

# Plasma beam dump, and possible experiment tests at CLARA and AWAKE

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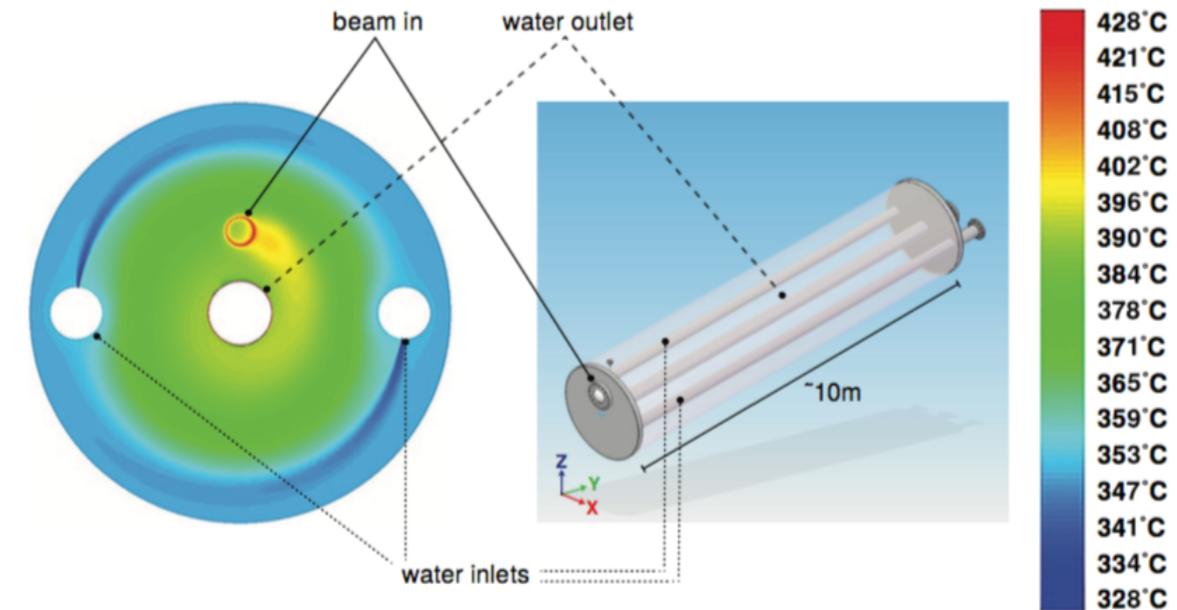
# Contents

- Conventional beam dump
- Plasma beam dump
- Modelling of plasma beam dump
- Experiment tests at VELA/CLARA
- Conclusion

# Conventional Beam dump-ILC

ILC beam dump design:

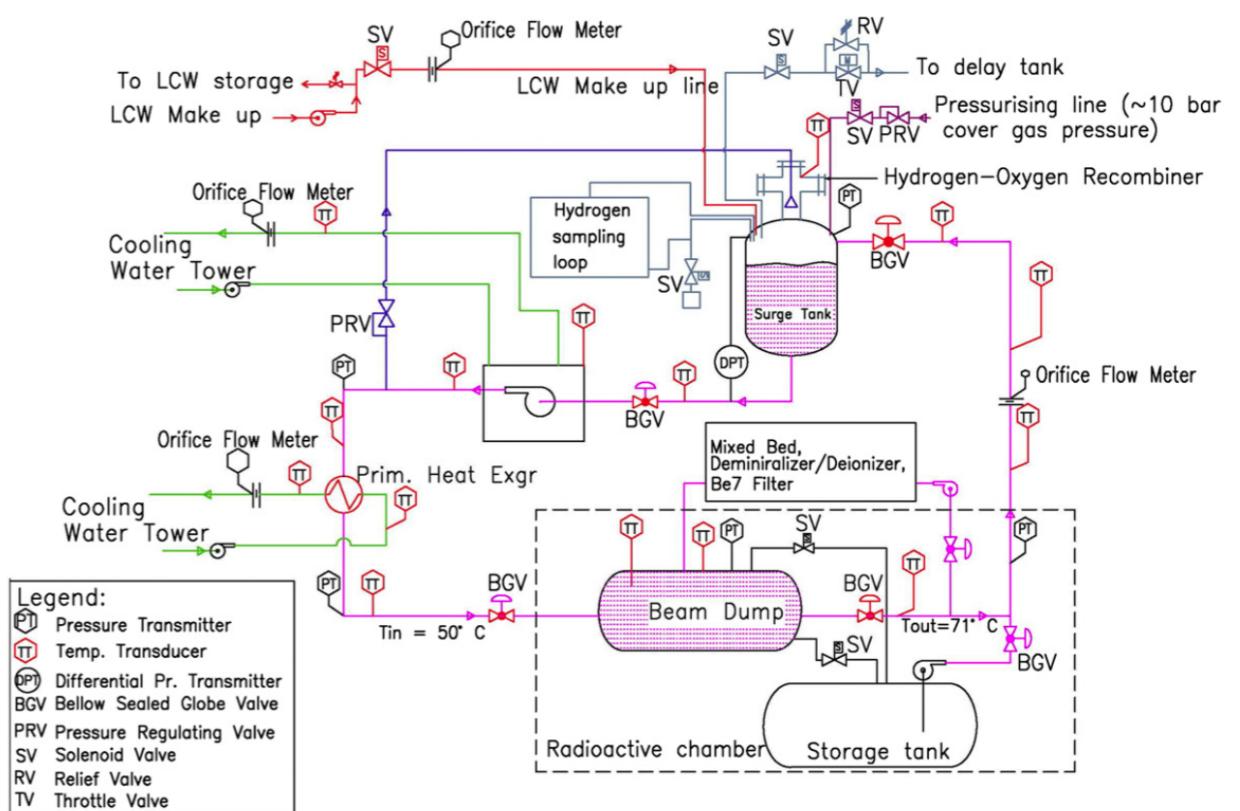
- Stainless steel pressure vessel
- 11 m length
- 10 bar pressure, plus 100% safety margin
- 155 °C water temperature



P. Satyamurthy et al., NIMA 679, 67 (2005)

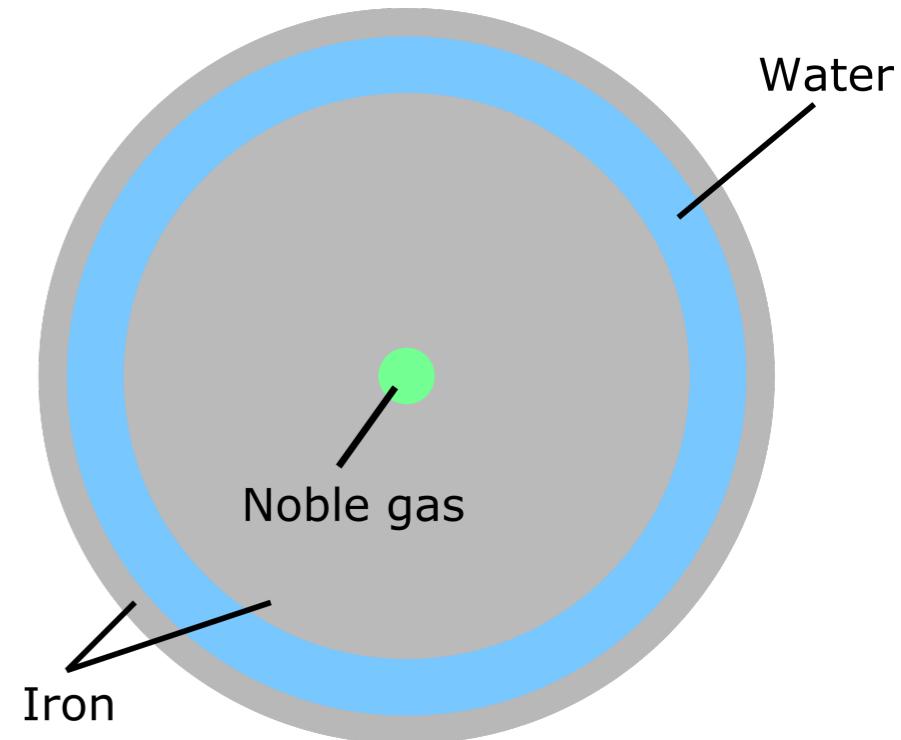
Challenges:

- Dump window must allow passage of beam while withstanding high pressure
- Radio-activation by photospallation
- Hydrogen/oxygen production

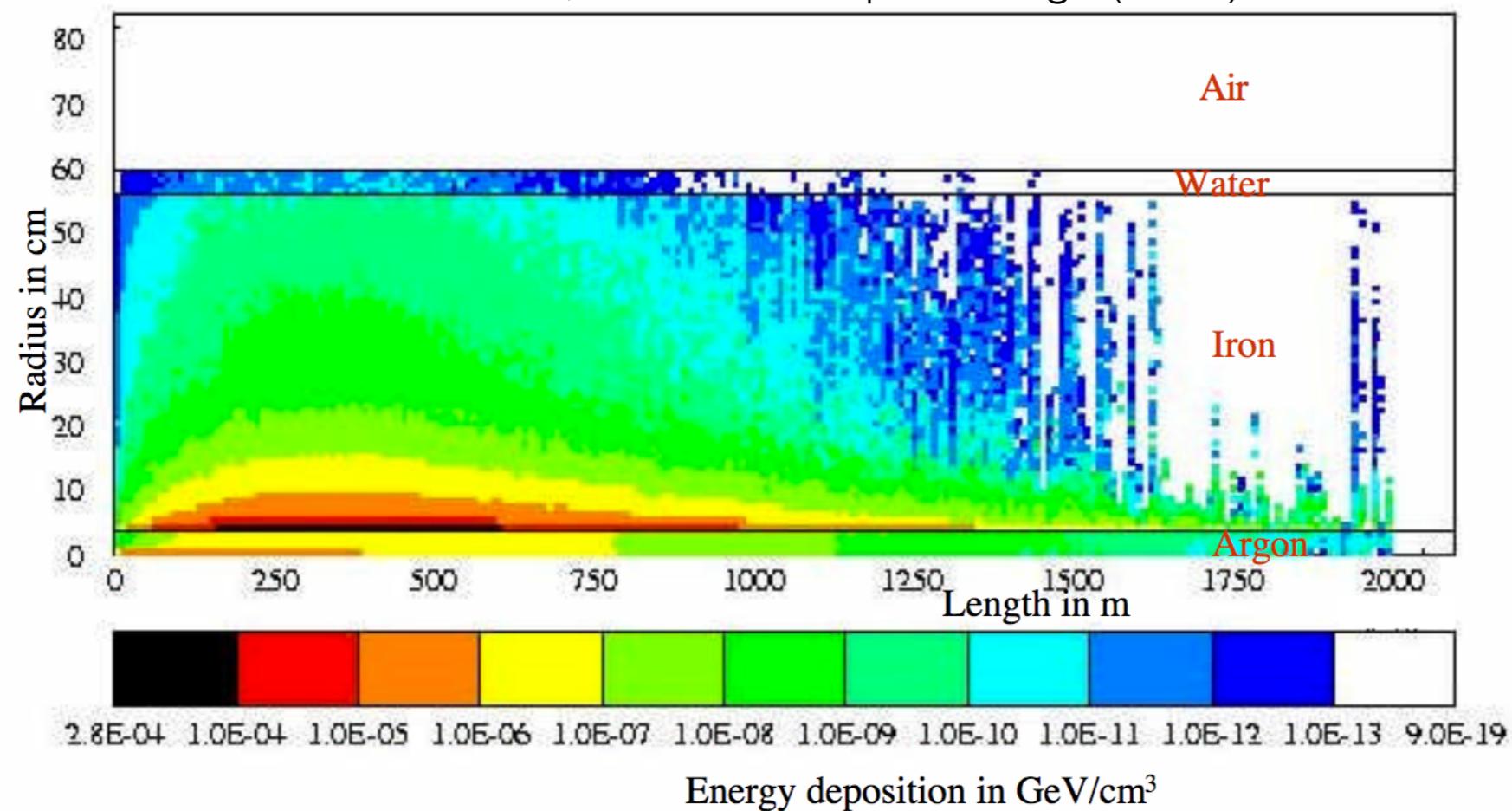


# Noble gas beam dump - an alternative

- Noble gas at atmospheric density
- 1000 m length
- Low power density
- Less reactive chemicals



A. Leuschner, LC-ABD dump meetings (2005)



# Plasma beam dump

A plasma beam dump offers high decelerating gradients in a low density medium:

$$E_{\text{wb}} = \frac{m_e c \omega_p}{e} = 9.6 \sqrt{\frac{n_e}{10^{22}}} \text{ GV m}^{-1}$$

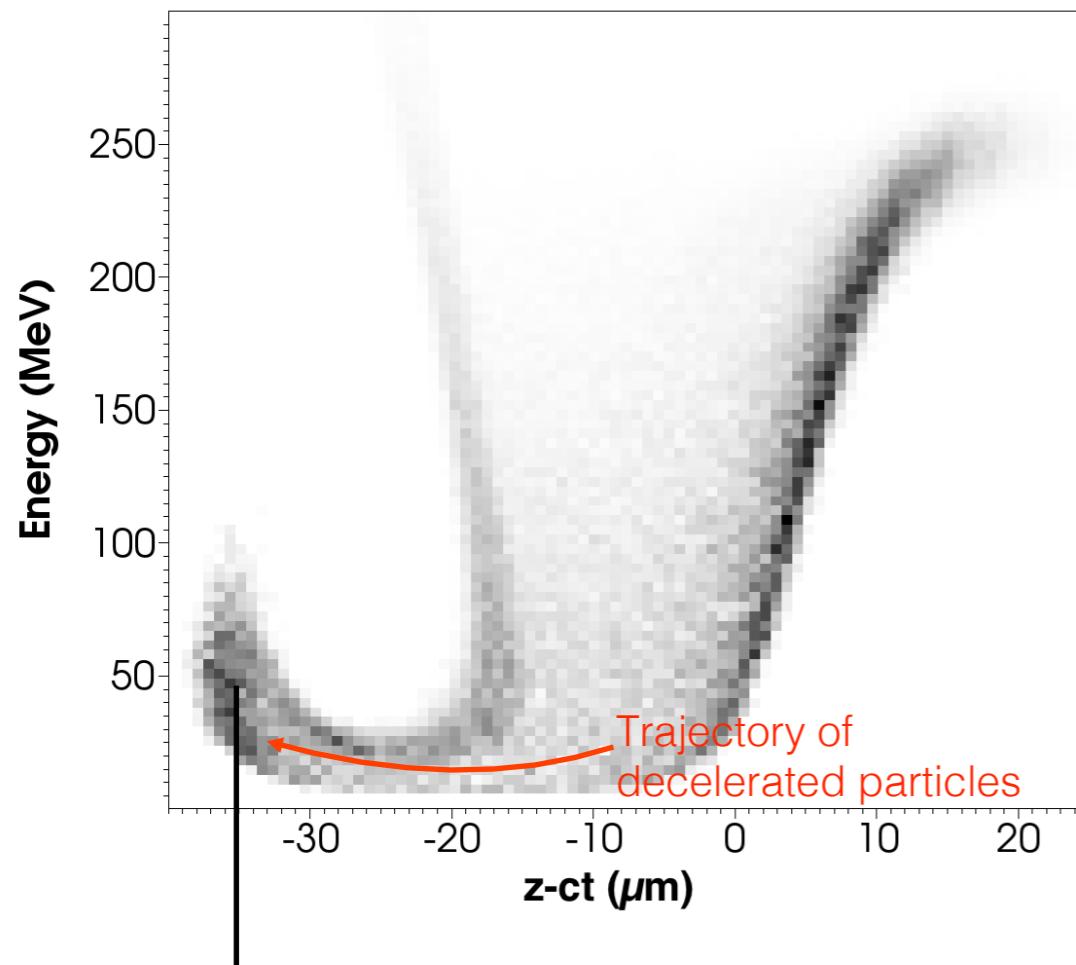
For  $n_e = 10^{24} \text{ m}^{-3}$ ,  $E_{\text{wb}} = 96 \text{ GV/m}$ .

c.f. density of air at 1 atm  $\sim 10^{25} \text{ m}^{-3}$

- Compared with the stopping power in a solid material e.g. ILC beam dump 500 GeV in 11 m = 45 GV/m.
- Plasma density is orders of magnitude lower than solid e.g graphite  $\sim 10^{29} \text{ m}^{-3}$ .
- Plasma beam dump can also be applied to positrons/muons with high decelerating gradient.

