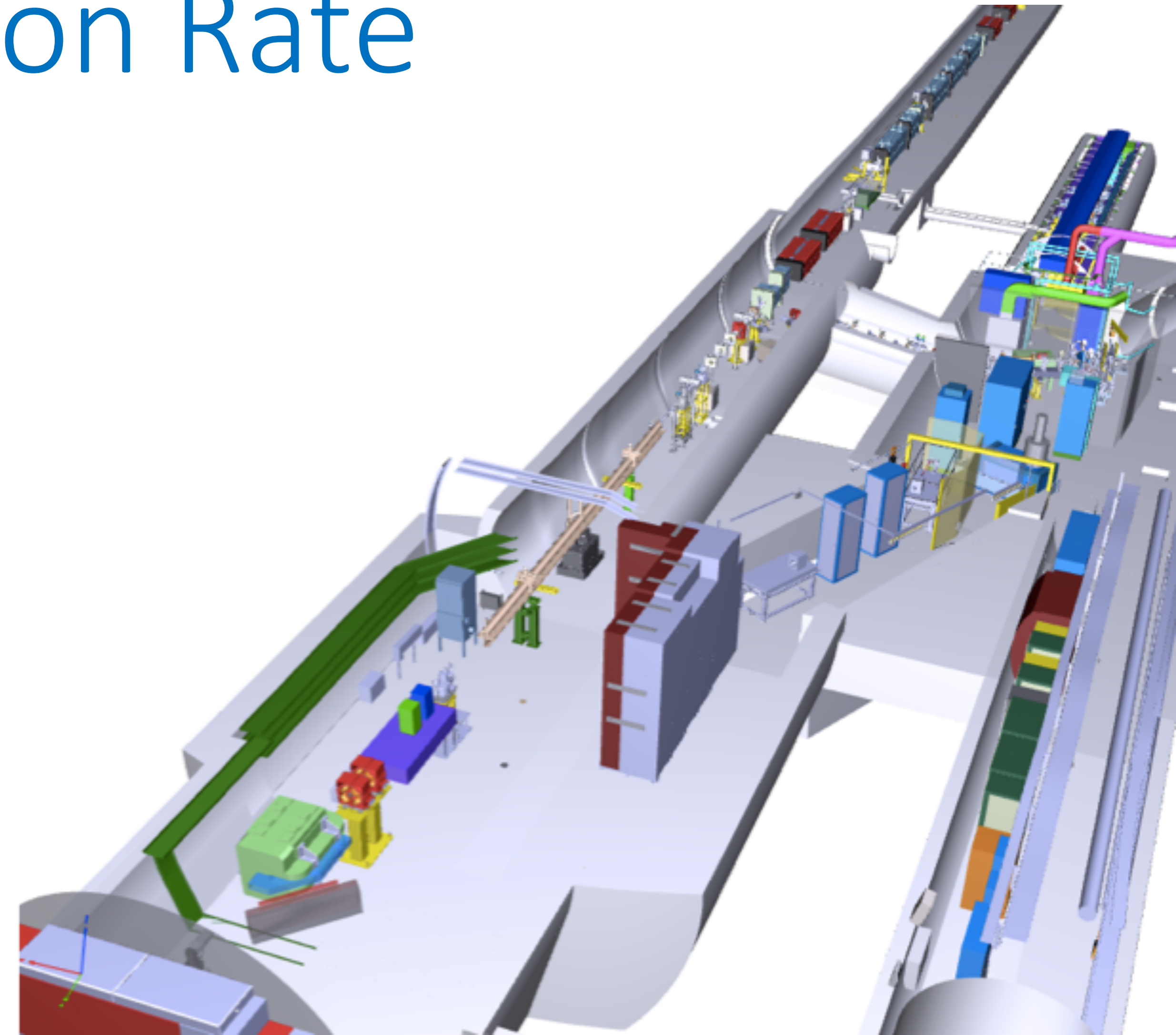
# Beam-Based Measurements of the Plasma Recombination Rate

Spencer Gessner

On Behalf of the AWAKE Collaboration

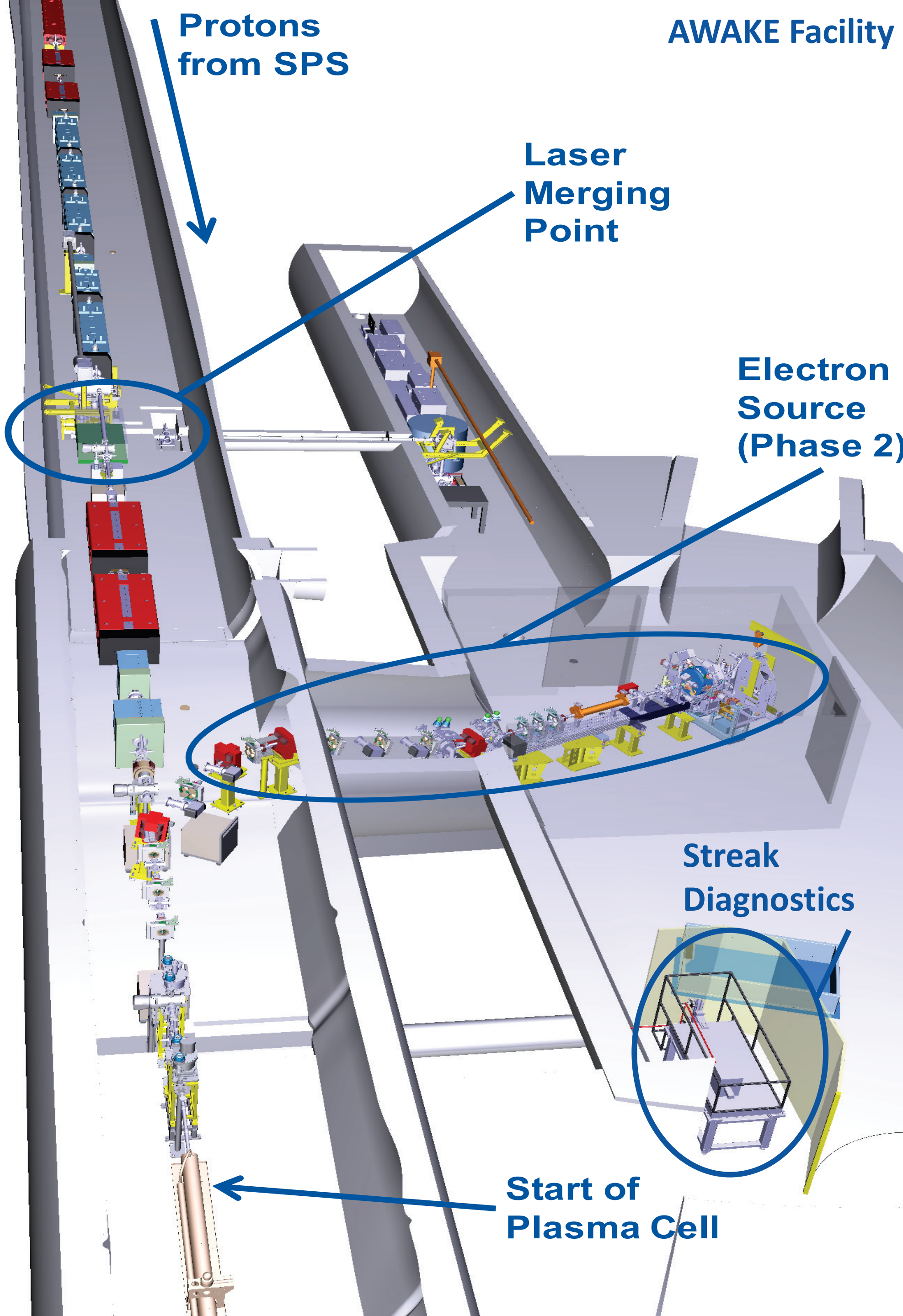
25 September

EAAC, Elba, Italy, 2017



# A Brief Introduction to AWAKE

- AWAKE is the world's first proton beam-driven plasma wakefield experiment.
  - AWAKE uses the 400 GeV proton beam from CERN's SPS accelerator.
  - AWAKE uses a 10 meter-long Rubidium vapor source (the longest of its kind).
  - A TW-class laser ionizes the Rubidium.
  - The proton beam is modulated by the plasma and forms microbunches, which in turn drive a high-amplitude wakefield.
  - A streak cameras captures OTR light and extracts information about the modulation.

