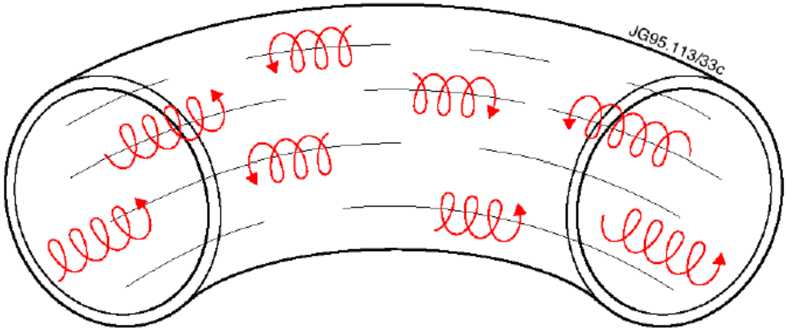
Magnetically Confined Thermonuclear Grade Plasmas

K.Lackner

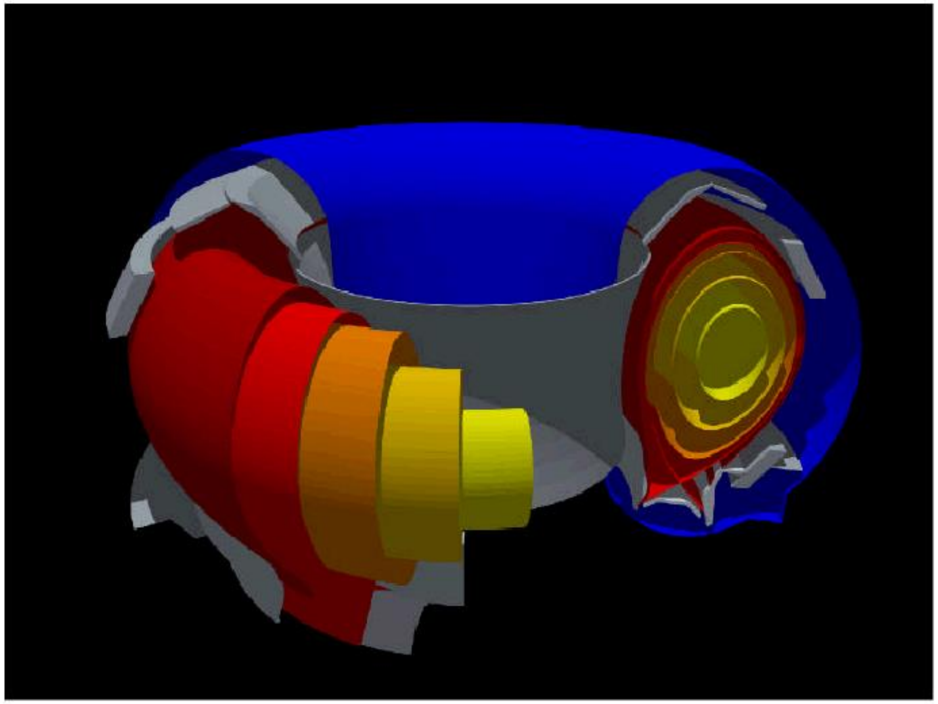
Max-Planck Institut für Plasmaphysik, D-85748 Garching

- **introduction: toroidal magnetic confinement**
- **parameter regime of magnetic fusion**
  - **temperatures, pressures, nTτ**
  - **the dimensionless parameters of magnetic fusion**
- **the non-local nature of thermodynamic equilibria**
  - **axisymmetric (tokamaks)**
  - **general toroidal (stellarators)**
- **frontier physics issues of magnetic confinement**
  - **turbulent transport - transport barriers**
  - **fast particle driven global instabilities**
- **conclusions:**

principle of toroidal magnetic confinement



end losses avoided by nested, closed toroidal flux surfaces



magnetic field reduces drastically perpenticular mobility of particles

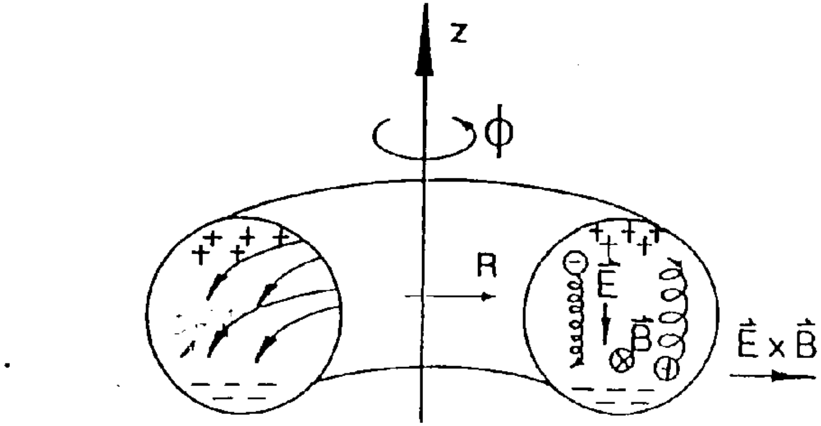
balances the plasma pressure (O(10atm))

produces thermal insulation (200 Million K)

$$\beta = \frac{k\langle n_e T_e + n_i T \rangle}{B^2 / 2\mu_o}$$

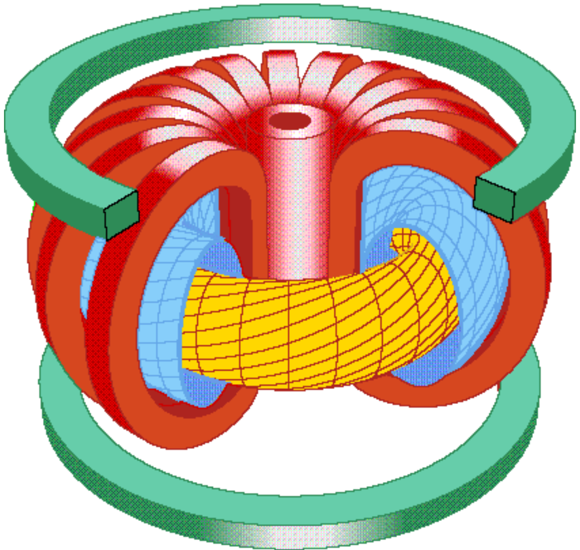
$$\tau_E = \frac{\frac{3}{2} k\langle n_e T_e + n_i T \rangle V_p}{P_{heat}} = H \cdot \tau_{E,scaling}$$

the need for a „rotational transform“ : iota

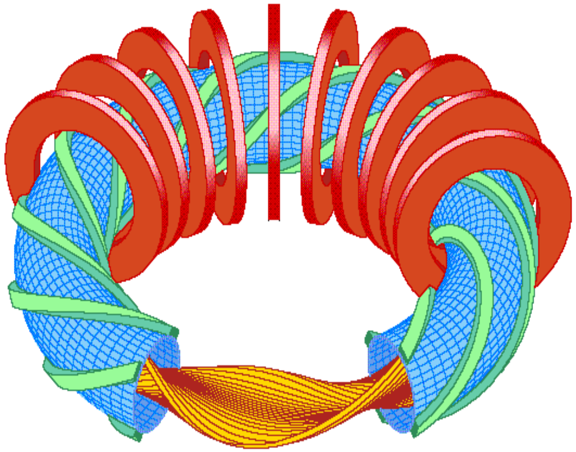


build-up of charge separation field leading to radial drift

superposition of poloidal field component allows particle motion along field lines to cancel out charges „Rotationstransformation“: iota= 1/q



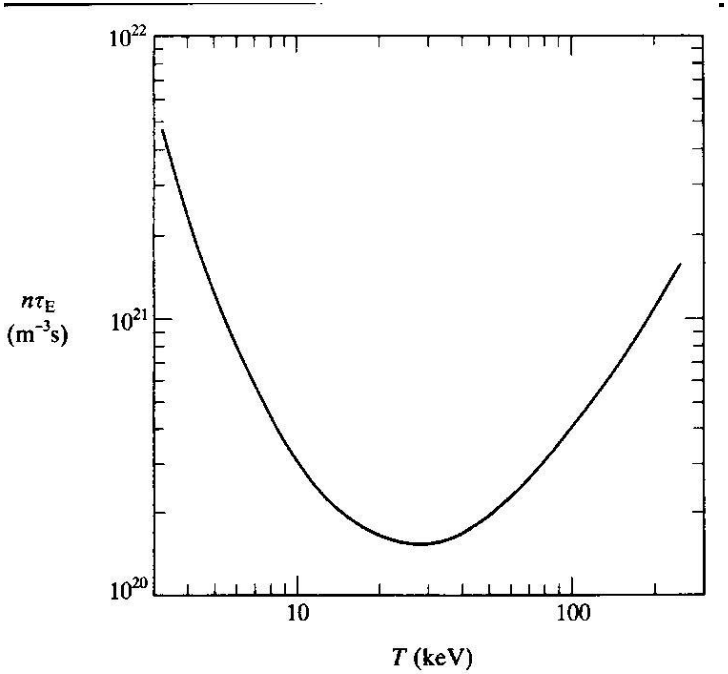
can be produced either by a toroidal net current, or by giving up axi-symmetry

