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E.R. Solano, J. Jacquinot et al

Introduction to Fusion Research at JET

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Information from the JET team and collaborators, compiled by. E. R. Solano and J. Jacquinot.

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and collaborators:
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From time to time, fusion researchers are called upon to give a talk about fusion or tokamaks to an audience of non-specialists.

The set of transparencies that form this report was made and collected to facilitate that task. Some basic concepts are explained, defined and illustrated. Where examples or illustrations are called for, relevant JET results are presented. The authors are indebted to the JET team researchers and collaborators for information, ideas and material.

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This report should not be quoted as a reference in scientific publications: the original sources of information should be sought and quoted instead.

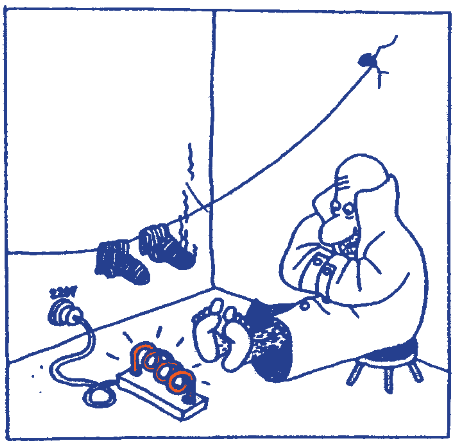
Fusion, Energy

Fusion – Main issues

Heating

- Ohmic
- Neutral Beam Injection
- Ion Cyclotron Resonance
- Lower Hybrid systems
- α particle heating

➡ 350 Million °C



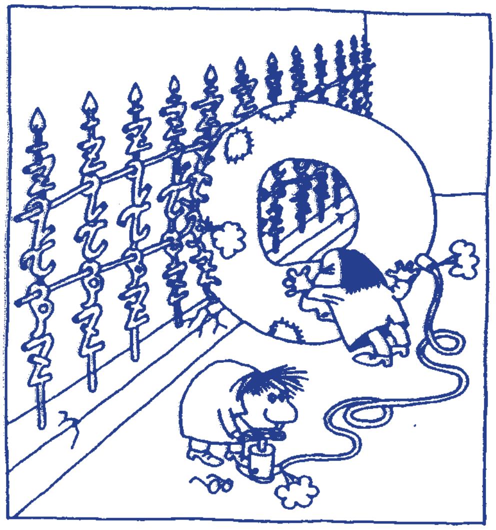
Containment

Tokamak (Toroidal device)

- Particle orbits
- MHD instabilities
- Micro-instabilities

➡ Anomalous transport

- Scaling laws
- Bifurcations



Impurities

- Heat and particle exhaust
- Plasma surface interactions

➡ Edge and divertor physics

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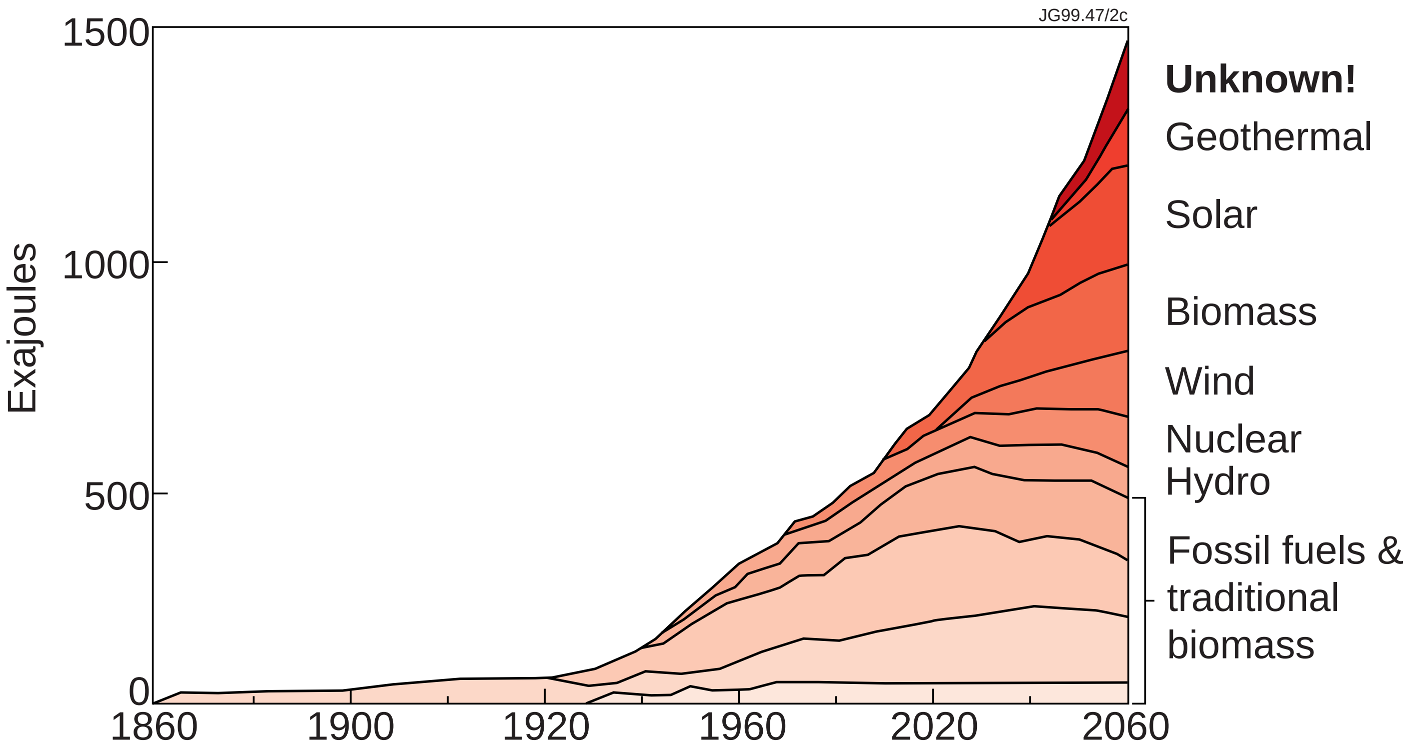
How can Fusion help our Energy needs?



Shell Oil company scenario for sustainable growth in 2060

Fusion Energy – Advantages

- **Fusion fuels have very large energy density:**
  - ***1 gram*** of fully reacted ***Deuterium-Tritium*** fuel gives around about ***26000 kW·hr*** of ***electricity***, enough for about 5000 households for 1 day.
  - ***1 gram*** of fully burnt ***Coal*** gives only about ***3W.hr*** of ***electricity (ie 10 million times less)***

- **Fusion fuels are abundant and geographically widespread:**
  - ***Deuterium*** (extracted from sea water), enough for ***300 thousand million years***
  - ***Tritium*** is made from ***Lithium*** using a fusion reaction.
  - ***Lithium*** (abundant on land and in the oceans), enough for ***about 2000 years***

Fusion Energy – Advantages (continued)

- **Fusion fuels are 'clean':**
  - Fusion does not give rise to Greenhouse gases (CO_2) or Acid rain gases (SO_2, NO_2)

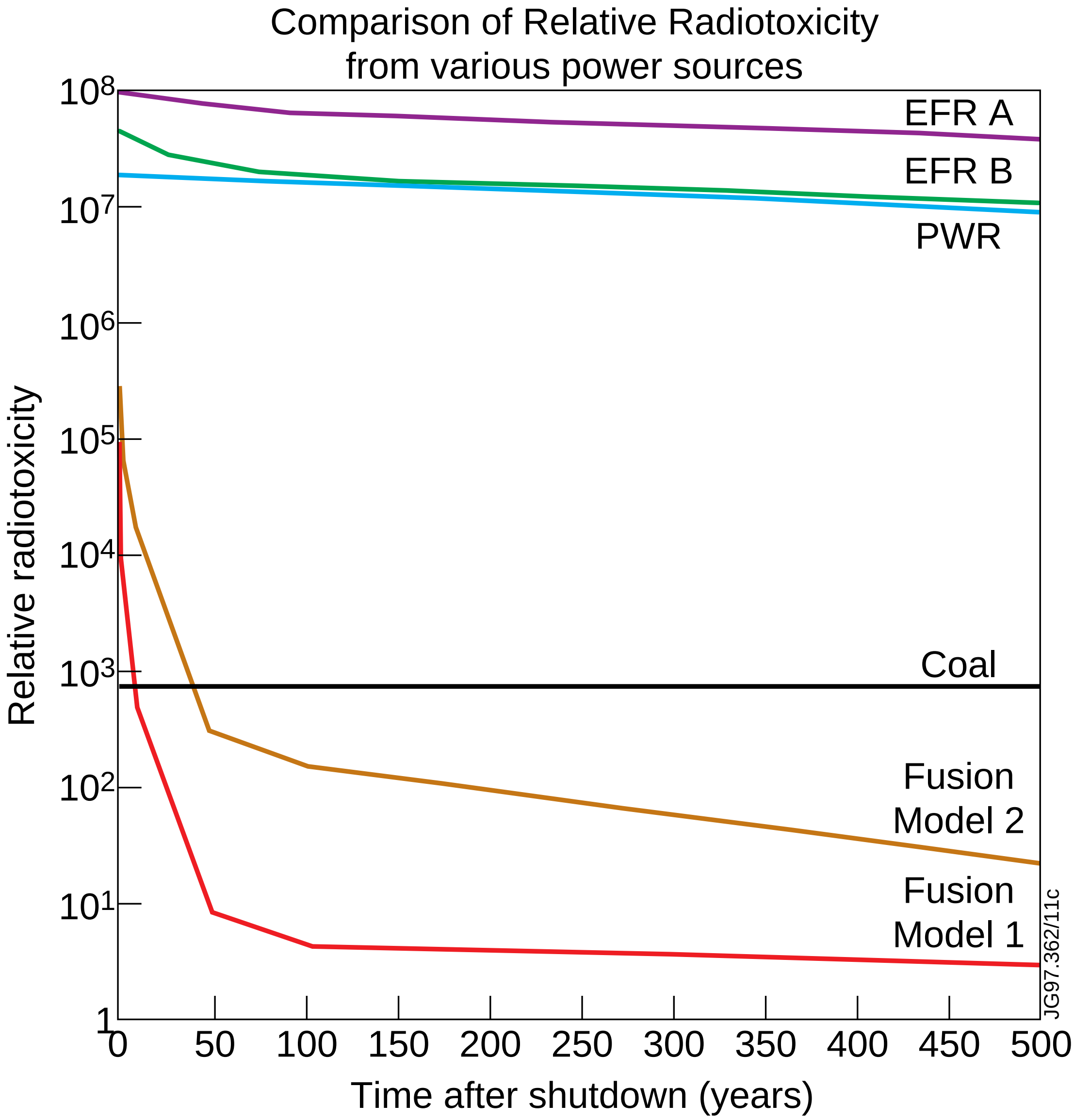
- **Fusion reactors are inherently safe:**
  - A very small quantity of fuel is kept in the reactor region (only enough for a few tens of seconds operation)
  - 'Critical' or 'meltdown' situations associated with Nuclear Fission are physically impossible
  - Accidents are self limiting and Public evacuation would not be necessary

Fusion Energy – Advantages (continued)

- **Fusion fuels are not involved in nuclear proliferation problems:**
  - No plutonium
  - Tritium remains on site in the fuel cycle

- **Fusion reactors leave no long lived highly radioactive waste:**
  - No long-lived radioactive waste from the fuel cycle
  - After around 100 years the Fusion reactor using selected materials would only leave low level radio-active structural components

No Long-lived Radioactivity after Shutdown



'Fusion Model 1': advanced materials (Vanadium alloys) requires development

'Fusion Model 2': Low activation Stainless Steel/ water cooled

Near-term technology

Fusion Energy – Disadvantages

- **Fusion reaction is difficult to start!**

  High temperatures (Millions of degrees) in a pure High Vacuum environment are required

  Technically complex and ***high capital cost*** reactors are necessary

- **More Research and Development is needed to bring concept to fruition**

  The physics is well advanced but requires sustained development on a long time scale (20 to 40 years)

JET Project
&
Device

Fusion research: Science and Energy

Research is mission-driven.

JET has a clearly defined objective:

"to obtain and study a plasma in conditions and dimensions approaching those needed in a thermonuclear reactor. These studies will be aimed at defining the parameters, the size and the working conditions of a Tokamak reactor."

This requires work in four main areas:

(i) The study of scaling of plasma behavior as parameters approach the reactor range;

(ii) The study of plasma-wall interaction in these conditions;

(iii) The study of plasma heating;

(iv) The study of alpha-particle production, confinement and consequent plasma heating.

JET

- A European project "***to obtain and study plasmas in conditions and dimensions approaching those needed in a reactor. These Studies will be aimed at defining the parameters, the size and the working conditions of a Tokamak reactor***."

- In practice:
  - Size adequate to confine α particles $\rightarrow$ $I_p \gtrsim 3MA$, $R \gtrsim 3m$
  - 30 MW of heating (several methods)
  - Flexibility in:
  - Plasma topology
  - Heat and particle exhaust.

- Members: the European Commission and all the EU countries (+ Switzerland) working in fusion

- Budget ~ 70 million Euros

- Operated since 1983

Objectives of JET

The essential objective of JET, set originally (1975), is:

"to obtain and study a plasma in conditions and dimensions approaching those needed in a thermonuclaer reactor. These studies will be aimed at defining the parameters, the size and the working conditions of a Tokamak reactor."

This requires work in four main areas:

(i) The study of scaling of plasma behaviour as parameters approach the reactor range;
(ii) The study of plasma-wall interaction in these conditions;
(iii) The study of plasma heating;
(iv) The study of alpha-particle production, confinement and consequent plasma heating.

Objective of New Phase (1992-1996) is to establish in deuterium:

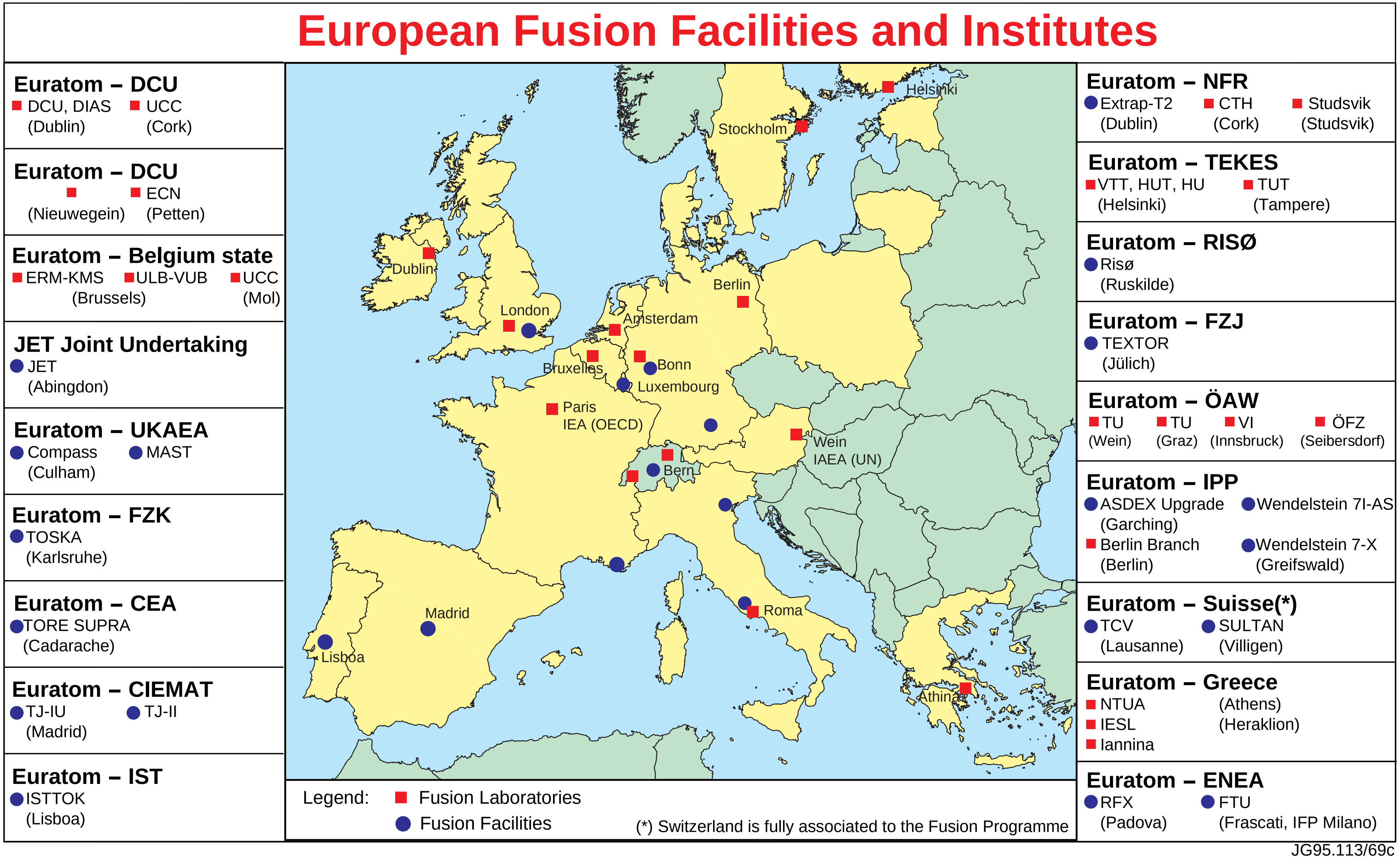
"reliable methods of plasma purity control under conditions relevant for the Next Step Tokamak"

Purpose of the present programme (to end–1999) is:

"to provide further data of relevance to ITER"

- In particular, to:
  (i) make essential contributions to the **development and demonstration of a viable divertor concept for ITER**,
  (ii) carry out experiments using **deuterium-tritium plasmas** in an **ITER-like configuration**;

  while allowing key **ITER-relevant technology activities**, such as the demonstration of **remote handling and tritium handling,** to be carried out.



European Fusion Facilities and Institutes
Euratom – DCU
DCU, DIAS (Dublin)
UCC (Cork)
Euratom – DCU
(Nieuwegein)
ECN (Petten)
Euratom – Belgium state
ERM-KMS
ULB-VUB
(Brussels)
UCC (Mol)
JET Joint Undertaking
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TORE SUPRA (Cadarache)
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TJ-II
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Euratom – TEKES
VTT, HUT, HU (Helsinki)
TUT (Tampere)
Euratom – RISØ
Risø (Ruskilde)
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FTU (Frascati, IFP Milano)
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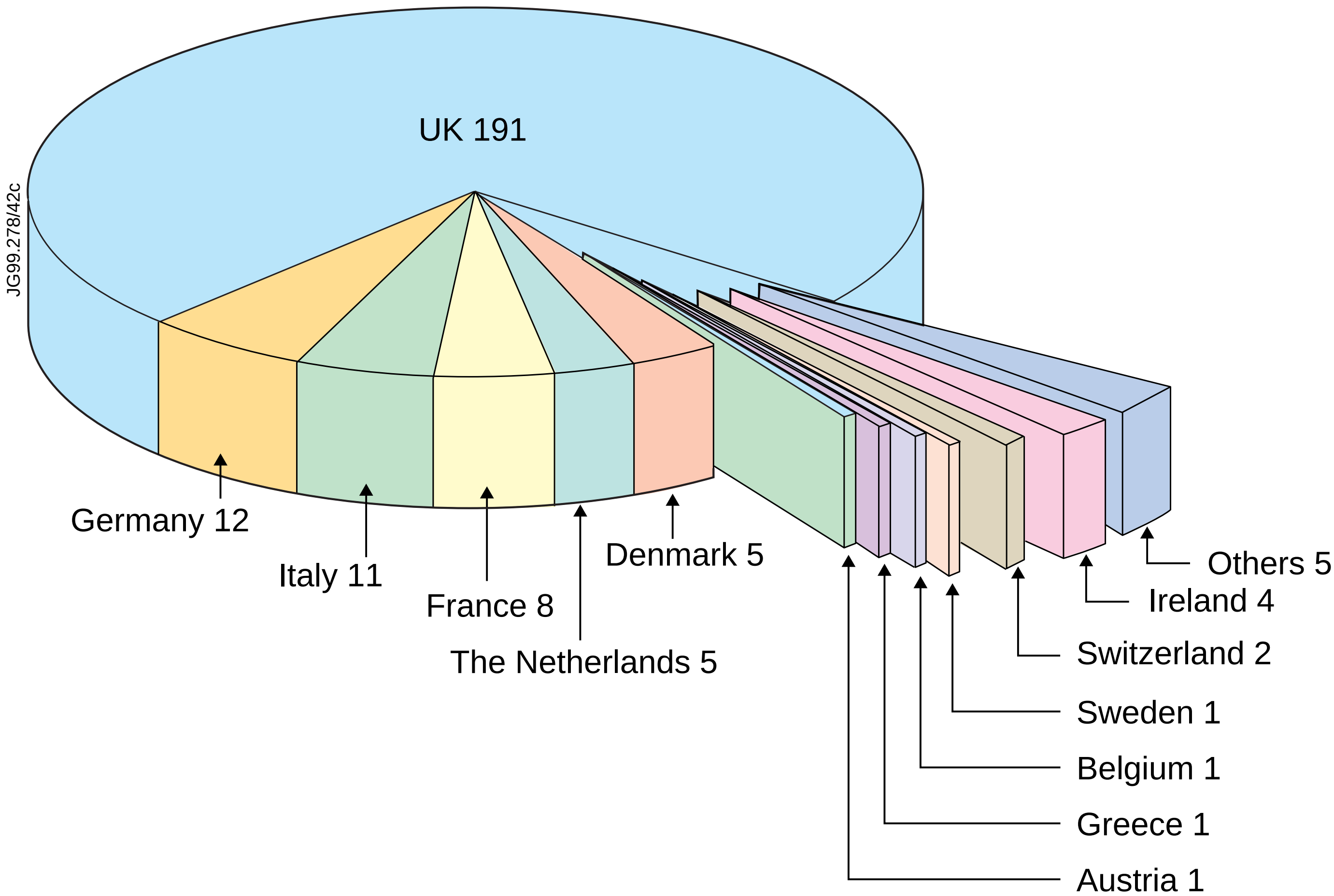
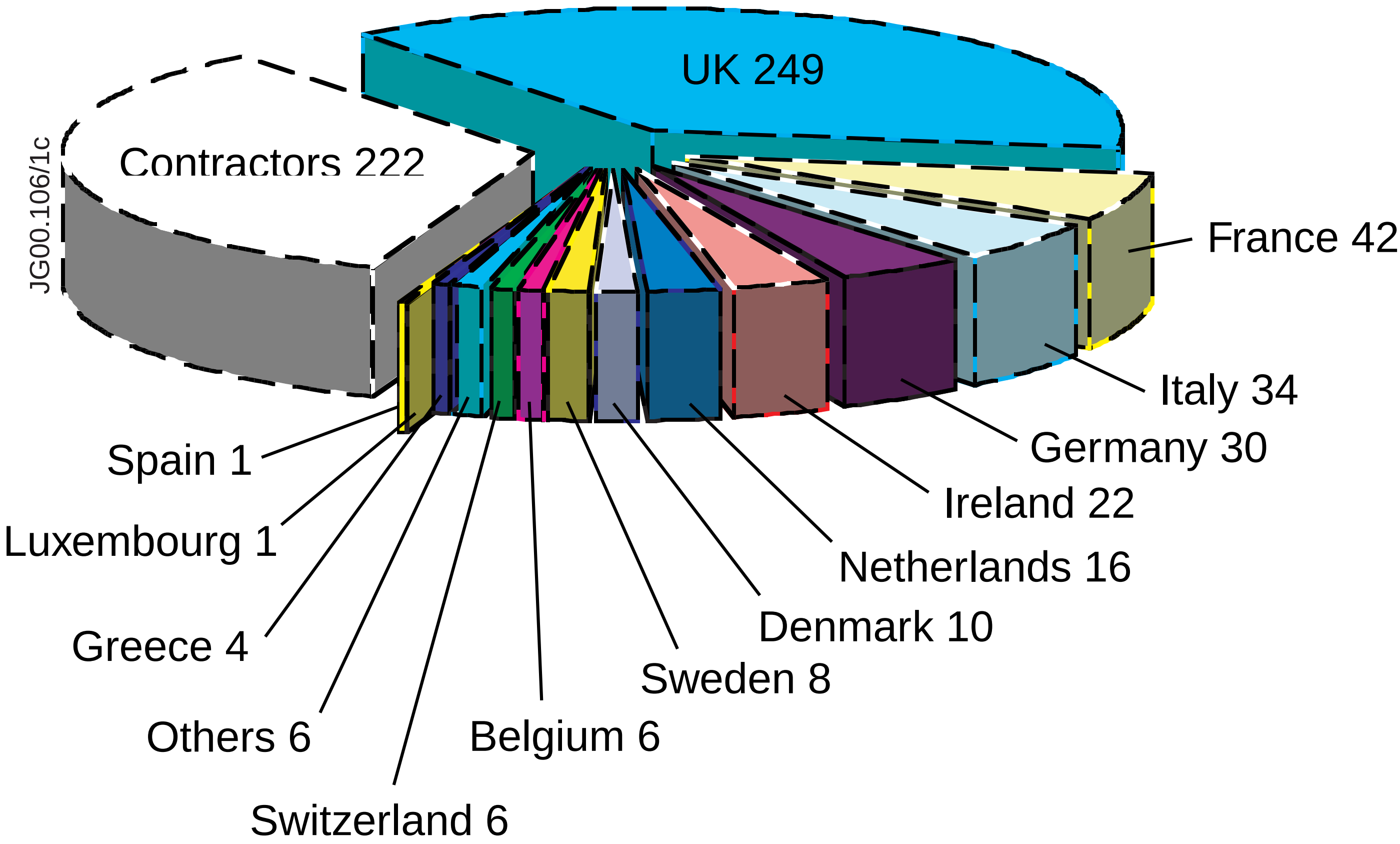
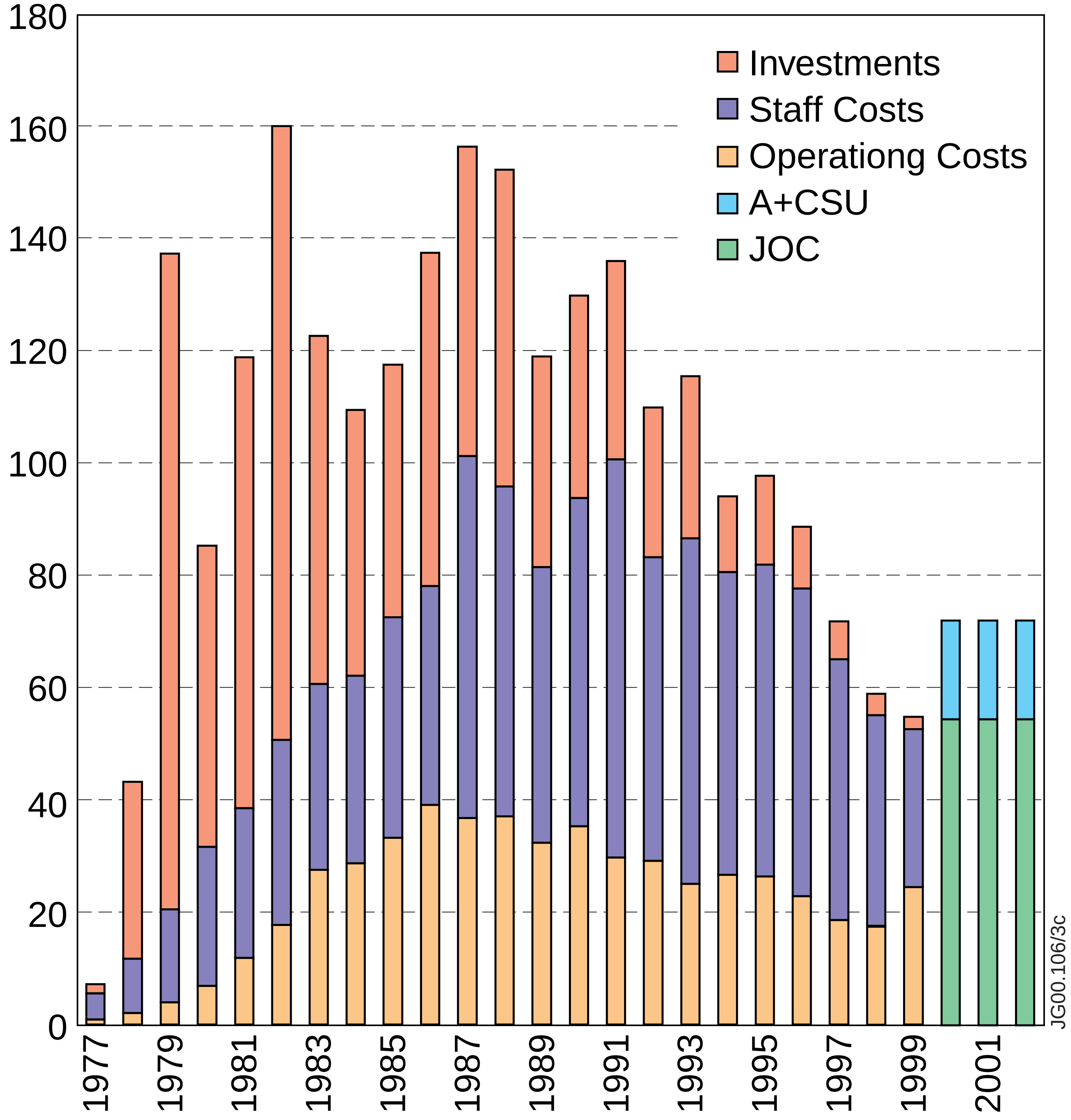
Composition of JET Team by Nationality in 1998



Composition of JET Team plus contractors (by Nationality) in 1990: 657



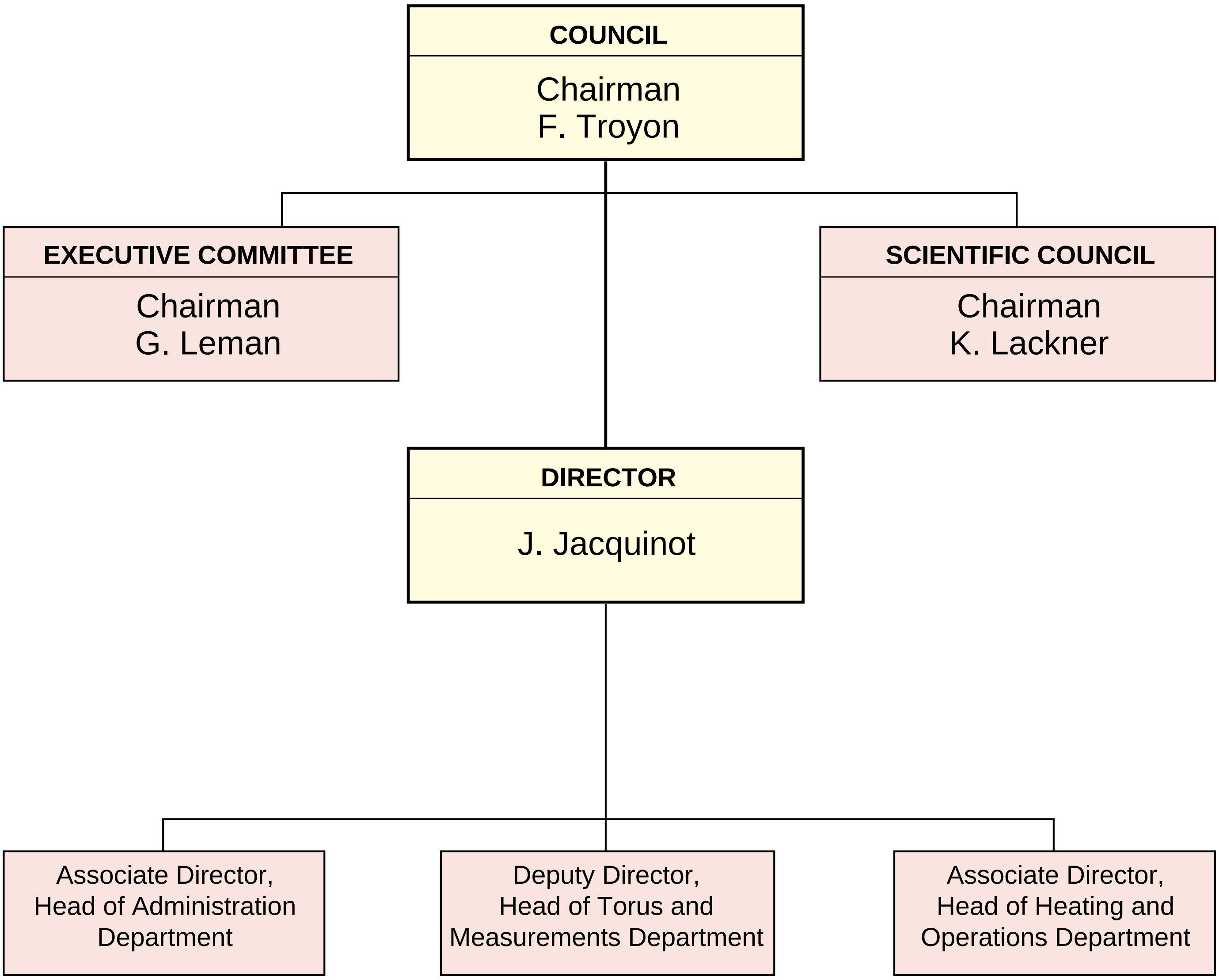
Annual Phasing of JET Costs (Commitments) in 1997 MioECU



Percentage Contributions to JET for 1998, based on the Euratom participation in Associations' Contracts for 1998

MEMBER	%	Mio ECU
EURATOM	80.0000	60.61
BELGIUM	0.1817	0.14
CIEMAT, SPAIN	0.4186	0.32
CEA, FRANCE	1.8581	1.41
ENEA, ITALY	1.8395	1.39
RISO, DENMARK	0.0827	0.06
LUXEMBOURG	0.0037	0.00
ICCTI, PORTUGAL	0.0970	0.07
DCU, IRELAND	0.0378	0.03
KFA, GERMANY	0.5388	0.41
IPP, GERMANY	2.4385	1.85
FZK, GERMANY	0.7578	0.57
NFR, SWEDEN	0.2299	0.17
SWITZERLAND	0.4978	0.38
FOM, NETHERLANDS	0.3158	0.24
TEKES, FINLAND	0.0895	0.07
UKAEA	10.5921	8.02
ÖAW, AUSTRIA	0.0207	0.02
	100.0000	**75.76**

JET: Overall Project Structure



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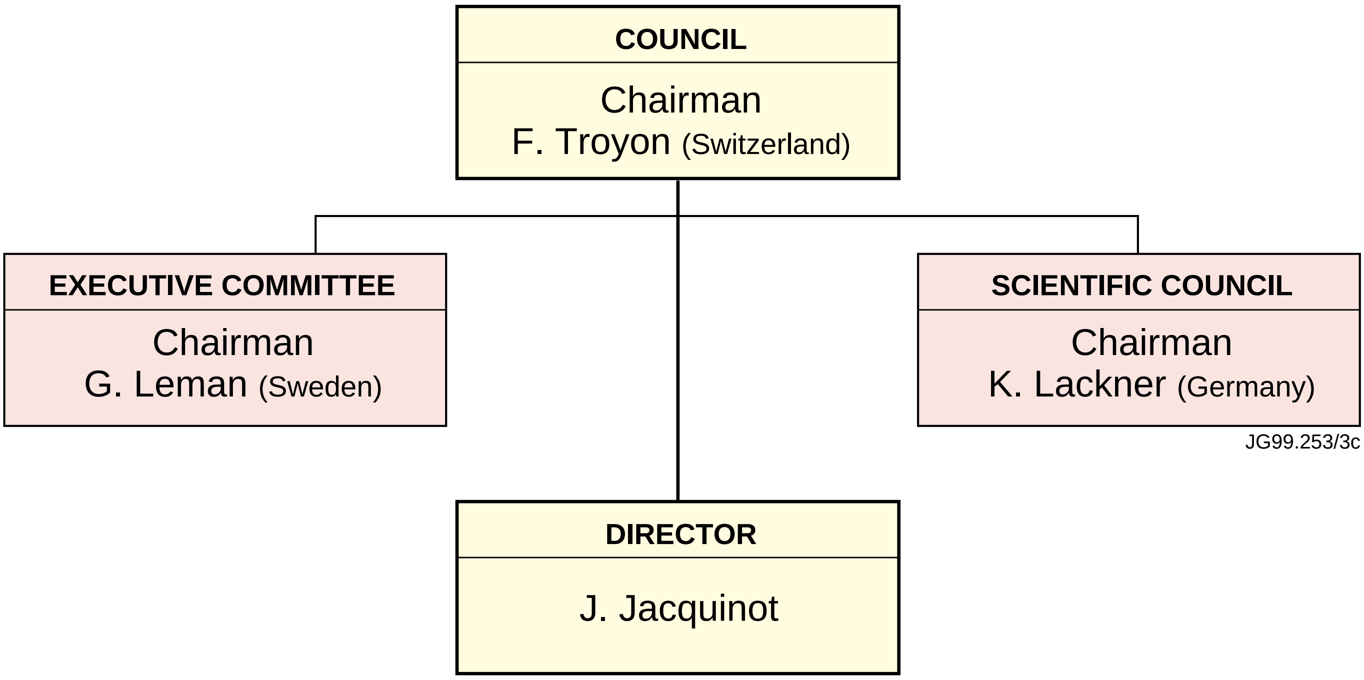
JET: Overall Project Structure



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- **JET encourages staff to publish.**
  - Official permission must first be obtained.
  - Approval required for all publications, eg books, journal articles, reports, letters, lectures, broadcasts, etc.

