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Magnetic reconnection phenomena in magnetically confined fusion plasmas in the reversed-field pinch configuration

M. Zuin

A. F. Almagri, J. K. Anderson, F. Auriemma, D. Bonfiglio, S. Cappello, A. Cintora de la Cruz, R. Cavazzana, L. Cordaro, A. Kryzhanovskyy, E. Martines, S. Molisani, B. Momo, P. Porcu, J. S. Sarff, S. Spagnolo, G. Spizzo, M. Spolaore, M. Veranda, N. Vianello and the RFX-mod team

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University of Wisconsin-Madison

RFX-mod2: a flexible facility with MHD feedback control

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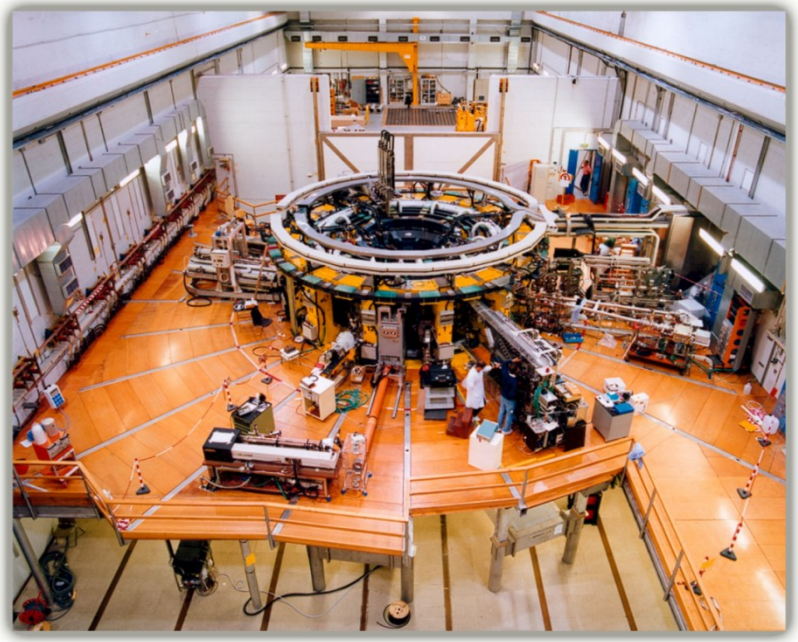
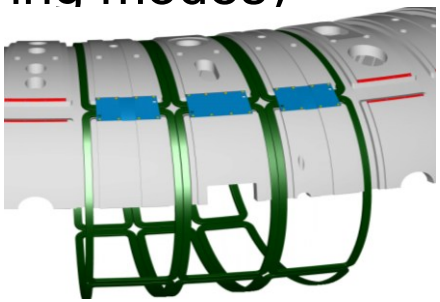
Largest existing Reversed-field pinch

R_0 = 2 m

a = 0.46 m



- Up to 2 MA plasma current, 60 MW coupled power, at low magnetic field $B_\phi(a) < 0.1$ T
- Full coverage, 192 feedback-controlled saddle coils for boundary optimization
- (real-time feedback control of RWM and Tearing modes)



- RFX-mod2 also as low field (0.6T) **tokamak** and **Ultra-low q (<1)**.

Main topics: H-mode (ELM control through MP), RWM control, Runaway mitigation through MP, low-q(a) operation, density limit studies….

Zuin et al., **NF** (2017)
Gobbin et al., **NF** (2016)
Spolaore et al., **NF** (2017)

RFX-mod ⟶ RFX-mod2 (starting in 2027)

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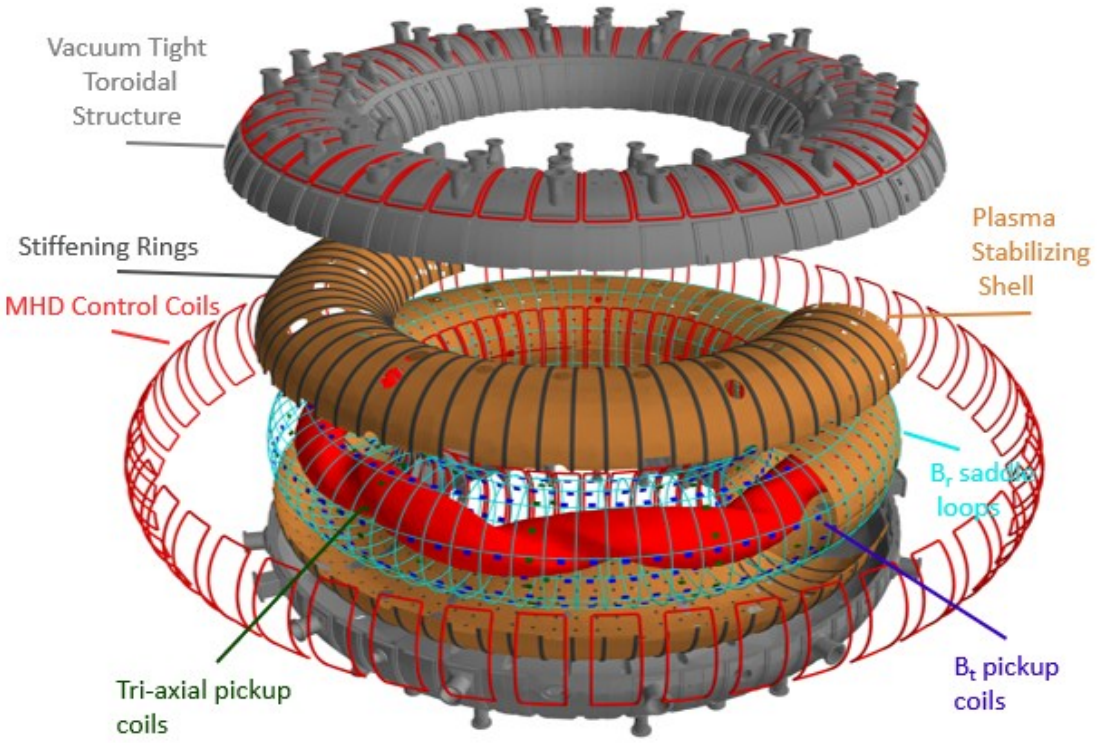
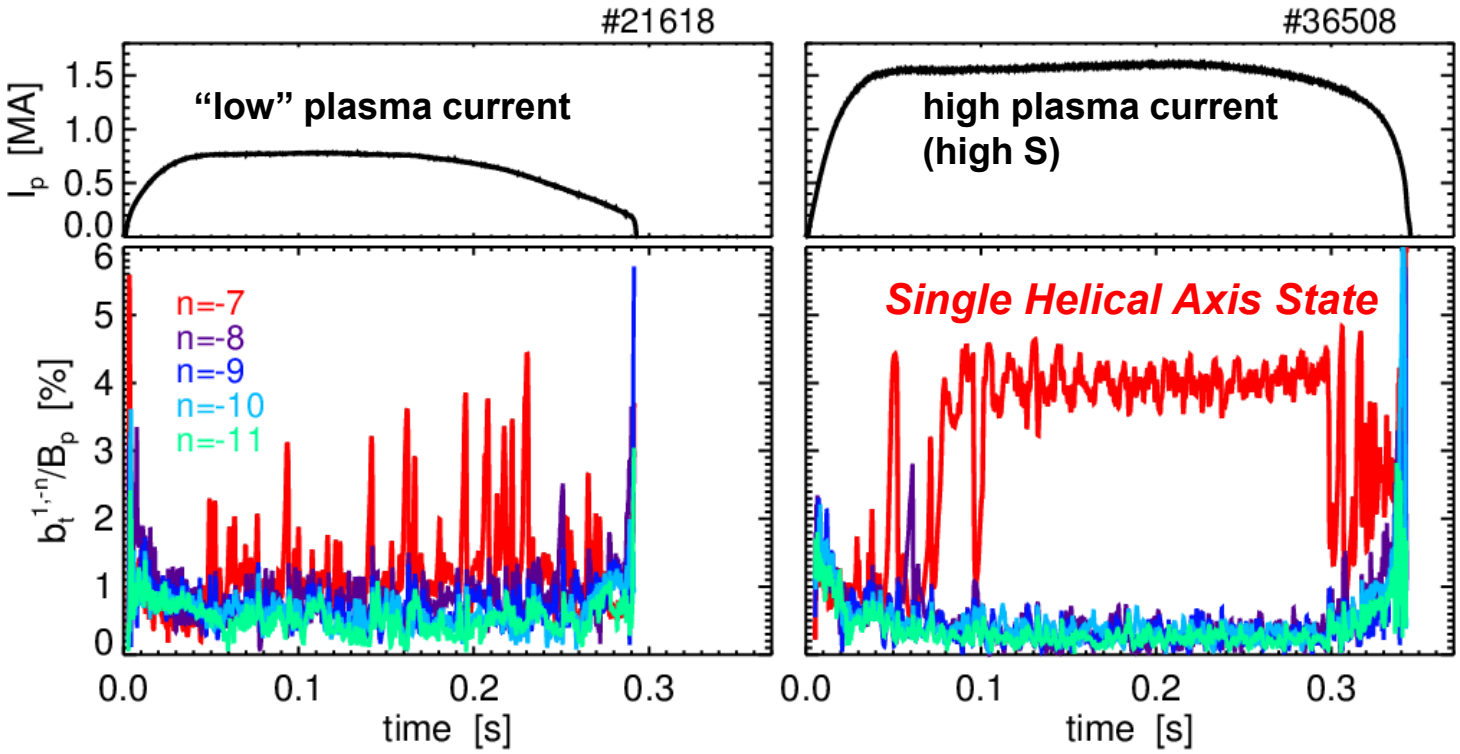


