Mitigation of Drift Instabilities by a Small Radial Flux of Charged Particles through the Landau-Resonant Layer

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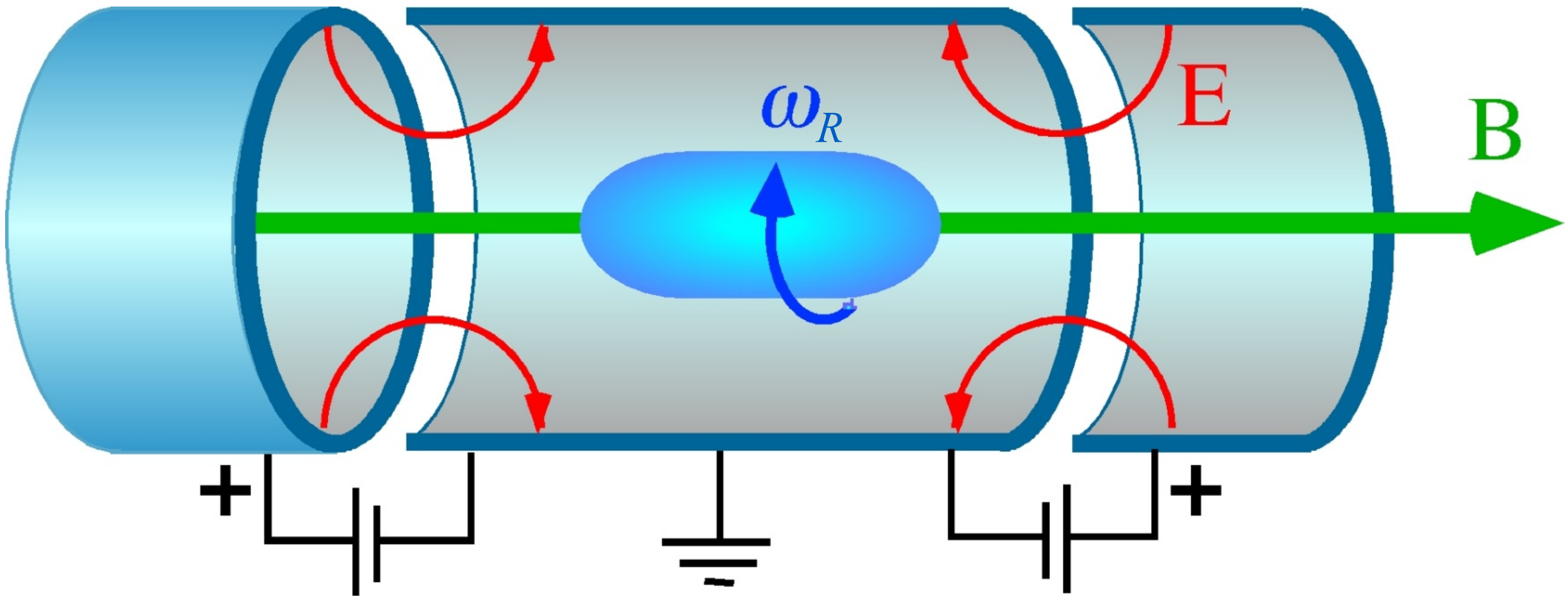
OUTLINE

Flux-driven *algebraic* damping of **E**×**B** drift (diocotron) modes
(*a close cousin, but distinct from, spatial Landau damping*)

Ion-induced instabilities of diocotron modes in electron plasmas
(*similar to a curvature-driven flute instability in (quasi)neutral plasmas*)

Flux-driven mitigation of the ion-induced diocotron instabilities
(*controlled small losses to prevent a major disruption*)

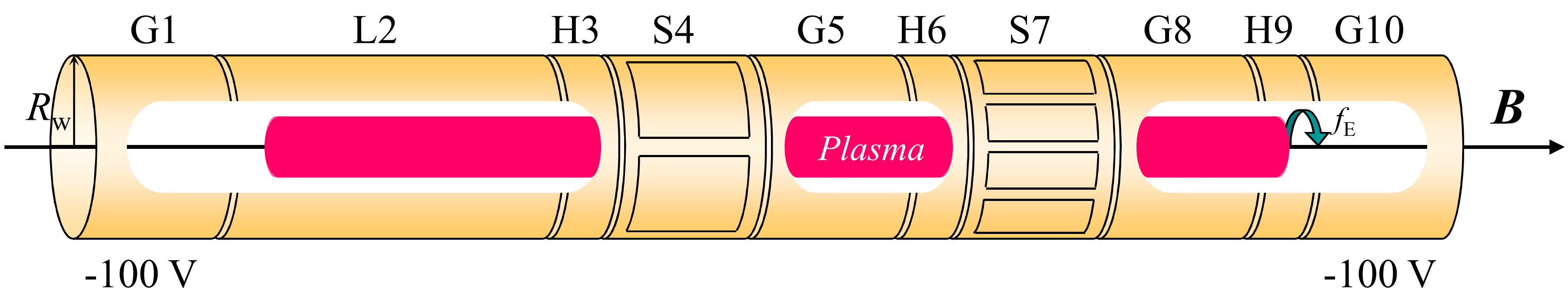
Nonneutral plasmas are confined by static electric and magnetic fields in a Penning-Malmberg trap



Cylindrical symmetry, single sign species => long confinement time

$$P_\theta = \sum_{j=1}^{N}[m\omega_R r_j^2 + \frac{eB}{2c} r_j^2] = const. \qquad P_\theta \approx \frac{eB}{2c}\sum_{j=1}^{N} r_j^2 = const.$$

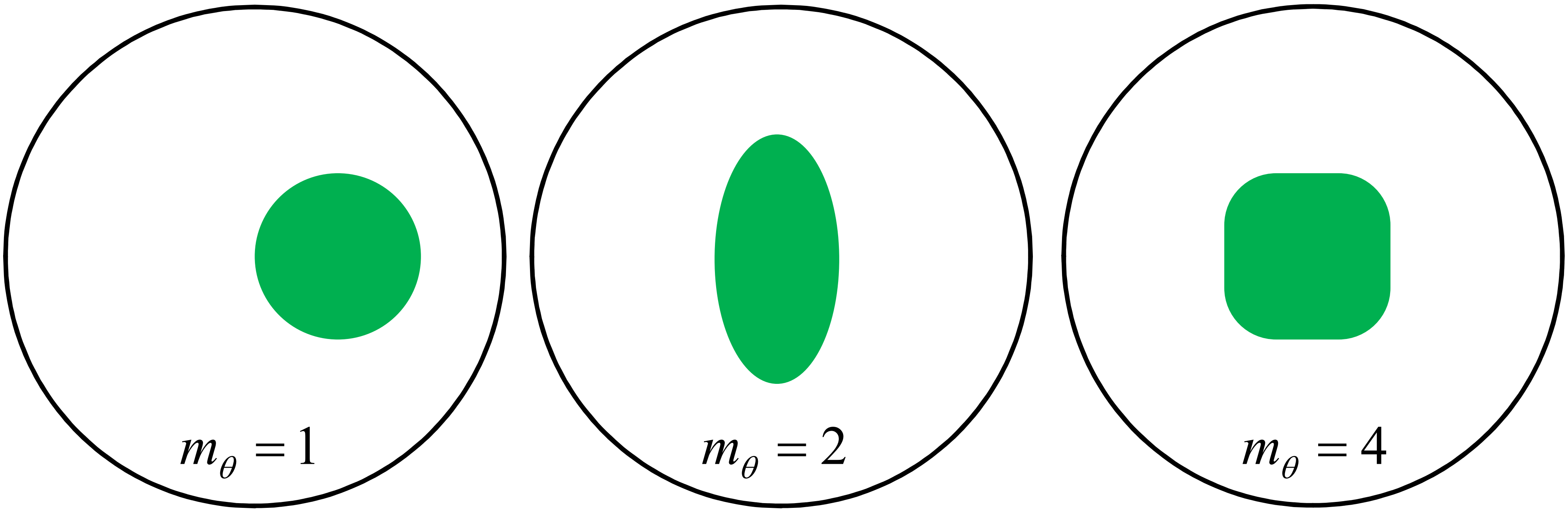
central density:	$n_c \approx 1.5\times10^7$ cm^{-3}
central potential:	$\phi_c \approx -30$ V
plasma core radius:	$R_c \approx 1.2$ cm ($R_w = 3.5$ cm)
equilibrium temperature:	$T \geq .03$ eV ($\lambda_D \approx R_c/30$)
magnetic field:	$B \leq 20$ kG
E×B rotation frequency:	$f_{E\times B} \approx 10$ kHz (20kG/B)
neutral pressure:	$P \approx 10^{-11}$ Torr



