Measurements of Magnetic Field in NSTX using the MSE-LIF Diagnostic

F. M. Levinton*, J. Foley†, D. DiCicco*, D. Cylinder*, H. La Fleur*, H. Yuh*
*Nova Photonics, Inc. Princeton, NJ
†Twinleaf, Princeton, NJ

55th Annual Meeting Of The American Physical Society
Division Of Plasma Physics

November 11-15, 2013

Denver, CO

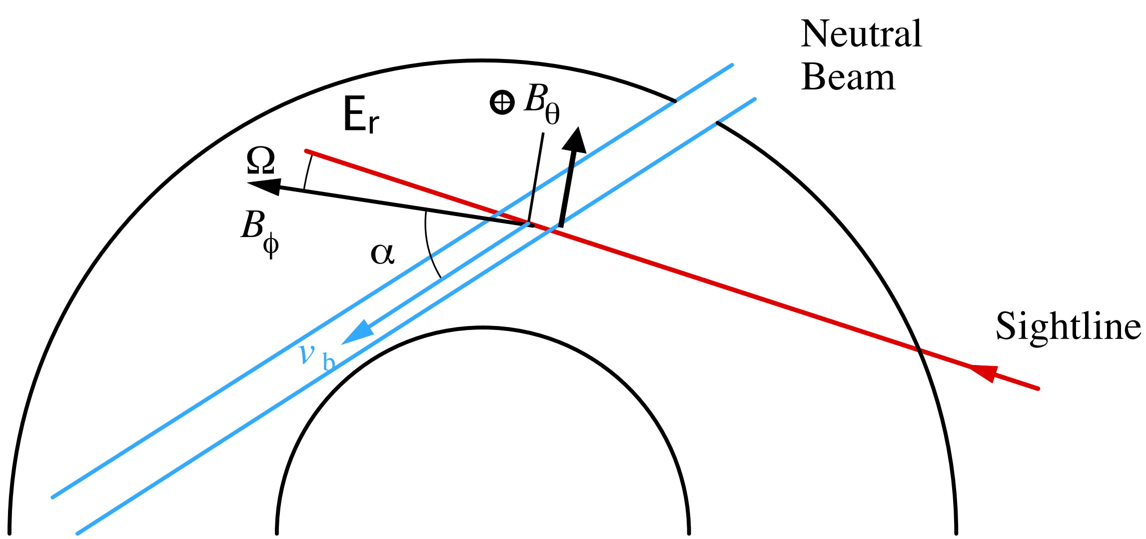
Abstract

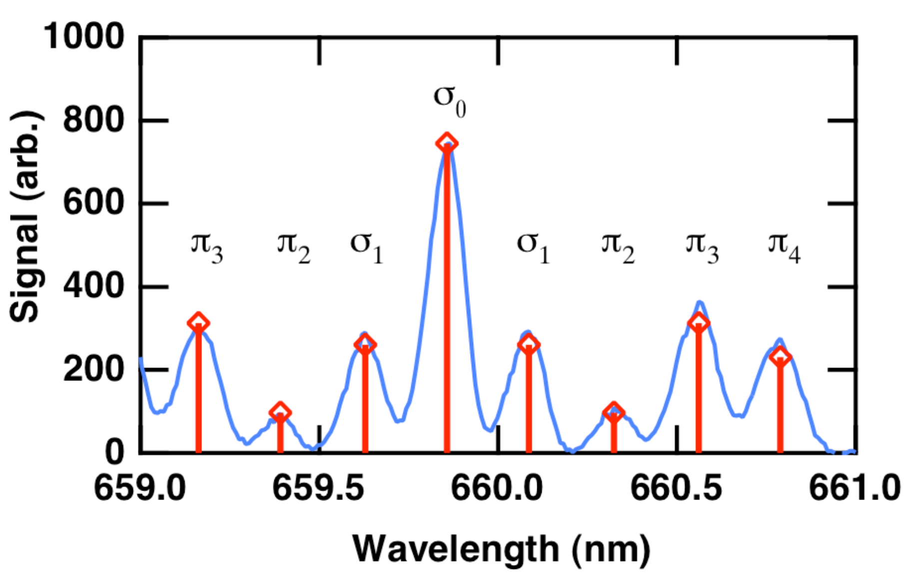
The motional Stark effect with laser-induced fluorescence diagnostic (MSE-LIF) was installed on NSTX in the 2011 run year. The MSE-LIF will enable radially resolved measurements of the magnetic field pitch angle and magnitude, both of which can be used to constrain plasma equilibrium reconstructions. A diagnostic neutral beam with low axial energy spread, low divergence, and high reliability has been developed. It operates routinely at 35 kV and 40 mA. A laser has been developed with high power (~10 W) and optimal linewidth match to the neutral beam (~6GHz). The laser wavelength is near 651 nm for a match to the Doppler-shifted Balmer-alpha transition in the beam neutrals. The unique high-power, moderate linewidth laser system utilizes a 19 emitter diode laser bar and feedback from a volume holographic grating. A magnetic shield protects the ion source from the NSTX stray fields. Initial data in a gas-filled torus and low magnetic fields was taken on NSTX and is presented here.

Overview

- Fundamentals of MSE and Motivation for MSE-LIF: Magnetic Field Magnitude and Pitch Angle Measurements
- Foundation for MSE-LIF: Low-Field, Neutral Gas Measurements
- MSE-LIF at Intermediate Field in Plasma: Challenges and Responses
- Laser Development: 651 nm, 10 W, 6 GHz Linewidth
- Installation and Initial Operation on National Spherical Torus Experiment (NSTX)

Motional Stark Effect Diagnostic





- Emission from hydrogenic neutral beam split and polarized due to Stark effect from $\vec{v} \times \vec{B}$ electric field
- Balmer alpha (n=3 -> n=2) transition observed. Δm=0 are π, Δm=±1 are σ
- Pitch angle determined by polarimetry on single line of spectrum
- Radial profile of pitch angle used with external magnetics to reconstruct equilibrium
- Sensitive to radial electric fields

Advantages of MSE-LIF system:

MSE-LIF uses laser to excite H-alpha transition in diagnostic neutral beam

Field Range:

MSE measurements from ~0.001 T and up. Traditional MSE limited by overlap of spectral lines as field decreases

Measurement of |B| as well as pitch angle:

Measure |B|, use to compute pressure, current profiles

Sensitivity to E_r:

Can use MSE-LIF in conjunction with additional MSE system to determine E_r

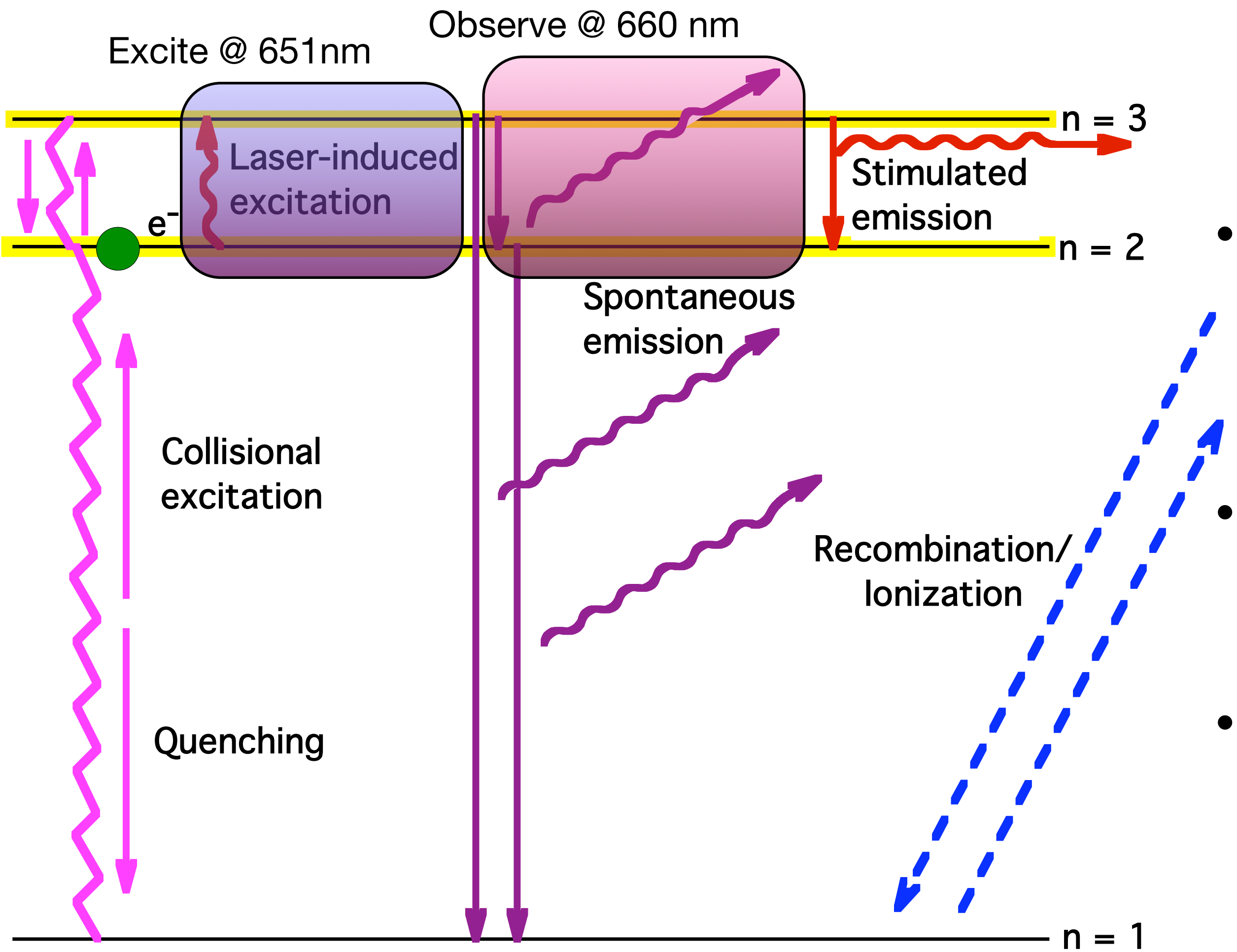
Ease of Calibration:

Insensitive to polarization effects in optics

Operational Flexibility:

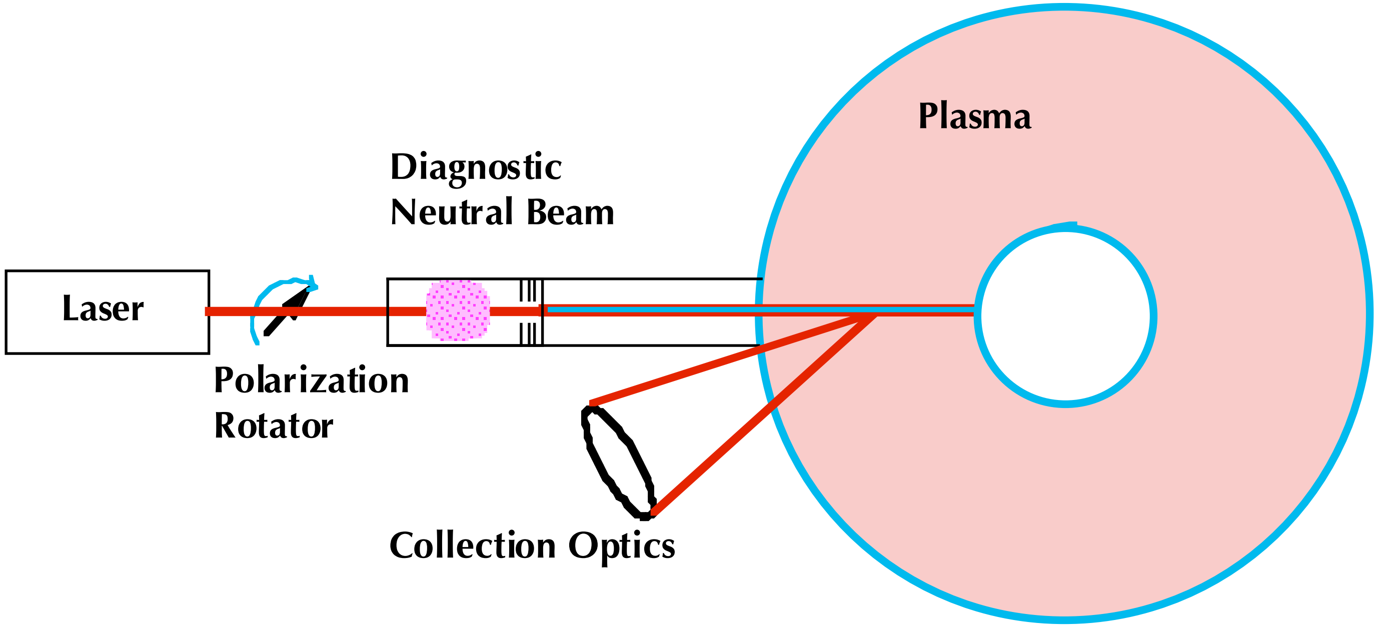
Use of diagnostic neutral beam enables MSE measurements in absence of heating beam, for start-up, RF studies, or in small machines

LIF Scheme



- Excite n=2 to n=3 transition in Hydrogen: Doppler shifted to 651 nm
- Observe same transition: Emission Doppler shifted to near 660 nm
- Laser wavelength match to beam voltage
- Laser polarization match to Stark transition

Pitch Angle Measurement

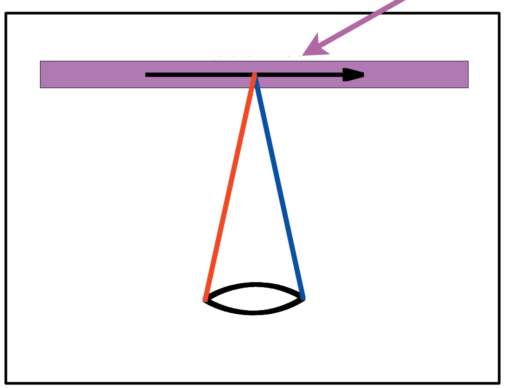


- Laser collinear with neutral beam for Doppler match everywhere.
- Polarization information set by input laser: no need for polarimetry in detection system
- Optional radial beam injection eliminates pitch angle sensitivity to E_r