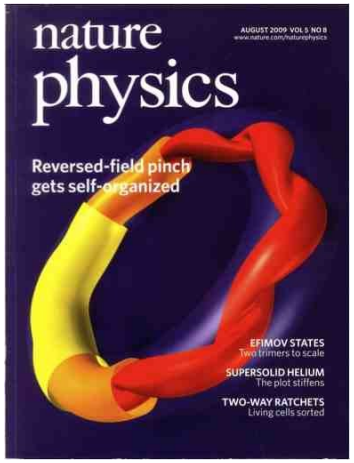
- New magnetic boundary, stabilizing in-vessel copper shell for **improved passive-active MHD control**
- Significant **diagnostic capability improvement**
  - > 2500 e.m. sensors
  - ion/electron vdf
  - Neutrons and γ's
  - Fast insertable probes
  - ….

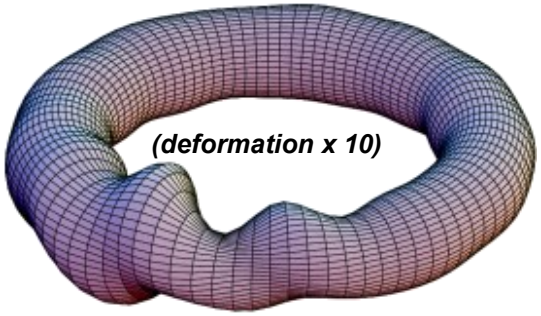
'**NEFERTARI**' (**N**ew **E**quipment for **F**usion **E**xperimental **R**esearch & **T**echnological **A**dvancements with **R**fx **I**nfrastructure) project of the National Recovery and Resilience Plan, Italian Ministry of University and Research

Carraro, Zuin et al., **NF** (2024)
Zuin et al., **NF** (2017)

Topological bifurcation at high Ip



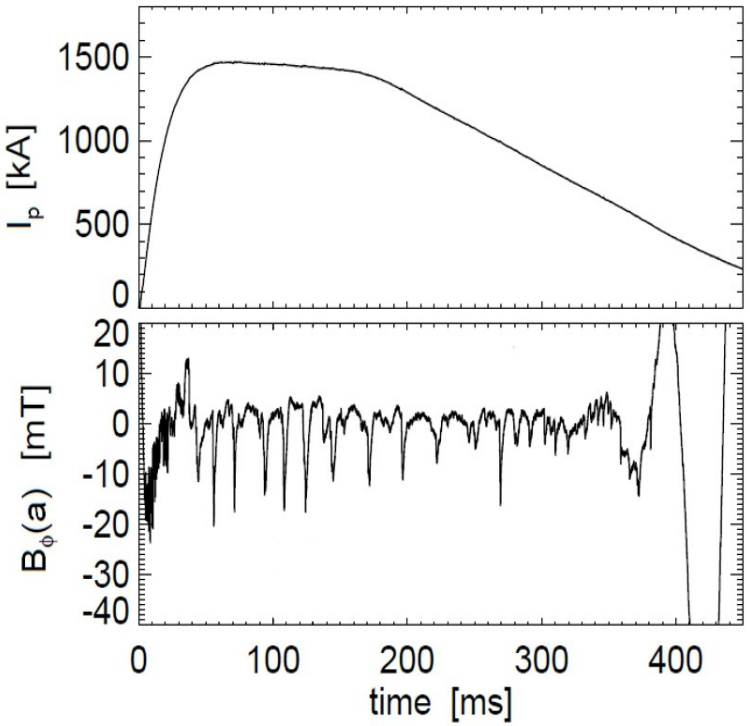




Bifurcation of RFP equilibria predicted by 3D MHD modeling before the experimental observation

- Lorenzini et al, **Nature Physics** (2009)
- Escande et al, **PRL** (2000)

Magnetic reconnection in RFP plasmas



Zuin **PPCF** (2009)

Along with the continuous dynamo action, RFP plasmas exhibit:

-impulsive relaxations of the magnetic profile

-generation of toroidal magnetic flux

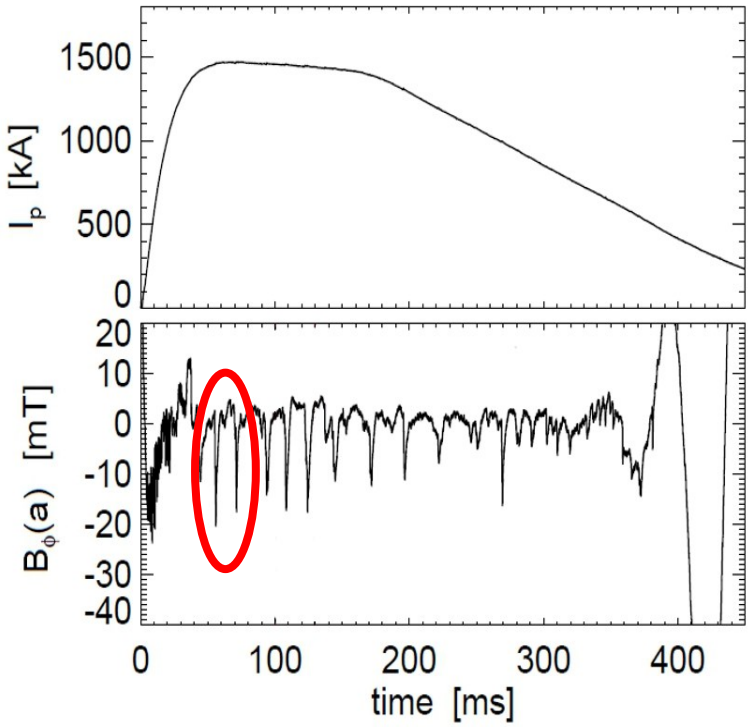
-ion heating

associated to spontaneous, almost cyclic, reconnection processes

Large, rapid variation of the edge and average toroidal fields

$B_\phi(a)$ and $\langle B_\phi \rangle$

Magnetic reconnection in RFP plasmas



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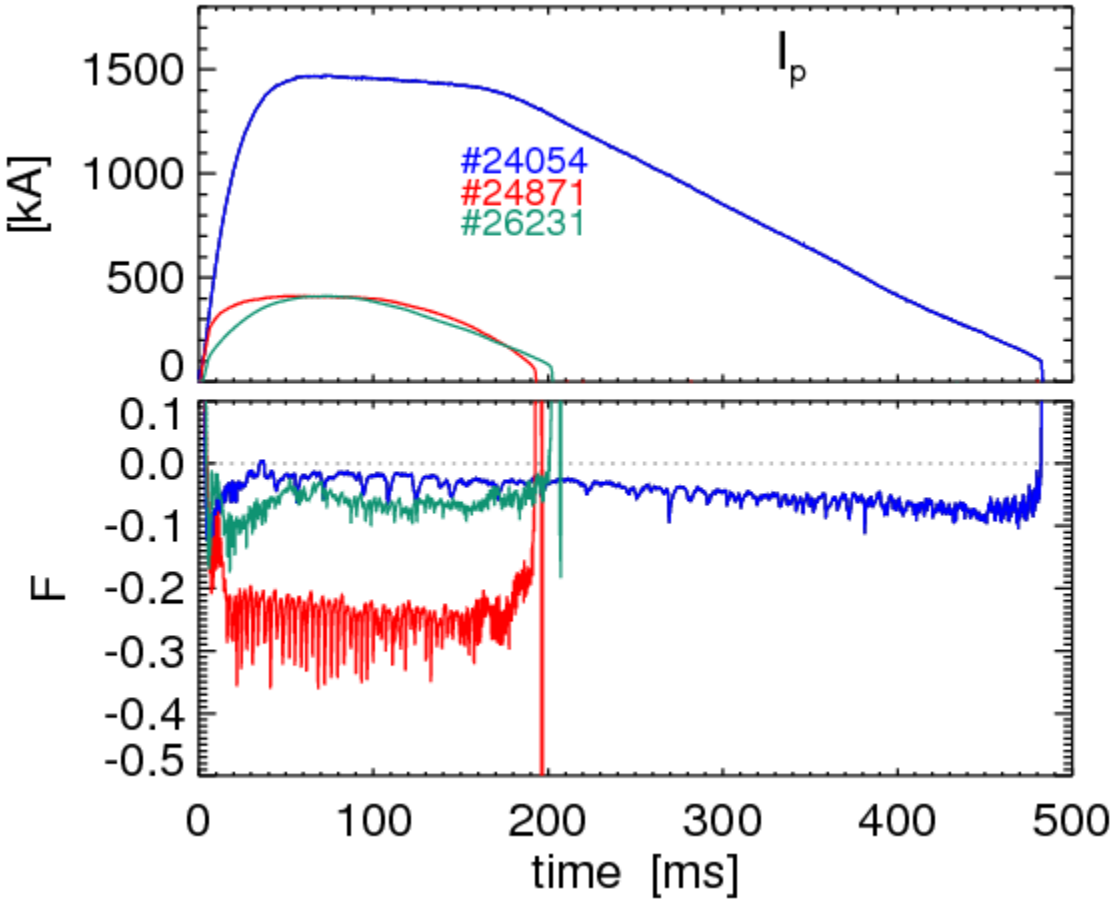
Equilibrium and Lundquist number effects on reconnection