Pure electron plasma is contained in (up to) ten electrically isolated cylinders, with the cylinders S4 and S7 divided into up to 8 azimuthal sectors to excite, manipulate and detect various $m_\theta \neq 0$ modes. Axial plasma confinement is provided by -100 V on the end cylinders. Radial confinement is provided by the axial magnetic field $\boldsymbol{B}$. Plasma density z-integrated 2D-distribution $n(r, \theta)$ is measured by instantaneous grounding the end cylinder, thereby allowing the plasma to stream onto a phosphor screen with attached CCD camera.

Diocotron Waves

Diocotron waves are flutelike $(m_\theta \neq 0, k_z = 0)$ surface density perturbations, which are neutrally stable $(\gamma_m = 0)$ for an idealized "top-hat" profile $n_e(r)$



$$d_m(t),\ \omega_m \equiv 2\pi f_m(t),\ \gamma_m(t)$$

$$\omega_m \approx \bar{\omega}_{E\times B} \times \left[(m-1) + (R_c/R_w)^{2m} \right], \text{ where } \bar{\omega}_{E\times B} \equiv 2\pi ec\bar{n}_e/B$$

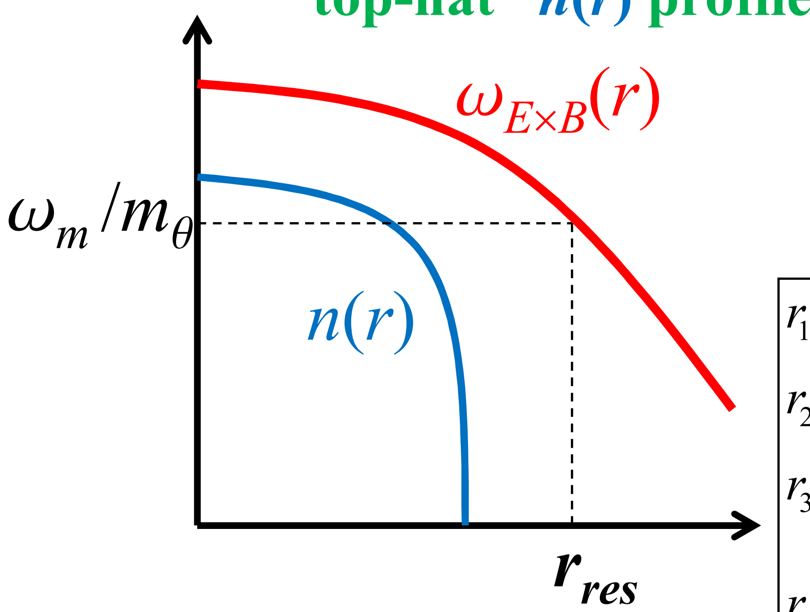
(Spatial) Landau Damping of Diocotron Modes

Landau damping is the phase mixing of density perturbations near the resonant radius $r_{res}(m_\theta)$, where the fluid rotation rate $\boldsymbol{\omega_{E\times B}(r_{res})}$ equals the wave phase rotation rate $\boldsymbol{\omega_m / m_\theta}$

$$\boldsymbol{\omega_{E\times B}(r_{res}) = \omega_m / m_\theta}$$

$$r_{res}(m_\theta) \approx R_c \sqrt{\frac{m}{m-1+(R_c/R_w)^{2m}}}$$

no damping for a "top-hat" $n(r)$ profile



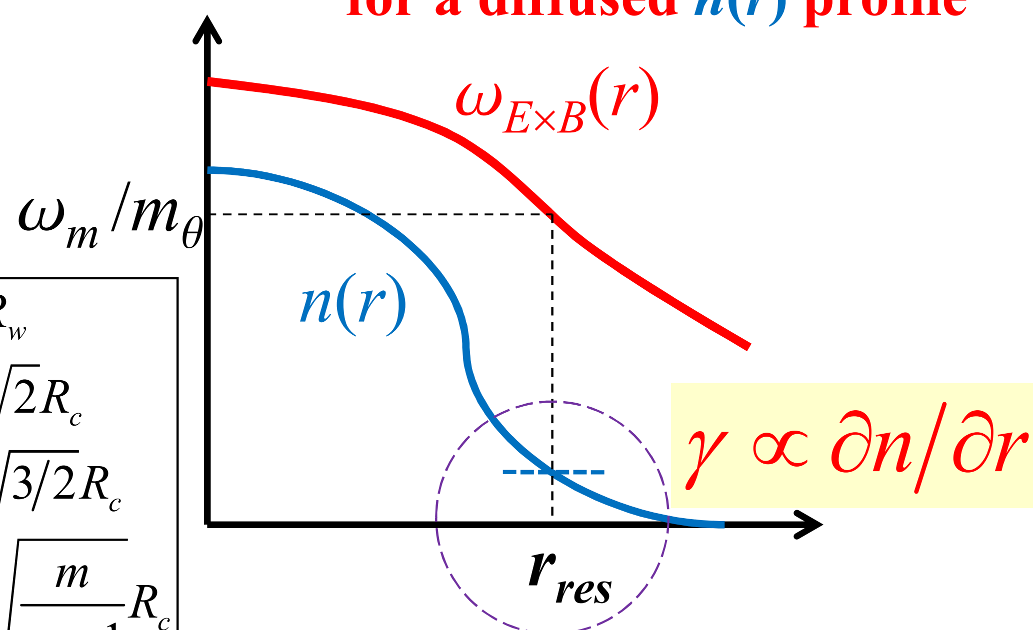
$r_1 = R_w$

$r_2 \approx \sqrt{2} R_c$

$r_3 \approx \sqrt{3/2} R_c$

$r_m \approx \sqrt{\frac{m}{m-1}} R_c$

exponential Landau damping for a diffused $n(r)$ profile



$$f_1(t) \approx \frac{ceN(t)}{\pi B R_w^2}\left\{1+\frac{R_w}{L_p}\left[1.2\cdot\left(\frac{1}{4}+\ln\frac{R_w}{R(t)}+\frac{T(t)}{e^2 N}\right)-0.671\right]\right\}\left[1-\sigma\frac{D^2}{R_w^2}\right]^{-1}$$

