# Initial operation of the NSTX-U Real-Time Velocity diagnostic

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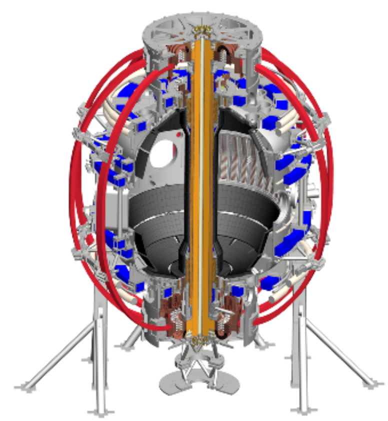

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# Abstract

A Real-Time Velocity (RTV) diagnostic based on active charge-exchange recombination spectroscopy is now operational on the National Spherical Torus Experiment-Upgrade (NSTX-U) spherical torus. The system has been designed to supply plasma velocity data in real time to the NSTX-U Plasma Control System, as required for the implementation of toroidal rotation control. Measurements are available from four radii, spanning from the core to the plasma edge, at a maximum sampling frequency of 5 kHz. Post-discharge analysis of RTV data provides additional information on ion temperature, toroidal velocity and density of carbon impurities. Initial results from RTV measurements are presented and compared with those from the main NSTX-U charge-exchange recombination spectroscopy system. Examples of physics studies enabled by RTV measurements from initial operations of NSTX-U are then discussed, with emphasis on the effects of plasma disturbances such as sawteeth and MHD instabilities on toroidal velocity and its temporal evolution.