- **Approval procedure intended to ensure that:**
  - Consistent data and results are presented and that proper attributions and acknowledgements are made to relevant contributors;
  - Information is released in properly regulated manner (in keeping with Euratom and JET Statutes);
  - High standards (particularly, on quality) are maintained from the Project;
  - Proper records are maintained throughout the history of the Project.

To obtain approval for dissemination of JET information, the text of the article should be attached to Form JCA1 (Rev 7/84).

- **The series of Reports is as follows:**
  - EUR-JET-R (JET Report Series);
  - JET-P (JET Preprint Series);
  - JET-IR (JET Internal Report Series);
  - JET-TN (JET Technical Notes);
  - JET-DN (JET Divisional Notes);

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(A) An author must have made a substantial contribution to a major part of the work reported and be in a position to defend (to a specialist in the subject) the detailed scientific and technological content relating specifically to his/her contribution;

and

(B) the author must be in a position, generally, to take a personal share of responsibility for the overall content and accuracy of all scientific and technological information contained in the document.

At October, 1998

THE JET TEAM

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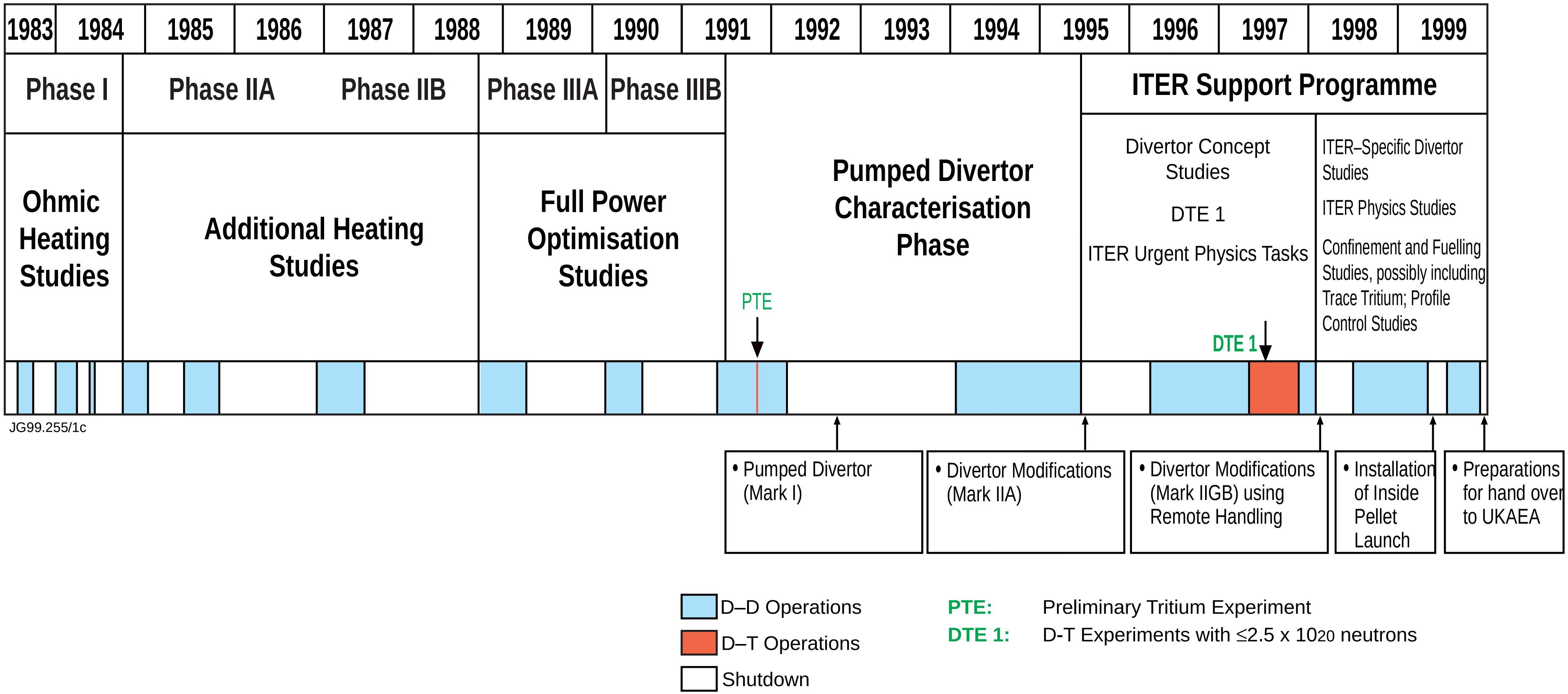
JET Programme to the end of 1999

(Assuming further use of the JET Facilities after 1999)



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Requirements for JET Site

1) Technical suitability

- High demand for electrical power
- Ability to handle small amounts of tritium
- ability to dispose of radioactive portions of JET device as needed
- Expertise and facilities for safe working in radioactive conditions

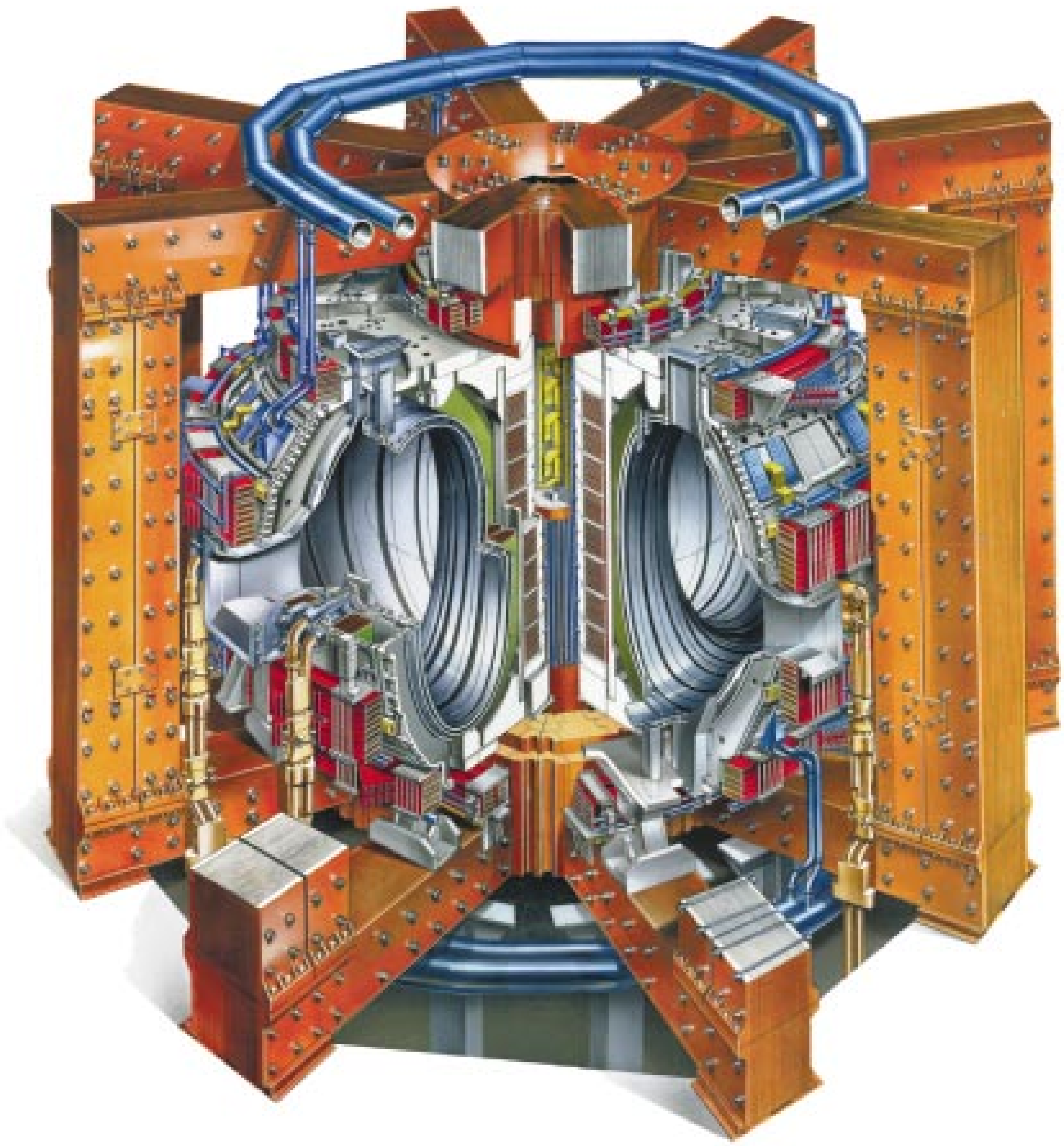
2) Buildings and Services

- General-purpose ans specially designed buildings
- Support services (Workshops, computing facilities, medical and catering services etc.)
- Road, Rail and Air transport
- Possibility of expansion within site

3) Social aspects

- Ample living accommodation
- Good shopping other amenities
- Appropriate school facilities

JET



JET is a ***Tokamak*** with:

– Torus radius	3.1m
– Vacuum vessel	3.96m high x 2.4m wide
– Plasma volume	$80m^3$ – $100m^3$
– Plasma current	up to 6MA
– Main confining field	up to 4 Tesla

Key aspects developed at JET

- **Diagnostics - Lidar and 70 other diagnostics**

- **Heating and current drive (total ~ 35 MW)**
  - Neutral Beam Injector 80 to 140 KeV
  - Ion Cyclotron Resonance 25 to 55 MHz
  - Lower Hybrid Systems 3.7 GHz

- **Confinement**
  - MHD stability limits
  - Bifurcations to different states
  - Scaling laws, energy and particle transport

- α particle heating (D/T experiments)

- **Particle and power exhaust**
  - Divertors (4 versions!)

- **Key fusion technologies**
  - Remote handling
  - Active gas handling (tritium components)

Introduction Fusion Physics (Basic)

Magnetic Fusion

- Needs for additional energy resources in the 21st Century - Fusion energy and the environment

- Maintain a plasma at 200 million degrees (20 keV) and a pressure of 1 to 2 atmospheres with energy confinement time (τ) of 2 to 4 seconds.
  - Self heating by D-T fusion born α-particles
    $\Rightarrow$ **energy gain**.

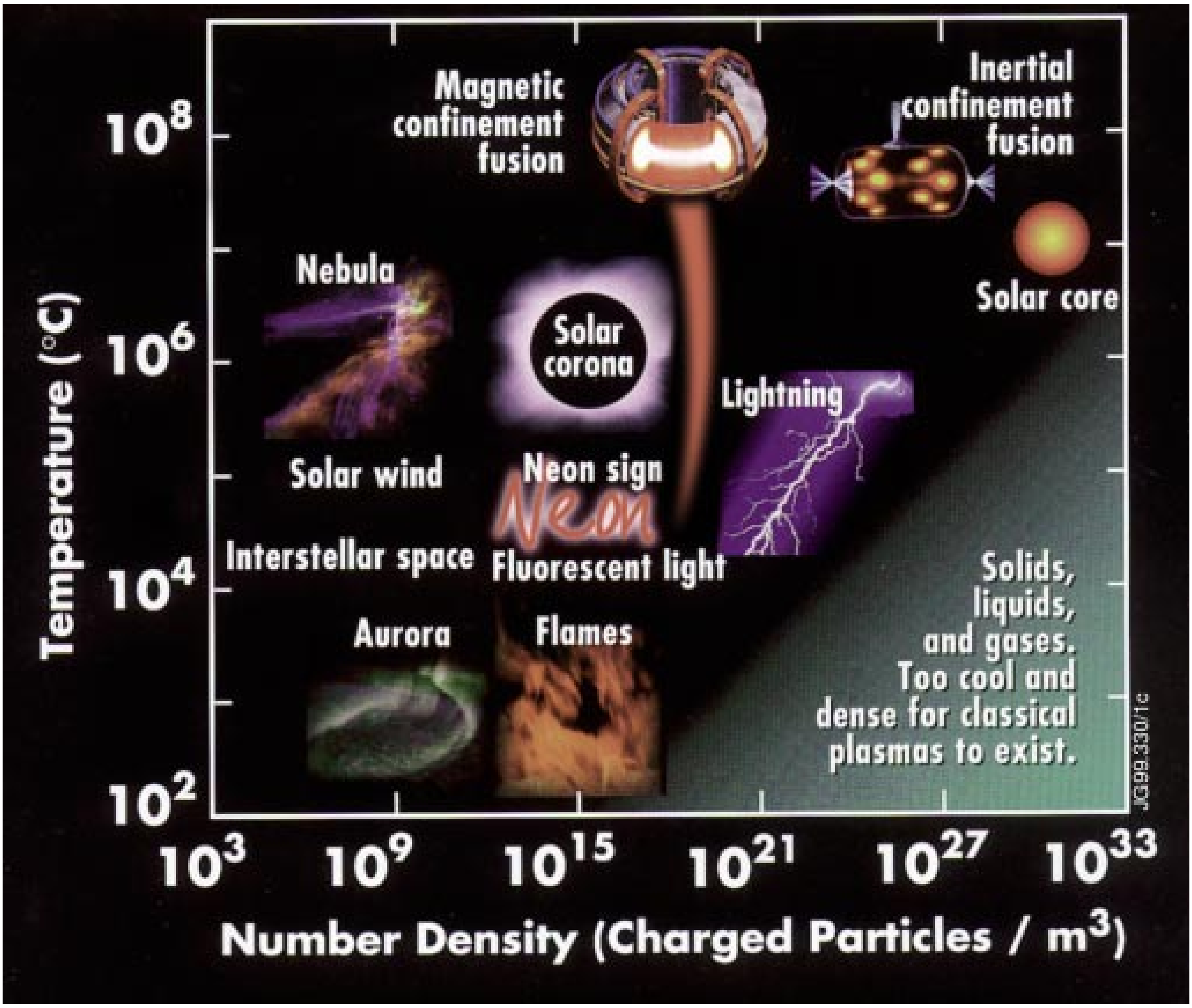
- Plasmas, the 4th state of matter, are dominated by collective effects and non-linear behaviour.
  - Anomalous transport
  - Self organisation resulting in bifurcations

$\Rightarrow$ **Research on fusion grade plasma is essential**

Theory - Code modelling - Experimental flair

Control - Instrumentation - Materials - High Power Technology - Mechanics... and Large Installations ($\tau \sim a^2$)

Plasma:
The fourth state of matter



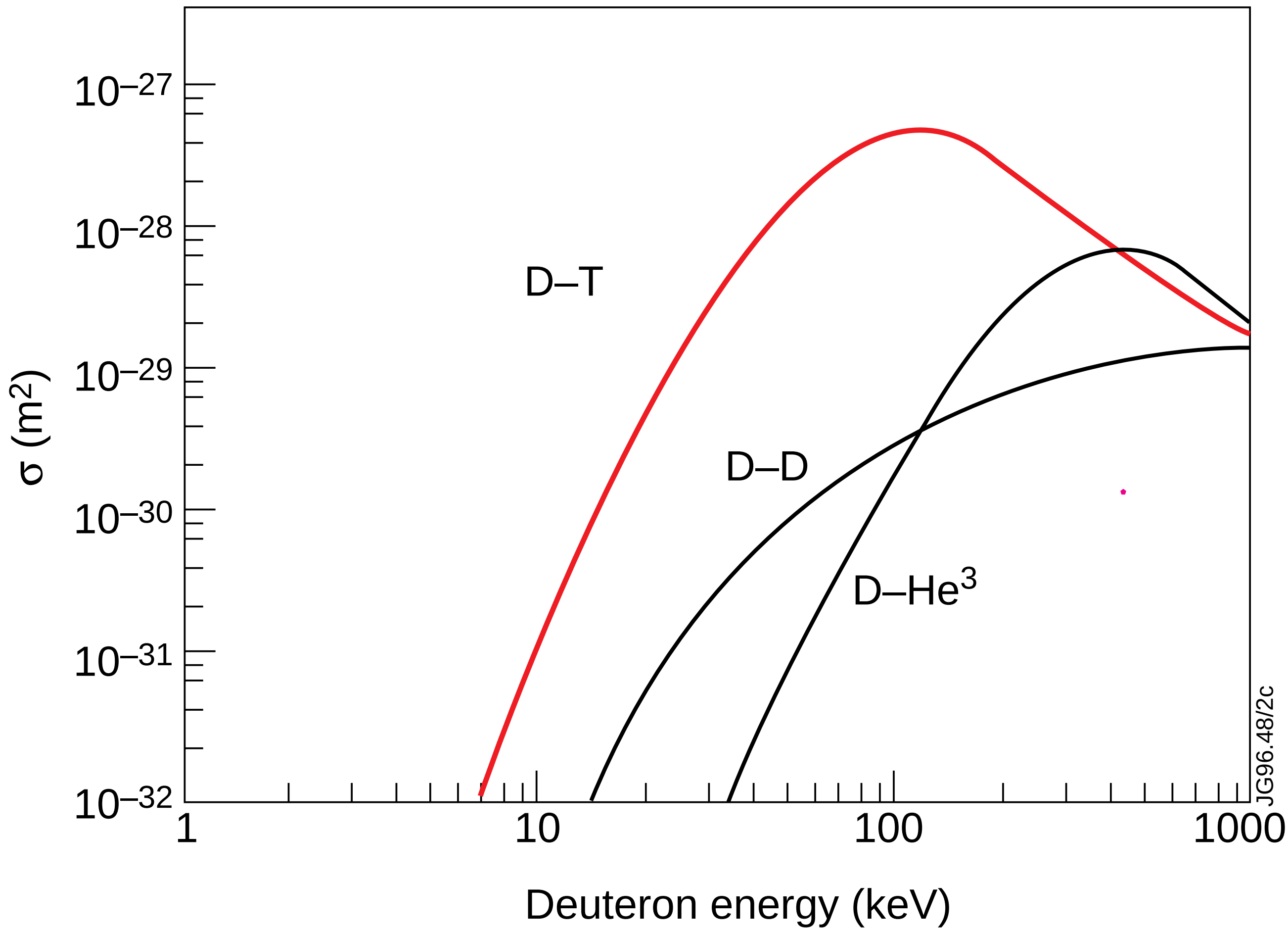
Most matter in the universe is in plasma state

Physics domains in Magnetic Fusion

- **Particle orbits** → confinement devices
  - Toroidal devices
    - **Tokamak** (internal current)
    - Stellarators (no internal current)
- **MHD**
  - stability vs large scale perturbation
  - Operating domain
    - pressure limits
    - low q limit
- **Micro-instability**
  - small scale turbulence → **anomalous transport**
  - bifurcations → **improved confinement**
- **Edge and divertor physics**
  - Heat and particle exhaust
  - Plasma surface interactions

Fusion Reactions

D + D	$\rightarrow$ T (1.0MeV)	+ p (3.0MeV)	
D + D	$\rightarrow$ He^3 (1.0MeV)	+ n (2.4MeV)	
D + T	$\rightarrow$ He^4 (3.5MeV)	+ n (14.1MeV)	easiest
D + He^3	$\rightarrow$ He^4 (3.7MeV)	+ p (14.7MeV)	



Cross-sections for fusion reactions

Q, the fusion gain factor

Power density from D-T fusion

$$P_{fusion} = \frac{1}{4} n^2 < \sigma v > E_{fusion}$$

$$P_{\alpha} \sim \frac{P_{fusion}}{5}$$

- Energy loss from plasma core: by thermal conduction

  Define energy confinement time τ_E: $\quad P_{loss} = \frac{3nT}{\tau_E}$

  For ***steady state***, $P_{loss} = P_{external} + P_{\alpha}$

- $Q = \frac{P_{fus}}{P_{heat}} = \frac{5P_{\alpha}}{P_{external}}$ is the fusion gain factor

- $Q = 1 \Rightarrow$ 20% of plasma heating by fusion α's

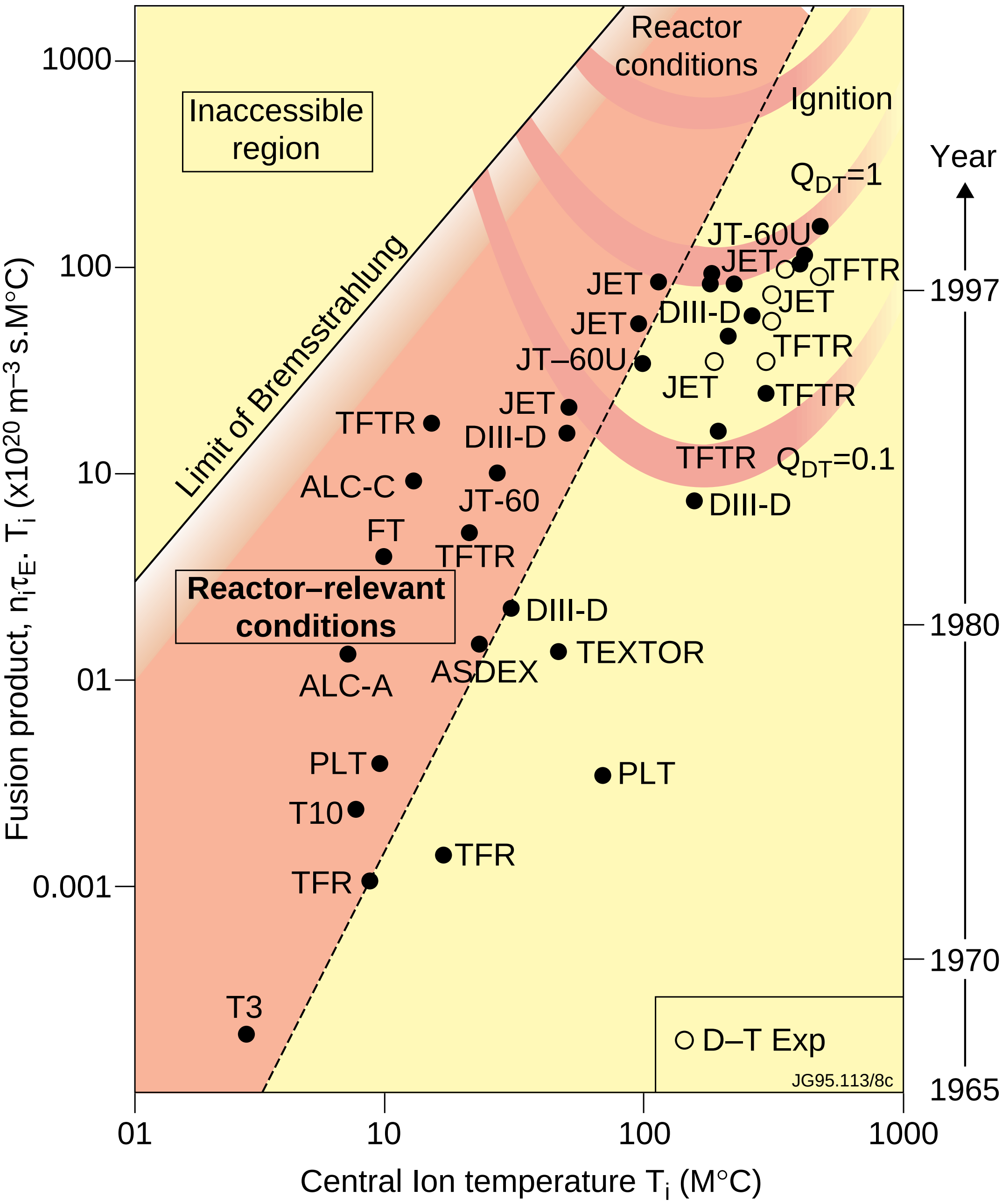
- $Q = \infty$: *ignition* (no external heating applied)

- For energy production, $Q \geq 10$ is adequate

Fusion triple product

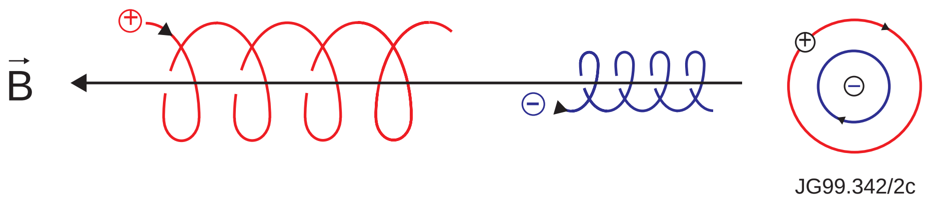
- The fusion amplification factor, Q is related to the triple product, $n\tau_E T_i$

$$Q = \frac{n^2 \langle\sigma v\rangle E_{fusion}}{3nT/\tau_E} = n\tau_E \frac{\langle\sigma v\rangle}{T} \sim nT\tau_E$$



Particle Orbits, I

In a uniform magnetic field, cyclotron motion:



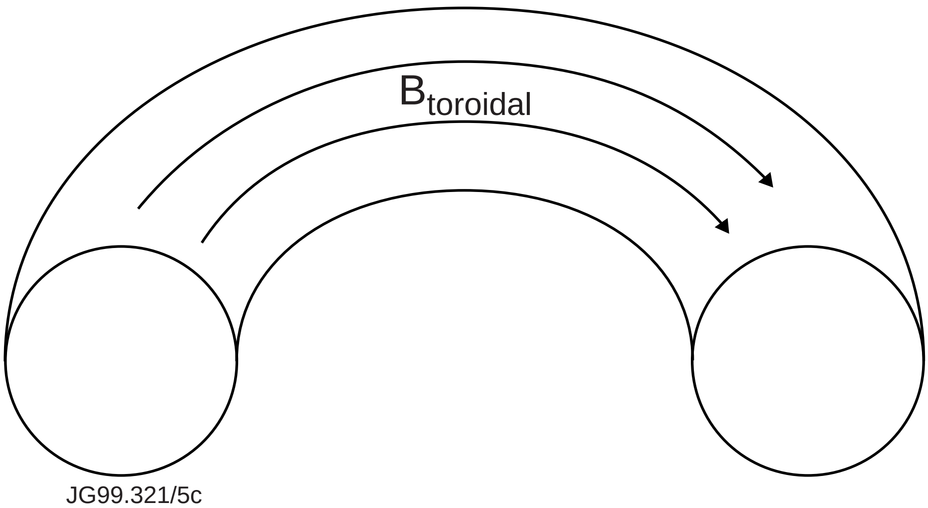
Larmor radius $\rho_L = \dfrac{mv_\perp}{eB}$ and guiding center drifts

Implications:

- adiabatic invariant $\mu = mv_\perp^2/B$
- Perpendicular collisional transport has step size ρ_L

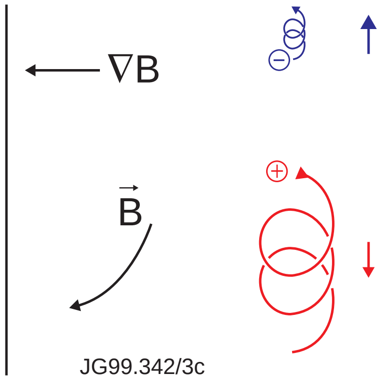
$$D_{classical} = \rho_L^2 \, \nu_{Coulomb}$$

- Particles stream freely along field lines
  "close" field lines to magnetically confine orbits.



Particle Orbits, II

- In a toroidal magnetic field Fermi drifts are present (∇B and curvature drifts)

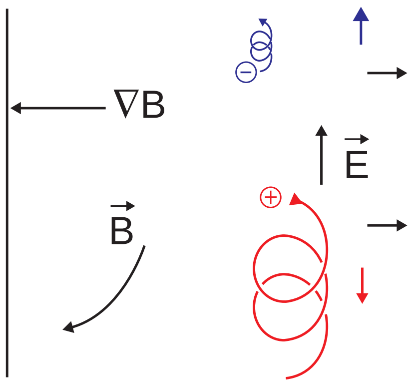


JG99.342/3c

$$v_{\nabla B} = \frac{\mu}{\pm|e|B}\,\frac{B \times \nabla B}{B}$$

Neutral plasma: drift cannot be corrected with $\vec{E}$ field.

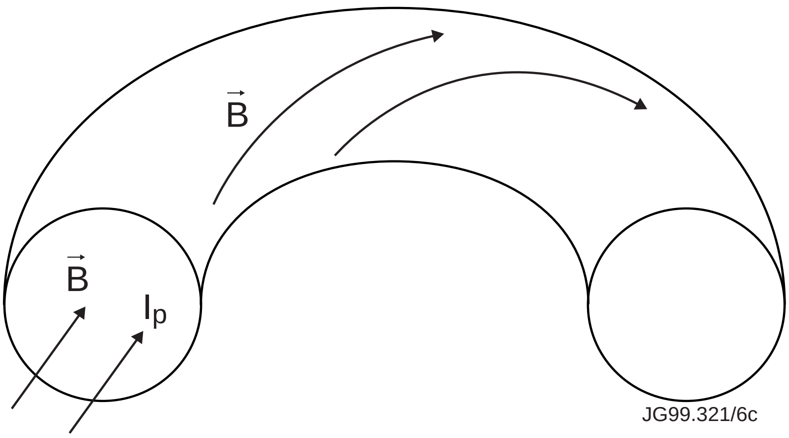
- In fact, charge separation from $v_{\nabla B}$ leads to loss of confinement, via the $\vec{E} \times \vec{B}$ drift:



JG99.342/4c

$$\vec{v}_{E \times B} = \frac{\vec{E} \times \vec{B}}{B^2}$$

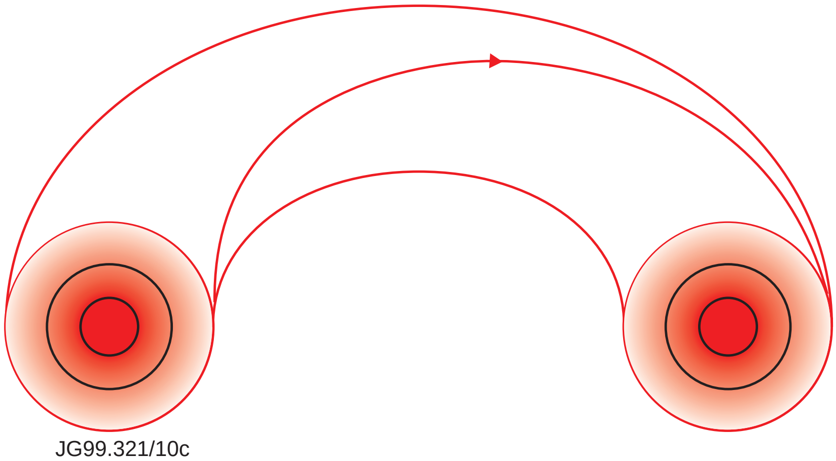
A solution is to add a *poloidal* field.



$\vec{B}_{poloidal}$ created by I_p, a toroidal current flowing in the plasma itself.

