Edge Current Density Determination Using Laser-Enhanced LIBEAM on DIII-D

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Edge Current Density Determination Using Laser-Enhanced LIBEAM on DIII-D[1] D.M. THOMAS, K.H. BURRELL, P. GOHIL, General Atomics, R. JAYAKUMAR, D. NILSON, B.W. RICE, Lawrence Livermore National Laboratory — The specific structure of the edge current profile has profound effects on the stability and ultimate performance of many advanced tokamak (AT) modes. This is true for both bootstrap and externally driven currents used to tailor the edge shear. Absent a direct local measurement of $j(r)$, the best alternative is a determination of B_{pol}. Measurements of the precision (0.1–0.01 deg in magnetic pitch angle and 1–10 ms) necessary to address issues of AT control are difficult to do in this region ($\rho = 0.9$–1.1). Using Zeeman polarization spectroscopy of the 2S-2P DIII–D lithium beam resonance line emission, measurements of the various field components may be made to the necessary precision in exactly the region of interest for these studies. Measurement time response may be improved by utilizing laser enhancement of the fluorescence signal with subsequent polarization analysis, or direct determination of the polarization state using a laser beam with time-varying polarization. Improvements to Ti:sapphire laser output power in the 670 nm region should permit pumping the Li 2P state to near saturation levels with a relatively simple system.

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☐ Prefer Oral Session
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Special instructions: DIII-D Poster Session 2, immediately following L Zeng

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Measuring edge current distributions with LIBEAM polarimetry

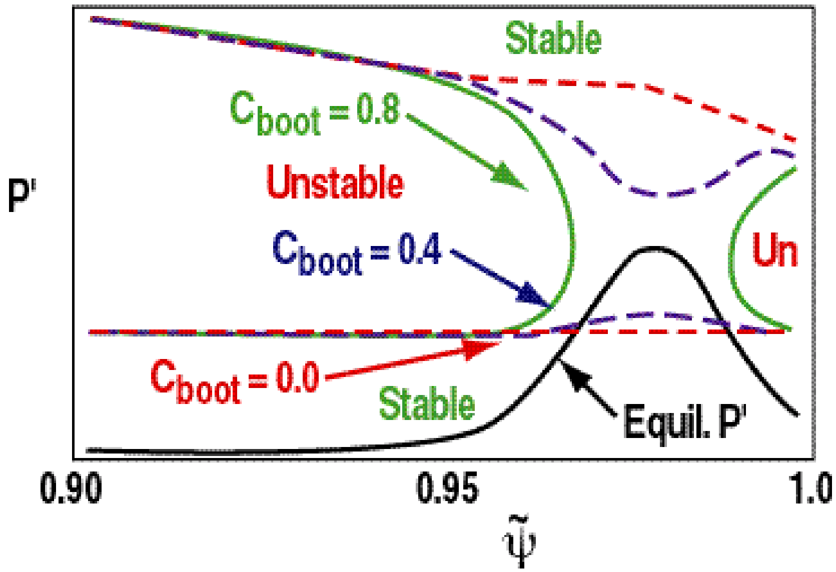
- **Principle of measurement:**
  - **Use Zeeman Polarimetry of injected Lithium atoms to determine local direction of magnetic field--deduce poloidal component, then differentiate to retrieve current density**
- **Required precisions**
- **Possible views on DIII-D** **midplane or vertical injection possible**
- **Performance estimates from LIBEAM experience**
- **Enhancements using laser pumping**
- **Conclusions**

Determining and controlling edge current density will be crucial for extending DIII-D AT performance.

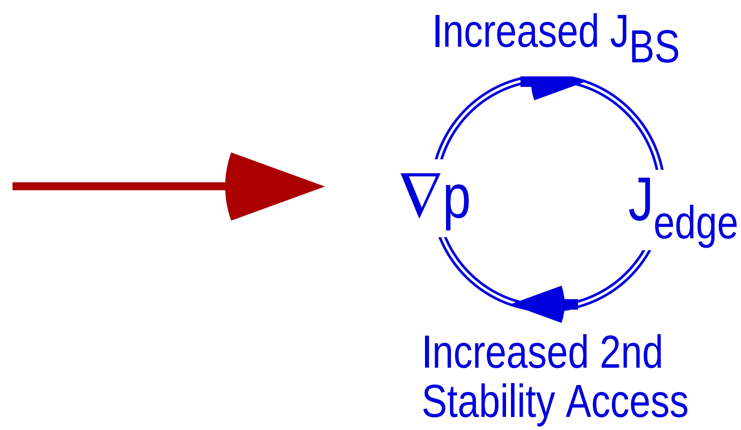
- **Edge stability is sensitive to details of edge current density**
- **Can modify stability of tearing modes by tailoring the current profile in vicinity of rational surfaces (Glasser, 1975)**
- **Coupling between ballooning (∇p-driven) and peeling modes (j-driven) can determine stability of DIII-D edge (Wilson, 1998 APS)**
  - **Edge current density is destabilizing to the peeling modes. If magnetic well not deep enough, prevents second access to stability. If well is deepened further, can decouple the modes. [ELITE code results]**
- **The marginally stable peeling mode structure is much more localized to the outside than ballooning mode.**
- **Associated confinement issues-control of ELM character and behavior.**

GOAL OF EDGE STABILITY STUDIES: TO EXPLORE AND DEVELOP TECHNIQUES TO CONTROL THE EDGE CURRENT, EDGE PRESSURE GRADIENT, AND EDGE 2ND STABILITY ACCESS

(MURAKAMI, IAEA TCM on Steady-State Operation, Fukuoka, Japan,1999)



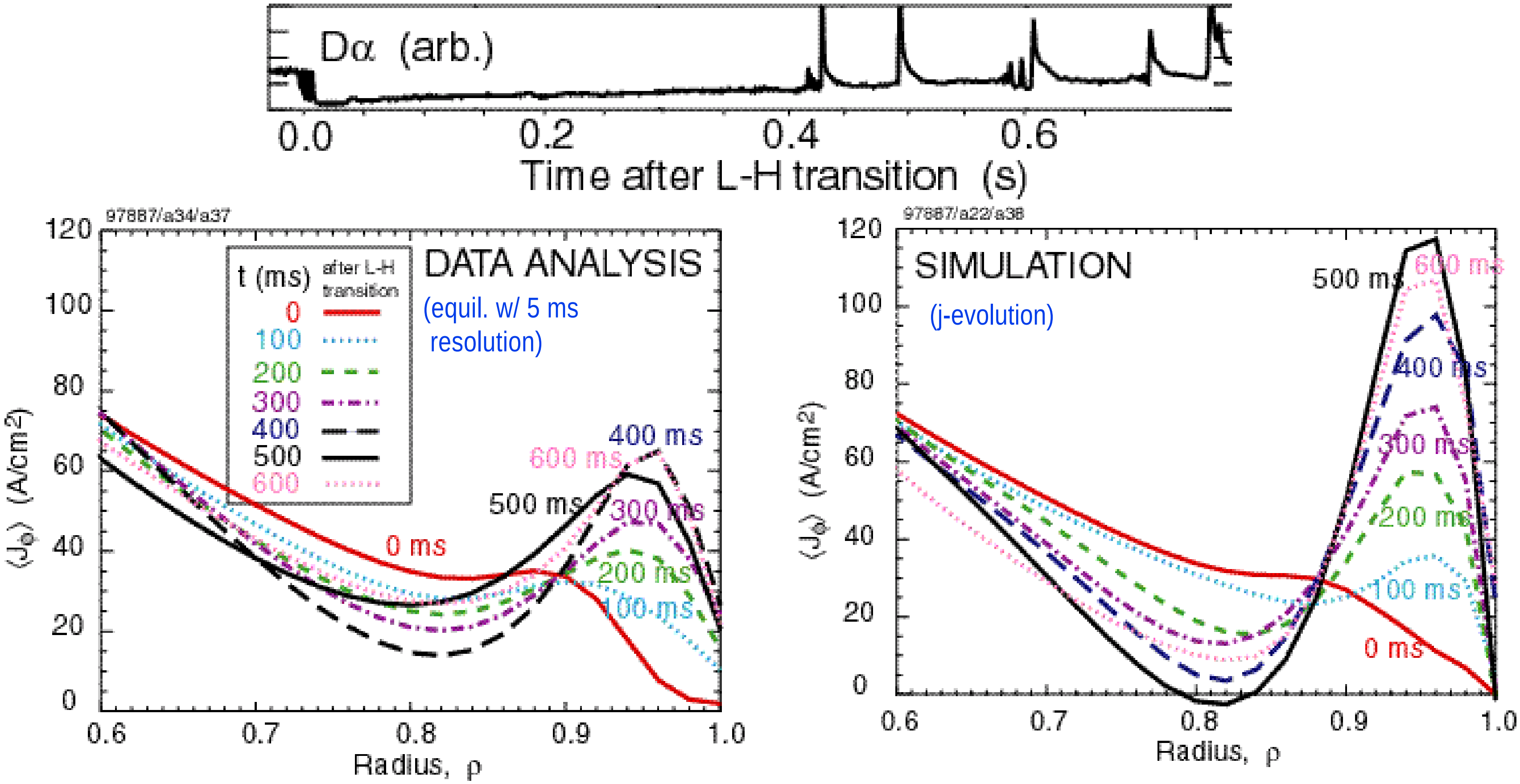
$C_{boot} = J_{edge} / J_{BS}$



- The improved confinement from the edge transport barrier leads to large p and large J_{edge} which often drive MHD instabilities terminating the discharge or reducing the performance
- Removing 2nd stability access will reduce edge p and amplitude of ELM perturbation

