Beam Propagation

Effects and parameters of the accelerated beam

CAS High Gradient Wakefield Accelerators
11-22 March 2019, Sesimbra, Portugal

Ralph W. Aßmann
Leading Scientist Accelerator R&D
DESY
Contents

1. Accelerators – Ultra-High Gradients and High Frequency
2. The Plasma Linear Regime
3. The Energy Spread Challenge
4. Solutions
5. Conclusion
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1. Accelerators – Ultra-High Gradients and High Frequency
2. The Plasma Linear Regime
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5. Conclusion
How to Advance the Field of Particle Accelerators?
Looking for solutions

**Hadron (p) circular collider**

\[ p = e \cdot R \cdot B_y \]

- Increase bending field
- SC bend magnet work (FCC-hh)
- Increase radius = size (FCC-hh)

**Lepton (e-,e+) circular collider**

\[ p \propto E_0 \cdot \sqrt[4]{\rho \cdot U_0} \]

- Increase supplied RF voltage
- (FCC-ee)
- Increase mass of acc. particle (muon)
- Increase radius = size (FCC-ee)

**Lepton (e-,e+) linear collider**

\[ p = L \cdot G_{acc} \]

- Increase accelerating gradient
  - (a) Pushing existing technology (ILC, CLIC)
  - (b) New regime of ultra-high gradients (plasma, dielectric accelerators)
- Increase length (ILC, CLIC)
The R&D on Compact Accelerators

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BIG factors → Novel concepts pursue transformative concepts that can open new horizons in energy reach for HEP research

Factor 206.8 higher mass muon versus electron

Increase mass of acc. particle (muon)

Factor 100 – 1000 higher accelerating gradient

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# High Gradient – High Frequency – Small Dimensions

Understanding frequency bands and its basic properties

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<td>Ku band</td>
<td>12 to 18</td>
<td>n/a</td>
<td>1.3 – 0.8</td>
<td></td>
</tr>
<tr>
<td>K band</td>
<td>18 to 27</td>
<td>n/a</td>
<td>0.8 – 0.6</td>
<td></td>
</tr>
<tr>
<td>Ka band</td>
<td>27 to 40</td>
<td>70</td>
<td>0.6 – 0.4</td>
<td>Investigated for a possible CLIC linear collider technology at 30 GHz but abandoned after damage problems.</td>
</tr>
<tr>
<td>V band</td>
<td>40 to 75</td>
<td>n/a</td>
<td>0.4 – 0.2</td>
<td></td>
</tr>
<tr>
<td>W band</td>
<td>75 to 110</td>
<td><strong>&gt; 1000</strong></td>
<td><strong>0.2 – 0.1</strong></td>
<td>Advanced acceleration</td>
</tr>
</tbody>
</table>
High Gradient – High Frequency – Small Dimensions

Powering novel accelerators

| High Gradients (1 – 100 GV/m) | High Frequencies (> 100 GHz) | Small Dimensions (< 1 mm) |

• No **klystrons** for high frequencies!
• Use **particle bunches or laser pulses** as drivers.
• Material limitations solved through “new cavities”: dielectric materials, plasma cavities, …

• **Two main directions:**

1. **Microstructure Accelerator**
   Laser- or beam driven
   Vacuum accelerators
   Conventional field design

2. **Plasma Accelerator**
   Laser- or beam driven
   Dynamic Plasma Structure
   Plasma field calculations
Accelerators: RF and Novel Regimes

High Gradients - High Frequencies - Small Dimensions

Fit based on the analytical law for the cavity diameter with the $TM_{010}$ mode divided by $\pi$
**Accelerators: RF and Novel Regimes**

**High Gradients - High Frequencies – Small Dimensions**

**RF regime:**
- **SRF:** High quality, high average power acceleration, long trains → CW (ST1)
- **S/X band:** Generate high brightness beams for all purposes, ultra-fast science and diagnostics (ST3), injector for novel accelerators (ST4)

**Novel regime:**
- Novel drivers, in particular high tech lasers for compact photon science and medical applications. (ST4)
- **RF beam drivers** mainly for HEP or other high average power. (ST4)
- **Compact** foot-print, low pulse charge, **high repetition rate.** (ST4)
- **Challenges of micro and nano dimensions** – assess with modern tools (synergy with ultra-fast).

