Ion Temperature Measurements in the PEGASUS Toroidal Experiment

M.G. Burke, M.W. Bongard, R.J. Fonck, D.J. Schlossberg, A.J. Redd



University of Wisconsin-Madison

52nd Annual APS-DPP

Chicago, IL
November 8, 2010



PEGASUS Toroidal Experiment

Abstract

Ion temperature measurements are being made on the Pegasus Toroidal Experiment in OH and helicity-injection driven plasmas using thermal Doppler broadening of emission spectra. The system consists of a 0.75 meter monochromator with UV sensitive optics, an image intensifier, and a high speed imaging system that can achieve a 5 kHz frame rate. Presently the system achieves a spectral resolution of 0.21 Å, and collects light over a single radial chord. Of particular interest is the ion temperature evolution during non-solenoidal startup using point source helicity injection. Turbulent magnetic reconnection during helicity injection is expected to provide strong ion heating, as seen in lab and astrophysical plasmas. Indeed, $<T_i>$ is measured to be 0.5 keV while $<T_e>$ is estimated to be $\leq$ 0.1 keV from passive impurity spectroscopy. Presently the system is used to compare the T_i evolution of plasmas produced through helicity injection, OH drive, and hybrid current drive scenarios. Future upgrades will provide plasma rotation measurements using multiple tangential views in Pegasus.

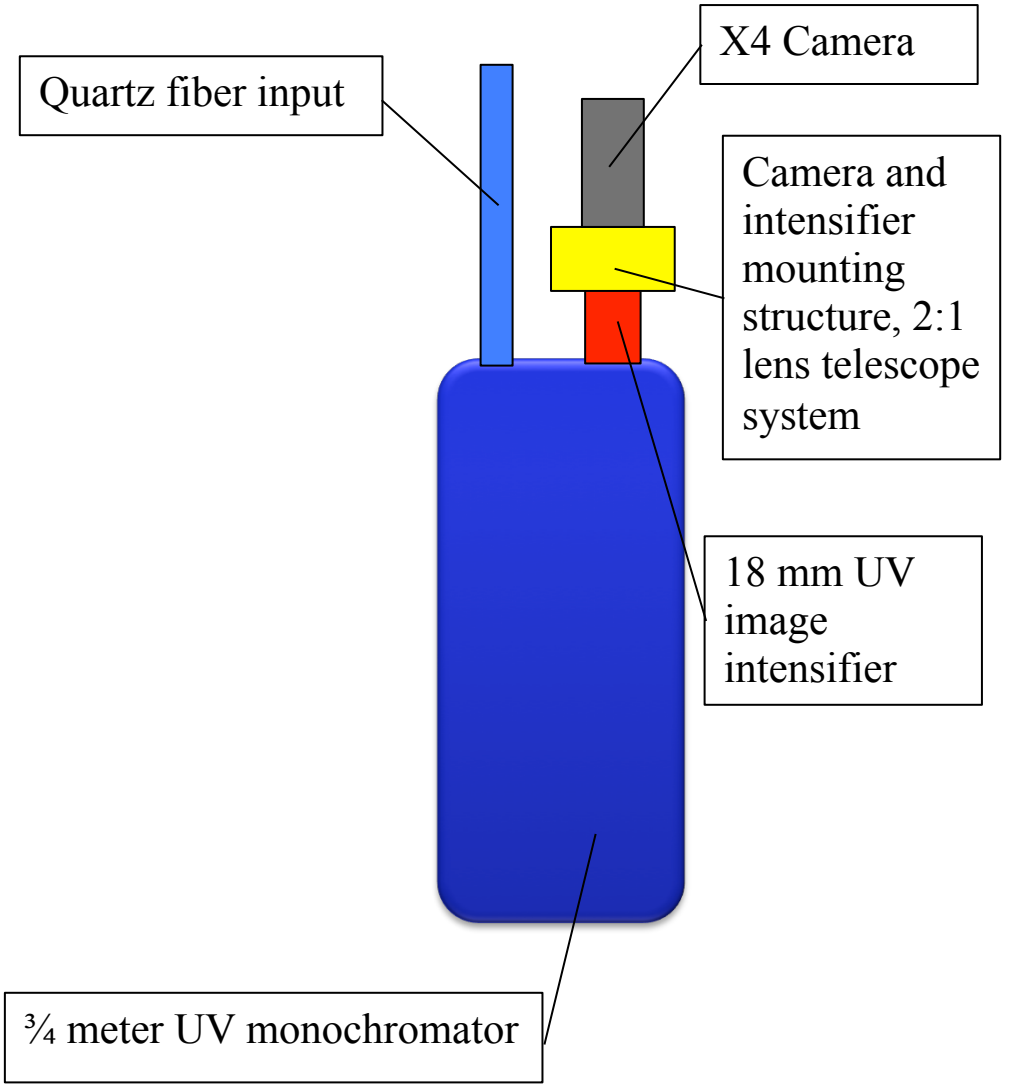
Work supported by U.S. DOE Grant DE-FG02-96ER54375

Summary

- Substantial differences in T_i and T_e are observed in ohmic driven plasmas (T_i ~ 100 eV) and helicity-injection driven plasmas (T_i ~ 700 – 1000 eV) on the PEGASUS toroidal experiment
- This is in contrast to T_e for helicity injection is 50-100 eV based on impurities while T_e for ohmic drive is ~200 eV based on SPRED confinement estimates
- A peak ion temperature of 1 keV is reached on NIII charge state during helicity-injection startup
- This is in contrast to a peak ion temperature of 0.1 keV during ohmic drive as measured on OV
- Turbulent magnetic reconnection is thought to provide strong ion heating, as shown on MST by Gangadhara *et al.,* Phys. Plasma 15, 056121 (2008)
- MHD activity during helicity-injection is shown to correspond sharply with ion heating and is thought to be the source of that heating

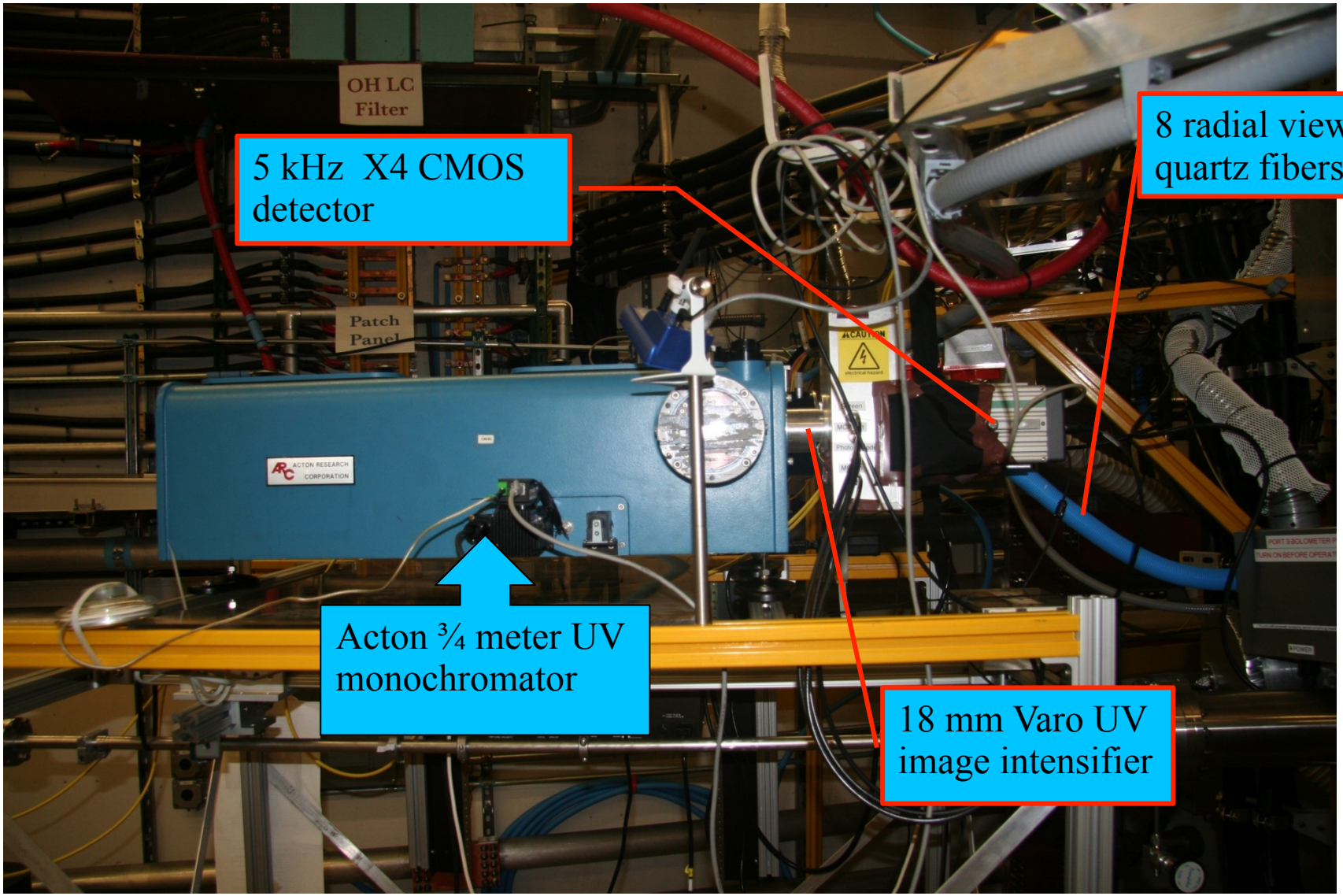
High speed passive ion spectroscopy system used to measure T_i at max 5 kHz

