# Electron acceleration within the *Bubble – Regime*

Why fast electrons are fancy.


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# Outline

**Electrons as sources for high energetic X-rays:**

The higher the energy -
the shorter the wavelength and the smaller the targets.

Medical applications.

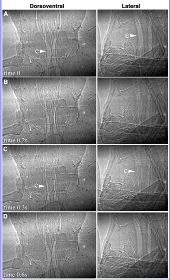



Figure: Image of the thorax of the beetle Platynus Decentis.(Science, Vol. 299. no. 5606, pp. 558 - 560)

Imaging of molecules / atoms.

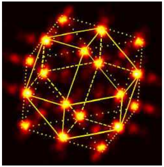


Figure: Reconstruction of cobalt atoms in a lattice.(Phys. Rev. Lett. 82 , 4847)

**High energetic electrons as beams:**

Energy transfer for fast-ignition fusion.

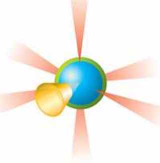


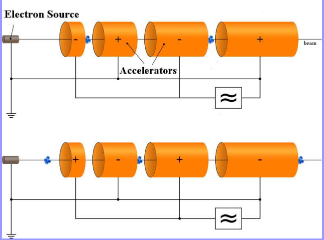
Figure: Electrons ignite compressed hydrogen.

Driver for positron-acceleration.

Figure: Object is accelerated on a steep gradient.

Common ways to accelerate particles: $W = \vec{E}L$

**Linear Accelerator (LinAcc):**



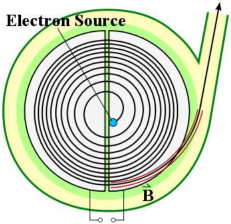

Advantage:

No radiation loss

Disadvantage

Short acceleration length $L$

**Cyclotron:**




Very long acceleration length $L$

Synchrotron radiation

For these applications $GeV$-electrons are necessary ($E_{electron} \approx 10^9 eV$).

For such accelerations huge facilities are necessary.

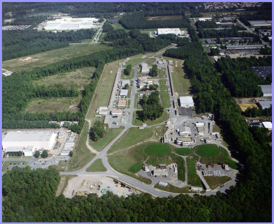


Figure: Aerial on the Thomas Jefferson National Accelerator Facility[2].

TJNAF:

Size: $\sim 0.8km^2$

Cost: $\sim$ 50Mio.€

Lenght of each LinAcc: $\sim 1.4km$

**For many applications this is too big and too expensive!**

[2] http://www.jlab.org/

Comparison to recent *Laser-Wake-Field-Acceleration*(*LWFA*)-experiments:

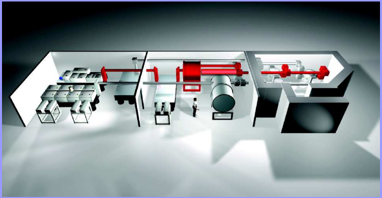


Figure: Beamline of the Arcturus-Laser-Facility[4].

ILPP - Arcturus:
Size: $\sim 50m^2$
cost: $<<$ 10Mio.€
acceleration length: $\sim 1cm$

**More reasonable for electrons in *MeV* - *GeV* range!**

[4] courtesy of T.Toncian, ILPP

- Ultrarelativistic[5] laser pulses act with a strong ponderomotive[6] force on charged particles.
- This force pushes particles out of the laser spot.
- In a plasma this disturbance of the electron density distribution creates oscillation of electrons.
- Since the laser pulse is moving these oscillations create a wake.

Figure: Wake of a driver (swan) on the surface of a lake.

[5] $a_0 = eA_0/m_e c^2 >> 1$
[6] $F_{pon} \sim \nabla(E \cdot E)$

For a laser in an under-dense[7] plasma this leads to

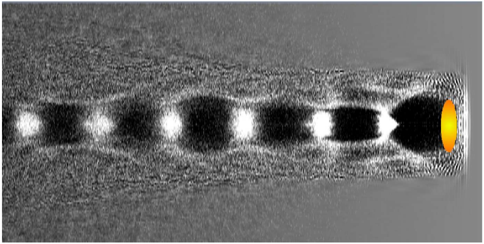


Figure: Laser pulse followed by a wake.

