Experimental and Theoretical Studies of Electrostatic Confinement

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Outline

I. Electrostatic Basics

II. Motivation

III. Review of Periodically Oscillating Plasma Sphere physics

IV. Potential "Show Stoppers"

V. Equilibrium and Stability of Virtual Cathodes

VI. Experiment

VII. Spherically Convergent Ion Focus (SCIF) Systems

VIII. INS as a neutron Source

IX. Conclusions

Electrostatic Basics

I. $T \sim V_{applied}$ (easy)

A. Inexpensive machines give lots of neutrons

B. Near-term applications as neutron sources

C. Advanced fuels are easier than in conventional systems

II. $\tau_{classical} \rightarrow \infty$ (not too bad)

A. Confine plasma in deep potential wells

B. No cross-field diffusion size limit

III. Density limited by $\lambda_{Deff}/a \sim 1$ (difficult)

A. Low density => Low power density

B. Power density $\sim 1/r^4$, Power out $\sim 1/r$

IV. Summary

A. Small size, high voltage (difficult technology problem)

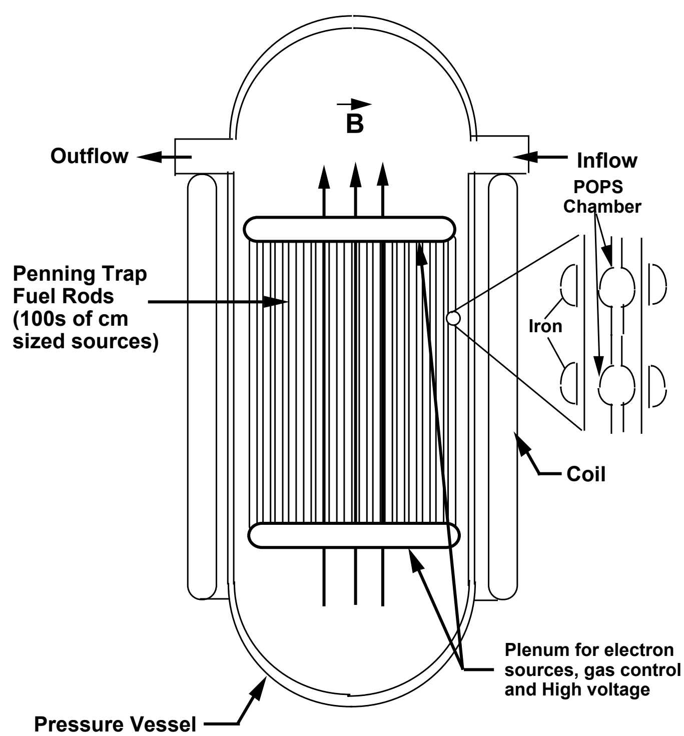
B. Density enhancement scheme required

1. Focused ion plasma (subject to Nevins problem)
2. Oscillating thermal plasma

Why IEC?

* Massively Modular Penning Trap Reactor

Penning Trap Reactor Vessel



* Mass Power Density for Modular Reactors is a paradigm shift from conventional systems.

$$MPD = \frac{2 \pi \eta P_{wall}}{\rho} \frac{a^2}{a(2at + t^2)} \frac{F a}{r_{tube}}$$

* High MPD (~ LWR) can be achieved with conventional wall loads.

* Why can we do this with IECs?

- Confinement doesn't depend on size
- Power out ~ $1/r_{tube}$

* Problem: Beam Systems have Trouble getting Q > 1.

Power Scaling

I. **Poisson's Equation**

$n_e \sim \nabla^2\phi \sim \Delta\phi/a^2$ **(note: here "a" is the r_{tube})**

II. **Average ion density ~ 10% electron density**

$n_i \sim .1n_e$

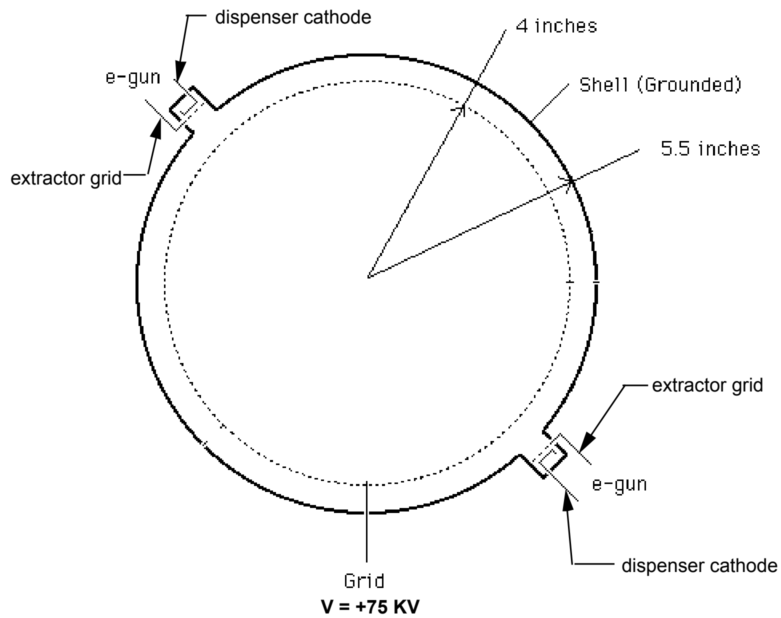
III. **Fusion power density**

$p = 1/2(n_i)^2<\sigma v> \sim 1/a^4$

IV. **Total power**

$P = 4/3\pi a^3 p \sim 1/a$

POPS Ion Physics[2,3]



1. **1-D Time and space separable solutions exist.**

2. **Solutions are stable.**

3. **Stable spectrum has an infinite number of discrete modes with accumulation point at ω=0.**

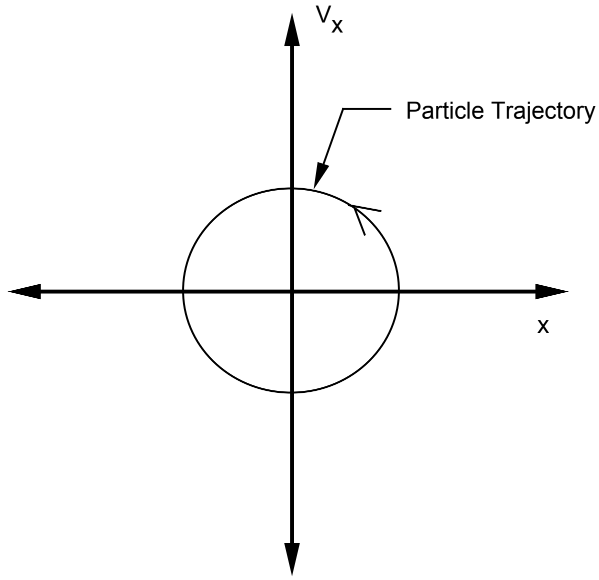
4. **Density profile is Gaussian in radius, Maxwellian in velocity.**

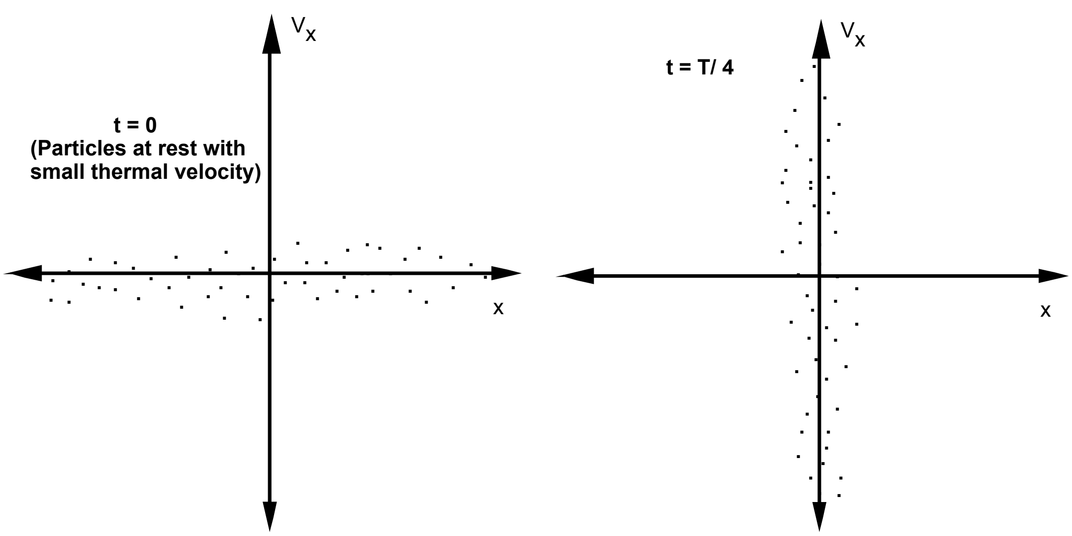
5. **Profiles remain in l.t.e. throughout oscillation (eliminates "Nevins Problem")**

6. **Solutions likely to be attractors.**

2. D. C. Barnes, R. A. Nebel, ***Physics of Plasmas*** **5**, 2498 (1998).
3. R. A. Nebel, D. C. Barnes, ***Fusion Technology*** **38**, 28 (1998).