COMPARISON BETWEEN EXPERIMENT ANALYSIS AND SIMULATION YIELDS REASONABLE AGREEMENT ON GROWTH OF EDGE CURRENT

(MURAKAMI, IAEA TCM on Steady-State Operation, Fukuoka, Japan,1999)



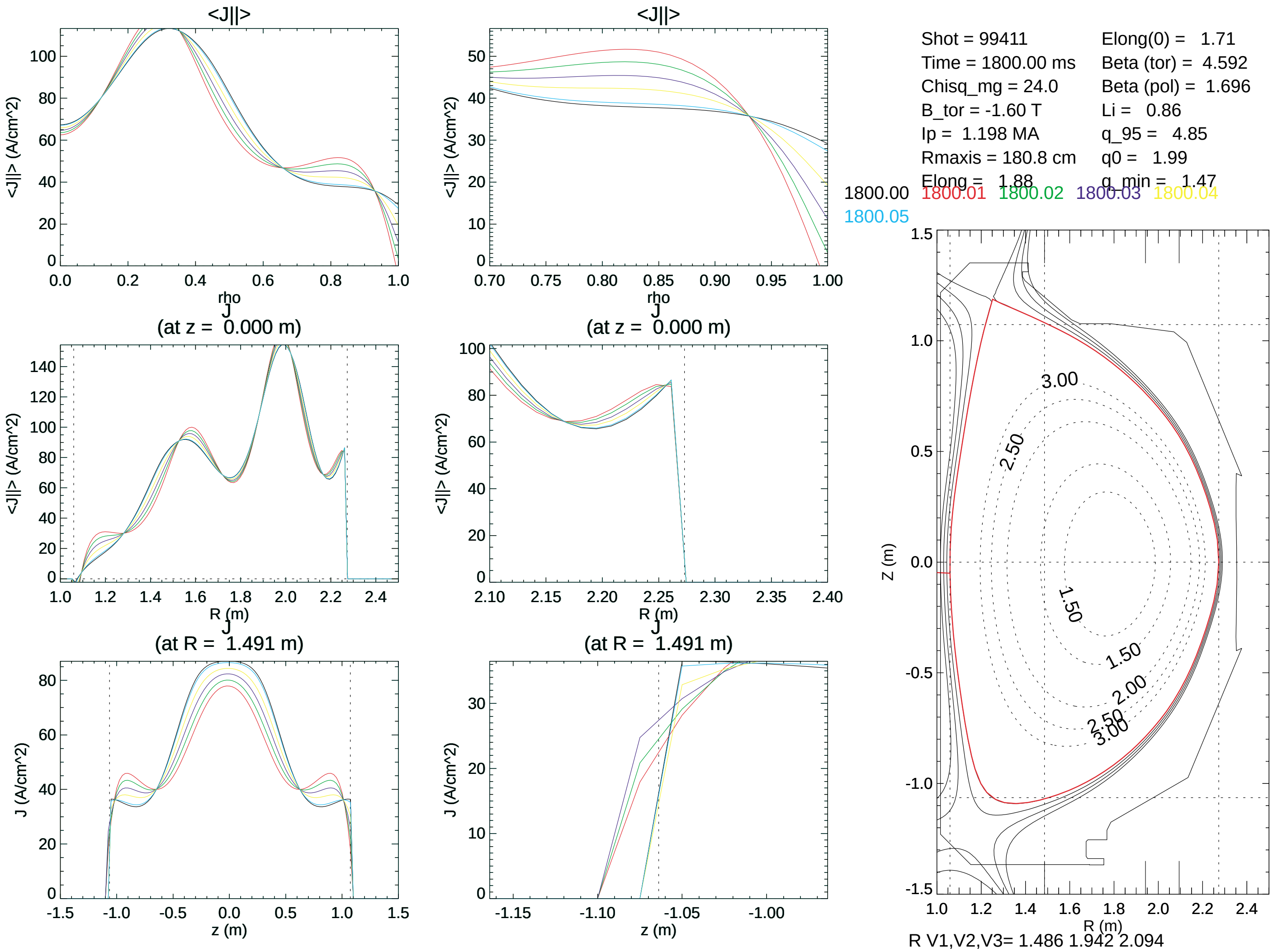
- **We would like to follow the evolution of these currents experimentally.**
- **So need resolutions ~ 10 - 10 A/cm²**

Characterizing these edge currents will require substantial precision in the measurement

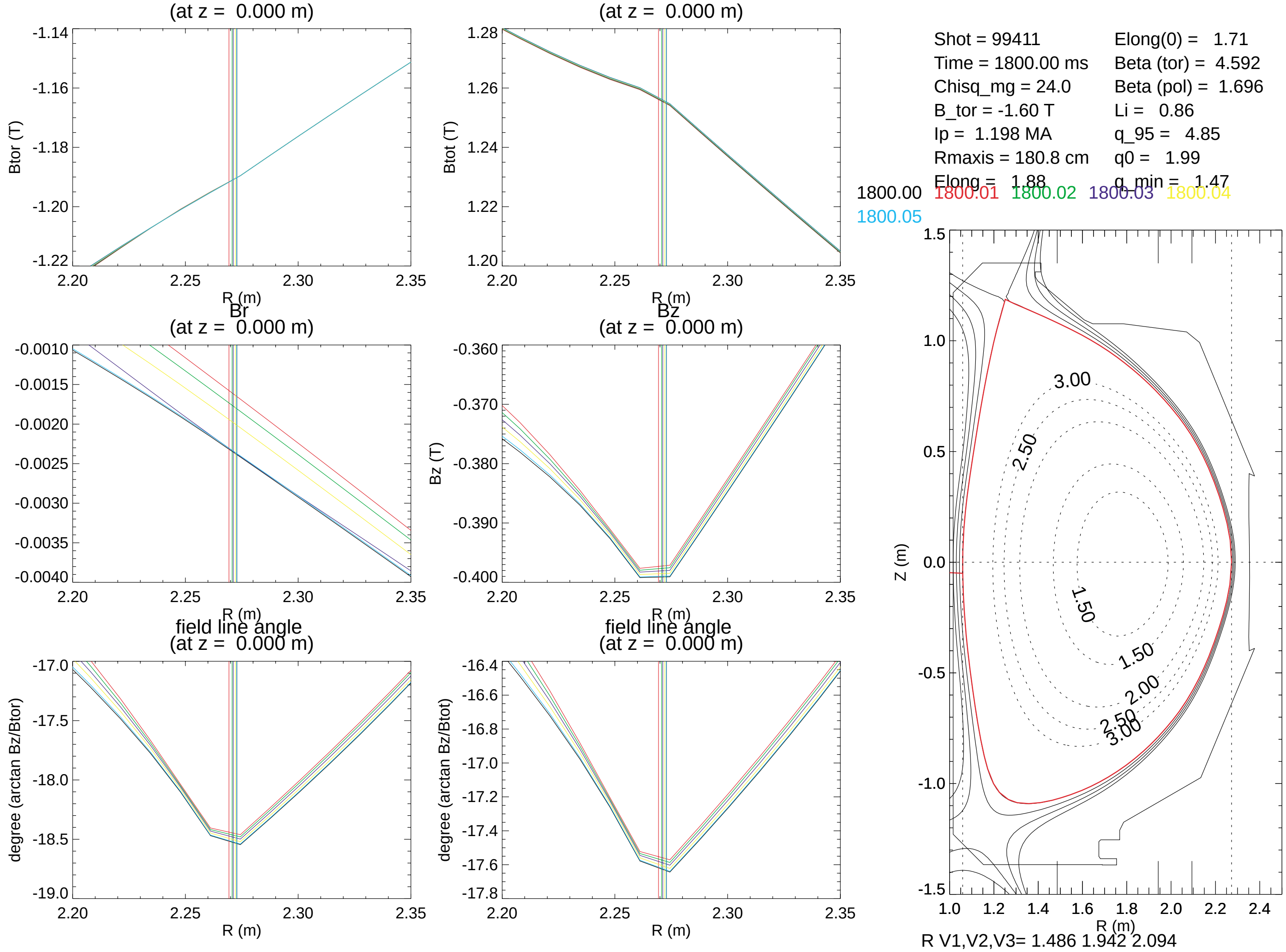
- **Examined several AT-relevant shots to see whether an edge current variation would be observable**
  - **95983 - hi performance 1.6 MA /2.1 T SN**
  - **98549 - high density 1.2 MA /1.6 T DN**
  - **99411 - lower density 1.2 MA /1.6 T DN**
- **Series of EFIT runs with edge (rho= 0.8 - 1.0) perturbations and outer MSE constraints turned off to mimic edge currents in the range of**

