Results on Laser Plasma Generation at MPP

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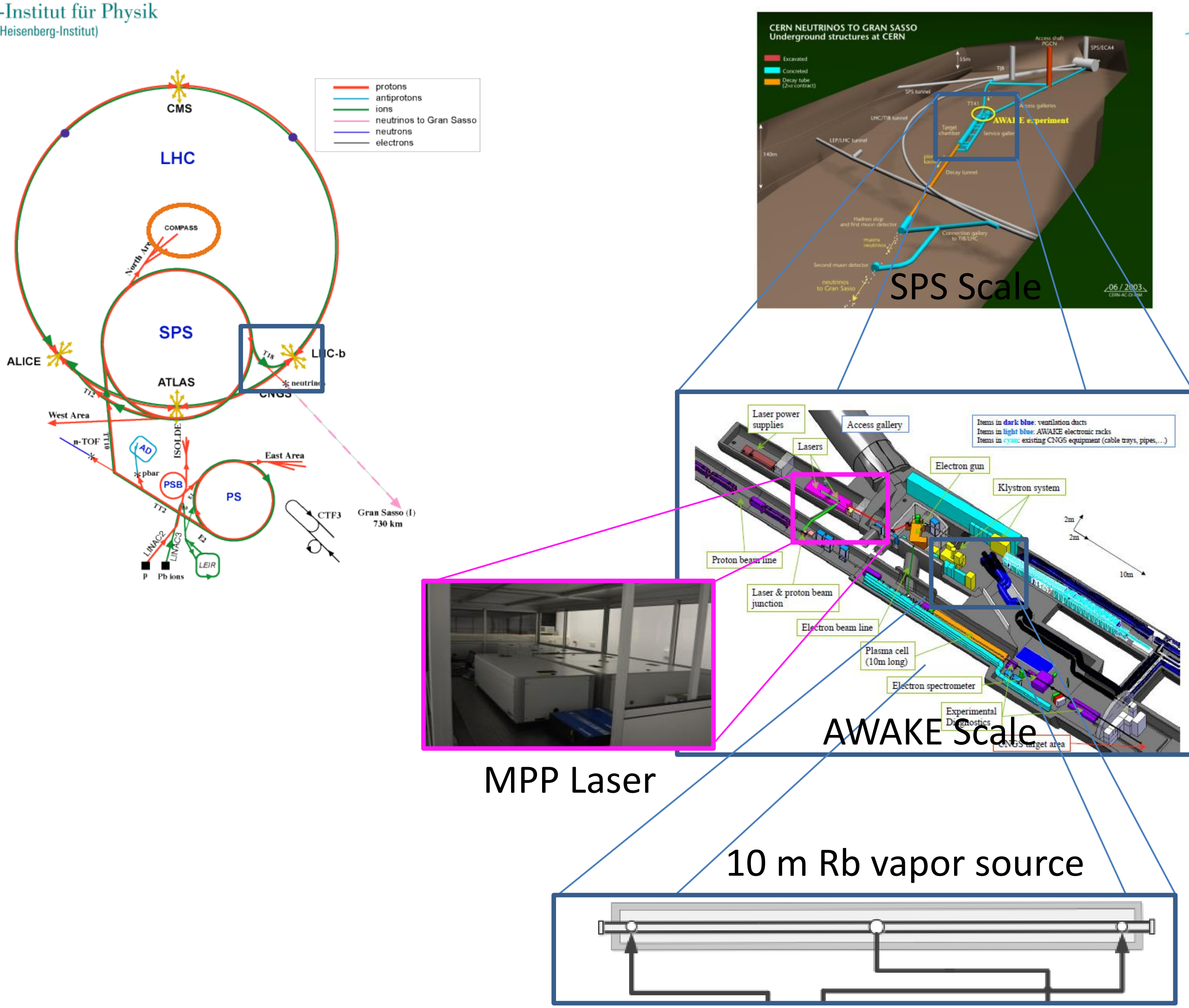
AWAKE Plasma Source at CERN



Photoionization Requirements for AWAKE

Ionization laser must do three things:

- Provide a singly ionized plasma from the Rb vapor that has a density profile identical to that of the vapor
- The radial extent of the plasma must be greater than trajectory of plasma electrons
- Seed the Self Modulation Instability (SMI) by turning on the plasma at a timescale at or shorter than the plasma period in the middle of the proton beam

Self Modulation of Proton Beam

- Laser is set near the peak in time of the proton beam
- Ionization occurs in timescale less than plasma period
- Sudden change in plasma density seeds self modulation instability

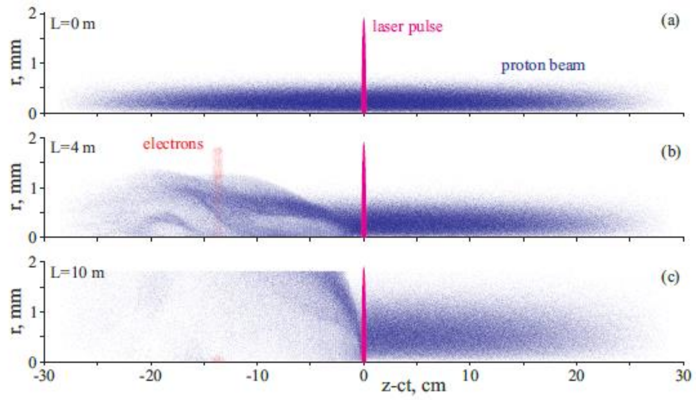
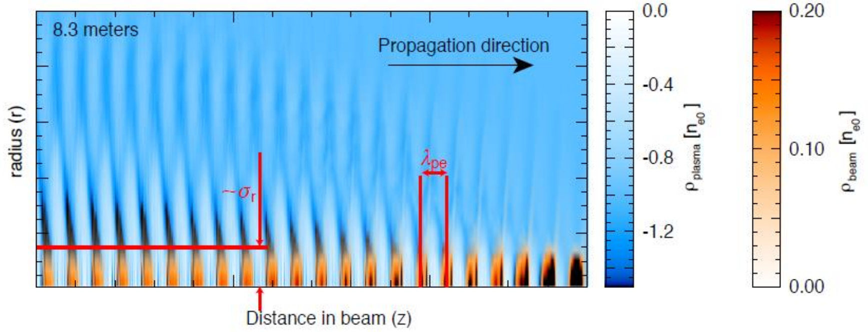


Fig. 5: Distribution of the beams at (a) the entrance to the plasma, (b) after propagating 4 m in the plasma, and at (c) the exit from the plasma cell. Protons are blue, electrons are red and the laser pulse is the line at $z - ct = 0$. The laser pulse seeds the SMI for the proton bunch.



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Statement of the Problem for Ionization of Rb Vapor and Laser Propagation

Objective

To understand over source on a timescale of ~100ps timescale:

- Electron density, ρ_e
- Laser field, $\vec{E}$

Maxwell's Equations in Nonmagnetic Medium

$$\vec{\nabla}\cdot\vec{D} = \rho_{\text{Total, Free}} \qquad \vec{\nabla}\cdot\vec{B} = 0$$

$$\vec{\nabla}\times\vec{E} = -\frac{d\vec{B}}{dt} \qquad \vec{\nabla}\times\vec{B} = \mu_0\left(\vec{j}+\frac{d\vec{D}}{dt}\right)$$

$$\vec{D} = \varepsilon_0\vec{E}+\vec{P}$$

$\vec{P}$ → Average 'macroscopic' response of bound electrons

Laser Field Wave Equation

$$\nabla^2 \vec{E} - \frac{1}{c^2}\frac{d^2\vec{E}}{dt^2} = \mu_0\left(\frac{d\vec{j}}{dt} + \frac{d^2\vec{P}}{dt^2}\right) + \left(\frac{\rho - \vec{\nabla}\cdot\vec{P}}{\varepsilon_0}\right)$$

Homogeneous Part

Transverse Spatial inhomogeneity (for TEM)

- As a simple model we can ignore the div P term and source terms.

$$\vec{P} = \varepsilon_0\left(\chi^{(1)}\vec{E} + \chi^{(2)}\vec{E}\vec{E} + \ldots\right)$$

$$\chi_{bound} = \frac{Ne^2}{m\varepsilon_0}\left(\frac{f_1}{\omega_{01}{}^2 - \omega^2 - i\Gamma_1\omega} + \frac{f_2}{\omega_{02}{}^2 - \omega^2 - i\Gamma_2\omega}\right)$$

Material Dispersion Responses

- Lorentz Model for bound states
- Drude model for free charges
- Damping based upon energy losses
- Need to track densities for ionized states
- Then can input these values dynamically into propagation model

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Rubidium Valence Electronic States

