Studies of fast electrons and corresponding kinetic modes on QUEST

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Studies of fast electrons and corresponding kinetic modes on QUEST

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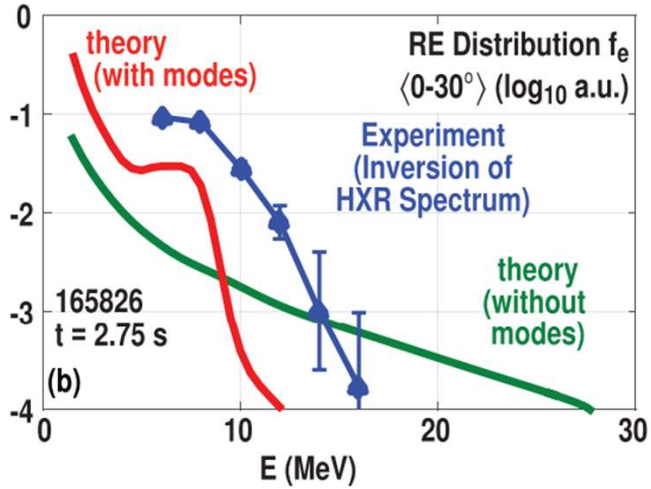
- Importance of the WPI on fusion energy development
- Challenge to probe fast electrons
  -Energetic Particle Probe principle
  -Brief introduction of previous results
    1. Pitch-angle distribution of fast electrons
    2. Fluctuation of fast electrons with kinetic modes
- Rotation drive experiment
- Summary

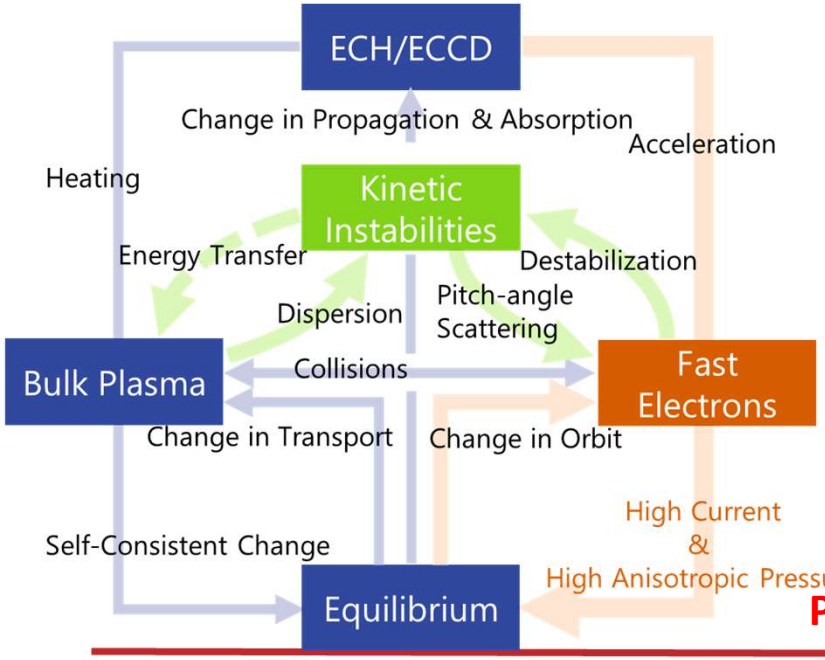
Importance of fast electrons on (Spherical) Tokamak

1. Suppression of runaway electrons(RE)

- Avalanche generation of RE by fast electrons
- Whistler wave driven by RE *Spong+ PRL2018, Heidbrink+ PPCF2019 et al.*
- Effective critical electric field raised by kinetic waves *Chang Liu+ PRL 2018*
- Experimental assessment of RE suppression during wave excitation

C. Paz-Soldan+ NF 2019 →





2. Plasma current start-up using EC waves

- **Excessive fast electrons govern the system**
  Superior absorption efficiency, Good current carrier
  Current drive efficiency with fast electrons >> normal
  >1 A/W@EXL-50 (*D. Banerjee+ JOP 2022*)
  ↔ Inhibition of bulk electron heating
- **Coupling of bulk and fast electrons through kinetic waves**
  R. Ikezoe+ IAEA 2023

Pursuing kinetic waves as an attractive control method for fast electrons.

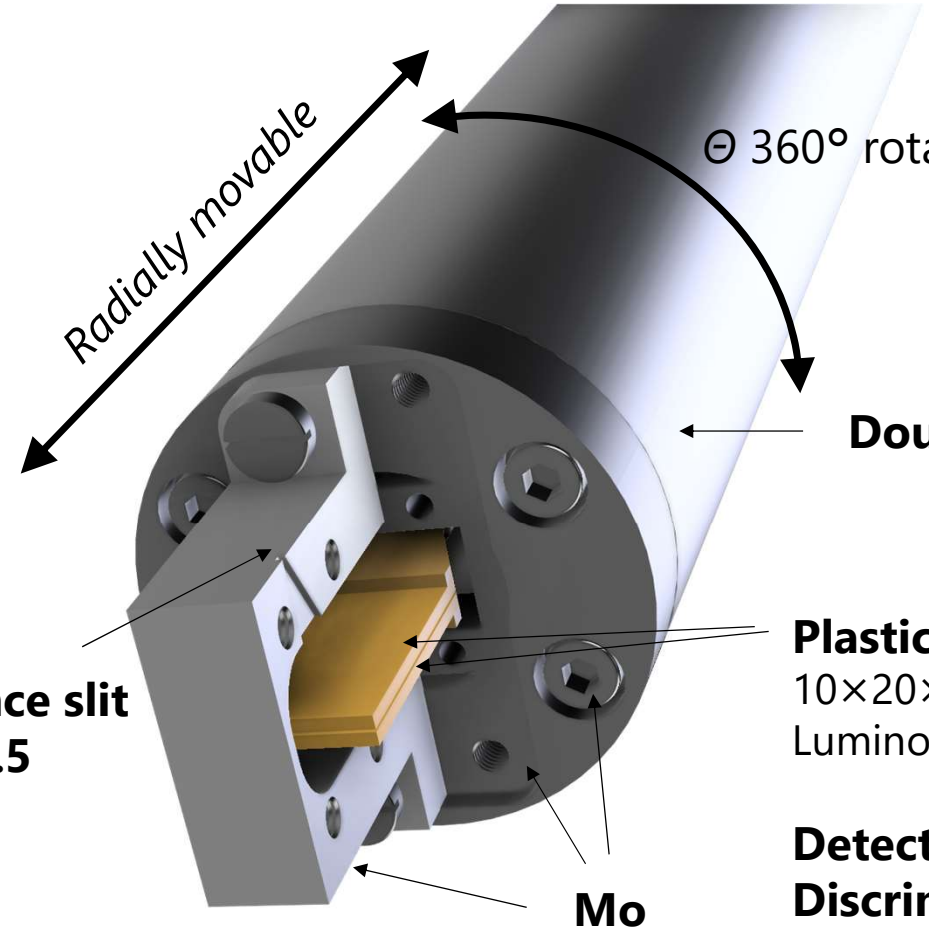
Challenge to probe fast electrons in ST

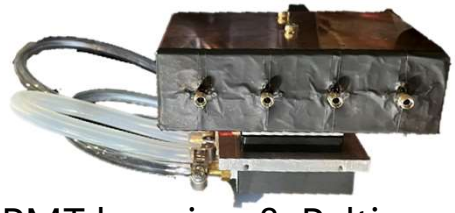
- In geospace, nice measurements have been achieved for WPI research by satellite.
- Hot and dense condition makes measurement of fast electrons difficult in fusion plasma devices.
- As a non-contact measurement, hard X-ray is fascinating. Elaborate analysis could invert hard X-rays camera data to HXR spectrum, however, detailed discussion on WPI would be difficult.
- Probe-type measurement is limited to periphery, but it generally has excellent locality and accuracy if the principle is solid. Large orbit of fast electrons in a low field region can be used to resolve their pitch angles.

↓

- The problem of Probe-type would be 1. high-intensity hard X-rays as dominant noise, and 2. heat. → Try to eliminate 1. HXR noise.

