Multi-point, high-speed passive ion velocity distribution diagnostic on the Pegasus Toroidal Experiment

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PEGASUS
Toroidal Experiment

Abstract

A passive ion temperature polychromator has been deployed on the Pegasus Toroidal Experiment to study power balance and non-thermal ion distributions arising during helicity injection. A single radial viewing chord provides a line averaged ion temperature from Doppler broadening. Nine tangential viewing chords provide a tangential velocity profile, ranging from major radius of 48 to 78 cm. Spectra are recorded from a 1 m F/8.6 Czerny-Turner polychromator whose output is recorded by an intensified high-speed camera. The use of high orders allows for a dispersion of 0.02 Å/mm in 4^{th} order and a bandpass of 0.14 Å (~13 km/s) at 3131 Å in 4^{th} order with 100 um entrance slit. The instrument temperature of the spectrometer is 15 eV. Light from the output of an image intensifier in the spectrometer focal plane is coupled to a high-speed CMOS camera, which records 20 spatial points along the entrance slit at 0.5 ms time resolution. During point-source dc helicity injection, stochastic magnetic fields keep T_e low (~100 eV) and thus low ionization impurities penetrate to the core. Under these conditions, high core ion temperatures are measured ($T_i \approx 1.2$ keV, $T_e \approx 0.1$ keV) using spectral lines from Carbon III, Nitrogen III, and Boron IV.

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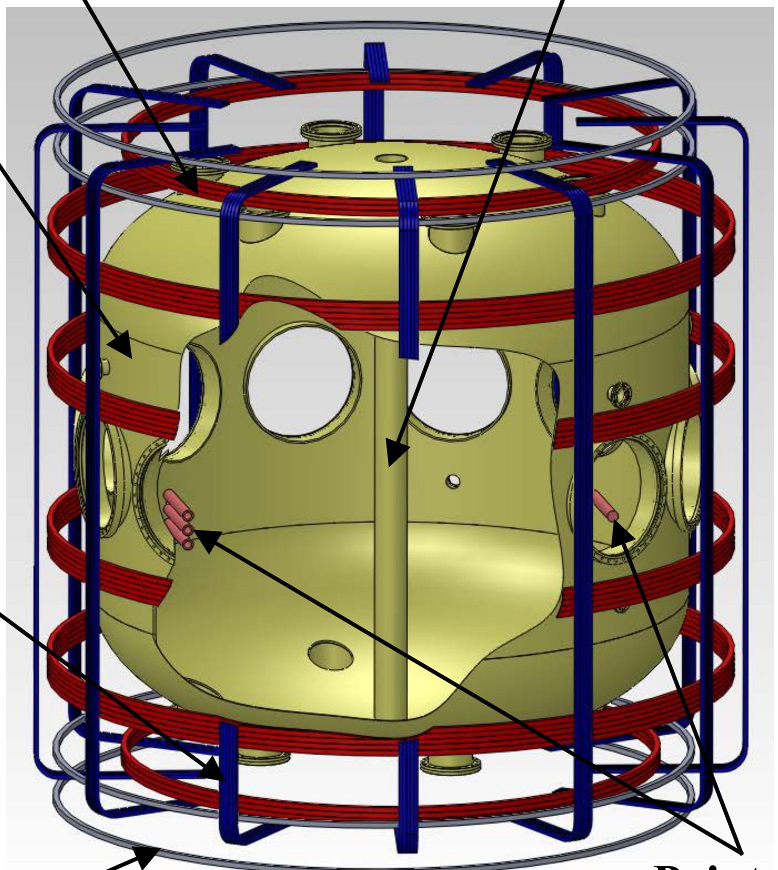
Summary

- A passive, high speed, ion doppler spectrometer (IDS) has been developed for Pegasus to study substantial ion heating and velocity distributions during helicity injection
- Initial motivation for diagnostic was plasma rotation with outboard bias; initial results reveal much more complex system
- The diagnostic consists of a 1m Czerny-Turner polychromator optimized for UV sensitivity coupled with a high speed Phantom V310 detector
- Coupling is achieved using a 25mm image intensifier
- High orders are used to achieve a 0.1 A bandpass (~13 km/s at 2296 Å)
- Substantial differences in T_i are observed in ohmic (T_i ~100 eV) and helicity-injection driven plasmas (T_i ~ 1.2 keV)
- A bipolar flow has been observed
- Heating and flow similar to TS-3 recent results

Pegasus is a compact ultralow-A ST



Experimental Parameters

Parameter	Achieved	Goals
A	1.15 – 1.3	1.12 – 1.3
R(m)	0.2 – 0.45	0.2 – 0.45
I_p (MA)	$\leq$ .21	$\leq$ 0.30
I_N (MA/m-T)	6 – 12	6 – 20
RB_t (T-m)	$\leq$ 0.06	$\leq$ 0.1
κ	1.4 – 3.7	1.4 – 3.7
τ_{shot} (s)	$\leq$ 0.025	$\leq$ 0.05
β_t (%)	$\leq$ 25	> 40
P_{HHFW} (MW)	0.2	1.0

