Spectroscopy as a Window into Plasma: Impurity Diagnostics and Transport studies

L. Carraro [1,2] RFX-mod team

1 Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete SpA), C.so Stati Uniti 4, 35127 Padova
[2] ISTP- Istituto per la Scienza e la Tecnologia dei Plasmi – Consiglio Nazionale delle Ricerche

Consorzio RFX – Located within the CNR Research Area of Padua

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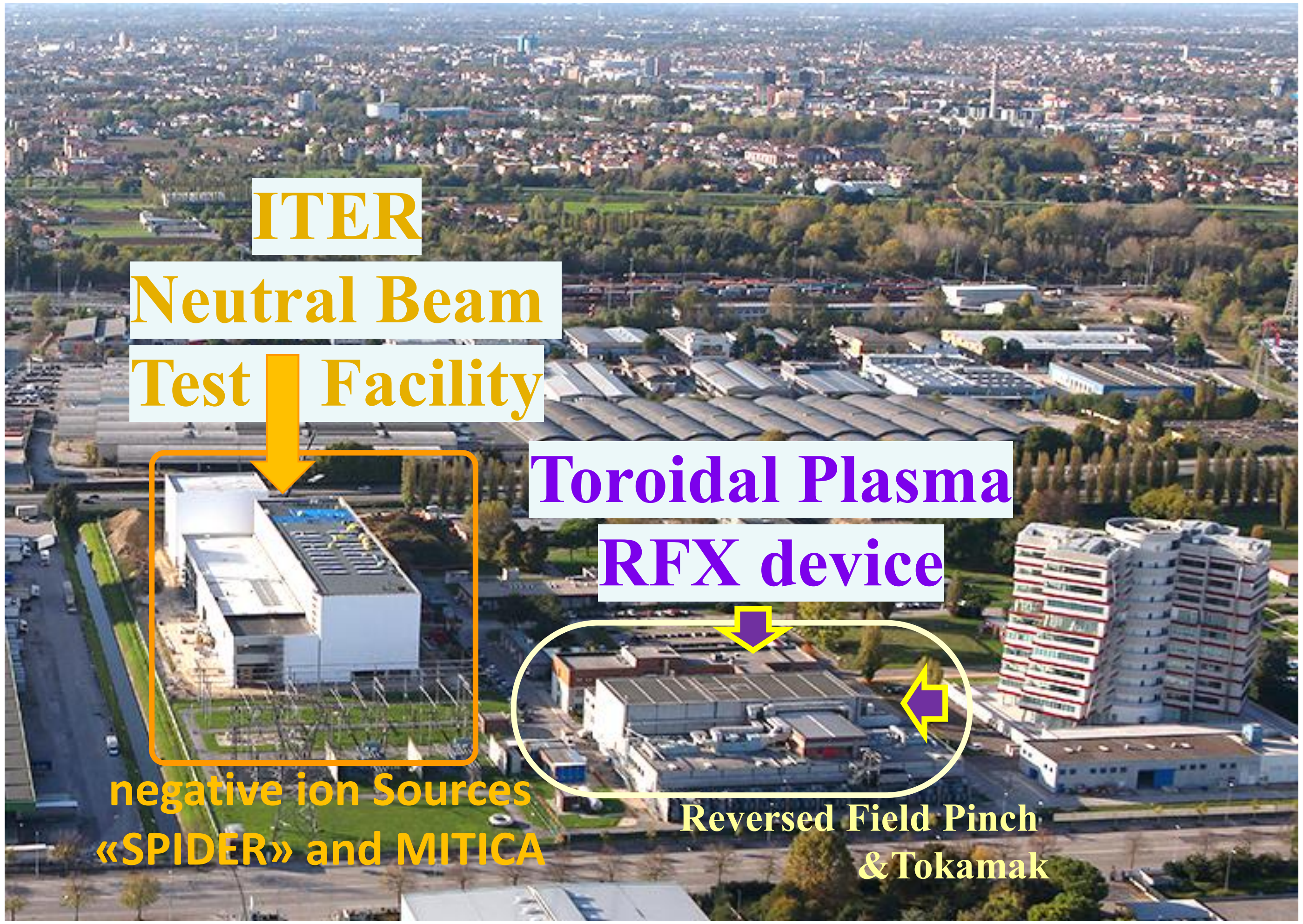


RFX infrastructure funded by PNRR NEFERTARI project
Upgraded device: RFX-mod2

NBTF A. Pimazzoni:
Plasma physics in negative ion sources and challenges for MeV neutral beam injectors for fusion

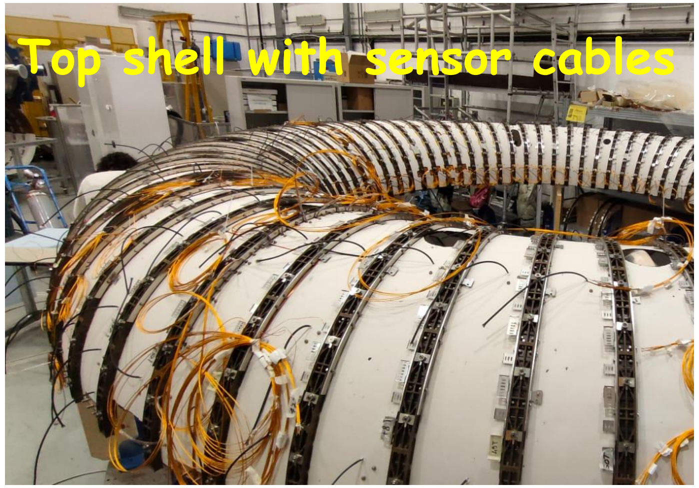
Reversed Field Pinch, RFP, partners:
USA - Sweden - Japan – China

RFX-mod2: New Device Reassembly Underway

Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
Consiglio Nazionale delle Ricerche
Università degli Studi di Padova
Università degli Studi di Napoli Federico II

PNRR NEFERTARI program—the new **RFX-mod2** facility :
upgraded diagnostics and a reinforced real-time control system
(>1500 in vessel magnetic sensor signals, > 500 in vessel electrostatic sensor signals)
Broaden knowledge and understanding of plasma physics -RFP and tokamak configurations

POR 2014/2020 FESR / REGIONE DEL VENETO
UNIONE EUROPEA REGIONE DEL VENETO

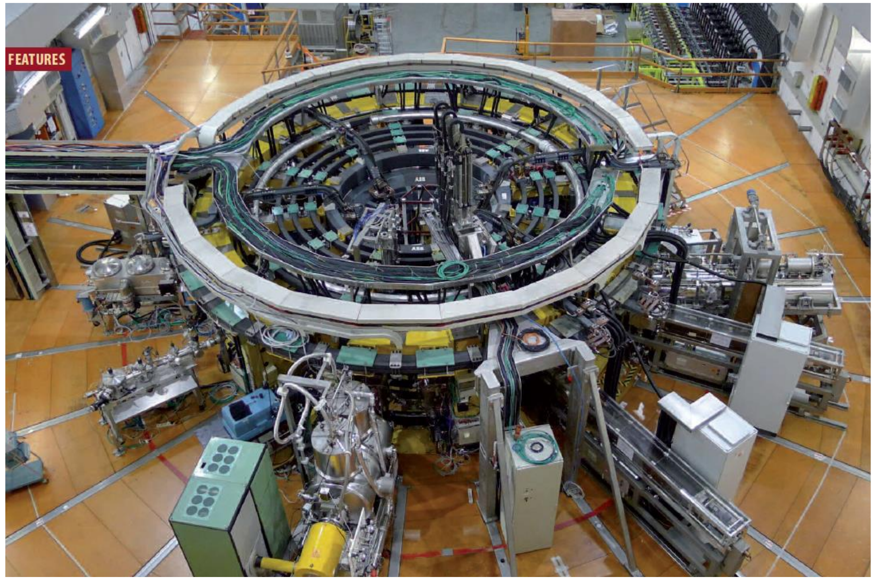


S.Peruzzo, et al., "The new vessel complex for the RFX-mod2 experiment: An effective synergy between fusion research and technological development", Fus Eng and Design(2023)

Outline

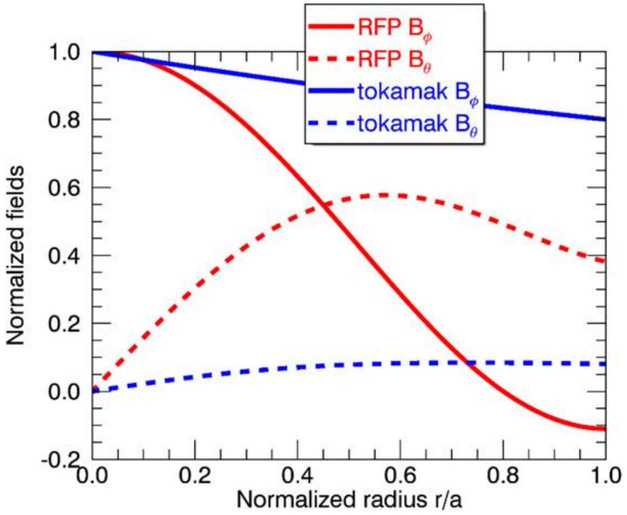
- RFX-mod – Highly flexible toroidal device for magnetic confinement fusion (RFP, tokamak and other scenarios)
- High-current RFP plasmas – Improved confinement regimes; Quasi-Single Helicity (QSH) helical states arising from self-organization
- Impurities play important roles in plasma properties
- Plasma emission measurements in RFX-mod RFP: from SXR to visible
- Impurity transport in RFX-mod RFP: impurities do not penetrate the plasma
- RFX-mod high current RFP: impurity m = 1 flow pattern on a poloidal cross-section in agreement with 3D MHD simulations.
- RFX-mod2 – New device reassembly underway (upgraded diagnostic)
- Summary and conclusions

RFX-mod: A Flexible Device for Cross-Configuration Studies

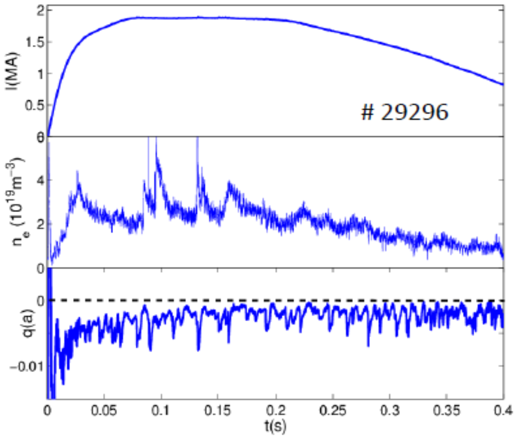


Torodal device with Circular cross-section :

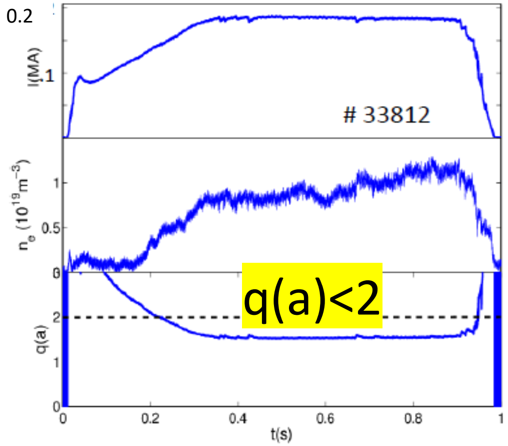
- *a=0.459 m , R=2 m*
- *Ip ≤ 2 MA RFP, 0.2 MA Tokamak*
- *$B_{T,max}$=0.5 T*
- *Te≤1.5keV*
- *ne ≤10^{20} m-3*
- *ohmic, no divertor*
- ***Advanced MHD stability control system:***
  192 saddle coils independently driven
- Exploited both in RFP and Tokamak configuration



