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Toroidal Alfven eigenmodes driven by runaway electrons during minor disruptions in SUNIST ohmic plasmas

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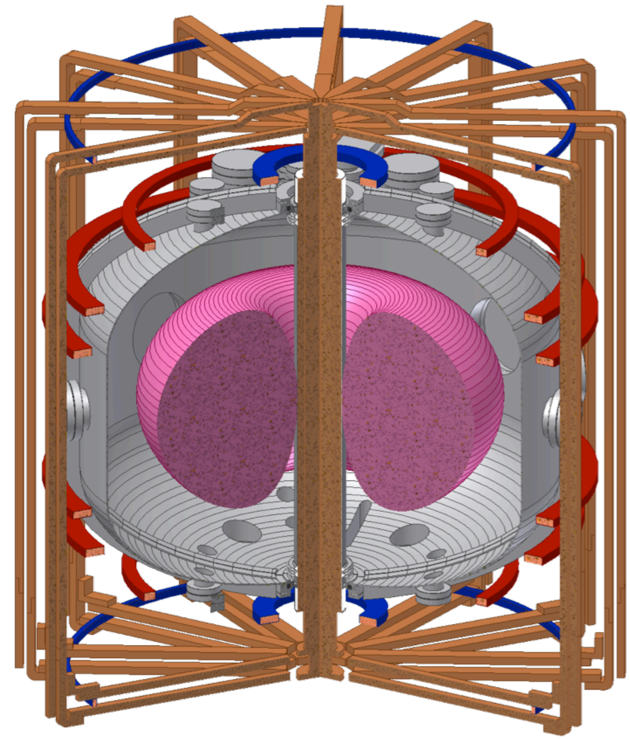
Alfven Eigenmodes (AEs)

- AEs (typically, TAEs) are important in burning plasmas
- TAEs can be excited by energetic ions: firstly observed in TFTR (Wong 1991)
- Also by fast electrons: firstly in Compass-D (Valovic 2000)

Device	Heating and power	MHD type	Mode character	Energy	Reference
Compass-D	ECRH, <1.3MW	TAE	$m/n=1/1$? f~250-450kHz	10-100keV	Valovic, 2000
C-Mod	LHW, <1MW	TAE	n=1-6, f~200-800kHz	40-100keV	Snipes, 2008
HL-2A	ECRH, 0.4-1.5MW	Fishbone, BAE	$m/n=1/1$, f~5-15kHz; $m/n=3/1$, f~ 10-25kHz	30-70keV	Chen, 2009,2010 Ding, 2013
LHD	ECRH, ~3MW	BAE or BAAE?	n=1,2, f~10-20kHz	60-300keV	Isobe, 2015

The SUNIST device

- **Main parameters**
  - Major radius (R_0): 0.3 m
  - Minor radius (a): 0.23 m
  - Aspect ratio: ~ 1.3
  - Elongation: ~ 1.8
  - Toroidal field at R_0: < 0.15 T
  - Plasma current: ~ 50 kA
  - Pulse duration: < 20 ms (Ohmic)
  - n_e: 0.1 ~ 3×10^{19} m^{-3}
  - T_e: ~ 100 eV

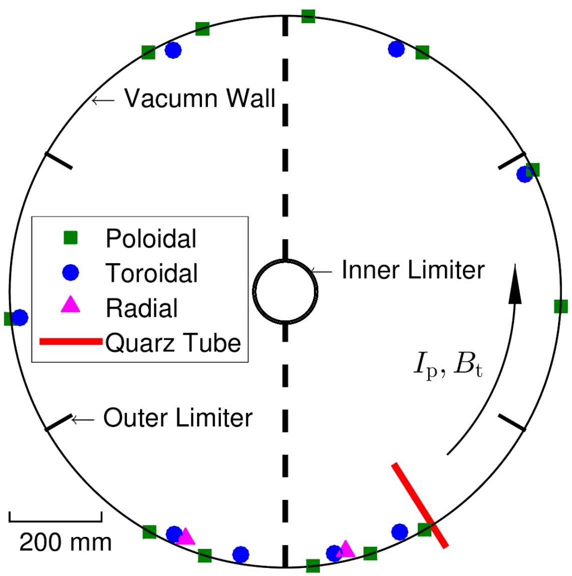


- **No NBI, No ECH and No other waves injection in this exp. We have only runaway electrons.**

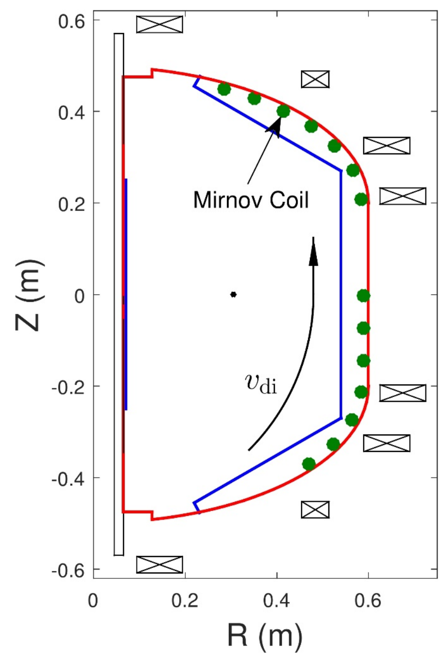
Outline

- Observation of high frequency MHD during minor disruptions
- Identification of TAE
- Driving mechanism
- Summary

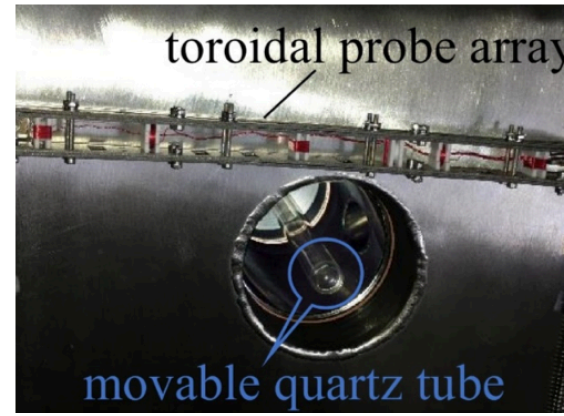
Diagnostics: High Frequency Magnetic Probes