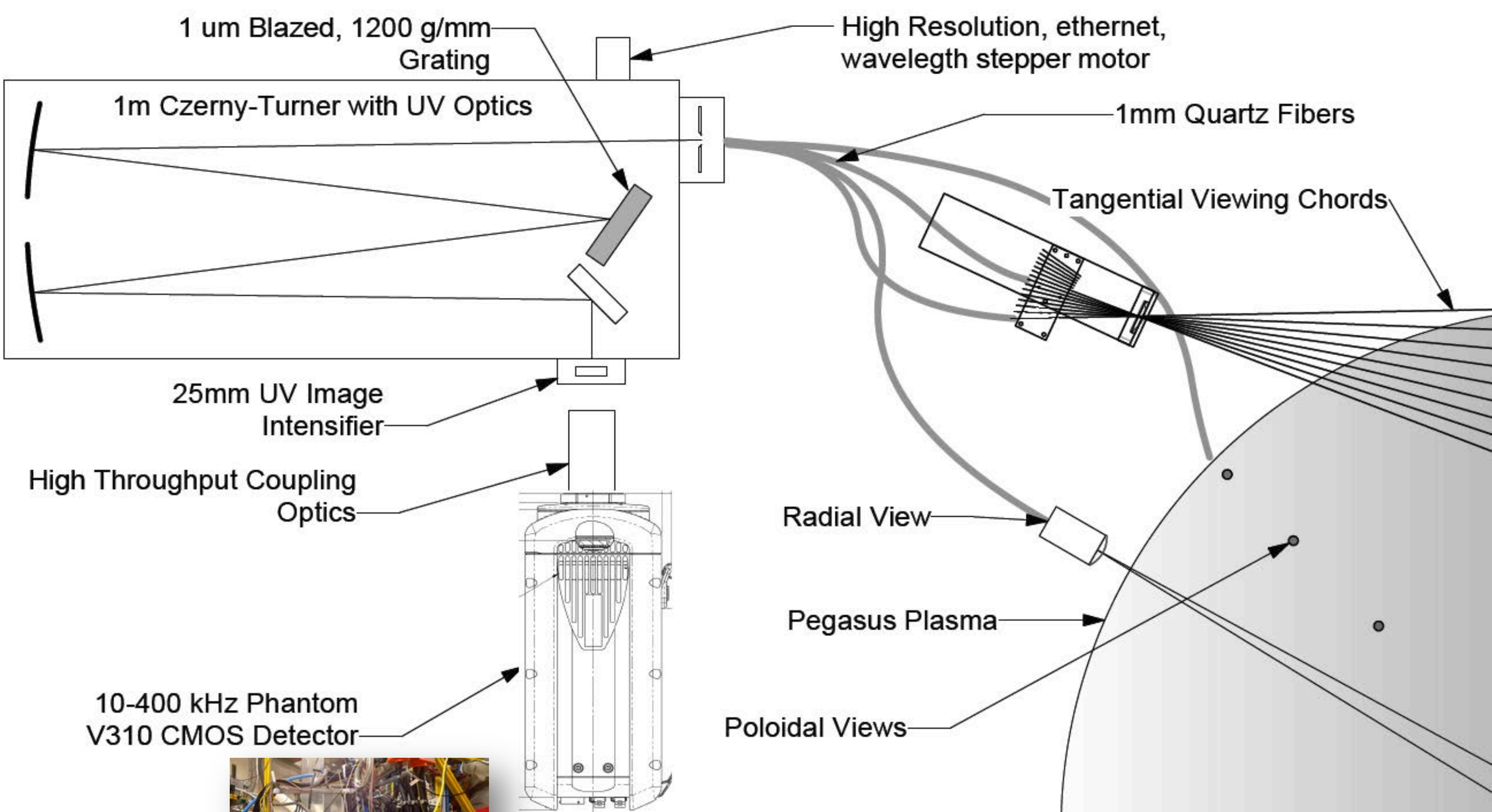
Major research thrusts include:

- *Non-inductive startup and sustainment*
- *Tokamak physics in small aspect ratio:*
  - *High-I_N, high-β operating regimes*
  - *ELM-like edge MHD activity*

Motivation

- Initial motivation for diagnostic was to look for plasma rotation due to outboard bias of helicity injectors
- Radial and tangential velocity profiles reveal a much more complicated system, exhibiting dramatic ion heating (~1.2 keV) and bipolar toroidal ion flows
- Large scale magnetic reconnection through Taylor relaxation has been shown to occur during coaxial helicity injection
- Magnetic reconnection is know to lead to ion heating and ion flows as shown by multiple reconnection experiments as well as during sawtooth crashes in Tokamaks
- Characterizing of ion velocity dynamics during helicity injection