RFX-mod RFP



RFX-mod Tokamak



RFX-mod: A multi-configuration fusion facility for three-dimensional physics studies *P.Piovesan et al (2013)*
RFX-mod2 as a flexible device for reversed-field pinch and low-field tokamak research *D.Terranova et al (2024)*
Overview of RFX-mod science activities *M.Zuin et al. (2017)*
H-mode achievement and edge features in RFX-mod tokamak operation *M. Spolaore et al (2017)*
Self-organized helical equilibria as a new paradigm for ohmically heated fusion plasmas *R.Lorenzini et al (2009)*
The reversed field pinch *L. Marrelli et al (2021)*

High-Current RFPs: Improved Confinement Helical States as the Result of Self-Organization

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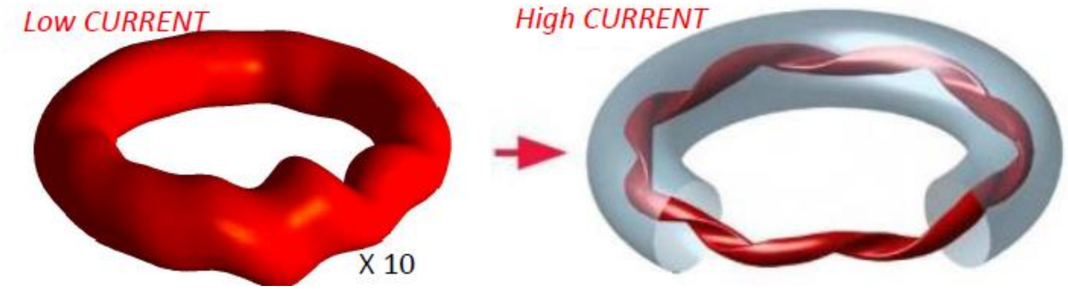
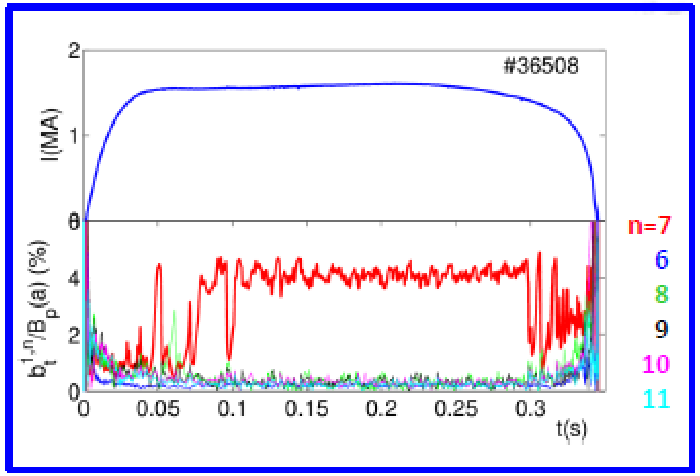
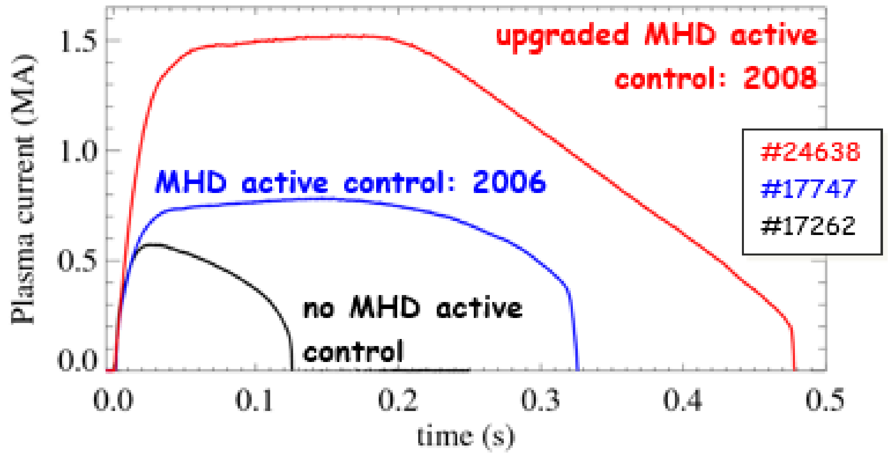
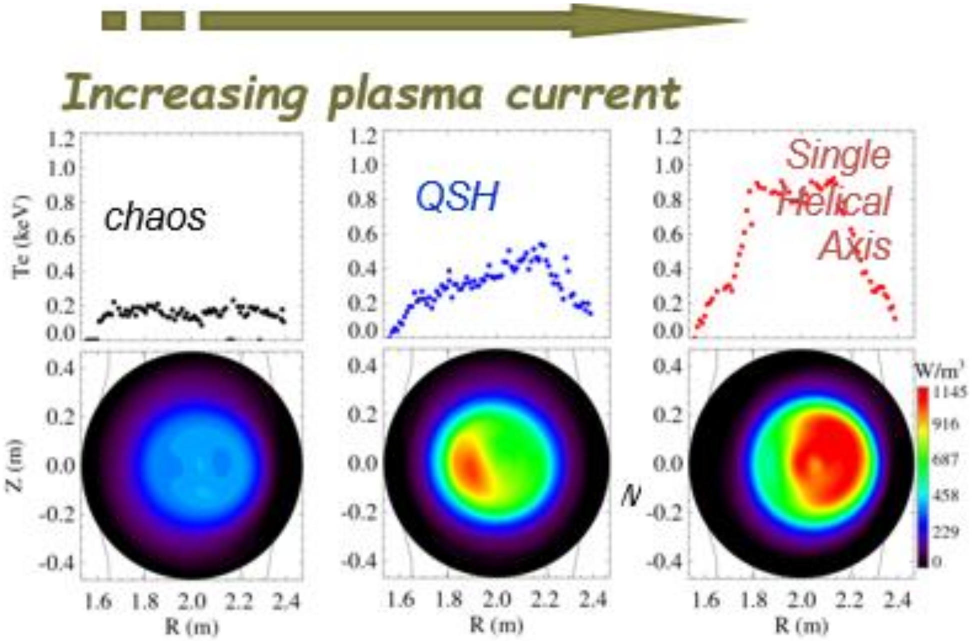




RFX-mod RFP at high current: new physics regimes achieved with m=1, n=7 helical equilibrium

Increasing plasma current :Te and energy confinement improve





The Role of Impurities

Radiation in a plasma comes from

- main gas
- impurity coming from the wall (PWI)
- Impurity injected for diagnostic purposes or PWI mitigation

Impurities play important roles in plasma performances:

•Plasma dilution and reduced plasma reactivity ☹

•Increased radiation power loss ☹

•Reduction of heat fluxes on plasma facing components☺

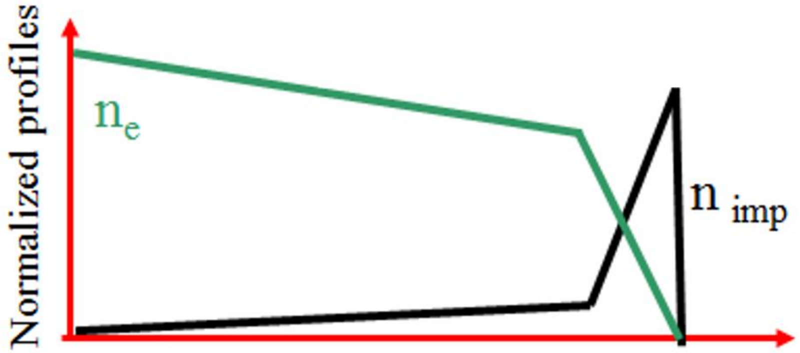
Therefore, it is essential to

•keep as low as possible the total impurity content.

• control the impurity peaking

Griem, Hans R. (1997). Principles of Plasmas Spectroscopy. Cambridge: University Press

IDEAL SITUATION

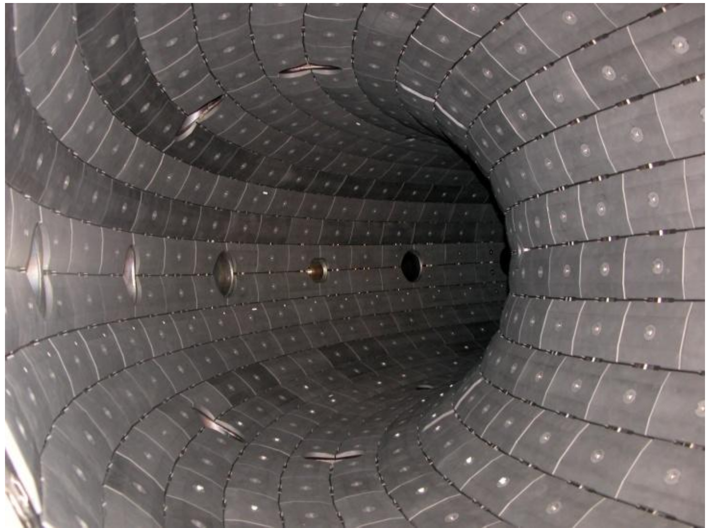


RFX-mod Plasma Emission Measurements – Overview

Plasma spectroscopy: powerful and non-perturbative

- Spectroscopy aims: to understand what the emission reveals about the emitting plasma (species identification and quantification; temperature; motion; etc.)
- Line-of-sight emission → non-local measurement . Emitter position must be known independently(e.g. impurity transport simulations)

RFX-mod has a full carbon wall➔ C and O are intrinsic impurities at low concentrations (~1%).



He, B and Li appear after wall cleaning/conditioning operations.

Laser blow-off from a solid target at the plasma edge , gas puffing, or doped cryogenic pellet, to inject particles and measure their emissions.

RFX-mod Plasma Emission Measurements – Overview

RFX-mod spectroscopic diagnostics span VIS–UV, VUV, and XUV ranges:

High plasma temperatures result in emission dominated by VUV and X-ray region.

Visible emission remains valuable: it is easier to observe and allows straightforward absolute calibration.

RFX-mod Plasma Emission Measurements – Overview

RFX-mod spectroscopic diagnostics span VIS-UV, VUV, and XUV ranges:

- VIS: Particle influxes (H, He, Li, B, C, O) from low ionization emission lines collected by interference filters.
- VIS: T_e and n_e at the edge :Thermal Helium Beam
- VIS-UV : Multichannel spectrometer (flow and Ti LoS averaged)
- VUV (10-110 nm) Impurity Monitor Survey spectrometer
- XUV Grazing incidence spectrometer (with 600g/mm grating: 1-35 nm) C,O He/H-like resonant line emission
- SXR Bremsstrahlung tomography (impurity distribution,Te from double filter technique)
- Prad tomography

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RFX-mod spectroscopic diagnostics span VIS–UV, VUV, and XUV ranges.

