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Ministero dell'Università e della Ricerca
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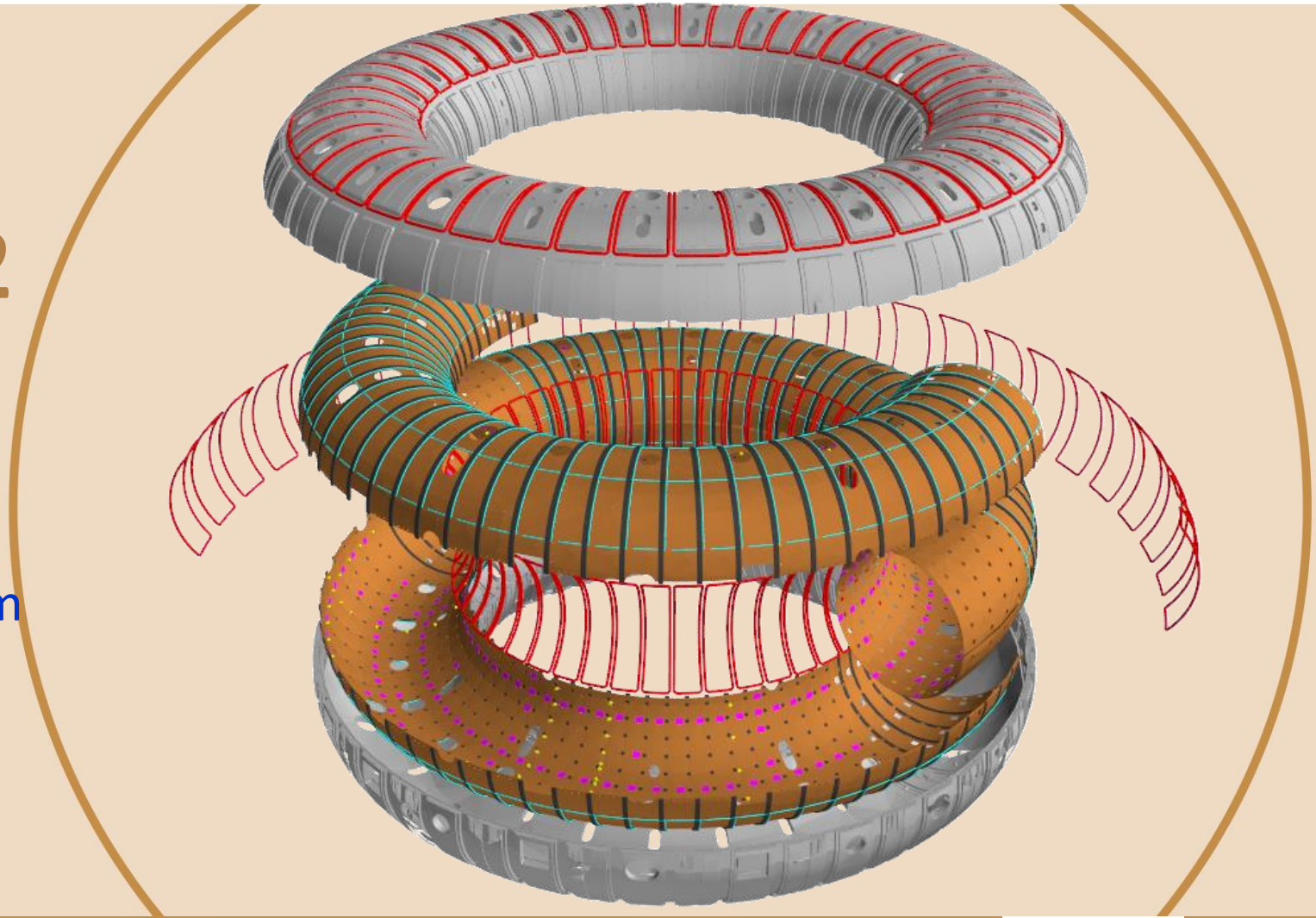
Consiglio Nazionale delle Ricerche
Università degli Studi di Padova
Università degli Studi di Napoli Federico II

The RFX-mod2 experiment



CUP: B53C22003070006

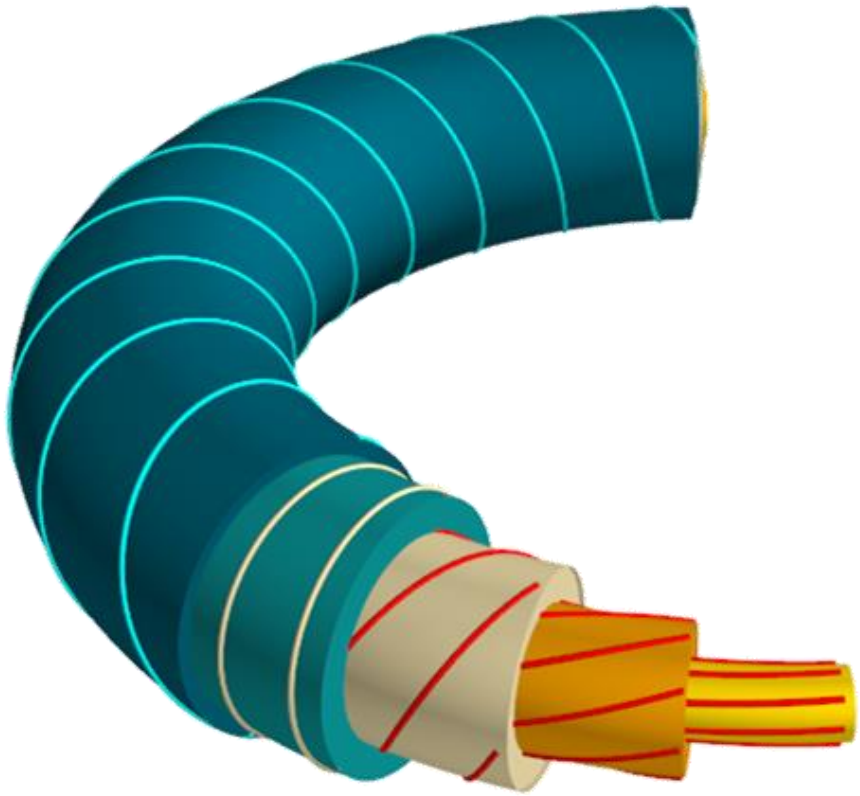
L. Marrelli and the RFX-mod2-team

NEFERTARI Final Workshop

Padova, 22-25/3/2026

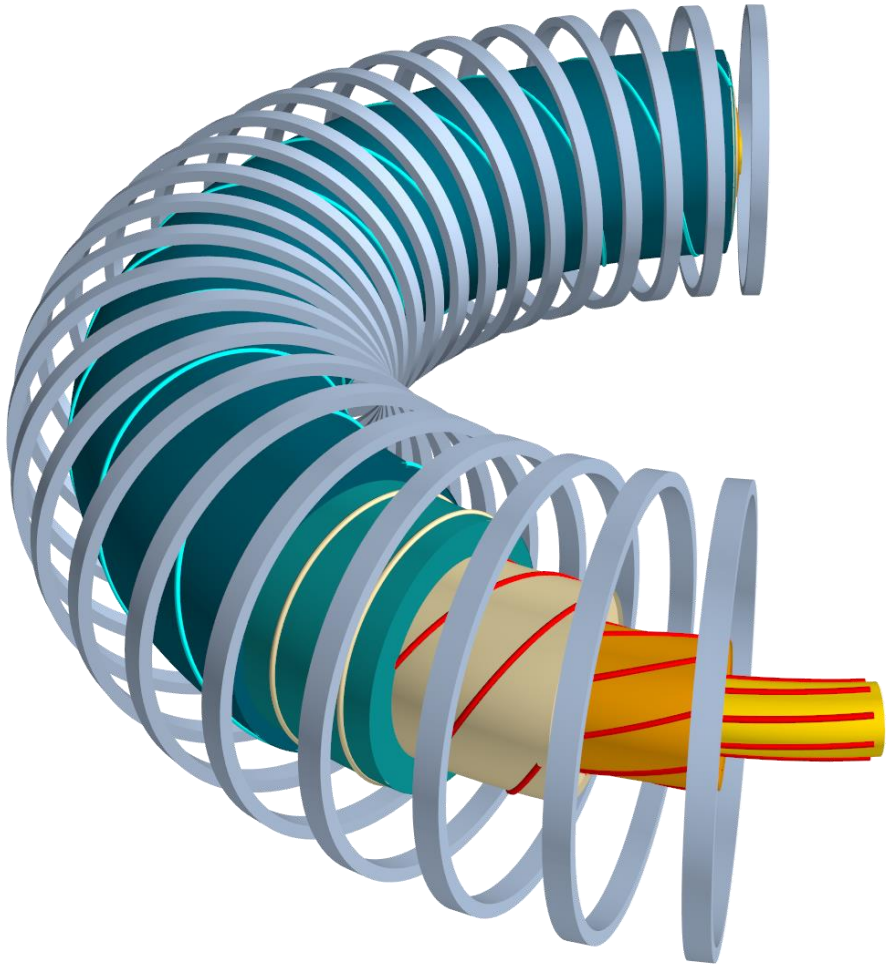
RFX-mod2 is a Reversed Field Pinch

- RFX-mod2 is the second modification of the Reversed Field eXperiment which is a Reversed Field Pinch (RFP) (R=2m,a=0.49)
  - **Paramagnetism:** Bulk B-field self-generated by plasma.
  - **Field Reversal:** Inverted edge pitch (Cyan vs. Red lines)



