AWAKE Laser Propagation 2019 Kickoff Meeting

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(Werner-Heisenberg-Institut)

Purpose of Meeting

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- Present a vision for our subset of AWAKE
  - Where do we fit into AWAKE in general?
  - What makes our way of doing things novel or interesting?
  - What are our goals here?
  - How will we realize these goals?
- Summarize what we have done so far
- Planning
  - Create specific plans for doing analysis, preparing for the July experiments
  - Allocation of resources: People, time, motivation, etc
- Hopefully this can be first of meetings every 2 weeks to review, discuss and consult on model verification and validation

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What these meetings are NOT

- Orders from on high
  - We are a collaboration, we should work together to release the best possible results to the scientific community
  - If you have an idea on how to do something better I want to hear it and discuss it with the rest of our sub group, we can adjust our plans accordingly
- Lectures
  - I want these meetings to be informal. During presentations we should welcome questions and comments as we go
  - If you have an idea it doesn’t have to be ‘publication ready’ to discuss it.

Vision-AWAKE

<u>Where do we fit in at AWAKE?</u>

- At collaboration meetings Patric says we are a ‘fun physics’ project
  - He is only partially correct
- Laser propagation can have direct effects on the plasma wakefields
  - The plasma boundary is NOT at infinity
  - Some of our cases have the expected column width only a few plasma skin depths
  - The initial plasma density distribution n(z,r)
  - May have direct design consequences when we try to push the capabilities of the accelerator to its limits:
    - Increased density
    - Longer plasma for acceleration
- The ‘fun physics’ project is understanding the details of laser / Rb/ plasma interaction
  - Our vapor source should be a playground of sorts for exploring nonlinear/ionizing laser propagation
  - The spectral changes to the laser pulse appear to be very interesting
- The fun physics and our mission at AWAKE are not completely decoupled but as long as there is a well understood plasma density distribution, most of AWAKE doesn’t care about the details of the laser propagation

Vision-Novel

How is our project novel or interesting?

- Rb vapor source
  - 40mm x 10 meter
  - Density stabilized over the entire length
  - Density up to 10^{15} cm^{-3}
  - Novel capability of AWAKE
- Laser ionization the way we are doing it
  - Long Rayleigh range
  - Transitional Keldysh regime
    - Depends on how close we are to depletion / collapse
    - Leading and Radial edges of our pulse experience potentially different ionization regimes
    - Keldysh parameter is order 1 for peak laser field
    - Low number of photons required to ionize
  - Plasma dominated non diffractive pulse propagation, not nonlinear bound stated dominated in ‘operational mode’
    - Operational mode is for laser energies above depletion regime
    - Opposite from conventional mentality of filamentation community where:
      - » Nonlinear bound state propagation -> ionization equilibrium

Vision-Goals

Goals

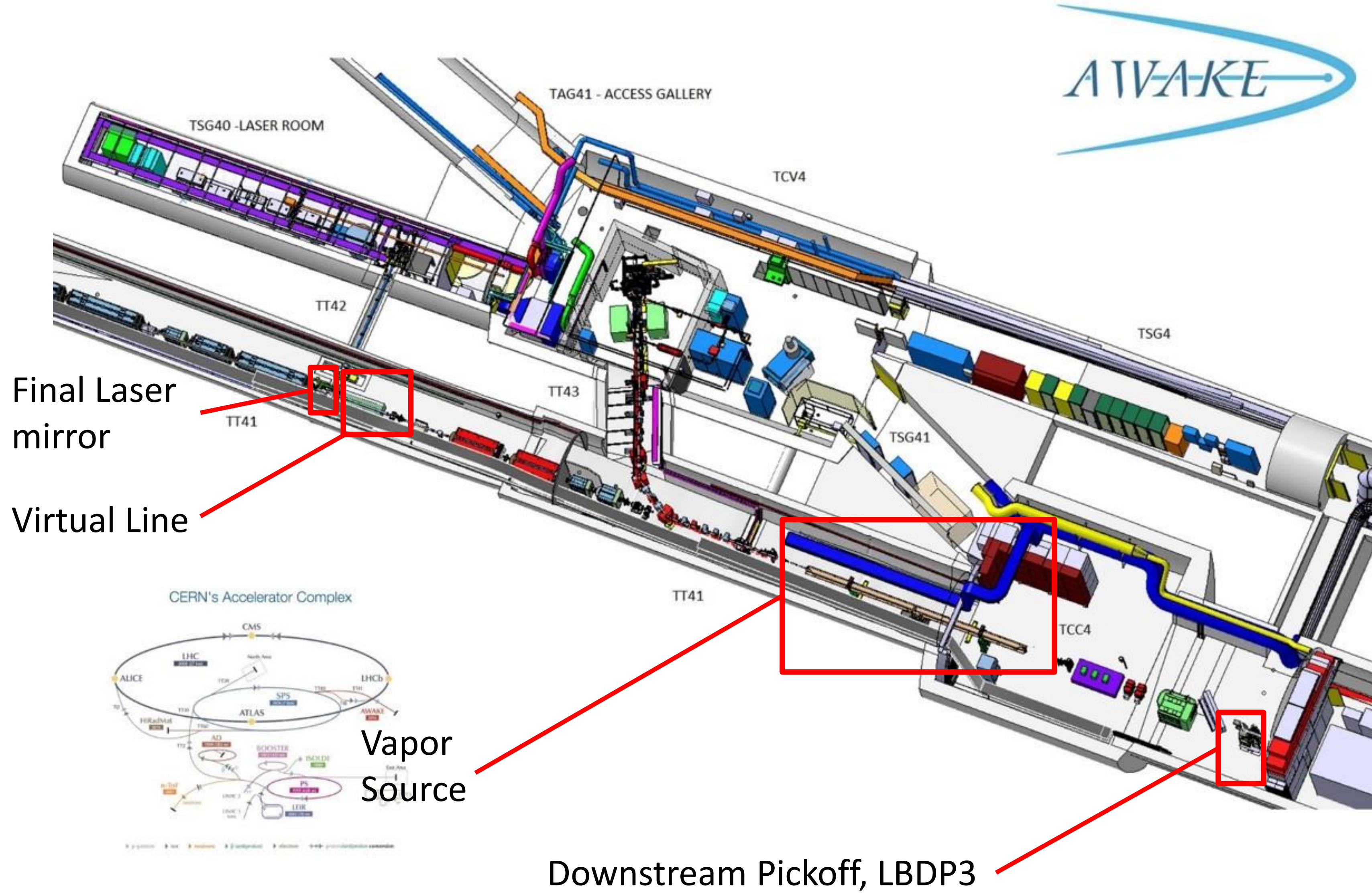
- Two high quality publications:
  - Plasma Profile Publication:
    - Detailing the plasma density distribution
    - Possibly detail the full distribution function, f(r,v,t) or ‘temperature’ if we can guarantee that LTE is reached
    - Explore the limits of what can be done with this source. What is the largest nL product we can reasonably make work with our current laser? If we push beyond this what kind of laser parameters would we need to make the plasma source work?
    - This publication is most suited for the accelerator or plasma community, so we should select journals accordingly
  - Laser pulse propagation publication:
    - Explain feature changes around depletion
    - Explain spectral features:
      - Blue to red shift at depletion limit

Method of Attack: Summary of Subprojects

- Determination of plasma column
  - Transverse mode analysis
    - Determining initial conditions
    - Model verification
    - Statistical Analysis (Bayesian?)
  - Transverse Schlieren
    - Transverse Mode Analysis cross-check
    - Longer timescale time dependency, expansion of plasma column due to ambipolar diffusion
    - Calibration of schlieren signal (MPP)
  - Interferometric methods?

- Complete Description of Laser/Rb/Plasma Interaction
  - Model validity?
    - Gabor's model may not explain observed spectral features. Can the Unige psuedospectral split-step model do the job? Do we need a more sophisticated model?

