Ten Meter Laser Propagation with Resonance Enhanced Ionization of Rubidium for Plasma Generation at AWAKE

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And the AWAKE Collaboration

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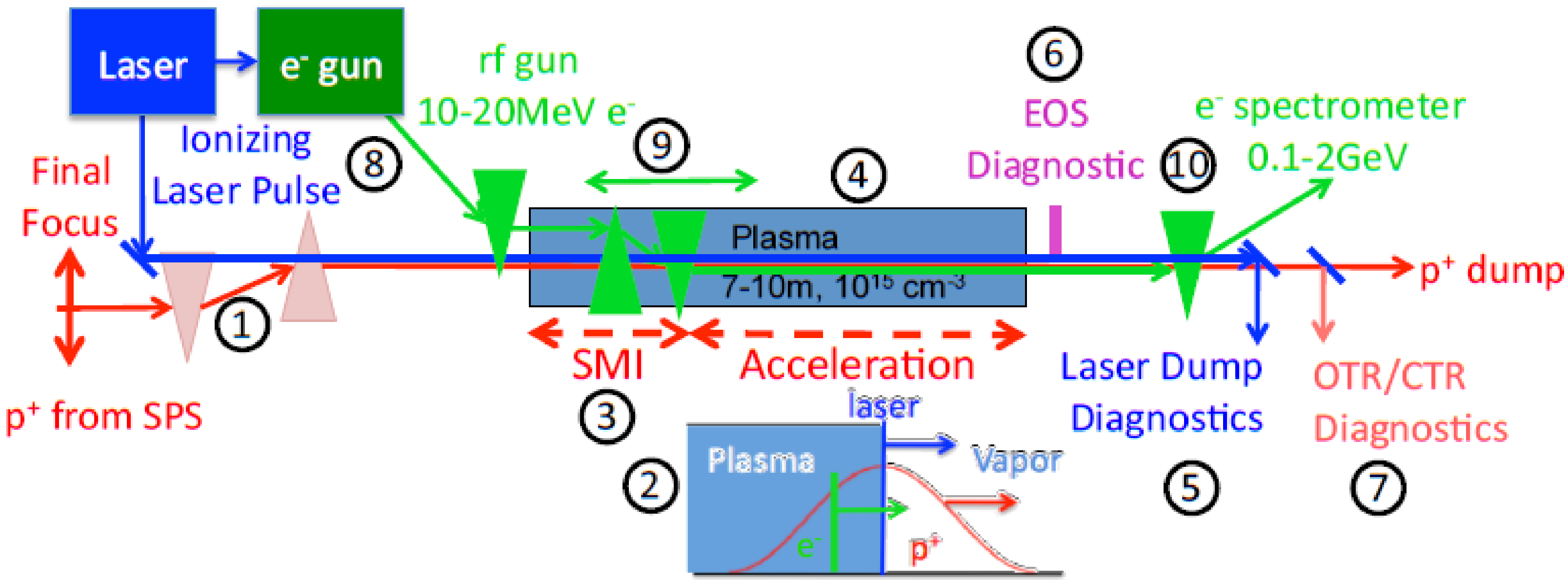
What is AWAKE?

AWAKE stands for Advanced WAKefield Experiment

- Proton driven wakefields over 10 meters of plasma
- Self modulation of proton beam driver
- Saturated wakefields are > 100MV/m



****See Patric Muggli's plenary invited talk tomorrow at 9:50 for AWAKE overview and first experimental results*****

AWAKE Plasma Source

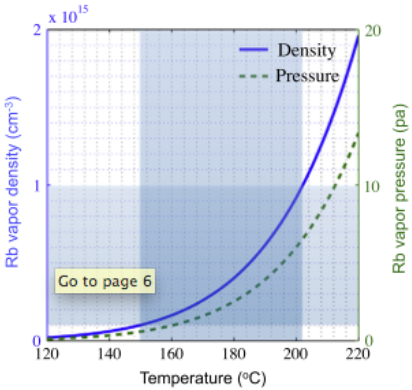
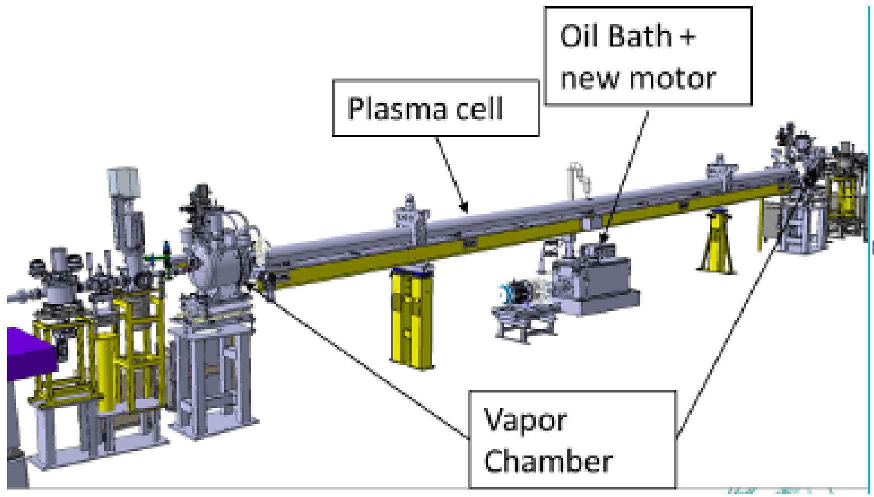
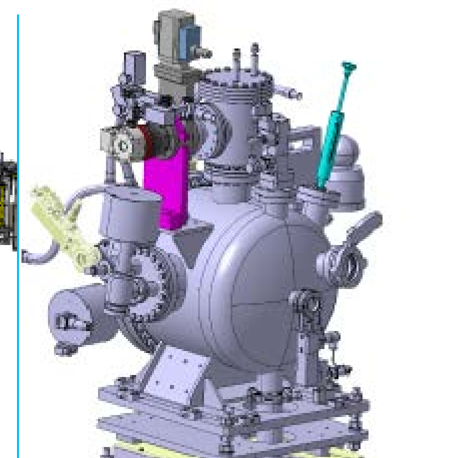


