Review of plasma acceleration

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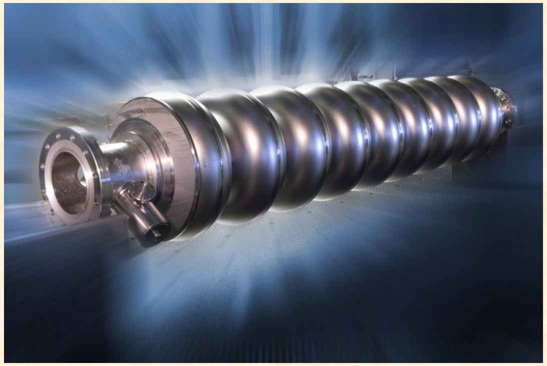
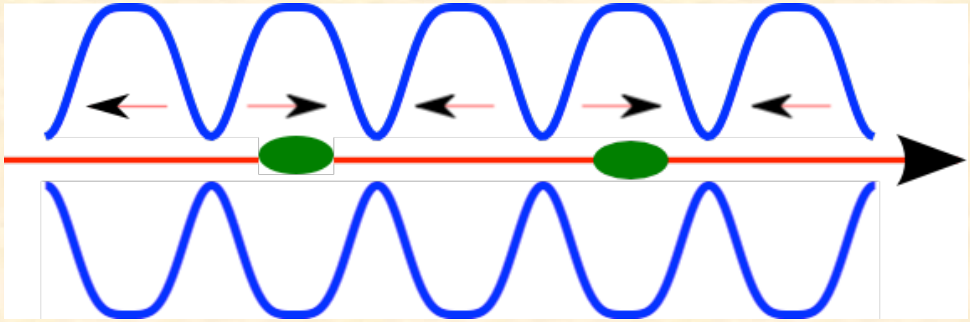
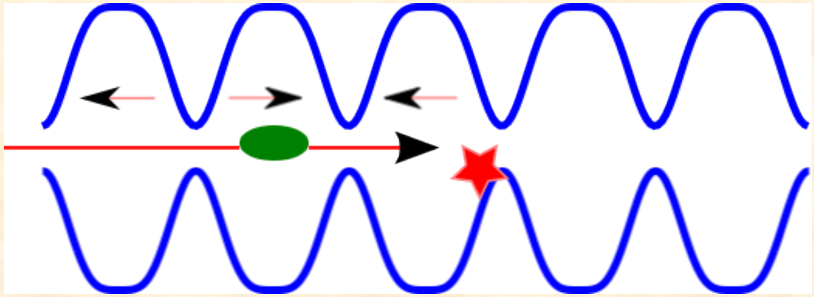
Limitations of current acceleration techniques

- In an accelerator particles are accelerated by an electromagnetic wave creating an accelerating gradient when the particles pass.





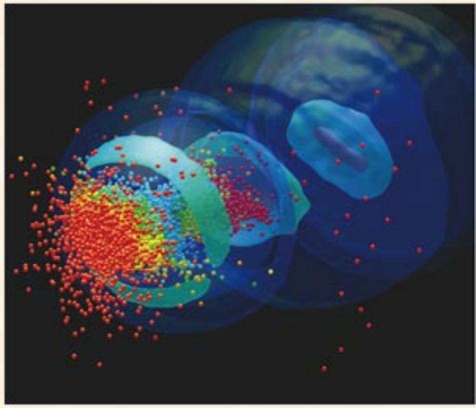
- If the gradient is too high an imperfection in the cavity may concentrate too much EM power and create a spark (breakdown) leading to the loss of the beam and possible damages to the cavity.
- So far accelerating cavities are limited to less than 100MV/m.



Plasma acceleration

- If the cavity is replaced by something that can not be damaged, much higher accelerating gradients can be reached.
- This can be done by creating a wake field in a plasma.
- Different tools are used to create such plasma accelerator:
  - Lasers (Tajima and Dawson, PRL, 1979)
  - Electron beams (Hogan et al., PRL, 2005)
  - Proton beams (Caldwell et al., Nature Phys., 2009)

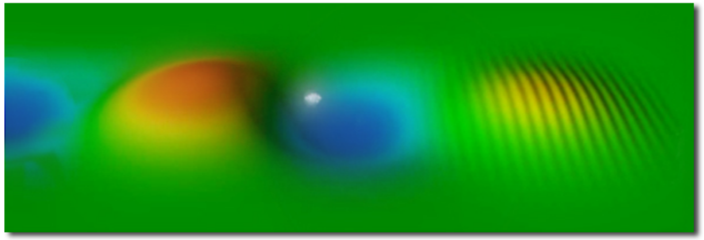
Example of wake field
Source: http://www.arwenmarine.com



Wakefield in a plasma
Source: CERN Courier

Wake field

- A high intensity beam travelling in a plasma leaves a wake behind, like a boat on the sea.
- Particles can surf that wake field and be accelerated.
- This is the basic principle of plasma acceleration.

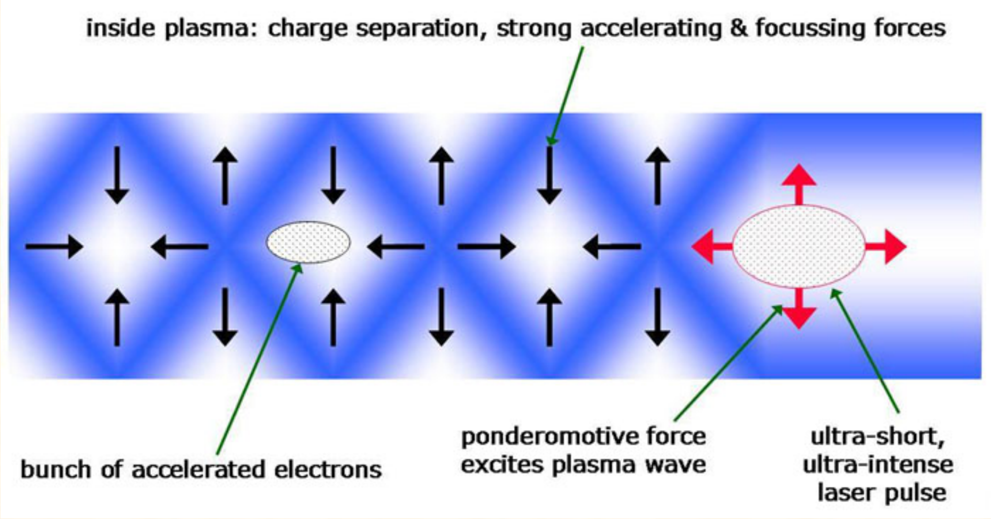


Ponderomotive force

- The force that accelerate the particles in the plasma is the ponderomotive force.

$$F_P = -\frac{e^2}{4m\omega^2}\nabla E^2$$

- The oscillation frequency will depend on the nature of the plasma and in particular to its density.
=> different plasma densities will lead to different acceleration regime.