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**Transverse diameter (mm)**

<table>
<thead>
<tr>
<th>Frequency of accelerating field (GHz)</th>
<th>Transverse diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1                     10                   100                  1000              10000</td>
<td></td>
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</tbody>
</table>

**Fit based on the analytical law for the cavity diameter with the TM_{010} mode divided by π**
Challenges of High Frequency: $\alpha$ Parameter

In Ultra-High Gradient Structures

- Kwang-Je Kim introduced in 1989 a parameter $\alpha$ that is easily calculated and governs the whole longitudinal beam dynamics of a photo-injector.

- Jamie Rosenzweig and Eric Colby:
  - This immediately gives the result that the scaling of an rf design with wavelength implies that $\alpha$ must be kept constant as the wavelength is varied.

- Klaus Flöttmann (PRSTAB 2015):
  - For $\alpha \geq 1$, the particle dynamics shows relativistic effects within one period of the wave.
  - Hence, $\alpha$ is typically 1.5–2.0. It is instructive to make a rough estimate of the energy gain in the vicinity of the cathode in the gun.
  - 1000 times higher frequency $\Rightarrow$ 1000 times higher gradient required.

![Diagram showing the formula for $\alpha$]

$$\alpha = \frac{eE_0}{2m_ec^2k}$$

- RF wave number $= \omega/c$
  - (here is the frequency, e.g. 3000 GHz)
Challenges of High Frequency: $\alpha$ Parameter

In Ultra-High Gradient Structures

$\alpha$ = acceleration compared to one wavelength
Challenges of High Frequency: $\alpha$ Parameter

In Ultra-High Gradient Structures

Working guns for high brightness electron bunches (low $\varepsilon$) in pC charge regime

Frequency of accelerating field (GHz)

$\alpha$ = acceleration compared to one wavelength
Challenges of High Frequency: $\alpha$ Parameter

In Ultra-High Gradient Structures

- Working guns for high brightness electron bunches (low $\varepsilon$) in pC charge regime
- General trend to lower $\alpha$ for higher frequency accelerators (C $\rightarrow$ X $\rightarrow$ W band).
- Consequence: Problem to miniaturize the injector $\rightarrow$ big injector on small accelerator
Challenges of High Frequency: $\alpha$ Parameter

In Ultra-High Gradient Structures

- General trend to lower $\alpha$ for higher frequency accelerators ($C \rightarrow X \rightarrow W$ band).
- Consequence: Problem to miniaturize the injector $\rightarrow$ big injector on small accelerator.
- Plasma injectors fulfill $\alpha$ criterion quite well $\rightarrow$ very high frequency but at the same time very high accelerating field.
- Potential to provide high quality beam.
Laser-Driven Micro Structures (Vacuum - THz)

Vacuum dielectric accelerator

- 1 GeV/m possible but low absolute energies achieved so far
- **AXSIS project (ERC synergy grant)** at DESY/Uni Hamburg: THz laser-driven accelerator with atto-second science → Kärtner/Fromme/Chapman/Assmann

**SMALL DIMENSIONS**
Laser-Driven Micro Structures (Vacuum - Optical)

Vacuum dielectric accelerator

- **“Accelerator on a Chip”** grant from Moore foundation for work by/at Stanford, SLAC, University Erlangen, DESY, University Hamburg, PSI, EPFL, University Darmstadt, CST, UCLA

- Lasers drive **structures that are engraved on microchips** (e.g. Silicium)

- Major breakthroughs can be envisaged:
  - **Mass production**
  - **Implantable accelerators** for in-body irradiation of tumors
  - Accelerators for **outer space**

**SMALL DIMENSIONS**
The Plasma Accelerator
Overcome high-field limitations of metallic walls with dynamic plasma structures (undestructible)

New idea in 1979 by Tajima and Dawson: Wakefields inside a homogenous plasma can convert

transverse forces into longitudinal accelerating fields

- Ponderomotive force of a laser
- Space charge force of a charged particle bunch (e-, p+)
- Accelerating gradients of 10 GeV/m to 1,000 GeV/m

Options for driving wakefields:

- **Lasers:** Industrially available, steep progress, path to low cost
  Limited energy per drive pulse (up to 50 J)

- **Electron bunch:** Short bunches (need μm) available, need long RF accelerator
  More energy per drive pulse (up to 500 J)

- **Proton bunch:** Only long (inefficient) bunches, need very long RF accelerator
  Maximum energy per drive pulse (up to 100,000 J)

Courtesy M. Kaluza
Laser Plasma-Acceleration

Internal injection

Works the same way with an **electron beam as wakefield driver**. But then usually lower plasma density. Ponderomotive force of laser is then replaced with space charge force of electrons on plasma electrons (repelling).

