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Ion Extraction from a Helicon Plasma for ^{3}He IEC Experiments

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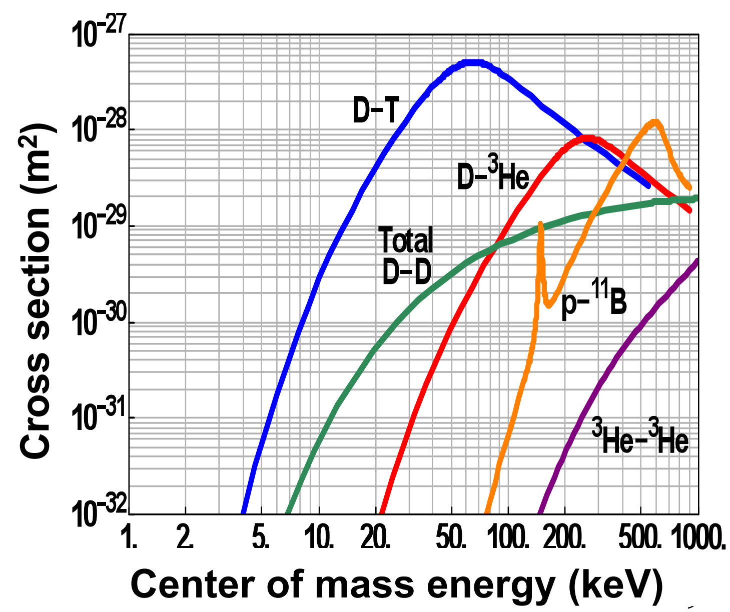
Outline

- Motivation for ^{3}He IEC experiments
- HELIOS experimental setup
- Extracted ion current measurement methods
  - Witness plate technique
  - Faraday cup
- Plasma parameter measurements
  - Spectroscopy: line intensity ratio method
  - Double Langmuir probe
- Summary and conclusions

Neutron production from helium-3 fusion is minimal

- High-energy neutrons:
  - induce radioactivity in reactor walls
  - cause extensive material damage
- $^3He(^3He,2p)^4He$ 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

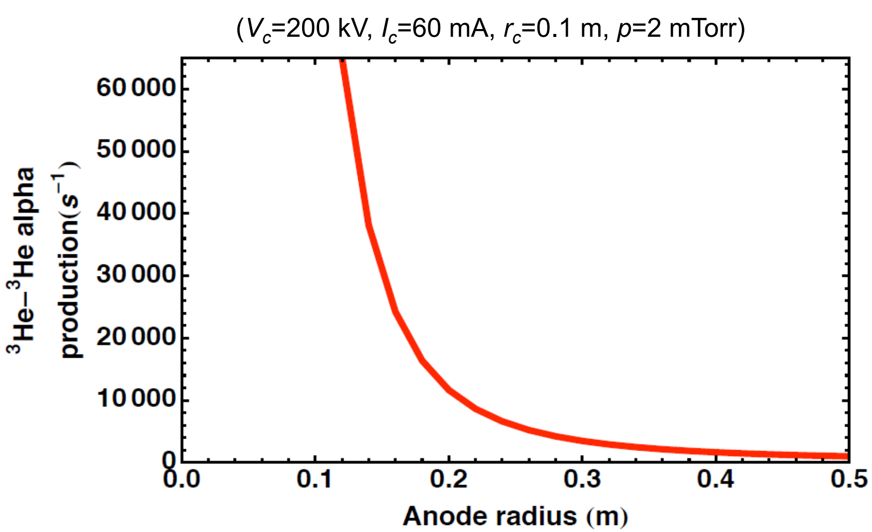
Neutron rate per watt of fusion (from fuel only)	
Reaction	**Neutrons/s (MeV)**
D-T	4×10^{11} (14.1)
D-D	9×10^{11} (2.45)
D-^{3}He	2×10^{10} (2.45)
^{3}He-^{3}He	~ 0

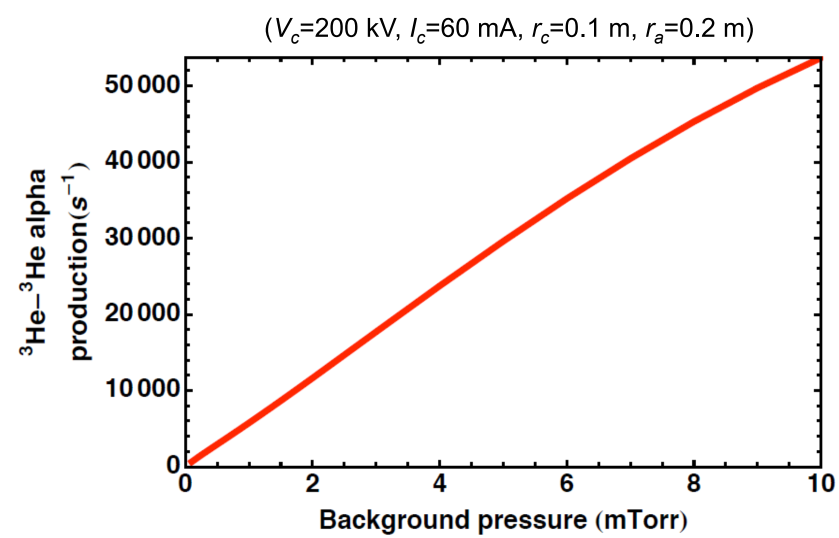


Helium-3 fusion experiments can benchmark the VICTER code

- VICTER is a numerical code on spherically convergent ion flow with atomic and molecular processes*. The code models fusion reactions with background gas only.
- Experiments can help benchmark VICTER in its single-ion species formalism (plus He^{2+}, see G. Emmert's talk).

Plots from VICTER code calculations



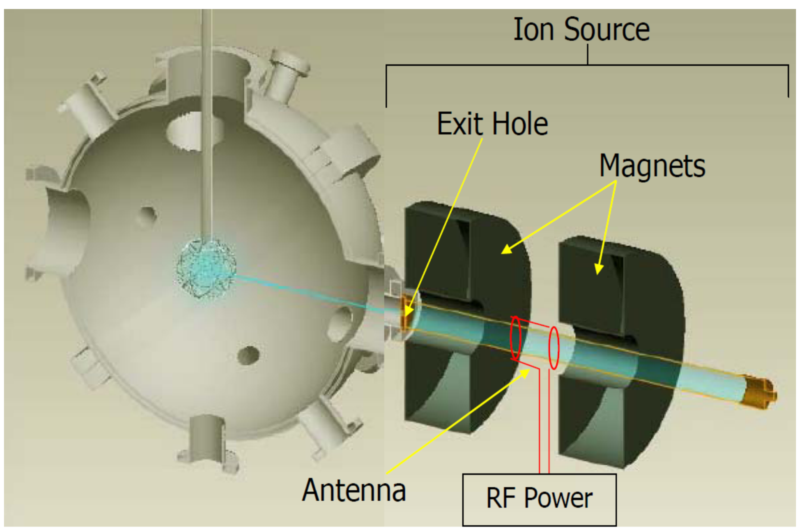


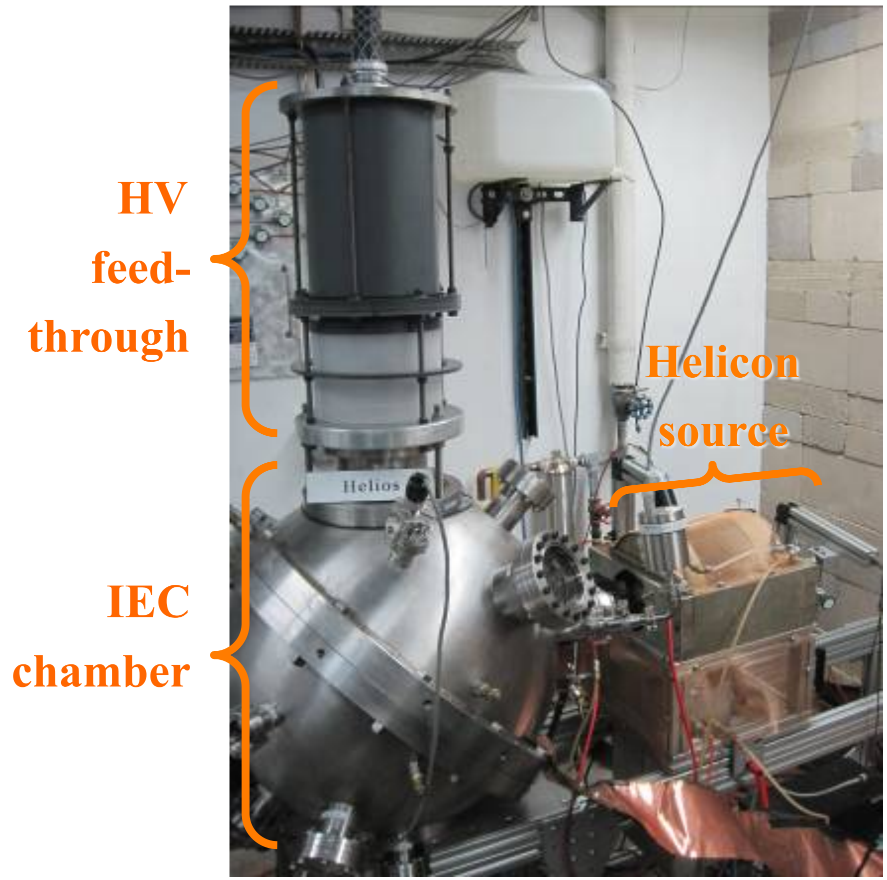
*G.A. Emmert and J.F. Santarius, *Phys. Plasmas* **17**, 013502 (2010).