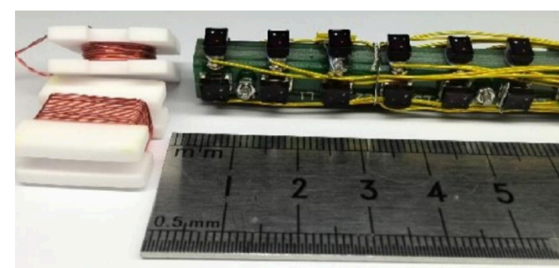


Toroidal distribution



Poloidal distribution



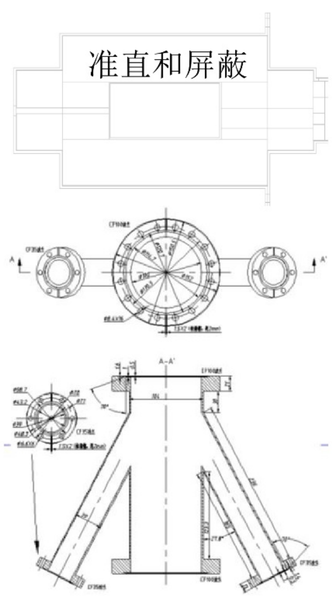


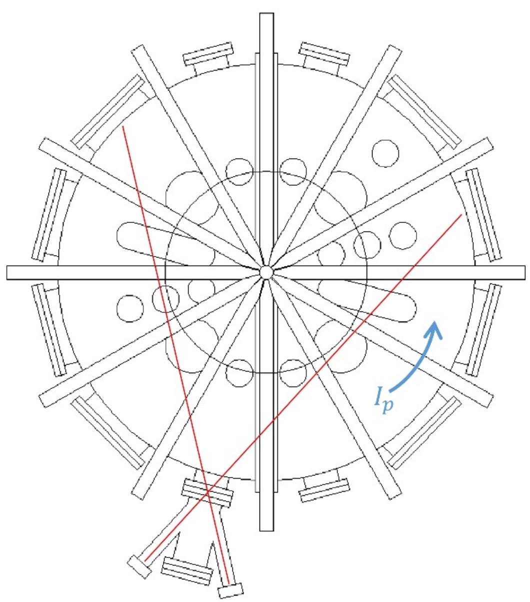
- **Frequency response > 2 MHz**

Liu Y.Q., RSI, 2014

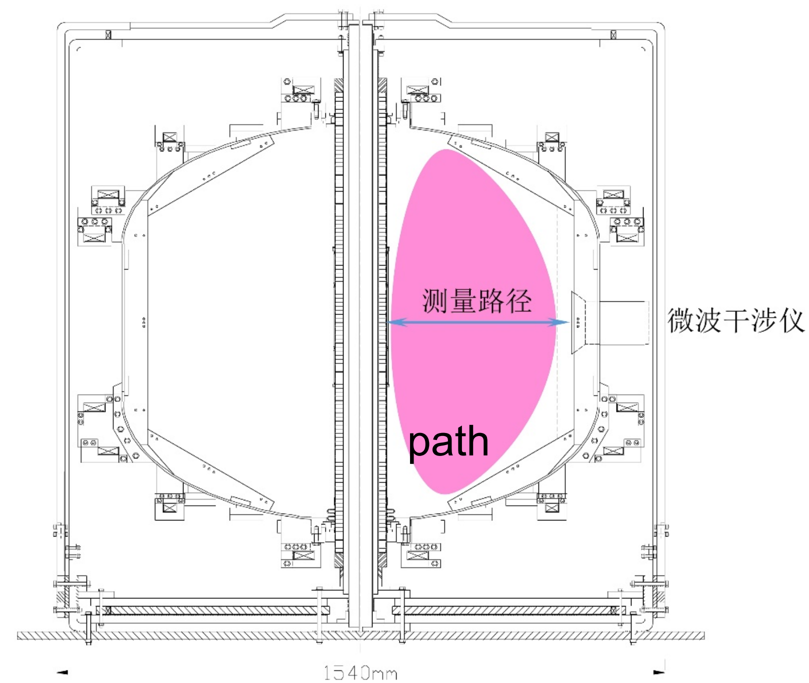
Diagnostics: HXR and interferometer

- **CdZnTe HXR detector**