Diagnostic Setup on Pegasus



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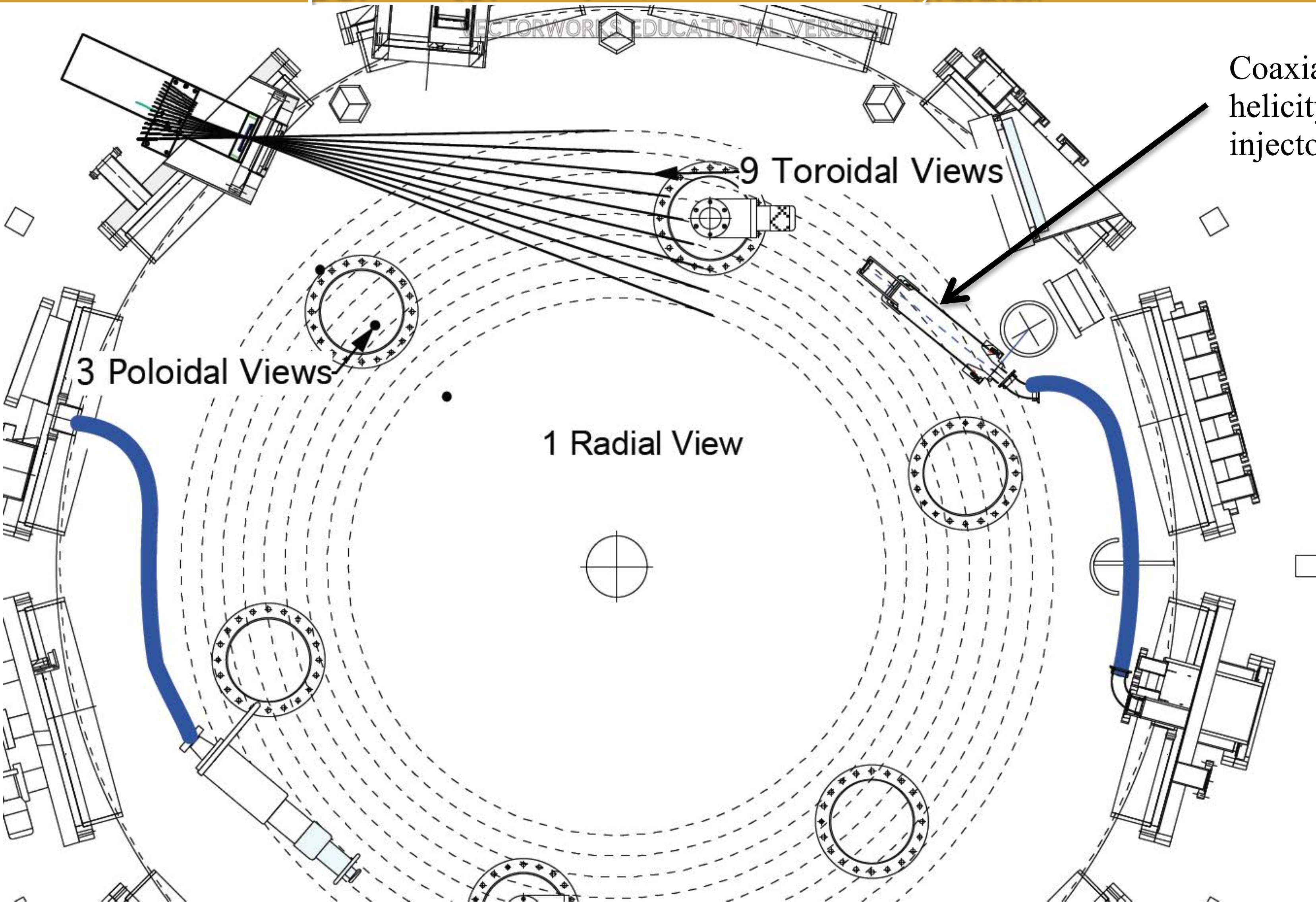
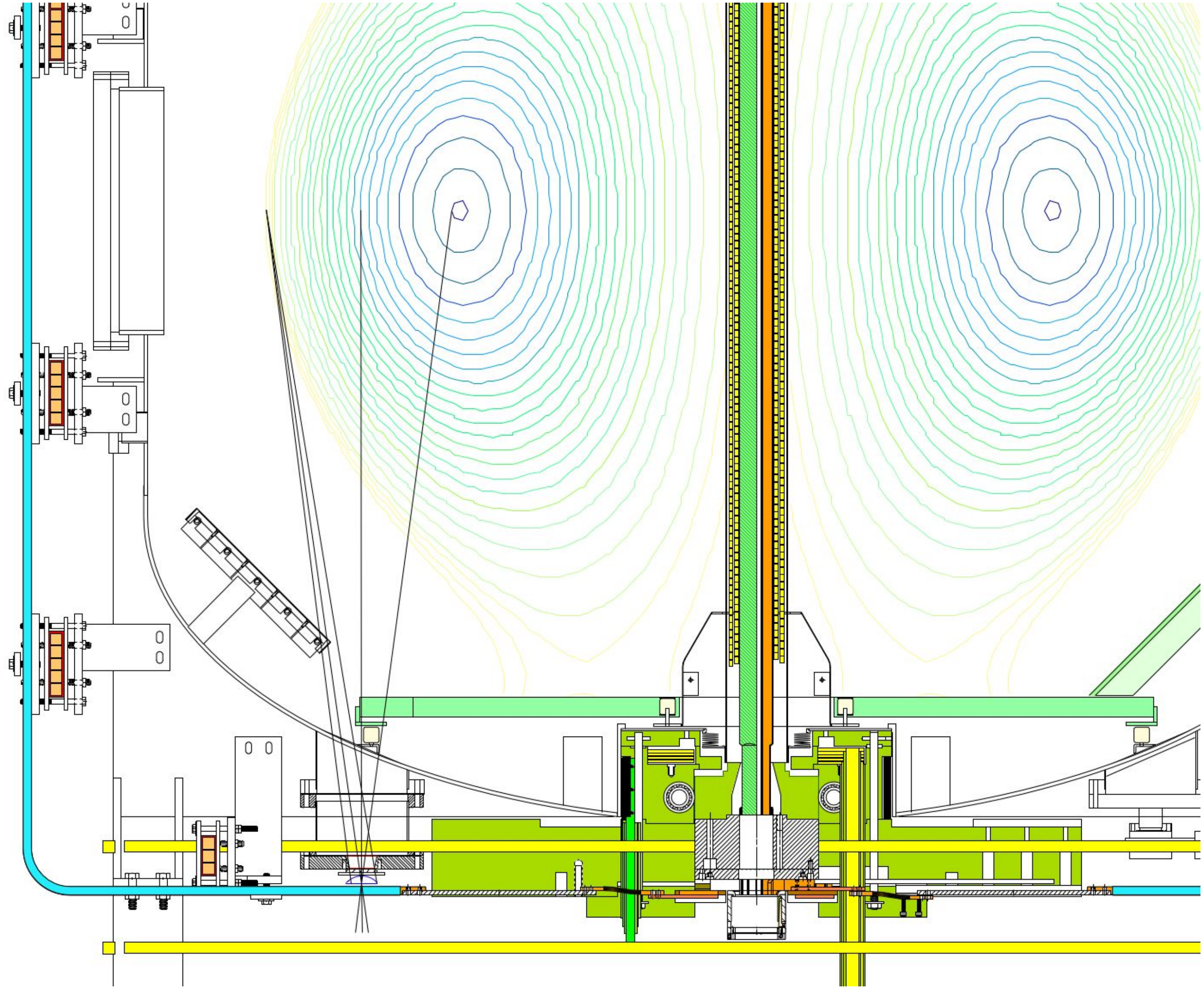
Multiple views allow for measurement of V_{pol}, V_{tor}, $T_i(r)$, and $\langle T_{i,radial} \rangle$



