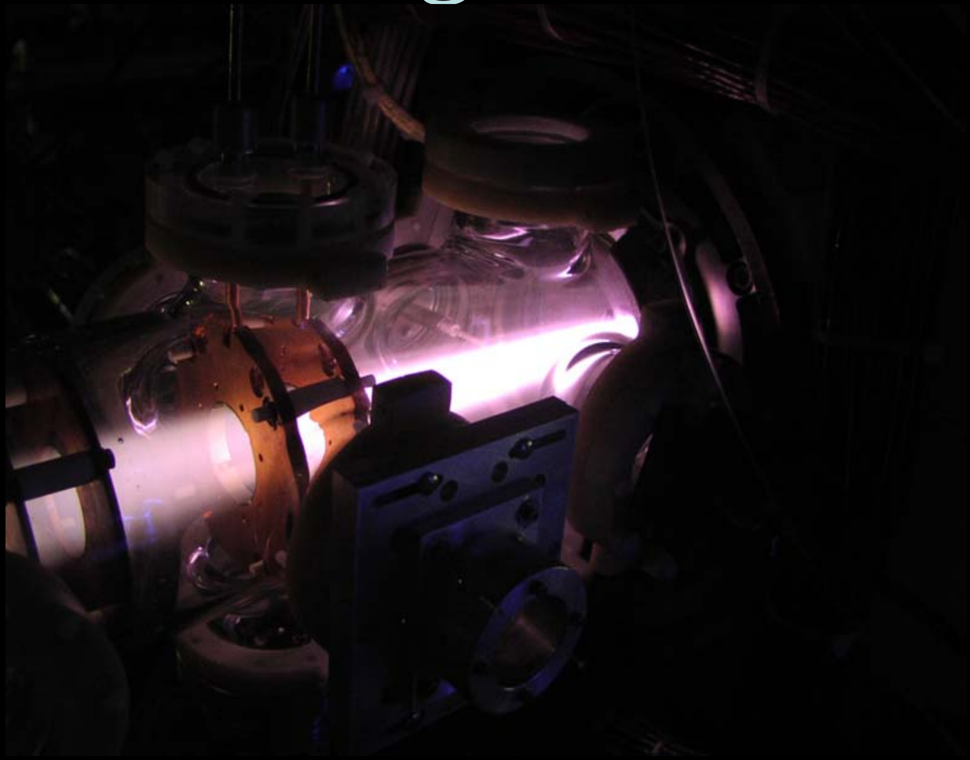
On collisionless ion and electron populations in the Magnetic Nozzle Experiment



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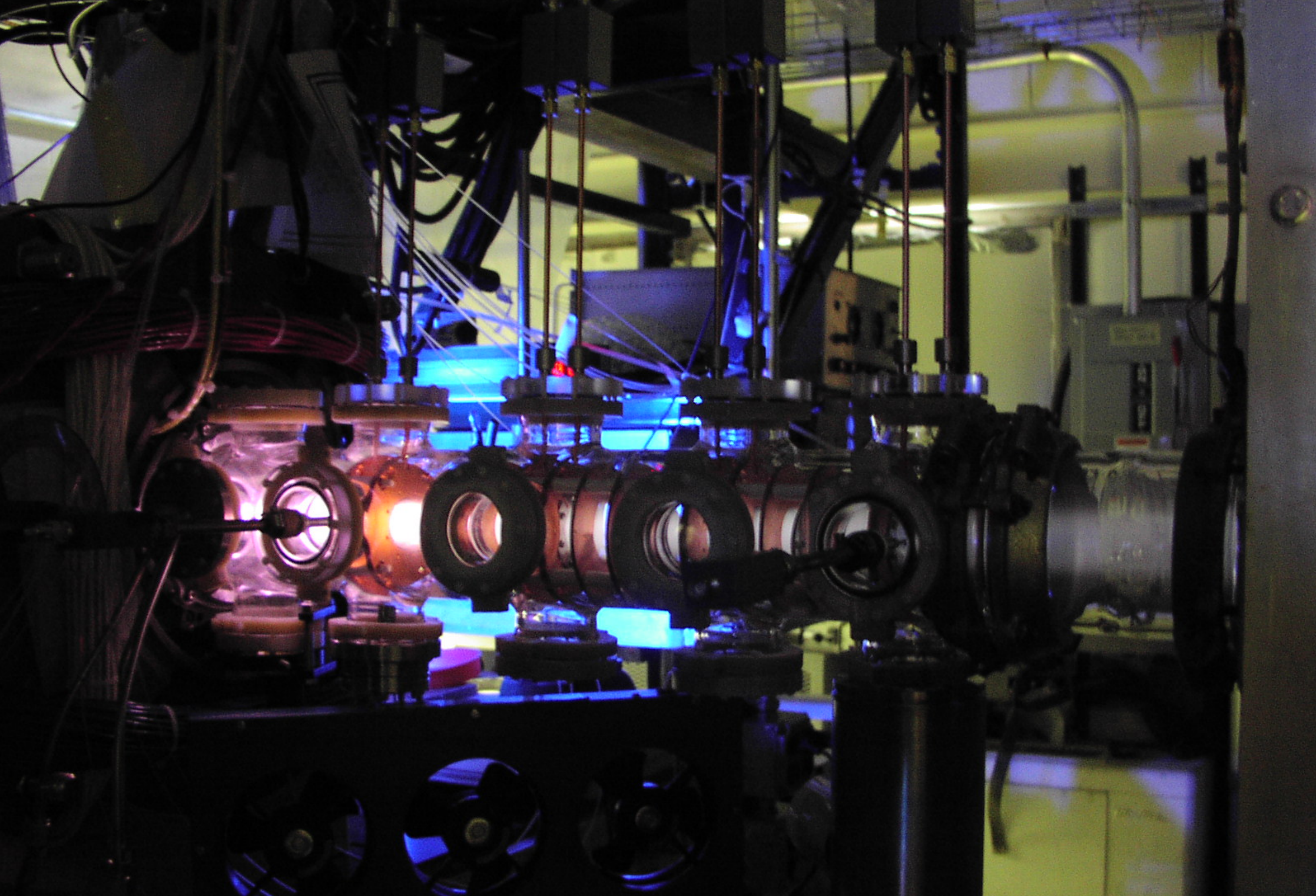