  10-30 A/cm2 (rho= 0.8 - 1.0)
- **Look in midplane (R0 trajectory) and near separatrix (V-1 trajectory)**
- **Resultant pitch angle changes of 0.1-0.2° observed, consistent with earlier crude estimates.**
- **Focus on <u>H-mode edges</u> as they represent the most challenging case.**

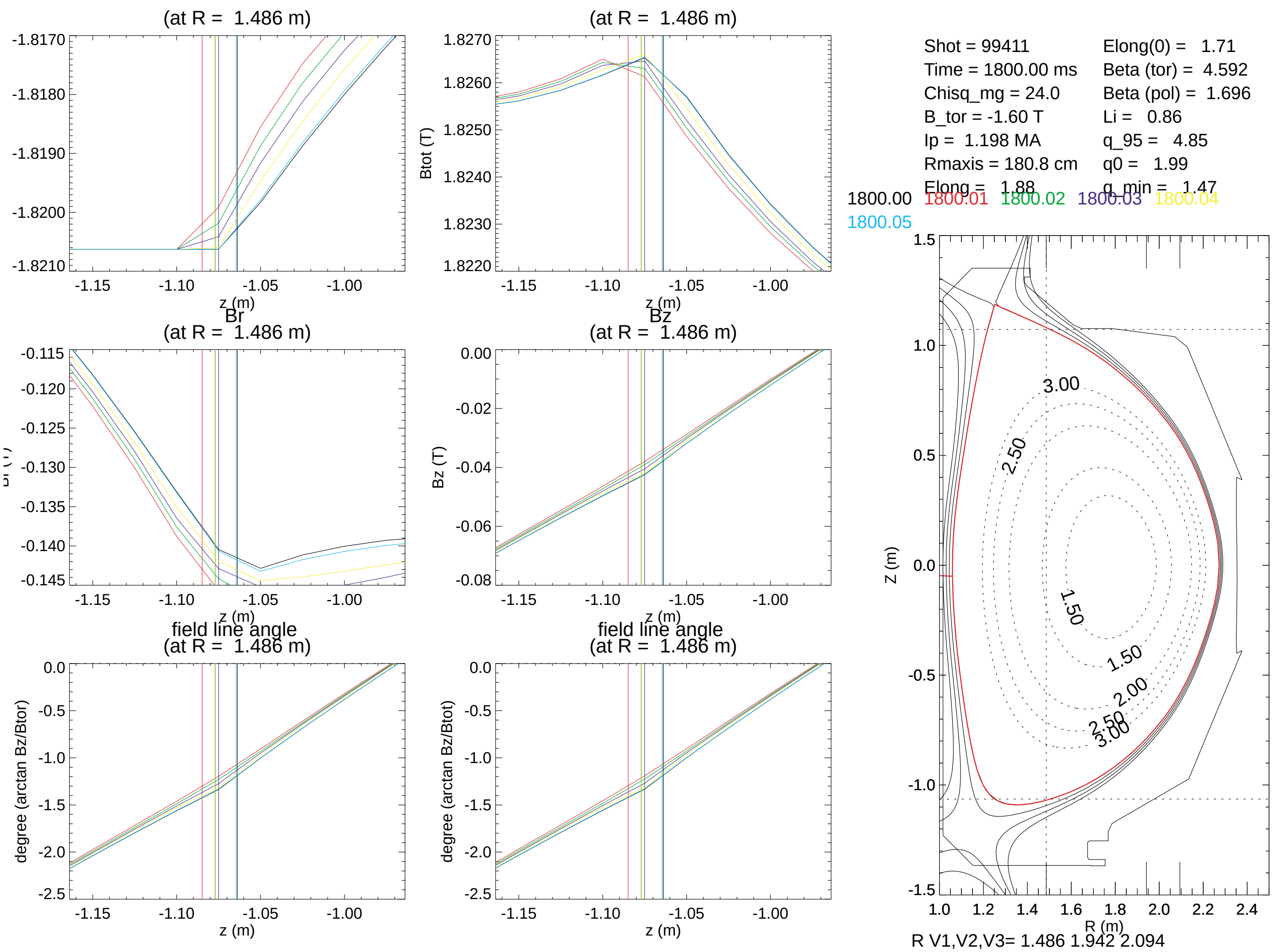
Variation of edge current for 99411



Midplane pitch angle changes by ~0.1°



Flux expansion near separatrix makes pitch angle resolution about 2x better using V-1 trajectory

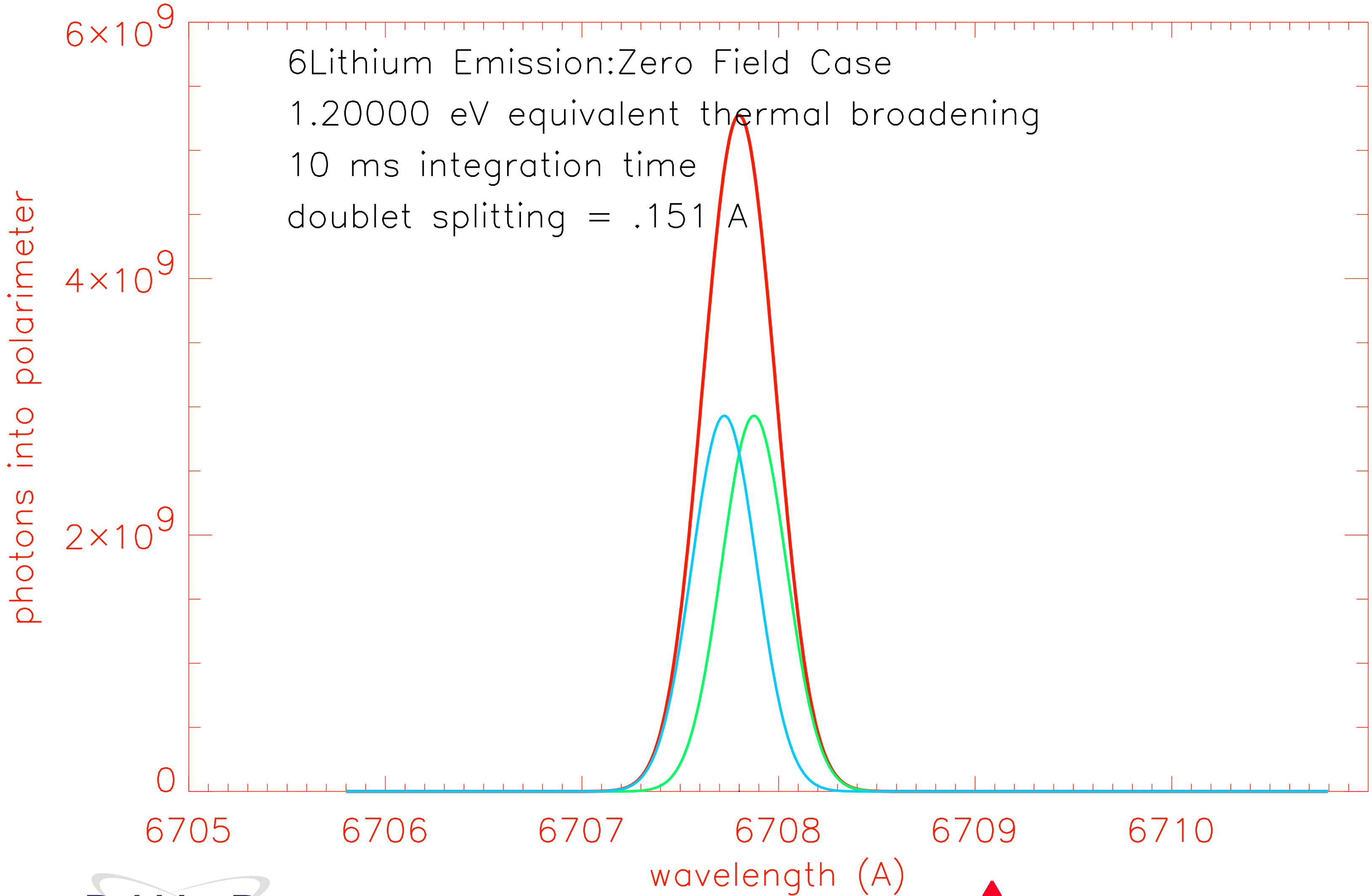


Method- inject LIBEAM, analyze the direction of polarization of emitted resonance radiation in edge region to determine precise angle of field line

