MAGNETIC NUCLEAR FUSION AND FAST ION DRIVEN ALFVÉN INSTABILITIES

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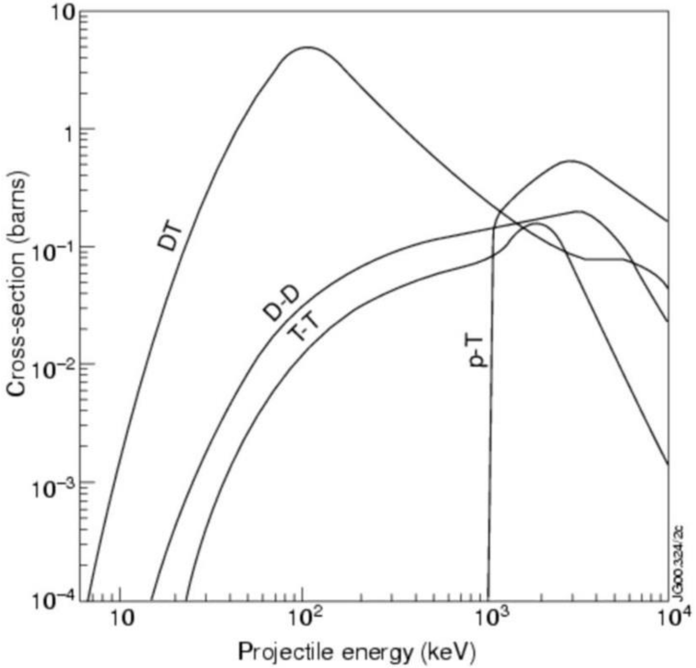
FUSION ENERGY

OUTLINE

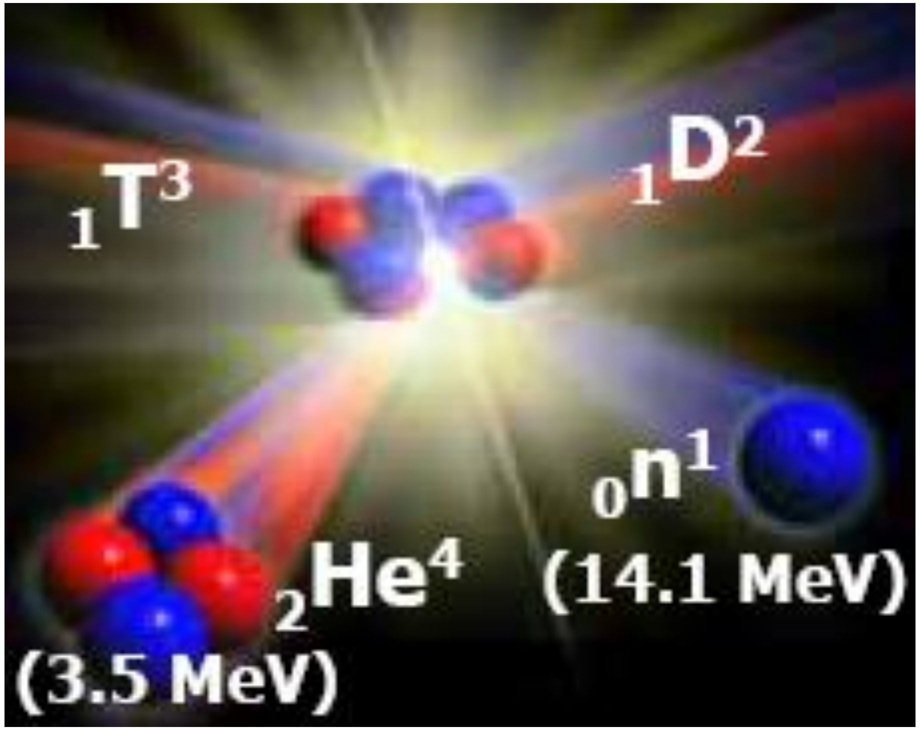
- Nuclear fusion
- Magnetic confinement of plasma
- Three main avenues of magnetic nuclear fusion
- Burning DT plasmas and the problem of fusion-born ions
- Fast ion-driven Alfvénic instabilities: experiment and modelling
- Summary

NUCLEAR FUSION



- Nuclear Fusion powering the stars and the Sun quite surprisingly is possible on Earth and the aim is to make it available for energy producing
- This is thanks to quite large cross-section (a measure of the ability to fuse) of D-T reaction at plasma temperatures 10-20 keV (corresponding the peak at 100 keV in the rest frame where only deuteron is moving in Figure above).

NUCLEAR FUSION OF HYDROGEN ISOTOPES D&T



- Nuclear fusion reaction D+T = He + n +17.6 MeV of hydrogen isotopes deuterium (D) and tritium (T) is the “easiest” to access.

ENVIRONMENTAL ADVANTAGES OF D-T FUSION

- Deuterium is naturally abundant (0.015% of all water), Tritium must be obtained from lithium, $^6Li + n = T + ^4He$. Raw materials are water & lithium.

- To generate 1GW for 1 year (equivalent to a large industrial city):

  COAL: 2.5 Mtonnes – produces 6 Mtonnes CO_2;
  FISSION: 150 tonnes U – produces several tonnes of fission waste;
  FUSION: 1 tonne Li + 5 Mlitres water.

- Fusion gives no “greenhouse” gasses.

- Fusion reactor structure will become activated but will decay to a safe level in < 100 years. Tritium is radioactive: half life is 13 years.

- No plutonium or long-lived (thousands of years) active waste from fuel cycle.

D-D and D-^{3}He NUCLEAR FUSION

- Other fusion reactions used in present day machines to simulate the D-T reaction, which may become essential in future on their own:

$$D + D = T + p + 4\ \text{MeV}$$

$$D + D = {}^3He + n + 3.27\ \text{MeV},$$

$$D + {}^3He = {}^4He + p + 18.35\ \text{MeV}$$

- Fuel for D-D fusion is Deuterium only, which is naturally abundant (0.015% of all water)

- Fuel for D-^{3}He is Deuterium and very rare ^{3}He. This can be found in significant quantities on the Moon or obtained from nuclear reactors

PLASMA

- How to make the nuclear forces work? Nuclei of D and T must approach each other to a “nuclear” distance ~10^{-12} cm, but they need to overcome the Coulomb electrostatic force between two positive nuclei!
- The solution: provide the colliding nuclei with kinetic energy larger than the Coulomb potential energy, i.e. the fuel must be hot enough. Optimum fusion rate for D-T is at $T_D \approx T_T \approx$ 10-20 keV (100-200 Mdeg)
- At that temperature, the hot DT fuel is a plasma – a mixture of positively charged nuclei (“ions”) and negatively charged electrons

— *Increasing Temperature* →						
Solid	→	Liquid	→	Gas	→	Plasma
	Melts		*Vaporises*		*Ionises*	

- Plasmas conduct electricity and can be controlled by magnetic fields

THERE ARE THREE CONDITIONS FOR FUSION

- Fuel must be hot enough, $T_i \approx$ 10-20 keV, to overcome Coulomb force between D and T;

- Hot plasma must be insulated from walls
  Energy confinement time τ_E = Plasma energy/ Heat loss is high enough

  Plasma with energy $W = n\ T\ V$ (V is the volume of plasma) cools down as

  $$dW/dt = -\ W/\ \tau_E$$

  in the absence of any heating sources

- Fuel density n_D and n_T must be high enough that fusion reactions occur at a suitable rate. Maximum density is limited by impurities and instabilities

SELF-SUSTAINING FUSION REACTION

- Fusion alpha-particles (20% of fusion energy, $P_\alpha = 0.2\, P_{FUSION}$) heat the plasma and balance heat loss, i.e. the energy balance for steady-state is

$$dW/dt = - W/ \tau_E + P_\alpha = 0$$

- Neutrons (80% of energy) breed new tritium and generate steam.

- The “ignition” condition for self-sustaining fusion reaction

$$n\, T\, \tau_E > 5 \times 10^{21}\ m^{-3}\ keV\ s\ (\approx 10\ atm\ s)$$

POSSIBLE METHODS OF FUSION PLASMA CONFINEMENT

Gravity (Sun and stars) – works well but dimensions are too large;

