Plasma Theory and Advanced Simulation

Physics Group :

Susanna Cappello, Daniele Bonfiglio,
Artur Kryzhanovskyy, Italo Predebon,
Fabio Sattin, Luca Spinicci,
Marco Veranda (speaker)

collaborations:

EU: EuroFusion

IT: DTT

USA: LANL Los Alamos National Laboratory

February 22nd 2024

CONSORZIO RFX

Ricerca Formazione Innovazione

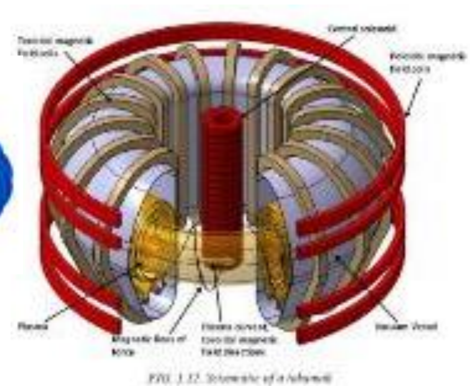
Research groups at Consorzio RFX

strong interaction between Physics and Engineering

- FB group - Plasma Boundary and Cold Plasmas (Matteo Zuin)
- FO group - Plasma Analysis by Optical Diagnostics (Lorella Carraro)
- FS group - Scenario and Transport (David Terranova)
- **FT group - Theory and Simulation** (Susanna Cappello)
- IP group – Thermo-mechanics, Vacuum and Plasma Engineering
- IE group - Electric and Magnetic Fields Engineering
- AI group - Automation Engineering and Information Technology
- SE group - Power Systems Engineering

(https://portal.igi.cnr.it/wiki/index.php?title=Research_groups)

Magnetic Configurations for fusion energy

stellarator	tokamak	reversed-field pinch
		

Increasing plasma current

R = 5.5 m W7-X

R = 3 m JET

(R = 6.21 m ITER)

R = 2.0 m RFX

(1.5 m MST USA
1.4 m KTX Hefei China)

[*] Fusion Physics IAEA 2012

[**] Marrelli et al 2021 Nuclear Fusion

Several physics issues common to the different configurations:

- complex plasma system;
- transport barrier formation (structures);
- magnetic relaxations;
- RFP dynamo/Flux pumping (DEMO reactor);
- density limit;
- "anomalous" ion heating (like in solar corona)

Two main approaches to study plasmas:

i) conducting **fluid** for macroscopic description (**M**agneto**H**ydro**D**ynamics)

ii) distribution of **particles** for microscopic description (**G**yro-**K**inetic)

- **numerical computation** (Fortran - C for **HPC**, Python, Mathematica)
- simple approximations suitable for analytic solutions

General topics:

nonlinearity / collective behavior /

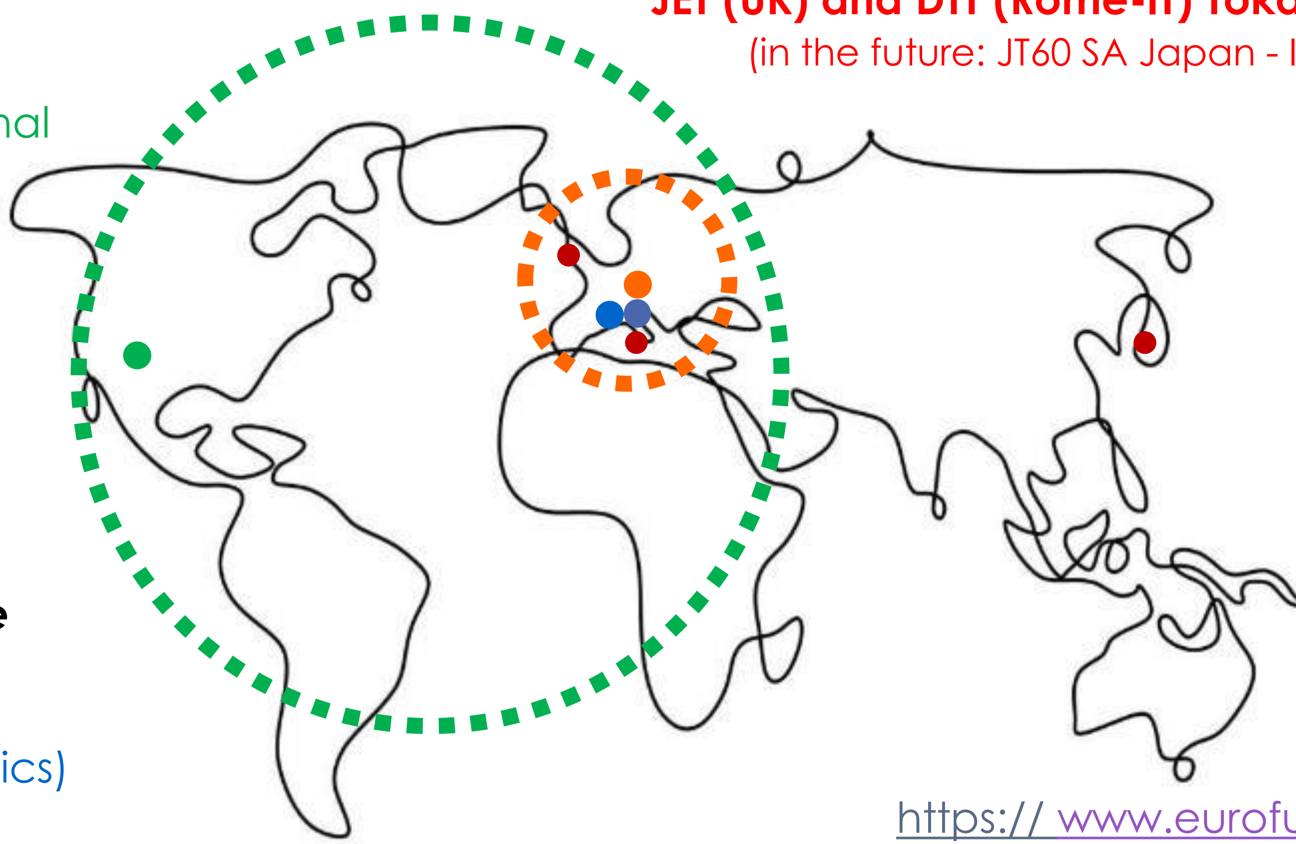
chaotic dynamics / self-organization

Collaborations

Luis Chacón
Los Alamos National Laboratory
(advanced computational techniques)

JOREK team / EUROfusion
IPP Garching – Germany (EU)
(extended MHD code)

JET (UK) and DTT (Rome-IT) Tokamaks
(in the future: JT60 SA Japan - ITER)



Dominique Escande
Aix-Marseille Universitè
(theoretical plasma physics)

https:// www.eurofusion.org
https:// www.iter.org
https://www.igi.cnr.it/

Best practices

- **Verification:**
  - numerical codes provide correct solutions
  - comparison with analytic solution in simplified conditions
  - benchmarks
- **Validation:**
  - comparison with EXPERIMENTAL results
  - **data analysis …**

Tentative themes

Role of triangularity in the pedestal transport of H-mode tokamak plasmas

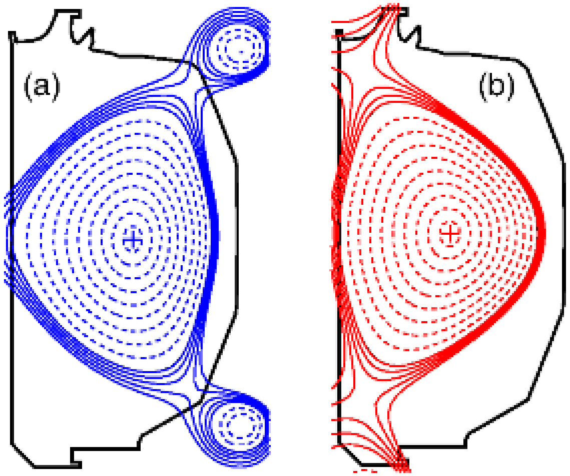
Particle heating mechanisms by low-frequency waves in magnetized plasmas

