

Nuclear Fusion and Plasma Physics

Lecture 7

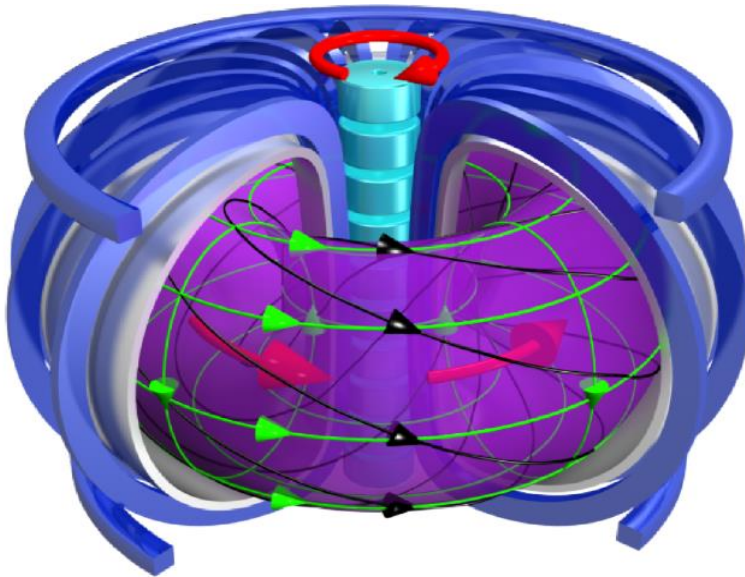
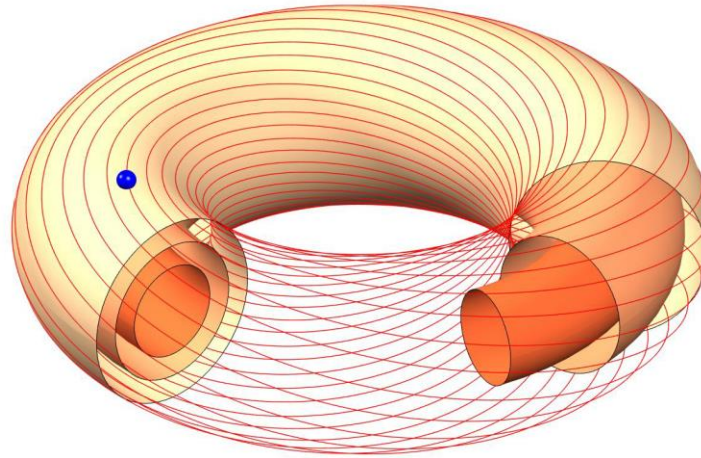
Ambrogio Fasoli

Swiss Plasma Center

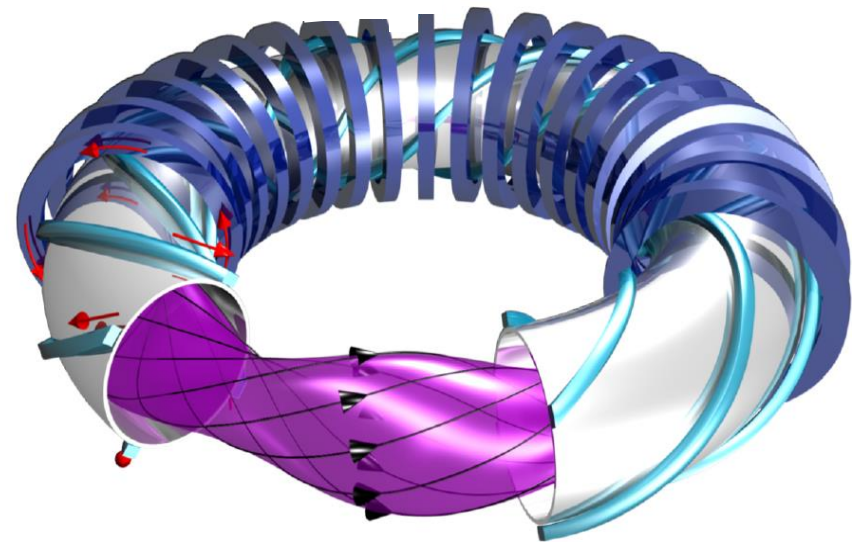
Ecole Polytechnique Fédérale de Lausanne