Laser Pulse (200 TW, ~30 fs, $E_{\text{transv}} \sim TV/m$)

Plasma electrons
(plasma cell, $\sim 10^{19} \text{ cm}^{-3}$)
Laser Plasma-Acceleration

Internal injection
Laser Plasma-Acceleration

Internal injection → strong fields in the bubble suck in plasma electrons to form the electron beam.
Laser Plasma-Acceleration

Internal injection

This accelerator fits into a human hair

~25 μm

Trapped electron beam

Bubble ($E_{long} \sim 100$ GV/m)

Laser Pulse ($E_{transv} \sim$ TV/m)

~35 μm (120 fs)

Plasma electrons
(plasma cell, $\sim 10^{19}$ cm$^{-3}$)

SMALL DIMENSIONS
Laser Plasma Acceleration

External injection

Electron beam

Laser Pulse (200 TW, ~25 fs, $E_{\text{transv}} \sim TV/m$)

Plasma electrons (plasma cell, $\sim 10^{17}$ cm$^{-3}$)

~70 μm

~100 μm (330 fs)

Plasma cavity ($E_{\text{long}} \sim 10$ GV/m)

Electron beam

Laser Pulse ($E_{\text{transv}} \sim TV/m$)

Plasma electrons (plasma cell, $\sim 10^{17}$ cm$^{-3}$)

SMALL DIMENSIONS
Challenges of Small Dimensions
In Ultra-High Gradient Structures

• We like to build small accelerators and small they are with consequences for the electron beam:
  • With high RF frequency we get very small RF wavelength.
  • To fit the short wavelength the bunch length must scale down to achieve small energy spread.
  • The transverse dimensions of the hole for the beam (aperture) also shrink down rapidly with the higher frequency as a consequence of the short wavelength.
  • In order to fit into the aperture the beam size must shrink with higher frequency.
  • As beam emittance is invariant we need very strong focusing to reduce and maintain the small transverse electron beam size.
  • Therefore high frequency accelerators require small 3D beam volumes (high density) and very strong focusing.

K.J. Kim:

Thus it usually will be necessary to focus the beam immediately after leaving the cavity.
Scaling Laws with Accelerating Wavelength $\lambda$

Rosenzweig and Colby – here assume a factor 1000 higher frequency $\rightarrow$ 1000 times shorter wavelength

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Required for higher frequency</th>
<th></th>
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<tr>
<td>Acc. gradient:</td>
<td>$E_0 \propto \lambda^{-1}$ Higher gradients</td>
<td>x 1000</td>
</tr>
<tr>
<td>Bunch length:</td>
<td>$\sigma_z \propto \lambda$ Short bunch length</td>
<td>/ 1000</td>
</tr>
<tr>
<td>Focusing field:</td>
<td>$B \propto \lambda^{-1}$ High focusing field (Solenoid)</td>
<td>x 1000</td>
</tr>
<tr>
<td>Bunch transv. size:</td>
<td>$\sigma_{x,y} \propto \lambda$ Small beam size</td>
<td>/ 1000</td>
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Can we a lot of charge in an ever smaller volume?
Space Charge

The Coulomb Force and Magnetic Attraction

• We have just seen that we squeeze the electrons into a smaller and smaller volume for high frequency RF accelerators.

• Consider two electrons of charge $e$ at rest with distance $r$: they will experience repulsion due to the Coulomb force.

$$F_{coulomb} = \frac{1}{4\pi\varepsilon_0} \frac{e^2}{r^2}$$

Distance $r$ matters

• When travelling with velocity $v$: we then have two parallel currents: $I = v \cdot e$

which attract each other through their magnetic fields.

• This we call the space charge force or just space charge.