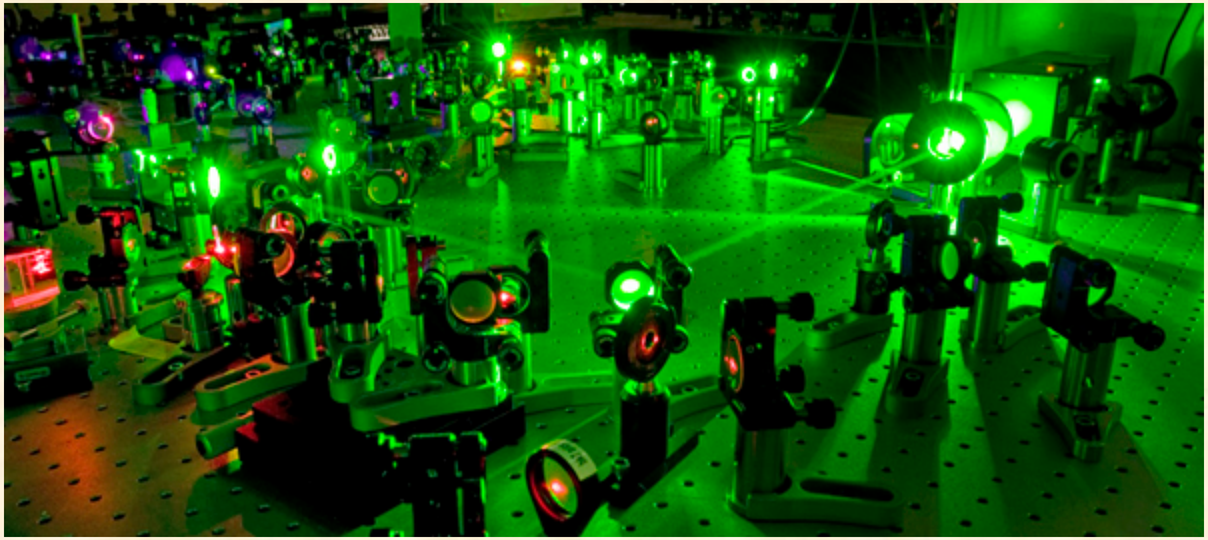


Source: http://phys.strath.ac.uk/alpha-x/pub/Project/lwfa.html

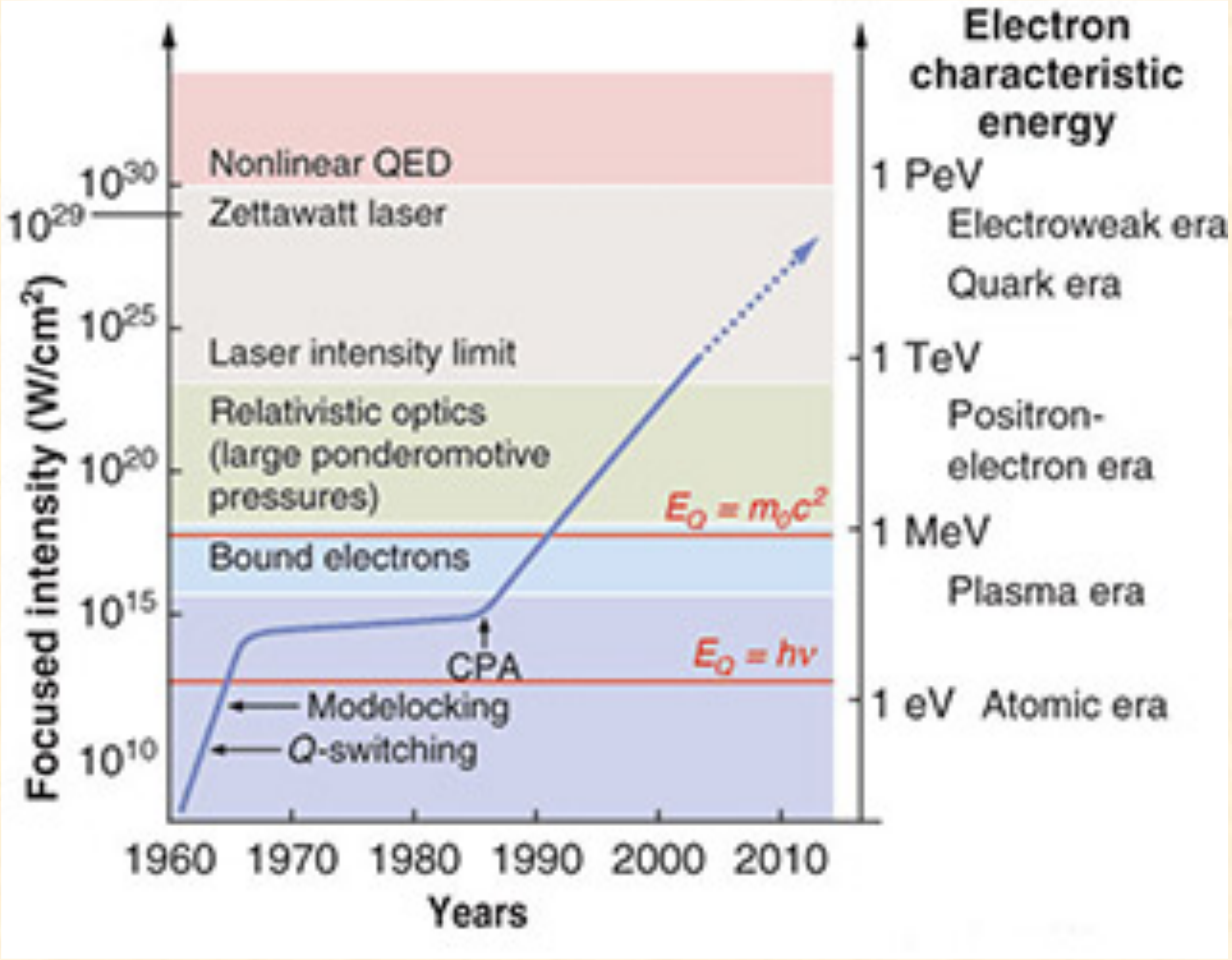
Laser-driven and bean driven

Different type of beams can be used to generate such wake field:

- high intensity lasers (100 TW, PW class)
  => this is done in many laser/plasma labs
- charged particle beams (e-, e+, p,…)
  => SLAC and soon CERN



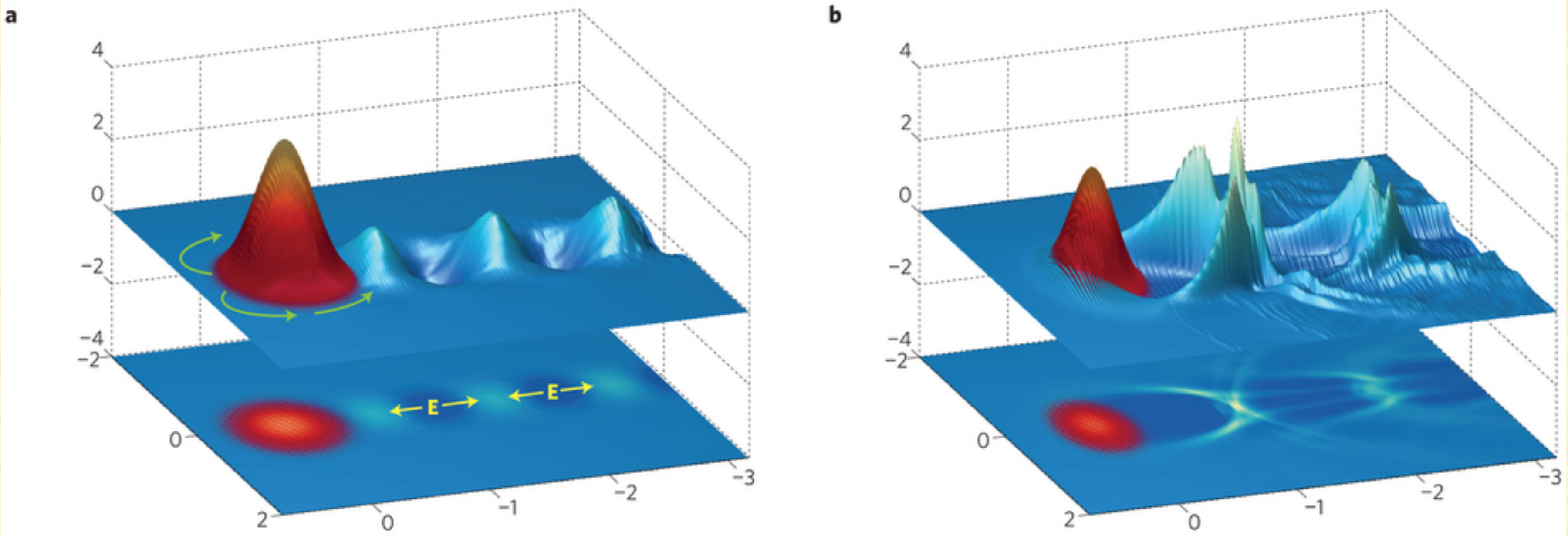
Progress in laser technology



Plasma regime

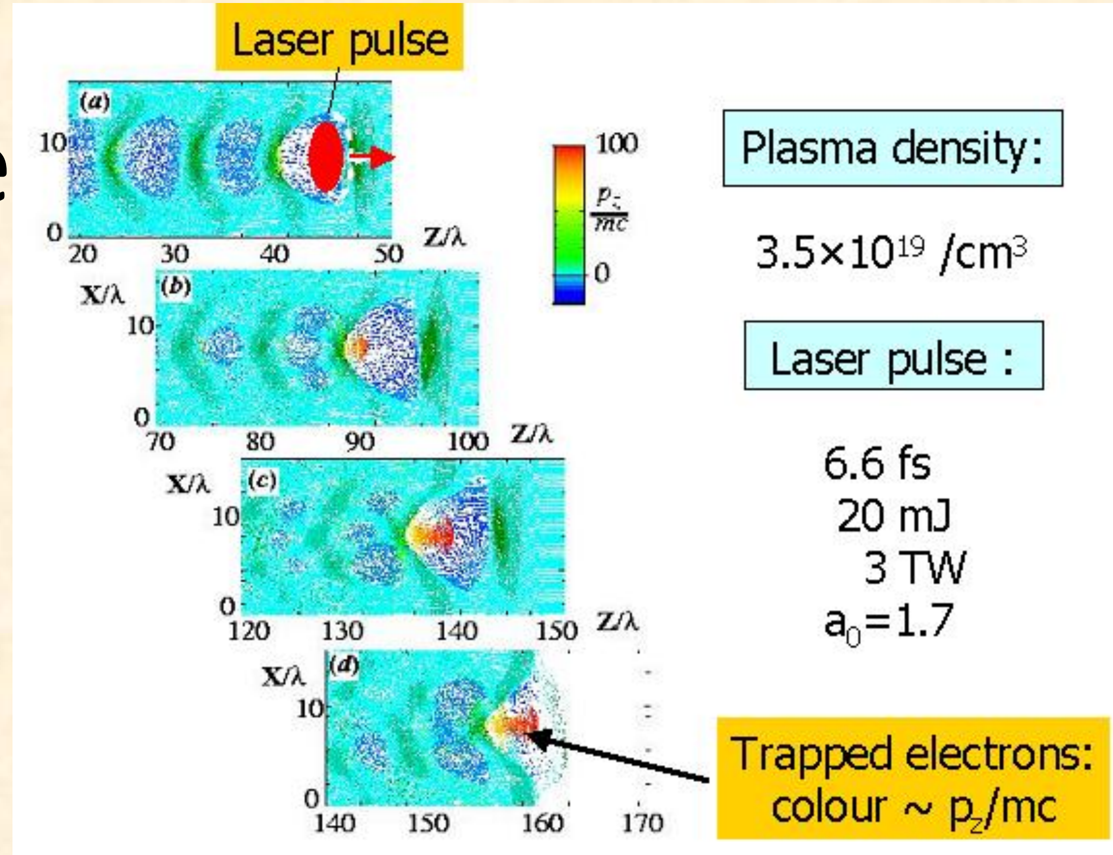
$$a_0 = \frac{eE_0}{m_e \omega c}$$

- Different laser intensities or different plasma densities lead to different wake field regime.
- Left: moderate laser power (a_0=0.5) => Linear regime
- Right: much stronger laser power (a_0=4) => non linear, formation of a bubble/cavity



