EUROPEAN FUSION DEVELOPMENT AGREEMENT

Experimental Studies of Instabilities and Confinement of Energetic Particles on JET and on MAST

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[*] See Annex of J Pamela et al., this conference, paper OV/1-X

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Fast ions in burning plasma

1) ITER: P_α/P_{in} = 2 for Q=10 $\Rightarrow$ different fast ions of comparable energy content:

- Fusion-born α's with T$\approx$ 1 MeV
- Deuterium NB injected at $\approx$ 1 MeV
- ICRH-accelerated ions of H, ^{3}He, …

$\Downarrow$

Diagnostics measuring simultaneously several groups of fast ions are required

2) For assessing fast ion effects on Alfvén Eigenmodes (AEs), fishbones, sawteeth etc. measurements of fast ion profiles are desirable with time resolution of at least $\Delta t \sim 1/\nu_{eff}$ (time for establishing the fast ion distribution)

3) The diagnostics must be compatible with DT operation.

4) Good theory/modeling and experimental data base must exist for identifying all the crucial fast ion problems.

What can we achieve on existing facilities?

Alpha Simulation Experiment in JET Helium Plasma

**Studies complimentary to
T-trace Exp. (paper by D.Stork OV/4-1),
but performed at very low neutron rates
in not-activating environment**

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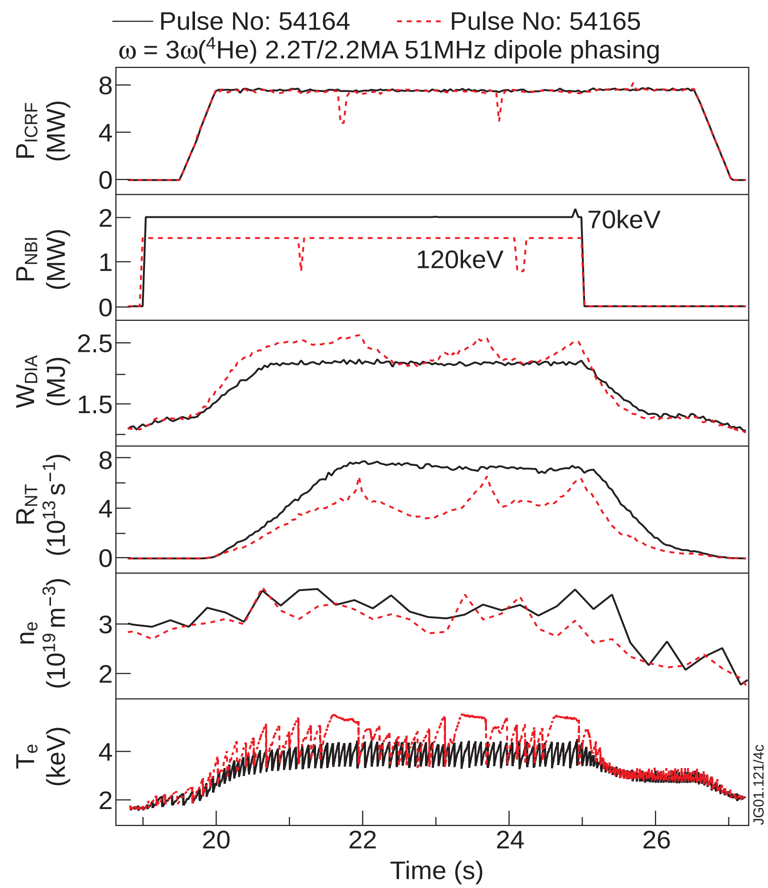
JET

^{4}He acceleration with 3ω(^{4}He) ICRF heating of ^{4}He NBI (2002)



^{4}He plasma + 8 MW of ICRH at 3ω(^{4}He) + 120 keV ^{4}He beam of power 1.5 MW

⇓

H-mode with MeV energy ^{4}He ions:

T_{Hot} = 1.1 ± 0.4 MeV,

$n_{Hot} / n_e \sim (\Delta W_{DIA}/W_{DIA})*(T_e/T_{Hot}) \sim 10^{-3}$

M.Mantsinen et al., Phys.Rev.Lett. 88 (2002)105002

Fast ion parameters are close to these in record DT discharge #42976:

$T_{Hot} \approx$ 1MeV, $n_{Hot} / n_e \sim 4{\cdot}10^{-3}$,

but achieved at four orders lower neutron rates

⇓

NO ACTIVATION

Very good scenario for developing and testing α-diagnostics !

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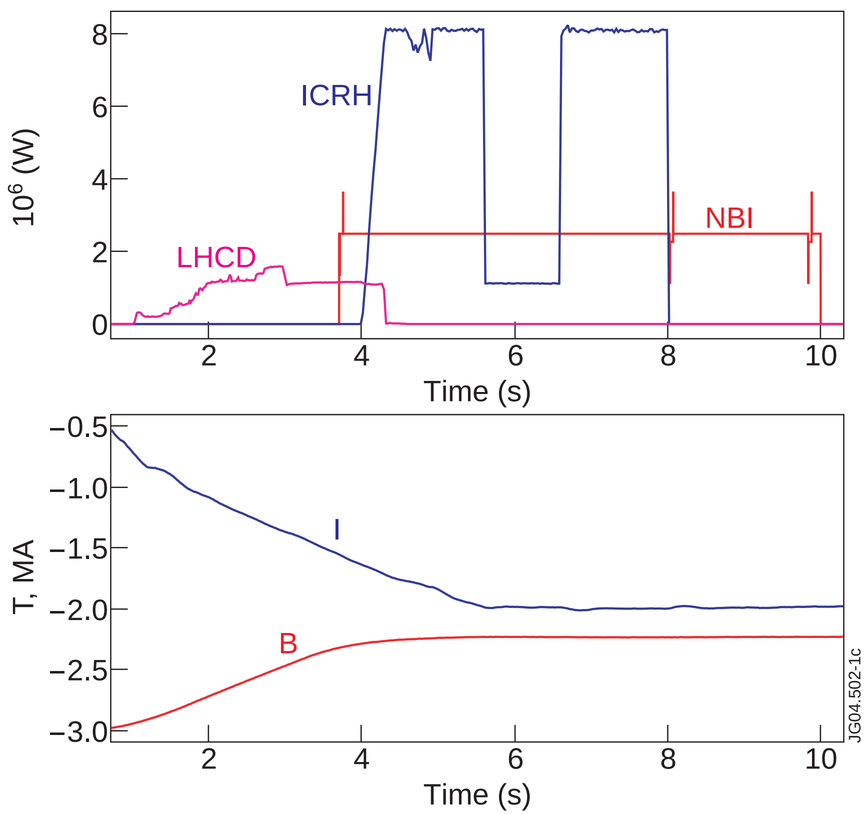
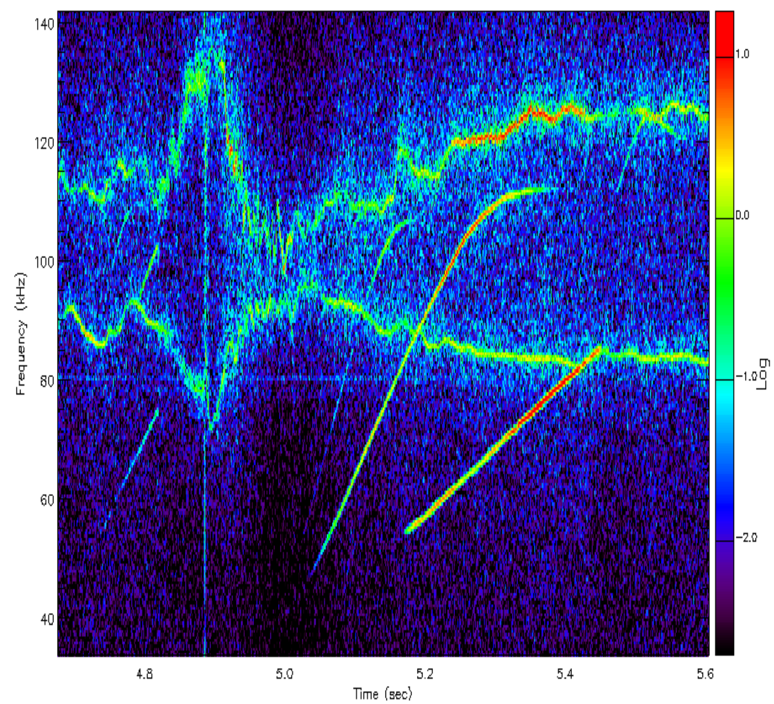
^{4}He acceleration technique in reversed shear plasmas (2004)



B= 2.2 T, ω_{ICRH} = 51 MHz, I = 1.5÷2 MA



Alfvén Cascades excited by ^{4}He ions in JET reversed-shear discharge #63038.