Gas Puff Imaging (GPI)
Turbulence studies

Thermal Helium Beam (THB)
Te(a),ne(a)

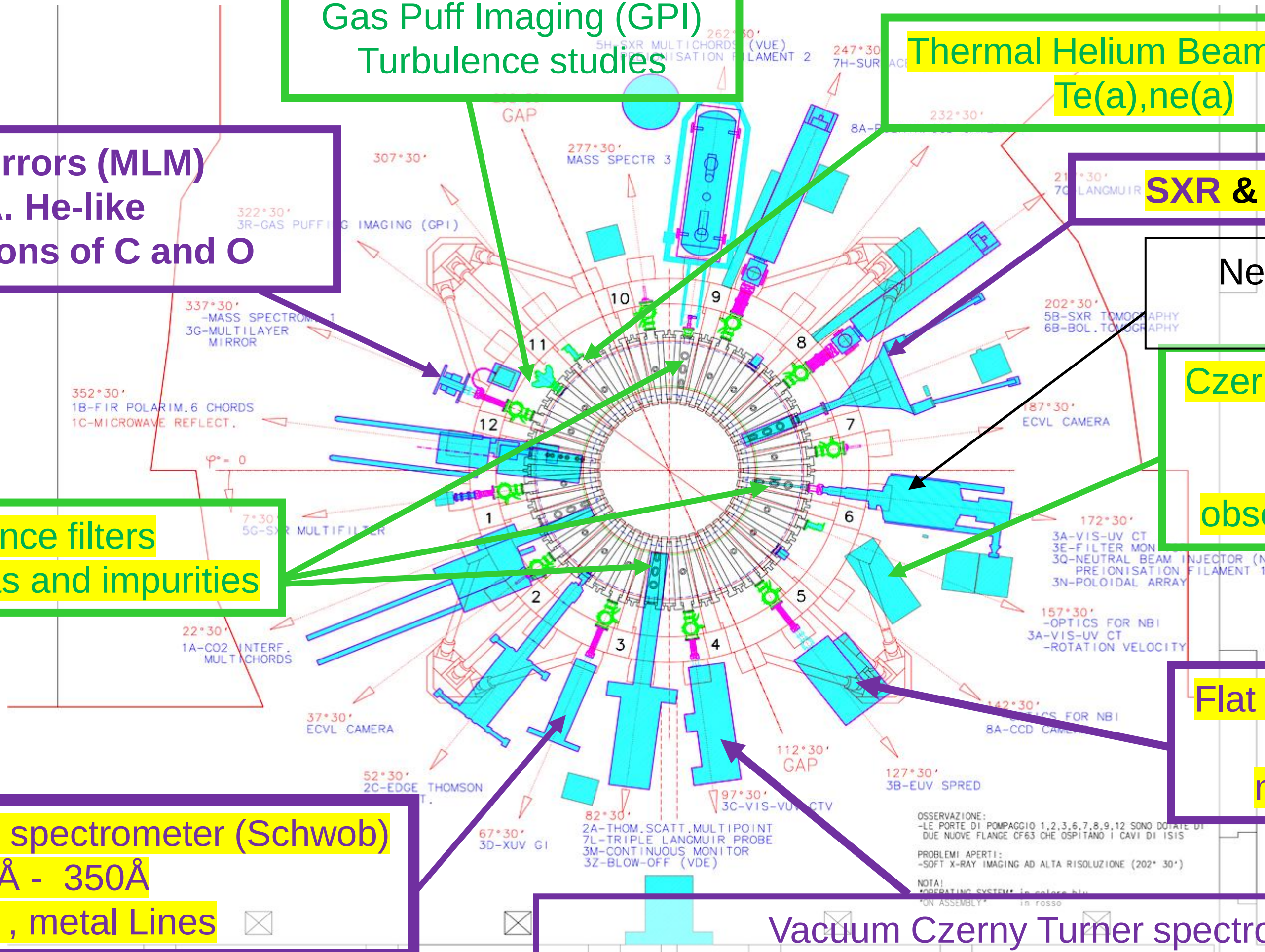
Multi Layer Mirrors (MLM)
18 Å - 60 Å. He-like
resonant transitions of C and O

SXR & Prad Tomography

Neutral Beam Injector (DNBI)
50 keV for 50 ms 4 A

Czerny Turner spectrometer (CT)
2000 Å - 8000 Å
spectrally resolved
observations on several chords

22 Interference filters
influxes of mail gas and impurities

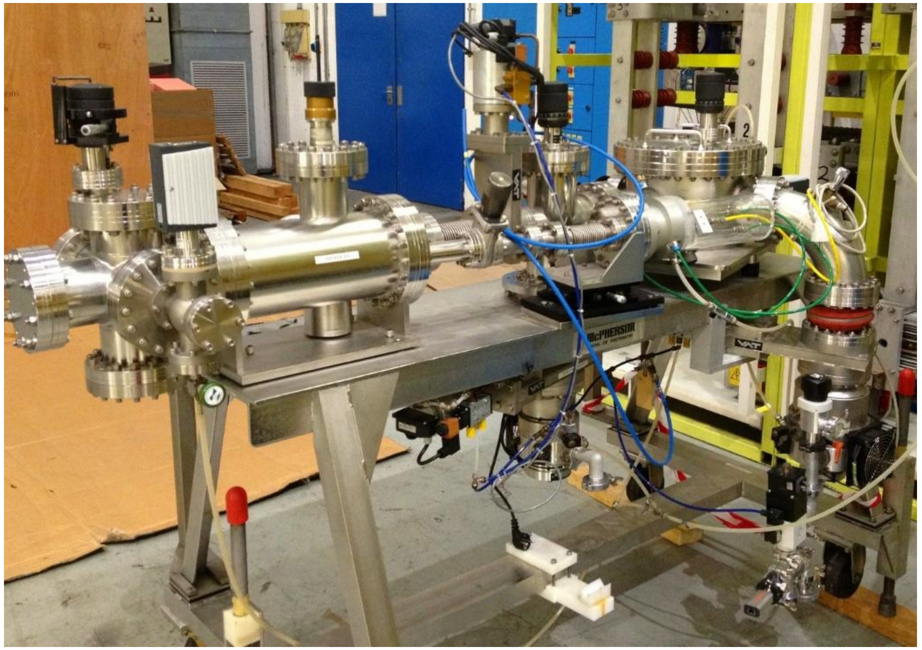


Flat Field spectrometer (SPRED)
100 Å - 1100 Å
monitor impurity emission

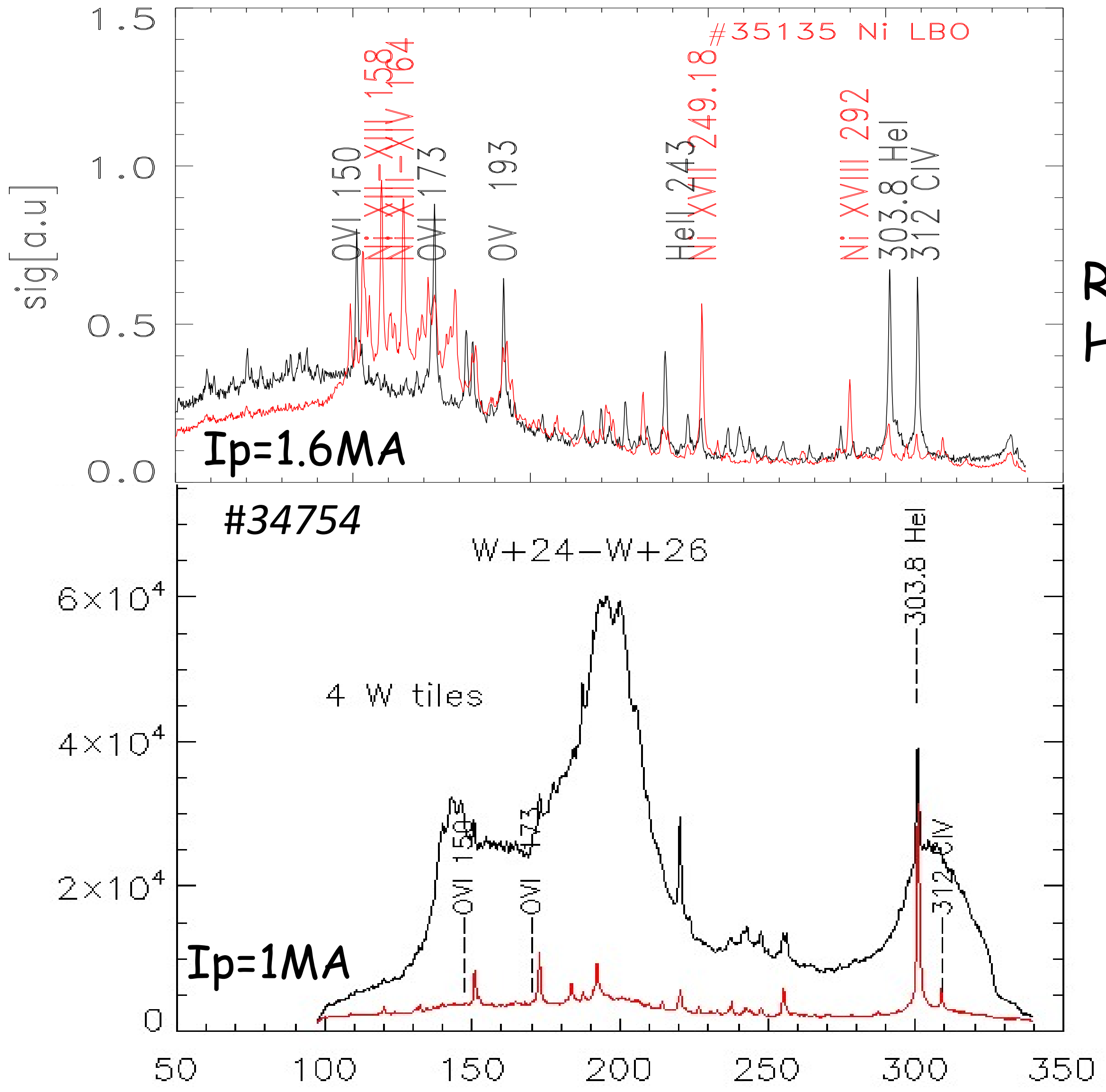
Grazing Incidence spectrometer (Schwob)
10 Å - 350Å
CV,CVI , metal Lines

Vacuum Czerny Turner spectrometer (CTV)
1150 Å - 8000 Å
CV OVII LOS (equat diameter) averaged Ti, absolute brightness

