Summary of experimental & (some) modeling contributions

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PPPL, USA

16th IAEA Technical Meeting on Energetic Particles
in Magnetic Confinement Systems & Theory of Plasma Instabilities

September 3 – 6, 2019
Shizuoka City, Japan

Topics

- Physics of Alfvén Eigenmodes and other instabilities
- Energetic particle transport
- Physics of Runaway electrons
- Mode control and scenario optimization
- Diagnostics and measurement techniques

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- **Physics of Alfvén Eigenmodes and other instabilities**
- Energetic particle transport
- Physics of Runaway electrons
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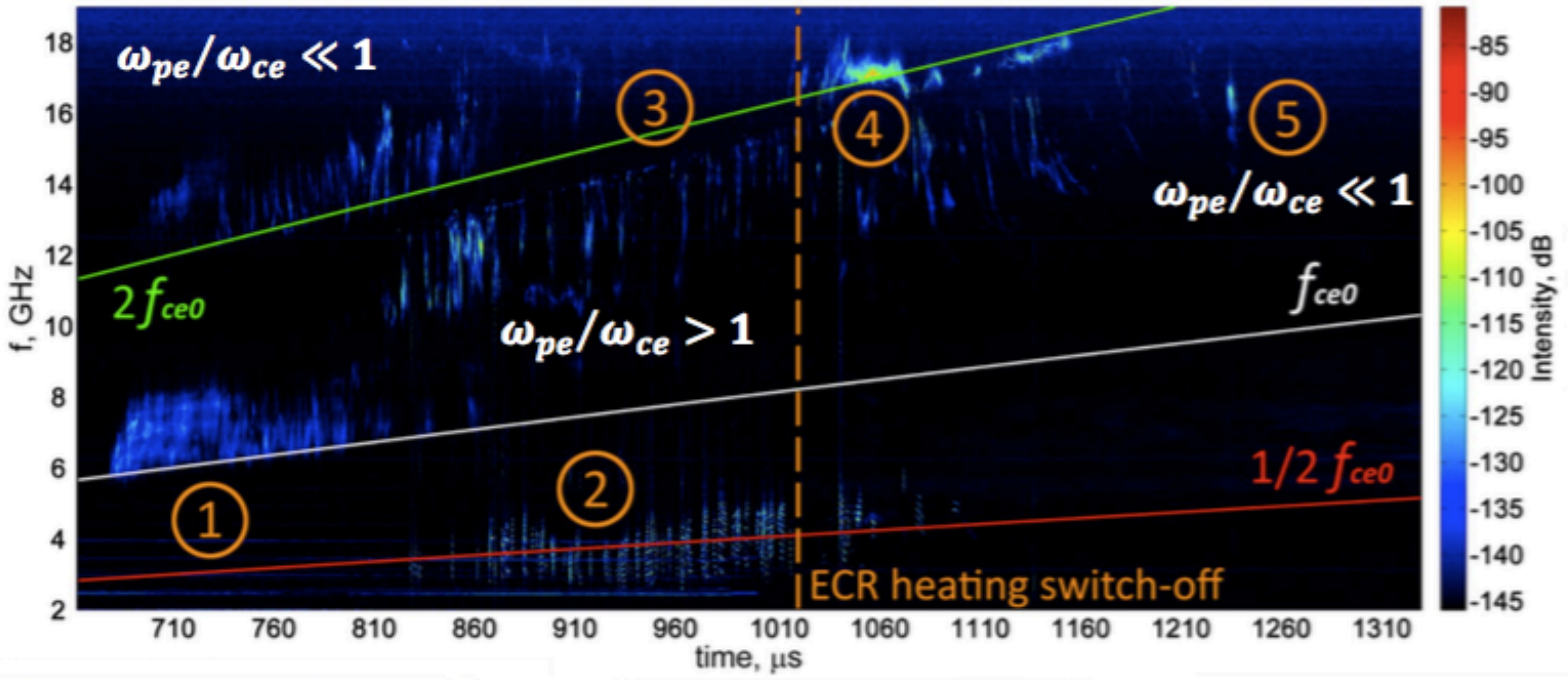
Mirror device SMIS-37 shows rich variety of sweeping/chirping instabilities



- Similarities with instability behavior observed in tokamaks
- Test-bed for Quasi-Linear theory
- ... and beyond

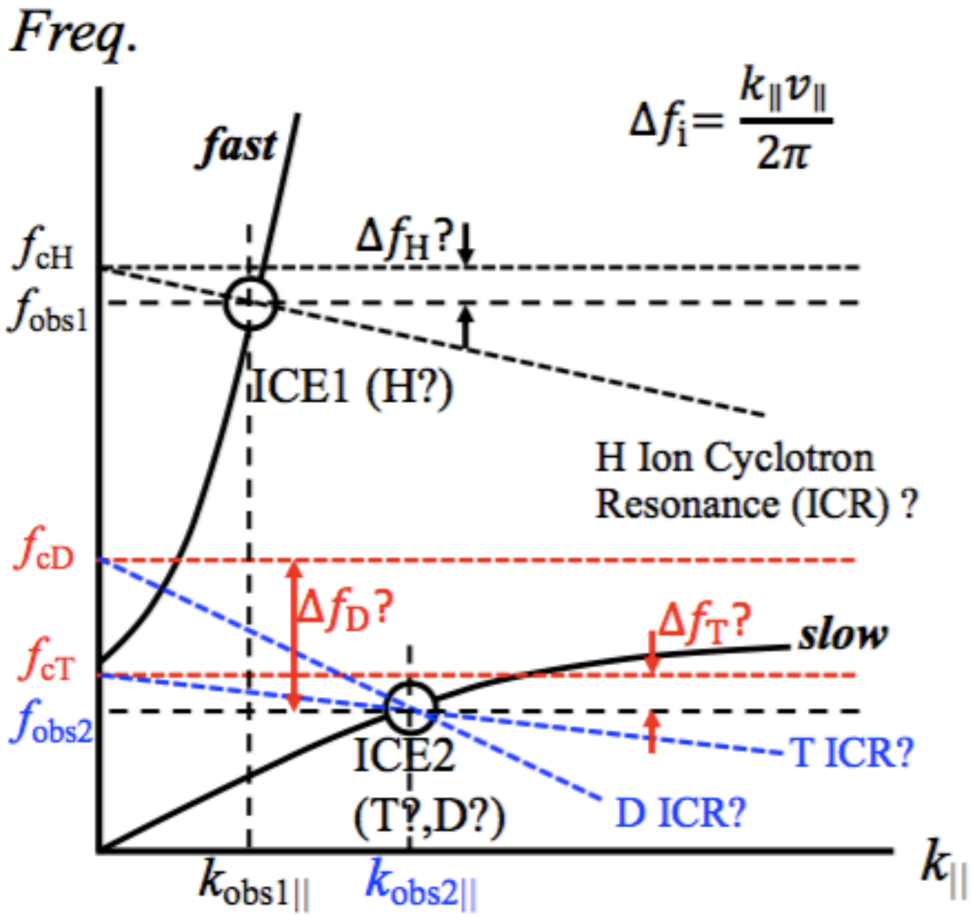
I-14 Viktorov

ICE driving source identified for JT-60U plasmas by matching dispersion relation & fast ion drive

O-16 Sumida

Possible driving sources

- ICE1 :   H
- ICE2 : T, D

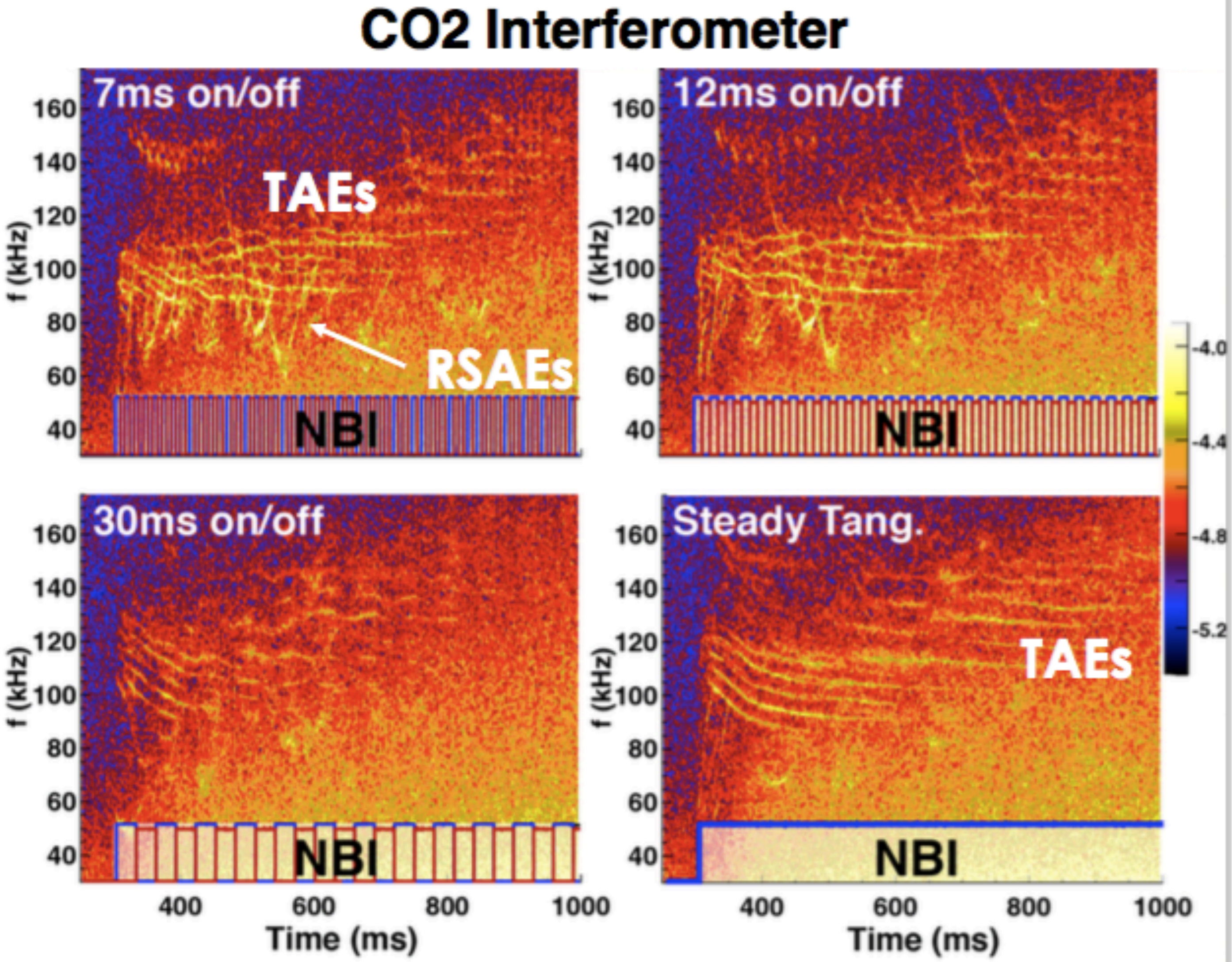


- 4 types of ICE, corresponding to fast & slow wave branches

- Drive for two different ICEs identified: H, (T,D) ions

Changes in NB modulation parameters used to assess AE drive, saturation -> model validation

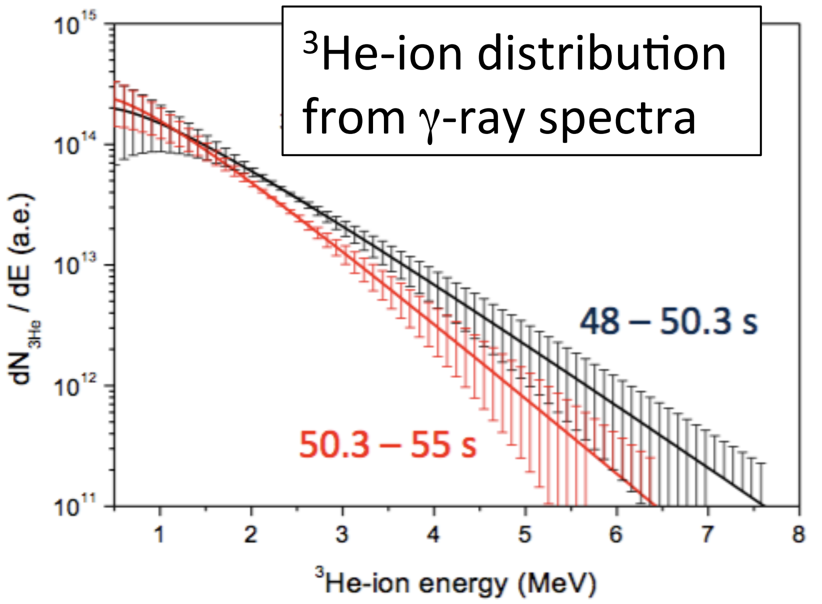
I-1 Van Zeeland



- NB modulation used as tool to tailor fast ion distribution
  - E.g. generate bump-on-tail vs slowing-down distributions

