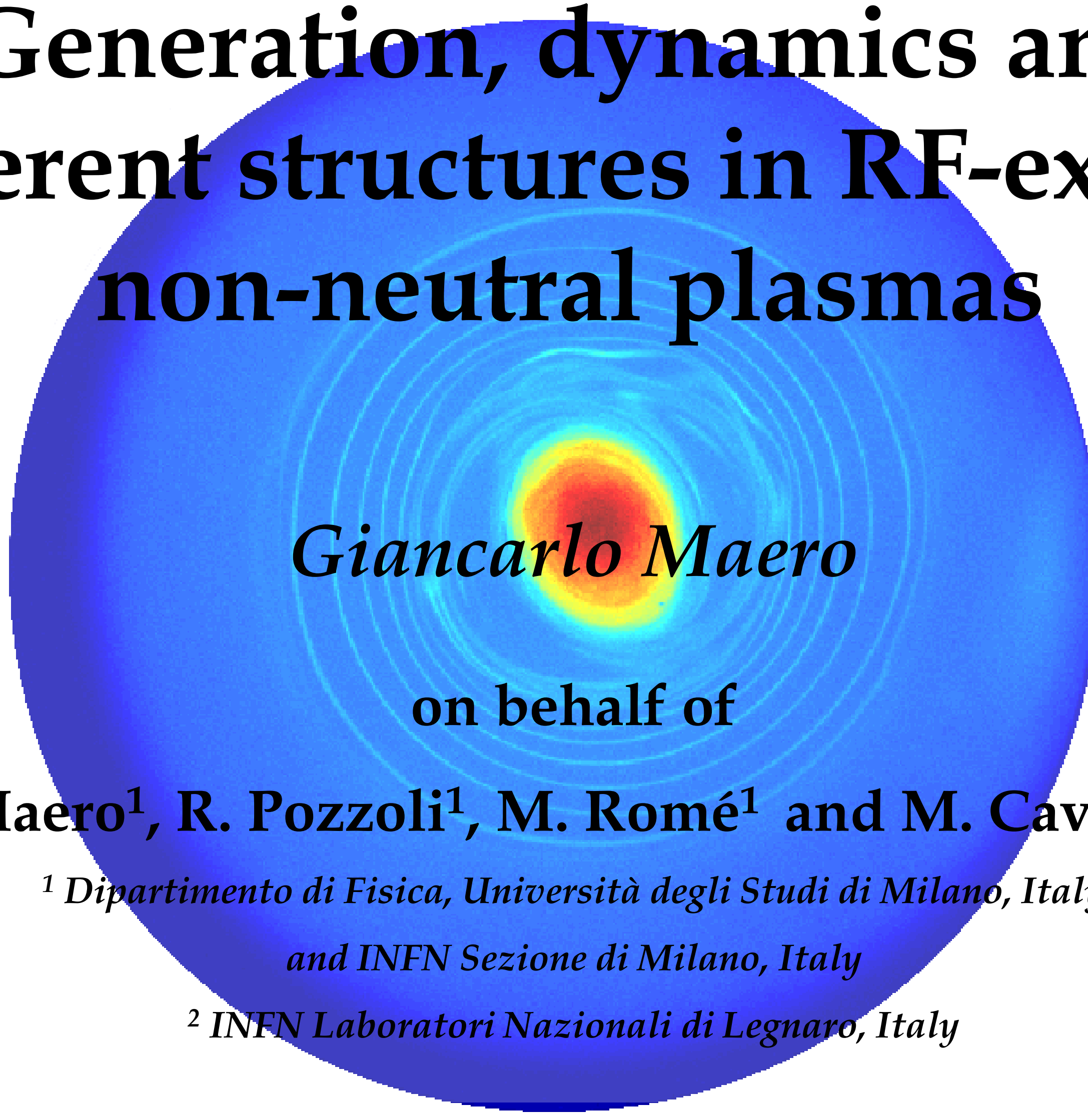
Generation, dynamics and coherent structures in RF-excited non-neutral plasmas



Giancarlo Maero

on behalf of

G. Maero[1], R. Pozzoli[1], M. Romé[1] and M. Cavenago[2]

[1] Dipartimento di Fisica, Università degli Studi di Milano, Italy

and INFN Sezione di Milano, Italy

[2] INFN Laboratori Nazionali di Legnaro, Italy

Synopsis

Introduction

- Penning-Malmberg traps (basics)
- The experimental device (ELTRAP)

How to subvert simple things (and then scratch your head)

- Radio-frequency electron plasma generation: Empirical observations
- Equilibrium structures: Single and double vortex

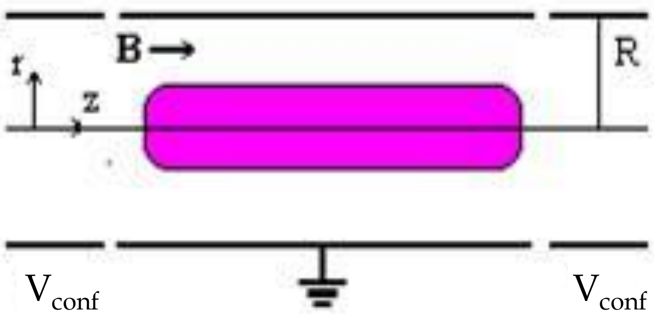
Getting to know something: Measurements and interpretations

- Formation and evolution: The role of trapped ions
- Equilibrium structures: Resonant manipulation

Conclusions and outlook

Penning-Malmberg traps and non-neutral plasma confinement

Penning traps in a nutshell: three (or more) electrodes (axial confinement) in an axial magnetic field (radial confinement) and ultra-high vacuum conditions.