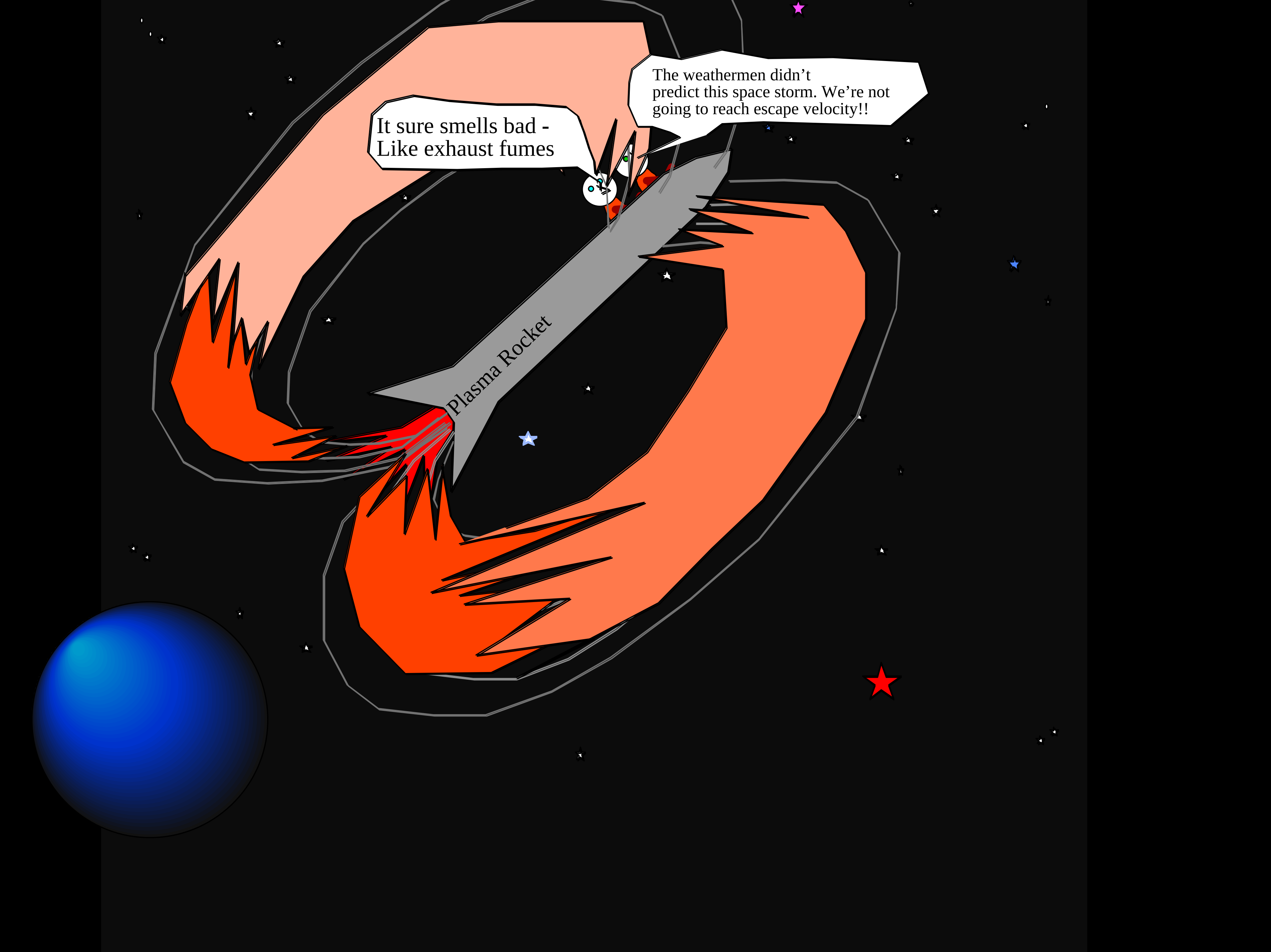
Acknowledgements to: B. Berlinger, V. Corso, R. Feder, F. Levinton, A. Keesee.
U.S. Department of Energy Contract No. DE-AC02-76-CHO-3073.

Organization

- Motivation
- Experimental techniques
- Review of measurements and results
  - LIF
  - Electric (probes and structures)
  - Emission spectroscopy
- Unresolved questions and plans for future research

Magnetic Nozzle Experiment (MNX)

- Explore physics of warm plasmas expanding along magnetic fields
  - Plasma acceleration and cooling
  - Plasma detachment
  - LIF and optical diagnostics
- Develop applications related to the physics
  - Advanced space-propulsion method (VASIMR)
  - Materials processing
  - Fusion


It sure smells bad - Like exhaust fumes
The weathermen didn’t predict this space storm. We’re not going to reach escape velocity!!
Plasma Rocket

Ways to promote ion detachment

1. Super-Alfvenic flows (Breizman, Gale'ev, Hooper)
2. Recombination (Cohen)
3. Asymmetry (Eubank & Schmidt)
4. Non-adiabaticity (Chang-Diaz & Ilin)
5. Hall thruster geometry & techniques
6. Charge-exchange neutralization

Methods to increase specific impulse

$I_{sp} \equiv \mathbf{v}/g$

Ambipolar double layer

- Increase T_e by
  - Lowering pressure
  - Adding electron beam

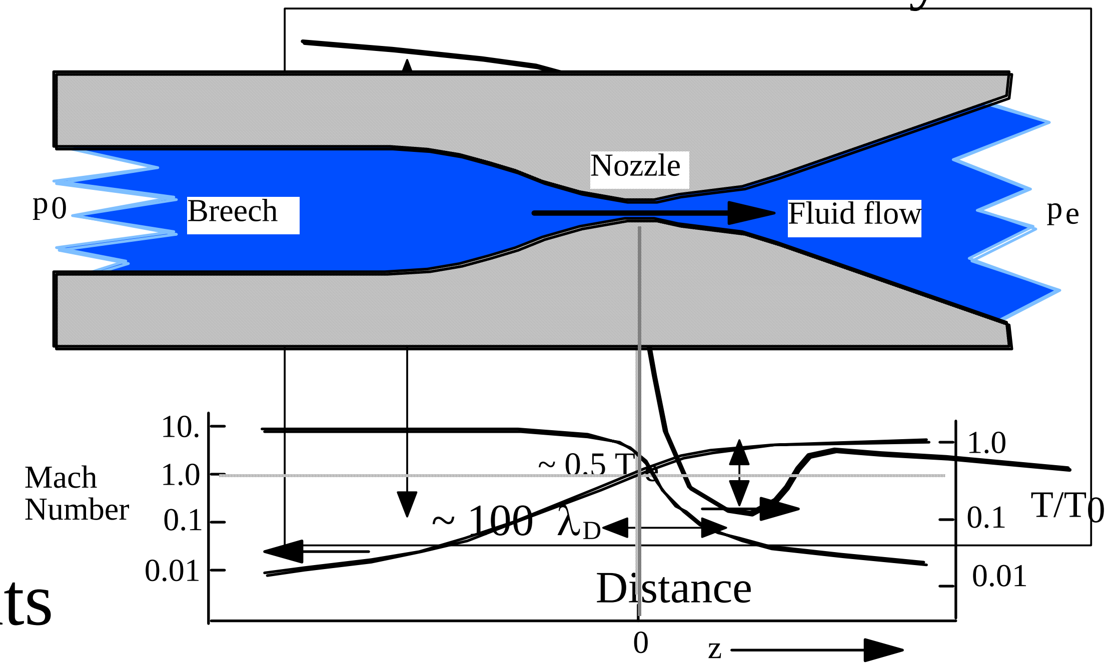
ICRF heating

Laval nozzle

ExB

Use low-AMU propellants

Ion-acoustic double layer



Target: I_{sp} = 3000 s --> E = 180 eV for Ar

Earlier (related) work on ion acceleration

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- M.E. Koepke, M. Zintl, C. Teodorescu, et al., Phys. Plasmas **9**, 3225 (2002).