ICRF 3-ion scheme used to destabilize AEs in JET

O-19 Kiptily

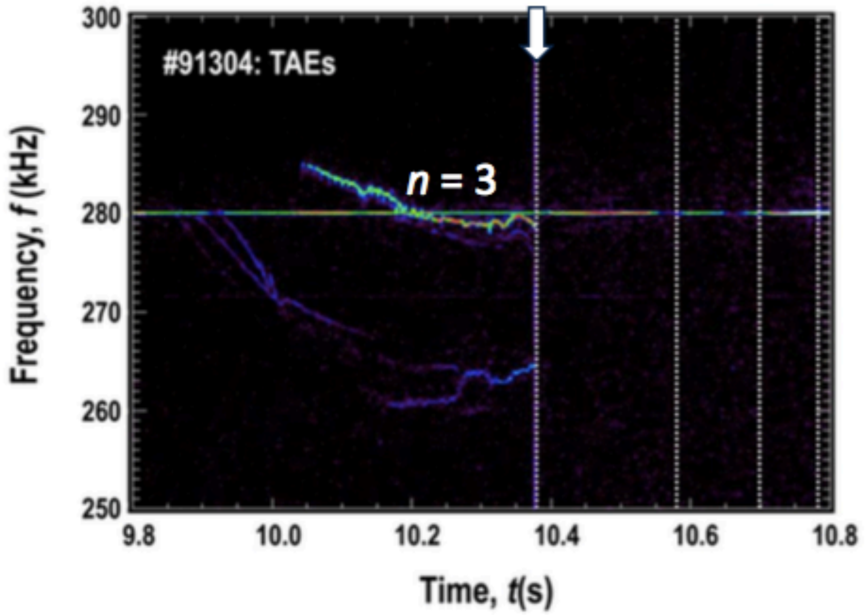


^{3}He-ion distribution from γ-ray spectra

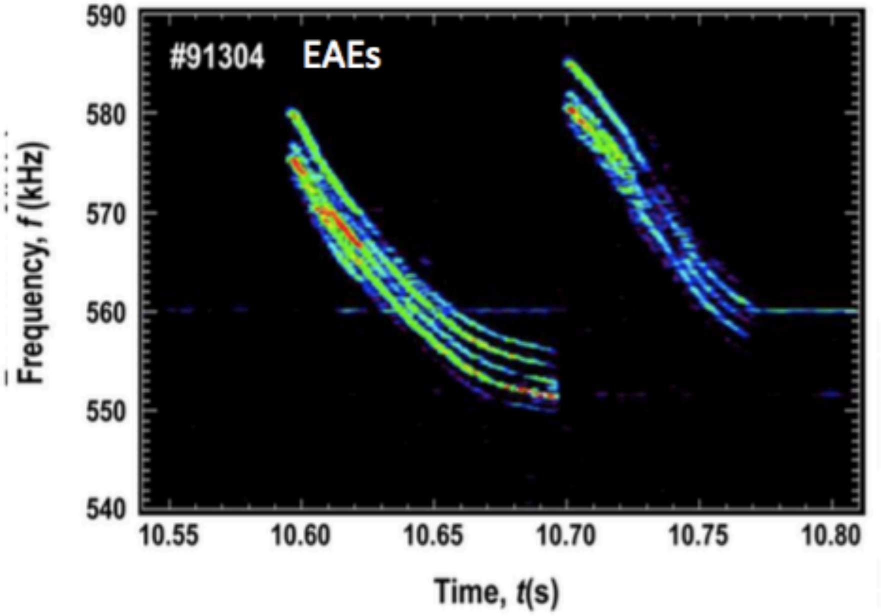
- Modes destabilized by ^{3}He ions in H-rich plasmas w/ 3-ion ICRF heating
- EAEs and TAEs observed, cause EP losses
- *Proxy for alphas before D-T*

Toroidal AE: n = 2, 3 and 4 at *f* ≈ 280 kHz

ST: *q*=1 at *R* ≈ 3.2m

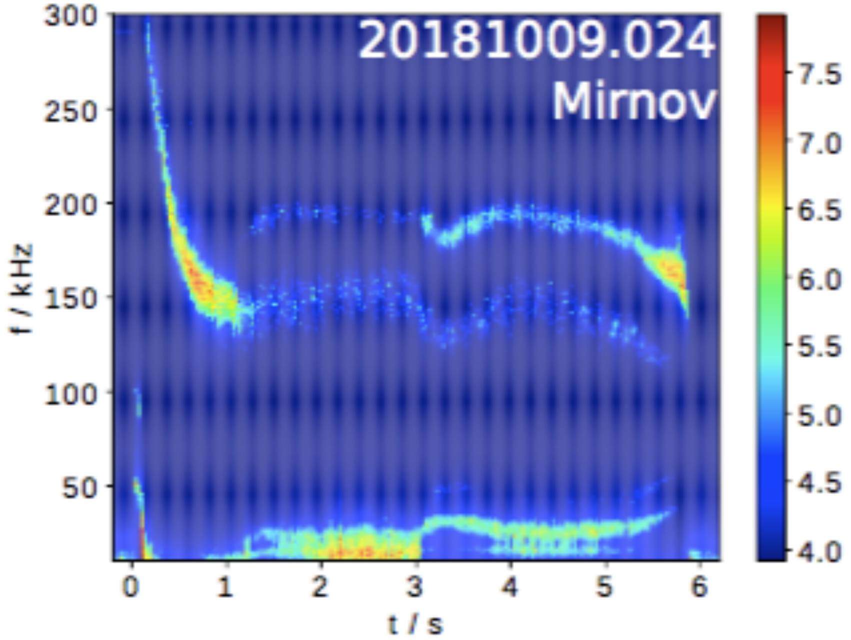


Elliptic AE: n= ±1, ± 3 & ± 5 at *f* ≈ 560 kHz



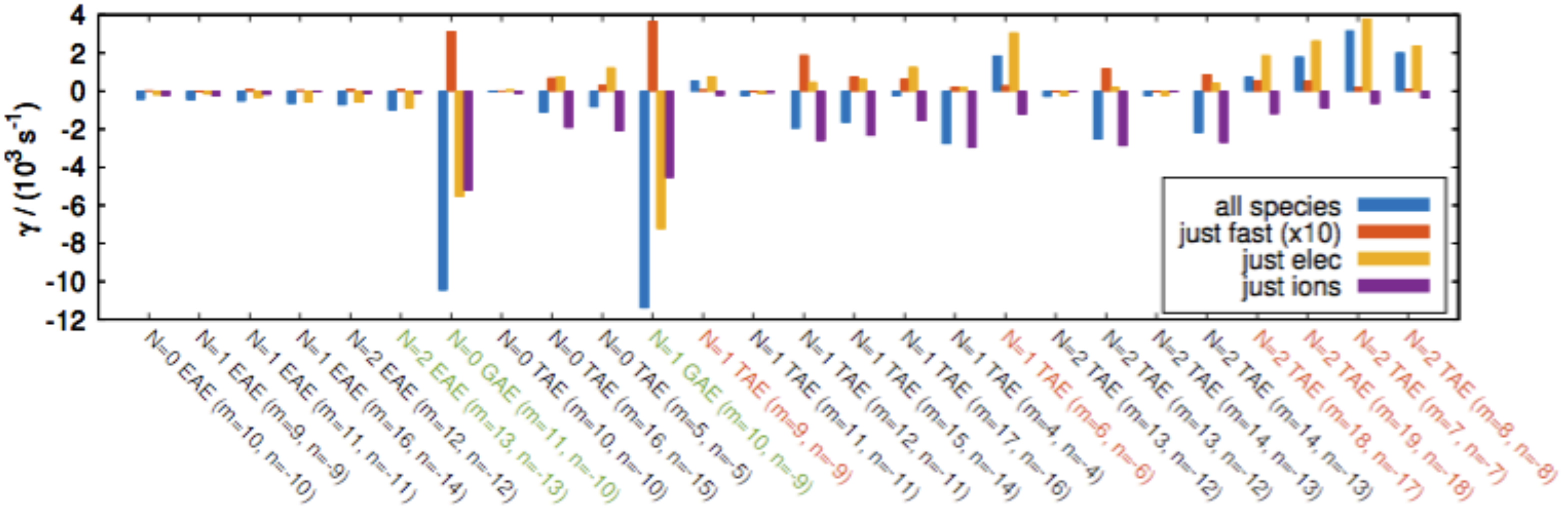
First studies of EP-driven modes in W7-X show variety of unstable Alfvénic modes

O-17 Slaby



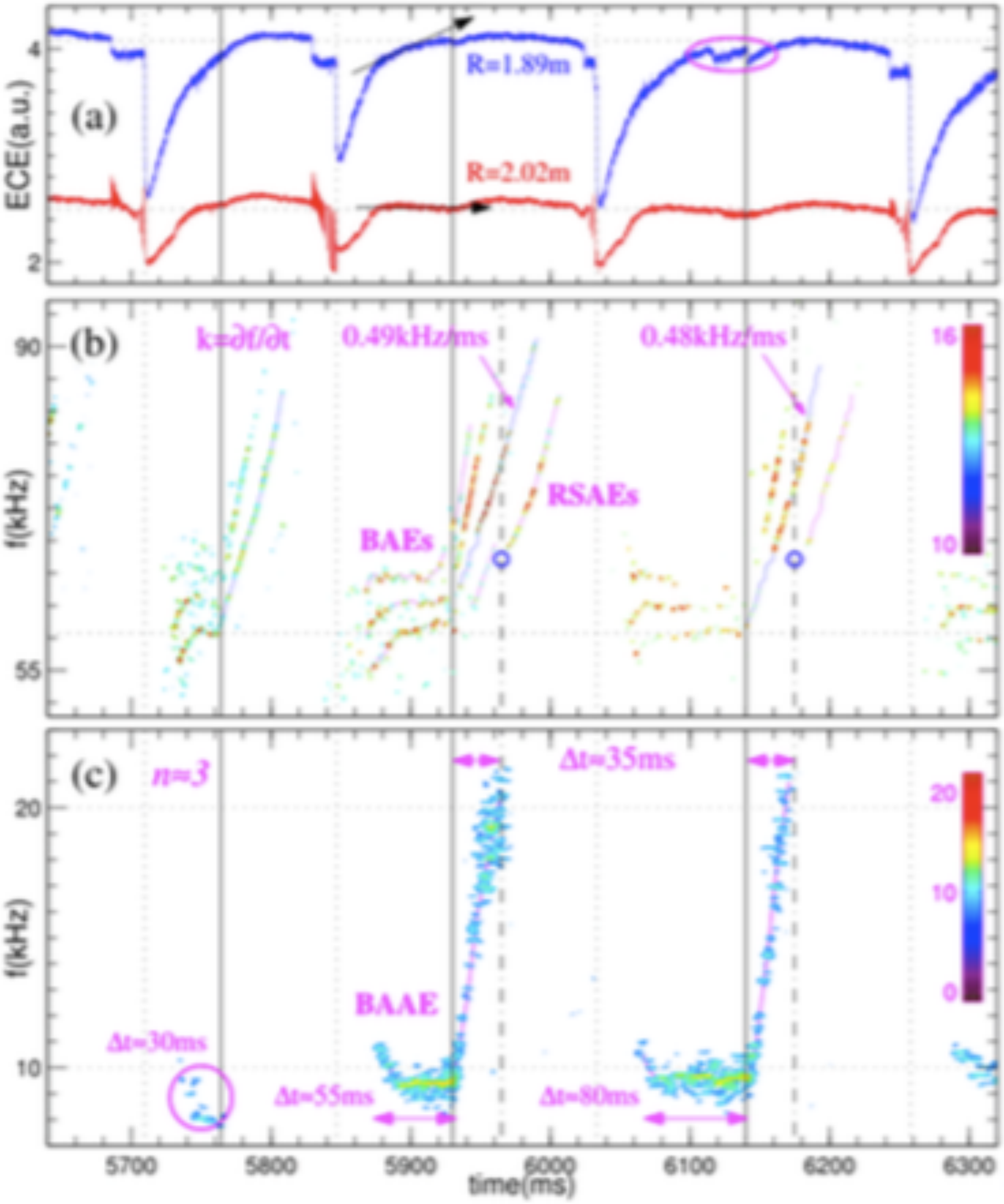
- AE modes identified during NB operations
- Modeling started to identify type of mode, drive, damping, ...

- CKA-EUTERPE used to compute growth and damping rates of the modes (ions, electrons, or fast ions used as kinetic species)



EAST plasmas: multiple AEs destabilized in between sawtooth crashes

O-2 Xu



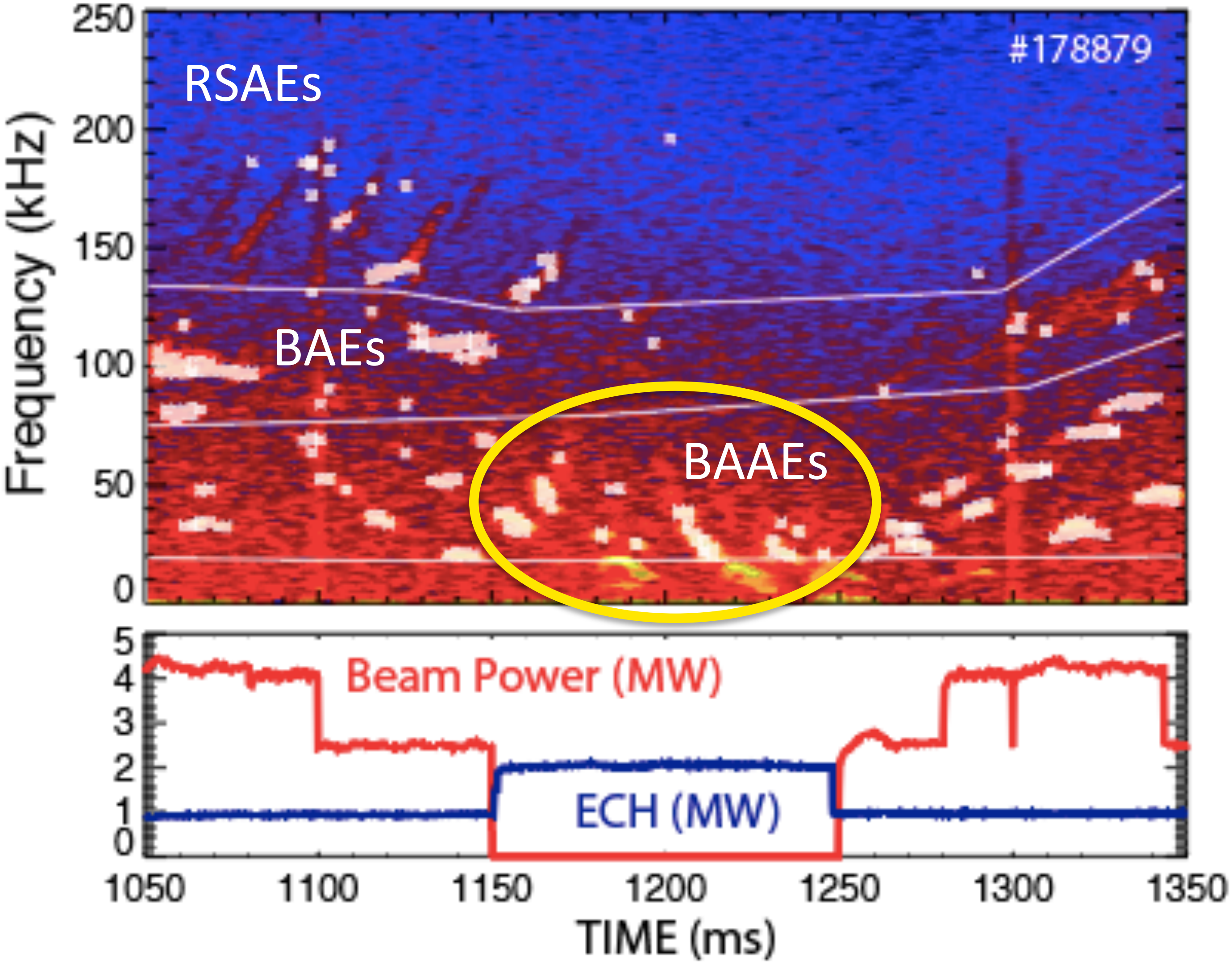
- Repetitive sawteeth crashes
- BAEEs, BAEs and RSAEs all observed in between sawteeth
- Weak 3/2 NTM also present

