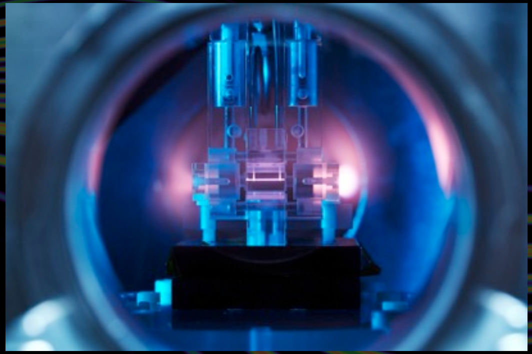
# Beam Propagation



## Effects and parameters of the accelerated beam

CAS High Gradient Wakefield Accelerators

11-22 March 2019, Sesimbra, Portugal

European Network for Novel Accelerators
EuroNNAc 3
*supported by EU via ARIES*

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

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

AXSIS

erc
European Research Council
Established by the European Commission

ACHIP
Accelerator on a Chip International Program

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MT
MATTER AND TECHNOLOGIES

DESY

# Contents

# Contents

# 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

## Looking for solutions

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

### Hadron (p) circular collider

$$p = e \cdot R \cdot B_y$$

Increase b
SC bend m

Increase radius = size (FCC-hh)

### Lept

**Factor 206.8 higher mass muon versus electron**

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

Increase supplied RF voltage (FCC-ee)

**Increase mass of acc. particle (muon)**

Increase radius =

**Factor 100 – 1000 higher accelerating gradient**

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

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# High Gradient – High Frequency – Small Dimensions

## Understanding frequency bands and its basic properties

| Band Designator | Frequency [GHz] | Gradient [MV/m] | Cell length [cm] | Comments |
|---|---|---|---|---|
| L band | 1 to 2 | 24 | 15 – 7.5 | This band is used by super-conducting RF technology. The dimensions are large, accelerating gradients are lower and disturbing wakefields are weak. |
| S band | 2 to 4 | 21 | 7.5 – 3.8 | Technology of the SLAC linac that was completed in 1966. This is still the technology behind many accelerators. |

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| C band | 4 to 8 | 35 | 3.8 – 1.9 | Newer technology developed in Japan and used for the construction of the SACLA linac in Japan. |

# High Gradient – High Frequency – Small Dimensions

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| C band | 4 to 8 | 35 | 3.8 – 1.9 | Newer technology developed in Japan and used for the construction of the SACLA linac in Japan. |
| X band | 8 to 12 | 70 – 100 | 1.9 – 1.3 | Technology developed from the 1990's onwards for linear collider designs, like NLC and CLIC. The cell length is up to a factor 10 shorter than in L band. |

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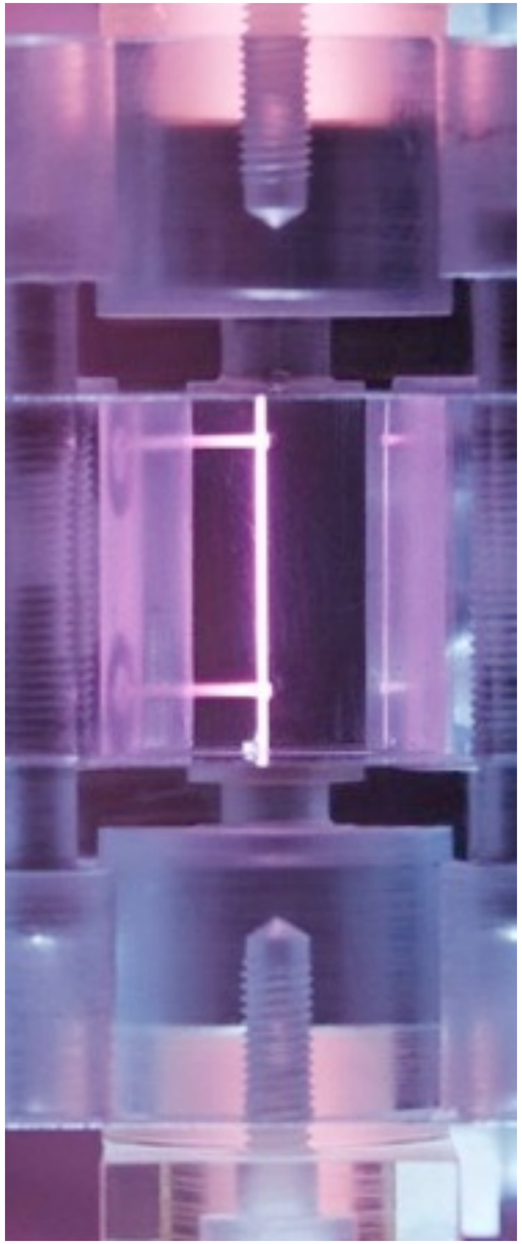
| X band | 8 to 12 | 70 – 100 | 1.9 – 1.3 | Technology developed from the 1990's onwards for linear collider designs, like NLC and CLIC. The cell length is up to a factor 10 shorter than in L band. |
| Ku band | 12 to 18 | n/a | 1.3 – 0.8 | |
| K band | 18 to 27 | n/a | 0.8 – 0.6 | |
| Ka band | 27 to 40 | 70 | 0.6 – 0.4 | Investigated for a possible CLIC linear collider technology at 30 GHz but abandoned after damage problems. |
| V band | 40 to 75 | n/a | 0.4 – 0.2 | |
| W band | 75 to 110 | > 1000 | 0.2 – 0.1 | Advanced acceleration |

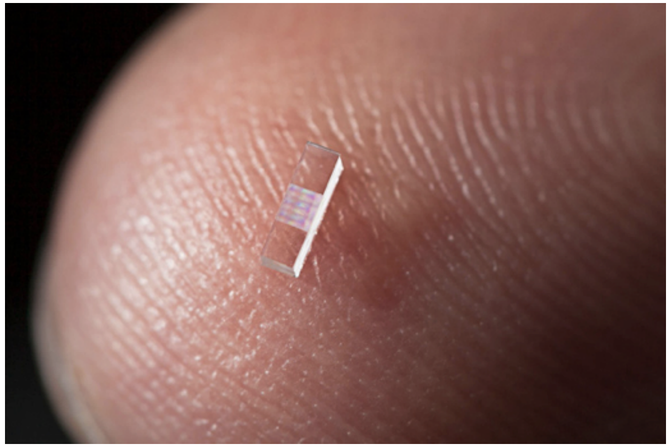


# High Gradient – High Frequency – Small Dimensions

## Powering novel accelerators

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

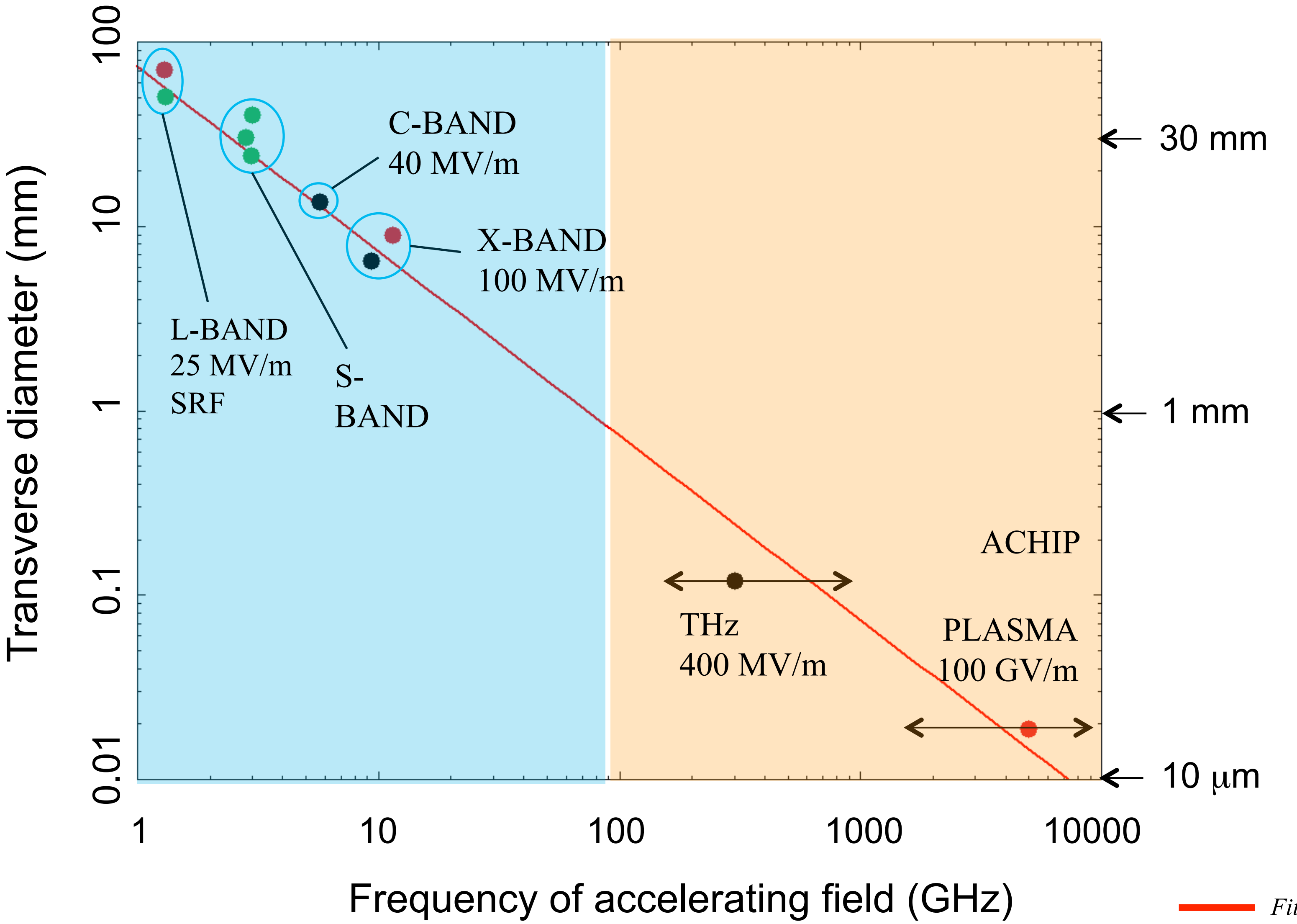
- No **klystrons** for high frequencies!
- Use **particle bunches or laser pulses** as drivers.
- Material limitations solved through “new cavities”: dielectric materials, plasma cavities, …
- **Two main directions**:



| 1 | 2 |
|---|---|
| **Microstructure Accelerator**<br>Laser- or beam driven<br>Vacuum accelerators<br>Conventional field design | **Plasma Accelerator**<br>Laser- or beam driven<br>Dynamic Plasma Structure<br>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

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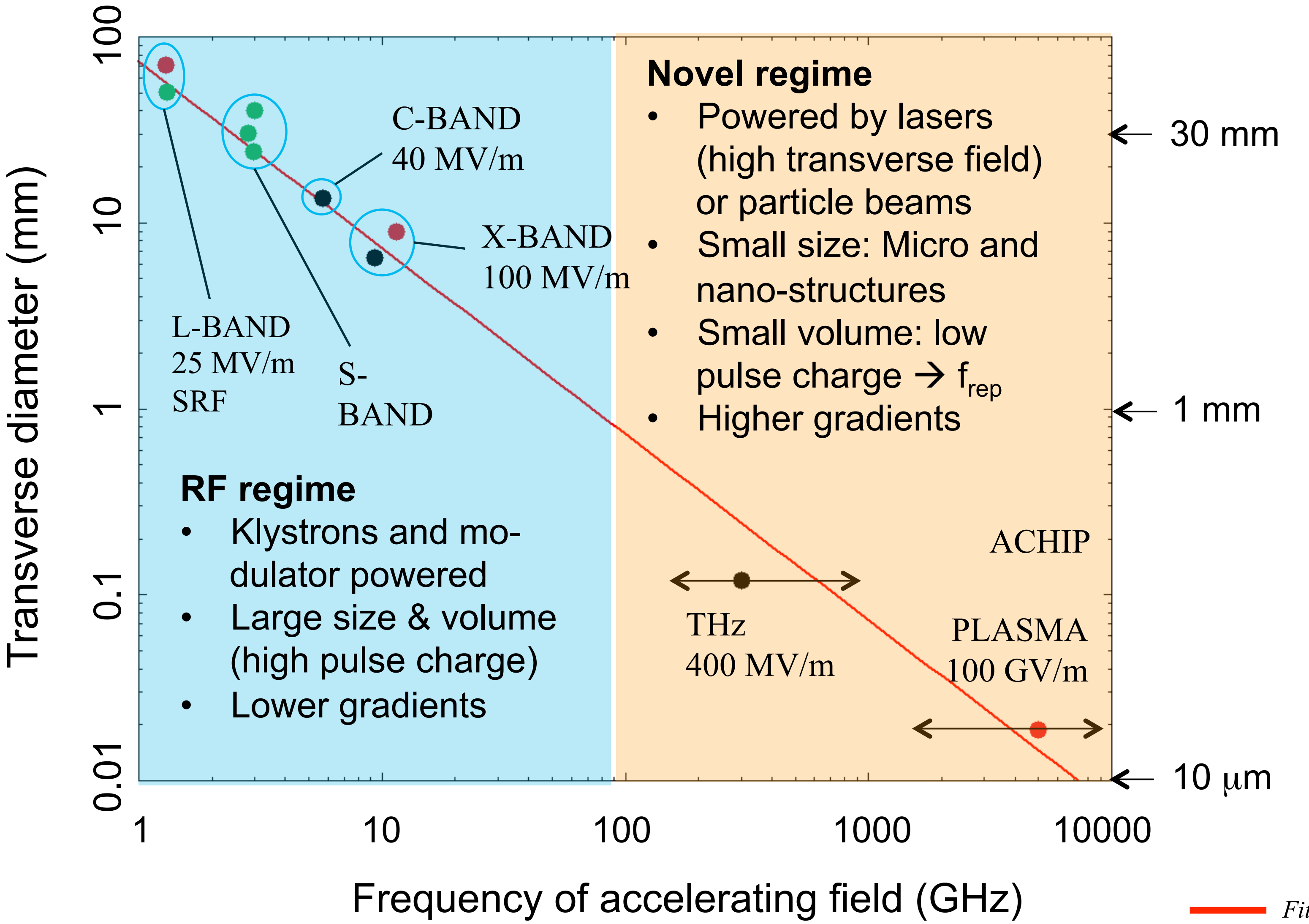



*Fit based on the analytical law for the cavity diameter with the $TM_{010}$ mode divided by π*

**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).

# Challenges of High Frequency: α 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 α **must be kept constant as the wavelength is varied**
- Klaus Flöttmann (PRSTAB 2015):
  - For α ≥ **1**, the particle dynamics shows relativistic effects within one period of the wave.
  - **Hence, α 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 → 1000 times higher gradient required

Nuclear Instruments and Methods in Physics Research A275 (1989) 201–218 201
North-Holland, Amsterdam

**RF AND SPACE-CHARGE EFFECTS IN LASER-DRIVEN RF ELECTRON GUNS**

Kwang-Je KIM
*Accelerator and Fusion Research Division, Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720, USA*

Received 9 September 1988

$$\alpha = \frac{eE_0}{2m_e c^2 k}$$

Electron charge

Magnitude accelerating field

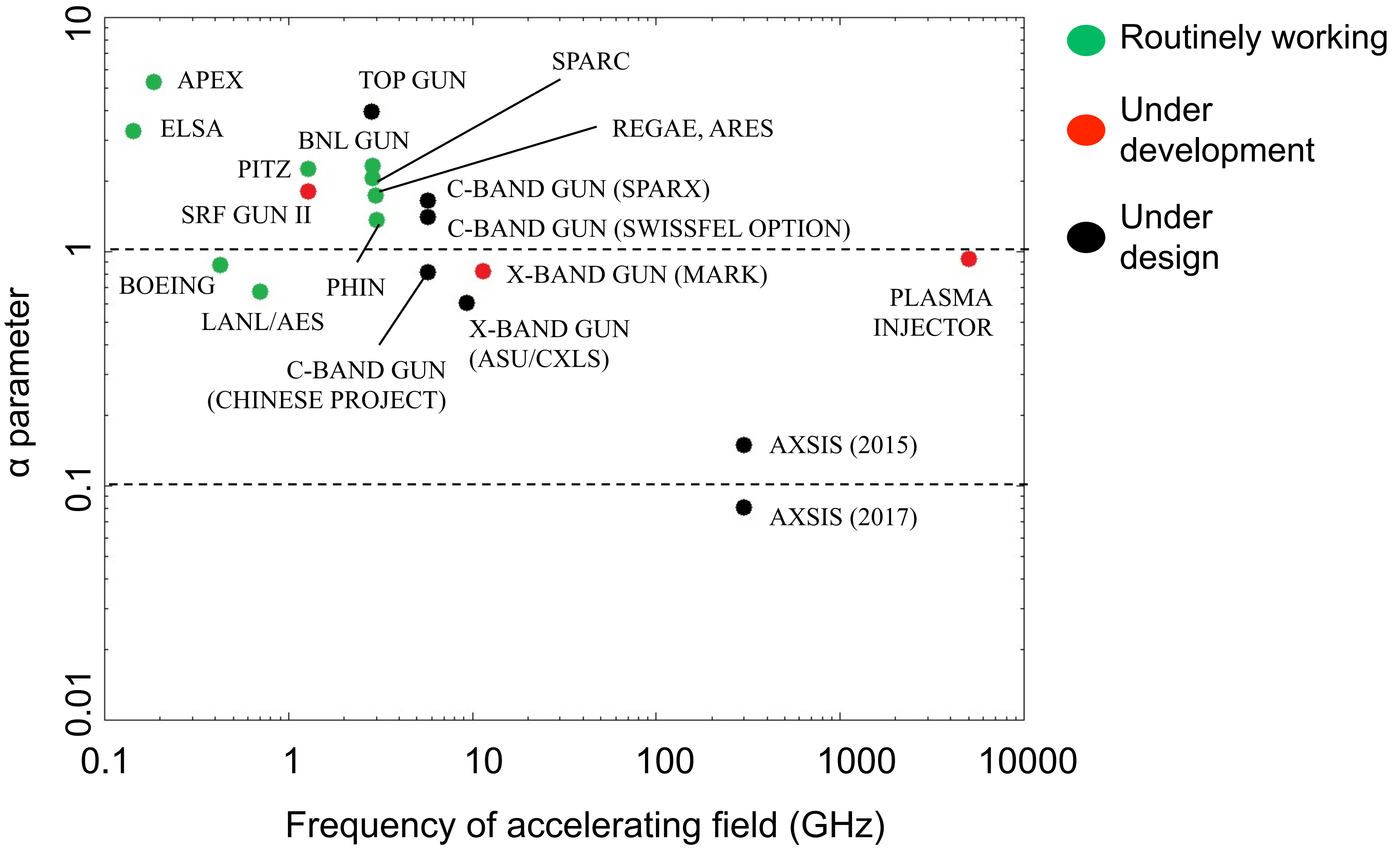
Electron mass

Light velocity

RF wave number = ω/c
(here is the frequency, e.g. 3000 GHz)