  - 10keV-1.3MeV
  - Forward & backward direction

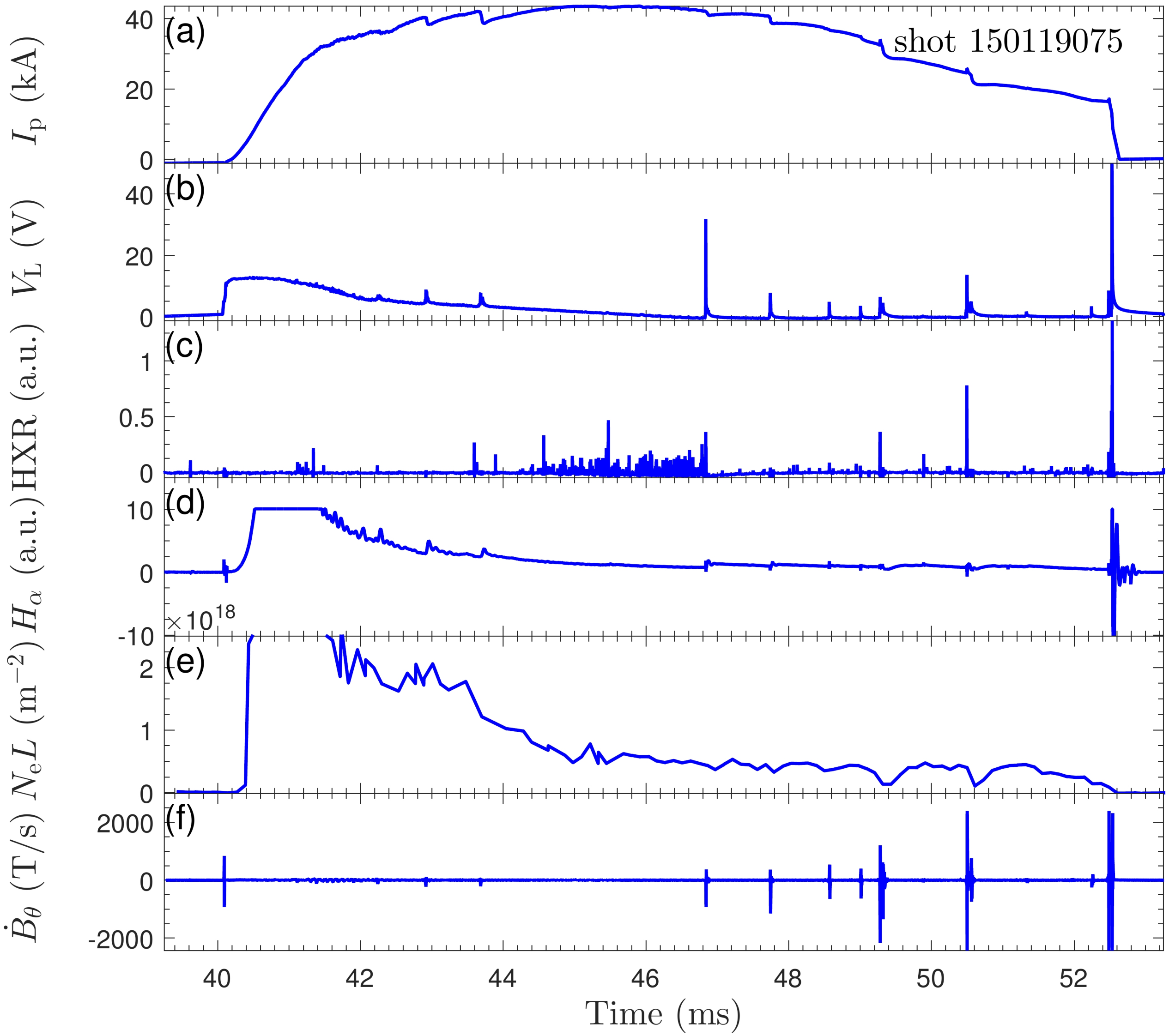




- **Microwave interferometer**
  - 94GHz
  - Horizontal path

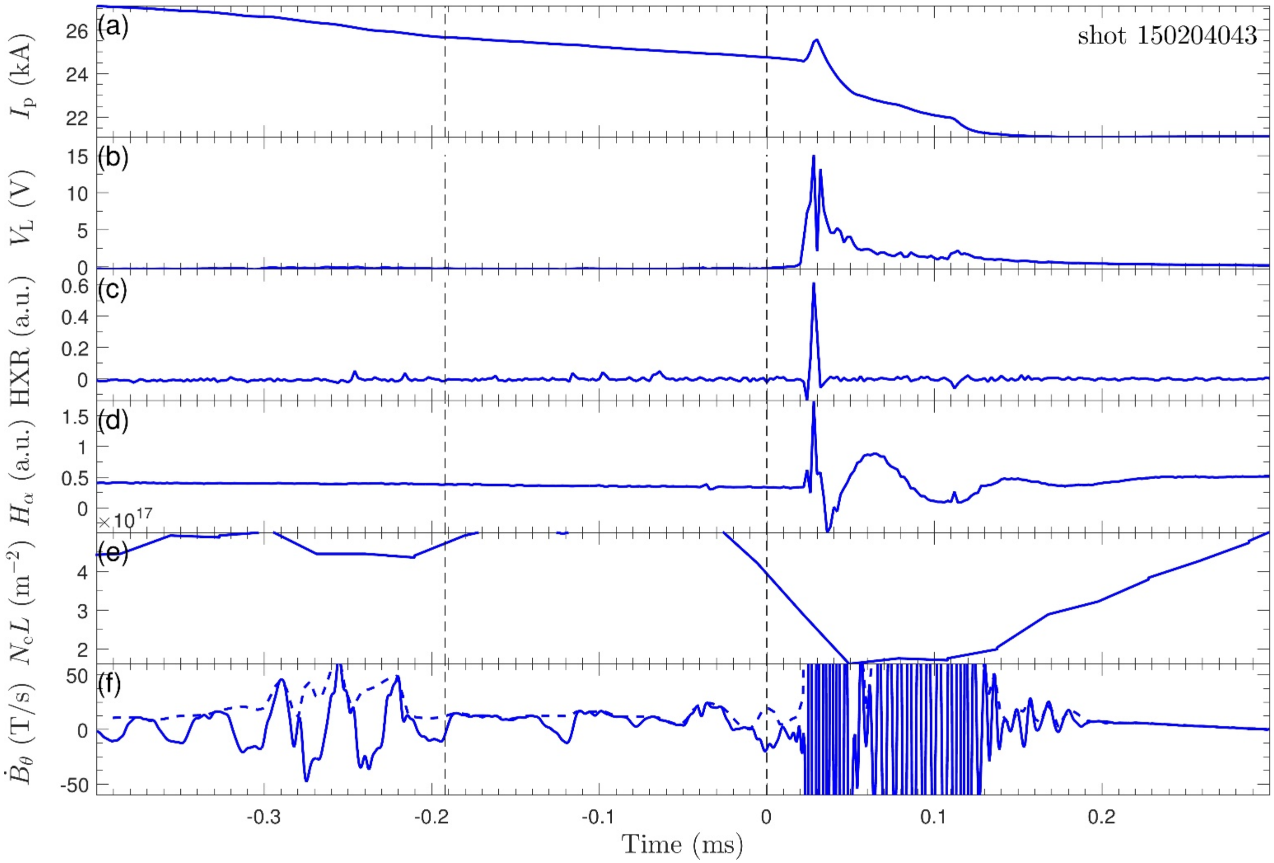


Typical discharge with minor disruption in SUNIST



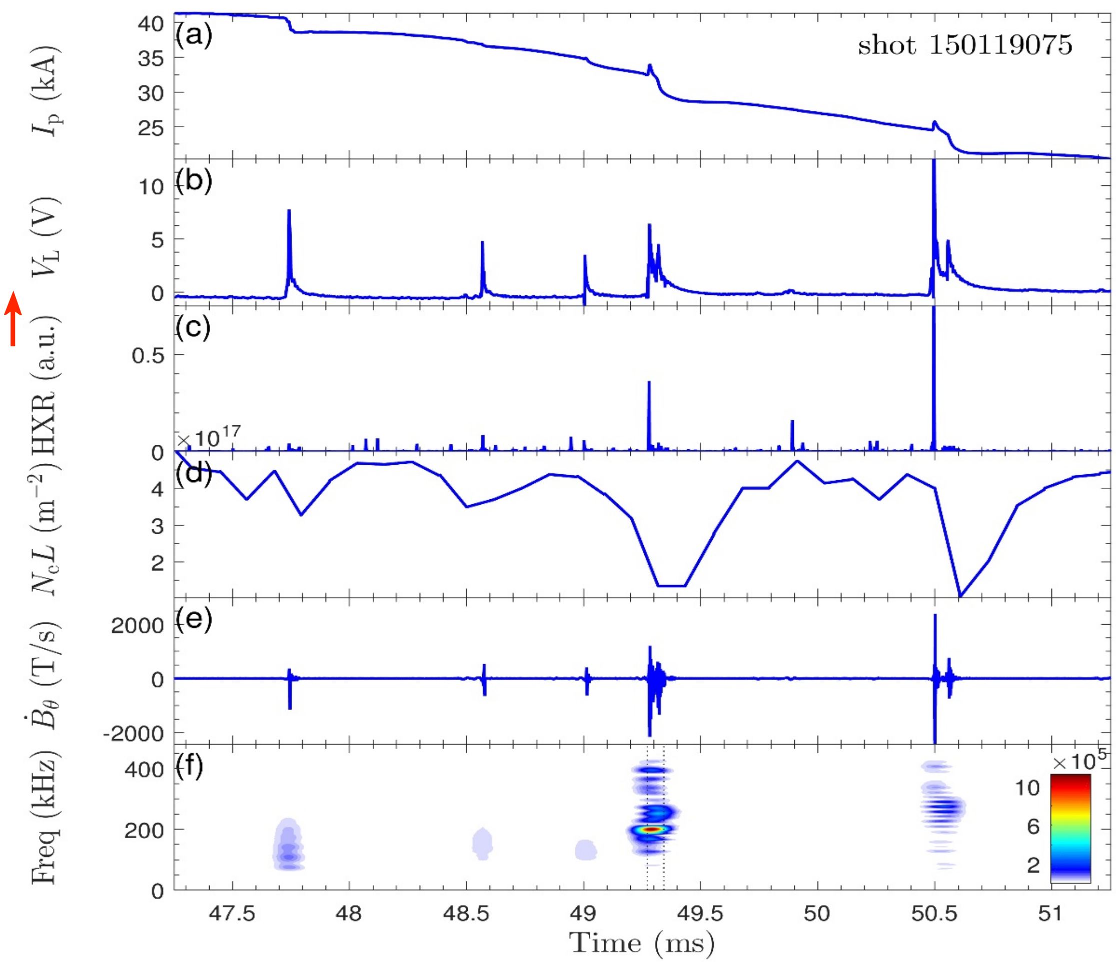
MHD activities during minor disruption