New poloidal views added this summer



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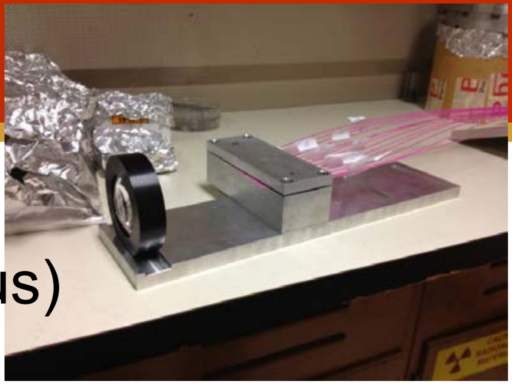
Simultaneous, multiple views



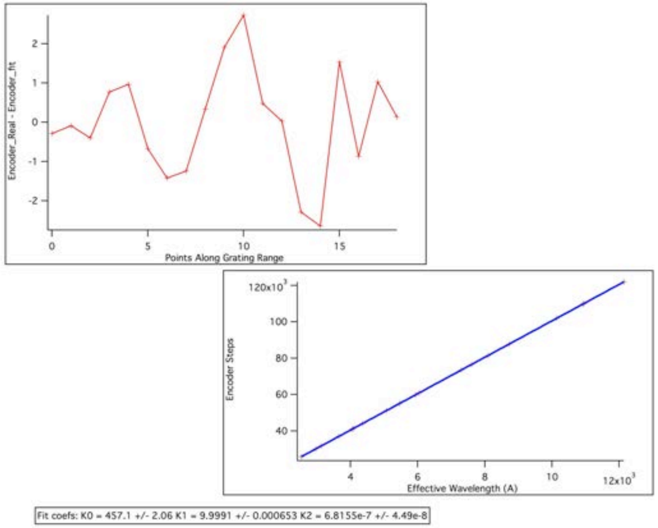
- 9 toroidal views (48 cm to 78 cm major radius)
  - Focused using 100m f/2 plano-convex lens
  - Each view is single 1mm Quartz, more fibers can be added for throughput
- 3 poloidal views
  - Focused using 75mm f/1.5 plano-convex lens
- 1 radial view
  - Focused using 100mm f/2 plano-convex lens
  - Single 1mm Quartz fiber
- Fibers are kept as short as possible in order to reduce UV attenuation (~ 1 db/m @ 2000 Å)
- ~20 fibers can be illuminated onto slit
- Etendue of plasma views are ~$1.6*10^{-3}$ cm^2str

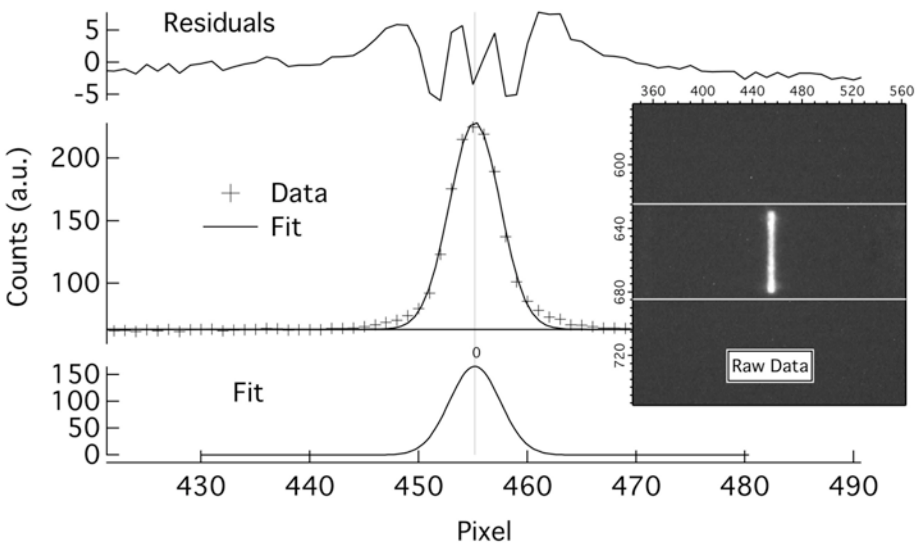
1m f/8.6 polychromator allows for use of high orders

- Mirrors have Acton VUV coating
- Wavelength range: 2000 – 6000 Å (depending on order)
- Grating: 110*110 mm, 1200 g/mm, 1 um blaze, MgF2-Al coatings
- High blaze allows for observation of UV lines in 3-5th order
- Linear dispersion of 0.016 A/mm in 5^{th} order
- Bandpass of 0.14 A with 100 um slits (~13 km/s at 2296 Å)
- Etendue of spectrometer 1.81×10^{-4} $cm^2 str$, 7.24×10^{-6} per spatial channel
- Spectrometer is the limiting etendue of the system
- If throughput is an issue, f/4 Echelle spectrometer available (~4.5 more light and larger slits) as well as increased plasma view etendue
- Highly resolved peaks lead to easier fitting and interesting subtleties

