e- / H- Plasmas: Enhanced Centrifugal Separation and Other Disparate Mass Effects

Charles F. Driscoll and Andrey Kabantsev

UCSD Physics

Recent experiments quantify the strong centrifugal separation effects in e-/H- plasmas, here cylindrical columns with ne~10^7/cm3, Bz~10.kG, T~25.meV, and H- fractions from 1% to 10%.

-- Most striking is the outward transport of H- on the sub-second timescale, substantially faster than the 10^4 sec predicted for collisional drag between species. [1] Here, the H- ions couple to the collective diocotron mode, causing algebraic damping of the mode at a rate proportional to the H- creation and outward transport

-- The thermalization of *axially* hot H- ions onto cold electrons is observed to be 20-40 times slower than expected for radially-overlapping species. In contrast, H- ions perp-heated by ICRH couple energy rapidly into parallel e- motion, suggesting a collective process. Similarly, the "inter-species" drag" damping of excited TG waves depends strongly on their radial mode number.

-- The recently developed "plasma modes thermometer" comparing diocotron and TG mode frequencies provides quantitative non-destructive information on the plasma temperature and H- fraction evolutions; but quantitative analysis of collisional and collective species couplings necessitates a MCP dump diagnostic for imaging H-.

[1] A.A. Kabantsev et al, AIP Conf. Proc 1928, 020008 (2018)

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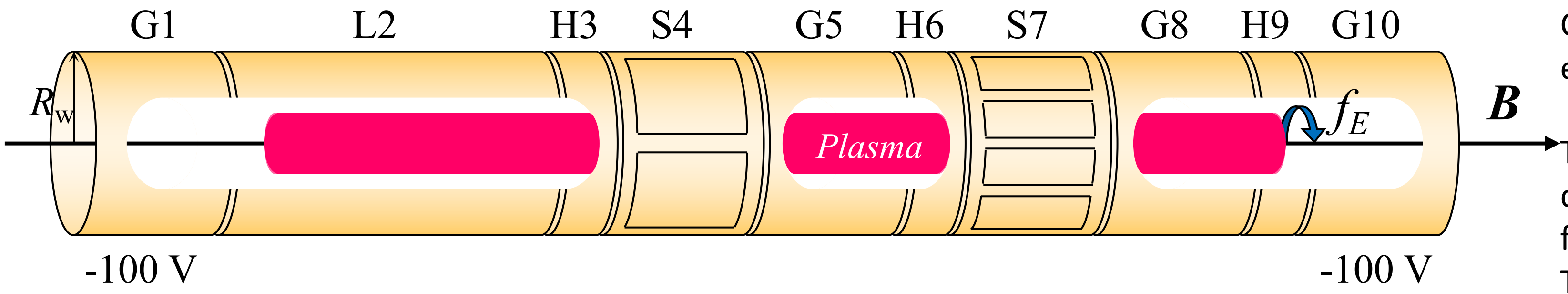
"Pure" electron plasmas: excellent confinement properties,

$$\tau(B) \sim 10^{4} \rightarrow 10^{6} \text{ sec}$$



central density:	$n_0 \approx 10^7$ cm^{-3}
central potential:	$\varphi_0 \approx -30$ V
plasma radius:	$R_P \approx 1.2$ cm ($R_W = 3.5$ cm)
plasma length:	$L \approx 34$ cm (H3-H9)
equilibrium temperature:	$T = 0.025 \rightarrow 1$ eV
magnetic field:	$B = 8 \rightarrow 16$ kG
collision frequency	$\nu_c = 20 \rightarrow 0.1$ kHz
E×**B** rotation frequency:	$f_E \sim 10$ kHz
axial bounce frequency:	$f_{be} \sim 100 \rightarrow 600$ kHz
electron plasma frequency:	$f_{pe} \sim 30$MHz, $f_{TG1} \approx 2.9$MHz

Vacuum Pressure
P ~ 10^{-10} Torr

$e^- + H_2^* \rightarrow H^- + H$

CAMV is a Penning-Malmberg trap with a phosphor and CCD camera downstream of G10 for quantitative dump diagnostic of electrons.

Electrons are emitted from a hot tungsten filament adjacent to G1.

Cyclotron radiation causes the un-neutralized electron plasma to cool to ~25.meV within 10.sec.

This temperature evolution can be quantitatively diagnosed by simultaneously measuring the frequencies of several diocotron (drift) modes and Trivelpiece-Gould (plasma) modes.

Hydrogen-minus ions are observed to form within the electron column, by electron attachment/replacement reactions on excited H_2 molecules transiting the column. The H- has binding energy E_{bind} ~ 0.74eV .