- MHD (m=-3/n=-1,f~26kHz) grows → mode locking →current quench→ HF MHD burst & RE plateau



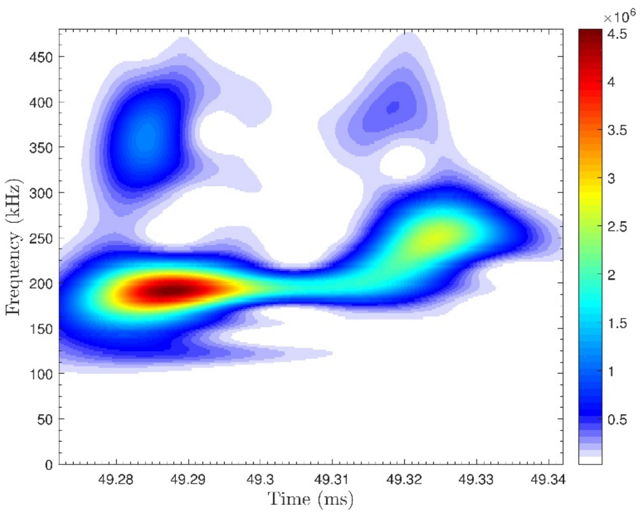
Repeatable behaviors during several minor disruptions in one shot

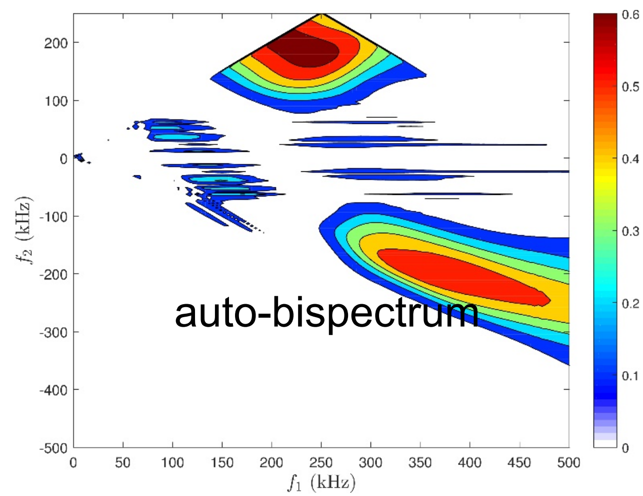
- **Spiky loop voltage**
- **High HXR burst**
- **Density ↓, frequency ↑**