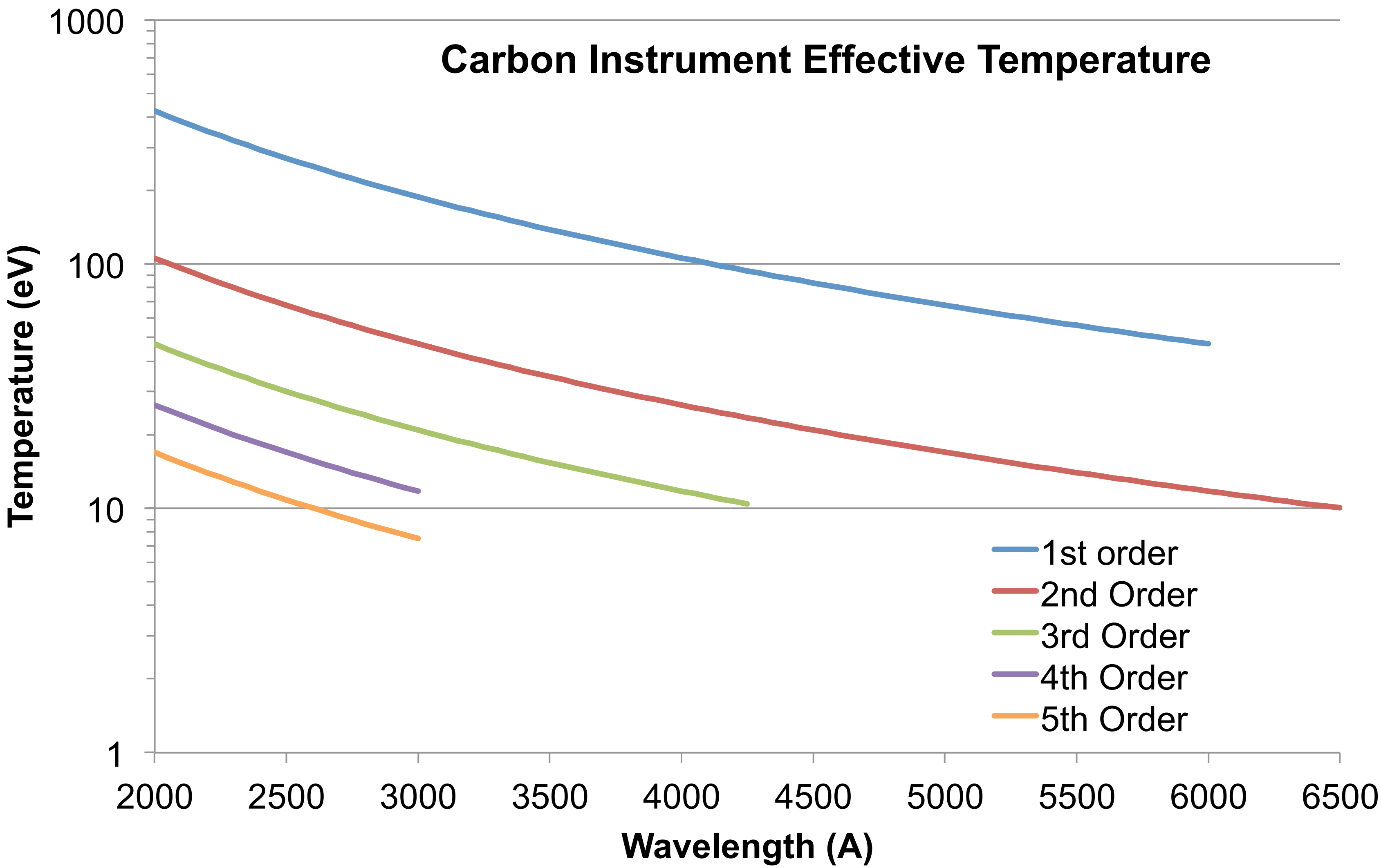
Spectrometer calibrations

- Wavelength calibration done with 2000 steps/Å, encoded stepper motor
- Dispersion
- Slit width calibration
- Mirror focusing
- Instrument profile measured throughout whole system
  - With 100 μm slits, Instrument Profile is 5.5 pixels FWHM or ~ 15 eV @ 2000 Å in 5th order



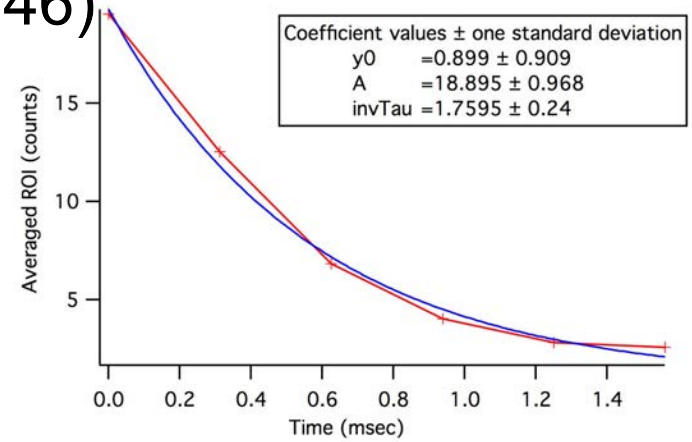


Higher orders and low instrument profile allow for high ion temperature dynamic range



