Laser Plasma Acceleration

Accelerator Research and Development
ARD
A program by the Helmholtz association

HELMHOLTZ
ASSOCIATION

R.W. Aßmann

Leading Scientist DESY

JUAS Seminar

Archamps, 3.2.2016

European Network EuroNNAc for Novel Accelerators

EuCARD²

DESY

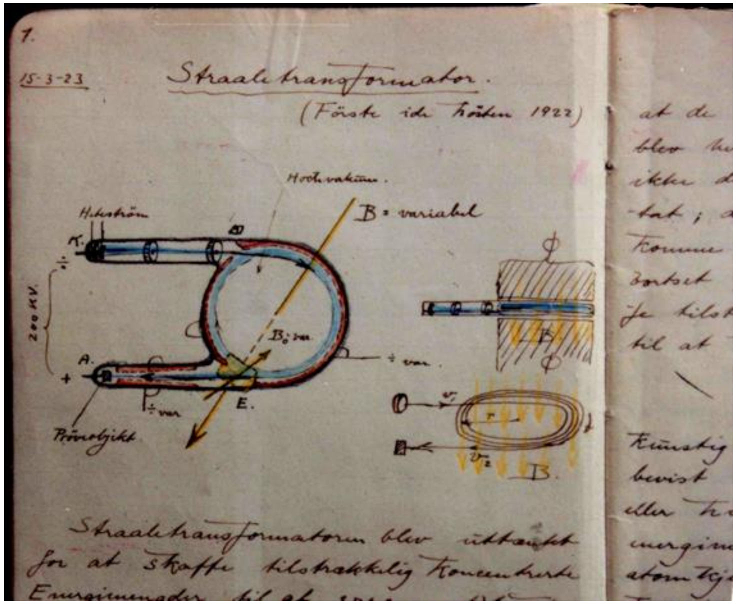
Content

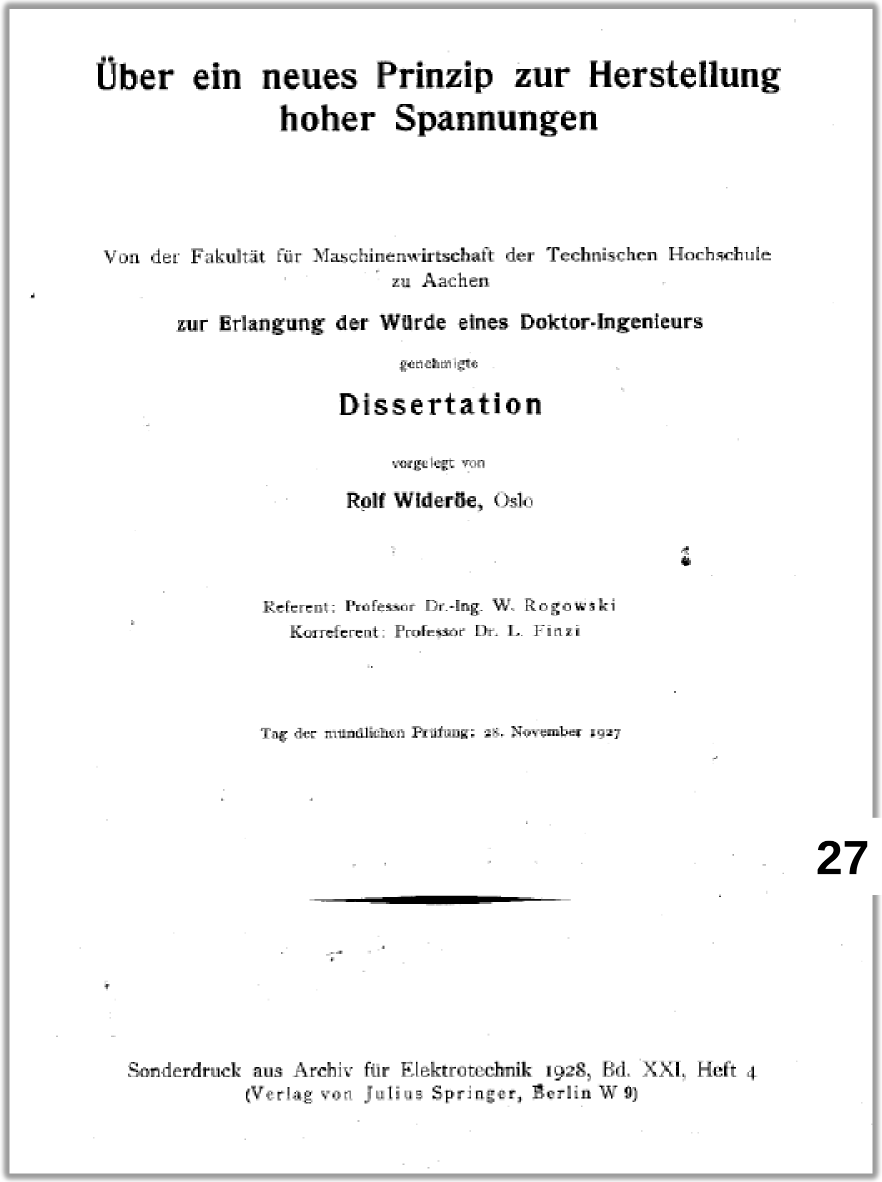
1. Accelerators – From Conventional Techniques to Plasmas
2. The Linear Regime
3. The Non-Linear Regime
4. Tolerances
5. Outlook for Europe

Content

1. **Accelerators – From Conventional Techniques to Plasmas**
2. The Linear Regime
3. The Non-Linear Regime
4. Tolerances
5. Outlook for Europe

First RF Linac Setup: PhD Wideröe 1927 in Aachen





Über ein neues Prinzip zur Herstellung hoher Spannungen

Von der Fakultät für Maschinenwirtschaft der Technischen Hochschule zu Aachen

zur Erlangung der Würde eines Doktor-Ingenieurs

genehmigte

Dissertation

vorgelegt von

Rolf Wideröe, Oslo

Referent: Professor Dr.-Ing. W. Rogowski
Korreferent: Professor Dr. L. Finzi

Tag der mündlichen Prüfung: 28. November 1927

Sonderdruck aus Archiv für Elektrotechnik 1928, Bd. XXI, Heft 4
(Verlag von Julius Springer, Berlin W 9)

27 pages

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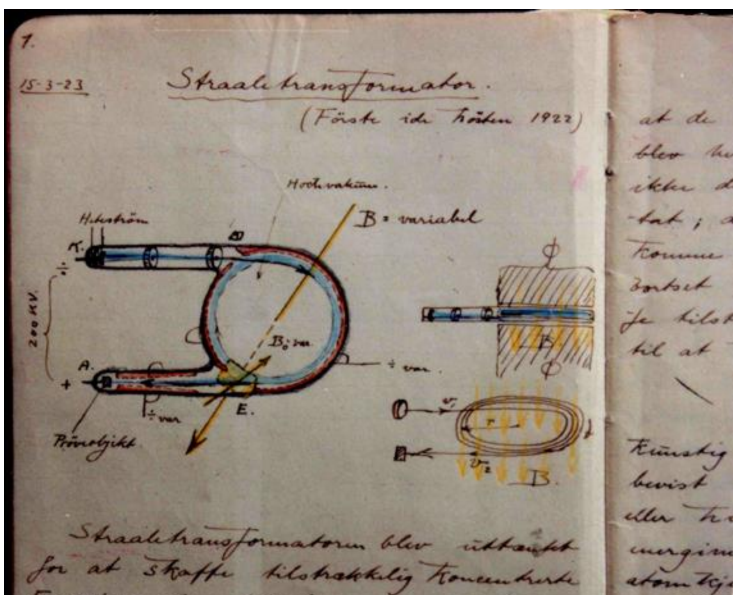

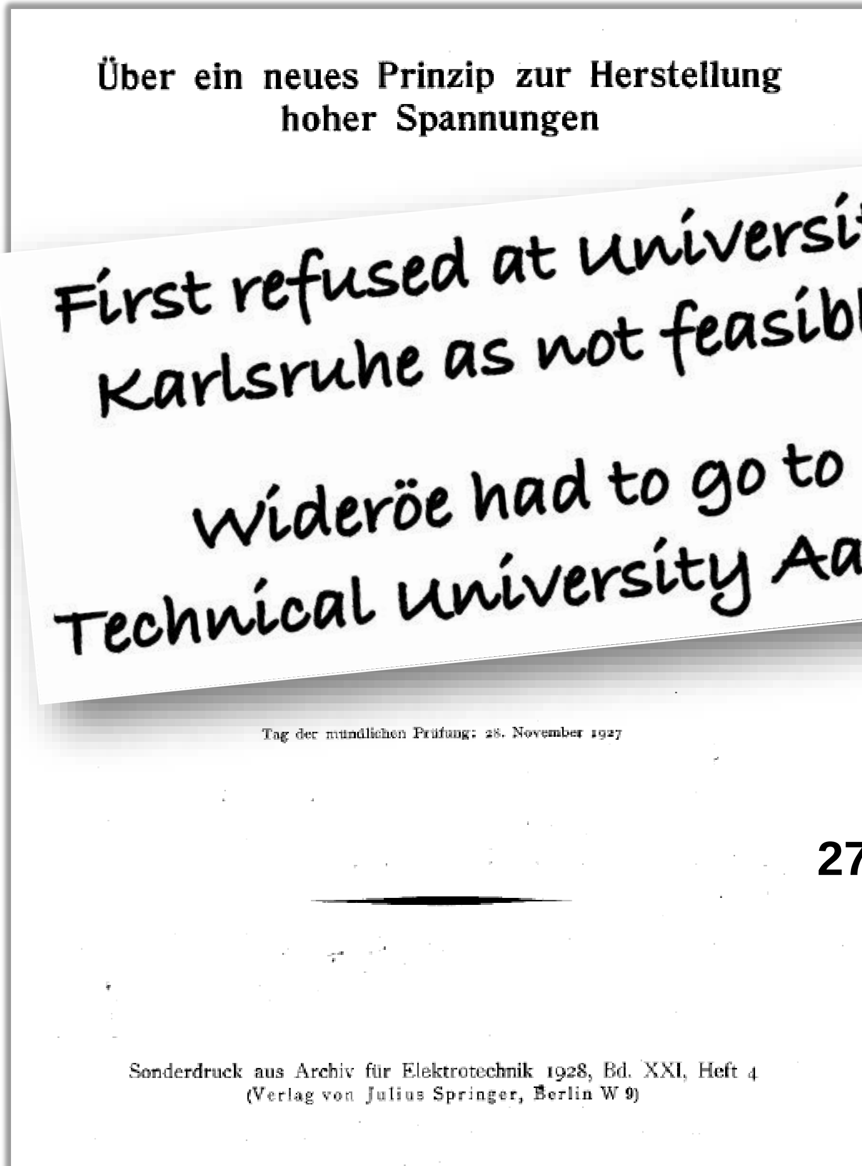

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(Verlag von Julius Springer, Berlin W 9)

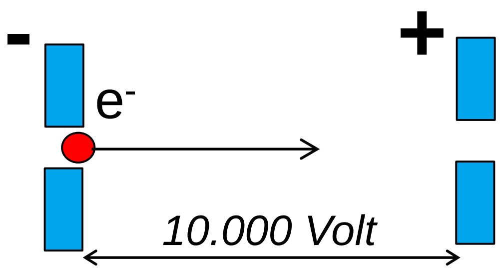
First refused at university Karlsruhe as not feasible!

Wideröe had to go to Technical University Aachen

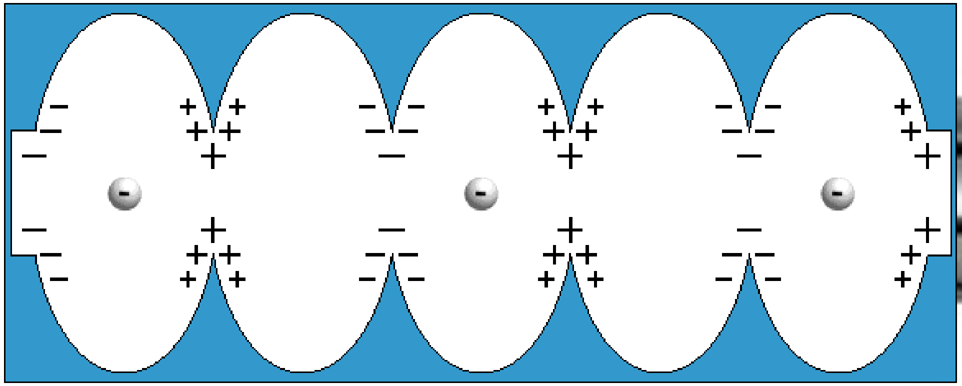
27 pages

Electron Acceleration: The Success of RF

- Areas with positive and negative charge; free electrons in between.
- Free electron (e^-) is accelerated towards the positive charge (anode) („**Gegensätze ziehen sich an**”).



- For a voltage of 10.000 Volt the electron gains 10.000 electron-Volt („eV”).
- Higher energies with **alternating voltage („RF“)**:



Sketch Padamse, Tigner

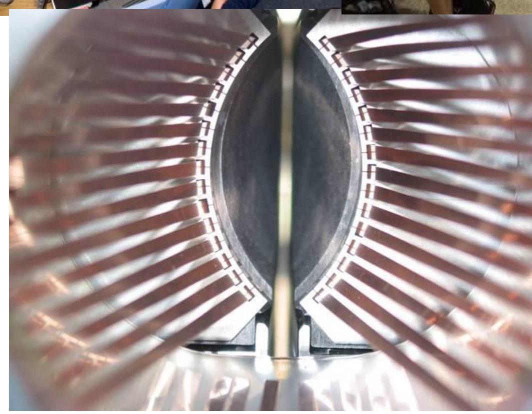
“Runzelröhre”

<u>20.000.000 Volt per Meter</u>

80 Years (and many inventions) later:
LHC as a Masterpiece of Accelerator Science

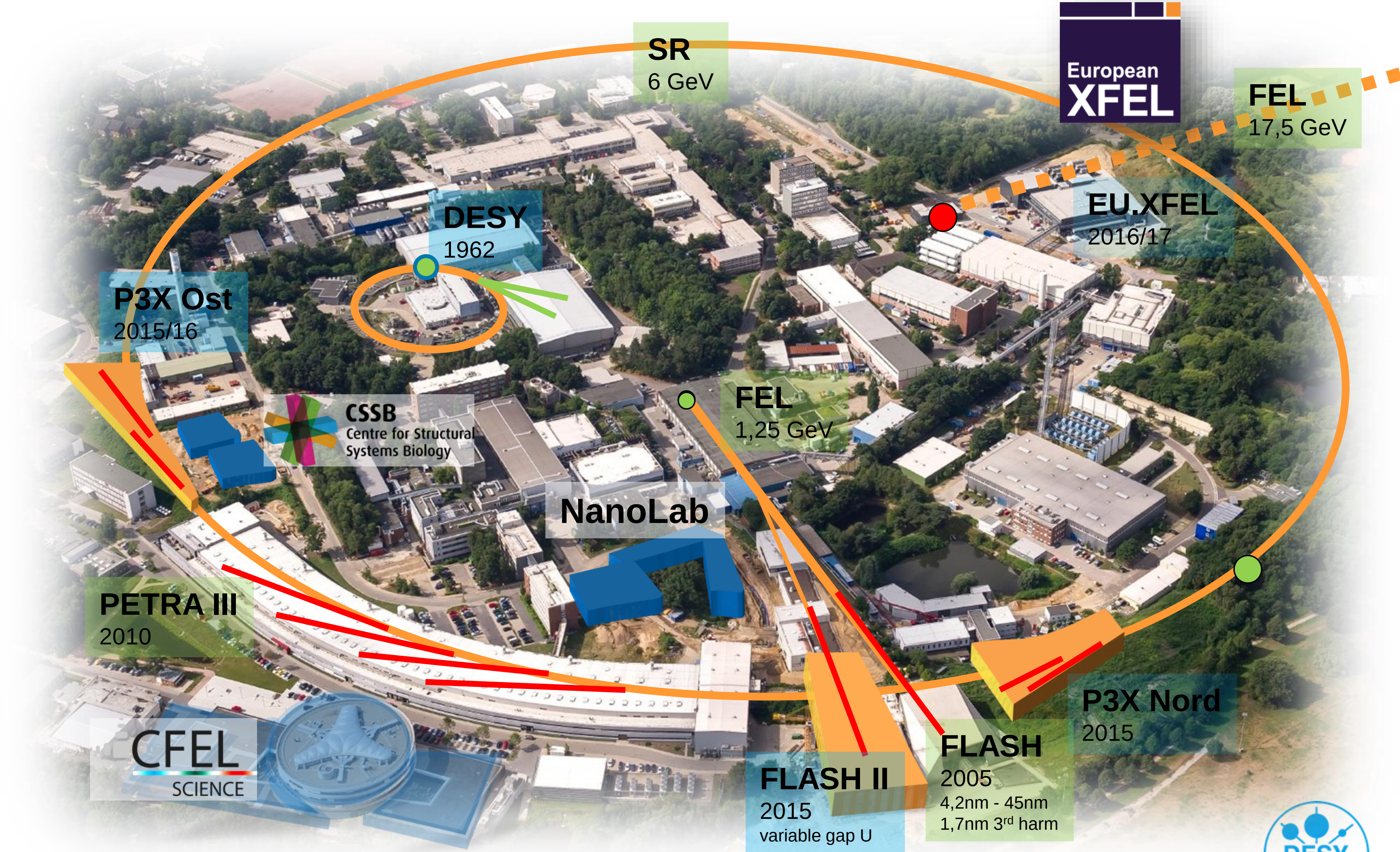
Higgs Sem. 4.7. 2012

First beam 10.9. 2008



DESY 50 Years ago...

Today: X-Ray Facilites at DESY. *Masterpieces for photon science*



Acceleration: Conventional and Advanced

Surfer gain velocity and energy by riding the water wave!

Charged particles gain energy by riding the electromagnetic wave!

Modern lasers generate light pulses with very large transverse fields:

Many 1.000 billion volt per meter

Plasma or metallic structures couple fields to our particles!

DESY

ANGUS Laser Lab (200 TW, DESY & University Hamburg)

The Laser Promise: Transverse Electrical Field

$$E_0 = \sqrt{2 \cdot \frac{I_0}{c\,\epsilon_0}}$$

$$\epsilon_0 = \text{Dielectric constant}$$

$$c = \text{Light velocity}$$

$$P = 100\,\text{TW}$$

$$r_0 = 10\,\mu\text{m}$$

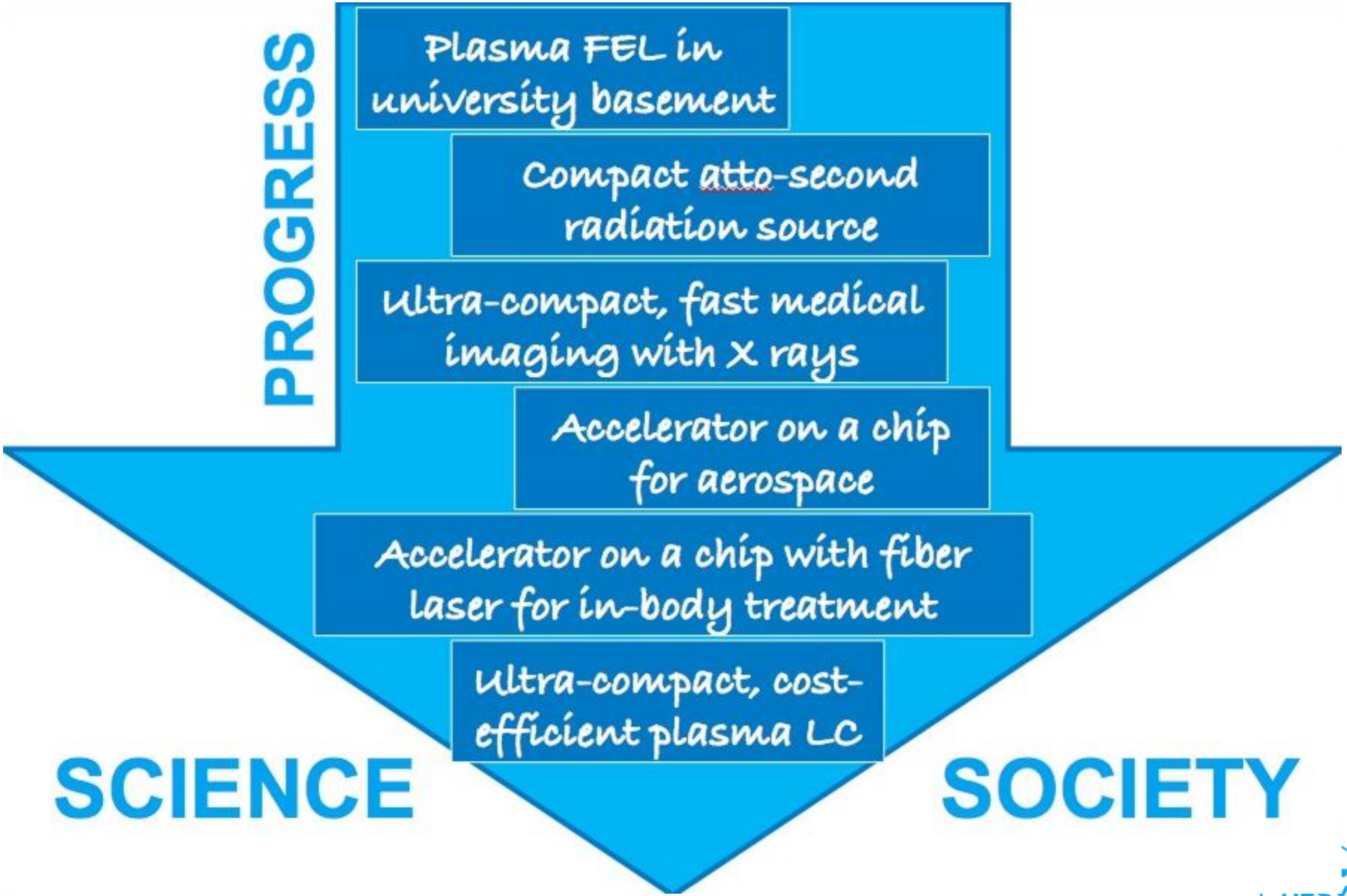
$$I_0 = 6.4 \cdot 10^{19}\,\text{W}/\text{cm}^2$$

$$E_0 = 22\,\text{TV}/\text{m}$$

This is what we need!