The Tokamak: Fields

$B_{pol} \sim B_{tor}/10$



- **Nested closed flux surfaces**: p, n, T, Φ constant on flux surfaces, because of fast streaming //B, slow diffusive transport ⊥B

- **Helically twisted** $\vec{B}$ field lines are needed for particle confinement, force balance and stability.

$$q = \frac{\text{\# toroidal circuits}}{\text{1 poloidal circuit}} = \textbf{safety factor} \sim \frac{aB_t}{RB_p}$$

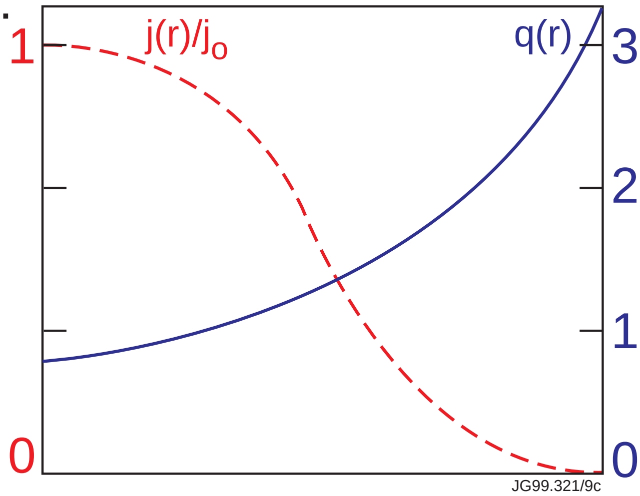
Stability also depends on **magnetic shear**, $s = \frac{q}{r}\frac{dq}{dr}$

Typical j current density, q profiles:

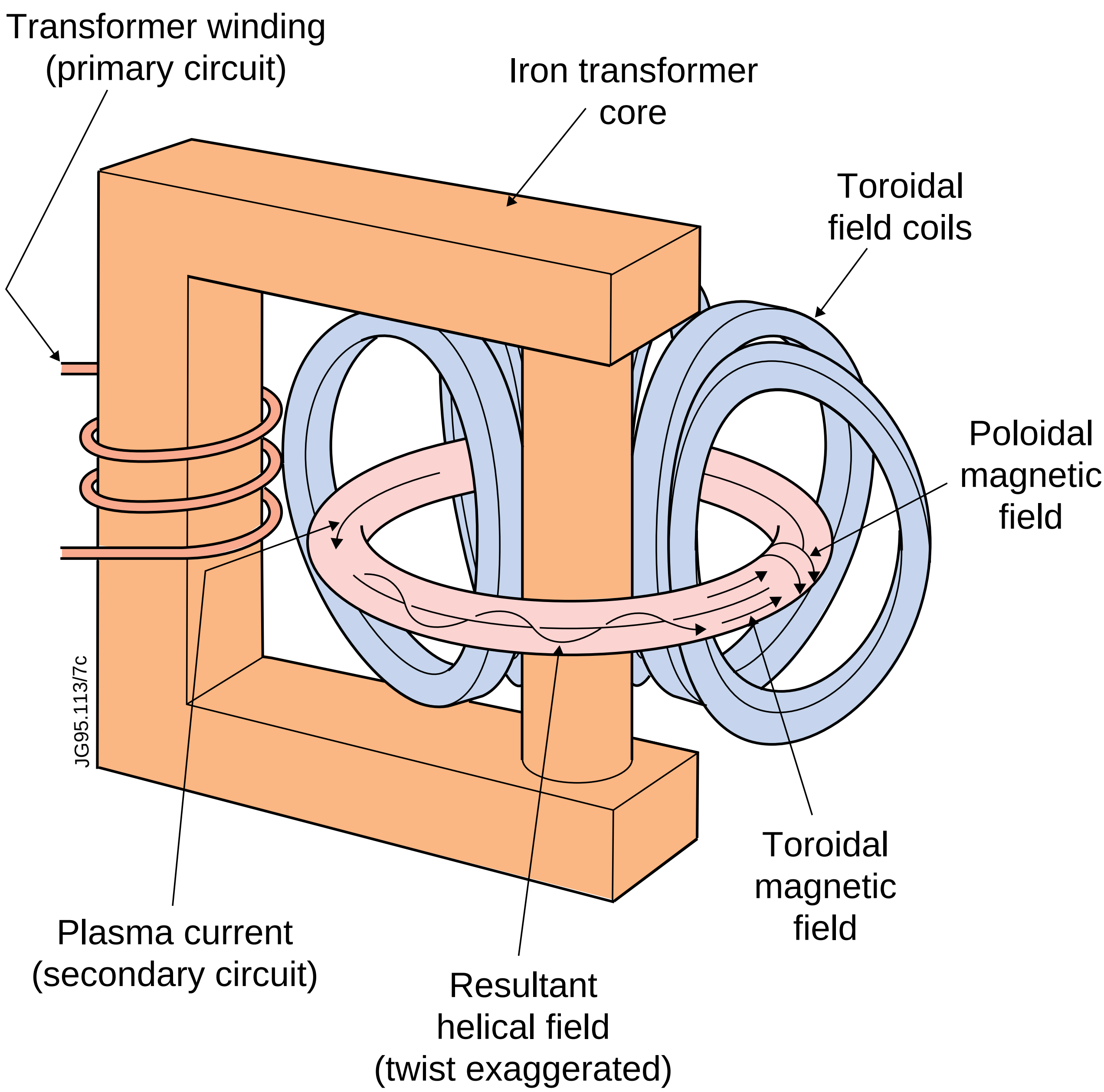
q_{axis}<1: sawteeth

q_{edge}<2: Disruptions!

Rationals!

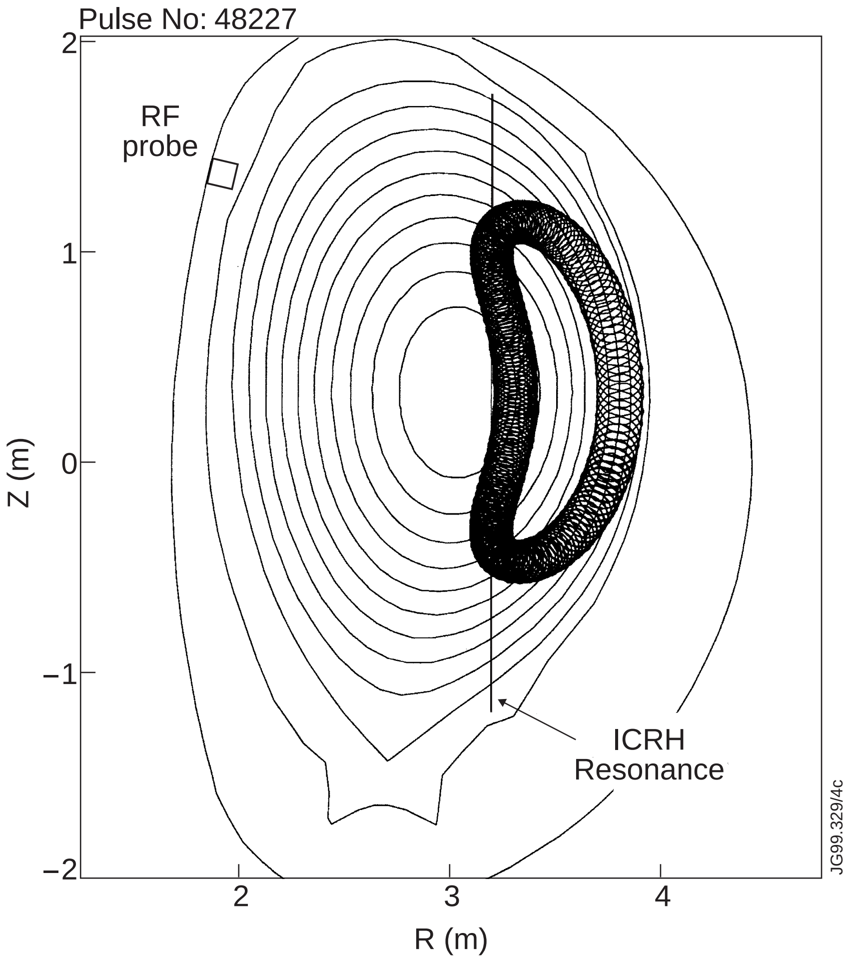


Schematic of Tokamak



The Tokamak: Orbits

Banana orbit (3MeV)



Poloidal Larmor radius: $\rho_{pol} = \dfrac{mv_\perp}{eB_{pol}}$

Neoclassical diffusion:

$$D_{neocl} = \rho_{pol}^{2}\, \nu_{Coulomb} \sim 100 \times D_{classical}$$

Ion transport can be near neoclassical, but typical electron transport is 10–100 x larger than neoclassical.

Fluids: MHD

Because of the **long range** of the Coulomb interaction, single particle orbits are only part of the story.

In fact the plasma can be modeled as a **fluid** (or a set of interpenetrating fluids).

The combination of fluid and Maxwell's equations lead to **Magnetohydrodynamics** (MHD).

From the point of view of MHD, the concept of β becomes important (Raleigh-Taylor instabilities):

$$\beta = \frac{p}{B^2 / 2\mu_0} = \frac{\text{kinetic pressure}}{\text{magnetic pressure}}$$

Linear, ideal MHD is rather well understood: plasma equilibrium can be established in tokamaks and gross instabilities can be avoided.

Non linear and resistive MHD leads to more complex phenomenae, many still under investigation

Instabilities

1) Magneto hydrodynamic instabilities

At rational flux surfaces ($q=m/n$ with m and n integer numbers) resonant modes can occur.

These influence particle and heat transport.

2) Turbulence:

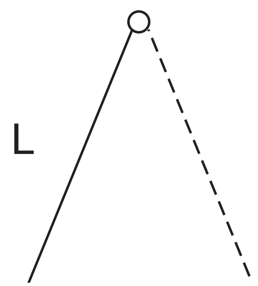
Turbulence spectrum is very complex due to many degrees of freedom.

Electrostatic turbulence: Important for both ion and electron heat transport.

Electromagnetic turbulence: Important for electron heat transport.

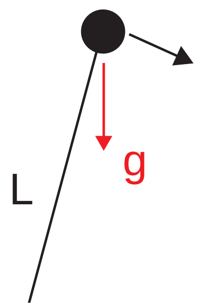
Reversed or low magnetic shear has stabilising effect on turbulence.

Stable Pendulum



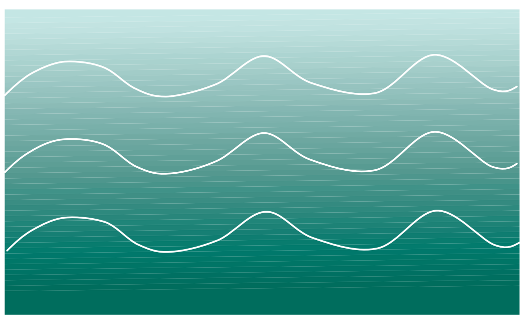
Unstable Inverted Pendulum

(rigid rod)



Density-stratified fluid

$\rho = \exp(-y/L)$

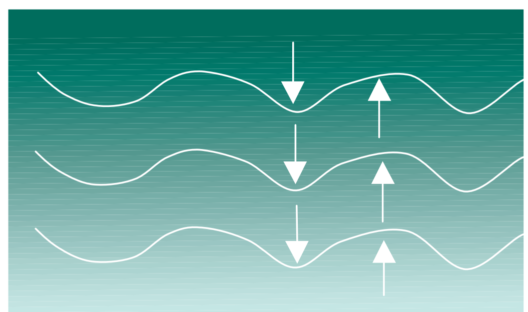


stable $\omega = (g/L)^{1/2}$

Inverted-density fluid

$\Rightarrow$ Rayleigh-Taylor Instability

$\rho = \exp(-y/L)$



JG99.342/11c

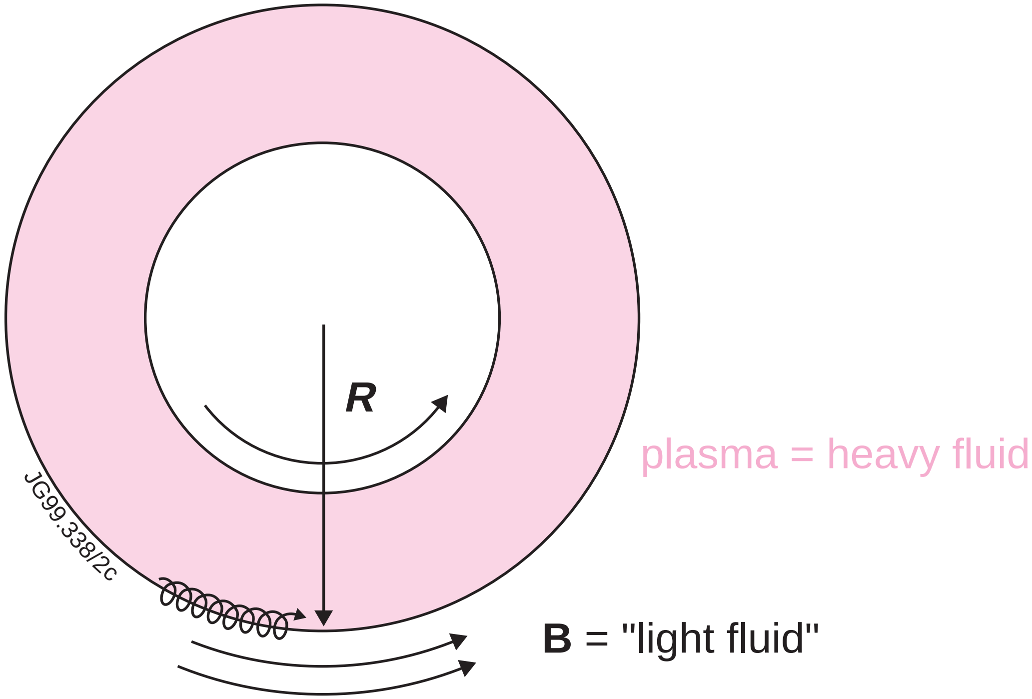
Max growth rate $\gamma = (g/L)^{1/2}$

G. Hammet

JG00.106/41

"Bad Curvature" instability in plasmas ≈ Inverted Pendulum / Rayleigh–Taylor instability

Top view of Toroidal plasma:



$g_{eff} = \frac{v^2}{R}$ centrifugal force

Growth rate:

$$\gamma = \sqrt{\frac{g_{eff}}{L}} = \sqrt{\frac{v_t^2}{RL}}$$

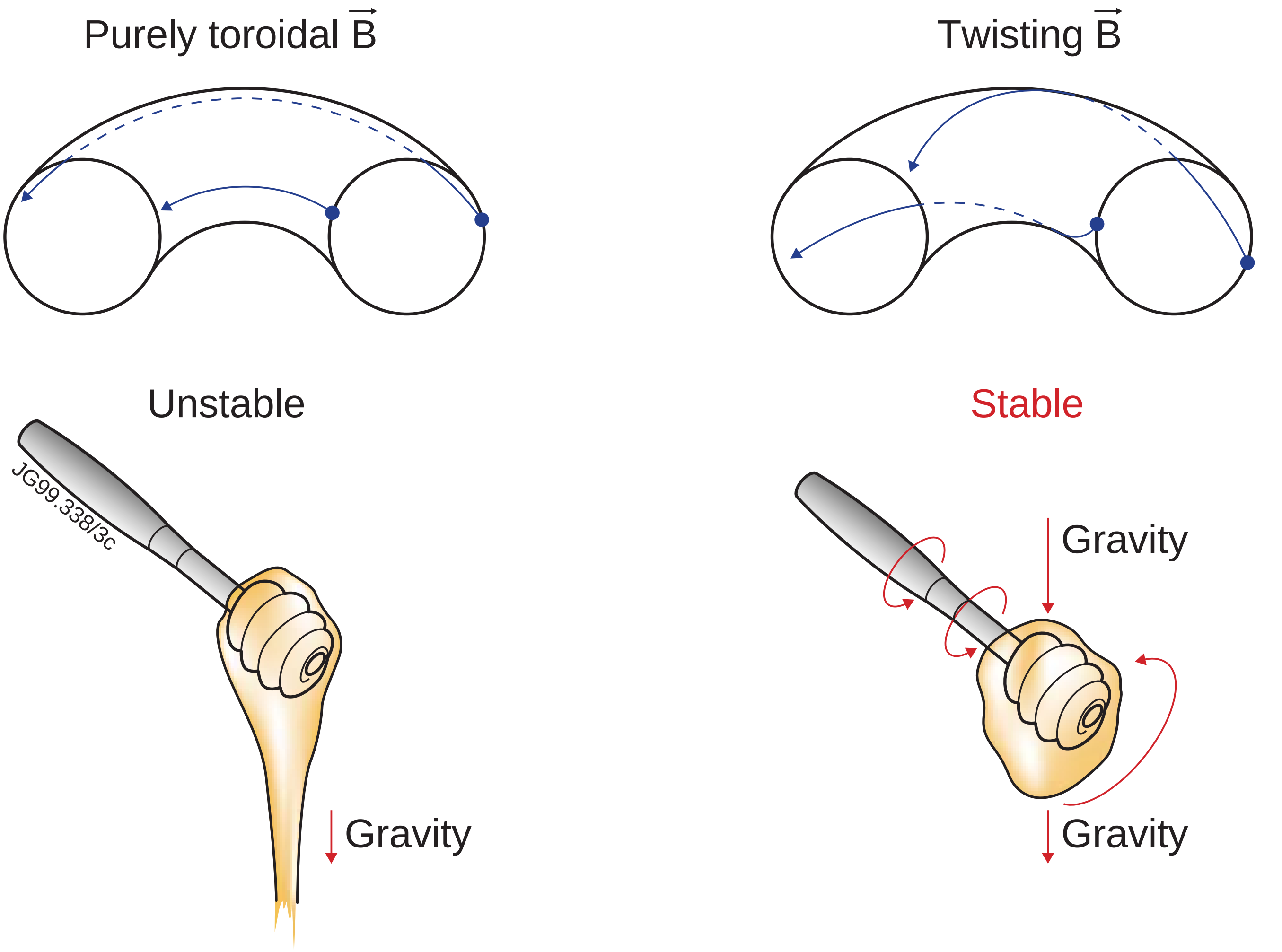
Similar instability mechanism in MHD & drift/microinstabilities

G. Hammet

JG106/42

Stabilising gross MHD instabilities

Twist in $\vec{B}$ carries plasma from bad curvature region to good curvature region:

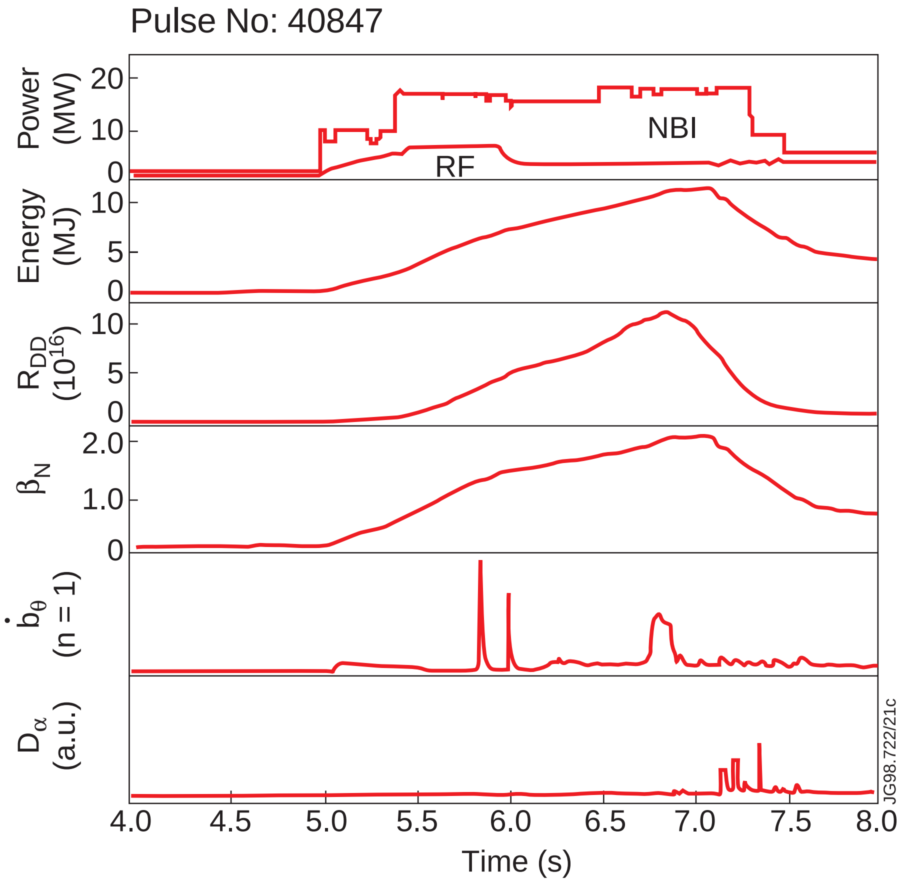


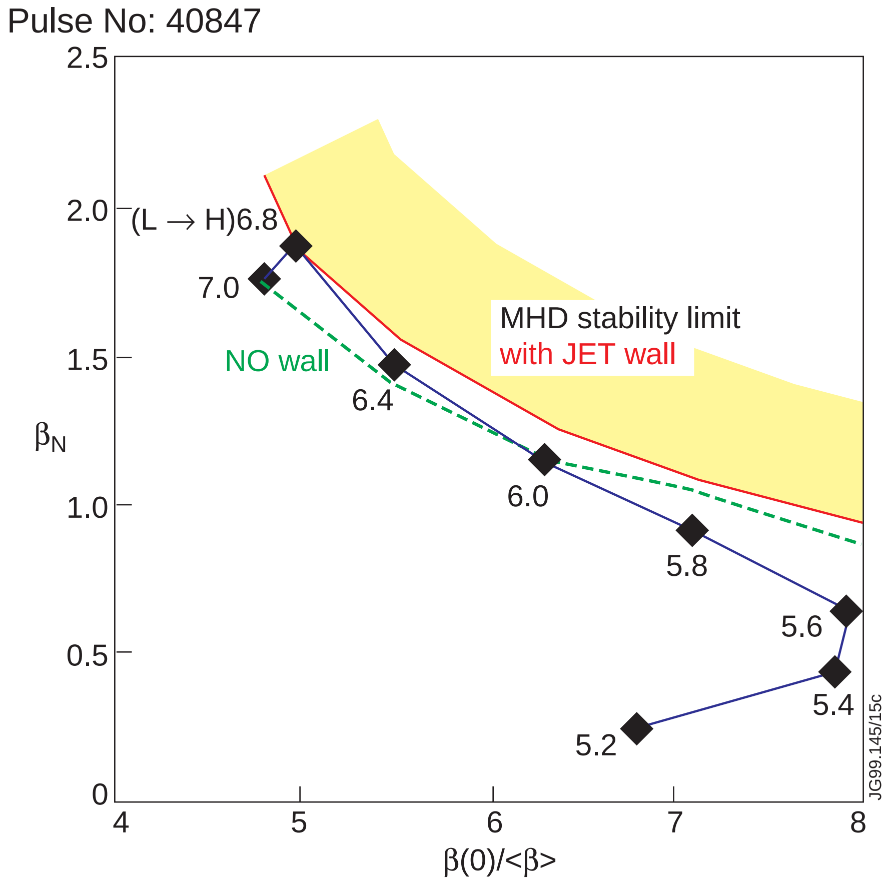
Similar to how twirling a honey dipper can prevent honey from dripping.

Tokamaks are ***stable***, on average up to a ***critical pressure***

G. Hammett

High Performance by Operating Discharge Close to MHD Stability Boundary

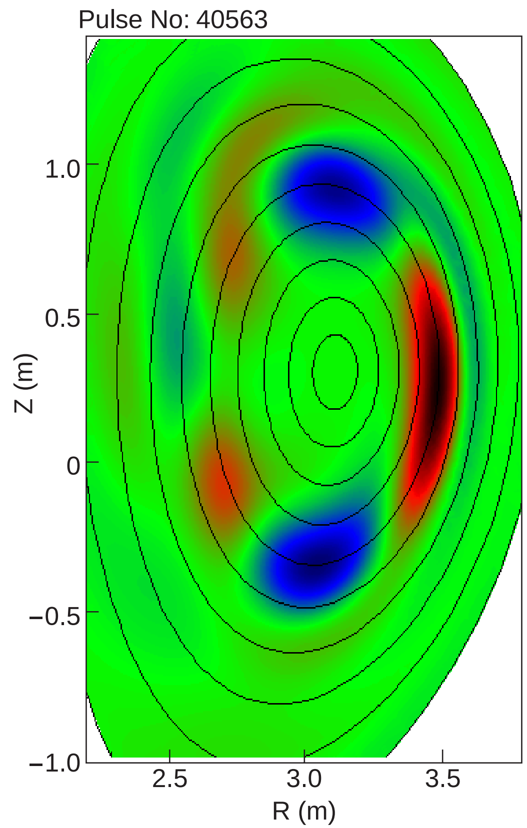




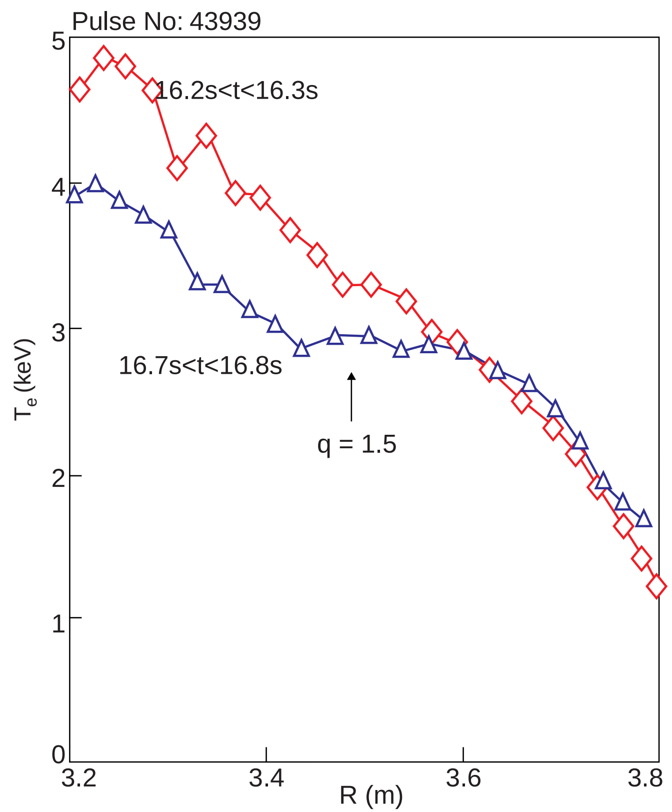
- Real time control of heating power allows operation close to MHD stability boundary for more than 1 second, avoiding disruption and achieving highest neuton rate ($5.4x10^{16}\ s^{-1}$)

Structure of Neoclassical Tearing Modes

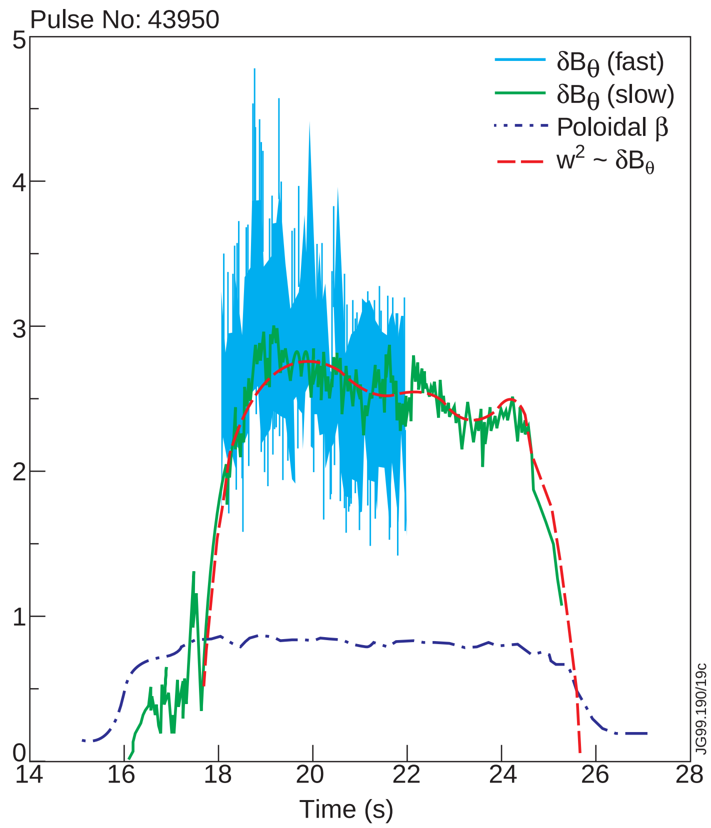
SXR Tomography



Flattening in T_e



Island Evolution



- Mode structure shows an n=2 mode with coupled m=2 and m=3 poloidal harmonics
- NTM causes local flattening in Te around q=1.5, characteristic of an island
- Island evolution follows neoclassical theory [Sauter, Lausanne]

JG00.106/46

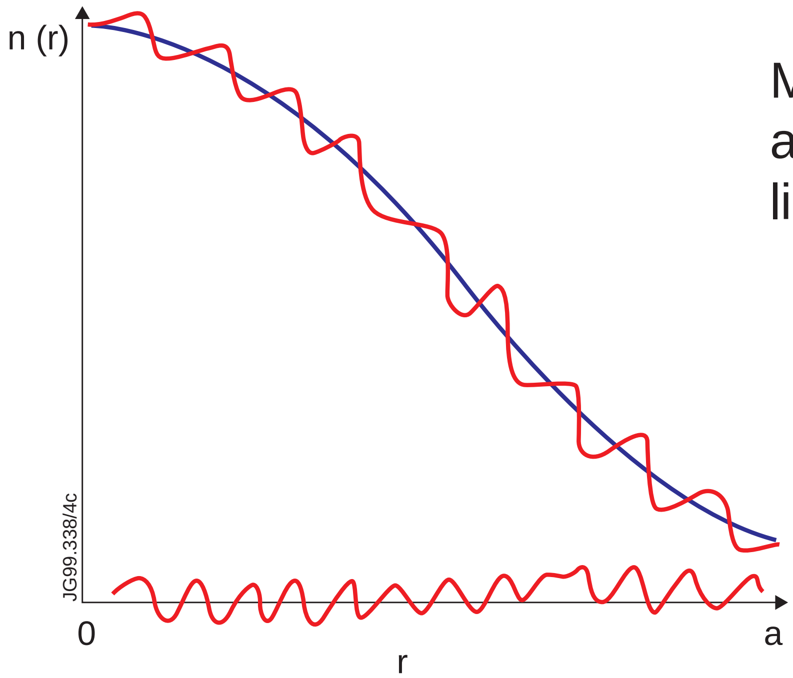
Turbulence and anomalous transport

Small amplitude microinstabilities drive anomalous transport in tokamaks

$$\left(\frac{\tilde{n}}{n} \sim \frac{\tilde{\Phi}}{T} \sim \frac{\tilde{T}}{T} \sim 1\%\right)$$

Measure small fluctuations can describe

observed transport in tokamaks (*1-100* x neoclassical)



Micro-instabilities have small amplitude, but still are non-linear

$$n = n_0(r) + \tilde{n}(x,t)$$

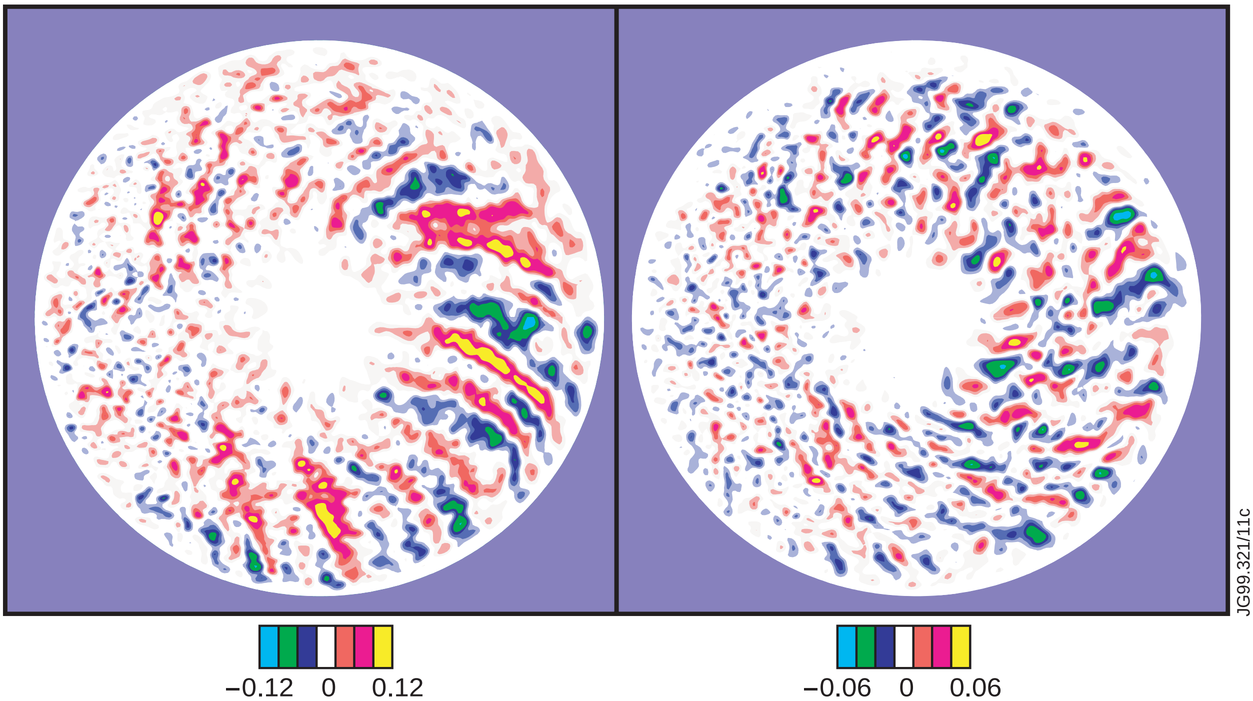
$$n_0 \gg \tilde{n}$$

$$\text{but} \quad \nabla n_0 \sim \nabla \tilde{n}$$

Understanding turbulent transport is very interesting from the physics point of view.

Turbulence reduction from shear in plasma rotation

Contour plots of turbulence amplitude, $\frac{e\tilde{\Phi}}{T}$ (simulation)



Without Sheared Flow ***With*** Sheared Flow

Z. Lin, Science 281,1835(1998)

Shear in the $\vec{E} \times \vec{B}$ poloidal flow (due to the dominant radial electric field) is responsible for the reduction in amplitude and radial extent of fluctuations in density and electrostatic potential.