• It is always repulsive but cancel if particles travel with $v = c$. Space charge very large at low energy, disappears at high energy.
From K.H. Schindl, “Space Charge”, CERN

Coulomb force and magnetic attraction (= space charge) must be included for meaningful predictions. They decide achievable performance!
Space Charge

The Coulomb Force and Magnetic Attraction

• Defocusing wave number (defocusing forces on bunch):

\[ k_{sc}^2 = \frac{2c}{I_0 \beta^2 \gamma^3} \left[ \frac{Q}{g \sigma_z \sigma_x^2} \right] f\left(\frac{\sigma_x}{\beta \gamma \sigma_z}\right) \]

Bunch independent constant
Charge
Dependent on bunch aspect ratio

Energy
Distribution shape dependent constant
Bunch transverse size
Bunch length

From scaling laws with acceleration wavelength (1000 times smaller) we had:

• 1000 times smaller transverse beam size
e.g. 100 µm → 100 nm
• 1000 times shorter bunch length
e.g. 100 µm → 100 nm

Aim at same defocusing space charge force:

• At the same energy \( \gamma \) we get 1000 times less charge for same quality!?
• Not fully true → gain from very high accelerating gradient (quickly accelerate to high energy)
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1. Accelerators – Ultra-High Gradients and High Frequency
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Can be analytically solved and treated. Here comparison beam-driven (PWFA) and laser-driven (beat wave = PBWA).
Linear Wakefields (R. Ruth / P. Chen 1986)

The formulae behind it all

\[ \mathcal{E}_z \approx -A \left(1 - \frac{r^2}{a^2}\right) \cos(k_p z - \omega_p t) \]

\[ \mathcal{E}_r \approx 2A \frac{r}{k_p a^2} \sin(k_p z - \omega_p t) \]
Linear Wakefields (R. Ruth / P. Chen 1986)

The formulae behind it all

Accelerating field

\[ \mathcal{E}_z \simeq -A(1 - \frac{r^2}{a^2}) \cos(k_p z - \omega_p t) \]

Transverse field

\[ \mathcal{E}_r \simeq 2A \frac{r}{k_p a^2} \sin(k_p z - \omega_p t) \]

Depends on radial position \( r \)
Linear Wakefields (R. Ruth / P. Chen 1986)

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Depends on radial position \( r \)

Changes between accelerating and decelerating as function of longitudinal position \( z \)

Transverse field

\[ \mathcal{E}_r \approx 2A \frac{r}{k_p a^2} \sin(k_p z - \omega_p t) \]

Depends on radial position \( r \)

Changes between focusing and defocusing as function of longitudinal position \( z \)

\( \pi/2 \) out of phase
The Useful Regime of Plasma Accelerators

Where do we put the electron bunch inside the wave (or the surfer on the wave)

Two conditions for an accelerator:

1. **Accelerated bunch must be in accelerating regime.**
2. **Accelerated bunch must be in focusing regime.**

These two conditions define a useful range of acceleration!

Reminder metallic RF accelerator structures:

no net transverse fields for beam particles $\rightarrow$ full accelerating range is available for beam $\rightarrow$ usually place the beam on the crest of the accelerating voltage
Plasma Accelerator Phasing

Finding the useful regime

![Diagram showing the phase from wake origin with maxima for (W_z) and (W_f/r) with accelerating and focusing regions marked.](image)
Plasma Accelerator Phasing

Finding the useful regime
Plasma Accelerator Phasing

Finding the useful regime

![Diagram showing phase from wake origin with accelerating and focusing regions]
Plasma Accelerator Phasing

Finding the useful regime

![Diagram showing phase from wake origin with labels (W_z)_{max}, (W_r/r)_{max}, Head of e^− Bunch, Accelerating, and Focusing zones.]}
Plasma Accelerator Phasing
Finding the useful regime

Half of beam is in decelerating regime
Plasma Accelerator Phasing
Finding the useful regime
Plasma Accelerator Phasing

Finding the useful regime

![Diagram showing plasma accelerator phasing with phase from wake origin on the x-axis and normalized energy on the y-axis. The diagram illustrates the head of electron bunch and regions of accelerating and focusing, leading to the conclusion that the beam is in defocusing regime and will explode.](image-url)
Plasma Accelerator Phasing
Finding the useful regime
Plasma Accelerator Phasing

Finding the useful regime

This works, but the bunch sits on the slope of acceleration → head gets lower energy than tail → energy spread.
Comparison with OSIRIS simulation

Finding the useful regime

Calculation J. Grebenyuk

Plasma density $10^{17} \text{ cm}^{-3}$

$W_{z,0} = 30.4 \text{ GV/m}$

$W_{z,x}/W_{z,0}$
Comparison with OSIRIS simulation

Finding the useful regime

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Calculation J. Grebenyuk
Plasma Accelerator Phasing