RFX-mod2: Toroidal field Coils

- RFX-mod2 is the second modification of the Reversed Field eXperiment which is a Reversed Field Pinch (RFP) (R=2m,a=0.49)
  - **Paramagnetism:** Bulk B-field self-generated by plasma.
  - **Field Reversal:** Inverted edge pitch (Cyan vs. Red lines)
  - **Toroidal Field Coils: Low Engineering Demand**
    - **Reduced External Field:** Plasma-generated bulk field.
    - **Moderate Mechanical Stress:** Low Lorentz forces on windings



RFX-mod2: Poloidal Field Coils

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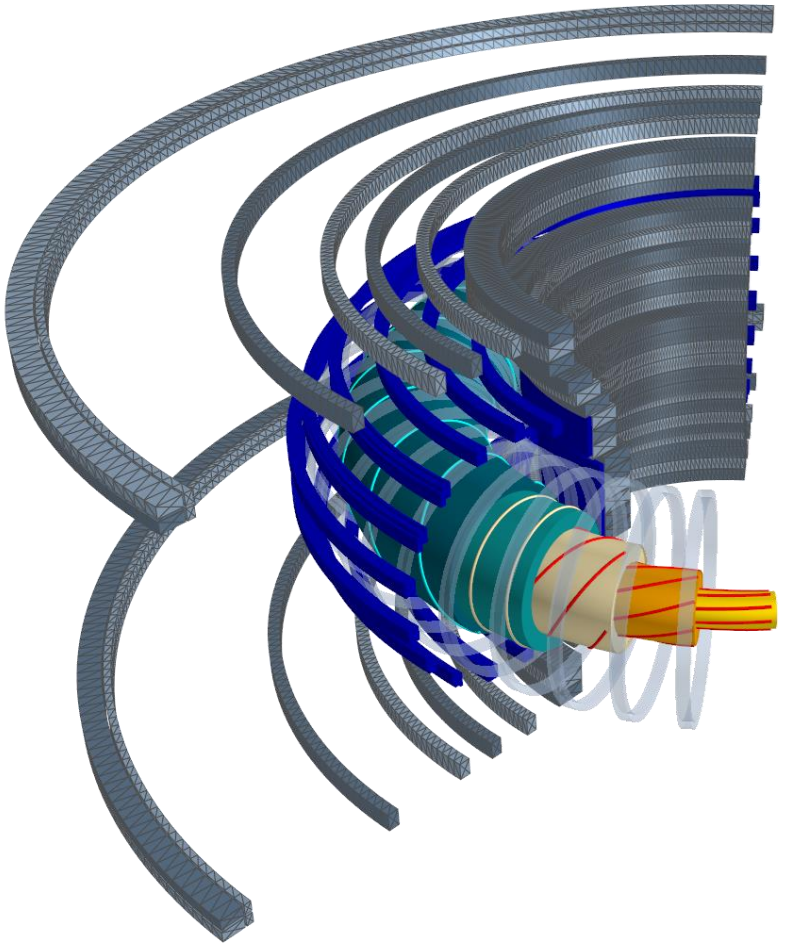
  - **Field Reversal:** Inverted edge pitch (Cyan vs. Red lines)
  - **Toroidal Field Coils: Low Engineering Demand**
    - **Reduced External Field:** Plasma-generated bulk field.
    - **Moderate Mechanical Stress:** Low Lorentz forces on windings
  - Poloidal field coils: Air core high flux swing (15 Vs)
    - **Pure Ohmic Heating:** No auxiliary heating required for RFP



RFX-mod2: Power supplies

- RFX-mod2 is the second modification of the Reversed Field eXperiment which is a Reversed Field Pinch (RFP) (R=2m,a=0.49)
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    - **Reduced External Field:** Plasma-generated bulk field.
    - **Moderate Mechanical Stress:** Low Lorentz forces on windings
  - Poloidal field coils: Air core high flux swing (15 Vs)
    - **Pure Ohmic Heating:** No auxiliary heating required for RFP
    - **Versatile MW-class power plant** featuring modular ac/dc units

RFX-mod2: high power test facility

- RFX-mod2 is the second modification of the Reversed Field eXperiment which is a Reversed Field Pinch (RFP) (R=2m,a=0.49)
  - **Paramagnetism:** Bulk B-field self-generated by plasma.
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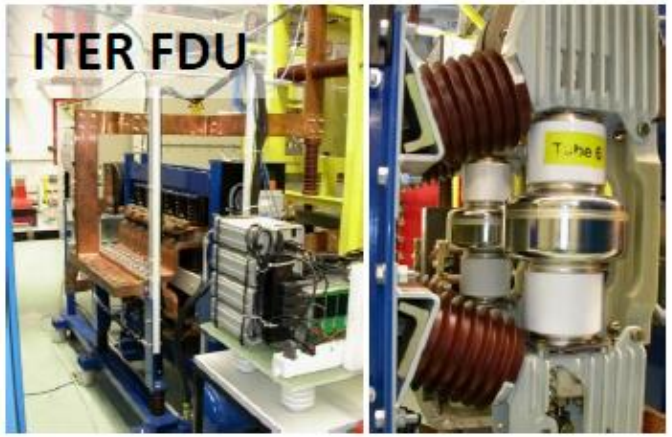
  - **Toroidal Field Coils: Low Engineering Demand**
    - **Reduced External Field:** Plasma-generated bulk field.
    - **Moderate Mechanical Stress:** Low Lorentz forces on windings
  - Poloidal field coils: Air core high flux swing (15 Vs)
    - **Pure Ohmic Heating:** No auxiliary heating required for RFP
    - **Versatile MW-class power plant** featuring modular ac/dc units
      - **Qualification tests for** ITER Fast Discharge Units FDU (70kA,24kV), JT-60SA Quench Protection Unit QPC (25 KA, 4kV) and **development** of next step reactors Magnetic Energy Storage and Transfer system (MEST)