- X4 High Speed Camera
  - Capable of 5 kHz frame rate @ 512 X 512
  - 8 Quartz fiber channels look radially by center column
- 0.75 meter Vacuum Monochromator
  - Sensitivity range 2000 to 8000 A
  - Dispersion in 1st order: 7 A/mm
- 18 mm Varo Image Intensifier
  - Quarts input window with
  - P20 Phosphor screen
  - Luminous Gain: 7 – 10 k
- Effective resolution of system
  - 0.64 A with slit size of 50 um



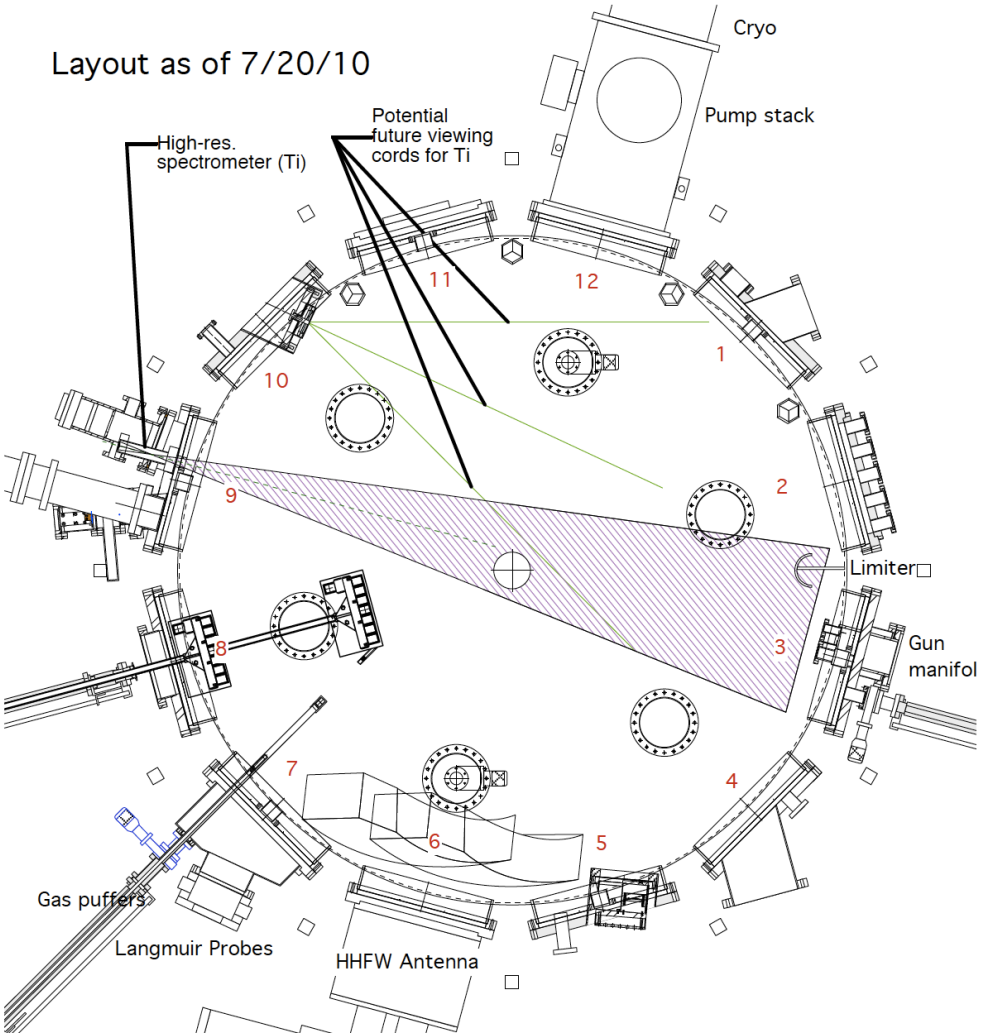
THE UNIVERSITY of WISCONSIN MADISON

T_i spectrometer system fiber optically coupled to PEGASUS



Current radial view allows for passive ion temperature spectroscopy of plasma

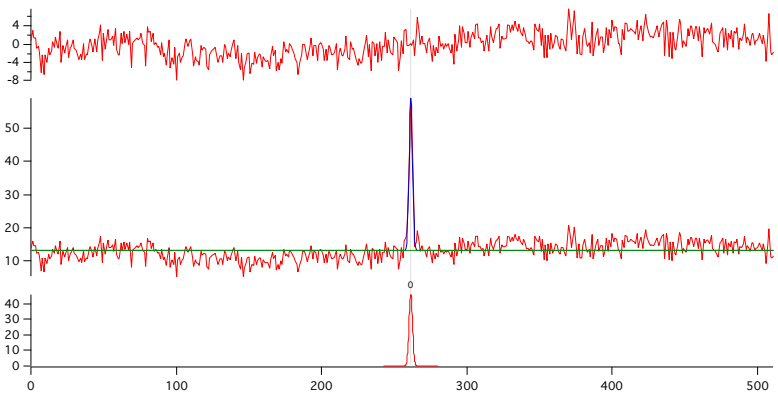
- Current plasma view allows for passive ion temperature spectroscopy
- Future tangential view will allow for $T_i(r,t)$ and $v_\Phi(r,t)$



THE UNIVERSITY of WISCONSIN MADISON

Calibrations show instrumental profile of 60 eV

- White field calibrations done to reduce optical vingetting
- White field calibrations indicate intensifier saturates before camera
- Spectrometer instrument function measured using Hg vapor lamp at three different slit sizes: 50, 100, 150 microns
- $T_{instrument}$ for 50 micron slit @ 4097 A NIII line is 57 eV
- $T_{instrument}$ for 50 micron slit @ 2nd order 2781 A OV line is 32 eV



50 um slit:
FWHM = 2.8 ± 0.3

THE UNIVERSITY of WISCONSIN MADISON

Measurement of Doppler broadening assumes thermal distribution

- Thermal distribution of ion charge states can be modeled using a Gaussian distribution

$$P_\lambda(\lambda)d\lambda = \sqrt{\frac{mc^2}{2\pi kT\lambda_0^2}}\exp\left(-\frac{mc^2(\lambda-\lambda_0)^2}{2kT\lambda_0^2}\right)$$

- Equation for ion temperature can then be derived based on the full width half maximum of the spectral line

$$\Delta\lambda_{FWHM} = \sqrt{\frac{8kT\ln 2}{mc^2}}\lambda_0$$

- Gaussian fits seem to break down during rapid heating of the ions in helicity-injection discharges

THE UNIVERSITY of WISCONSIN MADISON

Multicoefficient algorithm used to minimize χ^2 and output FWHM of spectral peaks