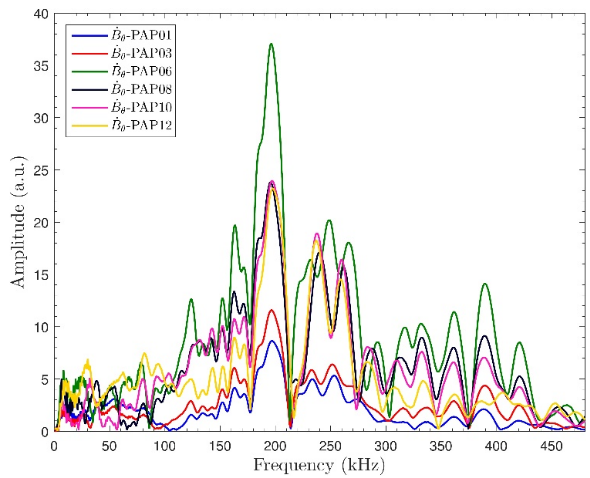


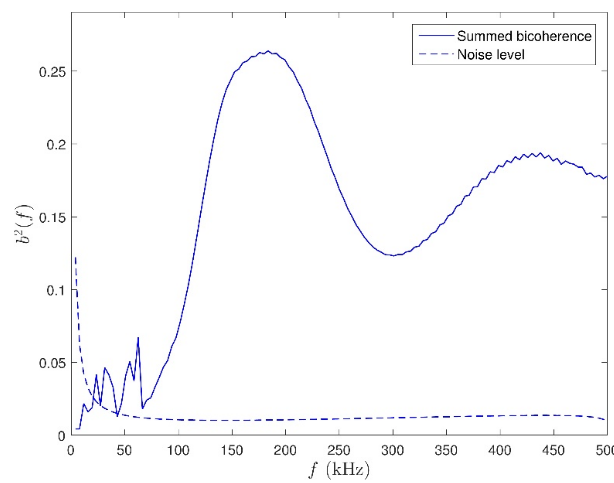
Mode characters: frequency

- f~150-300kHz
- double freq. due to NL coupling



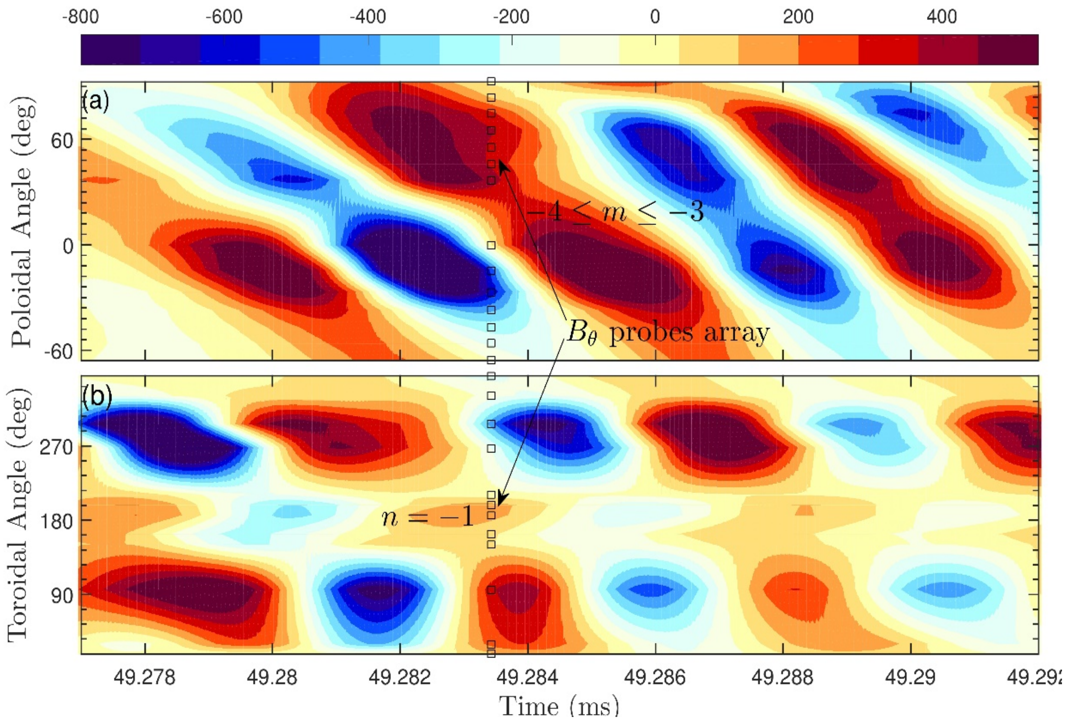




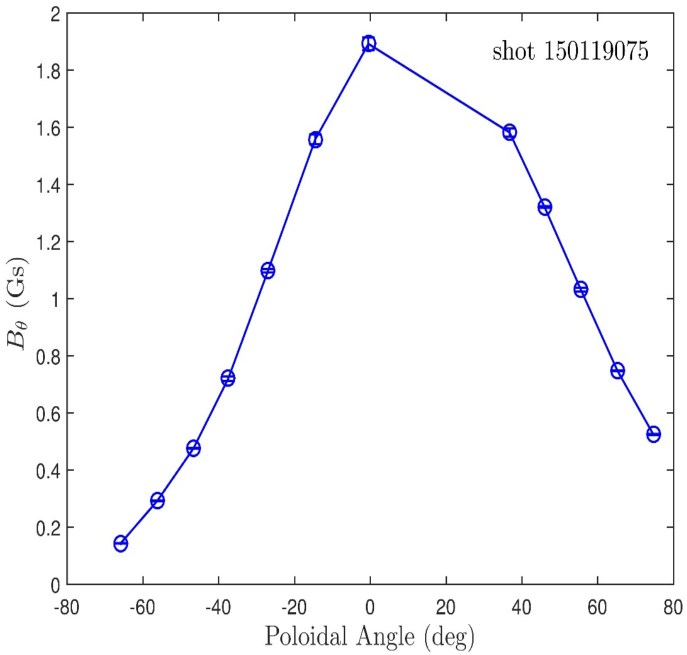


Mode characters：structure

- n=-1, -3>m>-4

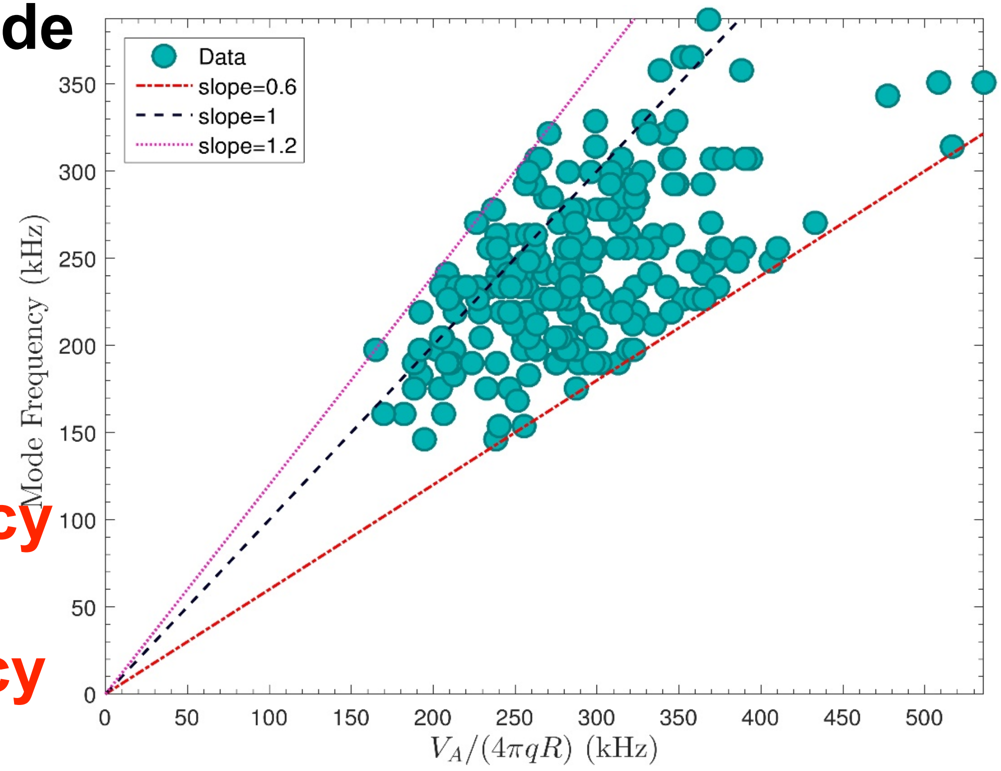


- Ballooning character

