Implementation of a Fast Broadband ECE Measurement on DIII-D

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Presented at the Forty-First Annual Meeting of the APS
Division of Plasma Physics

November 17, 1999

Seattle, Washington

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ABSTRACT

A new broadband ECE diagnostic has been implemented on the DIII-D tokamak. This instrument features a spectral range of 50-300 GHz and a frequency response from DC up to 1 MHz. ECE emission from the plasma is split from the input beamline of the Michelson interferometer and directed by Gaussian optics to an InSb detector. A variety of filters, such as dichroic plates (high-pass) and Fabry-Perot etalons (narrow bandpass), may be introduced into the optical path to tailor the measurement to desired frequency ranges. Applications of this instrument include fast third-harmonic electron temperature measurement, identification of mode numbers of MHD instabilities in conjunction with the heterodyne radiometer, and spectral measurement of high-harmonic emission by runaway electrons. It is shown that the measurements from this instrument agree quantitatively with those from the absolutely calibrated Michelson interferometer.

This work was supported by the U.S. Department of Energy under Contract Number DE-AC03-99ER54463 and Grant Numbers DE-FG03-86ER52126 and DE-FG03-97ER54415.

A new broadband ECE diagnostic has been implemented on DIII-D

- The diagnostic is called FLECE for FLexible ECE
  - A variety of spectral filters may be inserted into the beamline

- Composed of a single diagnostic channel
  - Uses spare InSb detector in Michelson cryostat

- Bandwidth is roughly 50 - 500 GHz
  - Lower limit set by plasma characteristics and transmission line
  - Upper limit set by transmission characteristics of corrugated waveguide

- Time domain response is up to 1 MHz
  - This limit is set by the InSb detector
  - Noise may ultimately reduce this limit

- Operation began in May 1999

This diagnostic is a useful counterpart to the existing set of DIII-D ECE diagnostics

- The existing profile diagnostics each have limitations
  - Michelson Interferometer: broad spectral range (50-500 GHz) but slow time response (50 Hz)
  - Heterodyne Radiometer: fast time response (100 kHz) but narrower spectral range (84-114 GHz)

- The FLECE diagnostic complements these two
  - Broad spectral range (50-500 GHz) and fast time response (< 1 MHz)
  - Single channel only

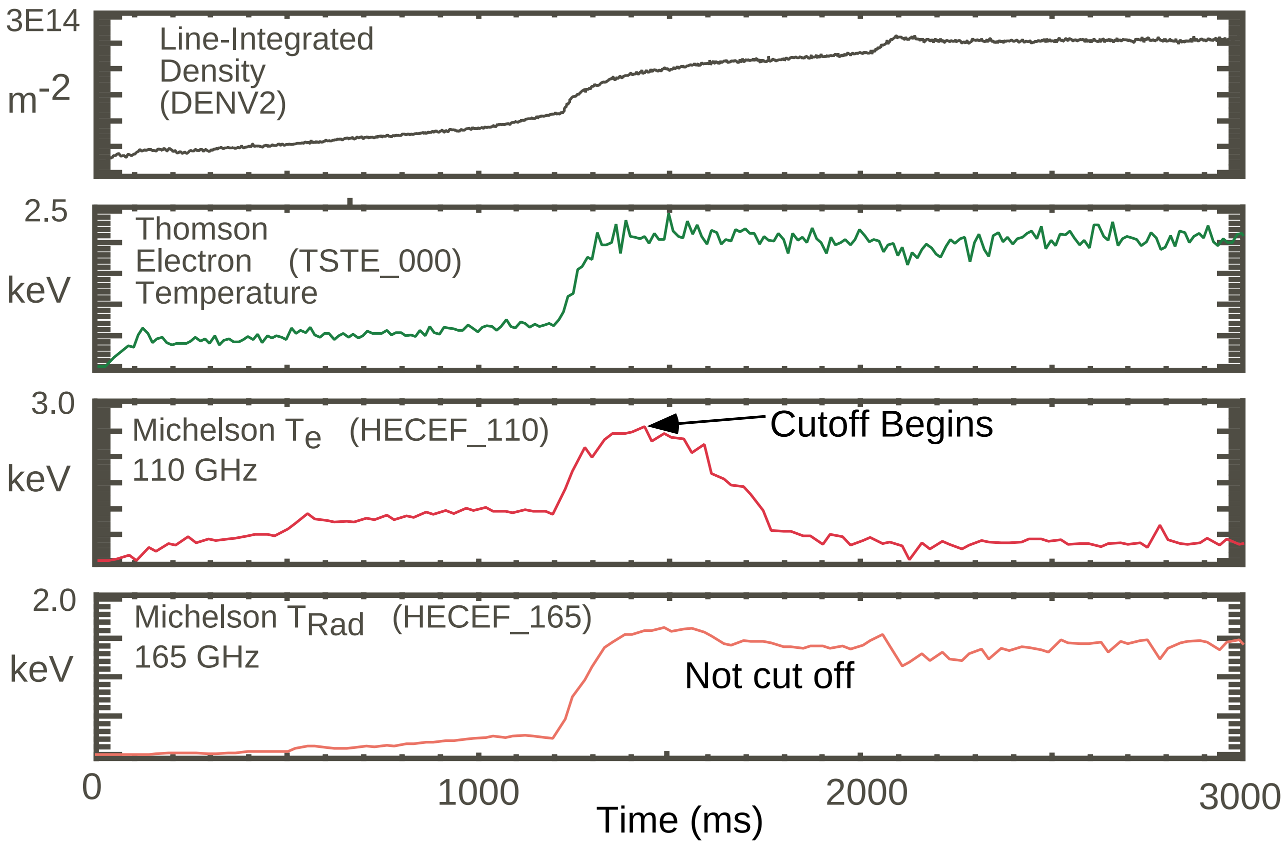
- There are a number of applications for which FLECE is well suited:
  - Fast third-harmonic core T_e measurement (see next page)
  - Analysis of toroidal mode numbers of MHD activity
  - Detection and measurement of energetic electrons due to disruptions and internal reconnections
  - Other ideas are still being developed

One of the most useful features of the FLECE diagnostic is the ability to make a fast third-harmonic T_e measurement

- The central ECE is often cutoff in high-performance DIII-D discharges
  - There is presently no fast central T_e measurement in these cases

