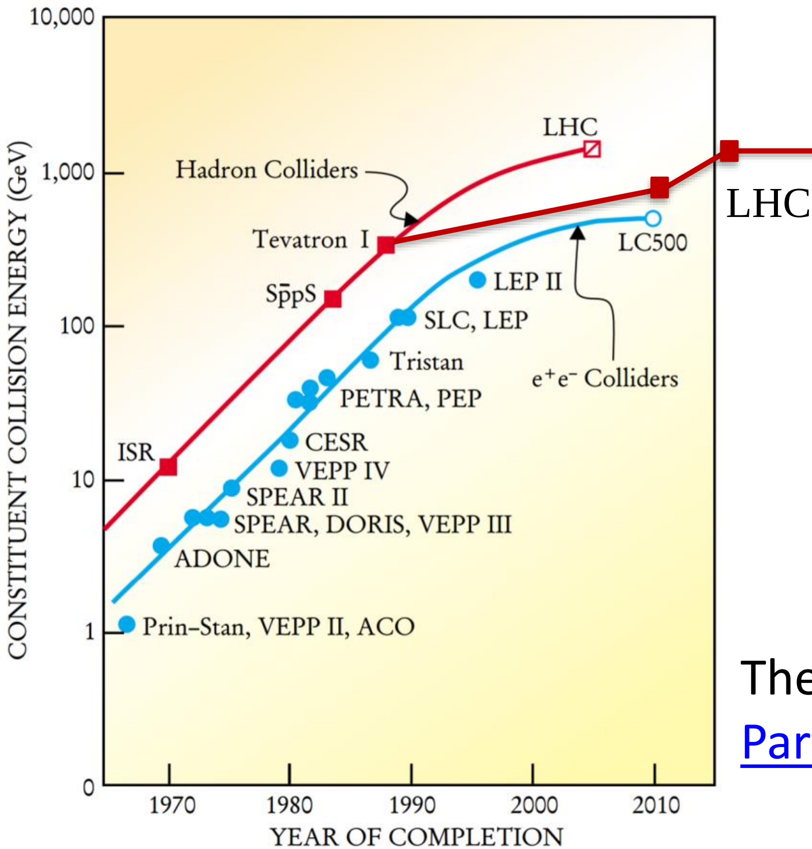
Particle acceleration driven by a high-energy hadron beam

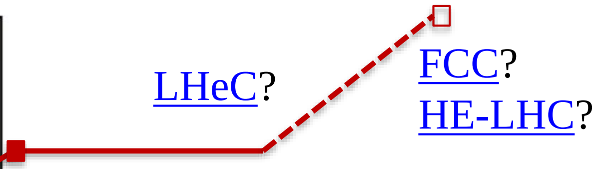
Alexey Petrenko (CERN)

Fermilab's Accelerator Physics and Technology Seminar, Feb. 14, 2017

Outline

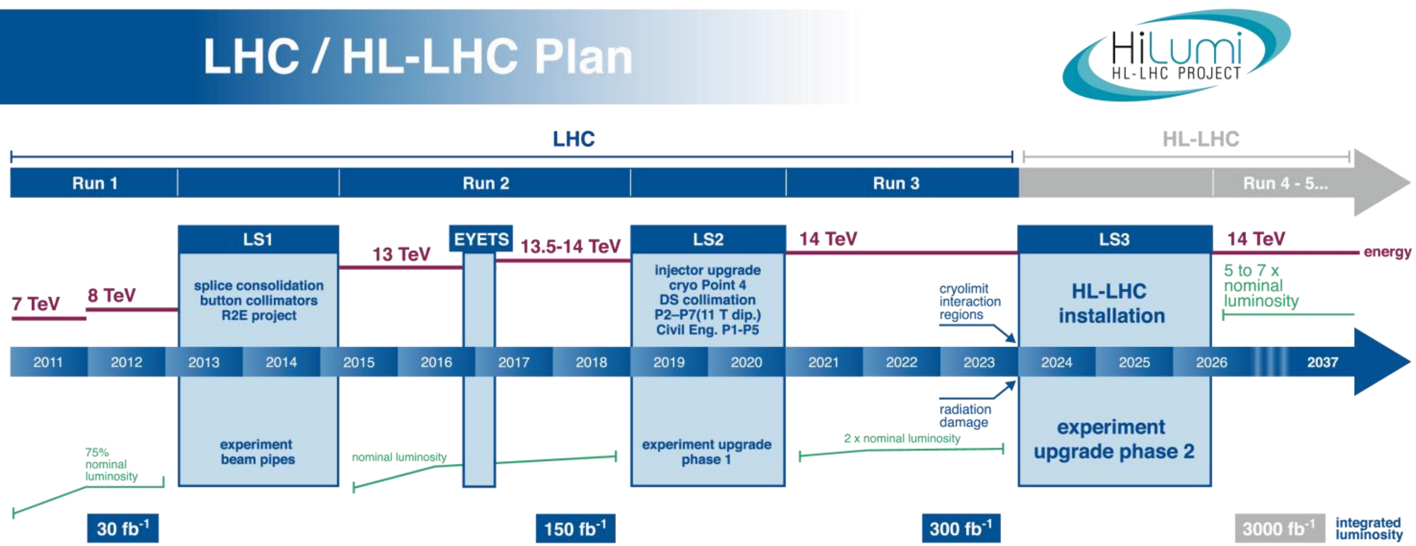
- Motivation
- Early ideas and some scalings
- mm-wavelength linacs vs plasma
- AWAKE experiment at CERN
- Summary





For the foreseeable future hadron beams will have the highest energies available in the laboratory.

The plot from M. Tigner's. [Does Accelerator-Based Particle Physics Have a Future?] Physics Today (2001).



[hilumilhc.web.cern.ch]

Looks like no plans to have higher energy collisions for the next 20 years at least.

Motivation

LHC nominal beam parameters:
(2808 bunches)*(1.15e11 protons)*(7 TeV) = 360 MJ

Fully loaded A320 (80 t) at take-off speed (300 km/h) carries similar amount of kinetic energy (280 MJ).
(However the momentum of the airplane is ~ $c/v \sim 10^6$ times larger than the LHC beam momentum)

Single LHC proton bunch **(7 TeV, 1.2e11 protons)** carries **130 kJ**
Single SPS proton bunch **(0.4 TeV, 3e11 protons)** carries **19 kJ**
Single ILC electron bunch **(0.5 TeV, 2e10 e+/e-)** carries **1.6 kJ**

Average design beam power of **ILC (11 MW)** is only about **10-20 times higher** than that of **SPS (0.8 MW) and LHC (360 MJ/1000 sec = 0.4 MW)**.

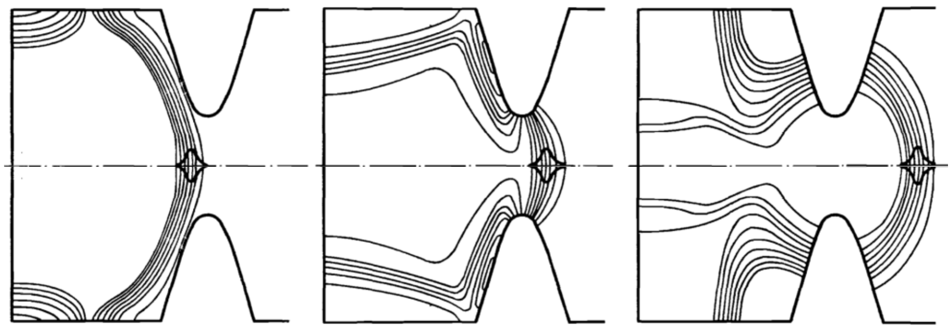
Can we use LHC/SPS beam as a driver to obtain TeV-level (e-/e+/muons) in a single stage?

Such an accelerator probably can’t compete with the ILC or CLIC in terms of luminosity but maybe there is some interesting physics at high energy but low luminosity:

A. Caldwell. Collider physics at high energies and low luminosities. Eur. Phys. J. (2014).
A. Caldwell, M. Wing. VHEeP: a very high energy electron–proton collider. Eur. Phys. J. (2016).
-- some electron-proton cross sections grow with energy.

The extremely compressed proton bunch case

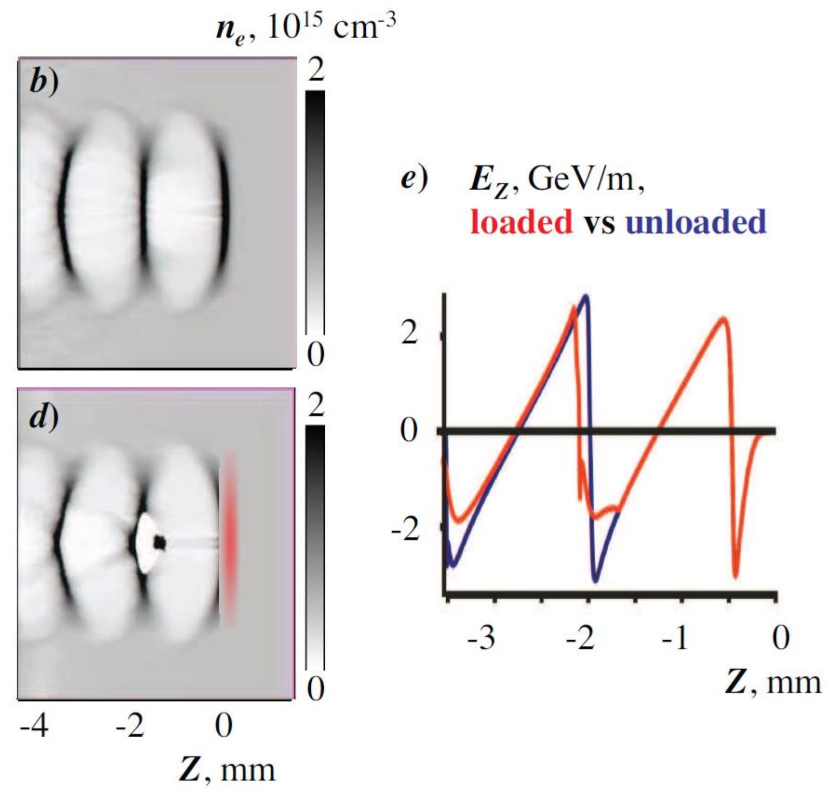
V. E. Balakin, A. V. Novokhatsky, The method of accelerating electrons with maximum high gradient by a proton beam; Preprint INP (1979). Also: ECFA-RAL Meeting 1982, HEACC'86 (rus).