# Outline

The RTV system

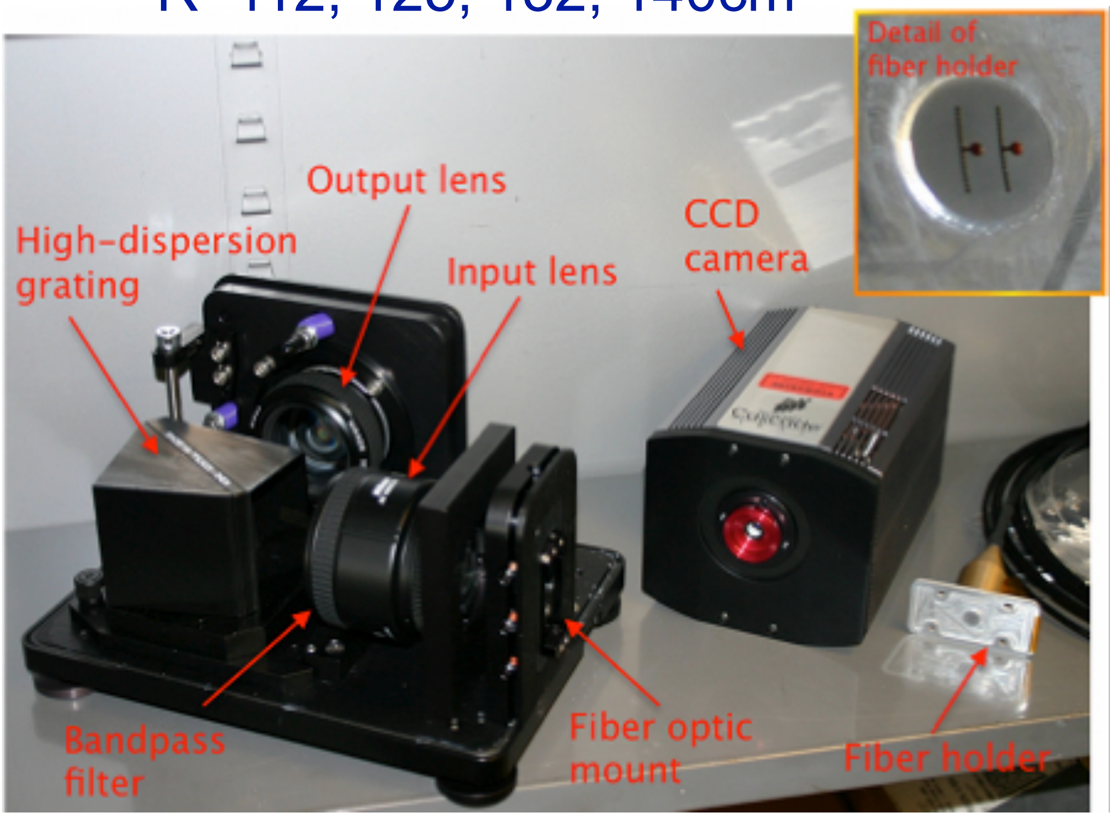
Analysis of RTV data

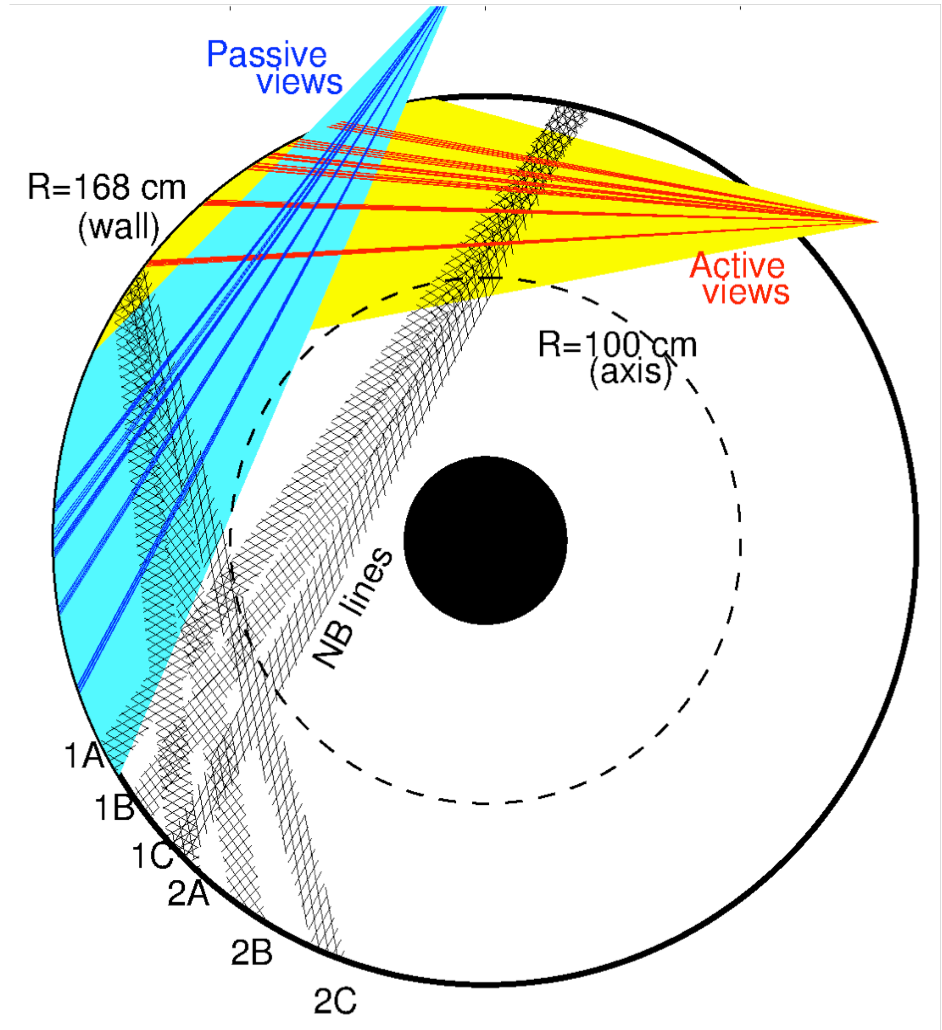
Example of physics studies

Summary & outlook

# Real-Time Velocity (RTV) is a fast system based on active spectroscopy

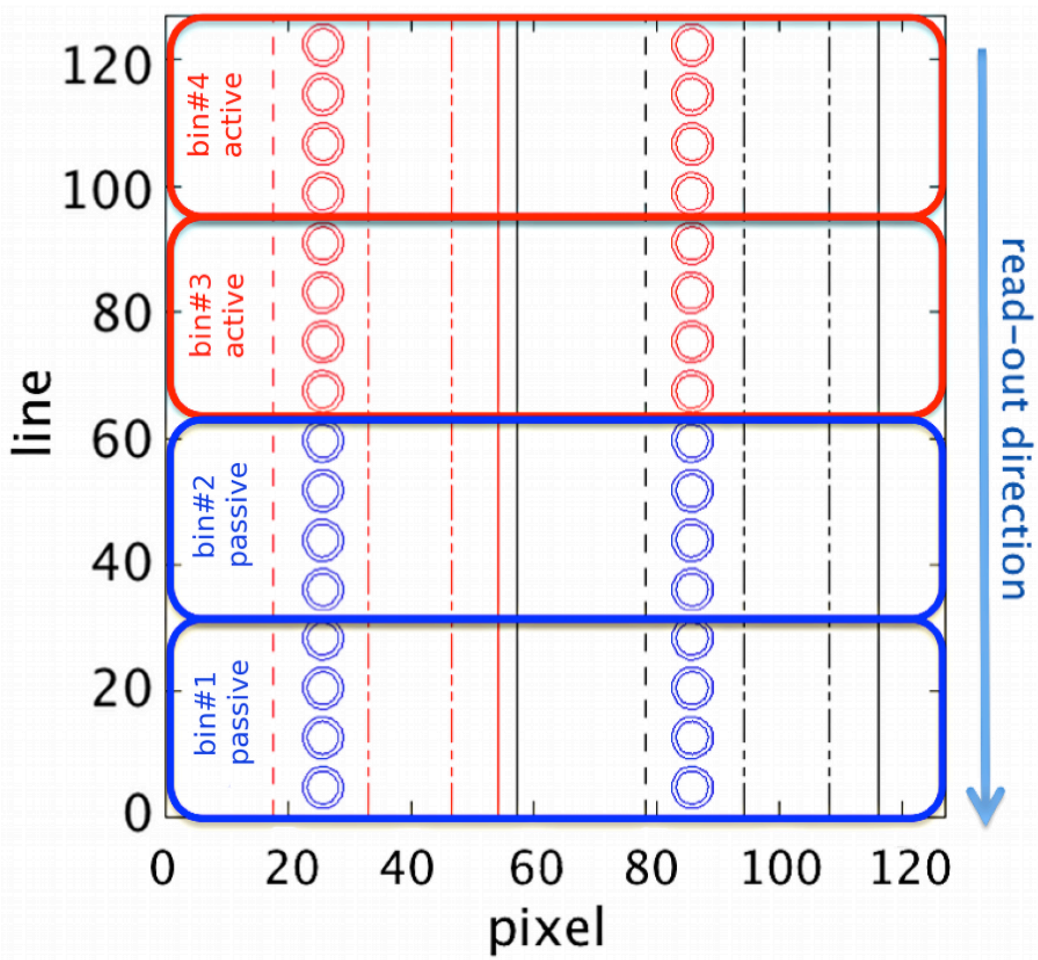
- System based on active charge-exchange spectroscopy (NB1 line)
- Monitor C VI, n=8-7 line @ 5291nm
- RTV views interleaved with CHERS views at midplane
- 4 views available
  - R=112, 125, 132, 140cm



# Fiber arrangement on detectors is optimized for real-time operation

*Fiber arrangement on each of two (identical) systems:*




- 7-8 fibers aiming at same radial location
- Each "channel" is composed by pairs of active and background views
- Simplified system for higher sampling rate
  - no chopper (flexible timing)
  - no entrance slit (collect more light)

# RTV complements CHERS information with high temporal but low spatial resolution data

| *System* | CHERS | RTV | |
|---|---|---|---|
| *Channels* | 51 (39) | 4 (4) | * |
| *Fibers/channel* | 2 (1) | 8 (7) | |
| *Chan. radii [m]* | 0.85-1.55 | 1.1,1.25,1.35,1.4 | |
| *Frame rate [kHz]* | 0.1 | $\leqslant 5$ | * |
| *Measurements* | $v_\phi, T_C, n_C$ | $v_\phi$, $T_C$ $(n_C)$ | * |
| *Monitored line [Å]* | C VI, 5290.5 | | |
| *Dispersion [Å/pixel]* | 0.21 | 0.43 | |
| *Instrum. width [keV]* | 0.1 | 0.2 | * |

TABLE I. Main parameters of the CHERS and RTV systems. Values in parenthesis refer to the background views. For RTV, $n_C$ data are are available only from post-discharge analysis. (Additional RTV views are installed at $R = 137, 145$ cm [10] but are not used in the present work).