The HELIOS IEC device

HELIOS was designed specifically for ^3He fusion experiments*:

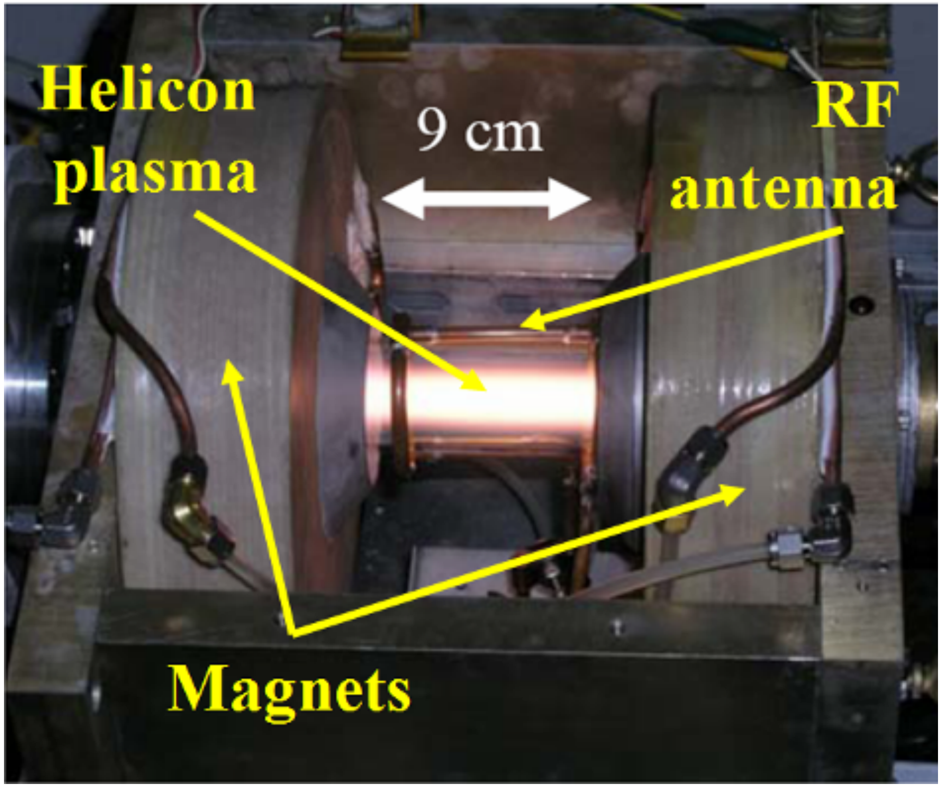
- uses an external helicon plasma as source of ions
  - high density, allows for lower neutral pressure in chamber
- single grid acts as cathode, chamber walls as anode

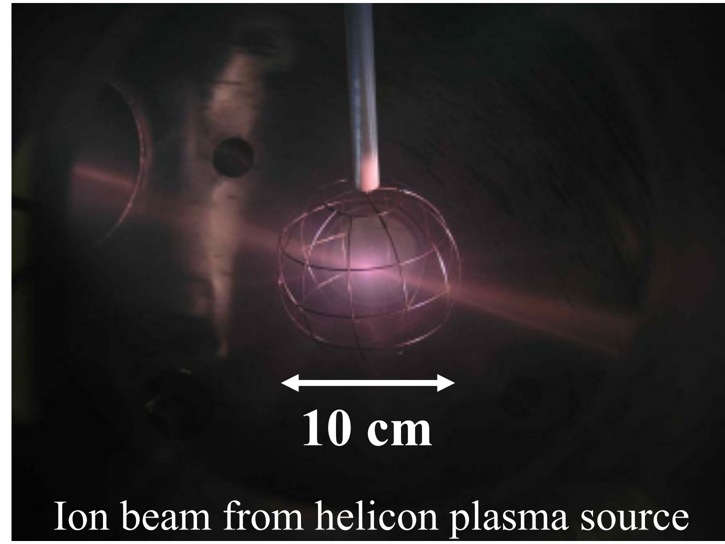




*G.R. Piefer et al., *Fusion Sci. and Technol.* **47**, 1255 (2005).

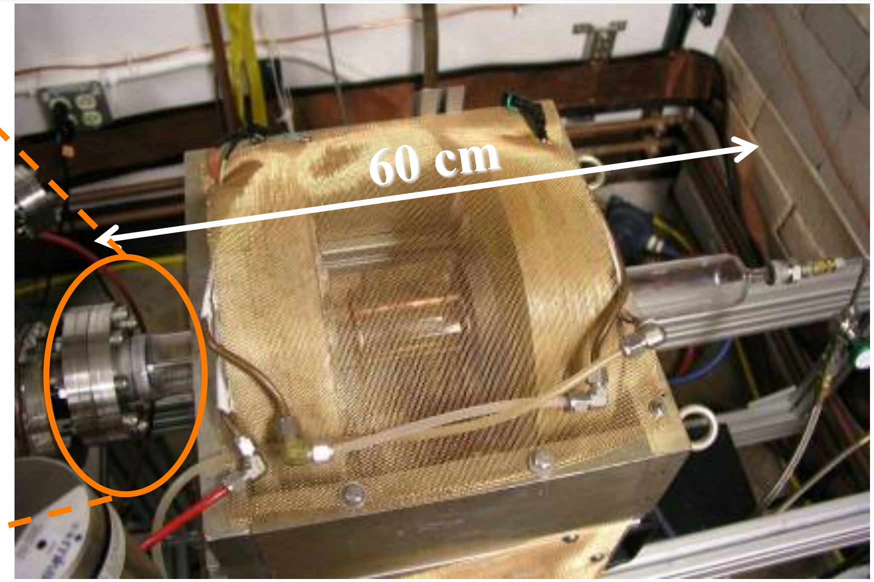
Helicon source and ion beam



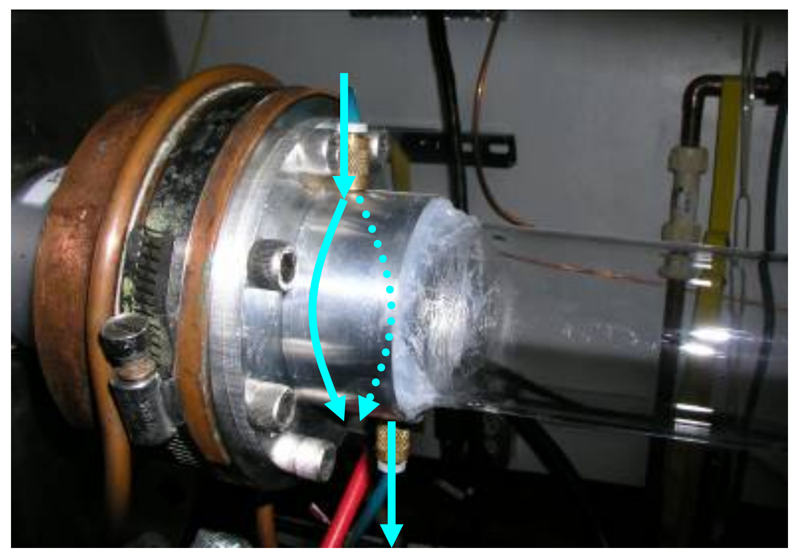


Hydrogen helicon plasma
1 mTorr, 500 W, 500 G

Helicon discharge chamber



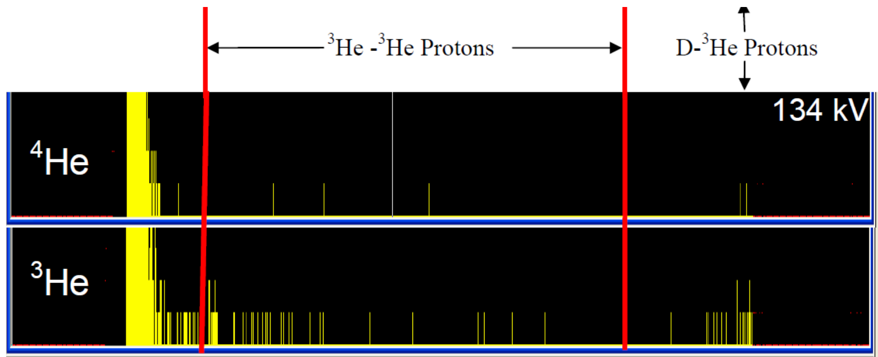
New quartz-to-metal seal allows higher temperatures and lower impurities than previous O-ring seal.



Water-cooling sleeve recently added to actively cool quartz-to-metal seal.

^{3}He fusion protons previously detected, but higher fusion rates required for better statistics

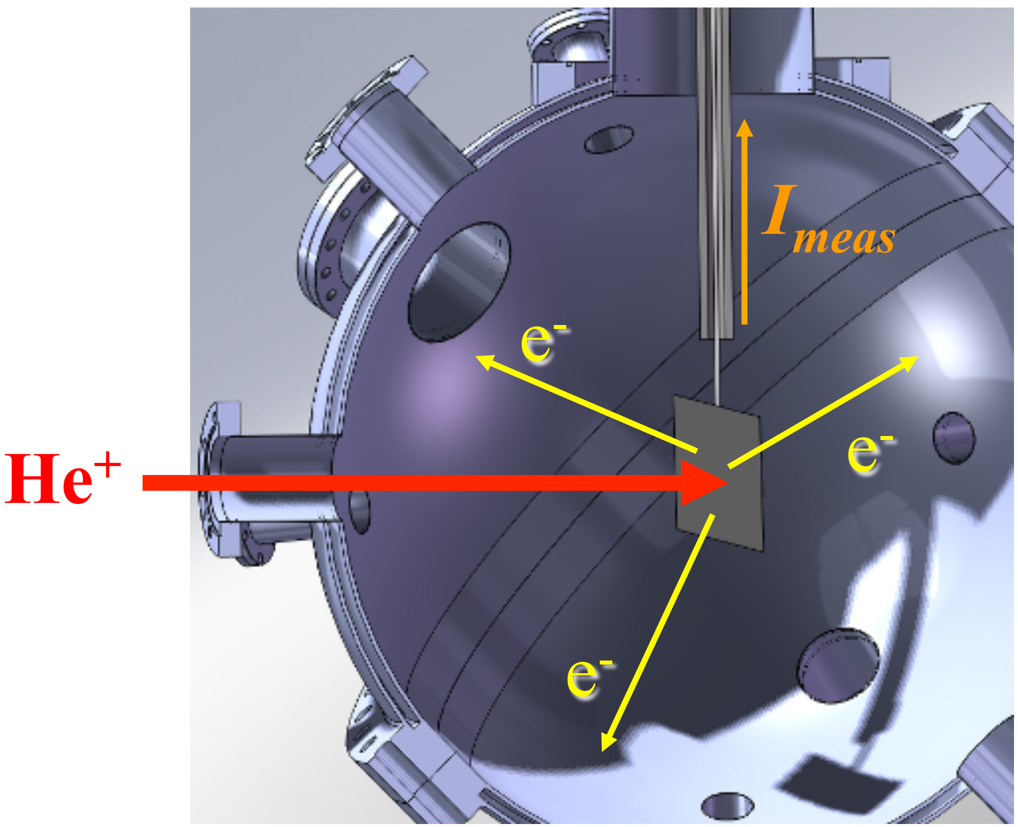
- Piefer, 2006: ^{3}He fusion protons in an IEC device first detected.