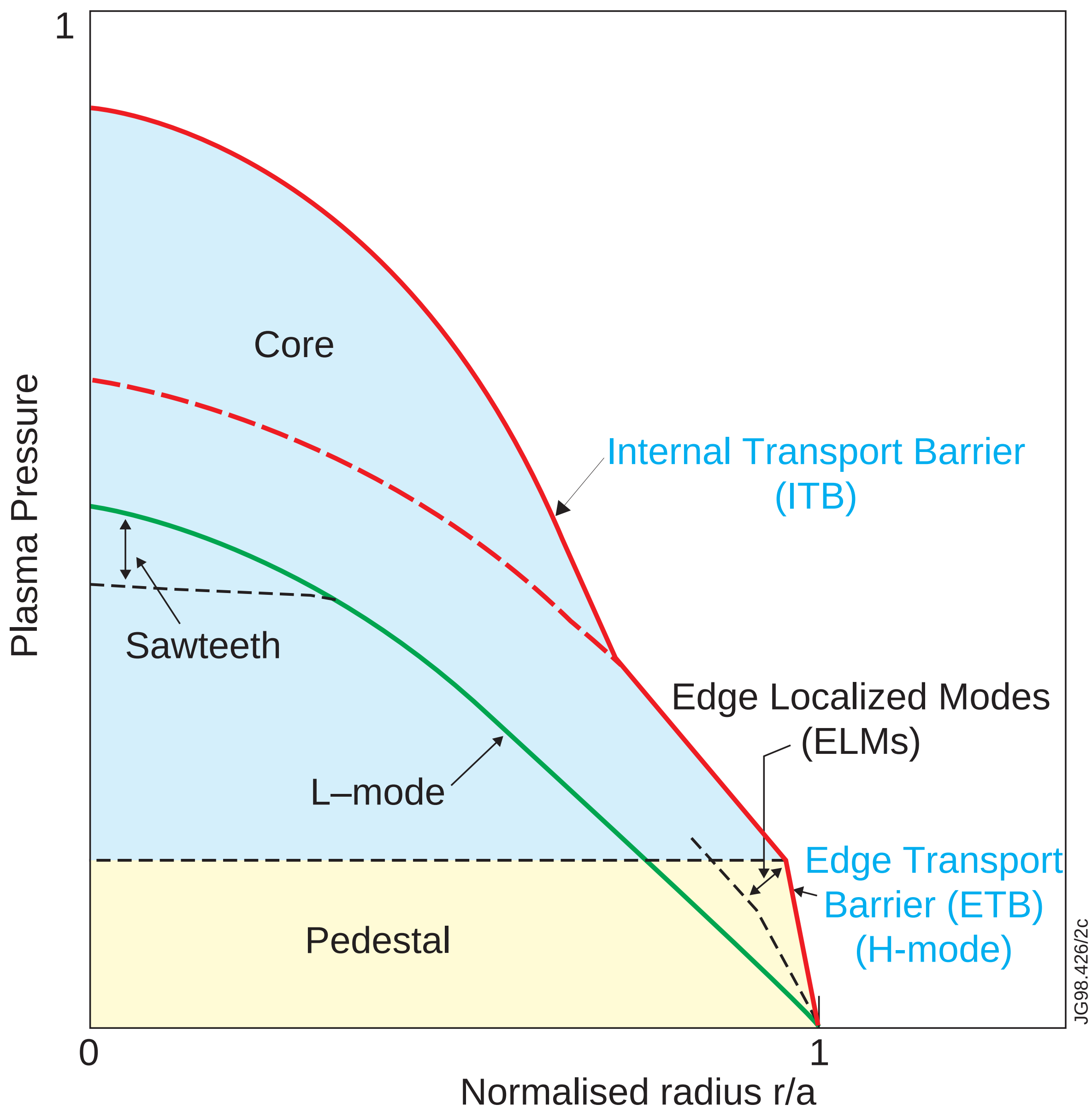
Theory, aided by numerical simulation, is beginning to understand the many complex mechanisms that lead to self-regulated turbulent transport in tokamak plasmas.

Confinement:
The different zones

In magnetic fusion small scale microinstabilities dominate transport.

Bifurcations to states with reduced transport occur.

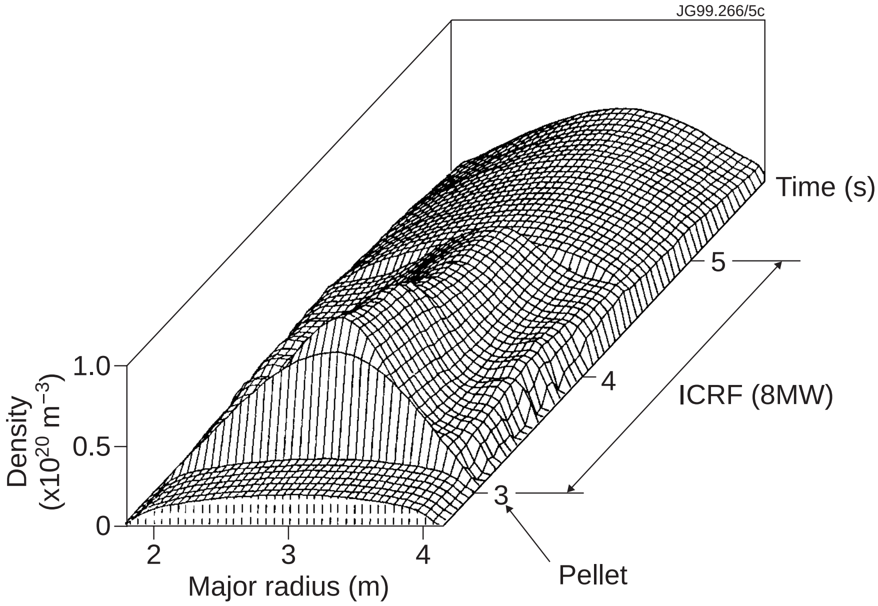
Regions with reduced transport (*"Transport Barriers"*) can appear in the edge or the core of tokamak plasmas, (or in both).

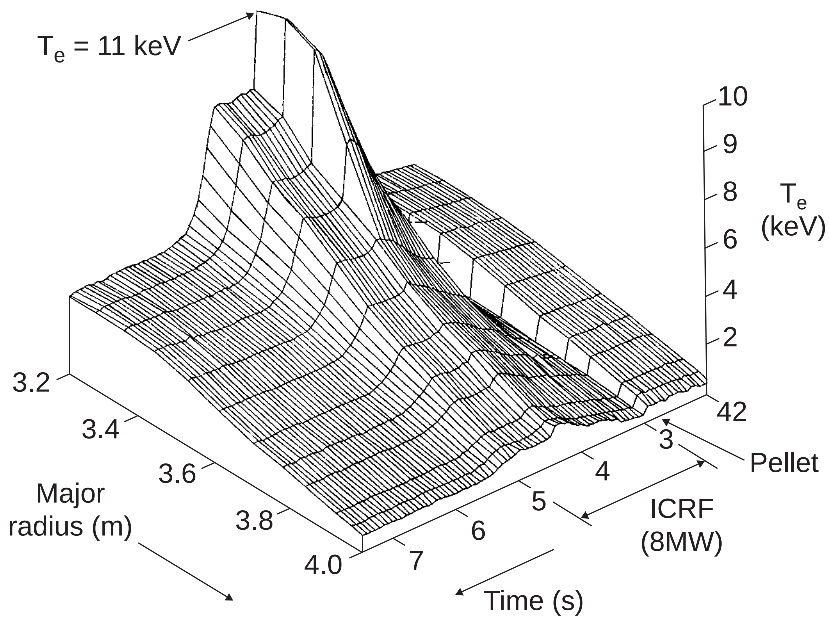


PEP mode, Snakes, Monster Sawteeth

The PEP Mode
(Pellet Enhanced Performance)

Injection of frozen deuterium pellets into the centre of the plasma result in the formation of a transport barrier in the plasma core:

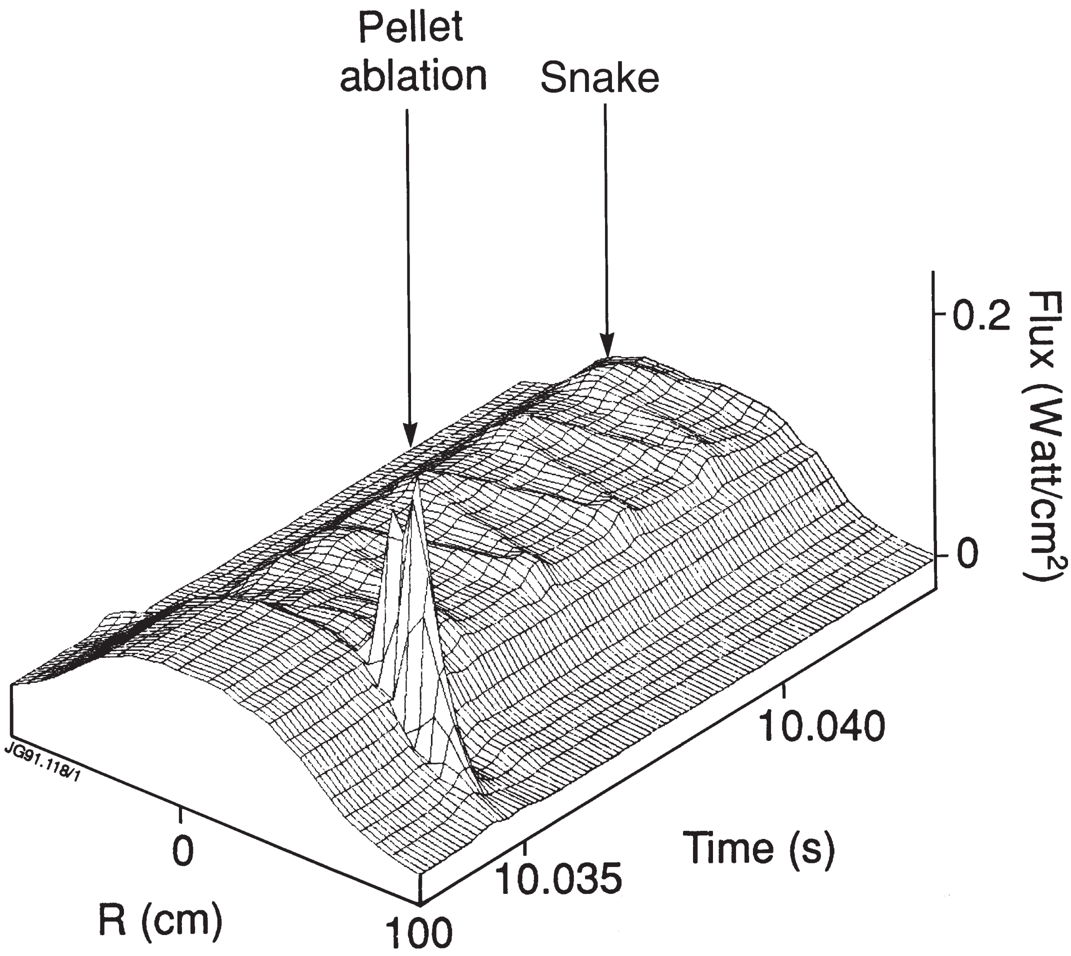




The transport barrier may be due to the stabilizing effect of reversed magnetic shear on MHD modes, associated with hollow current density profiles

The Snake

The snake is a *long-lived* (100ms) structure that appears after pellet injection.

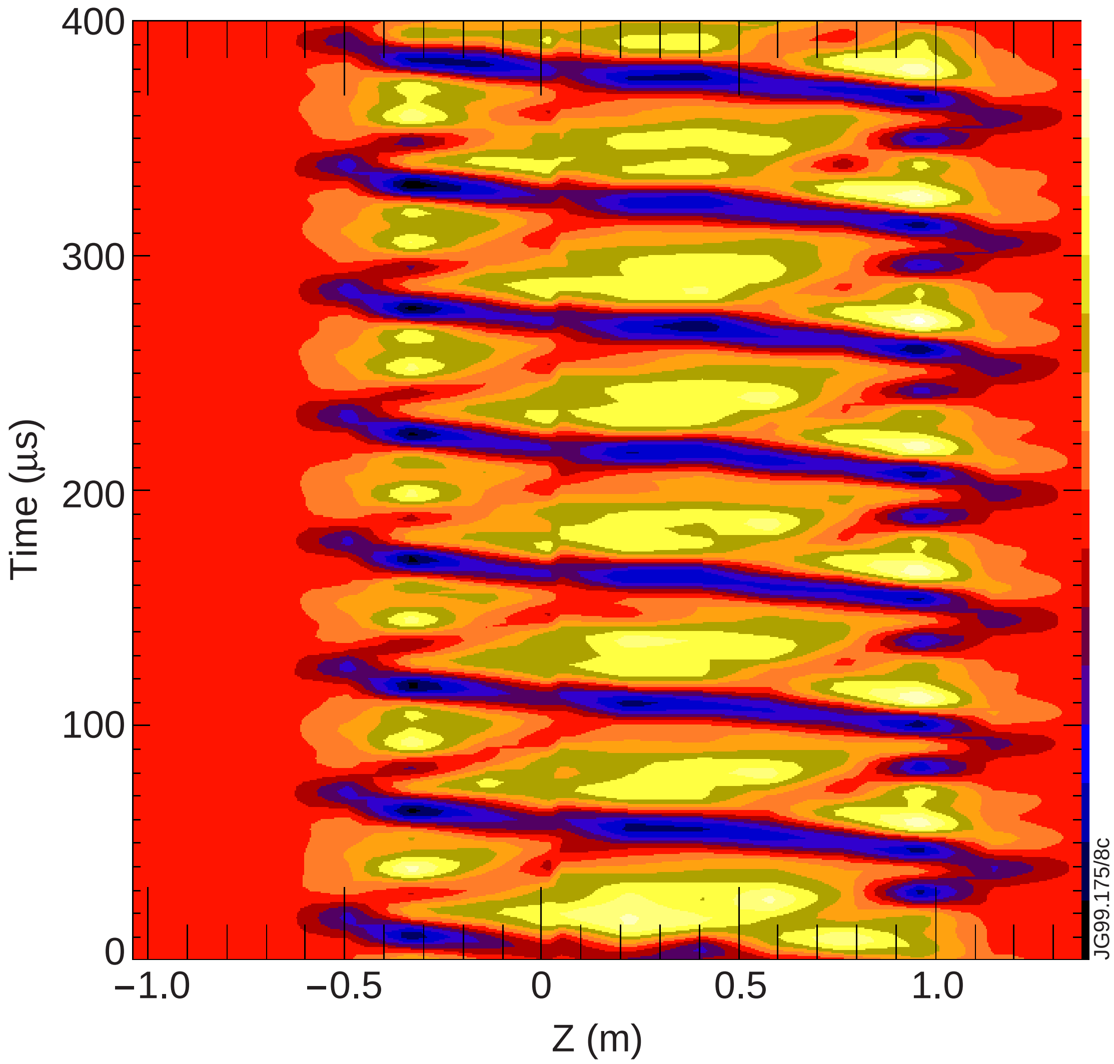


This snake is a region of higher pressure plasma.

Pellet induced snakes were usually associated with (1,1) modes at the q=1 surface, but (3,2) modes were also observed.

More snakes

Snakes form spontaneously in Optimized Shear Discharges.



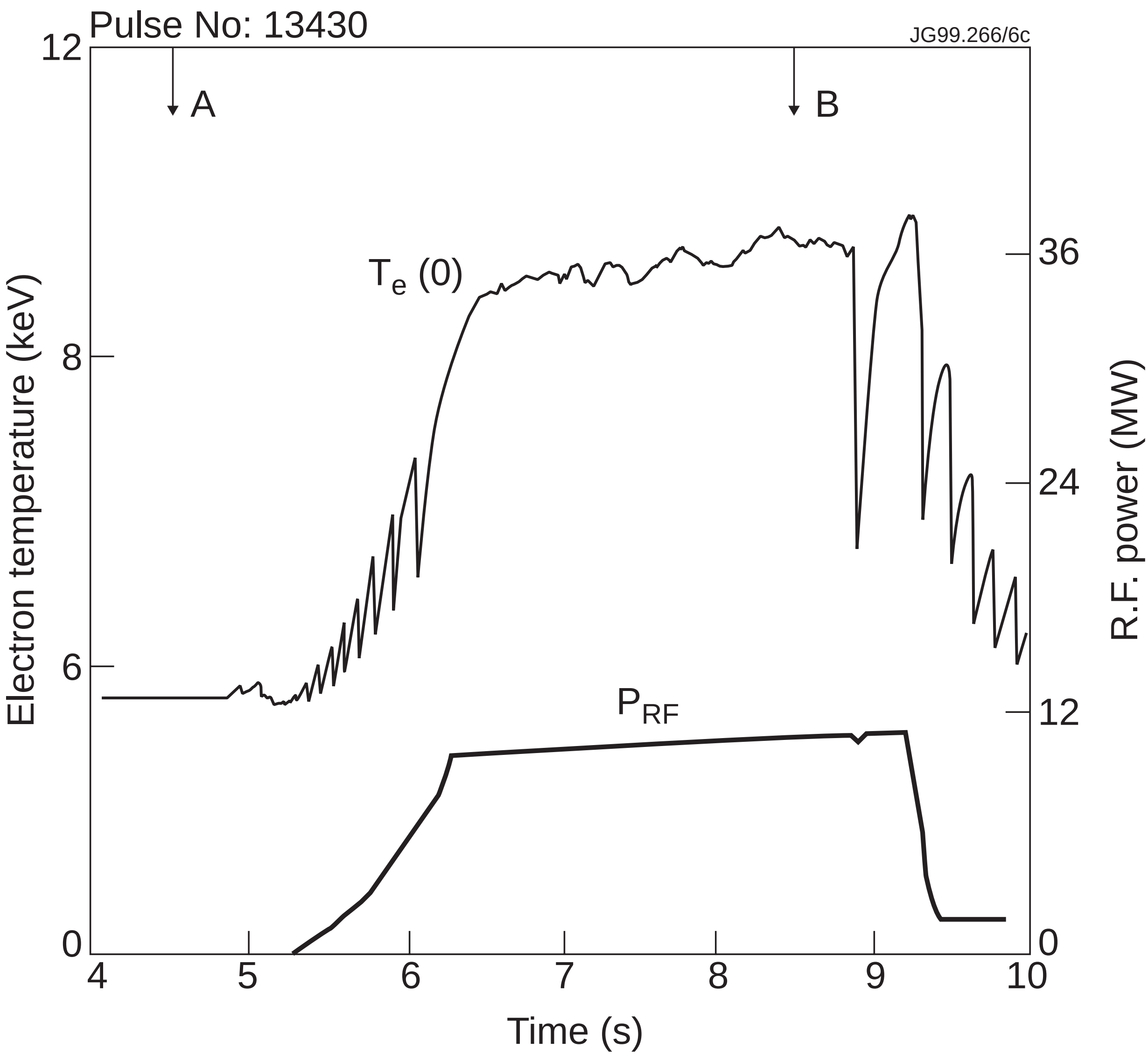
Fluctuation in Soft X-ray emission profile.

Blue double helix is a hot snake (polarity can invert).

- These snakes are usually associated with q=2
- More than one (2,1) mode may be present in the same surface.
- These snakes appear spontaneously.

Monster sawteeth

Plasma are modulated by sawtooth-like oscillations.



Sawteeth can be stabalized by:

- **Current profile control (avoiding q = 1 surface)**
- **Fast particles inside q = 1 surface**

Monster sawtweeth are expected in burning plasmas due to alphas

Scaling Laws

Scaling Laws
Wind tunnel techniques in Tokamaks

- Diffusive confinement $\rightarrow \tau_E \sim \dfrac{a^2}{D_{turb}} \sim \dfrac{a^2}{\lambda^2 / \tau_c}$

τ_C = correlation time

- If $\tau_E = \tau_E(n,B,T,a)$, the invariance properties of the Fokker-Plank equations lead to a scaling relation:

$$\tau_E \propto \frac{m}{eB} F\left(\frac{T}{a^2 B^2}\right) \propto \frac{1}{\Omega} F\left(\frac{T}{a^2 B^2}\right)$$

- Choosing appropriate dimensionless variables:

$$\rho^* \sim \rho_i/a,\ \beta \sim nT/B^2,\ \nu^* \sim \frac{\nu}{v_{th}/qR}$$

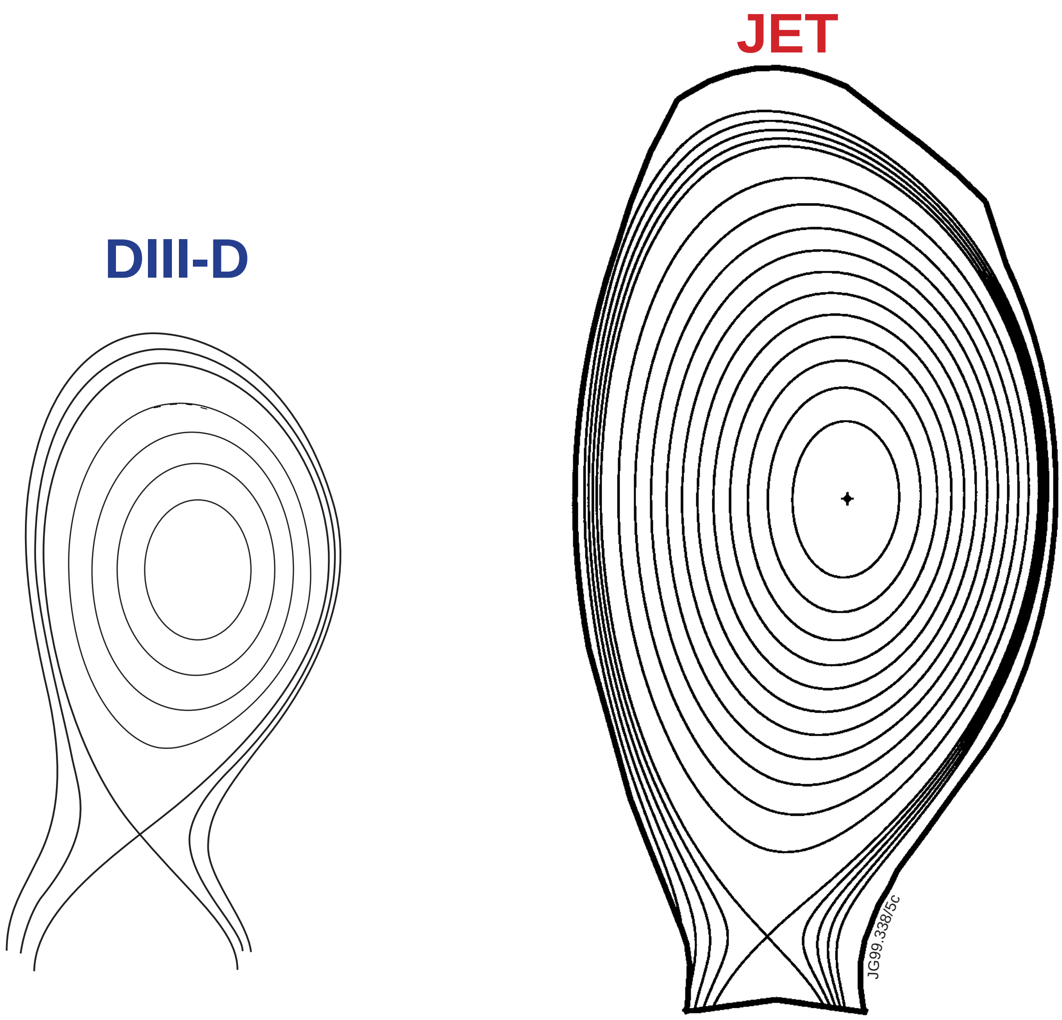
the confinement time can be expressed as:

$$\tau_E = \frac{1}{\Omega} \rho^{*\alpha} F(\beta, \nu^*, q\ldots)$$

$\alpha = -1$	Stochastic,	$\lambda \sim a$
$\alpha = -2$	Bohm scaling,	$\lambda \sim (a\rho_i)^{1/2}$
$\alpha = -3$	Gyro-Bohm,	$\lambda \sim \rho_i$

Dimensionless Identity Experiments

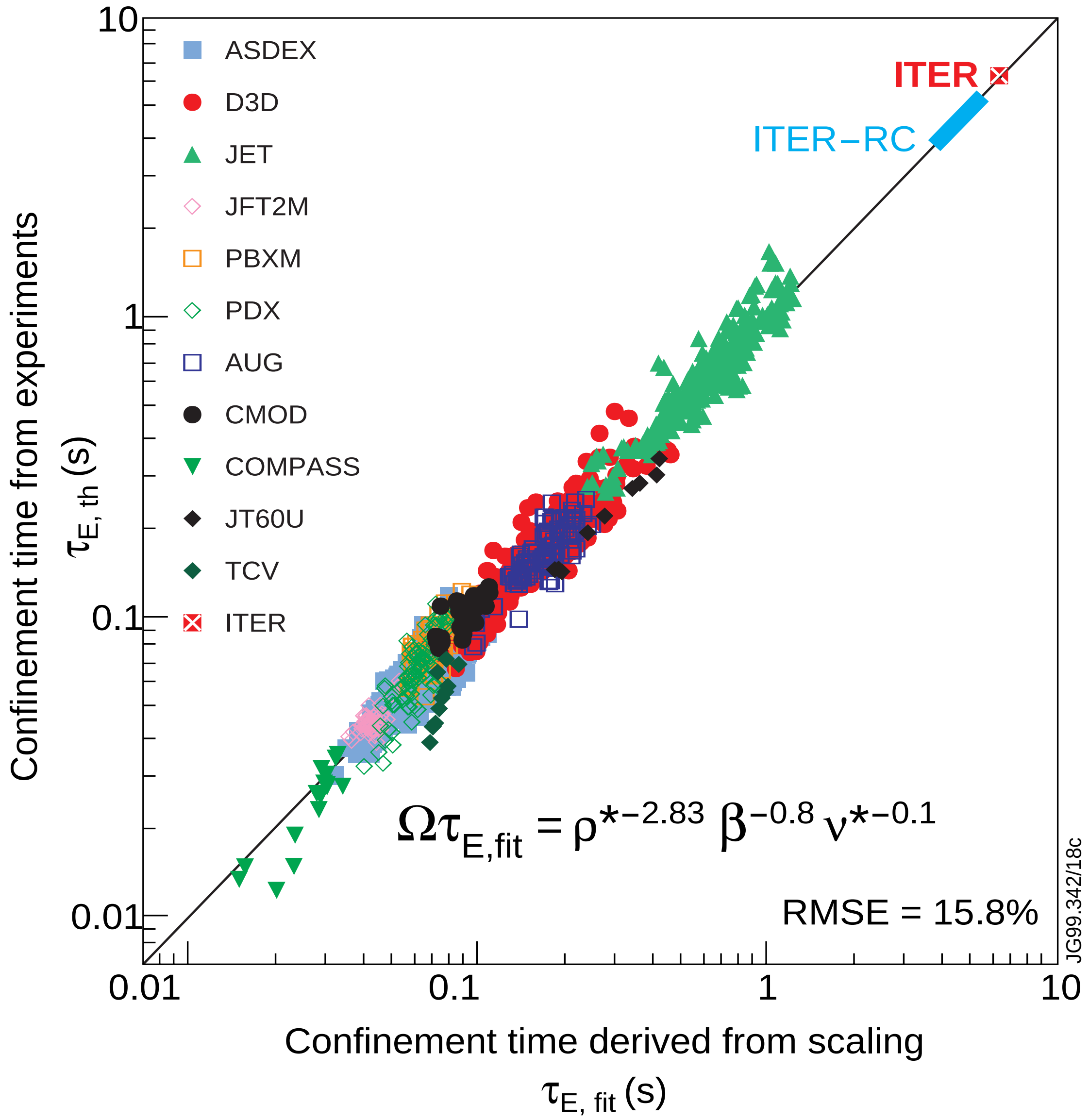
Dimensionless scaling can be tested by comparing $\Omega\tau_E$ values in different machines with identical values of ρ^*, β, ν^*, q.



	DIII–D	JET
R(m) =	1.69	2.96
a (m) =	0.55	0.95
B(T) =	2.15	1.07
τ_E(s) =	0.16	Predicted 0.32 (0.31 actual)

Extrapolation to a reactor

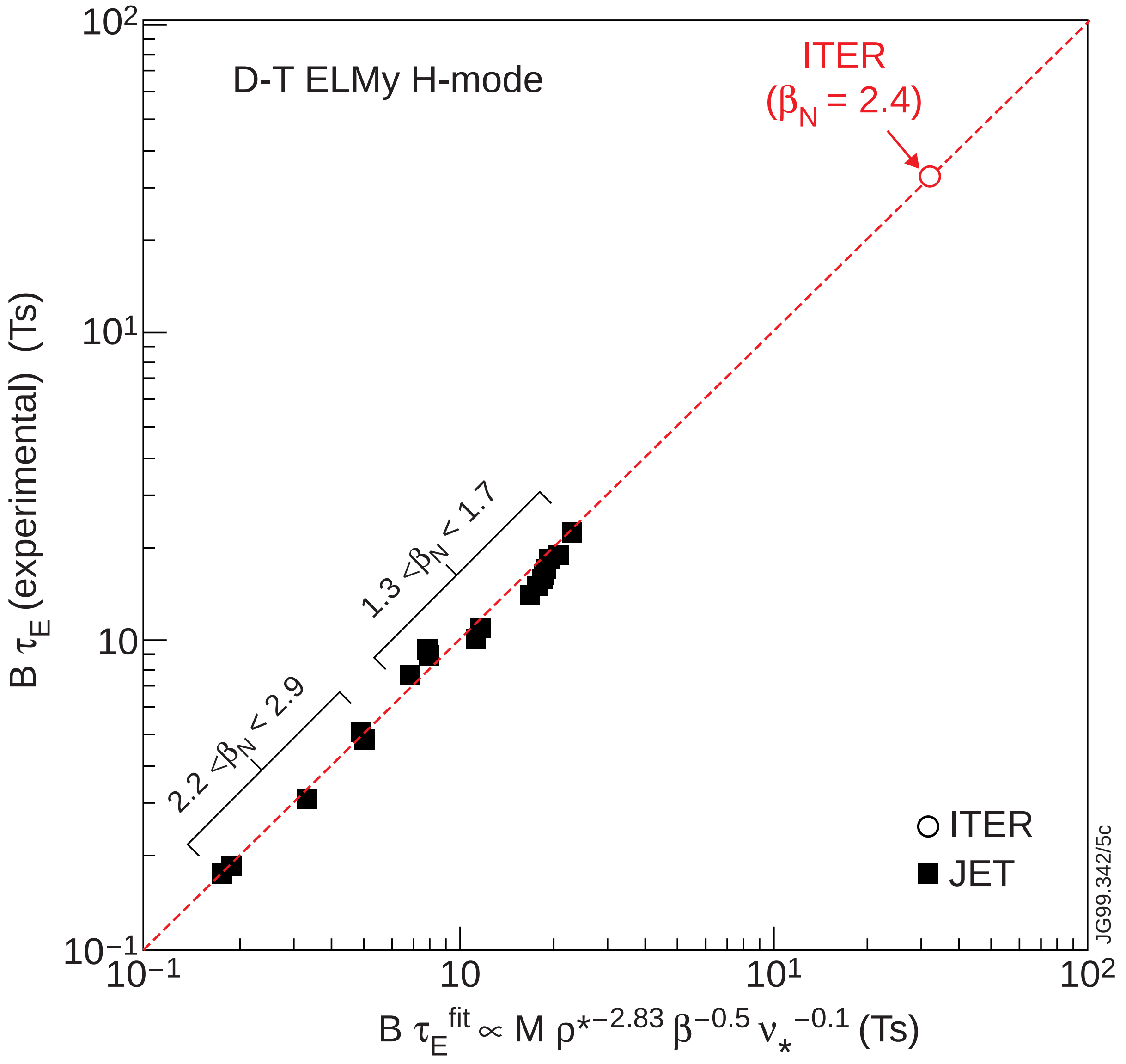
Scaling laws, derived from experimental data from various machines, are used to extrapolate confinement time estimates to other devices.