AWAKE Experimental Area



AWAKE Plasma Source

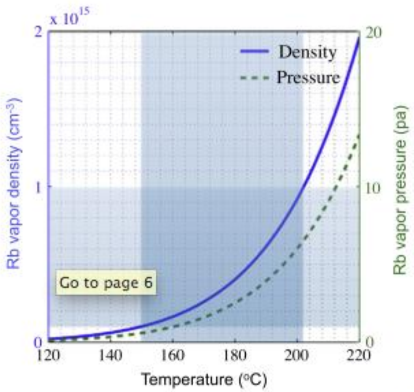
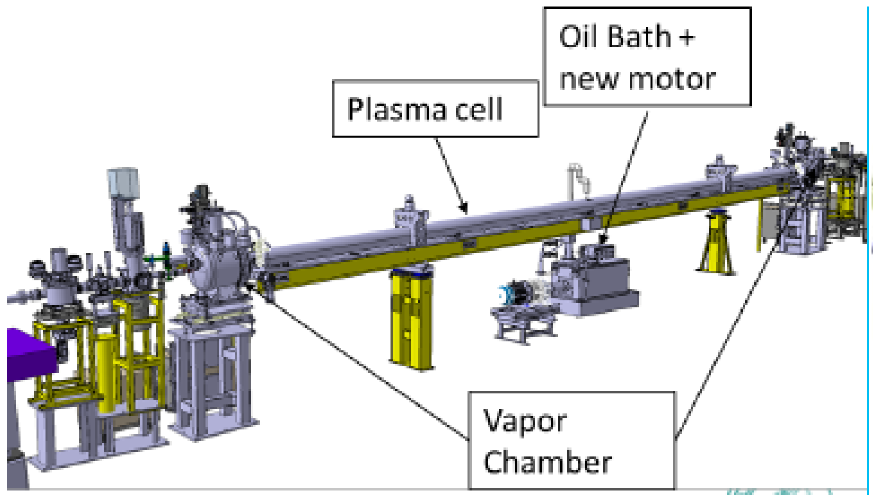
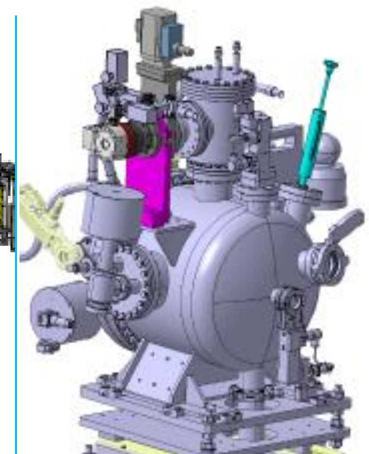
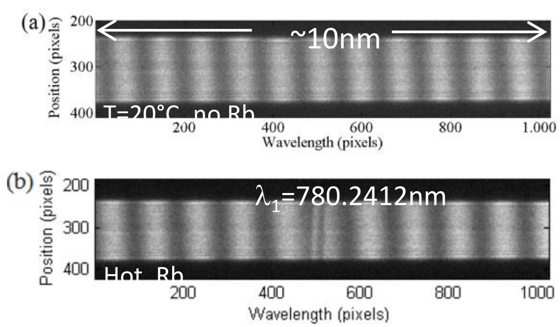
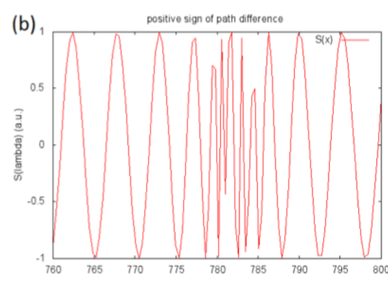


Fig. 1. Rubidium vapor density (blue line) and vapor pressure (green dashed line) as a function of temperature. Region between 1×10^{14} cm^{-3} and 1×10^{15} cm^{-3}, and the corresponding temperature show the parameter range of interest for the PDPWFA. (For interpretation of the references to color 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 (1-10) e14/cm^3
- Rubidium neutral density is measured by white light interferometry
- Vapor is photo-ionized by peak power 4.5 TW Ti:Sa laser

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TW LASER

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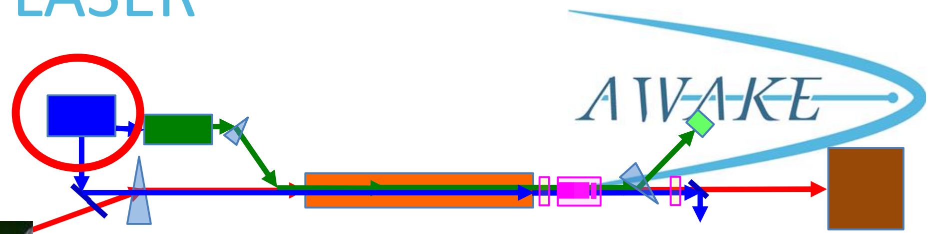

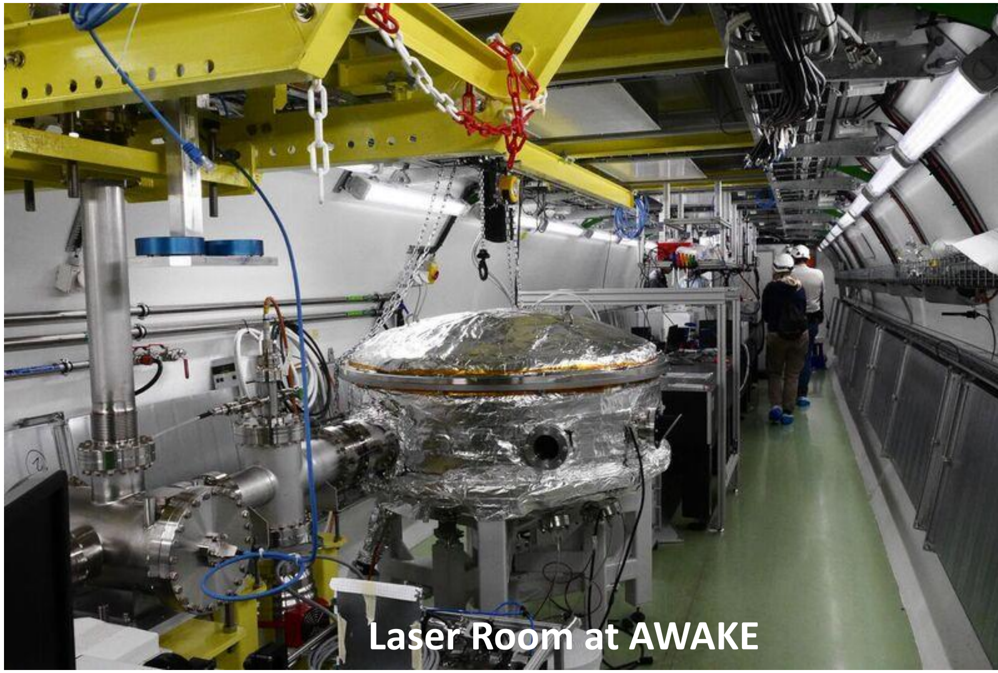

Laser System	
Laser type	Er:Fiber/ OscillatorTi:Sapphire
Pulse wavelength	λ_0 = 780 nm
Pulse length	120 fs FWHM
Maximum Pulse energy (after compressor)	**450 mJ**
Maximum Laser power	**4.5 TW**
Focused laser size	**$\sigma_{x,y}$ = 1 mm**
Rayleigh length Z_R	~3.5 m
Energy stability	±1.5% r.m.s.
Repetition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

Amplitude Technologies Centarus X

- 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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Keldysh Theory of Photoionization

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Electron density evolution set by ionization rate

$$\frac{dn_e}{dt} = w_{ionization} n_{neutral} - w_{recombination} n_e^{\ 2}$$

For AWAKE recombination rate ~1/microseconds
Timescales of interest for experiment are set by time between laser and electron: sub-nanosecond

Keldysh Theory PPT computes the ionization rate given

$$w_{ionization}(U_I, I, \omega)$$

Minimum Number of photons required for ionization

Scaled Applied Electric Field

Intensity definition

$$I = \frac{U_{Laser}}{\pi \sigma_t w_{e2}^{\ 2}}$$

Field Definition

$$E = \sqrt{\frac{2I}{c\varepsilon_0}} = \sqrt{2IZ_0}$$

Keldysh parameter definition

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

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.

Computed Nonresonant Ionization Rates for AWAKE

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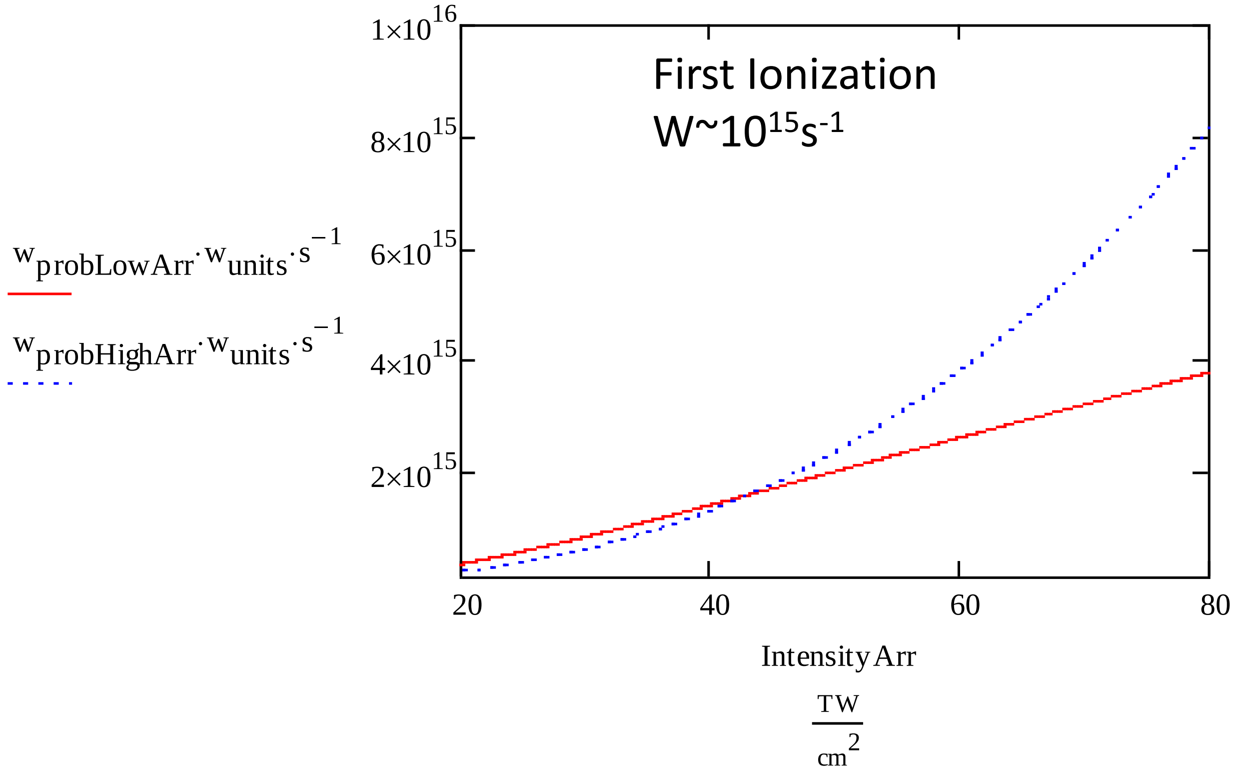
Keldysh theory predicts in both high and low gamma approximations in our Intensity regime, that the ionization rate should be on the order of fs^{-1}