S.M. Hooker, Nature Photonics 7 775 (2013). DOI:10.1038/NPHOTON.2013.234

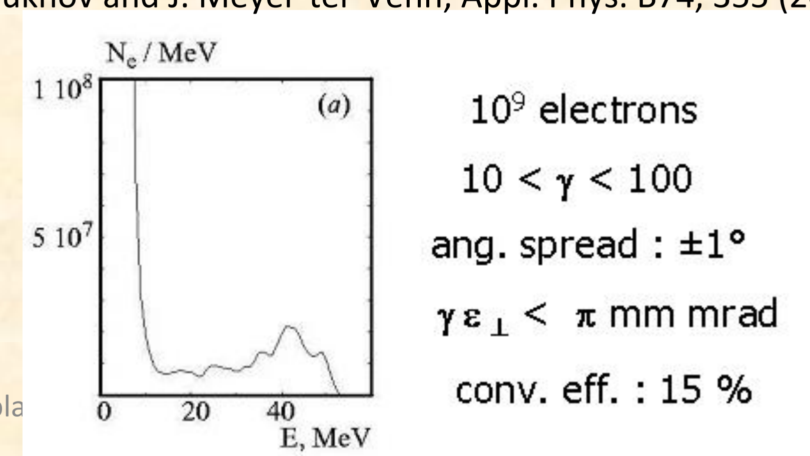
Bubble regime



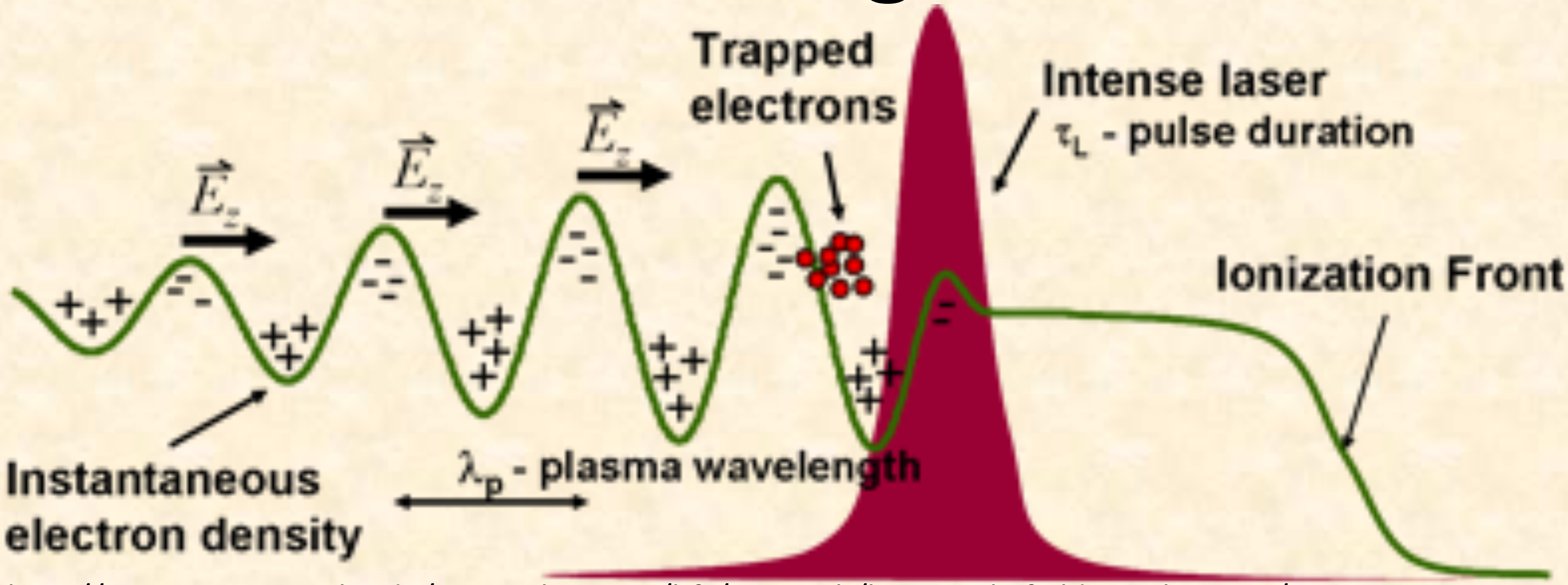
In the bubble regime some "wavebreaking" occurs: at the back of the bubble some plasma electrons "fall" in the bubble and are accelerated by the ponderomotive force.

However this will lead to large energy spread and large divergence.

http://www.mpq.mpg.de/lpg/research/LWFA/LWFA.html
A. Pukhov and J. Meyer-ter-Vehn, Appl. Phys. B74, 355 (2002)



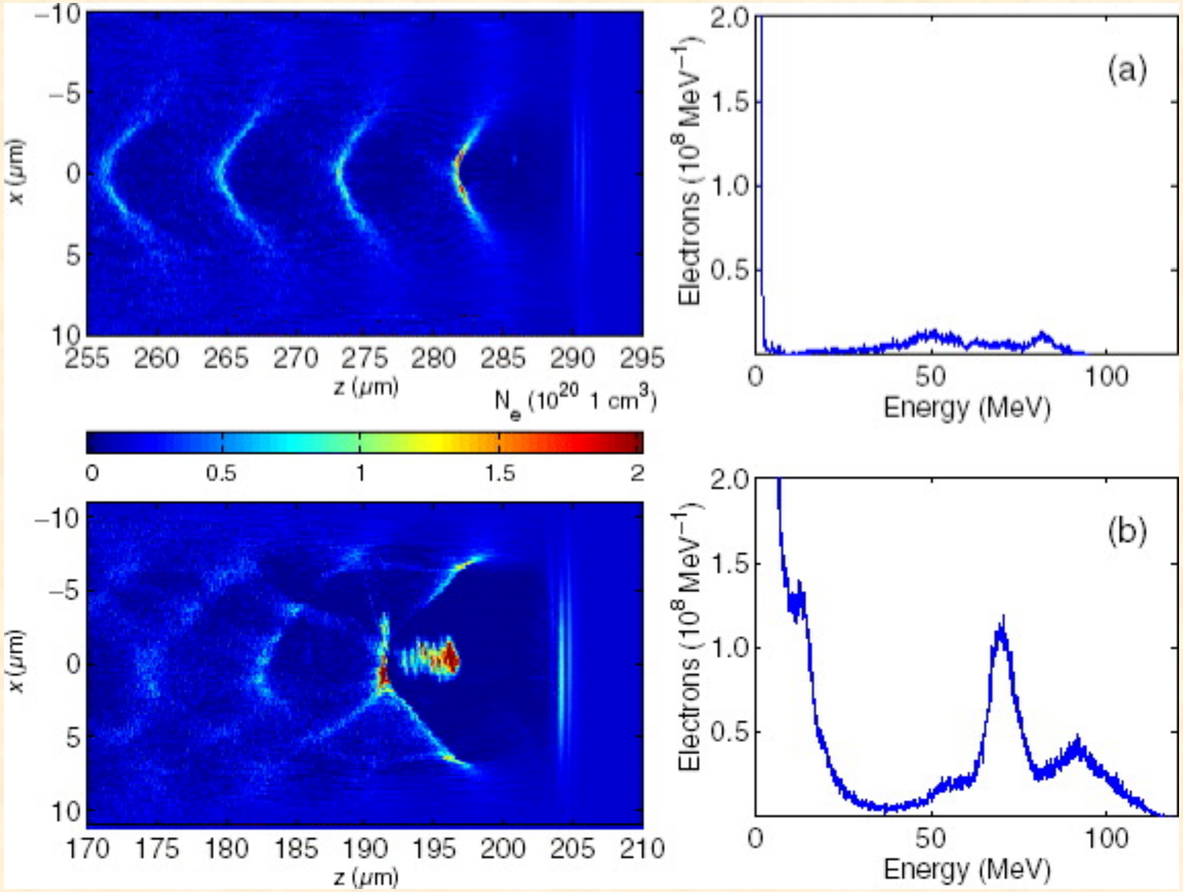
Linear regime



http://cuos.engin.umich.edu/researchgroups/hfs/research/laser-wakefield-acceleration/

- In the linear regime the waves are more regular and the acceleration better controlled.
- However, the electrons need to come from an external source…

Effect of laser density



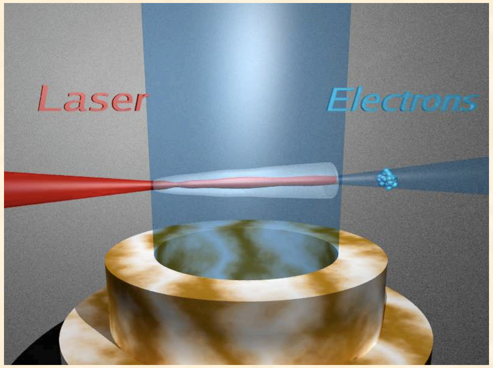
- Top: linear regime
- Bottom: bubble regime
- http://iopscience.iop.org/1367-2630/12/4/045005/fulltext/ Geissler M *et al* 2006 *New J. Phys.* **8** 186

Laser speed in plasma

- The laser does not propagate at c in the plasma, whereas electrons that reach an energy of a few MeV do.
- There will be a slippage between the electrons and the laser.
- This limits the acceleration length.
- As the speed of the laser depends on the plasma parameters, the maximum acceleration length will also depend on the laser parameters…
  ... As does the Ponderomotive force!

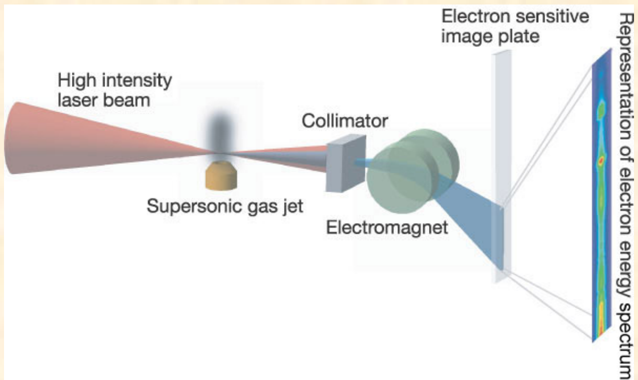
"Dream beam" in the bubble regime

- In 2004, 3 groups manage to achieve significant acceleration:
  86 MeV to 170MeV.
- Nature: "dream beam" papers
  - RAL/IC/UK: Mangles et al.
  - LOA/France: Faure et al.
  - LBNL/USA: C.G.R. Geddes et al.