Ion Phase Space Motion in a Harmonic Oscillator





- **Distribution Functions Move as a Rigid Rotor.**
- **Density and Velocity Profiles Exchange Every 1/4 Period.**
- **Maxwellian velocity distribution requires Gaussian density profile**

Potential Show Stoppers

- **High Voltage, Small Size**
  - **How bad is it?**
  - **Stability limits on Virtual Cathode (Electron Cloud).**

- **Electron Cloud Uniformity**
  - **Attractor $\Rightarrow$ Energy Flow-through Issue**
  - **How fast do the ions relax and thermalize?**

- **Space Charge Neutralization During Ion Collapse**

- **Impurity Control**

- **Oscillation Phase Locking and Control**

- **Insulator Integrity**

Virtual Cathode Equilibrium and Stability

Equilibrium

Pressure balance and Poisson's equation lead to

$$\phi_{0eff}(r) = \phi_{00eff}(1 - (r/a)^2)$$

where

$$\phi_{00eff} = -e(n_0-n_b)a^2/(6\varepsilon_0)$$

and

$$p_0(r) = p_{00} + en_0(\phi_{0eff}(r) - \phi_{00eff})$$

Stability

Energy principle leads to sufficient condition for stability

$$ds/d\phi_{0eff} < 0. \quad \text{(Rayleigh-Taylor criterion)}$$

where $s=p/(m_e n)^\gamma$ is the entropy density. But for constant density

$$ds/d\phi_{0eff} = (dp/dr)/(d\phi_{0eff}/dr) = en_0 > 0$$

which is always violated everywhere in the plasma.

Dimensionless Linear Eigenvalue Equations

$$\phi'' + 2/x\,\phi' - l(l+1)/x^2\phi = 6n$$

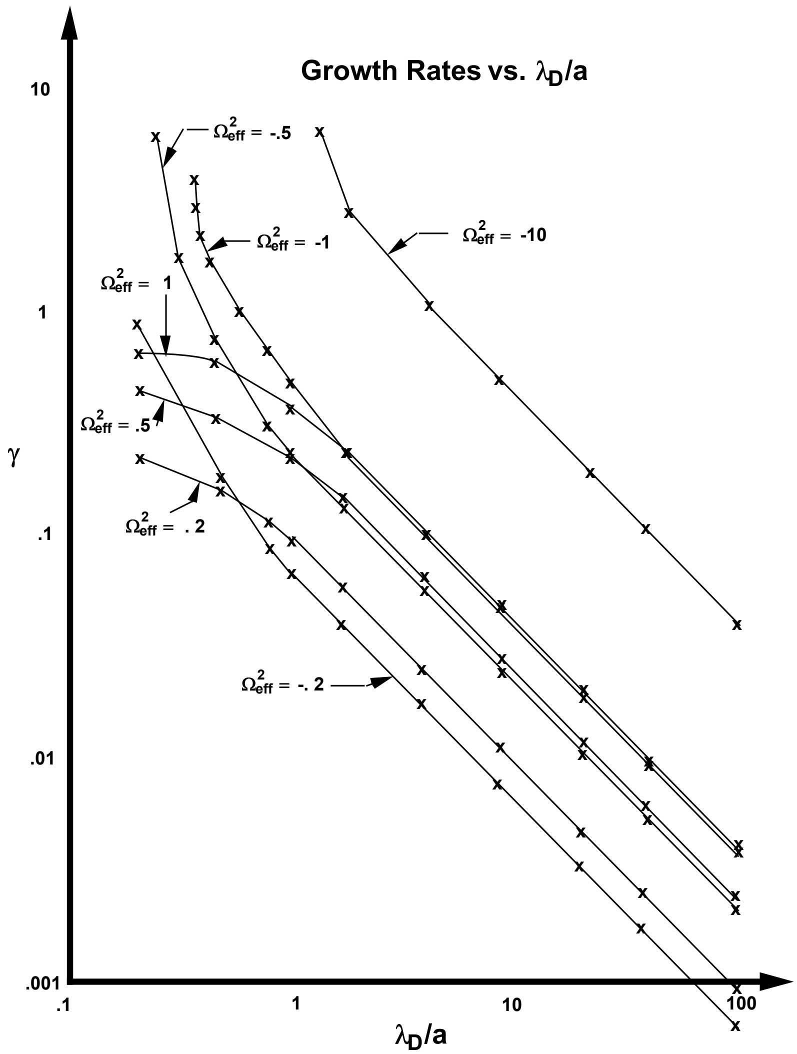
$$(-\Omega^2 + \Omega_{eff}^2 + 1)n - (\lambda_D/a)^2[p'' + 2/x\,p' - l(l+1)/x^2\,p] + (\Omega_{eff}^2 x/3)n' = 0$$

$$-\Omega^2(\lambda_D/a)^2 p + \Omega_{eff}^2 x/3[-(\lambda_D/a)^2 p' + \phi'/6 + (\Omega_{eff}^2 x/3)n] + \Gamma[(\lambda_D/a)^2 + \Omega_{eff}^2 x^2/6]\Omega^2 n = 0$$

where $\omega_{pe}^2 \equiv e^2 n_0/(\varepsilon_0 m_e)$, $\omega_{eff}^2 \equiv \omega_{pe}^2 - e^2 n_b/(\varepsilon_0 m_e)$, $\Omega^2 \equiv \omega^2/\omega_{pe}^2$, $\Omega_{eff}^2 \equiv \omega_{eff}^2/\omega_{pe}^2$,
$\lambda_D \equiv [\varepsilon_0 k_B T_{00}/(n_0 e^2)]^{1/2,}$ $x \equiv r/a$, $p \equiv \delta p/p_{00}$, $n \equiv \delta n/n_0$, $\phi \equiv -\delta\phi/\phi_{00}$.

The equations form a fourth order, self-adjoint system of equations. The only dependences are on λ_D/a, ω_{eff}^2, Γ, and ω_{pe}^2.

Growth Rates



Growth rate versus λ_D/a for various values of Ω_{eff}^2.

- **No window of absolute stability**

- **Marginal points at Brillouin limit and $\lambda_D/a \rightarrow$ infinity.**

- **$\gamma \sim 1 / (\lambda_D/a)$ for large λ_D/a (incompressible Rayleigh-Taylor limit).**

Stable Virtual Cathodes

Do stable profiles exist that are sufficiently close to the desired harmonic oscillator potential that the POPS scheme will work?

Combine the marginally stable compressible Rayleigh-Taylor profile:

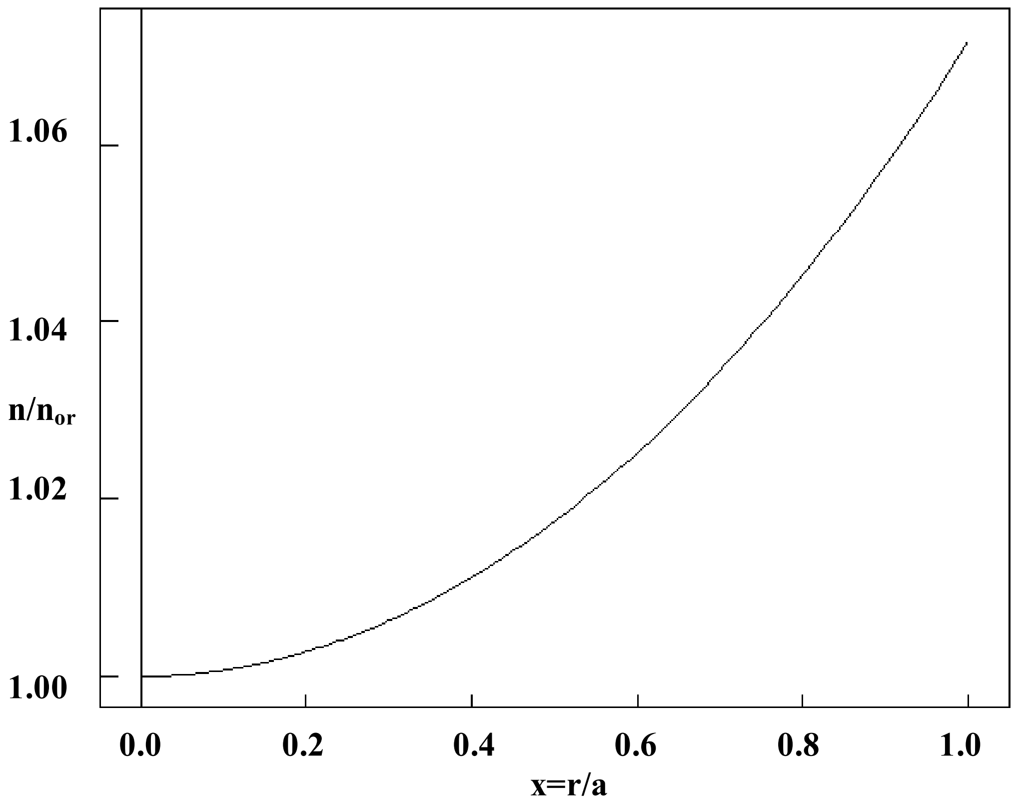
$$d(p/n^{\Gamma})/dr = 0$$

with pressure balance and Poisson's equation and write in dimensionless form:

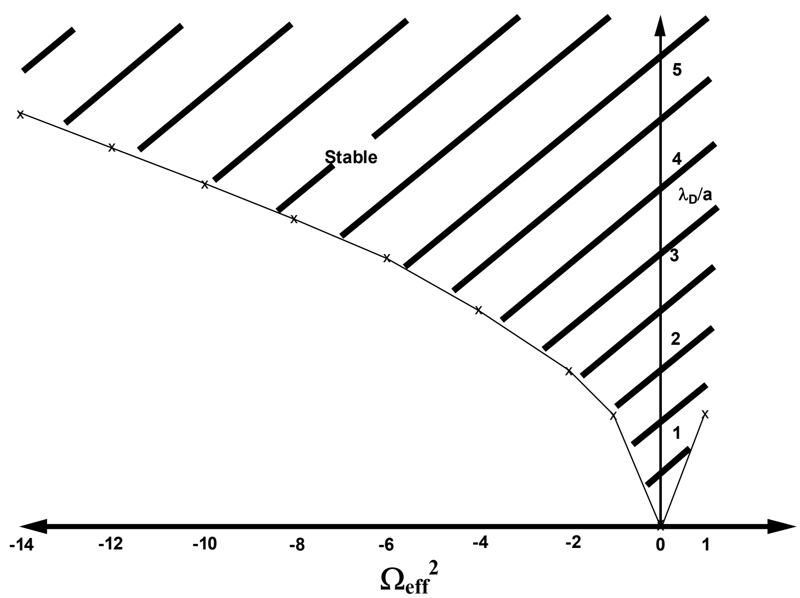
$$\nu'' + 2/x\,\nu' + [(\Gamma-2)/\nu](\nu')^2 - \Gamma/(\lambda_D/a)^2\,\nu^{(2-\Gamma)}(\nu - \nu_b) = 0$$

where $\nu \equiv n/n_{or}$ **and** $\nu_b \equiv n_b/n_{or}$.

Marginal Stability

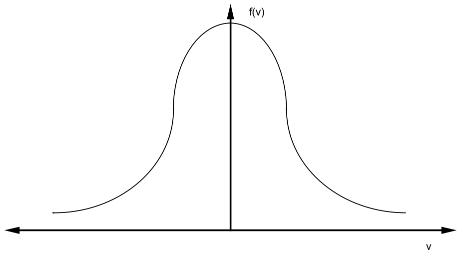


Marginally stable density profile for λ_D/a = 1.2, $\delta\phi/\phi$ = .1%



Stability Diagram

Kinetic Effects



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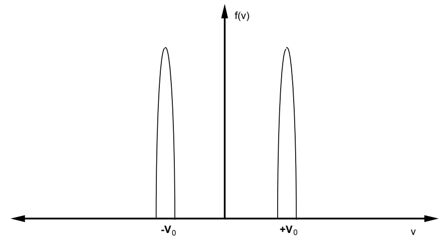


Compressible Rayleigh-Taylor → **Electron-Electron Two-Stream**

* **Approximations**

- **Cold beam**
- **Slab geometry**

* **Dispersion relation**

$$1 = \omega_{pe}^2[1/(\omega + kV_0)^2 + 1/(\omega - kV_0)^2]$$

* **Marginal Limit**

$$\omega_{pe}^2 = k^2V_0^2/2$$

or

$$(\lambda_{Deff}/a)^2 = 1$$

where

$$\lambda_{Deff} \equiv [\varepsilon_0 k_B V_0^2/(2n_0e^2)]^{1/2}$$

* **Conclusion:**

$1 \le (\lambda_{Deff}/a)_{crit}$ **for two-stream stability**

* **Does a critical value for λ_{Deff}/a exist?**

$(\lambda_{Deff}/a)_{crit}$

Fluid results (thermal electron distribution):

Stable virtual cathodes exist which are "close enough" to the desired harmonic oscillator potential if:

$$1.2 < \lambda_{Deff}/a.$$

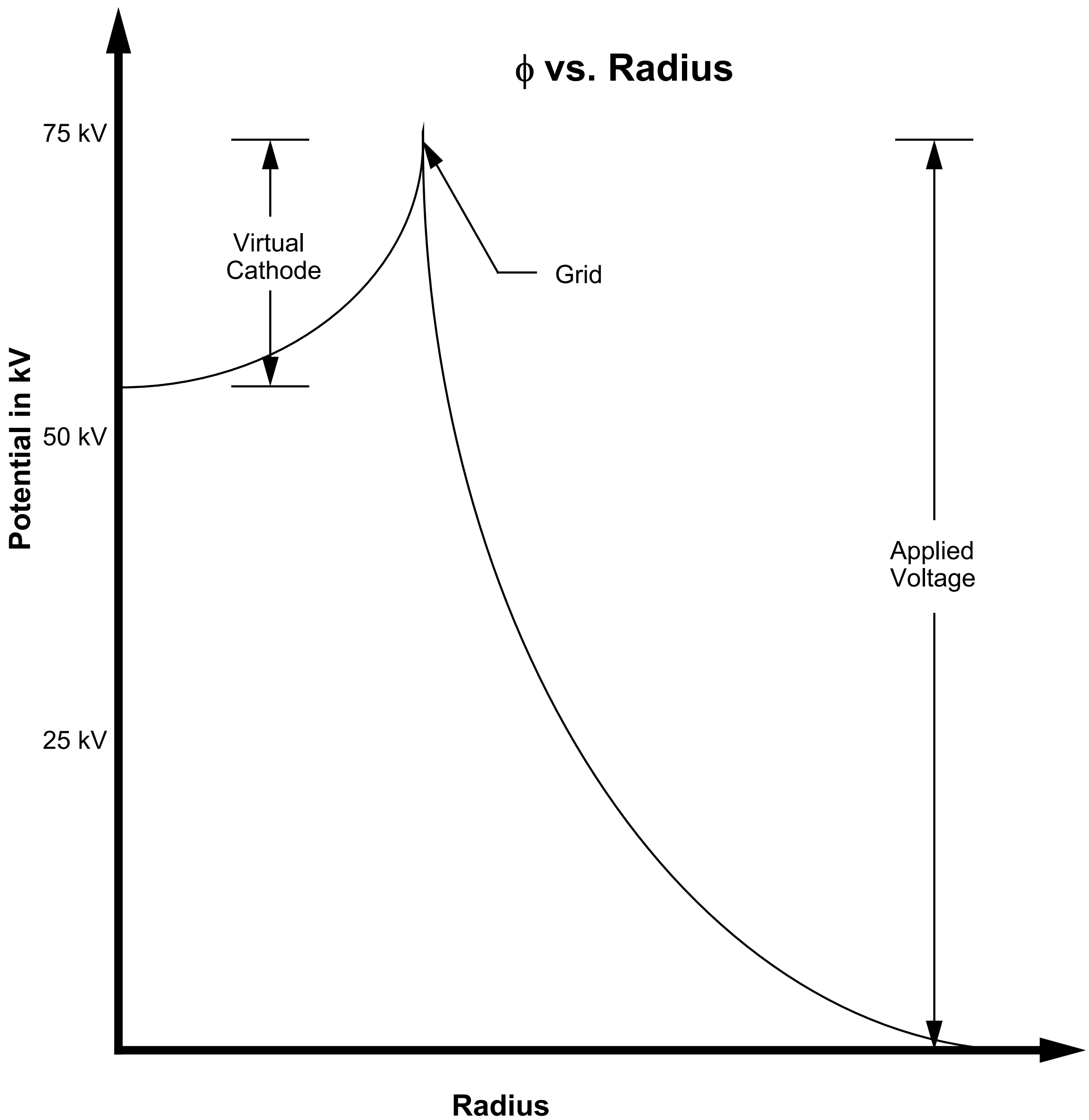
Kinetic results (self-colliding beam distribution):

Stable virtual cathodes exist if:

$$1 < \lambda_{Deff}/a.$$

We propose to find $(\lambda_{Deff}/a)_{crit}$ experimentally.