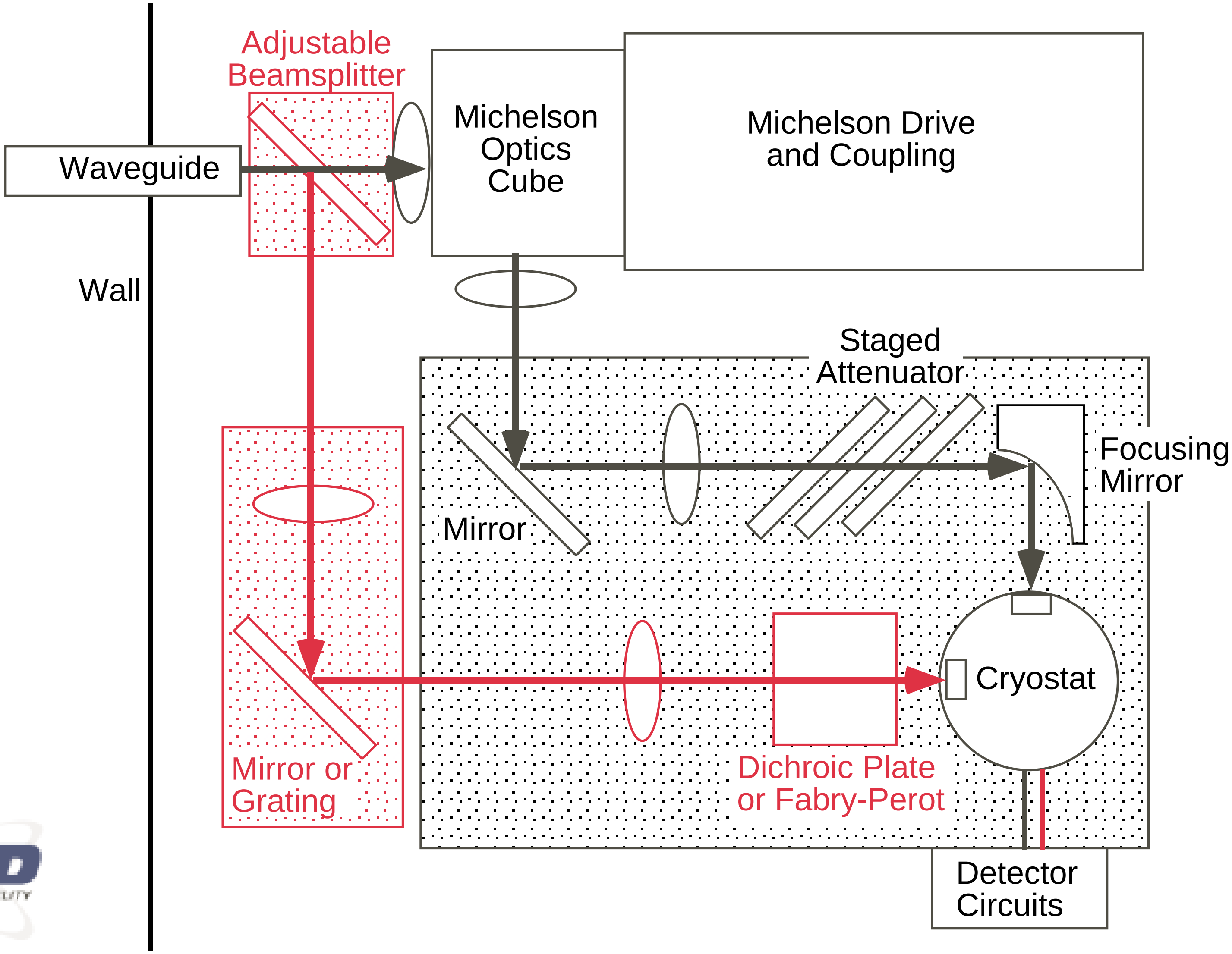
- Thomson scattering and Michelson 3rd harmonic give slow central T_e

- FLECE can give a fast measurement if an appropriate narrow-bandpass filter (Fabry-Perot etalon) is installed



Layout of FLECE and Michelson optics

- Michelson hardware in **black**; FLECE hardware in **red**
- Radiation beamlines are thick arrows
- FLECE optics are a Gaussian telescope
  - Beam is nearly parallel entering the detector

