The Motional Stark Effect With Laser-induced Fluorescence Diagnostic

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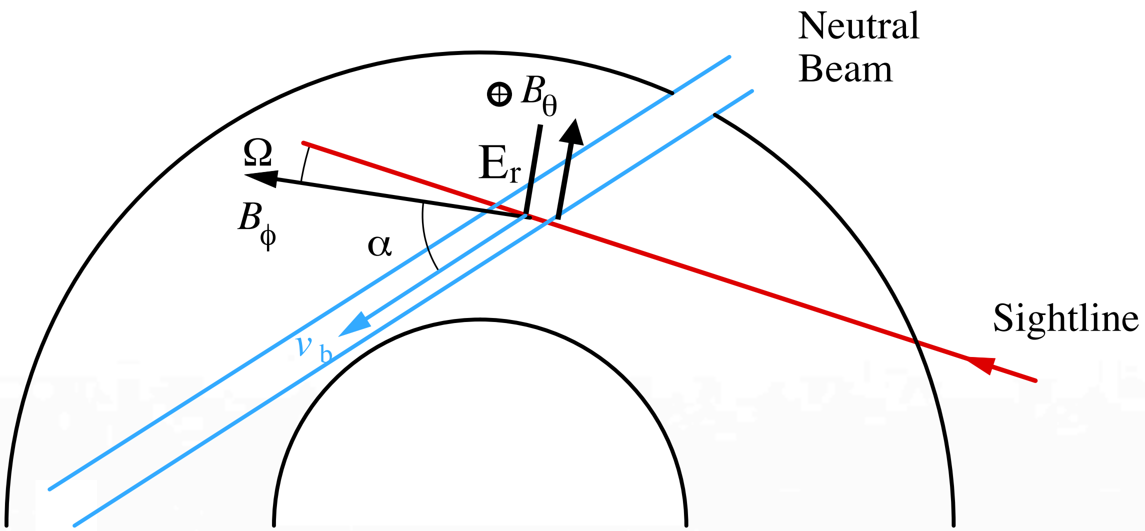
APS-DPP 52nd Annual Meeting
November 8, 2010
Chicago, Illinois

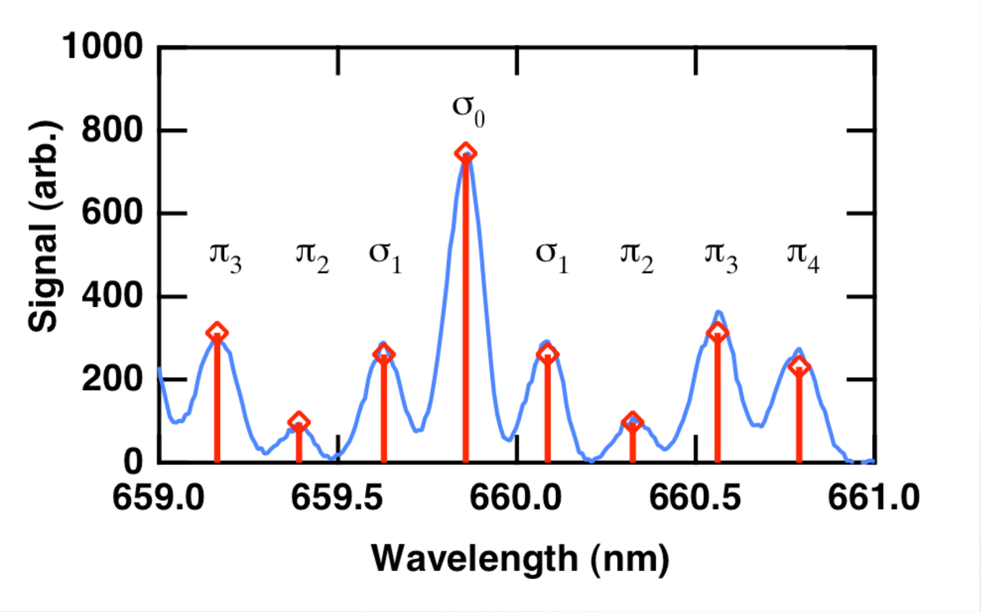
Overview

- 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
- Installation on National Spherical Torus Experiment (NSTX)
- MSE on ITER

Motional Stark Effect Diagnostic: Fundamentals and Addition of Laser-Induced Fluorescence

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 to 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

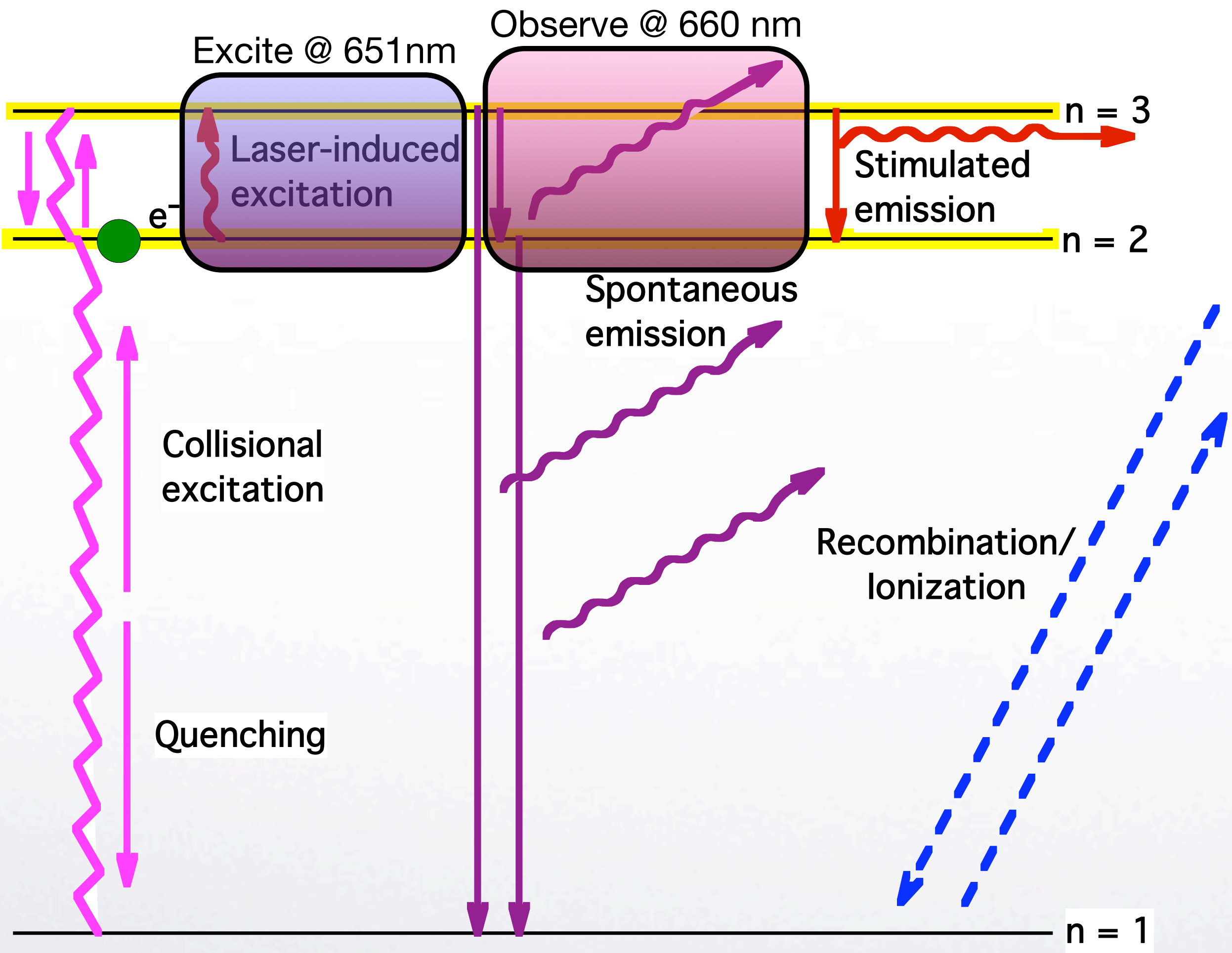
Sensitivity to E_r:

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

Ease of Calibration:

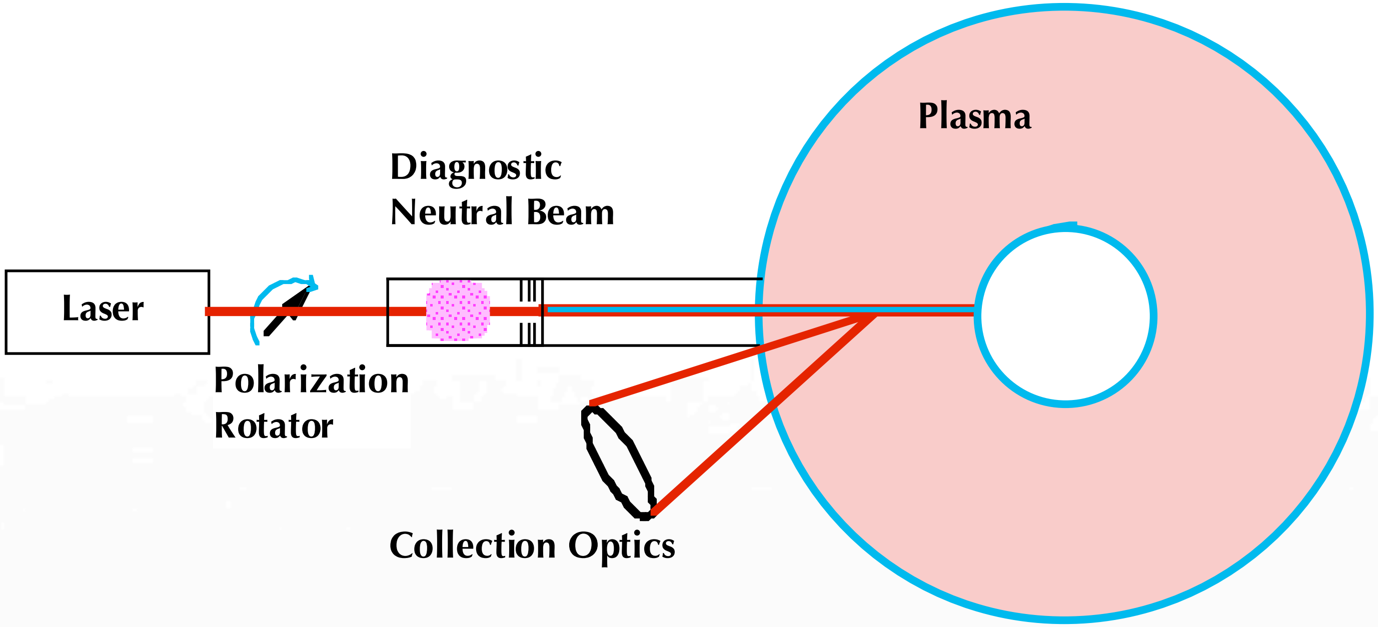
Insensitive to polarization effects in optics

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

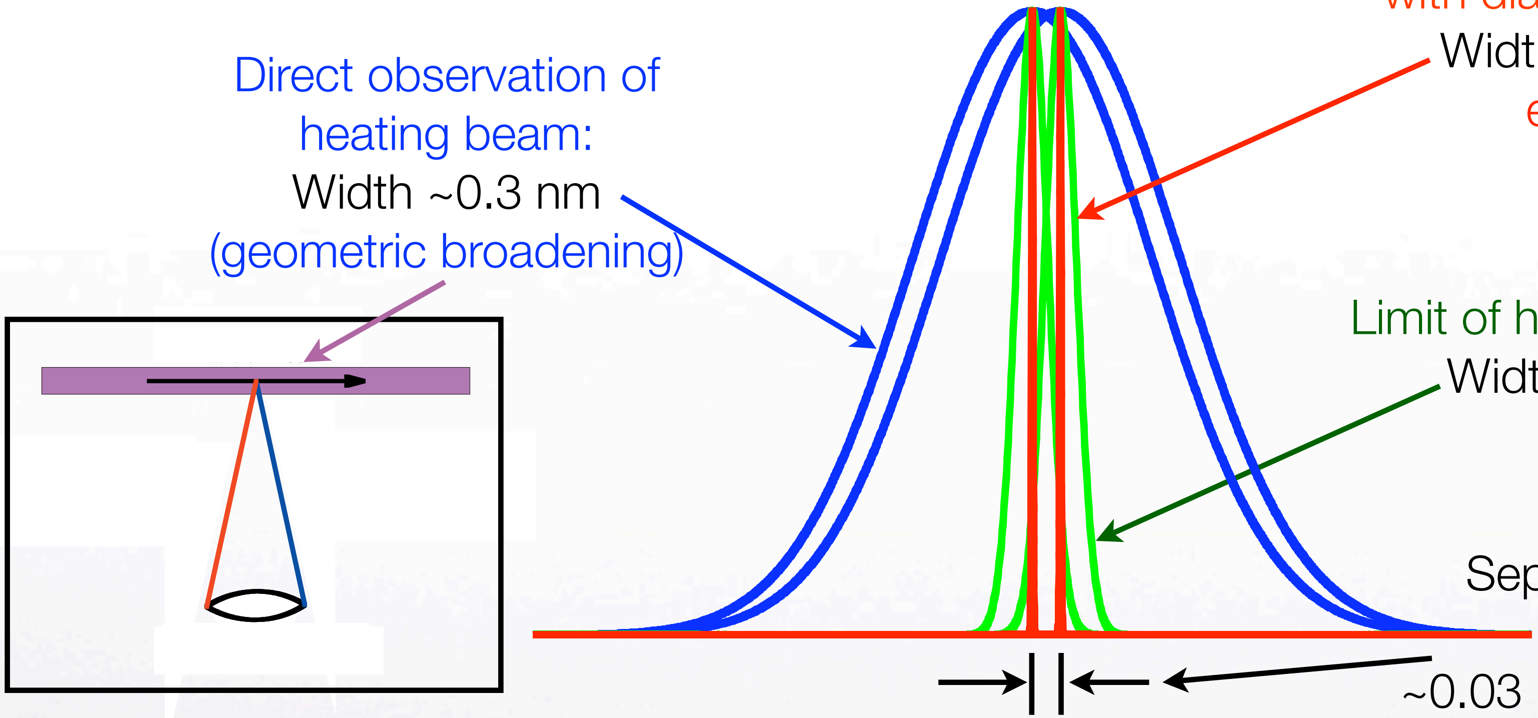
Pitch Angle Measurement



- 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)