Rubidium's first ionization is 4.2 eV
Rubidium's second Ionization is 27.2 eV.

$$n_{ef} = n_0(1 - e^{-\Delta t \cdot w_{ion}})$$

$$n_{ef1} = 10^{15}(1 - e^{-100})$$

$$\frac{n_{ef2}}{n_{ef1}} = 10^{-13}$$



Nonresonant PPT model predicts >99.9 % ionization within laser pulse for > 40 TW/cm^2

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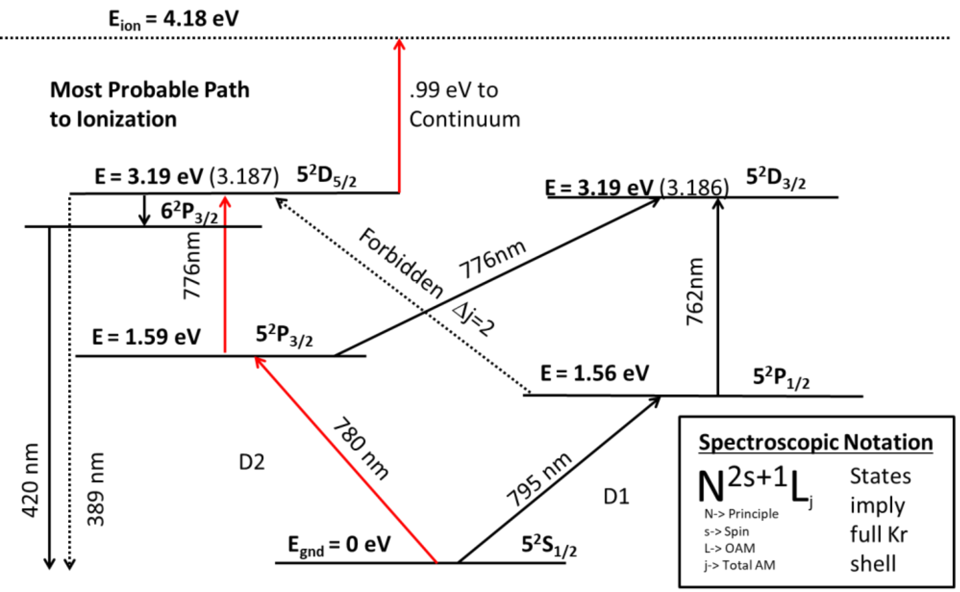
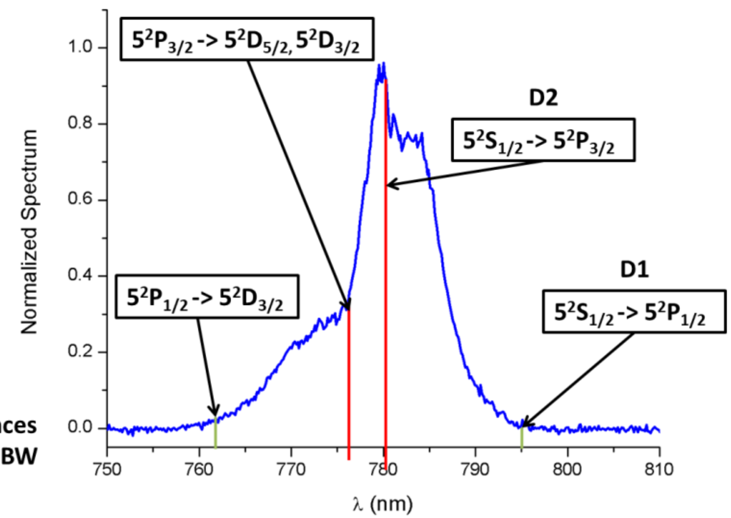
Resonant Transitions



Primary state path to ionization

Two Resonances near peak of BW



Resonant lines within laser bandwidth

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Pulse Propagation in the Linear Regime

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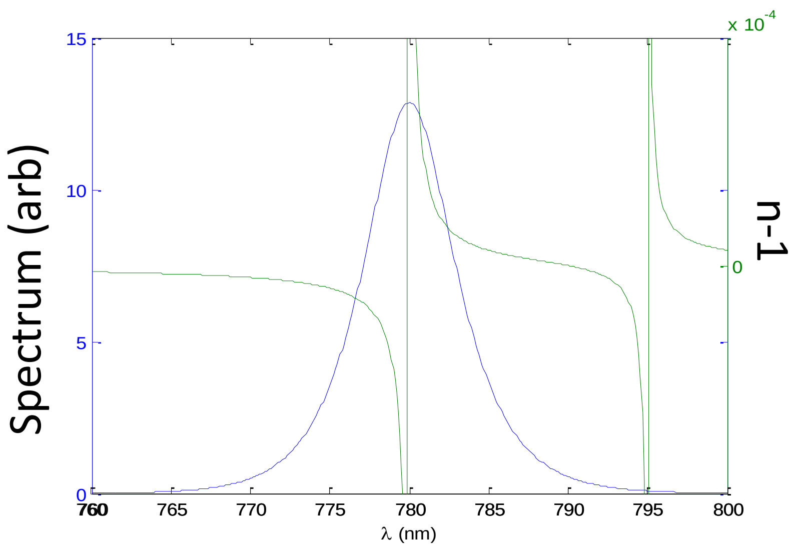
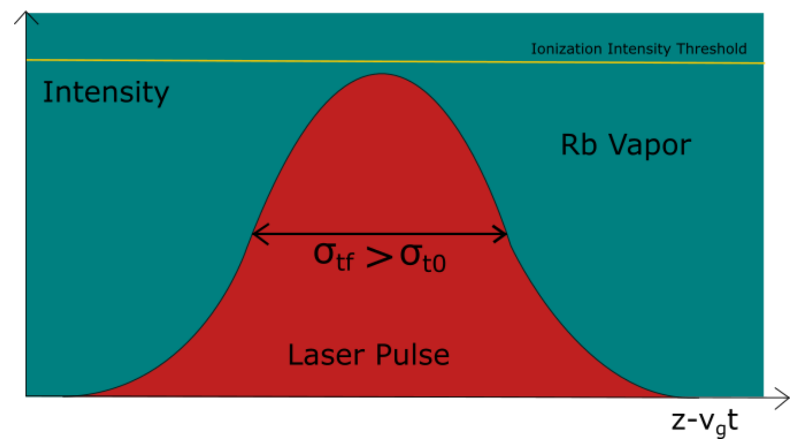
$$\chi_{bound} = \frac{Ne^2}{m\varepsilon_0}\left(\frac{f_1}{\omega_{01}{}^2 - \omega^2 - i\Gamma_1\omega} + \frac{f_2}{\omega_{02}{}^2 - \omega^2 - i\Gamma_2\omega}\right)$$

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





We would expect pi phase shift across the bandwidth within a cm

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 behavior like this in the wings of the distribution

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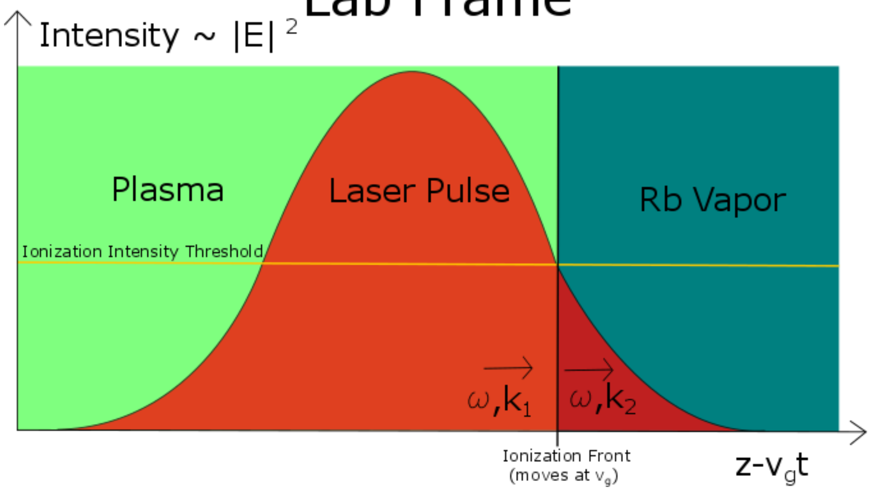
High Intensity Laser pulse

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}

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

Simulation Model

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

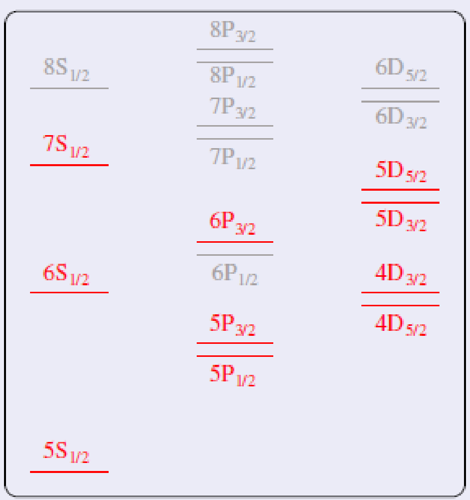
$\Swarrow$

Material optical response:

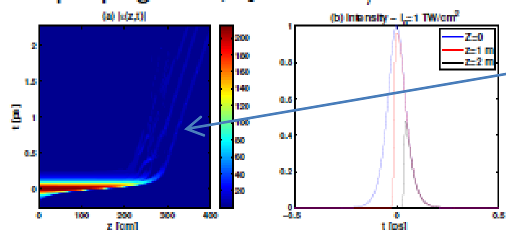
$P(r,t) = \mathcal{N}\langle\Psi|\hat{d}|\Psi\rangle + \text{ionization loss}$

