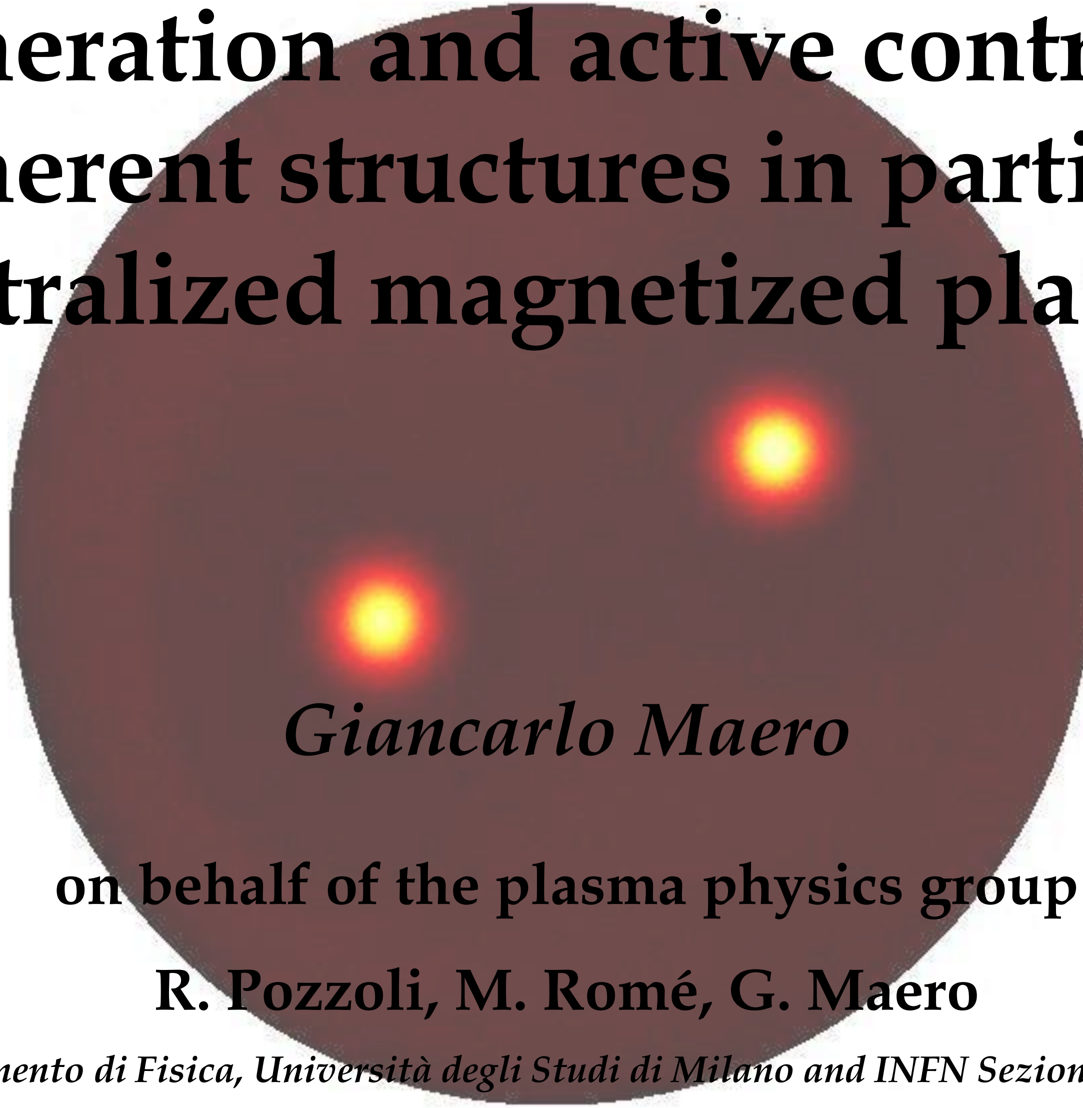
Generation and active control of coherent structures in partially neutralized magnetized plasmas



Giancarlo Maero

on behalf of the plasma physics group

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Synopsis

Introduction

- Penning traps and non-neutral plasma confinement
- Kelvin-Helmholtz instability
- Excitation and control of diocotron (KH) modes

Radio-frequency (RF) generated electron plasmas

- RF electron plasma generation
- Persistent structures: off-axis vortex – stable and modulated equilibrium
- Autoresonant excitation at the modulation frequency
- Higher-order diocotron modes: RF effects on stability

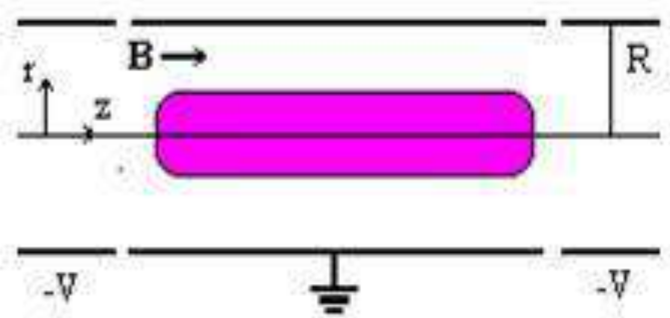
Conclusions and outlook

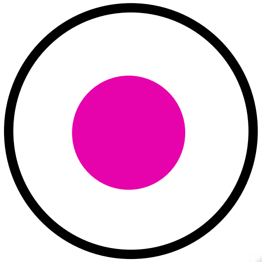
Penning-Malmberg traps and non-neutral plasma confinement

Confinement principle:

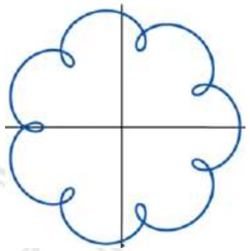
≥ 3 biased cylinders (axial confinement) + axial magnetic field (radial confinement)

Results in superposition of axial and transverse oscillatory motions





Single-particle picture: fast cyclotron + ExB drift



Collective picture: the natural equilibrium state is a round, centered column (single vortex) in a ***rotational equilibrium***

$$P_\vartheta = \sum_j \left(m v_{j,\vartheta} r_j + q_j \frac{B r_j^2}{2c} \right) \approx \sum_j \left(q_j \frac{B r_j^2}{2c} \right) = \frac{qB}{2c} \sum_j r_j^2$$

high magnetization (≈) *single species* (=)

Kelvin-Helmholtz (diocotron) instability

Transverse dynamics: E x B – collective KH (diocotron) modes and vortices (isomorphic to 2D Eulerian fluid).

plasma

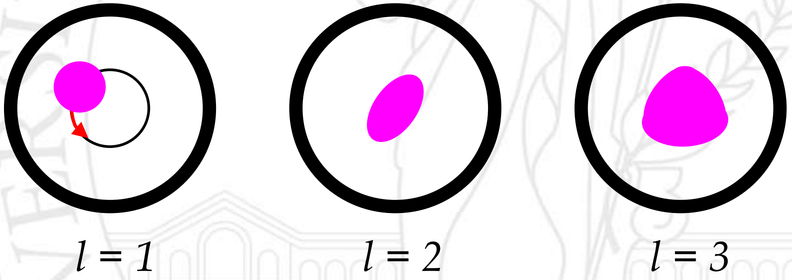
$$\begin{cases} \dfrac{\partial n}{\partial t} + \vec{v} \cdot \vec{\nabla} n = 0 \\ \vec{v} = -\dfrac{\vec{\nabla}\Phi \times \hat{e}_z}{B} \\ \nabla^2 \Phi = \dfrac{en}{\varepsilon_0}, \quad \Phi(r_W, t=0) \end{cases}$$

fluid

$$\begin{cases} \dfrac{\partial \varsigma}{\partial t} + \vec{v} \cdot \vec{\nabla} \varsigma = 0 \\ \vec{v} = -\vec{\nabla}\psi \times \hat{e}_z \\ \nabla^2 \psi = \varsigma \end{cases}$$

$$\frac{en}{\varepsilon_0 B} \sim \varsigma = \left(\vec{\nabla} \times \vec{v}\right)_z \qquad \frac{\Phi}{B} \sim \psi \qquad \vec{v} \sim \vec{v}$$

$$n(r,\theta,z) = n^0(r) + \sum_{l=-\infty}^{+\infty} \delta n^l(r) e^{i(l\theta - \omega t)}$$