Energetic Particle Probe（EPP）





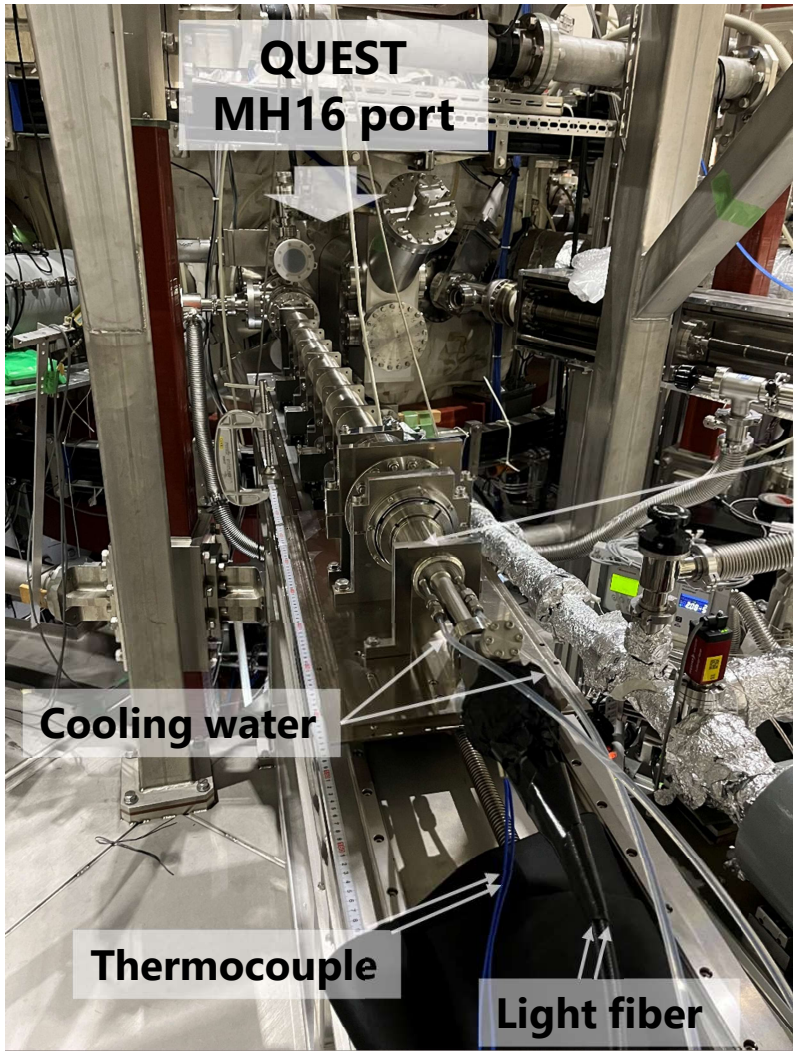
PMT housing & Peltier cooling

Photo multiplier tube ×2

Digital Pulse Processor 1GHz, 14bit

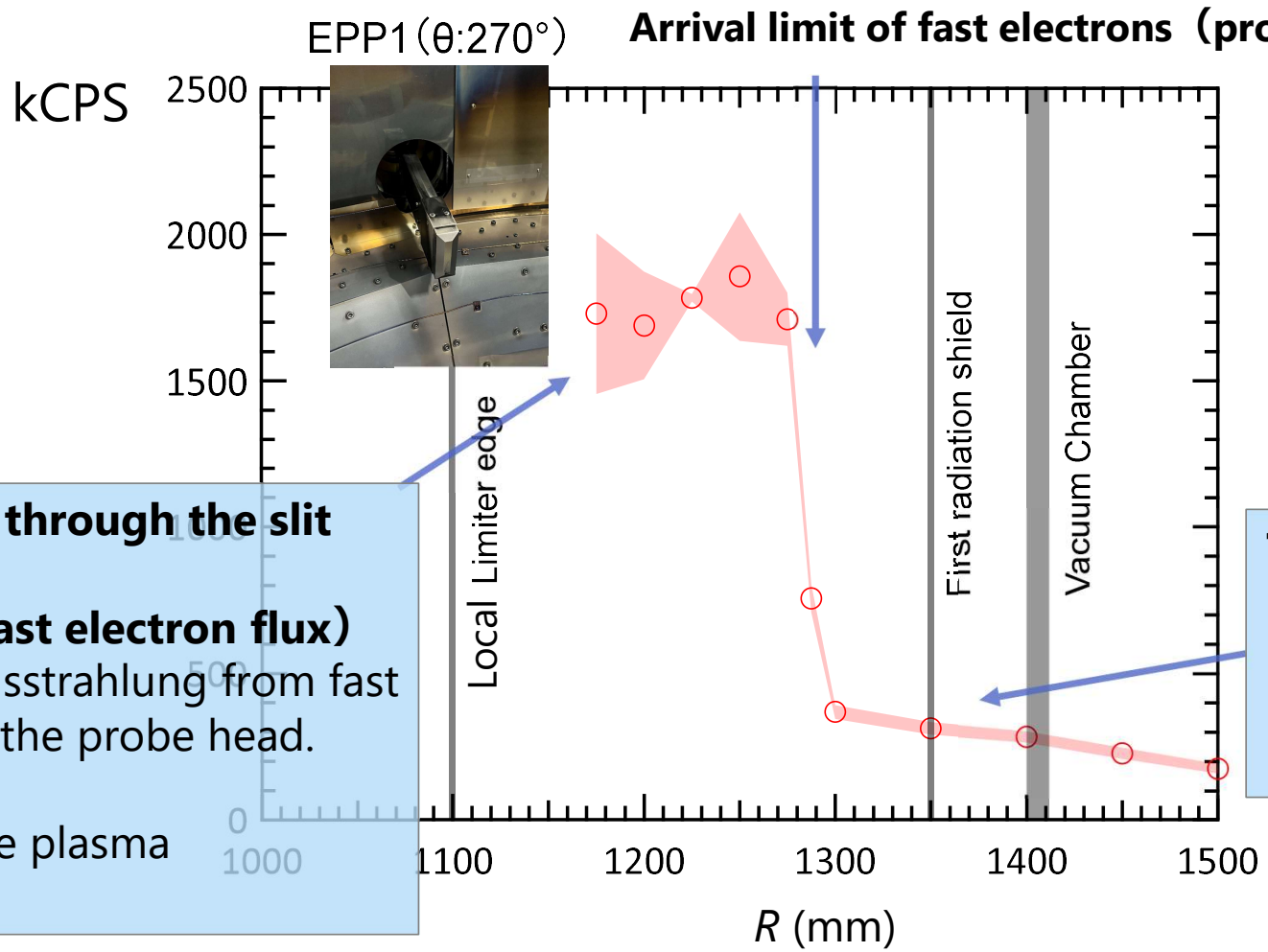
Detects both hard X–rays & energetic charged particles
Discriminate from difference in two identical sensors

Photos of EPP



Rotation motor

Observation of three contributions for the counts & the radial arrival limit exceeded the local limiter



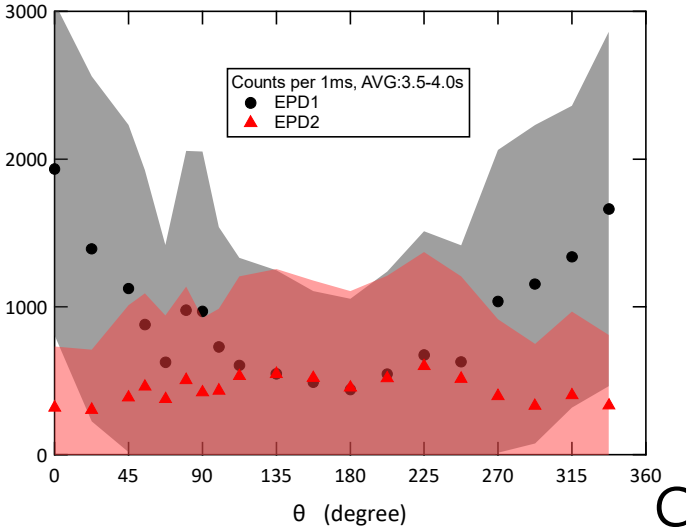
2. Fast electrons through the slit

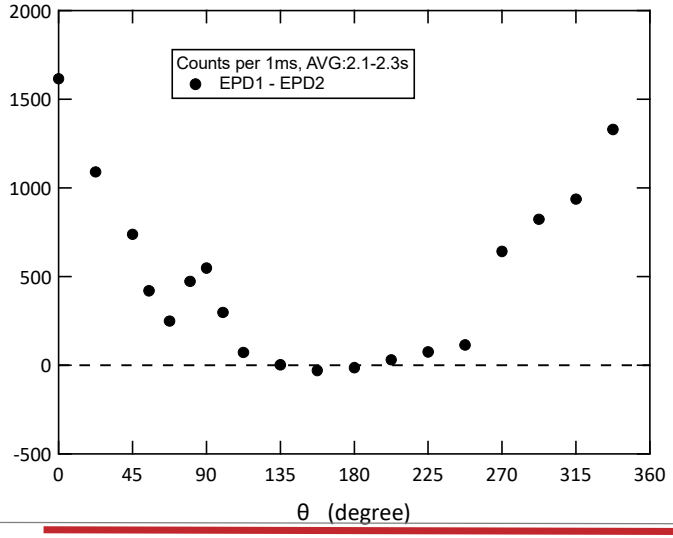
3. Local HXR （fast electron flux）
Thick target bremsstrahlung from fast electrons that hit the probe head.