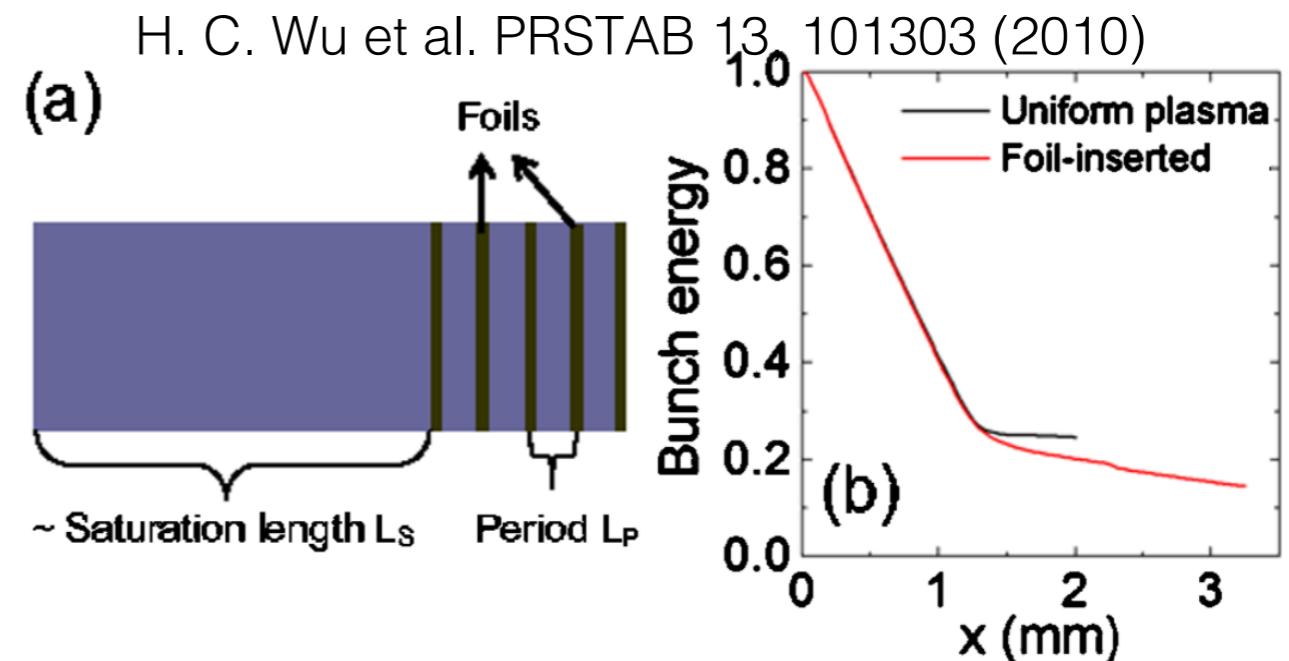
# Plasma beam dump

Longitudinal phase space of plasma decelerated bunch



Re-accelerated portion of bunch

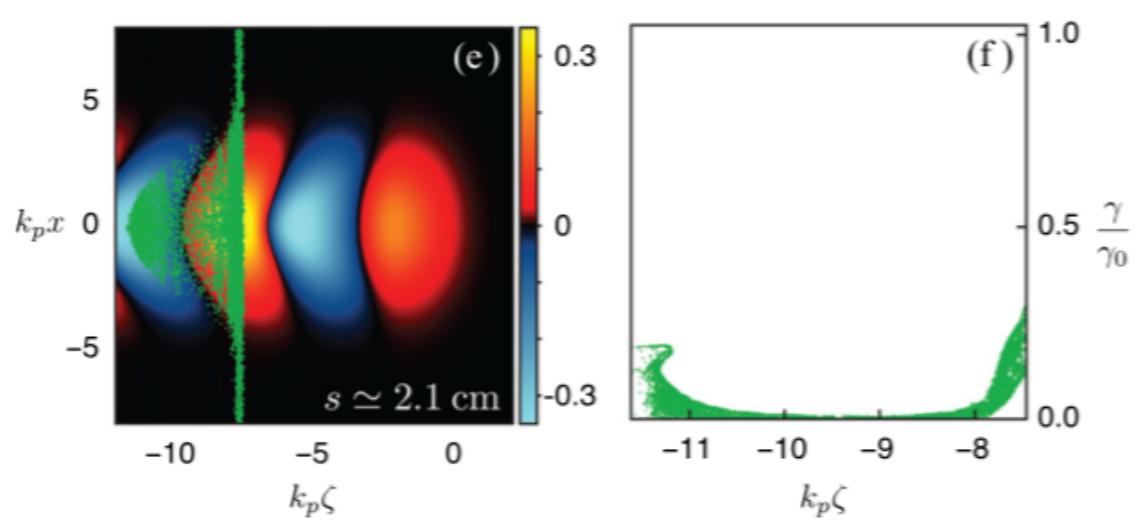
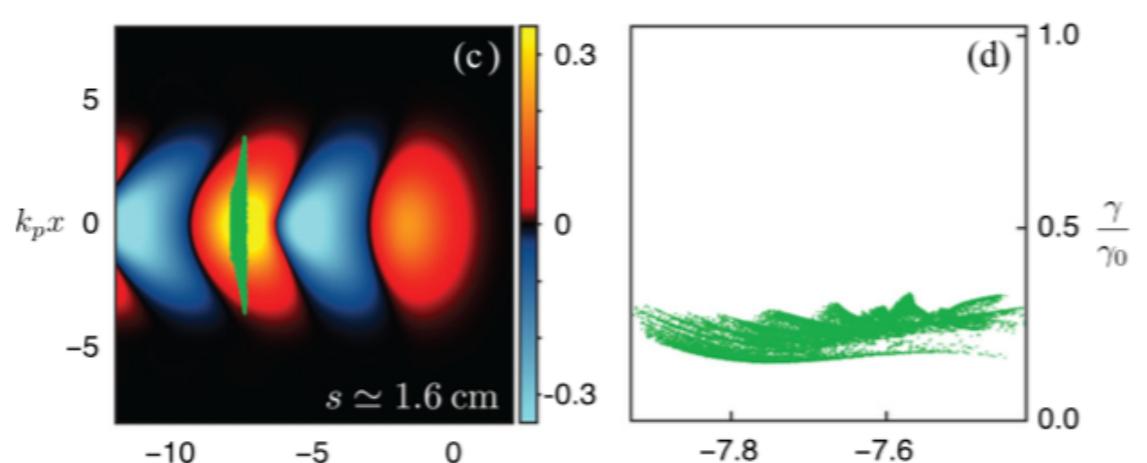
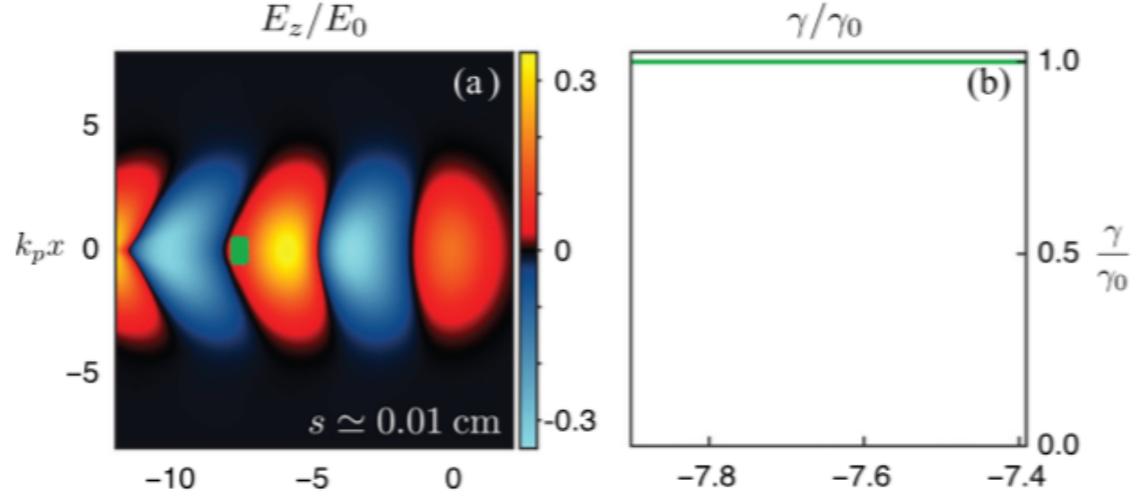
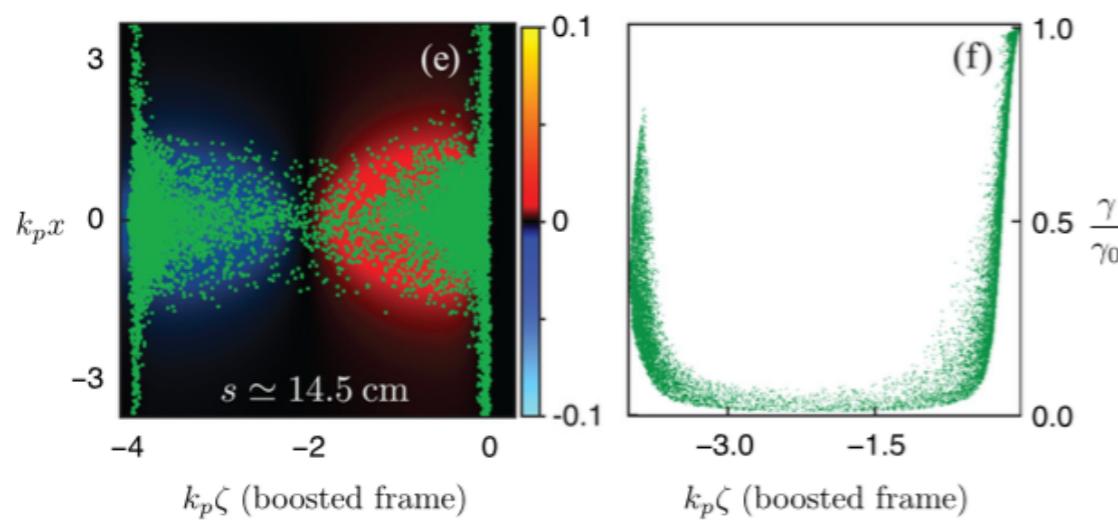
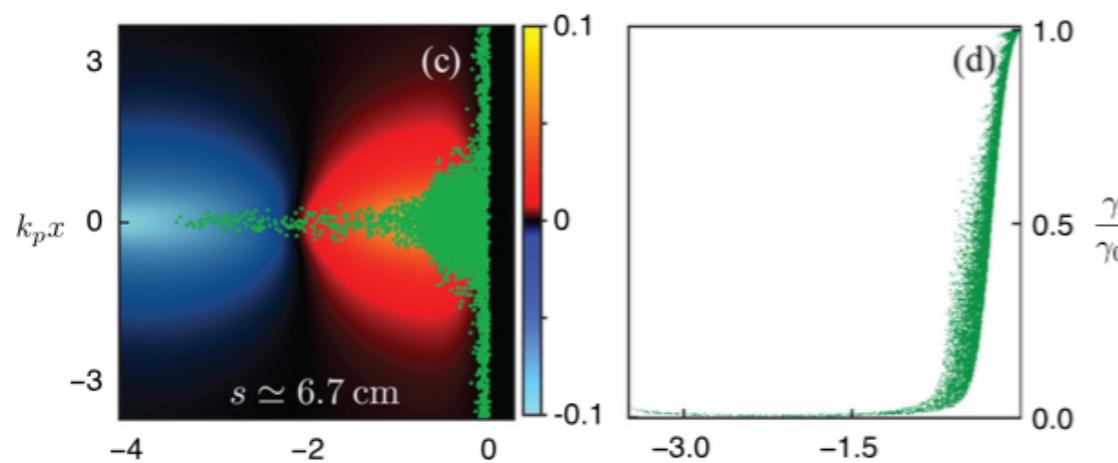
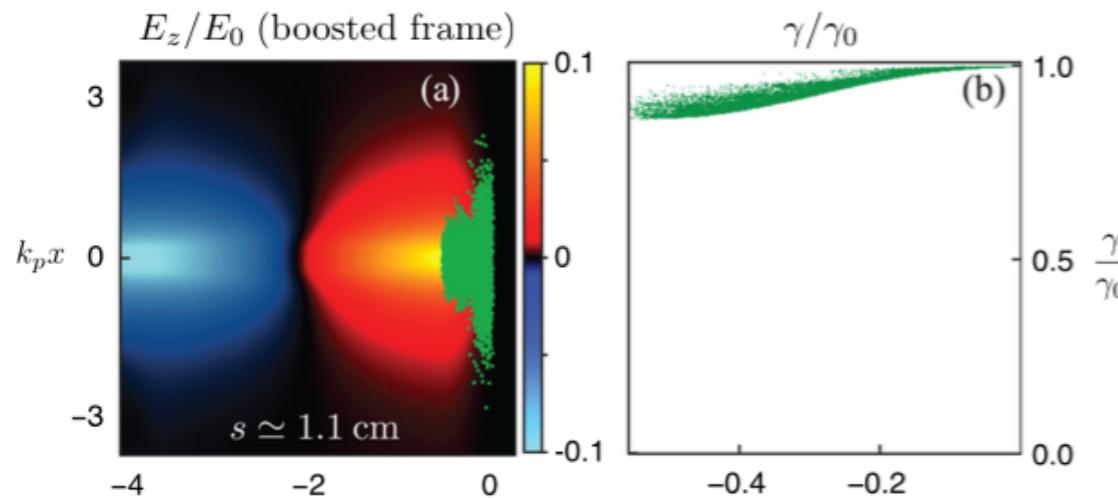
Wu et al. proposed using foils to absorb low-energy particles.



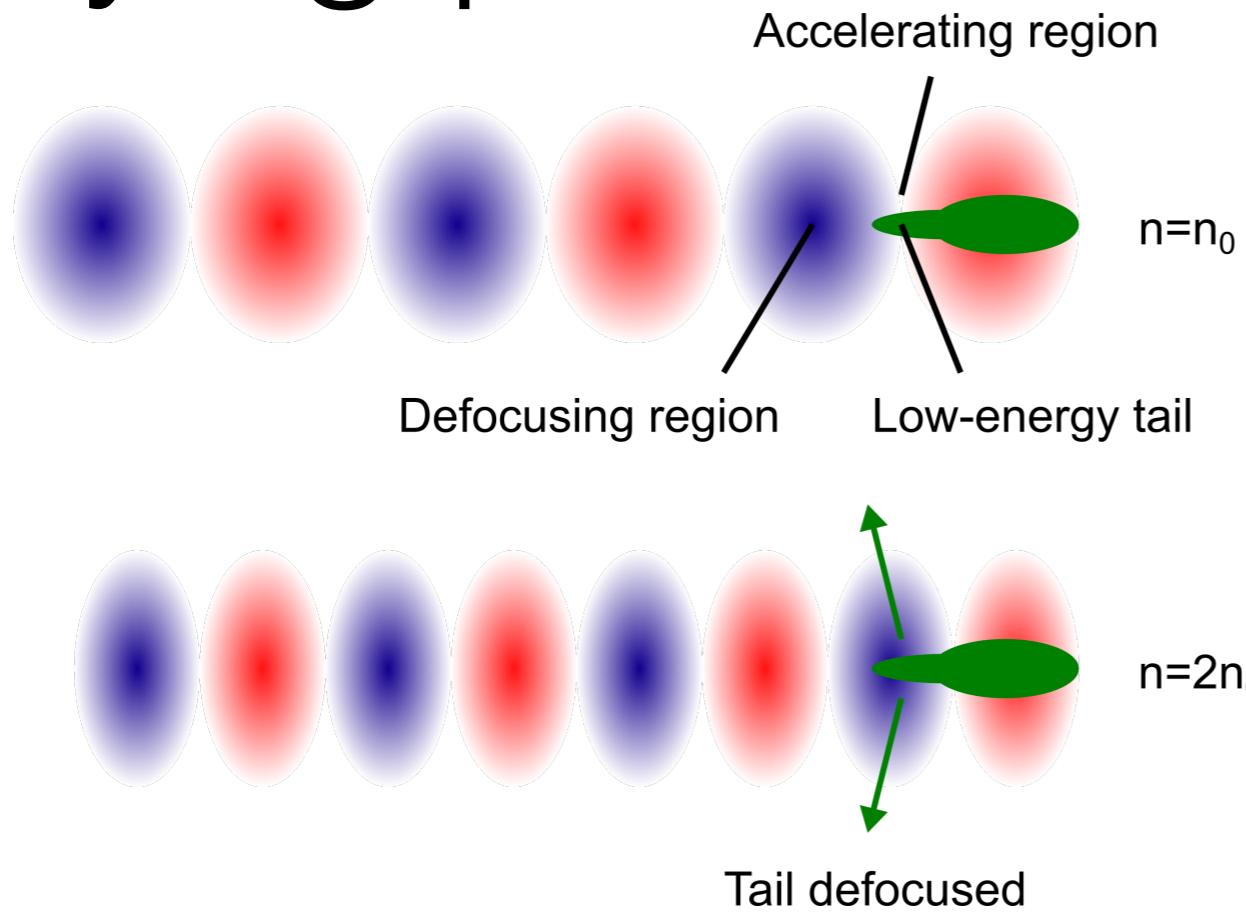
# Active beam dump

## Passive beam dump

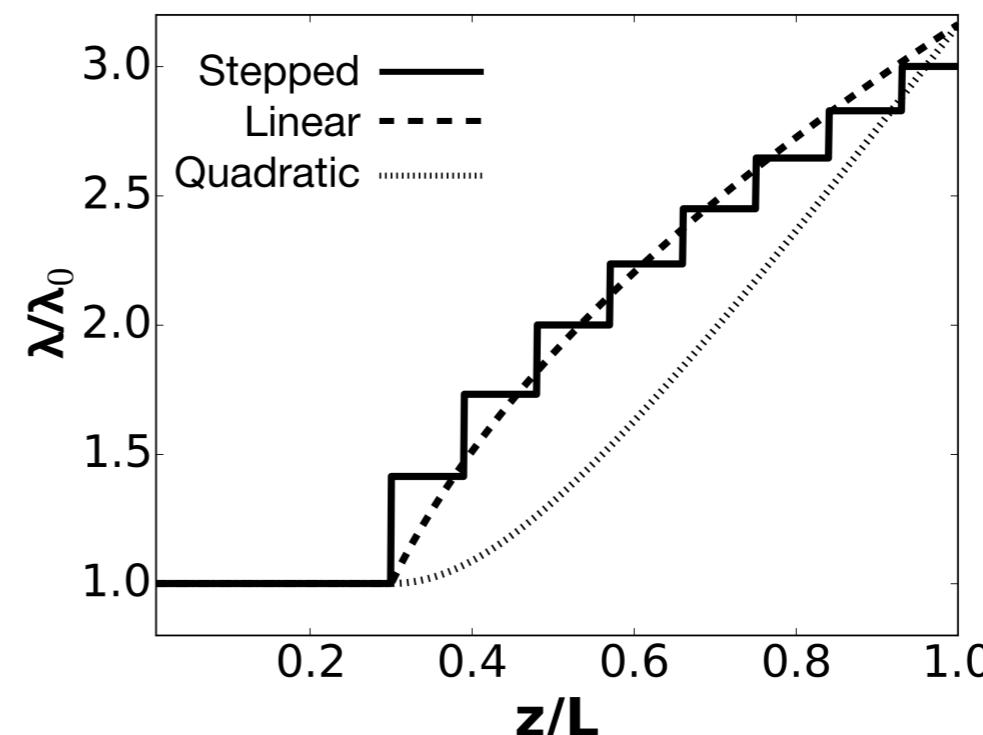
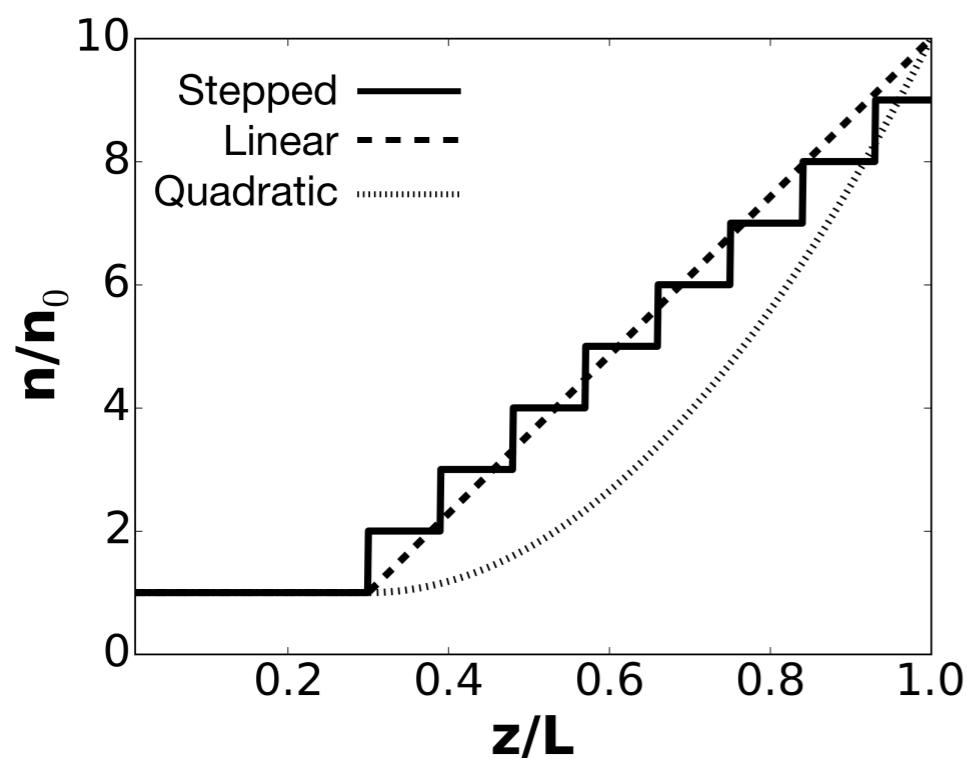
## Active beam dump