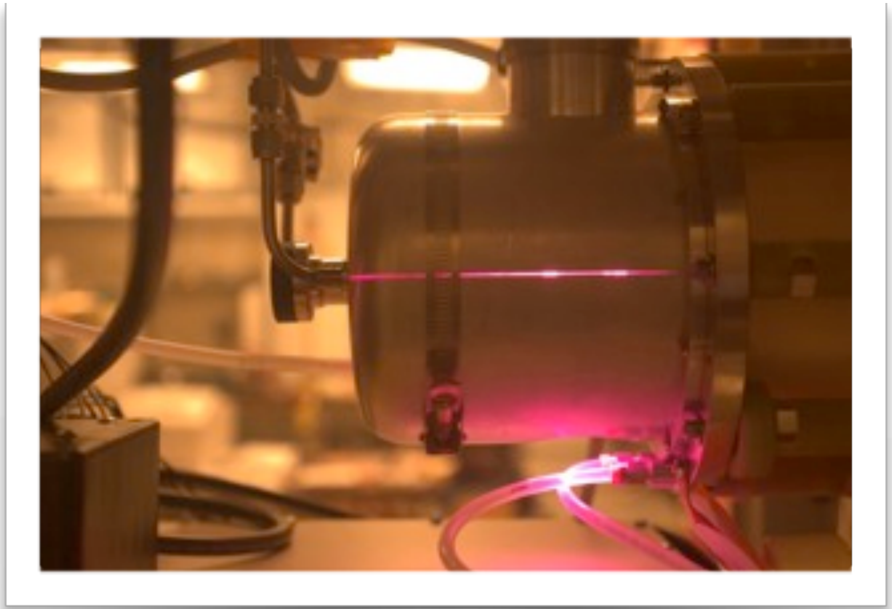
Limit of heating beam resolution:
Width ~0.04 nm (beam divergence)

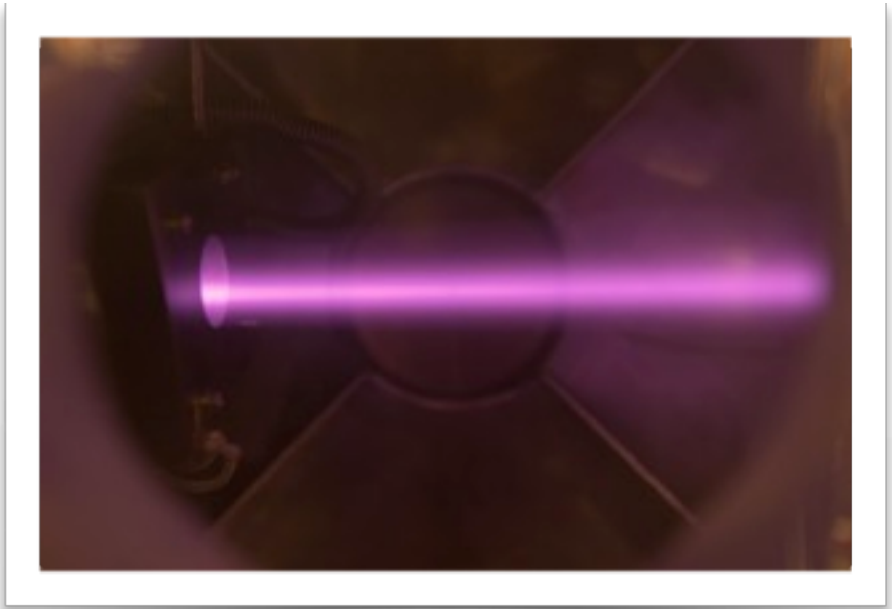
Separation between Stark components
~0.03 nm (90 kV D beam, 0.4 T)

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

MSE-LIF Measurements in Low Field, Neutral Gas Background

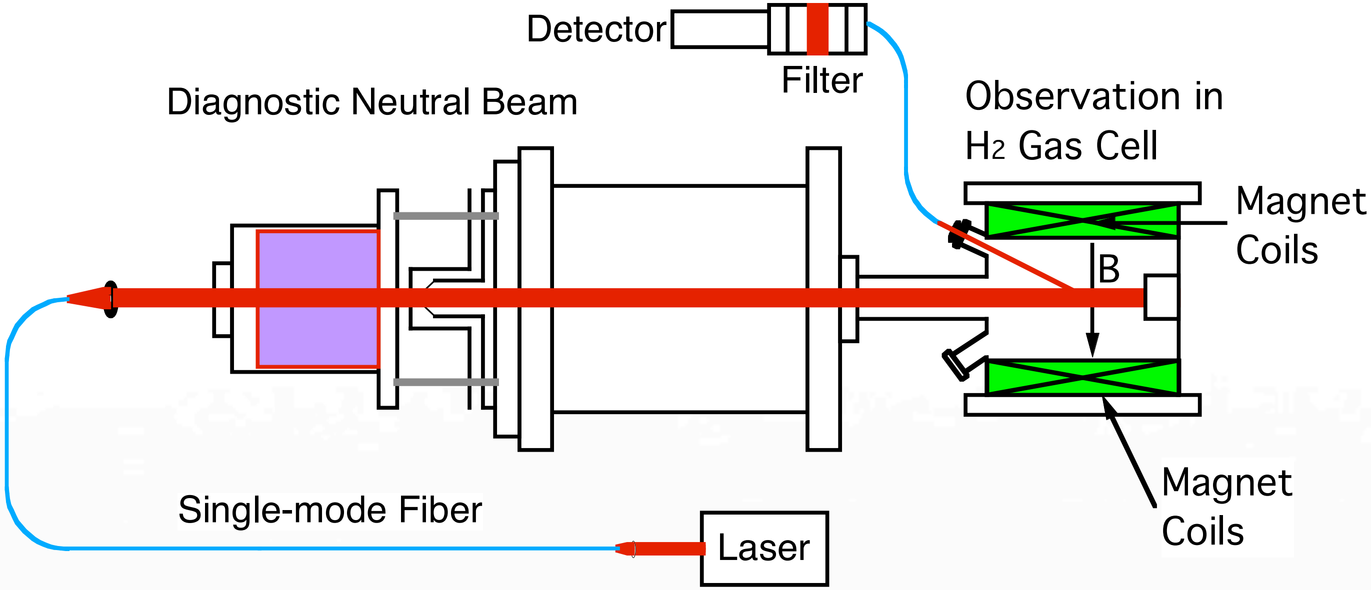
Diagnostic Neutral Beam





- 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

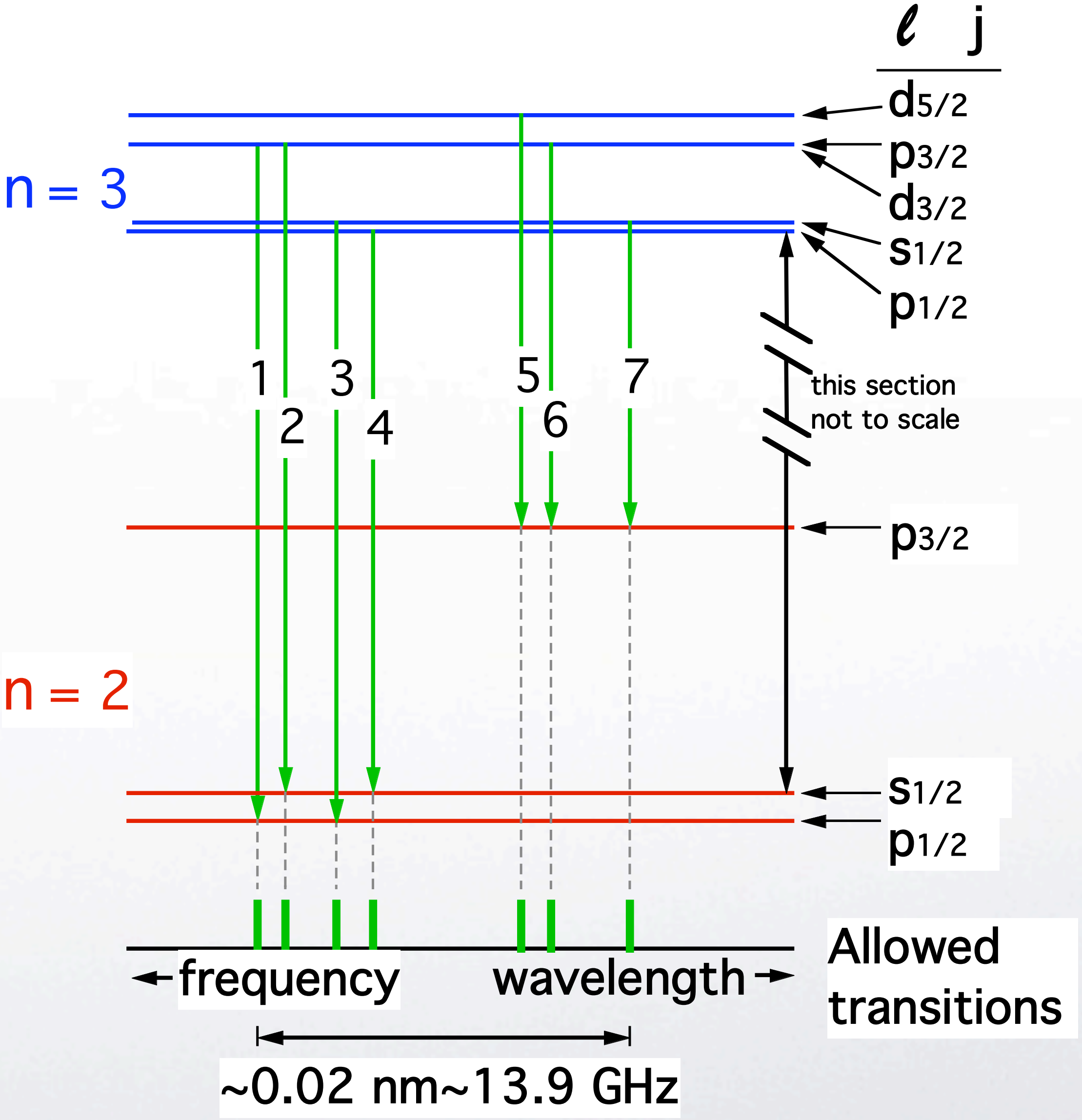
Initial Testing: Beam Into Gas at Low B



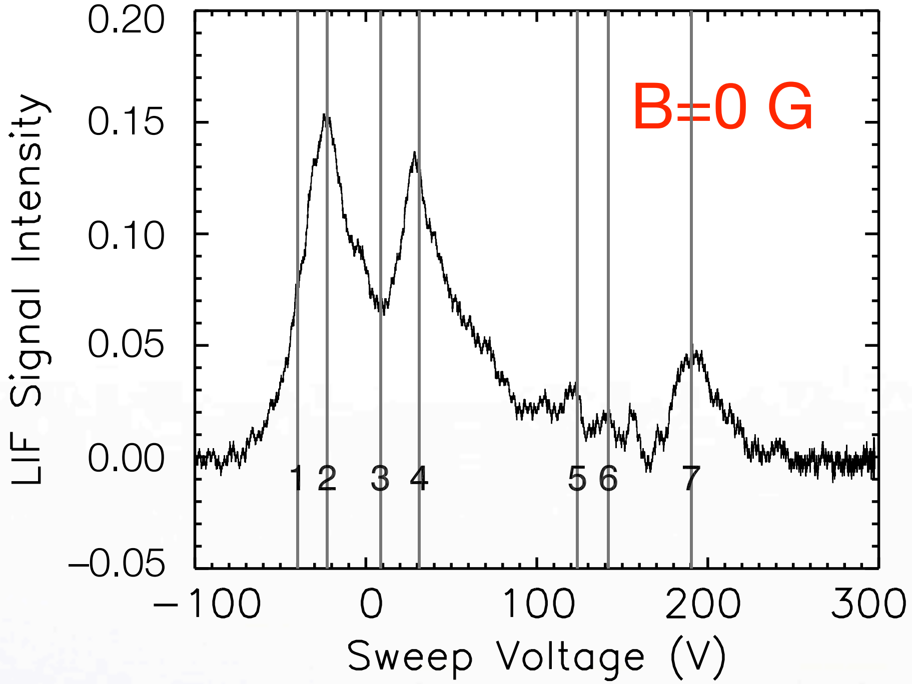
- Tunable ring dye laser (Coherent 899-21) near 650 nm, <1 MHz Linewidth, 300 mW, pumped by 514 nm argon ion laser
- Molecular hydrogen gas in present target chamber
- Magnetic field coils for up to 100 Gauss