Frequency $f_1(t)$ of the $m_\theta = 1$ diocotron mode is naturally sensitive to time variations in plasma radius $R(t)$ and temperature $T(t)$ as

$$\frac{\Delta f_1}{f_1} \approx 1.2\left(\frac{R_w}{L_p}\right)\left(\frac{\Delta T}{e^2 N} - \frac{\Delta R}{R}\right)$$

$R_w / L_p \approx 1/15$

$e^2 N \approx 10eV$

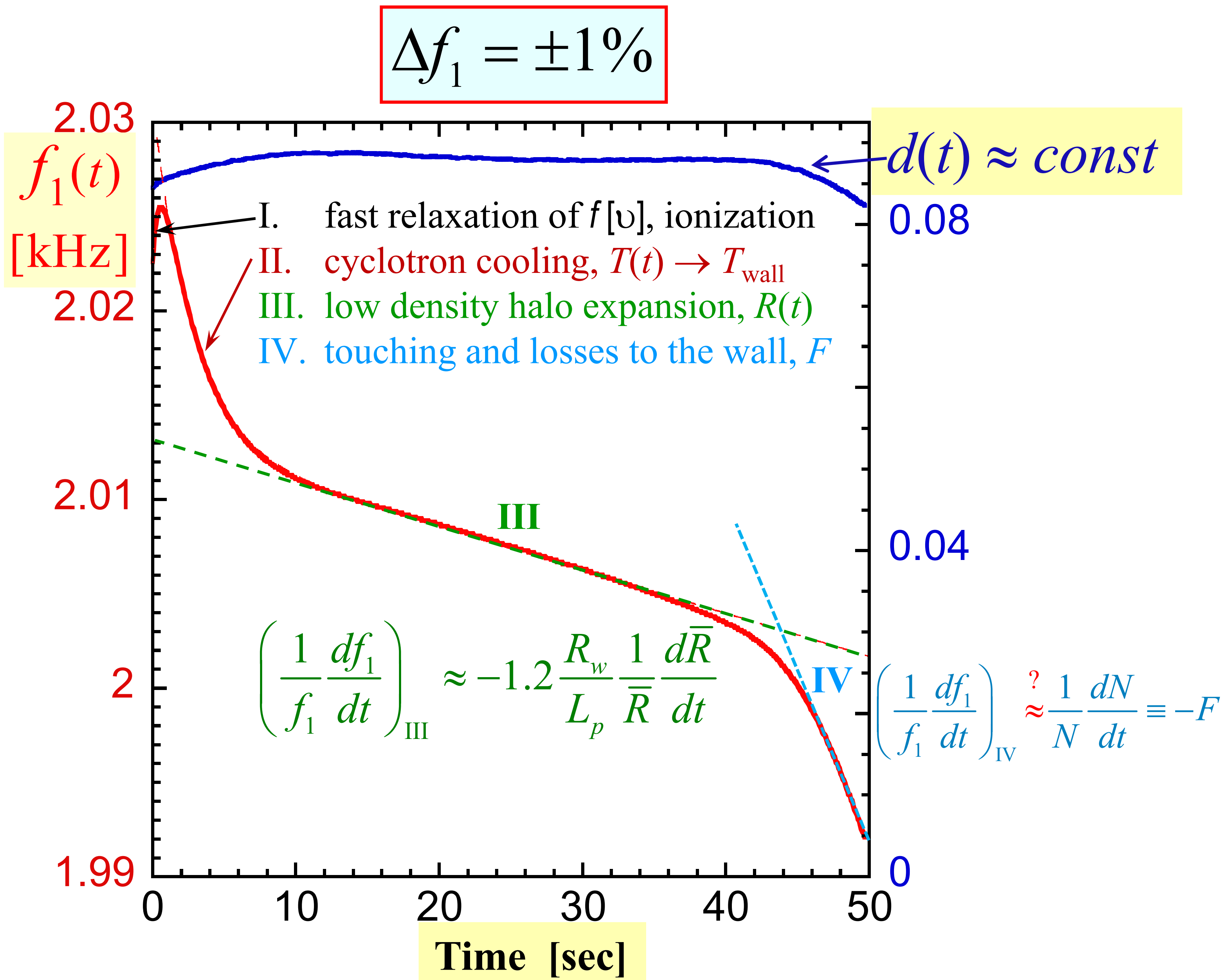
$\frac{\Delta f_1(1eV)}{f_1} \approx .008$

Since $\Delta f_1 / f_1$ can be measured with a great precision ($\leq 10^{-4}$) for a steady-state and small amplitude *D*-waves,

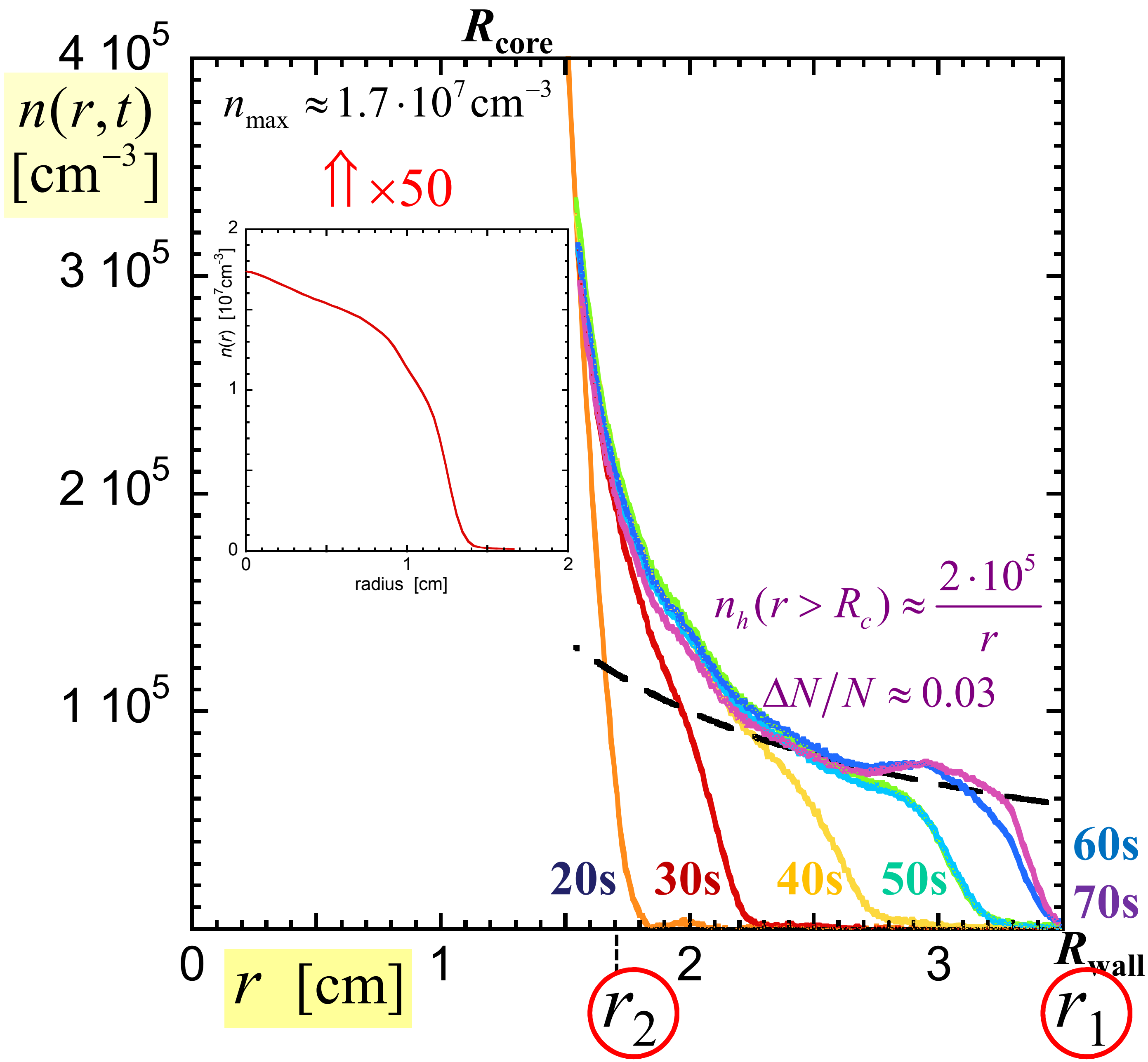
i.e., when $\frac{\Delta D \cdot D}{R_w^2} \ll \frac{\Delta f_1}{f_1}$,