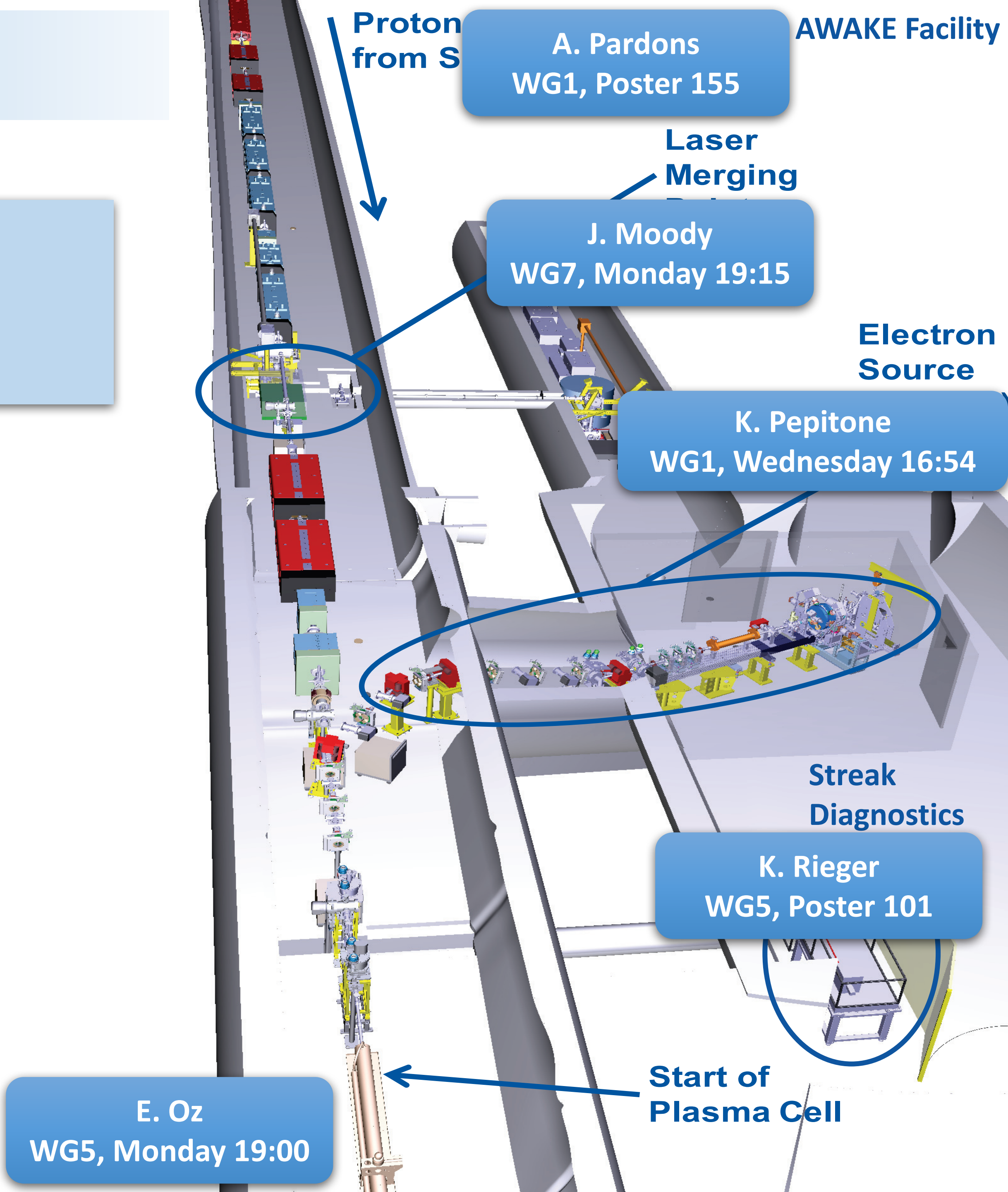


# A Brief Introduction to AWAKE

- See overview talk:
  - **P. Muggli, Plenary 3, Tuesday at 09:50.**

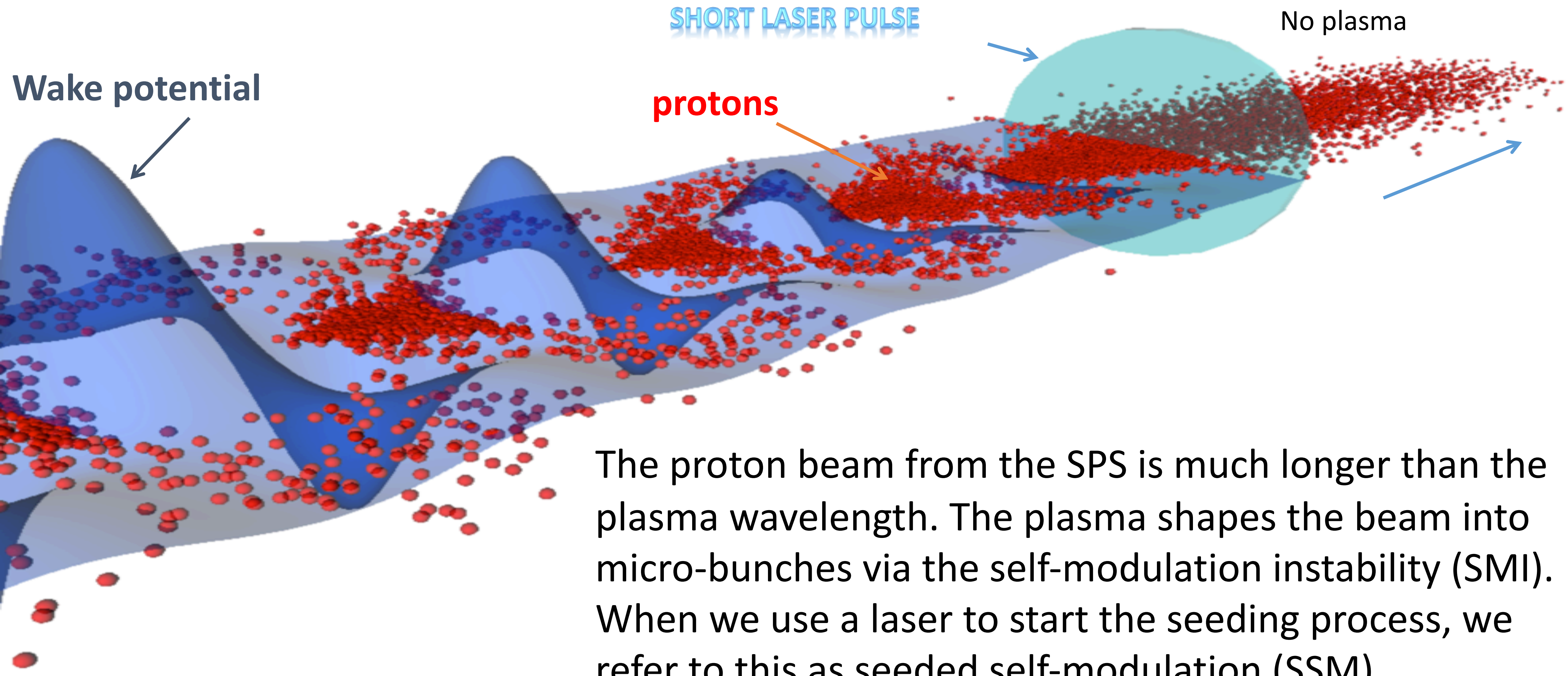
- AWAKE Result talks:
  - M. Turner, WG1, Wednesday at 16:00
  - M. Martyanov, WG1, Wednesday at 16:18
  - F. Braunmuller, WG1, Wednesday at 16:36

- AWAKE Result posters:
  - F. Batsch, WG5, Poster 159



# Seeded Self-Modulation

A. Petrenko, CERN




The proton beam from the SPS is much longer than the plasma wavelength. The plasma shapes the beam into micro-bunches via the self-modulation instability (SMI). When we use a laser to start the seeding process, we refer to this as seeded self-modulation (SSM).

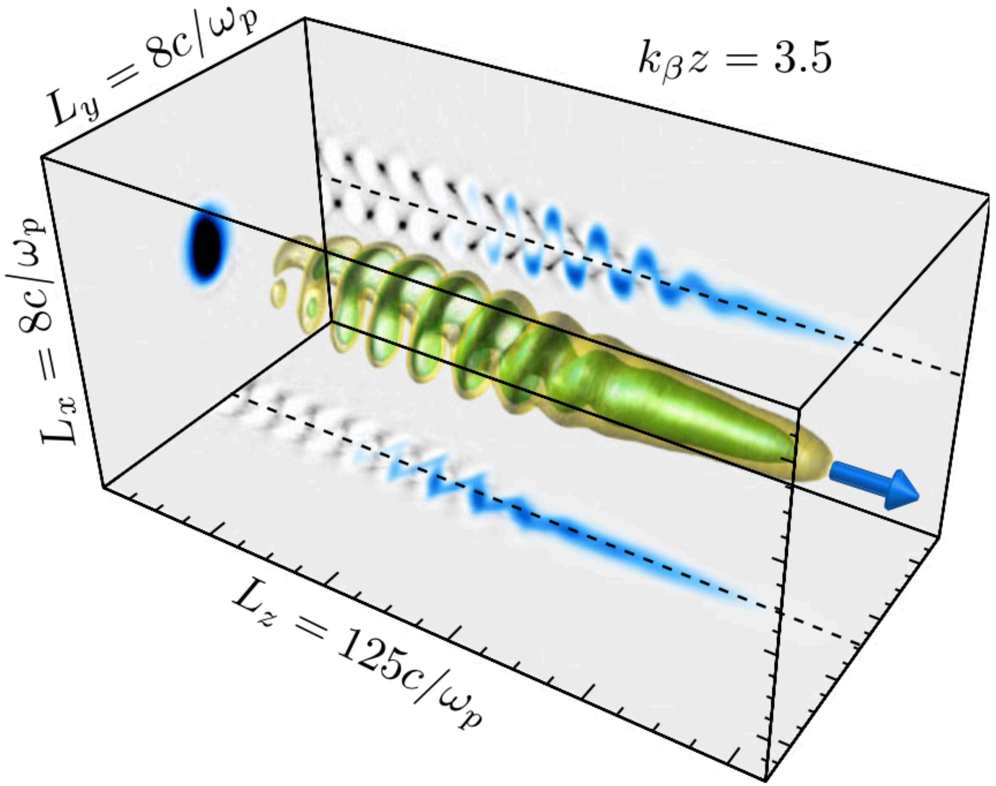
# Seeded vs. Unseeded Modulation

The self-modulation instability shapes the long proton beam into microbunches, which can be used to drive a high-amplitude wakefield.