Impurity Identification from Line Emissions: VUV-XUV Spectroscopy

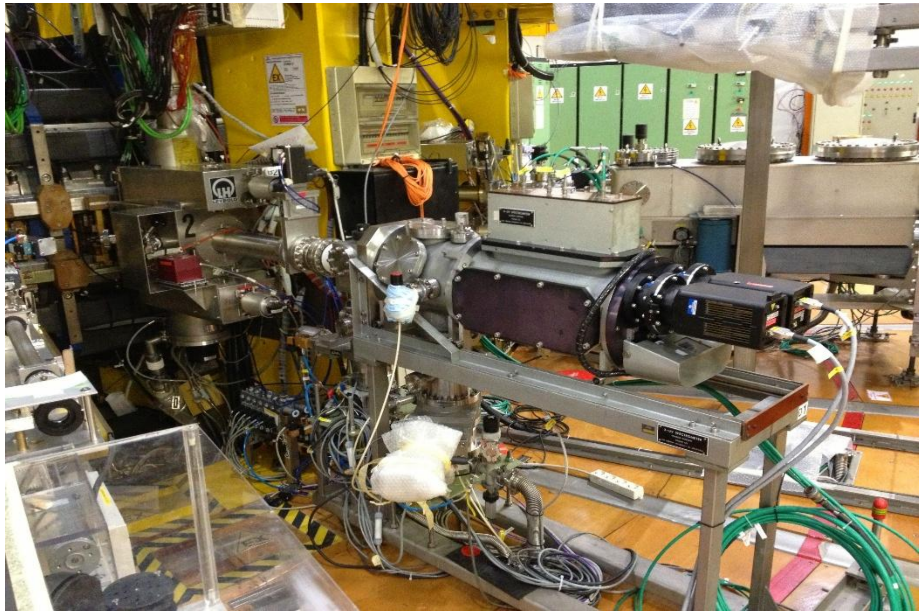


VUV SPRED spectrometer
Impurity survey/monitor

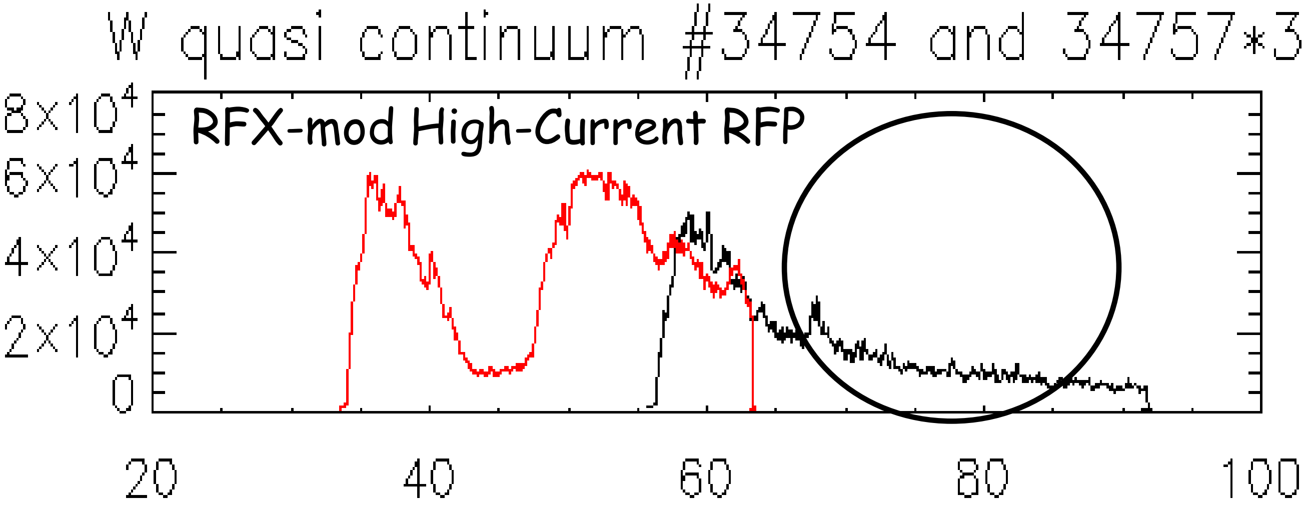


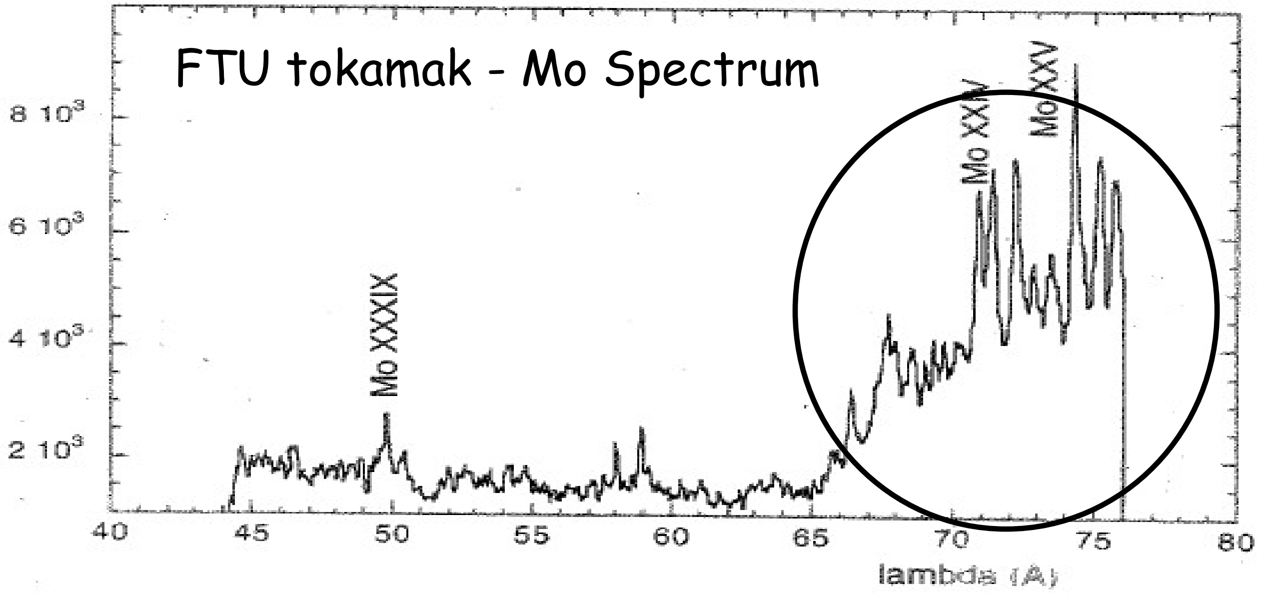
RFX-mod
High-Current RFP

Impurity Identification from Line Emissions: VUV-XUV Spectroscopy



RFX-mod XUV-GI SOXMOS Spectrometer





On RFX-mod
Mo (layer under that of W)
spectral features not seen

Impurity Transport: System of Impurity Continuity Equations with Diffusion (D) and Convection (V)

n_z (r,t) z=0,…,Z: radial impurity density profile (cylindrical simmetry)

$$\frac{\partial n_z}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}(r \cdot \Gamma_z) + S$$

Transport

Atomic physics and Particle influxes from the wall

$$\Gamma_z = -D \cdot \frac{\partial n_z}{\partial r} + V \cdot n_z$$

Diffusive term

Convective term

Peaking factor

at the steady state:

$$\frac{\nabla n_z}{n_z} = \frac{V}{D}$$

<0 n_z impurity peaked profiles

>0 n_z impurity hollow profiles

Impurity Transport: D(r) and V(r) Evaluation

He, Li, B, C, O, Ne, and Ni impurity transport studies in RFX-mod RFP:

D(r) and V (r) obtained by simulating the experimental emission patterns time behaviors.

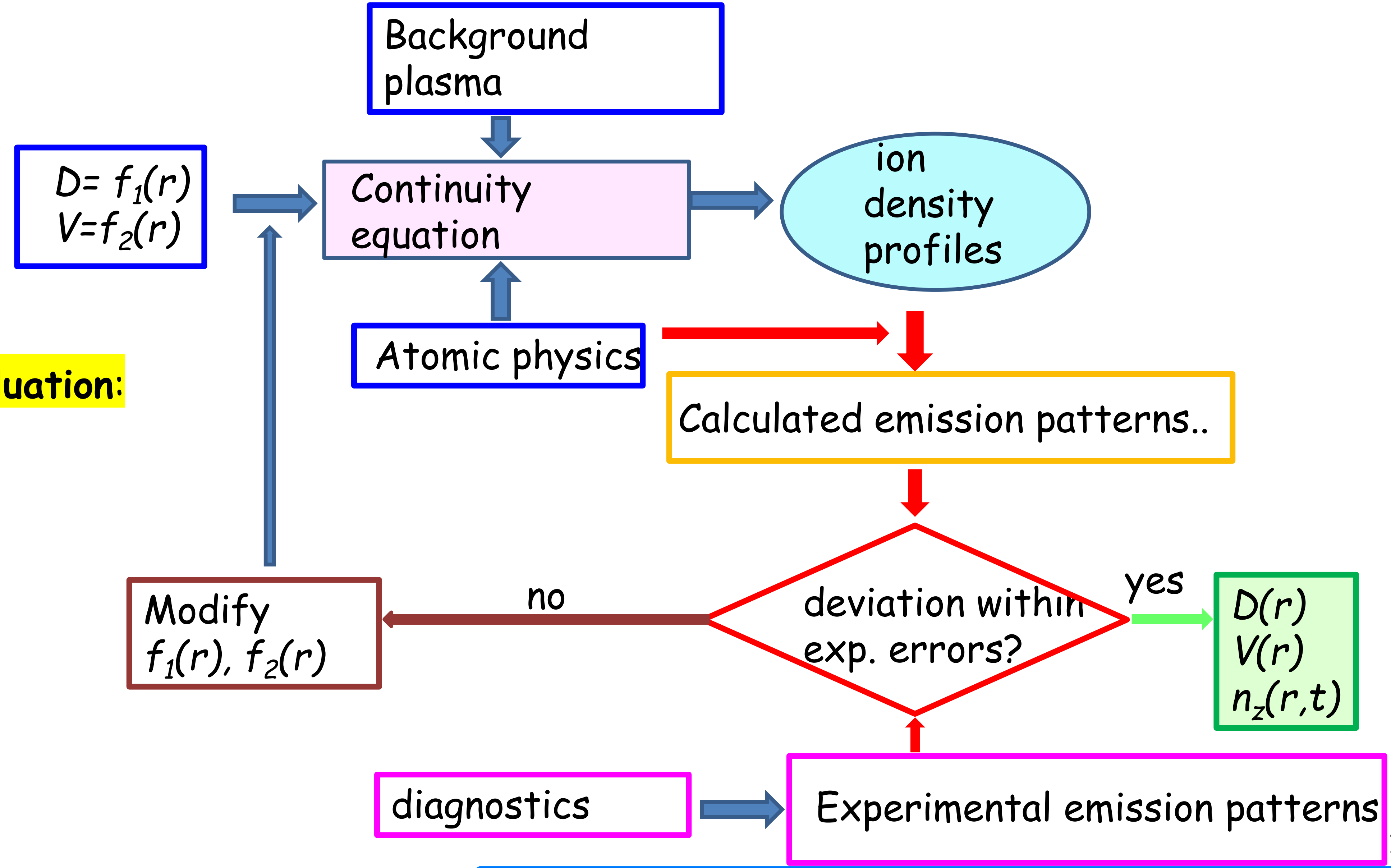
Boundary conditions /sources are measured influxes from the wall

T.Barbui et al. Plasma Phys. Control. Fusion (2015)

S.Menmuir et al., *Plasma Phys. Control. Fusion* (2010)

Impurity Transport: Iterative Scheme for Evaluating D(r) and V(r)

Iterative Scheme
for **D(r) and V(r) evaluation**:



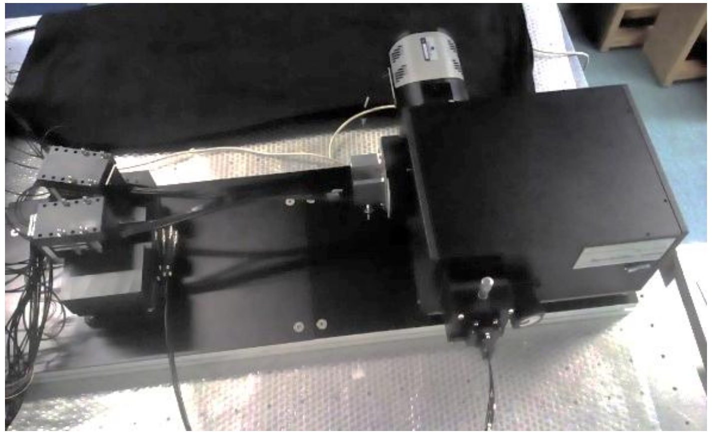
Particle Influx Measurements, Edge T_e and n_e Profiles from the Thermal Helium Beam Diagnostic

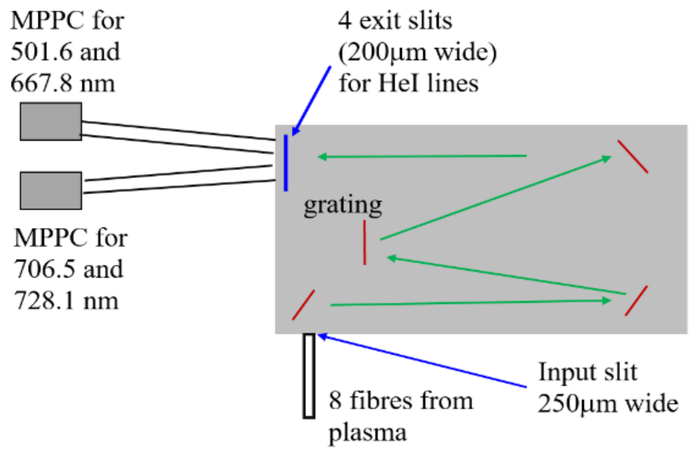
Boundary conditions of the continuity equation, Particle influxes from the wall (Γ) , from neutral (or Z=1) visible lines brightness (I) :

$$\Gamma = 4\pi \cdot I \cdot \frac{S}{XB}$$

S/XB from atomic models as a function of edge Te and ne measured by the Thermal Helium Beam (THB)

8 LoS, 4 emission lines :
501 nm, 667.8 nm , 706.5 nm and 728 nm.
$I_{728}/I_{706.5}$ depends on **Te**
$I_{667.8}/I_{728}$ depends on **ne**
I_{501}/I_{728} depends on **photon reabsorption**

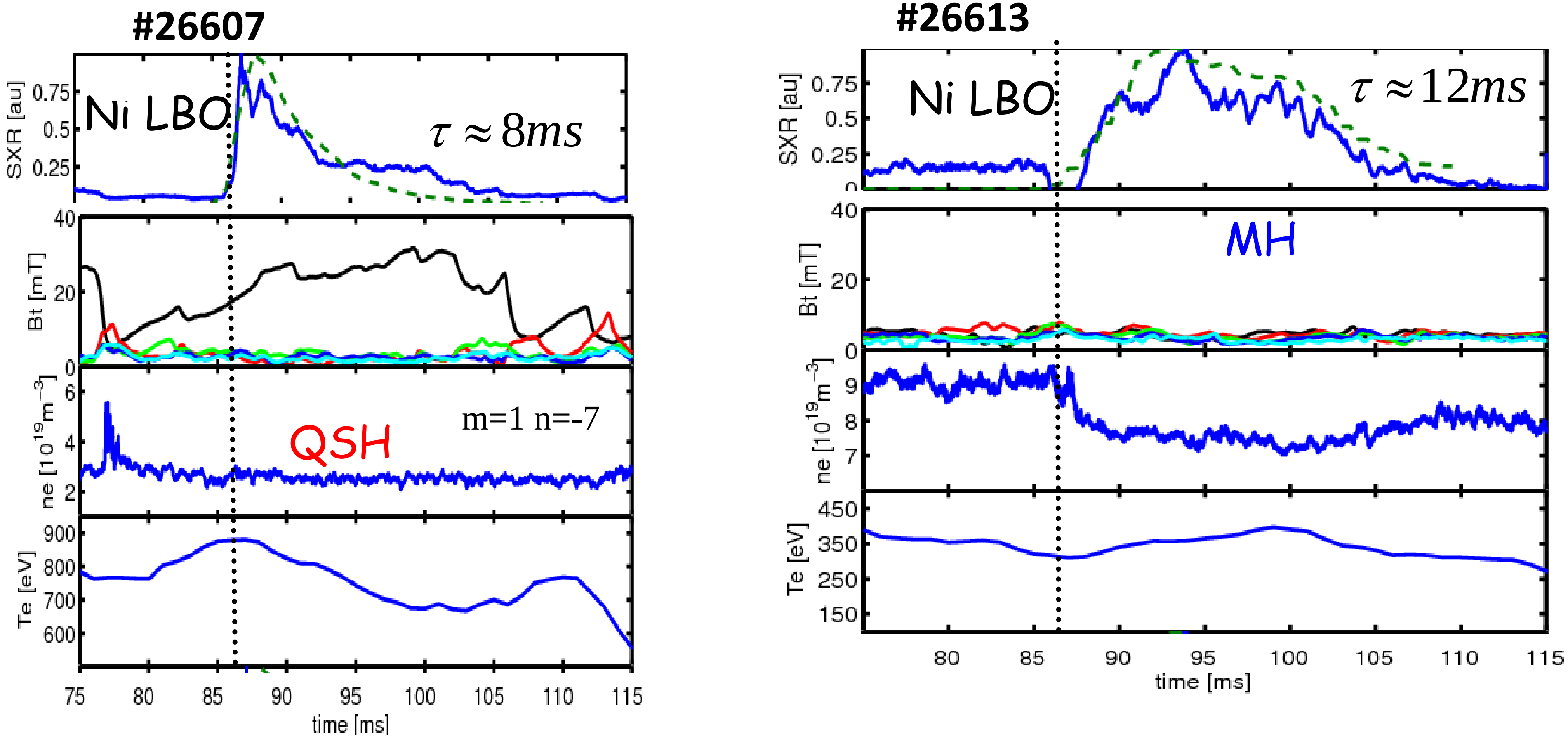




- Spectrograph for light dispersion
- 4 exit slits for the 4 wavelengths
- Multi-Pixel Photon Counter (MPPC) detectors (not sensitive to B)
- 1 MHz acquisition rate

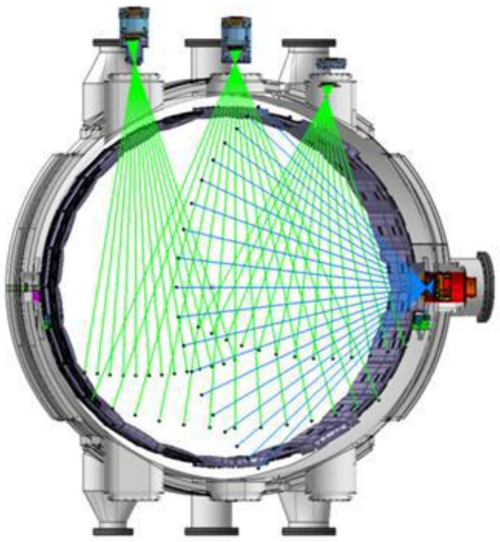
E.Hintz and B.Schweer Plasma Phys. Control. Fusion (1995)
M.Agostini et al Rev. Sci. Instrum. (2015)
M.Ugoletti et al Rev. Sci. Instrum. (2024)
L.Carraro et al J. Nucl. Mater. (1995)

RFX-mod RFP: Impurities Do Not Penetrate the Plasma Core



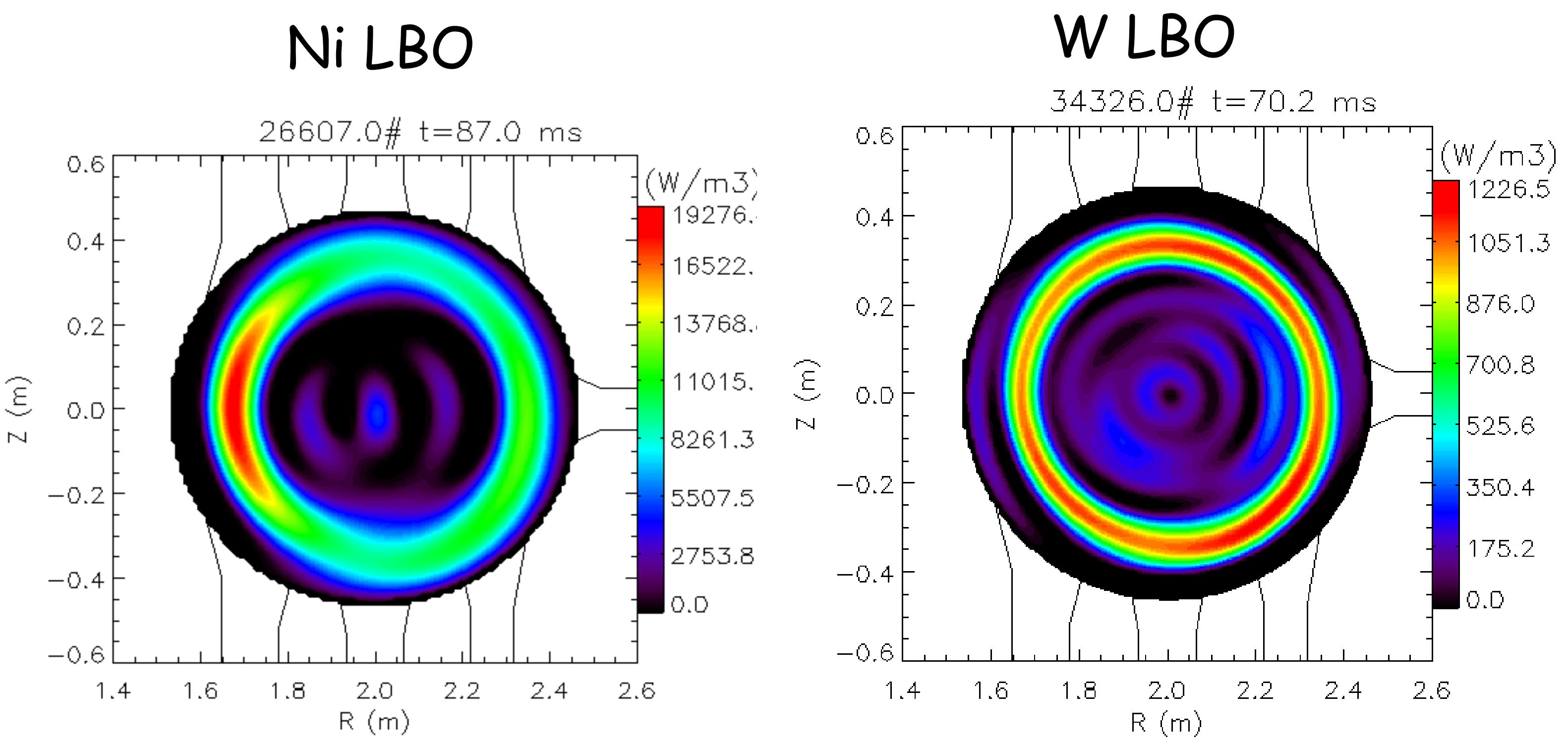
Ni LBO I_p ~1.5 MA, QSH and MH SXR decay rapidly => no accumulation