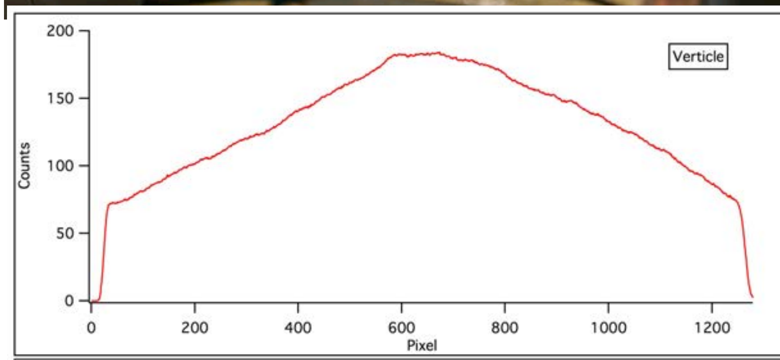
UV image intensifier

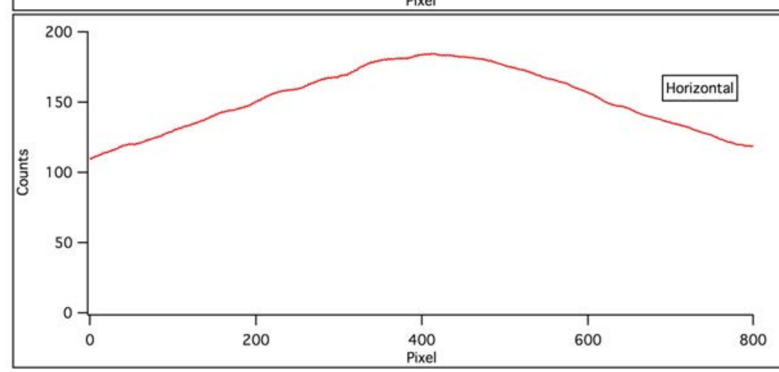
- 25 mm active area (~20 fibers)
- UV enhanced S20 photocathode
- P43 phosphor screen with measured decay time (1/e) of 0.5 msec
- Peak quantum efficiency of ~16% over range of interest
- Gain at 480 nm is 6500 W/W
- 50 lp/mm resolution, not limiting
- Faster phosphor possible (P46) but with loss of efficiency

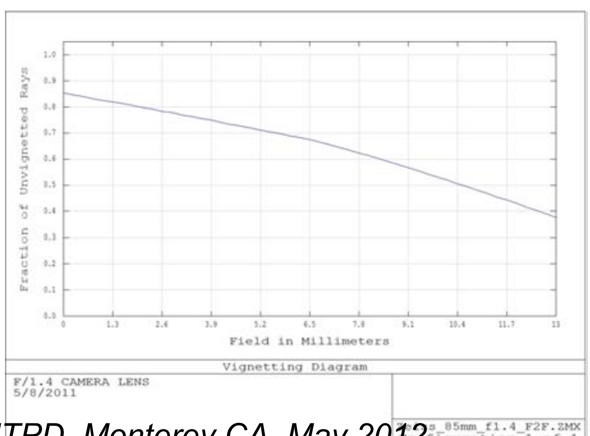


High throughput coupling optics with low vignetting

- 2 Zeiss 85mm f/1.4 lenses face to face
- Use of high focal length and low f/# allow for optimum coupling with low vignetting at the edge
- Vignetting at edge ~40%
- No change in magnification, no dispersion effect







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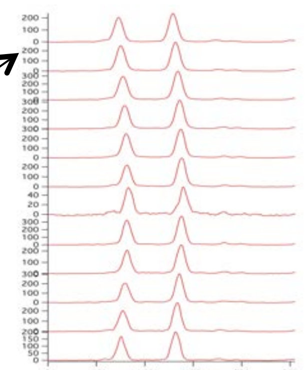
High Speed CMOS detector

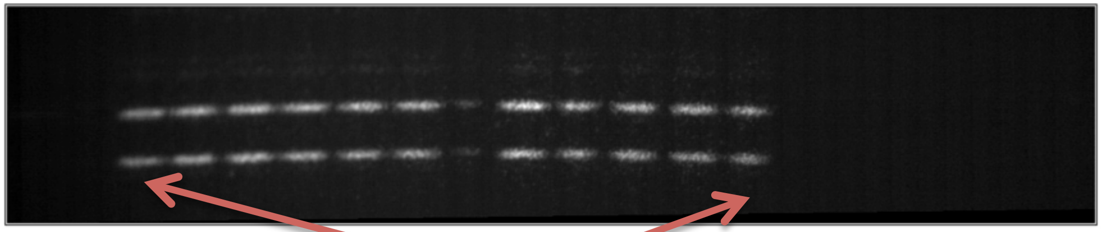
- High speed CMOS detector used to capture spectra
- ~20 spatial points recorded at 10 kHz, single channel at ~400 kHz (limited by phosphor)
- 12 bit depth keeps noise floor low with 26 e^- over 1 msec at zero gain
- Quantum efficiency of detector at phosphor peak wavelength is ~ 33%
- Plug-n-play nature of detector allows for easy setup and analysis

Spectral Analysis done in IgorPro

- Raw data is corrected for FPN (fixed pattern noise), dark current, and white field
- Line curvature fixed digitally
- Abel inversion technique can used to extract toroidal and poloidal velocity profile
- Spectral analysis done in IgorPro
- Fitting coefficients are found using the Levenberg-Marquardt algorithm to minimize chi-squared
- Profiles can be fit with Gaussian, Lorentzian, or Voigt profiles