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Energy Spread Challenge
State of the art in plasma accelerators versus requirements

Plot version A. Walker et al
Energy Spread Challenge

State of the art in plasma accelerators versus requirements

Plot version A. Walker et al.
Energy Spread Challenge
State of the art in plasma accelerators versus requirements

Plot version A. Walker et al

State of the art in plasma accelerators versus requirements

Multi-stage dechirping
Current FEL facilities

FEL applications
STATE OF THE ART COLLIDER
STATE OF THE ART FEL

Beam Energy [GeV]
0.01 0.1 1 10 100 1000 10000

Relative Energy Spread
$10^0$ $10^{-1}$ $10^{-2}$ $10^{-3}$ $10^{-4}$
Energy Spread Challenge
State of the art in plasma accelerators versus requirements

STATE OF THE ART COLLIDER
STATE OF THE ART FEL
STATE OF THE ART PLASMA ACCELERATORS

Efforts to handle large energy spread beams for FEL applications → decompression, TGU undulator (not discussed here)

Plot version A. Walker et al
Optimization: Minimal Energy Spread

Avoid creation of too much energy spread (cannot be fully avoided by principle explained before)

Reduce energy spread (head to tail $\rightarrow$ correlated with $z$)

Minimize: Ratio of accelerated bunch length over $\lambda_{\text{plasma}}$

Minimize length accelerated bunch

Ultra-short bunches (fs, as)

Ultra-fast science

Increase plasma wavelength

Lower plasma density

Lower accelerating gradient

and/or
**Gedankenexperiment – Zero Bunch Length**

Infinitesimally short bunch will not see any slope of accelerating voltage

\[ n_0 = 10^{17} \text{ cm}^{-3} \]

Here, longitudinal field independent of radial position

Zero bunch length \( \rightarrow \) all particles at same longitudinal coord. and see the same acceleration.

Why does energy spread not go to zero for zero bunch length?

1 fs = 0.3 \( \mu \text{m} \) when travelling with light velocity \( c \)
Strong plasma focusing: Betatron motion

Plasma works as a focusing quadrupole

- A plasma has a very strong focusing field in both planes.
- Focusing strength and phase advance depends on plasma density.
- Experiment with a beam-driven plasma at SLAC in 2001: Send an electron beam into a plasma and measure beam sizes at exit point.
**Strong plasma focusing: Betatron motion and X rays**

Wiggling electrons emit X rays → a plasma accelerator as accelerator and undulator at once

- If an electron beam is injected mismatched into a plasma, we expect strong beta mismatch oscillations of the beam size.
- The oscillating electrons should radiate X rays.
- This was seen in a SLAC experiment in 2001.
- Plasma acts as an undulator!

![Image of X-ray emission from Betatron motion in a Plasma Wiggler](https://example.com/x-ray-emission.png)
Plasma Accelerator Physics I

Small accelerators exhibit also very small tolerances – here is the difficulty

- A plasma of density $n_0$ (same density electrons - ions) is characterized by the plasma frequency:

$$\omega_p = \sqrt{\frac{n_0 e^2}{\varepsilon_0 m_e}}$$

- This translates into a wavelength of the plasma oscillation:

$$\lambda_p \approx 1\text{ mm} \cdot \sqrt{\frac{10^{15}\text{ cm}^{-3}}{n_0}}.$$  

0.3 mm for $n_0 = 10^{16}\text{ cm}^{-3}$

- The wavelength gives the longitudinal size of the plasma cavity... Lower plasma density is good: larger dimensions.
Plasma Accelerator Physics II

Small accelerators exhibit also very small tolerances – here is the difficulty

- The plasma oscillation leads to **longitudinal accelerating fields** with a gradient of (higher plasma densities are better):

  \[
  W_z = 96 \frac{V}{m} \cdot \sqrt{\frac{n_0}{\text{cm}^{-3}}} \propto \frac{N_b}{\sigma_z^2}
  \]

  \[
  9.6 \text{ GV/m for } 10^{16} \text{ cm}^{-3}
  \]

- The **group velocity of the laser in a plasma** is as follows for \( \omega_p << \omega_l \): (note \( \omega_l \) is laser frequency)

  \[
  v_g = c \cdot \sqrt{1 - \frac{\omega_p^2}{\omega_l^2}}
  \]