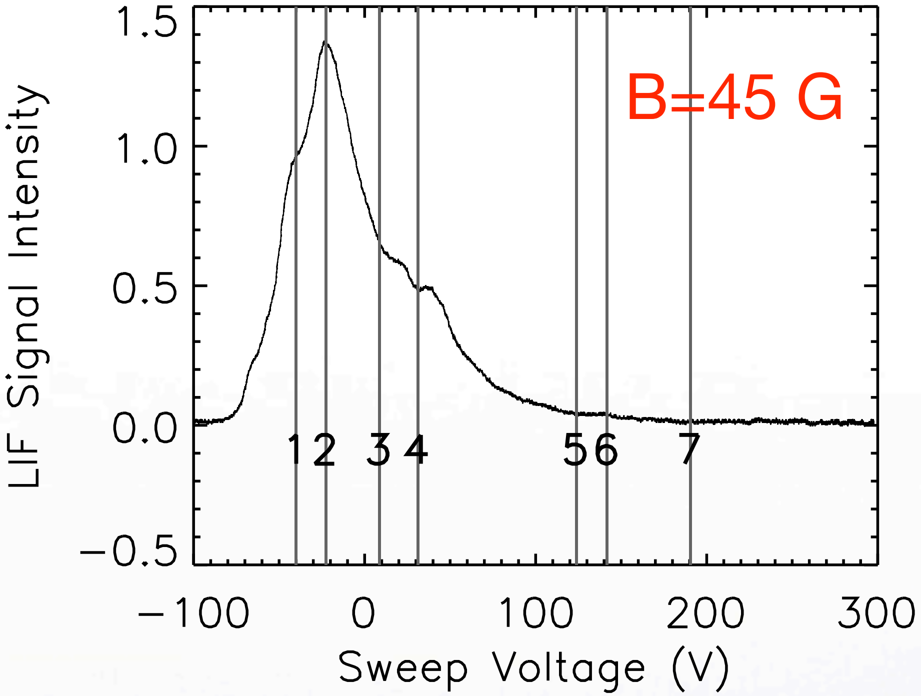
H-alpha Fine Structure

- 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 ℓ ±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

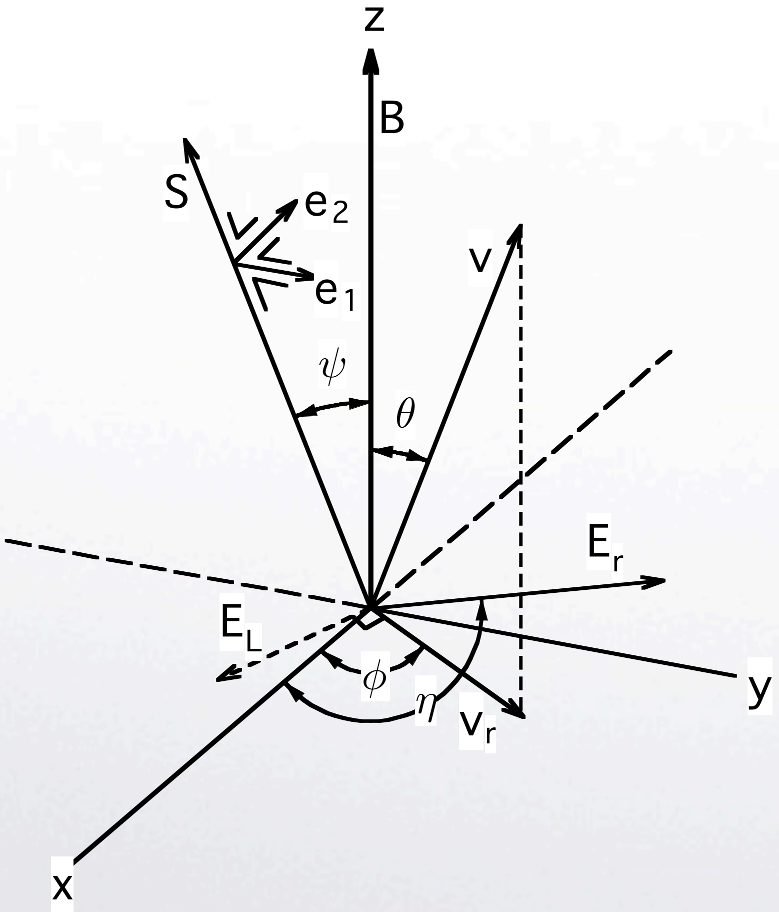
E. L. Foley and F. M. Levinton. J. Appl. Phys. 98(9):093101, (2005)

Quantum Mechanics Calculation

Fully General Calculation

Fine Structure: Spin-Orbit Coupling, Relativistic Effects, Lamb Shift.

$E_0 ... E_n$ from experiments.



Linear Zeeman Effect:

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

Motional Stark Effect:

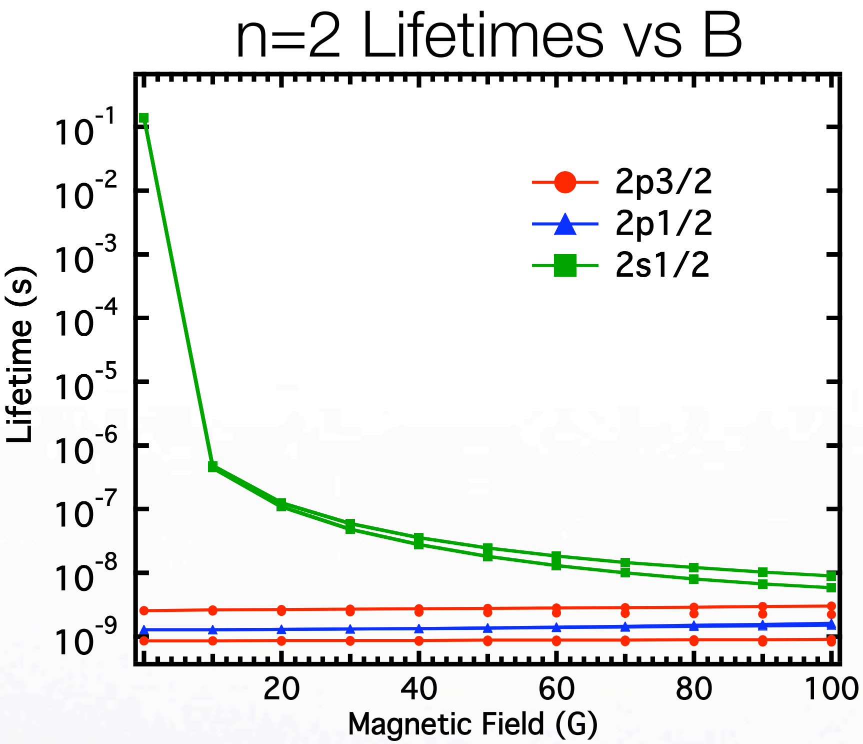
$$\vec{E}_L = \vec{v} \times \vec{B}$$

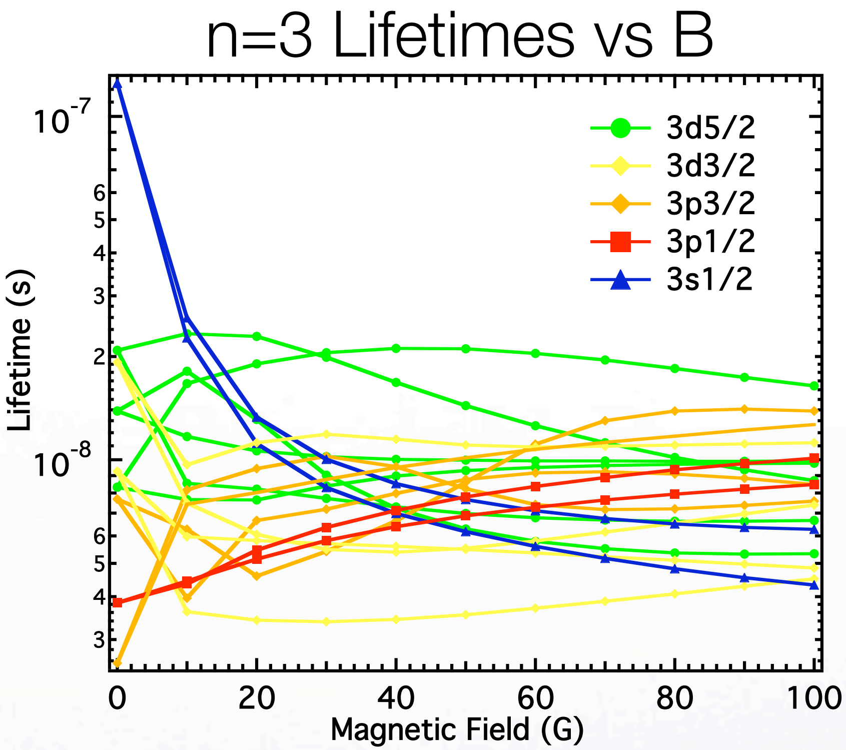
$$\mathbb{H}_L = eBv_r(\vec{x}sin\phi - \vec{y}cos\phi)$$

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

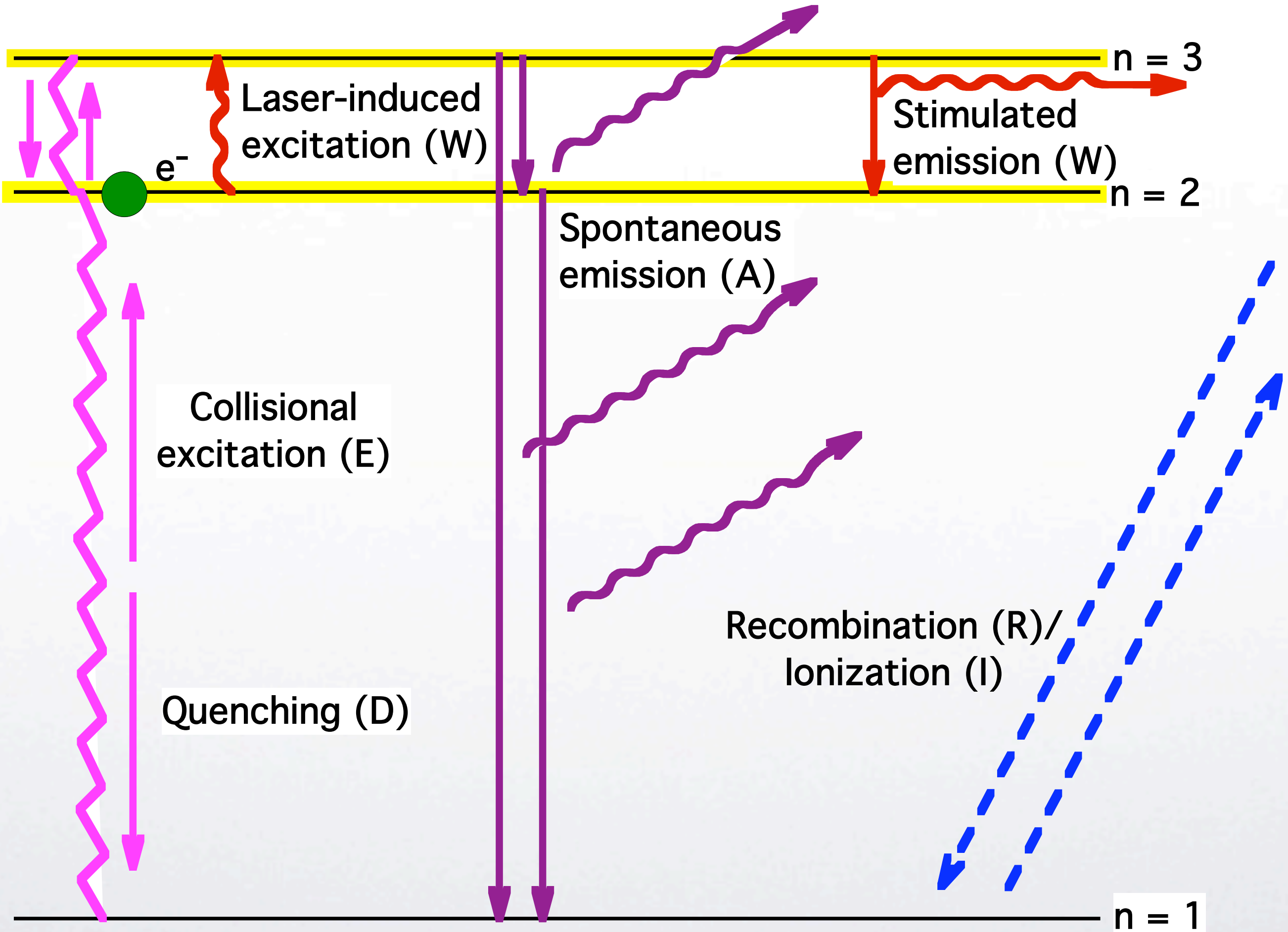




- 2s is metastable in absence of field, lifetime changes rapidly over field range
- In zero-field case, long 2s lifetime gives large population
- As field increases, new transitions allowed - signal increases
- Higher field removes excess 2s population, signal in gas reduced