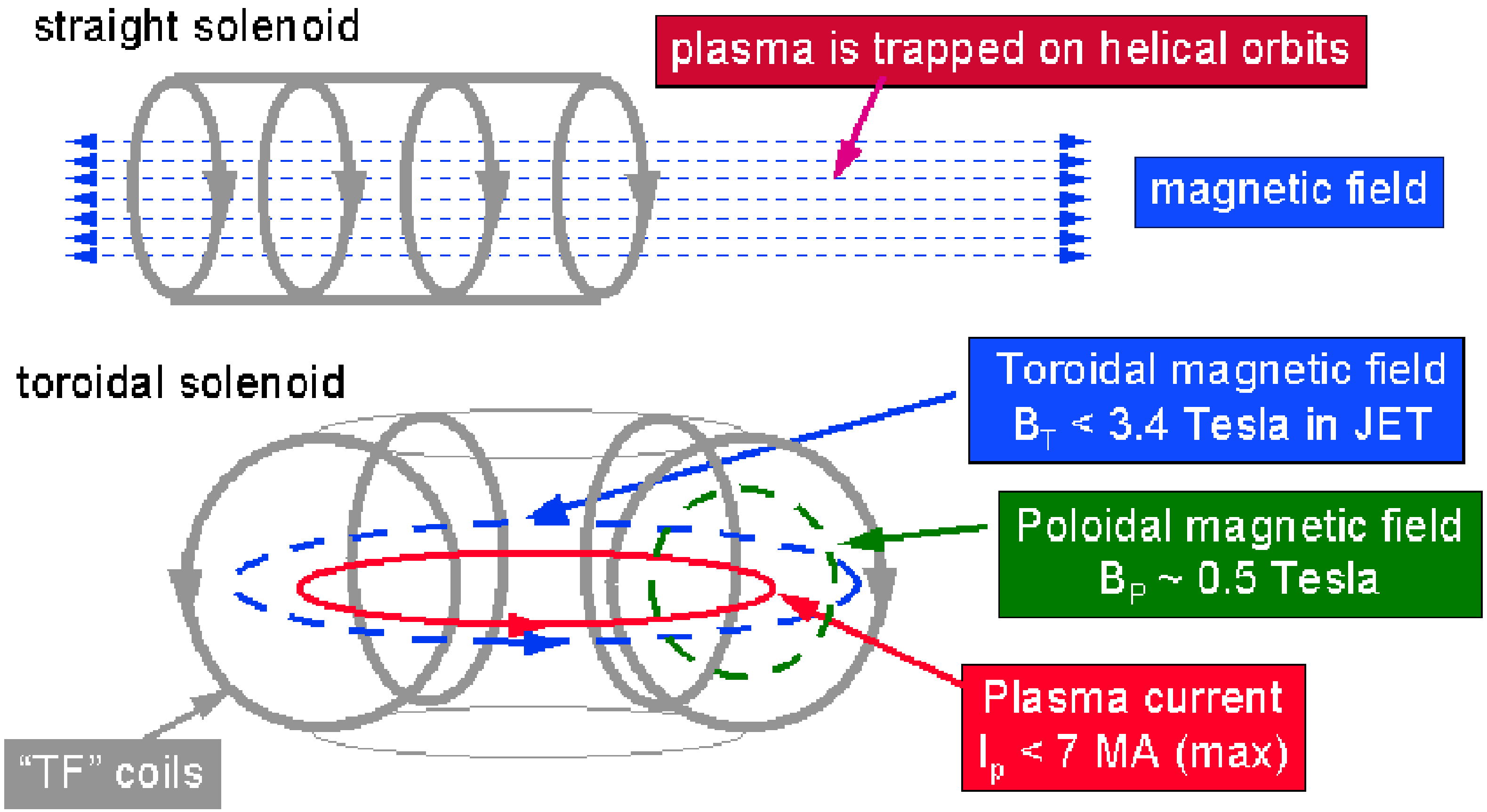
Inertial (Hydrogen bomb, lasers or beams) – works well, needs pressure 10^{12} atm for very short times 10^{-11} s.
Largest H-bomb tested was 10 x [all explosive used in 2nd World War]

Magnetic – few atms x few seconds, plasma is confined by magnetic field B.

THE IDEA OF MAGNETIC CONFINEMENT:

- **In the presence of strong magnetic field, charged particles of plasma are trapped on helical orbits attached to magnetic field lines**

MAGNETIC CONFINEMENT OF PLASMA



straight solenoid

plasma is trapped on helical orbits

magnetic field

toroidal solenoid

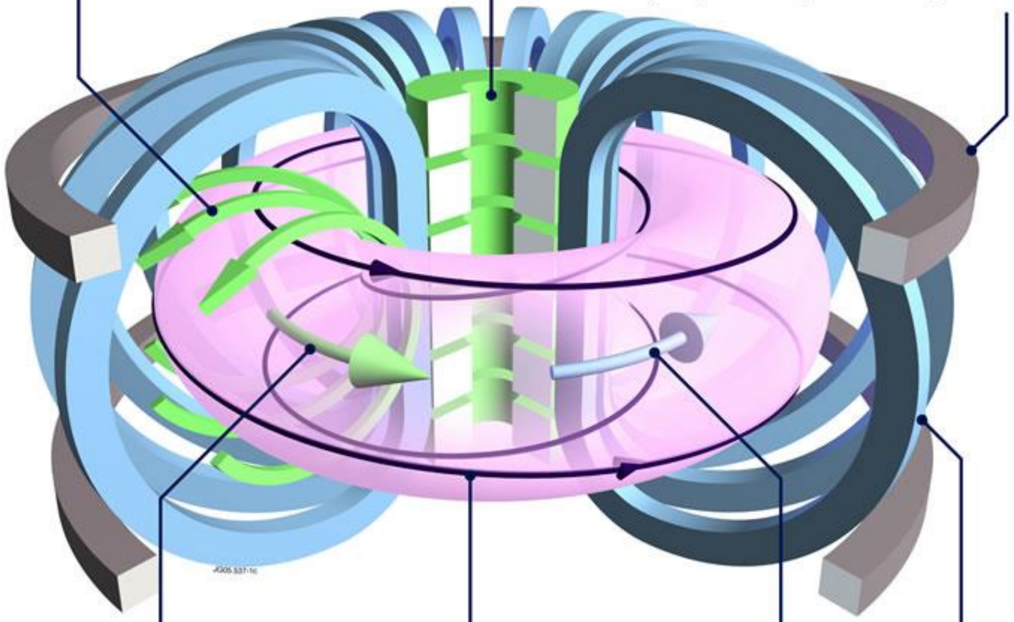
Toroidal magnetic field
$B_T < 3.4$ Tesla in JET

Poloidal magnetic field
$B_P \sim 0.5$ Tesla

Plasma current
$I_p < 7$ MA (max)

“TF” coils

THE COILS



Inner Poloidal field coils
(Primary transformer circuit)

Poloidal magnetic field

Outer Poloidal field coils
(for plasma positioning and shaping)

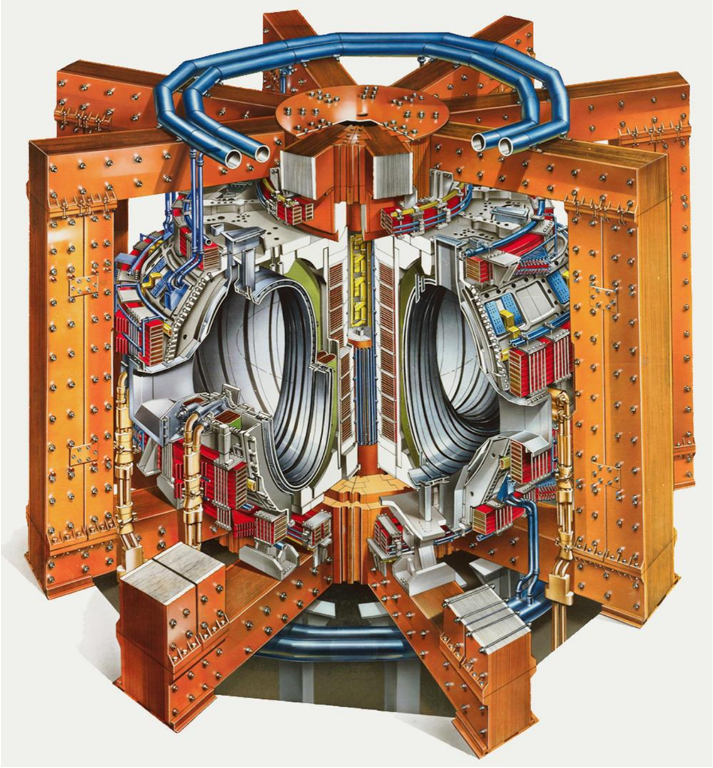
Resulting Helical Magnetic field

Toroidal field coils

Plasma electric current
(secondary transformer circuit)

Toroidal magnetic field

TOKAMAK JET (JOINT EUROPEAN TORUS)



Volume = 100 m^3; B_{max} = 4 T; I_{max} = 7 MA; P_{FUS} = 16 MW

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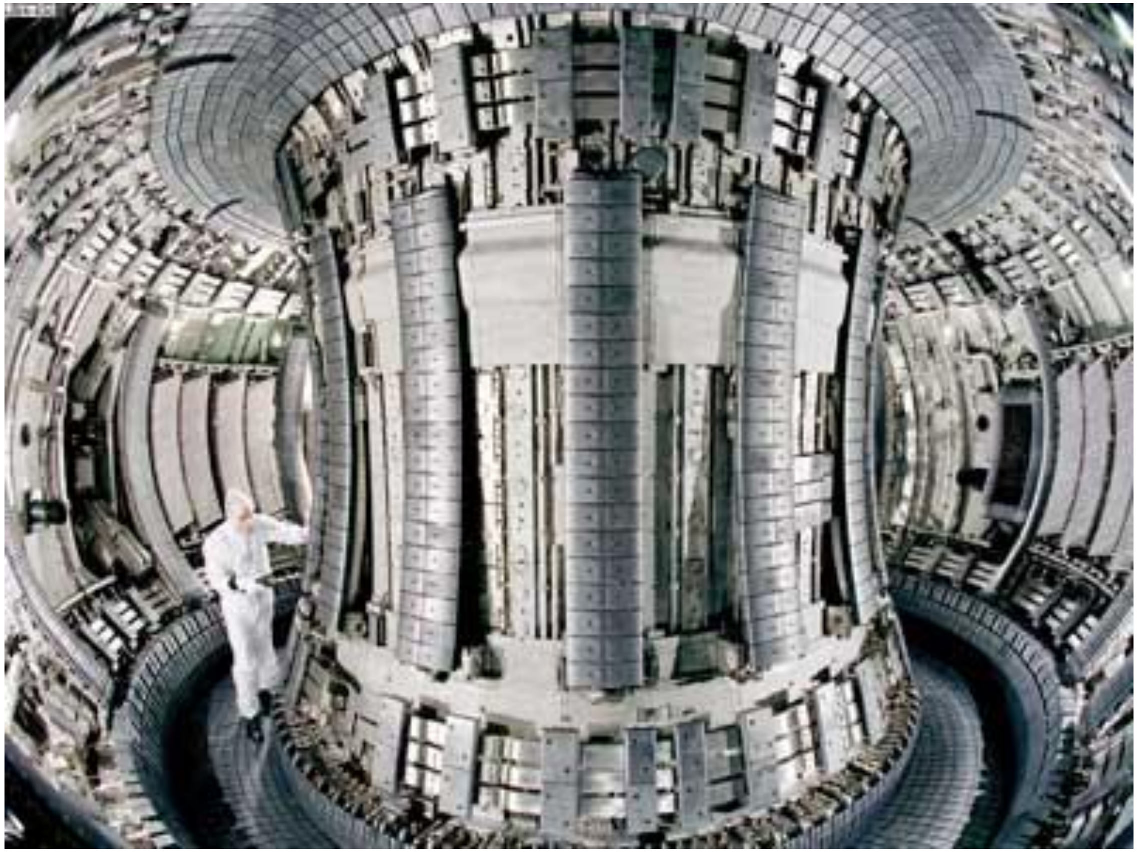
JOINT EUROPEAN TORUS