- Record rate: 1.1×10^3 reactions/s (V_c = -134 kV, I_{ion} = 7 mA)
- Too low for diagnostic investigations of 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

Witness-plate ion current measurement accounts for secondary electron contribution to total current

- Total cathode current at these voltages can be mostly secondary electrons going outward, which are not relevant to fusion rates.
- Previous measurement: witness plate method (G. Piefer and S. Zenobia)



$$I_{meas} = I_{He+} + I_e$$
$$= (1 + \gamma)\, I_{He+}$$

$$\boxed{I_{He+} = \frac{I_{meas}}{1 + \gamma}}$$

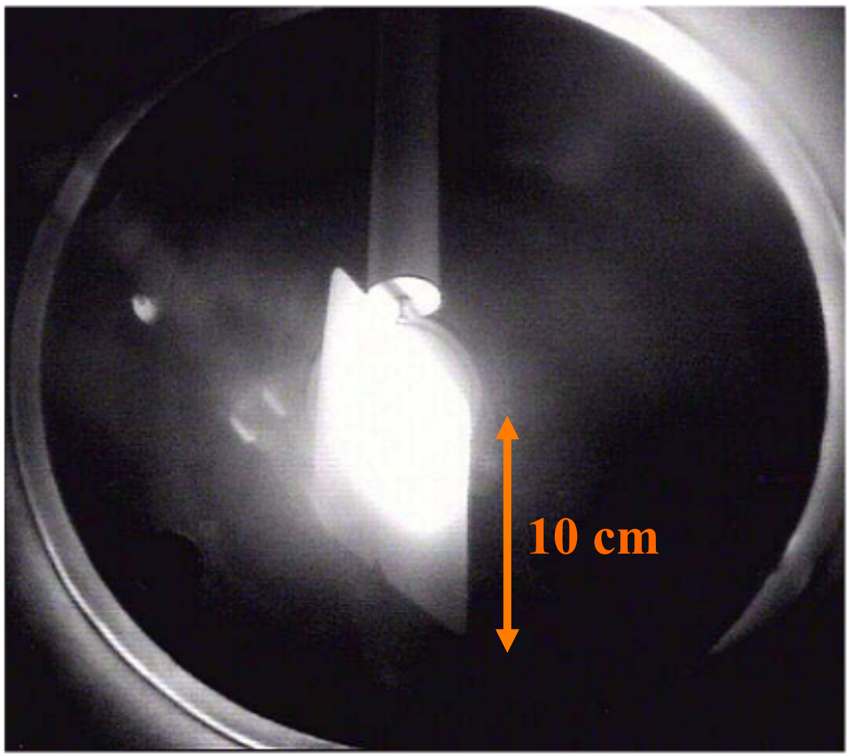
Secondary emission coefficient

$\gamma = \gamma(E_{He+})$

taken from literature

A large beam size was observed during the witness plate measurements

- From pictures of the plate during and after ion irradiation, it appears like the beam size is quite large (diameter ~ 10 cm), much larger than plasma electrode aperture size (< 1 cm).



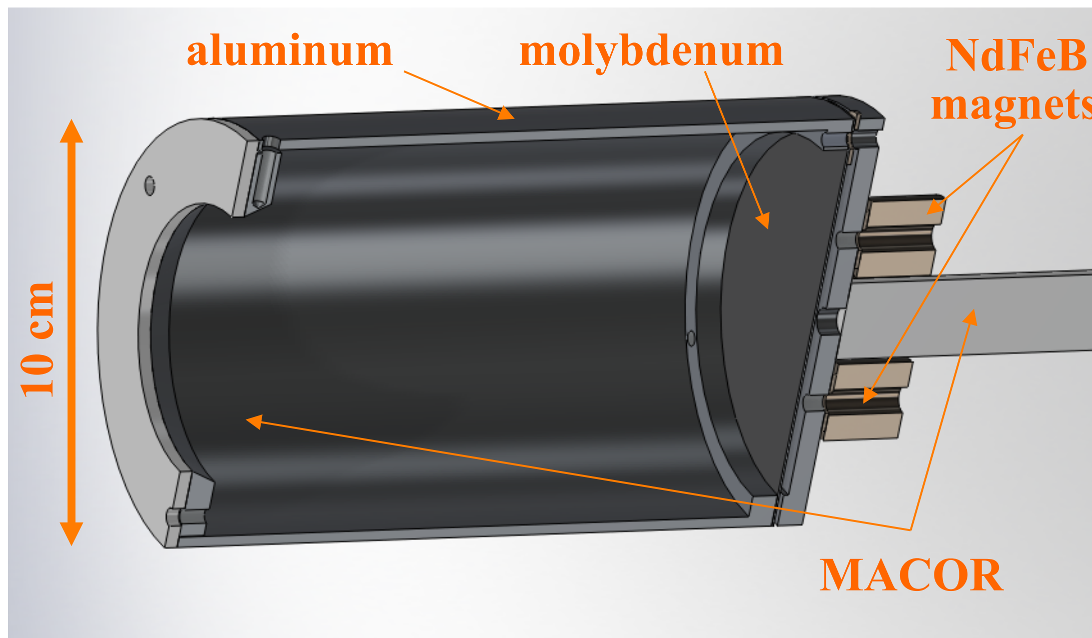
G. Piefer, Ph.D. thesis (2006).

The assumed secondary emission coefficient γ, and thus the ion current, are susceptible to error

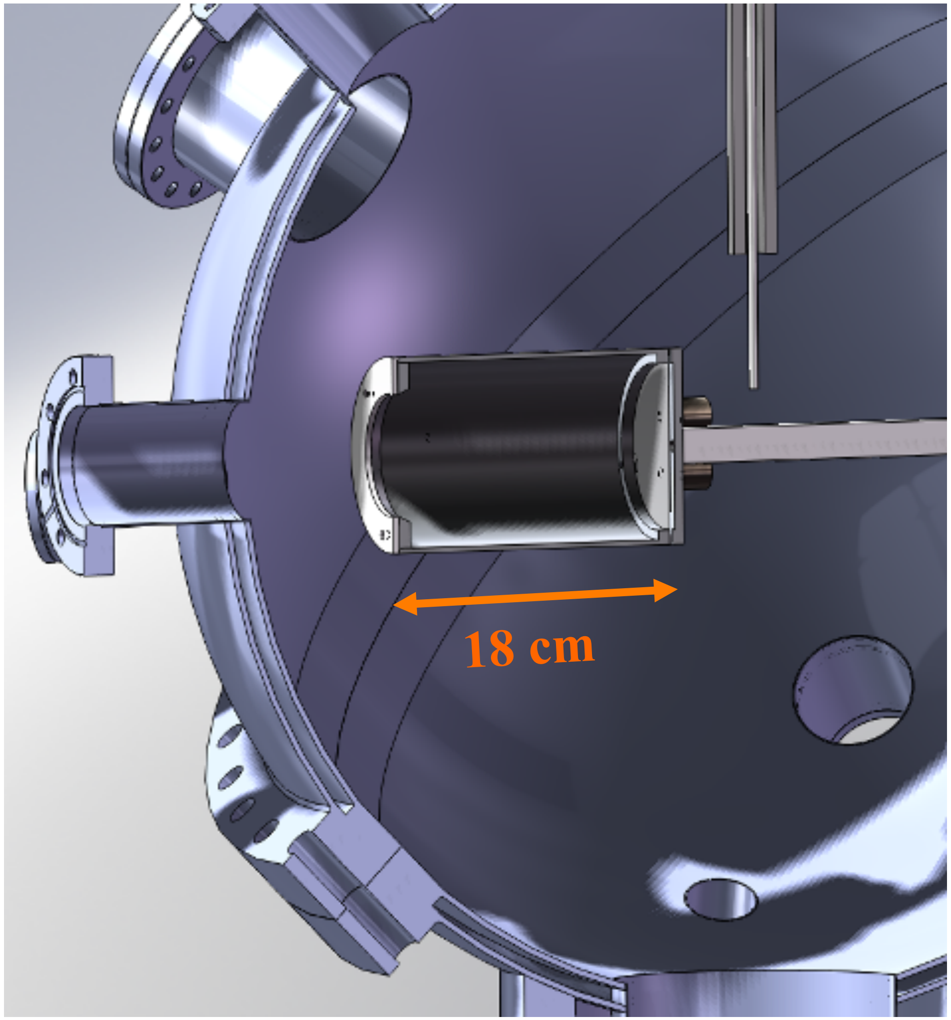
- The applicability of the secondary emission coefficient is problematic, so the witness plate measurements are not reliable.

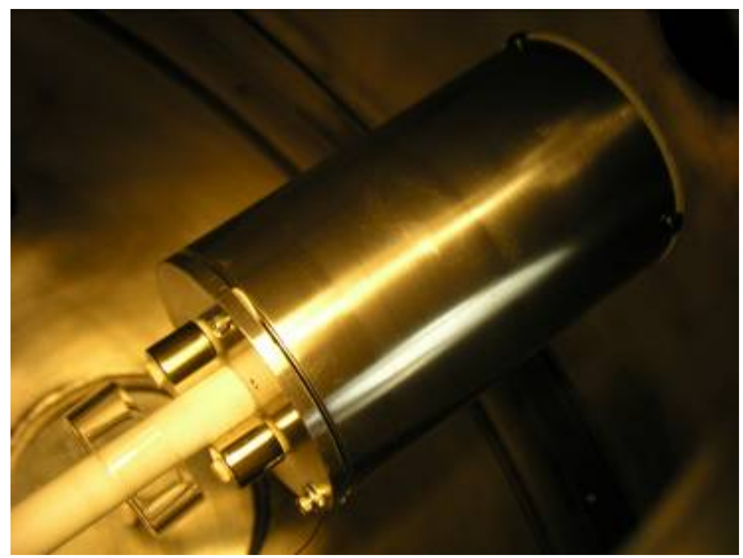
- A Faraday cup suppresses secondary electrons, which can give a more direct measurement of the ion current.

- Faraday cup design:
  - Beam size makes a suppression electrode impractical.
  - Magnets used to provide transverse magnetic field (up to 500 gauss).