Fig. 1. Rubidium vapor density (blue line) and vapor pressure (green dashed line) as a function of temperature. Region between 1×10^{14} cm^{-3} and 1×10^{15} cm^{-3}, and the corresponding temperature show the parameter range of interest for the PDPWFA. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)





- 10 meter rubidium vapor source
- Rubidium is controlled to within .2% neutral density, gradients can be controlled
- Vapor is photo-ionized by peak power 4.5 TW Ti:Sa laser

See Erdem Öz 's presentation in WG5 for details

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Photoionization Requirements for AWAKE

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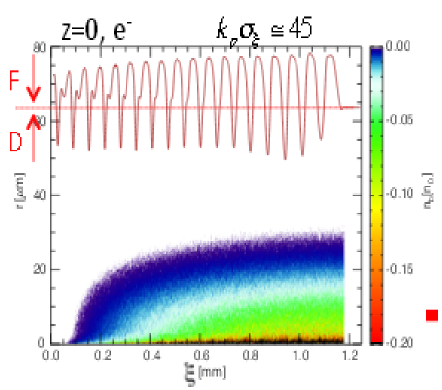
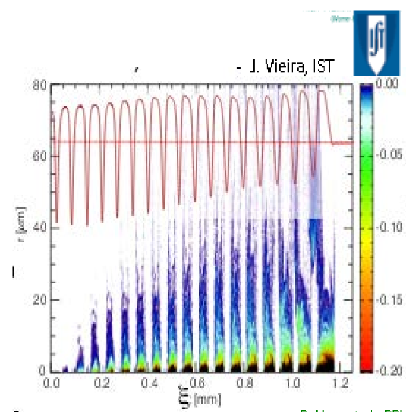
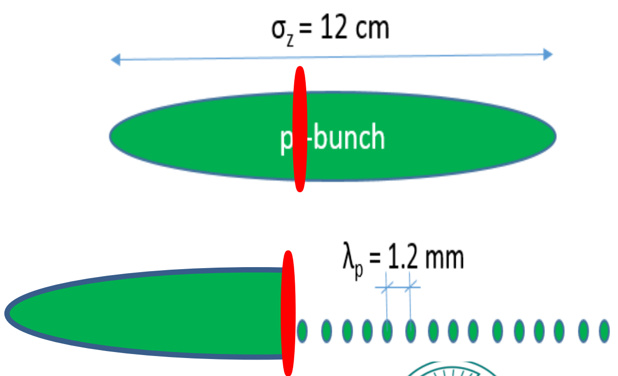
Ionization laser must do three things:

- Provide a singly ionized plasma from the Rb vapor that has a density profile identical to that of the vapor **for the entire length of the vapor source**
- The radial extent of the plasma must be greater than trajectory of plasma electrons
- **Seed** self modulation by igniting on the plasma at a timescale at or shorter than the plasma period where the proton beam can drive the wakefields





Pukhov et al., PRL 107, 145003 (2011)
Schroeder et al., PRL 107, 145002 (2011)



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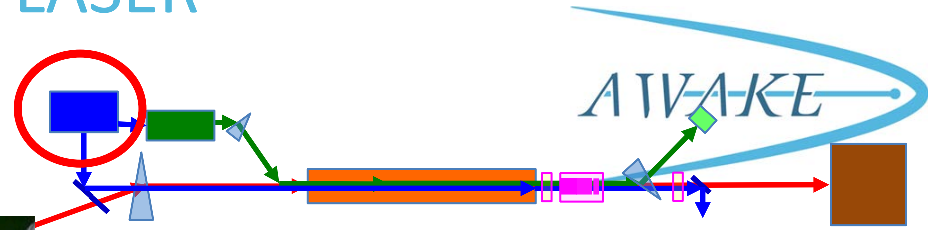
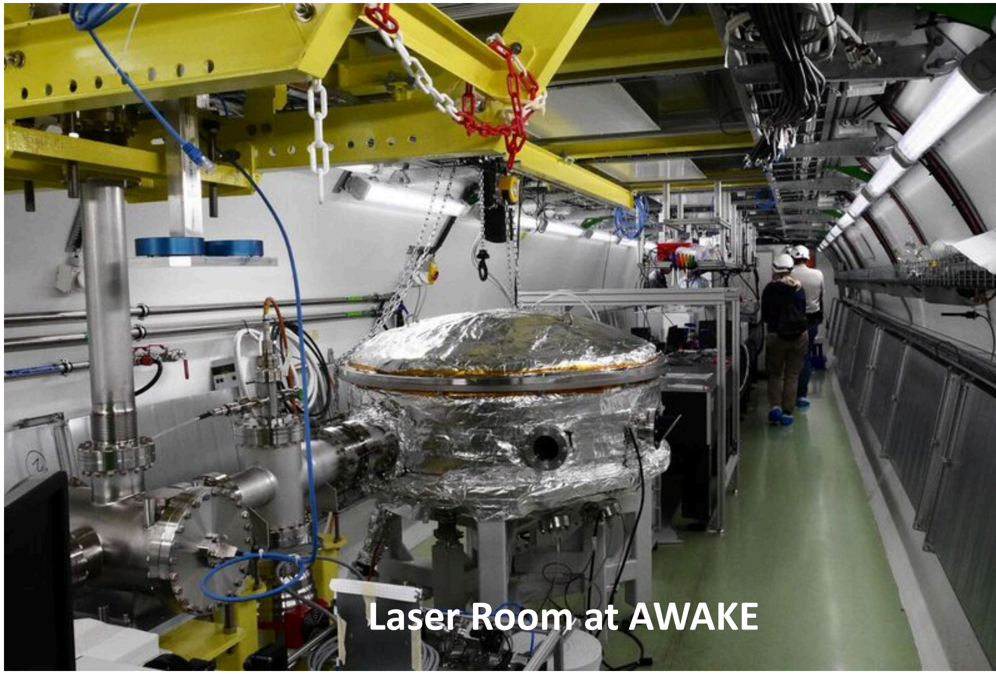
TW LASER