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WAYS OF ACHIEVING IGNITION IN MAGNETIC FUSION

- The "ignition" condition for self-sustaining fusion reaction

$$n\ T\ \tau_E > 5 \times 10^{21}\ m^{-3}\ keV\ s\ (\approx 10\ atm\ s)$$

- The ignition criterion for magnetic fusion can be better expressed via B and $\beta = P_{plasma}/P_{magnetic} = 4\mu_0(nT)/B^2$ as

$$\beta\ \tau_E\ B^2 > 4\ T^2\ s$$

Three main avenues exist for magnetic fusion:

1) Increasing energy confinement time τ_E

2) Increasing magnetic field B

3) Increasing β

INCREASING ENERGY CONFINEMENT TIME

4) **Increasing τ_E: larger size fusion reactors since energy balance for steady-state is determined by $P_\alpha = 0.2\ P_{FUSION}$:**

$$\frac{dW}{dt} = -\frac{W}{\tau_E} + P_\alpha = 0$$

$$\downarrow$$

$$P_\alpha = \frac{W}{\tau_E} = nT\frac{V}{\tau_E}$$

5) **For a desired power P_{FUSION}, achieving ignition via the increase of τ_E means a larger size machine. For 1 GW power the volume must be $V \approx 1000\ m^3$**

6) **Next step project ITER has $V \approx 800\ m^3$ → will approach the volume needed**

7) **Note: Largest volume present day machine is JET $\approx 100\ m^3$. This means that so far tokamak experiments are done with sub-critical volumes**

INCREASING MAGNETIC FIELD

- Increasing B: technologically challenging to obtain B > 5 T !!!

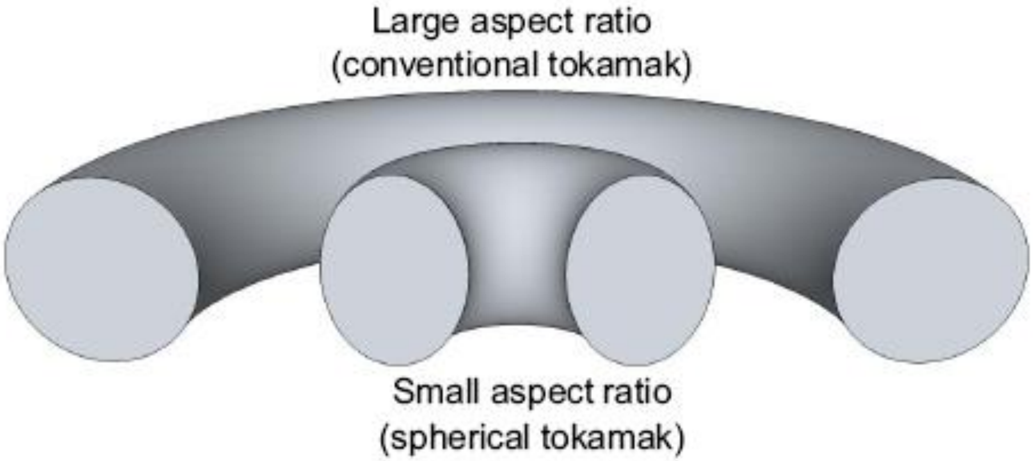
  Present-day Alcator C-MOD (US),

  Next step: IGNITOR (Italy), FIRE (US)

INCREASING BETA

- **Beta is limited by MHD instabilities at a level of few %. In contrast to technological difficulties in the first two avenues above, this one is controlled by the “law of nature”.**

- **Spherical tokamaks with a/R ≈ 1 achieve volume averaged $<\beta> \approx 40\%$ Present day MAST (UK), NSTX (US), next step project, e.g. STPP (UK)**



SUMMARY OF PROGRESS

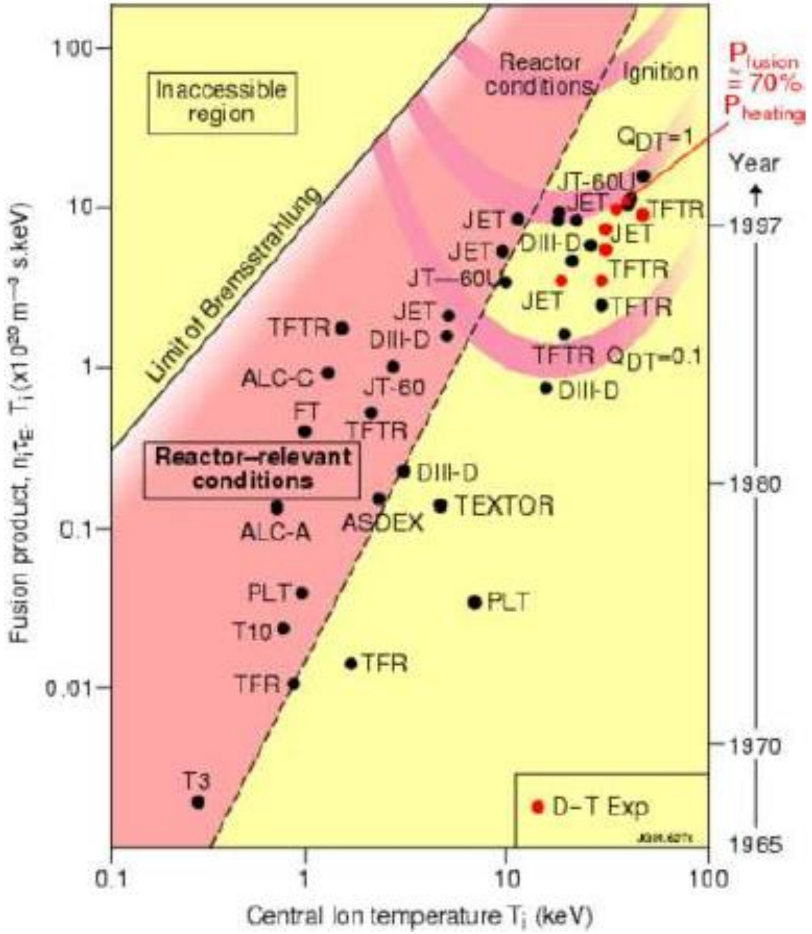
n T τ_E (in D-D plasma)

- 1970 – 25,000 times too small for ignition
- 1983 – 100 times too small
- 1995 – only 5 times too small

Fusion power (in D-T plasma)

- 1991 – JET – 1.7 MW (10% T; 10 MW heating)
- 1995 – TFTR – 10 MW (50% T; 40 MW heating)
- 1997 – JET – 16 MW (50% T; 22 MW heating)
-

FUSION TRIPLE PRODUCT APPROACHING BREAK-EVEN



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THE NEXT STEP: ITER ACHIEVING Q=P_{out}/P_{in}=10

(Being Built in Cadarache, France)