The frequency (and the "intensity") of the reconnection events can be controlled by means of discharge parameters:

- Plasma current
- Electron density
- Reversal parameter F

Higher plasma current (and/or lower density) means higher Lundquist number

=> Less frequent reconnection process

The diagnostic set-up: RFX-mod2

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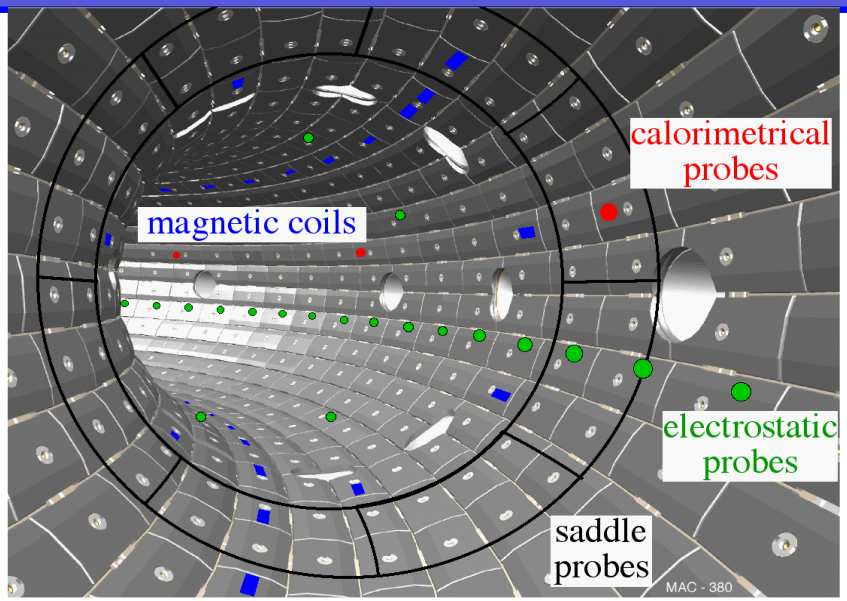
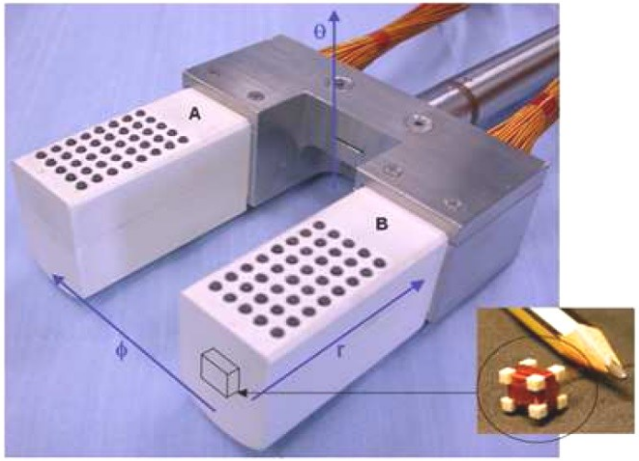
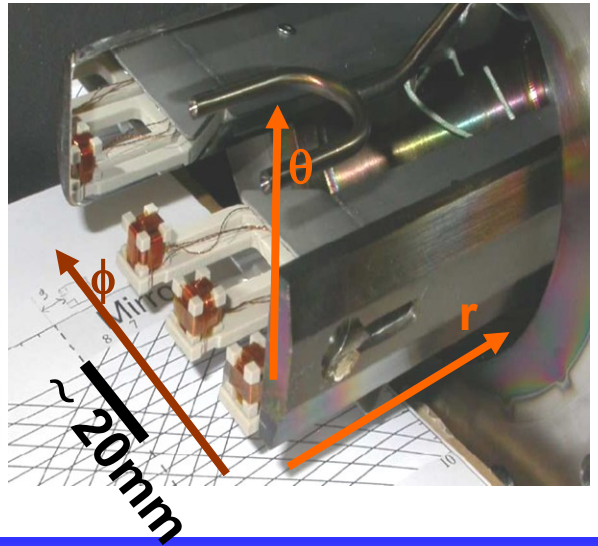


Systems of in-vessel **>2000** magnetic coils measuring the time derivative of the three components of the magnetic field (**b'_r, b'_p, b'_t**) in various radial, poloidal and toroidal positions (behind the graphite tiles) + >500 electrostatic probes

+ Insertable edge electromagnetic tri-axial magnetic probes (17) – «CLUSTER – like»



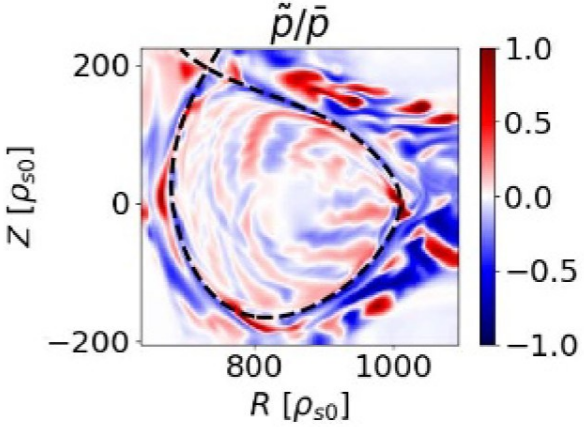


- **sampling rate: up to 10 MHz**
- **probe location: r/a~1**
- **Coils distance: 20 mm**

High mode numbers estimation:

$$m \leq 16$$
$$n \leq 350$$

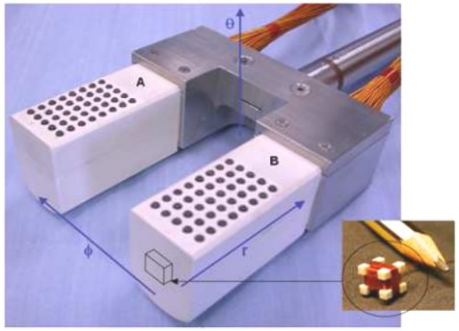
Fast movable system for edge probes

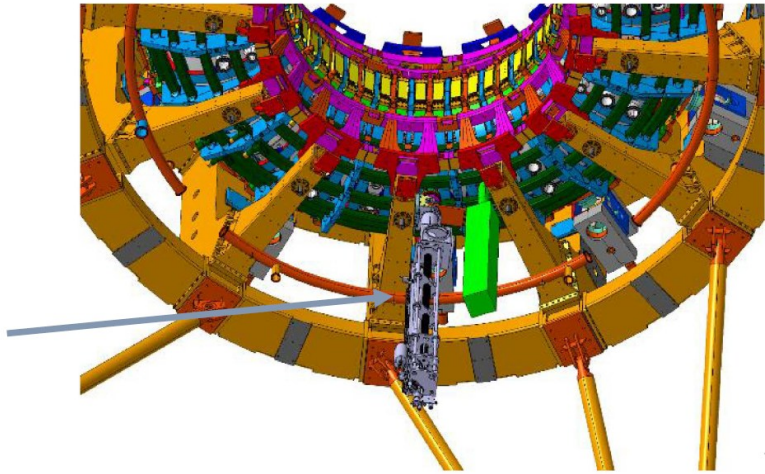


M. Giacomin, NF 2025

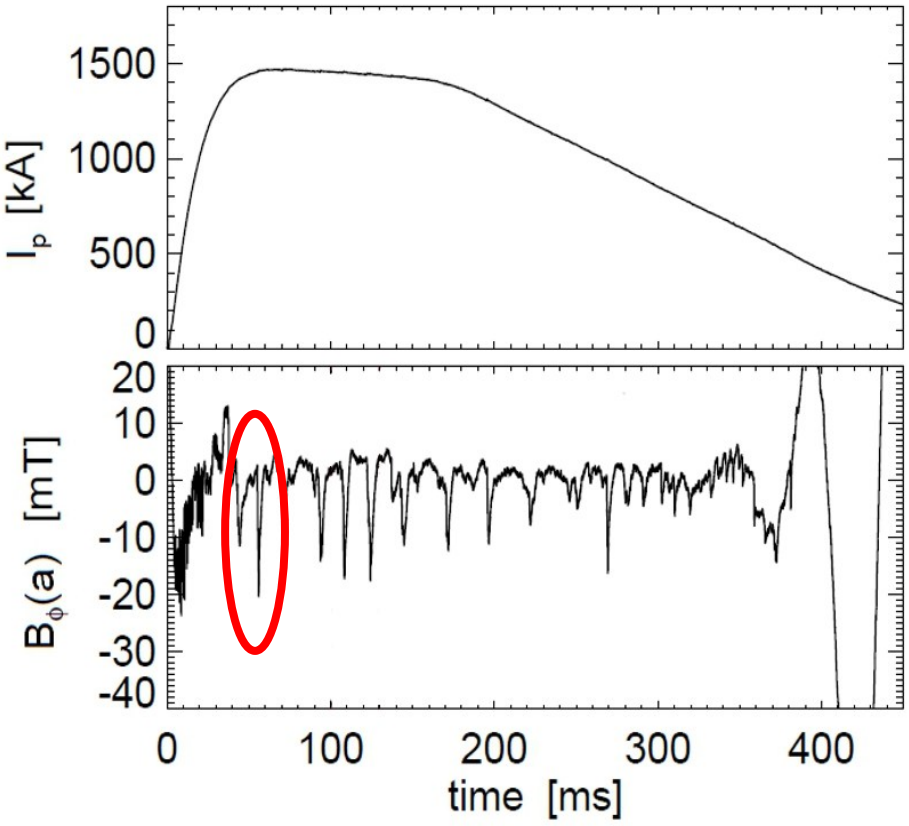
- Characterization of edge plasma electromagnetic turbulence in the wide range of achievable experimental conditions (tokamak, RFP@2MA, Ultra low-q) in RFX-mod2 requires a system capable of **reducing heat load on insertable edge probes** (short-time exposition: 50-200 ms)

- Experimental activity and design complemented by intense 3D **nonlinear turbulence modeling**



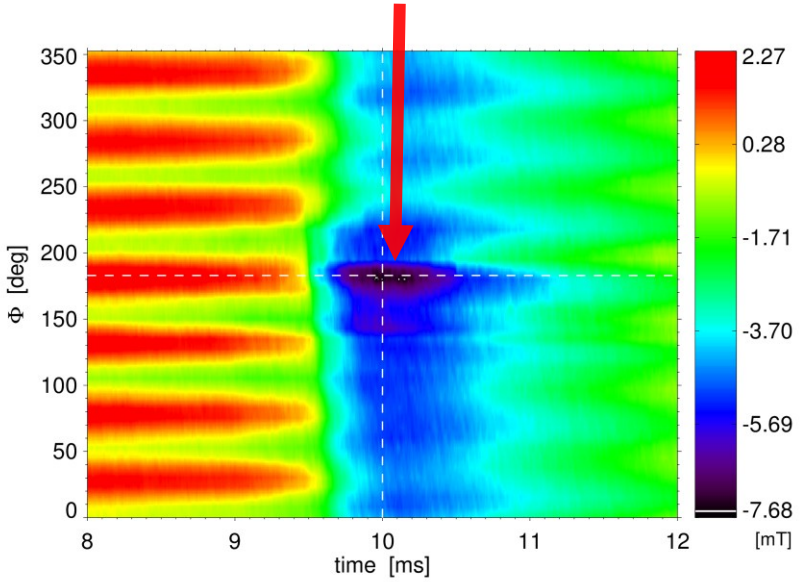


Magnetic reconnection dynamics in the RFP



Reconnection processes occurr as local events and can perturb or even destroy the helical structure

Local generation of a guide-field aligned current sheet



Zuin et al, **PPCF** (2009)

Current sheet and edge plasma evolution

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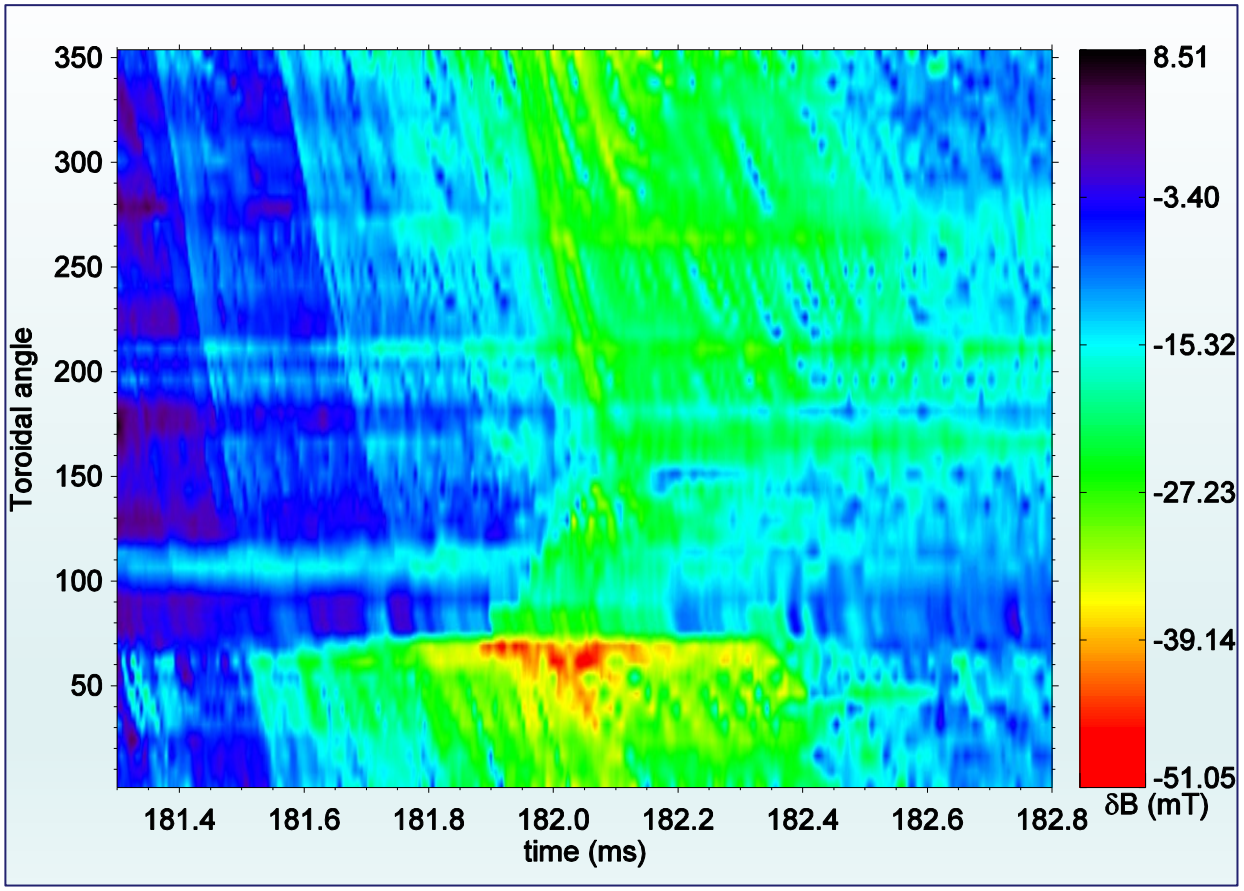
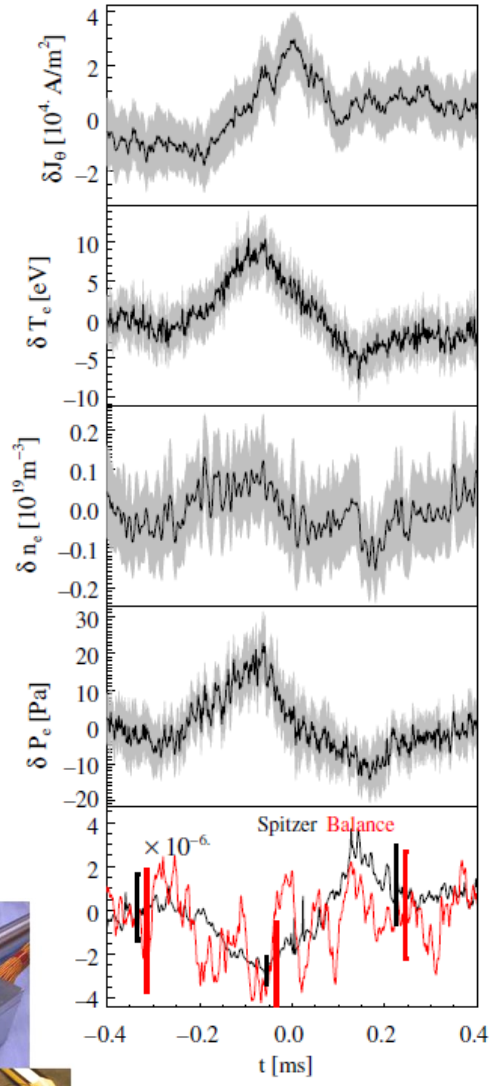
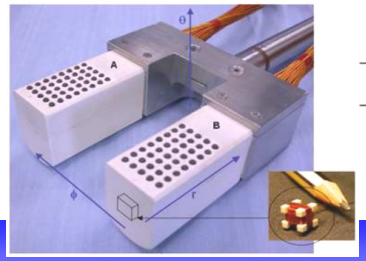
Current sheets are hotter and denser than surrounding plasma, with complex structure