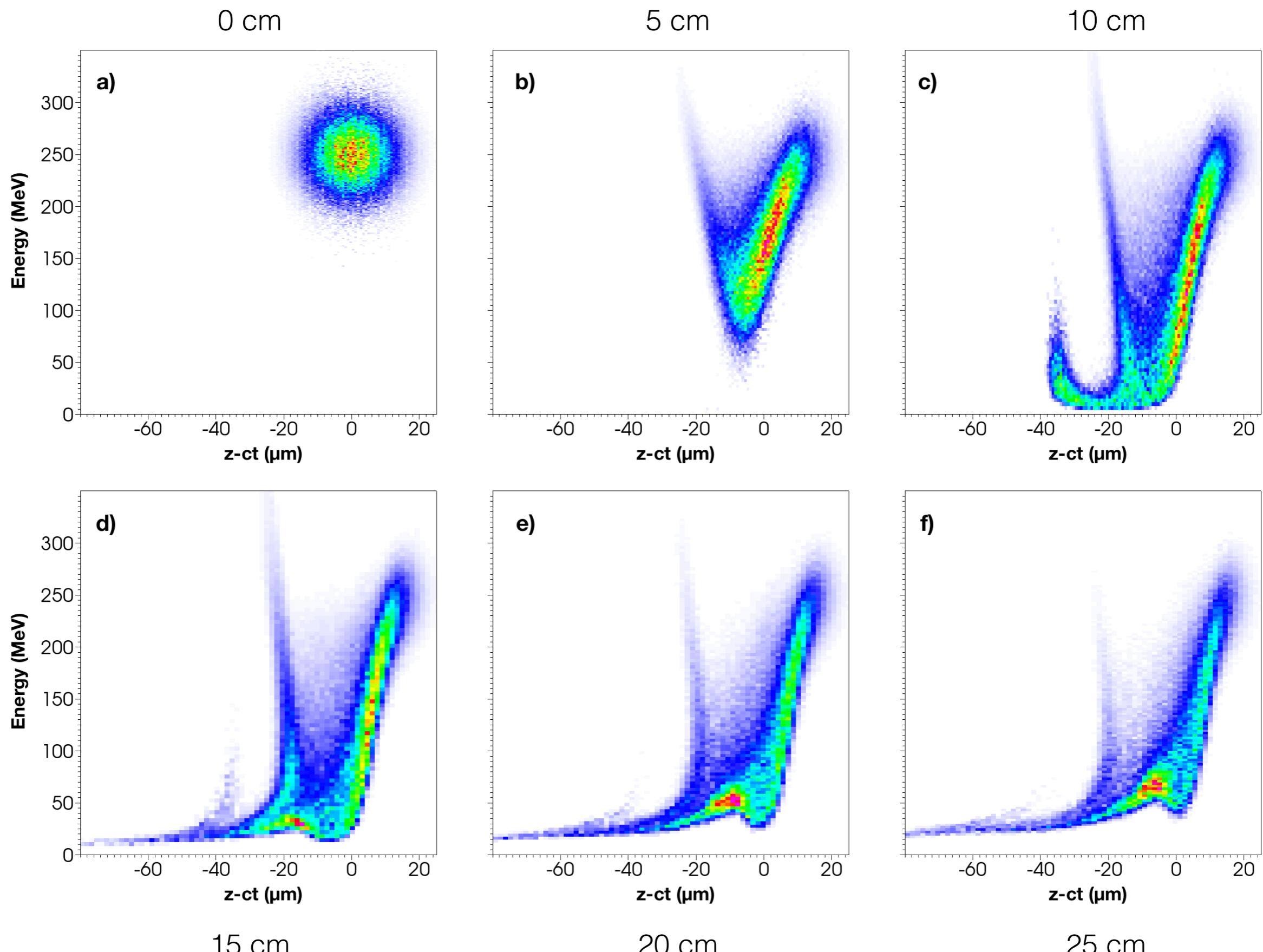
# Varying plasma density



Plasma density increase puts low energy tail of the bunch into defocusing region

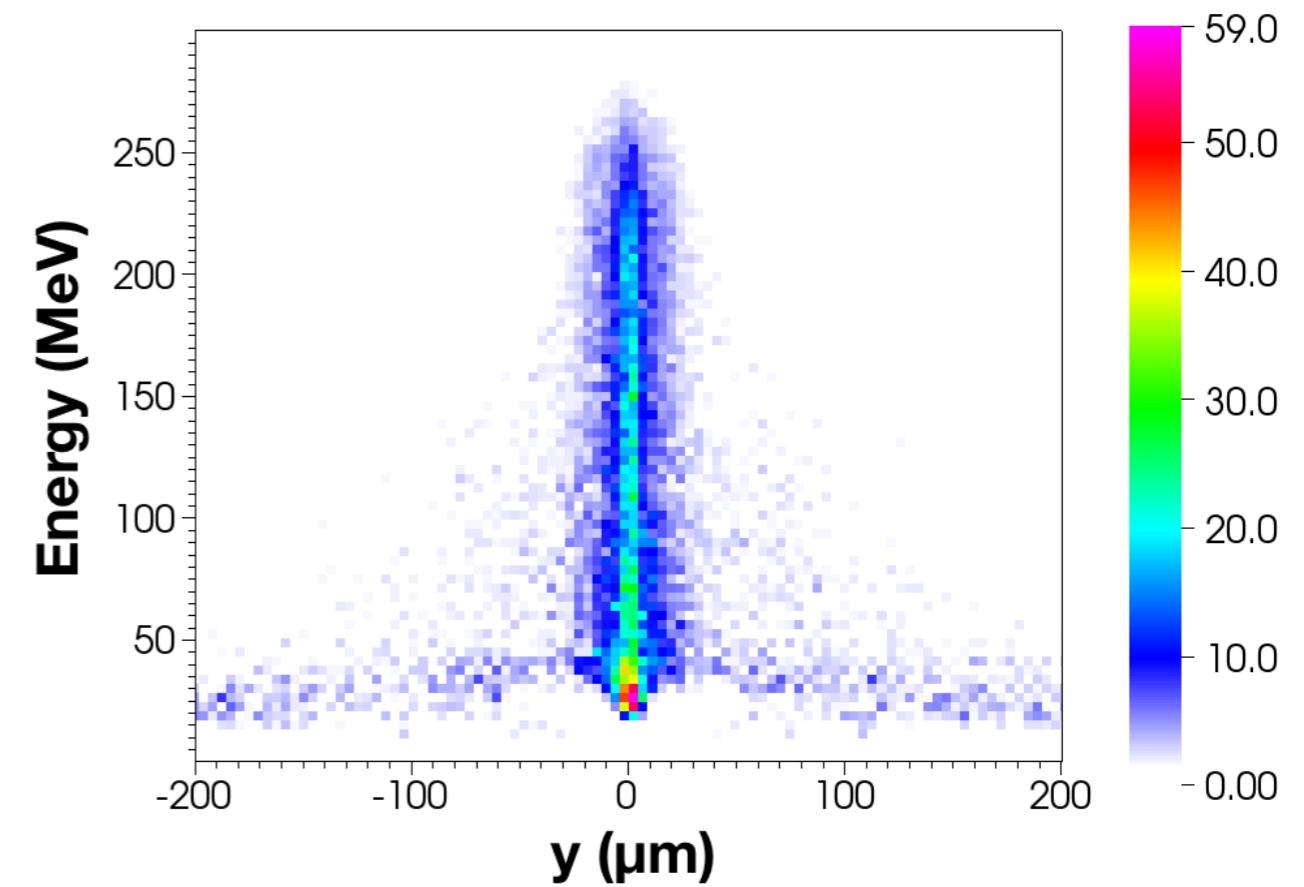
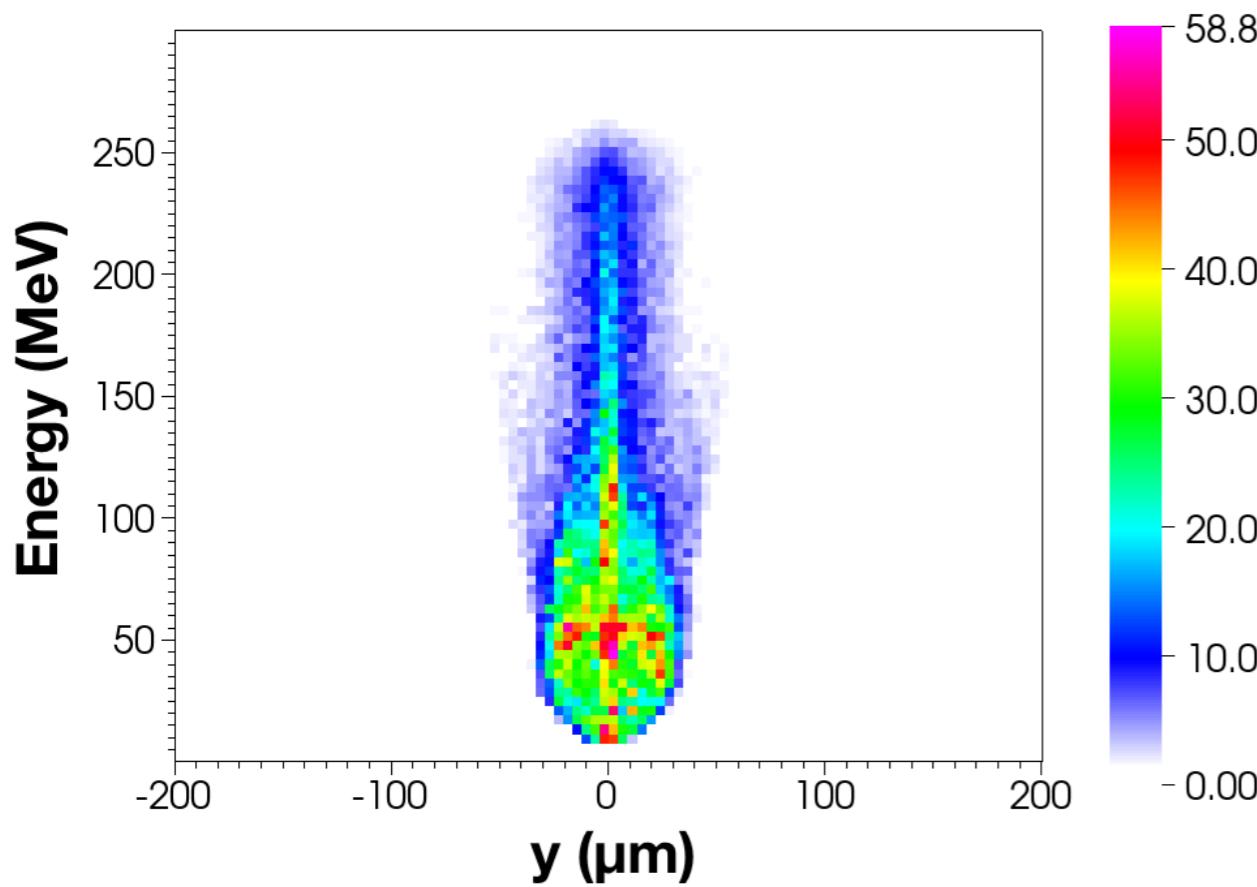


# Varying plasma density

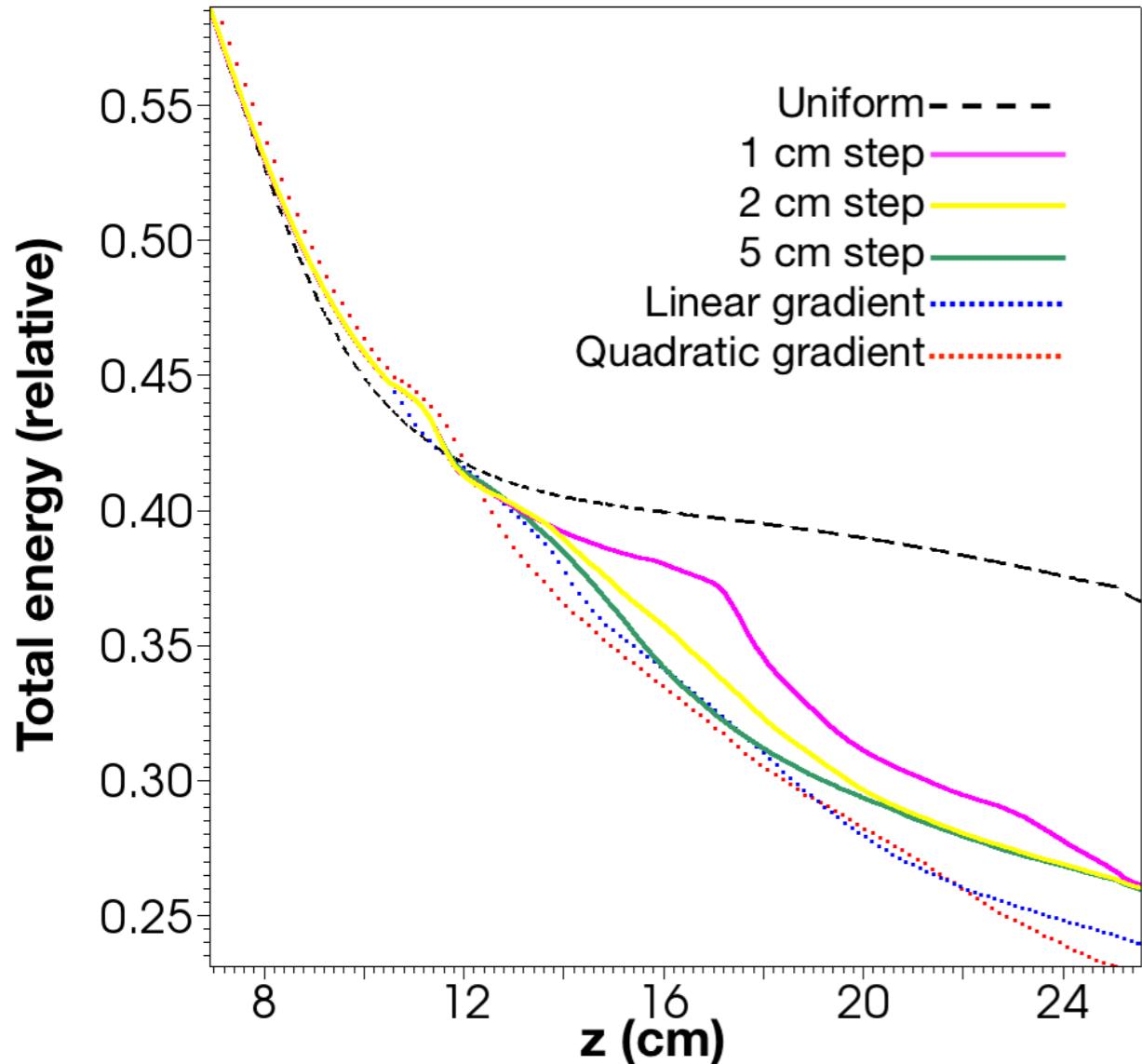


# Varying plasma density

Energy/transverse position plots after saturation length for uniform plasma (L) and gradient plasma (R).

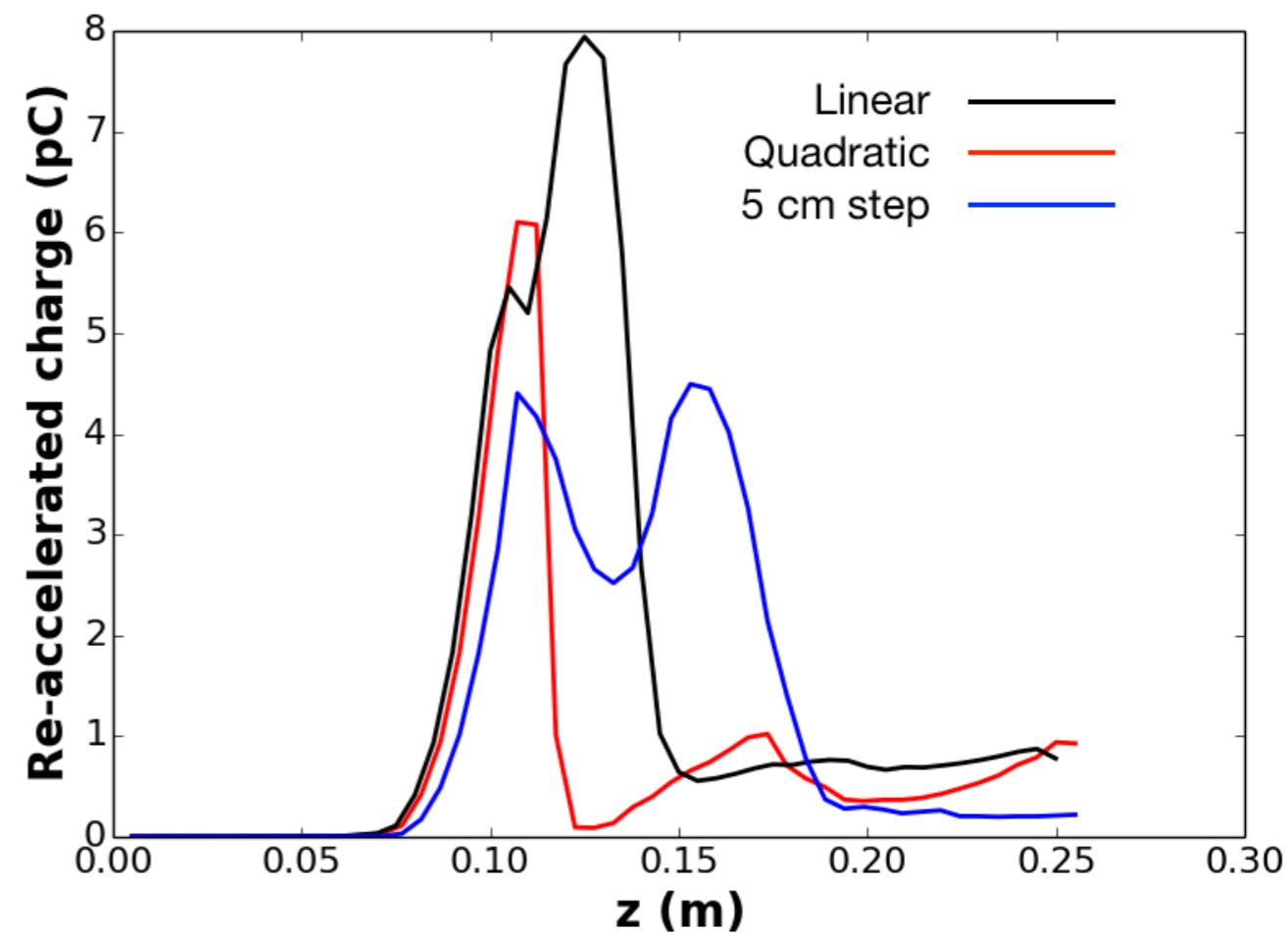


# Varying plasma density

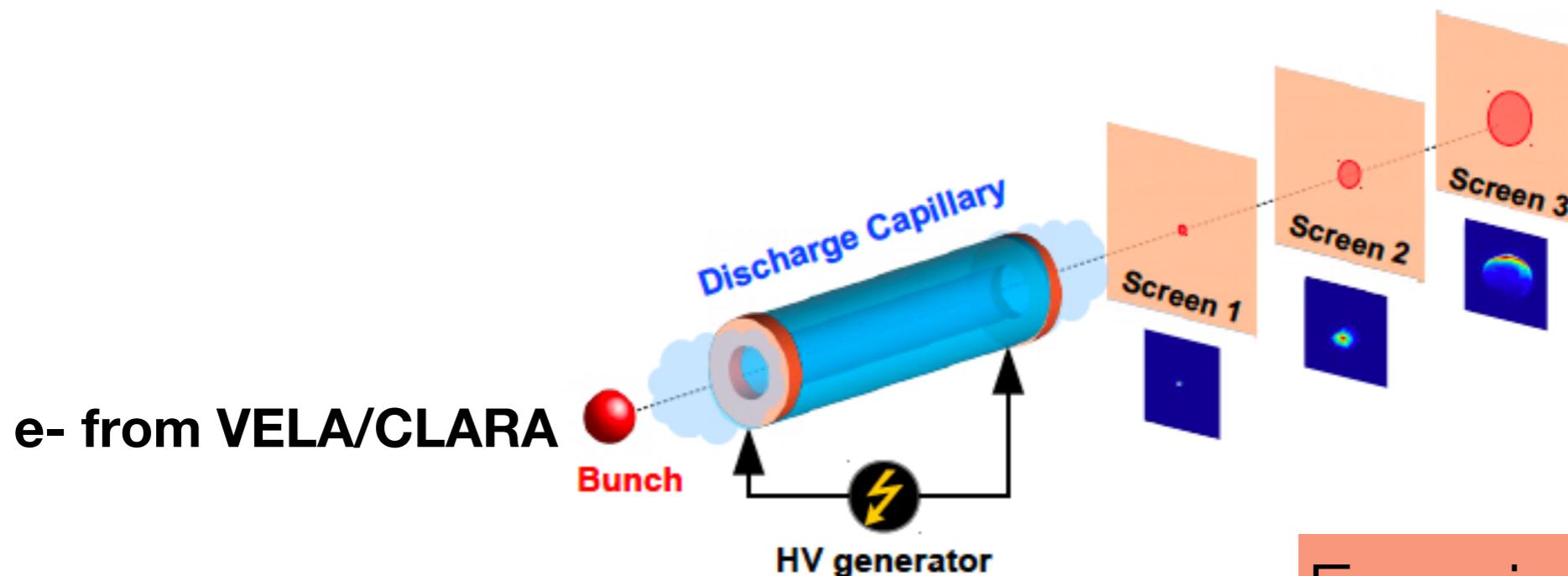


Quantity of charge in a region  
30  $\mu\text{m}$  behind bunch head  
with energy > 30 MeV

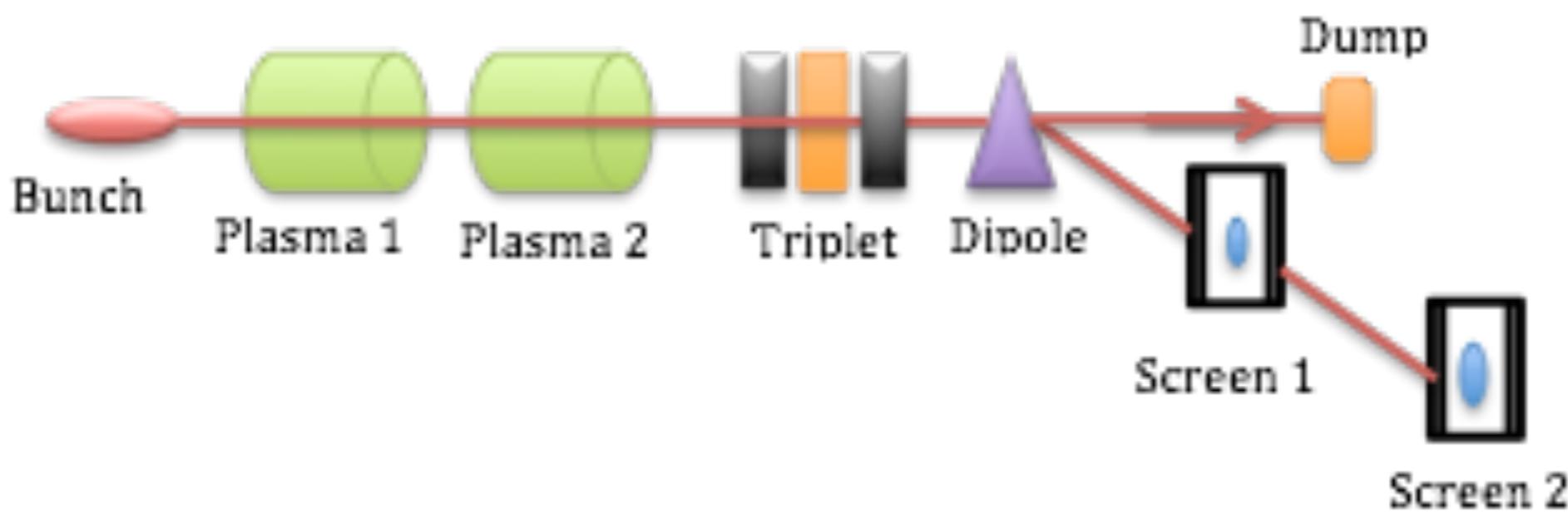
Total bunch energy loss for  
different plasma density  
schemes