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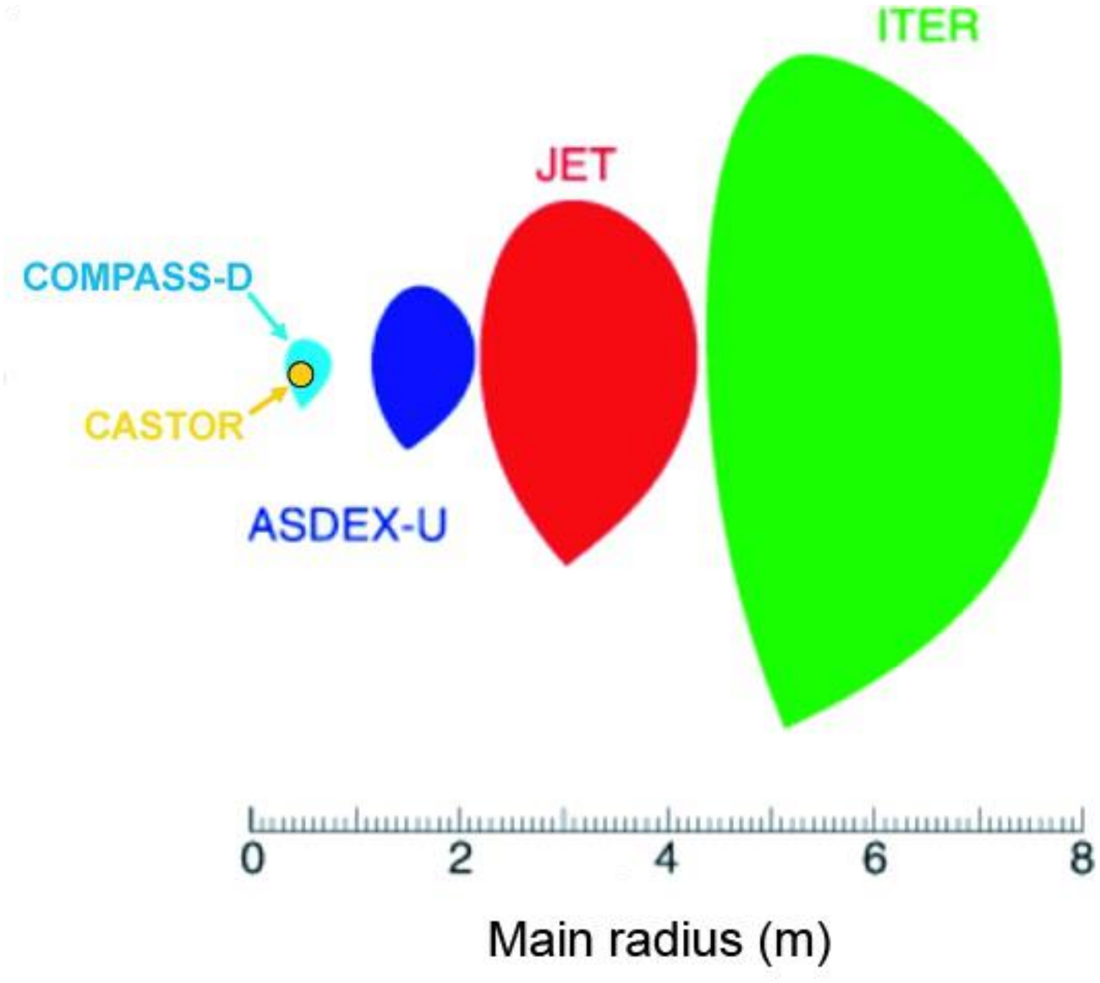
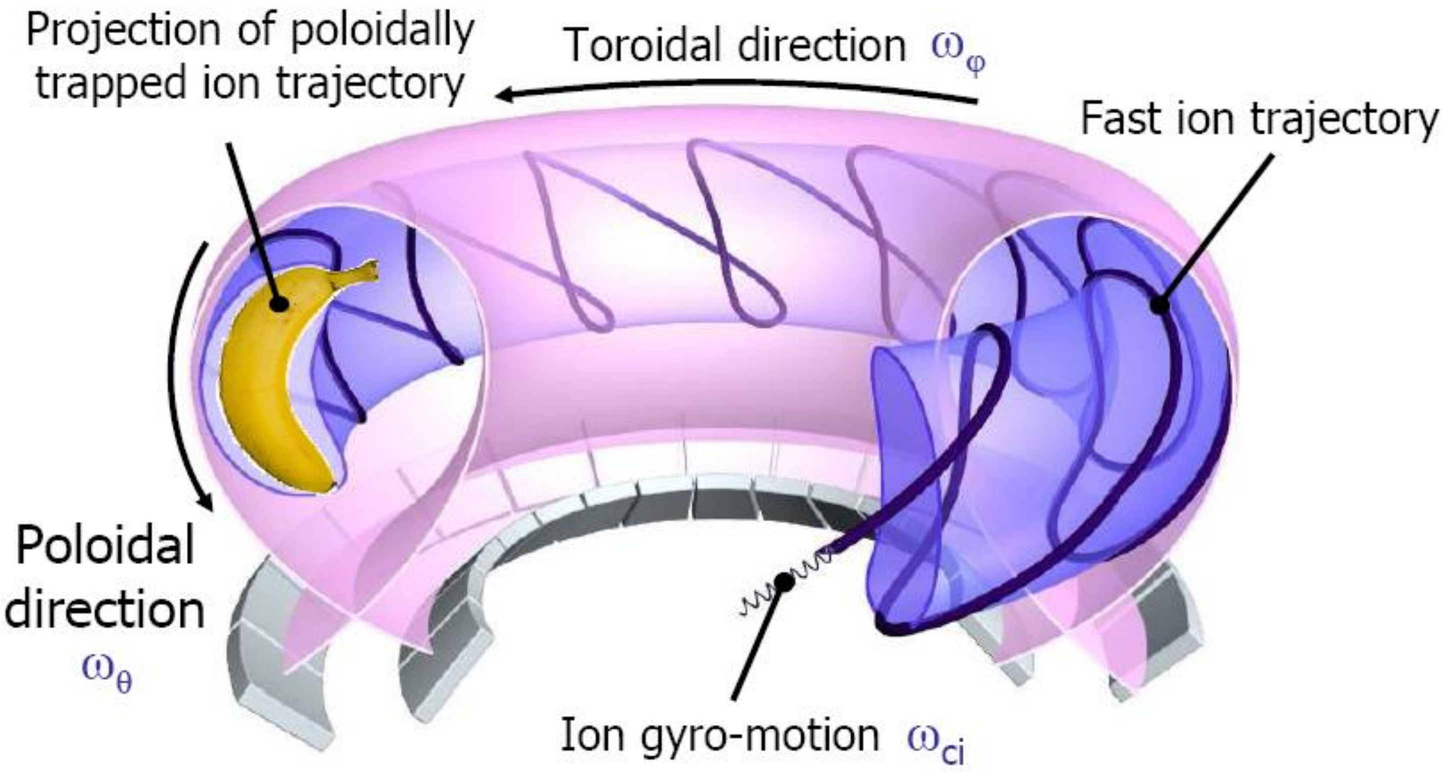

ITER
JET
COMPASS-D
CASTOR
ASDEX-U
0
2
4
6
8
Main radius (m)

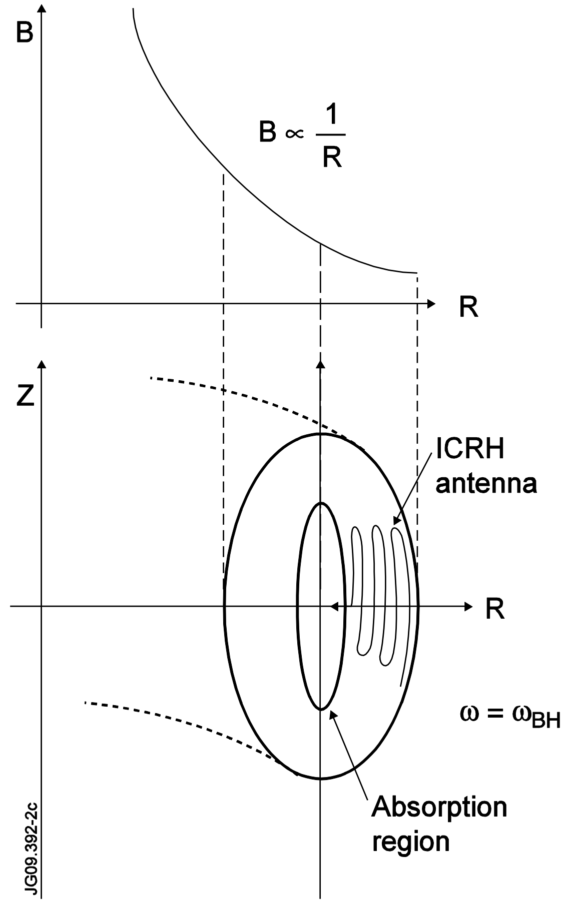
AS BURNING PLASMA EXPERIMENT APPROACHES, WE HAVE TO BE CONFIDENT ABOUT CONFINEMENT OF IONS IN THE MeV ENERGY RANGE

(FUSION-BORN ALPHA-PARTICLES HAVE E=3.5 MeV)

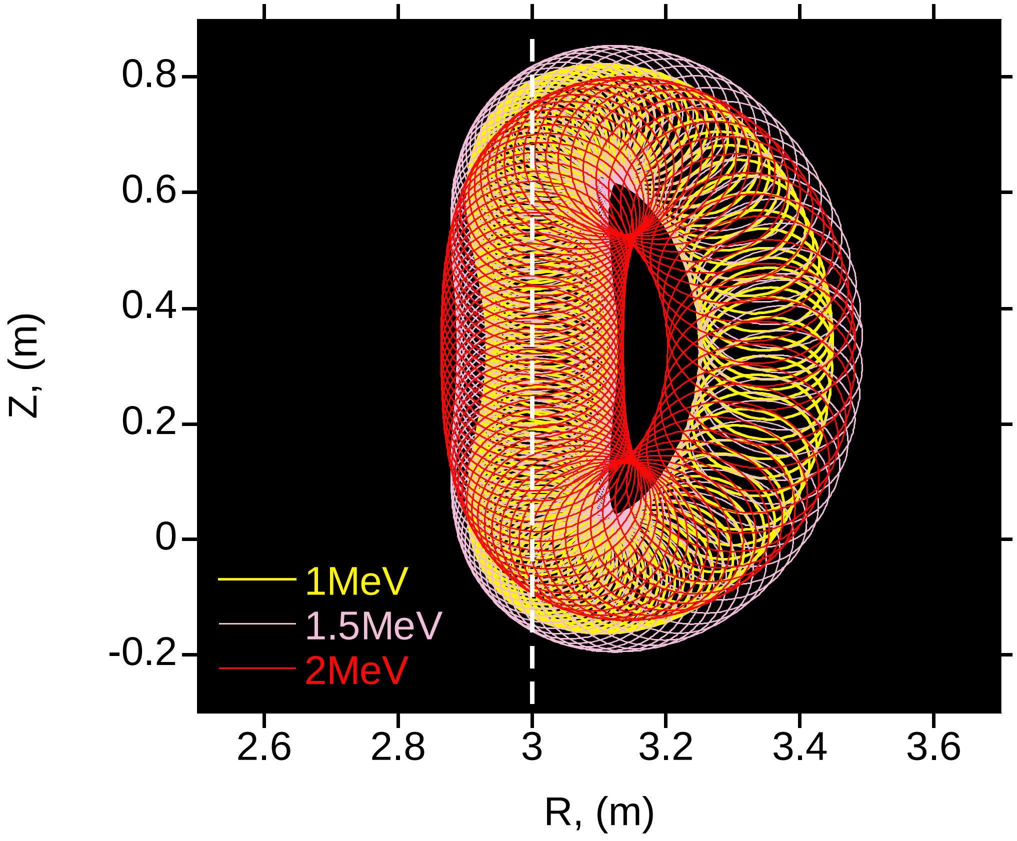
FAST PARTICLE ORBITS: TRAPPED ORBITS



MAIN TECHNIQUE OF OBTAINING MeV-RANGE IONS IS ION CYCLOTRON RESONANCE HEATING



ORBITS OF ICRH-ACCELERATED IONS IN JET



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ENERGETIC IONS IN JET VERSUS ALPHAS IN ITER

Machine	JET	JET	JET	JET	ITER
Type of fast ions	Hydrogen	He^3	He^4	Alpha	Alpha
Source	ICRH tail	ICRH tail	ICRH tail	Fusion	Fusion
Mechanism	minority	minority	3rd harm. NBI	DT nuclear	DT nuclear
$V_f(0)/V_A(0)$	≈2	≈1.5	≈1.3	1.6	1.9
τ_S (s)	1.0	0.9	0.4	1.0	0.8
P_f (0) (MW/m^3)	0.8	1.0	0.5	0.12	0.55
n_f (0) / n_e (0) (%)	1.0	1.5	1.5	0.44	0.85
β_f (0) (%)	2	2	3	0.7	1.2
$\langle\beta_f\rangle$ (%)	0.25	0.3	0.3	0.12	0.3
max| $R\beta'_f$ | (%)	≈5	≈5	5	3.5	3.8

Ratio of on-axis velocities $V_f(0)/V_A(0)$, slowing down time, τ_S , heating power per volume, P_f (0), ratio of the fast ion density to electron density, n_f (0) / n_e (0), on-axis fast ion beta, β_f (0), volume-averaged fast ion beta, $\langle\beta_f\rangle$, and normalised radial gradient of fast ion beta, max| $R\beta'_f$ |, in JET vs. ITER projected parameters.

