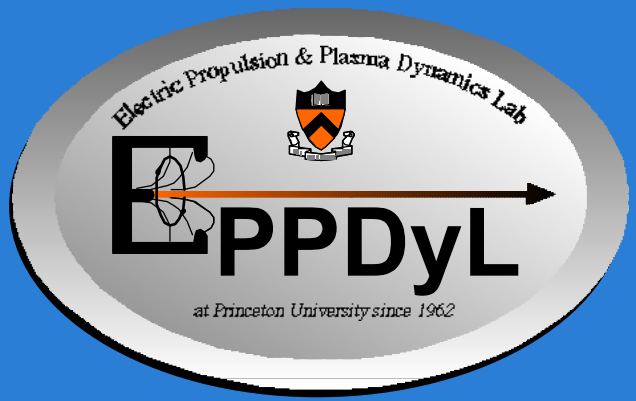
Advanced Electrodeless Plasma Propulsion Concepts



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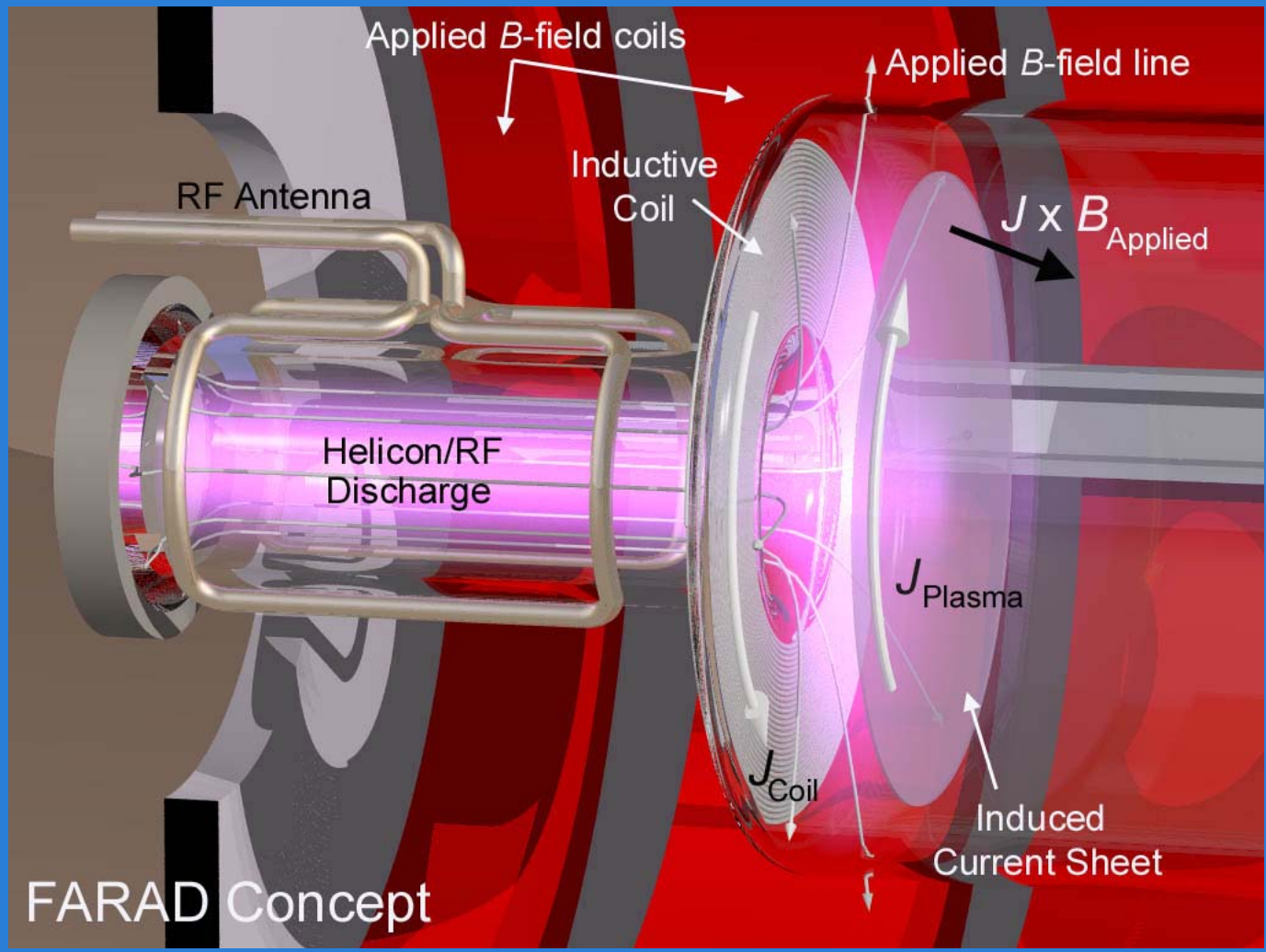
Outline

- I. FARAD: Faraday Accelerator with RF-Assisted Discharge
  - Basic Concept
  - Advantages
  - Basic Questions and Approach
  - Results of Proof-of-concept Experiment
- II. Ion Acceleration by Beating Electrostatic Waves
  - Basic Concept
  - Advantages
  - Basic Challenges
  - Status of Research

FARAD: Faraday Accelerator with RF-Assisted Discharge



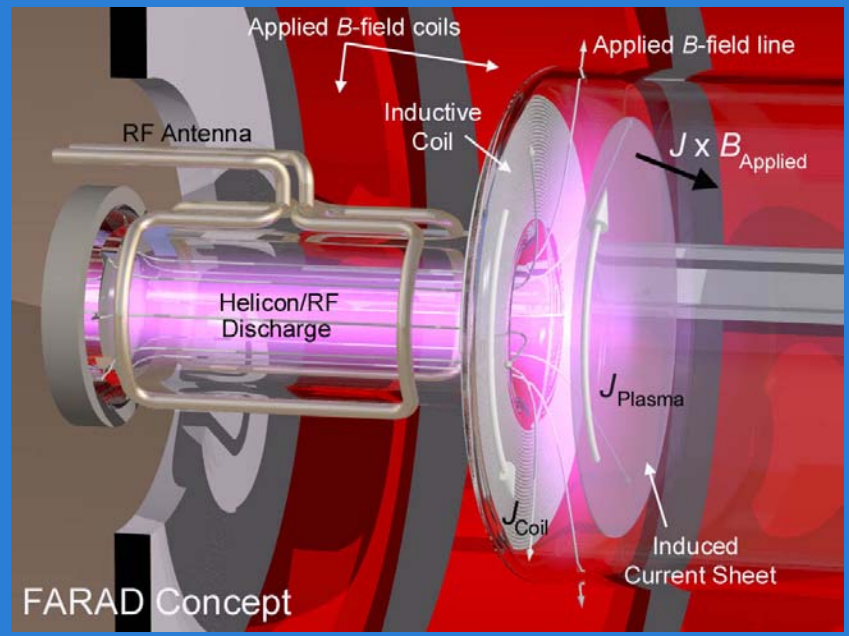
FARAD: Advantages

General:

- Completely electrodeless
- EM acceleration: High thrust density & I_{sp}
- Compatibility with a wide variety of propellants
- High mass utilization efficiency
- Accelerating forces are *always* perpendicular to ***B:*** No detachment issues
- Pulsed: can be used on power-limited s/c

With respect to PIT:

- Much more compact device
- No obstacles in plasma stream
- Additional axial Lorentz force: $J_\theta B_r$
- Plasma confinment through $J_\theta B_z$ leads to low wall losses



FARAD: Basic Questions

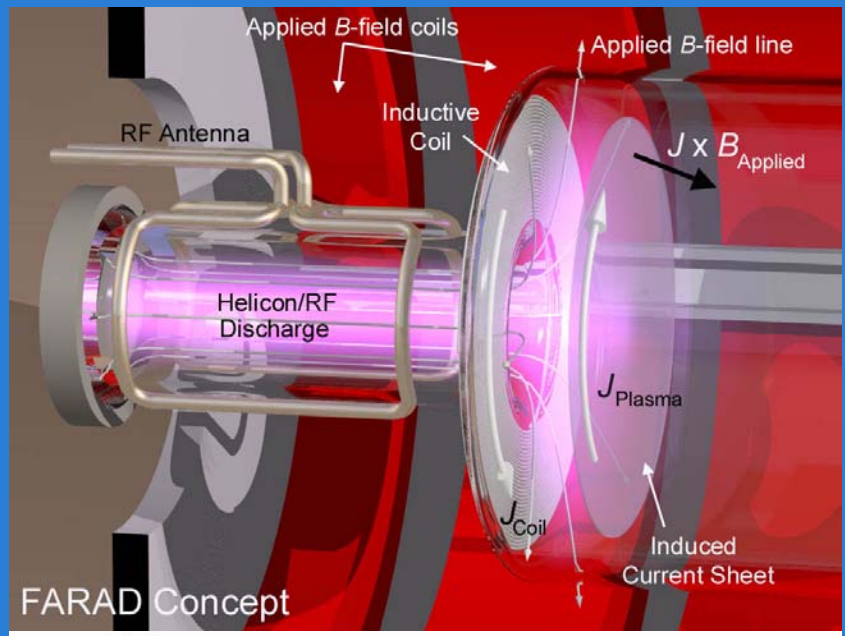
- What are the fundamental features and governing relations of the acceleration mechanisms?
- What are the fundamental limitations and major loss mechanisms?
- What are the scaling laws?
- How to choose the various controllable parameters (propellant, injected mass bit, RF power, B-field strength and topology, RF pulse length, inductive coil current and pulse length, geometrical dimensions, etc.) in order to optimize the performance?