1. HXR from entire plasma （minority）

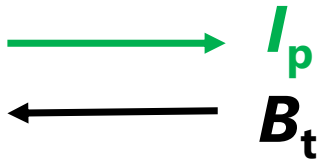
1. **HXR from entire plasma**
no θ dependence & same amount for EPP1&2

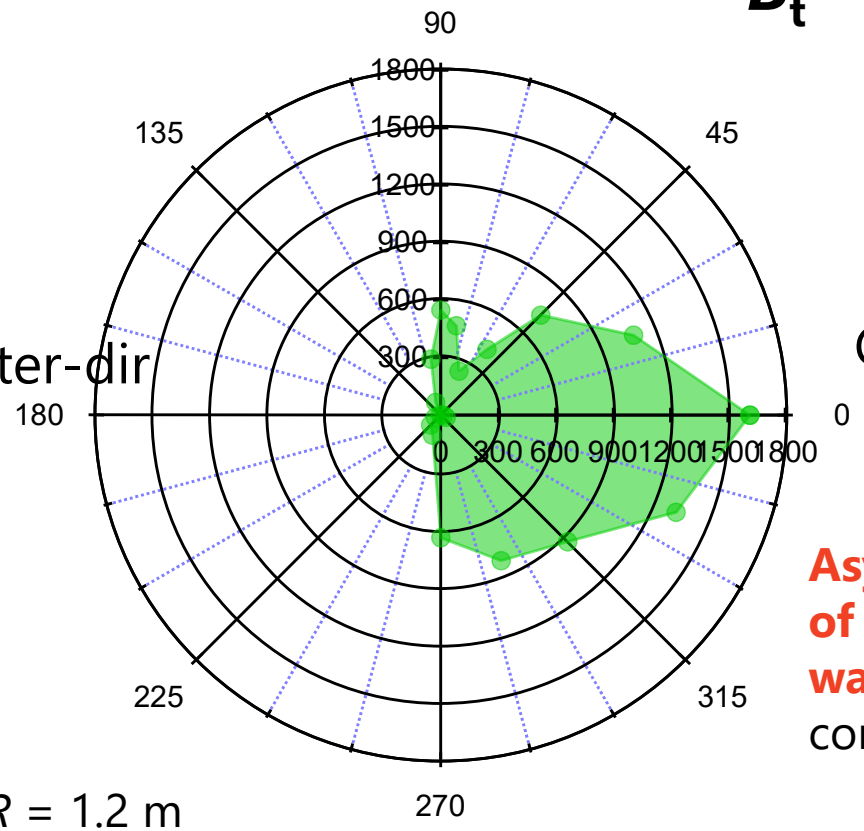
Pitch-angle distribution of >100 keV fast electron flux at SOL





Seen from plasma side





Counter-dir

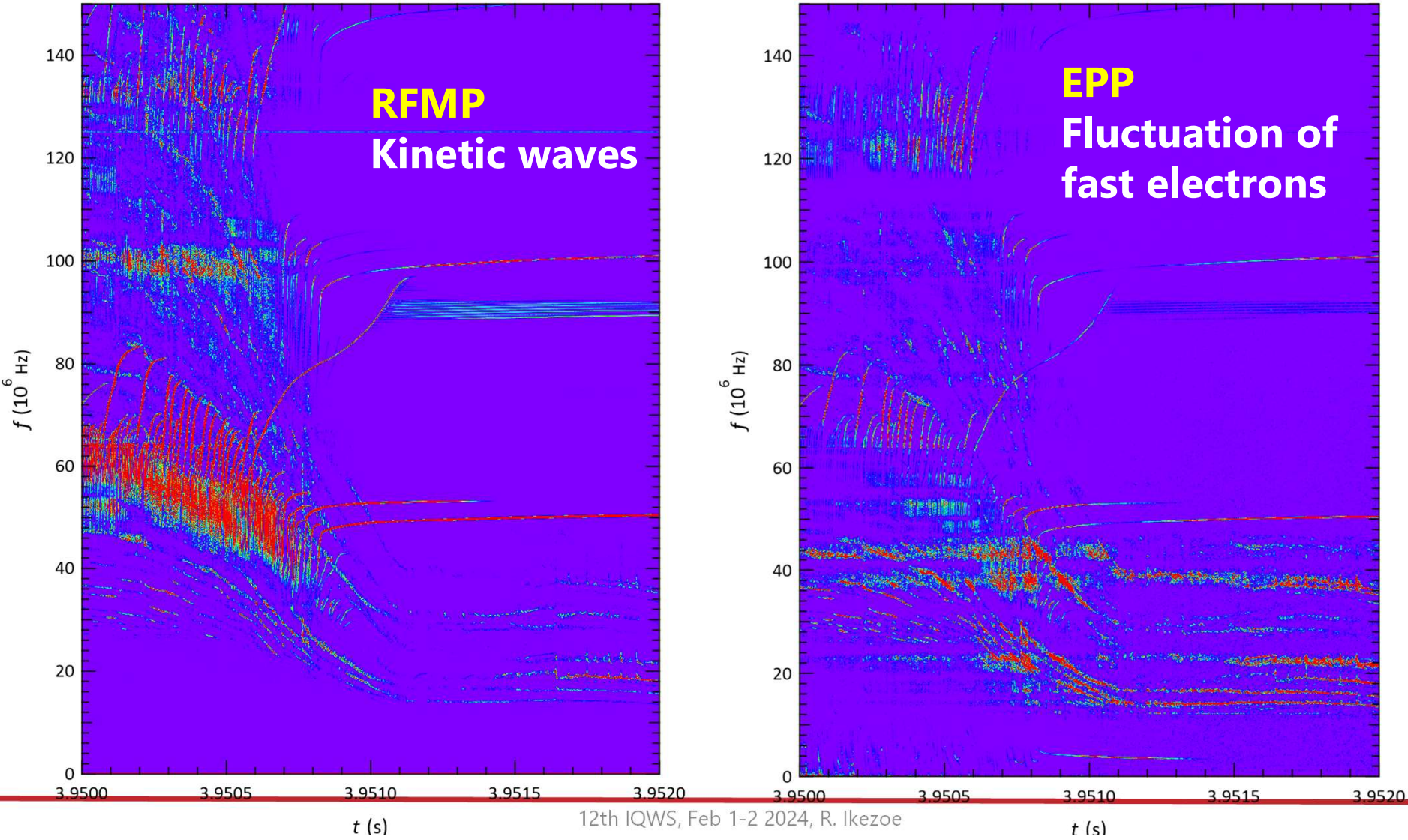
Co-dir

Asymmetric generation of fast electrons by EC wave was experimentally confirmed.

R = 1.2 m

t = 2.1−2.3 s (Initial I_p ramp-up period)

Experimental evidence of the interaction between fast electrons and high-frequency modes



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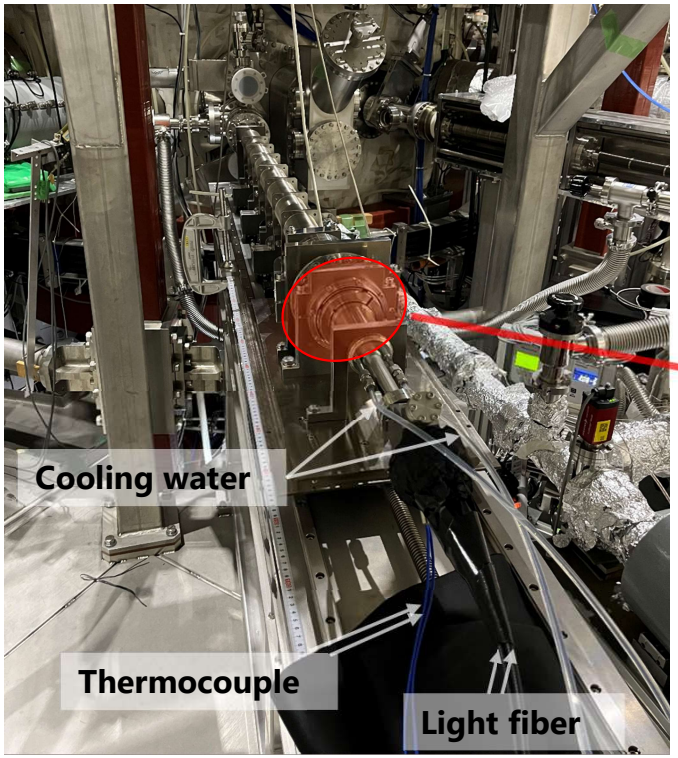
- **Rotation drive experiment**
- Summary

Installation of stepping motor control to EPP



Stepping motor

Vacuum rotary feedthrough
(hollow shaft, magnetic coupled)

Manufacture's driver soft

Live and manual control possible

Raspberry Pi system (EXP hall)

Trigger

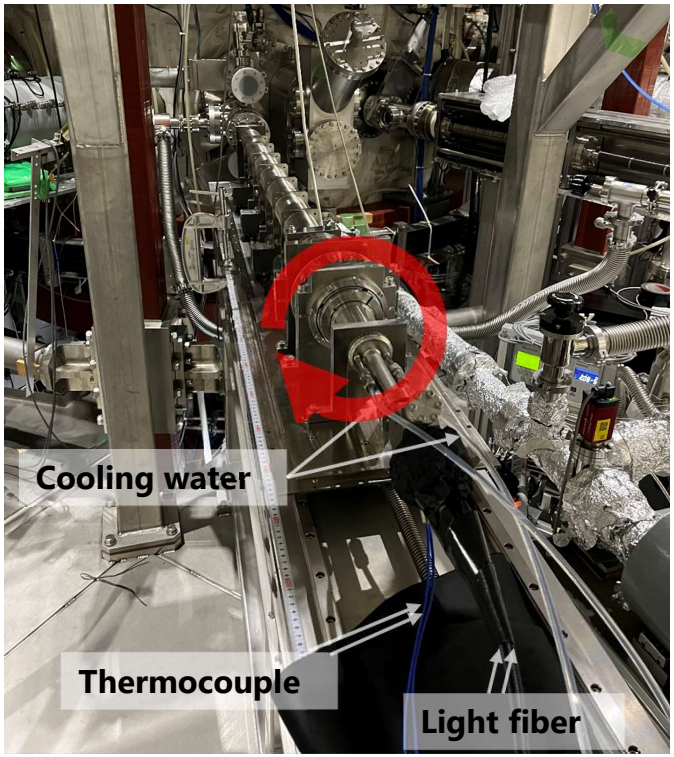
Labview

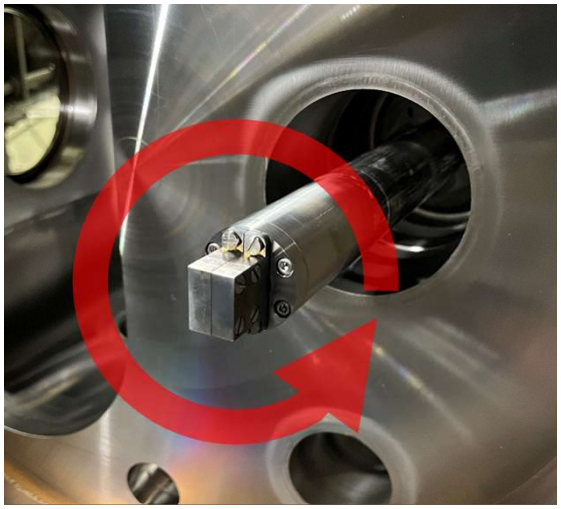
Flexible pre-program
Timing control
Angle data acquisition