Double layers, some with 2-T_e distributions

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- L. R. Block, “A double layer review,” Astrophysics and Space Science **55**, 59 (1978).
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- R. Schrittwieser, I. Axnas, T. Carpenter, and S. Torven, “Observation of double layers in a convergent magnetic field,” IEEE Trans. on Plasma Science **20**, 607 (1992).
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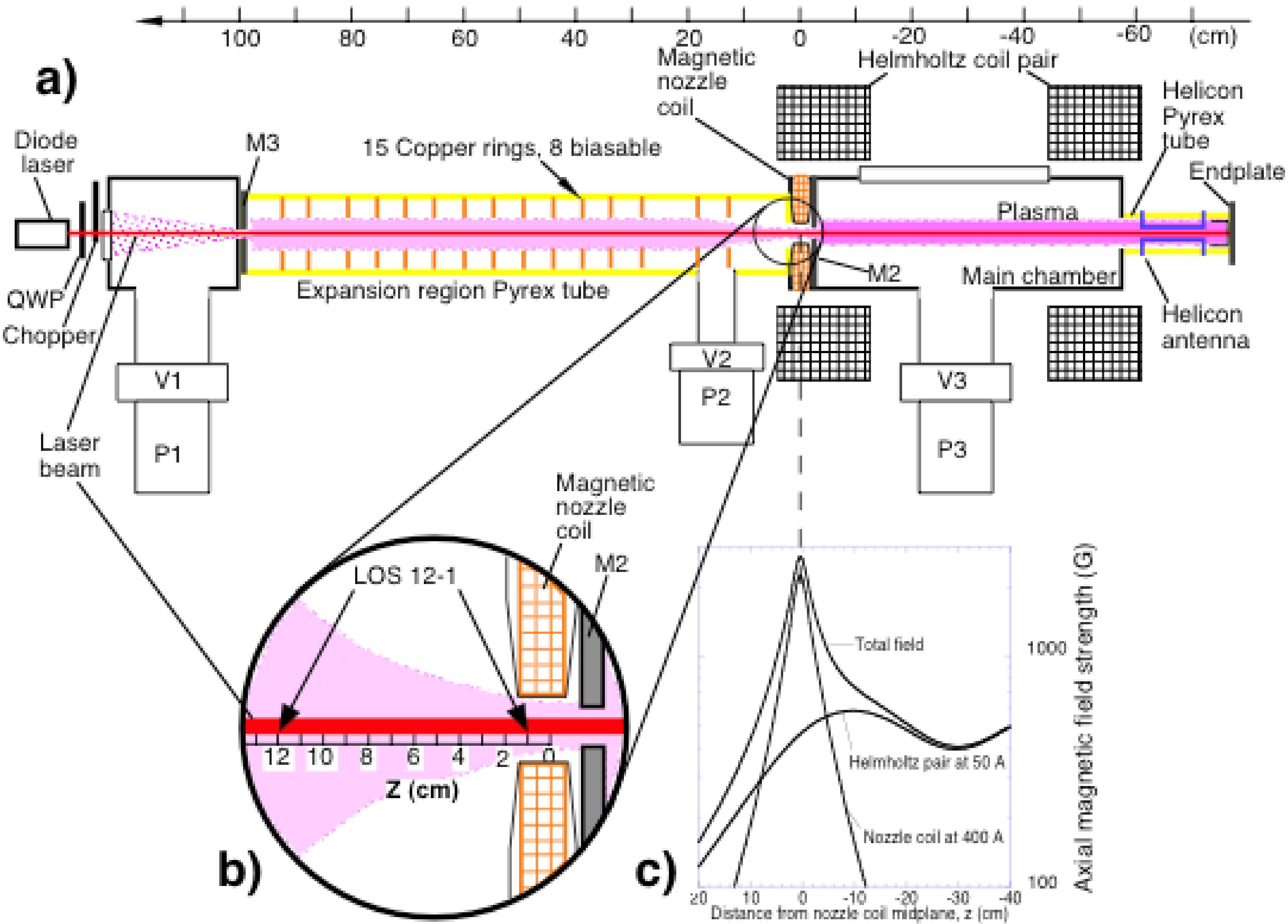
- N. Plihon, C. S. Corr, and P. Chabert, “Double layer formation in the expanding region of an inductively coupled electronegative plasma,” Applied Physics Letters **86**, 091501 (2005).
- X. Sun, A. M. Keesee, C. Biloiu, E. E. Scime, A. Meige, C. Charles, and R. W. Boswell. “Observations of Ion-Beam Formation in a Current-Free Double Layer,” Physical Review Letters **95**, 025004 (2005).

Primary questions discussed today

Can MNX get to parameter ranges representative of those necessary to test detachment processes? $E_i > 70$ ev

Are suprathermal electrons responsible for the high ion energies?

Magnetic Nozzle Experiment



MNX device parameters:

$L_p \sim 2$ m; $r_p \sim 4$ cm

$B_H = 0.3\text{-}5.0$ kG; $B_n = 0\text{-}2.5$ kG

RF system: double saddle antenna to 2 kW at 27 MHz

$p_B \sim 3\text{e-}8$ T $p_{operation} \sim 0.4\text{-}25$ mT

MNX plasma parameters @ 1 kG:

$f_{ci} = 4\text{e}4\ s^{-1}$; $f_{ce} = 3\text{e}9\ s^{-1}$; $f_{LH} = 1\text{e}7\ s^{-1}$

$\lambda_D = 5\text{e-}4$ cm; $\delta = c/\omega_{pe} = 0.1$ cm; $\beta = 0.01$

${}_M\lambda_{ee} = 2$ cm; ${}_M\lambda_{ii} = 5\text{e-}3$ cm; ${}_M\nu_{ii} = 1\text{e}7\ s^{-1}$

${}_{ER}\lambda_{ee} = 200$ cm ; ${}_{ER}\lambda_{ii} = 10$ cm; ${}_{ER}\nu_{ii} = 4\text{e}3\ s^{-1}$

Ions collisional in main chamber but collisionless in expansion region

Diagnostic methods:

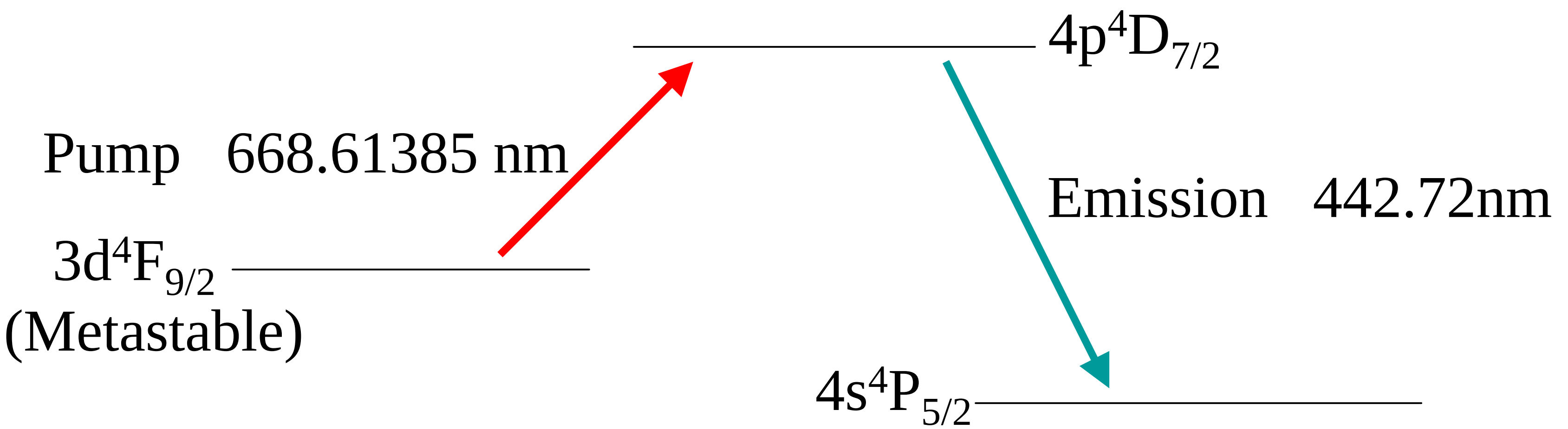
Plasma density and electron temperature by Langmuir probes, microwave interferometry and visible spectroscopy

Ion temperature and flow by LIF

LIF SYSTEM (MNX)

