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

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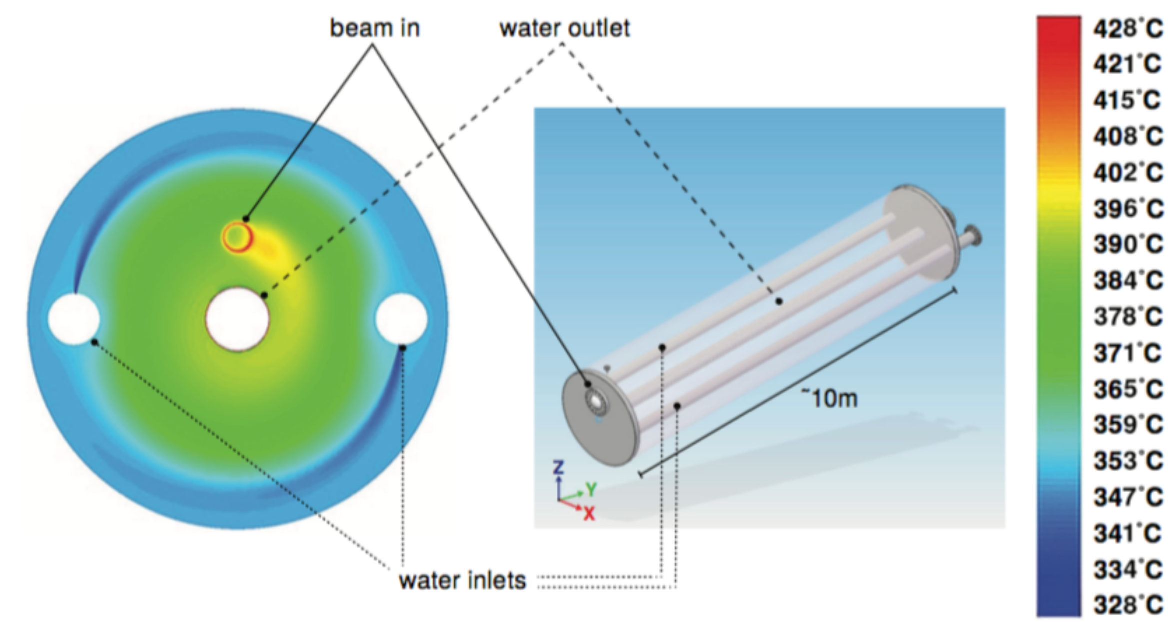
- Conventional beam dump
- Plasma beam dump
- Modelling of plasma beam dump
- Experiment tests at VELA/CLARA
- Conclusion

Conventional Beam dump-ILC

ILC beam dump design:

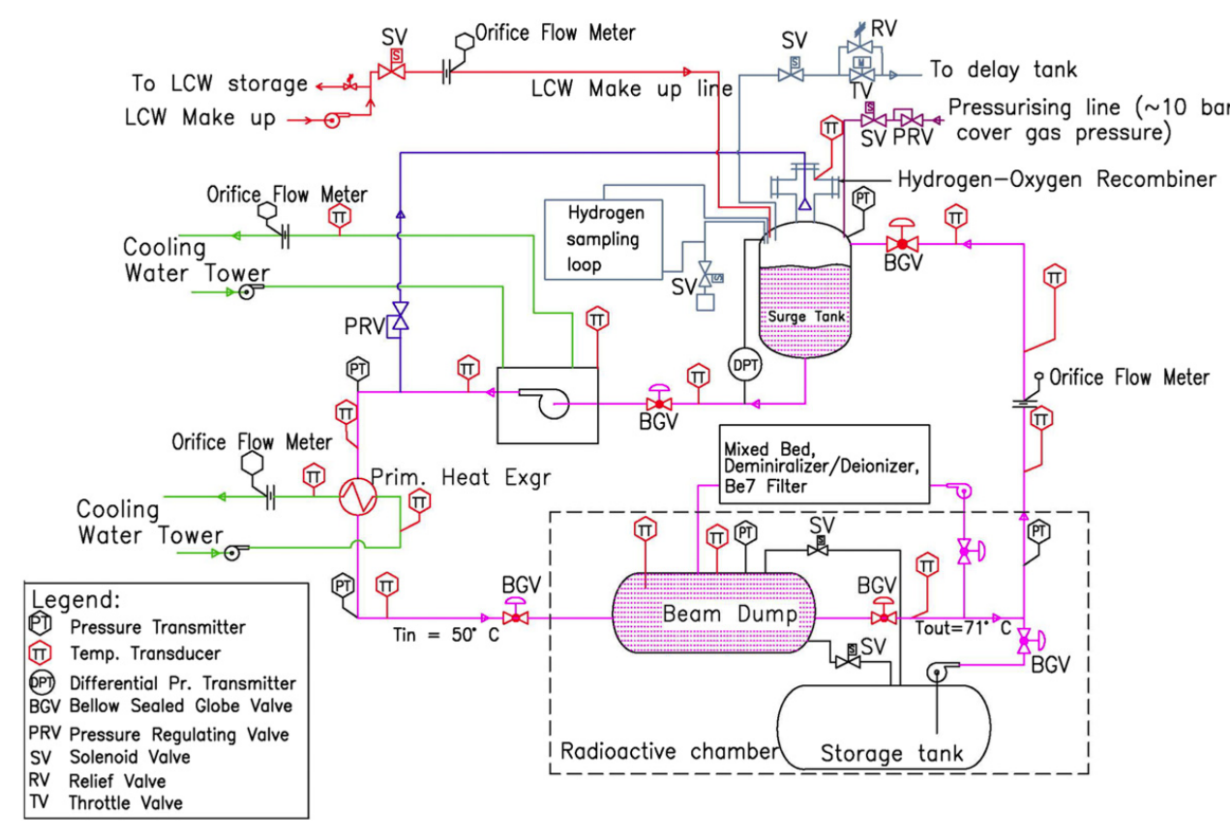
- Stainless steel pressure vessel
- 11 m length
- 10 bar pressure, plus 100% safety margin
- 155 °C water temperature



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

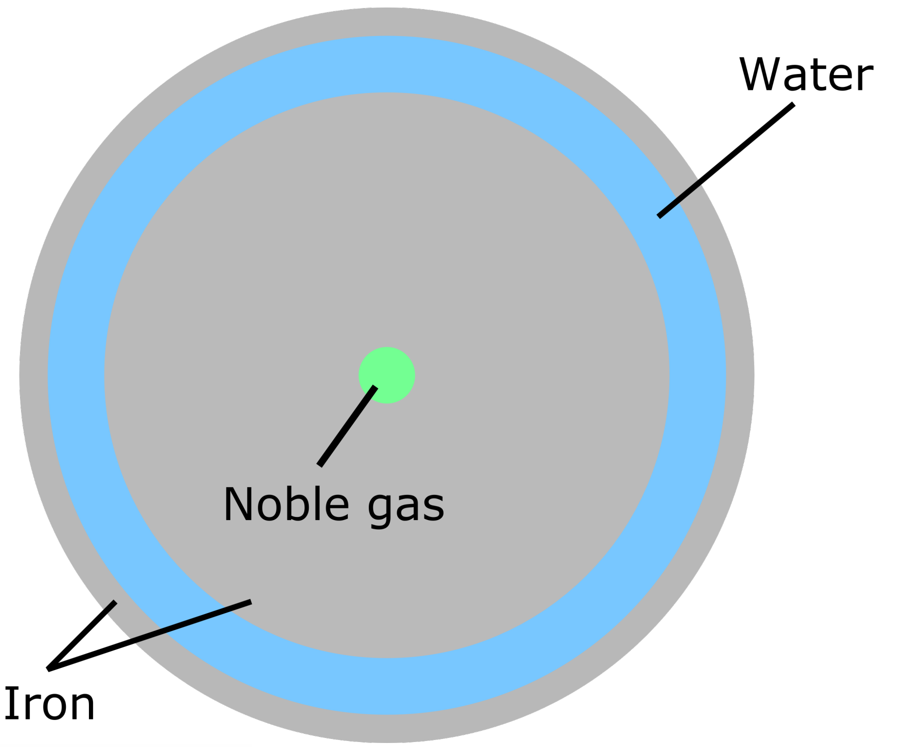
Challenges:

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

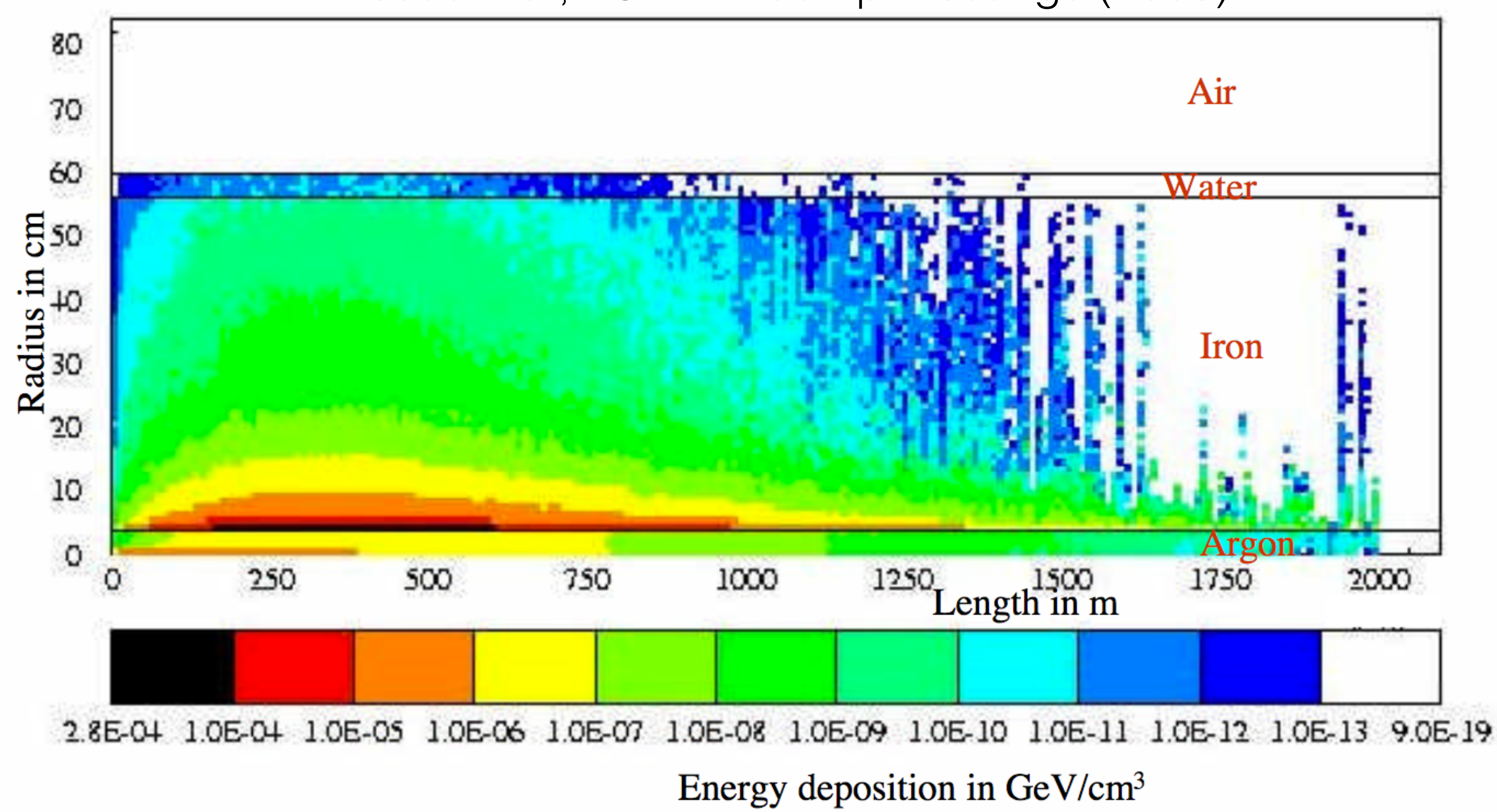


Noble gas beam dump - an alternative

- 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:

$$E_{\mathrm{wb}} = \frac{m_{\mathrm{e}} c \omega_{\mathrm{p}}}{e} = 9.6 \sqrt{\frac{n_e}{10^{22}}}\ \mathrm{GV\ m^{-1}}$$

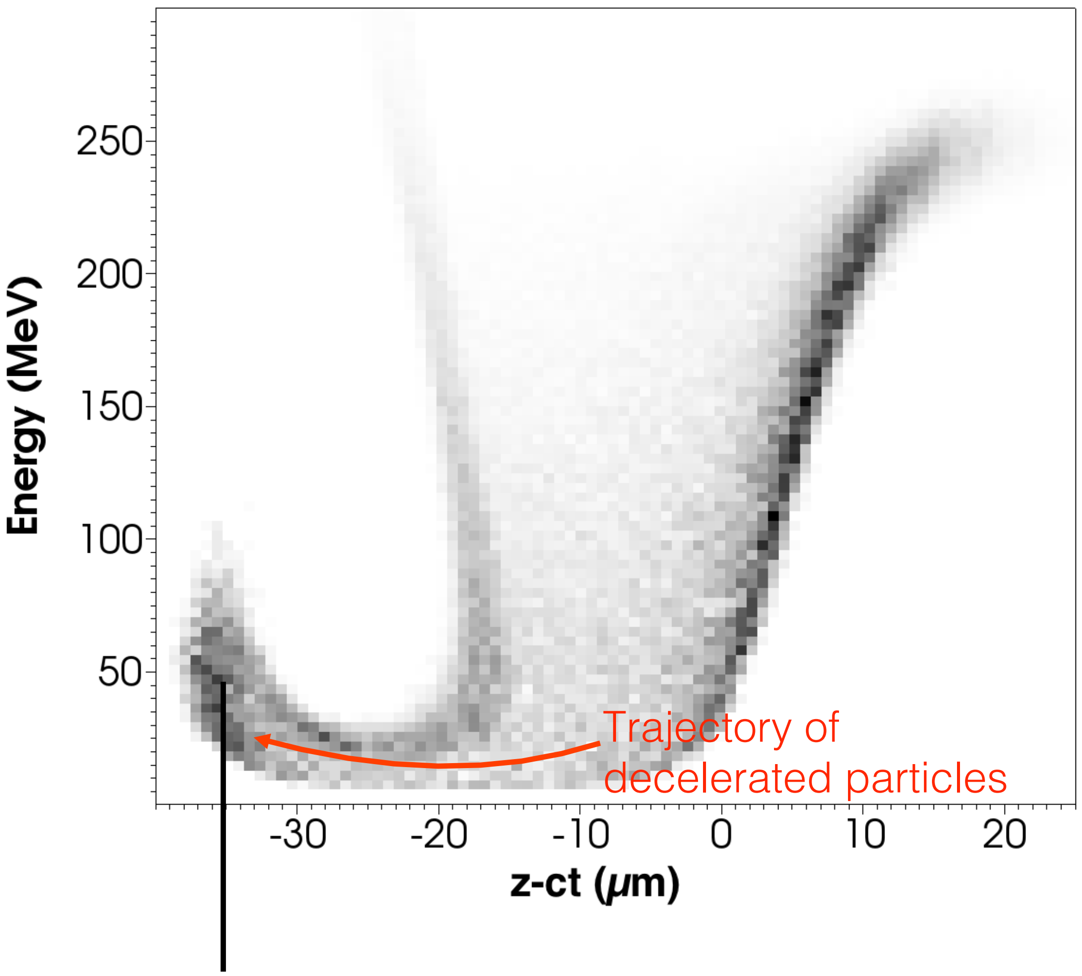
c.f. density of air at 1 atm ~10^{25} m^{-3}

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

- 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 ~ 10^{29} m^{-3}.
- Plasma beam dump can also be applied to positrons/muons with high decelerating gradient.

Plasma beam dump

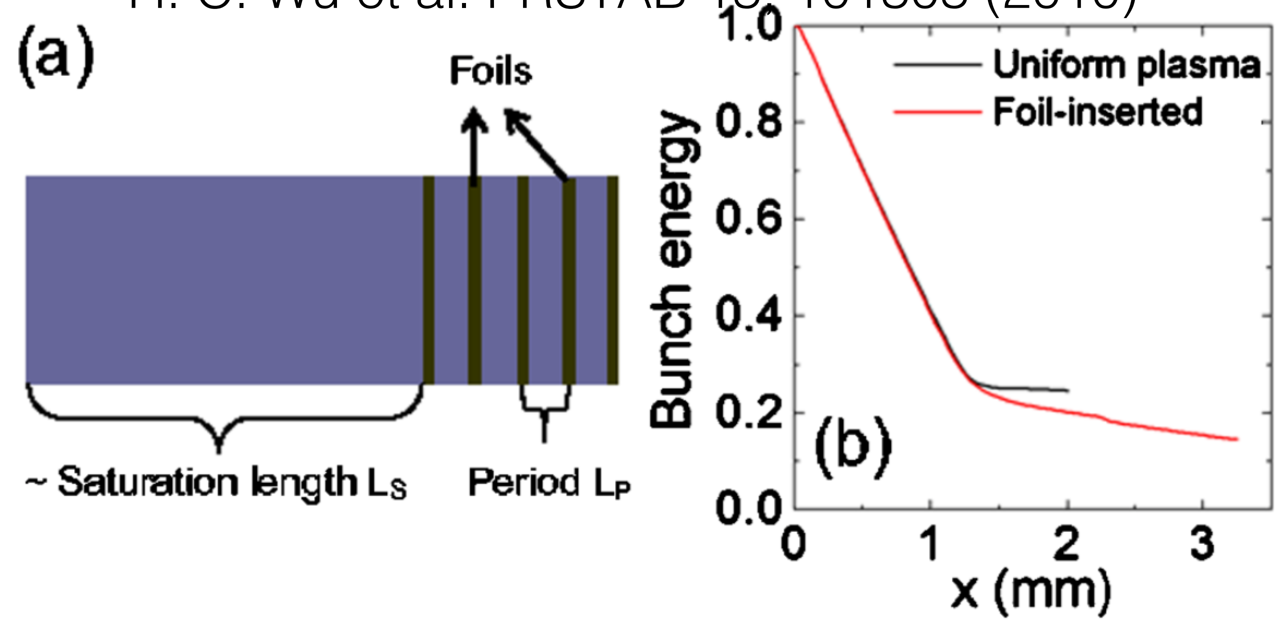
Longitudinal phase space of plasma decelerated bunch



Re-accelerated portion of bunch

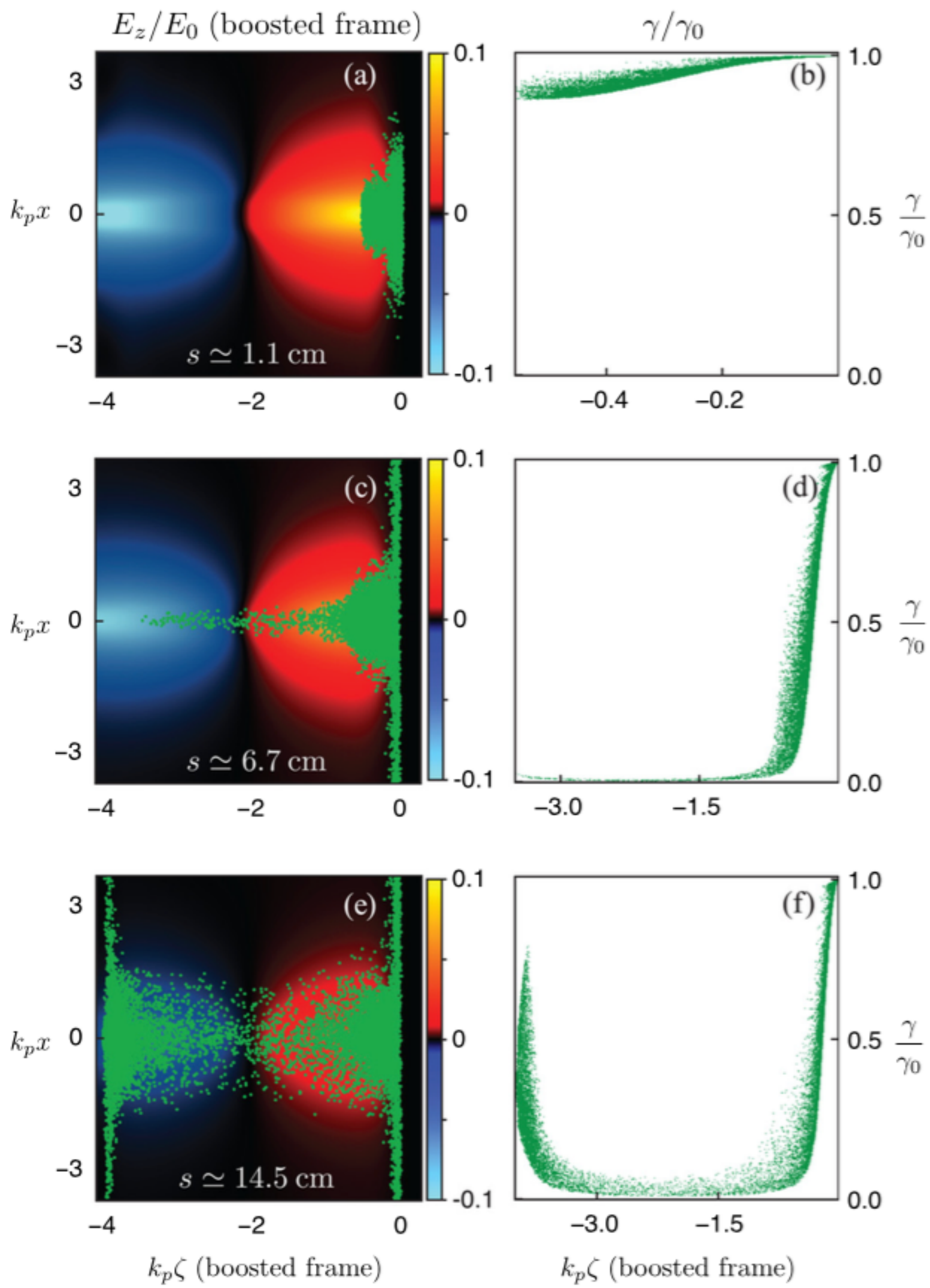
Wu et al. proposed using foils to absorb low-energy particles.