$\Nwarrow$

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



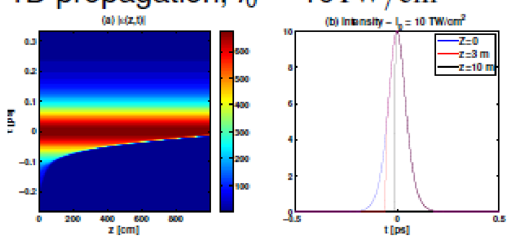
1D propagation, $I_0 = 1\mathrm{TW/cm^2}$



Laser Pulse collapse

“Slow pulse”

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



Steepening of leading edge

Further extended to 2D

G. Demeter

Gabor's Preliminary Simulation Result

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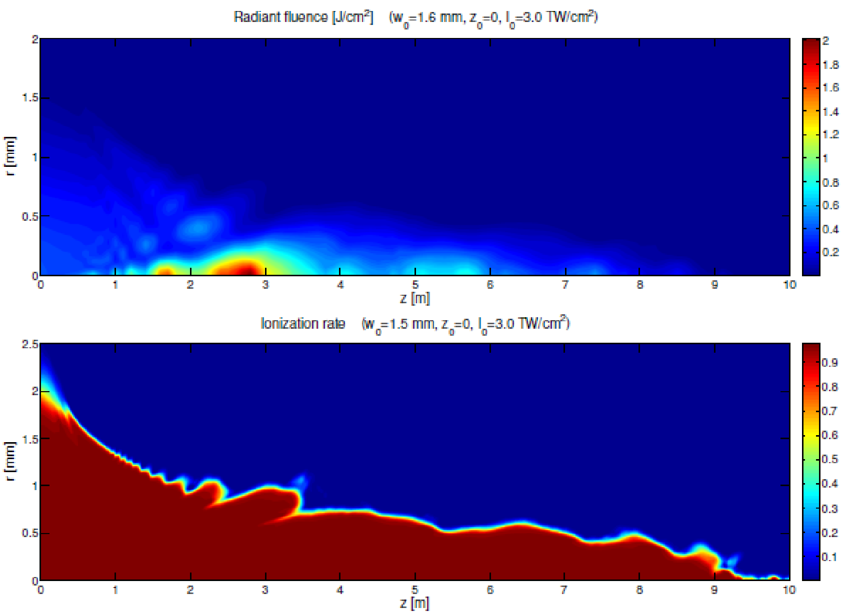

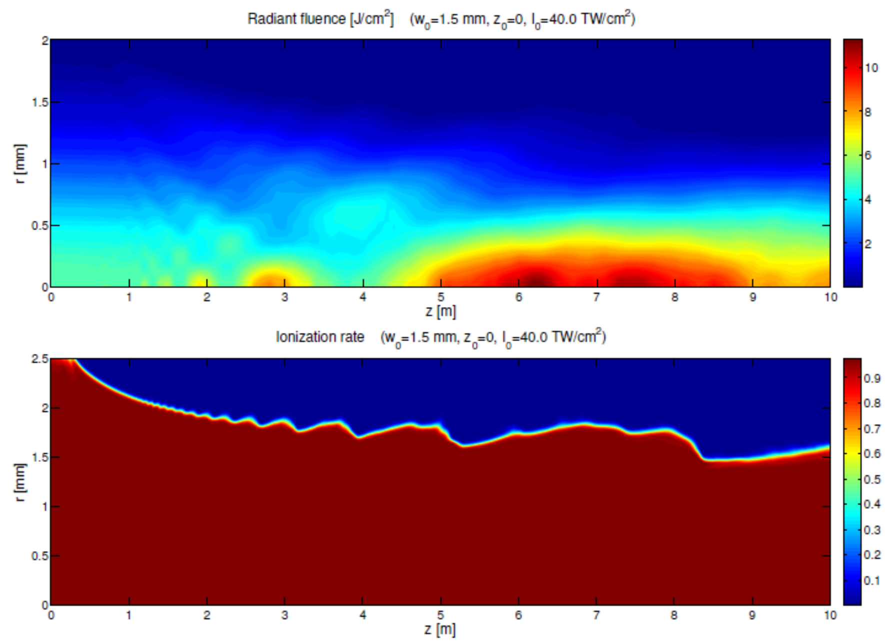

I_0: 3 TW/cm^2

I_0: 40 TW/cm^2

Subthreshold:
Ionization channel collapse,
Output laser pulse destroyed

Super Threshold:
Stable ionization channel,
Stable laser output

G. Demeter

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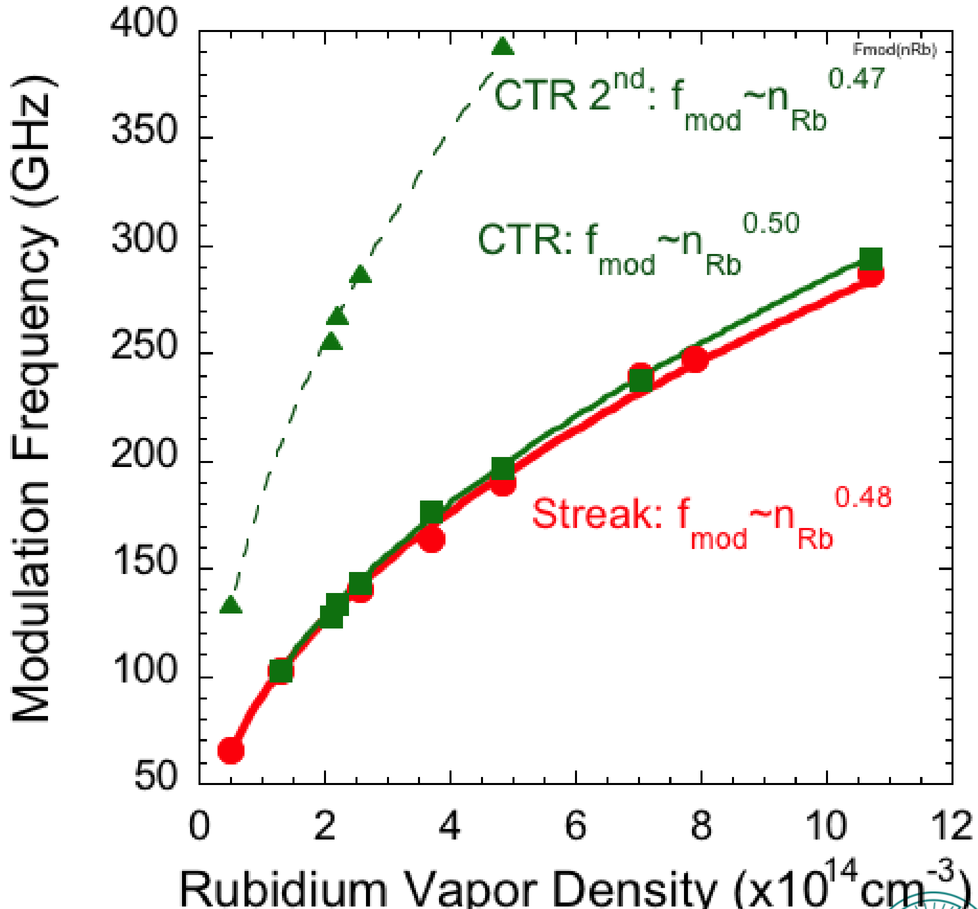
Why Two Numerical Models?

- Wigner and UniGe have different numerical models to try to describe this process
- Cross verification using different methods
- One may be better suited for specific aspects of the project
  - Apply model with lightest resource use that still demonstrates physics to within uncertainty