Other instabilities exist. Hosing is the most prominent instability that “competes” with SMI. The ionizing laser seeds the SMI while suppressing hosing.

Important question for AWAKE:

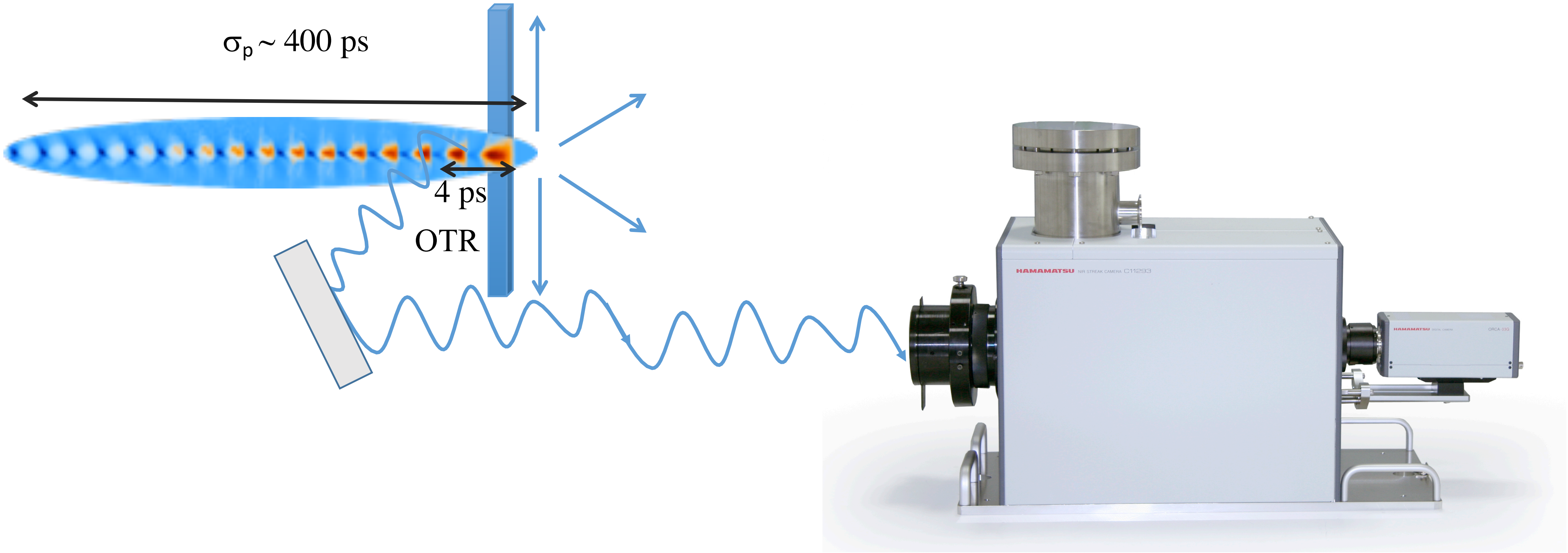
- How does the seed point influence the development of microbunches?
  - *We scan the time delay between ionizing laser pulse and proton beam in order to investigate.*




*Hosing Instability Suppression in Self-Modulated Plasma Wakefields*
J. Vieira, W. B. Mori, and P. Muggli
Phys. Rev. Lett. **112**, 205001

# Measuring SMI: Streak Camera

K. Rieger, M. Martyanov, P. Muggli, MPP

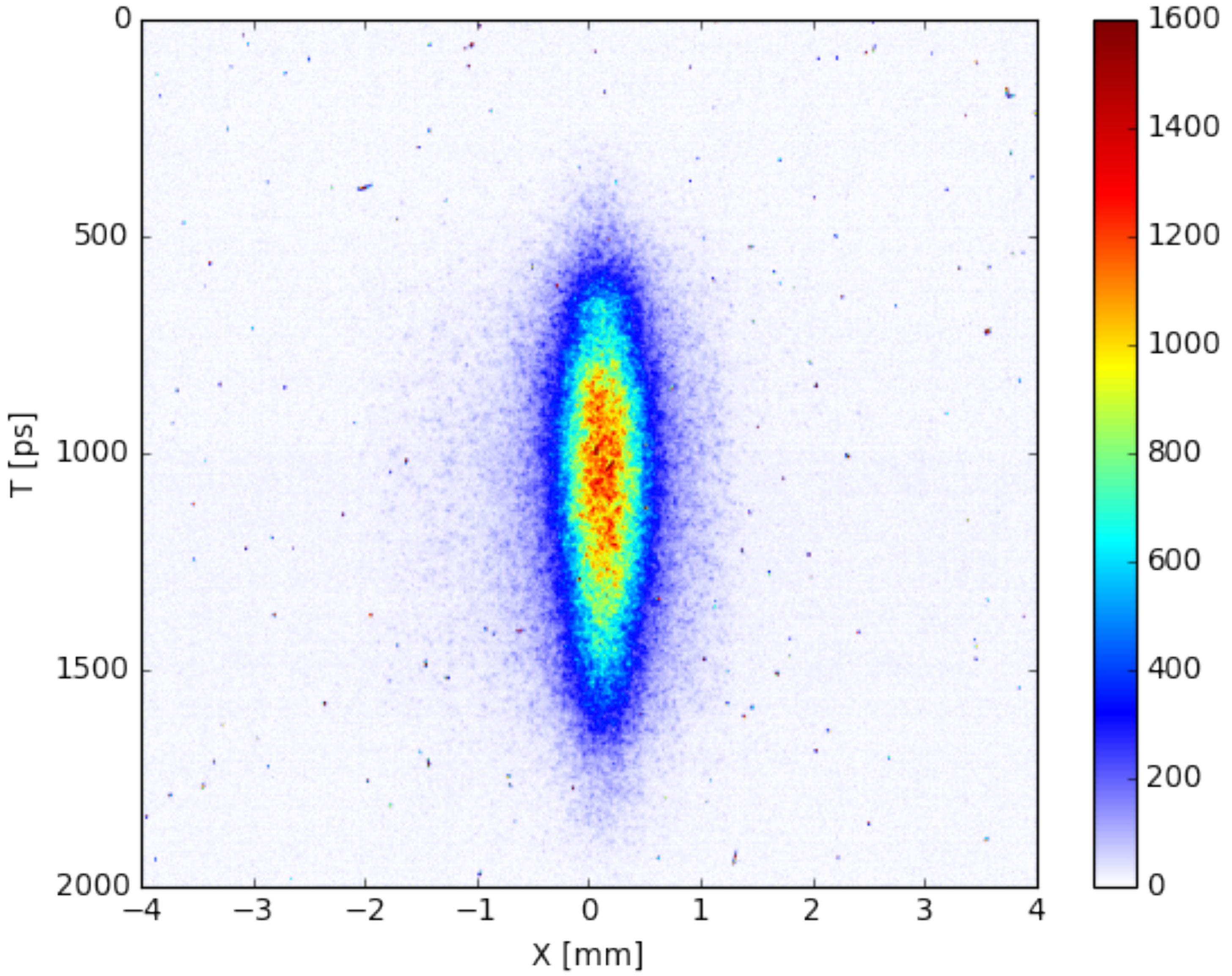



The modulated proton bunch is sent through a metal foil where it generates optical transition radiation (OTR). This radiation is sent to the streak camera.