Addressing Validation of 3D MHD advanced simulation tools

Role of triangularity in the pedestal transport of H-mode tokamak plasmas

- Theoretical background on gyrokinetic theory and MHD equilibria. Role of plasma triangularity: potential advantages/disadvantages in terms of stability and transport. Use of the gyrokinetic code GENE in local approximation.
- Application of GENE to the pedestal of H-mode tokamak plasmas. Possible visits to IPP Garching or IFS Austin, if needed (tbd).
- Global investigation of ion-Larmor-radius-scale electromagnetic turbulence in the pedestal.
- Italo Predebon
- **Isotope mass dependence of pedestal transport in JET H-mode plasmas**
- Nuclear Fusion 2023 https://iopscience.iop.org/article/10.1088/1741-4326/acb44f

NEGATIVE AND POSITIVE TRIANGULARITY



* M. E. Austin et al Physical Review Letters **122**, 115001 (2019)

Particle heating mechanisms by low-frequency waves in magnetized plasmas

- The wave turbulence spectrum in magnetized plasmas is usually peaked around frequencies well below the particle Larmor one: the energy transfer between waves and particles is strongly penalized.

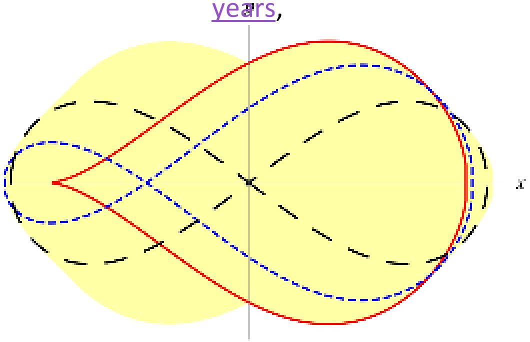
- An efficient non-resonant energy transfer mechanism exists [1]. The candidate will participate in an ongoing theoretical activity aimed at identifying variants to this mechanism which allow to abate the threshold, widening the scope of the mechanism, and apply it to different scenarios, relevant to fusion and astrophysics.

- [1] D.F. Escande, P. Gondret, F. Sattin , *Scientific Reports* **9**, 14273 (2019)

"Relevant heating of the quiet solar corona by Alfven waves: a result of adiabaticity breakdown"
https://www.nature.com/articles/s41598-019-50820-x

- Fabio Sattin

The starburst galaxy Centaurus A, with its plasma jets extending over a million light years,



Tentative themes

Addressing Validation of 3D MHD advanced simulation tools

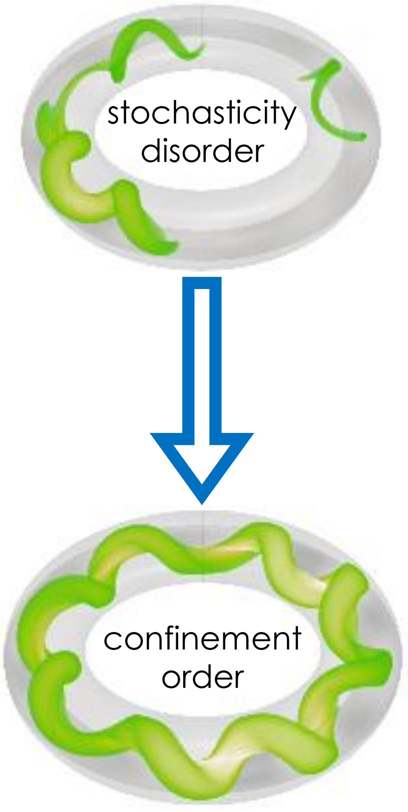
- Knowledge of magnetic field profiles in a RFP device is of utmost importance. A comparison between the predictions from 3D nonlinear MHD and reconstructions from measured experimental data is extremely valuable.