Why is $(\lambda_{Deff}/a)_{crit}$ important?



$$|\phi_{applied}| \,/\, |\phi_{virtual}| \sim (\lambda_{Deff}/a)_{crit}^{2}$$

Theoretical Prediction:

If $(\lambda_{Deff}/a)_{crit}^{2} = 1$ then $|\phi_{applied}| \,/\, |\phi_{virtual}| = 7$

Virtual Cathode Stability Summary

- **POPS virtual cathodes violate a compressible Rayleigh-Taylor stability criterion for electrons.**

- **Growth rates fall at large λ_{Deff}/a and near Brillouin limit, but no window of absolute stability exists in the fluid model.**

- **Stable profiles that are "close enough" exist for $\lambda_{Deff}/a \geq 1.2$**

- **Kinetic 2 stream limit suggests that a critical value of λ_{Deff}/a for stability exists and that this value is ~ 1.**

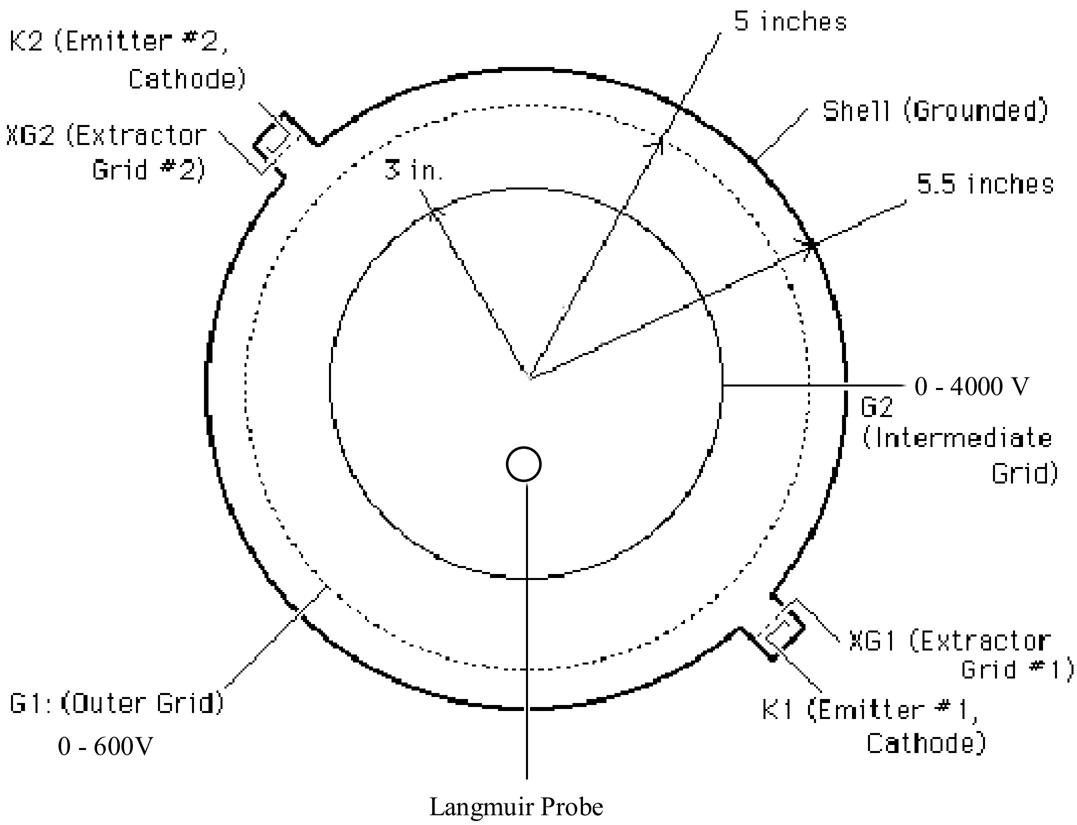
- **Since $\phi_{applied} \sim (\lambda_{Deff}/a)_{crit}^2$ determining $(\lambda_{Deff}/a)_{crit}$ is critical to POPS performance.**

Experimental Program

* Equilibrium and Stability of Virtual Cathodes.

INS Device

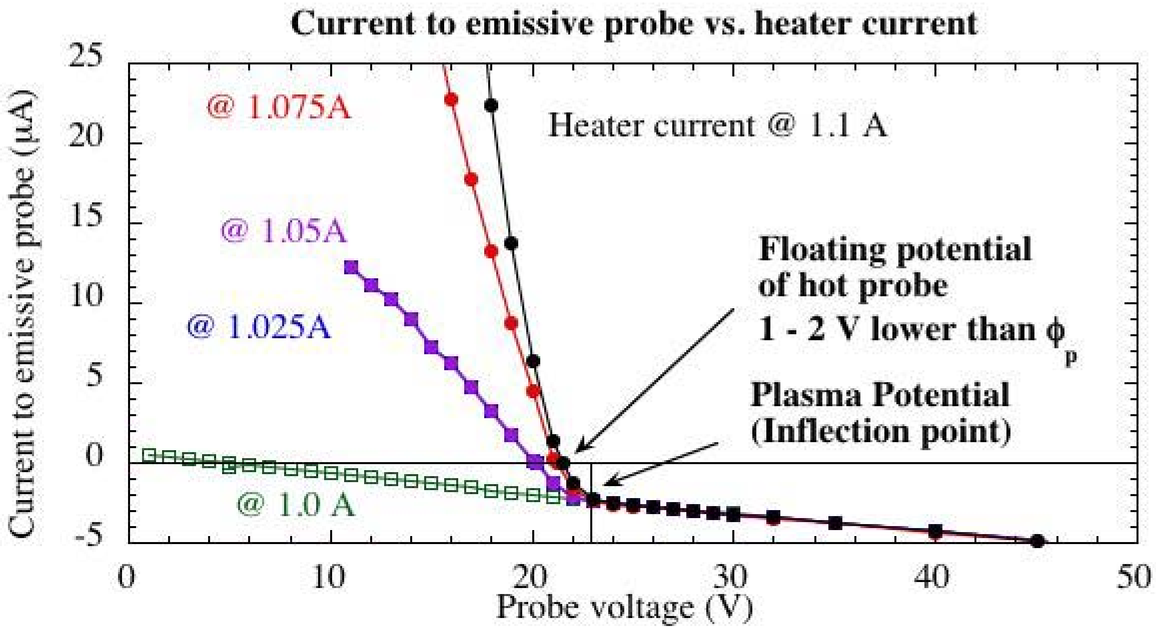
INS Device Configured for Virtual Cathode and POPS



- **Emissive Probe Used to Measure Plasma Potential**

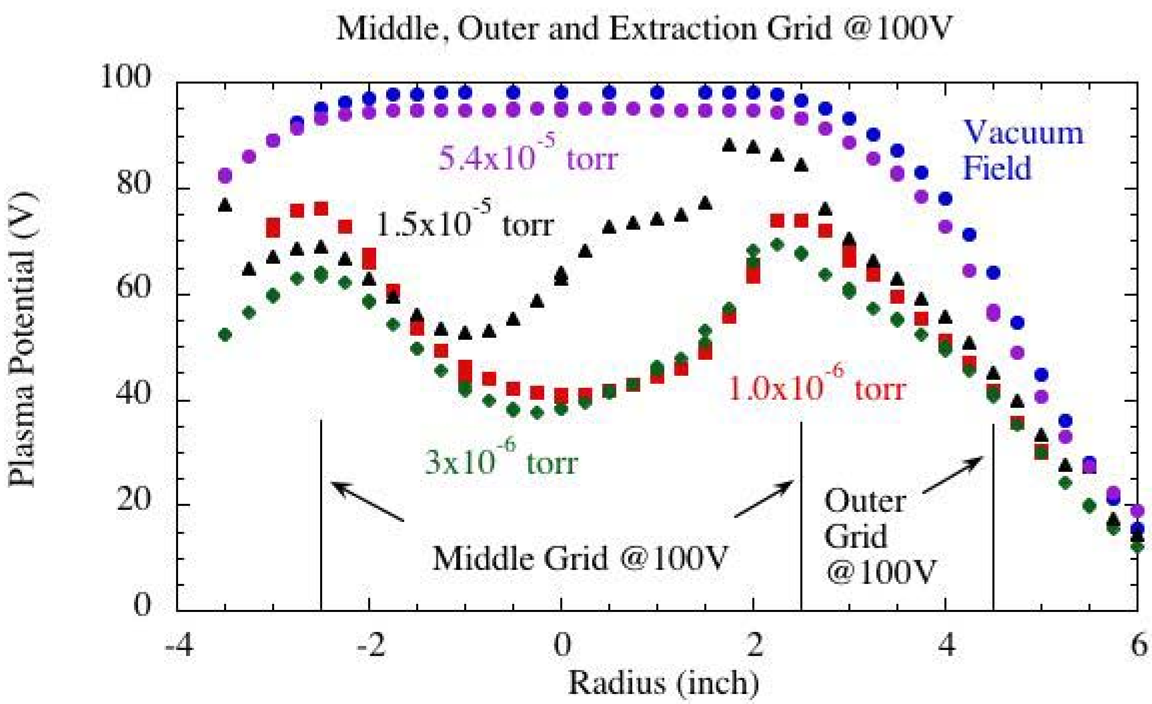
Emissive probe for plasma potential measurement

- Made of thoriated tungsten (0.076 mm x 1 cm) in alumina tube (3.2 mm O.D.)
- Better suited than Langmuir probe due to electron beam
- Floating potential of hot probe ~ plasma potential (within 1-2 V)
  - following results are taken from floating potential of hot probe
- May disturb plasma: via ion loss to alumina tube