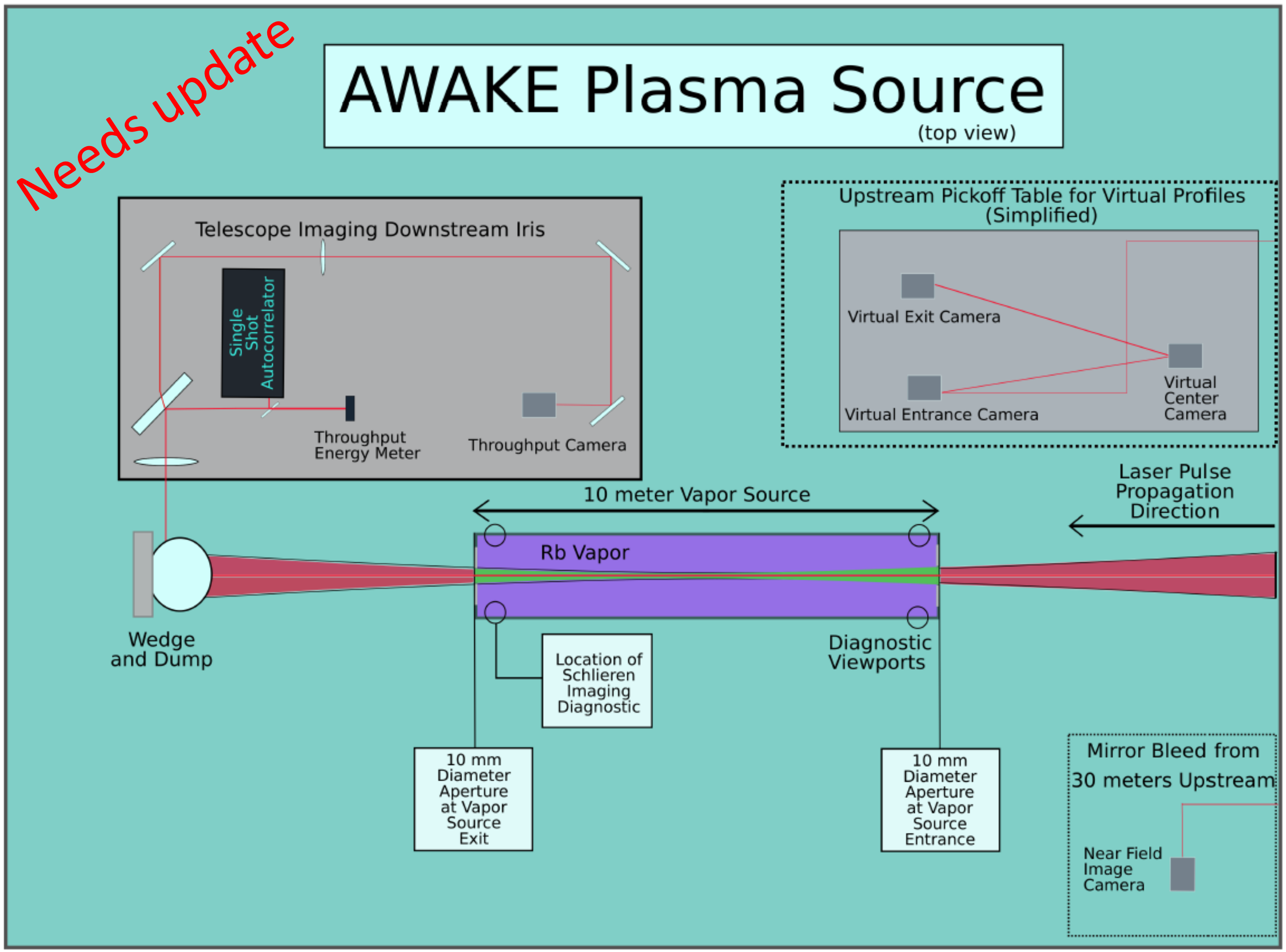
What Level of Ionization Do We Have?

Self modulation frequency as determined by CTR and OTR diagnostics vs neutral density demonstrates consistency with complete ionization within 5%

Self modulation frequency as determined by CTR and OTR diagnostics vs neutral density demonstrates consistency with complete ionization within 5%



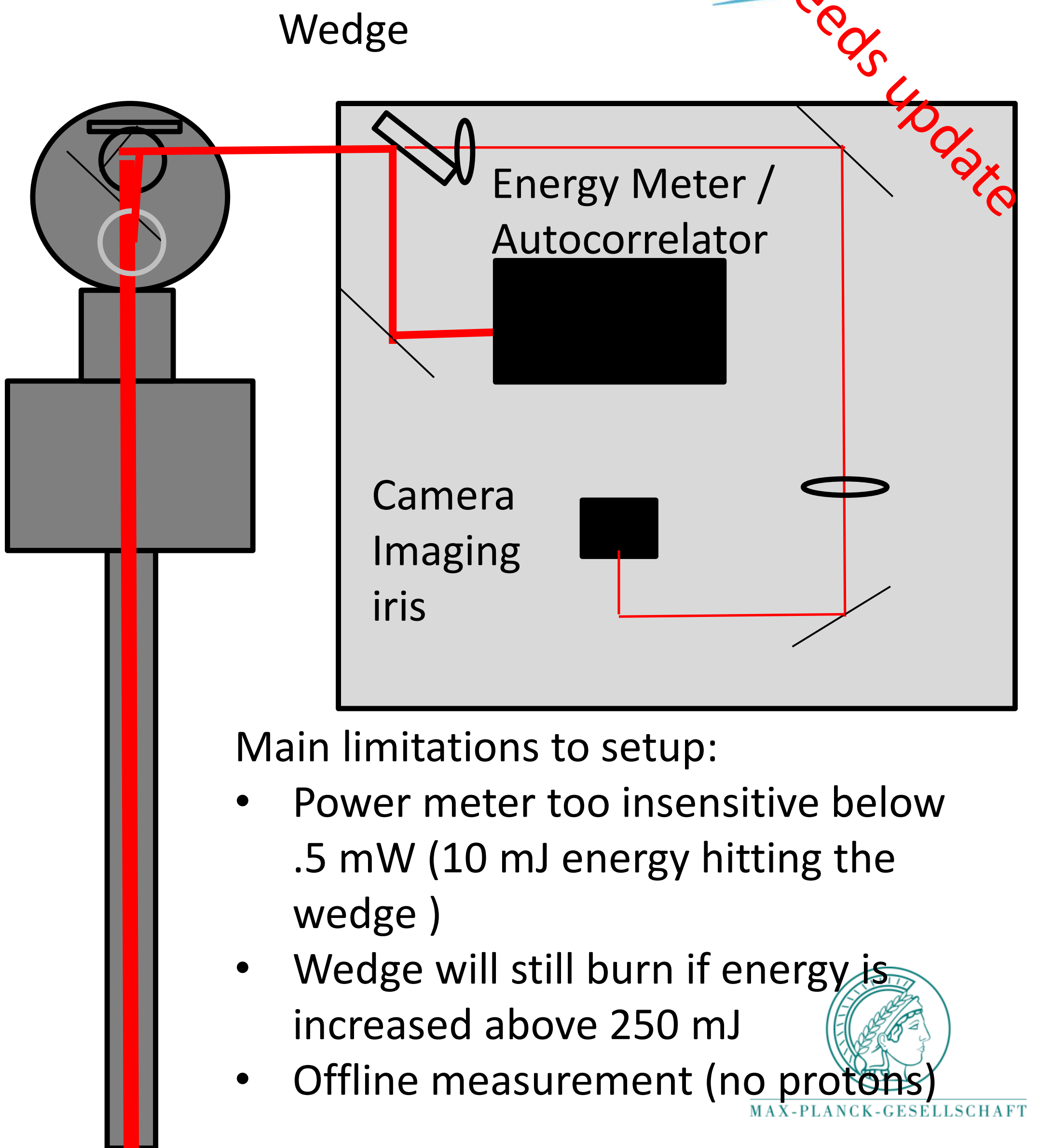
Investigation Setup



Pickoff Setup

Avoid nonlinearity in sampling by:

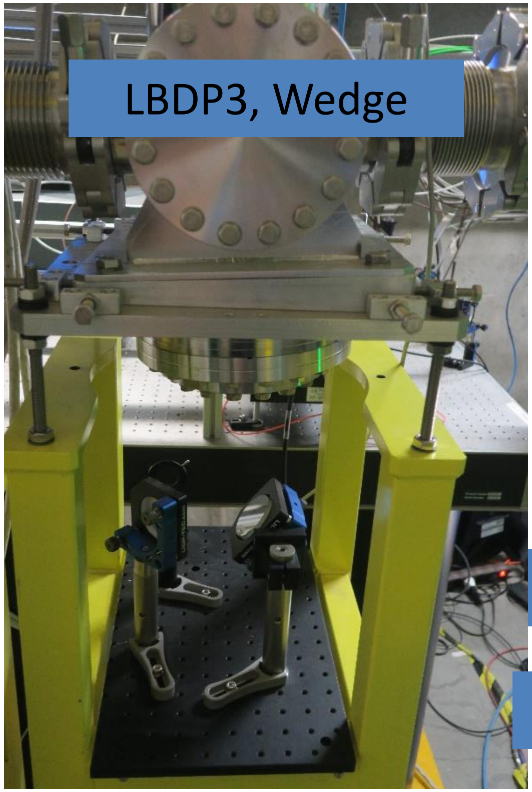
- Wedge picked off .5% of laser (close to Brewster's angle)
- Mirror splits beam to autocorrelator or power meter and bleedthrough goes to transverse measurement
- Telescope images downstream iris of the vapor source

