Initial results from the NSTX Real-Time Velocity diagnostic

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NSTX

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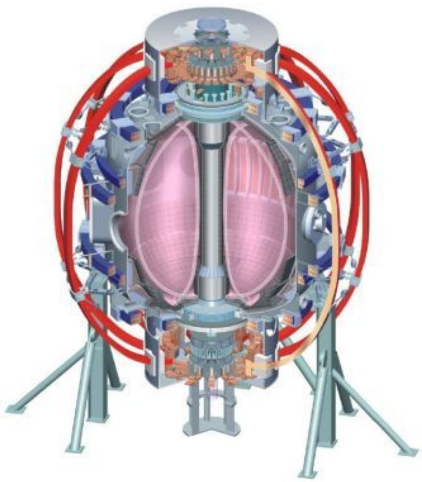

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Abstract

A new diagnostic for fast measurements of toroidal plasma rotation through active charge-exchange recombination spectroscopy (CHERS) was installed on NSTX. The diagnostic infers toroidal rotation from carbon ions undergoing charge-exchange with neutrals from a heating Neutral Beam (NB). Each of the 4 channels, distributed along the outer major radius, includes active views intercepting the NB and matched background views missing the beam. Estimated uncertainties in the measured velocity are <5% at the maximum sampling rate of 5000 Hz (or <1% at 1000 Hz), to be compared with <0.5% at 100 Hz of the main NSTX CHERS system. Signals are acquired on 2 CCD detectors, each controlled by a dedicated PC. Spectra are fitted in real-time through a C++ processing code and velocities are made available to the Plasma Control System for future implementation of feedback on velocity. Results from the initial tests of the system during a Neon glow are discussed.

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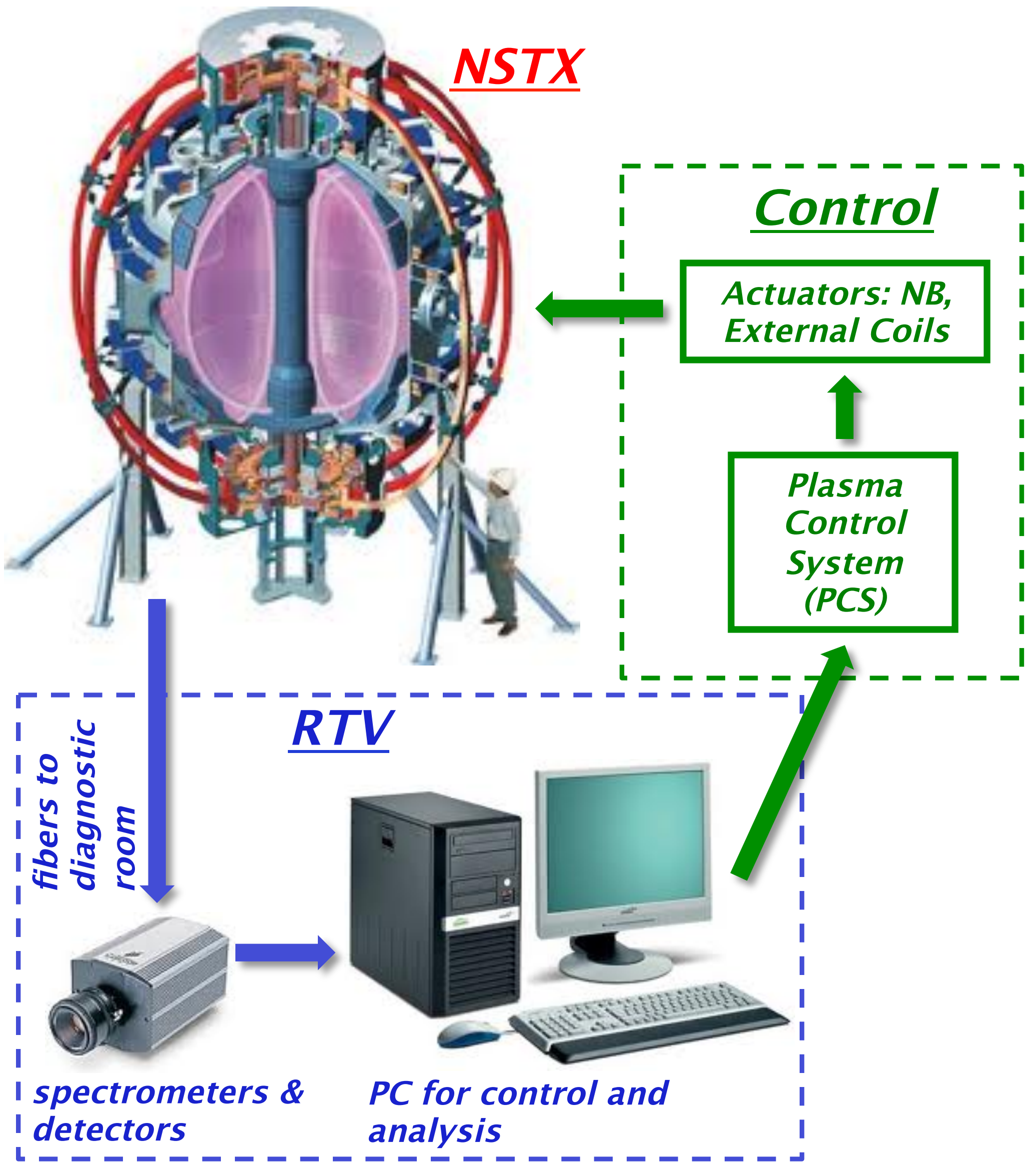
A *Real-Time Velocity (RTV)* diagnostic is required to implement real-time velocity control on NSTX