A Faraday cup has been constructed and will be used to measure the extracted ion current in HELIOS





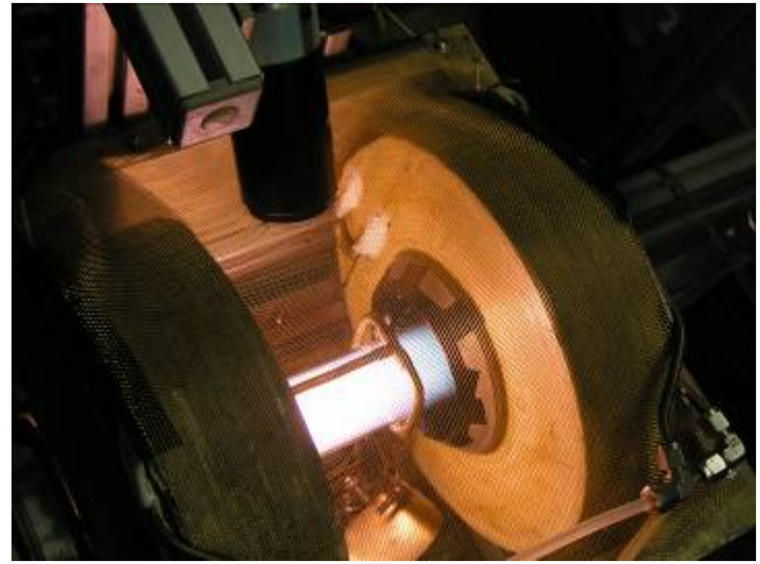
Extracted ion current measured by witness plate method has been much less than expected

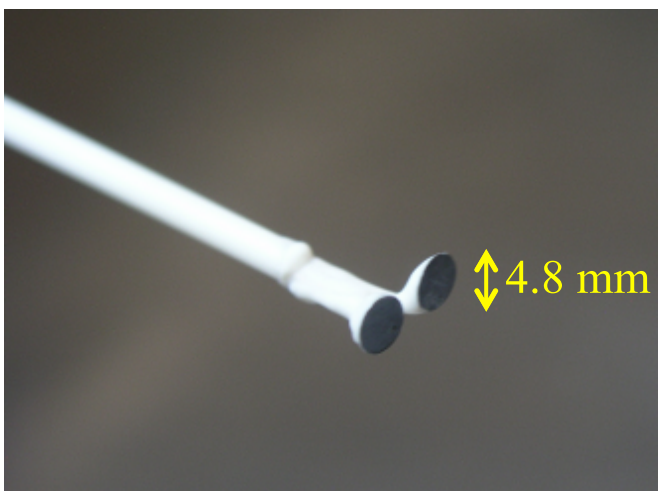
- Ion source theory predicts that ion current extracted should be the Bohm current $I_B \sim n_0 T_e^{1/2} A$

	Maximum ion current, witness plate method		Maximum Bohm current, from measured n_0 and T_e	
	Piefer [2006]	Zenobia [2010]	Alderson [2008] Spectroscopy	Becerra [2011] Double probe
H_2	-	-	100 mA	45 mA
D_2	-	30 mA	-	40 mA
^4He	12 mA	20 mA	-	85 mA

Characterization of the helicon plasma parameters: spectroscopy and double probe

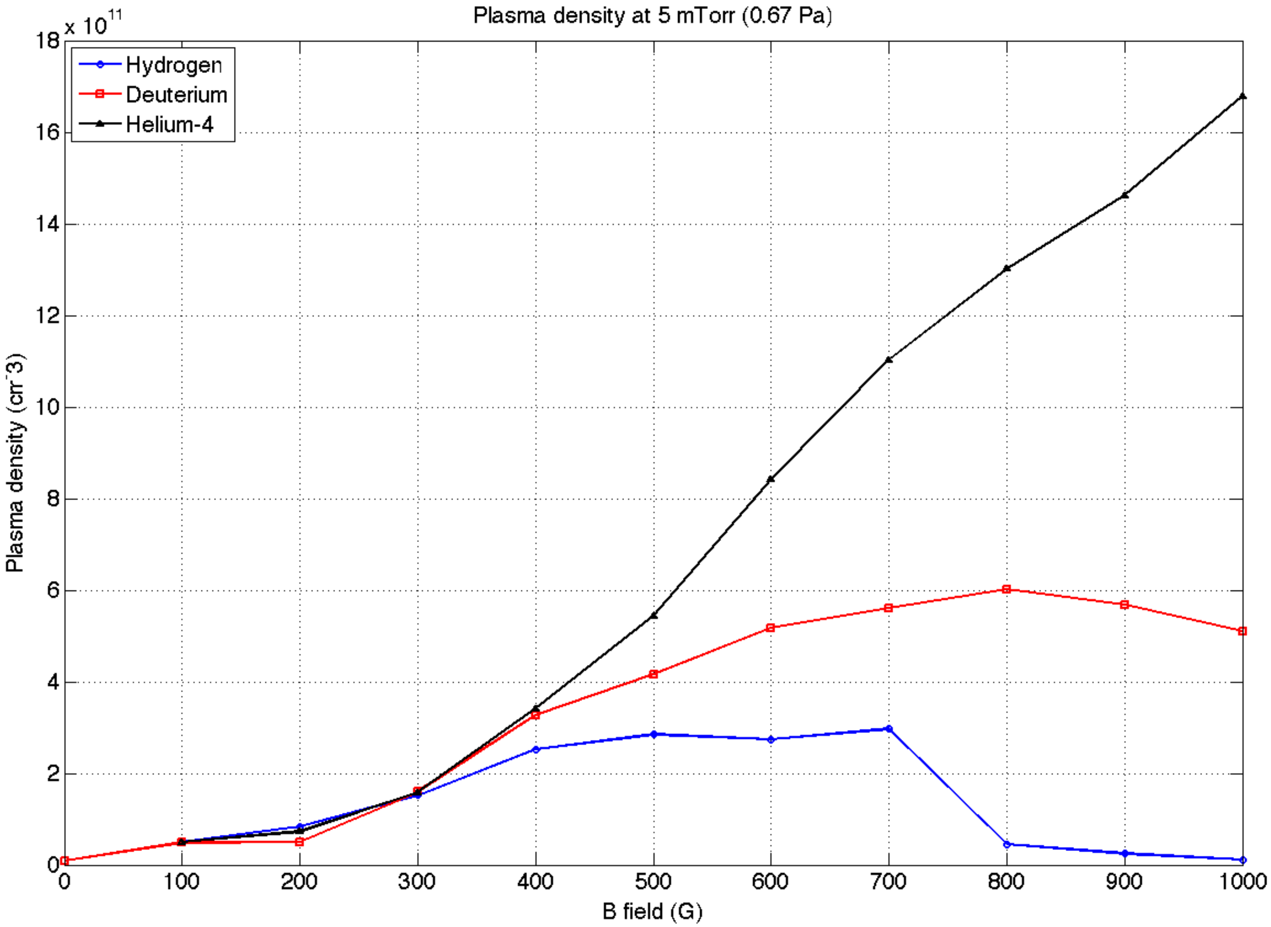
- Spectroscopic method: line intensity ratios measured using a spectrometer and mapped to plasma parameters using a collisional-radiative model (hydrogen only)
- Alderson operated at higher pressure, looked at the antenna region. Also, the quartz discharge chamber and the antenna were different, but similar in dimensions.





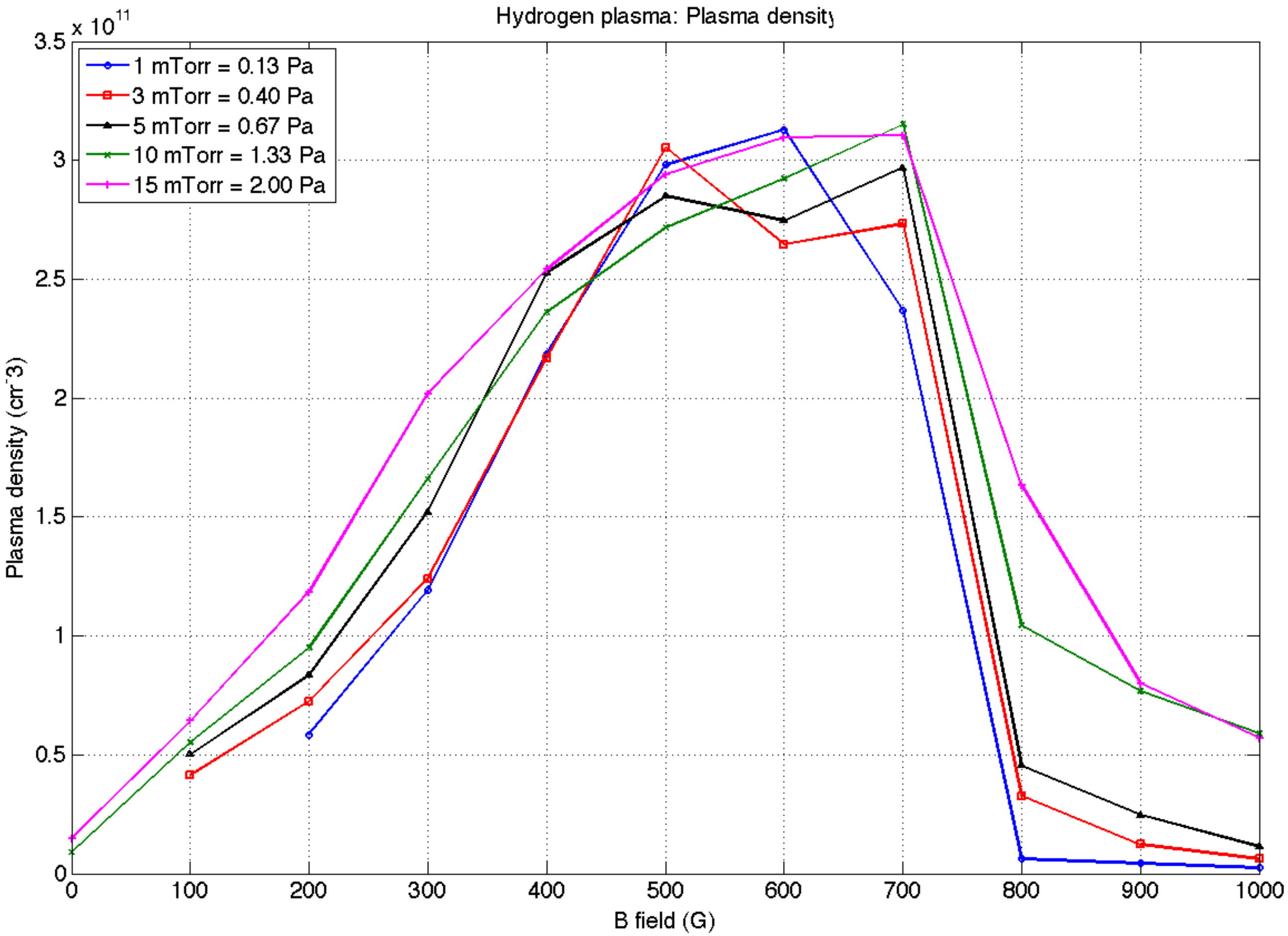
- Double probe: floats with the rf variation, intrinsically compensating for helicon plasma oscillations. Much lower heat load than single probe.
- Ion saturation current is directly proportional to Bohm current at aperture.
- Densities measured were lower but comparable to Alderson results, electron temperatures much higher (10-20 eV instead of 4-6 eV).