Tokamak and stellarator

Need helical field lines to
confine particle orbits

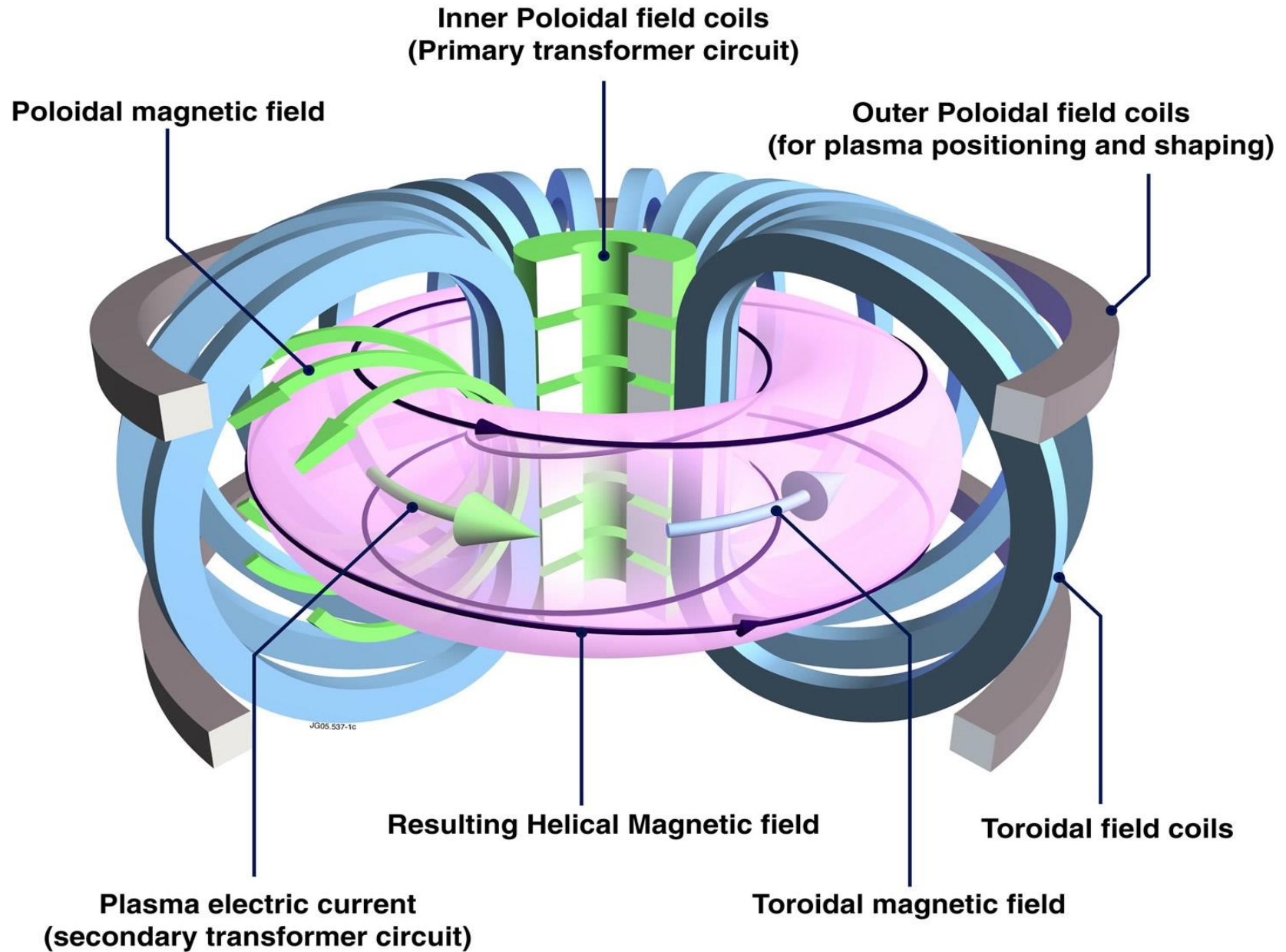


Tokamak

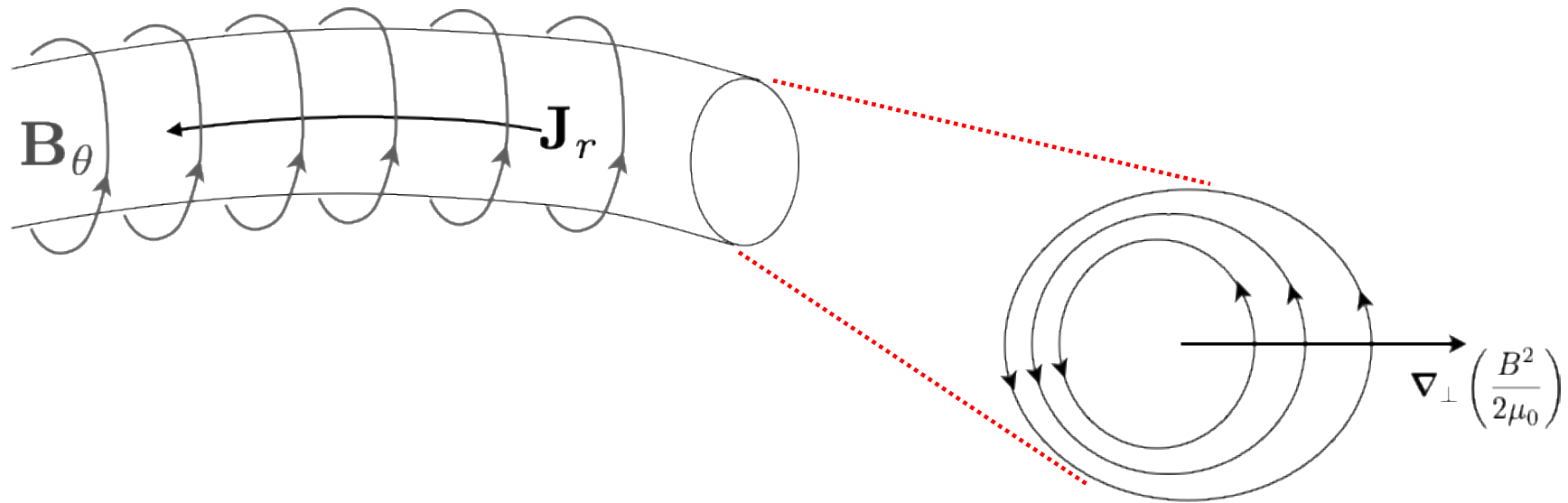


Stellarator

The Tokamak



EPFL Why a vertical field in a tokamak ? reminder



Axi-symmetric torus, large toroidal magnetic field, small poloidal magnetic field, large pressure

Four main features/components

- Toroidal field coils

 - main confinement field

- ‘Ohmic’ transformer

 - current for equilibrium, heating

- Vertical field system

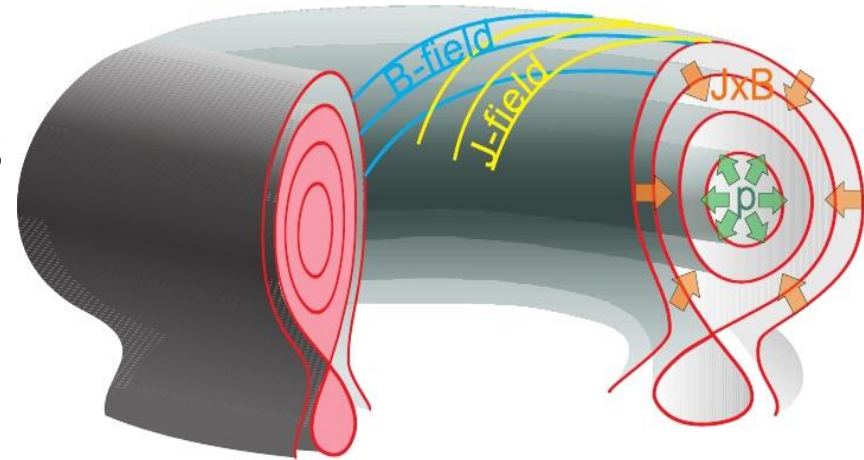
 - toroidal force balance, contrasts hoop force

- Shaping coils

 - to improve MHD stability and alleviate plasma-wall interactions

$$\mathbf{j} \times \mathbf{B} = \nabla p$$

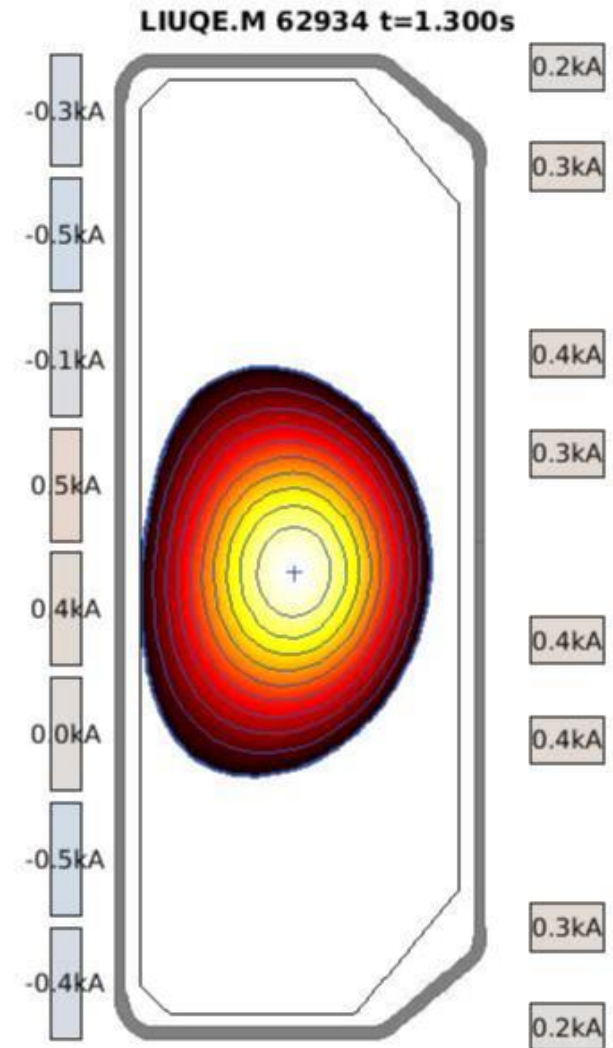
Nested magnetic surfaces on which p is constant and current lies