Laser Room at AWAKE

Laser System	
Laser type	Er:Fiber/ OscillatorTi:Sapphire
Pulse wavelength	λ_0 = 780 nm
Pulse length	120 fs FWHM
Pulse energy (after compressor)	**450 mJ**
Laser power	**4.5 TW**
Focused laser size	$\sigma_{x,y}$ **= 1 mm**
Rayleigh length Z_R	~3.5 m
Energy stability	±1.5% r.m.s.
Repetition rate	10 Hz

- Fiber laser chosen for stability on long runs
- Laser BW is only 15nm with peak spectrum at 780nm
- Several Rb lines within spectrum

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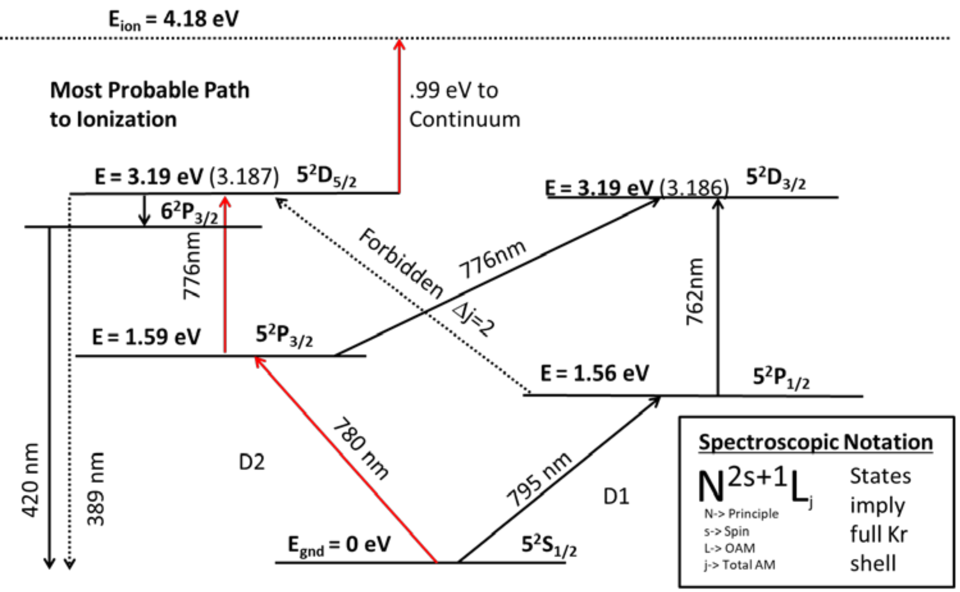
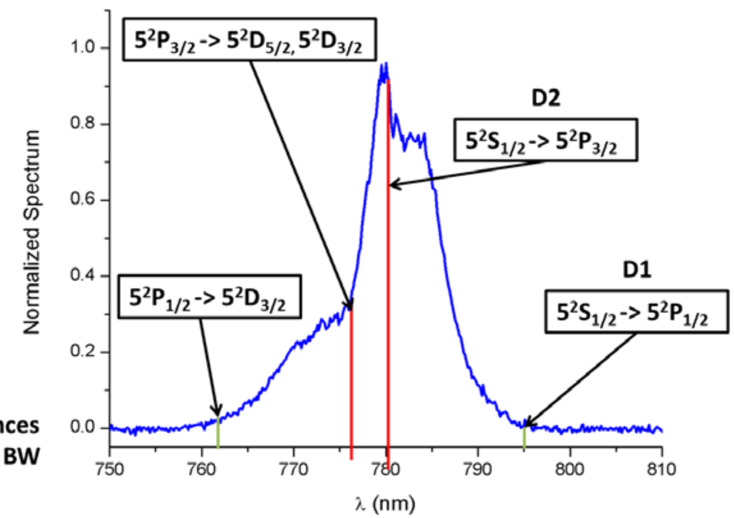
Resonant Transitions



Two Resonances near peak of BW



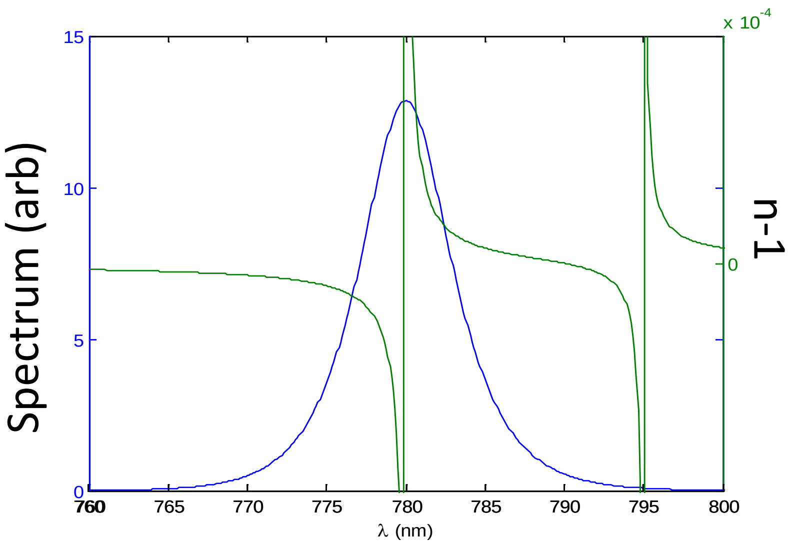
Primary state path to ionization

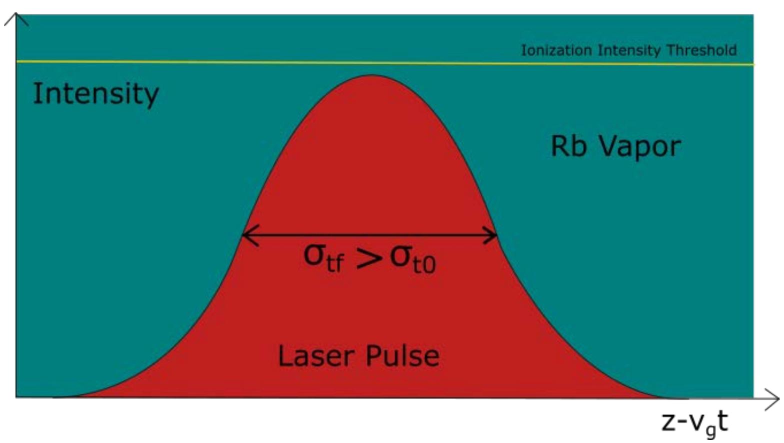
Resonant lines within laser bandwidth

Pulse Propagation in the "Linear Regime"