Scientists wonder: Can we use the strong transverse electrical fields to accelerate our beam?

High fields trigger imagination of scientists and public…



DIE WELT

SAMSTAG, 28. MÄRZ 2015

Bremse für Superbeschleuniger

Größer, schneller, teurer geht's nicht mehr. Bis zu sechs Milliarden Dollar kosten die Teilchenschleudern in Genf oder anderswo. Materieforscher müssen sich etwas einfallen lassen

Hamburger Abendblatt

WISSEN

Der Mini-Teilchenbeschleuniger

Kleiner, günstiger, aber mit mehr Leistung: Hamburger Physiker erproben neue Technik mit Blick auf Industrie und Medizin

DER SPIEGEL

DER SPIEGEL 11/2015

Im Bann von Waxahachie

Physik Forscher bauen immer gewaltigere Teilchenbeschleuniger, um die Geheimnisse des Universums zu enträtseln. Geht es auch eine Nummer kleiner?

Unter den Feldern von Texas erstreckt sich ein verlassener Tunnel, knapp 23 Kilometer lang. Die Zugänge sind verschüttet, in der Röhre sammelt sich Wasser.

Die Ruine nahe dem Städtchen Waxahachie steht für das Trauma der Teilchenphysik: Hier baute die stolze Zunft einst

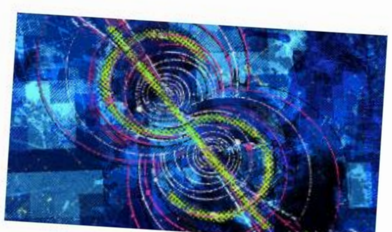
The Economist

Particle physics

A new awakening?

Accelerators are getting bigger and more expensive. T… them smaller and cheaper

Jan 31st 2015 | From the print edition



FOR more than 80 years particle physicists have had to think big, even though the things they are paid to think about are the smallest objects that exist. Creating exotic particles means crashing quotidian ones (electrons and protons) into each other. The more exotic the output desired, the faster these collisions must be. That extra speed requires extra energy, and therefore larger machines. The first cyclotron, built in 1931 in Berkeley, California, by Ernest Lawrence, had a circumference of 30cm. Its latest successor, the Large Hadron Collider (LHC) at CERN's laboratory near Geneva—which reopens for business in March after a two-year upgrade—has a circumference of 27km.

High Gradient Accelerators

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

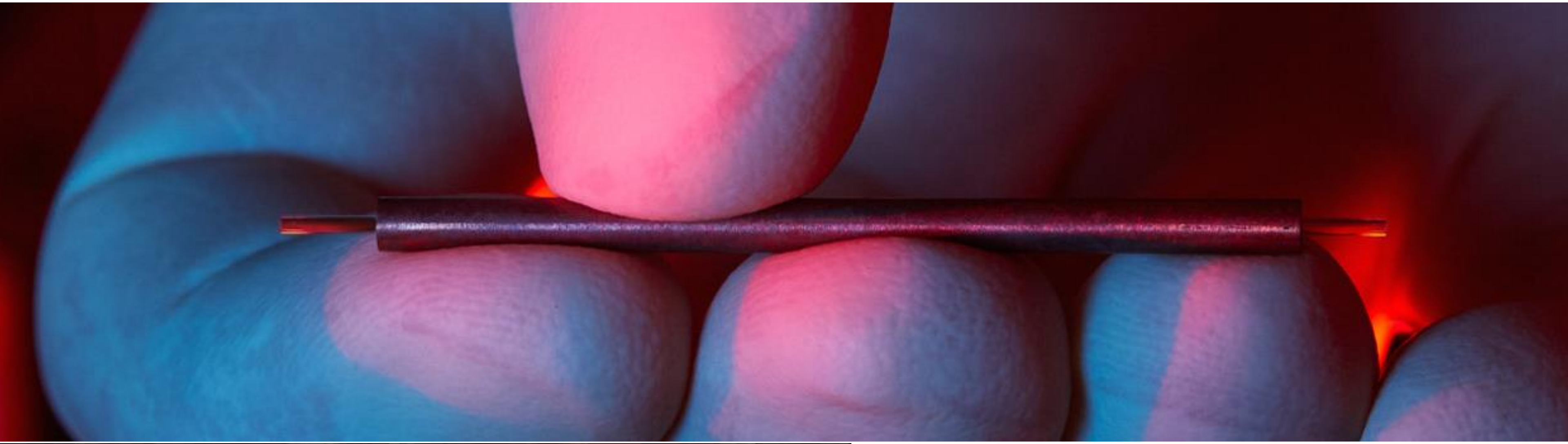
- No **klystrons** for high frequencies!
- Use particle bunches or laser pulses as drivers.
- Material limitations solved through “new cavities”: dielectric materials, plasma cavities, …
- Two main directions:

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

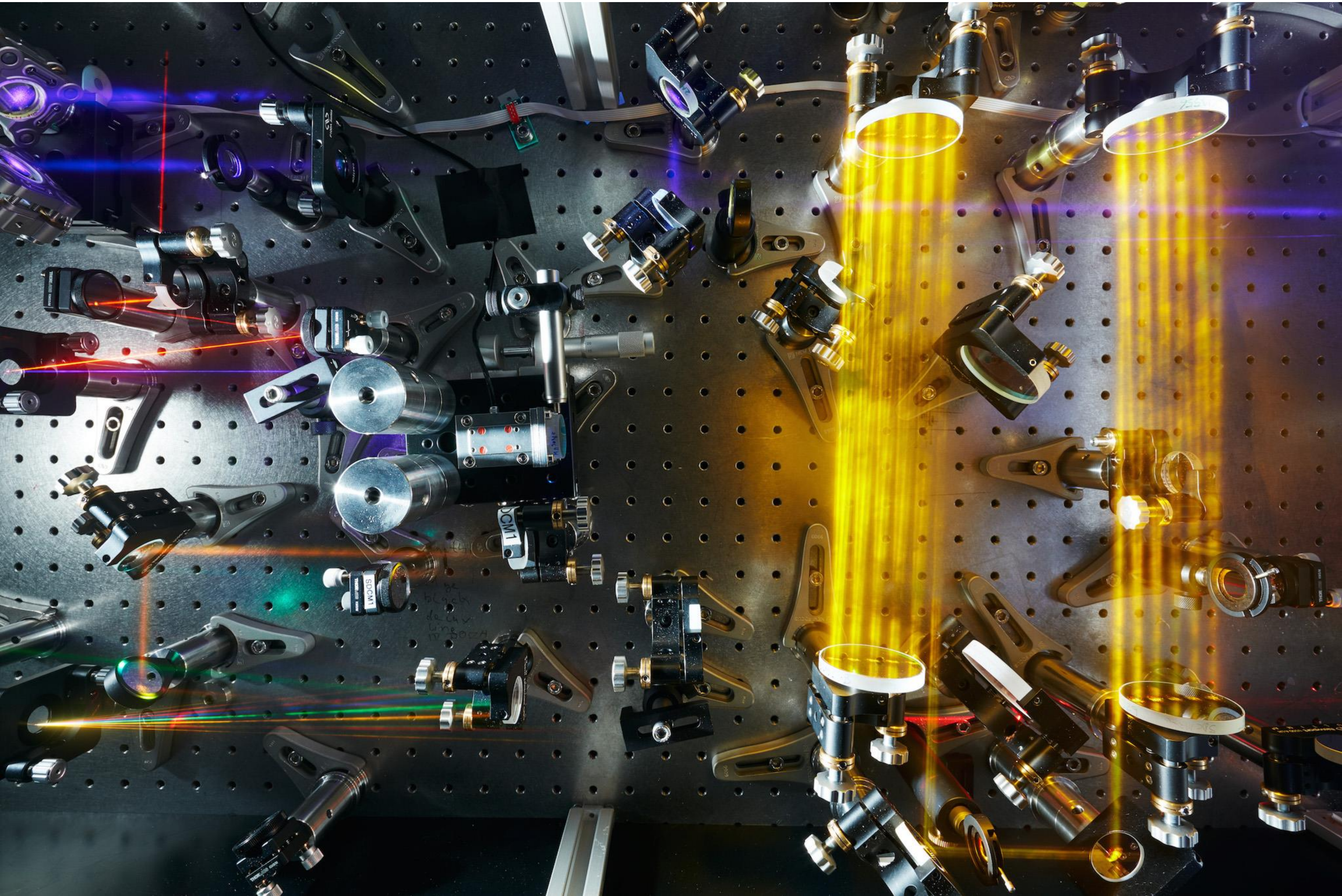
2 Plasma Accelerator
Laser- or beam driven
Dynamic Plasma Structure
Plasma field calculations

Laser-Driven Micro Structures (Vacuum) – 1

- 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*

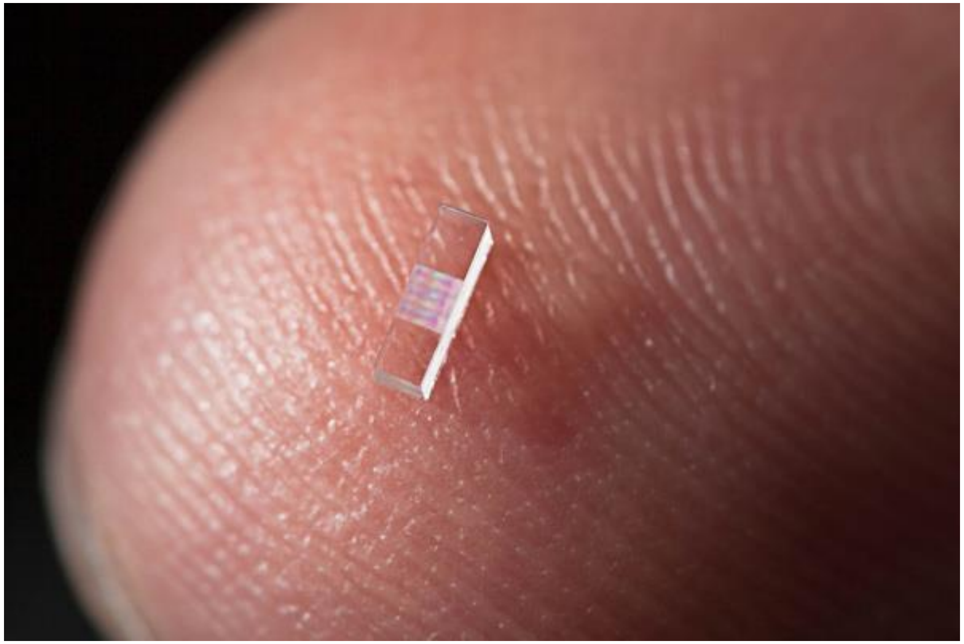


THz Laser Lab (DESY, CFEL, University Hamburg)



Laser-Driven Micro Structures (Vacuum) – 2

- **"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**



Financed by Silicon Valley billionaire...

GORDON AND BETTY MOORE FOUNDATION

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ABOUT

Intel co-founder Gordon and his wife Betty established the foundation to create positive change for future generations.

Courtesy of Hawley Peterson Snyder

Courtesy of Susanna Frohman, San Jose Mercury News

Our Founders

We're inspired by the innovation, compassion and focus of our founders, Gordon and Betty Moore. Gordon's thinking was part of the birth of Silicon Valley in the late 1950s. Betty's commitment to improving the lives of patients resulted in a regional collaborative that is making a difference in the care that Californians receive. Together, they've identified places where they, and the foundation, could create positive change for future generations.

Read More

Our Science Program invests in the development of new technologies, supports the world's top research scientists and brings together new–often groundbreaking–scientific partnerships. Our passion for discovery reflects that of our founders, Gordon and Betty Moore.

We believe in the inherent value of science and the sense of awe that discovery inspires. Scientific advancement and societal benefits will occur if we find ways to unleash the potential of inquiry and exploration. So we take risks, we incubate change, and we foster the kind of excitement that inspires third-graders to become scientists. We look for opportunities to transform, or even create, entire fields.

DESY

The Laser Promise: Transverse Electrical Field

$$E_0 = \sqrt{2 \cdot \frac{I_0}{c\,\epsilon_0}}$$
$$\epsilon_0 = \text{Dielectric constant}$$
$$c = \text{Light velocity}$$

$$P = 100\,\text{TW}$$
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This is what we need!

Scientists wonder: Can we use the strong transverse electrical fields to accelerate our beam?

Lorentz Force F

$$\mathbf{F} = q\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right)$$

q = Charge

$\mathbf{v}$ = Velocity

Longitudinal electrical field to accelerate a particle

Transverse magnetic field to guide a particle

Laser Plasma Accelerator: Transverse to Longitudinal

- Idea: Use a plasma to convert the transverse space charge force of a beam driver (or the electrical field of the laser) into a longitudinal electrical field in the plasma!

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.

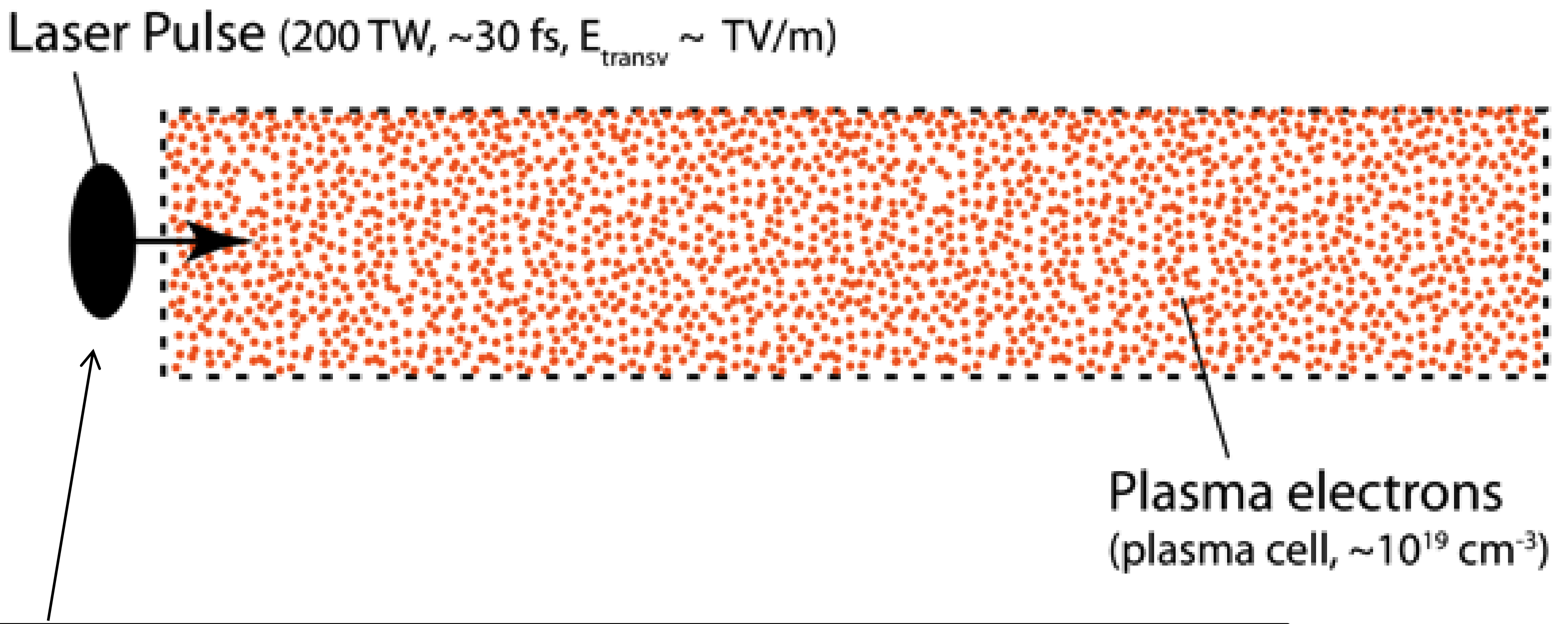
Collective plasma accelerators have recently received considerable theoretical and experimental investigation. Earlier Fermi[1] and McMillan[2] considered cosmic-ray particle acceleration by moving magnetic fields[1] or electromagnetic waves.[2] In terms of the realizable laboratory technology for collective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

the wavelength of the plasma waves in the wake:

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

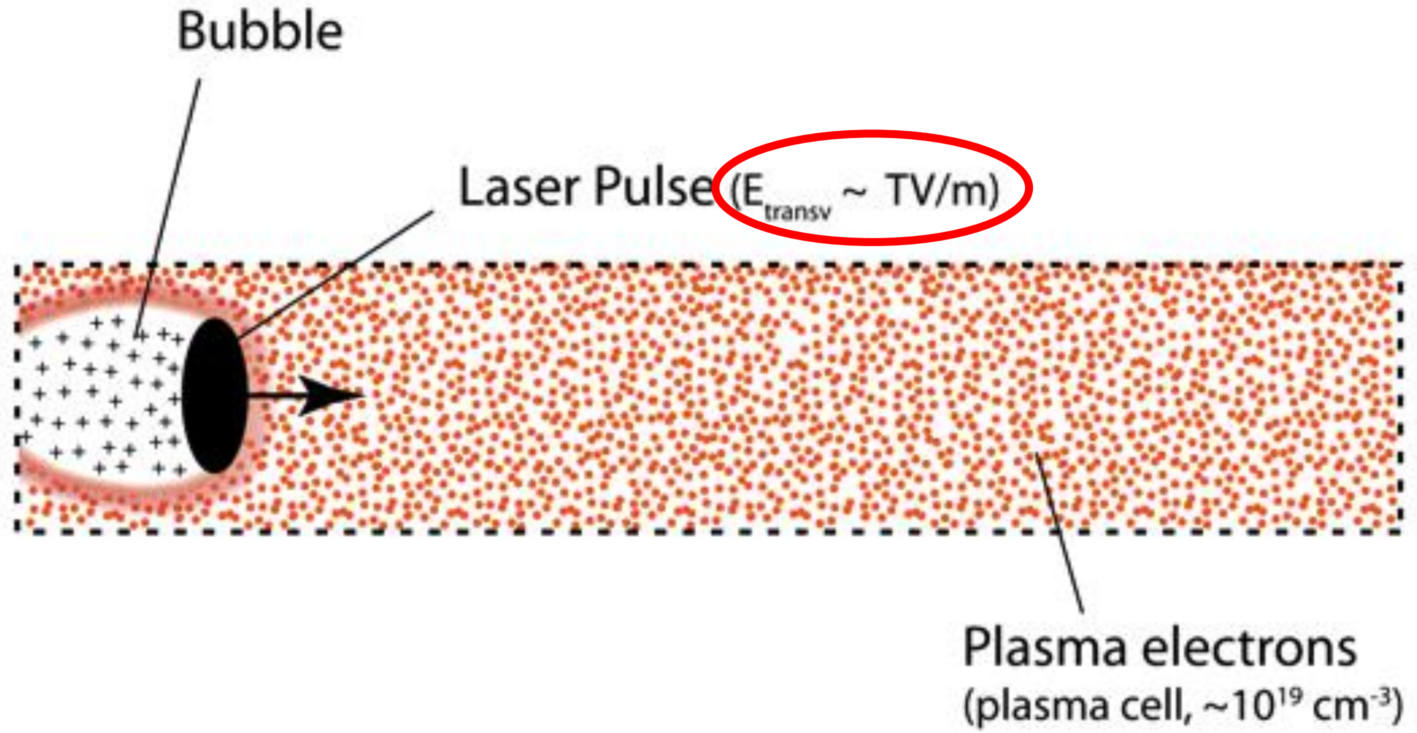
An alternative way of exciting the plasmon is to inject two laser beams with slightly different frequencies (with frequency difference $\Delta\omega \sim \omega_p$) so that the beat distance of the packet becomes

Laser Plasma-Acceleration (Internal Injection)