Study of BAE and BAAE excitation on DIII-D shows surprise: high-energy NB ions do NOT drive BAAEs!

I-5 Heidbrink

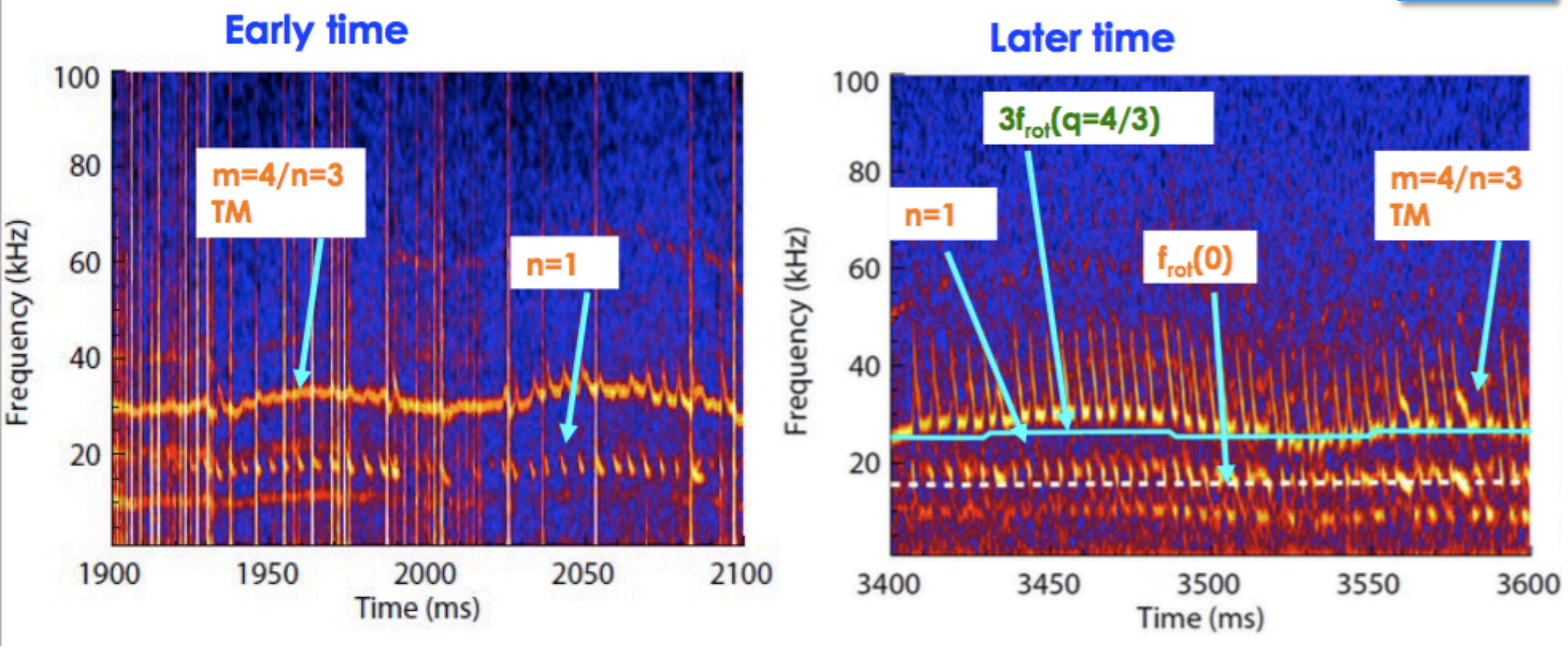
Notch NB injection:

- RSAEs & BAEs are suppressed
- BAAEs persist during beam notch
- Frequency drops as rotation decreases



DIII-D hybrid scenarios exhibit variety of low-frequency modes – all affecting EP confinement

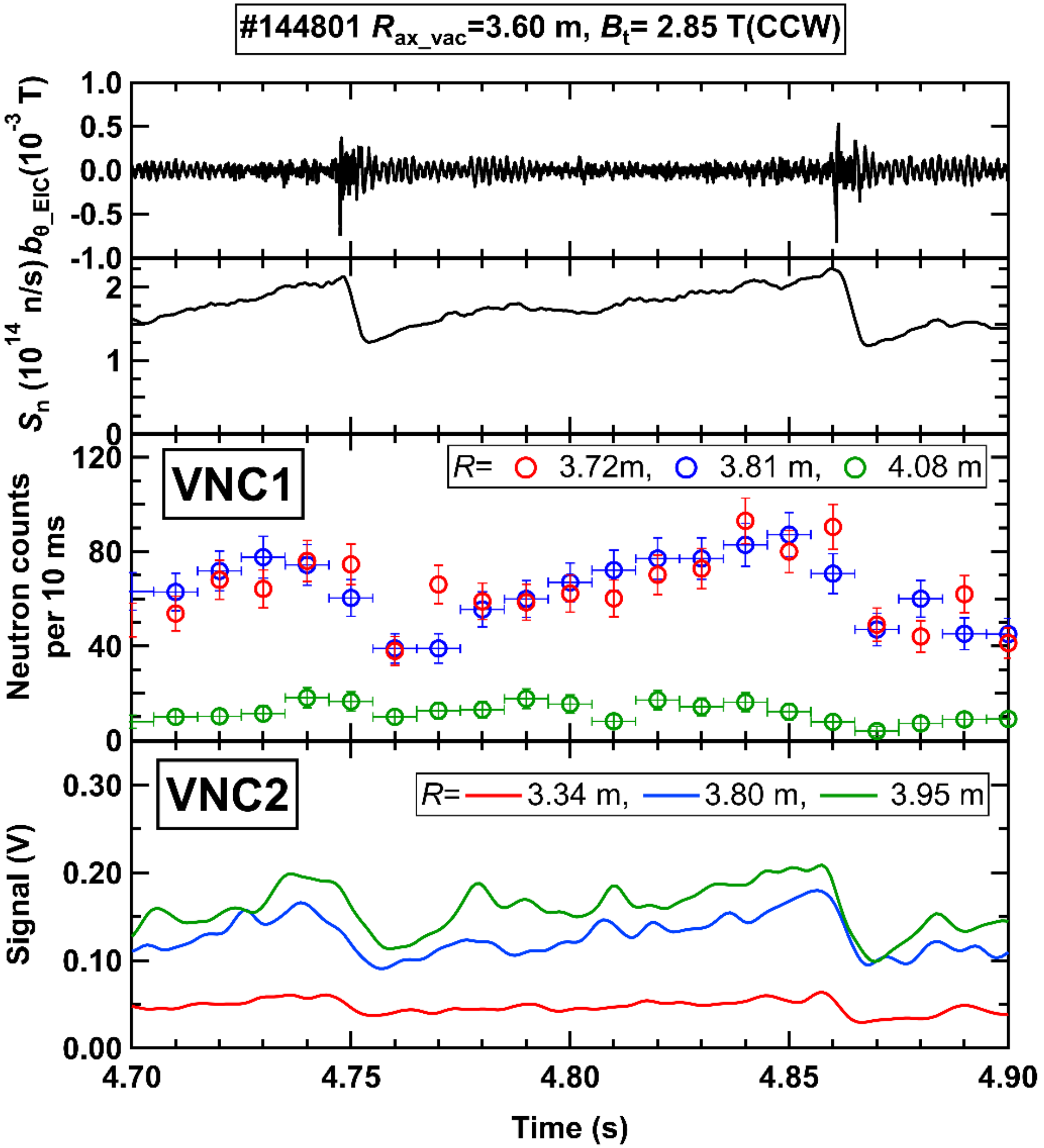
O-5 Liu



- Role of fast ion distribution & q-profile being investigated to explain competition between NTMs, fishbones and AEs

In LHD, perpendicular NBI excites resistive Interchange mode (EIC) limiting high-T_i sustainment

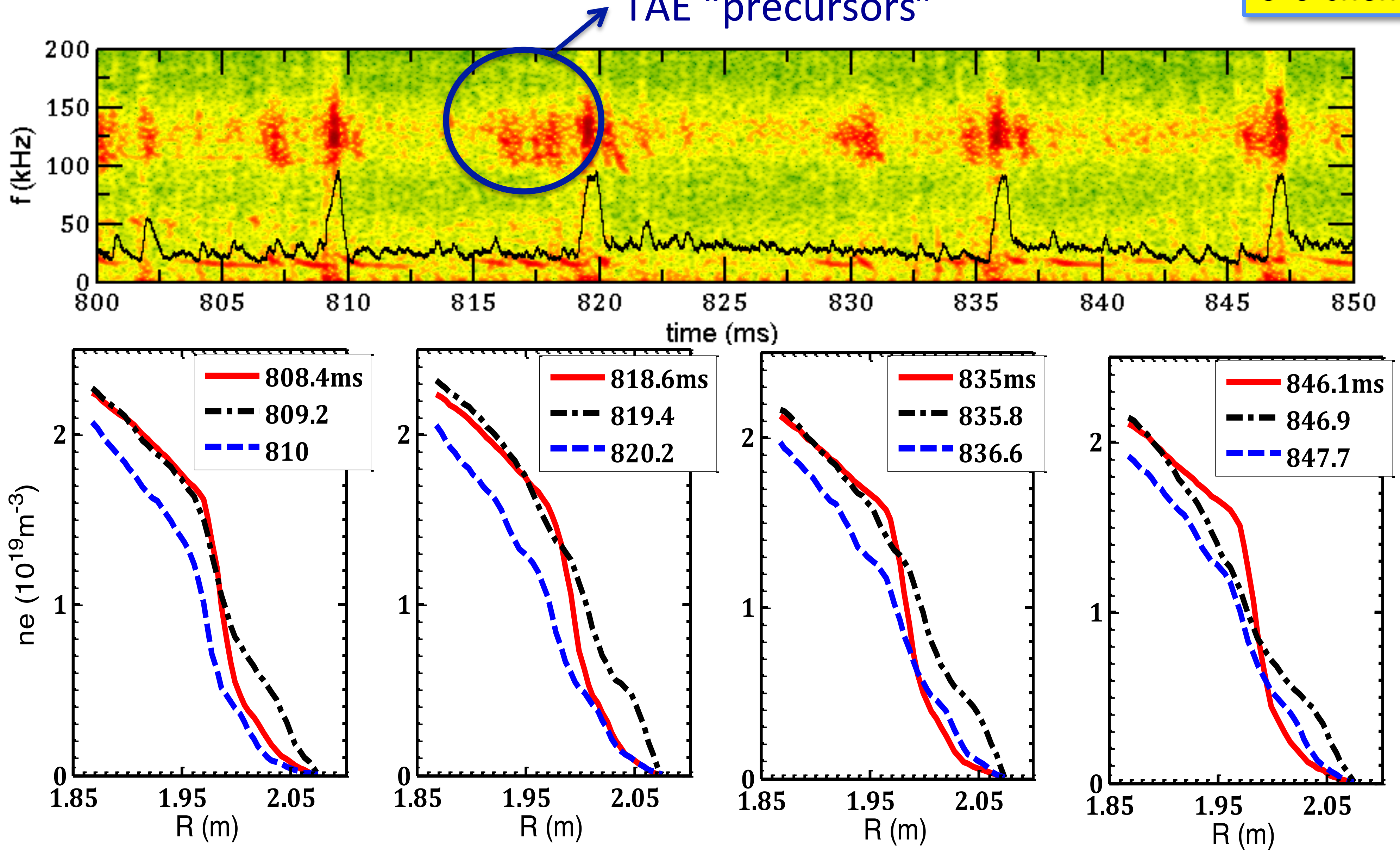
I-16 Ogawa



- EP transport induced by EP-driven resistive interchange (EIC)
- EP transport characterized through comprehensive set of neutron diagnostics