JET is nearest to the reactor range, and tritium experiments provide mass scaling: $\tau_E \propto \frac{m}{B}\rho^{*-3}$ ($\propto mB^2$, more favourable than Bohm)

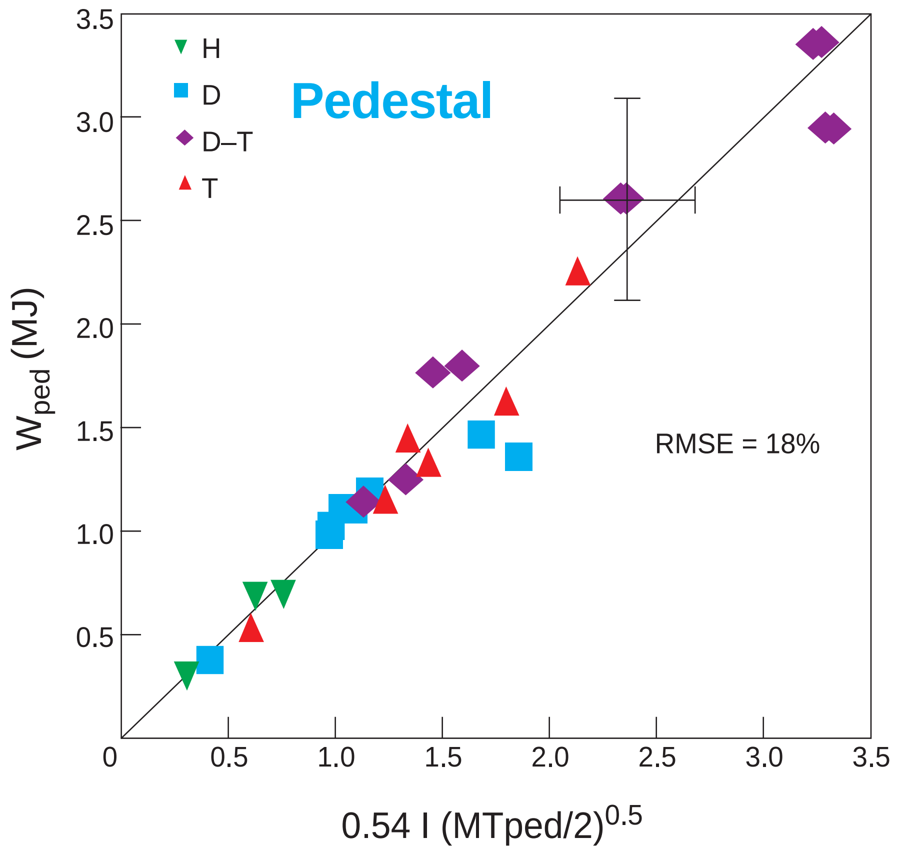
JET

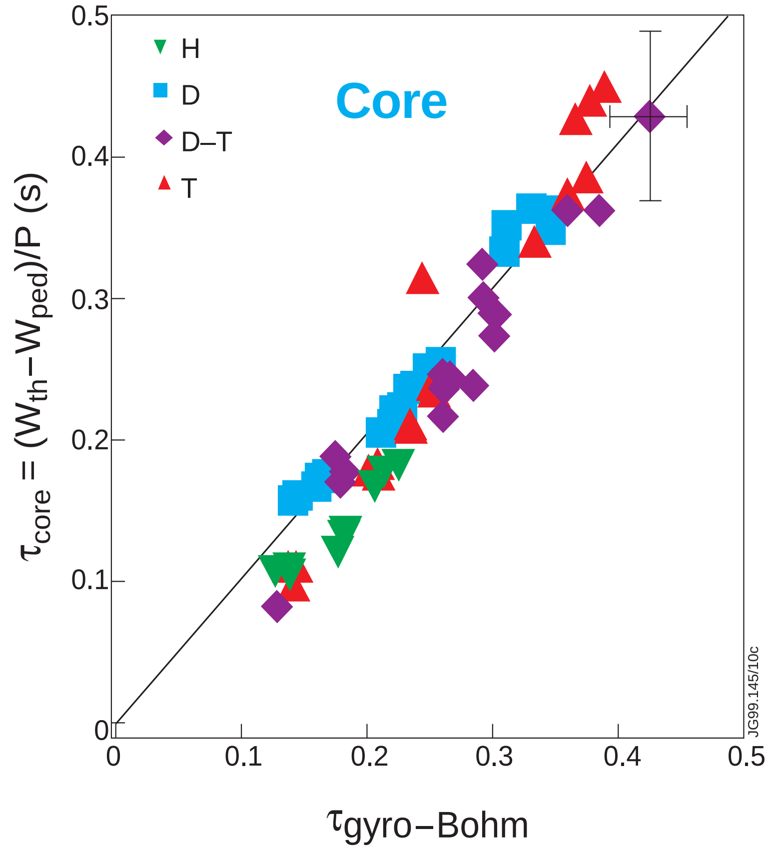
and JET can use Tritium, providing information on Mass scaling



Core confinement time exhibits near gyro-Bohm scaling with $\tau_E \propto (m/B)\rho^{*-3}$ ($\propto m B^2$, cheaper than Bohm)

Separate Plasma Energy into Pedestal and Core





- Pedestal energy scales strongly with mass ($M^{0.5}$) as if edge is at ideal pressure limit.
- Subtracting pedestal energy from total plasma energy results in **core confinement time consistent with gyro-Bohm scaling ($M^{-0.2}$)**

Confinement is sum of core + edge: $\omega_c \tau_E \sim \langle\rho^*\rangle^{-3} (1 + c \langle\rho^*\rangle^2/\beta_N^2)$

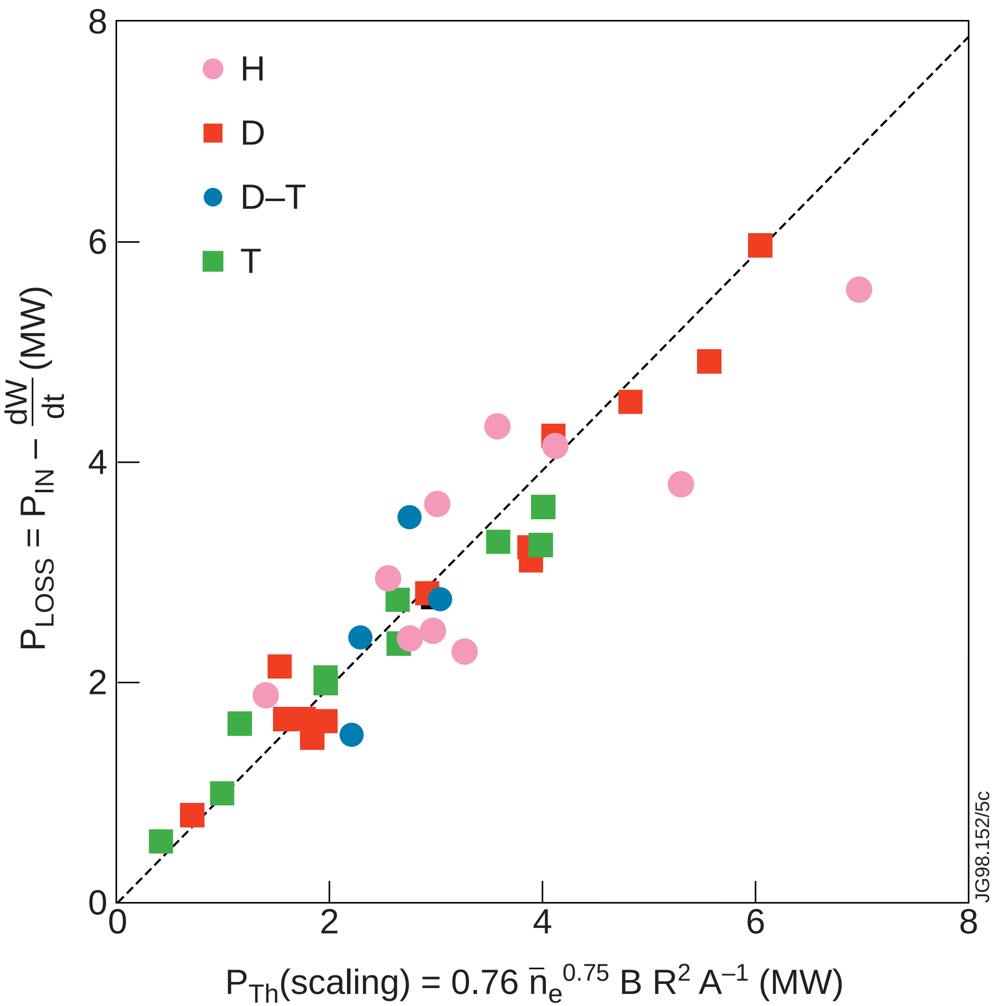
H-mode Threshold Power Varies Inversely with Mass

- **H-mode threshold** in H, D, D-T and T **decreases** with increasing isotope mass **as A^{-1}**.

Very favourable for ITER

- 33% reduction in power to access H-mode in pure tritium (e.g. during start up).

- 20% reduction in power to maintain high fusion operation.



JG00.106/61

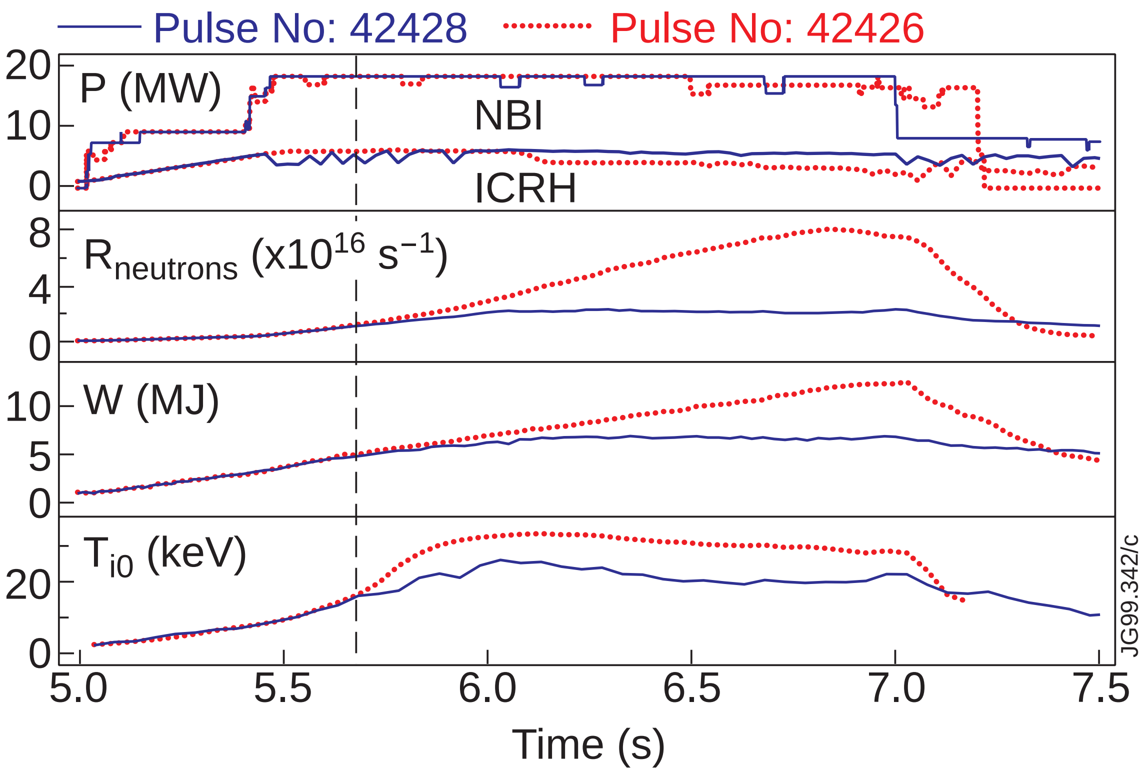
ITER Databases to which JET is a major contributor

1) L-mode and Ohmic Global Confinement
2) L–H threshold
3) H-mode ELM-free and ELMy Global Confinement
4) Profile, contains profiles for all types of pulses
5) Disruption
6) Divertor/Edge
7) Pedestal

Internal Transport Barrier
ITBs

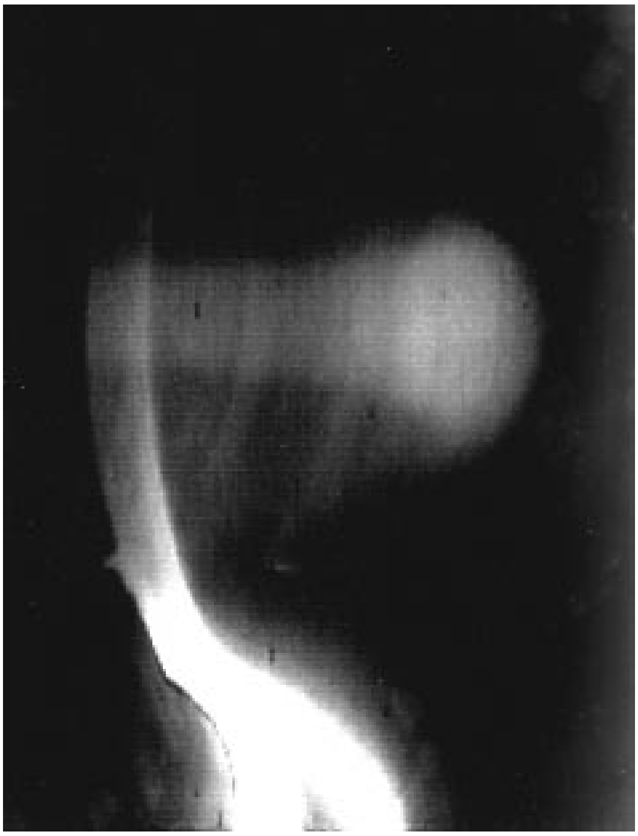
Confinement bifurcation in optimised shear

Two 'similar' discharges show the difference between a plasma without (#42428) and with (#42426) a strong internal transport barrier.

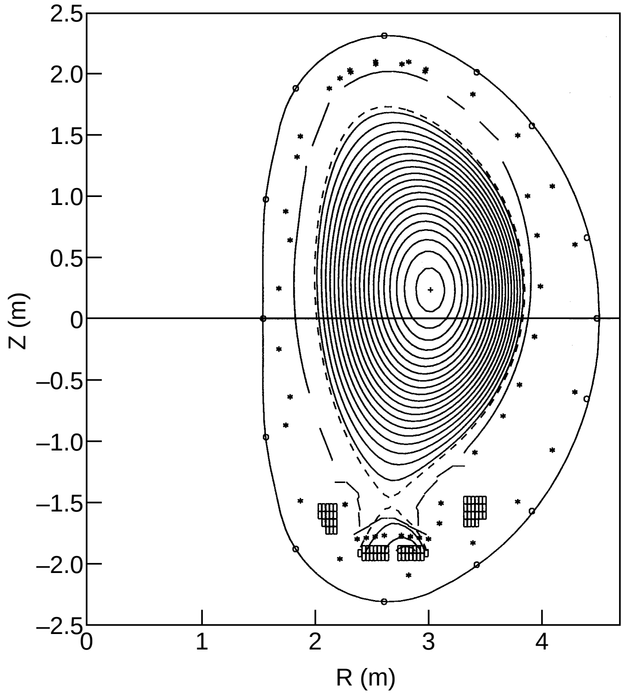


Dense Core with Optimised Shear

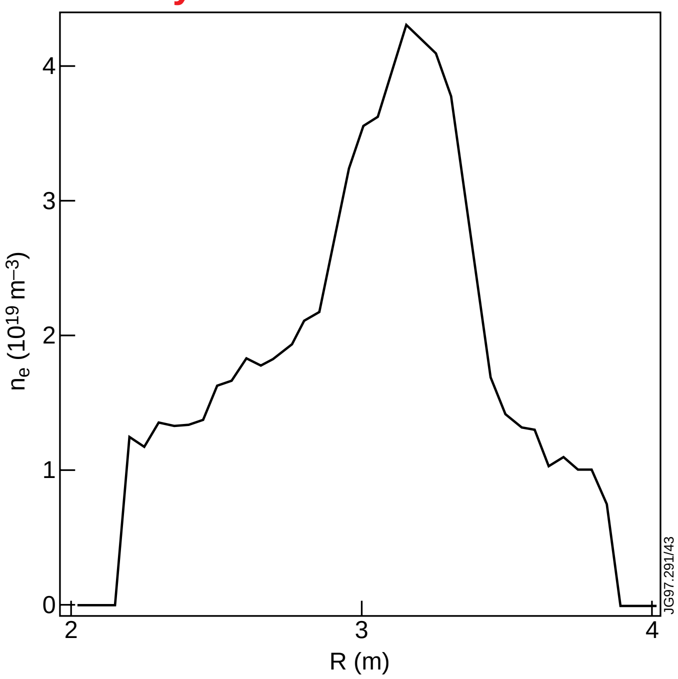
(Pulse No: 39571, t = 7.8s)



Magnetic Configuration

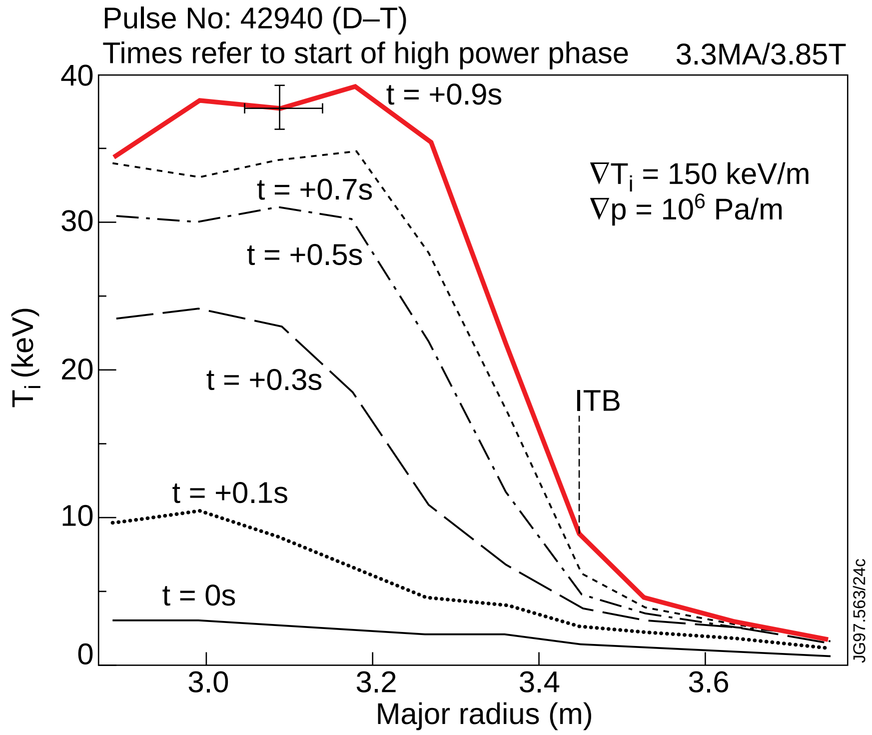


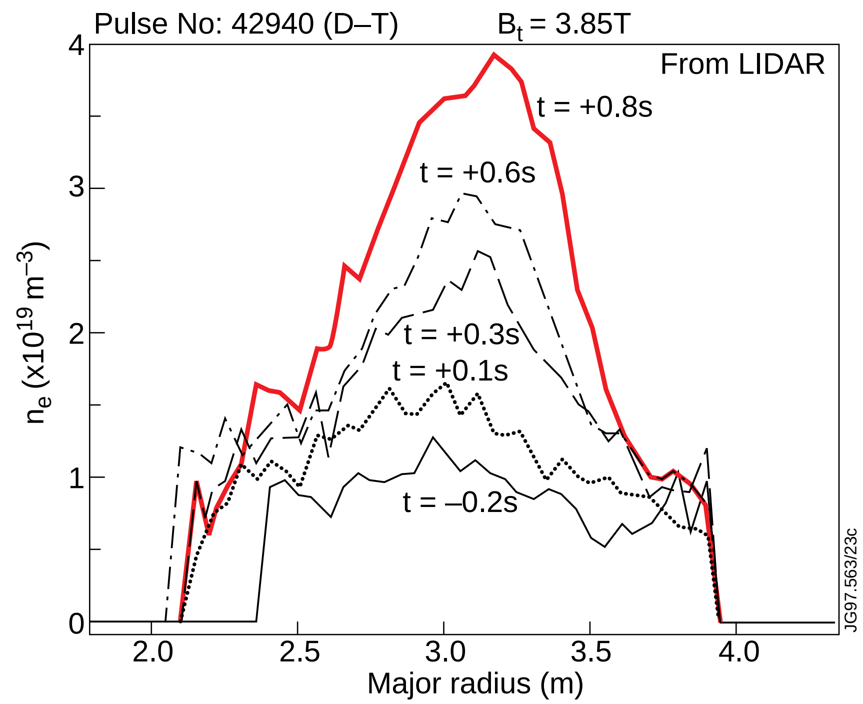
Density Profile



- Strong density peaking in the plasma core.

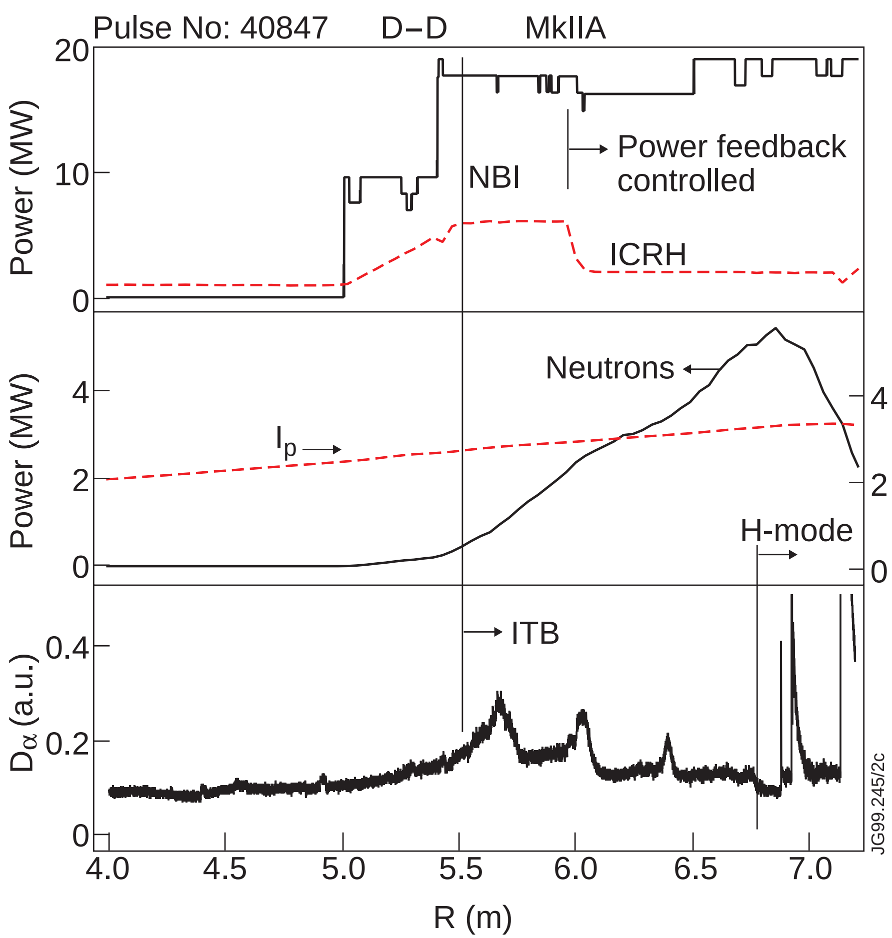
Continuous Operation with Internal Transport Barrier

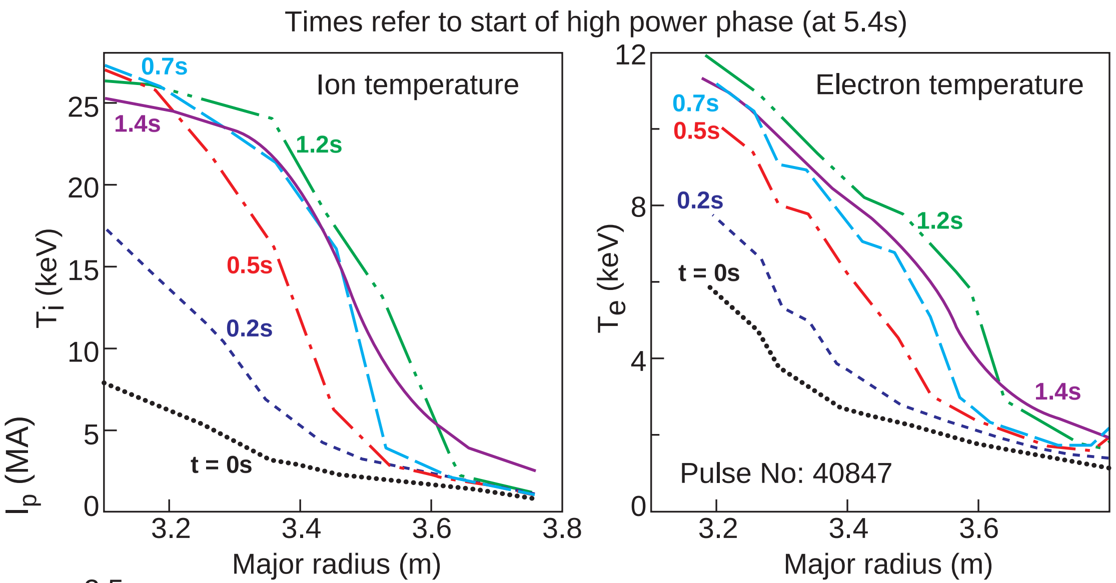


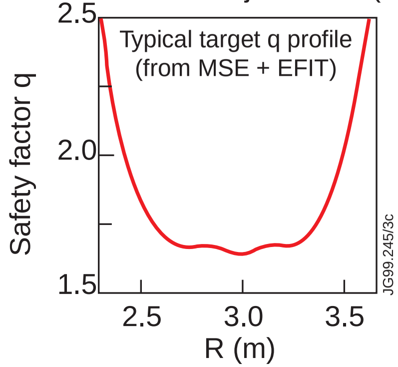


- Substantial increases in density and ion temperature result within the Internal Transport Barrier (ITB).

Internal Transport Barriers produced by appropriate heating during plasma current ramp-up phase



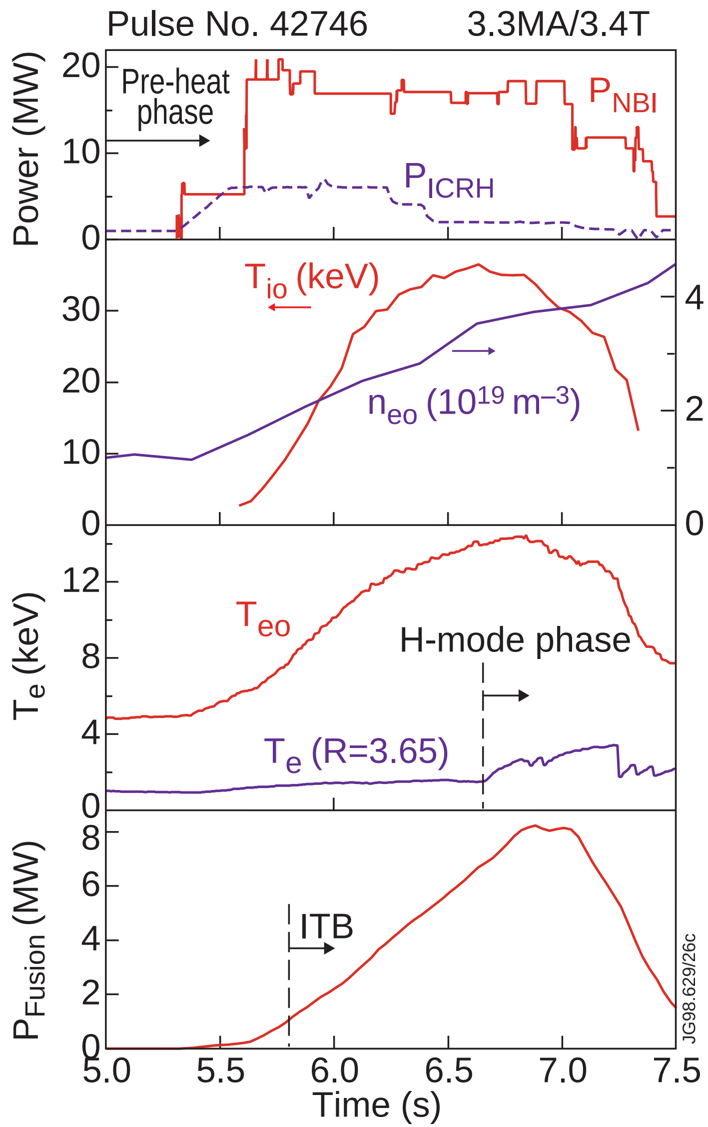


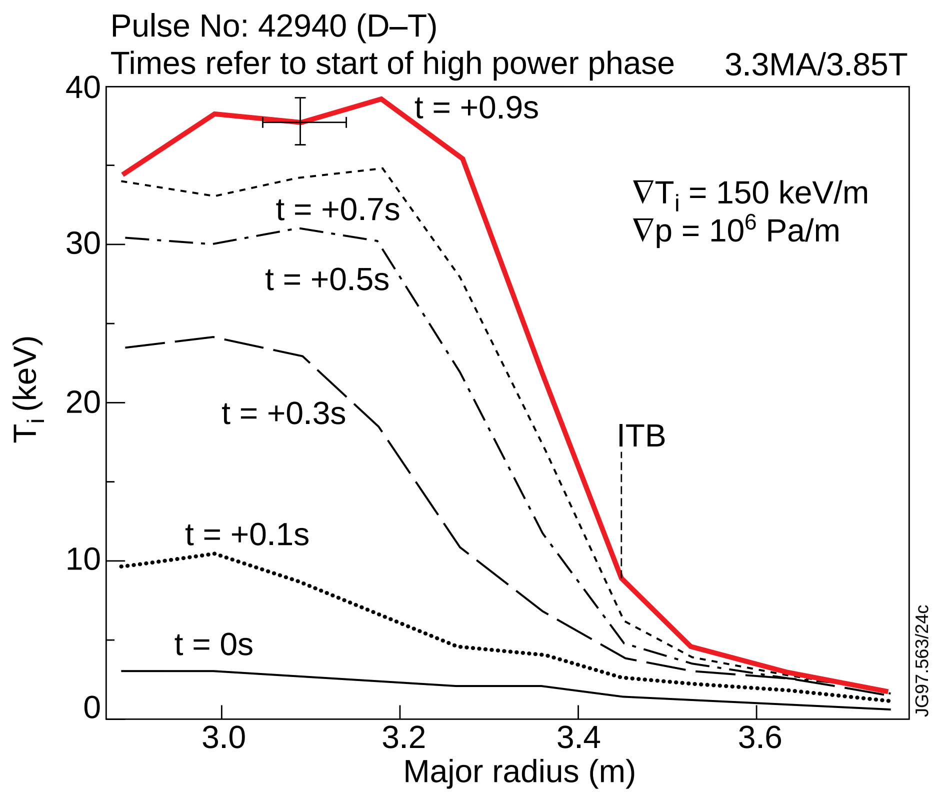


- In JET, ITBs are best produced when q_{ax} close to 2 at start of main heating.
  (also reported in JT-60, TFTR, RTP.
  (C Challis)

- Record yield in JET D-D plasmas

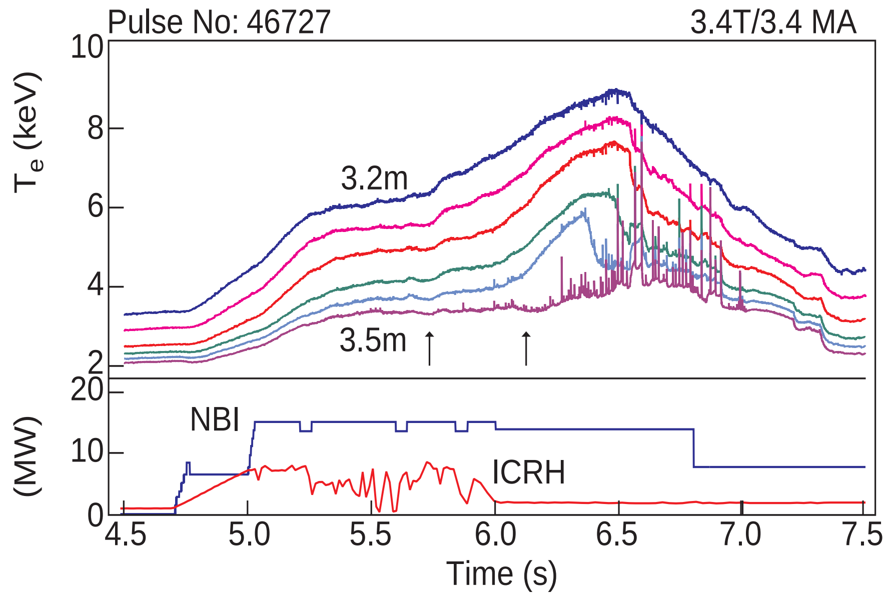
Optimised Shear Discharges in D-T

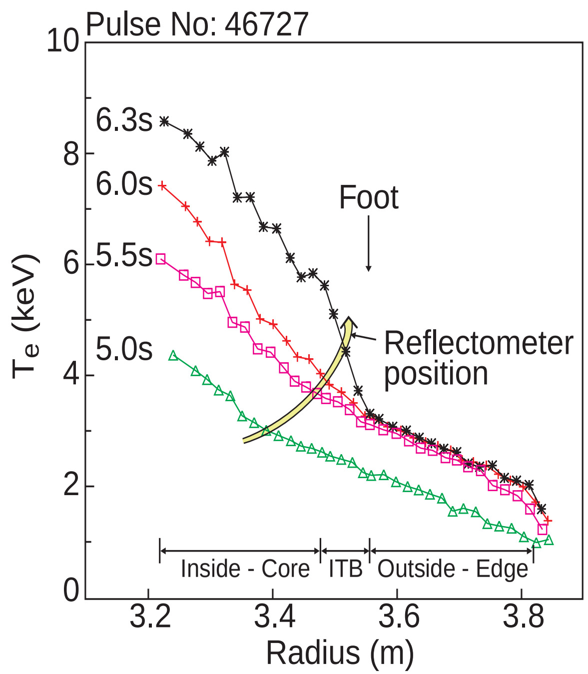




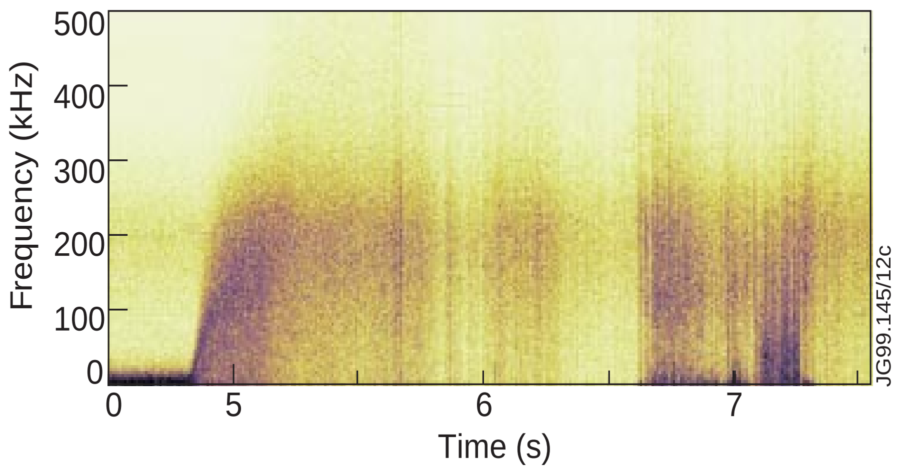
- ITBs in n_e, T_e and T_i readily obtained in D-D and D-T and with similar powers.
- 8.2MW of fusion power produced, even though optimisation incomplete.

ITB Formation and Turbulence Suppression





Density fluctuations in plasma



- High power heating generates region of high toroidal velocity shear which suppresses low frequency turbulence throughout plasma core ⇒ global decrease in χ_i.
- Formation of ITB linked, via feedback between enhanced ∇P and ExB shear, to localised suppression of high frequency turbulence ⇒ localised drop in χ_e.