RFX-mod RFP: Impurities Do Not Penetrate the Plasma Core



RFX-MOD SXR Tomography
78 lines of sight
plasma emissivity reconstruction
P. Franz *et al* 2001 *Nucl. Fusion* **41** 695

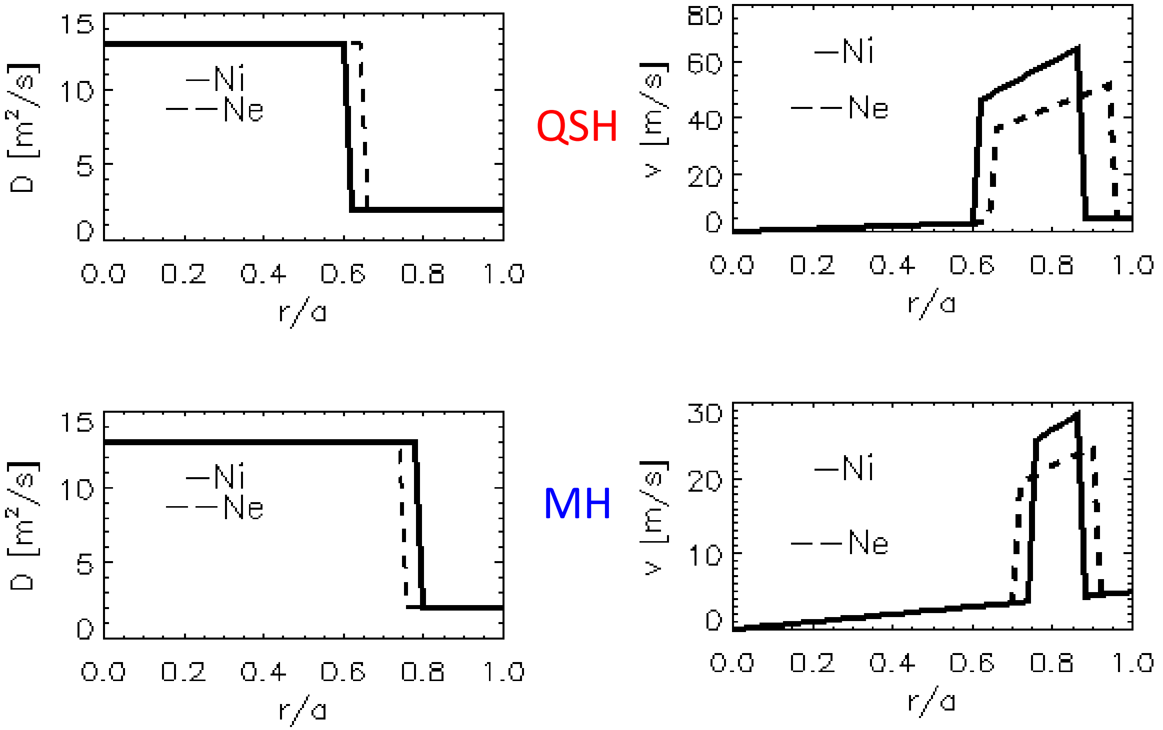
externally peaked *SXR profiles*



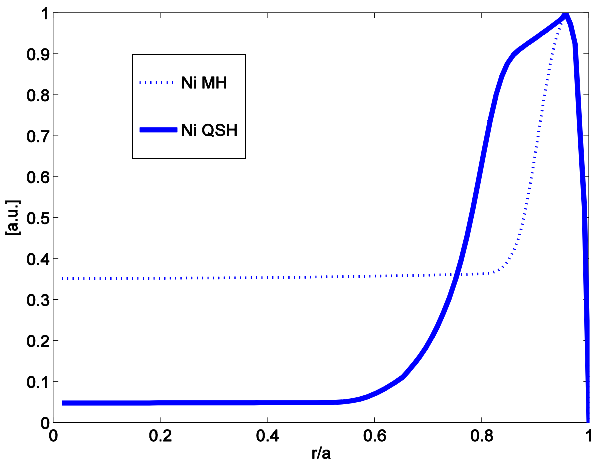
W LBO experiments in QSH scenario confirm core penetration prevention (W Transport code not available)

RFX-mod RFP: Impurities Do Not Penetrate the Plasma Core
Outward V for Ni and Ne in QSH and MH

External region with outward convective velocity in both QSH and MH regimes, wider in QSH .
Impurity core penetration results prevented both in MH and (even more efficiently) in QSH



Nearly identical V and D for Ne and Ni, as for intrinsic C and O, showing no mass or charge dependence



Outward convection found ➔ hollow impurity steady state profiles

S Menmuir et al 2010 PPCF,
T.Barbui et al 2015 PPCF

Impurity Ion Temperature and Flow in RFX-mod RFP (Visible-UV Doppler Spectroscopy)

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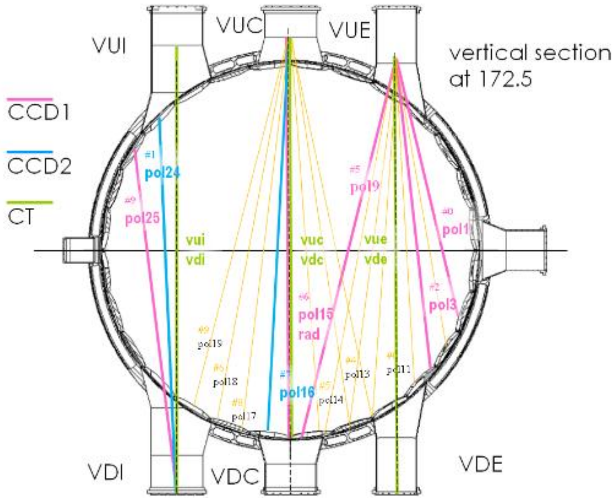
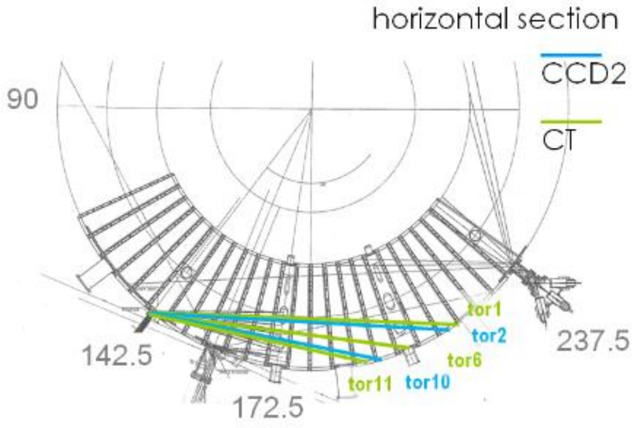
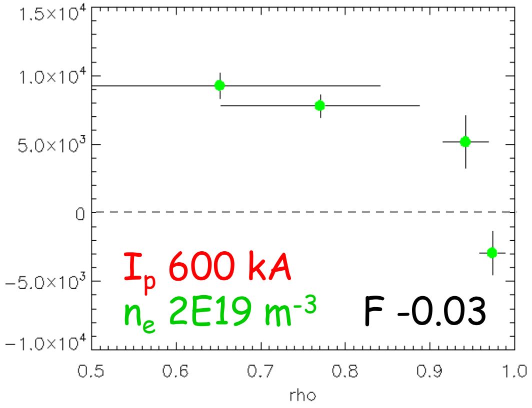




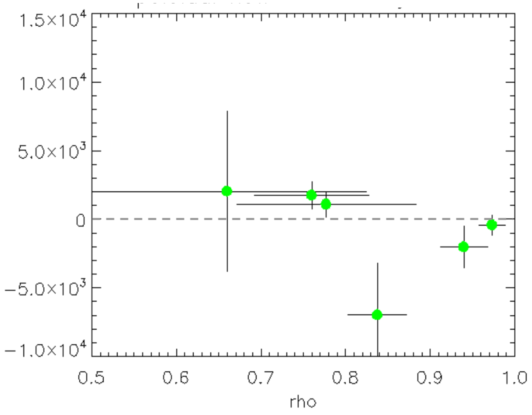
Diagnostics: 14 LOS
Measured parameters (LOS averaged)
- ion temperatures
- toroidal and poloidal ion flows

1-D transport simulations of the experimental brightness are used to 'localize' the ions.