***Achieved performance meets or exceeds requirements for real-time $v_\phi$ control**

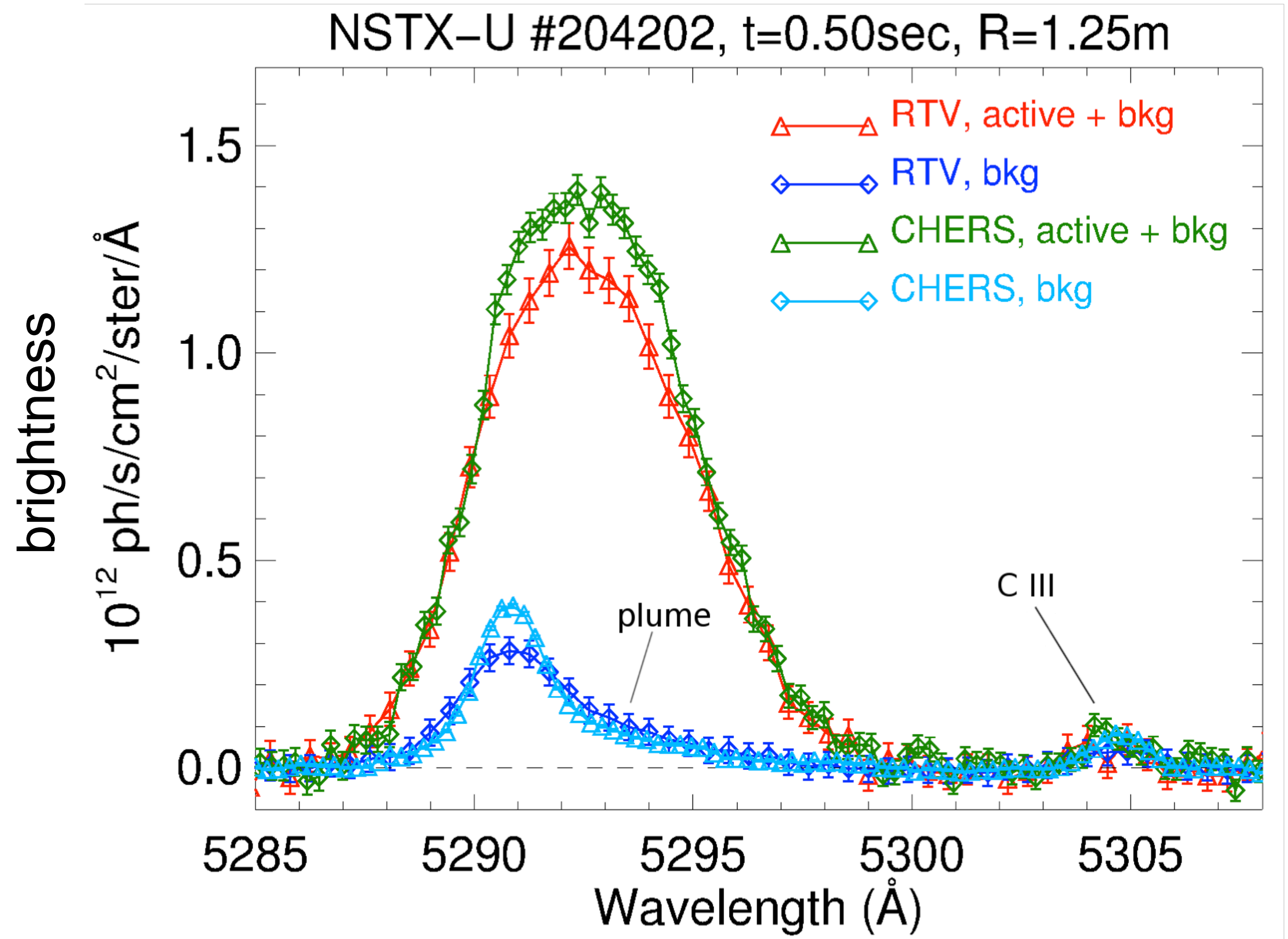
*[M. Podestà, PPCF 2016 (in press)]*

# Diagnostic was first tested in FY11; Up & running since first NSTX-U plasma

- RTV systems assembled in 2011
  - Tested with Ne lamps, He glow; calibrated *[M. Podestà, RSI **83** 033503 (2012)]*
- Acquisition and analysis software improved after first data from NSTX-U plasmas
  - Demonstrated RT analysis for $v_\phi$, possibly $T_i$ (limited to $T_i$>150eV)
  - Developed post-discharge analysis tools
    - $v_\phi$ from real time analysis available right after shot
    - Quick analysis ($v_\phi$, $T_i$) available ~1 minute after shot
    - Full analysis (CHERS-like: $v_\phi$, $T_i$, $n_C$) available ~5 minutes after shot
- Implemented & tested data transfer to PCS
  - Thanks to PCS Group!

> *Data now routinely available to develop & test $v_\phi$ control algorithm(s) in PCS*

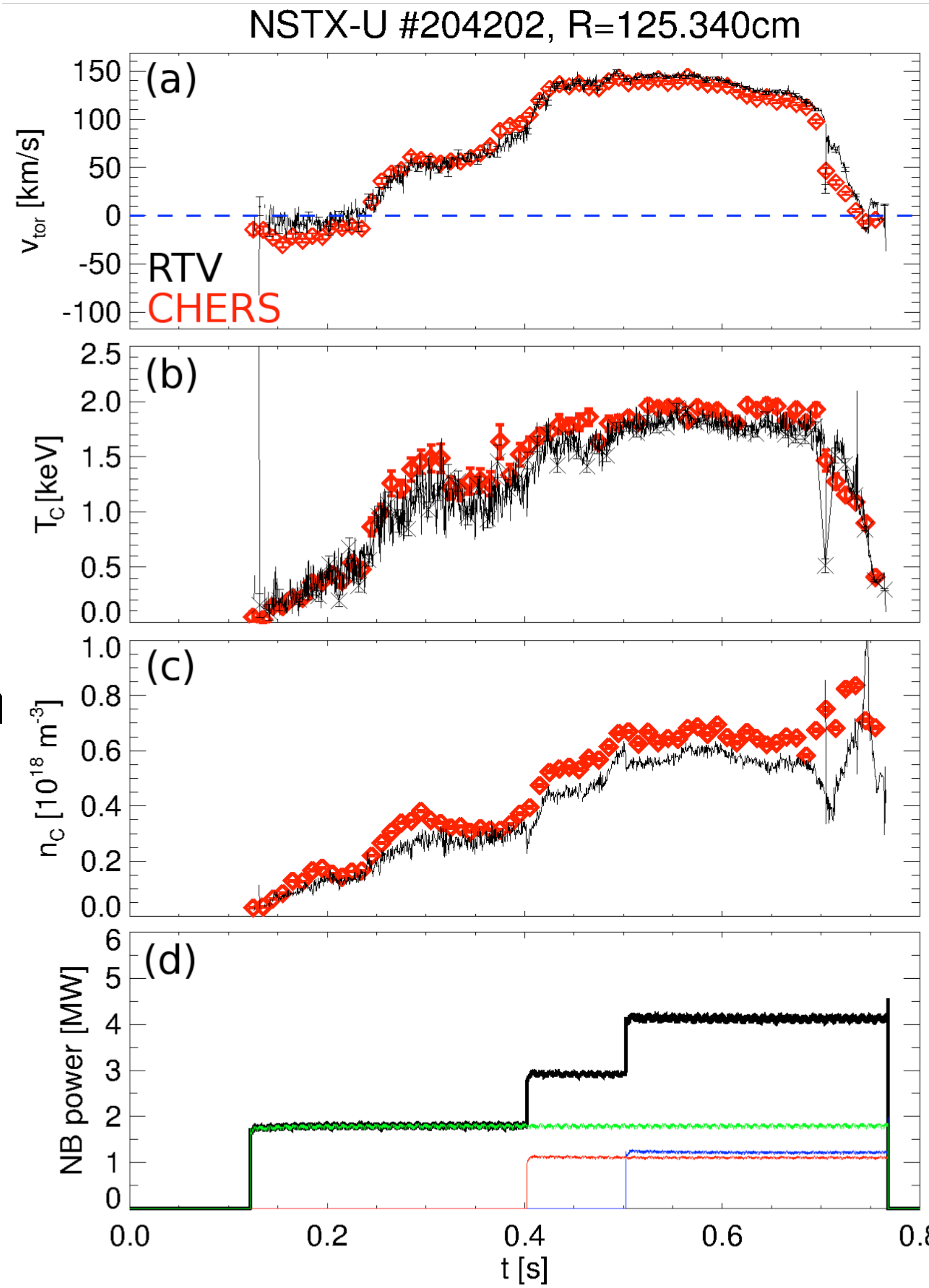
# Measured spectrum features good S/N ratio for $P_{NB}$>2MW; $P_{NB}$~1MW marginal but measurable