Binned spatial channels

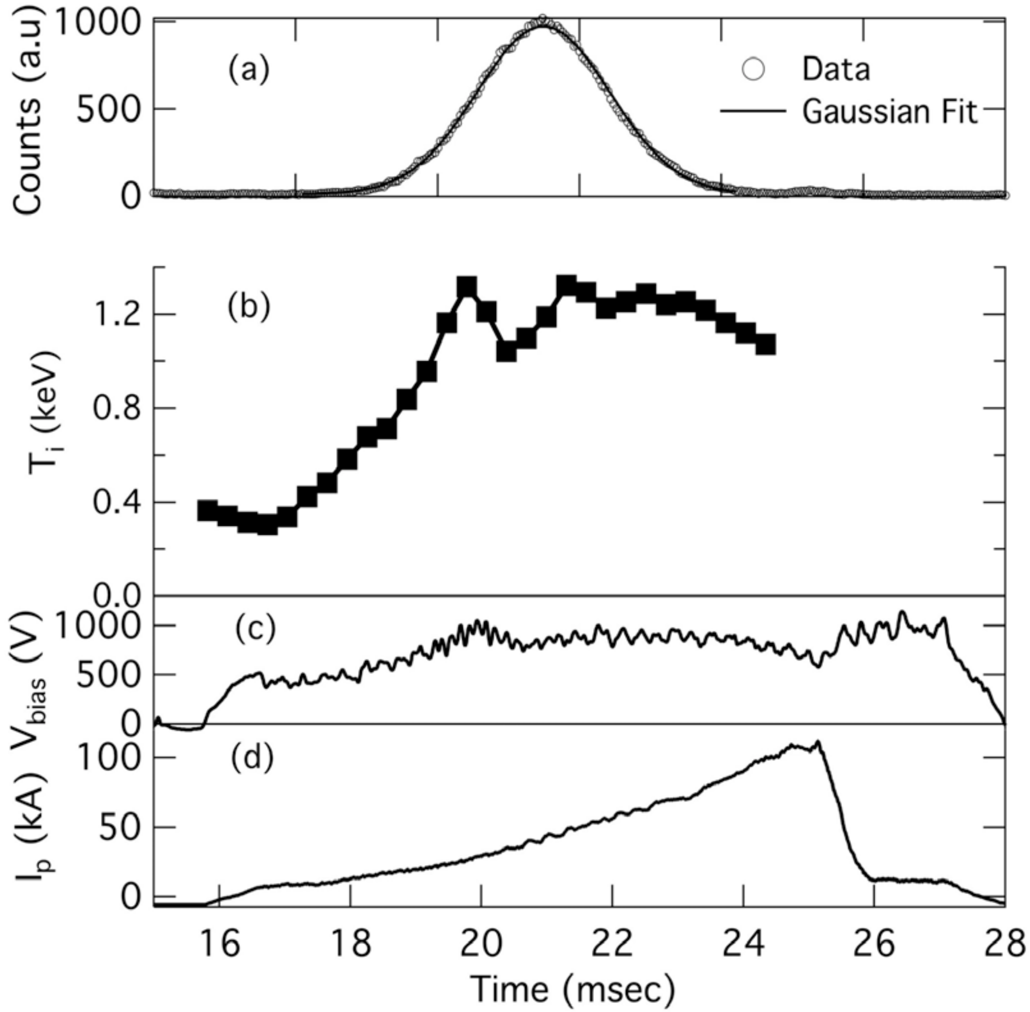




Single time point, raw toroidal data

Dramatic ion heating seen on radial view during helicity injection

- Radial line averaged ion temperature
- Highly resolved peak is Gaussian
- Dramatic heating is seen on radial viewing chords during helicity injection startup
- Temperatures as high as 1.2 keV have been observed on some impurity lines
- Ion temperature follows V_{bias} indicating that majority of power is being channeled to ions



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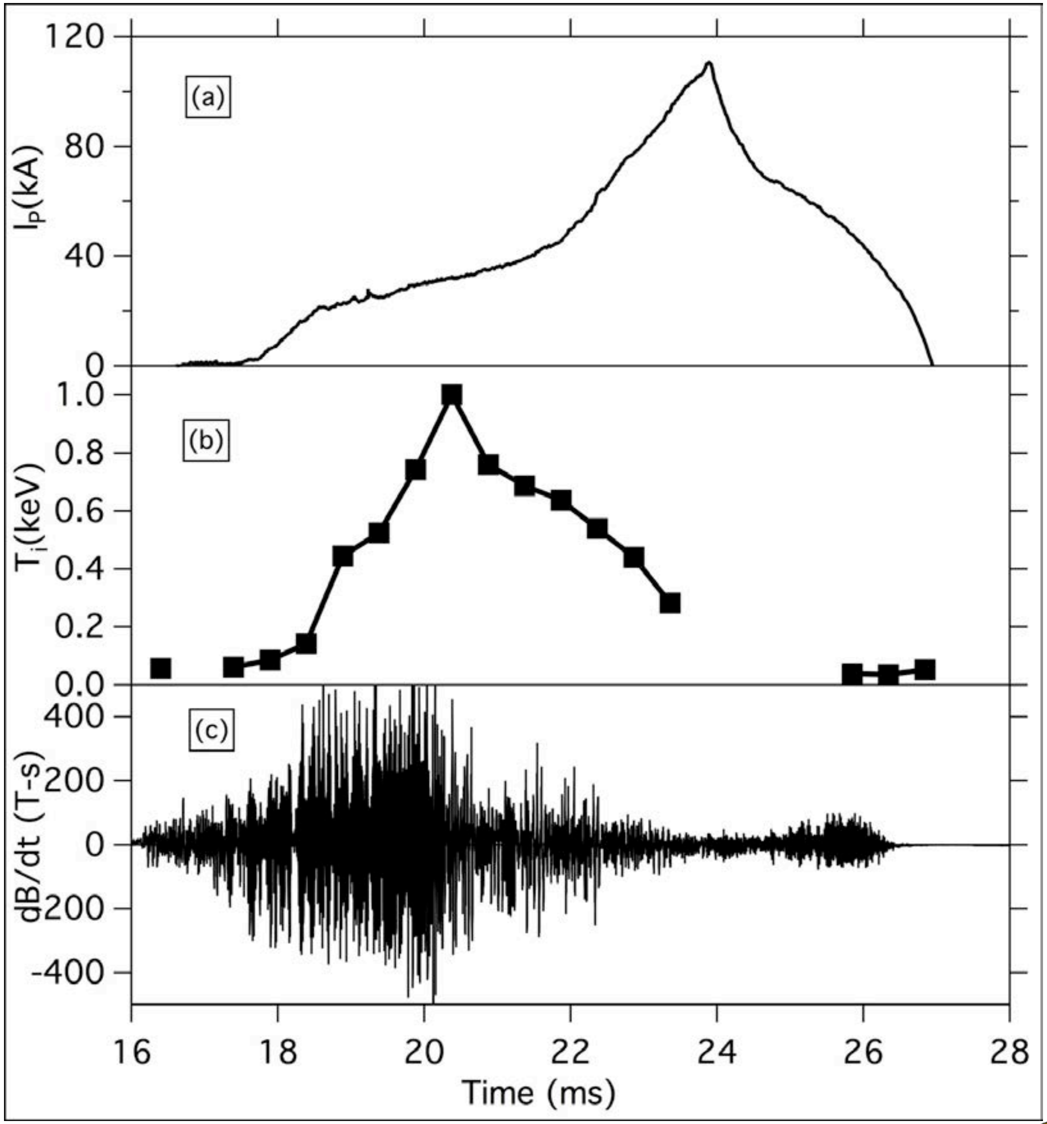
Large scale MHD activity correlated with ion temperature rise