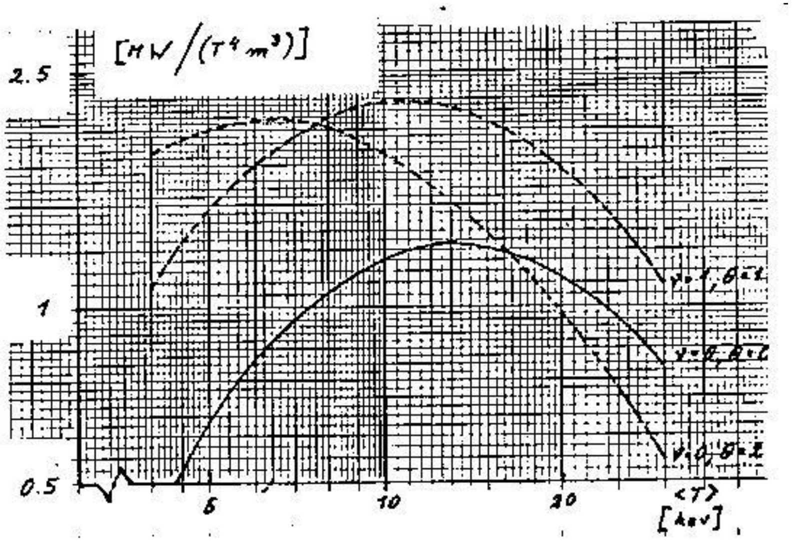


parameter regime of magnetic fusion

DT fusion requires T in 10 keV-range

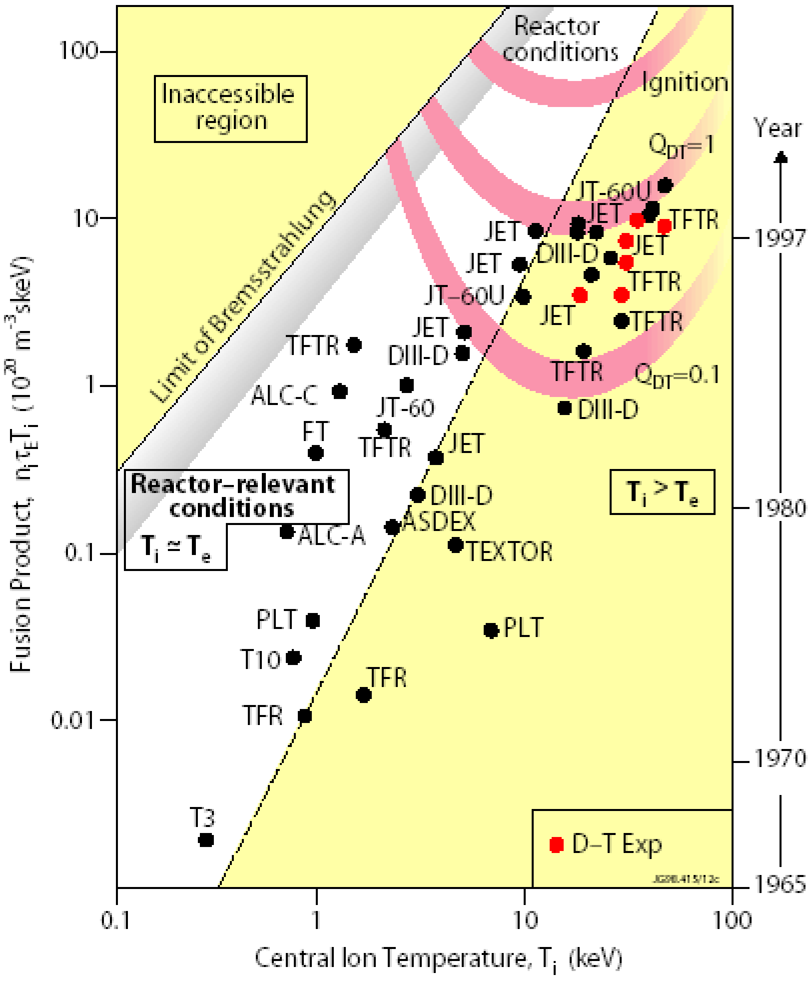
to balance conductive heat losses (~ nTV/τ_E)



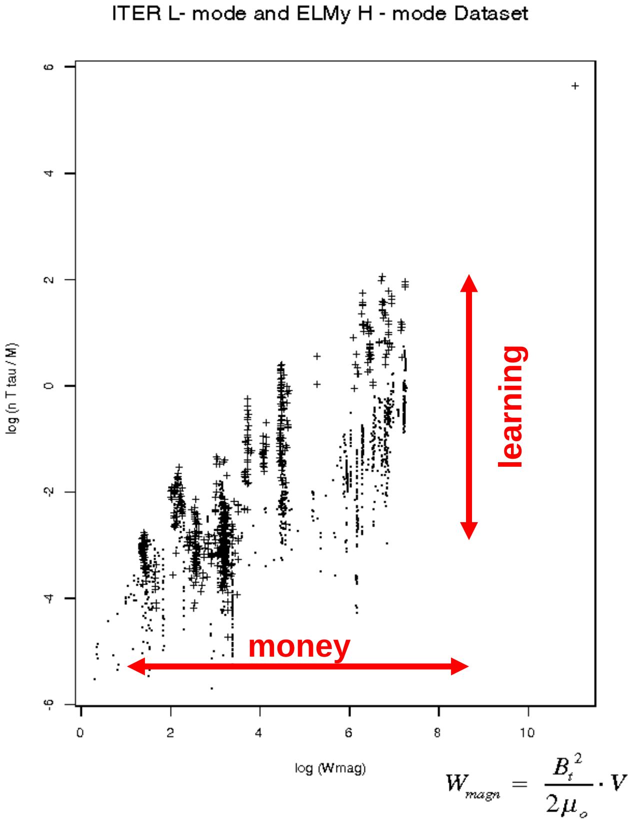


to maximize fusion power density (~ $p^2(\langle\sigma v\rangle/T^2)$)

the push to ignition (high Q ~nTτ)

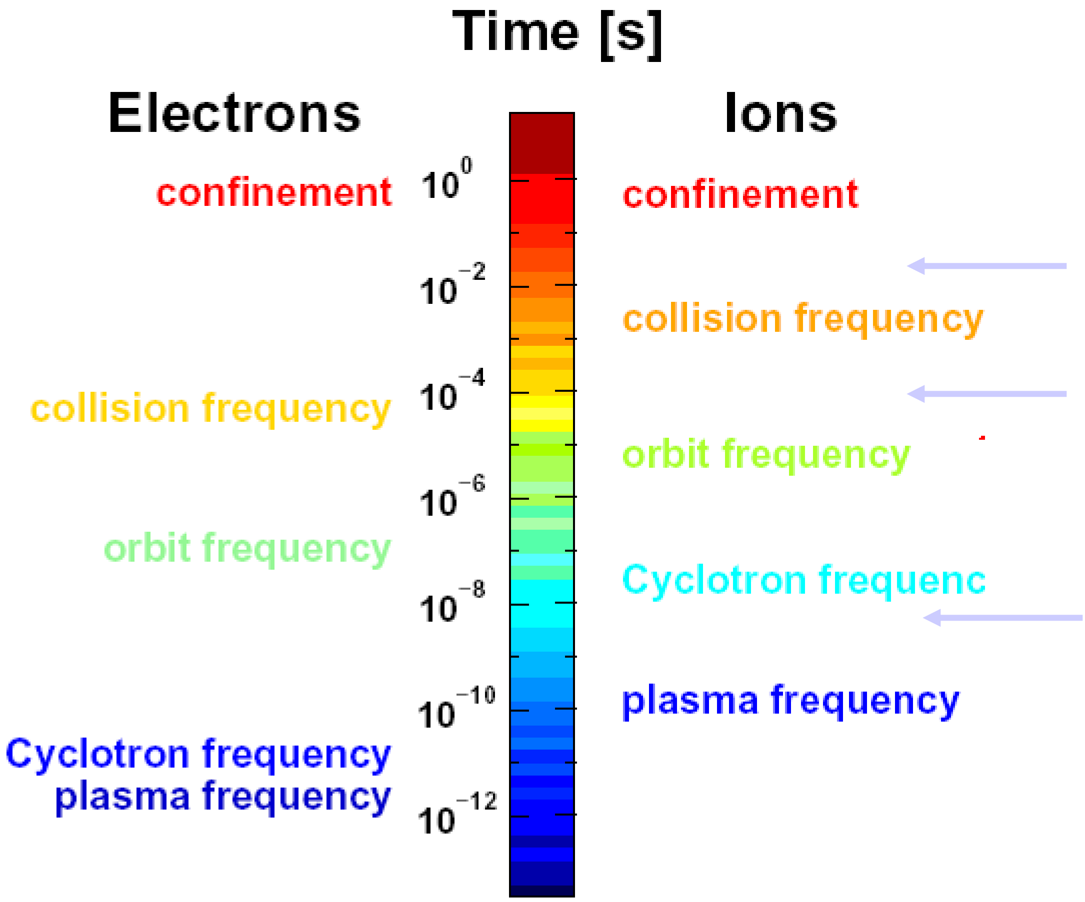


progress not only size and time, but also „new regimes“



$$W_{magn} = \frac{B_t^2}{2\mu_o} \cdot V$$

time scales of a of fusion plasma physics



Electrons

confinement

collision frequency

orbit frequency

Cyclotron frequency
plasma frequency

Ions

confinement

collision frequency

orbit frequency

Cyclotron frequenc

plasma frequency

both particle species are well thermalized - although not necessarily at $T_e = T_i$

Particles complete many orbits between 90^{o} deflections

Fusion plasmas can be generally considered quasineutral

basic science aspect of magnetic fusion plasmas

A quasi-neutral plasma (for given geometrical configuration) characterized by 3 dimensionless parameters - 4 dimensional ones: n,B,T, R

-> allows for „dimensionless identity experiments“

$$\rho_i = \rho / R = 0.0032\sqrt{\mu_i T}\,/(RB_t)$$

$$\nu * = Rq / \lambda_{mfp} = 10^{-22}\, Rn_e q / T^2$$

$$\beta_t = 8\times10^{-22}\, n_e T / B_t^2$$

finite orbit effects

collisionality

Plasma pressure modification of magnetic field

$$n_e = 1.3\times10^{16}\left(\frac{\mu}{R^2}\times\frac{\beta}{\rho^2}\right)$$

$$B_t = 1.1\times10^{-4}\left(\frac{q\mu^3}{R^5}\times\frac{\beta}{\nu\rho^6}\right)^{1/4}$$

$$T = 0.0011\left(\frac{q\mu}{R}\times\frac{\beta}{\nu\rho^2}\right)^{1/2}$$

Basic science - plasma physics interest:

- nearly collisionfree
- orbits small compared to dimensions
- plasma pressure significant

$$\nu * \sim \frac{\beta}{\rho *}\cdot\frac{1}{aT^2}$$

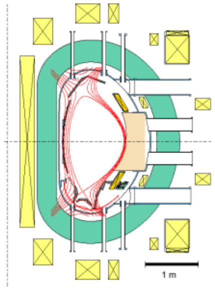
Applied (energy science) interest:

- fusion temperatures
- confinement
- effective use of magnetic pressure

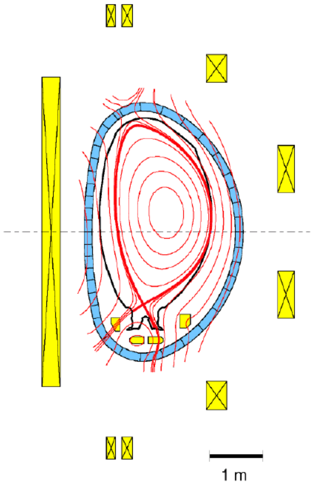
novelty of plasma physics regime of a reactor (ITER)

(ASDEX-Upgrade/DIII-D; JET/JT60-U are geometrically similar, scaled versions of ITER)

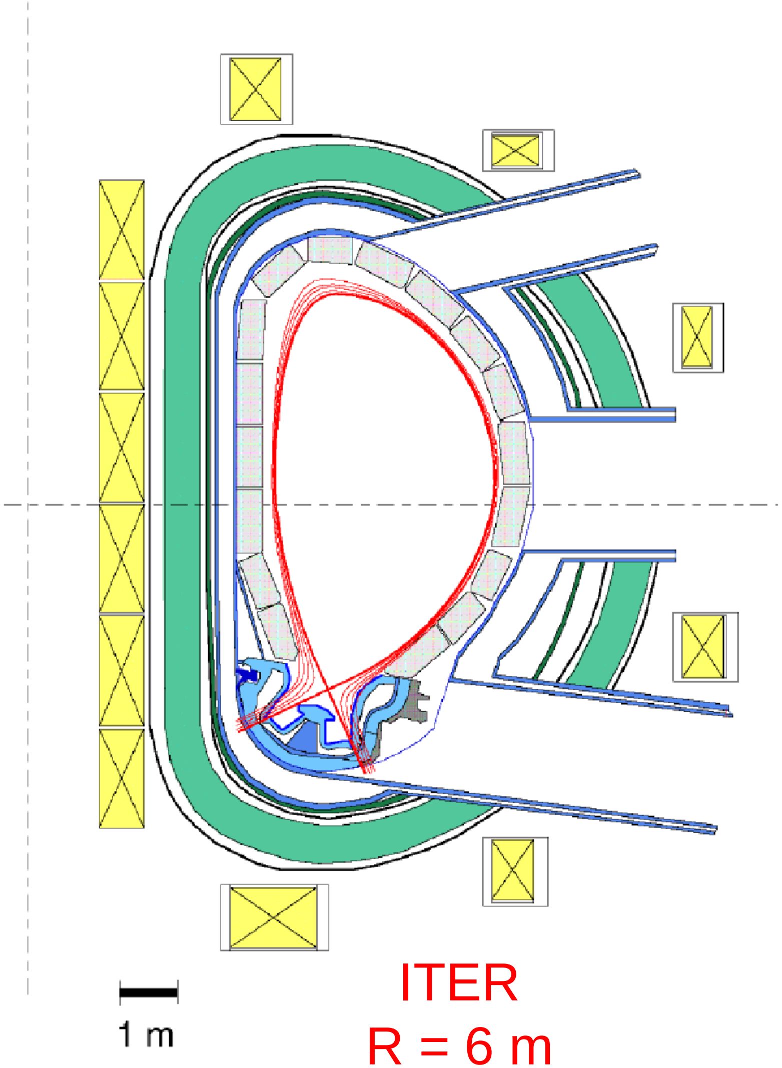
(examples EU)



ASDEX-Upgrade
R = 1.6m



JET
R = 3m



ITER
R = 6 m

novelty of plasma physics regime of a reactor (ITER)

We can define also dimensionless „machine properties“ (known a priori)

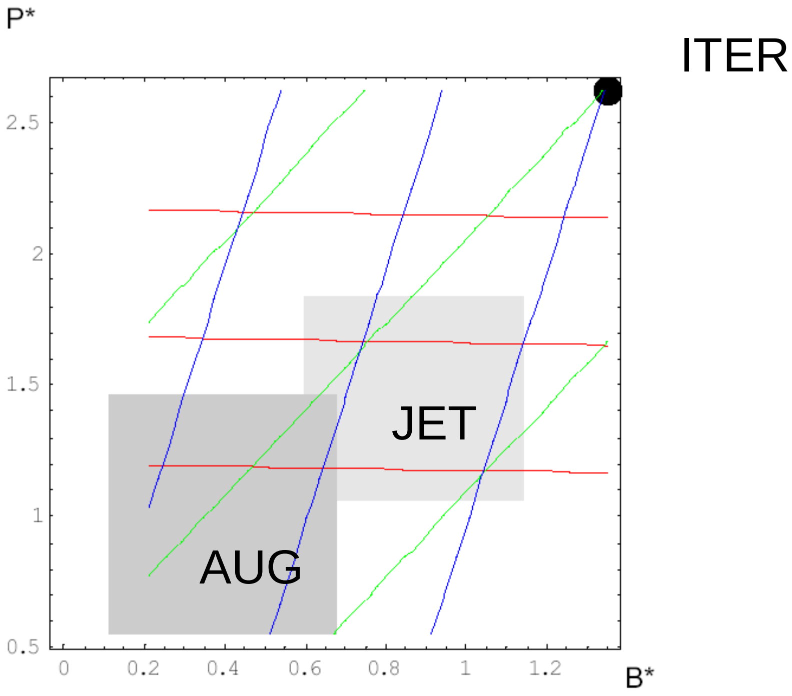


Fig 3: Lines of constant $\rho*$ (blue), $\nu*$(red), β(green) respectively, with contours a factor of two apart (for β and $\rho*$ decreasing from left to right, $\nu*$ decreasing from bottom to top).

at constant *n**, for ITER98(y,2)

$$B_t* = B_t a^{5/4}$$

$$P* = P_{heat} a^{3/4}$$

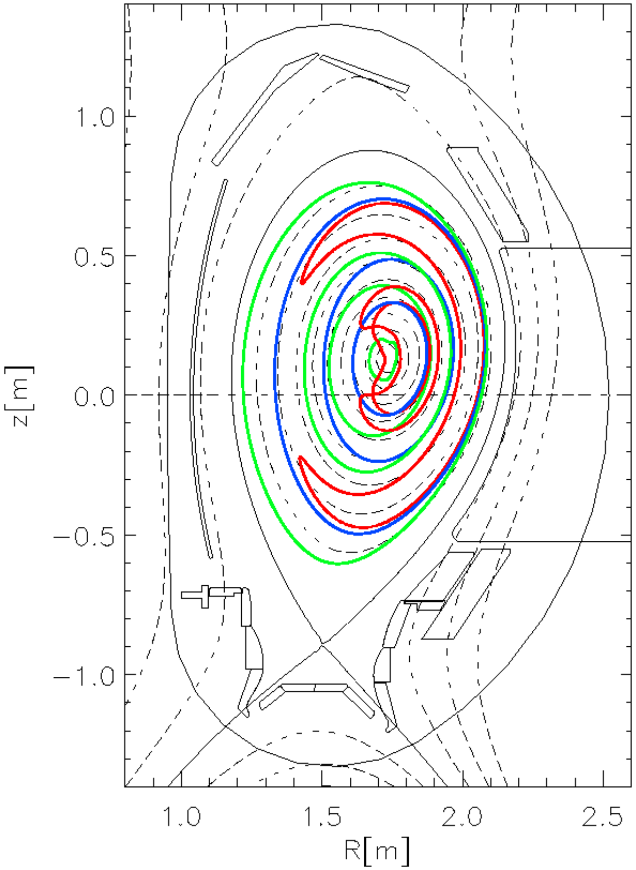
$$n* = \frac{na^{3/4}}{B_t}$$

ITER (and a reactor):

- will have similar β, n*
- $\rho*$, $\nu*$ significantly smaller

consequences of the nonlocal equilibrium distribution

finite orbit size, different orbit classes + steep gradients



in rigorous axisymmetry (ideal tokamak):

conservation of generalized toroidal momentum (in addition to magnetic moment and energy)

$$\mu = m v_\perp^{\,2} / \left(2\left|B\right|\right)$$
$$\varepsilon = m(v_\perp^2 + v_{//}^2)/2 + Ze\Phi$$
$$P_\phi = R\left(v_\phi + ZeA_\phi\right)$$

$RA_\phi = \Psi$...poloidal flux function

$f(\varepsilon,P) \approx e^{-\varepsilon / kT(P)}$

equilibrium distribution:

$$f(\varepsilon,P) \approx e^{-\varepsilon / kT(P)}$$

collisions tend to reconcile conflict between *g(P)* and $\gamma(\Psi)$ .... -> „neoclassical“ transport

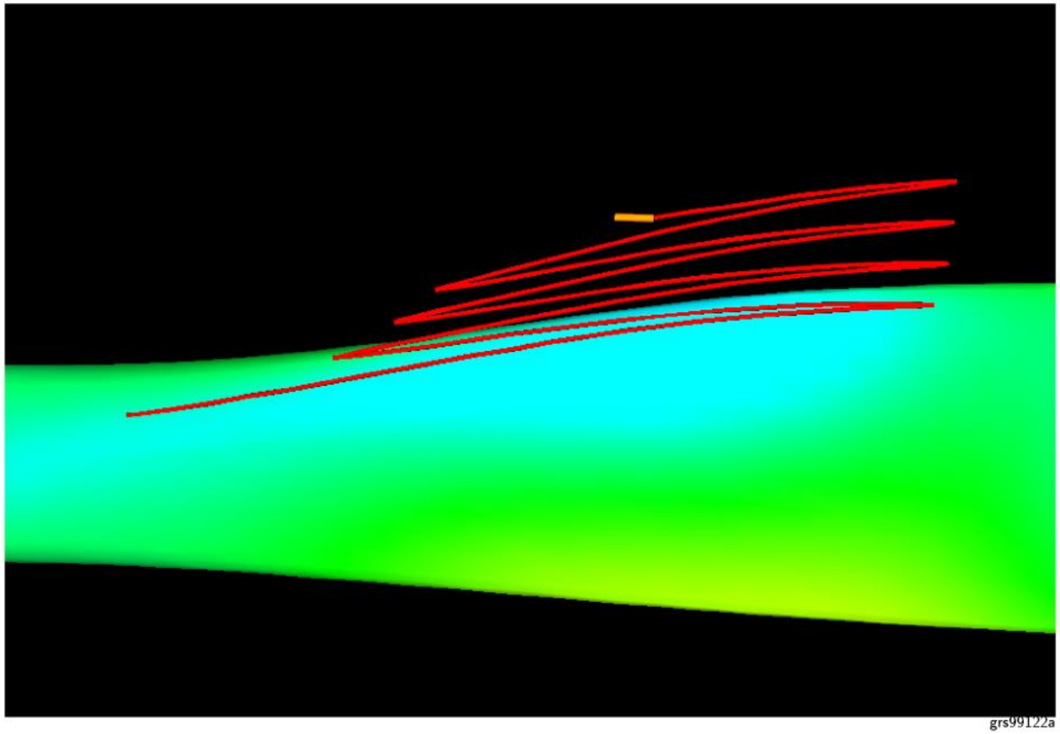
For tokamak:

- neoclassical transport resolved in 60ies
- broad range of implications: - off-diagonal terms
  - bootstrap-current (a pressure driven current)
  - Ware-Pinch (an E-field driven inward drift)

classical transport in a stellarator

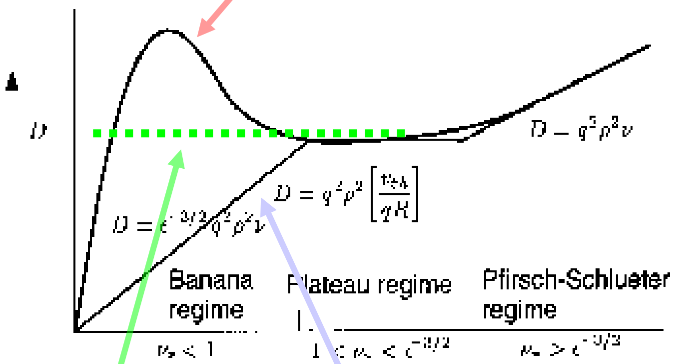
absence of „ignorable coordinate“ <->

no momentum-like constant of motion



gyration-averaged motion of particle on „loss-orbit“

collisional tansport in „non-optimized“ stellarator

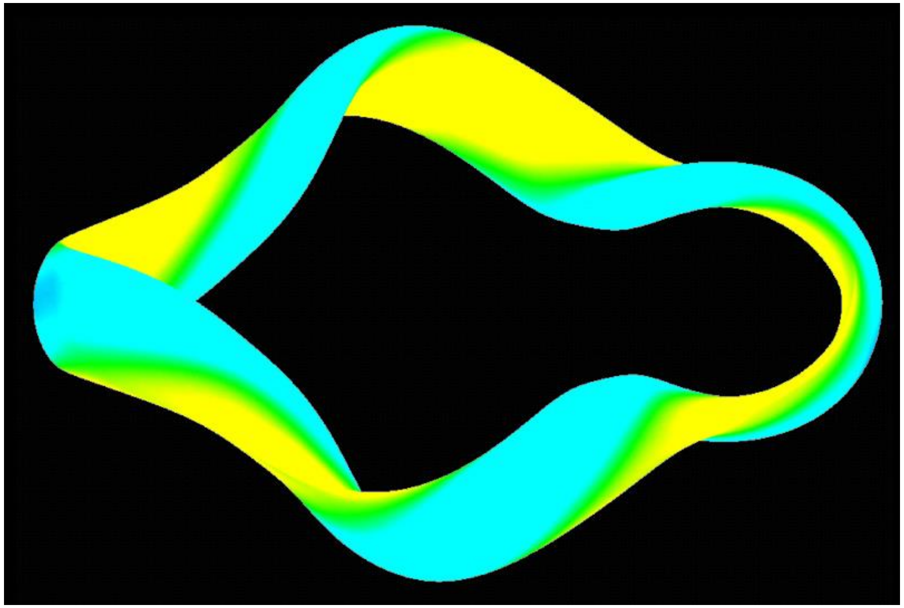


collisional tansport in tokamak

(typical level of) turbulent transport in tokamaks

Boozer/Nührenberg: otimized stellarator

In „drift-approximation“ (gyro-averaged motion): particle motion dependent only on variation of *|B|* on flux-surface ...“quasi-symmetry“