That is, each (well-confined) electron may become a (less-well-confined) heavy H- ion at a rate ~1./ksec .
This rate is about 10x lower when the apparatus walls are "cold", so experiments can be done at various "controlled" e- to H- conversion rates.

Frequency of the primary ($m_\theta = 1$) diocotron mode represents *the total (net) charge line density* of the plasma, $N_L(t)$, as

$$N_L(t) \equiv N_e(t) + N_{H^-}(t) - N_{H_2^+}(t), \text{ and}$$

$$f_{1d}(t) = \frac{ceN_L}{\pi B R_W^2}\left\{1 + \frac{R_W}{L}\left[\frac{j_{01}}{2}\left(\frac{1}{4} + \ln\frac{R_W}{R_p} + \frac{T}{e^2 N_L}\right) - 0.671\right]\right\}\left[1 + \sigma\frac{D_1^2}{R_W^2}\right]$$

Frequency of the primary ($m_\theta = 0$, $k_z = 1$) *eTG*-mode represents *the electron charge line density* of the plasma, $N_e(t)$, as

$$f_{eTG1}(t) = \frac{1}{2L}\sqrt{\frac{2e^2 N_e}{m_e}\ln\frac{R_W}{R_p}} \cdot \left\{1 + \frac{3}{4\ln(R_W/R_p)}\frac{T}{e^2 N_e}\right\}$$

$$e^2 N_e \sim 10\text{eV}$$

The mθ=1, kz=0 diocotron (drift) mode frequency f_{1d} depends equally on the electron and H- charge densities.
This mode shows weak exponential growth exp(Γ t) due to "wall resistance".

The mθ=0, kz=1 Trivellpiece-Gould (plasma) mode frequency f_{eTG1} depends only on the electron density, since the heavier H- ions would oscillate at a 45x lesser frequency.

These mode frequencies depend differently on line-charge denity N_L, plasma radius Rp, plasma length L, and temperature T.
The plasma temperature can thus be obtained from comparison of these and other (mθ, kz) modes

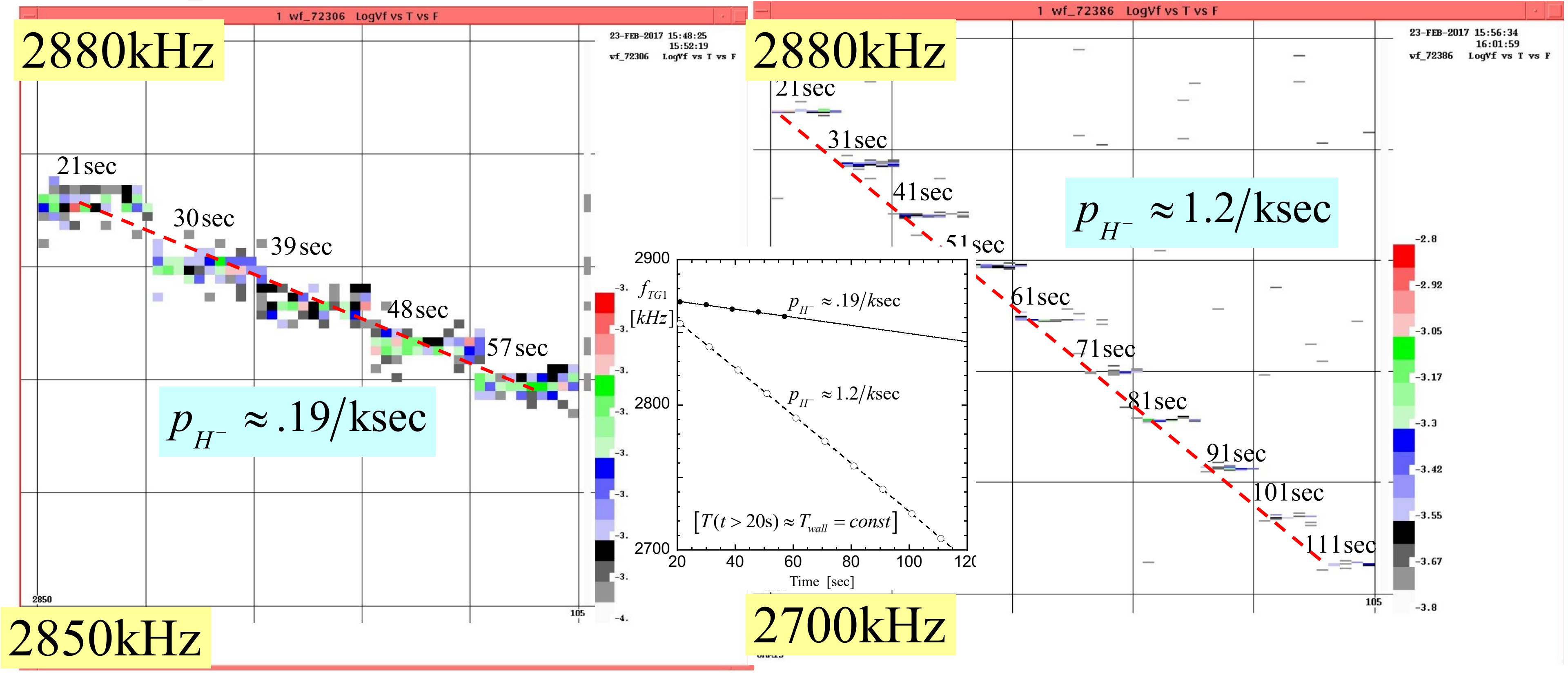
Dissociative electron attachment (the main in plasma volume H^- production process) conserves the total charge line density $N_L(t)$