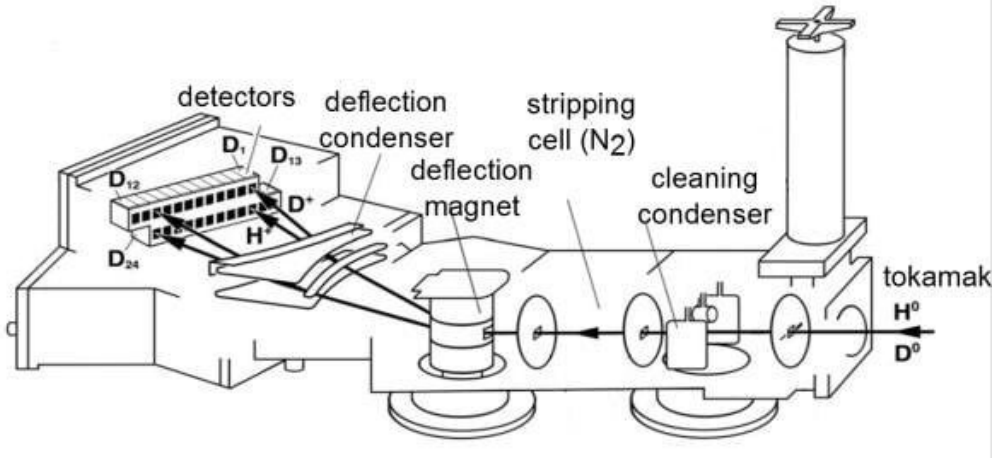




Radial extent: ion skin depth $c/\omega_{pi} \approx 7$ cm

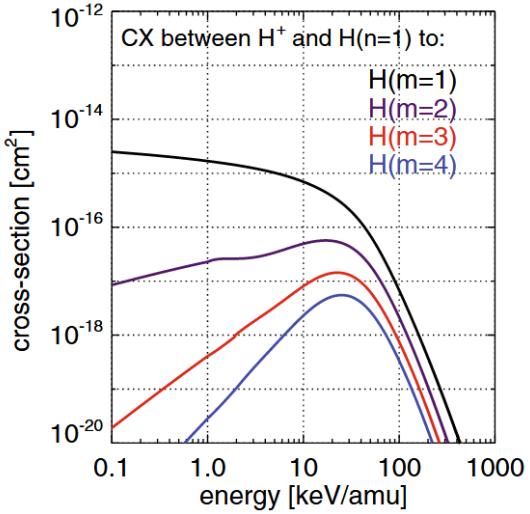
Zuin et al, **PPCF** (2009)

Ion f(v): Neutral Particle Analyzer (NPA)

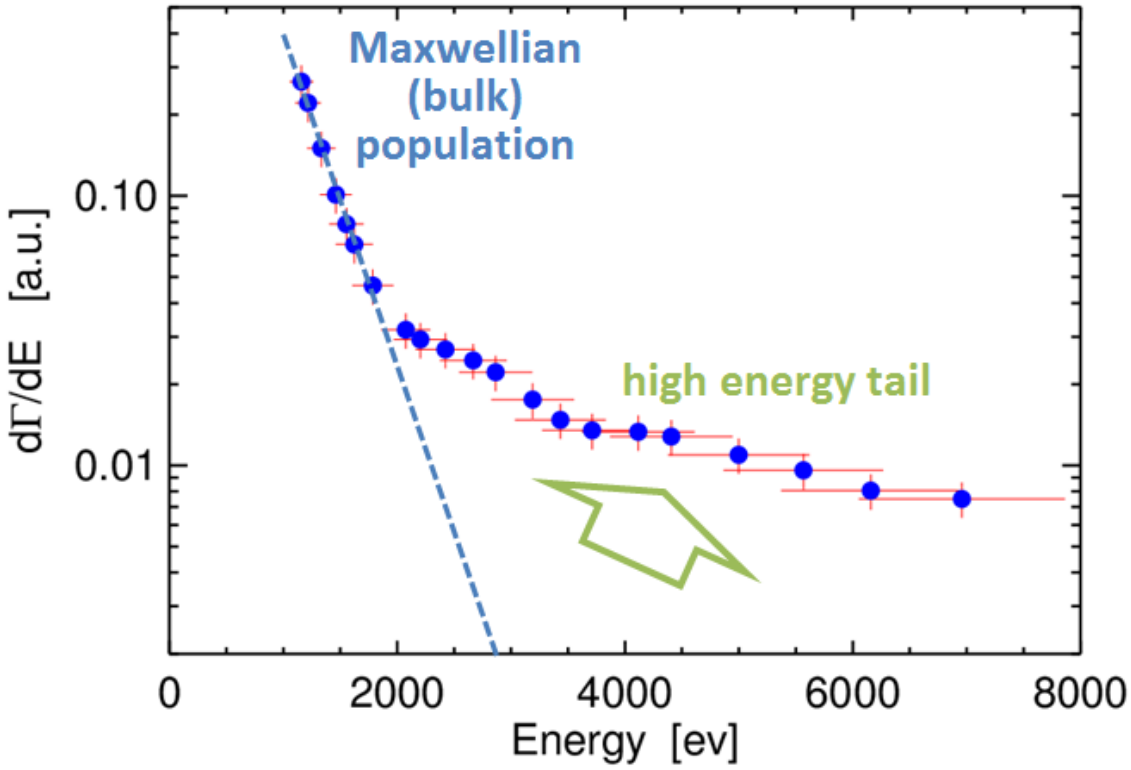


- $H^+_{fast} + H^0 \rightarrow H^0_{fast} + H^+$
- Detect neutrals escaping after **charge-exchange**
- Measure of fast-neutrals distribution function: indirectly of fast-ions
- ☺ energy resolution, SNR, localized measurement (if active)
- ☹ spatial resolution and velocity space resolution (if passive)

[K. Mitosinkova et al, 2015]



Ion f(v): non-maxwellian tail in Ohmic plasmas



Ion distribution function
(from charge-exchange neutral particles, NPA)

Maxwellian + non-Maxwellian high energy tail

?

Zuin et al. , **EPS** (2015)