Penning-Malmberg version:

- Elongated cylindrical structure → axial potential with a flat bottom
- Confinement of many particles/plasma column (10^6-10^8 cm^{-3})
- Nearly 2D system where self-consistent potential dictates transverse (single-particle and collective) dynamics by ExB effect $\omega_c >> \omega_z >> \omega_l$
- Applications: accumulation and cooling (for spectrometry, antimatter), basic plasma and fluid physics (equilibrium and stability properties, turbulence)

Pure electron plasma and fluid analogy

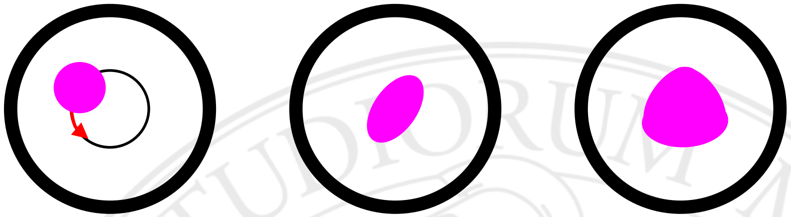
Transverse dynamics: <u>E</u>x<u>B</u> – collective (diocotron) modes and vortices (isomorphic to 2D Eulerian fluid). Conditions: single species, (near) absence of perturbations, forcings, sources of dissipation. Integral quantities conserved (charge, energy, angular momentum).

plasma

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

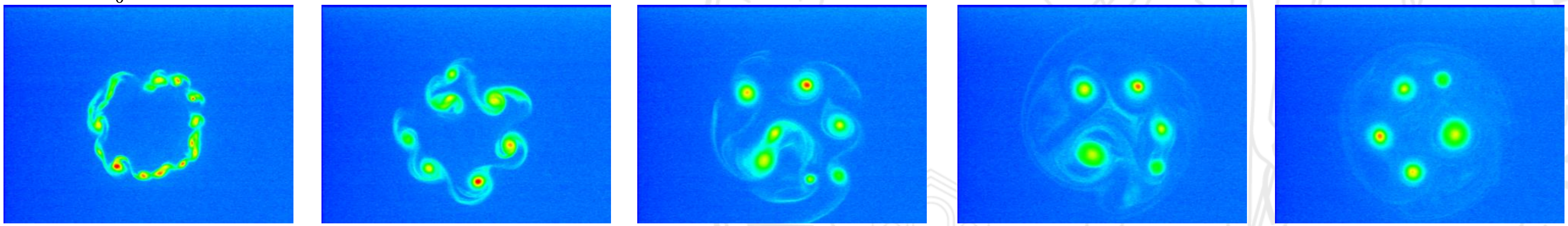
fluid

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



l = 1 *l* = 2 *l* = 3 etc.

