EUROfusion

V Kiptily et al

Excitation of EAE and TAE modes by ^{3}He-ions of the MeV-energy range in hydrogen-rich JET plasmas

16th IAEA TM on Energetic Particles, Shizuoka City, Japan 3rd – 6th September 2019

CCFE
CULHAM CENTRE FOR FUSION ENERGY

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Acknowledgements

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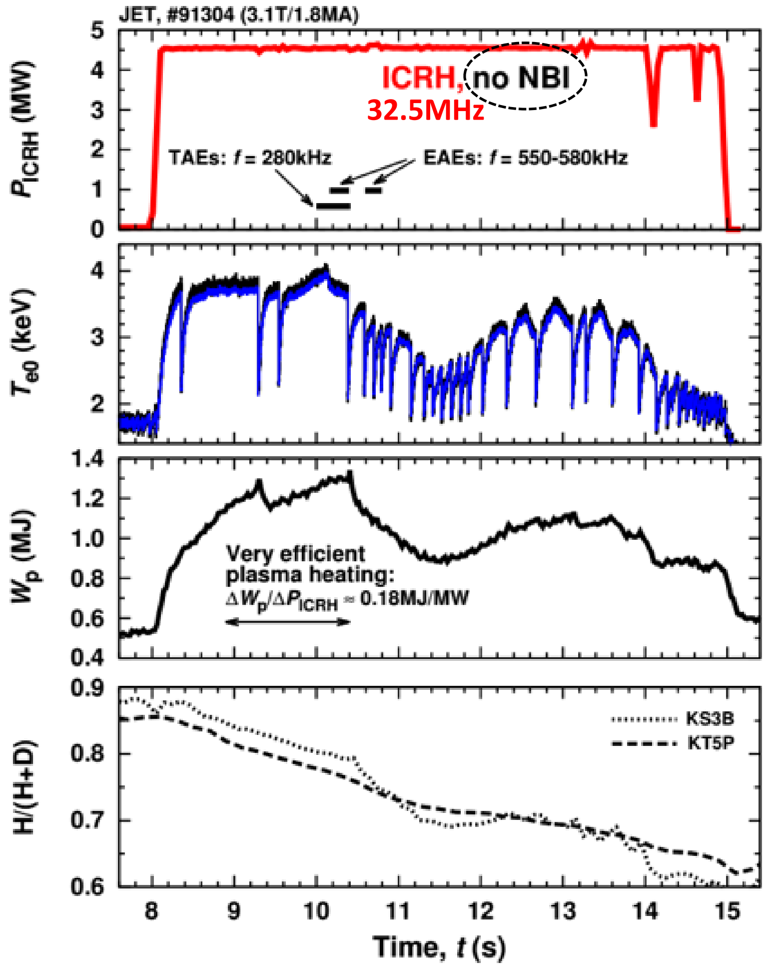
Outline

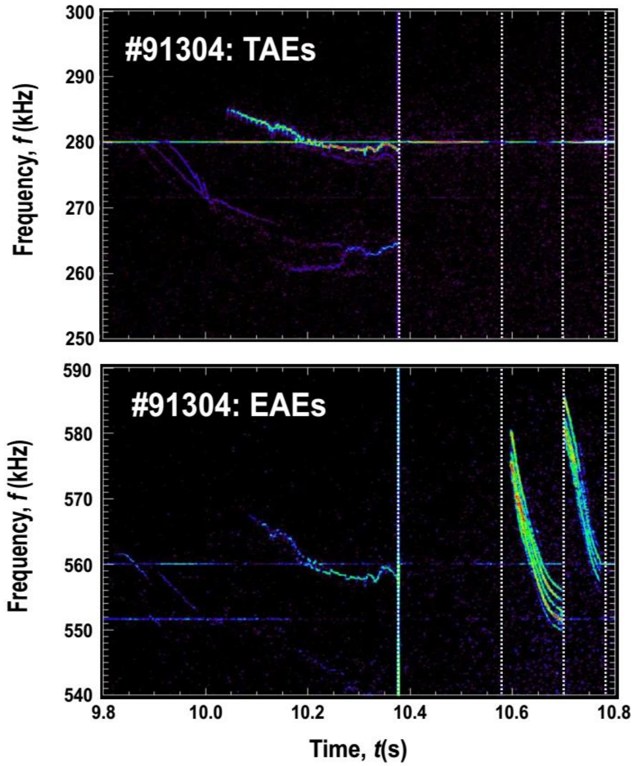
- Introduction
  - 3-ion ICRF plasma heating: D-(^{3}He)-H scheme
- Fast ion instrumentation
- Observation of the confined MeV-energy ^{3}He-ions
  - Gamma-ray spectra
  - Neutron rate
- TAE and EAE modes vs ^{3}He losses
- MHD analysis
- Summary and conclusions

D-(^{3}He)-H ICRF heating

B_T(T)	I_p(MA)	P_{ICRH} (MW)	n_e ($\times10^{19}$ m^{-3})	H, %
3.1	1.8	4.4	4.5	70-80

- The discharge with 3-ion ICRF heating scheme at very low ^{3}He-concentration (<1%)
- TAE and EAE modes were excited





16th IAEA TM EP, Shizuoka City, Japan, 3rd – 6th September 2019:
V Kiptily et al – Excitation of EAE and TAE modes by ^{3}He-ions

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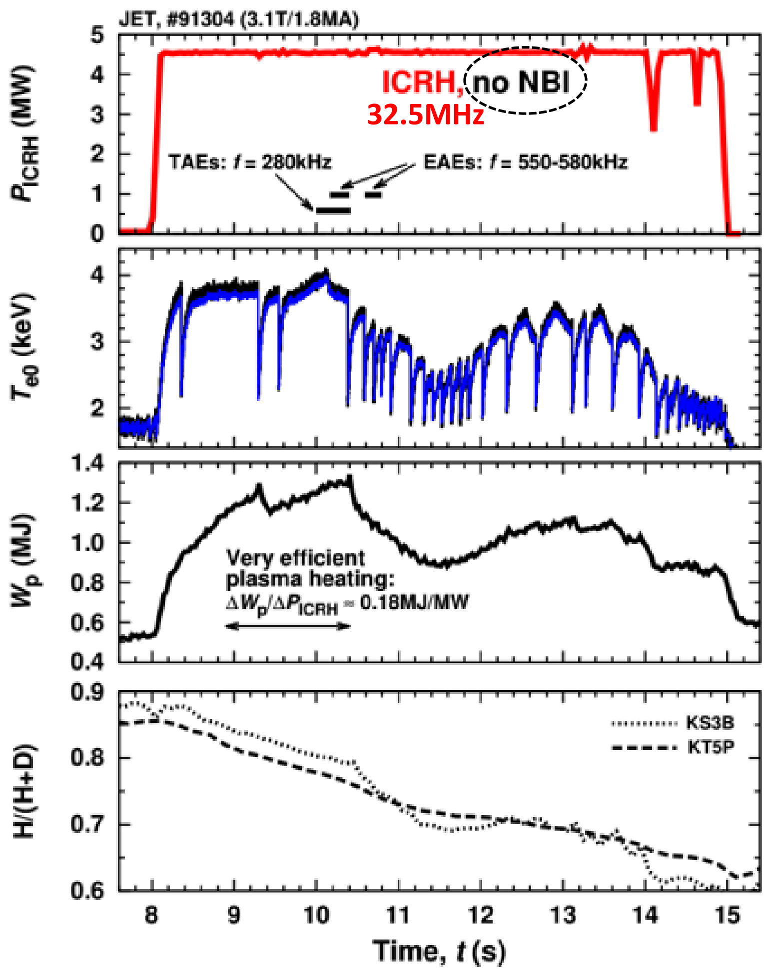
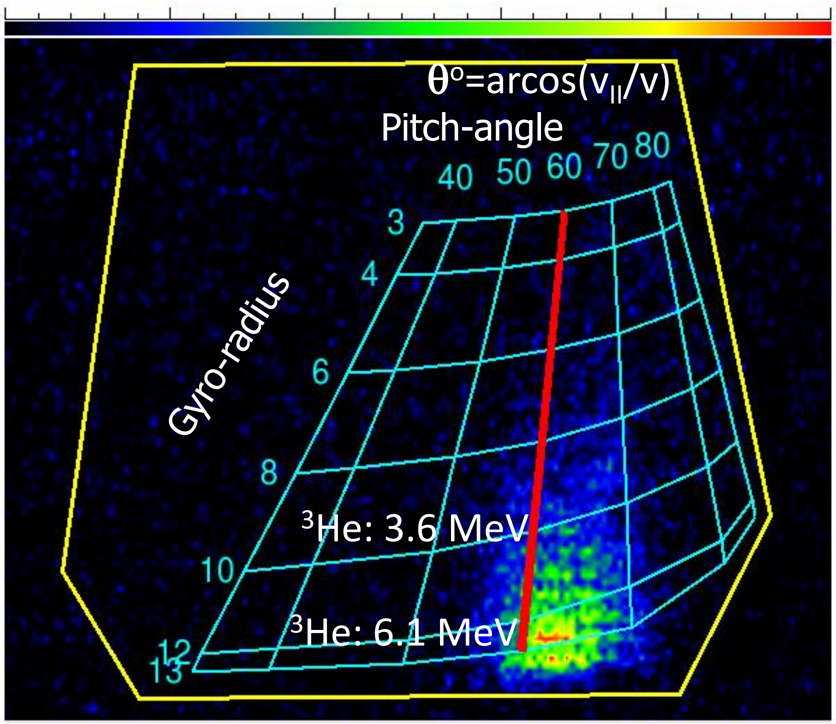
D-(^{3}He)-H ICRF heating