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

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

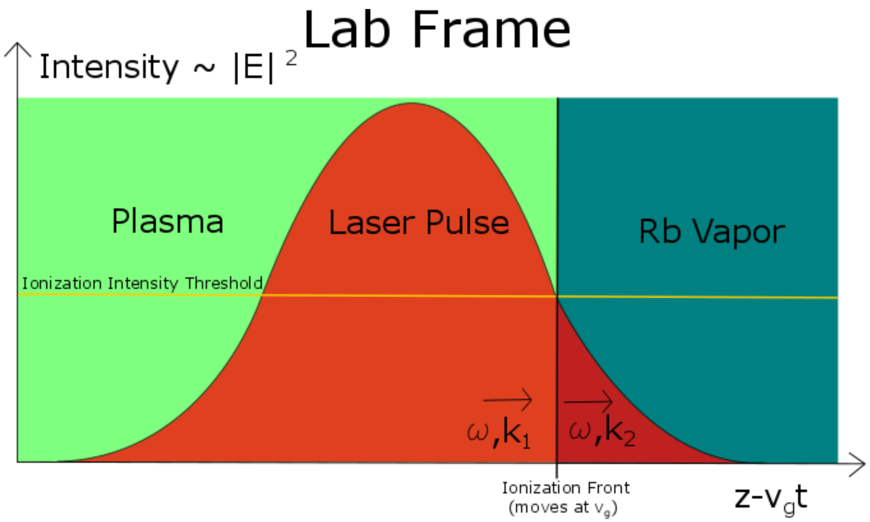




Two resonances would cause anomalous dispersion, pulse stretching, etc. If it is different across the beam then the beam can blow up, multifilament, etc.

We can expect some behavior like this in the wings

High Intensity Laser pulse



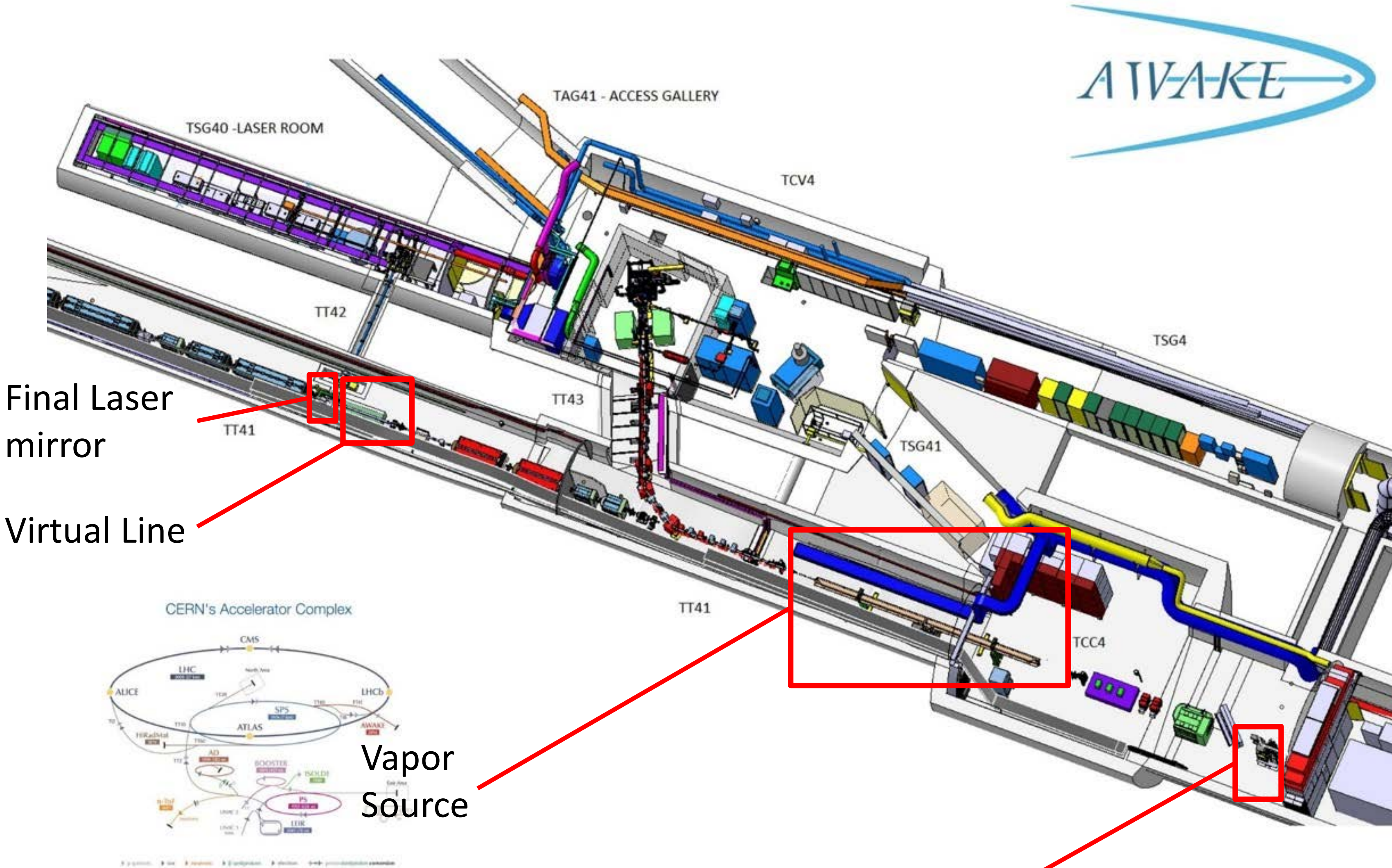
$$k_{bound} = \frac{\omega}{c}\sqrt{1+\chi(\omega)}$$