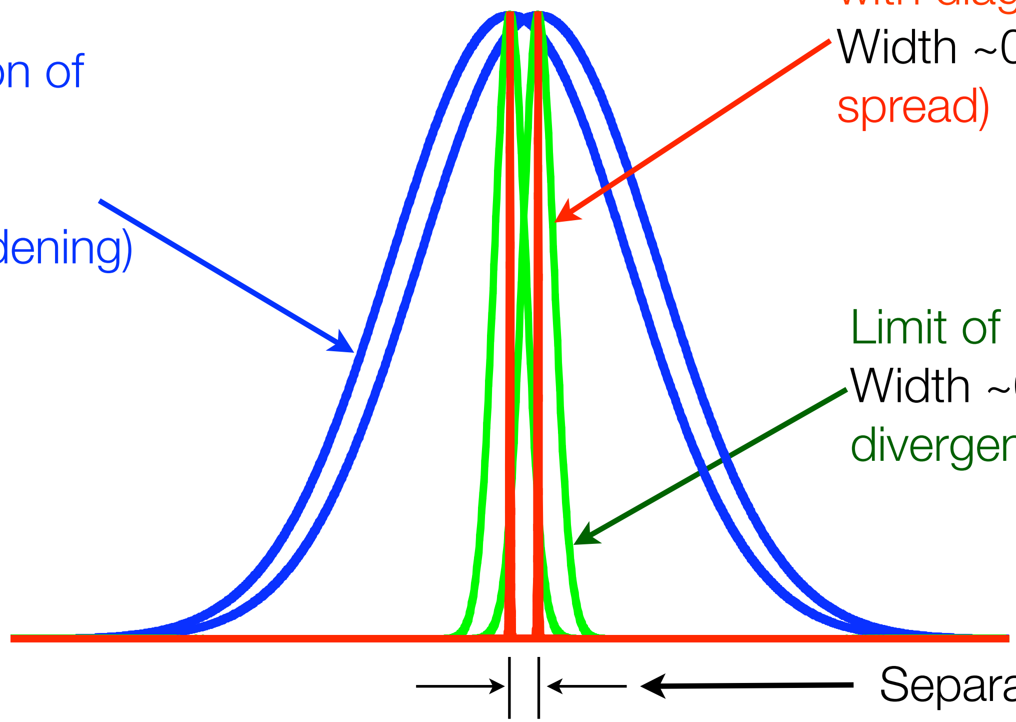
Unprecedented Spectral Resolution

Example: NSTX at ~0.4 T

Direct observation of heating beam:
Width ~0.3 nm
(geometric broadening)



MSE-LIF system
with diagnostic neutral beam
Width ~0.01 nm (beam energy spread)

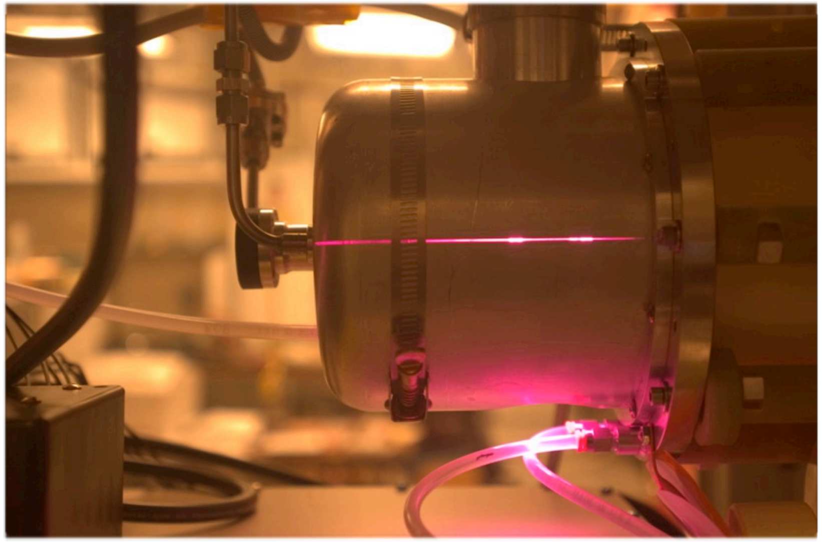


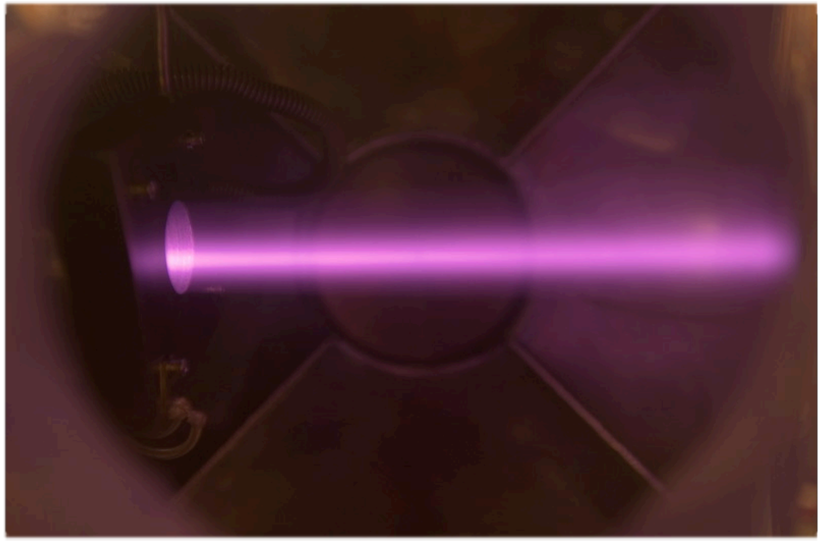
Limit of heating beam resolution:
Width ~0.04 nm (beam divergence)

Separation between Stark components
~0.03 nm (90 kV D beam, 0.4 T)

- Measurement at lower fields than traditional MSE.
- Precise measurement of |B| with laser or beam voltage sweep: Use to reconstruct pressure and current profiles.

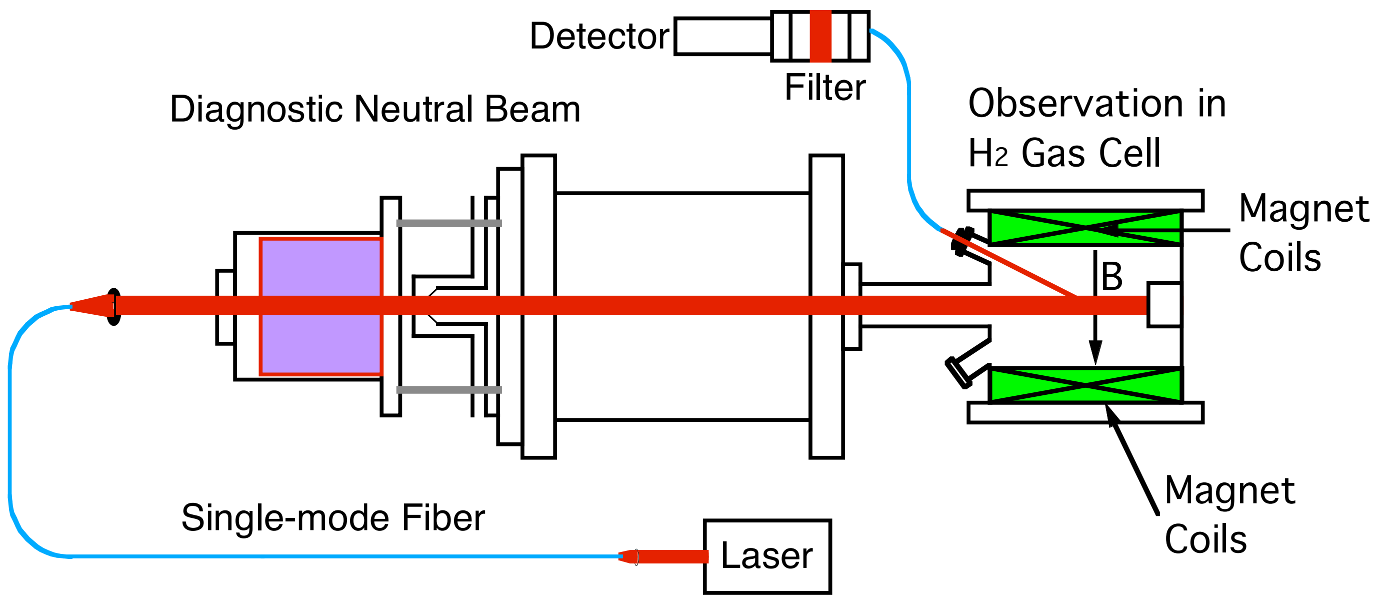
Diagnostic Neutral Beam





- RF source built in collaboration with LBNL
- Low noise HV power supply and sweep capability built in collaboration with PPPL
- Routine operation in development lab: 30–40kV, 40 mA (1.5 kW) 0.26° divergence, ~70% full-energy fraction, ~65% neutral fraction, ~1 cm diameter, CW operation

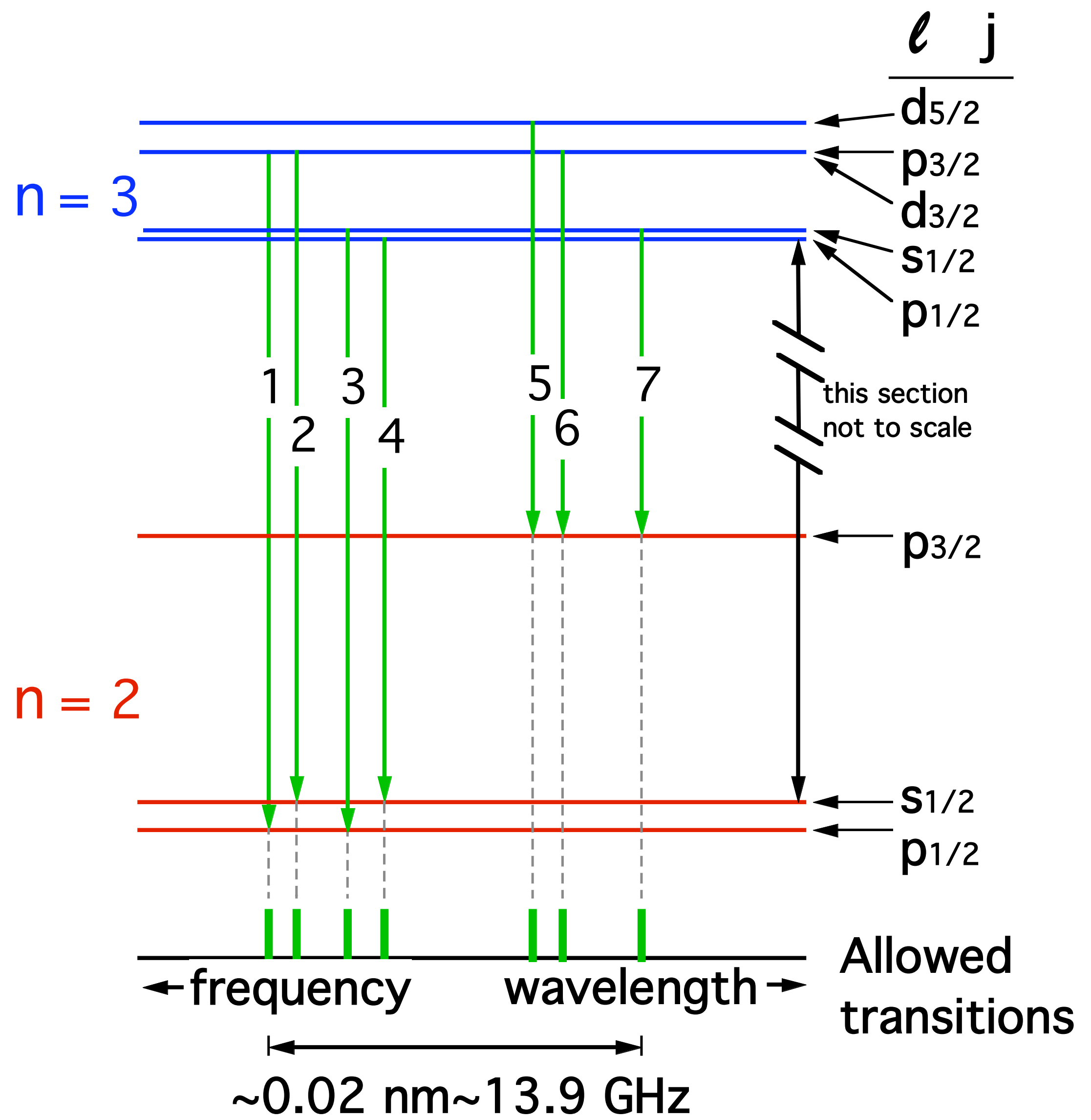
Initial Testing: Beam Into Gas at Low B



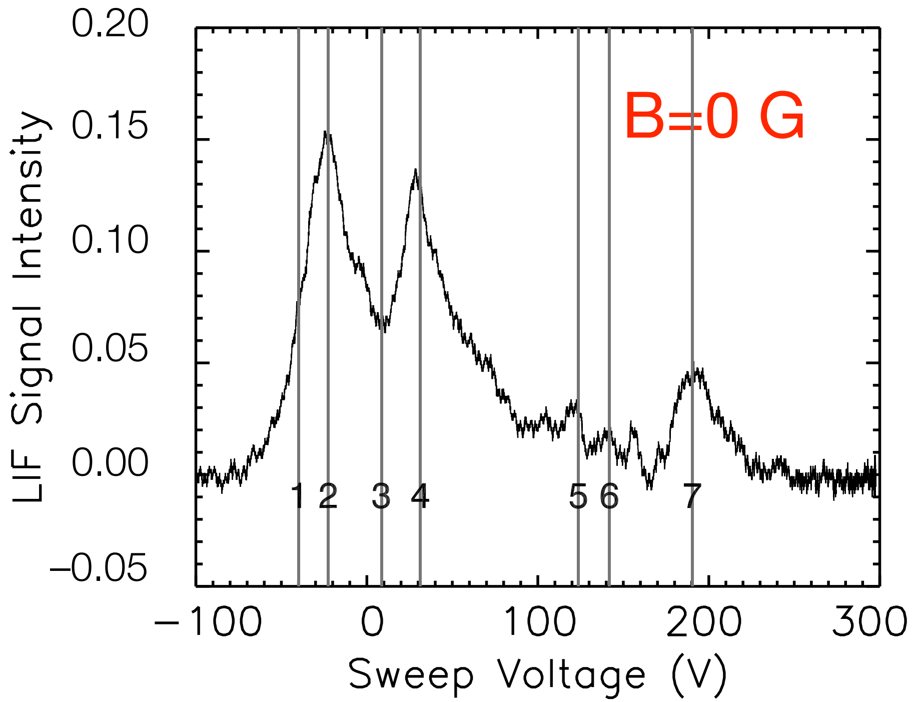
- Tunable ring dye laser (Coherent 899-21) near 650 nm, <1 MHz Linewidth, 300 mW, pumped by 514 nm argon ion laser
- Molecular hydrogen gas in present target chamber
- Magnetic field coils for up to 100 Gauss