Collisional Radiative Model

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



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:

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

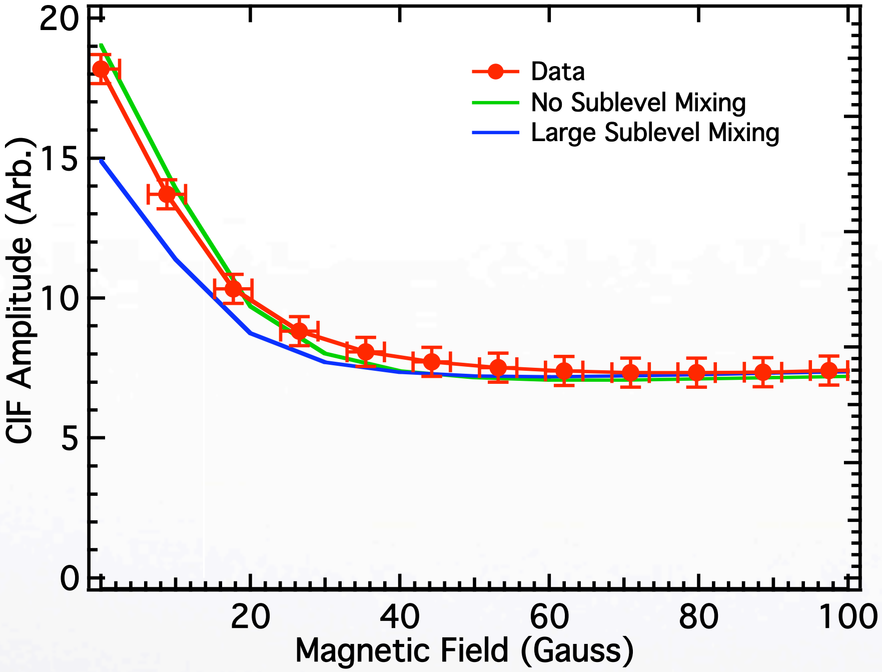
Oscillator Strength:

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

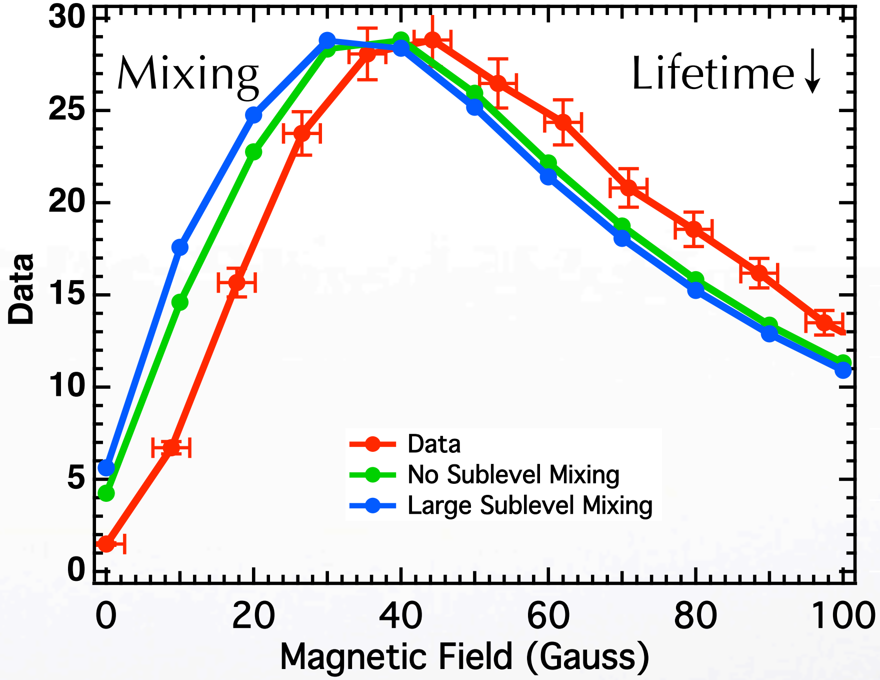
E. L. Foley and F. M. Levinton. J. Phys. B 39 (2006) 443-453

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.

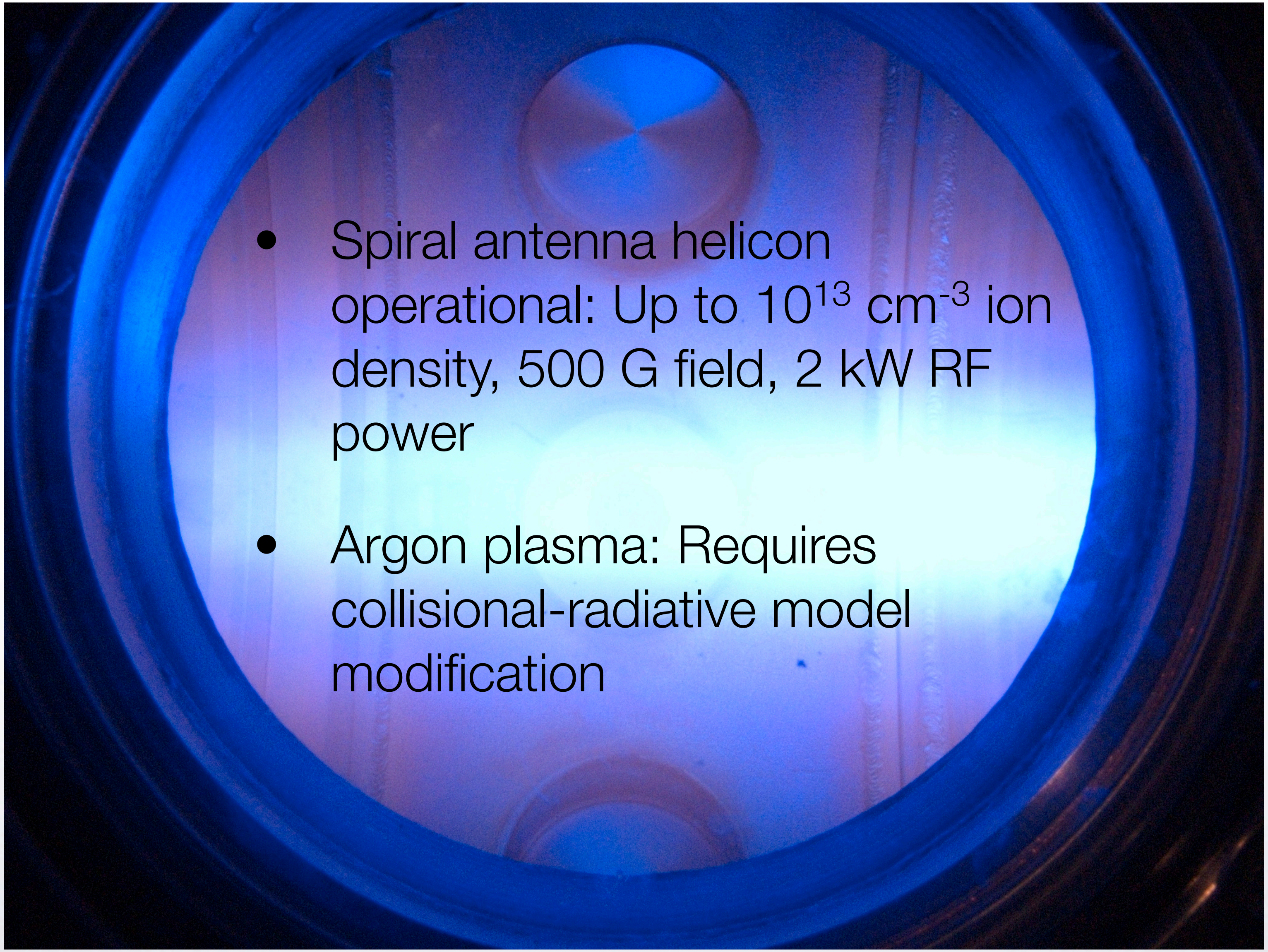
MSE-LIF at Intermediate Field in Plasma: Challenges and Responses

MSE-LIF at Intermediate Field

Challenge: Signal Level

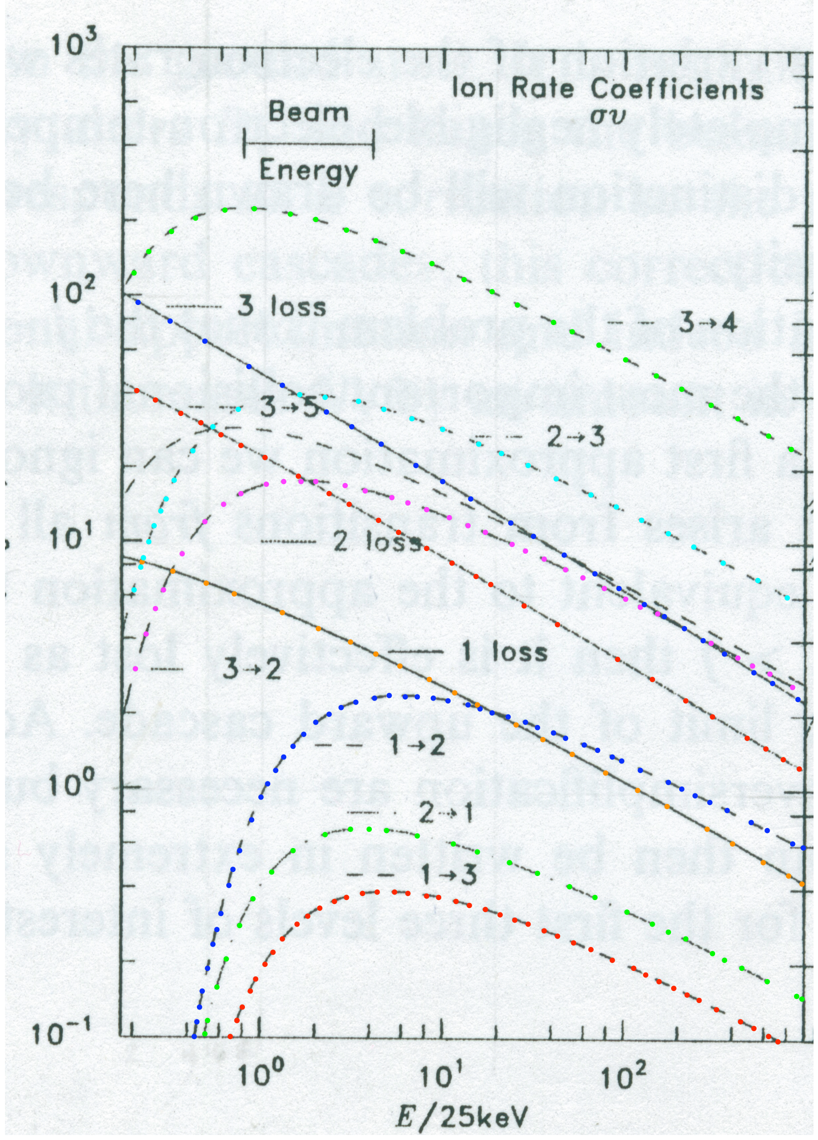
- Increase n=2 population available for excitation
  - Ensure full beam neutralization
  - Reduce re-ionization in beamline
  - Provide greater collisional excitation from n=1
- Improve linewidth match of beam and laser
  - Reduce beam linewidth
  - Increase laser linewidth

Plasma Testbed

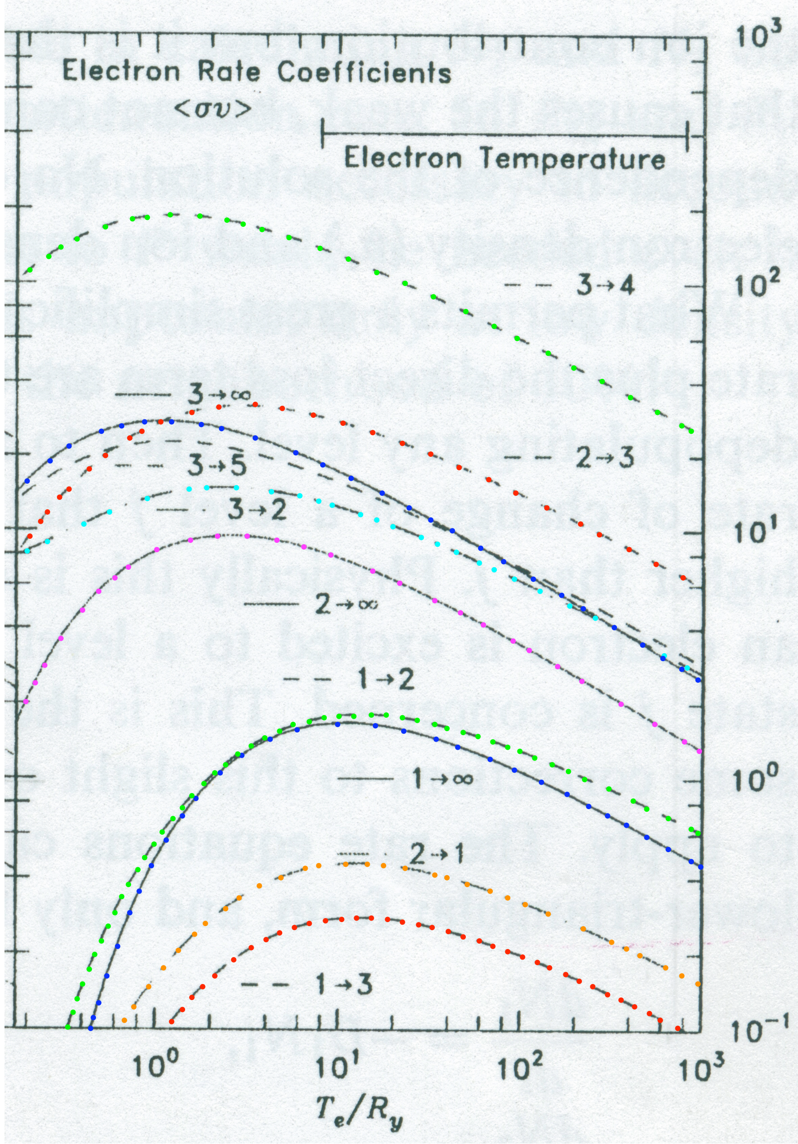


- Spiral antenna helicon operational: Up to 10^{13} cm^{-3} ion density, 500 G field, 2 kW RF power
- Argon plasma: Requires collisional-radiative model modification