$$e + H_2(V_X) \to (H_2^-)^* \to H^- + H$$

$$N_L(t) = N_e(t) + N_{H^-}(t) = const$$

*eTG*1 mode frequencies decrease as electrons "convert" to H-. Shown are 2 "controlled" conversion rates $p_{H^-} = 0.19$ and 1.2 /ksec, giving H- accumulation of 1.9% and 12% in 100.sec

$$\frac{1}{N_L}\frac{dN_e}{dt} = \frac{2}{f_{eTG1}}\frac{df_{eTG1}}{dt} = -p_{H^-} \equiv -\frac{1}{N_L}\frac{dN_{H^-}}{dt}$$

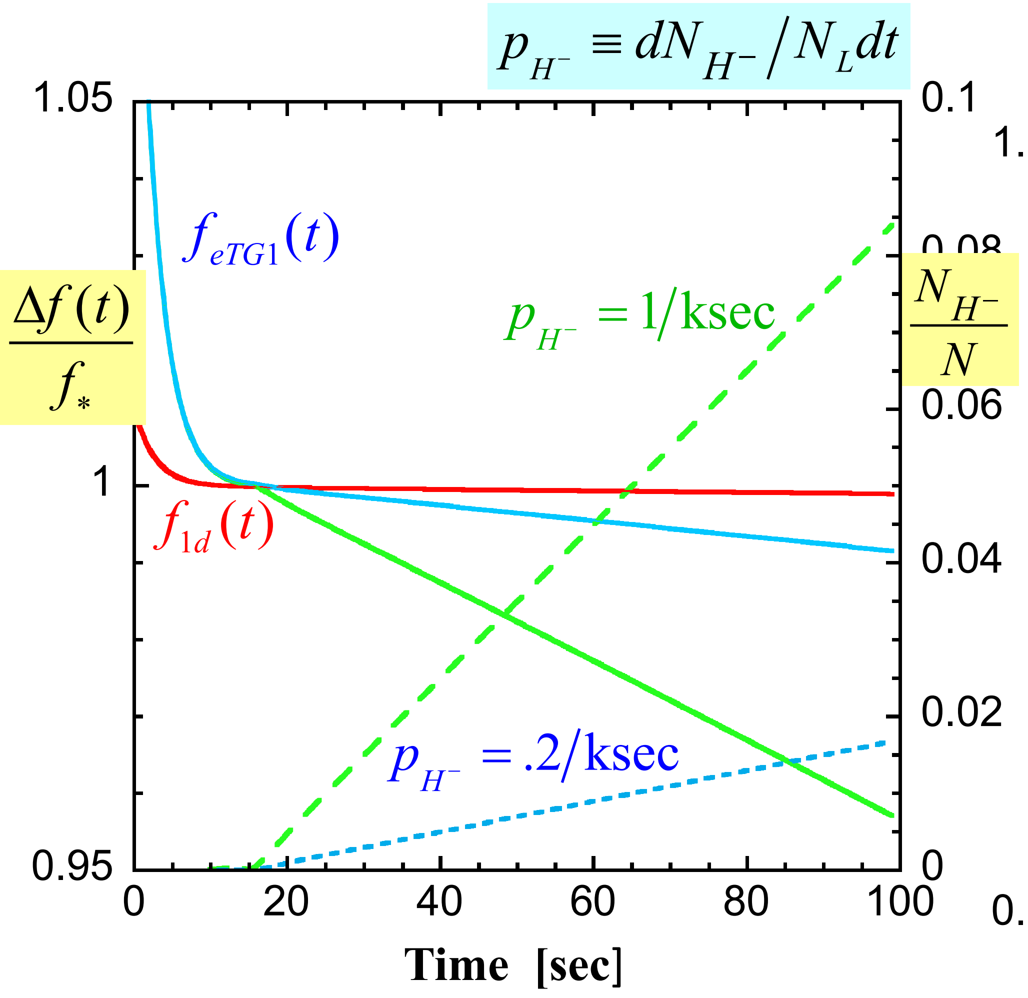


The mθ=0, kz=1 Trivellpiece-Gould (electron plasma) mode frequency f_{eTG1} decreases as electrons convert to H-, since the H- do not respond at the electron oscillation frequency.