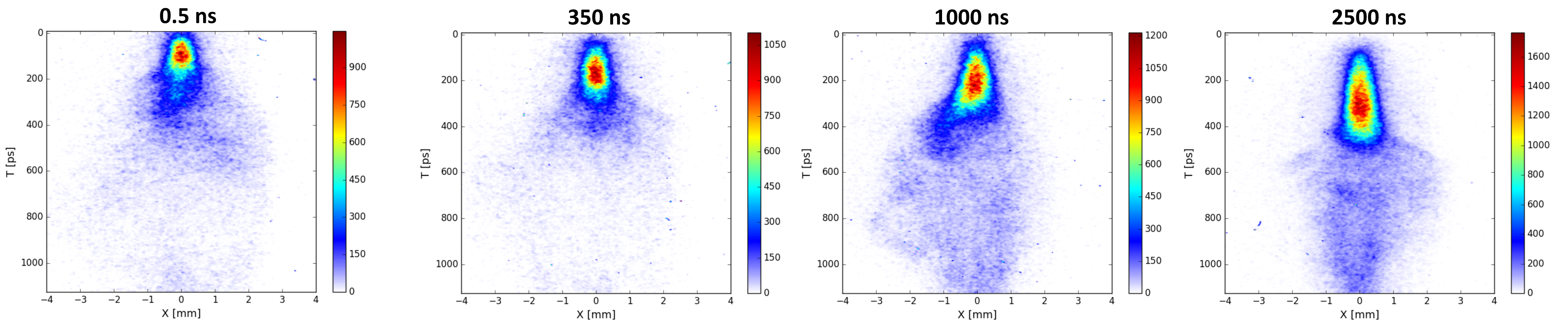
# Nominal Beam

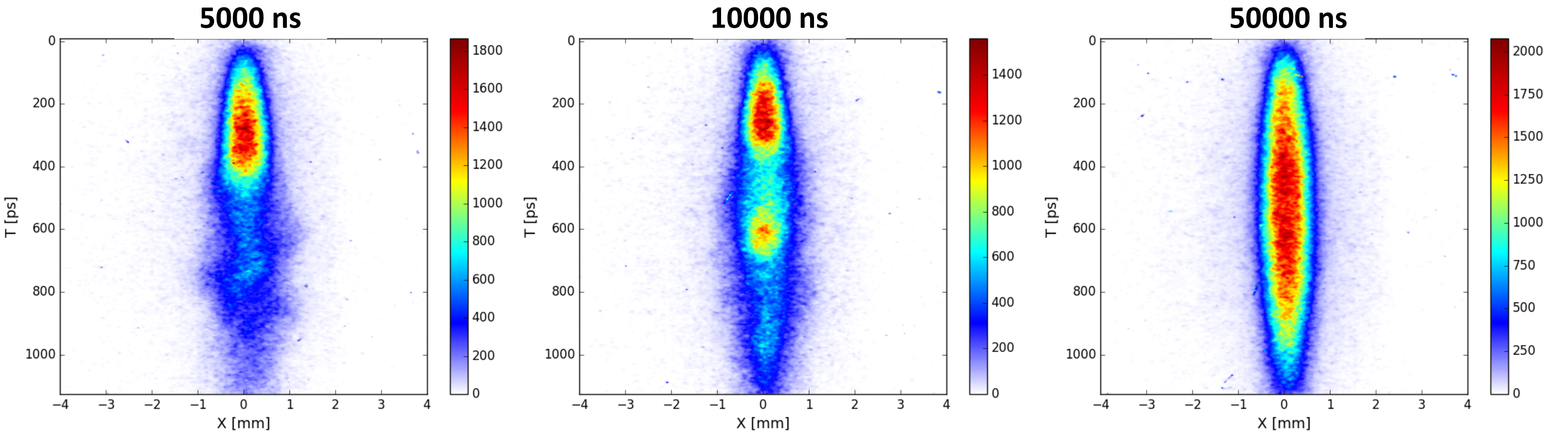
The SPS delivers a 400 GeV proton beam with 3E11 $p^+$, and an rms bunch length of approximately 400 ps (12 cm).

The bunch is typically straight with no visible structure.



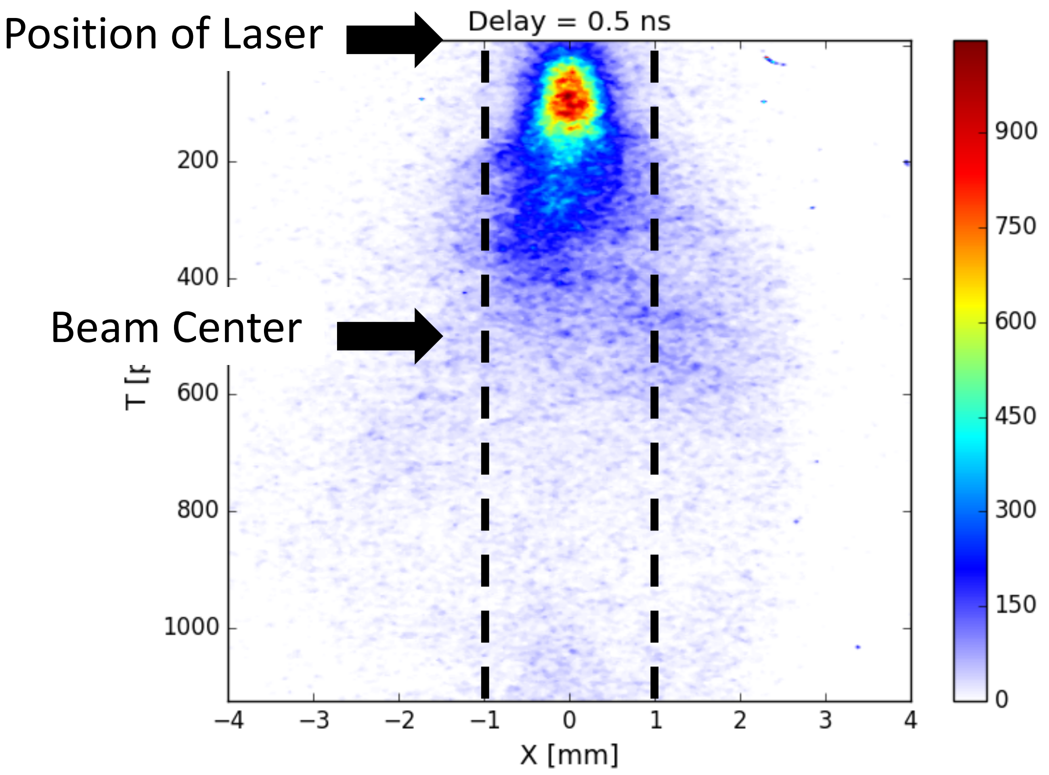
# Time Delay Scan (1 ns streak time-scale)

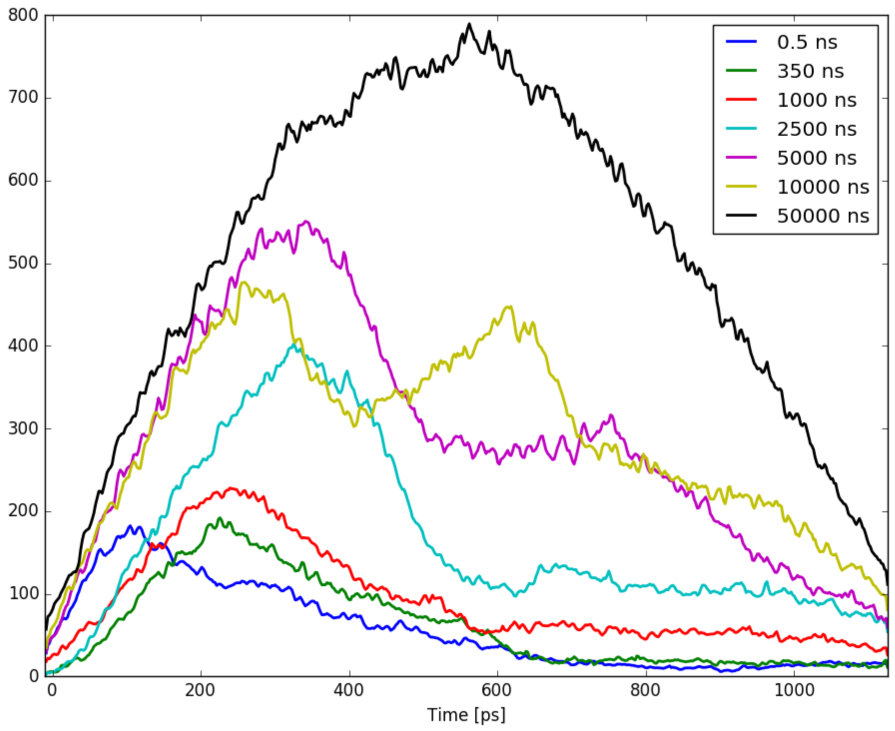



We scan the time between the ionizing laser pulse and proton beam in successively larger intervals, starting from 0.5 ns (measured with respect to the center of the proton beam) to 50,000 ns (15 km ahead of the beam).

# Time Delay Scan (1 ns streak time-scale)



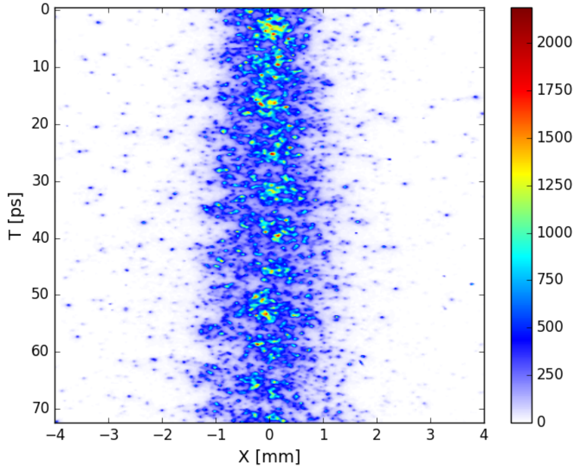

For each of shots on the previous slide, we take a projection of the image within the band outlined by the dashed black lines. Each line is a single representative shot for the time delay.