Stepping motor safely drives rotation of EPP

Stepping motor

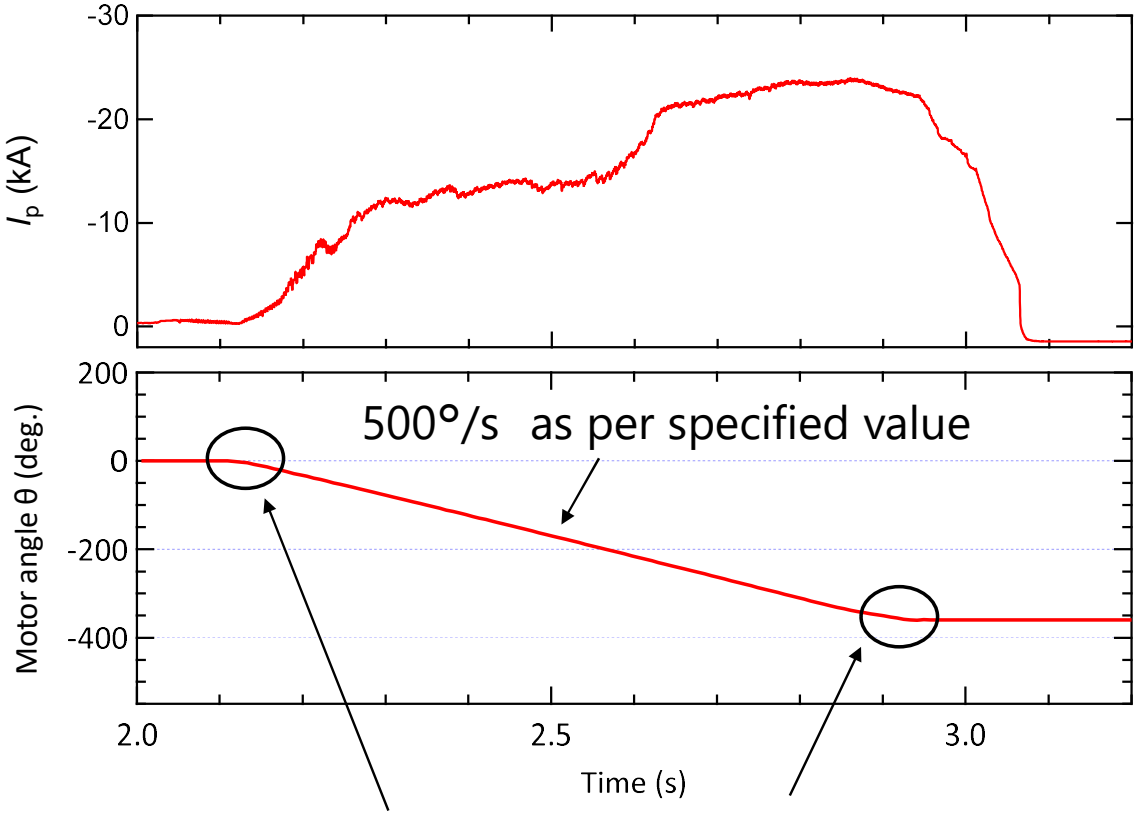
Vacuum rotary feedthrough (hollow shaft, magnetic coupled)





- ✓ To reduce the effects of twisting, the cables behind the EPP have a long straight section.
- ✓ Rotation angle is limited to **one rotation** in the command.
- ✓ Confirmed that the rotation did not affect the signal or anything else.
- ✓ Tested sequentially up to **500 deg/s** at max.

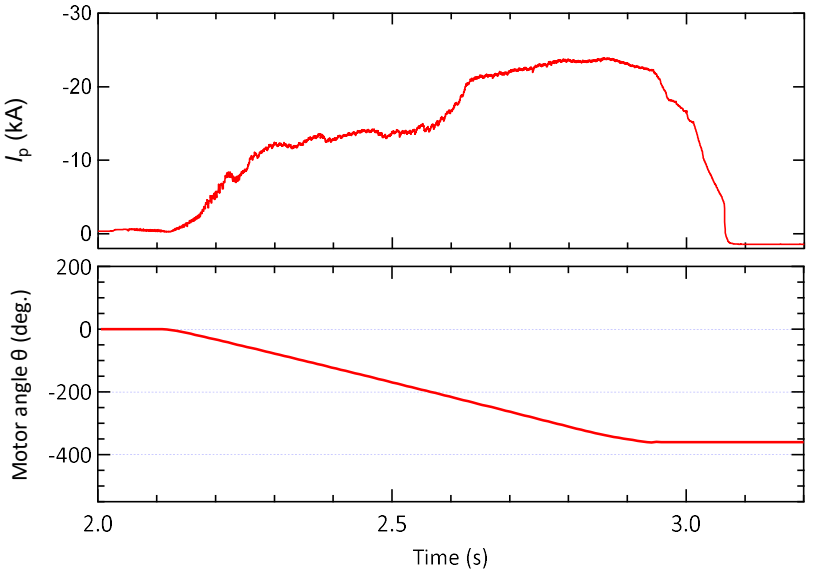
Demonstrates 500°/s smooth rotation.



Immediately after starting rotation and immediately before stopping, acceleration is automatically limited to a certain range, helping to soften the impact.

Timescale of EPP rotation at 500°/s, and resolutions.

Rotation drive



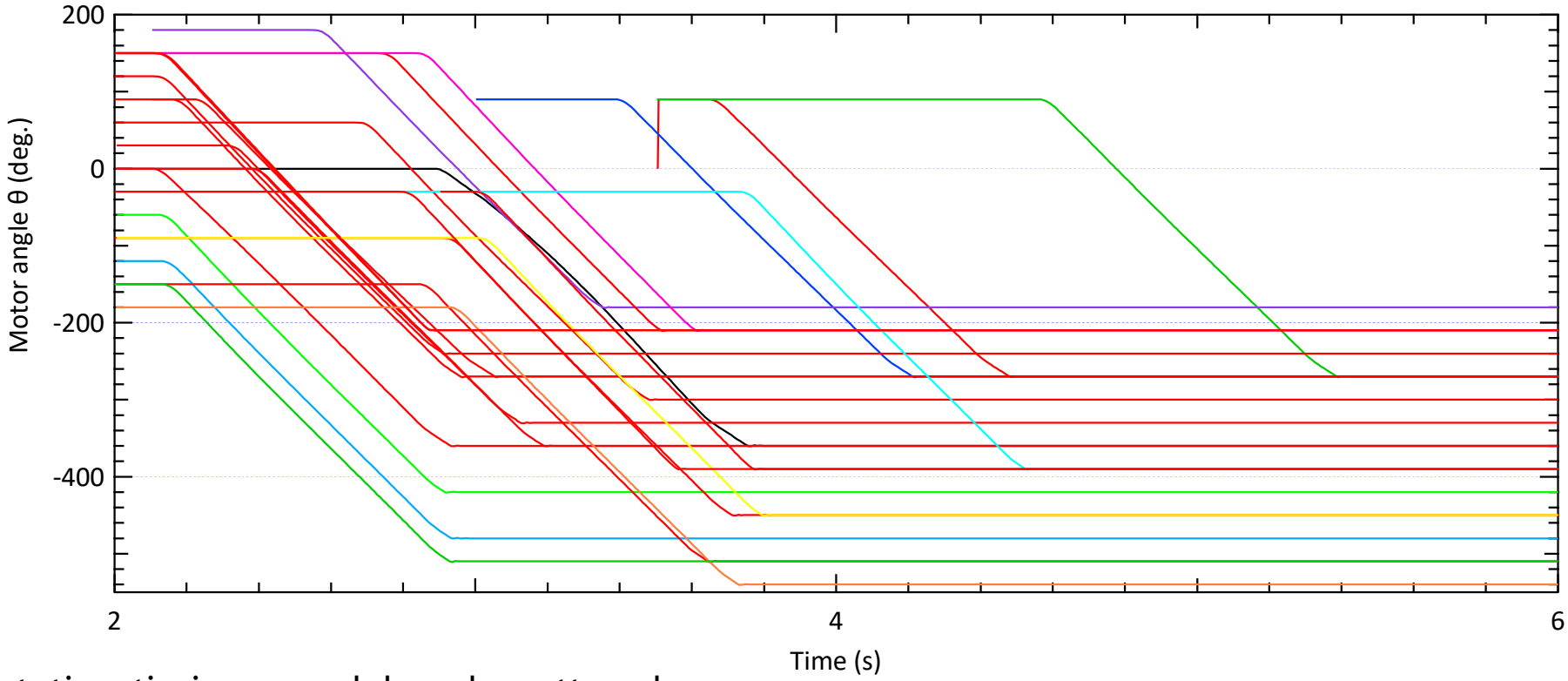
- Pitch-angle (PA) distribution **with a single discharge** for a long-pulse operation of >> 1s
- Evolution during EC ramp-up **still needs** identical multiple discharges.