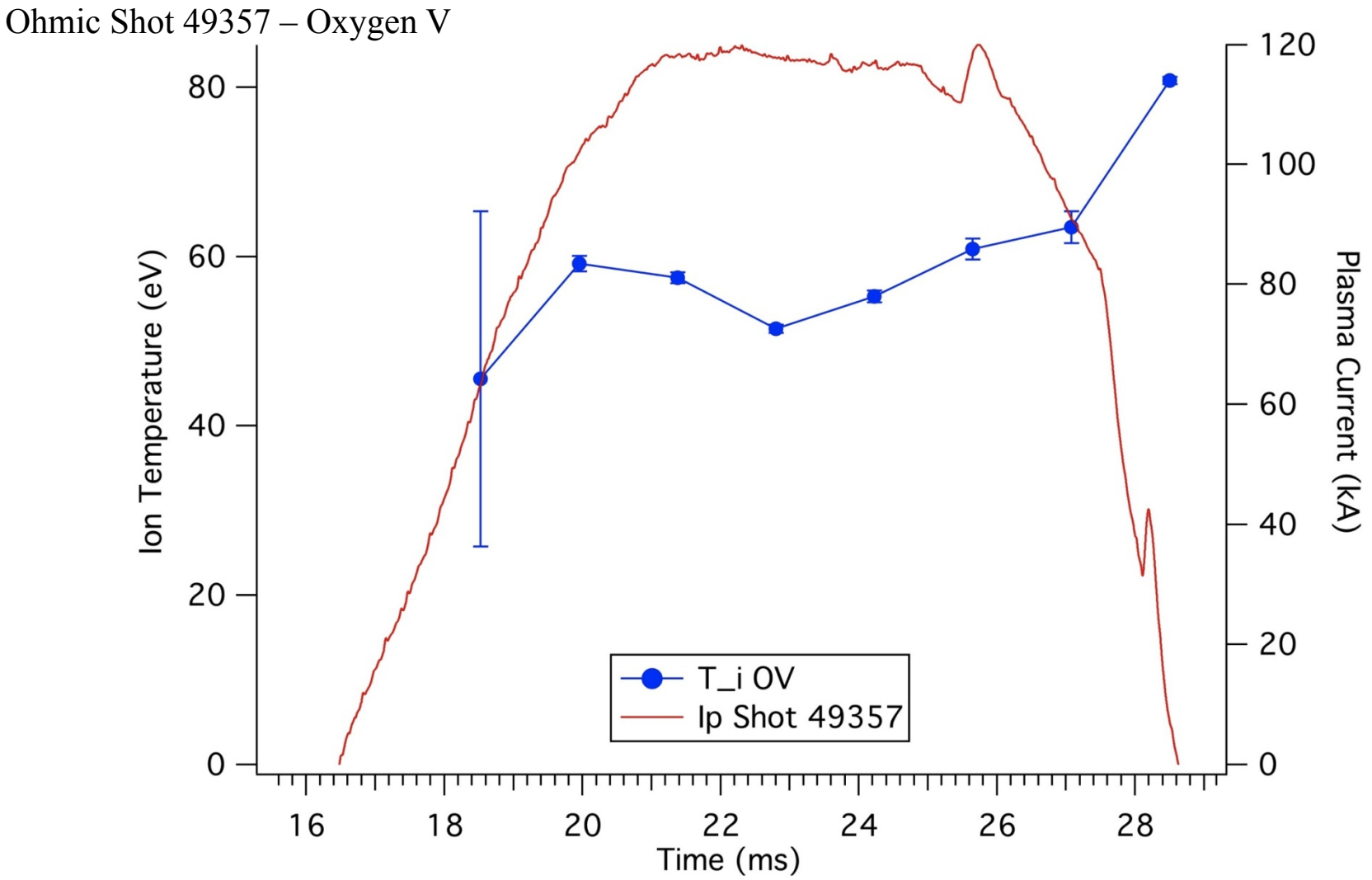
- Igor Pro 6.2 Multi-peak fit program used to fit Gaussian or Voigt functions to spectral lines
- Program uses Levenberg-Marquardt algorithm to search for coefficients that minimize chi-squared
- Output of FWHM used to calculated ion temperature
- Weighting calculated using RMS value of detector noise
- Future clarification of photon and detector noise needed to accurately calculate uncertainty of peak parameters
- Clarification of CMOS detectors as scientific grade instruments needed

Ohmic heated plasmas show high T_e and low T_i

- 2 charge states used to measure ion temperature during ohmic current drive: Oxygen V and Carbon III
- Used OV line at 2781 A in 2nd order, $E_{ionization}$ = 114 eV
- Used CIII line at 4647 A in 1st order, $E_{ionization}$ = 48 eV
- Peak ion temperatures of 80 and 50 keV have been measured on the OV and CIII lines respectively
- SPRED confinement estimates and Oxygen burnout indicate a T_e of ~200 eV

