Unstable beta-induced ion temperature gradient (BTG) eigenmodes in JET plasmas with ITB and elevated monotonic q-profiles.

Nicolas Fil[1,2]

S.E. Sharapov[1], M. Fitzgerald[1], G.J. Choi[3], Z. Lin[3], R.A. Tinguely[2], H.J.C. Oliver[1], K.G. McClements[1], P.G. Puglia[4], R.J. Dumont[5], D. Keeling[1], A.C.A. Figueiredo[6], M. Porkolab[2], J. Mailloux[1], E. Joffrin[5], and JET Contributors*

1 CCFE Culham Centre for Fusion Energy
2 PSFC
3 UCI
4 EPFL
5 cea Cadarache
6 ipfn Instituto de Plasmas e Fusão Nuclear
* JET

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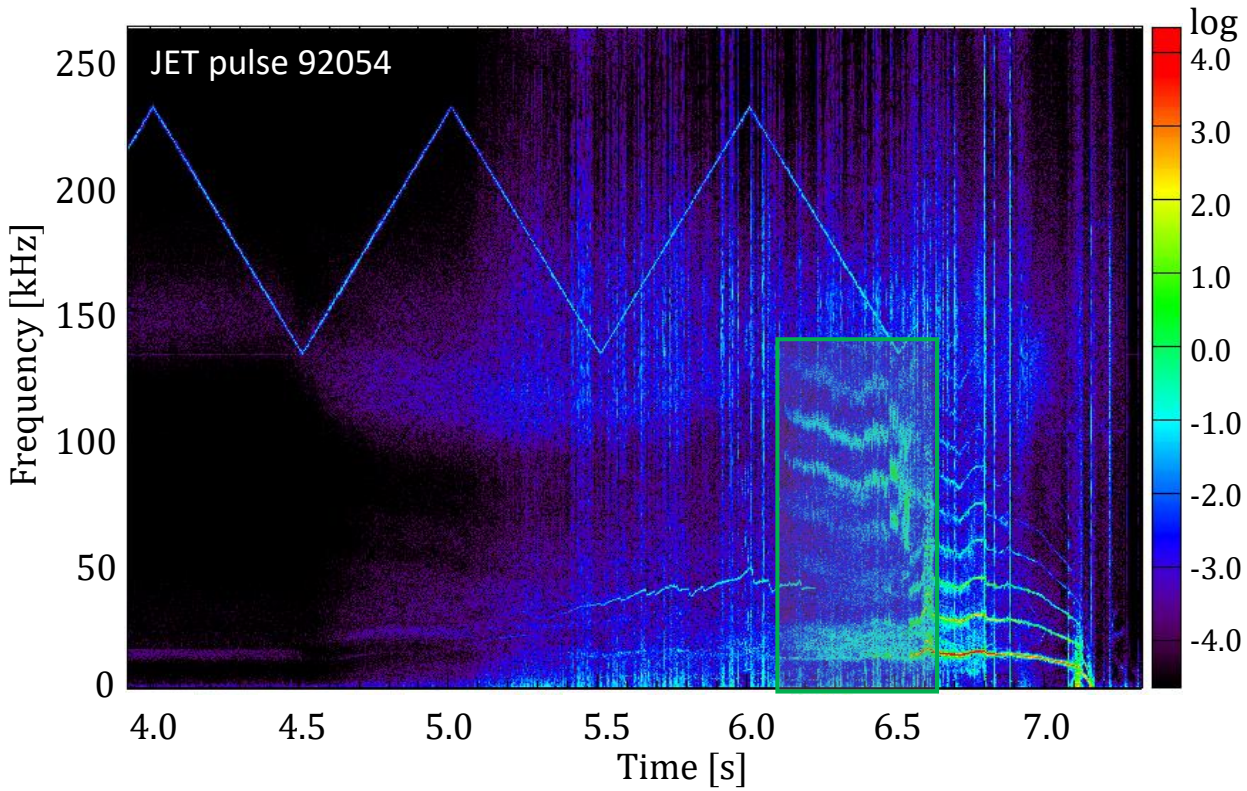
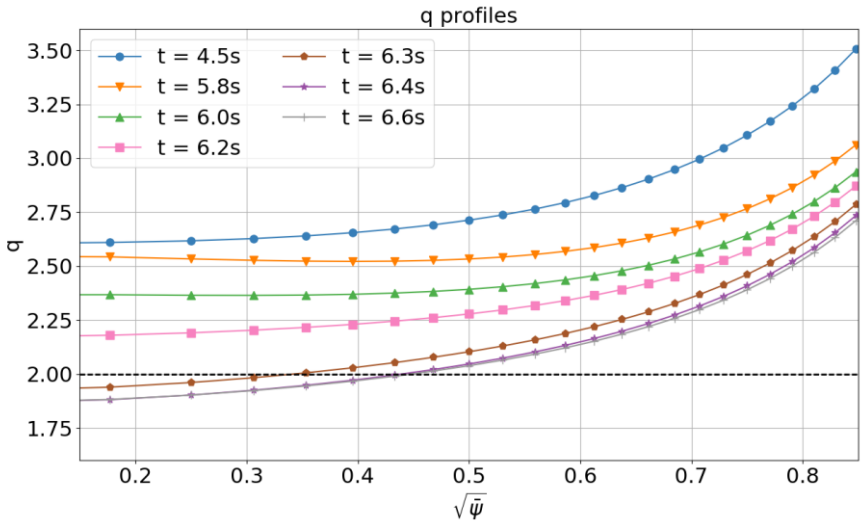
Interpretation of low-frequency electromagnetic (EM) perturbations in JET.

Modes in the sub-TAE frequency range in JET plasma with elevated q-profile

JET pulse 92054





TAE frequency range

Present work: study these observed EM modes

Can we match experimental observations vs analytic theory vs simulations?

- JET pulse 92054: an excellent example
  - Clear observations of the EM modes on many diagnostics.
  - Extensively studied in [1]
- Identification of experimental characteristics of the EM modes.
- Comparison with BTG analytic theory.
- Comparison with gyrokinetic (GK) simulations.
- BTG modes saturation may correlate with neutron-rate roll-over.

[1] Dumont et al., Nuclear Fusion, 58 (2018)

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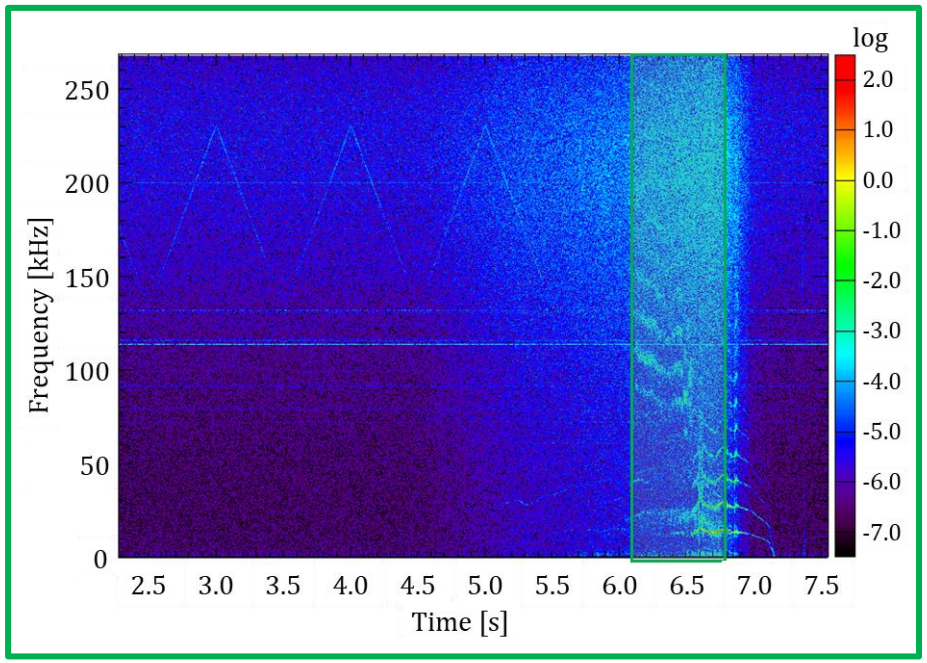
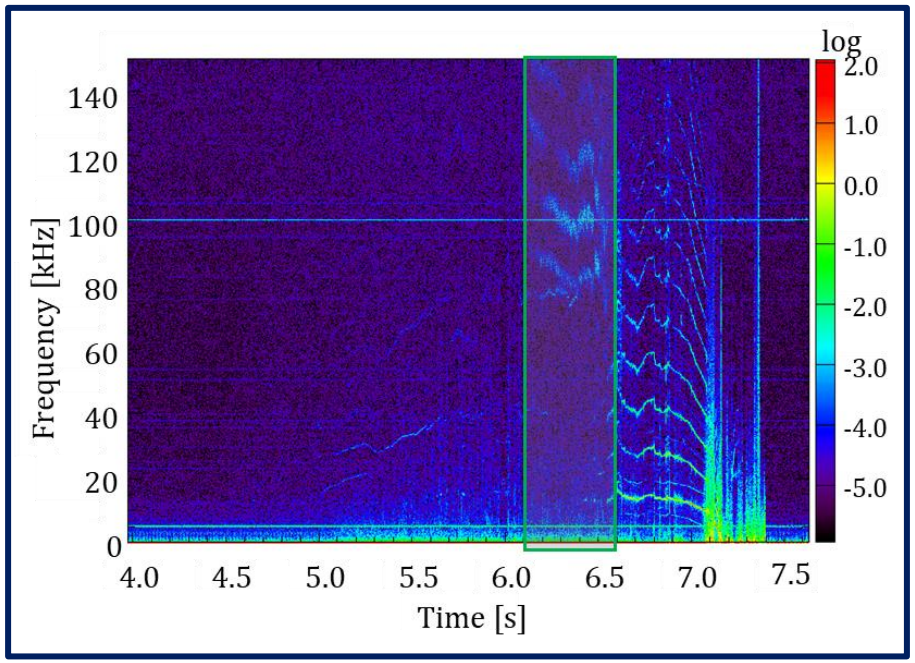
Clear observations of the EM modes on many diagnostics.

