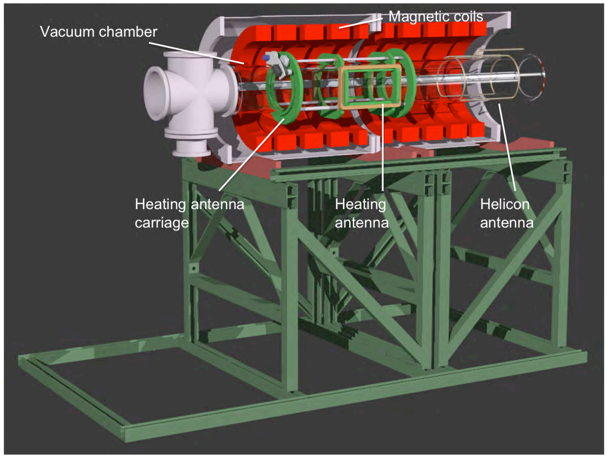
Ion acceleration by beating electrostatic waves



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Seminar at the Michigan Institute for Plasma Science and Engineering
The University of Michigan
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Can nature inspire us a new plasma propulsion concept?

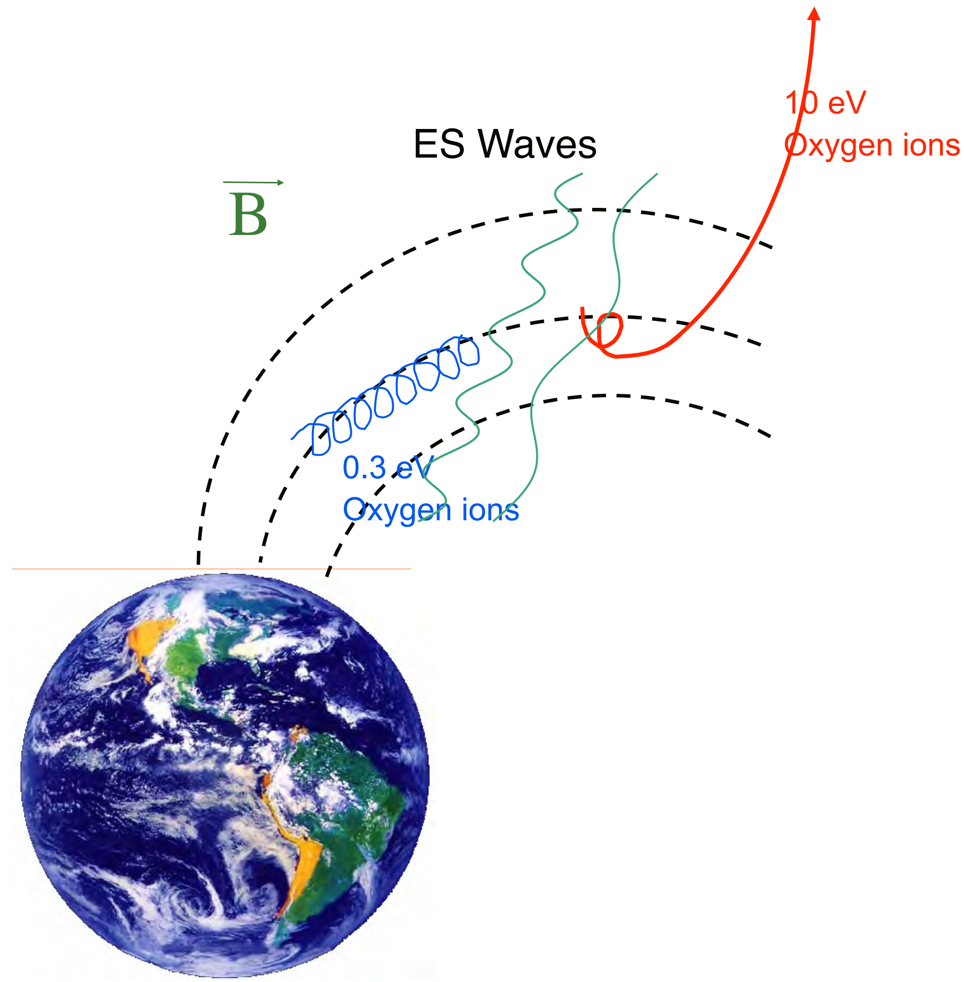
Why is it promising?

Under what conditions can it occur?

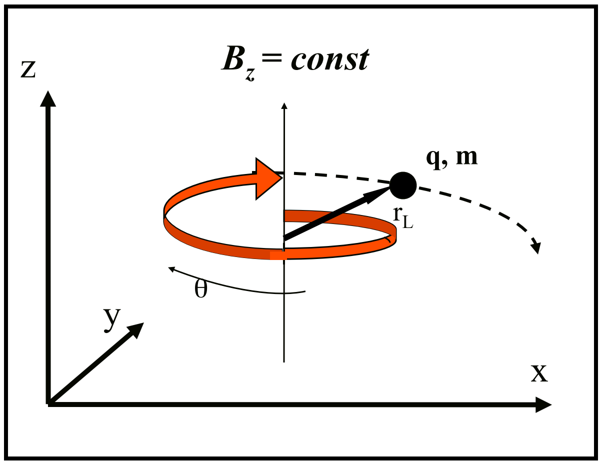
How does it work?

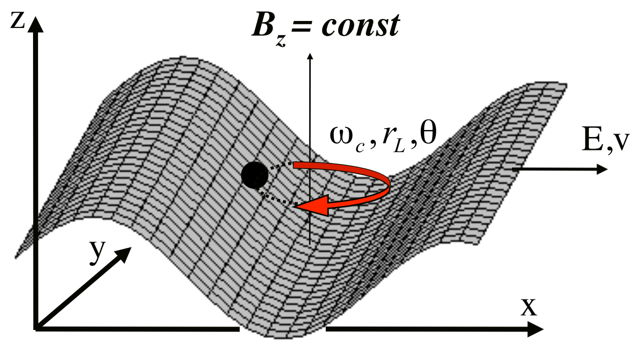
Can it be replicated in the lab?

Can nature inspire us a new plasma propulsion concept?


ES Waves
$\vec{B}$
10 eV
Oxygen ions
0.3 eV
Oxygen ions

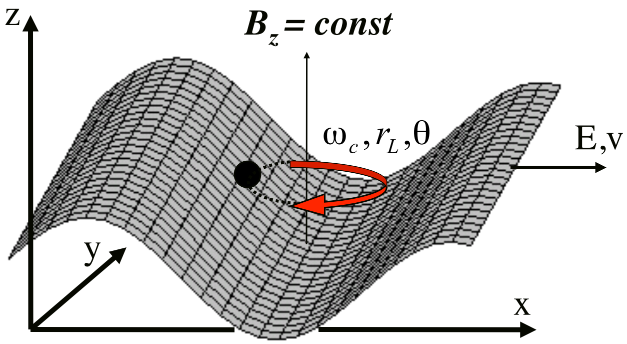
Ion Acceleration by ES Waves

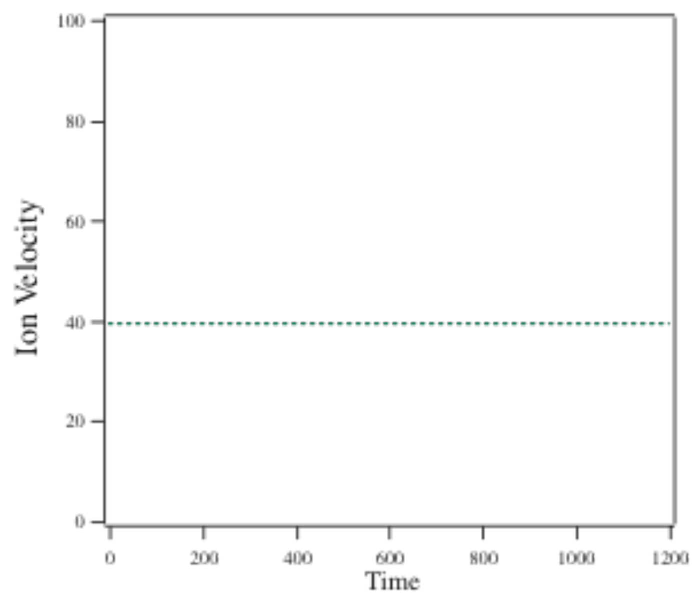




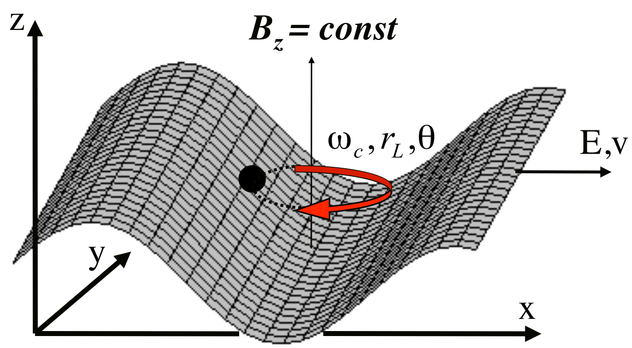
$$\ddot{x} + \omega_{ci}^2 x = \frac{q}{m} \sum_i E_i \cos(k_i x - \omega_i t)$$