HL-2A: TAEs can couple to *n=1* mode and trigger ELMs, causing pedestal collapse

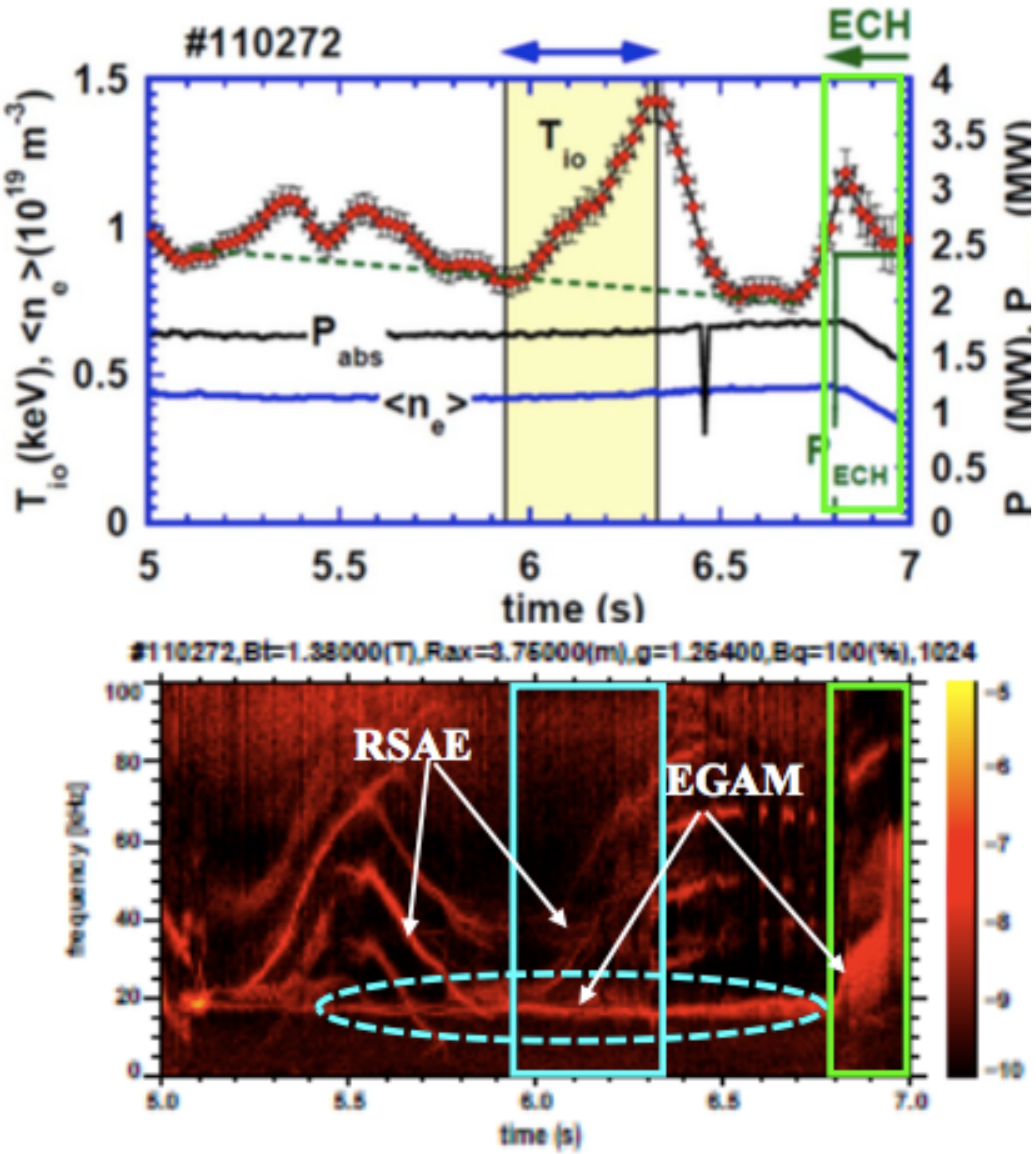
O-8 Chen



TAE “precursors”

Favorable effects of EP-driven modes and EP losses observed in LHD

I-7 Toi



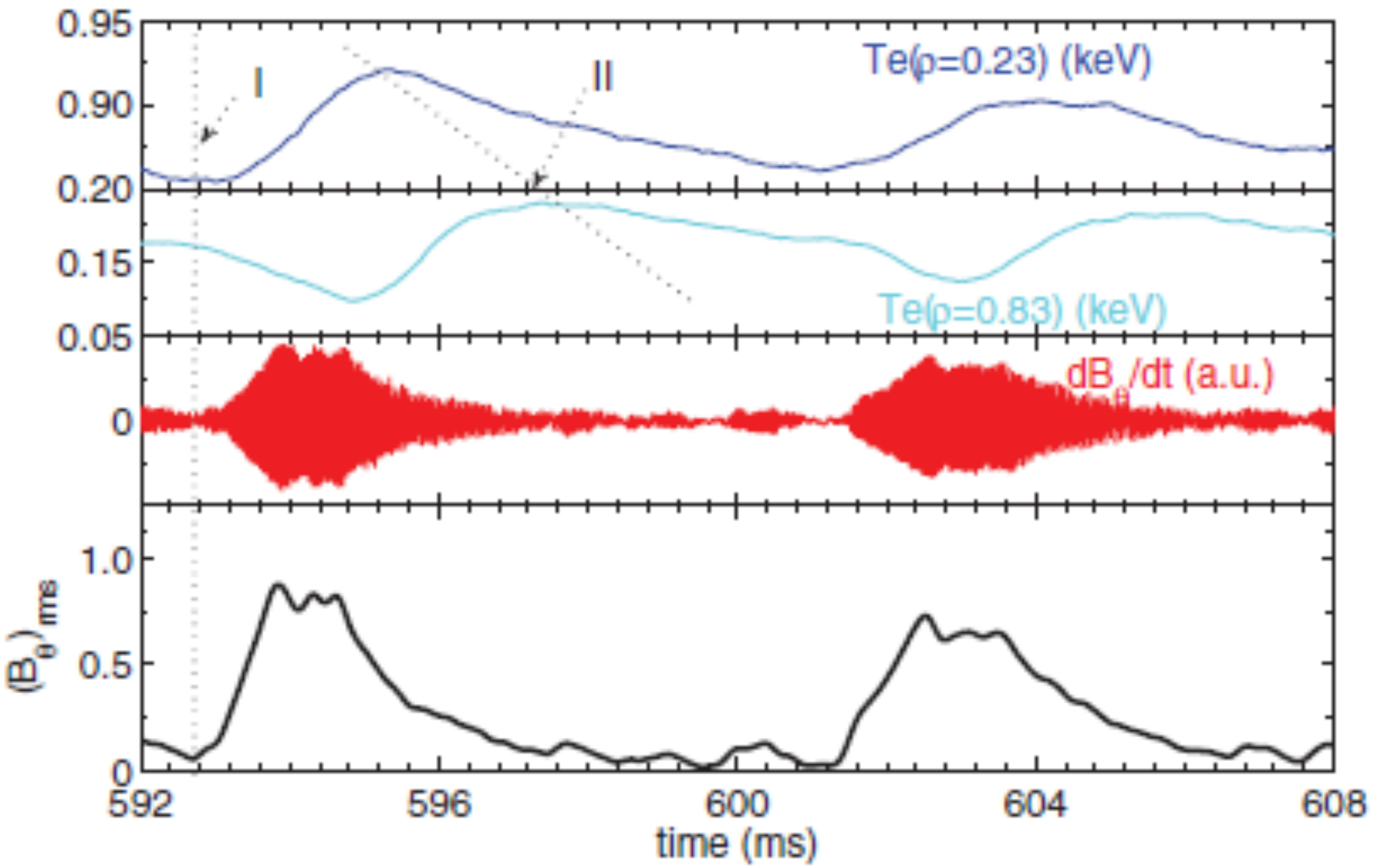
Two possible mechanisms:

- Non-ambipolar loss can lead to E_r increases -> transport barrier
- Energy channeling mediated by eGAM leads to increased T_i

Also see: **P-40 Wang**

Fishbones can trigger ITBs on MAST

O-7 Michael



Trigger for ITB formation?

- One possibility: EP losses induce E_r -> rotation increases -> turbulence is suppressed -> ITB forms

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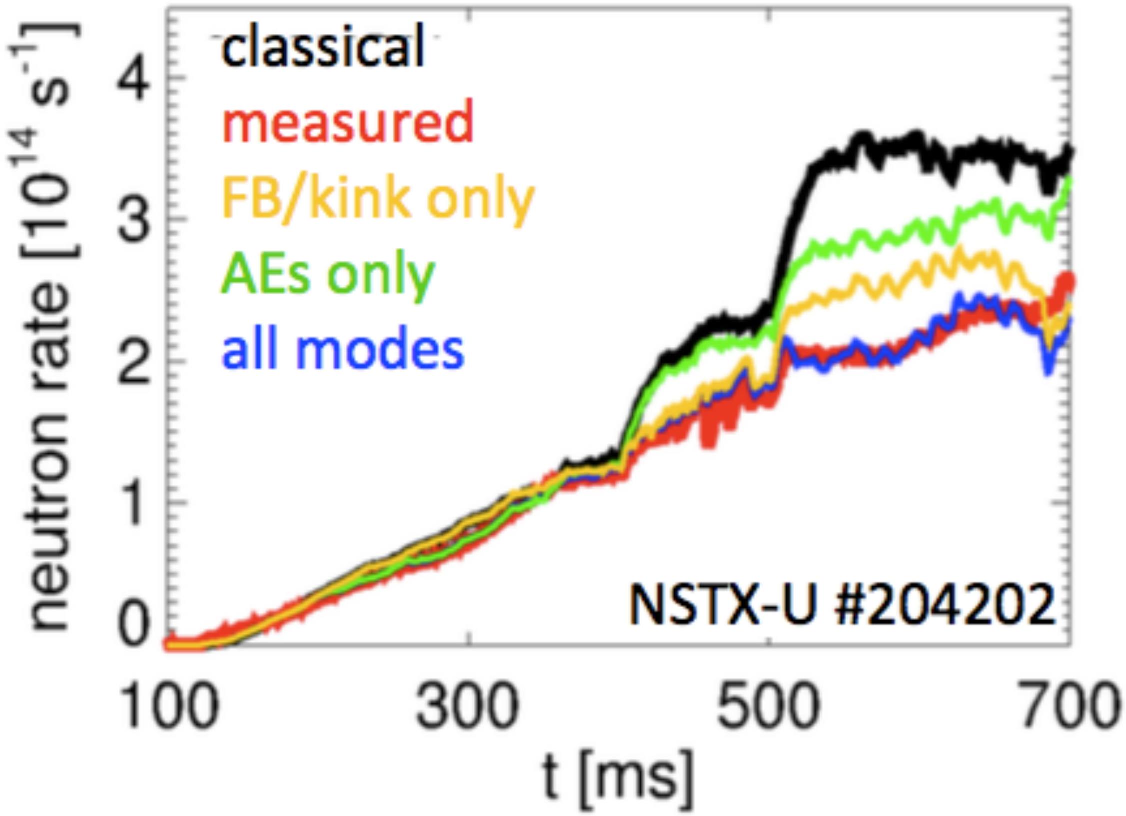
Multi-mode EP transport included in Integrated Simulations challenges predictive simulations

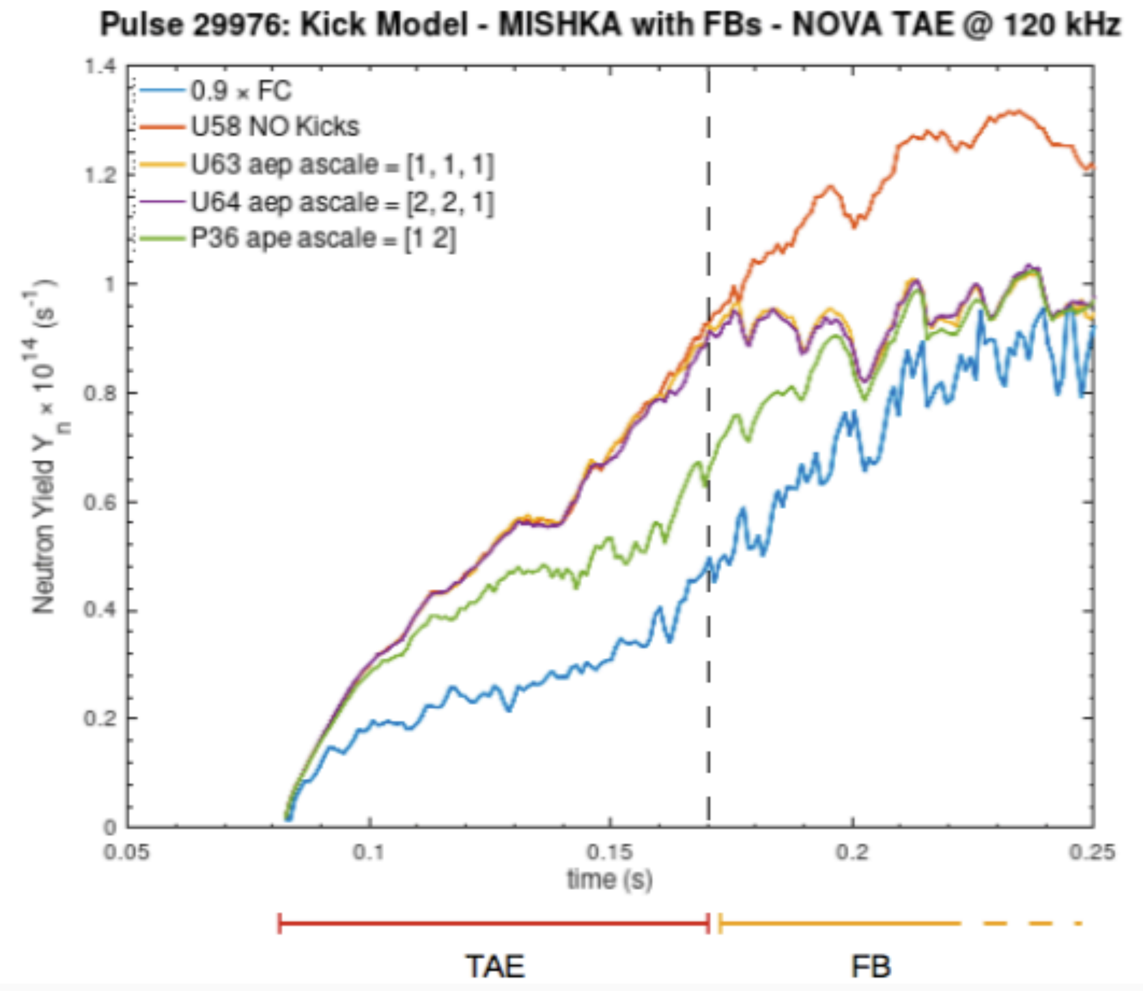
I-11 Podestà



- Multiple types of instabilities, e.g. AEs and kinks, can work synergistically -> enhanced EP losses
- “Coupling” between modes -> challenging scenario for simulations including self-consistent mode evolution