Peaking plasma density for H_2 and D_2 may suggest issues with double probe data at high fields



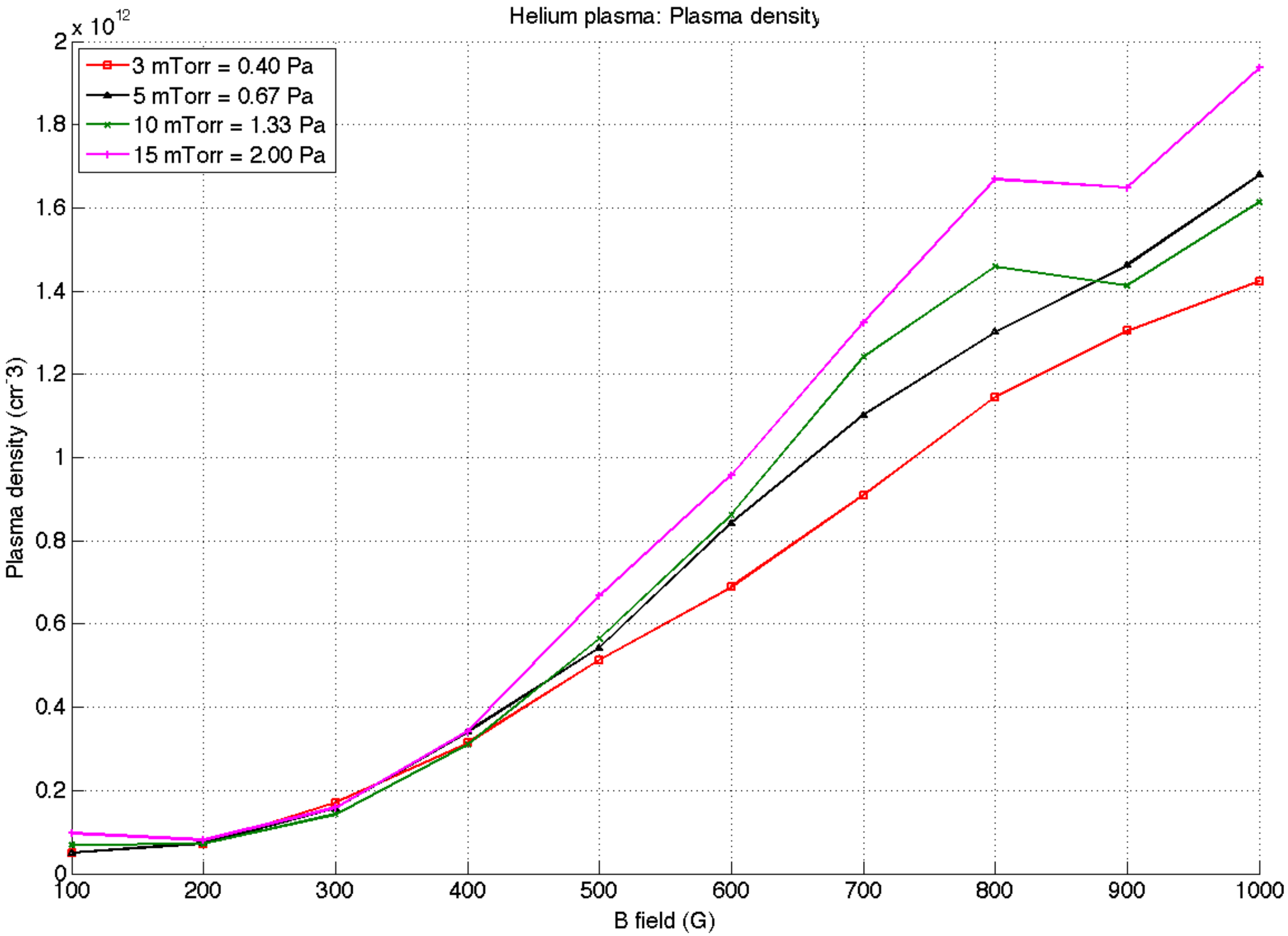
- Plasma density was expected to increase monotonically with magnetic field
- Density measurements peak for H_2 and D_2
- Would ^{4}He density peak at some B > 1000 G?
- Peaking may hint at problem with double probe data at high B-fields: ion collection by probe?
- Ion mass seems critical: higher n_0 due to slower diffusion to walls, and different gyroradii

Hydrogen plasma density is essentially independent of neutral pressure at high densities



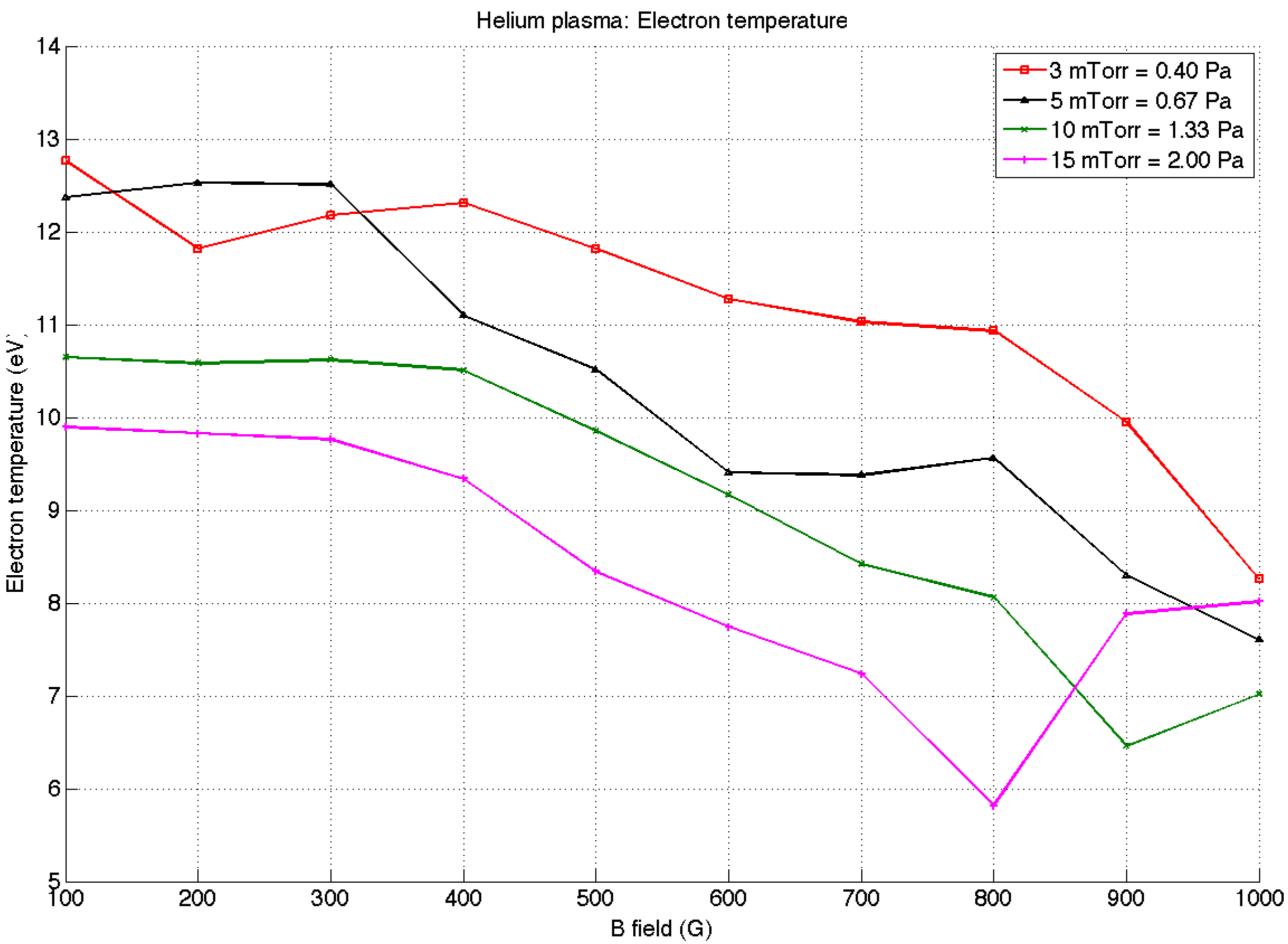
- Plasma density shows a very weak dependence on neutral gas pressure
- Densities are very low for helicon mode, typical of inductively coupled discharges
- Peaking behavior is very similar to 2011 double probe results
- Maximum ion saturation currents correspond to a Bohm current of ~65 mA at aperture

Helium densities show stronger dependence on pressure and are closer to typical helicon mode densities



- No peaking for He, so this parameter space should be within the region of validity of double probe method
- Neutral pressure plays a stronger role than with hydrogen, though the effect is still small
- Densities are closer to those typical of helicon mode plasmas, but the expected sudden jump of mode transition is absent
- $I_{B,\max} \sim 160$ mA

Electron temperature seems consistent with Alderson's spectroscopic measurements at higher pressure



- As expected, higher neutral pressure leads to greater energy loss of electrons due to collision and thus to lower electron temperature

- This is consistent with Alderson's higher pressure runs leading to much lower T_e measurements than previous double probe data

Extracted ion current measured by witness plate method has been much less than expected

• Ion source theory predicts that ion current extracted should be the Bohm current $I_B \sim n_0 T_e^{1/2} A$

	Maximum ion current, witness plate method		**Maximum Bohm current, from measured n_0 and T_e**		
	Piefer [2006]	**Zenobia [2010]**	**Alderson [2008] Spectroscopy**	**Becerra, Double probe**	
				2011	**2012**
H_2	-	-	100 mA	45 mA	65 mA
D_2	-	30 mA	-	40 mA	70 mA
^4He	12 mA	20 mA	-	85 mA	160 mA

• The main reason for the discrepancy between 2011 and 2012 results is likely better tuning to impedance matching condition.