- Plasma rotation affects stability and plasma performance

- Measurements every 3 ms (or less) are required to implement real-time rotation control
  - Use Neutral Beams (NB), external coils (*plasma braking*) as actuators to affect rotation
  - Time-scales for plasma response are >10 ms

- Fast (~1 ms) measurements of toroidal plasma velocity are not routinely available on NSTX
  - Present CHERS (*charge-exchange recombination spectroscopy*) systems acquire at 100 Hz frame rate
  - Transient phenomena not well resolved
    - L-H transition, ELMs, instabilities

NSTX device and RTV overview



Major radius	0.85 m
Aspect ratio	1.3
Elongation	2.7
Triangularity	0.8
Plasma current	~1 MA
Toroidal field	<0.55 T
Pulse length	<2 s

3 Neutral Beam sources:

$P_{NBI} \leq 6$ MW, $E_{injection} \leq 95$ keV

Actuators for v_{tor} control:

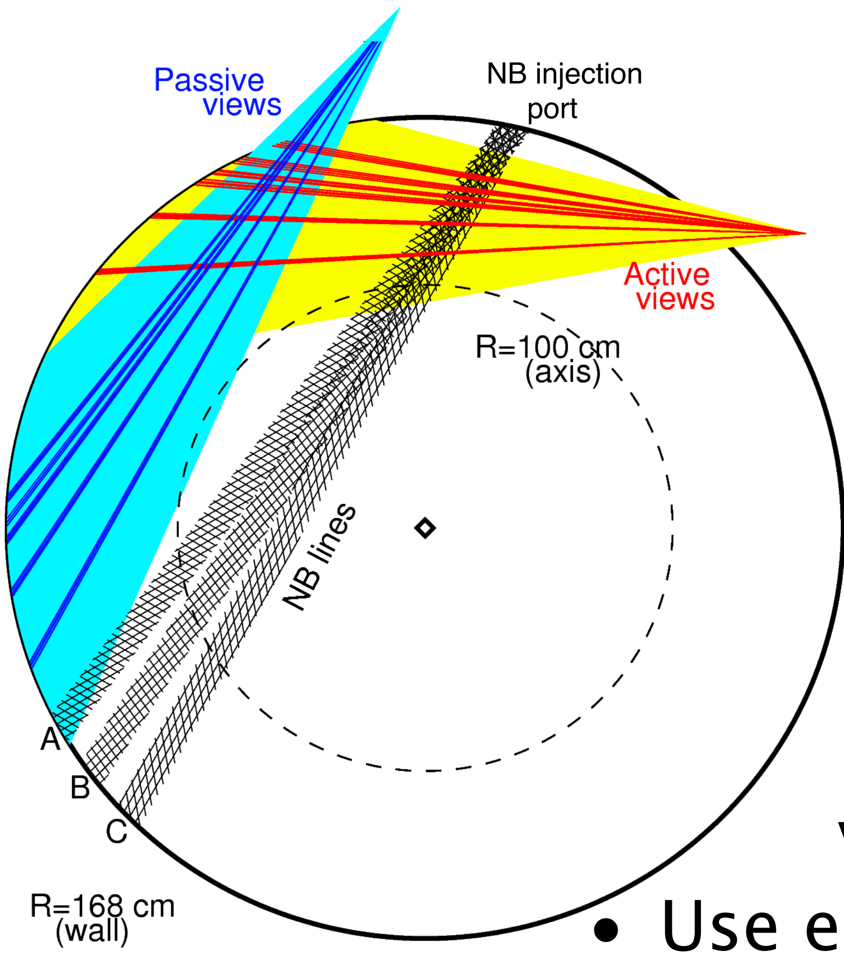
- NB (core plasma)
- External coils (edge, braking)

RTV hardware – Design constraints and criteria

- Use present CHERS system as reference
- Increase frame rate with respect to CHERS:
  - More fibers/channel
  - No entrance slits, no chopper
  - High throughput spectrometer
- Reduce number of channels/detector to accommodate all fibers
  - Typically 4 channels (paired active/passive views)
  - > 2 detectors
- Use spare CHERS fibers for active views
  - 210 μm core diameter

Component	Parameters
Spectrometer	KOSI with HD grating
Grating	528.0-530.8 nm
	C VI @ 529.1 nm
Camera	2x Cascade 128+
	max 5kHz sampling
	4 views/camera (2x active+passive pairs)
	8 fibers/view
	16bit resolution
	Flexible binning
Target ops	1kHz sampling
	real-time analysis: v_{tor}
	<5% error on v_{tor}

System design based on data from CHERS: must increase collected light for faster frame rate, similar uncertainties



System	CHERS	RTV
No. of channels	51 (39)	6 (5)
Fiber diameter [μm]	210 (600)	210 (210)
Fibers/channel	2 (1)	8 (7)
Frame rate	100 Hz	$\leqslant$ 5 kHz
Measured quantities	$v_\phi, n_C, T_C,$	v_ϕ
Monitored line	C VI, 5291 Å	