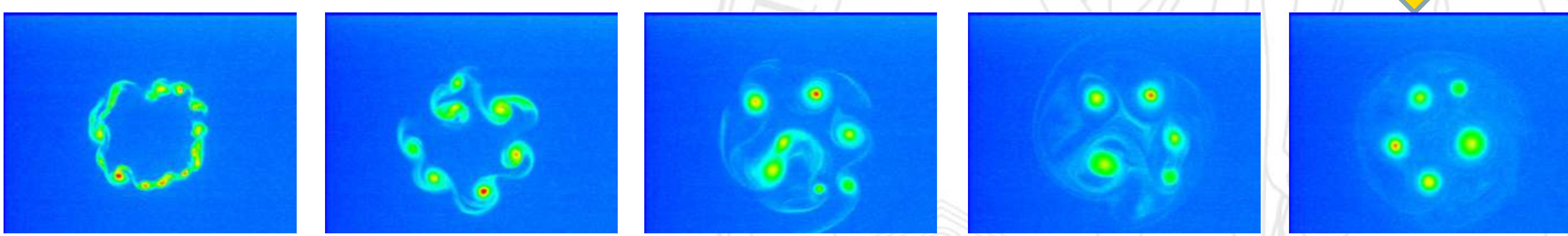


etc.

Kelvin-Helmholtz instability – turbulence

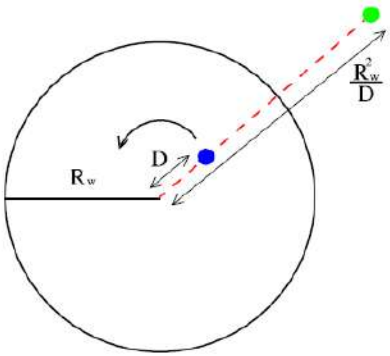
KH instability: in layers of **fluid** having a **velocity shear**, **vorticity** is created

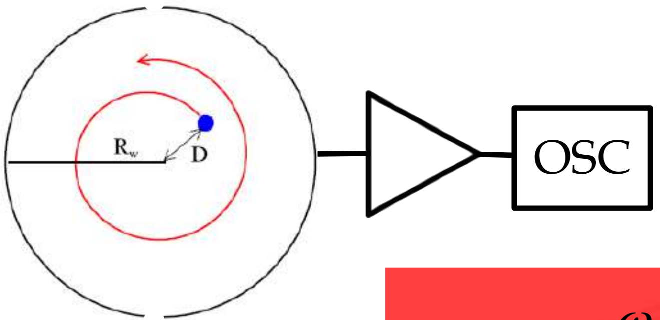
M. Romé, poster 38



2 μs   16 μs   48 μs   78 μs   458 μs

l = 1 mode features and instability





$$\omega_1 = \frac{\omega_d}{1 - D^2 / R_W^2}, \; with \quad \omega_d = \frac{\lambda_p}{2\pi\varepsilon_0 B R_W^2}$$

'Negative energy' mode: dissipation leads to amplitude growth and loss

Sources of instability:
** resistive-wall dissipation*
** presence of opposite-sign particles*
… and in general anything related to injection/loss of P_θ (static and RF perturbations, charge and density variation, axial/transverse mode coupling…)

Autoresonance in non-linear oscillators

How to excite an oscillator? Start at low amplitude, at linear frequency. But then you must:

- adjust the forcing frequency
- stay in phase with the oscillator

(= feedback system needed)

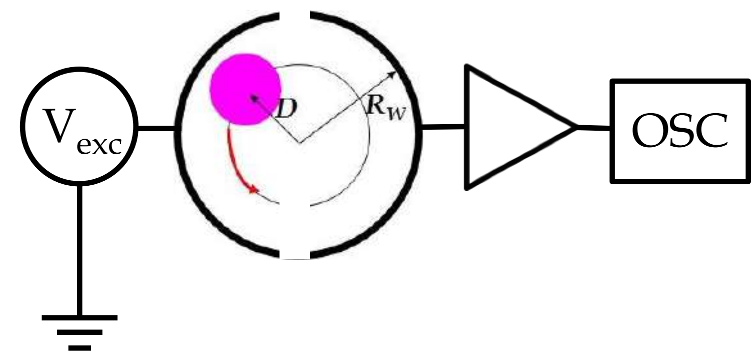
A practical alternative? **Autoresonance:**

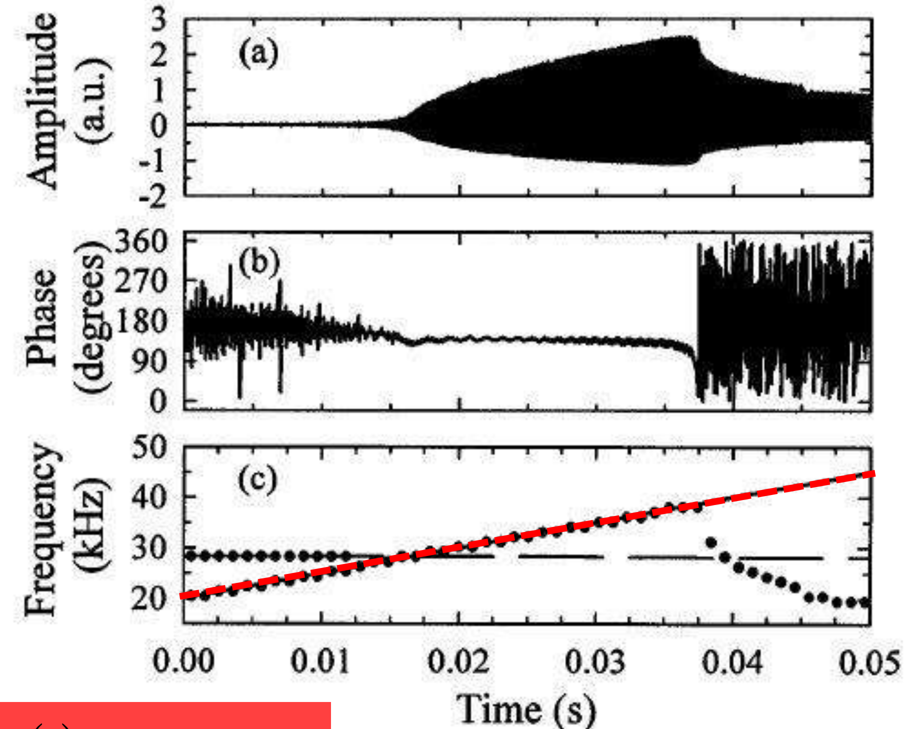
Chirped forcing swept across the oscillator's resonant frequency
→ oscillator locks in with drive and follows drive frequency change
→ amplitude automatically adjusts follow the oscillator's A - ω relation

Threshold phenomenon (always works beyond threshold amplitude)
No need to tune the drive phase (the system takes care)

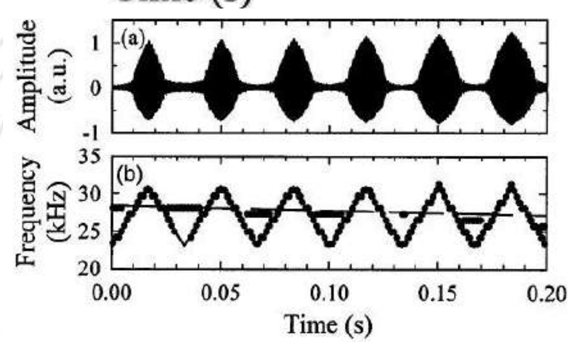
Autoresonant plasma manipulation: mode 1

