OVERVIEW OF THE RFX FUSION SCIENCE PROGRAM
OV/5-3Ra

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OVERVIEW OF RESULTS IN THE MST REVERSED FIELD PINCH EXPERIMENT
OV/5-3Rb

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RFP: explore, focus and co-operate

• The **RFP scientific mission is evolving** to adapt to the needs of the ITER era:
  
  – **Exploration and assessment of the RFP potential** as low applied magnetic field fusion concept
  
  – **Bridging to tokamak and stellarator** to analyze key fusion issues and support ITER development
    • in flexible devices, using the same tools and language
    • in a wider and otherwise unexplored region of the fusion parameter space

• **Main goal: help to achieve fusion faster.**
Exploring high current/high temperature plasmas

- RFP devices are now exploring plasmas which are comparable to mid/large size tokamaks (with much smaller applied toroidal field) in terms of:
  - current, temperature and density,
  - plasma control and diagnostic tools (NBI & MHD feedback systems),

RFX-mod: 2 MA design value achieved

MST: \( T_e \approx 2 \text{ keV} \) and \( T_i > 1 \text{ keV} \)

\[ P_\Omega = 2 \text{ MW} \]

\[ B(a) \sim 0.25 \text{ T} \]
A successful story

1) Confinement and performance
2) Ion heating, momentum transfer & current drive
3) Active control of MHD stability
4) Conclusions
Confinement and performance
RFP magnetic equilibrium

- Safety factor $q$ is low, and negative at the edge.
- $m=1$ and $m=0$ resonant surfaces in the plasma
  - (e.g. $m=1$, $n=7$ innermost resonance in RFX-mod)

Low applied magnetic field in RFP has advantages:
- High engineering beta, no need for superconducting coils, ohmic heating only
Magnetic self-organization

RFP equilibrium based on TOROIDAL and POLOIDAL plasma current

- Magnetic axis-symmetry breaking is the drive of self-organization

- At high current/low collisionality symmetry breaking obtained with the Quasi Single Helicity state
  - Helical RFP

Ohmic drive

\( J_{\text{tor}} \)  \( J_{\text{pol}} \)

Self-Organized Current transport

\( m=1, n=7 \)
Current Profile Control

RFP equilibrium based on **TOROIDAL** and **POLOIDAL** plasma current

- Alternatively, $J_{pol}$ may be externally driven, **avoiding altogether the need** for self-organization mechanism
  - Pulsed Poloidal Current Drive (PPCD)

- Only transient drive up to now, but it allows **probing RFP dynamics and energy/particle transport** w/o current transport mechanism
Record low transport in MST with external poloidal current replacement

$\tau_E = 12$ ms is comparable to a same-size, same-current tokamak, but with 5X smaller $\langle B \rangle$
Very high $\beta$ in MST with pellet injection and PPCD

- Maximum $\beta = 2\mu_0 <p>/B^2(a) = 26\%$ for $I_p = 0.2\ MA$
- No hard disruption for $n/n_G = 1.5$
- Reduction in magnetic fluctuations is smaller than for the low density case
Single Helical Axis state (SHAx) at high current

- Helical core embedded in an almost axisymmetric boundary
- Predicted by theory
- Improved performance in the helical core due to magnetic chaos healing

- Strong focus on 3D physics in a strong partnership with stellarator and tokamak
  - e.g. VMEC adapted to RFP by ORNL/PPPL collaboration
- Collaborations on helical transport and stability codes under development
Improved performance in the Mega Ampère realm

**Linear increase** of electron temperature with plasma current in RFX-mod, which explores $I \approx 2 \text{ MA}$

![Graph showing linear increase of electron temperature](image)
Electron Internal Transport Barrier in RFX-mod

• Strong internal electron transport barrier at the boundary of the helical core at \( I_p > 1.5 \) MA
  ✓ both for H particle and energy
  ✓ and for impurities

• \( \chi_{Ee,min} \approx 5 \) m\(^2\)s
• \( D \approx 5 \) m\(^2\)s

• Edge transport barriers also observed @low density, with 1 keV pedestal, not necessarily together with SHAx

PUIATTI, M.E. EXC/P4-10
eITB: magnetic and flow shear

- The location of eITB in RFX-mod coincides with a point of null magnetic shear in the helical equilibrium.