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

- 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}

If beam does not deplete, it can make it through without stretching or destroying mode quality, creating a stable sized plasma channel

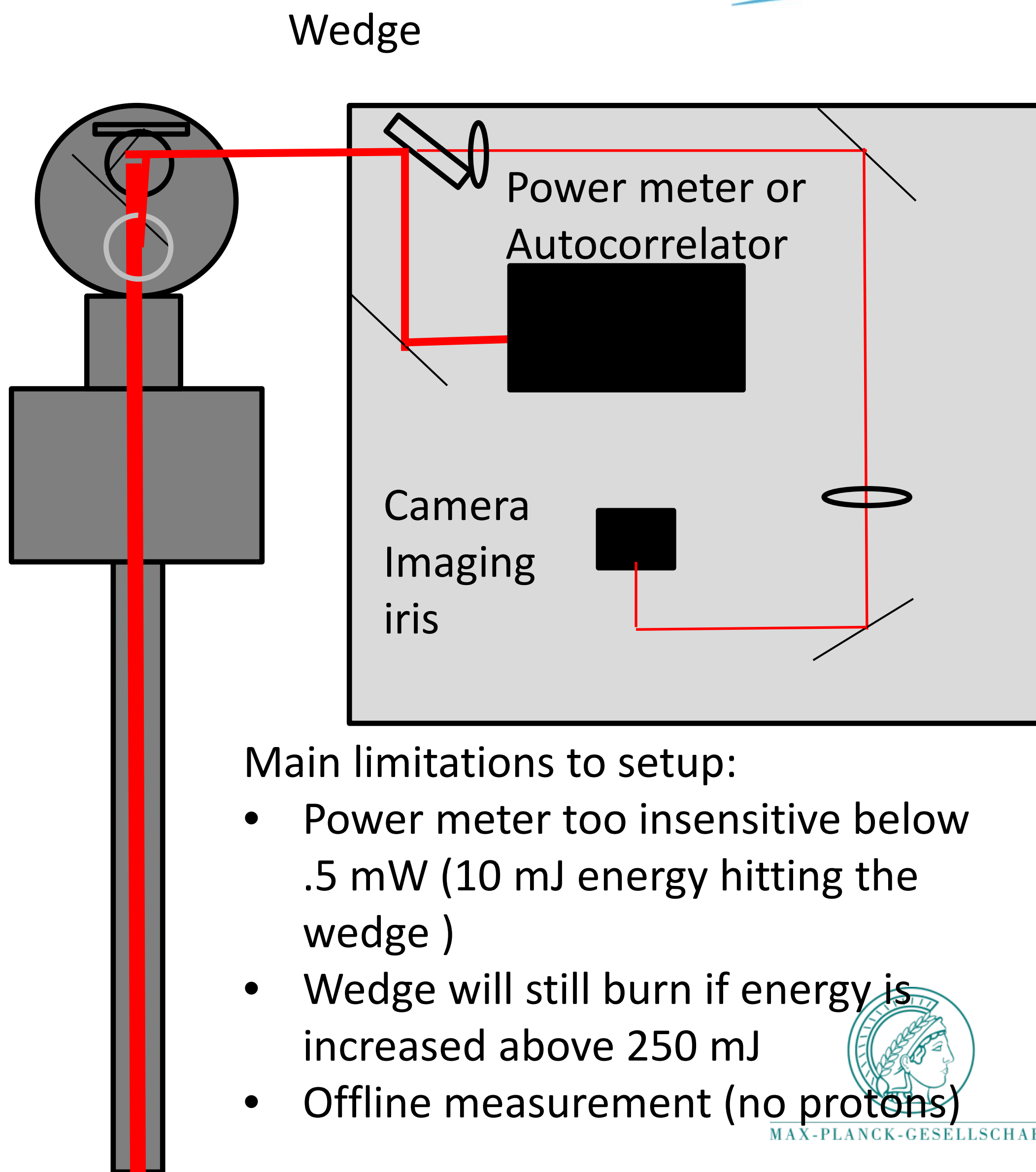
AWAKE Experimental Area



Pickoff Setup

Avoid nonlinearity in sampling by:

- Wedge picked off .5% of laser (close to Brewster's angle)
- Mirror splits beam to autocorrelator or power meter and bleedthrough goes to transverse measurement
- Telescope images downstream iris of the vapor source



Main limitations to setup:

- Power meter too insensitive below .5 mW (10 mJ energy hitting the wedge)
- Wedge will still burn if energy is increased above 250 mJ
- Offline measurement (no protons)

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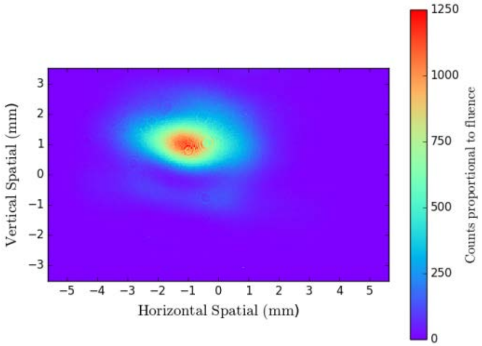
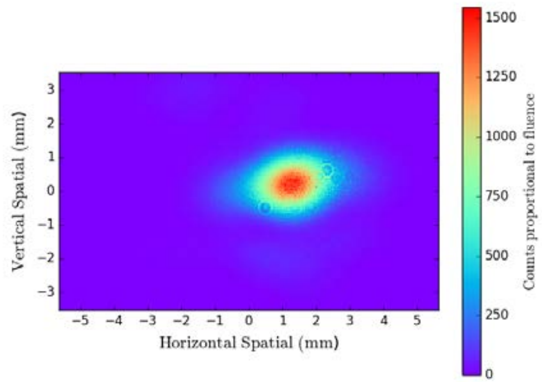
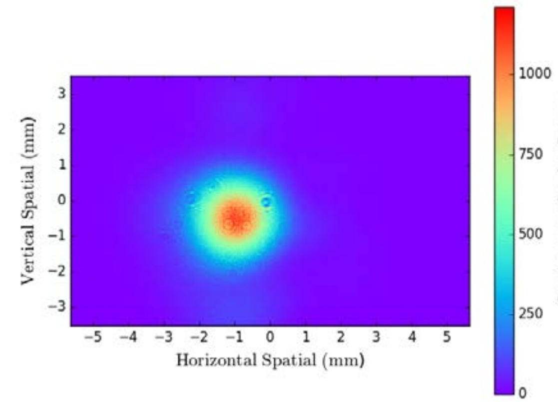
Virtual Line Images
Initial Conditions of Laser / Vacuum Behavior