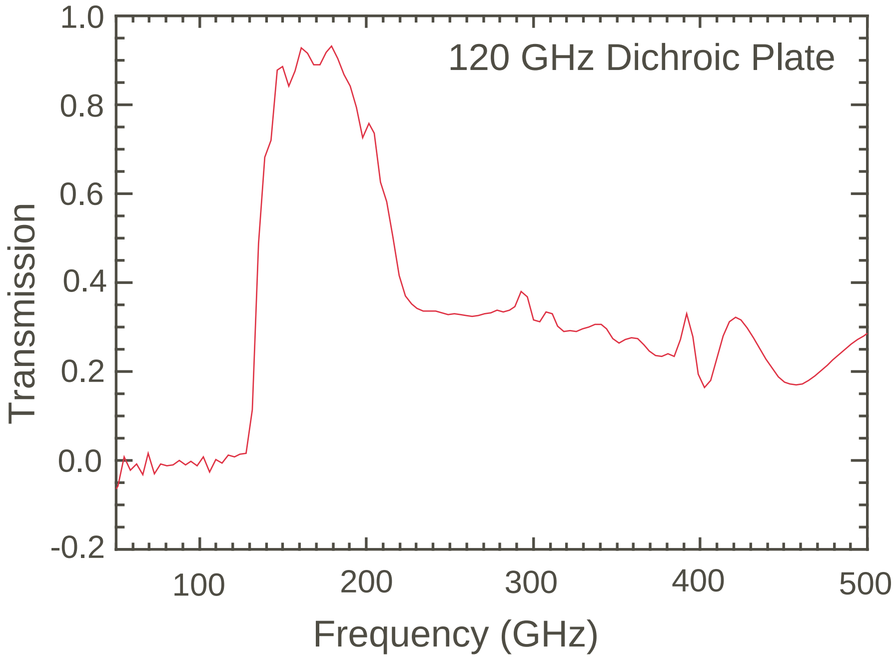


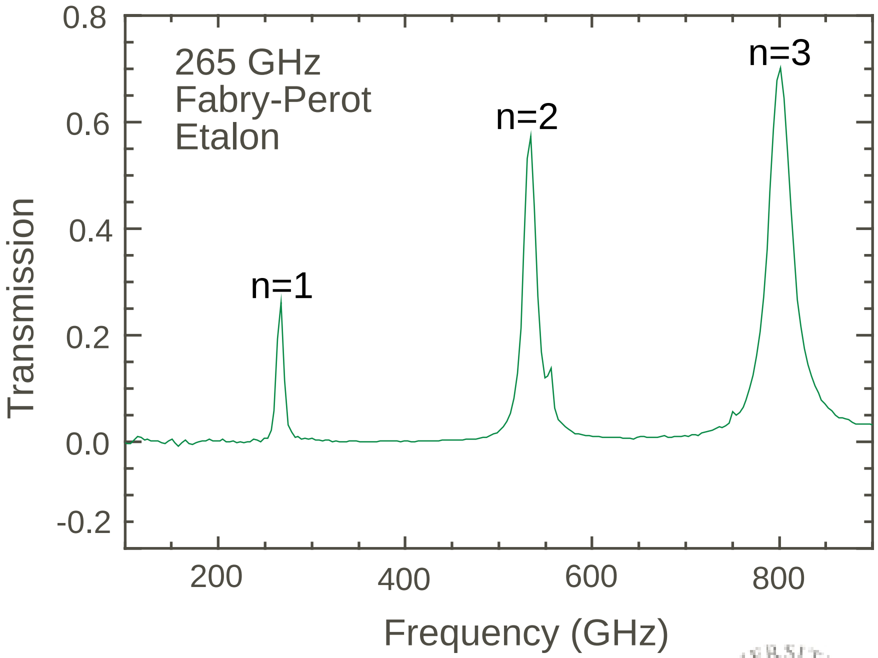
Three types of spectral filters are available

- Diffraction gratings: Low-pass filters (not illustrated)
  - Have not been used on FLECE
  - Primary purpose would be to eliminate harmonics of Fabry-Perot

- Dichroic plates: High-pass filters
  - Used to examine high-harmonic emission from energetic electrons

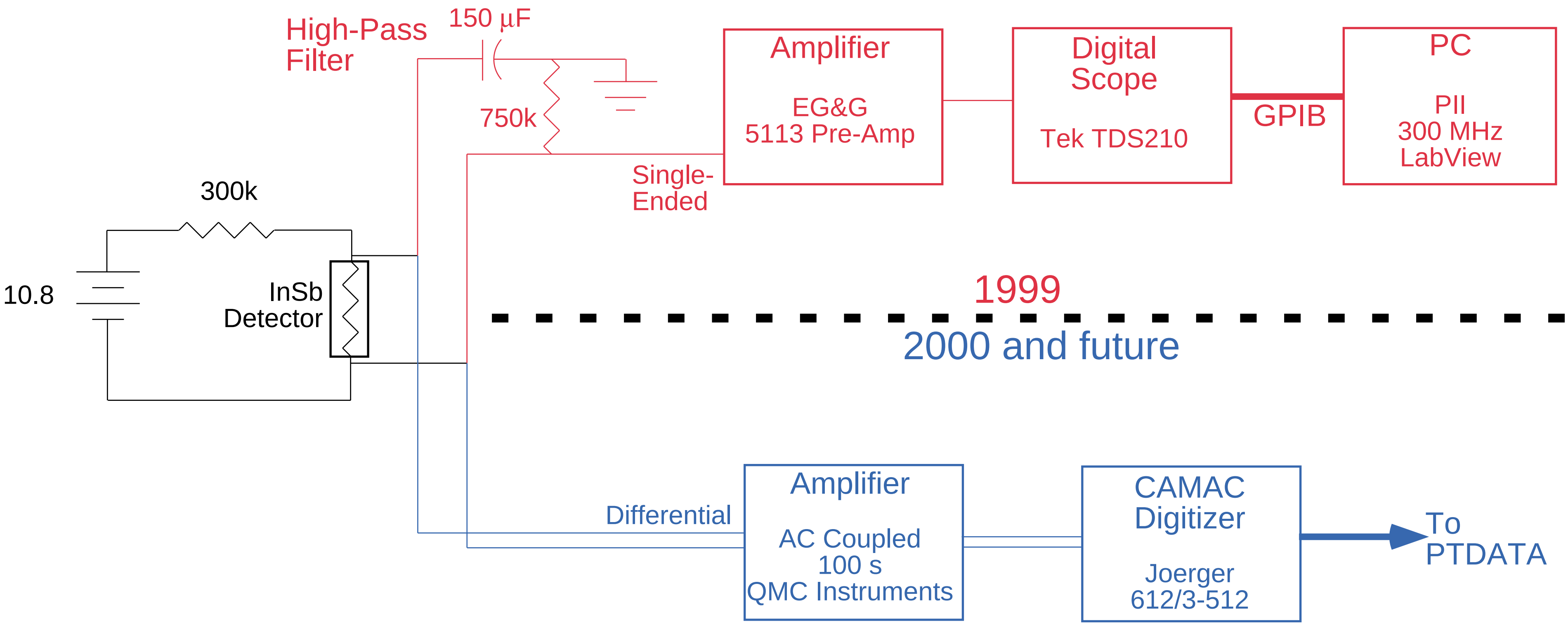
- Fabry-Perot etalons: Narrow bandpass filters
  - Used to examine emission at specific frequencies for T_e measurement





Schematic of FLECE signal conditioning and acquisition

- Electronics used in 1999 for testing and debugging are shown in **red**
- Electronics to be used in 2000 and later are shown in **blue**