FARAD: Approach

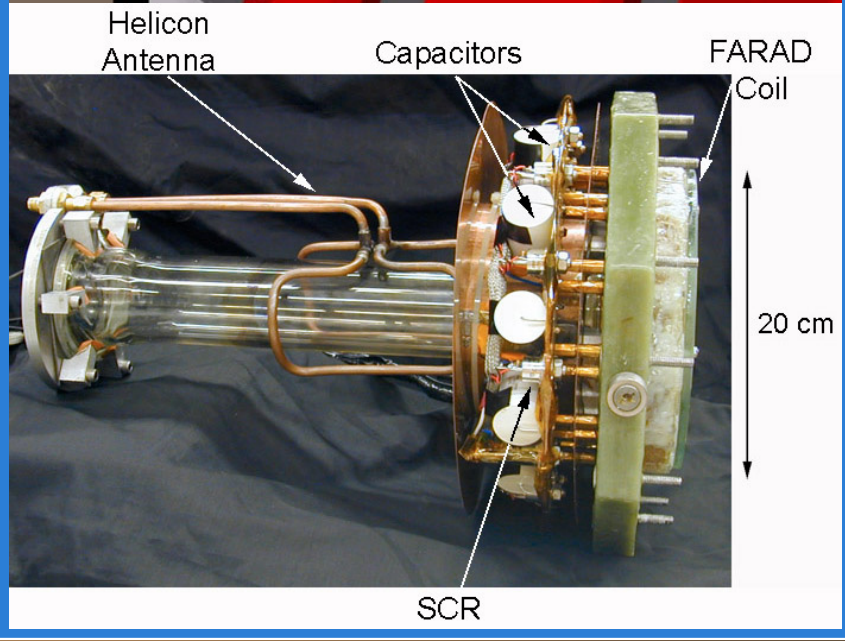
- ✓ Develop **Proof-of-concept Experiment** and demonstrate current sheet formation and acceleration.
- Extensive Characterization of Plasma, Current Sheet and accel. mechanisms
- Analytical and Numerical Modeling
- Optimization of Operational Parameters
- Design and Manufacturing a Prototype FARAD Thruster
- Extensive Performance Testing and Optimization

FARAD: Proof-of-Concept Experiment

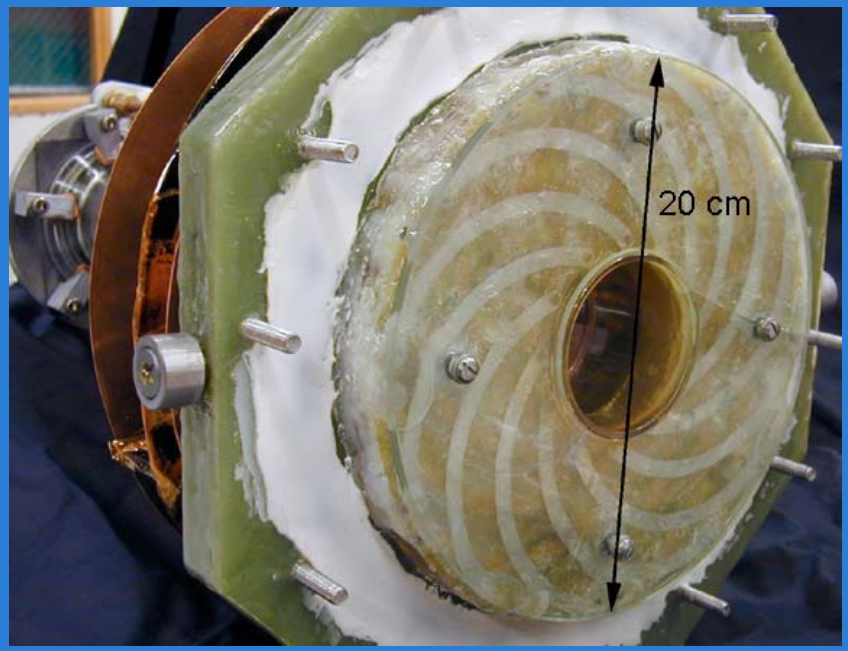
Concept

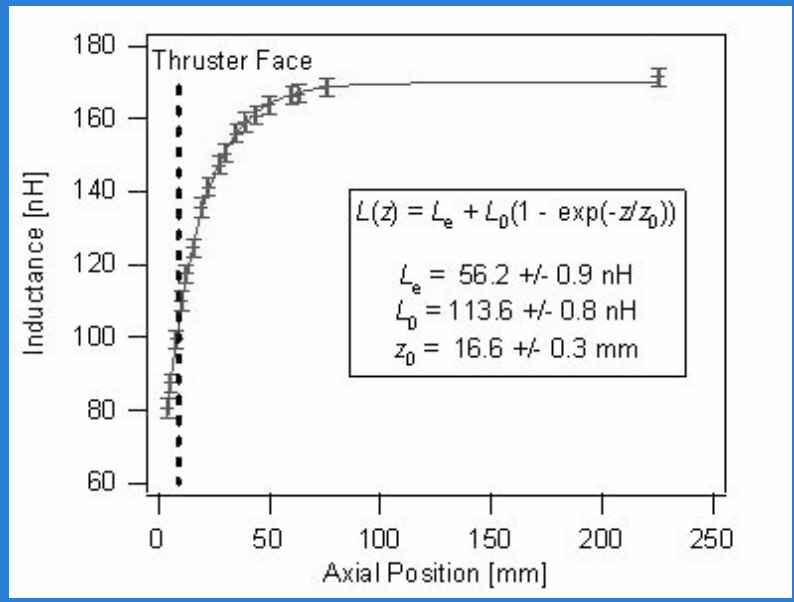


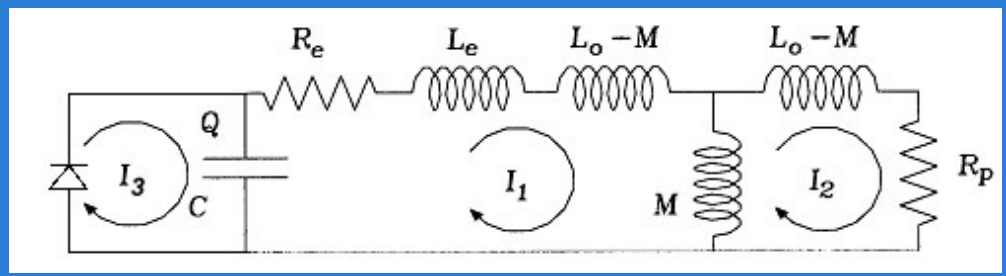
Experiment



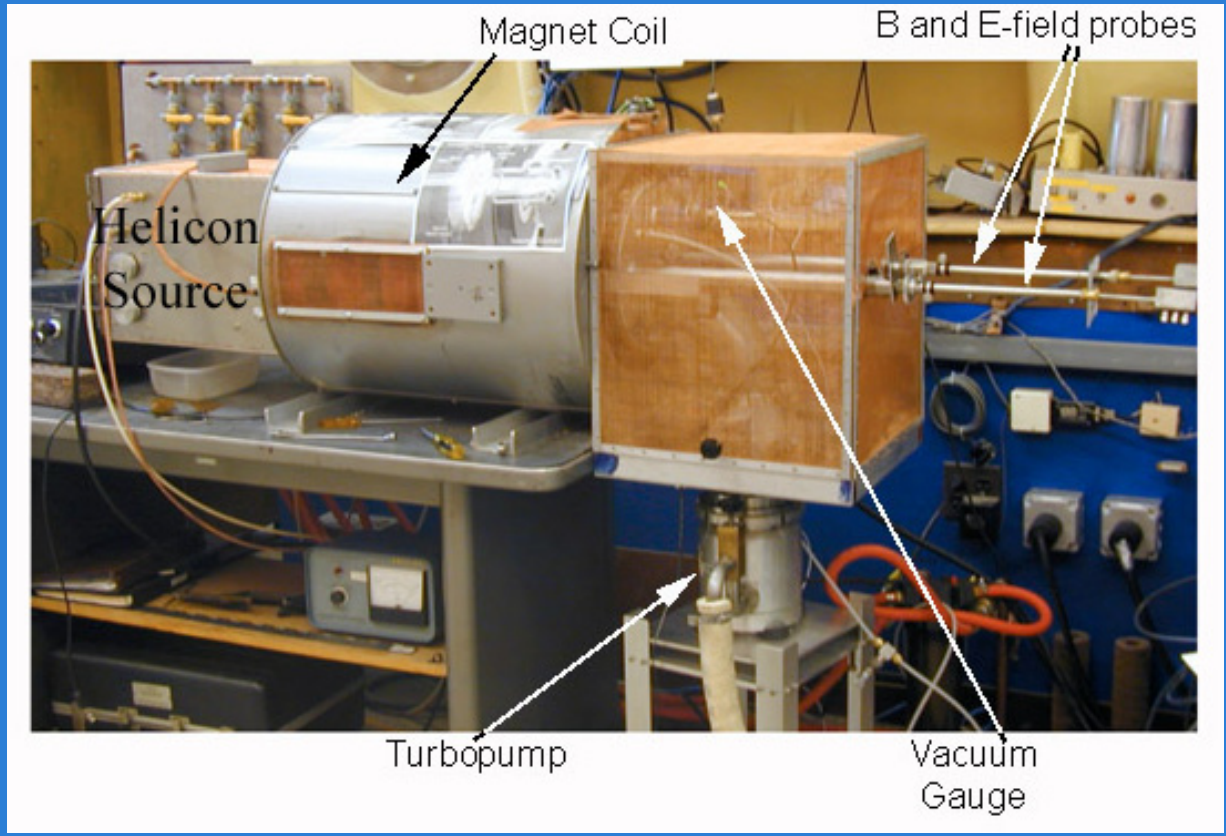
FARAD: Proof-of-Concept Experiment: J_θ coil