- Possible works:

(i) Identification, using rudimentary machine learning algorithms, of a common subset of plasmas between the numerical and the RFX-mod databases.

(ii) Comparison of the predicted profiles, with assessment of associated confinement and transport properties, especially in ordered states

(iii) A preliminary period of training upon the main tools employed: SpeCyl, Newcomb routines, MHD physics of RFP/tokamak will be needed.



Fabio Sattin, Marco Veranda

Contacts

To discuss possible research themes VISIT US !

CONSORZIO RFX involves the research institutions:

- Consiglio Nazionale delle Ricerche, (CNR_Istituto ISTP)
- Università degli Studi di Padova,
- INFN,
- ENEA

Speaker: *marco.veranda@igi.cnr.it*

Group:

Susanna Cappello
[3D nonlinear MHD (head of the group)]

*nome.cognome**@igi.cnr.it***

Fabio Sattin
[particle statistics and wave-particle]

Daniele Bonfiglio
[3D nonlinear MHD]

Italo Predebon
[gyrokinetics, MHD]

Marco Veranda
[3D nonlinear MHD, magnetic topology]

Emanuele Spada
[high voltage holding (MITICA-NBTF) / theoretical studies]

Artur Kryzhanovskyy
[3D nonlinear MHD]

Luca Spinicci
[3D nonlinear MHD]

\+ international collaborators

Spare slides…

Consorzio RFX at CNR research area

"Palazzo della ragione"