B_T(T)	I_p(MA)	P_{ICRH} (MW)	n_e ($x10^{19}$ m^{-3})	H, %
3.1	1.8	4.4	4.5	70-80

- The discharge with 3-ion ICRF heating scheme at **very low ^{3}He-concentration** (<1%)
- Losses of extremely energetic ^{3}He-ions were observed with FILD during the discharge





JET

3-ion ICRF heating schemes

Target plasma: two (or more) main ion species with different ω_{ci} (i.e. H and D)

→ $|E_+|$ wave field strongly enhanced in the vicinity of mode conversion layer(s)

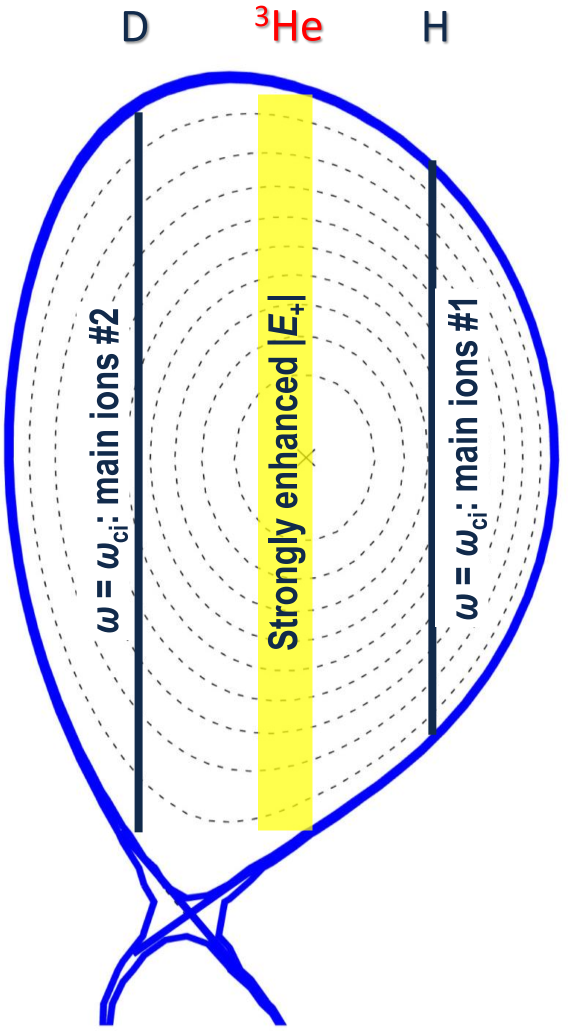
Strong wave damping can occur in this region by ions that fulfill the resonance condition $\omega \approx \omega_{ci} + k_{||}v_{||}$

Resonant ions: small number of ions, which can be either

- main ions with large $v_{||}$, e.g. NBI ions
- minority ions with $(Z/A)_2 < (Z/A)_3 < (Z/A)_1$
  i.e. $1/2 < 2/3 < 1/1$

3-ion ICRF schemes: demonstrated as a very efficient technique for fast-ion generation and plasma heating on Alcator C-Mod, AUG and JET

Y. Kazakov et al., Nature Physics (2017)
M. Mantsinen et al., EPS-2019



Fast ion instrumentation

Gamma-rays

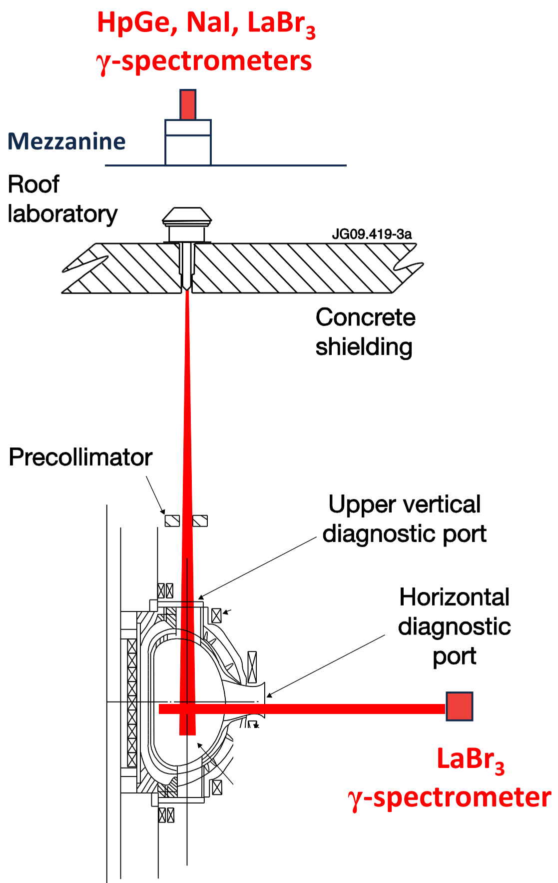
- γ-ray emission is produced due to nuclear reactions between fast ions, fuel and main impurities (i.e. Be) in the plasma
- Nuclear reactions used in JET for confined fast ion studies:

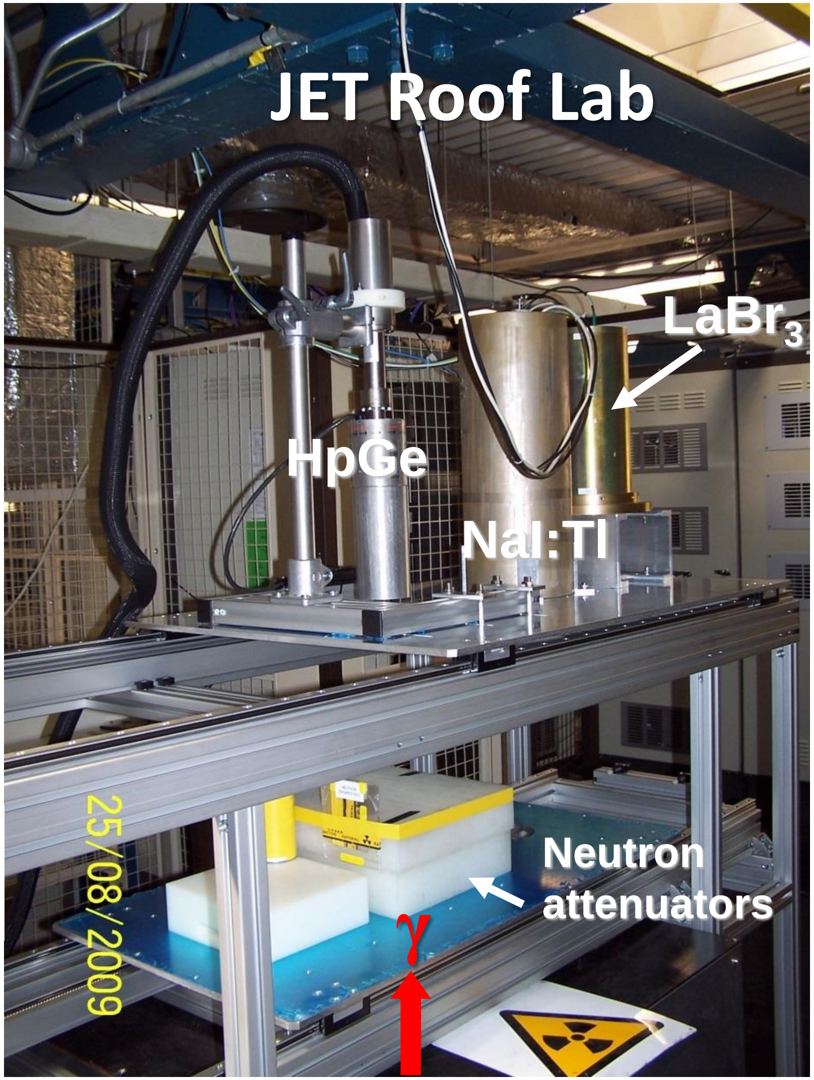
Protons	Deuterons	Tritons	^{3}He-ions
$D(p,\gamma)^3He$	$^9Be(d,p\gamma)^{10}Be$	$D(t,\gamma)^5He$	$D(^3He,\gamma)^5Li$
$T(p,\gamma)^4He$	$^9Be(d,n\gamma)^{10}B$	$^9Be(t,n\gamma)^{11}B$	$^9Be(^3He,p\gamma)^{11}B$
$^9Be(p,\gamma)^{10}B$	$^{12}C(d,p\gamma)^{13}C$	$^{12}C(t,\gamma)^{15}N$	$^9Be(^3He,n\gamma)^{11}C$
$^9Be(p,p'\gamma)^9Be$		$^{12}C(t,n\gamma)^{14}N$	$^9Be(^3He,d\gamma)^{10}B$
$^9Be(p,\alpha\ \gamma)^6Li$		$^{12}C(t,\alpha\gamma)^{11}B$	$^{12}C(^3He,p\gamma)^{14}N$
$^{12}C(p,p'\gamma)^{12}C$			