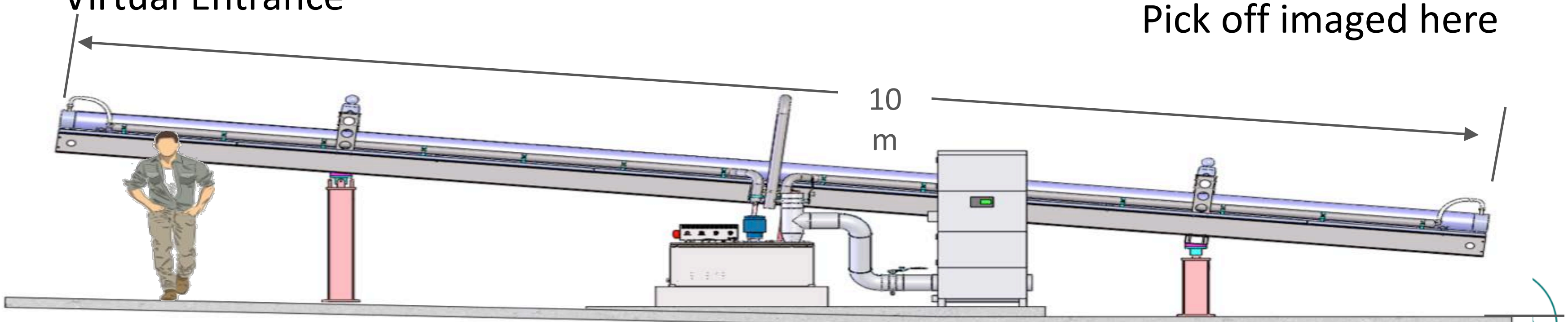




Virtual Entrance

Virtual Center

Virtual Exit
Pick off imaged here



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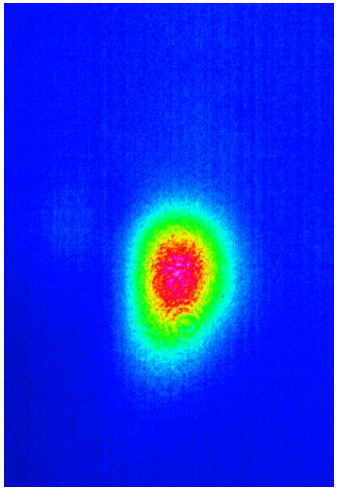
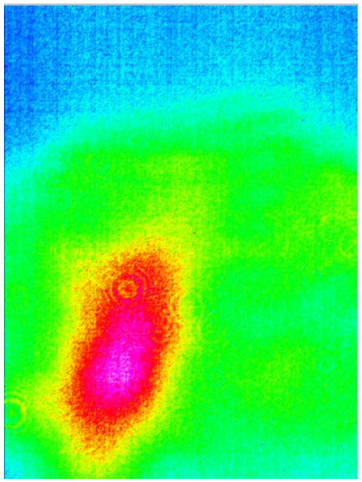
Preliminary Propagation Results