Modeling ramp-up scenario with AEs and fishbones in MAST: transport very sensitive to mode properties

O-12 Cecconello



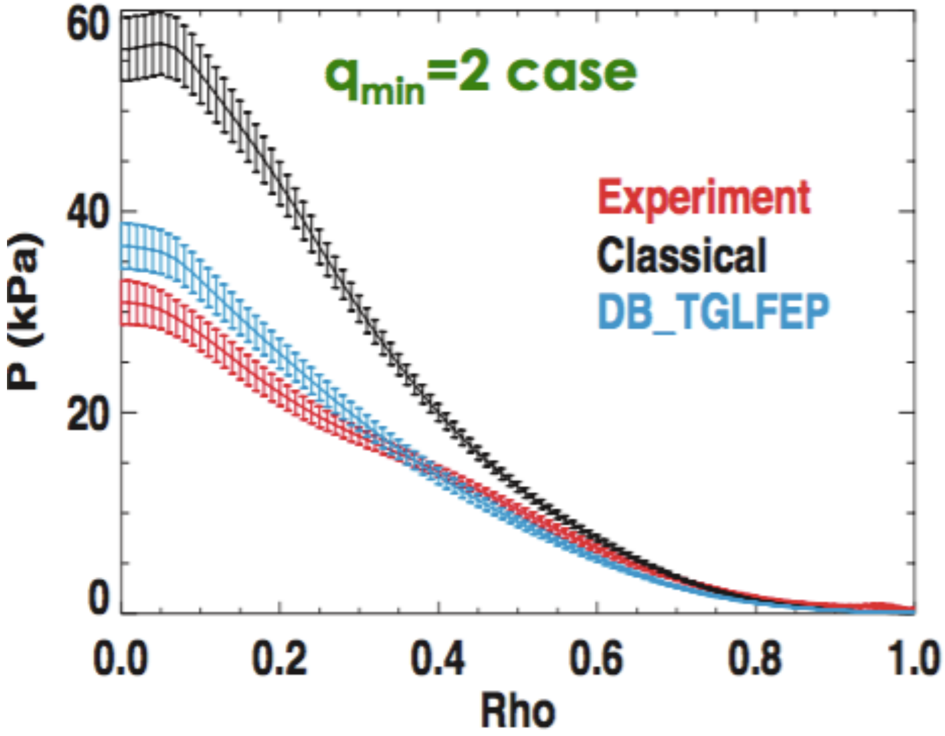
- TRANSP + ‘kick’ modeling reveals importance of mode properties used in simulations
- Comparison with phase-space resolved diagnostics ongoing

Critical gradient model TGLF-EP/ALPHA reproduces AE-induced profile relaxation in DIII-D

O-22 Bass

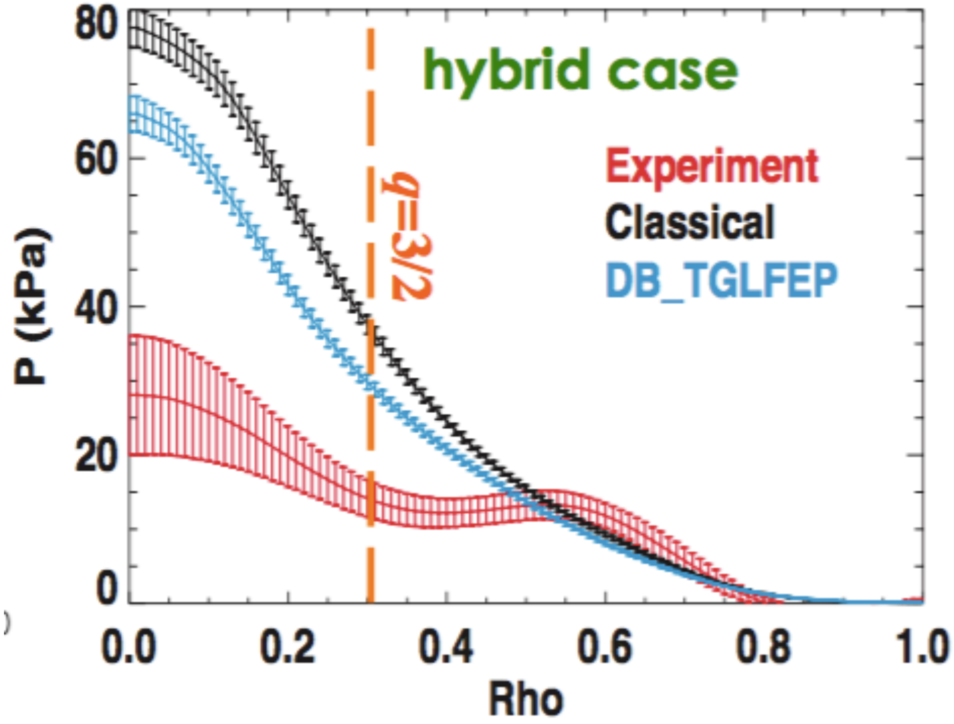
DIII-D #153072

EP pressure profile



DIII-D #161401

EP pressure profile



- Predicted profiles within +/-20% of measurements
- Larger discrepancies observed when modes other than AEs (e.g. NTMs) are present

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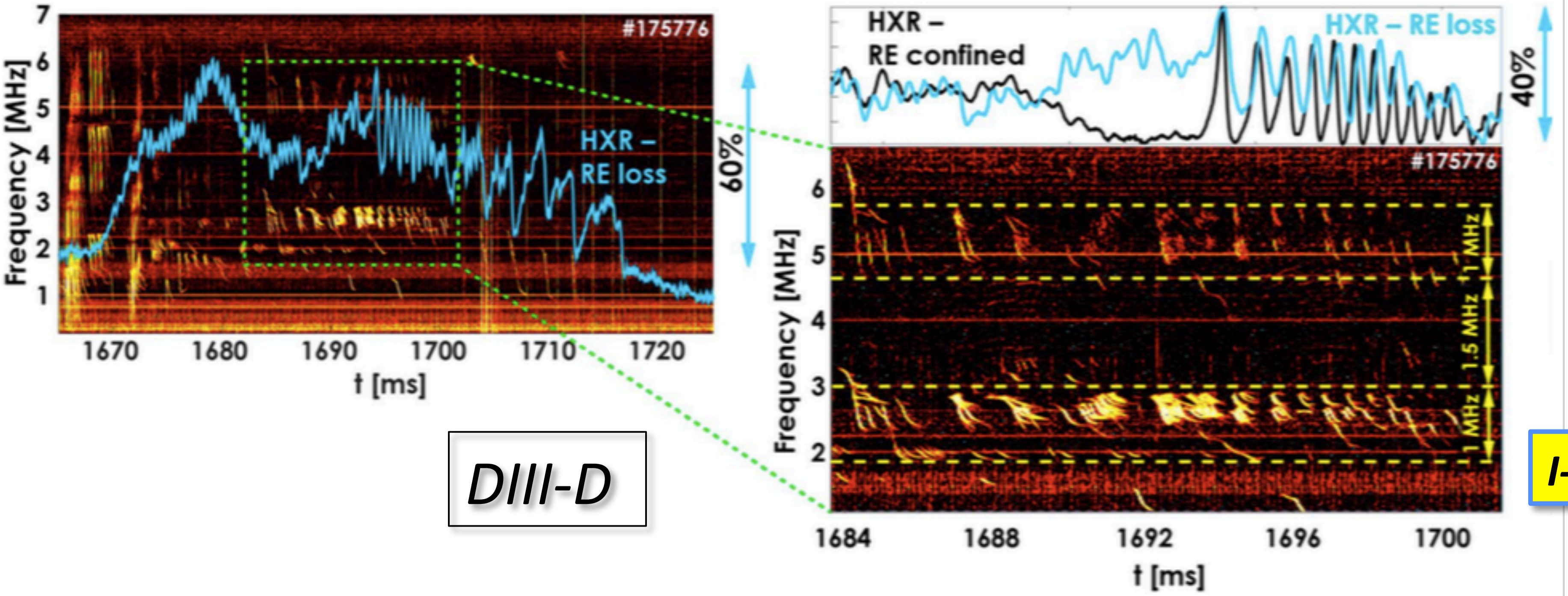
- **Physics of Runaway electrons**
- Mode control and scenario optimization
- Diagnostics and measurement techniques

Several instabilities can provide mechanism to dissipate Runaway energy



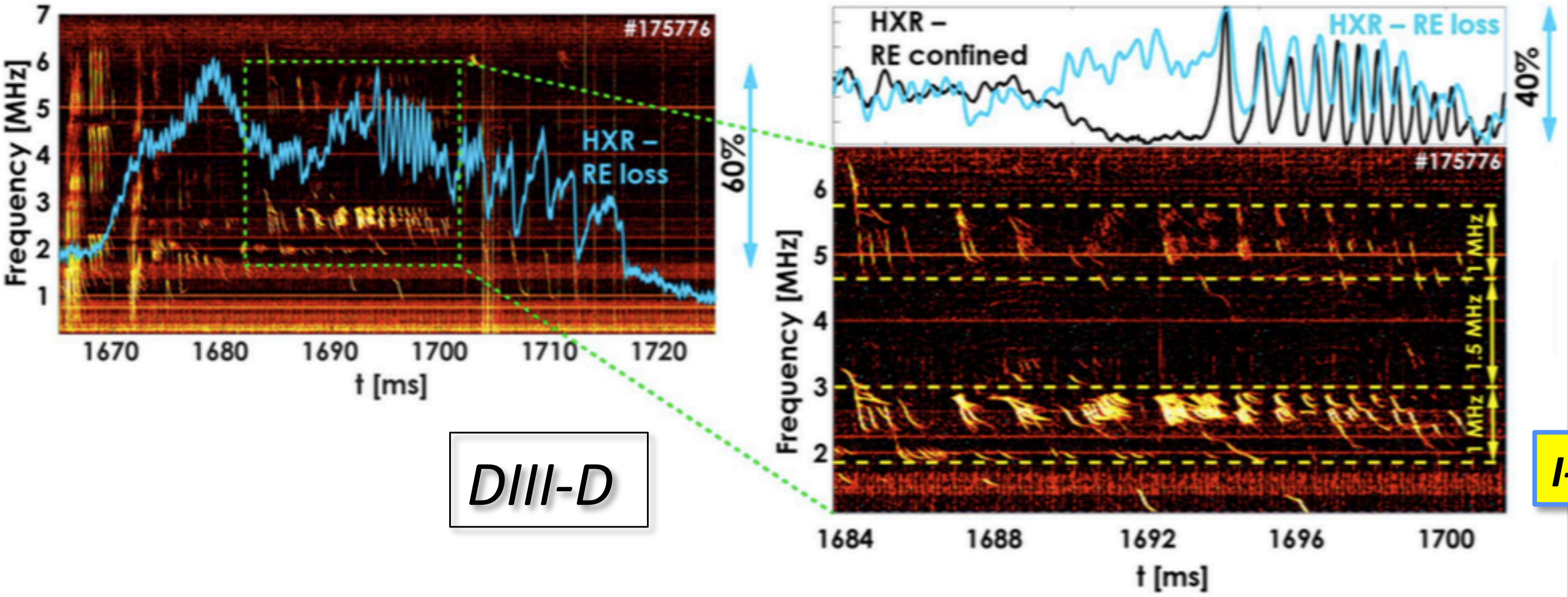
DIII-D

I-9 Lvovsky

- Chirping instabilities in DIII-D dissipate RE energy
- Extensive database from DIII-D experiments

P2-69 DeGrandchamp

Several instabilities can provide mechanism to dissipate Runaway energy



I-9 Lvovsky

- Chirping instabilities in DIII-D dissipate RE energy
- Extensive database from DIII-D experiments

P2-69 DeGrandchamp

- Runaways can drive GHz-range instabilities on KSTAR
- Also provide dissipation for Runaways
- *Can same modes be excited by external actuators?*

