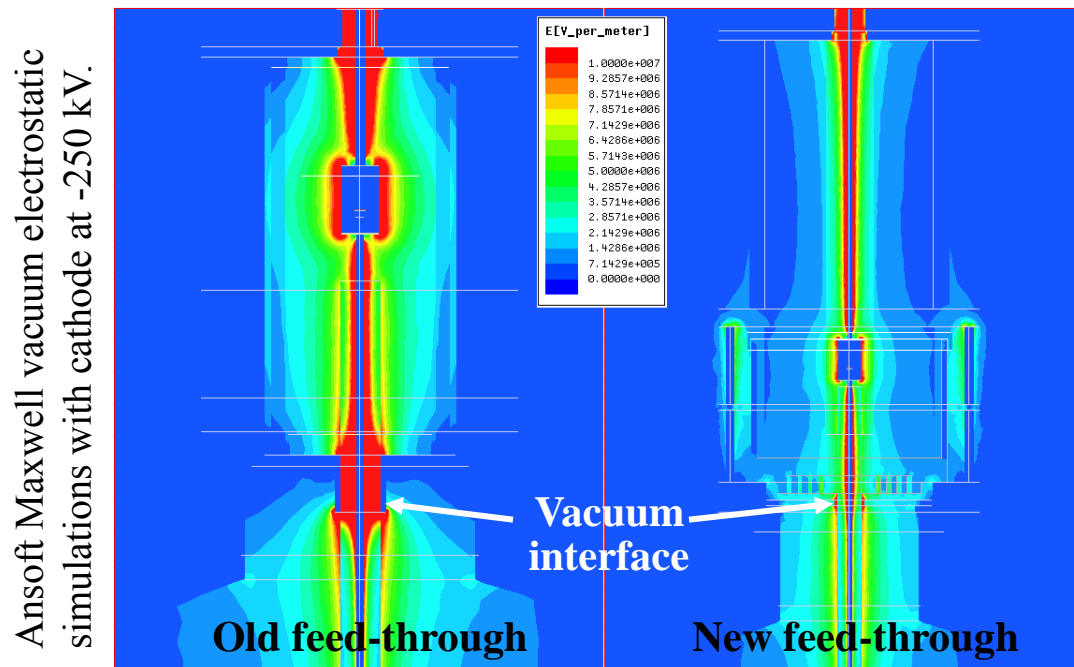




High-voltage capabilities



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



- 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 ^3He - ^3He 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.