Neutron-induced baseline drift has been a problem

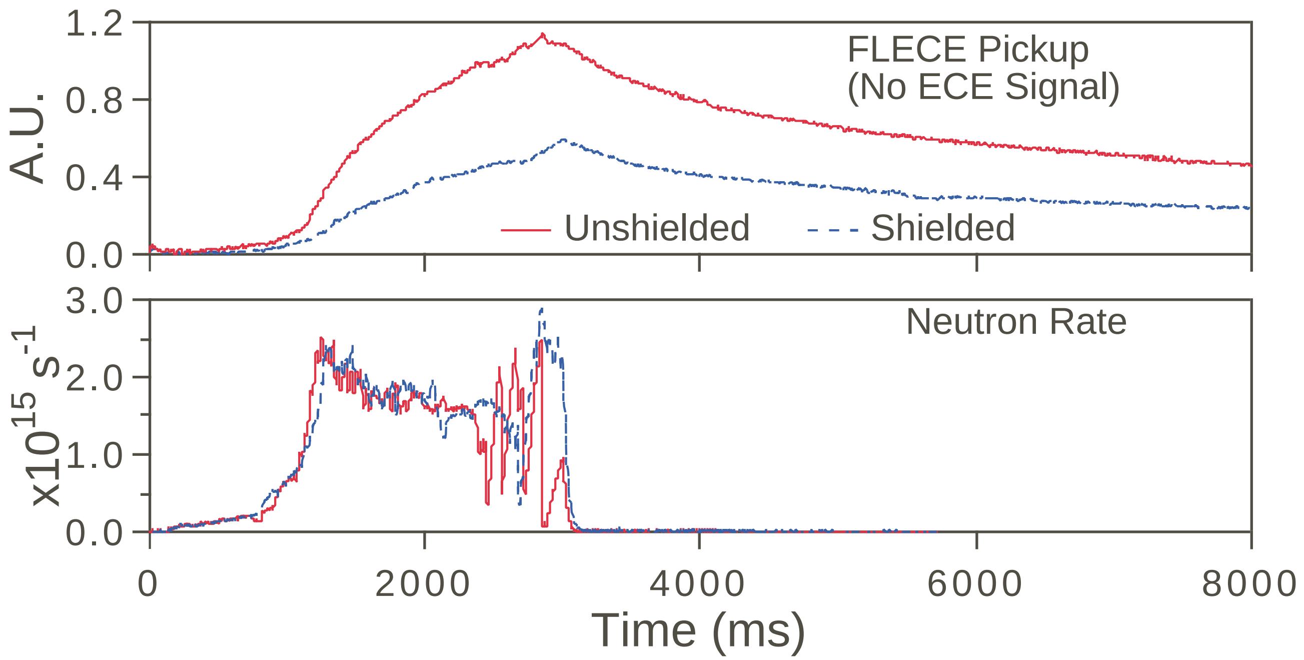
- Baseline drift is almost always observed
  - In some cases the pickup dominates the measurement
  - It is **not** observed on the Michelson's detector -- why?

- Baseline drift is not caused by:

- ECE effects	- Amplifier effects
- Magnetic pickup	- Ground loops

- Long time-scale decay not consistent with μs response of InSb bolometer

- Signal is correlated with neutrons from tokamak
  - Drift appears when neutron rate rises
  - InSb detectors are known to be sensitive to neutron flux (Tait, Phys. Fluids **24**, 1981, 719.)
  - Detector is 10 meters from tokamak with 0.75 m concrete shield
  - Shielding clearly reduces pickup:

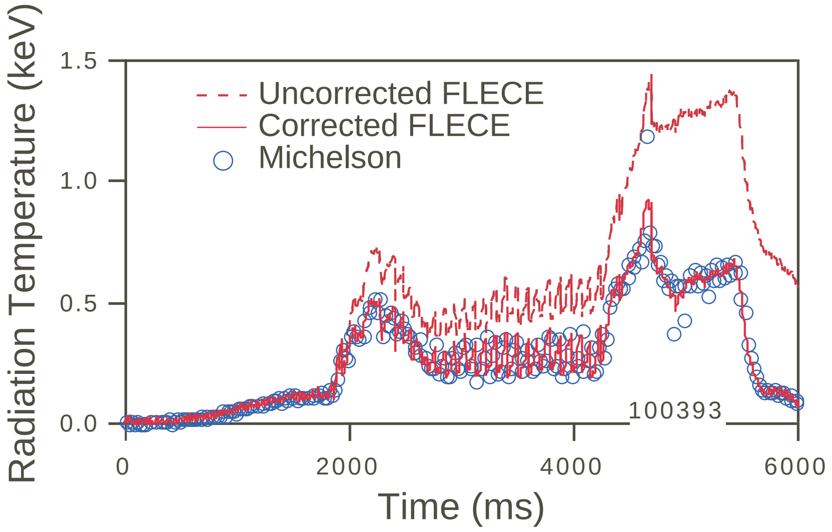


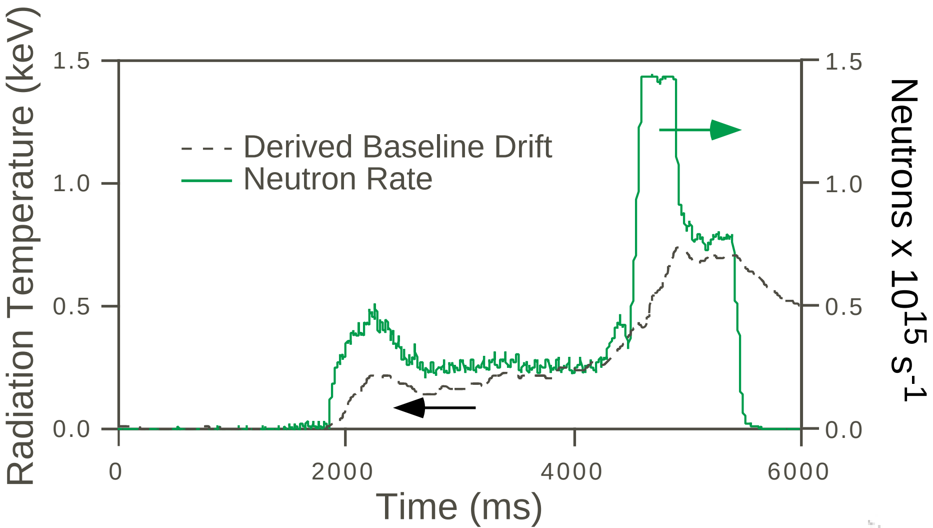
Baseline drift can be removed by normalizing to the appropriate Michelson signal

- The FLECE signal is not an absolutely calibrated signal
  - It is always reported after it is normalized to the Michelson
  - This makes amplifier settings, zero levels, etc. irrelevant to the calibration

- FLECE is primarily useful for observing fast events

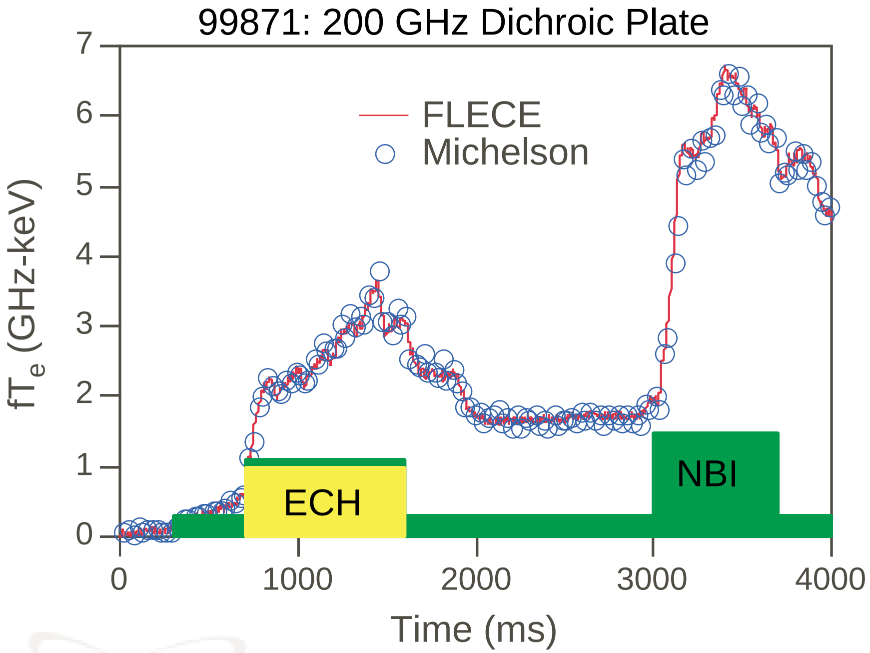
- The FLECE signal can be normalized to the Michelson
  - Require a neutron-free period at the beginning of the shot
  - Establish baseline and scale factor during neutron-free period
  - Then subtract the Michelson signal from FLECE to find drift
  - Average this signal out over a few hundred ms (typical time scale of drift) in order to preserve the fast time scale of the FLECE signal
  - Subtract "background" from the FLECE signal