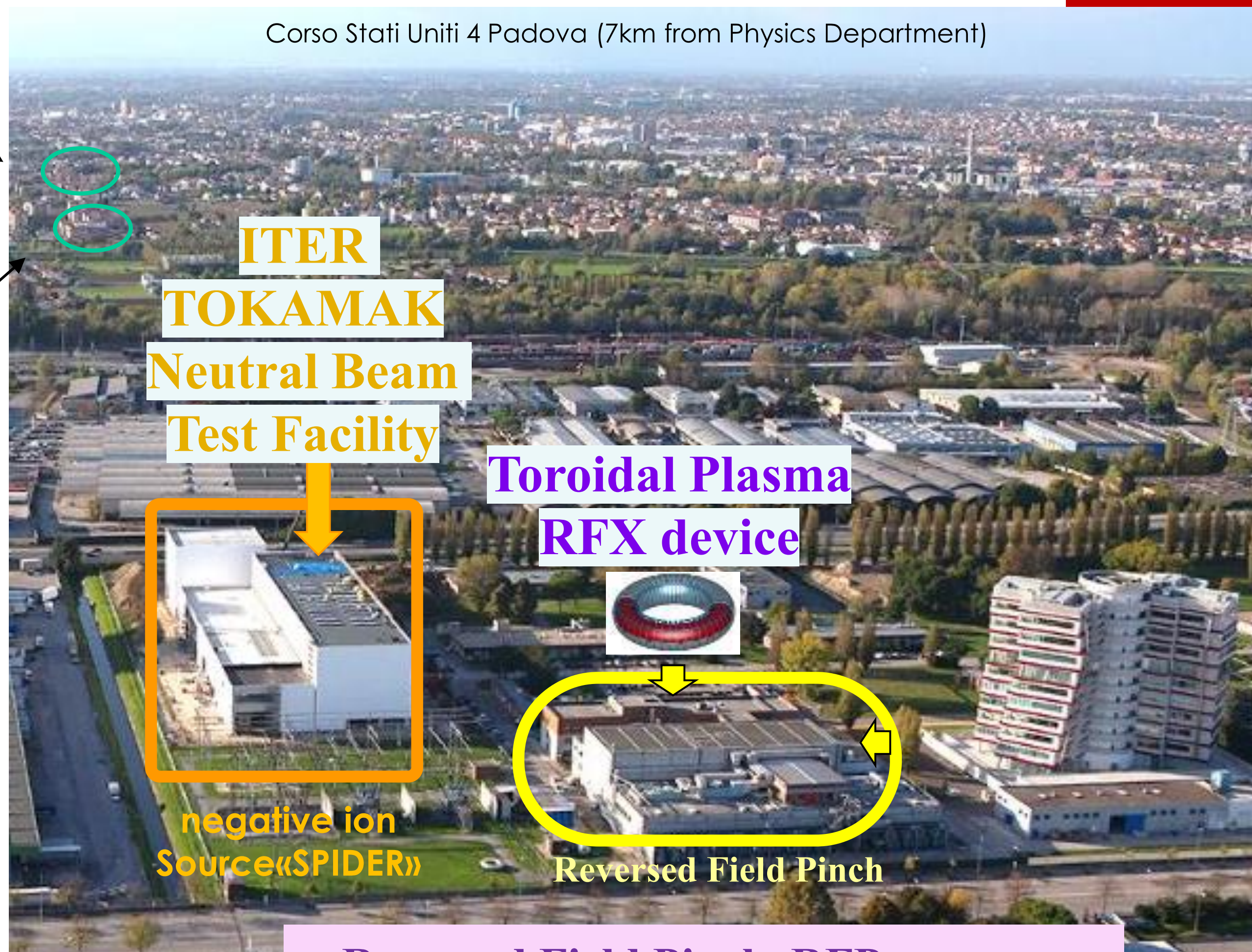
From the web

https://en.wikipedia.org/wiki/Palazzo_della_Ragione,_Padua

Padova University historical site

From the web

https://en.wikipedia.org/wiki/University_of_Padua

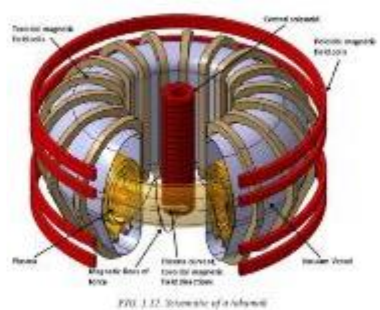


Reversed Field Pinch, RFP, partners:
USA - Sweden - Japan – China

Magnetic Configurations for fusion energy

stellarator

tokamak



reversed-field pinch

Increasing plasma current

	stellarator	tokamak	reversed-field pinch
👍	Steady state	Confinement	Light Tech expected
👎	Coils Complexity	Disruption risk	Confinement

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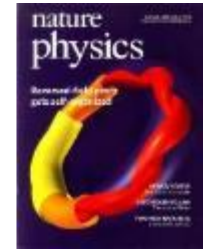
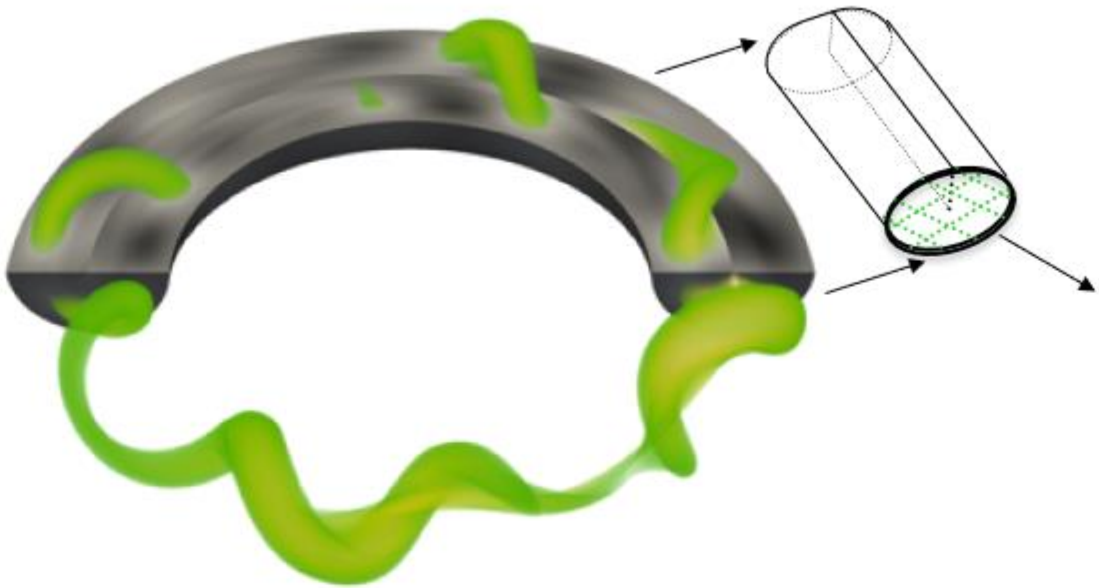
Example