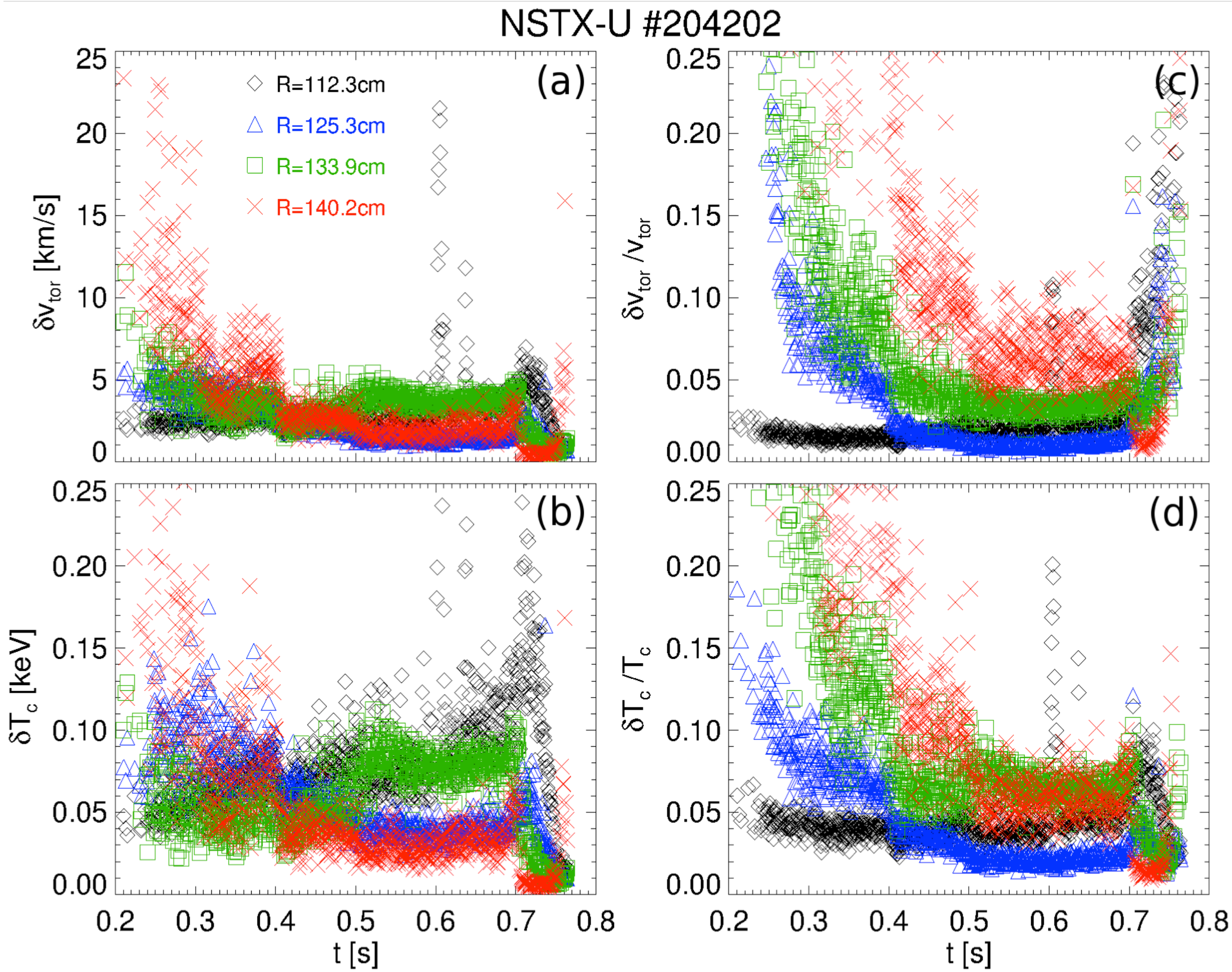

- Shown here is CHERS @100Hz vs RTV @2kHz for $P_{NB}$~4.2MW
- All typical feature appear in RTV spectra
  - Active CX component, background, plume, C III
- Plume contribution removed during RT analysis for core channels

# Post-discharge analysis compares well with CHERS results

- NSTX-U #204202
- $P_{NB}$ increases from 1.7MW up to 4.2MW
- Mid-radius channel, R~125cm
- Low carbon content
  - $Z_{eff}$~1.2-1-5 from CHERS
- Good match for $v_\phi$, $T_i$ at all four RTV radii
- Larger discrepancies >20% for carbon density
  - Suspect uncertainties in RTV vs. CHERS absolute calibration (performed summer 2014!)
  - Spot size is different (larger for RTV)
  - Also: window coating at Bay B-mid?
  - *Analysis relies on MPTS for $n_C$ analysis: lower "effective" time resolution*



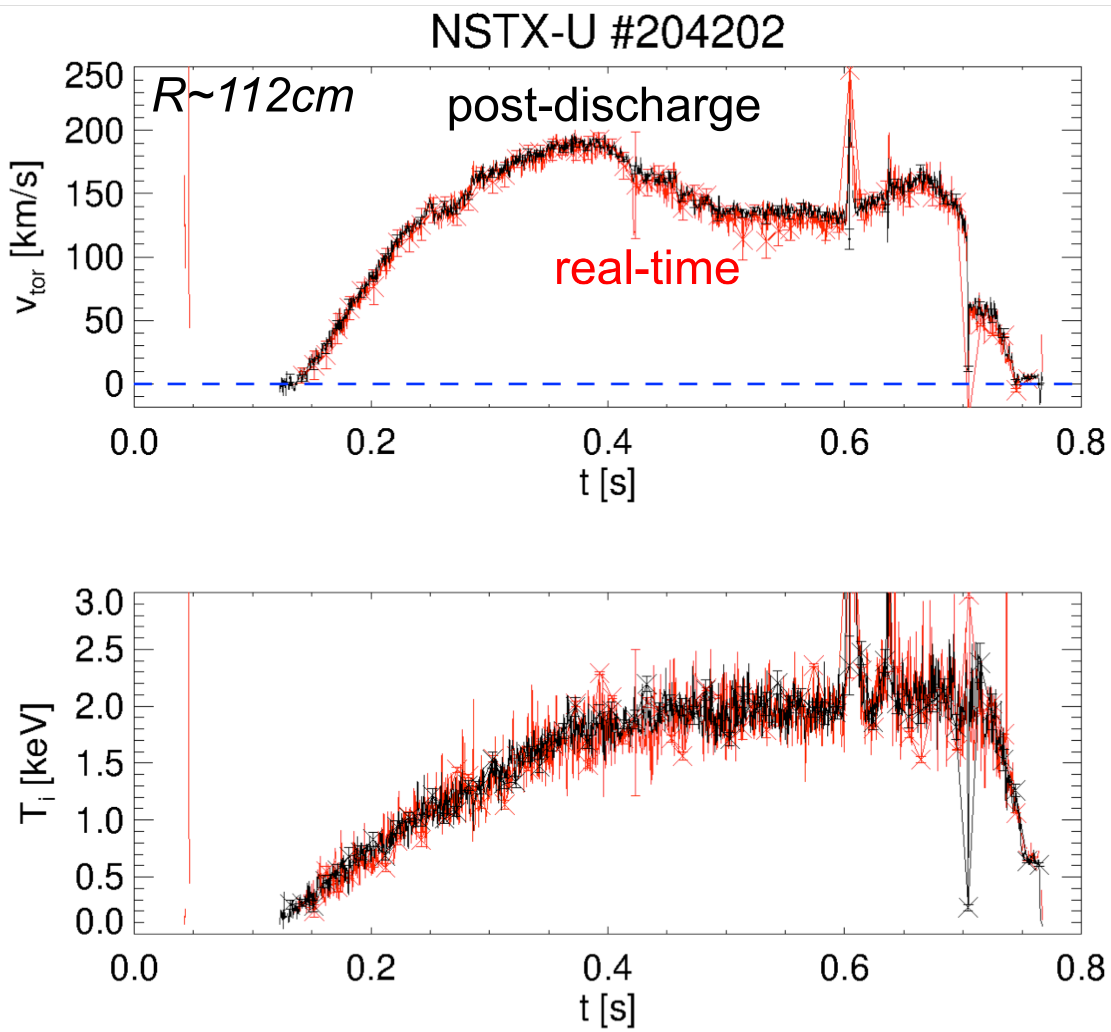
# Uncertainties on velocity, temperature are <10% when $P_{NB}$>2MW