then the $m_\theta = 1$ diocotron frequency monitoring is a powerful diagnostic tool !

Monitoring of the $m_\theta = 1$ diocotron frequency as a diagnostic tool

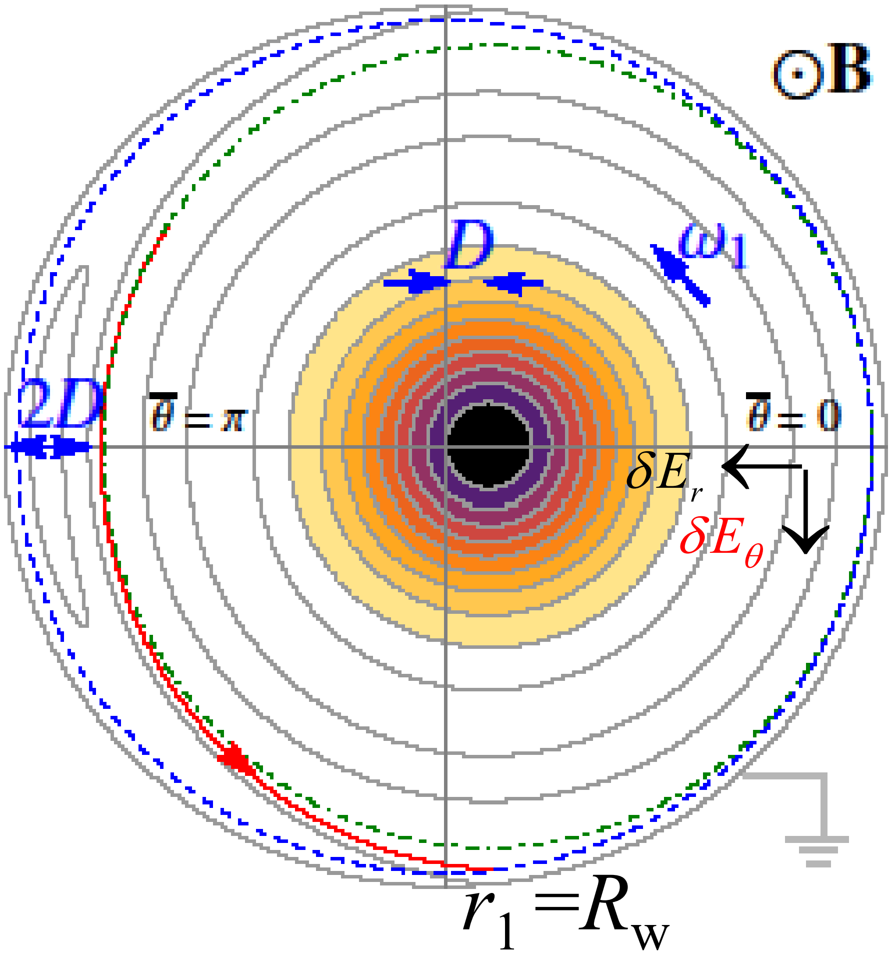


As the plasma core radiatively cools down to the room temperature, a low-density halo ($n_h \sim .01 n_c$) starts to leak out of the core, expanding slowly (~ 50s) to the wall



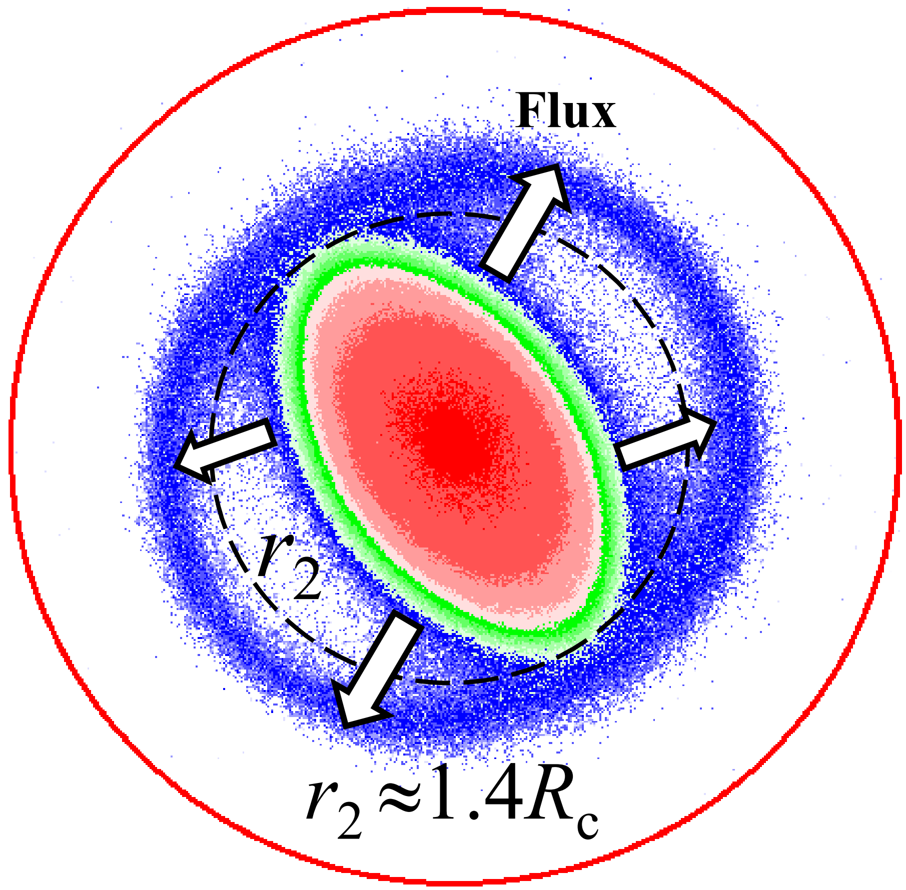
Cross Section of an Electron Plasma Column in Diocotron Perturbation D_m

$m_\theta = 1$



resonant particles ($r \le R_w$) *form a dipole field* $\boldsymbol{\delta E_\theta}$ *that causes the core to* $\boldsymbol{E}\times\boldsymbol{B}$ *drift back to the axis*