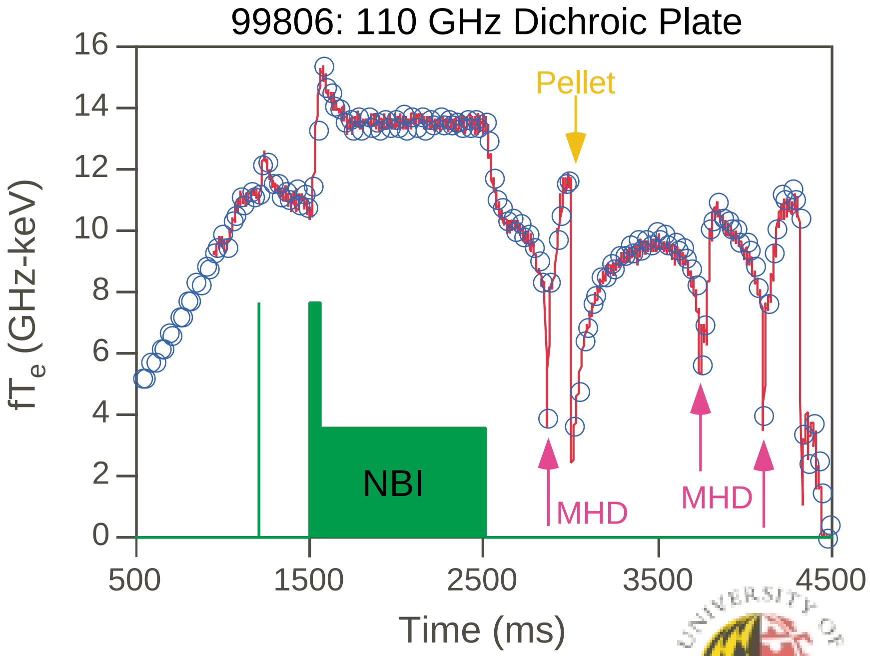




FLECE signals obtained with a dichroic plate in the beamline match Michelson signals well

- The raw signal from the FLECE channel is compared to the Michelson spectra integrated from the filter cutoff to 300 GHz
  - The Michelson signal must be convolved with the filter function
- The signals match within a few percent over the discharge
  - Baseline drift is relatively small in these cases due to large signal level
- Indicates that the diagnostic is working as expected
- In these two examples FLECE follows the Michelson through several different events





Electron temperature can be derived from the third-harmonic signal even if the plasma is not optically thick

- Begin with the equation of radiation transport:

$$I\omega = I_{\omega}^{(0)} e^{-\tau 0} + \int^{\tau 0} S\omega(\tau) e^{-\tau} d\tau$$

  - I_{ω} = emission intensity
  - $I_{\omega}^{(0)}$= radiation reflected off inner wall
  - S_{ω} = source function
  - τ = optical depth
  - τ^{0} = optical depth across plasma
  - $I_{\omega}^{(0)} e^{-\tau 0}$ is typically small

- For a Maxwellian distribution, S_{ω} is known:

$$S\omega = \frac{\omega^2}{8\pi^3 c^2} T_e$$

- The radiation transport equation reduces to:

$$T_r(\omega_3) = T_e(\omega_3)\left(1 - e^{-\tau_3}\right) + T_e^{(2)}(\omega_3) e^{-\tau_3}$$

  - $T_e(\omega_3)$ = electron temperature at 3rd harm. resonance
  - τ_3 = optical depth at 3rd harm. resonance
  - $T_e^{(2)}(\omega_3)$ = electron temperature at 2nd harm resonance of ω_3

- The equation can be solved iteratively for $T_e(\omega_3)$ and τ_3 if $T_e^{(2)}(\omega_3)$,$T_r(\omega_3)$,and $n_e(\omega_3)$ are known
- This method is used routinely on DIII-D when second harmonic is cutoff
- Reference Austin *et al.*,Phys. Plasmas **3** (1996) 3725.