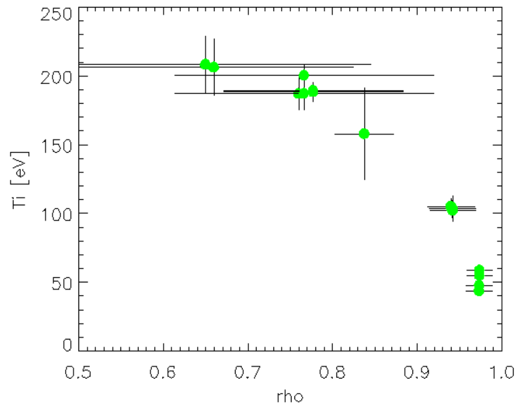
Toroidal flow



Poloidal flow



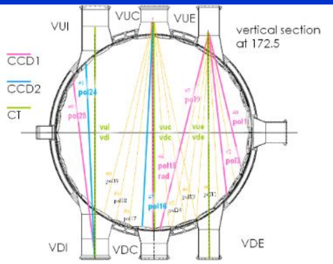
Ion temperature



From core to edge: BV 494.4 nm, CV 227 nm, C III 465 nm, OV 650 nm

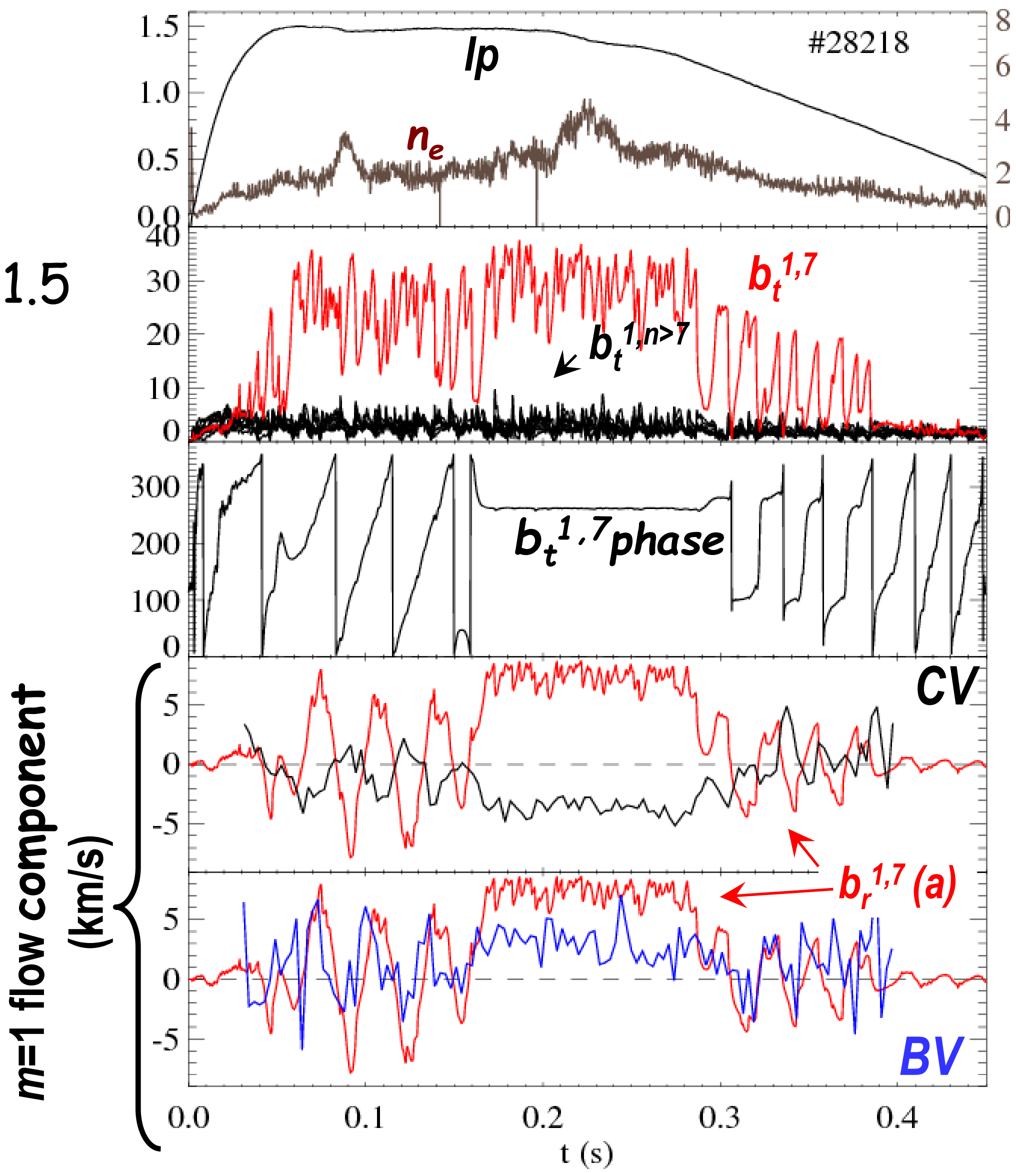
F.Bonomo et al Nucl. Fusion (2011)

RFX-mod High-Current RFP: Correlation Between Magnetic Helix and Flow



- Example of poloidal flow measurements for a 1.5 MA shot: extraction of an *m=1* structure associated with the *m=1,n=7* mode

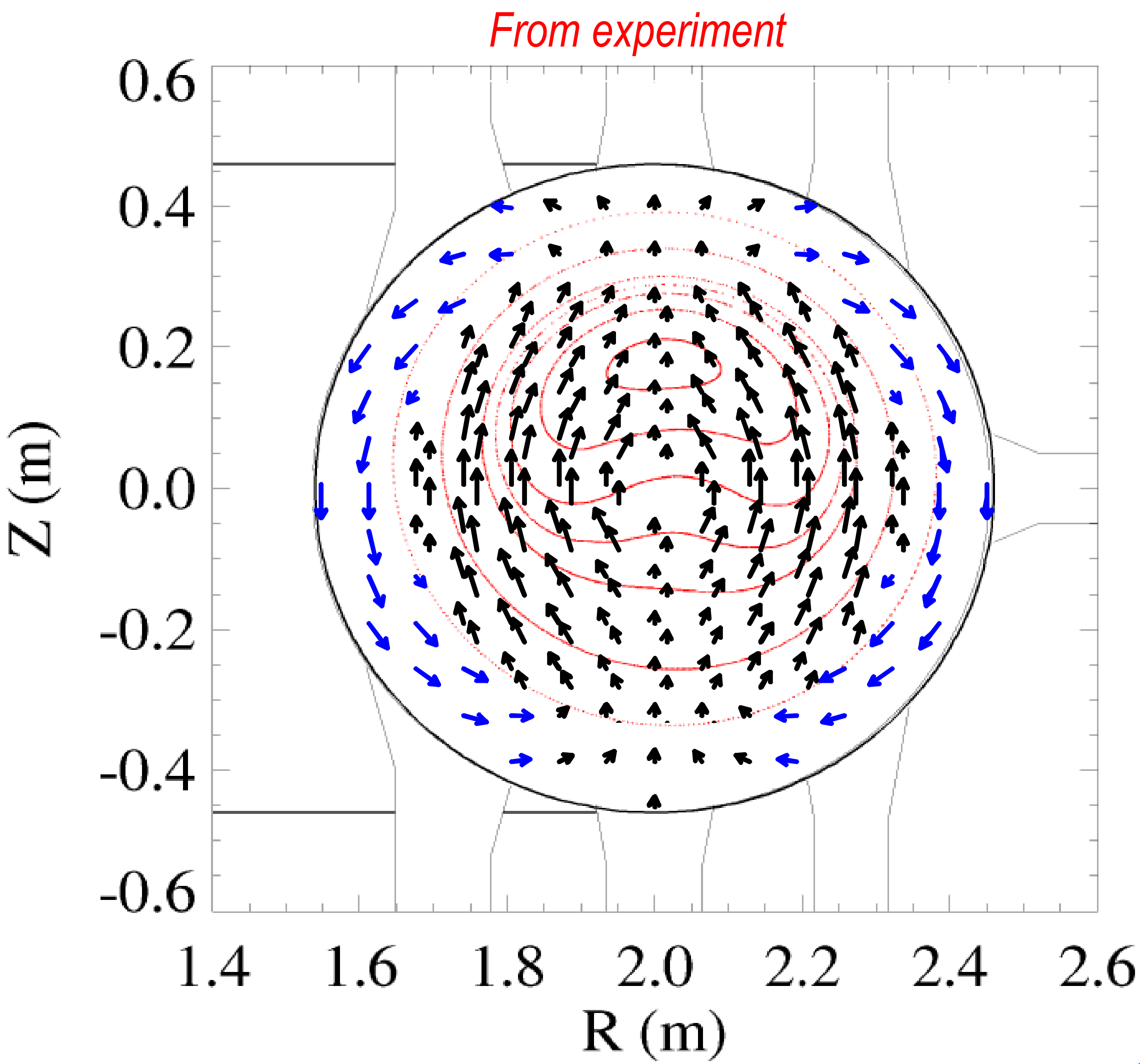
$b_r^{1/7}(a)$ and m=1 flow measurements are correlated



F.Bonomo et al. *Nucl. Fusion 51 (2011)*

RFX-mod High-Current RFP: m=1 Flow Pattern Reconstruction on a Poloidal Cross Section

Convective Cell experimentally observed



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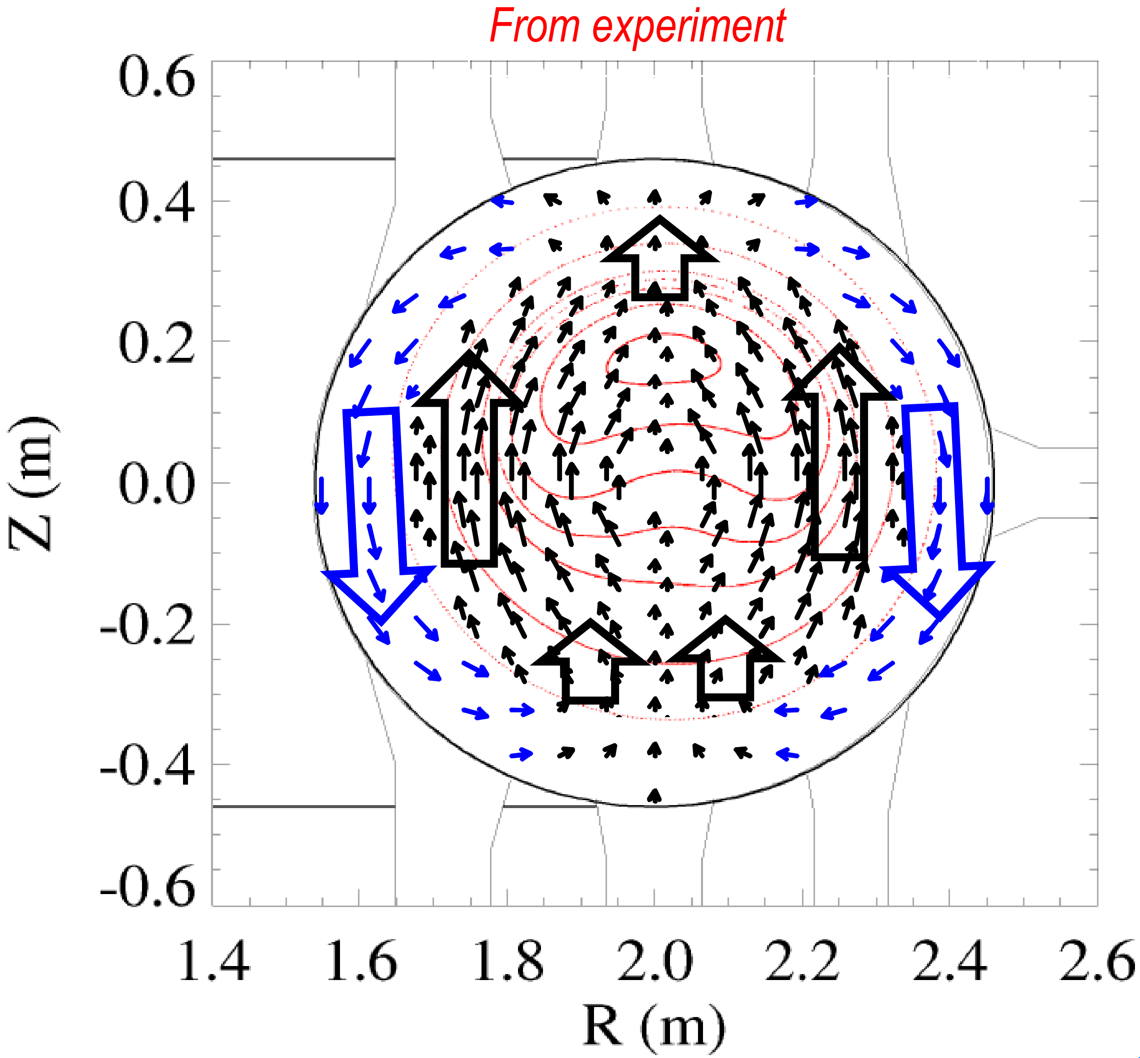