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



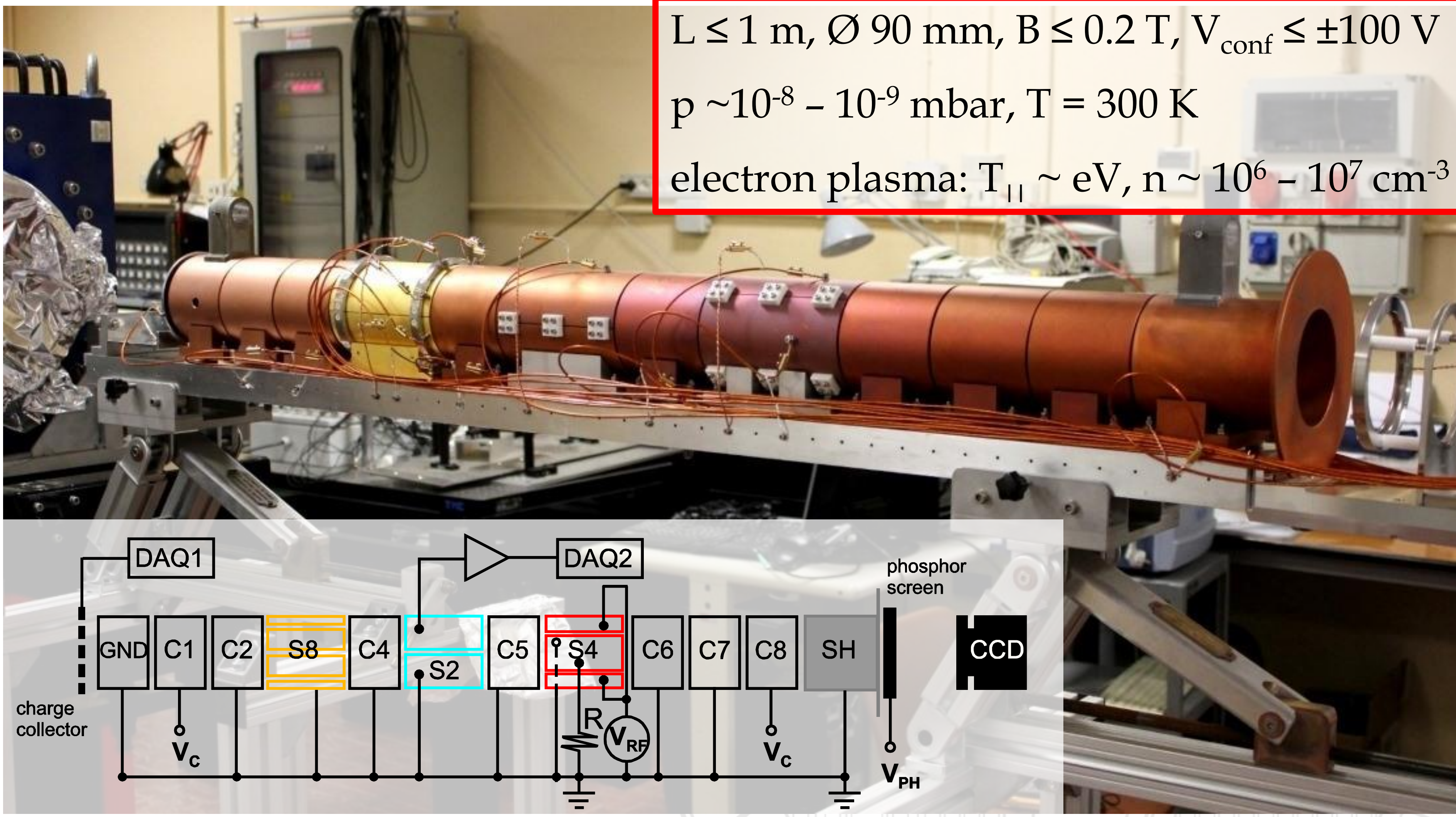
2 µs 16 µs 48 µs 78 µs 458 µs

ELTRAP

L ≤ 1 m, Ø 90 mm, B ≤ 0.2 T, V_{conf} ≤ ±100 V

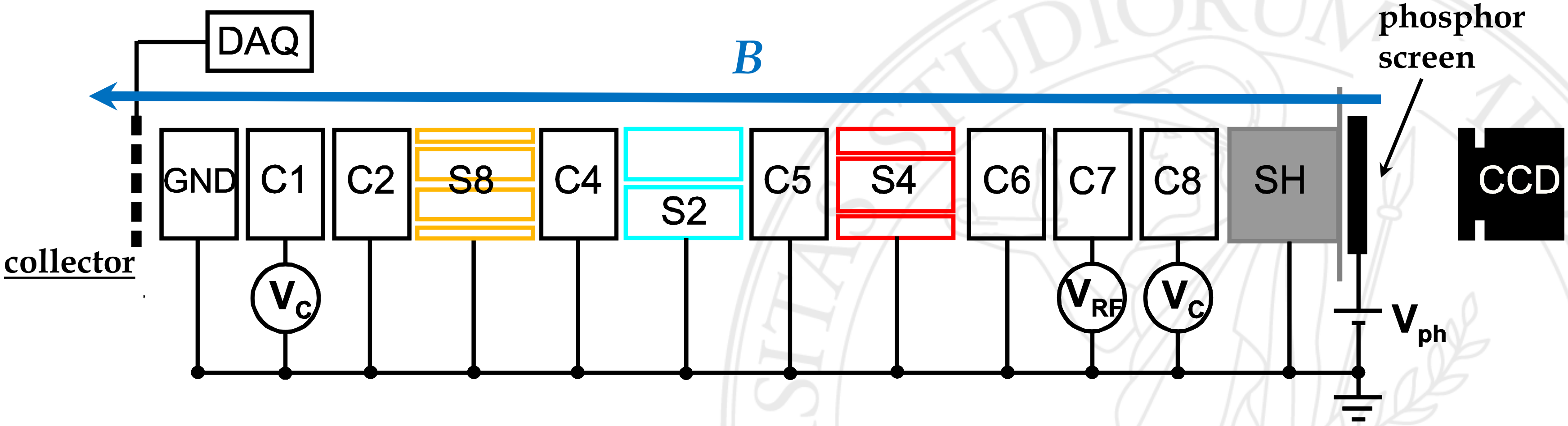
p ~10^{-8} – 10^{-9} mbar, T = 300 K

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



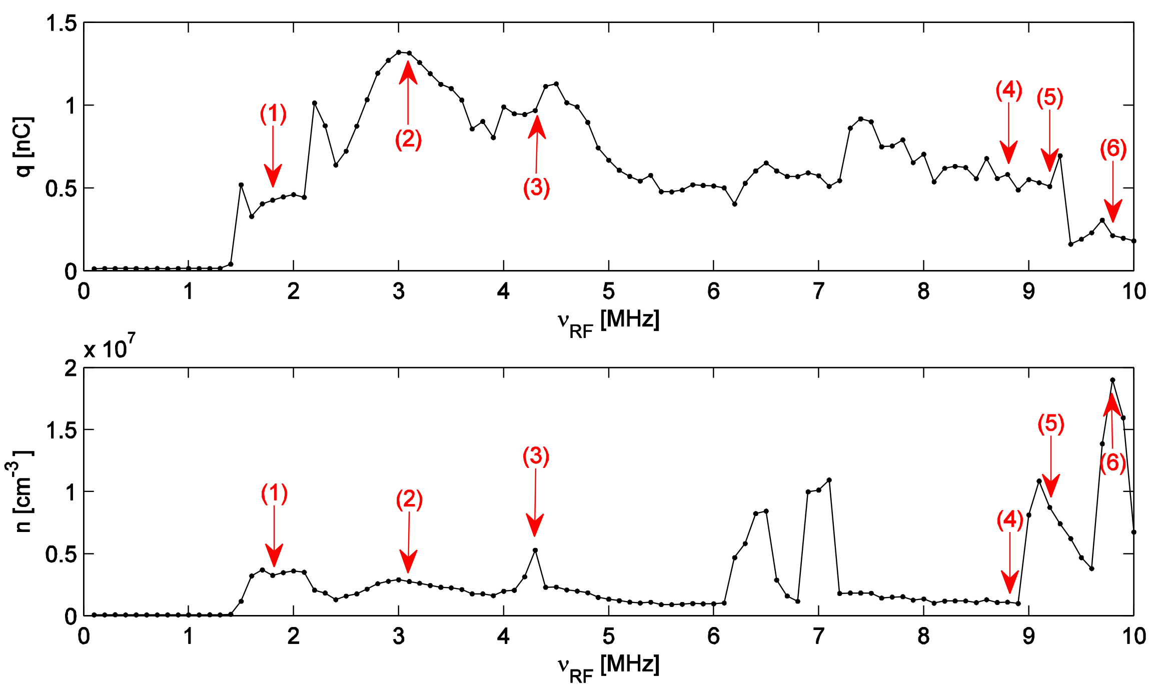
RF electron plasma generation

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**.