Here, thermally-excited TG modes are observed in 0.1msec time slices every few seconds, under "slow" and "fast" p_{H-} conversion conditions.

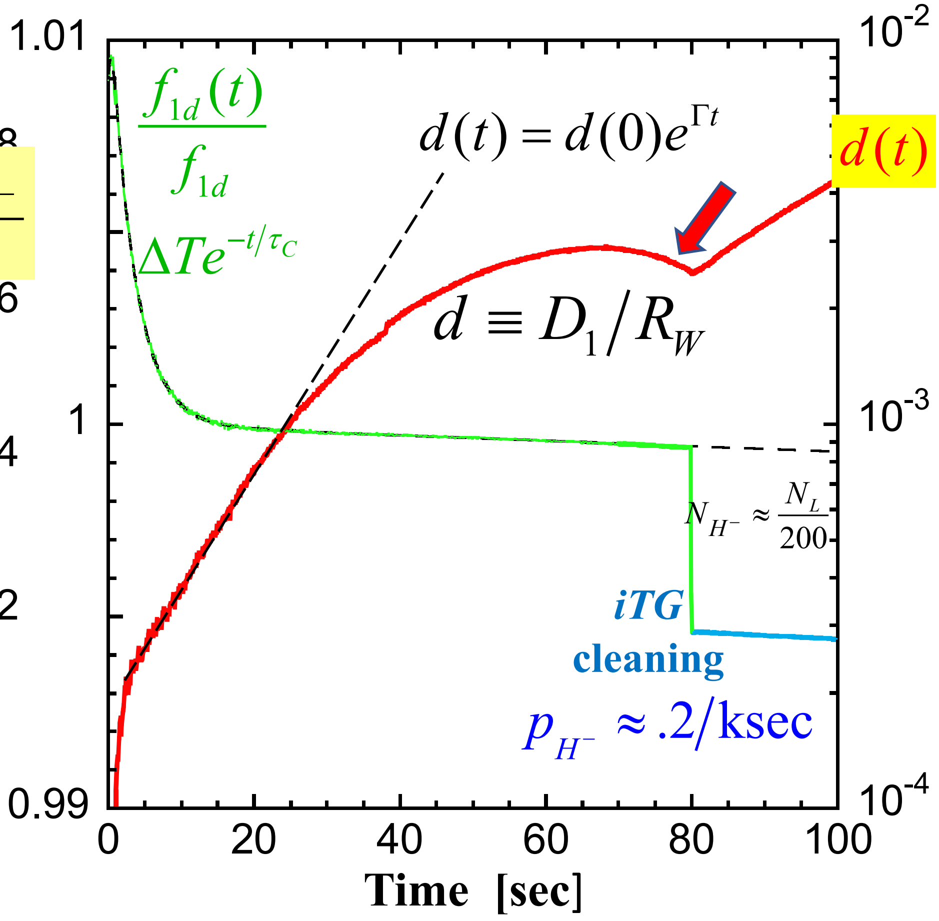
The central plot shows the observed f_{TG1} decreasing proportional to H- accumulation.

$$\frac{\Delta f_{1d}(T)}{f_{1d}(0)} \approx \frac{R_W}{2L}\frac{\Delta f_{eTG1}(T)}{f_{eTG1}(0)} = \frac{1}{20}\frac{\Delta f_{eTG1}(T)}{f_{eTG1}(0)}$$



iTG-shaked cleaning of accumulated H^- gives the instant

$$N_L(t_*) = N_e(t_*) = N_L(0) - N_{H^-}(t_*)$$



The injected electron plasma cools from T~1eV to T~25.meV in 10.sec.

When cold, plasma electrons become heavy H- ions at (controlled) rates: 1/ksec (green) or 0.2/ksec (cyan), accumulating to 2% or 8% in 100.sec.