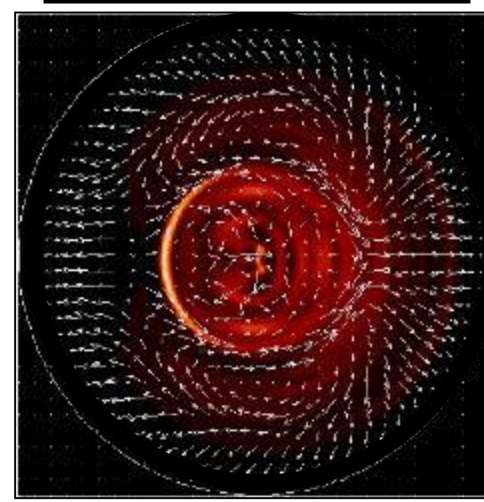
Advanced magneto fluid simulation (3D nonlinear)

The plasma shape intermittently becomes an helics

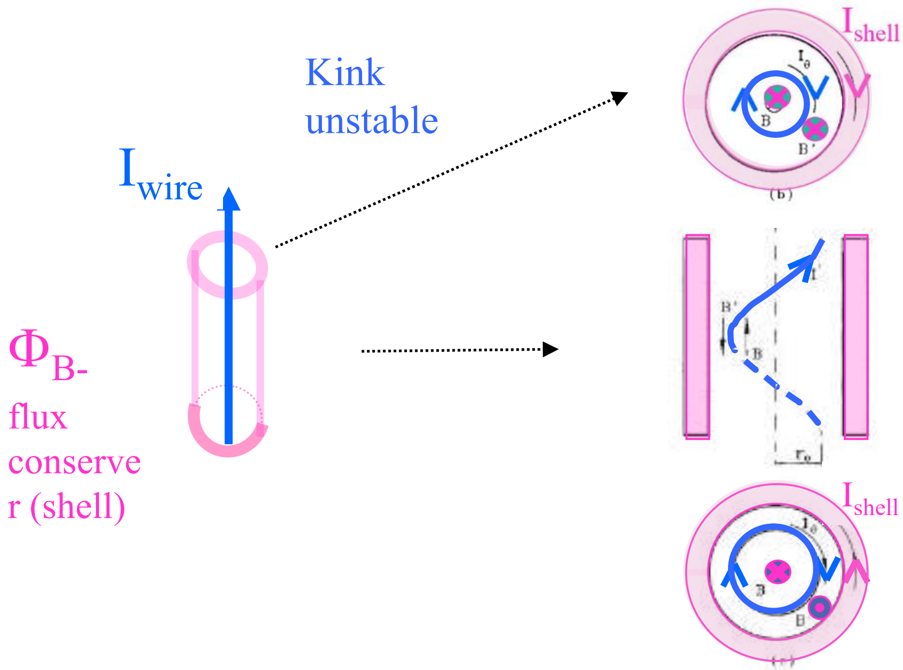


At collapse intense localized patterns
… plasma heating?