**SXR channels 9 and 12 appeared broken*

- Magnetics: EM perturbations observed on all available Mirnov coils (no radial information)
- Soft X-Ray: EM perturbations observed on most of the channels (6, 7, 8, 10, 11, 13, 14) except edge ones (2,3,4,5,15)*.
- Interferometry: only the two channels looking at the plasma core (V02 and V03) measured density fluctuations.
  - The observed modes have not a clear ballooning nor anti-ballooning structure.

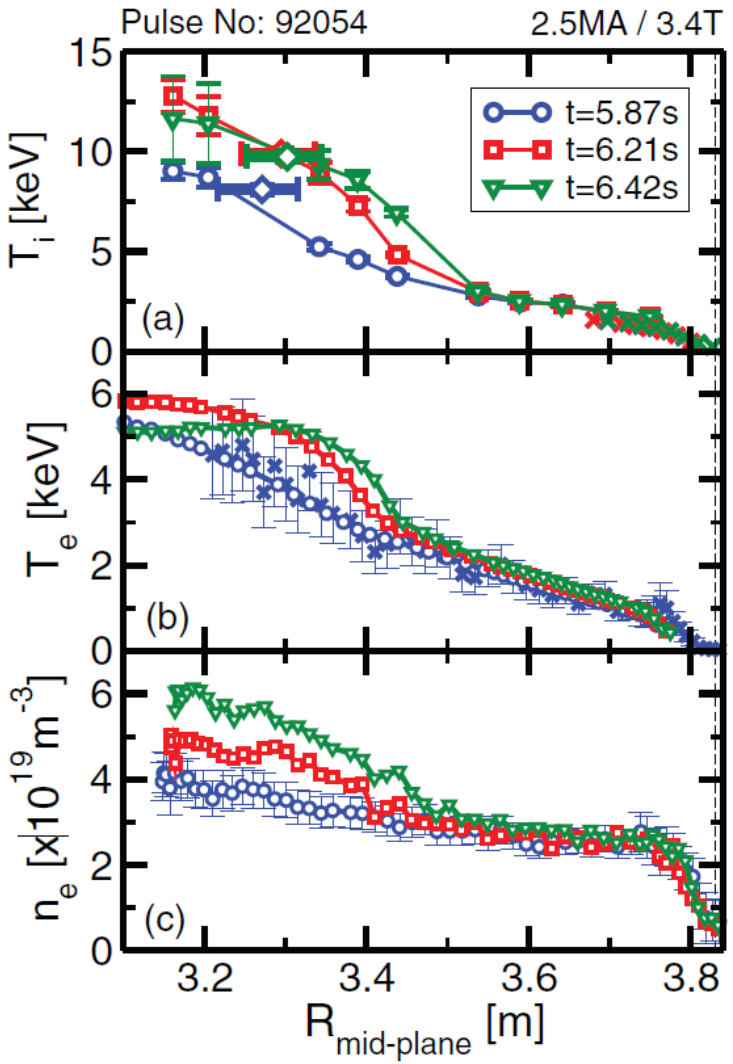




- Reflectometer: limited operational range during this JPN 92054 ($R > 3.35m$), modes detected for $R(m) \in [3.35,3.42]$

JET pulse 92054 – an excellent test case

- high q_{min} (on the magnetic axis),
- Internal transport barriers (ITBs) clearly achieved for the 1st time in JET-ILW, probably linked to $q = 2$ surface.



[Dumont et al., NF 58 (2018)][Figure 6.]

Plasma parameters at 6.4s	
B_0	3.44 $[T]$
I_P	2.67 $[MA]$
P_{NBI}	25.1 [MW]
P_{ICRH}	0 [MW]
R_{NT}	1.44 $[10^{16}\ s^{-1}]$
n_{e_0}	5.43 $[10^{19}\ m^{-3}]$
T_{e_0}	5.36 $[keV]$
n_{i_0}	4.80 $[10^{19}\ m^{-3}]$
T_{i_0}	12.96 $[keV]$
q_0	1.86
R_0	3.03 $[m]$
V_A	7.06 $[10^6\ m.s^{-1}]$

JET pulse 92054 – an excellent test case

- high q_{min} (on the magnetic axis),
- Internal transport barriers (ITBs) clearly achieved for the 1st time in JET-ILW, probably linked to $q = 2$ surface.
- High-β regime* → candidates for the EM modes are beta-induced modes:

Alfvén Eigenmode: **AE**

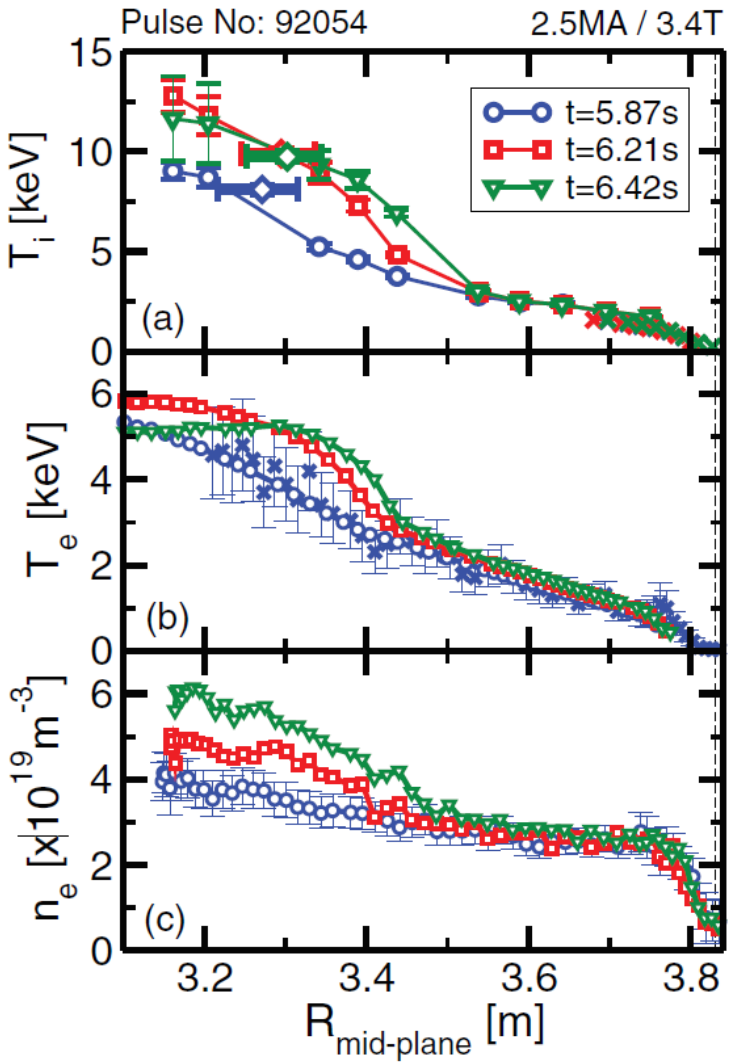
∇T_i

BAE | **B**AAE | **B**TG

Acoustic **AE**

BTG: electromagnetic mode analogue of ITG electrostatic mode.

$$\beta = \frac{nT}{B^2/2\mu_0} \equiv \frac{thermal\ energy\ density}{magnetic\ energy\ density}$$



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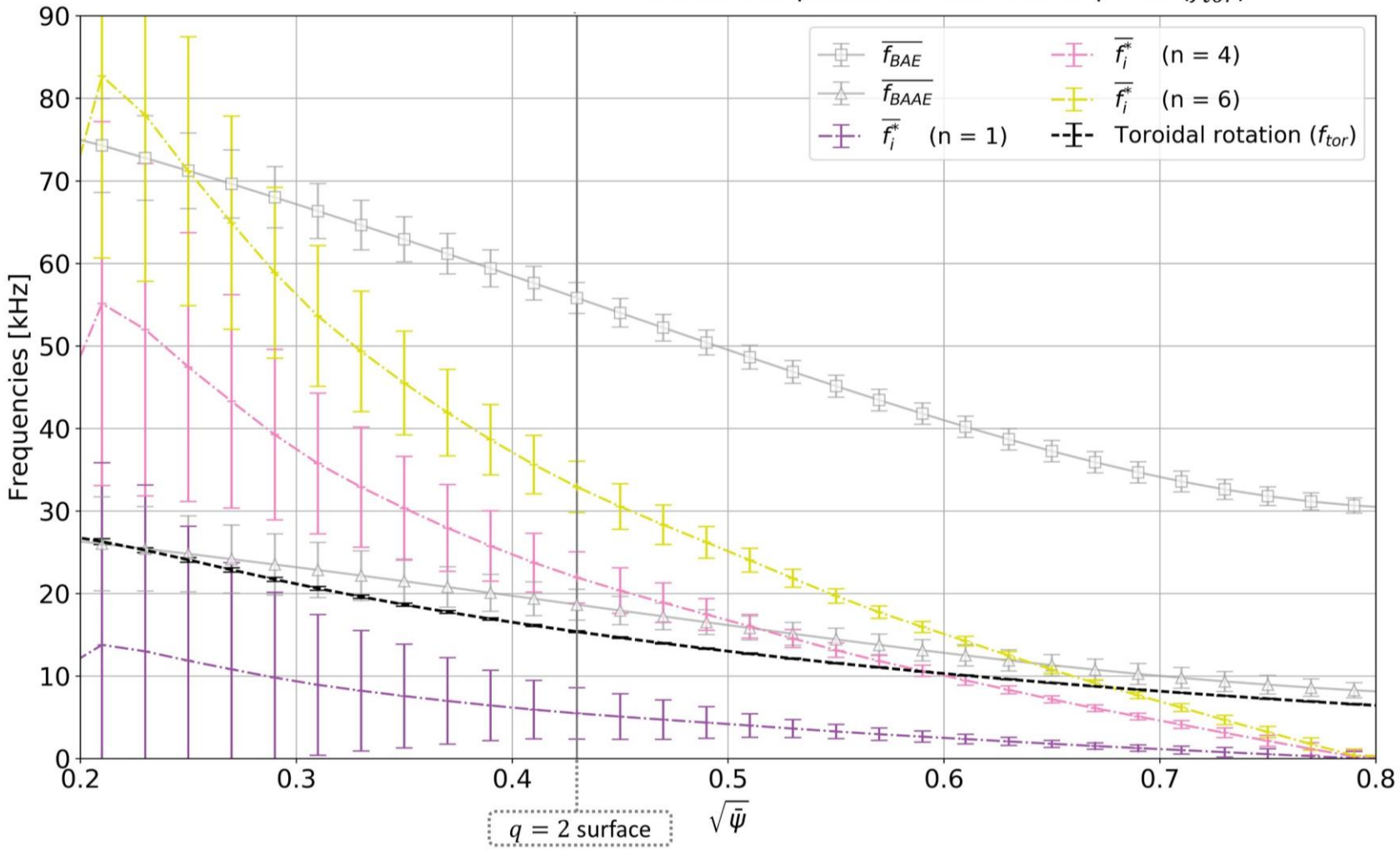
Plasma frame frequencies for BAE, BAAE and BTG modes.