Fast ion acceleration during reconnection

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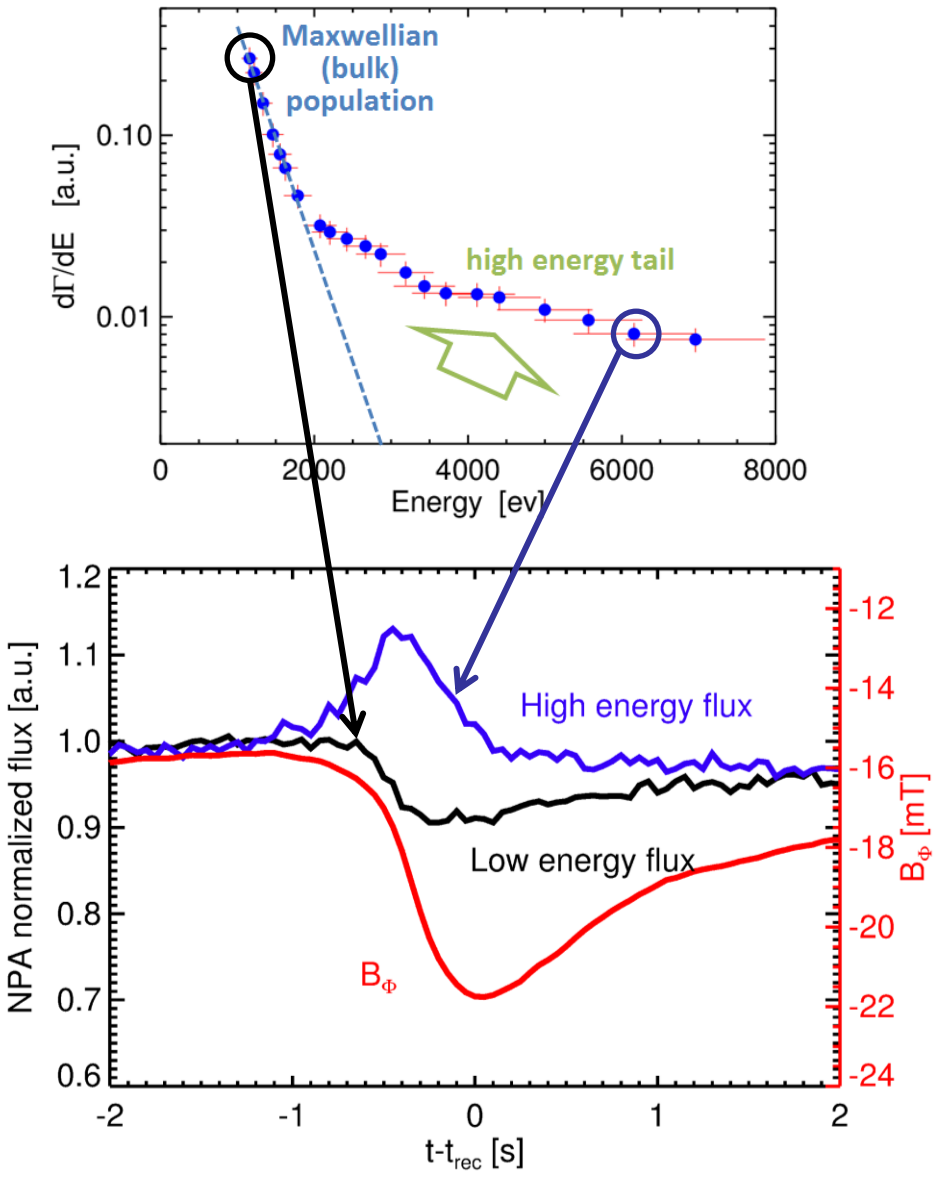
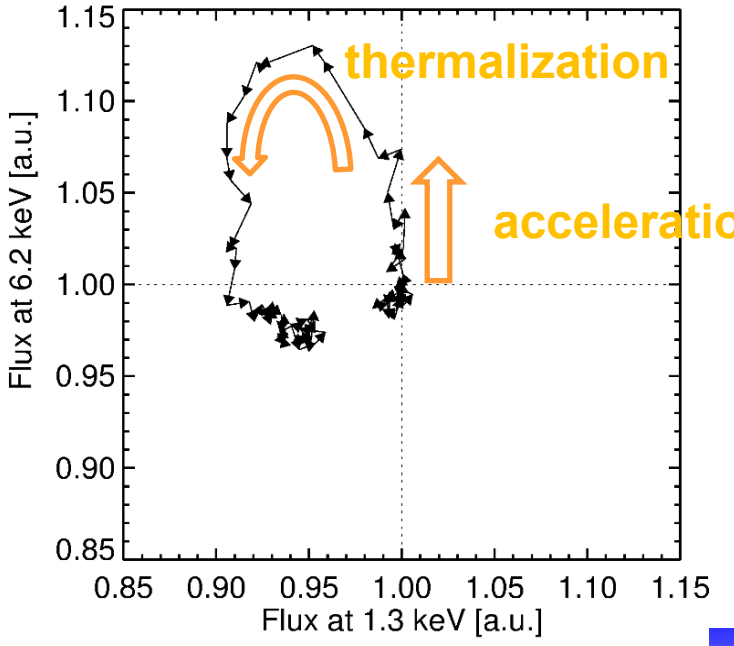


- **High energy ion flux increases => the non-maxwellian tail is enhanced**
- **Thermal population is then also affected**



Neutron-gamma rate

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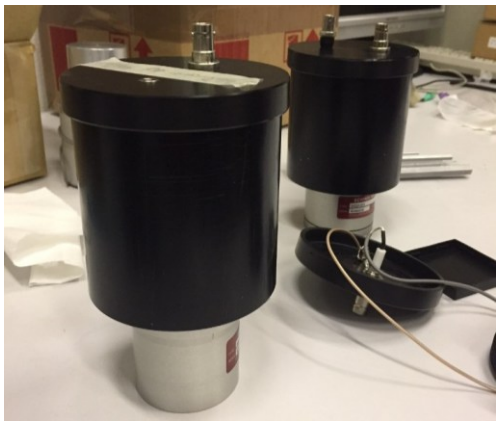
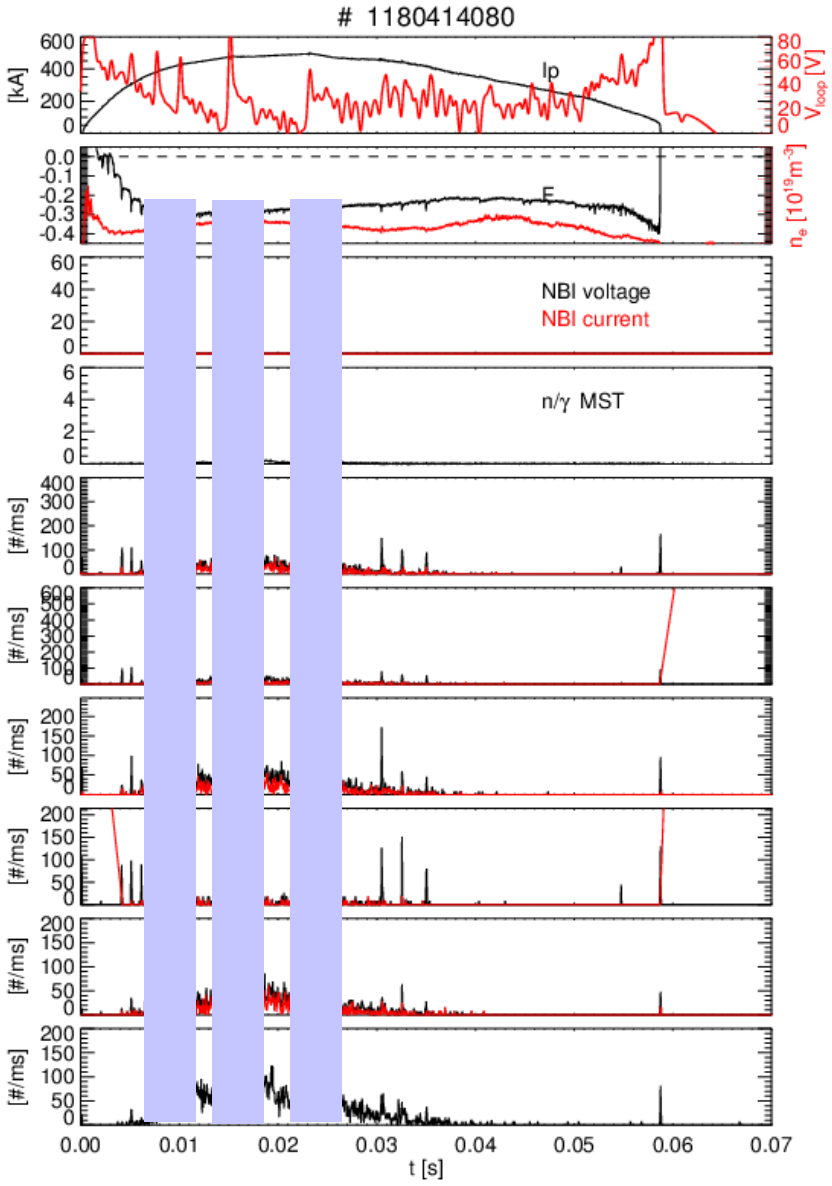
DD – enhanced fusion neutron rate (MST)

The experimental system is composed of:

- *#6 scintillators + photomultipliers*
- *Module Digitizer DT5725 CAEN*





Electron f(v): Gas Electron Multiplier soft-X ray diagnostic in RFX-mod2

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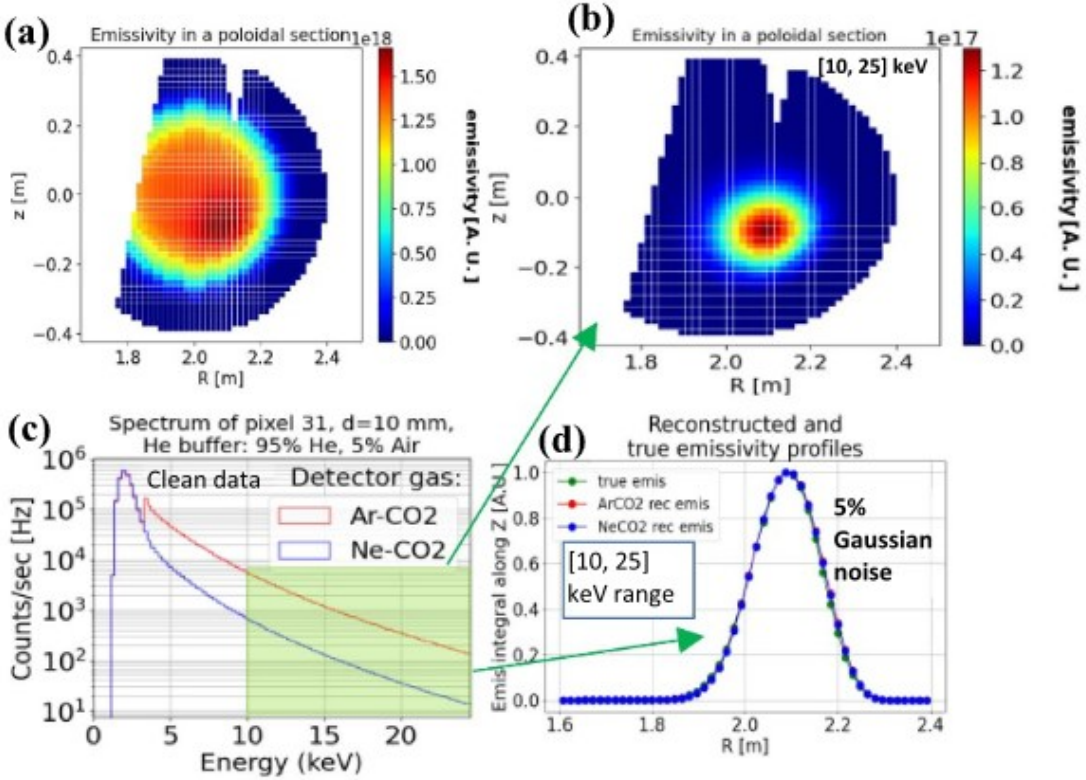
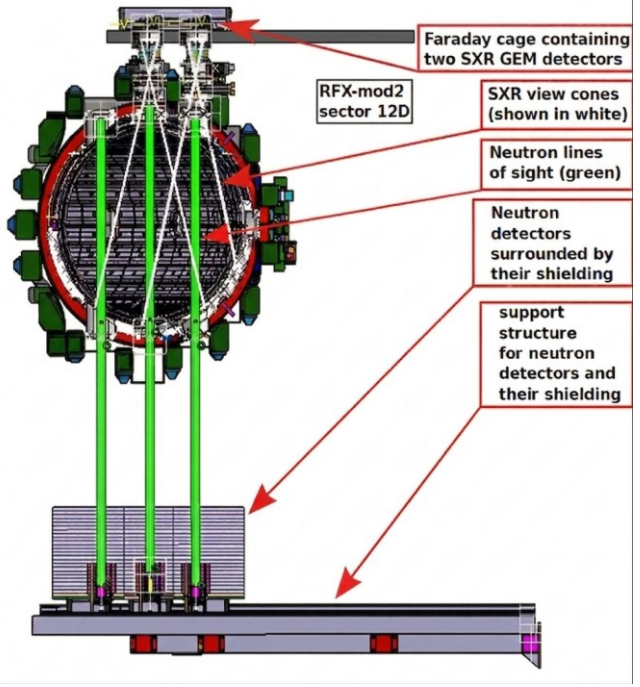
- **Energy – time – space resolved** electron **f(v)** tomographic reconstruction will allow a more detailed investigation of electron acceleration processes





Alfvén waves: fast ion effect in Ohmic plasmas

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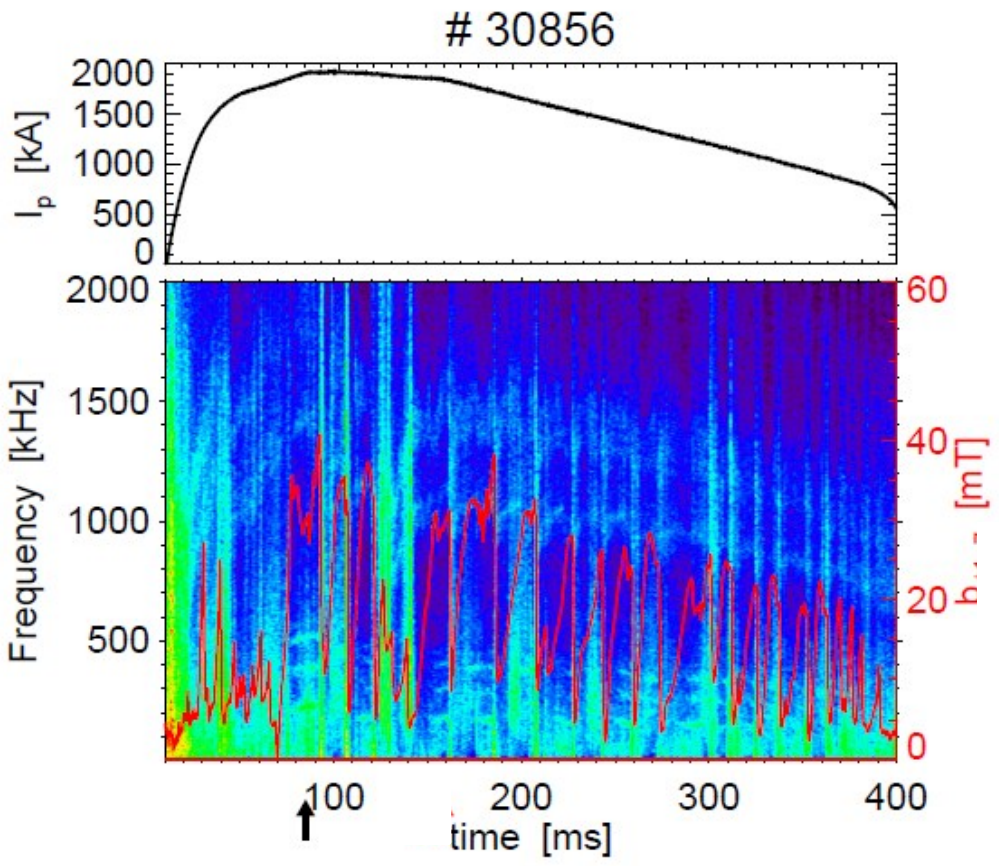
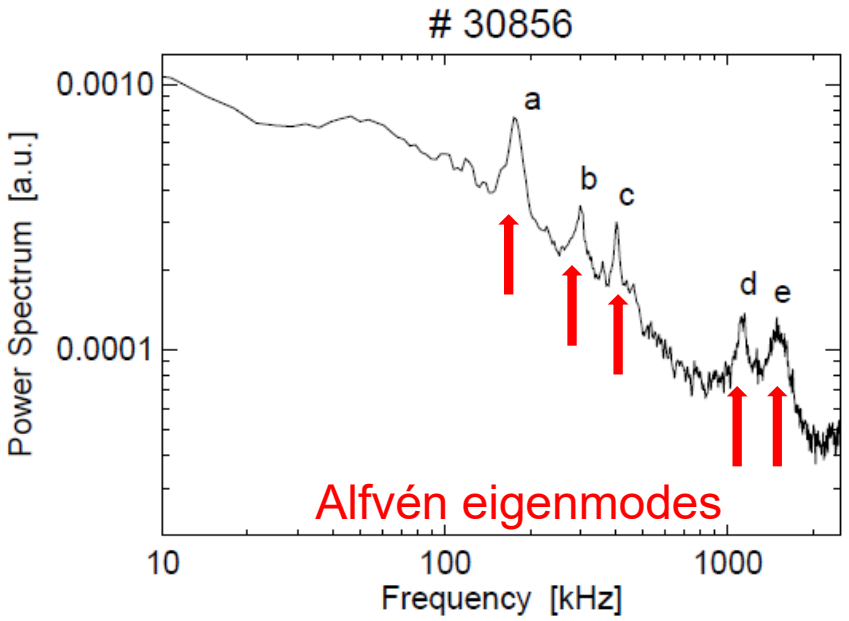