H. C. Wu et al. PRSTAB 13, 101303 (2010)

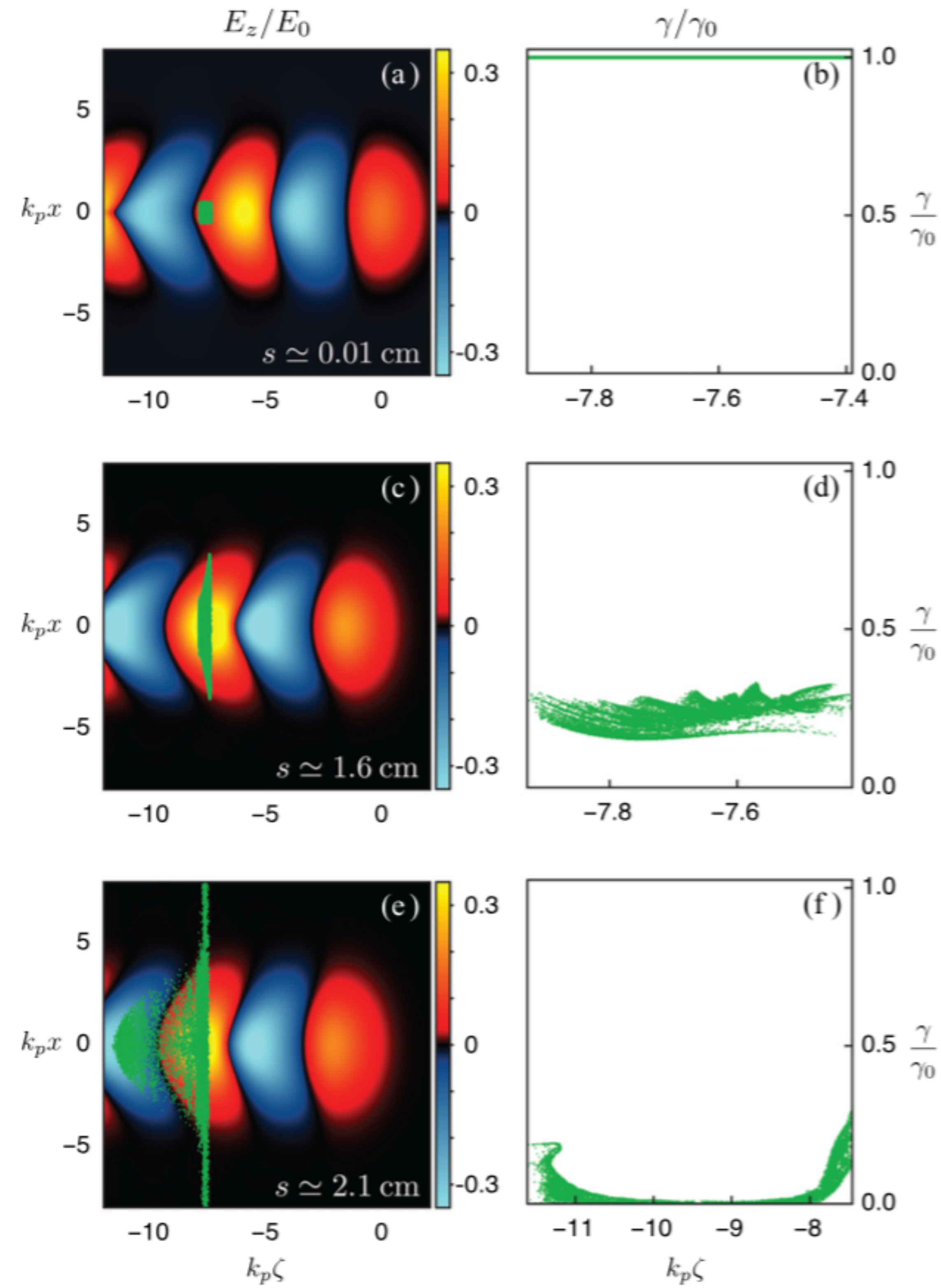


Active beam dump

Passive beam dump

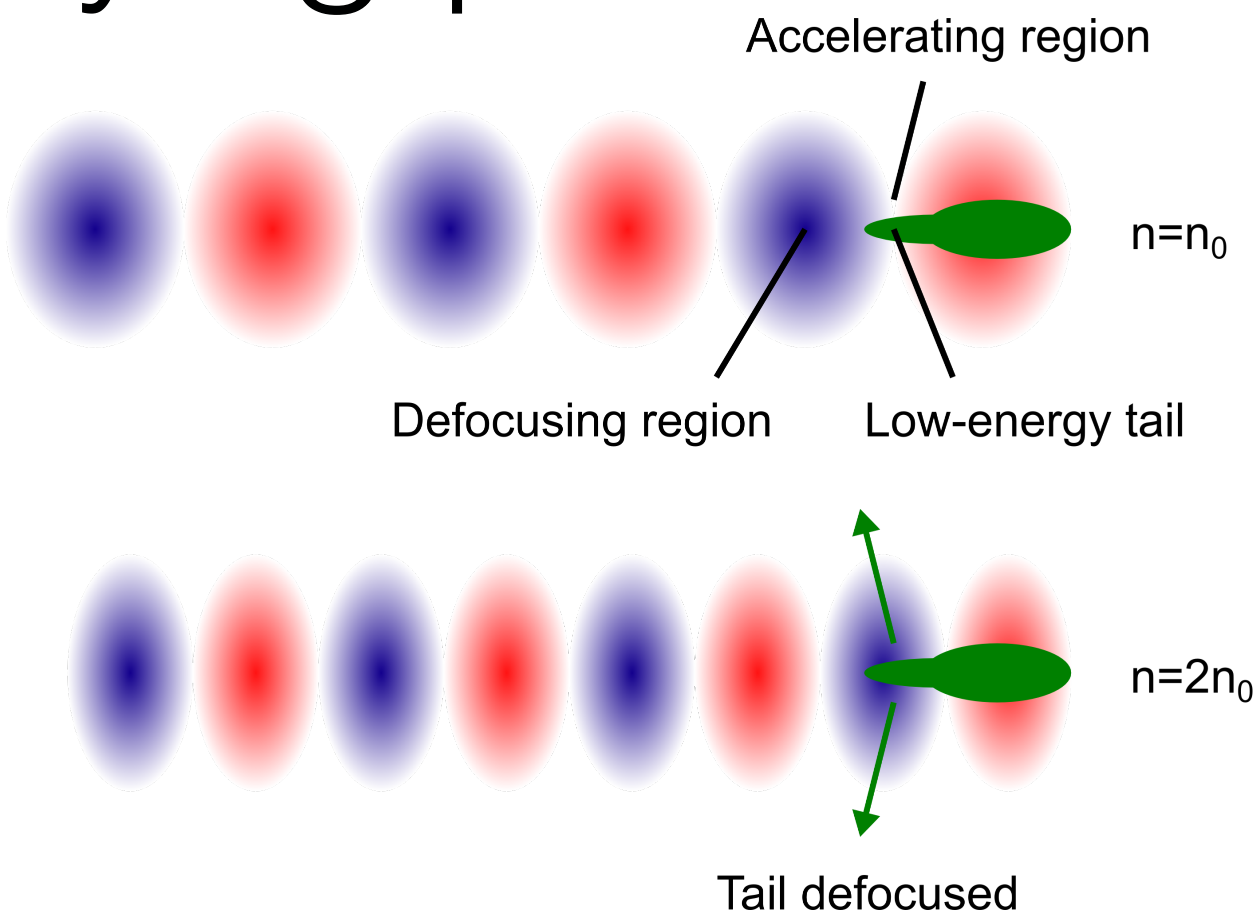


Active beam dump

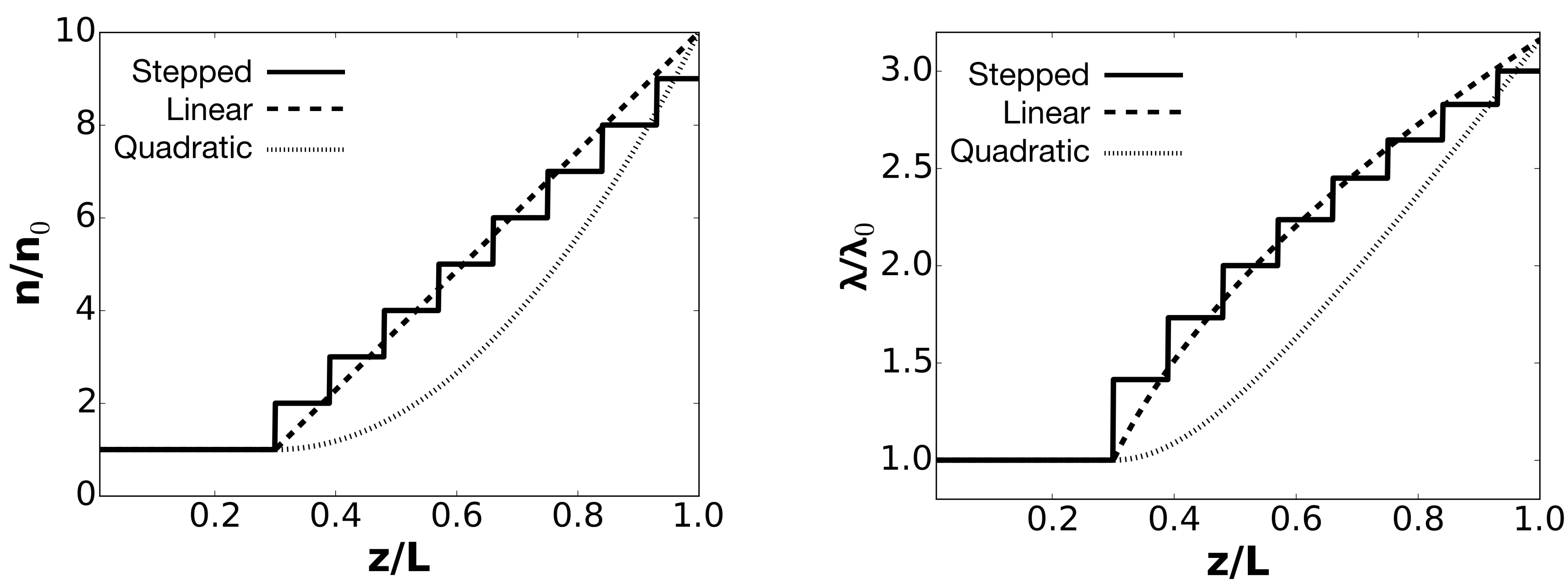


A. Bonatto et al. Phys. Plasmas 22, 083106 (2015)

Varying plasma density

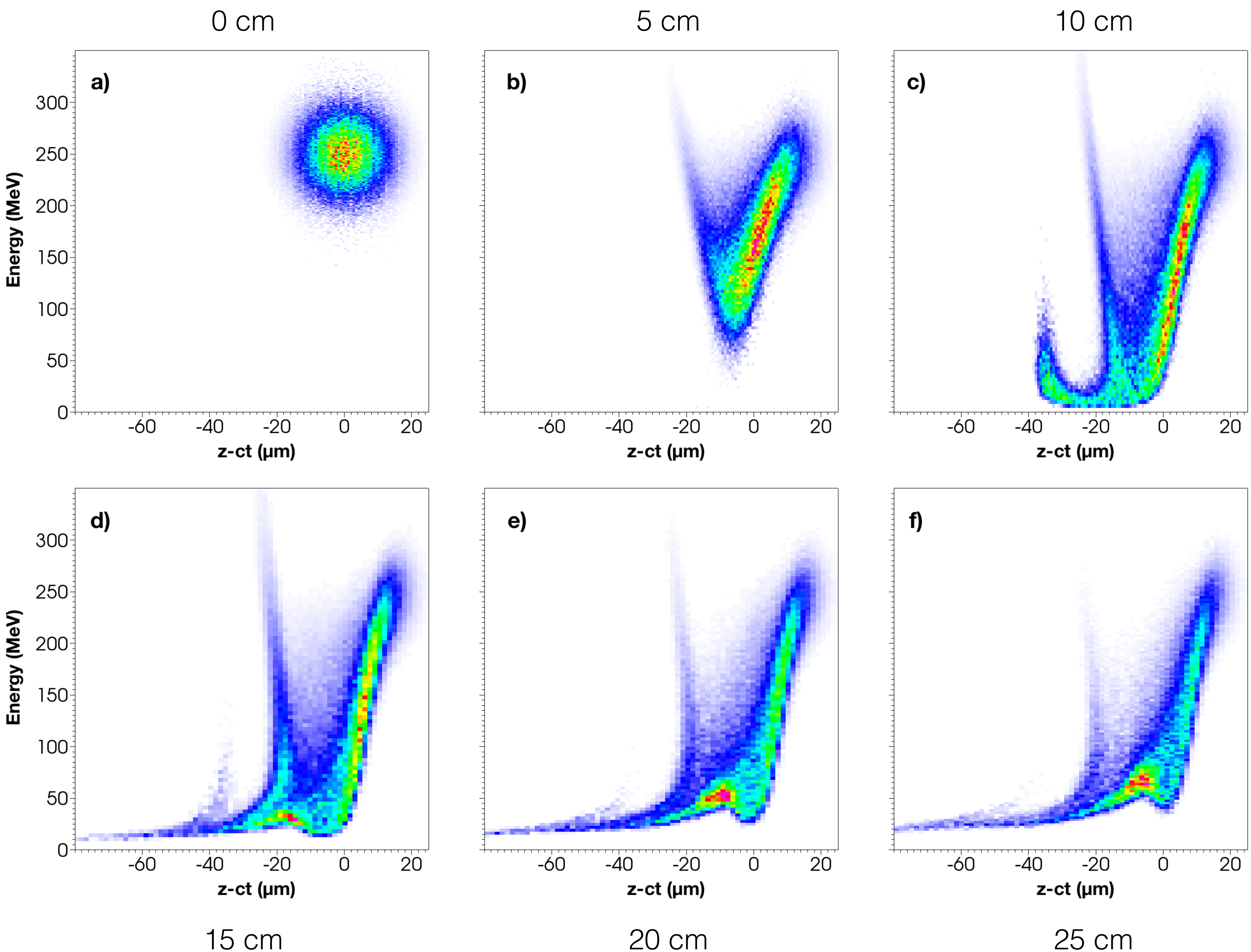


Plasma density increase puts low energy tail of the bunch into defocusing region



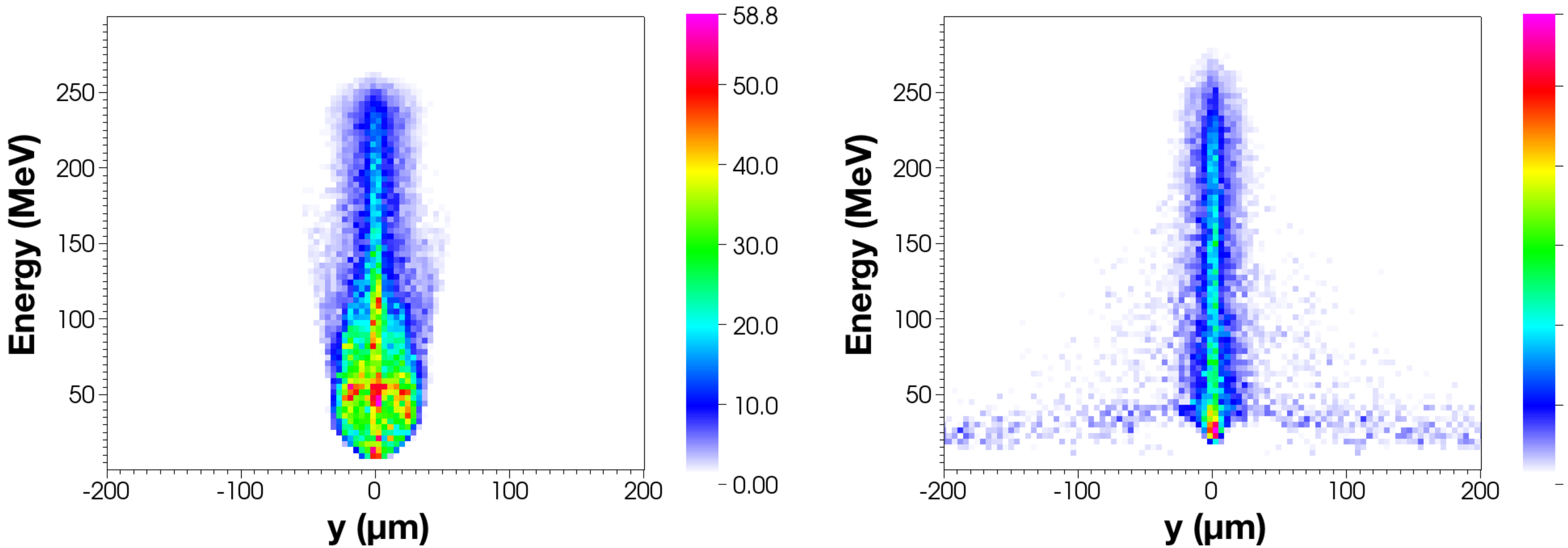
K. Hanahoe, et al., Phys. Plasmas 24, 023120 (2017)