The first three delays look fairly similar, despite the fact that the seed pulse is just within the tip of the bunch for the 0.5 ns delay.

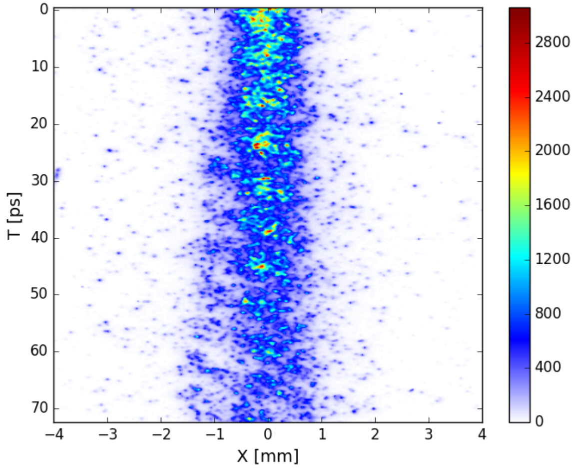
At longer delays, more charge is retained in the core of the beam and the instability seems to develop later along the bunch.

# Time Delay Scan (fast time-scale)

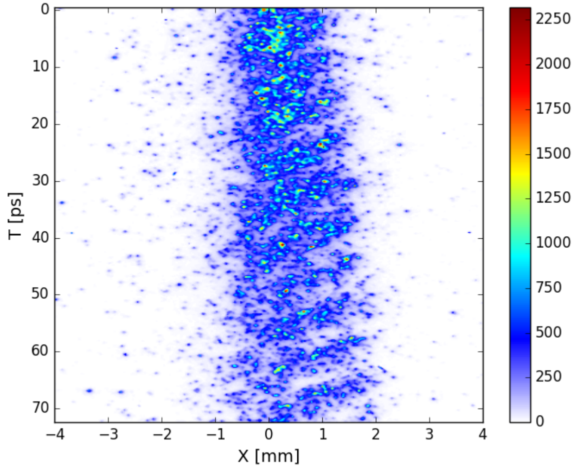
**0.5 ns (70 ps time scale)**



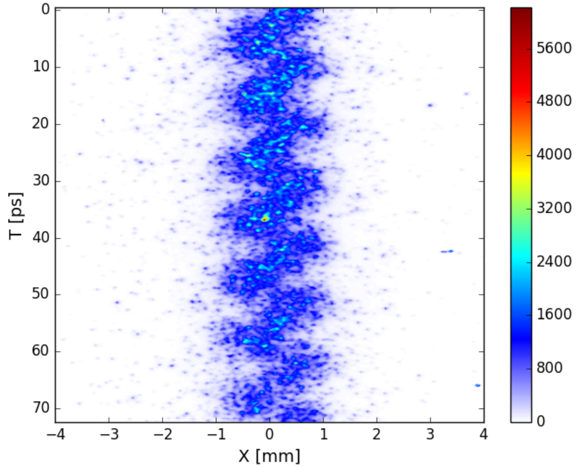

**350 ns (70 ps time scale)**




**1000 ns (70 ps time scale)**




**2500 ns (70 ps time scale)**

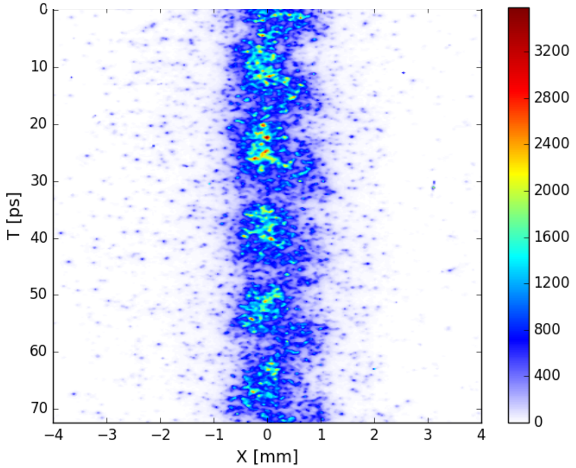



Here we zoom in on the bunch to observe the SMI frequency.

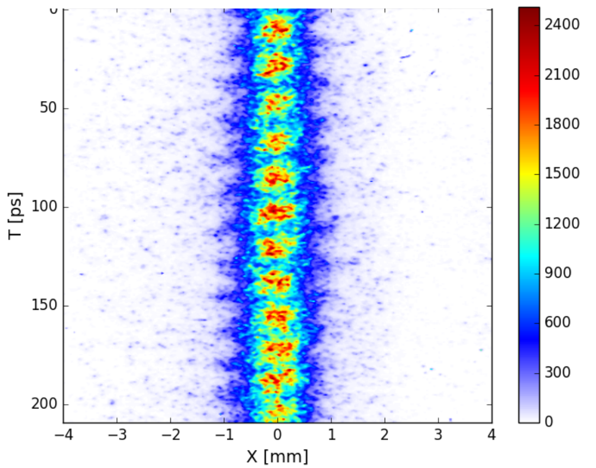
Hosing is apparent on some, but not all, shots.

We record approximately 10 shots at this time scale for each delay.

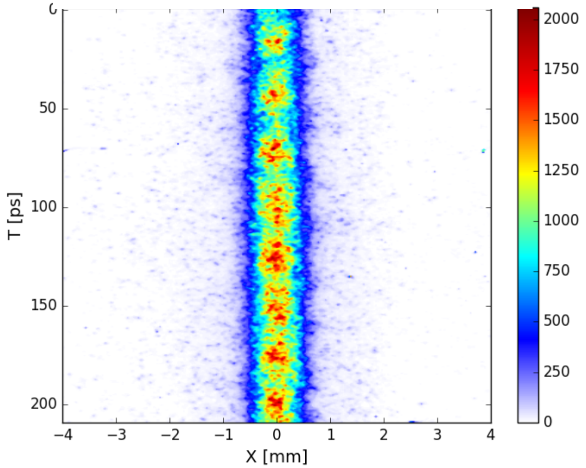
**5000 ns (70 ps time scale)**




**10000 ns (210 ps time scale)**




**50000 ns (210 ps time scale)**



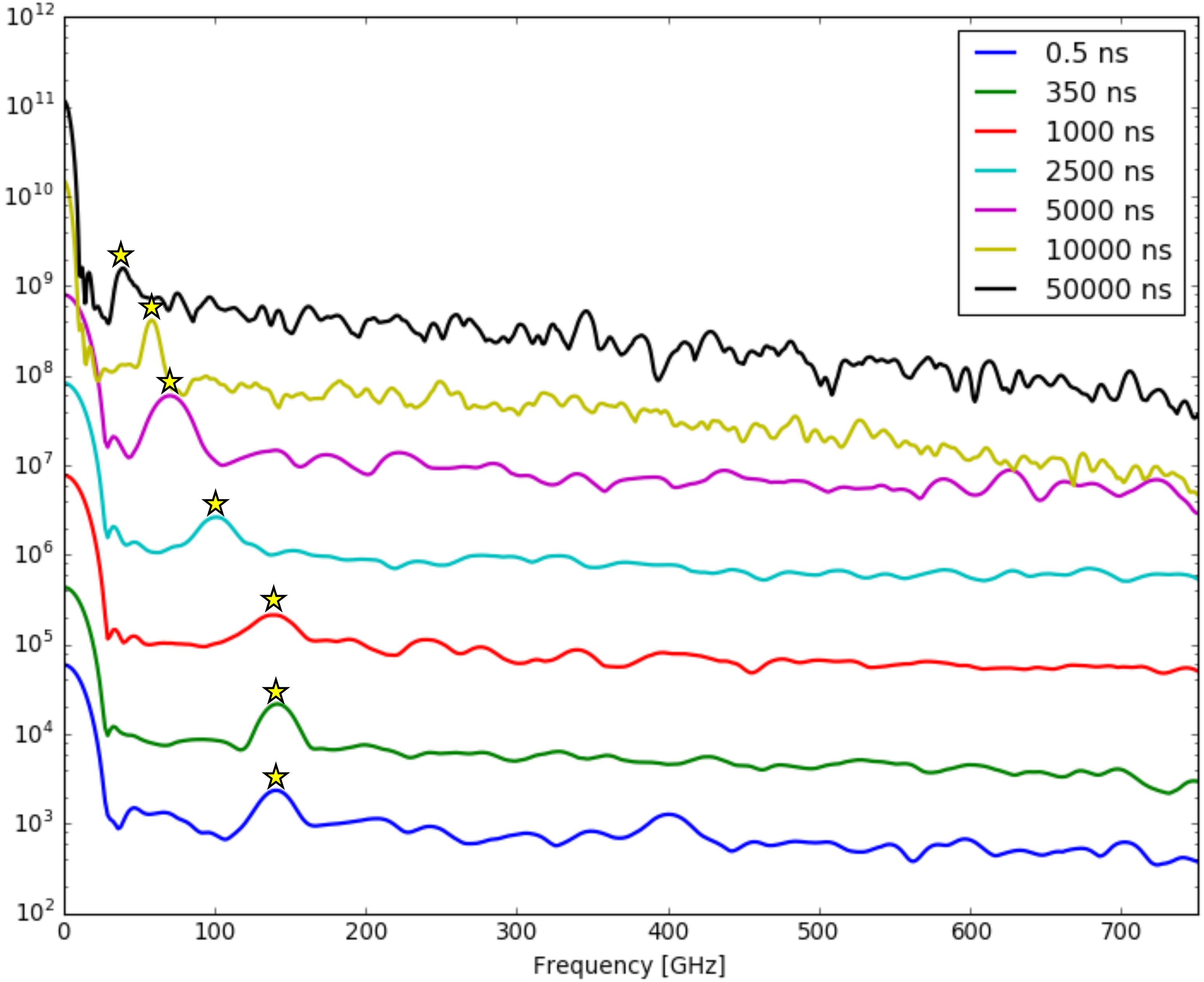
# Extracting Frequency Content

For every delay, we take the FFT of each shot. Before calculating the FFT, we apply a Hann filter and embed the image projection in an array of zeros.* We then average the FFTs for every delay to produce the image on the right.