***Flow lines** and J · B*



Toy model a current carrying wire in a flux conserver:



solenoidal effect by the wire itself:
- core B increase

by flux conservation:
- edge B decrease

… saturates when edge field reversal is reached

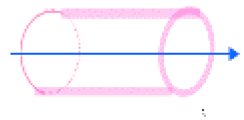
Early elements:
Verhage-Furzer-Robinson NF 1978
Kadomtsev 1992 (Sawer PoF1959)

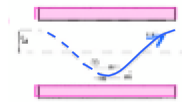
Elaborated in:
Benisti Escande EFTC 1998
Escande et al. PPCF 2000

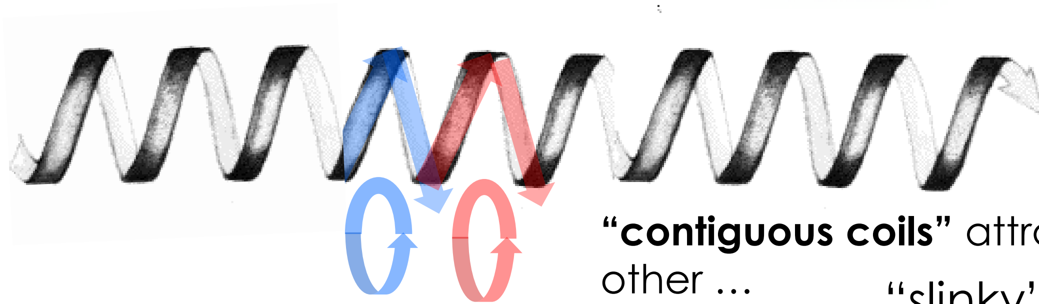
$r_0 \rightarrow 1$ (disruption) for too small $\frac{I_{wire}}{\Phi}$
(Tokamak case)

RFP Toy model: useful to describe the "slinky -phase locking- effect "

After kinking …



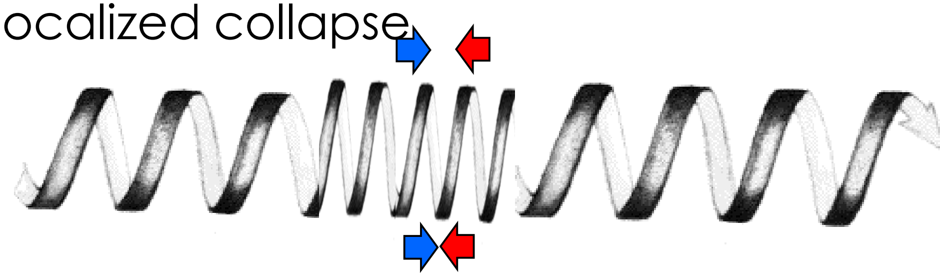


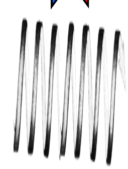


"**contiguous coils**" attract each other …

…"slinky" instability

… localized collapse





plasma buldging-collapse at a toroidal location, similarly in nonlinear modeling and experiments …