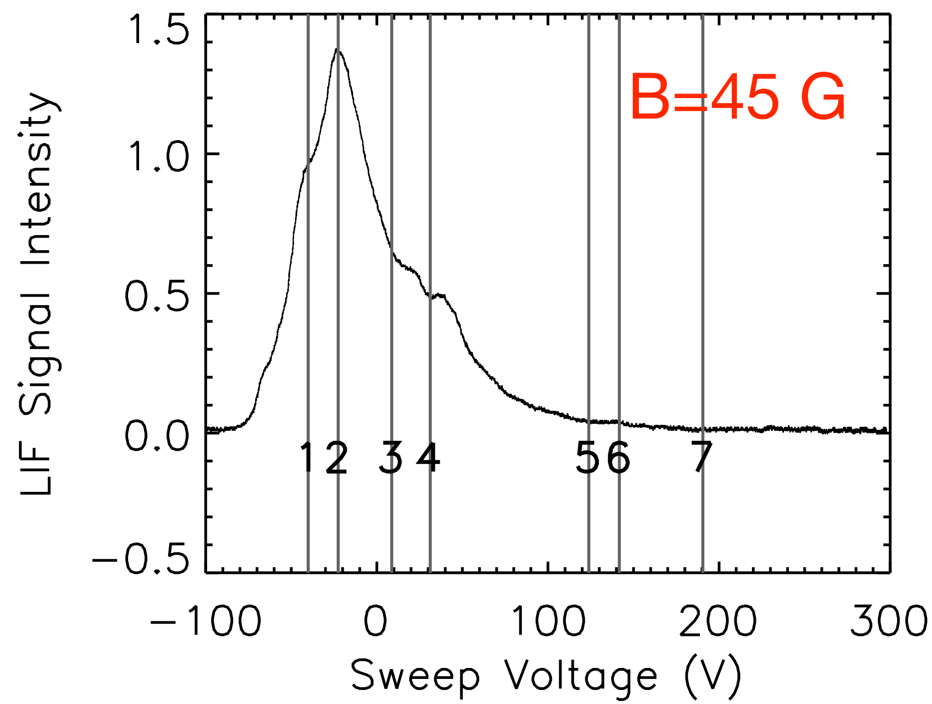
H-alpha Fine Structure

- Fine structure spectrum spans 0.02 nm at zero field
- Comparable to ~0.03 nm separation between Stark lines in NSTX at 0.4 T
- ℓ is orbital angular momentum quantum number, j is total angular momentum quantum number $\ell \pm 1$
- Seven allowed transitions: Shown in diagram



LIF Enhancement at Low Field



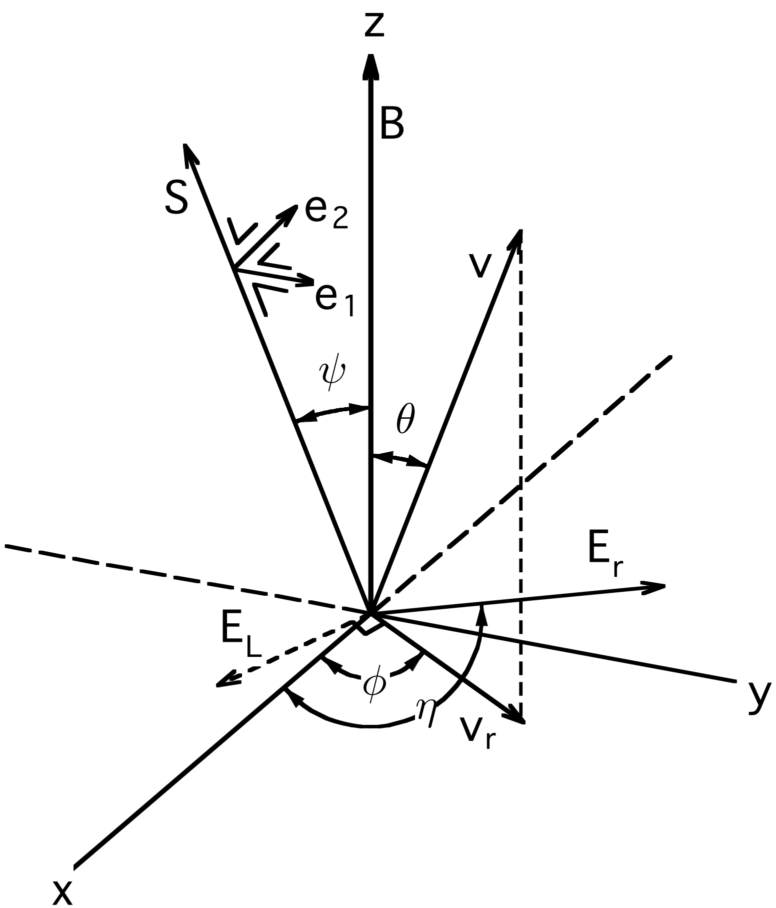


- Laser fixed, beam voltage swept across wavelength range of fine structure spectrum (Doppler shift varies with voltage - lower energy to right on plot)
- Peak signal increase nearly 10X (note change in scale)
- Motional Stark field causes levels to mix, allowed transitions change

Quantum Mechanics Calculation

Fully General Calculation

Fine Structure: Spin-Orbit Coupling, Relativistic Effects, Lamb Shift.
from experiments. $E_0 \ldots E_n$



Linear Zeeman Effect:

$$\mathbb{H}_{Zn} = (g_l \mathbb{L}_z + g_s \mathbb{S}_z)\mu_B B_z$$

Motional Stark Effect:

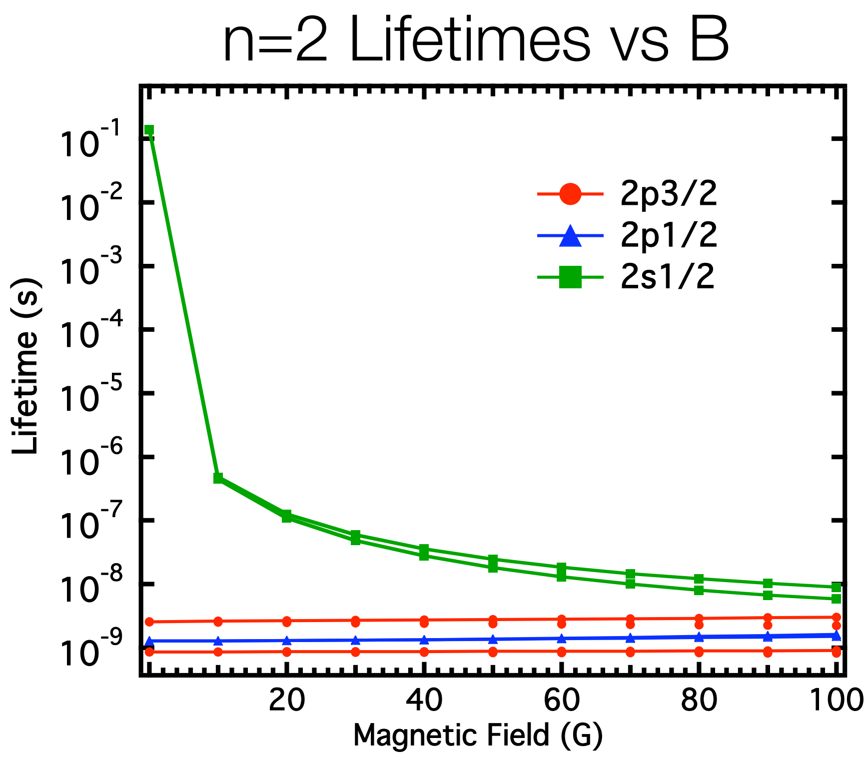
$$\vec{E}_L = \vec{v} \times \vec{B}$$

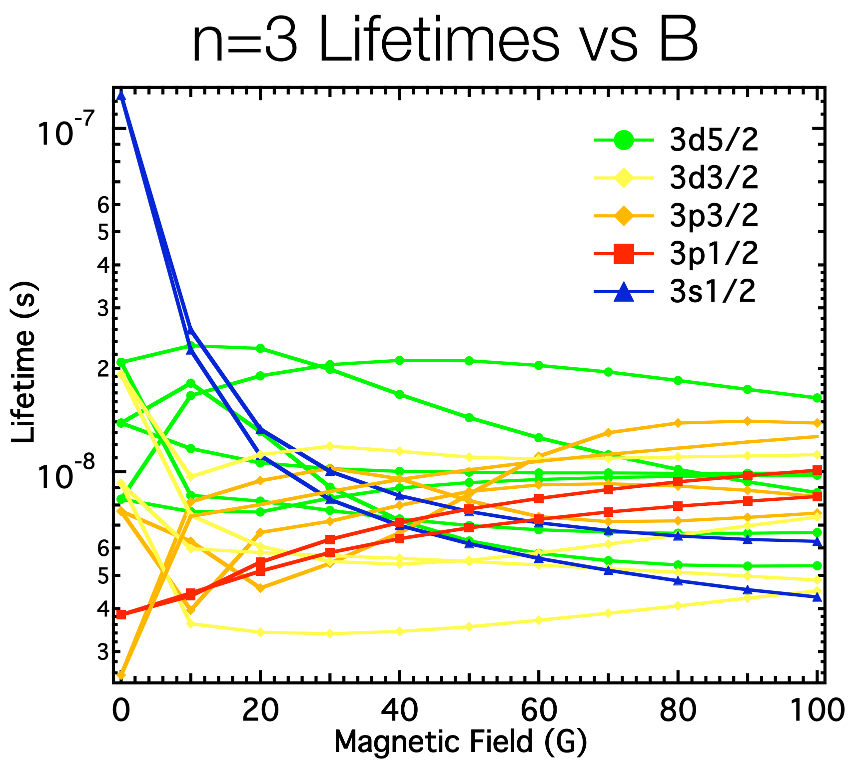
$$\mathbb{H}_L = eBv_r(\vec{x}sin\phi - \vec{y}cos\phi)$$

Stark Effect of Radial Electric Field:

$$\mathbb{H}_{Er} = e\vec{E}_r(\vec{x}cos\eta + \vec{y}sin\eta)$$

State Mixing: Results from QM model

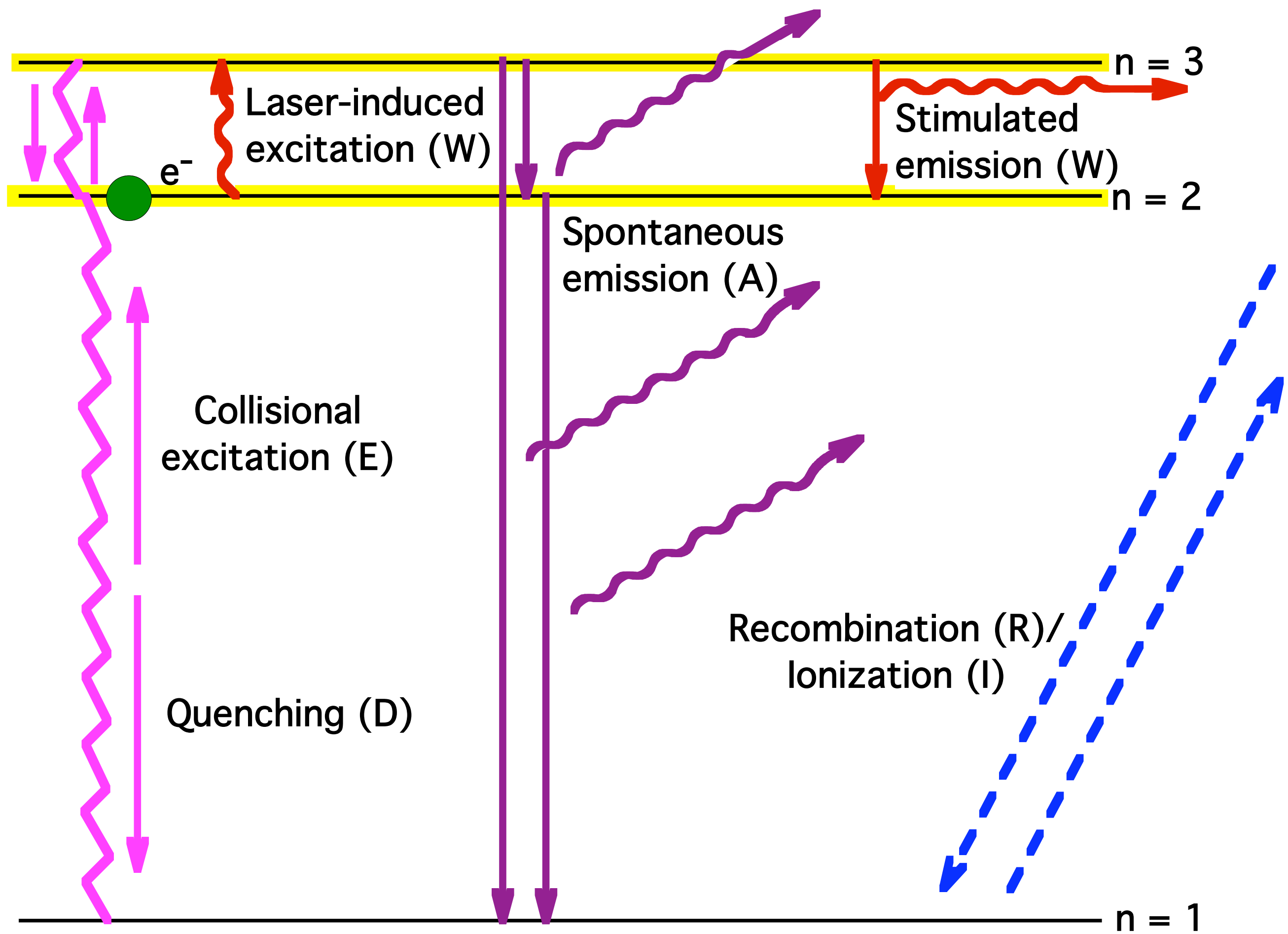




- 2s is metastable in absence of field, lifetime changes rapidly over field range
- In zero-field case, long 2s lifetime gives large population
- As field increases, new transitions allowed - signal increases
- Higher field removes excess 2s population, signal in gas reduced