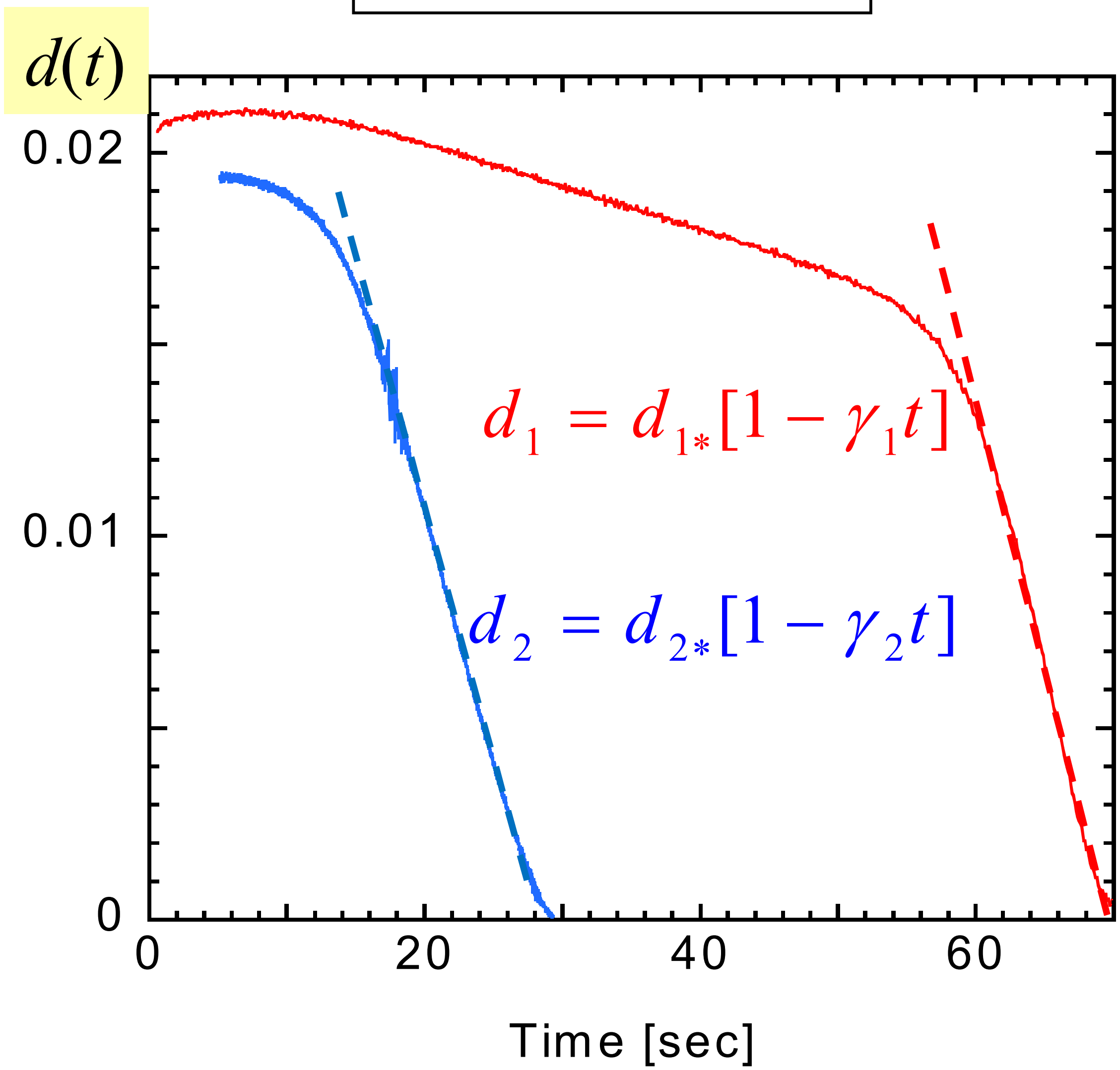
$m_\theta = 2$



resonant particles ($r_2 - \Delta \le r \le r_2 + \Delta$) *form a quadrupole flux asymmetry*

Flux-Driven Algebraic Damping of the $m_\theta = 1$ and $m_\theta = 2$ Diocotron Modes

$$\gamma_m \sim F \equiv -\frac{1}{N}\frac{dN}{dt}$$



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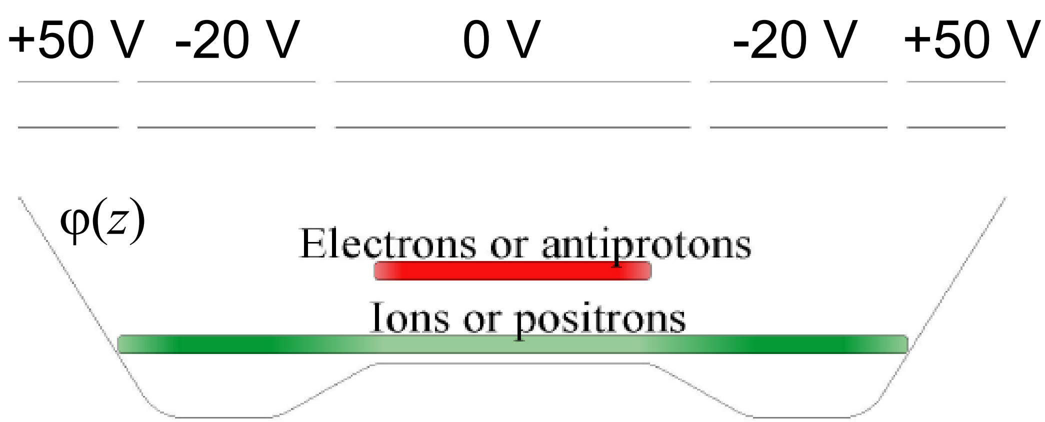
Double-Well (Nested) Traps

Double-well traps can be used to confine particles with opposite signs



Is there a problem with E×B drifts stability ?