Radial displacement autoresonantly controlled by swept drive $V_{exc}(t)$ via the non-linear relation $\omega_1 = f(D)$



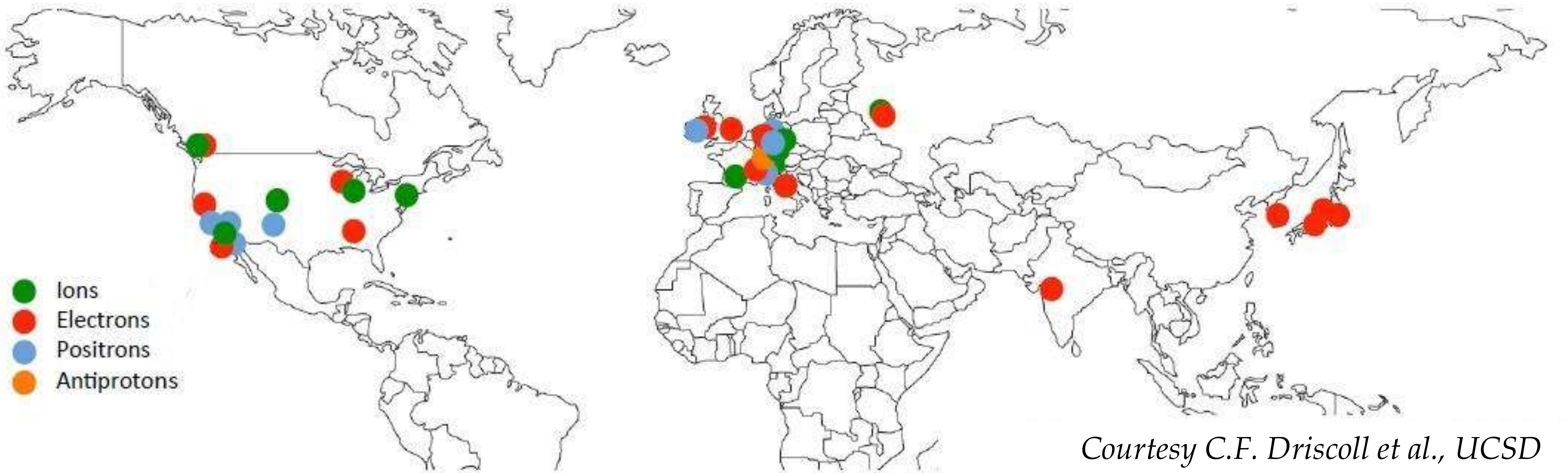


$$\omega_1 = \frac{\omega_d}{1 - D^2 / R_W^2}, \quad V_{exc}(t) = V_0 \sin[\omega(t) t], \quad \omega(t) = \omega_{in} + \varepsilon \cdot t$$



J. Fajans, E. Gilson and L. Friedland, Phys. Rev. Lett. ***82****, 4444 (1999)*

Penning traps around the world



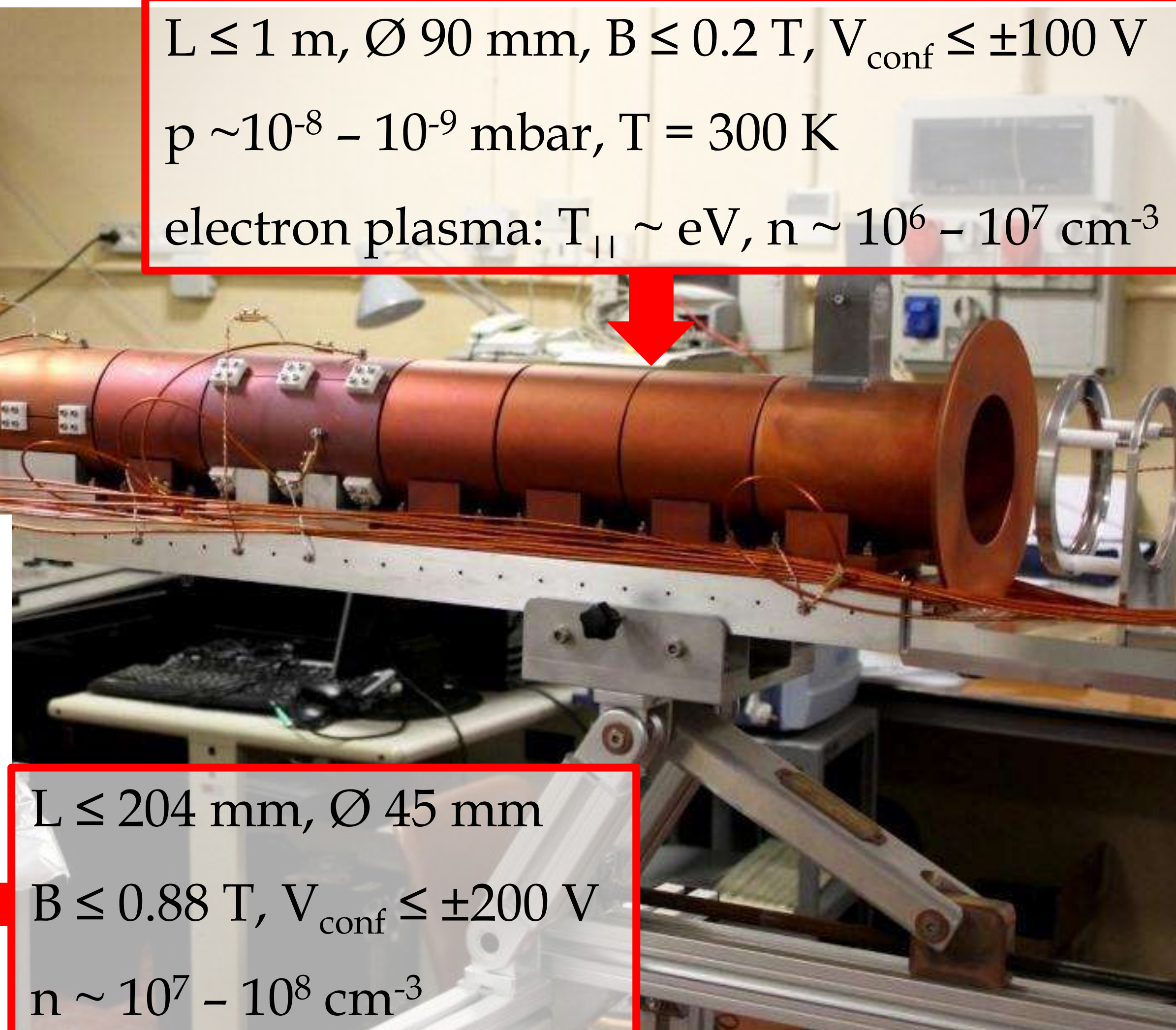
Courtesy C.F. Driscoll et al., UCSD

Applications

- *Penning (harmonic potential, few particles)*: mass spectrometry, spectroscopy, fundamental constants
- *Penning-Malmberg (flat-bottomed potential, many particles)*: plasma and fluid (collective) physics (also related to other ExB-dominated systems, e.g., thrusters, ion sources, fusion plasmas), turbulence, accumulation and cooling (spectrometry, antimatter synthesis)

NOTE: systems are often not 'ideal' (multiple species, RF perturbations…)