Collisional Radiative Model

$$v_b\frac{dn_i}{dx} = -\left[I_i+\sum_{j>i}E_{ij}+\sum_{j<i}D_{ij}+\sum_{j<i}A_{ij}+W_{ij}\right]n_i+\left[\sum_{j<i}E_{ji}+\sum_{j>i}D_{ji}+\sum_{j>i}A_{ji}+W_{ji}\right]n_j+R_i n_{ions}$$



Unique aspects of CRISP CRM

Includes all fine-structure sublevels: 18 states in n=3, 8 in n=2, 2 in n=1

Complete QM calculation of radiative transition parameters and their dependence on background E and B fields

Transition Probability:

$$A_{nn'}(B) = \frac{4e^2\omega^3}{3\hbar c^3} \mid \vec{r}_{nn'}(B) \mid^2$$

Lifetime:

$$\tau_i(B) = \frac{1}{\sum_k A_{ik}(B)}$$

Laser Pumping Term:

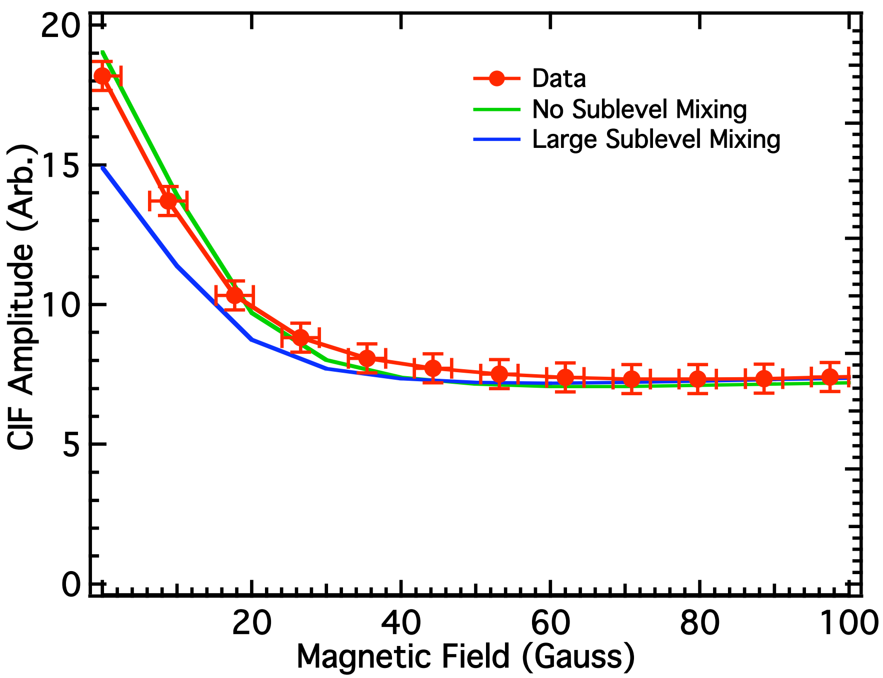
$$W(B) = \frac{2\pi^2 r_o c f_{lu}(B) I(\omega_{ul})}{\hbar\omega_{ul}}$$

Oscillator Strength:

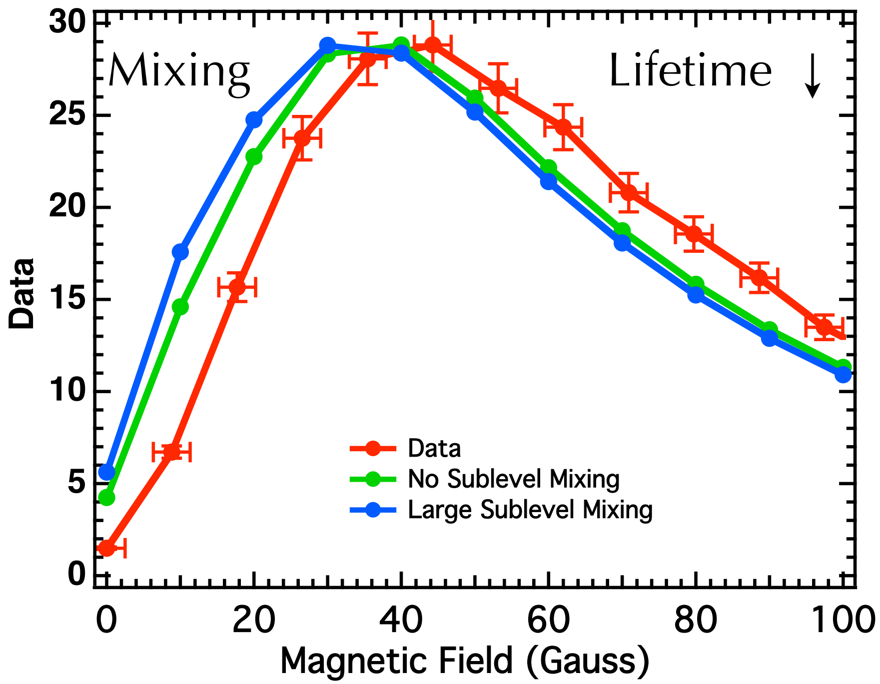
$$f y_{nn'}(B) = \frac{2m\omega_{nn'}}{\hbar} \mid y_{nn'} \mid^2$$

Model Agreement with Data

Variation of collisionally-induced fluorescence (CIF) signal with magnetic field



Variation of ratio of LIF/CIF signal with magnetic field

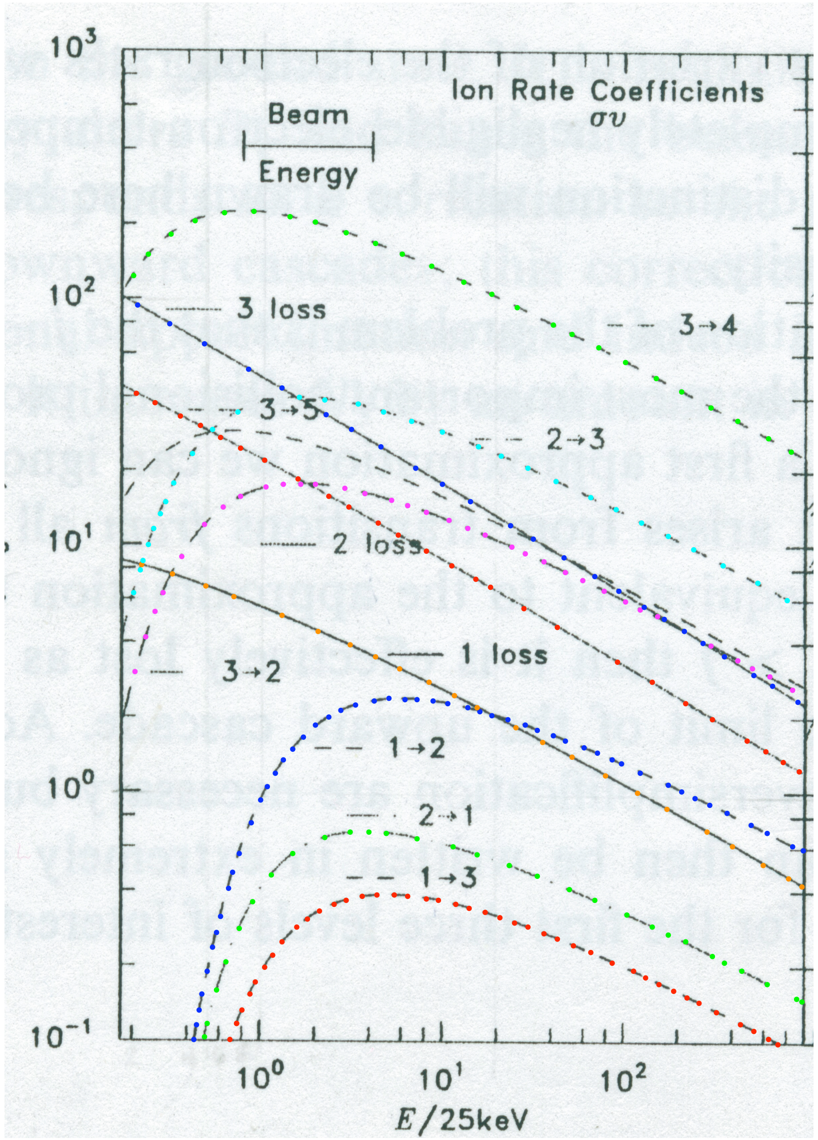


- CRISP model shows good agreement with Collisionally-Induced Fluorescence (CIF) and LIF behavior
- CIF signal decreases as 3s loses population due to lifetime decrease
- LIF first rises with applied field, as new transitions are allowed, then drops as 2s population lost to ground.

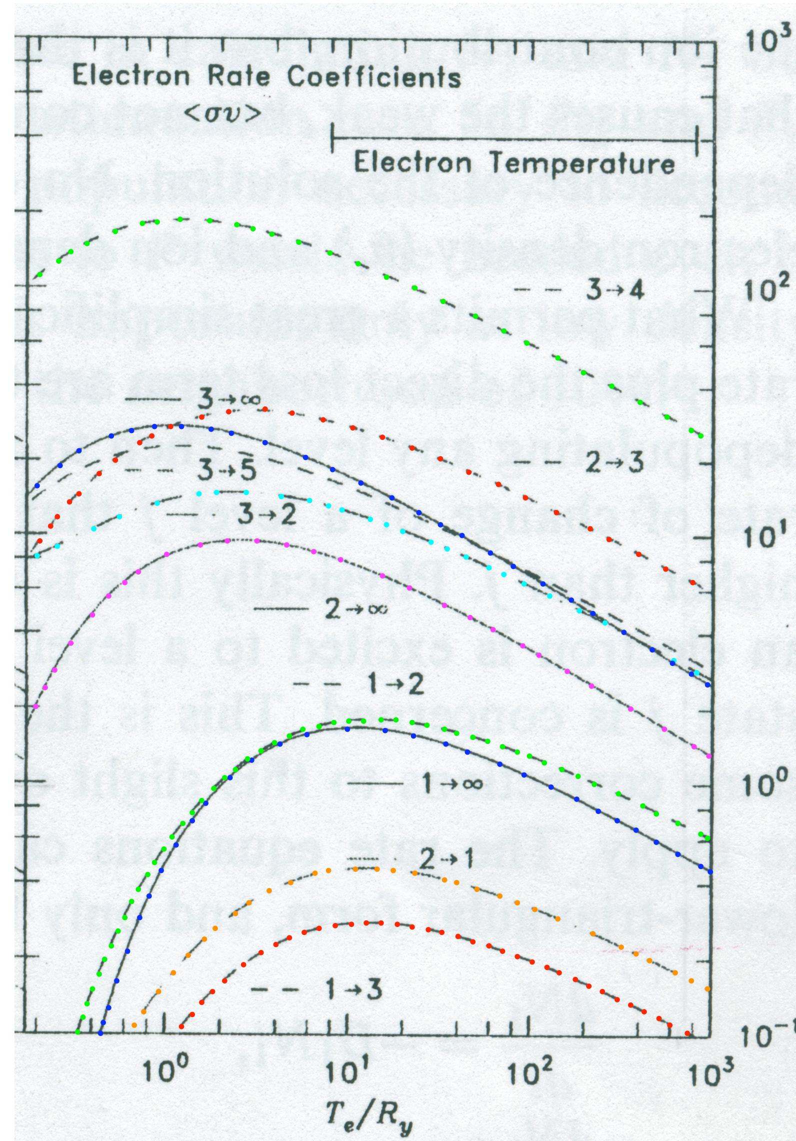
Challenge: Signal Level

- Increase n=2 population available for excitation
  - Ensure full beam neutralization
  - Reduce re-ionization in beamline
  - Provide greater collisional excitation from n=1
- Improve linewidth match of beam and laser
  - Reduce beam linewidth
  - Increase laser linewidth

Collisional Excitation in Plasma



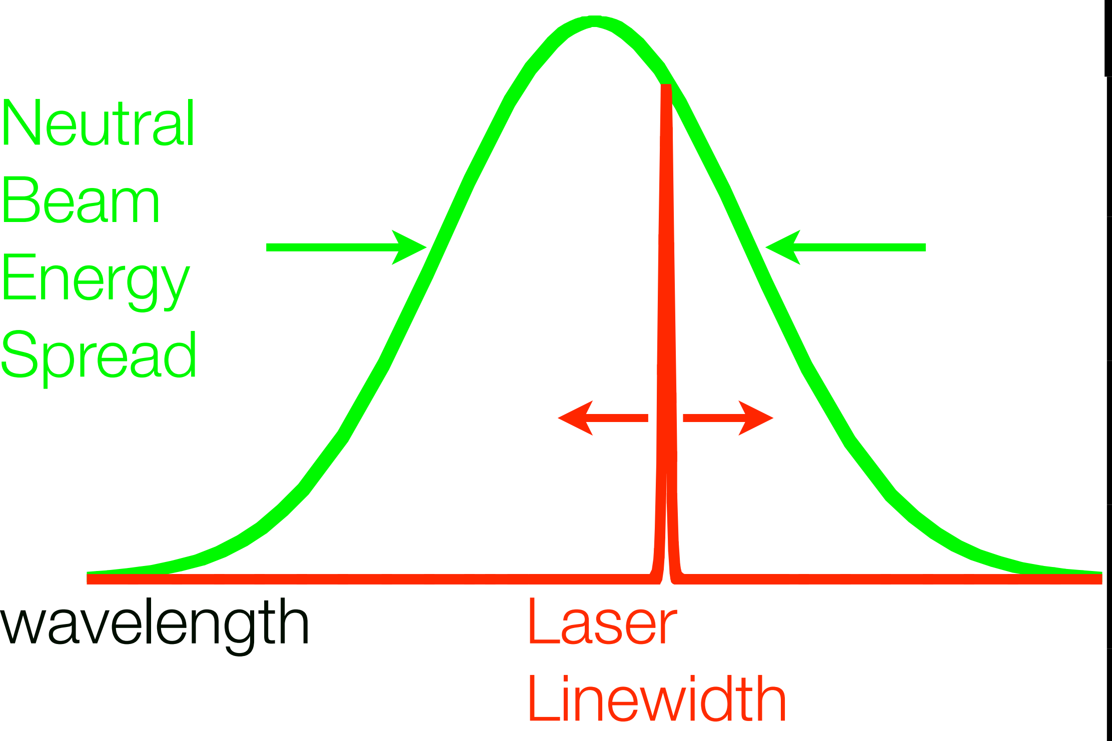
Model with hydrogen plasma background - rates from Hutchinson '02.