Conditions are very different: external forcing, ionization, continuous creation and loss of e^- and ions → sources of dissipation (instabilities)

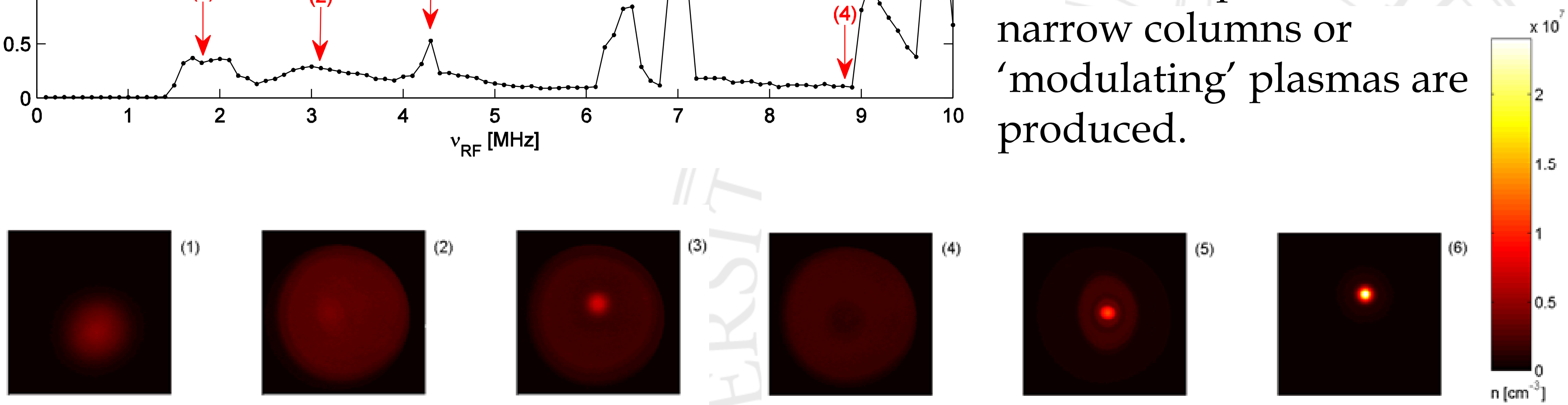
RF electron plasma generation



Total charge and density comparable to conventional trapped plasmas injected from conventional sources.

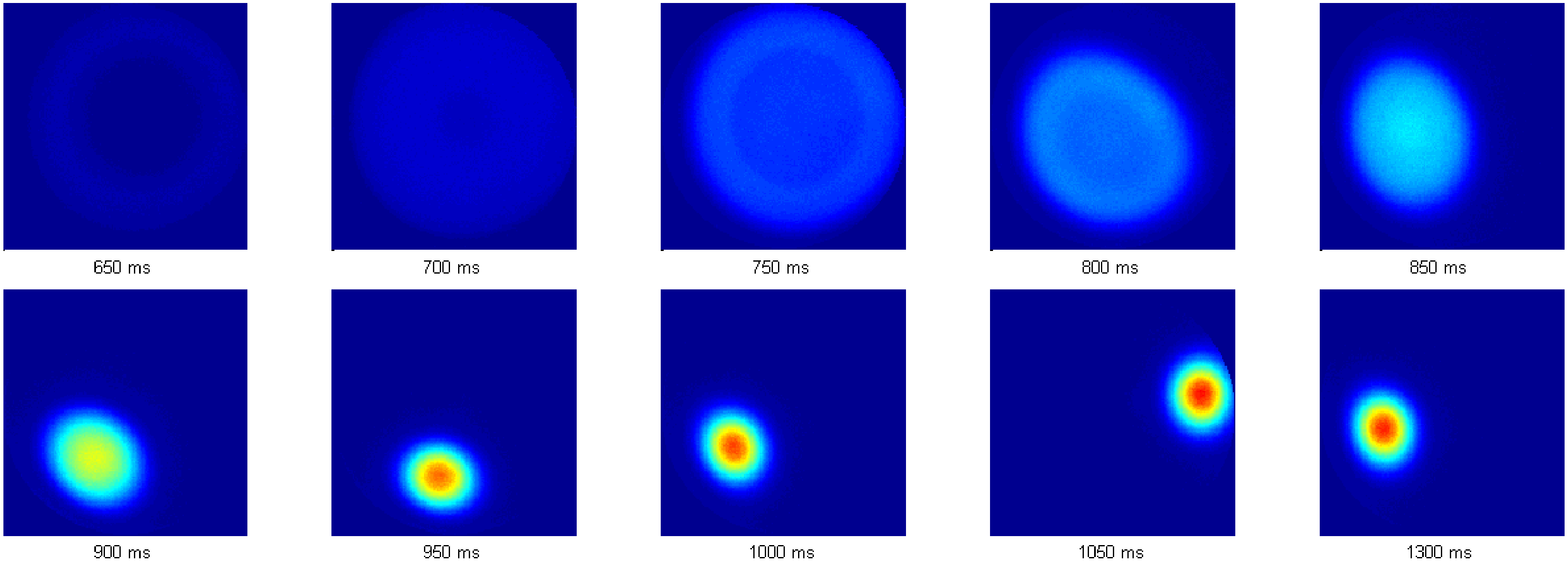
Very good repeatability for set and stable experimental conditions.