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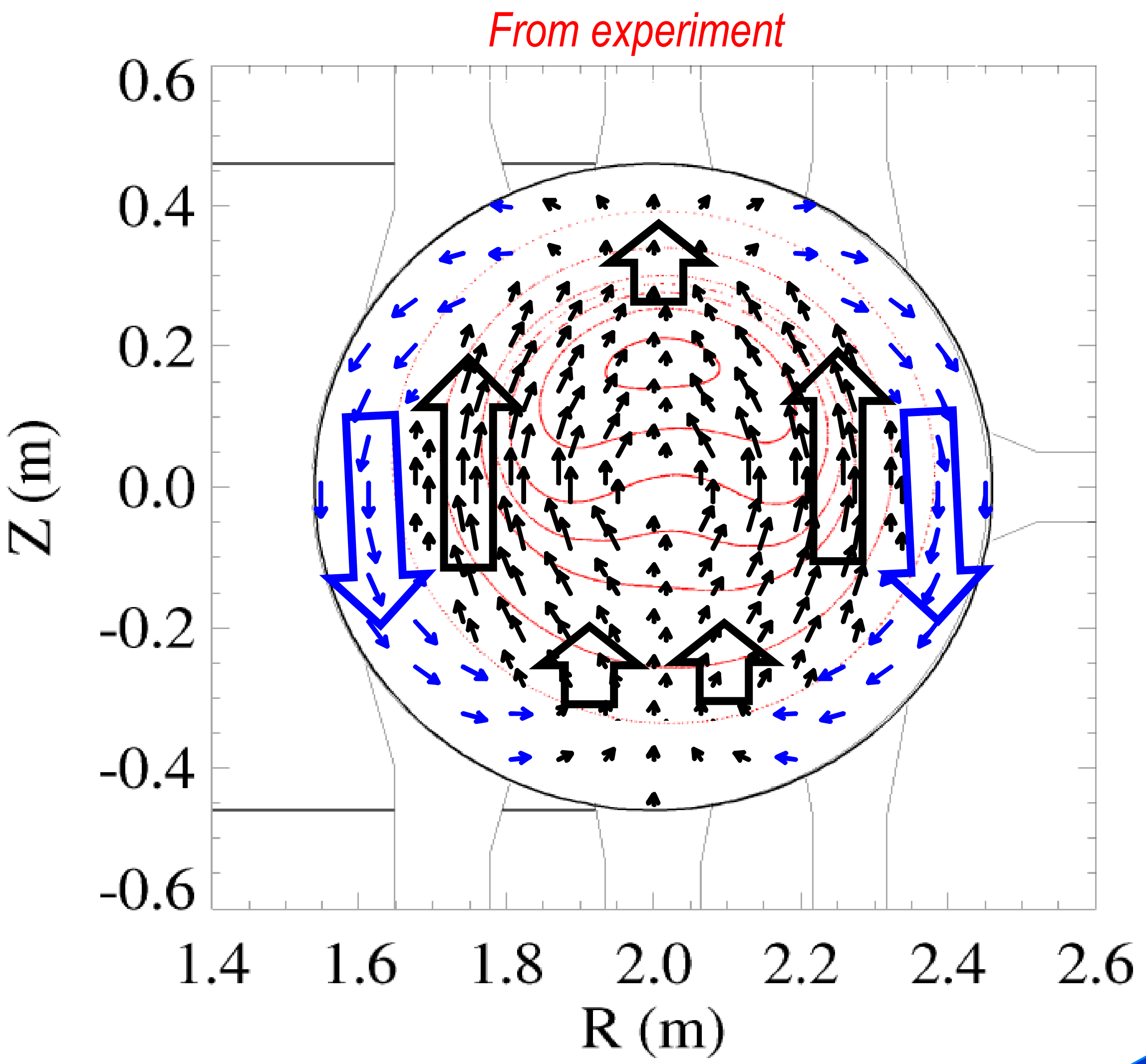
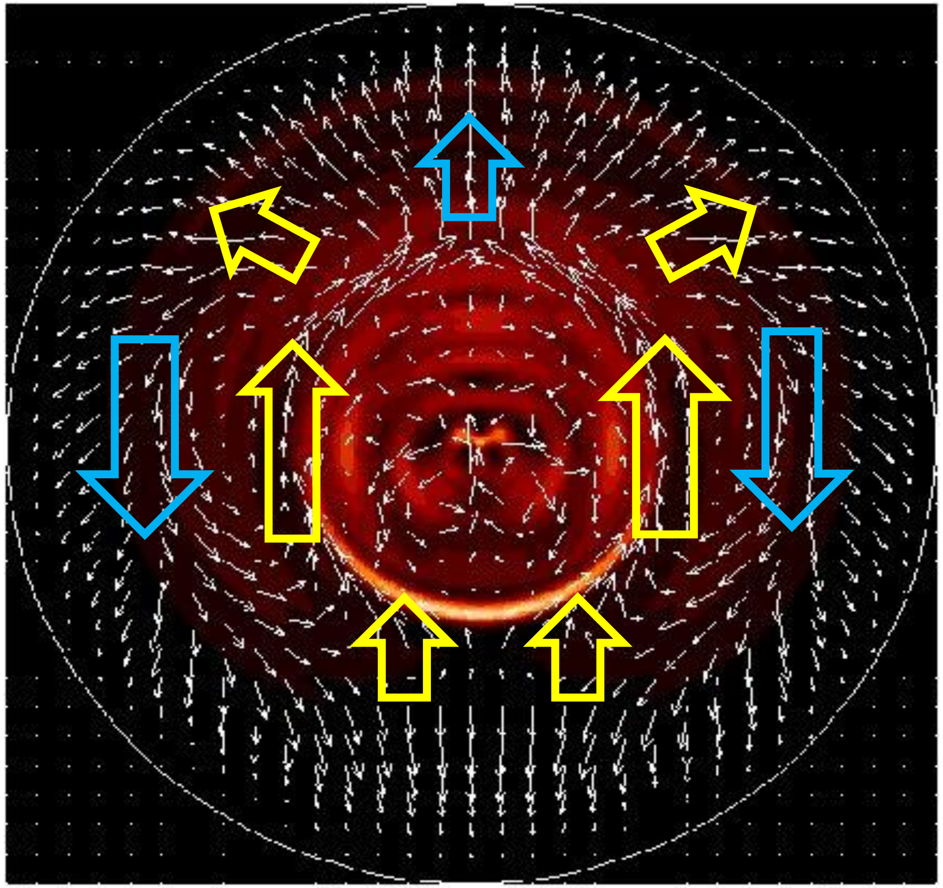
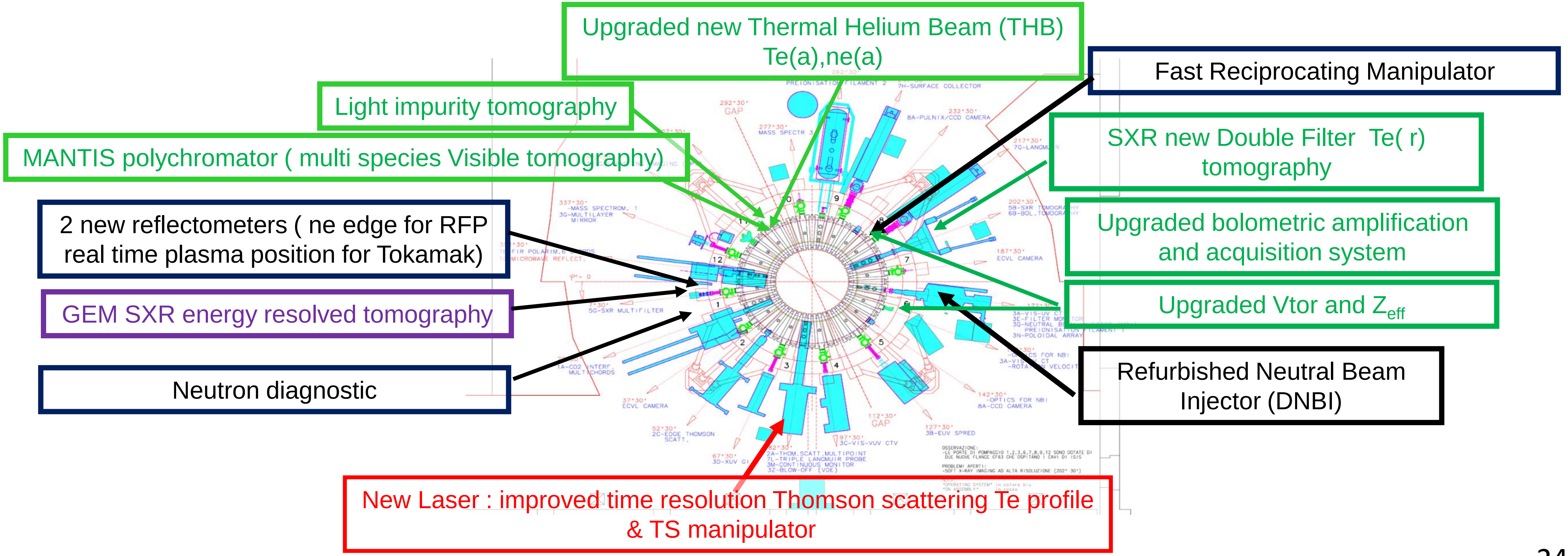


Flow pattern from Specyl simulation
QSH during RFP sawtoothing
poster Cappello et al P.27



PNRR NEFERTARI Program: The New RFX-mod2 Facility

PNRR NEFERTARI program—the new **RFX-mod2** facility : upgraded diagnostics and a reinforced real-time control system (four times more signals than RFX-mod).



Summary and Conclusions

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-In all RFX-mod RFP scenarios, emission measurements and 1D time-dependent transport show that impurities remain edge-localized due to outward convection, resulting in a hollow radial impurity density profile.

-The upgraded RFX-mod2 system—equipped with enhanced diagnostics and real-time control (PNRR NEFERTARI project) will significantly expand our capability to investigate plasma physics in both low-current tokamak and RFP regimes

- The RFX-mod team is involved in diagnostic projects for DTT (VIS and UV, Thomson scattering) and JT-60SA diagnostics (VUV divertor imaging, Thomson scattering, feasibility studies for pedestal VUV and THB diagnostics).

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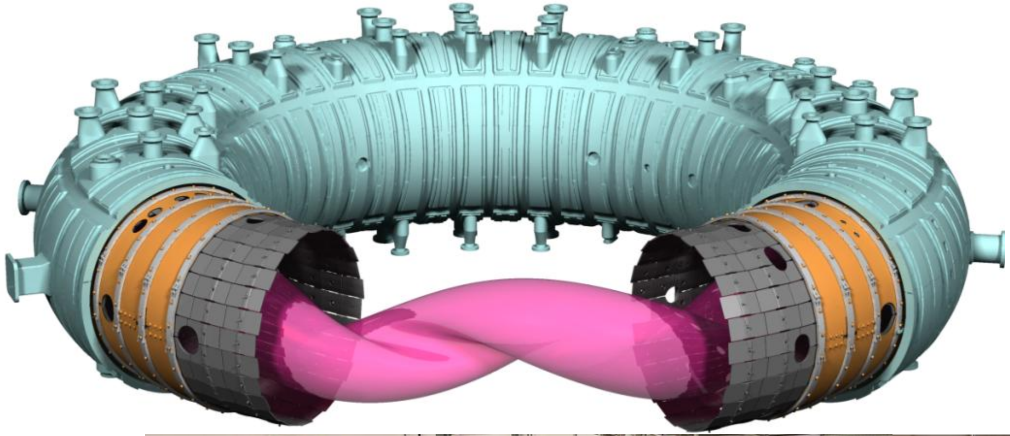

Thank You