# Experiment tests at VELA/CLARA

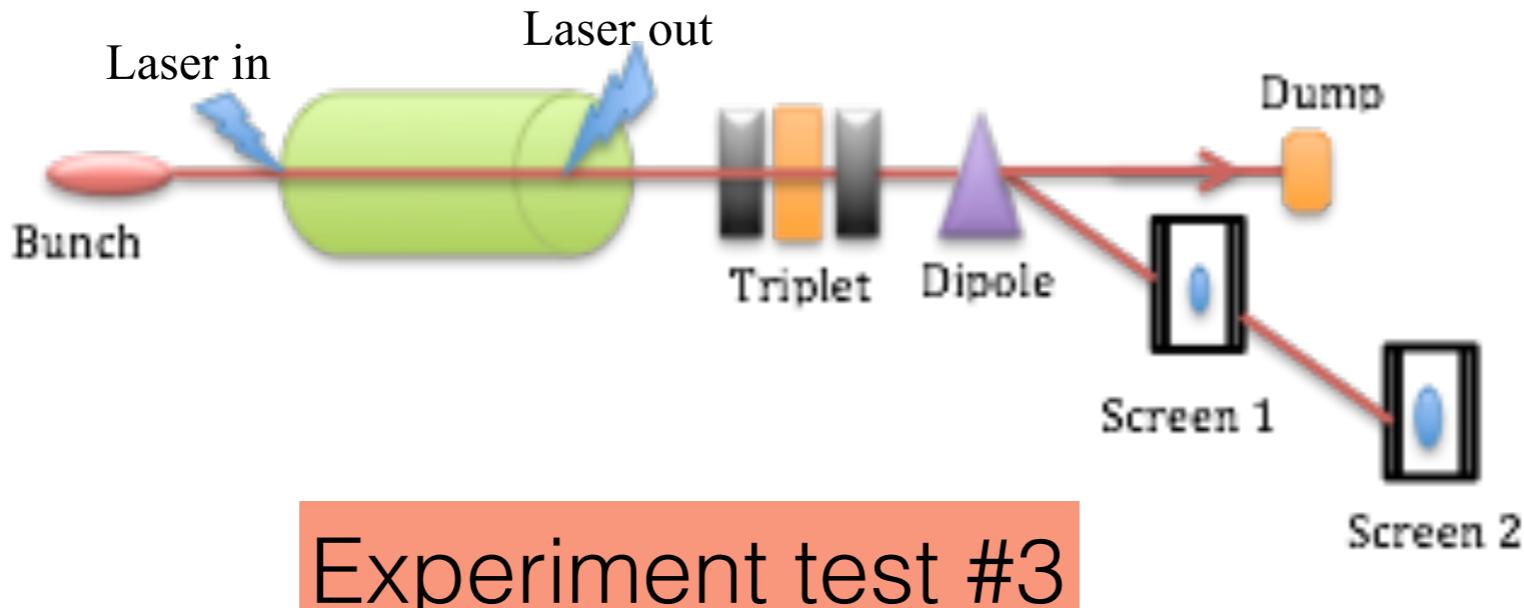


Experiment test #1



Experiment test #2

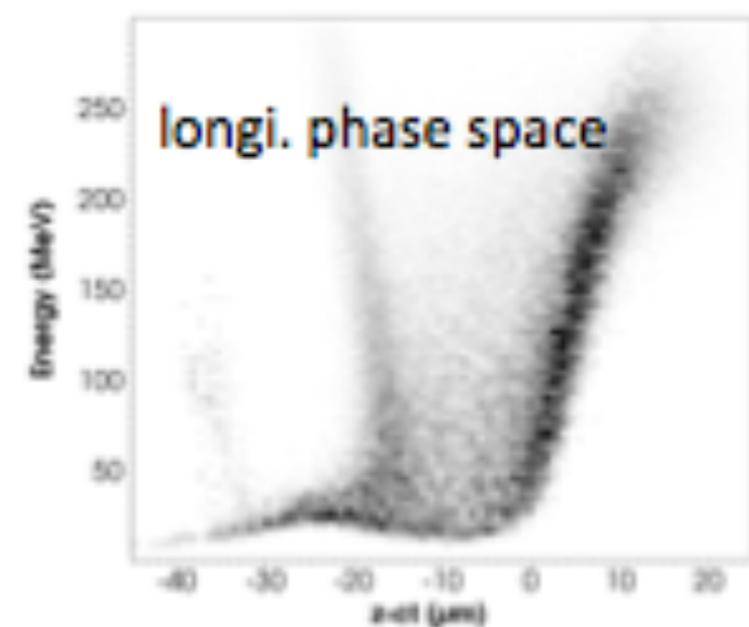
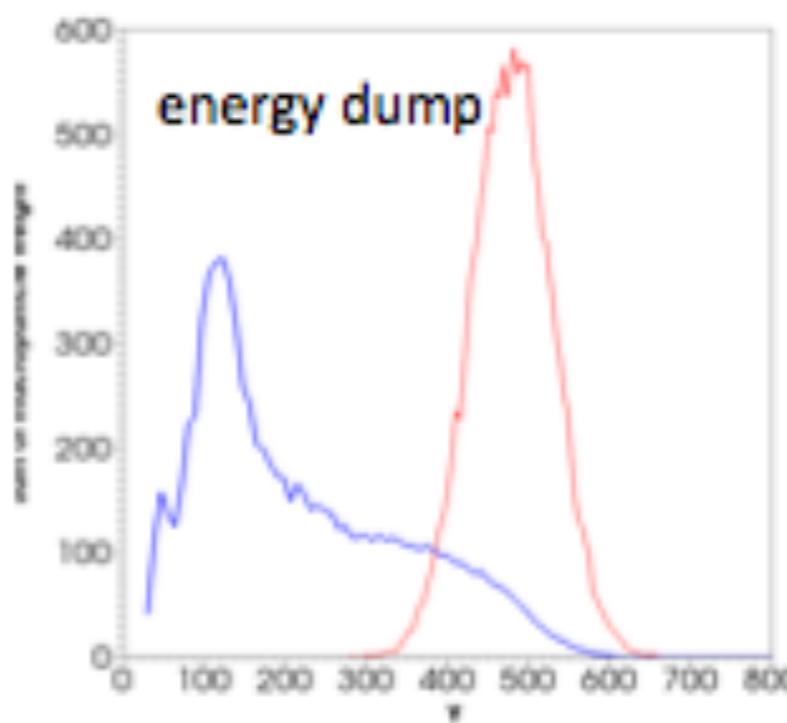
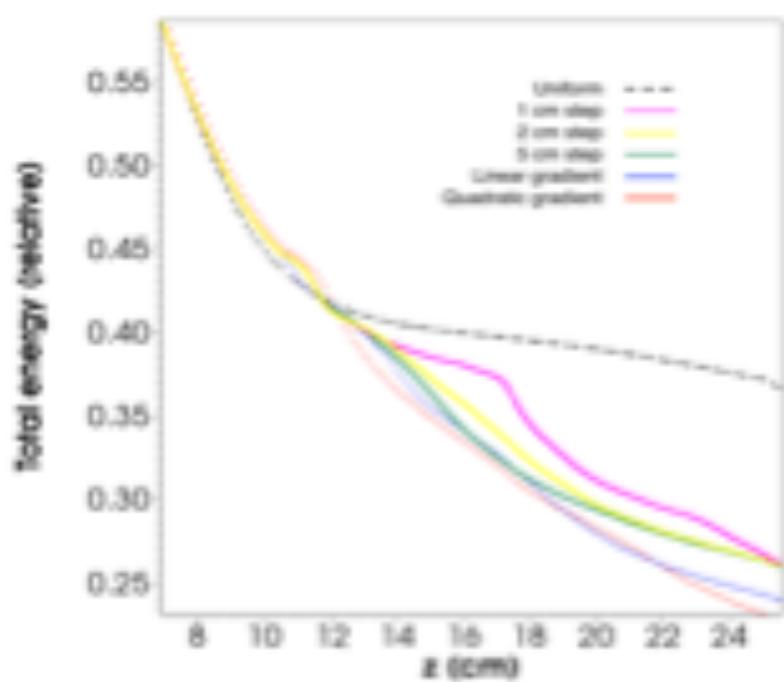
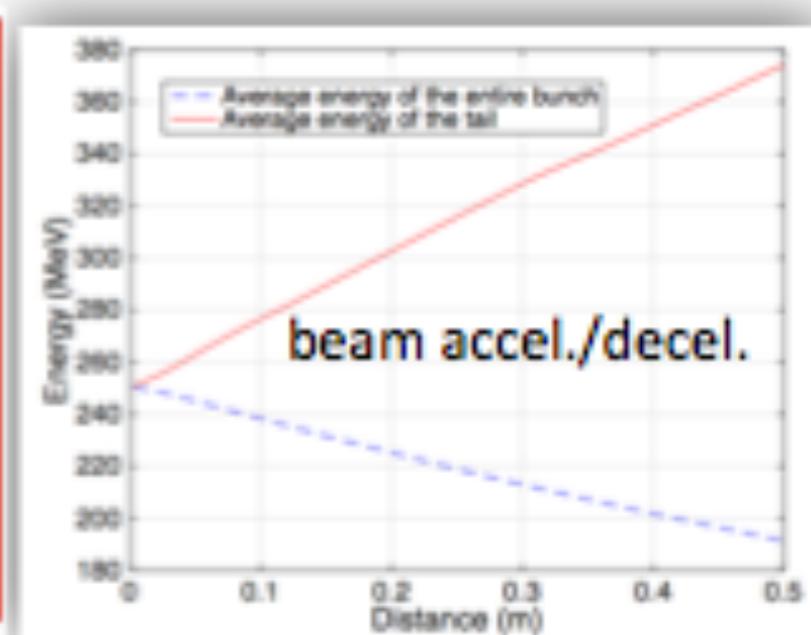
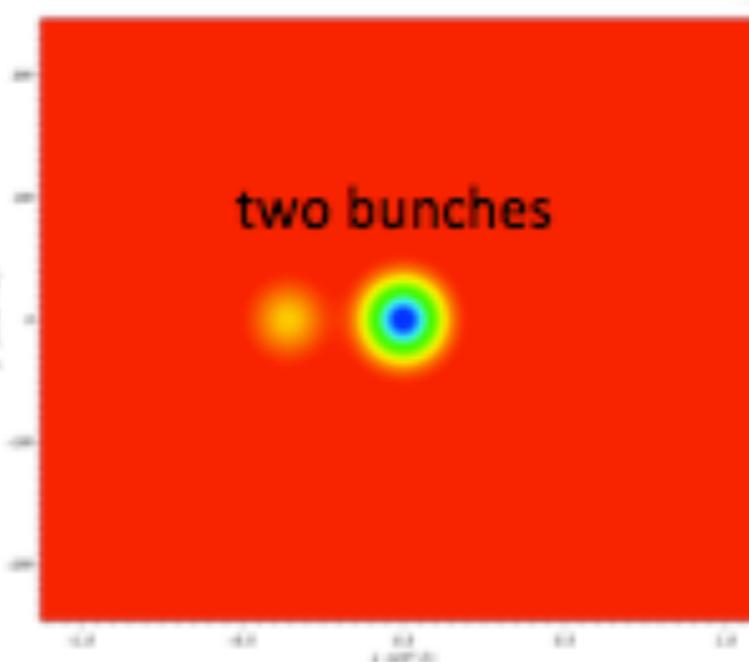
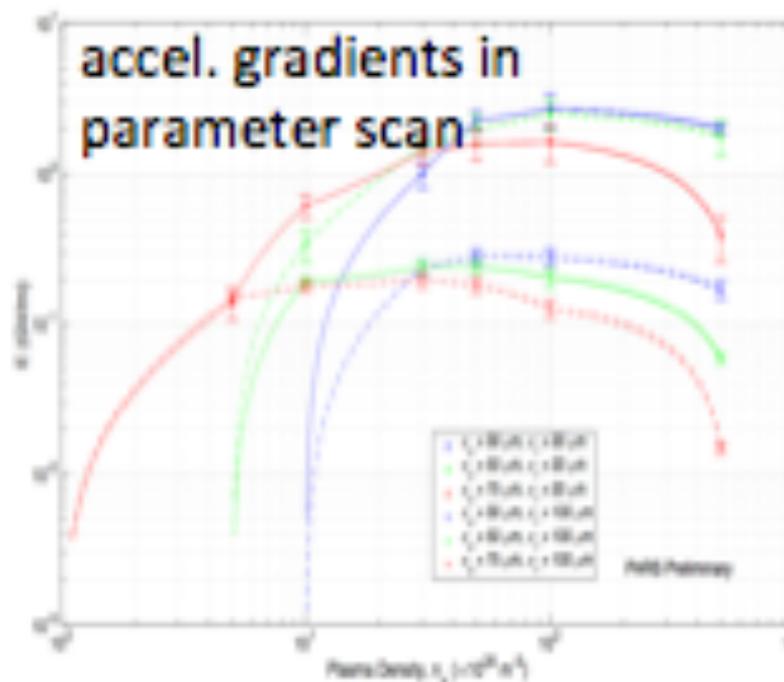
# Experiment tests at VELA/CLARA



- With the possibility to study the energy recovery in plasma
- High impact to the accelerator community (e.g. ILC) and novel accelerator community (e.g. EuPRAXIA)
- Key issues will be discussed in today's workshop, with collaborators worldwide

# Possible PWFA activities

## PWFA activities at CLARA



G. Xia, et al., NIM-A 740, 165 (2014)

O. Mete, et al., Physics of Plasmas 22, 103117 (2015)

G. Xia, et al., NIM-A 829, 43 (2016)

K. Hanahoe, et al., Plasma Phys. Control. Fusion 58, 034002 (2015)

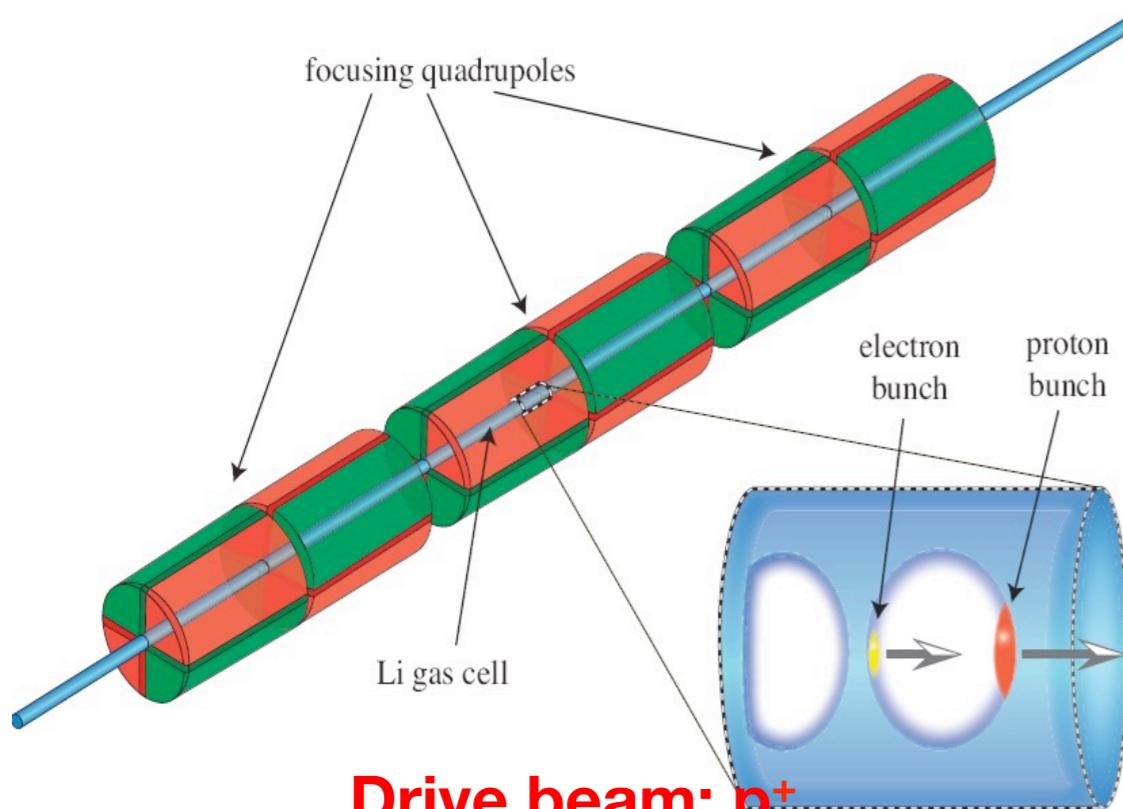
K. Hanahoe, et al., Physics of Plasmas 24, 023120 (2017)

# Why proton?

- Large energy stored in proton machines like Tevatron, HERA, SPS and LHC
- The SPS/LHC beams carry significant energy for driving plasma waves
  - SPS (450 GeV, 1.3e11 p/bunch) ~ 10 kJ
  - LHC (7 TeV, 1.15e11 p/bunch) ~ 140 kJ
- SLAC (50 GeV, 2e10 e/bunch) ~ 0.16 kJ
- ILC (250 GeV, 2e10 e/bunch) ~ 0.8kJ

One stage proton wakefield acceleration can generate energy frontier electron beam

# Proton-driven PWFA



**Drive beam:  $p^+$**

$E=1 \text{ TeV}$ ,  $N_p=10^{11}$   
 $\sigma_r=0.43 \text{ mm}$ ,  $\sigma_\theta=0.03 \text{ mrad}$ ,  
 $\sigma_z=100 \mu\text{m}$ ,  $\Delta E/E=10 \%$

**Witness beam:  $e^-$**

$E_0=10 \text{ GeV}$ ,  $N_e=1.5 \times 10^{10}$

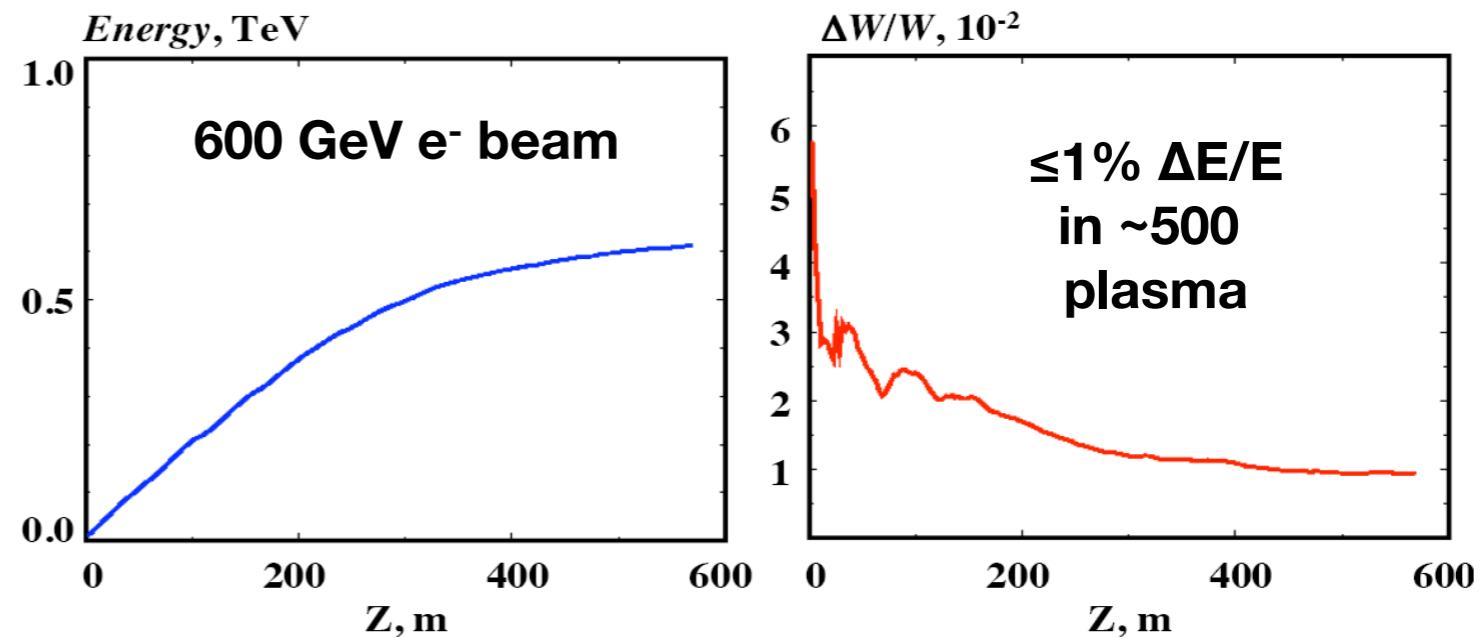
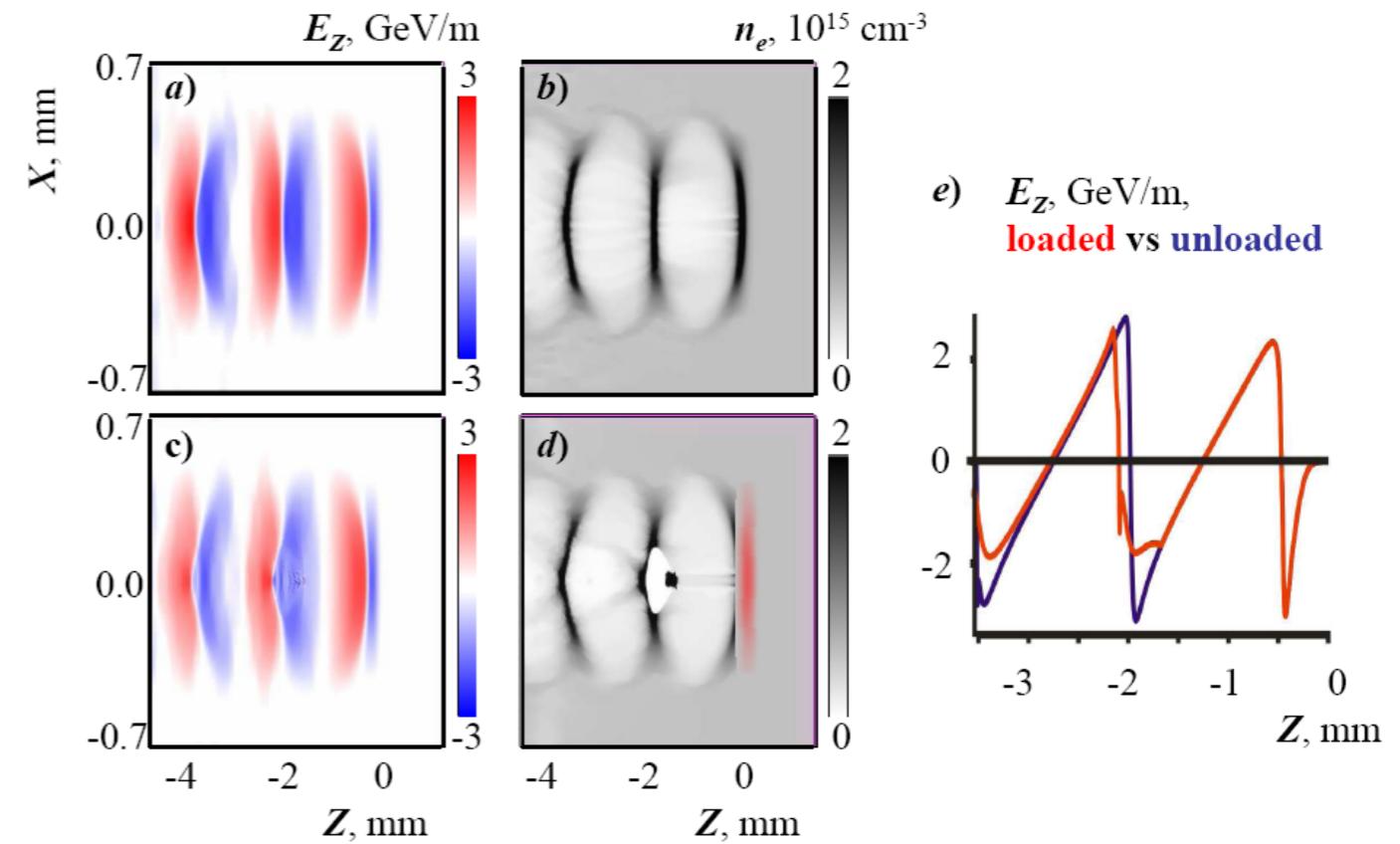
**Plasma:  $\text{Li}^+$**