Main discrepancies when narrow columns or 'modulating' plasmas are produced.



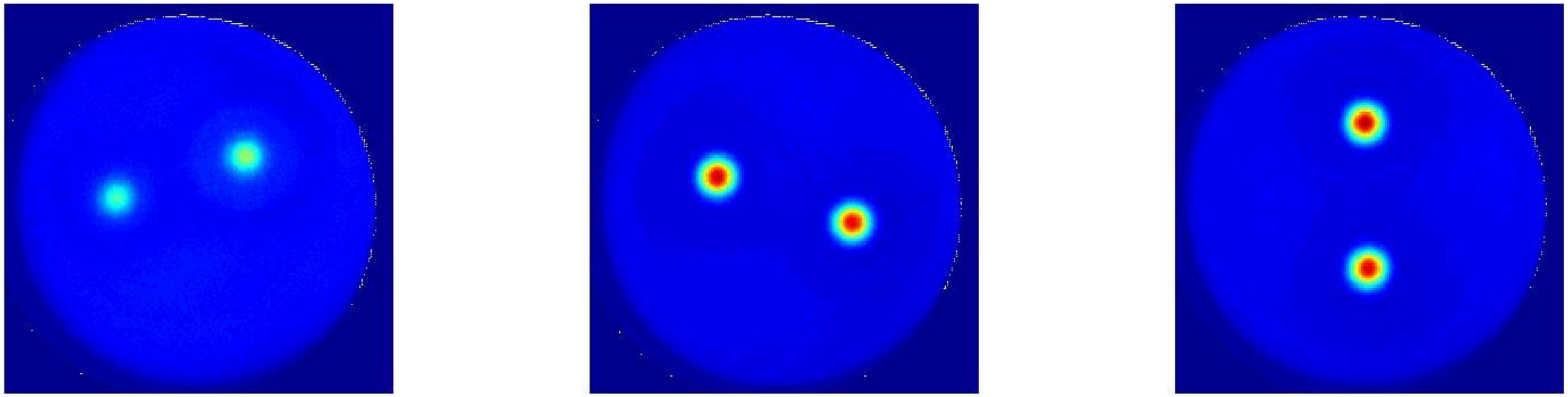
*[B = 0.1 T, L_{trap} = 570 mm, C7 excitation: V_{RF} = 1.5 V, ν_{RF} = 0.1-10 MHz, **t = 4.5 s**]*

Persistent structures: Single vortex

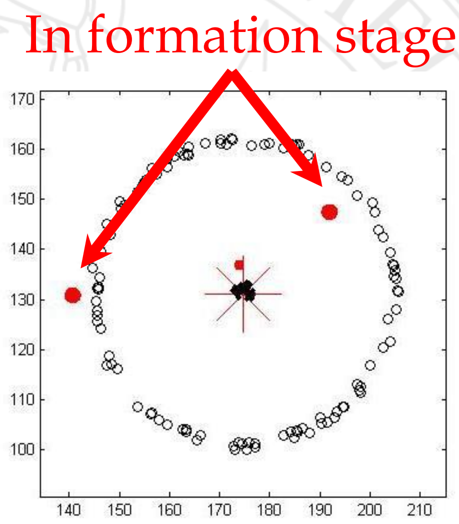


Diffuse, low-density plasma typically formed at large radii (higher electric field, more heating and ionization). But then the density profile may evolve to **high-density structures**, eventually showing **enhanced stability** with respect to perturbations or common sources of dissipation (e.g., resistive-wall dissipation) **as long as RF is on**.