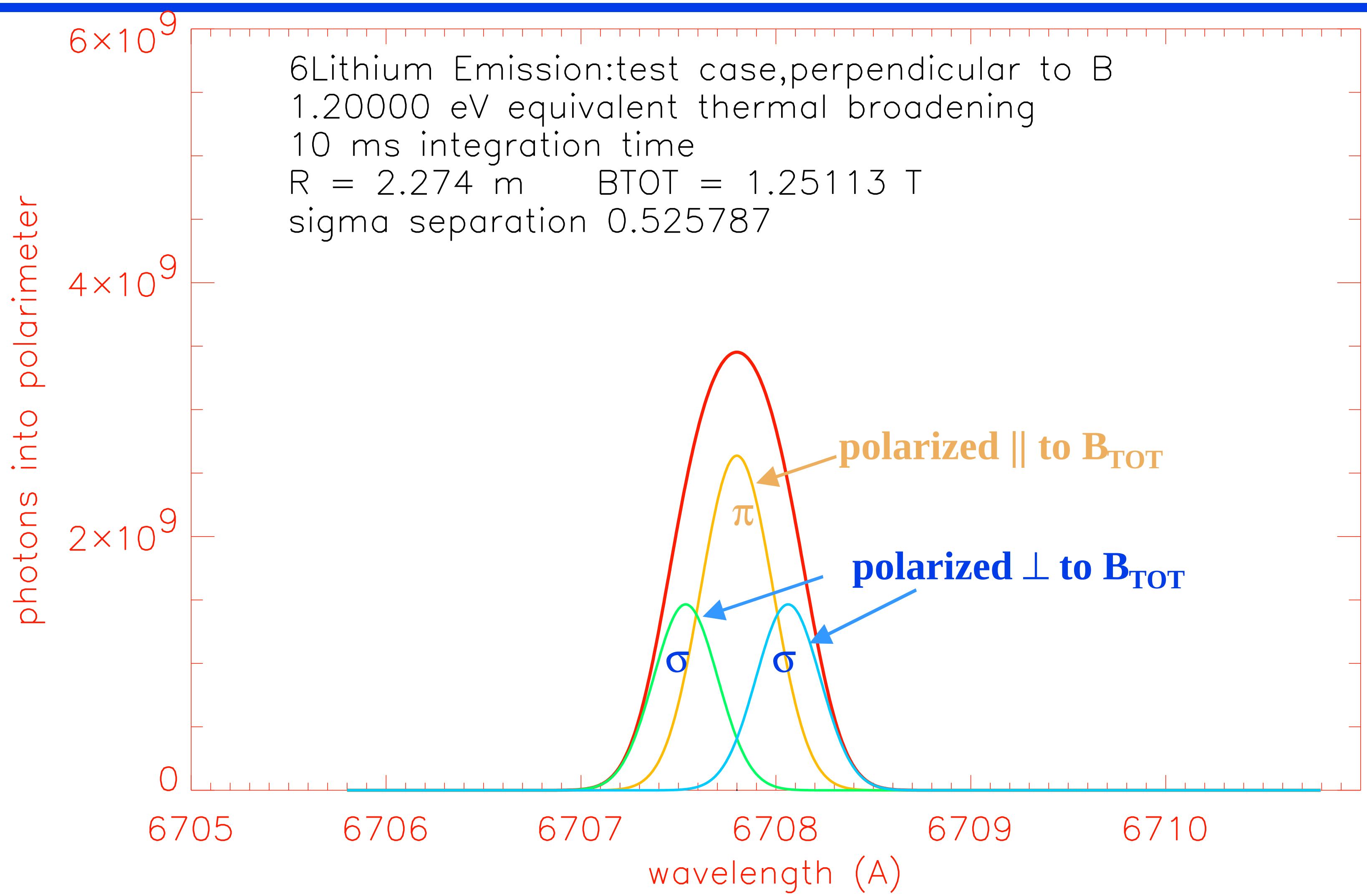
- **LIBEAM: 30 kV , 5-20 mA neutral equivalent current, 1-2 cm diameter.**
- **In magnetic field, Li 2S-2P resonance line splits up into components associated with non-degenerate magnetic sublevels due to Zeeman effect.**
- **these components have well determined splitting and polarization characteristics.**
- **Wide spacing of 2S, 2P states ensures no Stark mixing, no electric field sensitivity/ambiguity - measurement is purely a B-field effect.**
- **Small diagnostic beam + large excitation rate = good signals, good spatial localization.**

Li resonance doublet:

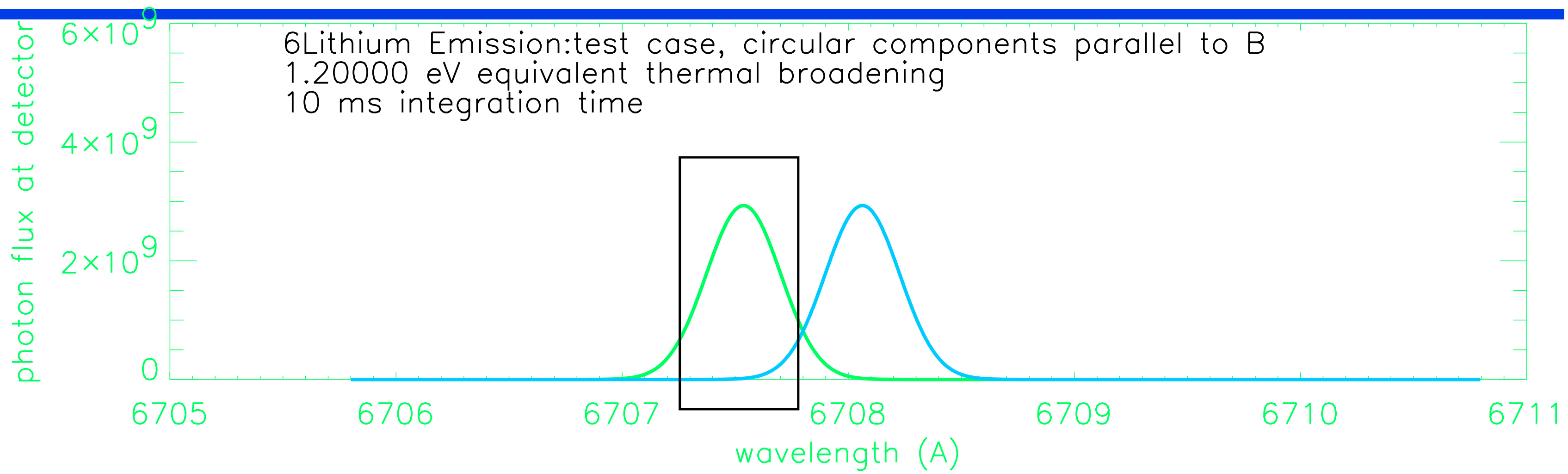
Shot 77411 with B-Field turned off

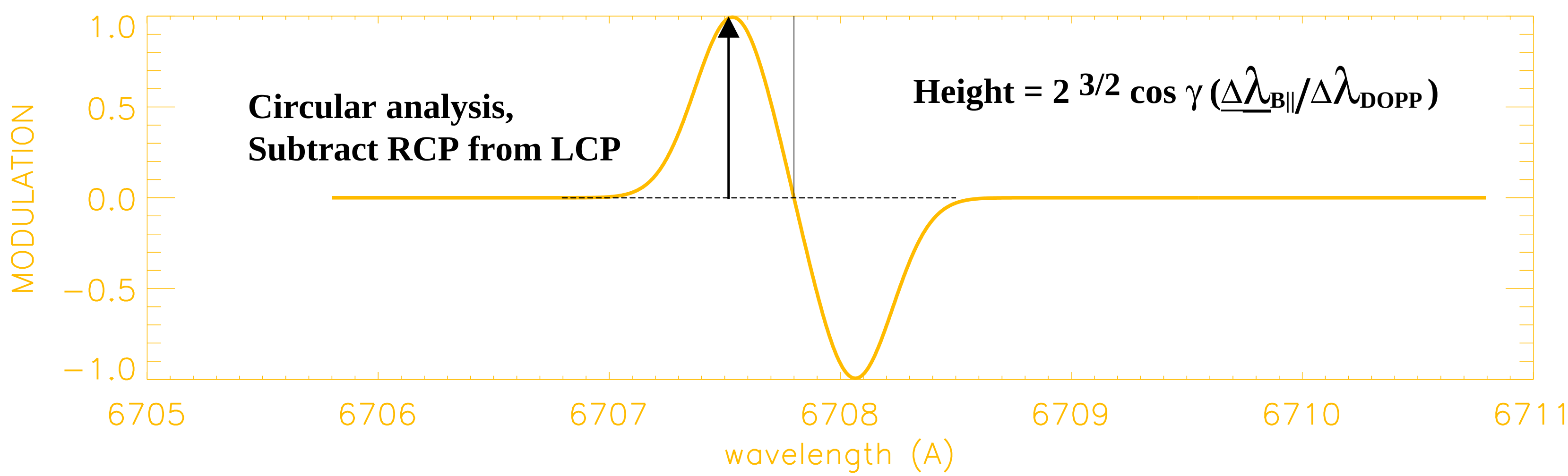


For finite B, get Zeeman triplet.
Viewing perpendicular to B: three linearly polarized components