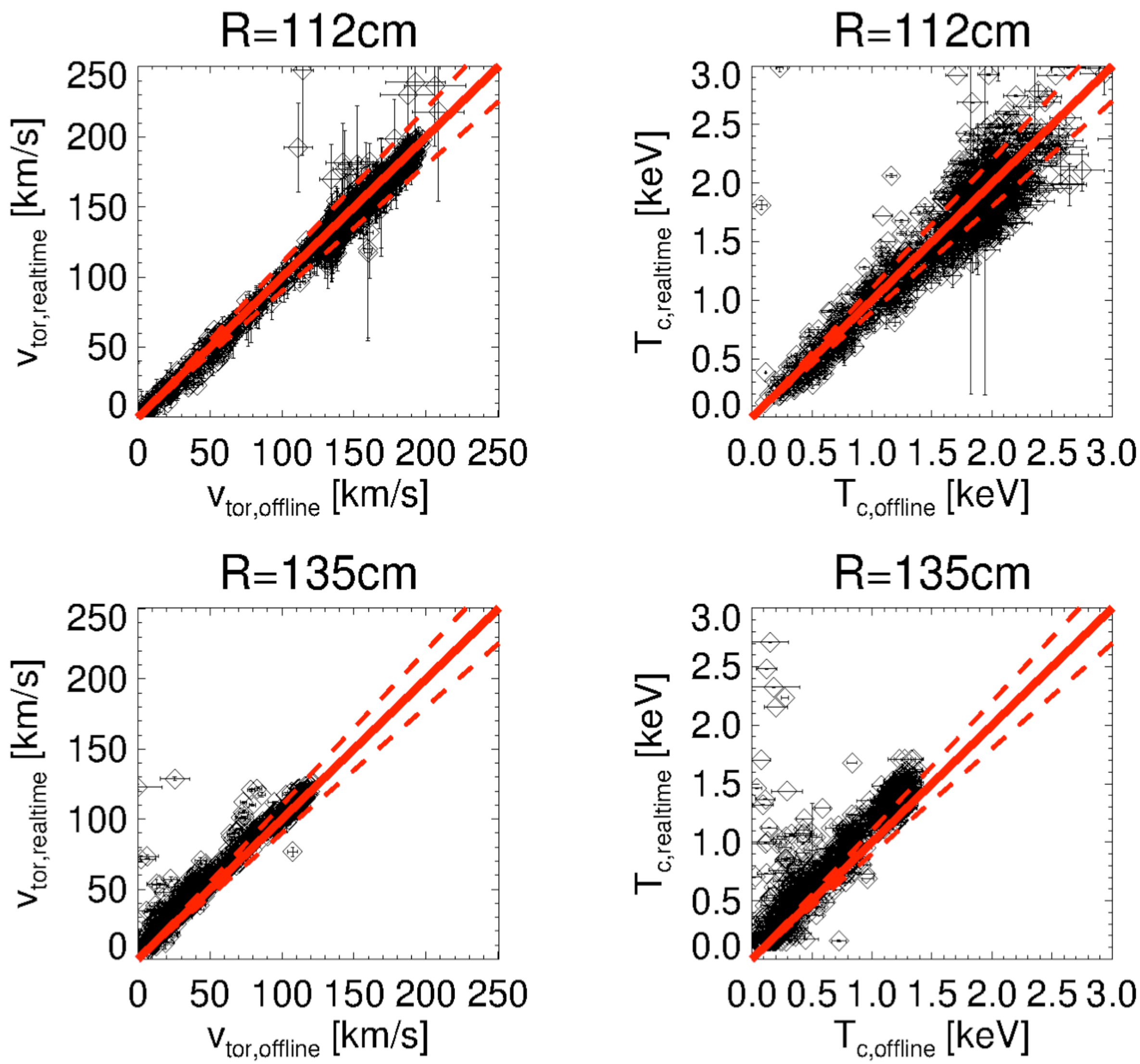

- Absolute & relative uncertainties within expected range
- Relative uncertainties <10% for sufficiently high $P_{NB}$

# Real-time analysis provides accurate data for rotation feedback (and more) /1

- Good match for both $v_\phi$ and $T_i$ between real-time and post-discharge analysis
- Larger uncertainties for RT analysis (as expected)
  - Simplified analysis
    - E.g. to account for instrumental function, plume contribution, background baseline
  - Reduced number of fit iterations



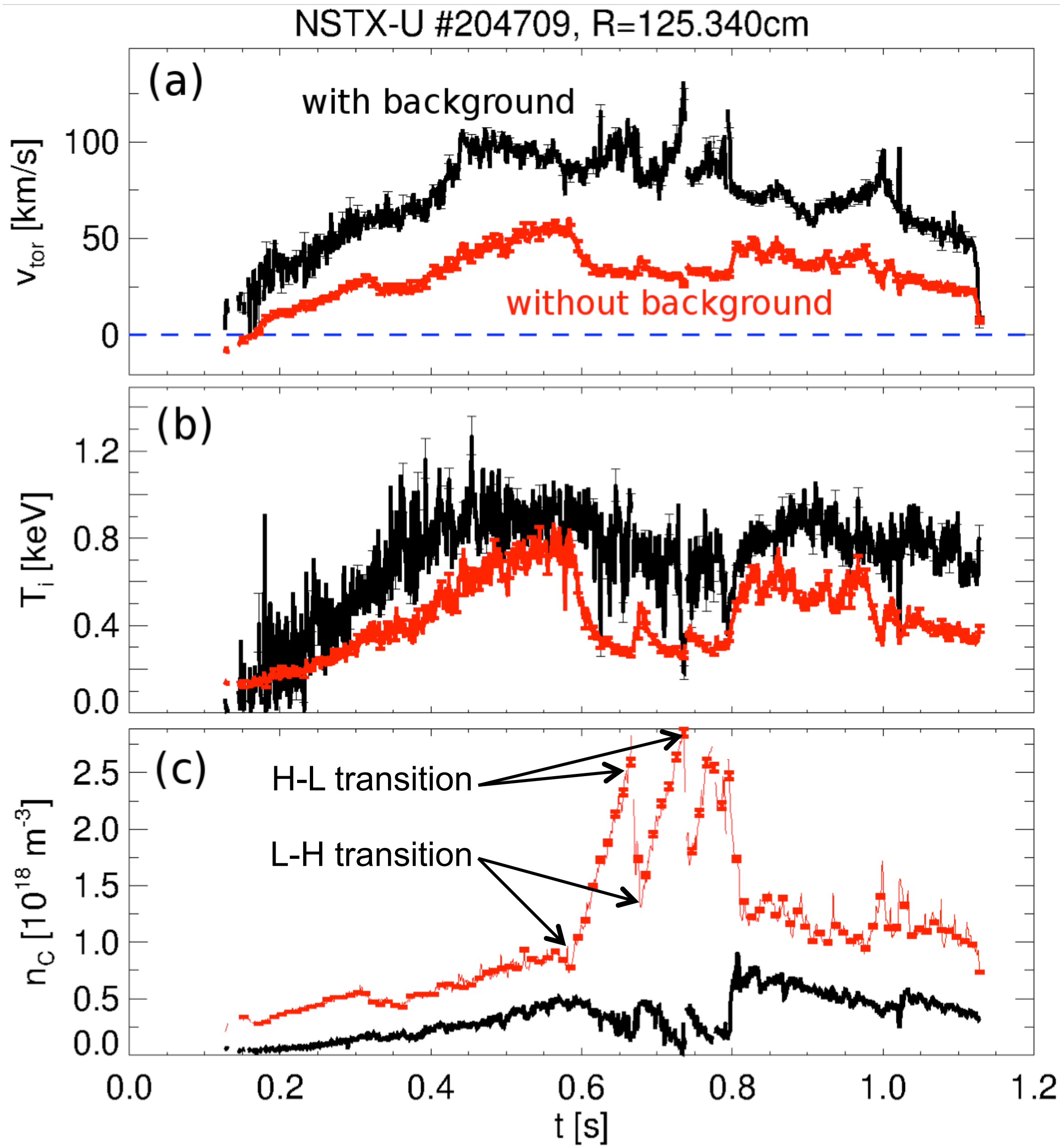
# Real-time analysis provides accurate data for rotation feedback (and more) /2