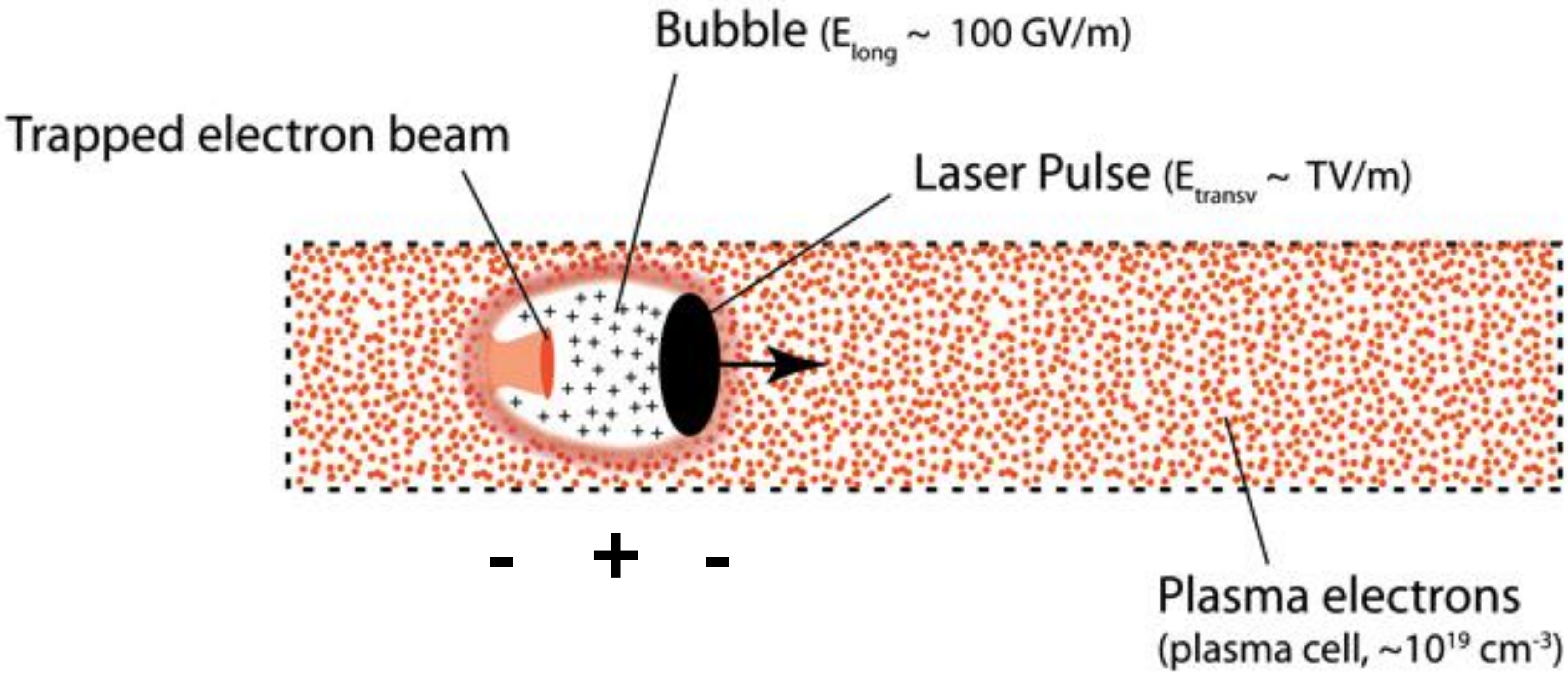


Works the same way with an **electron beam as wakefield driver**. But then usually lower plasma density. Ponderomotive force of laser is then replaced with space charge force of electrons on plasma electrons (repelling).

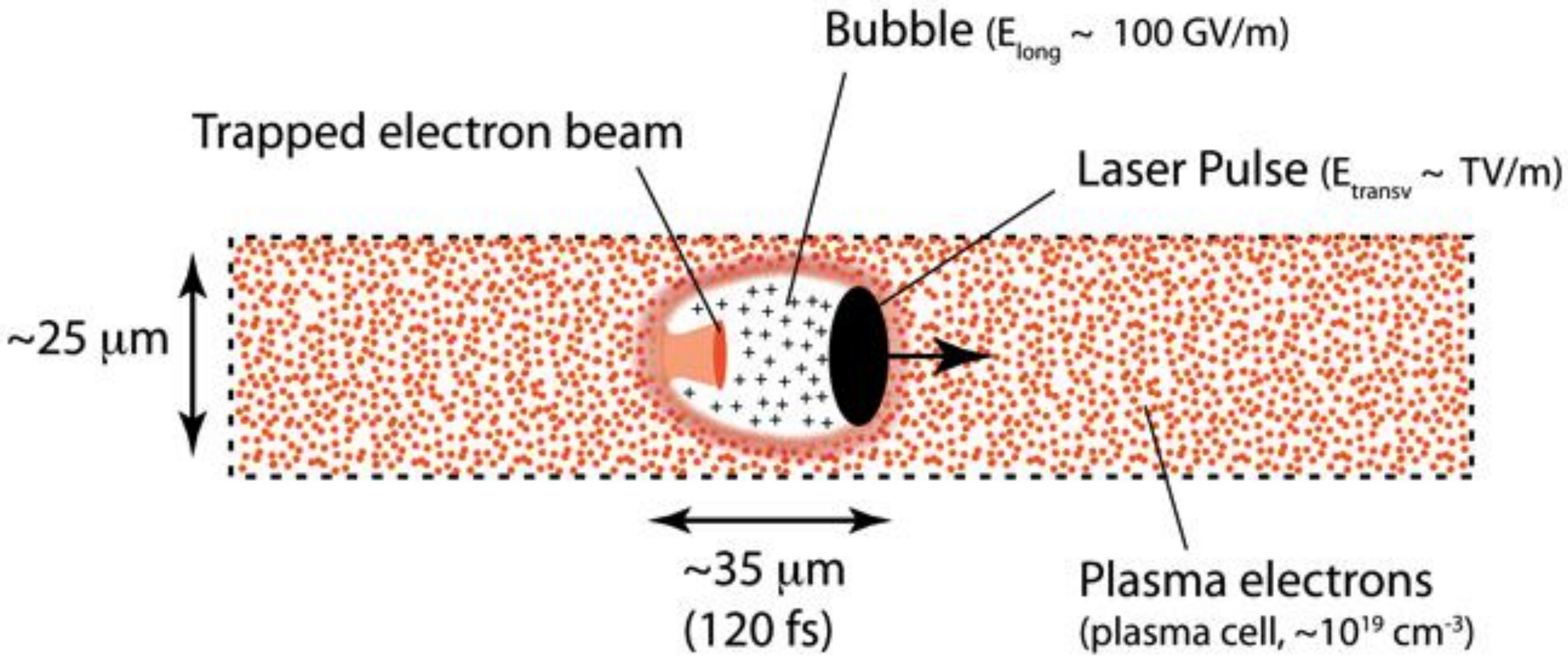
Laser Plasma-Acceleration (Internal Injection)



Laser Plasma-Acceleration (Internal Injection)

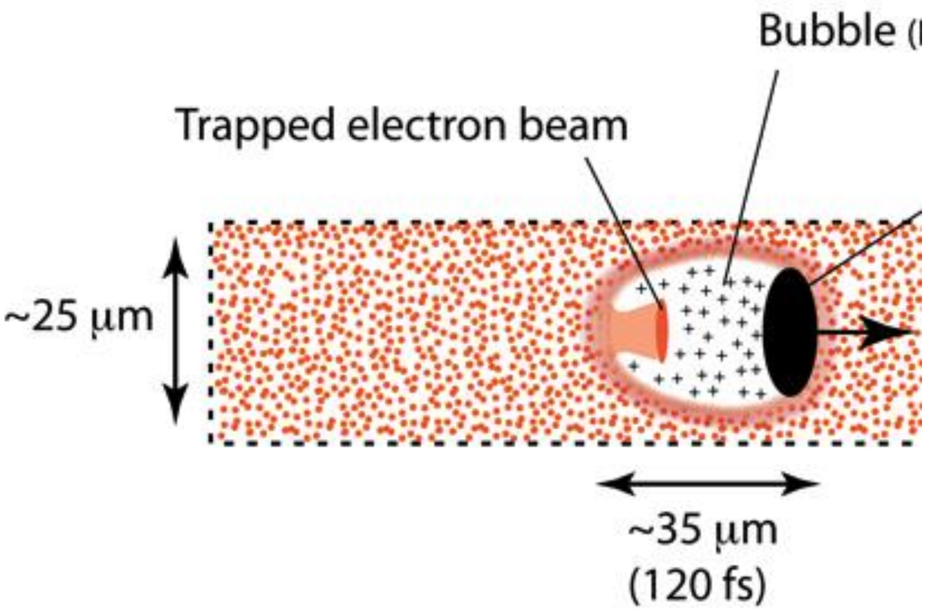


Laser Plasma-Acceleration (Internal Injection)



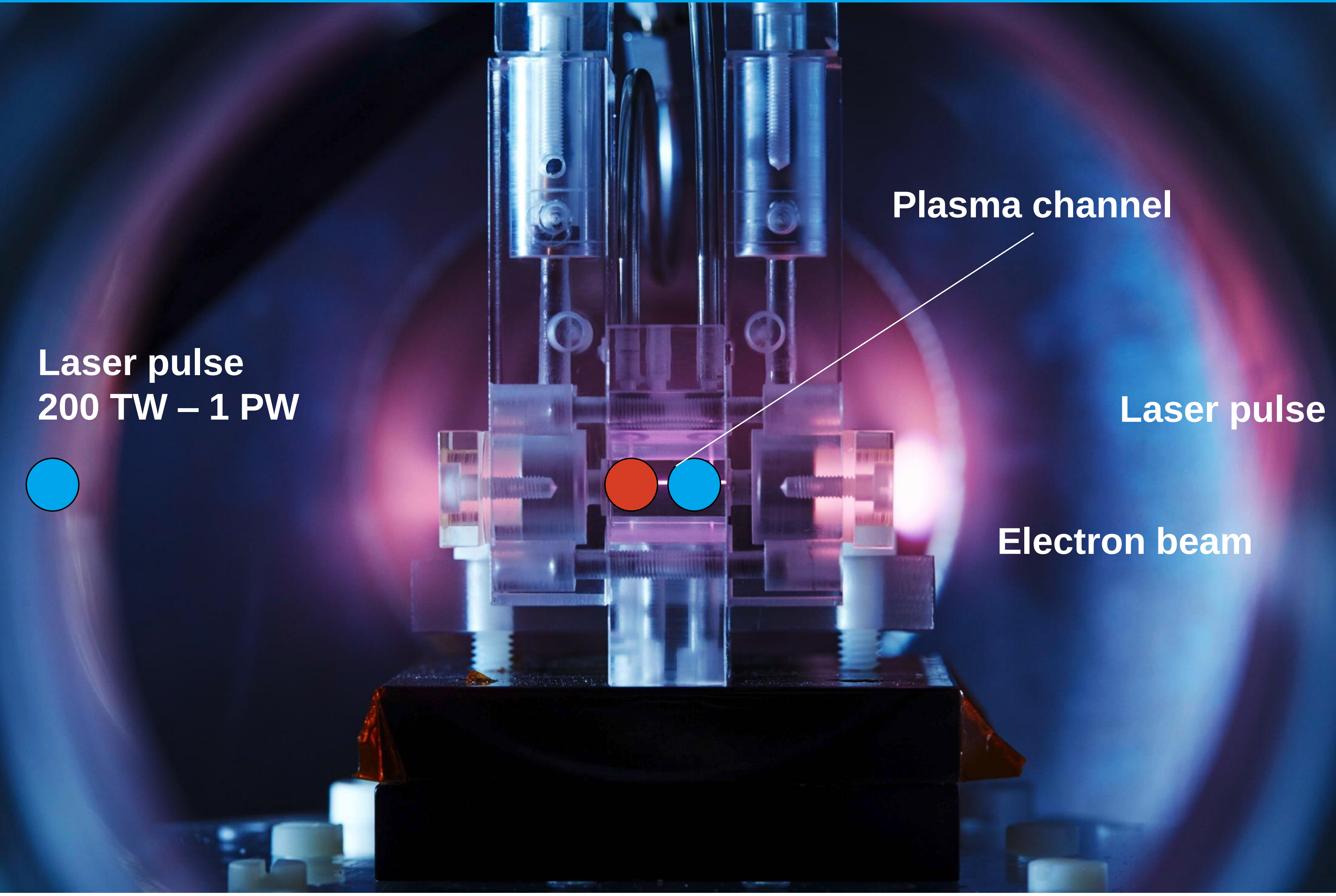
This accelerator fits into a human hair!

Laser Plasma-Acceleration (Internal Injection)



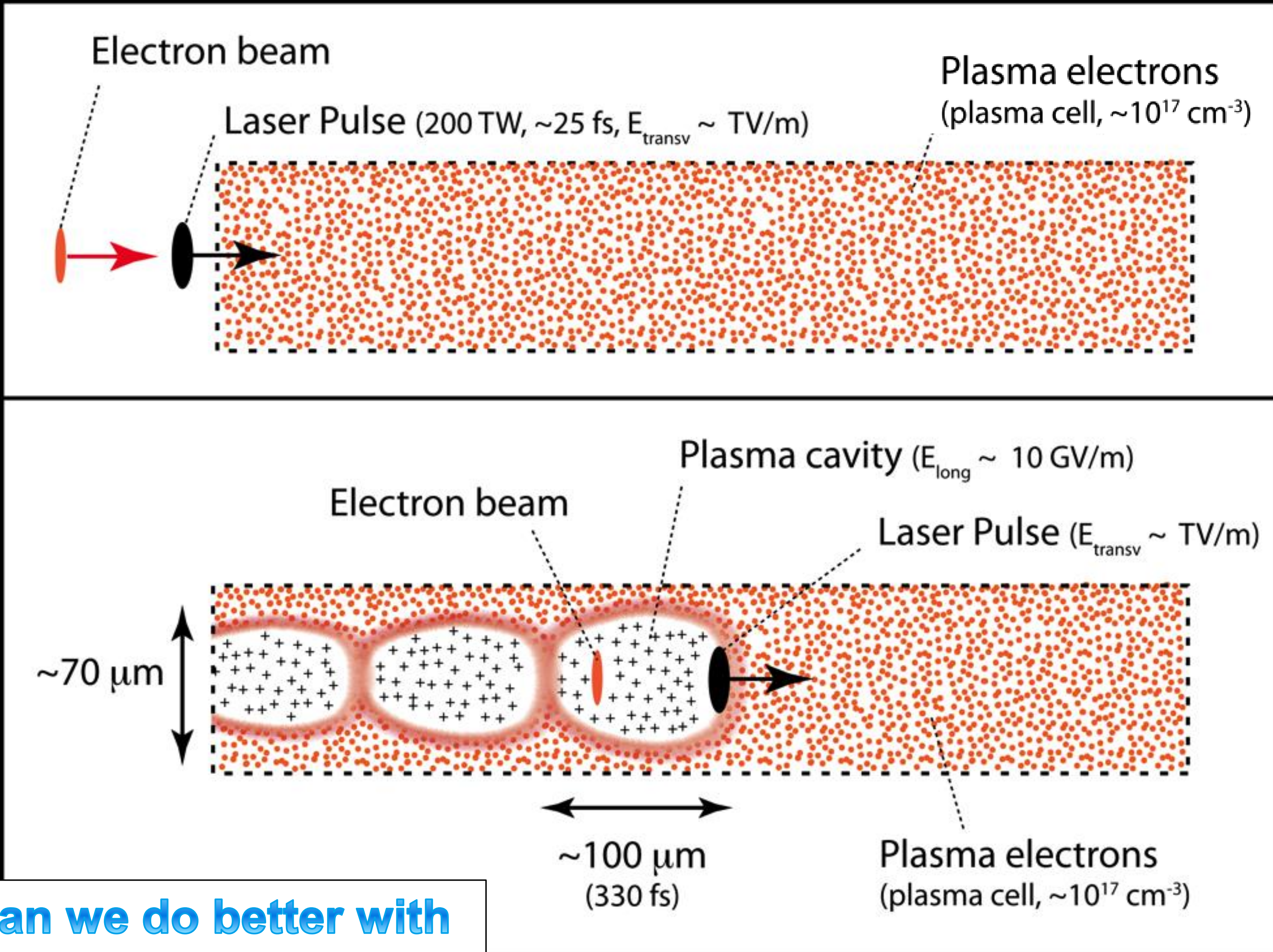
- This proved highly successful with electron bunches of **up to 4.25 GeV produced over a few cm**.
- Small dimensions involved → few **micron tolerances**!
- Highly compact but also **highly complex** accelerator: generation, bunching, focusing, acceleration, (wiggling) all in one small volume.
- Energy spread and stability at the few % level.

Laser Plasma Accelerators for Electron Beams



And the Plasma Accelerator is Compact…

External Injection…



Can we do better with external injection?

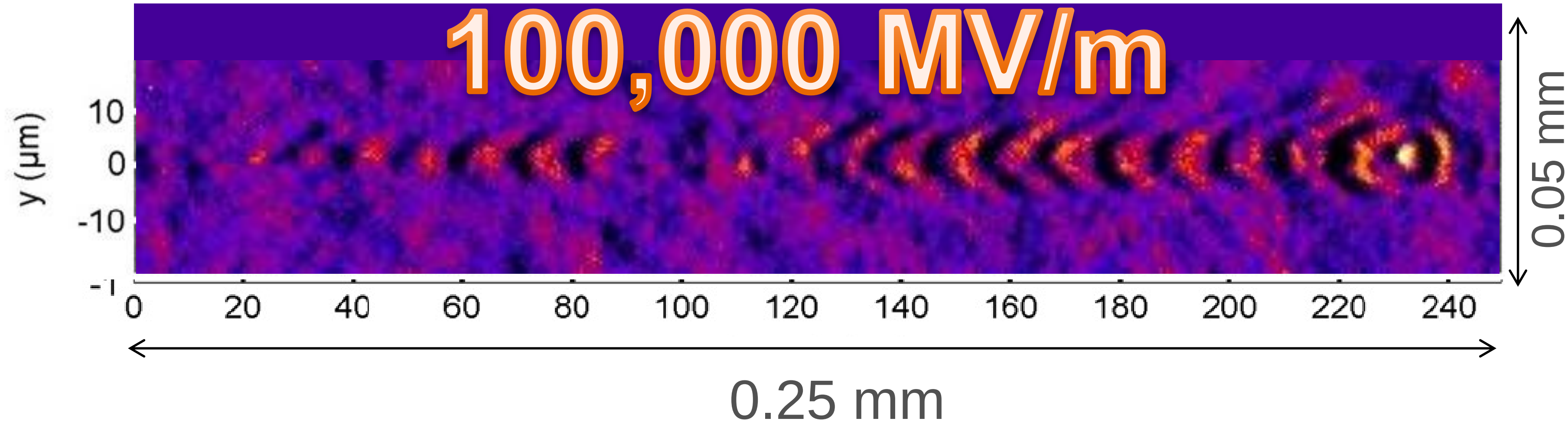
Foto Laser-Plasmabeschleuniger

APPLIED PHYSICS LETTERS 103, 191118 (2013)

Few-cycle optical probe-pulse for investigation of relativistic laser-plasma interactions

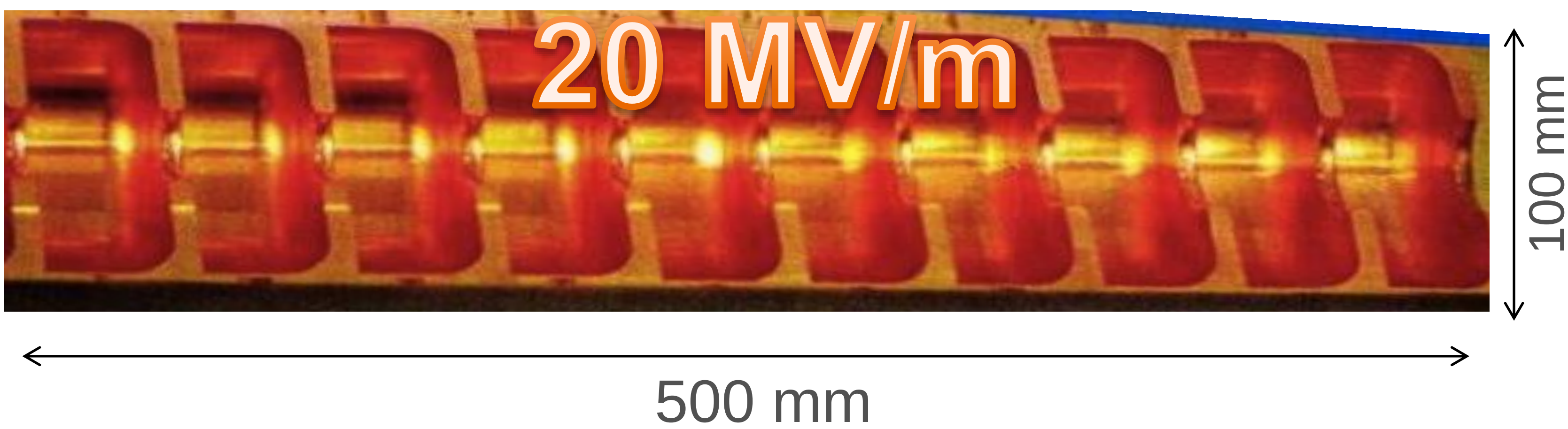
M. B. Schwab,[1,a)] A. Sävert,[1] O. Jäckel,[1,2] J. Polz,[1] M. Schnell,[1] T. Rinck,[1] L. Veisz,[3] M. Möller,[1] P. Hansinger,[1] G. G. Paulus,[1,2] and M. C. Kaluza[1,2]
[1]Insitut für Optik und Quantenelektronik, Max-Wien-Platz 1, 07743 Jena, Germany
[2]Helmholtz-Institut Jena, Fröbelstieg 3, 07743 Jena, Germany
[3]Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany

2013



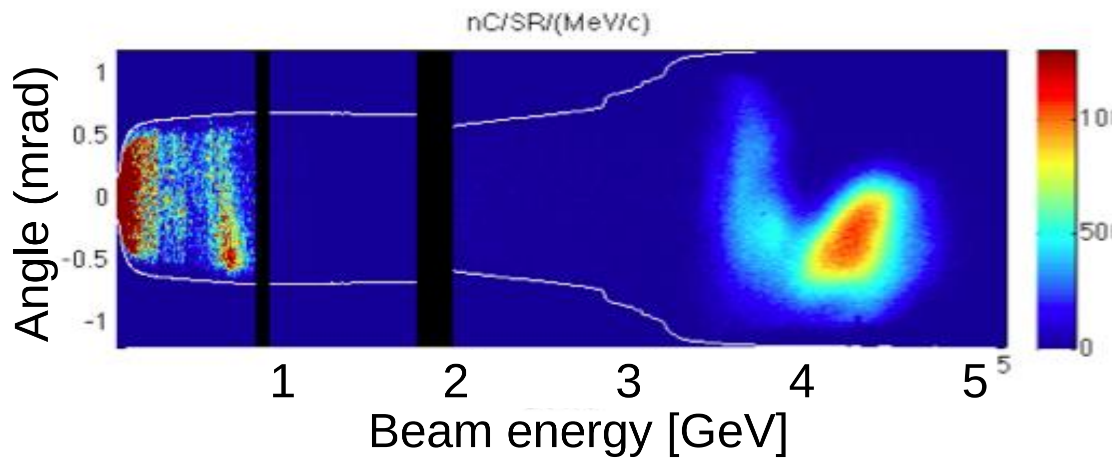
Metall (Kupfer) S band Linac Struktur

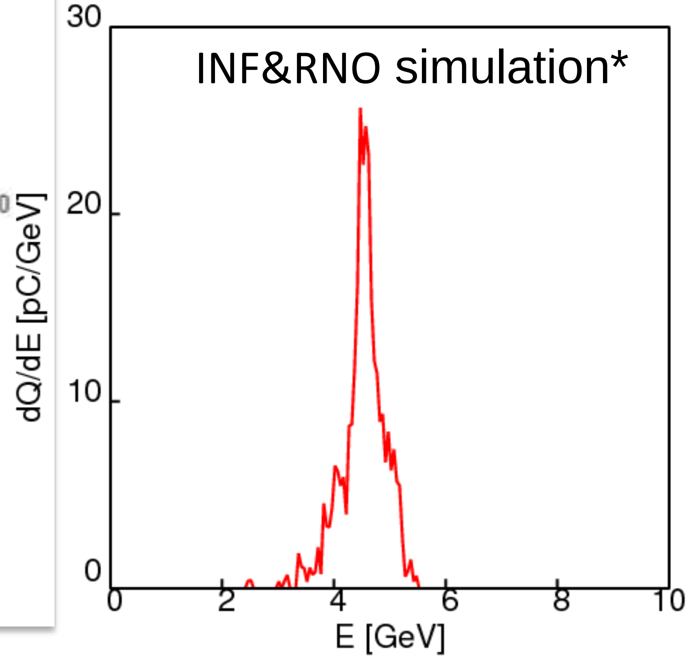
Mikro-Wellen zur Wellener-zeugung



4.25 GeV beams have been obtained from 9 cm plasma channel powered by 310 TW laser pulses **(15 J)**

*C. Benedetti et al., proceedings of AAC2010, proceedings of ICAP2012





Slide: W. Leemans

- **Laser** (E=15 J):
  - Measured longitudinal profile (T_0= 40 fs)
  - Measured far field mode (w_0=53 µm)
- **Plasma:** parabolic plasma channel (**length 9 cm, n_0~6×10^{17} cm^{-3}**)

W.P. Leemans et al.,PRL 2014, in print

	Exp.	Sim.
Energy	**4.25 GeV**	4.5 GeV
ΔE/E	5%	3.2%
Charge	~20 pC	23 pC
Divergence	0.3 mrad	0.6 mrad

Wait one moment… Compact and Cost-Effective?

- Consider laser-driven plasma: Presently one can buy **1 Peta-Watt Ti:Sa** lasers from industry for a low double digit million € cost.
- The most compact 1 PW laser is installed in HZDR, Dresden, Germany (part of ARD):

Required space: 120 m^2
(can be visited)

- The laser size drives the size of such an accelerator facility. With such a 1 PW laser electrons of **4.25 GeV have been produced within 9 cm** (see LBNL result).
- The 1 PW laser should be sufficient for a **10 GeV accelerator within about 20 cm**. Total footprint: about 200-300 m^2 (incl. all infrastructure).
- Now do this conventionally and compare size and cost!
(e.g. ***10 GeV = 500 m of conventional acceleration with 20 MV/m****)*
- Need to bring up quality, efficiency and repetition rate.

Content

1. Accelerators – From Conventional Techniques to Plasmas
2. **The Linear Regime**
3. The Non-Linear Regime
4. Tolerances
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The Linear Regime

- Analytical treatment
- Placement of beams in the plasma accelerating structure
- Maximum acceleration (transformer ratio)
- Optimizations: Energy spread, phase slippage, stability, reproducibility

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

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

$$r \ll a$$

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

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

ε= electrical field
z = long. coord.
r = radial coord.
a = driver radius
ω_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 and laser-driven (beat wave).

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

Accelerating field

Depends on radial position r

Changes between accelerating and decelerating as function of longitudinal position z

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

π/2 out of phase

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

Transverse field

Depends on radial position r

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

The Useful Regime of Plasma Accelerators

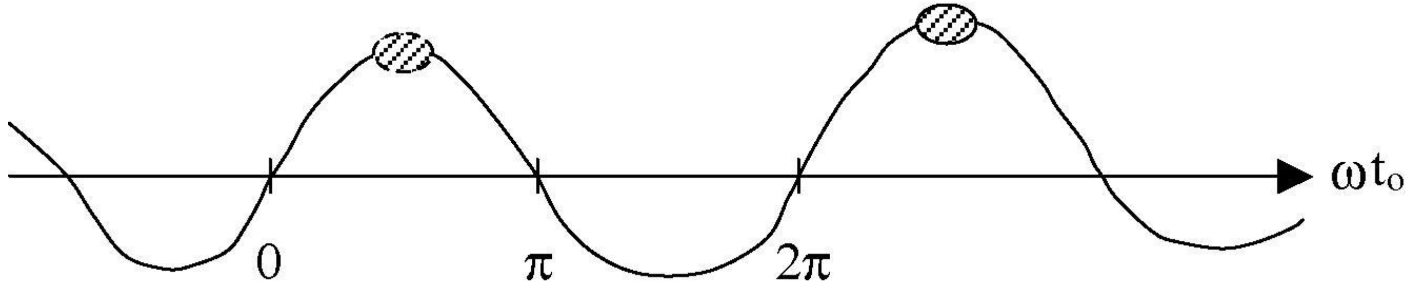
Two conditions for an accelerator:

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

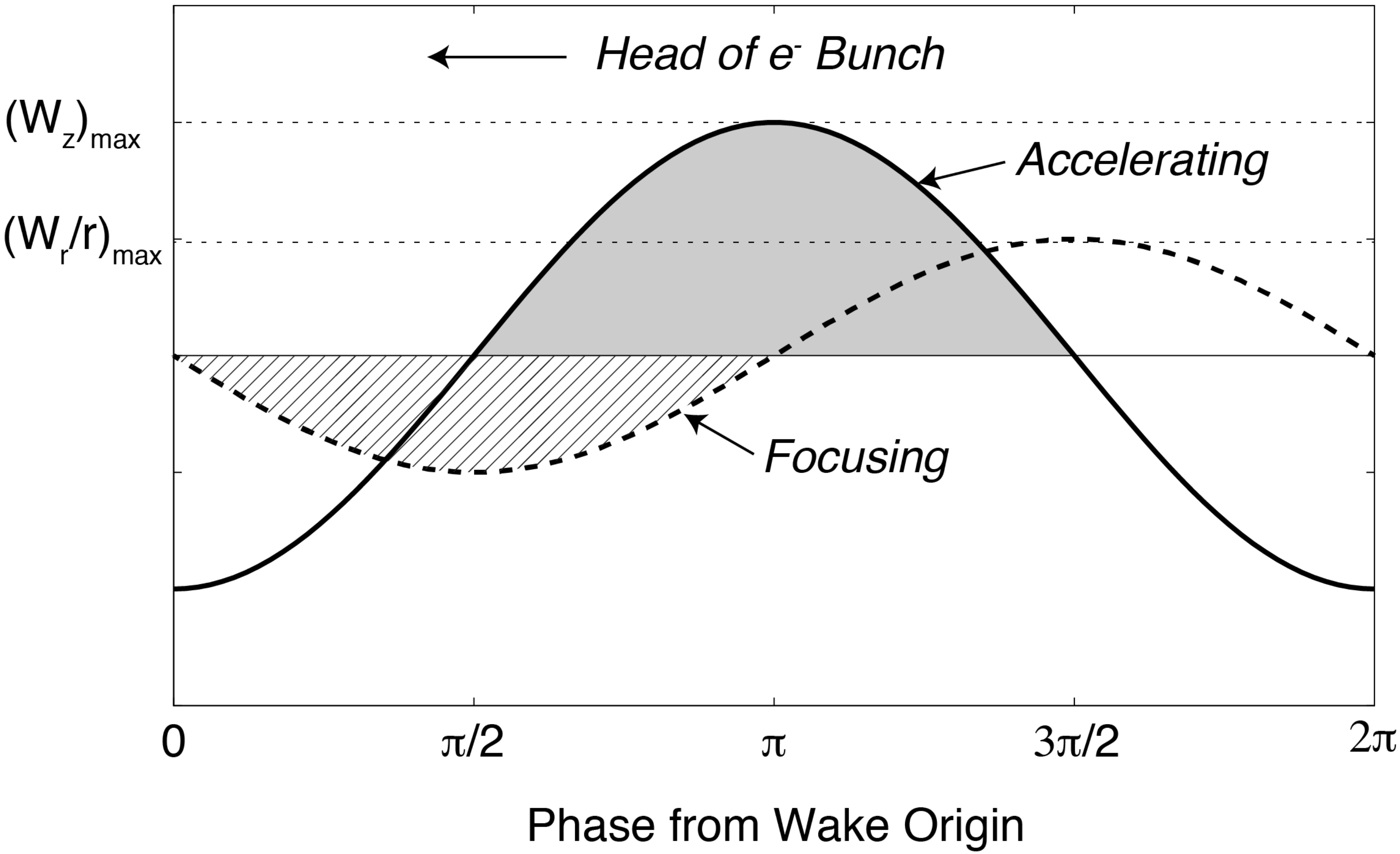
These two conditions define a useful range of acceleration!

Reminder metallic RF accelerator structures:

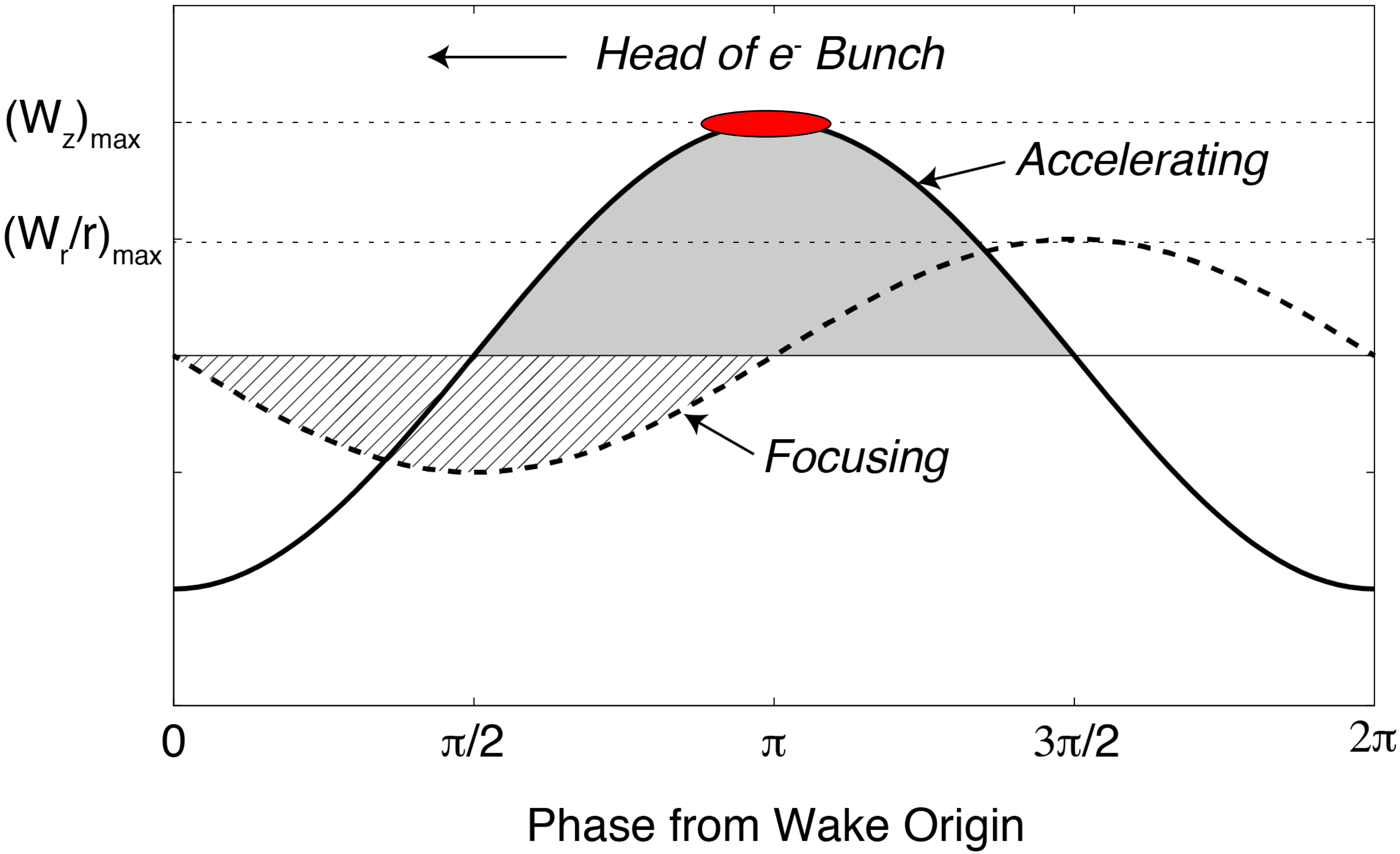
no net transverse fields for beam particles → full accelerating range is available for beam → usually place the beam on the crest of the accelerating voltage