- **Fine PA distribution**
  ~1° (Geometric structure of EPP head) > 0.01° (Stepping motor)

  Trade-off: PA resolution & time resolution vs the number of counts (statistical accuracy).

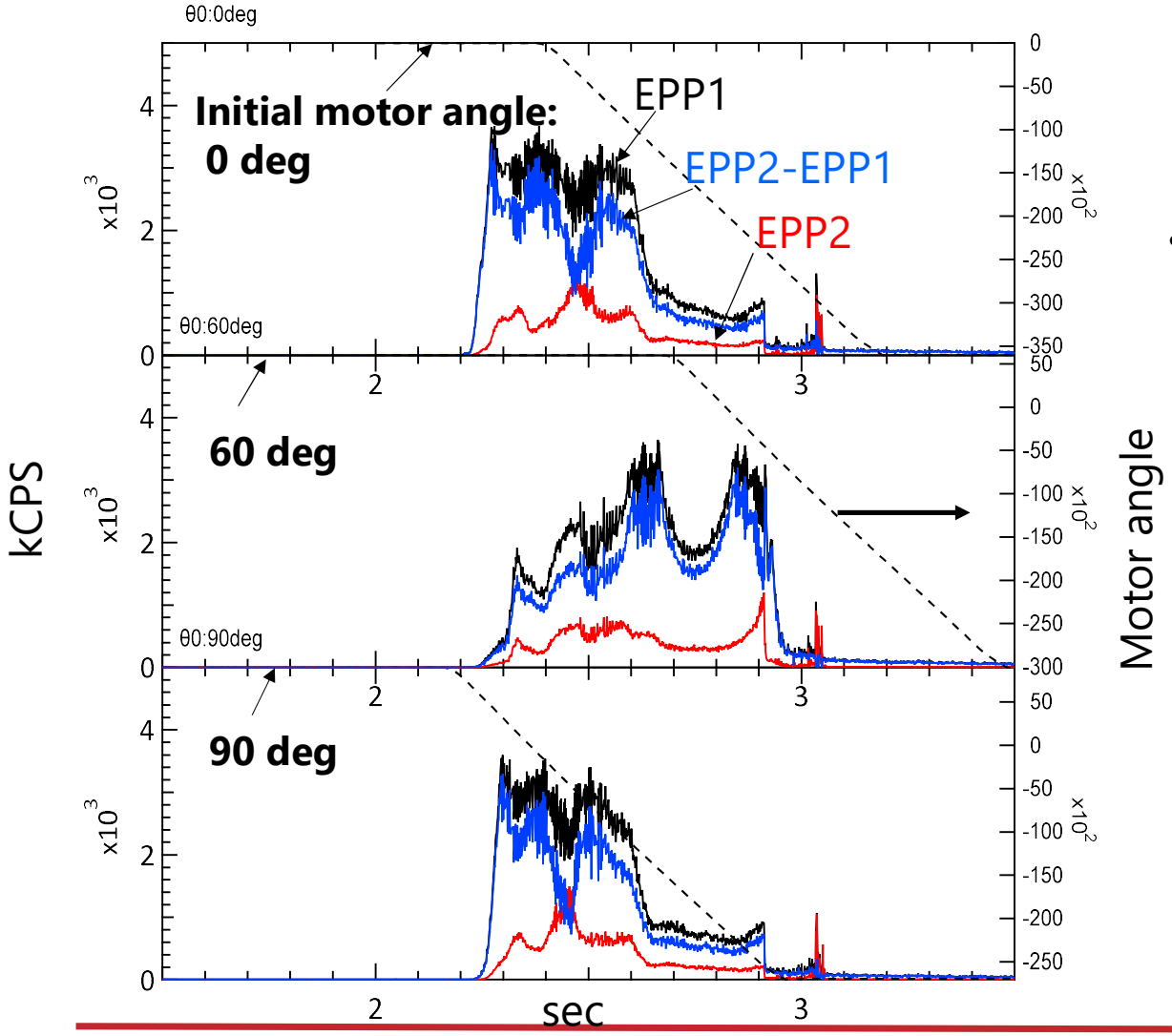
PA distribution measurement using EPP with rotation drive

- Produced 28-GHz 2nd EC start-up plasma with a good reproducibility.
- Repeatedly made identical discharges with varying the initial angle of EPP.



- Rotation timing was delayed, scattered.
- Problem was found on the communication scheme of stepping motor. → Modified, waiting test.

Examples of EPP signal during the rotation @R=1.275 m



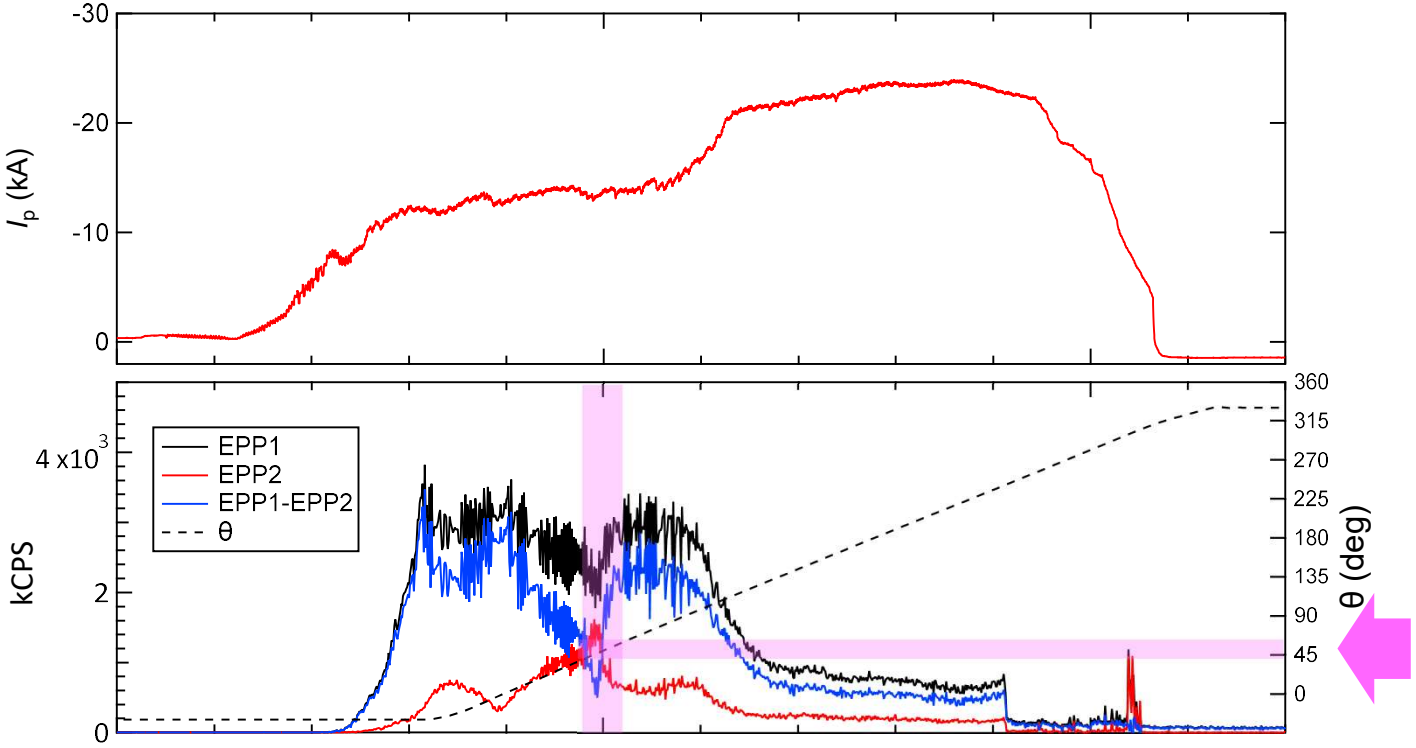
- **Temporal variation is a mixture of variations in plasma and pitch-angle.**

  ↓

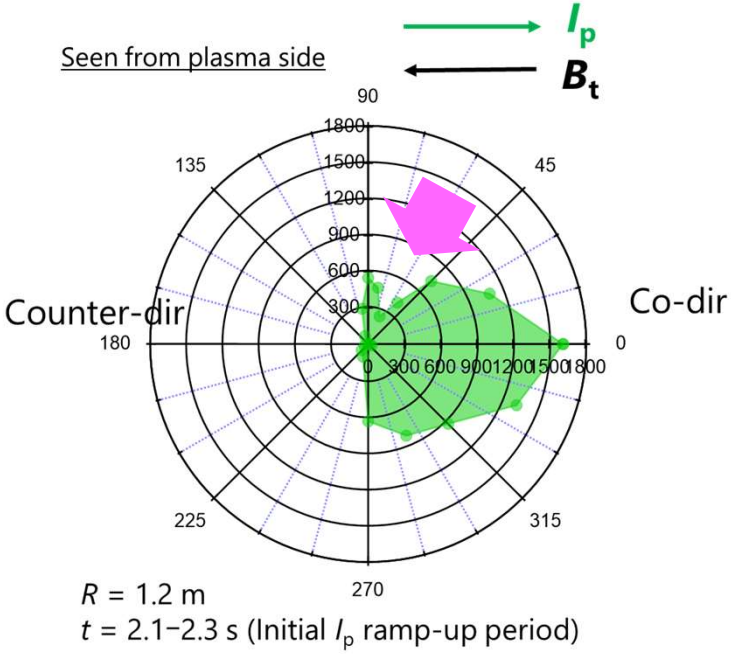
  Difficult to interpret until complete set of data is taken.