$$\mathbf{j} \times \mathbf{B} = \nabla p$$

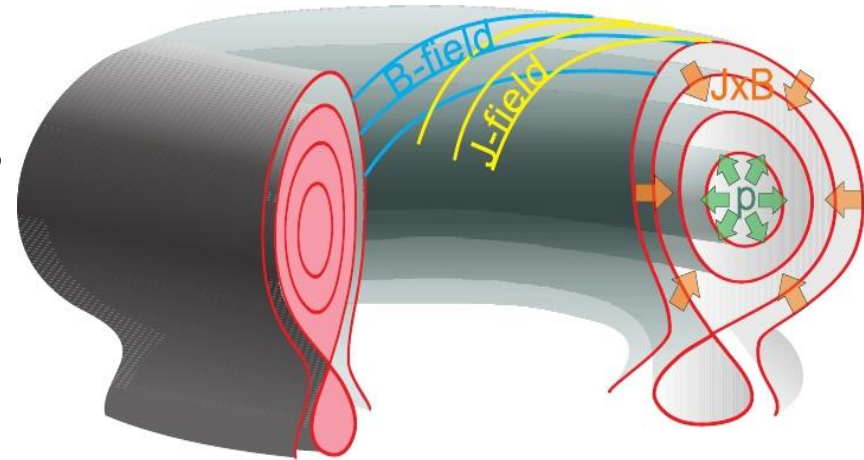
Nested magnetic surfaces on which p is constant and current lies

Ex. of TCV plasma evolution



$$\mathbf{j} \times \mathbf{B} = \nabla p$$

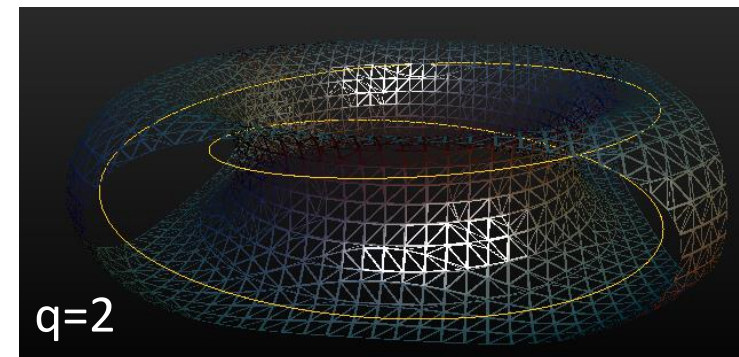
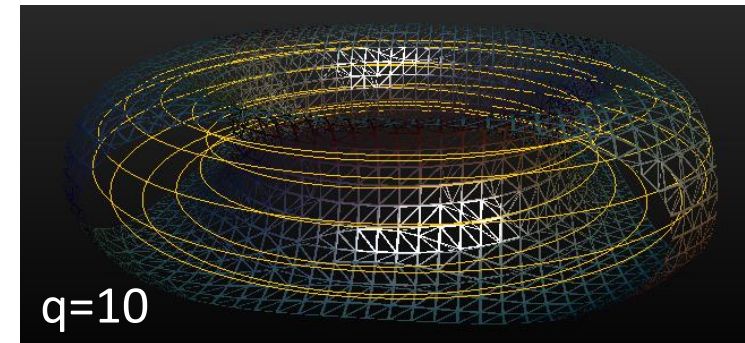
Nested magnetic surfaces on which p is constant and current lies



Tokamak equilibrium characterised by

Safety factor q = toroidal turns / poloidal turns (pitch of field lines)

Normalised pressure $\beta = nT/(B^2/2\mu_0)$



Stability

Destabilising: gradients of current and pressure

Stabilising: B-field line bending and compression

Instabilities

Ideal ($\eta=0$): fast, no change in B-field topology

Resistive ($\eta\neq 0$): slower, possibility of feedback control, change in B-field topology (magnetic islands)

MHD stability imposes limits on optimisation of fusion parameters

Current limit

Limits energy confinement time

$$\tau_E \propto 1/q \sim I_p \text{ for fixed B-field}$$

Can be improved by shaping the plasma

Limit in normalised pressure $\beta \propto nT/B^2$

Limits fusion power for given B (cost!)

$$P_{\text{fus}} \propto \beta^2 B^4$$

Can be improved by shaping the plasma

Density limit

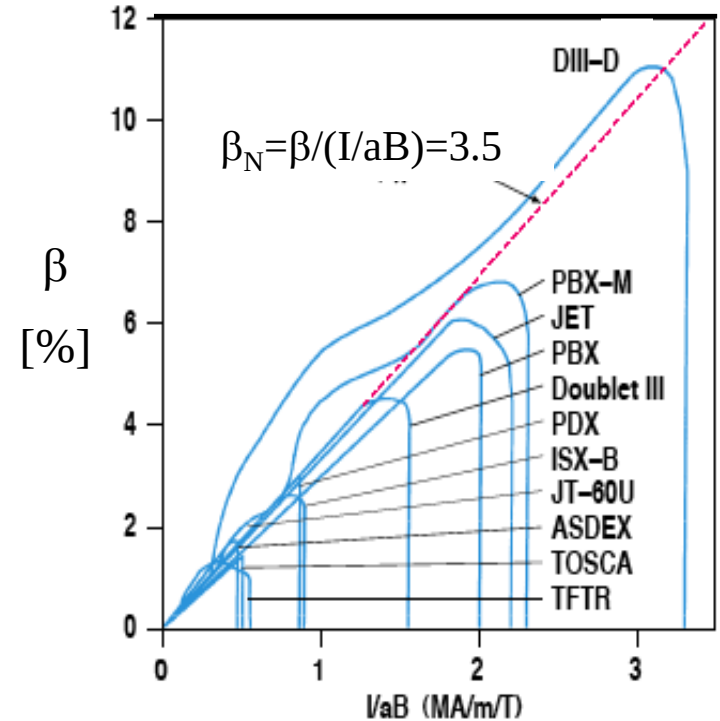
Limits fusion power

$$P_{\text{fus}} \propto n^2 \langle \sigma v \rangle$$

Can be improved by peaked radial profiles

Ideal limit in β and current is generally understood

The need to optimise fusion power ($P_{\text{fus}} \propto \beta^2$) pushes operation close to limits



Violation of linear stability results in rapid loss of plasma: disruptions

Toroidal E-field can lead to *runaway* electrons, damaging wall
Plasma currents intercepted by conducting surfaces and fast variation of flux lead to large thermal loads and e.m. forces

Tokamak *physics* challenges

Large power density and gradients (10MW/m^3), anisotropy, no thermal equilibrium

Macro-instabilities and relaxation processes

solar flares, substorms

Dual fluid/particle nature

Wave-particle interaction (resonant, nonlinear)

coronal heating

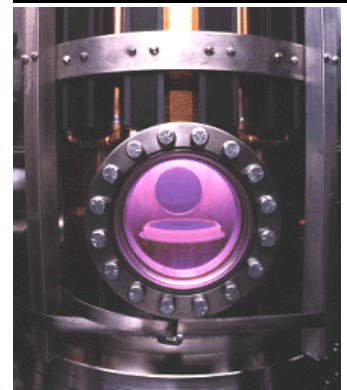
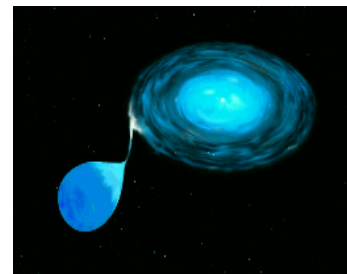
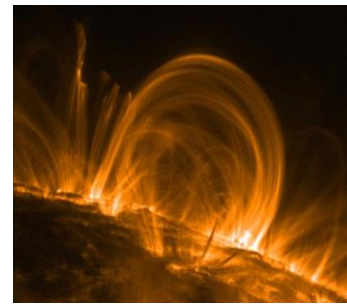
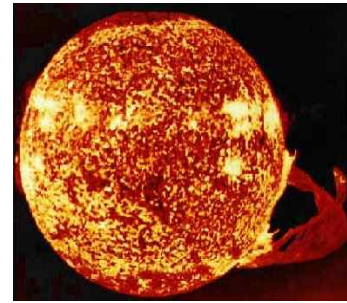
Turbulent medium