Viewing parallel to B: two circularly polarized σ components





Polarization Analysis using PEMs

- **Can using optics analogous to existing MSE optics to analyze Stokes parameters, polarization state of beam as function of spatial location.**
- **Analysis similar to MSE.**
- **Analyze either polarization angle, separation, or ellipticity**
- **Must do spectral as well as polarization analysis.**
  - **Many other possible approaches: static polarimetry (Voslamber), difference of circularly polarized line profiles to determine field component in direction of observation (Huang), fast Fabry-Perot +FFT correlation technique(Kuramoto)**

Modeling results show there is enough beam to attempt these measurements

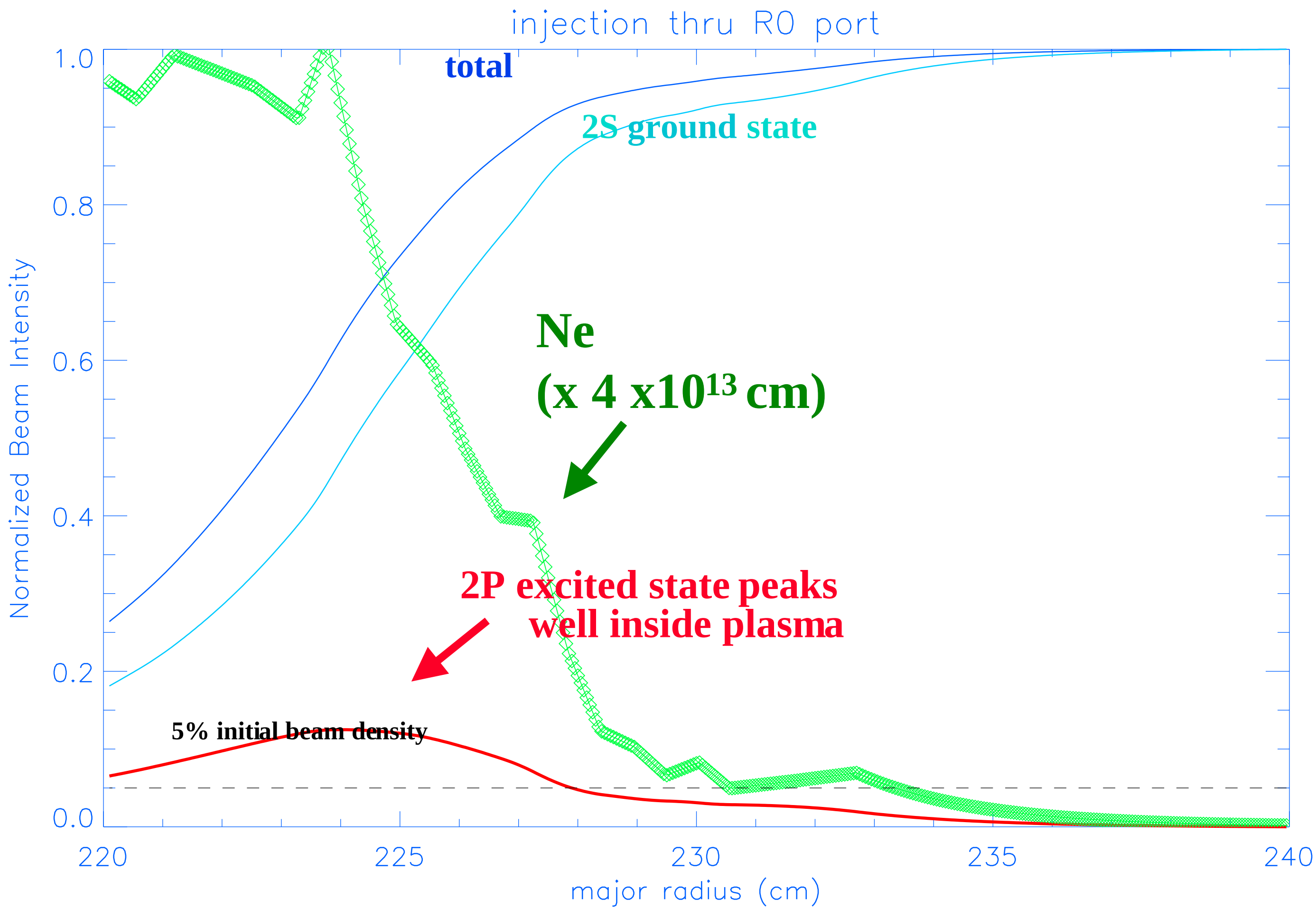
- **Reactivated 8-state collisional-radiative Lithium penetration code.**
  - Calibrated on TEXT, DIII-D Libeams
- **Use Thomson, EFIT inputs for code runs on various trajectories**
- **Get 5-10% in 2P state into psin of 0.7-0.8 in midplane**
  - **(note emission cross-section is about 500 x Dalpha)**
- **For beams we achieved 5 years ago, expect emissivities of 5×10^{14} - 10^{15} photons/sec/cm^3. For realistic solid angles, emission volumes, and transmission efficiencies this translates to 5×10^{8} - 10^{9} photons/sec into polarimeter.**
- **Statistical error consistent with required spatial and temporal resolutions. (10^{-3} in 1-10 ms, 5mm x 2cm emission area)**
- **Systematic errors should be better than for existingMSE**
  - **Injection prior to plasma permits in-situ offset calibration**

Injection in midplane and tangential viewing gives good radial resolution

- Tradeoff-beam penetration vs flux expansion for light collection
- Historically, used near-radial injection at 75R0, tangential view.