RFX-mod2: active control

- RFX-mod2 is the second modification of the Reversed Field eXperiment which is a Reversed Field Pinch (RFP) (R=2m,a=0.49)
  - **Paramagnetism:** Bulk B-field self-generated by plasma.
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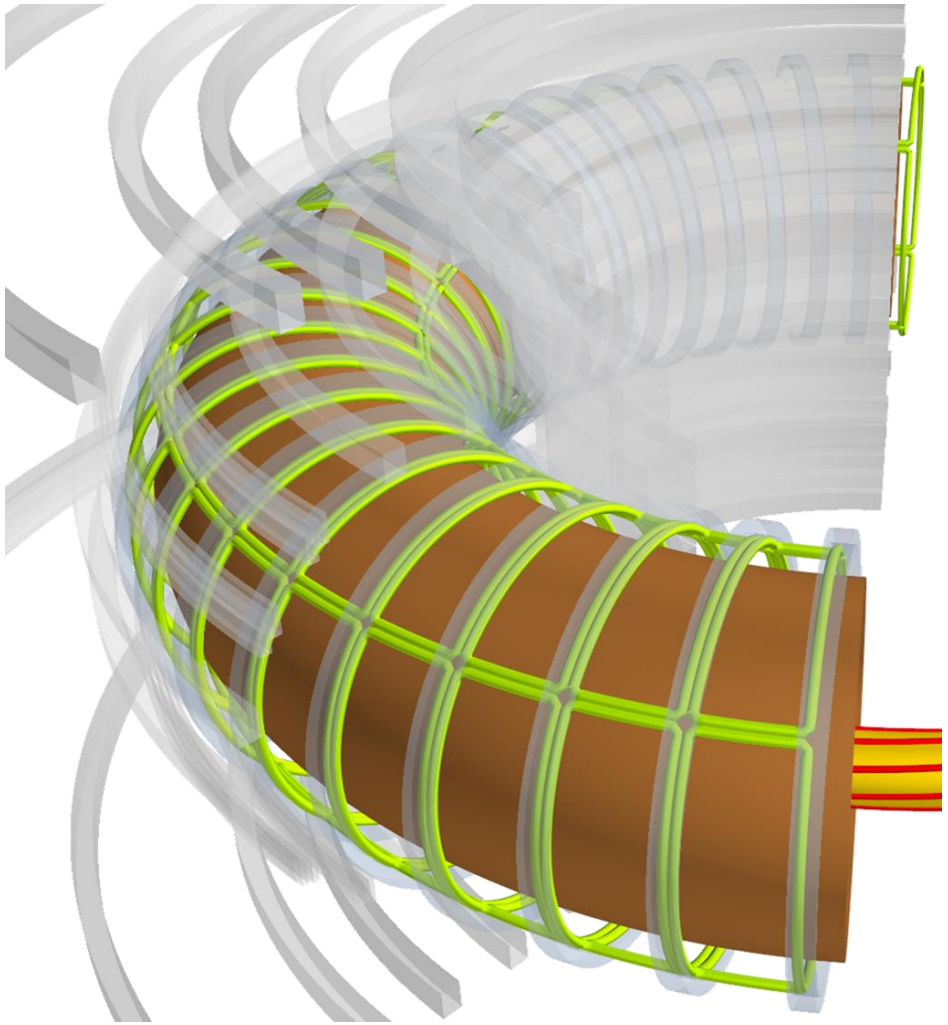
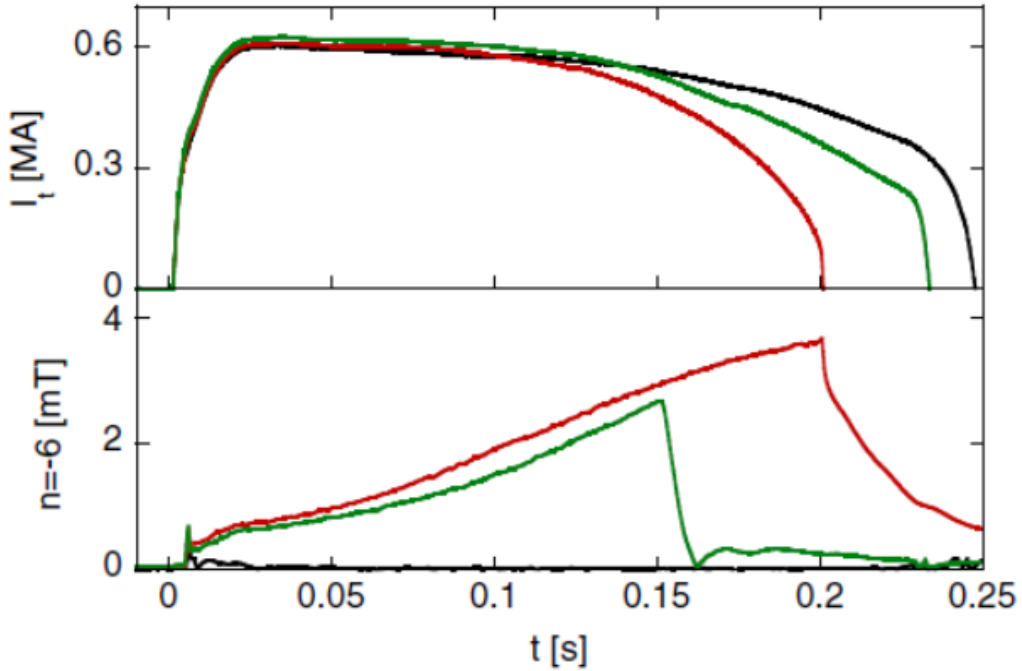
  - **Toroidal Field Coils: Low Engineering Demand**
    - **Reduced External Field:** Plasma-generated bulk field.
    - **Moderate Mechanical Stress:** Low Lorentz forces on windings
  - Poloidal field coils: Air core high flux swing (15 Vs)
    - **Pure Ohmic Heating:** No auxiliary heating required for RFP
    - **Versatile MW-class power plant** featuring modular ac/dc units
  - Active control of MHD instabilities; (*J.D. Lawson 1977 proposal*)
    - 3mm thick copper shell
    - 48x4 independent coils



J.D. Lawson, (1977) Reversed Field Pinch Reactor Studies. Part I., Physical Principles, CLM-R171
C.M. Bishop, (1989) Plas. Phys. Contr. Fus, 31, 1179

RFX-mod results: multiple Resistive Wall Modes stabilization

- RFX-mod proved that multiple RWMs can be simultaneously suppressed [1,2]

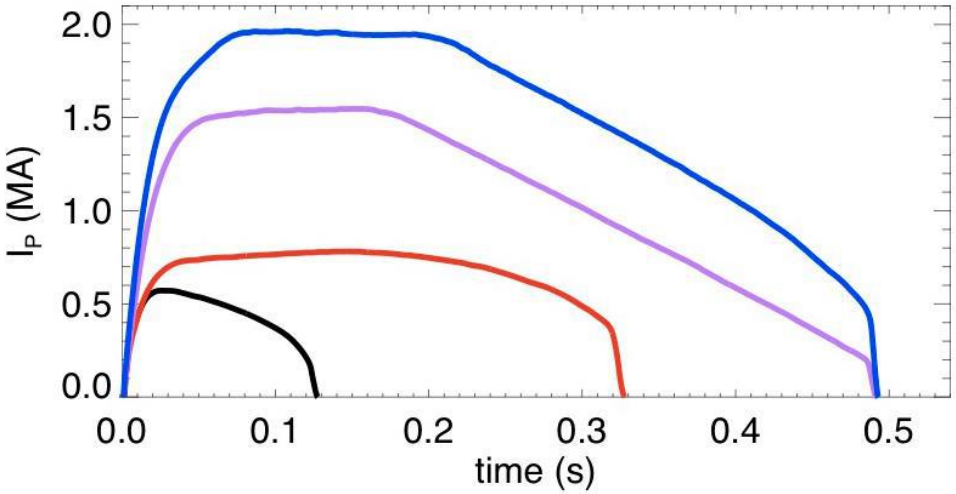


Without Control
Controlled after 150ms
Fully controlled

[1] S.Ortolani, Active MHD control experiments in RFX-mod. Plas Phys Contr Fus. 2006;48(12B):B371
[2] Bolzonella T, et al. Resistive-Wall-Mode Active Rotation in the RFX-Mod Device. Phys Rev Lett 2008; 101: 165003

RFX-mod-results: highest plasma current for an RFP

- Reversed-Field pinch 2 MA plasma current target level was achieved in RFX-mod thanks to
  - Advanced mode control strategies [2]
  - Power supplies configuration flexibility [1] (15.8 Vs flux swing)



Power supply reconfiguration [1]

Advanced ModeControl [2]

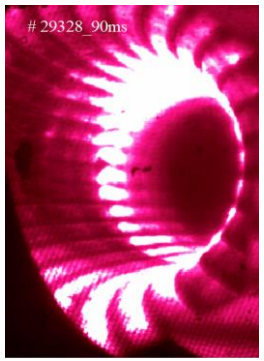
Simple Virtual Shell [3]

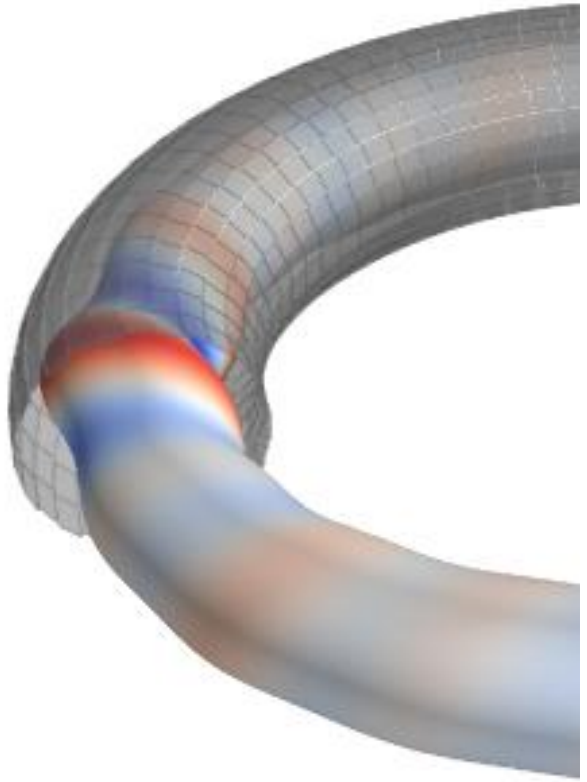
No MHD control

[1] Novello, et al (2011). "Enhancement of the power supply systems in RFX-mod towards 2 MA plasma current". ''Fusion Engineering and Design'' 86: 1393-1397,
[2] Zanca, Marrelli, Manduchi, Marchiori (2007). "Beyond the intelligent shell concept: the clean-mode-control". ''Nuclear Fusion'' 47: 1425-1436.
[3] Ortolani and RFX-mod team, (2006) Plasma Physics and Controlled Fusion 48, B371

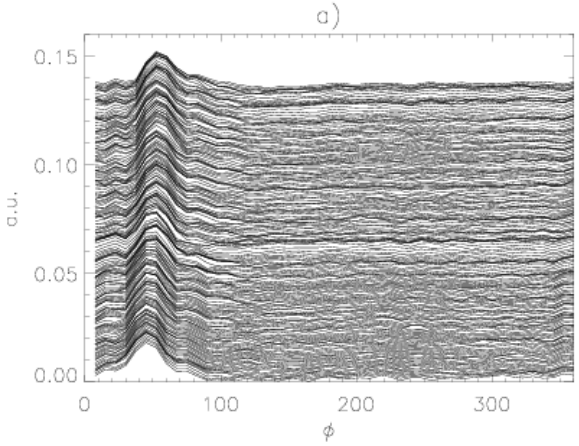
RFX-mod results: From Multiple Helicity

- At low plasma currents many tearing modes are present, spooling performances and generating localized bulging of the plasma column.