Plasma Accelerator



Plasma Accelerator



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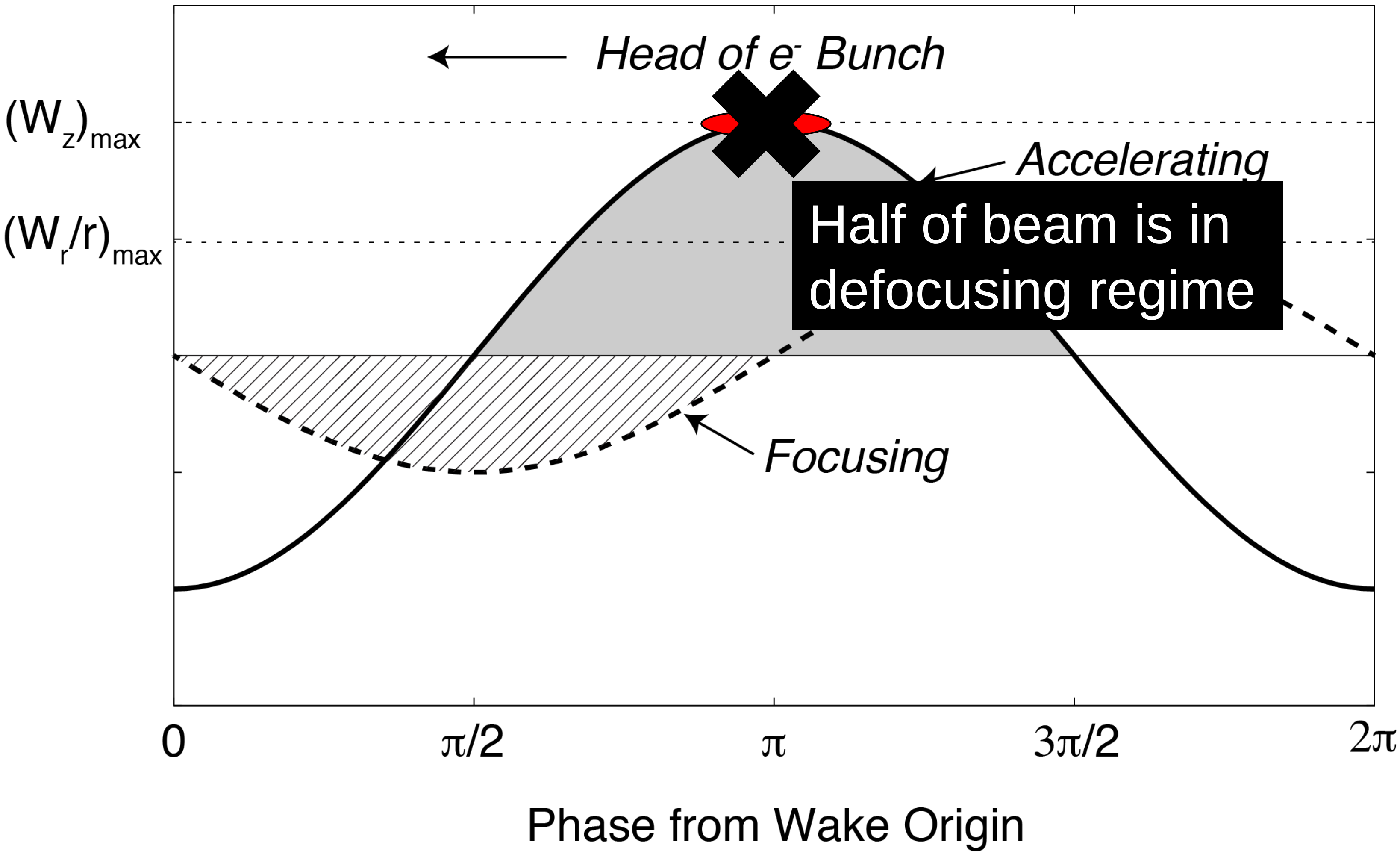
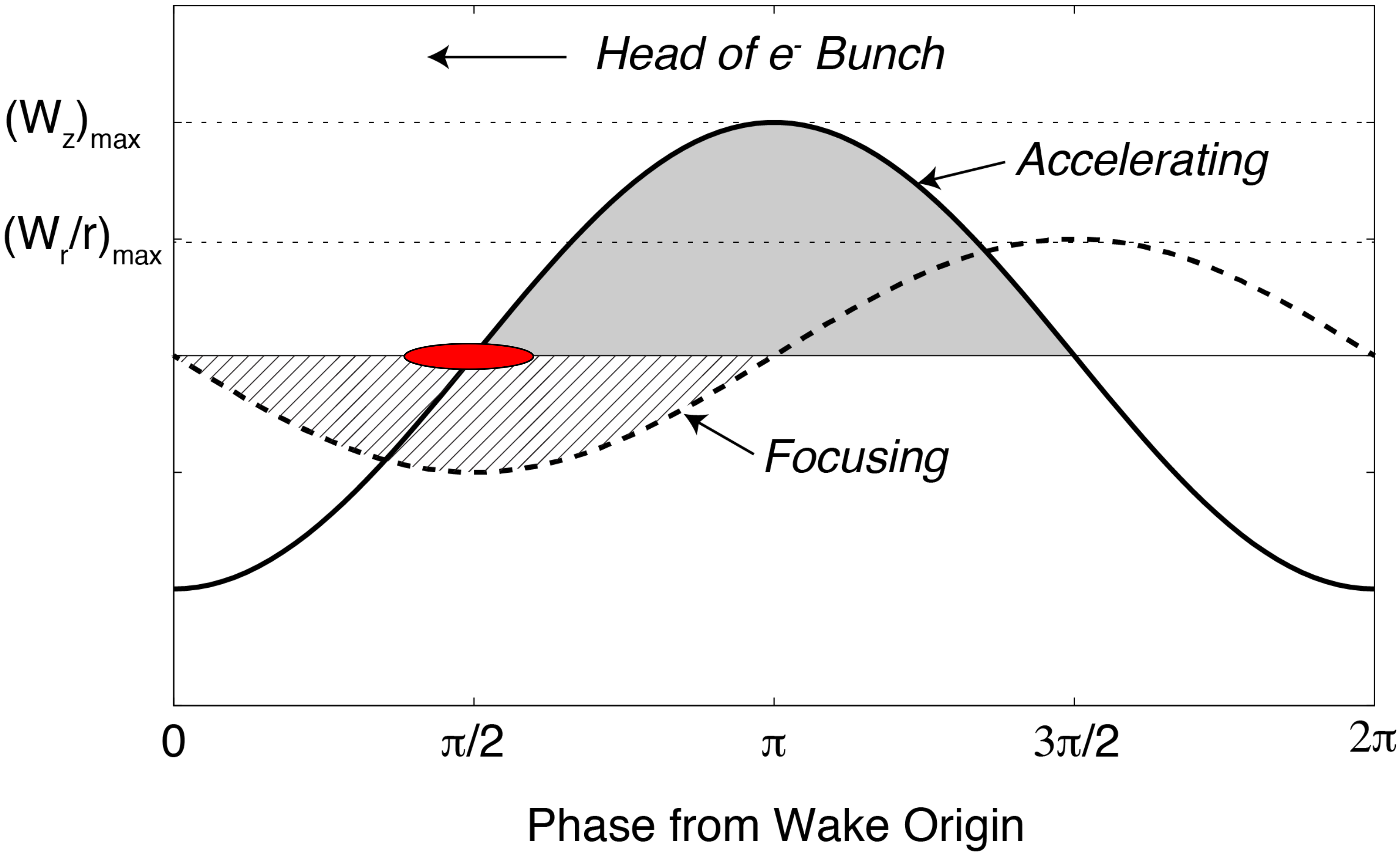
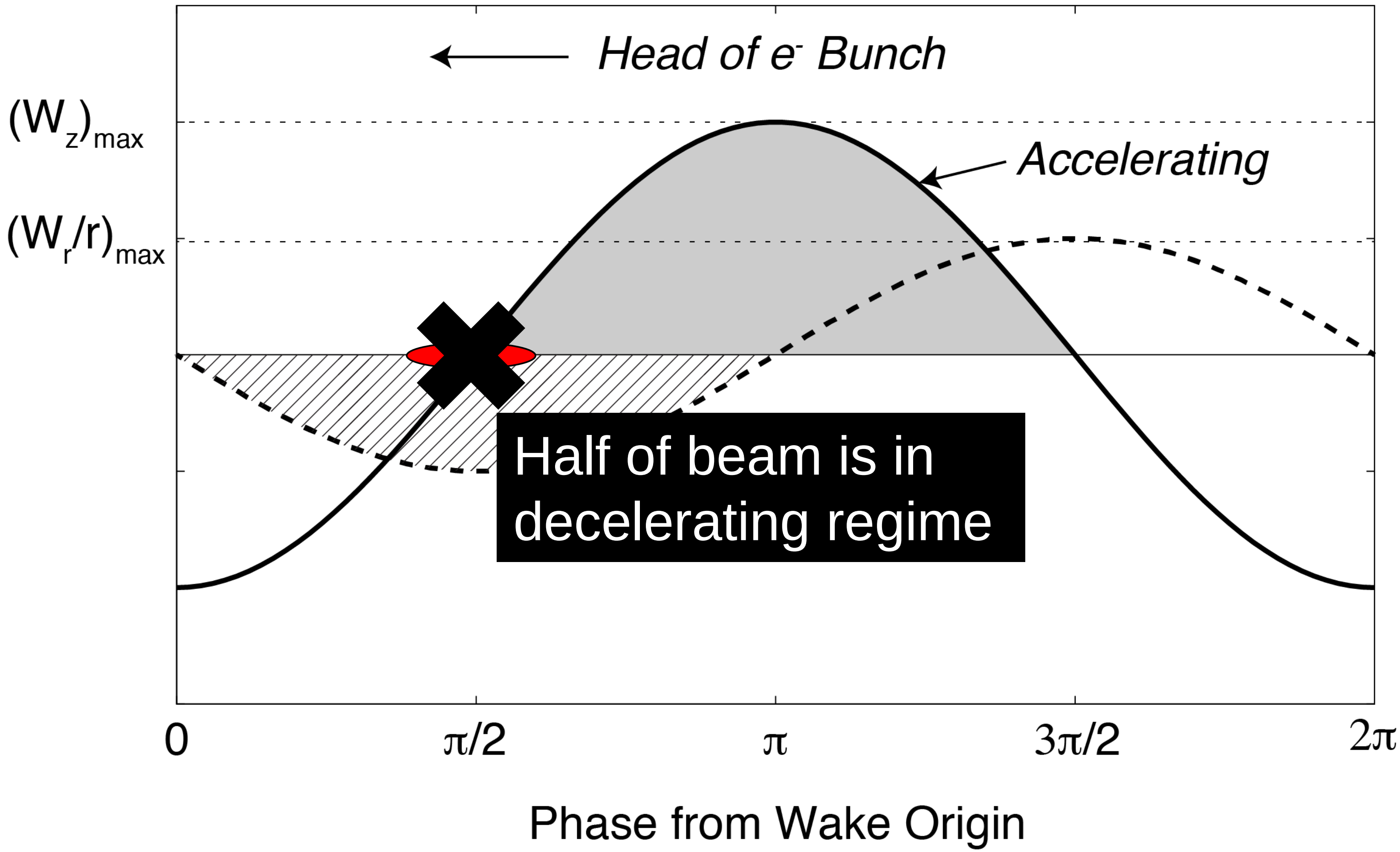


Plasma Accelerator



Plasma Accelerator



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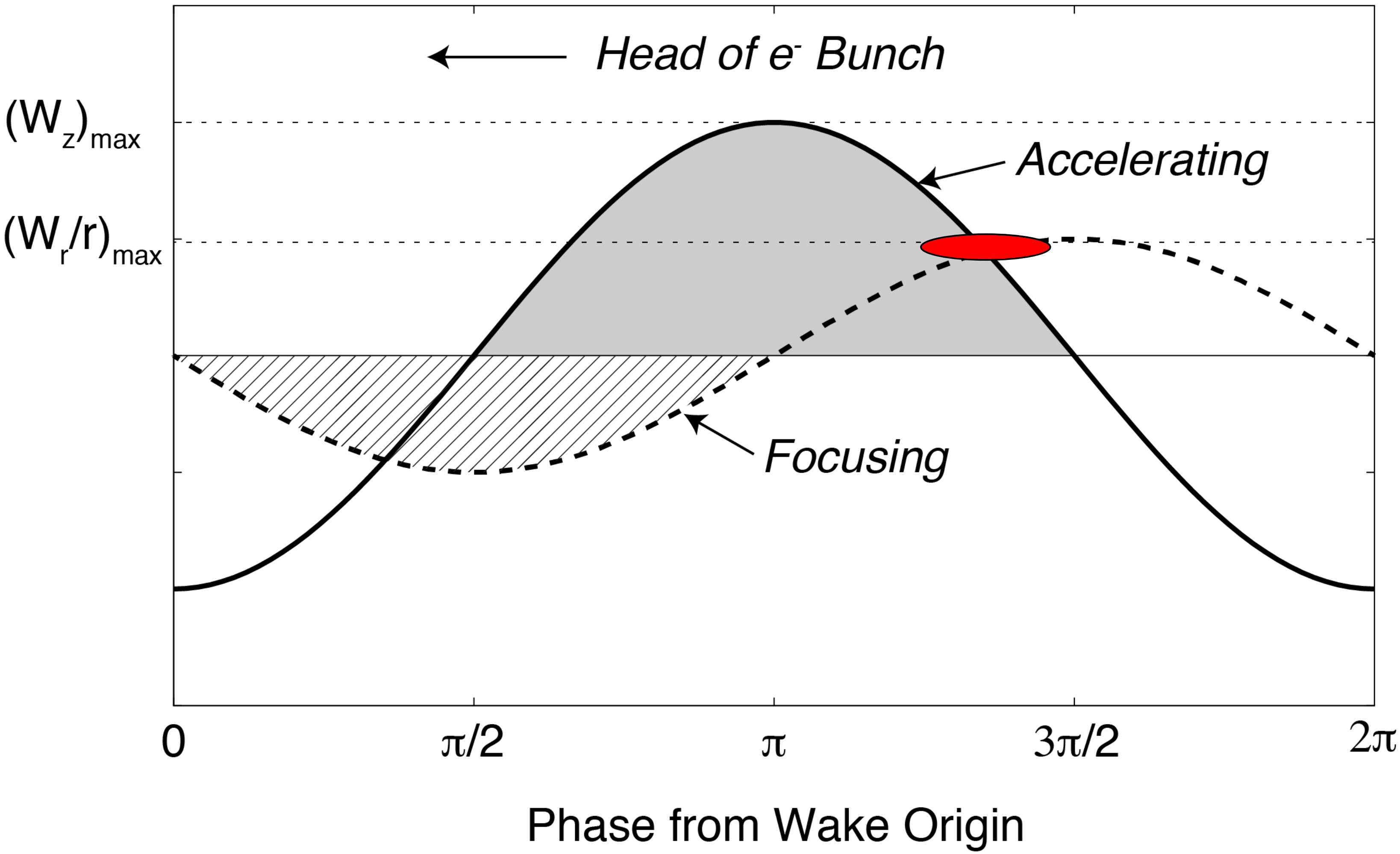

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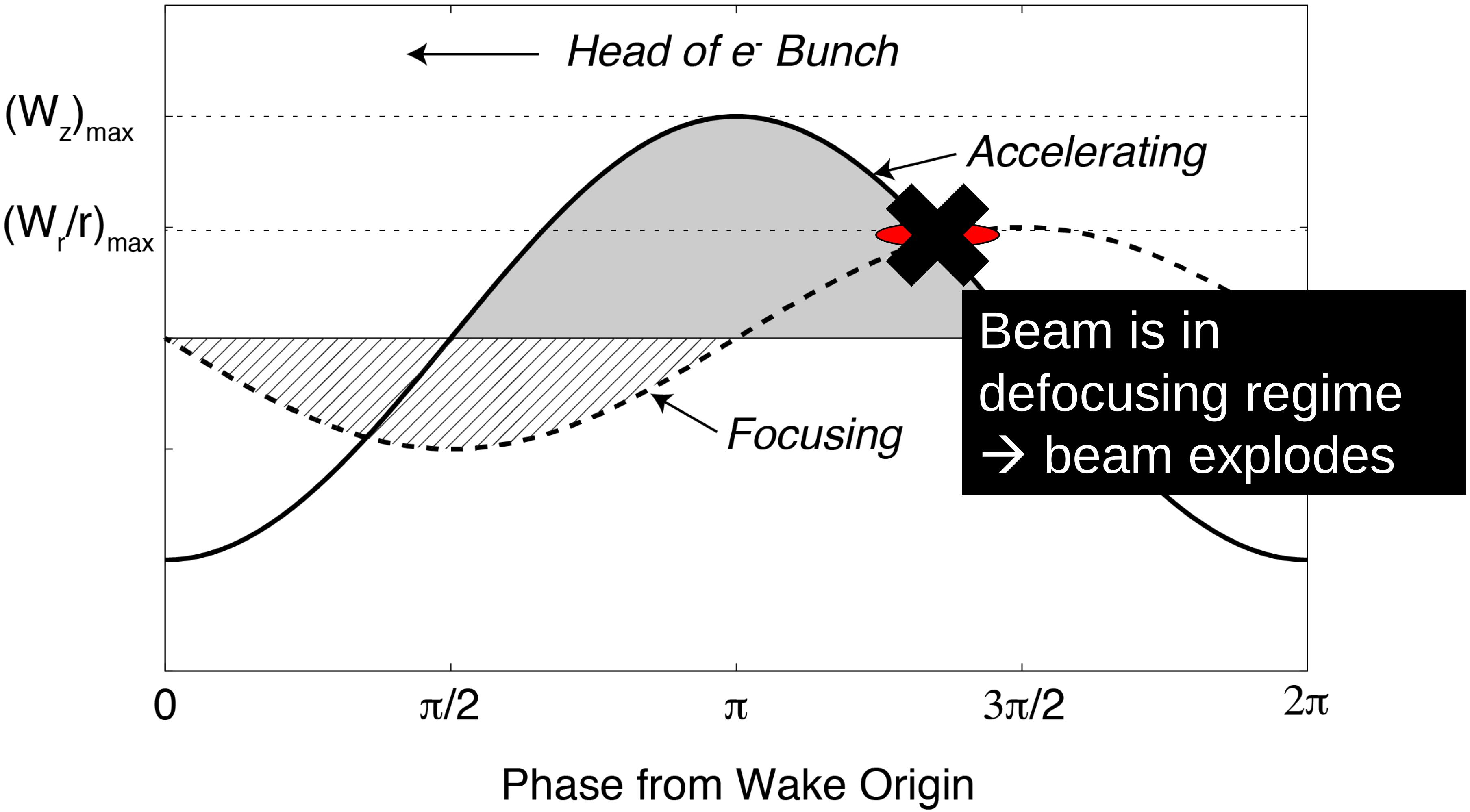
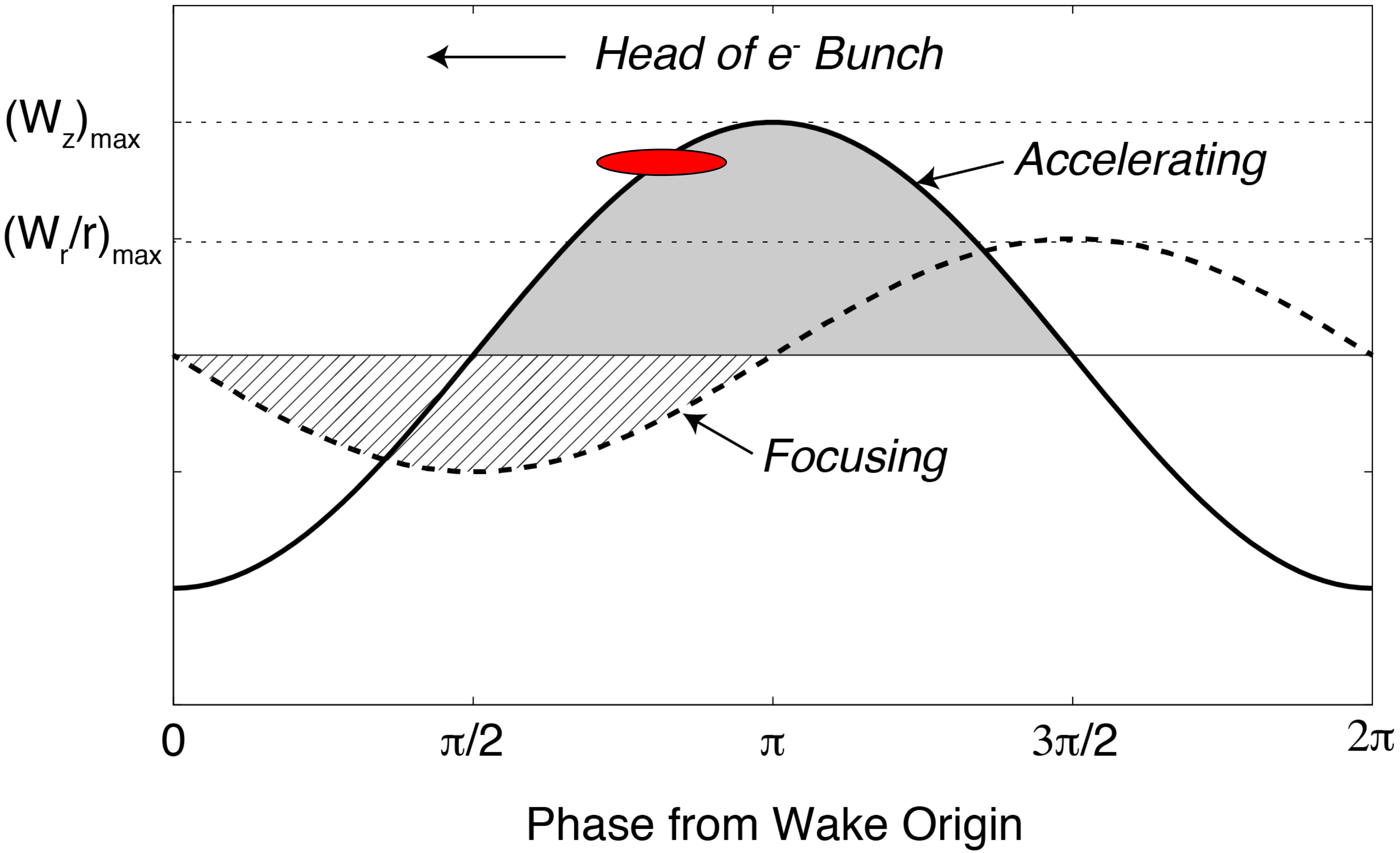
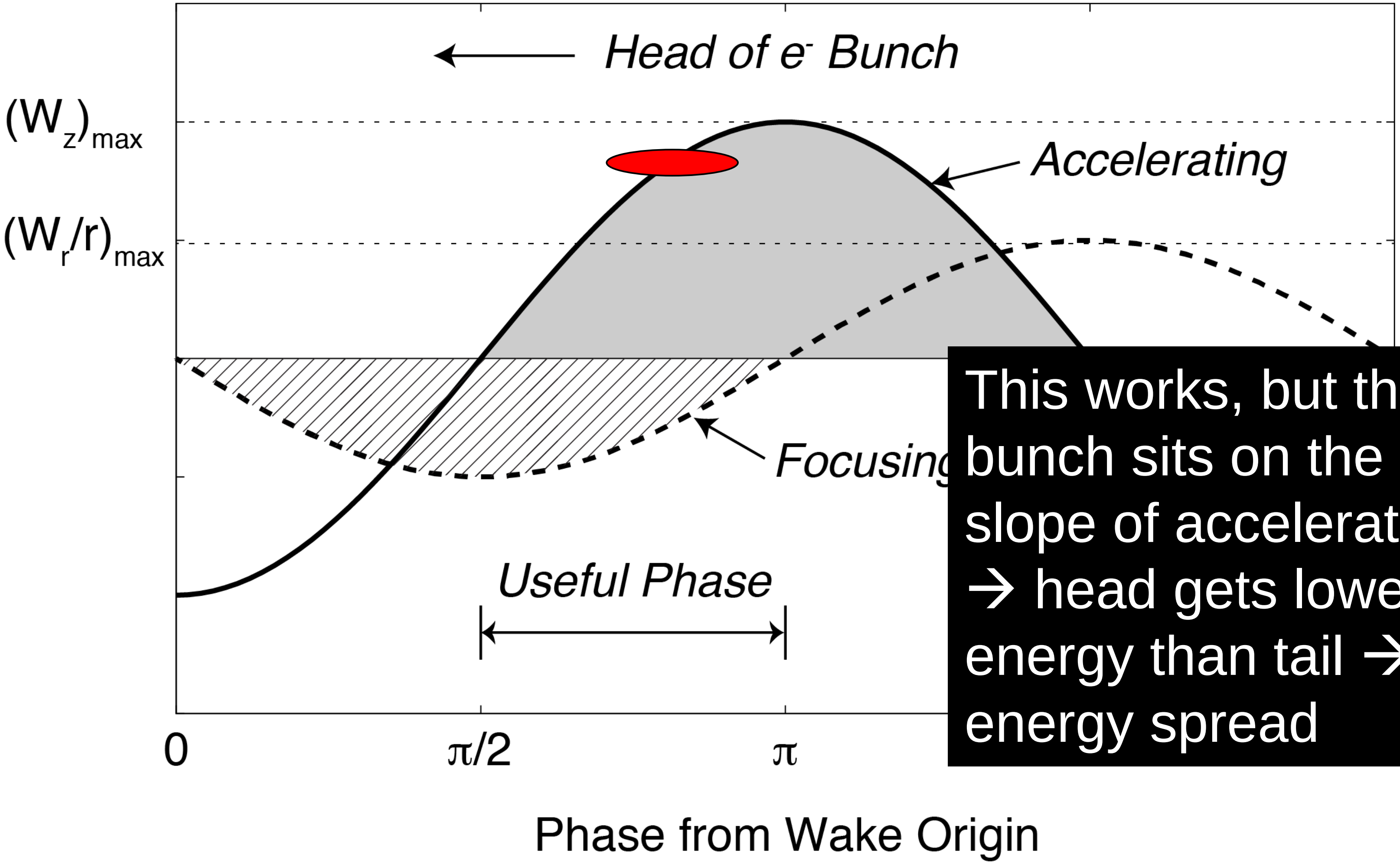