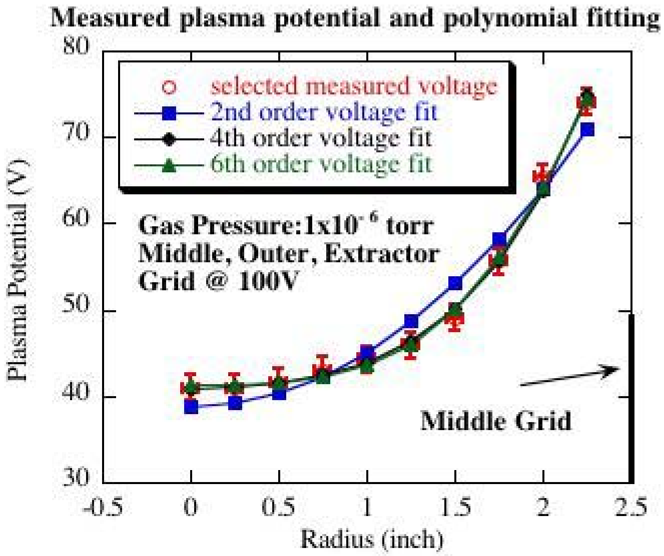
Radial Plasma Profile as a function of Gas Pressure

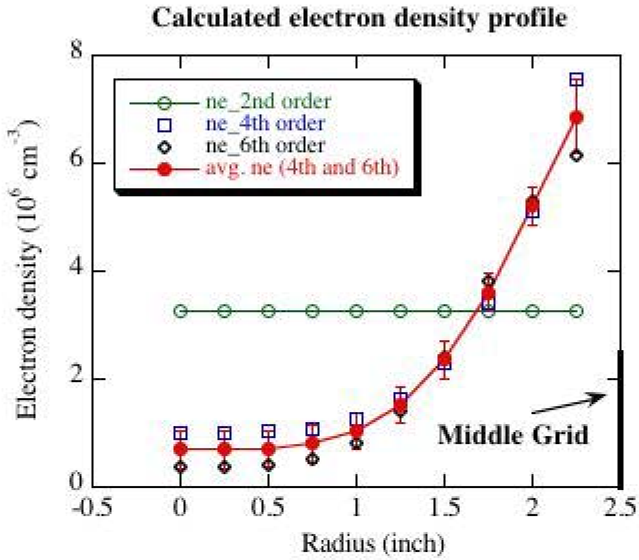
- Low Gas pressure ~ deep potential well (up to 60% of bias voltage)
- Increasing gas pressure ~ smaller well depth, radial asymmetry, bifurcation
- High Gas pressure ~ no well formation



Electron density profile from plasma potential

- Low pressure case ~ low ion density, compared to injected electrons due to low background ionization
- Ignoring n_i, n_e can be solved fr om Poisson equation (low n_i verified later)
- n_e profile from average of 4th order and 6th order polynomial fit of ϕ_p
- Off-peak radial density profile: stable profile from fluid dynamics standpoint
- Average electron density in the well ~ 3.3×10^6 cm^{-3} , consistent with electron density calculation from circulating current inside middle grid.





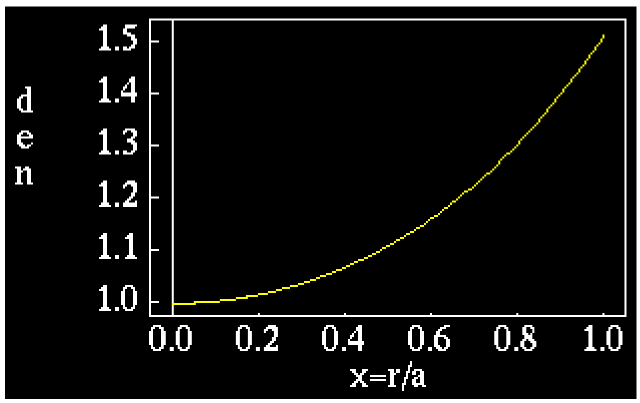
Profile Results

Theoretical Prediction:

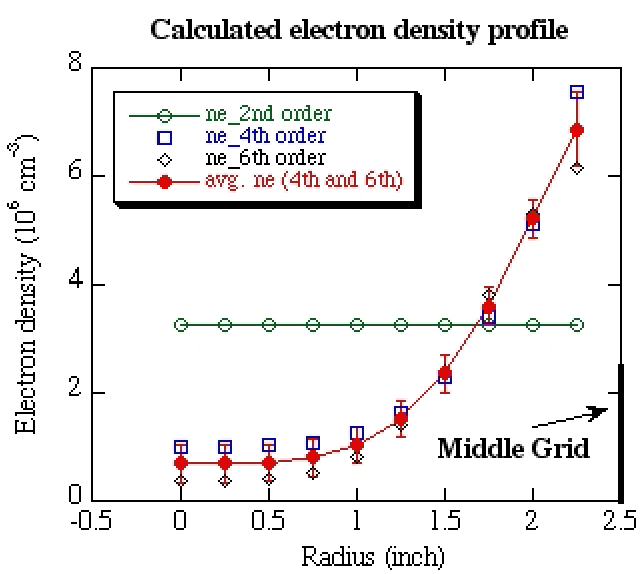
If $(\lambda_{Deff}/a)_{crit}^2 = 1$ and $n_e = n_{e0}$ then $|\phi_{virtual}| / |\phi_{applied}| = .143$

Experimental Observation:

$|\phi_{virtual}| / |\phi_{applied}| \sim .6$



Theoretical Electron Density Profile at Marginal Limit

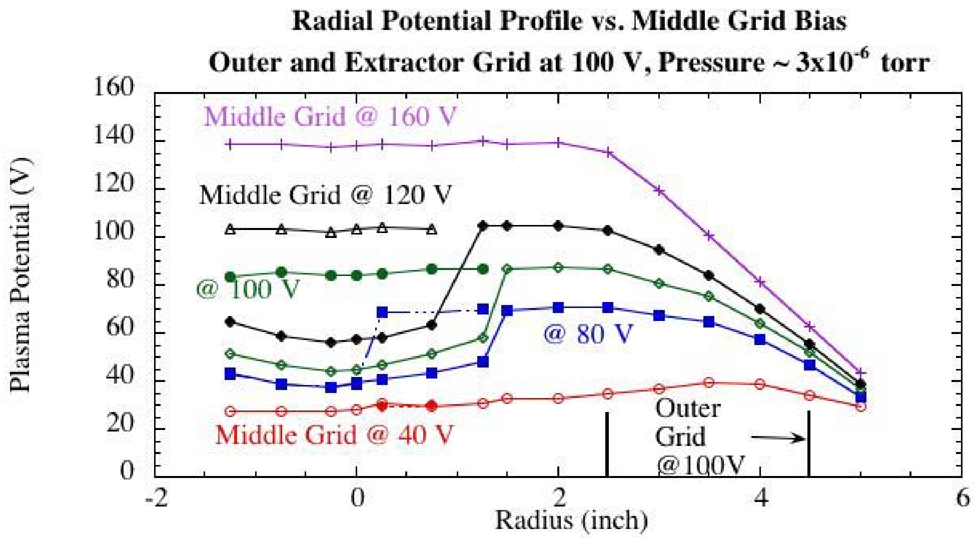


Experimental Electron Density Profile

- **Experimental Profile should be stable**

Bifurcation of Radial Plasma Potential Profile

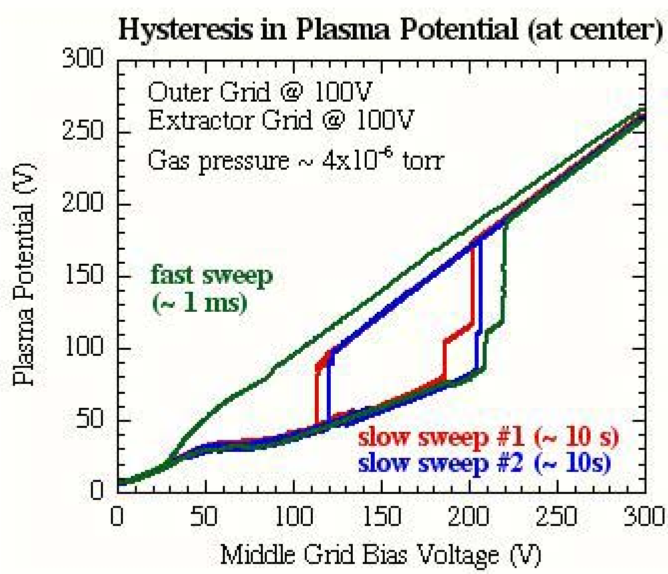
- Two stable equilibria for radial plasma potential profile
- Deep well: well depth of 50-70 V @120 V bias (note the radial inhomogenity)
- No well: well depth of less than a few voltage
- No bifurcation: low grid voltage (e.g. < 50V)or high grid voltage (e.g. > 120V)