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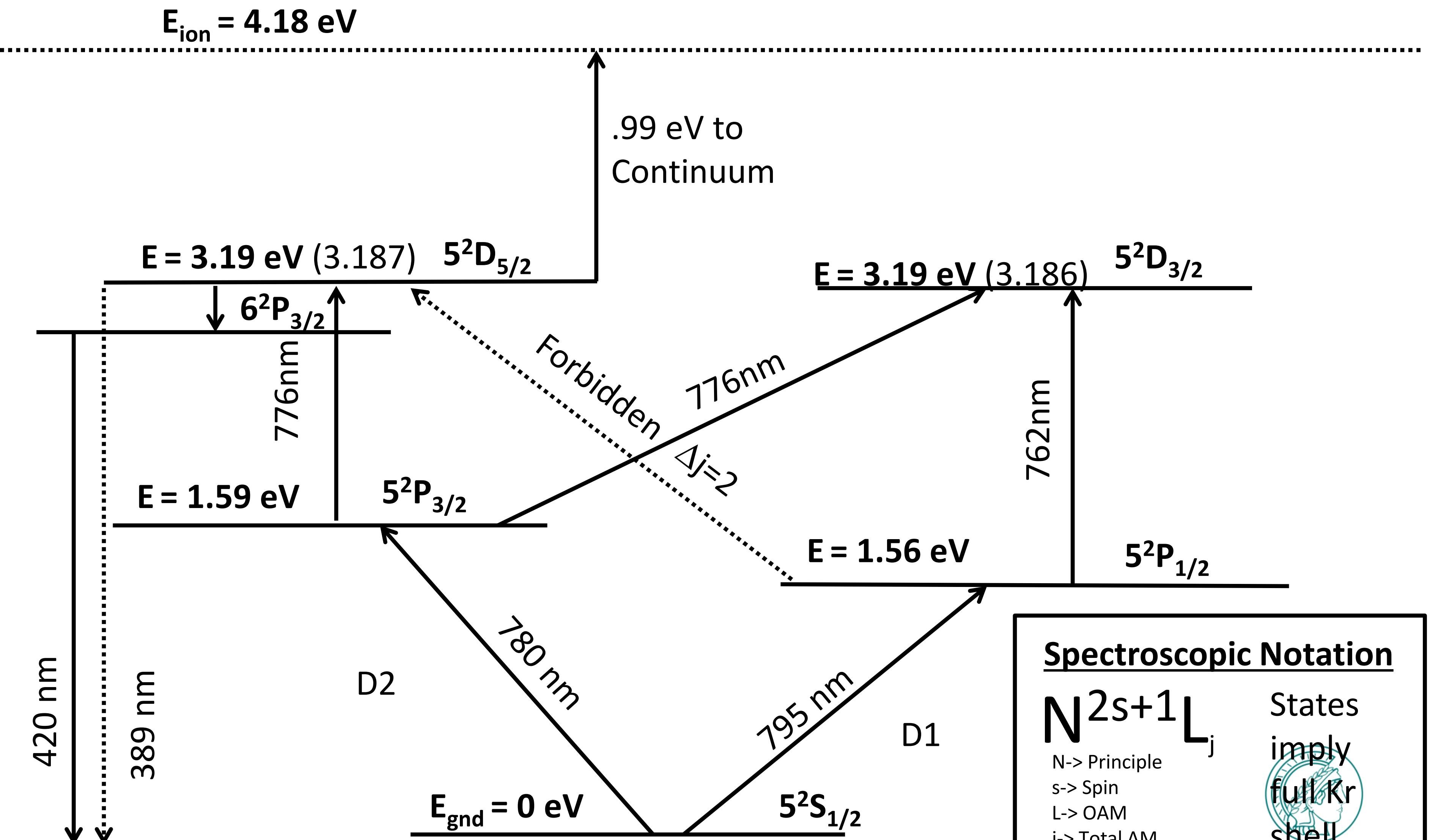

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Timescale for Ionization Set by Keldysh (Adiabaticity) Parameter

Keldysh Parameter compares electron dynamic timescale to laser field period

$$I = \frac{U_{Laser}}{\pi \sigma_t w^2} \qquad E = \sqrt{\frac{2I}{c\varepsilon_0}} = \sqrt{2IZ_0}$$

$$\gamma = \frac{\omega}{\omega_t} = \frac{\omega\sqrt{2mU_I}}{eE} = \frac{1}{2K_0 F}$$

1. Popov, Vladimir S. "Tunnel and multiphoton ionization of atoms and ions in a strong laser field (Keldysh theory)." *Physics-Uspekhi* 47.9 (2004): 855.

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Regimes of Photoionization

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Valid for limits, order of magnitude accuracy

$$w(F,\omega) \propto \begin{cases} \exp\left\{-\frac{2}{3F}\left[1-\frac{1}{10}\left(1-\frac{1}{3}\xi^2\right)\gamma^2\right]\right\}, & \gamma \ll 1, \\ (K_0F)^{2K_0} \sim J^{K_0}, & \gamma \gg 1, \end{cases} \quad (2.4)$$

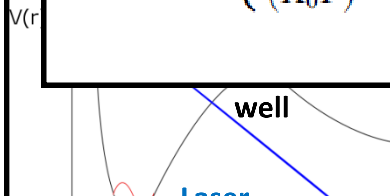
Non-Perturbative

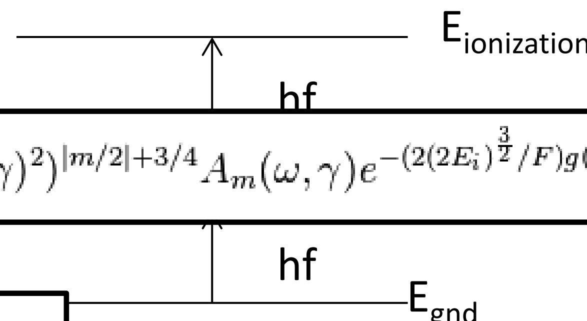
$$pE \sim U_I$$

Perturbative

$$pE \ll U_I$$

Doesn't





$$W_{PPT} = |C_{n^*l^*}|^2\sqrt{\frac{6}{\pi}} f_{lm} E_i (2(2E_i)^{\frac{3}{2}}/F)^{n^{*2}-|m|-3/2}(1+\gamma)^2)^{|m/2|+3/4} A_m(\omega,\gamma) e^{-(2(2E_i)^{\frac{3}{2}}/F)g(\gamma)}$$

Ionization

Valid for all Keldysh parameter regimes, accurate to ~10%

d Strength

Slow Field, Fast Electron Dynamics

Relative Time Scale

Fas
Slo

$$\gamma \ll 1$$

Nonresonant PPT model predicts >99.9 % ionization within laser pulse for AWAKE

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Pulse Propagation in the "Linear Regime"

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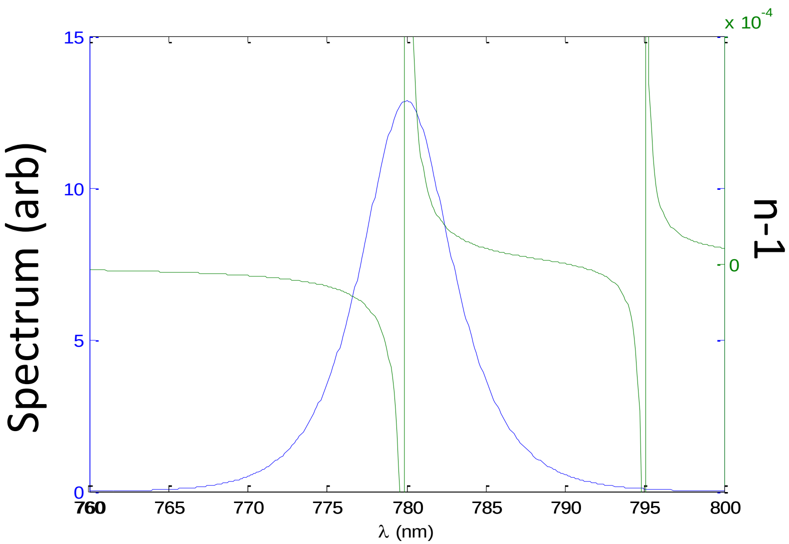
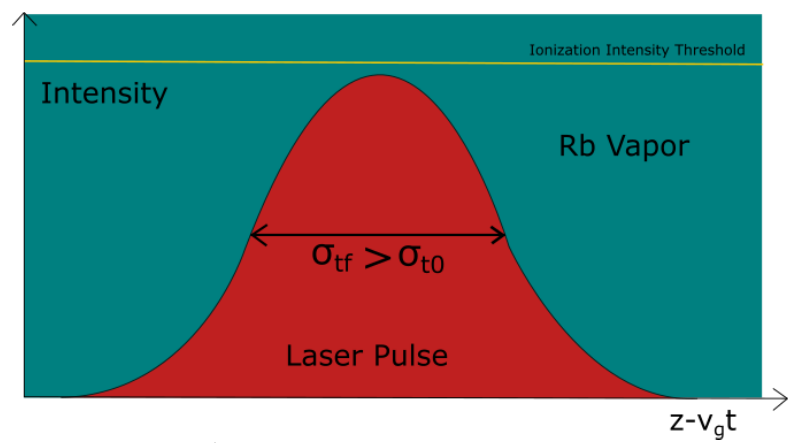
D1 and D2 lines dominate spectrum