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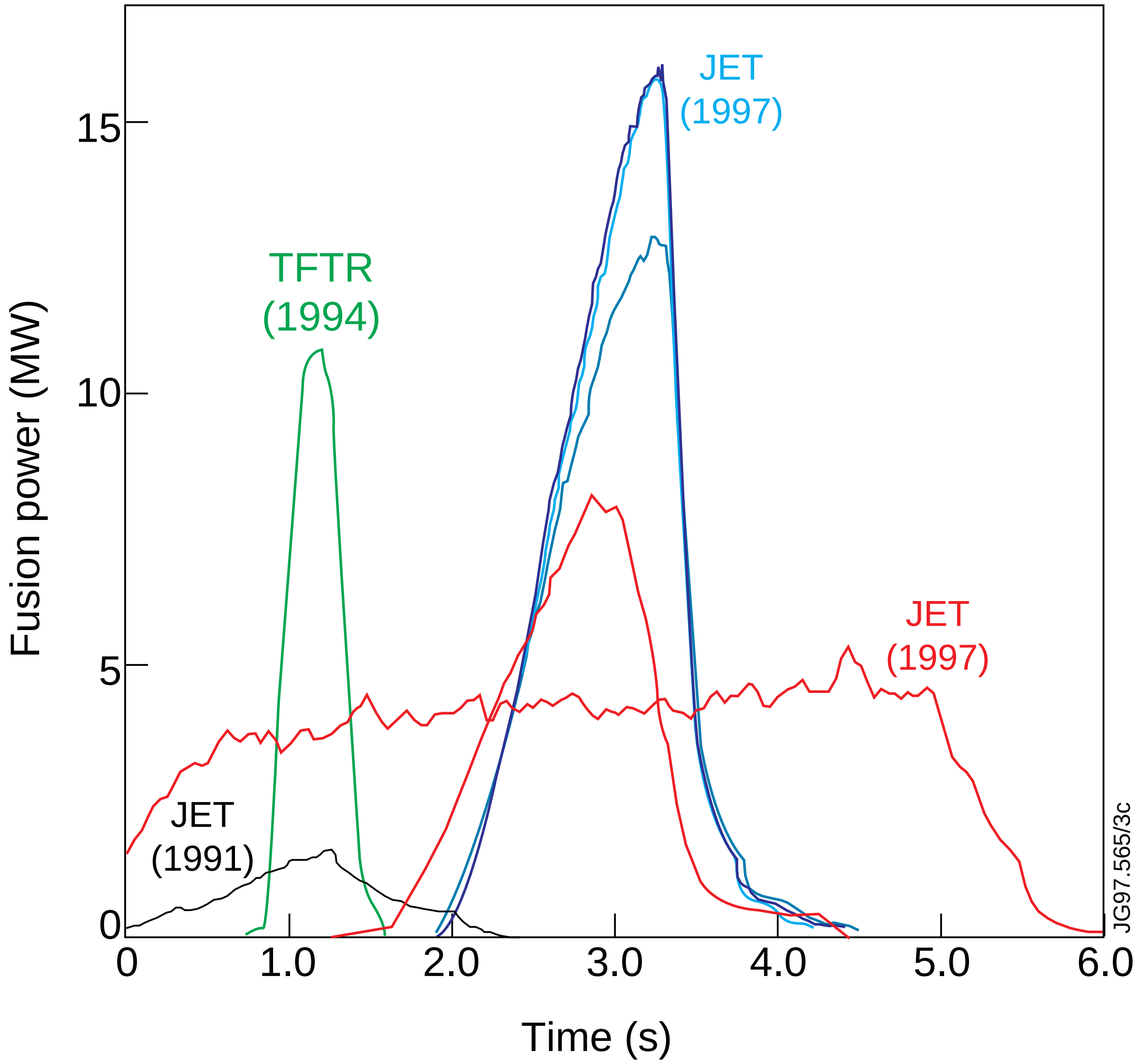
Fusion in JET

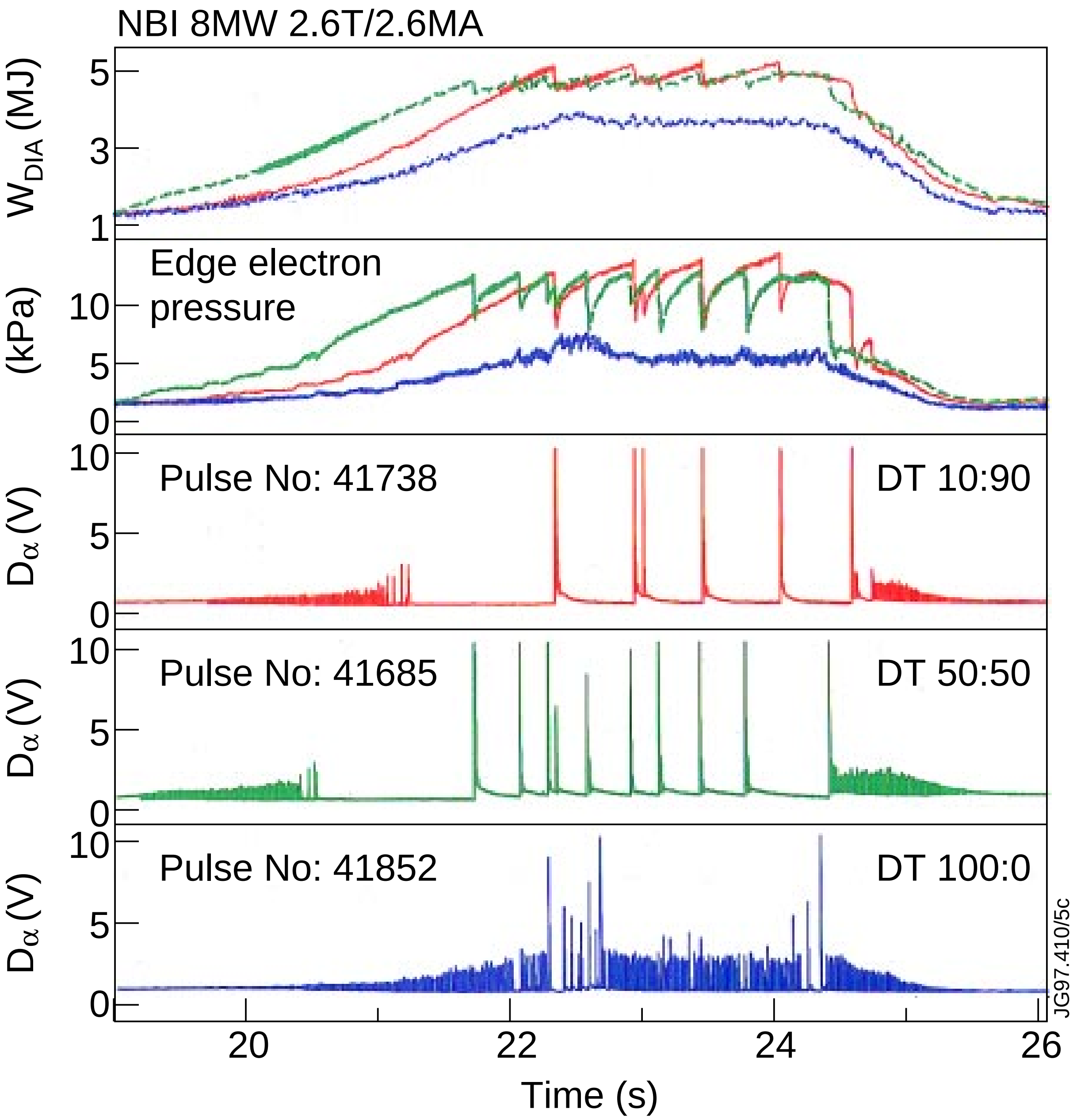
Fusion Power Development



The diagram encompasses :

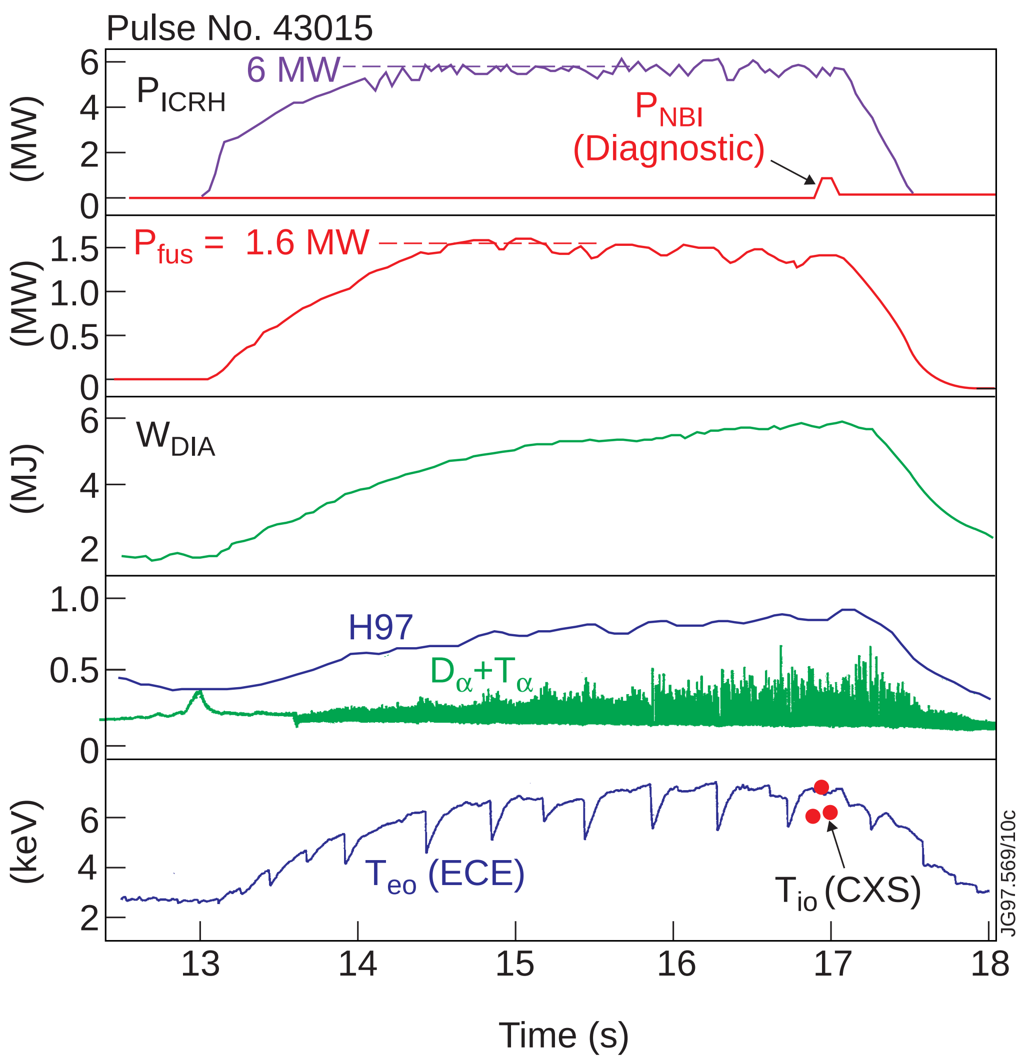
- 10% T in D experiments in JET in 1991;
- a result from the D-T studies on TFTR (1993 to 1997);
- high fusion power and quasi steady-state fusion power in the JET D-T experiments of 1997.

Isotope ratio scan
(with 8MW of Neutral Injection)



- Stored energy, density and edge pressure are higher in tritium.
- ELM frequency lower.
- 8MW insufficient to reach Type I ELMs in D–D.

Record Steady-State D-T Q-value



- (D)T ICRH
  I_p = 3.7MA, B_T = 3.7T,
  f = 28MHz D:T = 9:91
- P_{fus} = 1.67MW
  P_{RF} = 6MW
- $Q(3\tau_E) = 0.22 = E_{fus}/E_{in}$
- τ_E = 0.87s
- H97 = 0.9
- Small ELMs
- $T_{io} \sim T_{eo}$

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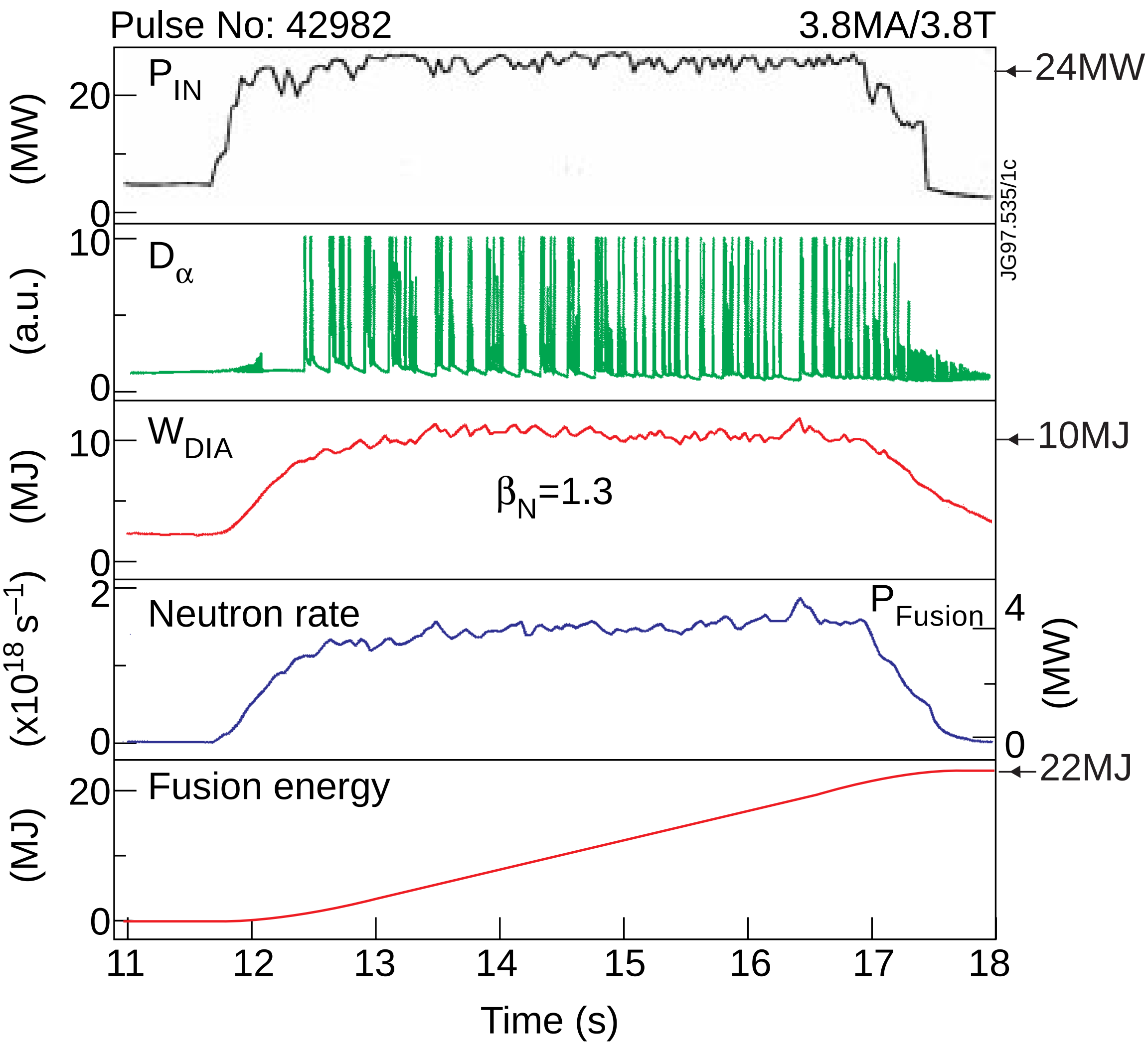
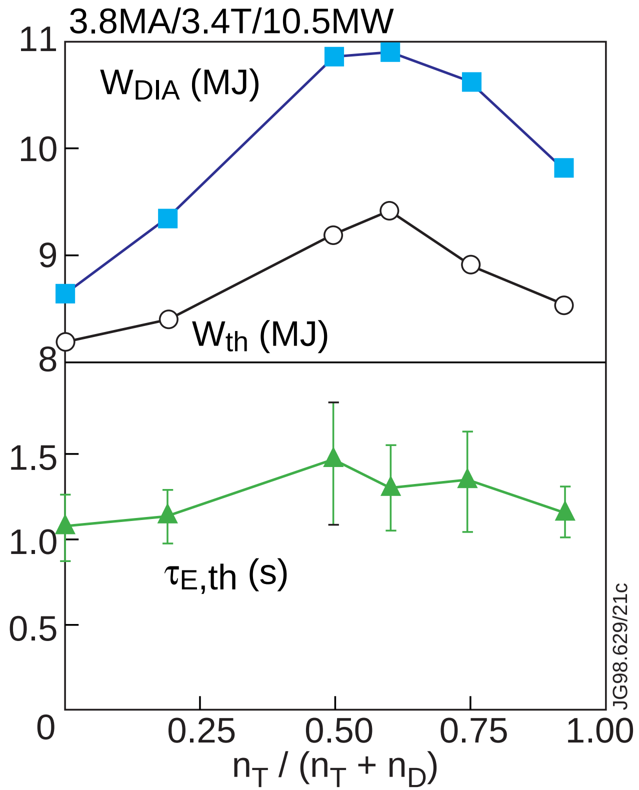
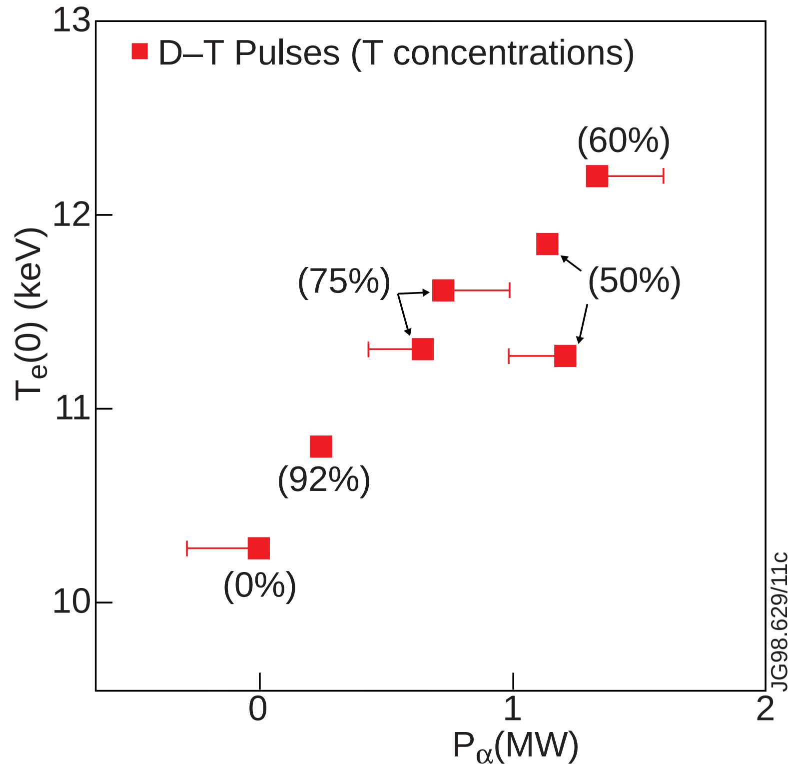
Record Fusion Energy in 'Steady State' ELMy H-mode



- DT fusion energy 21.7 MJ in ITER geometry
- 4 MW Fusion power at Q = 0.2
- Duration of 4.5 s (10 x τ_E) limited by NB duration
- Central $T_e \approx T_i \approx$ 8 keV; β_N = 1.3

Alpha Particle Heating Clearly Observed



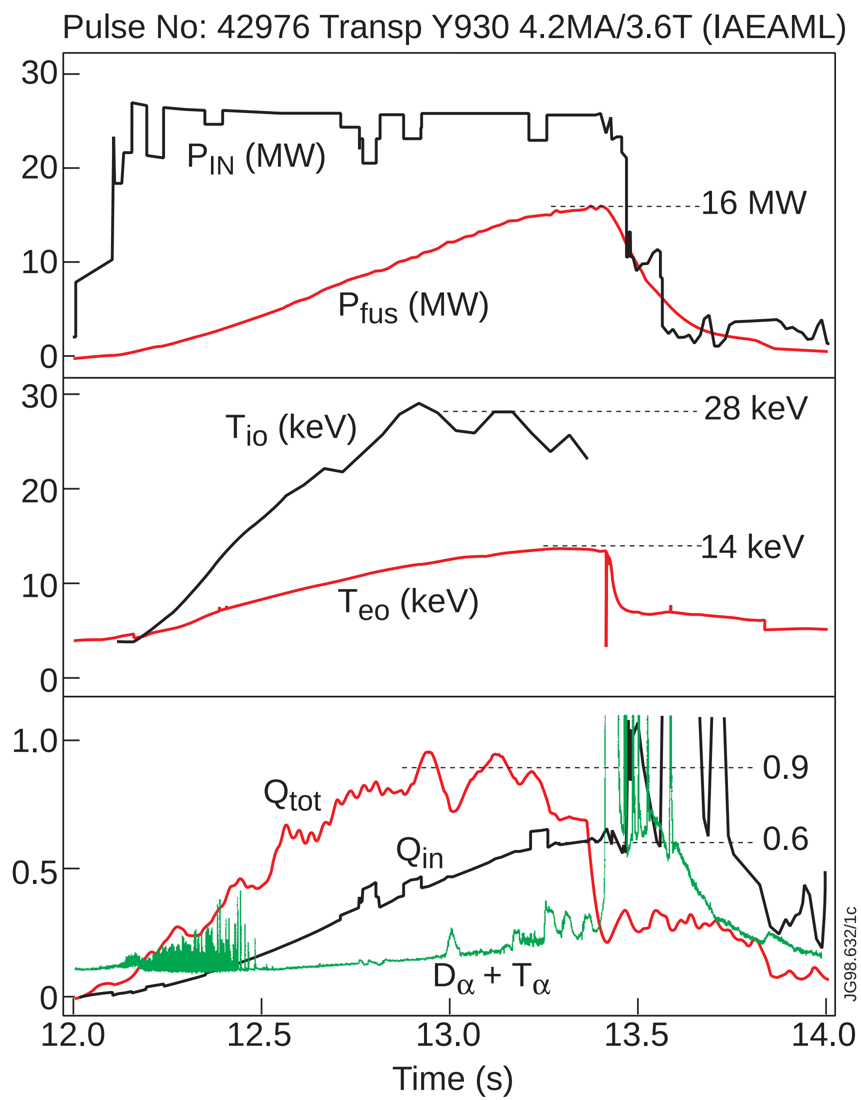


- D-T mixture scan shows:
  - no or very weak isotope effect on global energy confinement;
  - strong correlation between diamagnetic energy and optimum (40:60) D-T mixture.
- Highest electron temperature shows a clear correlation with the maximum alpha particle heating power and the optimum D-T mixture.

Confirms process by which ignition would occur in a reactor

16.1MW of D-T Fusion Power

- Reproducible hot ion ELM-free H-modes in D-D and D-T at high plasma current and combined NB+ICRF heating power.
- Performance increases until terminating MHD in edge (large sawtooth, giant ELM, external kink driven by edge current).
- Good mixture and density control allowed record fusion power, P_{fus}, and Q, albeit transiently:
  – **P_{fus} = 16.1MW (>10MW for 0.7s)**; and
  – **$Q_{tot} = P_{fus}/(P_{loss} - P_{\alpha}) = 0.94 \pm 0.17$** ($P_{fus}/P_{in} = 0.62$).



Divertors

Divertor

- Plasma is forced to flow along **diverted lines into a private region** where the heat and particles can be extracted.

- **This allows:**
  - to pump the helium ash
  - to control plasma-wall interactions
  - to radiate some power to reduce the thermal loading of the target plates

- **Results**
  - good agreement with theory
  - τ_ρ^*/τ_E ~ 7.5 (< 10 is required)
  - good impurity control

- **However**
  - power bursts due to edge MHD (ELMs)
  - true steady-state operation (active cooling)

Divertor Physics

The hotter and more fusion relevant the plasma core is, the harder it is to deal with the plasma edge.

The last plasma closed flux surface can be defined by a material wall, which scrapes off field lines.

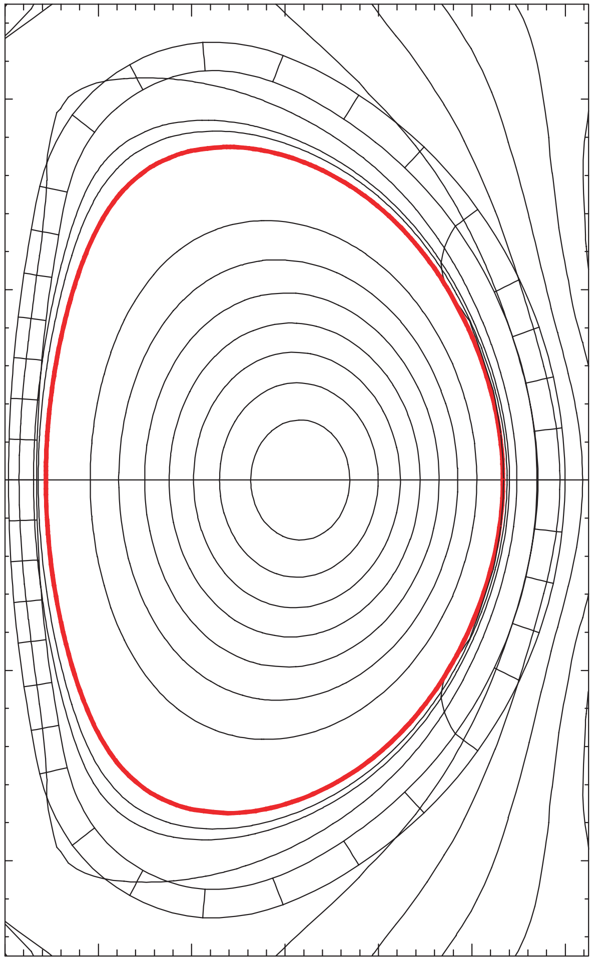
Or topology can help: the ***divertor*** concept. An ***X-point*** is created in the poloidal magnetic field, taking the ***plasma-wall interaction*** away from the core.

A delicate balancing game

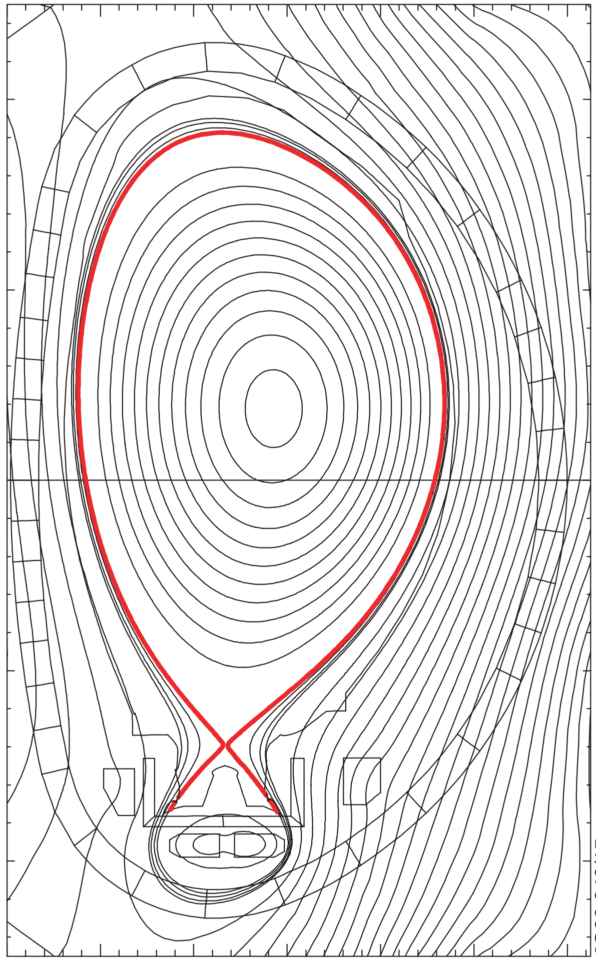
- Plasma cleanliness: keeping impurities out
- Detachment: choosing where to radiate
- Divertor Closure, for particle control
- He enrichment for He ash removal
- Power handling
- Edge Localized Modes

Different Plasma Edges

Limiter



Divertor



Plasma-wall interaction
further away from plasma

Divertor

Fuel ***impurities*** are a major threat to the success of a reactor

There are ***two primary sources of impurities***:

He ash

Plasma-wall interactions

These impurities must be controlled

Radiation reduces plasma T

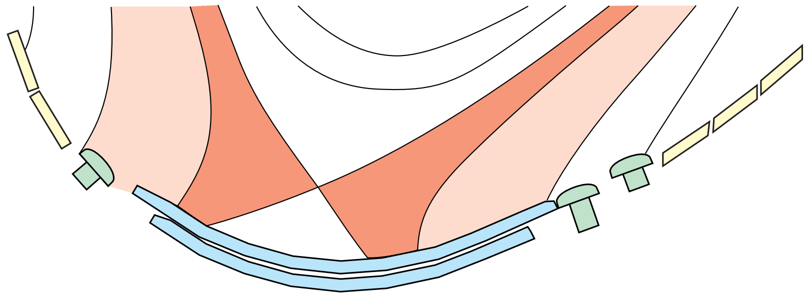
Dilution of fusion fuel

Pumped Divertor

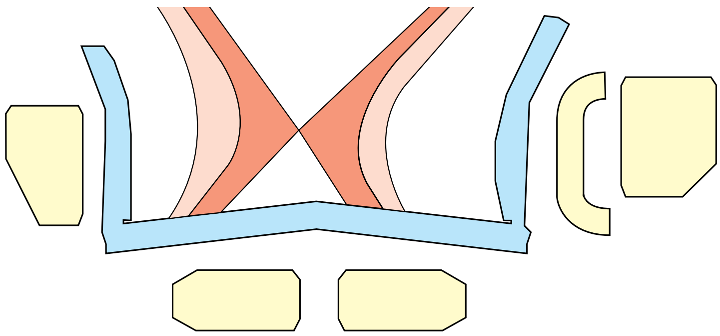
For particle control (extract ash, neutrals)

Atomic, Molecular and Materials Physics, Technology

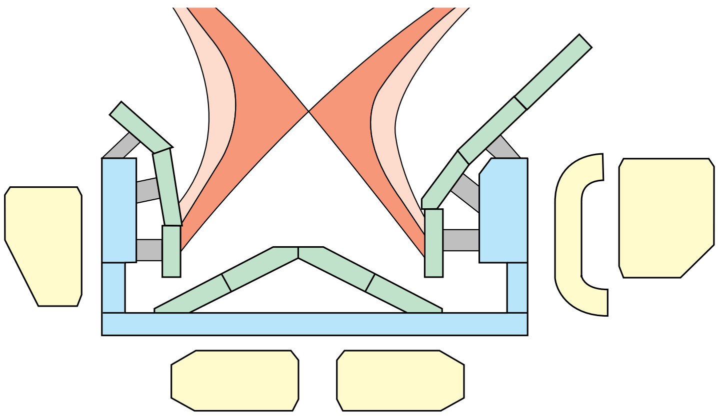
Divertors in JET



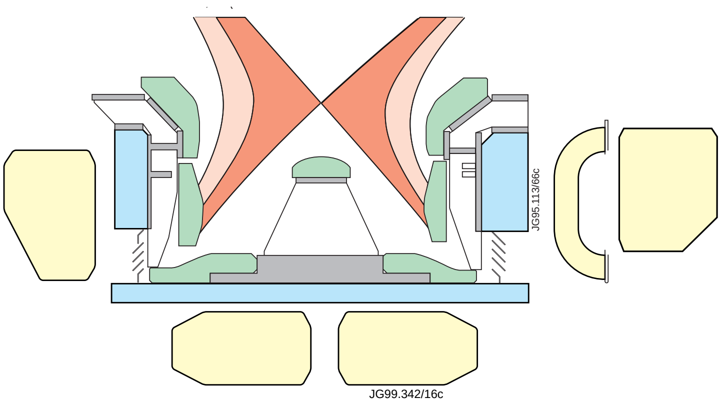
Pre-94
Mark 0
No specific divertor coils.
Large plasma volume,
very “open”.