Non-collisional transport and losses

accretion disks

Plasma-neutral transition, wall interaction

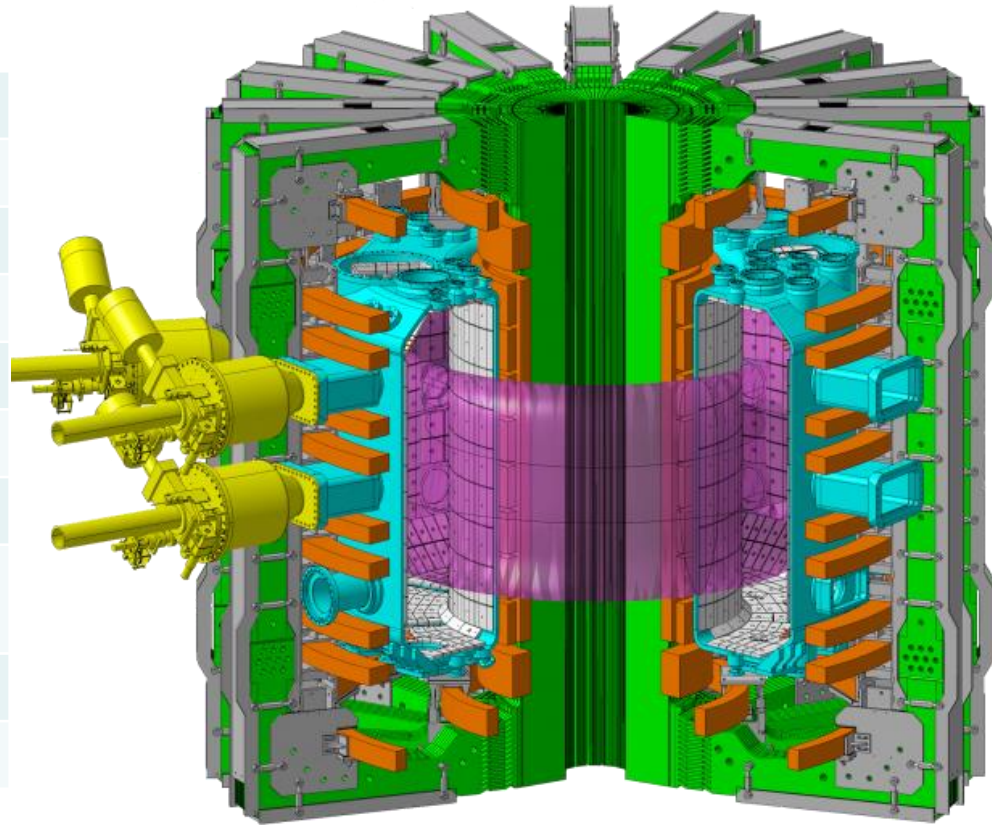
plasma manufacturing



Huge range in temporal ($10^{-10} \rightarrow 10^5$ s) and spatial scales ($10^{-6} \rightarrow 10^4$ m)

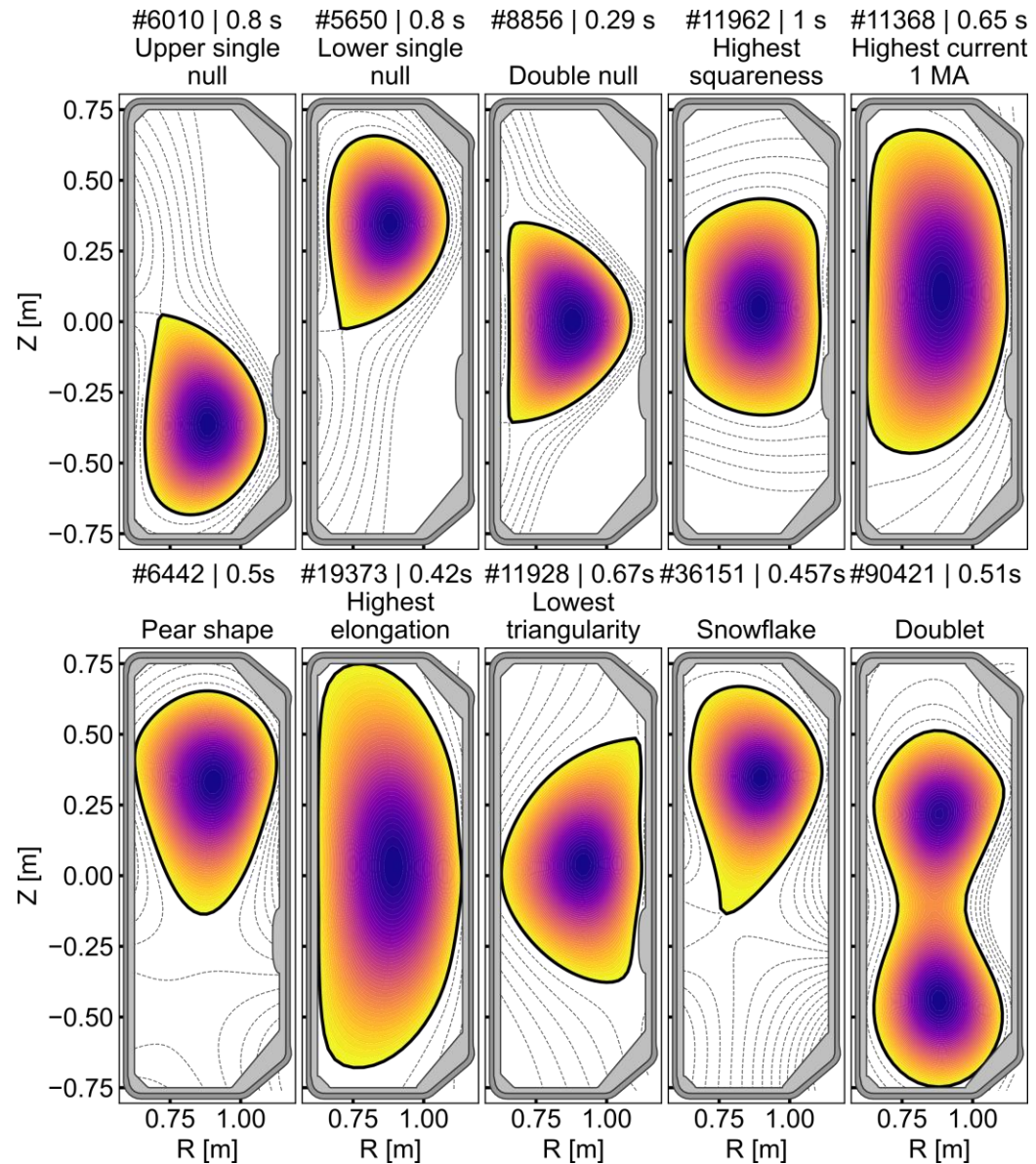
EPFL The Tokamak à Configuration Variable (TCV)