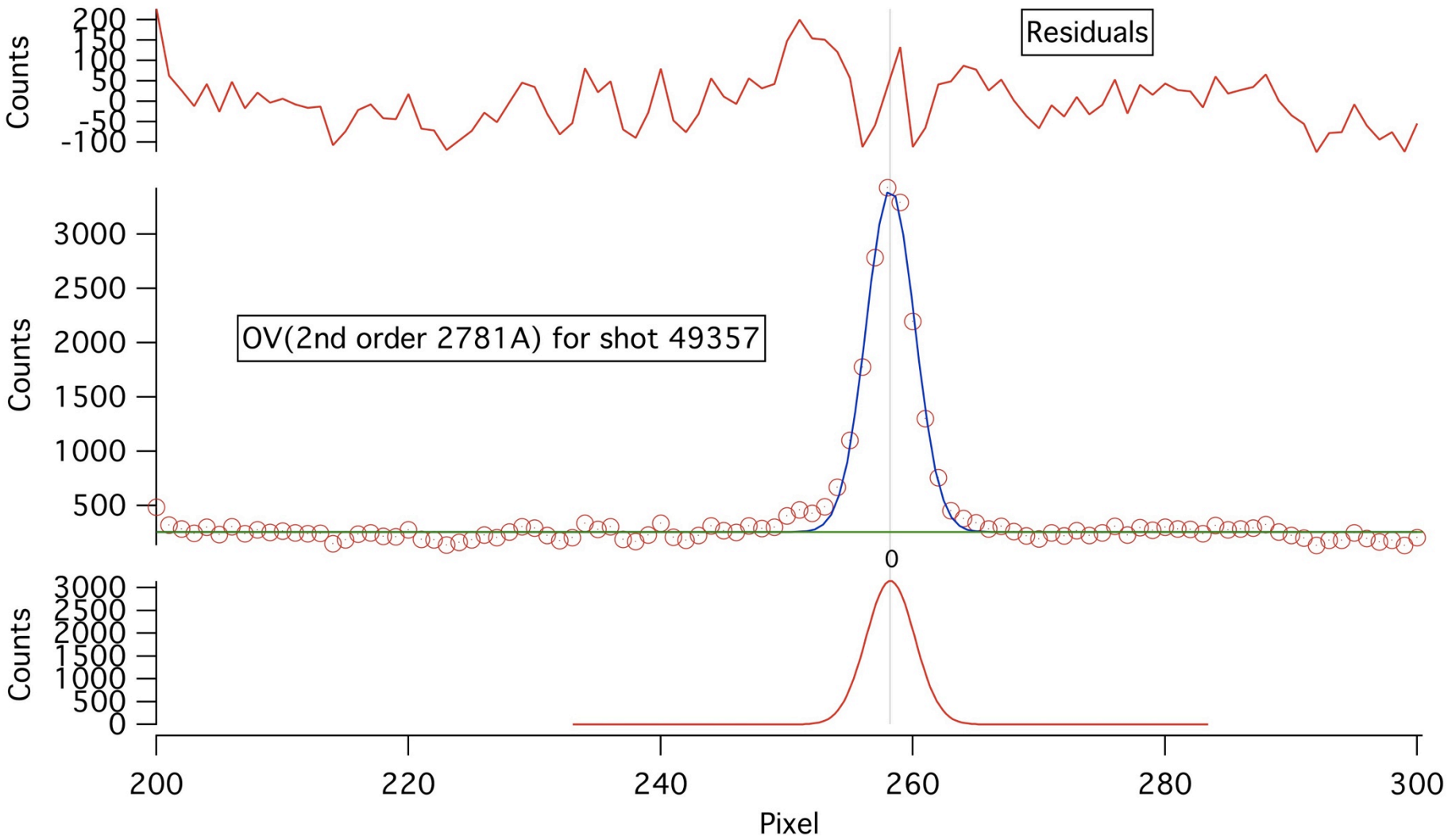
THE UNIVERSITY of WISCONSIN MADISON

Peak ion temperature of 60 eV measured during ohmic heating on Oxygen V



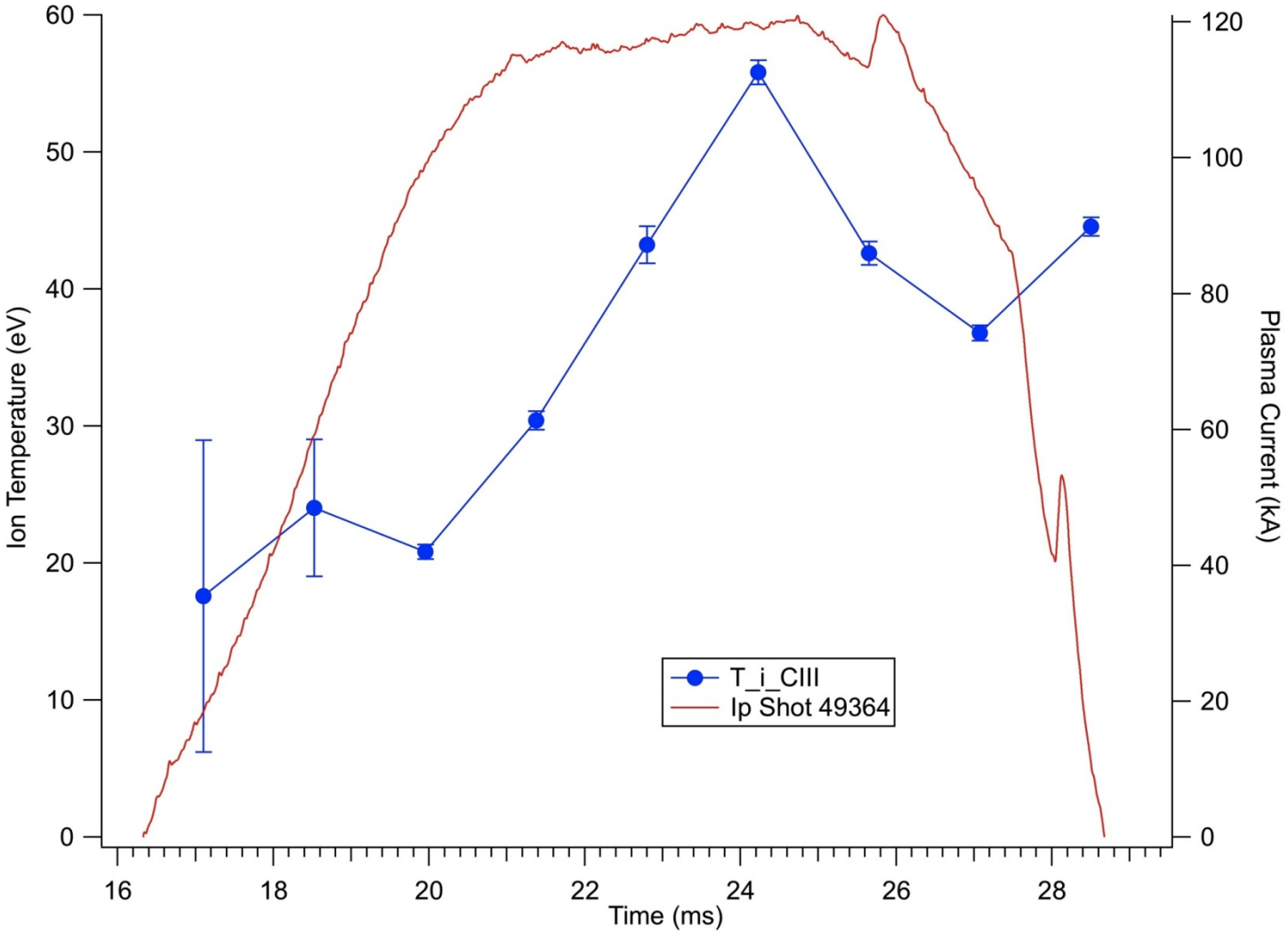
THE UNIVERSITY of WISCONSIN MADISON

Sample Ohmic OV fit at 24 msec shows good Gaussian fit



THE UNIVERSITY of WISCONSIN MADISON

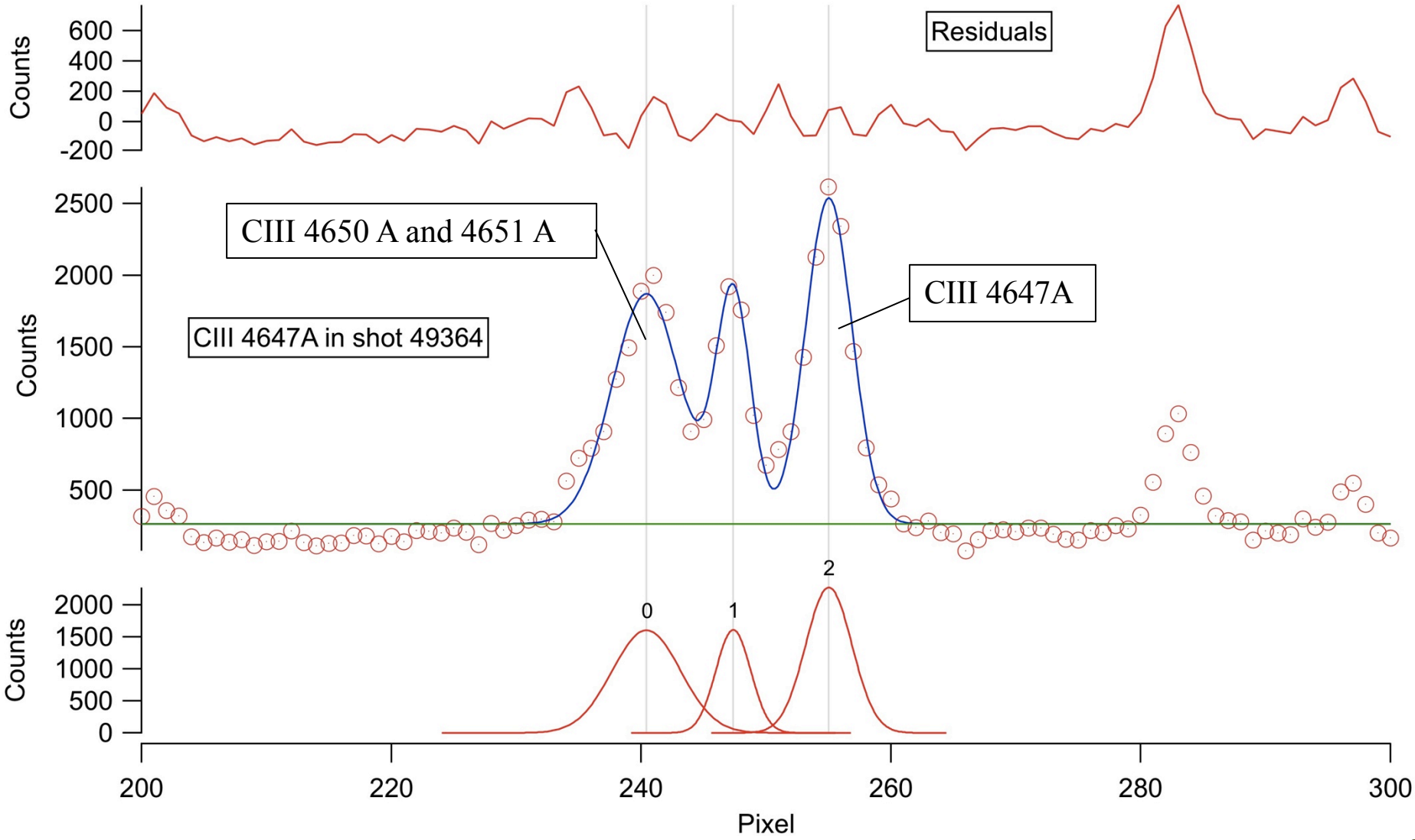
Carbon III shows similar temperature of 60 eV but different time evolution



Ohmic shot 49596 – Carbon III

THE UNIVERSITY of WISCONSIN MADISON

Sample OH CIII fit at 24 msec

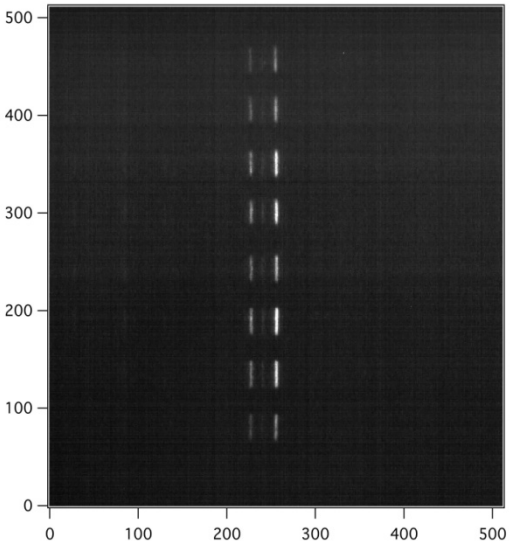


THE UNIVERSITY of WISCONSIN MADISON

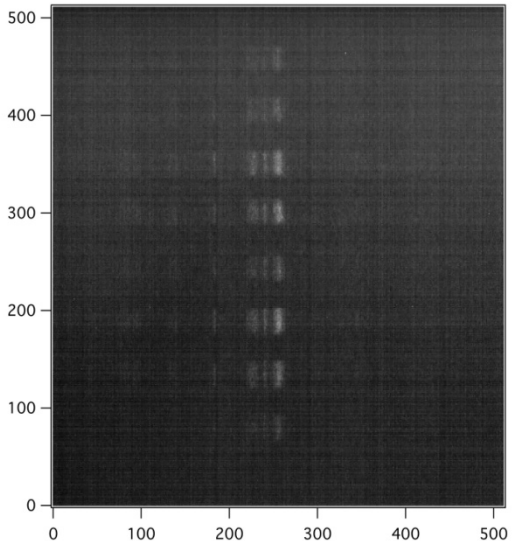
Gun current drive produces rapid and substancial ion heating on Nitrogen lines while T_e remains low

- 3 plasma guns provide helicity injection into the plasma
- T_i max of 1 keV measured as opposed to T_e of 50 -100 eV
- Used NIII line at 4097 A in 1st order, $E_{ionization}$ = 47 eV
- Used NIV line at 3478 A in 1st order, $E_{ionization}$ = 77 eV
- Ion temperature peaks rapidly in roughly 1 msec and then decays back to ohmic T_i levels in roughly 3 msec
- During heating phase, spectral lines show evidence of non thermal distribution and are best fit via Voigt distribution
- T_i decay region spectral lines show good agreement with Gaussian thermal distribution