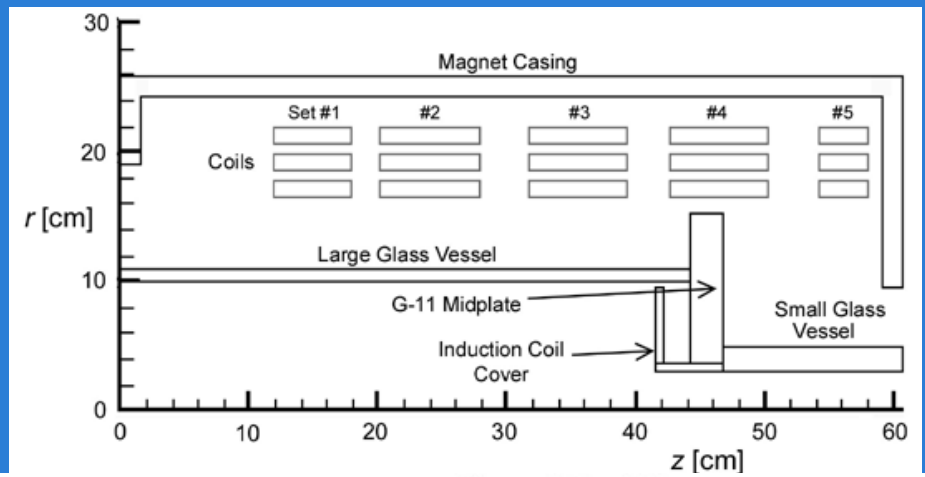


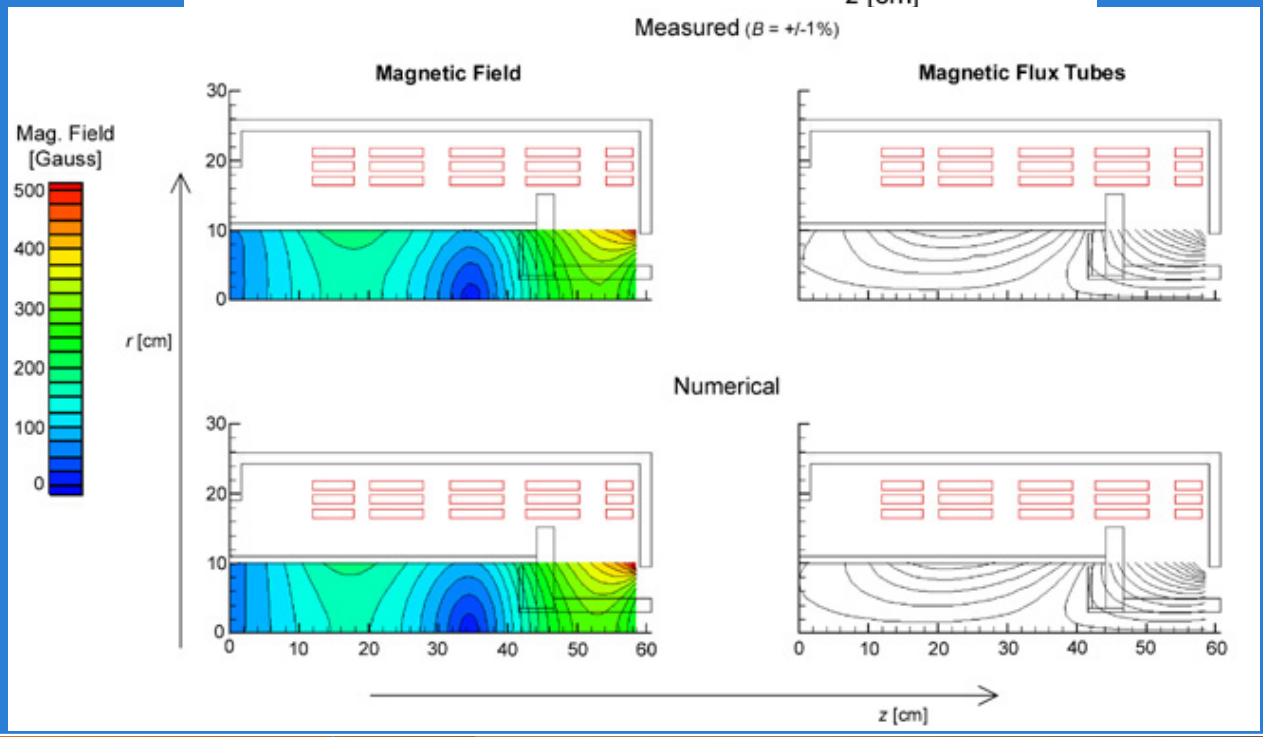


FARAD: Proof-of-Concept Experiment: Set-up

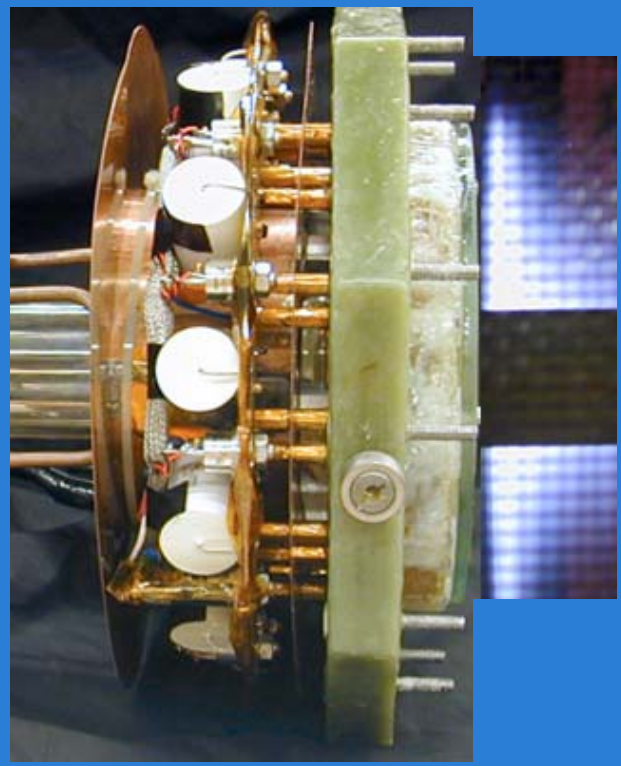


Field

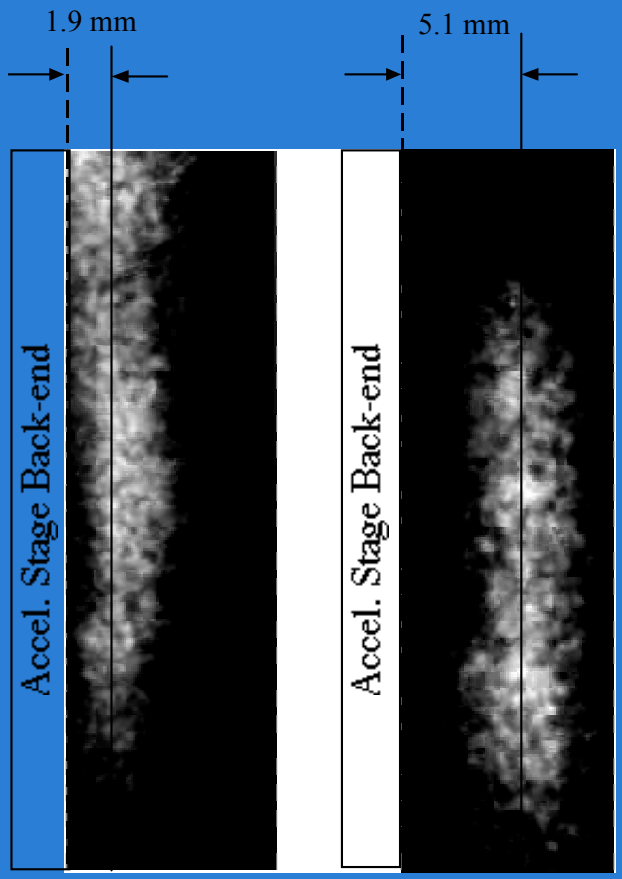

Magnet Casing
Set #1
#2
#3
#4
#5
Coils
r [cm]
Large Glass Vessel
G-11 Midplate
Small Glass Vessel
Induction Coil Cover
z [cm]


Measured (B = +/-1%)
Magnetic Field
Magnetic Flux Tubes
Mag. Field [Gauss]
r [cm]
Numerical
z [cm]

FARAD: Proof-of-Concept Experiment:
Demonstration of passive plasma feeding

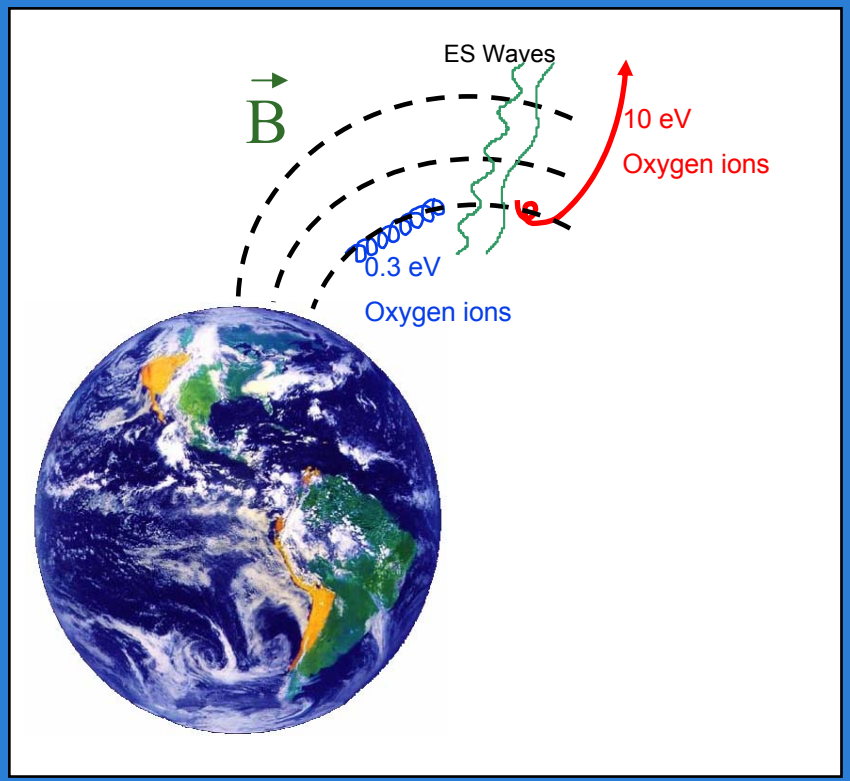


FARAD: Proof-of-Concept Experiment:
Demonstration of Current Sheet Formation and Acceleration



