



Design of DIVO: a new diagnostic system to evaluate the ion velocity distribution functions in fusion devices

S. Molisani^{1,2}, G. Nicolaou³, D. Verscharen³, M. Zuin^{1,4}, D. Abate¹, A. Belpane¹, C. Owen³, O. Pezzi⁴, I. Predebon^{1,4}, F. Pucci⁴, L. Sorriso Valvo⁴, and N. Vianello¹

¹ Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete SpA) - Padua, Italy

² CRF - Università di Padova - Padua, Italy

³ Department of Space and Climate Physics, Mullard Space Science Laboratory, University College London, UK

⁴ Istituto per la Scienza e la Tecnologia dei Plasmi, CNR, Italy

sara.molisani@igi.cnr.it

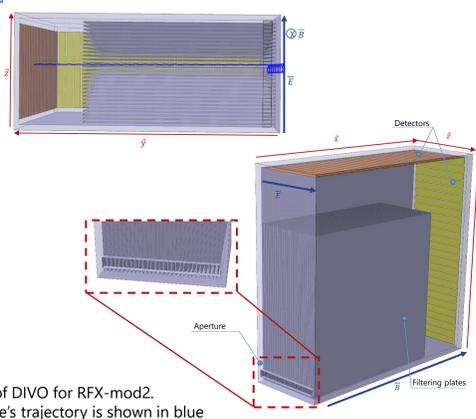
1. Introduction

- DIVO (Diagnostic for Ion Velocity Observation) resolves the two components of the ion velocity, parallel and perpendicular to the magnetic field, allowing for the reconstruction of the **ion velocity distribution functions (VDFs) in velocity space**.
- The knowledge of the VDFs is fundamental to understand many dynamical processes that are associated to kinetic effects, ion acceleration, and heating mechanisms, such as magnetic reconnection^[1,2] and also to strong turbulence activity.
- DIVO can be used at the **plasma edge of fusion machines**. The proposed design is optimized for its usage in RFX-mod2^[3], that has been upgraded with a modified magnetic boundary and several improvements on the diagnostic capabilities^[4].
- Numerical simulations are run to optimize the design of the device, as well as to assess its expected velocity resolution, to define its operational range, and to compute its characteristic geometrical factor.

2. Design & Working principle

Key components of the device:

- Thin aperture** perpendicular to the main magnetic field direction
- Metallic filtering plates** with small gap to filter the ions
- 2 arrays of **miniaturized detectors**, placed on two screens, to record the landing position of the ions
- 2 **electrodes** to apply a uniform perpendicular \vec{E} field of the order of kV/m

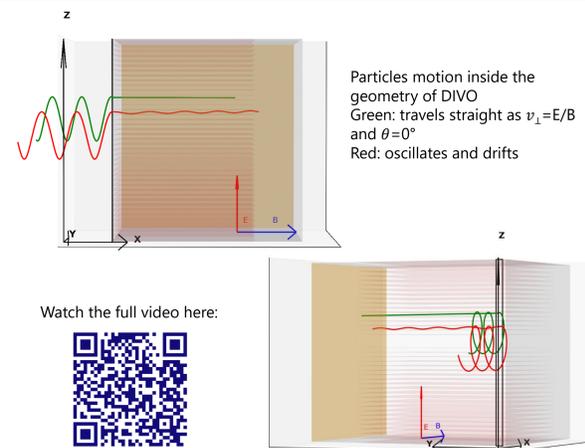


- Balance between the electric and the Lorentz forces, with the aim of **interrupting the Larmor gyration** of the ions

$$m \frac{d\vec{v}}{dt} = q (\vec{E} + \vec{v} \times \vec{B}) \rightarrow v_{\perp} = \frac{E}{B}$$

- A generic ion experiences the force due to E and B and **oscillates and drifts** for $E \times B$. If $E = -v_{\perp} B$ is satisfied, the ion **travels straight** till it impacts a detector