$$\chi_{bound} = \frac{Ne^2}{m\varepsilon_0}\left(\frac{f_1}{\omega_{01}{}^2 - \omega^2 - i\Gamma_1\omega} + \frac{f_2}{\omega_{02}{}^2 - \omega^2 - i\Gamma_2\omega}\right)$$

$$k_{bound} = \frac{\omega}{c}\sqrt{1+\chi(\omega)}$$



2π differential phase shift on cm scale



Our initial fear: **Laser pulse stretching!!**

- Lowers Intensity!
- Lowers ionization probability

HOWEVER: Not the end of the story

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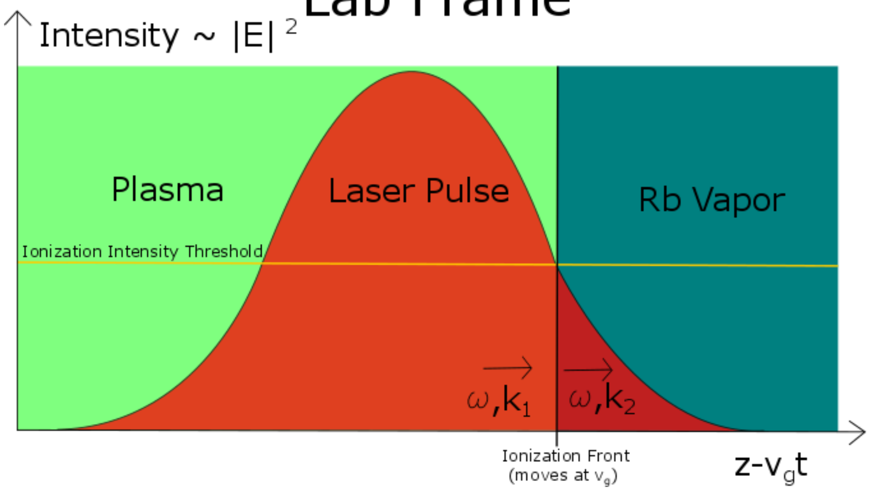
High Intensity Laser pulse

Lab Frame



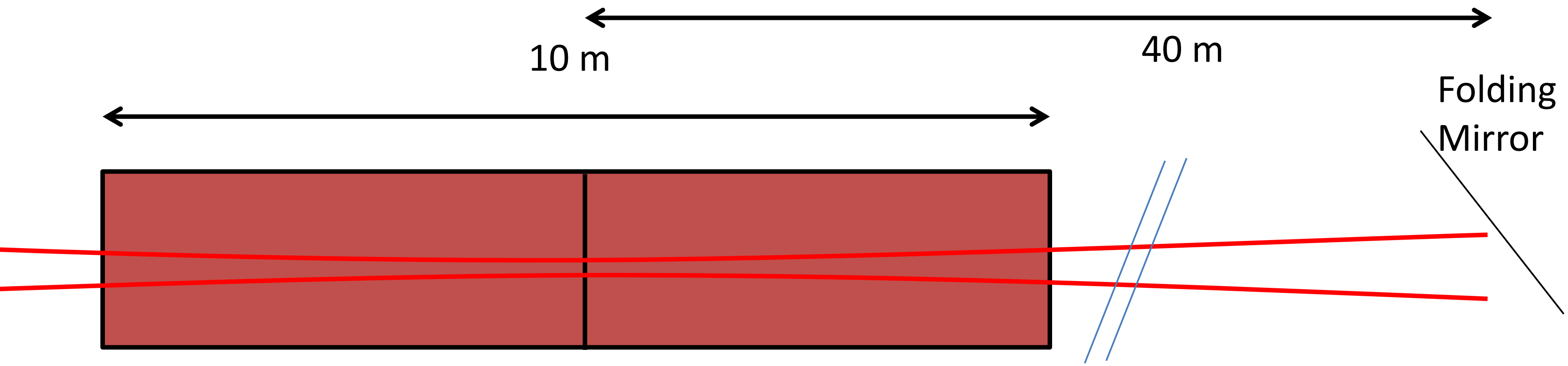
$$k_{bound} = \frac{\omega}{c}\sqrt{1+\chi(\omega)}$$

$$k_{plasma} = \frac{\omega}{c}\sqrt{1-\frac{\omega_p^{\,2}}{\omega^2}}$$

- Leading edge of the pulse ionizes or saturates the transition
- Most of the pulse travels through plasma, samples plasma dispersion, which has a differential index on the scale of 10^{-8}

Expect no pulse stretching of most of pulse!!!

AWAKE CASE (Vacuum Propagation)

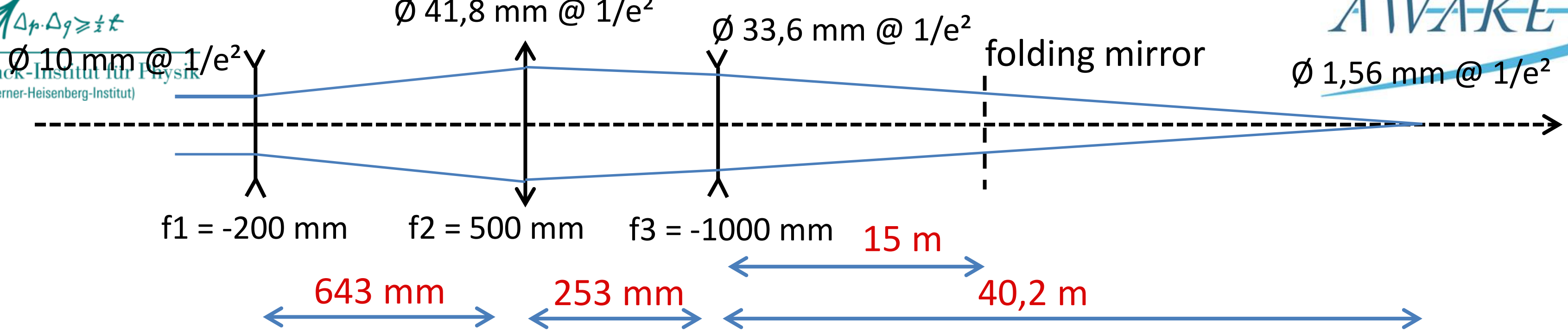


<u>AWAKE Case</u>

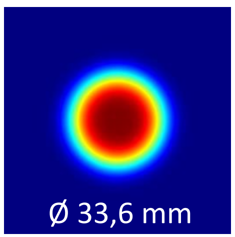
N_{Rb}=7e14 cm^{-3}
Maximum Laser Energy = 450 mJ
Pulse width (no Rb) = 100 fs FWHM
Diameter = 1.5 mm
Z_r=2 m

Avg Intensity at entrance: ~20 TW/cm^2
Keldysh parameter: 1.36
W_{MP}~$10^{15}s^{-1}$
Order 1 transition in fs timescale

Full energy configuration

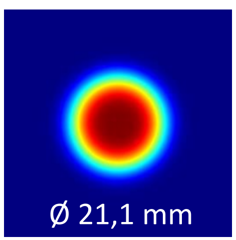


Effective propagation of the 10 mm beam to the folding mirror : 2,3 m



4th order supergaussian beam profile on lens 3

Fmax = 120 mJ/cm² for E = 650 mJ at 0°incidence



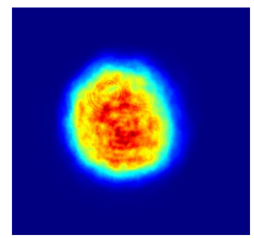
Propagated beam profile on the folding mirror