Varying plasma density



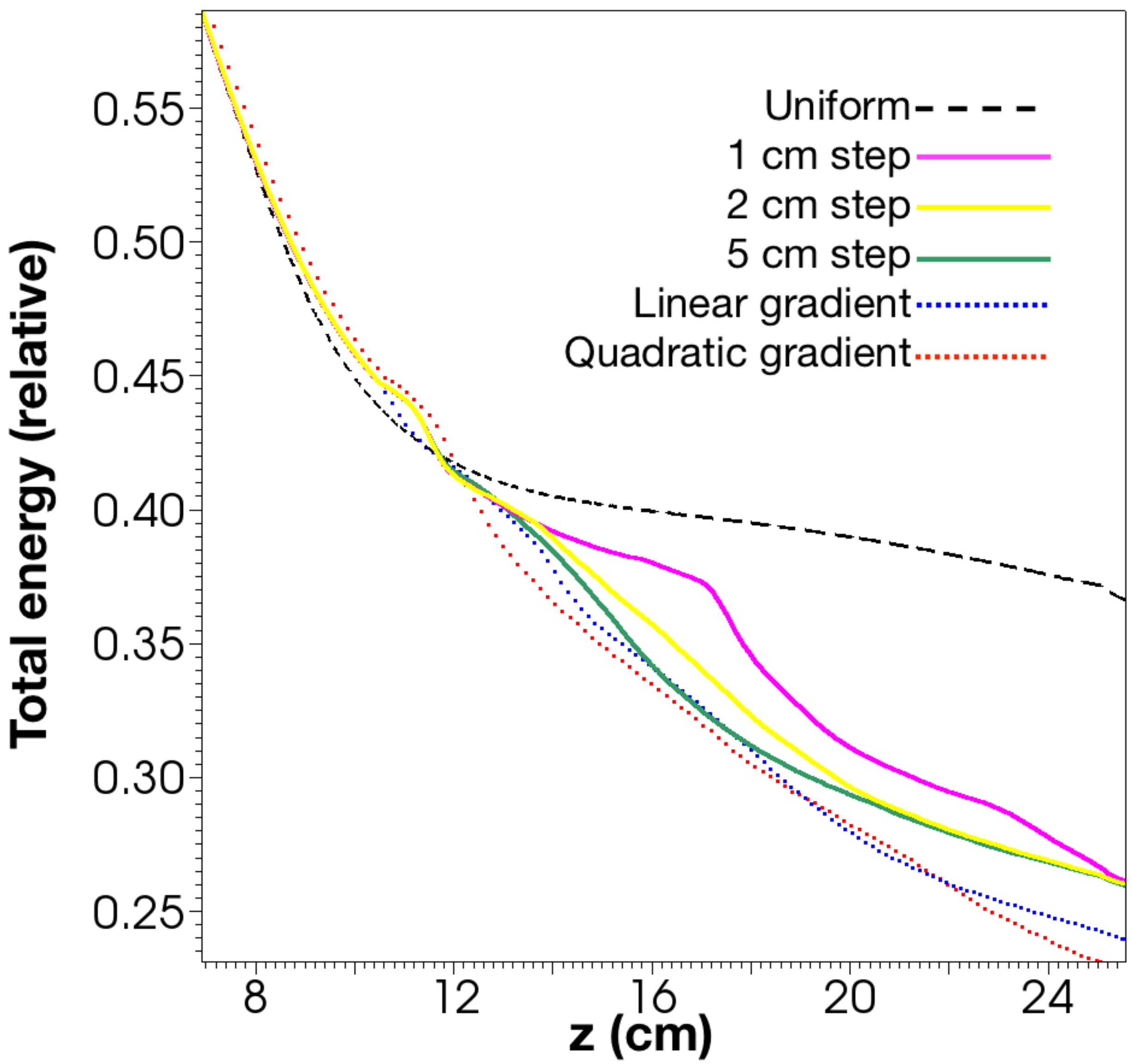
Varying plasma density

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

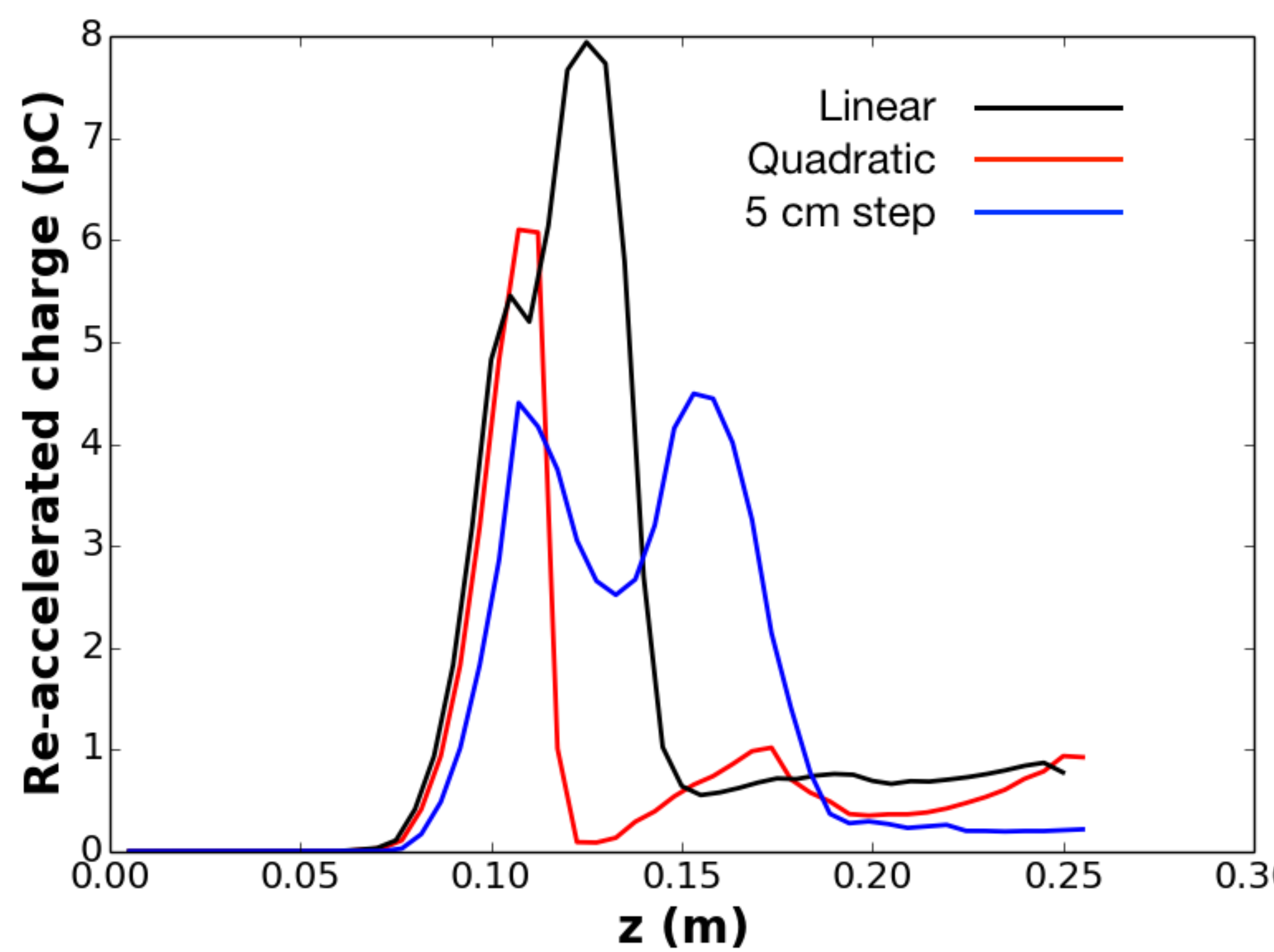


K. Hanahoe, et al., Phys. Plasmas 24, 023120 (2017)

Varying plasma density

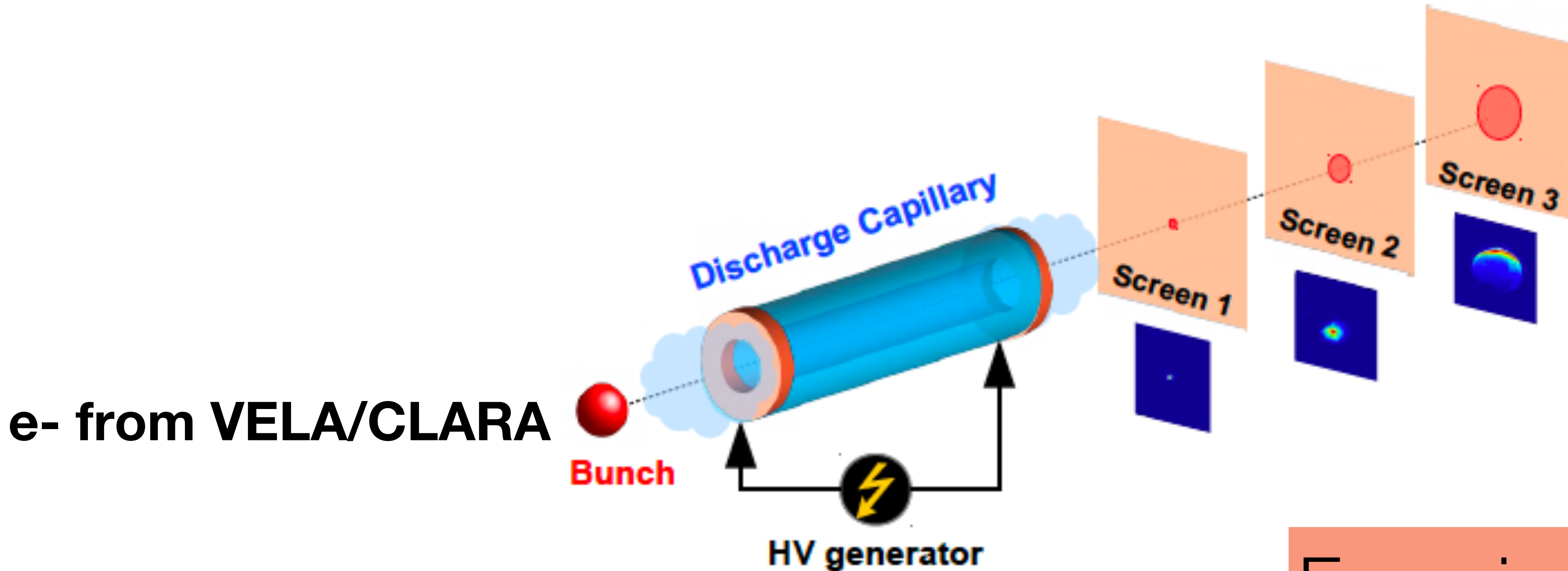


Total bunch energy loss for different plasma density schemes

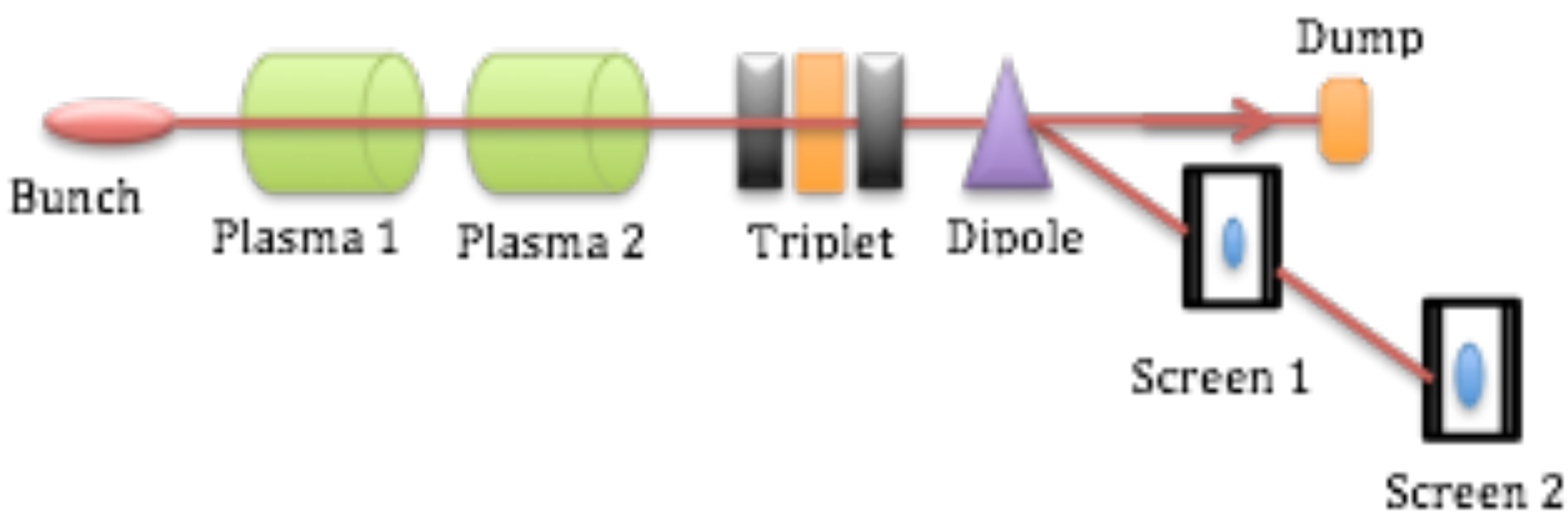


Quantity of charge in a region 30 μm behind bunch head with energy > 30 MeV

Experiment tests at VELA/CLARA

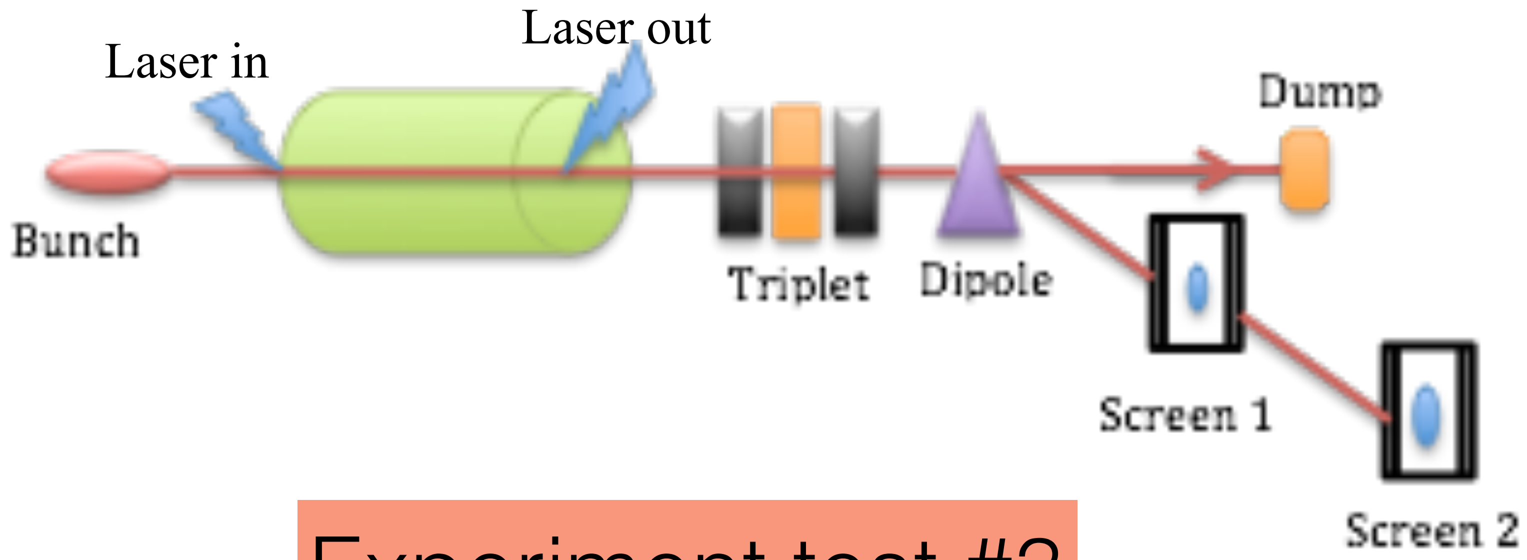


Experiment test #1



Experiment test #2

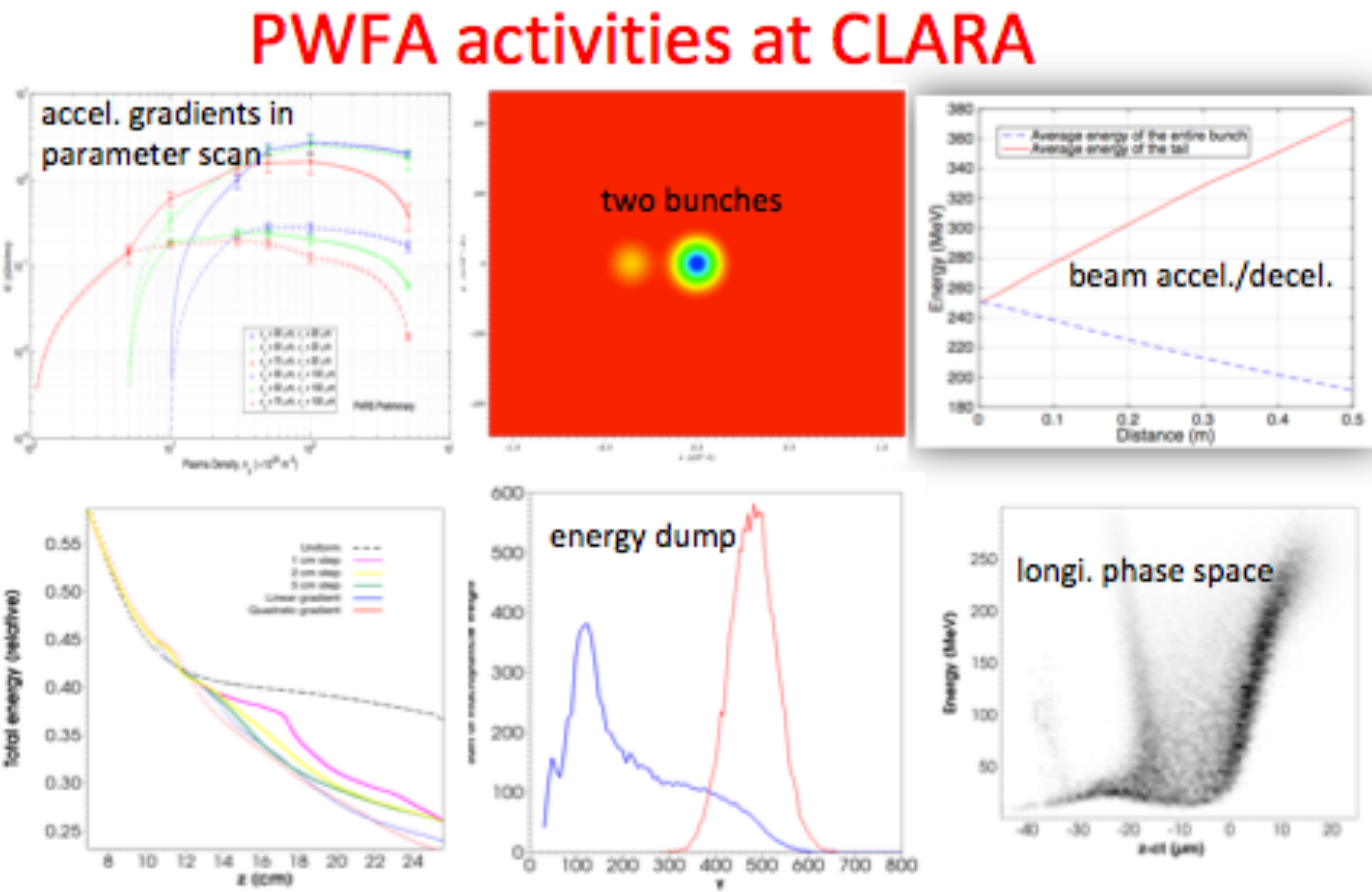
Experiment tests at VELA/CLARA



Experiment test #3

- 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



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?