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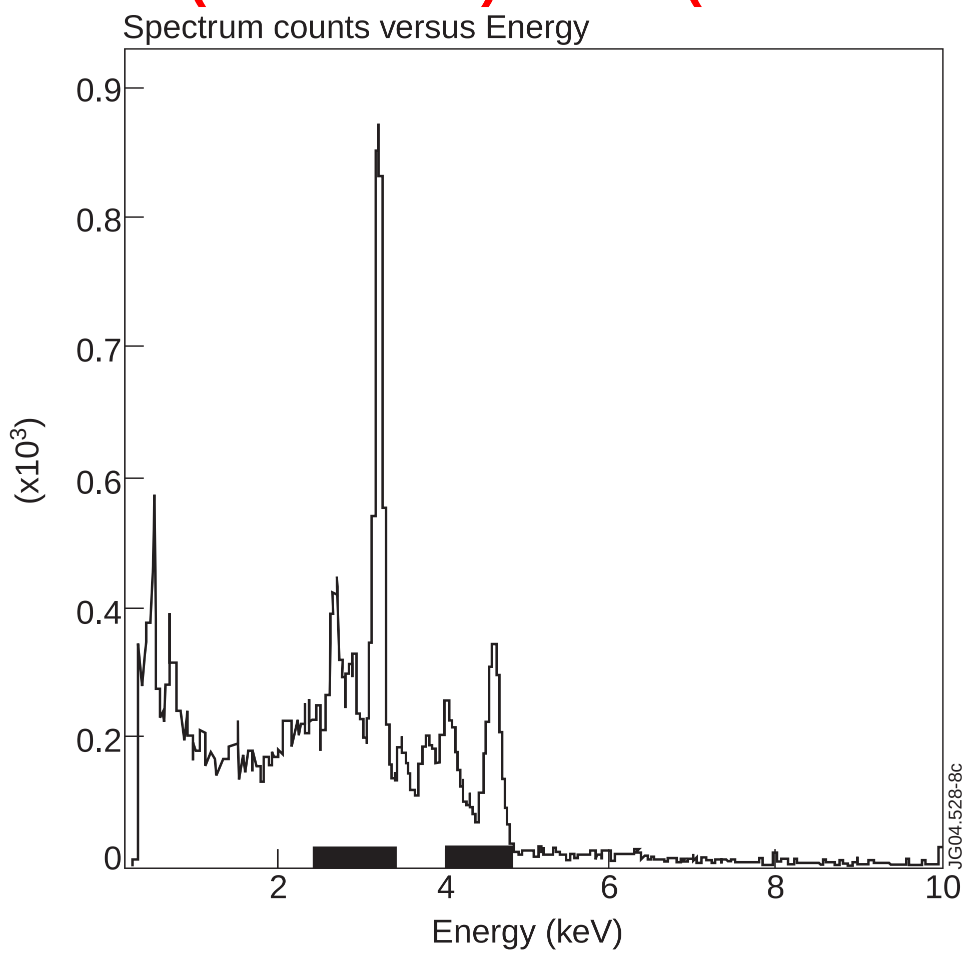
Simultaneous Measurement of ^{4}He (E>1.7 MeV) and D (E>0.5 MeV)

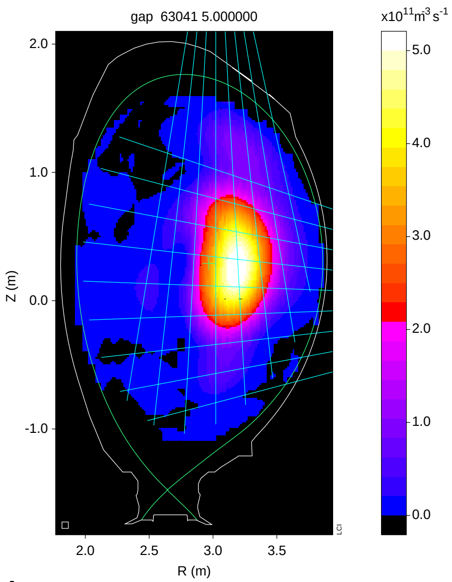
Energy windows for ALL Gamma Camera channels

I > 2.0 MeV (total)
II 2.5 - 3.5 MeV (D+C)
III spare
IV 4.0 - 5.0 MeV (^{4}He+Be)

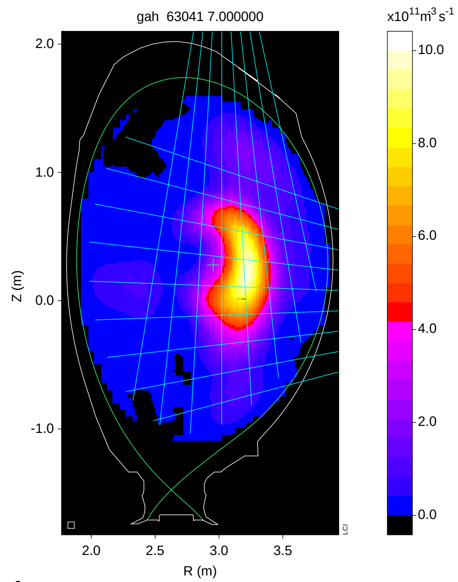


E U R O P E A N   F U S I O N   D E V E L O P M E N T   A G R E E M E N T

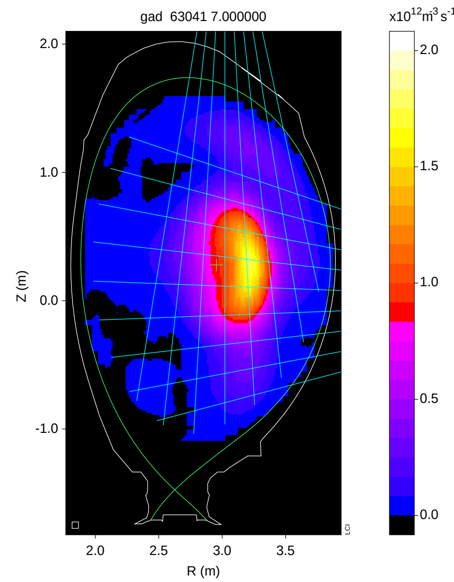
Gamma-ray Images of ^{4}He (E>1.7 MeV) and D (E>0.5 MeV) in Reversed and Positive Shear JET Plasmas