BAE: $f_{GAM}^2 = \frac{1}{4\pi^2}\left[\frac{2}{m_i R^2}\left(T_e + \frac{7}{4}T_i\right)\left(1 + \frac{1}{2q^2}\right)\right]\frac{2}{\kappa^2+1}$

BAAE: $f_{BAAE}^2\Big|_{MHD} = \frac{1}{1+2q^2} f_{GAM}^2$

BTG: $\omega_i^* = -\frac{nq}{r}\frac{m_i}{\omega_{ci}}\frac{T_i}{P_i}\frac{dP_i}{dr}$

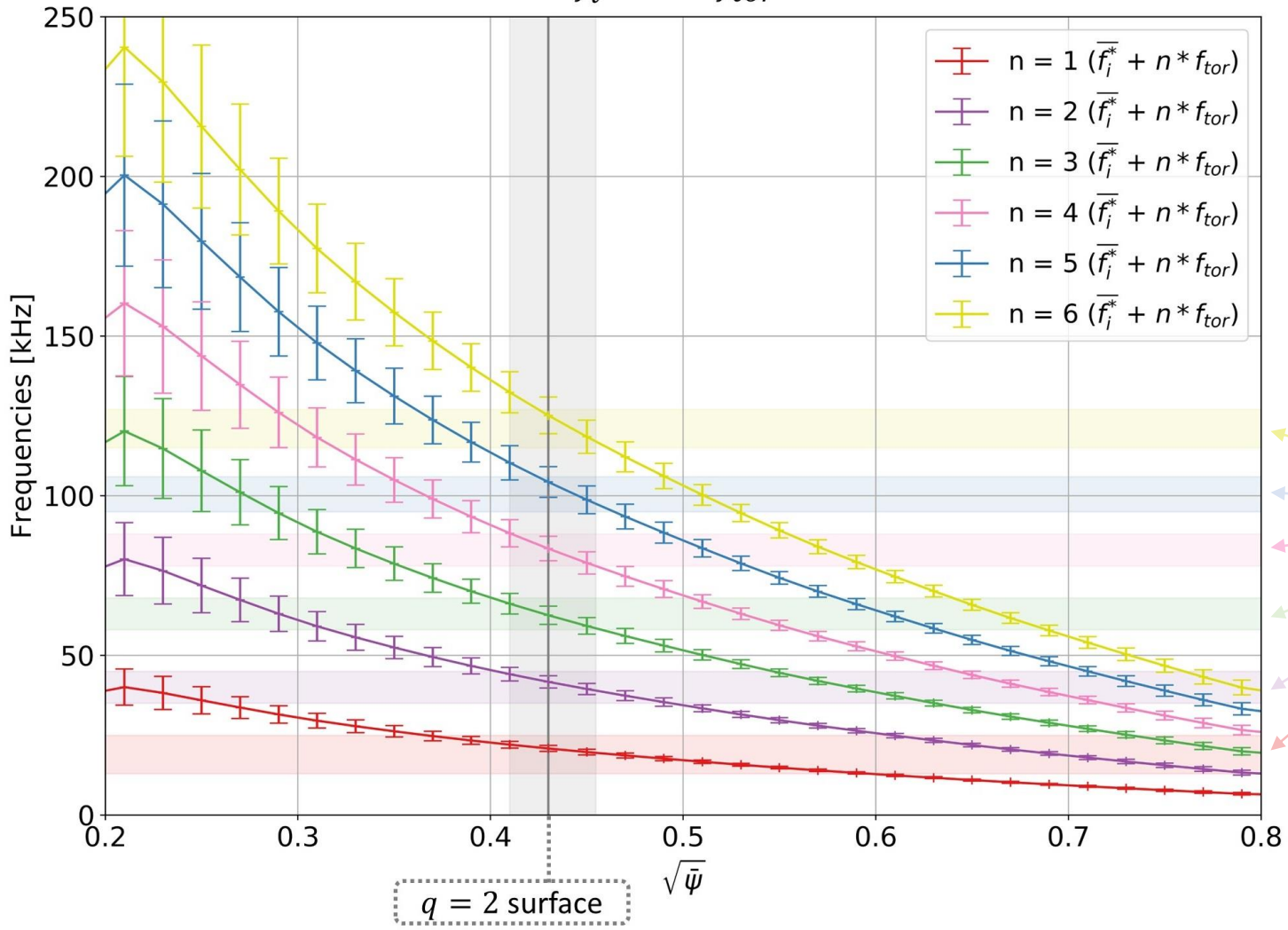
Beta-induced modes' characteristics frequencies in the **plasma frame** & measured plasma toroidal rotation profile (f_{tor})

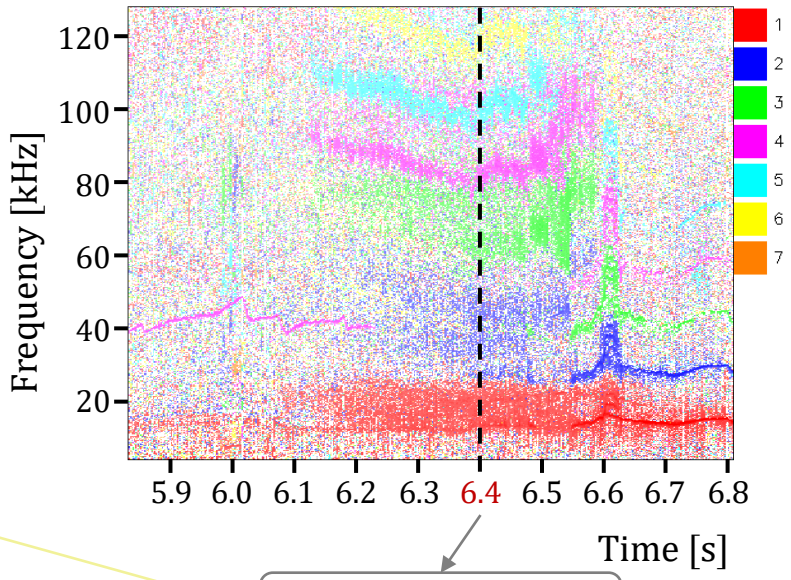


Lab frame frequencies match ion diamagnetic frequencies (BTG)

Ion diamagnetic frequencies in the **lab frame**:

$f_i^* + n * f_{tor}$



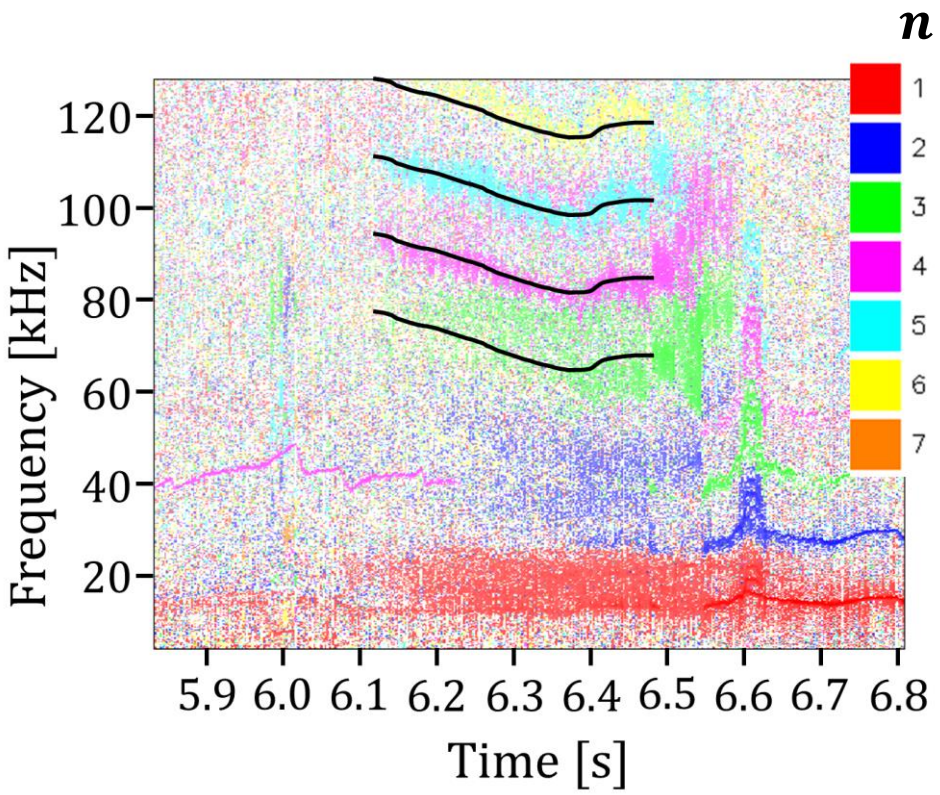


Frequency ranges

Frequencies ~ ω_i^*
Localisation ~ $q = 2$

~~BAE~~ | ~~BAAE~~ | **BTG**

Experimental characteristics | EM perturbations frequency vs plasma parameters



- Time evolution of mode frequency vs plasma parameters
  - Several radial positions ($q = q_0, 2, 9/4, 10/4, 11/4$ and 3)
  - $\frac{1}{\sqrt{n_e}}, T_e, \nabla T_e, \frac{1}{\sqrt{n_i}}, \frac{1}{\sqrt{T_i}}, \nabla T_i, \frac{1}{\sqrt{n_{fi}}}, T_{fi}, \frac{1}{\mathrm{p}}, p', f_{Alfvén_{\mathrm{on-axis}}}, \omega_i^*, \omega_e^*, f_{GAM}, f_{BAAE}$.