Measurements also show flow shear around barrier location, as predicted by numerical simulations.
Confinement improves at higher current and density

- Still transitional with helical state optimization
- High $n/n_G$ operation is difficult because of:
  - high recycling of graphite first wall
  - lack of core particle fueling with gas puffing & ITB
- Lithization ad pellet injection effective tools to broaden operational density range (DAL BELLO, EXD/P3-06, SCARIN, EXD/P3-29)

Next challenges:
- Edge and density control
- Further improvement of active control and magnetic boundary

Data at $0.15 < \frac{n}{n_g} < 0.20$
Trapped particles do not affect transport at low collisionality

- When trapped particles drift out of the helical core, they reach a region where the helical ripple decreases since the boundary is almost axis-symmetric.
- They become almost passing without being lost, at least at low collisionality.
- The $1/\nu$ regime typical of un-optimized Stellarators is not observed in numerical simulations (ORBIT)

![Graph showing particle diffusion](image)

**DKES** transport run started, based on VMEC equilibria

- Neoclassical particle diffusion $\approx 1/5$ of the experimental value

**MARRELLI, EXS/P5-10**
Gradient-driven transport: ITG & Micro Tearing

- When magnetic fluctuation is reduced – as in advanced regimes like QSH or PPCD - limit to confinement in the RFP could be micro-turbulence as seen in tokamak and stellarator
  - Same tools used, extending the knowledge basis on basic micro-turbulence transport (GYRO, TRB, GS2, integral eigenvalue...)
  - Instability characteristics like critical gradient and mode structure are different → physics validation

**ITG**

\[
\frac{\gamma_{max}}{k^2} \quad \text{versus} \quad \frac{a}{L_{T_i}}
\]

**Micro tearing**

\[
T_e \quad \text{vs} \quad r/a
\]

\[
\gamma \quad \text{vs} \quad \nu_{th,i}/a
\]

CAPPELLO, THC/P4-03, TANGRI, THC/P4-26
Ion heating, momentum transfer & current drive
Non collisional ion heating in MST

- Heating is anisotropic, depending on the plasma density
- The fraction of equilibrium magnetic energy transferred to the ions is measured to increase with the majority ion mass.

Parallel/Perpendicular Anisotropy

Ion Mass Dependence

\[ T_{\parallel} \quad \text{and} \quad T_{\perp} \]

\[ n = 0.7 \times 10^{19} \text{ m}^{-3} \quad \text{and} \quad n = 1.1 \times 10^{19} \text{ m}^{-3} \]

\[ T_{i} \quad (\text{eV}) \]

\[ \Delta W_{\text{thermal}} \quad \Delta W_{\text{mag}} \]

(Rutherford scattering)

CHERS C\(^{6+}\))
Increased plasma flow velocity with NBI in MST

- Tangential, 1 MW, 25 keV neutral beam injector operating on MST
- Fast ion confinement time > 20 ms
- Flow shear increased in the core region
- Reduction in the inner-most resonant tearing mode amplitude
Tentative observation of Alfven eigenmodes with NBI

- 25 keV ions from NBI are super-Alfvenic
- Candidate modes observed (only with NBI)
- Correct scaling with $n^{-1/2}$ and $B$

Based on STELLGAP/VMEC
Oscillating Field Current Drive for steady state current sustainment

- 10% increased current with OFCD in MST agrees well with 3D, nonlinear, resistive MHD computation
- Cycle-average energy confinement with OFCD the same as for steady induction

- Similar results obtained in RFX-mod
- Encouraging for efficient current sustainment

MCCOLLAM, EXW/P2-06
3 Active control of MHD stability
RFPs at the leading edge of MHD feedback control

RFX-mod and EXTRAP T2R are equipped with the best systems of active coils ever built for a fusion device
- 192, each independently driven, in RFX-mod
FULL “FLIGHT SIMULATOR” FOR FEEDBACK CONTROL DEVELOPED AND VALIDATED IN RFX-mod FOR THE FIRST TIME
FULL “FLIGHT SIMULATOR” FOR FEEDBACK CONTROL DEVELOPED AND VALIDATED IN RFX-mod FOR THE FIRST TIME

Integrated plasma + 3D boundary model CarMa (CARIDDI + MARS-F)
“Flight-simulator” impressive agreement with experiment

Experimental (red) and model (blue) growth rates vs. controller proportional gain.