  However, several noticeable changes exist.

Noticeable change was confirmed around Pitch-angles 45°-90°

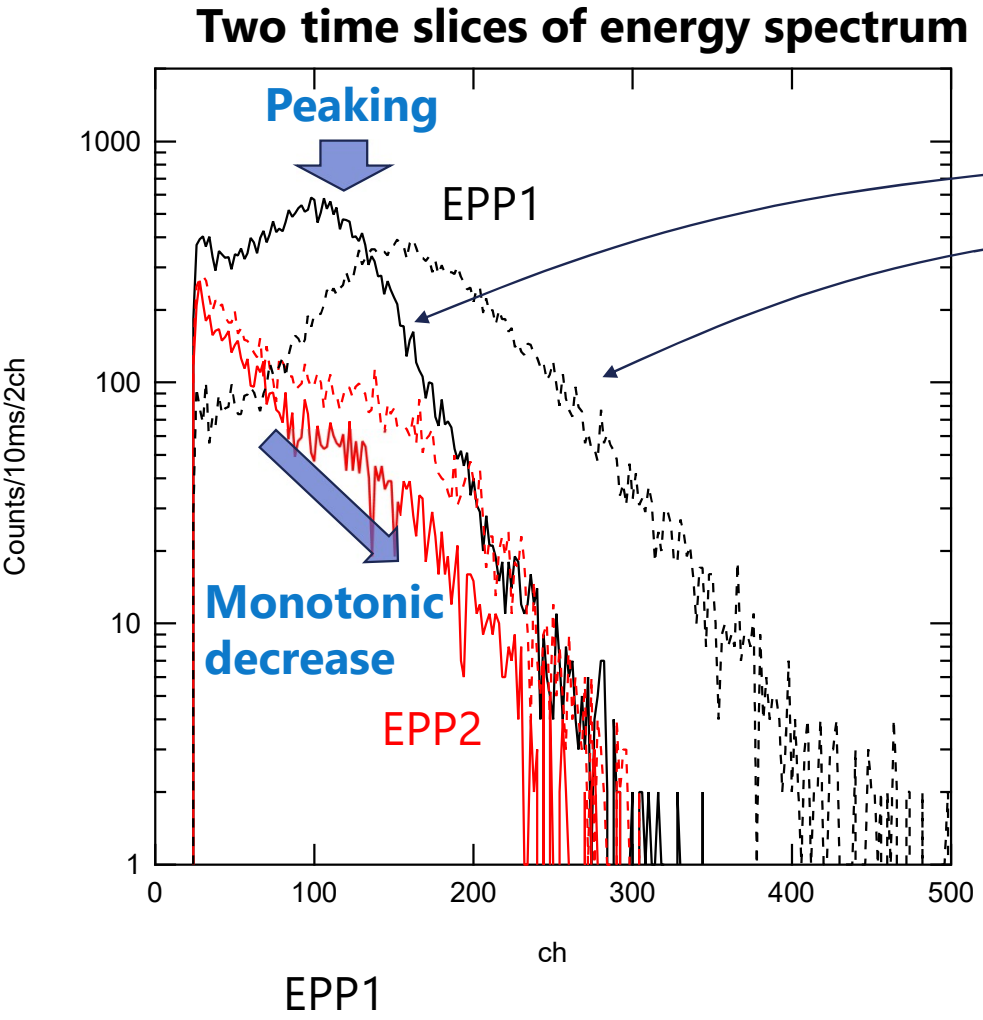


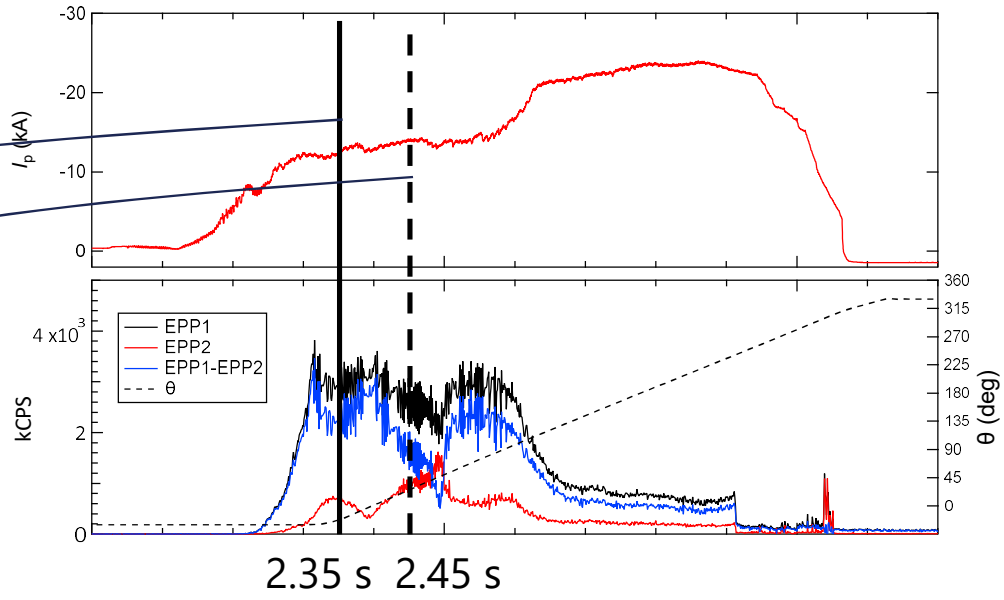
Previous result



- The feature seen in the previous coarse pitch-angle distribution, which was obtained by fixed EPP for different plasmas, was again captured.
  ➔ Strong characteristics of far SOL fast electrons (>100 keV) on QUEST.

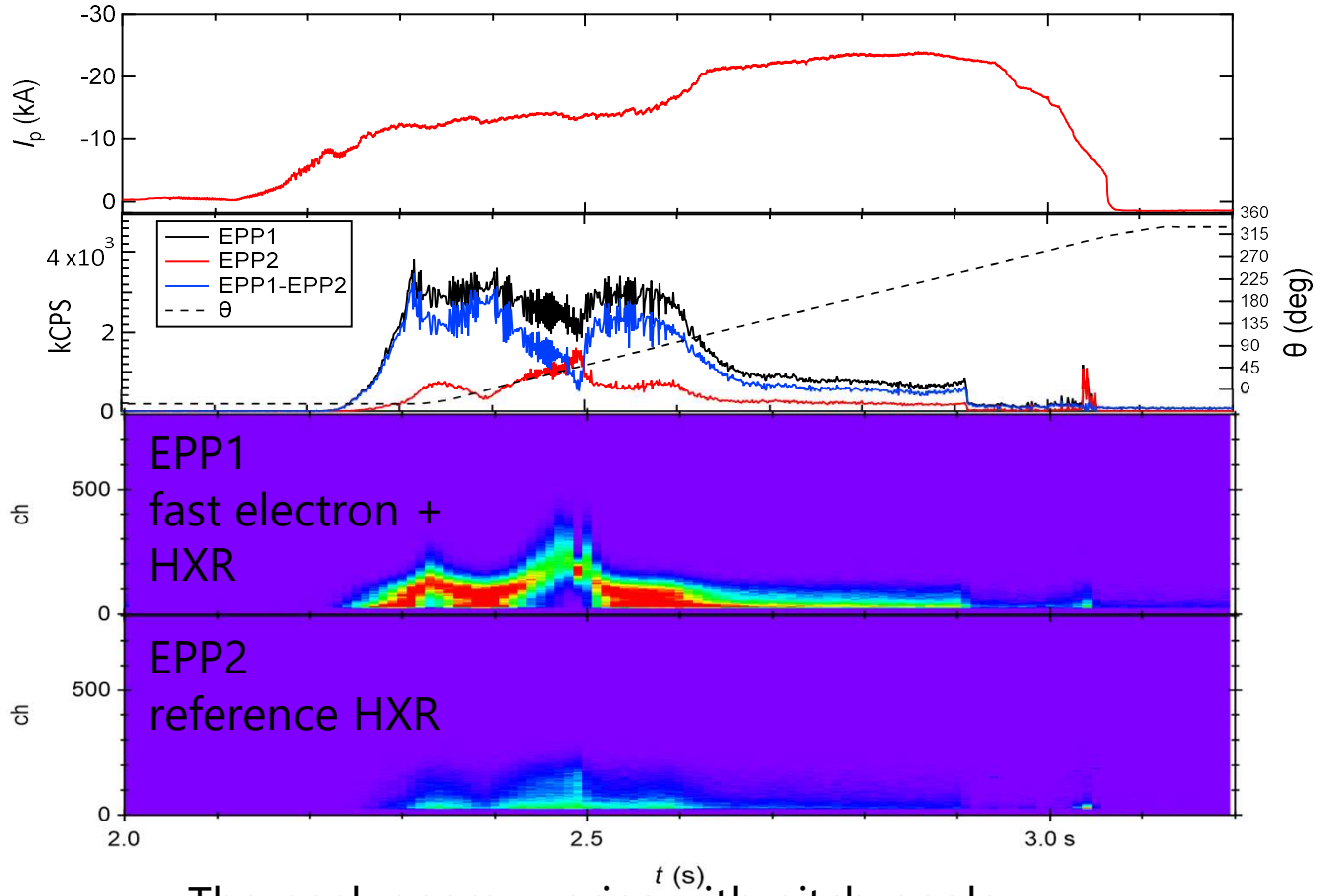
Unusual peaked spectra were obtained by EPP1