O-11 Kim

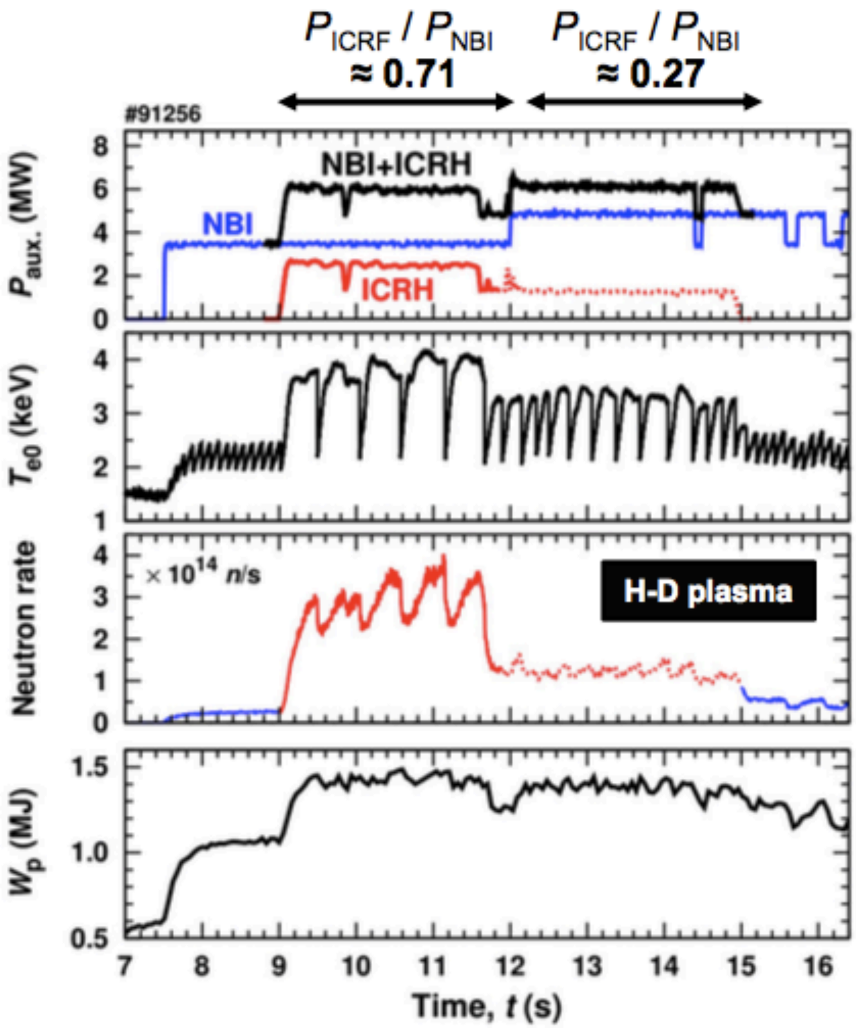
Measurements of RE distribution: ***P-60 Nocente***

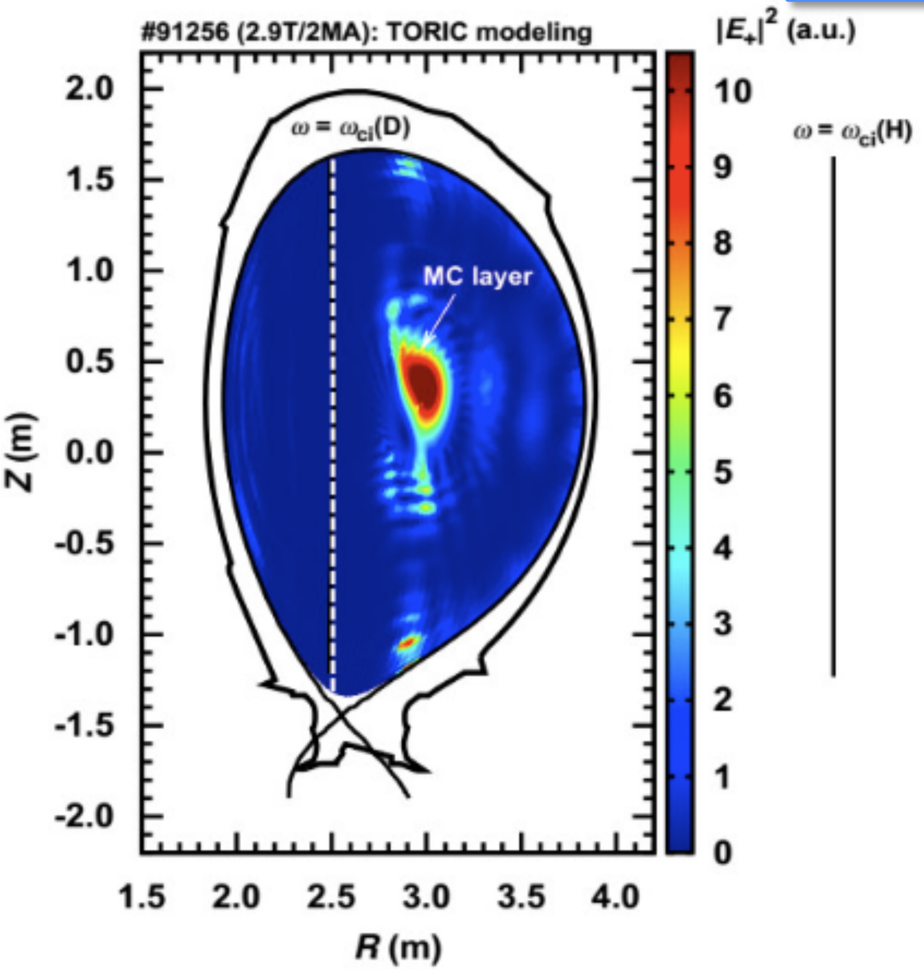
Topics

- Physics of Alfvén Eigenmodes and other instabilities
- Energetic particle transport
- Physics of Runaway electrons
- **Mode control and scenarios, including RF+NBI**
- Diagnostics and measurement techniques

3-ion ICRF scheme on JET provides controlled ion acceleration, expand operating scenario

O-1 Kazakov



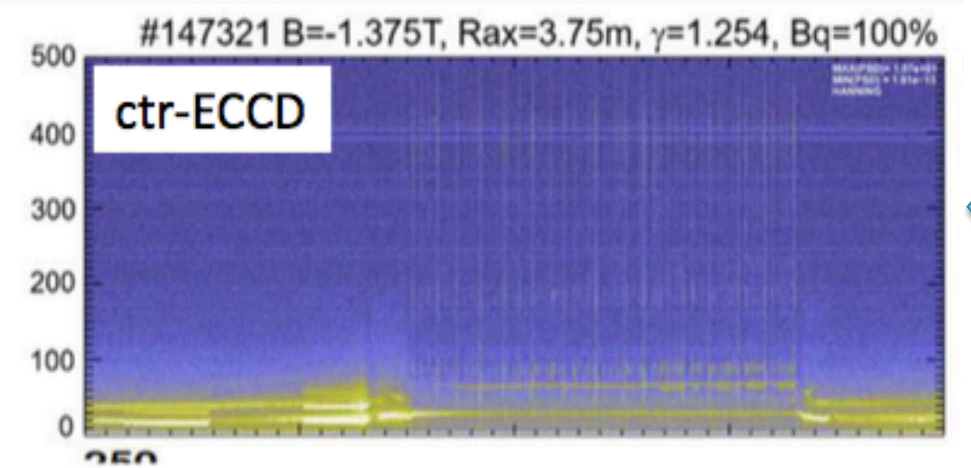


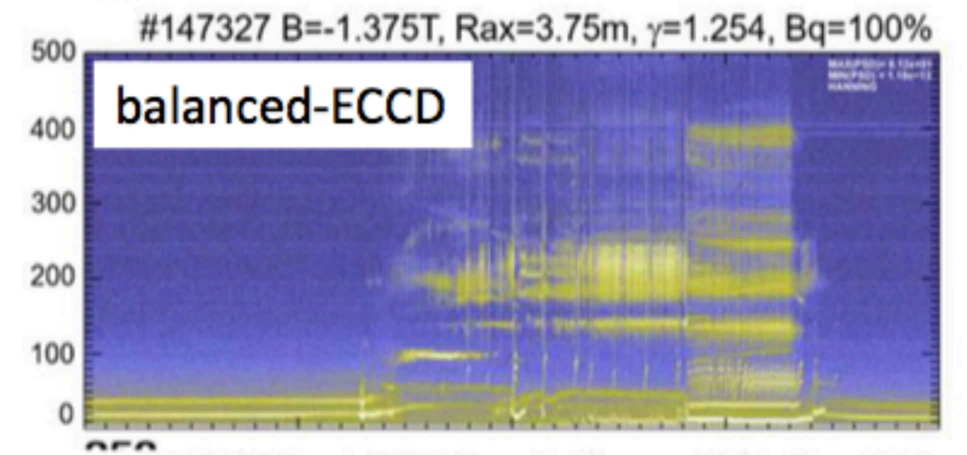
- Vary absorption, EP acceleration energy through P_{rf}/P_{nb}
- Highlights strength of EP diagnostics in JET