$n_p=6 \times 10^{14} \text{ cm}^{-3}$

**External magnetic field:**

Field gradient:  $1000 \text{ T/m}$

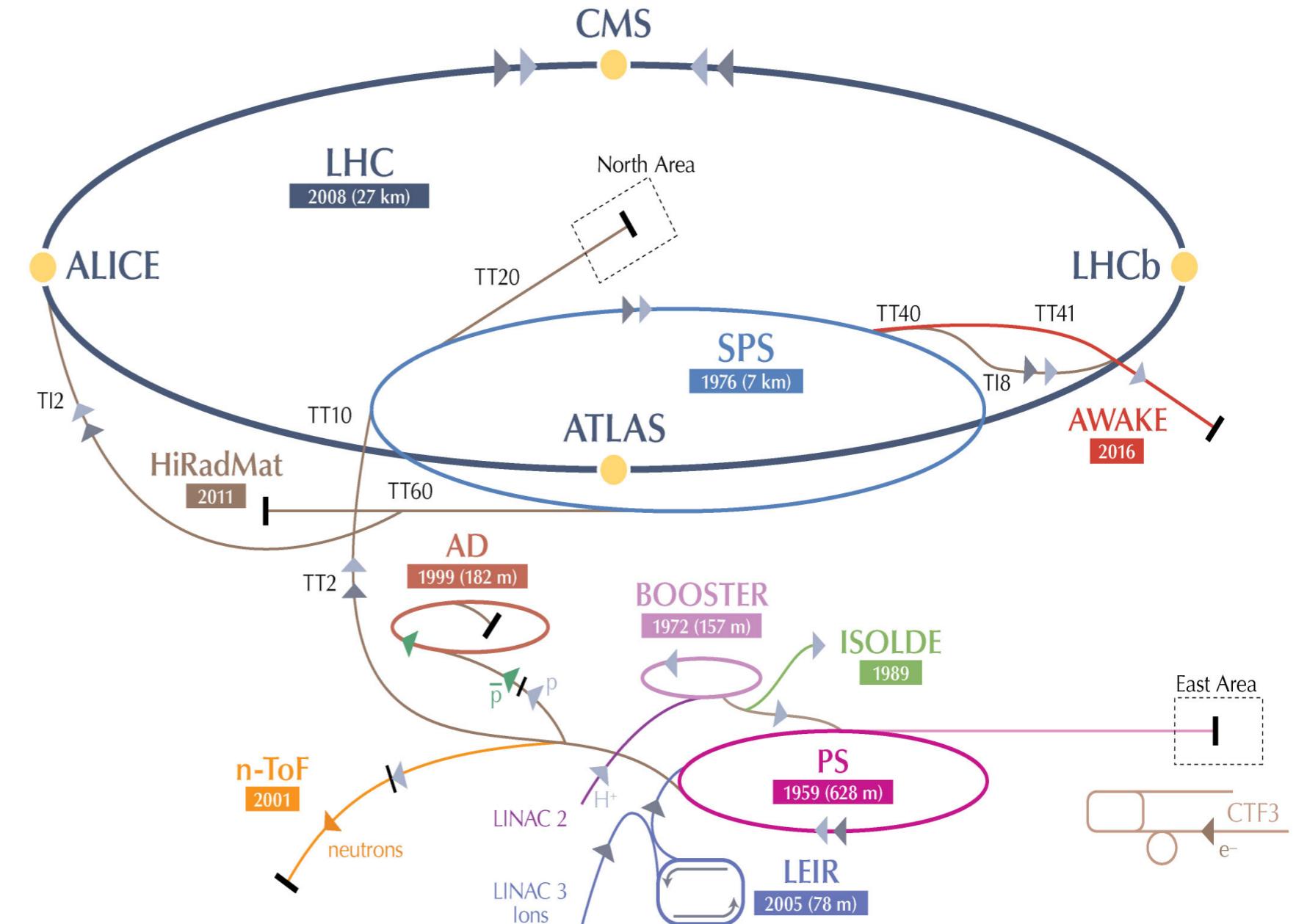
Magnet length:  $0.7 \text{ m}$



Caldwell et al., Nature Physics 2009

# AWAKE: Advanced WAKEfield experiment

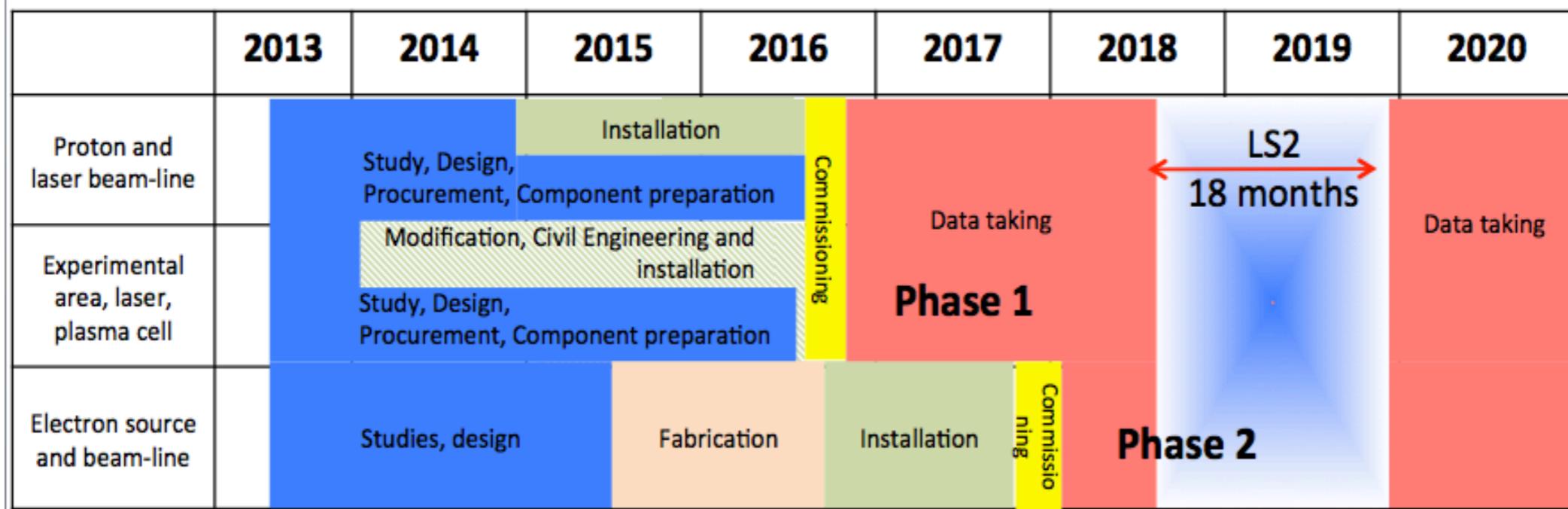
The primary goal of AWAKE is to demonstrate acceleration of a 16 MeV single bunch electron beam up to **1 GeV** in a **10 m** of plasma.



# AWAKE timeline

- ▶ 2013
  - Approval** of project at CERN including funding profile.
- ▶ 2014-2015
  - Design, procurement and installation of the equipment, development of **plasma cells**.
  - Modification and installation of the **beam line and the experimental facility**.
- ▶ 2016
  - First proton beam** to the AWAKE experiment, beam–plasma commissioning.
  - Beginning taking data
- ▶ 2017
  - Installation of the electron source and beam line and diagnostics.**
  - Delivery and installation of the electron photo-injector**, commissioning of the magnetic spectrometer.
- ▶ **More data taking!**
- ▶ International Effort
- ▶ 16 institutions in 9 countries across Europe and Asia.

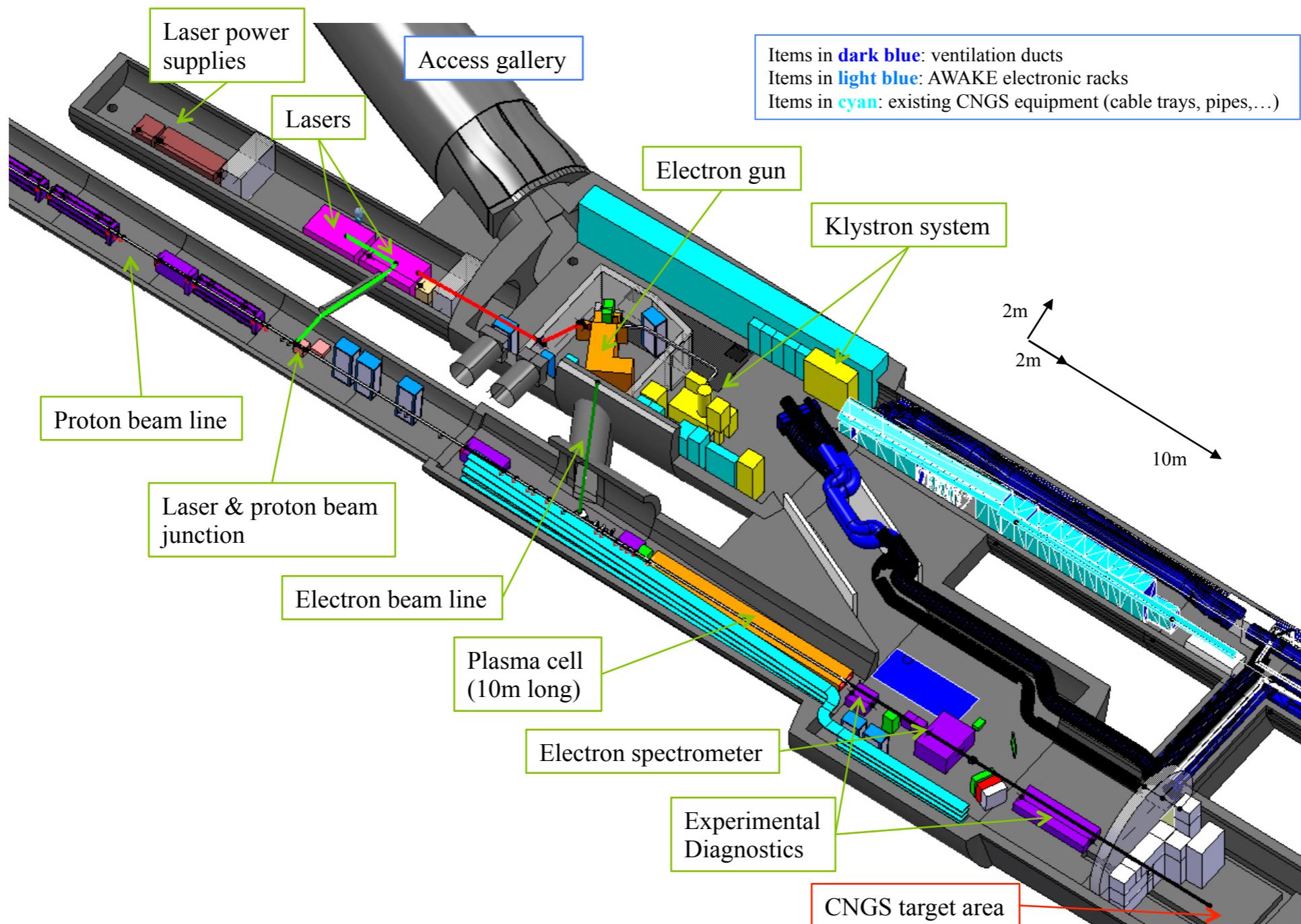
# AWAKE timeline



2016 Phase 1: Self-Modulation Instability physics  
 2017-18 Phase 2: Electron acceleration physics

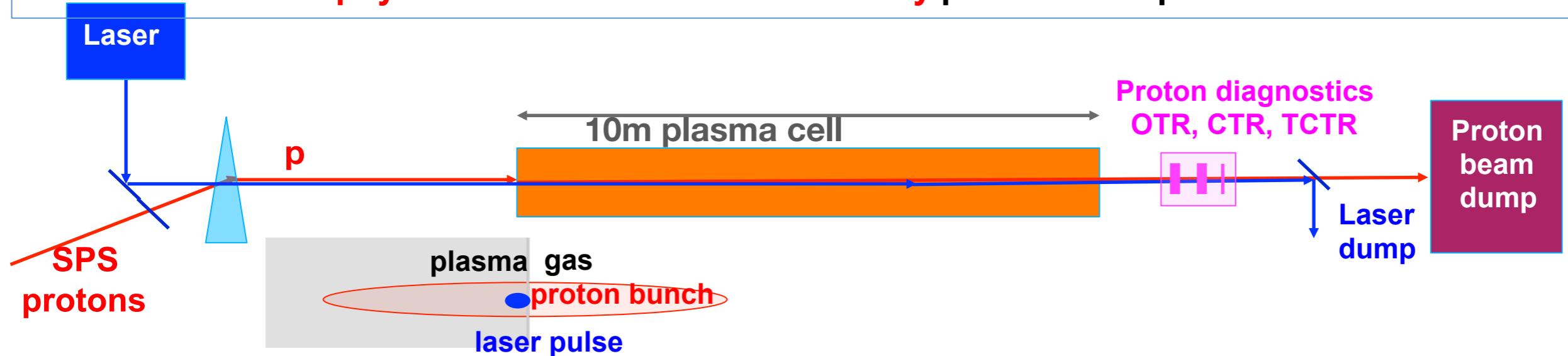
Run-scenario	Nominal
Number of run-periods/year	4
Length of run-period	2 weeks
Total number of beam shots/year (100% efficiency)	162000
Total number of protons/year	$4.86 \times 10^{16}$ p
Initial experimental program	3 – 4 years

# AWAKE experiment layout

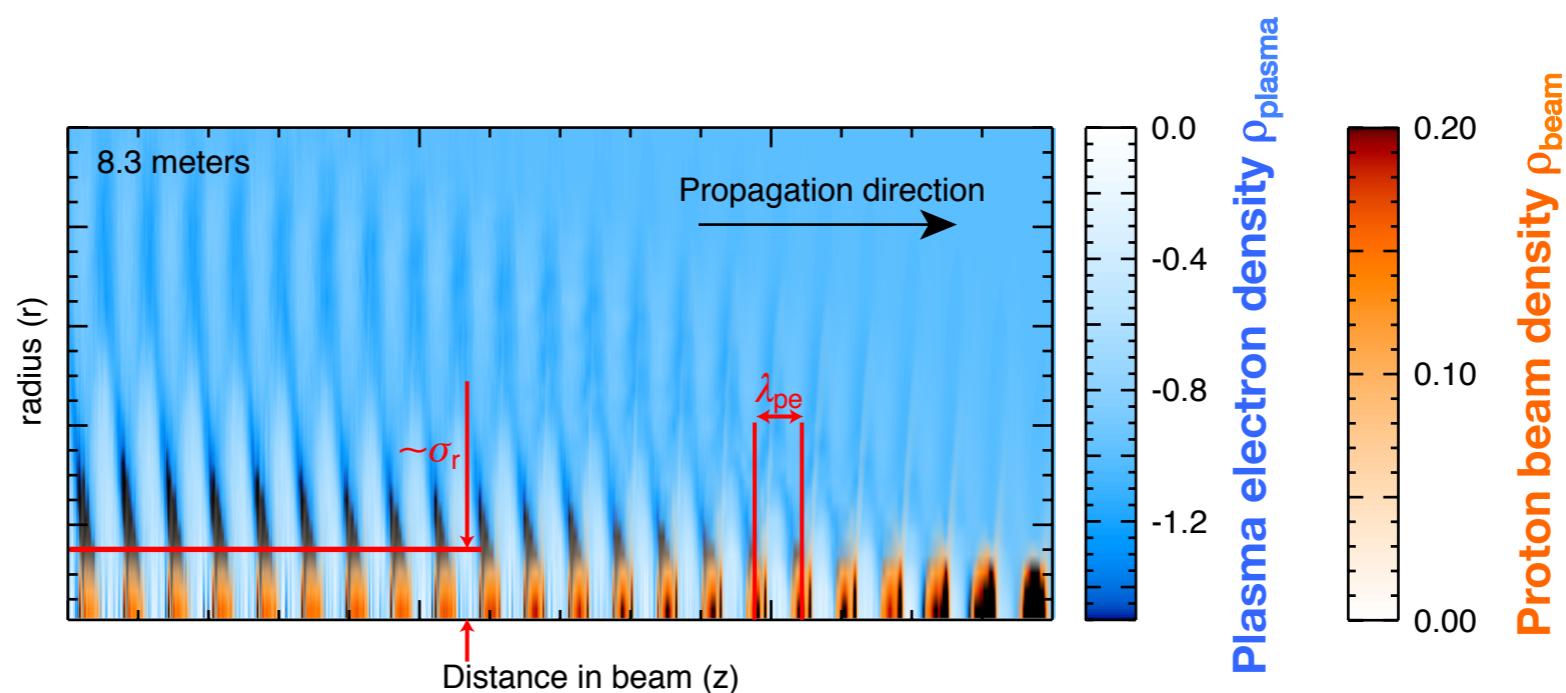


# AWAKE Run I, Phase I

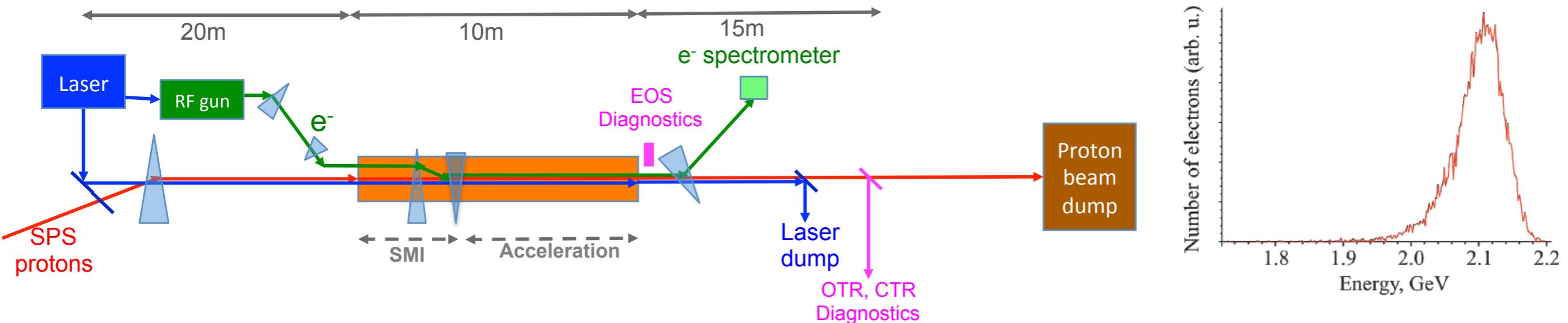
- Perform **benchmark experiments using proton bunches** to drive wakefields for the first time ever.
- Understand **the physics of self-modulation instability processes in plasma**.



**Self-modulated proton bunch resonantly driving plasma wakefields.**



# AWAKE Run I, Phase II



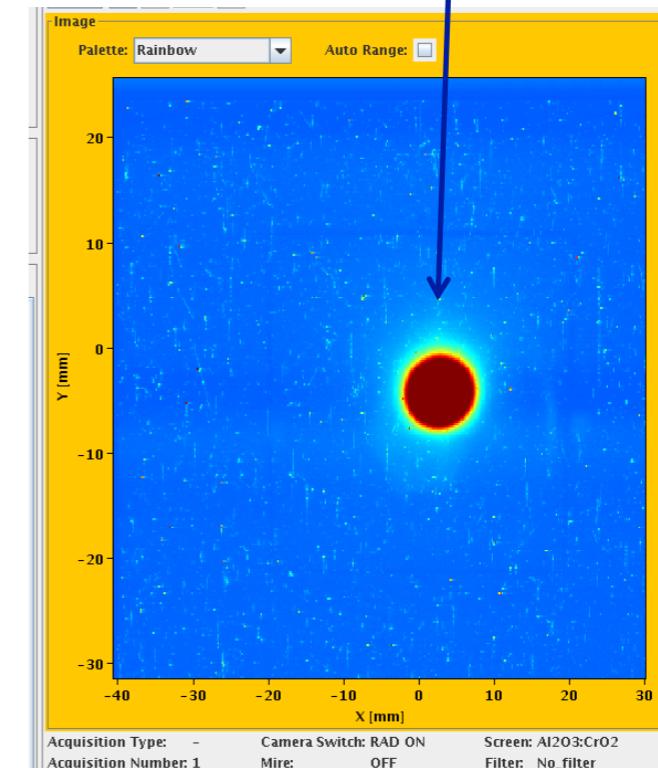
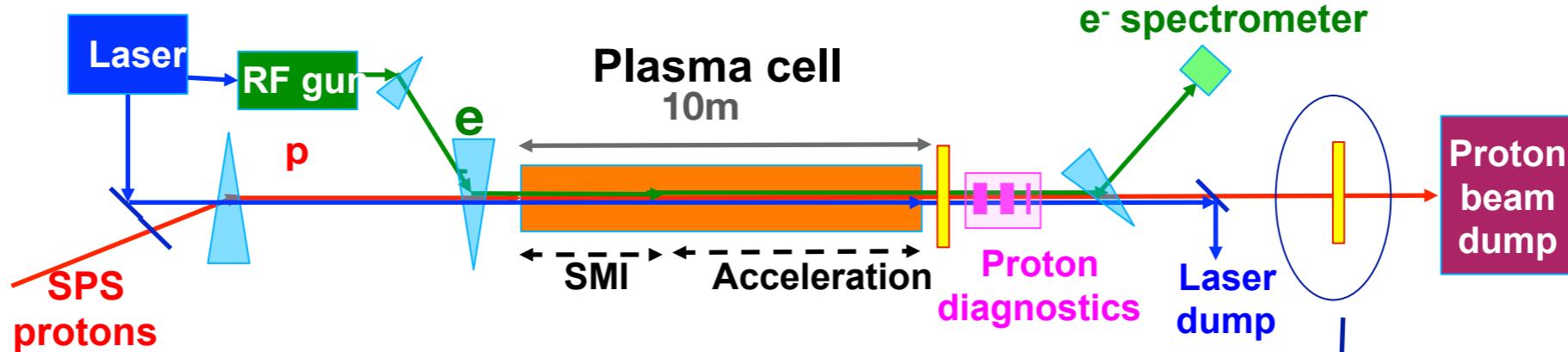
- Inject 10-20 MeV electron beam
- Acceleration of electrons to multi-GeV energy range after the plasma exit.