Pearson correlation coefficients ($q = 2$)

$\frac{1}{\sqrt{n_e}}$	T_e	∇T_e	$\frac{1}{\sqrt{n_i}}$	$\frac{1}{\sqrt{T_i}}$	∇T_i	$\frac{1}{\sqrt{n_{fi}}}$	T_{fi}	$\frac{1}{\mathrm{p}}$	p'
0.71	-0.56	0.85	0.77	0.18	0.98	-0.81	0.72	-0.65	0.09

f_{A0}	ω_i^*	ω_e^*	f_{GAM}	f_{BAAE}
-0.97	0.92	-0.93	0.87	0.05

Strong dependence on thermal ion

~~BAE~~ | ~~BAAE~~ | BTG

n: toroidal mode number
m: poloidal mode number
$q = m/n$

JET

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Beta-induced Temperature-gradient eigenmode (BTG), analytic theory

BTG: electromagnetic mode analogue of ITG electrostatic mode.

<u>Conditions of existence for BTG modes</u> [2]:

i. positive relative ion temperature gradient (η_i): $$\eta_i = \frac{\partial \ln(T_i)}{\partial ln(n_i)} > 0$$

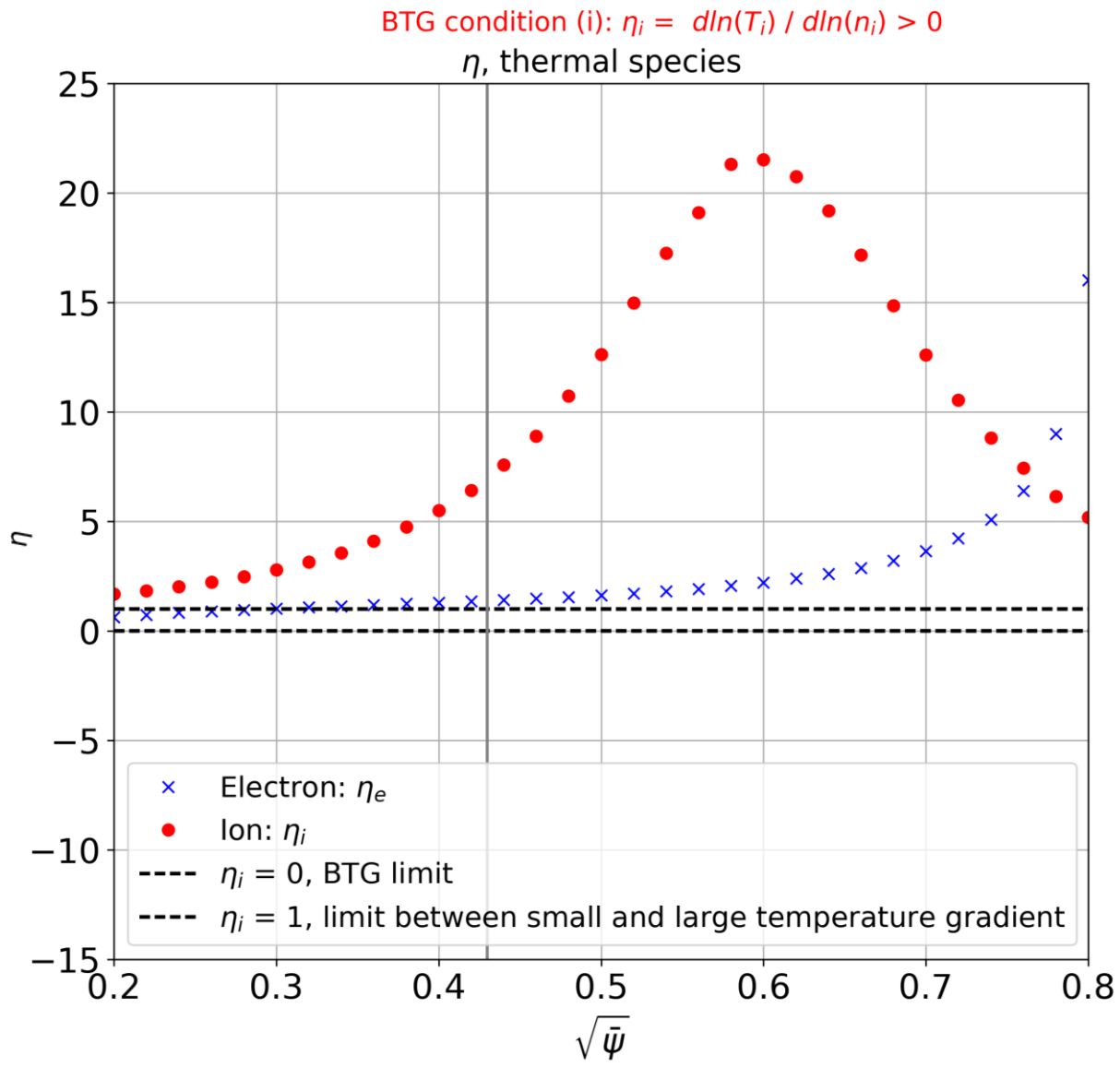
ii. ion beta (β_{ion}) higher than a critical value (β_i^{crit}): $$\beta_{ion} > \beta_i^{crit} \equiv 9/2\, q^2 S^2 L^2 / R^2$$

iii. magnetic shear condition ($U_0 < 2$): $$U_0 = -\frac{8\,\pi\, r\, p_0'}{S^2 B_0^2}(q^2 - 1)$$

$S = rq'/q$ the magnetic shear,
L: characteristic scale length of the plasma inhomogeneity
R: major radius of the tokamak
p_0': pressure gradient
B_0: toroidal magnetic field on-axis

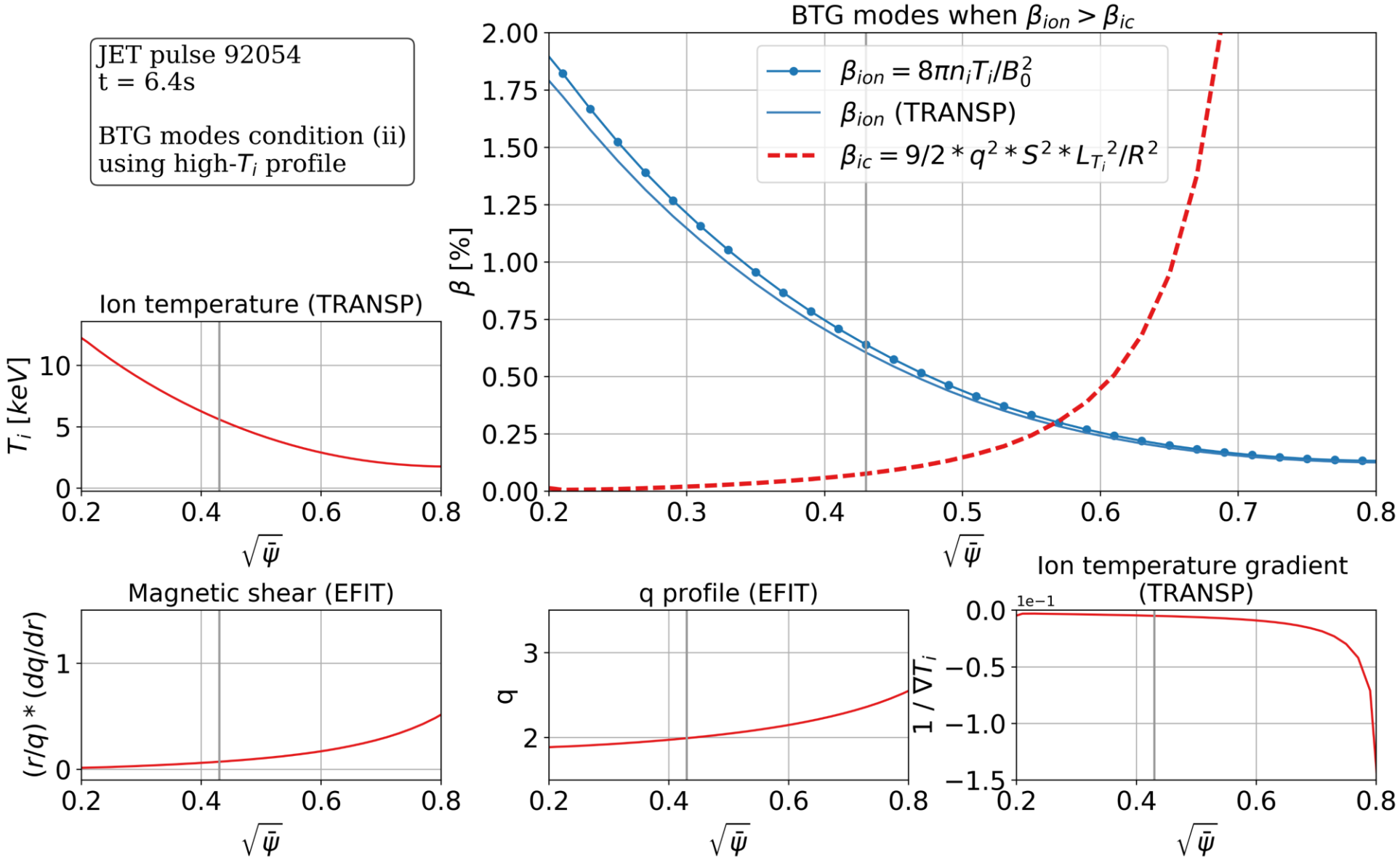
[2] Mikhailovskii, Sharapov, Plasma Phys. Rep. v.25, p.911 (1999)
See also JET reports: MHD [JET–P(98)18] & Kinetic [JET–P(98)12] theories