Plasma Accelerator

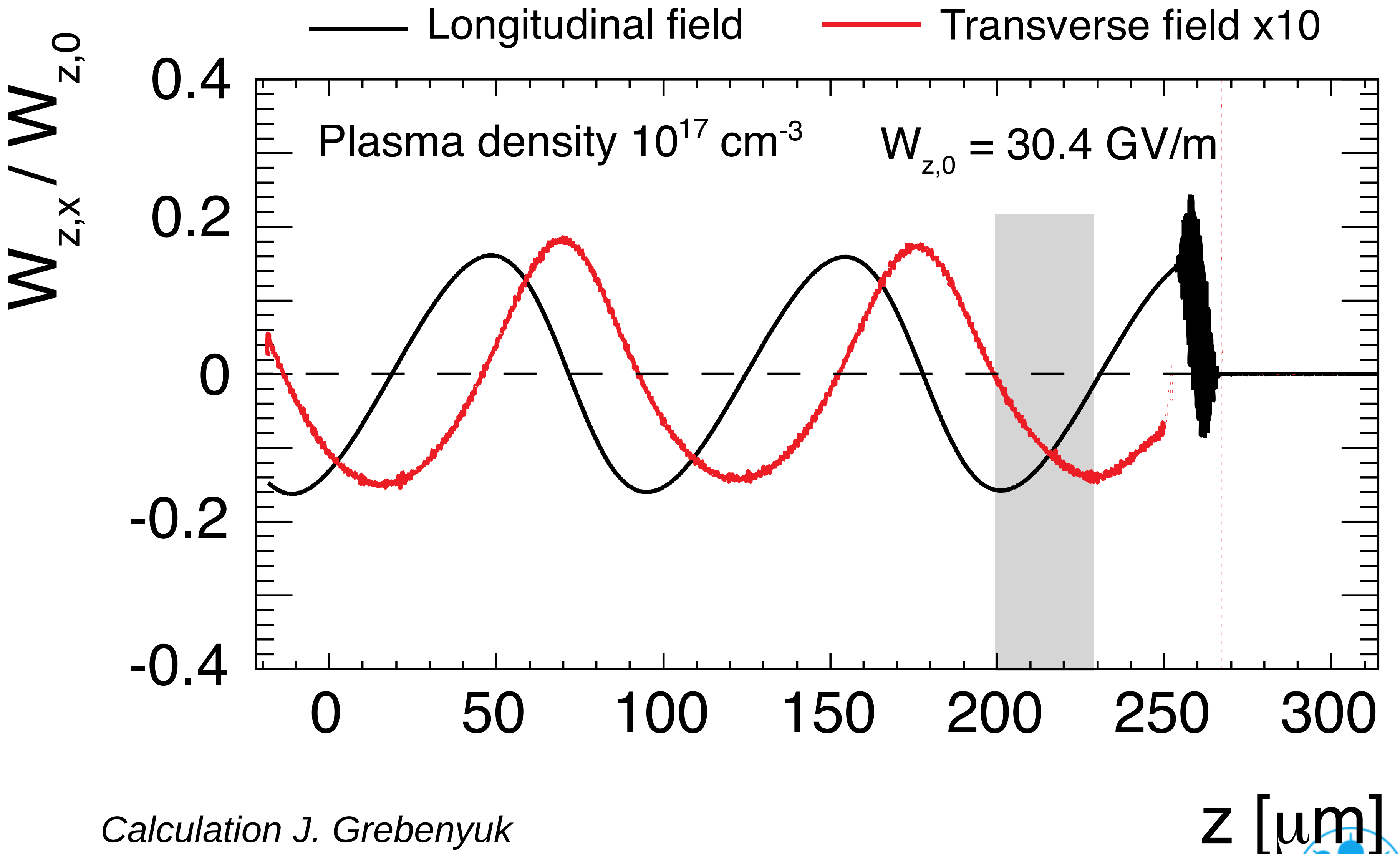


Plasma Accelerator



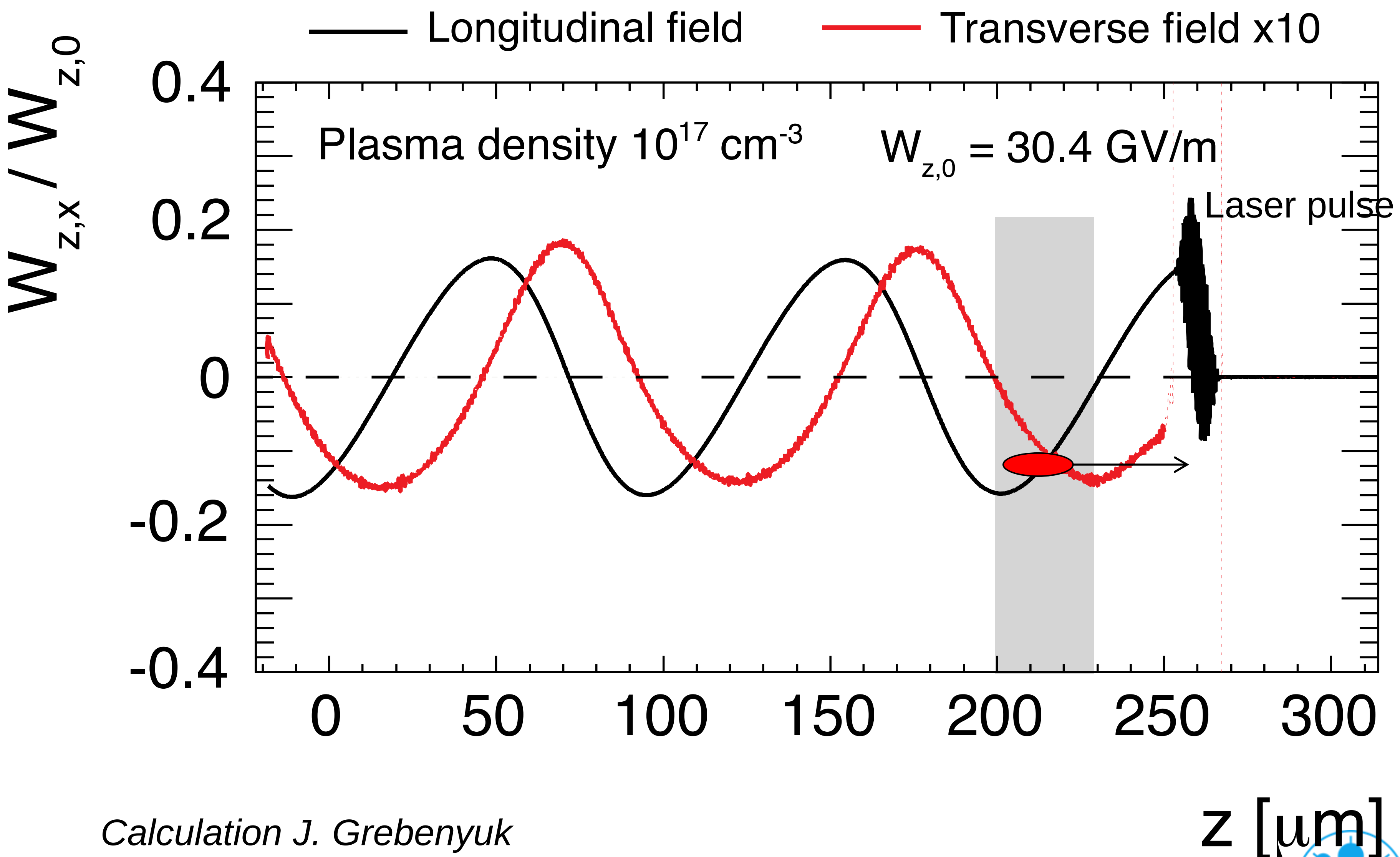
This works, but the bunch sits on the slope of acceleration → head gets lower energy than tail → energy spread

Comparison with OSIRIS simulation



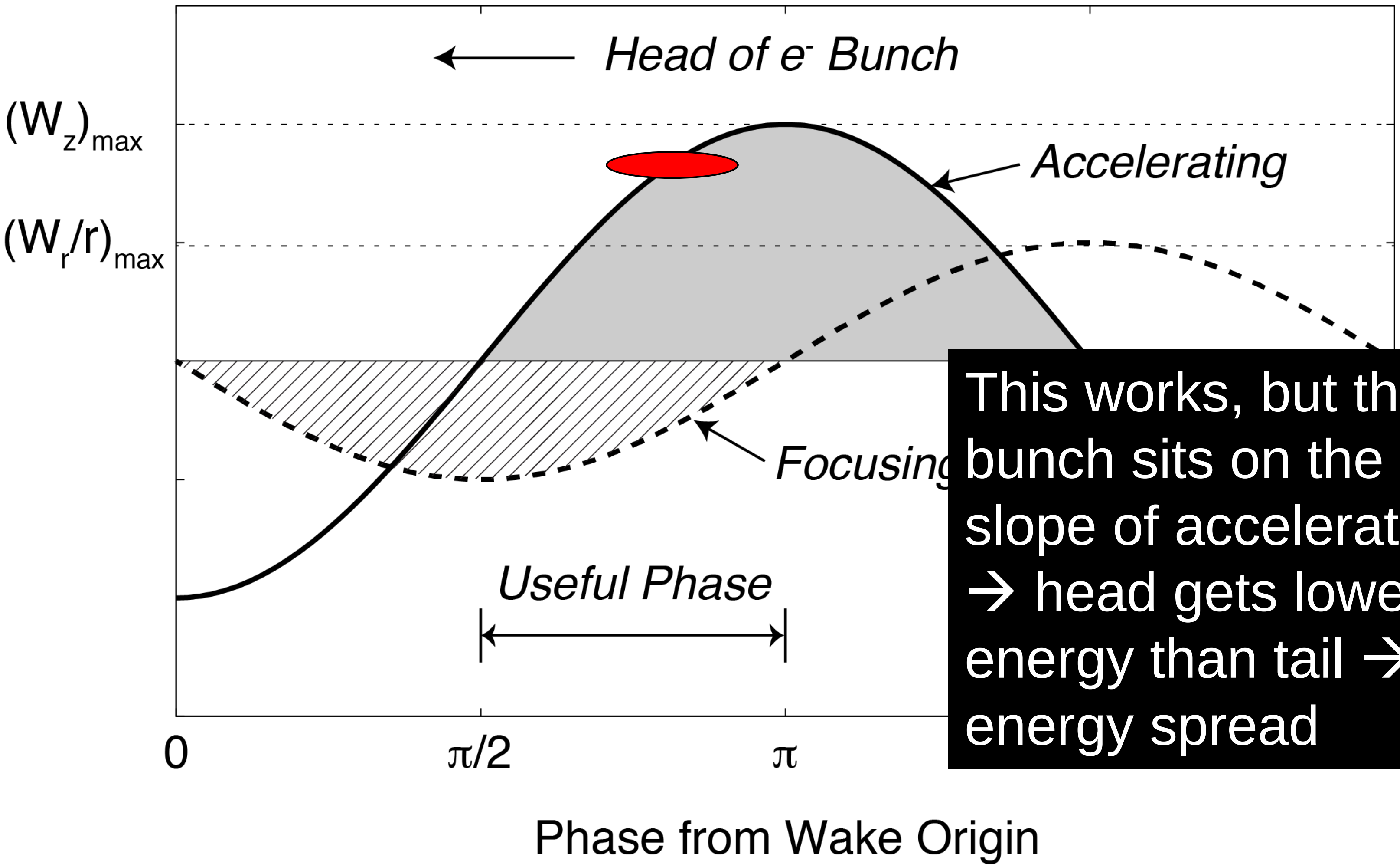
Calculation J. Grebenyuk

Comparison with OSIRIS simulation



Calculation J. Grebenyuk

Plasma Accelerator



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

Optimization 1: Energy Spread

Reduce energy spread (head to tail → correlated with z)

Minimize: Ratio of accelerated bunch length over ¼ plasma wavelength!

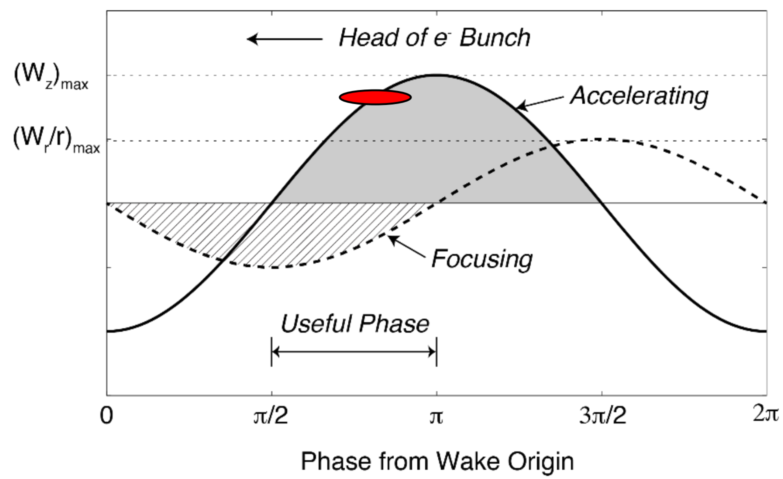
Minimize length accele-rated bunch and/or Increase plasma wavelength

Ultra-short bunches (fs, as)

Ultra-fast science

Lower plasma density

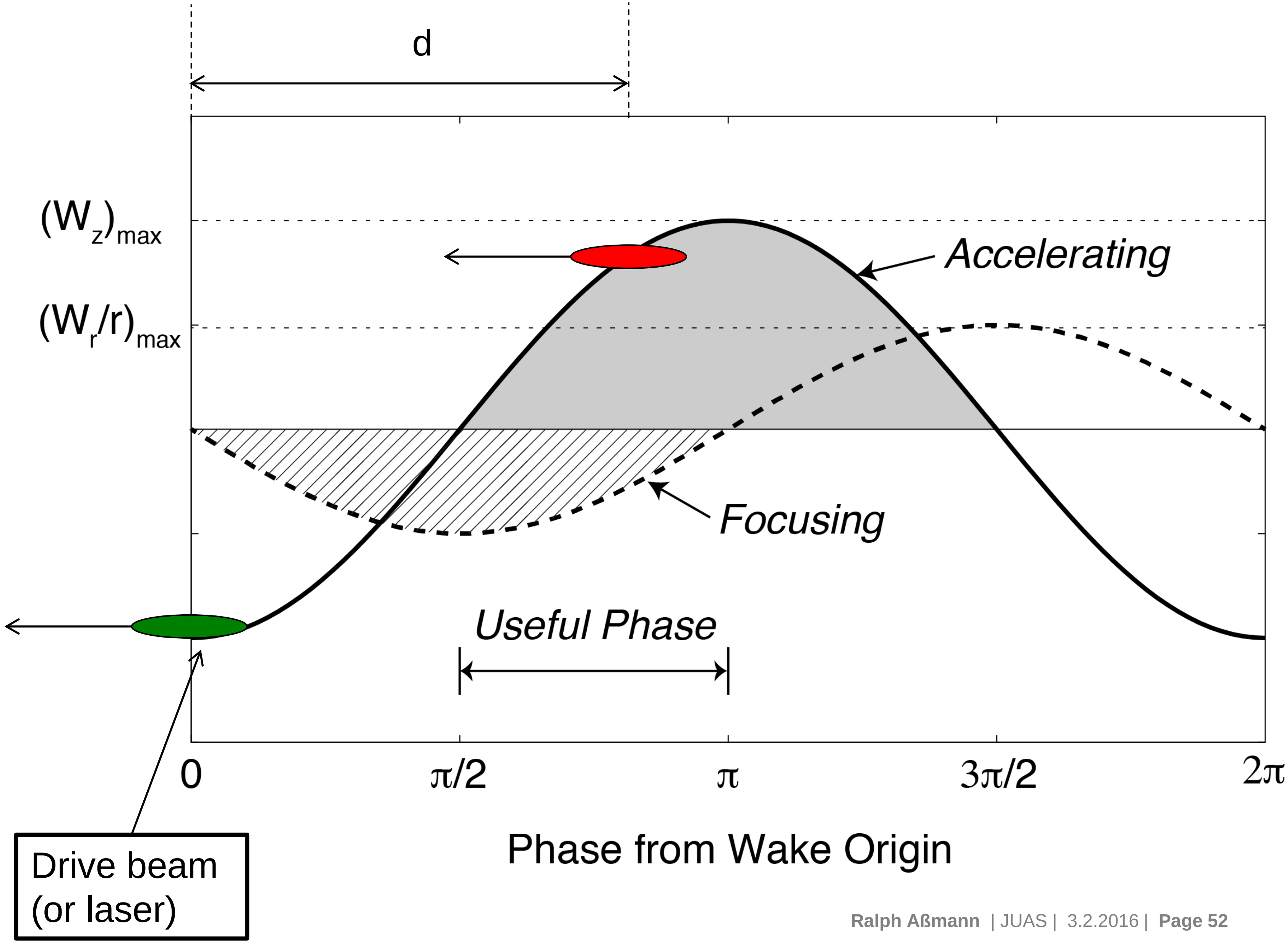
Lower accelerating gradient



1 fs = 0.3 μm

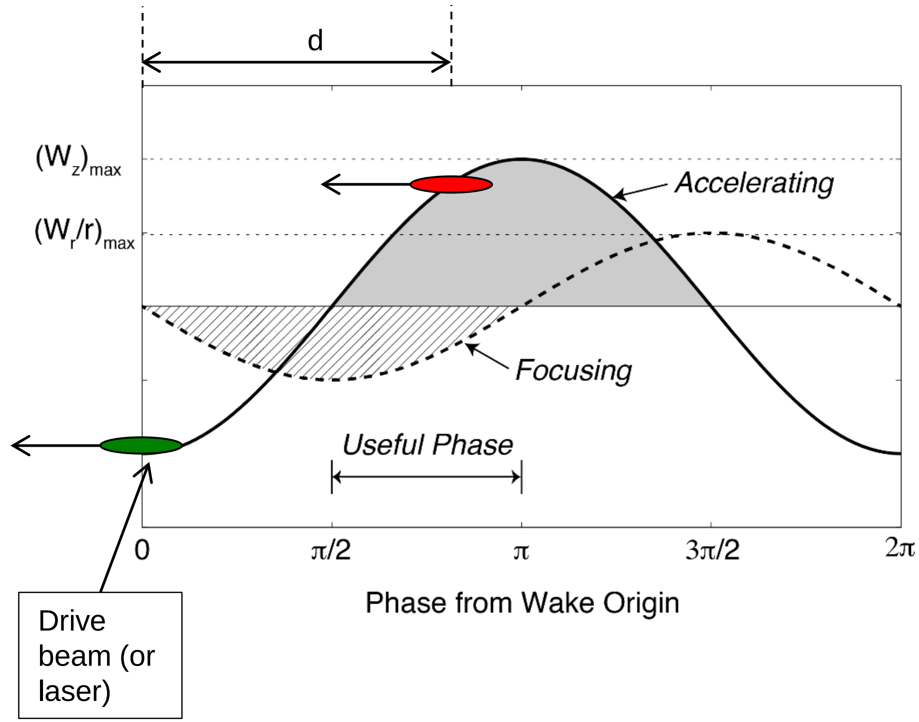
when travelling with light velocity c

Phase Slippage

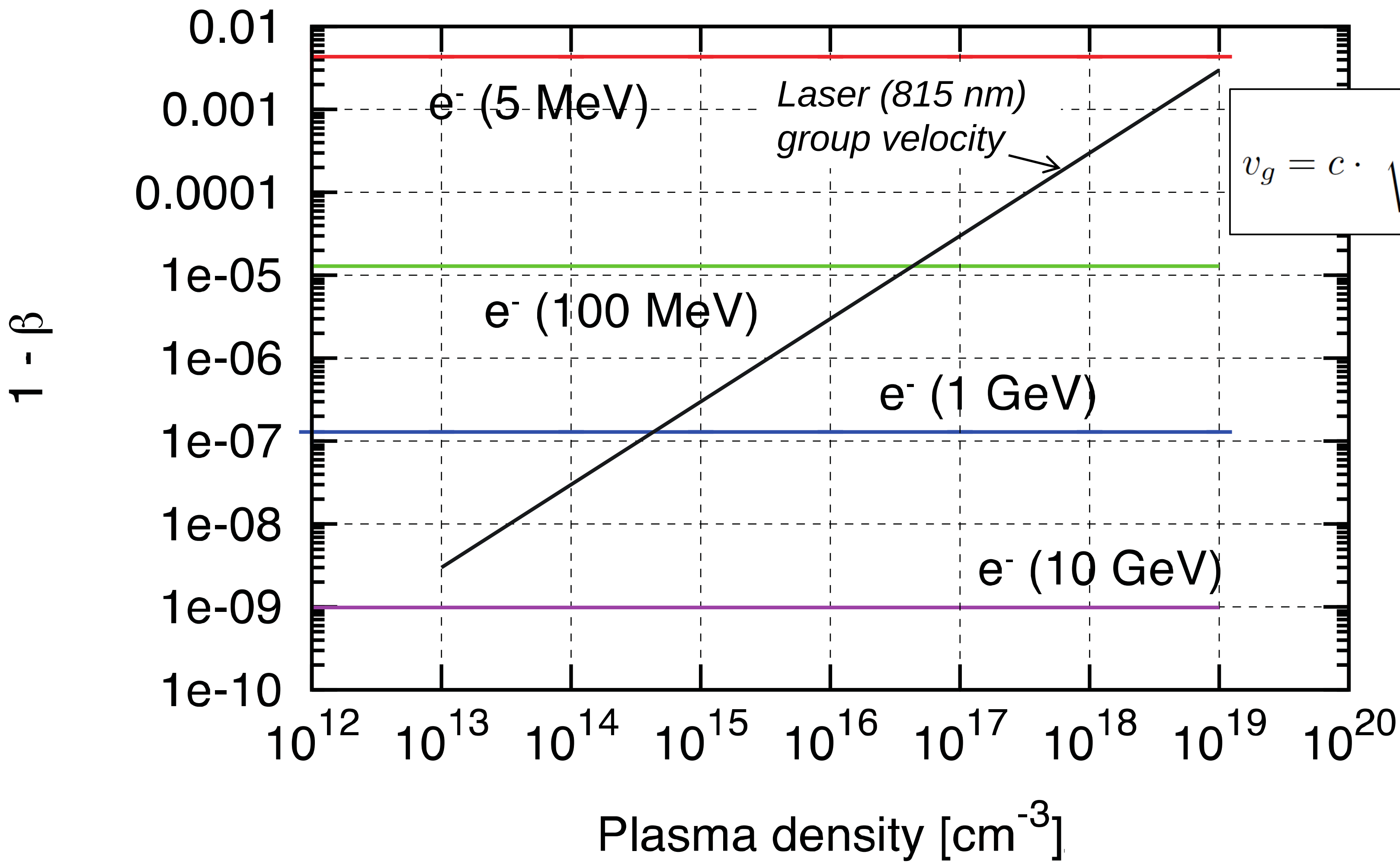


Phase Slippage

- Keep distance d constant for maximum acceleration and minimum energy spread.
- **Problem 1**: Drive beam loses energy and (slightly) slows down.
- **Problem 2**: Accelerated beam starts at low energy, gains energy and (slightly) speeds up.
- **Problem 3 (for lasers)**: Laser group velocity depends on plasma density and is slower than light velocity c.