CRM in Plasma

	Neutral Gas	Helicon Plasma*	NSTX Plasma
n2/n1	2s~10^{-3} 2p~5×10^{-5}	8×10^{-4}	3×10^{-3}
n3/n1	5×10^{-5}	3.5×10^{-4}	1×10^{-3}

Linewidth Match of Beam and Laser

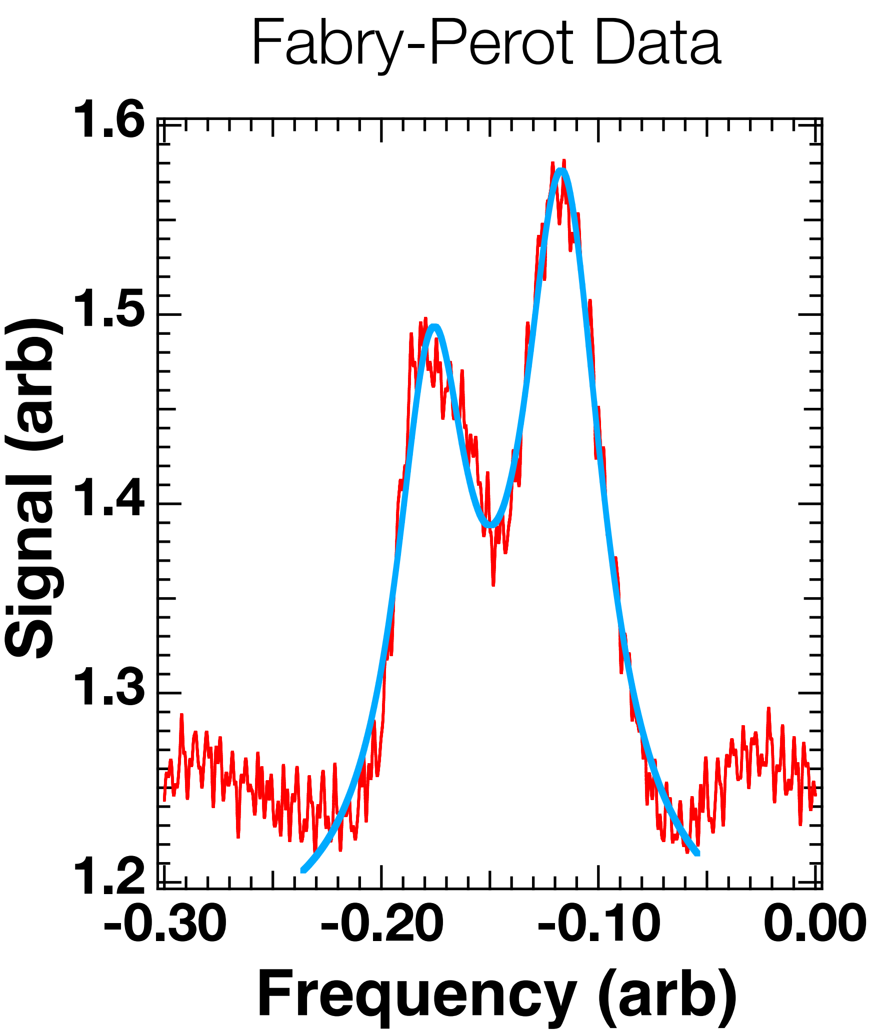


Parameter	Linewidth
Natural linewidth	~100 MHz
Laser linewidth	~100 MHz
RF on accel. grid	~2 V = ~120 MHz
RF AM line noise	~2 V = ~120 MHz
Line ripple on HV	~1 V = ~60 MHz
Energy straggling	~50 V = ~3 GHz
Low p broadening	~50 V = ~3 GHz

Need to maximize overlap of laser and neutral beam energy distribution

Neutral Beam Energy Spread

Recent measurements of neutral beam emission with Fabry-Perot show fine structure of collisionally-induced fluorescence
FWHM ~6 GHz (~100 V)



New Laser Development

Required Laser Characteristics:

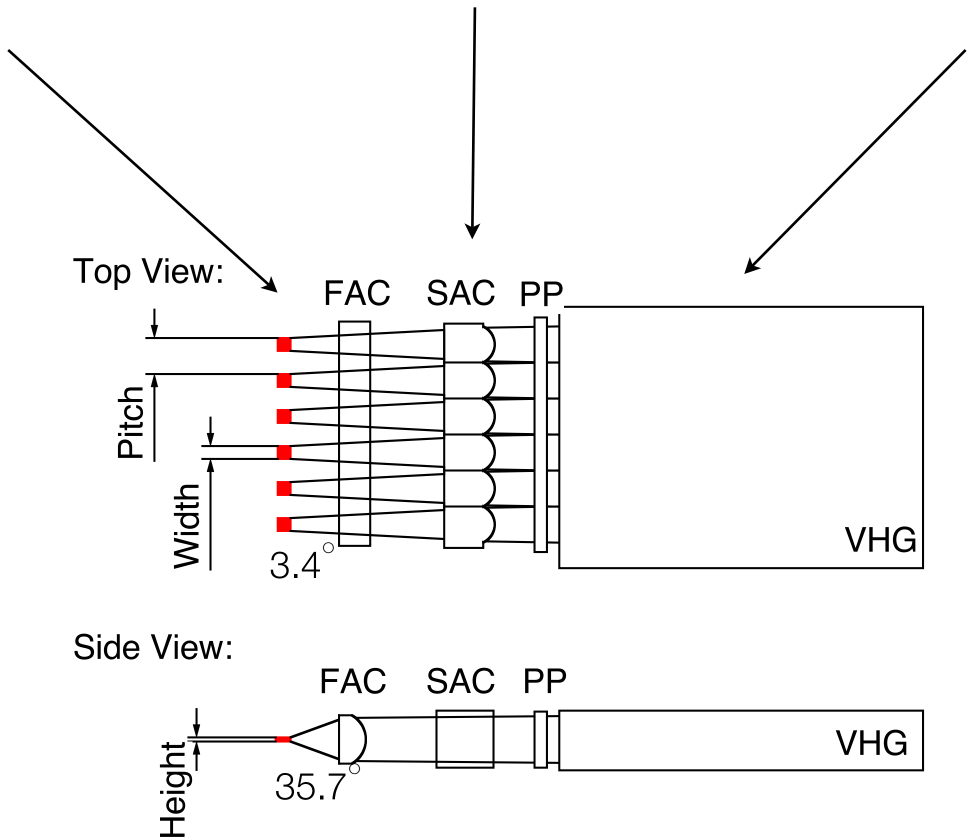
- Tunable near 651 nm
- Linewidth to match neutral beam energy spread (~6 GHz)
- Power per unit linewidth comparable to dye laser experiments: 1.5 W/GHz
- Good beam quality to match 1 cm neutral beam diameter and 0.26° beam divergence
- Reliable operation
- Ease of use (compared to dye system)

Diode Laser Array with VHG Feedback

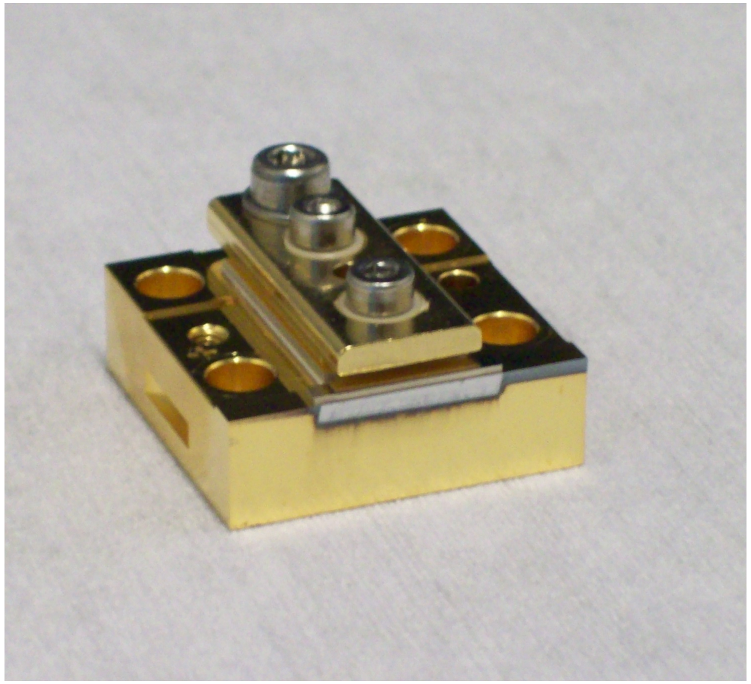
Multiple emitter diode array:
651 nm
10+ W
2-3 nm linewidth