Electrons are mixed with highly compressed proton beam. Protons loose energy => there is a strong decelerating field => electrons gain energy. Breakdown happens after the passage of the beam.

$$E\left[\frac{\mathrm{GV}}{\mathrm{m}}\right] = \frac{4}{\sigma^2_{[\mathrm{mm}]}}\left(\frac{N_p}{10^{13}}\right)$$

A. Caldwell, K. Lotov, A. Pukhov, F. Simon, Proton-Driven Plasma-Wakefield Acceleration. Nature Physics (2009):



$$E = 240(\mathrm{MV\,m^{-1}})\left(\frac{N}{4\times 10^{10}}\right)\left(\frac{0.6}{\sigma_z(\mathrm{mm})}\right)^2$$

In both cases strong external quadrupole focusing is required.

Unfortunately it's very difficult to compress long hadron beam to sub-mm longitudinal size.

The “proton klystron” idea by E. A. Perevedentsev and A. N. Skrinsky

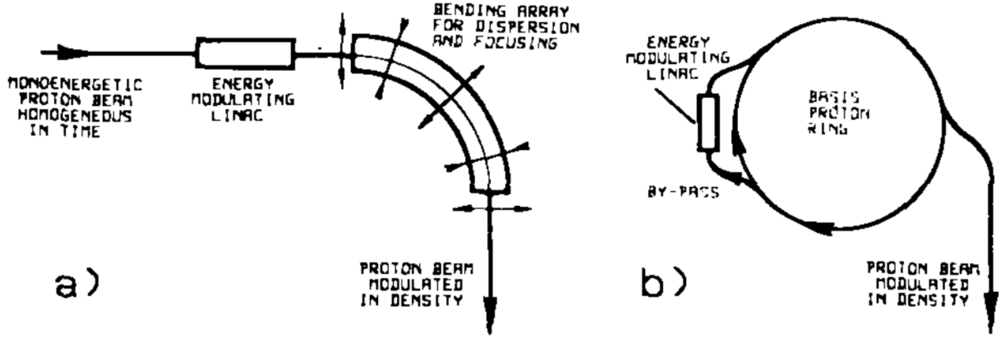


Fig. 1. Two versions of the bending modulator.

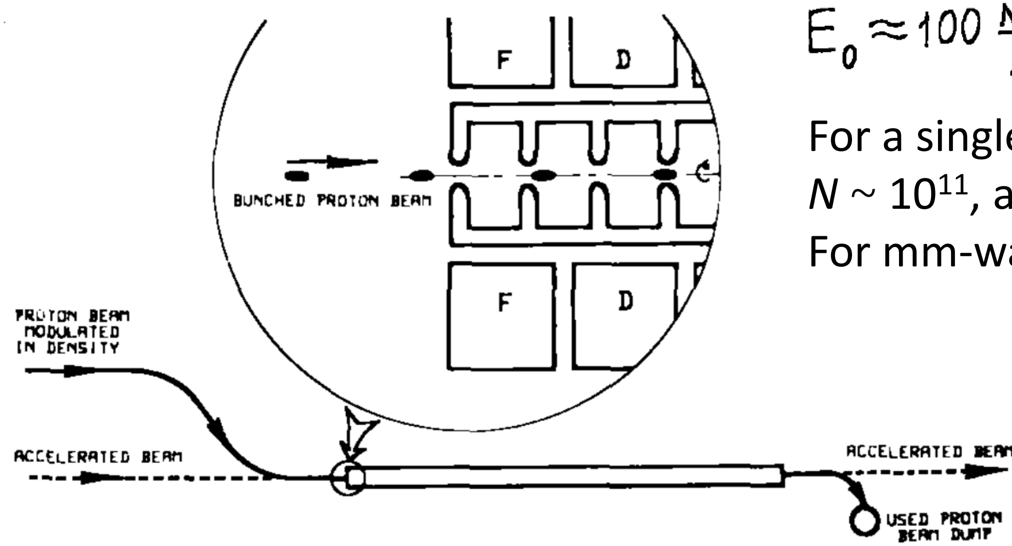


Fig. 2. A linac structure excited with the proton beam.

$$E_0 \approx 100 \frac{Ne}{\lambda^2} \approx 1.5\cdot 10^{-11} \frac{N}{\lambda^2_{cm}} \, (MV/cm)$$

For a single SPS/LHC bunch with $N \sim 10^{11}$, and $\lambda = 1$ cm, $E_0 \sim 100$ MV/m. For mm-wavelength $E_0 \sim 1$ GV/m.

$$L_{\Sigma}^{e^+e^-} = 10^{31} \, cm^{-2} s^{-1}.$$

$$L_{\Sigma}^{\mu\mu} = 3\cdot 10^{31} \, cm^{-2} s^{-1}.$$

100-1000 times less than ILC/CLIC.

For details see ON THE PROTON KLYSTRON, HEACC‘1983. E. Perevedentsev and A. Skrinsky. And earlier BINP preprint.

The proton klystron modulator at mm-wavelength:

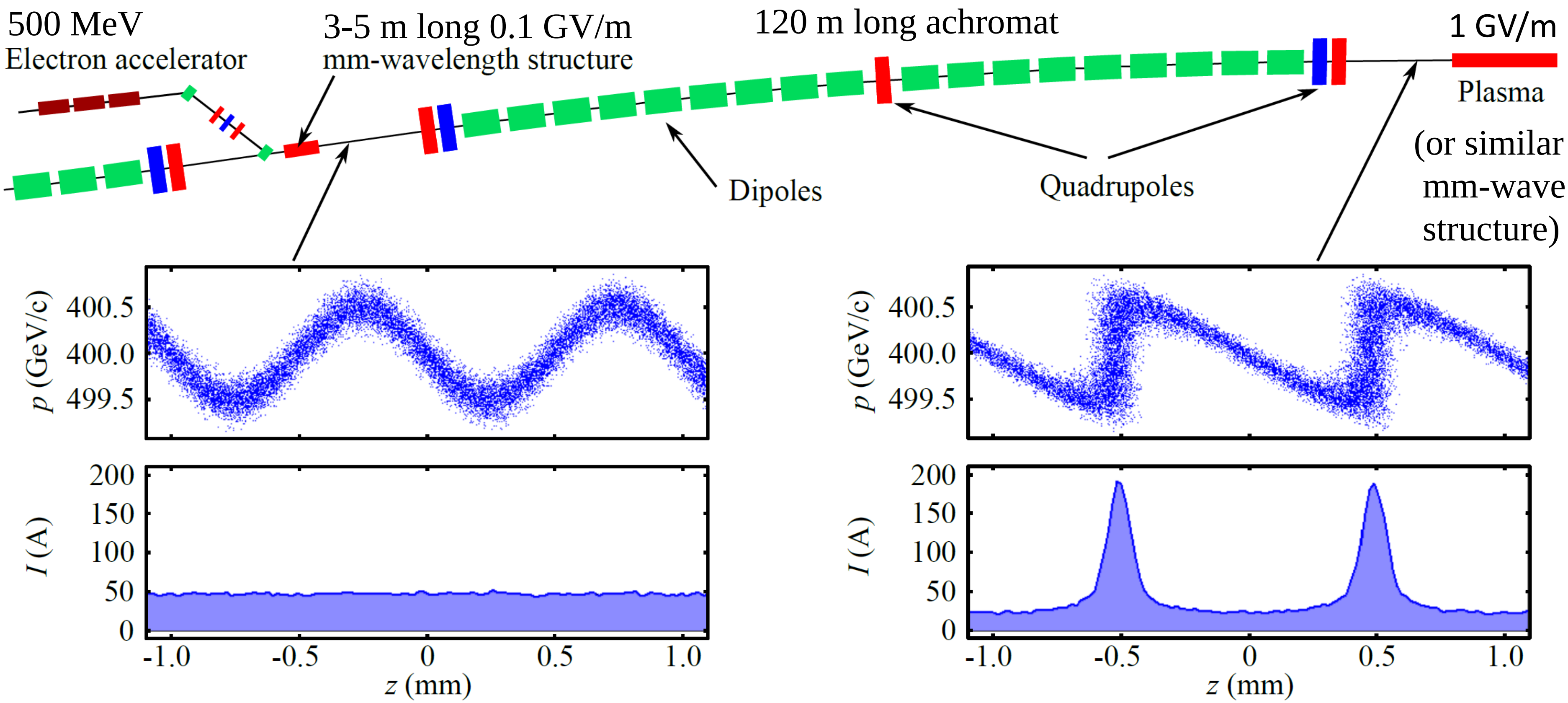


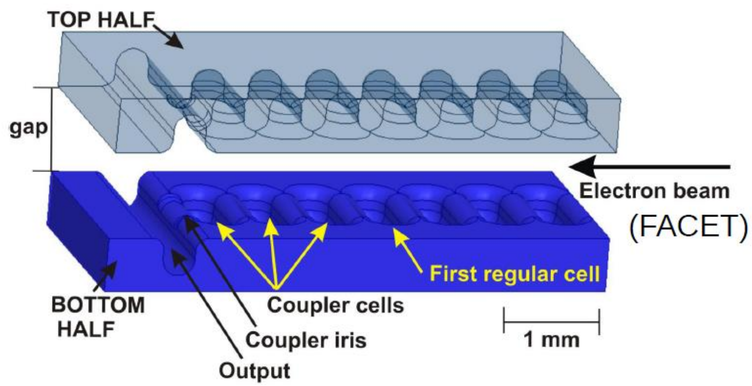
Figure 1: General layout of the proposed micro-bunching system. Proton beam current and proton momentum modulation along the beam are shown before and after the achromat. The realistic proton beam is much longer ($\sigma_z = 5 - 10$ cm) and it can produce around 100 of such micro-bunches.