# Challenges of High Frequency: α Parameter

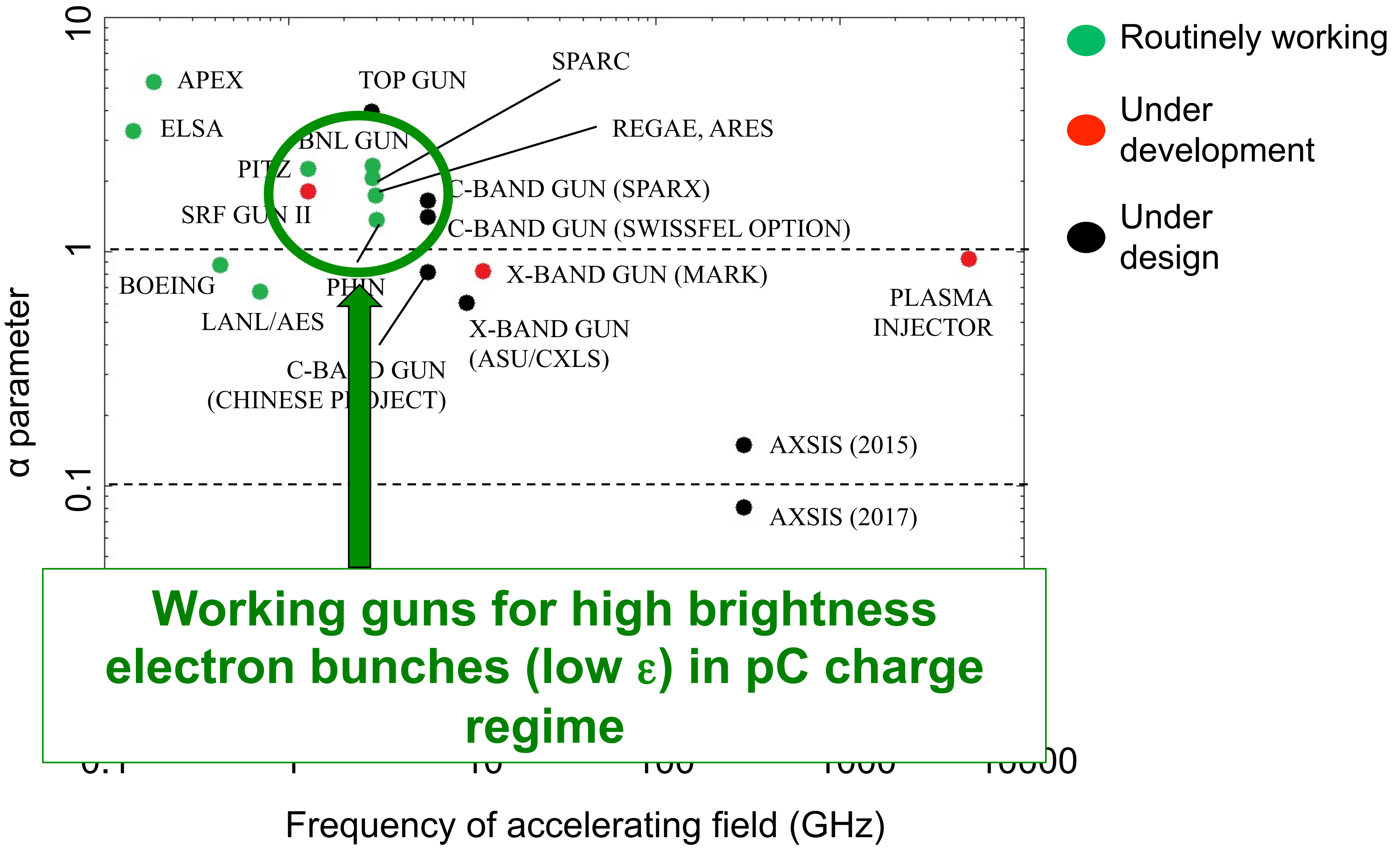
## In Ultra-High Gradient Structures




**α = acceleration compared to one wavelength**

# Challenges of High Frequency: α Parameter

## In Ultra-High Gradient Structures

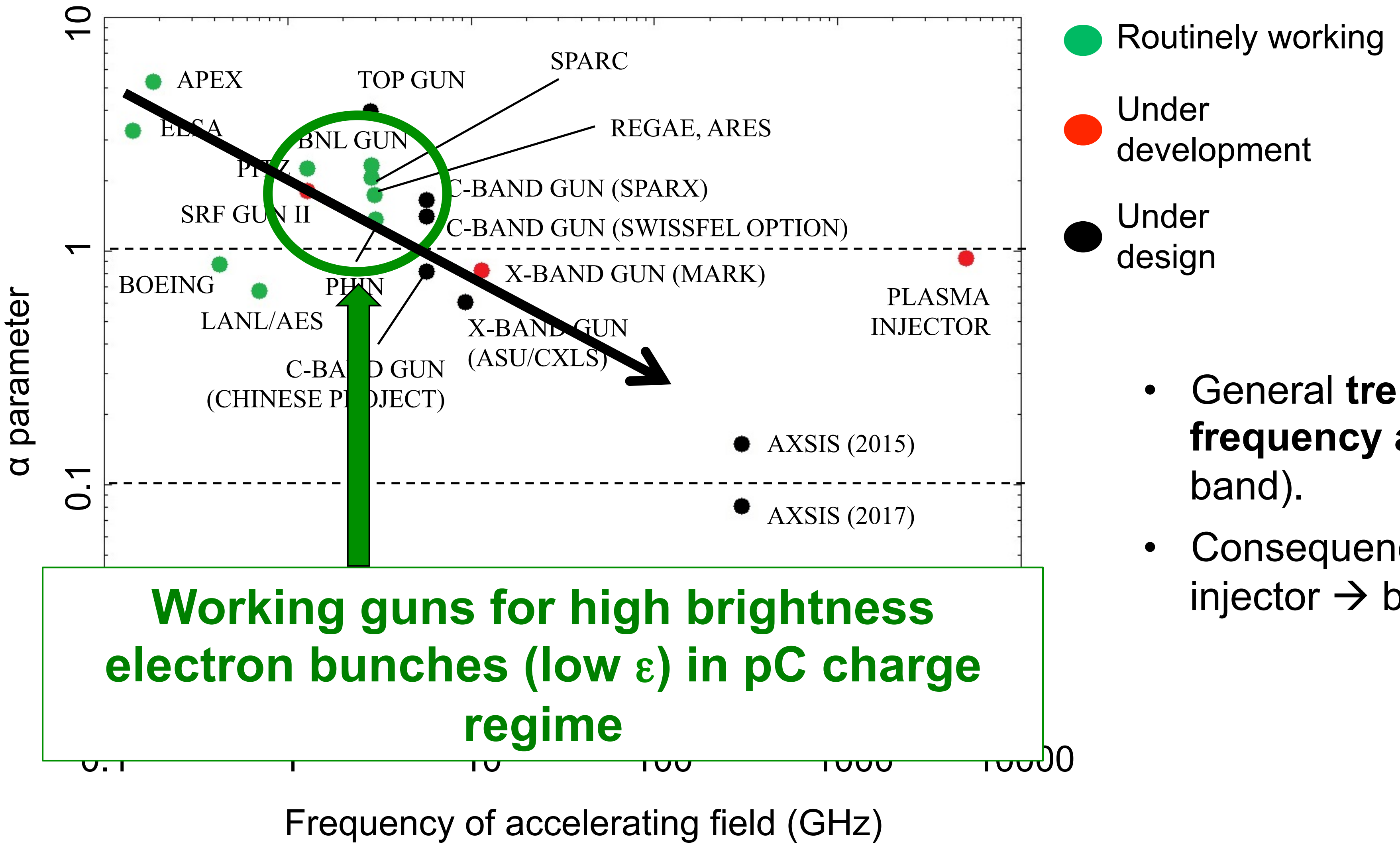



**Working guns for high brightness electron bunches (low ε) in pC charge regime**

**α = acceleration compared to one wavelength**

# Challenges of High Frequency: α Parameter

## In Ultra-High Gradient Structures



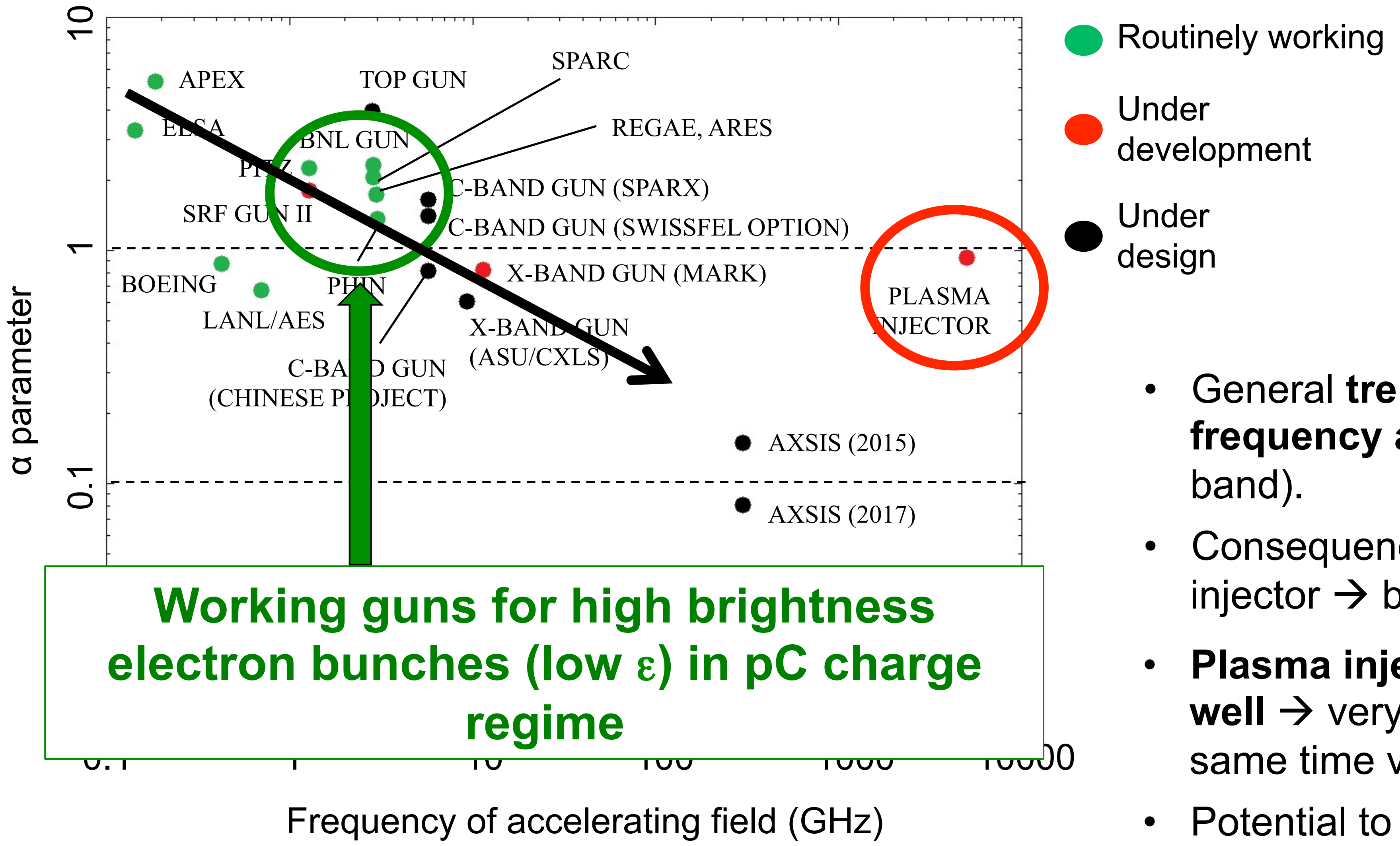

**Working guns for high brightness electron bunches (low ε) in pC charge regime**

**α = acceleration compared to one wavelength**

- General **trend to lower α for higher frequency accelerators** (C → X → W band).
- Consequence: Problem to miniaturize the injector → big injector on small accelerator

# Challenges of High Frequency: α Parameter

**In Ultra-High Gradient Structures**




**α**

**=**

**acceleration compared to one wavelength**

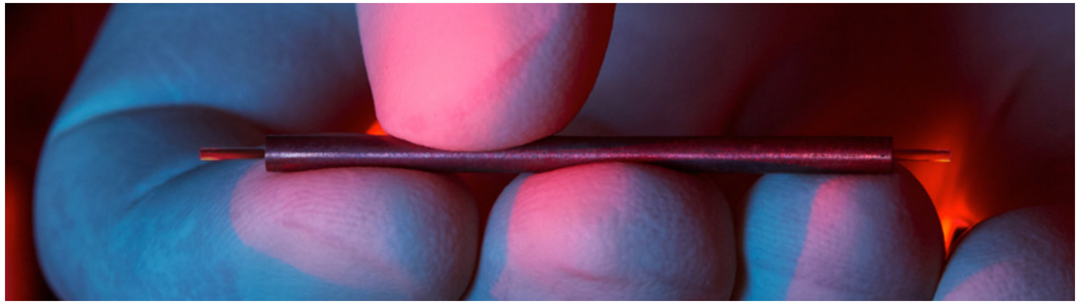
- General **trend to lower α for higher frequency accelerators** (C → X → W band).
- Consequence: Problem to miniaturize the injector → big injector on small accelerator
- **Plasma injectors fulfill α criterion quite well** → very high frequency but at the same time very high accelerating field
- Potential to provide high quality beam

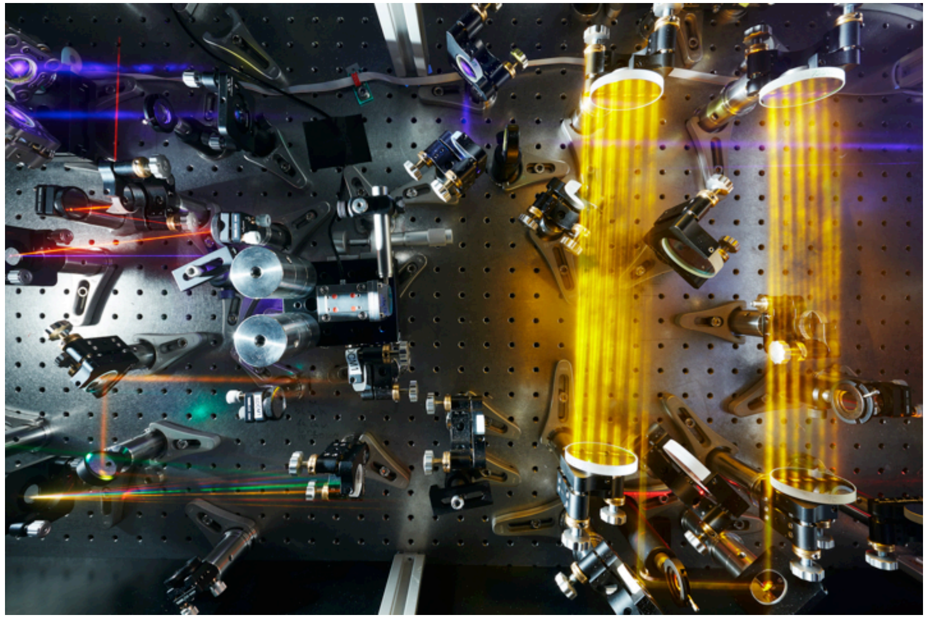
# Laser-Driven Micro Structures (Vacuum - THz)

## Vacuum dielectric accelerator

European Research Council
Established by the European Commission

- 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*



AXSIS

SMALL DIMENSIONS

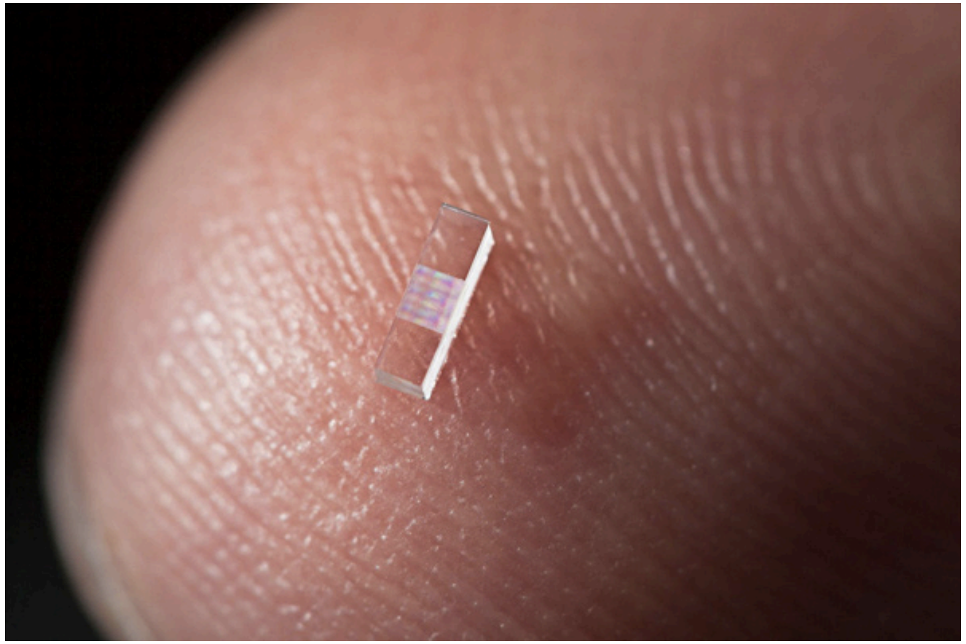
# Laser-Driven Micro Structures (Vacuum - Optical)

## Vacuum dielectric accelerator

ACHIP

Accelerator on a Chip International Program

- **"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

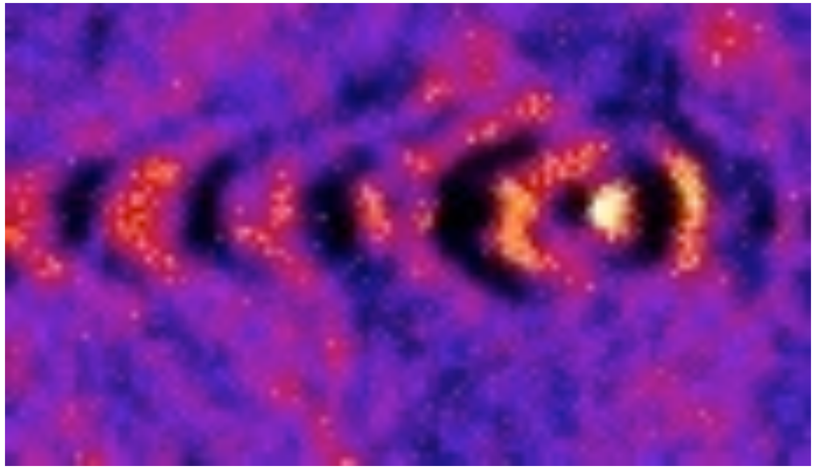
**Overcome high-field limitations of metallic walls with dynamic plasma structures (undestructible)**

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

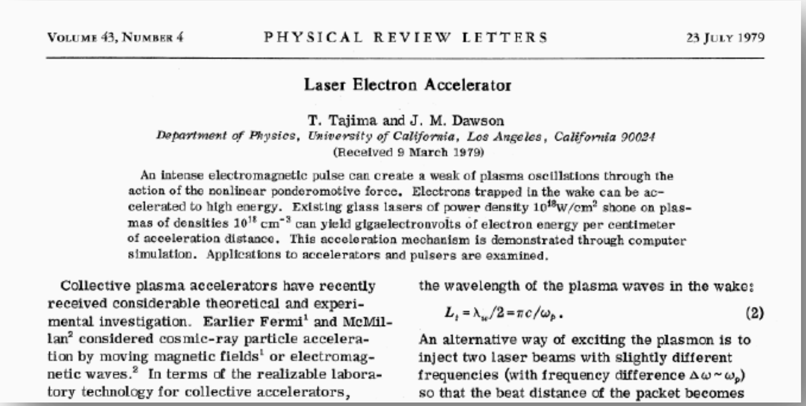
**transverse forces** into **longitudinal accelerating fields**

Ponderomotive force of a laser or Space charge force of a charged particle bunch (e-, p+) → transverse forces

longitudinal accelerating fields → Accelerating gradients of 10 GeV/m to 1,000 GeV/m



*Courtesy M. Kaluza*



Volume 43, Number 4 PHYSICAL REVIEW LETTERS 23 July 1979

**Laser Electron Accelerator**

T. Tajima and J. M. Dawson

*Department of Physics, University of California, Los Angeles, California 90024*

(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density $10^{18}$W/cm$^2$ shone on plasmas of densities $10^{18}$ cm$^{-3}$ can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

Collective plasma accelerators have recently received considerable theoretical and experimental investigation. Earlier Fermi[1] and McMillan[2] considered cosmic-ray particle acceleration by moving magnetic fields[1] or electromagnetic waves.[2] In terms of the realizable laboratory technology for collective accelerators,

the wavelength of the plasma waves in the wake:

$$L_t = \lambda_w/2 = \pi c/\omega_p. \quad (2)$$

An alternative way of exciting the plasmon is to inject two laser beams with slightly different frequencies (with frequency difference $\Delta\omega \sim \omega_p$) so that the beat distance of the packet becomes

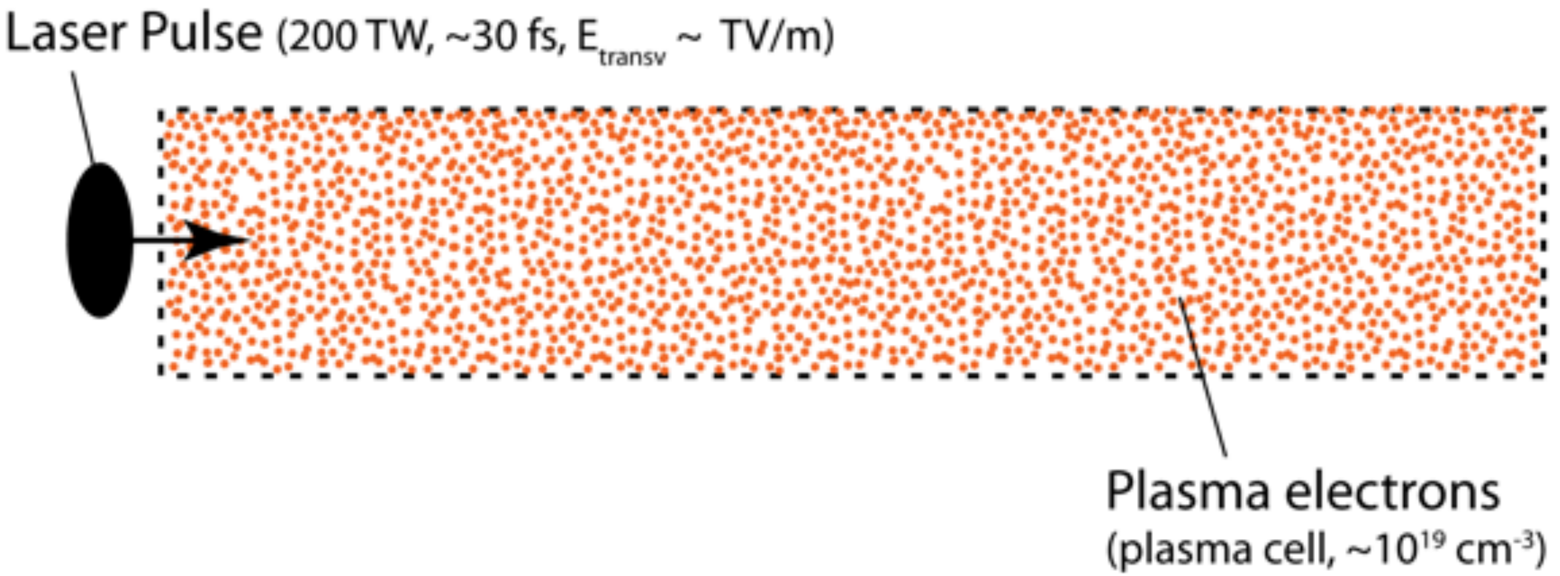
## Options for driving wakefields:

- **Lasers**: Industrially available, steep progress, path to low cost
  Limited energy per drive pulse (up to **50 J**)
- **Electron bunch**: Short bunches (need $\mu$m) 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**)

# Laser Plasma-Acceleration

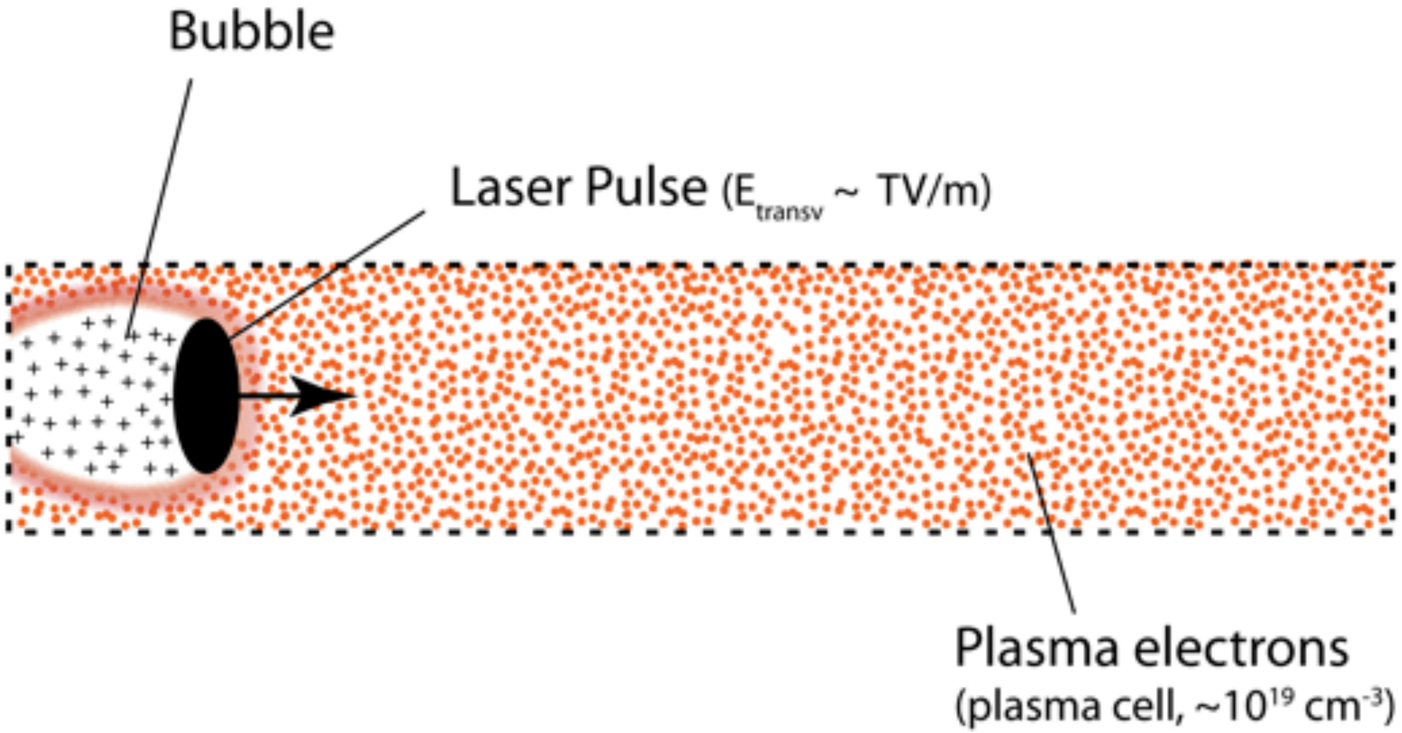
## Internal injection

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).