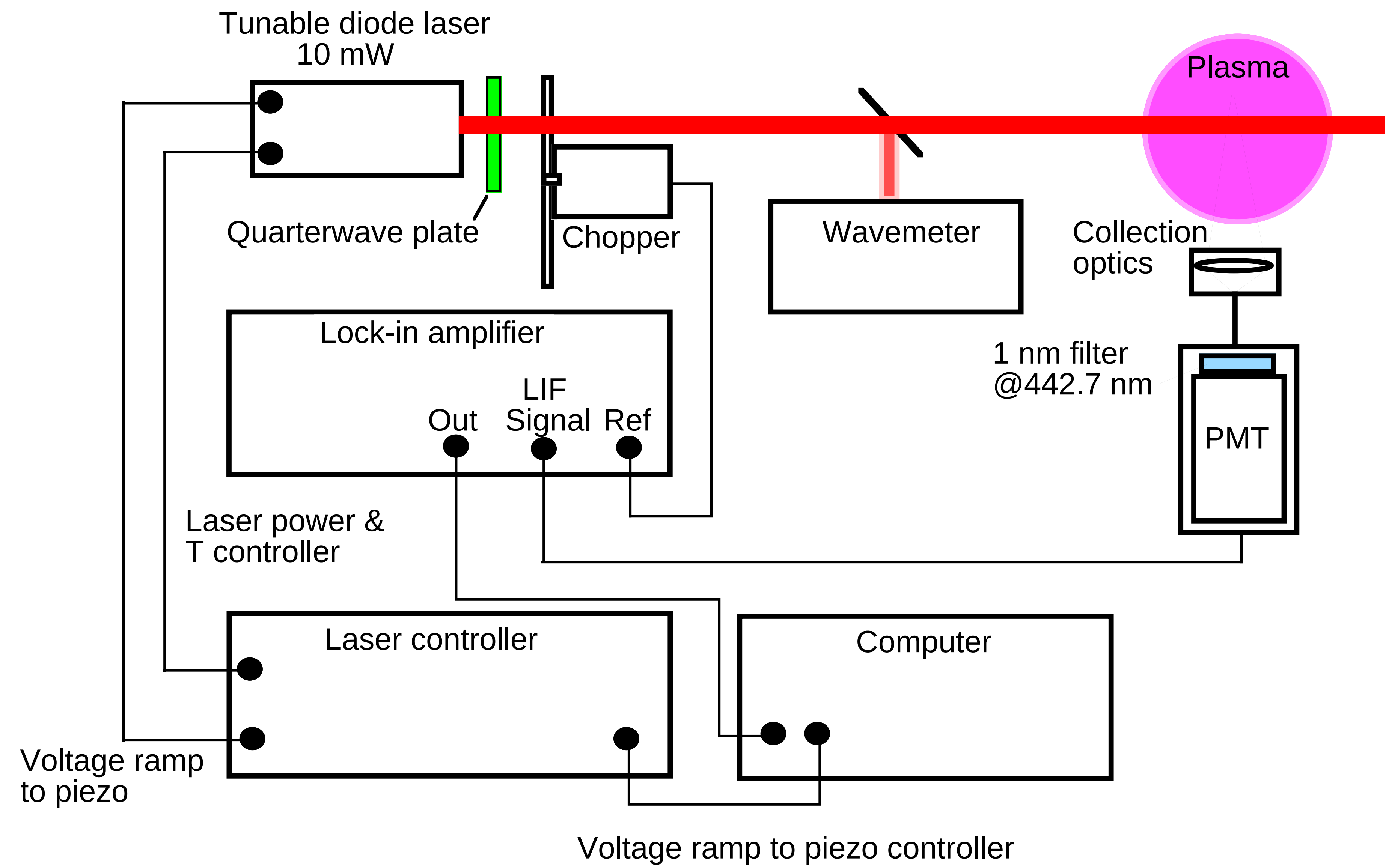
Laser: Diode (Sacher Lasertechnik TEC 100)
LIF volume V ≈ 7 x 10^{-2} cm^3
Laser power output ≈ 12 mwatt
Laser bandwidth ~ 1 MHZ
Laser Sweep ≈ 14 GHz (0.21 Å)

LIF SCHEME FOR Ar II



R. Boivin, E. Scime (WVU)

Laser-induced fluorescence arrangement



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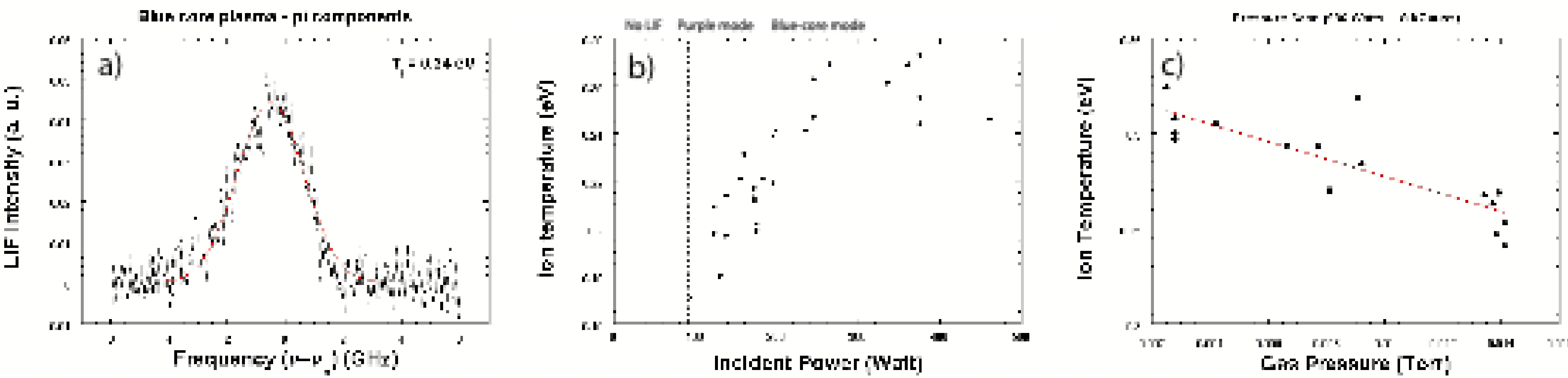
Ion energy distribution in main chamber

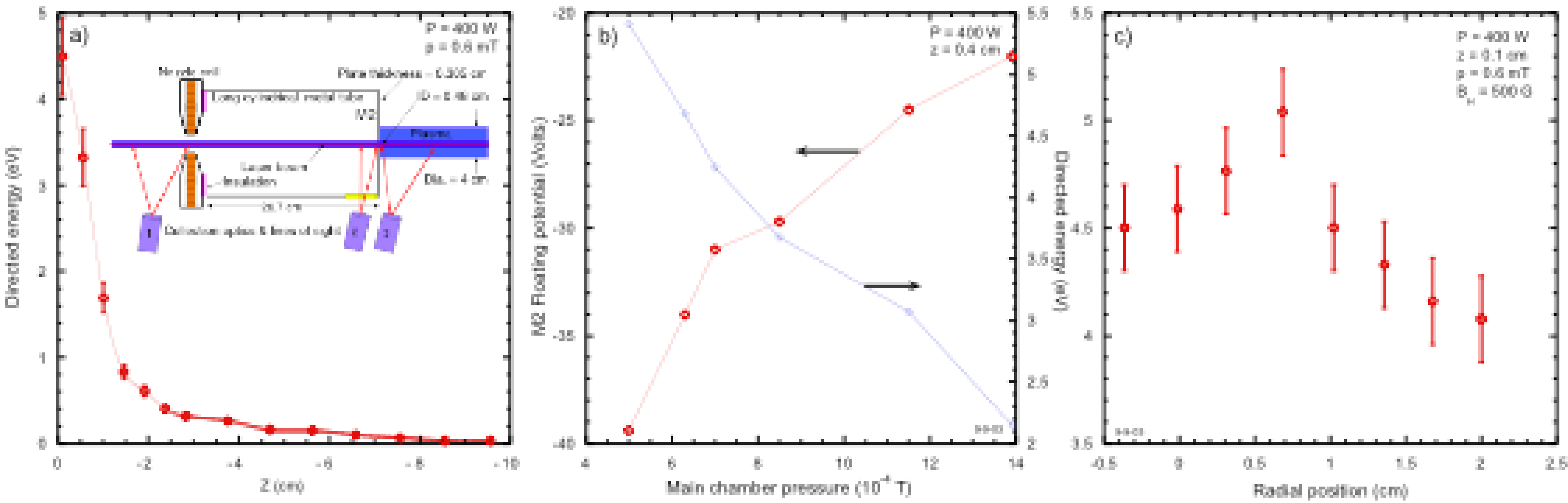
- Cool ions, *ca.* 0.2-0.6 eV, T_i increases as pressure decreases
- LIF brightness decreases with increasing pressure.
- Some spectral asymmetry, but negligible flow seen *except*...