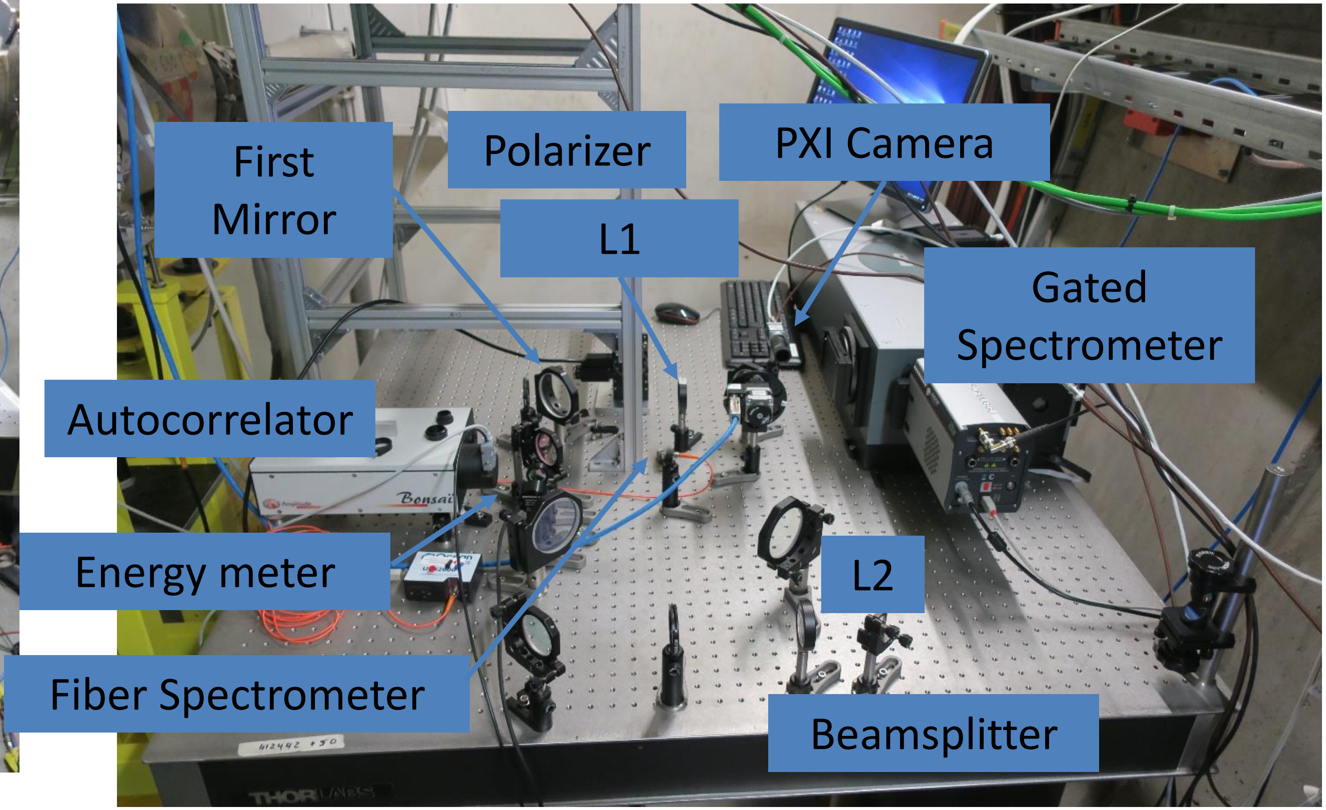


Main limitations to setup:

- 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)

Latest Setup Pictures





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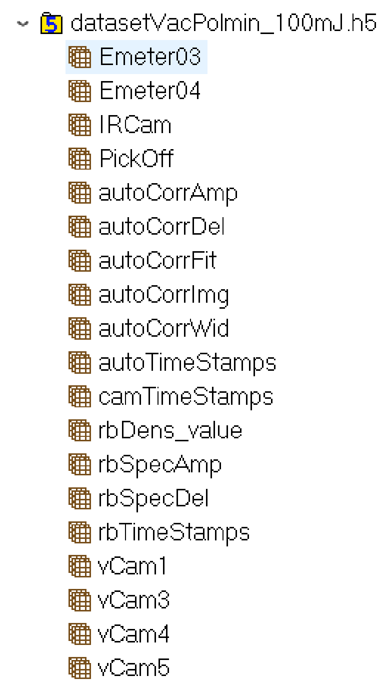
Data Summary

- Data were taken over several years and by several people
  - Special thanks to the following people who were directly involved with data gathering:
    - Anna, Valentina, Bela, Mark, Falk, Fabian, Spencer, Edu, Valentin
- Each time more data is taken, more is understood but full quantitative analysis has not been done of the data
- Data sets are backed up between Wigner (Mark), Valentina, CERN (awakeop/laser_data/), and myself
- We need coordinated effort to analyze all back data and form a consistent picture of the processes with help from our numerical models

Most Recent Laser Propagation Data

- Data sets from Laser Propagation
  - Three data file types:
    - .hd5 files including:
      - 6 transverse profile images at known distances
        - » 5 virtual line images to reconstruct the laser field at entrance of vapor source
        - » One image
      - Input and output energy of pulses into and out of vapor source
      - Autocorrelator data
      - Neutral Rb Data
      - Timestamps for data verification
    - Ocean optics "long timescale" spectrum
      - Simple files, ASCII two column - wavelength and signal
    - Andor gated camera spectrum '.sif' files
      - Python .sif reader class from github needed to be modified (fujisoup's version lightingghost's version did not work on our .sifs) to read out the gating information, as standard versions do not
      - This problem highlights some of the issues Anna had with controlling the gated camera on a previous run with the CERN BI developed GUI. The properties for the gating are different than that of standard control / data sets for Andor devices such as exposure.

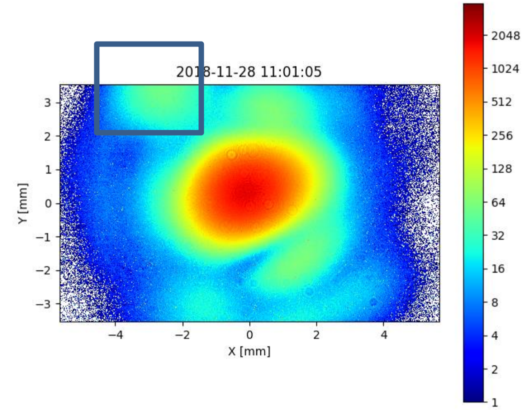


Transverse Mode Examples

Data Checking

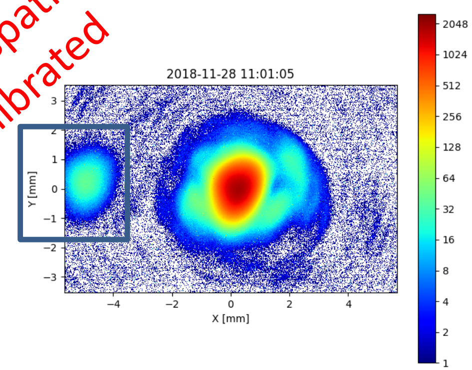
- Log scale comparisons of vacuum profiles
- Reconstruction not perfect, but pretty good
  - Reflection artifacting
  - Minor distortion

Reflection artifacts



Virtual Line Exit

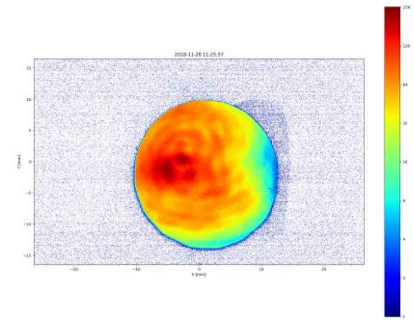
Not spatially calibrated



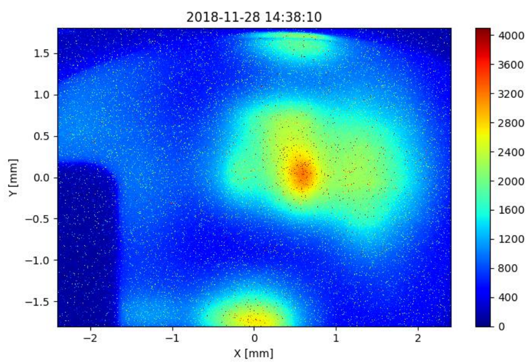
Imaged Exit

Camera Spatial Calibration

- Cameras need spatial calibration
- VLC Camera 3,4,5 are **direct** no lenses, just take calibration from camera spec sheets
- VLC Camera 'NF', CAM1 are **imaged** and therefore need care taken in their calibrations



NF Camera 20mm aperture

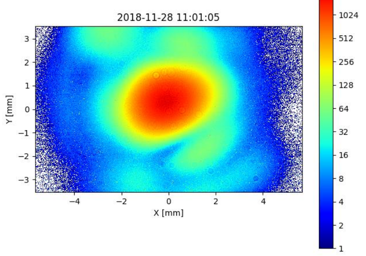


CAM1 Shadow of MP5 (45 degree projection)

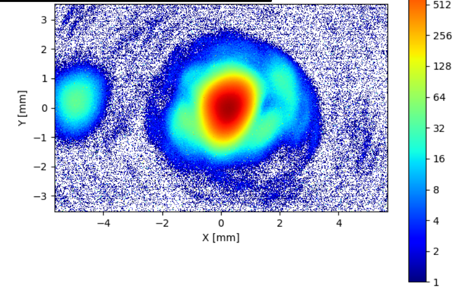
Output Camera Calibration

- What about our Output Calibration?
- Could calculate from telescope
- Could calibrate from ‘edge scrape’ of vapor source iris
- If image of CAM5 is good (sidelobe structures resolved) could simply scale
- Can do all three and cross-check for consistency

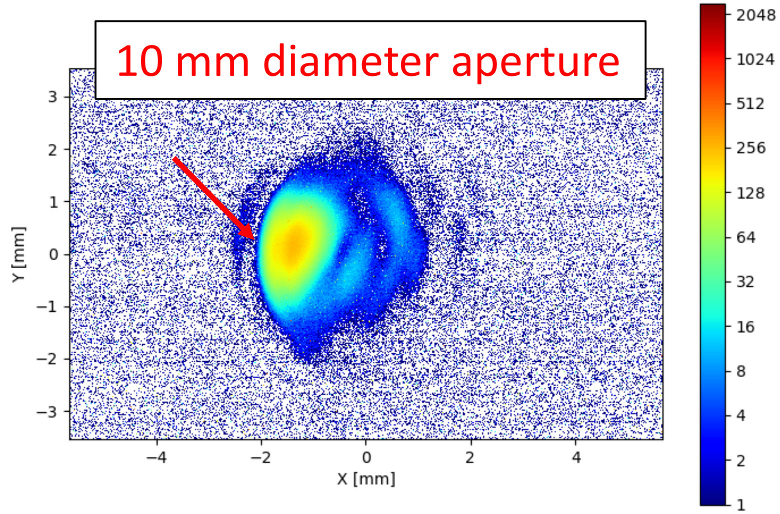
Rotate, Flip and Scale



Virtual Line Exit



10 mm diameter aperture



Iris Edge Scrape

Transverse Distribution Trends

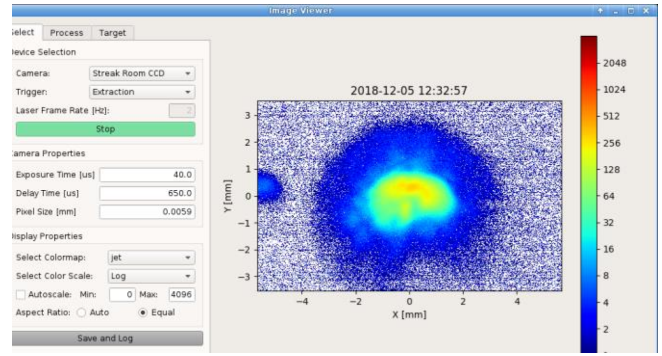
- These seem consistent with the data we have seen previously
  - Not incredibly interesting but crucial for model validation and verification
- The spot size monotonically reduces as we lower the energy toward depletion/collapse
- The latest dataset appears has better imaging so the systematics have been reduced
- We need to compare the output transverse distributions, energy, pulse width from autocorrelator with numerical models