Due to the different fraction-indices self-focussing-effects conserve the pulse.

If all parameters are chosen correctly the laser pulse travels a long distance through the plasma.

[7] $n_{plasma} < n_{critical} = m_e\omega_0^2/4\pi^2$

**How to accelerate particles with LWFA?**

One possibility is the *Bubble* – *Regime*[8]

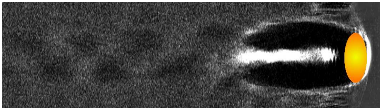


Figure: Electrons trapped inside a *Bubble*.

Strong pulses lead to wave-breaking, which leads to strong turbulances.

The Laser pulse is followed by an volume of reduced electron density called *the Bubble*.

During the turbulences electrons can be trapped inside the Bubble.

[8] Appl. Phys.B 74, 355-361 (2002)

Electrons in the *Bubble* are accelerated.

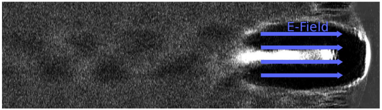



Figure: Electrons trapped inside a *Bubble*.

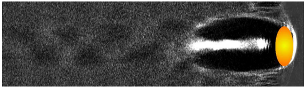
Strong gradients inside the Bubble push electrons like a wave pushes a surfer.

Trapped electrons travel with about speed of light with the laser pulse.

Until reaching the final acceleration length $L_{acc}$ electrons gain energy from the laser pulse.

# The Bubble-Regime

Two of the conditions for forming a *Bubble*:



- Laser pulse has to be super relativistic: $a_0 >> 1$.
  Otherwise no wave breaking occurs. Without wave breaking no electrons are trapped.

- Pulse length[9] must be shorter than plasma length[10]:
  $FWHM < \lambda_p/2$.
  Otherwise it will lead to Direct Laser Acceleration (DLA).

[9] Full Width at Half Maximum(FWHM): distance from spot centre at which the intensity falls at half the maximum

[10] $\lambda_p = 2\pi c\omega_p$

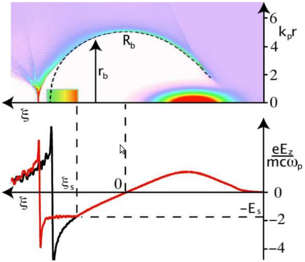



Figure: Electric field inside the *Bubble*[12]. $\xi_s$: position of the electrons, $R_b$: maximum radius of the bubble (in regard to the $\xi$-axis), $\xi = ct - x$.

- The $x$-component of the E-Fiels is almost uniform at each certain $x$-position.
- The gradient becomes negative close to the pulse $\rightarrow$ deceleration phase.

[12] Tzoufras et al., PRL 101, 145002 (2008)

Given a similar starting momentum of trapped electrons and the field, the electrons are accelerated quasi-monoenergetic[13].

$$E_{mono} \approx 0.65 m_e c^2 \sqrt{\frac{P}{P_{rel}}} \frac{c\tau}{\lambda}$$

with $P_{rel} = m_e^2 c^5 / e^2 \approx 8.5 GW$, $\tau$: pulse duration and $P$: laser pulse power.

This energy is gained after an acceleration length of

$$L_{acc} \approx 0.7 \frac{c\tau}{\lambda} Z_R$$

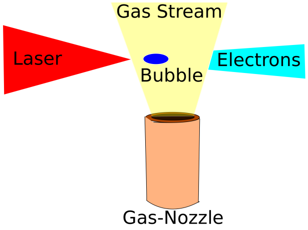
with the Rayleigh length $Z_R = \pi R^2 / \lambda$.