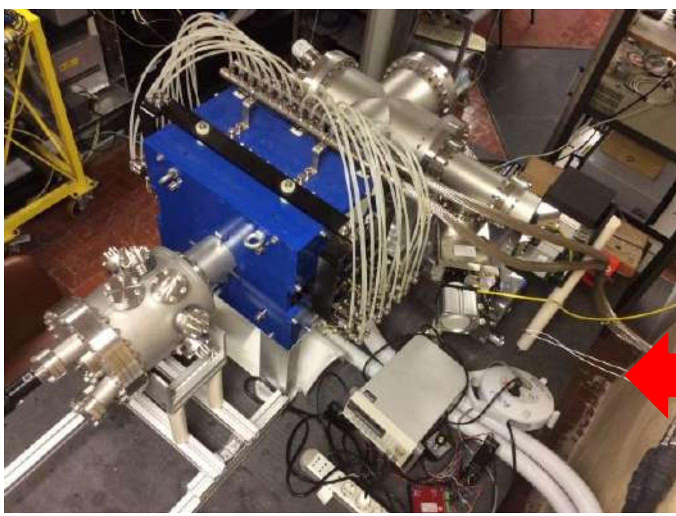
Our set-ups: ELTRAP and DuEl traps



$L \leq 1$ m, Ø 90 mm, $B \leq 0.2$ T, $V_{conf} \leq \pm 100$ V

$p \sim 10^{-8} - 10^{-9}$ mbar, $T = 300$ K

electron plasma: $T_{||} \sim$ eV, $n \sim 10^{6} - 10^{7}$ cm^{-3}



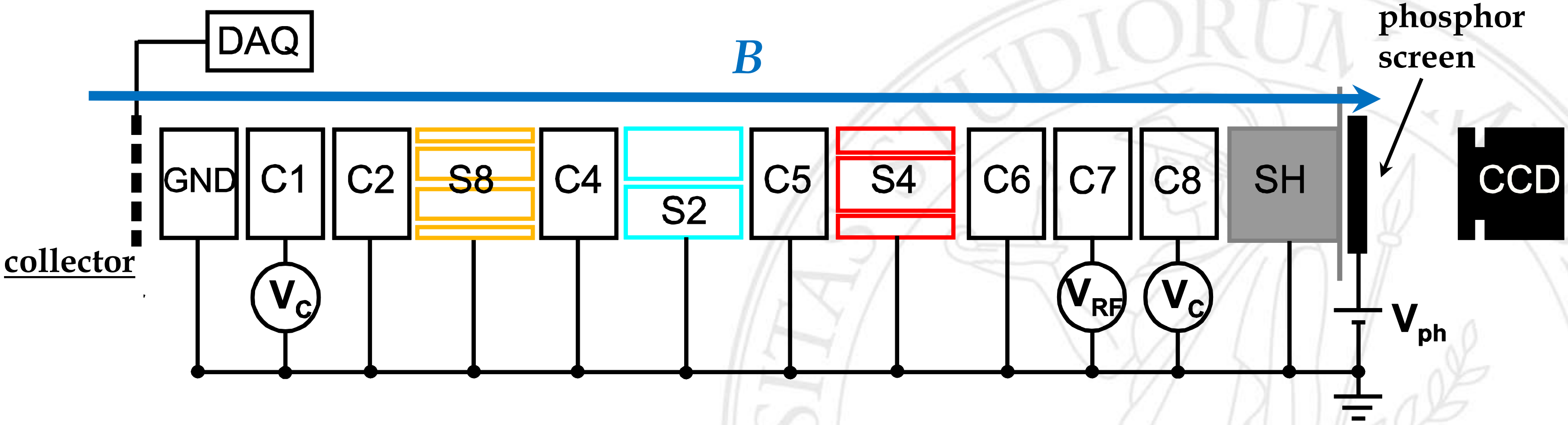
$L \leq 204$ mm, Ø 45 mm

$B \leq 0.88$ T, $V_{conf} \leq \pm 200$ V

$n \sim 10^{7} - 10^{8}$ cm^{-3}

RF electron plasma generation

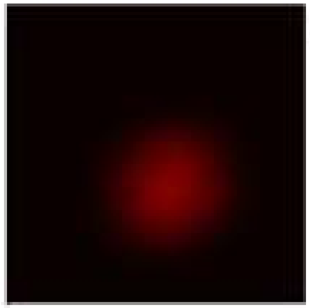
The application of a RF excitation on one of the inner electrodes heats the free electrons in the background gas leading to ionization.
Typical RF parameters: $f(t)=V_{RF}\sin(2\pi\nu_{RF}t)$, V_{RF}~1-5 V, ν_{RF}~**1-30 MHz** (vs diocotron mode frequencies in the **10-100 kHz** range).
A balance is established in a time range of **seconds**.



Very different from externally-injected, 'quiescent' plasma: external forcing, ionization, continuous creation and loss of e^- and ions → sources of dissipation (instabilities)

Equilibrium states

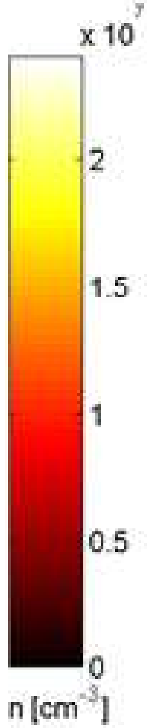
Generation parameters: *B = 0.1 T, L_{trap} = 570 mm, C7 excitation: V_{RF} = 1.5 V, ν_{RF} = 0.1-30 MHz,* ***t = 4.5 s***

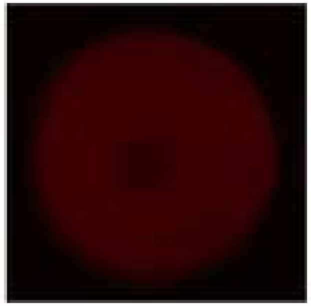


ν_{RF} = 1.8 MHz

ν_{RF} = 3.1 MHz

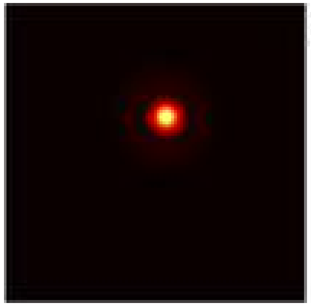
ν_{RF} = 4.3 MHz



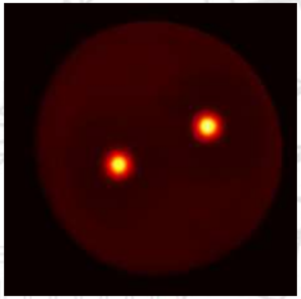


ν_{RF} = 8.9 MHz

ν_{RF} = 9.2 MHz



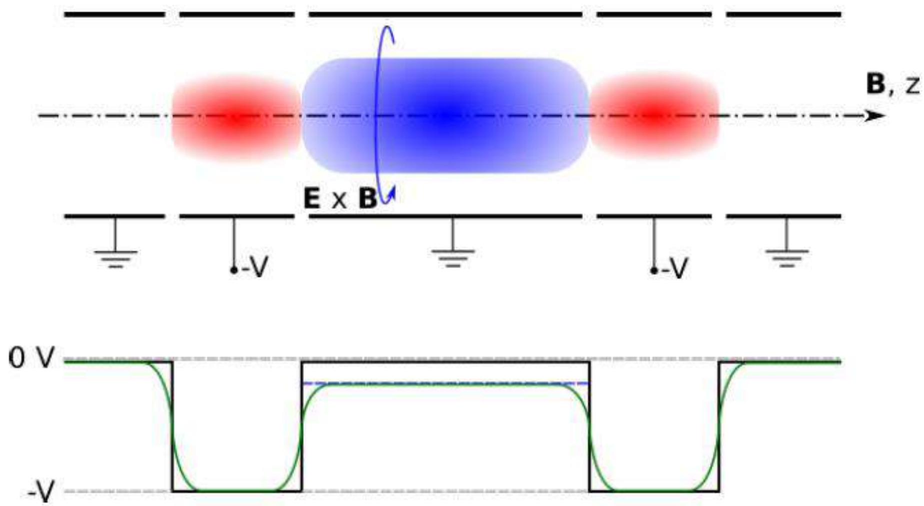
ν_{RF} = 9.8 MHz



diffuse, centered columns vs *dense, small-scale off-axis structures:*

how do they form and can we get the best of both?