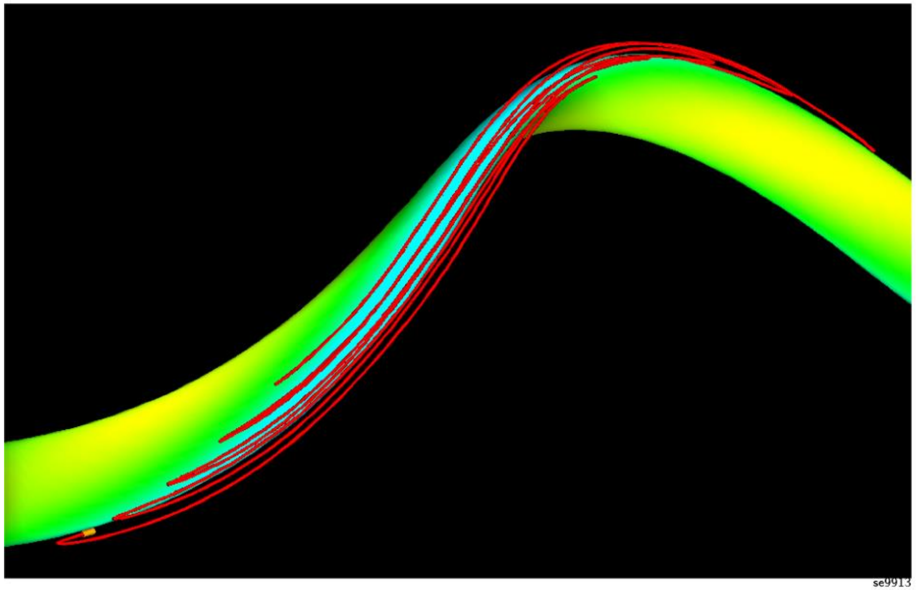


In quasi-symmetry: gyro-centers remain on closed surfaces

-> “tokamak-like” neoclassical transport

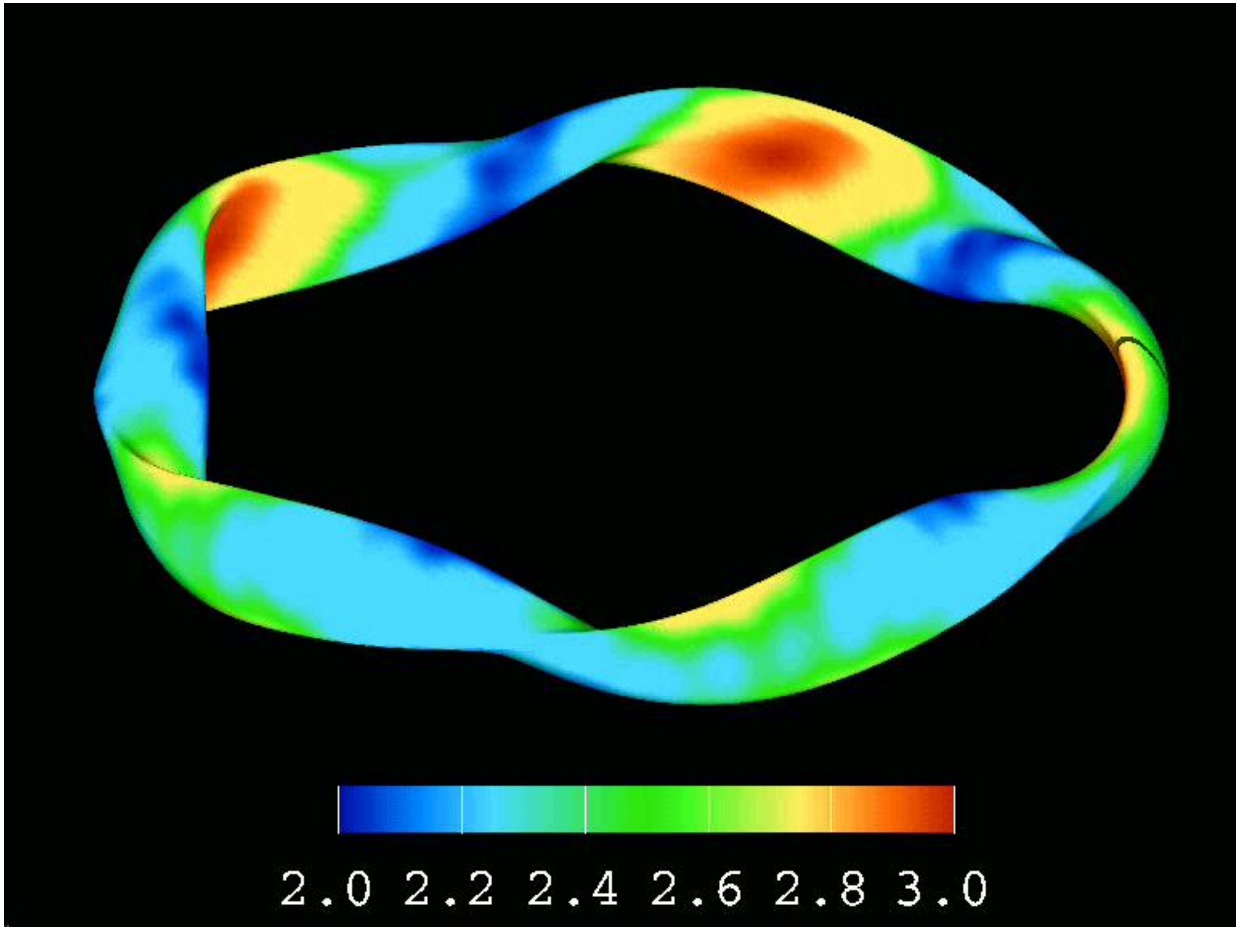
e.g.: quasihelikale Symmetrie

$B = B(s, \theta - \varphi)$



optimised stellarators: a field of vivid research on configurations

strict quasi-symmetry“ not needed for sufficient collisional confinement



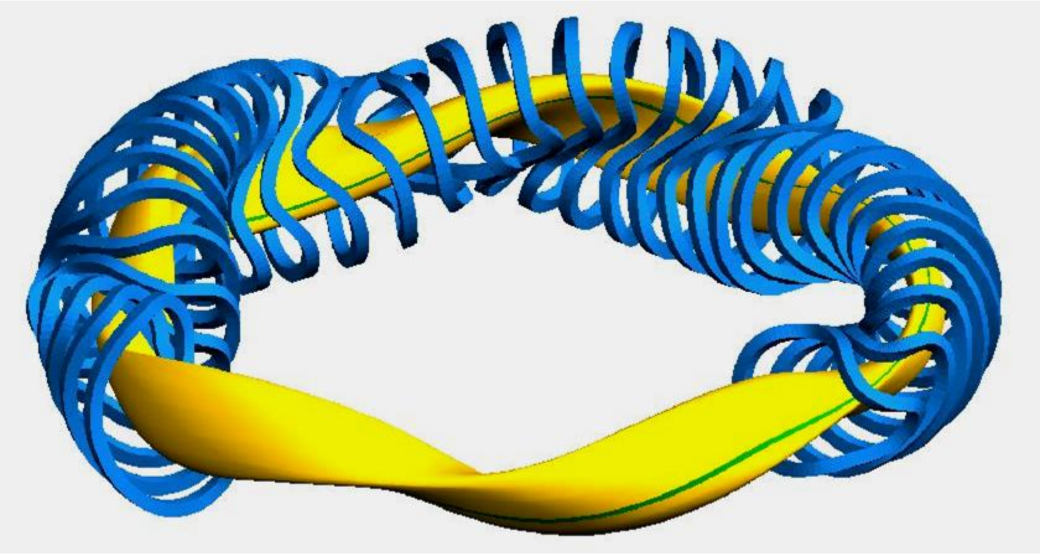
W7X

freedome can be used to satisfy additional requirements

optimised stellarators:
a field of vivid research on configurations

strict quasi-symmetry“ not needed for sufficient collisional confinement

- adequate collisional confinement
- high stable β
- suppression or utilisation of bootstrap-current
- characteristics of turbulent transport
- divertor compatibility
- reactor compatible coil configurations



most active magnetic confinement physics areas: (1) turbulence and turbulent transport

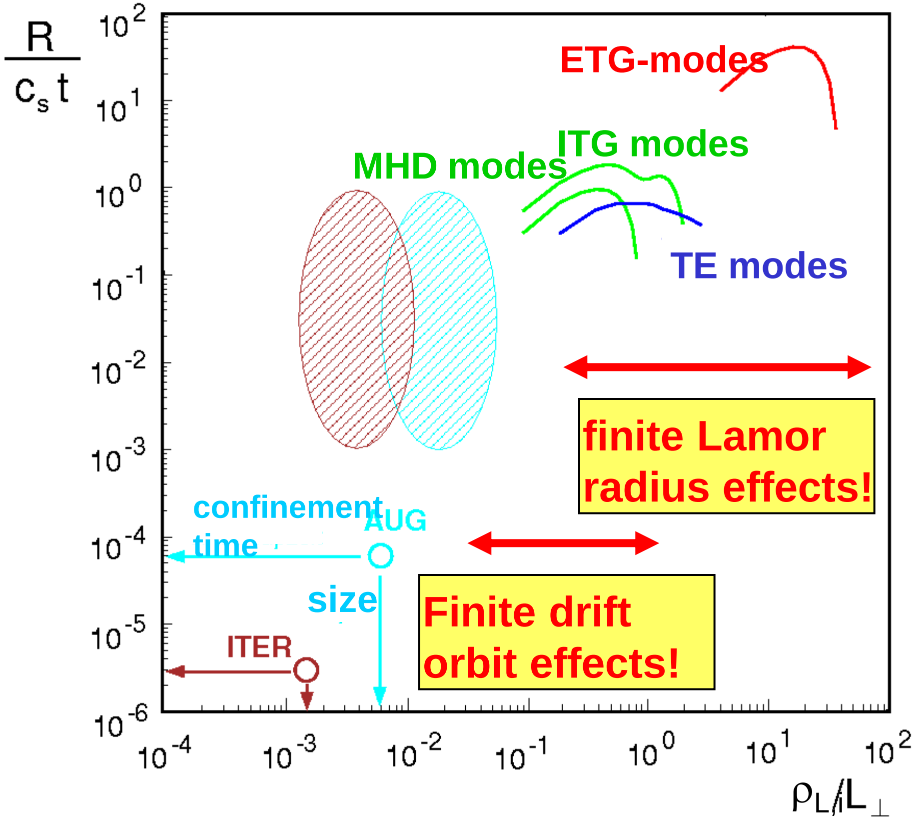
Turbulence (and nonlinear MHD) imply 3-d structures:
differences stellarator - tokamak diminish

1/t frequency unit: sound wave transit

L mode scale unit: ion gyroradius

unstable driving modes span broad range of space and time scales:

- **orbit effects and orbit classes of particles important**
- **(generally) kinetic description needed (only gyromotion can be treated by averages)**



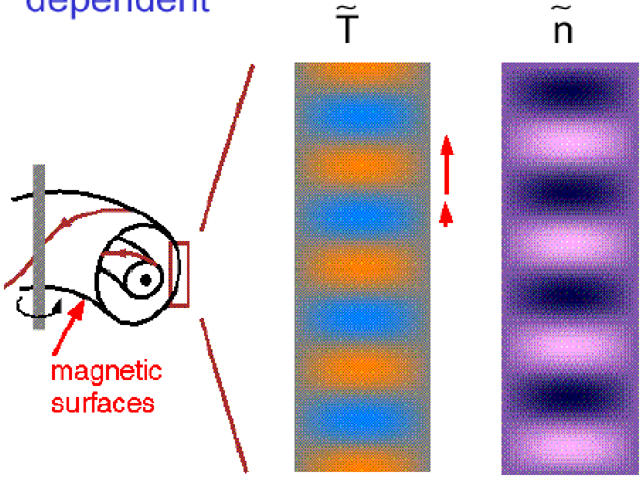
finite Lamor radius effects!

Finite drift orbit effects!

turbulence and turbulent transport:

(important) example: drive by ion-temperature gradient - instability

Drift due to inhomogeneous magnetic field is temperature dependent



$$\vec{V}_d = \frac{v_\parallel^2 + v_\perp^2/2}{\omega_c B} \vec{b} \times \nabla B$$

Initial temperature perturbation causes density perturbation (90° phase shift)

compression produces an E-field

$$\vec{E} = - \frac{T \nabla n_e}{e n_e}$$

E-field gives rise to a drift

$$\vec{v}_E = - \frac{c}{B^2} \vec{B} \times \vec{E}$$

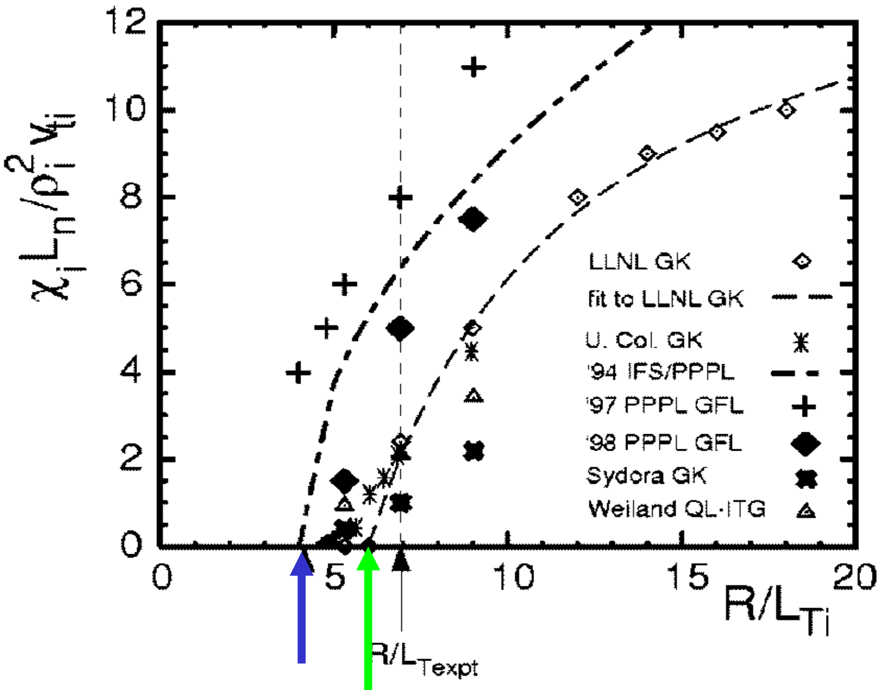
which on the “outer” side of the torus brings hot plasma from the core

- in phase with original perturbation

ITG turbulence predictions:

kinetic vs. fluid modelling:
cyclone benchmark case

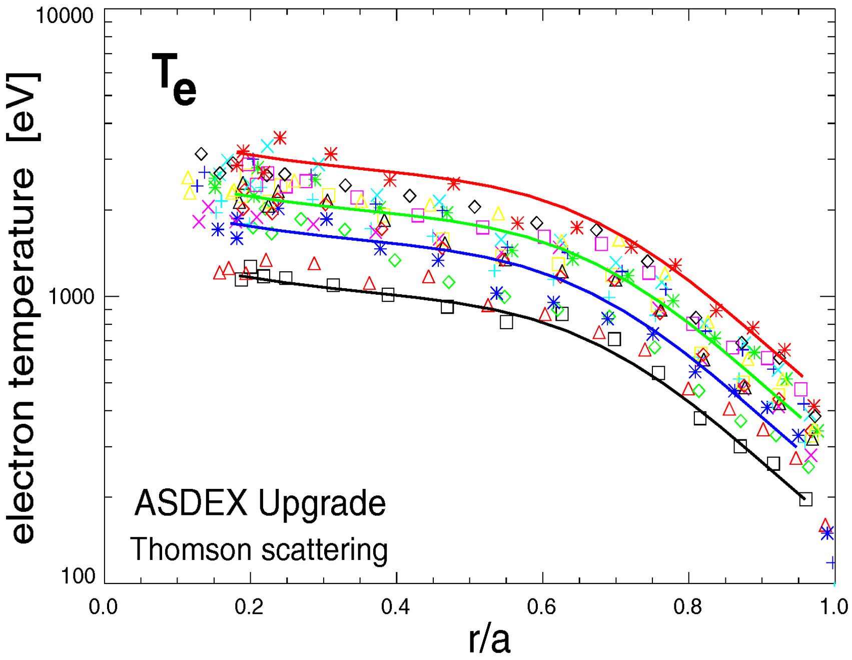
“critical gradient” R/L_{Ti} and steep rise of $\chi(R/L_{Ti})$ produce stiff logarithmic T-profiles