- Agreement with post-discharge analysis is typically better than 20%

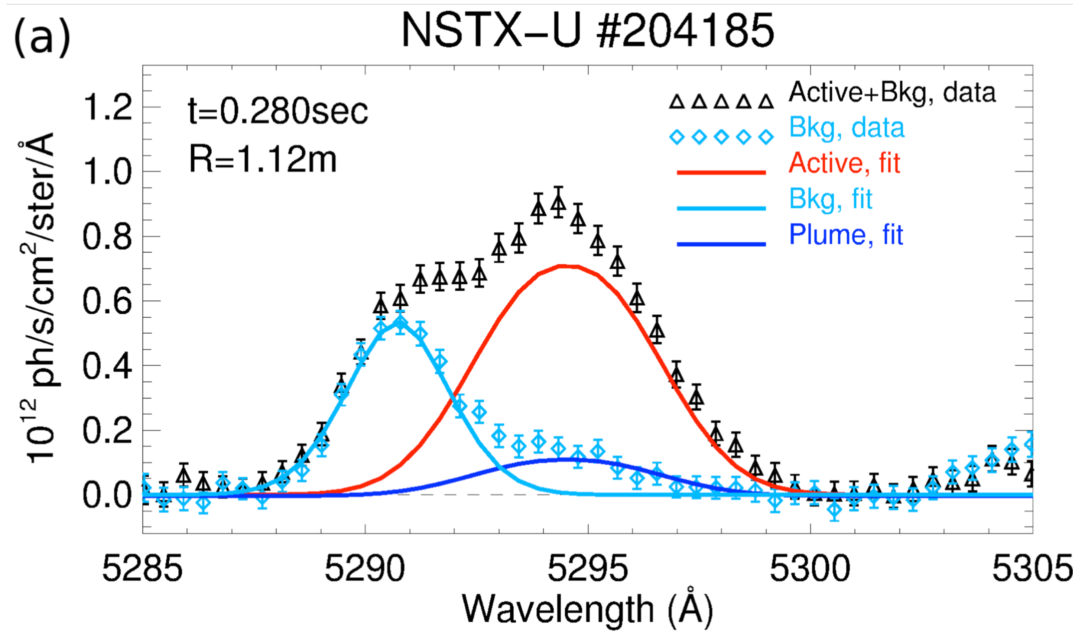
# Background measurements are critical for reliable RTV results

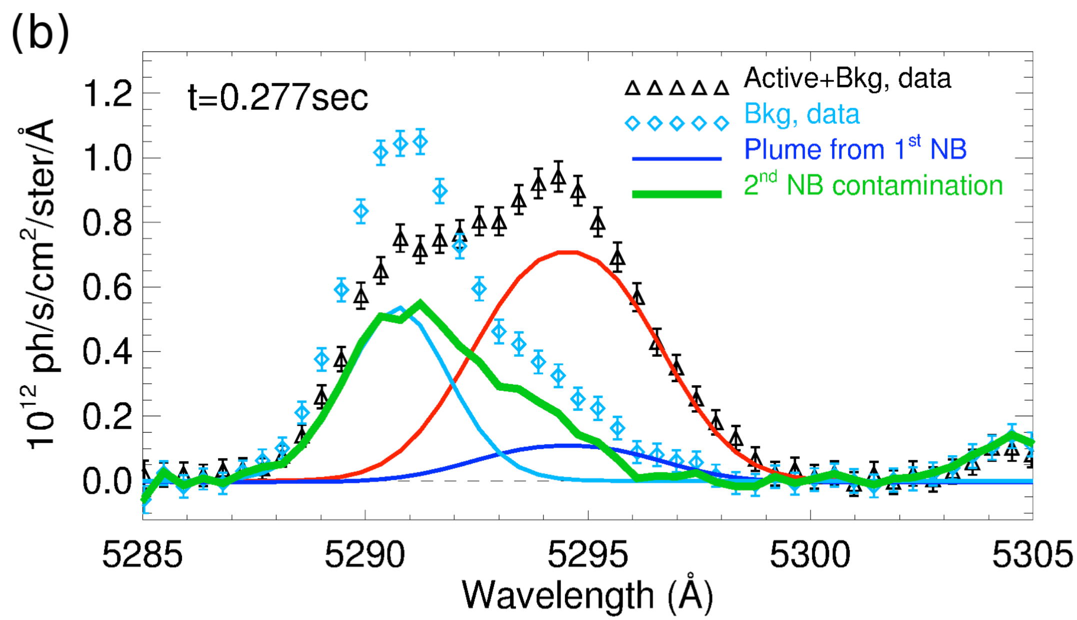
- Paired active/background views are key for successful background removal in real time
- Results off by 2x or more if no/negligible background is assumed
- *Drawback: background views intercept second NBI line*
  - *No RT results if 2nd NB lines are injecting*



# Injection from second NB line compromises RTV (and CHERS) measurements

- Beam turn-off provides estimate of $2^{nd}$ NBI contamination
- (a) only NB1 sources ON
- (b) NB1 + NB2 ON
  - Assume NB1 emission is unchanged from (a)
  - Subtract Active, Bkg from (a) to infer contamination from NB2
  - Signal from NB2 comparable to Active, Bkg
  - Spectrum is distorted
    - Superposition of active, background & plume from both NB lines
  - Cannot resolve lines (especially in real time)