Persistent structures: Double vortex



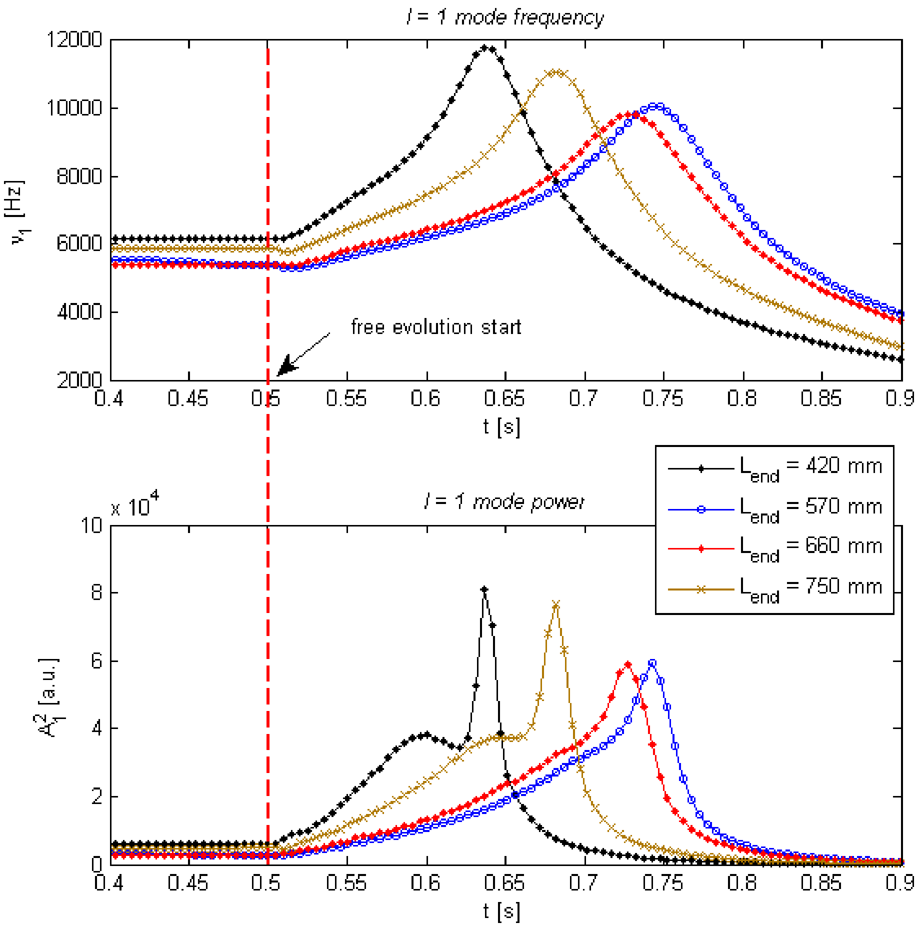
[B = 0.15 T, L_{trap} = 570 mm, quadrupolar excitation: V_{RF} = 0.9 V, ν_{RF} = 9.9 MHz, ***t = several seconds****]*

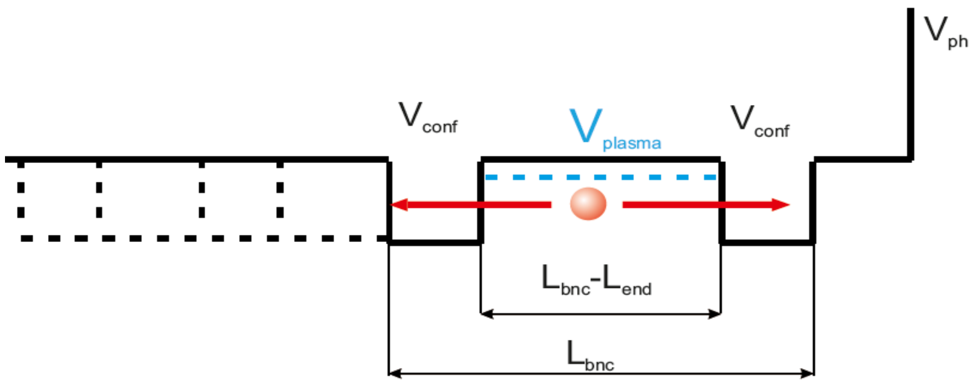


Peak vortex density: $1.5 \cdot 10^7$ cm^{-3}, background density: $2 \cdot 10^6$ cm^{-3}, **indefinite lifetime:** Double vortex sets on a stable (charge, distance) configuration (with a residual *l=1* mode) lasting for many seconds, no mergers.

Ion trapping – ion instability

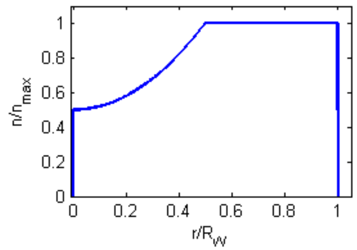
l=1 growth rate (with RF off): $\gamma_1 = (N_i / N_e)\nu_1 [1 - \cos(2\pi\tau_{end} / \tau_{bnc})]$