In preparation: Boivin *et al.*

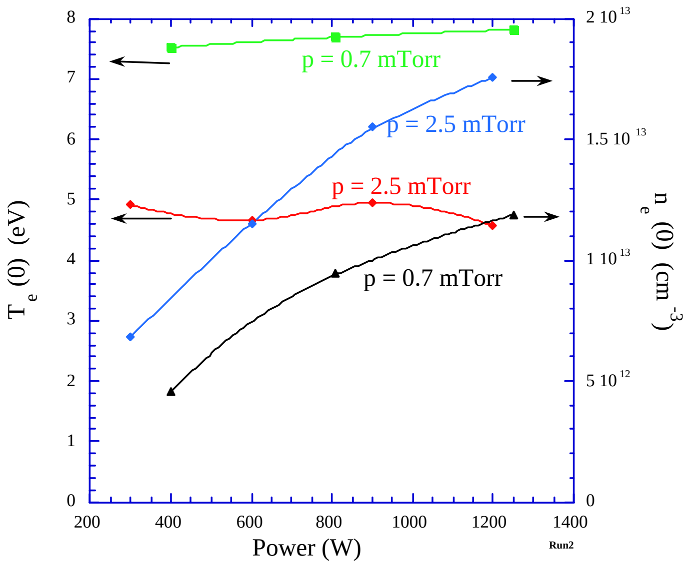
Presheath ion population

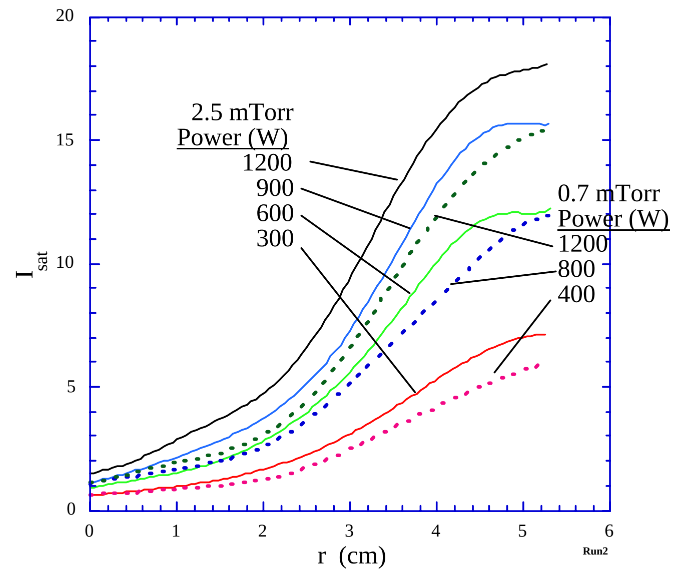
- E_z rises to T_e (not $T_e/2$)
- E_z and M2 V_f decrease with increasing pressure
- E_z weak function of radius
- Length of acceleration region ~ λ_{ii}, λ_{in}



Submitted to Phys. Plasmas, Sun *et al.*

Main chamber plasma parameters





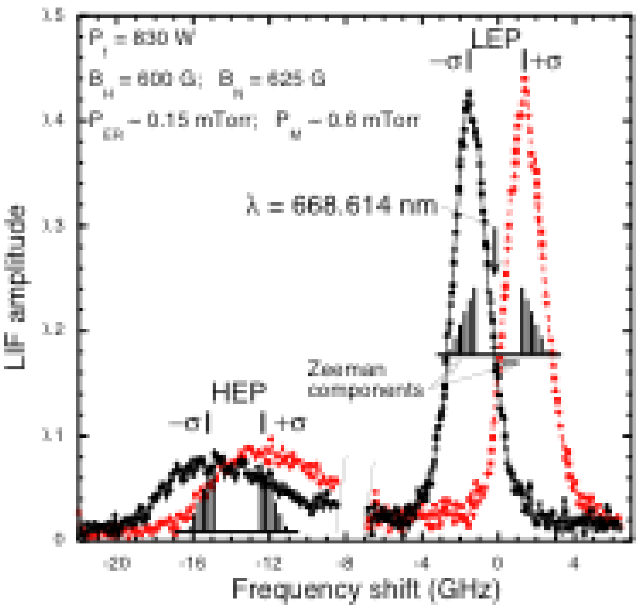
B_H = 500 G

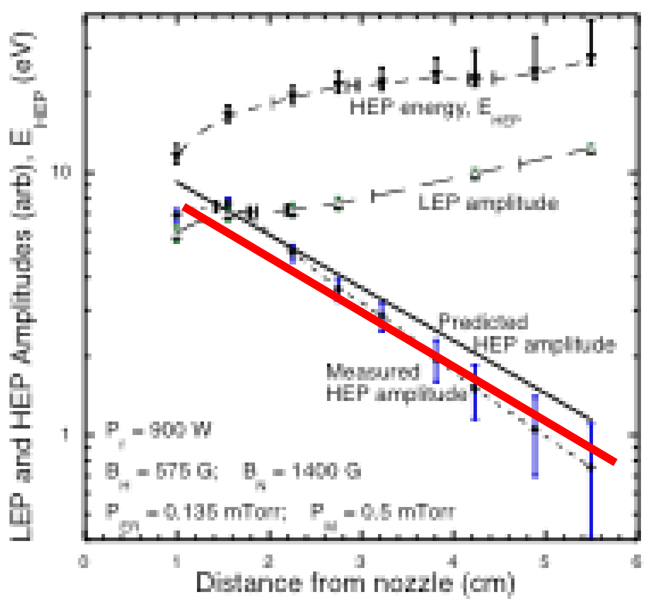
Run	Power (W)	Main chamber Pressure (mTorr)	Helmholtz field (kG)	Nozzle field (kG)
1	800	0.6, 0.9, 2.7, 6.2	0.5	0
2a	300, 600, 900 1200	2.5	0.5	0
2b	400, 800, 1200	0.7	0.5	0
3	800	0.7	0.5	0, 0.3, 0.6, 1.2, 2.4
4	800	0.7	0.5, 1.0, 1.5	

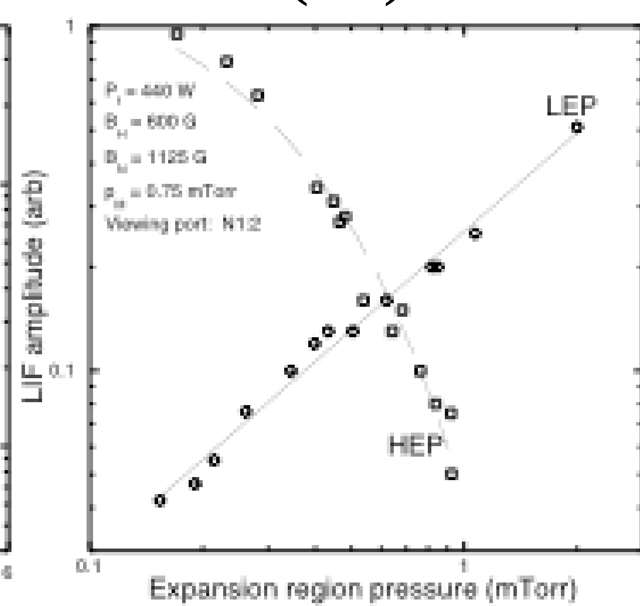
Siefert, *et al.* BAPS 2003

Expansion region (ER)