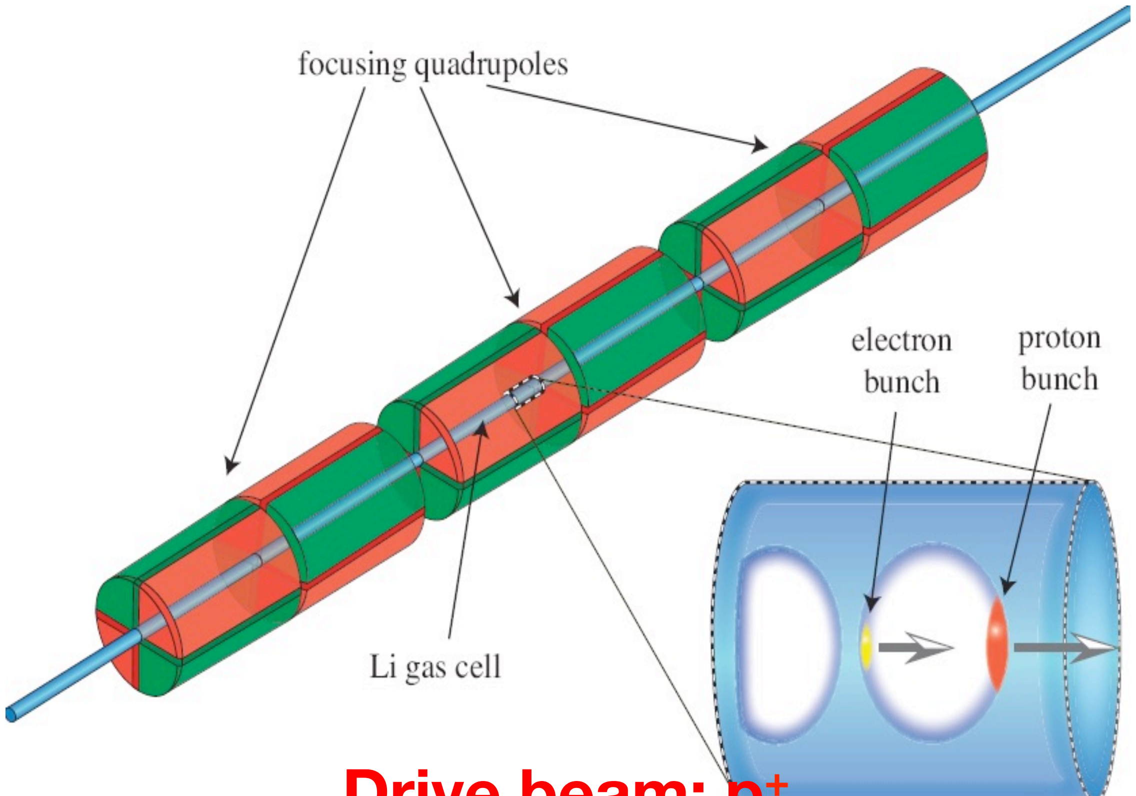
- Large energy stored in proton machines like Tevatron, HERA, SPS and LHC
- The SPS/LHC beams carry significant energy for driving plasma waves

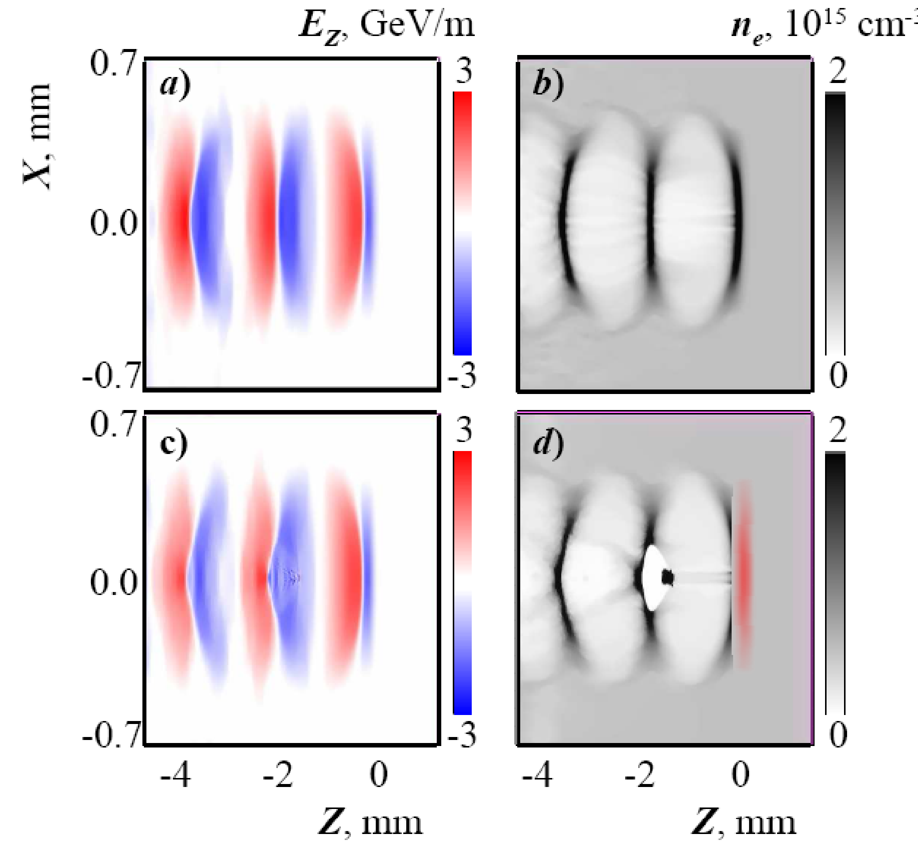
  - SPS (450 GeV, 1.3e11 p/bunch) ~ 10 kJ
  - LHC (7 TeV, 1.15e11 p/bunch) ~ 140 kJ

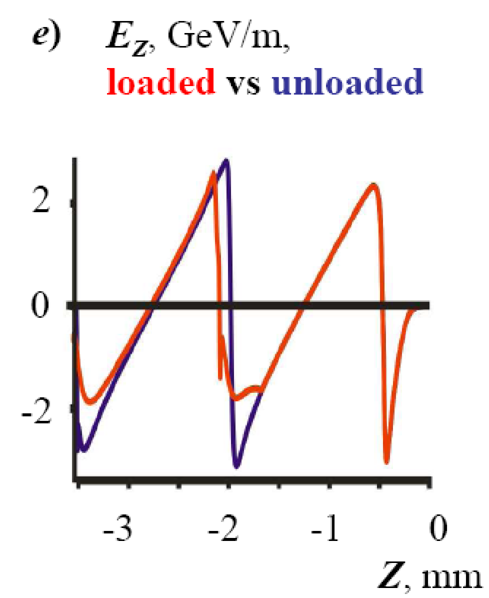
  - SLAC (50 GeV, 2e10 e/bunch) ~ 0.16 kJ
  - ILC (250 GeV, 2e10 e/bunch) ~ 0.8kJ

One stage proton wakefied acceleration can generate energy frontier electron beam

Proton-driven PWFA







Drive beam: p^+

E=1 TeV, $N_p=10^{11}$

σ_r=0.43 mm, σ_θ=0.03 mrad,

σ_z=100 μm, $\Delta E/E$=10 %

Witness beam: e^-

E_0=10 GeV, $N_e=1.5\times10^{10}$

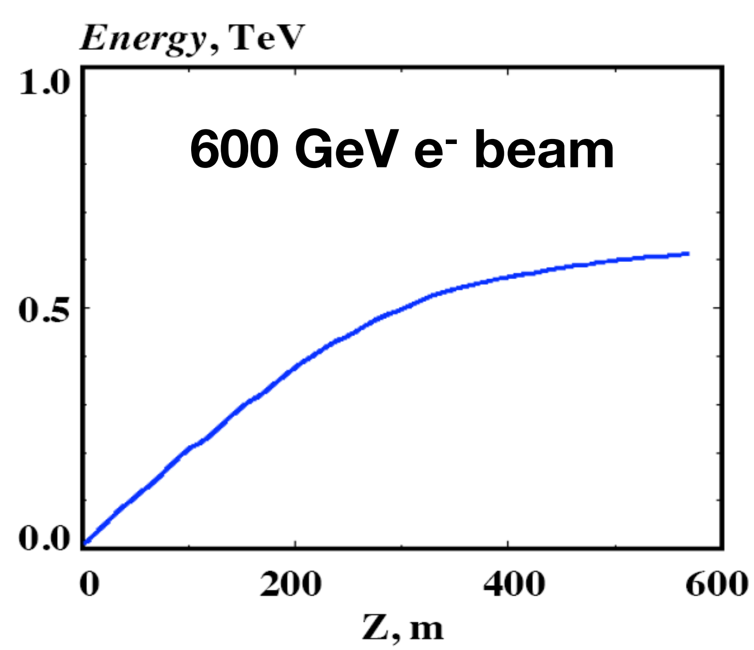
Plasma: Li^+

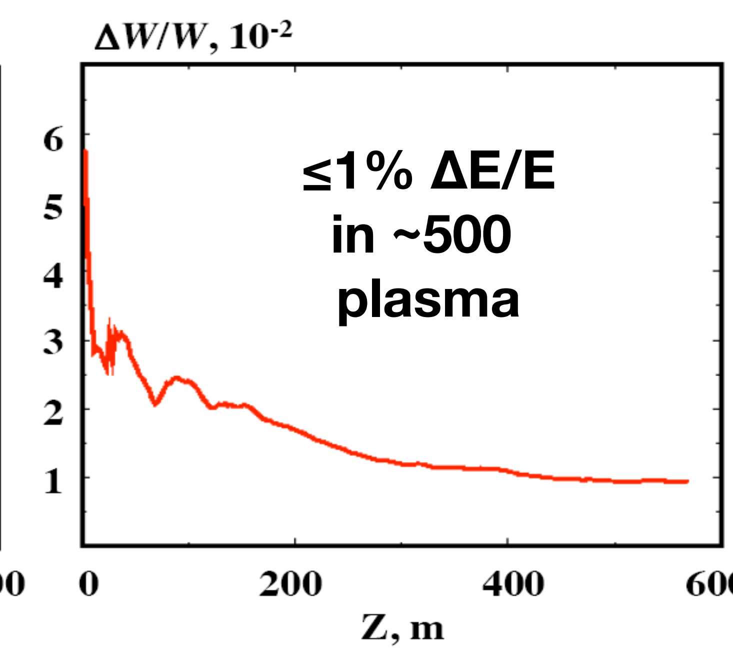
$n_p=6\times10^{14}$cm^{-3}

External magnetic field:

Field gradient: 1000 T/m

Magnet length: 0.7 m

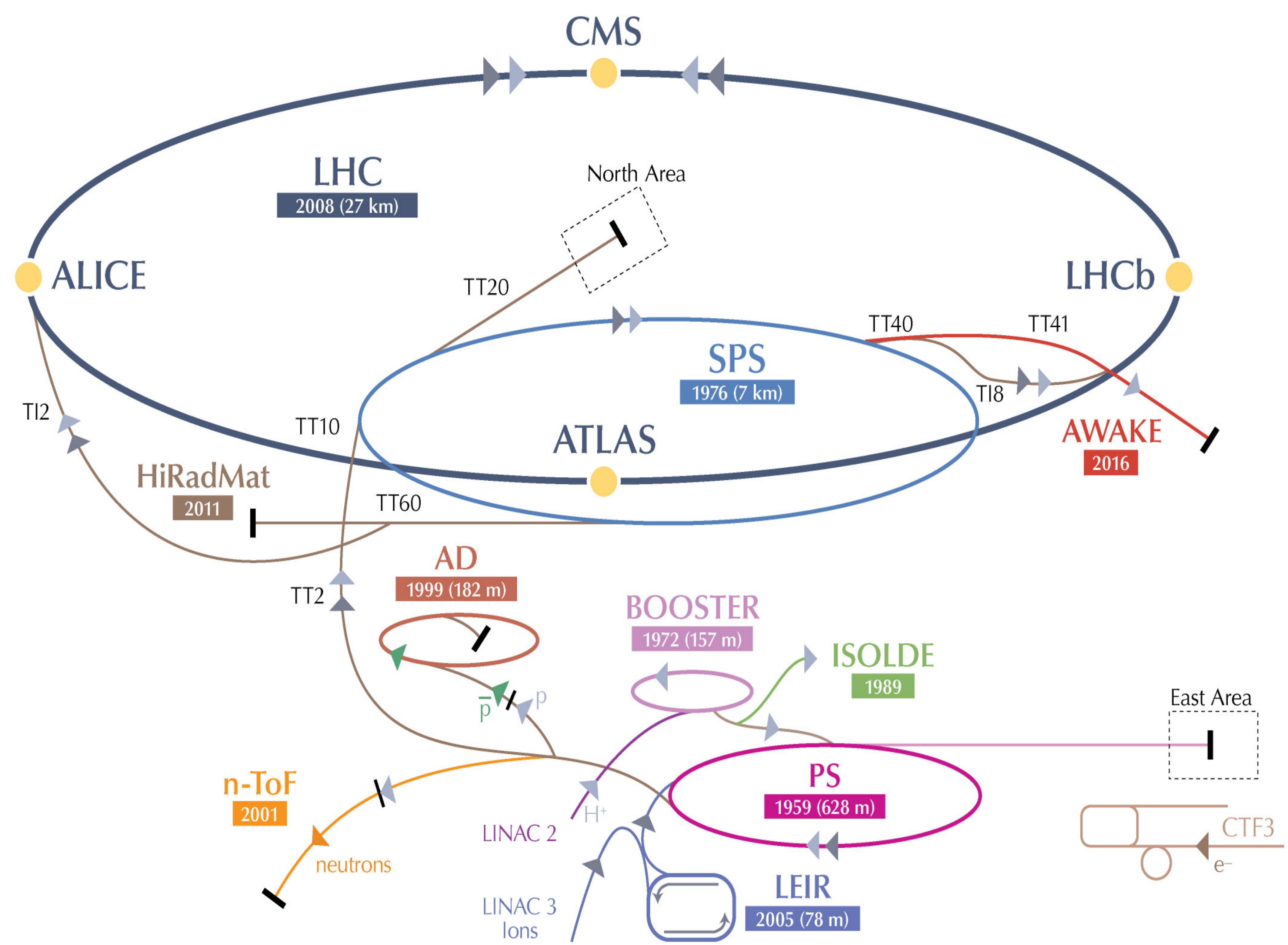




Caldwell et al., Nature Physics 2009

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

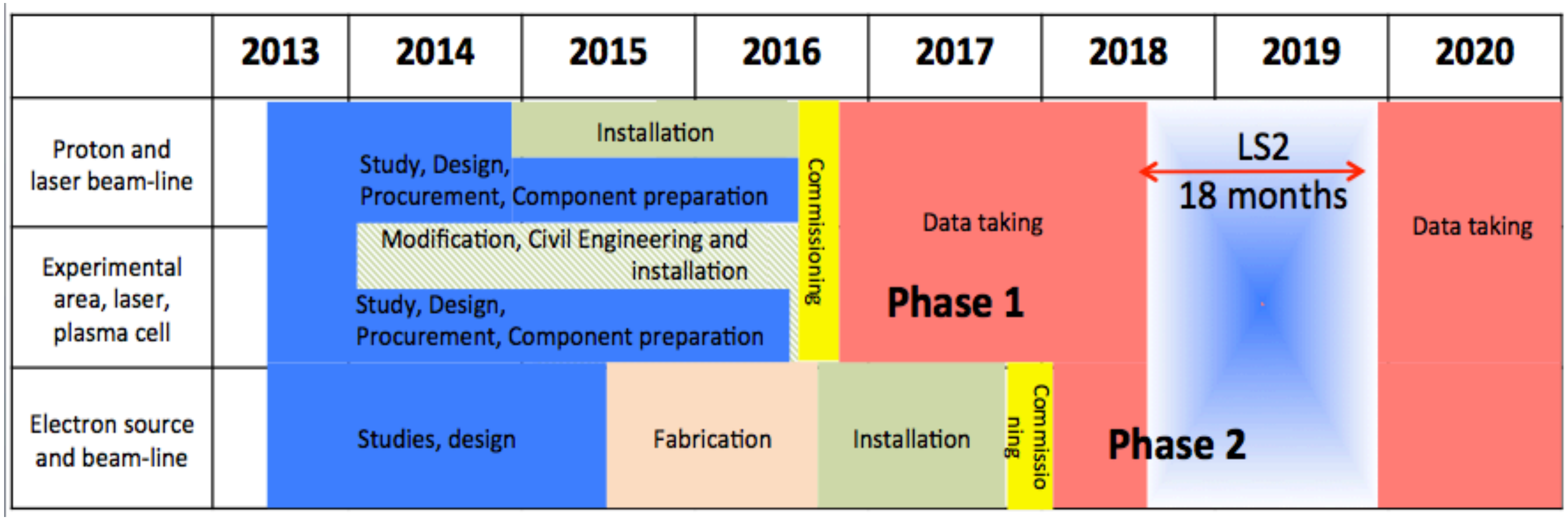
  First proton beam to the AWAKE experiment, beam–plasma commissioning.

  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	**4.86×10^{16} p**
Initial experimental program	**3 – 4 years**

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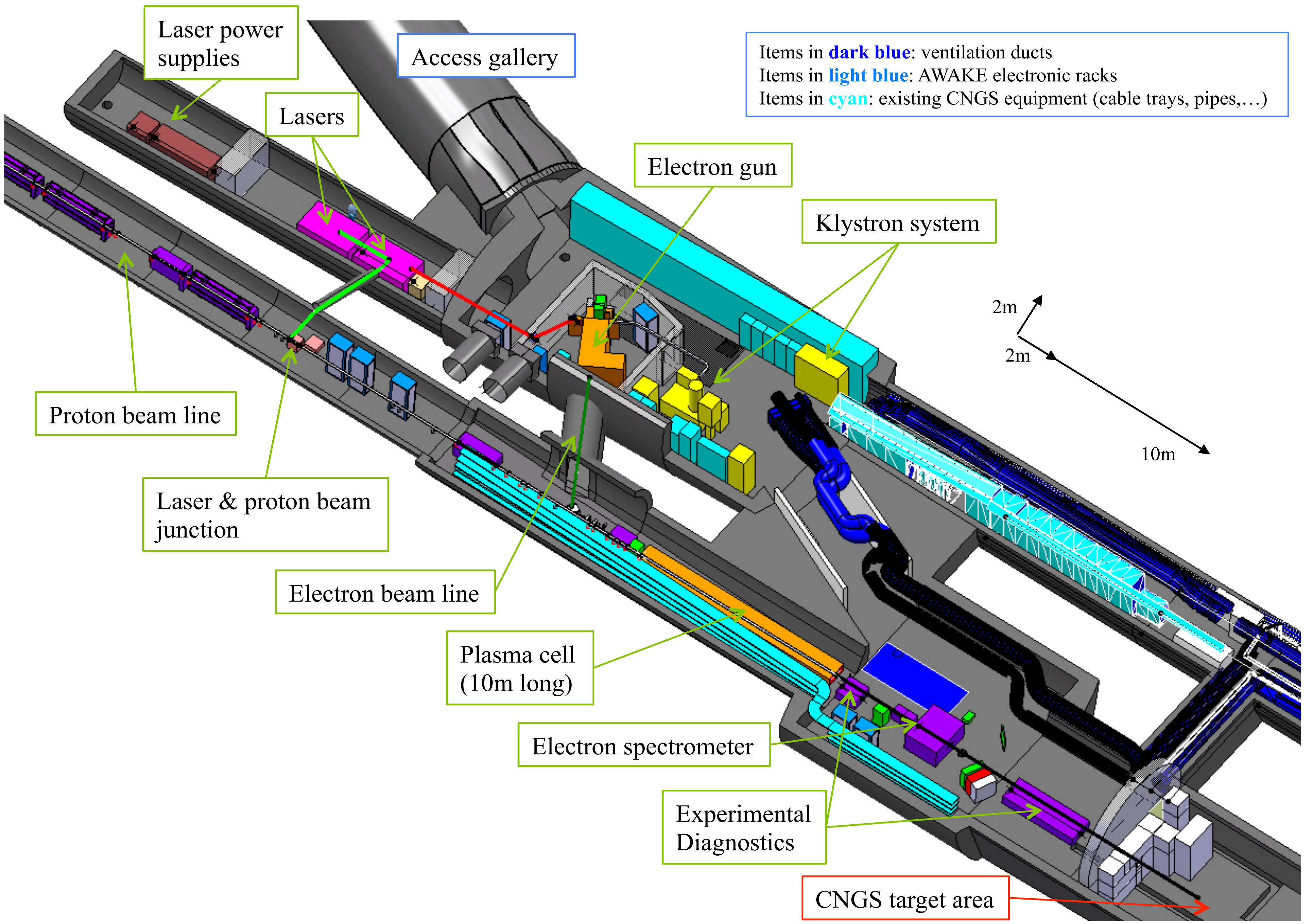
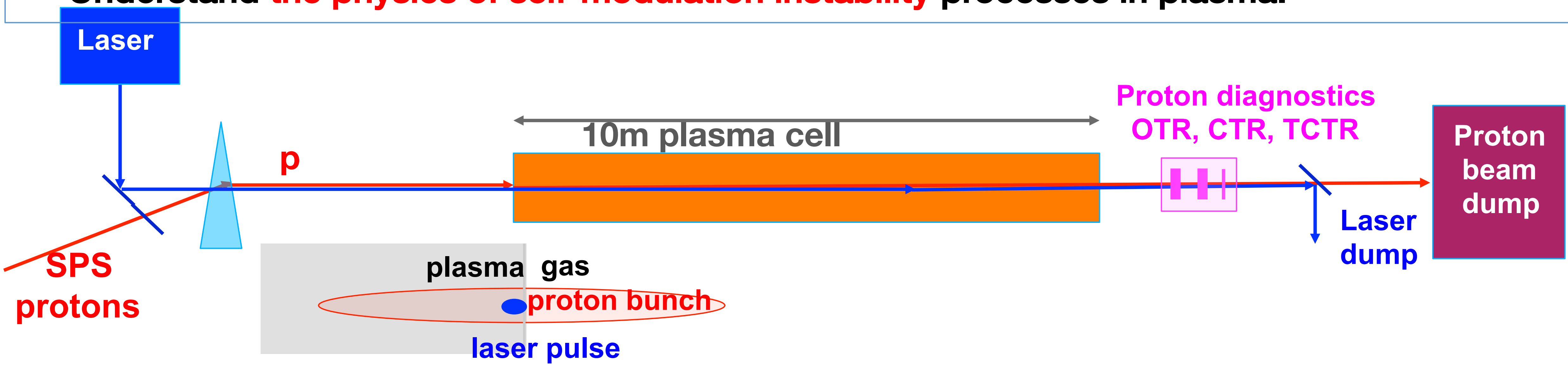
AWAKE experiment layout