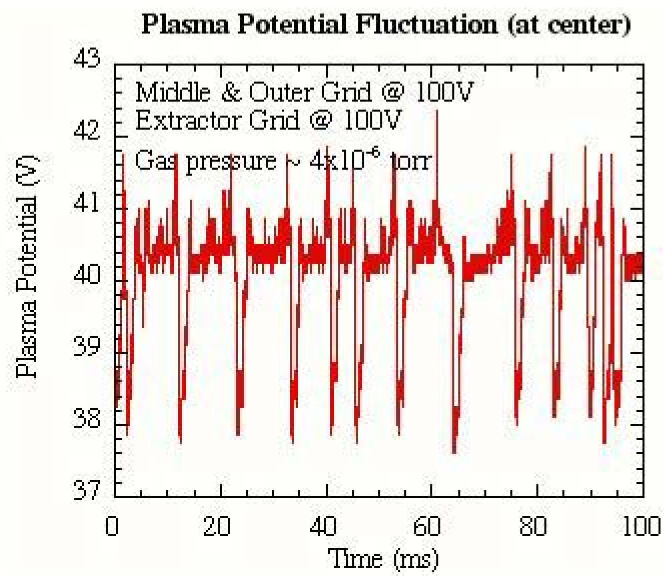


Hysteresis and Fluctuation of Plasma Potential

- Hysteresis of plasma potential
- Different hysteresis path for different rate of voltage sweep
- Fast process for well disappearance vs. slow process for well formation
- Important time scale ~ 0.1-10 ms

- ϕ_p slow fluctuation ~ 100 Hz
- Typically observed in deep well phase but much smaller in no well phase.
- Slow time scale --> ion motion & ionization rate.





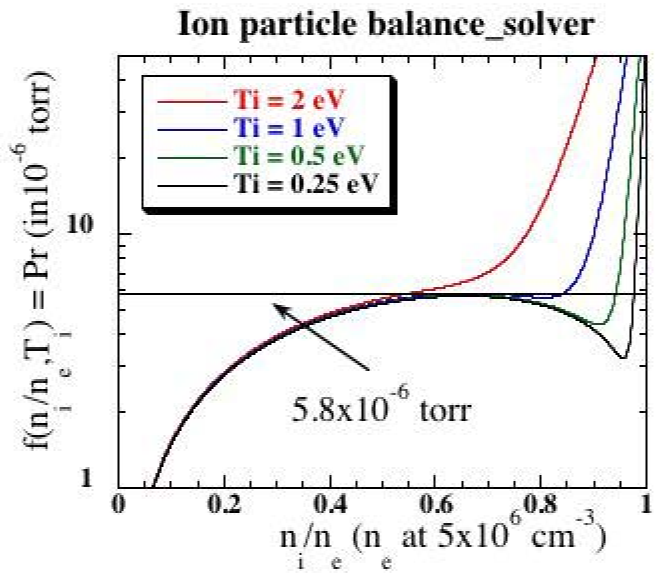
Ion Particle Balance Model (0D)

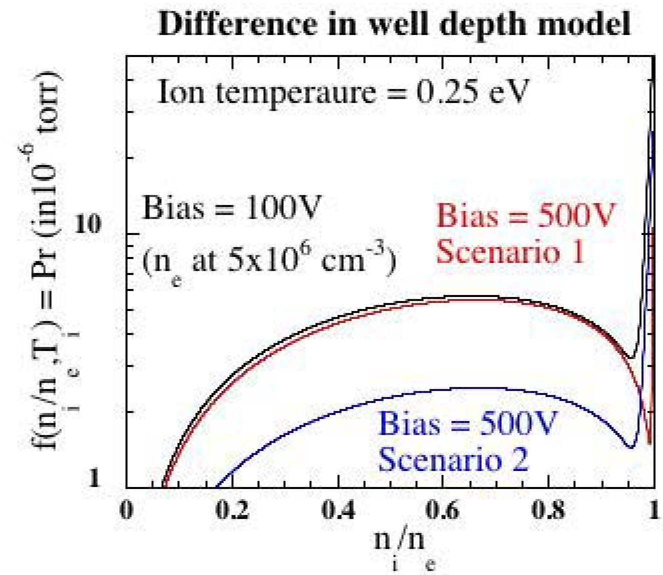
- Ion source in the well = Ion loss out of the well
- Ion source: ionization of background neutrals (gas pressure dependent)
  - $S_{ion} = n_e\, n_n <\sigma v_e> V_{well}$, σ: ionization cross section, v_e: electron velocity, V_{well}: well volume
- Ion loss: loss to the probe structure + loss out of well due to random thermal motion and well anisotropy
  - $L_{ion} = 0.25{*}n_i\, v_i\, A_{probe} + 0.5{*}n_i\, v_i\, A_{well} \exp(-\Delta V/T_i)$, v_i: ion velocity, A_{probe}: probe surface area (alumina tube), A_{well}: well surface area, ΔV: well depth
- Poission equation: $6\, \Delta V/a^2 \sim q/\varepsilon_0\, (n_e - n_i)$, a = well radius ~ 1.5 inch
- Well depth: function of bias voltage and electron injection
- $S_{ion} = L_{ion}$ --> $f(n_i/n_e, n_e, T_i) = n_n$ (after rearranging terms)
- Relevant numbers:
  - $\sigma \sim 1\text{x}10^{-16}$ cm^2 for 40 - 100 eV , $n_n = 3.5\text{x}10^{10}$ cm^{-3} x Pr (Pressure in 10^{-6} torr)
  - $v_e \sim 4.2\text{x}10^7{*}\,(V_0 - \Delta V/2)^{0.5}$, V_0: bias voltage (100V)
  - $\Delta V \sim 7.8\, {*}(1 - n_i/n_e)\, {*}n_e$ (in 10^6 cm^{-3}), $n_e \sim 5\text{x}\,10^6$ cm^{-3} (from measurement)
  - $v_i \sim 4.9\text{x}10^5{*}(\Delta V + T_i)^{0.5}$
  - $A_{probe} = 6.3$ cm^2 (at the center), $V_{well} = 232$ cm^3, $A_{well} = 182$ cm^2

Solutions from ion particle balance model

- Graphically solving $f(n_i/n_e, n_e, T_i) = n_n$
- Low pressure: one solution (deep well)
- Medium pressure: 3 solutions (2 stable, 1 unstable), bifurcation between deep well and no well
- High pressure: one solution (no well)
- Consistent with experiments

- Scenario 1: well depth proportional to bias voltage (n_e increase with bias, not limited by electron injection)
- Scenario 2: well depth limited by electron injections (n_e = fixed)
- Experiments indicate #2 case --> need to enhance electron injection

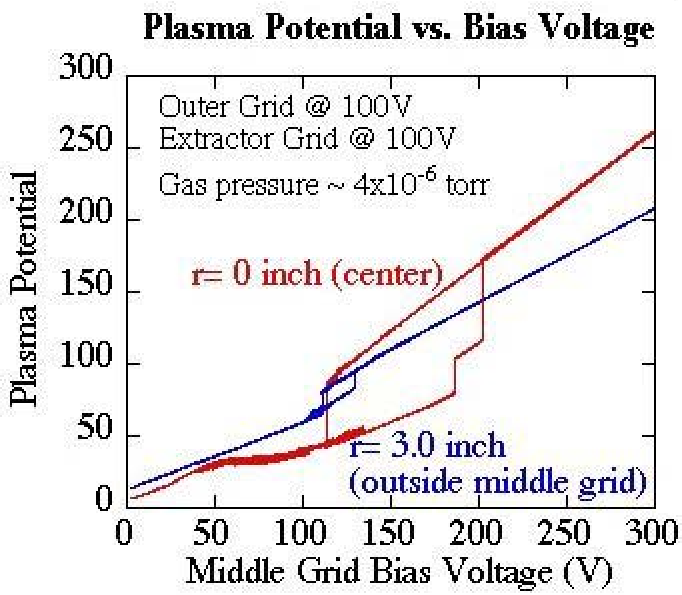


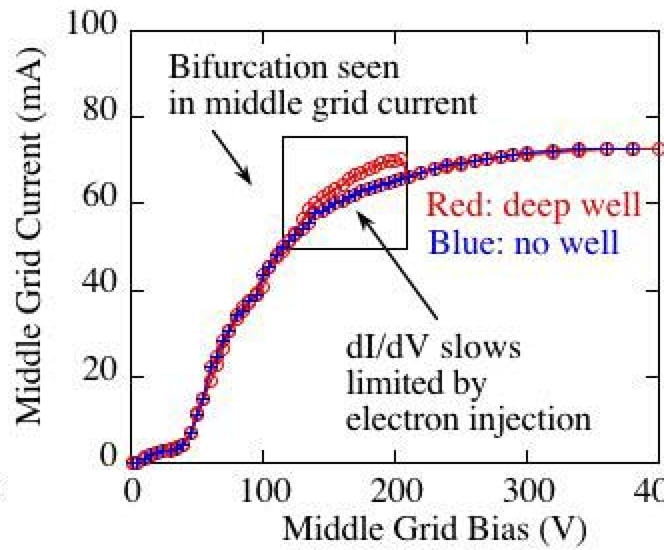


Comparison with Experiments

- Bifurcation or 3 solutions are seen at center
- Potential well exist without ion loss to the probe (r=3.0 inch, outside the well)
- Potential well disappears with increasing bias voltage --> electron density limited by injection

- Middle grid current ~ electron density (assuming const. grid transparency)
- Bifurcation seen by middle grid current
- dI/dV (middle grid) slow above 150V, electron density limited by injection
- Enhanced electron injection --> deeper potential well





INS Experiment Summary

* Potential profiles have been measured with an emissive probe

* Bifurcated equilibria have been observed (three different states)

* Bifurcated equilibria can be understood qualitatively and quantitatively with a simple ionization model.