- α-particle diagnosis is based on the $^9Be(\alpha,n\gamma)^{12}C$ reaction

Kiptily et al NF **43** (2002) 999

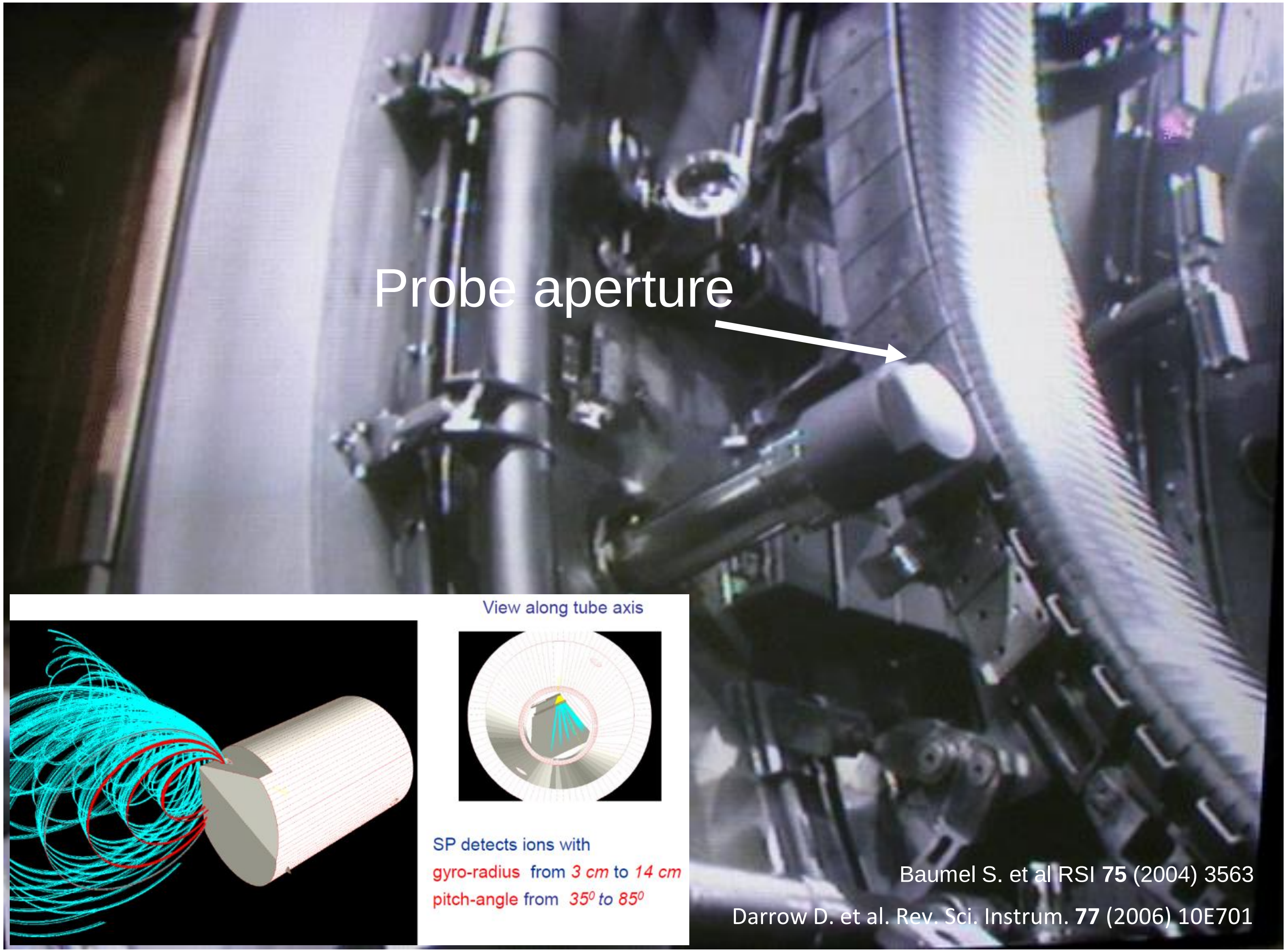
JET γ – ray spectrometers





Kiptily et al NF **50** (2010) 084001
Tardocchi et al PRL **107** (2011) 205002
Nocente et al NF **52** (2012) 063009
Nocente M et al IEEE Trans. Nucl. Sci. **60** (2013)

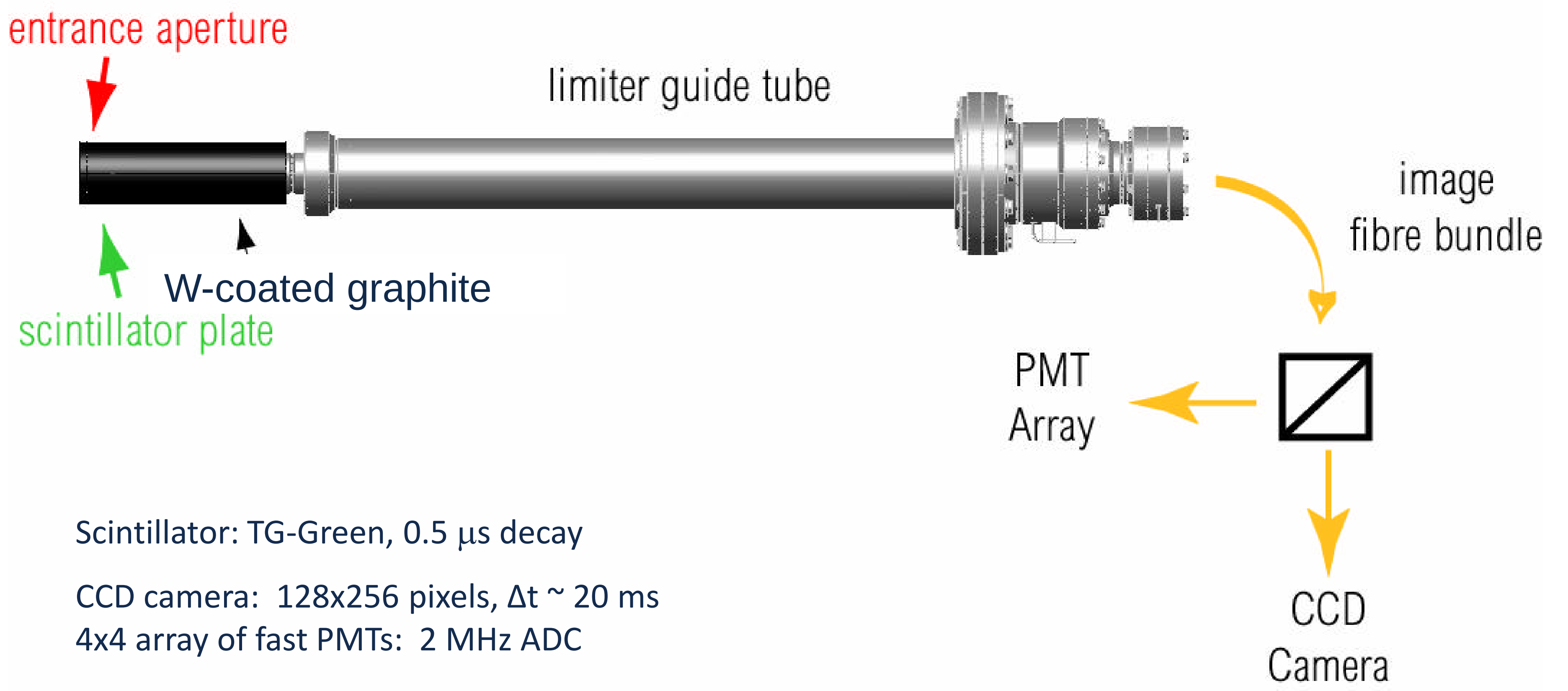
Fast Ion Loss Detector



Baumel S. et al RSI **75** (2004) 3563

Darrow D. et al. Rev. Sci. Instrum. **77** (2006) 10E701

JET FILD setup

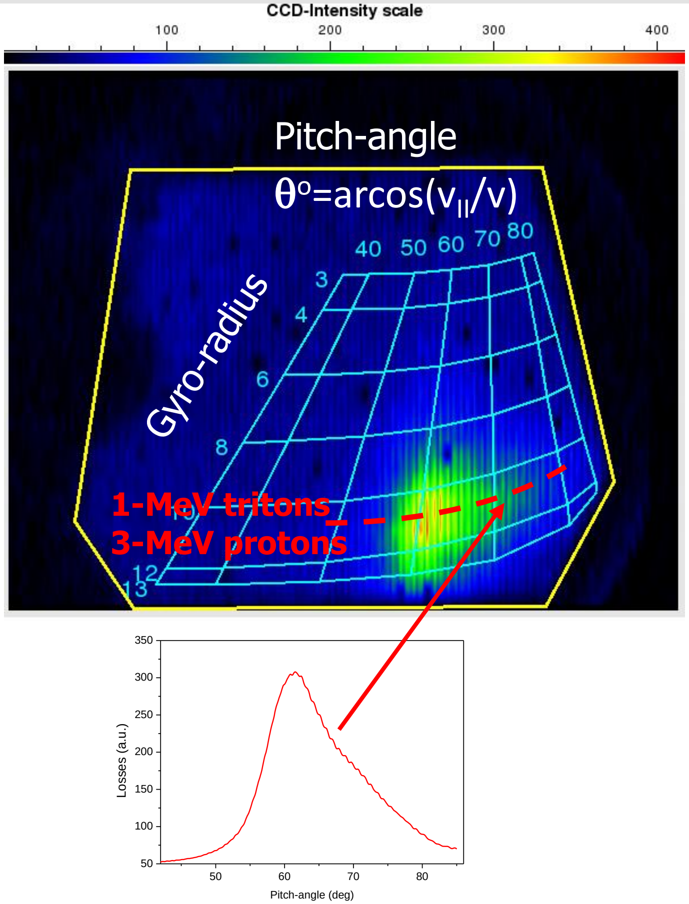


Scintillator: TG-Green, 0.5 μs decay

CCD camera: 128x256 pixels, Δt ~ 20 ms
4x4 array of fast PMTs: 2 MHz ADC

Kiptily et al Nucl. Fusion **58** (2018) 014003

CCD camera and PMTs

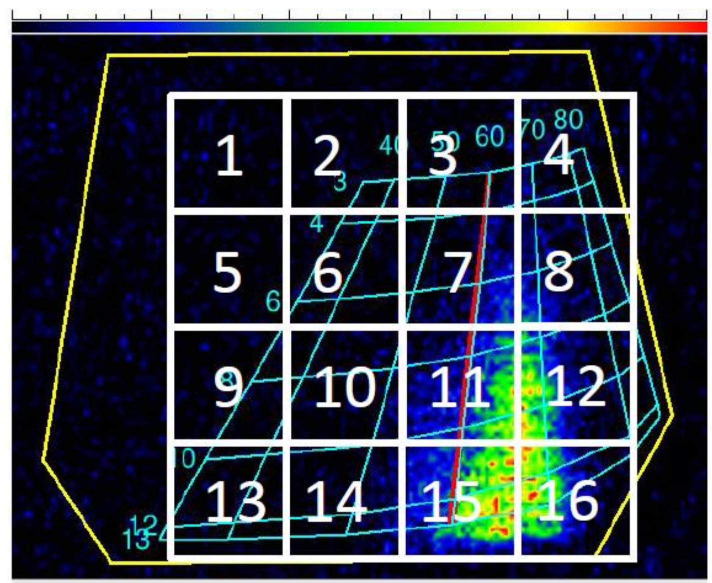


A typical footprint of the fusion t and p prompt losses during the NBI plasma heating