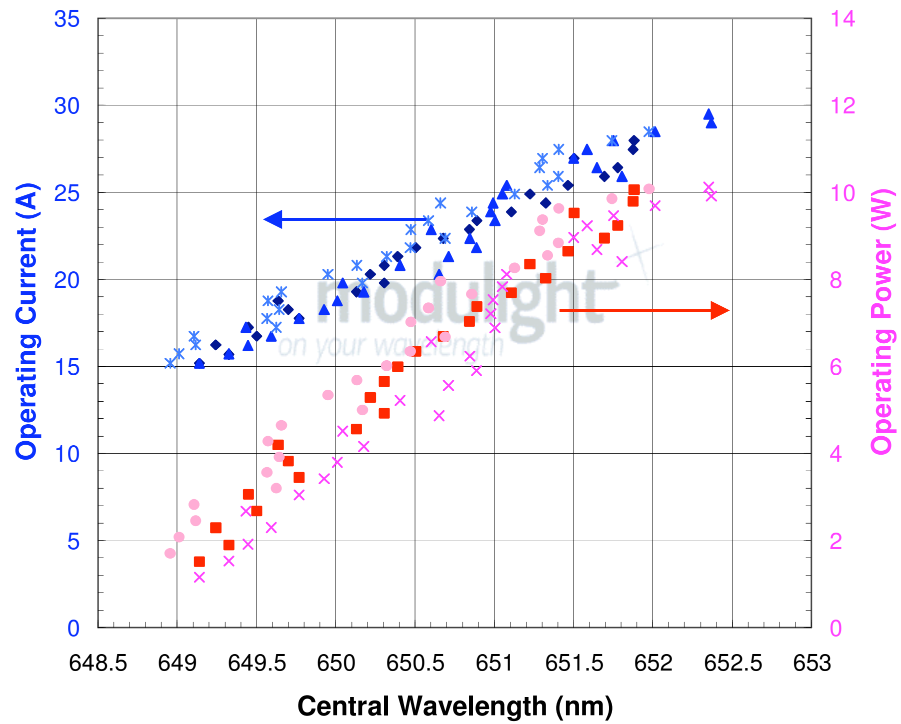
Precision collimation optics

Volume holographic grating: 5-7 GHz linewidth, temperature tunable



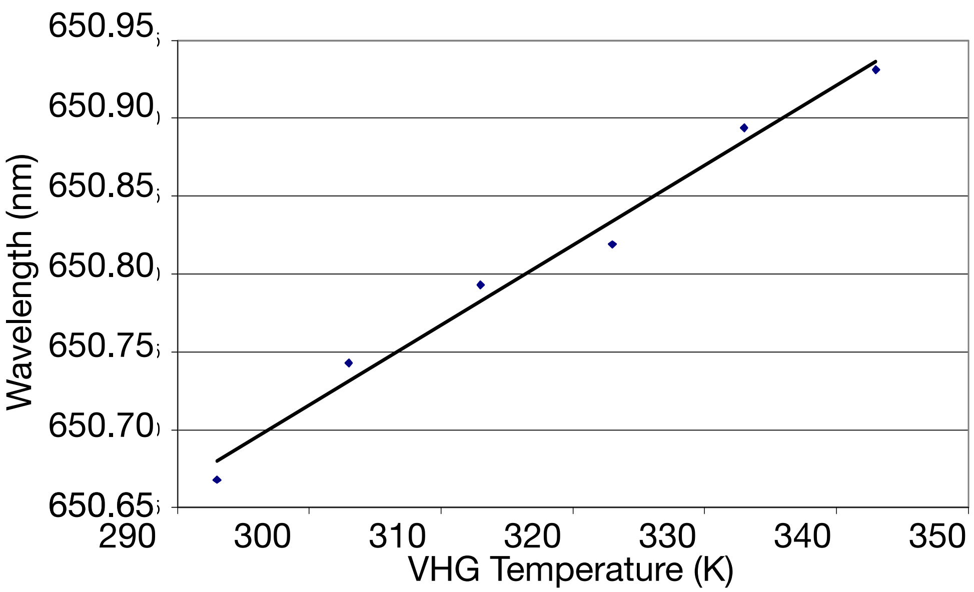
651 nm Diode Array

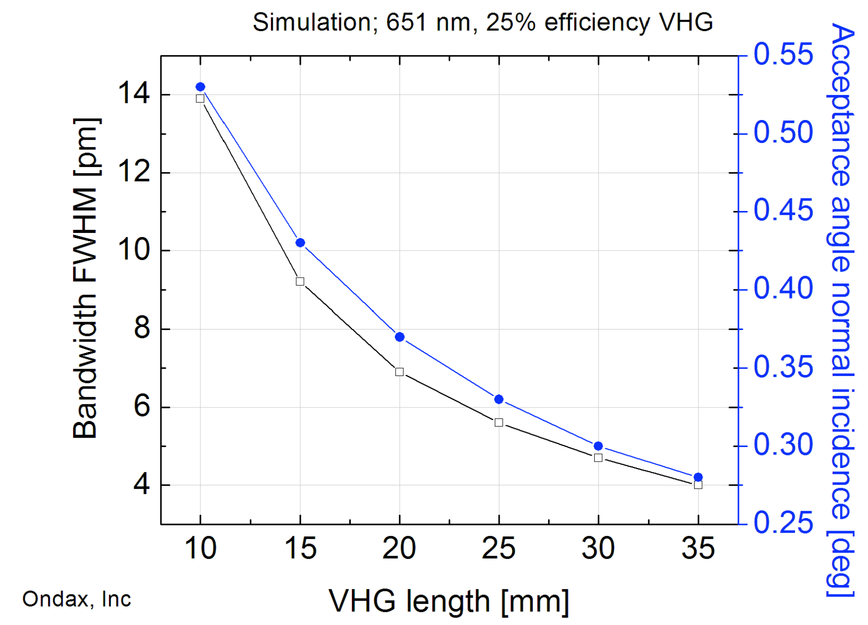




- Custom wafer growth by Modulight Inc
- 10 W, 652 nm @ 20˚C - operate at 15˚C for 651 nm
- 19 emitter array, 150 micron emitter width

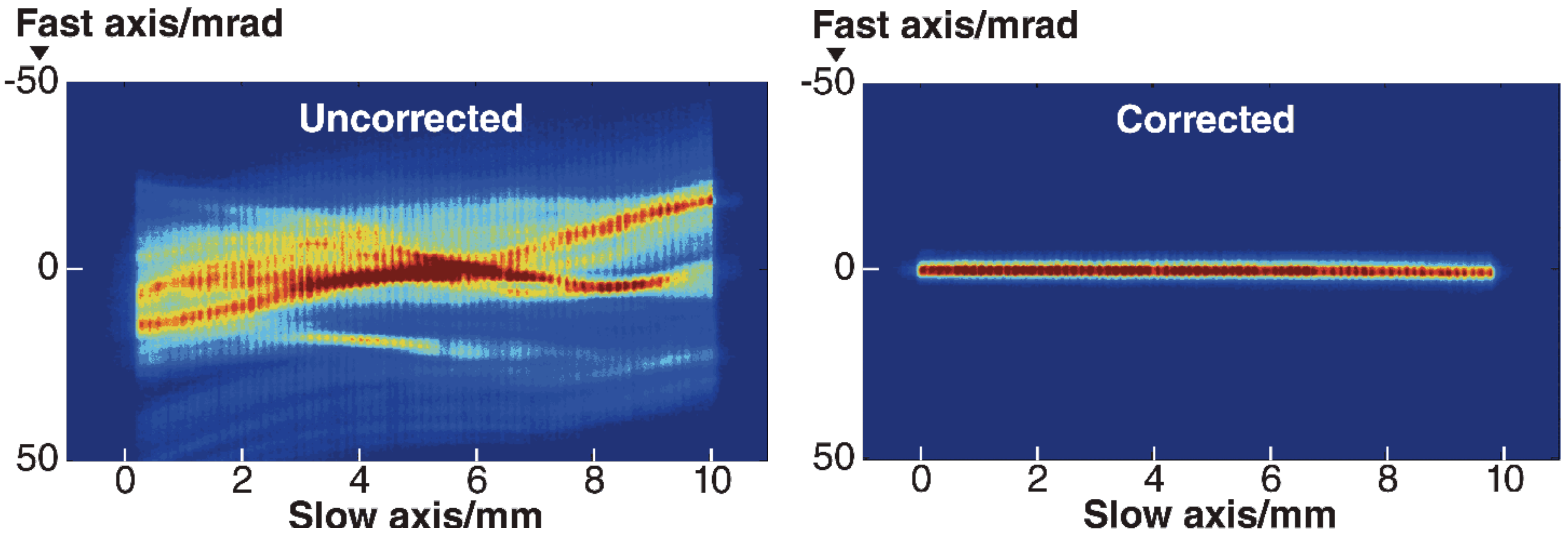
Volume Holographic Grating





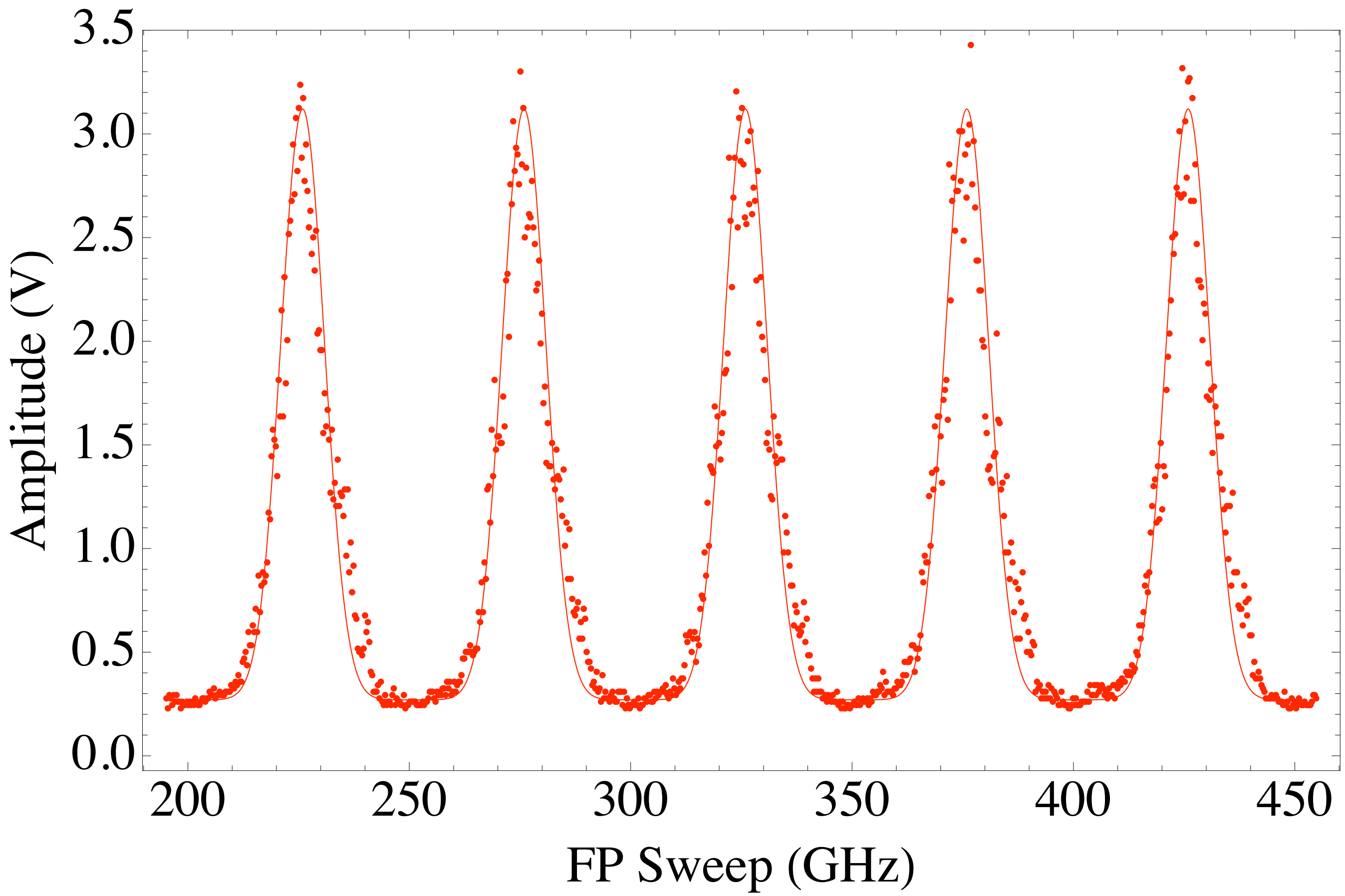
- VHG created with 3D image of interference pattern between coherent optical fields in photorefractive glass
- Allows selection of narrow wavelength range - $\Delta\lambda$ depends on length
- Angular acceptance also narrow

Precision Collimation Optics



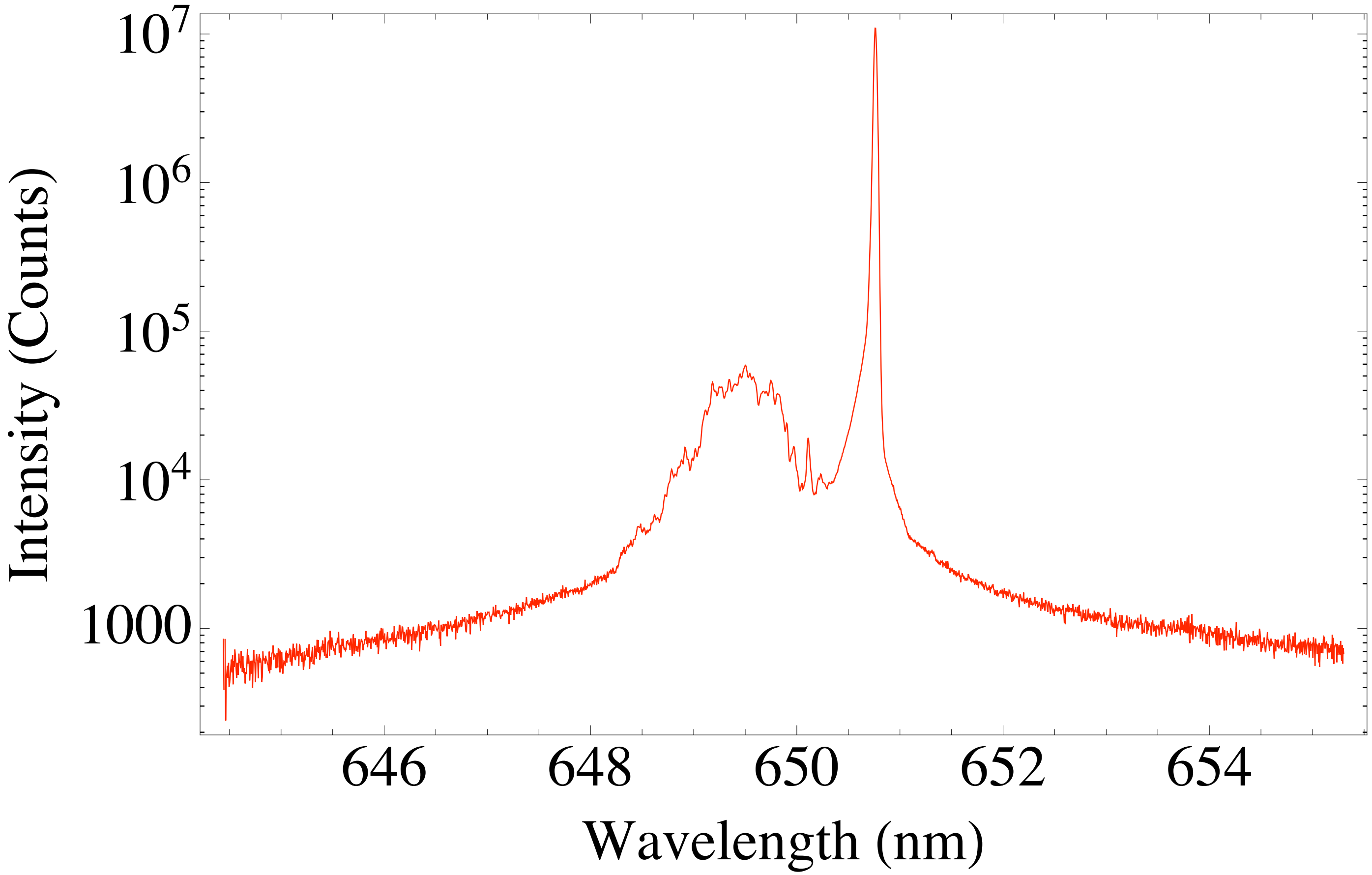
- Theoretical limit throughput gives only 20% of laser light accepted to grating
- Can't afford to lose light to smile, pointing errors, other misalignment
- Procure custom phaseplate tailored to individual diode array in desired operating conditions
- Technology developed at Heriot-Watt University, available from Power Photonic