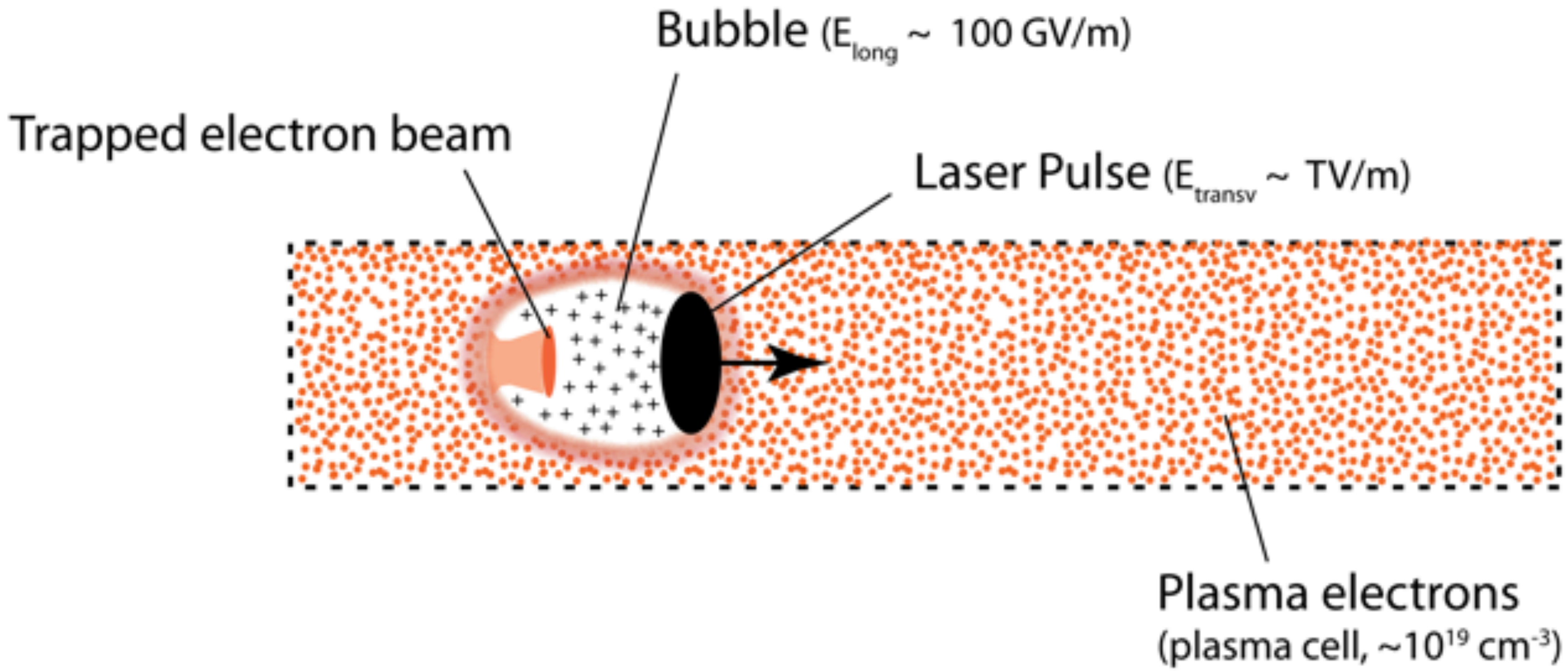
# Laser Plasma-Acceleration

## Internal injection



# Laser Plasma-Acceleration

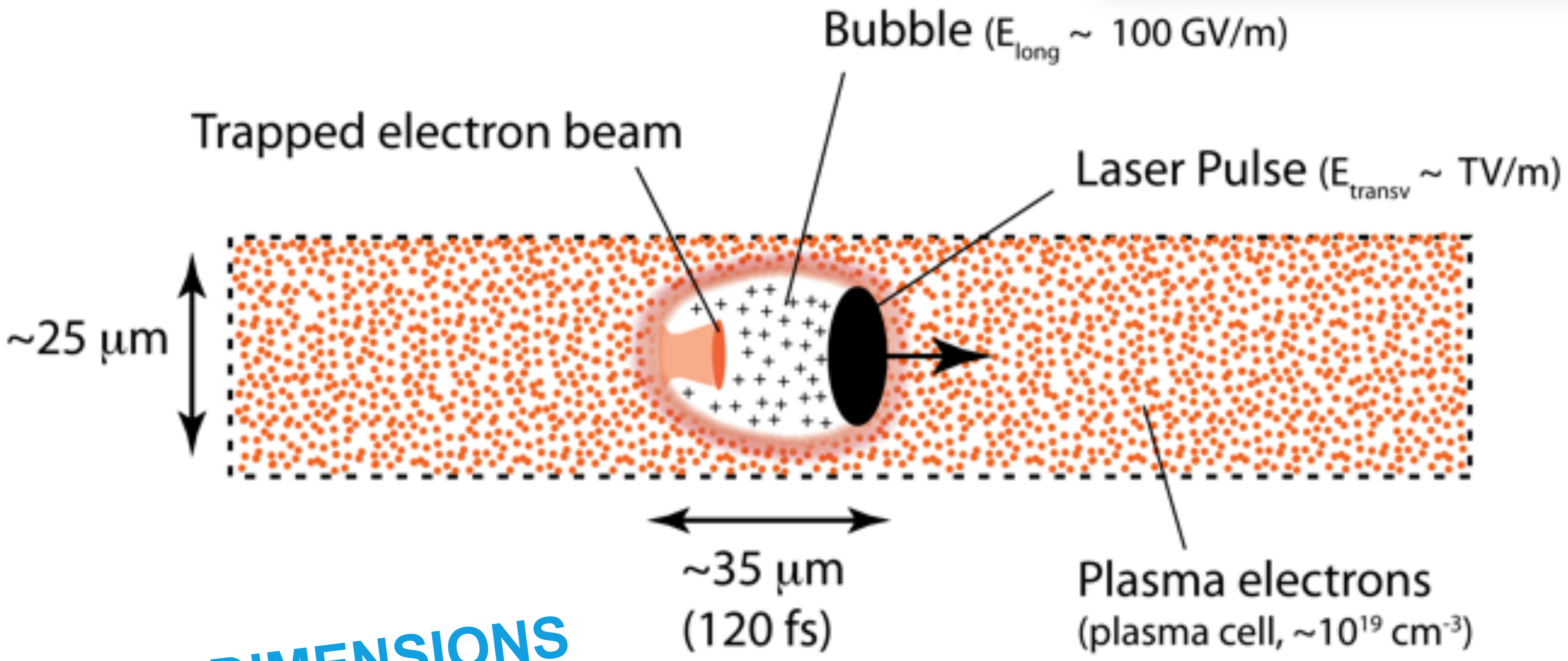
**Internal injection → strong fields in the bubble suck in plasma electrons to form the electron beam**



# Laser Plasma-Acceleration

## Internal injection

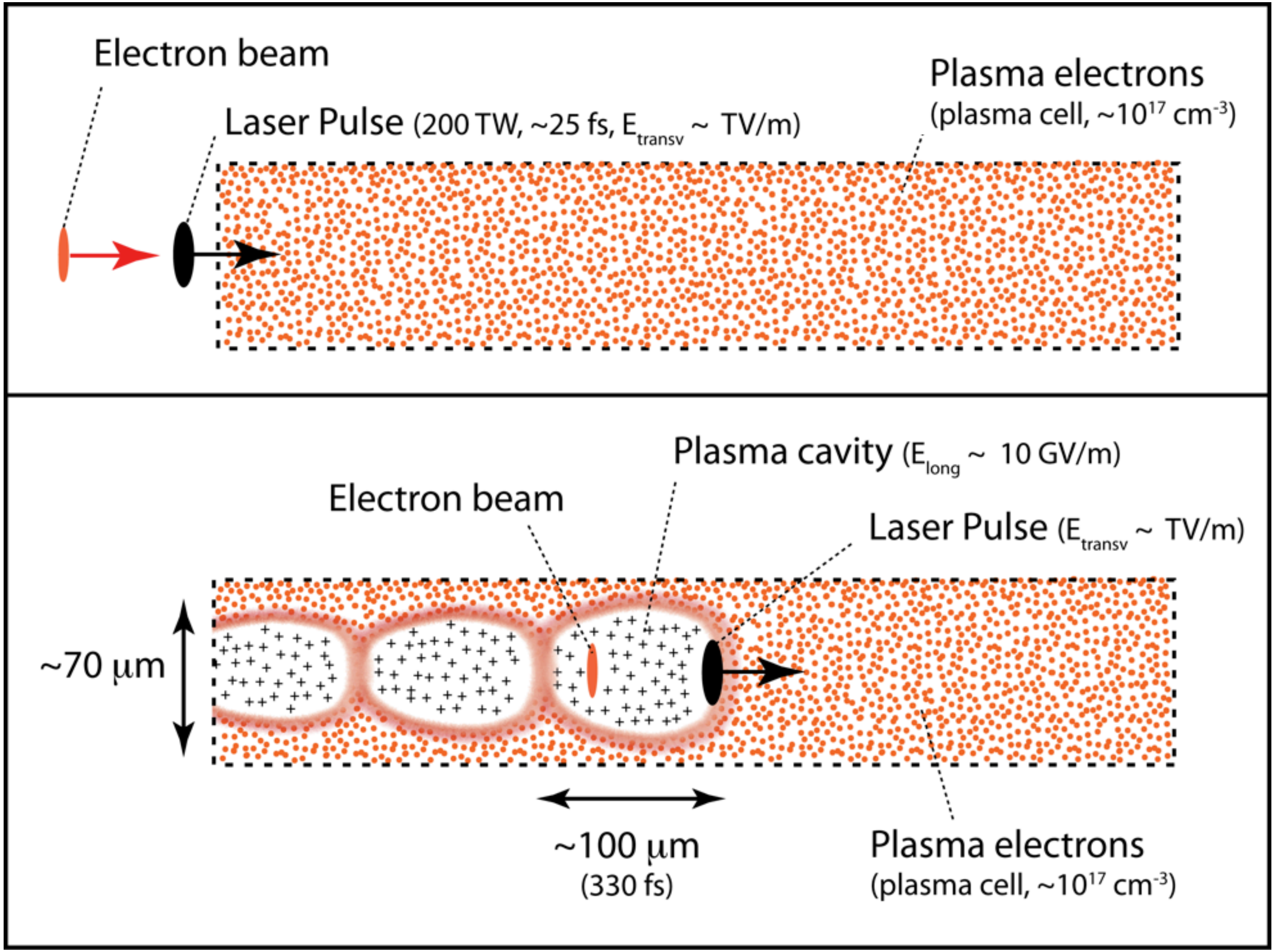
This accelerator fits into a human hair




SMALL DIMENSIONS

# Laser Plasma Acceleration

## External injection




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 λ

**Rosenzweig and Colby – here assume a factor 1000 higher frequency → 1000 times shorter wavelength**

| *Parameter* | | *Required for higher frequency* | |
|---|---|---|---|
| • Acc. gradient: | $E_0 \propto \lambda^{-1}$ | Higher gradients | **x 1000** |
| • Bunch length: | $\sigma_z \propto \lambda$ | Short bunch length | **/ 1000** |
| • Focusing field: | $B \propto \lambda^{-1}$ | High focusing field (Solenoid) | **x 1000** |
| • Bunch transv. size: | $\sigma_{x,y} \propto \lambda$ | Small beam size | **/ 1000** |

***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.**

# Space Charge

## The Coulomb Force and Magnetic Attraction

*Applies in all directions and couples them – true 3D effect.*

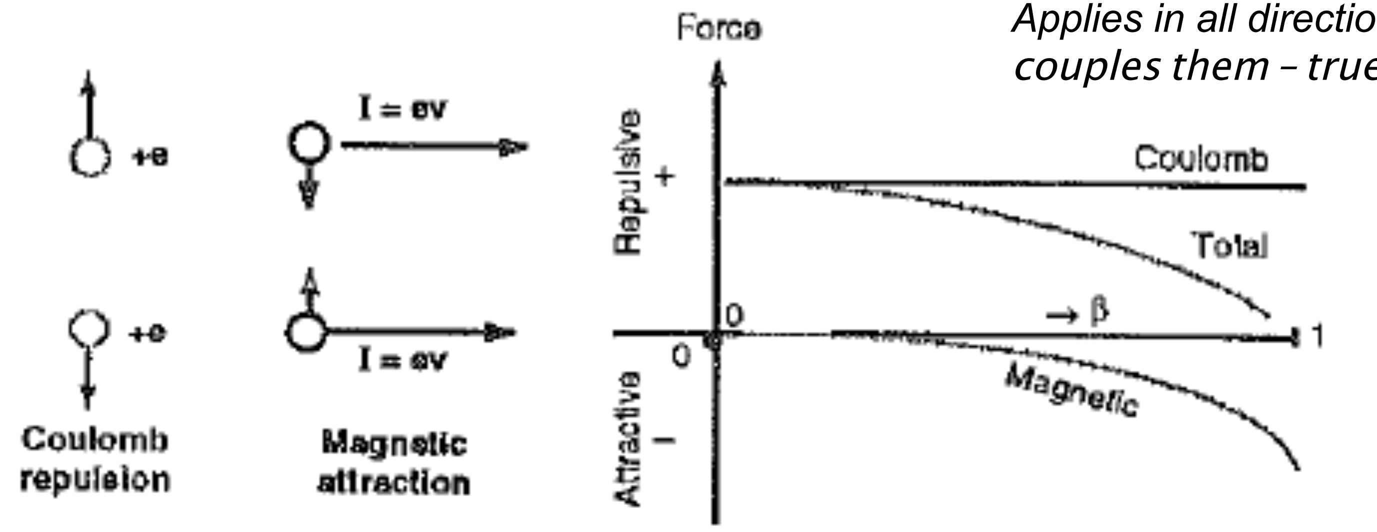



Figure 1: Coulomb repulsion and magnetic attraction between two particles of equal charge, at rest and travelling.

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):

Bunch independent constant

Charge

Dependent on bunch aspect ratio

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

Energy

Distribution shape dependent constant

Bunch length

Bunch transverse size

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)

# Contents

# Linear Wakefields (R. Ruth / P. Chen 1986)

## The formulae behind it all

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

$$r \ll a$$

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

$$A = \begin{cases} \dfrac{\omega_p \tau k_p e E_0^2}{8\omega^2 m} & PBWA \\ \dfrac{8eN}{a^2} & PWFA \end{cases}$$

| | |
|---|---|
| ε | = electrical field |
| z | = long. coord. |
| r | = radial coord. |
| a | = driver radius |
| $\omega_p$ | = plasma frequency |
| $k_p$ | = plasma wave number |
| t | = time variable |
| e | = electron charge |
| N | = number e- drive bunch |
| ω | = laser frequency |
| τ | = laser pulse length |
| $E_0$ | = laser electrical field |
| m | = mass of electron |

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

**Accelerating field**

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

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

**Transverse field**

# Linear Wakefields (R. Ruth / P. Chen 1986)

## The formulae behind it all

Accelerating field

Depends on radial position r

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

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

Transverse field

Depends on radial position r

# Linear Wakefields (R. Ruth / P. Chen 1986)

## The formulae behind it all

Accelerating field

Depends on radial position r

Changes between accelerating and decelerating as function of longitudinal position z

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

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

Transverse field

Changes between focusing and defo-cusing as function of longitudinal position z

Depends on radial position r

# Linear Wakefields (R. Ruth / P. Chen 1986)

## The formulae behind it all

Accelerating field

Depends on radial position r

Changes between accelerating and decelerating as function of longitudinal position z

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

π/2 out of phase

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

Transverse field

Changes between focusing and defo-cusing as function of longitudinal position z

Depends on radial position r

# The Useful Regime of Plasma Accelerators

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

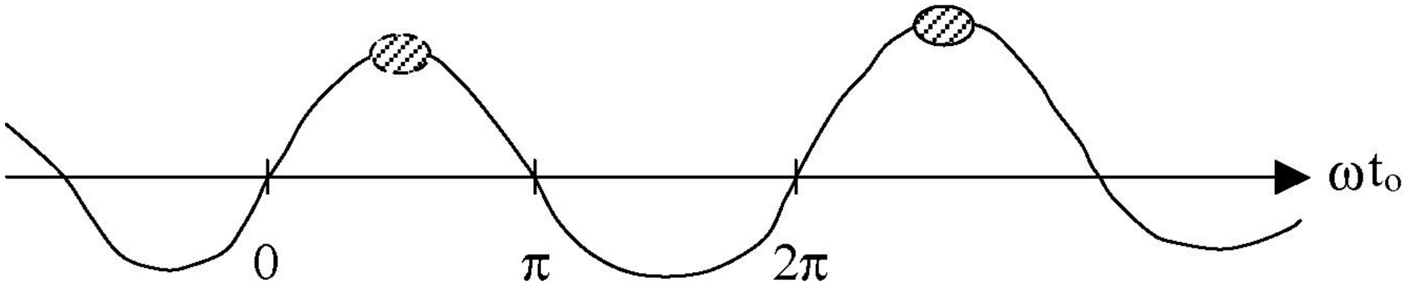
Two conditions for an accelerator:

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!

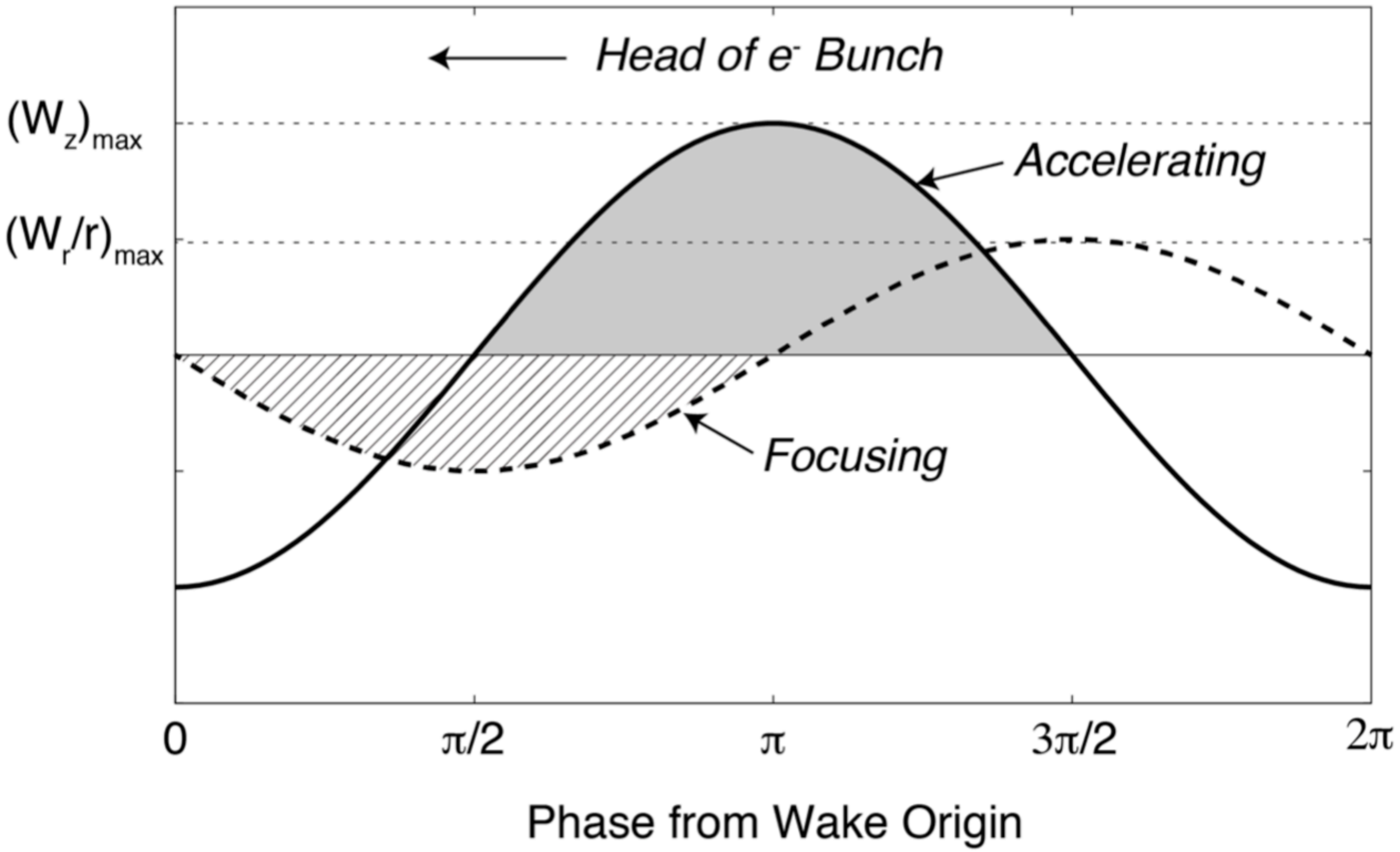
Reminder metallic RF accelerator structures:

no net transverse fields for beam particles → full accelerating range is available for beam → usually place the beam on the crest of the accelerating voltage