D + D => t(1 MeV) + p(3 MeV)

The grid (R_{gyr}, θ) on the scintillator probe calculated using EFIT equilibrium

Footprint of ICRH losses and areas of the scintillator, which are seen by PMTs

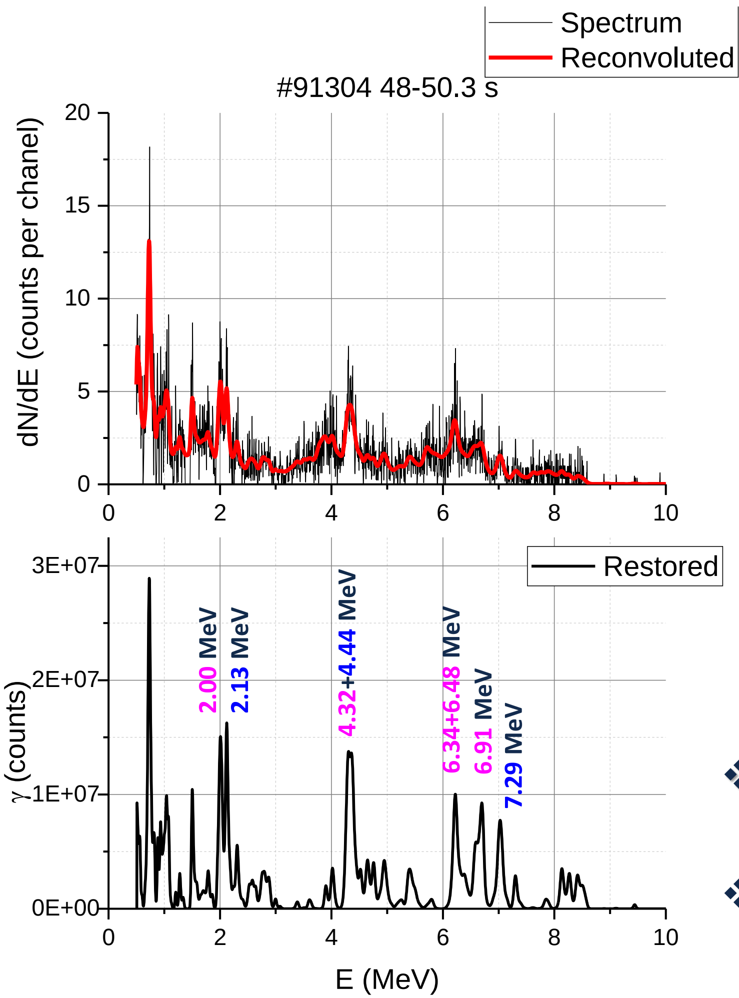


The major radius at the ion bounce reflection and the pitch-angle of the grid are related by

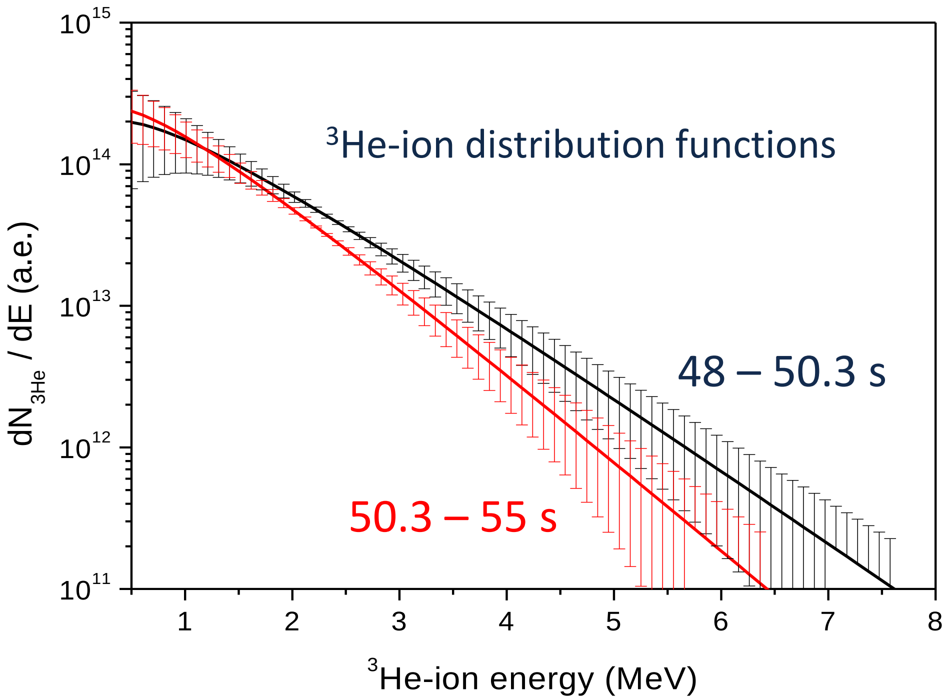
$$R(\theta)=R_{FILD}\sin^2(\theta)$$

Observation of the confined MeV-energy ^{3}He-ions

γ – ray spectra



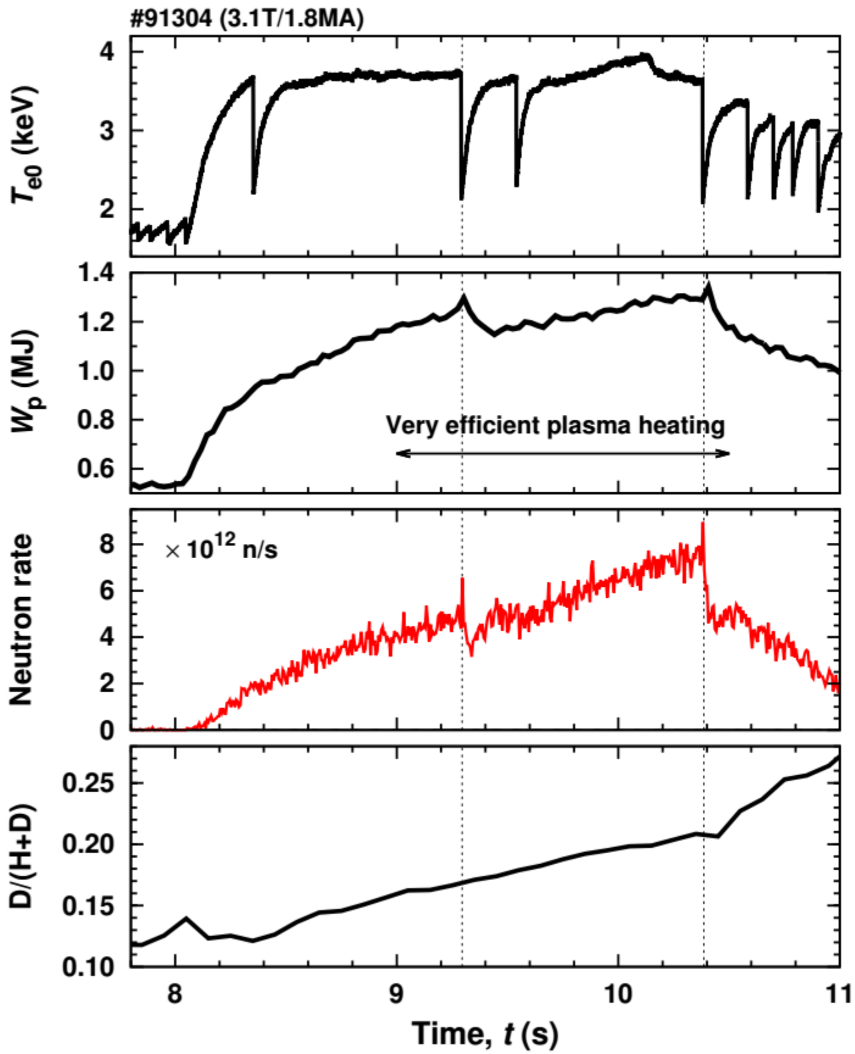
$^{9}Be(^{3}He, n)^{11}C$ & $^{9}Be(^{3}He, p)^{11}B$