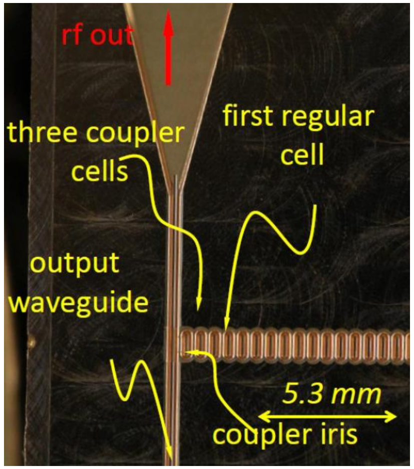
I. Sheinman, A. Petrenko. High-Energy Micro-Buncher Based on the mm-wavelength Dielectric Structure // Proceedings of RuPAC'2016, Saint Petersburg, Russia.

Single SPS bunch can excite ≈ 1 GV/m wakefield over the length of at least few 10s of meters in a similar mm-wavelength linac (before the beam break-up instability grows significantly). In plasma it can be stable transversely over much longer distance.

mm-wavelength accelerator technology

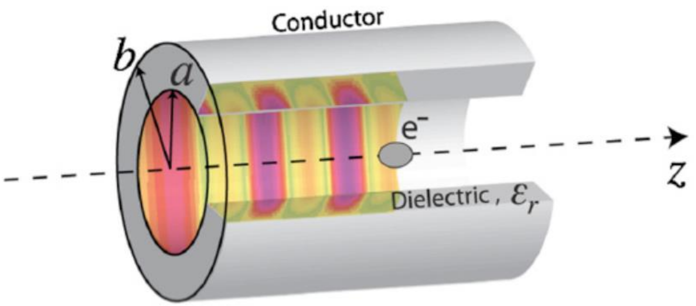
mm-size copper cavities:





From V. Dolgashev's EAAC'2015 talk: [High gradient, X-band and above, metallic RF structures]().

Metal pipe with a dielectric layer:



(From J. Rosenzweig et al. SLAC-PUB-15153).

For more details see this recent review presented at EAAC'2015 by A. Kanareykin. Advanced Acceleration and THz Generation by Dielectric Based Structures.

30-meter long dielectric-based linac is proposed for the FEL light source:

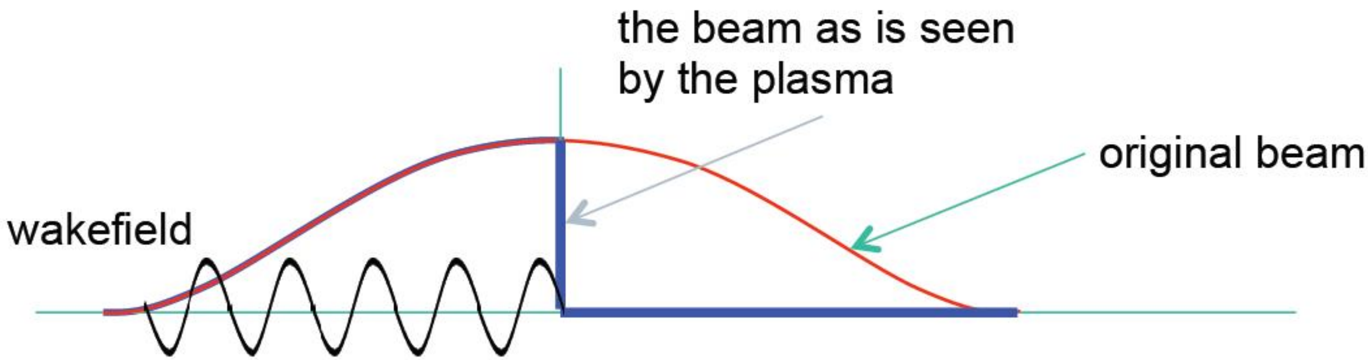
A. Zholents et al.. A COLLINEAR WAKEFIELD ACCELERATOR FOR A HIGH REPETITION RATE MULTI BEAMLINE SOFT X-RAY FEL FACILITY. FEL2014 proceedings.

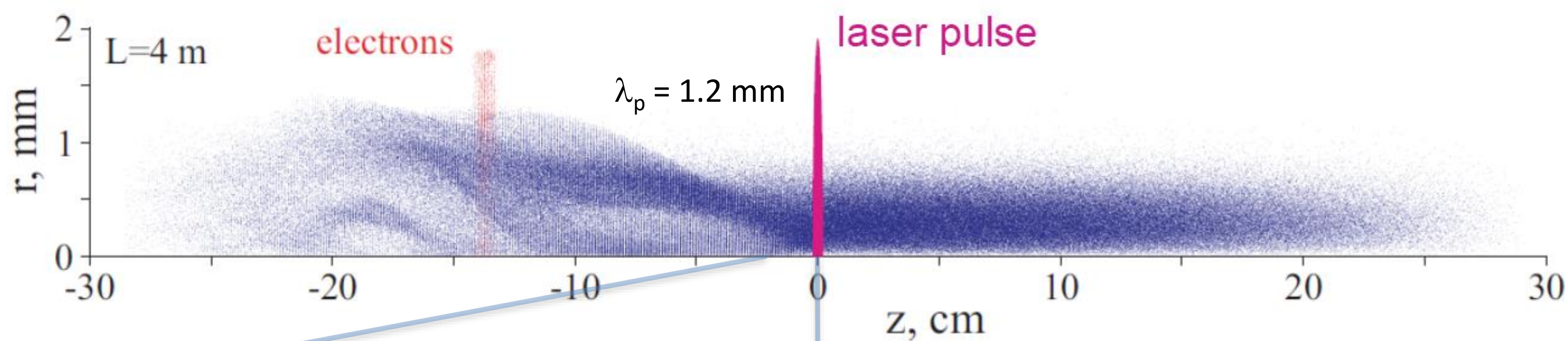
D. Shchegolkov, E. Simakova, and A. Zholents. Towards a Practical Multi-Meter Long Dielectric Wakefield Accelerator: Problems and Solutions. 2015, IEEE TRANSACTIONS ON NUCLEAR SCIENCE.

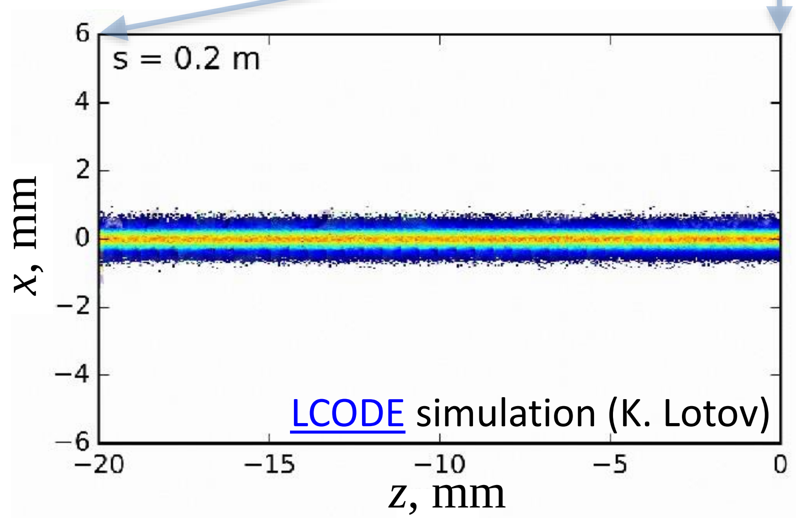
Both technologies are under development in many labs (SLAC, Argonne, BNL), offer similar accelerating gradients (few 100 MeV/m) and need similar drive beam in our case.
The beam break-up instability seems to be the major challenge for mm-wavelength linacs.

Self-modulation of long proton bunch in plasma

N. Kumar, A. Pukhov, K. Lotov, Phys. Rev. Letters (2010):

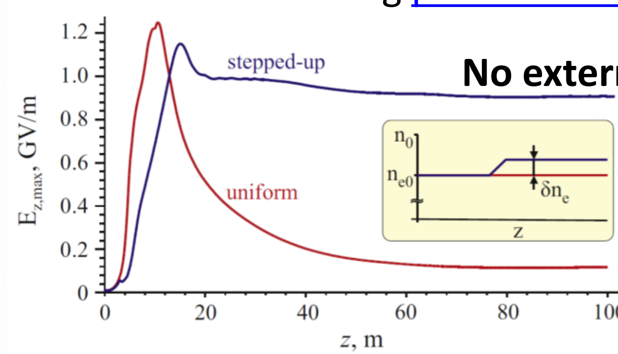






LCODE simulation (K. Lotov)

Self-modulated proton bunch resonantly drives plasma wakefields. The micro-bunches can be stabilized using plasma density step:



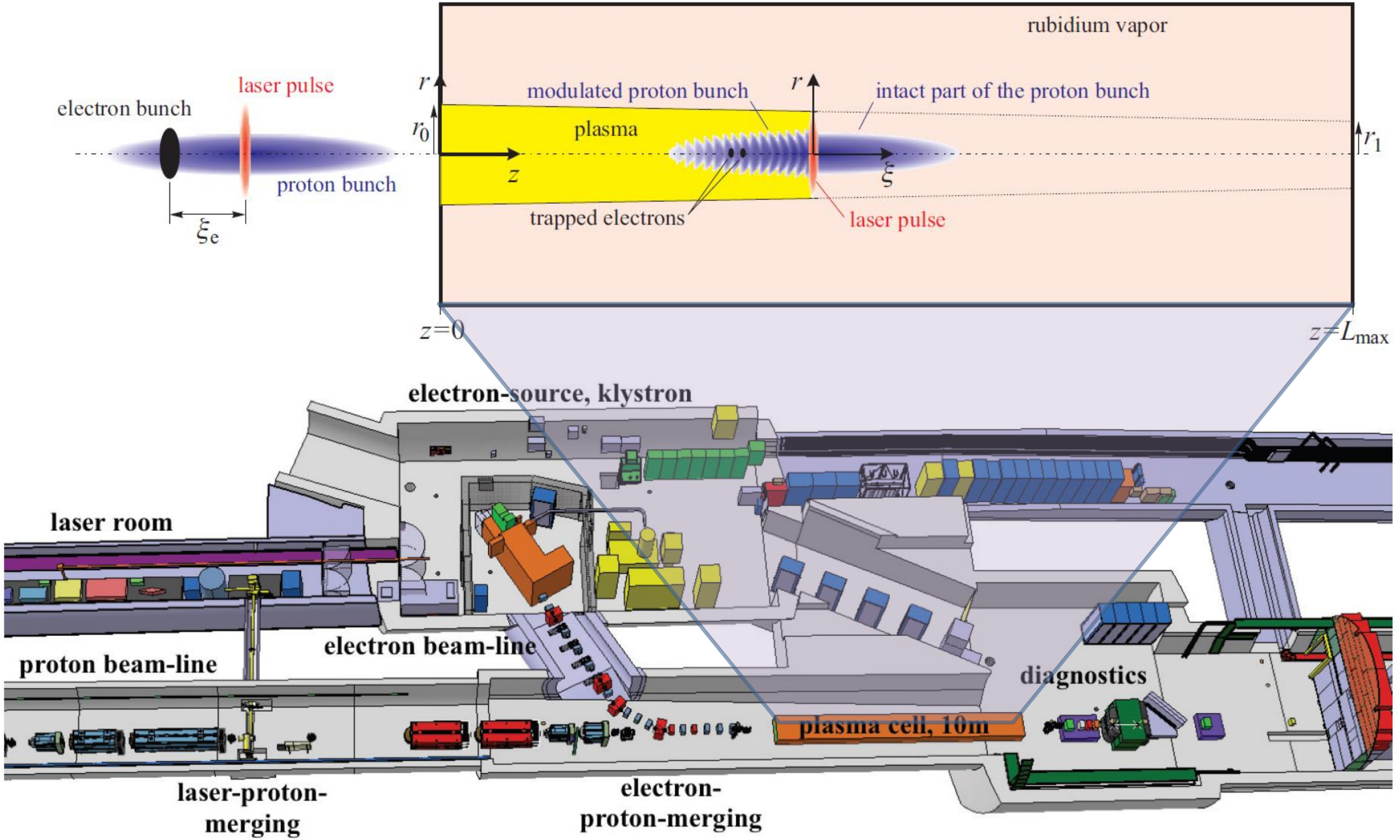
No external focusing!

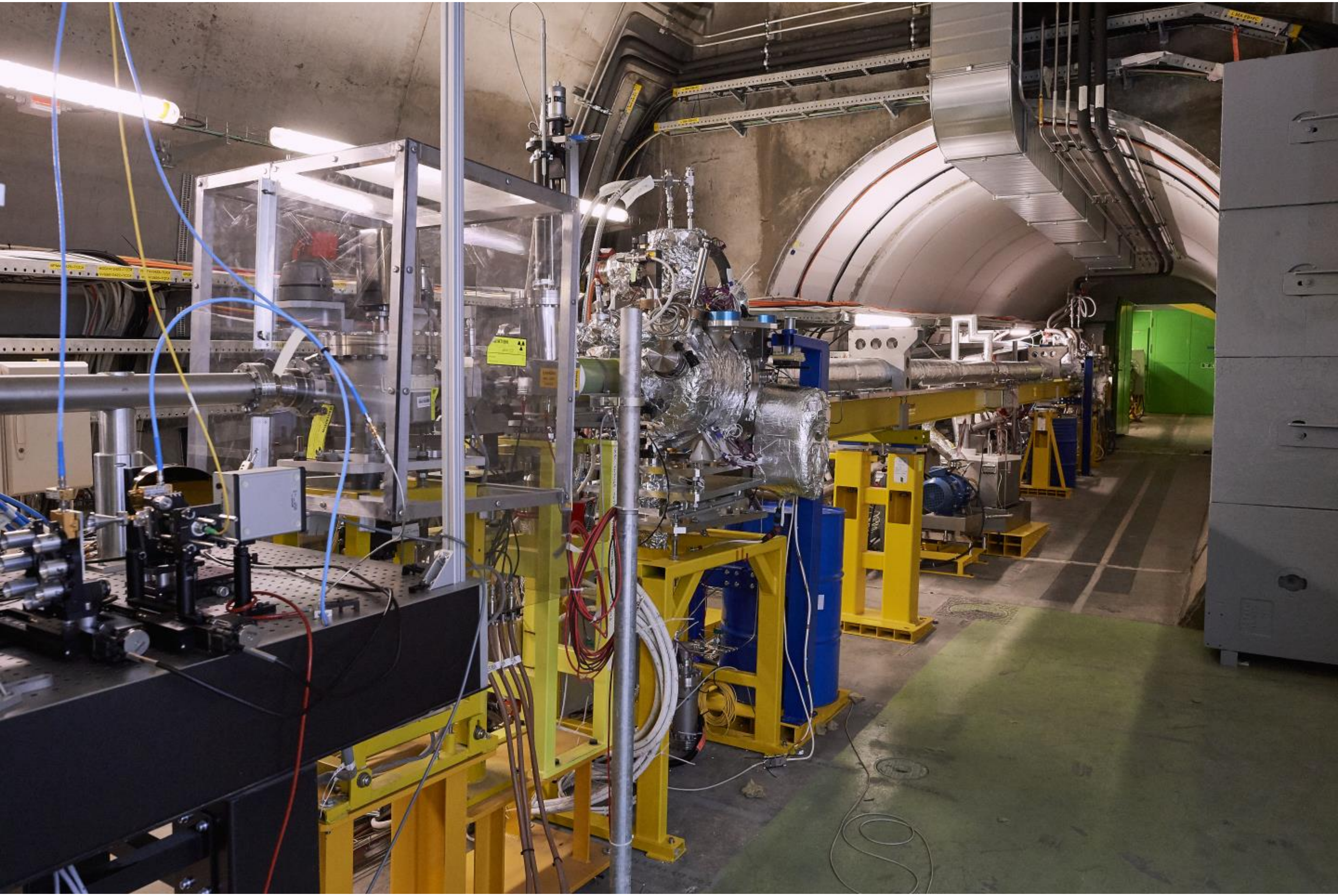
What is the AWAKE experiment?

- AWAKE: Advanced Proton Driven Plasma Wakefield Acceleration Experiment
  - Use SPS proton beam as drive beam (Single bunch 3e11 protons at 400 GeV)
  - Inject electron beam as witness beam
- Proof-of-Principle Accelerator R&D experiment at CERN
  - First proton driven plasma wakefield experiment worldwide
  - First beam expected in 2016
- AWAKE Collaboration: 16 Institutes world-wide:

cern.ch/awake

Layout of the AWAKE experiment:

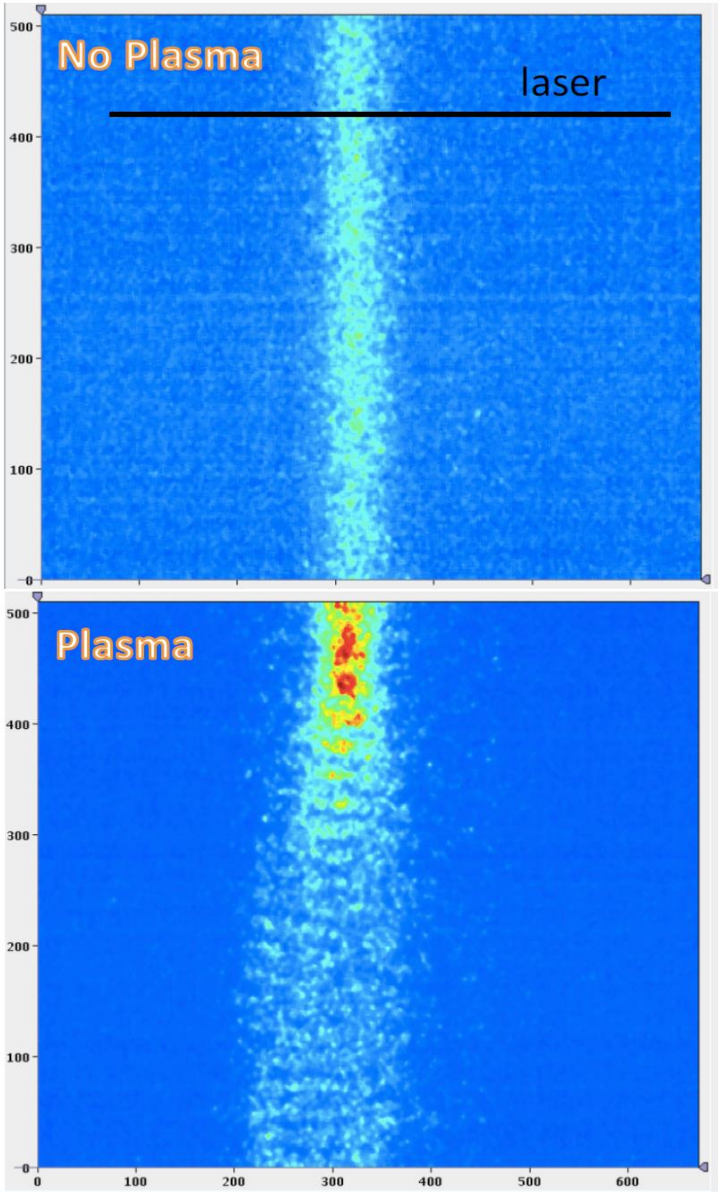




Photograph: Maximilien Brice (more photos: http://cds.cern.ch/record/2238554)

First observation of beam self-modulation (12 Dec. 2016):