- Near 0 GHz: Low Energy
- Above 8 GHz: High Energy
- HEP energy grows with z
- HEP amplitude decreases with z
- LEP amplitude increases with z
- Metastable Ar^+ $3d^4F_{9/2}$ quenching Q_m = 515 ±100 $(\text{A}^\circ)^2$

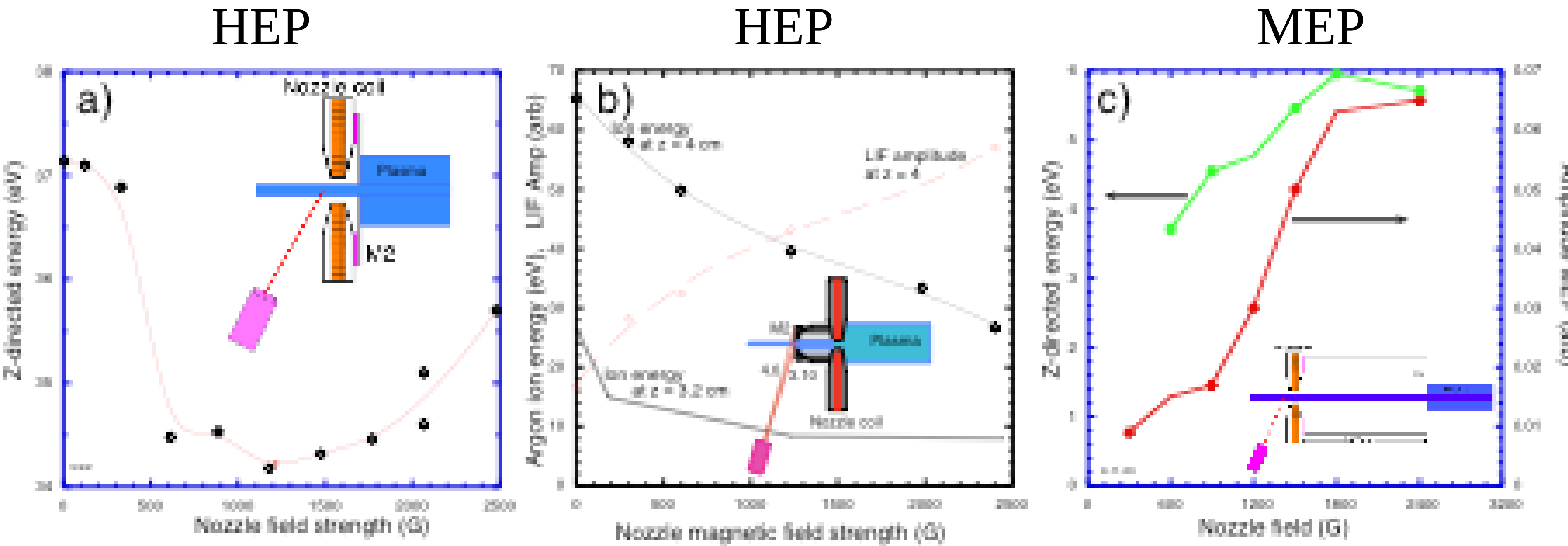






Cohen, et al. PRL (2002

Effects of nozzle field



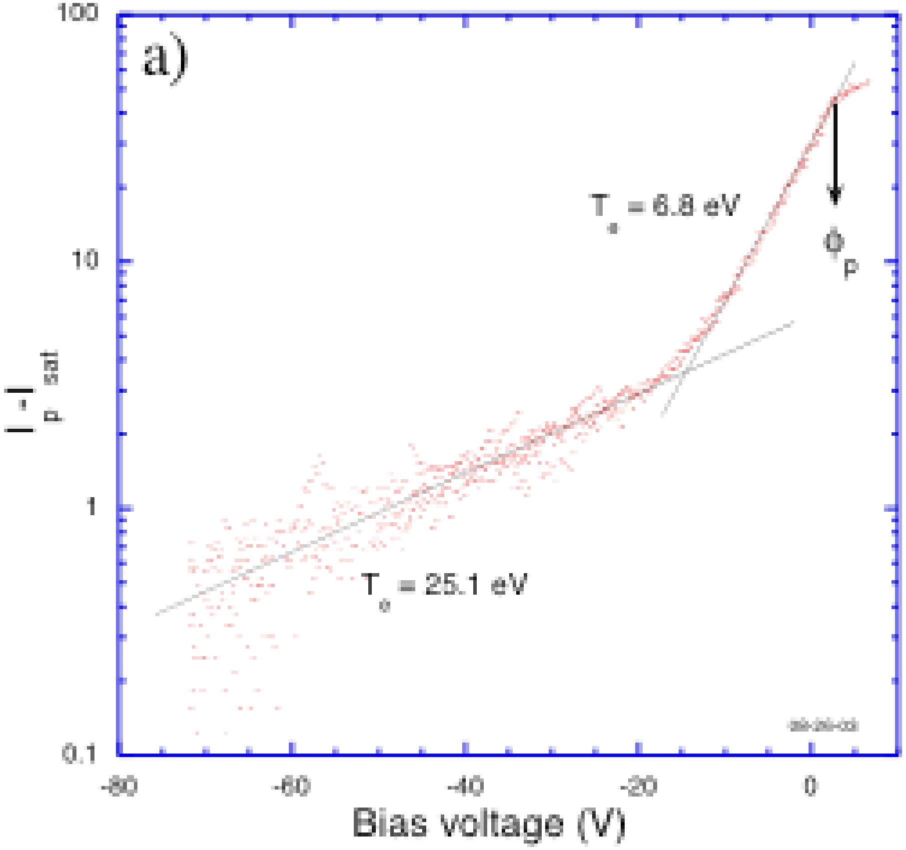
- Energy of HEP ions falls with increasing Bn
- Do fast electrons have high pitch angle distribution?