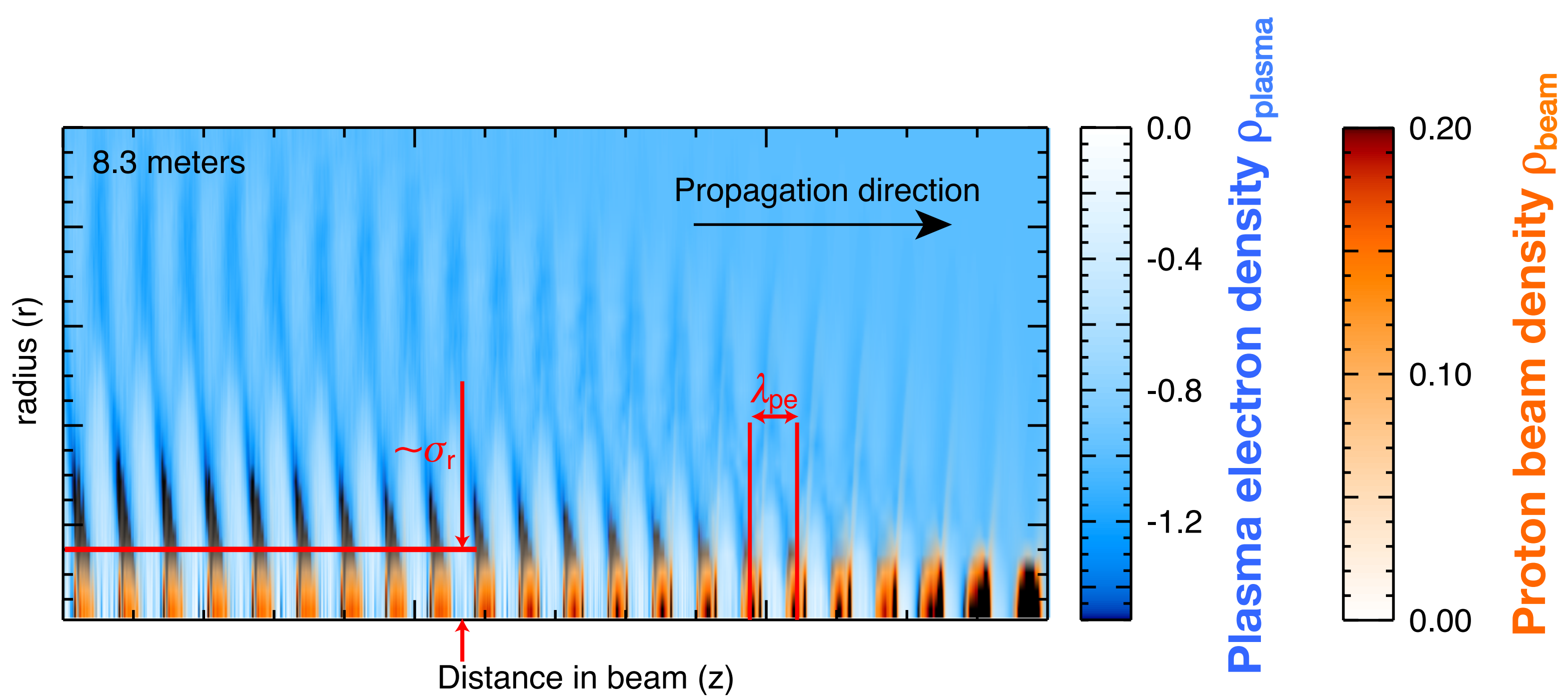


AWAKE Run I, Phase I

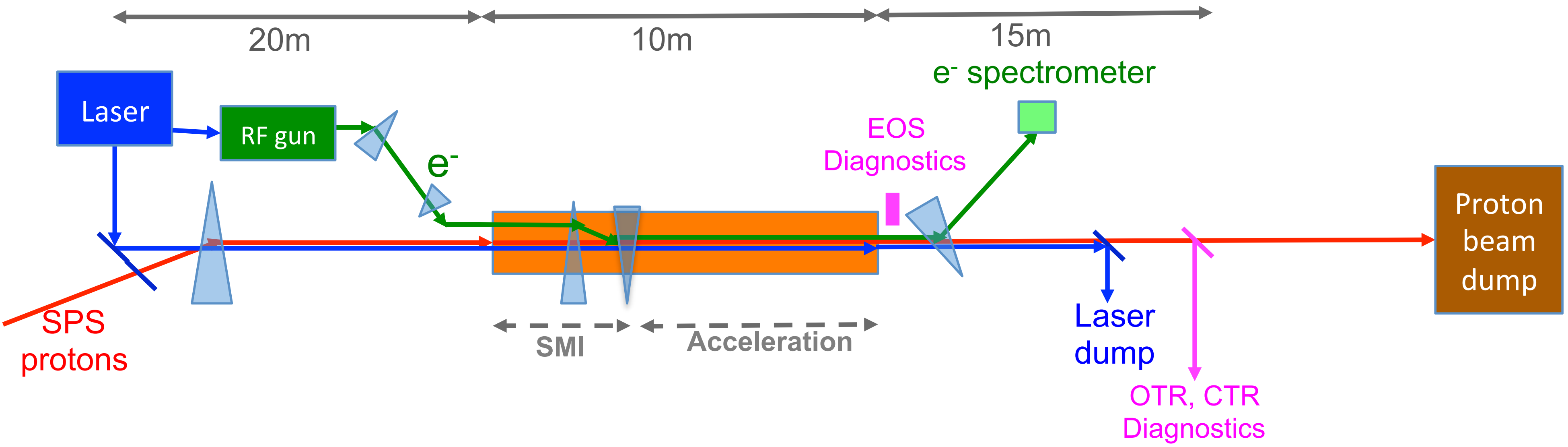
- Perform benchmark experiments using proton bunches to drive wakefields for the first time ever.
- Understand the physics of self-modulation instability processes in plasma.

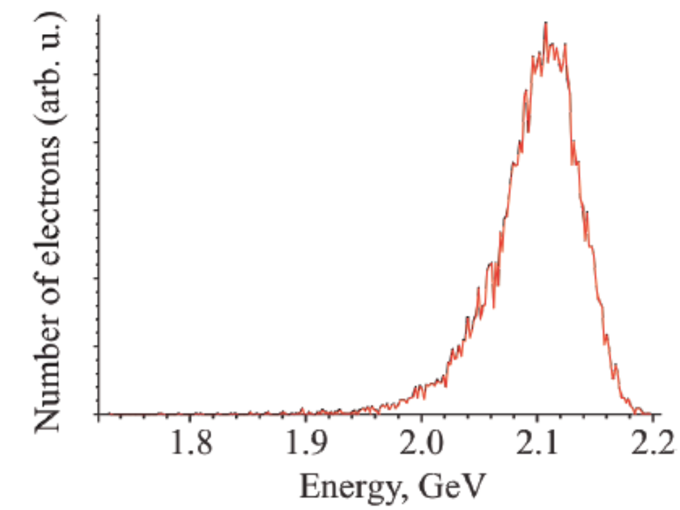


Self-modulated proton bunch resonantly driving plasma wakefields.



AWAKE Run I, Phase II





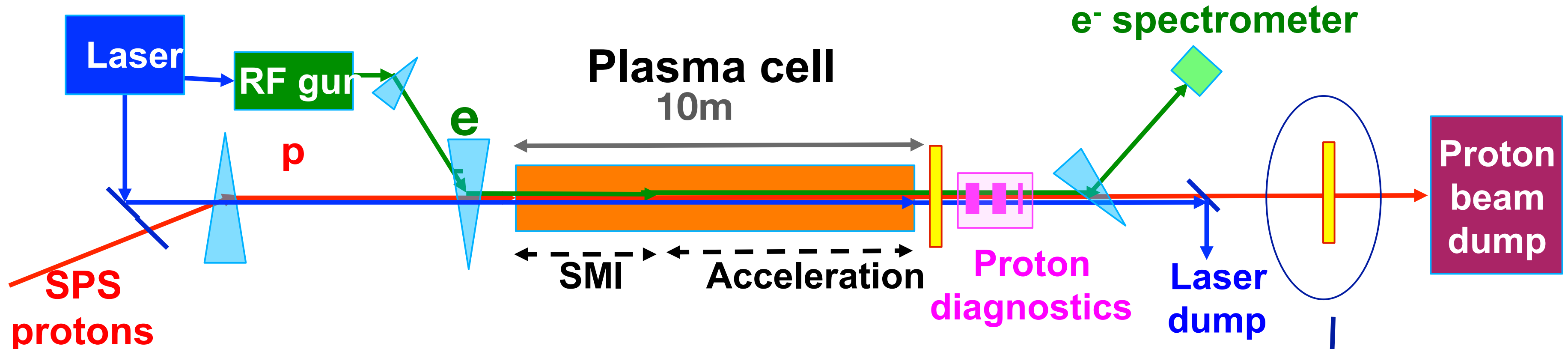
- **Inject 10-20 MeV electron beam**
- **Acceleration of electrons to multi-GeV energy range after the plasma exit.**

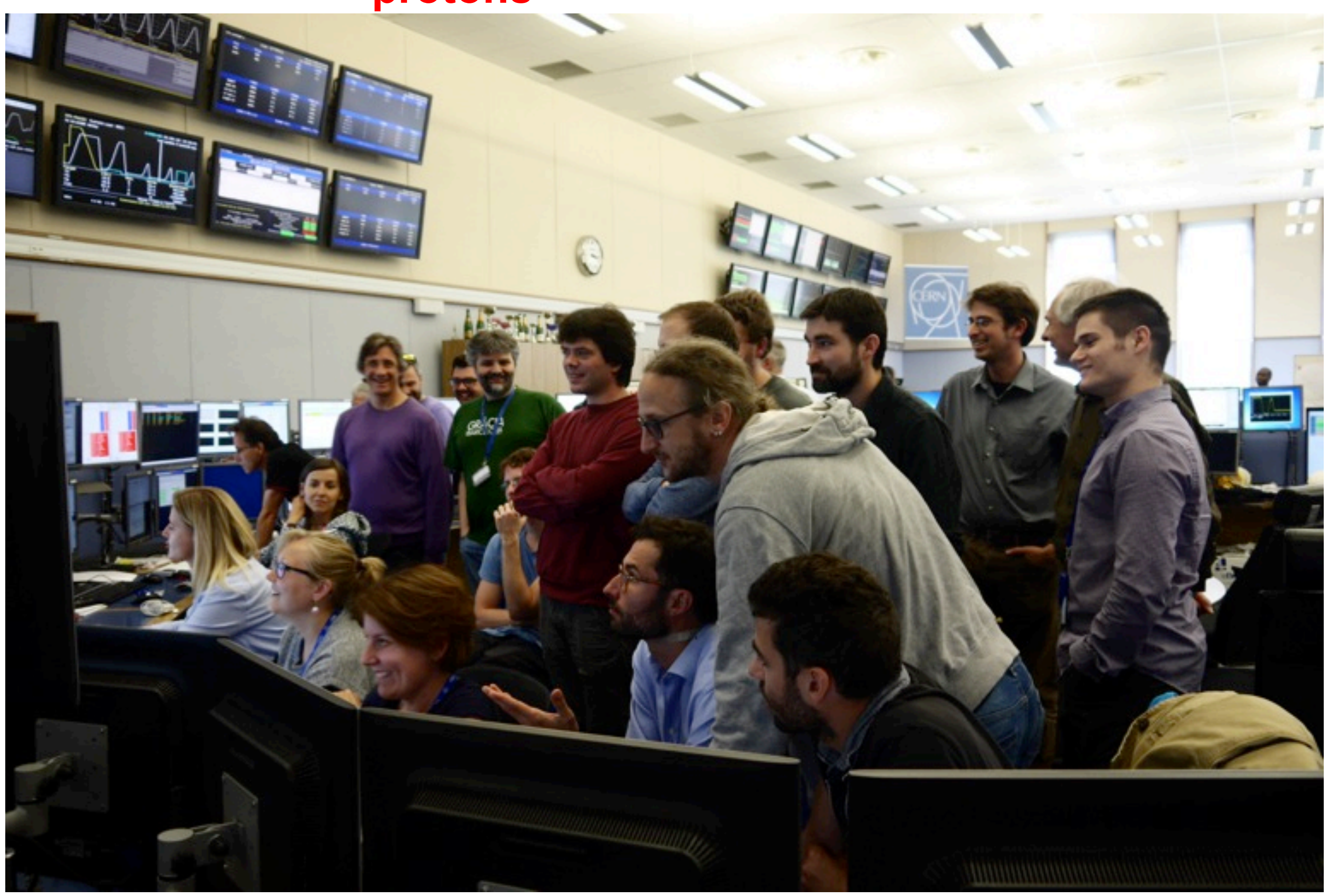
Scientific goals

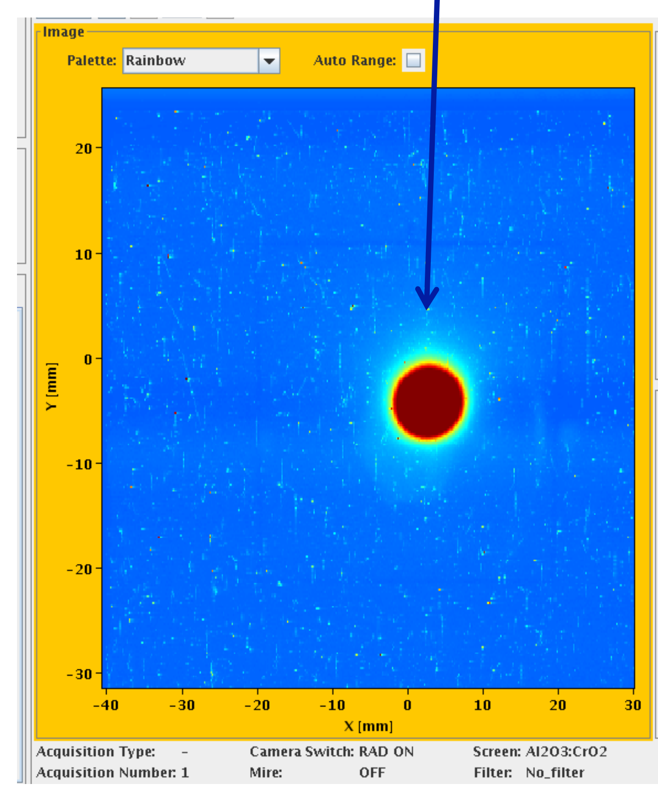
1. **Demonstrate self-modulation effect of a long proton bunch and realize 1 GeV electron energy gain with a ~10 m plasma**
2. **Develop and test the diagnostic equipments for the first and later experiments**
3. **Benchmark data against simulation results**
4. **Provide inputs for future experiment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

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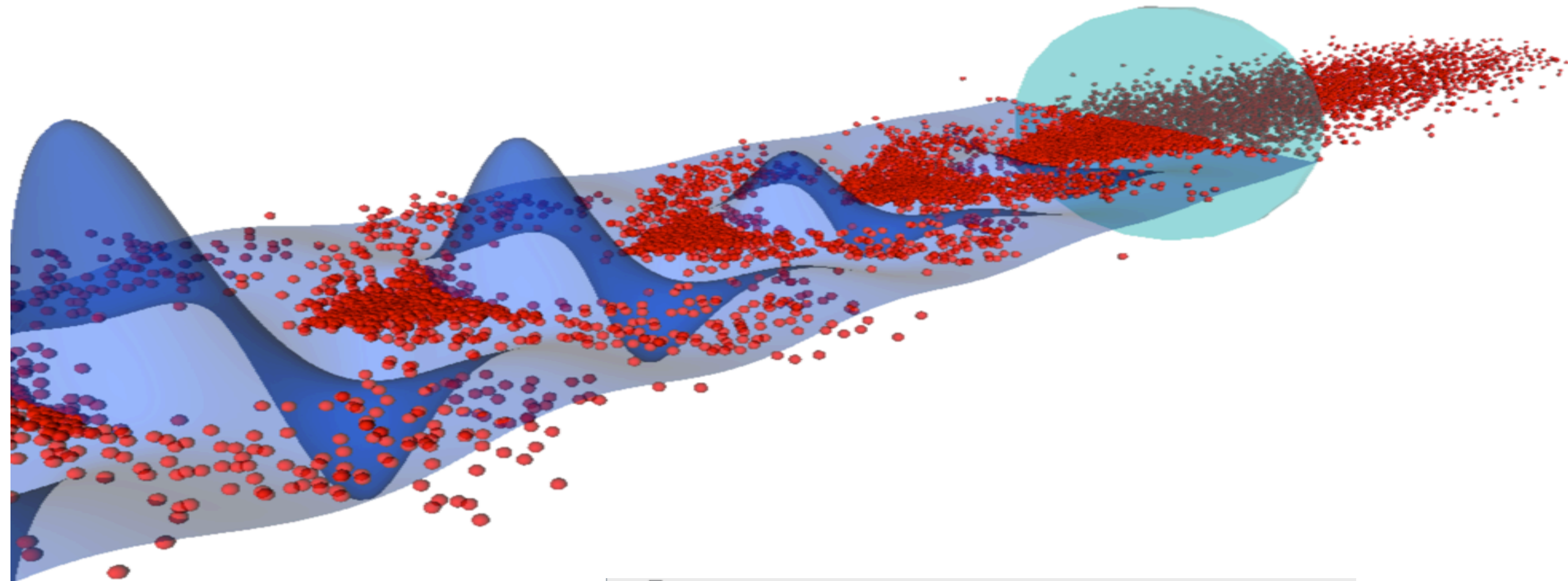
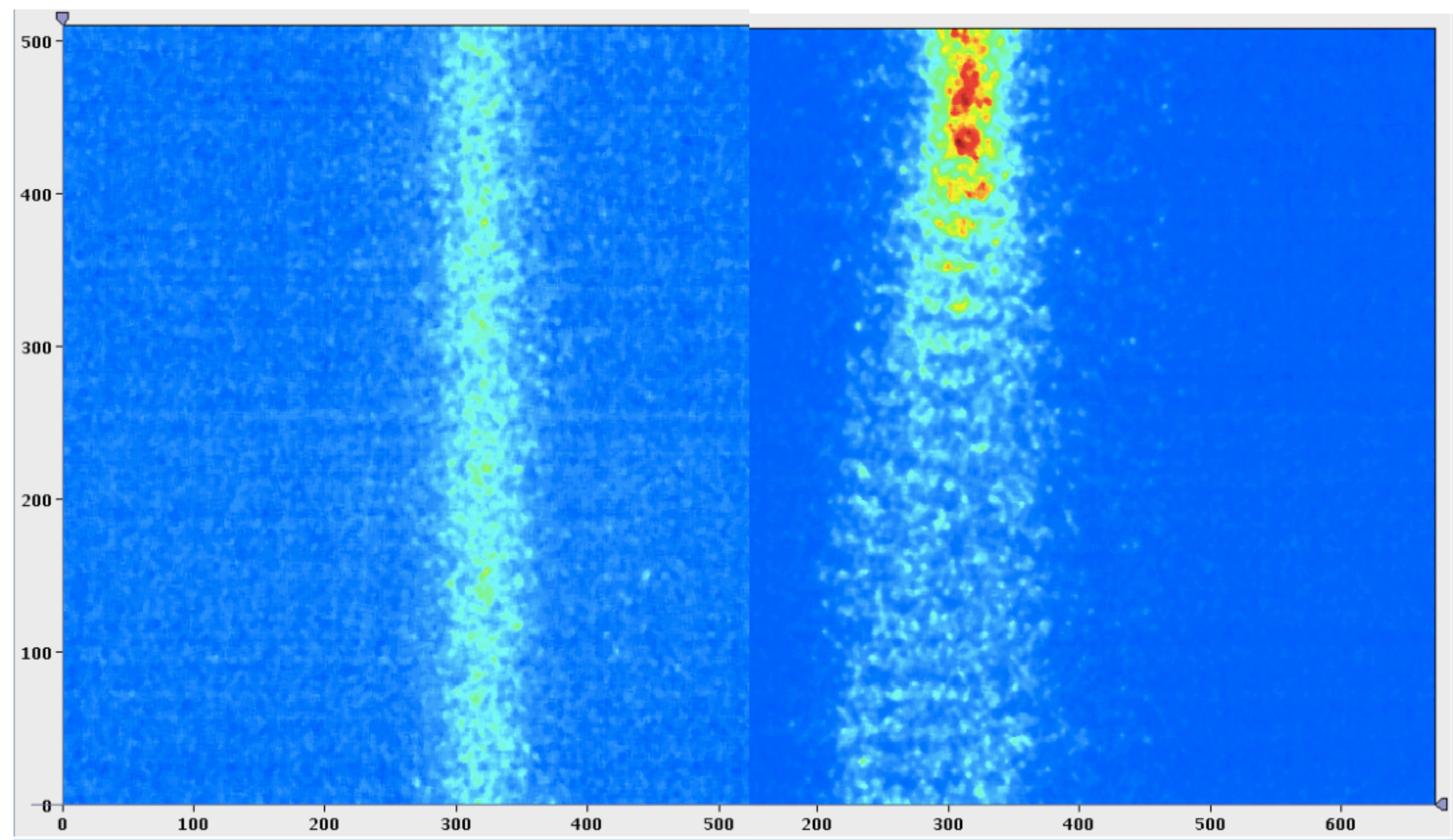
First milestone-self modulation (Dec. 2016)