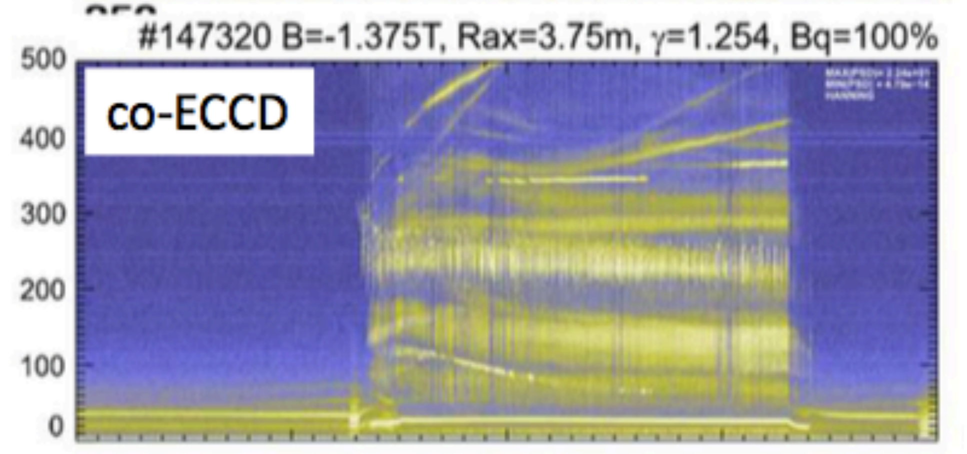
P-76 Sahlberg

ECCD dramatically affects AE behavior in LHD

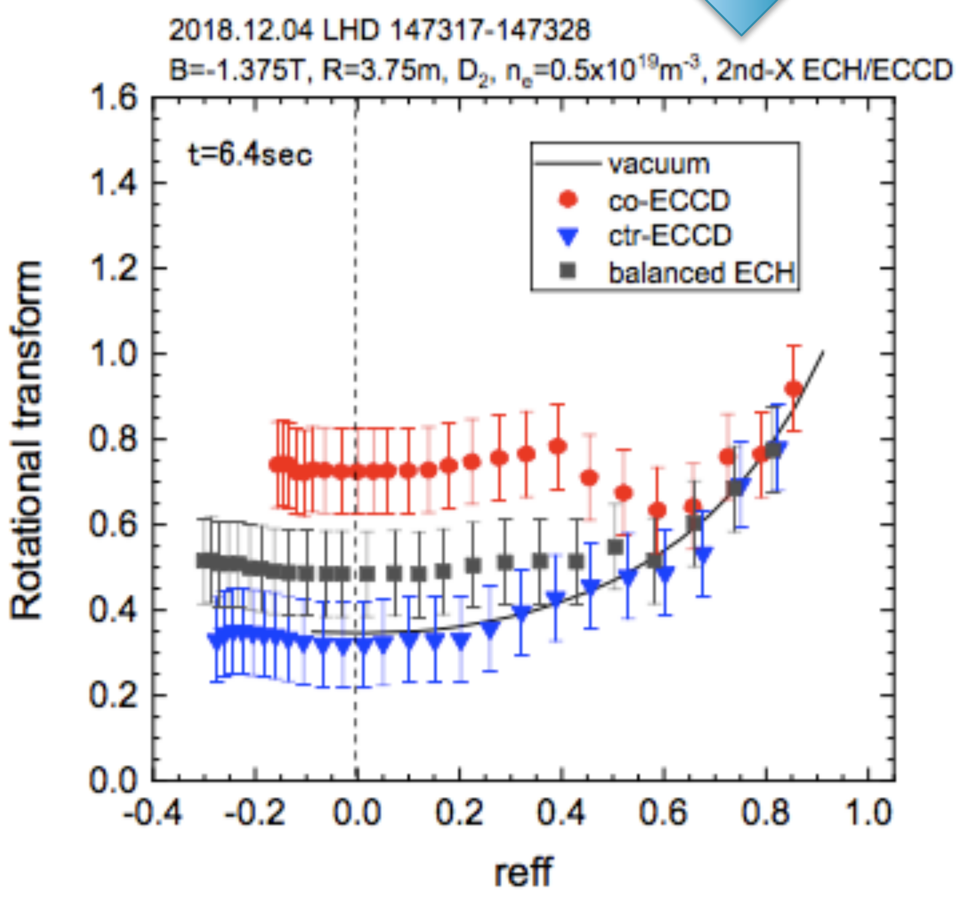
I-2 Nagaoka







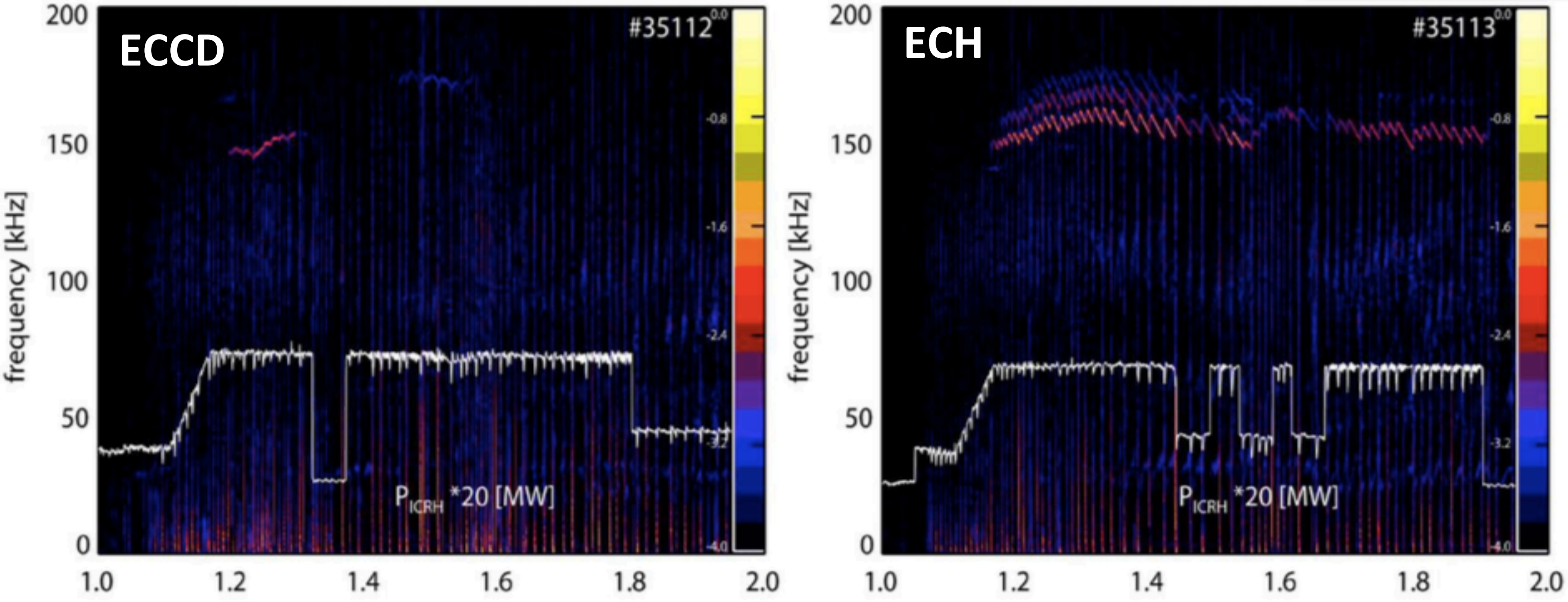
- cntr-ECCD: stabilizing
- co-ECCD: de-stabilizing
- large changes in *iota*


2018.12.04 LHD 147317-147328

B=-1.375T, R=3.75m, D_2, n_e=0.5x$10^{19}$$m^{-3}$, 2nd-X ECH/ECCD

ECCD suppression of AEs in ASDEX-Upgrade explained by local changes in magnetic shear

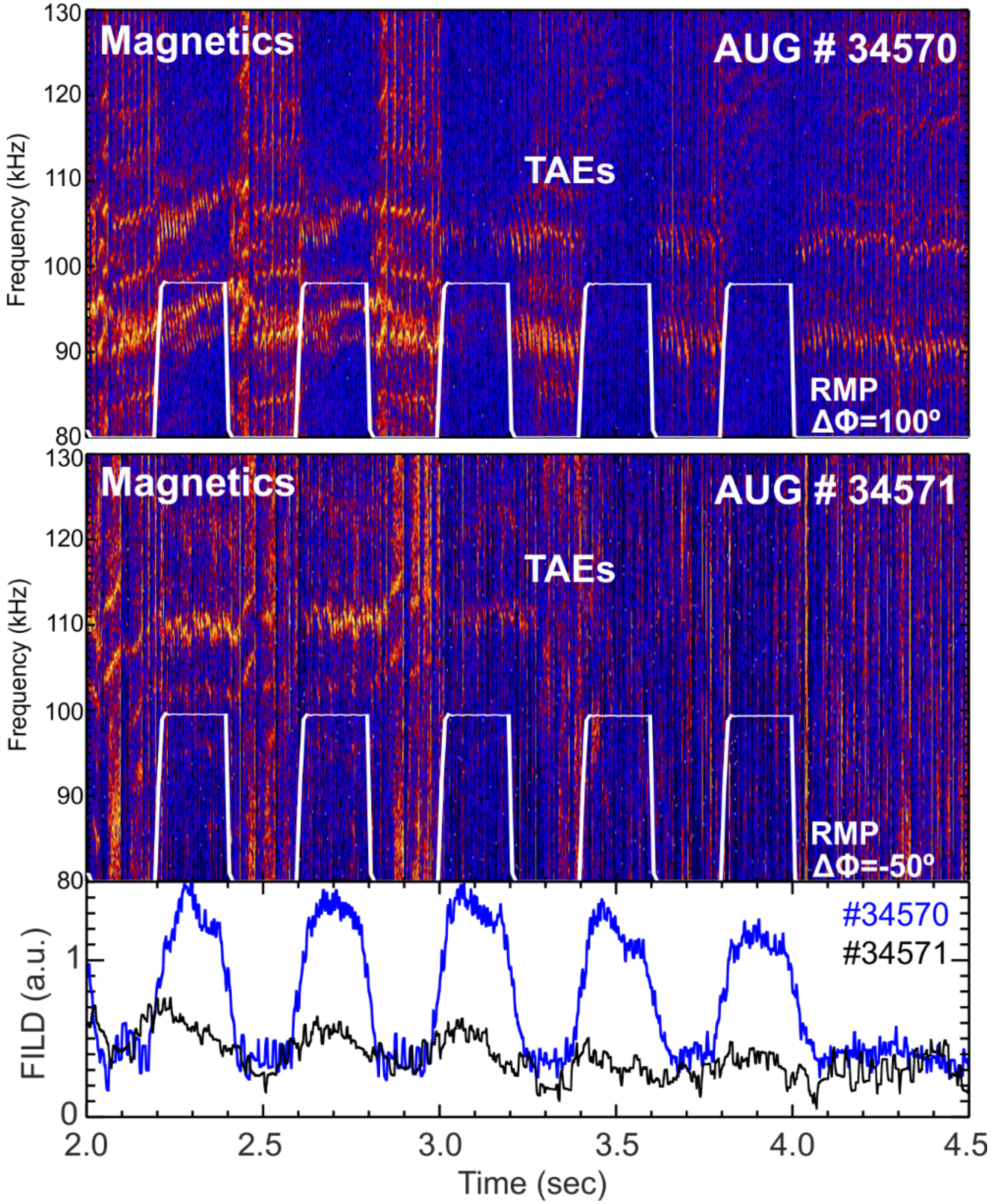
I-12 Sharapov



- Suppression of AEs observed in ECCD discharges
- AE activity much reduced in ECCD than in ECH discharge
- Modeling reveals critical role of *local* magnetic shear
- Experiments also conducted on KSTAR

P-32 J. Kang ***P-49 J. Kim***

TAE activity successfully controlled by externally applied RMPs on ASDEX-Upgrade



O-14 Garcia-Muñoz

- n=2 RMP has strongest impact with full suppression / excitation
- <u>Plasma response</u> to RMP may expand capability to control EP distributions over extended radial region
- Effects on rotation, EP losses:

P-97 Cano-Megias

I-8 Rivero Rodriguez

O-9 Dominguez Palacio

- 3D fields effects on EPs also observed on KSTAR

P-52 K. Kim

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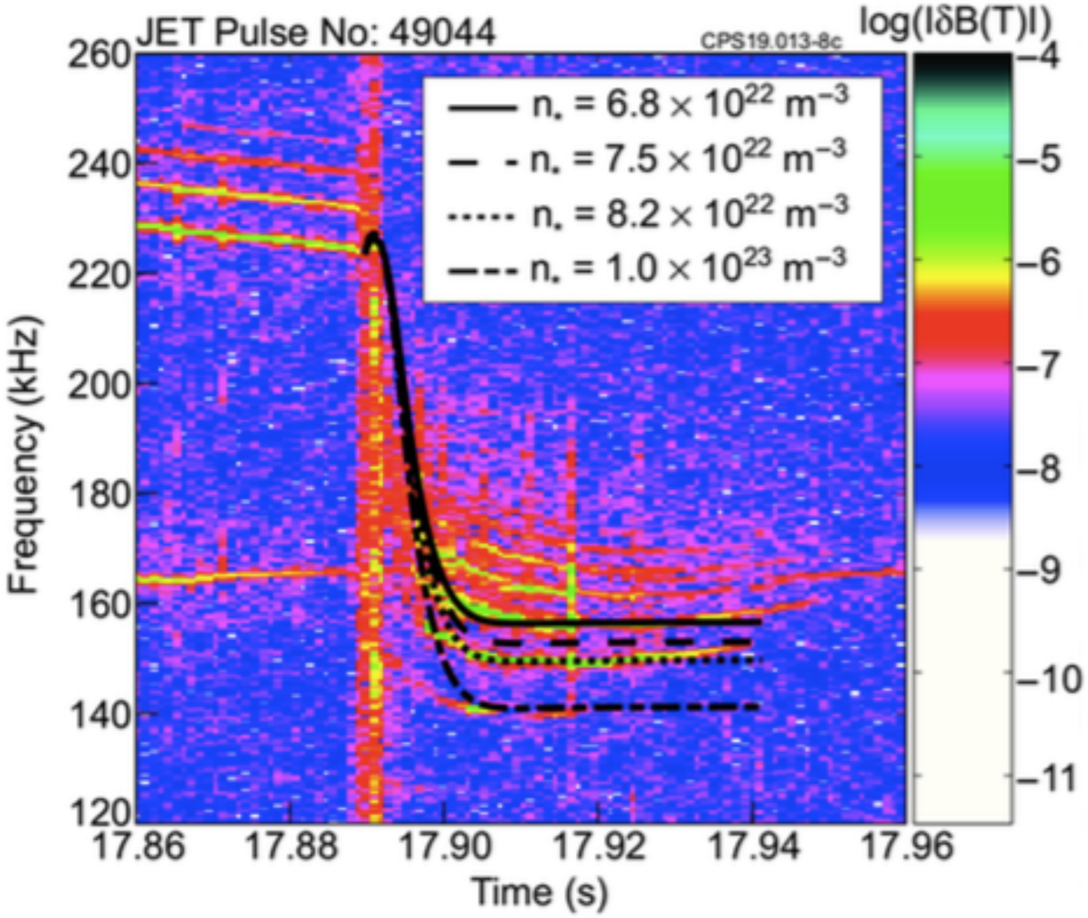
- **Diagnostics and measurement techniques**

MHD spectroscopy can be used to infer properties of pellet density "wake"

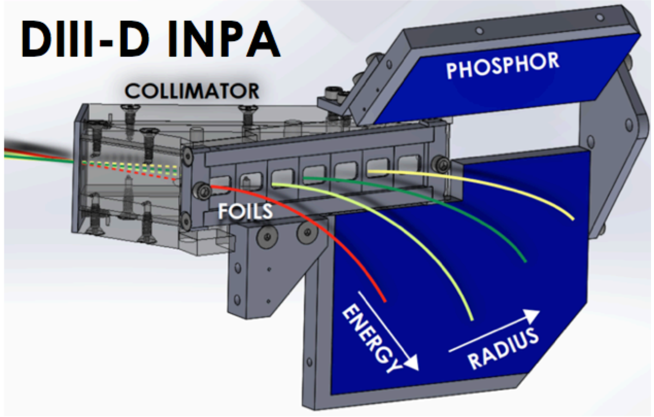
O-4 Oliver

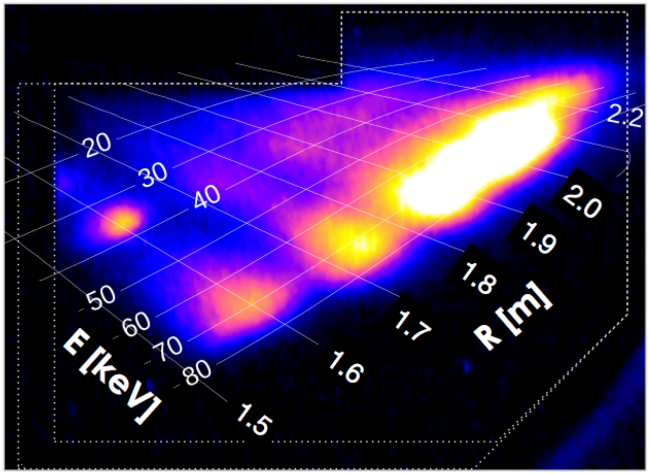


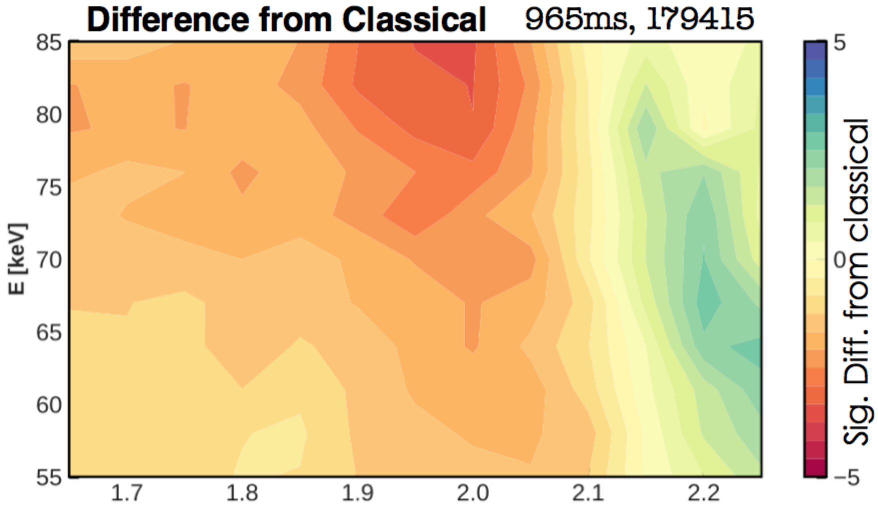
- Applied to pellet-injected plasmas in JET
- Model for wake expansion vs experimental AE data provides wake density at mode location