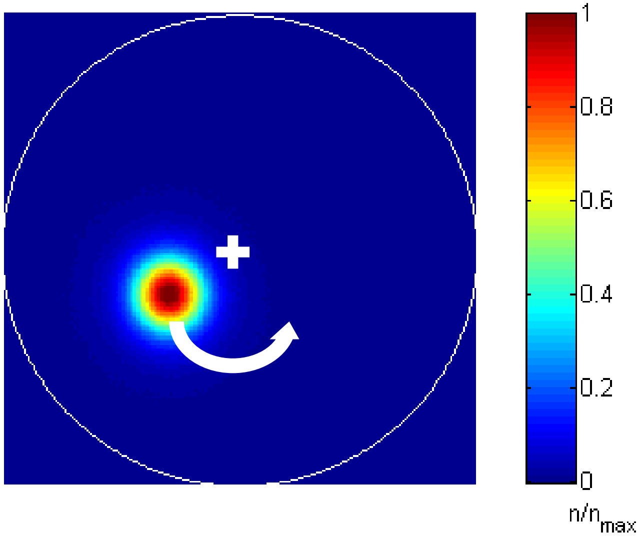
Ion trapping – *l=1* ion-driven instability



- Ions are co-trapped due to e^- space charge (→ multiple trap crossing and accumulation, with time scales ~100 ms)
- Differential drift → change in angular momentum (→ mean square radius) of the column and instability
- Both *l=1* mode instability and direct trapped-ion measurements indicate N_i/N_e as high as 10^{-2} - 10^{-1} (significant plasma neutralization)

A. Franzetti and L. Gavassino, BSc theses 2016; N. Cantini and E. Villa, BSc theses 2017

Equilibrium states: off-axis vortex

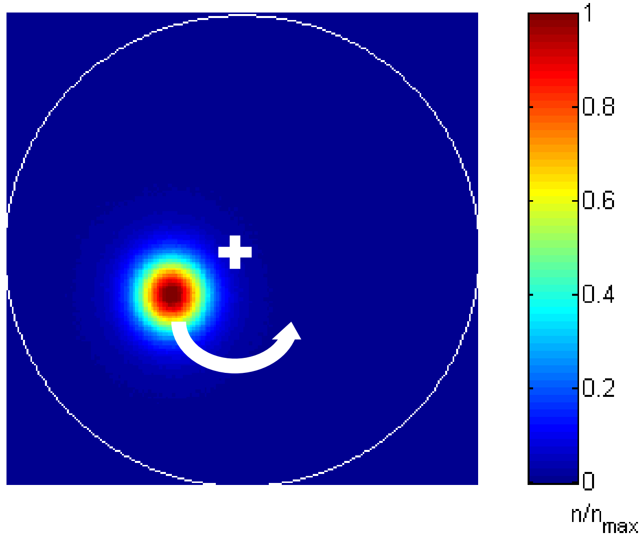


As long as the RF drive is present, an off-axis equilibrium states may exist for a single vortex.

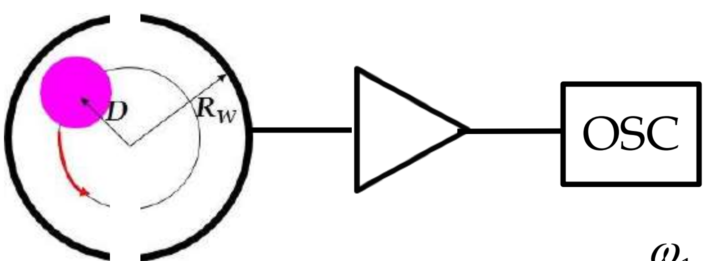
But: *l=1* mode is prone to a number of destructive instabilities if RF is switched off, so what?

And worse: *l=1* autoresonant control does not work…

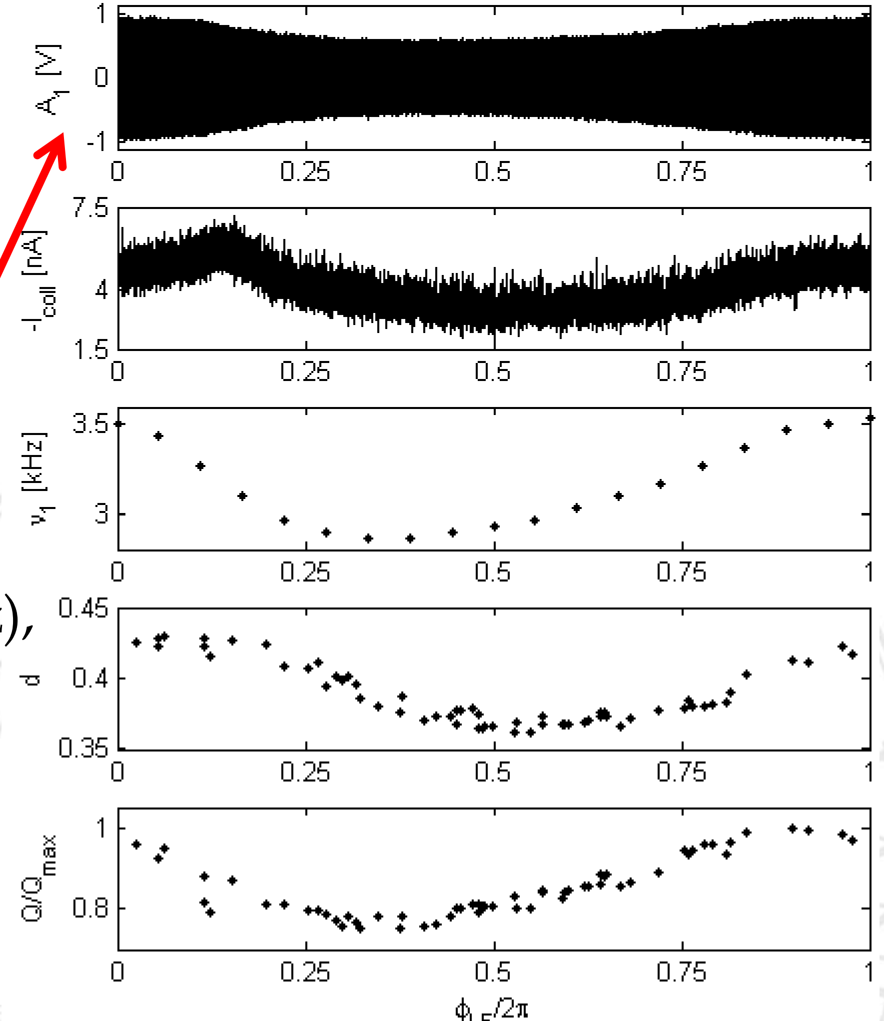
l=*1* diocotron mode modulation



The *l*=*1* mode may be modulated (1-10 Hz), yet stable against impulsive perturbations



$$\omega_1 \propto \frac{\lambda_d}{1-d^2}$$



B = 0.15 T, L_{trap} = 570 mm, V_{RF} = 0.9 V, ν_{RF} = 9.9 MHz]