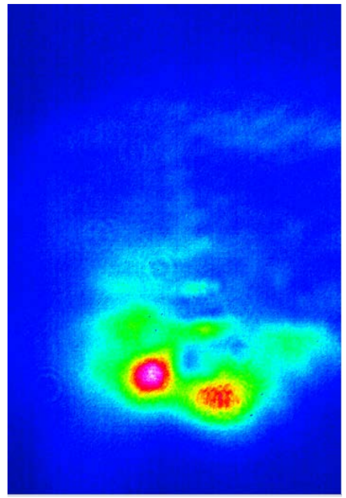
Rb n = 7e14 / cm^3



Vacuum

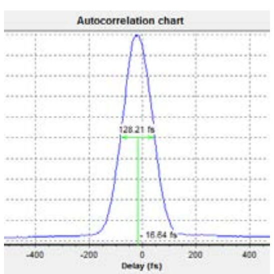


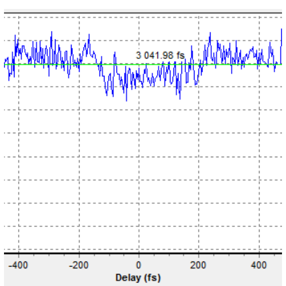
En = 40 mJ

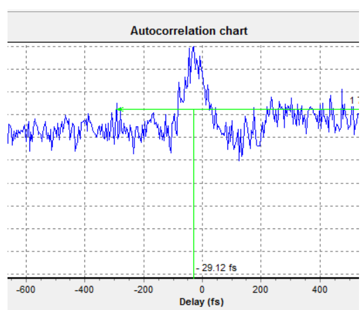


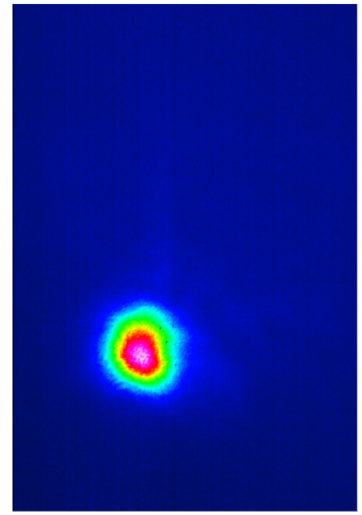
En = 55 mJ

Beam Blowup, multifilamentation

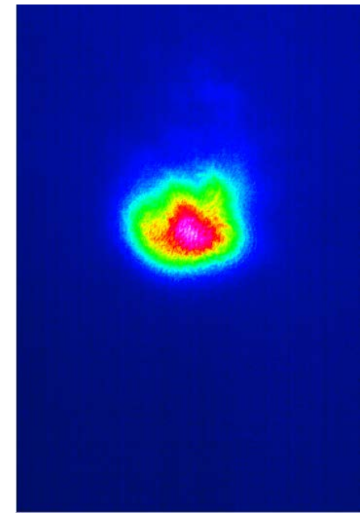






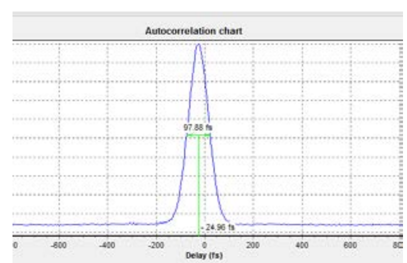


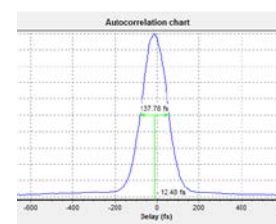
En = 60 mJ



En = 240 mJ

Beam Stable





Simulation Model

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Maxwell for E:

$$\nabla^2 E(r,t) - \frac{1}{c^2}\frac{\partial^2 E(r,t)}{\partial t^2} = \mu_0 \frac{\partial^2 P}{\partial t^2}$$

$\Rightarrow$

Schrödinger for atoms:

$|\Psi\rangle = \sum \alpha_i |i\rangle$, $\hat{H}_I = -\hat{d}E$
phenom. loss terms

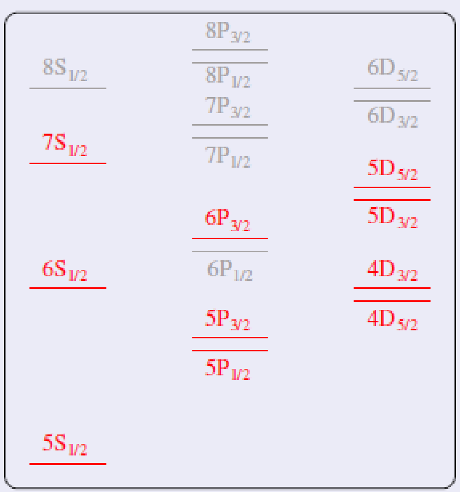
$\swarrow$

Material optical response:

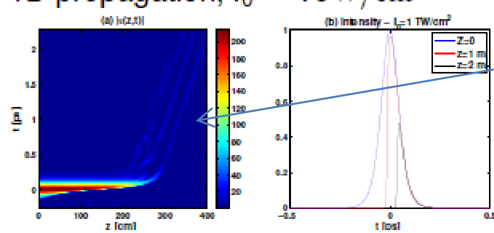
$P(r,t) = \mathcal{N}\langle\Psi|\hat{d}|\Psi\rangle + \text{ionization loss}$

$\nwarrow$

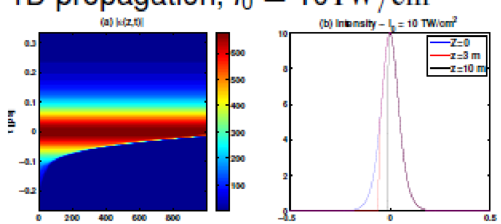
- Atomic models of varying complexity (4 / 18 / 10 levels)
- Ionization as loss (PPT rates)
- 1D propagation



1D propagation, $I_0 = 1\mathrm{TW/cm}^2$



1D propagation, $I_0 = 10\mathrm{TW/cm}^2$



Steepening of leading edge

Laser Pulse collapse
“Slow pulse”

Further extended to 2D

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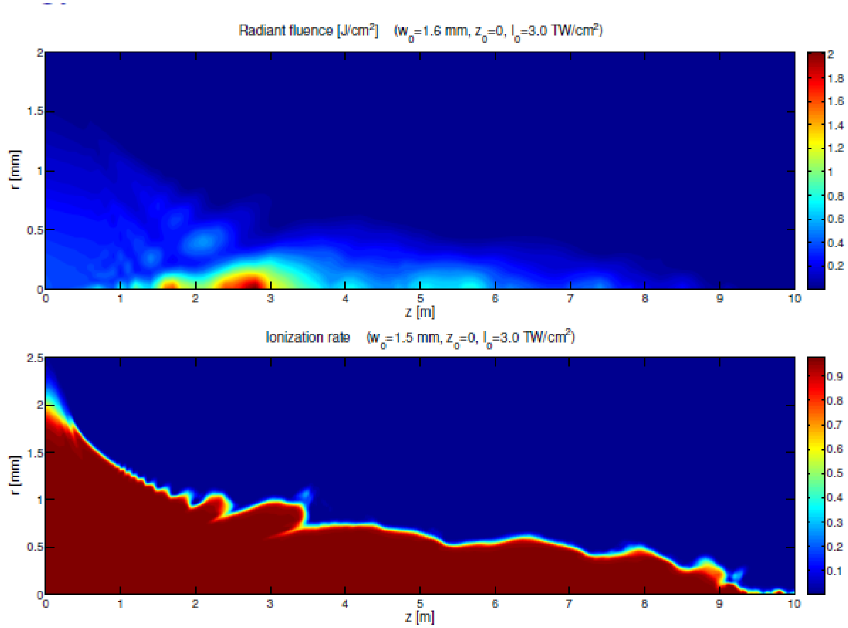
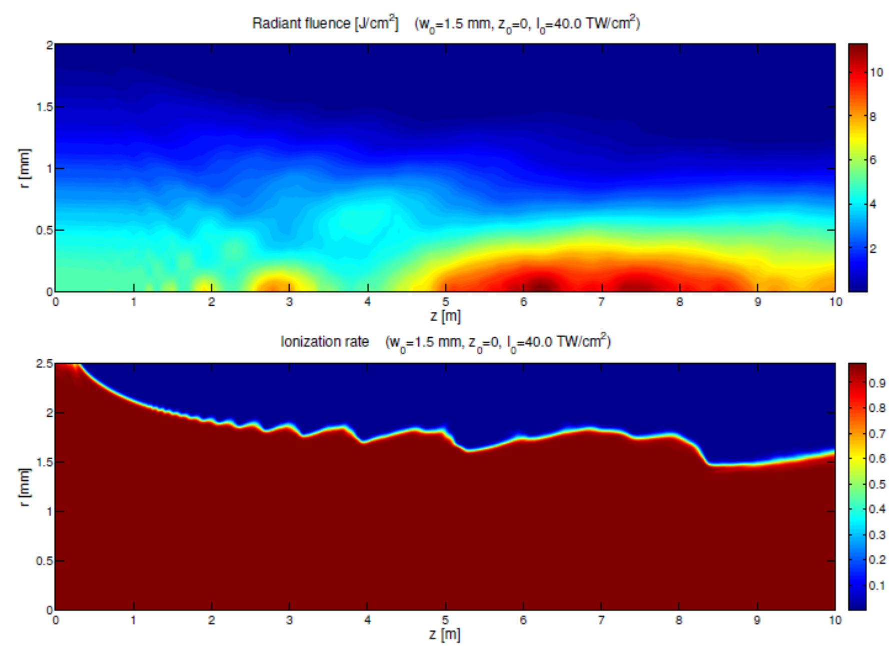
Preliminary Simulation Results