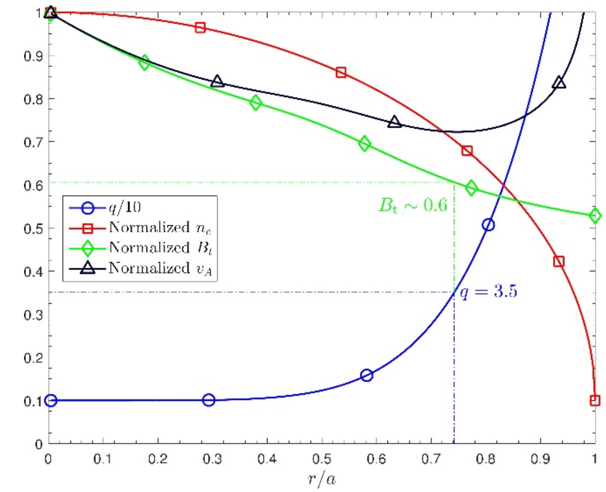


Parameter dependences

- **Toroidal Aflven Eigenmode**
  - **m&m+1 degenerate**
  - $f_{TAE}=V_A/4\pi qR,\ nq=m+1/2$
- **Mode structute (Exp.)**
  - **m=-3~-4/n=-1**
  - ***q*=3.5**
- **Observed mode frequency scales linearly with the calculated TAE frequency**
  (central toroidal field and line -averaged density used)