ALFVÉN INSTABILITIES:

LARGEST UNCERTAINTY IN CONFINEMENT OF FAST IONS

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ALFVÉN WAVES IN FUSION PLASMA

- Alpha-particles (He^4 ions) are born in deuterium-tritium nuclear reactions with birth energy 3.52 MeV, i.e. these fusion-born ions are *super-Alfvénic*,

$$V_{Ti} << V_A=B/(4\pi\rho)^{1/2} \leq V_\alpha << V_{Te}$$

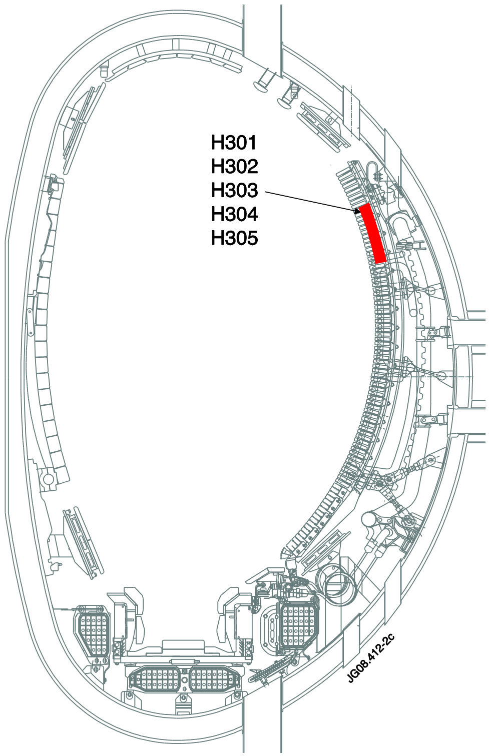
- During slowing-down of alpha-particles, they cross the resonance condition

$$V_A = V_{\parallel\alpha}$$

  and may excite Alfvén waves

- Free energy source: radial gradient of alpha-particle pressure. The instability results in radial re-distribution /losses of alpha-particles if the Alfvén wave amplitude is high.
- On present day tokamaks, fast particles produced by ICRH and Neutral Beam Injection (NBI) do excite numerous Alfvén instabilities

DETECTING ALFVÉN INSTABILITIES WITH MIRNOV COILS



JET cross-section showing the position and directivity of five Mirnov coils separated in toroidal angle

- **Mirnov coils are used for measuring magnetic flux**

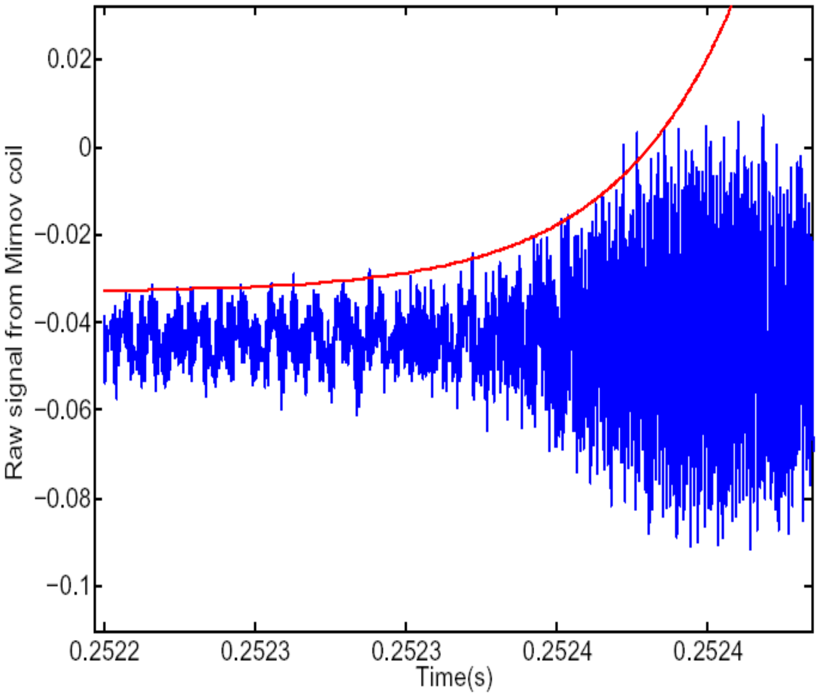
$$\frac{\partial}{\partial t}\delta B_{\vartheta}^{edge} \cong \omega \cdot \delta B_{\vartheta}^{edge}$$

- **The coils are VERY sensitive for high frequencies, e.g. for values of** $\omega \cong 10^{6}\ \ \sec^{-1}$ **perturbed fields** $\left|\delta B_{\vartheta}^{edge} / B_{0}\right| \cong 10^{-8}$ **are measured**

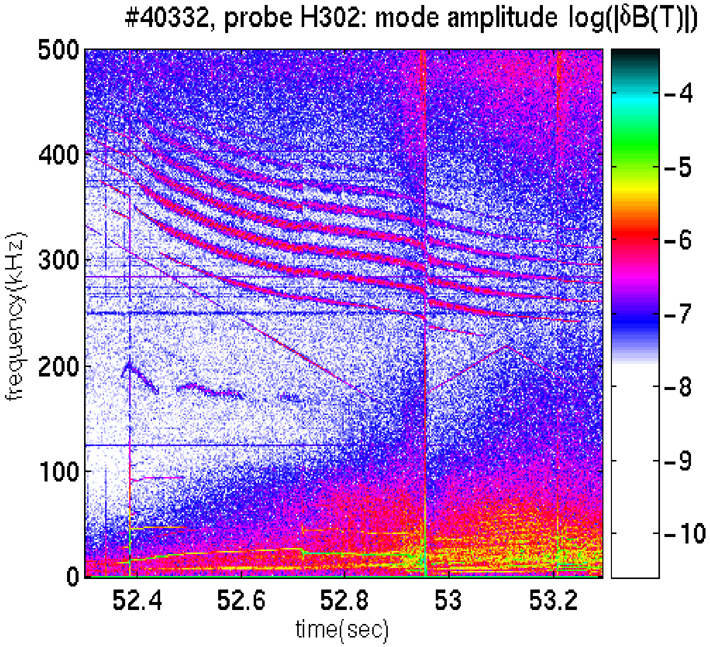
- **Sampling rate 1 MHz allows measurements of AE up to 500 kHz to be made**

- **The coils are well calibrated, i.e. give same amplitude and phase response to the same test signal**

TYPICAL MIRNOV COIL DATA

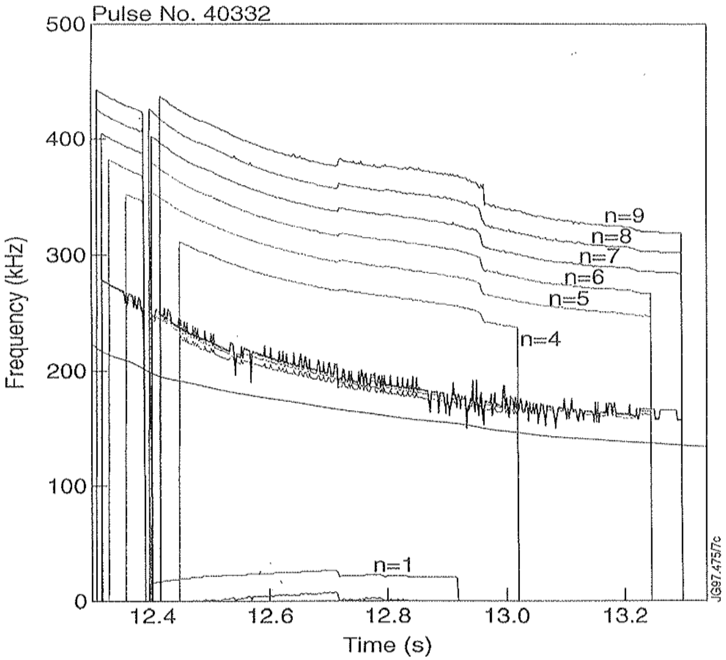


Raw data from a Mirnov coil just outside the plasma

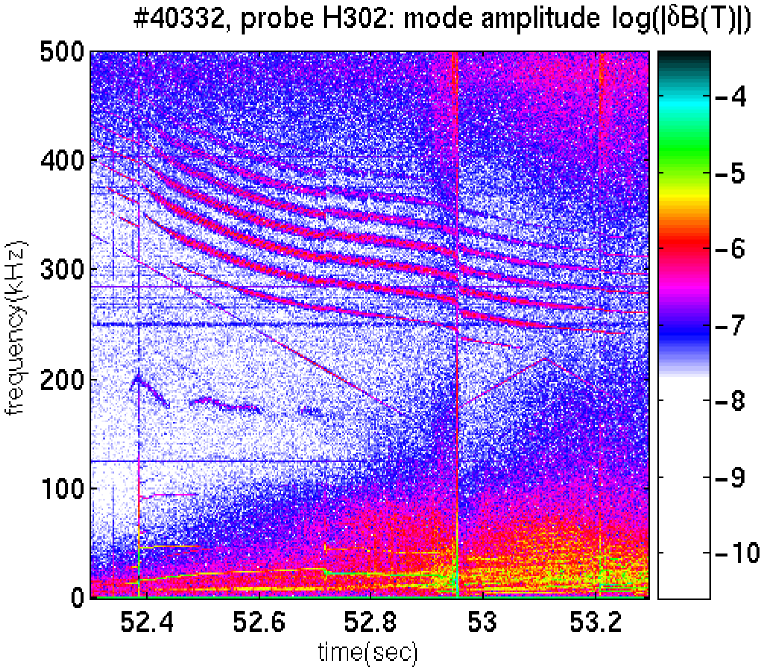


Magnetic spectrogram (Fourier decomposition as function of time) of a Mirnov signal

COMPUTED VERSUS OBSERVED TAEs



Eigenfrequencies of TAEs with n=4…9 computed for equilibrium in JET discharge #40332. Added Doppler shift matches the experiment



Discrete spectrum of TAE observed in JET discharge #40332. Plasma starts at t=40 sec. Frequency changes due to plasma density increase, $f \sim B/\sqrt{n_i M_i}$.