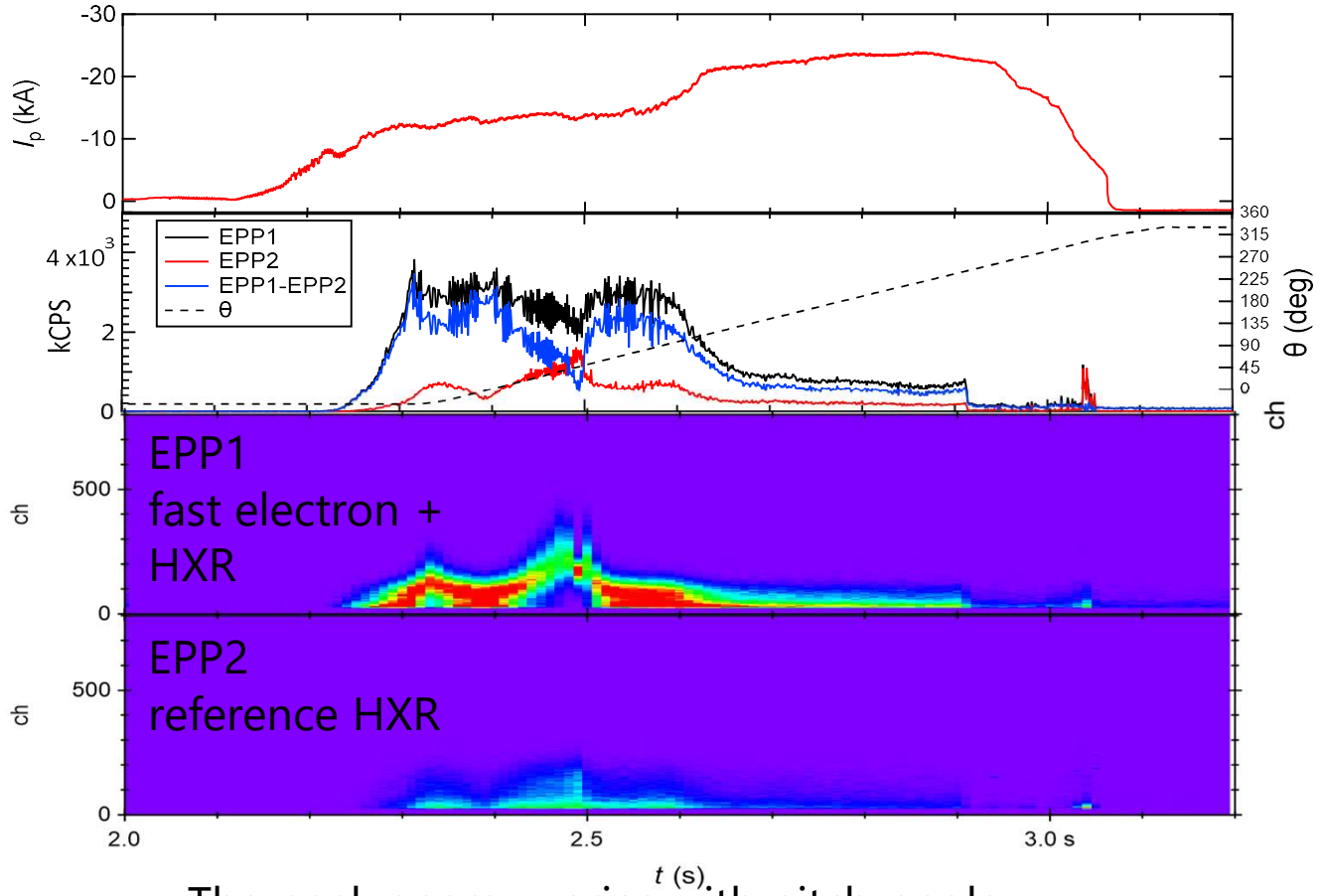
- While **EPP2 (HXR reference)** shows normal decreasing spectra of hard X-rays, **EPP1 (fast electrons + HXR)** shows peaked energy spectra.
  → Sign of fast electrons
  Contribution of fast electrons are favorably dominant in EPP1 signal for this experimental condition as evident from the difference in CPS.

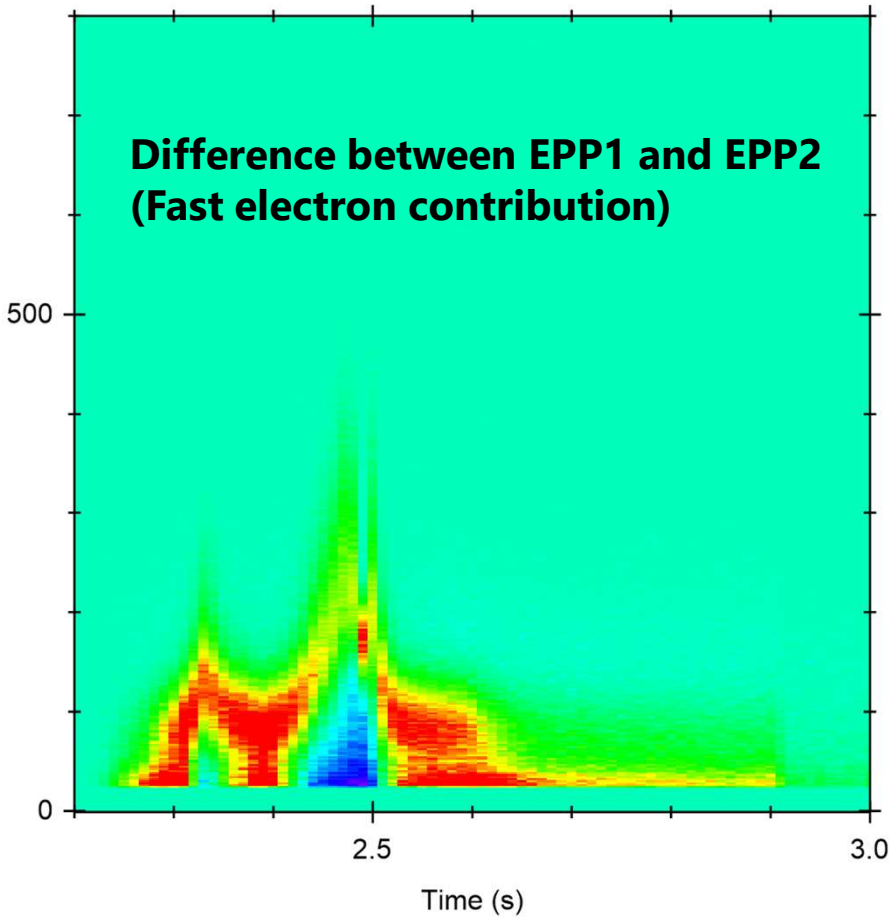
Energy spectrum shows strong correlation with pitch-angle



- The peak energy varies with pitch-angle.
  Strong correlation between energy and pitch-angle was found, indicating that the velocity distribution of fast electrons covers relatively narrow region.