Major and minor radii	0.88 / 0.25 m
First wall material	Carbon (graphite)
Max magnetic field	1.54 T
Max plasma current	1.0 MA
Max elongation	2.8
Triangularity	-0.6 / +0.9
Pulse duration	2 s (4 s)
ECH power	2.4 MW – X2 +1.9 MW – X3
NBI power	2.5 MW
Main species	D, H, He



See C. Theiler *et al* 2026 Nucl. Fusion **66** 116007

16 independently controlled poloidal-field coils enable a wide range of plasma shapes and magnetic configurations

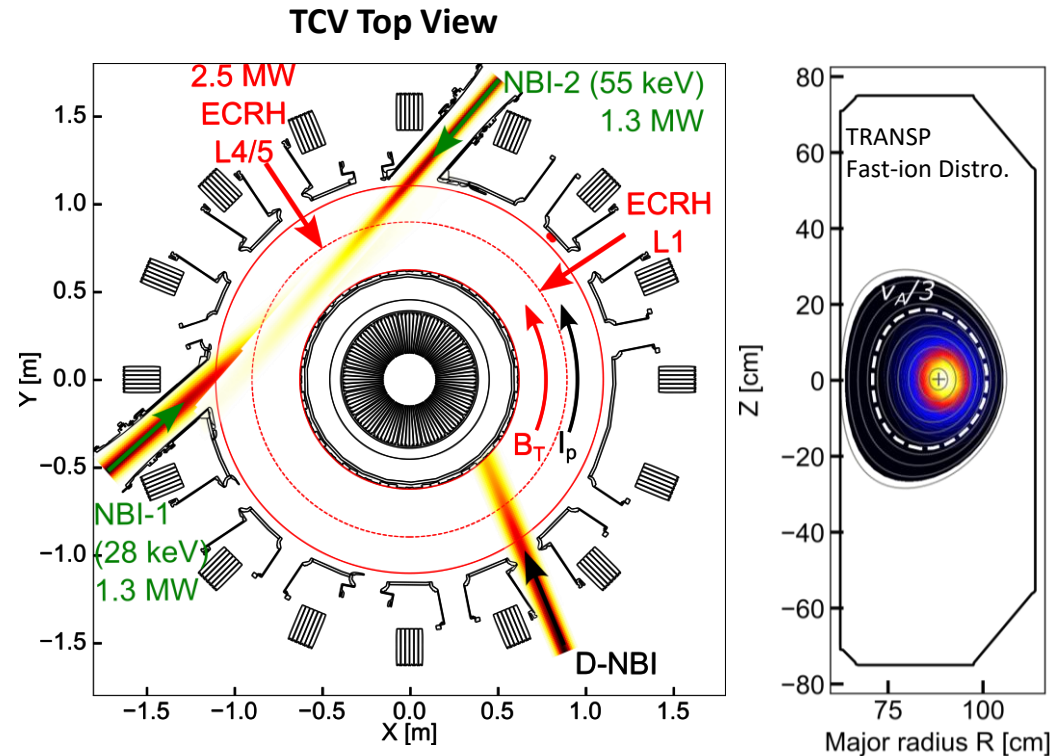


Electron Cyclotron Resonance Heating (ECRH)

- X2: Three real-time steerable launchers, up to 2.5 MW
- X3: Two launchers, up to 1.9 MW

Neutral Beam Injection (NBI)

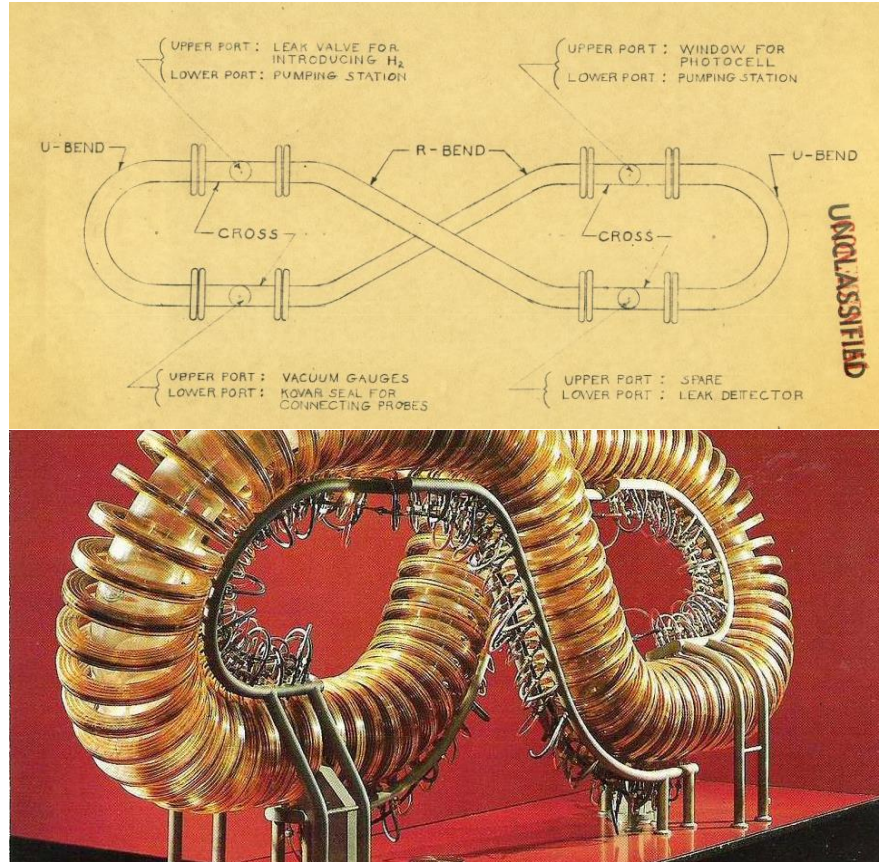
- NBI1: 28 keV, up to 1.3 MW [1]
- NBI2: 55 keV, up to 1.3 MW
- Diagnostic beam: 50 keV H, 70 kW



Courtesy of Anton Van Huuren

EPFL Idea and potential advantages of stellarators

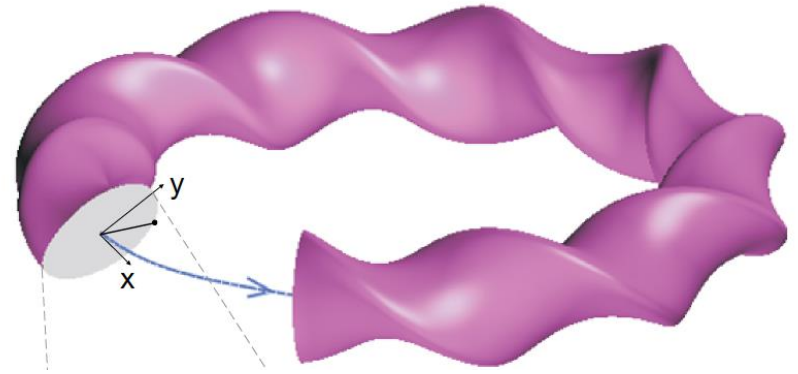
A twist in the B-field lines can be generated without a plasma current



Mattherhorn Project (1950's)

One can either twist the torus itself out of the plane....