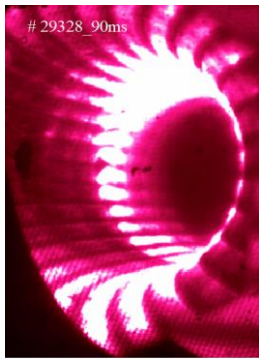


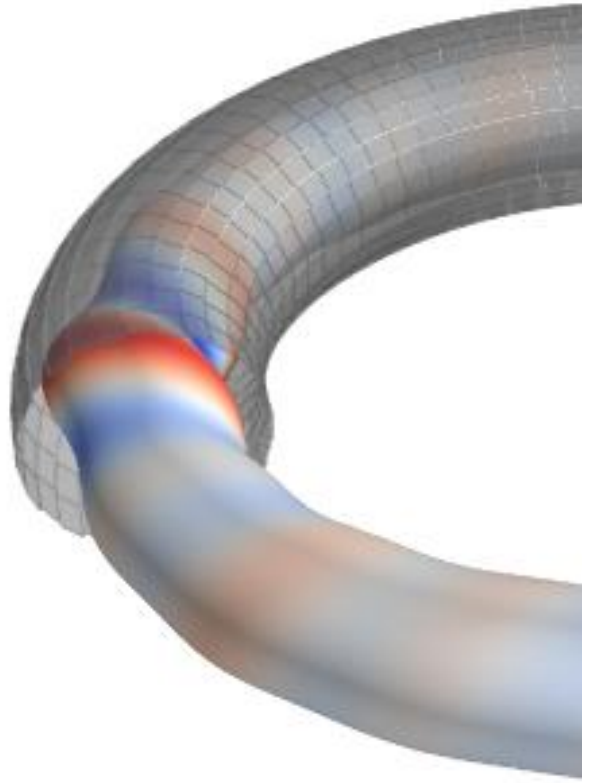
RFX (and RFX-mod with non optimal control)



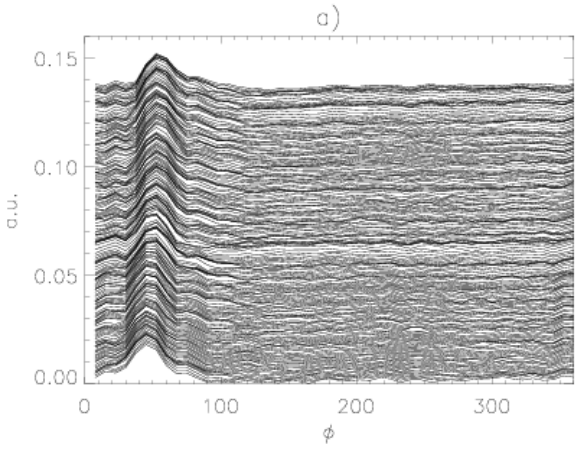
RFX-mod results: From Multiple Helicity

- At low plasma currents many tearing modes are present, spooling performances and generating localized bulging of the plasma column.
  - RFX-mod was able to partially mitigate wall locking by slowly rotating the bulging

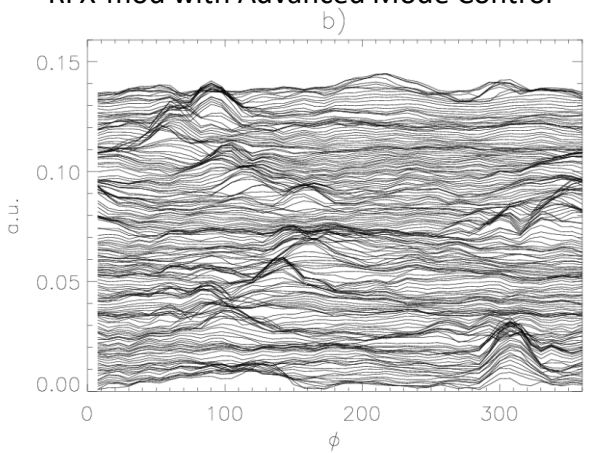




RFX (and RFX-mod with non optimal control)

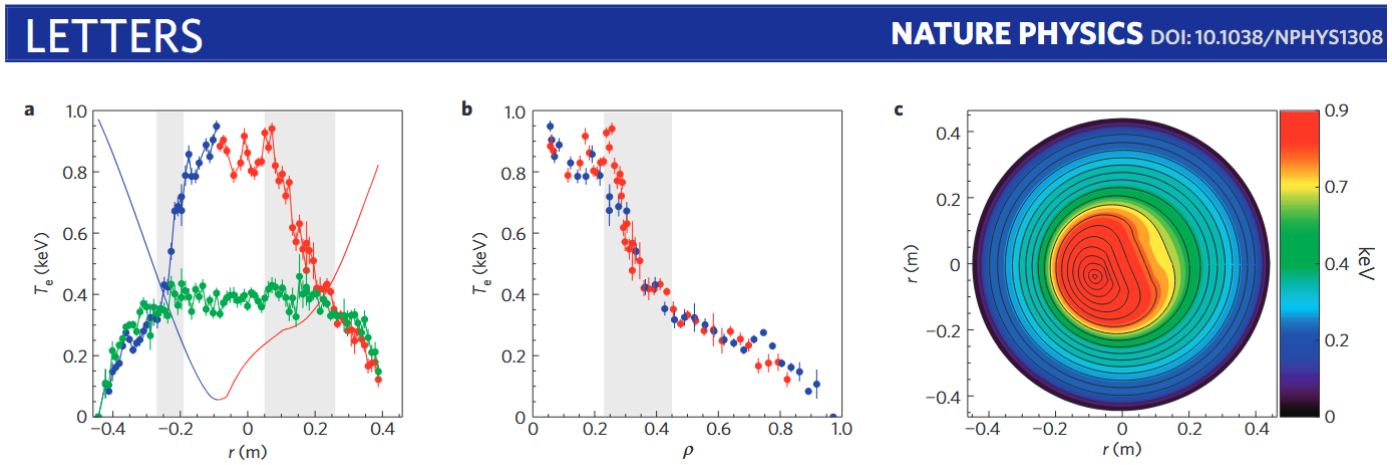


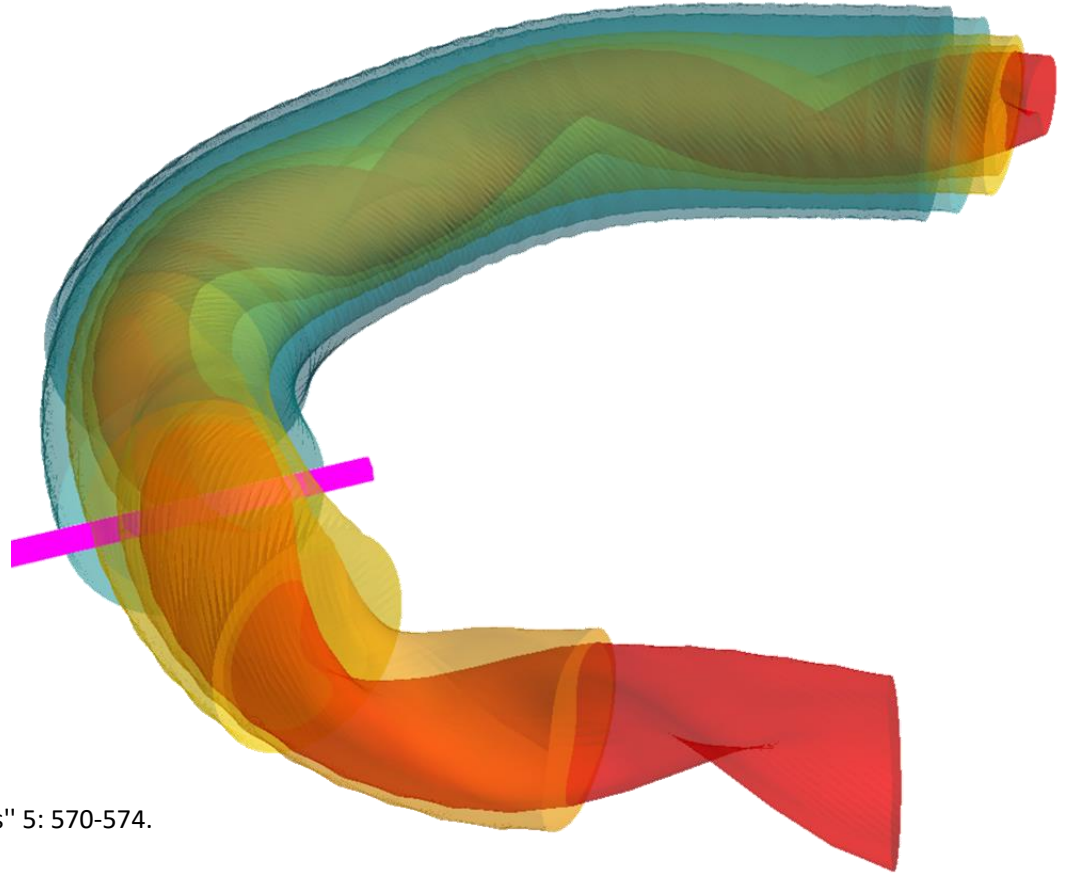
RFX-mod with Advanced Mode Control



RFX-mod results: From Multiple Helicity to Quasi single Helicity

- At high plasma currents (Ip > 1MA) one tearing mode dominates and the core plasma becomes helical with internal transport barriers