Hypotheses for low extracted ion current as measured by witness plate method

1. The witness plate method may not give an accurate ion current measurement

Technique is not reliable, but effect would not fully explain the discrepancy ✘

2. Ions are deflected and hit the inner surface of the port due to the expanding magnetic field near aperture

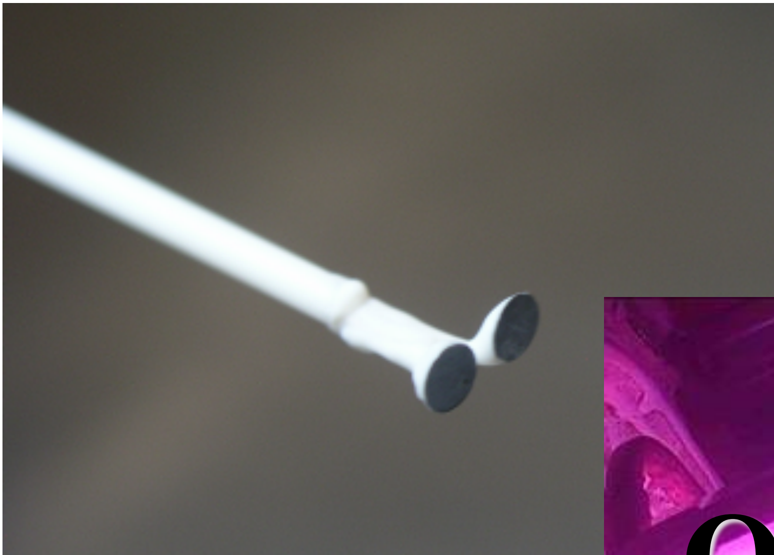
SIMION simulations show very weak effect of field on beam divergence ✘

3. Ions are deflected and hit the inner surface of the port due to space-charge beam repulsion ?

4. The Bohm current may not be the correct theoretical expression to use for extractable ion current (more complicated than simple ion sheath) ?

Summary and Tentative Conclusions

- The helicon source parameters suggest that more current should be extractable than has been observed, according to both double probe and spectroscopic measurements.
- A Faraday cup has been built and will be used to get a more reliable measurement of ion current.
- Double probe measurements may only be reliable up to a certain ion-mass-dependent magnetic field threshold.
- The most likely hypotheses to explain the discrepancy between measured and expected ion currents are:
    - Ions are lost to the walls before getting to the center of the chamber due to space-charge broadening of the beam
    - The usual ion source expression may not be applicable to this system due to complications in potential near the aperture.
- Helicon source possibly running in inductive rather than helicon mode



Questions?

Backup Slides

Extracted ion current measured by witness plate method has been much less than expected

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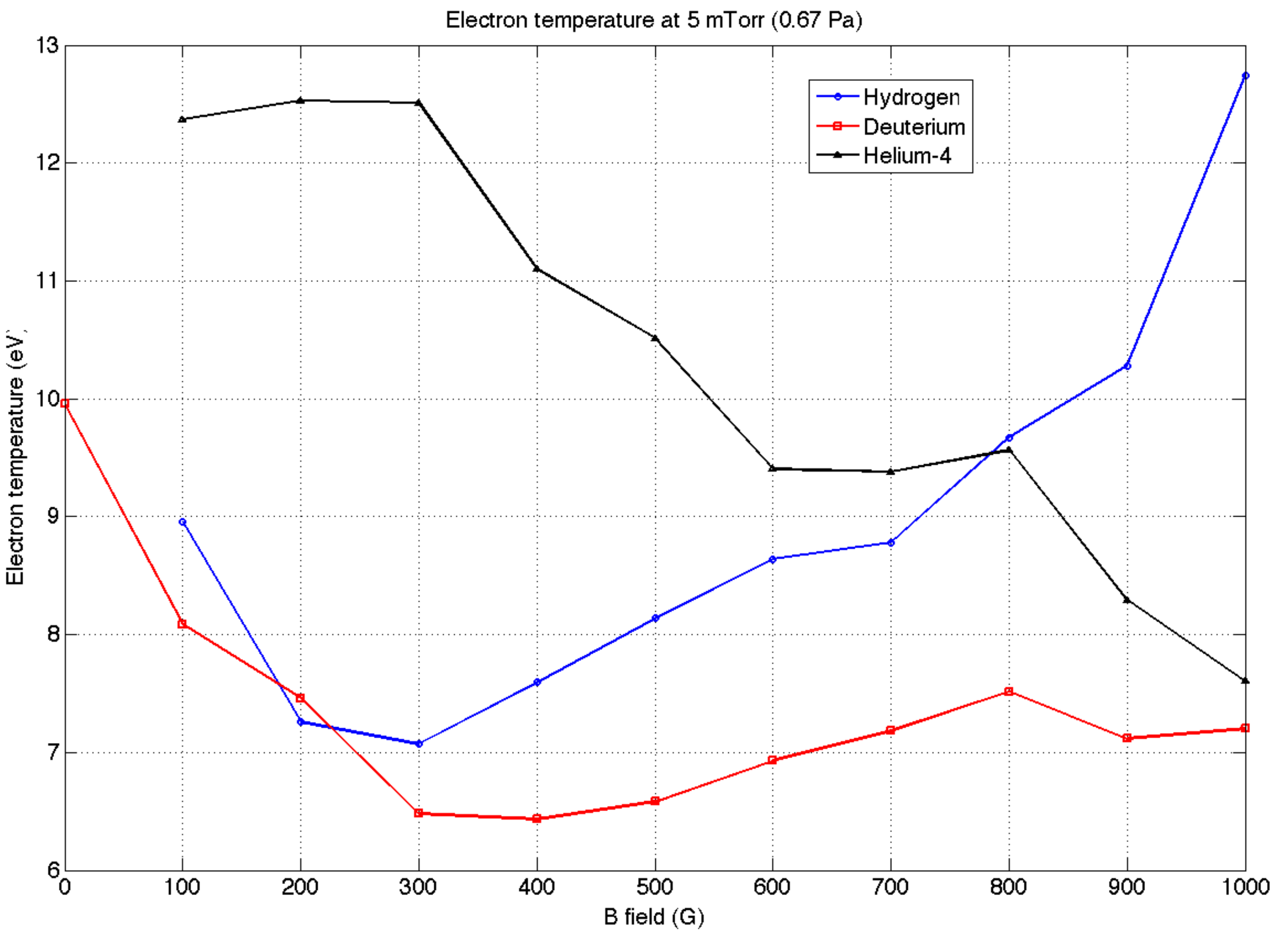
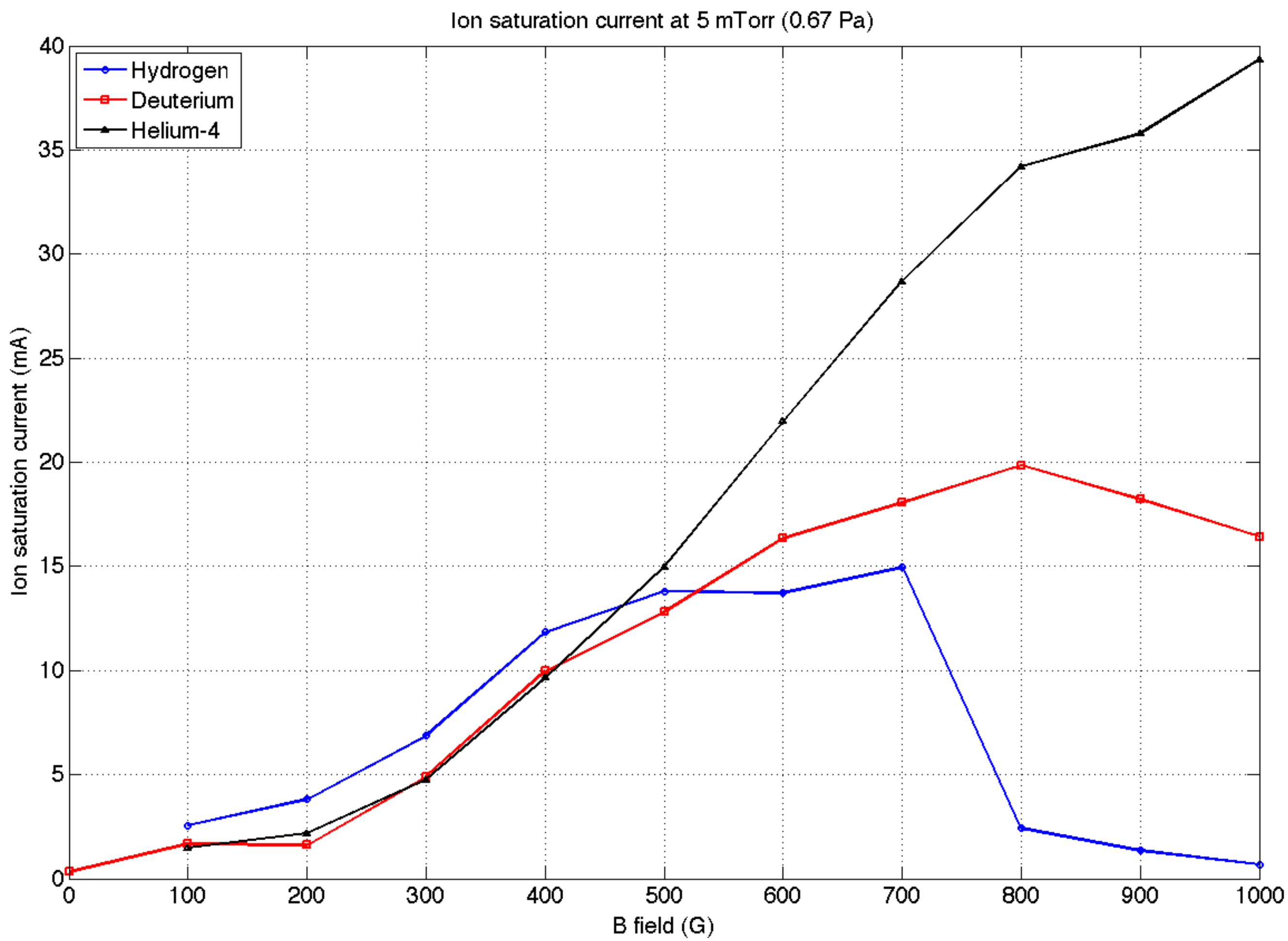
	Maximum ion current, witness plate method		**Maximum Bohm current, from measured n_0 and T_e**	
	Piefer [2006]	**Zenobia [2010]**	**Alderson [2008] Spectroscopy**	**Becerra [2011] Double probe**
H_2	-	-	100 mA	45 mA
D_2	-	30 mA	-	40 mA
^4He	12 mA	20 mA	-	85 mA
	Up to 2100 W Up to 1600 G	Up to 1200 W Up to 1100 G	Up to 1500 W Up to 1200 G	Up to 1000 W Up to 1000 G