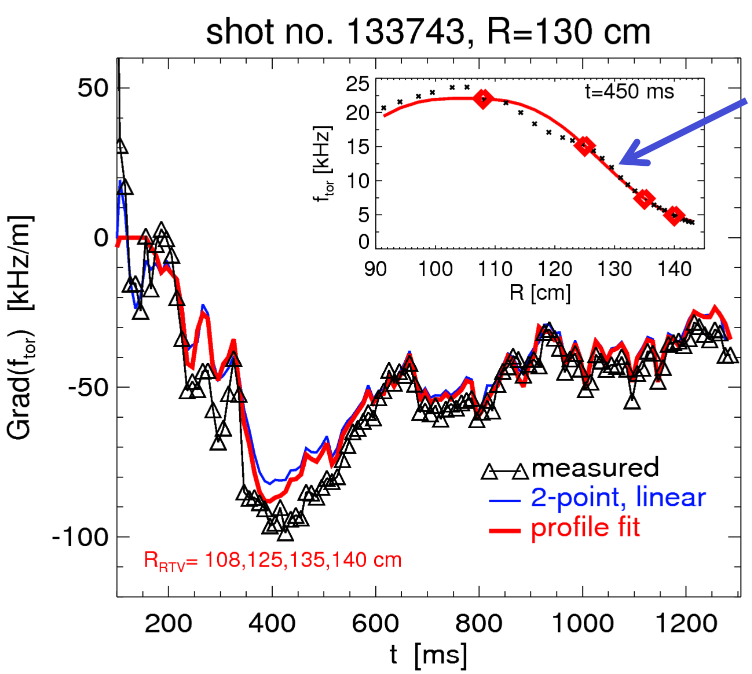
TABLE I. Main parameters of the CHERS and RTV systems. Values in parenthesis refer to the background views.

- Same CHERS approach of matched active+background views
- Use existing CHERS optics
- Relax requirements for instrumental function (T_C measurements): no input slit

Choice of number and location of RTV sightlines based on maximum information from a minimum number of views

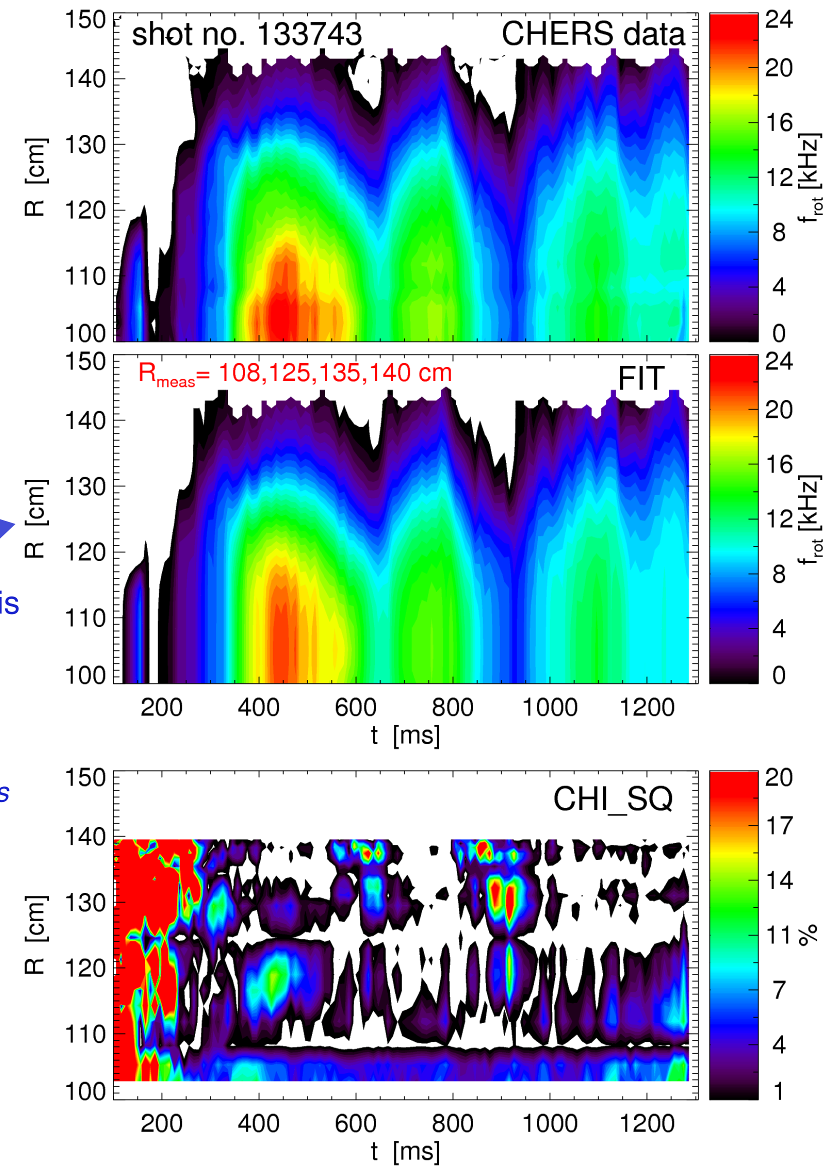
- Based on $v_{tor}(R,t)$ profiles from CHERS
- Use quality of reconstruction of rotation profile (modified gaussian), gradient as metric

> 4 radial points are a good compromise between quality of data and simplicity of the system