Compressor input energy 650 mJ → **455 mJ at the output for 70 % transmission**

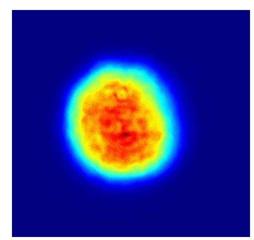
0°incidence : Fmax = 290 mJ/cm²

45°incidence : Fmax = 205 mJ/cm²

Propagation of an actual beam profile



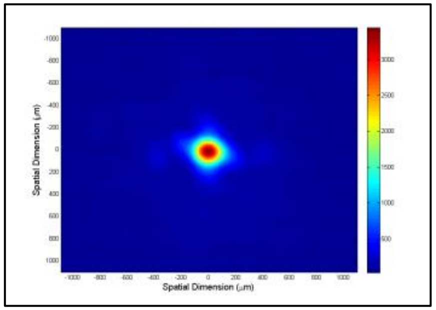
Input of the zoom



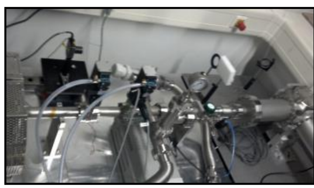
Folding mirror plane

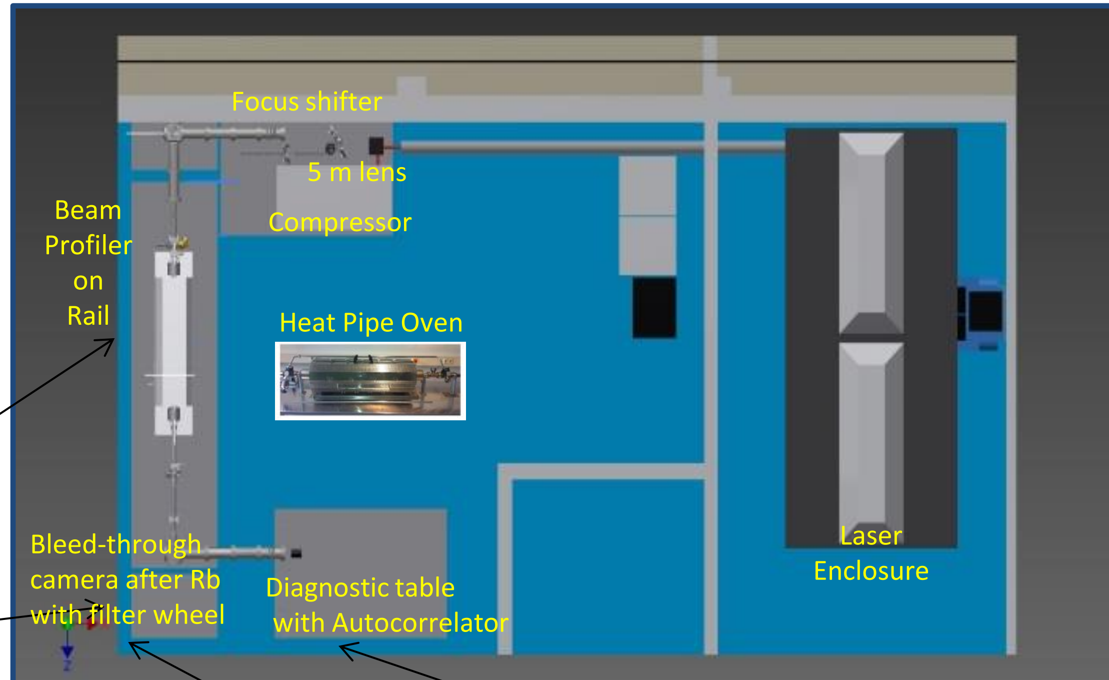
FROM AMPLITUDE TECHNOLOGIES

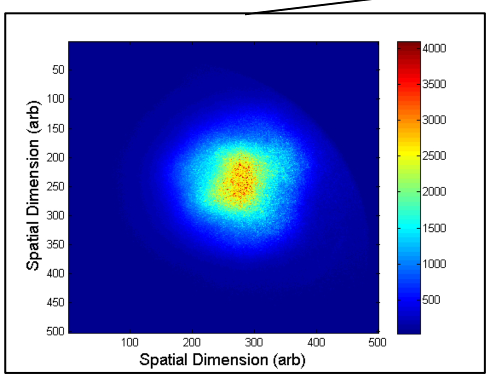
Laser Lab at MPP



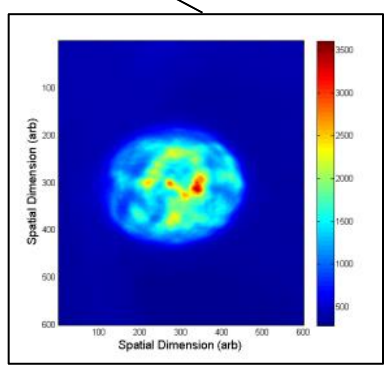
Spot at center first heater,
w0 radius is 200 um



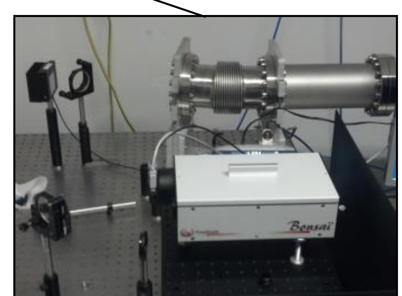




100uJ Pulse No Rb



10mJ Pulse Power with Rb



SHG Intensity AutoCorrelator

Laser Parameters from MPP OSAT (On Site Acceptance Test)

Erbidum Doped Fiber Oscillator used for stability

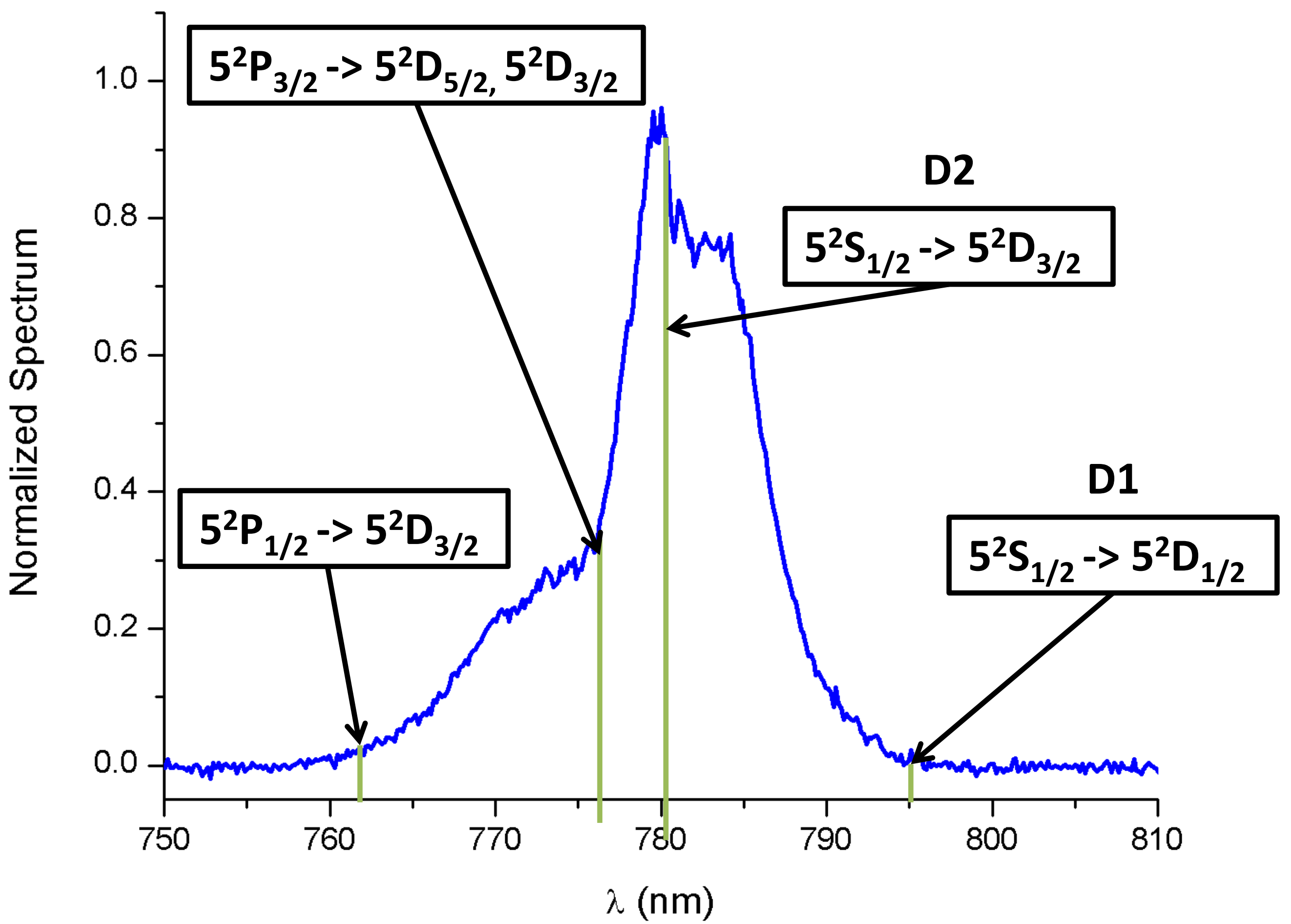
Chirped Pulse Amplification

Final energy lower than maximum due to in-air compression

Performance	Specified value	Measured value
Repetition rate	10 Hz	10 Hz
Central wavelength	Tunable from 780nm to 785nm	780nm to 785nm
Spectrum bandwidth	≥ 10nm	24nm
Pulse Duration	100 to 120 fs	81 fs
Main output Energy (uncompressed)	>650 mJ	663 mJ
Secondary output energy (uncompressed)	>2,5 mJ	3.0 mJ
Main Output energy (after compression)	≥250 mJ @785 nm	250 mJ with attenuator @ 50%
Energy stability	≤ 1,5 % RMS	1.02%
Beam pointing stability	<20 µrad	4.2 µrad
Temporal intensity contrast	$\leq 10^{-4}$ @ 10 ps	2.10^{-7}
	$\leq 10^{-6}$ @ >50 ps (ASE level)	2.10^{-7}
	$\leq 10^{-3}$ (replica)	$7.9\ 10^{-4}$
Polarization of the output beam (Linear)	100:1	250 :1