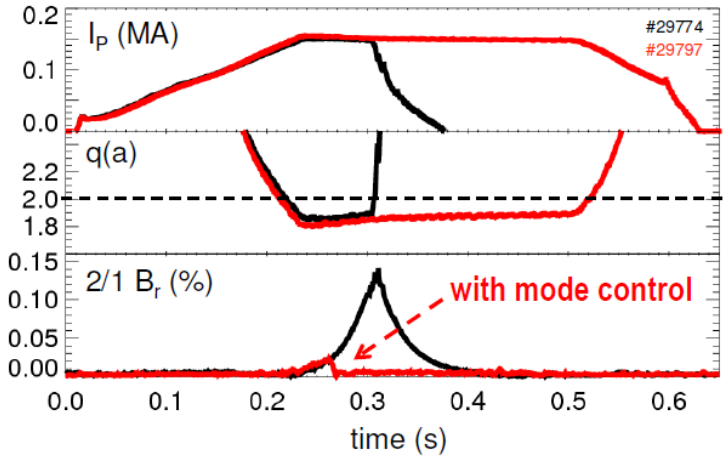


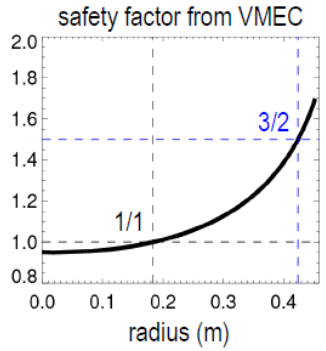


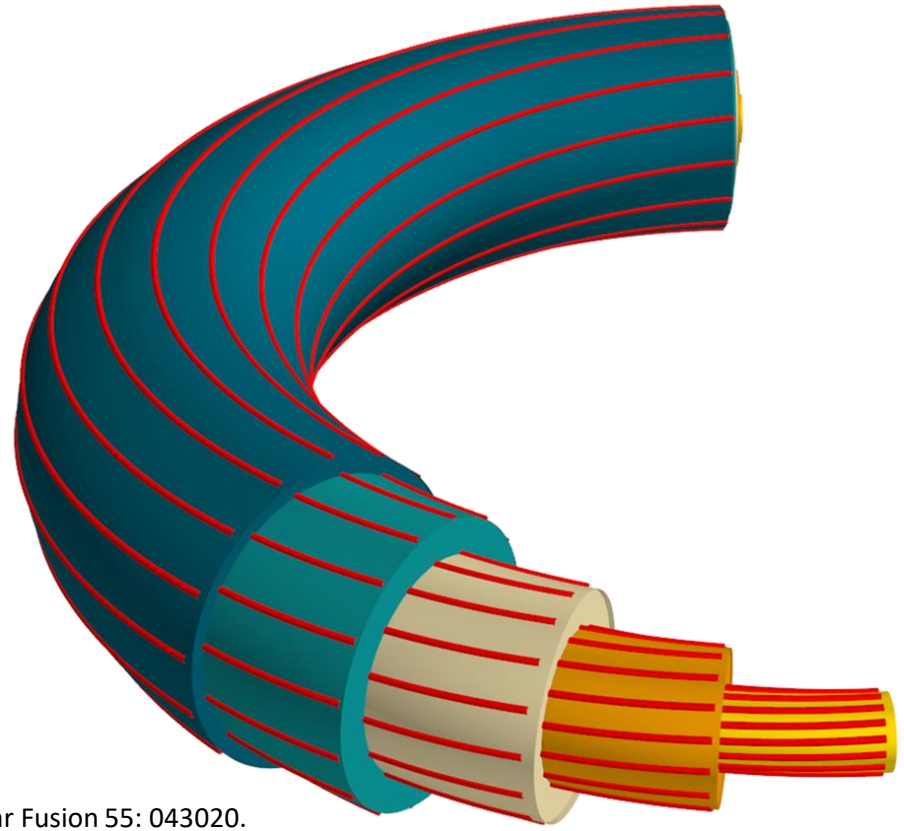
Lorenzini, (2009). "Self-organized helical equilibria as a new paradigm for ohmically heated fusion plasmas". ''Nature Physics'' 5: 570-574.

RFX-mod as a ohmic tokamak, Very Low q and Ultra Low q

- Thanks to TF coils design (0.5T for 1 s) and active feedback
  - RFX-mod also operated below the q(a)<2 limit [1]
  - Performed disruption prevention studies [2]
  - Performed runaway mitigation with RMP [3]



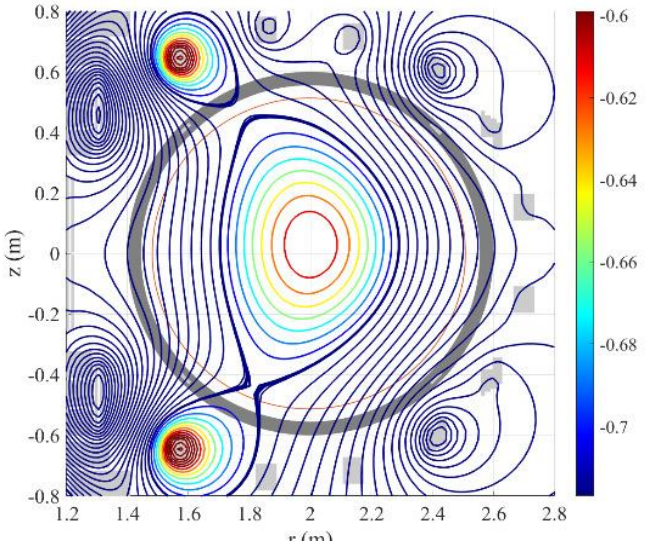


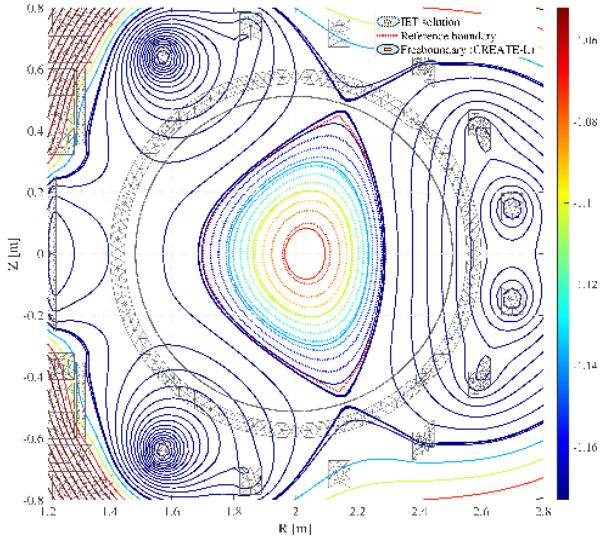


[1] Zanca P, et al.. Plasma Phys Control Fusion. 2012 Sep 1;54(9):094004
[2] Zanca P., et al. (2015). "An active feedback recovery technique from disruption events induced by m = 2, n = 1…, Nuclear Fusion 55: 043020.
[3] Gobbin, et al (2024). "Runaway electron mitigation by 3D fields application in ASDEX upgrade, COMPASS, and RFX-mod". ''Frontiers in Physics'' 12

RFX-mod: shaped tokamak

- Reconfigurable connections to field shaping coils allow shaping
  - Positive and Negative Triangularity
  - Single (upper and lower) Null, Double Null, Snow Flake