Electron temperature measurements also raise concerns about data at higher fields

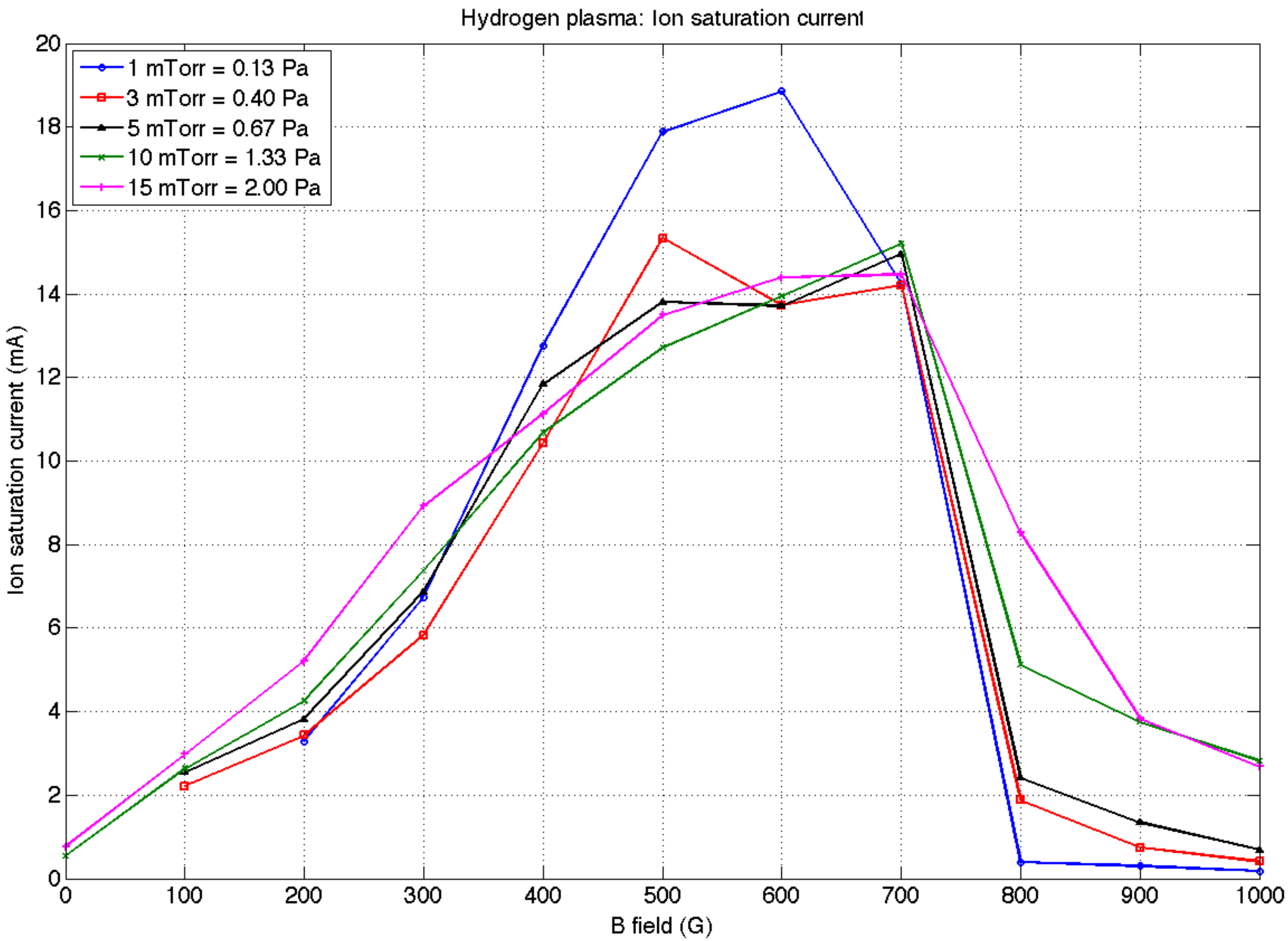


- Electron temperature also shows similar variation, with minima for hydrogen and deuterium at low magnetic fields
- Minimum in helium possibly beyond the explored field range
- Similar dependence of magnetic field at minimum on ion mass? Extrema here show up at lower fields than for plasma densities

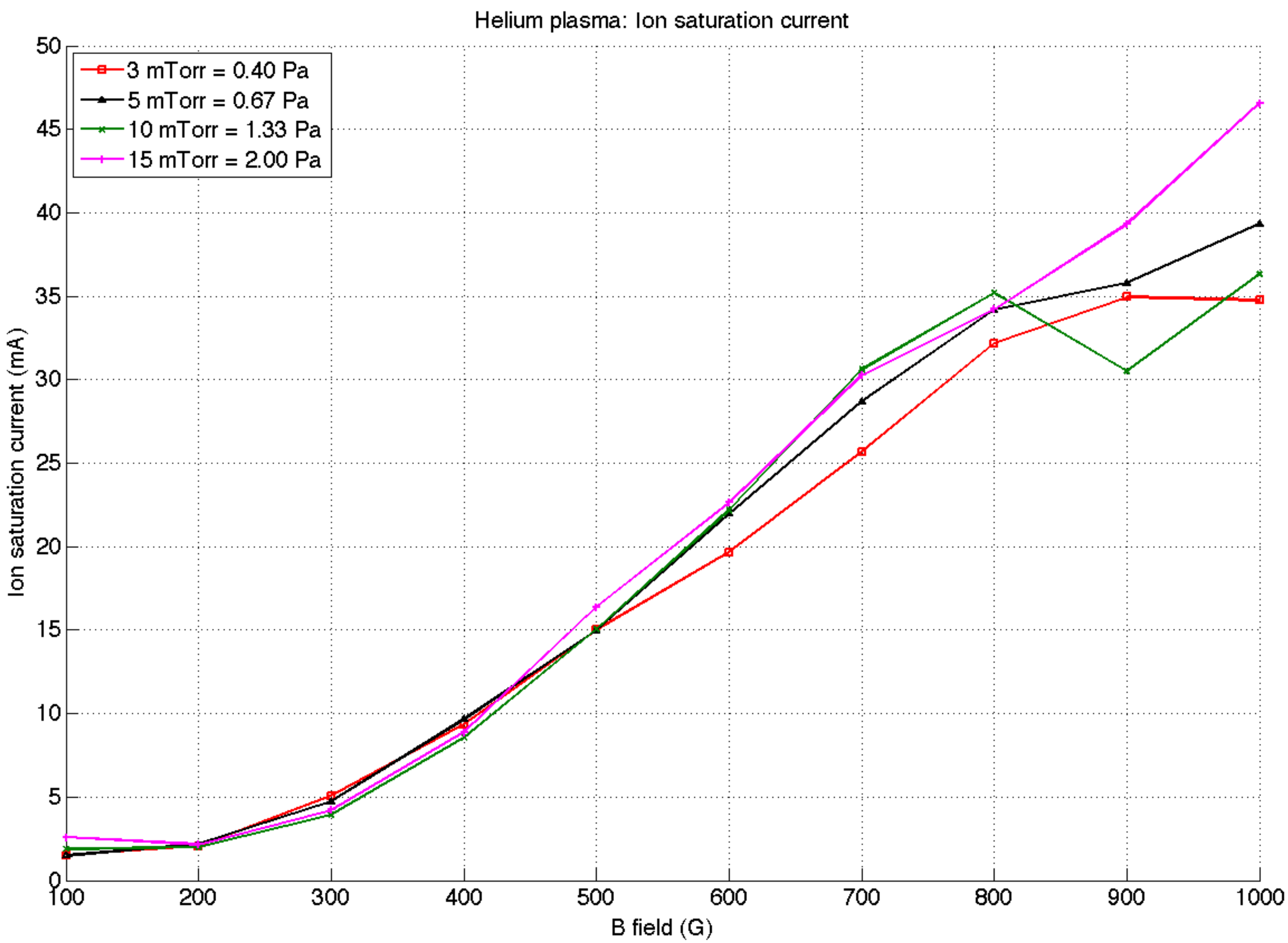
Ion saturation for different gases at 5 mTorr (0.67 Pa)



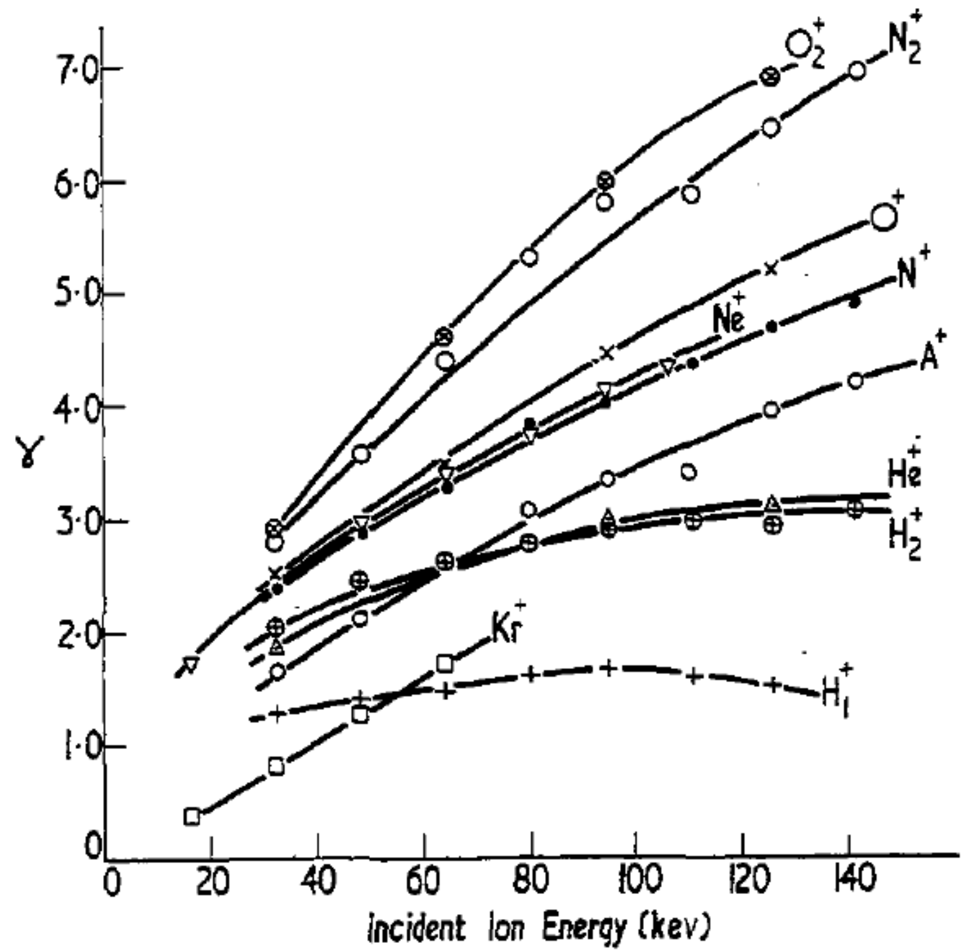
Ion saturation current, hydrogen



Ion saturation current, helium



Ion current measurement: Witness plate method



L.N. Large, Proc. Phys. Soc. 81, 1101 (1963)