Additionnal Measurement	Measured value
M^2	$M^2_X = 1.22$ $M^2_Y = 1.29$

Input Spectrum



Goals For Measurements at MPP

- Demonstrate that pulse doesn't stretch in Rb plasma at AWAKE level intensities
  - Autocorrelator measurements
- Show that ionization takes place
  - Examination of light spectrum
- Look for any change to the transverse profile
  - Bleed camera downstream

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Rb Sources

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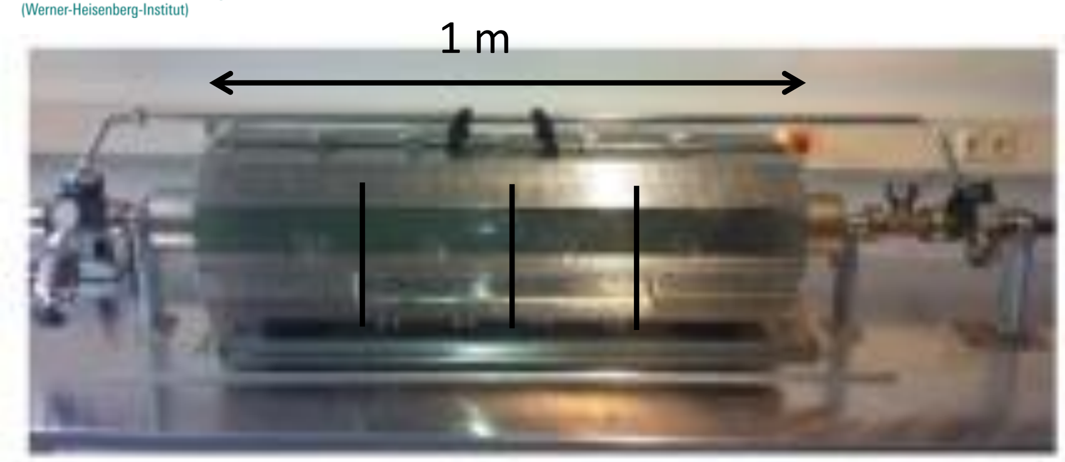
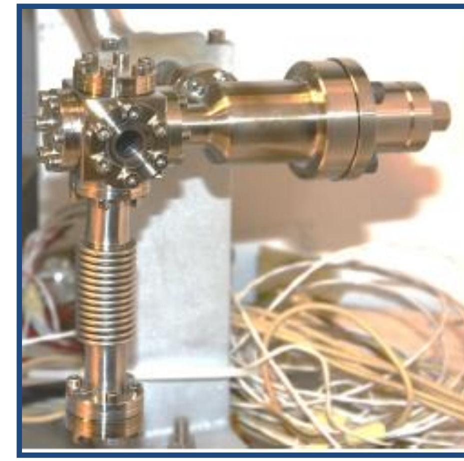
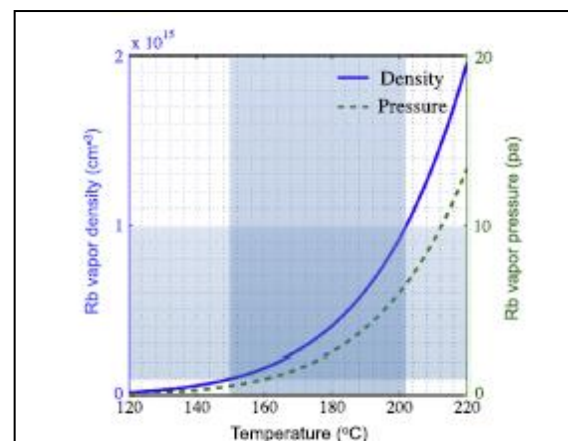


Heat pipe Oven



3.5 cm Rb cell

- Control of Rb vapor density through temperature
- Can easily get to 10^{15} cm^{-3} densities
- Heat pipe oven has 4 independent heaters with excellent insulation
- Uniform plasma but… no side ports!!
- Need to extract information about interactions from Rb from:
    - Laser pulse
    - Residual light (recombination, fluorescence)



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3.5 cm Cell Rb Cell ~6e14 cm-3
Peak Intensity: 1 GW/cm² (No focusing)

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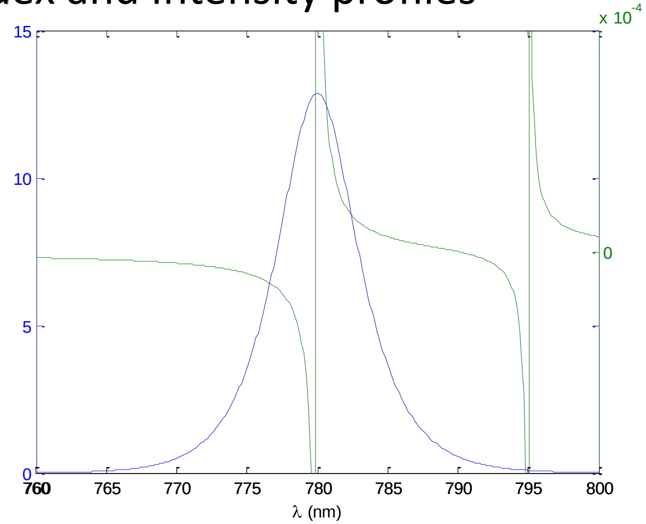
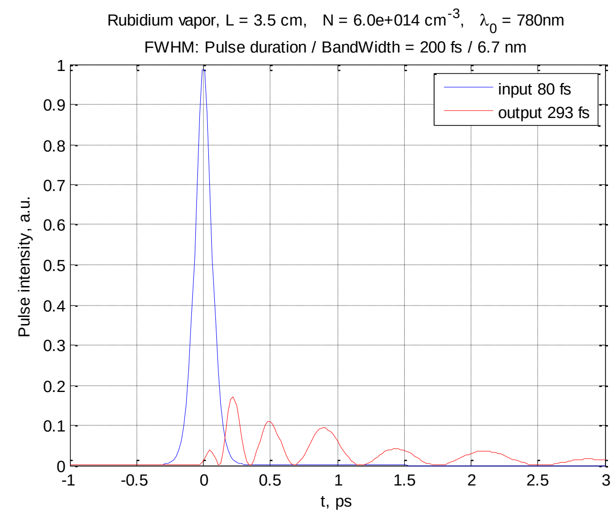
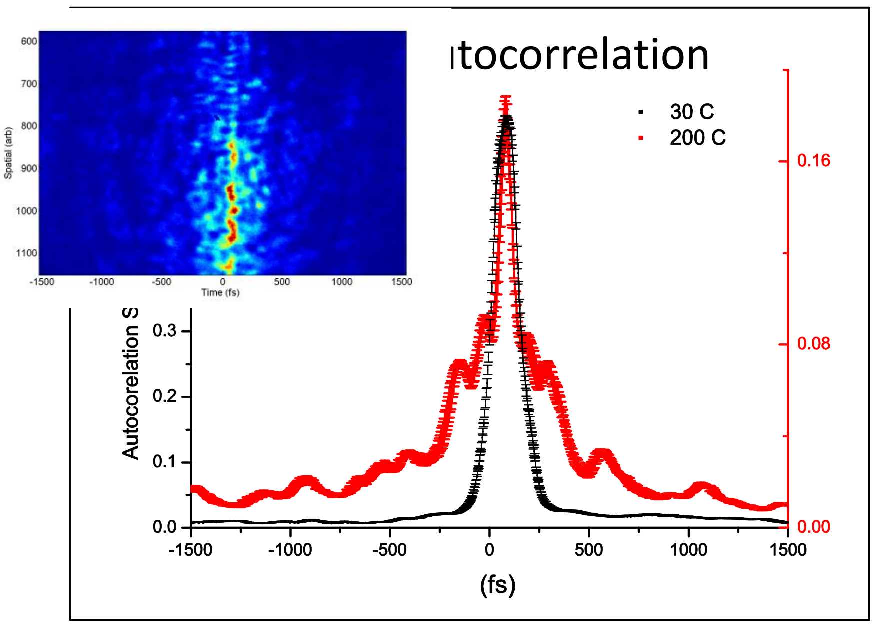
AWAKE