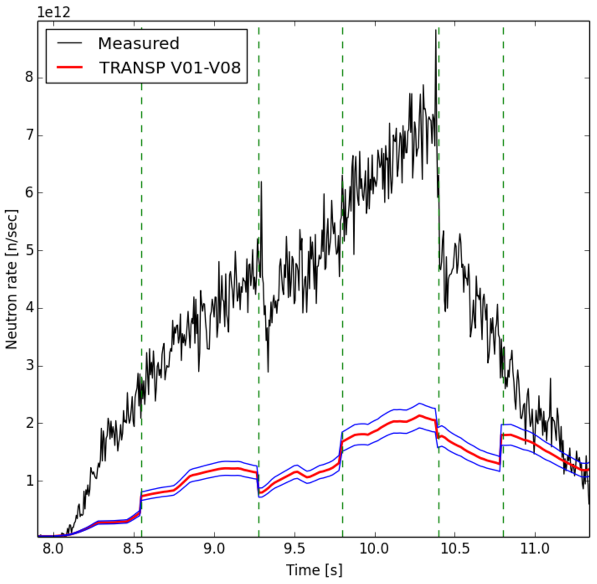
- $^{9}Be + ^{3}He$ reactions have been identified:
  => **E_{3He}>0.9 MeV** is needed
- Analysis of the γ-spectra has been carried out with DeGaSum code by means of deconvolution procedure considering the detector response function and background

Shevelev et al Nucl. Fusion 53 (2013) 123004

Neutron rate

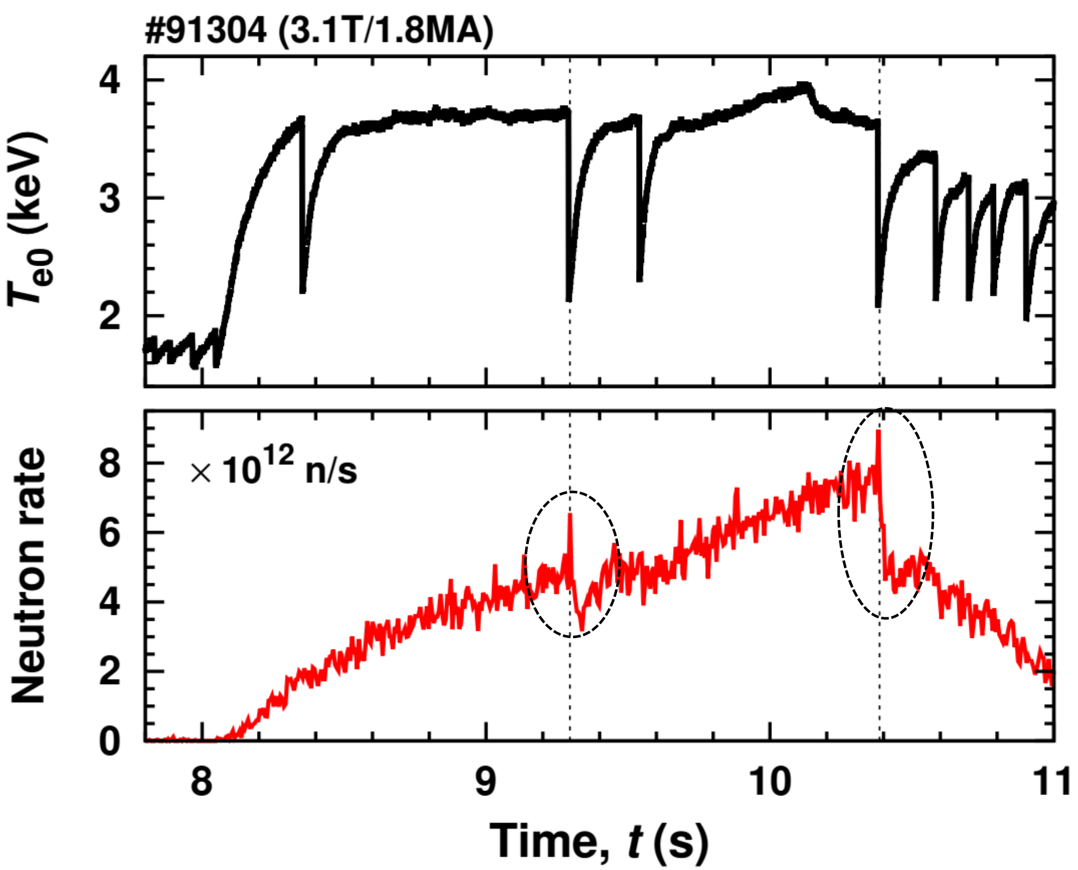


- During the both 1st and 2nd monster sawteeth, **neutron rate** grows dramatically
- The **TRANSP** calculations show that the experimental rate ~2 – 4 times higher than expected in the plasma with $T_i=T_e$



- To increase the neutron rate so high:
  - **Knock-on effect** – D(D,n)^{3}He reaction with energetic D-ions due to the ^{3}**He-ion elastic** scattering (Coulomb and nuclear)
  - ^{9}**Be(**^{3}**He, n)**^{11}**C** – reaction with MeV-energy ^{3}He-ions

Neutron rate spikes



Sharp transient spikes of the neutron rate at the sawtooth crashes can be caused by

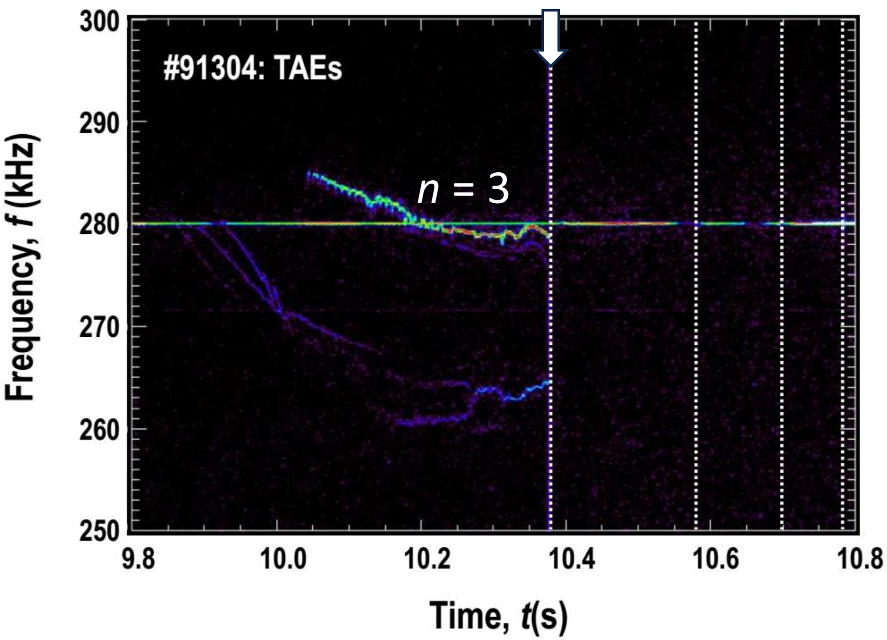
- ✓ D(D,n)^{3}He fusion reaction with D-ions accelerated by electric field generated in ST crash (a reconnection)
- ✓ ^{9}Be(^{3}He,n)^{11}C reaction due to massive escape of MeV-energy ^{3}He-ions to the first wall

TAE & EAE modes vs ^{3}He losses

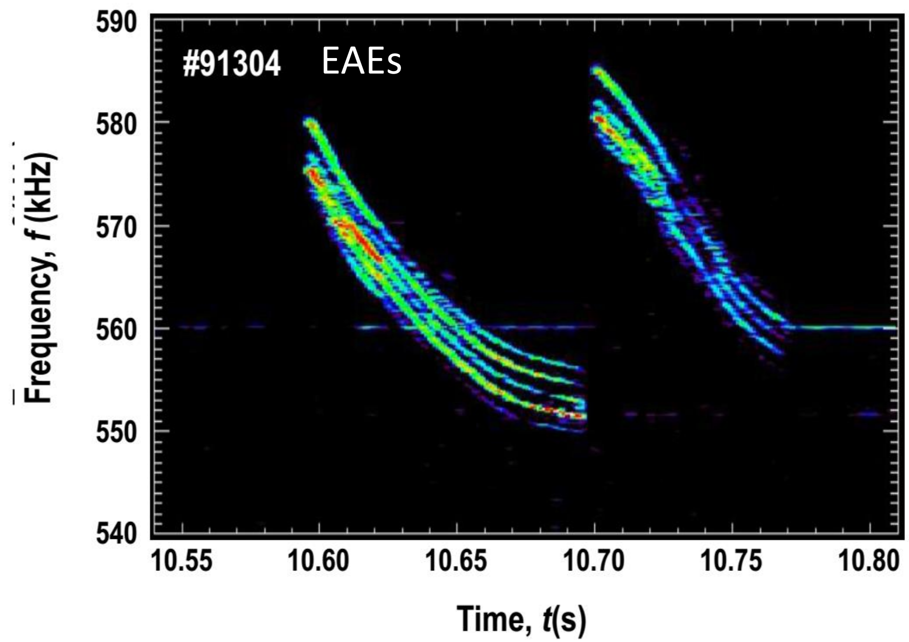
TAE & EAE modes

Toroidal AE: n = 2, 3 and 4 at $f \approx$ 280 kHz

ST: q=1 at *R* ≈ 3.2m



Elliptic AE: n= ±1, ± 3 & ± 5 at $f \approx$ 560 kHz



Fast magnetic probes:

@10.0-10.38s: TAEs and weak EAEs

@10.6-10.8s: strong EAEs

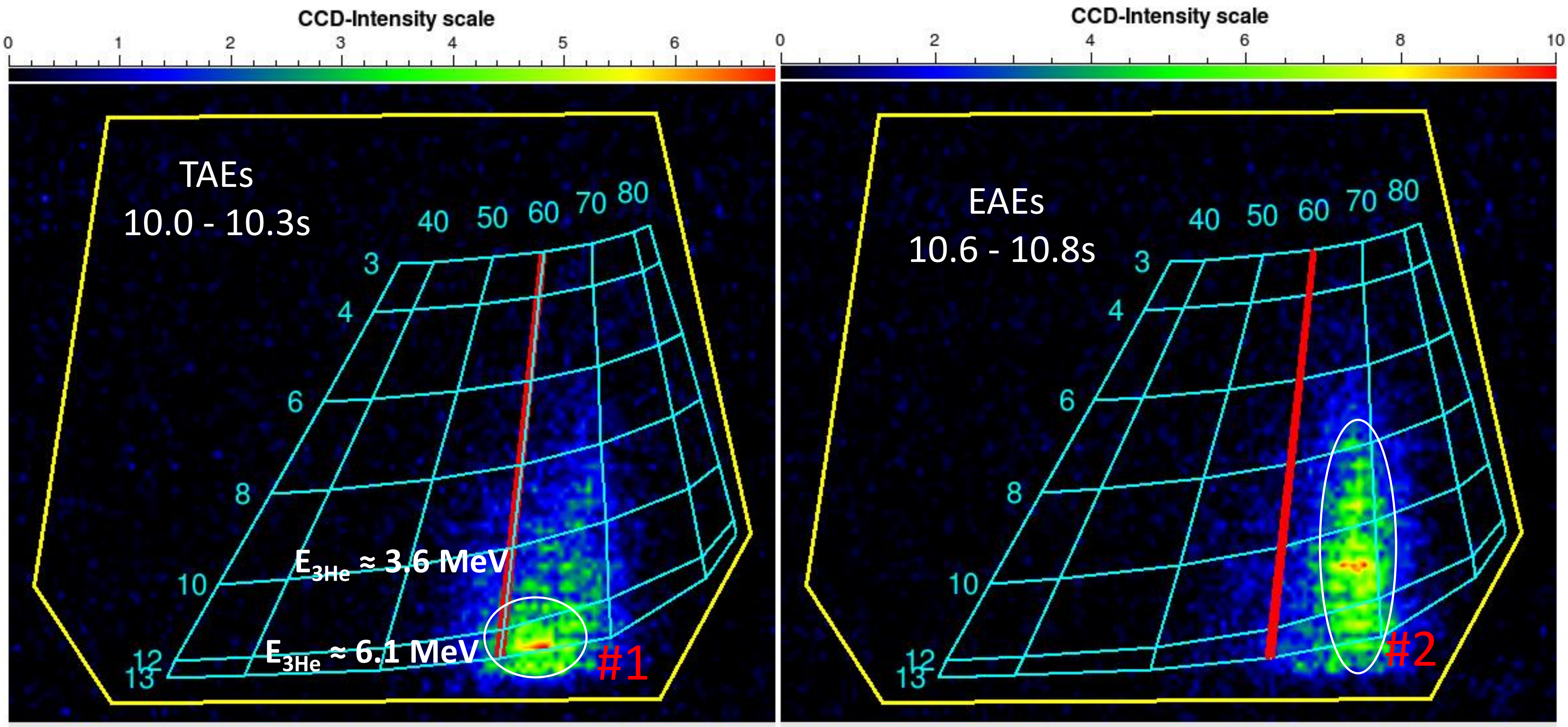
Mode localization from the reflectometer:

TAEs (tornados): *R* < 3.25m

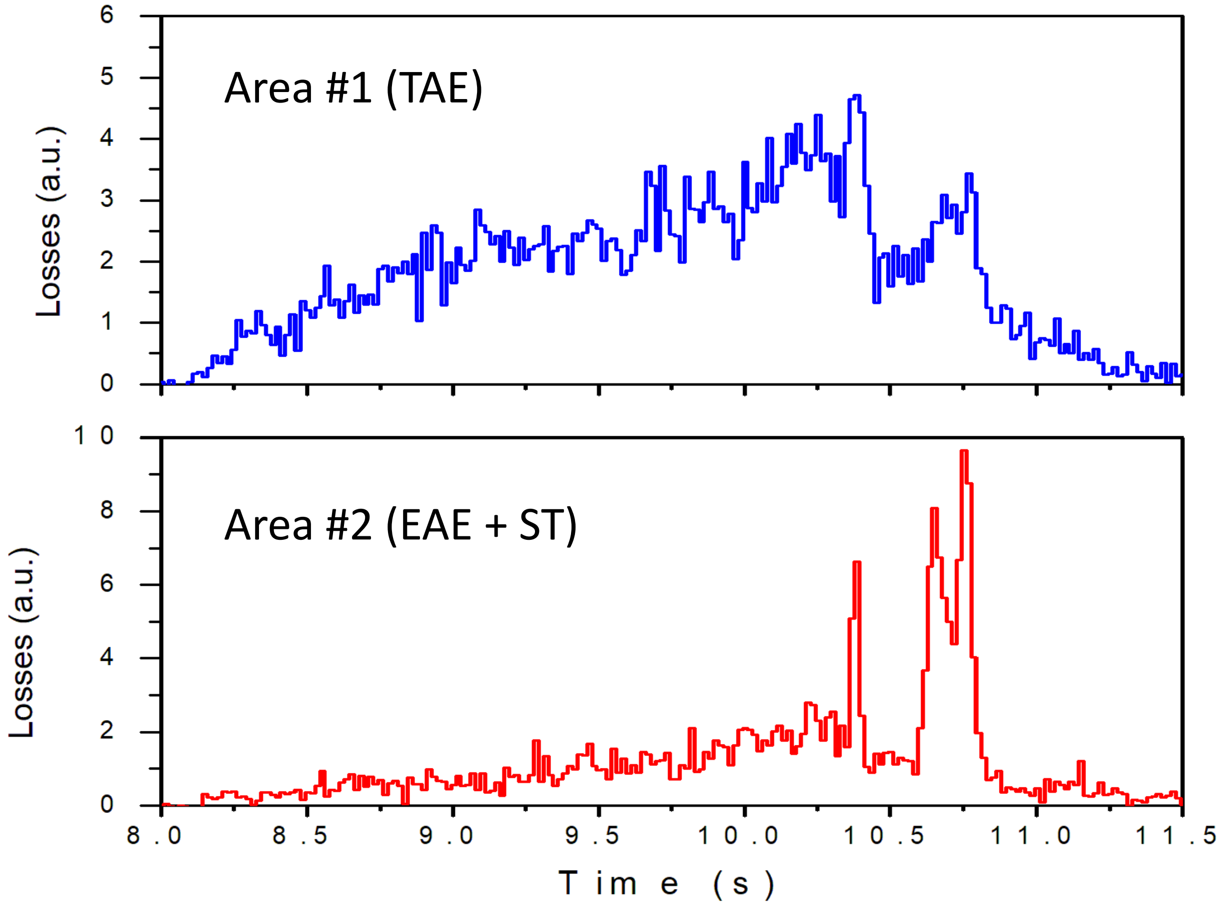
EAEs: *R* = 3.25m => 3.45m

Fast ^{3}He-ion loss footprints

Energetic ^{3}He-ion losses were observed during both TAE and EAE mode periods



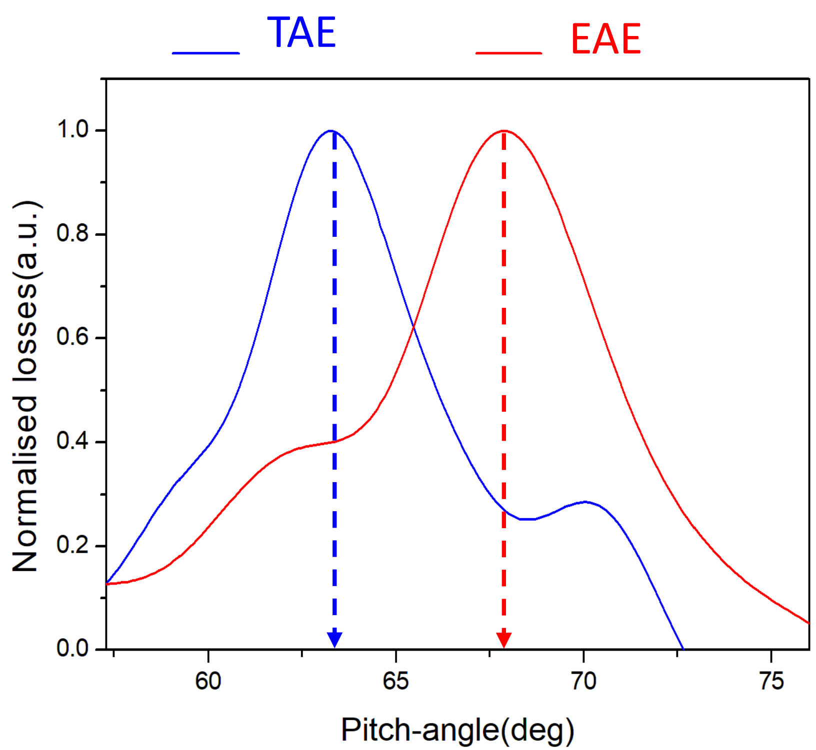
Fast ^{3}He-ion loss evolution



Waveforms of losses related to the scintillator areas: a strong correlation with appearance of the TAE and EAE modes in the discharge