Plasma off **Plasma on**

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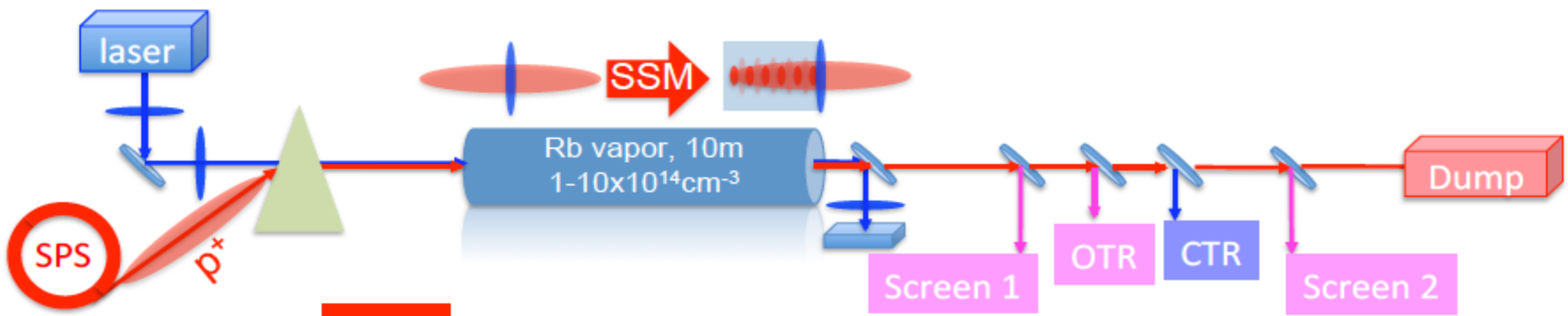
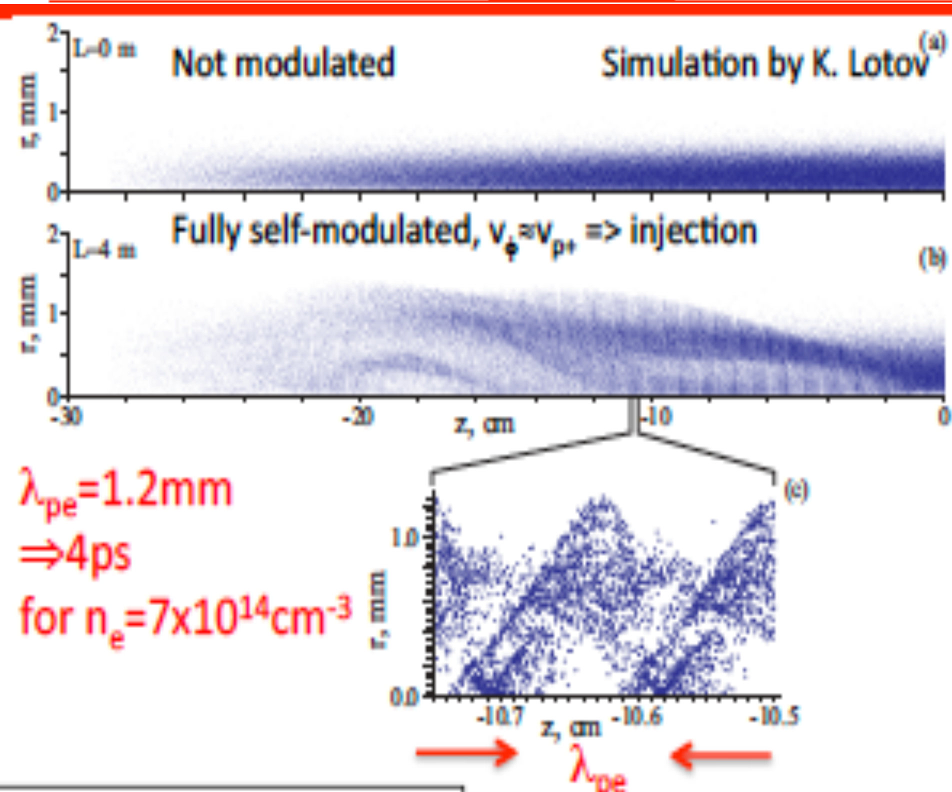
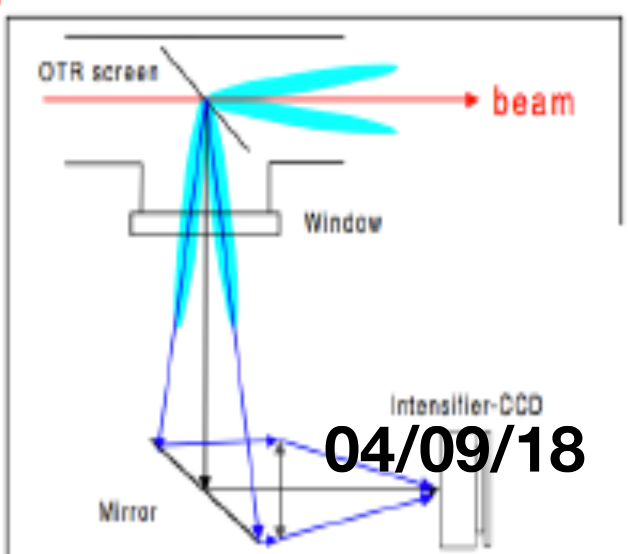
Seeded self modulation (SSM)



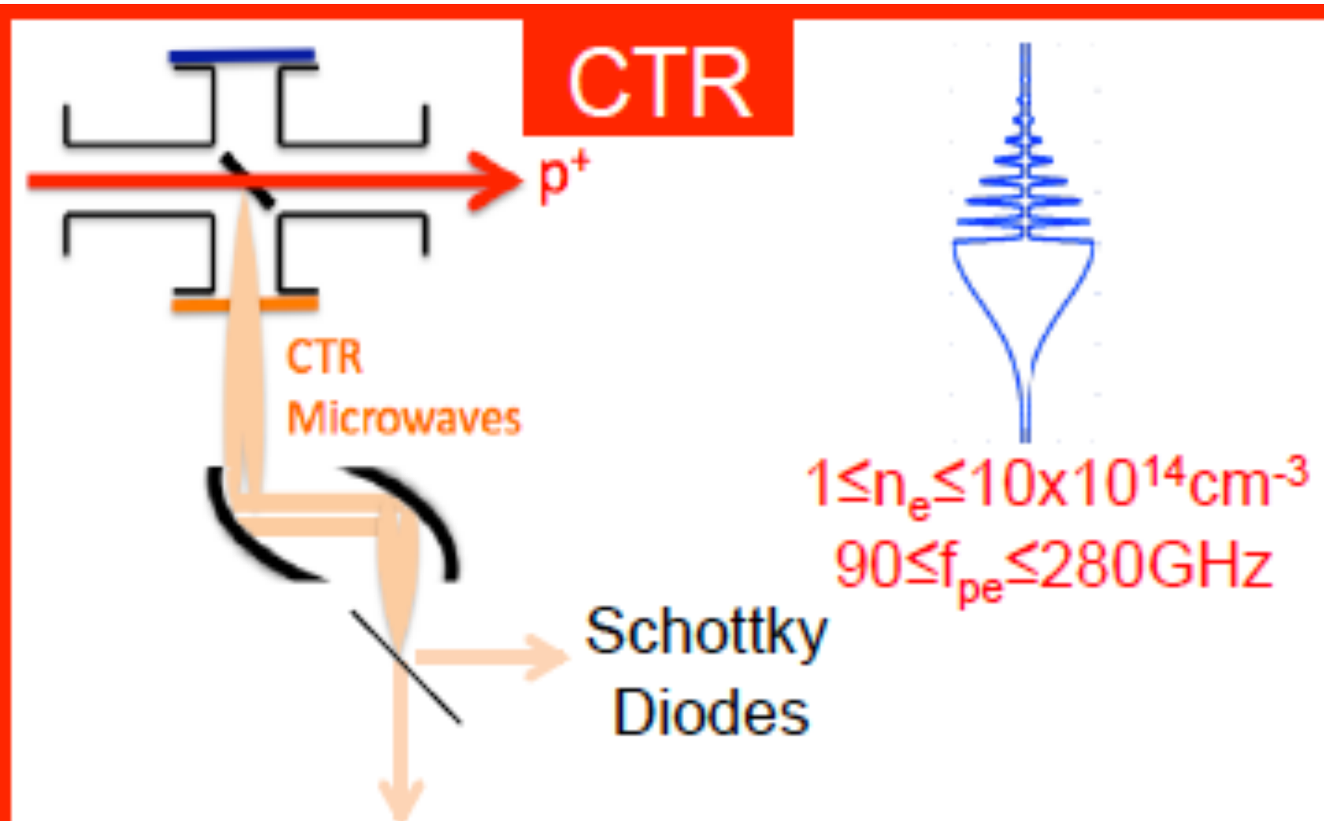
OTR

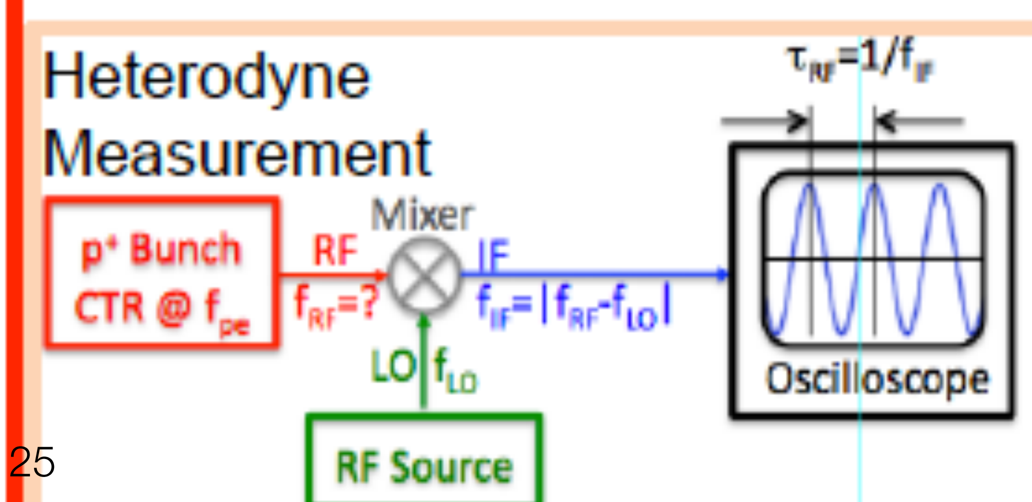




Streak Camera

CTR





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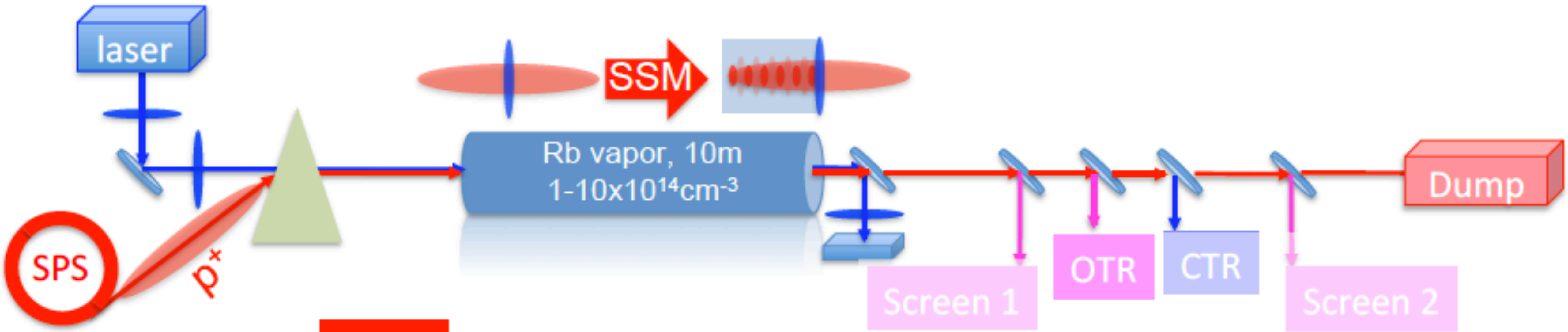
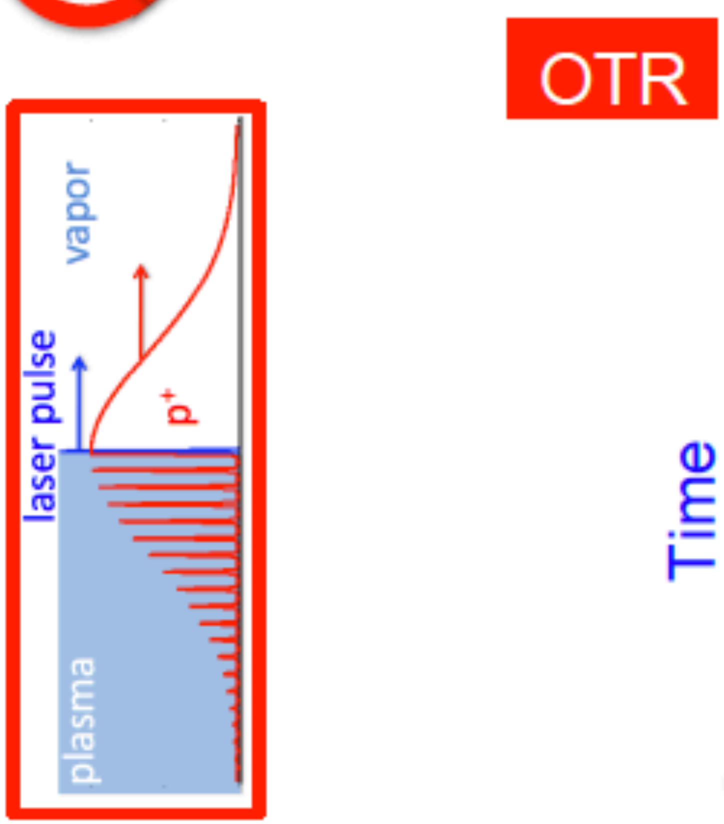
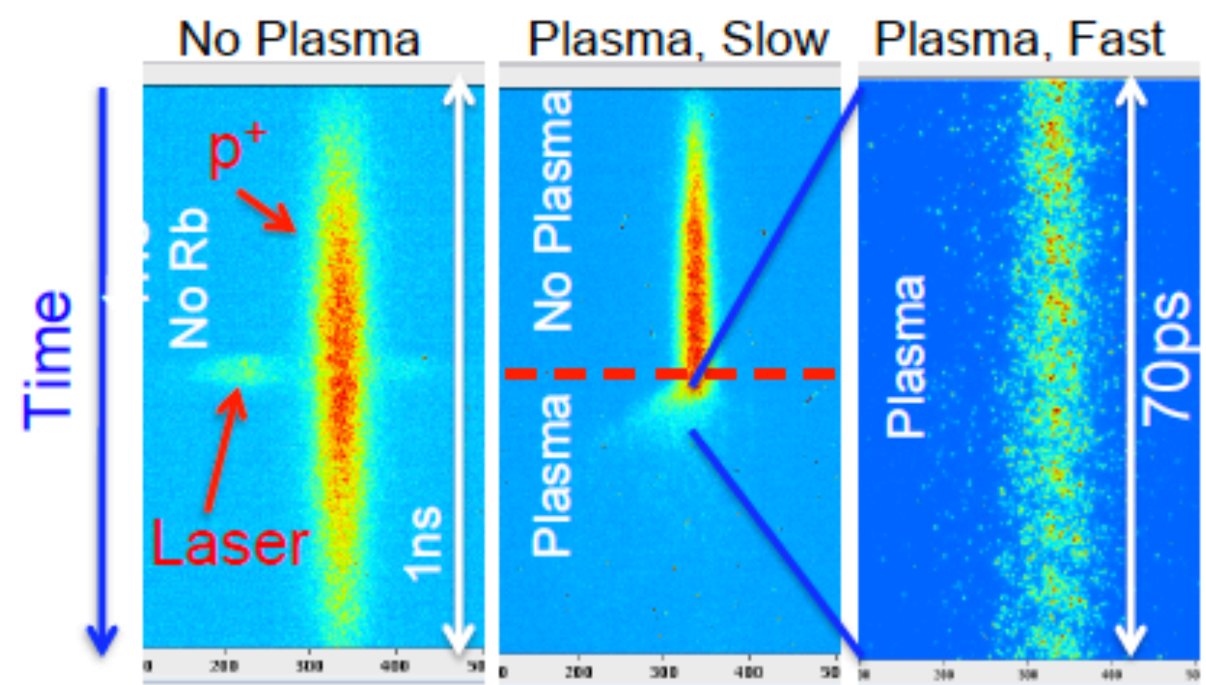
SSM





Streak camera Images



n_{Rb}=3.7x10^{14}cm^{-3}
N=3x10^{11}p^{+}
Long
f_{mod}~164GHz

Preliminary!!!

K. Rieger, MPP

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

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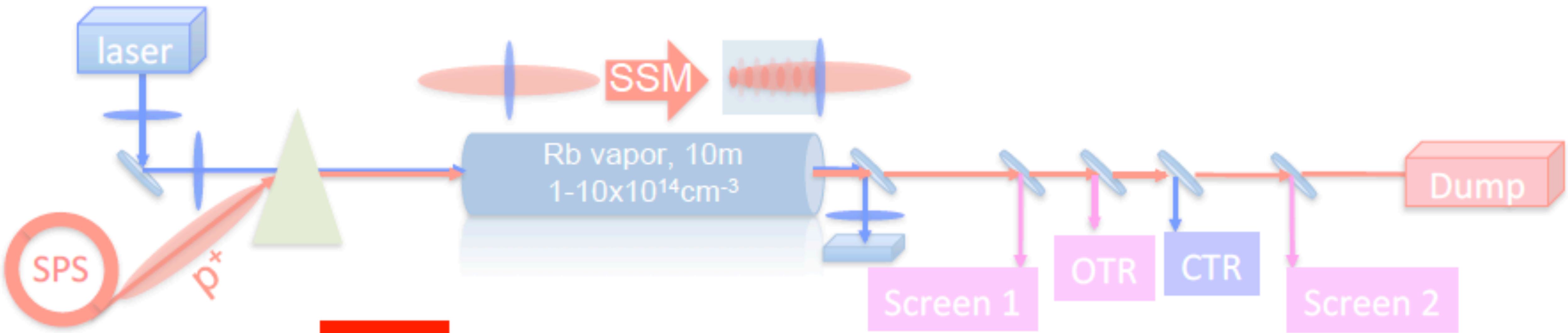
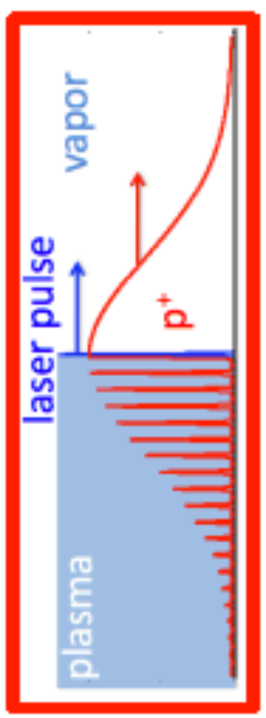
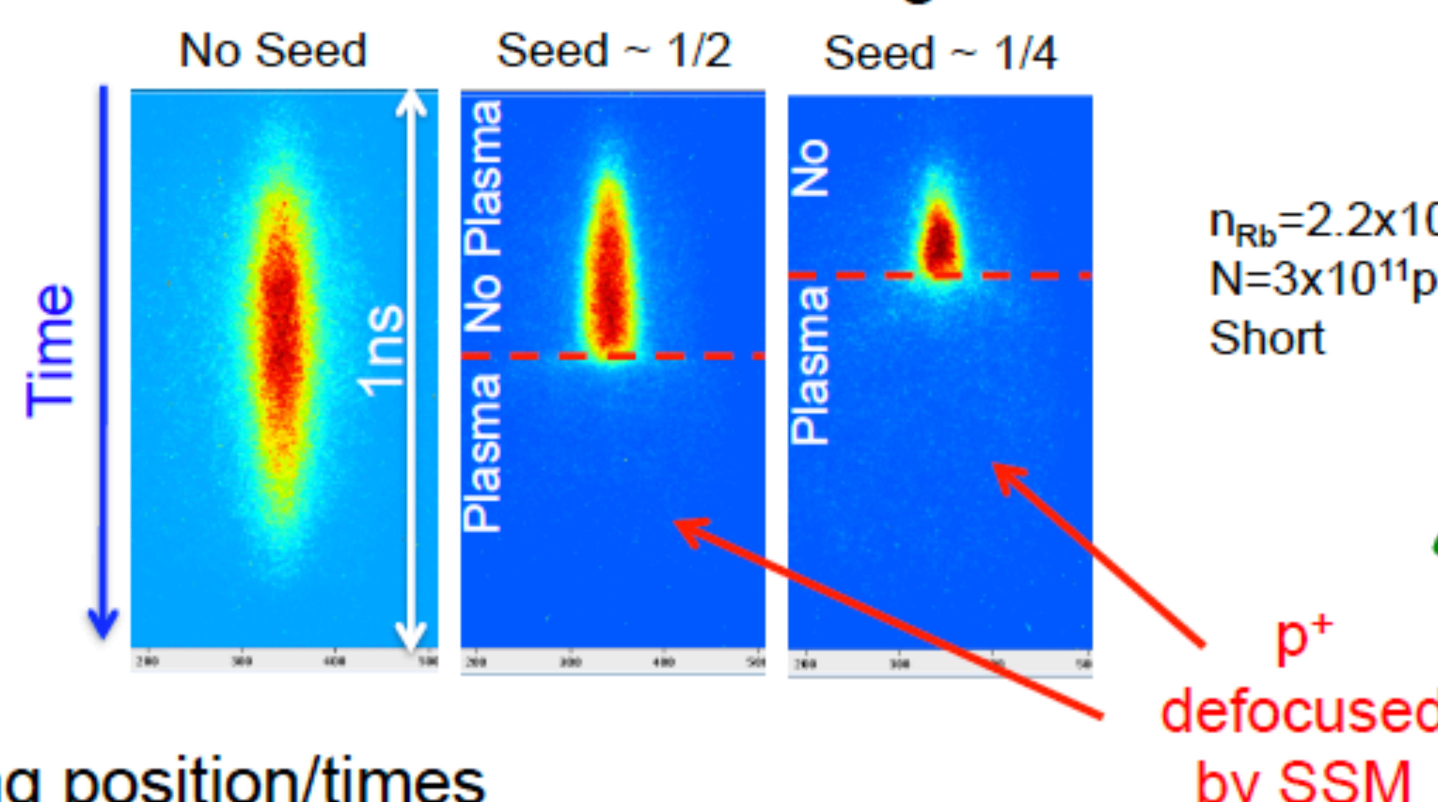
SSM