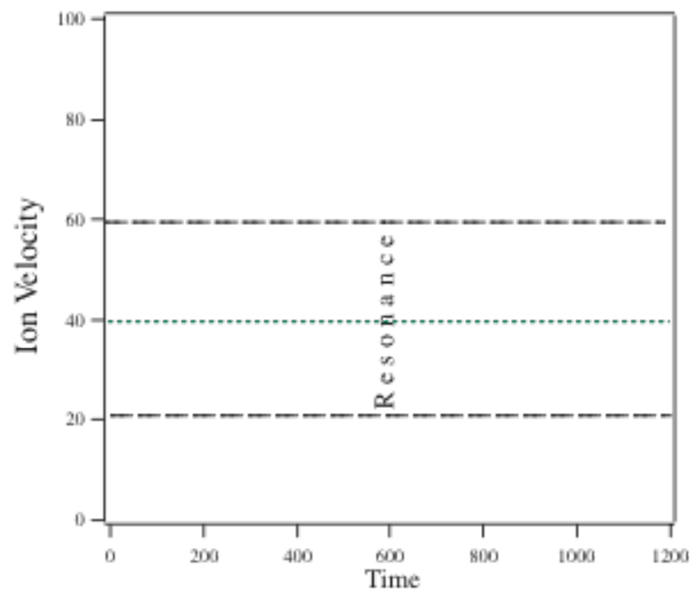
Ion Acceleration by ES Waves



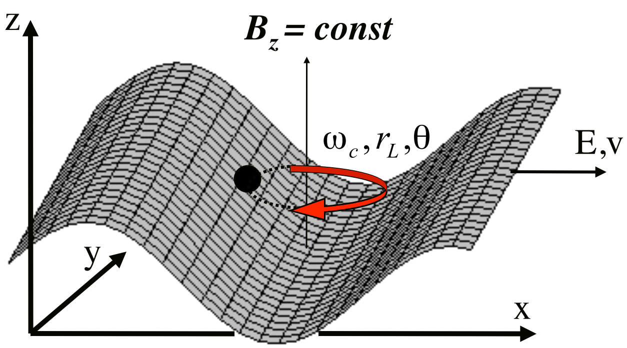


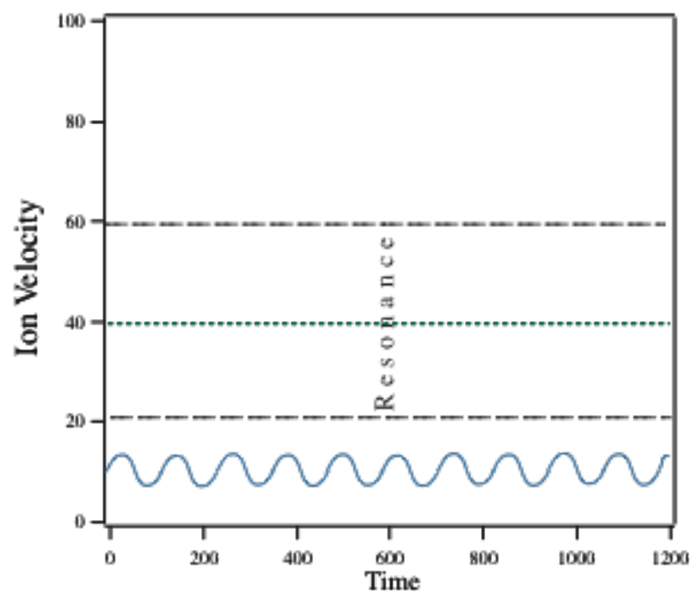
Ion Acceleration by ES Waves



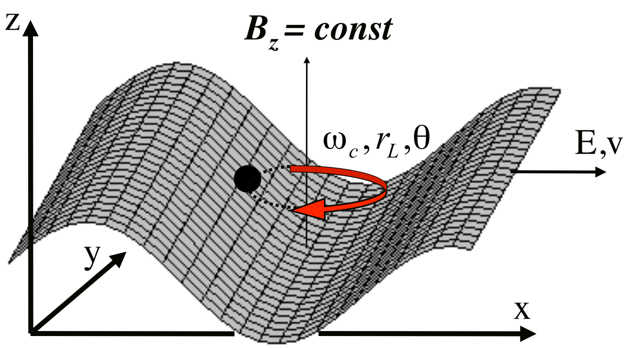


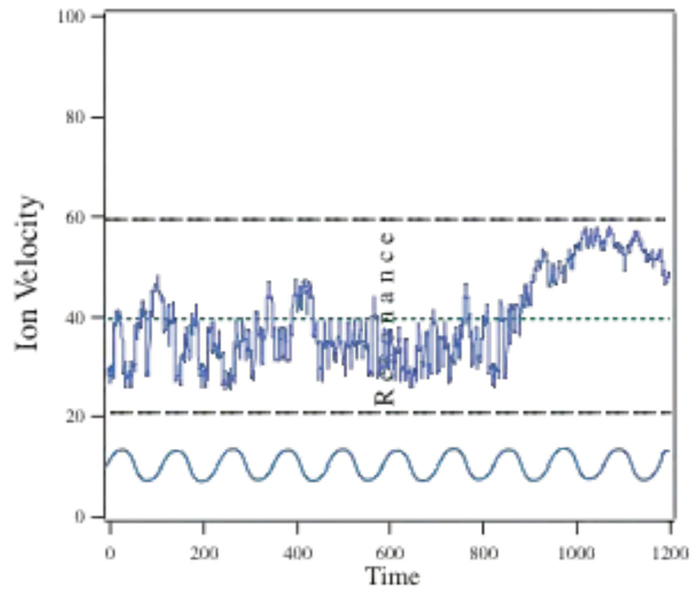
Ion Acceleration by ES Waves



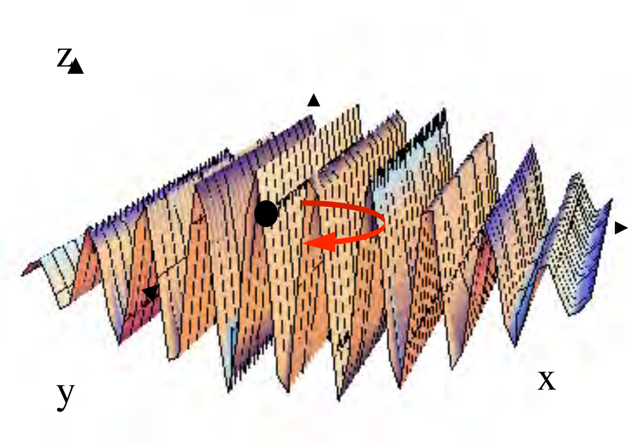


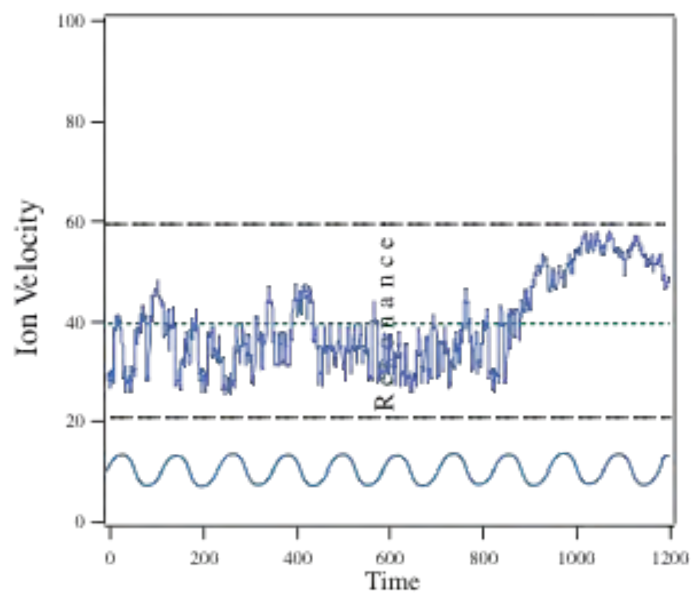
Ion Acceleration by ES Waves





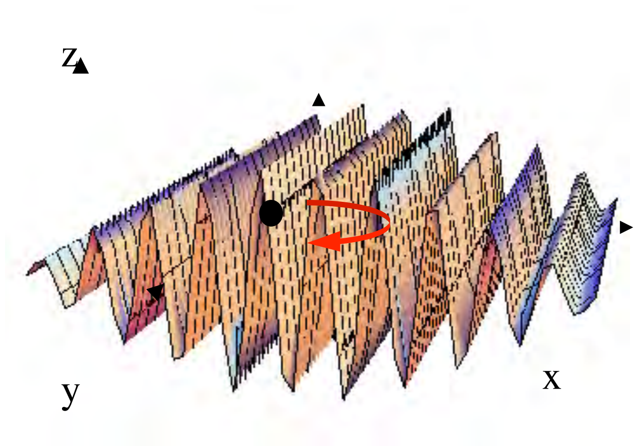
Two Beating waves: $\omega_1 - \omega_2 = n\omega_c$

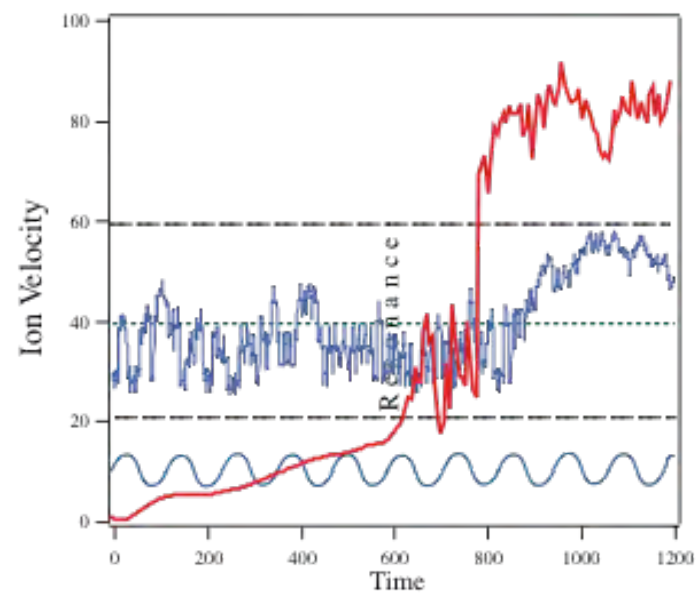




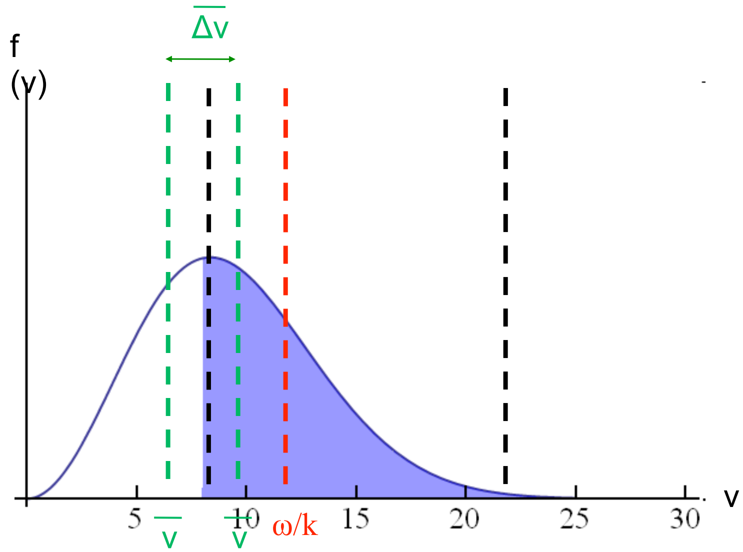
Why is it promising?