1994/95
Mark I
“open”,
very flexible



1996/97
Mark IIA
more “closed”,
horizontal and
vertical target

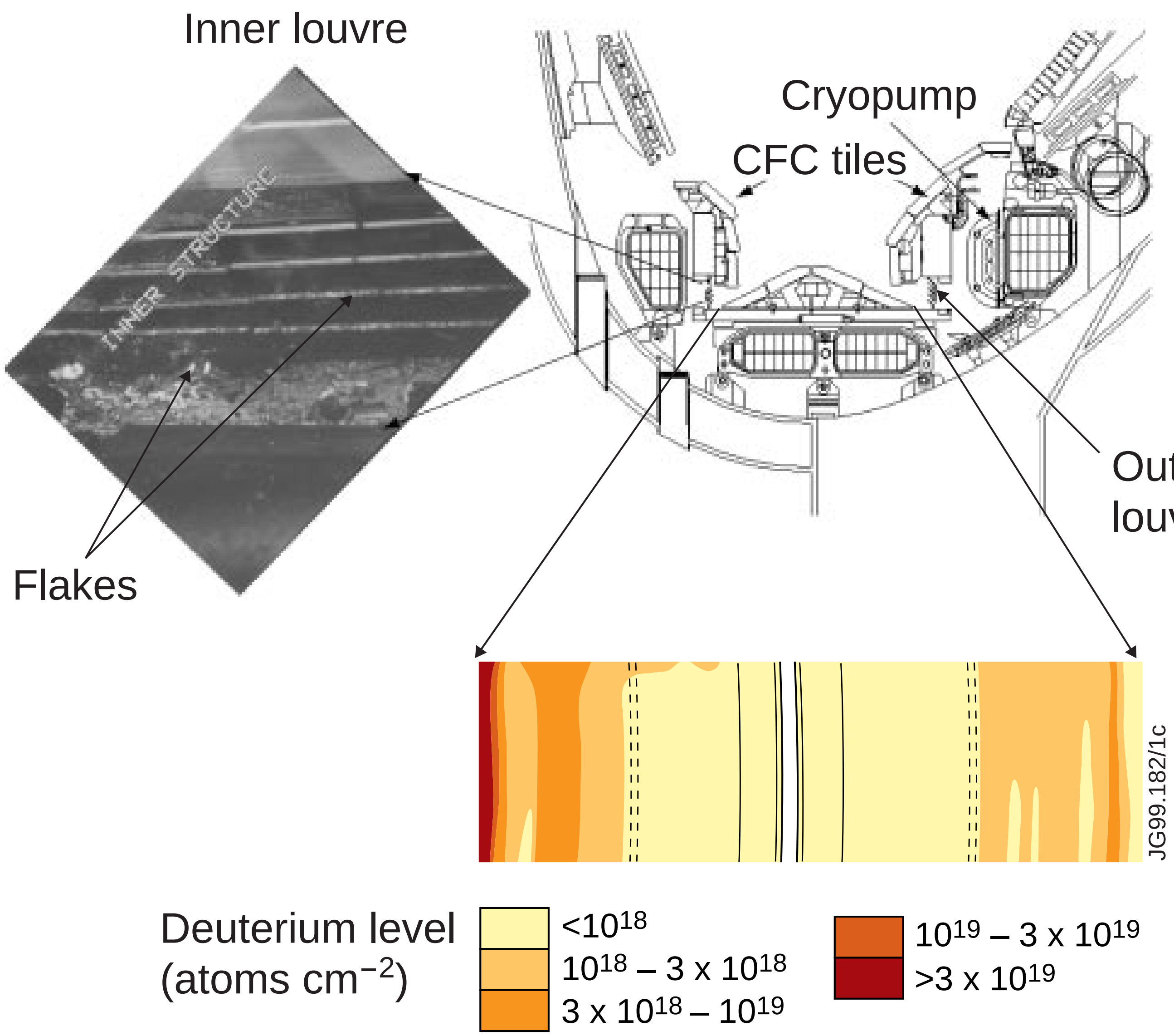


1998/99
Mark IIGB
“Gas -box” type
vertical target

Deposition in MkIIA

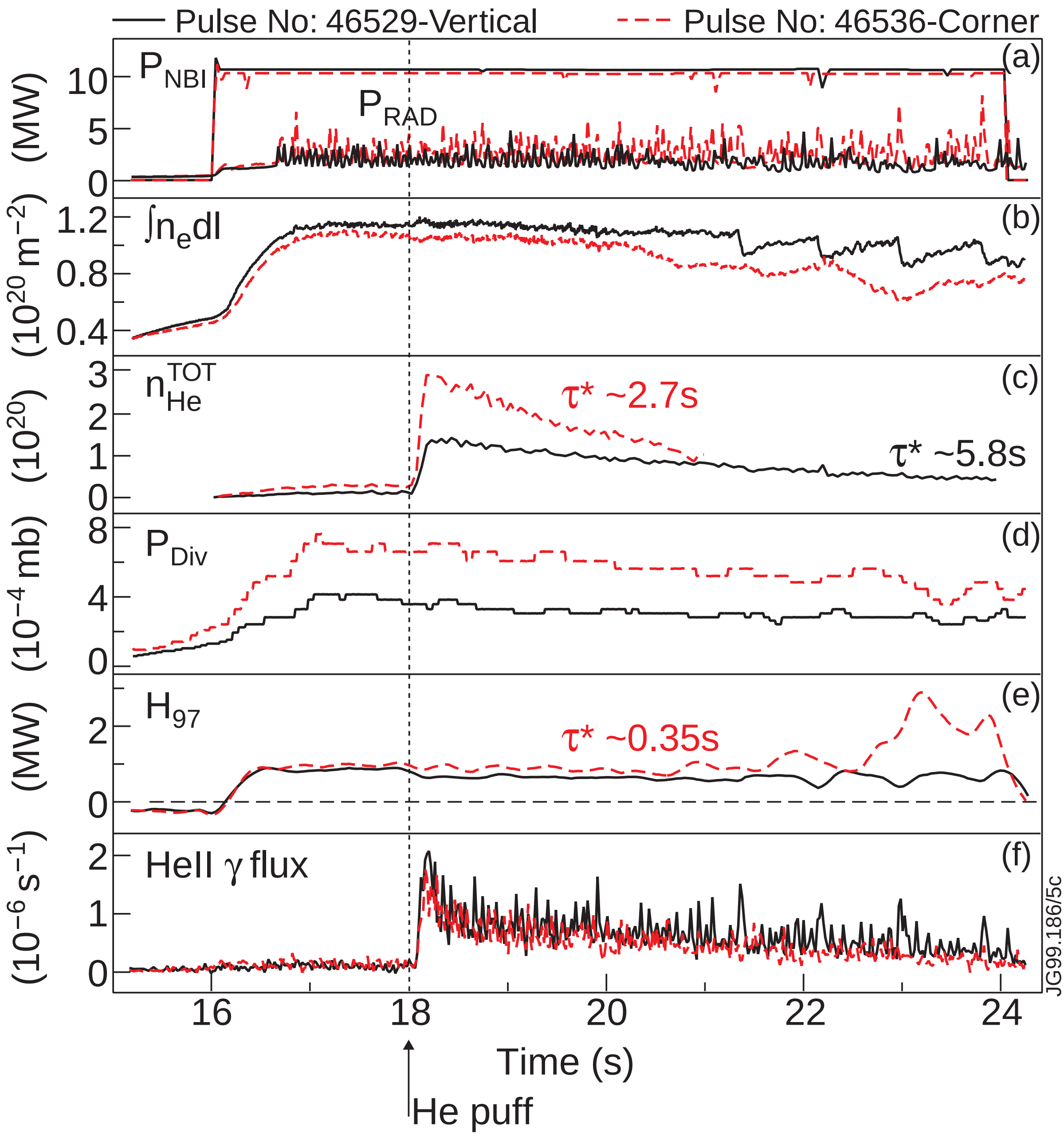
- **After 2000 Pulses**

JET MKIIa Divertor



- **In inner louvre region:**
  - No. of C atoms ~4% of D^+ flux to inner leg
  - Retained D ~6–8% of total gas fuelling

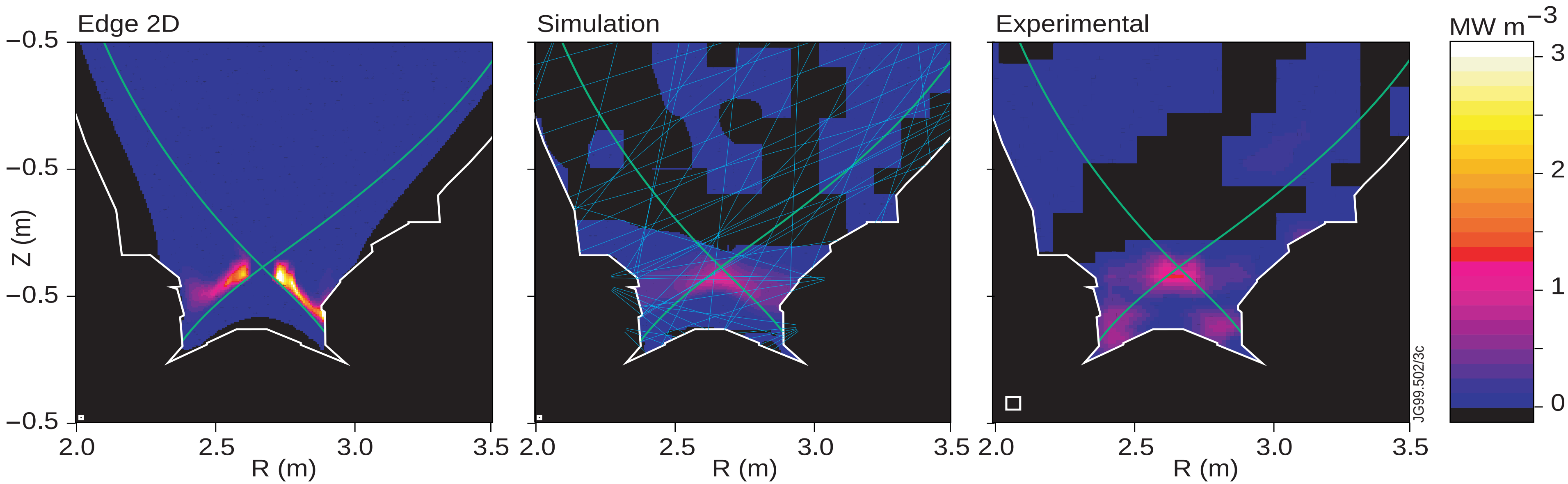
τ_p* (He)/τ_E~7.5 can be achieved



- He enriched factor η ~ 0.5 [Guo, EPS]

ITER requires η > 0.1

EDGE2D phantom, simulation and actual reconstruction Bolometer tomography L-mode DL 39587 t = 23–24s



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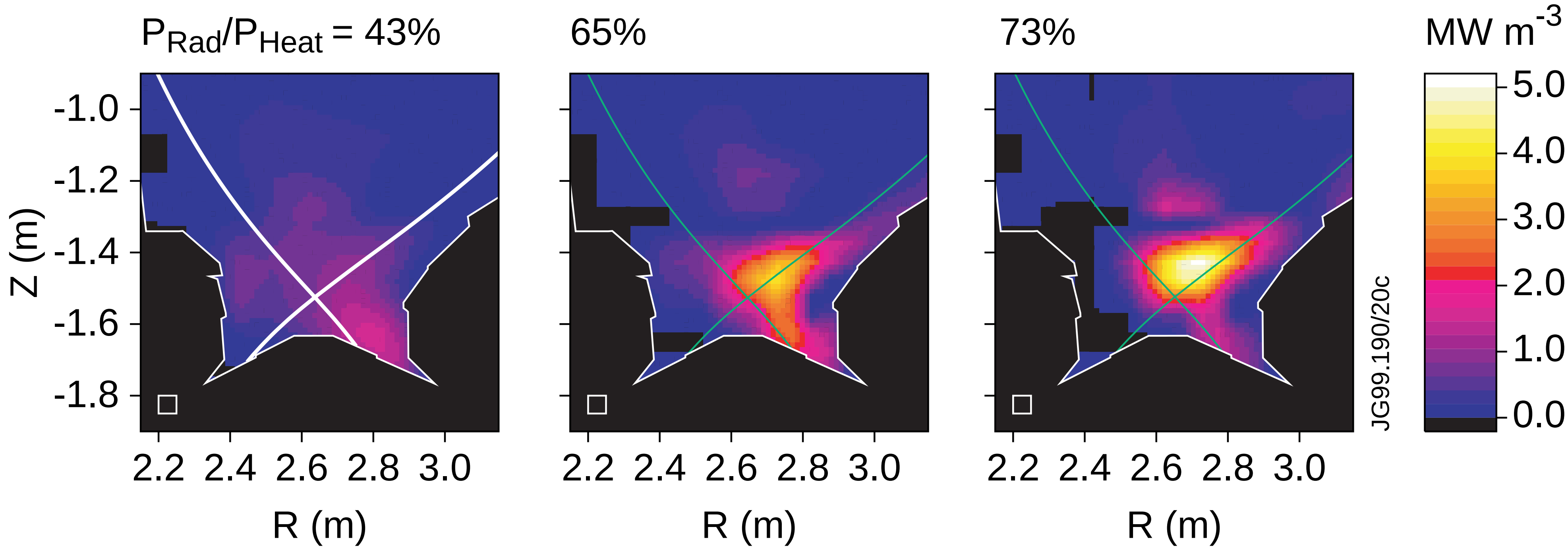
Radiative H-modes with impurity seeding

Pulse No: 37991 MarkIIA (N_2+D_2) PNB = 12MW



- Impurity seeding results in small ELMs and a 25% reduction in confinement
- Radiation in the detached divertor plasma migrates to the X-point

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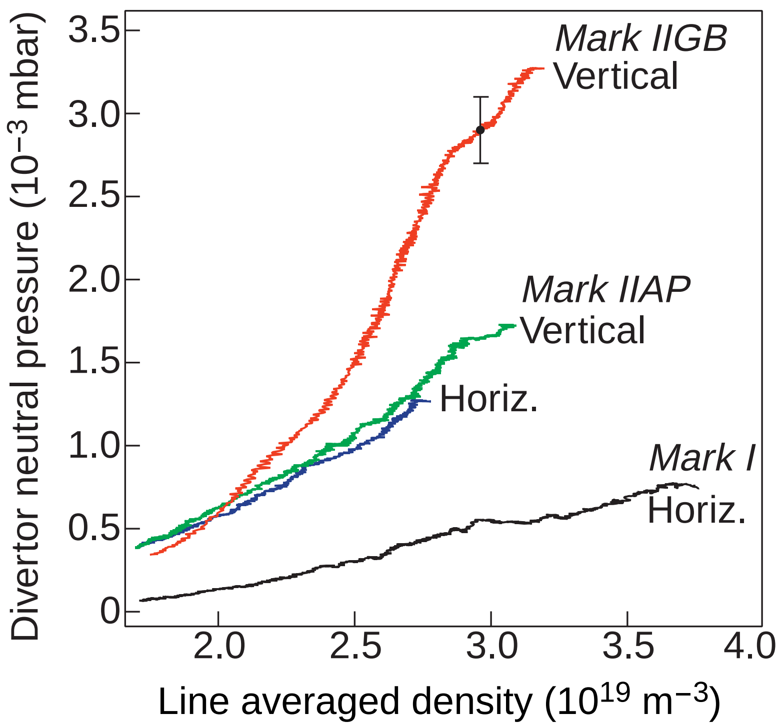
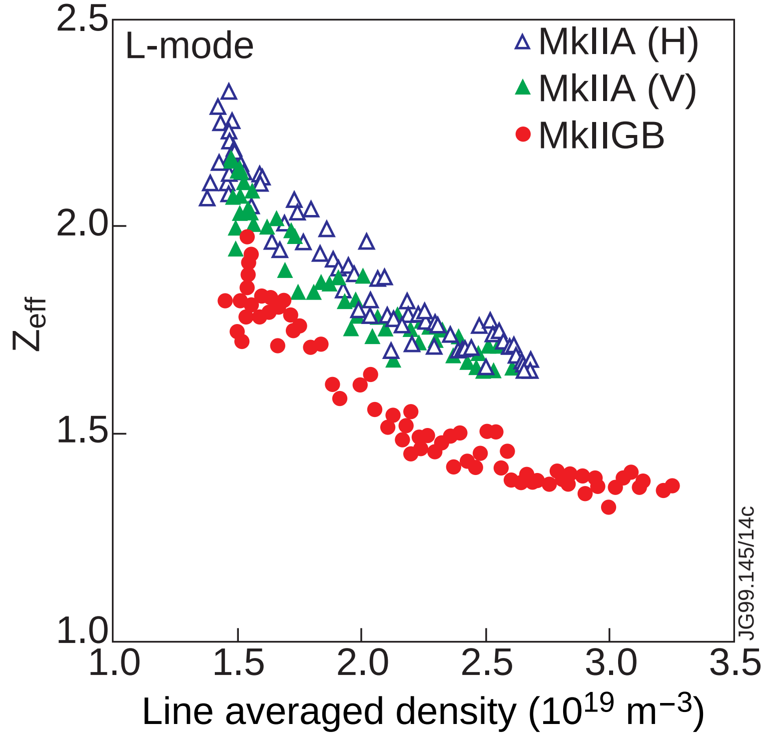
Effect of Closure on Divertor Pressure and Impurities

Divertor Pressure



- Neutral pressure at pump strongly increases facilitating pumping of He.

Impurities



- Z_{eff} in L-mode plasma decreases
- Effect less pronounced in H-mode due to ELM produced impurities

Gas puff/pump does not reduce Z_{eff} in JET due to strong intrinsic flows

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Technology and Diagnostics

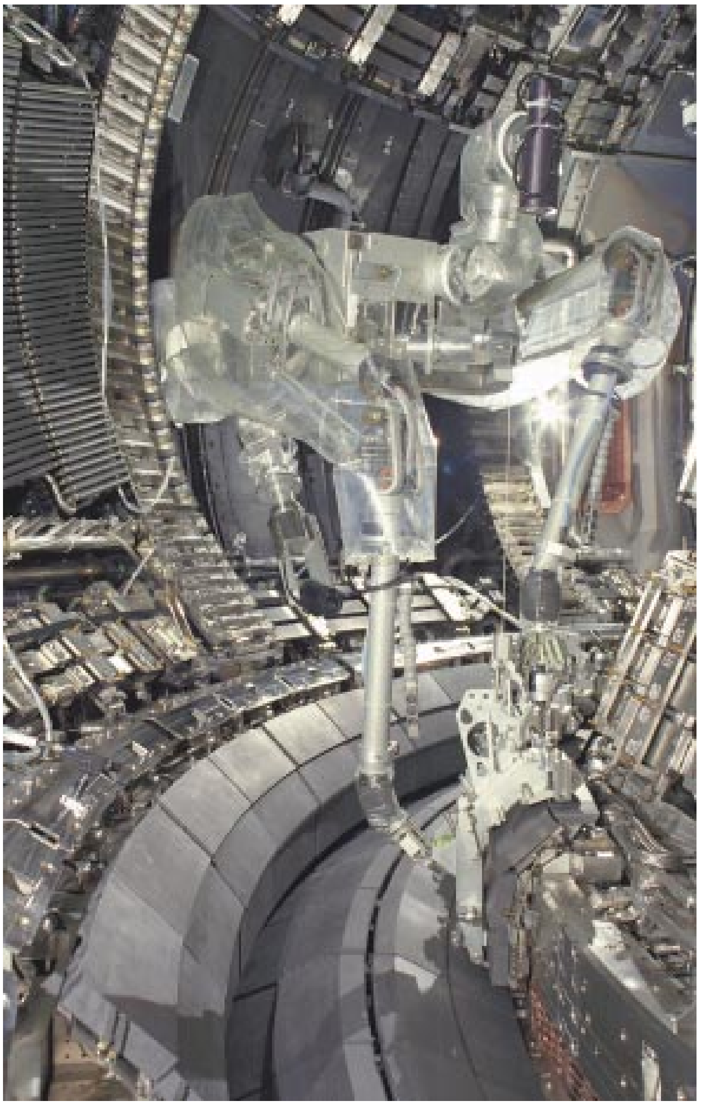
Highlights of JET Technology

- **Remote Handling Capability**
  - Change from Mark I divertor to MArk IIA divertor tested remote handling techniques
  - Change from MArk IIA to Mark IIGB fully by remote handling
- **Remote Handling Capability**
  - Unique in the world
- **Diagnostics developments**

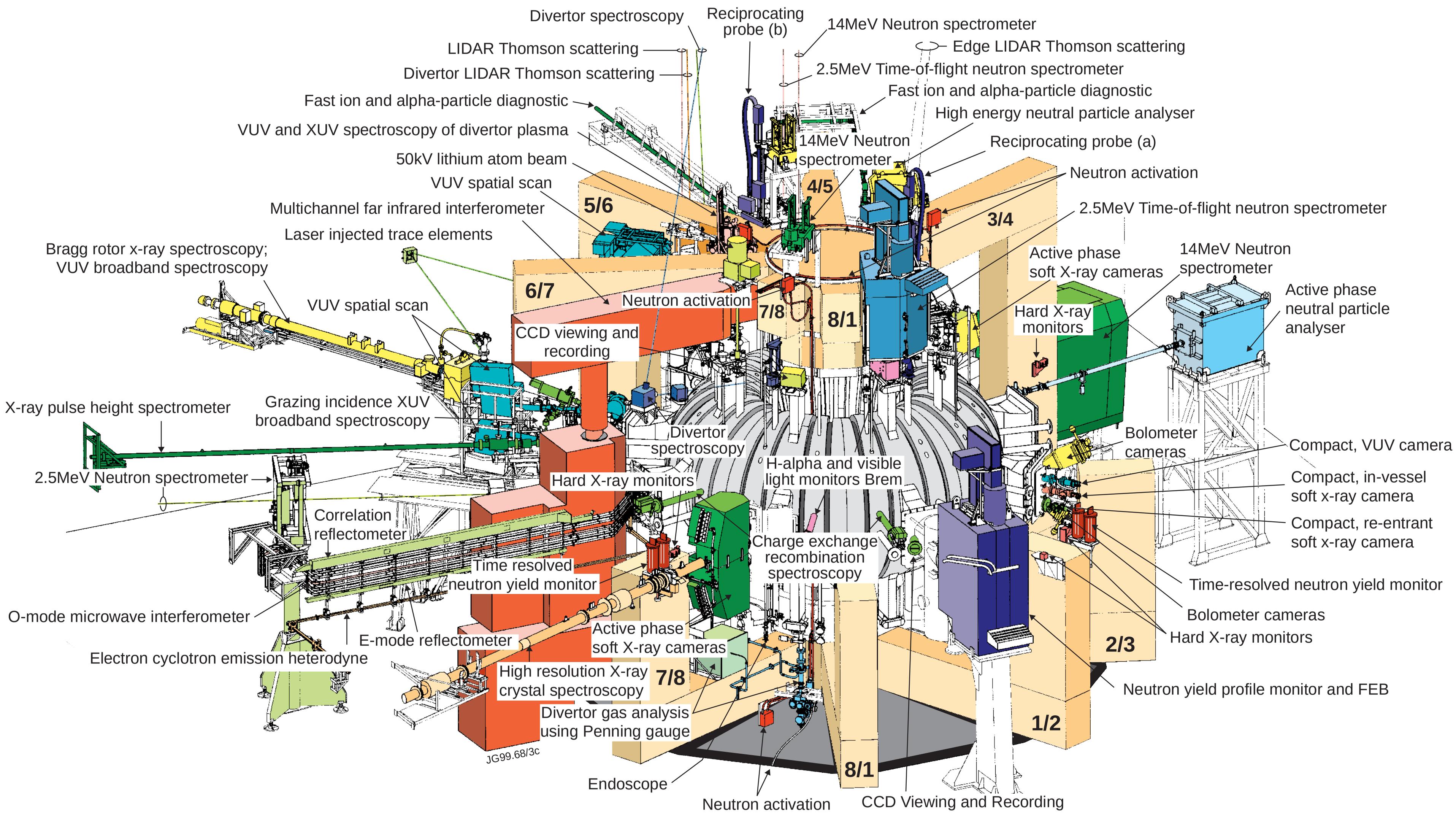
Mascot
Servomanipulator Station

Master

Slave



Overview of JET diagnostics



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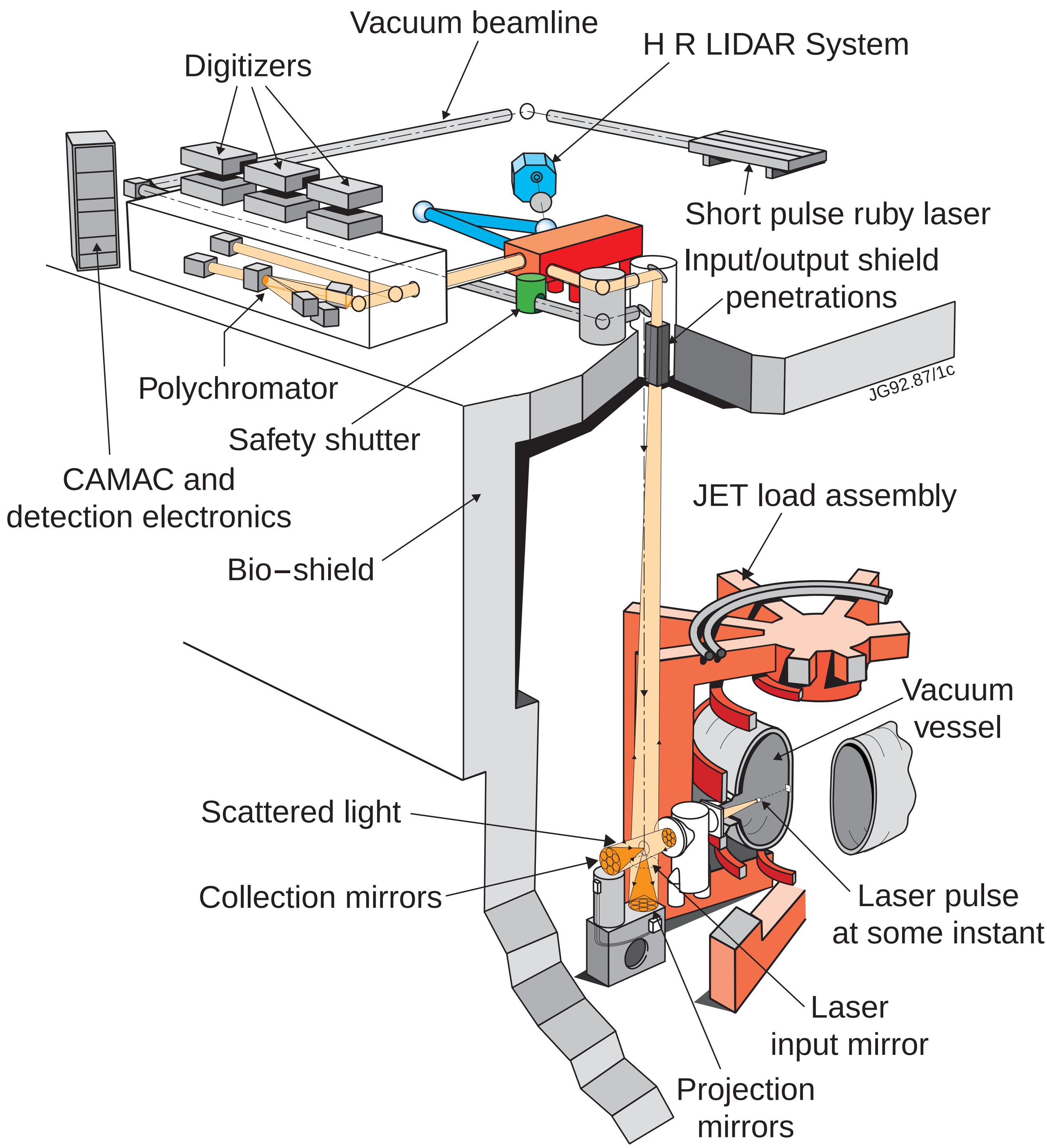
JET LIDAR Thomson scattering systems

LIght Detection And Ranging
(Time of flight)



Measures T_e (R), n_e (R)

LIDAR Thomson Scattering Diagnostic

- Measures radial profiles of electron temperature and density in JET plasmas

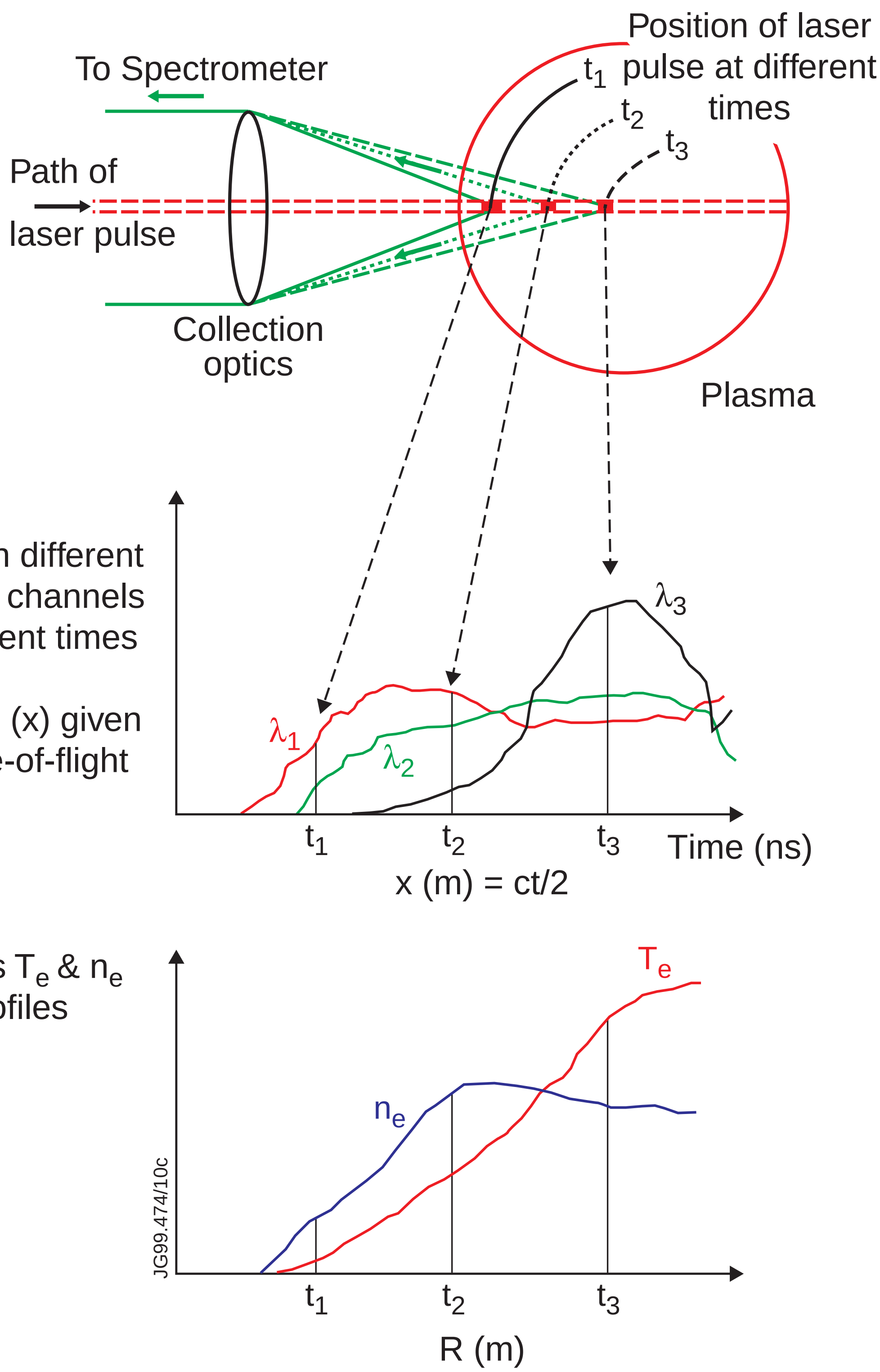
- Uses time-of-flight principle combined with Thomson scattering technique to obtain spatially resolved measurements

- In the Thomson scattering technique, light from a monochromatic laser is scattered and doppler shifted by fast moving electrons

- The width of the scattered spectrum is a measure of the electron temperature and the total intensity is proportional to the density

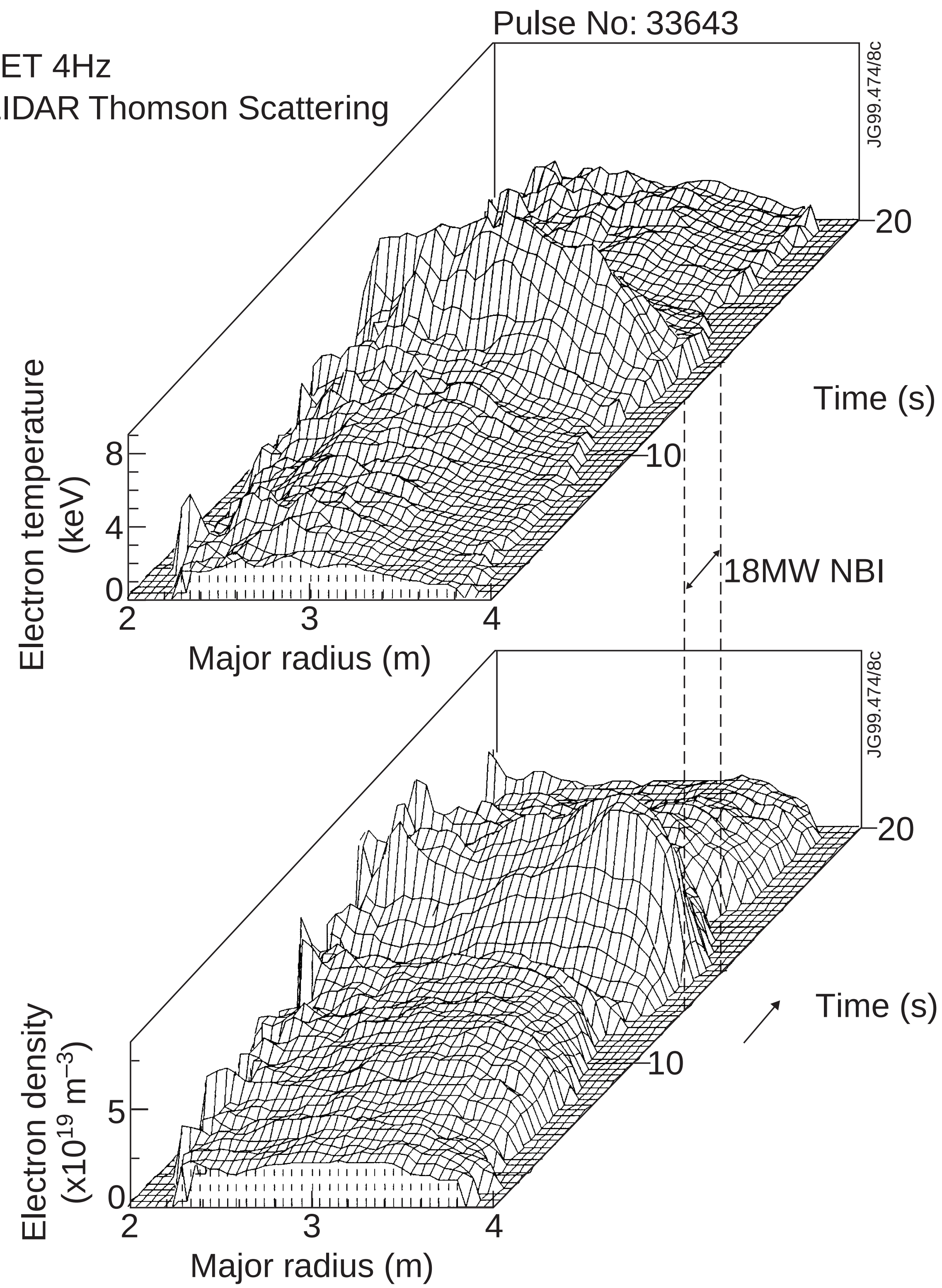
- Using a short laser pulse (300ps ≡ 10cm) and fast detection system the location of the instantaneous scattered spectrum can also be determined by time-of-flight so the temperature and density profiles can be measured as the laser pulse passes through the plasma