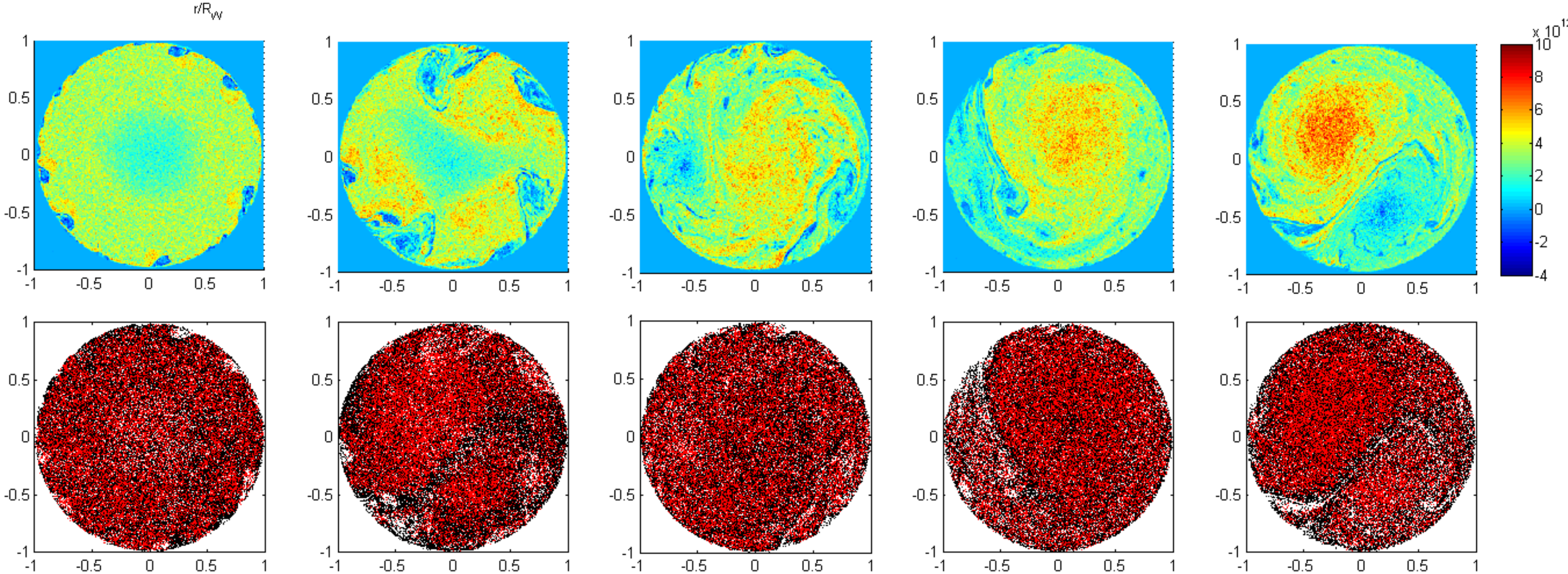


- Ions trapped in the e$^-$ space charge
- Differential drift → change in angular momentum (→ mean square radius) of the column and instability
- ≠ trapping lengths → ≠ drifts and growth rates
- N_i/N_e as high as 10^{-2} ?? *[preliminary]*

PIC simulation – e^- and H_2^+



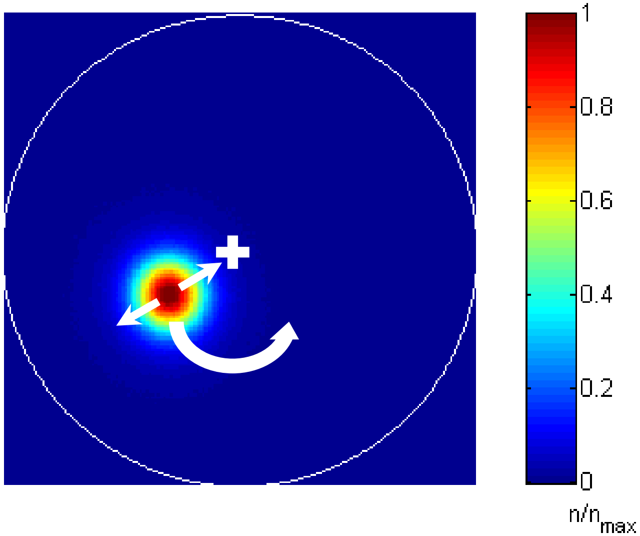
2D particle-in-cell simulation (fluid, ExB drift e^-; kinetic H_2^+). Initial hollow profile. Overall balance: Lost particles are randomly reinjected.