Each FFT has an arbitrary vertical offset for clarity.

| Delay [ns] | FFT Peak [GHz] | Equivalent *n* [$\times 10^{14}$ cm$^{-3}$] |
|---:|---:|---:|
| **0.5** | 141.2 | 2.47 |
| **350** | 141.2 | 2.47 |
| **1000** | 139.5 | 2.41 |
| **2500** | 101.6 | 1.28 |
| **5000** | 70.6 | 0.62 |
| **10000** | 58.5 | 0.42 |
| **50000** | 39.2 | 0.19 |

*K. Rieger et al., Rev. Sci. Inst., 88, 025110 (2017)



# Plasma Recombination

Naively, we expect the plasma decay to go as $t^{-1}$:

$$\frac{dn}{dt} = -\alpha n^2 \quad \Rightarrow \quad n(t) = \frac{n_0}{n_0 \alpha t + 1}$$

Plasma density

Recombination constant

But this doesn't capture the behavior at small *t*, where we do not observe decay of the plasma density.

F. Chen *Intro. to Plasma Physics*

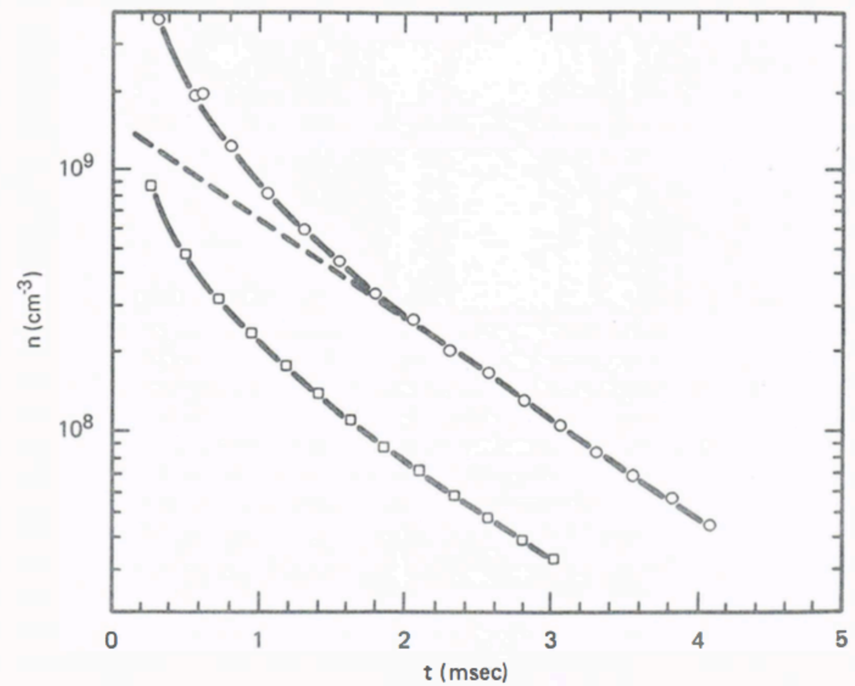



**FIGURE 5-9** **Density decay curves of a weakly ionized plasma under recombination and diffusion.** [From S. C. Brown, *Basic Data of Plasma Physics*, John Wiley and Sons, New York, 1959.]

# Plasma Recombination

Reality is more complicated. The recombination constant $\alpha$ depends on the plasma electron temperature:

$$\frac{dN_e}{dt} = -N_e^2(\alpha_r + N_e\alpha_3)$$

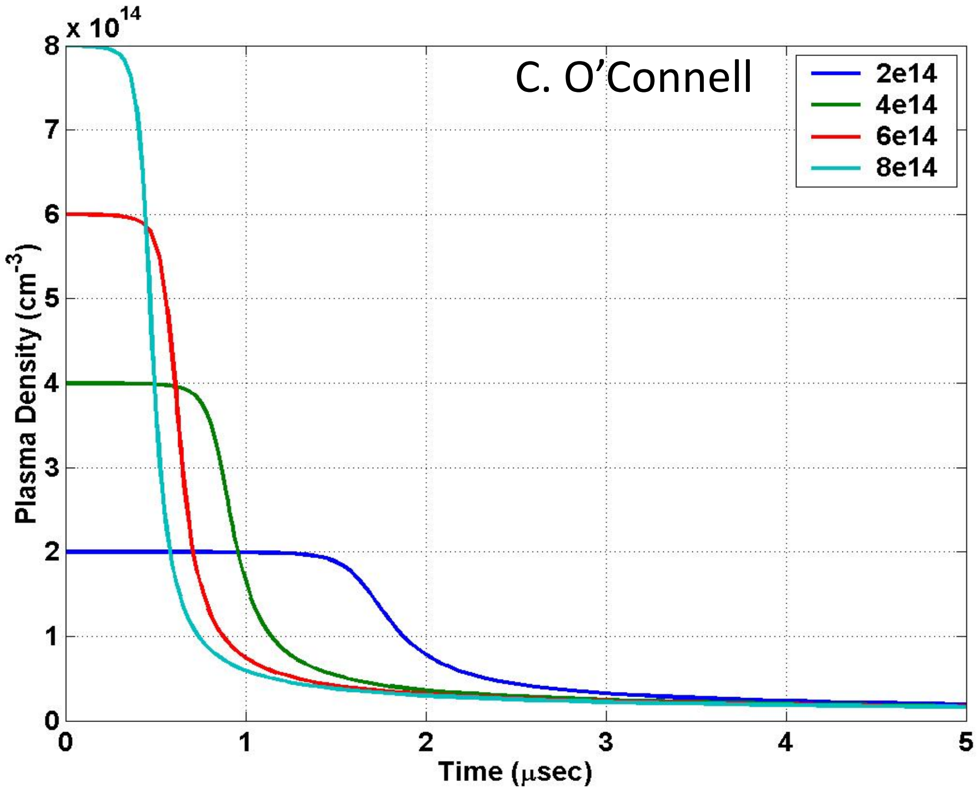
$$\alpha_r = 5.2\cdot10^{-14} Z(\frac{E_\infty^Z}{T_e})^{1/2}[0.43 + \frac{1}{2}\ln(\frac{E_\infty^Z}{T_e}) + 0.469(\frac{E_\infty^Z}{T_e})^{-1/3}]$$

$$\alpha_3 = 8.75\cdot10^{-27} T_e^{-4.5}$$

And the plasma electron thermalization rate depends on the density:

$$\frac{dT_e}{dt} = 1.8\cdot10^{-19}\frac{(m_e m_i)^{1/2} Z_e Z_i n_i \lambda_{ei}}{(m_e T_i + m_i T_e)^{3/2}}\cdot(T_i - T_e)$$

$$\lambda_{ei} = 23 - \ln(n_e^{1/2} Z T_e^{-3/2}) \text{ for } T_i\, m_e/m_i < T_e < 10Z^2\text{eV}$$