Energy spectrum shows strong correlation with pitch-angle





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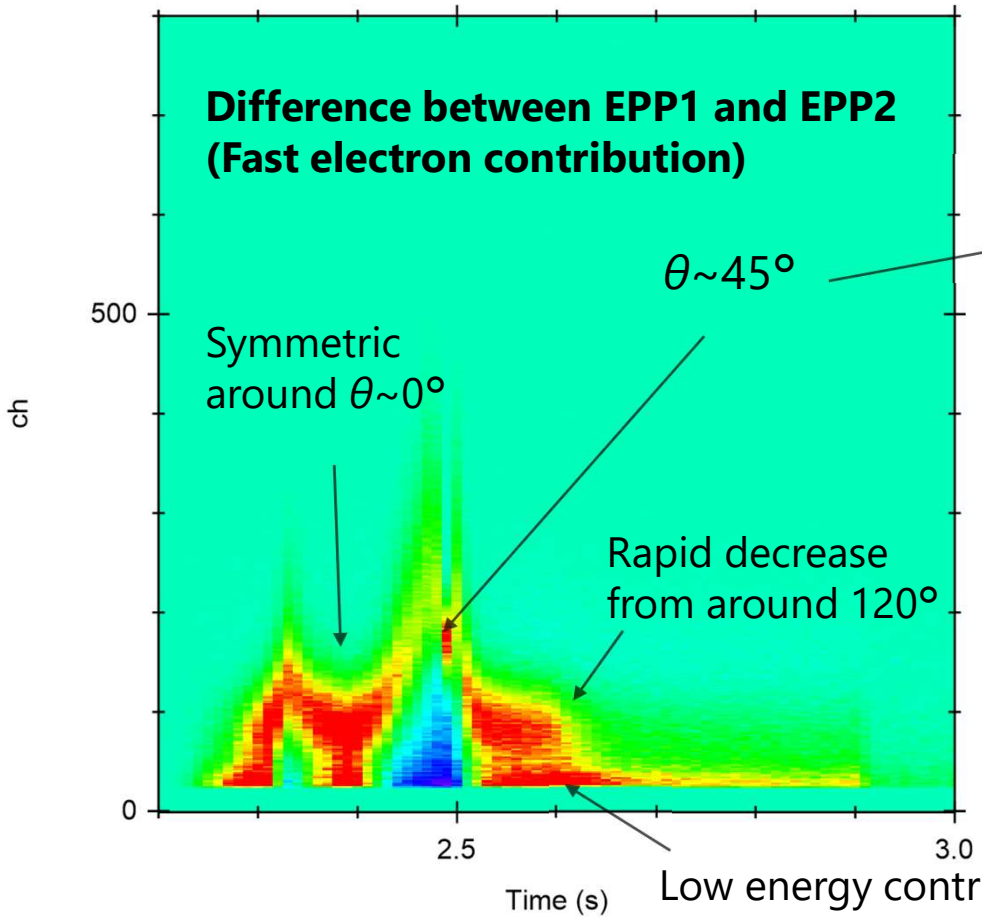
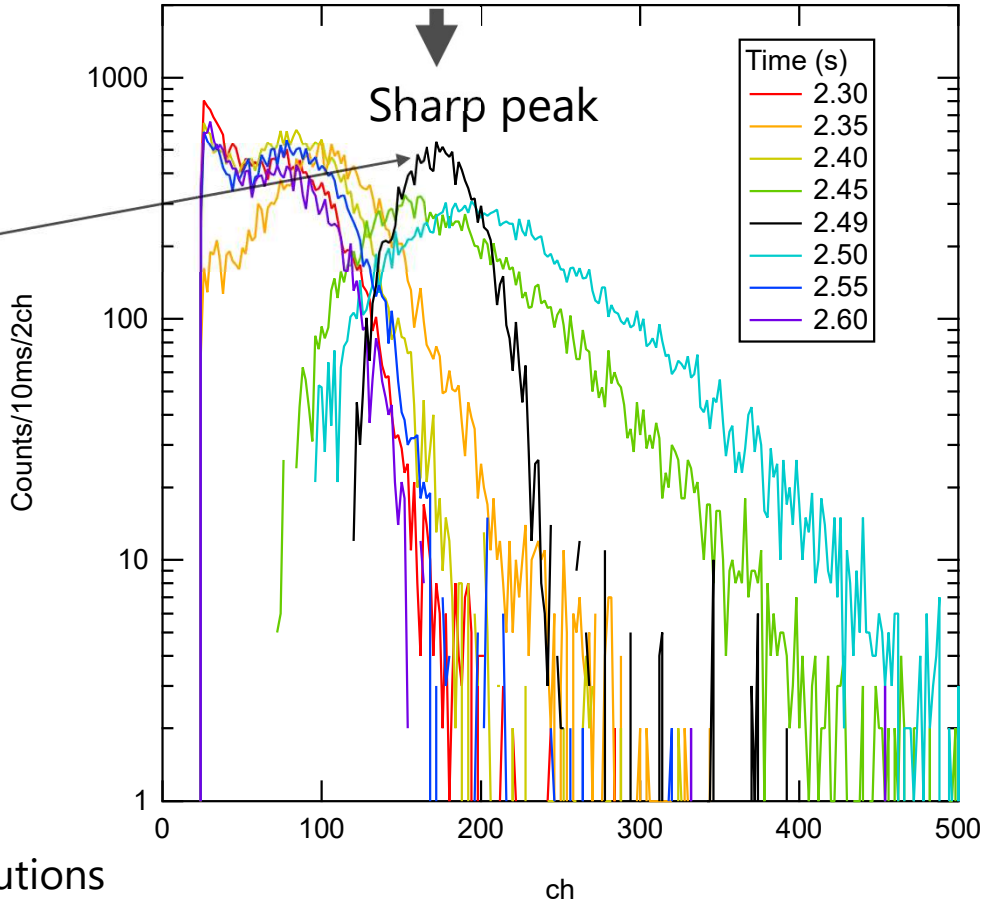
Characteristics of energy – pitch-angle relation

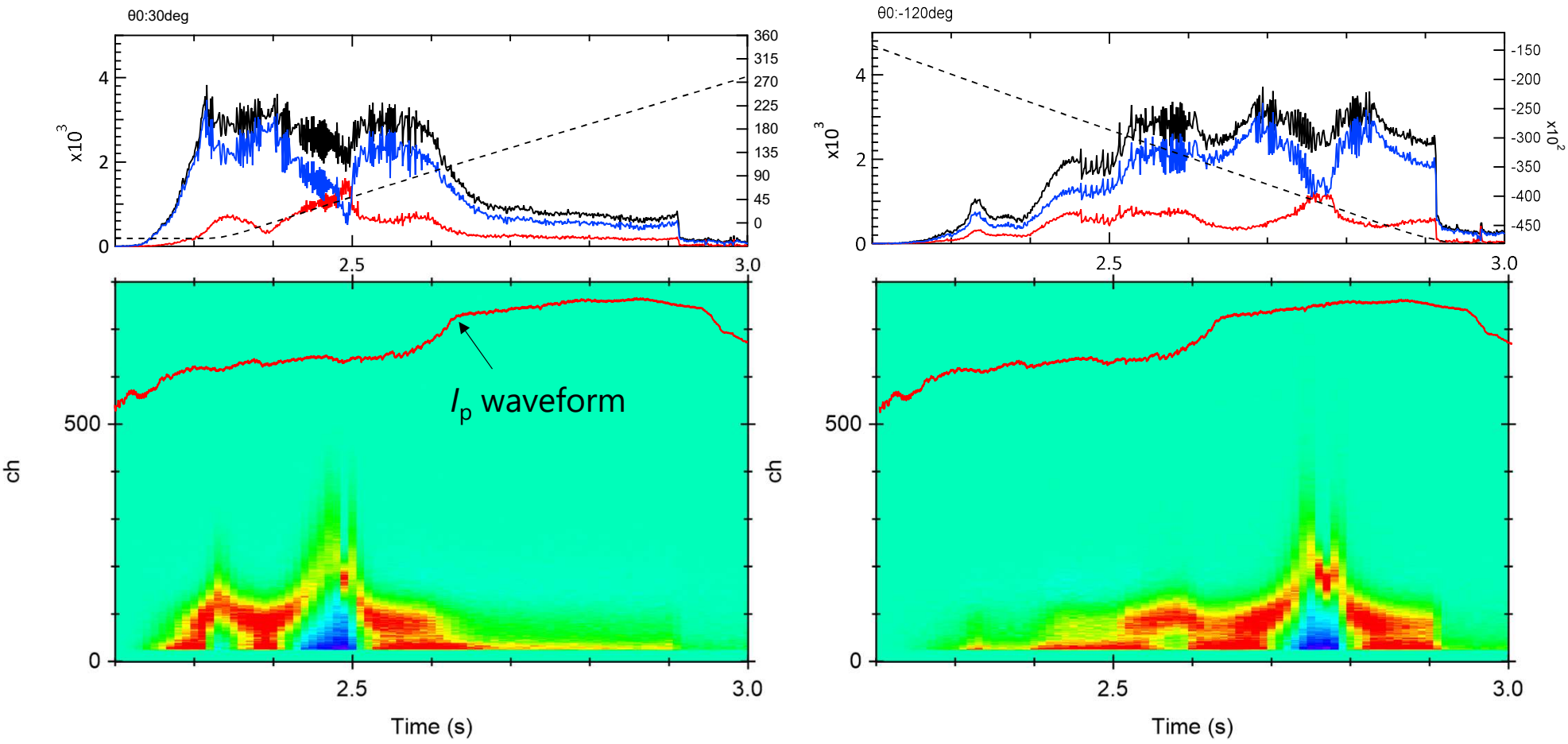


Very limited fast electrons exist with this pitch-angle



※Theta value is tentative (under checking the motor control system)

Check at different time period



- Similar trend was confirmed at later period.

Summary

- Energetic particle probe (EPP) developed on QUEST for the studies of fast electrons is introduced and some outstanding results are shown.
- **Rotation drive system has been attached** to the EPP, enabling pitch-angle distribution measurement in a single discharge.
- **Strong correlation was found between the pitch-angle and energy spectrum of fast electrons of >100 keV at far SOL on QUEST**, suggesting the narrow velocity distribution.
- Further optimization of EPP will give electron velocity distribution at the edge of ST in the future.