Excellent access to edge region using midplane injection

- **Good penetration using existing 30 keV beam energy**



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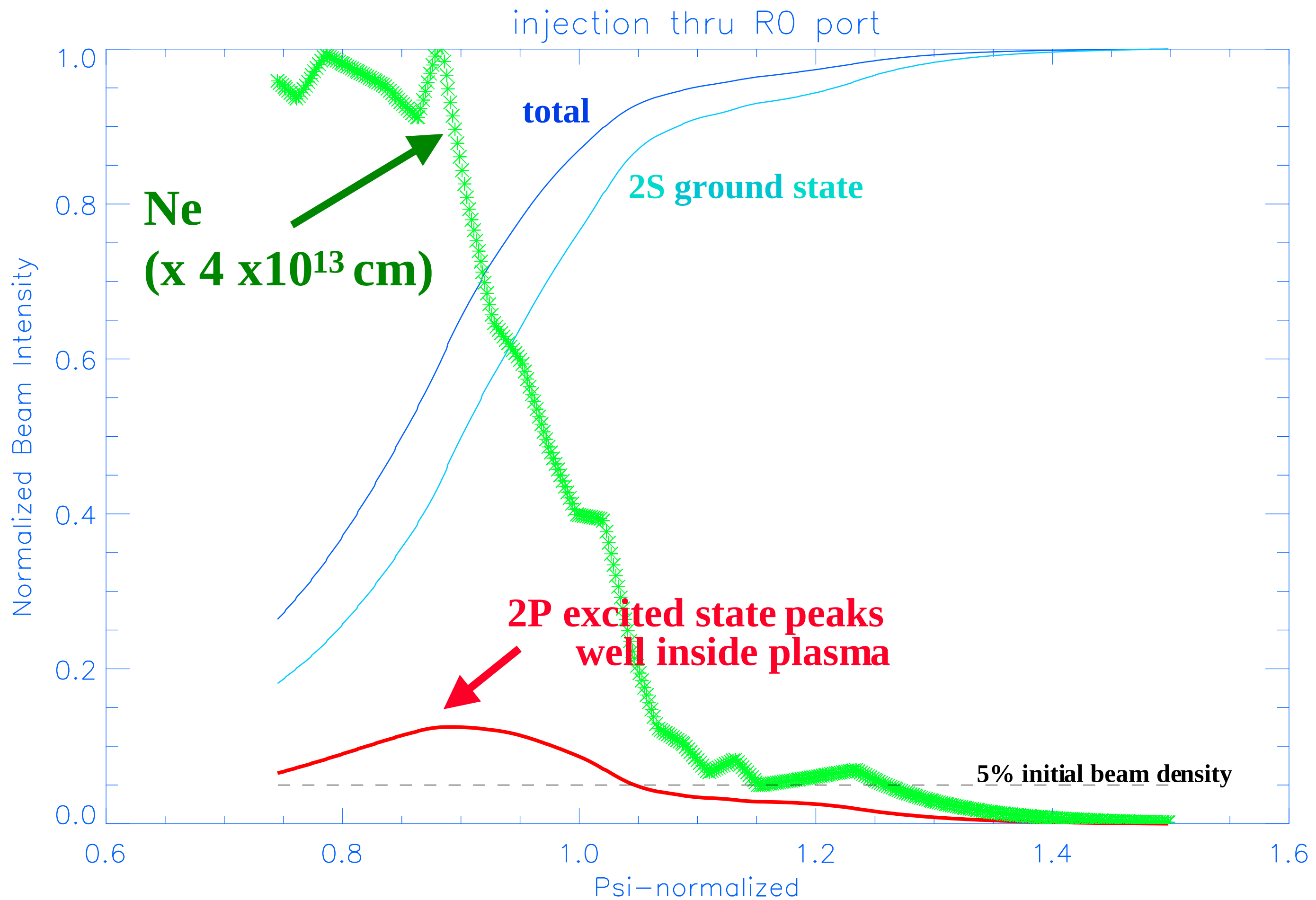
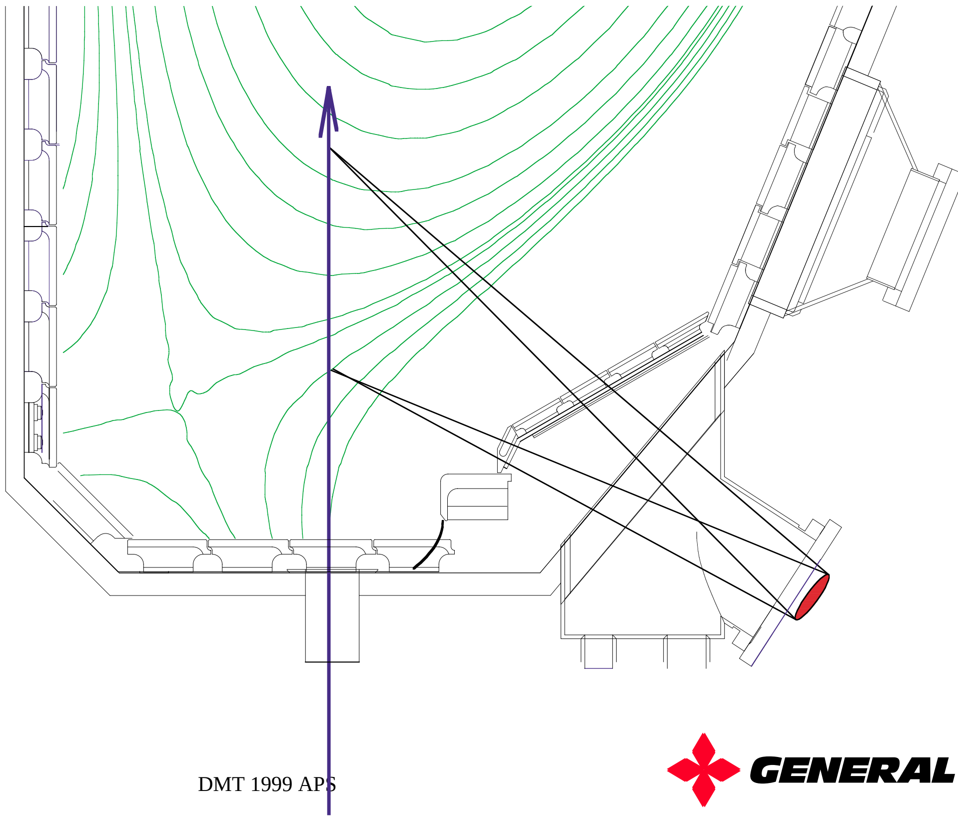
Excellent access to edge region using midplane injection

- **Good penetration using existing 30 keV beam energy**



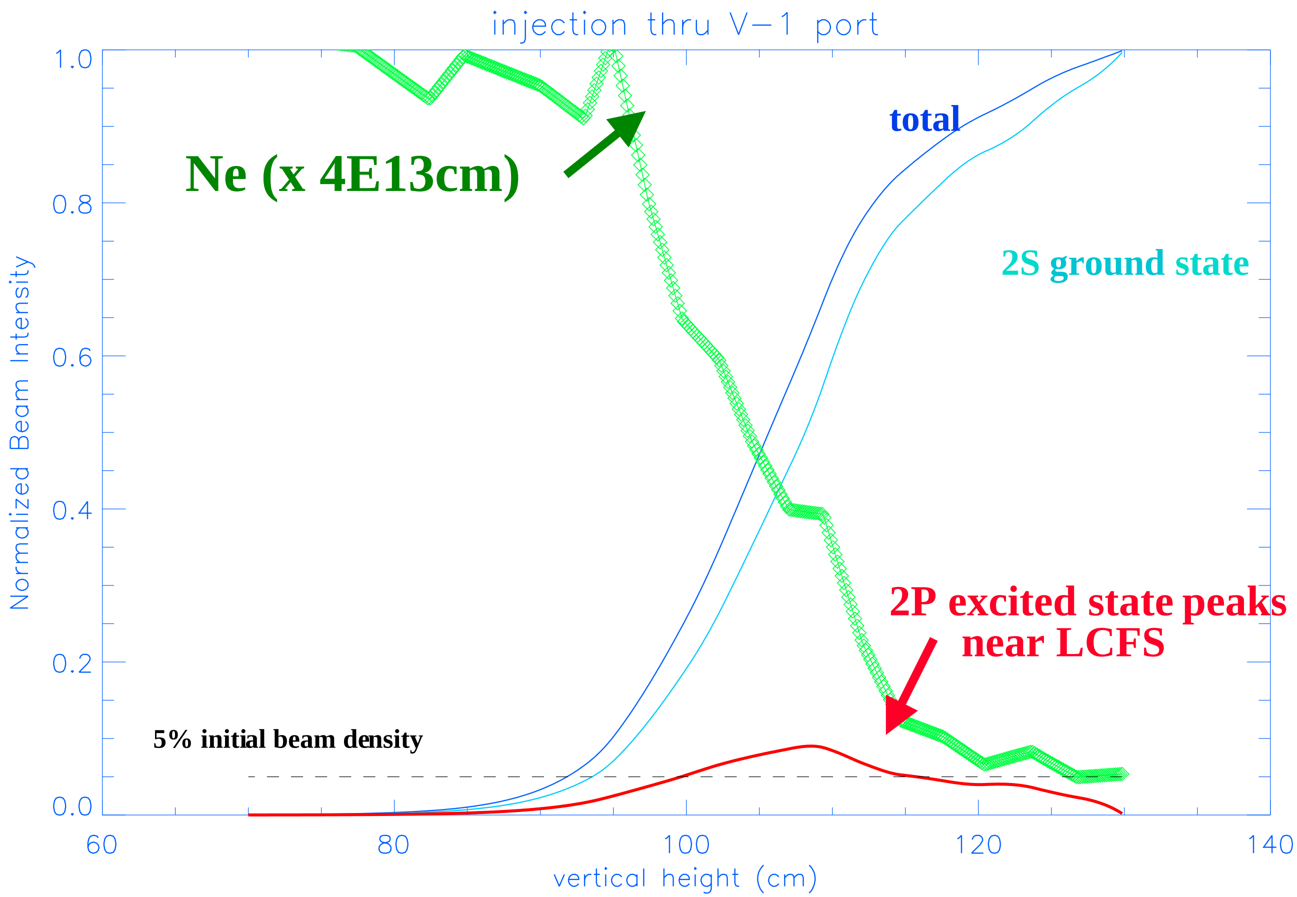
Vertical (V-1) injection offers some exciting possibilities

- Tradeoff beam penetration vs flux expansion, better spatial resolution
- Small (2-cm) slot required in divertor for R-3, might also consider R-2
- Some beam development required for vertical injection (seems possible)
- Opposing V+1 port at 30° give excellent access for counter-propagating laser beam.