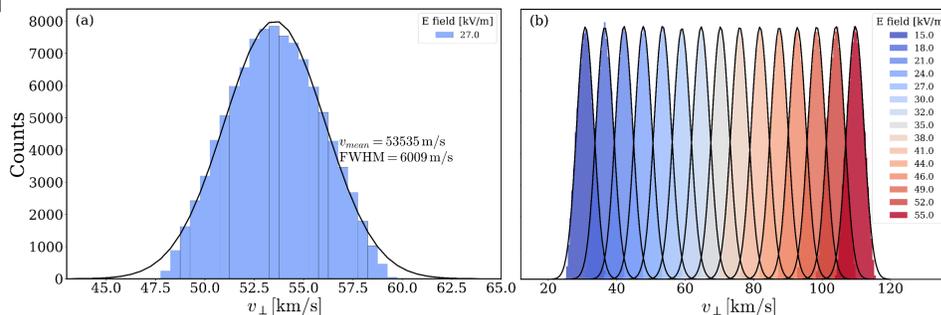
- v_{\perp} is selected by the specific electric field that is applied and by the filtering plates
- v_{\parallel} is measured from the arrival position on the detectors



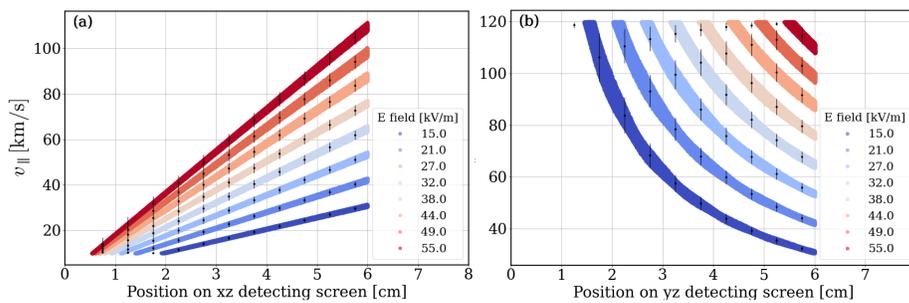
3. Velocity Resolution

Individual particles generated with random v_{\perp} and v_{\parallel} uniformly distributed between 10 and 120 km/s and independent to each other. Simulations at different values of the applied electric field. Here shown the case: gas = D2, B = 0.5 T

- v_{\perp} is characterized by a **Gaussian transmission curve**, whose mean value corresponds very closely to $v_{\perp} = \frac{E}{B}$
- Magnitude of applied E is optimized for a better reconstruction of the distribution.



- v_{\parallel} is characterized by a Gaussian transmission curve.
- Ions with the same v_{\parallel} reach a different final position for different E, as the **travelled distance depends on both v_{\perp} and v_{\parallel}**
- The relationship between position and v_{\parallel} is very different for the two screens.



- The v_{\perp} resolution is **strongly related to the Larmor radius** ($r_L \propto \frac{mv_{\perp}}{qB}$) of the incoming ions.

The plates used to filter the particles are more efficient at larger r_L , due to their fixed spacing

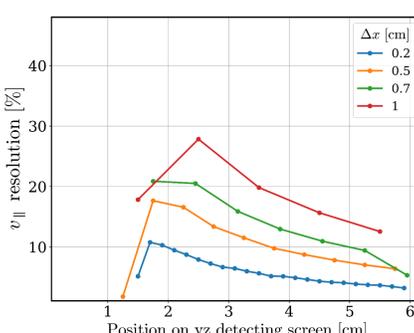
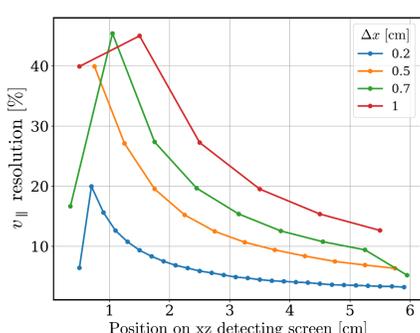
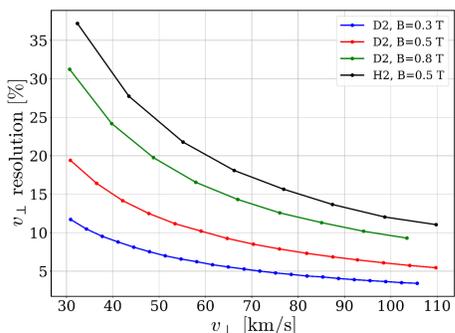
- Resolution between 5% and 19.5%.

$$v_{RES}[\%] = \frac{FWHM \cdot 100}{v_{mean}}$$

- The v_{\parallel} resolution **strongly depends on the size and number of detectors**.