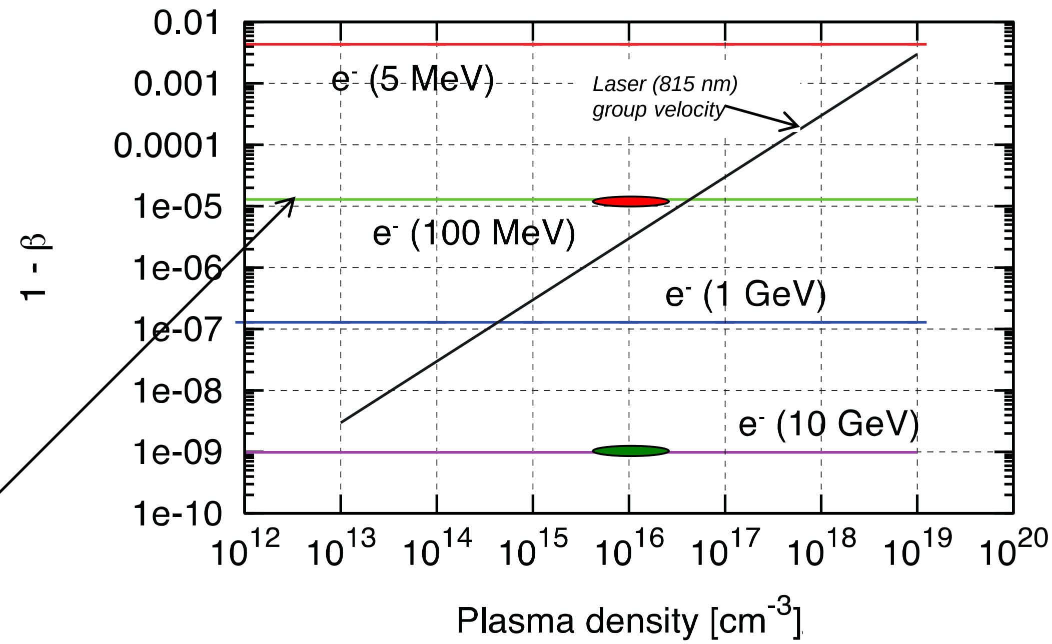
Dephasing (β = v/c, here consider relativistic beams)



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

Dephasing (β = v/c, here consider relativistic beams)

$$\Delta L = \frac{\Delta v}{c} \cdot L = \Delta\beta \cdot L$$

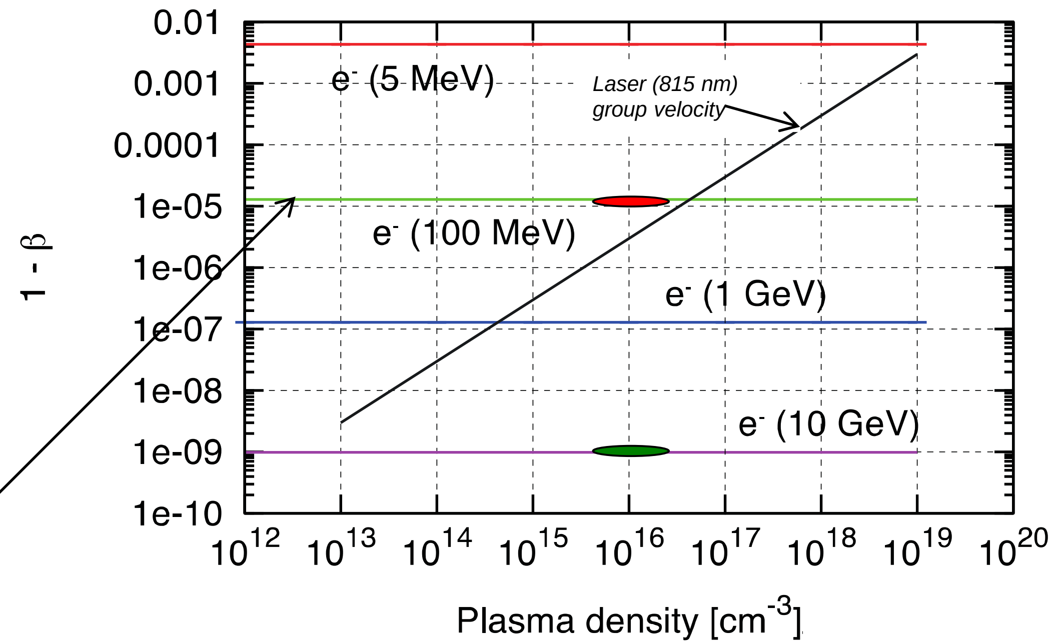


- Imagine **10 GeV beam driver**.
- Imagine **initial energy of accelerated electrons to be 100 MeV**.
- After 1 m slippage by ≈10^{-5} m = **10 μm**.
- Plasma wavelength: **10 μm (n_0=1e19) – 1 mm (n_0=1e15)**
- However:
  - Driver electrons are decelerated and slow down.
  - Accelerated electrons speed up.
- Big advantage of beam-driven…

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

Dephasing (β = v/c, here consider relativistic beams)

$$\Delta L = \frac{\Delta v}{c} \cdot L = \Delta\beta \cdot L$$



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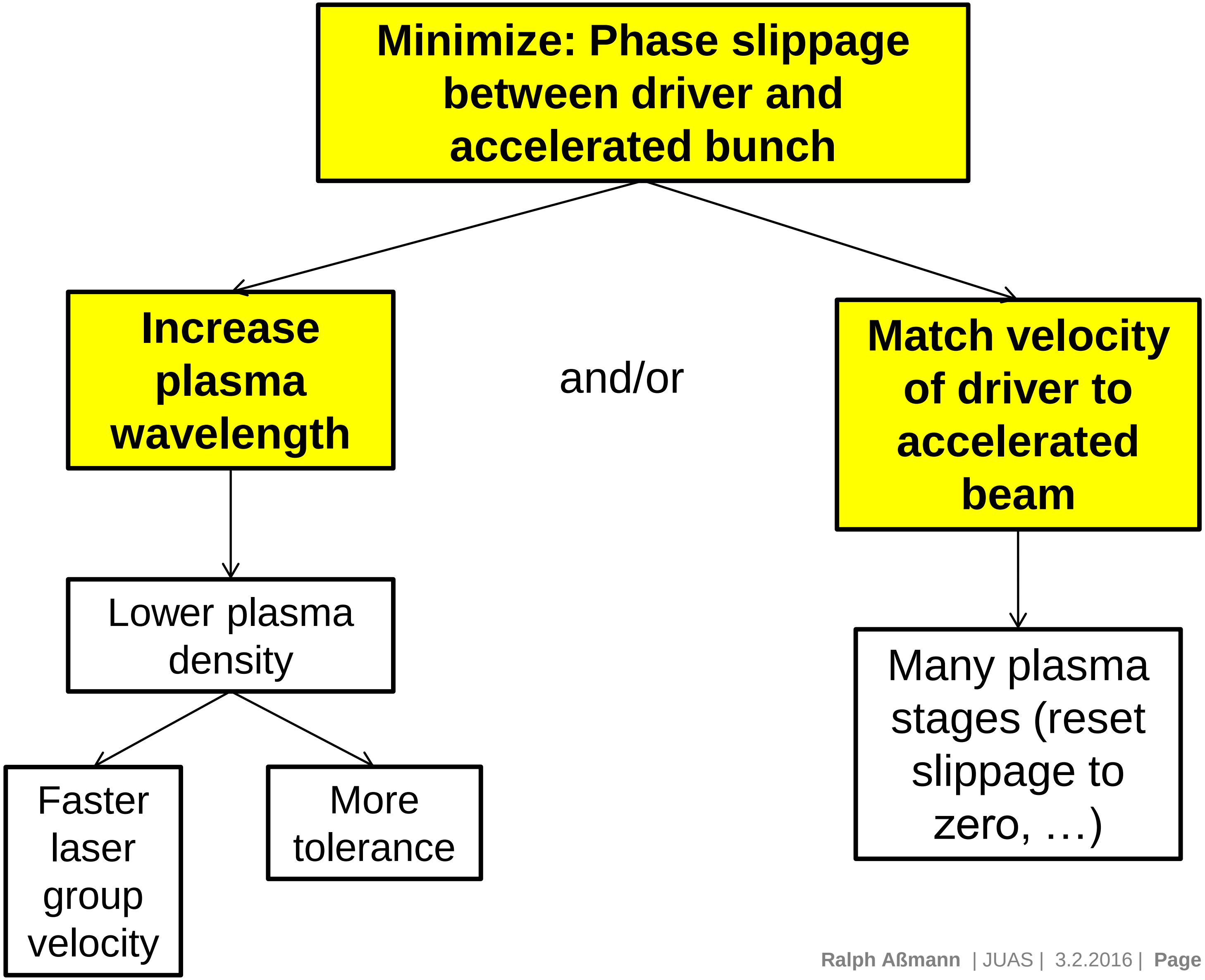
- After 1 m slippage by ≈10^{-5} m = **10 μm**.
- Plasma wavelength: **10 μm (n_0=1e19) – 1 mm (n_0=1e15)**
- However
  - Driver e
  - Acceler
- Big advantage of beam-driven…

3.6° - 360°

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

Optimization 2: Phase Slippage



Optimization 3: Stability / Reproducibility

Stabilize: Distance between driver and accelerated bunch.

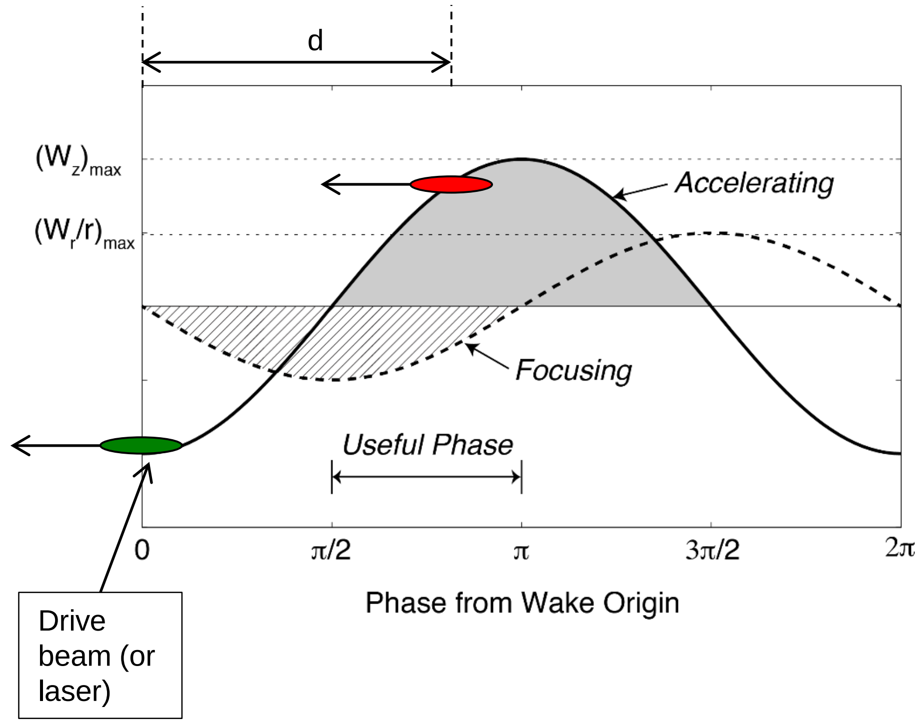
Internally generate accelerated electron bunch

High accelera-ting fields

High plasma density

Synchronize externally injected beam to driver

Synchronize with **30 fs to 0.3 fs accuracy** for few degree phase stability



Maximum Acceleration

- (Beam 1) **drive beam of N_1 electrons at E_1 (GeV)** that pumps its energy into the plasma wakefield.

  (Beam 2) **acc. electron beam of N_2 electrons** gets at **maximum ΔE**

- Energy conservation must be fulfilled:

$$E_{stored,1} = N_1 \cdot \frac{E_1}{(\mathrm{GeV})} \cdot 1.6022 \times 10^{-10}\mathrm{J}$$

$$E_{stored,2} = N_2 \cdot \frac{\Delta E}{(\mathrm{GeV})} \cdot 1.6022 \times 10^{-10}\mathrm{J}$$

- From $E_{stored,1} \geq E_{stored,2}$ we find:

$$\Delta E \leq E_1 \cdot \frac{N_1}{N_2}$$

Maximum Acceleration

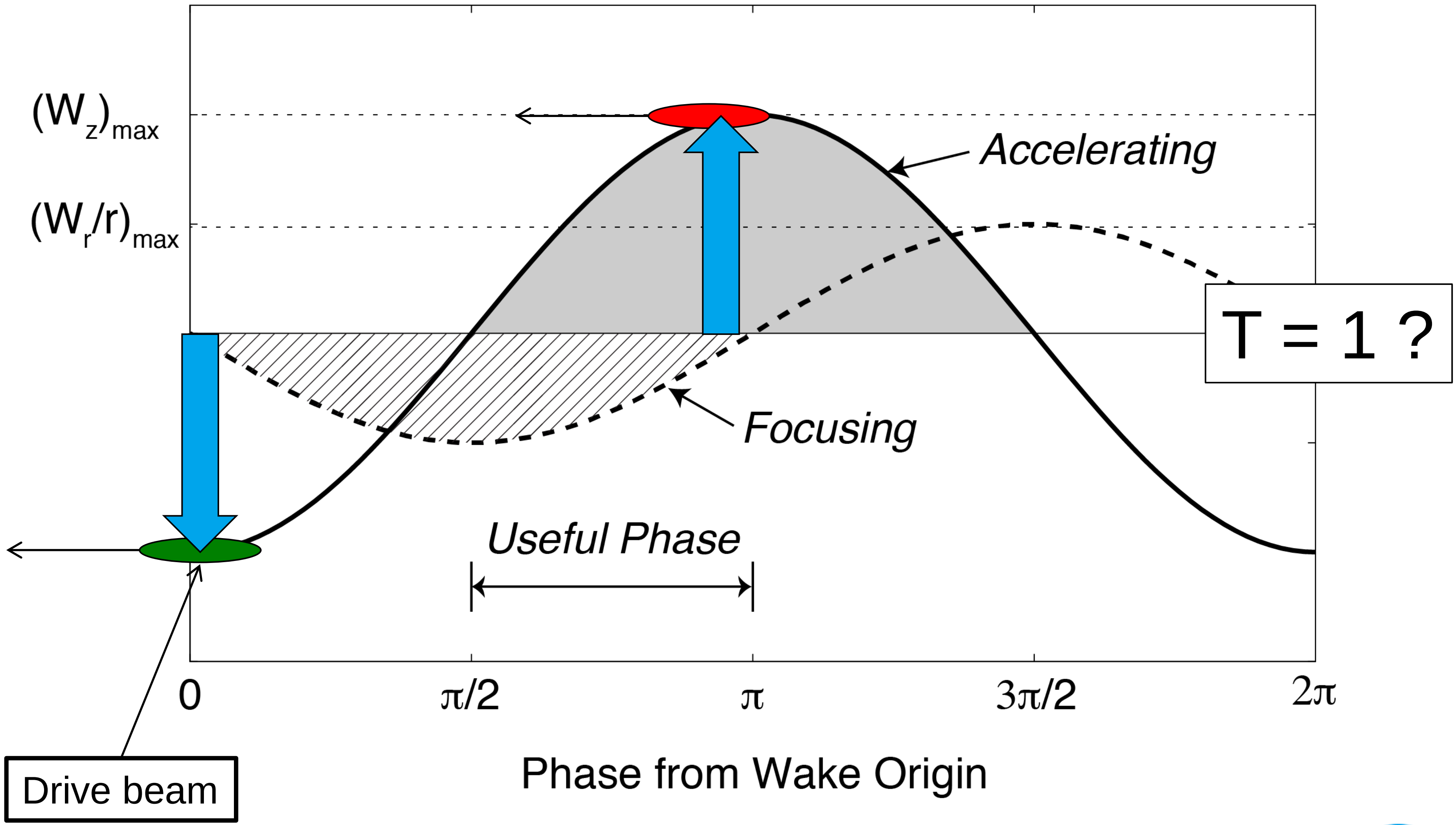
$$\Delta E \leq E_1 \cdot \frac{N_1}{N_2}$$

- Would be great. E.g. take a 1 GeV electron drive beam with 10^{11} electrons to accelerate 10^9 electrons by 100 GeV!
- This is, however, not possible in reality!
- Limited by **transformer ratio T** (short, symmetric bunches):

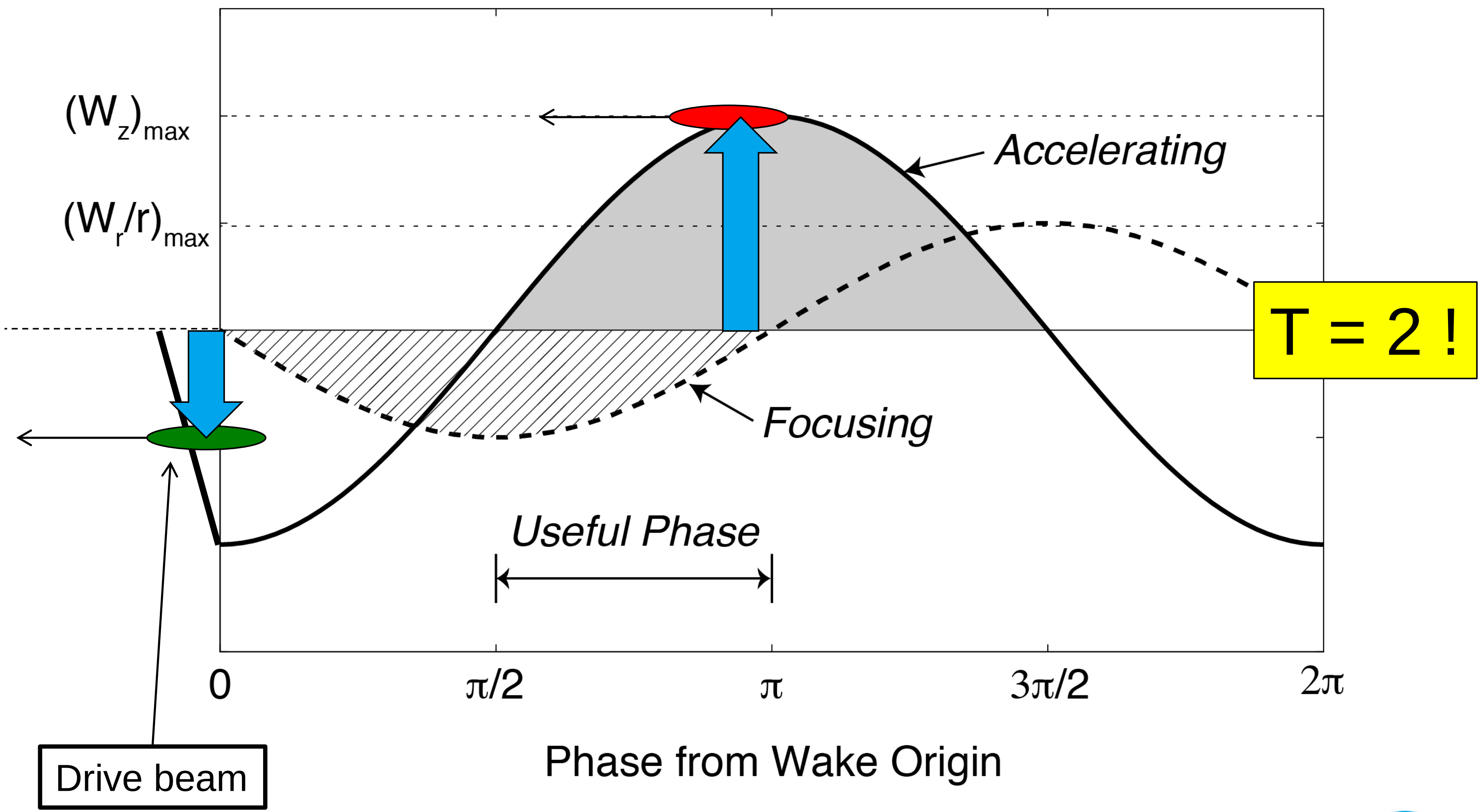
$$T = \left| \frac{\Delta E}{E_1} \right| = \left| \frac{\Delta E_{acc}}{\Delta E_{drive}} \right| \leq 2$$