R/L_{Ti}, linear

GK: R/L_{Ti}, non-linear

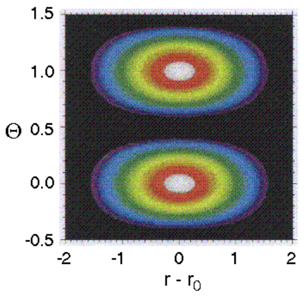
$$L_{Ti} = \left(\frac{\nabla T_i}{T_i}\right)$$

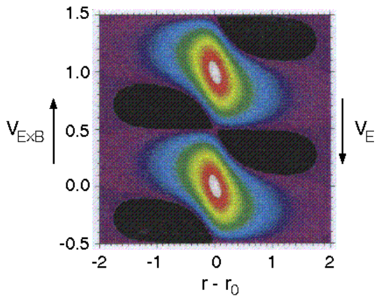


-> strong effect of edge *T*

the effect of sheared rotation:

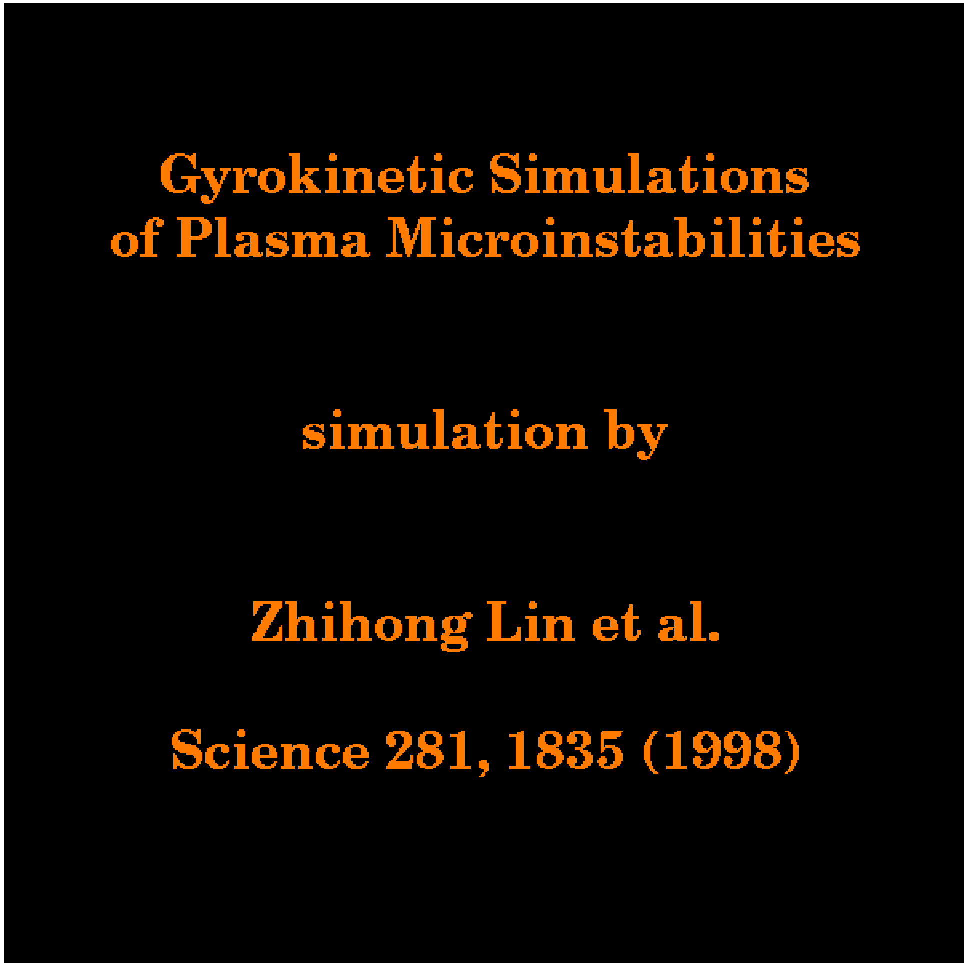
macroscopic sheared rotation squeezes /breaks radially extended eddies





radial transport proportional to radial eddy-size (~ correlation length)

turbulent Reynold stresses can self-generate macroscopic rotation*)



Gyrokinetic Simulations
of Plasma Microinstabilities

simulation by

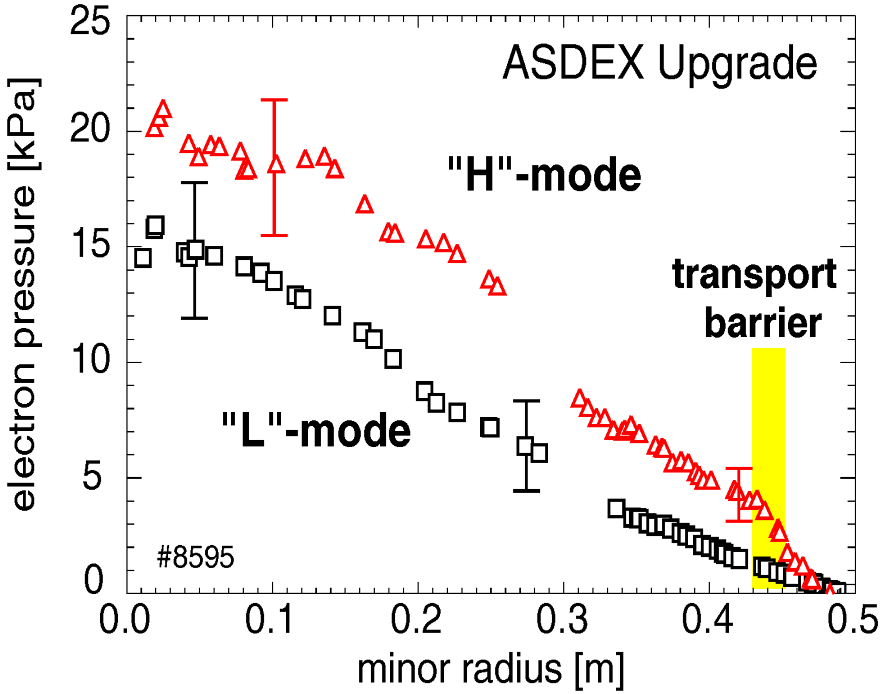
Zhihong Lin et al.

Science 281, 1835 (1998)

*) also fast-particle losses & neoclass. effects

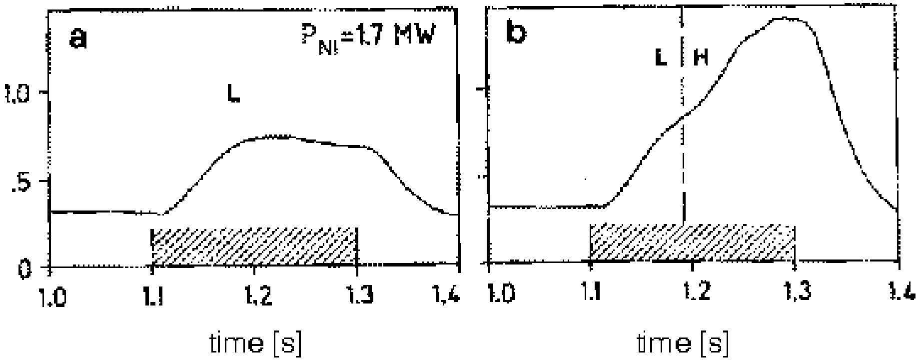
edge transport barriers

spontaneous formation of (narrow) zones of sheared rotation -> localized transport barrier



profile stiffness

- **amplifies edge pedestal**
- **bifurcation in confinement**



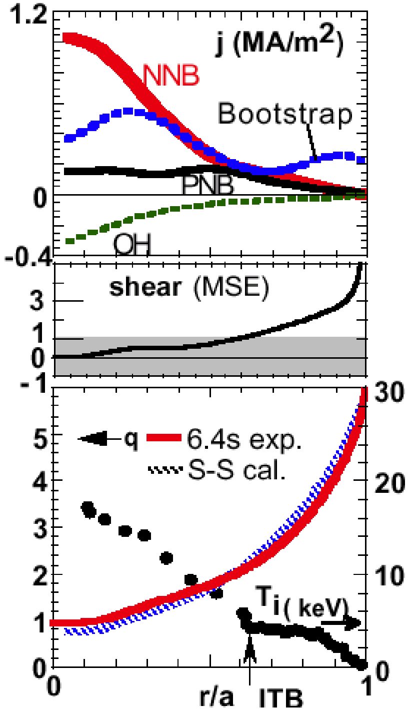
H-mode discovery on ASDEX (82)

internal transport barriers

variety of transport barriers also in plasma interior (also in combination with H-mode edge)

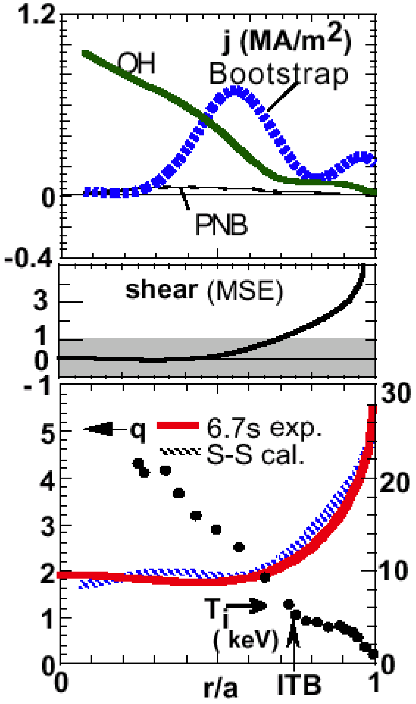
central CD+ bootstrap

$q_{95}=4.8$, $\beta_N=2.5$ HHy2=1.4



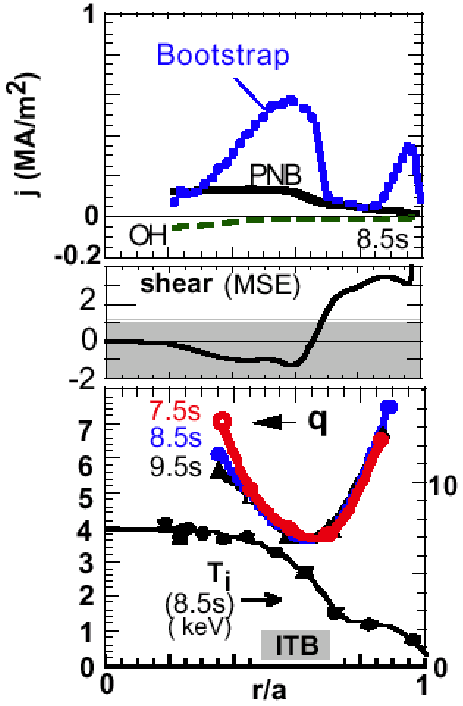
bootstrap

$\beta_N=2.8$ HHy2=1.5



broad CD + high bootstrap

$q_{95}=9.3$, $\beta_N=2.2$ HHy2=2.2



Importance: large bootstrap current

- **possibility of stationary operation**

issue: stationary control

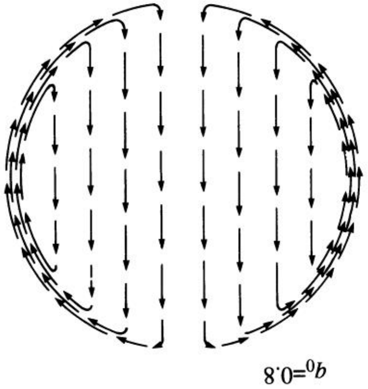
most active magnetic confinement physics areas: (2) fast particle interaction with global MHD modes