Collisional Excitation in Plasma



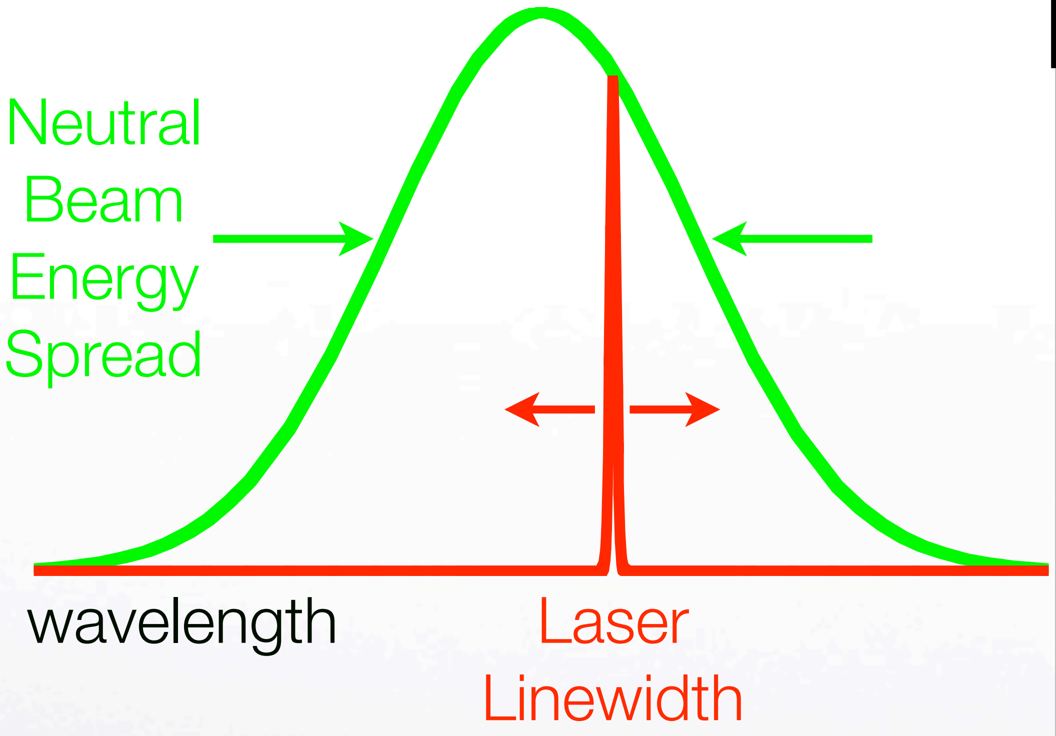
Model with hydrogen plasma background - rates from Hutchinson '02.



CRM in Plasma

	Neutral Gas	Helicon Plasma*	NSTX Plasma
n2/n1	$2s \sim 10^{-3}$ $2p \sim 5\times10^{-5}$	8×10^{-4}	3×10^{-3}
n3/n1	5×10^{-5}	3.5×10^{-4}	1×10^{-3}

Linewidth Match of Beam and Laser

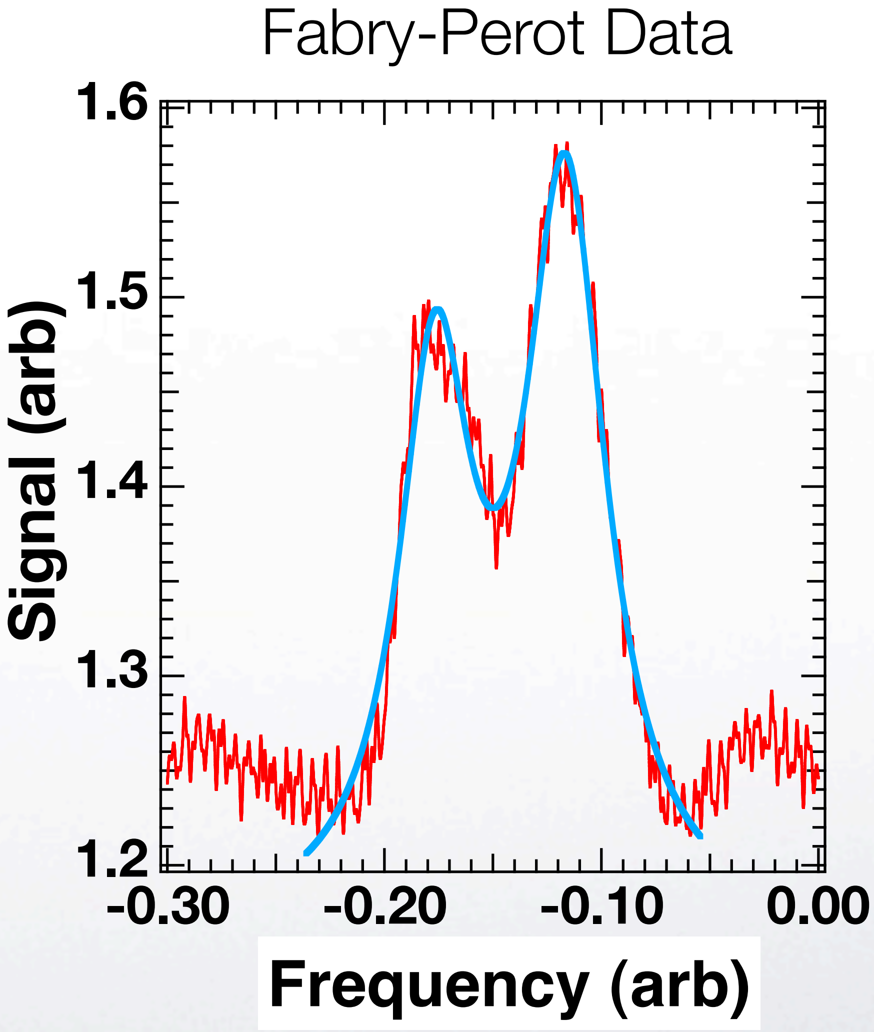


Parameter	Linewidth
Natural linewidth	~100 MHz
Laser linewidth	~100 MHz
RF on accel. grid	~2 V = ~120 MHz
RF AM line noise	~2 V = ~120 MHz
Line ripple on HV	~1 V = ~60 MHz
Energy straggling	~50 V = ~3 GHz
Low p broadening	~50 V = ~3 GHz

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



Laser Development:
651 nm, 10 W, 6 GHz

New Laser Development

Required Laser Characteristics:

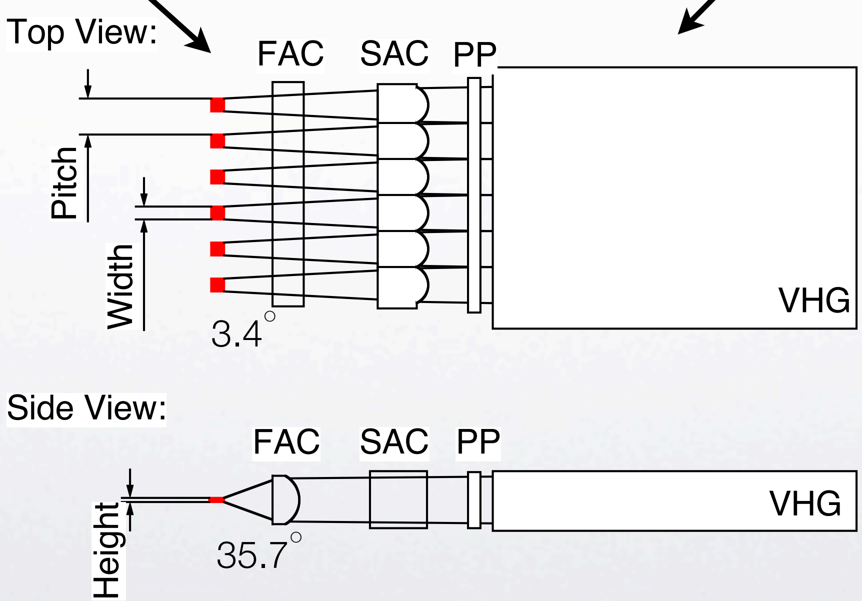
- Tunable near 651 nm
- Linewidth to match neutral beam energy spread (~6 GHz)
- Power per unit linewidth comparable to dye laser experiments: 1.5 W/GHz
- Good beam quality to match 1 cm neutral beam diameter and 0.26° beam divergence
- Reliable operation

Diode Laser Array with VHG Feedback

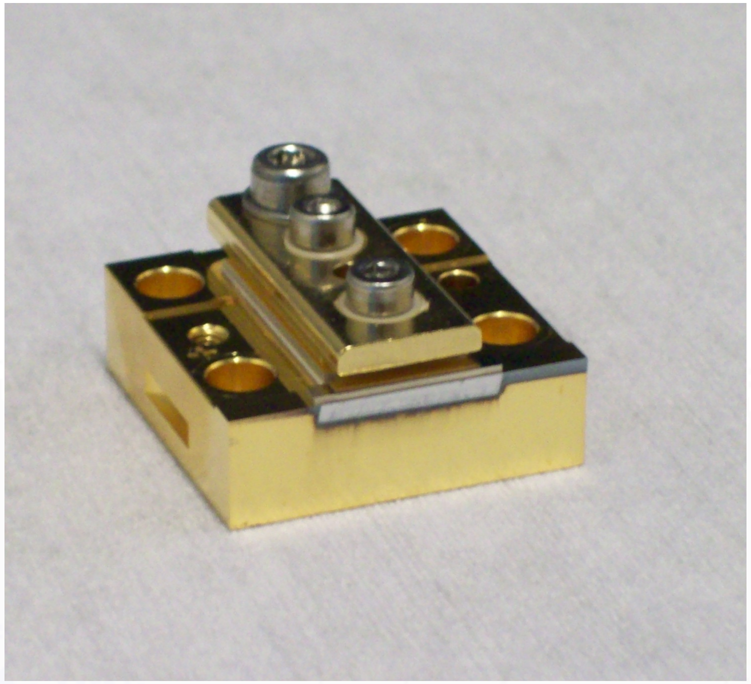
Multiple emitter diode array:
651 nm
10+ W
2-3 nm linewidth