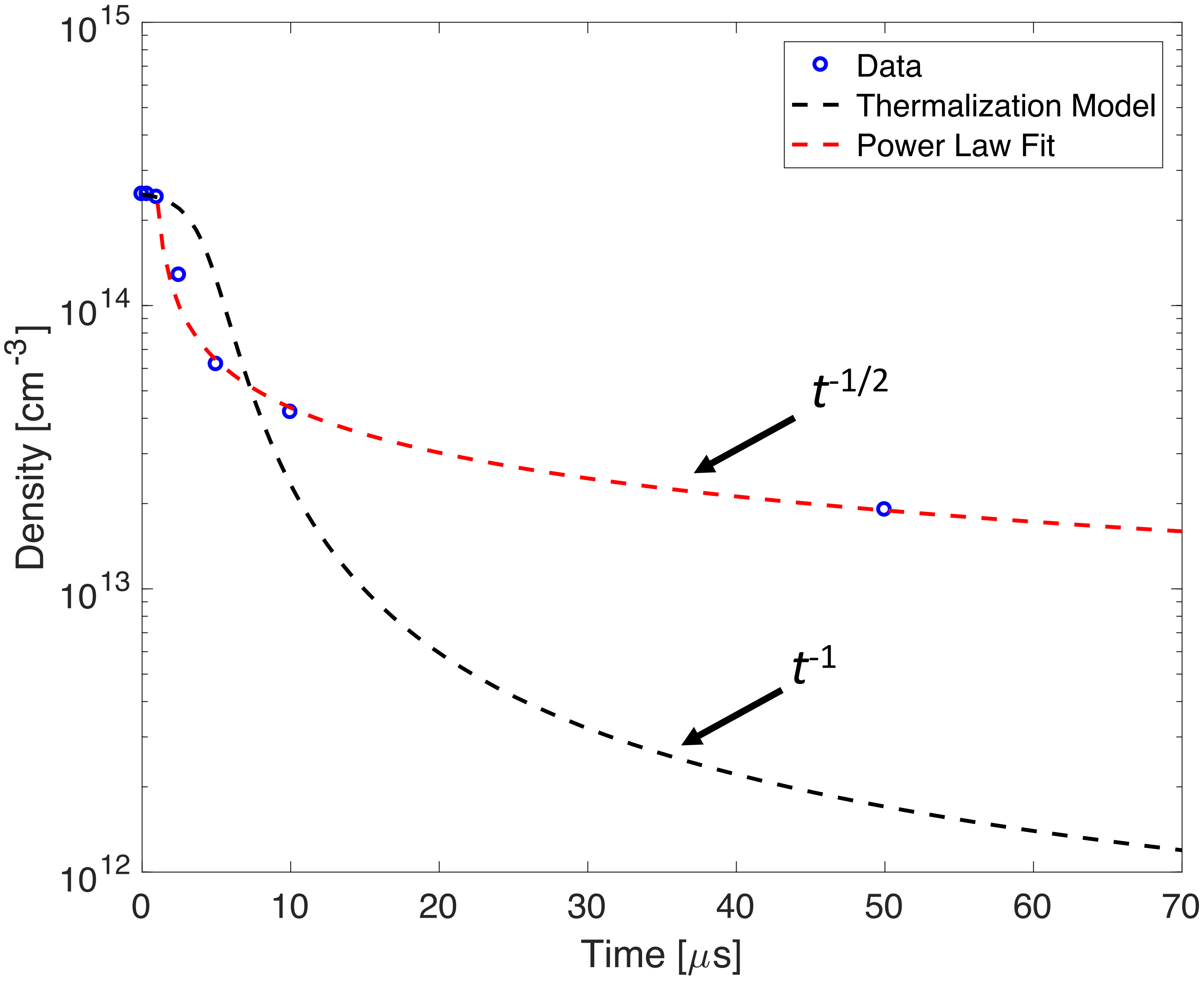

These equations are solved simultaneously. The plasma density does not decay during the thermalization period.*

*K. Marsh and P. Muggli, AAC Proc. 614 (2002)

# Fitting the Data

We attempt to fit the data with two different functions. First, we use the thermalization model presented on the previous slide. There are no free parameters, expect for the initial electron temperature. The ion temperature is $T_i = 0.041$ eV (~500 K). A value of $T_e = 0.46$ eV provides the best fit to the first three points of the dataset.

The thermalization model does not provide a good fit to the data at large $t$. Here, we fit the data with a power law $t^{-1/2}$. But this does not capture the small $t$ behavior during the thermalization period.



# Conclusion

- Modulation of a 400 GeV proton beam is a sensitive diagnostic for the plasma density.
- For approximately 1 microsecond after ionization, the plasma density remains stable before decaying rapidly.
  - This is because the plasma is thermalizing.
- The thermalization model does not fit the data for large time delays.
  - Other effects might be important. For instance spatial effects like ambi-polar diffusion and atomic effects like excited Rb states.
  - We plan to test our data against models that include these effects.

# Thank You!


Novosibirsk, Russia. March, 2017

# The AWAKE Collaboration

## AWAKE Collaboration: 18+2 Institutes world-wide:

**Collaboration members:**
- John Adams Institute for Accelerator Science
- Budker Institute of Nuclear Physics & Novosibirsk State University
- CERN
- Cockcroft Institute
- DESY
- Heinrich Heine University, Düsseldorf
- Instituto Superior Tecnico
- Imperial College
- Ludwig Maximilian University
- Max Planck Institute for Physics
- Max Planck Institute for Plasma Physics
- Rutherford Appleton Laboratory
- TRIUMF
- University College London
- University of Oslo
- University of Strathclyde

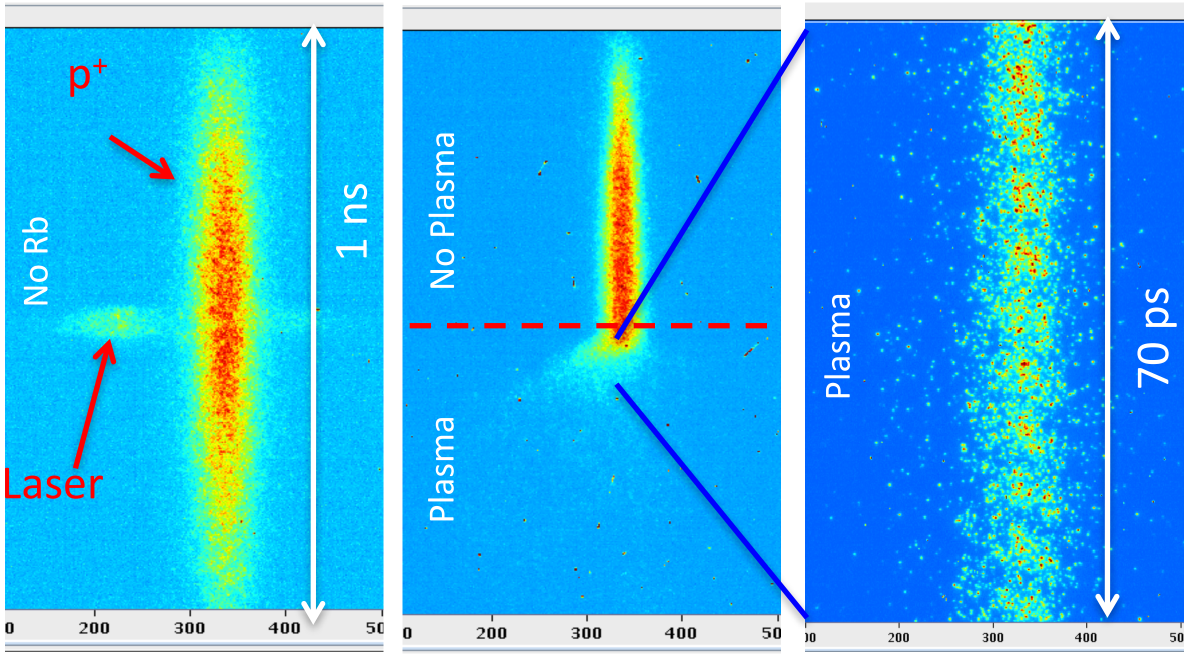

**Associated members:**
- Ulsan National Institute of Science and Technology (UNIST), Korea
- Wigner Institute, Budapest
- Swiss Plasma Center group of EPFL

**New Full members:**
- Ulsan National Institute of Science and Technology (UNIST), Korea
- Phillipps-Universitaet Marburg, Germany

# Backup Slides

# Observation of SSM

- We start by placing the seed pulse in the center of the bunch.
  - In this case, the SMI starts to develop a short distance behind the seed pulse.