Two Beating waves: $\omega_1 - \omega_2 = n\omega_c$



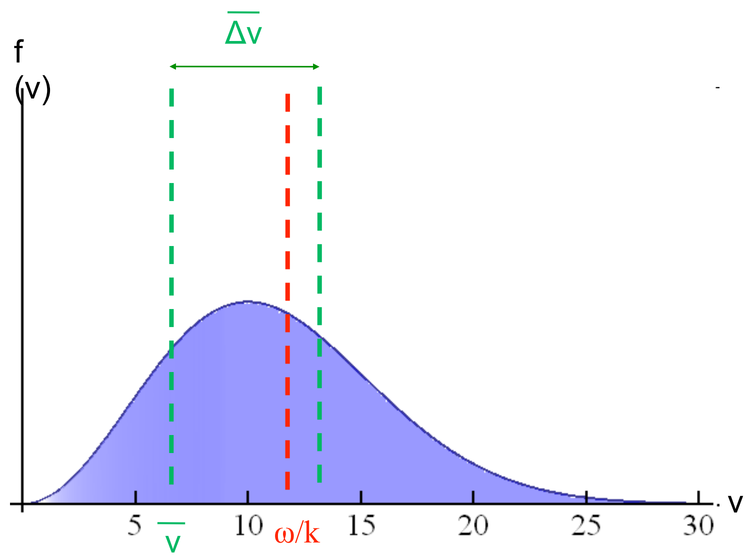


SEW



$\overline{\Delta v}$
f
(v)
5
$\overline{v}$
10
$\overline{v}$
ω/k
15
20
25
30
v

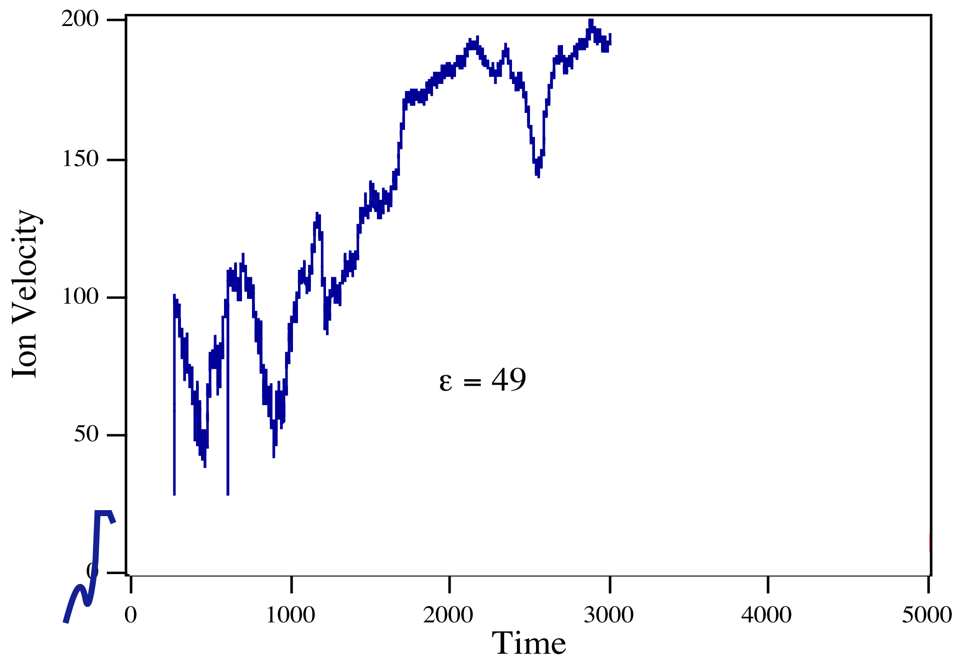
BEW



$\overline{\Delta v}$
f
(v)
5
$\overline{v}$
10
ω/k
15
20
25
30
v

Under what conditions can it occur?

Does it always occur?



No

Are there Necessary and Sufficient Criteria for Acceleration?

yes

Spektor & Choueiri, Physical Review E, March 2004

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

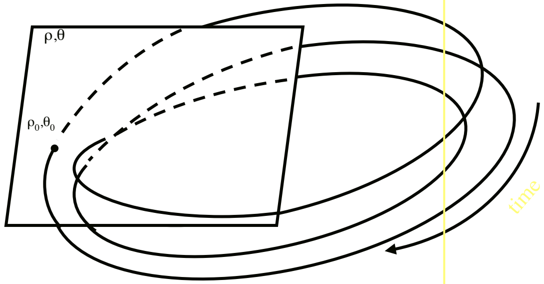
J. Comp. Phys. **92** *230 (1991)*

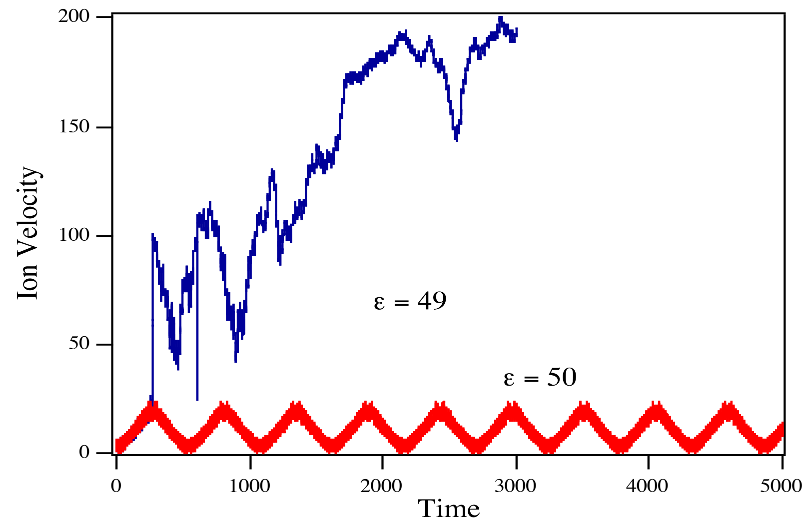
Analytical Solution:
2^{nd} order perturbation theory +
Lie transformations

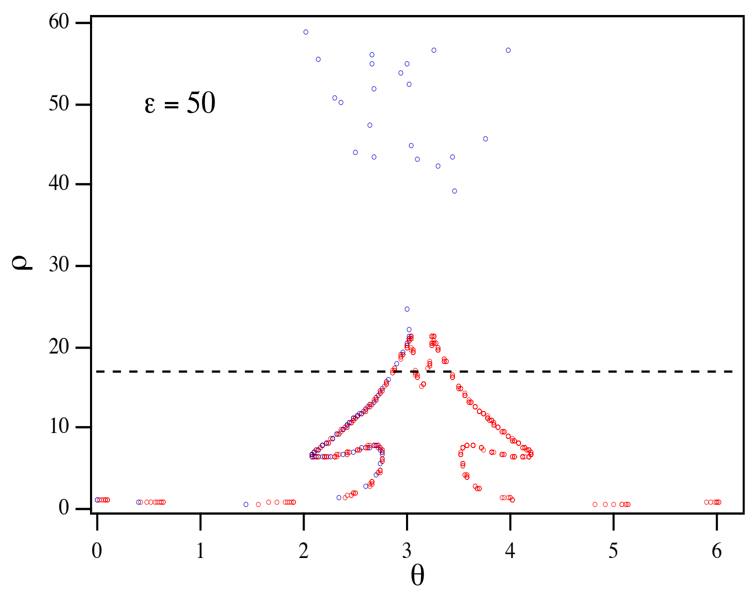
Phys. Plasmas **3***(5), May 1996, 1545*

Poincare surface of section
(Reduced phase space
diagram)

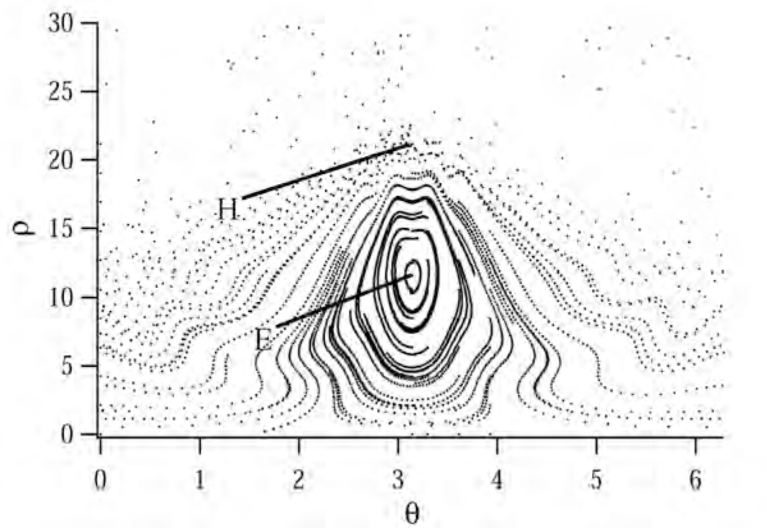
Poincare Cross Section



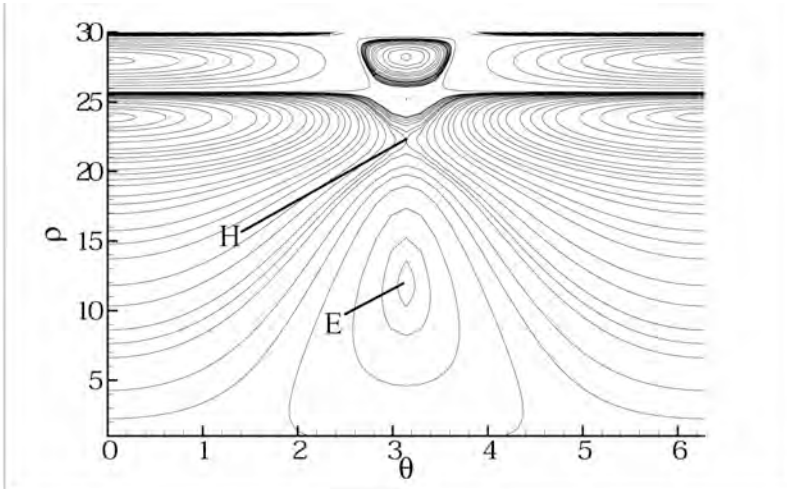


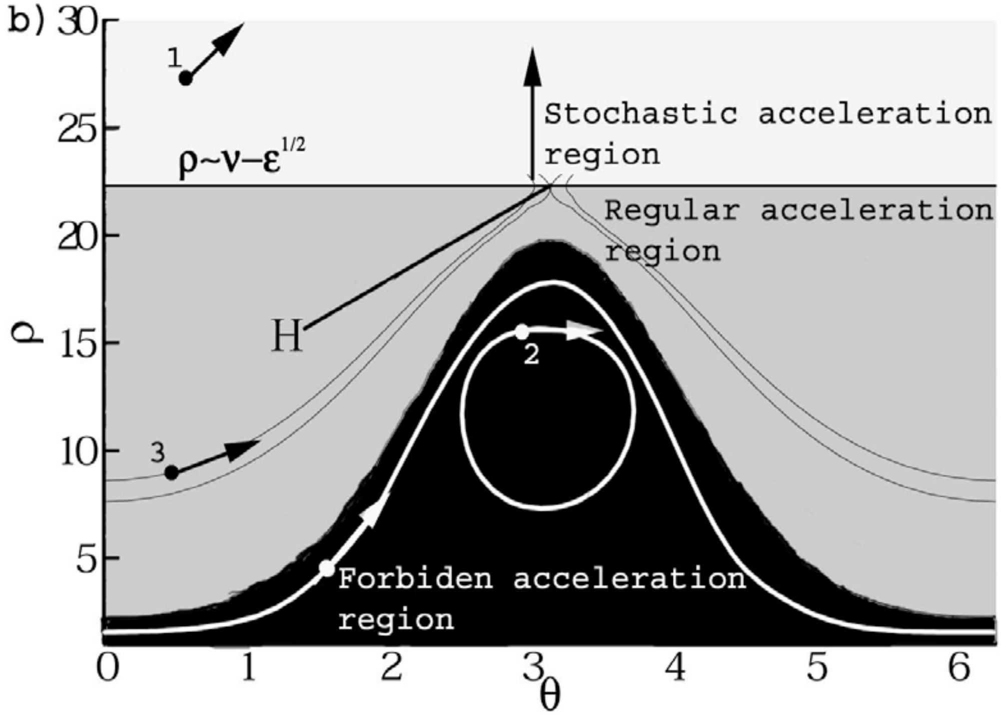


Numerical Simulation



2nd-order Perturbation Theory





b)
30
25
20
15
10
5
0
1
2
3
4
5
6
θ
ρ
1
2
3
H
ρ~ν−ε^{1/2}
Stochastic acceleration region
Regular acceleration region
Forbiden acceleration region