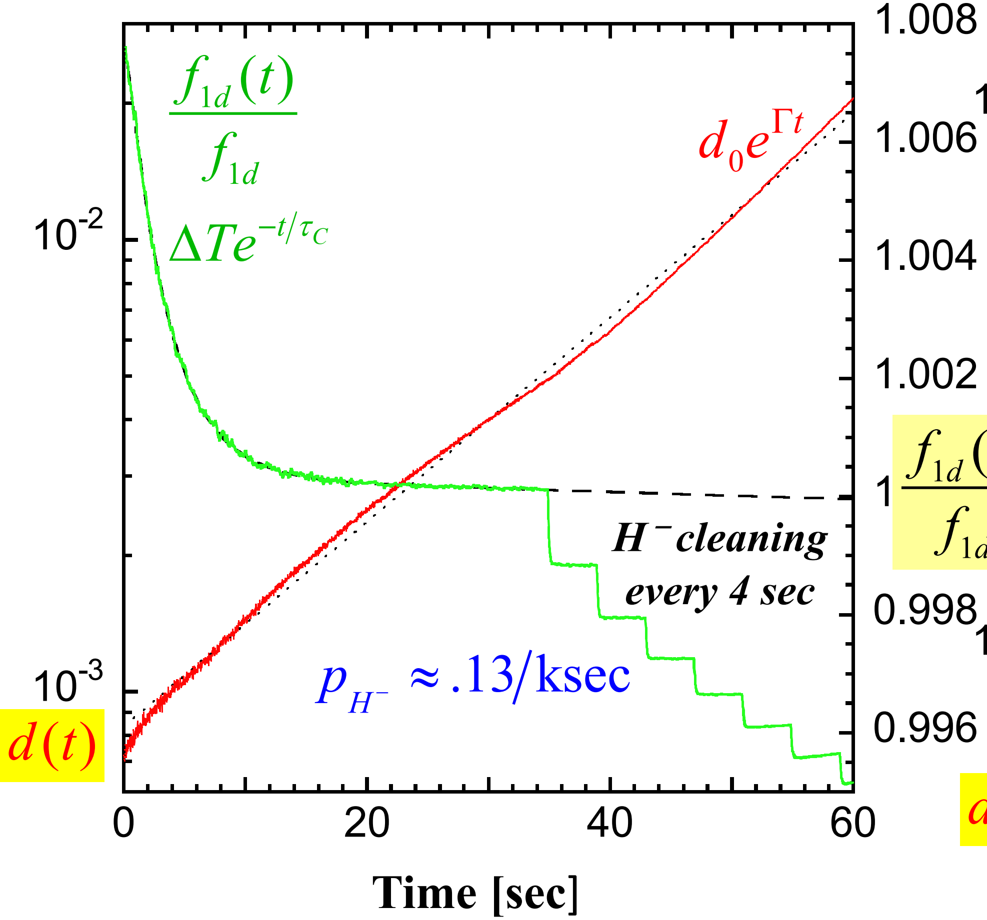
The TG mode frequency varies strongly during cooling, and further decreases proportion to H- accumulation rate (cyan vs green).

The diocotron mode frequency is insensitive to H- mass accumulation, but the mode is weakly unstable due to finite wall resistance.