BTG modes | criteria (i): positive relative ion temperature gradient



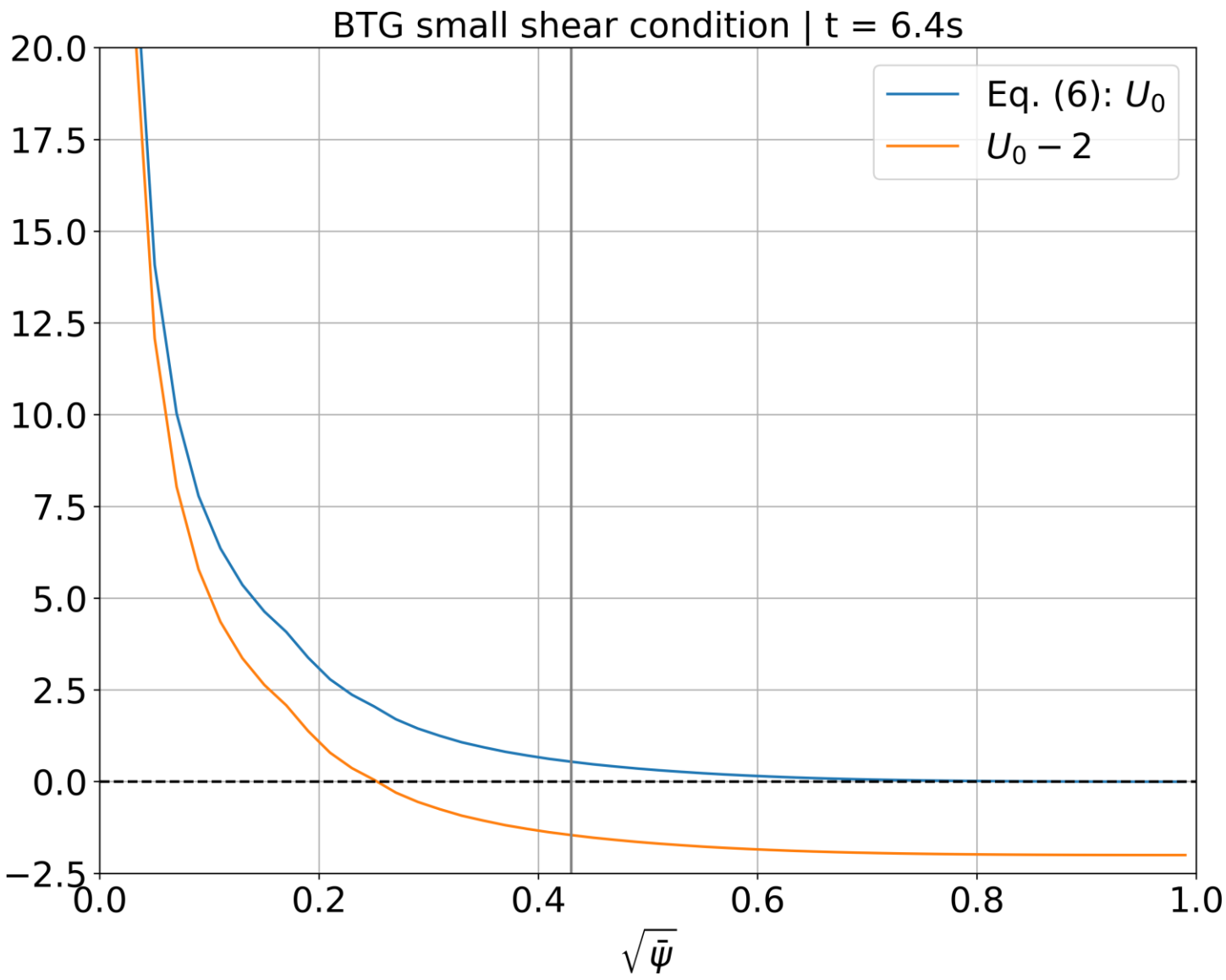
BTG modes | criteria (ii): Beta ion critique

$$\beta_{ion} > \beta_i^{crit} \equiv 9/2\, q^2 S^2 L^2 / R^2$$

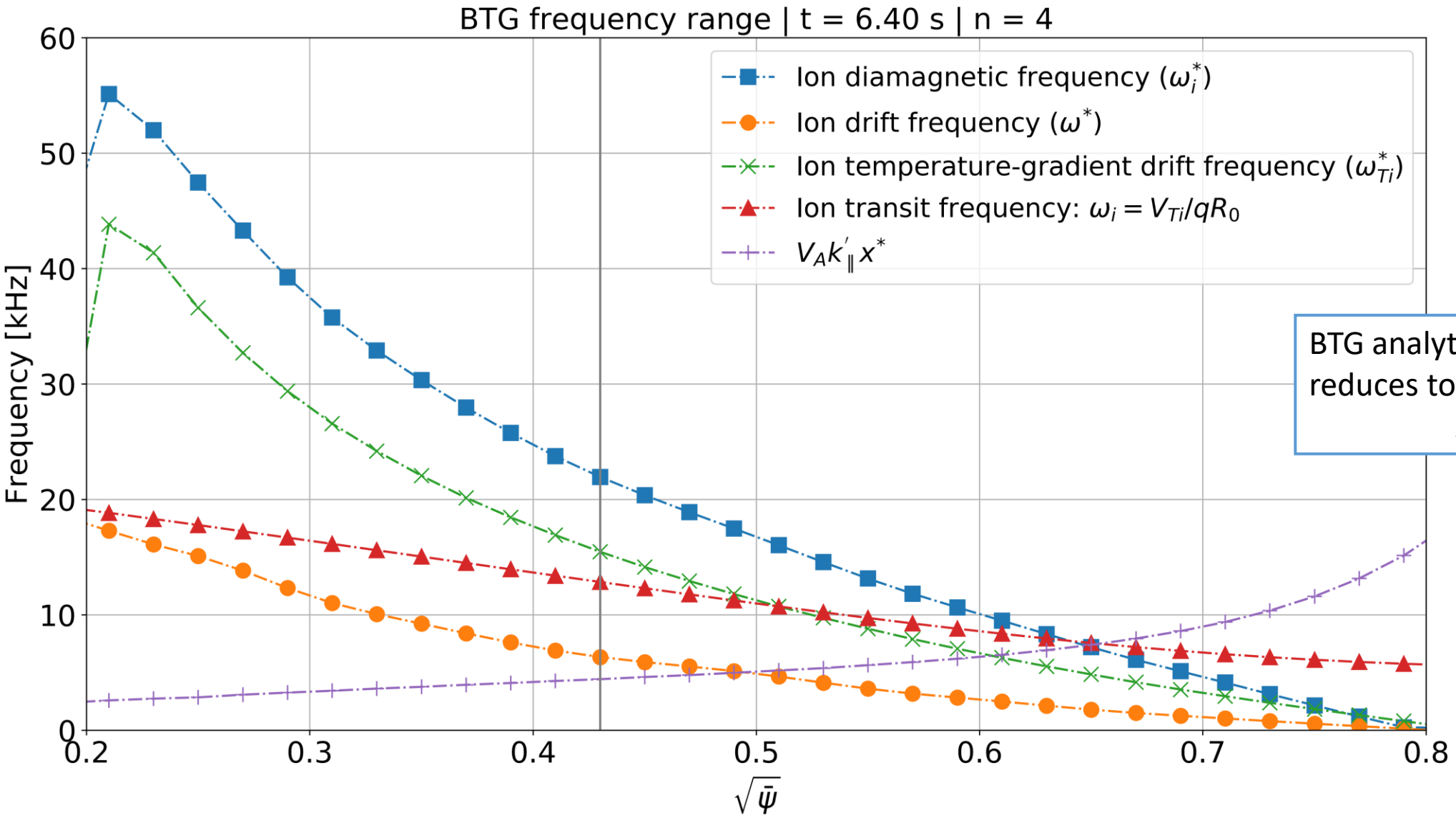


BTG modes | criteria (iii): magnetic shear condition

$$U_0 = -\frac{8\pi r p_0'}{S^2 B_0^2}(q^2 - 1) < 2$$



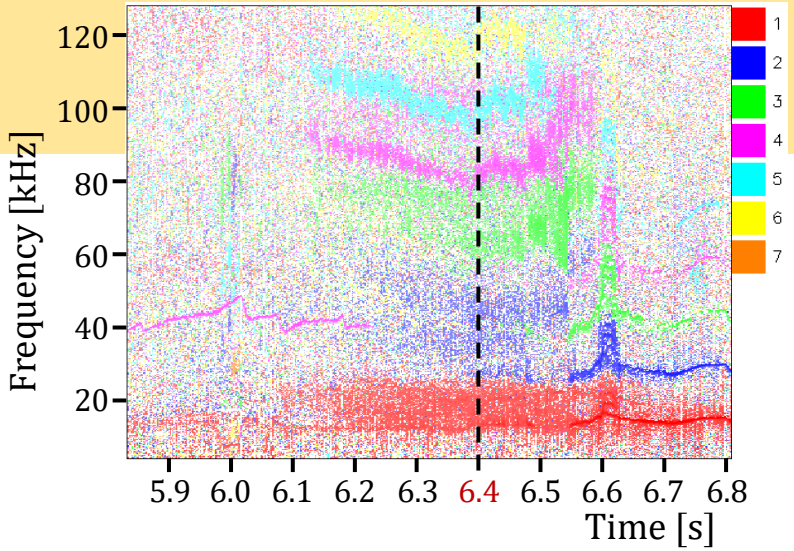
BTG modes | Characteristic thermal ion frequencies



BTG analytical dispersion relation reduces to:

$$\boldsymbol{Re(\omega) = \omega_i^*}$$

BTG conditions are met when unstable EM perturbations are observed.



BTG conditions vs time — $n = 4$

Time [s]	4.5-5.8	5.9-6.0	6.1	6.2	6.3	6.4	6.5	6.6	6.7
Unstable EM modes	✗	✗	✓	✓	✓	✓	✓	✗	✗
(i) $0 < \eta_{ion}$	11/4	10/4	10/4	9/4	8/4	8/4	8/4	8/4	8/4
(ii) $\beta_{ic} < \beta_{ion}$	✗	✗	10/4	9/4	8/4	8/4	8/4	8/4	8/4
(iii) $U_0 < 2$	11/4	10/4	10/4	9/4	8/4	8/4	8/4	8/4	9/4
$(i) + (ii) + (iii)$	✗	✗	10/4	9/4	8/4	8/4	8/4	8/4	✗
$q = 2$ (EFIT)	✗	✗	✗	✗	✓	✓	✓	✓	✓

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Modelling | Alfvén-acoustic continuum and characteristic modes frequencies