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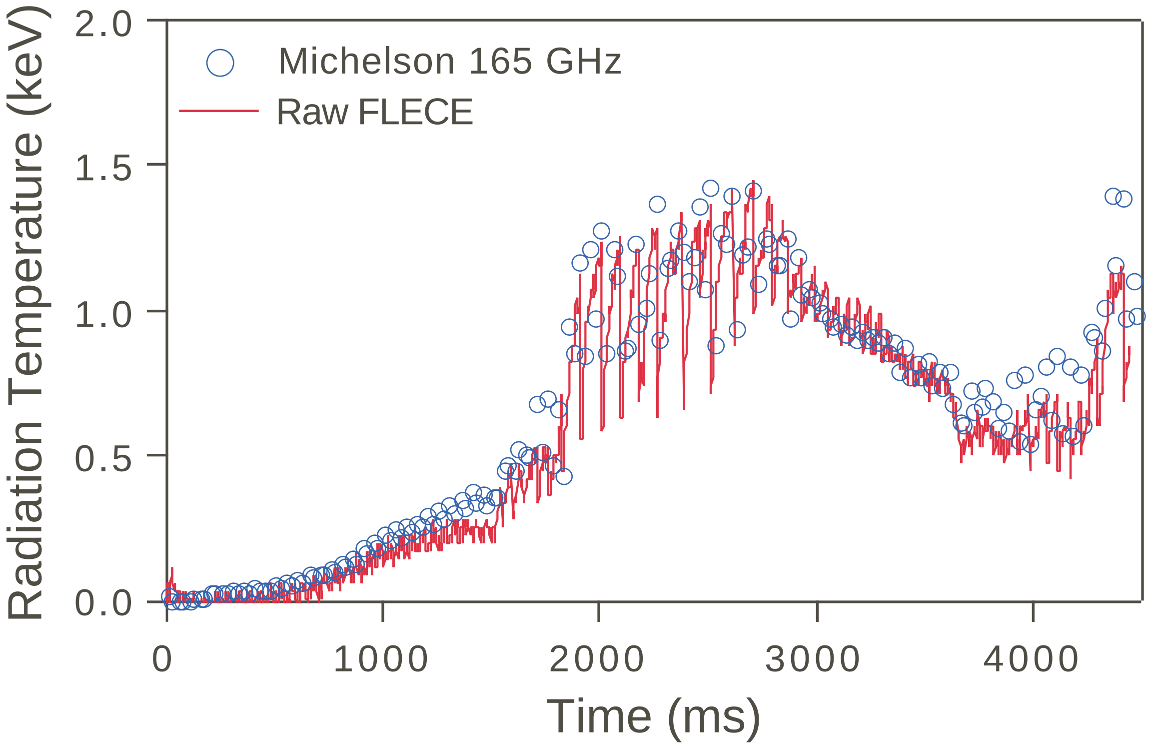
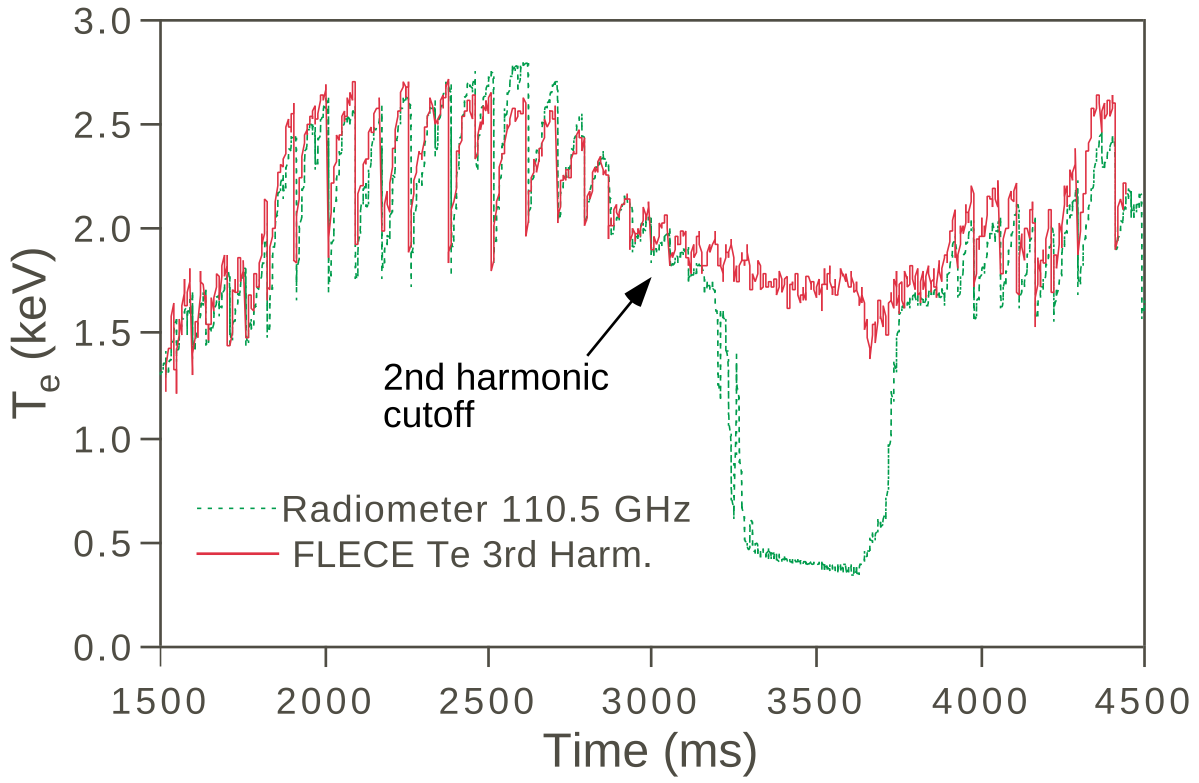
Measurements of third-harmonic emission have been made with Fabry-Perot etalons to determine electron temperature

- Measurements were made primarily at 165 GHz
  - For the case shown here, this puts the resonance at ρ=0.15 on the high-field side
- The FLECE signal is adjusted for baseline drift
  - This case uses background subtraction; leaves some residual drift
- Agreement is good but not excellent
  - Drift complicates analysis
  - Spectrum passed by poor etalon is too broad
  - Better etalons are required for the future

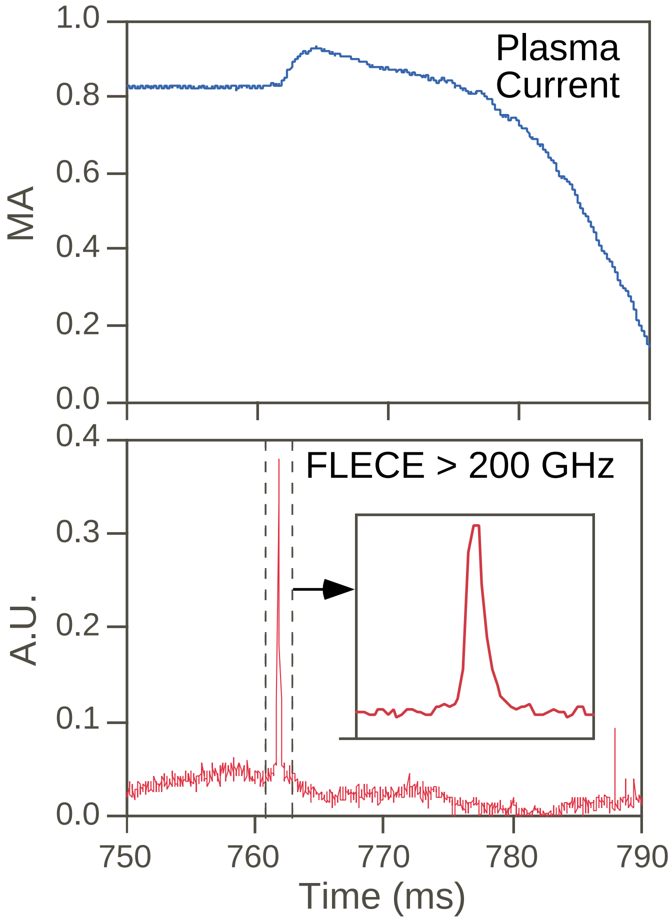


Derived third-harmonic temperature measurement matches the radiometer signal fairly well