l=1 diocotron mode modulation

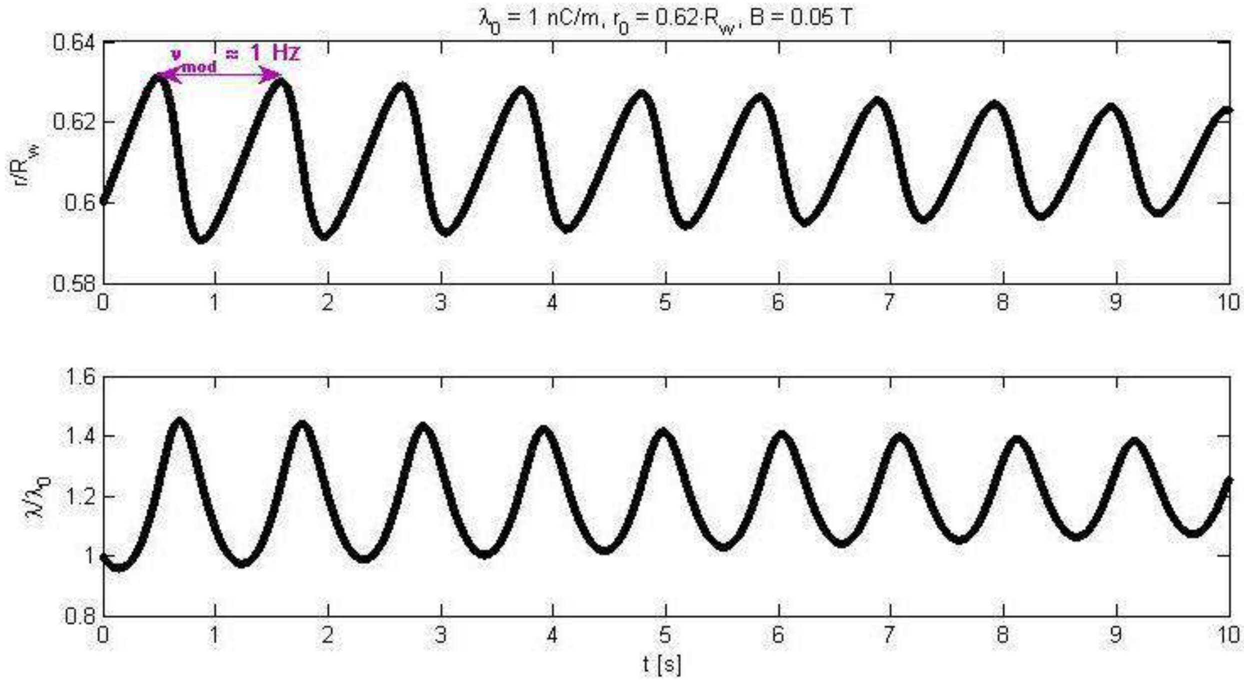
$$\underline{v} = \frac{\underline{E} \times \underline{B}}{B^2}$$ *fluid (guiding-center) drift motion*

$$\frac{d\underline{v}}{dt} = -\beta \underline{v}$$ *dissipation (generic, viscous-like)*

$$\frac{d\lambda_p}{dt} = f(r),$$ *charge balance (production and losses)*

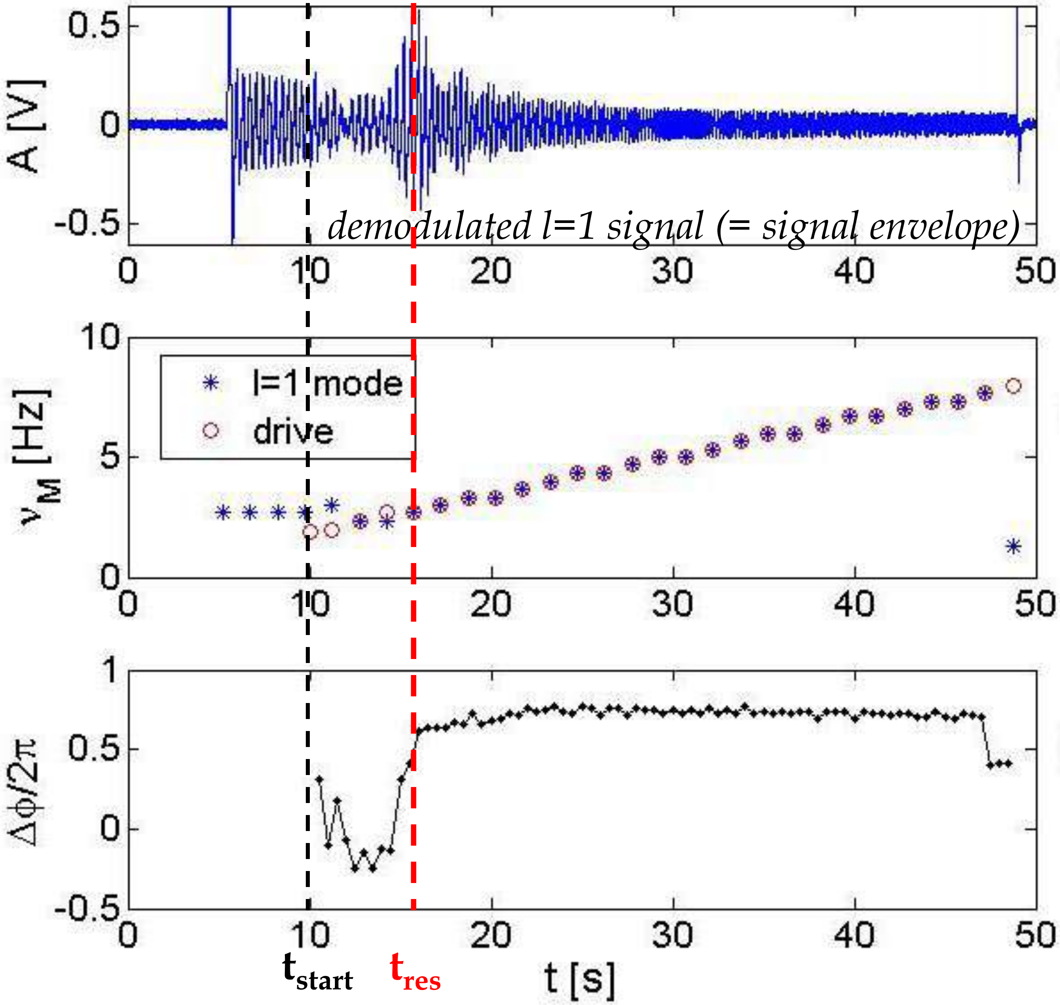
hyp.: linearize

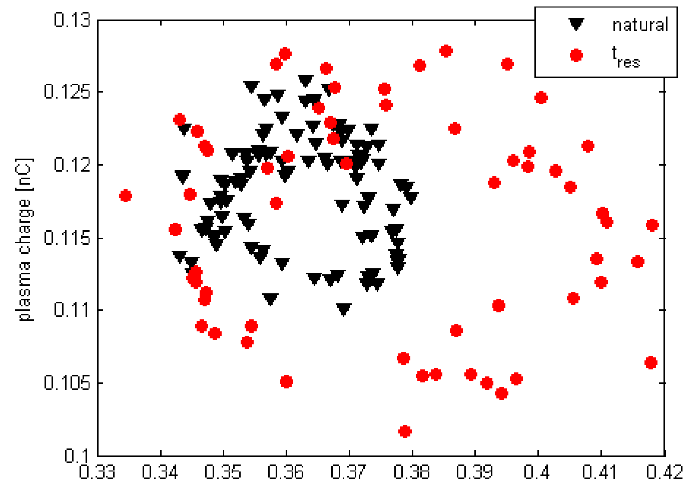
$$f(r) = \alpha(r - r_0) \quad r_0 \in (0, R_W)$$