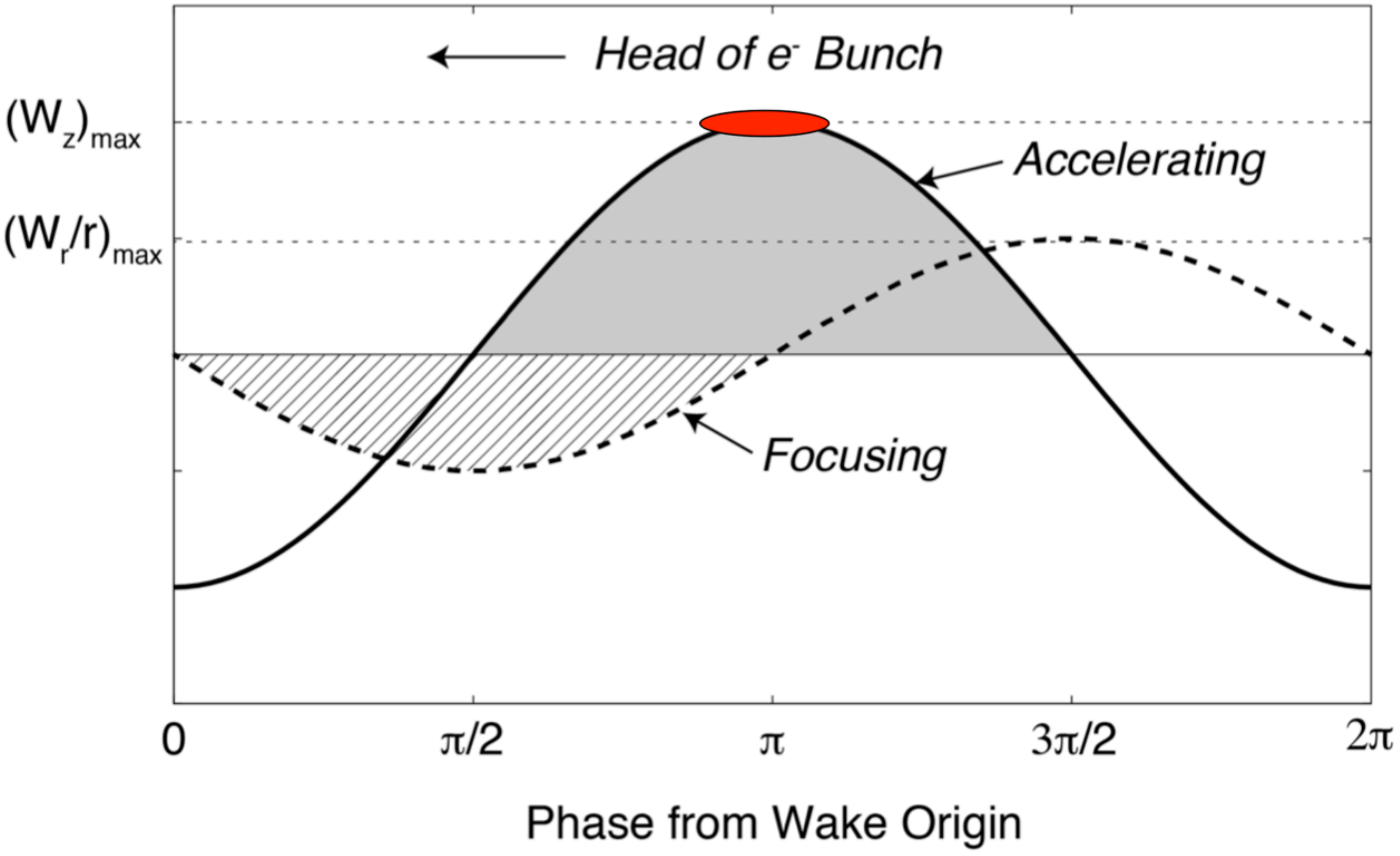
# Plasma Accelerator Phasing

## Finding the useful regime



# Plasma Accelerator Phasing

## Finding the useful regime



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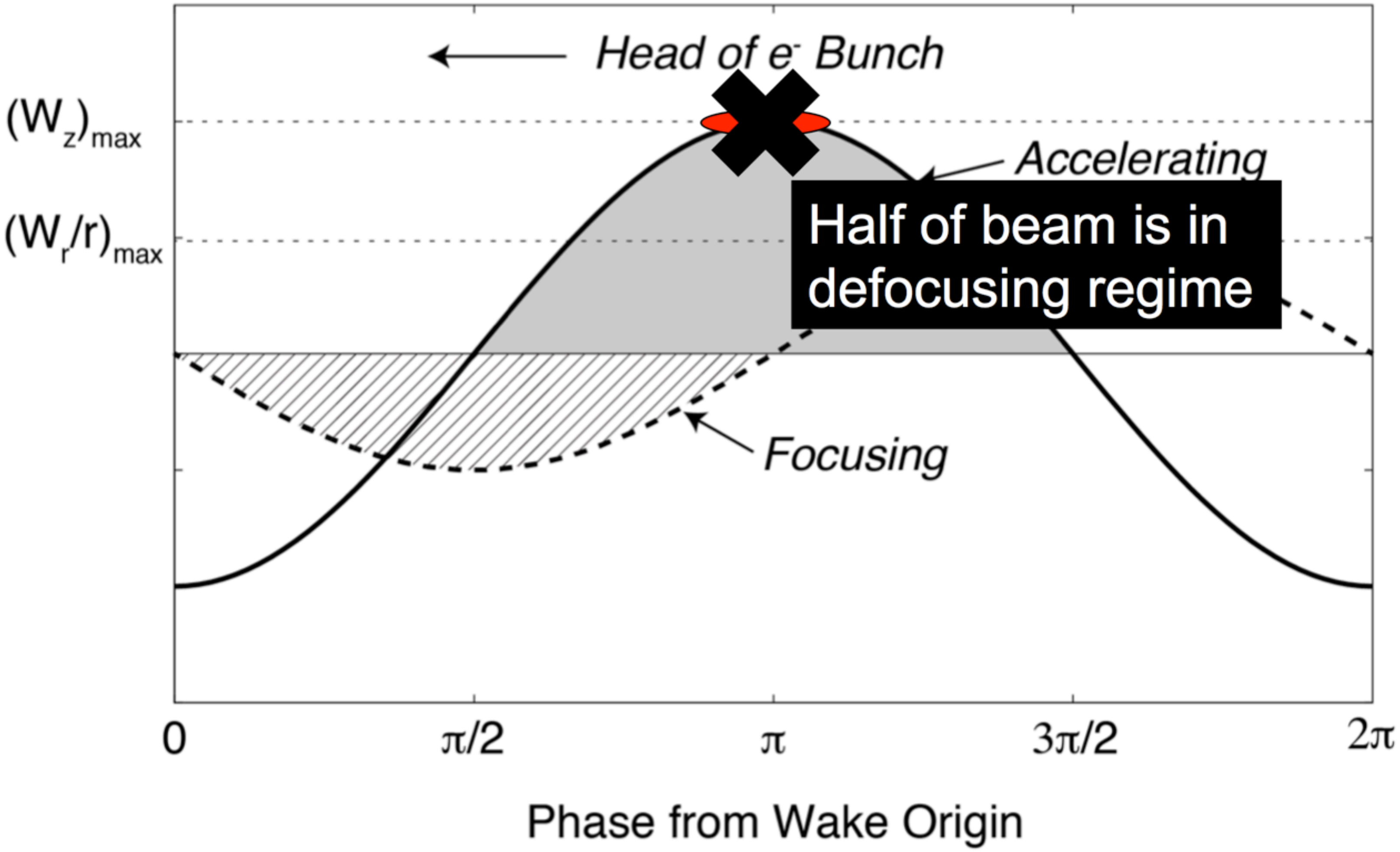

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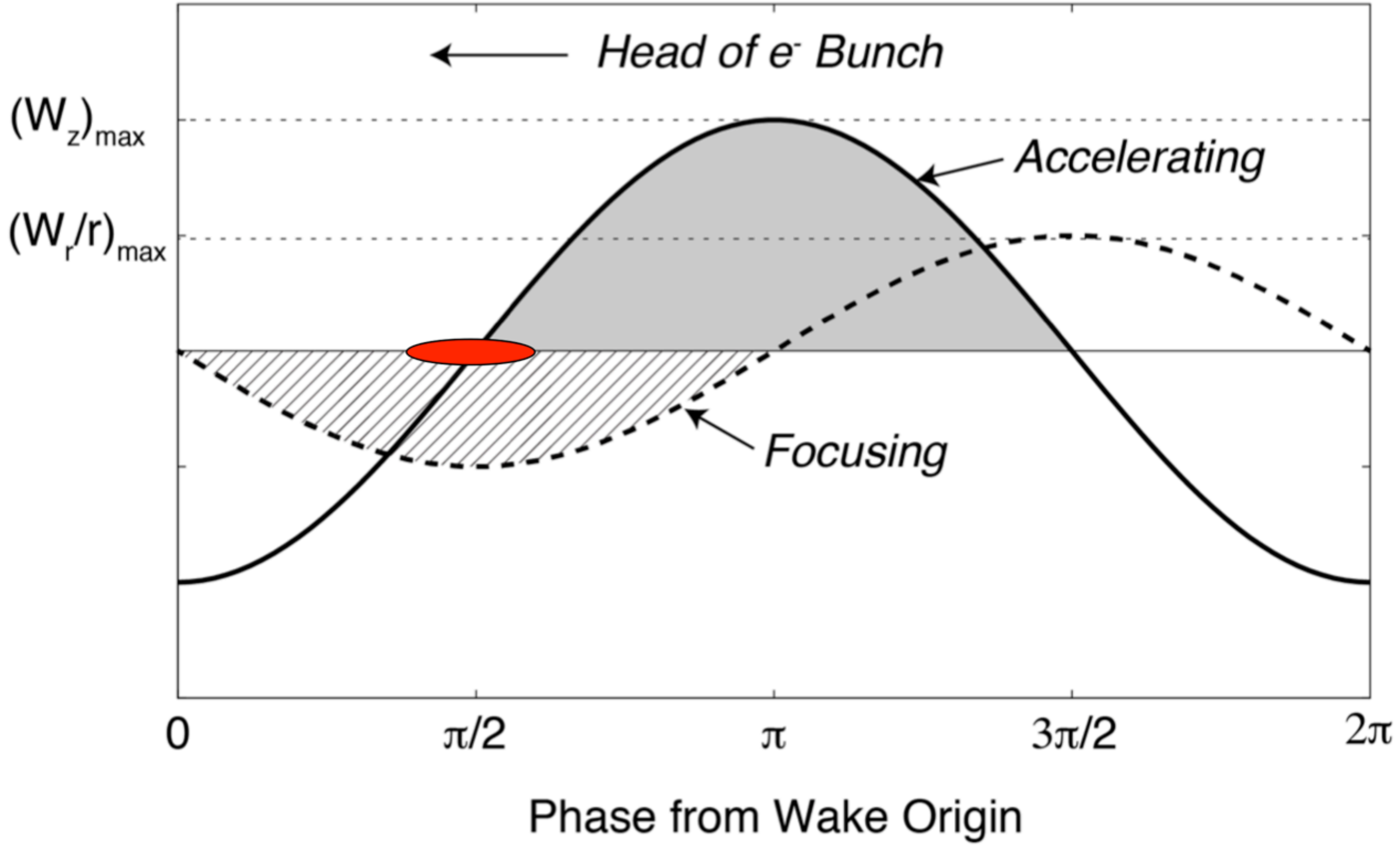

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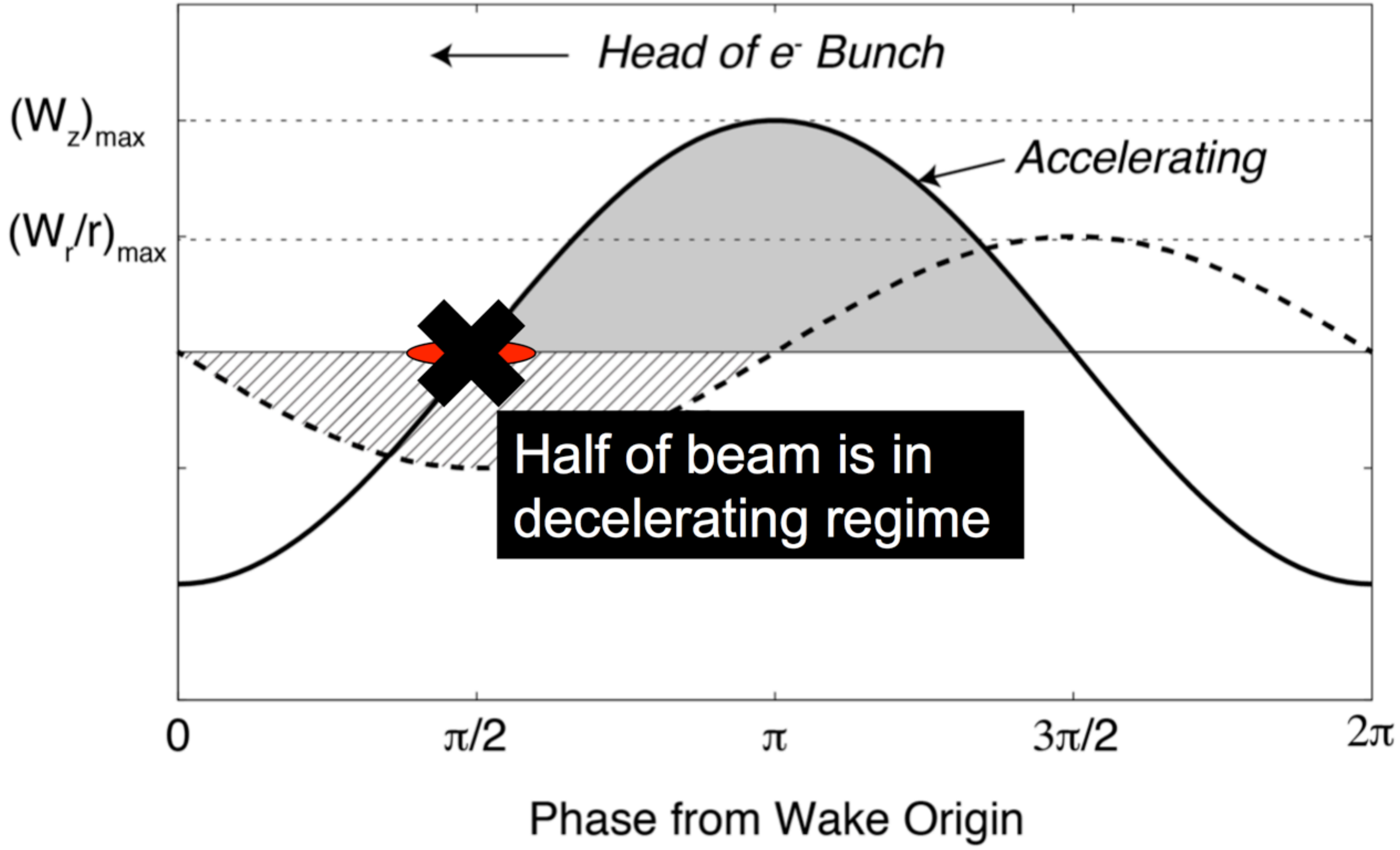

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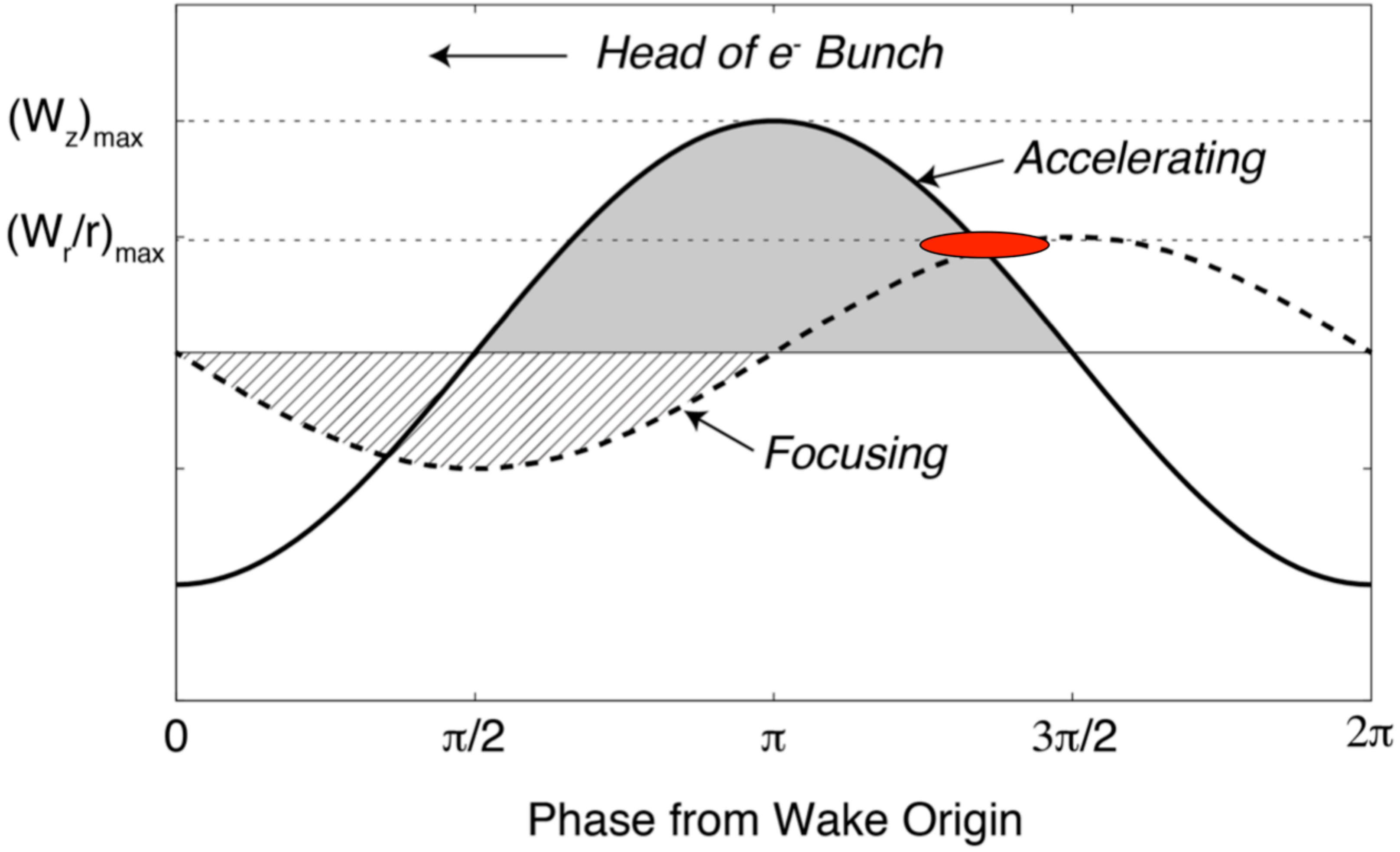

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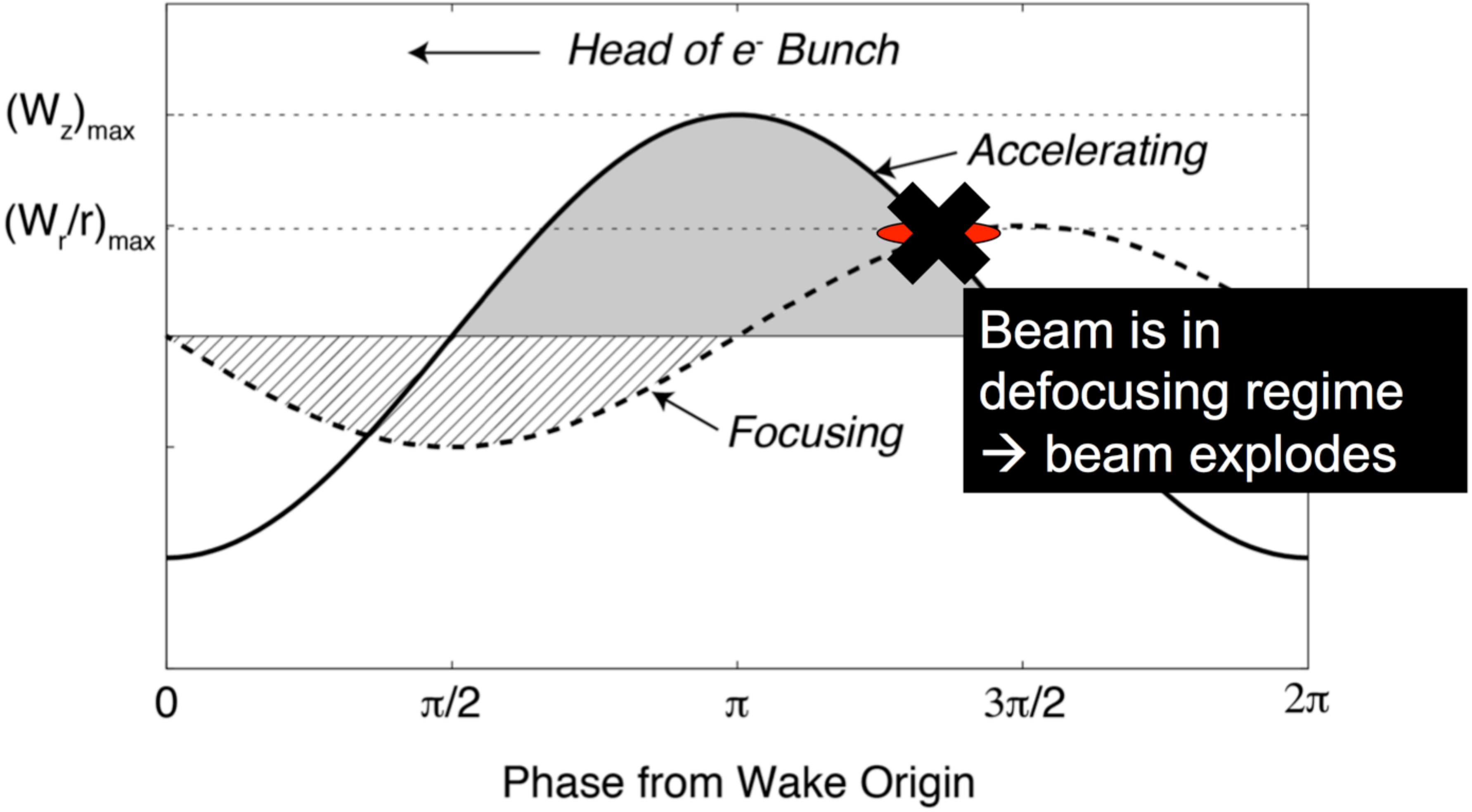