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

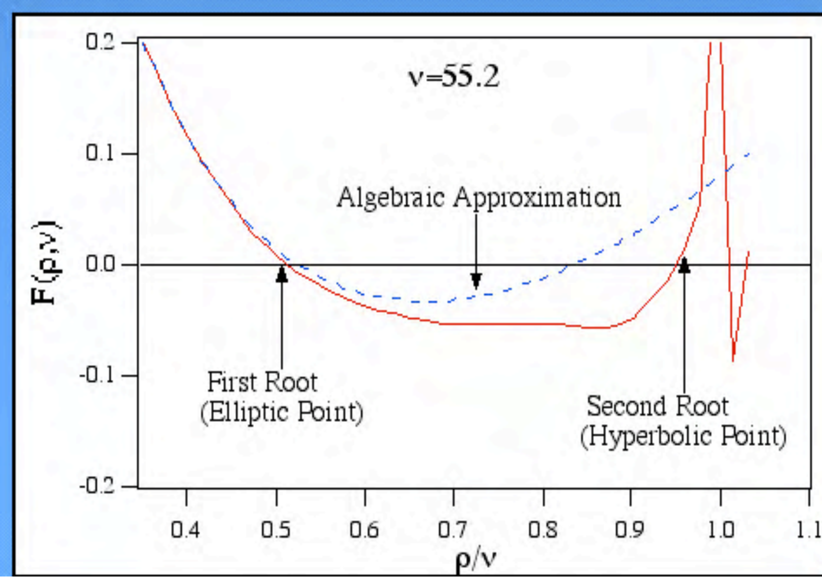
Spektor & Choueiri, Physical Review, E, 69(4):Article No. 046402, 2004.

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:

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

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

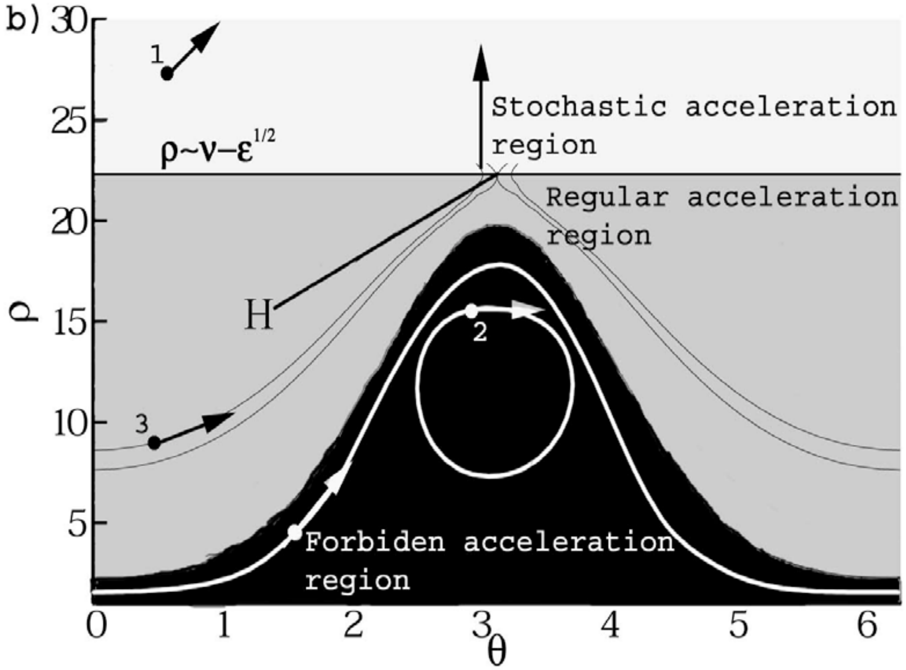
$$\downarrow$$

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

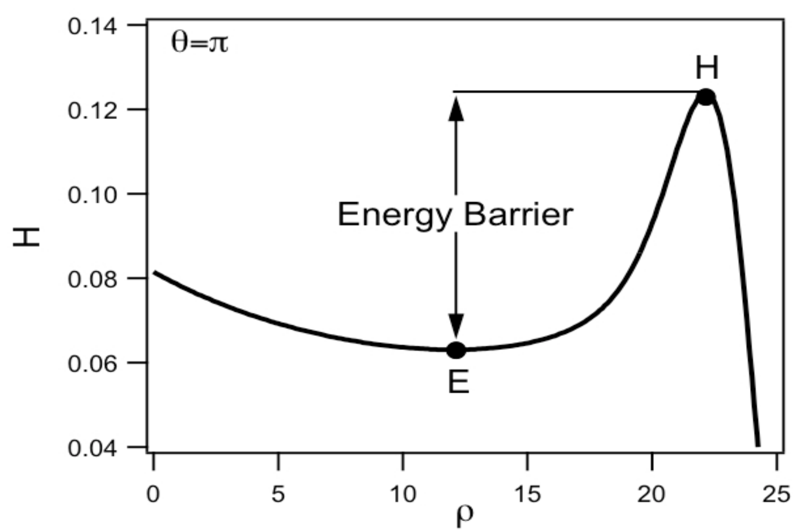
$$H_E = H(\rho \simeq \frac{\nu - \sqrt{\epsilon}}{2}; \theta = \pi).$$

$$\downarrow$$

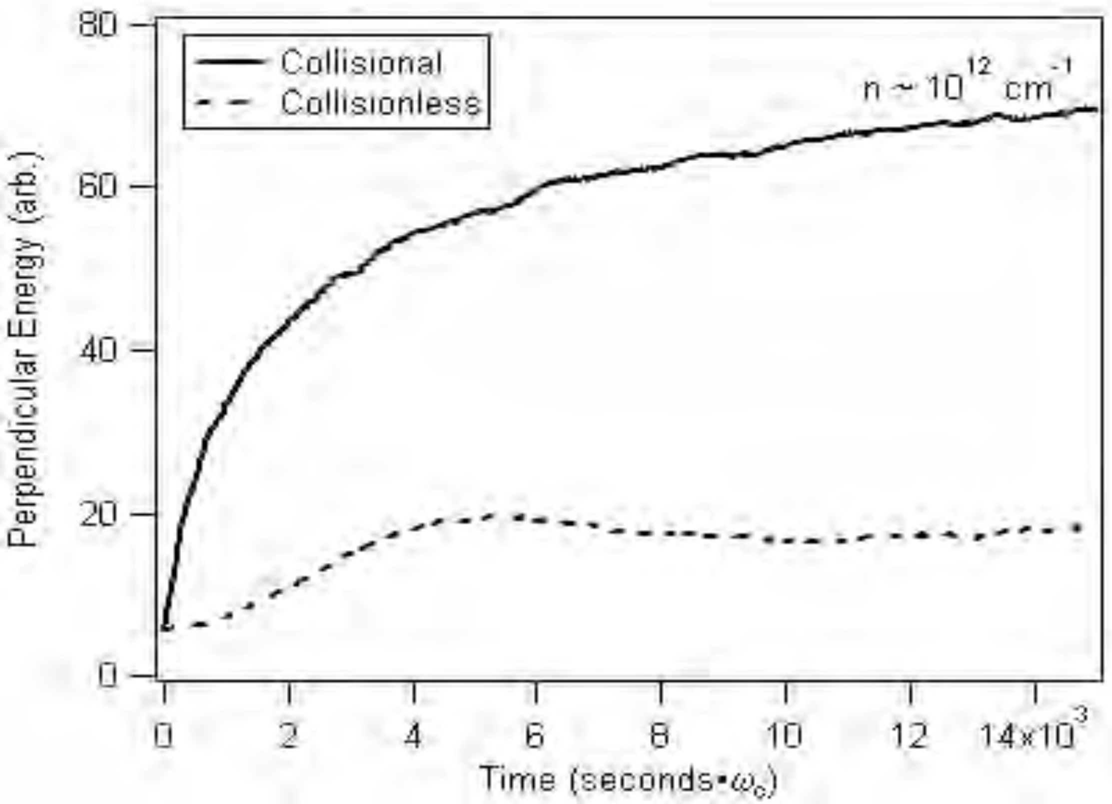
$$H_E \simeq H(v \simeq \frac{\omega}{2k}; \theta = \pi).$$



b)
Stochastic acceleration region
$\rho \sim \nu - \varepsilon^{1/2}$
Regular acceleration region
H
1
2
3
Forbiden acceleration region
ρ
θ