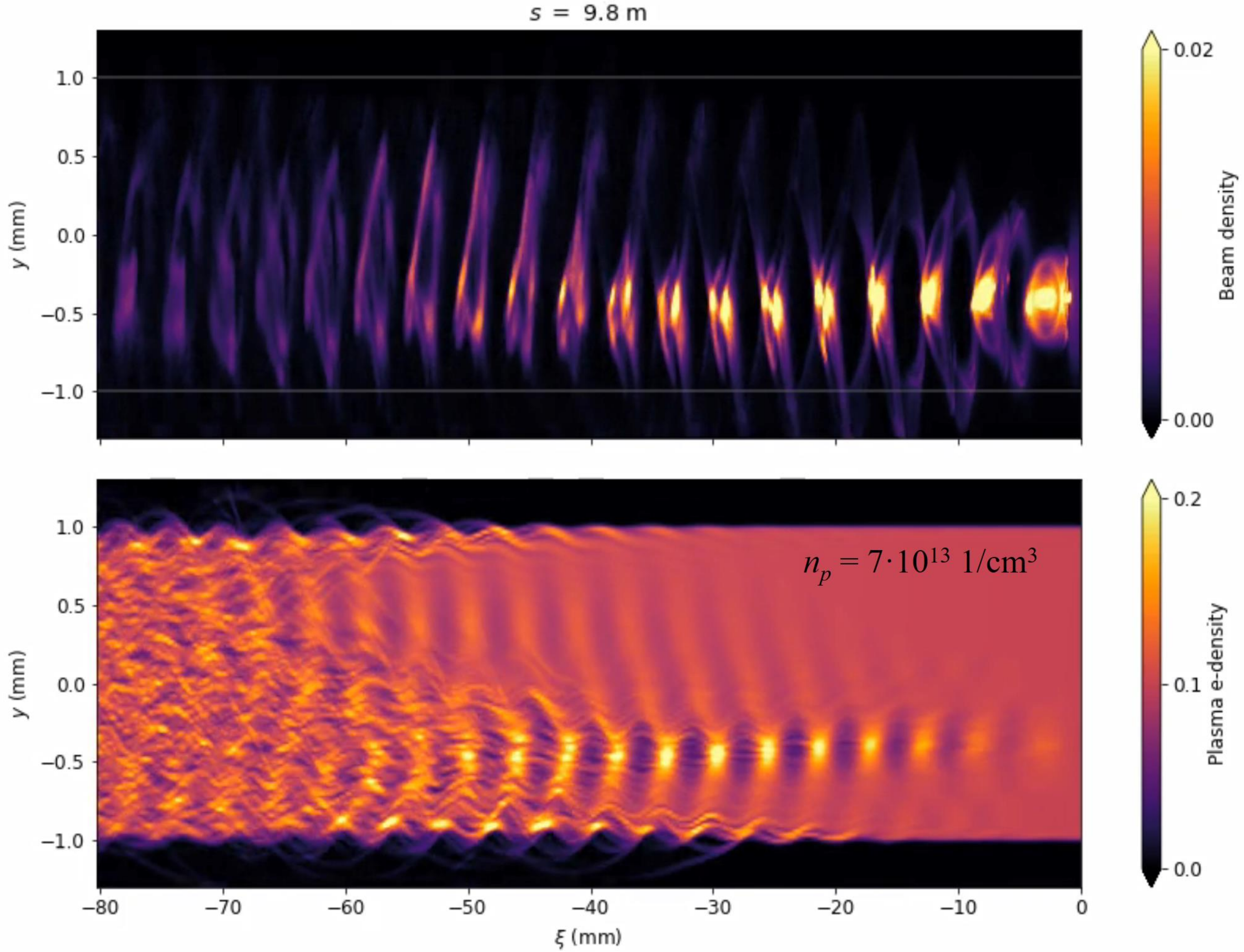
Streak-camera image of the proton beam:
(K. Rieger, MPP)



https://www.mpp.mpg.de/~caldwell/SPC.pdf

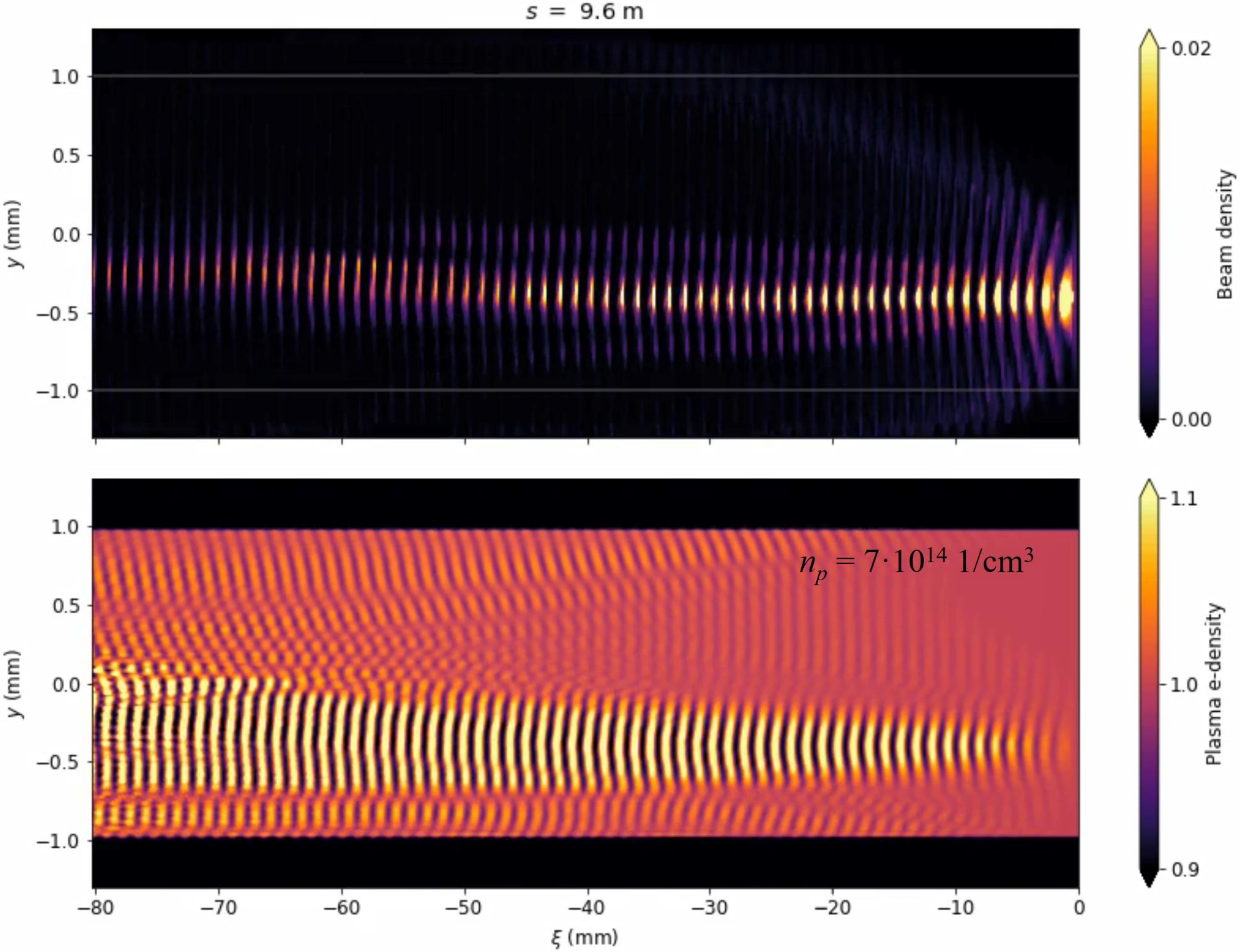
Simulation of misaligned proton beam self-modulation in low-density plasma:

3D quasi-static version of A. Pukhov's VLPL code. See [Particle-In-Cell Codes for Plasma-based Particle Acceleration](), CAS'2015.

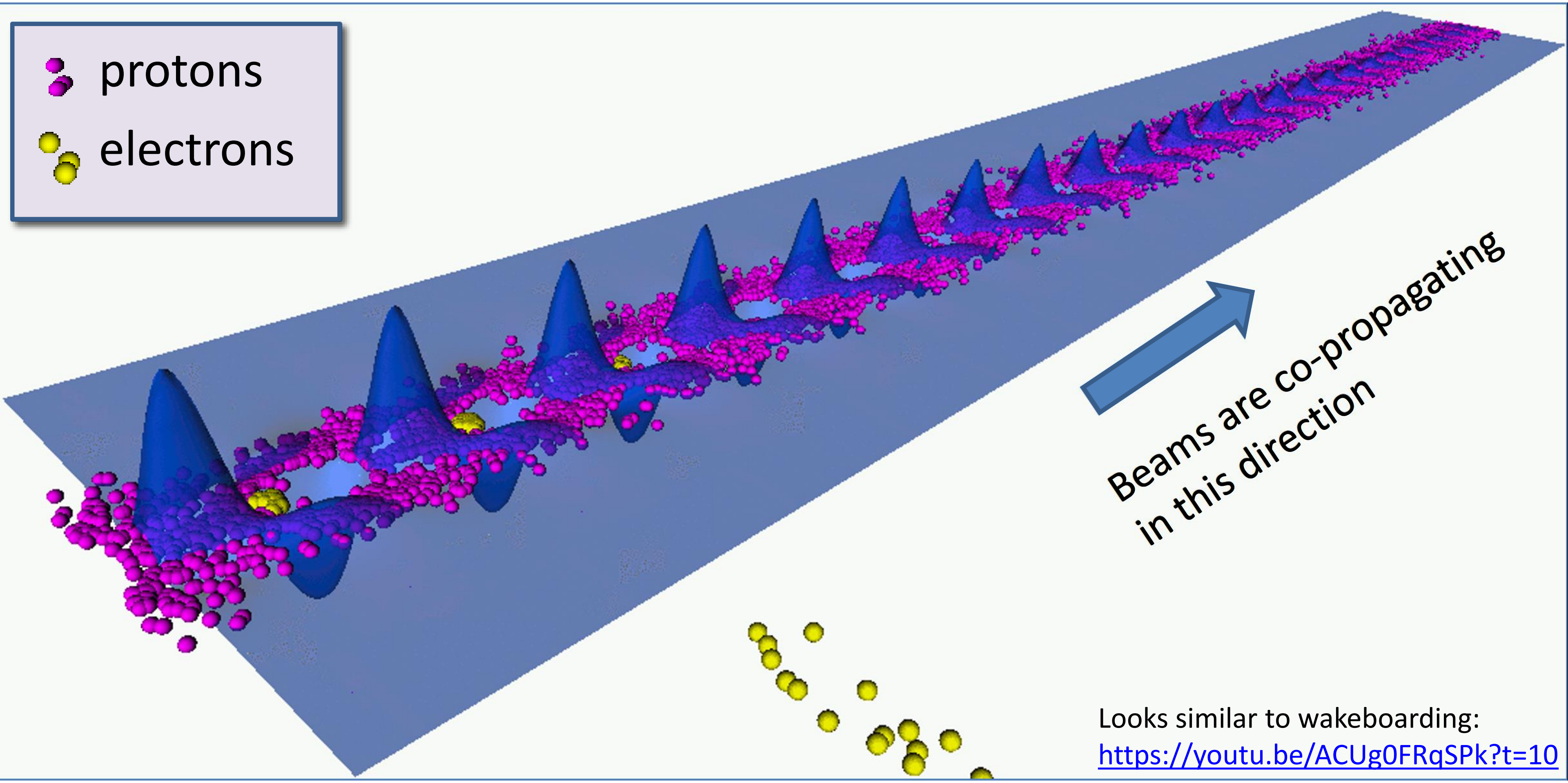


At the design n_p longer train of micro-bunches should be stable with respect to 3D-instability:

3D quasi-static version of A. Pukhov's VLPL code. See [Particle-In-Cell Codes for Plasma-based Particle Acceleration](), CAS'2015.