OTR



Streak camera images



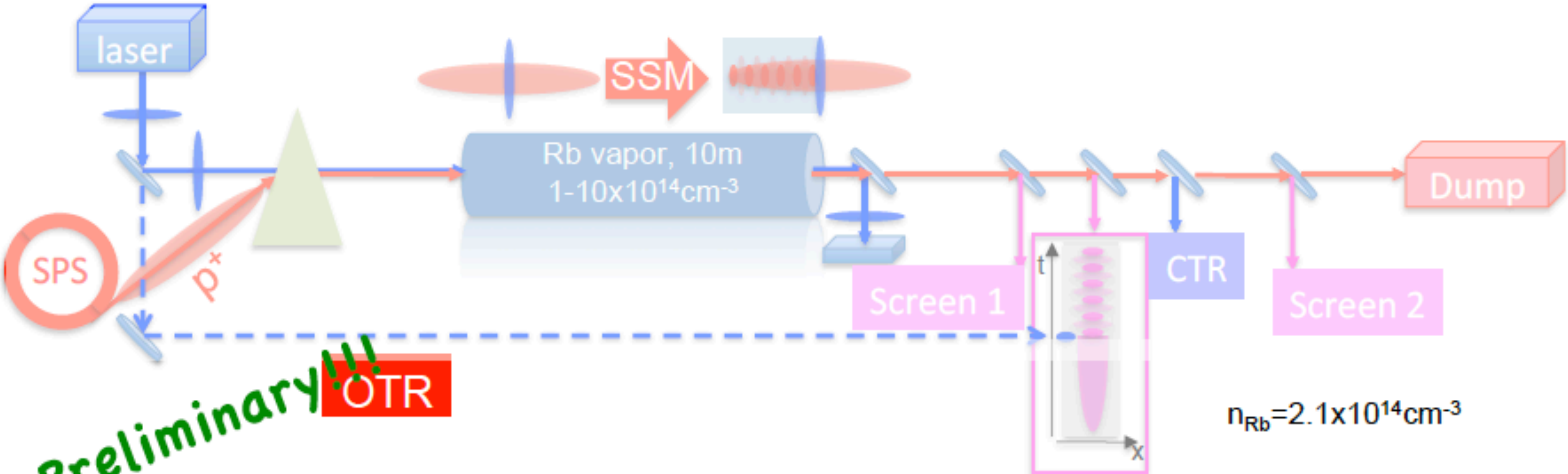
$n_{Rb}=2.2\times10^{14}cm^{-3}$
$N=3\times10^{11}p^{+}$
Short

Preliminary!!!

- ✧Various seeding position/times
- ✧Effect starts at laser timing → SM seeding

Stronger effects with seed at ¼ than ½ observed !

Micro bunch train

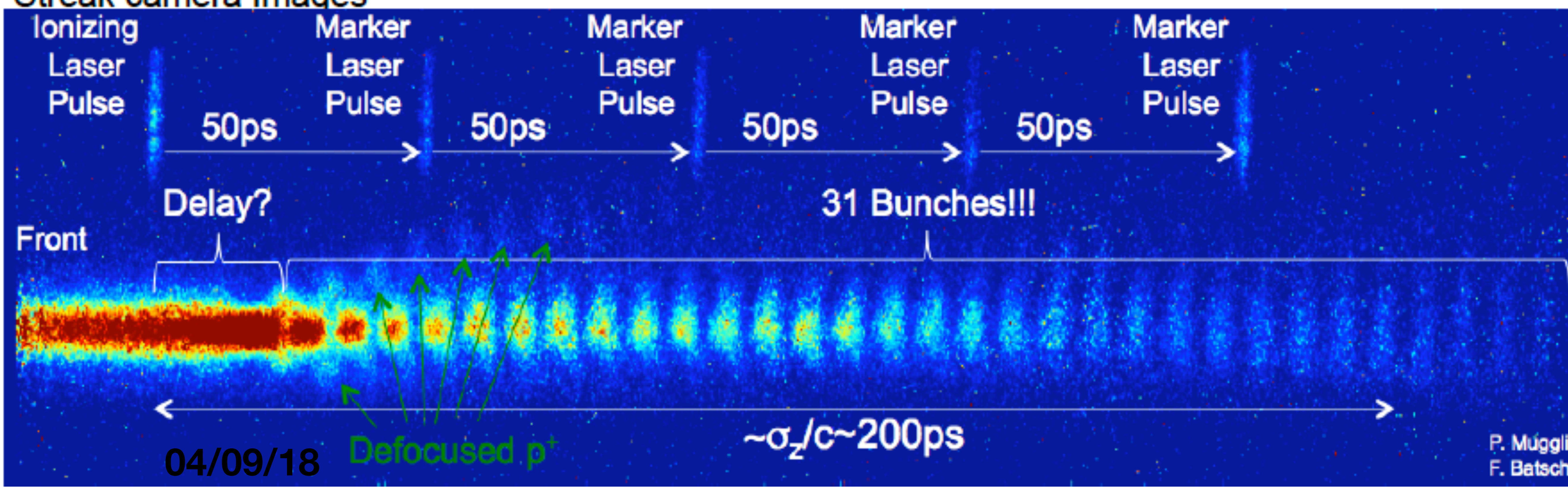


$n_{Rb}=2.1\times10^{14}cm^{-3}$

Preliminary!!!

Streak camera Images

5 sets
10 events each



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
- $f_{mod} \sim f_{pe}$

Preliminary!
analysis to come!

- Run II: (2021-): two plasmas, high quality of the accelerated e- bunch: ΔE/E, ε
- Application of AWAKE, e^-/p^+ collisions

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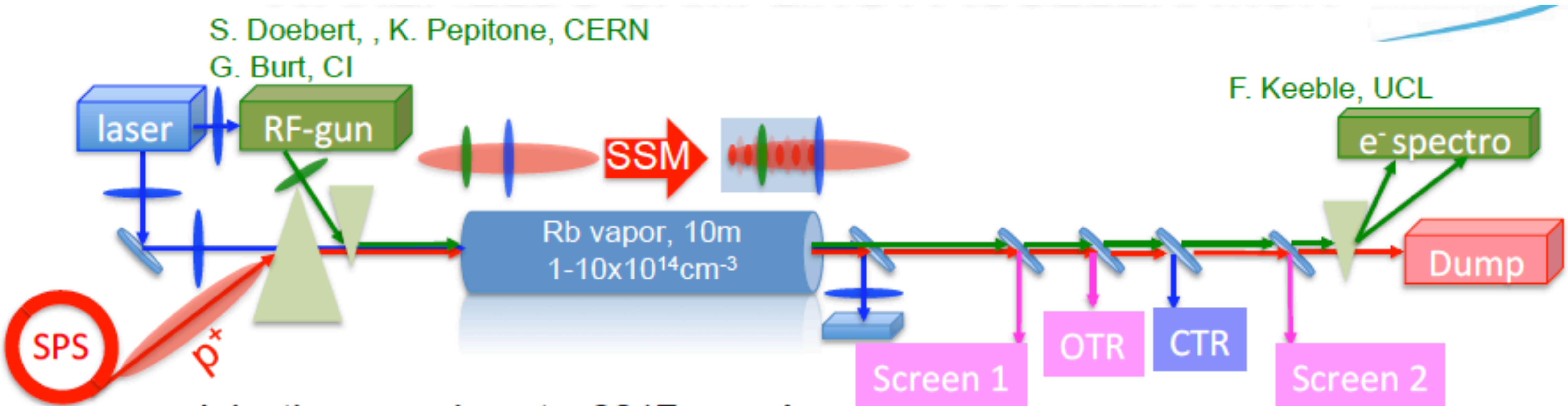
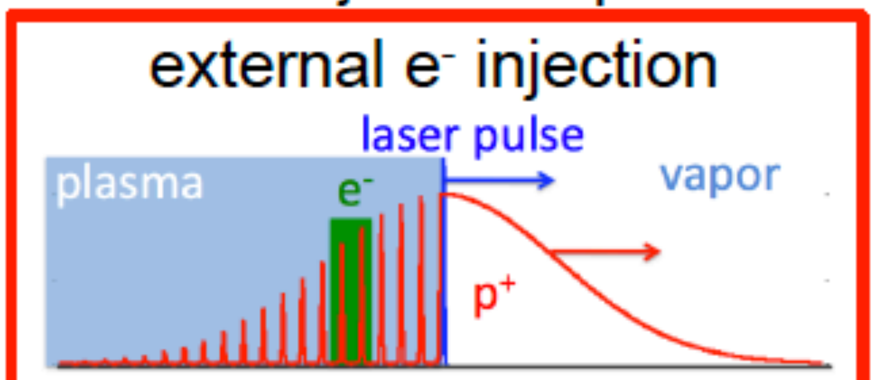
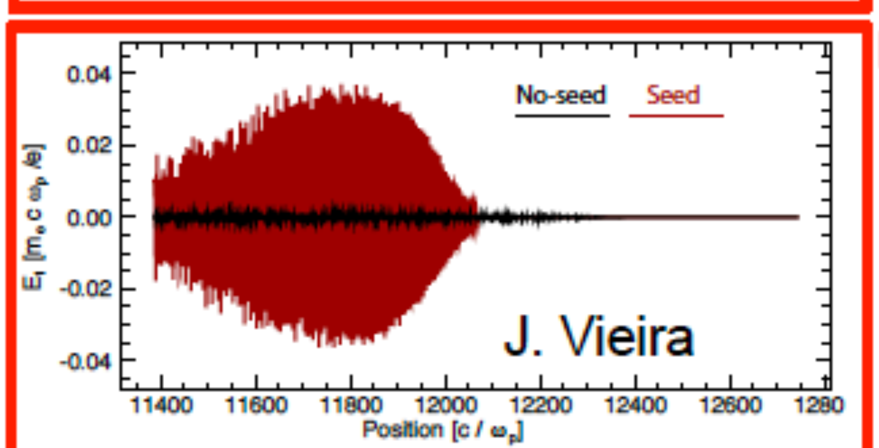
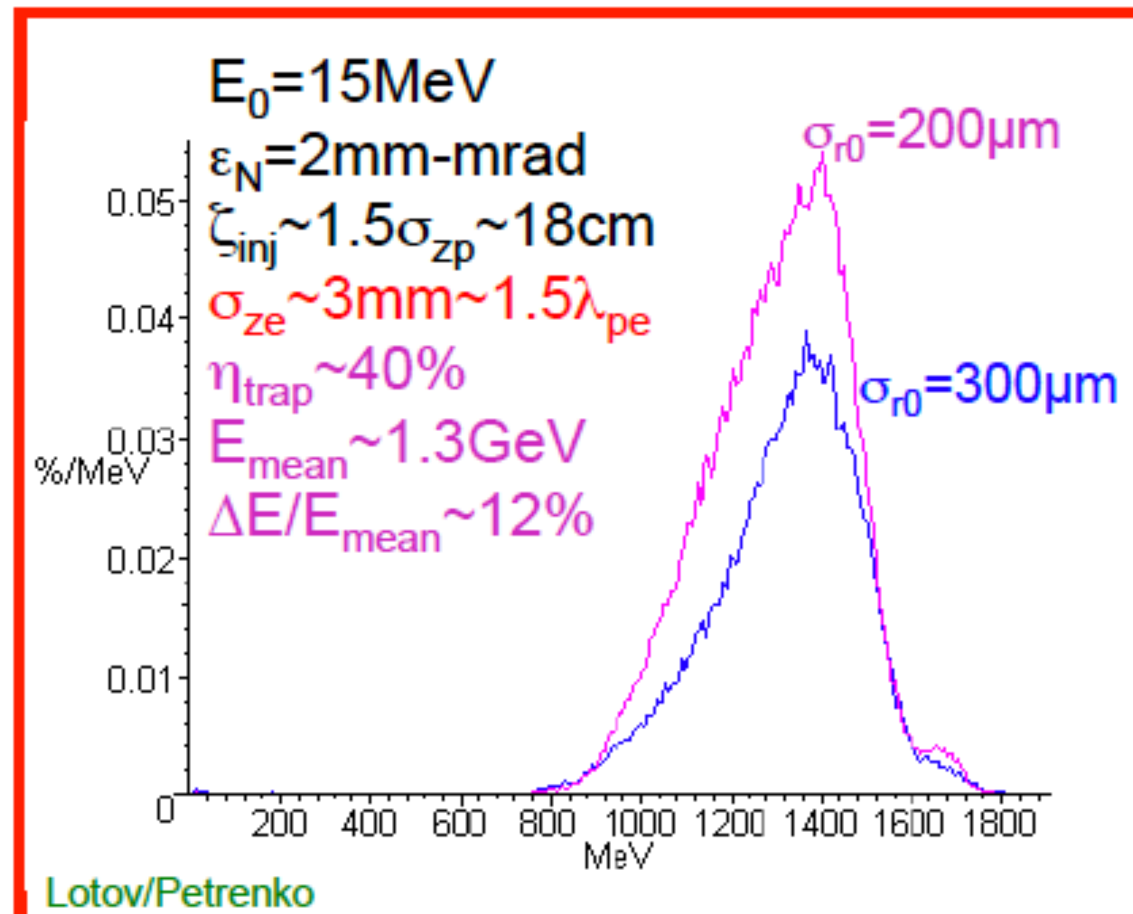
Wakefield sampling/acceleration



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







- Accelerate e⁻ to GeV energy with ~GeV/m gradient and finite $\Delta E/E$

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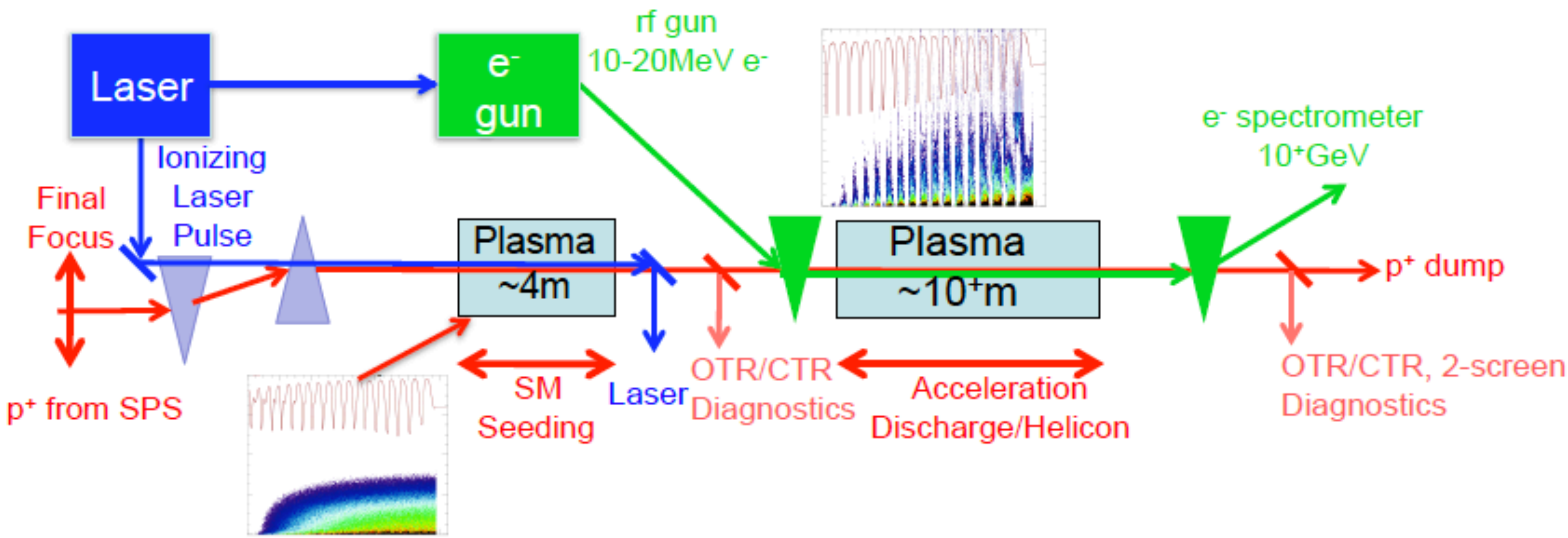
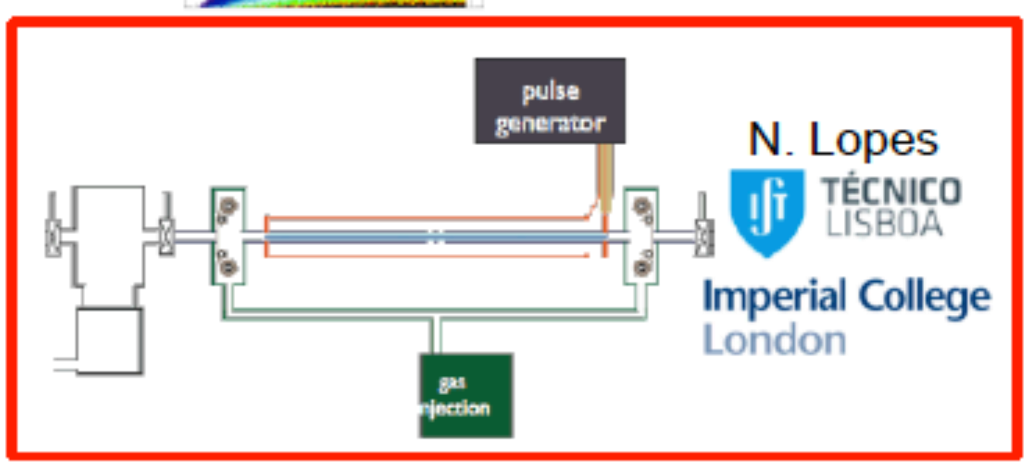
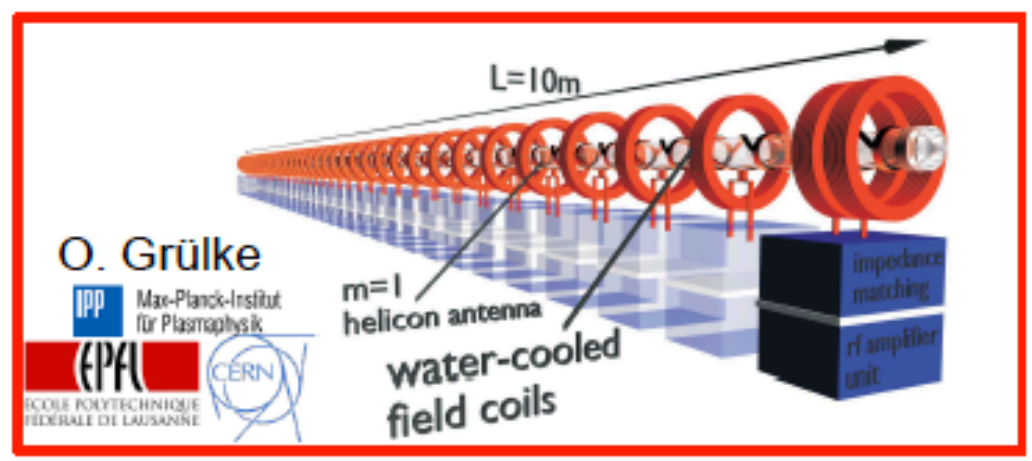
Experimental setup for Run II (2021-LS3)