II. Ion Acceleration by Beating Electrostatic Waves

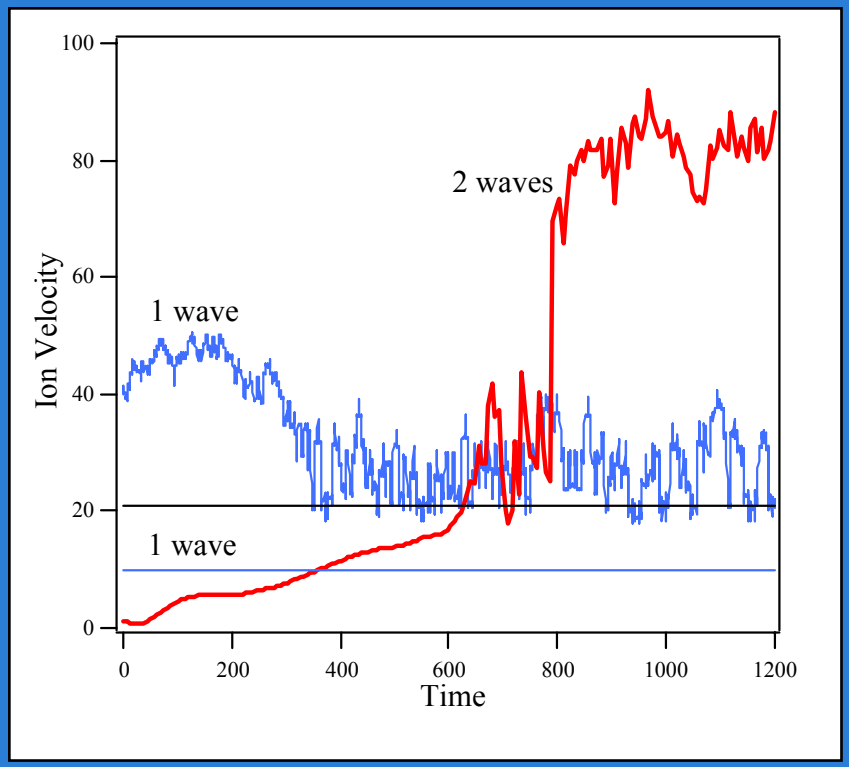
Inspiration : Ionospheric Observations



- Low-energy Ionospheric oxygen ions naturally accelerated and reach escape velocities.
- Intense Lower Hybrid Waves: ~ 100 mV/m, 2-12 kHz, Electrostatic in nature.
- Classical ion acceleration by (resonant) ES waves fails to explain the observations. (Initial ion velocity < Threshold interaction velocity)
- 1998: Benisti et. al. (MIT) propose that a beating of 2 ES waves may be responsible.

J. Geophys. Res. **103** *9431 (1998)*

Beating Waves Vs. Single Wave

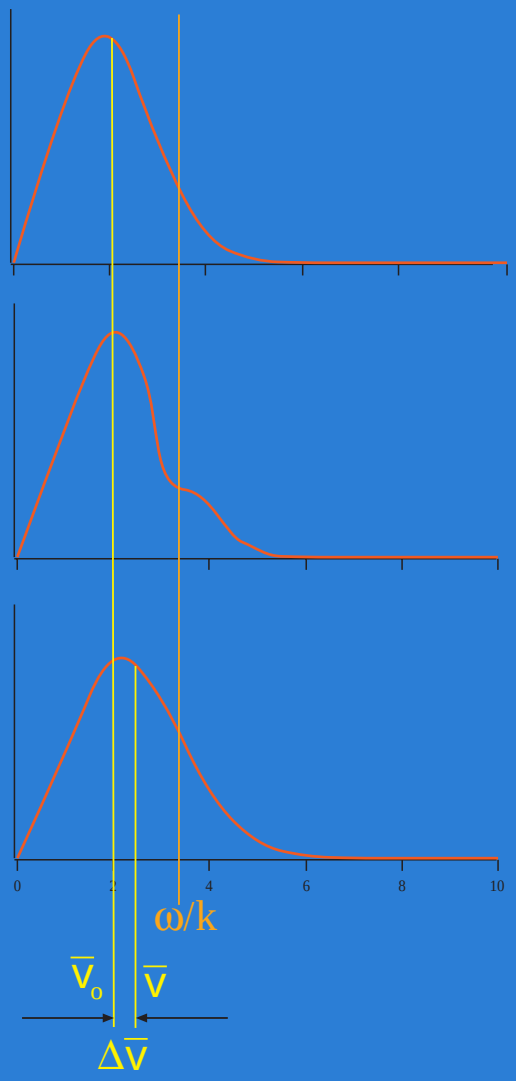


What are the conditions for Ion acceleration by Beating waves?

Necessary Condition: $\omega_i - \omega_j = n\omega_c$

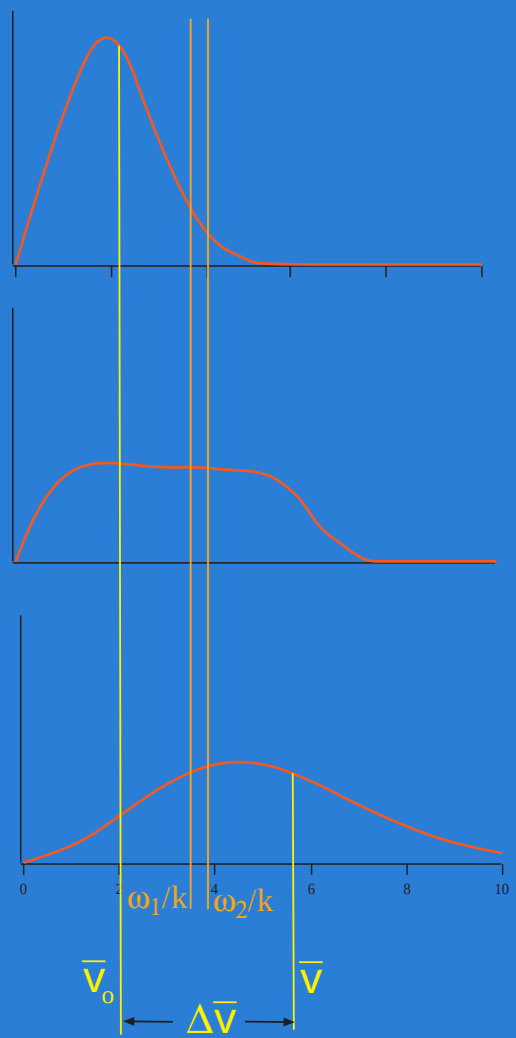
Resonant Energization

$\omega=\omega_{ci}$



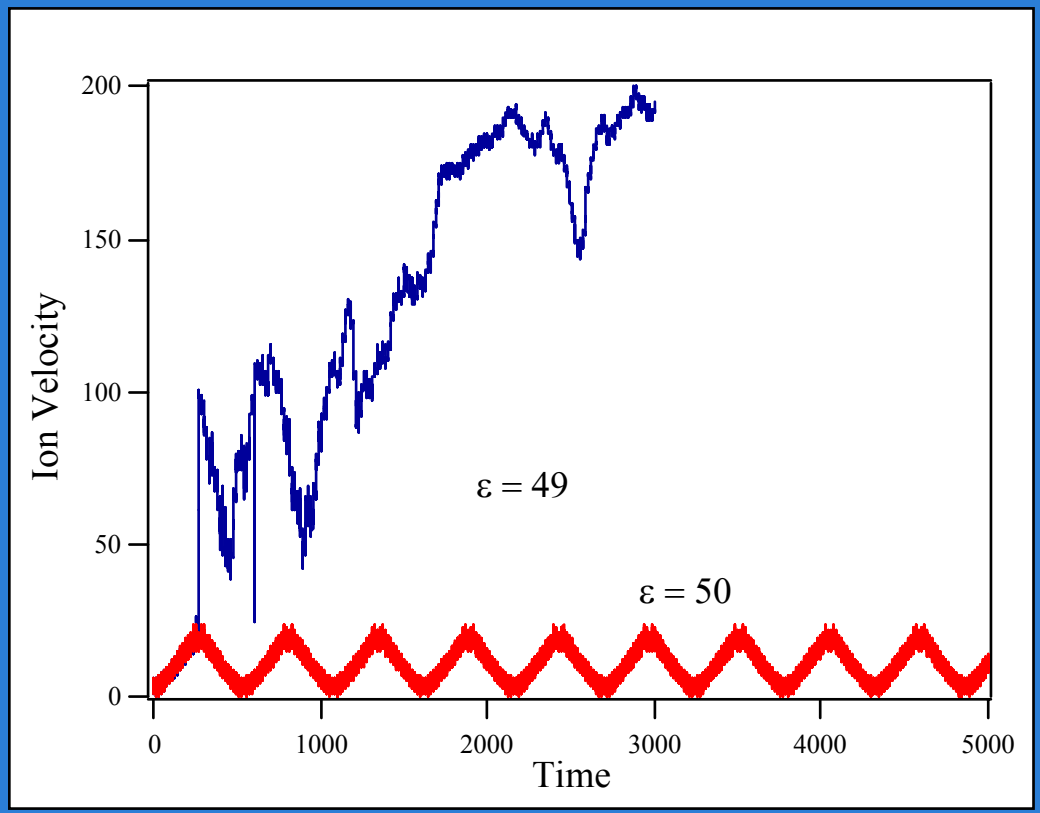
Beating Wave Energization

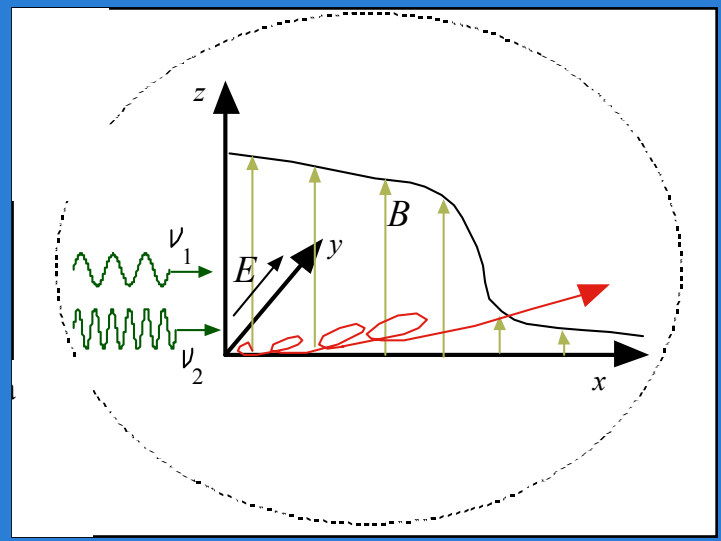
$\omega_2-\omega_1=\omega_{ci}$



Benisti's Criterion is not Sufficient!