Submitted to Phys. Plasmas, *Sun et al.*

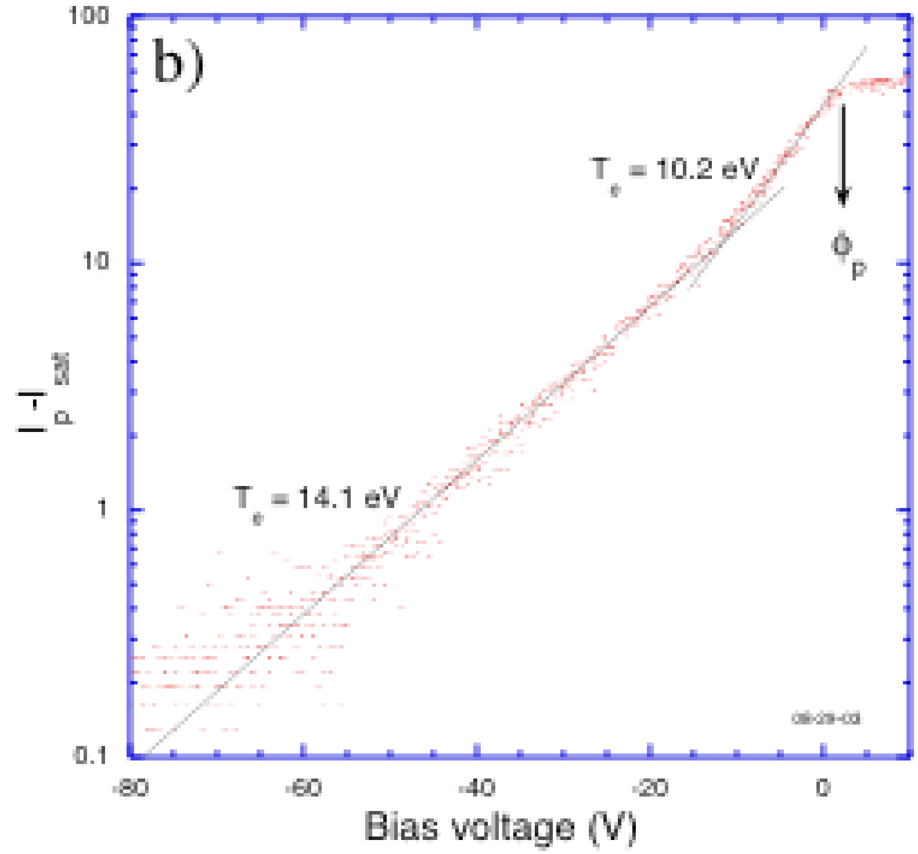
ER Langmuir probe characteristics

- EED in expansion region strongly affected by nozzle field

$B_n = 0$

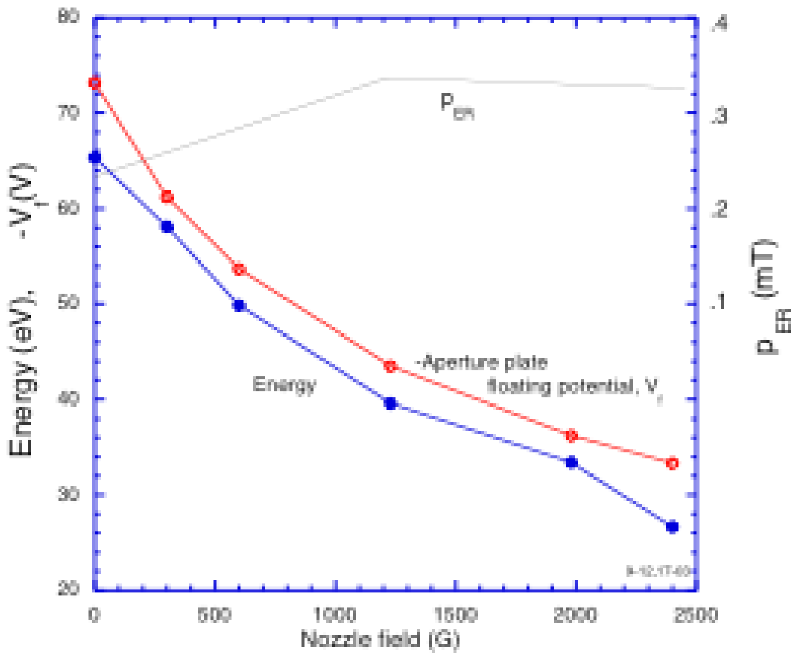


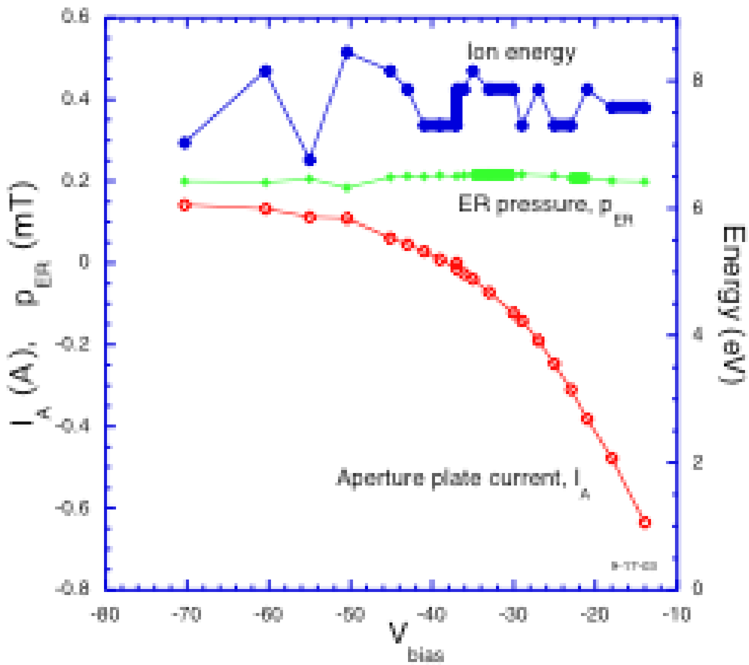
$B_n = 1500$ G



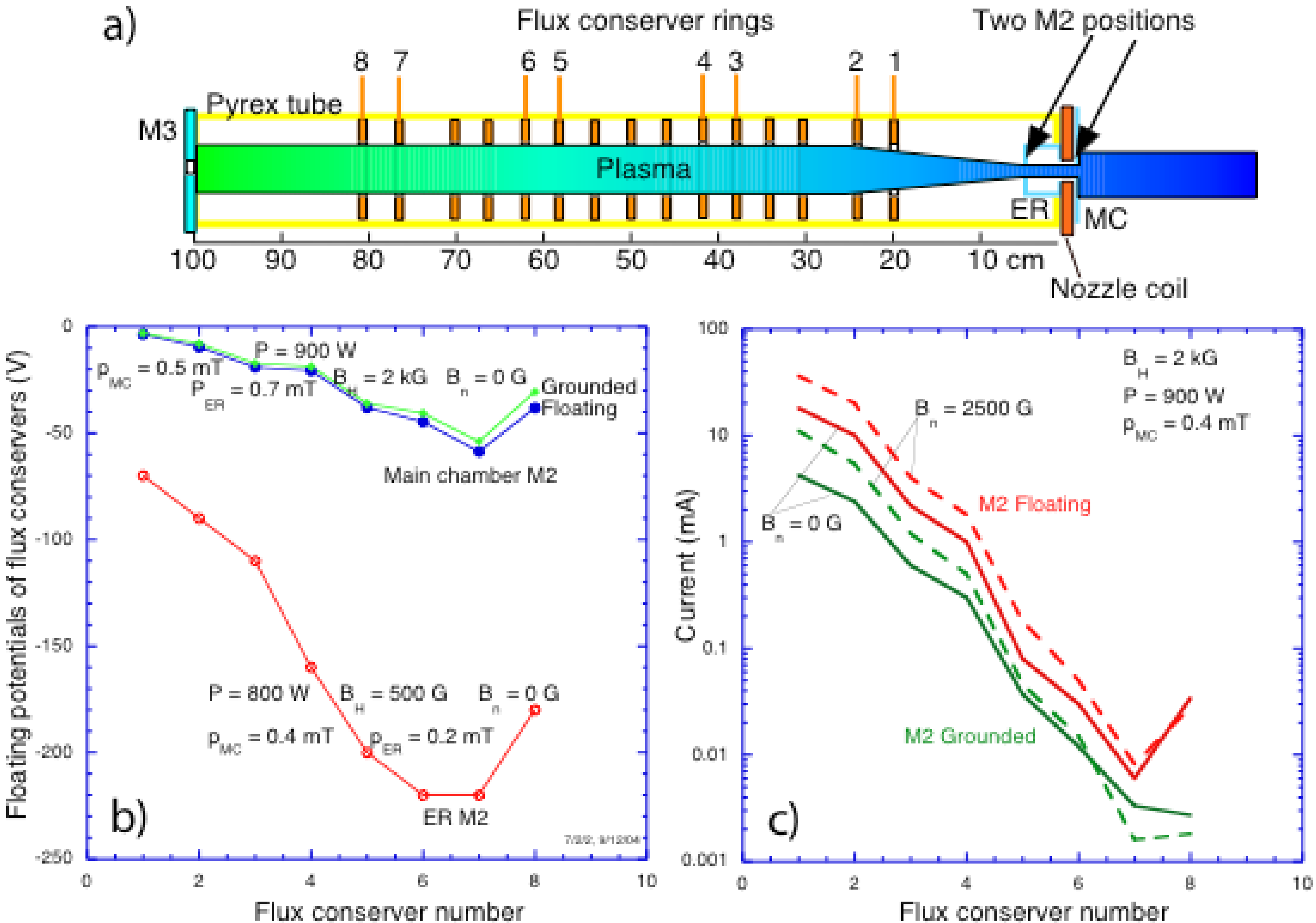
M2 aperture-plate floating potential

- M2 floating potential and ion energy are corrolated
- M2 floating potential ~ 10 T_e
- M2 floating potential becomes less negative with increase of B_n or neutral pressure
- Biasing M2 does not change plasma flow into ER or HEP ion energy