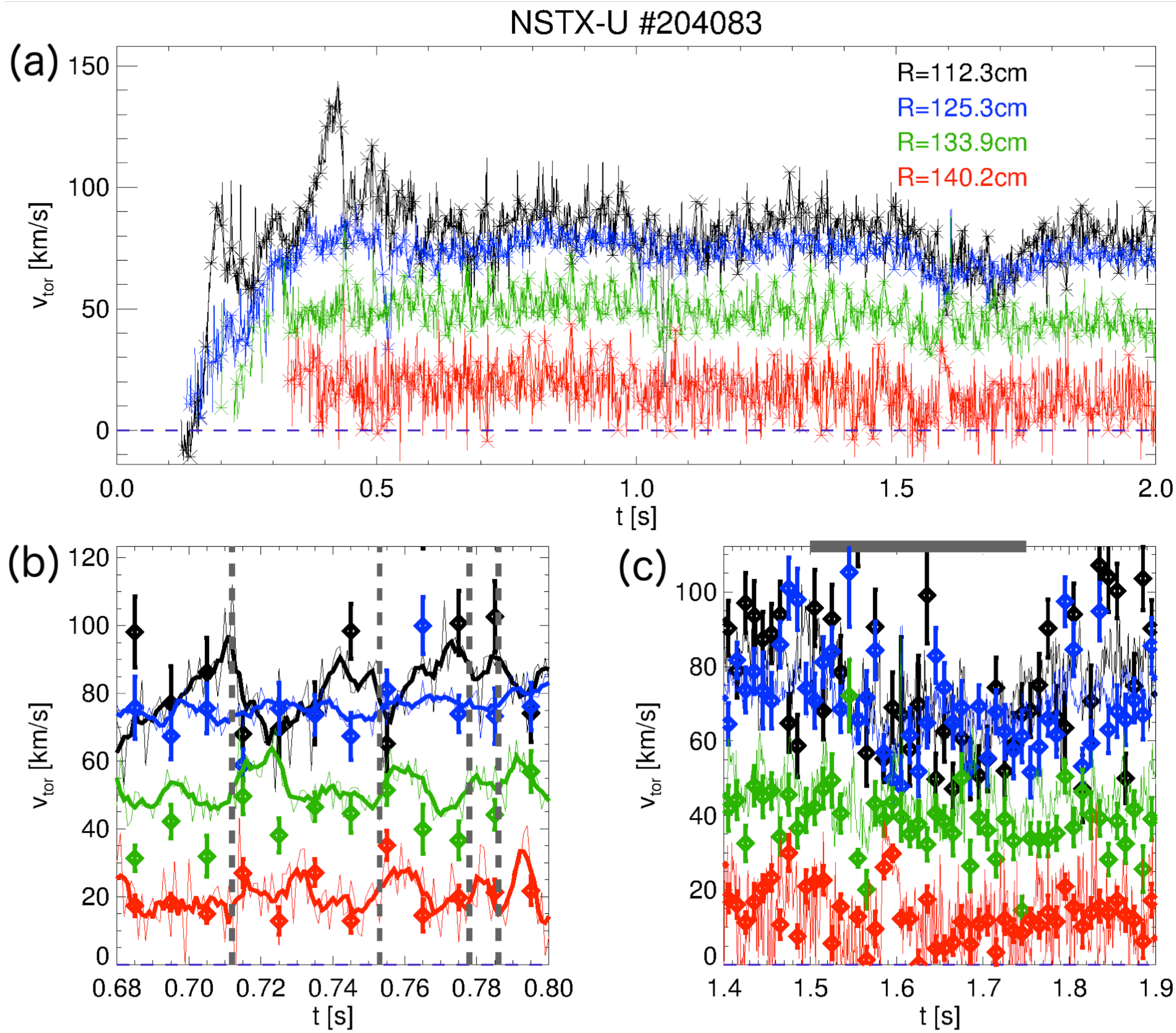


# Sawteeth redistribute momentum, core $v_\phi$ decreases by ~20%

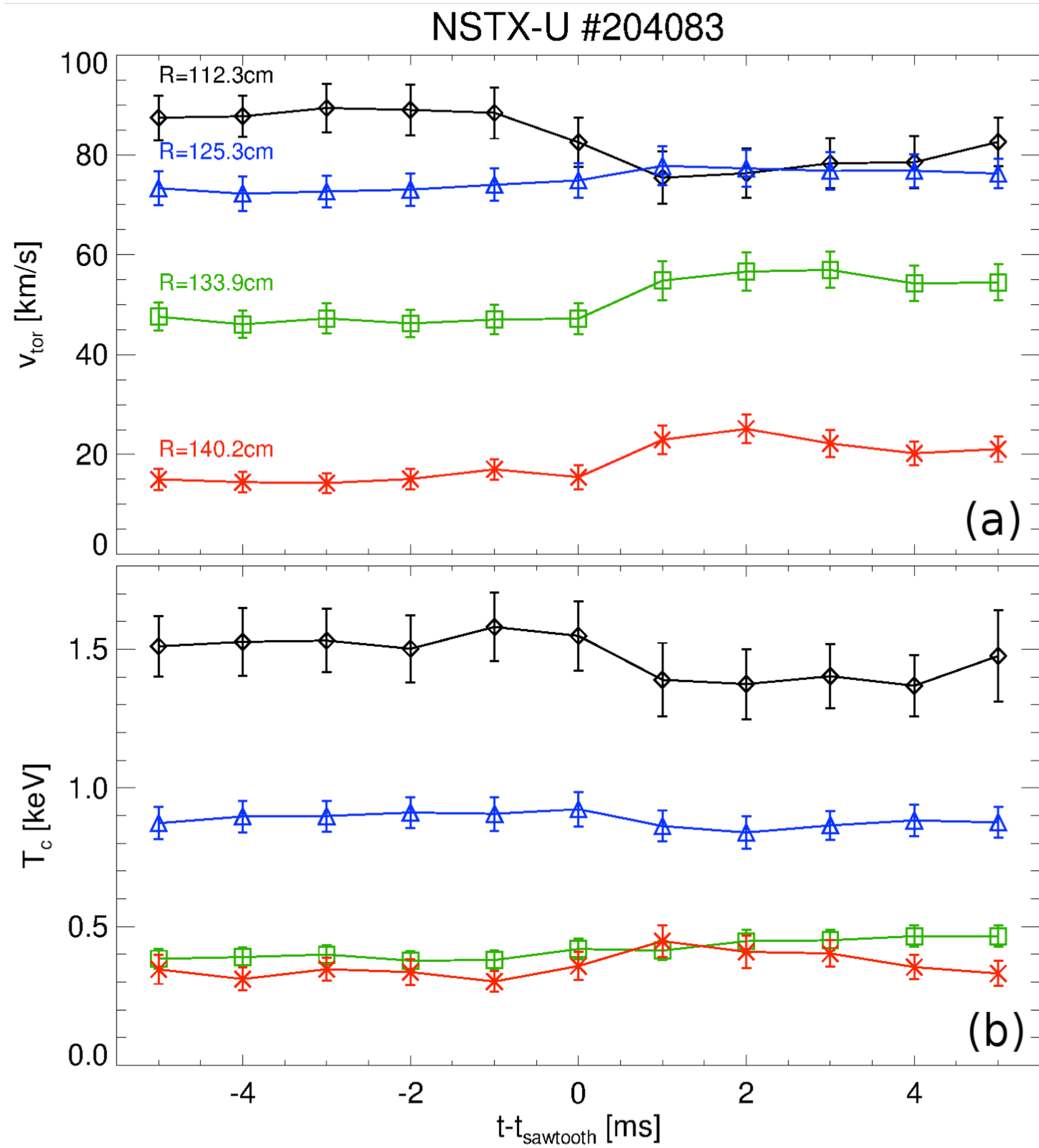
L-mode, $P_{NB}$~1MW

a) Sawteeth seen after t=0.5s
b) Crashes visible on $v_\phi(0)$, anti-correlate with increased $v_\phi$ at R>130cm
c) Large RMP pulse at 1.5s captured by RTV, CHERS