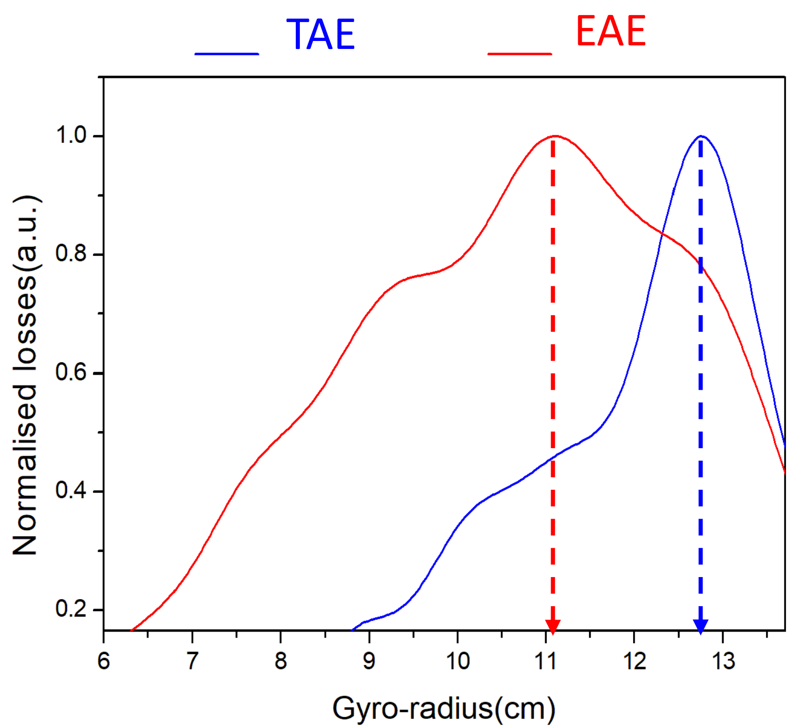
Fast ^{3}He-ion loss distributions

Pitch-angle distributions



$\theta^{TAE} \approx 63^0$ $\theta^{EAE} \approx 68^0$

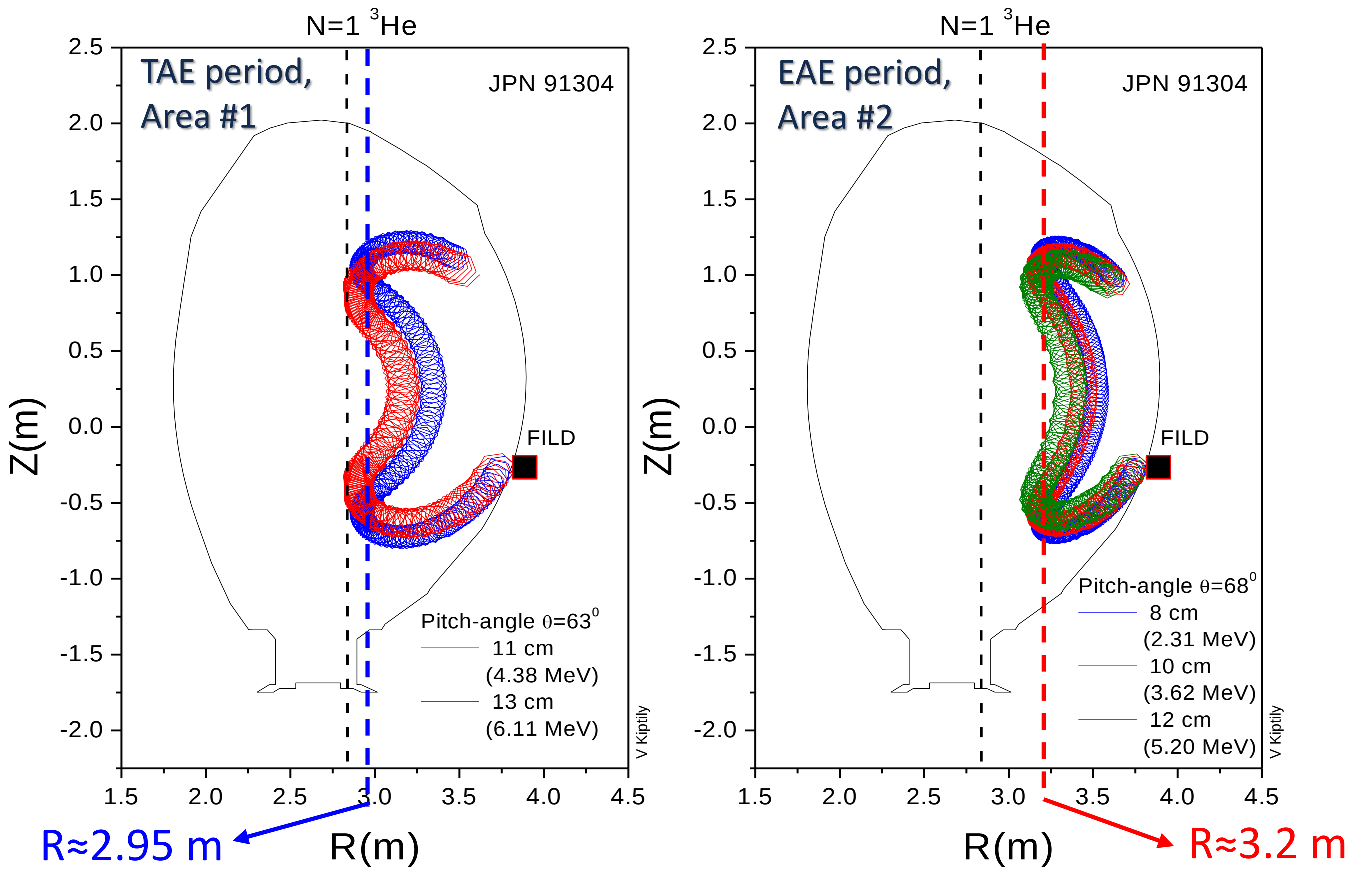
Gyro-radius distributions



$R_{gyr}^{EAE} \approx 11$ cm => 4.4 MeV

$R_{gyr}^{TAE} \approx 13$ cm => 6.1 MeV

Fast ^{3}He-ion loss orbits

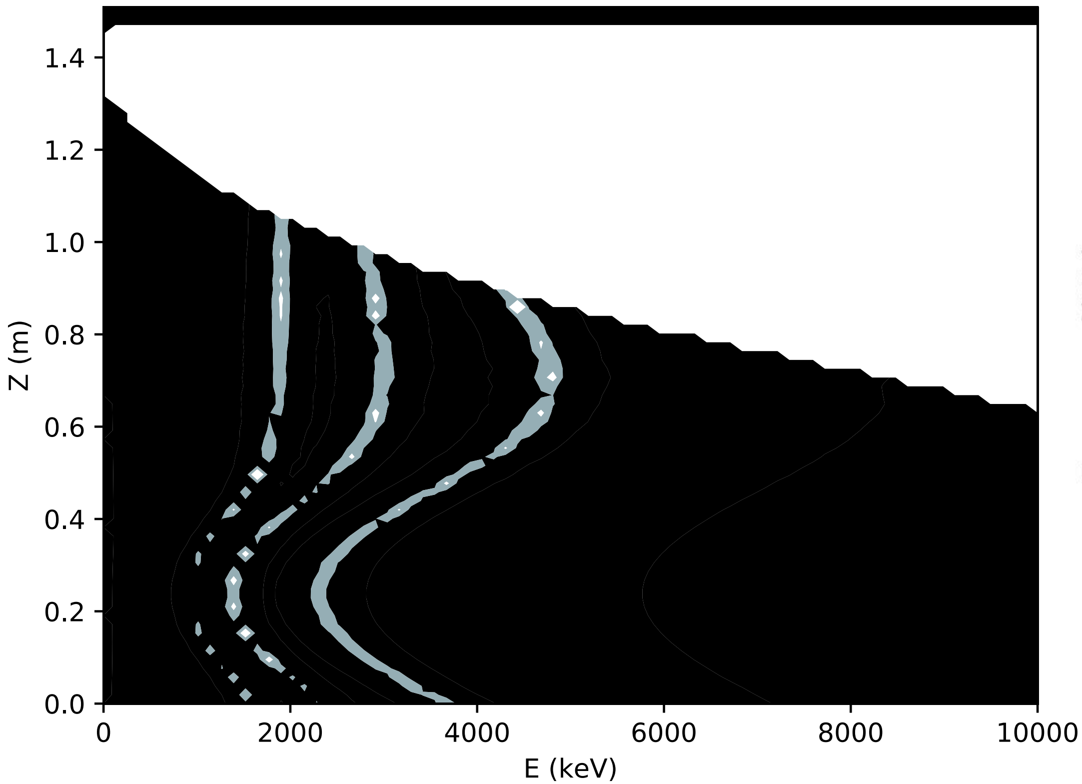


- ^{3}He-ion orbits calculated back-in-time from the footprints on the FILD scintillator plate
- TAE modes interact with core-localised ions; EAE modes – with ions on the low-field side

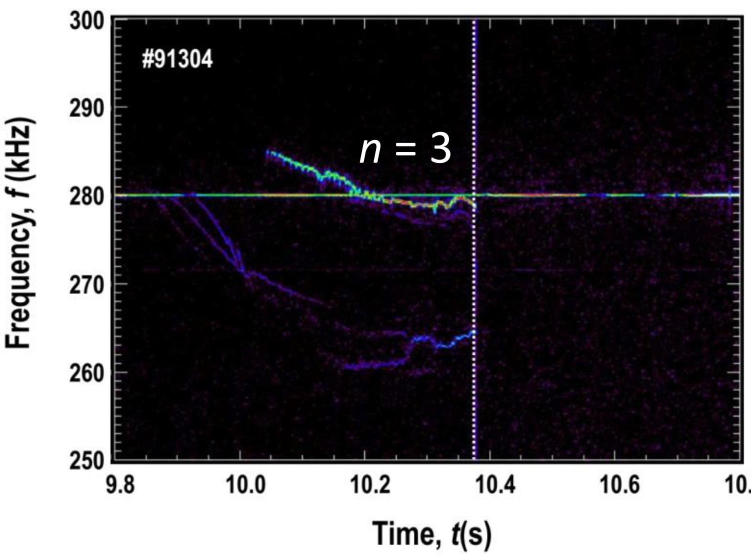
MHD analysis

TAE excitation

The resonance condition $\omega = n\omega_\phi - p\omega_\theta$ is plotted below