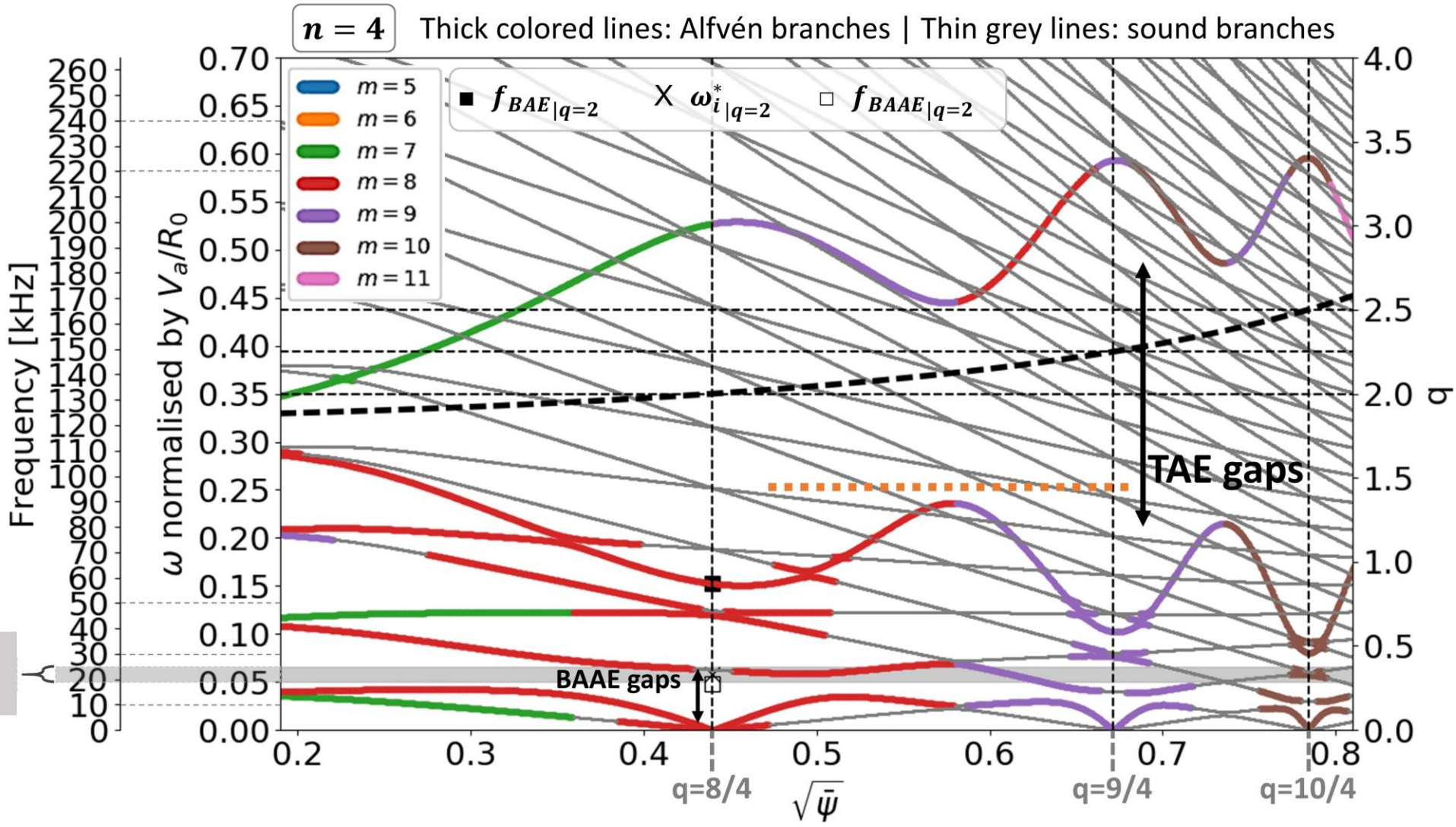
ALCON code [3] solve the ideal MHD Alfvén continuum using a poloidal-spectral method.

Finite compressibility of the plasma taken into account:

- coupling between Alfvén and sound waves.

<u>Limitation</u>: **no** ion drift effects taken into account:

- **no** "BTG gap"



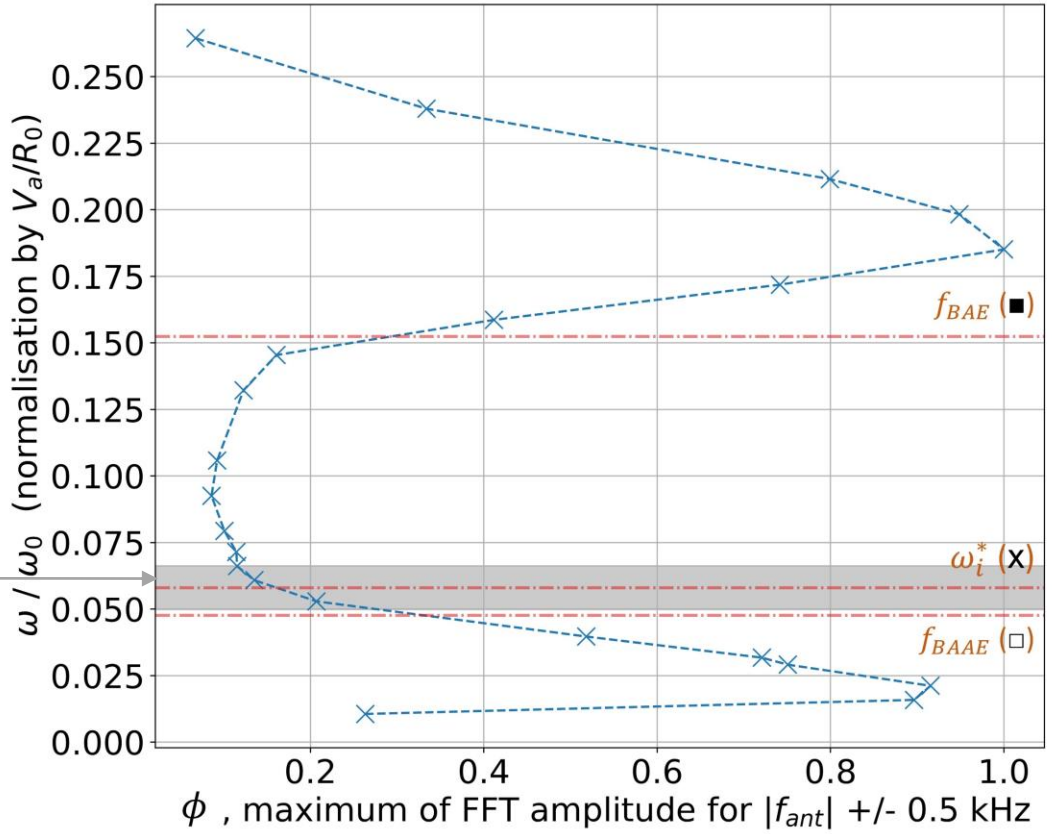
Experimental estimation of frequency range

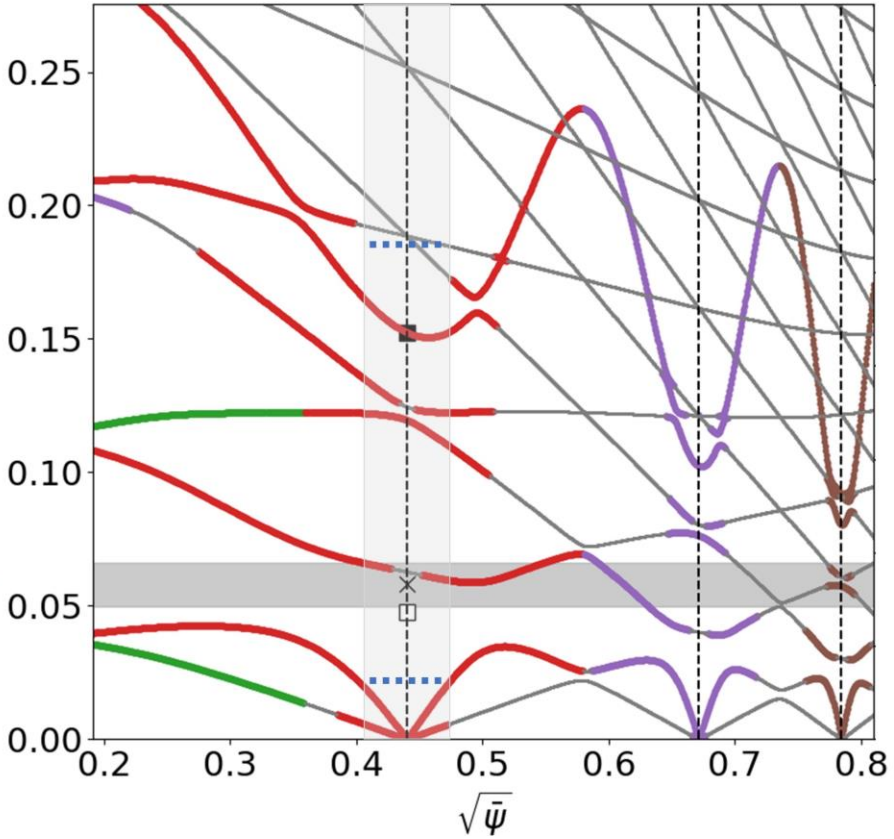
[3] W. Deng, et al. Nuclear Fusion 52 (2012) 043006.

Uniform thermal plasma, BAE and BAAE found with GTC using antenna perturbation.

- Uniform thermal plasma + synthetic antenna perturbation at a single frequency → frequency scan to probe resonance conditions
  - ➢ BAE and BAAE resonances
  - ➢ no clear resonance near the ion diamagnetic frequency (ω_i^*) for BTG mode.
    - Because there is no thermal plasma inhomogeneity effects (no ∇T_i to drive BTG modes).