- **fusion α-heating unique; isotropic, $v_\alpha > v_{Alfven}$**
- **loss would imply loss of heating**

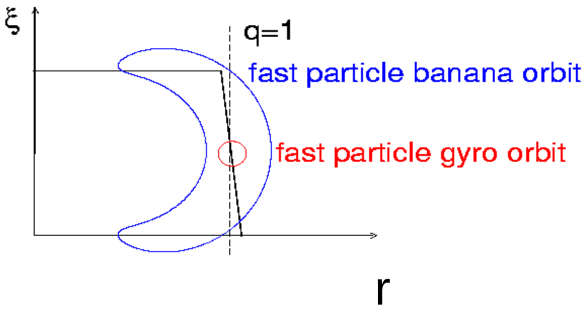
Detailled particle kinetics important for global mode interaction:

- **mode amplitude radial gradients over size of particles orbit**
- **resonance with particle motion**

displacement vector for m=1/n=1 mode



Large gradients in field perturbation

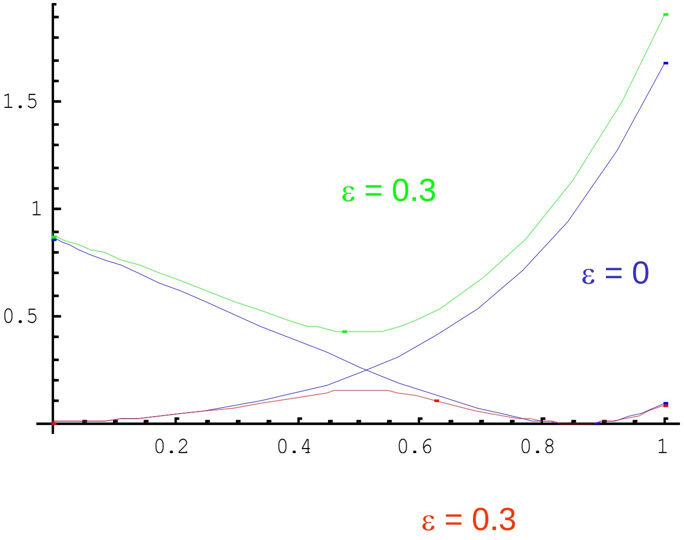


modes driven by resonance with particle motion: Alfvén-type modes

- **resonance with existing, marginally stable mode**
- **energy for mode growth from expansion energy**
  - **not accelerated slowing down but confinement loss**

cylinder:

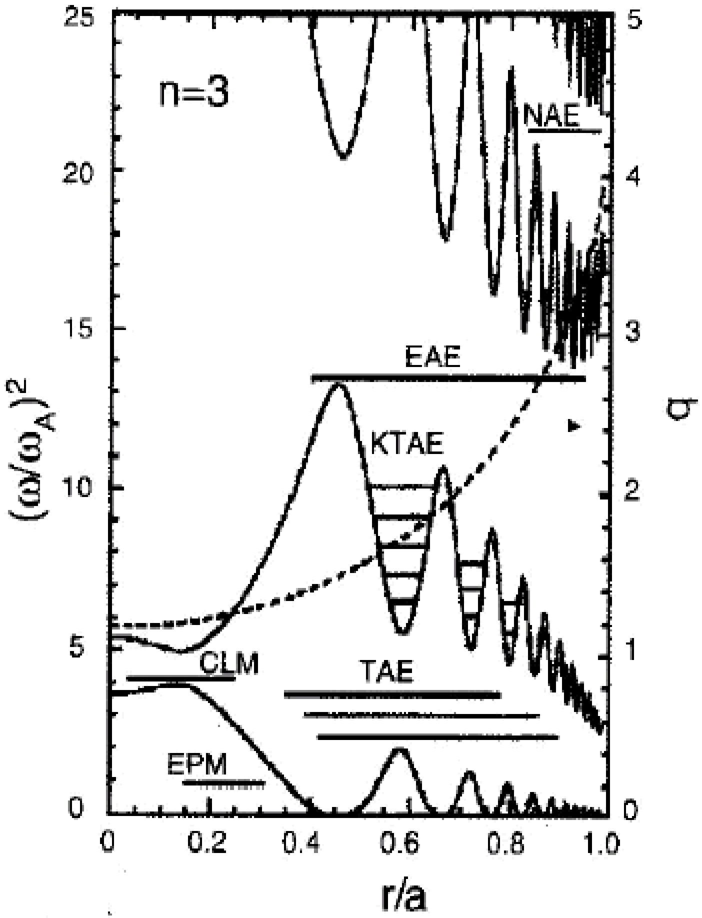
- continuum of localized modes
- phase mixing -> continuum damping



toroidal (or other) coupling:

- gaps
- global modes - excitable

realistic situation



TAE ....toroidicity

EAE ... ellipticiy

NAE ... triangularity induced Alfven eigenmodes

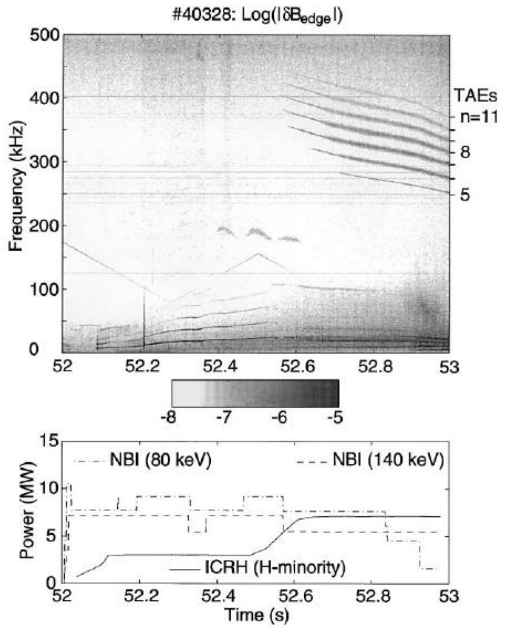
KTAE kinetic toroidicity...

CLM core localized TAEs

theoretical understanding & experimental verification

- **frequencies very precise (diagnostic tool)**
- **competition between stabilizing (other fast particles) - destabilizing terms good:**

  dependence on detailed particle distribution

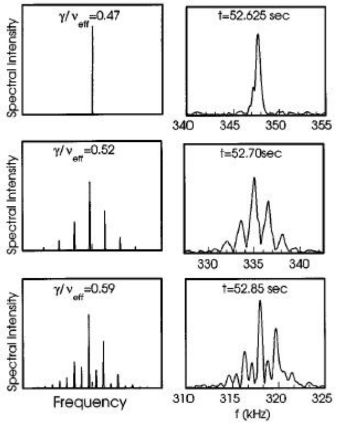


Manipulation of distribution function by heating method

explanation and modelling of nonlinear splitting as function of instability drive by

trapping of particles in wave

JET



theoretical understanding & experimental verification

observation of α-particle produced TAEs in deuterium-tritium experiments on TFTR

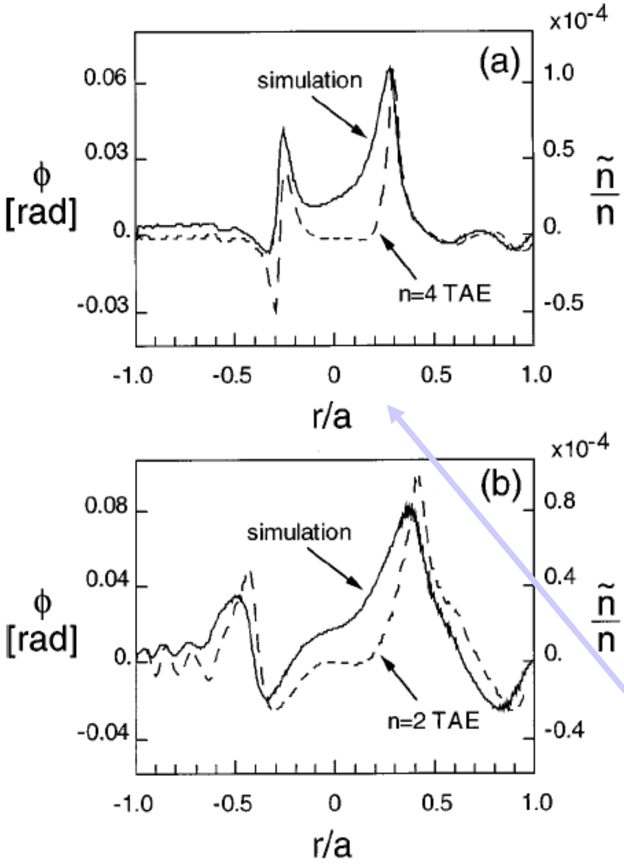
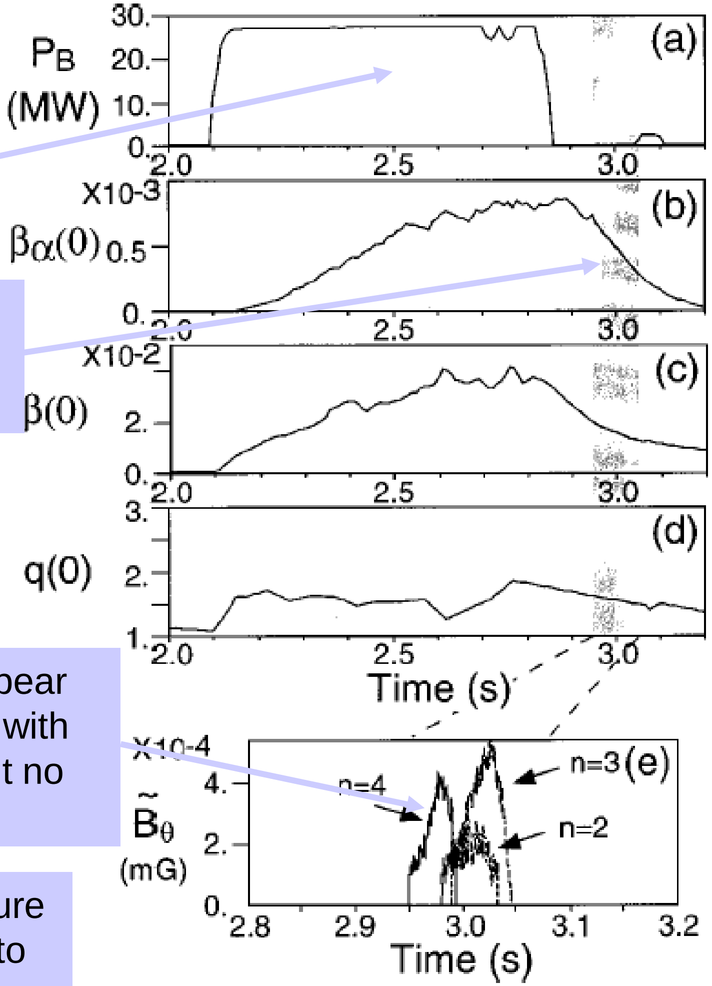