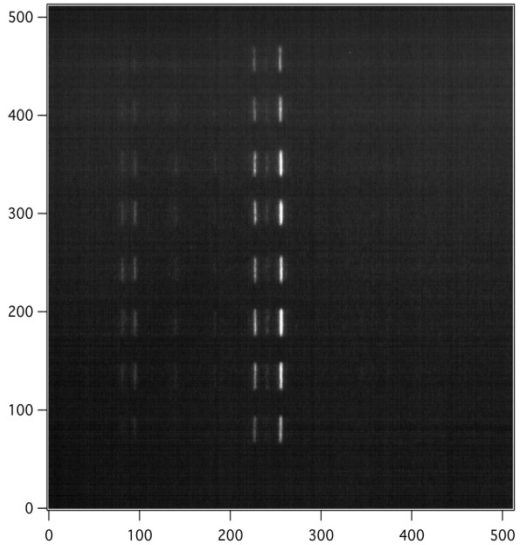
Substantial Doppler broadening is observed during helicity-injection current drive



Time: 16.9 msec



Time: 21.37 msec

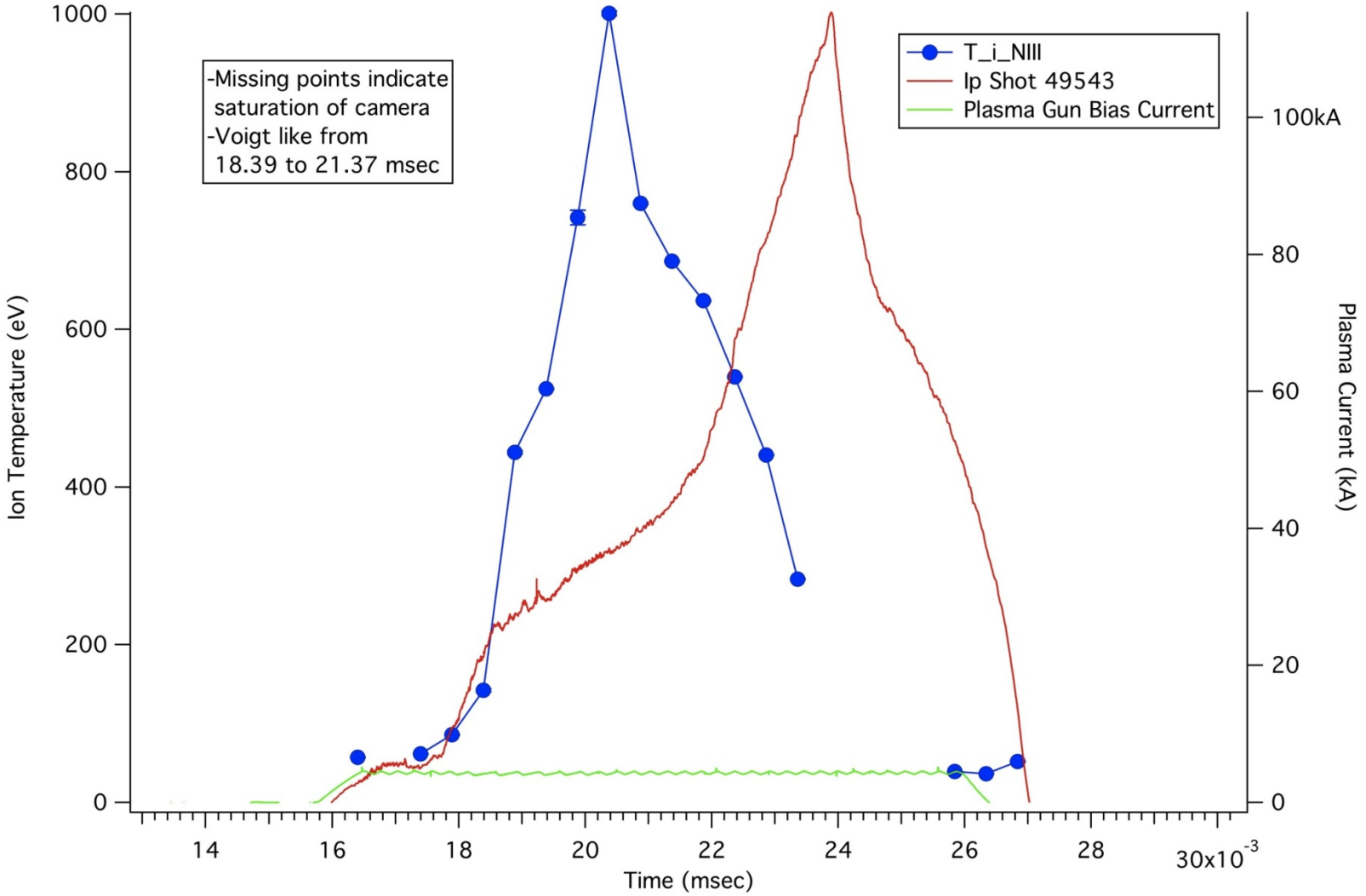


Time: 24.85 msec

- Impurities in helicity-injection drive suggest a T_e of 50-100 eV
- Density and transport calculations in MIST suggest a Nitrogen dominated plasma