....or produce corkscrew-shaped magnetic surfaces using external coils



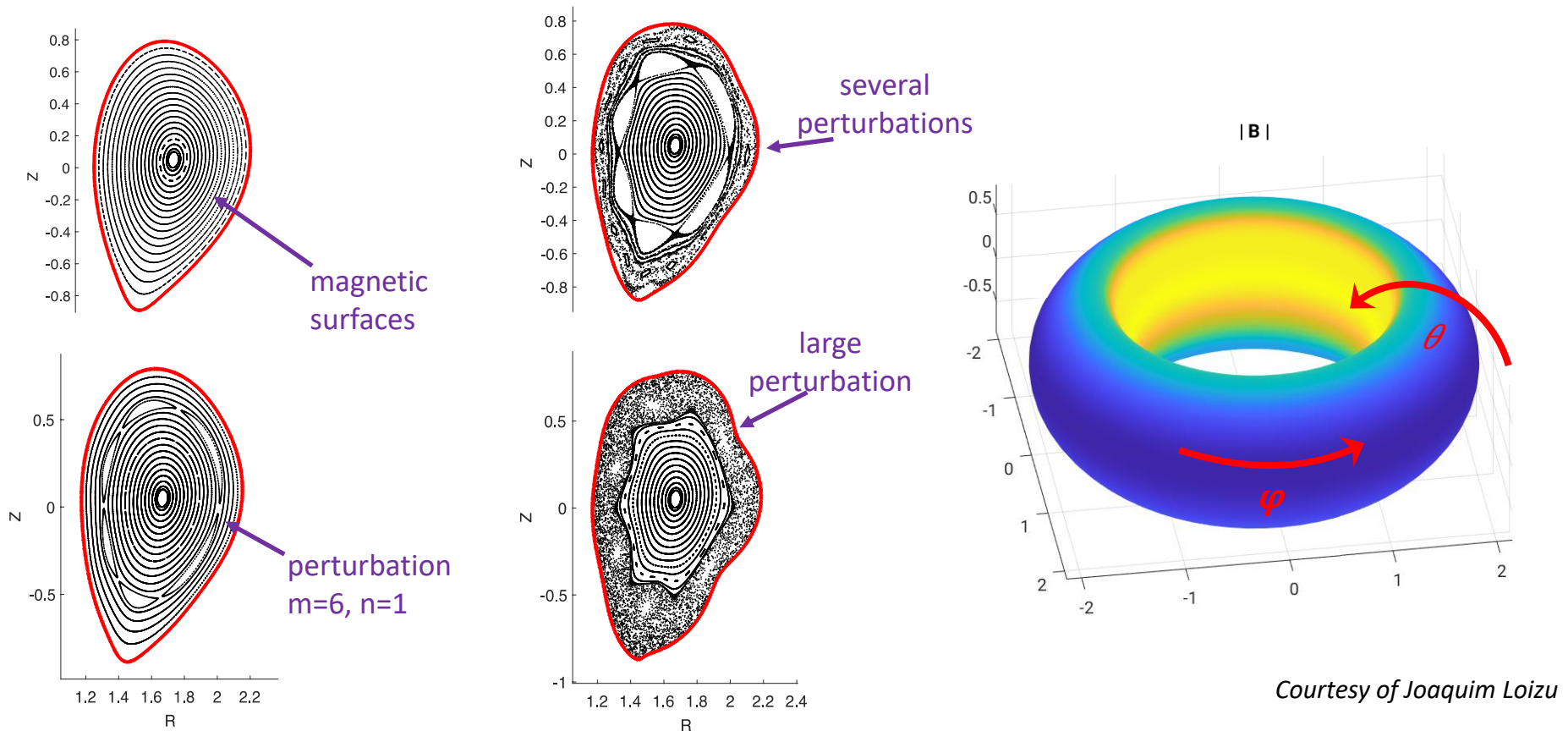
Courtesy of Joaquim Loizu

Stellarators can operate continuously and are not subject to disruptive instabilities (no plasma current!)

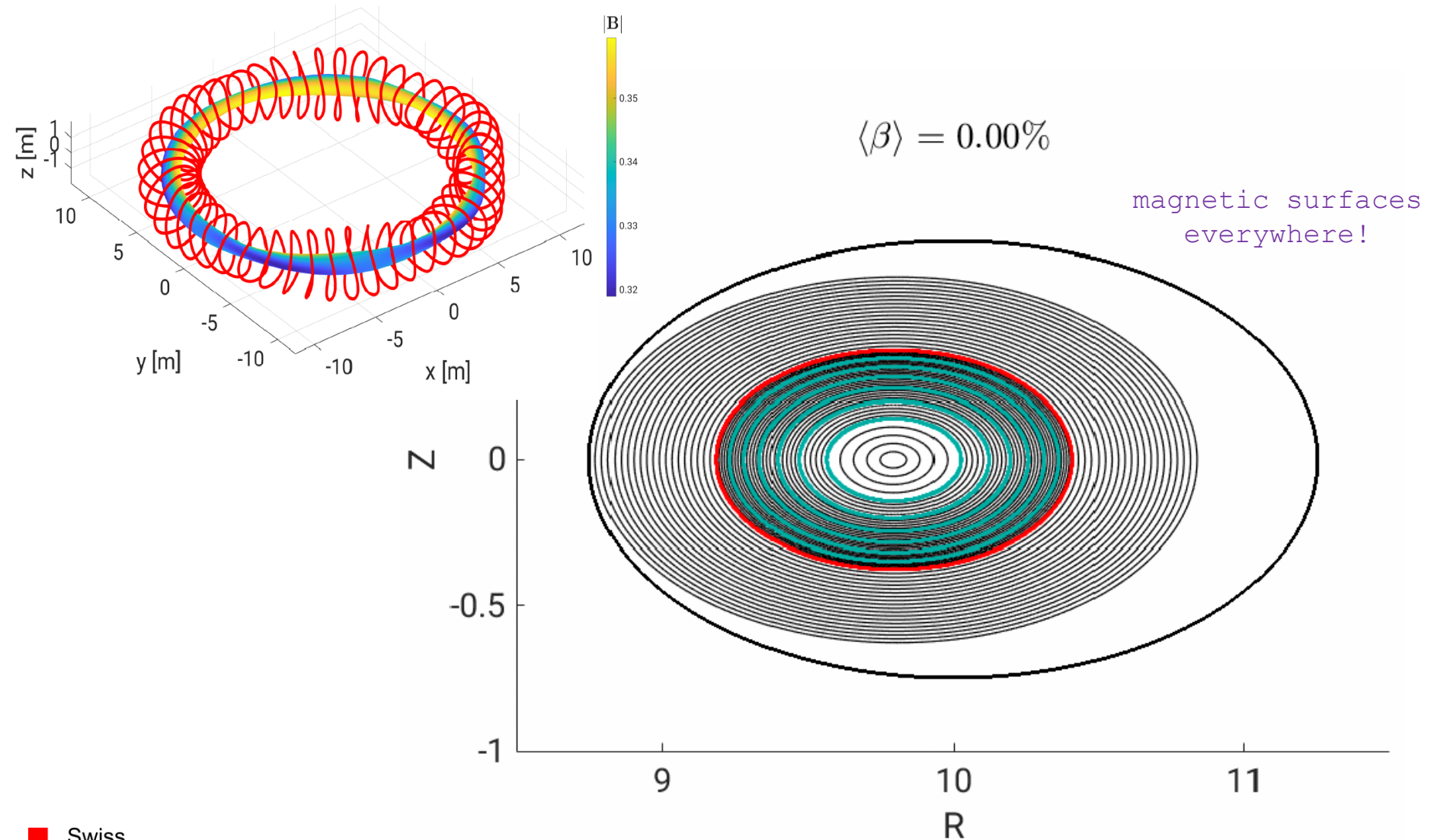


Very precise complex structure of B-field is needed to guarantee the existence of magnetic surfaces (and not only chaotic field lines)