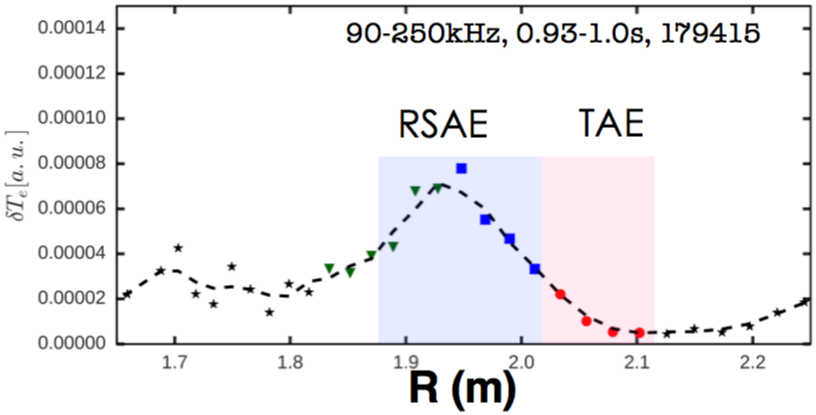
New Imaging NPA (INPA) on DIII-D enables detailed measurements of EP dynamics in phase space

I-15 Du





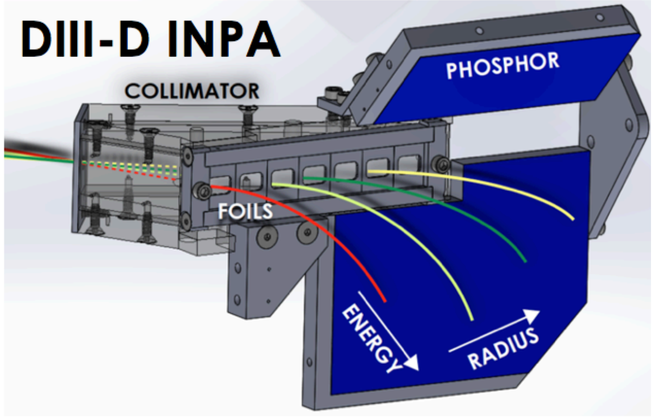


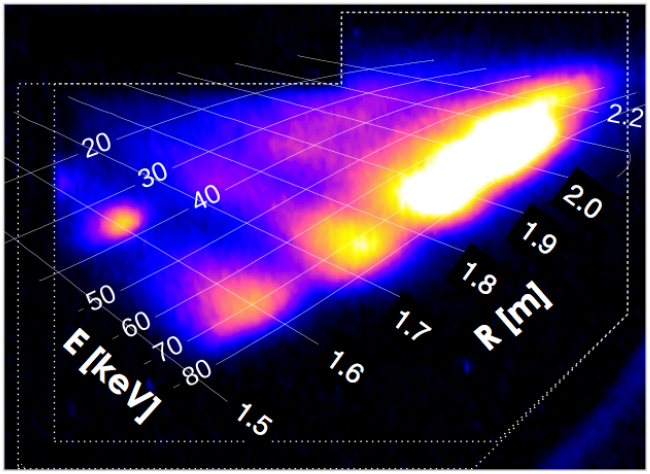


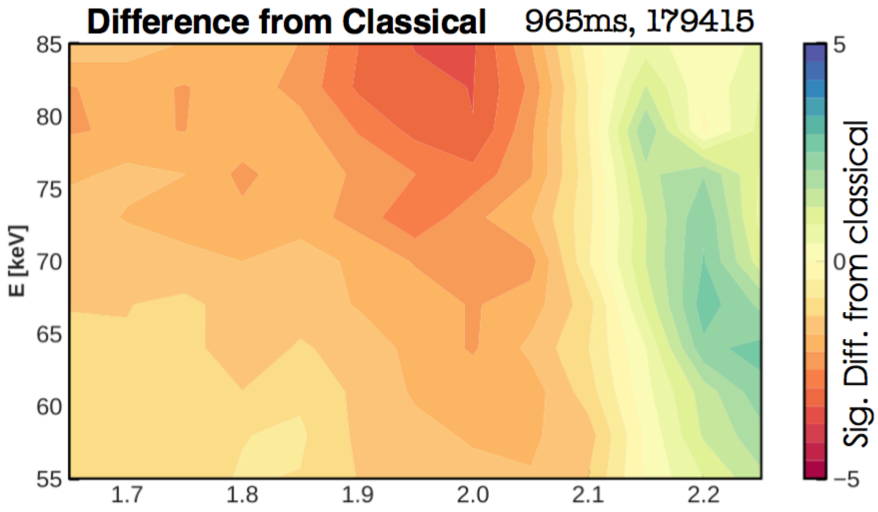
- Combination of traditional NPAs and FILDs, measures passing EPs across mid-plane
- EP transport by Sawteeth and AEs directly measured vs. time, energy and radius
  - Large transport is observed where AEs overlap
  - Core localized RSAEs cause redistribution from the core to large radius

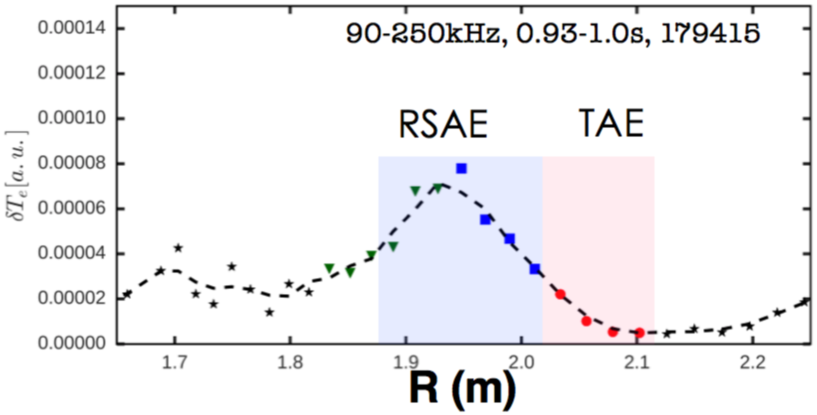
New Imaging NPA (INPA) on DIII-D enables detailed measurements of EP dynamics in phase space

I-15 Du









- Large amount of data enable tomographic inversion of F_{nb}
  - Demonstrated for sawtooth-induced EP losses
- FIDASIM, INPASIM used for interpretation of INPA data

P1-99 Garcia **P1-8 Lin**

FIDASIM on KSTAR: **P1-71 Yoo**

Comprehensive set of EP diagnostics available for EP studies in Deuterium LHD plasmas

O-21 Osakabe

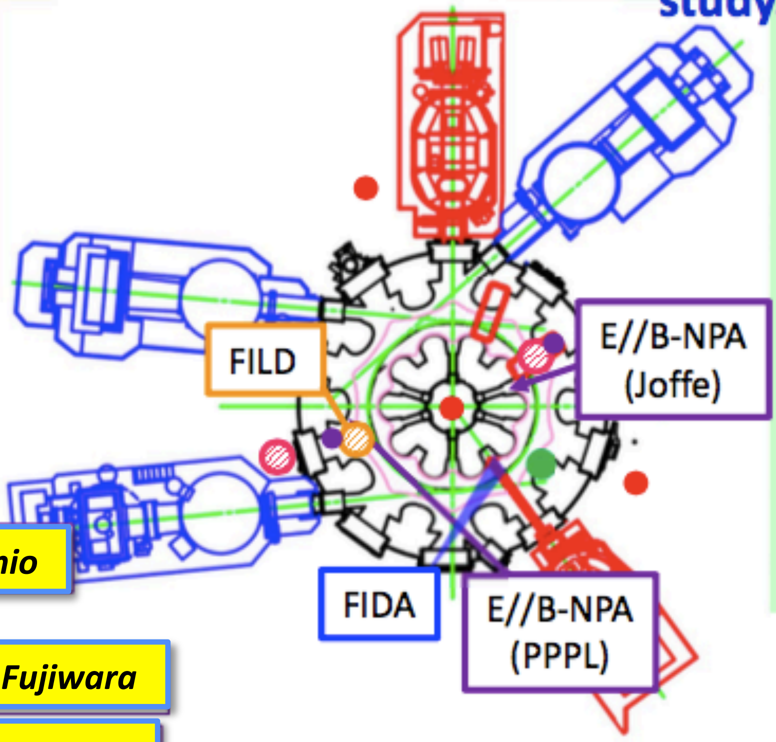
Powerful EP sources

- **Negative-NBI** (tangential)x 3, H16MW, D8MW@ 180keV
- Positive-NBI (radial) x 2 , H:12MW@40keV, D:18MW@60/80keV
- ICH (38.47MHz) x 2 1 MW

Other EP Diagnostics

- E//B-NPA **O-18 Kamio**
  - ✓ Tangential (PPPL-type)
  - ✓ Radial (Joffe-type)
- Fast Ion D/H Alpha (FIDA) **P1-10 Fujiwara**
  Tangential/Radial
- Fast Ion Loss Detector (FILD) **O-13 Seki**

etc



Neutron Diagnostics enable the global EP confinement study.

- 3 sets of Neutron Flux Monitors (U-235 Fission Chamber and He-3/B-10 proportional chamber)
- 2 Vertical Neutron Cameras
- 2 Sci.-Fi. 14MeV neutron detectors
- 2 Neutron Activation foil System

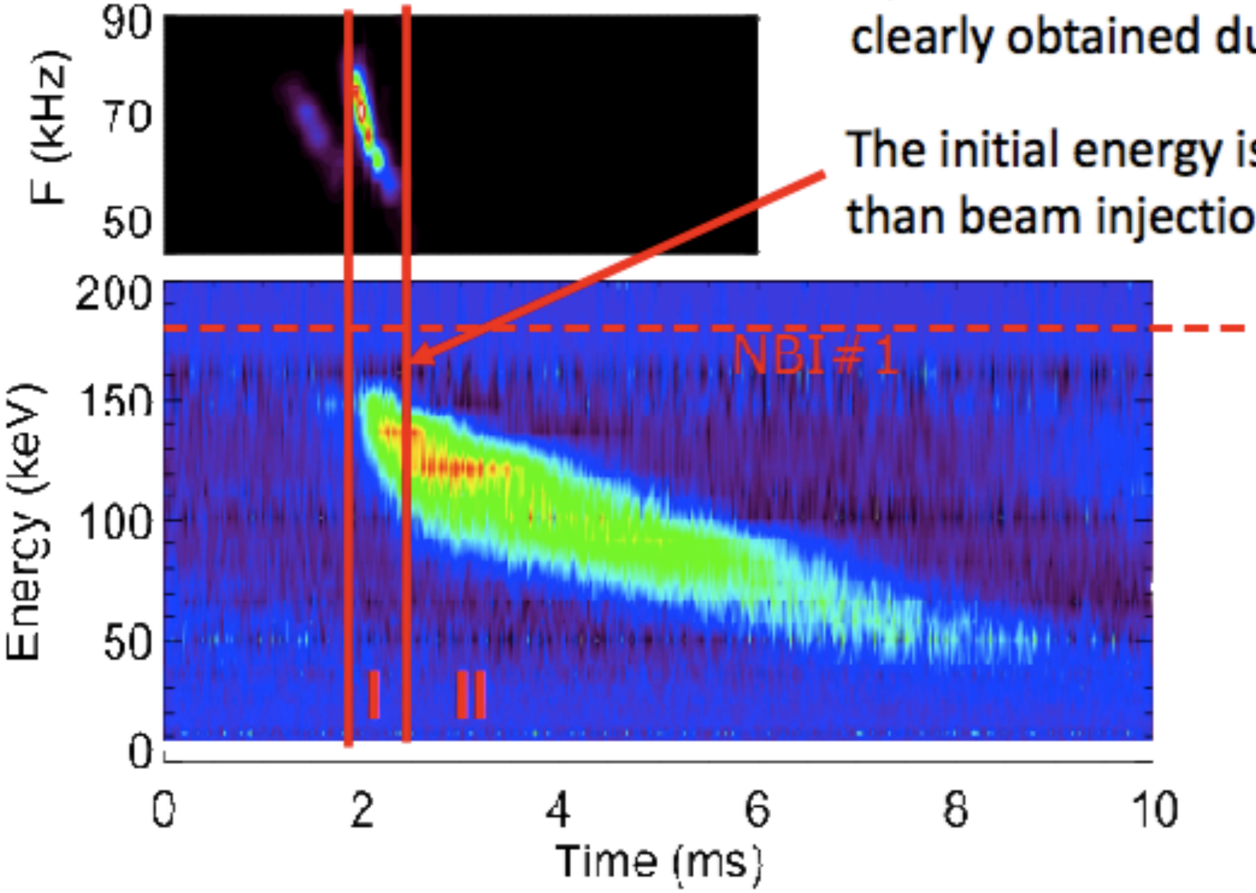
See more detail at
P1-18 Isobe & **I-16 Ogawa**

FIDASIM enhancements for LHD **P1-63 Fujiwara**

Also: development of fast neutron detector **P1-15 Takada**

Upgraded E//B NPA on LHD measures hole/clump response to TAE bursting modes

O-18 Kamio



By the conditional average, the shape of the clump clearly obtained during and after the TAE bursts.

The initial energy is 150 keV, which is less than beam injection energy of 180 keV.

Phase I (during the TAE burst)

Observed particle flux increase and energy decrease. The frequency of the fluctuation also decrease.

Phase II (after the TAE burst)

Energy slowing down.

τ_s ~ 5.5-6.0 ms