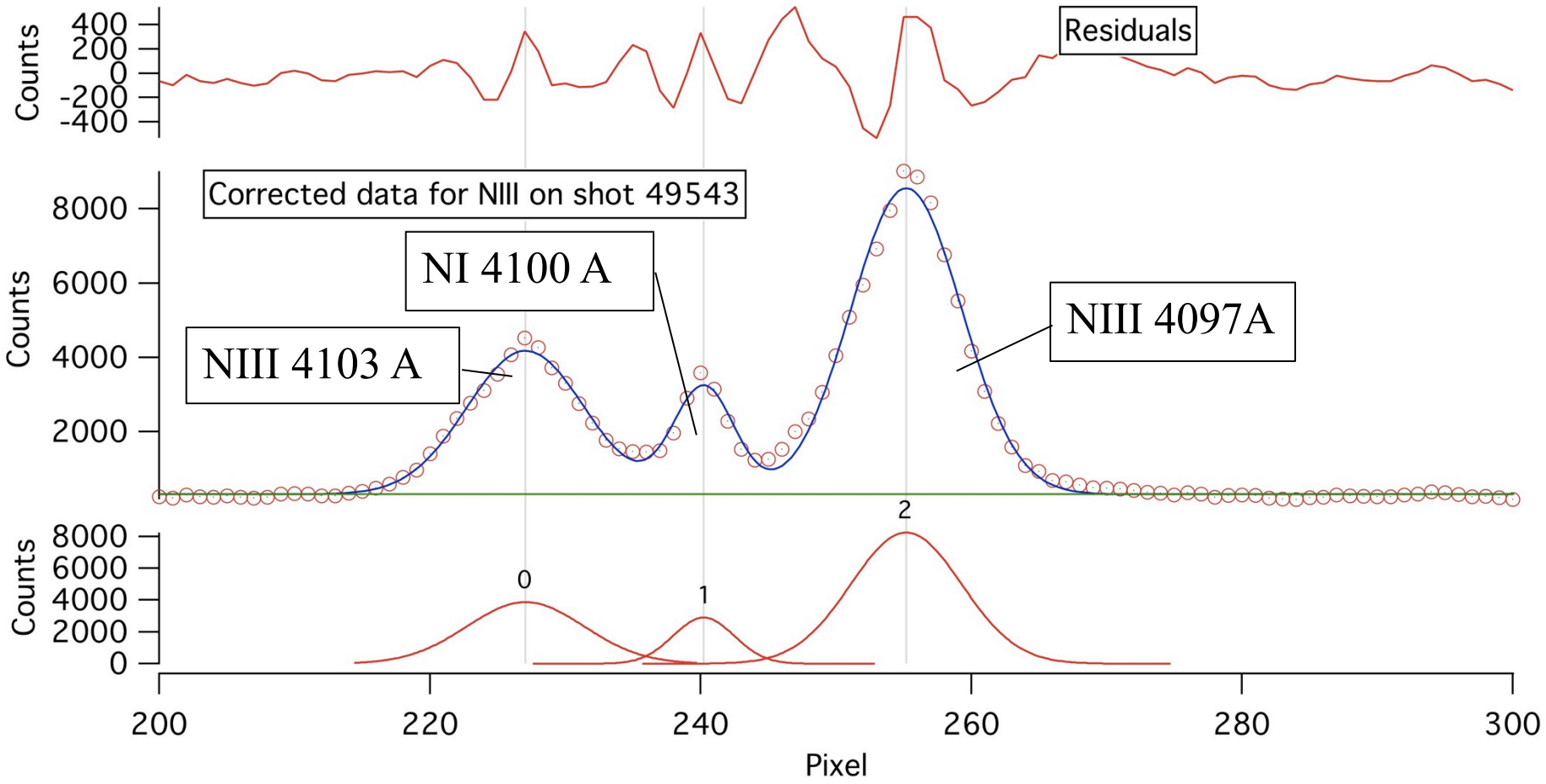
THE UNIVERSITY of WISCONSIN MADISON

Peak T_i of 1 keV reached during helicity-injection current drive



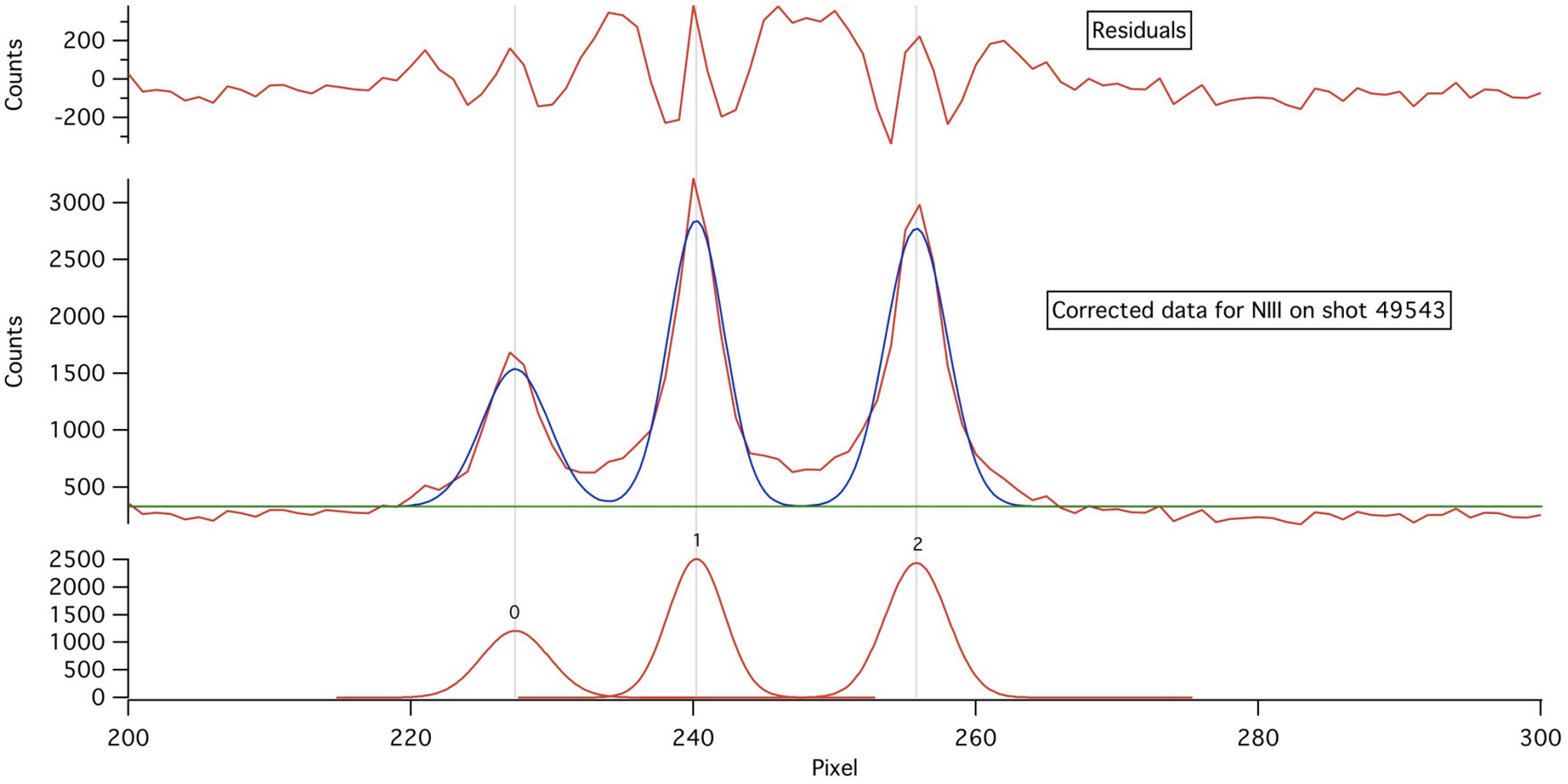
THE UNIVERSITY of WISCONSIN MADISON

Good Gaussian fit at 21.8 msec in thermal decay region



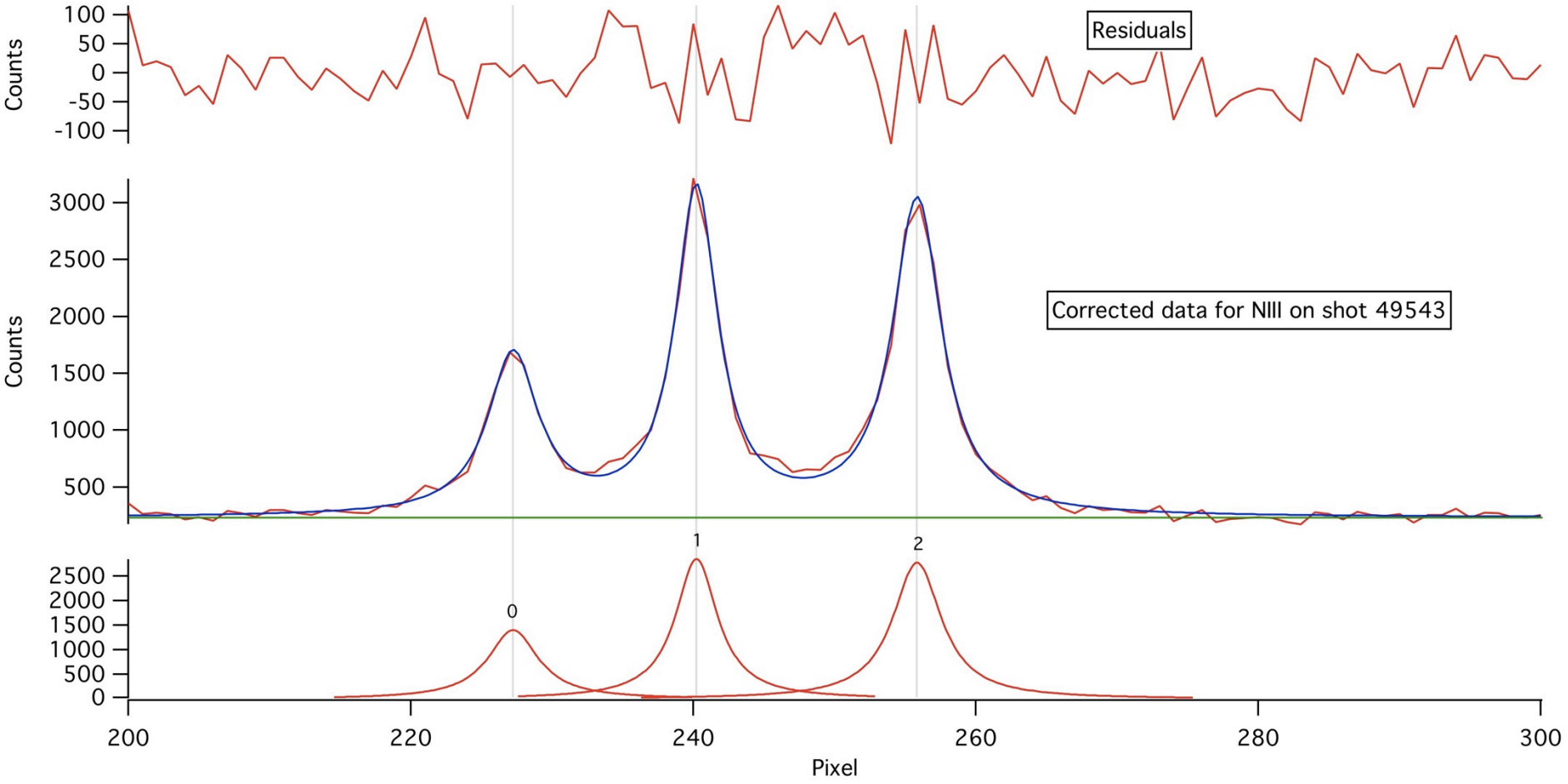
THE UNIVERSITY of WISCONSIN MADISON

Poor Gaussian fit at 18.4 msec



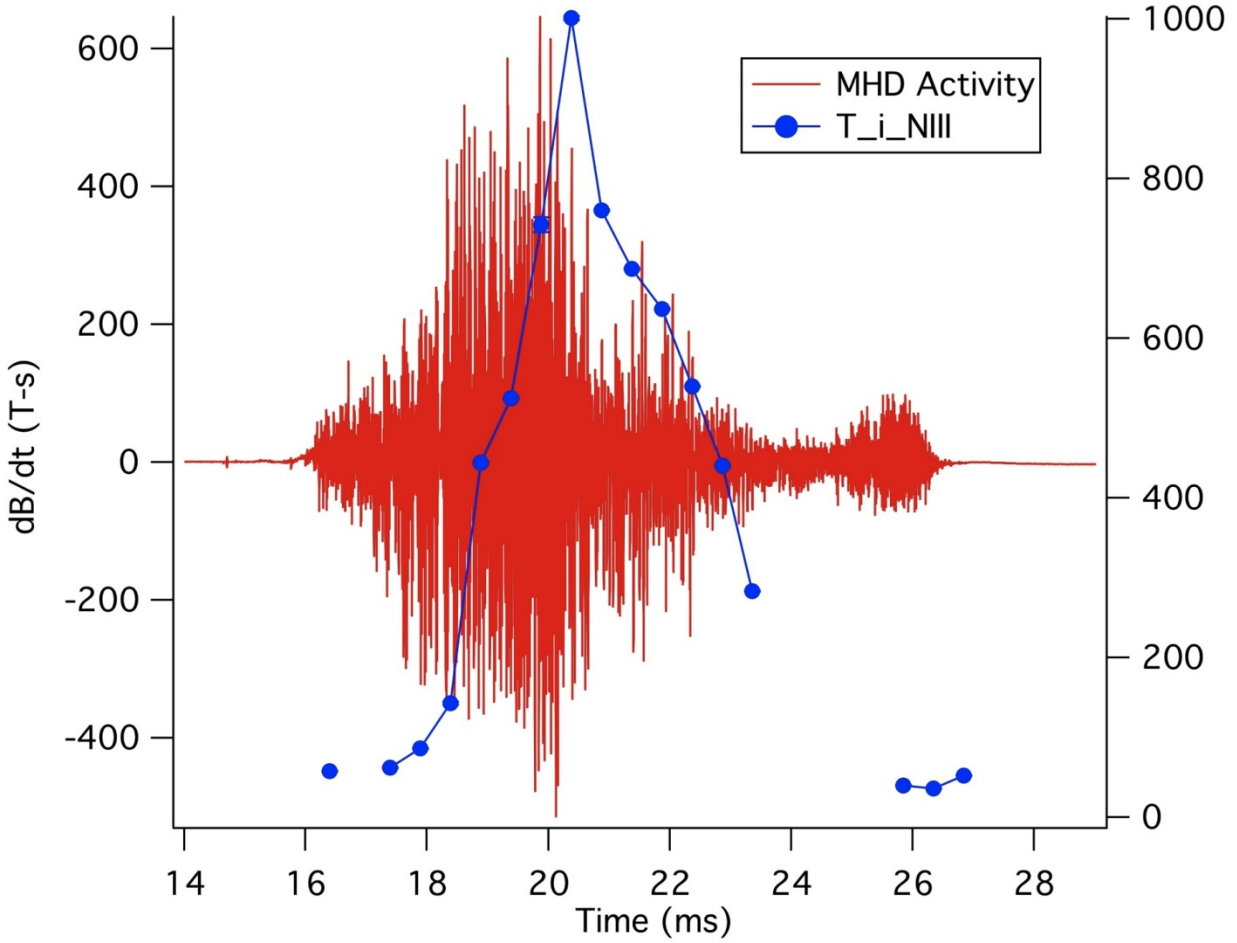
THE UNIVERSITY of WISCONSIN MADISON

Voigt Distribution gives a much better fit at 18.4 msec, suggesting a non-thermal distribution



THE UNIVERSITY of WISCONSIN MADISON