- Large MHD fluctuations correspond to rapid rise in T_i
- Figure shows NIII ion temperature in comparison with dB/dt
- Large scale magnetic reconnection is thought to be the culprit
- Stochastic field lines are thought to keep T_e low ~100 eV



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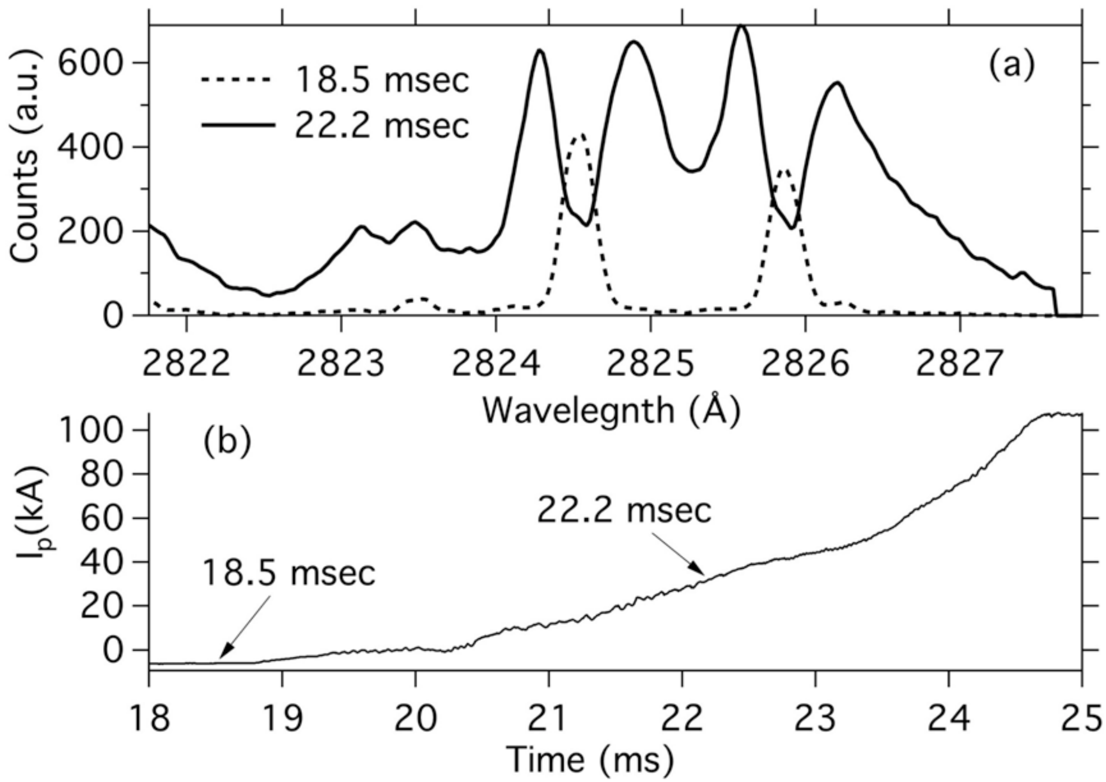
Additionally, tangential views reveal strong bipolar velocity flows

- Tangential views reveal strong bipolar flows of roughly equal value toroidally

- Splitting occurs during I_p ramp
- Line asymmetry also observed on receding line, this could be edge E-field from helicity injection
- This data motivates a poloidal plasma view to fully resolve ion flow during helicity injection



Future Work & Conclusions

- Possible Upgrades include:
  - ½ m f/4 Echelle spectrometer if throughput is an isussue
  - Similarly, throughput from plasma views can be increased by adding more fibers
  - Time resolution of intensifier can be increased by changing phosphor types but at a cost of efficiency
- A multipoint high-speed ion Doppler spectrometer has been deployed on the Pegasus Toroidal Experiment
- Initial measurements reveal high anomalous ion heating on multiple spectral lines during helicity injection