Index and Intensity profiles

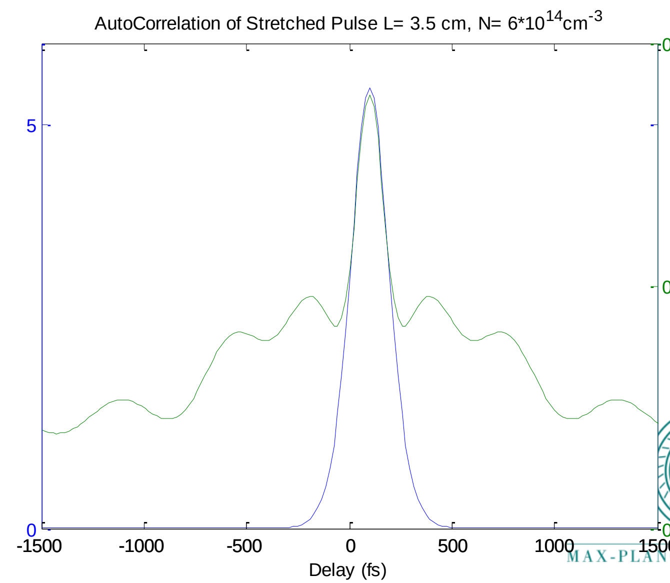


1D Code





Autocorrelation Calculated from 1D



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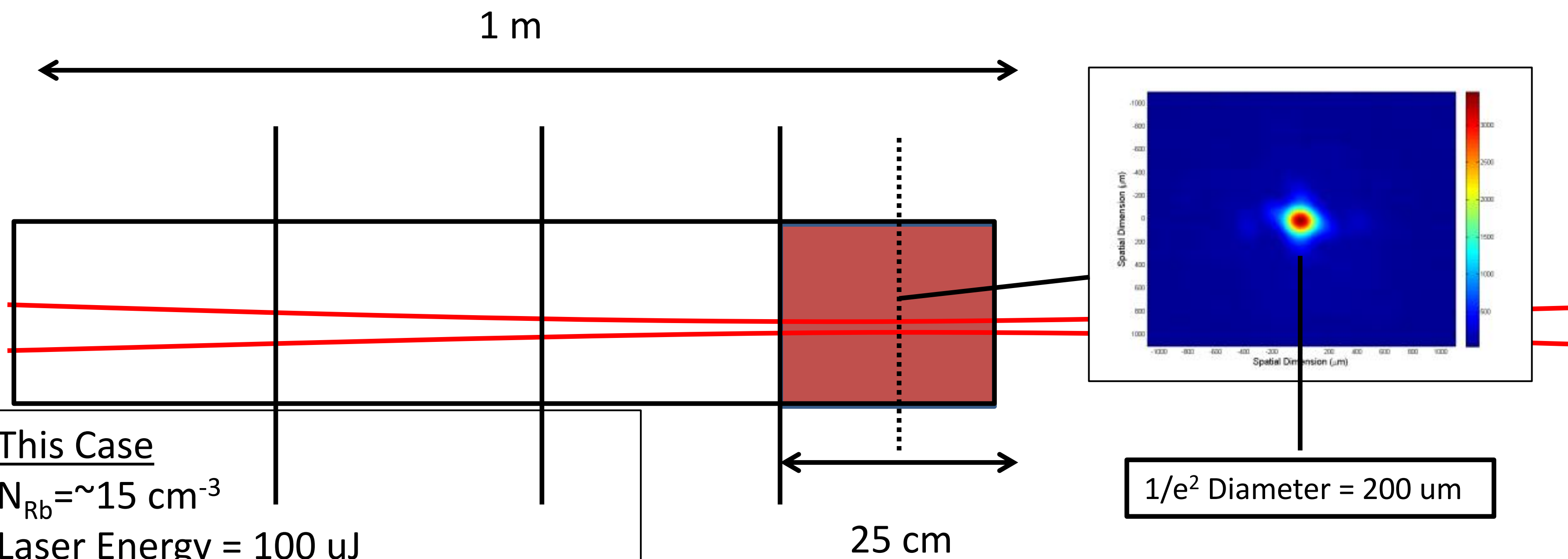
25 cm Rb, 300 GW/cm² to 1 TW/cm²



<u>This Case</u>

N_{Rb}=~15 cm^{-3}

Laser Energy = 100 uJ

Pulse width (no Rb) = 100 fs FWHM

Diameter min = 200 um

Z_r= 4 cm

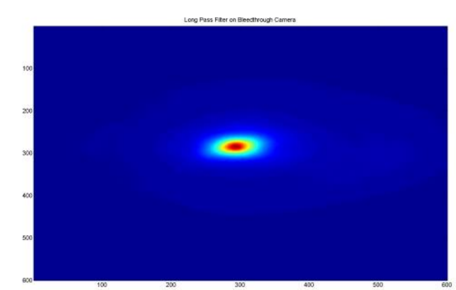
Avg Intensity at entrance: ~ 300 GW/cm^2

Keldysh parameter: 1.36

W_{MP}~$10^{11}s^{-1}$→1% ionization but…

Output

No “ring structure” observed that has been observed in higher density Rb



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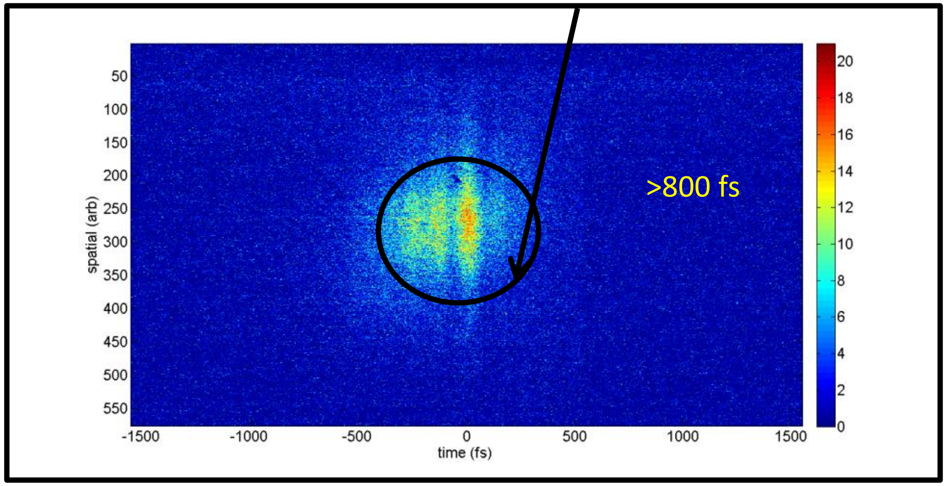
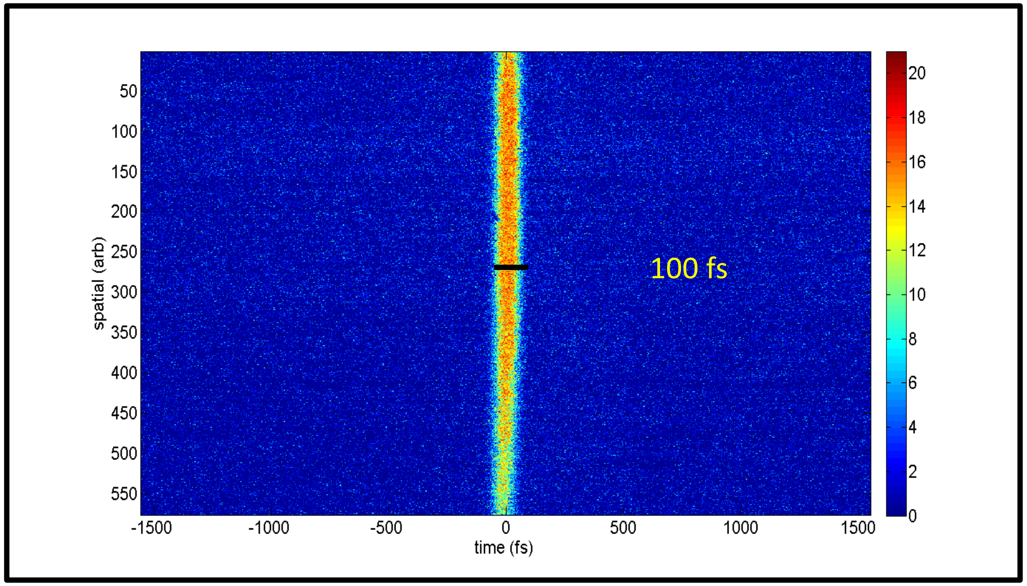
Demonstration of No Pulse Stretching

Spot size is set by aperture

Apertured laser through 25 cm Rb
Ipeak ~100 MW/cm^2



Autocorrelation image no focusing



Autocorrelation image with focusing (5m lens)