I_0: 3 TW/cm^2

I_0: 40 TW/cm^2

Subthreshold:
Ionization channel collapse,
Output laser pulse destroyed

Super Threshold:
Stable ionization channel,
Stable laser output

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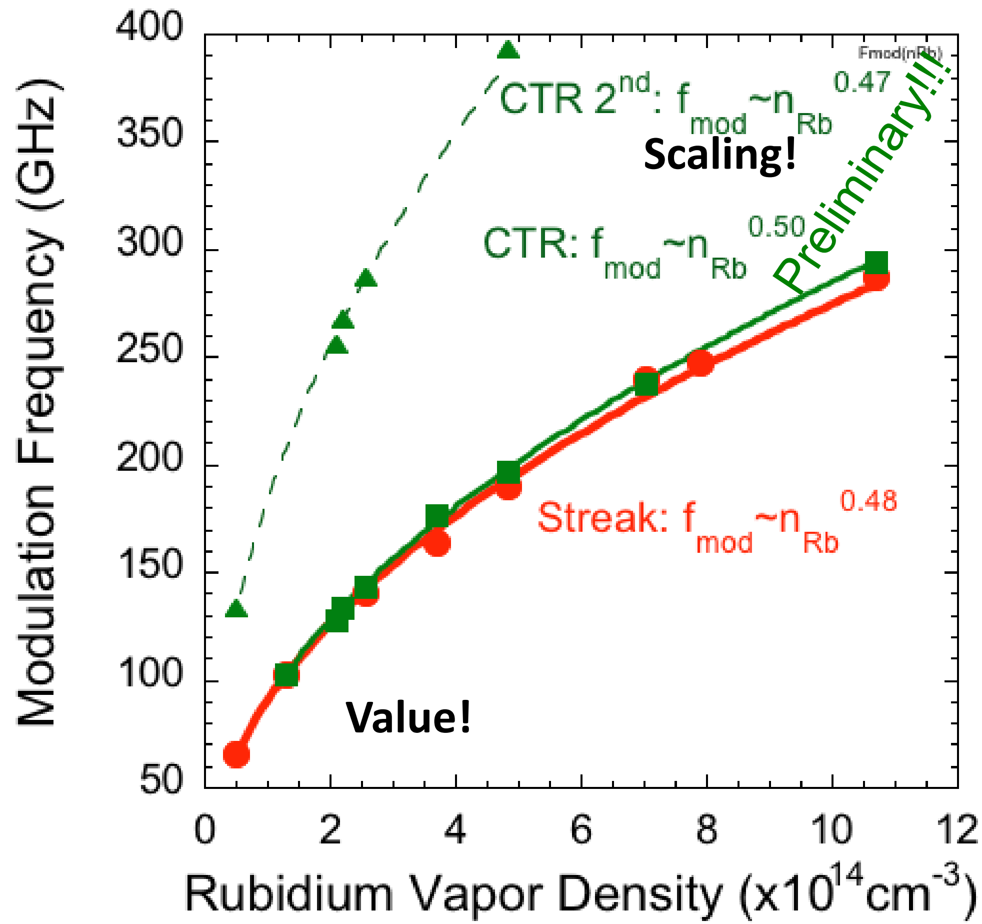
Propagation Confirmed but Ionization?

Self modulation frequency vs neutral density demonstrates consistency with complete ionization within uncertainties



AWAKE Typical run well above threshold energies: 200 mJ

See for details:
F. Batsch,
K. Rieger,
M. Martyanov,
F. Braunmueller

Conclusions and Outlook

Conclusions:

- Experimental demonstration of laser propagation above and below channel collapse limit
- Qualitative results of simulation match what is observed with experimental results
- Measured self modulation frequency versus neutral density consistent with full ionization
- A strength of resonance enhanced ionization is when laser depletion occurs ionization drops off sharply and a stable transverse laser mode fails to propagate out of plasma. This can serve as an diagnostic to ensure the plasma channel is the full length of the vapor source

Outlook:

- Experimental program for ionization experiments thus far limited by higher priority needs of AWAKE (SM experiments, electron beam development)
- A program with quantitative systematic study scheduled for early next year including:
  - Laser Spectrum
  - Time resolved plasma light spectrum (A-M Bachmann, M. Martyanov)
  - Energy depletion scaling
  - Precision neutral density dependencies
  - Input laser pulse length dependencies (chirped pulsing)
  - Input transverse mode quality dependencies
- Further numerical model development to compare new results