Vertical injection using V-1 port

- Somewhat worse attenuation due to longer penetration distance.
- May be compensated for by larger collection area (spatial constraint), better Zeeman splitting (larger average B_{TOT})



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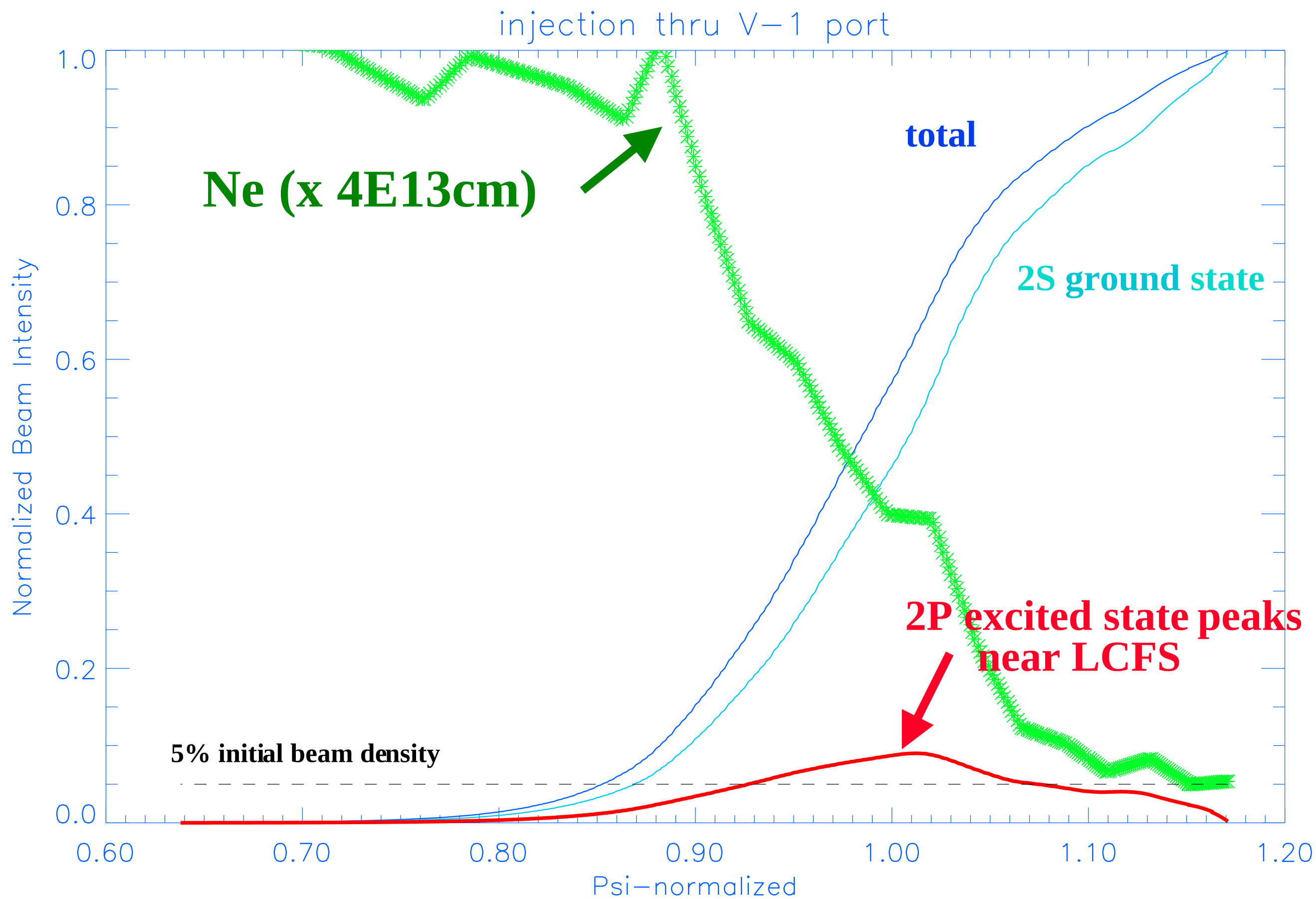

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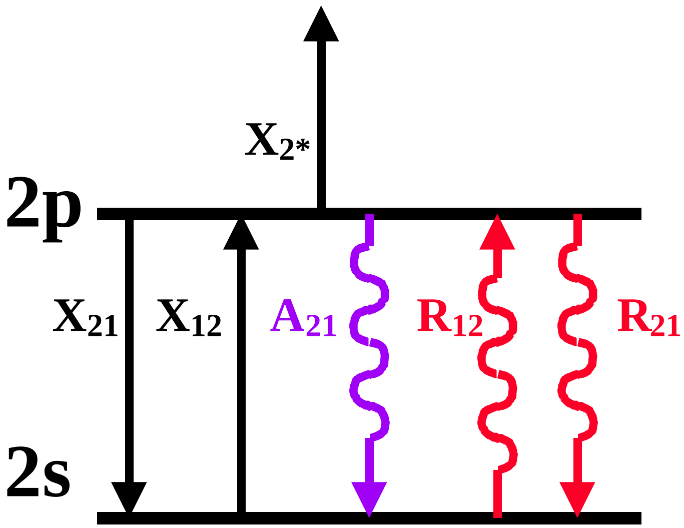
Enhancements using laser pumping

- **Can't do laser polarization analysis, because of finite lifetime effects (ala TEXT results).**
- **However can enhance emission levels, using laser as a supercharger**
  - **especially useful on open field lines,where collisional rate is low.**
- **Must use collinear laser beam of sufficient intensity, proper spectral overlap with atomic velocity distribution.**
- **Estimate enhancement factors of 2-10 in the region of interest should be achievable given the proper laser.**
  - n(2P)/n(2S) increases from 0.05-0.2 to ~ 3 (~ g_p/g_s)
  - tradeoff-enhanced ionization from 2P state results in larger beam attenuation & lower signals farther in.

Laser power required for saturation



Example:

1 eV beam temperature
=>0.21° A Doppler width
Te = 500 eV
Zeff = 2.5, presume C^{6+}

- **X_{12} (collisional (e^-, p^+, C^{6+}) excitation)**
  = 2.2 x 10E-6 n_e13 (Zeff=2.5)
- **X_{21} (collisional deexcitation)**
  = 6.6 x 10E-7 n_e13 (Zeff=2.5)
- **X_{2*} (collisional quenching & ionization)**
  = 8.75 x 10E-7 n_e13 (Zeff=2.5)
- **A_{21} (spontaneous emission)**
  = 3.72 x 10E7 s-1
- **R_{12} = I(ν) B_{12}(ν) (stimulated absorption)**
- **R_{21} = I(ν) B_{21}(ν) (stimulated emission)**

Reasonable enhancement factors require high laser power

Defining F_s as saturation factor

$$\frac{N_P}{N_S} = \frac{X_{12} + R_{12}}{X_{21} + A_{21} + R_{21}} = F_s\left(\frac{g_P}{g_S} \equiv \frac{6}{2}\right)$$

Then the saturation laser intensity $I_s(l)$ (in W/cm2 - A) for that factor

$$I_s(l) = \left(\frac{8\pi hc^2}{l^5}\right)\left(\frac{1}{A_{21}}\right)\left(\frac{F_s}{1 - F_s}\right)\left[X_{21} + X_{2*} + A_{21} - \left(\frac{g_S}{g_P}\right)X_{12}\right]$$

$$= \left(110.4\ \frac{W}{cm^2 - A}\right)\left(\frac{1}{3.72x10^7}\right)\left(\frac{F_s}{1 - F_s}\right)\left[3.72x10^7 + 8.75x10^{-7}(n_e x10^{13})\right]$$

EXAMPLE:

1 eV beam temperature(0.21A)
Ne = 1 x 10e13
Fs = .9 => (Fs/1-Fs) = 9
=> 608 W/cm2

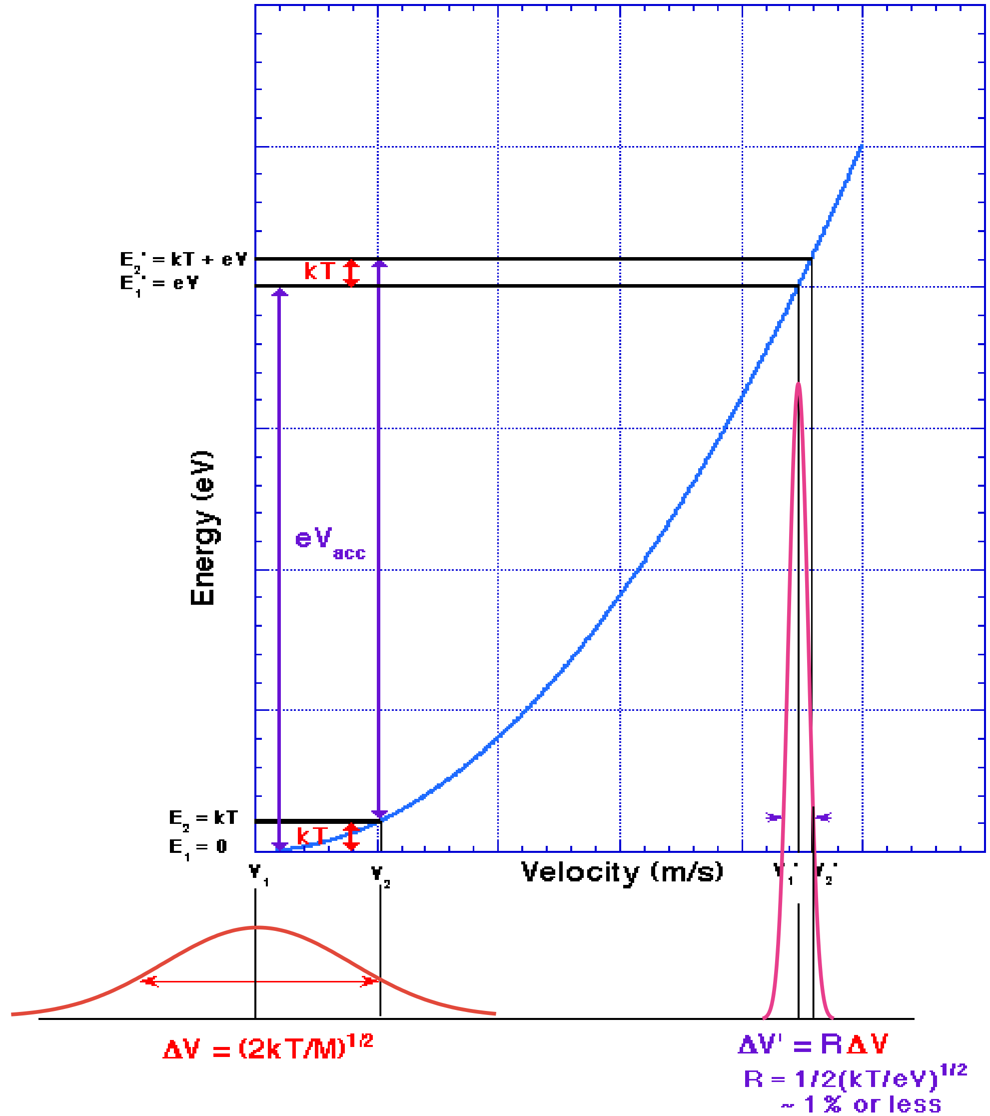
1 eV beam temperature(0.21A)
Ne = 5 x 10e13
Fs = .5 => (Fs/1-Fs) = 1
=> 118 W/cm2