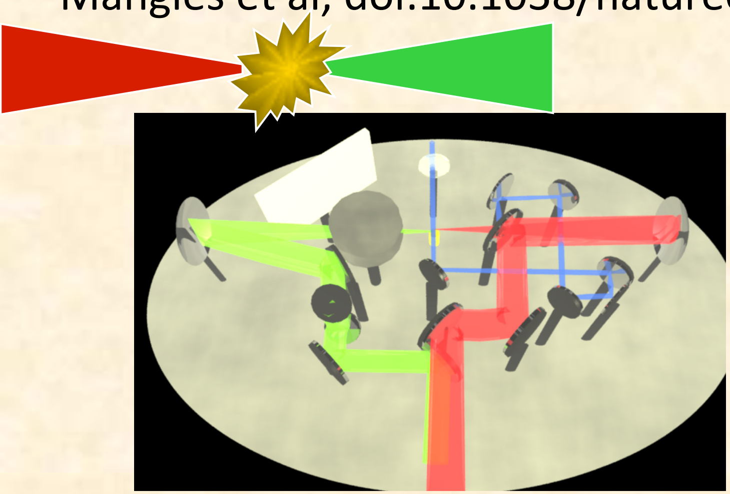


Dream beam…

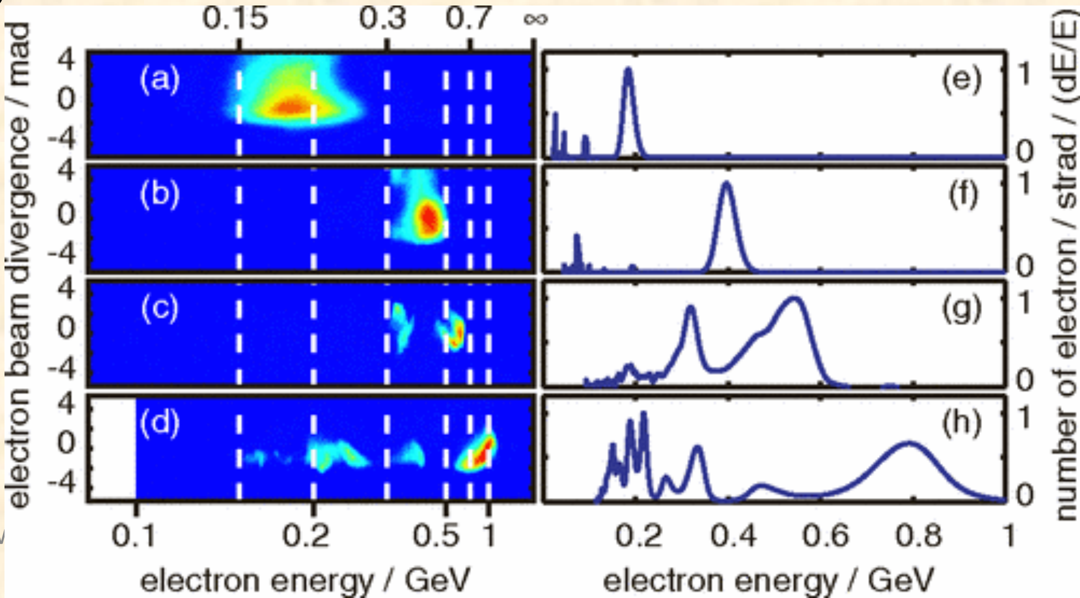
- In each case the electrons were accelerated in a gas jet.
- In 2008 about 800 MeV were achieved Phys. Rev. Lett. 103, 035002



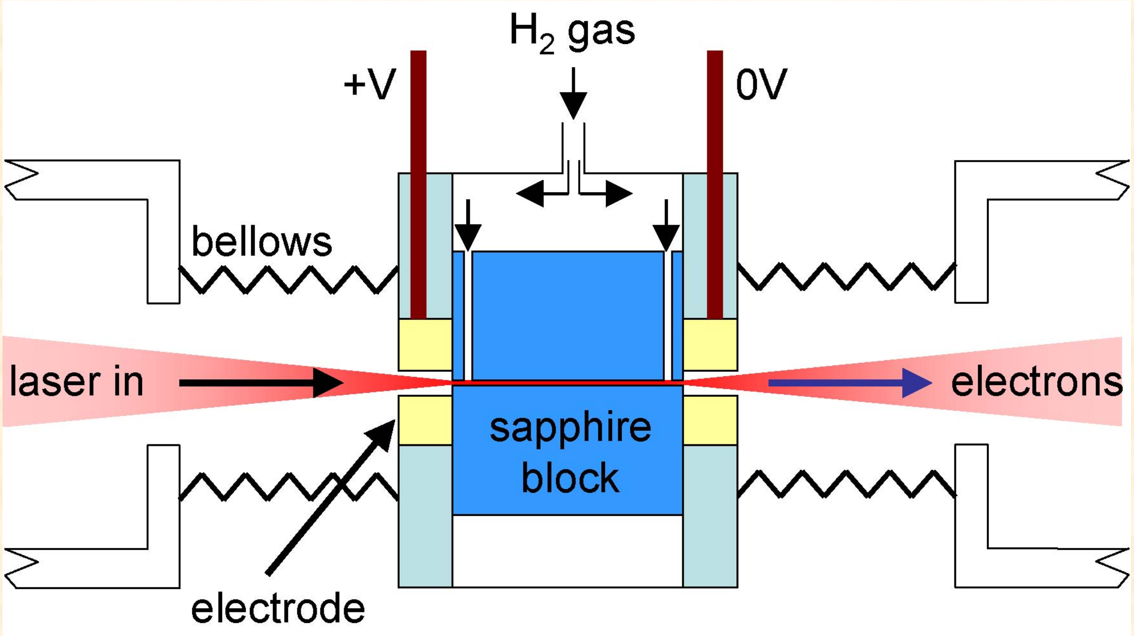
Mangles et al, doi:10.1038/nature02939



Faure et al., doi:10.1038/nature05393

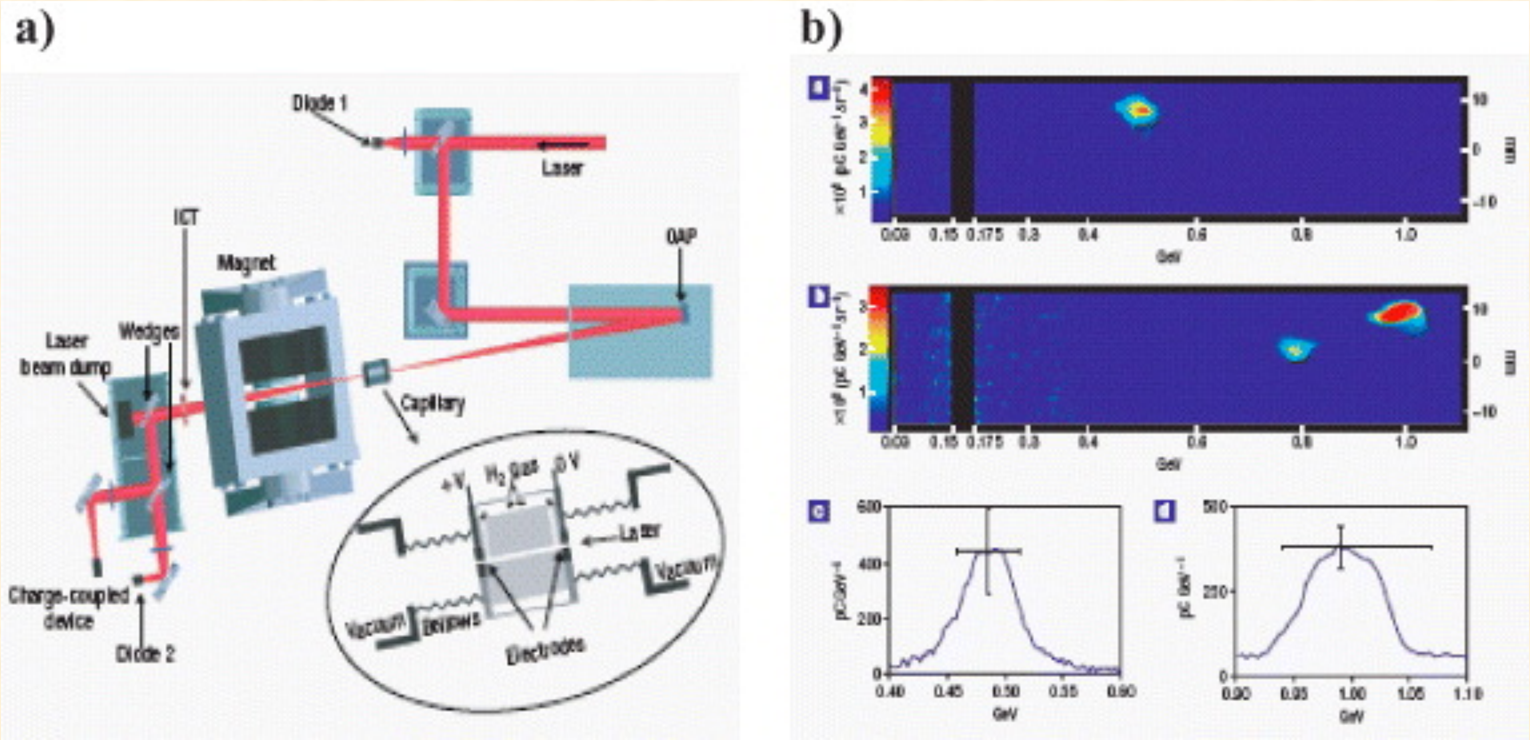


Acceleration in a capillary



- One solution to reduce the plasma density while keeping a long acceleration length is to contain the gas in a capillary.
- In some case plasma ionisation can be aided by a discharge in the gas.