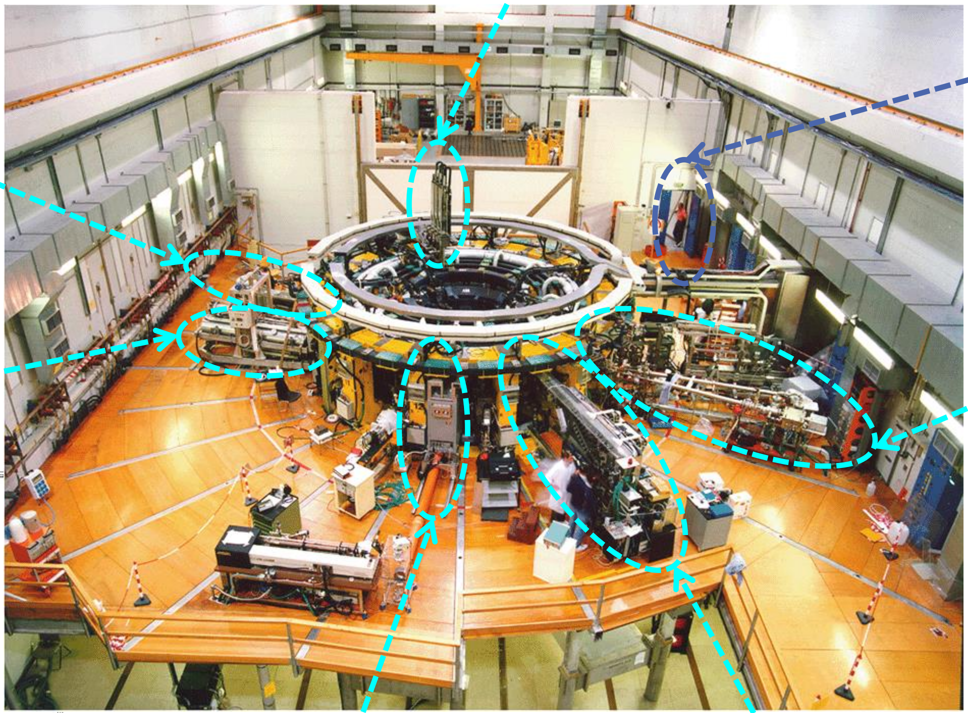
RFX regimes

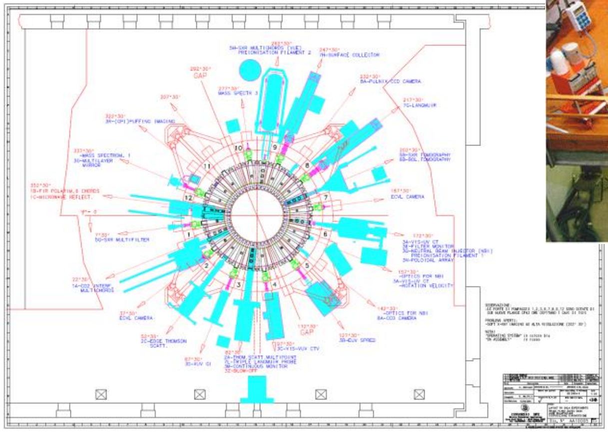
Cappello et al., Theory of Fusion Plasmas - Varenna 2008

RFX device

identified as high priority research infrastructure (PNIR)
PNRR funding 2022-2024 + 10 years exploitation

Plasma diagnostic systems

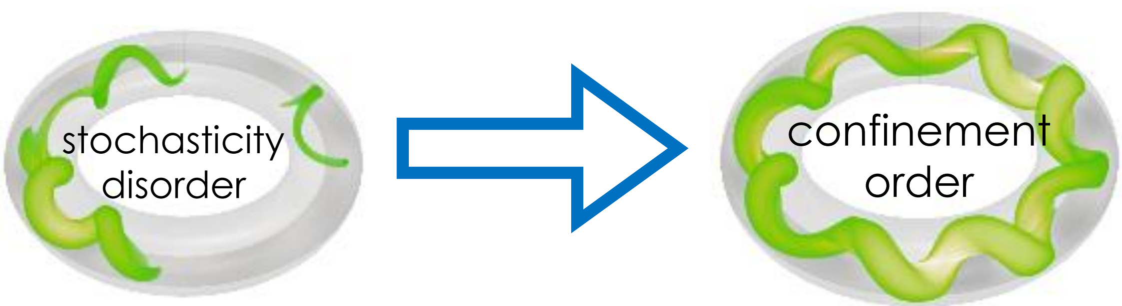




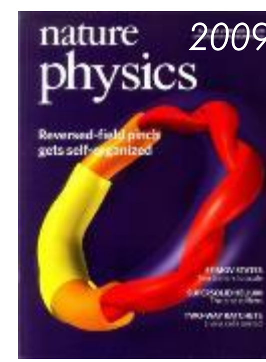
Summary - keywords:

- *gain a deep knowledge of*
  - advanced computing techniques for modeling
  - control techniques [to deal with a vivid plasma]
  - topology of the magnetic field [magnetic chaos]
  - data analysis: advanced statistical techniques

studying
- **helical self-organization** (in direct connection with experiment!)
- tokamak performance and control
- operational limits in fusion plasmas
- dynamics of particles in electromagnetic fields



helical self-organization of plasmas



RFP and **Tokamak** plasmas undergo **transitions dynamical regimes**
Control and optimization under development – not yet fully understood

FINE

Spare slides follow