OVERVIEW OF RFX-mod RESULTS
by P. Martin and the RFX-mod team (Consorzio RFX, Padova, Italy)

OVERVIEW OF RESULTS IN THE MST EXPERIMENT
by G. Fiksel and the MST team (University of Wisconsin, Madison, WI, USA)

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Two complementary facilities

**RFX-mod:** the largest RFP, located in Padova, Italy
Exploring RFP physics in the multi-MA regime
A fusion facility for MHD mode control
\[ a=0.459 \text{ m}, \quad R=2 \text{ m}, \quad \text{plasma current up to 2 MA} \]

**Madison Symmetric Torus (MST)**
University of Wisconsin, Madison
Exploring current profile control, current drive and basic physics issues
\[ a=0.52 \text{ m}, \quad R=1.5 \text{ m}, \quad \text{plasma current up to 0.6 MA} \]

**RFP:** tight link with University and a nursery for the fusion community
The fusion-oriented RFP mission

1. understanding the RFP physics and optimizing confinement to assess the configuration reactor’s potentials

1. Providing state-of-the-art facilities for developing active control of MHD stability in fusion devices and in ITER in particular

1. contributing to the understanding of fusion science, in particular:
   
   – to test tokamak physics at the extreme of low field
   – to improve predictive capabilities for the “numerical tokamak”
   – to study analogies and synergies with the stellarator
The distinctive feature of the RFP that motivates its interest as a fusion energy system is the weak applied toroidal magnetic field.

The RFP is similar to the tokamak...

..... but the applied toroidal field is ~10 times weaker!

Most of the RFP magnetic field is generated by self-organized current flowing in the plasma

No need for large toroidal coils.
The old story

For a long time it was considered that....

- ....a \( q < 1 \) configuration like the RFP would have been intrinsically unstable,
- with a broad spectrum of MHD resistive instabilities,
- causing magnetic chaos and driving anomalous transport.

This was viewed as an interesting scientific case but a show-stopper for the RFP reactor ambitions
An emerging view for the RFP

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Two strategies for chaos-free RFP: 1

- **Self-organized helical state:** at high current the plasma *spontaneously chooses* a helical equilibrium where only one saturated mode is present.

- This is *potentially chaos-free*.

- For $I_p > 1$ MA this is the *preferred state in RFX-mod*, with strong electron transport barriers and improved confinement.
Two strategies for chaos-free RFP: 2

- Control of the current profile to stabilize tearing modes
- Proof of principle experiment in MST to test RFP confinement and beta limits at the limit of negligible magnetic fluctuation (record values $\tau$ and $\beta$)
Outline of the talk

1) Confinement optimization in RFX-mod
   - Helical equilibrium with electron transport barriers at high current (> 1 MA)

1) Confinement optimization in MST
   - Current profile control for tearing modes reduction: extension to high density and achievement of high Ti

1) Real-time MHD stability control in RFX-mod

1) Summary
RFX-mod starts exploring the multi-MA regime

RFX-mod has the best feedback system for real time control of MHD stability ever realized for a fusion device

Full stabilization of multiple RWMs and control of individual tearing modes achieved in RFX-mod and EXTRAP T2-R

Demonstrates that a thick stabilizing shell is NOT needed

- 192 coils arranged in 48 toroidal positions cover the whole plasma surface
- Each is independently driven
- Digital controller elaborates real-time 576 inputs

LUCHETTA FT/P2-20 (TUE) – MARRELLI EX/P9-8 (FRI) – DRAKE EX/P9-7 (FRI)
A new regime is discovered, where the plasma spontaneously self-organizes in a single-axis helical state, with strongly improved core confinement.
Long periods with one large saturated $m = 1$ mode

RFP is not Kruskal-Shafranov unstable
Helical state is preferred at high current

PERSISTENCY = \[
\frac{\text{time spent in QSH state}}{\text{flat-top duration}}
\]

% 100
80
60
40
20
0

\[\begin{array}{c}
\text{Plasma current (MA)}
\end{array}\]

90%
Synergistic scaling with Lundquist number $S$

Strongly leading towards chaos-free plasmas

At higher current, when plasma gets hotter, the helical state is more pure

$$S = \frac{\tau_R}{\tau_A} \propto \frac{I_p T_e (0)^{3/2}}{Z_{\text{eff}} n_e^{1/2}}$$

Dominant mode ($m = 1, n = -7$)

Secondary modes ($1,-8$ to $-15$)
Breakthrough at high current

At high current the helical state:

– is more frequent

– is more pure

..and we also observe a topology change
Topology change at high current: from island to Single Helical Axis

At the time of 2006 FEC:

**Quasi Single Helicity states where reported:**

- both the helical axis and the original axisymmetric axis were present

- island-like structure
- predicted physics result
- strong T gradients

...but relatively small volume of plasma involved
The original axisymmetric axis is replaced by a helical magnetic axis thanks to the favourable S-scaling of the modes.