* Wells as deep as 60% of the applied voltage have been observed.

* Experimental density profiles are strongly peaked off-axis.

* Even though the potential wells are much deeper than expected, theory predicts that the observed density profiles should be stable.

* Stability limits of virtual cathode have not yet been tested.

The Next Steps

- **Flatten Density Profiles.**

  - **More focused electron beam from dispenser cathodes.**

- **Operate with deep well at higher voltages.**

  - **Pulsed discharges.**

  - **Ion removal techniques like POPS dumping?**

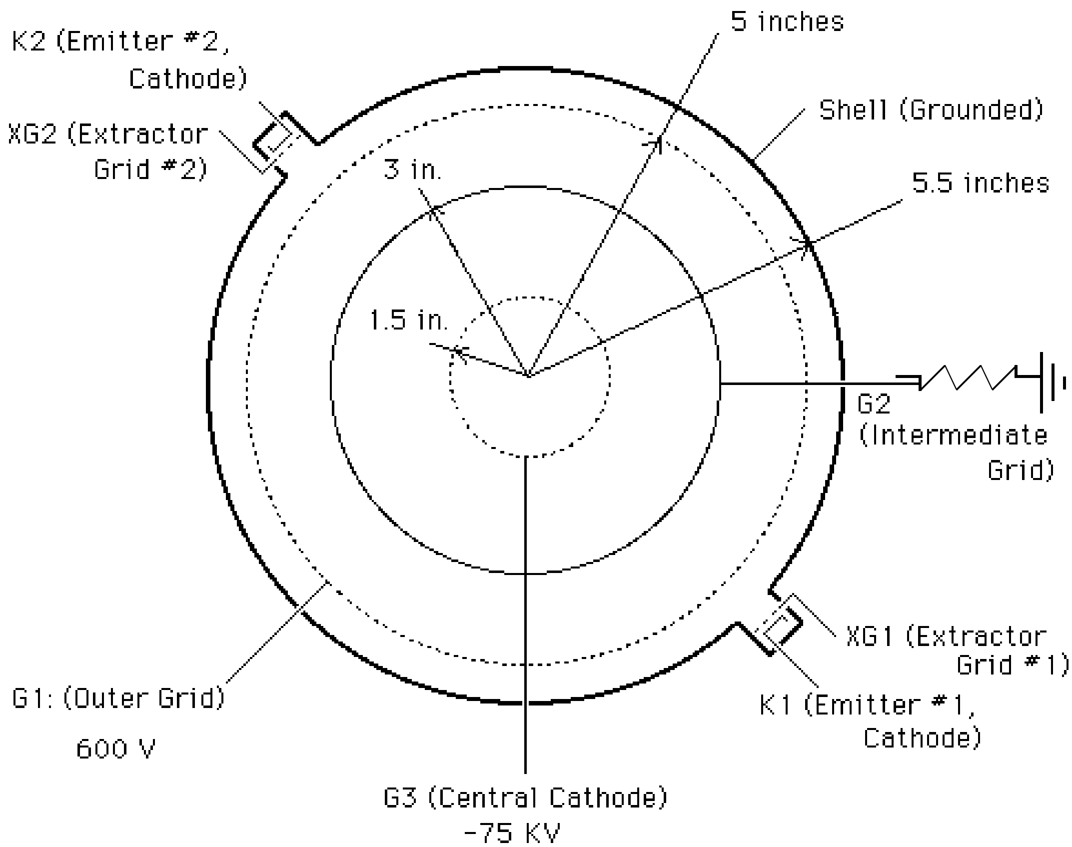
  - **More electron density in the well.**

- **Look for stability limit.**

- **Look at fluctuation data.**

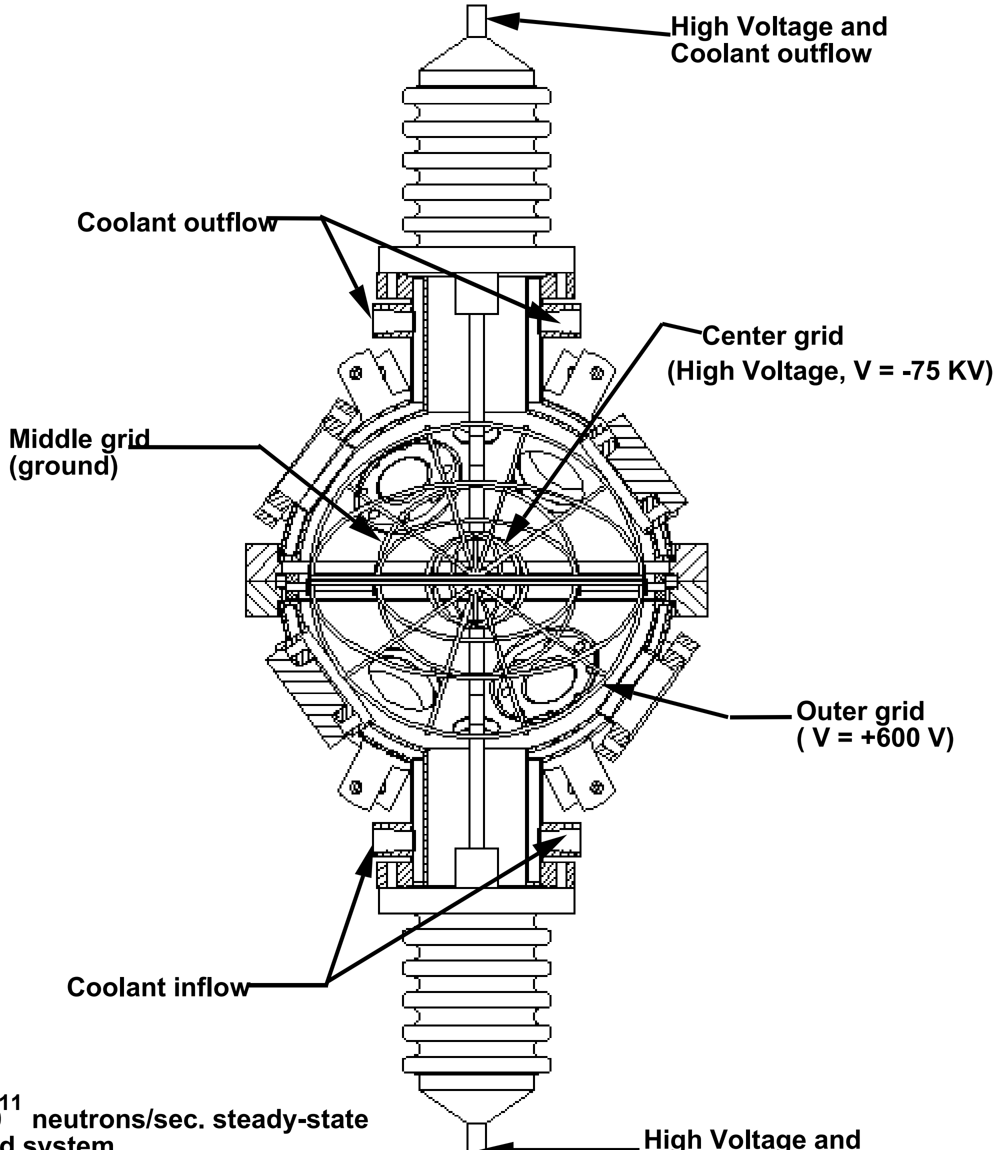
- **Look for ion current resonant response at POPS frequency.**

INS as Neutron Source



Parameter	Present	IEC Target or Already Proven
Neutron Yield (n/s)	10^8	10^{11} D-T or $5x10^8$ D-D
Lifetime (hours)	500	10,000
Operation	Pulsed	Pulsed or steady state
Nominal cost $k	$100k	Same
Power	1kW	25 kW