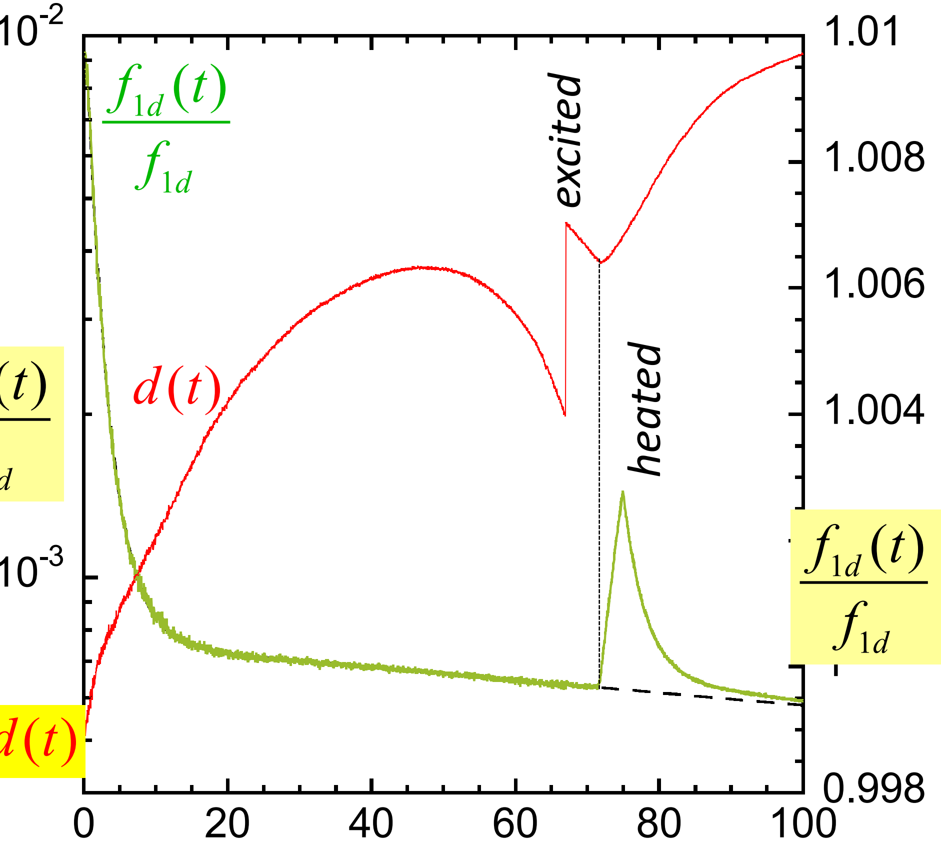
>> We observe *algebraic* damping of the diocotron mode proportional to the number of accumulated H- ions, and this damping may overcome the weak wall instability.

Cleaning the H- ions from the system by ion-TG-frequency "shaking" immediately decreases f1d and restores the weak exponential growth.

Exponential growth is sustained by continuous cleaning of H^-



Exponential growth is restored (algebraic damping is halted) by heating of electrons



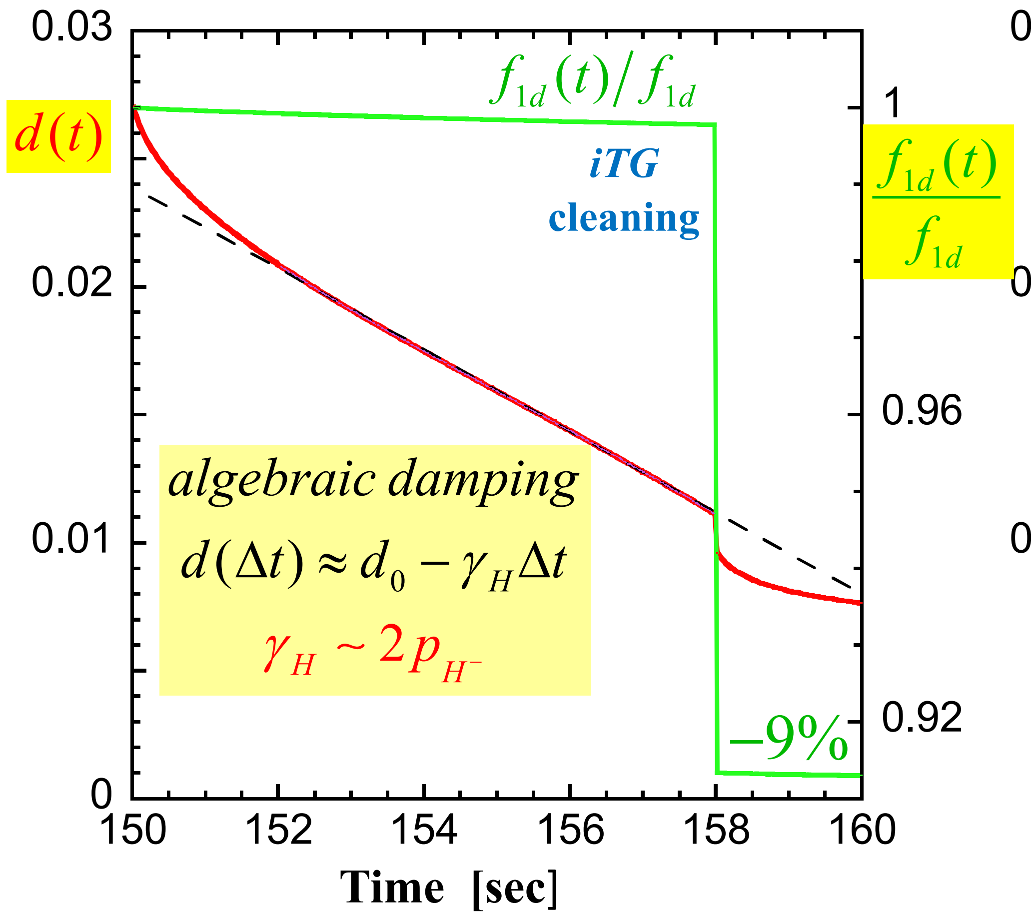
Right Plot : The slow *exponential* diocotron growth (due to the resistive wall) is negated by outward H- transport and *algebraic* mode damping when sufficient H- is accumulated.