[13] Pulhov, Gordienko, Phil. Trans. R. Soc. A 2006 364, 623-633

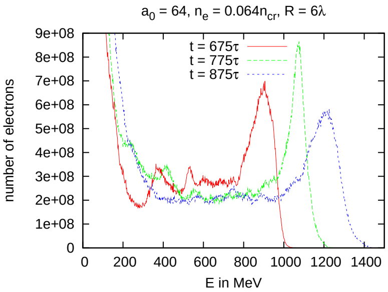
With the Arcturus-Laser ($a_0 \approx 4.7$, $c\tau = R \approx 11.25\lambda$) this would lead to

$$E_{Mono} \approx 445 MeV$$

$$L_{acc} \approx 2.5cm$$




- A laser pulse is focused just before a super sonic gas stream.
- The gas stream is ionised by the laser pulse. In the resulting plasma the pulse creates the *Bubble*.
- The *Bubble* travels through the plasma channel created by the laser until the stream ends ($\sim L_{acc}$).
- Accelerated electrons leave the gas in a very narrow arc.




- An energy peak corresponds to a bunch of quasi-monoenergetic electrons.
- As time goes by the electrons gain energy.
- After reaching $L_{acc}$ the peak decays. Electrons do not further accelerate.

To create X-ray-radiation from these electrons, an undulator is useful.

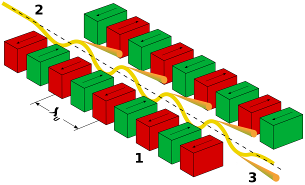



Figure: 1: Magnets with a distance of $\lambda_u$ between the center of to adjacent magnets. 2: The electron-beam. 3: Synchrotron-radiation.

The magnets force the electrons to oscillate around their line of propagation.

The oscillating electrons emit synchrotron-radiation.

All electrons emit radiation in the same direction.

To accelerate positrons electrons could be used as a driver.

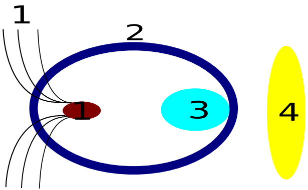
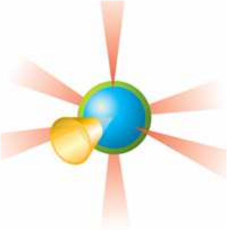



Figure: Preaccelerated positrons are inserted (1) into the *Bubble* (2) created by an electron beam (3). A laser pulse (4) creates the plasma in front of the electrons.

Electrons and positrons have opposing charges.
The very stable electron beam can efficiently accelerate positrons.
Opposing charge leads to no decelerating phase.

Bubble acceleration also could be used in Fast Ignition Fusion.



- Energy has to delivered from all sides.
- Energy has to get to the core.
- Electrons easier pass thick material than light does.

- Some nice applications need fast electrons (imaging, fast-ignition-fusion, positron acceleration,...).
- Conventional accelerators are huge and expensive.
- LWFA is an option to create *MeV* - *GeV* electrons.
- One interesting example of LWFA is the *Bubble – Regime*.
- The *Bubble – Regime* produces electrons which can be used cheap and easily for those applications.

# Feel free to ask questions!

There is a parametric dependency for $E_{mono}$ and $N_{mono}$ as functions of $a_0$, Laser spot radius $R$ and the pulse duraction $\tau$

$$E_{mono} \approx 0.65 m_e c^2 \sqrt{\frac{P(a_0,R)}{P_{rel}}\frac{c\tau}{\lambda}}, \quad N_{mono} \approx \frac{1.8}{k_0 r_e}\sqrt{\frac{P(a,R)}{P_{rel}}}, \quad (1)$$

with $P(a_0,R) \sim (a_0 R)^2$ for linear-/circular-polarised gaussian beams.

[2] $m_e$: Mass of electrons, $c$: speed of light, $P(a_0,R)$: Laser power as function of $a_0$ and $R$, $P_r el = m_e^2 c^5/e^2$, $\tau$: Puls duration, $\lambda$: Laser wave length, $k_0 = 2\pi/\lambda$, $r_e = e^2/m_e c^2$: classical electron radius