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

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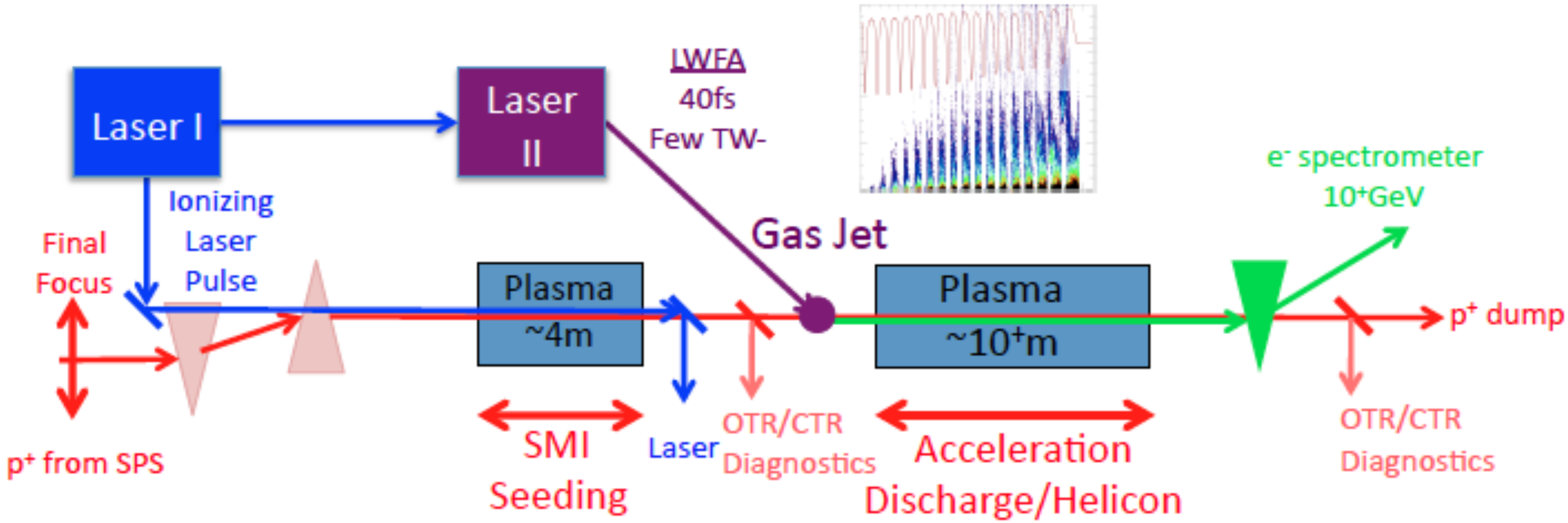
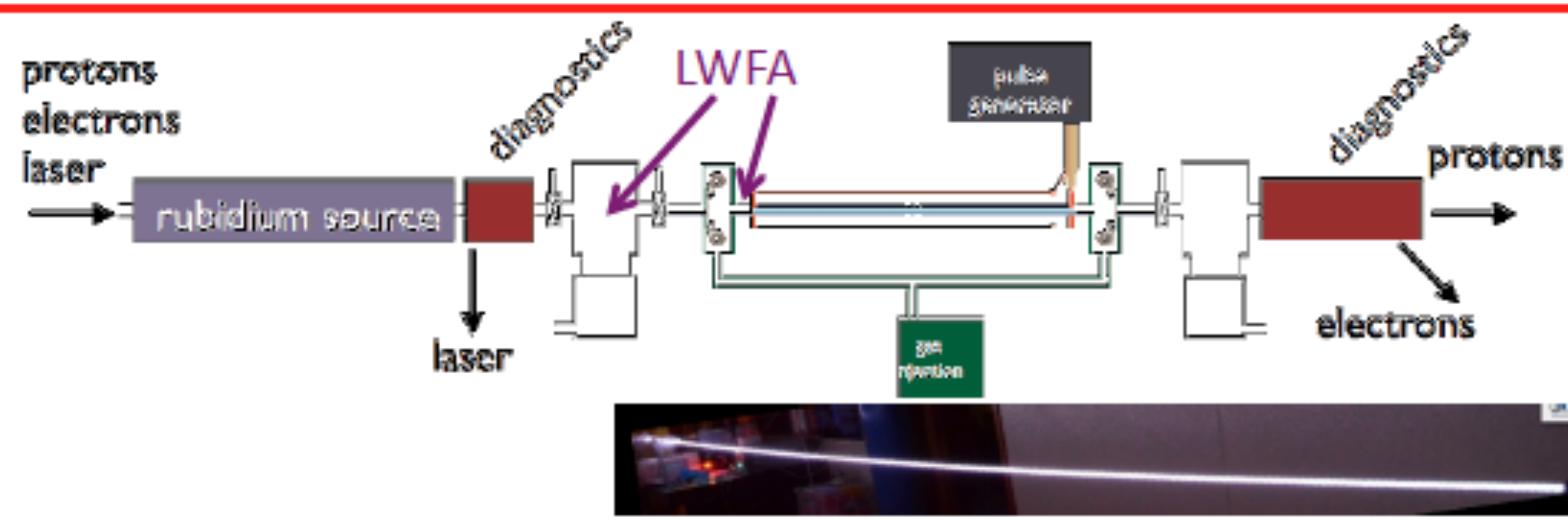
AWAKE Run II



N. Lopes
TÉCNICO LISBOA
Imperial College London



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

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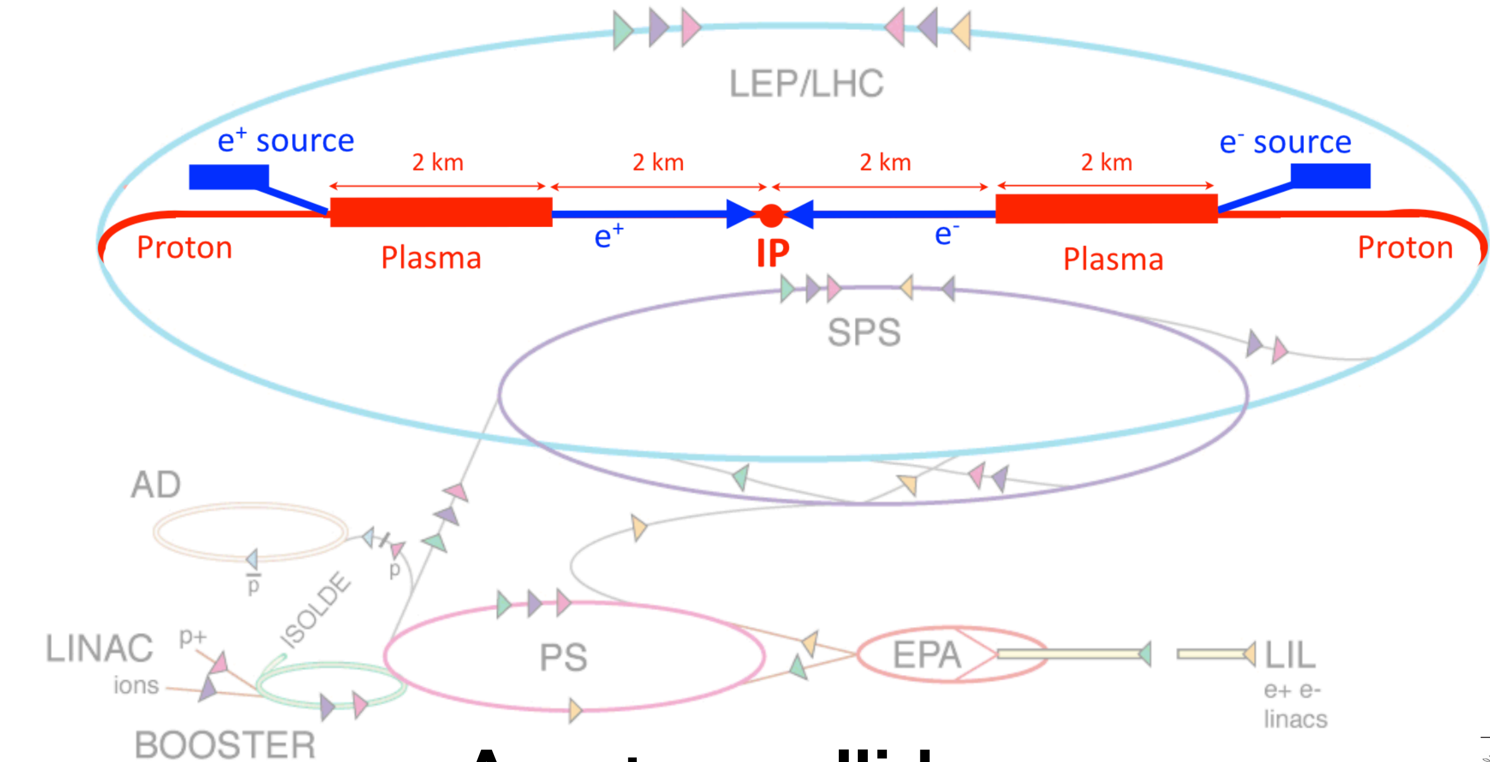
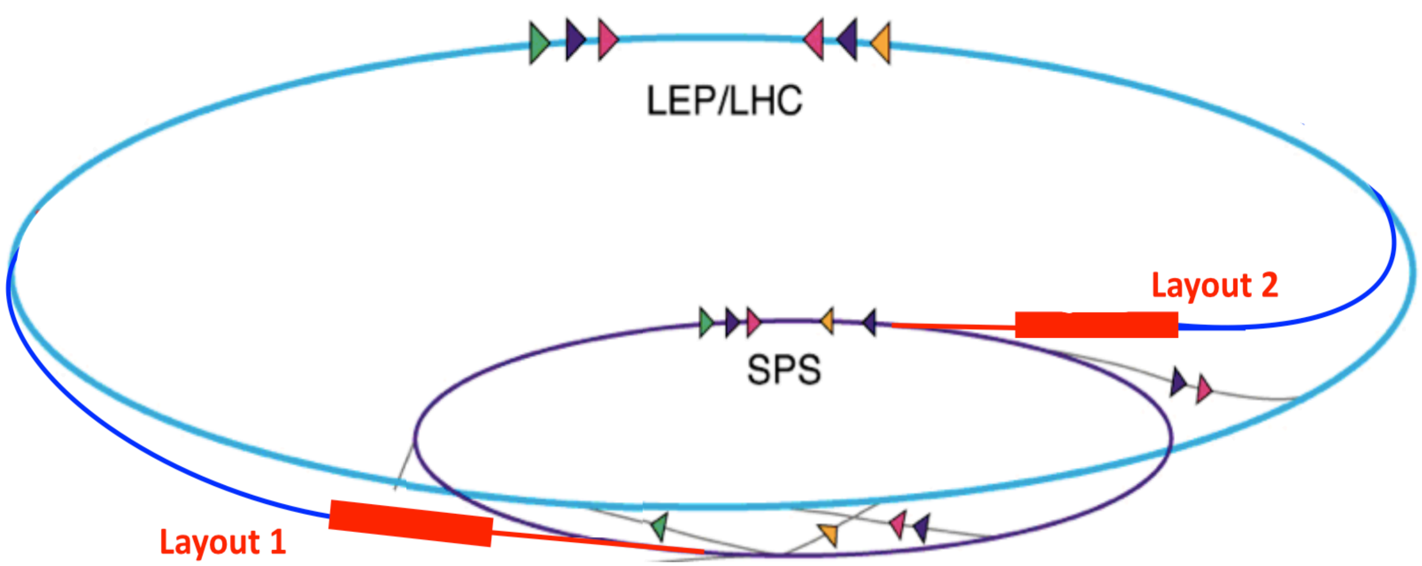
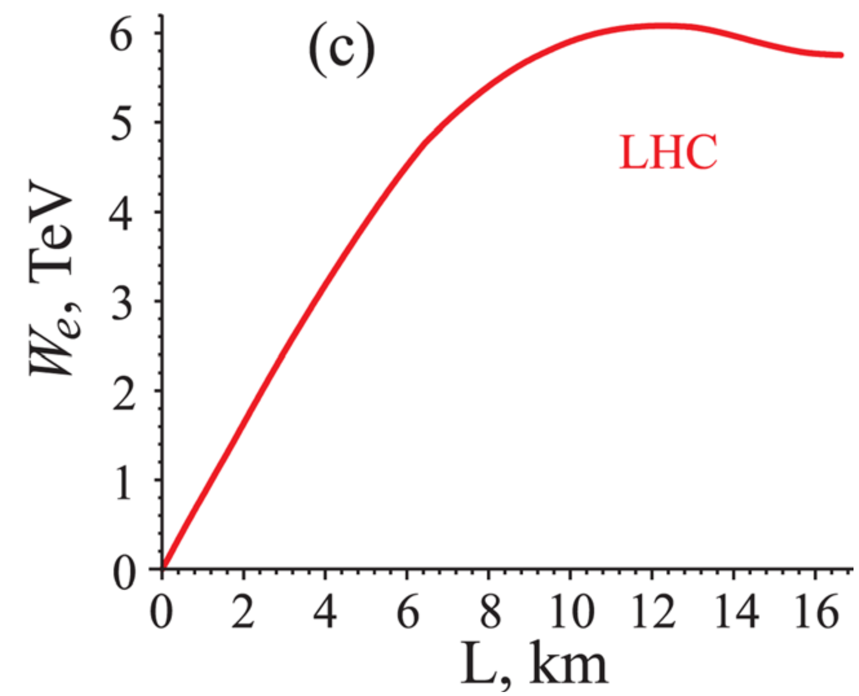
AWAKE applications



An e+ e- collider



An e-p collider



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Collider design issues based on proton-driven plasma wakefield acceleration

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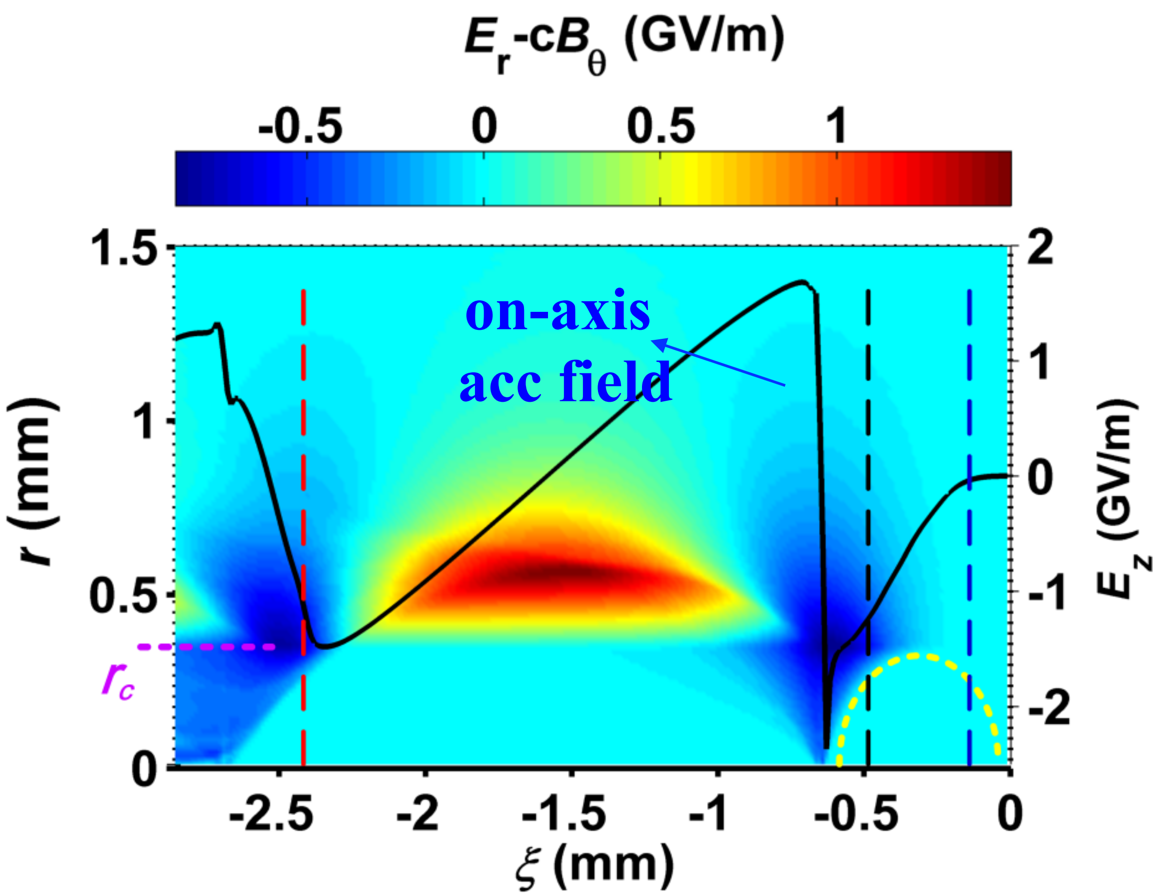
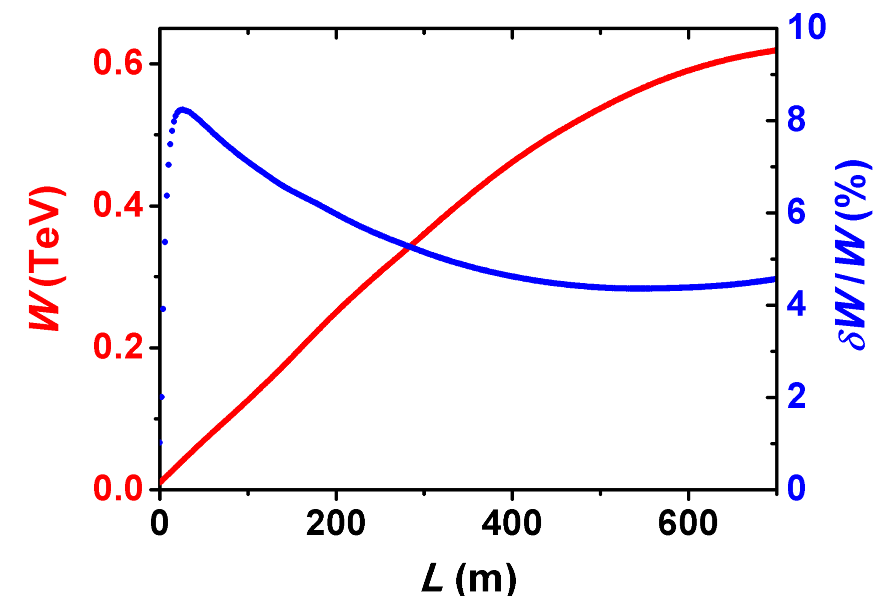
ABSTRACT

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.

Hollow plasma channel



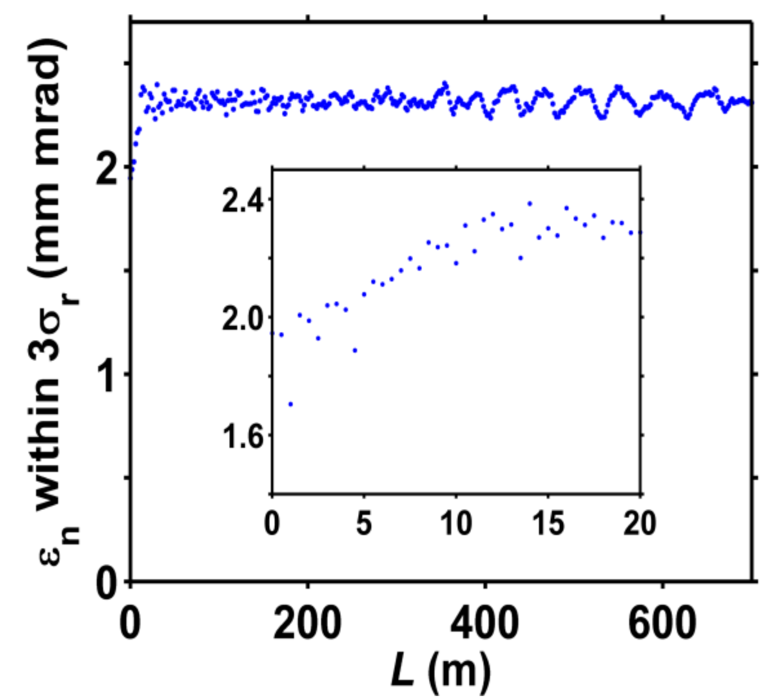
2D plasma wakefields



Mean energy and energy spread of the

Initial value: 2.0 mm mrad

2.4 mm mrad



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

Y. Li et al., to be published at Phys. Rev. Accel. Beams 2017

04/09/18

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 !