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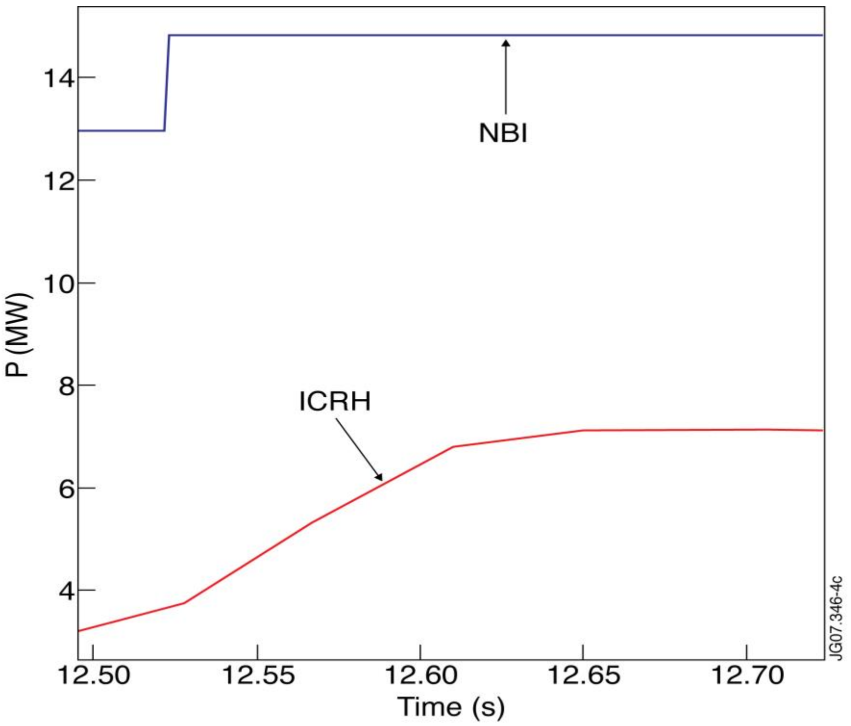
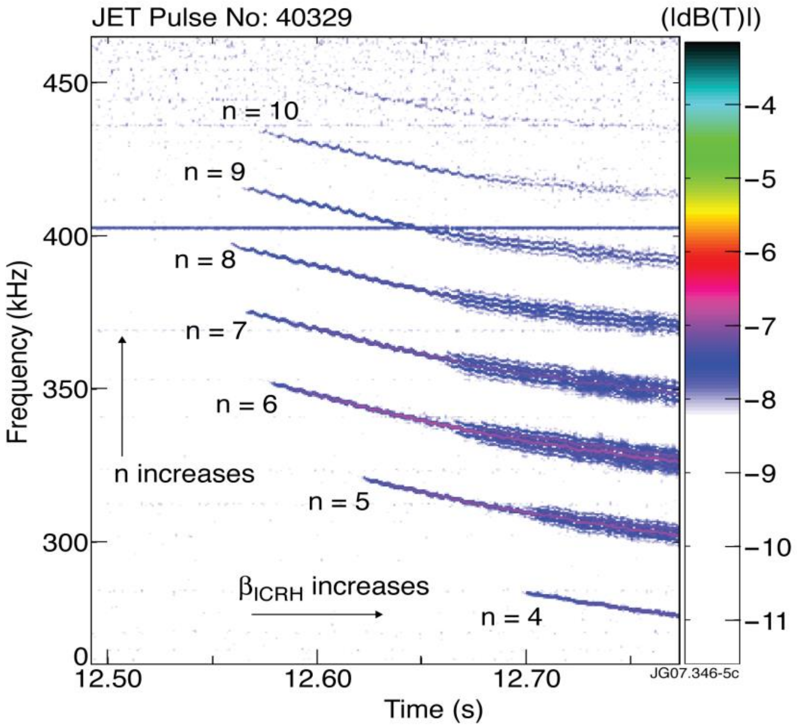
TAE EXCITATION AT INCREASING FAST ION PRESSURE



Power waveforms of ICRH driving TAE and NBI (NBI provides damping)



TAEs with toroidal mode numbers from n=4 to n=10 are seen separated by frequency ~ 25 kHz

EXAMPLE OF ENERGETIC ION RE-DISTRIBUTION DUE TO ALFVÉN PERTURBATIONS IN JET PLASMA

Example from *T.Gassner et al., Phys. of Plasmas 19 (2012) 032115*

ICRH ACCELERATION OF D IONS IN D PLASMA

- Parameters of JET discharge # 74951: B=2.24 T, I_{PLA}=2 MA, R_0=2.9 m, a~1 m
- Deuterium plasma
- Deuterium NBI at energy 110 keV, power 1.5 MW, 3 MW, 4.5 MW
- ICRH at 51 MHz (3rd harmonic of D cyclotron frequency) power 3 MW

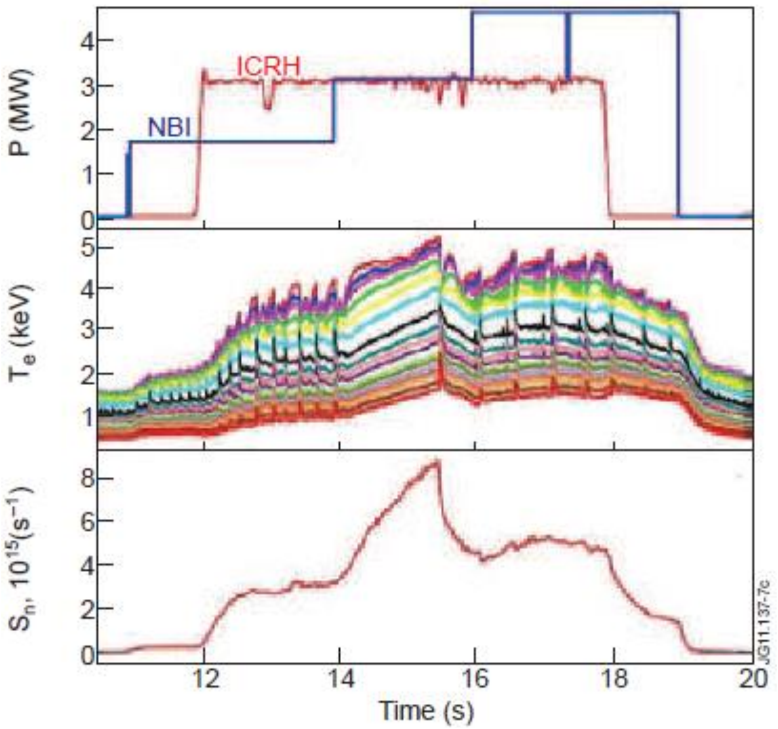
Fast particle diagnostics:

- Neutron spectrometer TOFOR measuring $f_n(E)$ for DD neutrons;
- 2D γ -ray camera measuring profile of γ's from D(E>700 keV)+$^{12}C \rightarrow C + p + \gamma$;
- Fast ion loss detector (scintillator)

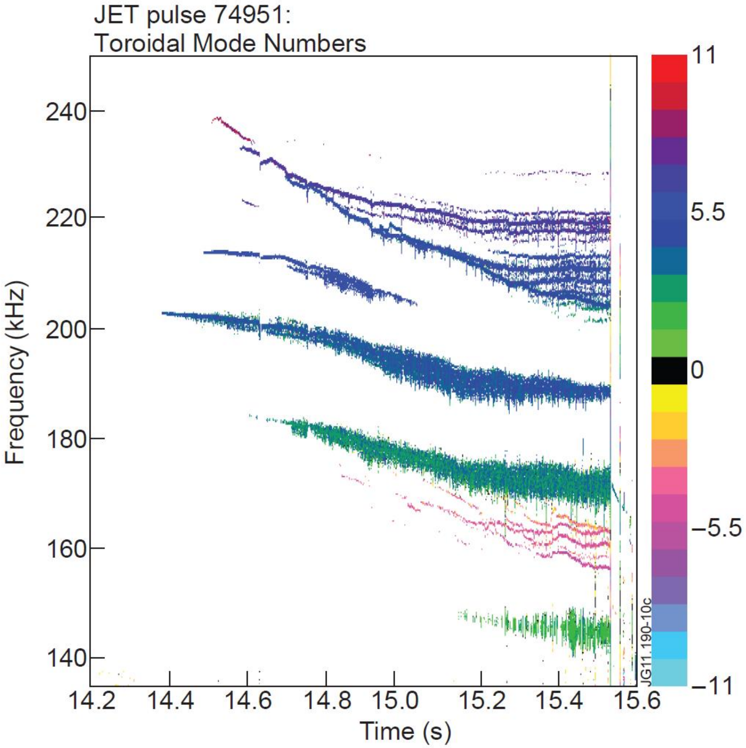
MHD diagnostics:

- High-frequency Mirnov coils;
- Far infrared (FIR) interferometry detecting δn_{TAE} in plasma core.

THE OBSERVATIONS



Top: power waveforms of ICRH and NBI; Middle: temporal evolution of T_e measured with multi-channel ECE; Bottom: the DD neutron rate.