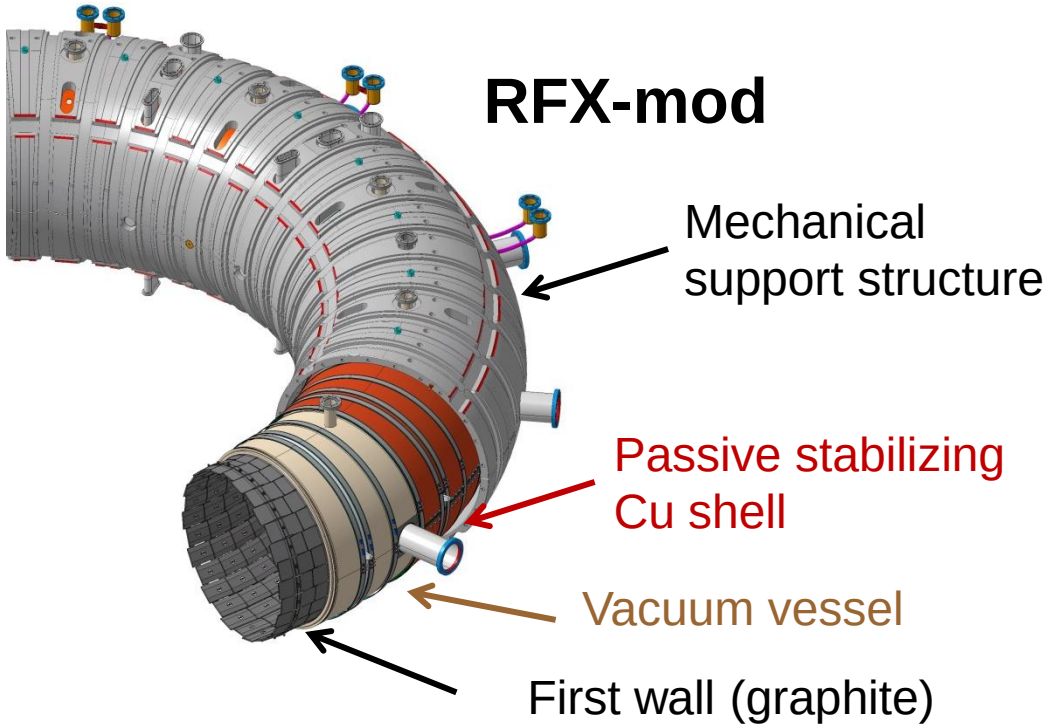




D. Abate, Plasma Phys. Control. Fusion 62, 085001 (2020)

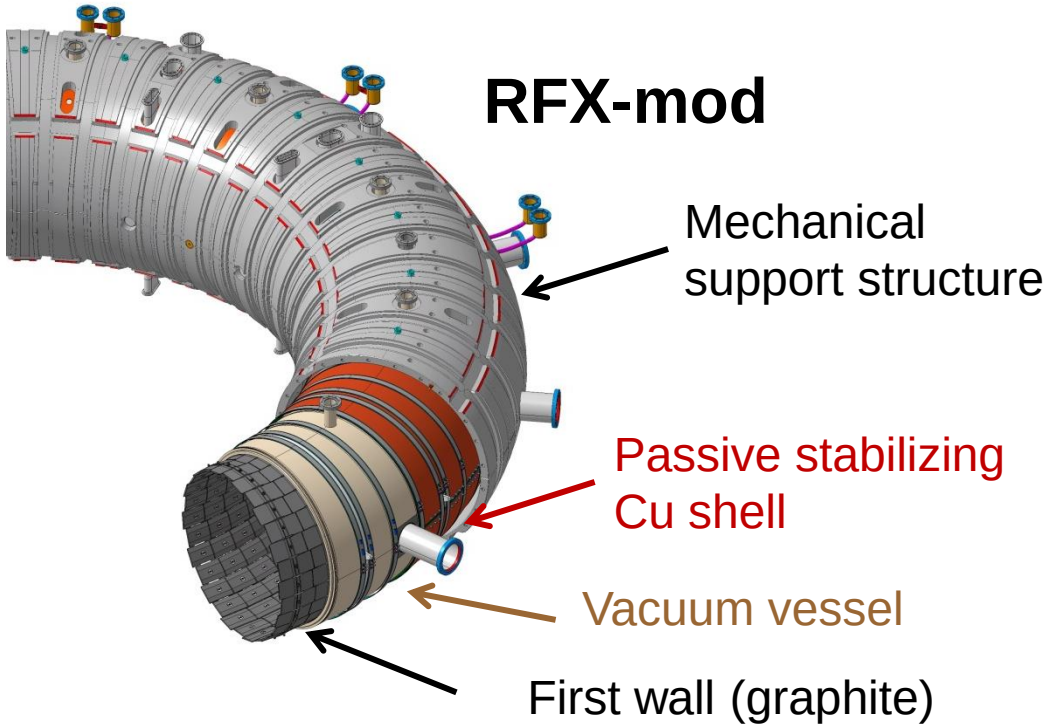
From RFX-mod

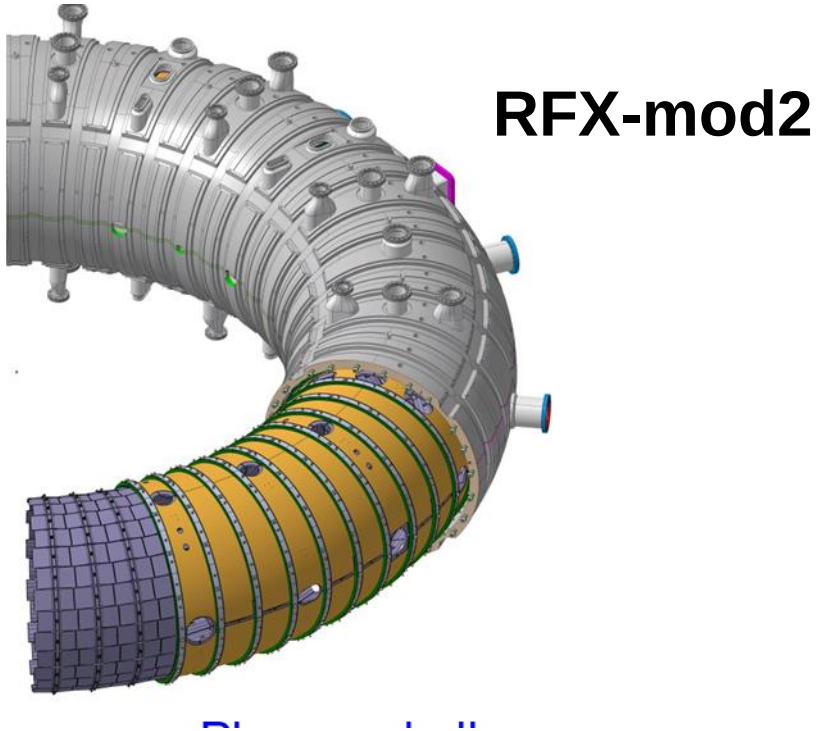
- RFX-mod performances were limited by the highly resistive Inconel Vacuum Vessel, causing wall locking of multiple Tearing Modes and subsequent localized Plasma Wall Interaction



From RFX-mod to RFX-mod2

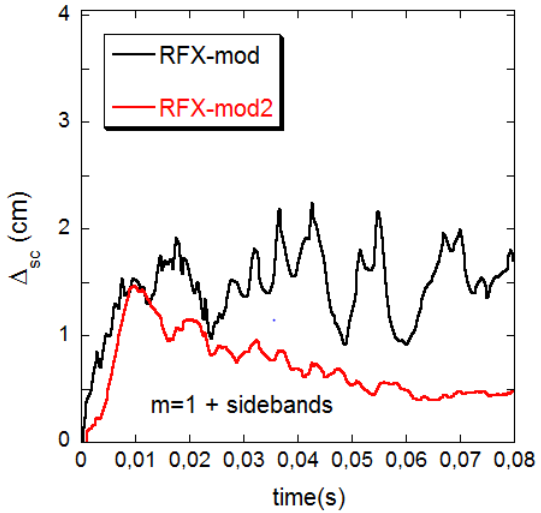
- RFX-mod performances were limited by the highly resistive Inconel Vacuum Vessel, causing wall locking of multiple Tearing Modes and subsequent localized Plasma Wall Interaction
- Thanks to POR FESR regional funding «MIAIVO», RFX-mod have been modified to remove the Inconel Vessel





RFX-mod2 expectations

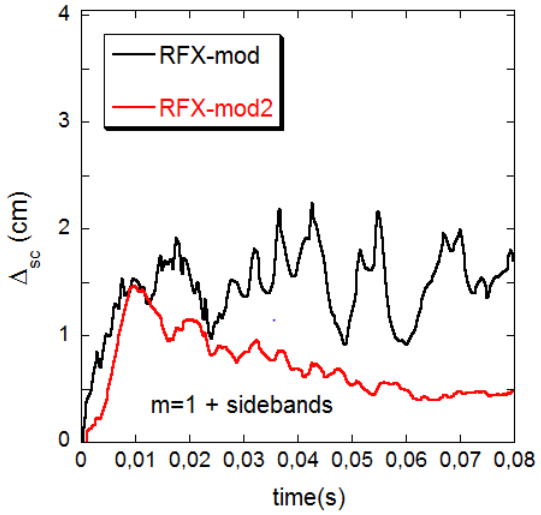
- With the new boundary the localized edge deformation decreases by a factor 3