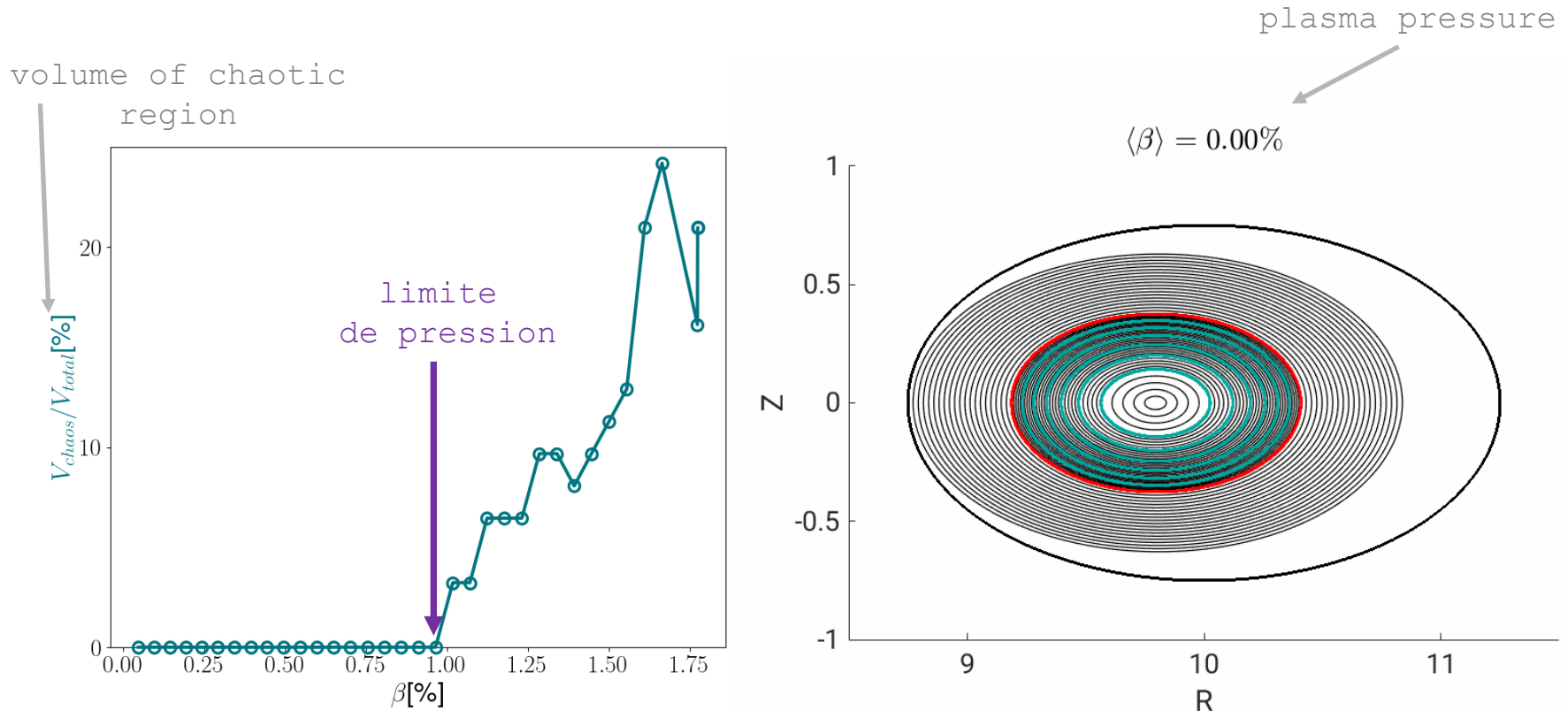
Magnetic surfaces are fragile when the field twist is a rational number n/m : if a perturbation $\delta\mathbf{B} \sim \cos(m\theta - n\varphi)$ is added to the symmetric magnetic field, the fragile surfaces generate 'islands', and eventually chaos



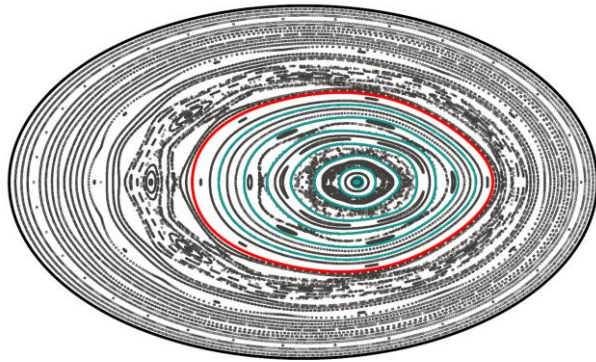
Optimisation guarantees magnetic surfaces in vacuum



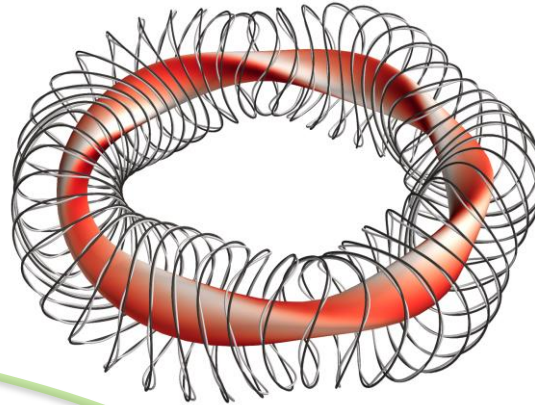
But beyond a certain value, plasma pressure destroys magnetic surfaces



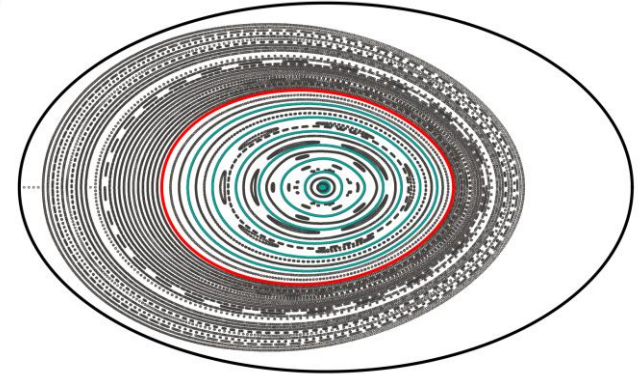
The level of chaos can be controlled at high plasma pressure by optimising the coils