- The laser-driven wakefield has a lower velocity than a fully relativistic electron \( \rightarrow \) slippage and dephasing. Lower densities are better.
Plasma Accelerator Physics III
Small accelerators exhibit also very small tolerances – here is the difficulty

- The ion channel left on axis, where the beam passes, induces an ultra-strong focusing field. In the simplest case:

$$g = 960 \pi \cdot \left( \frac{n_0}{10^{14} \text{ cm}^{-3}} \right) \text{T/m}$$

300 kT/m for $10^{16}$ cm$^{-3}$

- This can be converted into an optical beta function (lower density is better, as beta function is larger):

$$k_{\beta}^2 = 0.2998 \frac{g}{E} \quad \beta = \frac{1}{k_{\beta}}$$

$\beta = 1.1$ mm for 100 MeV

- The phase advance in the plasma channel is rapid:

$$\psi(s) = \int k_{\beta} s \, ds \propto \sqrt{E}$$
Plasma Accelerator Physics IV

Small accelerators exhibit also very small tolerances – here is the difficulty

- The **matched beam size** in the ion channel is small:

\[ \sigma_0 = \sqrt{\beta \varepsilon} \]

\[ \sigma_0 = 1.3 \ \mu m \text{ for } \gamma \varepsilon = 0.3 \ \mu m \]

- Offsets between laser and beam centres will induce betatron oscillations. Assume: full dilution into emittance growth (energy spread and high phase advance).

- Tolerances for **emittance growth** due to offsets \( \Delta x = \sigma_x \):

\[ \frac{\Delta \varepsilon}{\varepsilon_0} = \left( \frac{\sigma_x}{\sigma_0} \right)^2 \]

100% for 1.3 \( \mu m \) offset

- Lower plasma density better: larger matched beam size, bigger tolerances.

Now: Is there an Impact? → Transverse Oscillations

All electrons inside the bunch perform oscillations, assume relativistic electrons → qll = light velocity

+ 1σ normalized oscillation amplitude

0σ normalized oscillation amplitude

- 1σ normalized oscillation amplitude
Now: Is there an Impact? ➔ Transverse Oscillations

All electrons inside the bunch perform oscillations, assume relativistic electrons ➔ qll light velocity

\[ +1 \sigma \] normalized oscillation amplitude

\[ 0 \sigma \] normalized oscillation amplitude

\[ -1 \sigma \] normalized oscillation amplitude
Now: Is there an Impact? → Transverse Oscillations

All electrons inside the bunch perform oscillations, assume relativistic electrons → qll light velocity

![Graph showing transverse oscillations](image)

- $+1\sigma$ normalized oscillation amplitude
- $0\sigma$ normalized oscillation amplitude
- $-1\sigma$ normalized oscillation amplitude
Now: Is there an Impact? → Transverse Oscillations

All electrons inside the bunch perform oscillations, assume relativistic electrons → cll light velocity

Difference in path lengths → large oscillation particles have longer way → fall back and create banana shape
Differences in Path Length and Arrival Time

Another source for increased Energy Spread and Bunch Length

• Usually subtle effects become relevant for plasma accelerators with ultra-strong focusing fields and sub-femtosecond bunch lengths.

• Beam electrons have different transverse oscillation amplitudes $A_0$ and therefore different path lengths.

• Consequences:

  - Increased bunch length
  - Correlated energy spread
    Observed in 2014 by Assmann and Grebenyuk (IPAC’14)
  - Slice mixing
  - Uncorrelated (slice) energy spread
    Relevant for FEL applications

These dynamics were already pointed out by A. Reitsma and D. Jaroszynski, but no further studies (Laser Part. Beams 2004)

Here: Development of the first analytical model that describes these effects and limitations accurately for a particle bunch.