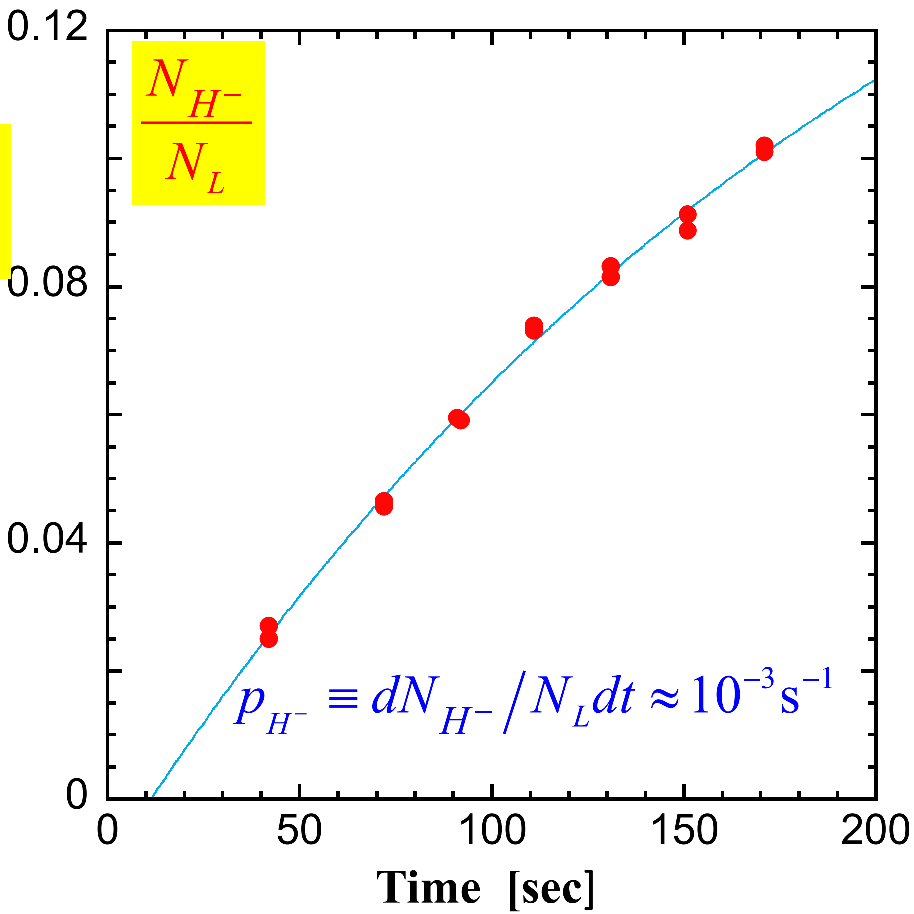
Exciting a 2x larger mode establishes 2x larger (algebraic) damping.

Heating the plasma to T~0.2eV restores the weak exponential growth, by killing the H- induced damping.

Left Plot : Similarly, cleaning" the H- axially out of the plasma prevents the H- algebraic damping.

H^- fraction up to 10% is accumulated in a cold electron plasma during ~ 100 sec. Then, an excited diocotron mode shows *algebraic* damping at rate γ_H, equilibrating to ~2x the H^- production (and loss) rate