## Scientific goals

1. Demonstrate self-modulation effect of a long proton bunch and realize 1 GeV electron energy gain with a ~10 m plasma
2. Develop and test the diagnostic equipments for the first and later experiments
3. Benchmark data against simulation results
4. Provide inputs for future experiment for 100 GeV in 100 m plasma

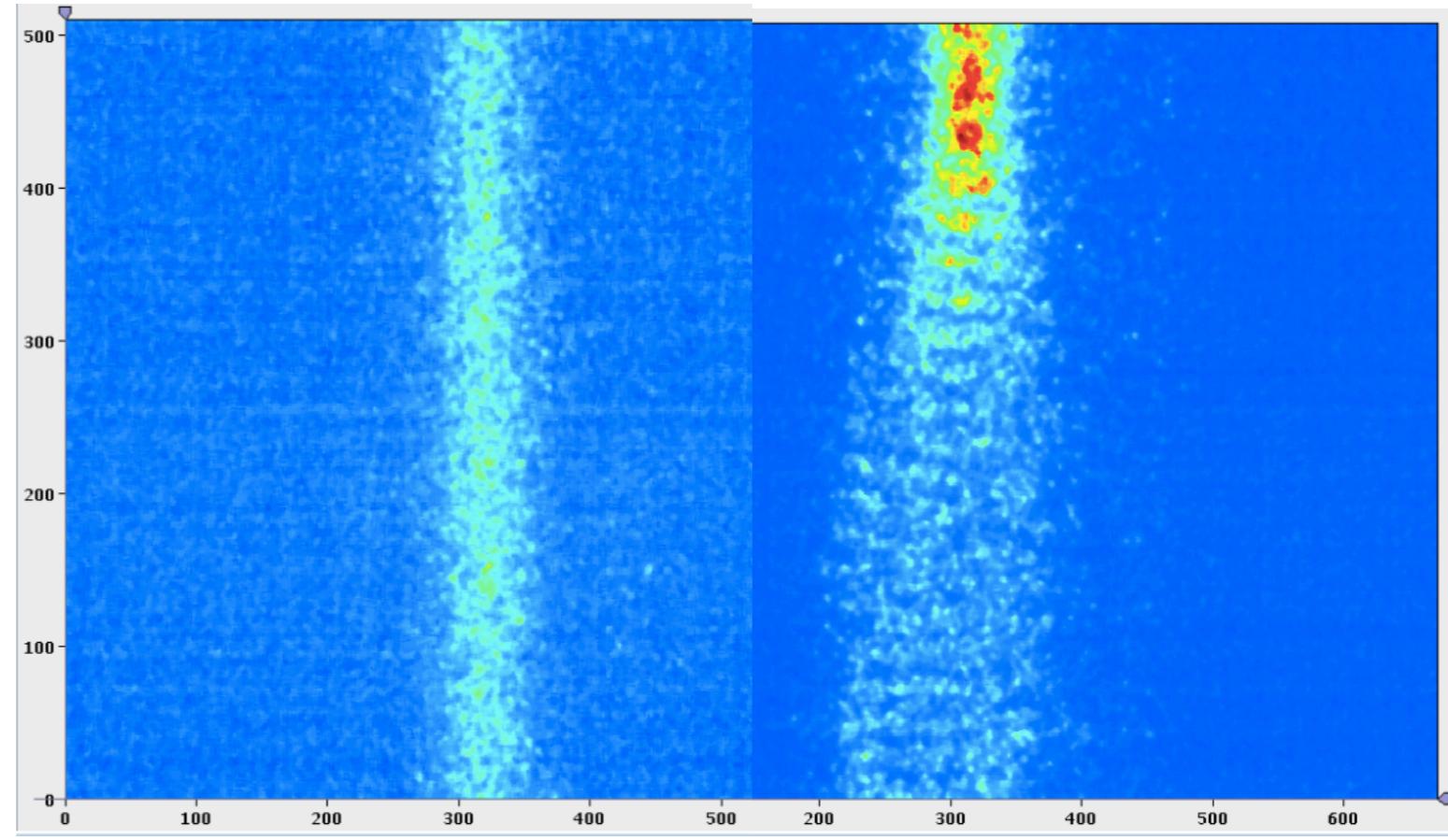
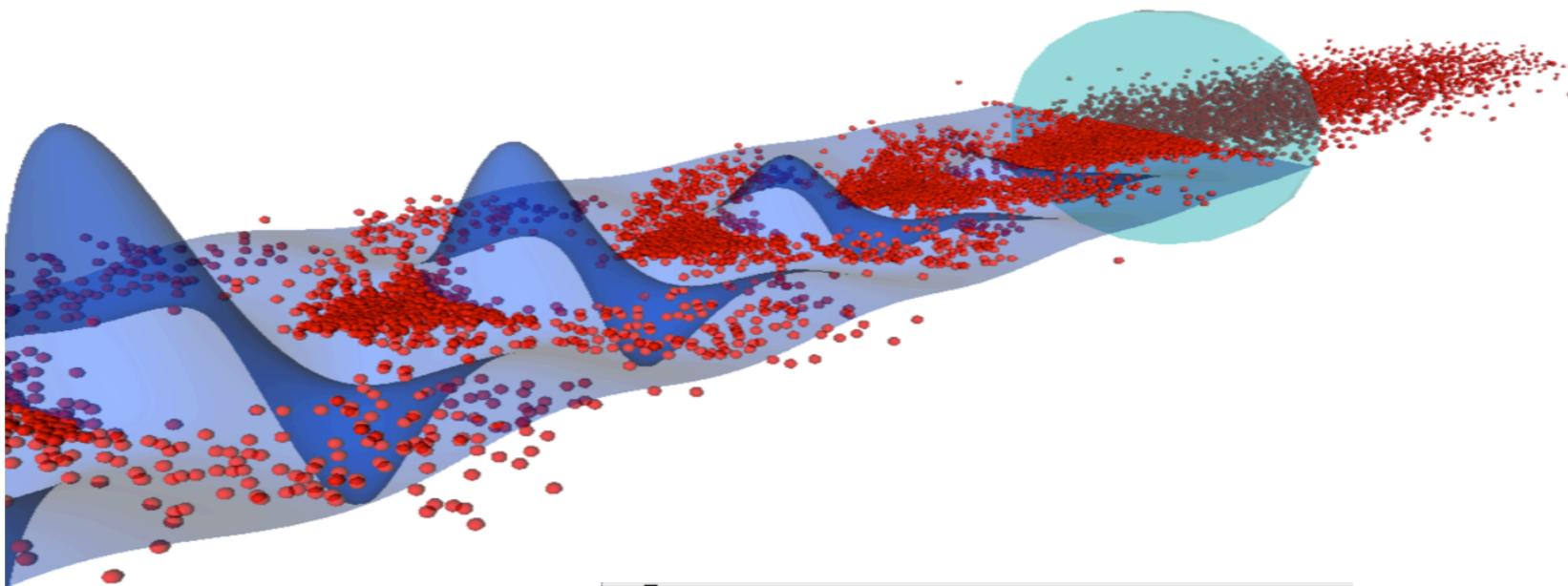
# First beam June 2016

- First extraction of proton beam along the AWAKE line to identify or discard any issues
- Check of optics, beam instrumentation, alignment of laser merging mirror, logging, etc...



Proton Beam Image in last  
BTV screen downstream  
plasma

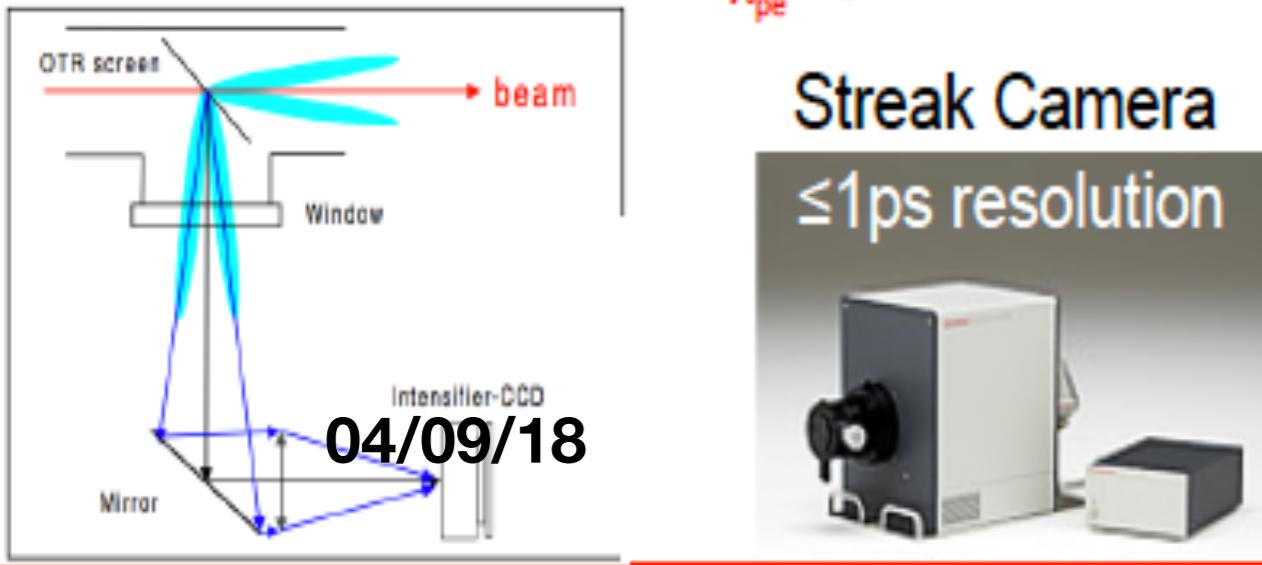
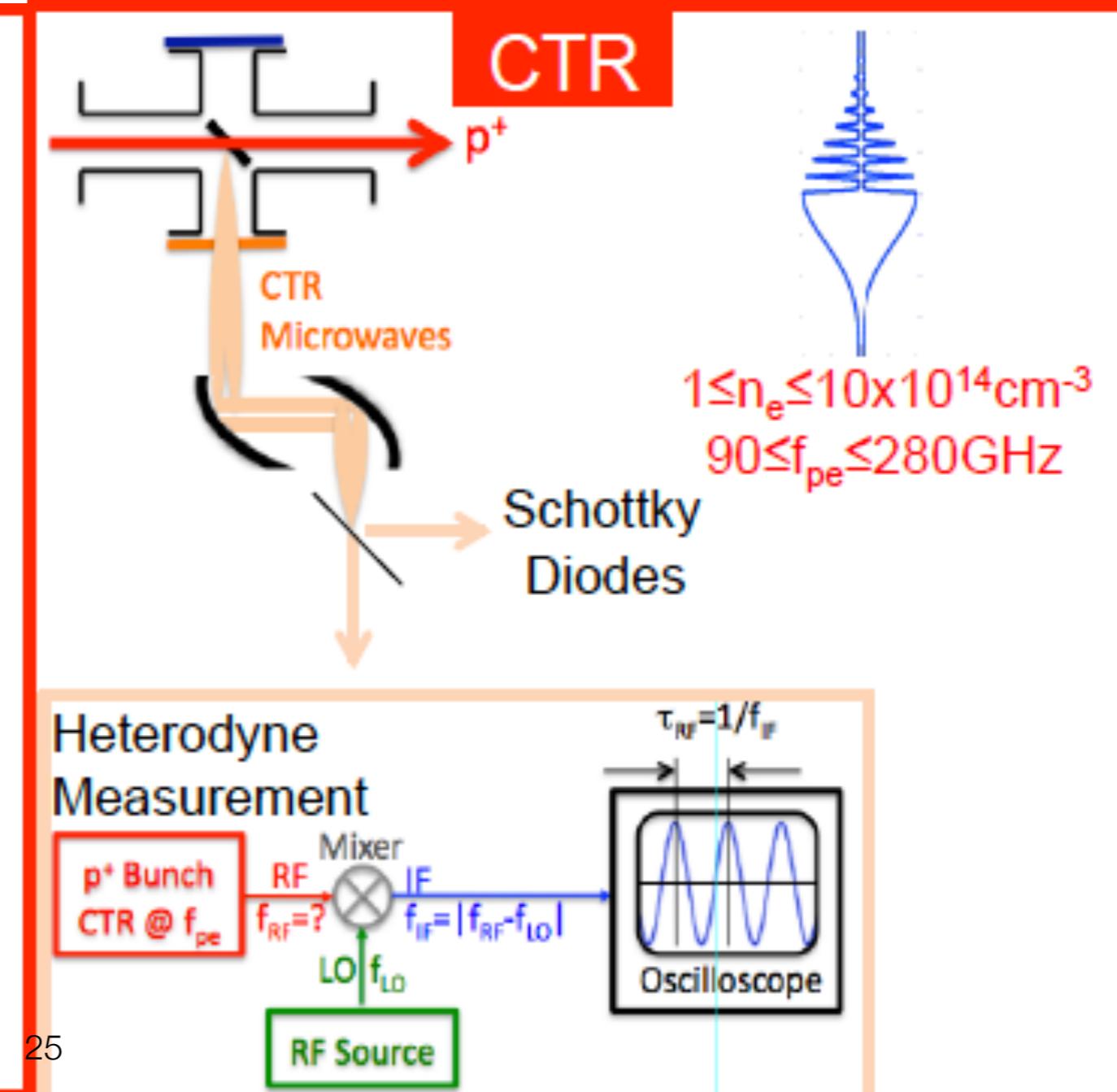
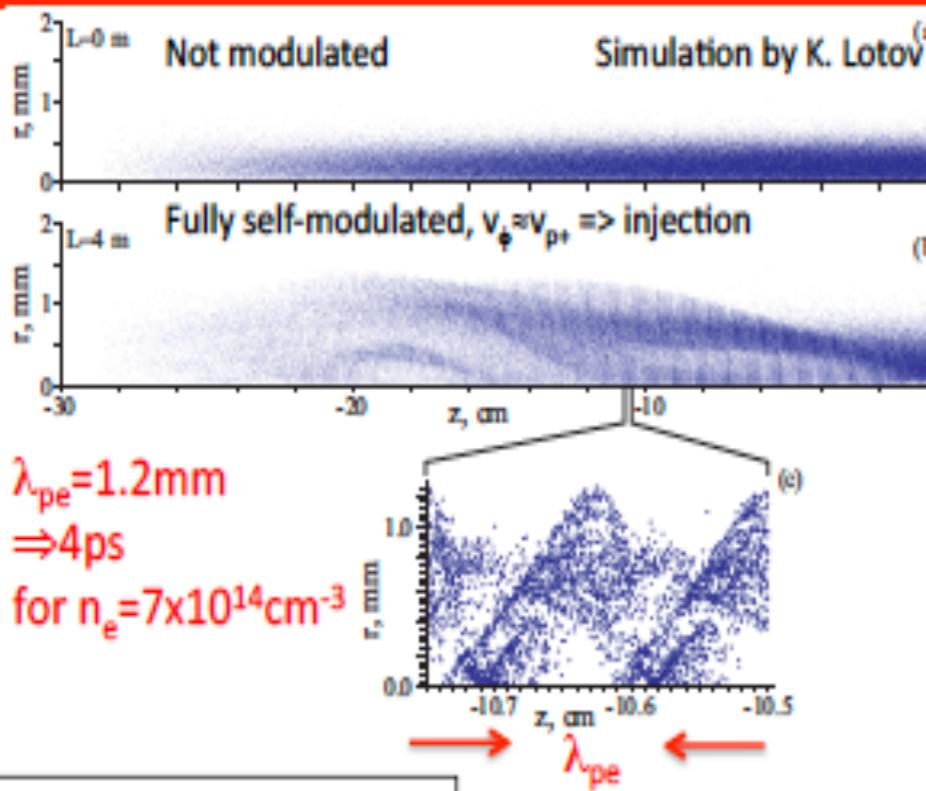
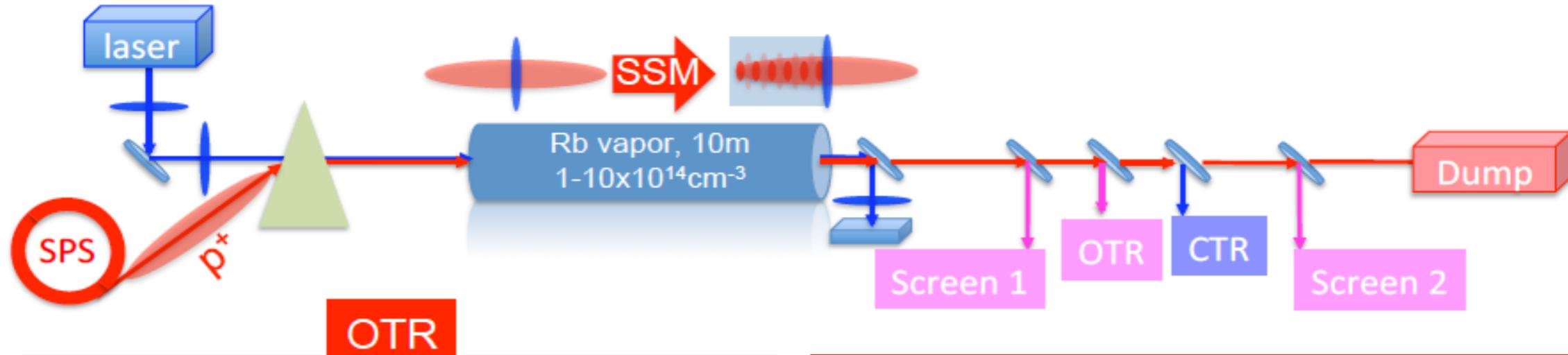
# First milestone-self modulation (Dec. 2016)



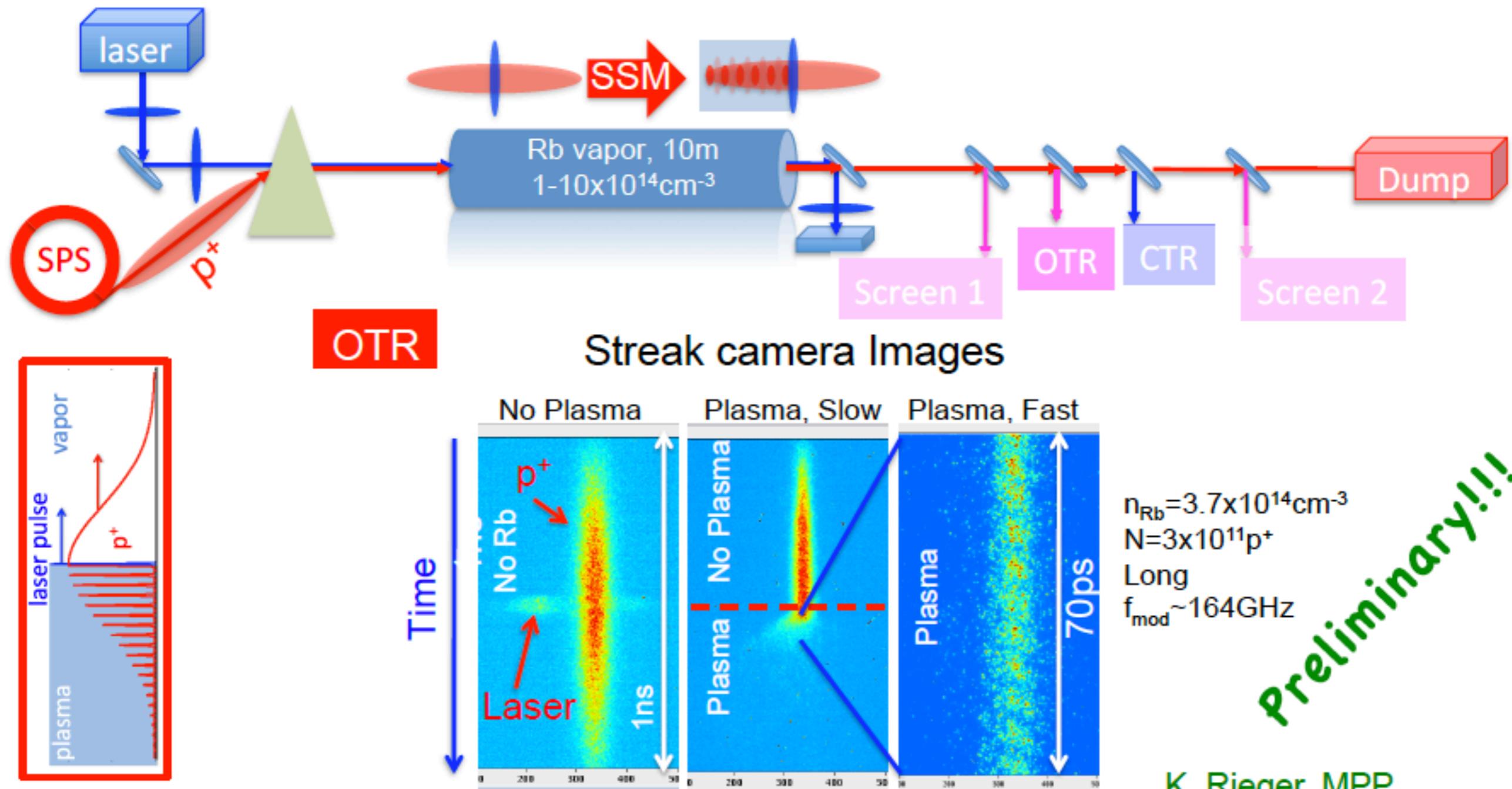
Plasma off      Plasma on

04/09/18

# Seeded self modulation (SSM)



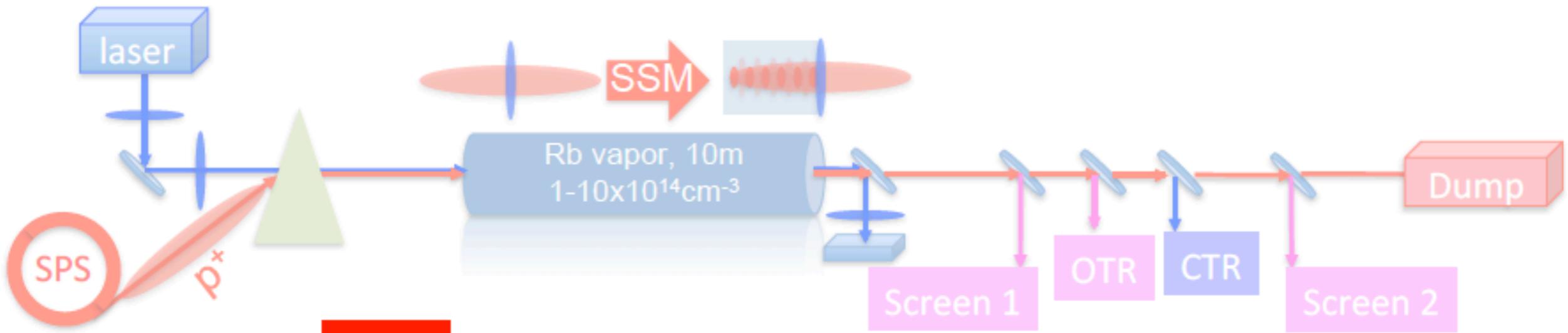
# SSM



- ❖ Timing at the ps scale
- ❖ Effect starts at laser timing → **SM seeding**
- ❖ Density modulation at the ps-scale visible