Ready for application to tokamak
Reconfiguration of the feedback coil system

• A complete set of coils can be by purpose downgraded to study the effect of partial coverage

• **Feedback downgrading experiment** performed in RFX-mod by the JT-60SA team to gather information for the JT-60SA coil design

• With proper selection of proportional gains full stabilization of the most unstable RWM with 4% coil coverage
Active control of (2,1) mode in RFX tokamak with $q_{\text{edge}} \approx 2$

(2,1) mode is feedback stabilized and tokamak plasma is run with $q_{\text{edge}} \approx 2$

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<tr>
<th>Graph 1</th>
<th>Graph 2</th>
<th>Graph 3</th>
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<tr>
<td>Plasma current</td>
<td>(2,1) amplitude</td>
<td>$q_{\text{edge}}$</td>
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<td>SXR emission</td>
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Conclusions
Summary

- **RFP fusion research is in great shape since last FEC, with solid results and strong synergy with the community:**
  - **Extending operational space:** MA, multi keV, high density and beta, 0.5 s plasmas routinely obtained
  - Broad portfolio of control tools, like NBI and feedback systems
  - **Transformational progress on confinement and beta** along two paths: profile control and self-organized helical RFP
  - **Increasing partnership with the tokamak and stellarator,** sharing and extending tools on
    - Feedback control, 3D physics, micro-turbulence, fast ion physics, code validation....
  - A new RFP device at USTC Hefei (PRC) is under study

- **Looking forward:**
  - Identifying limiting transport mechanism and scalings @ higher current
  - **Optimization of boundary** *(magnetic, plasma wall interaction)* and **plasma control** *(current profile, momentum, power and particle handling, MHD)*
  - **Upgrade of present devices** for optimized plasma control and maximal current capability
  - Develop **reactor scenarios** with integration of confinement and sustainment
MST and RFX posters

- **ALMAGRI, EXC/P8-01**, Non-collisonal ion heating and magnetic turbulence in the RFP.
- **ANDERSON, EXW/P7-01**, Radiofrequency current drive experiments on MST.
- **BROWER, EXC/P4-02**, Fluctuation-induced momentum transport and plasma flows in the MST reversed field pinch.
- **CHAPMAN, EXC/P5-01**, Helical structures and improved confinement in the MST RFP.
- **MCCOLLAM, EXW/P2-06**, Confinement measurements and MHD simulations of oscillating field current drive in a RFP.
- **MIRNOV, THS/P5-11**, Effects of toroidal geometry and FLR nonlocality on fast ions on tearing modes in the RFP.
- **TANGRI, THC/P4-26**, Gyrokinetic simulation of temperature gradient instability in the RFP.

- **BOLZONELLA EXS/P5-01**, “Advanced Control of MHD Instabilities in RFX-mod”
- **CAPPELLO, THC/P4-03** “Equilibrium and Transport for Quasi Helical Reversed Field Pinches”
- **DAL BELLO, EXD/P3-06** “Lithisation effects on density control and plasma performance in RFX-mod experiment”
- **MARRELLI, EXS/P5-10** “Three-dimensional physics studies in RFX-mod”
- **PUIATTI, M.E. EXC/P4-10**, “Internal and edge electron transport barriers in the RFX-mod Reversed Field Pinch”
- **SCARIN, EXD/P3-29** “Magnetic structures and pressure profiles in the plasma boundary of RFX-mod: high current and density limit in helical regimes”
- **SONATO, ITR/P1-13**, The ITER Neutral Beam Test Facility in Padua – Italy: a joint international effort for the development of the ITER heating neutral beam injector prototype
The end
Axis-symmetry breaking is growing topic in fusion

• By definition: **STELLARATOR**

• By necessity: **TOKAMAK**
  
  – RMP
  – External perturbation for MHD control @high beta
  – Field errors
  – Flow ↔ magnetic field perturbations
  – Current transport
  – …..

• **RFP community is addressing a key topic, with direct interaction with both tokamak and stellarator and using the same tools**