# Plasma Accelerator Phasing

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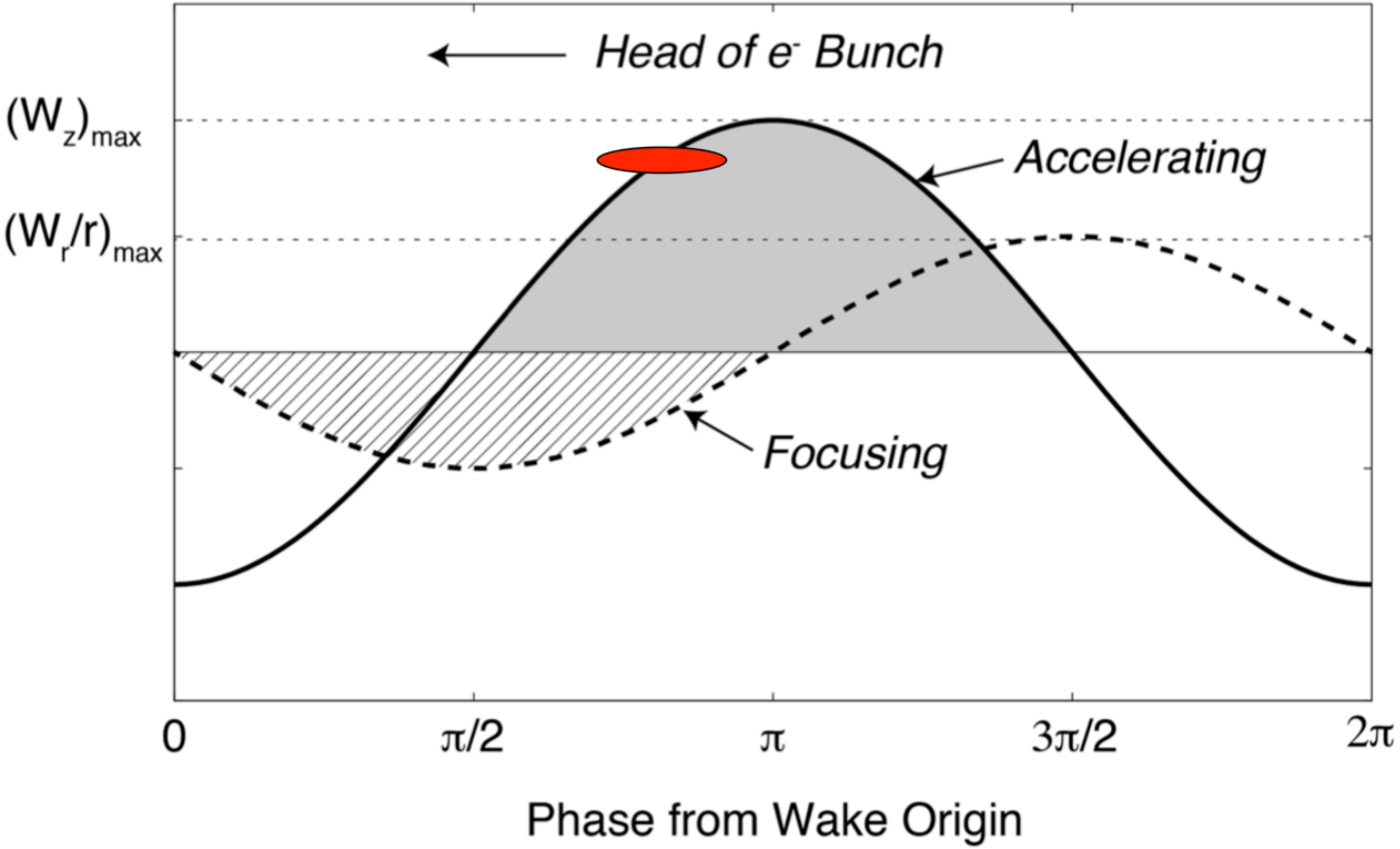
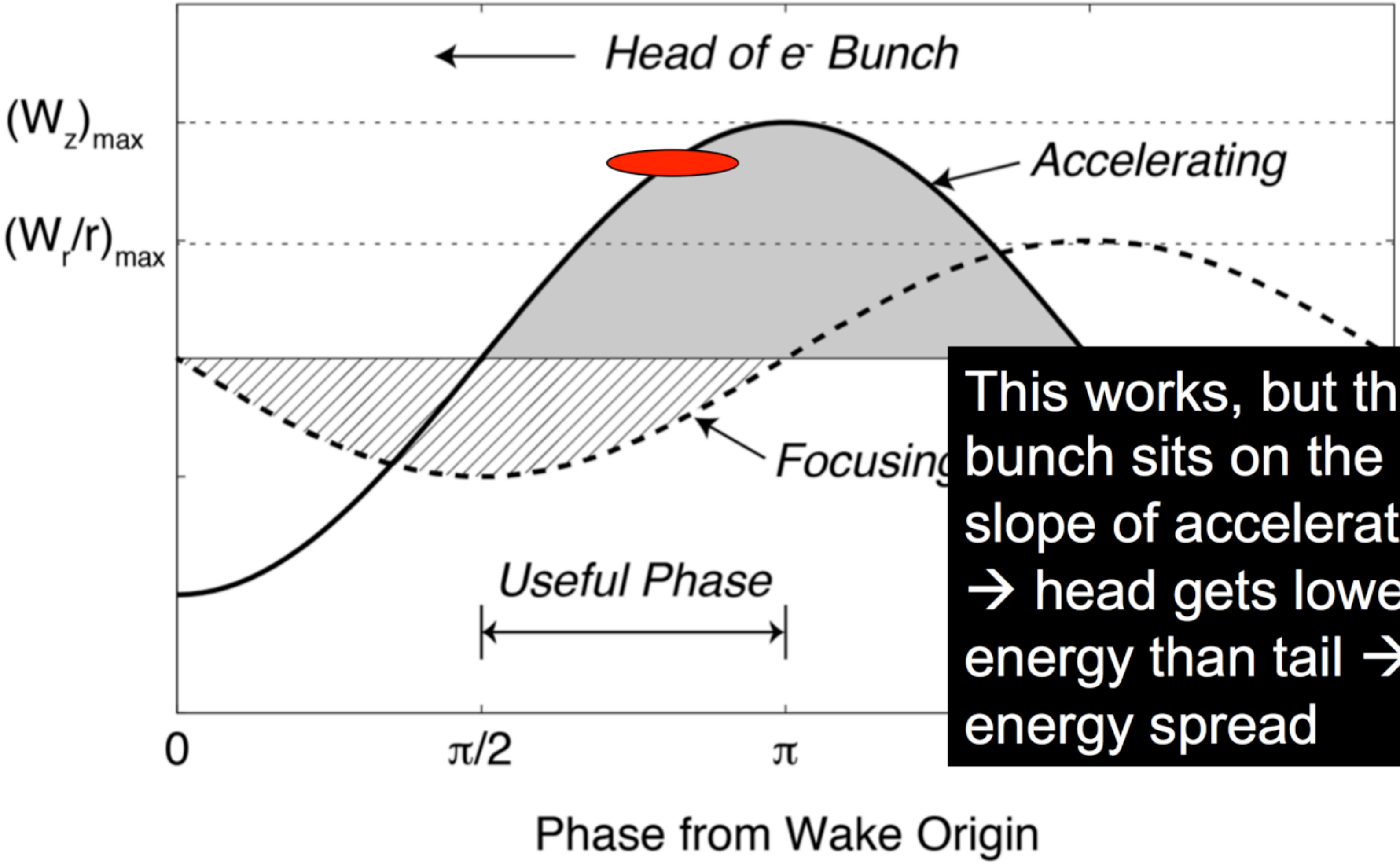


# Plasma Accelerator Phasing

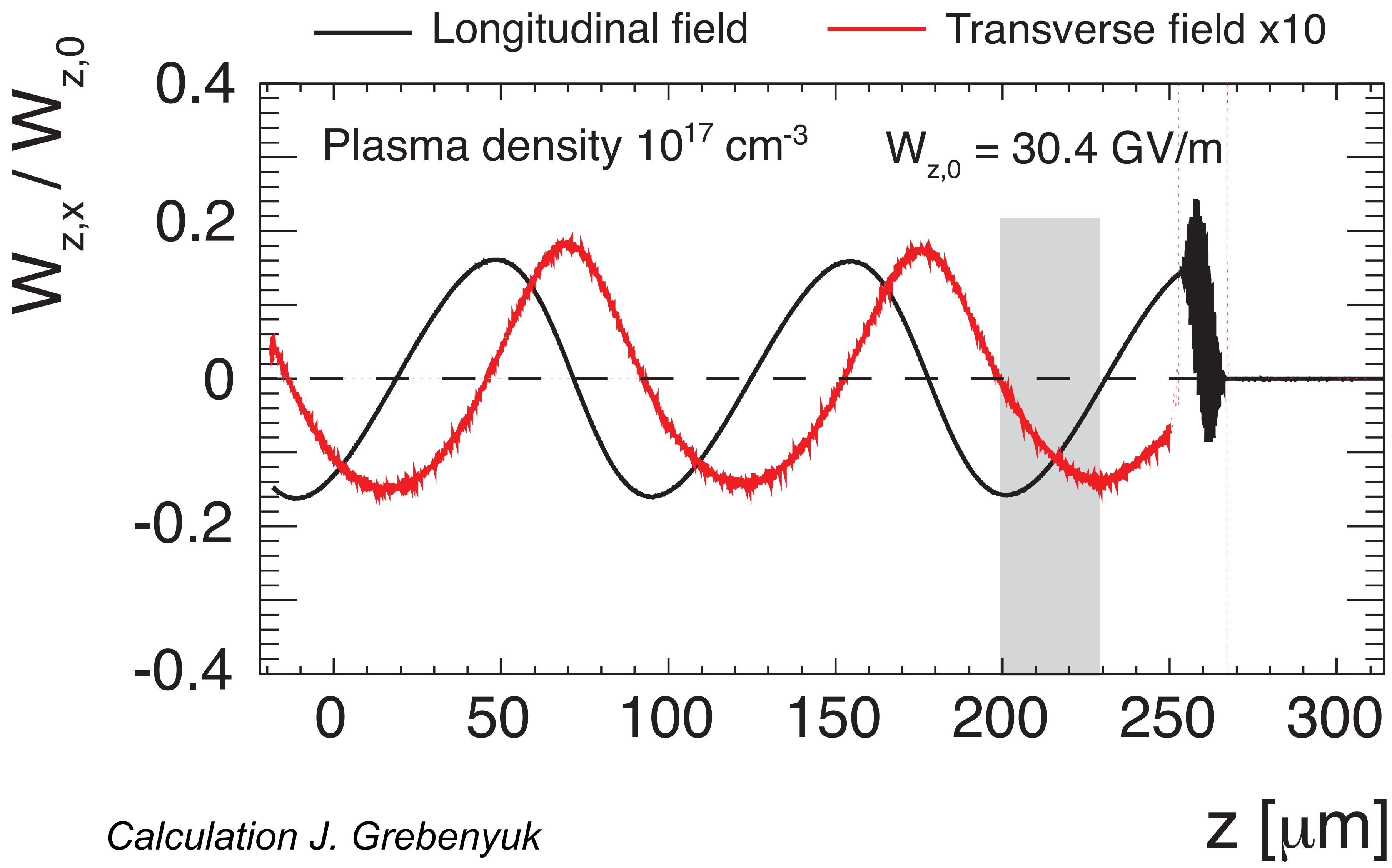
## Finding the useful regime




This works, but the bunch sits on the slope of acceleration → head gets lower energy than tail → energy spread

# Comparison with OSIRIS simulation

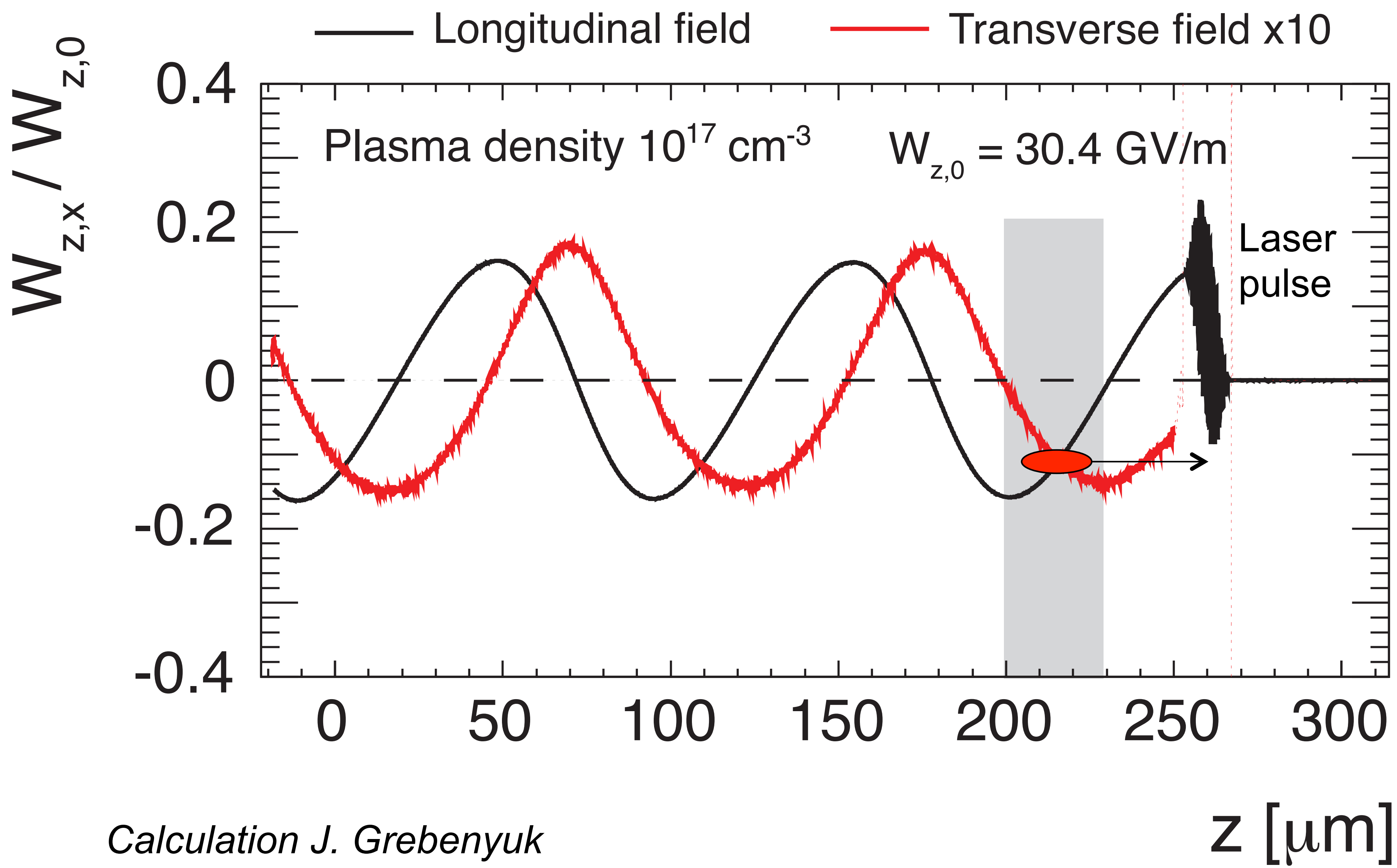
## Finding the useful regime




*Calculation J. Grebenyuk*

# Comparison with OSIRIS simulation

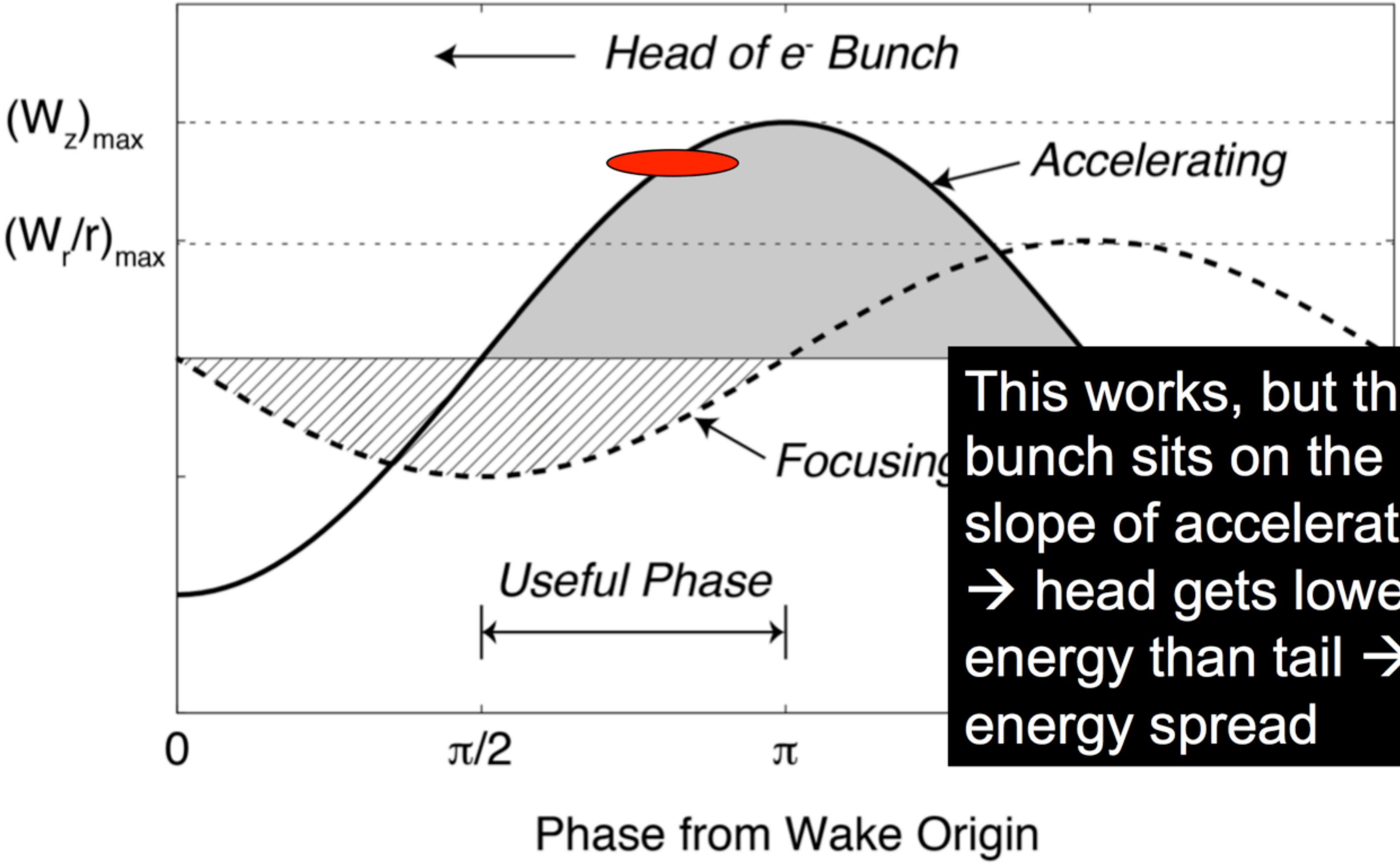
## Finding the useful regime




*Calculation J. Grebenyuk*

# Plasma Accelerator Phasing

## Finding the useful regime

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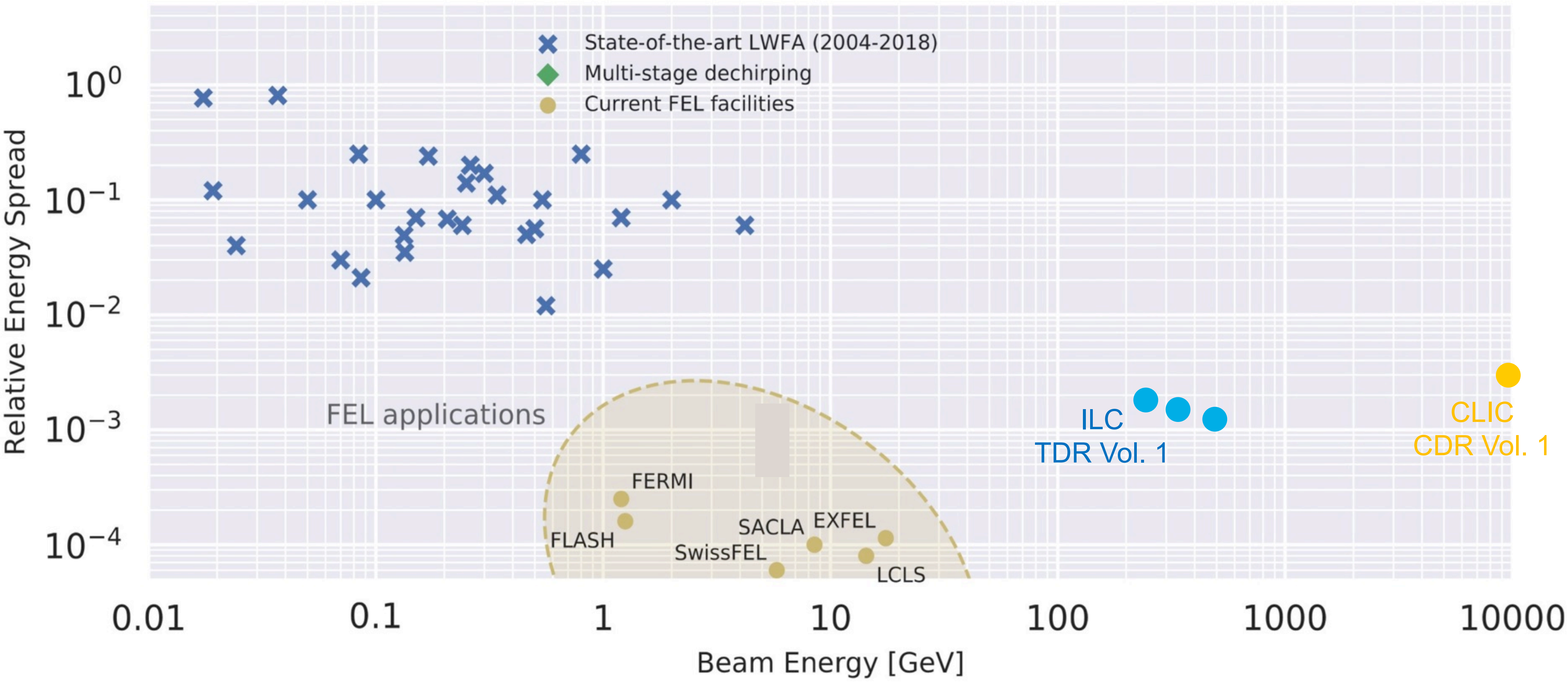
# Contents

# Energy Spread Challenge

**State of the art in plasma accelerators versus requirements**

*Plot version A. Walker et al*



# Energy Spread Challenge

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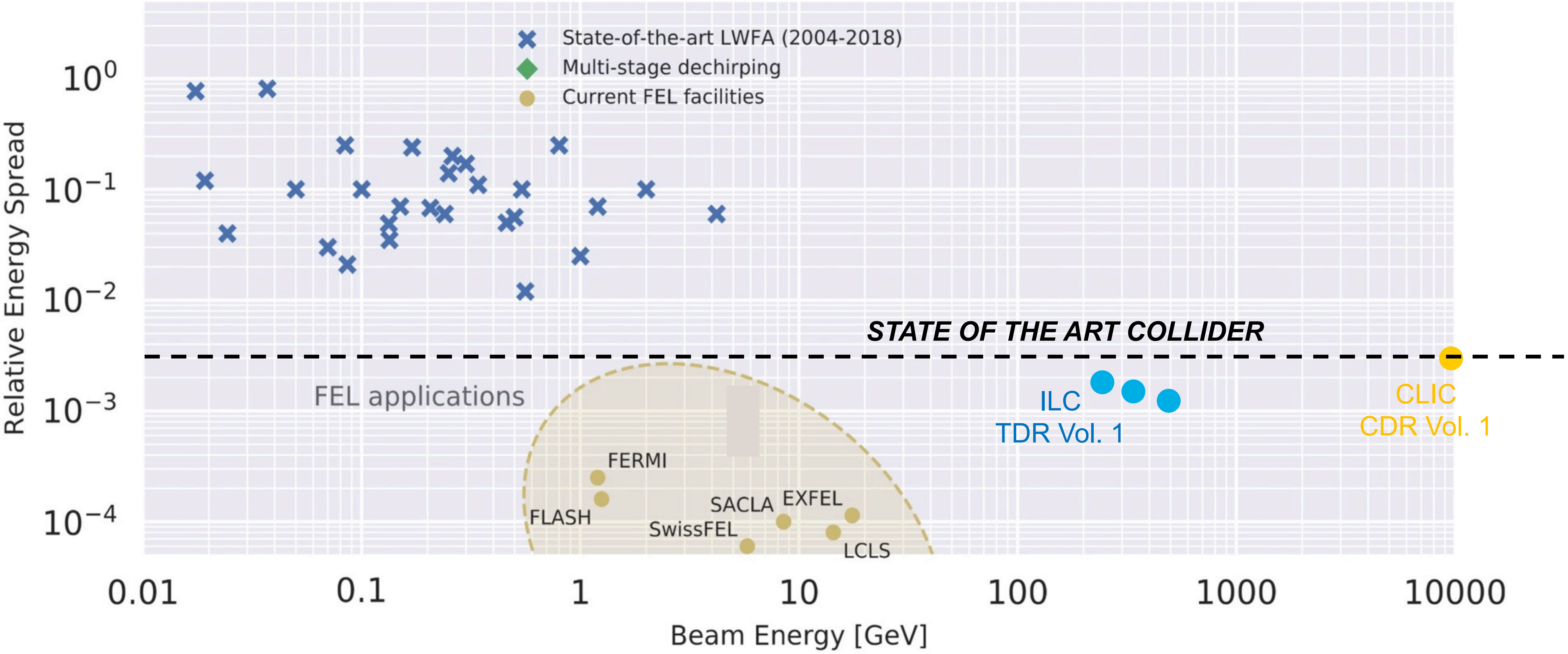