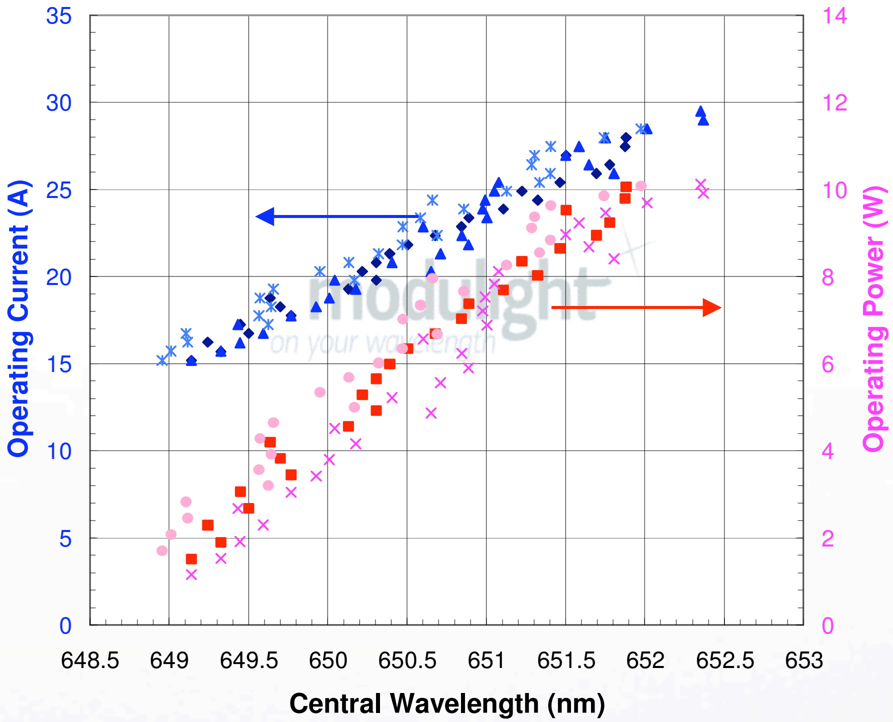
Precision collimation optics

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



651 nm Diode Array

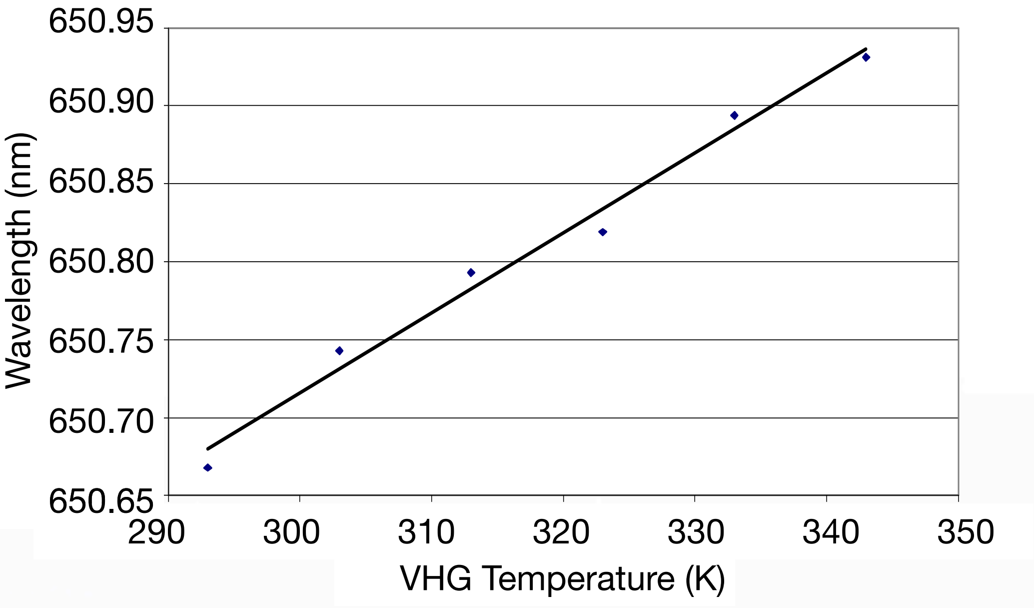


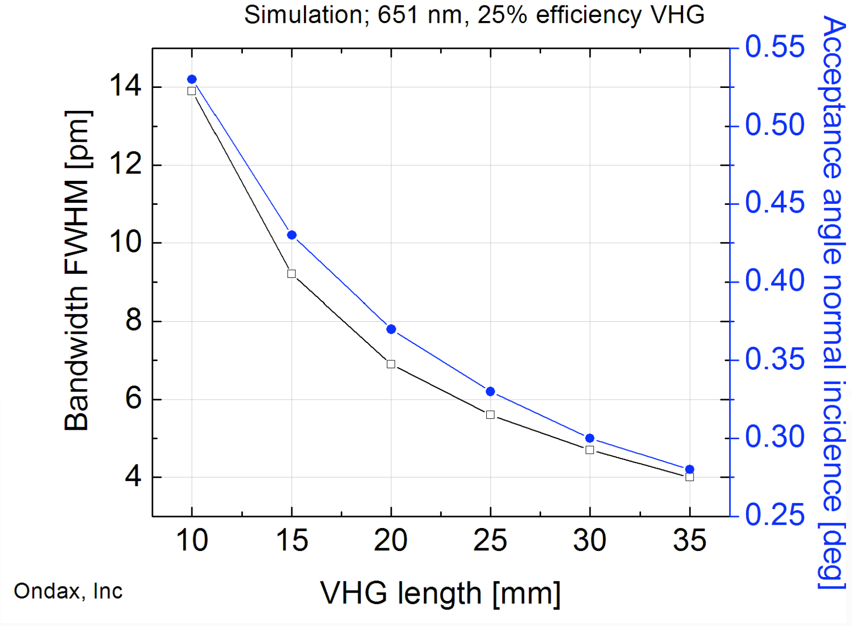


- Custom wafer growth by Modulight Inc
- 10 W, 652 nm @ 20°C - operate at 15°C for 651 nm
- 19 emitter array, 150 micron emitter width

Photo and data courtesy of Modulight inc

Volume Holographic Grating

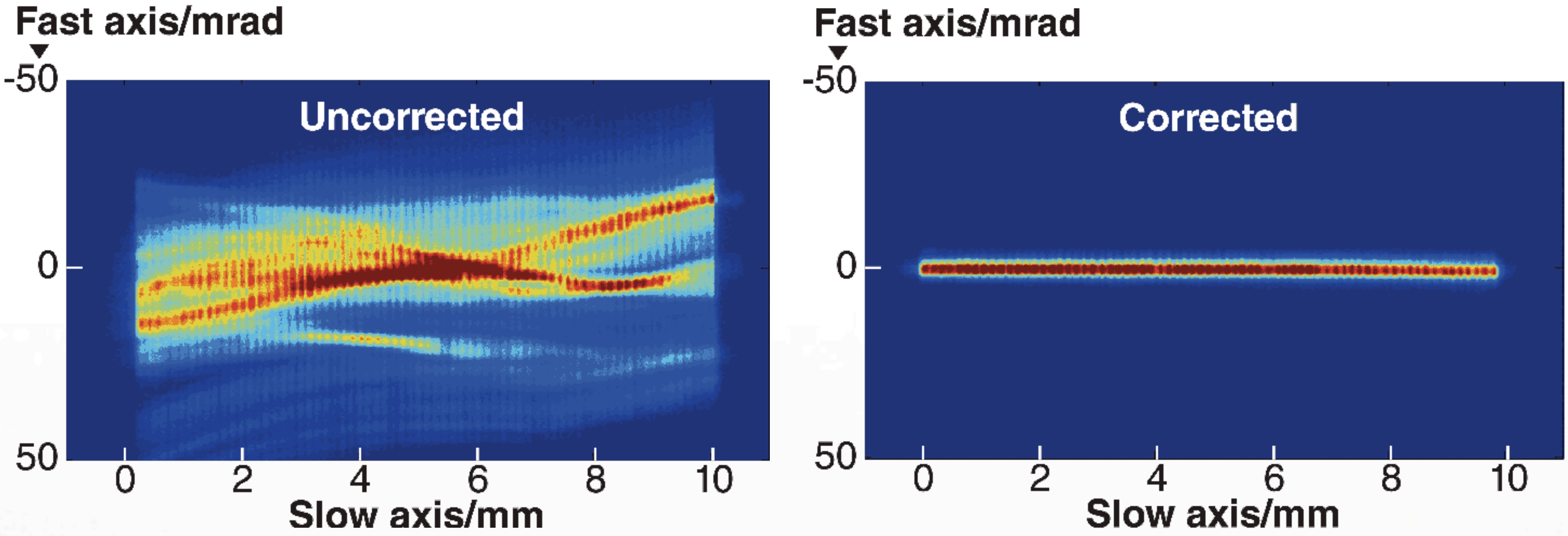




- VHG created with 3D image of interference pattern between coherent optical fields in photorefractive glass
- Allows selection of narrow wavelength range - $\Delta\lambda$ depends on length
- Angular acceptance also narrow

Simulation courtesy of Ondax inc

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

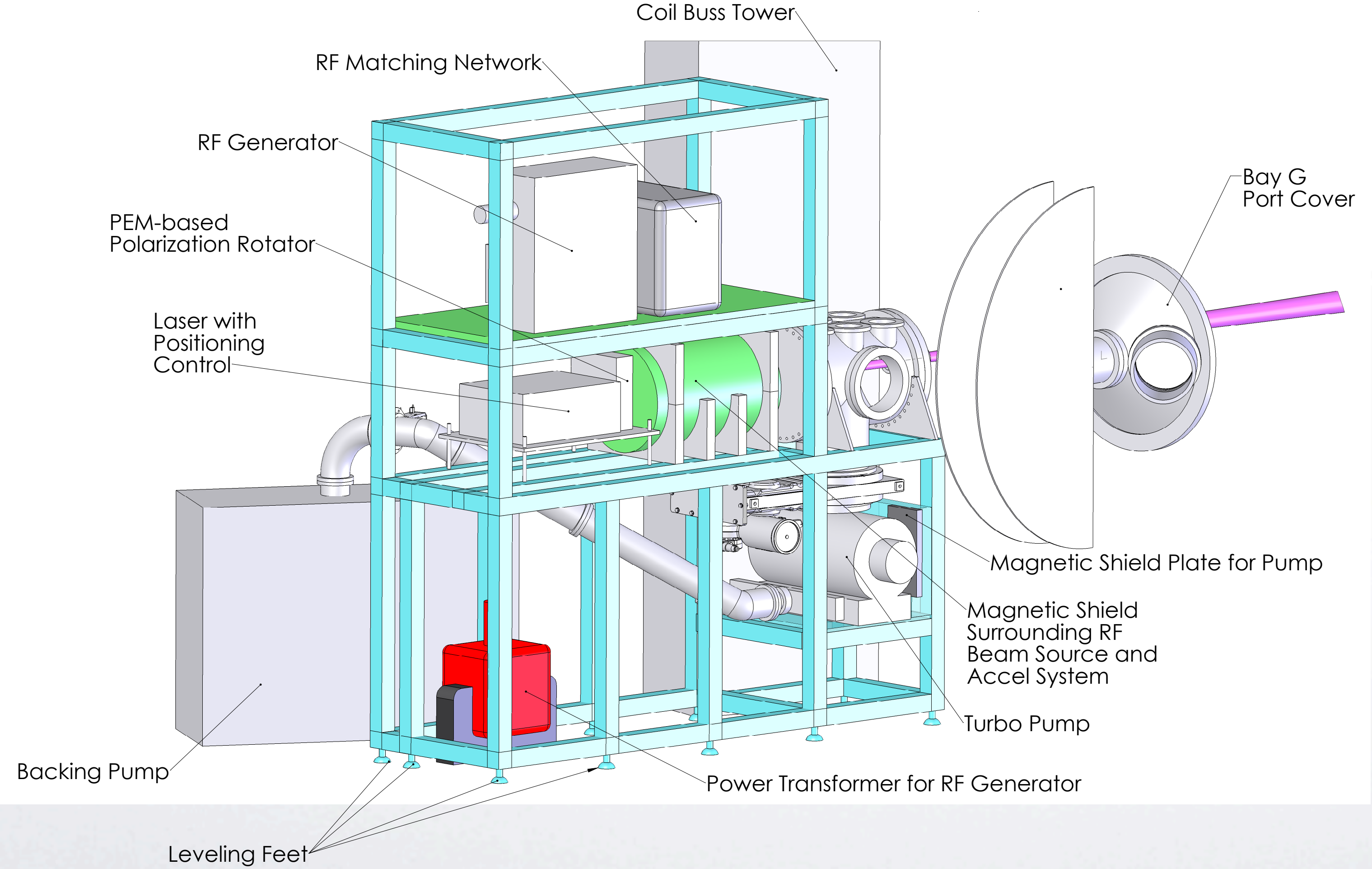
Images courtesy of Power Photonic

Installation on National Spherical Torus Experiment (NSTX)