Schematic of the $e^- + H_2^+$ experiment

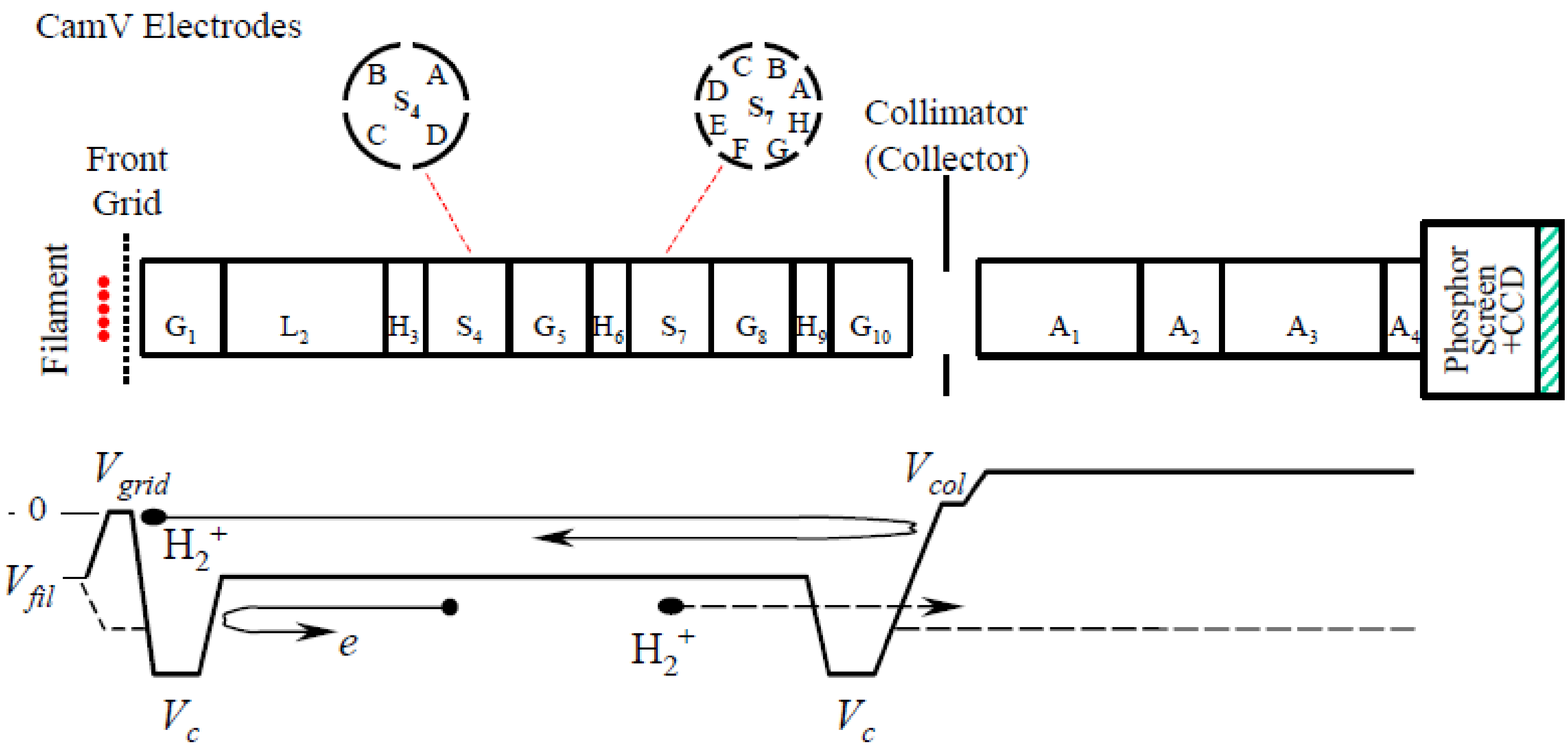
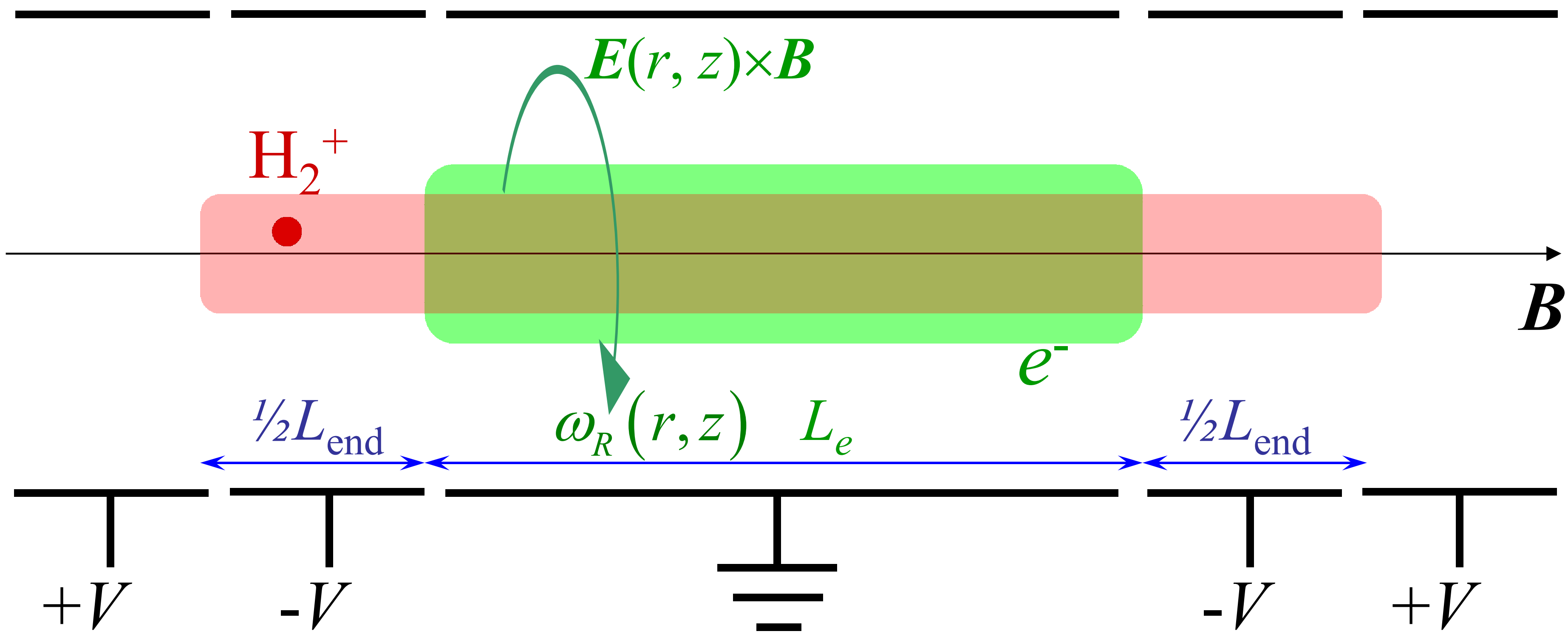


FIGURE 1. Cylindrical Penning-Malmberg trap and imaging diagnostics, with potential profiles for two configurations: a double-well configuration with axially *trapped* ions (solid); and a single-well configuration with *transient* ions (dashed).

Schematic of Double-Well (Nested) Trap Experiments

In a double-well trap the bounce-averaged ***E***×***B*** *drift rotation is different for ions and electrons. This leads to charge separation in a diocotron density perturbation* $\delta n_m(r, \theta)$ *and to instability of the mode*

$L_e \leq 53$ cm
$L_{end} \geq 14$ cm
$R_w = 3.5$ cm



Trapped (Multi-Pass) Ions

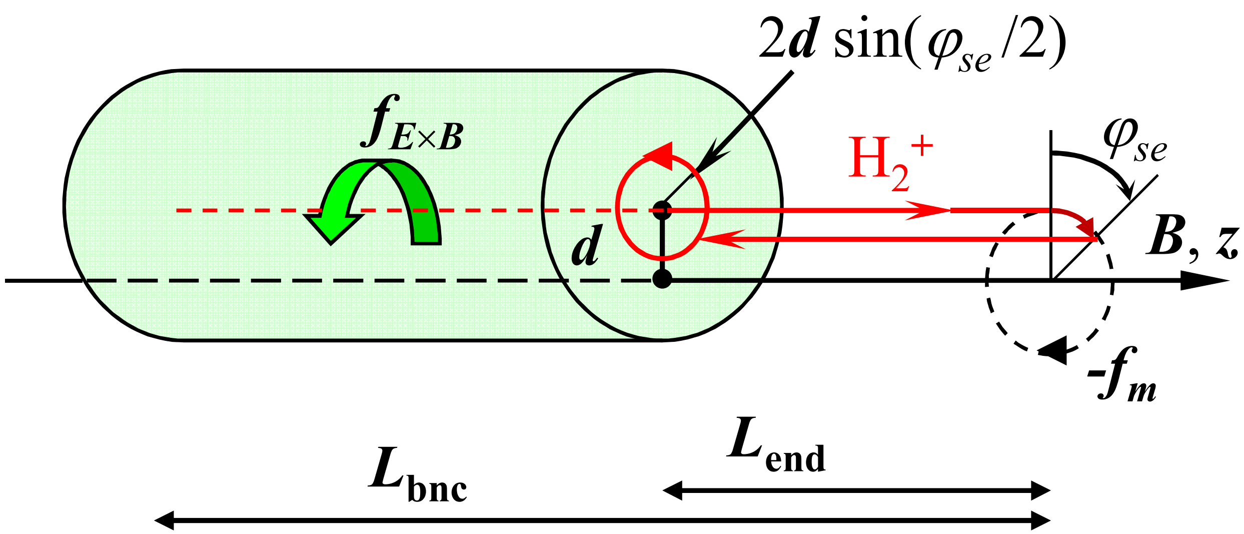
Schematic of Ion ***E***×***B*** Drift Trajectories in the Diocotron Mode Frame