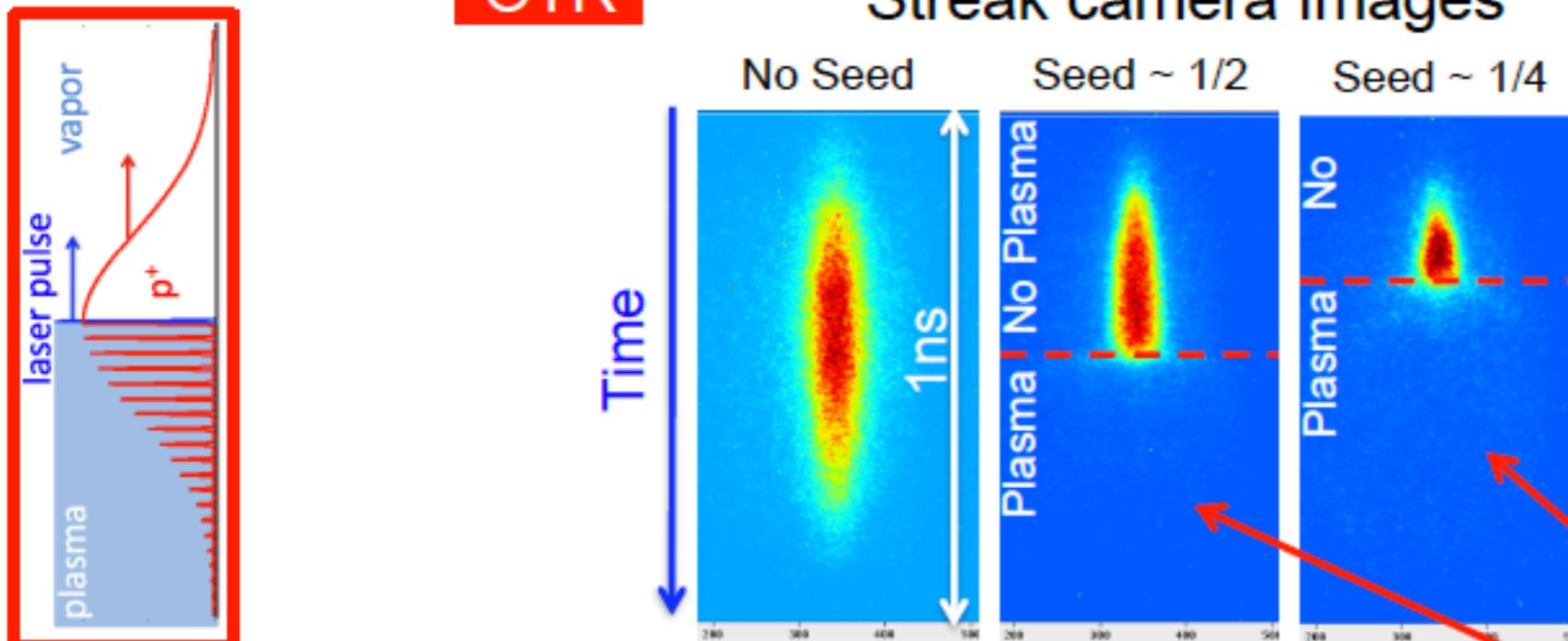
04/09/18

# SSM



OTR

Streak camera Images

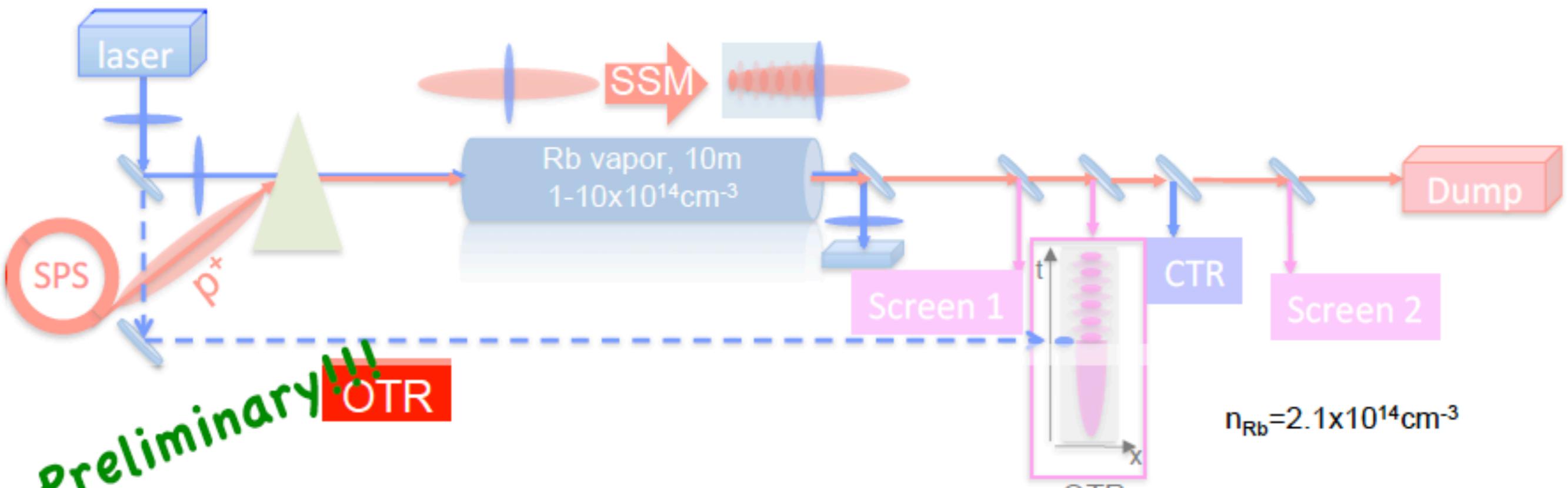


$n_{\text{Rb}} = 2.2 \times 10^{14} \text{ cm}^{-3}$   
 $N = 3 \times 10^{11} \text{ p}^+$   
 Short

Preliminary!!!

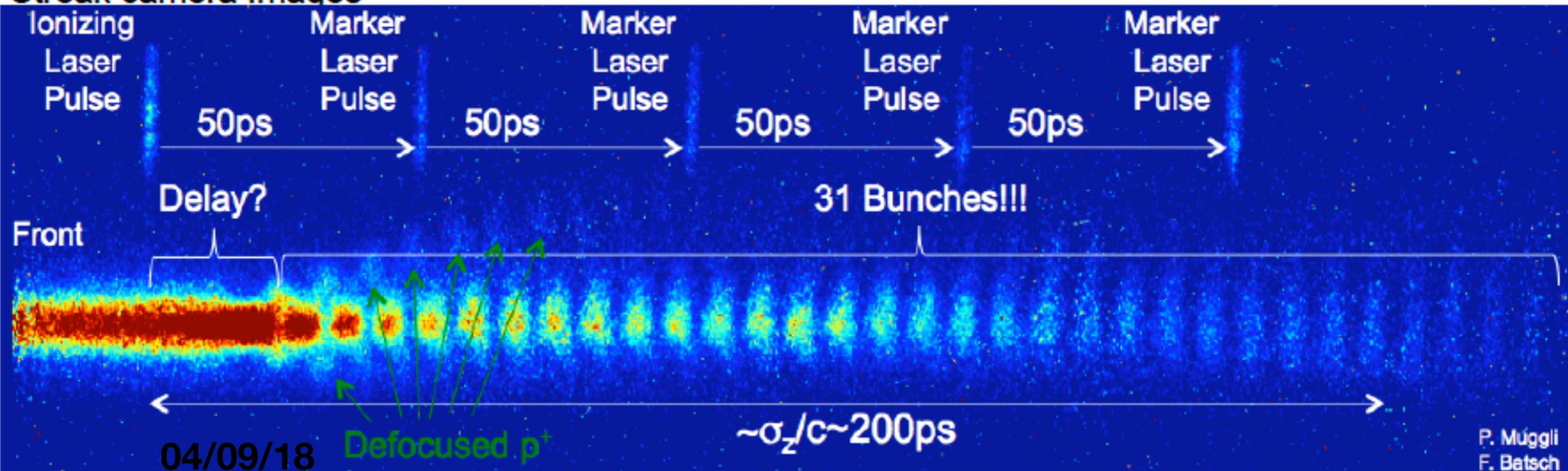
- ❖ Various seeding position/times
  - ❖ Effect starts at laser timing → SM seeding
- Stronger effects with seed at 1/4 than 1/2 observed !**

# Micro bunch train



Preliminary OTR

Streak camera Images



# Interesting results observed

Observe SSM (defocusing, micro-bunches)

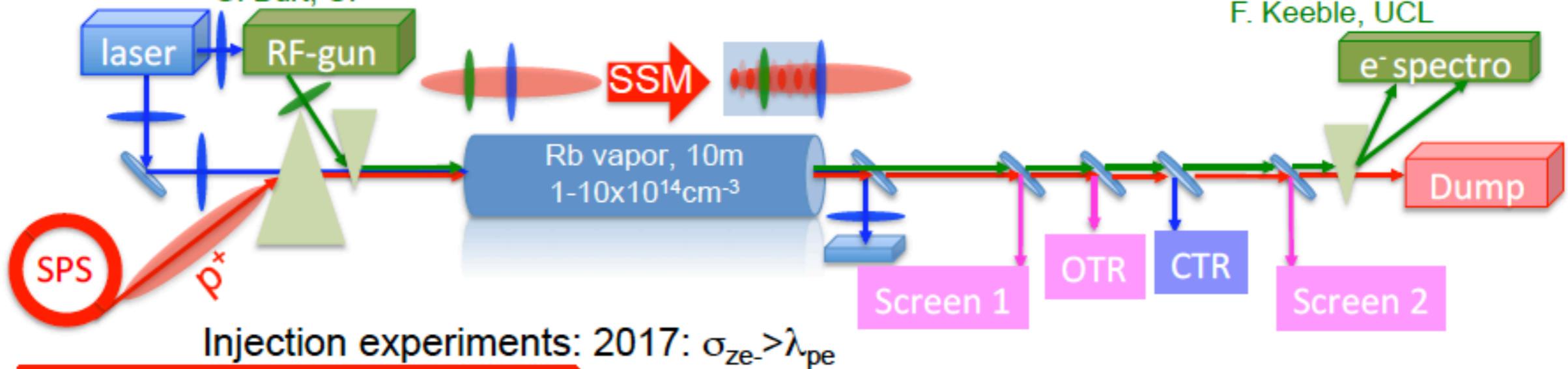
- Demonstrate seeding: SSM
- Micro bunch structure (very) stable against  $p^+$  variations: key for  $e^-$  injection and acceleration,
- No seeding=> SMI or hose instability
- $f_{\text{mod}} \sim f_{\text{pe}}$
- Run II: (2021-): two plasmas, high quality of the accelerated  $e^-$  bunch:  $\Delta E/E, \varepsilon$
- Application of AWAKE,  $e^-/p^+$  collisions

Preliminary!  
analysis to come!

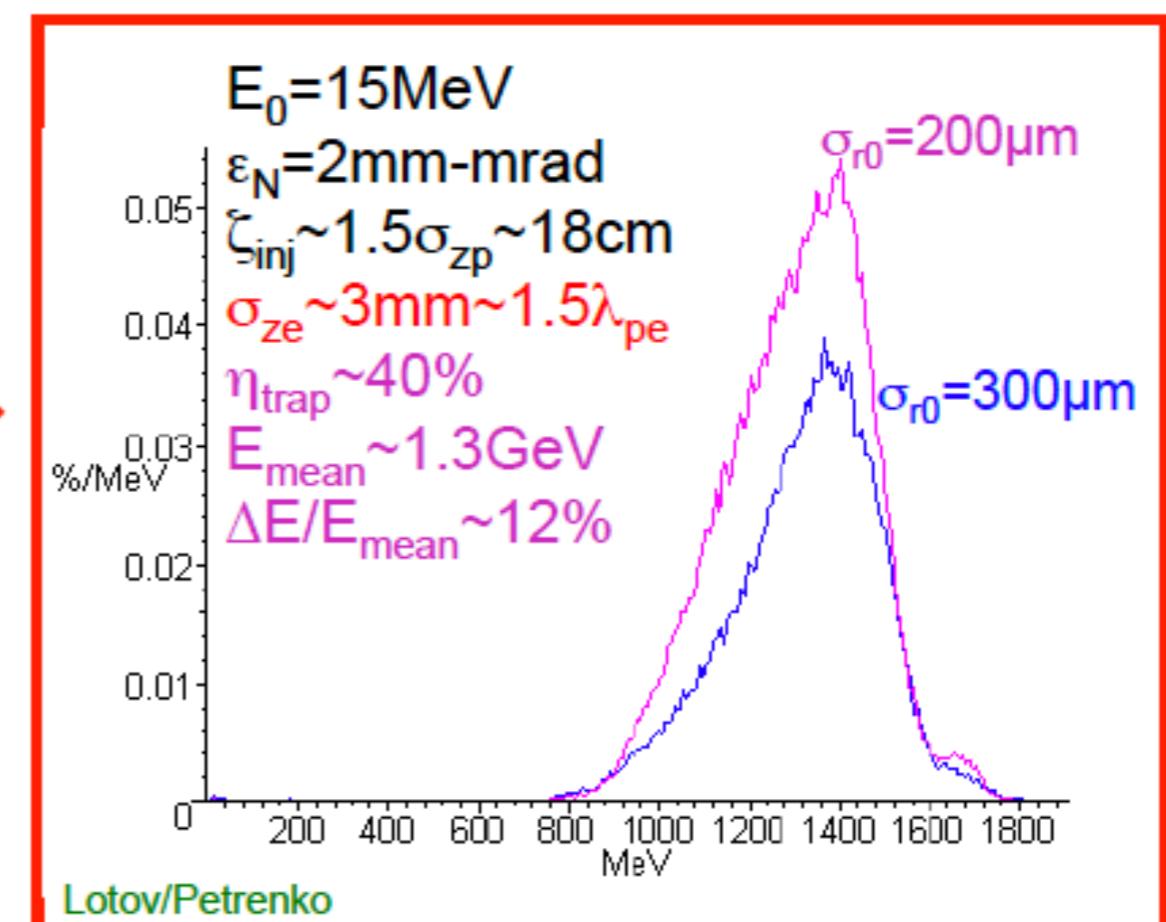
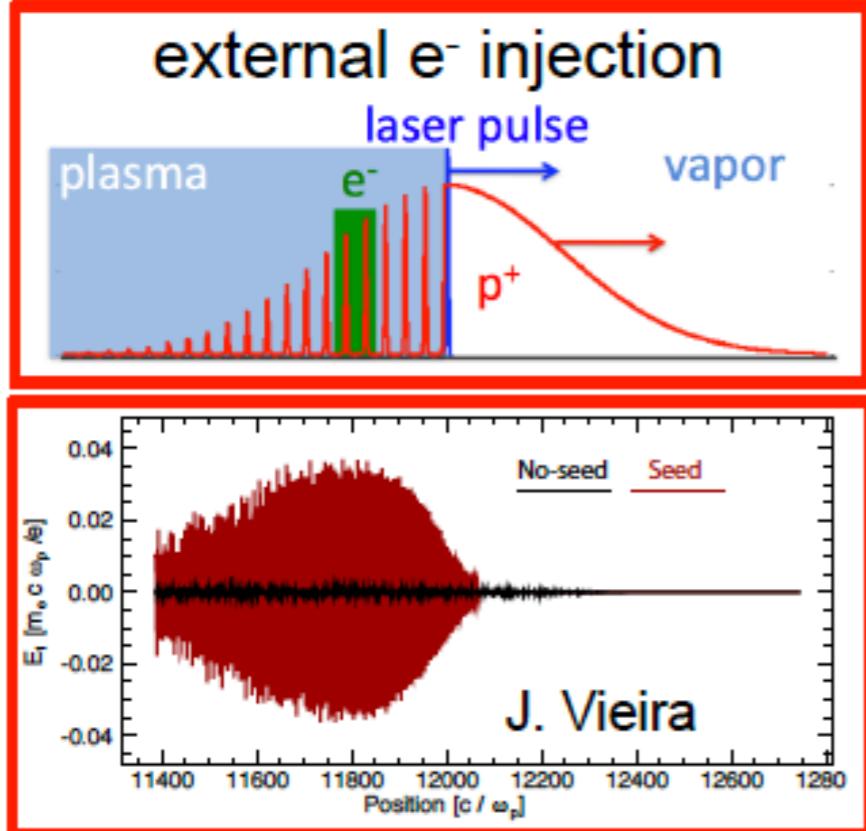
# Wakefield sampling/acceleration

S. Doeberl, K. Pepitone, CERN

G. Burt, CL



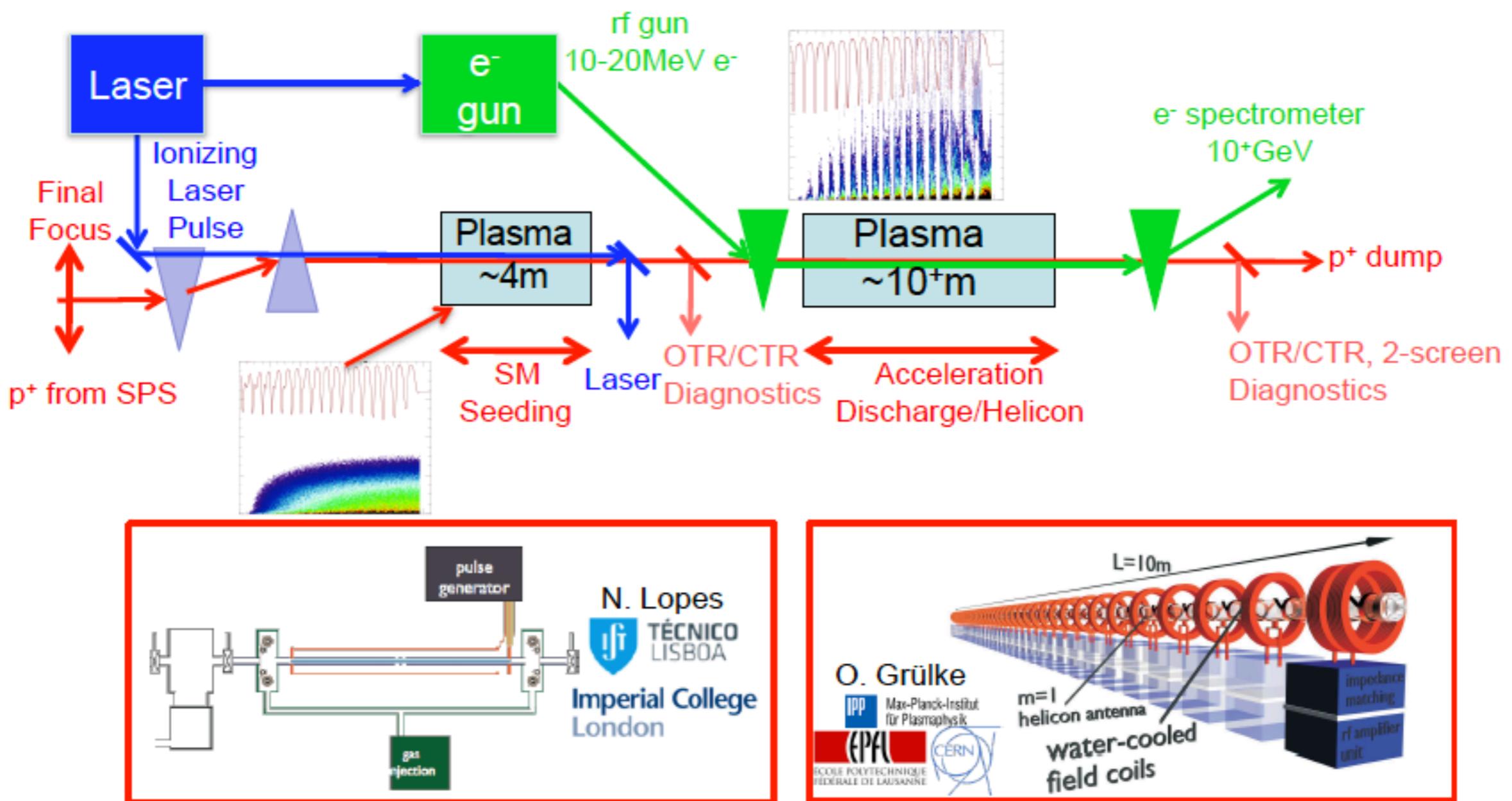
Injection experiments: 2017:  $\sigma_{ze} > \lambda_{pe}$