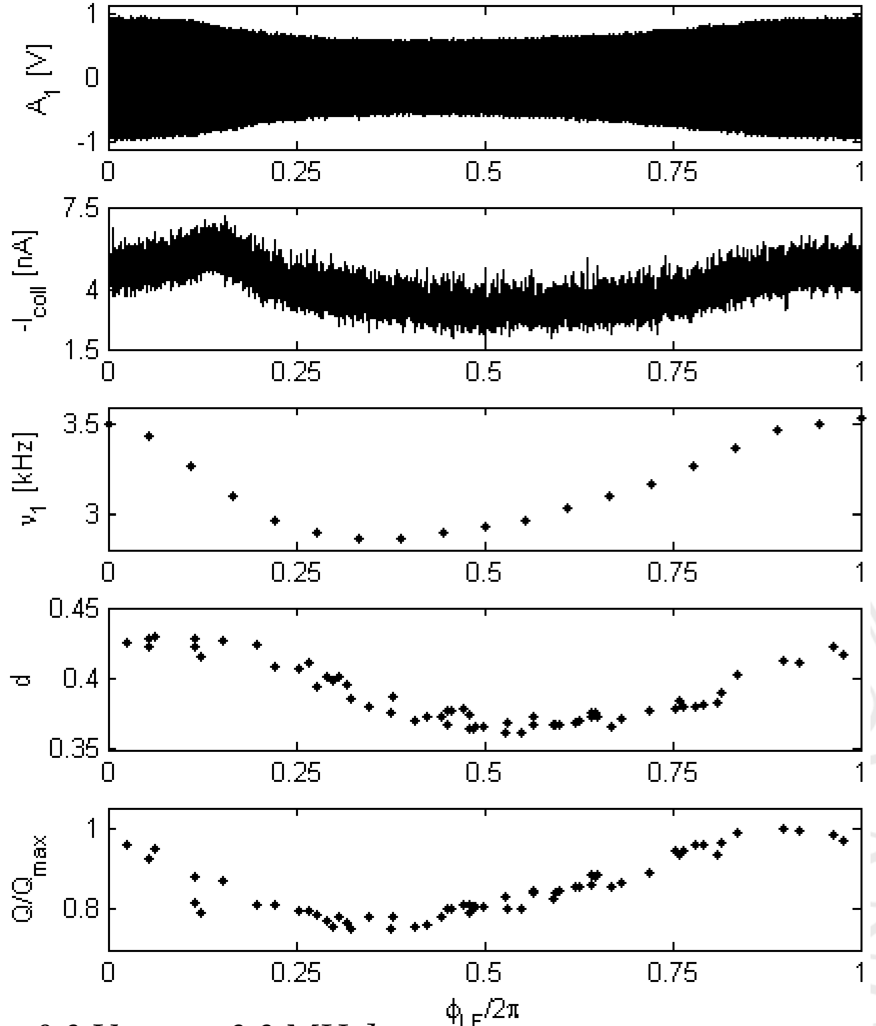


0.2 ms | 0.4 ms | 0.8 ms | 2.0 ms | 4.0 ms

*[B = 0.15 T, Ø $_{trap}$ = 45 mm, initial electron density 2.5-5 · 10^6, ion fraction **f = 0.3**. Black: electrons, red: ions.]*

$l=1$ diocotron mode modulation





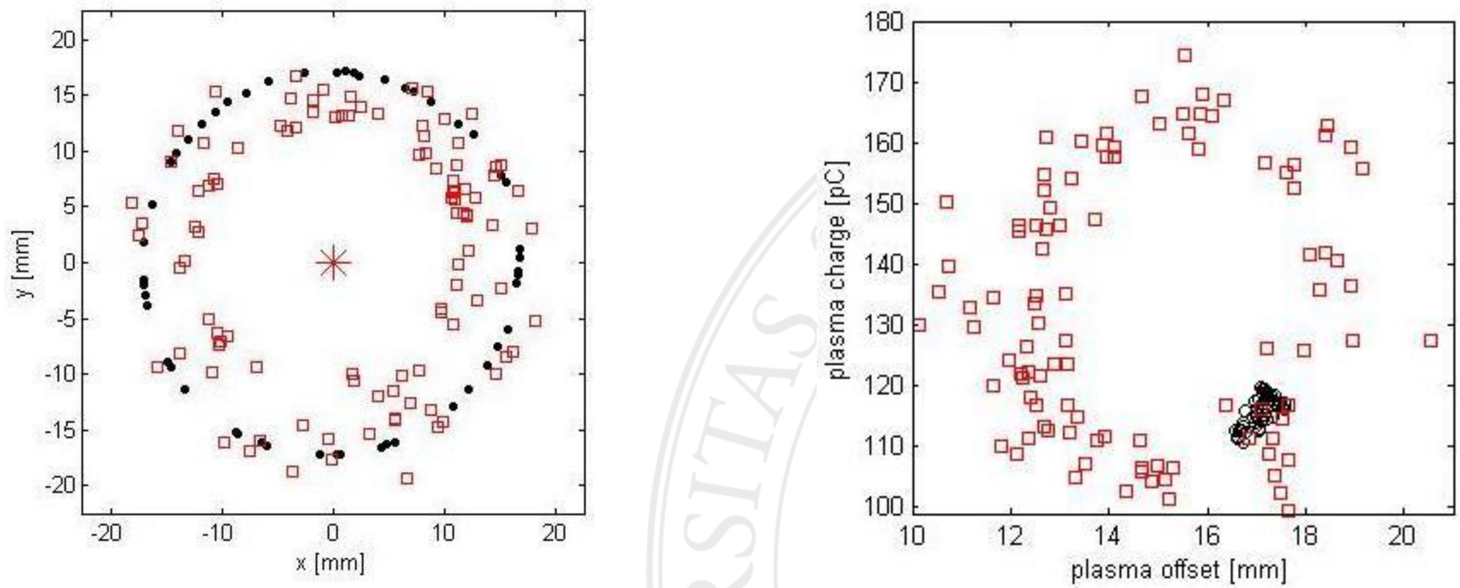
As long as the RF drive is present, the $l=1$ instability can be suppressed, but the mode may be modulated (1-10 Hz)

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

[B = 0.15 T, L_{trap} = 570 mm, quad. excitation: V_{RF} = 0.9 V, ν_{RF} = 9.9 MHz]

l=1 modulation: autoresonant excitation

Frequency-swept excitation crossing the natural *l=1* modulation frequency can increase/decrease the modulation frequency AND amplitude => a way to manipulate offset and charge variation (*autoresonant excitation*)



Dipole excitation 1.5 V, frequency sweep 2.3-5.2 Hz crossing the modulation frequency 4.0 Hz. No excitation (black): offset ***17.1±0.5*** *mm. With excitation (red): offset* ***10.1-20.5*** *mm.*

Conclusions and outlook

- RF plasma generation: A dirty (and interesting) business
- Forget 'easy' evolution of single-species non-neutral plasma
- Typical integrals (charge, angular momentum, energy) not conserved over whole evolution
- A balance can be reached involving particle loss and refurbishment, continuous excitation
- Ion-related instabilities are crucial in the evolution and structure formation
- Non-trivial equilibria beyond collision scales (1-2 vortices)
- More to do: better measure of electron and possibly ion evolution → experimental data into refined theoretical/simulation model