Choueiri & Spektor, AIAA-2000-3759, IEPC-01-209





What are the necessary and sufficient conditions for Ion acceleration by beating waves?

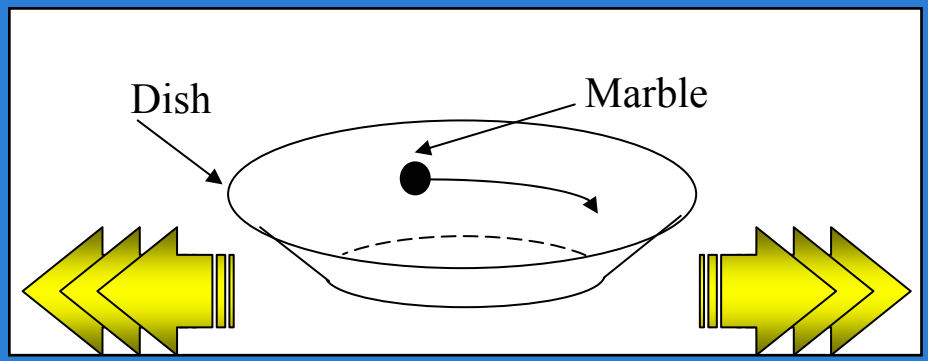
Are there Necessary and Sufficient Criteria for Acceleration?

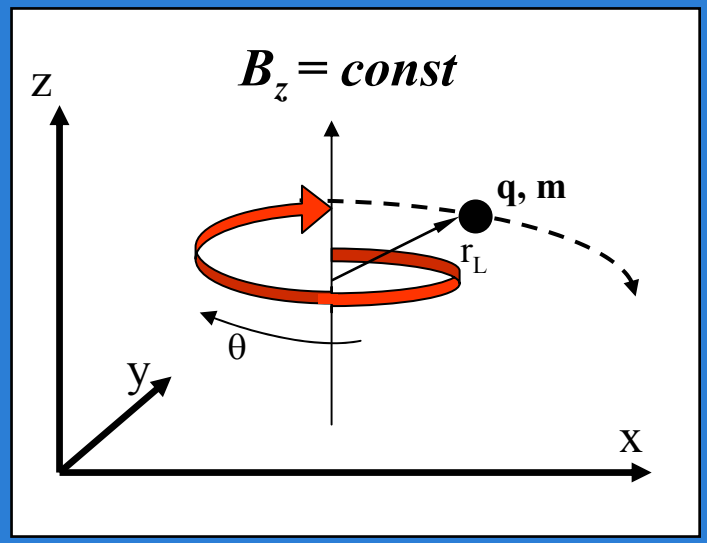
Yes

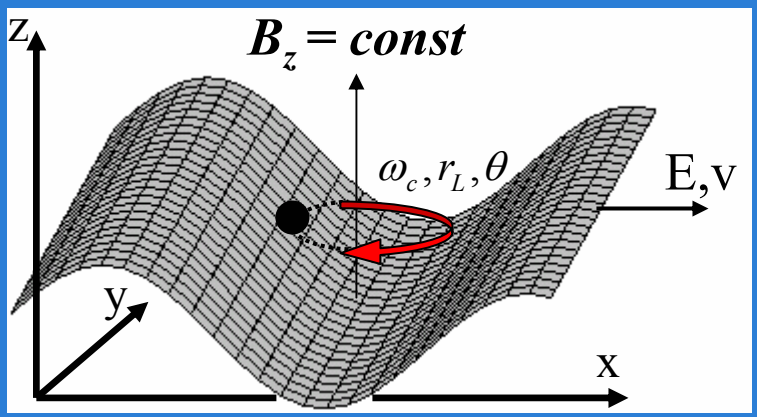
Spektor & Choueiri, *Physical Review E*, March 2004

Model – Basic Concept

Single particle, constant magnetic field, multiple waves







$$\ddot{x} + \omega_{ci}^2 x = \frac{q}{m} \sum_i E_i \cos(\kappa_i x - \omega_i t)$$

Approach

Hamiltonian

$$H = \frac{\rho^2}{2} + \sum_i \frac{\varepsilon_i}{\kappa_i} \cos(\kappa_i \rho \sin\theta - \nu_i \tau)$$

Numerical Solution: Symplectic Integration Algorithm

J. Comp. Phys. **92** *230 (1991)*

Analytical Solution: 2nd order perturbation theory + Lie transformations

Phys. Plasmas ***3****(5), May 1996, 1545*

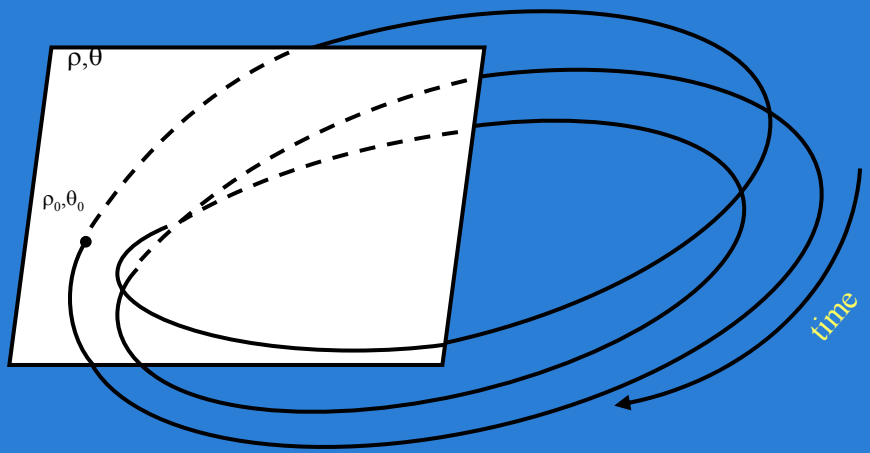
Poincare surface of section (Reduced phase space diagram)