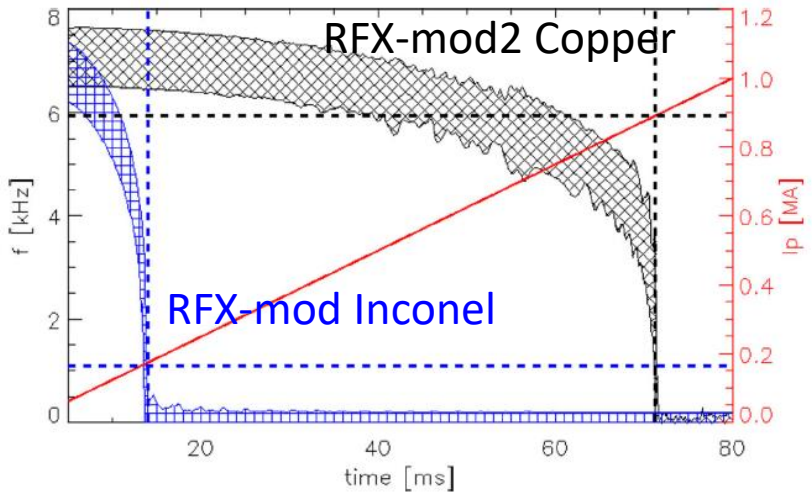
Zuin, et al (2017). Nuclear Fusion 57: 102012.

RFX-mod2 expectations

- With the new boundary the edge deformation decreases by a factor 3
- Wall locking is simulated to occur at 500-800 kA (instead of 100-150kA)



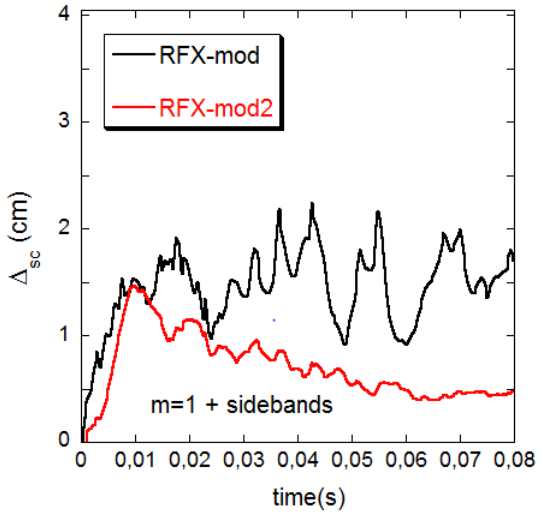
Zuin, et al (2017). Nuclear Fusion 57: 102012.

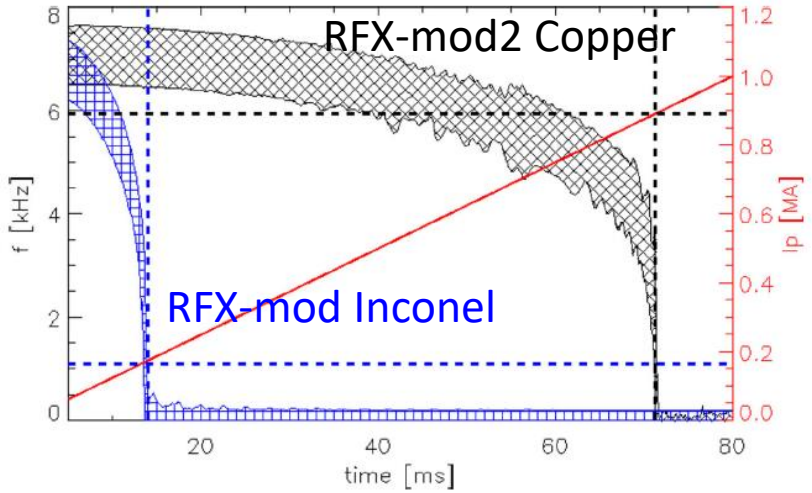


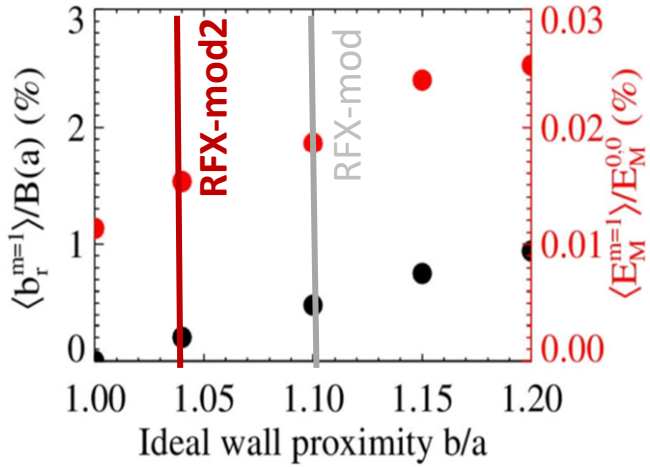
Marrelli L, et al.,. Nuclear Fusion. 2019 Jul 1;59(7):076027

RFX-mod2 expectations

- With the new boundary the edge deformation decreases by a factor 3
- Wall locking is simulated to occur at 500-800 kA (instead of 100-150kA)
- 25% reduction of tearing mode energy





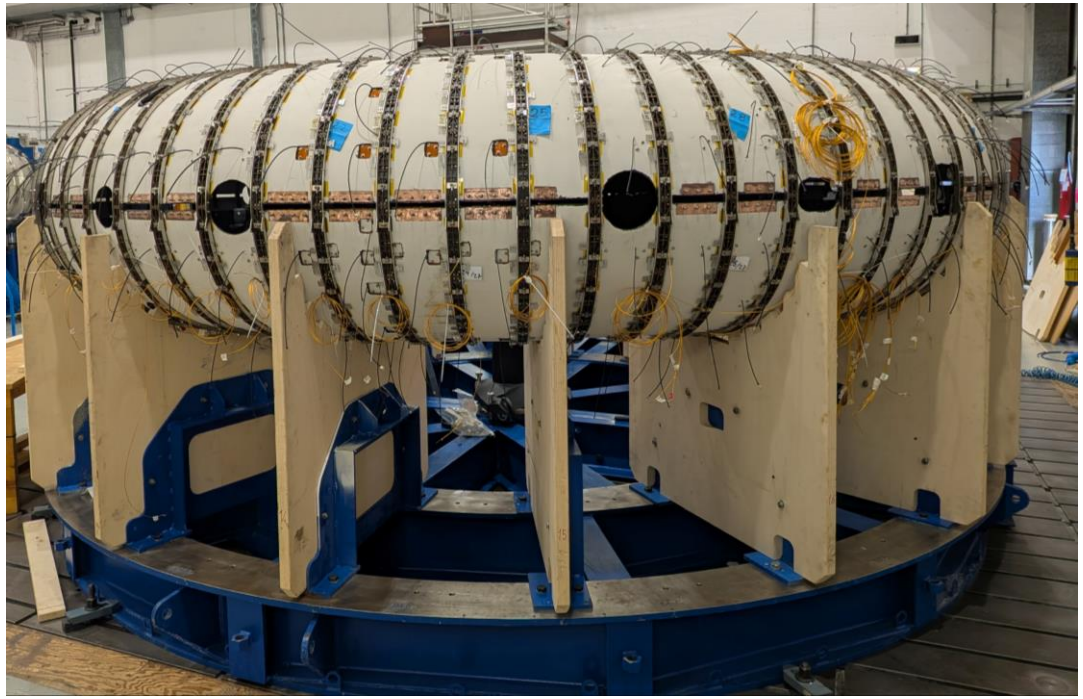


Zuin, et al (2017). Nuclear Fusion 57: 102012.