- Third harmonic temperature is calculated by the method described above
- The optical depth calculation requires density at the resonance location
  - Provided by Thomson and/or laser interferometers
  - Density dependence is weak => minor errors are negligible
  - τ_e is in the range of 0.1 - 1 for plasmas of interest
- $T_e^{(2)}$ is important if it exists in the plasma
  - Can be inferred from Thomson



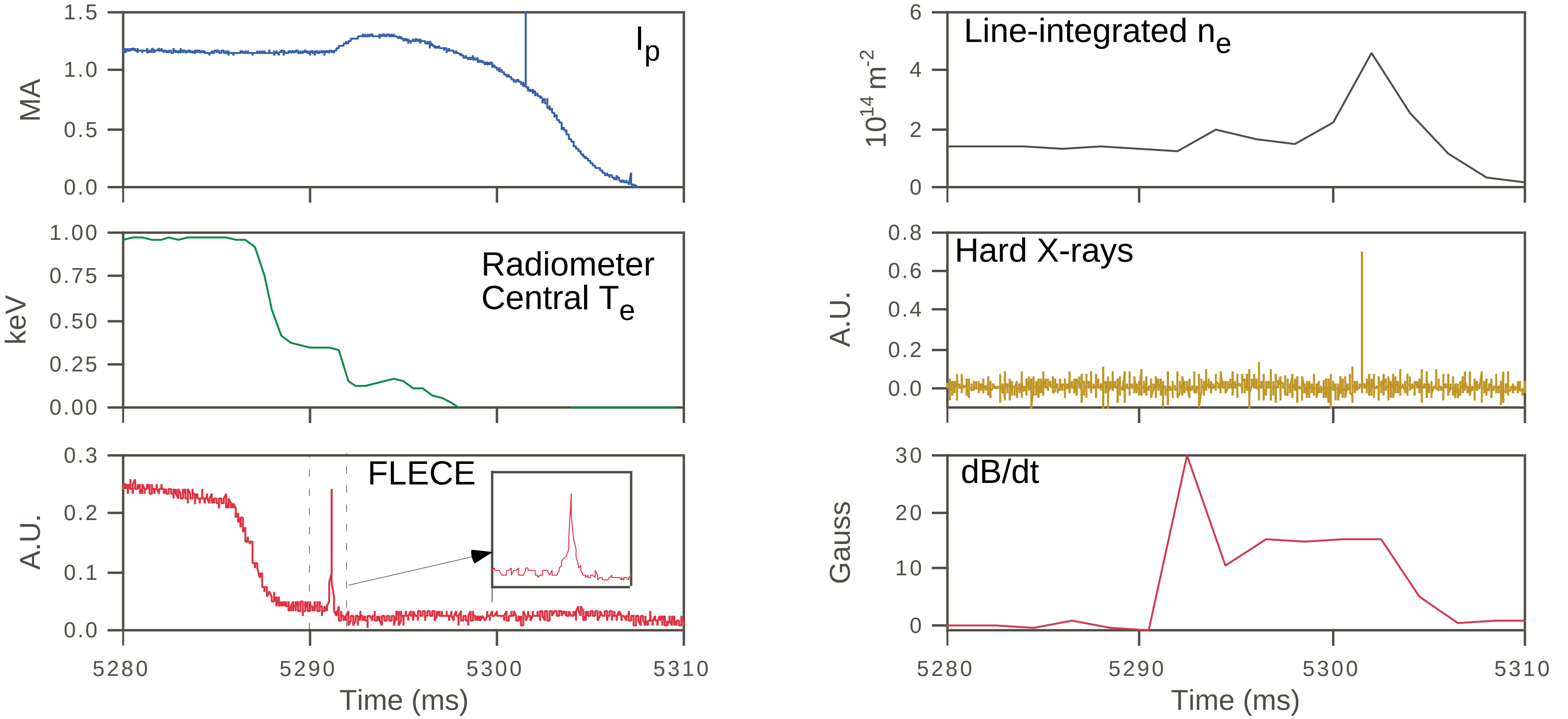
FLECE has detected energetic electrons created by disruptive events



- High-harmonic emission is observed with 200 GHz dichroic plate in the beamline
  - Eliminates the thermal emission
  - Allows for greater gain of small high-frequency part of spectrum
  - Waveguide attenuates signal above 300 GHz
- Short spikes of high-harmonic emission have been observed during disruptions
  - Correlate with the start of the current quench
  - Typically 0.5 ms long
- Similar spikes have also been observed during beta-collapses generated by resistive wall modes
- Do the spikes correspond to fast electrons generated by reconnections?
  - Appears to be some time-dependent structure
  - Possible avenue to study reconnection physics

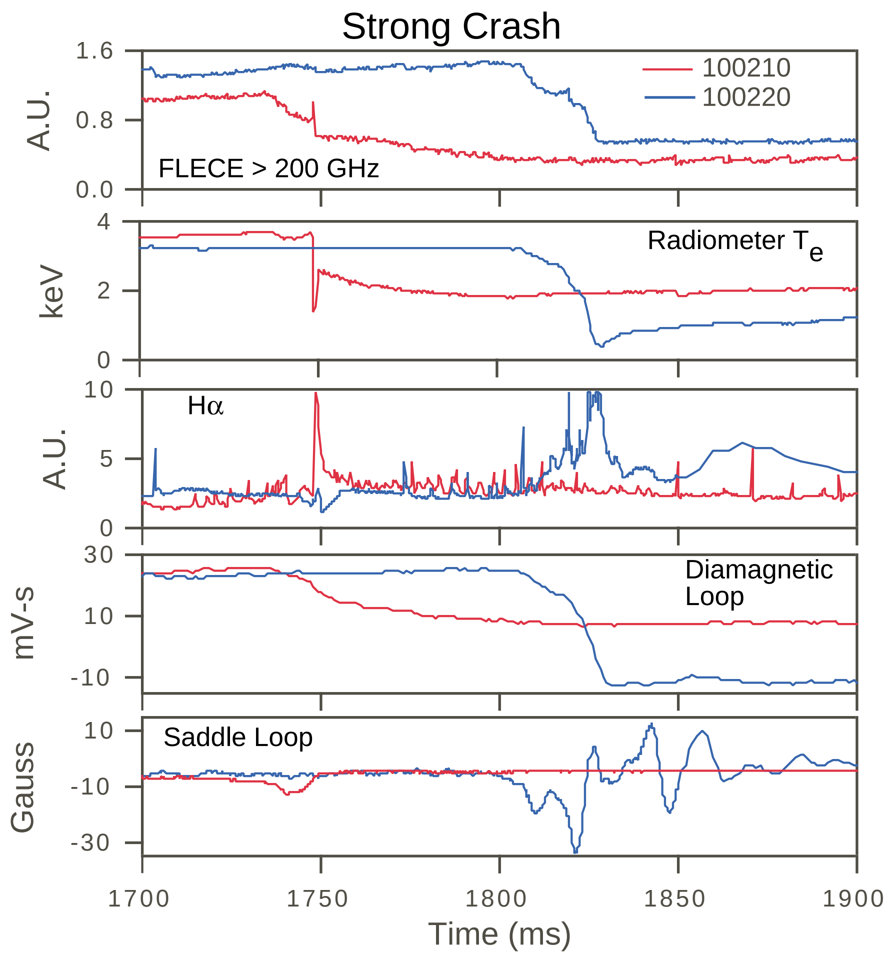
Fast electrons are generated by hard disruptions