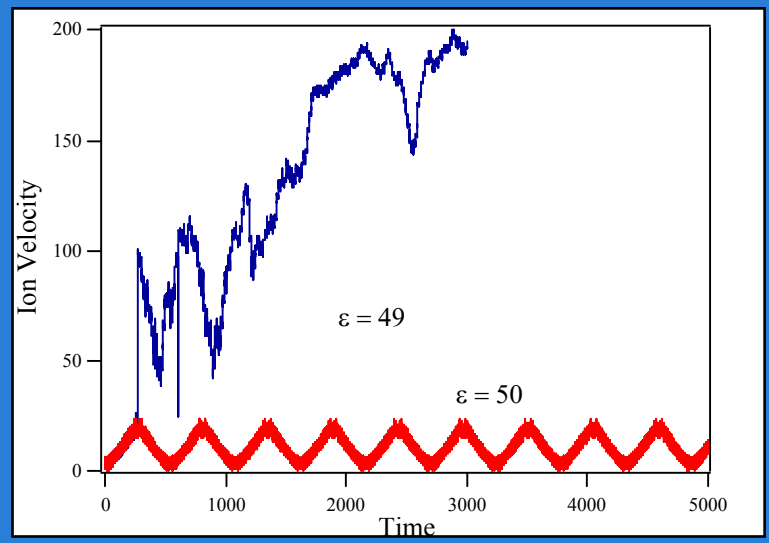
Poincare diagram construction

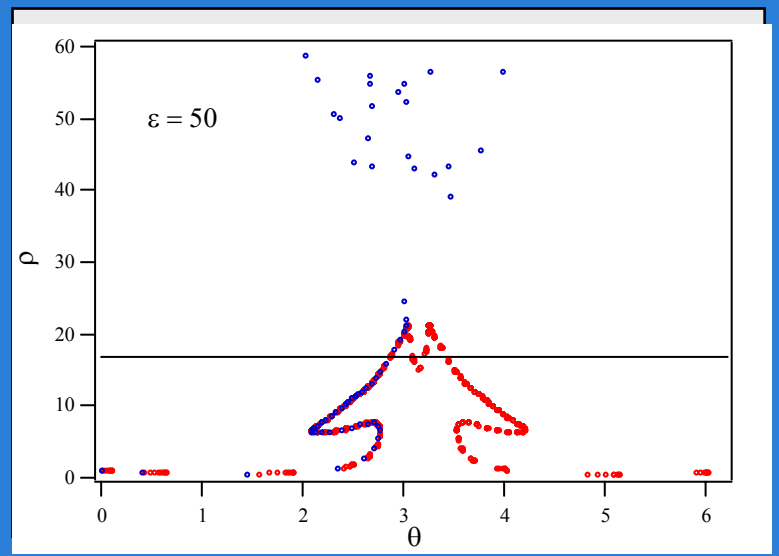
1 - D periodic Motion

$(\rho,\theta,t) = (\rho,\theta,t+T)$

T = period

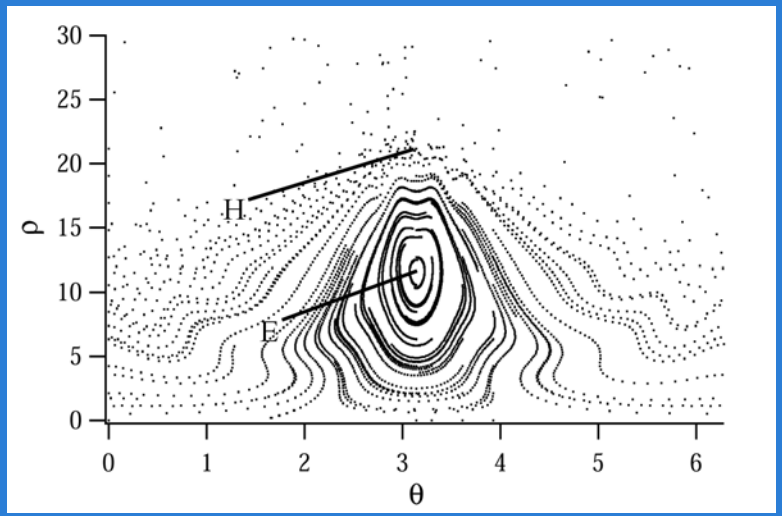




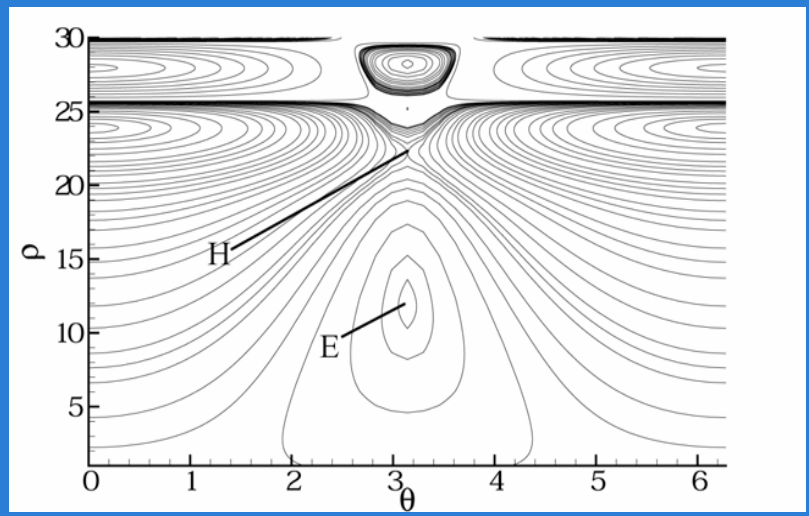


Trapped Particles & Domain of Allowed Acceleration

Numerical Simulation



2nd-order Perturbation Theory



Hamilton's Eqns

$$
\begin{aligned}
\dot{\rho} &= \frac{\partial H}{\partial \theta} = \varepsilon\{\nu_i J_{\nu_i}(\rho)\sin(\nu_i\theta) \\
&+ \nu_j J_{\nu_j}(\rho)\sin(\nu_j\theta)\} \\
&+ \varepsilon^2(\nu_i-\nu_j)S_6^{\nu_i,\nu_j}(\rho)\sin[(\nu_j-\nu_i)\theta] = 0, \\
\dot{\theta} &= -\frac{\partial H}{\partial \rho} = \varepsilon\{J'_{\nu_i}(\rho)\cos(\nu_j\theta) \\
&+ J'_{\nu_j}(\rho)\cos(\nu_j\theta)\} \\
&+ \varepsilon^2\{S_1^{'\nu_i}(\rho) + S_1^{'\nu_j}(\rho) \\
&+ S_6^{'\nu_i,\nu_j}(\rho)\cos[(\nu_i-\nu_j)\theta]\} = 0.
\end{aligned}
$$

$$
\begin{aligned}
H &= \frac{\varepsilon^2\pi}{8\sin\nu\pi}\left(1+\frac{\rho}{\nu}\cos\theta\right) \\
&\Big[- J_{\nu-1}(\rho)J_{-(\nu-1)}(\rho) + J_\nu(\rho)J_{-\nu}(\rho) \\
&+ J_{\nu+1}(\rho)J_{-(\nu+1)}(\rho) - J_{\nu+2}(\rho)J_{-(\nu+2)}(\rho)\Big]
\end{aligned}
$$

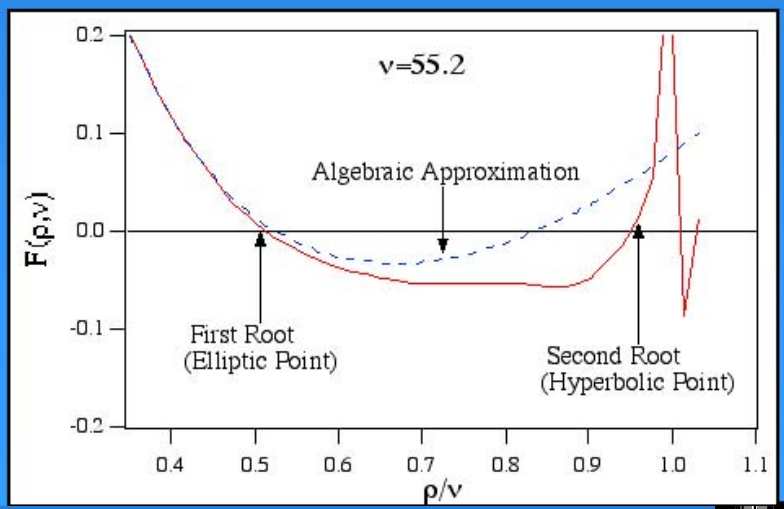
Hamiltonian from 2nd order perturbation theory + Lie Transforms

Bessel functions properties

$$
F(\rho,\nu) \simeq \frac{\rho}{\nu} - 1 + \frac{2}{3\left(f_{\nu-1} + f_{-(\nu-1)} + f_{\nu+2} + f_{-(\nu+2)}\right)} = 0
$$

where $f_\nu = f_\nu(\rho) \equiv J'_\nu/J_\nu$

Simplified Eqn. for locating critical points



Necessary and Sufficient Criteria

Benisti's beat criterion:

$$\omega_2 - \omega_1 = n\omega_c$$

Additional criterion:

$$H_H < H(\rho_0, \theta_0) < H_E$$

$$H_H = H(\rho \simeq \nu - \sqrt{\epsilon}; \theta = \pi).$$

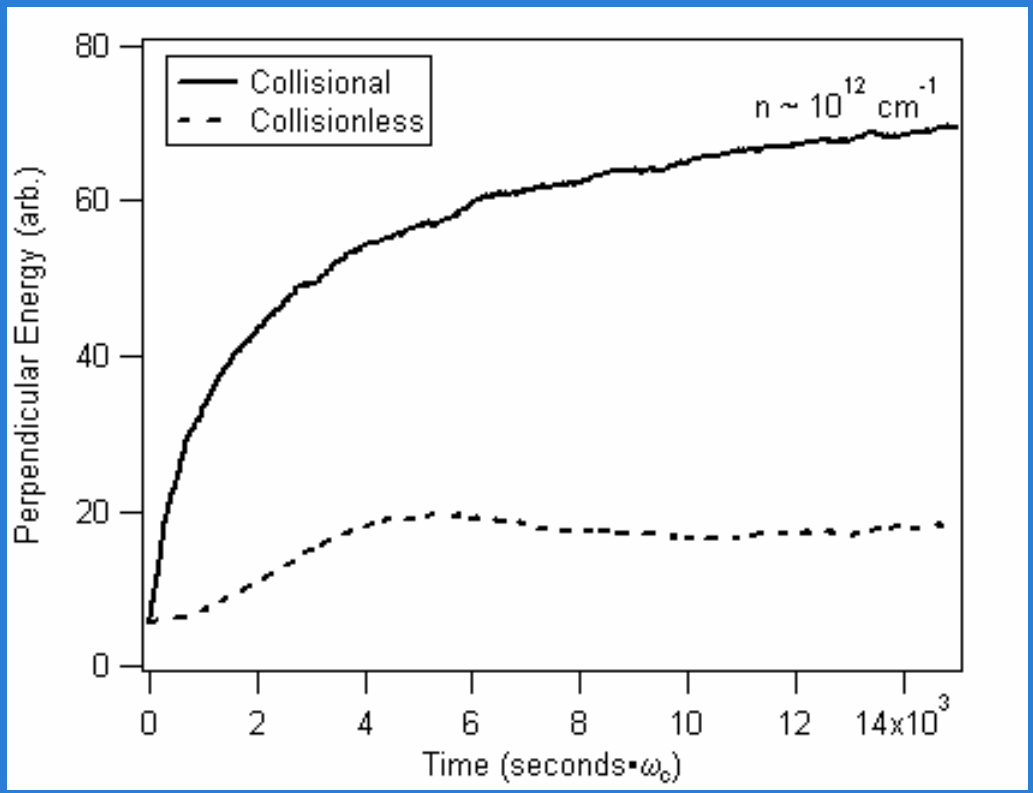
$$H_H \simeq H(v \simeq \frac{\omega}{k}; \theta = \pi).$$

$$H_E = H(\rho \simeq \frac{\nu - \sqrt{\epsilon}}{2}; \theta = \pi).$$

$$H_E \simeq H(v \simeq \frac{\omega}{2k}; \theta = \pi).$$

Does it work for many particles with collisions?

Monte Carlo simulations



$\nu_{ii} \sim 10 \bullet \omega_{ci}$

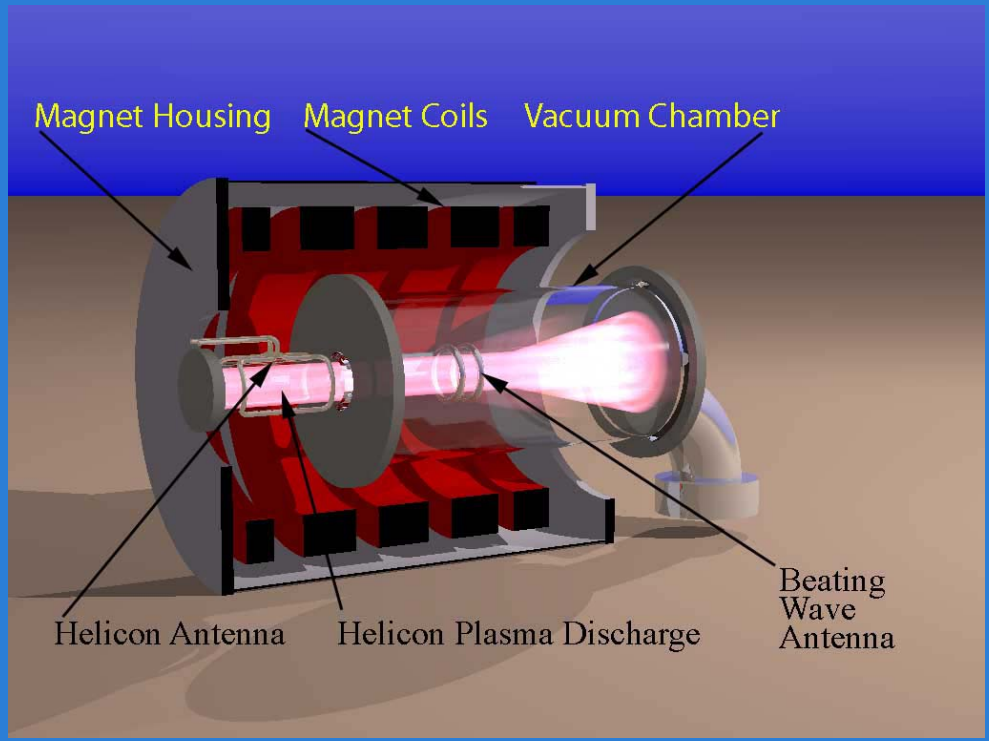
- Ion – ion collisions enhance acceleration!
- Ehancement is due to depopulation of trapped region of phase space due to collisions.