FIG. 9. Simulation of reflectometer phase measurement (solid line) of TAE



Damping by NBI supresses TAE

α-particle slowing - down slower

TAEs appear in phase with still α, but no NBI

Measured structure correspond well to simulation

Summary & Conclusions

in physics:

basic science interest the laboratory realization of plasmas, which are/have

- nearly collision-free,
- strongly magnetized,
- high kinetic/magnetic pressure ratio

and

requirements for realization of a burning plasma

are practically collinear

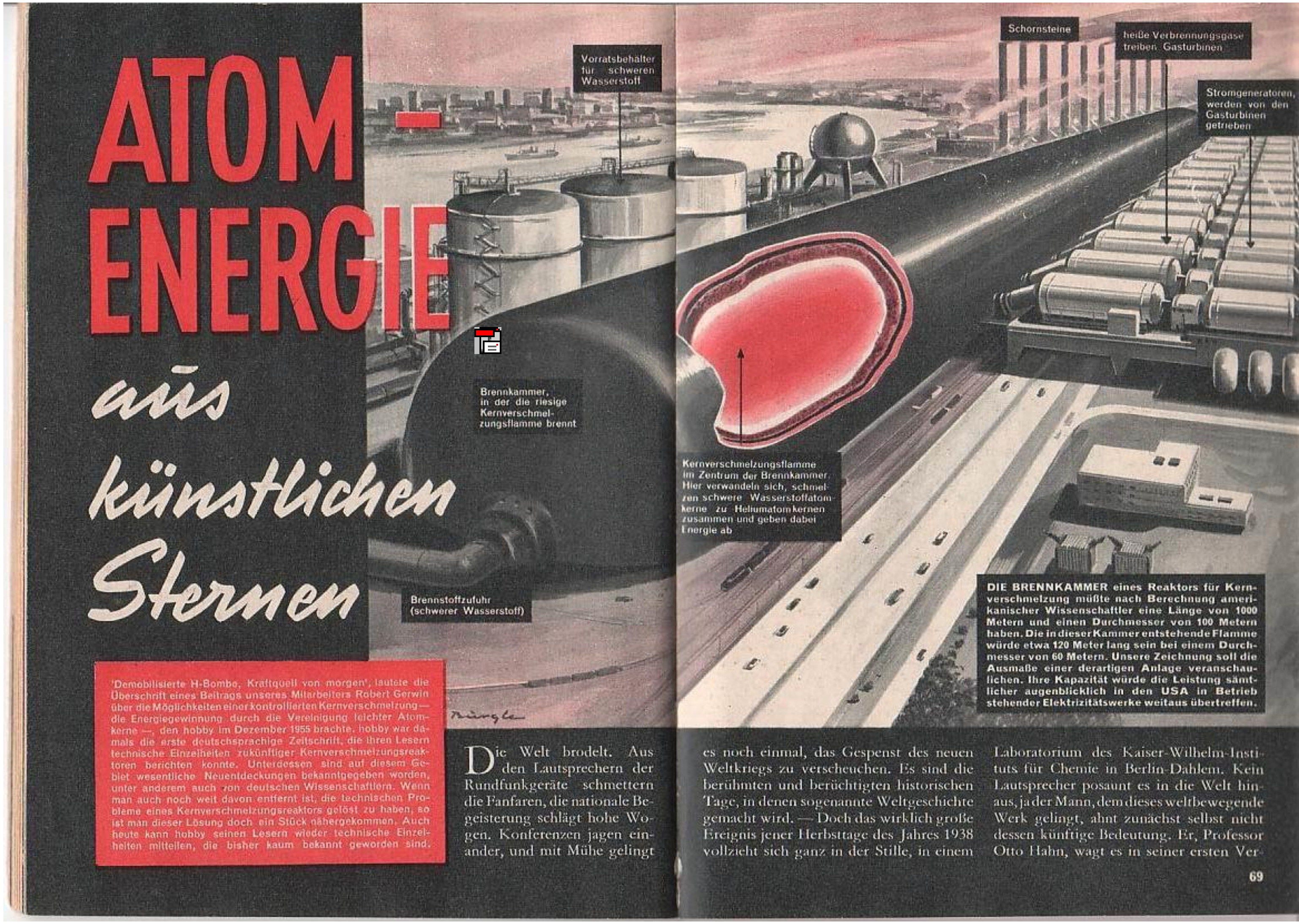
$$\nu^* \sim \frac{\beta}{\rho^*} \cdot \frac{1}{aT^2}$$

we are currently preparing construction/building two exciting, very different experiments:

ITER & W7-X

fusion: a vision from 50 years ago

hobby
Das Magazin der Technik
AUGUST 1957
JAHRGANG V



ATOM-ENERGIE aus künstlichen Sternen

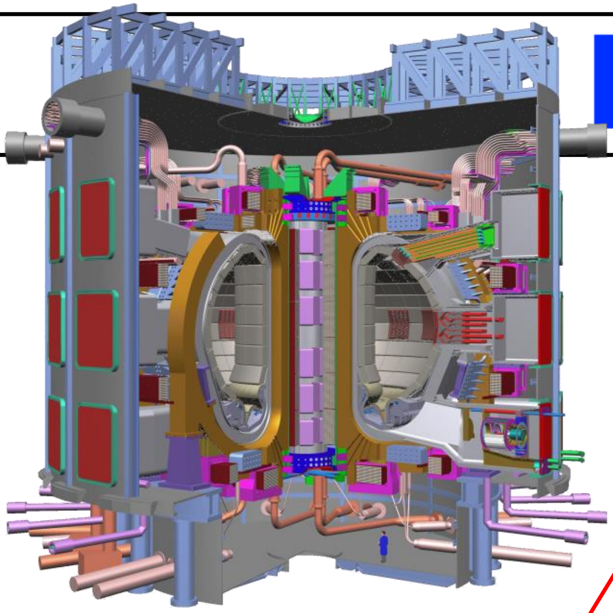
'Demobilisierte H-Bombe, Kraftquell von morgen', lautete die Überschrift eines Beitrags unseres Mitarbeiters Robert Gerwin über die Möglichkeiten einer kontrollierten Kernverschmelzung — die Energiegewinnung durch die Vereinigung leichter Atomkerne —, den hobby im Dezember 1955 brachte. hobby war damals die erste deutschsprachige Zeitschrift, die ihren Lesern technische Einzelheiten zukünftiger Kernverschmelzungsreaktoren berichten konnte. Unterdessen sind auf diesem Gebiet wesentliche Neuentdeckungen bekanntgegeben worden, unter anderem auch von deutschen Wissenschaftlern. Wenn man auch noch weit davon entfernt ist, die technischen Probleme eines Kernverschmelzungsreaktors gelöst zu haben, so ist man dieser Lösung doch ein Stück nähergekommen. Auch heute kann hobby seinen Lesern wieder technische Einzelheiten mitteilen, die bisher kaum bekannt geworden sind.

DIE BRENNKAMMER eines Reaktors für Kernverschmelzung müßte nach Berechnung amerikanischer Wissenschaftler eine Länge von 1000 Metern und einen Durchmesser von 100 Metern haben. Die in dieser Kammer entstehende Flamme würde etwa 120 Meter lang sein bei einem Durchmesser von 60 Metern. Unsere Zeichnung soll die Ausmaße einer derartigen Anlage veranschaulichen. Ihre Kapazität würde die Leistung sämtlicher augenblicklich in den USA in Betrieb stehender Elektrizitätswerke weitaus übertreffen.

Die Welt brodelt. Aus den Lautsprechern der Rundfunkgeräte schmettern die Fanfaren, die nationale Begeisterung schlägt hohe Wogen. Konferenzen jagen einander, und mit Mühe gelingt es noch einmal, das Gespenst des neuen Weltkriegs zu verscheuchen. Es sind die berühmten und berüchtigten historischen Tage, in denen sogenannte Weltgeschichte gemacht wird. — Doch das wirklich große Ereignis jener Herbsttage des Jahres 1938 vollzieht sich ganz in der Stille, in einem Laboratorium des Kaiser-Wilhelm-Instituts für Chemie in Berlin-Dahlem. Kein Lautsprecher posaunt es in die Welt hinaus, ja der Mann, dem dieses weltbewegende Werk gelingt, ahnt zunächst selbst nicht dessen künftige Bedeutung. Er, Professor Otto Hahn, wagt es in seiner ersten Ver-

69

from science fiction to the blueprints of a test reactor



ITER
(scaled)

hobby
Das Magazin der Technik
AUGUST 1957
JAHRGANG V