Next step is to probe the wake-fields by accelerating externally injected electron beam:



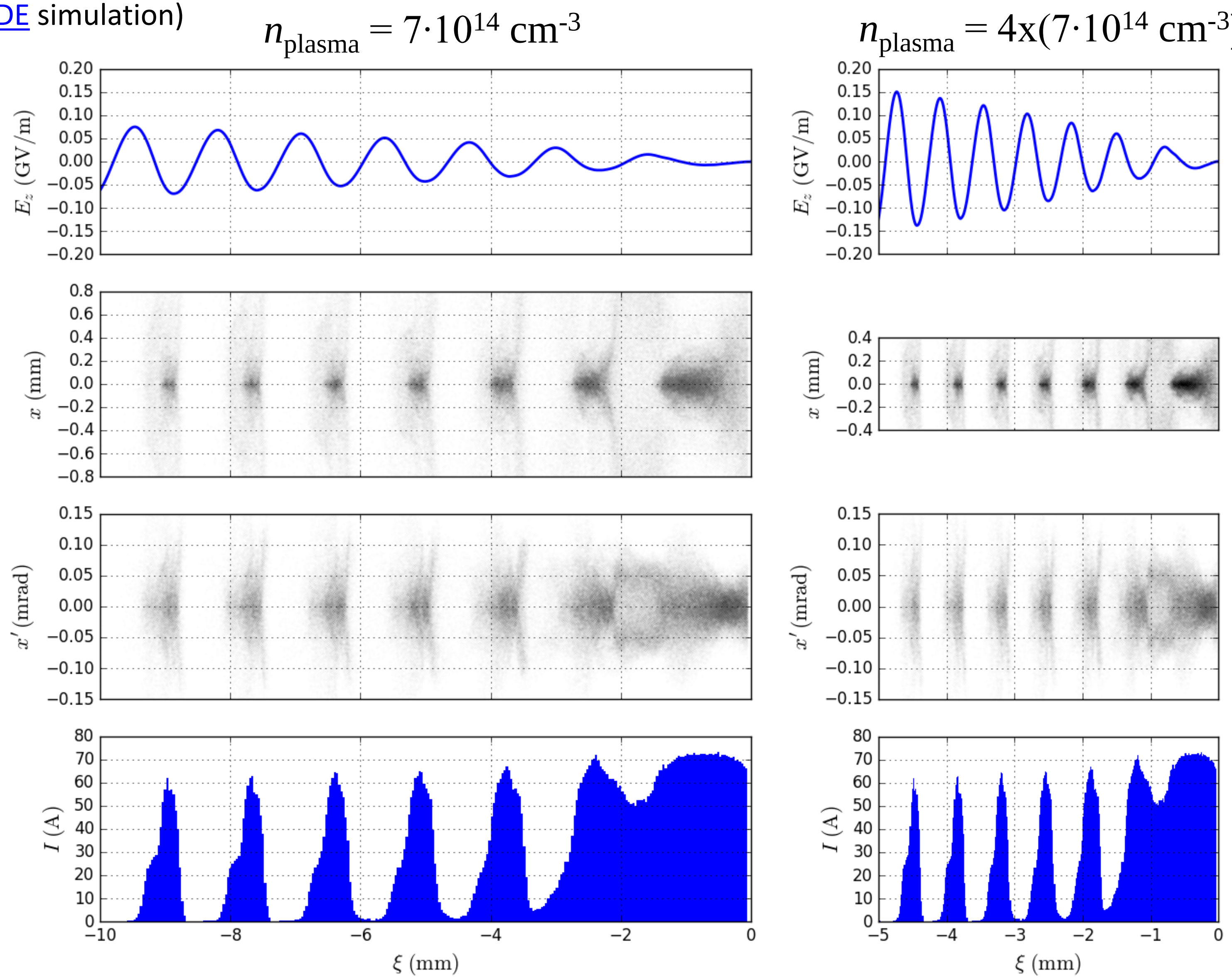
Looks similar to wakeboarding:
https://youtu.be/ACUg0FRqSPk?t=10

Visualization of 2D (cylindrical) simulation in the quasi-static LCODE developed by K. Lotov

See K. V. Lotov, A. Sosedkin, E. Mesyats, "Simulation of Self-modulating Particle Beams in Plasma Wakefield Accelerators" Proc. of IPAC'2013.

General scaling of required beam parameters with plasma density

(LCODE simulation)



2x higher wakefield

2x smaller transv. size => 4x higher beam density.

The same angular spread => 2x lower beam emittance required.

The same current => 2x less particles needed to drive 2x higher wake.
(Also 2x less accelerated particles).

10x less particles with 10x lower emittance and the same beam current will drive 10x higher wakefield.
Maximum plasma density is essentially defined by the transverse beam emittance.
Higher peak current is needed to reduce the number of micro-bunches => less strict tolerances on plasma density.

More ideas

- Many challenges can be solved by using higher quality/shorter hadron beams.
- Hadron beam cooling might be a very interesting option in the future:

1) Optical stochastic cooling of the LHC proton beam
2) Laser cooling of partially stripped ions

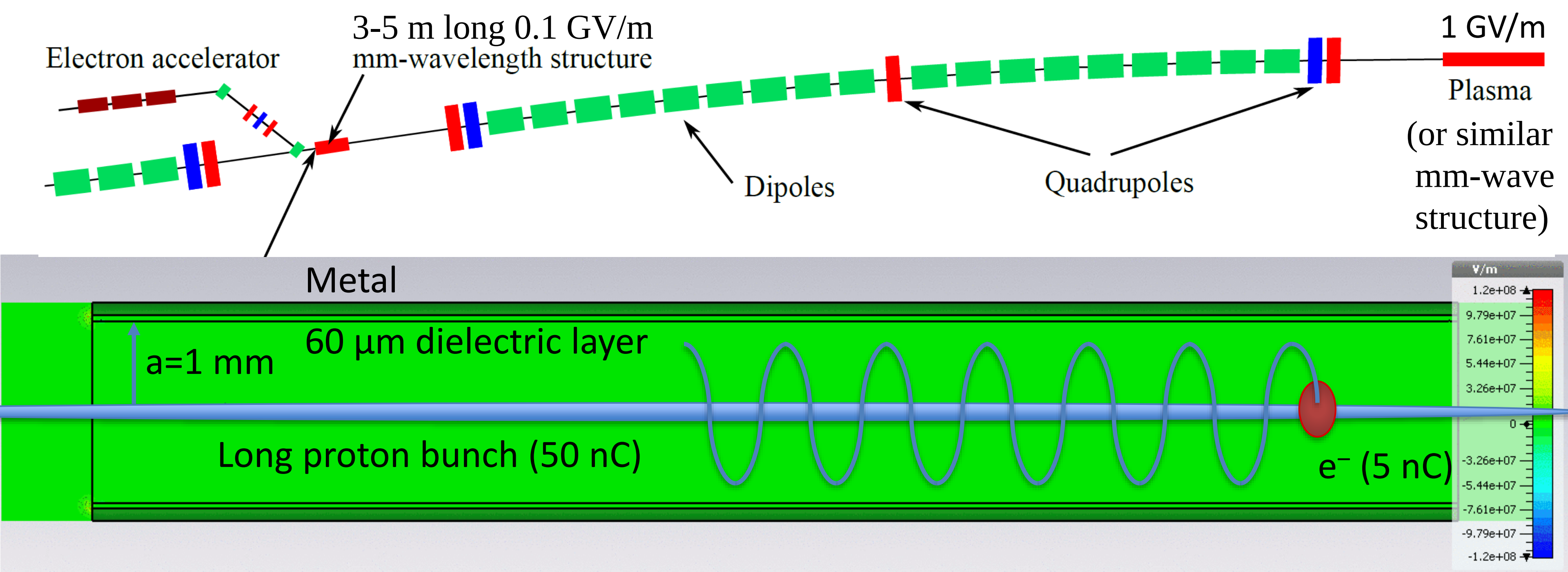
The main problem seems to be the stability of dense beam in the ring. Maybe it is possible to cool a single bunch fast and extract it immediately (there is no need to keep it circulating). In some sense this problem is opposite to what the storage rings are normally optimized for (wakefields and beam-beam effects are normally minimized).

Partially stripped ions in the LHC also can be used as a bright source of ~100 MeV gamma-photons (the proposal for Gamma-Factory based on the LHC).

Summary

- Hadron beam from a high-energy synchrotron can be used as drive beam for a high-gradient linear accelerator.
- Single proton bunch from SPS/LHC can excite the cm-wavelength cavities to ~100 MV/m and mm-wavelength or plasma-based accelerator to ~1 GV/m.
- The AWAKE experiment at CERN is the first R&D experiment to test the concept of proton driven plasma wakefield acceleration based on proton beam self-modulation in mm-wavelength plasma.
- The parameters of such an accelerator are defined by the properties of the drive beam. Hadron beam cooling can help to scale this technology to higher accelerating gradients.

Back-up slides



$$E_z \propto Q/a^2$$

$$E_\perp \propto Q/a^3$$ (for misaligned beam)

Transverse wake-fields caused by a misaligned beam can lead to beam break-up instability.