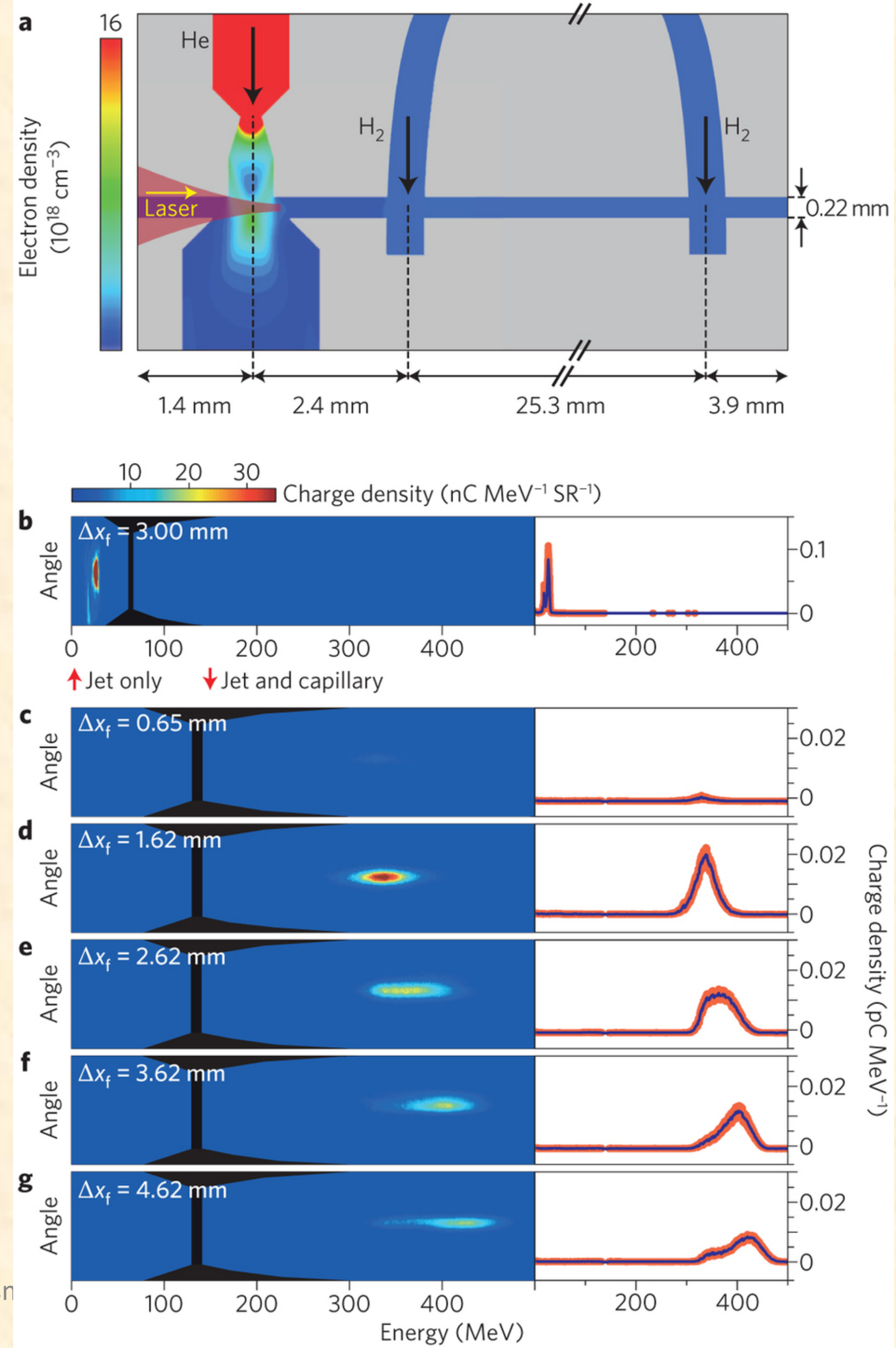
Acceleration with a capillary (2)



- In 2006, one group achieved 1 GeV by accelerating using a 33mm long capillary.

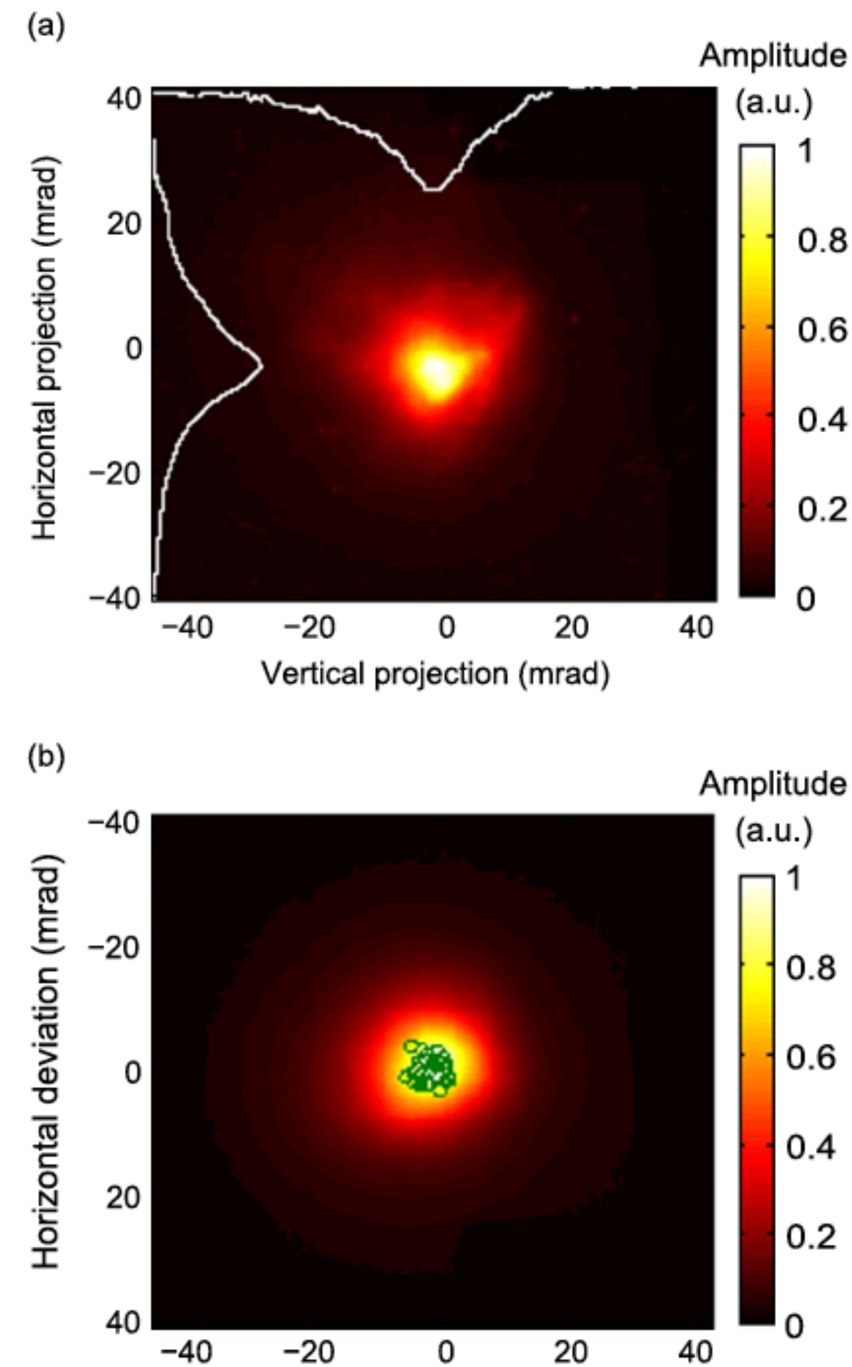
Effect of a density ramp

- By playing on the plasma density (gas pressure) it is possible to control the energy of the accelerated electrons.