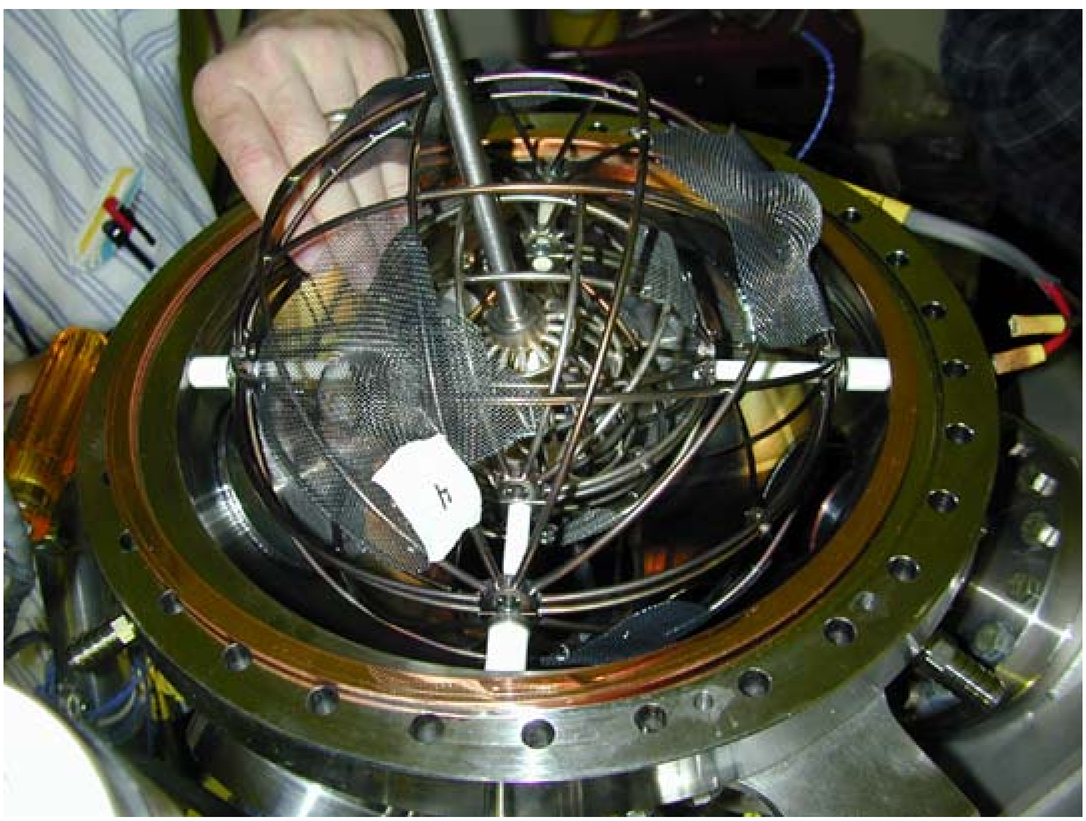
Cutaway view of INS showing grids



1×10^{11} neutrons/sec. steady-state
3 grid system
12 inches in diameter
Actively cooled
6 e-guns to ionize gas
25 KW of power (75 KV @ 335 mA)

INS Experiment

INS Device



Near-Term Applications

- Neutron source for "real-time" assay

  * HEU detection
  * Nuclear waste assay
  * Landmine detection
  * High explosive detection (Unexploded Ordnance)
  * Drug detection
  * Chemical and Biological Weapons

- Higher gain applications

  * Neutron tomography (imaging for the above)
  * Isotope production
  * Transmutation of waste
  * Power production (POPS required)

Nuclear Assay Applications

* **High Explosives Detection (UXO, Landmines, Chemical Weapons Dispersant, "Suitcase Sniffers", Truck Bombs, etc.)**

  - $H^2 + H^3 \rightarrow He^4 + n$ (14.1 MeV) (fusion reaction)
  - $N^{14} + n \rightarrow N^{15} + \gamma$ (10.8 MeV)

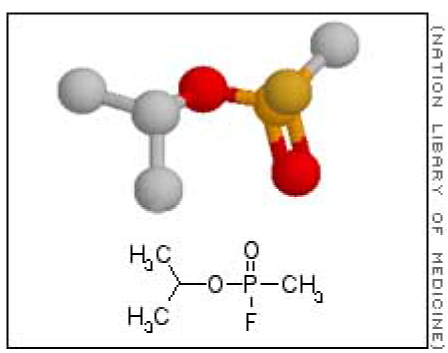
* **Special Nuclear Materials Detection**

  - $H^2 + H^3 \rightarrow He^4 + n$ (14.1 MeV) (fusion reaction)
  - $U^{235} + n \rightarrow fp + 3n$ (fission and neutron multiplication or delayed neutrons)

* **Spent Fuel Assay**

  - $H^2 + H^3 \rightarrow He^4 + n$ (14.1 MeV) (fusion reaction)
  - $U^{235} + n \rightarrow fp + 3n$ (fission and neutron multiplication)
  - $Pu^{239} + n \rightarrow fp + 3n$ (fission and neutron multiplication)

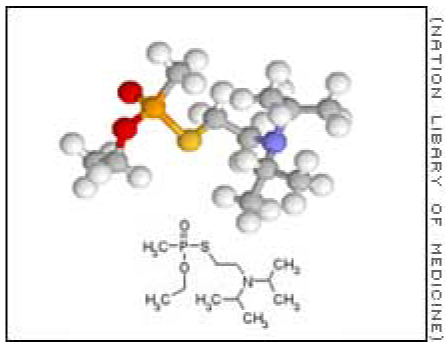
* **Sarin Detection**



  - $H^2 + H^3 \rightarrow He^4 + n$ (14.1 MeV) (fusion reaction)
  - $P^{31} + n \rightarrow P^{32} + \gamma$ (7.93 MeV)
  - $F^{19} + n \rightarrow F^{20} + \gamma$ (6.60 MeV)
  - $P^{32} \rightarrow S^{32} + e^-$ (1.17 MeV)
  - $F^{20} \rightarrow Ne^{20} + e^-$ (5.40 MeV)

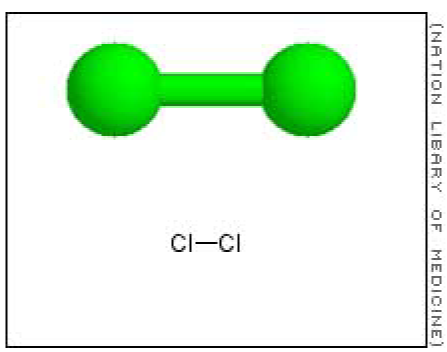
Nuclear Assay Applications cont.

* **VX**



- $H^2 + H^3 \rightarrow He^4 + n$ (14.1 MeV) (fusion reaction)
- $N^{14} + n \rightarrow N^{15} + \gamma$ (10.8 MeV)
- $P^{31} + n \rightarrow P^{32} + \gamma$ (7.93 MeV)
- $S^{32} + n \rightarrow S^{33} + \gamma$ (8.64 MeV)
- $P^{32} \rightarrow S^{32} + e^-$ (1.17 MeV)

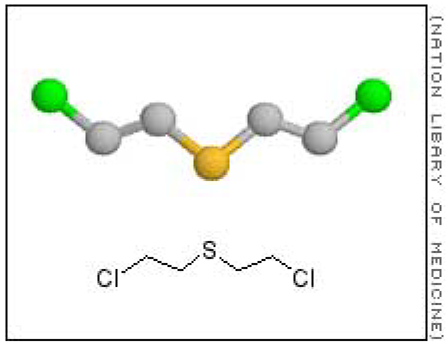
* **Chlorine**



- $H^2 + H^3 \rightarrow He^4 + n$ (14.1 MeV) (fusion reaction)
- $Cl^{35} + n \rightarrow Cl^{36} + \gamma$ (7.97 MeV)

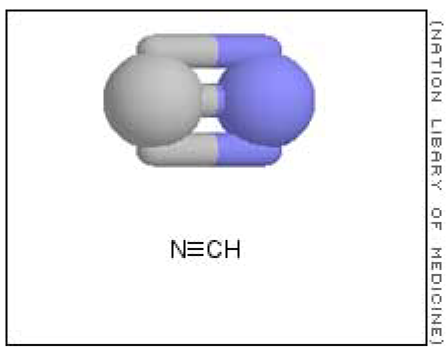
Nuclear Assay Applications cont.

* **Mustard gas**



- $H^2 + H^3 \rightarrow He^4 + n$ (14.1 MeV) (fusion reaction)
- $S^{32} + n \rightarrow S^{33} + \gamma$ (8.64 MeV)
- $Cl^{35} + n \rightarrow Cl^{36} + \gamma$ (7.97 MeV)

* **Cyanide**



- $H^2 + H^3 \rightarrow He^4 + n$ (14.1 MeV) (fusion reaction)
- $N^{14} + n \rightarrow N^{15} + \gamma$ (10.8 MeV)

* **Biological Weapons (Anthrax, Small Pox, etc.)**

- $H^2 + H^3 \rightarrow He^4 + n$ (14.1 MeV) (fusion reaction)
- n + processing chemicals $\rightarrow$ processing chemicals + γ

Conclusions

- **Potential profiles have been measured on INS-e with an emissive probe and compared with theoretical stability predictions.**

- **So far there is good agreement between theory and experiment, but the stability limits have not yet been accessed experimentally.**

- **Next Steps**

  - **Flatter Density Profiles.**

  - **Increase Voltage Operating Window.**

  - **Look for stability limit.**

  - **Look at fluctuation data.**

  - **Look for ion current resonant response at POPS frequency.**

- **Build a 1×10^{11} Ion-based D-T Source.**