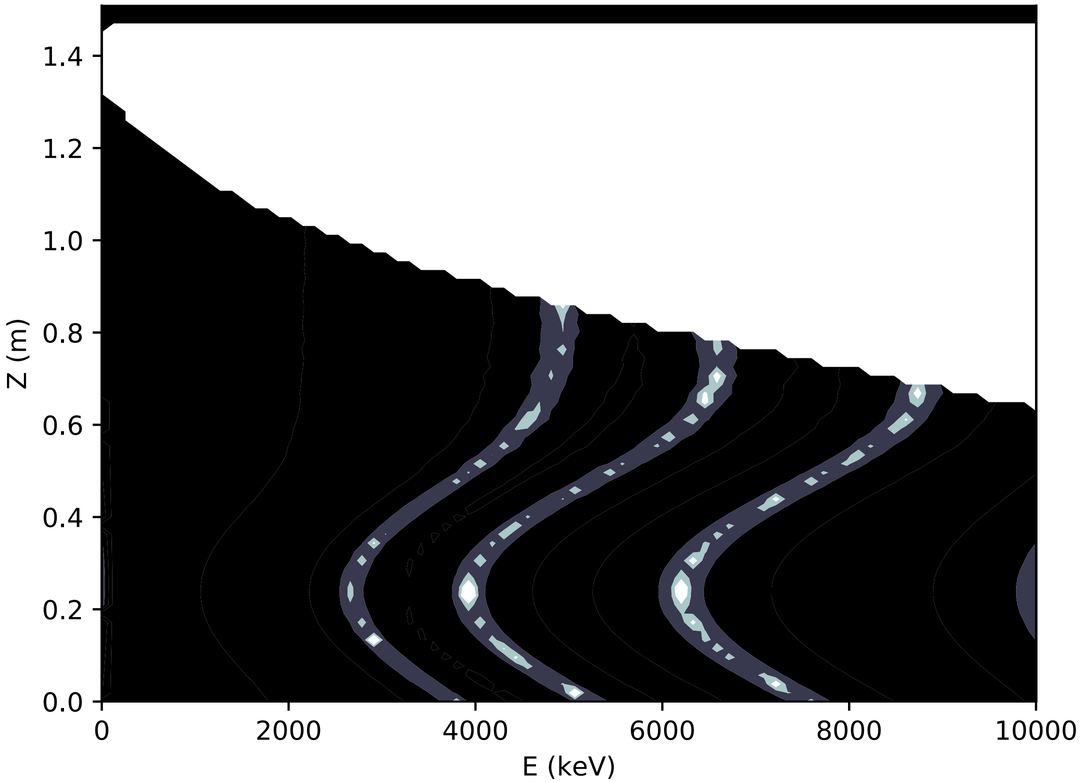
Magnetic spectrogram, f ~ 280kHz



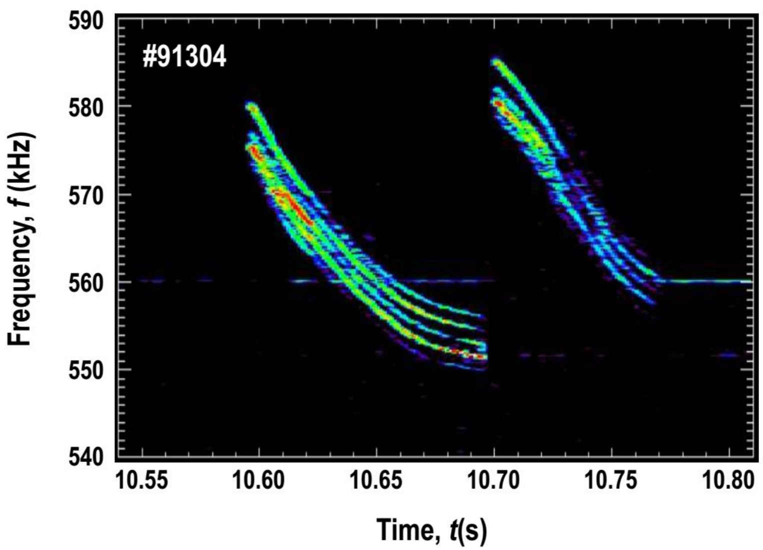
A resonance map for TAE with frequency and toroidal number $f = 280kHz, n = 3$, which indicates energies 3 – 4 MeV could excite the mode

EAE excitation

A resonance map for $f = 560\ kHz, n = 3\ \ p = [-2, -1, 0]$



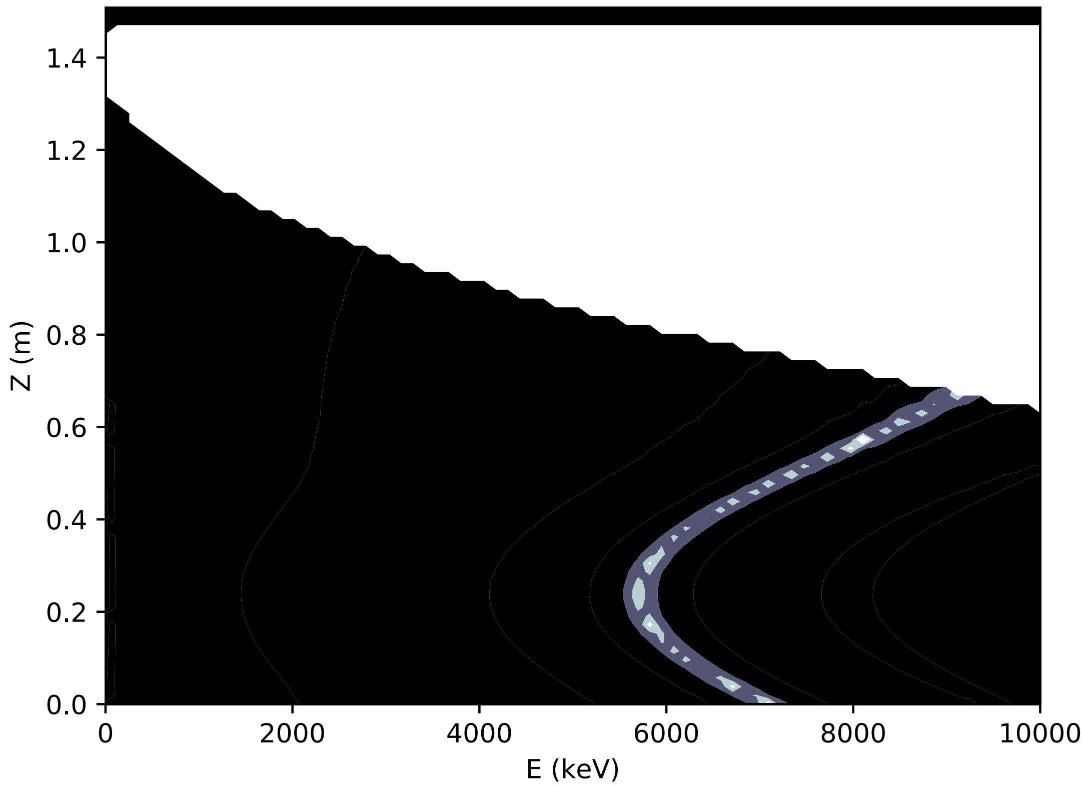
Magnetic spectrogram, f ~ 550-580kHz



The strongest wave particle interaction will occur for *p=0*, which implies energies of 6 MeV to excite the *n=3* modes with $560 kHz$

EAE excitation

A resonance map for $\mathrm{f} = 560\ kHz, n = 1\ \ p = [-2, -1, 0]$



n=1 modes with $560kHz$ are much more difficult to excite, only *p=-2* appearing at these energies

Summary and conclusions

- **3-ion ICRF heating scheme with ^3He-minority (< 1%)**
  - efficient heating of H-D mixed plasmas with multi-MeV ^3He-ions
- **JET pulse #91304 (3.1T/1.8MA): P_{ICRH} = 4.4MW, no NBI, X[H] ≈ 70-80%**
  - Efficient plasma heating: L-mode with $\tau_E/\tau_{E,\text{ L-mode}} \approx 1.4$ ($H_{98} \approx 0.84$)
  - Long-period sawteeth (~900ms)
  - γ-ray spectra show ^3He + ^9Be nuclear reactions
  - Anomalously high neutron rate
  - FILD observations: presence of ^3He-ions with energies 3-6MeV and higher
  - Excitation of TAE (tornados) and EAE modes observed
    - TAEs, f = 280kHz: excited by ~2-3MeV ^3He-ions
    - EAEs, f = 560kHz: requires more energetic ^3He-ions (~6MeV)
    - Localization of modes consistent with FILD and reflectometer observations
- **Highlight for future studies and applications**

  Plasmas with core electron heating, including a small population of MeV-range ^3He ions:
  - Mimicking the conditions representative for ITER plasmas
  - Contribute to the understanding of the impact of energetic ions on the plasma turbulence, in particular, the impact of alphas in ITER

    [J.Garcia et al., *PoP* 25 (2018) 055902]
  - Contribute to the understanding of fast-ion interaction with MHD modes

Thank you for your attention