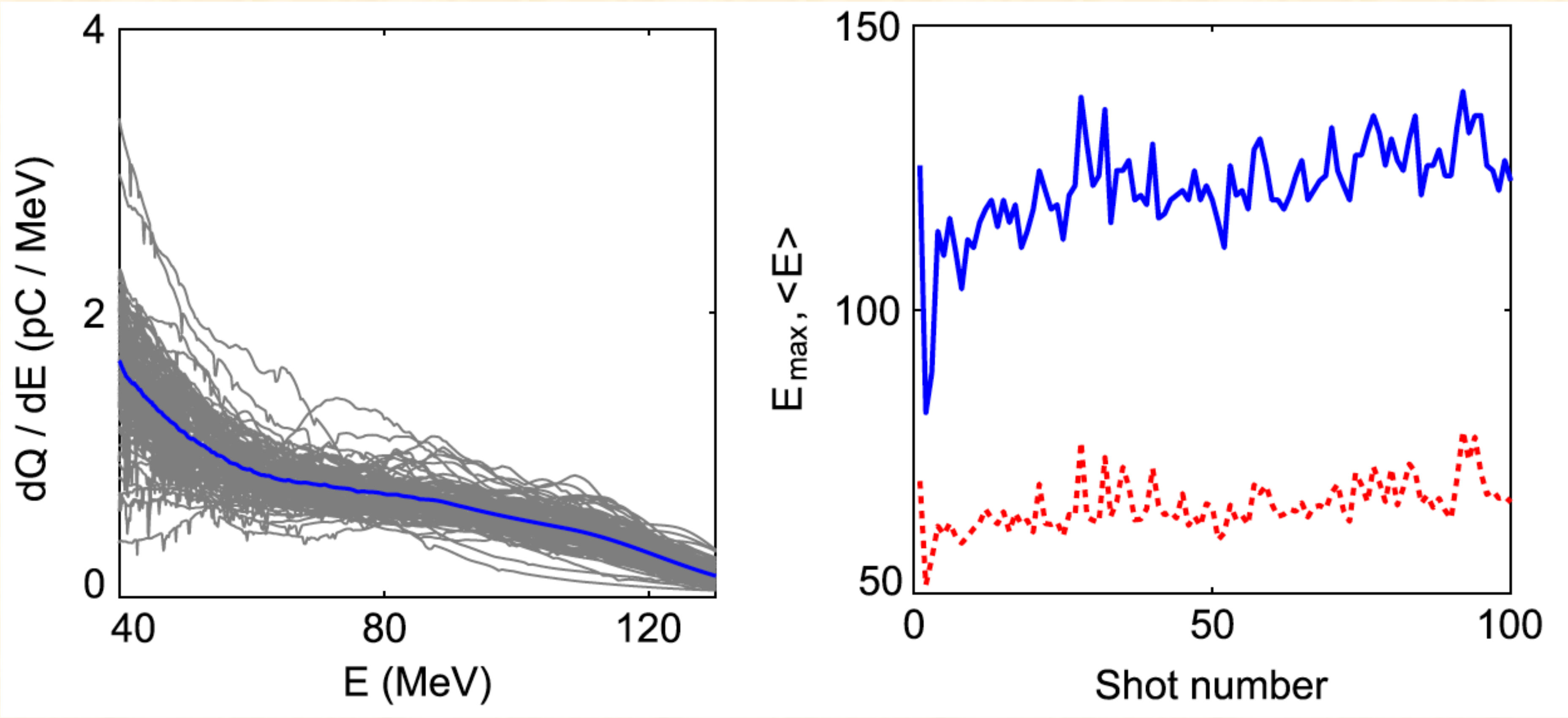
Typical gradient and beam properties

- The accelerating gradients achieved can be very high (1 GeV over 33mm).
- However it is not directly possible to put 2 accelerating cells after each other…
- Because the laser pulse is short the beams are also usually very short, but the measure is very difficult.
- Emittance transverse is small, dominated by the large divergence of the beam.
- Shot to shot stability is a problem…



F. Desforges et al *NIM A740, pp.54-59* (2014)

About beam stability & energy spread

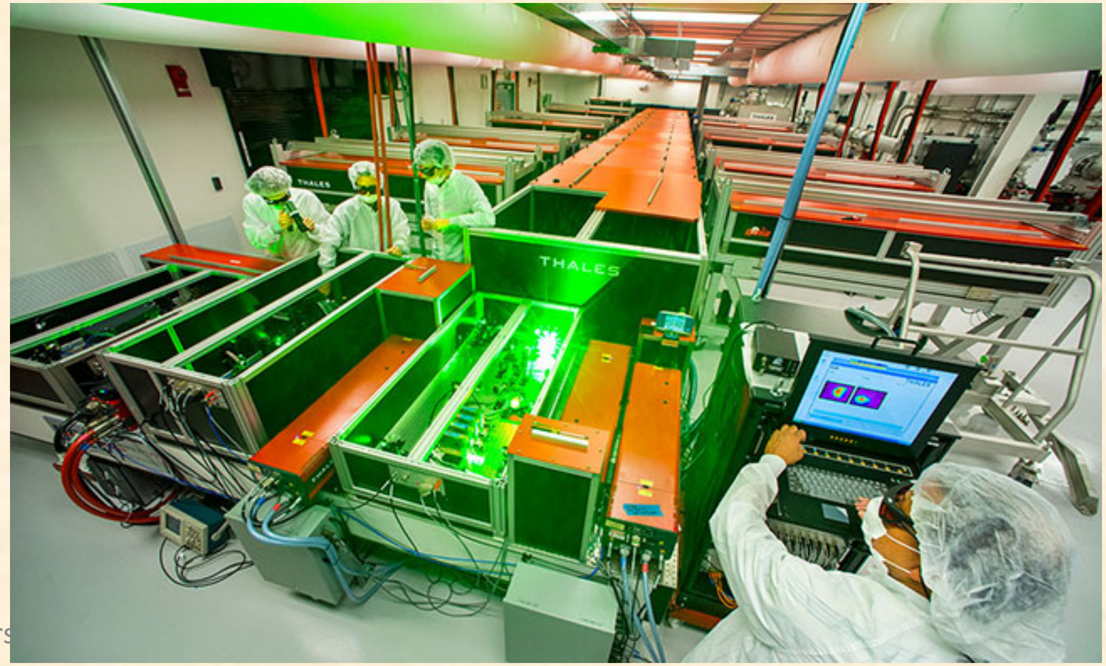


F. Desforges et al *NIM A740, pp:54-59* (2014)

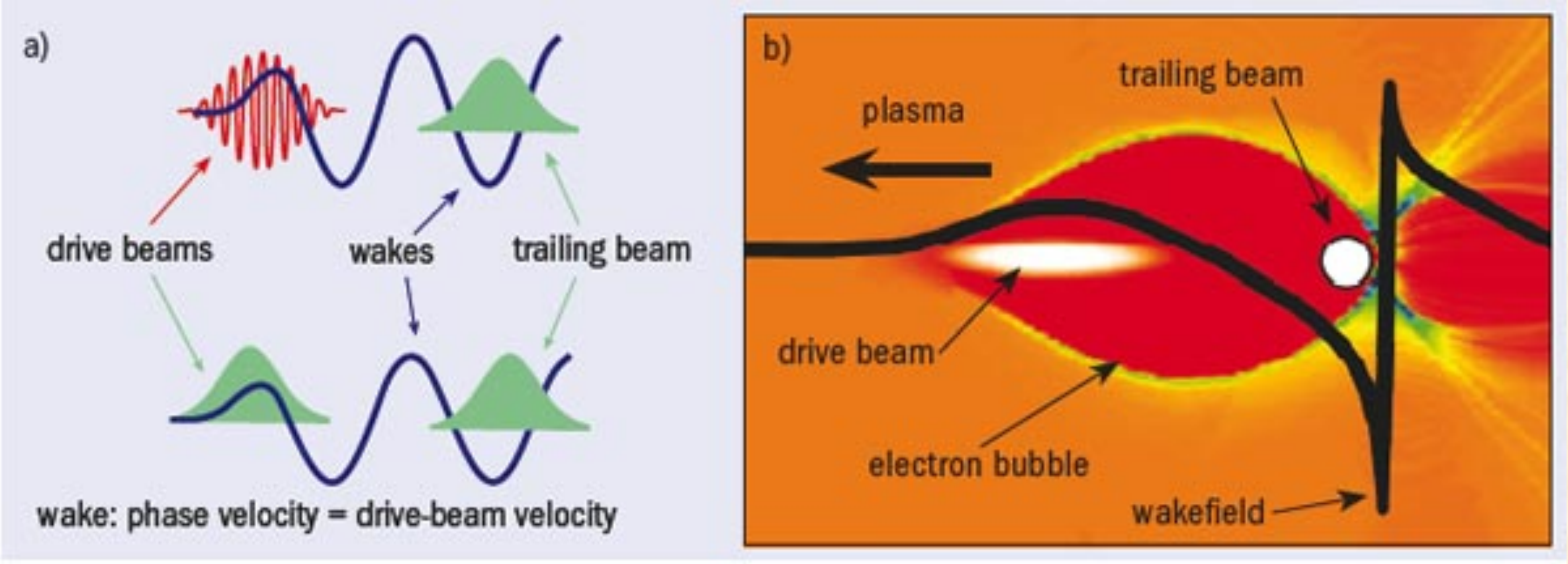
- Energy spread and shot to shot stability different from typical accelerator.

The BELLA project at LBL

- Following the success of the 2006 Oxford-LBL experiment Wim Leemans has received a big grant to build a large laser facility dedicated to laser-driven plasma acceleration.
  => BELLA project, aim: 10 GeV

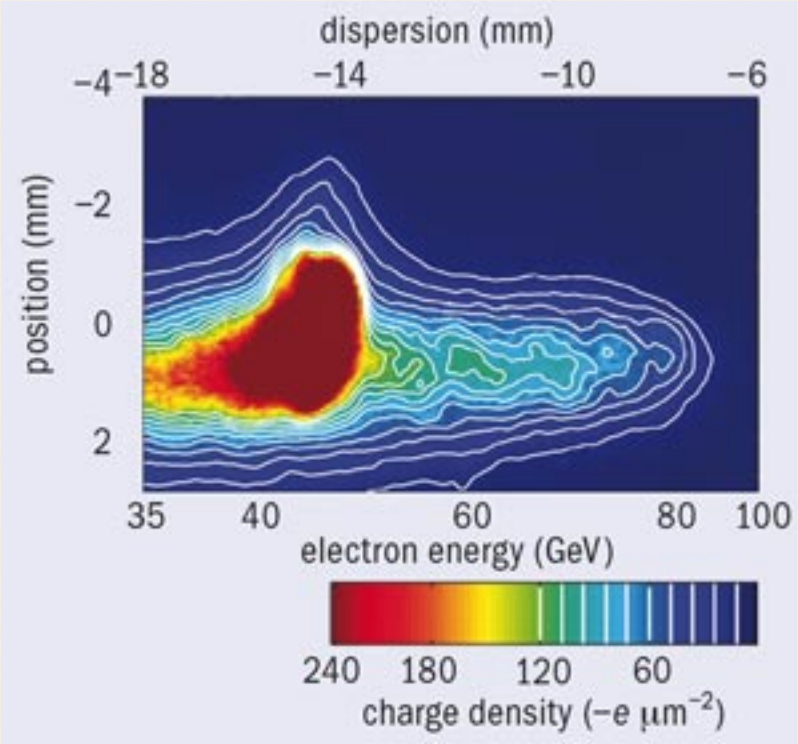


Beam-driven plasma acceleration



- The wakefield can also be created by a beam of charged particles.
- Here also there will be linear and non linear regimes.