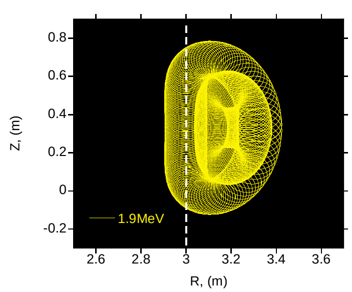
^{4}He in reversed-shear discharge

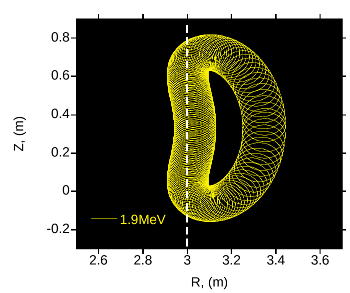


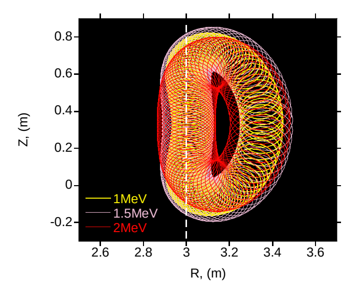
^{4}He in monotonic q(r)-plasma



D in monotonic q(r)-discharge







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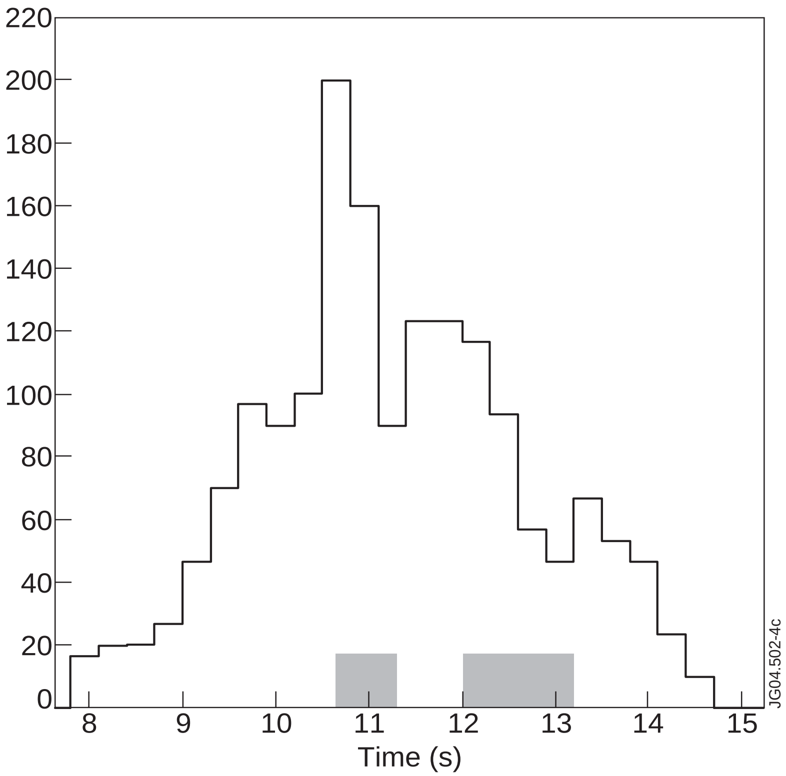
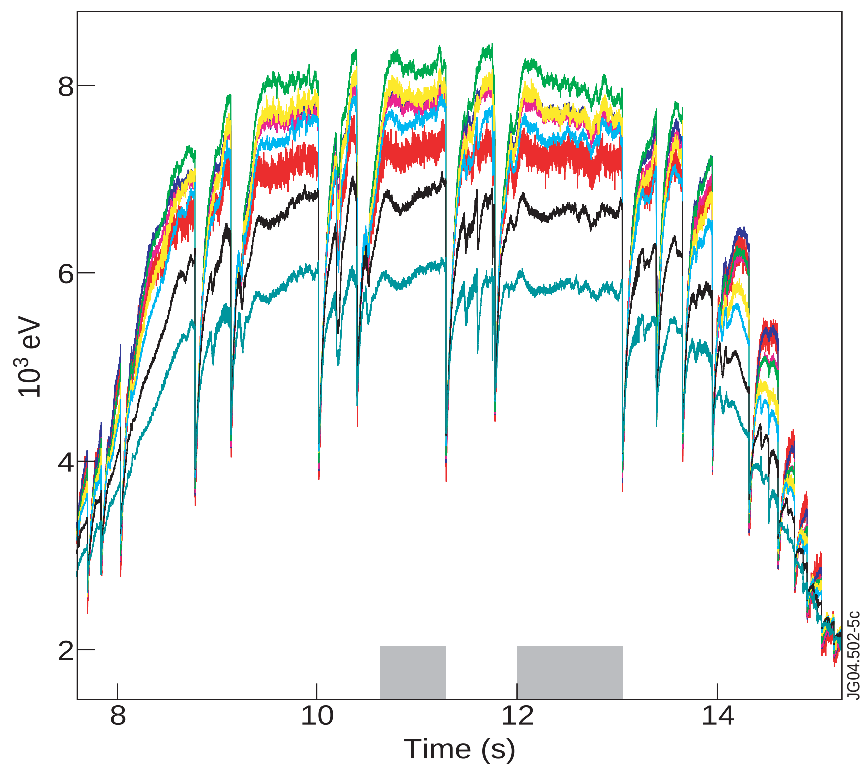
Effect of Alfven Eigenmodes on ICRH-accelerated protons in q=1 plasmas

This data supports previously published results from
JT-60U (Saigusa et al., PPCF 40 (1998) 1647)
TFTR (Bernabei et al., Phys. Rev. Lett. 84 (2000) 1212)
DIII-D (Heidbrink et al., Nuclear Fusion 39 (1999) 1369)

Gamma-ray intensity from 5MeV protons decreases 0.5–1 sec before sawtooth crashes



γ-rays from reactions $^{12}C(p, p'\gamma)^{12}C$



T_e at different radii show sawteeth at t=11.4, t=13 s occuring after decreases of γ- intensity

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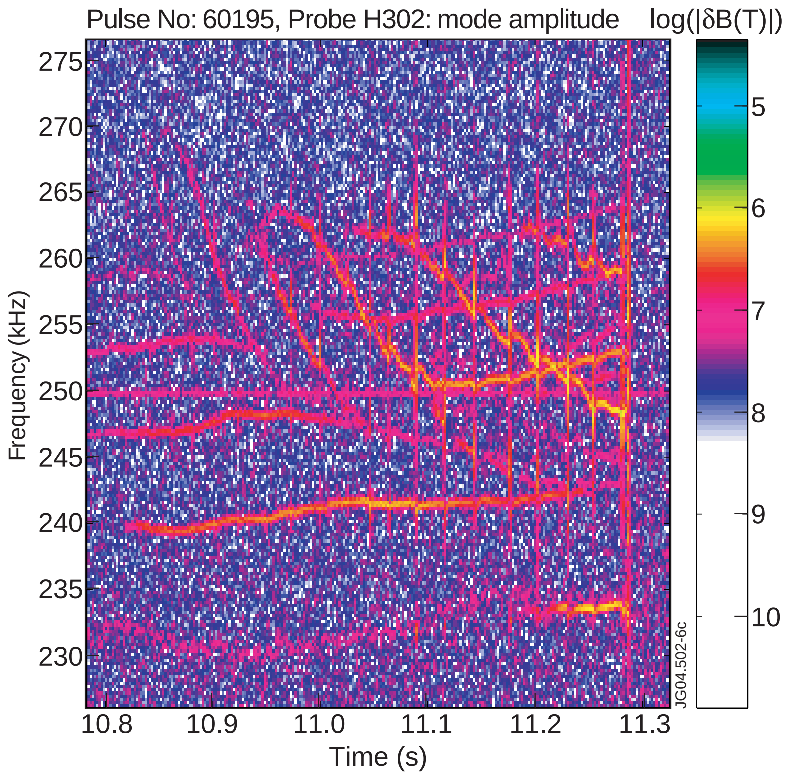
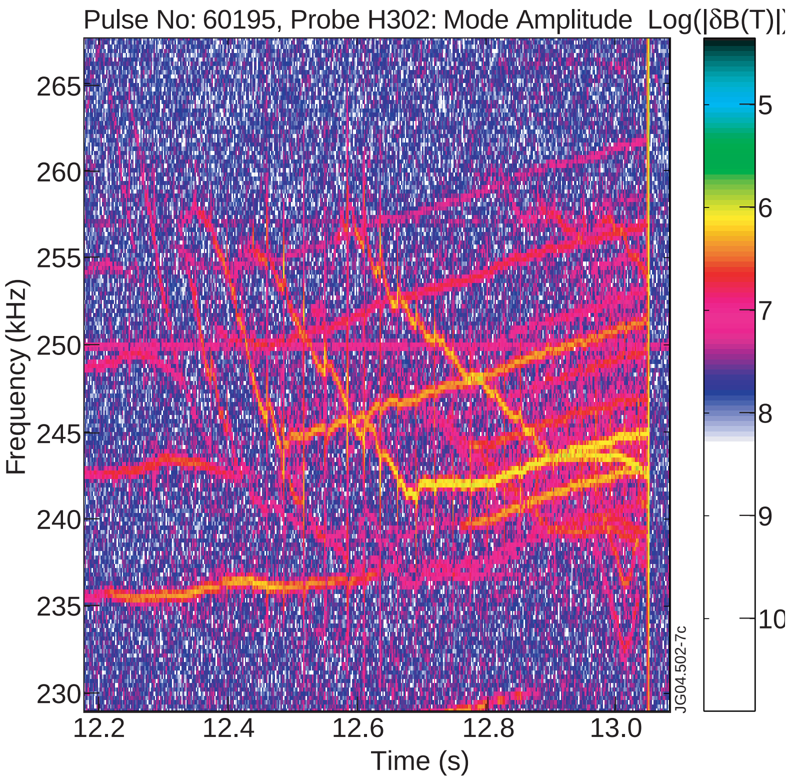
The Gamma-ray Decrease Happens when TAEs within q<1 (tornado modes) and TAEs outside q=1 coexist