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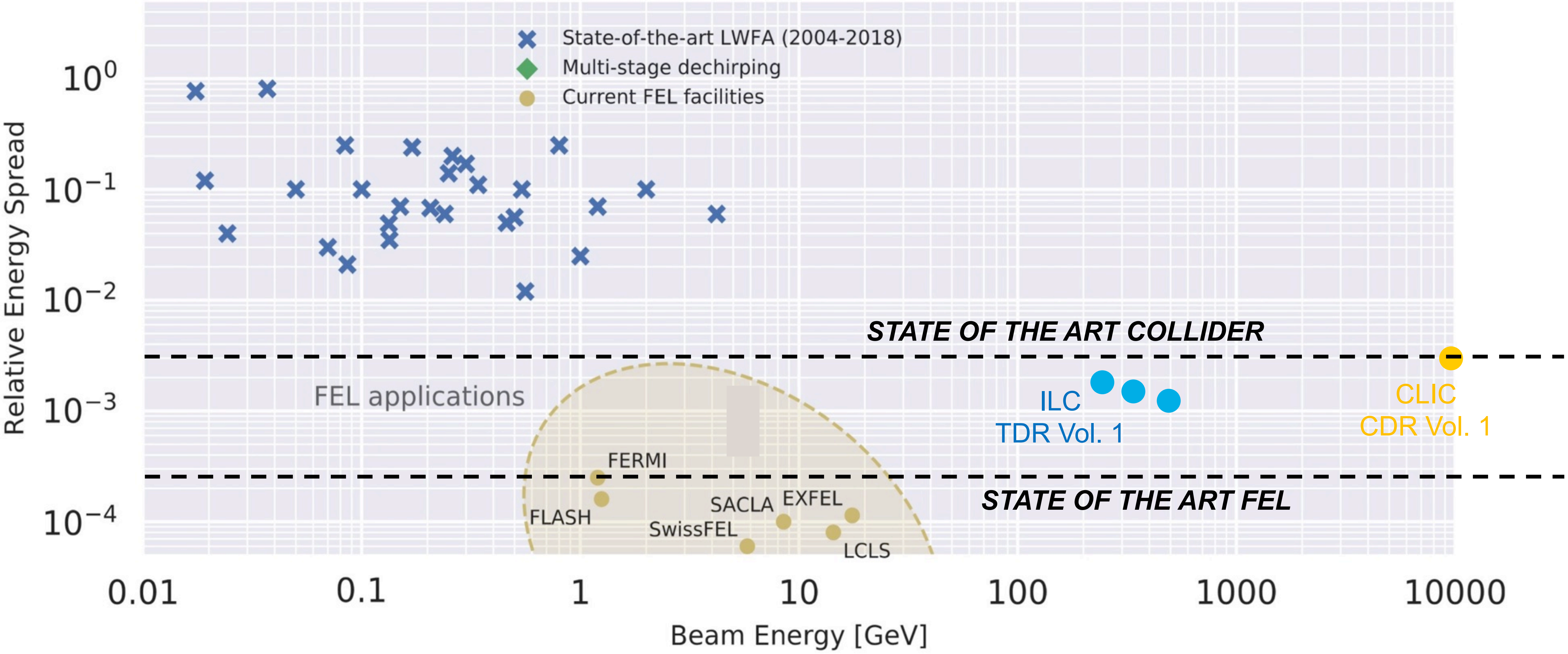

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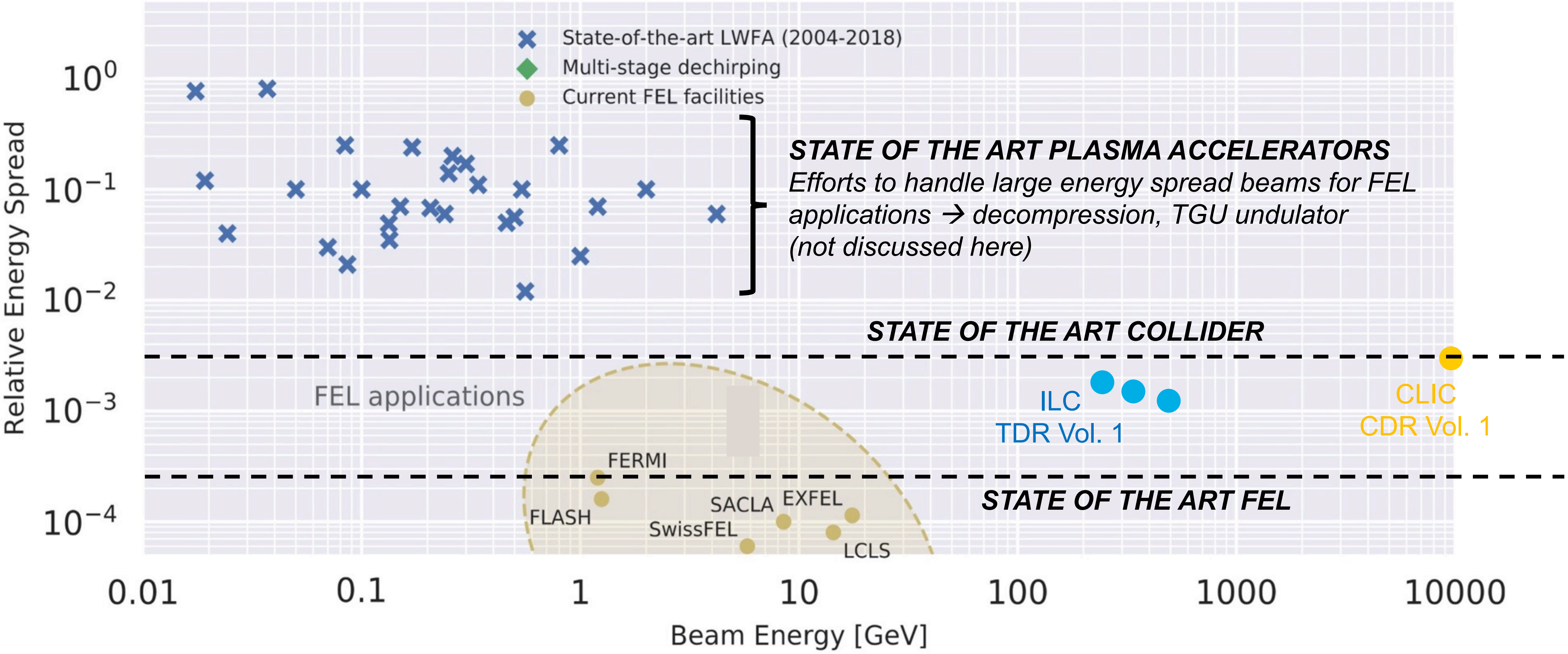
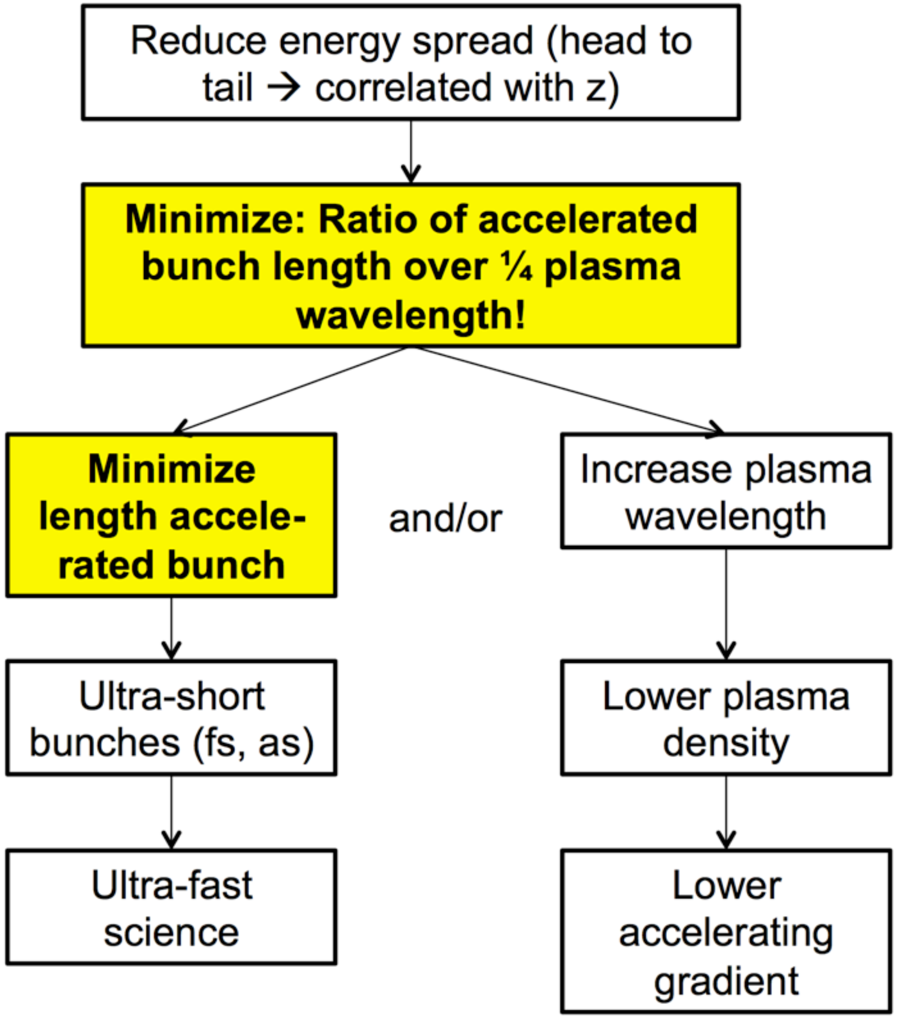


# Optimization: Minimal Energy Spread

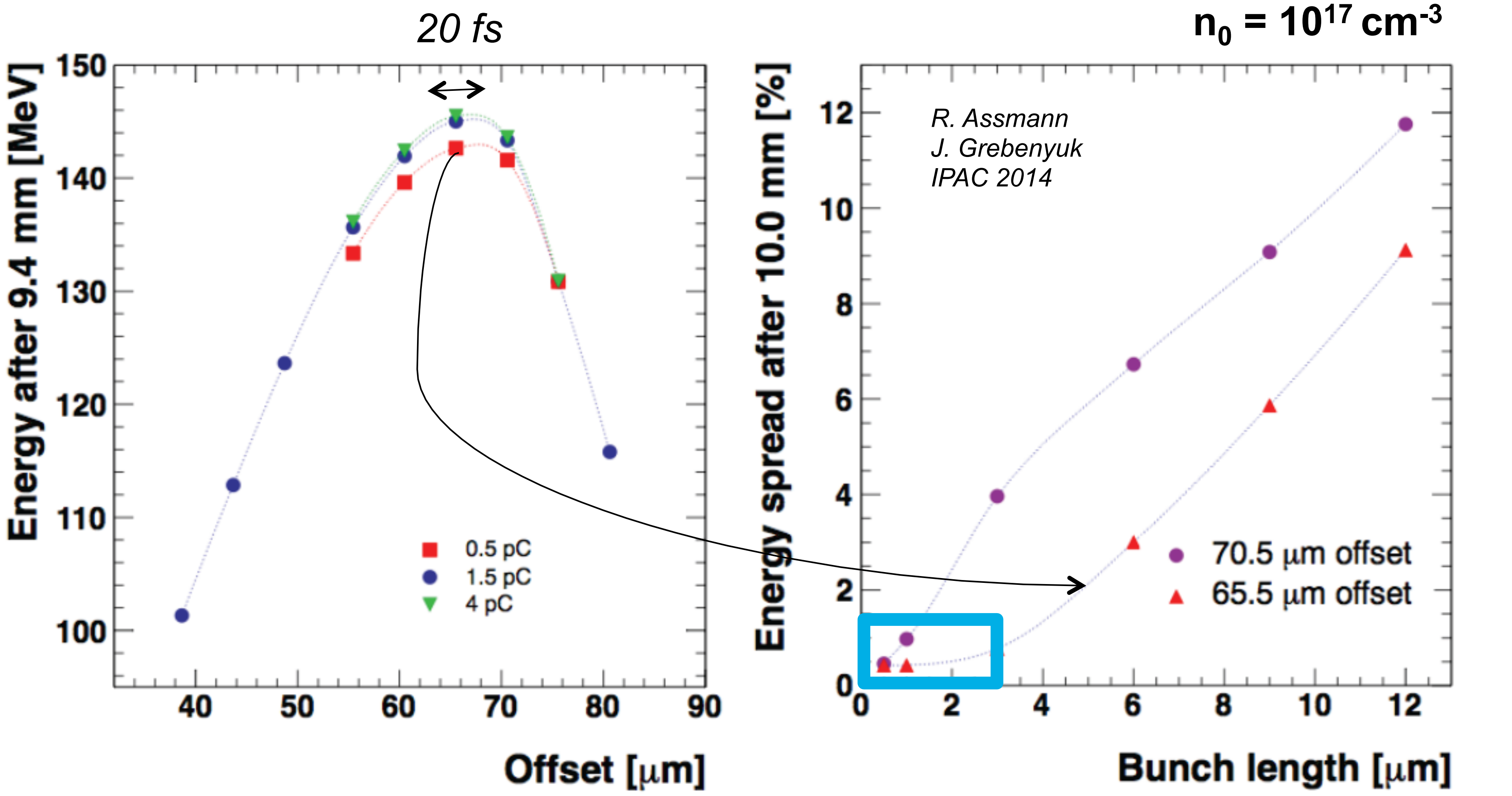
## Avoid creation of too much energy spread (cannot be fully avoided by principle explained before)



# Gedankenexperiment – Zero Bunch Length

**Infinitesimally short bunch will not see any slope of accelerating voltage**

1 fs = 0.3 μm when travelling with light velocity c




Here, longitudinal field independent of radial position

Zero bunch length → all particles at same longitudinal coord. and see the same acceleration.

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

# 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.

VOLUME 88, NUMBER 15 PHYSICAL REVIEW LETTERS 15 APRIL 2002

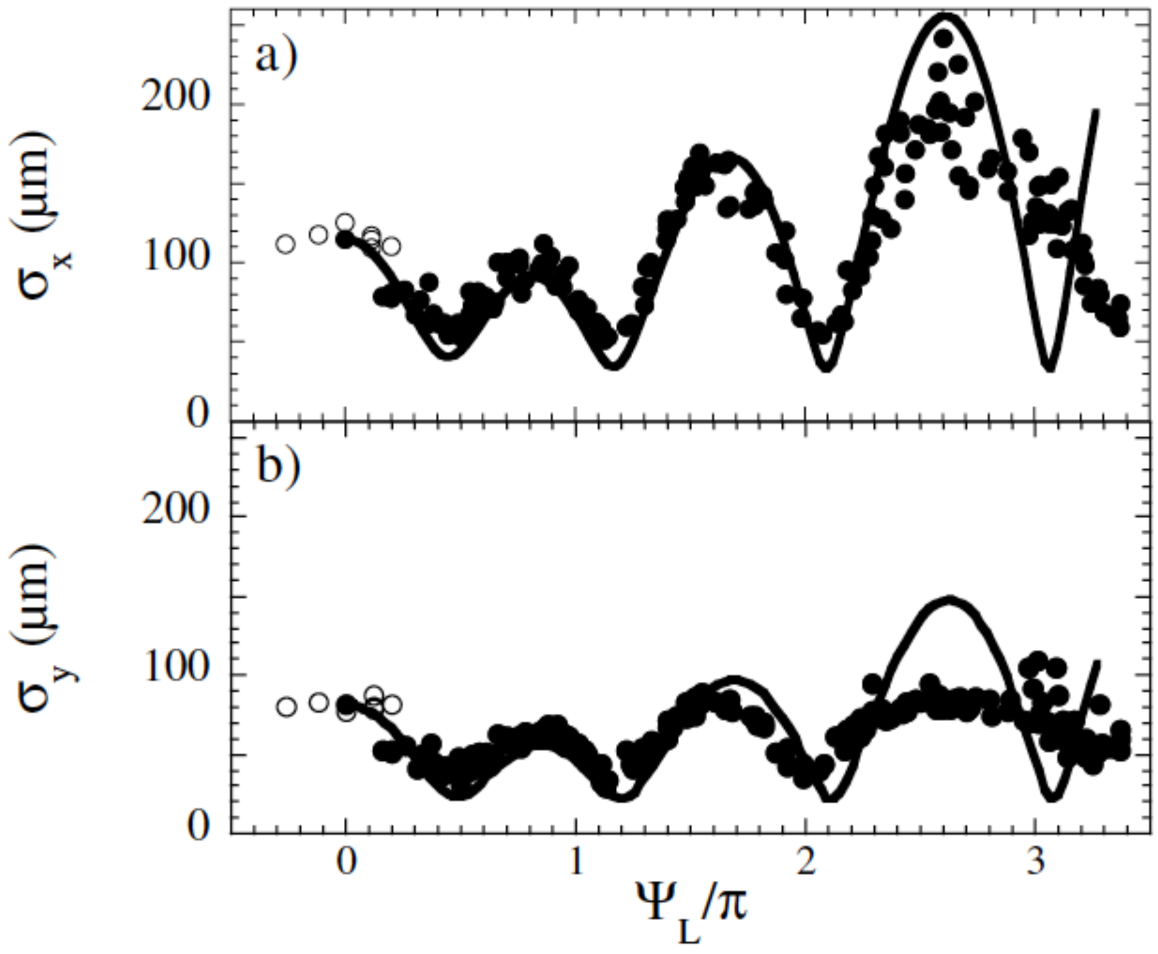
**Transverse Envelope Dynamics of a 28.5-GeV Electron Beam in a Long Plasma**

C. E. Clayton, B. E. Blue, E. S. Dodd, C. Joshi, K. A. Marsh, W. B. Mori, and S. Wang
*University of California, Los Angeles, California 90095*

P. Catravas, S. Chattopadhyay, E. Esarey, and W. P. Leemans
*Lawrence Berkeley National Laboratory, University of California, Berkeley, California 94720*

R. Assmann,* F. J. Decker, M. J. Hogan, R. Iverson, P. Raimondi, R. H. Siemann, and D. Walz
*Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309*

T. Katsouleas, S. Lee, and P. Muggli†
*University of Southern California, Los Angeles, California 90089*
(Received 9 October 2001; published 2 April 2002)



# 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 mis-matched 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 undulator!

VOLUME 88, NUMBER 13 PHYSICAL REVIEW LETTERS 1 APRIL 2002

**X-Ray Emission from Betatron Motion in a Plasma Wiggler**

Shuoqin Wang,[1] C. E. Clayton,[1] B. E. Blue,[1] E. S. Dodd,[1] K. A. Marsh,[1] W. B. Mori,[1] C. Joshi,[1] S. Lee,[2] P. Muggli,[2] T. Katsouleas,[2] F. J. Decker,[3] M. J. Hogan,[3] R. H. Iverson,[3] P. Raimondi,[3] D. Walz,[3] R. Siemann,[3] and R. Assmann[4]
[1]*University of California, Los Angeles, California 90095*
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[3]*Stanford Linear Accelerator Center, Stanford, California 94309*
[4]*CERN, Switzerland*
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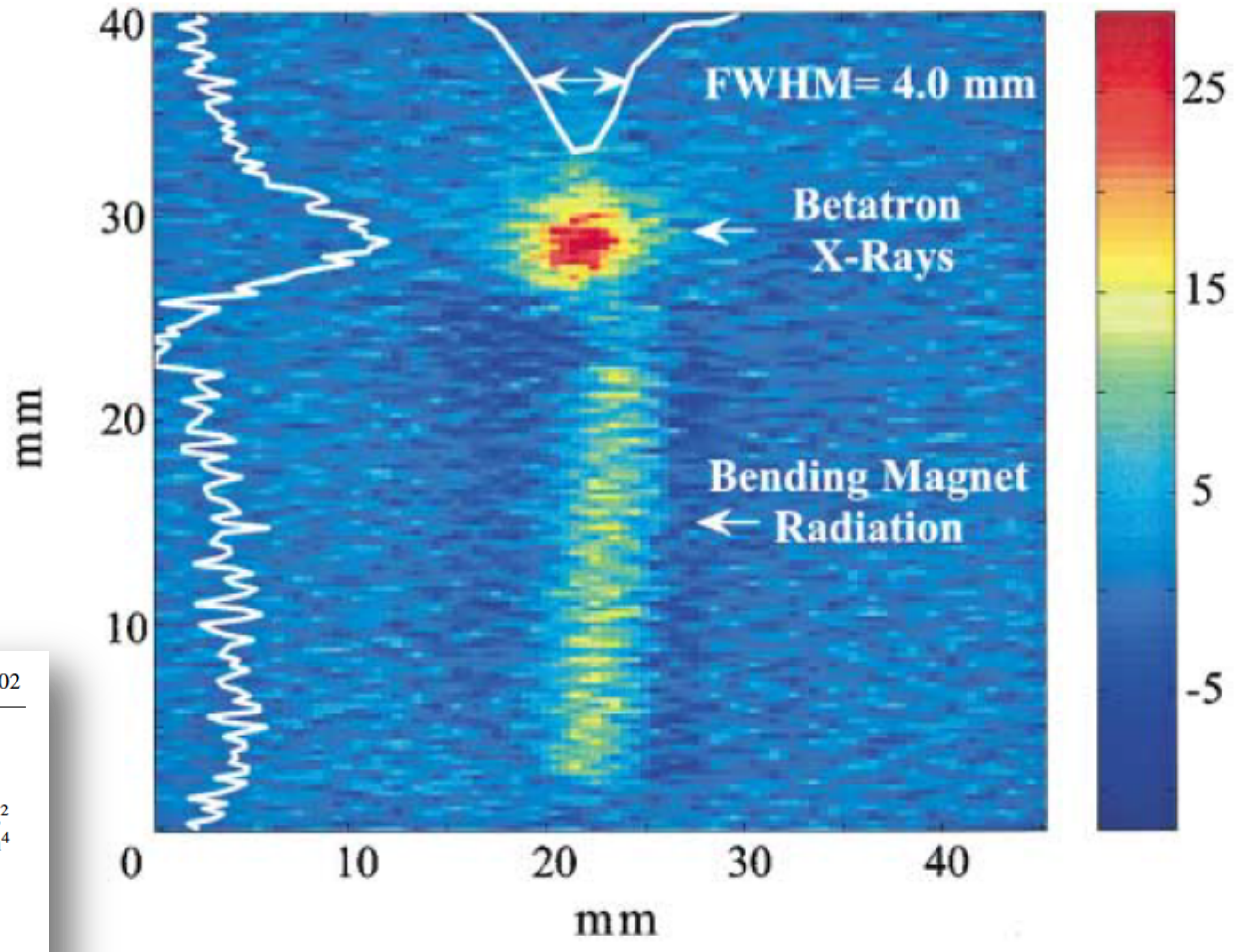


# Plasma Accelerator Physics I

## 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**:

$$\omega_p = \sqrt{\frac{n_0 \; e^2}{\epsilon_0 \; m_e}}$$

- 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 $n_0 = 10^{16}$ 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):

$$W_z = 96 \ \frac{\mathrm{V}}{\mathrm{m}} \cdot \sqrt{\frac{n_0}{\mathrm{cm}^{-3}}} \qquad \propto N_b / \sigma_z^2$$

**9.6 GV/m for $10^{16}$ 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 → 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:

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

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

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

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

**β = 1.1 mm for 100 MeV**

- The **phase advance** in the plasma channel is rapid:

$$\psi(s) = \int k_\beta s\,\mathrm{d}s \propto \sqrt{E}$$

# 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 μm for $\gamma\varepsilon$ = 0.3 μm**

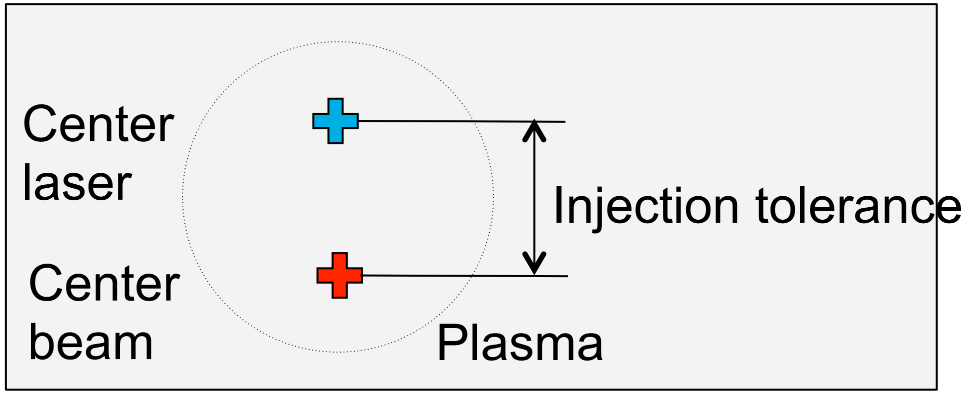
**DIFFICULTY**

- 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 $\Delta x = \sigma_x$:

**DIFFICULTY**

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

**100% for 1.3 μm offset**

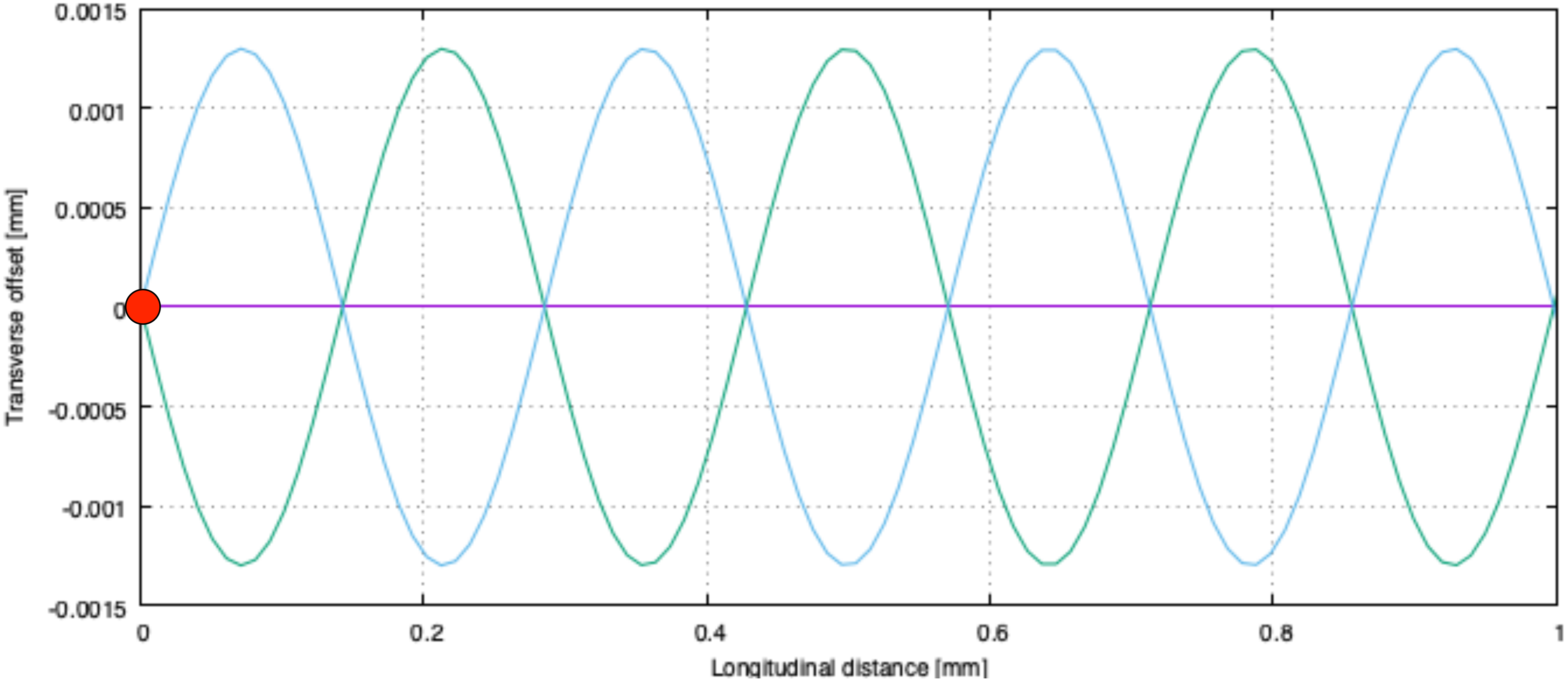



- Lower plasma density better: larger matched beam size, bigger tolerances.

*Assmann, R. and K. Yokoya. Transverse Beam Dynamics in Plasmas. NIM A410 (1998) 544-548.*

# Now: Is there an Impact? → Transverse Oscillations

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




**+ 1 σ normalized oscillation amplitude**

**0 σ normalized oscillation amplitude**

**- 1 σ normalized oscillation amplitude**

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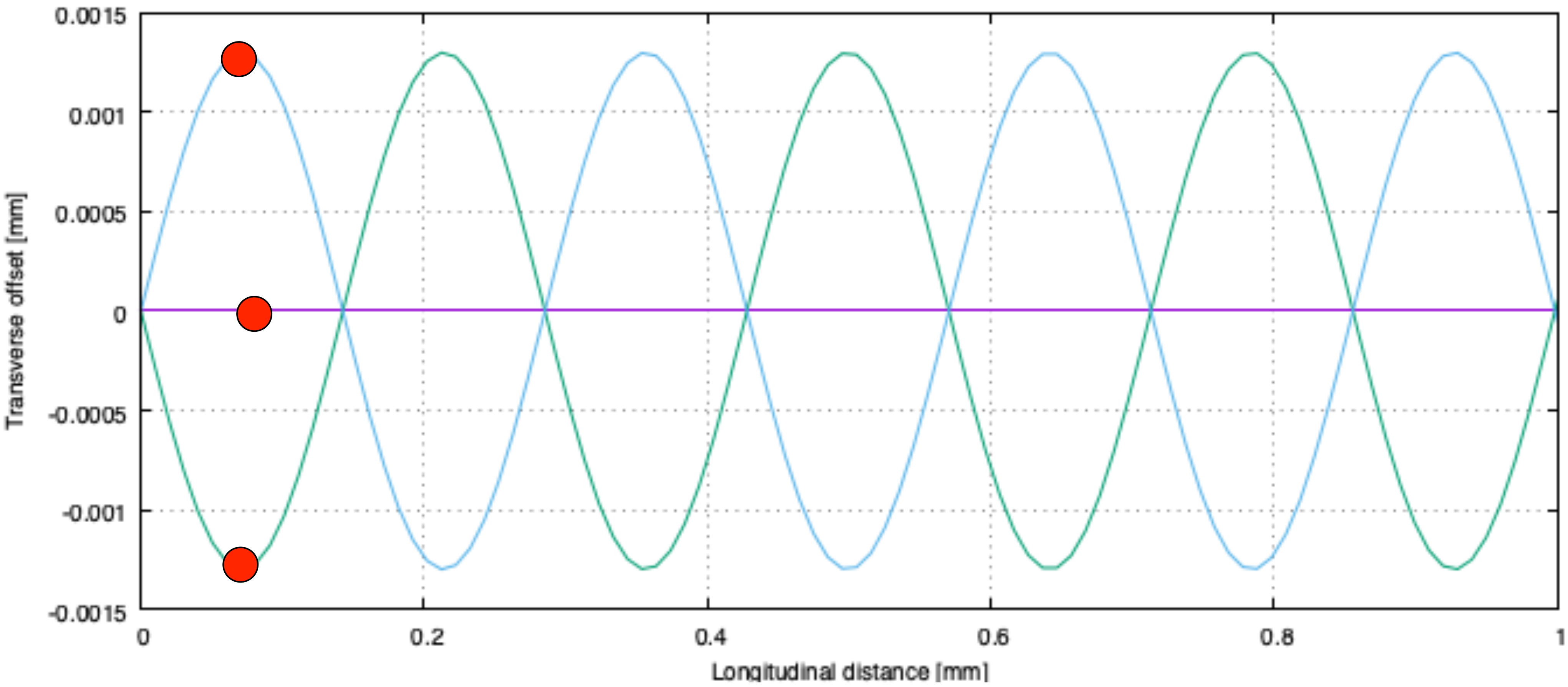


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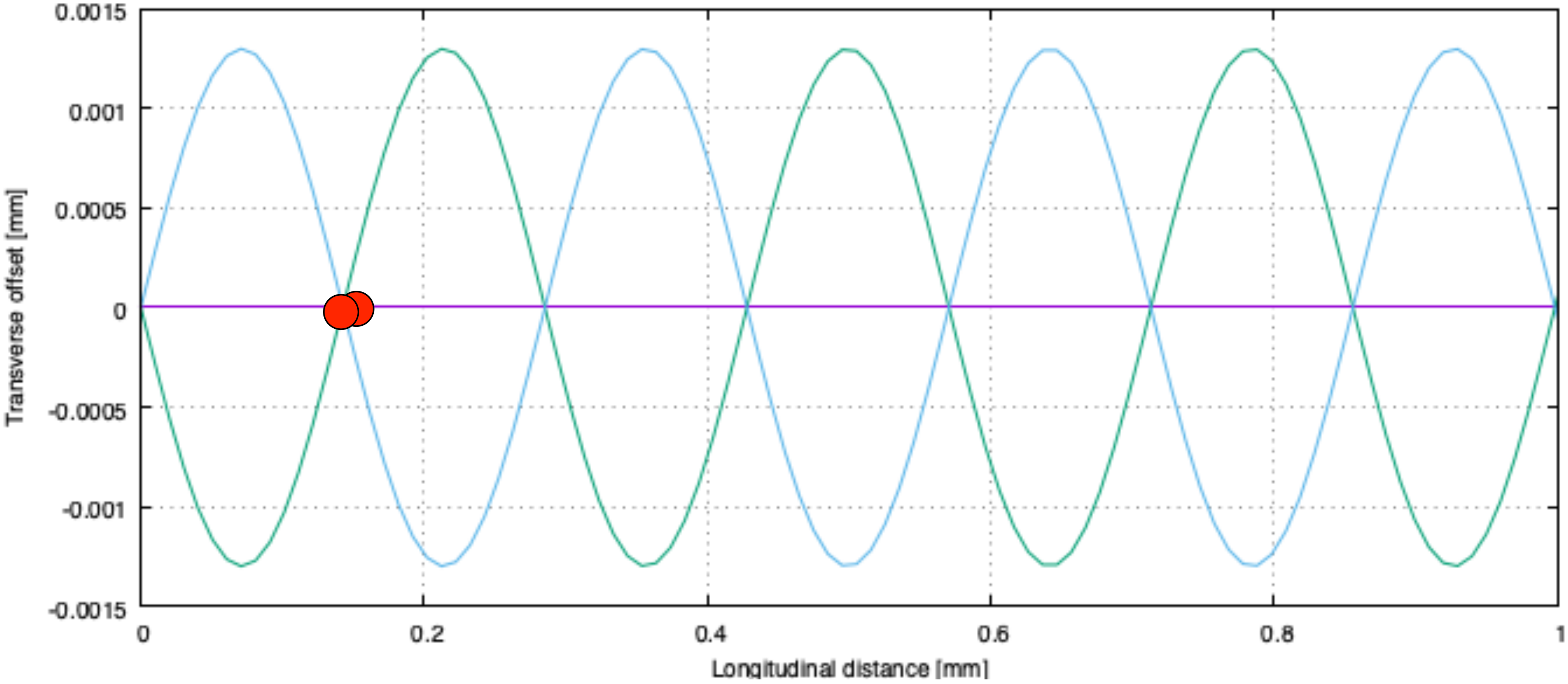


+ 1 $\sigma$ normalized oscillation amplitude

0 $\sigma$ normalized oscillation amplitude

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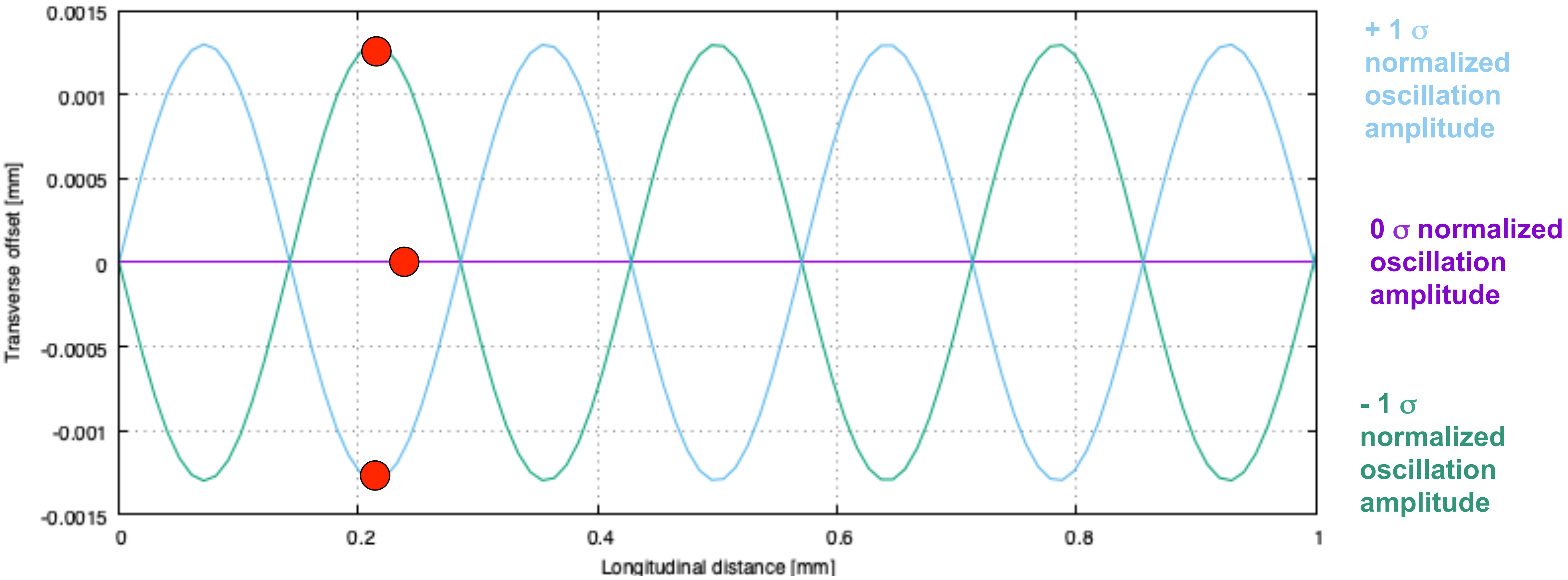



Difference in path lengths → large oscillation particles have longer way → fall back and create banana shape

# 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

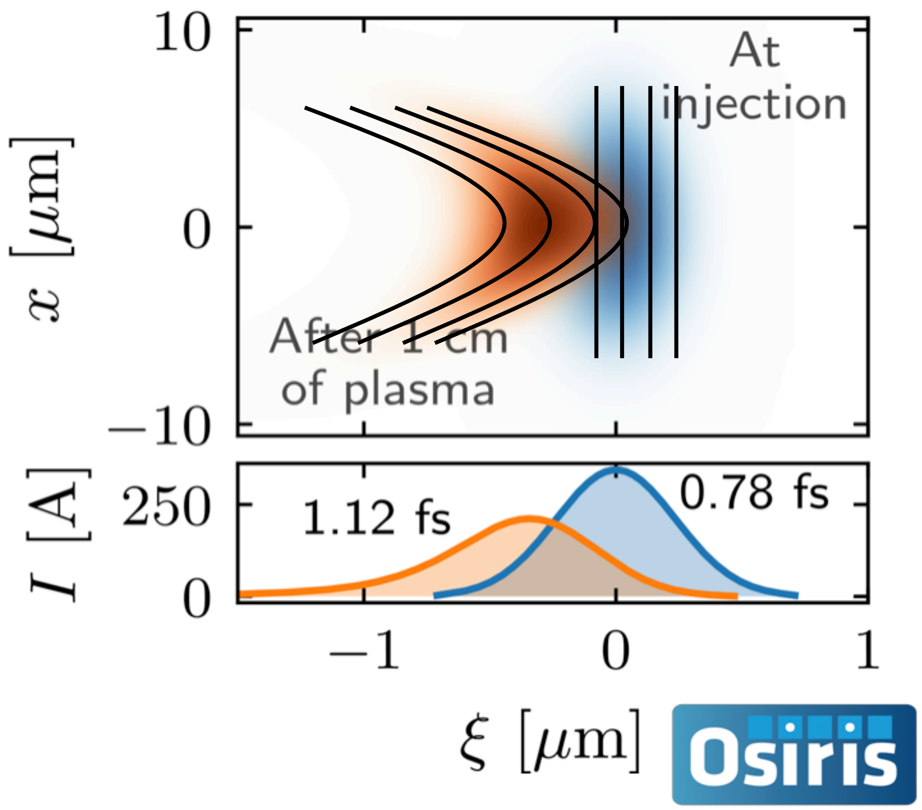
Observed in 2014 by Assmann and Grebenyuk (*IPAC'14*)

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

# Solutions: Towards low energy spread with Beam Loading

## Old proposal from Simon van der Meer

CERN/PS/85-65 (AA)
CLIC Note No. 3

IMPROVING THE POWER EFFICIENCY
OF THE
PLASMA WAKEFIELD ACCELERATOR

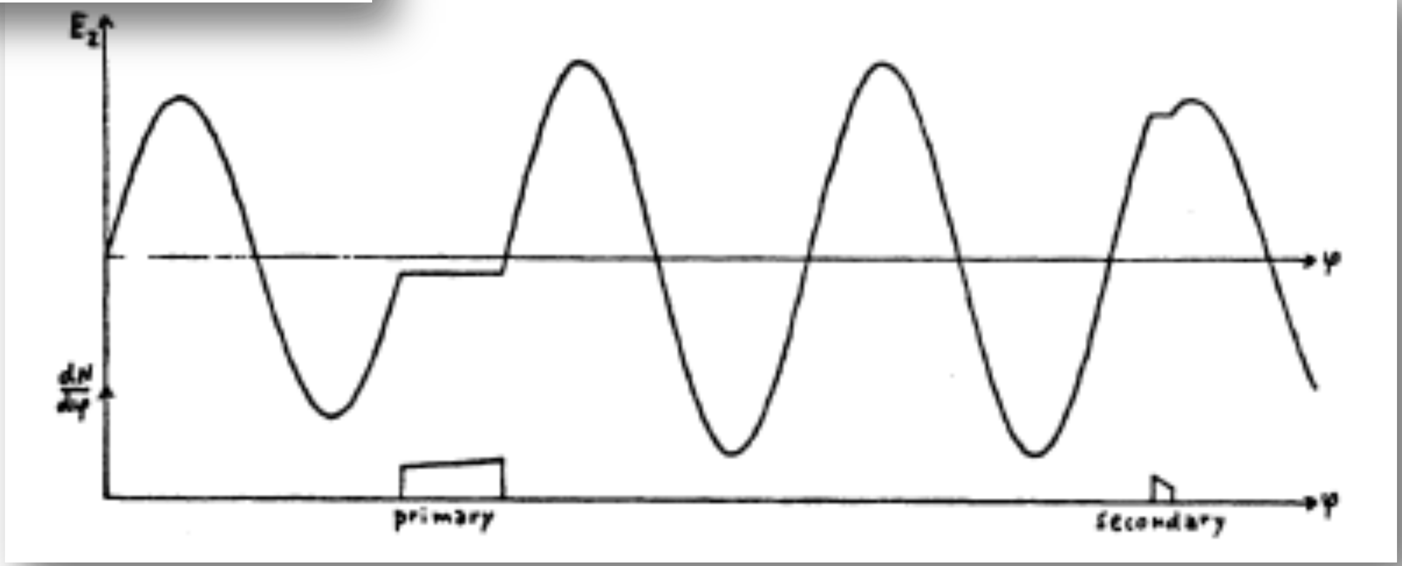
S. van der Meer

**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

PRL 118, 214801 (2017) PHYSICAL REVIEW LETTERS week ending 26 MAY 2017

**Chirp Mitigation of Plasma-Accelerated Beams by a Modulated Plasma Density**

R. Brinkmann,[1] N. Delbos,[2] I. Dornmair,[2] M. Kirchen,[2] R. Assmann,[1] C. Behrens,[1] K. Floettmann,[1] J. Grebenyuk,[1] M. Gross,[3] S. Jalas,[2] T. Mehrling,[1] A. Martinez de la Ossa,[4] J. Osterhoff,[1] B. Schmidt,[1] V. Wacker,[1] and A. R. Maier[2,*]

[1]*Deutsches Elektronen-Synchrotron DESY, Notkestrasse 85, 22607 Hamburg, Germany*

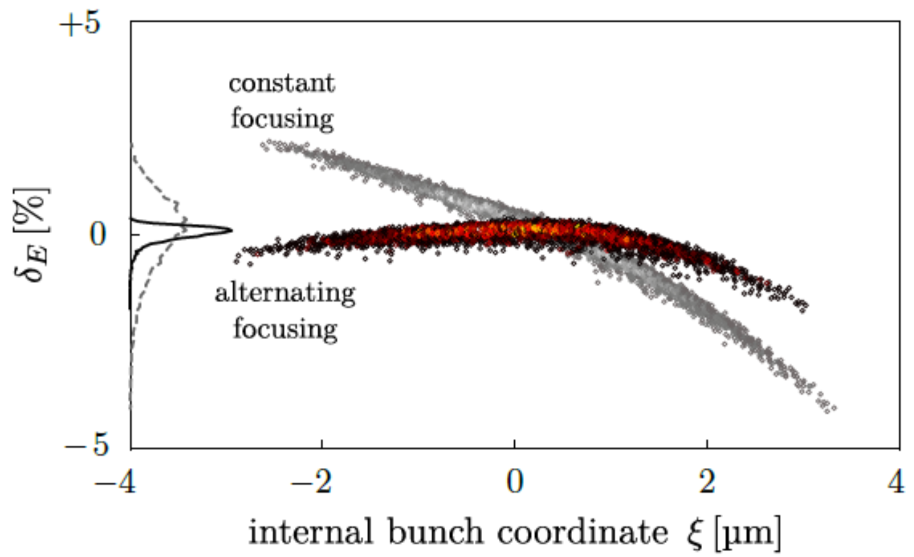
[2]*Center for Free-Electron Laser Science and Department of Physics, University of I*