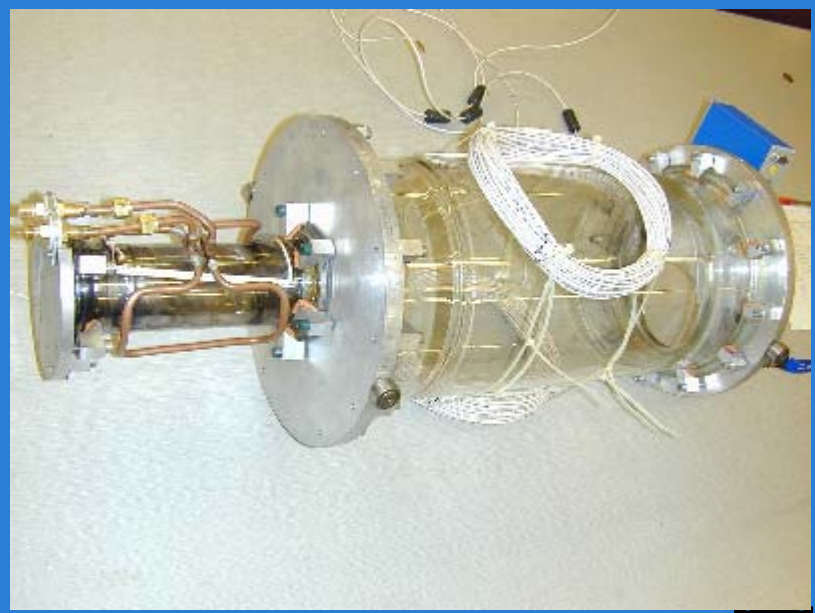
Summary of Theoretical Findings

- Previously proposed criterion is necessary but not sufficient.
- Poincare diagram shows that trapped particles lie between critical elliptic and hyperbolic points.
- New criterion found and relies on the value of the Hamiltonian at the motion's critical points.
- Collisions enhance the effect.
- Ions with arbitrarily low initial velocity can be accelerated in contrast with non-beating waves.
  - — Seems to occur naturally in the ionosphere
  - —Promise for propulsion applications and more efficient ion heating.

TIME FOR EXPERIMENTAL VERIFICATION

Experimental Apparatus





RF Power: 100 – 1200 Watt

Magnetic Field: 0.08 Tesla

Plasma Density: $10^{10} – 10^{13}$ cm^{-3}

$T_e \sim 3\text{-}5$ eV, $T_i \sim 0.1\text{-}0.3$ eV

Experimental Apparatus

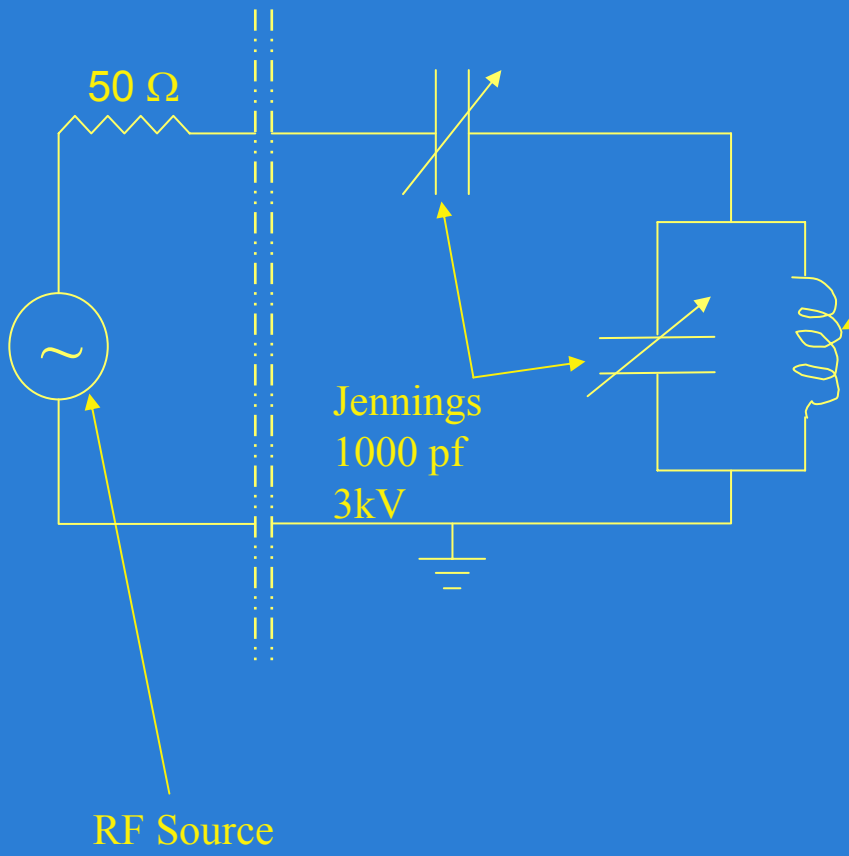
Base Pressure: ~ 10^{-6} Torr

Operating Pressure: ~ 10^{-3} Torr

Electric Circuit for Helicon Source

P_{RF} up to 1.2 kW

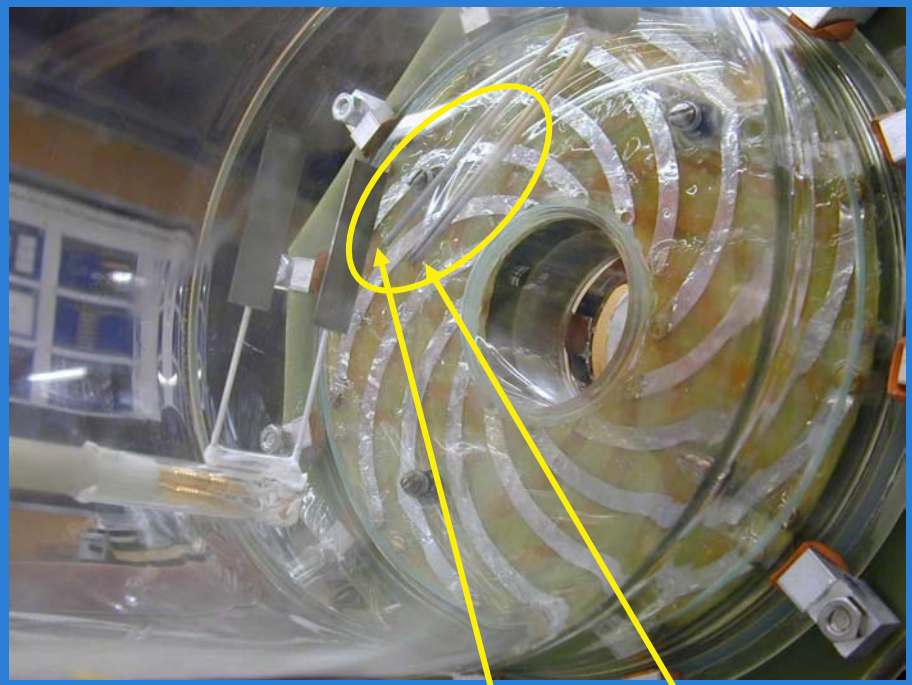
$\omega \sim 13.56$ MHz

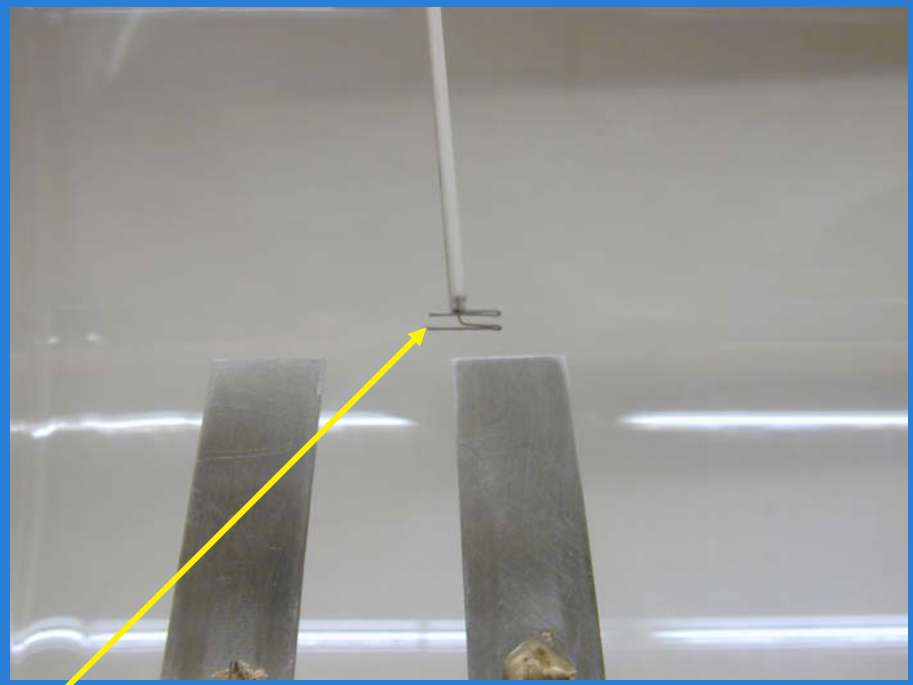


Dedicated Diagnostics

- Langmuir Probes (n_e, T_e)
- Hall Probes (B field)
- Probe interferometry (Dispersion Relation)
- Retarding Potential Analyzer (Ion velocity)
- LIF (Ion Velocity)