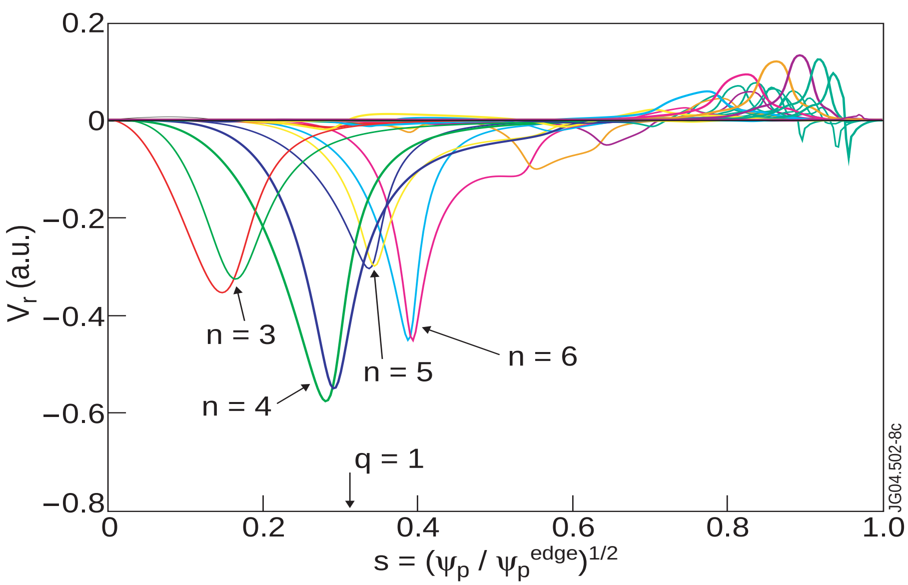


TAEs & tornadoes during first shaded time interval

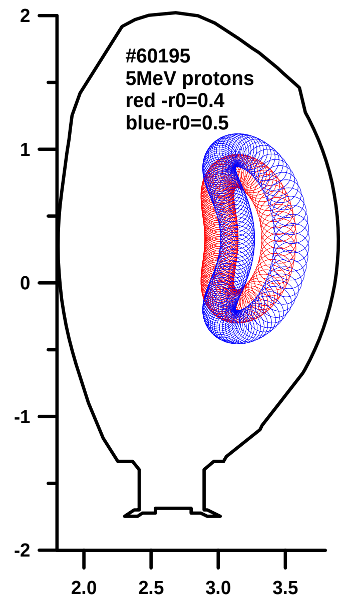


TAEs & tornadoes during second shaded time interval

The Gamma-ray Decrease Happens when TAEs within q<1 (tornado modes) and TAEs outside q=1 coexist



TAEs with n=3, 4 within the q=1 radius (tornado), and n=5,6 TAEs outside the q=1



Orbits of 5 MeV protons

- **Prompt losses of protons with *E*>5 MeV (orbit width $\Delta_f /a \leq 0.5$) enhanced by the TAEs are considered as a primary channel of proton losses.**

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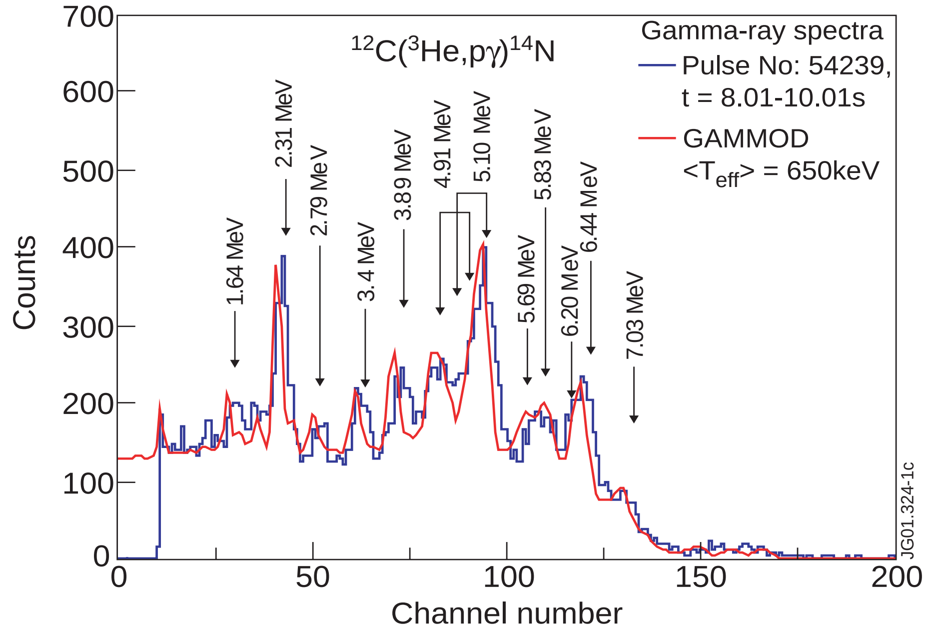
ICRF acceleration of ^{3}He: a step towards time resolved profiles of fast ions