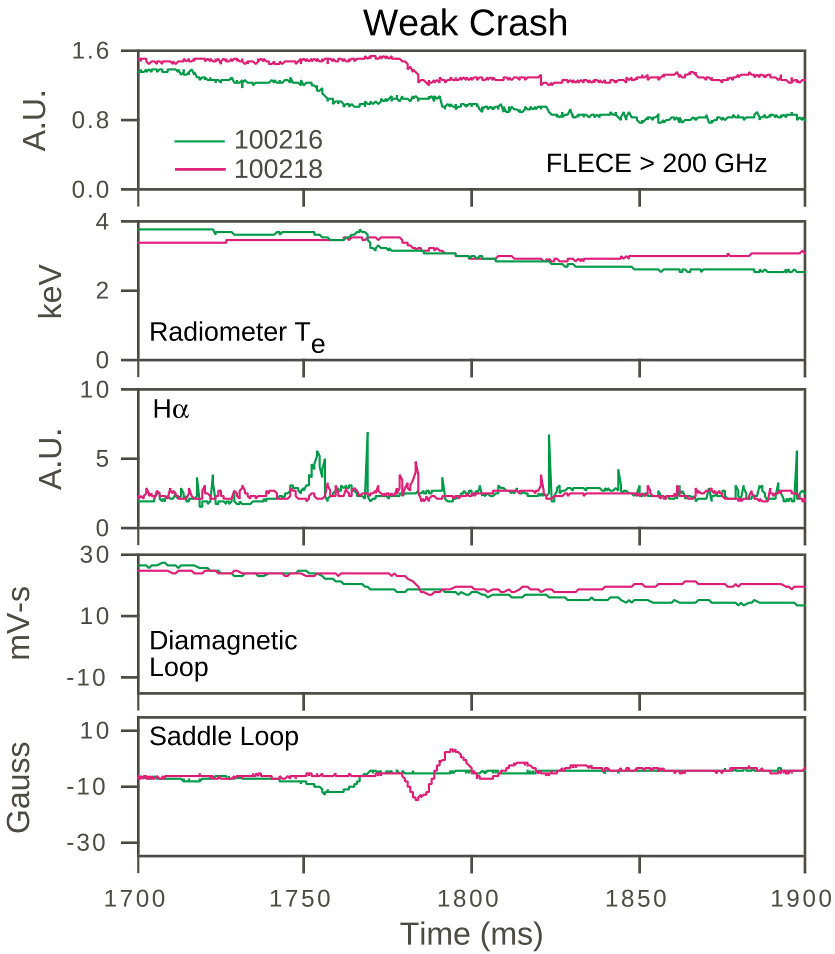
- High-harmonic emission spike correlates with the reconnection
- Emission is not an artifact; it is not correlated with:
  - Neutron emission
  - Hard X-rays
  - Thermal ECE
  - Density rise
- In this figure the FLECE filter is the 200 GHz dichroic plate



Emission spikes are also associated with resistive wall modes

- Spikes are not always observed
- Apparently correlated to the intensity of the reconnection
- Correspond to spikes in visible light and soft x-rays





Future Work: Hardware

- Obtain replacement InSb detector and test for pickup
  - Old detector may have flaws making it susceptible to baseline drift
- Test long-time-scale AC-coupled amplifier
  - Lower noise, sharper frequency cutoff than current system
- Re-attach IR filters to LHe heat sink in cryostat
  - Possibility that poorly-anchored filters are heating up during neutron irradiation
  - Also likely responsible for recent poor vacuum performance of cryostat
- Test beam chopper to characterize baseline drift
- Acquire fast digitizer and integrate into DIII-D data system
- Fabricate (or purchase) improved Fabry-Perot etalons
  - Plans exist to improve finesse of existing grid mounts
  - Ideally want a small set of high-quality filters
  - Best performance may be available from vendor-manufactured grids
- Fabricate improved optics mounts for filters

Future Work: Physics

- Refine third-harmonic capability
  - This is the most important function of FLECE
  - Need better routines for determining n_e and $T_e^{(2)}$

- Make fast temperature measurements
  - Evolution of central Te during gas-puff-induced disruptions
  - Study temperature relaxation of EC-heated plasmas
  - Determine other uses

- Investigate disruption-generated emission spikes
  - Use a variety of dichroic plates and F-P etalons to determine spectra
  - What are functional dependencies?

- Measure spectra of runaway electrons
  - Requires repeatable disruptions - difficult
  - Use dichroic plates with a range of cutoff frequencies to find evolution of emission spectra during disruptions
  - Gives insight into $T_{e,\perp}$ of runaways

Summary

- A new ECE diagnostic, called FLECE, has been implemented of DIII-D
  - Single channel with several spectral filters available (FLexible ECE)
  - Time response up to 1 MHz, ECE frequency response 50-500 GHz

- The signal measured with this diagnostic matches the Michelson signal well
  - Confirmed with several dichroic plate and Fabry-Perot measurements
  - Neutron-induced baseline drift is an issue being actively addressed

- Measurements of electron temperature have been made via third-harmonic ECE using Fabry-Perot etalons
  - Measurements agree with corresponding radiometer channels
  - Better Fabry-Perot etalons are required

- Spikes of high-harmonic emission have been observed during disruptions
  - Believed to be associated with fast electrons generated by reconnection
  - Occasionally observed during resistive wall modes