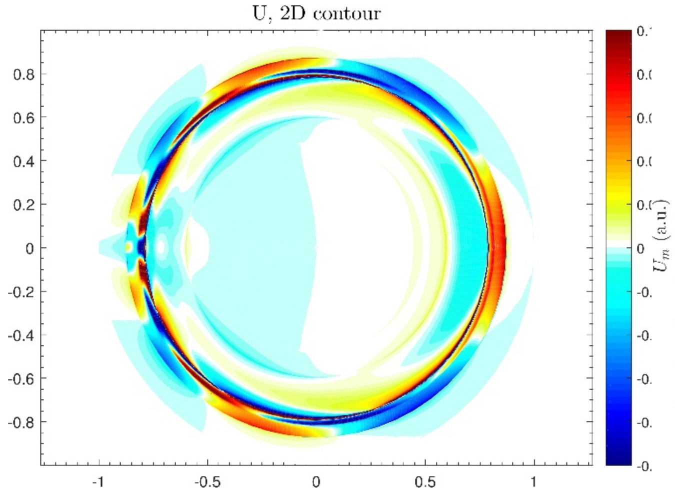
TAE calculation

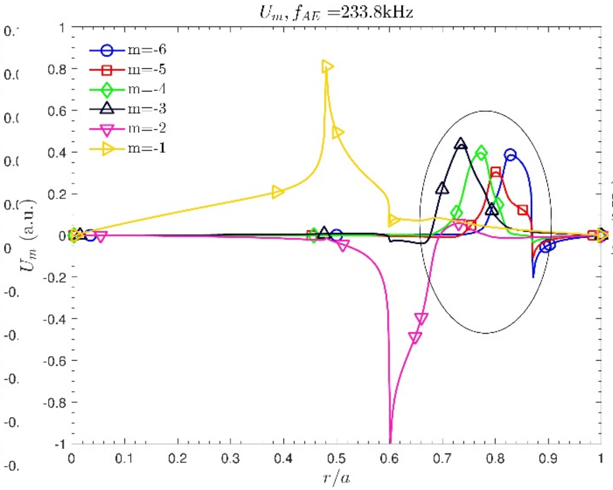


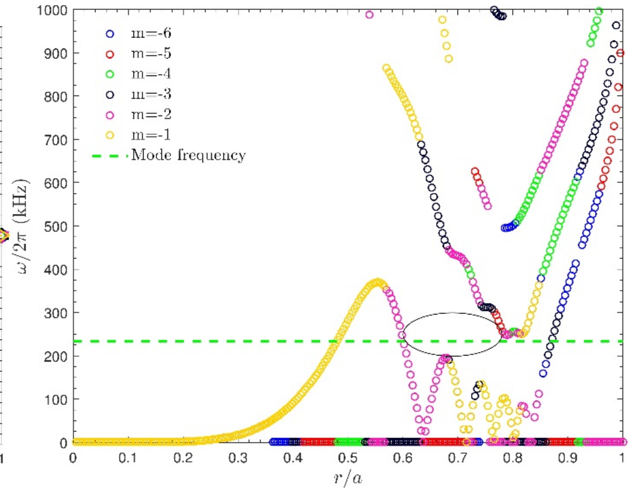
- **TAE calculated by AMC code**

Xie, PoP 2015

- ***f*=234kHZ**
- **Agree with experimental results**



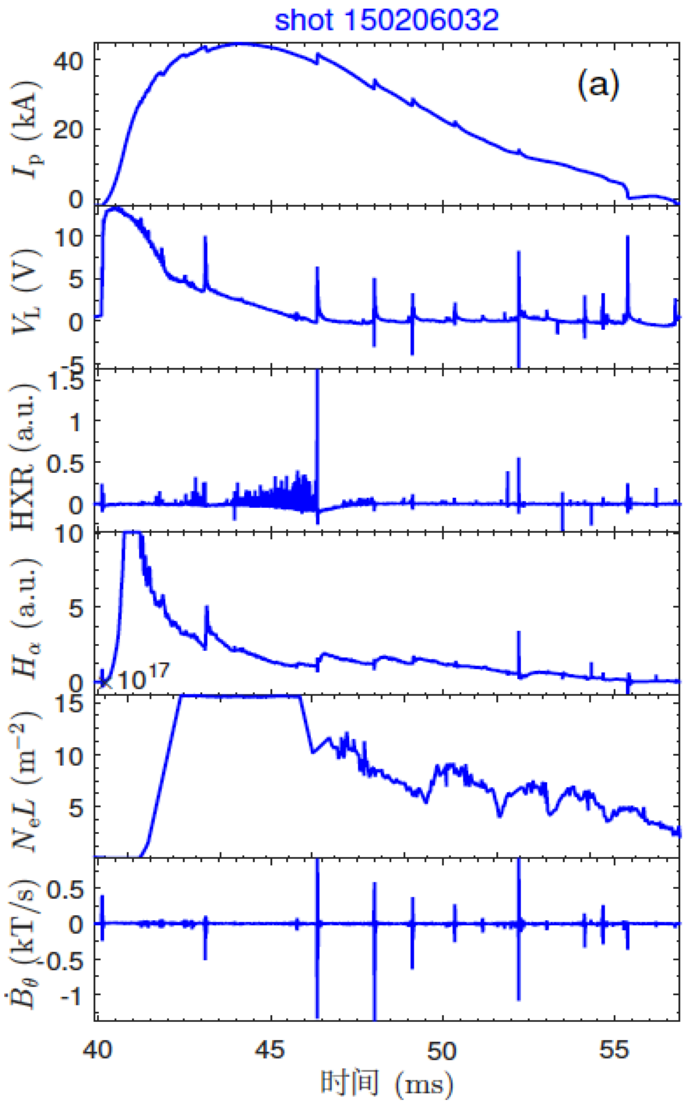




Excitation of the TAE

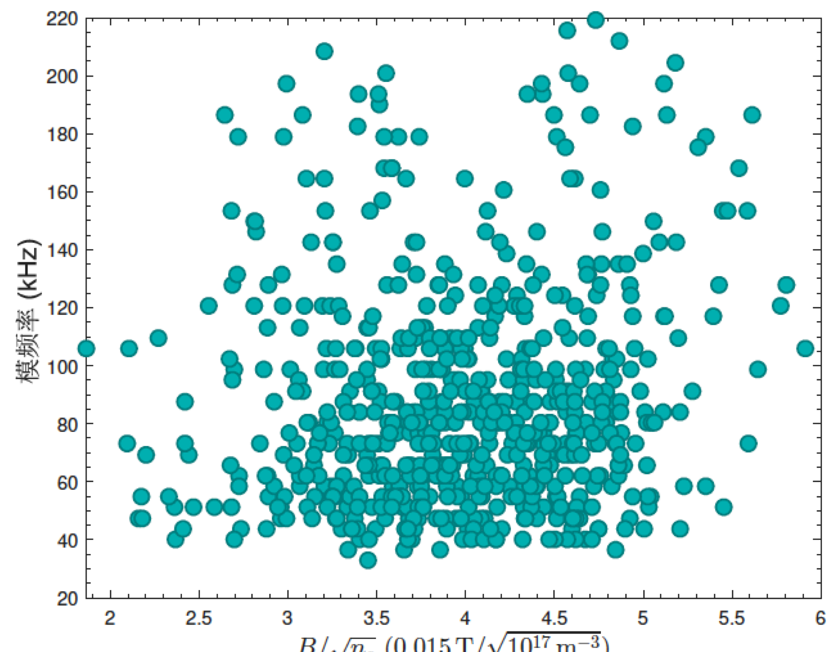
- **Ohmic plasma, no fast ions**
- **Mode in electron diamagnetic direction**
- **Only observed during minor disruption (high loop voltage spike, HXR burst, RE plateau)**

Discharge without TAEs



IREs dominant discharge

- Relative low loop voltage spike
- Slight HXR burst
- No runaway electrons
- High frequency MHD： 40-200kHZ, no Alfven scaling; 4/1 dominant