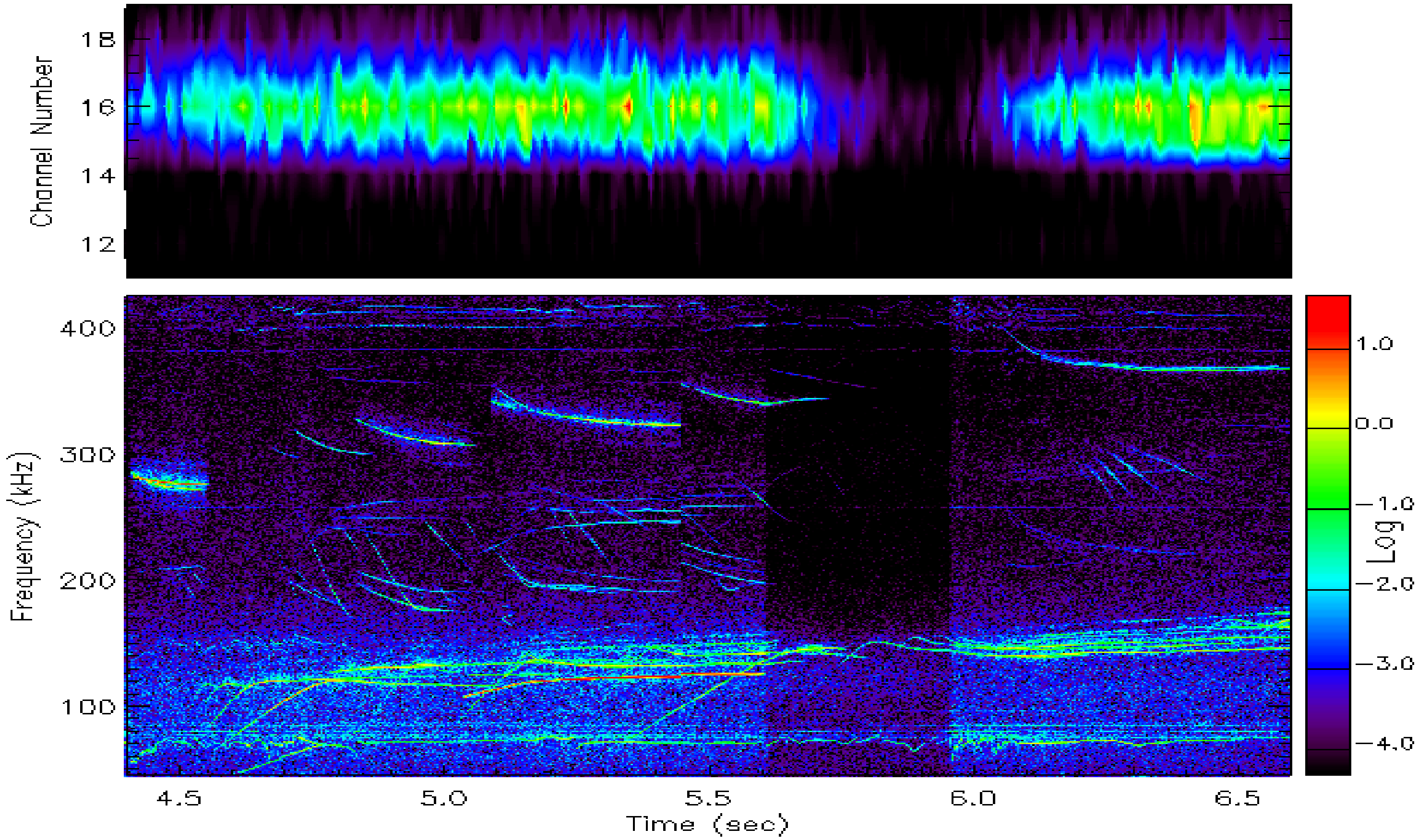
Why Fast ^{3}He in ^{4}He Plasma?

^{3}He with E>500 keV generates lots of gamma-rays when it collides with C and Be:



- **For given n_e ,T_i V_A / V_{Ti} is higher in He plasma ⇒ smaller AE damping on thermal ions**
- **Low neutron yield in ^{4}He plasma ⇒ excellent conditions for gammas**

Profile of Fast Ions (Top) Measured Simultaneously with AEs (Bottom)



Notches of ICRH power (5 MW →1MW) show modes most sensitive to ^{3}He ions

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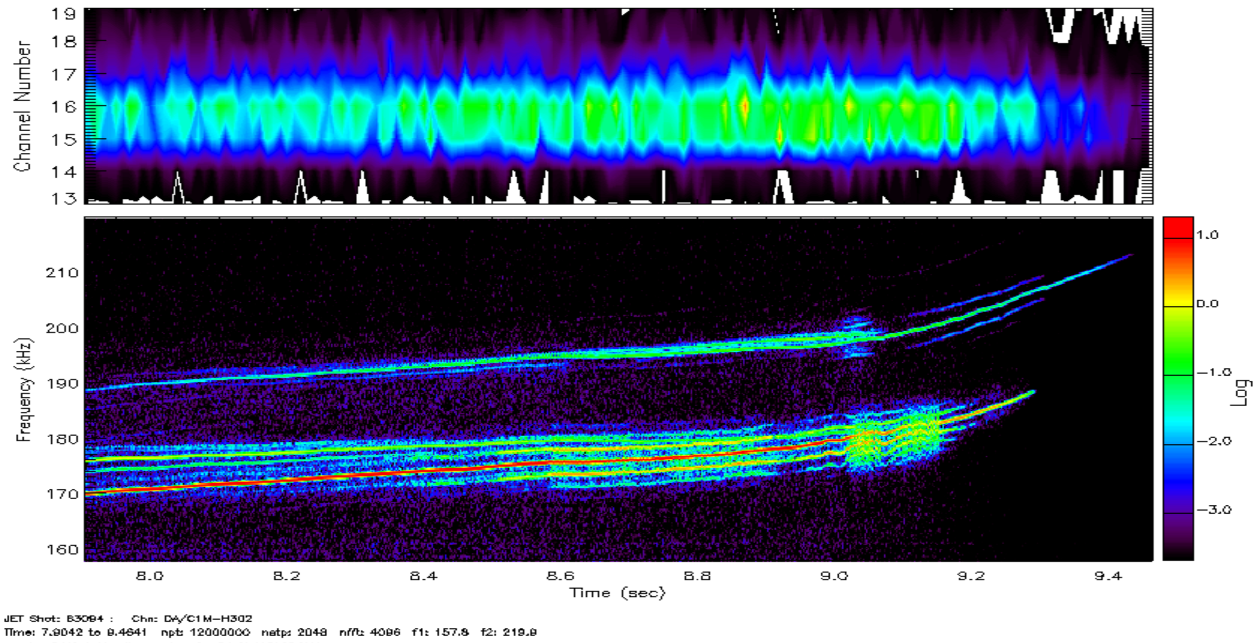
Linear and Nonlinear Characteristics of AEs Assessed from *Measured* Profiles of Fast Ions



Nonlinear pitchfork splitting of ICRH-driven TAE as $d\beta_{fast}/dr$ increases by ~40%

Tens of AEs were excited, but no degradation of fast ^{3}He observed in these I=2.3 MA discharges with orbit width of ^{3}He ions Δ_f/a <<1.

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Alfvén Eigenmodes in High-β Spherical Tokamaks

See also papers
G.F.Counsell (OV/2-4) and
H.L.Berk (TH/5-3)

Alfvén Instabilities Driven by Passing Super-Alfvénic Ions on MAST

- **JET: AEs driven by trapped ions,**
- **MAST: AEs driven by passing ions (more relevant for α-driven AEs)**
- **Wide variety of AEs on MAST:**
  - ***TAEs and EAEs;***
  - ***frequency-sweeping "chirping" modes;***
  - ***fishbones;***
  - ***modes above the AE frequency range.***

- **Larger range of β_{fast} / $\beta_{thermal}$ and $\beta_{thermal}(0) \sim 1$ on MAST**
- **Some of AEs observed on MAST are also obtained on larger-scale machines, but with sophisticated techniques, e.g. with NNBI on JT-60U or at low B on JET**