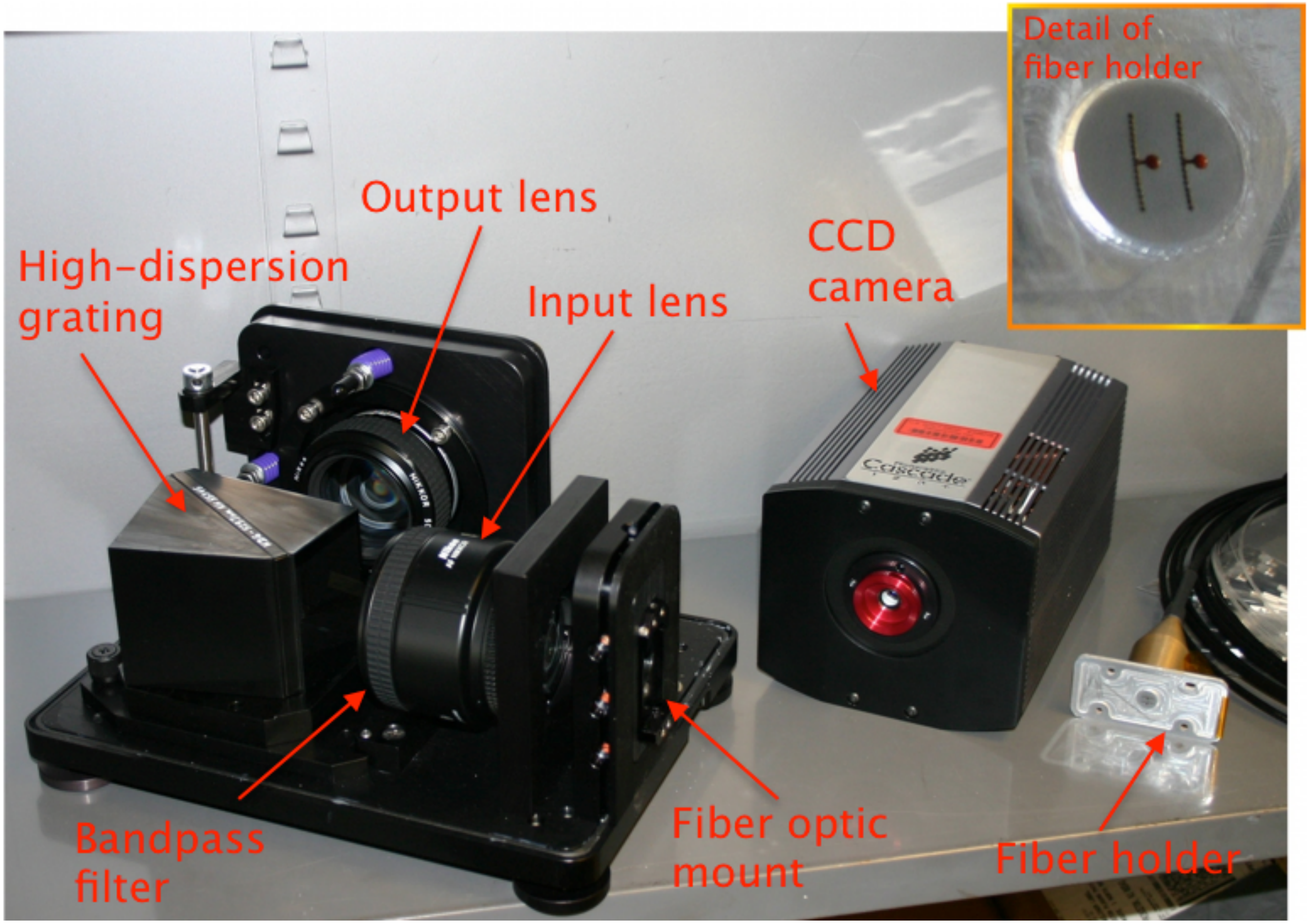


Modified gaussian* is a good model for velocity profiles on NSTX

*Additional parameter *s* sets *squareness*:
s<0 : triangular
s=1 : gaussian
s>1 : rectangular



Use high-throughput spectrometer coupled to CCD detector; combine signal from 8 fibers on same channel



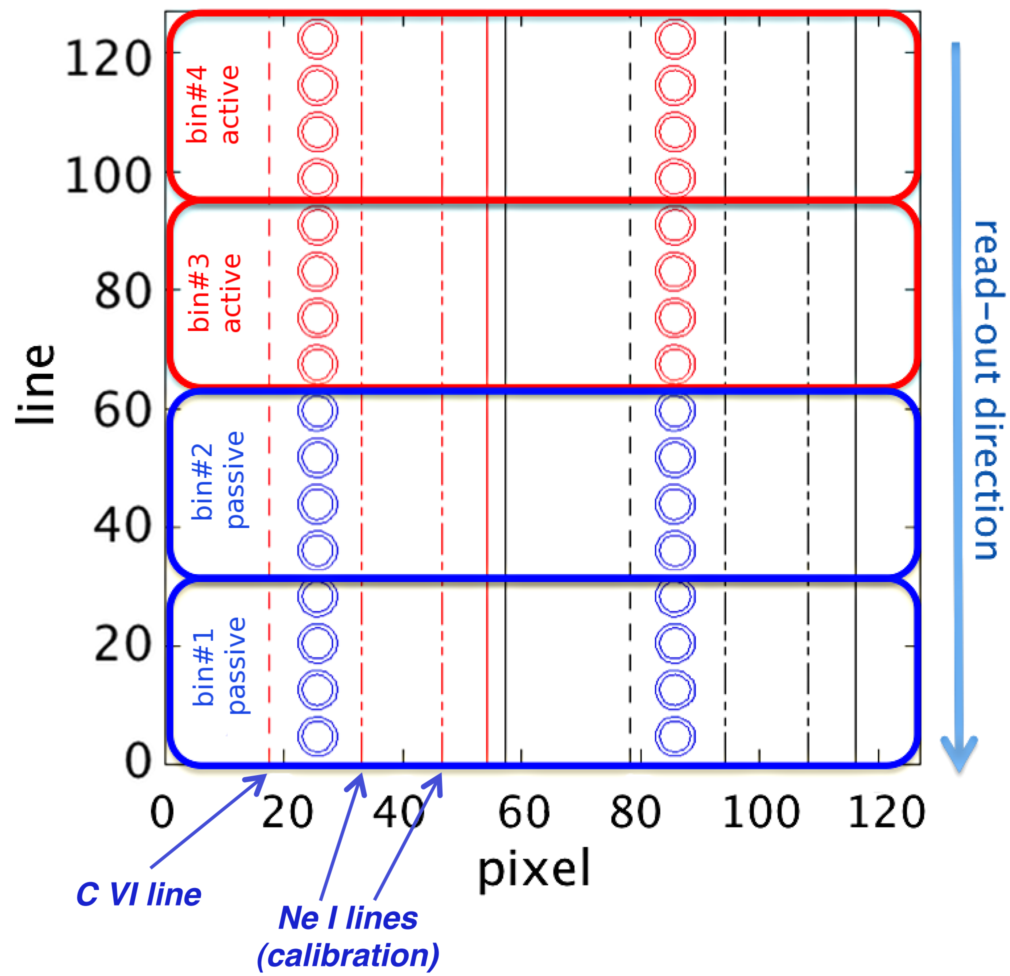
Use curved image at input to obtain straight vertical image on CCD