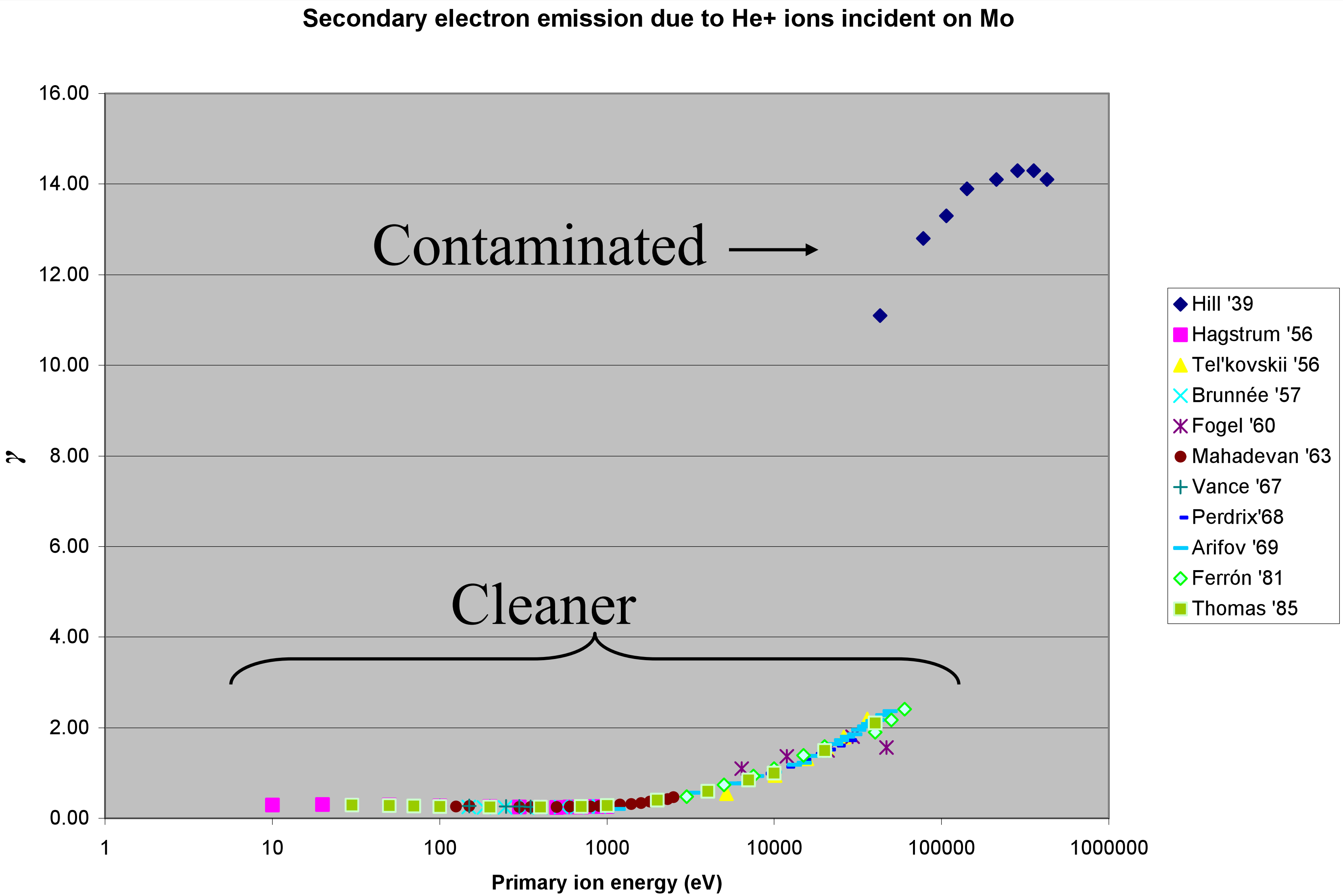
The witness plate method uses questionable assumptions, making it unreliable

The assumed secondary emission coefficient (γ) and therefore the ion current are susceptible to error due to:

• Contamination	**OVER**
• Surface damage during irradiation	**UNDER**
• Ion energy spread	**OVER**
• Incidence angle spread	**UNDER**
• Plate manufacturing	**?**
• Temperature dependence	**?**

Even though this cannot fully explain the low extracted current, and the overall effect of these may be small, this is not a truly reliable measurement.

Effect of contamination on secondary emission coefficient



Simulations: Beam size still not fully explained

- Using SIMION to simulate ion trajectories, including the presence of a magnetic field and initial forward and transverse velocities

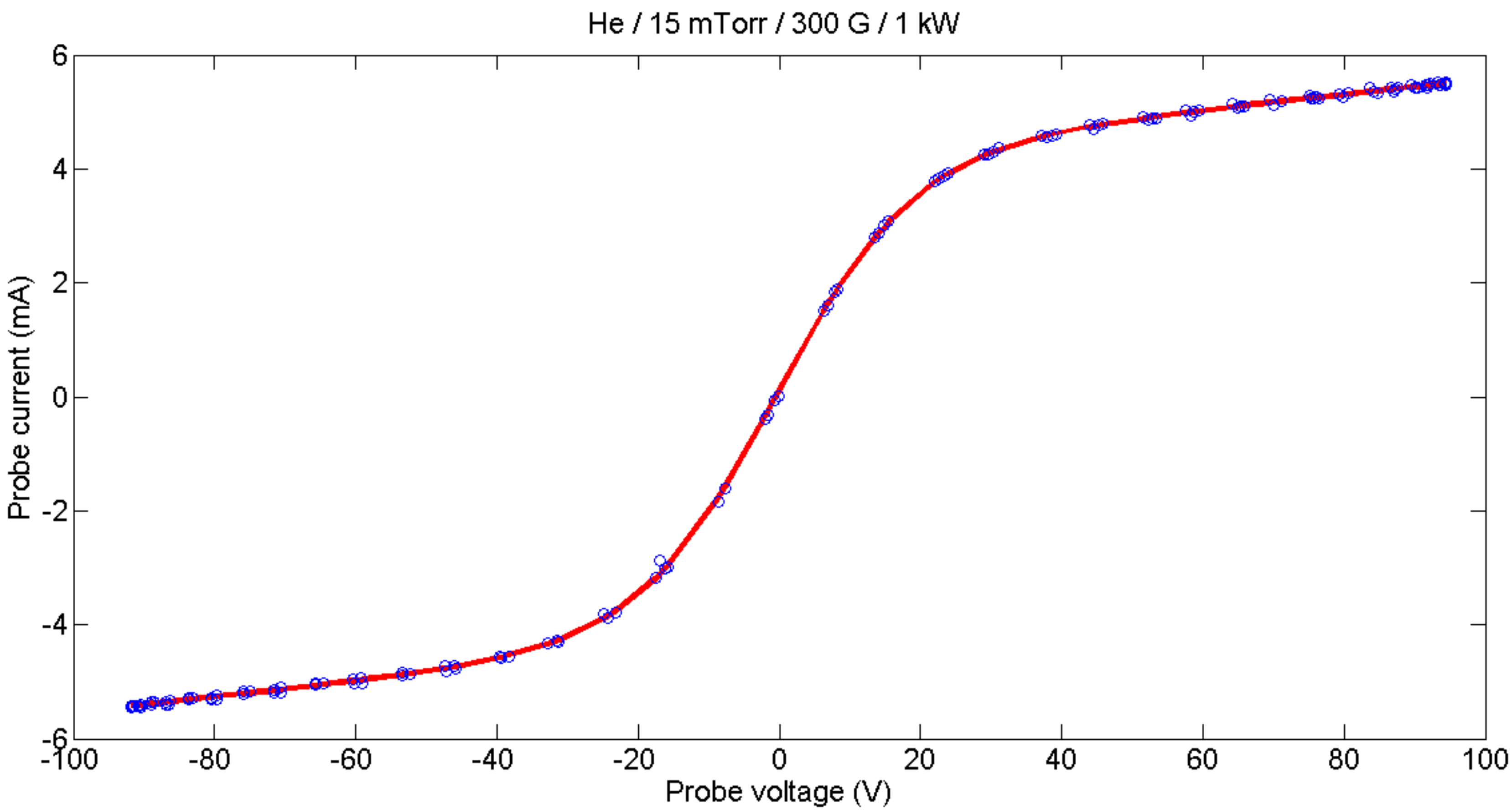
-30 kV, 0 kG, 0 eV

-30 kV, 2 kG, 20 eV, 6º cone in velocity space

Double probe basics

$$I = I_i^{sat}(-1 + \exp[e(V_2 - V_f)/T_e]) = -\,I_i^{sat}(-1 + \exp[e(V_1 - V_f)/T_e])$$

$$\rightarrow I = I_i^{sat}\tanh(eV_{probe}/2T_e), \text{ where } V_{probe} = V_2 - V_1$$



Length scales

Discharge characteristic dimension, $L \sim 5$ cm

Probe diameter, $d_p = 0.48$ cm

Ion Larmor radius, $r_{Li} \sim 7\times10^{-2}$ cm (H^+), 0.1 cm (He^+)

(for $T_i = 0.5$ eV, B = 1 kG)

Ion Debye length, $\lambda_{\mathrm{Di}} \sim 2 \times10^{-3}$ cm (for $T_i = 0.5$ eV, $n_0 = 10^{11}$ cm^{-3})

Electron Larmor radius, $r_{Le} \sim 5\times10^{-3}$ cm (for $T_e = 5$ eV, B = 1 kG)

Electron Debye length, $\lambda_{\mathrm{De}} \sim 5\times10^{-3}$ cm (for $T_e = 5$ eV, $n_0 = 10^{11}$ cm^{-3})

$$\lambda_{Di} << r_{Li} < d_p << L$$

$$\lambda_{De} \sim r_{Le} << d_p << L$$