TAE of different n's detected with Mirnov coils during time preceding the sawtooth crash at 15.6 s

DETECTION OF FAST ION RE-DISTRIBUTION DURING TAE

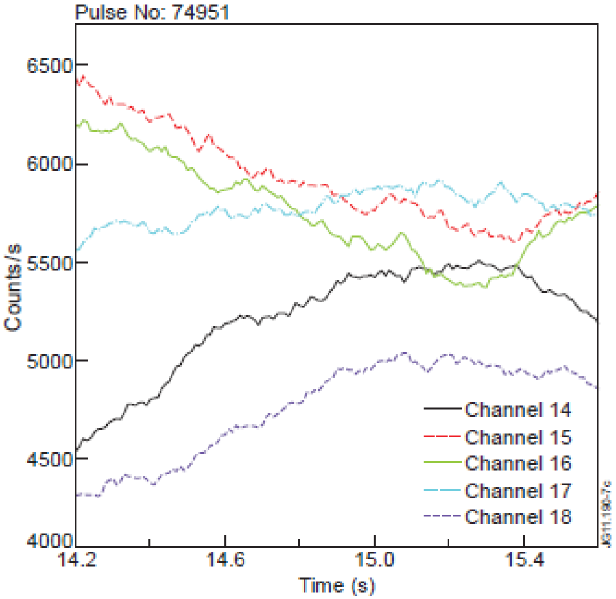


Figure: Redistribution of fast deuterons is observed in the gamma-ray signals for channels 14 - 18. Decreasing signal in central channels (15,16), increasing in outer channels(14,18). Gammas come from reaction $^{12}C(d,p\gamma)^{13}C$

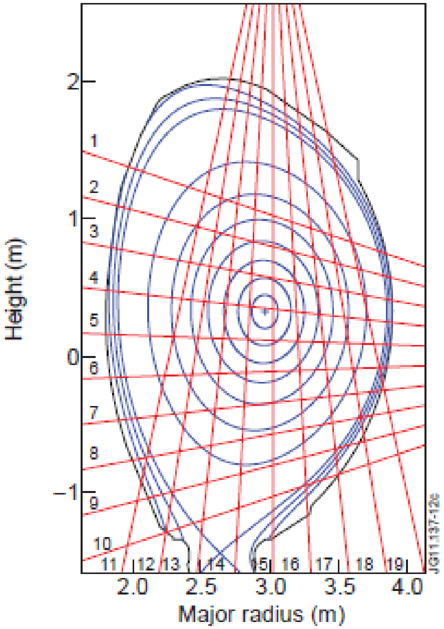


Figure: Lines of sight of the 2D gamma camera system on JET

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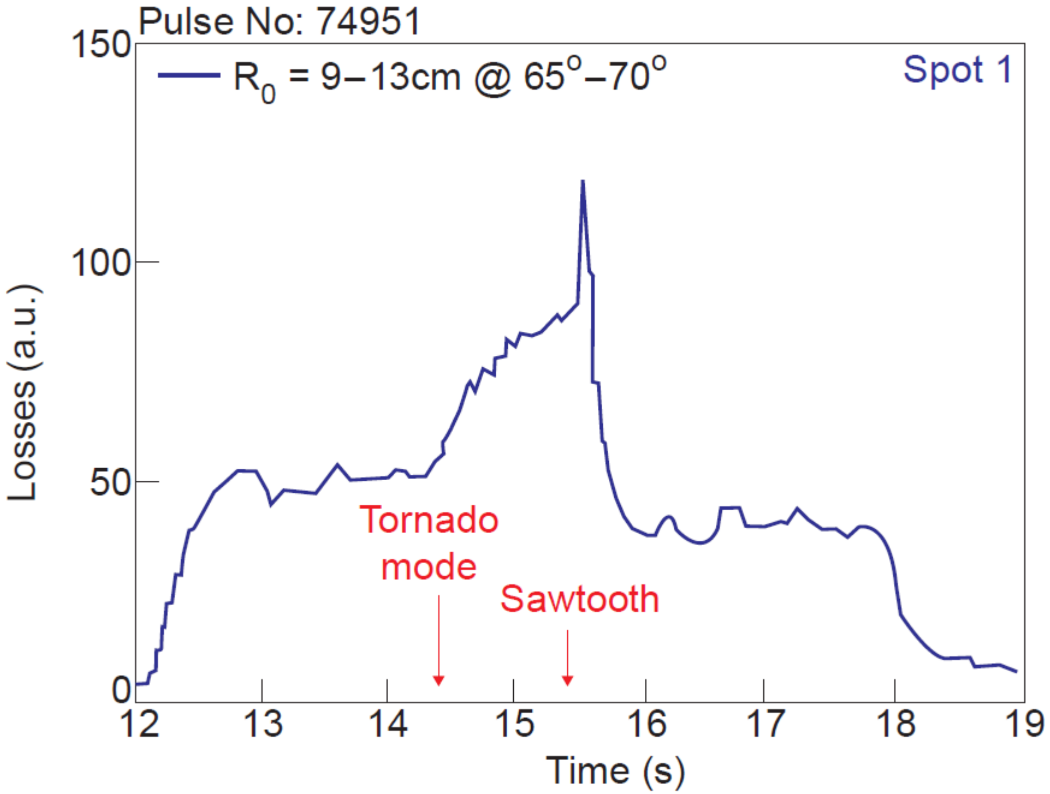
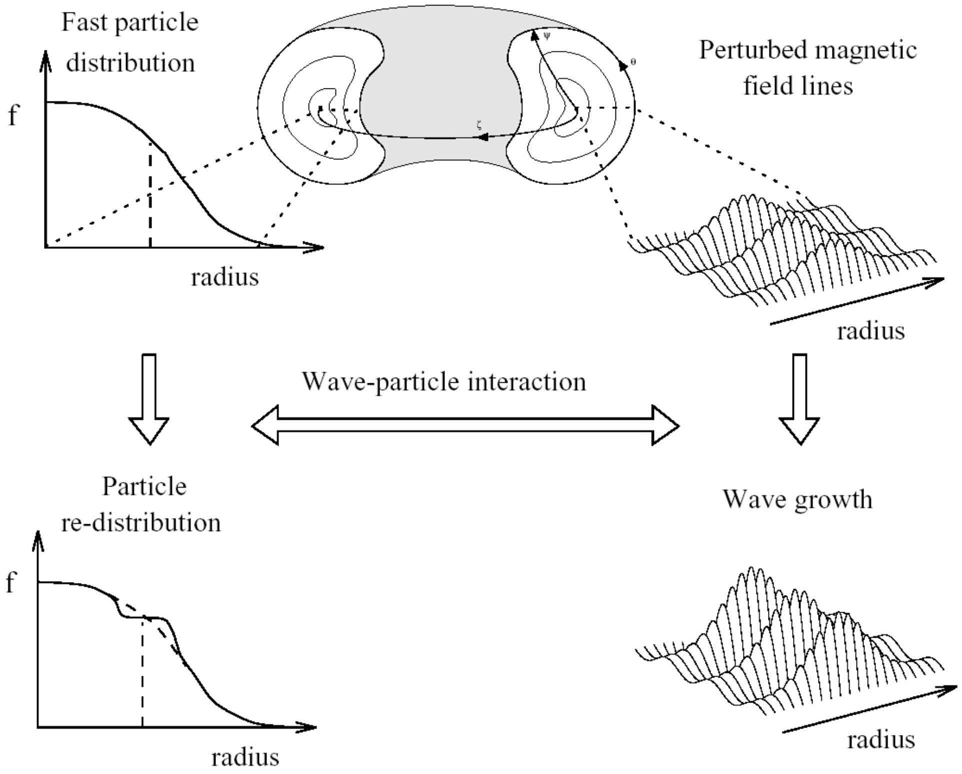
LOSSES OF FAST D IONS DETECTED WITH SCINTILLATOR DURING TAE



MODELLING TAE-FAST ION INTERACTION (HAGIS CODE)



Fast particle distribution

f

radius

Perturbed magnetic field lines

radius

Wave-particle interaction

Particle re-distribution

f

radius

Wave growth

radius

S.D.Pinches et al., Computer Physics Communications 111 (1998) 133

FAST ION DISTRIBUTION FUNCTION

Reconstruction of fast ion distribution

The distribution function of fast deuterons is modeled as product of three functions of constants-of-motion

$$f(E, P_\phi, \Lambda) = f_E(E) f_{P_\phi}(P_\phi) f_\Lambda(\Lambda)$$

- energy E
- toroidal angular momentum P_ϕ
- normalized magnetic moment $\Lambda \equiv \mu B_0 / E$

RADIAL DISTRIBUTION OBTAINED FROM 2D GAMMA-RAYS

Unperturbed profile from 2D gamma-camera data. Distribution $f(P_\phi)$ is measured!

Profile matching

- Synthetic diagnostic module in HAGIS
- f_E, f_Λ fixed
- Scan in P_ϕ-profiles
- Choose best fit