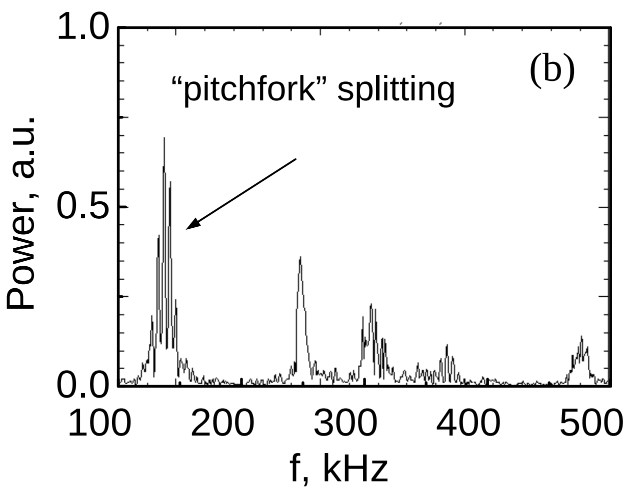
$\Downarrow$

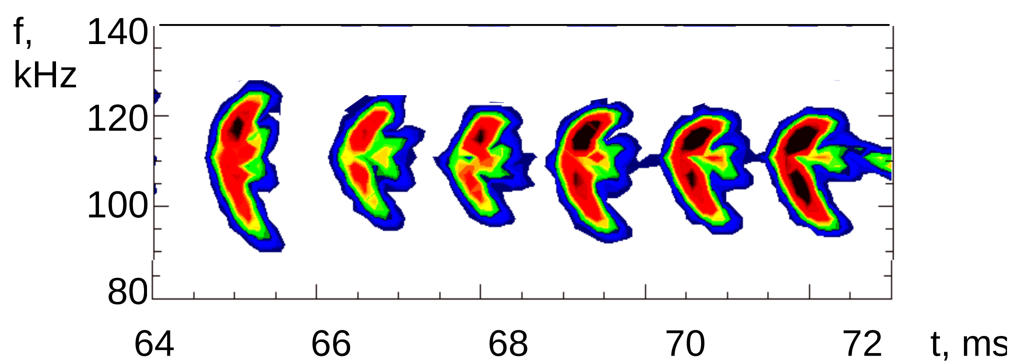
MAST is a perfect test-bed for studying AEs.

Strong Non-linear Effects Are Observed on MAST

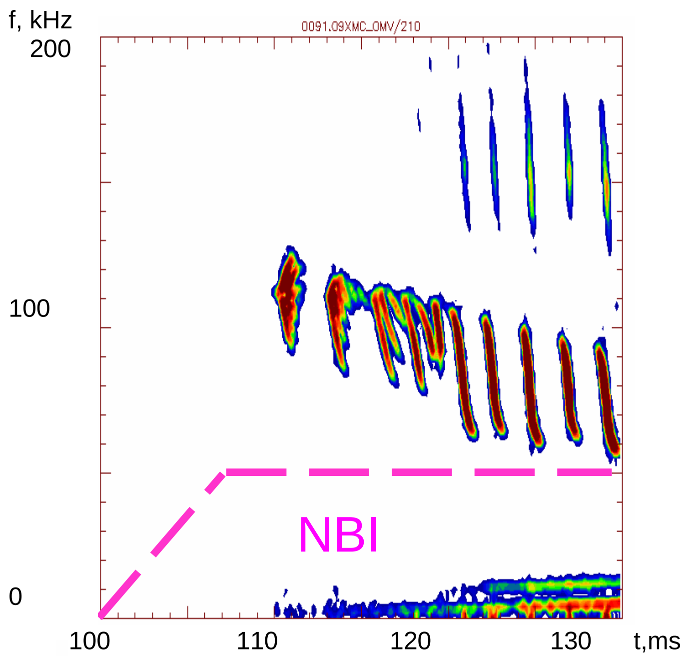
Nonlinear wave-particle effects observed for AEs on MAST:

- **Pitchfork splitting**
- **Up-down sweeping TAE modes (BGK-type modes, or "holes and clumps", also see H.Berk, this conference, TH/5-2Ra).**





Non-Perturbative "Chirping" Modes Are Common



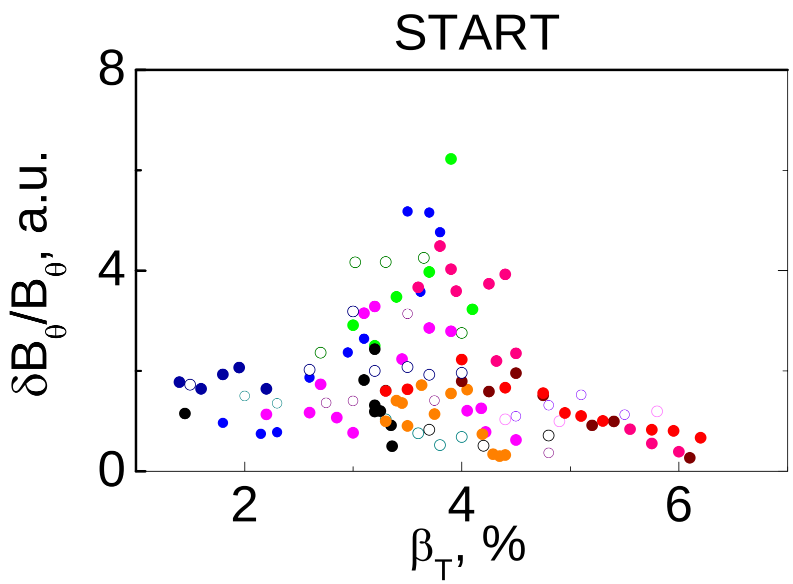
MAST #9109, 1.2 MW of 40 keV NBI at I_P flat-top, $\beta \approx 3\%$

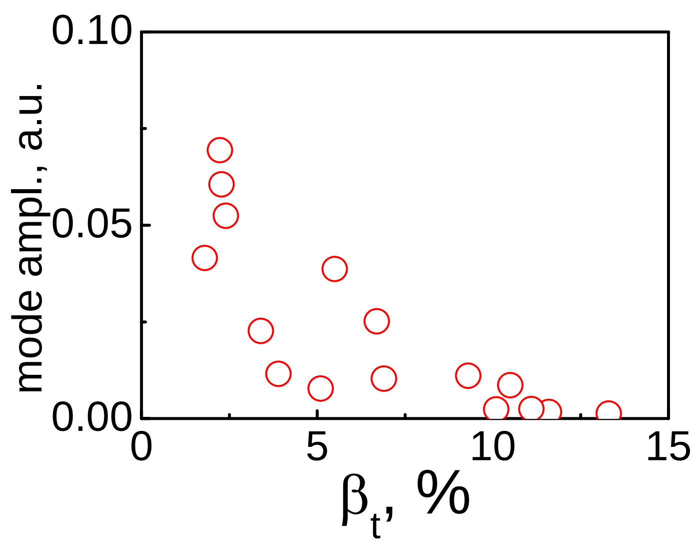
Profiles of fast ions resolved with $\Delta t \approx 1$ ms are needed for analysing these.

E U R O P E A N   F U S I O N   D E V E L O P M E N T   A G R E E M E N T

Suppression of AEs in Higher-β Plasmas

- **TAEs are suppressed by high-pressure effect at <β> ≥ 5%**
- **"Chirping" modes are suppressed by high-β due to thermal ion Landau damping (both MAST and START data)**





On START, chirping mode amplitude decreases as beta increases above 4%.

MAST: dependence on β of maximum amplitude of chirping modes.

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20th IAEA fusion energy conference
1st.-6th. Nov., Vilamoura, Portugal

JT-60U

Energetic ion transport by Alfvén eigenmode induced by Negative-ion-based Neutral Beam Injection in JT-60U Reverse Shear and Weak Shear Plasmas

M. Ishikawa, M. Takechi, K. Shinohara,Y. Kusama, C. Z. Cheng[3] , G. Matsunaga, Y.Todo[2], N. N. Gorelenkov[3], R. Nazikian[3] , G. J. Kramer[3] , A.Fukuyama[1]

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Introduction to Alfvén Eigenmode Study in JT-60U

Alfvén Eigenmode (AE) experiments have been performed by using
Negative-ion-based Neutral Beam (E_{NNB}>360keV, P_{NNB}>4MW)

- in Weak shear plasma

Abrupt Large-amplitude Events (ALEs), Fast Frequency Sweeping modes

(***K. Shinohara, et al.,Nucl. Fusion 41(2001) p603***)

(18th. IAEA Fusion Energy Conference)

- in Reversed shear plasma

Reversed-Shear induced Alfvén Eigenmode (RSAE), its transition to TAE

(19th. IAEA Fusion Energy Conference)