Still even more ambitious 20 m long mm-wavelength dielectric linacs are seriously considered in ANL:

Strong external quadrupole focusing is required:

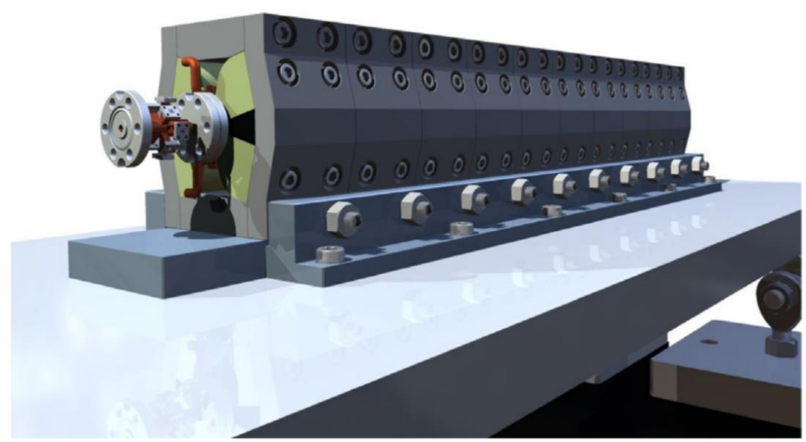
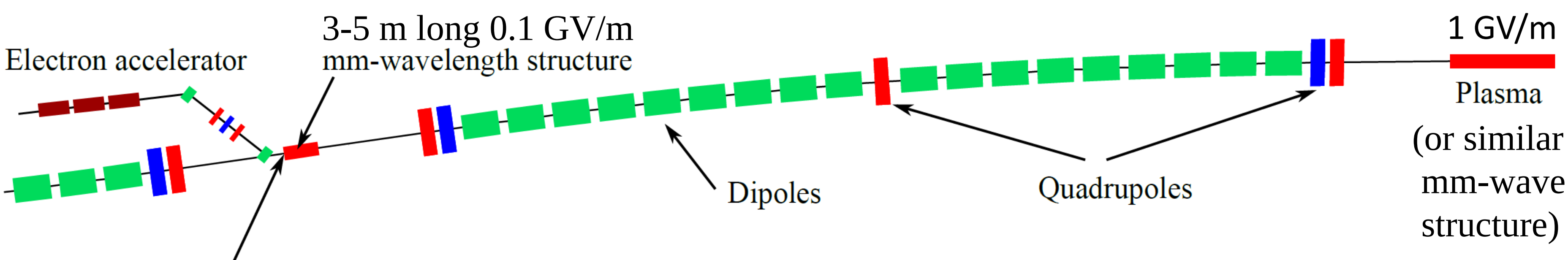
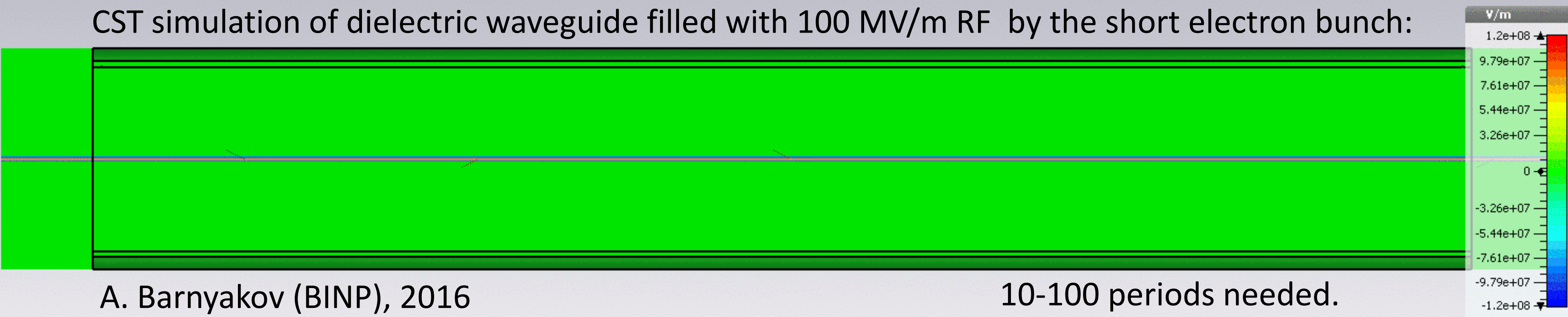


Fig. 2. A quadrupole wiggler.

A. Zholents et al. A preliminary design of the collinear dielectric wakefield accelerator. NIM A 829 (2016). Also see FEL-2014 Proceedings.



CST simulation of dielectric waveguide filled with 100 MV/m RF by the short electron bunch:



A. Barnyakov (BINP), 2016

10-100 periods needed.

$$E_z \propto Q/a^2$$

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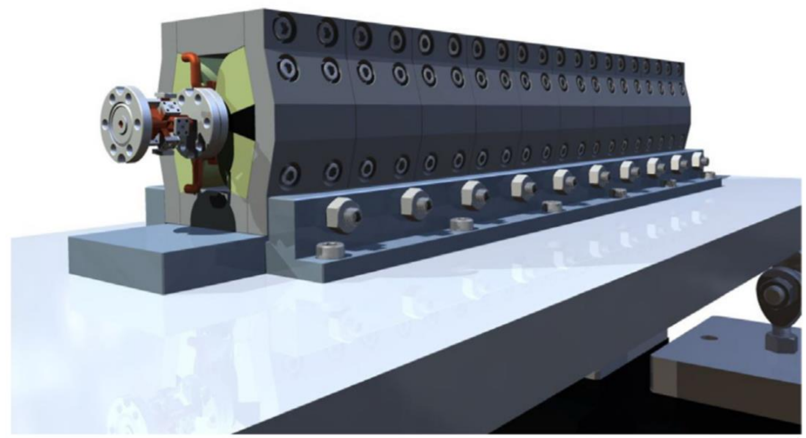

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A. Zholents et al. A COLLINEAR WAKEFIELD ACCELERATOR FOR A HIGH REPETITION RATE MULTI BEAMLINE SOFT X-RAY FEL FACILITY. FEL2014 proceedings:

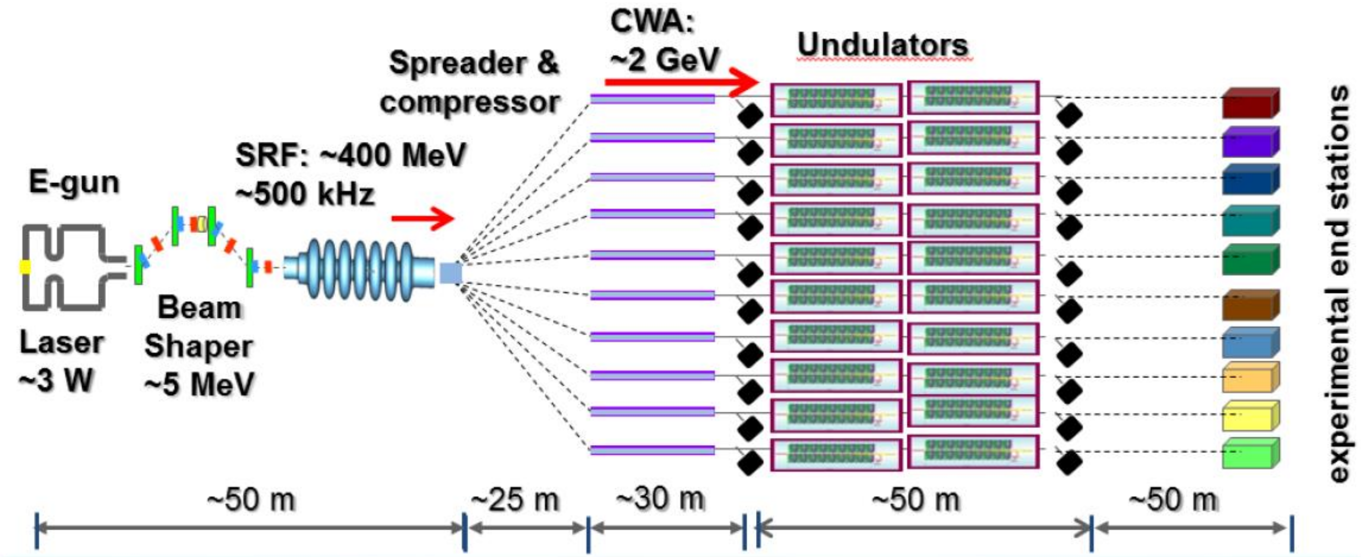
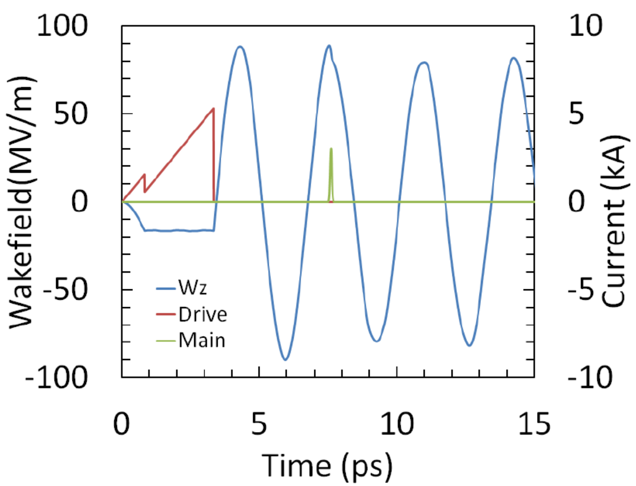
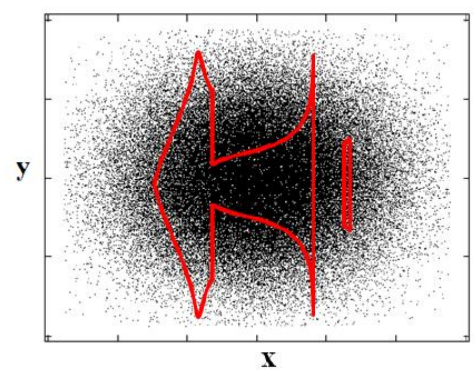


Figure 1: A schematic of the FEL facility showing (not to scale) an electron gun, bunch shaping section, cw superconducting linac, spreader and transport lines, an array of collinear wakefield accelerators, undulator arrays, and x-ray beamlines.