Experimental estimation of frequency range



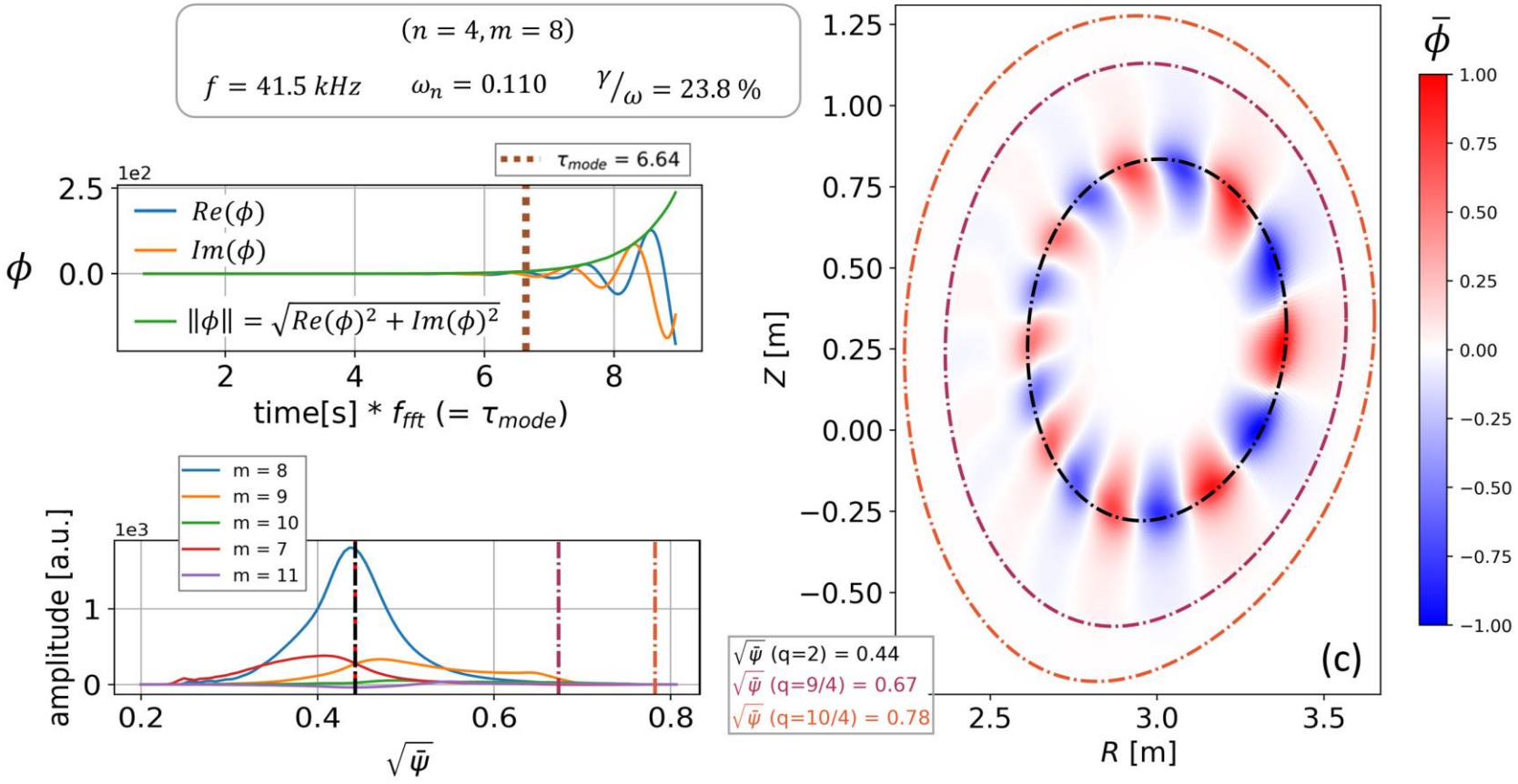


Non-uniform plasma | kinetically driven mode with BTG modes' characteristics

- <u>Linear electromagnetic global δf</u>

- Thermal ion:
  - Gyrokinetic (GK) treatment
  - Initial Maxwellian distribution
- Thermal electrons:
  - Massless fluid w/wo kinetic effect
- No collision, no (NBI) fast ion

- $n = 4$ & m $\in$ [7,11]
- Mode structure:
  - **Single dominant $m = 8$ poloidal harmonic**
  - **Localisation: q=2(=8/4)**
  - frequency: $f \cong 41.5$ kHz
  - **Dominant Alfvénic polarisation**
  - **Propagation in the ion diamagnetic direction**
- Stability:
  - **Kinetically driven by thermal ion**
  - $\frac{\gamma}{\omega} \sim 24\%$

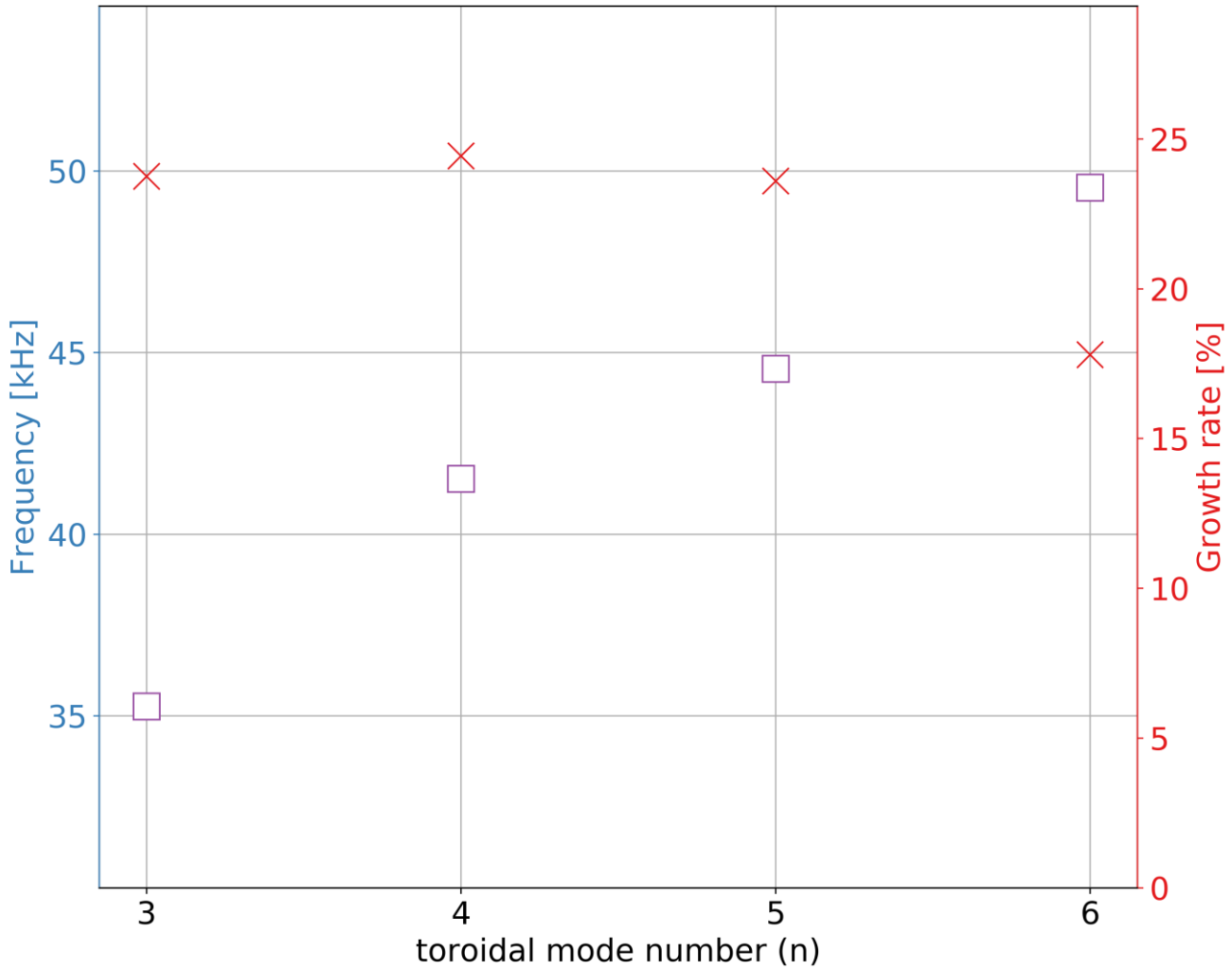


ϕ: electrostatic potential

[4] Z. Lin et al., Science 281 (1998) 1835

n scan | Frequencies n to $n+1$: $\Delta f \sim \omega_i^*$

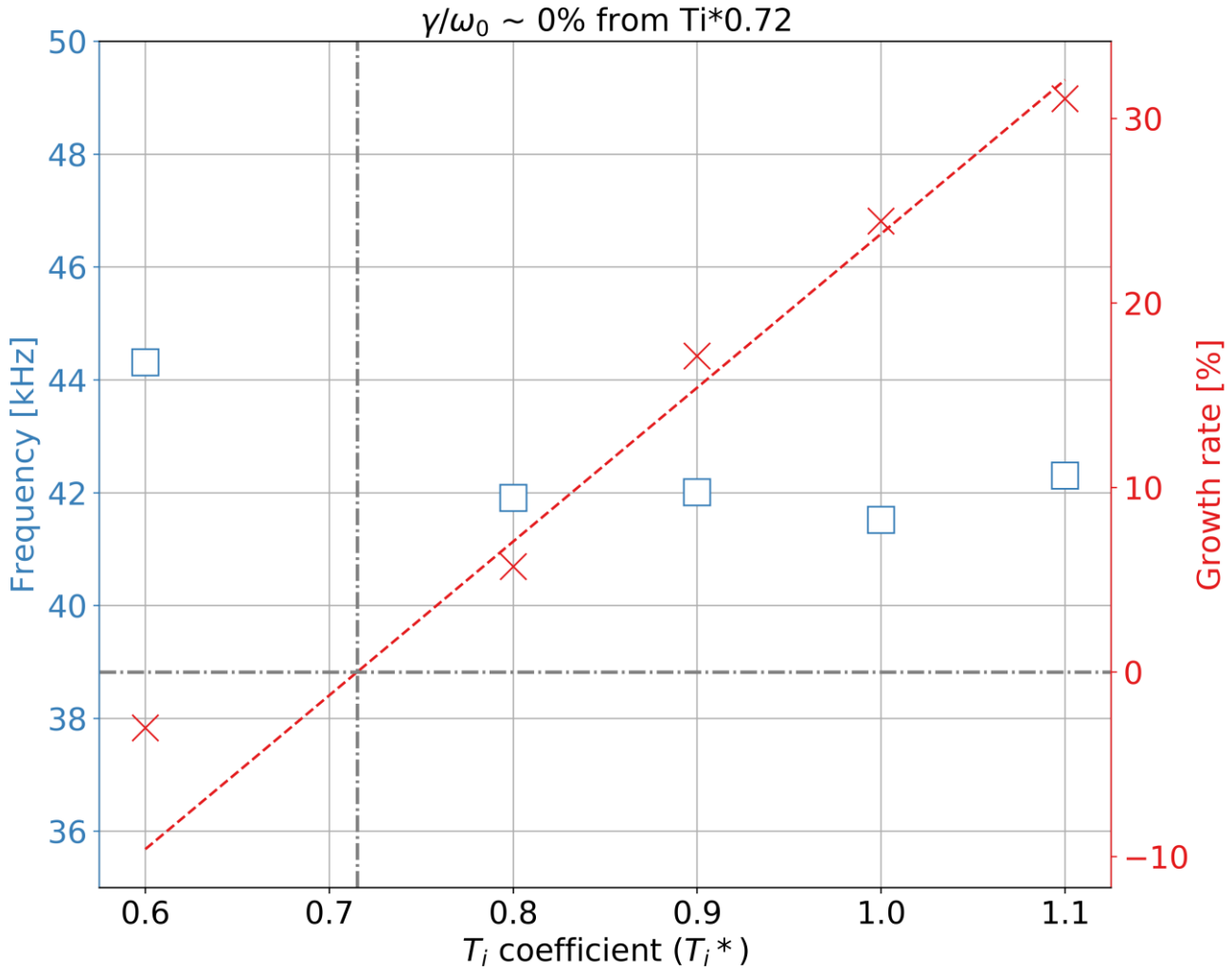
n scan: identical simulation parameters except for n ($\in [3,6]$)