-> Bin fibers without increasing effective instrumental function

- Split 4 channels over 2 spectrometers
- Group active/background views from same radius on same system for real-time analysis

Multiple fibers are grouped (*binned*) on the CCD to improve SNR; flexible binning schemes possible

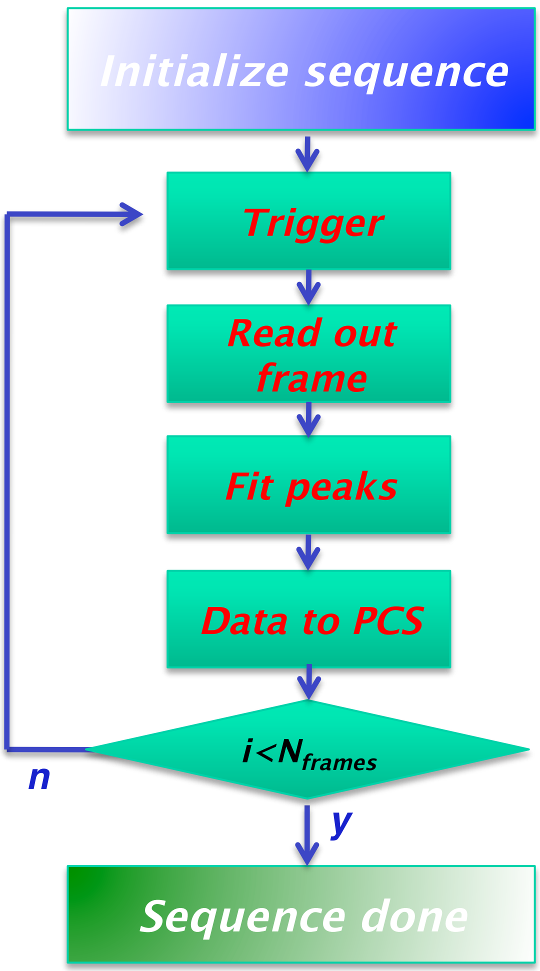
- 2 spectra on each row
- Arrange fibers depending on their expected signal
  - Read passive views first
  - Limit smearing (no chopper used) during read-out
- Active/passive pairs from same radius on same detector
  - Fit both spectra together for RT analysis