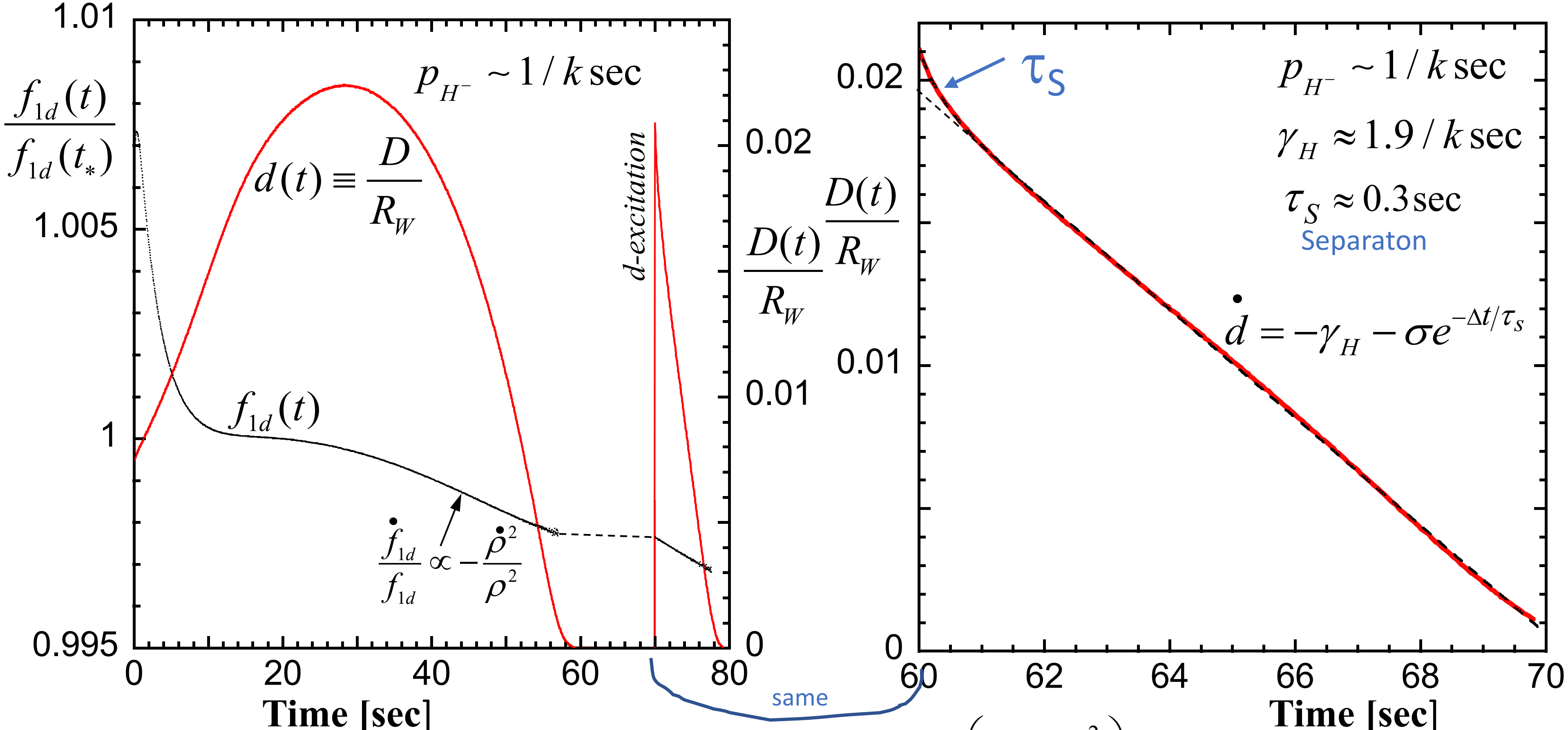


Left Plot : A diocotron mode is excited after 150.sec of H- accumulation and outward expansion. d(t) clearly shows algebraic rather than exponential damping.

Then, "cleaning" the H- ions by axial ejection causes a 9% decreace in total charge, as indicated by f_{1d}. It also reduces the H- damping to near zero.

Right Plot : Performing the "cleaning" at various times establishes the H- production rate p_{H-} .

Algebraic damping rate γ_H is compatible with the concurrent plasma transport rate as $\gamma_H \sim (dR_p^2/dt)/R_p^2$, as measured by (d/dt)f$_{1d}$ / f$_{1d}$



$$\frac{1}{f_{1d}}\frac{df_{1d}}{dt} \approx 1.6/k\sec \approx -\frac{j_{01}}{4}\frac{R_W}{L}\left(\frac{1}{R_p^2}\frac{dR_P^2}{dt}\right)$$

Summary

- **In the first e^-/H^- plasma experiments we have found that accumulation (production) of H^- ions causes *algebraic* damping of diocotron modes, with a corresponding accelerated radial transport (*mass separation*) of the H^- ions. The observed centrifugal separation time (< 1sec) is much faster than expected from inter-species collisional drag (~10^4sec), and independent of *B*.**

Some other interesting effects observed in the first e^-/H^- experiments:

- **Enhanced cooling of electrons in collisions with H^- ions (cooled by neutrals)**
- **Enhanced damping of plasma waves due to e^-/H^- collisional (viscous) drag**
- **Effective resonant acceleration (cleaning) of H^- ions at the *iTG* frequency**
- **Strong *exponential* damping of diocotron modes in a "floppy" H^- plasmas**

(after ejecting axially the electron component)