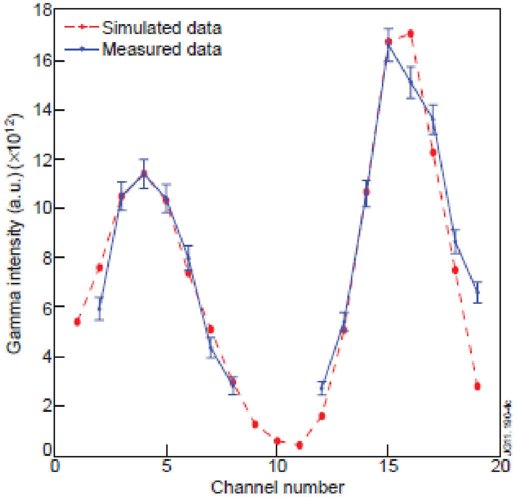
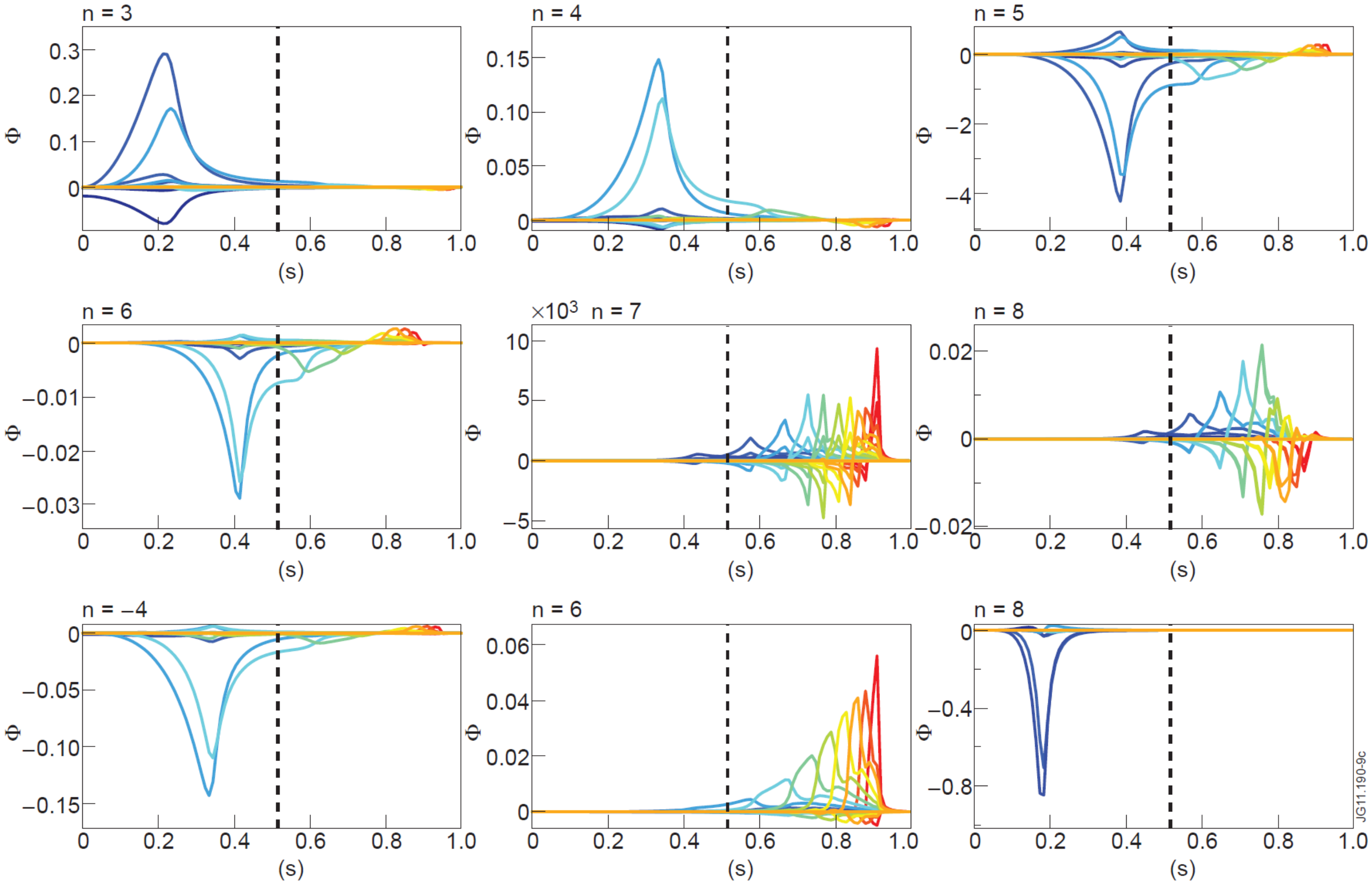


Figure: Line-integrated gamma-ray intensities (horizontal channels: 2-8, vertical channels: 12-19) at time 13.83 sec (solid line); simulated data for best fitting profile f_{P_ϕ} (dashed line)

COMPUTE ALL THE OBSERVED ALFVEN EIGENMODES



HAMILTONIAN APPROACH FOR δf IN THE HAGIS CODE

Trajectory of each individual macro-particle follows the Hamiltonian approach [White & Chance, Phys. Fluids 27 (10) 1984] leading to equations of the type:

$$\frac{\partial\psi_p}{\partial\vartheta}=\frac{1}{D}\left[I\frac{\partial\tilde{A}_\zeta}{\partial\vartheta}-g\frac{\partial\tilde{A}_\vartheta}{\partial\vartheta}\right];\ \frac{\partial\psi_p}{\partial\zeta}=\frac{1}{D}\left[I\frac{\partial\tilde{A}_\zeta}{\partial\vartheta}-g\frac{\partial\tilde{A}_\vartheta}{\partial\zeta}\right];\ \frac{\partial\psi_p}{\partial P_\vartheta}=\frac{g}{D};\ \frac{\partial\psi_p}{\partial P_\zeta}=-\frac{I}{D}$$

For the shear Alfvén modes, the assumption $\tilde{\mathbf{A}}=\tilde{\alpha}(\mathbf{x},t)\cdot\mathbf{B}_0$ is used;

Nonlinear code: for fixed eigenmode structure provided, the mode amplitude and phase are evolving through (schematically):

$$\frac{dA}{dt}=A_0+\sum_{particles}(\ldots)-\gamma_{damp}A\,;\qquad \frac{d\varphi}{dt}=\varphi_0+\sum_{particles}(\ldots),$$

for unchanged mode structure

δf technique is used for deviation from f_0 by launching $>10^5$ macro-particles

SELF-CONSISTENT TAE MODELLING

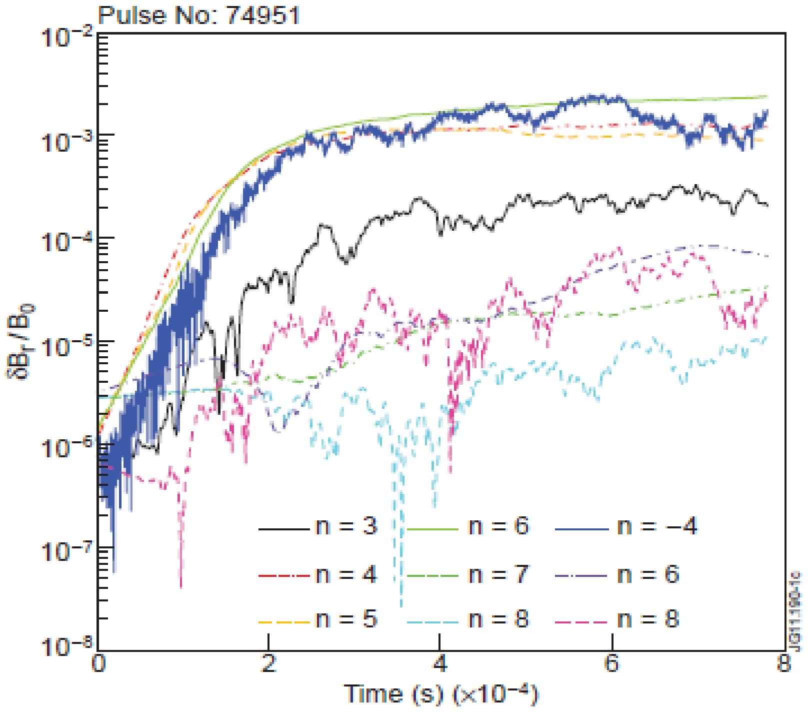


Figure: Logarithmic plot of the amplitudes $\delta B_r / B_0$

FAST DEUTERON RE-DISTRIBUTION

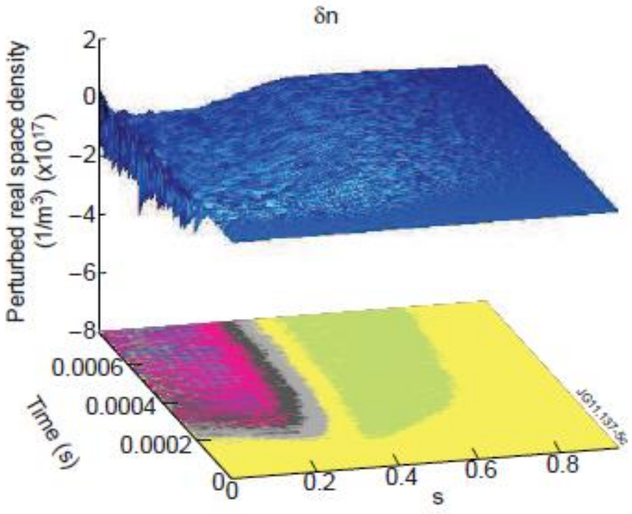


Figure: Perturbed real space particle density as a function of the radial coordinate *s*

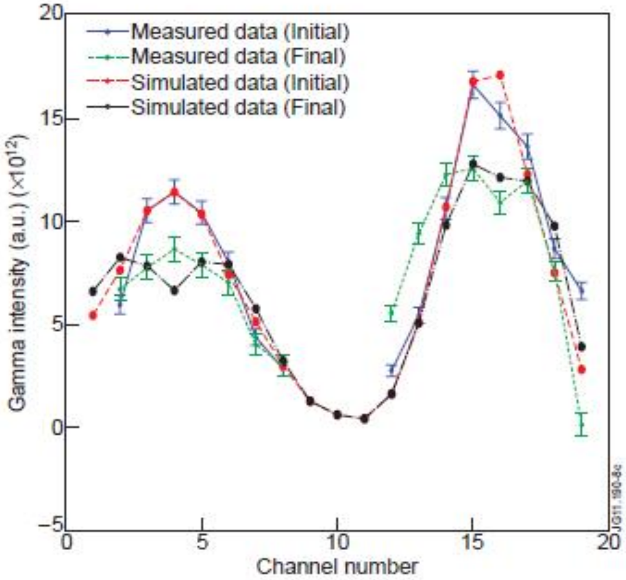


Figure: Gamma intensity: measured data before (blue) and after (green) redistribution; simulated gamma intensity in red (initial data) and black (after redistribution)

SUMMARY

- D-T fusion: for generating 1 GW power for 1 year one needs 1 tonne Li + 5 Mlitres water

- To overcome the Coulomb electrostatic force between two positive nuclei D and T, high kinetic energy is needed corresponding to 10-20 keV → plasma

- Plasma can be confined by magnetic field in, e.g. toroidal solenoid

- The triple-product ignition criterion $n\, T\, \tau_E > 5 \times 10^{21}\ \mathrm{m^{-3}\ keV\ s}$ for magnetic fusion yields $\beta\, B^2\, \tau_E > 4\ \mathrm{T^2\ sec}$

- Three main avenues are being developed for approaching ignited plasmas: high- τ_E (large volume), high-B, and high- β (spherical tokamaks) machines

SUMMARY (continued)

- As burning plasma experiment with significant alpha-particle heating approaches on ITER, studies of energetic ions similar to fusion-born alphas are being performed now

- ICRH is the best technique of generating the MeV-range ions in present-day tokamaks

- Alfvén instabilities driven by super-Alfvénic fusion-born alphas are an issue for all future tokamaks built in line with the three main avenues

- Experimental observations of energetic ion transport caused by Alfvénic instabilities are typical of present-day machines with fast ions

- Modelling of alpha-particle transport/ losses in the presence of Alfvénic instabilities is one of the major problems for successful control of the burning plasmas in future fusion experiments