Laser Fabry-Perot Data



- Data is shown with 11.6 GHz Gaussian overlay

Laser Power in Narrow Line

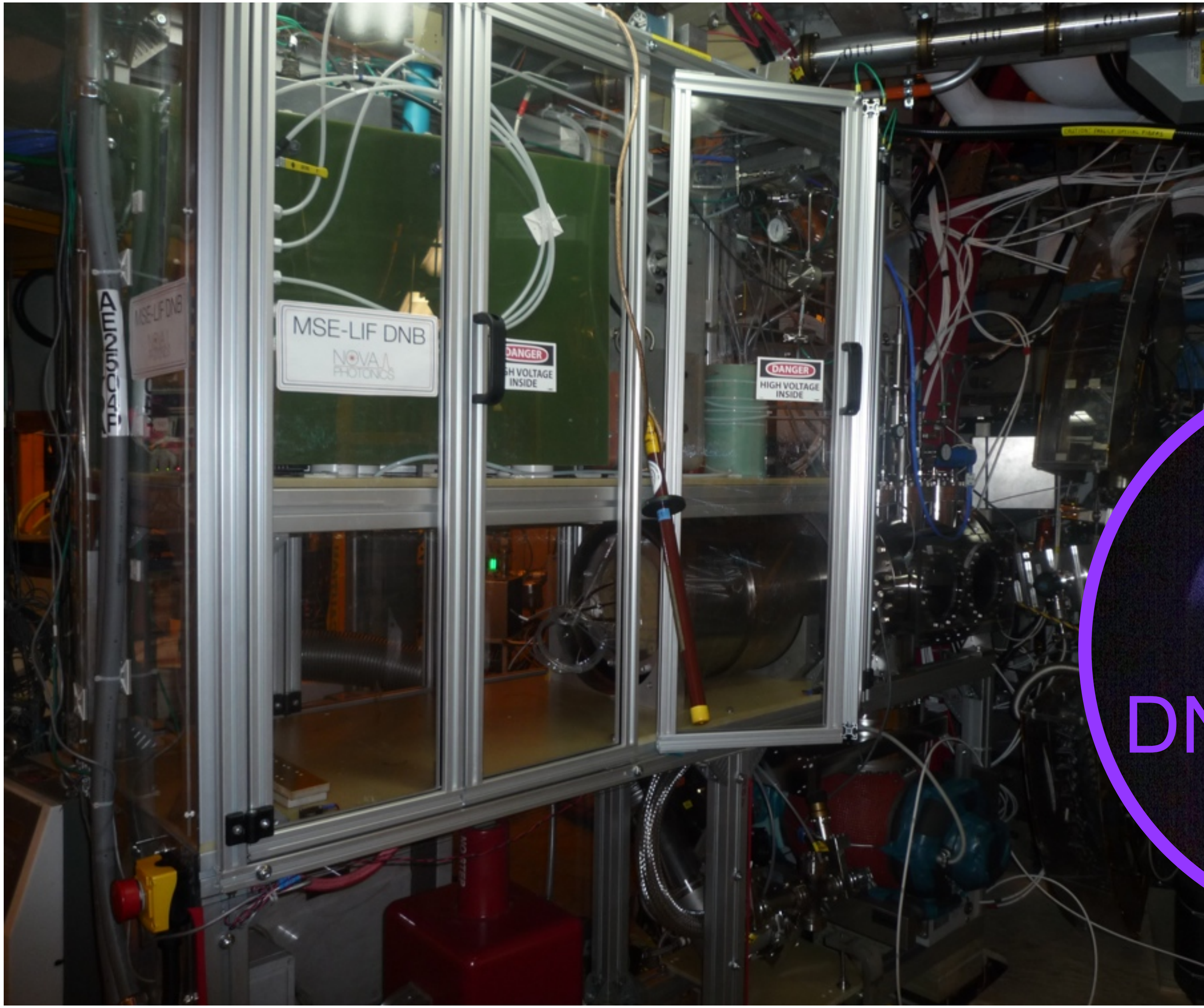


- Here, 87% of total power is in feedback mode

Performance on NSTX

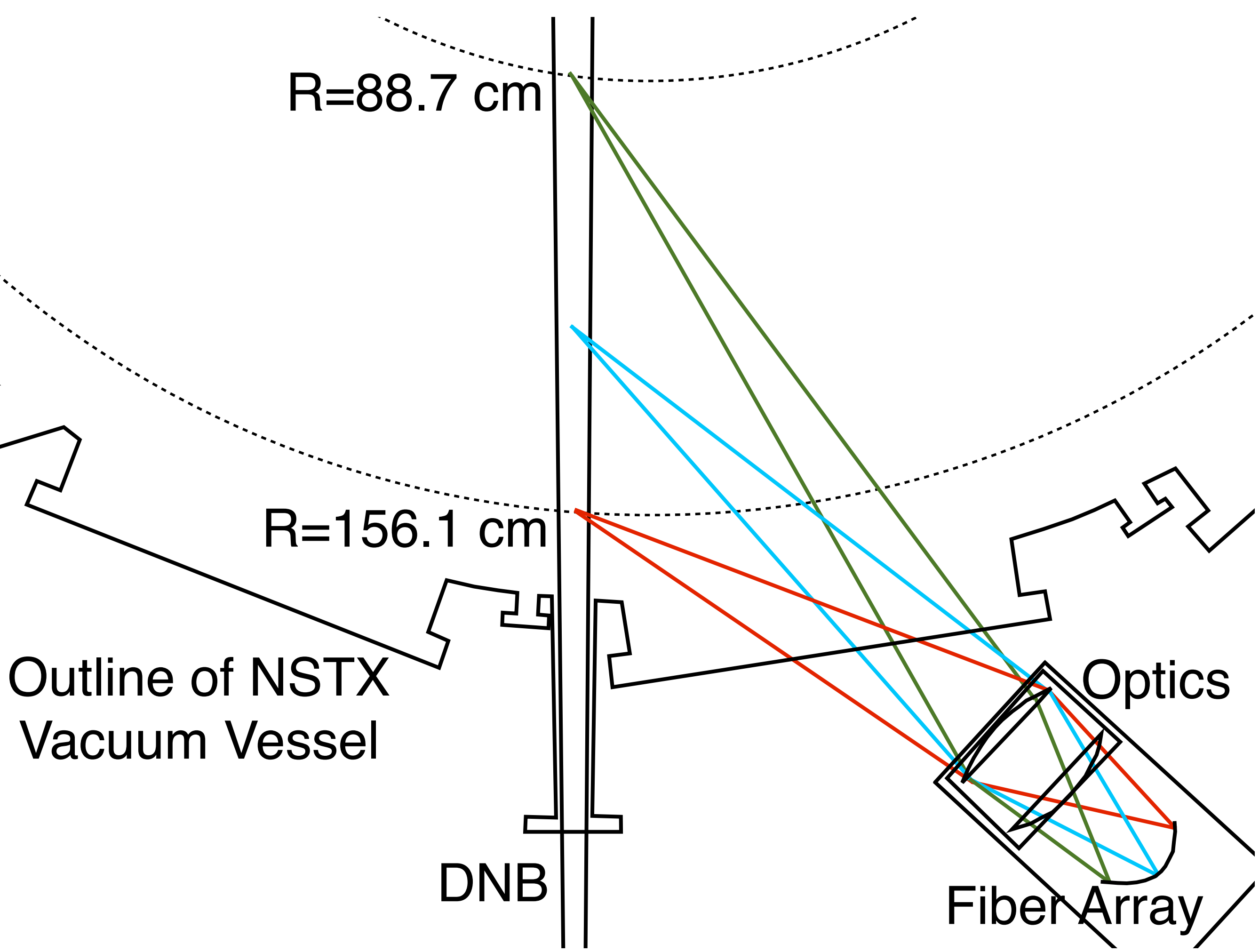
- MSE-CIF data from NSTX, MSE-LIF laboratory performance and collisional-radiative model used together to predict signal levels for NSTX - expect 10x higher photon count rates (at detectors) than CIF system. Time resolution of better than 10 ms expected.
- Magnitude of B resolved to few Gauss range, Pitch angle at least comparable to CIF system ~0.3 degrees.
- Spatial resolution improved over initial calculation - was limited by view angle with respect to beam, and beam size. Laser designed with vertical elongation and horizontal compression to reduce overlap. Fundamental limit due to emission decay time close to 1 cm.

NSTX Installation



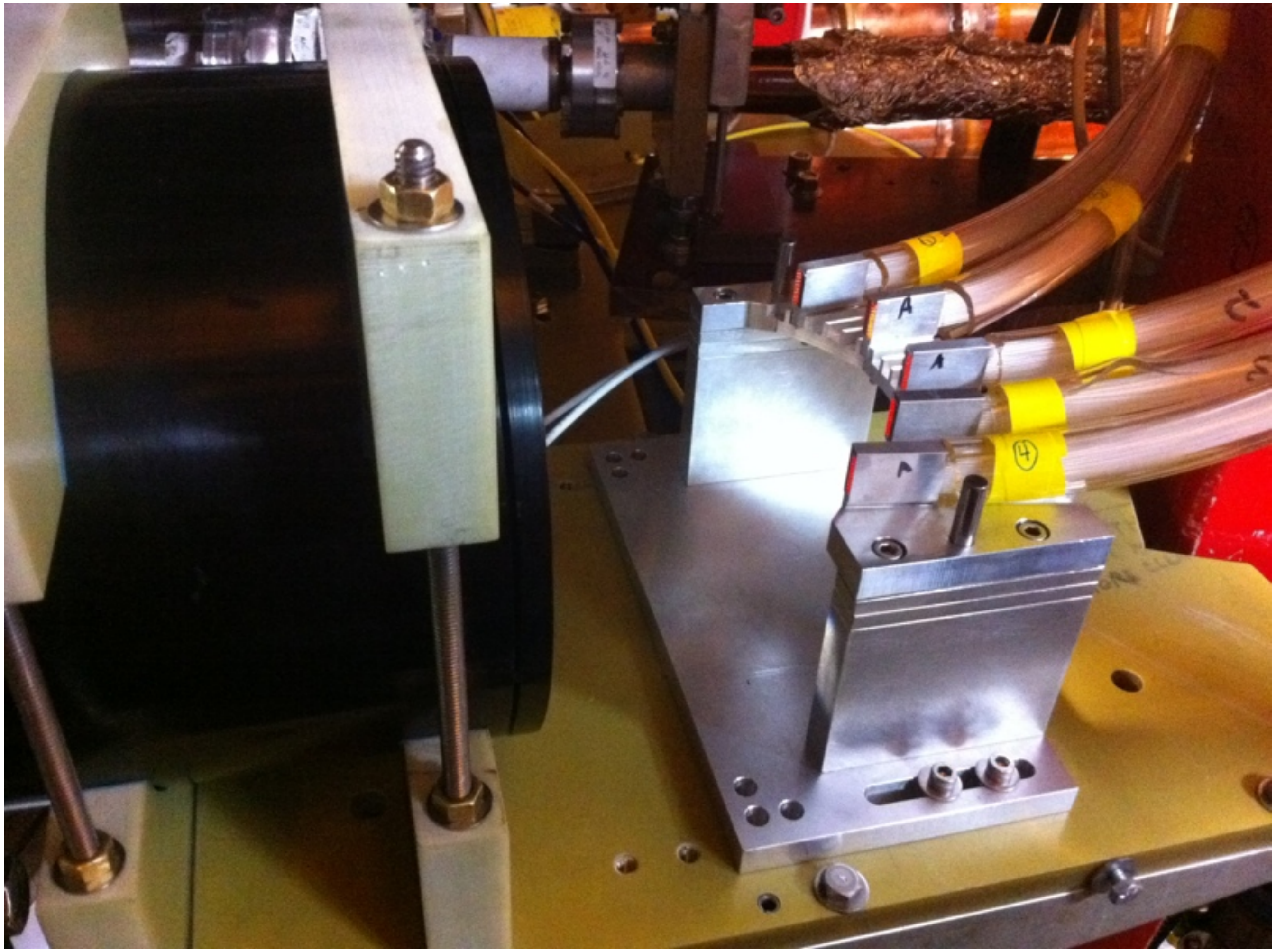
MSE-LIF installed on NSTX for 2011 run.

View Layout on NSTX



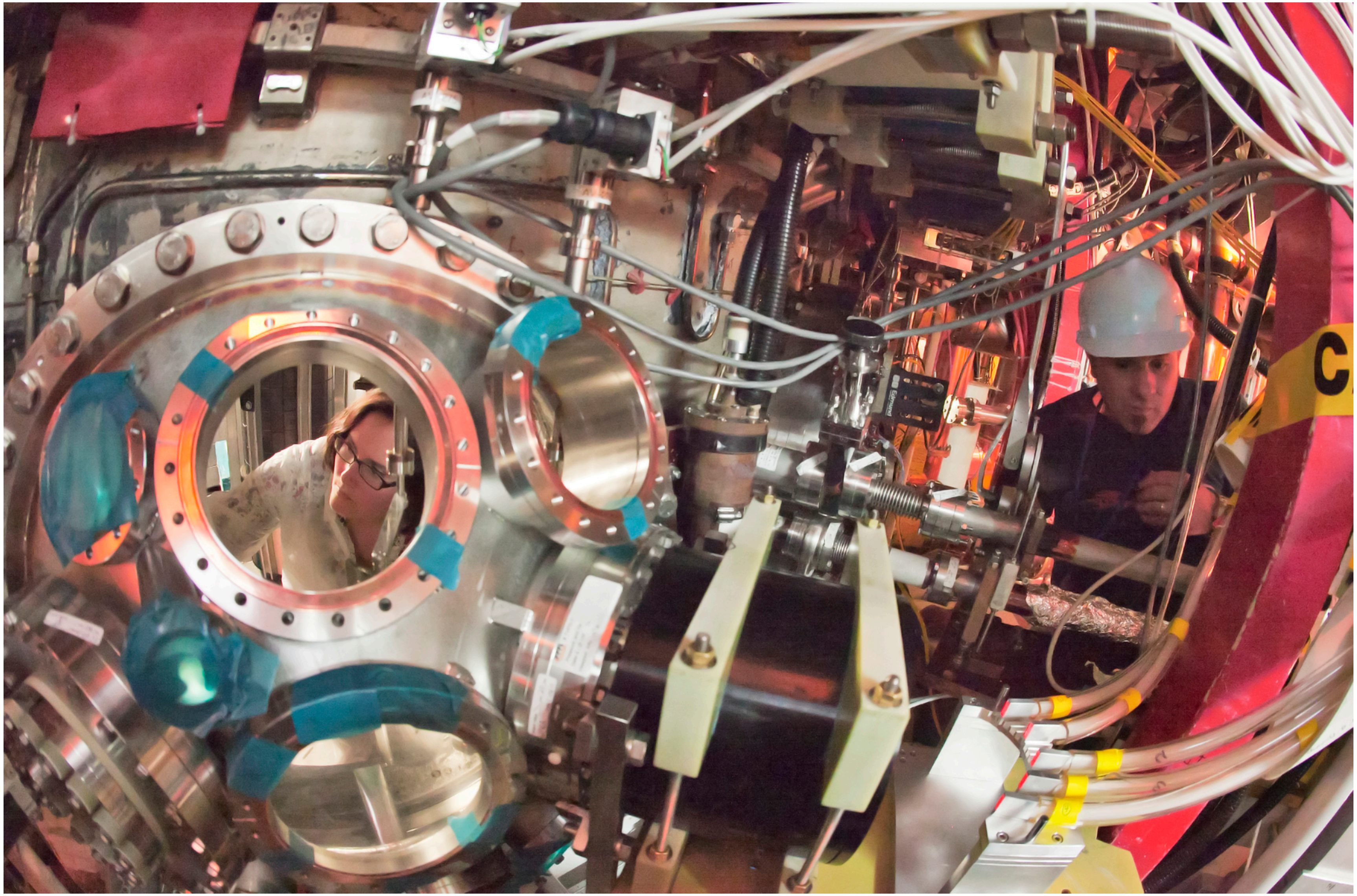
- 38 radial channels
- Radial range similar to that of MSE-CIF system
- Near-radial injection angle minimizes sensitivity to radial electric field on pitch angle measurement