❖ Accelerate e<sup>-</sup> to GeV energy with  
~GeV/m gradient and finite  $\Delta E/E$

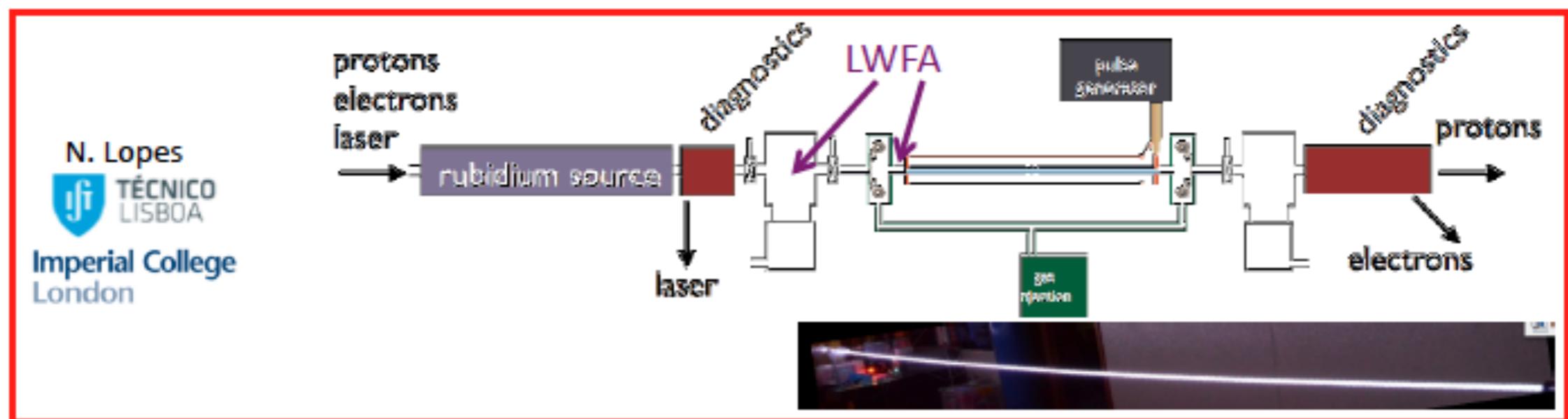
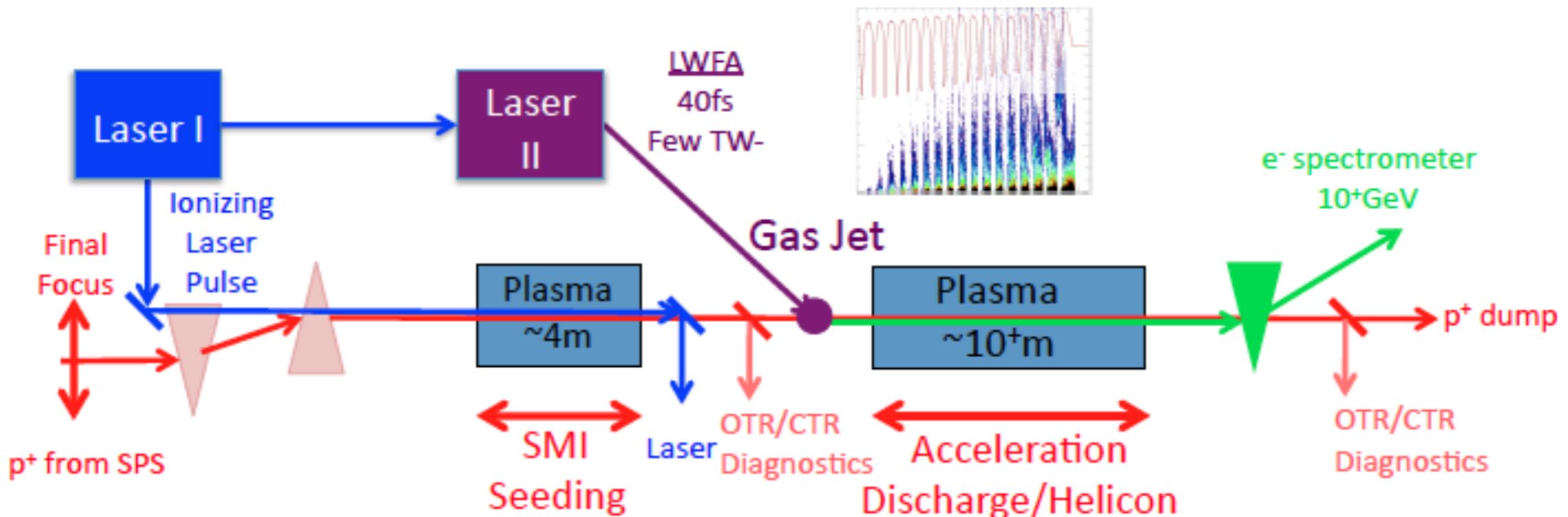
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# Experimental setup for Run II (2021-LS3)



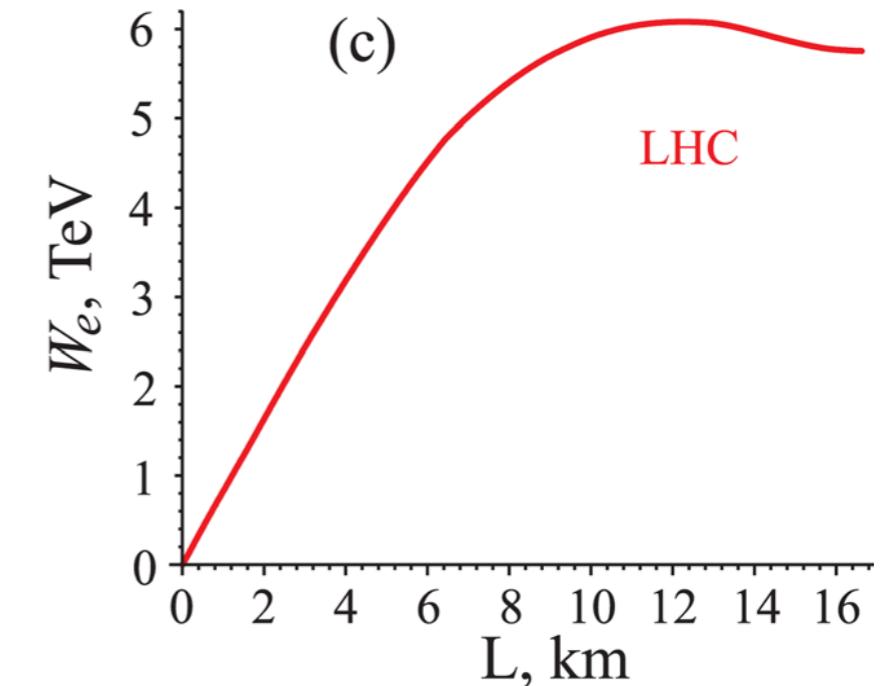
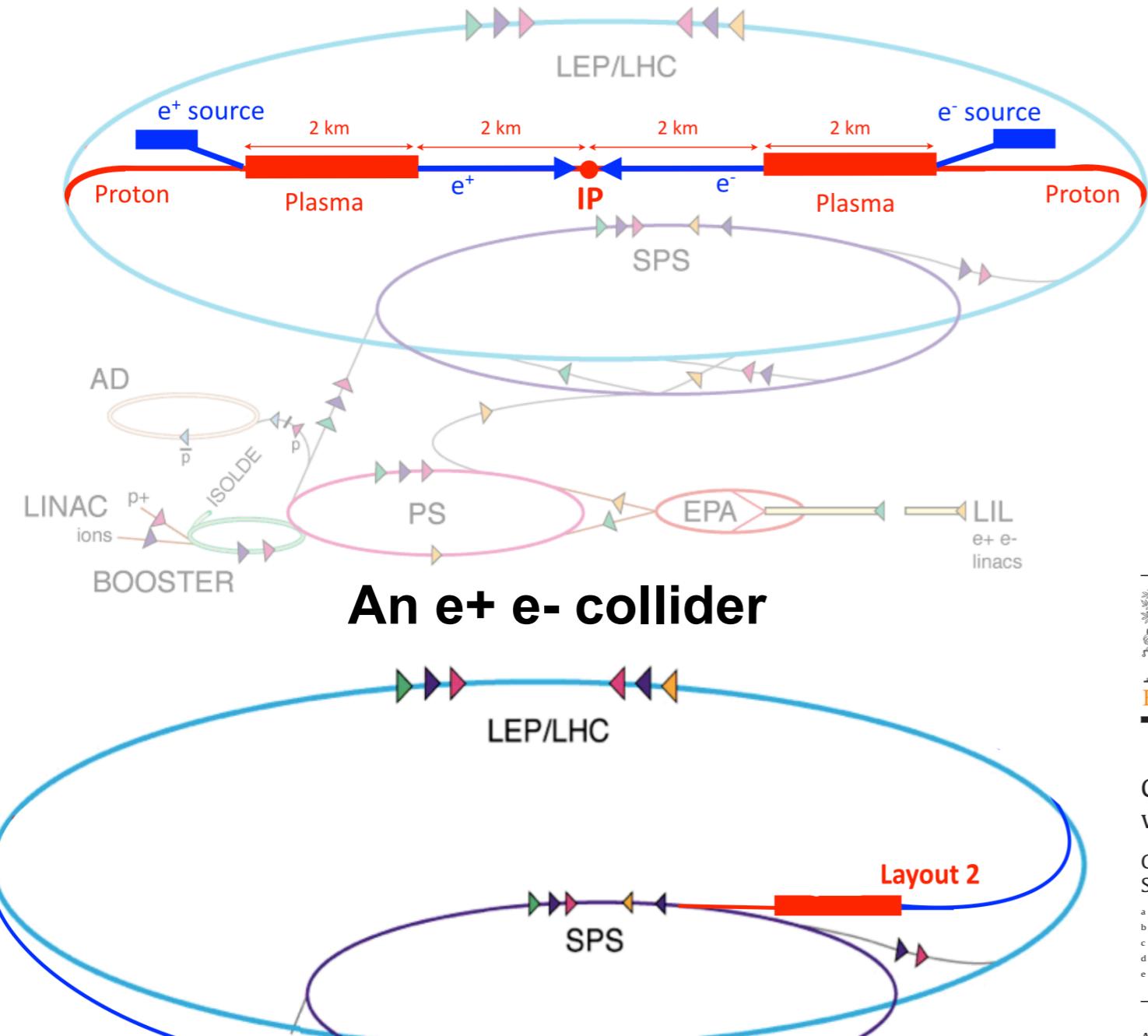
- ❖ Laser ionization of a metal vapor (Rb), 3-4m plasma for p<sup>+</sup> SSM only, SEEDING NECESSARY!
- ❖ ~10m discharge or helicon source for acceleration only (scales to 100's m)
- ❖ Inject short e<sup>-</sup> bunch ( $\sigma_z \ll \lambda_{pe}$ ), quality of the bunch:  $\Delta E/E$ ,  $\epsilon \Rightarrow$  beam loading and blow-out
- ❖ Density step to maintain accelerating gradient

# AWAKE Run II



**LWFA based e- injector: synchronization, short bunch, high energy (100 MeV), high current, beam loading, beam quality...**

# AWAKE applications



Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: [www.elsevier.com/locate/nima](http://www.elsevier.com/locate/nima)



Collider design issues based on proton-driven plasma wakefield acceleration

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<sup>c</sup> The University of Liverpool, Liverpool, United Kingdom

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## ARTICLE INFO

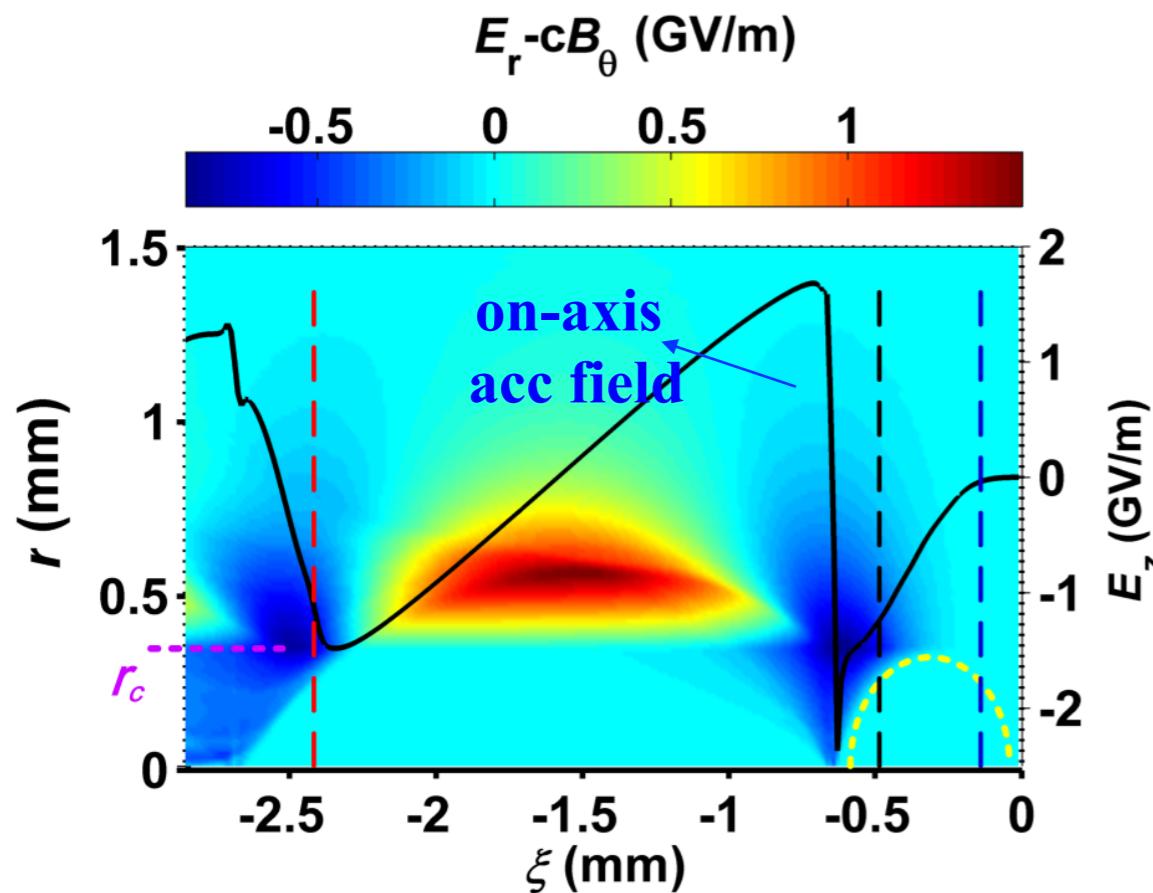
**Keywords:**  
PDPWA  
Colliders  
Self-modulation instability  
Dephasing

## ABSTRACT

Recent simulations have shown that a high-energy proton bunch can excite strong plasma wakefields and accelerate a bunch of electrons to the energy frontier in a single stage of acceleration. It therefore paves the way towards a compact future collider design using the proton beams from existing high-energy proton machines, e.g. Tevatron or the LHC. This paper addresses some key issues in designing a compact electron–positron linear collider and an electron–proton collider based on the existing CERN accelerator infrastructure.

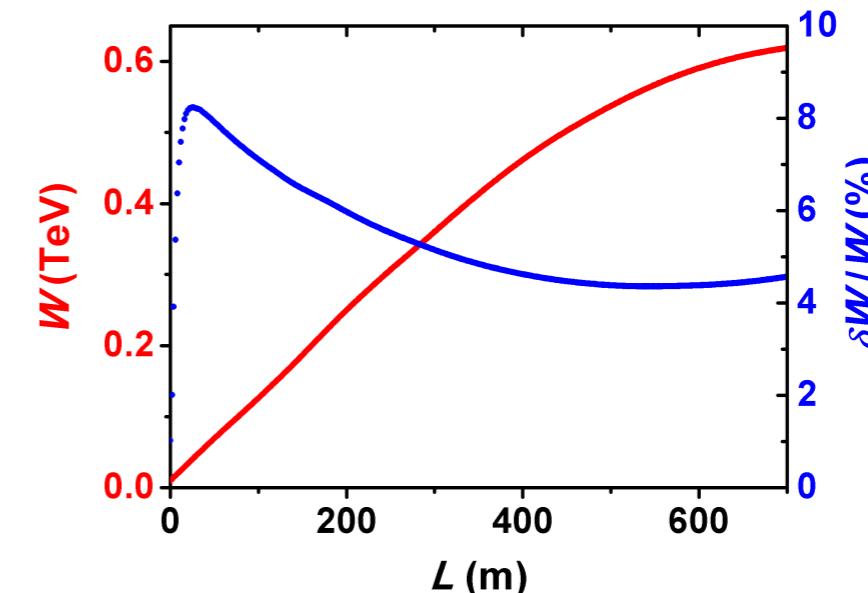
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# Hollow plasma channel



2D plasma wakefields

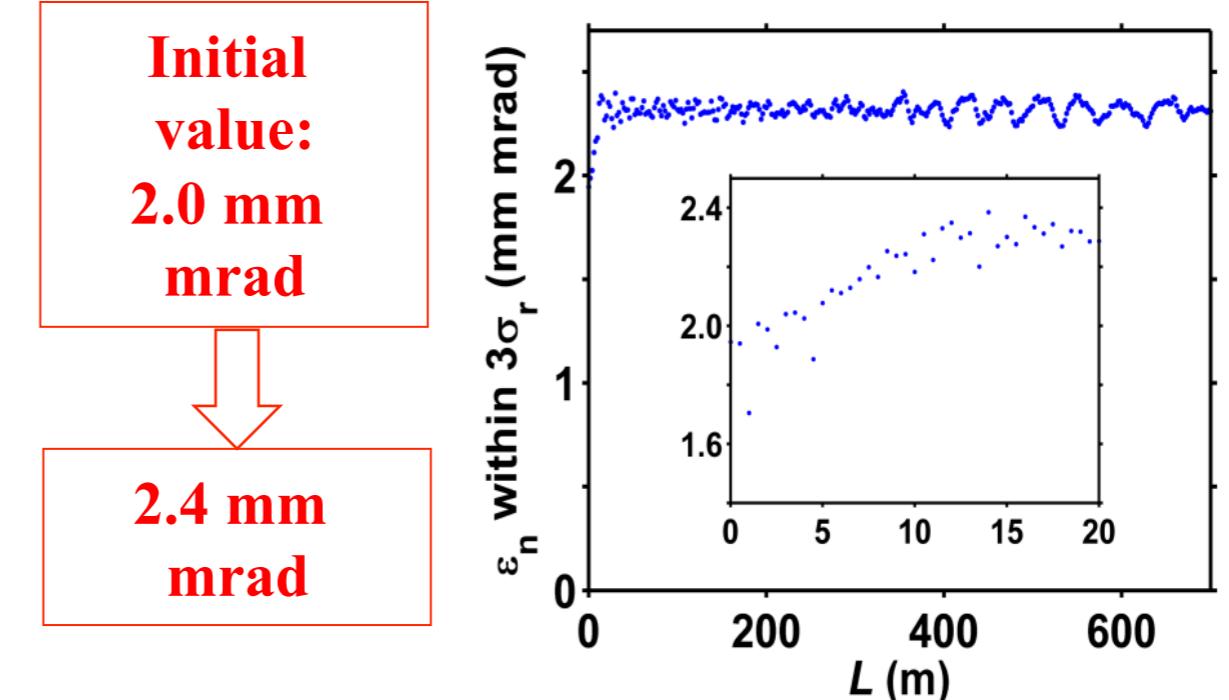
- No transverse plasma fields + larger acc gradients on the witness electron bunch



Mean energy and energy spread of the

Initial value:  
2.0 mm mrad

2.4 mm mrad



# Conclusions

- Plasma beam dump can absorb beam energy with reduced radio-activation
- Varying plasma density can be used to improve the energy loss of a passive plasma beam dump
- Plasma beam dump can be tested at the VELA/CLARA using the existing beam diagnostics
- VELA/CLARA and AWAKE facility can be used to test the energy recovery

**Thank you very much !**