To achieve decent spectral overlap, rely on "Acceleration Cooling" of atomic beam

- **Consider beam of thermal ions emitted by an ion source, temperature kT**
- **Acceleration of beam to energy eV results in the velocity distribution <u>along the beam direction</u> being narrowed by a large factor** (Anton, <u>PRL</u> 40, 10, 1978)
    - **$R = 1/2(kT/eV)^{1/2} \sim 2 \times 10^{-3}$**
- **Doppler widths can be reduced to order of natural linewidth of resonance line in beam propagation direction.**
- **Laser spectral intensity necessary to saturate transitions decreases by same factor:**
- **Need ~ 1 W/cm2 as opposed to ~ KW/cm2.**
- **These intensities are presently achievable for Li 670nm line, much tougher for Da 651nm line.**
- **<u>Laser must be coaxial with beam</u> or effect is lost.**

Acceleration Cooling

- **Ion gas of temperature T**
  - **$V_1 = 0$**
  - **$V_2 = (kT/2M)^{1/2}$**
  - **$\Delta V = 2\,(V_2 - V_1) = (2kT/M)^{1/2}$**
- **Acceleration through voltage V**
  - **All particles gain energy eV**
  - **$V_1' = (2eV/M)^{1/2}$**
  - **$V2' = (2eV/M + kT/2M)^{1/2}$**
- **Longitudinal velocity spread decreases substantially:**
  - **$\Delta V' = V2' - V1' = R\Delta V$**
  - **$R = 1/2(kT/eV)^{1/2}$**
  - **LIBEAM: E=30keV, T=1eV,**
    R= 5.7 x 10E-3
  - **Equivalent doppler width of**
    1.2 x 10E-3 A
- **A strictly kinematic effect:**
  - **No collisions involved**
  - **No transfer of momentum to transverse T.**

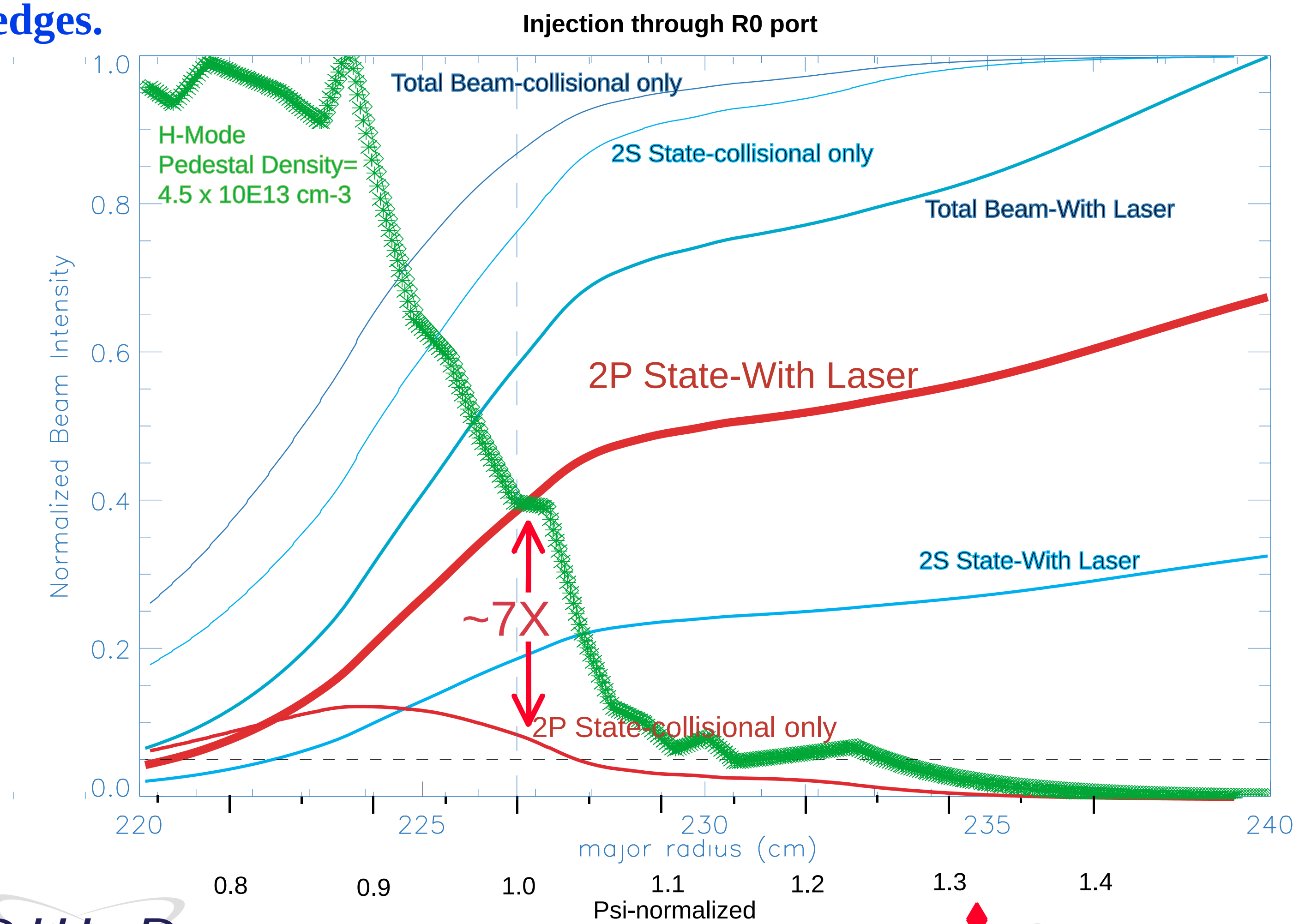


Laser Possibilities

- **Historically have used DCM dye/Ar^+ laser combination**
  - **0.1-1 W CW output at 670 nm range; worked but was very finiky, cumbersome and hazardous (carcinogens+DMSO…)**
- **Ti:Sapphire looks attractive**
  - **Higher output powers, somewhat wider bandwidths achievable. (but required wavelength is on edge of output power curve). No saturation or thermal lensing effects, output power limited by available pump laser power. Less babysitting required.**
  - **Several vendors now make reliable, off-the shelf units having more than enough power, at somewhat shorter wavelengths than are required**
- **Need to hit 6729Å for this to work.**

Results of modeling:Laser Enhancement of fluorescence should significantly improve the measurement of edge currents

Near saturation (Fs=0.9), we are able to improve the 2P fluorescence level substantially (compare two red lines) well inside the LCFS, even for high-density H-mode edges.



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Conclusions

- **Polarization analysis of LIBEAM collisionally induced fluorescence offers a powerful, relatively low-cost technique for studying AT-relevant edge current distributions.**
  - Utilizes mothballed accelerator; minimal development required. Existing MSE active polarization analysis setup looks attractive.
- **Laser Enhancement using Doppler-shifted coaxial beam has several advantages**
  - Large enhancements inside LCFS, even in H-mode.
  - Also permits measurements on open field lines.
- **We hope to begin making measurements (probably without the laser) in time for the 2001 campaign.**