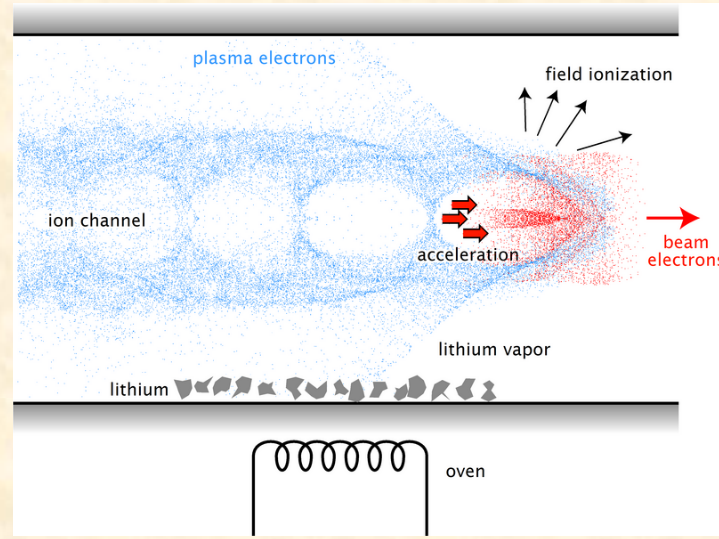
SLAC energy doubling

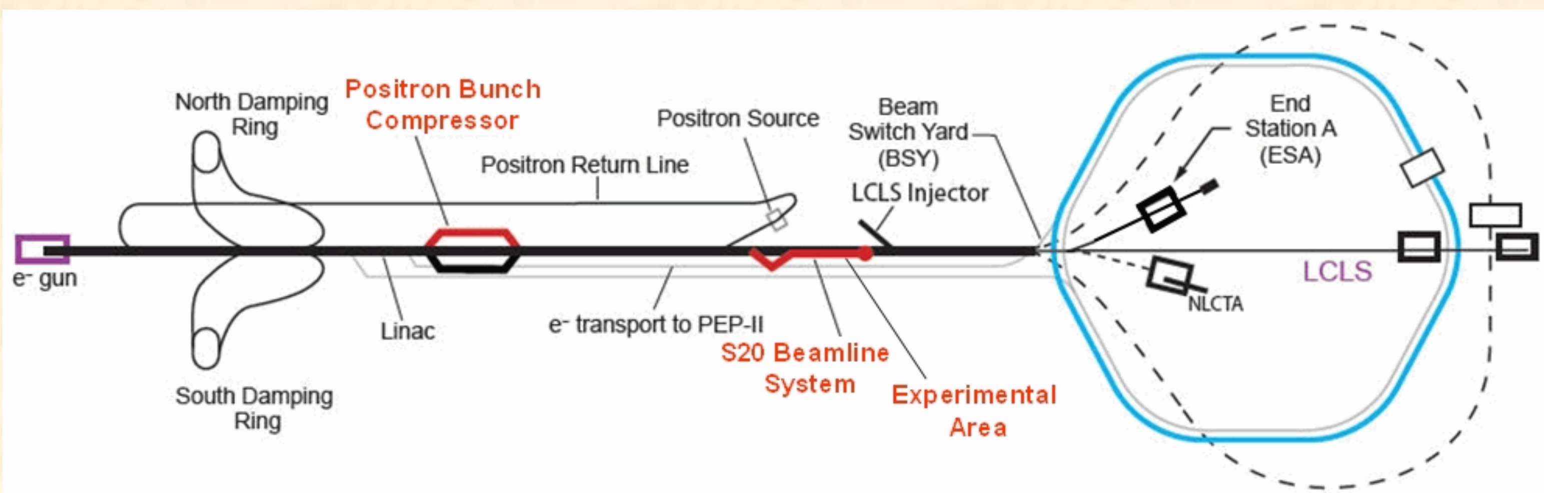


- In 2007 a team using the SLAC 42 GeV beam managed to double the energy of some of the electrons, up to 85 +/- 7 GeV.

FACET

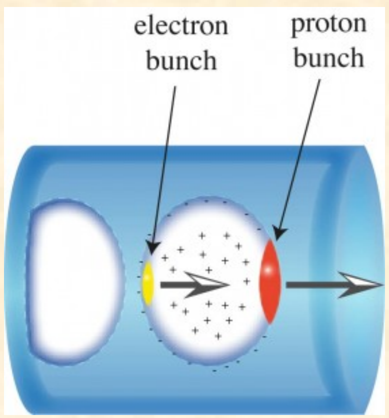
- The SLAC linac is now partially used by LCLS, but the remaining part is available for R&D on plasma acceleration
  => FACET.
- Dedicated studies of beam driven plasma acceleration.
- First nature paper to come out soon.

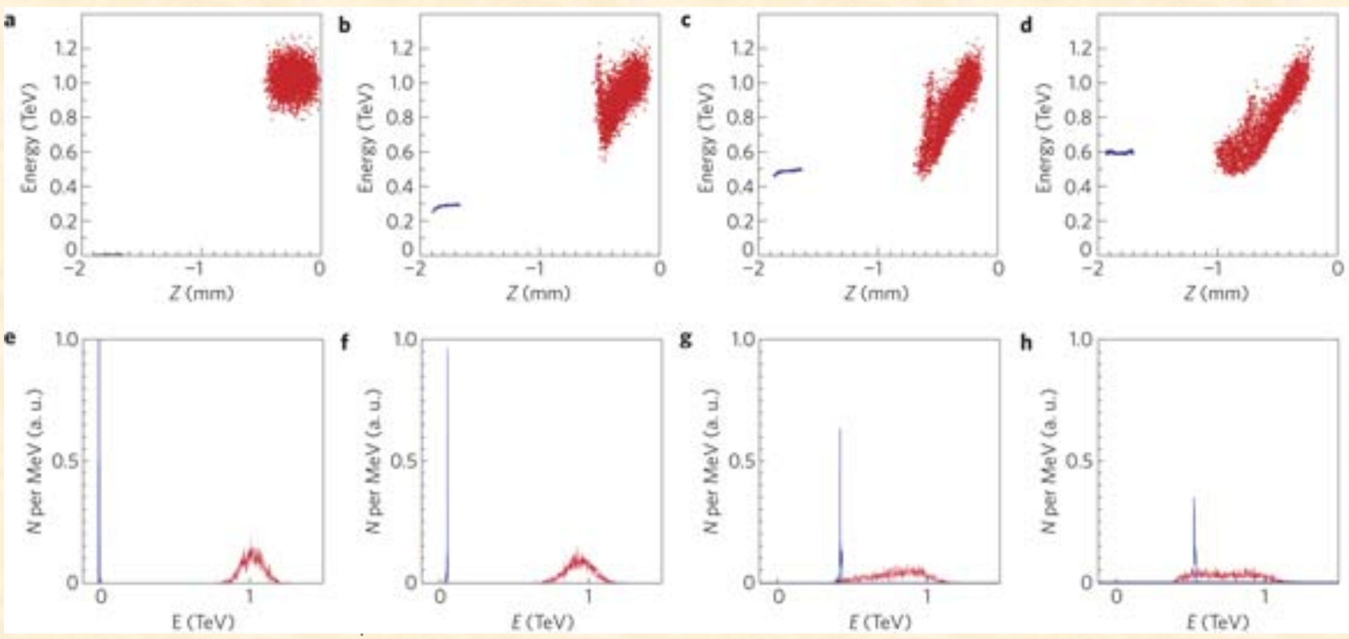




AWAKE

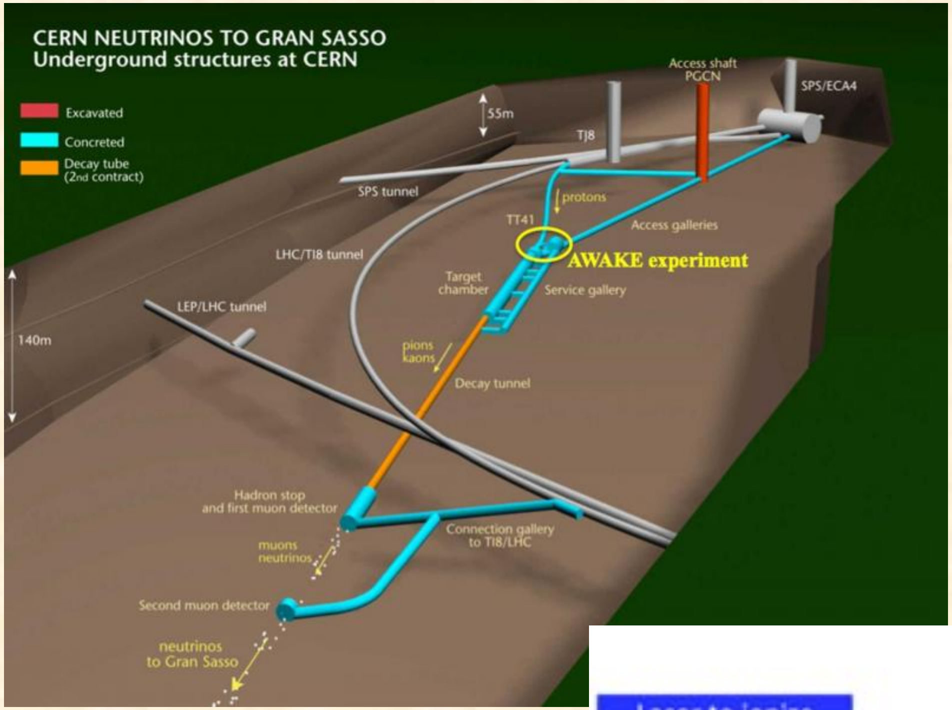
- Protons have a better transformer ratio than electrons => it is possible to reach higher energies using protons!
- AWAKE experiment at CERN.