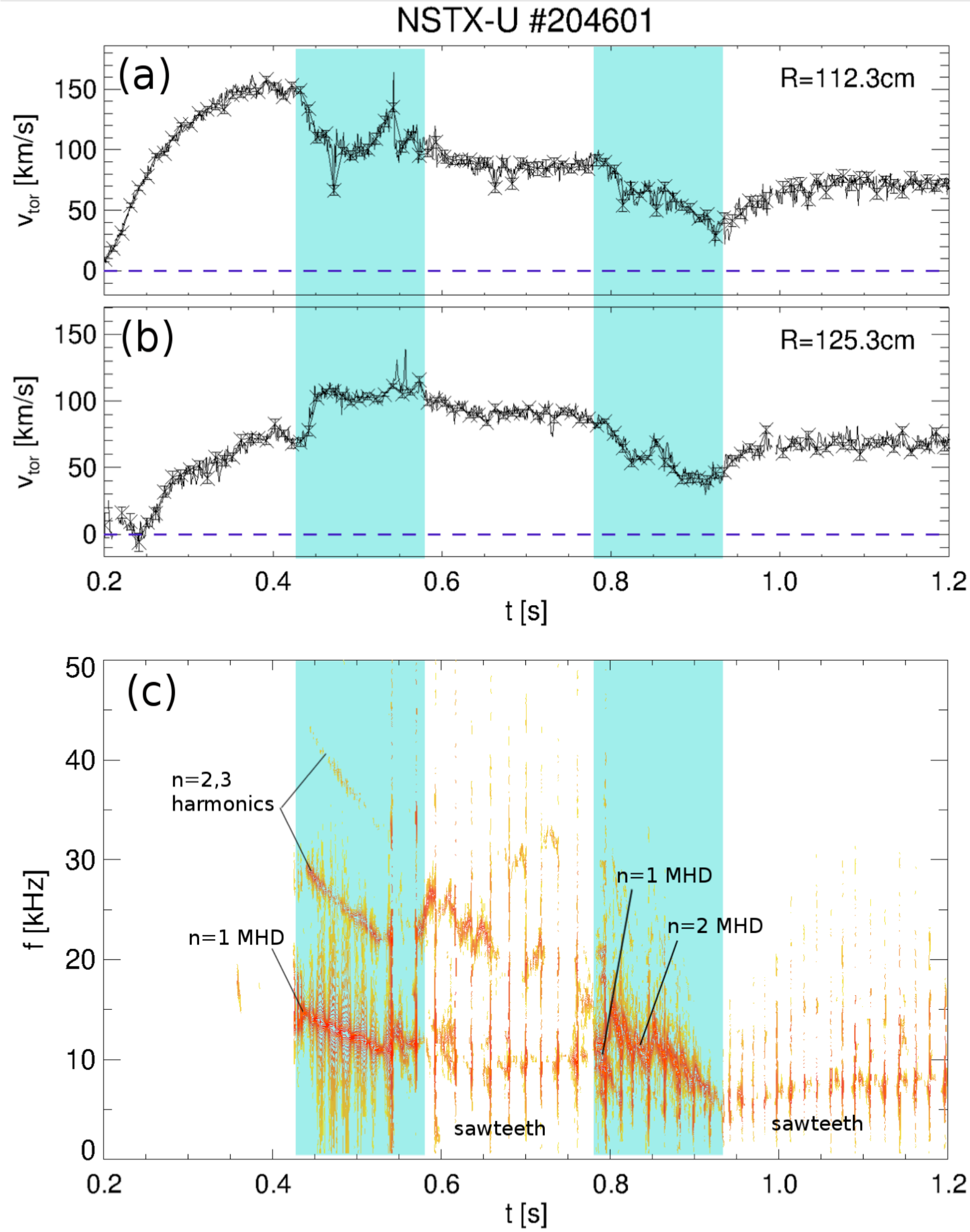


# High sampling rate enables Conditional Averaging of sawteeth effects

- Conditional sampling of data at $f_{samp}$=1kHz
- Clear drop in core rotation, $T_i$
  - Core $v_\phi$ drops by ~20% over 2ms
- Estimated inv. radius is R~125cm
- Data suggest different dynamics for $v_\phi$, $T_i$



# MHD, sawteeth can compete in $v_\phi$ redistribution; different time scales, high $f_{samp}$ enables separation

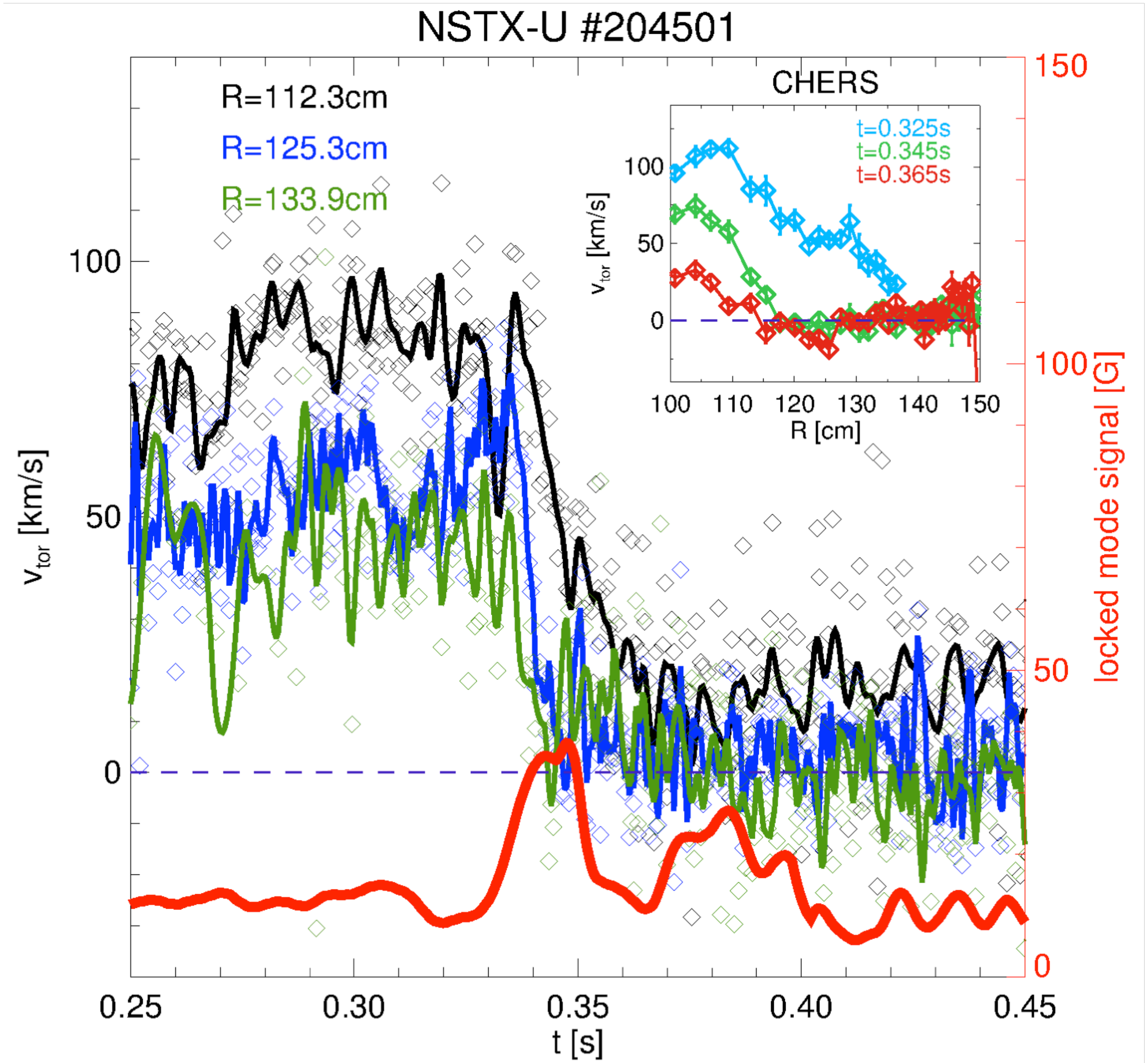



- Complex scenario
  - MHD n=1,2 modes act on ~10ms time scale
  - Sawteeth act on ~1ms time scale
- High $f_{samp}$ of RTV allows to differentiate time scales
- Complements high spatial resolution CHERS profiles

# Mode locking and associated fast dynamic clearly observed on RTV data

L-mode, $P_{NB}$~1.1MW

- Mode grows after t~0.33s, then locks over 10ms
- First, fast response observed outside mid-radius
  - Then propagates to the core
- CHERS provides full profiles pre/post locking (inset)



# Summary & outlook

- First RTV data from NSTX-U confirm achievement of design goals
- System is ready to support development & testing of real-time $v_\phi$ control on NSTX-U
- Much more physics insight can be gathered from post-discharge analysis
  - E.g. effects of RMPs, MHD, ELMs, pellets/granules on $v_\phi$, $T_i$, $n_C$
  - Complements high spatial resolution of CHERS with sub-millisecond time resolution (at 4 radii)
- Post-discharge automatic analysis tools implemented for routine operations
  - Under way: combine info from RTV and CHERS for high spatial & temporal profile data