Apparent Beam Guiding near depletion

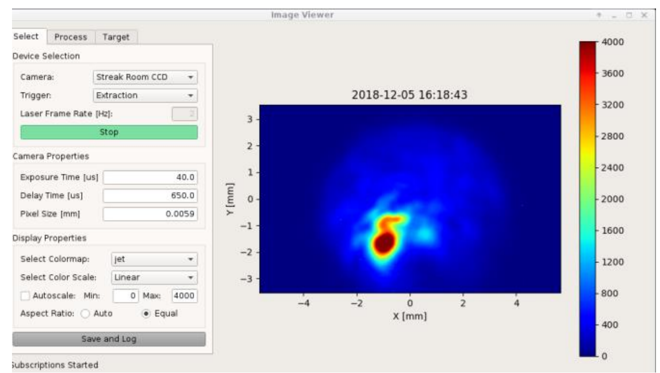
Rb density is $2e14/cm^3$

- Beam stays in vacuum position in position until close to depletion
- Jump in position occurs, consistent in same direction right at threshold

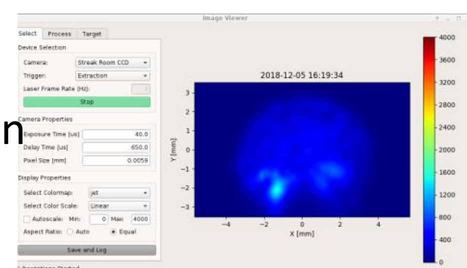
Beam location at 10% attenuator



Beam location at 5%

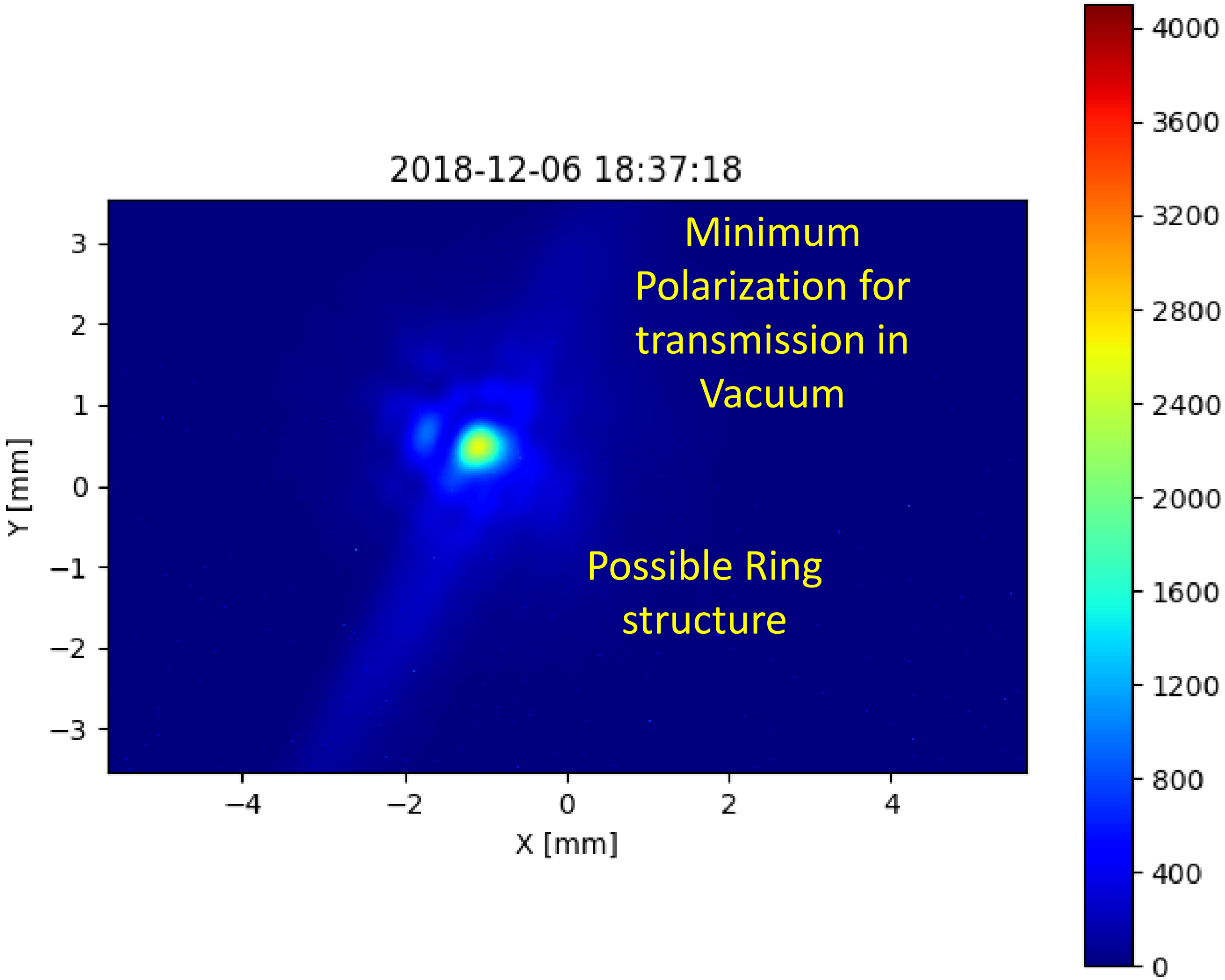


Beam location below 5%



Polarization

Polarization shift determined in light coming out of plasma



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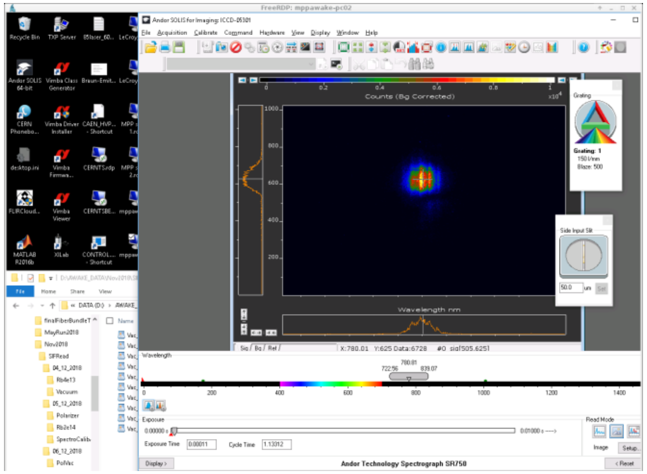
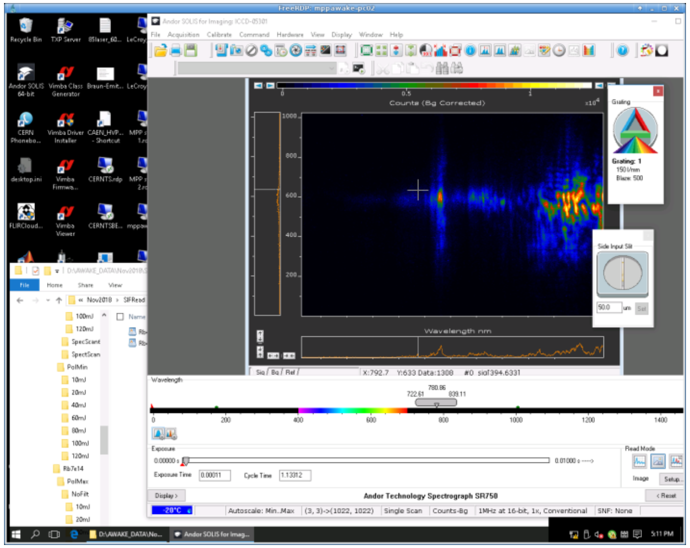
Spectral Examples