Electron Temperature and density: a) Lidar Thomson scattering

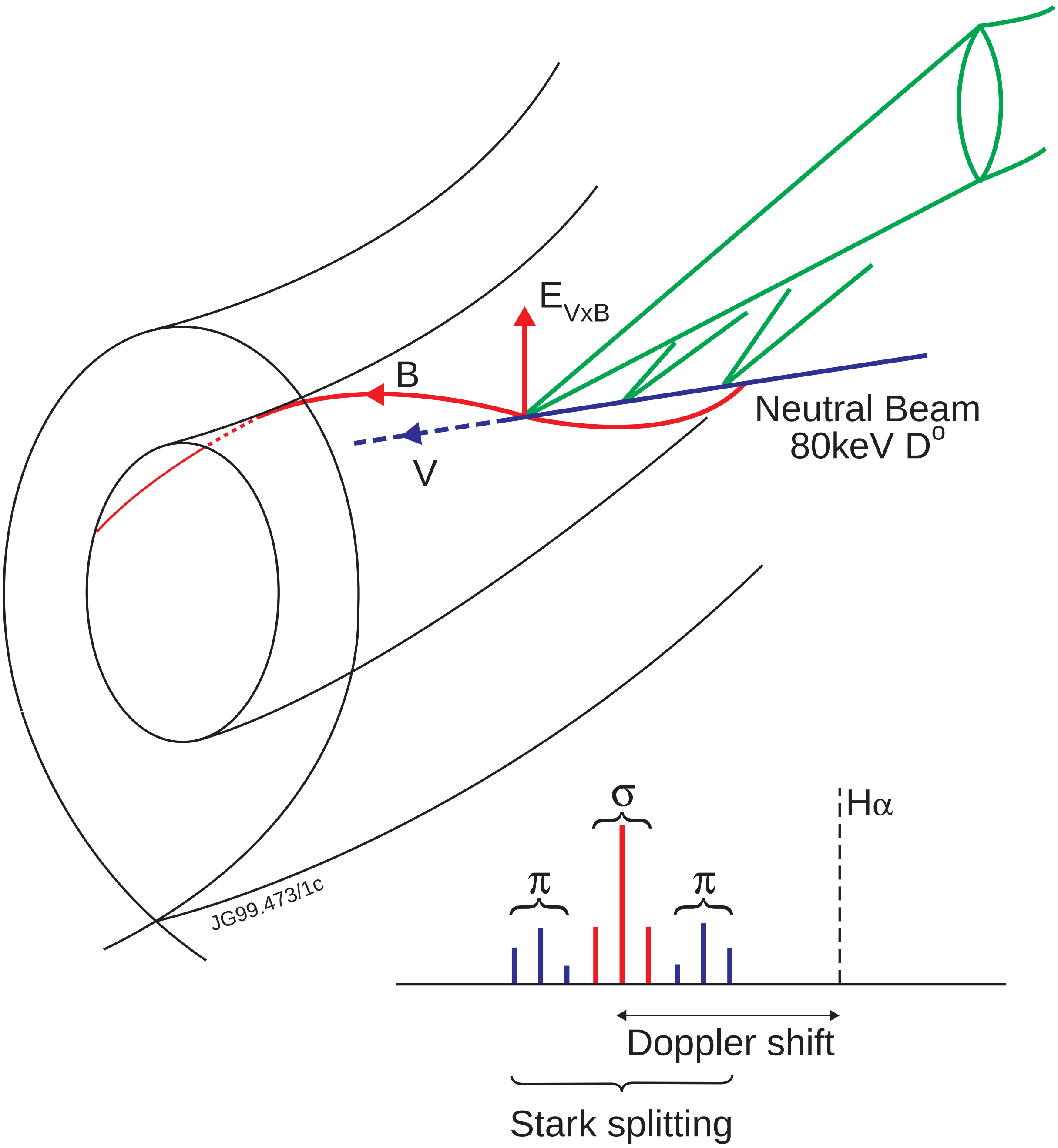


Example of Lidar measurement:

Plasma with Neutral Beam Heating



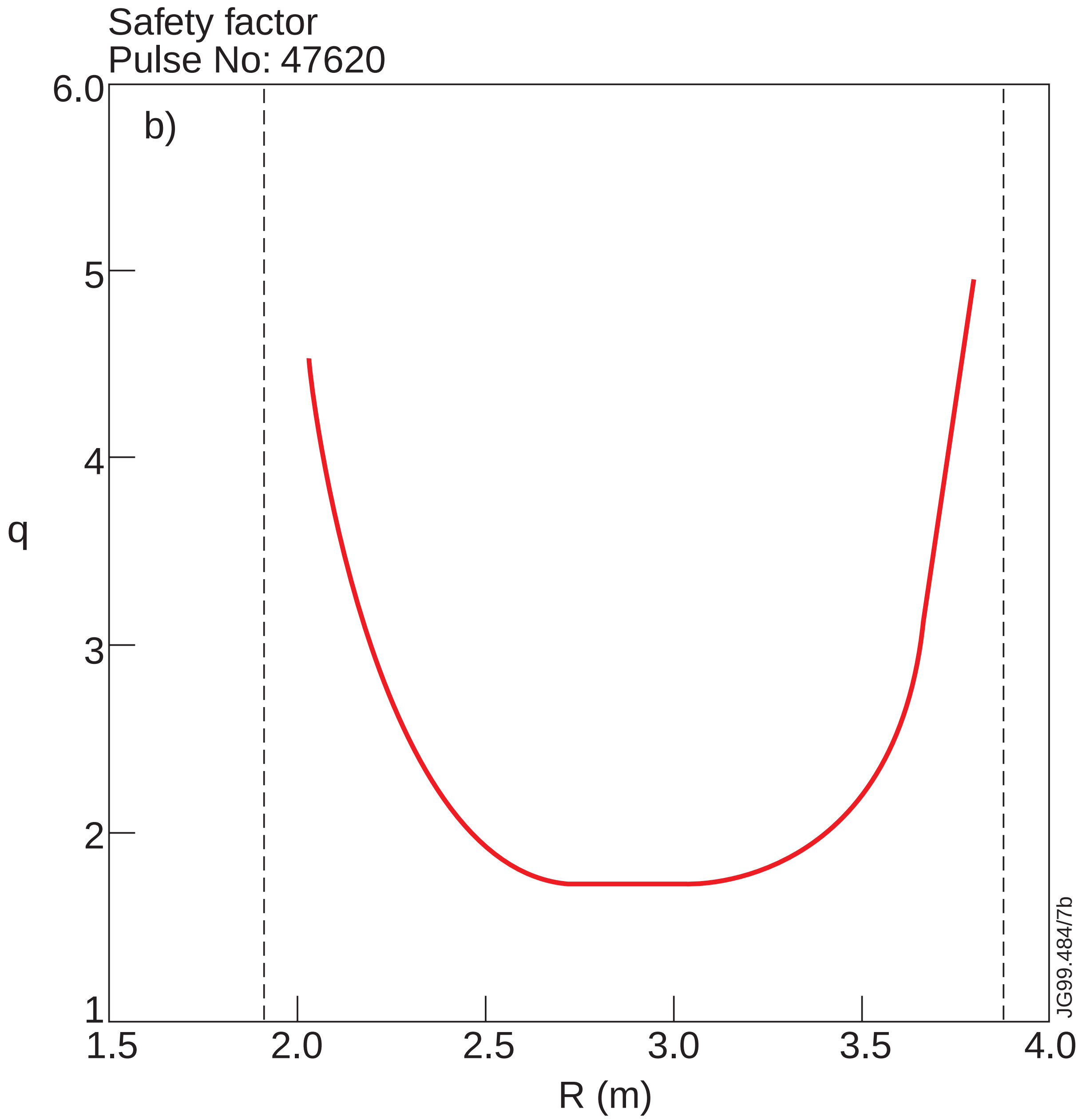
Measure q-profile: Motional Stark effect



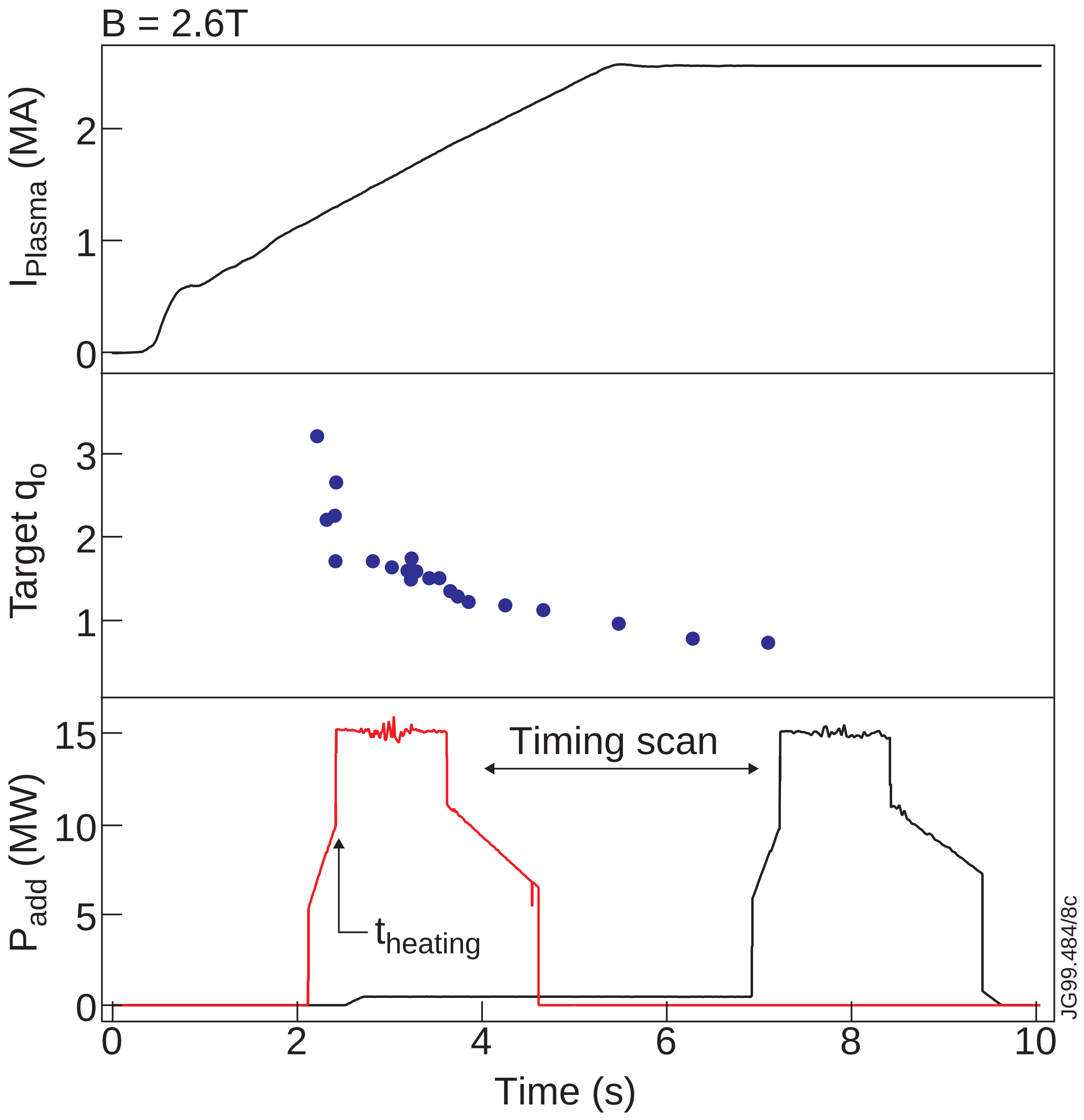
Measure polarisation of $E = v_{beam} \times B$

From polarisation angle: pitch angle of B: determine q

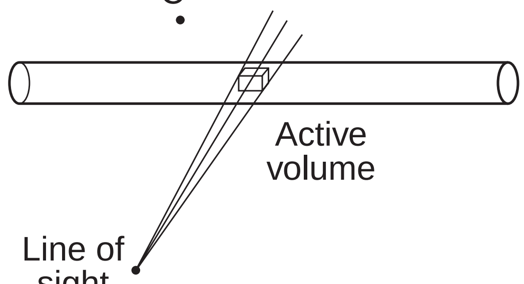
Typical example of a Motional Stark measurement:

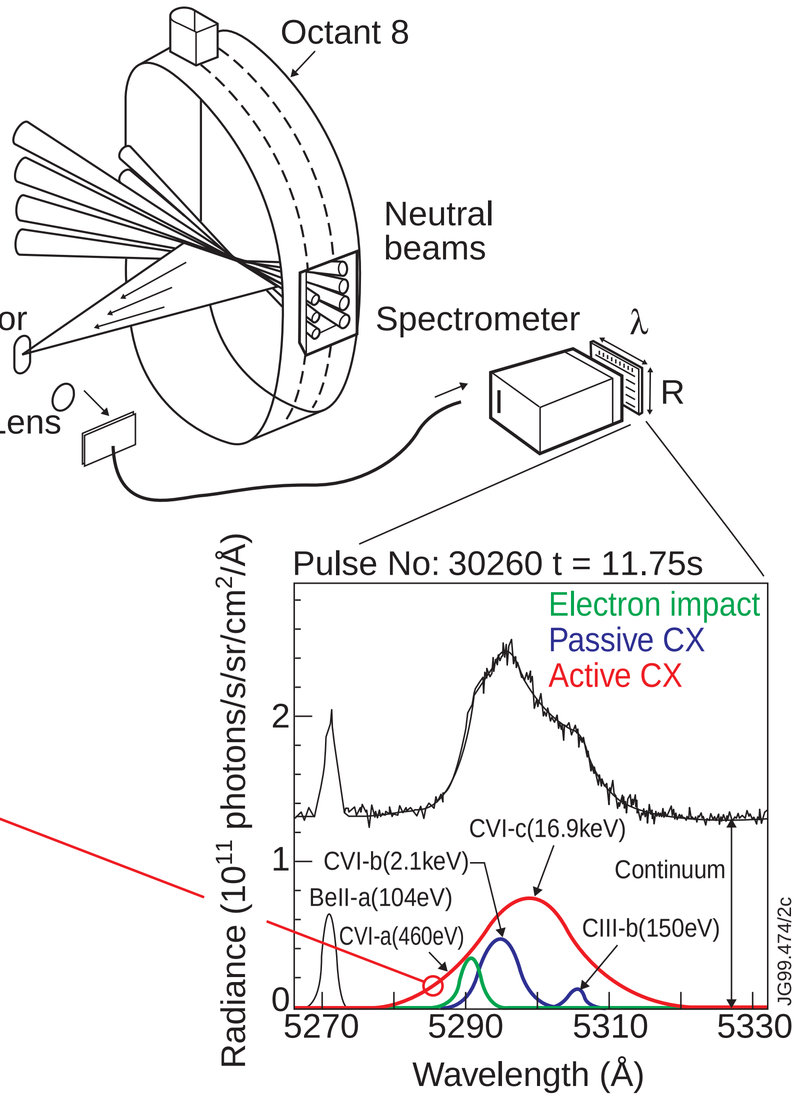


Timing of NBI Heating Affects q(0)



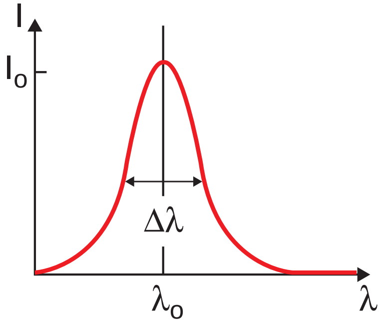
Measure Ti: Charge Exchange Spectroscopy





In active volume

$C^{6+} + D \rightarrow C^{*(5+)} + D^{1+} \rightarrow C^{5+} + h\nu + D^{1+}$



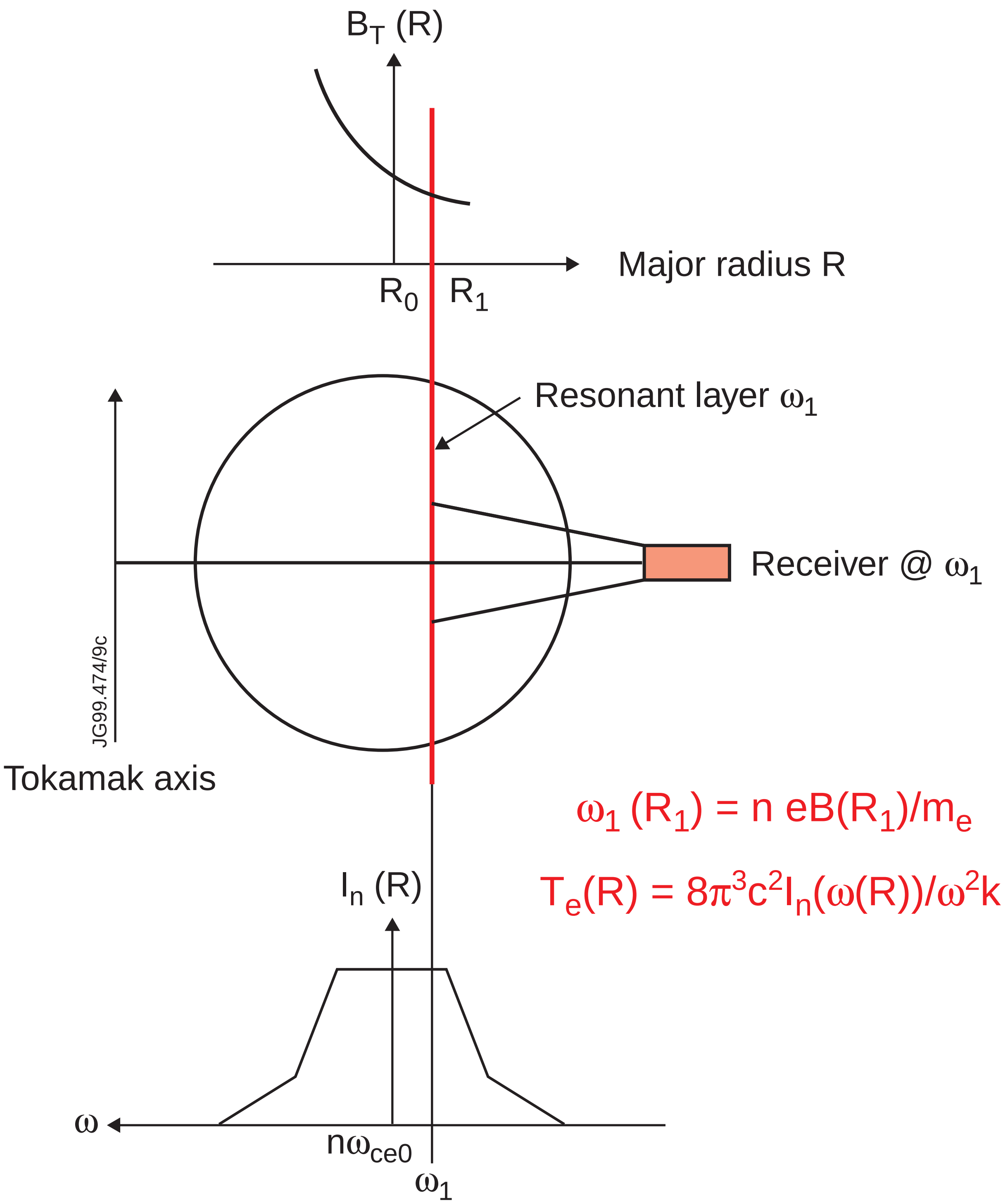
Provides local measurements of:

$\Delta\lambda \rightarrow T_i$

$\lambda_o \rightarrow w_c$

$I_o \rightarrow n_c$

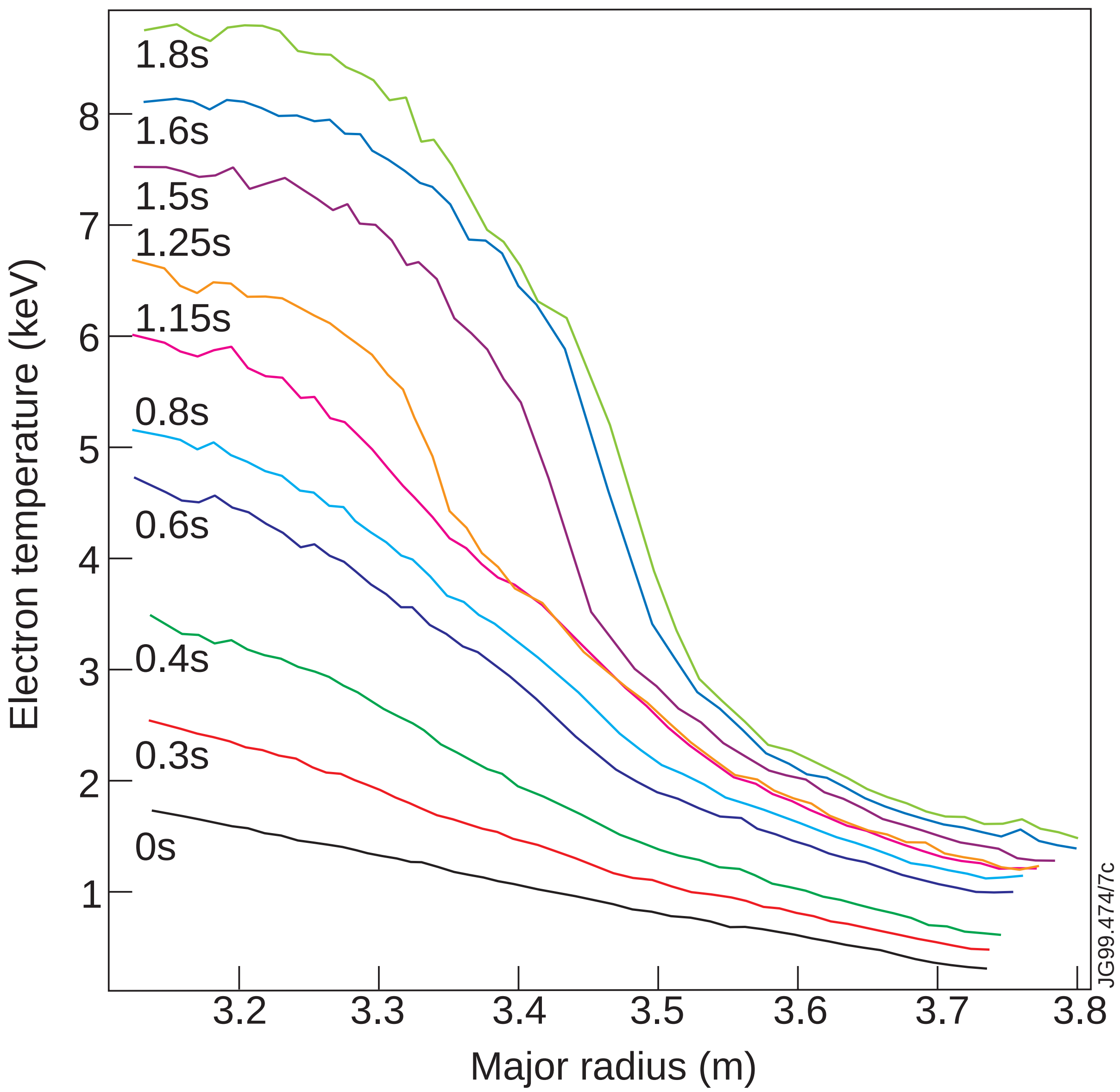
Electron Temperature:
b) Electron Cyclotron Emission



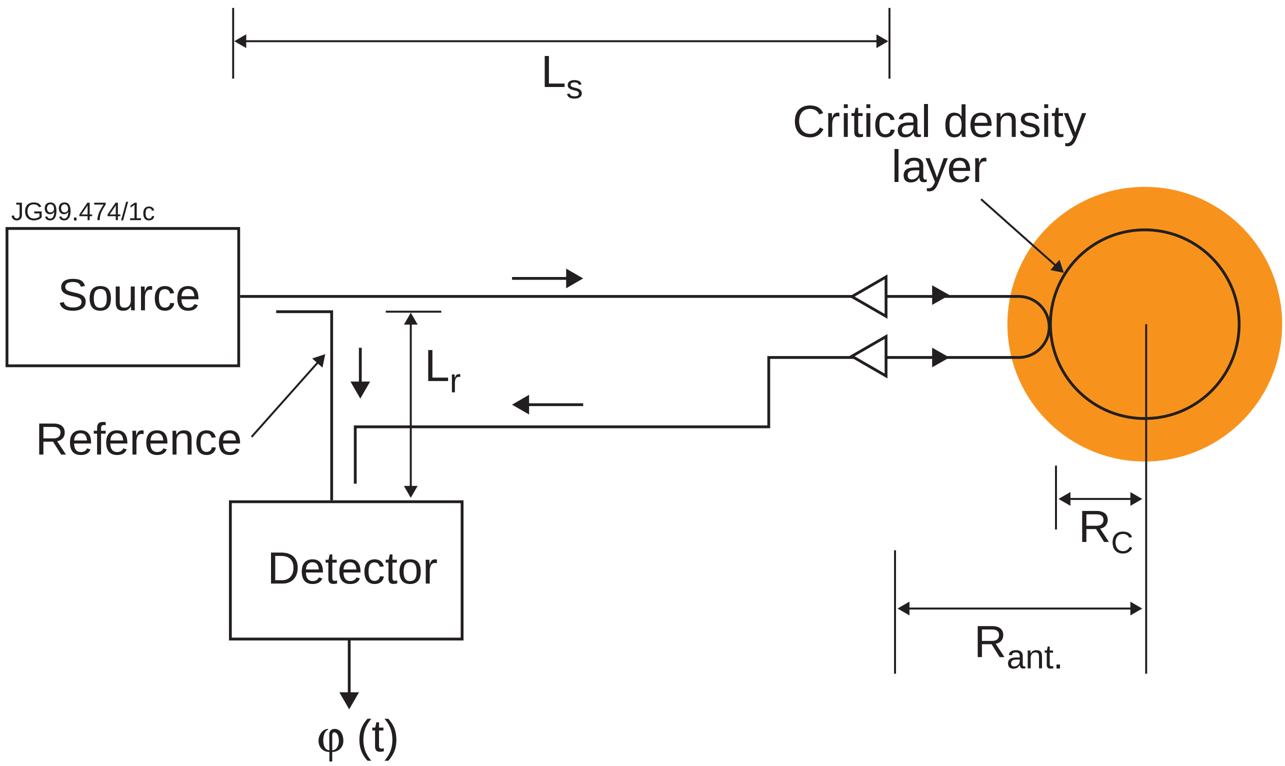
$$\omega_1\,(R_1) = n\,eB(R_1)/m_e$$

$$T_e(R) = 8\pi^3 c^2 I_n(\omega(R))/\omega^2 k$$

ECE measurement of electron internal transport barrier



Electron density: reflectometry

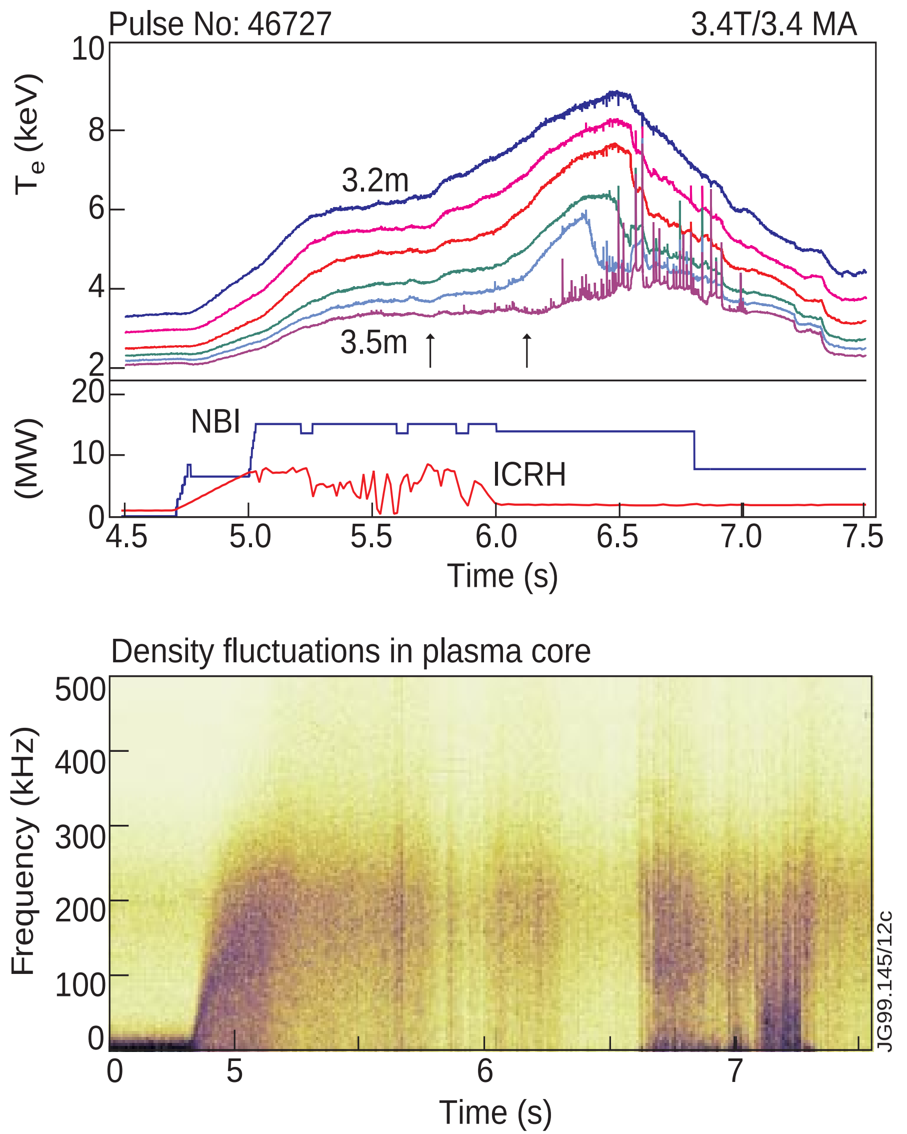


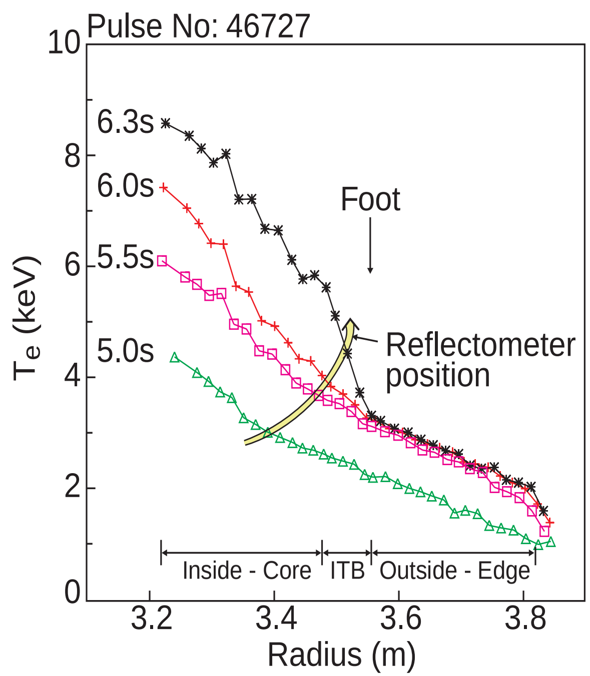
Critical Density

$$n_c = \frac{\varepsilon_o \, m_e \, \omega_c^2}{e^2}$$

Measure the phase difference between the reference beam and the beam reflected from the critical density layer in the plasma.

ITB Formation and Turbulence Suppression





- High power heating generates region of high toroidal velocity shear which suppresses low frequency turbulence throughout plasma core ⇒ global decrease in χ_i.
- Formation of ITB linked, via feedback between enhanced ∇P and ExB shear, to localised suppression of high frequency turbulence ⇒ localised drop in χ_e.

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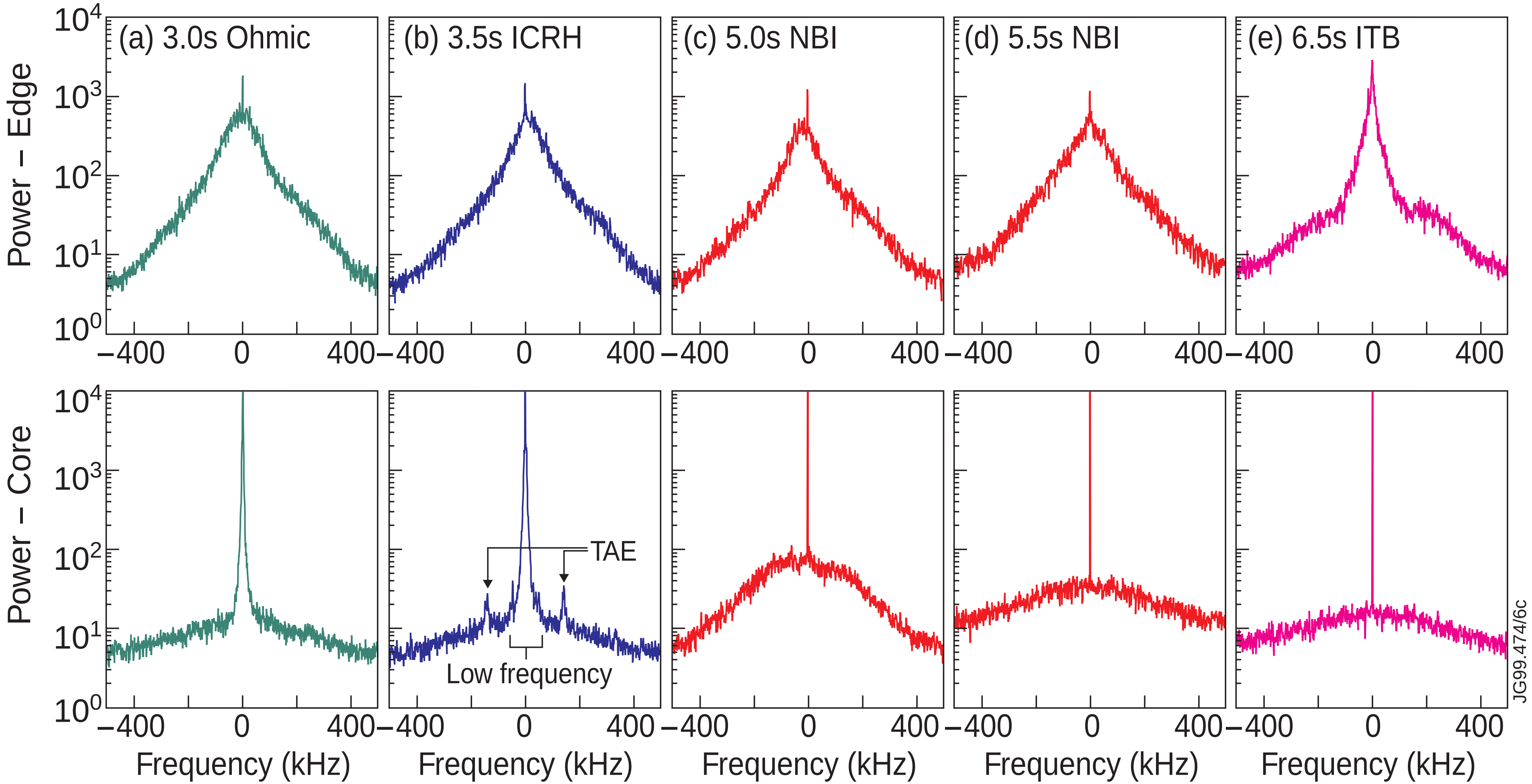
Turbulence suppression inside ITB.



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