NO PULSE BROADENING OBSERVED!!!
Ipeak~1TW/cm^2

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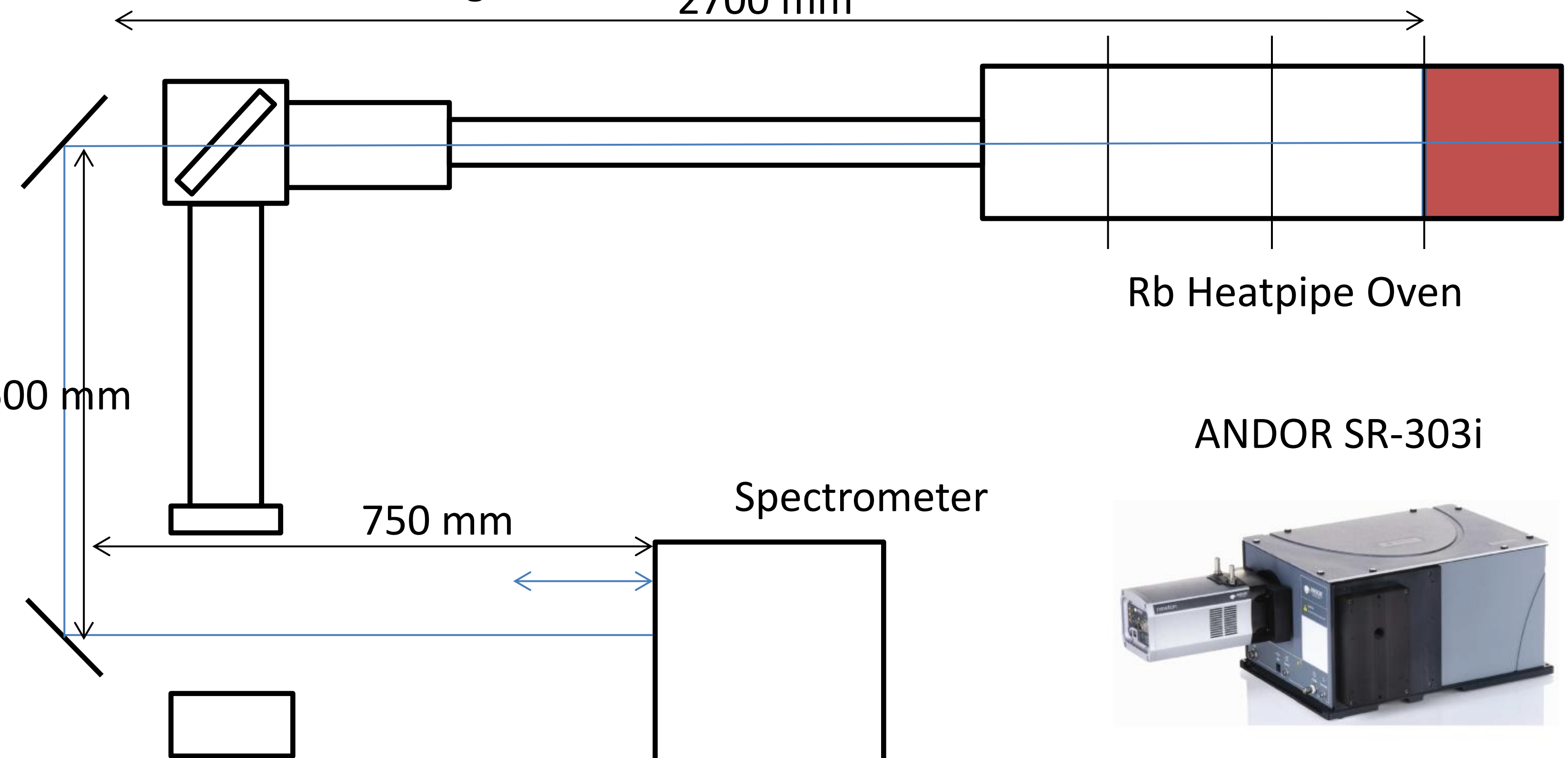
Spectral Measurement Setup

TLM1 780 Mirror Bleedthrough



Main Beam Dump

ANDOR SR-303i

Spectrometer Gratings

1: 150 lines / mm 800 nm grating

2: 600 lines / mm grating 500nm blaze

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Wide Band Spectroscopy

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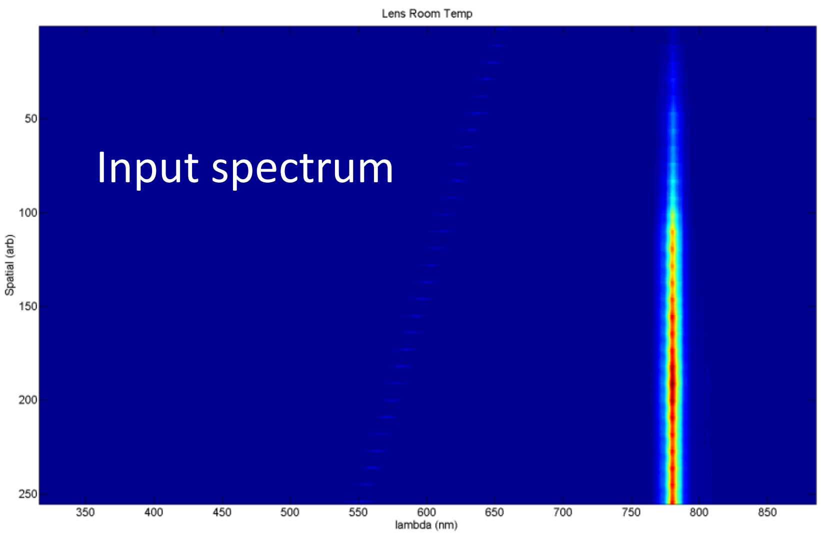
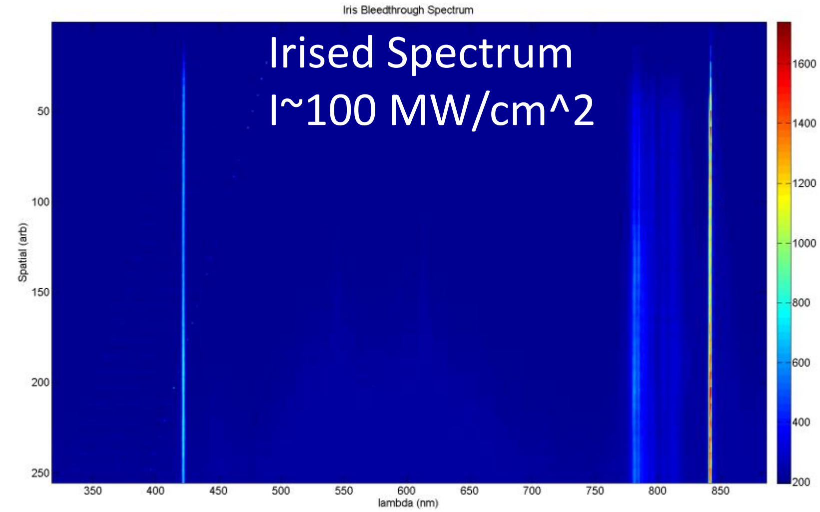
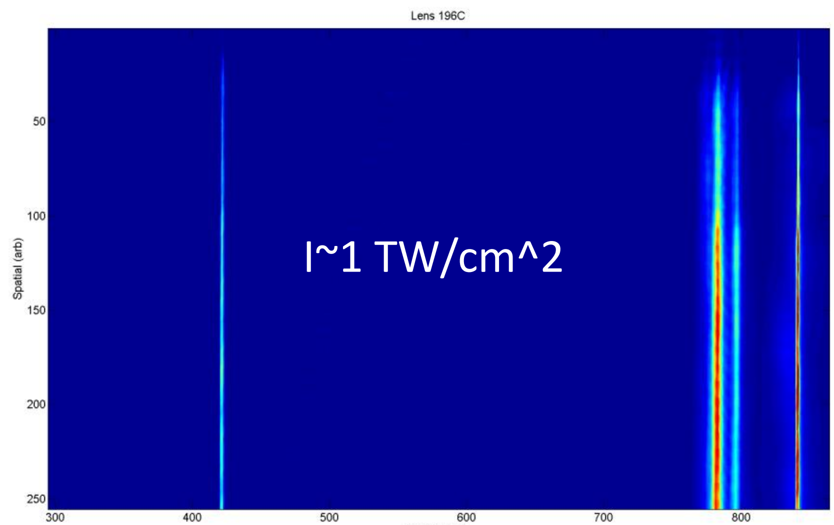




- The 420 nm line shows that a large population is being excited to at least the 5D state
- 420 emission comes from the 6p->5s state