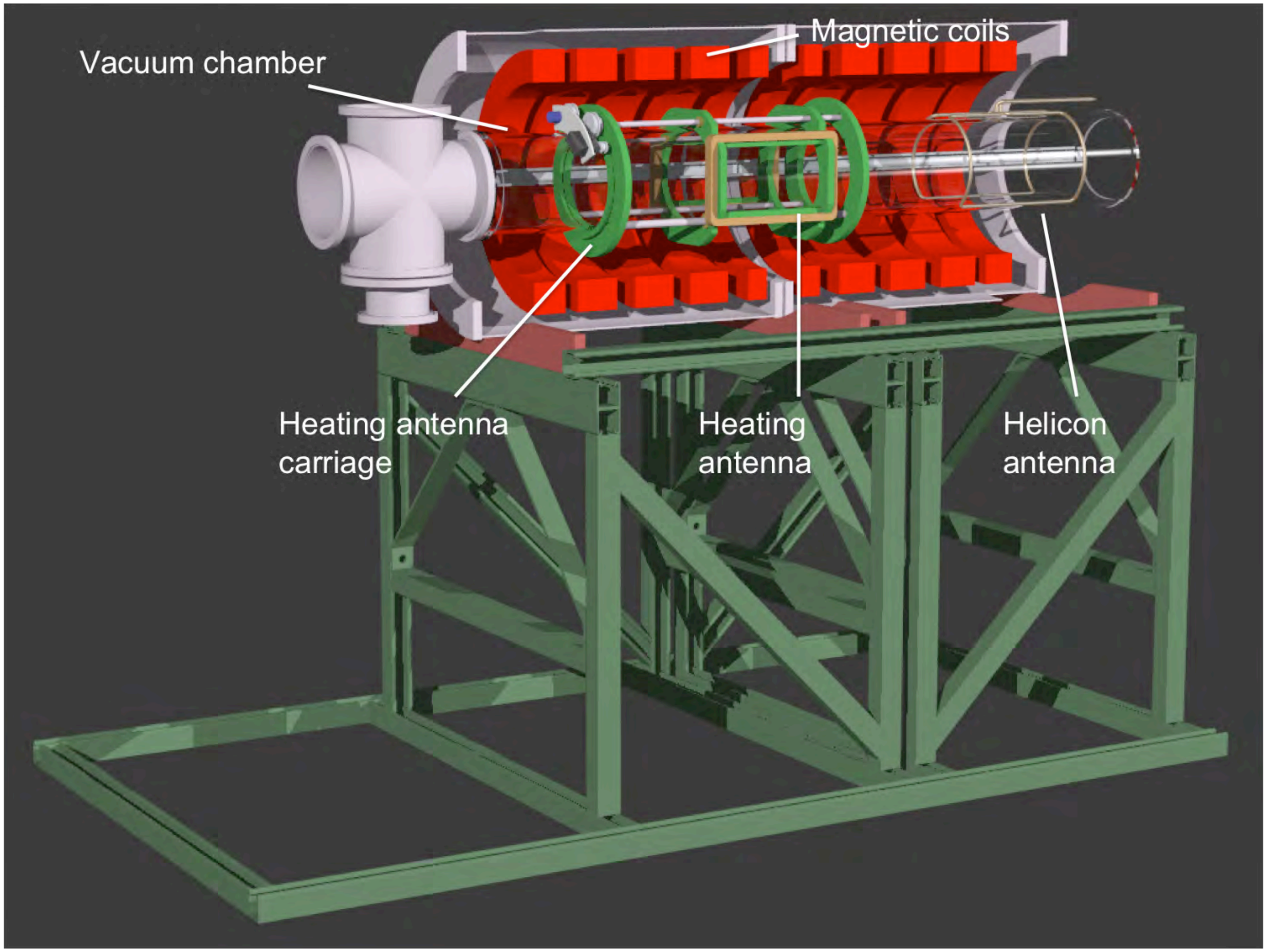


$\theta=\pi$
H
Energy Barrier
E
H
ρ



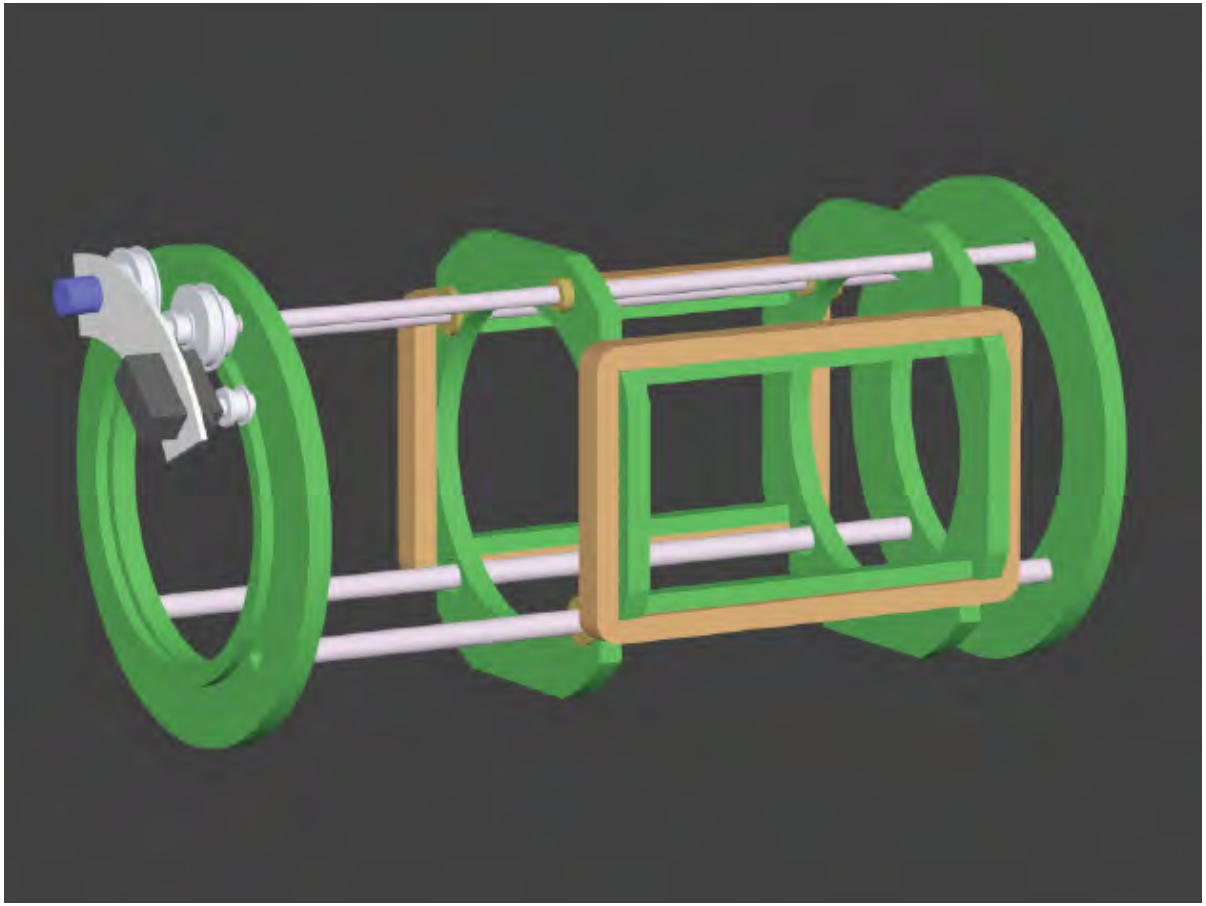
Collisional
Collisionless
n ~ 10^12 cm^-1
Perpendicular Energy (arb.)
Time (seconds•ωc)
0
20
40
60
80
0
2
4
6
8
10
12
14x10^3

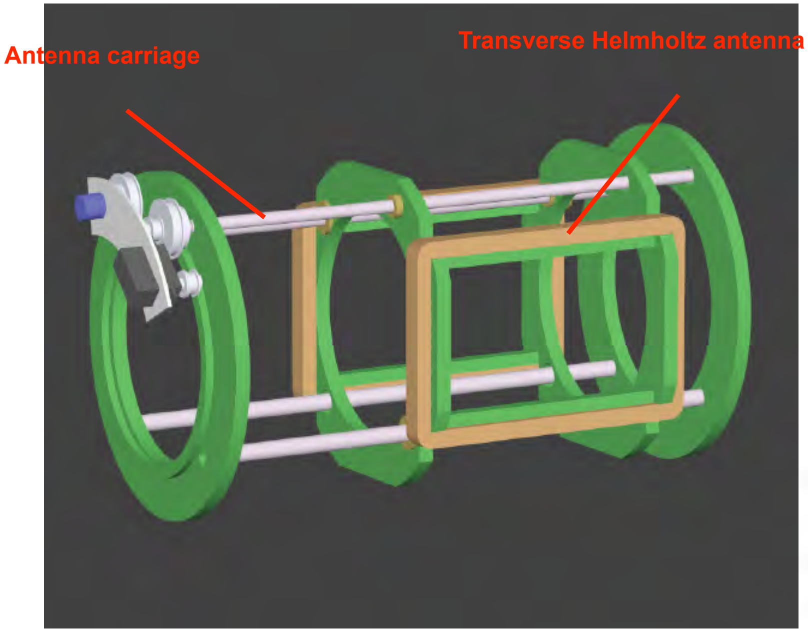
Can it be replicated/verified in the lab?



Magnetic coils
Vacuum chamber
Heating antenna carriage
Heating antenna
Helicon antenna

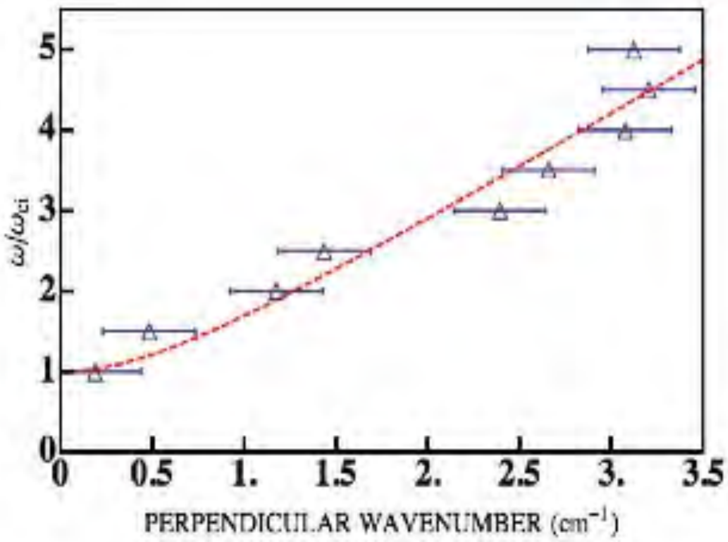
Transverse Helmholtz Antenna

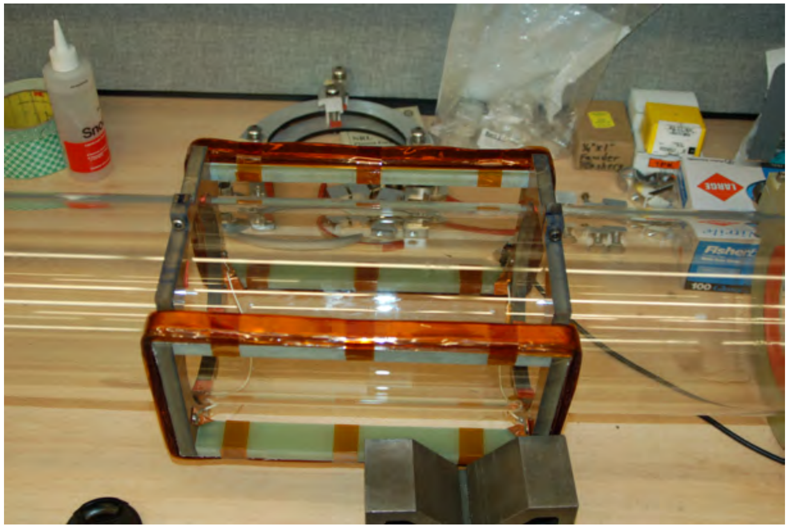


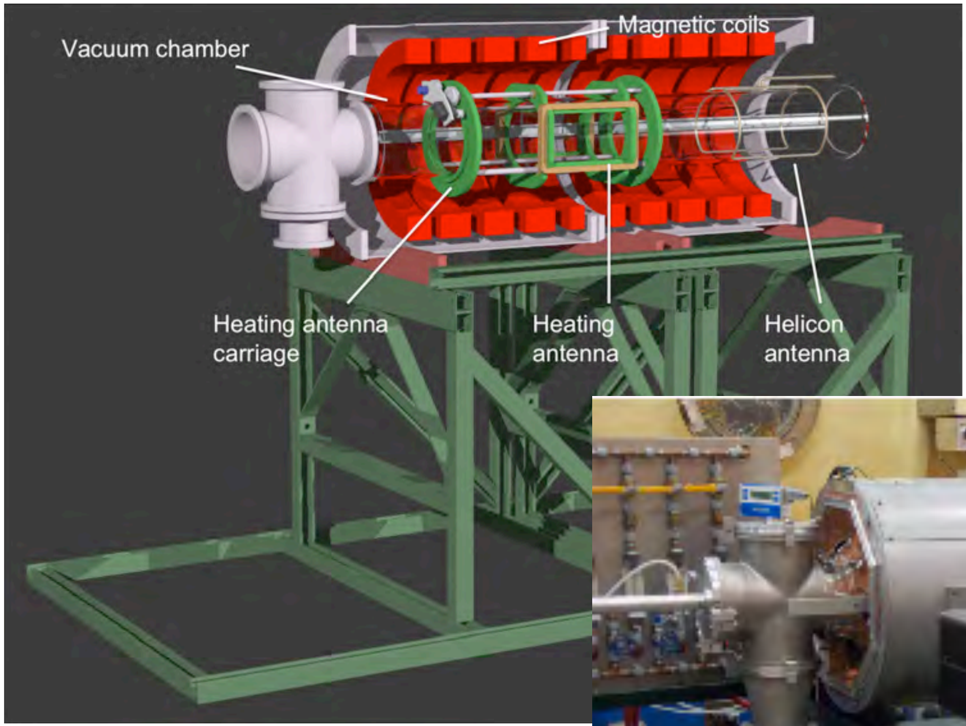


Configuration	Transverse Helmholtz*
Power Supply	100W ENI
Matching circuit	None
Frequency	$1.92f_{ci}$
Max RMS Field	15 G