Marrelli L, et al.,. Nuclear Fusion. 2019 Jul 1;59(7):076027

RFX-mod2: status of vessel complex reassembly

- RFX-mod2 Vessel Complex components in the assembly hall



The NEFERTARI opportunity: plants revamping and key diagnostics

- Revamped key auxiliary plants
  - Vacuum system (WP1)
  - Toroidal field power Supplies (WP1)
  - Wall conditioning systems: Glow Discharge (WP1) Cleaning and Pulse Discharge Cleaning (WP1)
  - Remote Manipulation (WP1)
  - Electromagnetic measurements and model based control (WP2)
- Revamped and enhanced existing diagnostics; allows applications of codes for experiment interpretations
  - Edge diagnostics (WP3)
  - Core diagnostics (WP4 & WP5)

- Foster the integration of expertise and pave the way for future common research
  - High Voltage Insulation (WP6)
  - Plasma Wall Interaction (WP7)
  - Neutron and SXR imaging diagnostics (WP8)
  - Spectroscopic diagnostics & advanced modelling (WP9)

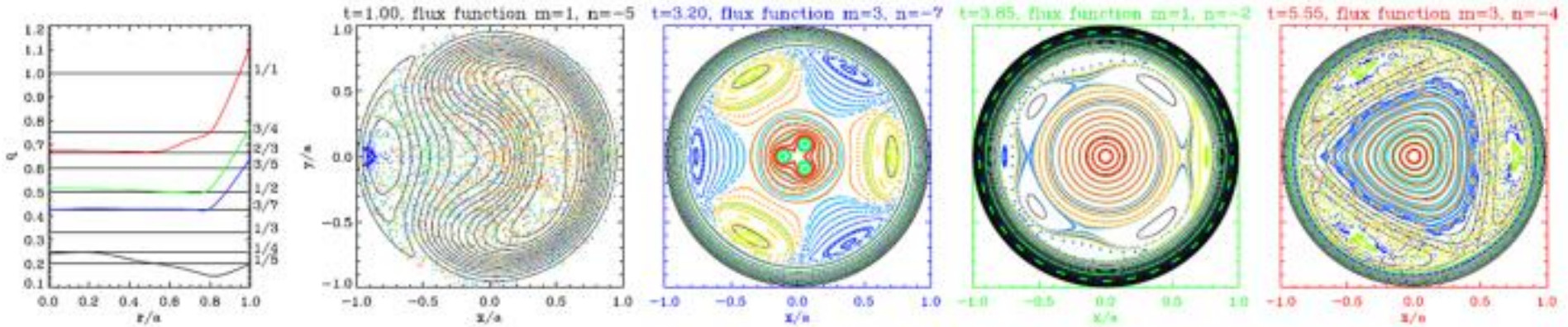
RFX-mod2 research themes

- Complete exploration of 2MA Reversed Field Pinch Exploit real-time control capabilities both for RFP and tokamak
  - Model based (machine learning) control algorithms
    - FEM, BEM of passive structures and plasma response
  - Non magnetic real-time plasma position control with reflectometry
- Explore 3D physics in high current Reversed Field Pinch plasmas
  - Plasma Wall Interaction
  - MHD dynamics with controlled 3D boundary
- Explore 3D effects in ohmic tokamak
  - Error fields
  - Experimental characterization of disruptions
    - electromagnetic induced forces direct measurements
- Fundamental Plasma physics studies in multiple configurations
  - Edge turbulence and microinstabilities
  - Magnetic reconnection and particles accelerations
  - Transport barriers characterization

- Spare Slides

Extreme configurations at low q

- **Tokamak operation with $q_{edge} < 2$** (circular and shaped) accessible thanks to advanced real-time magnetic control and adjustable plasma-stabilizing shell proximity
- **Ultra-low q regime (q < 1)**
  - Validation of modelling extrapolation of **stress forces** due to kink instability
  - Validation of MHD and gyrokinetic modelling
  - Anomalous ion heating (Ti > Te)
  - Influence of magnetic topology on energy confinement
- Fundamental mechanisms behind **density limit physics in multiconfiguration regimes**

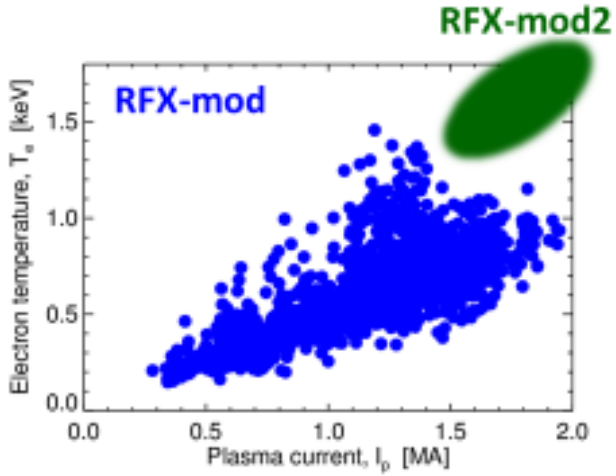


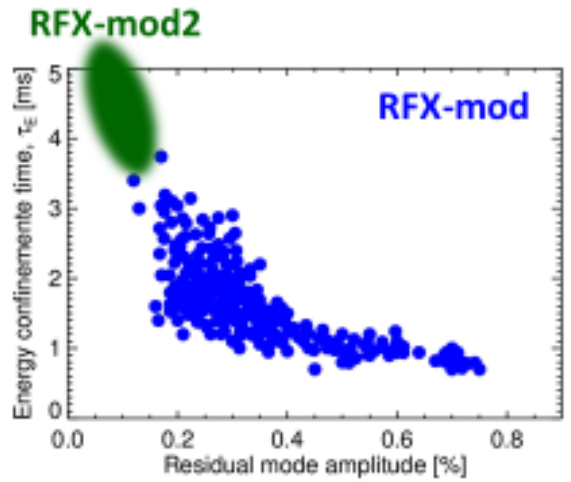
Magnetic topology at various q

M. Zuin, Nucl. Fusion 62, 066029 (2022)

RFX-mod2 the only device exploring the 2 MA Reversed-Field Pinch

- RFX-mod2 will assess the Reversed-Field Pinch as an **alternative magnetic configuration** for fusion plasma confinement featuring **low cost** and **construction simplicity,** thanks to the confining magnetic field mainly produced by the plasma current. The required external applied toroidal field is very low
  - RFP's are exploited in medium size experiments also in Stockholm (Sweden), Hefei (China) and Kyoto (Japan).
- RFX-mod2 will exploit a **new optimized magnetic front-end** with reduced passive stabilizing shell-to-plasma distance, aimed to minimize residual edge magnetic perturbations and to expand and improve the **positive confinement properties scaling with plasma current**
- RFX-mod2 **will guide** the feasibility study for an efficient low-cost **volume neutron source** based on a Reversed-Field Pinch as fusion core suitable for Breeding Blanket test RFX-mod2 **will guide** the feasibility study for a **fusion-fission hybrid reactor for efficient Tritium production** based on a Reversed-Field Pinch





L. Marrelli, Nucl. Fusion 61, 023001 (2021)

RFX-mod2 will give crucial indications for a Pilot Fusion-Fission Hybrid Reversed-Field Pinch based reactor for Tritium production

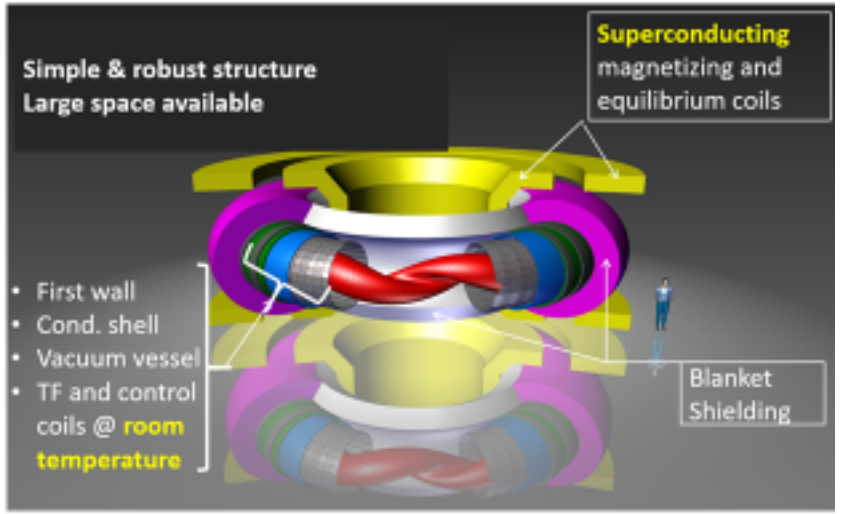
Hybrid reactors cover: efficient **Tritium production** for fusion reactors, nuclear waste transmutation, nuclear fuel fertilization and energy production

High density production of thermal neutrons with efficient Tritium production

Simplicity, efficiency, ease-of-maintenance and safety of fusion reactor with reduced/null Tritium production needs

Advantages of a Reversed-Field Pinch as fusion core in a hybrid reactor ($P_{fus}/P_{input} \approx 1$):

- **Extremely low applied magnetic field** (< 0.1 T) generated by toroidal field coils → copper coils at **room temperature**
- **Vacuum vessel, toroidal field coils and blanket outside the cryostat**
- **No plasma current limit:** @Ip=10 MA, B_ϕ (on axis)≈ 4.7 T, almost fully self-generated → fusion conditions with **ohmic heating only**; no additional heating, no aspect ratio constraints
- **Simple, robust** and with high accessibility machine → low cost



R. Piovan, IEEE Trans. Plasma Science, 48, 1708 (2020)

RFX @ Consorzio RFX

- RFX was a toroidal device for magnetic confinement in Reversed Field Pinch (RFP) configurations
  - (R=2m,a=0.457)
  - Operated in 1991-1999
- RFX was modified and became RFX-mod
  - Operated in 2004-2015