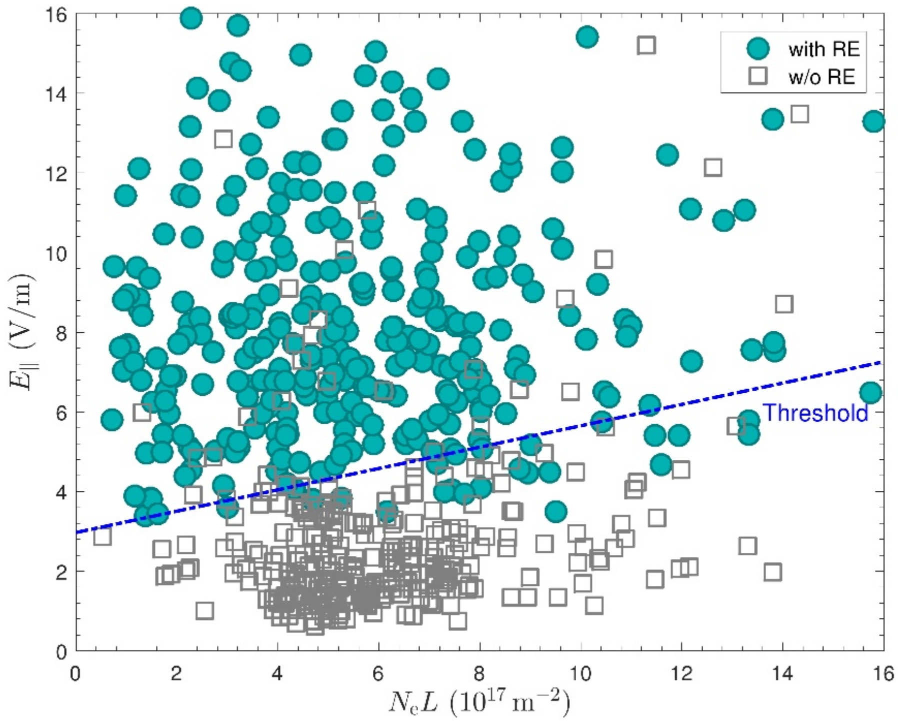


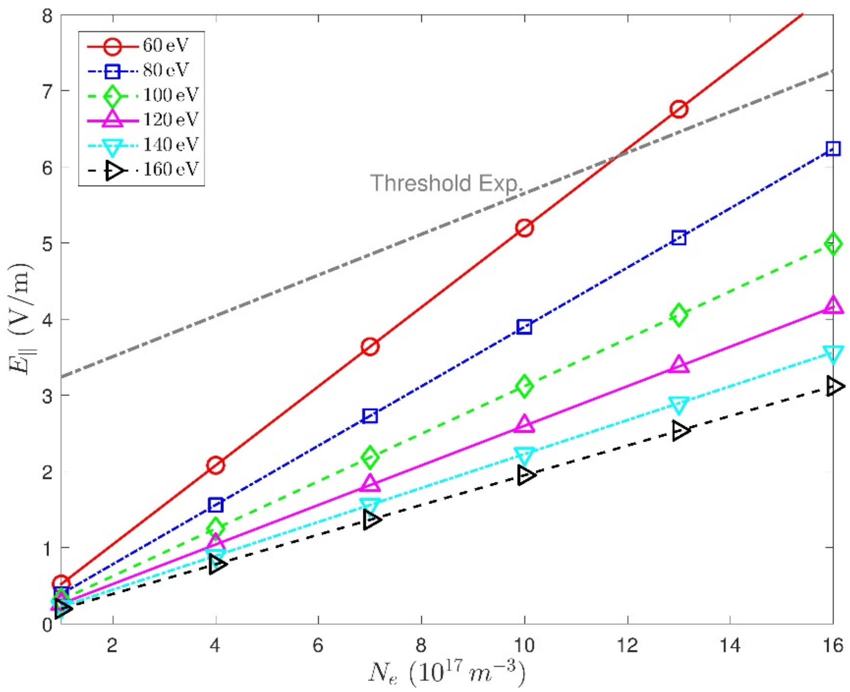
Excitation of the TAE

- Ohmic plasma, no fast ions
- Mode in electron diamagnetic direction
- Only observed during minor disruption (high loop voltage spike, HXR burst, RE plateau)
- TAE driven by RE?

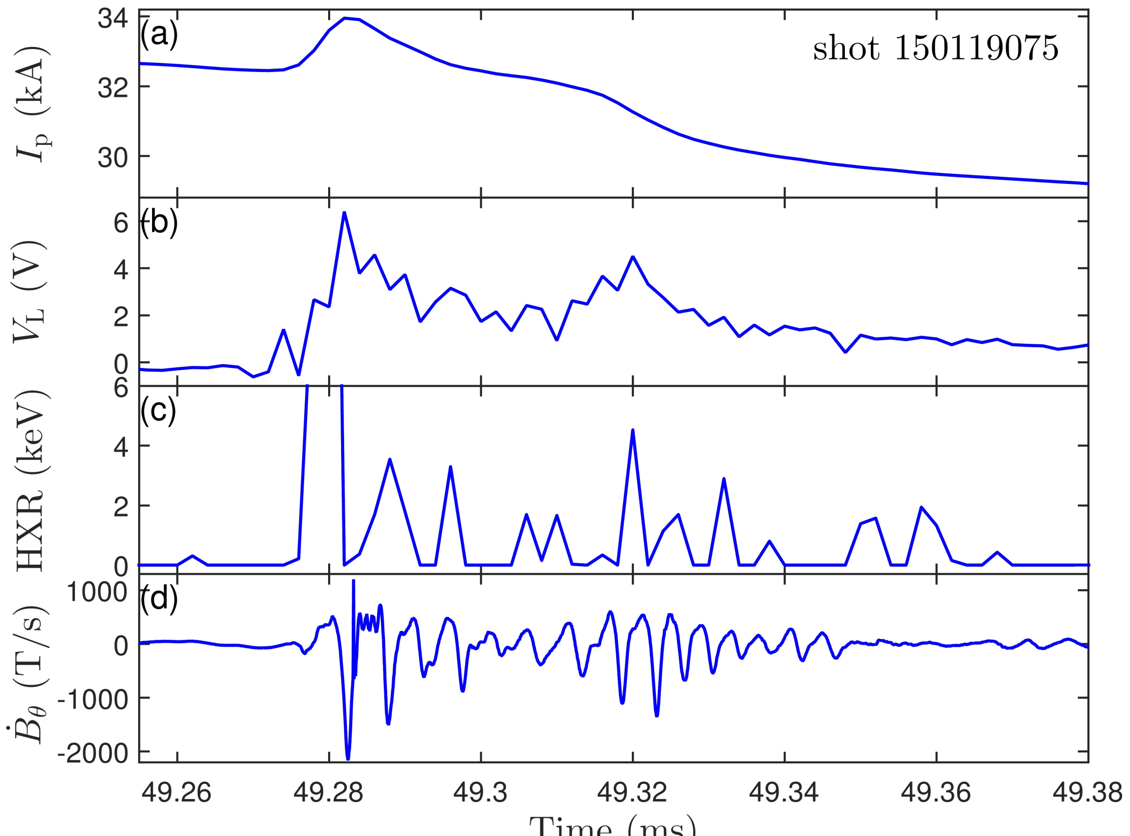
RE generation

- **Primary (Dreicer) generation dominates in SUNIST**
  - **Secondary avalanche multiplication ~$e^{0.05}$**
  - **Runaway $E_{||}$ roughly proportional to n_e**, $E_D = n_e e^3 \ln \Lambda/(4\pi\epsilon^2 T_e)$
  - **Te assumed constant during minor disruption ~60eV**





Time Evolution during MD



- **Appears in current quench phase with duration time ~20-60μs**
- **Possible dynamics**

  V_L spike→ high energy e (HXR) → TAE excitation→ HXR degrade → TAE damped

- **Effective HXR burst is above 2keV** (maximum 30keV at first burst)
- **During the RE plateau after TAE, no high energy HXR burst**

Possible mechanisms

- **Precession drift resonance $\omega \sim \omega_{pd}$**

$$T_h(\mathrm{keV}) \sim 1.1 \times 10^{13} \frac{B^2(\mathrm{T})}{\sqrt{n_i(\mathrm{m}^{-3})}} \frac{r_s(\mathrm{m})}{|n|q^2}$$

  - $B=0.15T$, $n_i=5*10^{17}m^{-3}$, $r_s=0.1m$, $n=1$, $q=3.5$
    $\rightarrow T_h=2.4keV$

- **Bounce resonance with TAE**
  - **generation of REs $\rightarrow$ the distortion of F_e near the trapped to passing boundary $\rightarrow$ bounce frequency of electrons resonance with TAEs [From F. Zonca]**

Summary

- A kind of high frequency MHD mode observed during minor disruptions in SUNIST ohmic plasma
- The mode is identified as the TAE from its frequency, mode structure and parameter dependence
- The TAE is though to be induced by high energy RE from minor disruption, although the exact mechanism is still open
- More theoretical and experimental efforts needed to interpret these observations.
- The excitation of TAE mitigates the RE…

- **High frequency MHD during disruptions in other devices?**

Device	Heating and power	MHD type	Mode character	Energy	Reference
TEXTOR	Runaway electron	TAE?	200kHz; 80kHz	No data	Zeng 2013 Zeng 2014 Papp 2014
TUMAN-3M	Runaway electron	AW (not TAE)	1MHz	No data	Tukachinsky 2014

Thanks for your attention.