- Flexible binning
  - Can differ between RT and off-line analysis

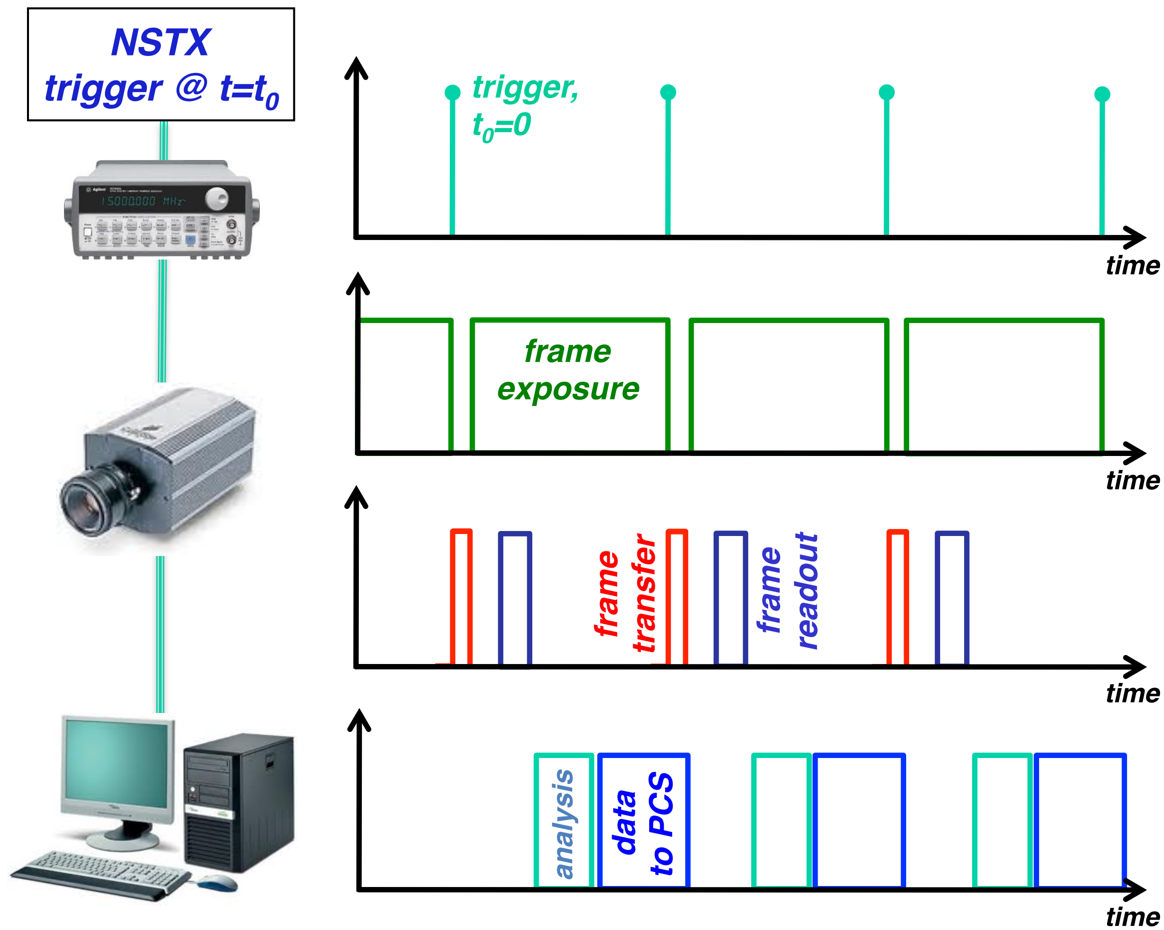
C++ software integrates control of the system and real-time analysis of spectra

Typical acquisition sequence:



- Control and Analysis software developed in C++ language
- IDL Graphical User Interface used to modify settings before shot
- Monitor shot evolution through MDSplus events
- Use OpenMP® to distribute computationally expensive tasks over multiple processors
  - Curve fitting is most time-consuming task
- Send analyzed data (v_{tor}) to Digital-to-Analog converter interfaced with Plasma Control System (PCS)
- Store data in NSTX MDSplus tree after sequence for off-line analysis

Camera timing controlled by programmable Waveform Generator for well-controlled, flexible operation



Data to PCS 16bit resolution: { ***4 velocity values***
4 velocity uncertainty values }

- Sequence initiated by NSTX clock
- Camera triggered by programmable function generator
- Allows well controlled, repeatable sequence
- Variable frame rate during shot possible
  - Optimize dynamic range, avoid CCD saturation

Up to 8 spectra can be "simultaneously" analyzed in <120 μs through RT analysis software

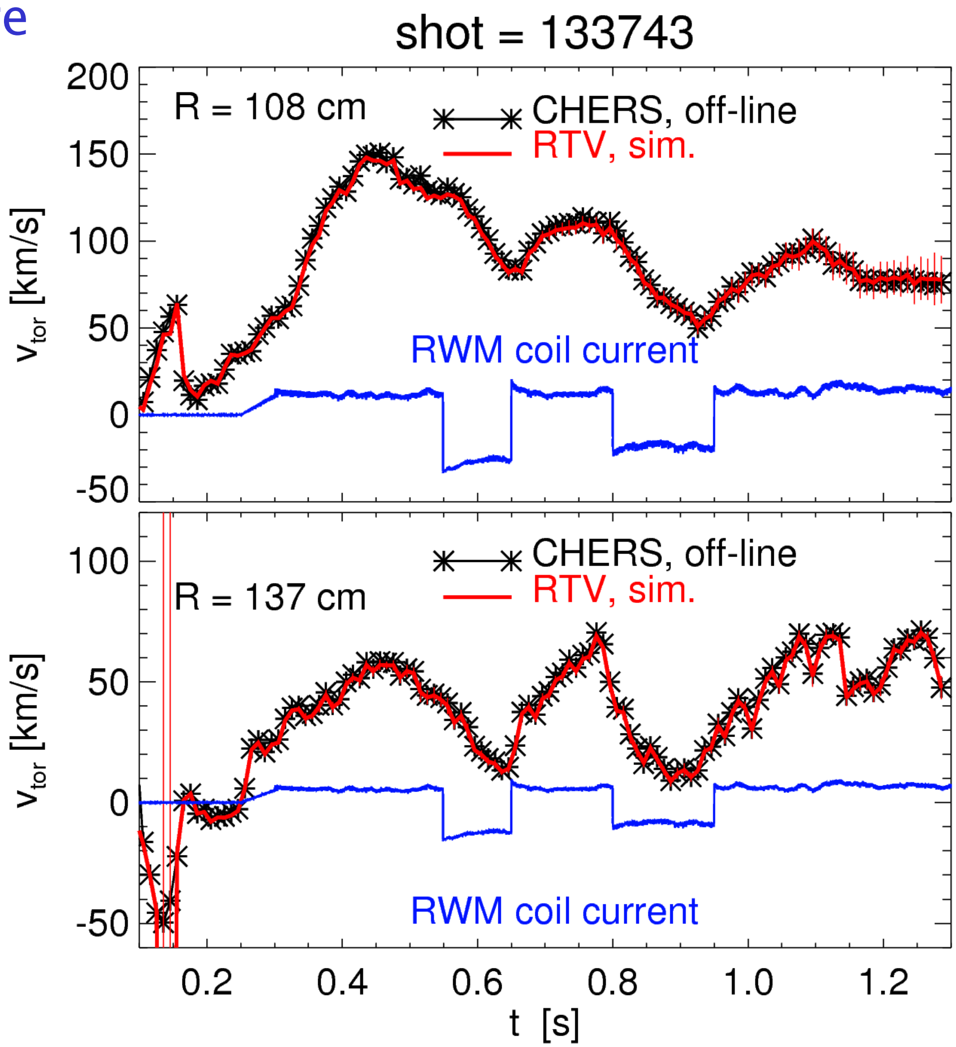
- Compare CHERS results with "Real-time" RTV analysis
  - Feed CHERS data to RTV software
- Fit active/background spectra at same time
- Good agreement
  - Stability, reliability of RT fitting routines under test