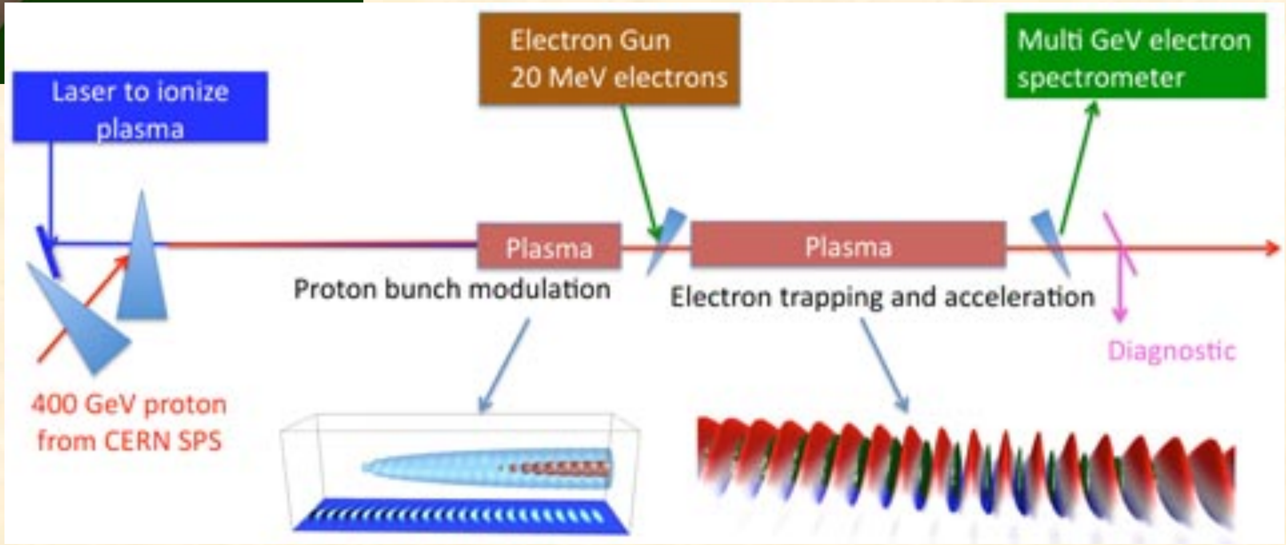


Caldwell et al.,
Nature Physics 5, 363 - 367 (2009)

AWAKE at CERN

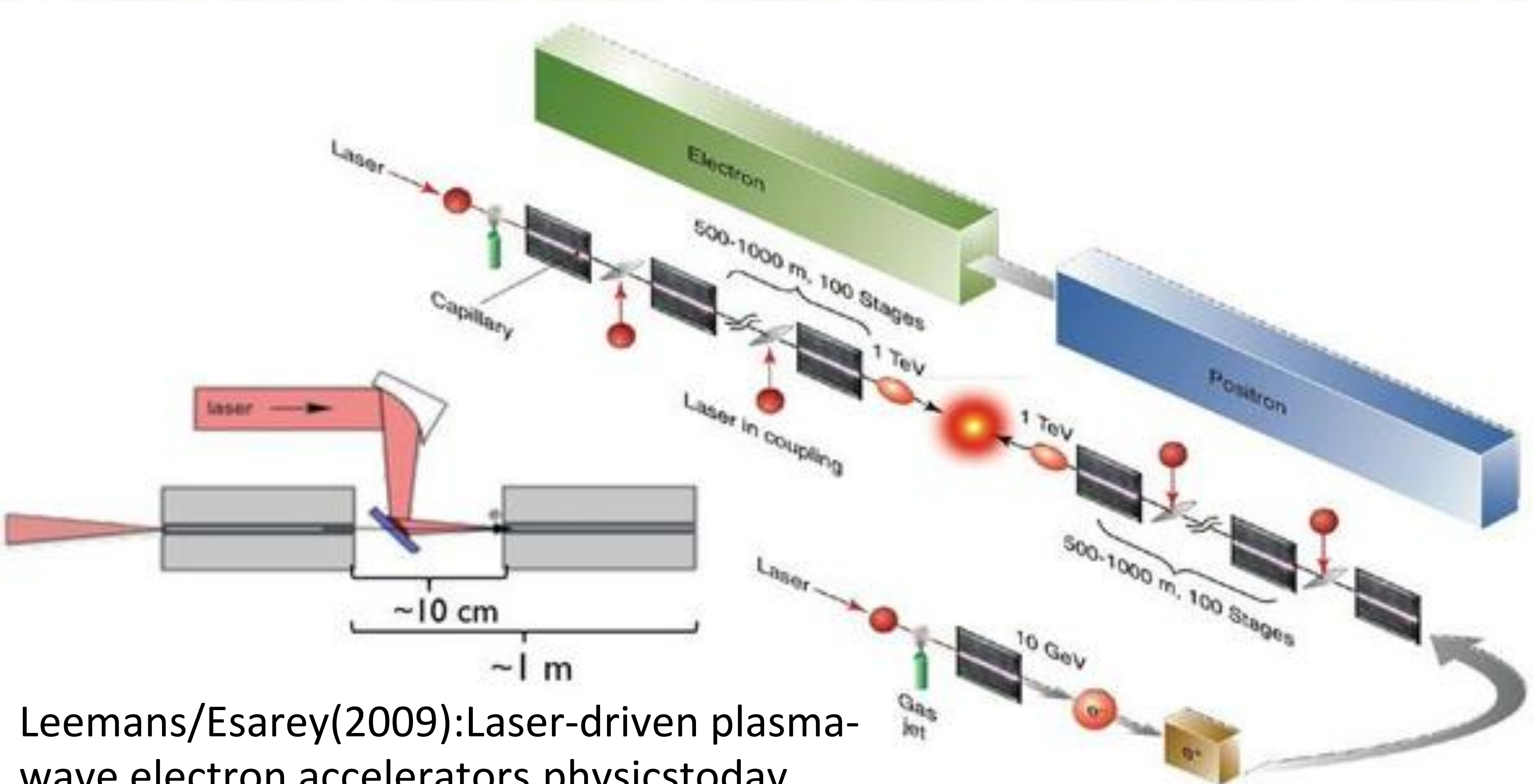


- Currently being built.
- Start after LS1, in 2016.



Nicolas Delerue, LAL Orsay

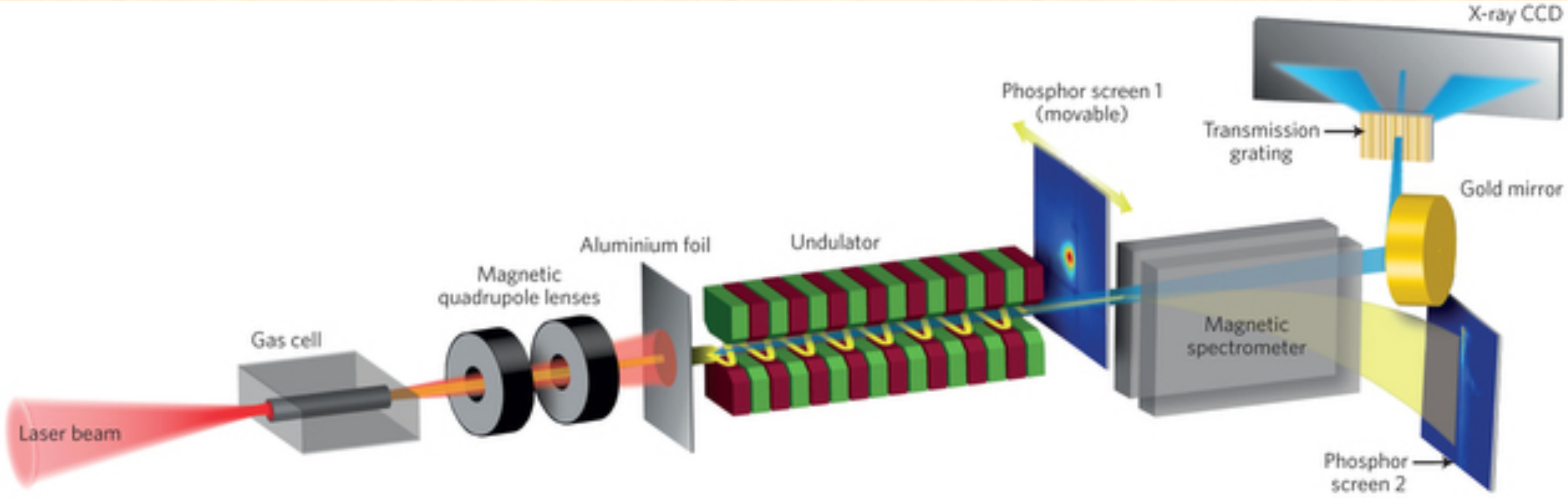
Possible application in HEP



Leemans/Esarey(2009):Laser-driven plasma-wave electron accelerators.physicstoday

- One could dream of a LC based on plasma acceleration!
- But there are still many hurdles to clear!

Plasma based FEL



- More likely than a collider is a X-ray Free Electrons Laser based on plasma acceleration:
  less sensitive to shot to shot instabilities and much smaller…
- Many projects worldwide on this, including some near Orsay.

Outlook

- Plasma acceleration has benefited from the progress of laser technology to make tremendous progress.
- Beam energies of up to a few GeV achieved.
- Could be a long term solution to replace accelerating cavities.
- However still many hurdles to clear! STABILITY!
- No major progress reported since 2008 but many groups involved in building large experiments…
- Progress in laser technology will also drive progress in plasma acceleration.

Reference

- S.M. Hooker, Nature Photonics 7 775 (2013). DOI:10.1038/NPHOTON.2013.234