- The yz screen detectors show a better resolution (5-20%) than the ones of the xz screen (5-40%).

- Central bins show a better resolution than the external bins.



4. Calibration

- Aim: to **reconstruct the original VDF** f from the detected counts C

- Need the **transmission function α** or its integration, the **geometric factor G**

$$C(v_{\parallel}^0, v_{\perp}^0, \theta^0) \sim G(v_{\parallel}^0, v_{\perp}^0, \theta^0) v_{\perp}^0 v_{\parallel}^0 f(v_{\parallel}^0, v_{\perp}^0, \theta^0) \Delta t$$

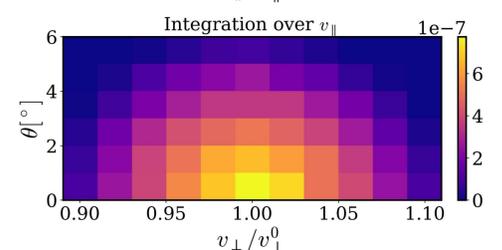
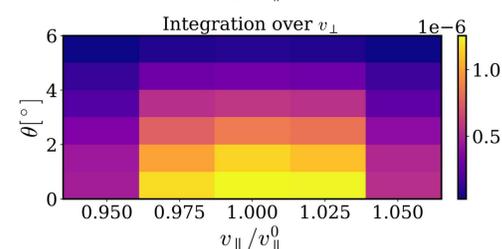
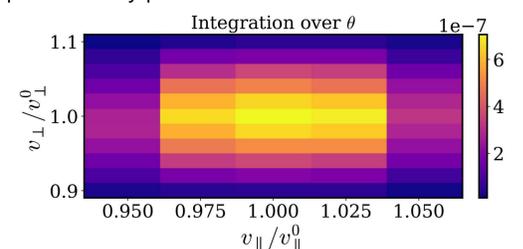
- assuming f to be constant over the velocity bandwidth of one detector

- G is different for each detector position, applied electric field, and plasma condition

- Numerically computed by simulating a known flux of ions, generated uniformly from area A_0 within the ranges of parameters $D\theta, Dv_{\perp}, Dv_{\parallel}$ and looking at the detected counts C^0 in one detector

$$G = \frac{C^0}{N} A_0 D\theta \frac{Dv_{\parallel}}{v_{\parallel}} \frac{Dv_{\perp}}{v_{\perp}}$$

- α for one detector shows small entrance angle, Gaussian shape in velocity peaked at the mean value.



5. Conclusions & Future work

- DIVO offers a direct and local measurement of the distribution functions in velocity space, with a good spatial resolution, in different kinds of magnetized plasmas where ions have a gyro-radius of few mm
- It is quite versatile, as the only requirement is that its aperture has to be aligned with the direction of the local magnetic field.
- Development and construction of DIVO's prototype and test in relevant plasma conditions

6. References

- [1] Yamada, M., Kulsrud, R., Ji, H., "Magnetic reconnection", 2010, Rev. Mod. Phys DOI: 10.1103/RevModPhys.82.603
- [2] Gobbin, M. et al "Ion heating and energy balance during magnetic reconnection events in the RFX-mod experiment", 2022 Nucl. Fusion DOI: 10.1088/1741-4326/ac39f2
- [3] Marrelli L. et al "Upgrades of the RFX-mod reversed field pinch and expected scenario improvements", 2019 Nucl. Fusion DOI: 10.1088/1741-4326/ab1c6a
- [4] Carraro L. et al "RFX-mod2 diagnostic capability enhancements for the exploration of multi-magnetic-configurations", 2024 Nuclear Fusion DOI: 10.1088/1741-4326/ad490a