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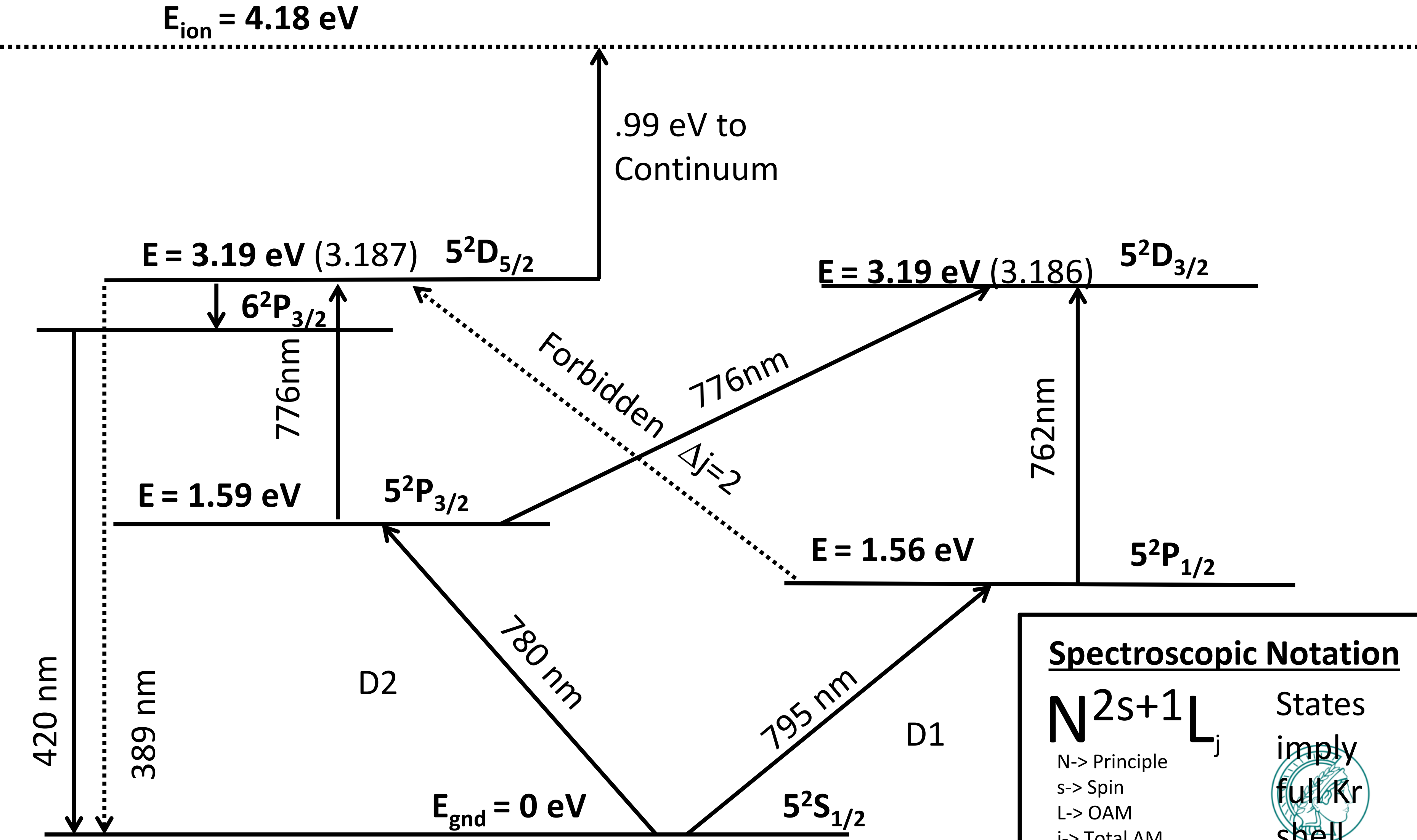
Rubidium Valence Electronic States



Spectroscopic Notation

$N^{2s+1}L_j$

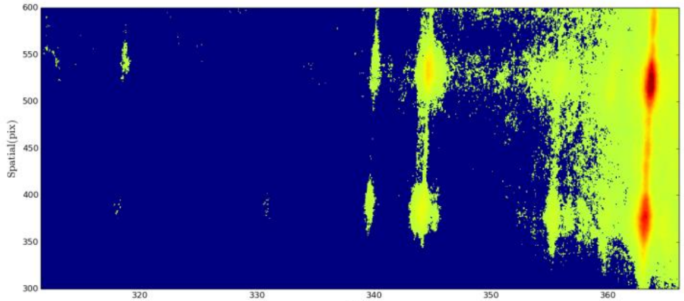
N-> Principle
s-> Spin
L-> OAM
j-> Total AM

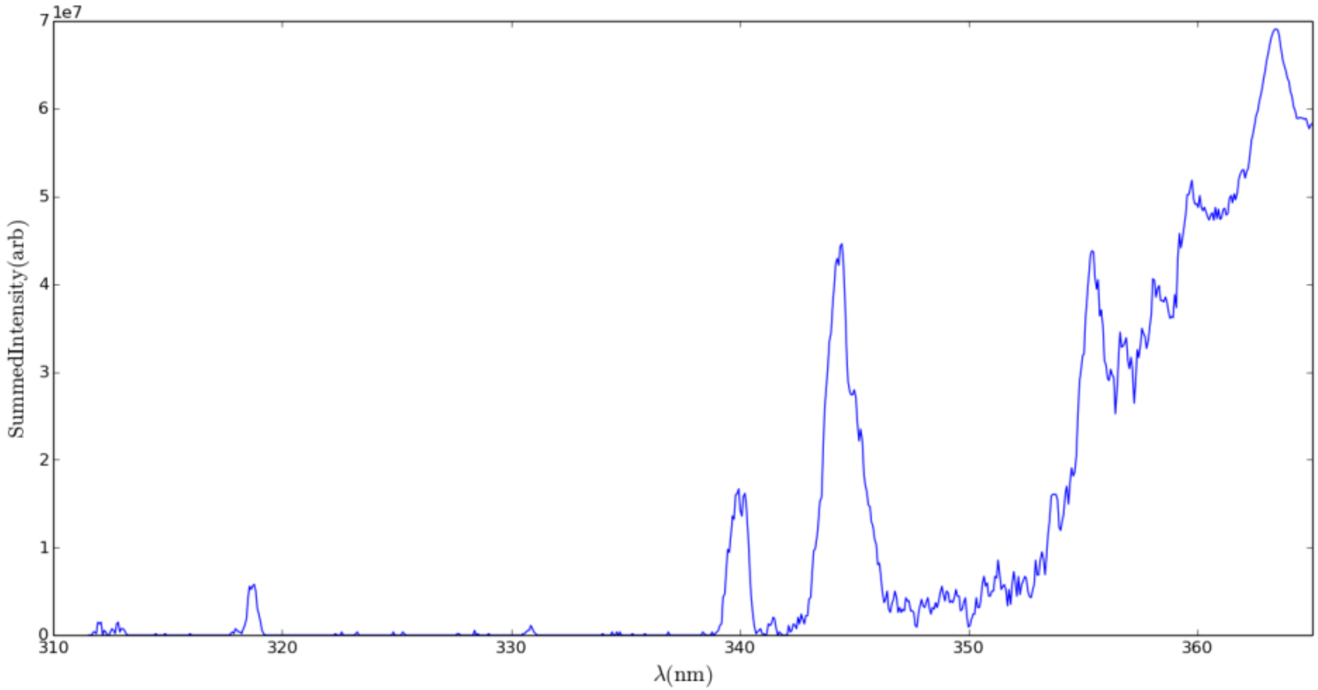
States imply full Kr shell

Potential Demonstration of Ionization (Not Conclusion)

Higher resolution grating used to search for lines above the 5D states

These higher states are not resonant, and are likely to fall from continuum.





Summary of Things Done

- We have demonstrated no detectable pulse broadening at and below intensity values for AWAKE
  - Could be all population is in second excited state: NO Anomalous dispersion (Good news for AWAKE)
- We examined high resolution spectrum for evidence of ionization. Found emission from states above 5D, likely to have been populated by falling from continuum.
- Some data left to process but qualitatively it seems that transverse mode is not affected at this scale.
- Laser now is at CERN, full scale ionization testing can be attempted after full commissioning of plasma cell and laser. (Vapor installation source dependent)

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Open Problems / Questions

- How do we demonstrate that we have >99.9% single ionization of the Rb vapor?
  - We have yet to find a definitive diagnostic for this
- What is the laser pulse speed travelling through the vapor at TW/cm^2 ?
  - If laser pulse falls behind proton beam seed dephases
  - We can measure this with output and cross correlation potentially
- What is the best numerical model to perform the propagation?
  - Is split step sufficient? (FT's seem not to do well with the sharp change in index)
  - Could FDTD codes work (typically numerically unstable)