Reduction of Total Neutron Emission Rate due to AEs has been observed

beam-thermal reaction is dominant

energetic ion transport due to AEs

However, It is not understood how energetic ions transport

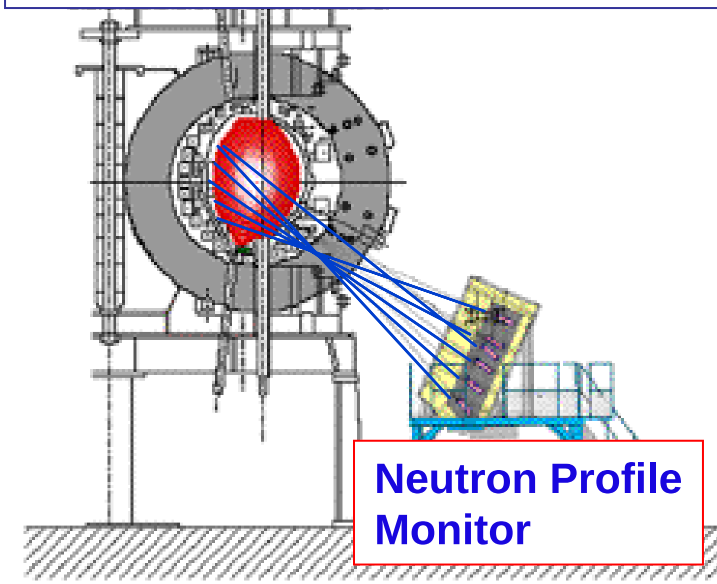
- **neutron emission profile**
- **detailed energy distribution of neutral particle fluxes**

have been newly measured in order to investigate energetic ion transport

Diagnostics for investigation of energetic ion transport

JT-60U

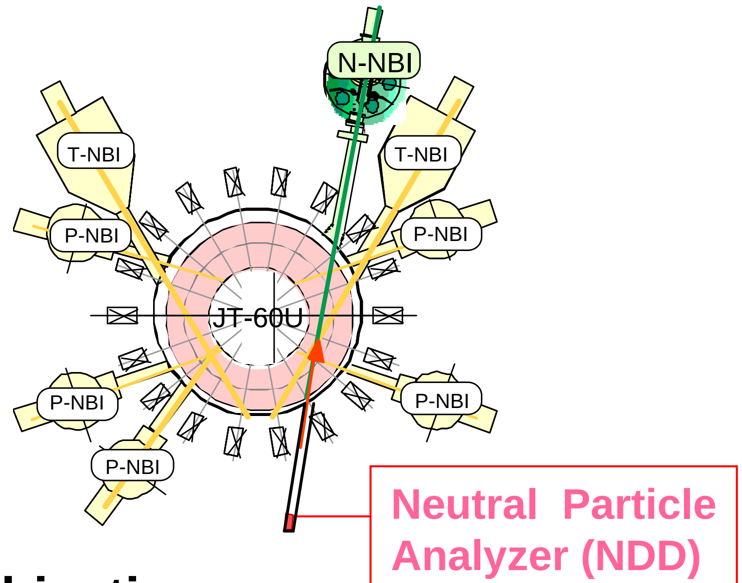
6 channel Neutron Profile Monitor



Objectives :

-Measure radial profile of neutron emission rate

CX-Neutral Particle Analyzer (Natural Diamond Detector)



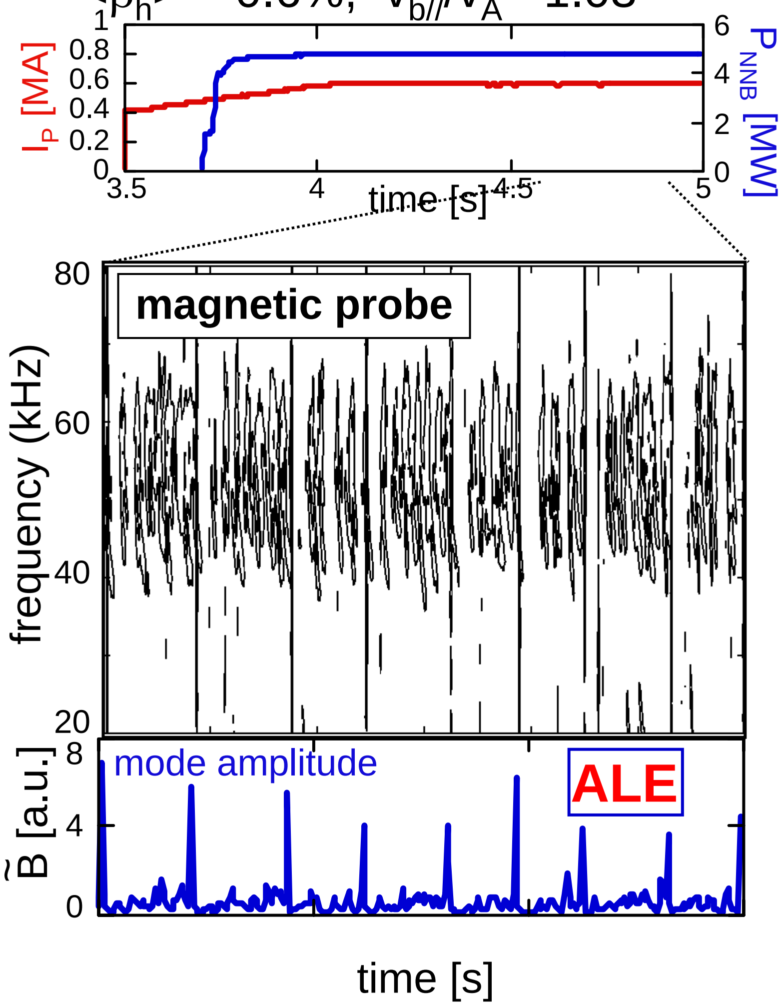
Objectives :

-Measure fast neutral particle fluxes and energy distribution

investigate energetic ion transport from change in neutron emission profile and enhanced neutral particle fluxes

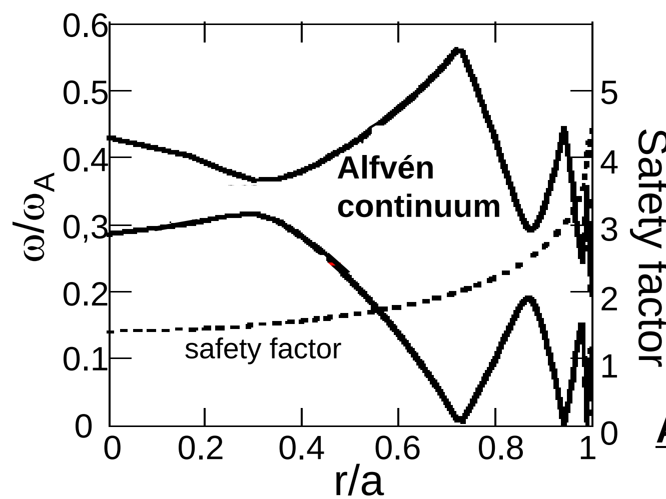
Bursting AE(Abrupt Large-amplitude Event, ALE) in Weak Shear Plasmas

E43014, I_P=0.6MA, B_T=1.2T
P_{NNB}~ 4.8MW, E_{NNB}~387keV
$<\beta_h>$ ~ 0.6%, $v_{b//}/v_A$ ~1.03



- Bursting modes called ALEs are observed in the frequency range of TAE during NNB injection.
- **mode amplitude of ALEs reaches $\tilde{B}_\theta/B_\theta$ ~10^{-4} at the first wall**
- Alfvén gap exist at r/a ~ 0.2-0.4