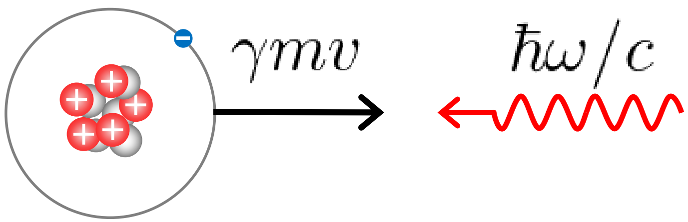
400 MeV high-current beam can drive the 2 GeV, 20 m long dielectric linac in this case.

Yu. Shchegolkov, E. Simakova. Design of an emittance exchanger for production of special shapes of the electron beam current. PR ST-AB 2014.

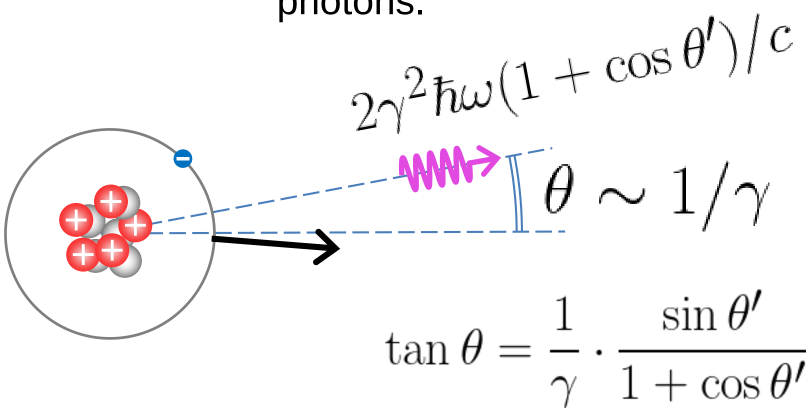
Laser cooling of partially stripped ions (Sep. 20 talk on cooling)

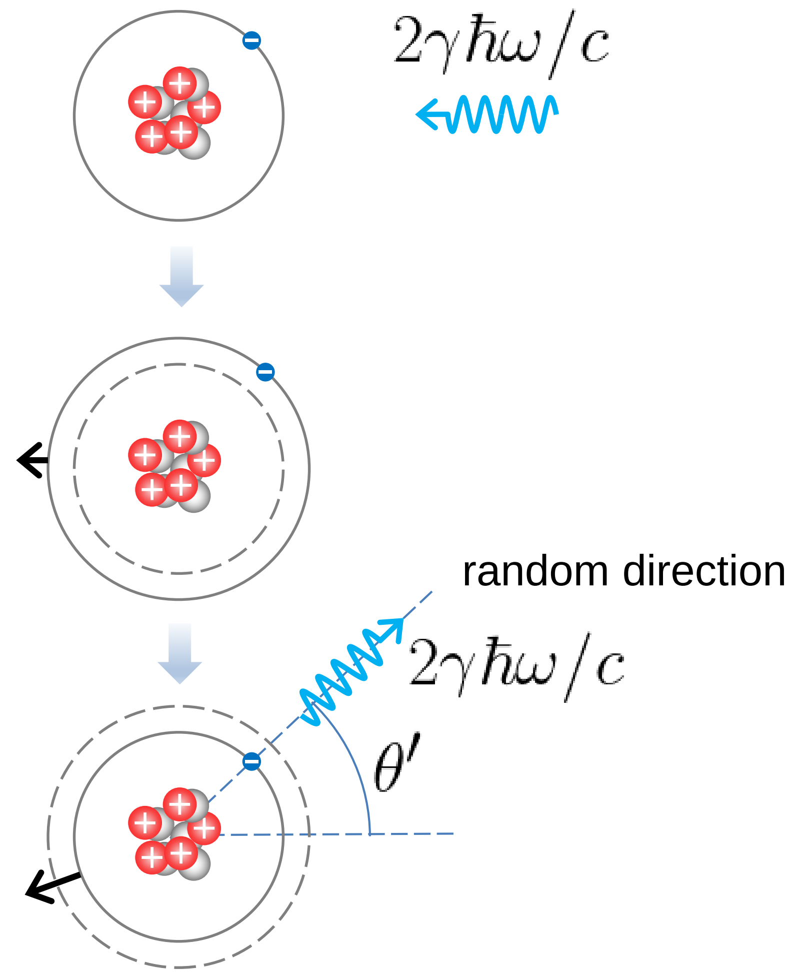
Synchrotron radiation of protons is weak below 10 TeV, but we can cool a beam of partially stripped ions using backscattering of laser radiation.

In the lab frame:	In the ion's frame:



Already in the SPS (gamma = 100-200) visible light (1-3 eV) is scattered back as ~100 keV photons.



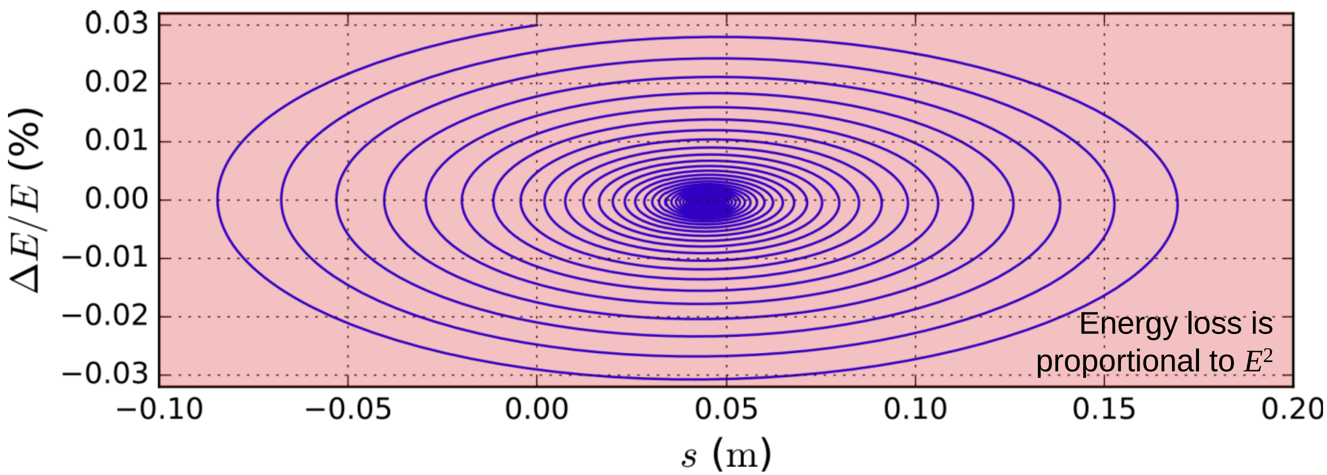


Laser cooling of partially stripped ions

The natural width of the absorption line (~10^{-6}) typically << Doppler shift due to energy spread (~10^{-4})

1. Broad-band laser covers the full spectrum of particle energies:

See: E. G. Bessonov and K.-J. Kim. [Radiative Cooling of Ion Beams in Storage Rings by Broad-Band Lasers](), PRL, 1996.

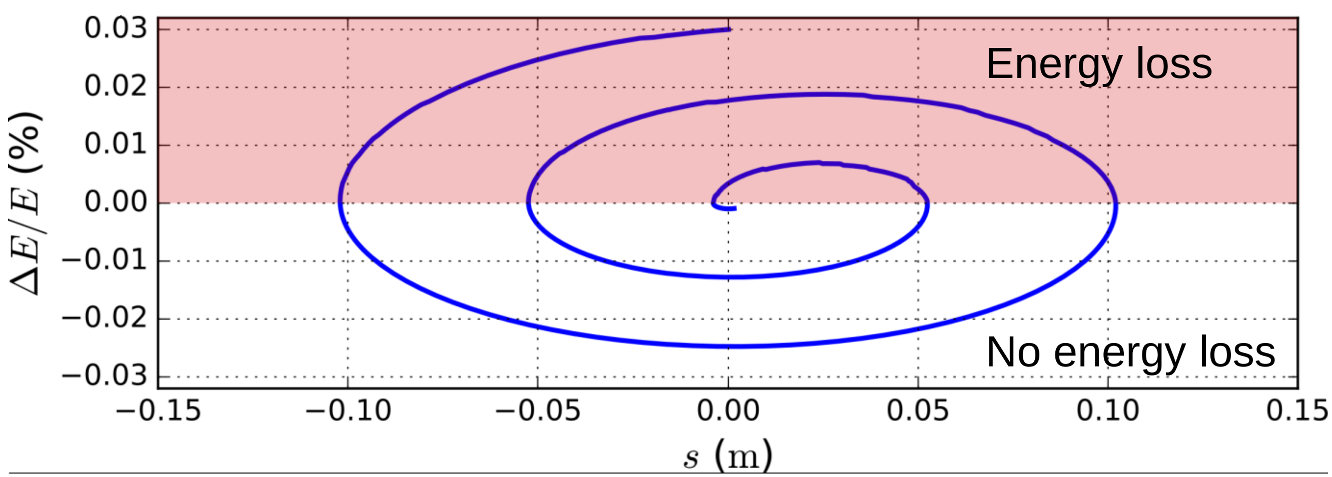


Cooling in all planes. The time of cooling is the time to **radiate full ion energy** E.

For the SPS at gamma = 200, and Z = 14 (H-like Si), scattered light ~100 keV => assuming ~100 scatterings per ion per turn (intense laser) $N_{\text{turns}} \sim 200 \cdot 14 \cdot 2 \cdot 0.932$ GeV / (100e-6 GeV · 100) ~ 10^6 turns or 20 sec (almost fast enough!)

2. Broad-band laser with a sharp low-frequency cut-off:

See: E. G. Bessonov, R. M. Feshchenko [Stimulated Radiation Cooling](). RuPAC'2008.



Much faster cooling, but only longitudinal. Time of cooling is the time to **radiate energy spread** ΔE.

Similar estimate for the SPS gives ~100 turns. This method is fast enough for the SPS even with only one scattering per ion per turn (t_{cool} ~ **0.1 sec**)