Example:

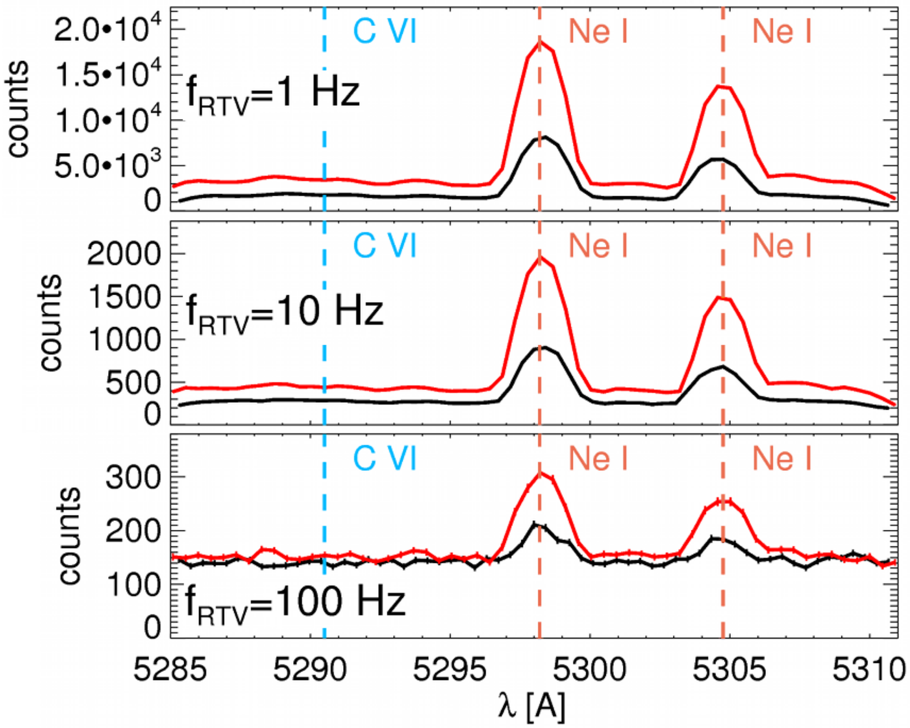
- 1 kHz simulated frame rate
- Use Waveform Generator as trigger
- 4 vertical bins, 8 spectra
- Combine 2 bins/channel

-> Computing time not a limiting factor for frame rate

-> Although simplified, RT analysis matches well off-line CHERS results

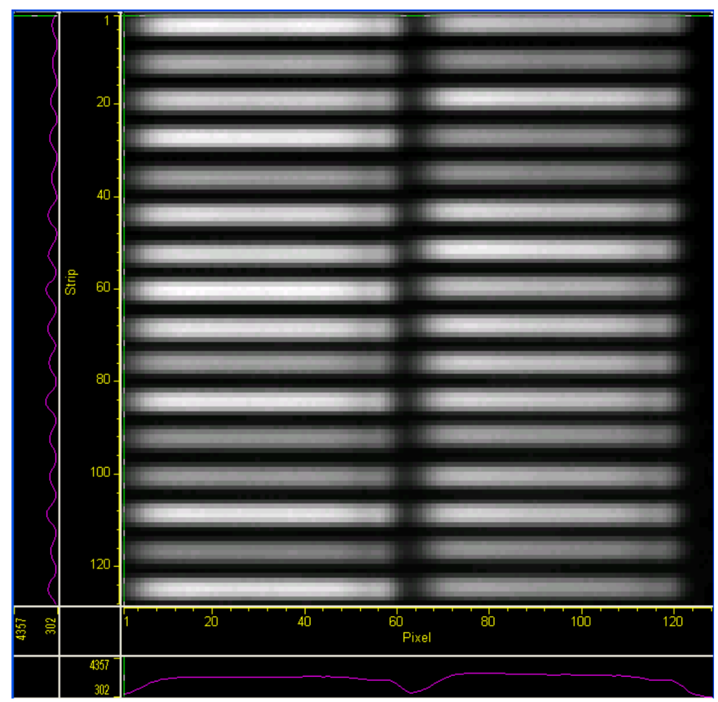


Initial tests of the system during Neon glow confirm achievement of target design parameters