T_i scan | Strong dependence on thermal ion temperature

T_i scan while keeping total plasma beta constant: $T_i * A(\%)$ & $T_e * \left(1 - (A(\%) - 1)\frac{T_i}{T_e}\right)$

$\nabla T_i / T_i$ remains constant



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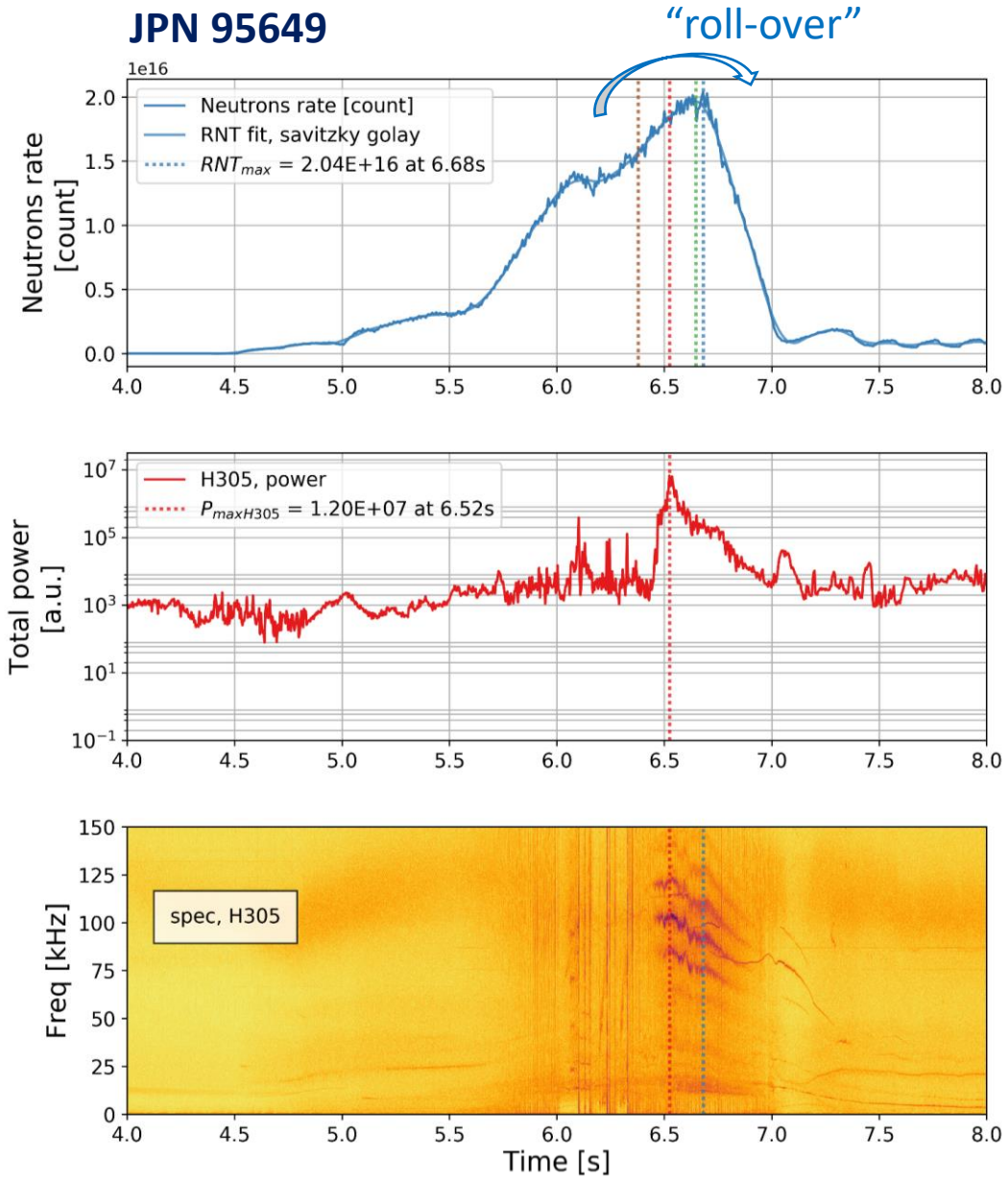
BTG modes are possible candidates for explaining the neutron-rate “roll-over”



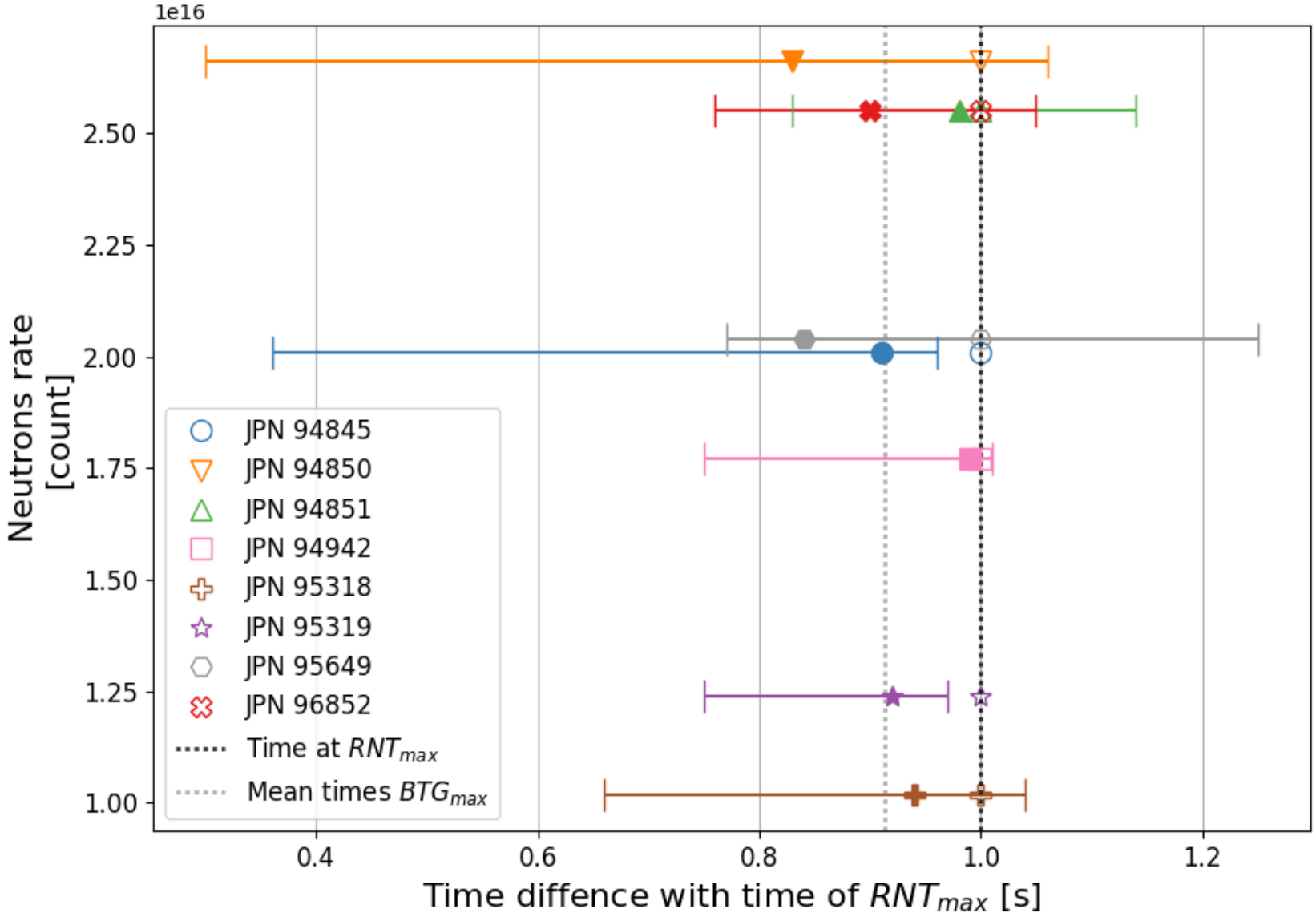
BTG modes are possible candidates for explaining the neutron-rate "roll-over"

- Empty markers indicate times and neutron rates at roll-over.
- Full markers indicate times at BTG modes maximum intensity.
- Error bars indicate BTG unstable modes (from magnetic Mirnov coils).

➢ BTG modes appear and peak before neutron rate roll-over.

➢ $(t_{RNT_{max}} - t_{BTG_{max}}) \sim 0.09\ s$

➢ $(t_{RNT_{max}} - t_{BTG_{max}}) \in [0.01, 0.17]$



Conclusions

- Electromagnetic modes observe in JET advanced tokamak scenarios with ITB are identified to be beta-induced ion temperature gradient (BTG) eigenmodes.
- Experimental measurements, analytic theory and gyrokinetic simulations agree on the mode characteristic:
  - One dominant poloidal harmonic ($m = n * q$).
  - Localisation: around $\boldsymbol{q}$=$\mathbf{2}$, related to the ITB.
  - Coupling of Alfvénic and drift waves.
  - Strong dependence on thermal ion temperature, especially its gradient ∇T_i.
  - Frequencies ~ ω_i^*
- <u>Future work</u>:
  - BTG modes are possible candidates for explaining the neutron-rate “roll-over”.
  - Experimental investigation of the correlations between other plasmas parameters (impurity accumulation, fast ions population, …) and the neutron-rate “roll-over”.
  - Non-linear gyrokinetic simulations of BTG modes and their effects on plasma stability.

EUROfusion

Thank you for your attention

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