Symmetry dictates that the bounce-average motion of trapped ions is well represented by the motion of an ion set initially at the center of elecron column.

Here, a single end run phase shift $\varphi_{se} = 2\pi\tau_{end} f_m$, # of such runs for a diocotron cycle is $1/(\tau_{bnc} f_m)$, an the average phase acquired during a diocotron cycle $\varphi = 2\pi\,\tau_{end}/\tau_{bnc}$,

τ_i is an average ion lifetime inside the electron column, ($f_m\tau_i$ gives the average number of d-cycles)

$\Delta f_m = (N_i/N_e)\, f_m$ is the net change of mode frequency f_m due to the fractional neutraliztion.



effective B-curvature

$$\tilde{E}_{m\theta} \propto d\,\frac{N_i}{N_e}\sin\!\left(\pi\frac{\tau_{end}}{\tau_{bnc}}\right)$$

$$0 \le \tau_{end} \le \tau_{bnc}$$

$$\Gamma_m = \frac{N_i}{N_e} f_m \times 2\sin^2(\varphi/2) \approx \Delta f_m \times \varphi^2/2$$

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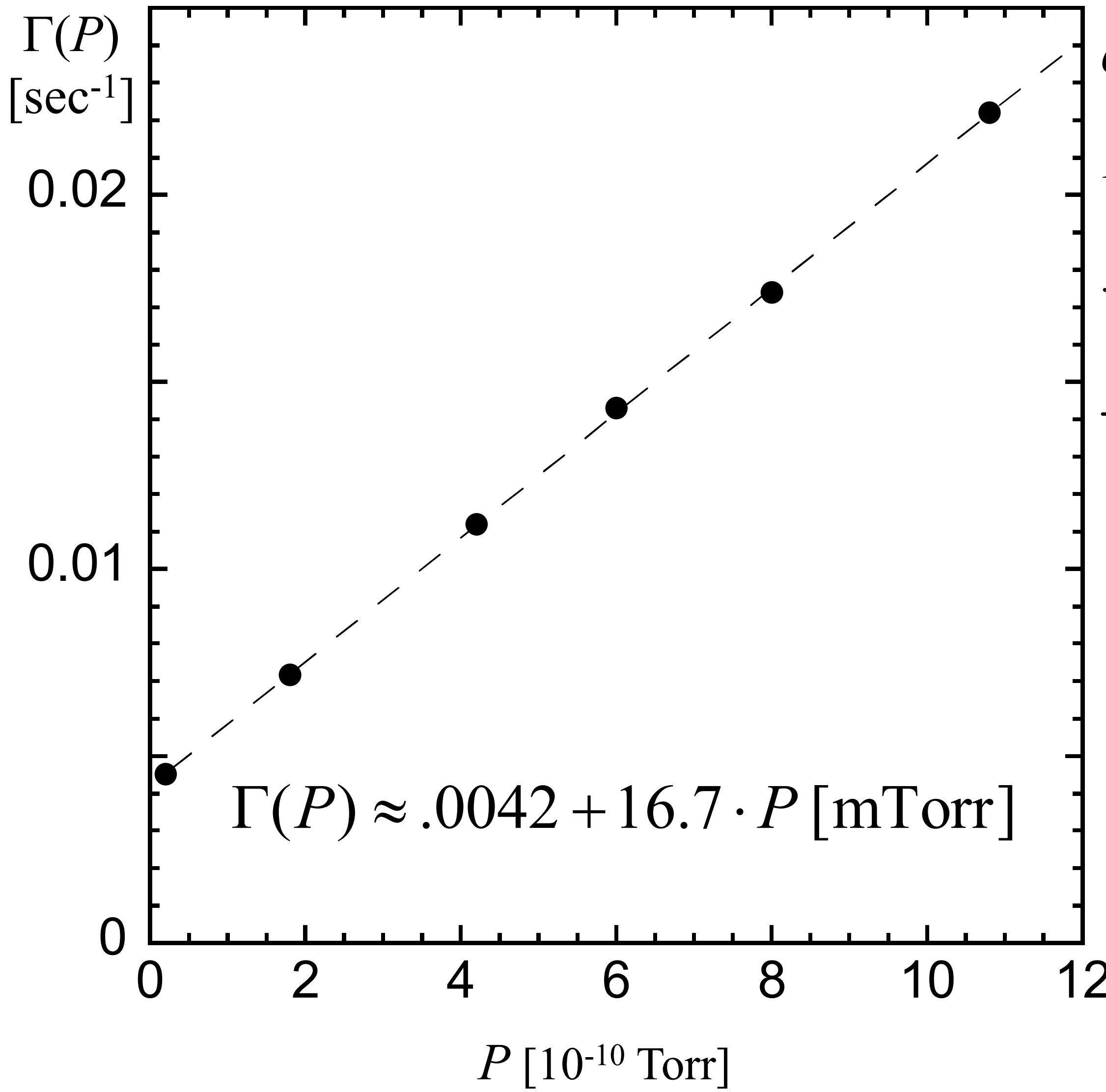
Ion-Induced $m_\theta = 1$ Diocotron Instability as Function of the Background Pressure