➡ It is considered that modes is localized in core region

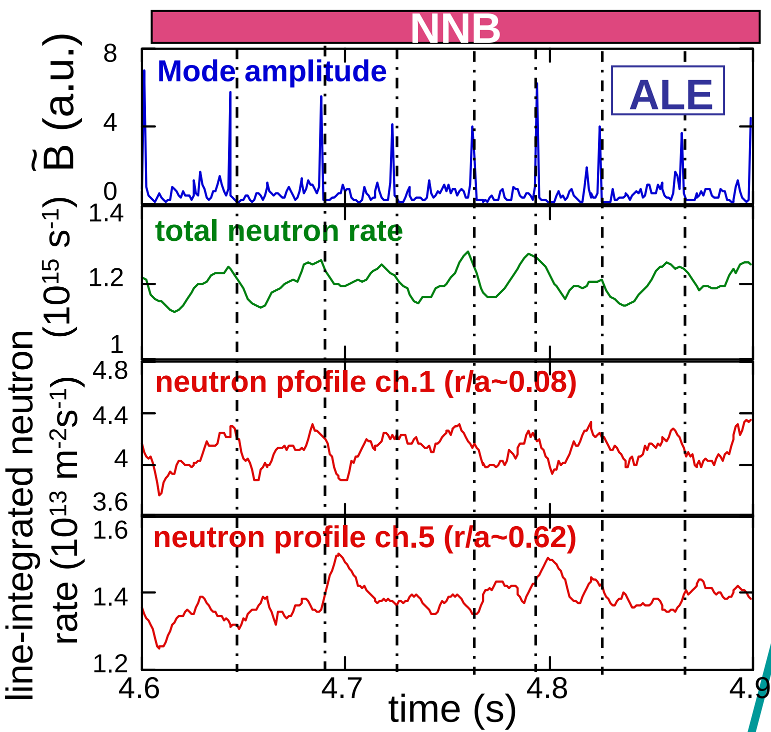


Alfvén continuum and safety factor

Change in neutron emission profile and energetic Ion density profile due to ALE

JT-60U

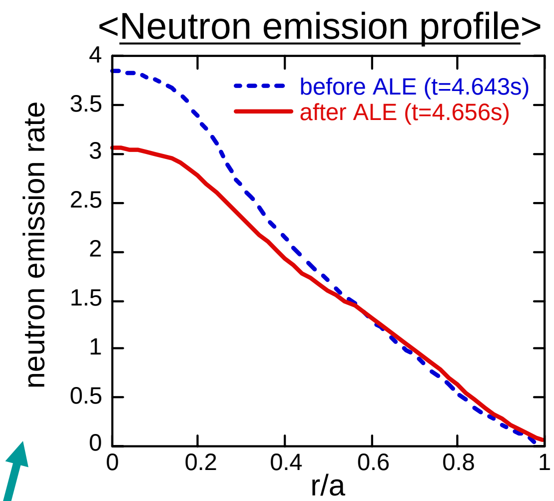
E43014 <Neutron Emission>

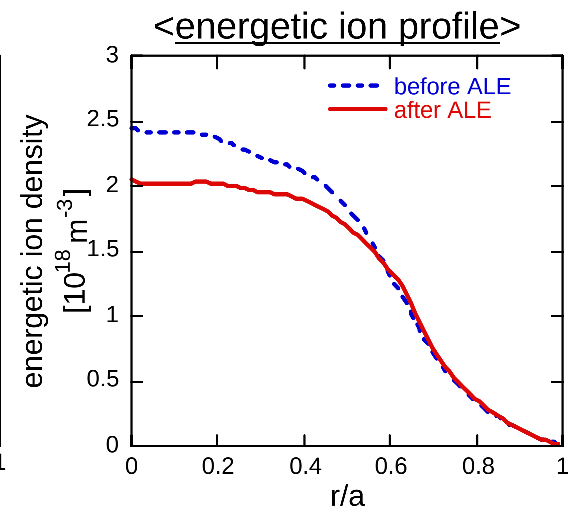


inner channels ---- decrease
outer channels ---- increase

Change in neutral emission profile

Change in energetic ion profile inferred from change in neutron emission profile taking into account fast neutral particle measurements.





Energetic ion reduced in central region (r/a < ~0.6), while slightly increased in peripheral region.

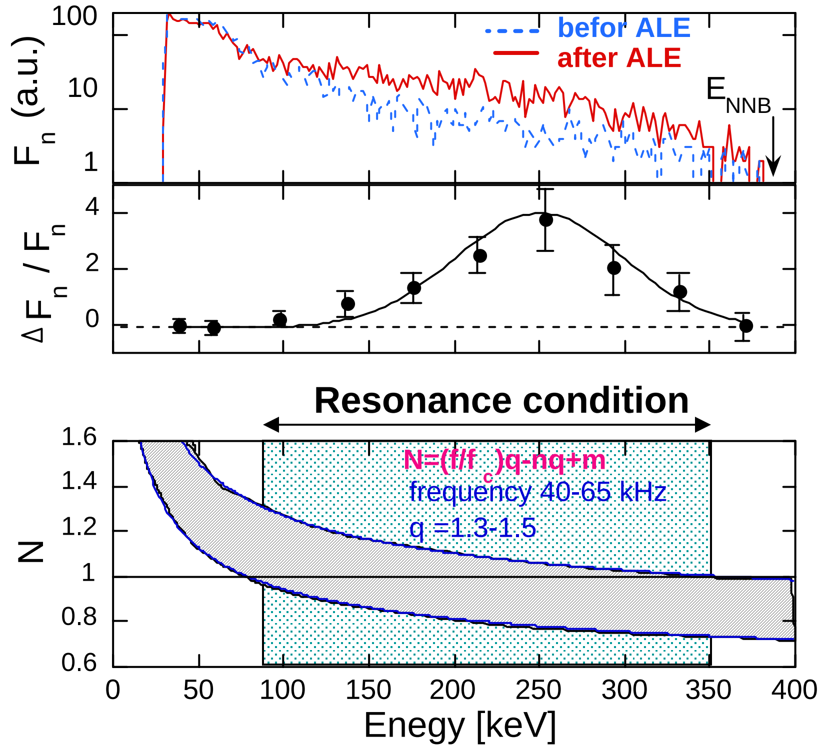
The total energetic ion population integrated over the volume is reduced by 4%

ALEs expel a significant energetic ion population from core to the outer region (redistribution and loss)

Change in energy distribution of neutral particle fluxes

JT-60U

- Detail of energy distribution of neutral particle fluxes has been measured.
- The energetic ions are neutralized through a charge exchange reaction with D^0 or C^{5+} in outer region



Enhance of neutral particle fluxes in

<u>limited energy range (100~370 keV)</u>

has been observed <u>for the first time</u>.

[Resonance condition with the mode]

(R. B. White *et.al.* Phys. Fluids 26 (1983) 2958)

$N = (f / f_c)\, q - nq + m = \text{integer}$

f = mode frequency (40 - 65 kHz)
q = safety factor (1.3 - 1.5)
n, m = troidal, poloidal mode number (1, 2)
F_c = troidal transition frequency of energetic ions

<u>Resonant energy range => 80 ~ 350 keV</u>

Energy region of enhanced neutral particle fluxes has agreed with that predicted form the resonant interaction between energetic ions and modes

Summary

- α-simulation experiment: fast ^{4}He measured in shear-reversed and monotonic-q(r) plasmas. ^{4}He losses - when orbit size Δ_f comparable to *a.*
- Simultaneous measurements of ^{4}He with E>1.7 MeV and D with E>500 keV
- Decrease of γ-rays from 5 MeV protons during "tornado" and TAE activity is interpreted as TAE-enhanced loss of protons with $\Delta_f \leq a$
- Time-resolved profile of ^{3}He ions (E>500 keV) measured simultaneously with AEs $\Rightarrow$ study with measured fast ion profiles becomes possible. No losses.
- A wide variety of AEs on MAST including "hole+clumps" and non-perturbative "chirping" modes. High-β suppresses TAEs and "chirping" modes.
- On JT-60U, Abrupt Large-amplitude Events (ALEs) excited by NNBI with E>360 keV ($V_{||}/V_A$~1.03) cause radial redistribution of fast ion profile in limited energy region (100 – 370 keV), with 4% losses.