Fiber Bundles and Collection Optics

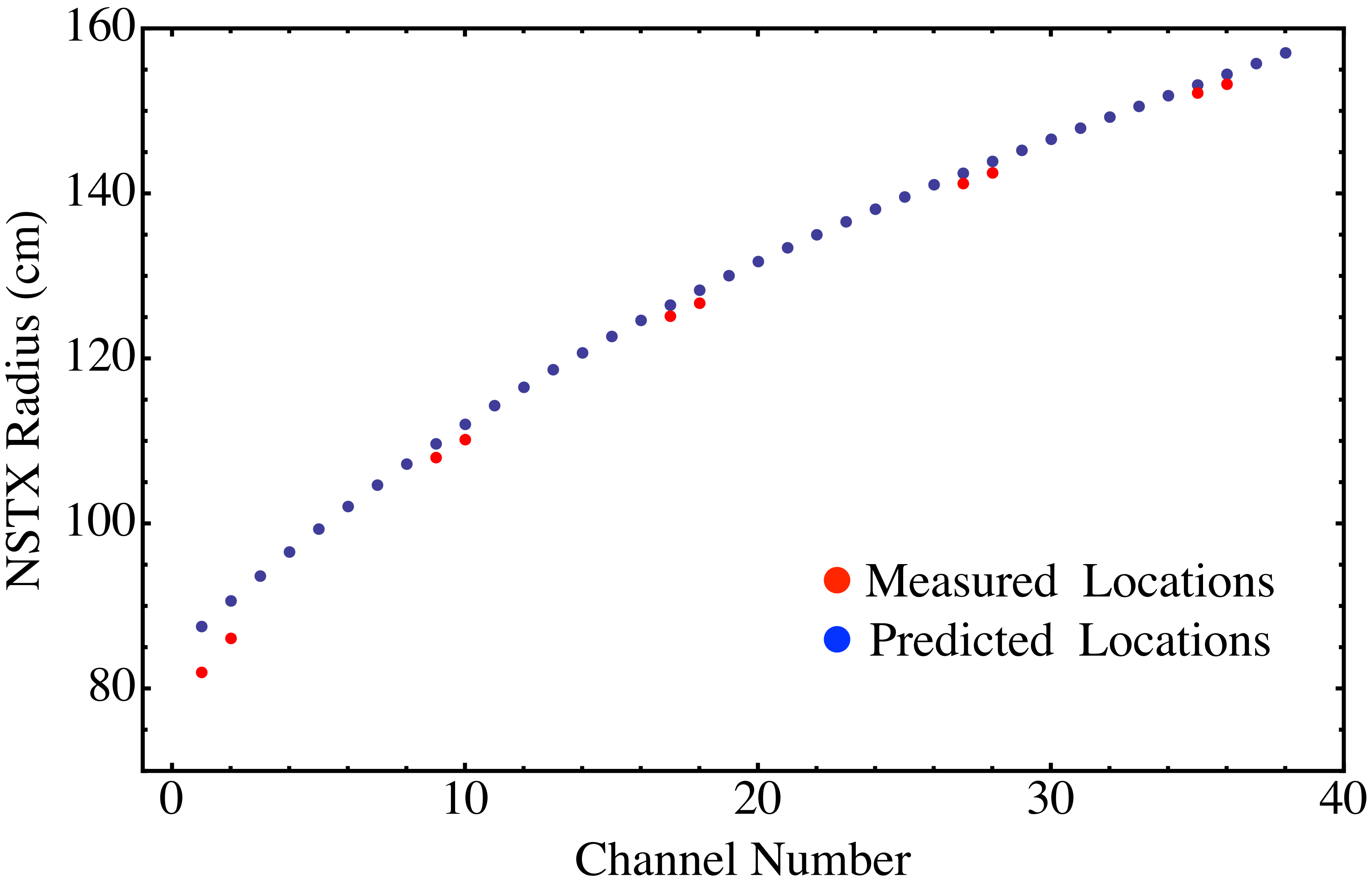


10 radial channels (in 5 fiber bundles) installed on NSTX, shown backlit. Additional 14 channels when NSTX-U starts in FY15.

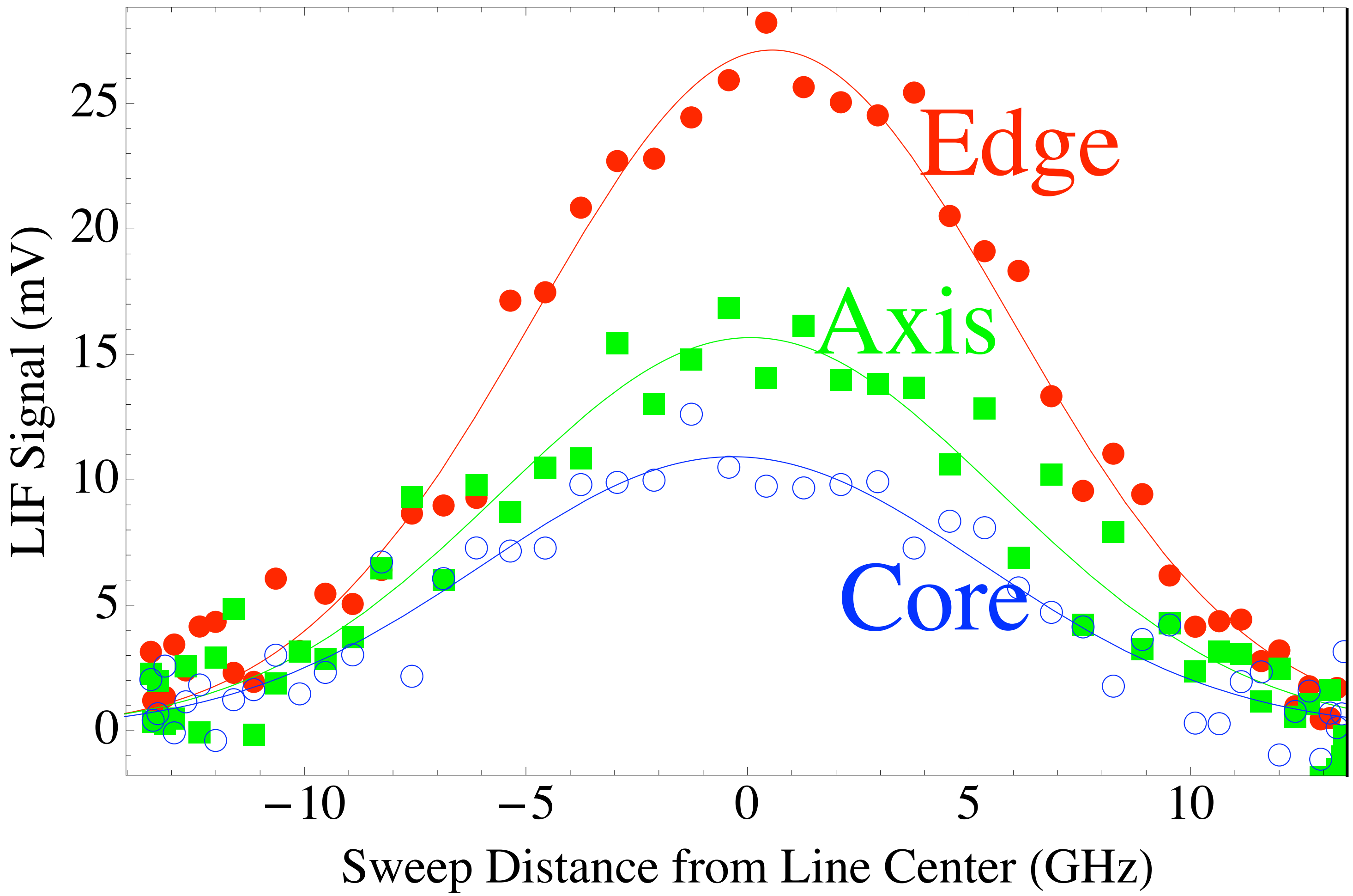
In-Vessel Calibration



Channel Locations in NSTX

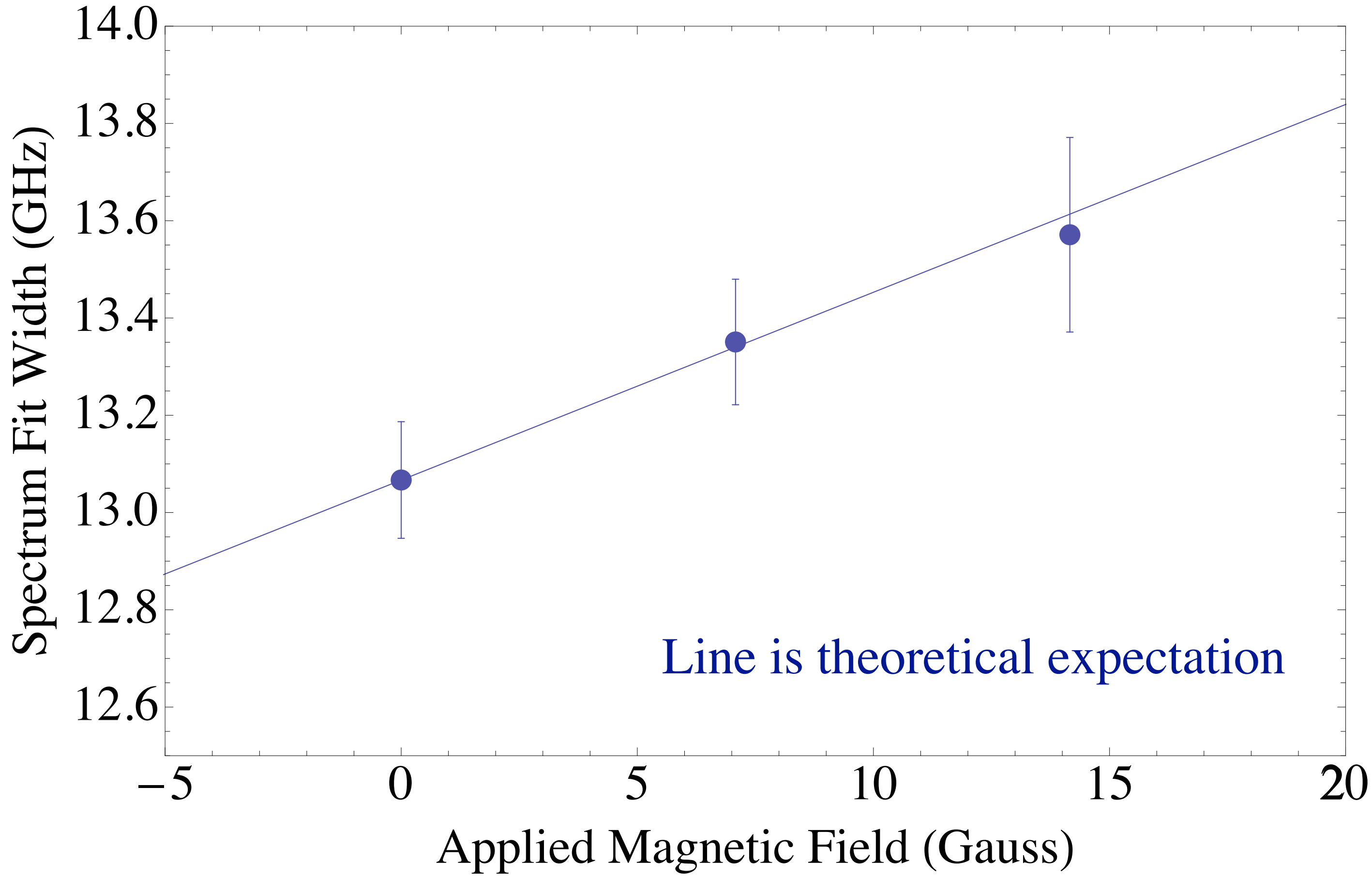


MSE-LIF Data in Gas-Filled NSTX



- Fully remote operation from NSTX control room
- Beam voltage swept over fixed laser wavelength

Magnetic Field Scan in Gas-filled NSTX



Summary

- Experiments and modeling done to establish foundation of understanding for Motional Stark effect with laser-induced fluorescence (MSE-LIF) measurement
- Laser development complete
- System installed on NSTX for 2011 run
- Coil failure prevented plasma data. Successful measurements made in gas-filled NSTX torus

Acknowledgments:

US DOE OFES Grant DE-FG02-01ER54616
PPPL: B. Stratton, D. Johnson, L. Grisham, S. Raftopoulos, J. Taylor & many more.
LBNL Group: K. N. Leung, S. Hahto, S. Wilde