Magnetic spectrogram

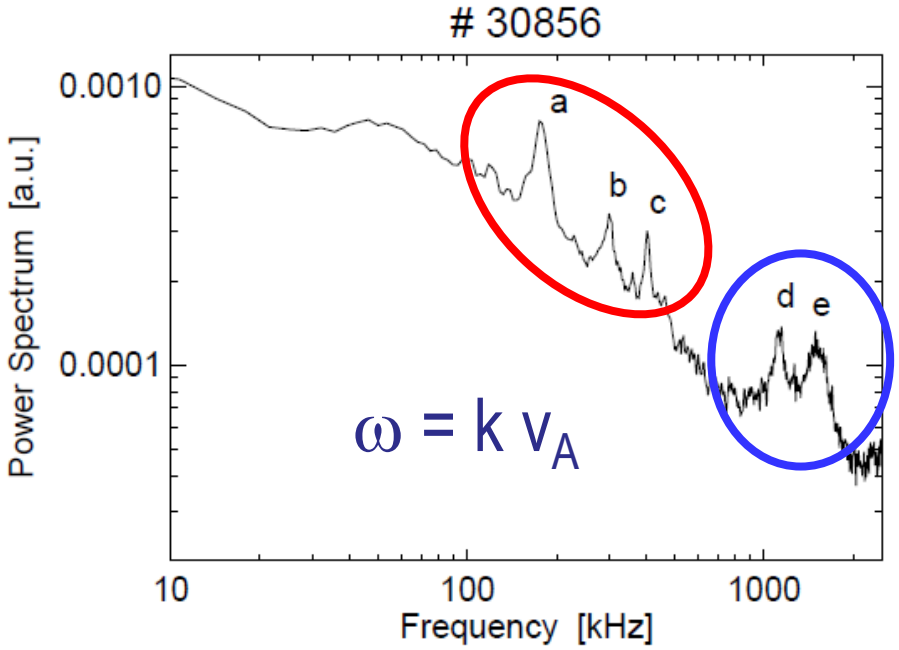
A variety of **Alfvén eigenmodes** are observed in RFX-mod plasmas, with no additional heating → presence of self-generated fast particle population

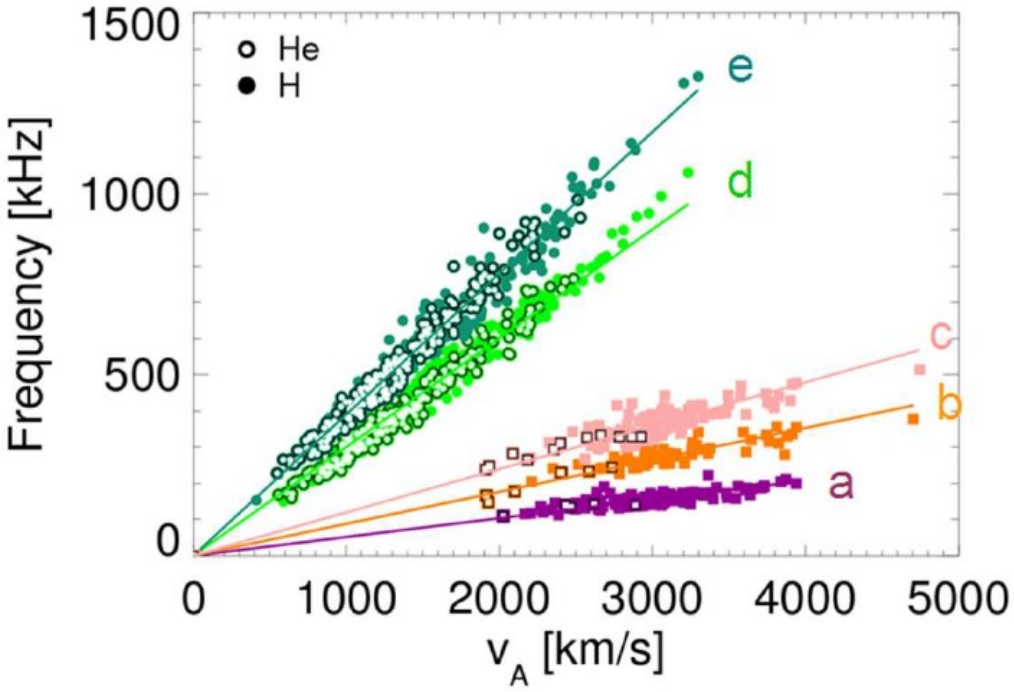


Spagnolo et al., **NF** (2011)
Zuin et al, EPS (2015)

Alfvénic scaling

Alfvénic nature of all Ohmic modes confirmed by the Alfvén scaling of the measured frequencies





The nature of the «helical» Alfvén modes still unclear

(helically induced or reversed shear Alfvén eigenmodes , … ?)

AEs enhancement during magnetic reconnection

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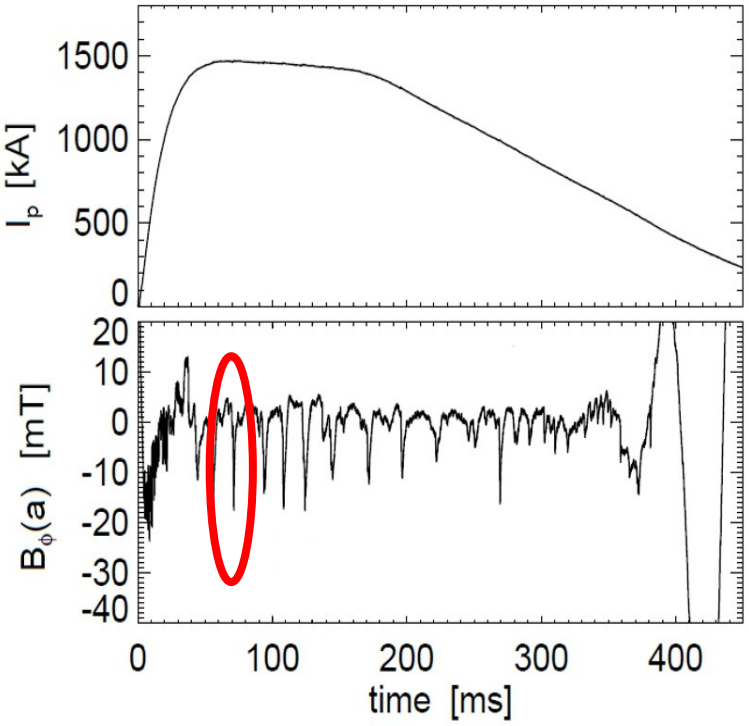
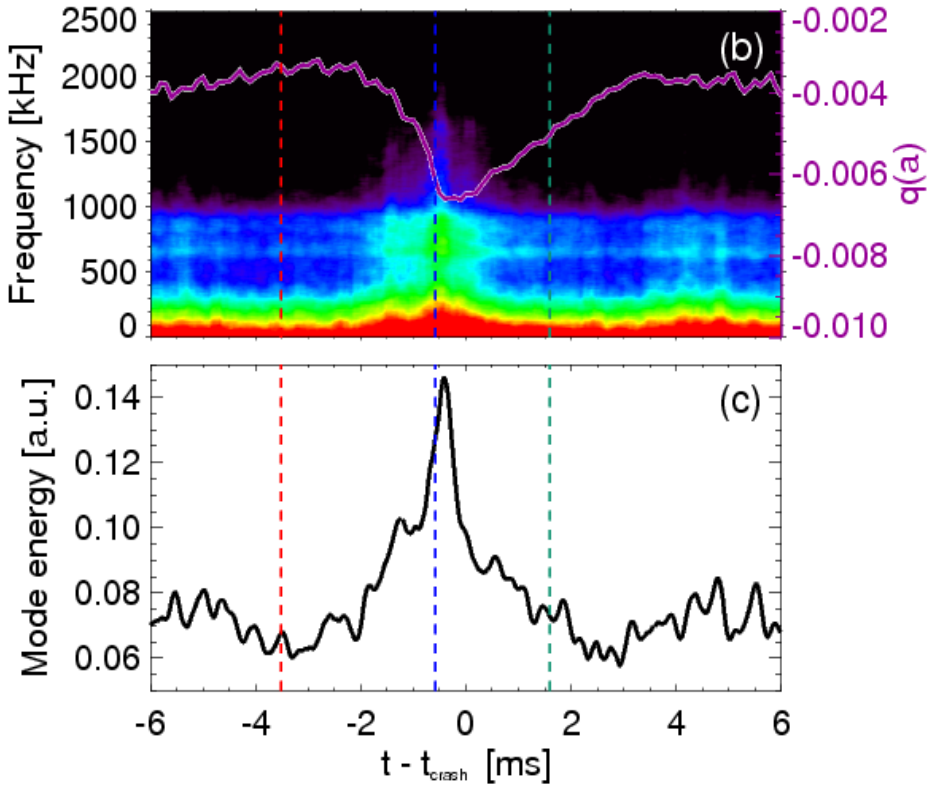
During magnetic reconnection events (rapid global rearrangement of the magnetic topology) the amplitude of the AE significantly grows





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Thank you