Ion spectrometer show that substantial heating occurs during virulent MHD activity

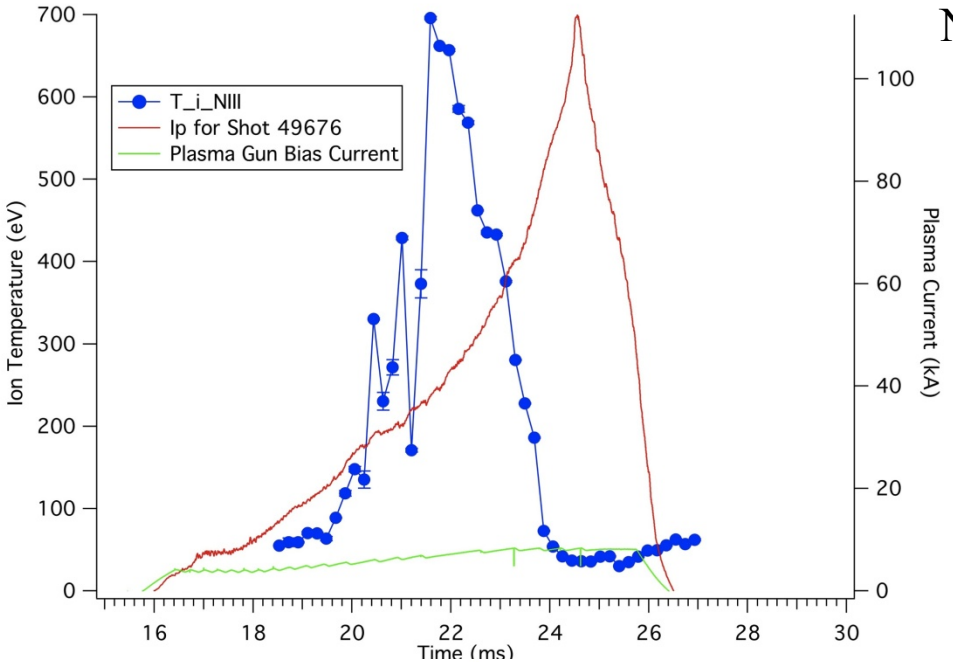


Gun Shot 49543 - NIII

- Subsequent T_i collapse occurs during relatively low MHD region

THE UNIVERSITY of WISCONSIN MADISON

Peak ion temperature of 700 eV reached during guns as electrodes current drive

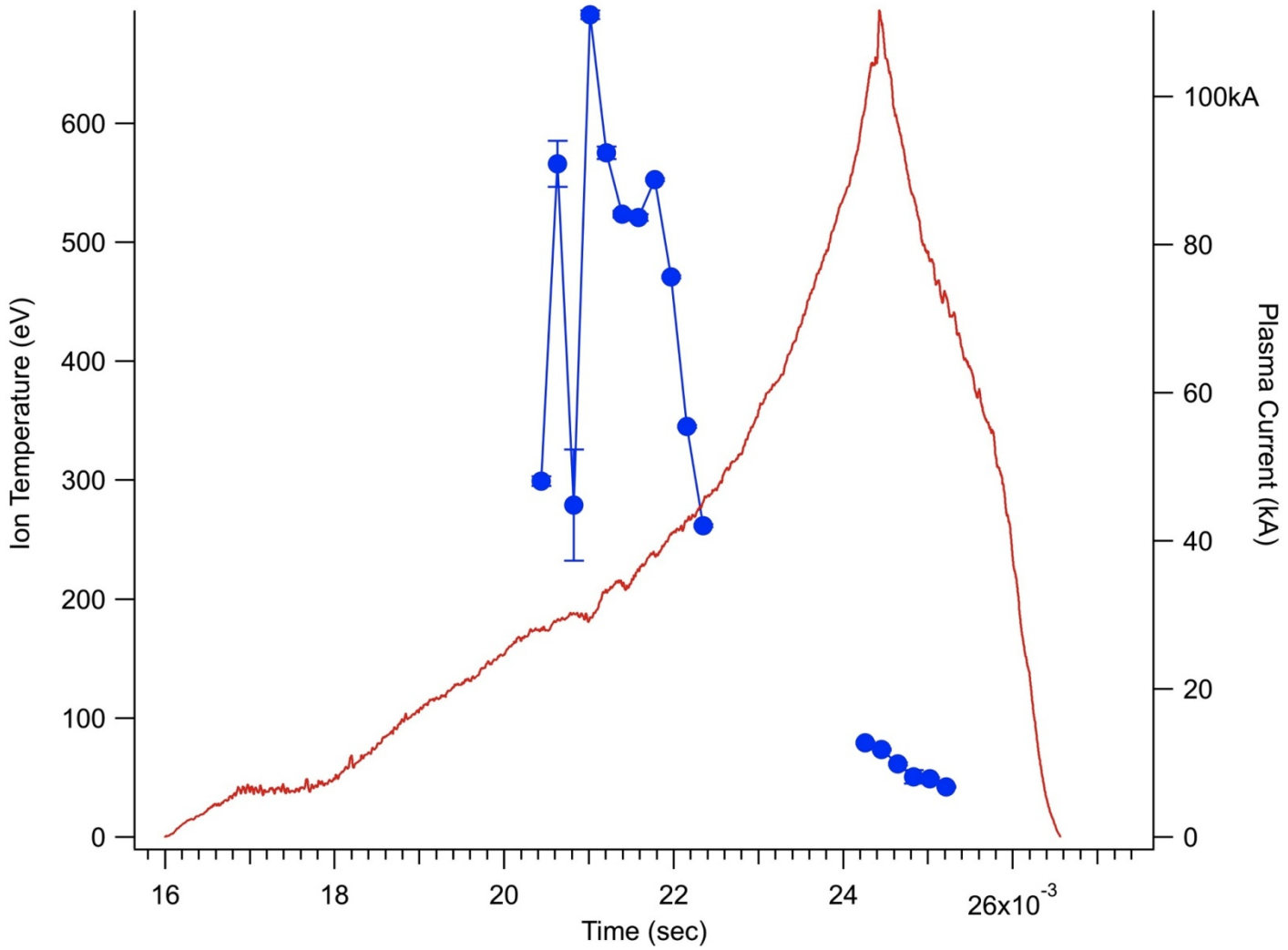


NIII Guns as electrodes Shot 49676

- Times of MHD cutoff, which occur at different times, corresponds strongly with decay of T_i for shots 49676 and 49543
- Faster exposure time shows fluctuations in T_i on the order of 100s of us