Performance on NSTX

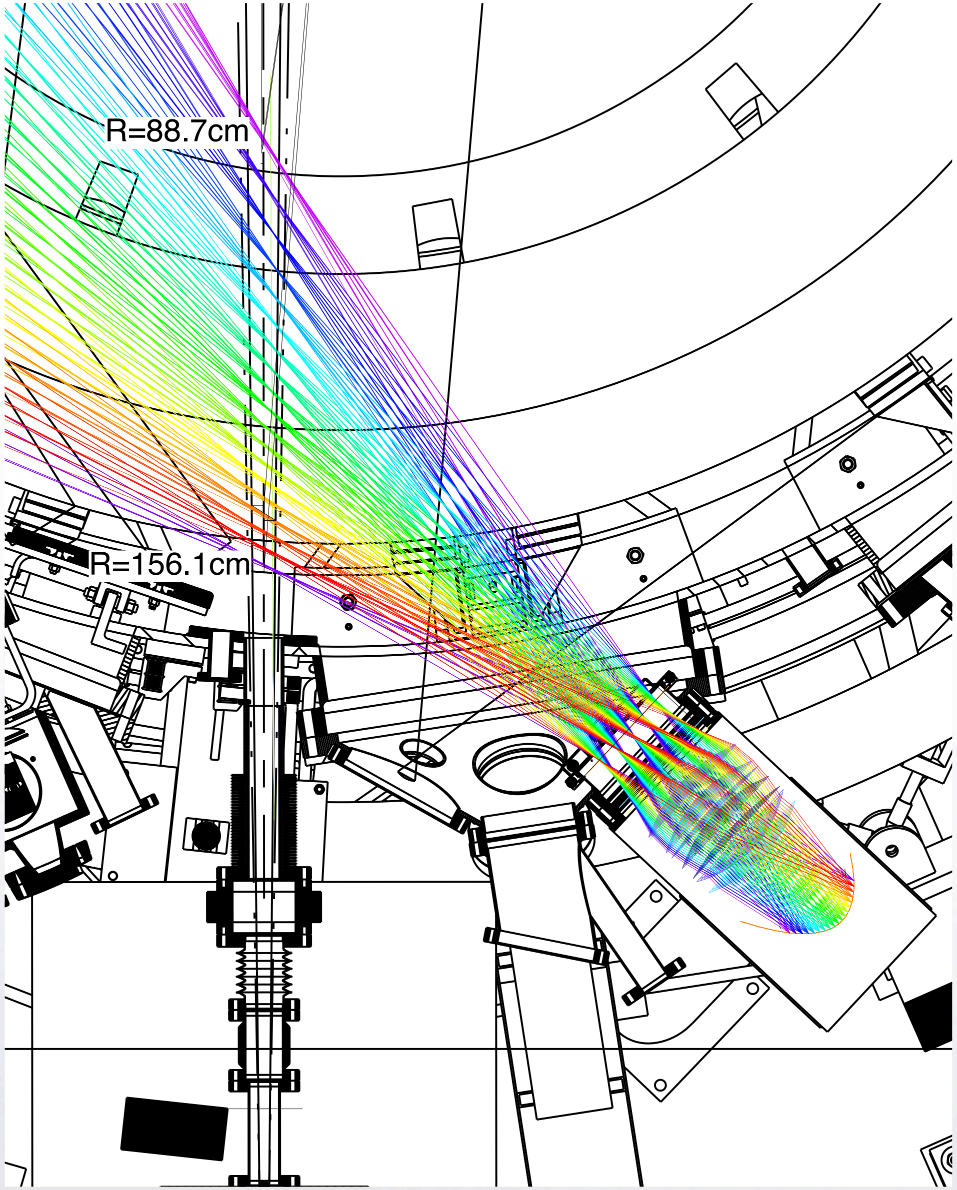
- MSE-CIF data from NSTX, MSE-LIF laboratory performance and collisional-radiative model used together to predict signal levels for NSTX - expect 10x higher photon count rates (at detectors) than CIF system. Time resolution of better than 10 ms expected.
- Magnitude of B resolved to few Gauss range,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

NSTX Installation



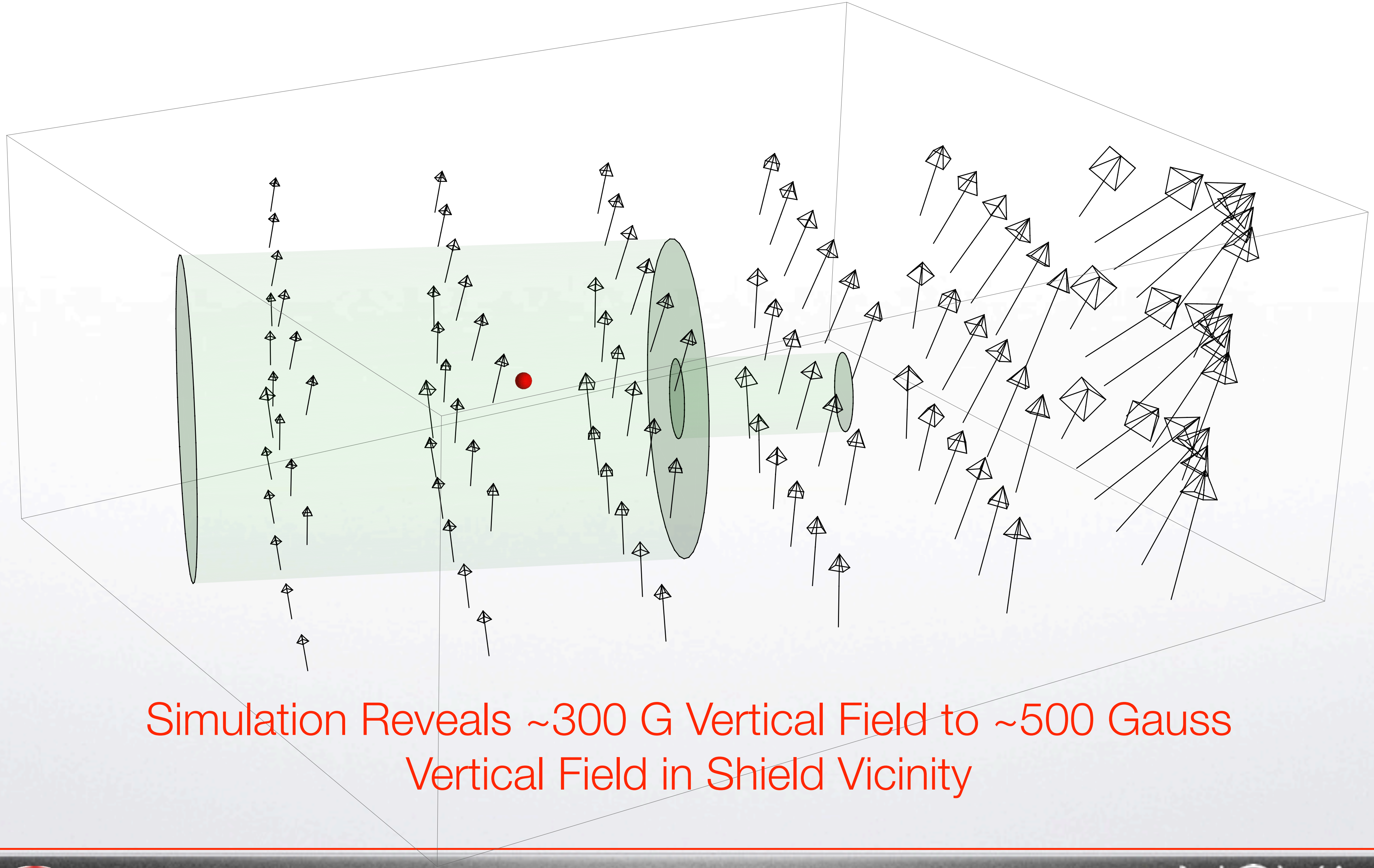
- MSE-LIF slated for installation in 2011
- PPPL: vacuum vessel, platform and neighboring diagnostic modifications
- Nova Photonics: diagnostic neutral beam stand, experimental control

View Layout on NSTX



- 19 radial points
- Aim to match existing MSE-CIF system radial locations
- Near-radial injection angle minimizes sensitivity to radial electric field on pitch angle measurement

Stray Magnetic Fields Near DNB

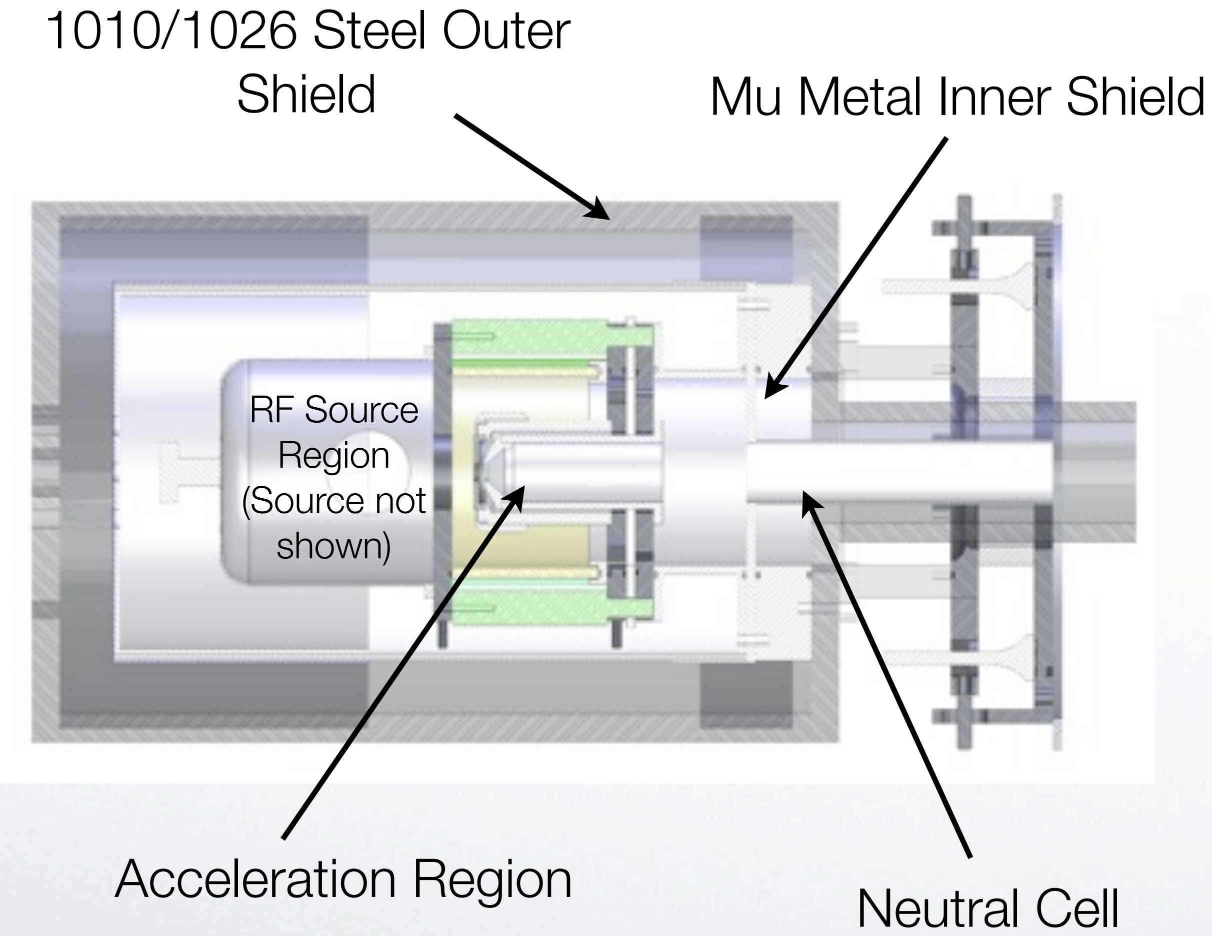


Simulation Reveals ~300 G Vertical Field to ~500 Gauss
Vertical Field in Shield Vicinity

Magnetic Shield Design

- 2-layer shield needed: Outer layer of high-saturation material, Inner layer of high permeability material
- Design goal to keep field in source and accel region under 0.5 Gauss
- Design must accommodate high voltage and ground potential nearby
- Design must be compatible with vacuum system layout
- Extensive design optimization performed in 2D and 3D

Magnetic Shield Design



1010/1026 Steel Outer Shield

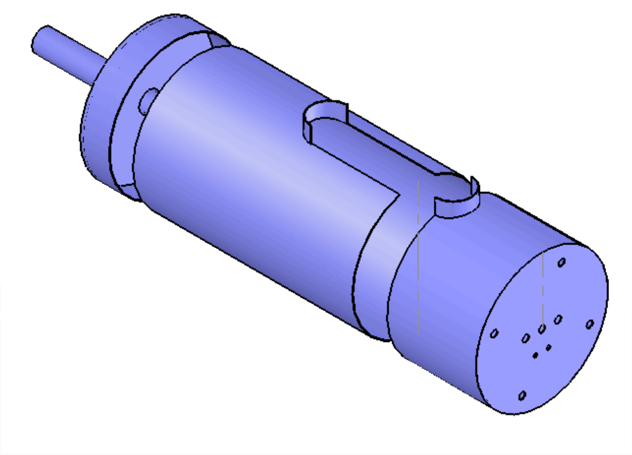
Mu Metal Inner Shield

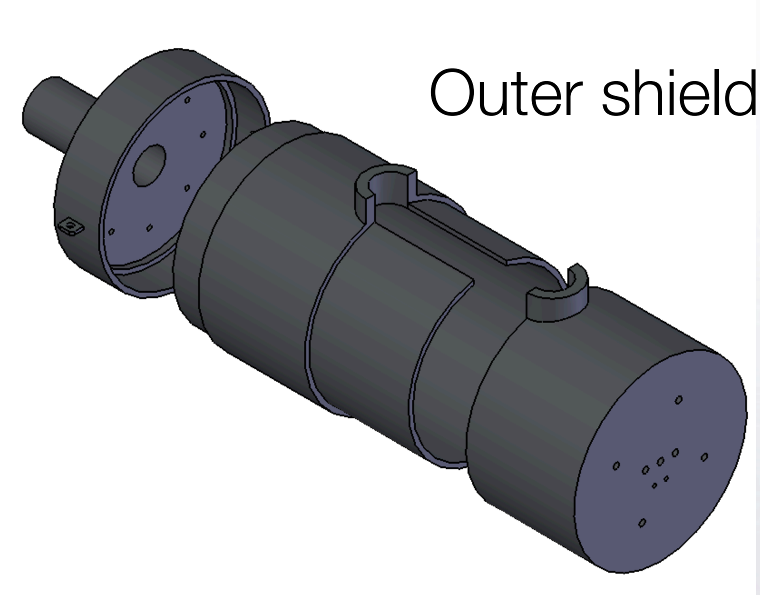
RF Source Region (Source not shown)