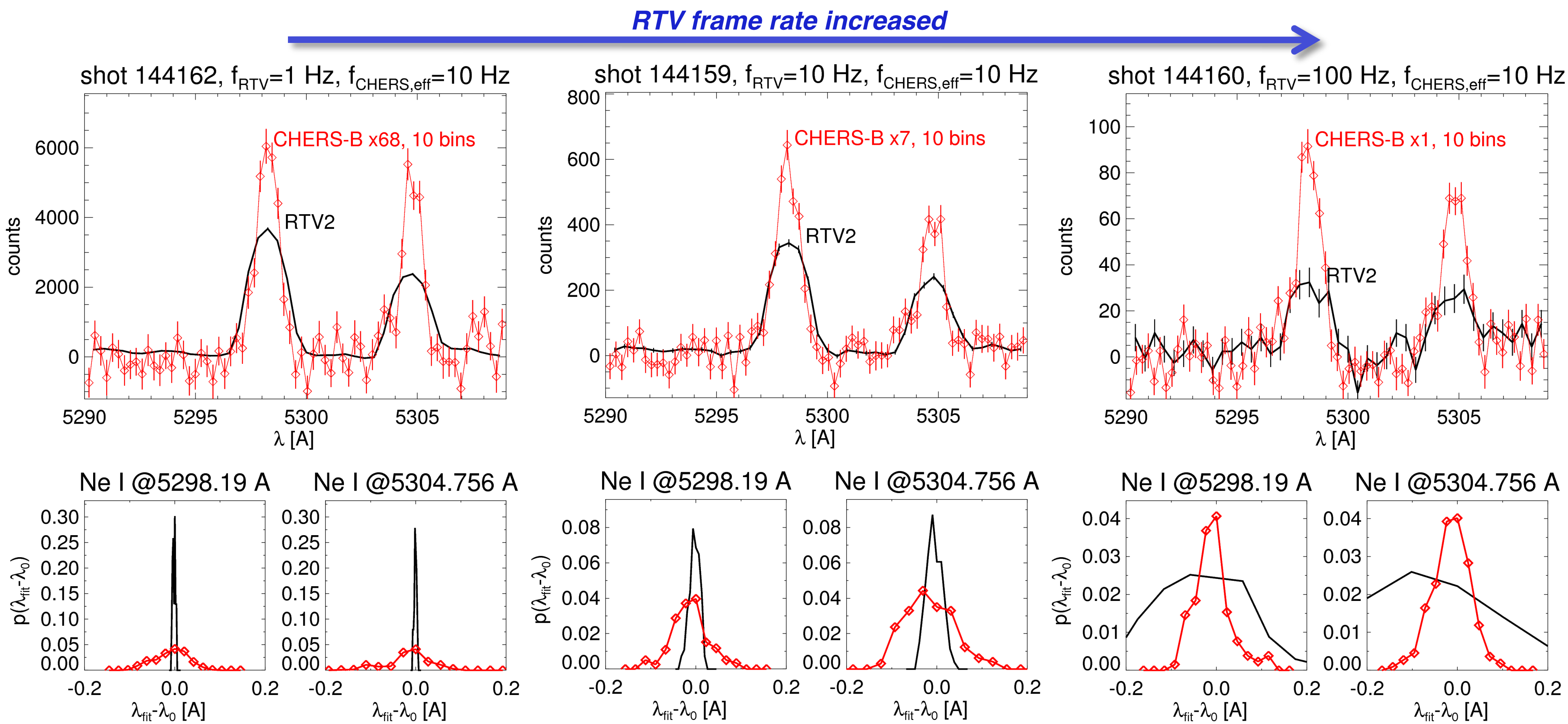
- Ne I lines (@ 529.8 nm, 530.5 nm) used for wavelength calibration
- Instrumental function ~4 pixels
- Dispersion ~0.43 A/pixel
  - Can infer T_C>300 eV, depending on SNR
- *Design parameters met or exceeded*

- Calibration includes absolute intensity
  - Fiber-to-fiber calibration performed using white target plate
  - Absolute scale of measured brightness
    - White target cross-calibrated against Calibration Sphere



Comparison with main CHERS system (Neon glow) confirms higher SNR for RTV at same sampling rates

- RTV: 4 fibers, CHERS: 1 fiber
- Keep CHERS timing fixed, vary RTV
- (Signal from Ne glow is ~50x dimmer than during plasma operations)



Current status of the NSTX RTV systems

- Diagnostics installed and tested
  - Spatial and intensity calibrations done
  - Wavelength calibration done from Ne glows
- Developed C++ prototype control software
  - Extensive tests with 'real' NSTX shot cycle performed
    - E.g., Control integrated with NSTX clock, MDS events; read/write data from/to MDSplus tree, etc.
  - Acquisition up to 5 kHz demonstrated
    - Sampling rate adjustable to optimize signal-to-noise
    - 4 bins, 2 spectra/bin as default, but configuration is flexible
    - Frame acquired <u>and analyzed</u> in <200 μs
  - Real-time fitting demonstrated in <120 μs, multiple bins
    - Multiple gaussians, active/passive spectra + linear background
    - Fit is most time-consuming step in v_{tor} analysis
    - Excellent comparison w/ off-line fit (IDL)
  - Tested Analog Output through PCI card
    - Works OK; no delays observed, well synchronized with other tasks
- Used Windows XP so far, plan to move to Unix for final implementation

Future applications

- RTV enables study of transient phenomena on sub-millisecond time-scale
- Examples of future application include
  - Velocity evolution at L-H transition
  - Effects of ELMs on edge velocity
  - Effects of other instabilities on toroidal rotation
    - Low-frequency MHD (kink)
    - Alfvénic modes, e.g. TAEs, causing large fast ion losses
  - Dynamics associated with plasma braking through external coils
    - Model validation
- Implementation of real-time velocity control
  - Use Neutral Beams, external coils (*plasma braking*) as actuators