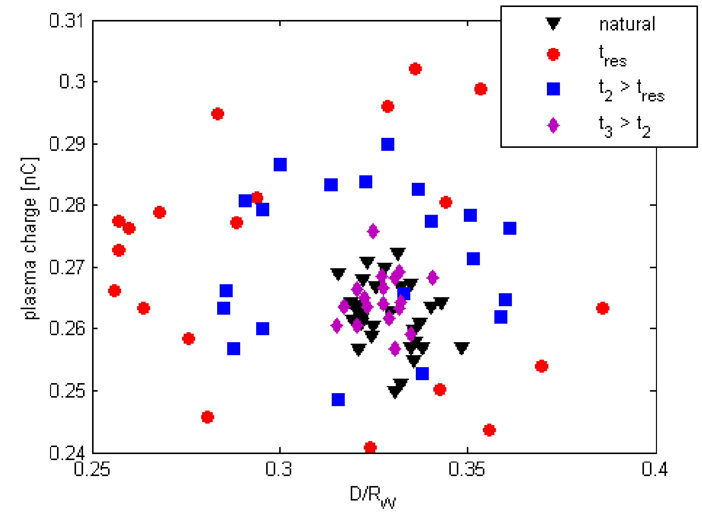


Autoresonant excitation at ν_{mod}

drive sweep: 1.9 - 8 Hz, 39 s





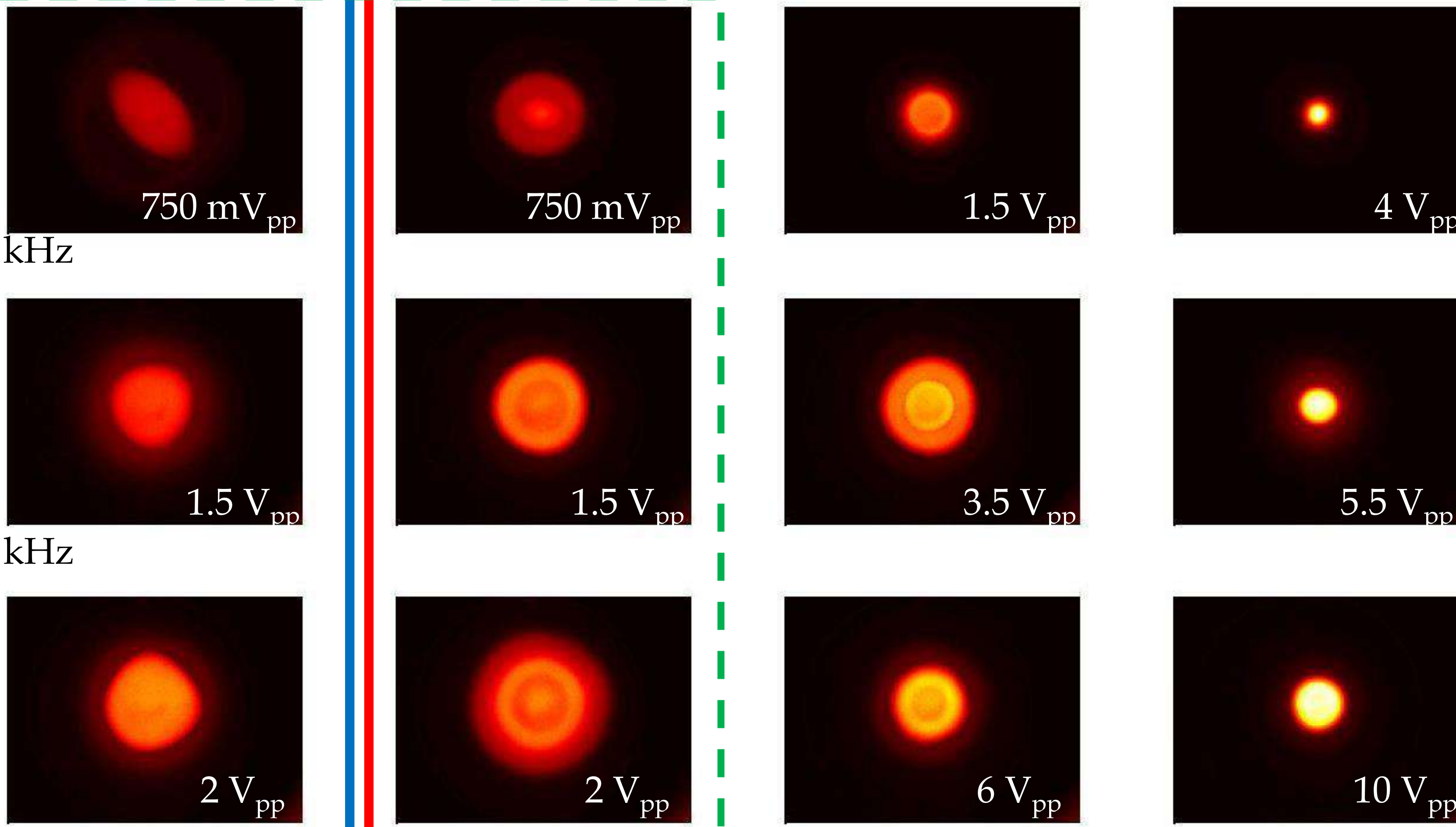


A. Da Col, MSc thesis 2017

Higher-order KH modes: RF effects on stability

Generation drive OFF

Generation drive ON (7.5 MHz, 5.5 V_{pp})



$\nu_2 \approx 18$ kHz

$\nu_3 \approx 34$ kHz

$\nu_4 \approx 51$ kHz

B. Achilli, BSc thesis 2017

Conclusions and outlook

- RF plasma generation: Forget 'easy' evolution of single-species non-neutral plasma; typical integrals (charge, angular momentum, energy) not conserved; usual manipulations techniques not efficient

- A balance can be reached involving particle loss and refurbishment, continuous excitation; non-trivial equilibria beyond collision scales (1-2 vortices)

- Play around this equilibrium: Autoresonance brings control of displacement AND total charge

More to do:

* Multipolar and rotating electric RF fields to improve stability, positioning, compression (again: it <u>does not work exactly as in freely-evolving plasmas!</u>)

* Take advantage of ion trapping (ion manipulation and extraction)

Collaborators and acknowledgments

Collaborators in activities related to trapped plasmas:
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and formerly F. De Luca, G. Bettega, B. Paroli, M. Ikram (Unimi); I. Kotelnikov (Budker Institute, Novosibirsk); V. Carbone group (Unical); C. Svelto group (Polimi)

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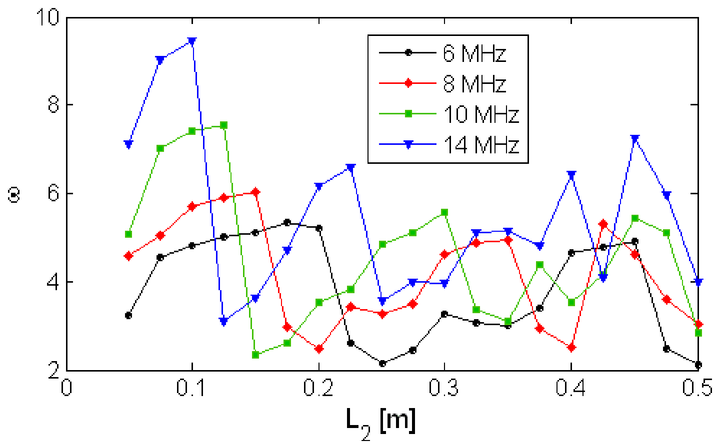
Additional material

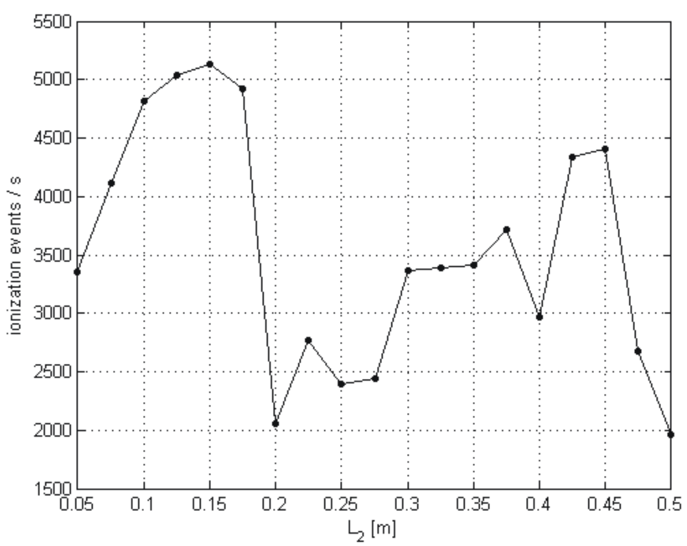
Chaoticity, heating, ionization efficiency