$$\boxed{\omega^2 = \omega_{ci}^2 + k^2 \frac{T_e}{m}}$$

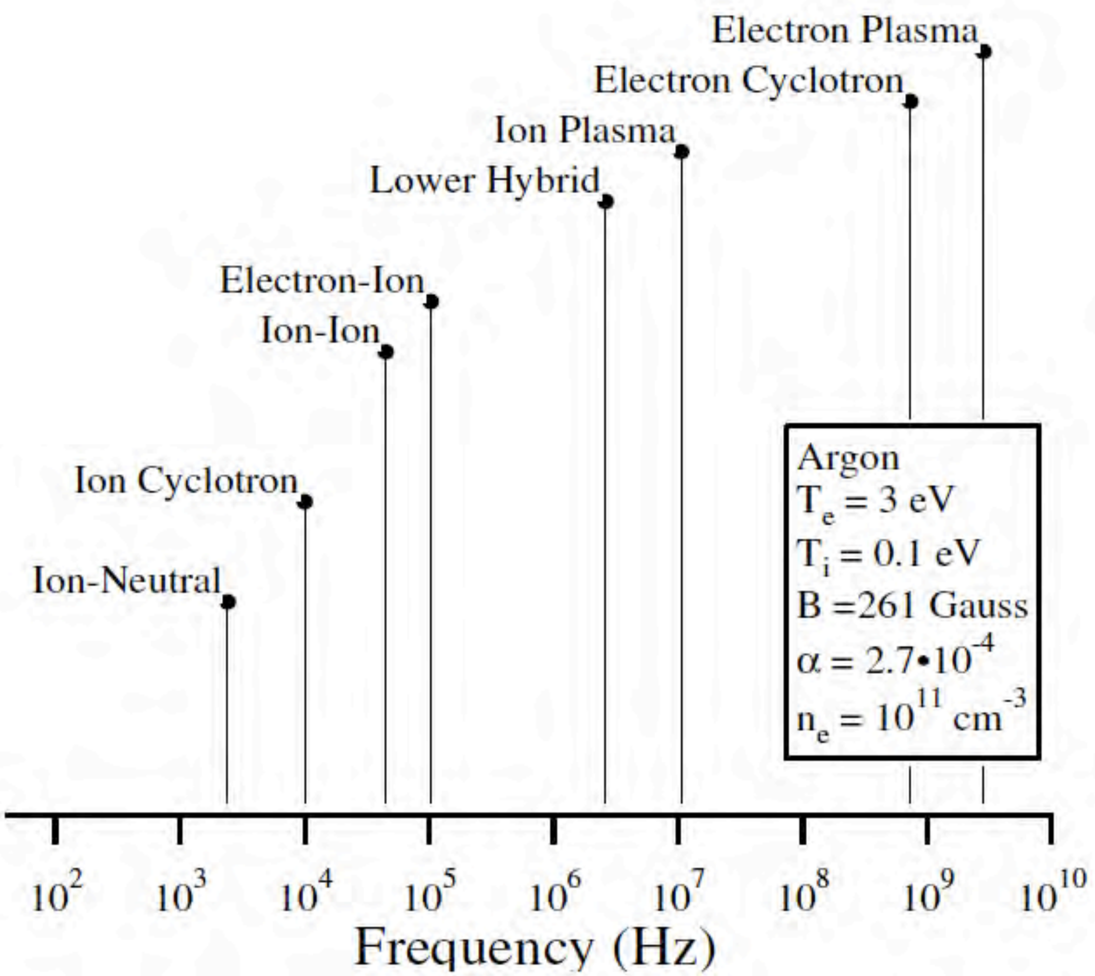



LARGE
Fisher

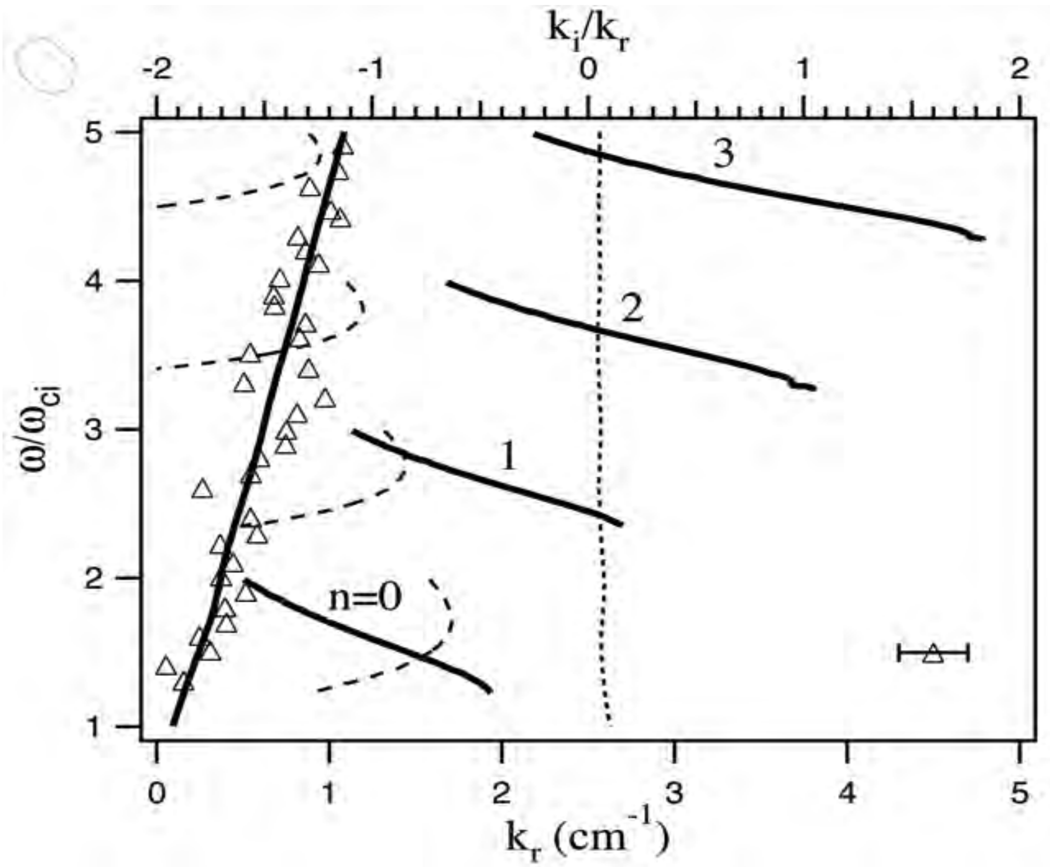


Parameters	
RF Power	250 W (13.56 MHz)
Mag. Field (B)	500 G
$\mathbf{f_{ci}}$	19 kHz
$\mathbf{P_B}$	~1 mT **Argon**
$\mathbf{T_i}$	0.09 eV
$\mathbf{P_A}$	30 W
$\mathbf{n_e}$	10^{11} cm^{-3}

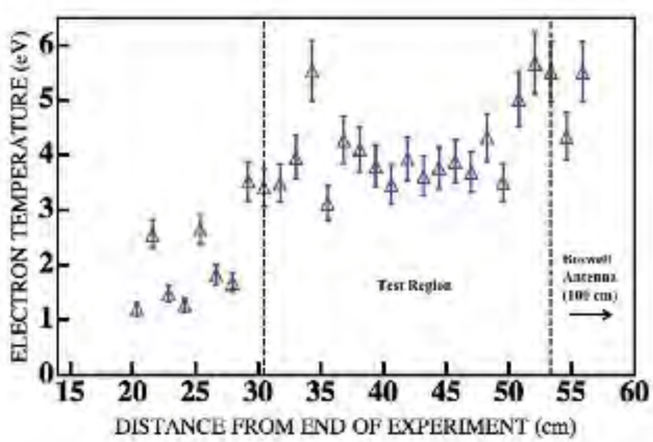
Plasma Characterization

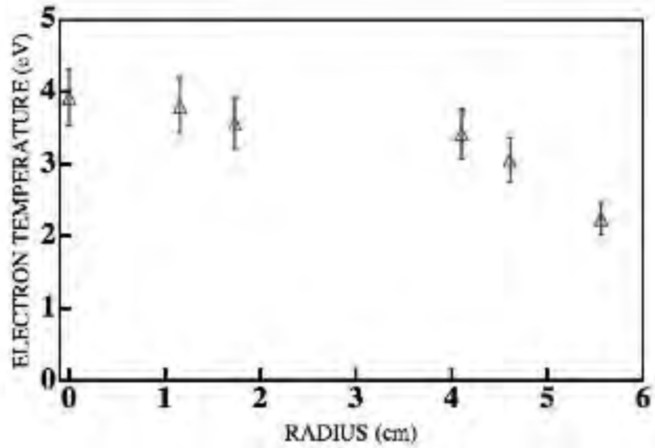


Dispersion Relation



Plasma is uniform





$$\frac{\nabla_z T_e}{T_e} r_i << 1$$

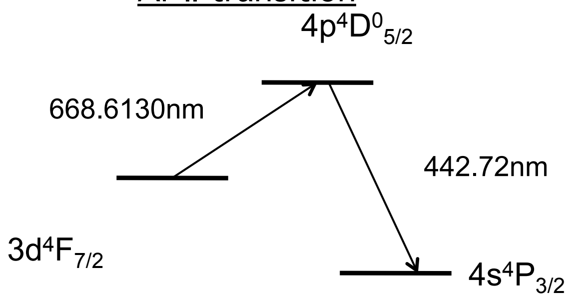
$$\frac{\nabla_z T_e}{T_e} \lambda << 1$$