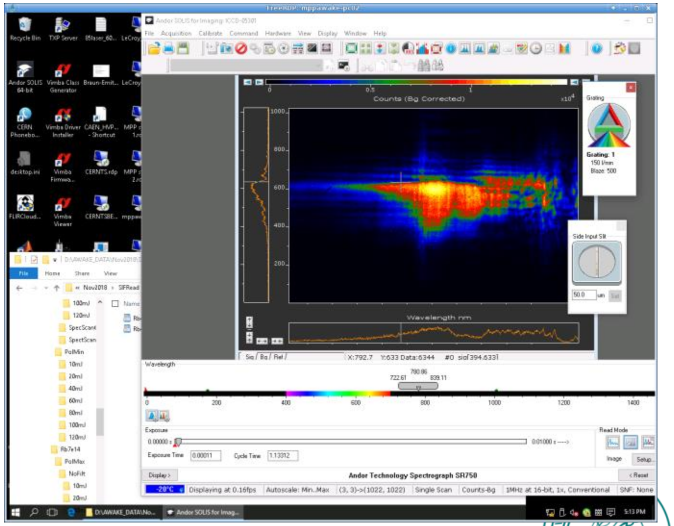
- Consistent Blue to Red shifts

Vacuum Spectrum





Sub near threshold spectrum



Super-near threshold spectrum

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More Spectral Modulation

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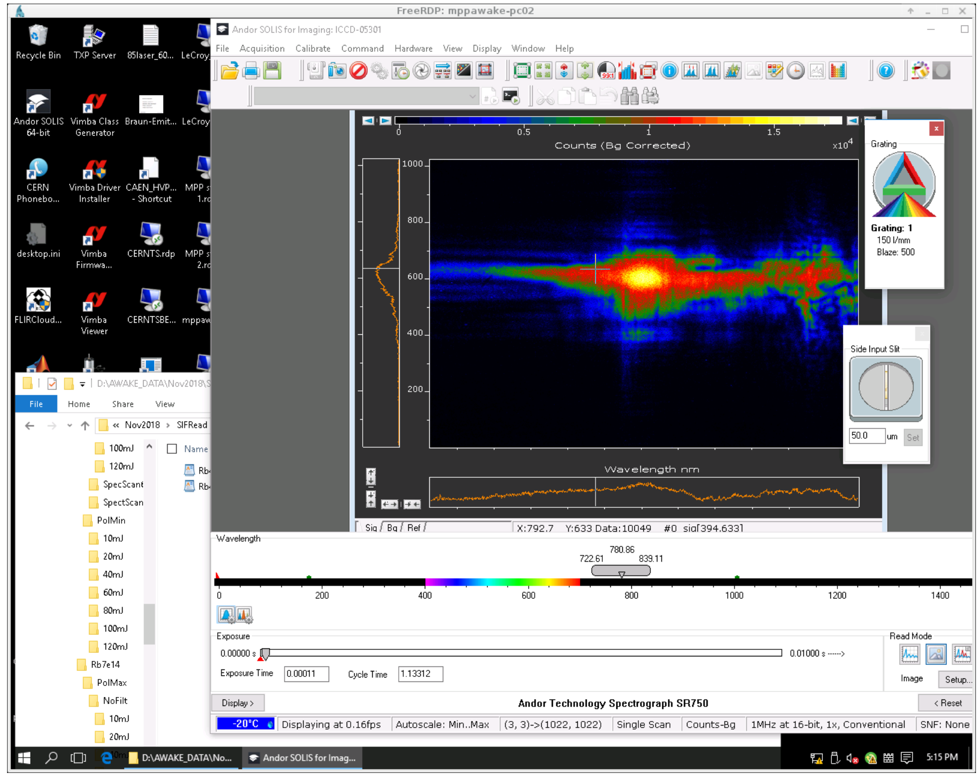
AWAKE

- We have a lot of this data and it seems that nearly all of the signal is within the **first time bin**, meaning it is not recombination light but some sort of SPM or mixing
- Gate widths and delays are contained as properties within the .sif files



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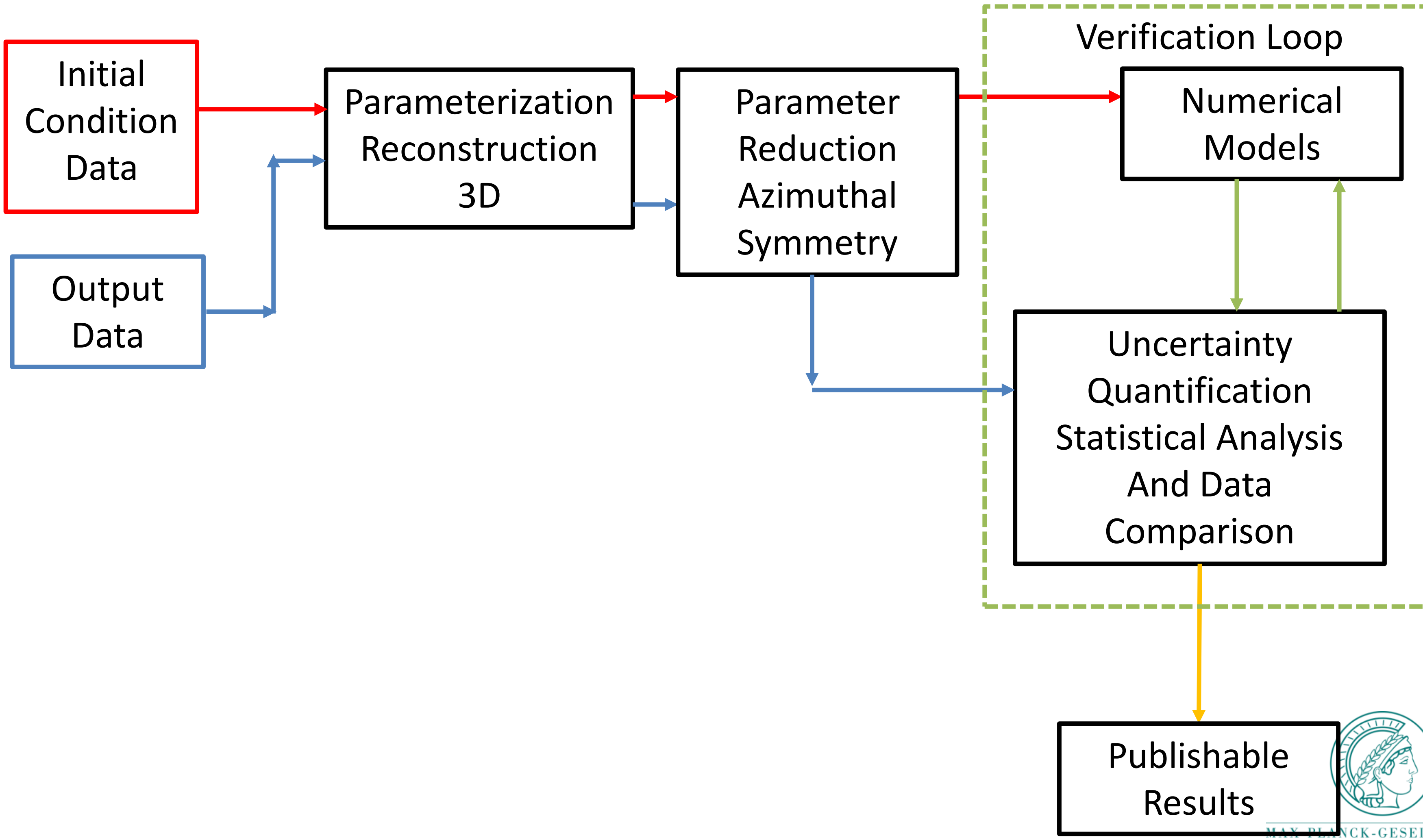
Python .sif reader

- Important for any one looking at Gated camera images:
  - Gated Spectrometer
  - Gated Schlieren
- .sif reader can be used on any data set that relies on the andor gated camera until integration into event builder can be completed via C++ SDK and file grabber
- .sif files have a complicated header / data sets with mixed ASCII and binary structures
- Most readers will only look for data and the standard header, ignoring the spectrometer and gating headers
- Needed to modify existing gihub reader to extract the gate delay and gatewidth

Standard header, sufficient for most andor cameras

Possible Analysis Workflow



Planning -Analysis

Analysis and Model Verification

- Valentina and Mark have made some progress with initial conditions and output spot size and energy scalings:
  - Valentina has demonstrated 5 image modified Gerchberg-Saxton reconstruction
  - She is now trying to do lineout / full profile Laguerre-Gaussian mode expansions
  - Mark is trying a similar approach, they can work together to do cross-checking
  - Gabor is waiting for usable initial conditions and parsed output

Planning – July Experiments

- Why another experiment?
  - Timescale accessibility:
    - We have sub ps timescale with Autocorrelator
    - We have +10 ns timescale with gated camera / spectrometer
    - Gated camera can give us accessibility to timescales of 1ps – 10ns, where we can see tails, etc.
  - Gated Schlieren
    - Same timescale arguments
    - Observe subnanosecond – 10 ns evolution of boundary
  - Backward Interferometry
    - Long timescale behavior
  - FROG
    - A phase measurement of what is coming out after ionization would give us a better idea of what is going on

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July Experiment Technical Concerns

Laser Propagation July Preparations

- Acquisition of FROG
  - Edu is looking into this
- Streak camera of laser throughput and Schlieren signal
  - Dedicated properly terminated precise triggers pulled to Schlieren and LBDP3 tables (Heiko / Ben)
  - Computer migration (Alastair & Co.)
- Back propagating interferometry
  - Build interferometer and place at table near MP1 in laser room (Wigner?)
  - Pull single mode fiber to laser room from diode laser source at LBDP3 table
  - Commissioning plan, establish background fringes without Rb, etc
- Plans for recommissioning of:
  - Vapor source
  - Laser system
  - DAQ

How to Organize (Suggested)

- Data Analysis
  - Josh, Valentina, Mark, any other volunteers
- Numerical Models
  - Jerome, Gabor
- Data comparison to Models
  - Everyone on this list, but in particular more experienced people like:
    - Patric
    - Jerome
    - Wigner Colleagues
- July Experiments
  - Streak Camera (Take all measures to protect equipment with direct laser)
    - Schlieren
      - Anna
    - Transverse Mode
      - Josh
  - Backward Interferometry
    - Wigner Colleagues
  - FROG
    - Edu
    - Josh

Conclusions

- We have a good amount of data, maybe enough to understand what is going on
- We need people to work on low level analysis, but especially experienced people to help with the validation/verification of the numerical models
- We can get two solid publications out of this
- The results of the plasma column determination has a direct impact on design choices for AWAKE going forward