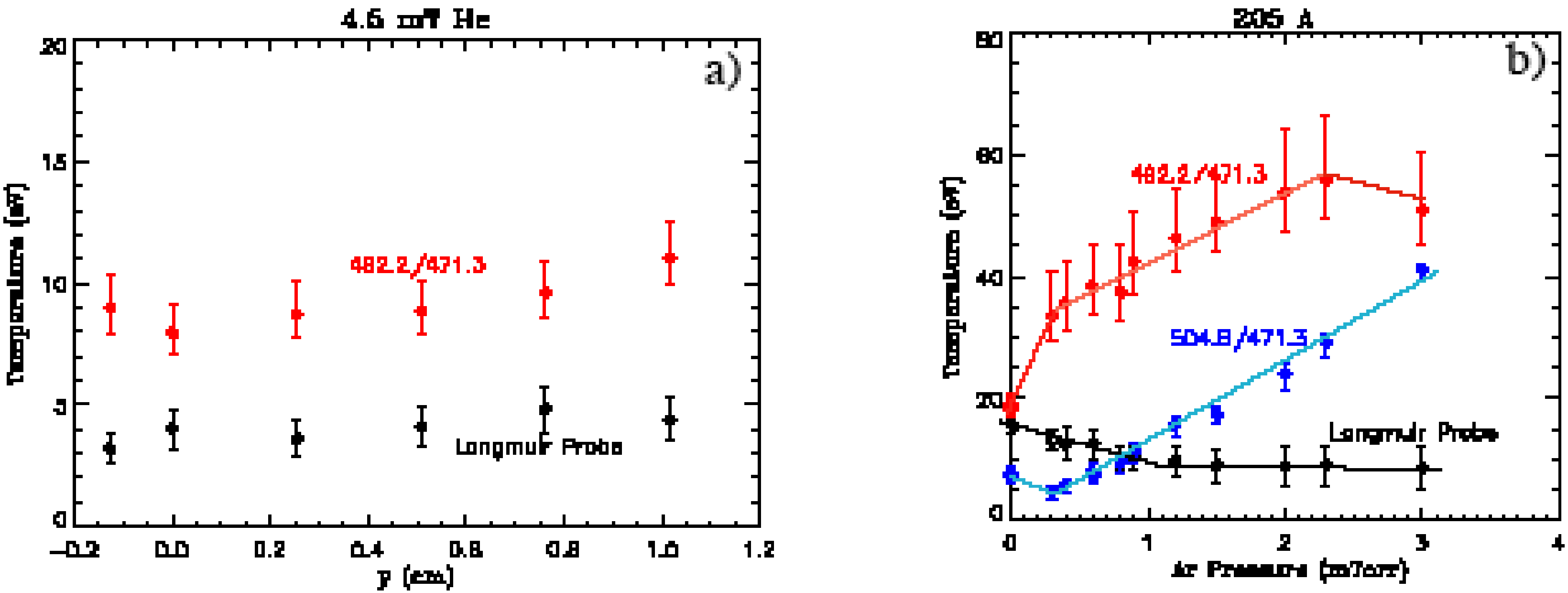


ER: Floating potentials



Collisional-radiative model *vs* Langmuir probe

- Emission spectroscopy measurement of T_e in strong disagreement with probe measurements
- One possible explanation is tenuous fast electron population



Pure helium plasma with argon added. Not blue-core mode.

Summary

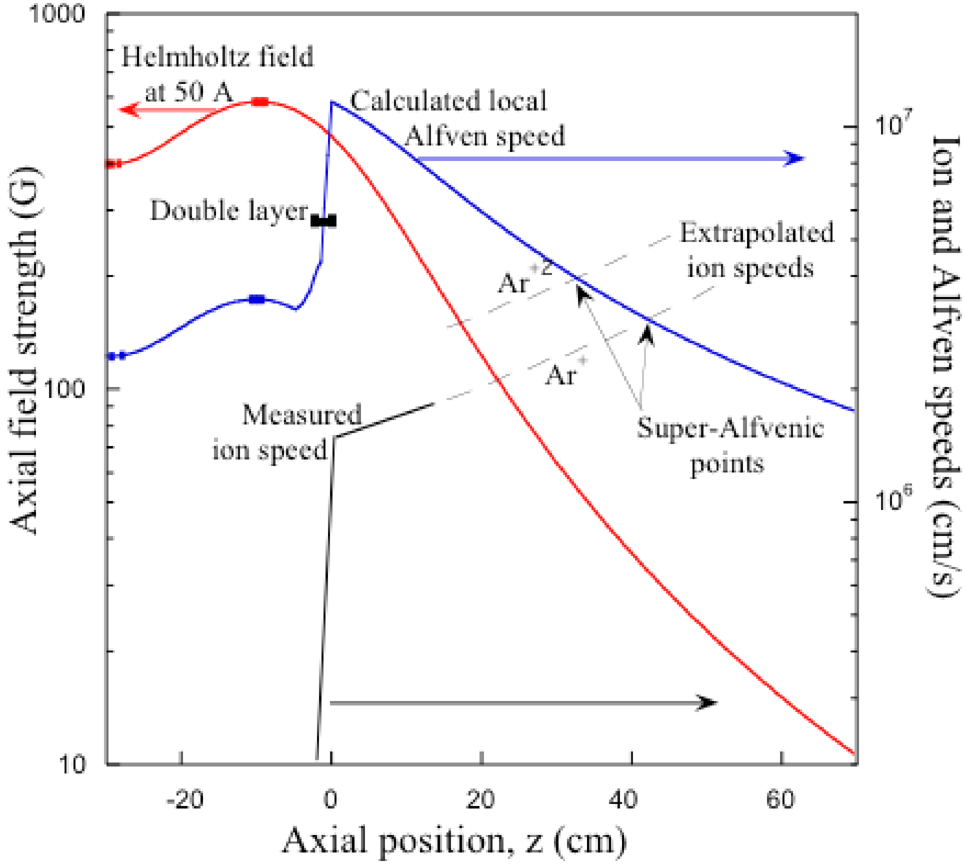
- Ions and electrons in MC are collisional because of high density and low temperature, with the possible except of a tenuous superthermal electron component.
- Ions and electrons in the ER are collisionless
- Evidence for the superthermal e^- population includes
  - M2 $V_f > 4\ T_e$ in MC; Flux conserver $V_f < -200$ Volts in ER
  - Strong presheath, $\Delta\phi_s = T_e$
  - Strong DLs, $\Delta\phi_{DL} = 10\ T_e$
  - Emission spectroscopy, line ratios
  - Ions accelerated to $E_z > 70$ eV
  - Langmuir probe measurements in ER

Unresolved

- Does a fast electron population exist in the main chamber?
  - Possible sources: landau damping, SEE, acceleration through DL
  - How to measure it?
  - How to control it?
  - Does it have high pitch-angle distribution? Why?
- Why does location of M2 affect DL strength?
- Streaming instabilities?
- Effects of curved *vs* straight expanding fields?
- Will super-Alvenic speeds be reached & detachment occur?
  - **B** expansion?
  - Fast(er) electrons?
  - Ion heating?

Towards super-Alfvenic speeds

- Two goals: high I_{sp} and v > v_{Alfven}
- Improve signal
  - Better pumping
  - Brighter LIF
- Increase acceleration
  - Create fast electrons
  - Look farther downstream
  - Use low amu propellants



Existence of downstream shocks?

Pictured (from Frank M. White, *Fluid Mechanics*, McGraw-Hill):
Normal shock inside a duct; Mach wave pattern to left.

Will the magnetic nozzle behave like a duct?