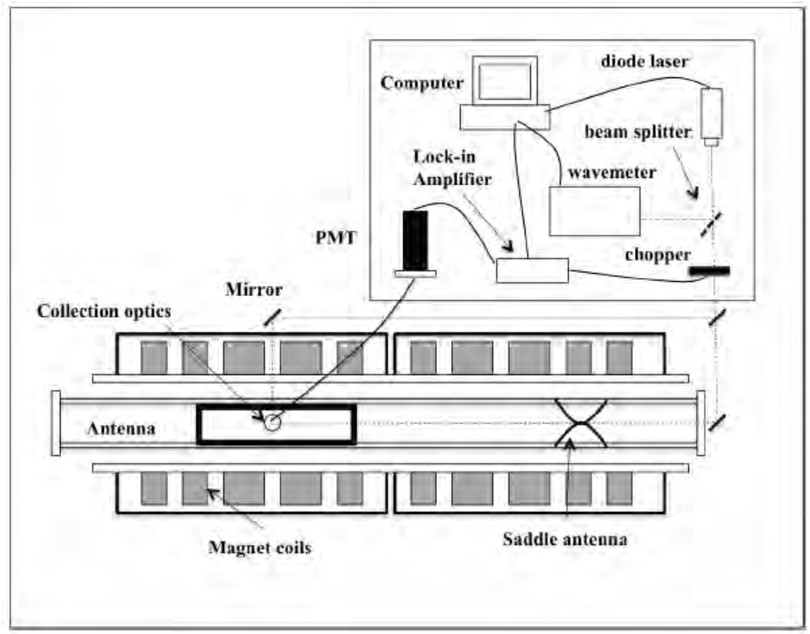
$$\frac{\nabla_r T_e}{T_e} r_i << 1$$

$$\frac{\nabla_r T_e}{T_e} \lambda << 1$$

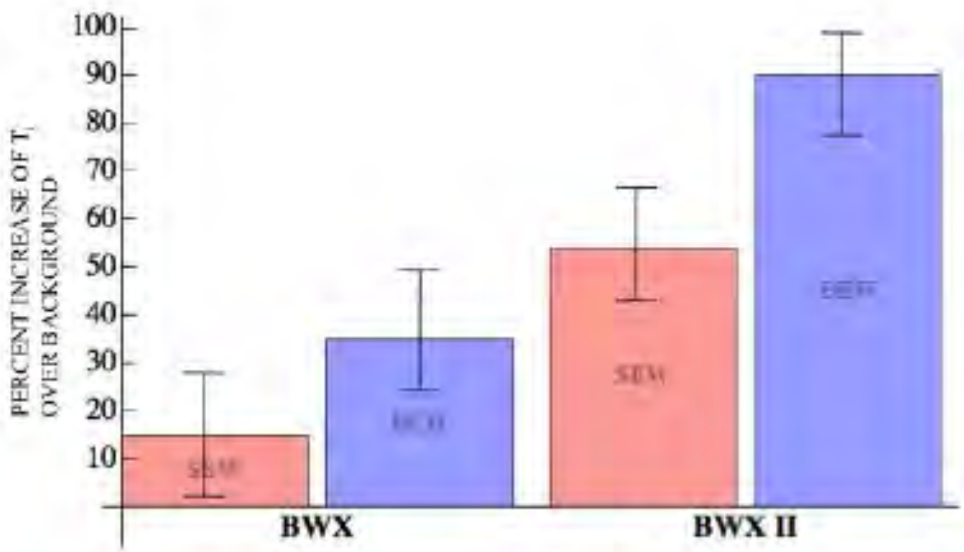
Laser Induced Fluorescence System

Ar II transition





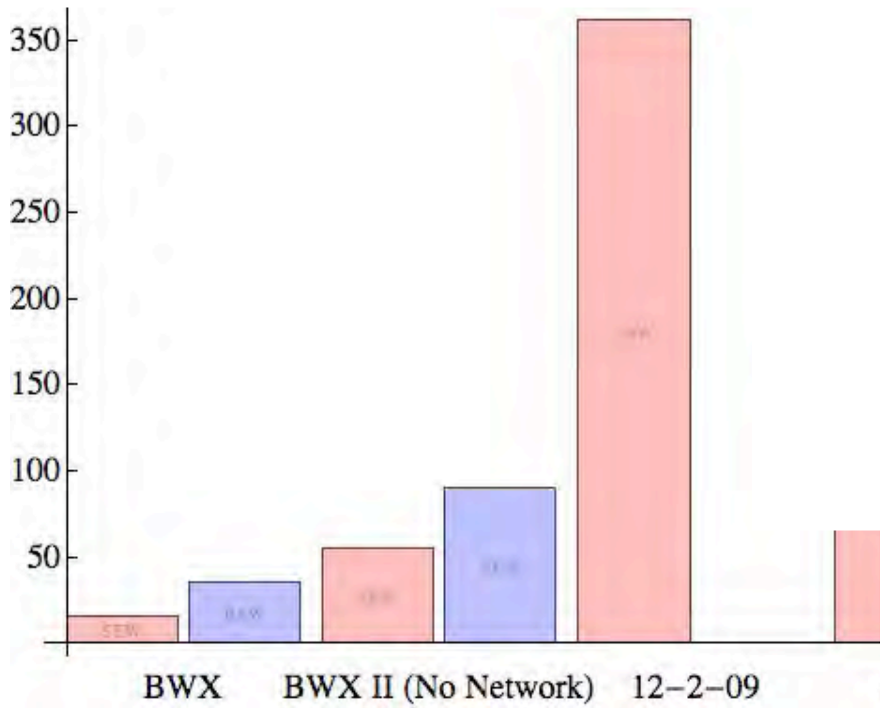
Ion Heating in BWX II



MAXIMUM HEATING	
SEW	55 ± 12%
BEW	90 ± 17%

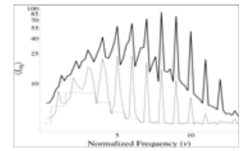
BEW is unambiguously superior

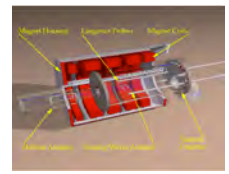
Possibility of improving result

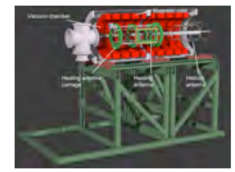


9/2010

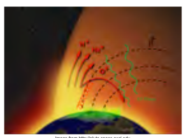
BEW Heating



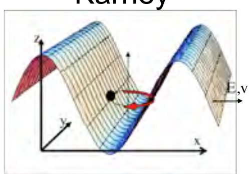




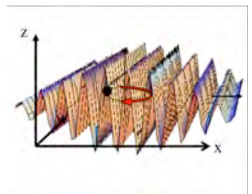
S3-3



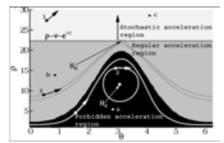
Karney



Benisti et. al



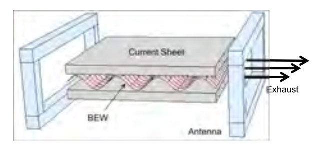
Spektor and Choueiri.