Launching Waves



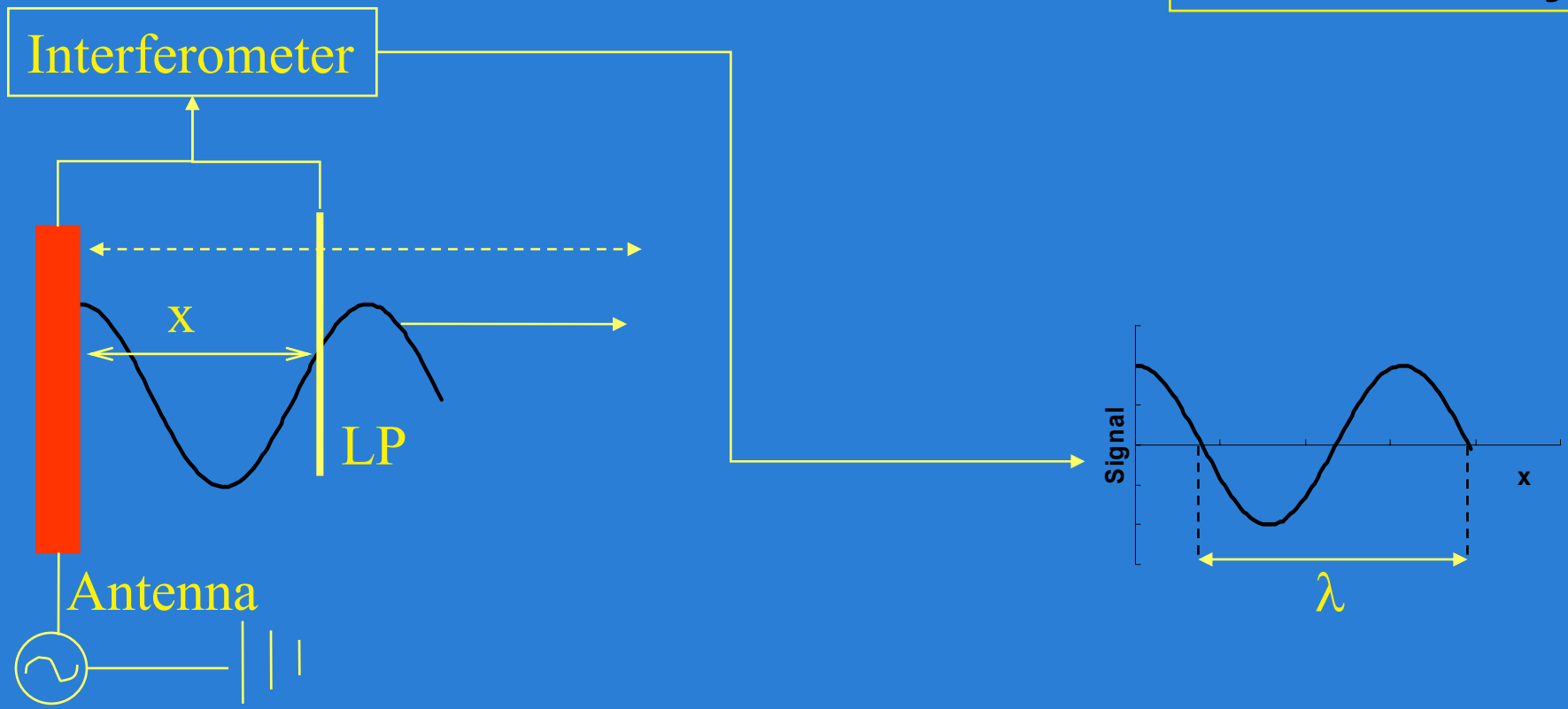


Langmuir Probes

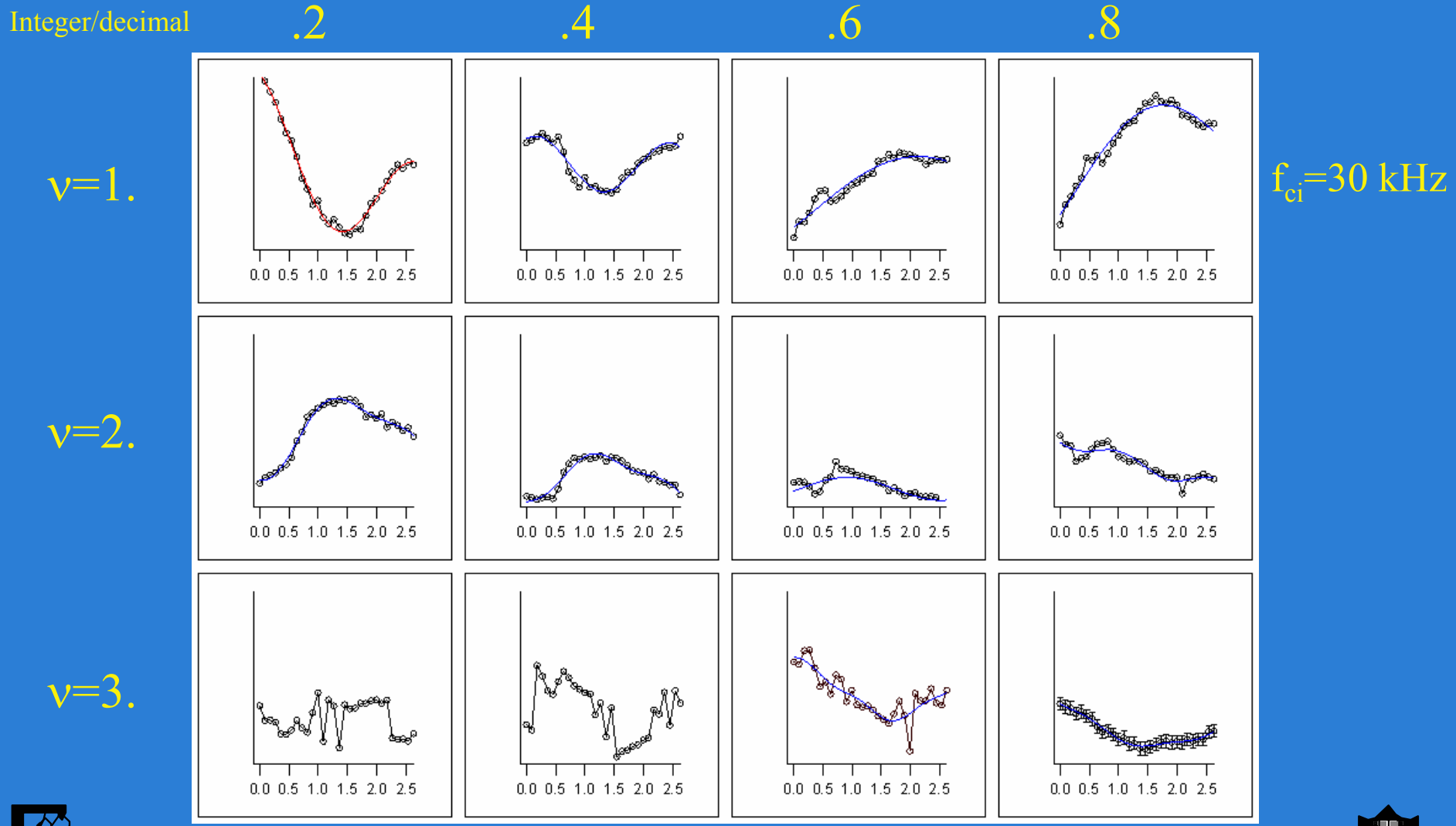
- Need to launch an electrostatic wave ⊥ to the magnetic field
- Measuring the dispersion to determine the nature of the wave

Detecting the Waves

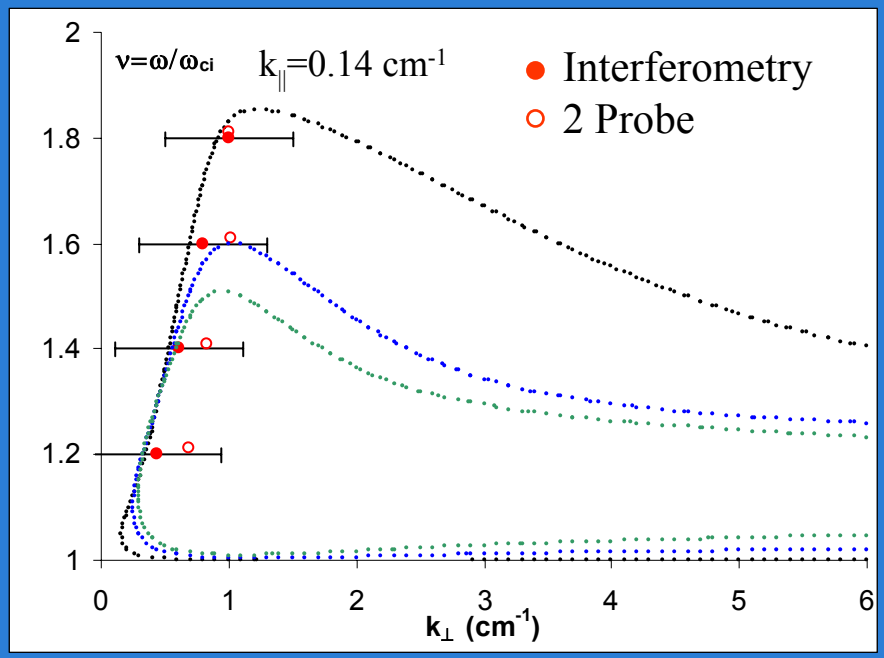
Interferometry



125 W Interferometry Data



Internal Antenna – Data Interpretation



- Electrostatic Ion Cyclotron fast wave is launched
- Good agreement with theory
- Indirect evidence of ion energization
- Direct evidence will be obtained next month with LIF

Conclusions

- Two electrodeless plasma acceleration concepts with promised for pulsed and steady-state propulsion are investigated

  - FARAD: Proof of concept experiment verified basic principle

  - Beating wave ion acceleration:

    - Found fundamental acceleration criteria
    - Monte Carlo simulation verified that the effect can exist in a real plasma with collisions
    - Dedicated experiment is yielding first laboratory observations of new acceleration mechanism.