K. Rieger, M. Martyanov, P. Muggli, MPP

# Observation of SSM

- We start by placing the seed pulse in the center of the bunch.
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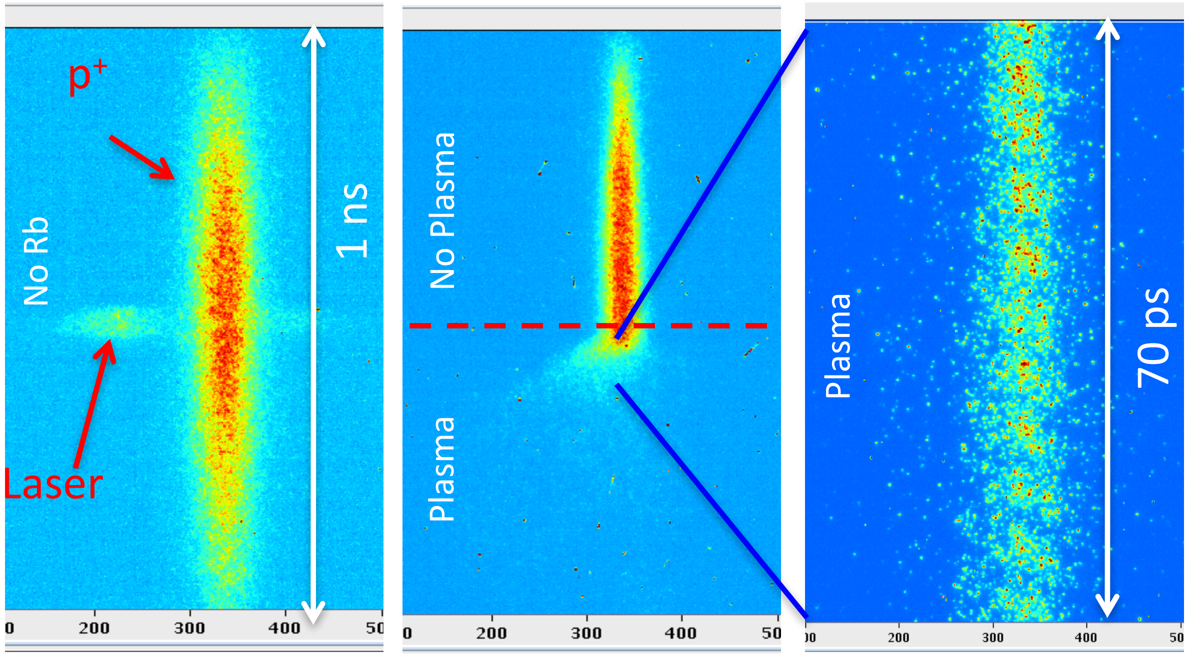
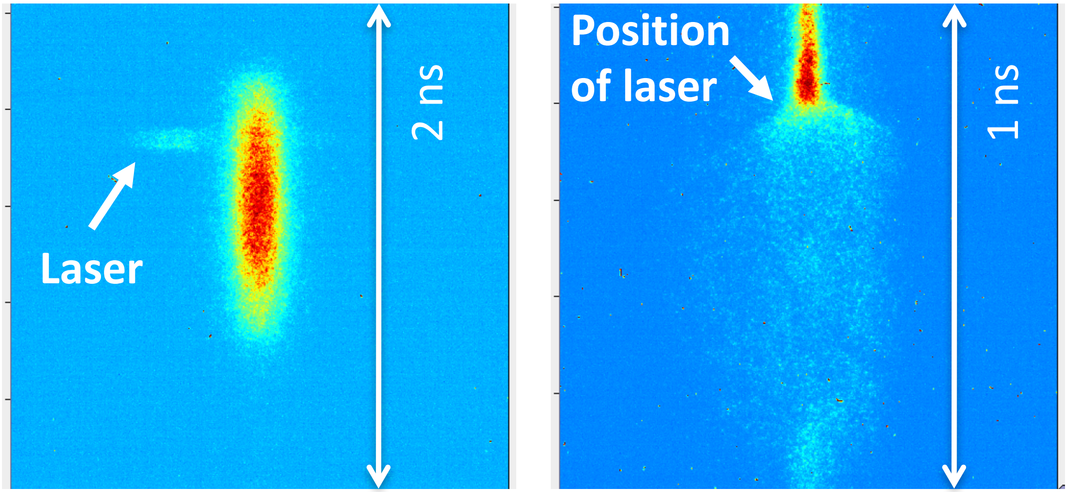



- Next we move the laser forward ¼ of the bunch length.
  - We observe that the SMI starts to develop just behind the seed pulse.

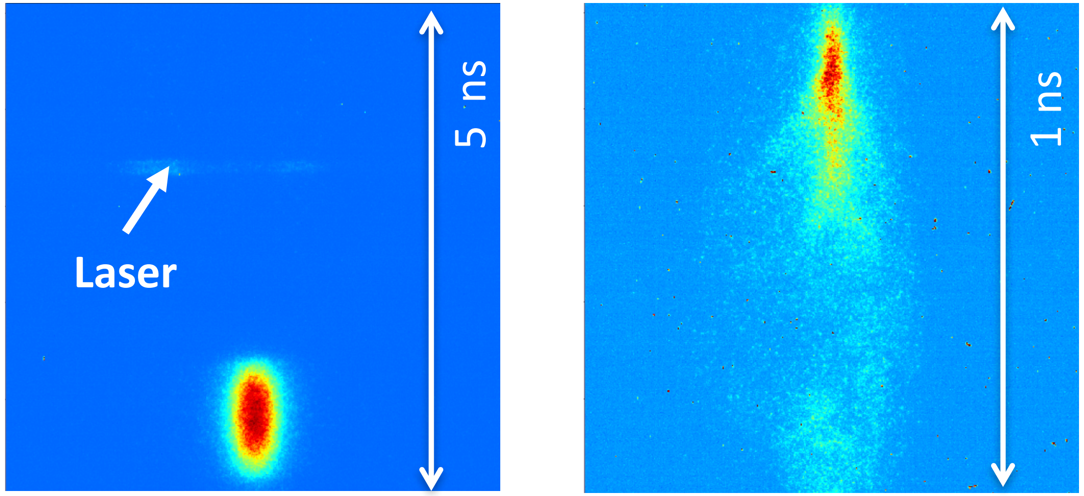



K. Rieger, M. Martyanov, P. Muggli, MPP

# Observation of Unseeded SMI

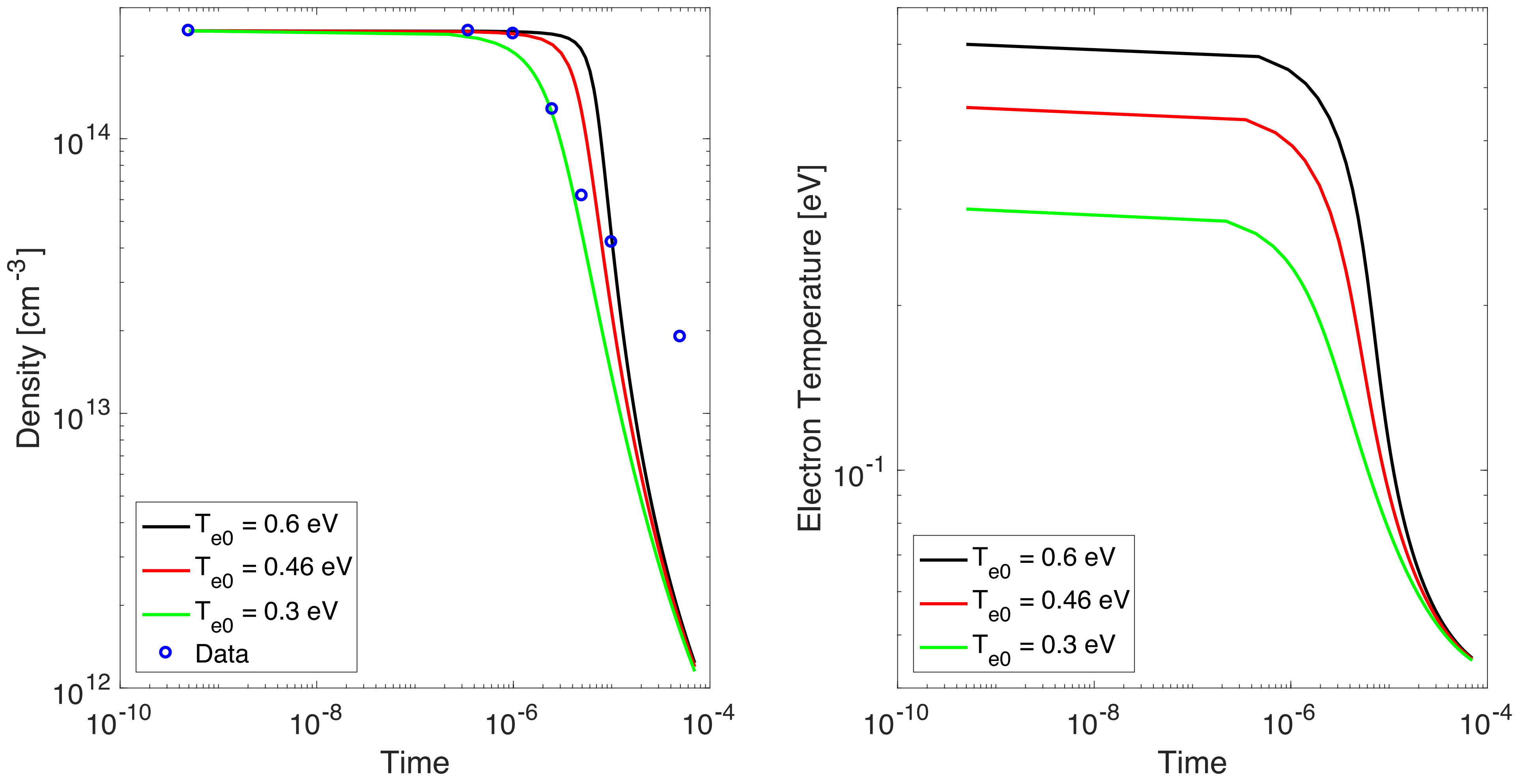
- Moving the laser well ahead of bunch, we see that the SMI appears at the same position of the proton beam as in the previous case.

- Where/How does SMI develop if laser is *much* further ahead of the proton beam? → Motivation for time-delay scan.




K. Rieger, M. Martyanov, P. Muggli, MPP

# Other Fits to the data




The electron temperature after ionization is bracketed between 0.3 and 0.6 eV.