initial

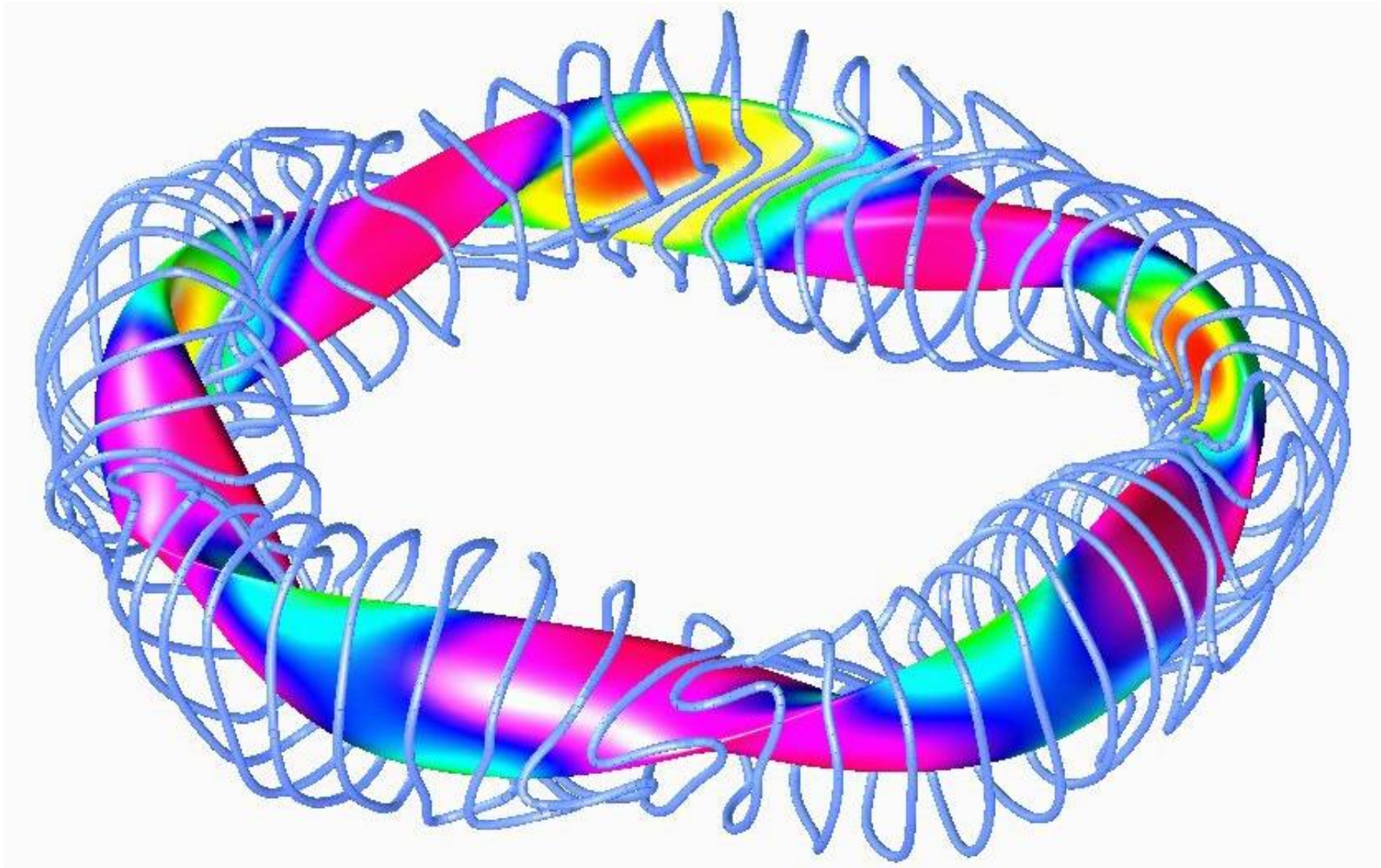


The Polaris mini-stellarator at EPFL-SPC

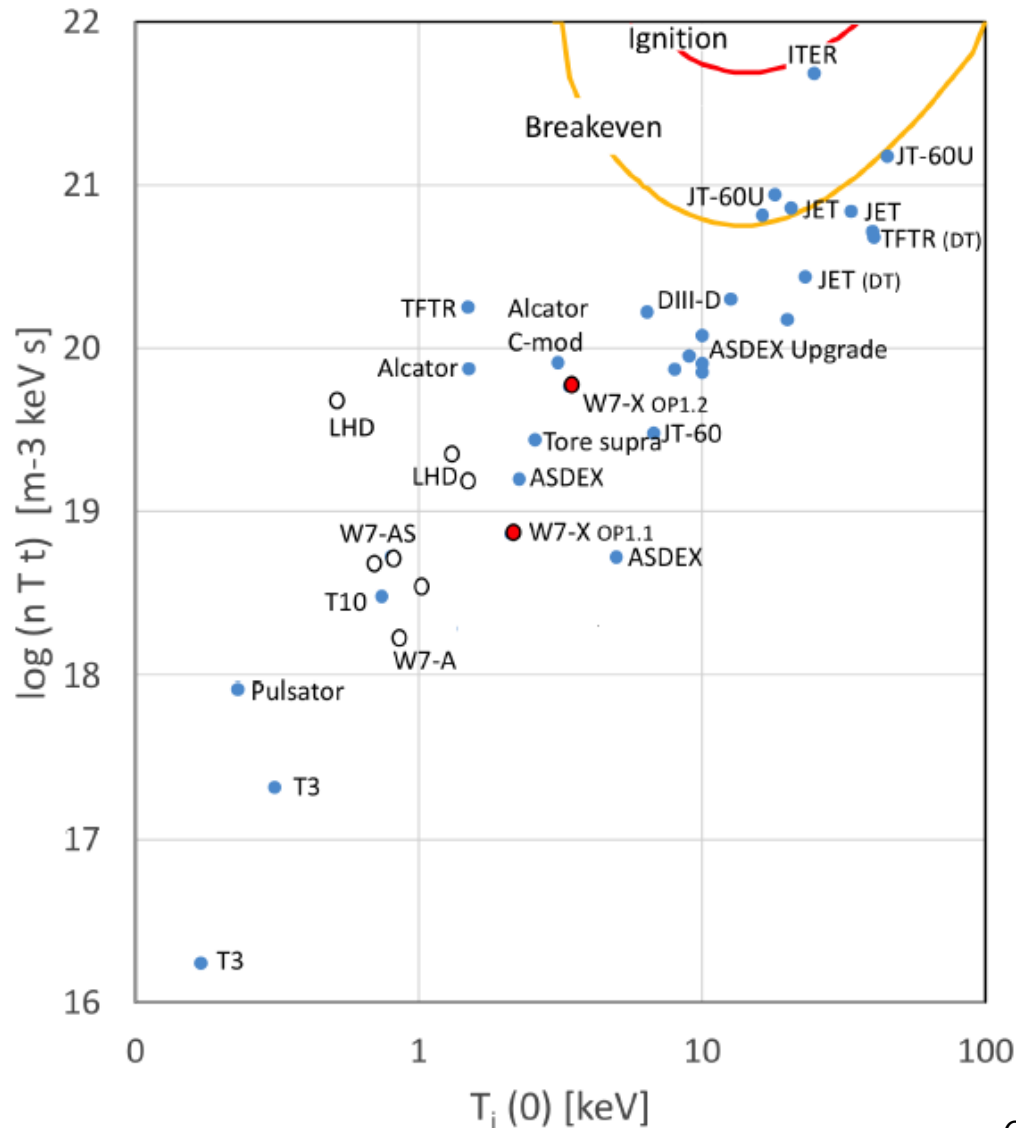


optimized

W7-X stellarator in Germany



Stellarator performances are approaching those of tokamaks





Technology	Global level (Amount in Millions of EUR)
Tokamak	6540
Field-Reversed Configuration	1279
Spherical Tokamak	748
Stellarator	438
Dynamic Stellarator	61
Magnetic mirror	44
Levitated Dipole	11
Centrifugal Magnetic Mirror	5
Poloidal magnetic confinement	1