*Luruper Chaussee 149, 22761 Hamburg, Germany*

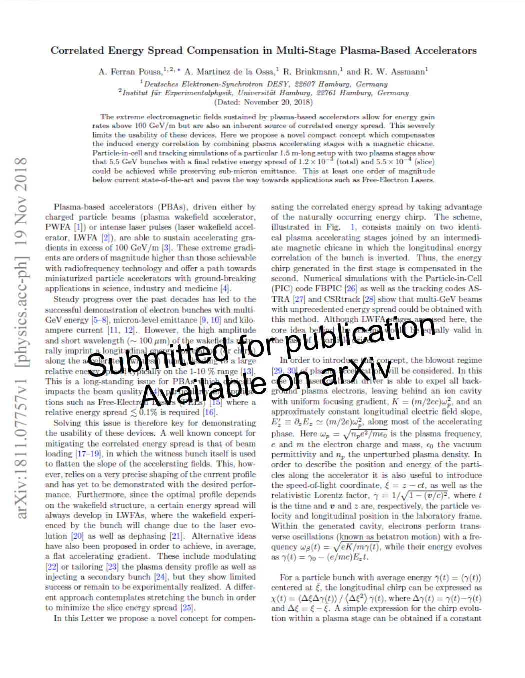
[3]*Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, 15738 Zeuthen, Ger*

[4]*Institut für Experimentalphysik, Universität Hamburg, 22761 Hamburg, Germ*

(Received 8 December 2015; published 23 May 2017)



# Solution: Low Energy Spread with 2 Stages



arXiv:1811.07757v1 [physics.acc-ph] 19 Nov 2018

**Correlated Energy Spread Compensation in Multi-Stage Plasma-Based Accelerators**

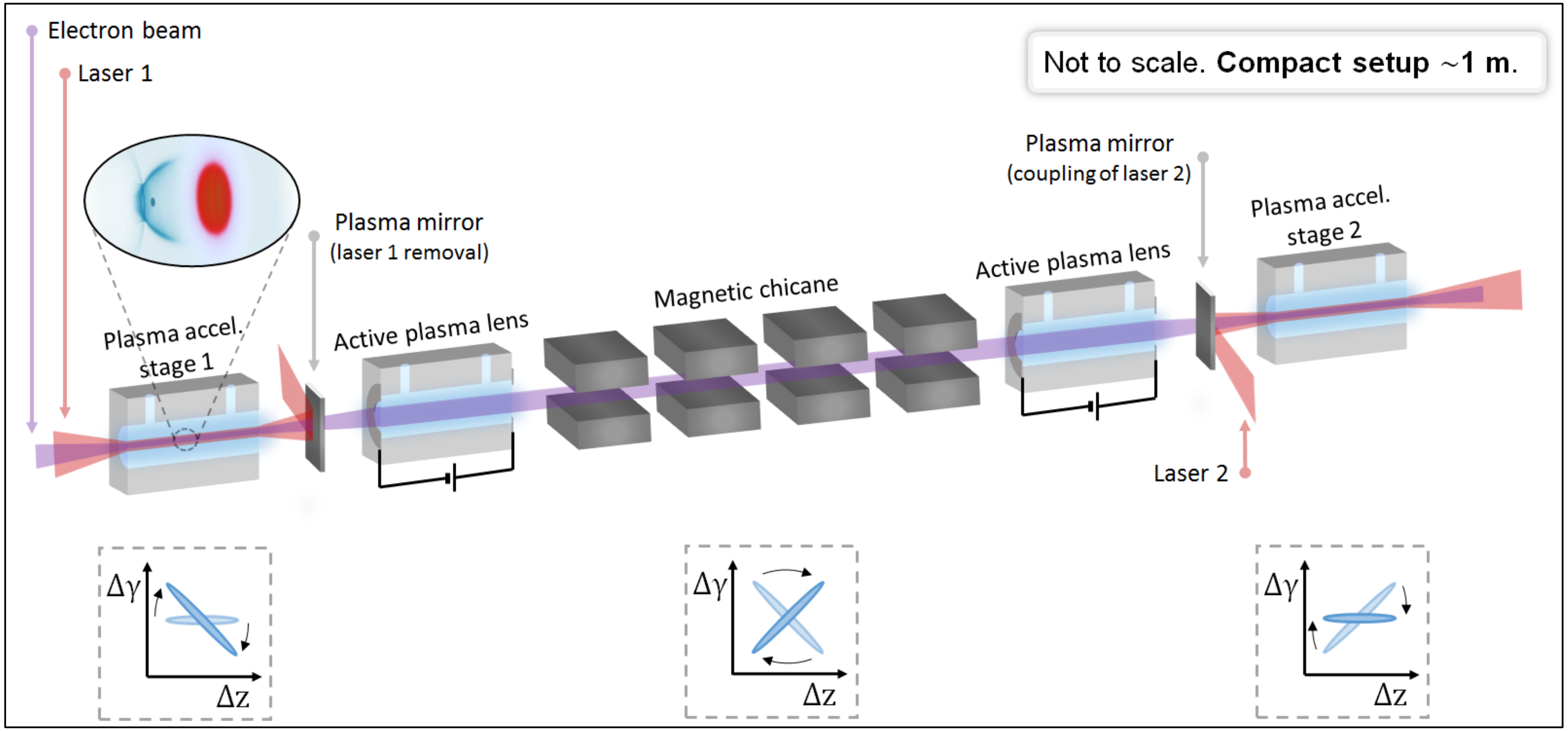
A. Ferran Pousa,[1,2,*] A. Martinez de la Ossa,[1] R. Brinkmann,[1] and R. W. Assmann[1]

[1]Deutsches Elektronen-Synchrotron DESY, 22607 Hamburg, Germany
[2]Institut für Experimentalphysik, Universität Hamburg, 22761 Hamburg, Germany
(Dated: November 20, 2018)

The extreme electromagnetic fields sustained by plasma-based accelerators allow for energy gain rates above 100 GeV/m but are also an inherent source of correlated energy spread. This severely limits the usability of these devices. Here we propose a novel compact concept which compensates the induced energy correlation by combining plasma accelerating stages with a magnetic chicane. 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.

Submitted for publication
Available on arXiv

<u>Ref.</u>: Ferran Pousa, Martinez de la Ossa, Brinkmann, Assmann, **arXiv: 1811.07757**

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Correlated Energy Spread Compensation in Multi-Stage Plasma-Based Accelerators

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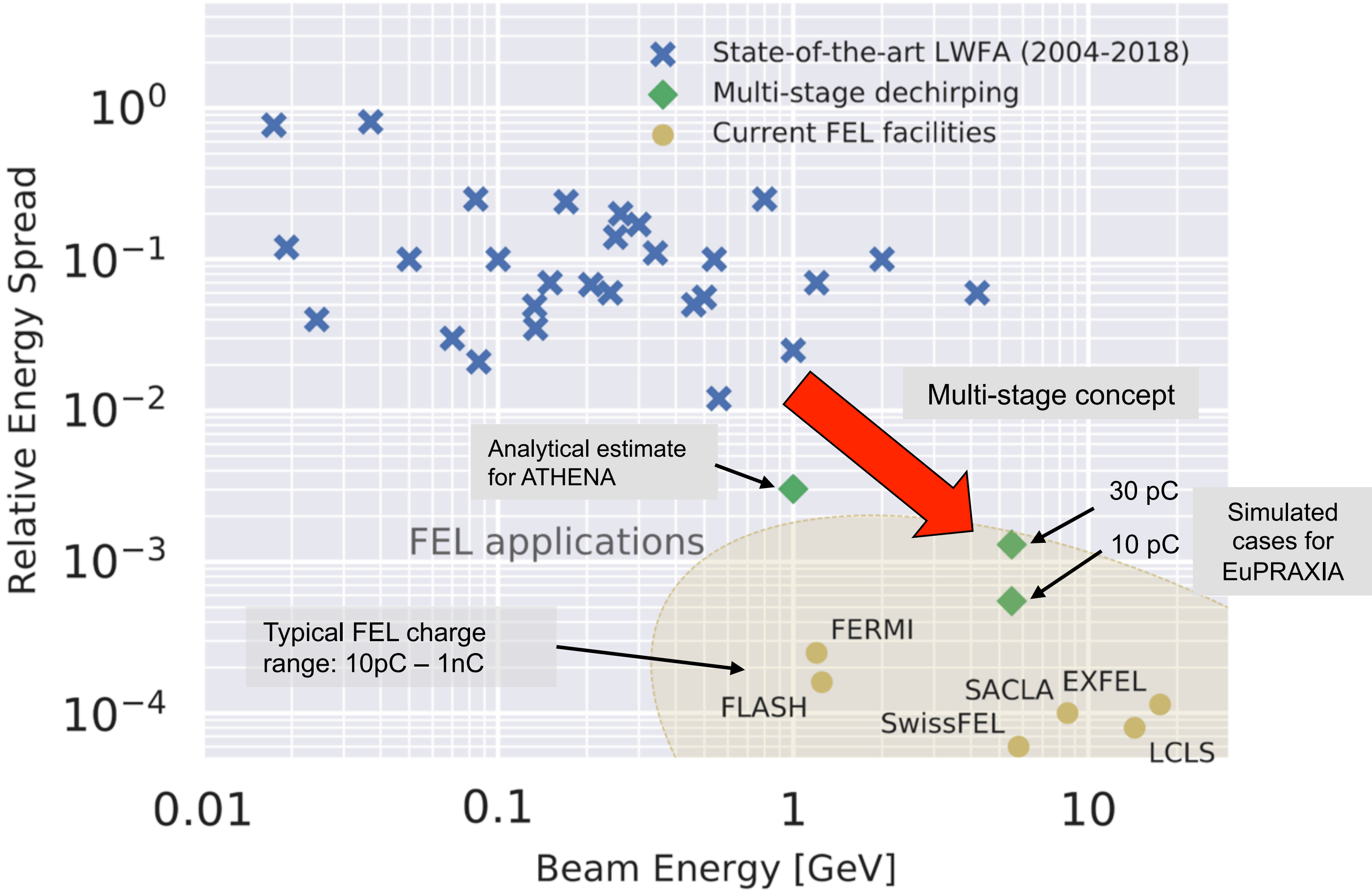


# Solve external timing for laser-driven plasma accelerators

**Achieve required sub-femtosecond timing and accuracy…**

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

A Ferran Pousa[1,2], R Assmann[1], R Brinkmann[1] and A Martinez de la Ossa[1,2]

[1] DESY, 22607 Hamburg, Germany
[2] Universität Hamburg, 22761 Hamburg, Germany

E-mail: angel.ferran.pousa@desy.de

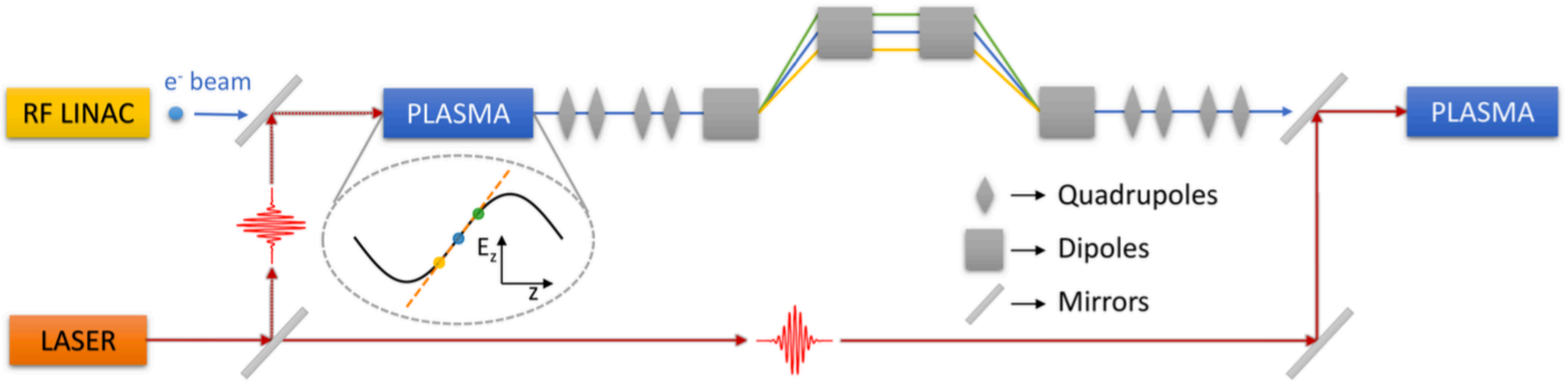



**Figure 1.** Schematic view of the synchronizing stage.

# 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**

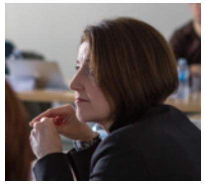
**Pilot users from FEL, HEP, medicine, ...**

## PRODUCTION FACILITIES

Plasma-based **linear collider** in 2040's

Plasma-based **FEL** in 2030's

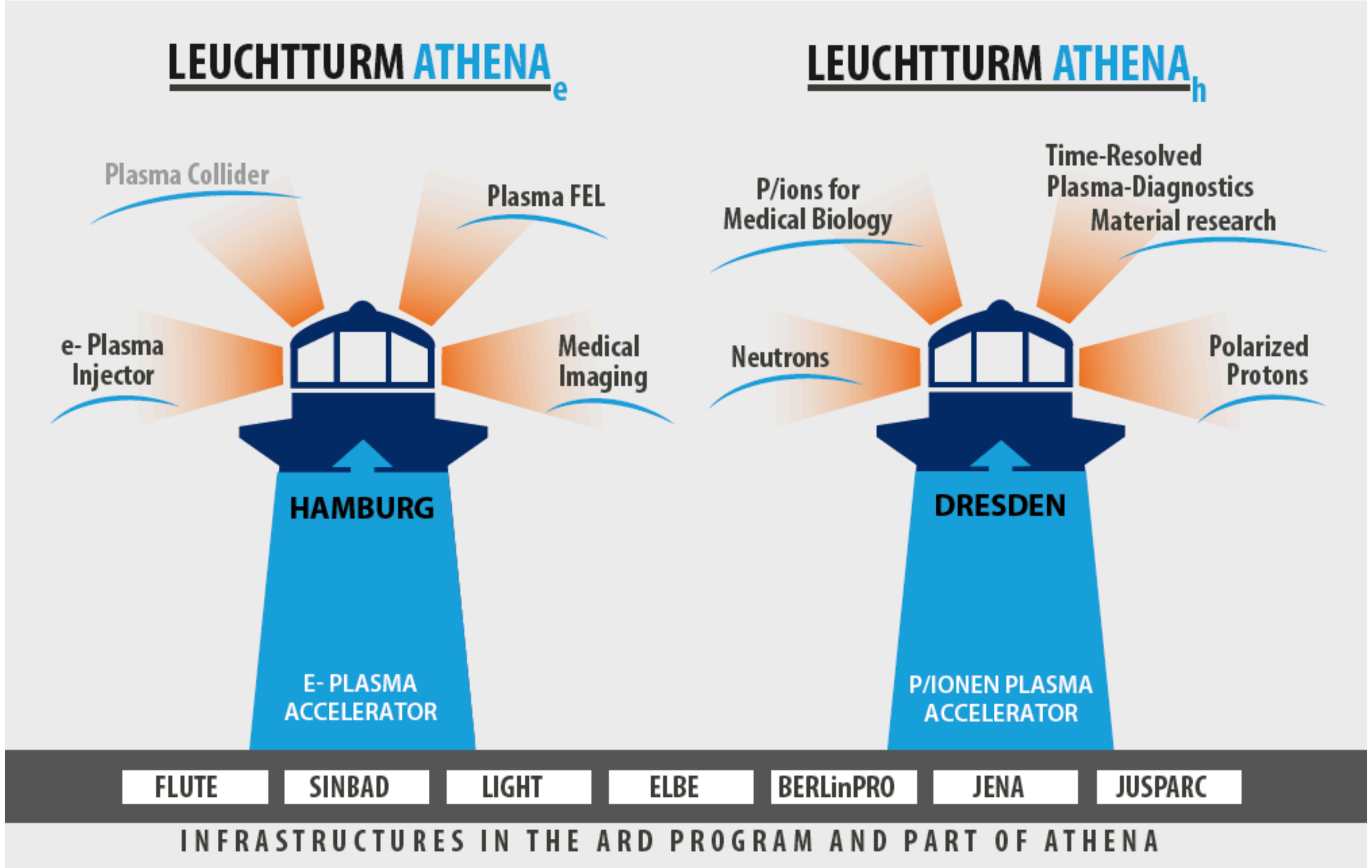
**Medical, industrial** applications soon



# The ATHENA Project

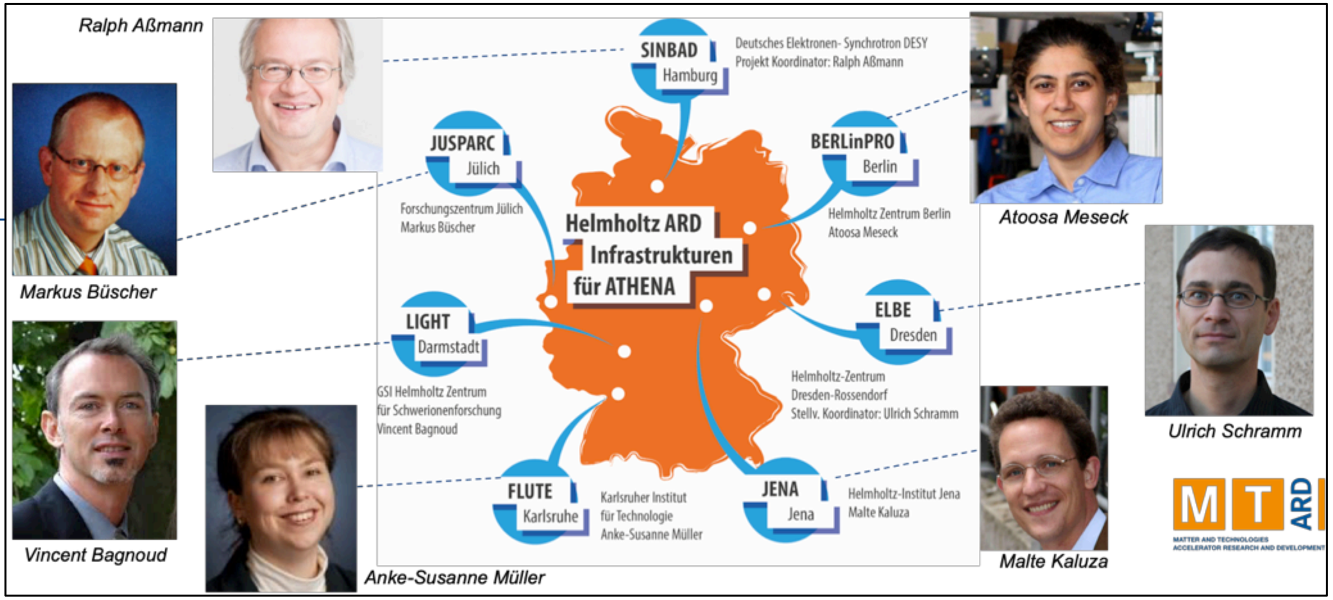
## Two Flagships Constructed Together

- **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**




DESY. HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF · JÜLICH FORSCHUNGSZENTRUM · KIT Karlsruhe Institute of Technology · GSI · HI JENA Helmholtz Institute Jena · HZB Helmholtz Zentrum Berlin

# ATHENA




**Project approval:** **Summer 2018**
Construction end: end of 2021
Operation start: 2022

## HEADLINES
### SCIENCE & TECHNOLOGY

**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

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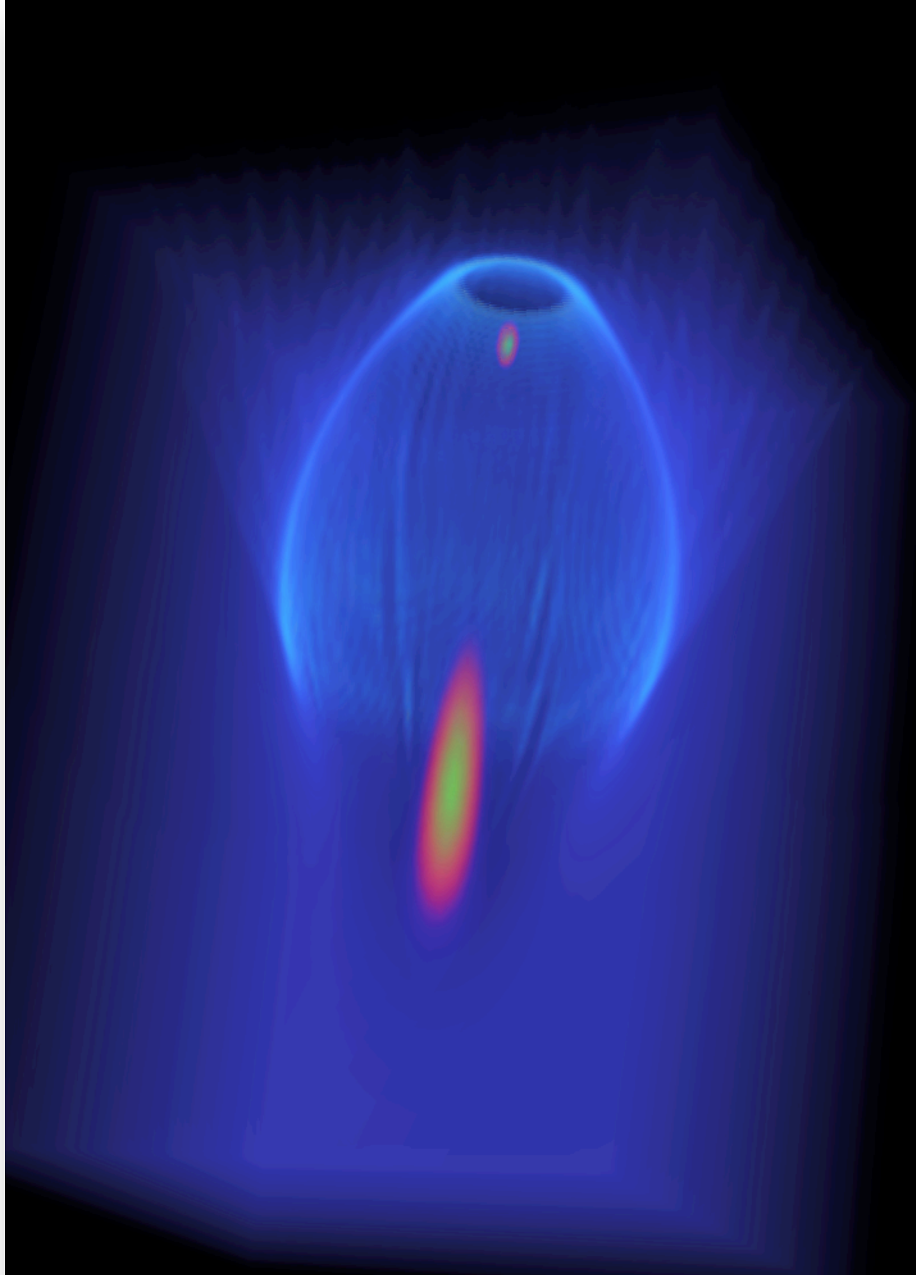
***→ Please contact us for questions and more information!***

# Contents

# 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*

# EAC 2019

## 15 - 20 September 2019

## Elba, Italy

**4th European Advanced Accelerator Concepts Workshop**

**Please reserve the dates for September 2019**

**We would be very glad to welcome you in Elba**

European Network for Novel Accelerators

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# Thank you for your attention