Acceleration Region

Neutral Cell

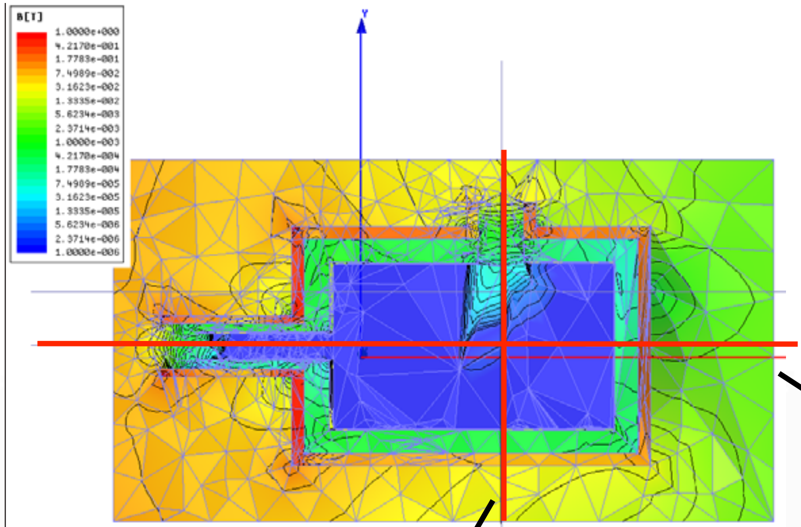
Inner shield

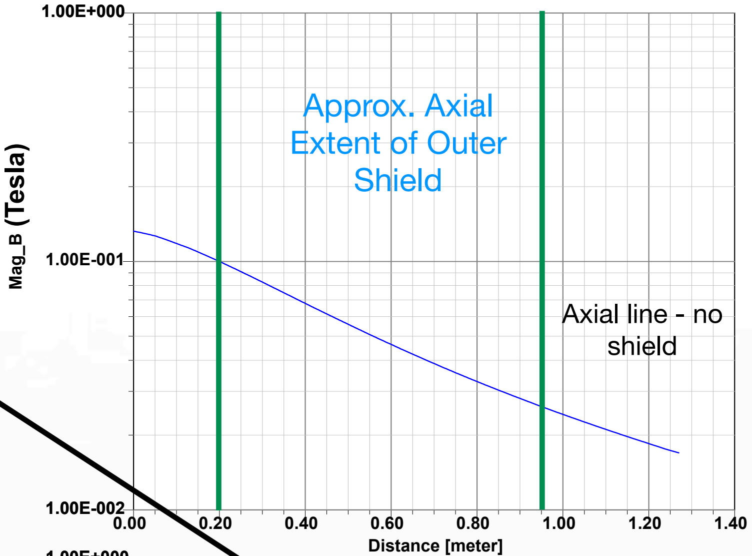




Outer shield

Magnetic Shield Simulations





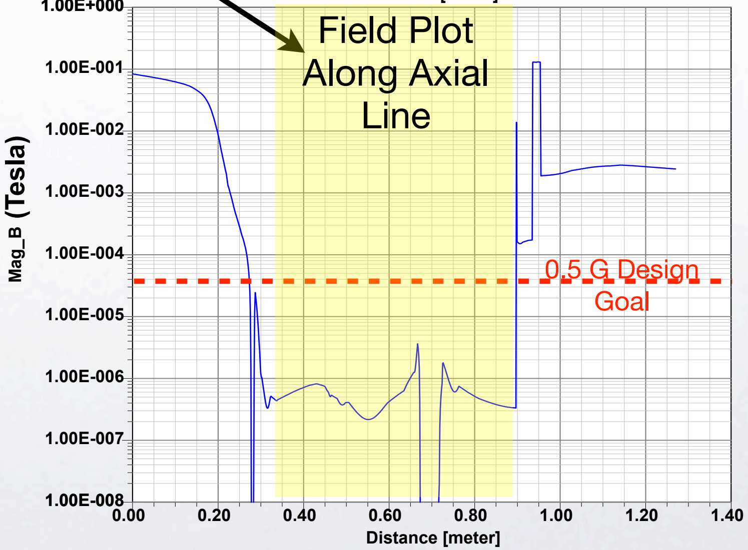
Approx. Axial Extent of Outer Shield

Axial line - no shield

Field Plot Along Vertical Line

0.5 G Design Goal

Field Plot Along Axial Line



0.5 G Design Goal

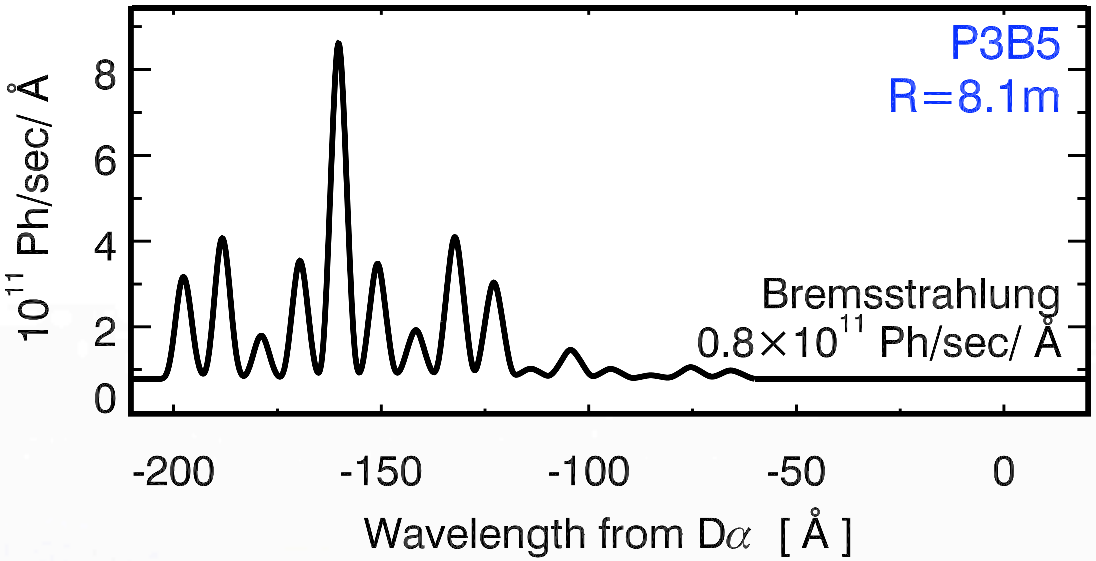
MSE on ITER

MSE on ITER

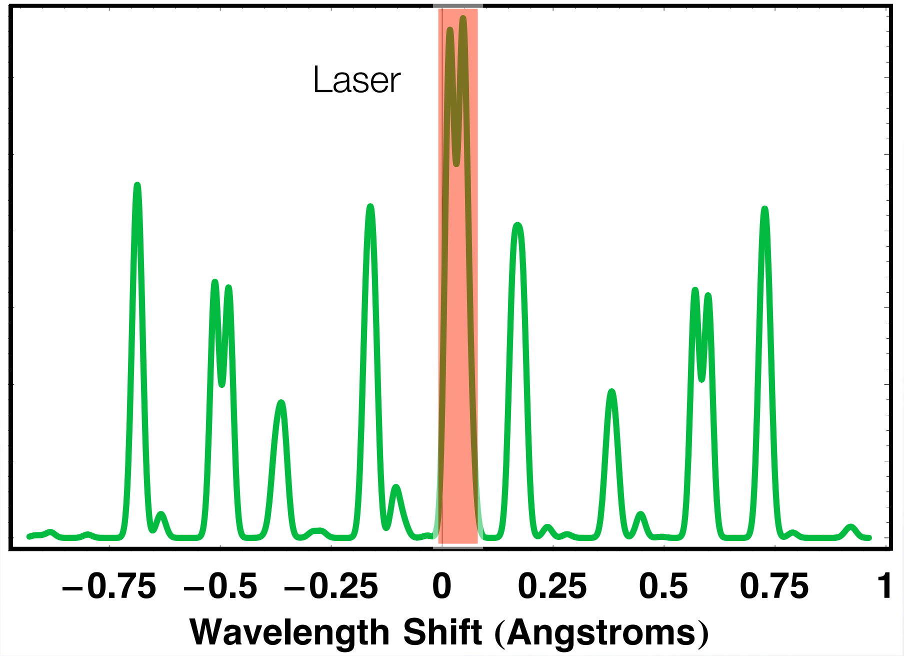
- ITER environment poses challenges for all optical diagnostics, including MSE
- Mirror labyrinth required for neutron shielding (refractive optics not an option)
- Plasma-facing mirror will suffer deposition and erosion which will have significant impact on polarized light propagation
- One option: Use spectrum for magnetic field magnitude measurement, like MSE-LIF makes possible on NSTX

NSTX as Testbed for ITER MSE

ITER Simulated Data From Heating Beams



MSE-LIF Prediction on NSTX



ITER high field and high beam energy conditions make spectrum relative width-to-spacing ratio similar to that on NSTX.

E. L. Foley, F. M. Levinton, H. Y. Yuh and L. E. Zakharov.
Nuc. Fusion 48 (2008) 085004
RSI 79 (2008) 10F521

MSE-LIF on ITER

- Potential advantage of ease of calibration
- Detailed collisional-radiative modeling must be done to determine feasibility
- Access for laser in heating beam sources must be incorporated into design
- Laser power required expected to be ~100x what is presently available - possible with arrays, further development

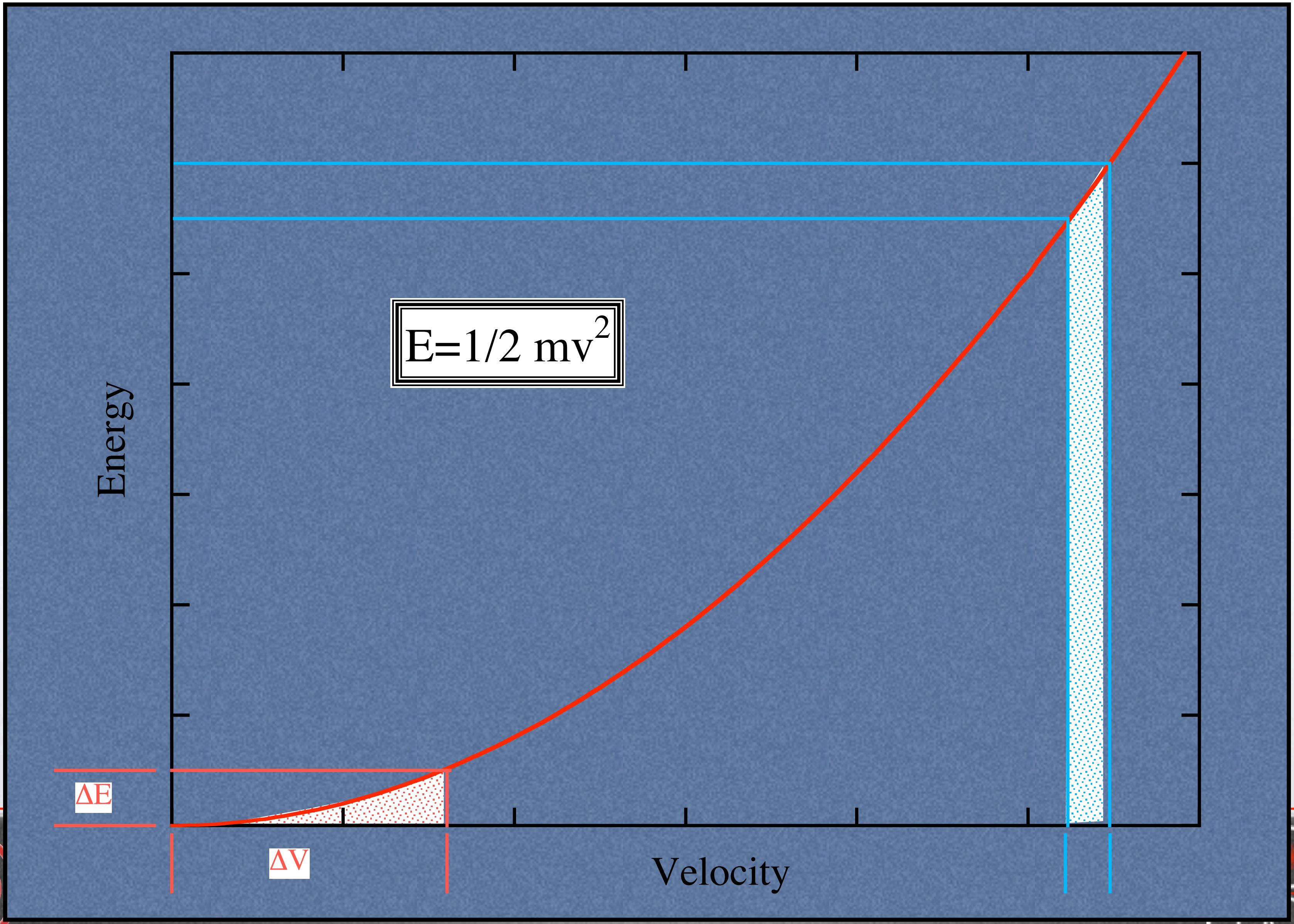
Summary

- Motional Stark effect with laser-induced fluorescence (MSE-LIF) system under development
- Experiments and modeling done to establish foundation of understanding for measurement
- Laser development near completion
- Diagnostic neutral beam upgrades underway
- NSTX Installation slated for 2011

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

Acceleration Cooling



Polarization Effects

LIF at 45 G