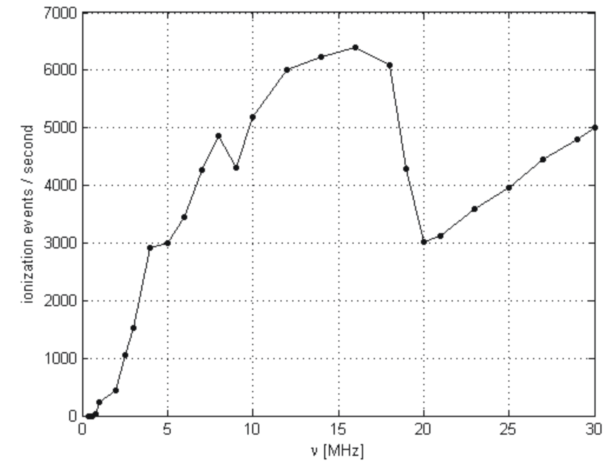
$$\omega(n) = \frac{1}{P}\sum_{i=1}^{P}\sqrt{\left\langle e_i^2(n)\right\rangle - \left\langle e_i(n)\right\rangle^2}$$

Left: Roughness ω (standard deviation of energy states) averaged over 500 initial conditions in the chaotic region. Parameters: V_0=0, V_1=3 eV, L_1+L_2=1 m. The roughness exhibits complex structuring and scaling with geometry and forcing parameters.

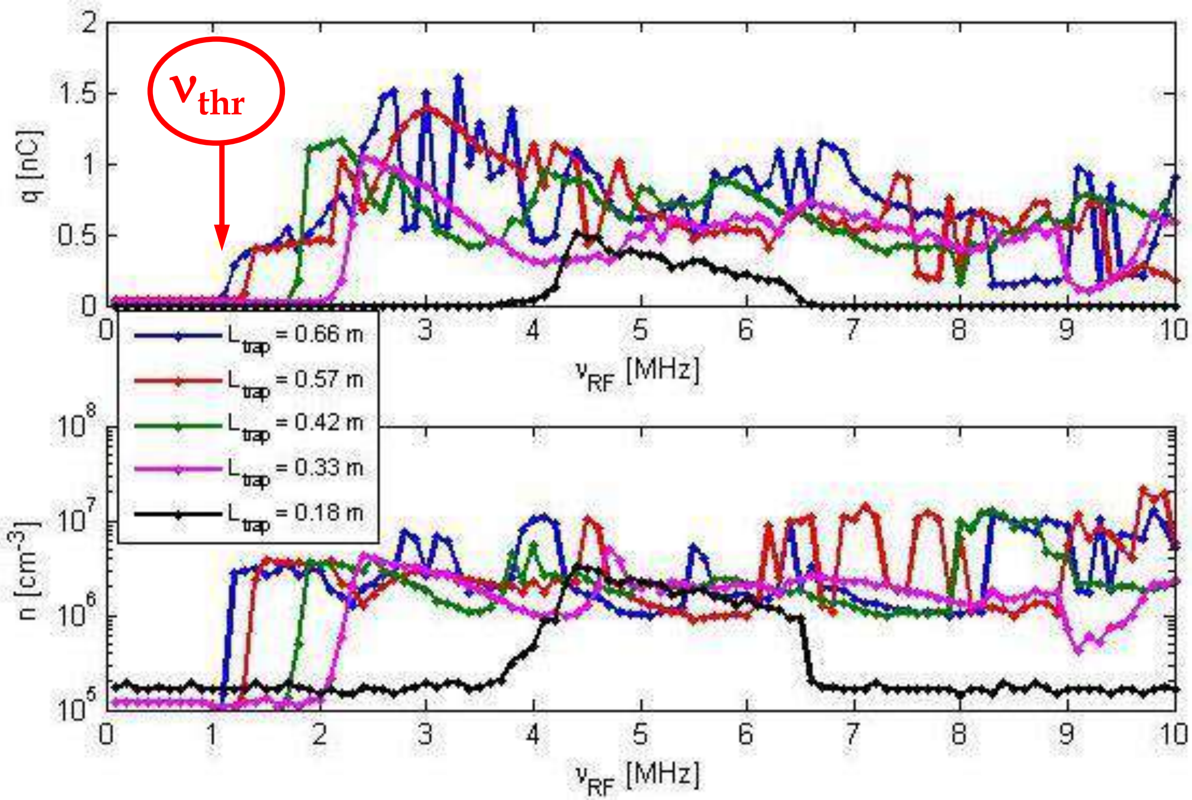
Ionization of H_2 background (10^{-8} mbar), which introduces weak dissipation in the chaotic map.



Ionization (left, ν=8 MHz, other parameters as above) follows well the rend of ω vs geometry. Peaks are found for trajectories exploring the energy range where cross section is maximum (right, geometry as above, 5 eV excitation).



RF electron plasma generation



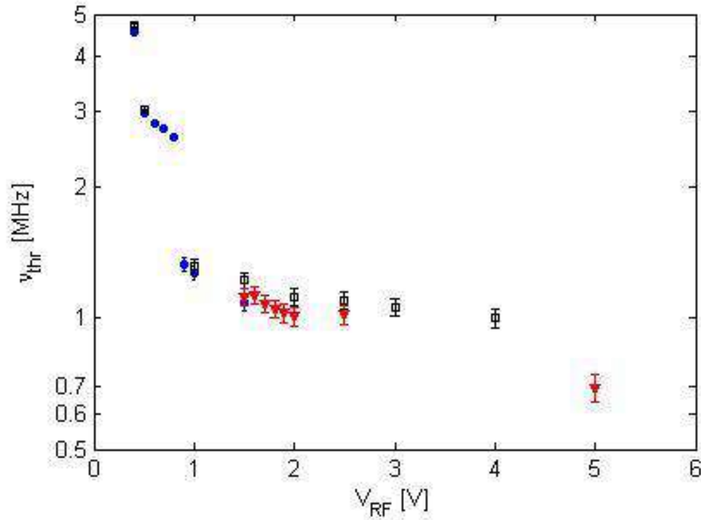
B = 0.1 T, 4.5 s excitation at V_{RF} = 1.5 V on C7 electrode

Frequency threshold ν_{thr}

$\nu_{thr} \sim L_{trap}^{-1}$

$\nu_{thr} \sim B^{-2}$

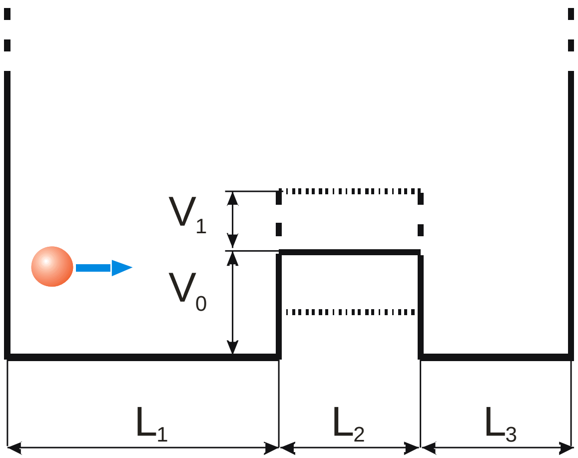
$\nu_{thr} \sim$??? V_{RF} ???



G. Maero et al., *J. Plasma Phys.* **81**, *495810503 (2015)*

RF generation and chaotic maps

Qualitative 1D model: particle bouncing in a well with forcing $\sim V_{RF}\sin(2\pi\nu_{RF}t)$



Net energy gain up to ionization threshold is possible in low-energy region (chaotic region)