Realistic plasma accelerator simulation demonstrating bunch length generation and banana shape
Contents

1. Accelerators – Ultra-High Gradients and High Frequency
2. The Plasma Linear Regime
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Solutions: Towards low energy spread with Beam Loading

Old proposal from Simon van der Meer

1985 van der Meer

van der Meer: Nobel Prize Physics for invention of stochastic cooling → SppS collider at CERN

Beam loading, energy spread and efficiency

→ Flatten wakefield (no slope)
Solution: Reduce energy spread by a FODO plasma scheme

Jump from positive (focusing) to negative phase (defocusing) of plasma accelerator → kind of FODO scheme
Solution: Low Energy Spread with 2 Stages

Particle-in-cell and tracking simulations of a particular 1.5 m-long setup with two plasma stages show that 5.5 GeV bunches with a final relative energy spread of $1.2 \times 10^{-3}$ (total) and $5.5 \times 10^{-4}$ (slice) could be achieved while preserving sub-micron emittance. This at least one order of magnitude below current state-of-the-art and paves the way towards applications such as Free-Electron Lasers.
Low Energy Spread with 2 Stages

Ref.: Ferran Pousa, Martínez de la Ossa, Brinkmann, Assmann, arXiv:1811.07757

Typical FEL charge range: 10 pC – 1 nC

Multi-stage dechirping
Current FEL facilities

Analytical estimate for ATHENA

Multi-stage concept

Simulated cases for EuPRAXIA

R. Assmann, EuPRAXIA at TIARA
Solve external timing for laser-driven plasma accelerators

Achieve required sub-femtosecond timing and accuracy...

External injection into a laser-driven plasma accelerator with sub-femtosecond timing jitter

A Ferran Pousa¹, R Assmann¹, R Brinkmann¹ and A Martinez de la Ossa²

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Figure 1. Schematic view of the synchronizing stage.
Some Projects to Realize these Accelerators...
EuPRAXIA Horizon2020 Design Study (DESY coordinated)
European Plasma Accelerator Infrastructure with Pilot Users, site-independent (now mid-term)

• Collaboration of 41 institutes
  • 16 EU laboratories are beneficiaries
  • 25 associated partners from EU, Europe, Asia and US contribute in-kind

• Collaboration brings together:
  • Big science labs: photon science, particle physics
  • Laser laboratories: high power lasers
  • International laboratories: CERN, ELI (associated)
  • Universities: accelerator research, plasma, laser

• Organized in 8 EU-funded work packages and 6 in-kind work packages
• 125 scientists in our work list
EuPRAXIA: A European Strategy for Accelerator Innovation

Do the required intermediate step between proof of principle and production facility – make one acc. unit!

PRESENT EXPERIMENTS

Demonstrating 100 GV/m routinely
Demonstrating GeV electron beams
Demonstrating basic quality

EuPRAXIA INFRASTRUCTURE

Engineering a high quality, compact plasma accelerator
5 GeV electron beam for the 2020’s
Demonstrating user readiness
Pilot users from FEL, HEP, medicine, ...

PRODUCTION FACILITIES

Plasma-based linear collider in 2040’s
Plasma-based FEL in 2030’s
Medical, industrial applications soon
The ATHENA Project

Two Flagships Constructed Together

- **30 M€** investment of Helmholtz association and BMBF.
- **Total volume: 42.5 M€** (incl. personnel). OP budget defined.
- Include **work in 7 research infrastructures** in Helmholtz
- Defines **two flagship projects**: e- in Hamburg, p/ions in Dresden
- Targets **applications**
Project approval: Summer 2018
Construction end: end of 2021
Operation start: 2022

Usable, smaller size (cost) e-/p/ ion accelerators: additional applications, better quality, improved rate

Ultra-short pulses: femto-s science at 1 GeV

Point-like photon emission: lateral resolution

Ultra-small emittance beams: nano emittance

Compact injectors for storage rings: damping

Coordinator: R. Assmann, Deputy coordinator: U. Schramm

→ Please contact us for questions and more information!
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Conclusion

Advanced Accelerator Physics High Gradient Schemes

• High gradient comes with **high frequency and very small dimension** → unique challenges arise and need to be addressed.

• **Plasma accelerators** have advanced nicely and are a possible game changer. Energy very promising but beam quality insufficient:
  - There are **now near future science applications outside HEP, e.g. FEL.** This can be the stepstone towards a plasma linear collider.
  - Important to understand the details of the accelerator physics → **limitations in energy spread and bunch length at important level**
  - **Novel solutions** promise major advances → beam quality close to big science beam quality?!

• A lot of great work done on plasma accelerators but there are **still new things to discover and to work out.**

• **Analytical theory and basic physics understanding** is important and provides the insights that we need!

*Picture A. Ferran-Pousan et al*
Please reserve the dates for September 2019

We would be very glad to welcome you in Elba
Thank you for your attention