1976 1978 1998 2004

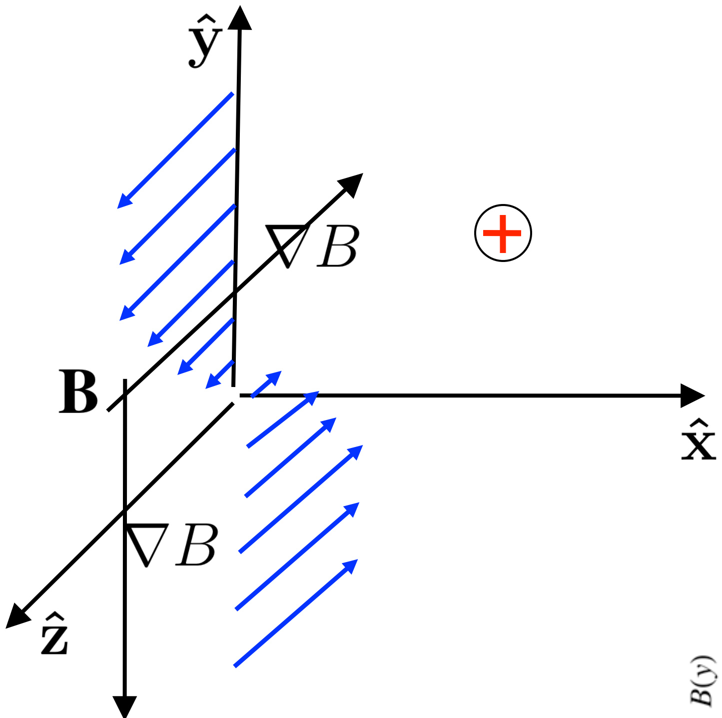
2006 2009 2010 >

2010 >



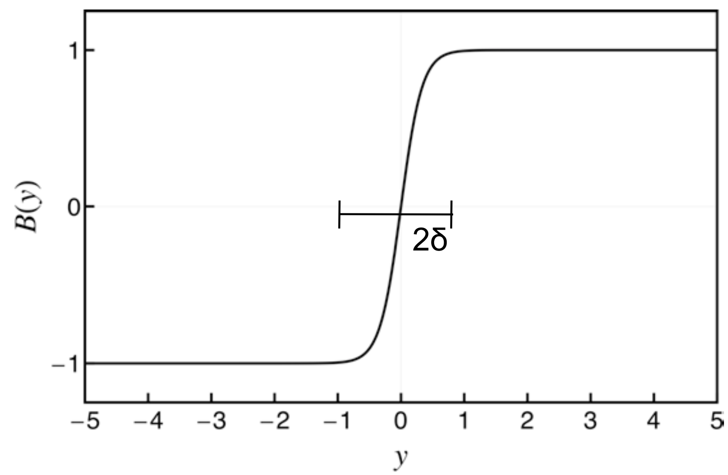
Directed ion acceleration

Geometry: magnetic slope

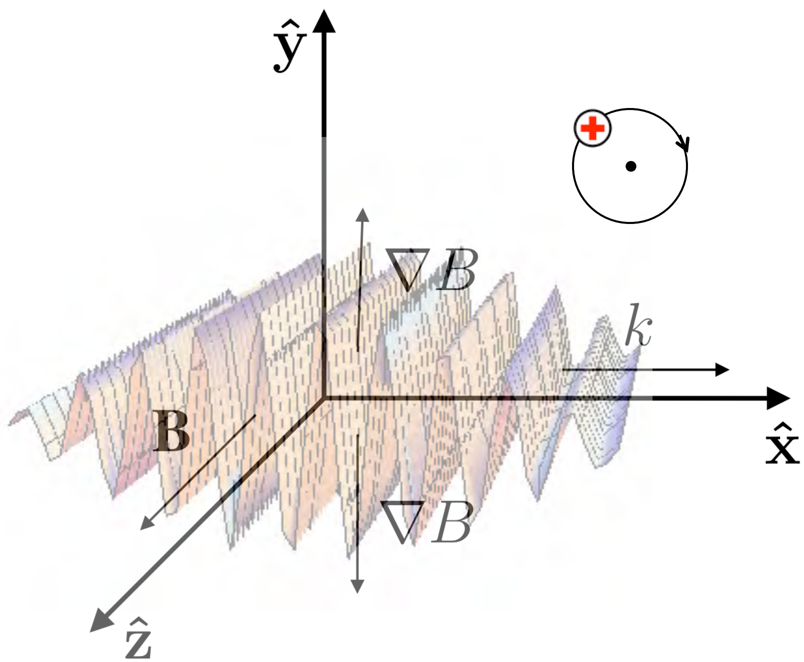


Geometry of system

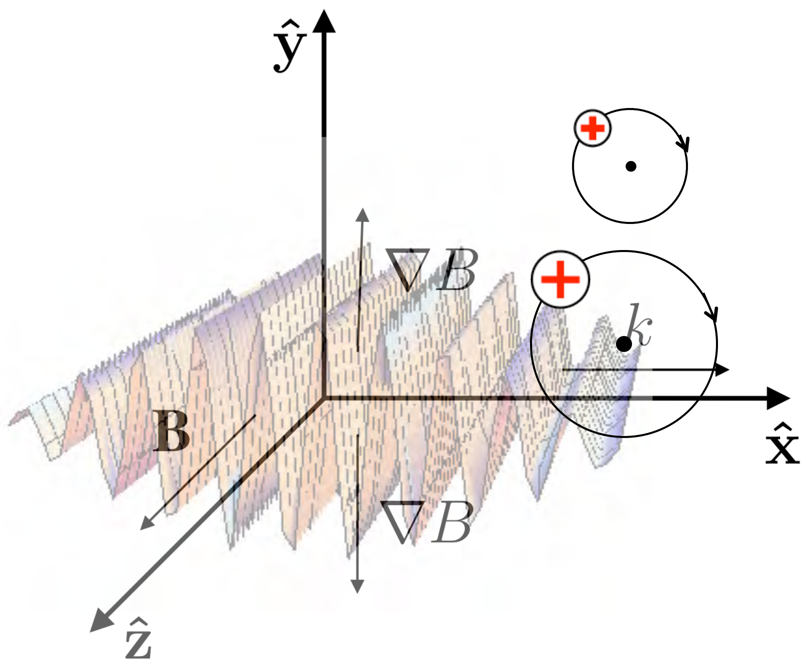
Field magnitude



BEW in a magnetic slope

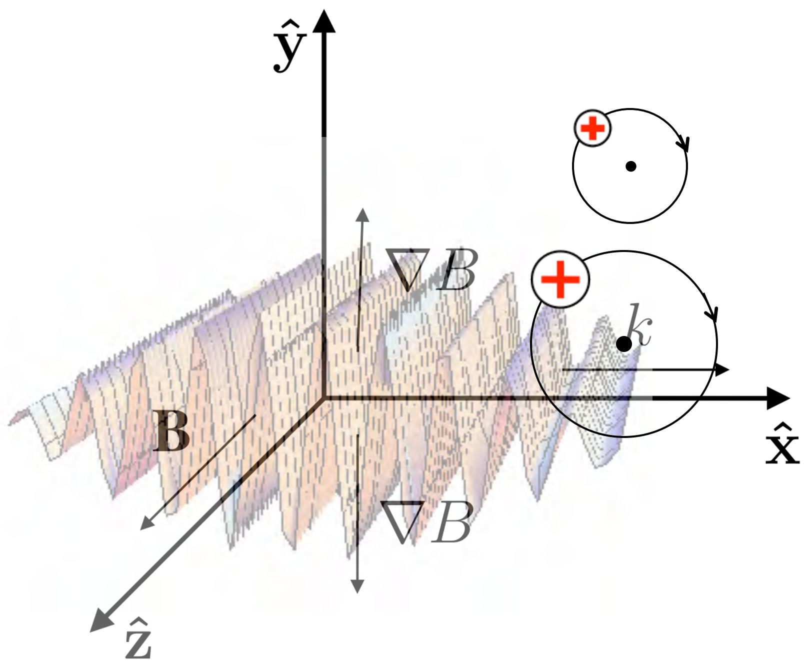


BEW in a magnetic slope



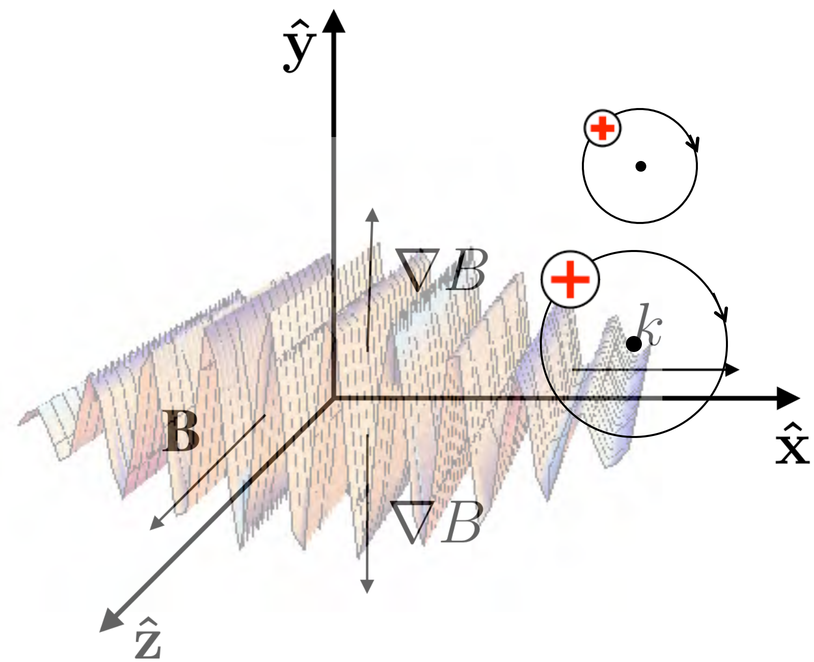
1. Guiding centers move toward magnetic null

BEW in a magnetic slope



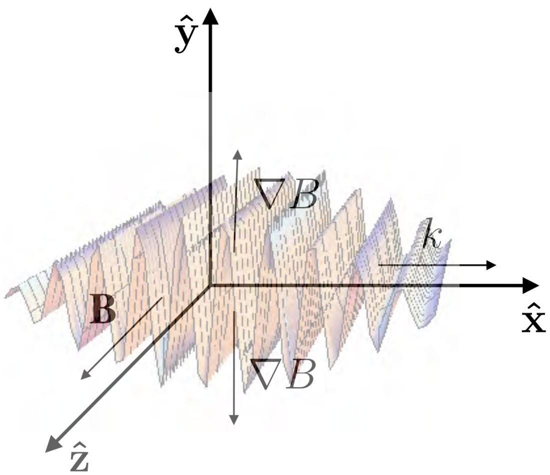
1. Guiding centers move toward magnetic null
2. Larmor radius increases

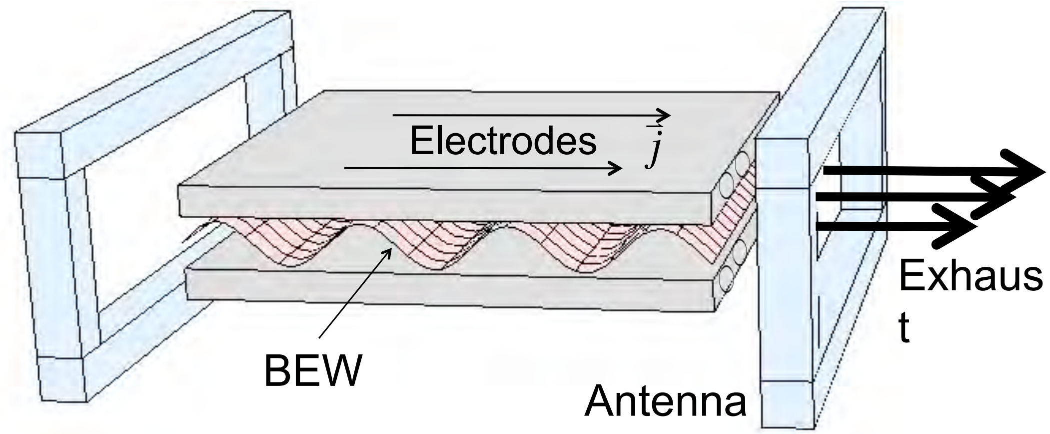
BEW in a magnetic slope

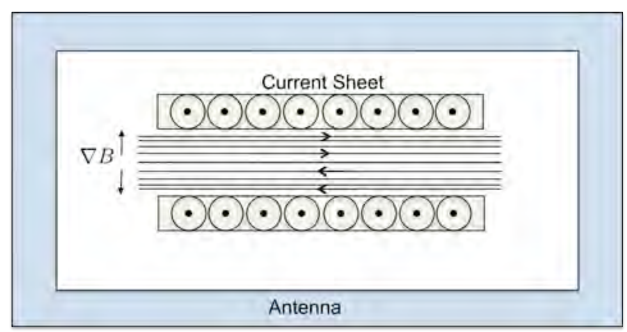


1. Guiding centers move toward magnetic null
2. Larmor radius increases
3. Trajectories pushed into magnetic slope

Thruster Proof of Concept



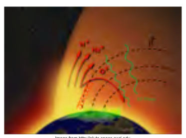




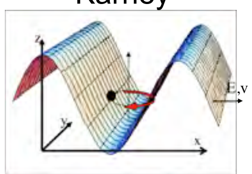
Front View

*Kline, Scime. *Physics of Plasma*, Dec. 1999

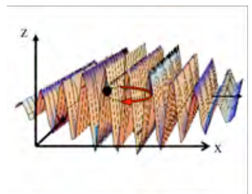
S3-3



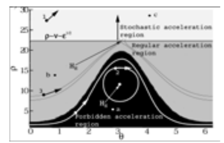
Karney



Benisti et. al

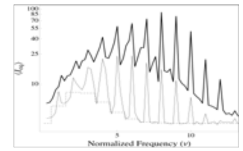


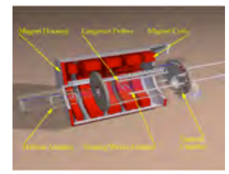
Spektor and Choueiri.

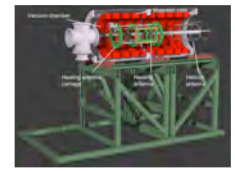


1976 1978 1998 2004

BEW Heating







2006 2009 2010 >

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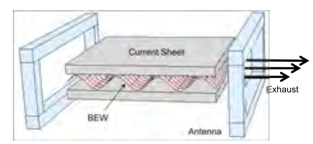
2010



Directed ion acceleration

Conclusions