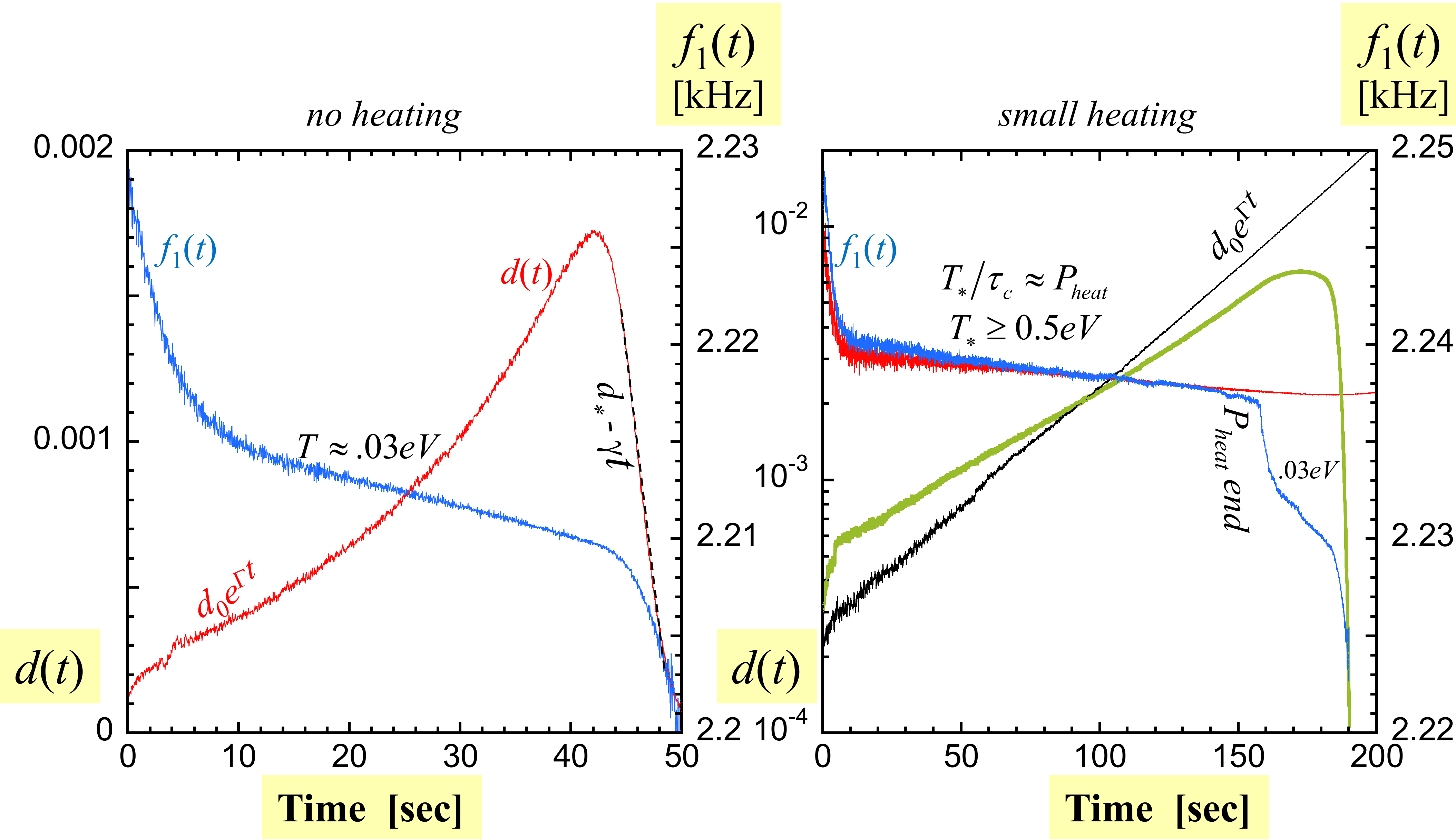
$$d(t) = d_0 e^{\Gamma(P)\cdot t}$$

$$B = 12kG$$

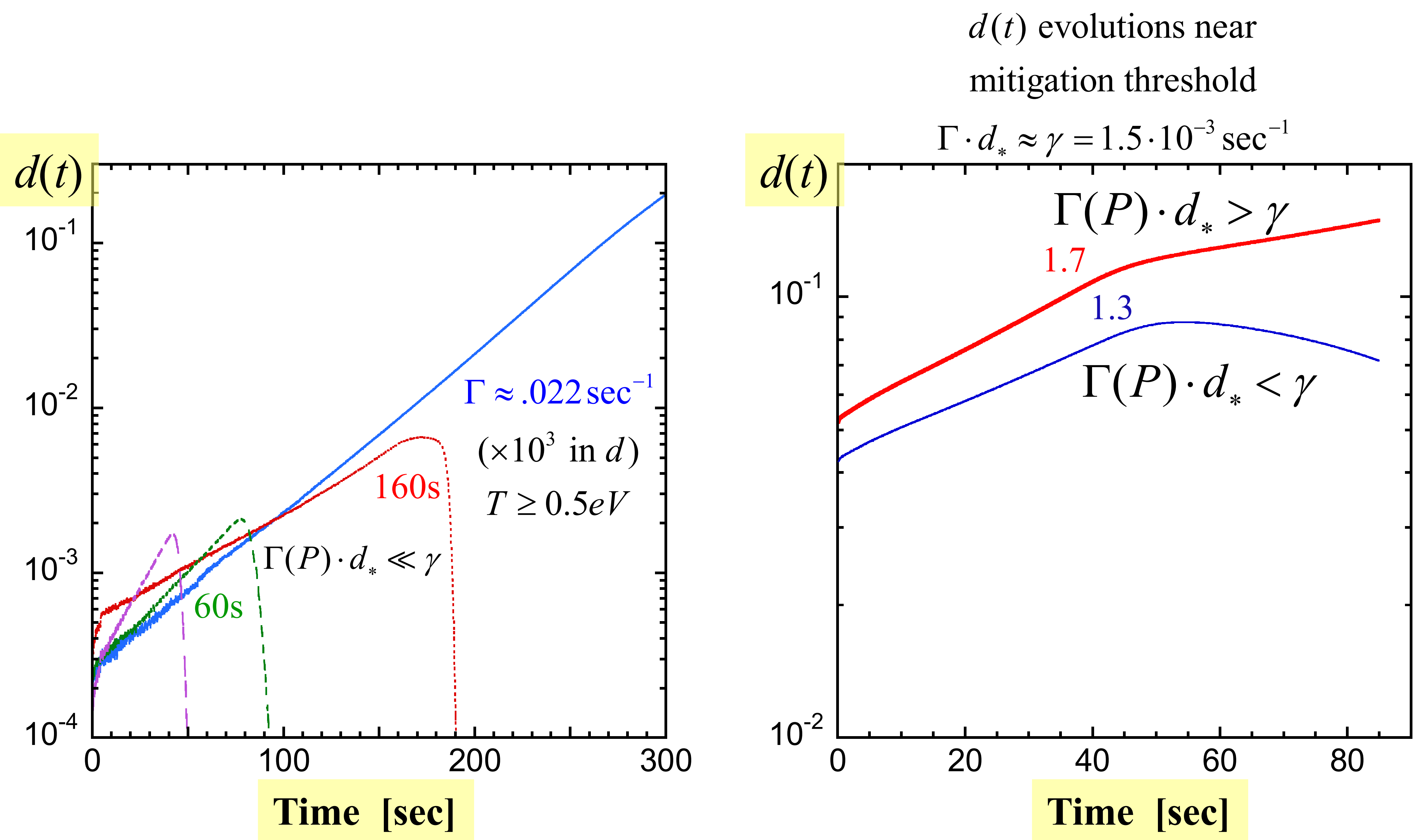
$$f_1 \approx 2.2kHz$$

$$\frac{\Gamma(P)}{f_1} \approx \frac{N_i(P)}{N_e} \approx 10^{-6} \div 10^{-5}$$

Flux-Driven Mitigation of the $m_\theta = 1$ Diocotron Instability



Flux-Driven Mitigation of the $m_\theta = 1$ Diocotron Instability



TAKE-HOME MESSAGE

❖ Adding even a tiny fraction of positive ions to electron plasmas gives rise to the (**E**×**B** drift) diocotron instabilities analogous to the flute instabilities in cylindrical (quasi)neutral plasmas

❖ Small flux of electrons through the wave-particle resonant layer leads to ***an algebraic*** damping of the corresponding wave

❖ Instabilities of drift modes are well controllable if one knows **what to trade-off**