- Temperature and density are constant on helical magnetic flux surfaces.
- $1/L \sim 20 \text{ m}$
- Strong electron transport barriers.
Substantial confinement improvement with SHAx

The energy confinement time in SHAx:
- \( \sim 2x \) wrt QSH with island
- \( \sim 4x \) wrt multiple helicity

Particle confinement time in SHAx up to
- \( \sim 8.5 \text{ ms} \) with pellet

No impurity accumulation

Optimization of fuelling on-going to achieve high \( n/n_g \) at high current
- Pellets now
- Lithization near future
  (Liquid Lithium Limiter)
$T_e$ increases with current: no saturation

Strong helical state
Outline of the talk

1) Confinement optimization in RFX-mod
   - Helical equilibrium with electron transport barriers at high current ( > 1 MA)

1) Confinement optimization in MST
   - Current profile control for tearing modes reduction: extension to high density and achievement of high Ti

1) Real-time MHD stability control in RFX-mod

1) Summary
Pulsed Poloidal Current Drive to modify J profile

With appropriate current profile modification, tearing modes can be reduced

$J_B / \|B\|$

Required for tearing reduction

Current profile transiently modified by applying a pulsed poloidal electric field

In MST previously reported 10x improvement in confinement time, but:

- @ low density and low current (0.2 MA)
- with low Ti (weak ion heating)

Present result overcomes these limitations

(see also Chapman’s talk FRIDAY Morning-EX/7-1Ra)
Efficient ion heating through reconnection in MST

- but the mechanism is inherently transient, and
- it is based on bursts of magnetic fluctuations (not good for transport, we want to avoid them)
Ion heat captured in low-chaos MST plasmas

With appropriate **timing** of the current profile control phase wrt reconnection events

![Graph showing tearing ampl. (G) and Ti(0) (eV) over time.](image)

- **Reconnection events**
- **Improved confinement**

$I_p=0.5$ MA
Now capturing both electron and ion heating

..and extending improved confinement with current profile tailoring to high current in MST

Global $\tau \sim 12 \text{ ms} \ @ \ 0.5 \text{ MA}$

Improved (effective heat diffusivity) $\chi = a / 4 \tau \sim 5 \text{ m/s}$

$\tau_E \sim 1 \text{ ms} \ without \ current \ profile \ control$
Extending performance improvement at high density

Density raised x4 with pellet during current control phase

Record value of $\beta$ achieved:
26% at $I_p=0.2$ MA and 17% at $I_p=0.5$ MA
(exceeding beta limit, see Chapman talk Friday)
Outline of the talk

1) Confinement optimization in RFX-mod
   - Helical equilibrium with electron transport barriers at high current (> 1 MA)

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1) Summary
Advanced RWM control and mode un-locking

RWM in RFP are stabilized by active feedback coils
(problem similar to AT with low rotation)

Active rotation of non-resonant wall‐locked RWM can be induced by applying complex gains (keeping the mode at the desired constant amplitude)

RWM amplitude

RWM phase

Bolzonella, Igochine et al, PRL 08
Benchmarking ITER stability code against RFX measurements

- **ITER** prediction codes need benchmarking against experimental data.
- **CARMA** (MARSF + CARIDDI) is a MHD ideal code coupled with an arbitrary 3D magnetic boundary.
- Used to assess role of 3D effects for stability predictions (holes, extensions..) and compare with 2D predictions.

Villone, Liu et al, PRL 08
A confident approach to the future

Both RFX-mod and MST prove that issue of magnetic transport in the RFP can be reduced with substantial improvement of confinement.

RFX-mod provides key contribution to advanced MHD stability feedback control.

Both give important results for broader fusion issues (density limit, fast ion physics, momentum transport, magnetic self-organization, beta limit, etc…)

FUTURE PLANS

- **RFX-mod**: optimization and exploitation of the 2 MA regime, new physics and technology for MHD active control, transport and MHD

- **MST**: optimize and extend duration of current profile control, current sustainment, beta limit physics, magnetic self organization

- **Both**: high power NBI to be installed next year in both experiments

Keep giving strong contribution to education and training thanks to built-in connection with University
The end
Experimental confirmation of helical equilibrium

Temperature and density are constant on helical magnetic flux surfaces, reconstructed from experimental data.

\[ \frac{1}{L} \approx 20 \text{ m} \quad \text{and} \quad \chi \approx 10-20 \text{ m s} \]

Lorenzini, Martines, Terranova et al, 2008
The RFP situation is similar to the advanced tokamak in presence of very low plasma rotation, where the most effective stabilizing mechanism is the feedback action of active coils.

The MHD feedback control system can be on purpose “downgraded” both in power and number of coils, to study tokamak-relevant problems

– The effect of reduced available power
– Effects of mode non-rigidity with a reduced set of coils
The RFP situation is similar to the advanced tokamak in presence of very low plasma rotation, where the most effective stabilizing mechanism is the feedback action of active coils.

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- The effect of reduced available power
- Effects of mode non-rigidity with a reduced set of coils
1.5 MA RFX-MOD Quasi-SH plasma

- Plasma current
- BLACK=DOMINANT MODE / color=secondary modes
- Density
- Electron temperature

Graph showing plasma current, density, and electron temperature over time.
A breakthrough for RFP perspectives

- The access to the record high plasma currents (> 1 MA) has allowed the discovery of a new regime, where the plasma spontaneously self-organizes in a single-axis helical state, with strongly improved core confinement.

- This new regime, theoretically predicted, represents a breakthrough in RFP physics and confinement perspectives, since it would correspond to the chaos-free helical ohmic equilibrium.

- Experiments clearly indicate that the plasma is naturally choosing this improved regime.
The Single Helicity RFP

Theory and 3D nonlinear MHD codes describe Single helicity RFP equilibria only one saturated resistive kink mode is present

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

A big leap since the last 2006 FEC

- **Present performance**
  - Dramatic improvement of confinement in low chaos RFP, showing that when magnetic chaos is controlled performance are similar to the tokamak, but in a simpler device

- **Physics understanding**
  - We know the details of the dynamo process: a sustainable single mode helical dynamo is possible and is observed

- **Confidence in the future**
  - Plasma improves as the current increases, approaching the theoretically predicted helical state

- **Integration with the international fusion programme**
Outline of the talk

1. Introduction
2. The quest for high confinement: high current regime and helical states
3. The quest for high confinement: current profile modification, extension of performance to high Ti, high density
4. Real time control of MHD stability
5. Conclusion