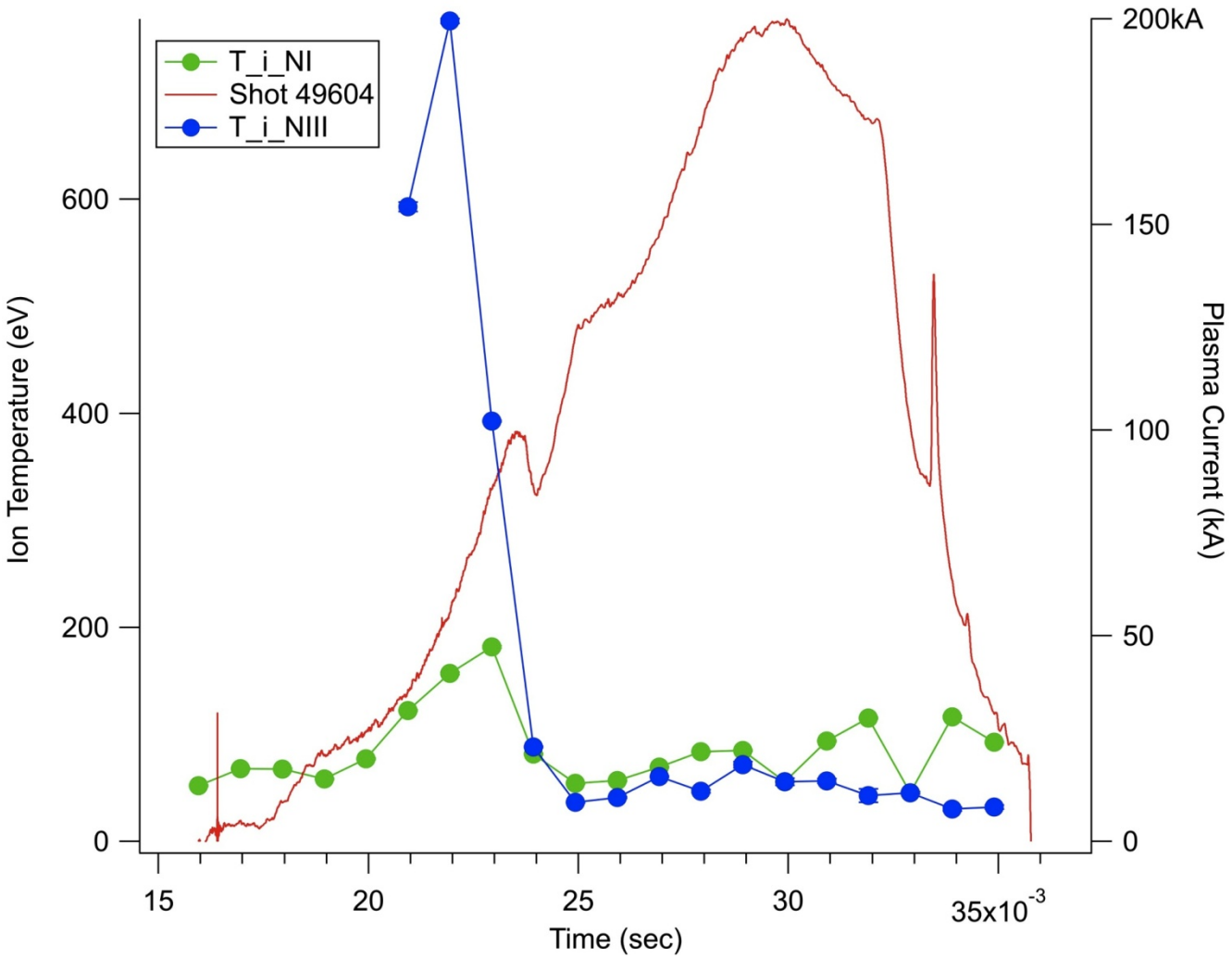
THE UNIVERSITY of WISCONSIN MADISON

Nitrogen IV shows similar peak T_i during gun as electrode current drive



Guns as Electrodes Shot 49677 – Nitrogen IV

Gun-ohmic handoff shows T_i decays back to normal ohmic heating levels on the order of the confinement time

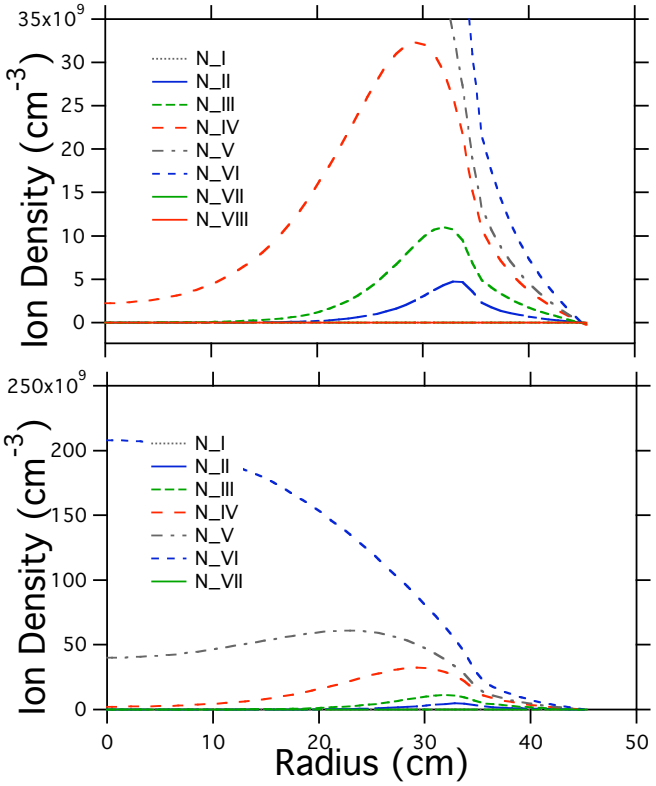


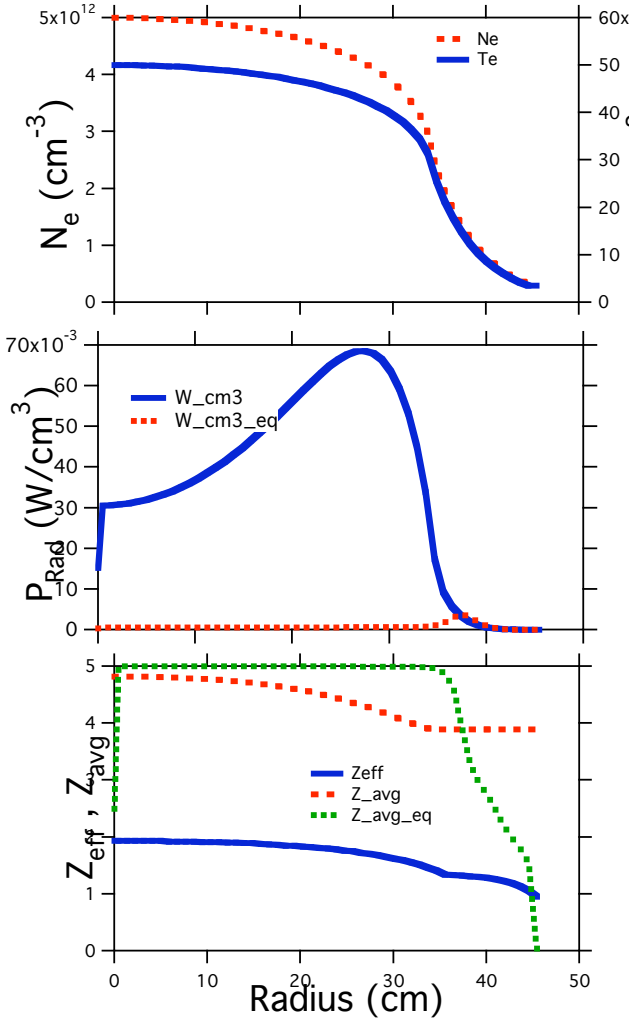
Gun Ohmic Handoff Shot 49596

THE UNIVERSITY of WISCONSIN MADISON

Density and diffusion calculations suggest a Nitrogen dominated discharge with NIII and NIV penetrating deep into the plasma

Nitrogen:
ltreq=1
NUCZ=7
FRACZ0 = 0.07
DAC=1.0E5 CVNE=1.0 SOFLX=5.0 LRNDEP=1





THE UNIVERSITY of WISCONSIN MADISON

Conclusions

- Substantial and rapid ion heating is seen in the turbulent magnetic reconnection period of helicity-injection current drive
- A peak ion temperature of 1 keV is measured during helicity-injection drive as opposed to only 80 eV during ohmic current drive
- Virulent MHD activity has strong effect on ion temperature
- T_i drops off rapidly down to ohmic levels of 50 to 100 eV after internal MHD activity dies off
- Non-thermal distribution is suggested during rapid increase in T_i
- Future upgrades to spectrometer and plasma view will allow for $T_i(r,t)$ and $v_\Phi(r,t)$