Here it is assumed, drive beam looses all its energy

Transformer Ratio (Short Symmetric Bunches)

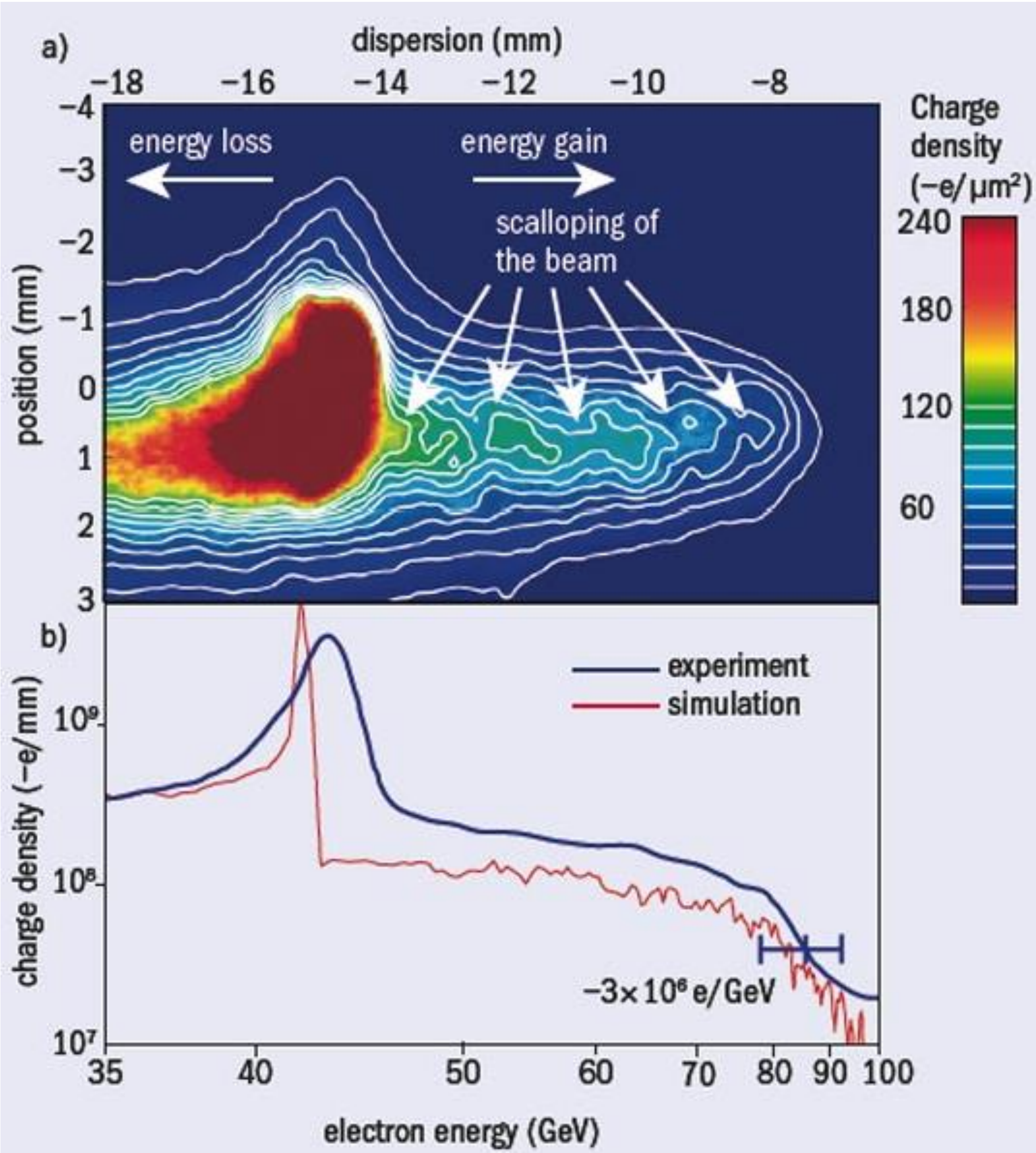


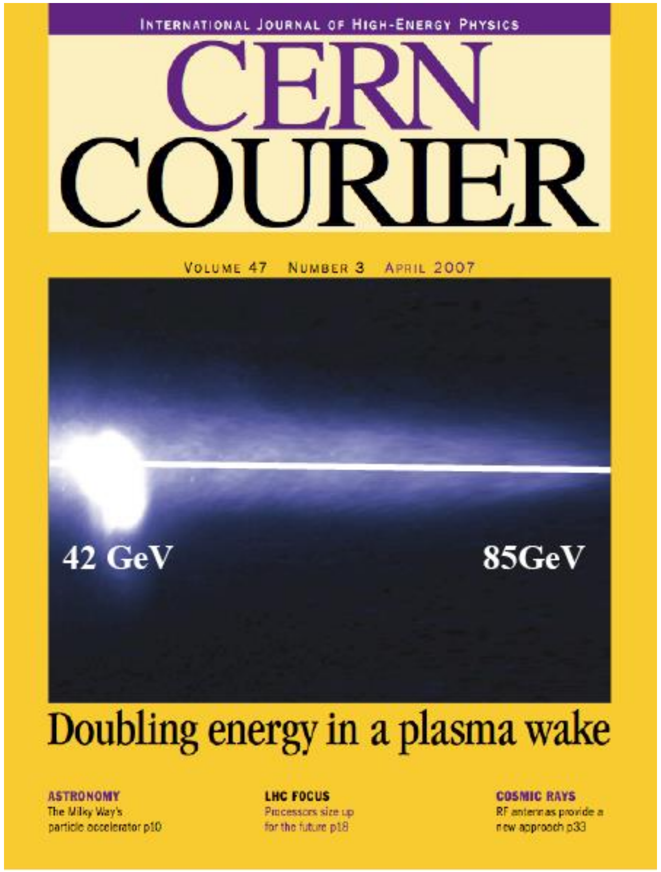
Transformer Ratio (Short Symmetric Bunches)



Head of driver sees no decelerating field

Record Acceleration: 42 GeV (beam-driven)





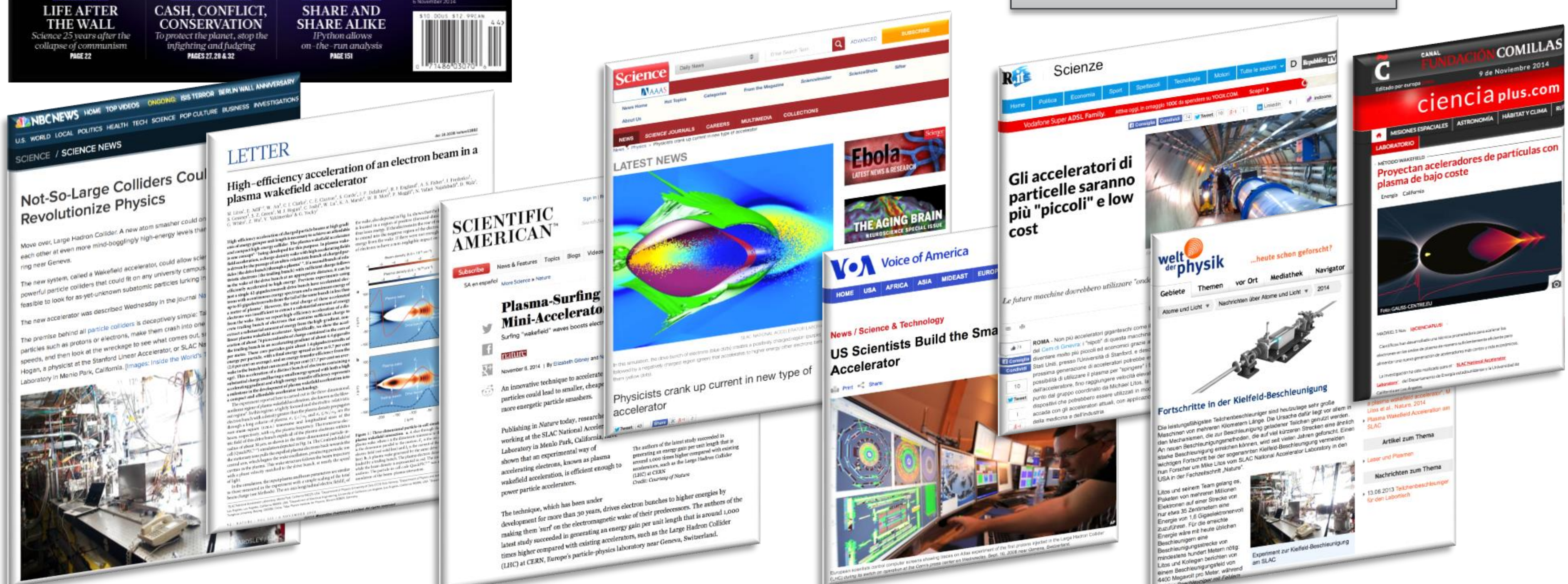
E167 collaboration
SLAC, UCLA, USC

I. Blumenfeld et al, Nature 445, p. 741 (2007)

FACET: *A National User Facility based on high-energy beams and their interaction with plasmas and lasers*

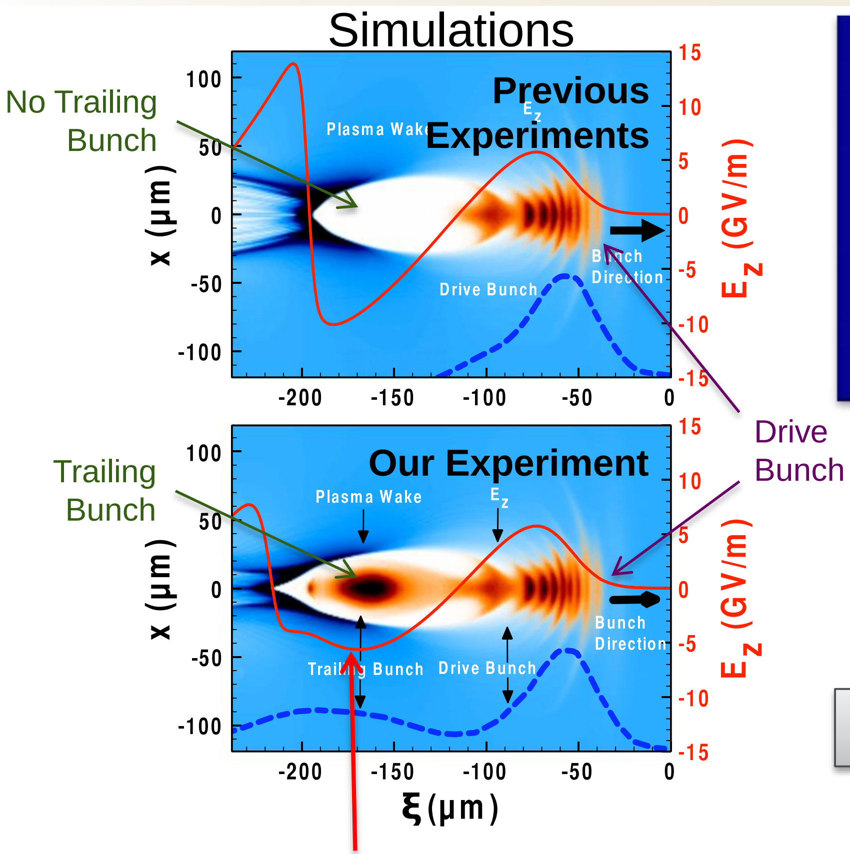
- Facility hosts more than 150 users, 25 experiments
- One high profile result a year
- Priorities balanced between focused plasma wakefield acceleration research and diverse user programs with ultra-high fields

Slide: V. Yakimenko

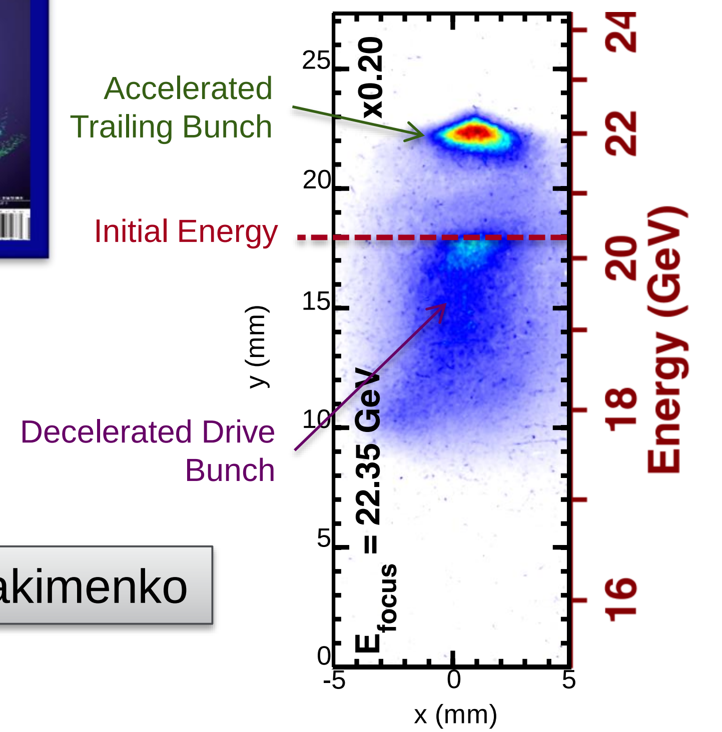


High-Efficiency Acceleration of an Electron Bunch in a Plasma Wakefield Accelerator

UCLA SLAC



Energetically Dispersed Beam After Plasma (**Data**)

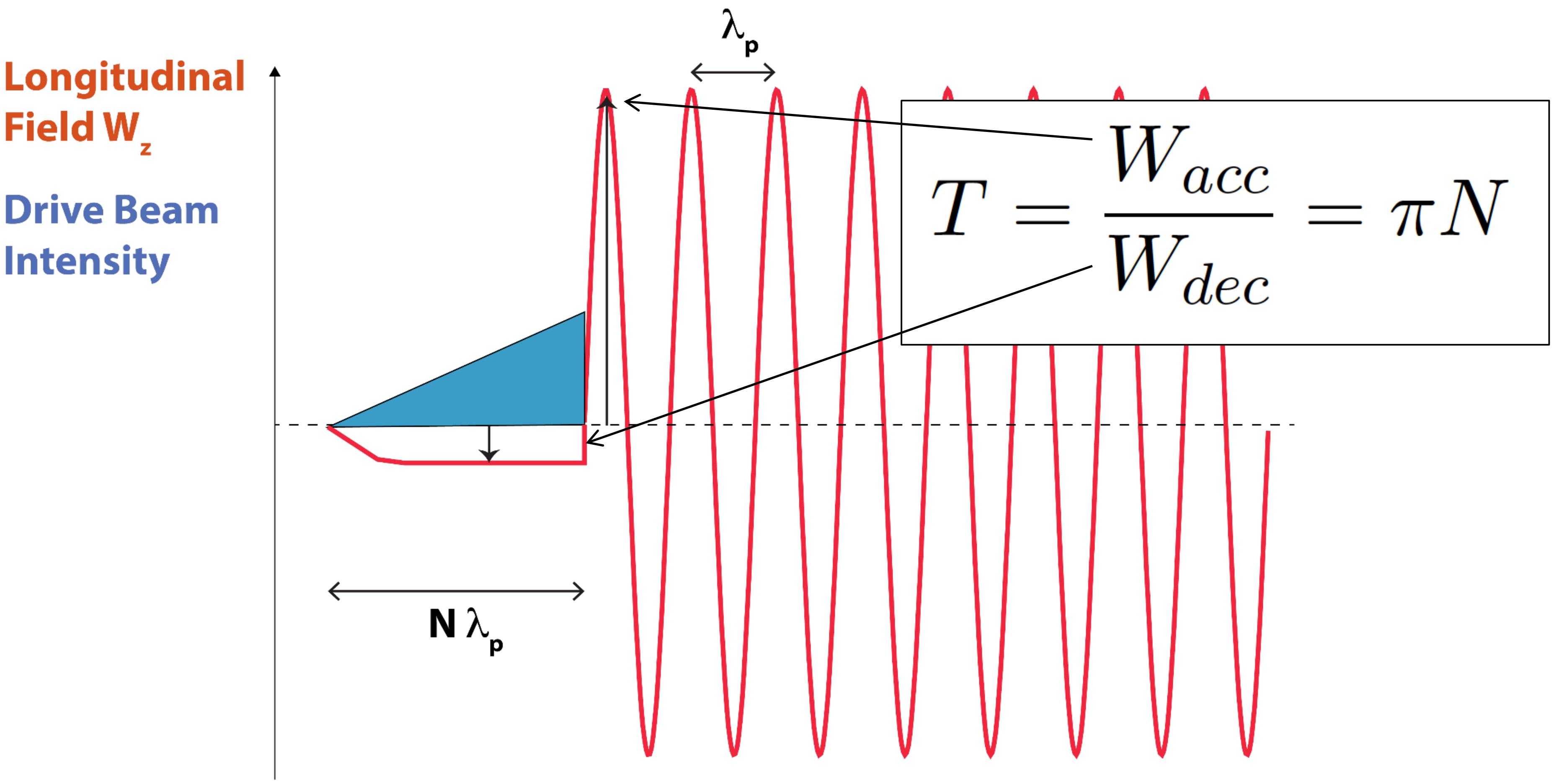


Slide: V. Yakimenko

- Electric field in plasma wake is loaded by presence of trailing bunch
- Allows efficient energy extraction from the plasma wake

This result is important for High Energy Physics applications that require very efficient high-gradient acceleration

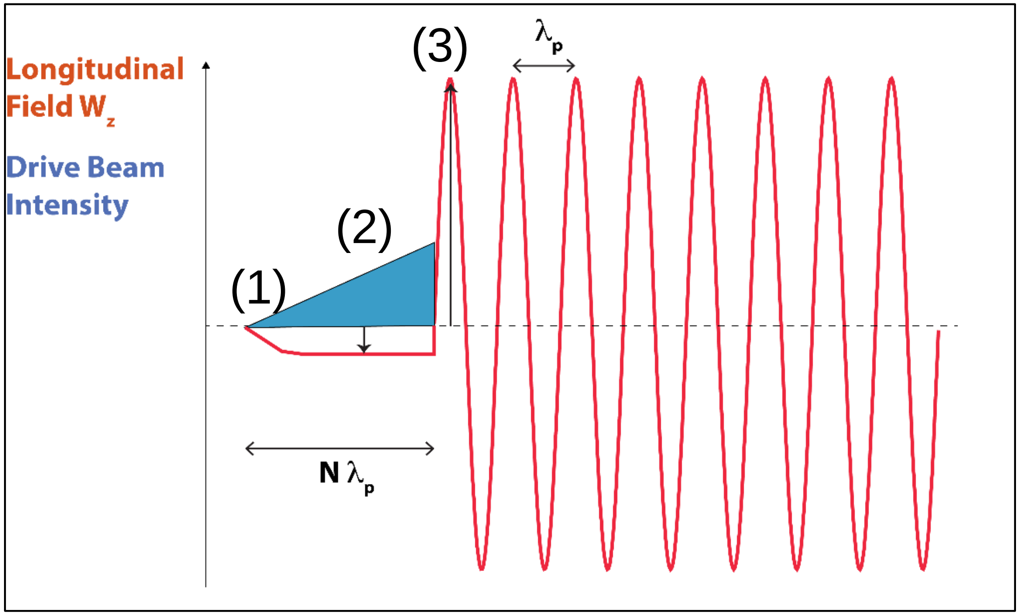
Increasing the Transformer Ratio



Physics of the Triangular Bunch Driver

(1) **Leading component** acts as precursor:

- Gives plasma electrons an impulse so that they flow out of the beam driver region with an increasing flux.
- End of precursor: depletion rate of plasma electrons is balanced by replacement rate of electrons in the drive bunch.



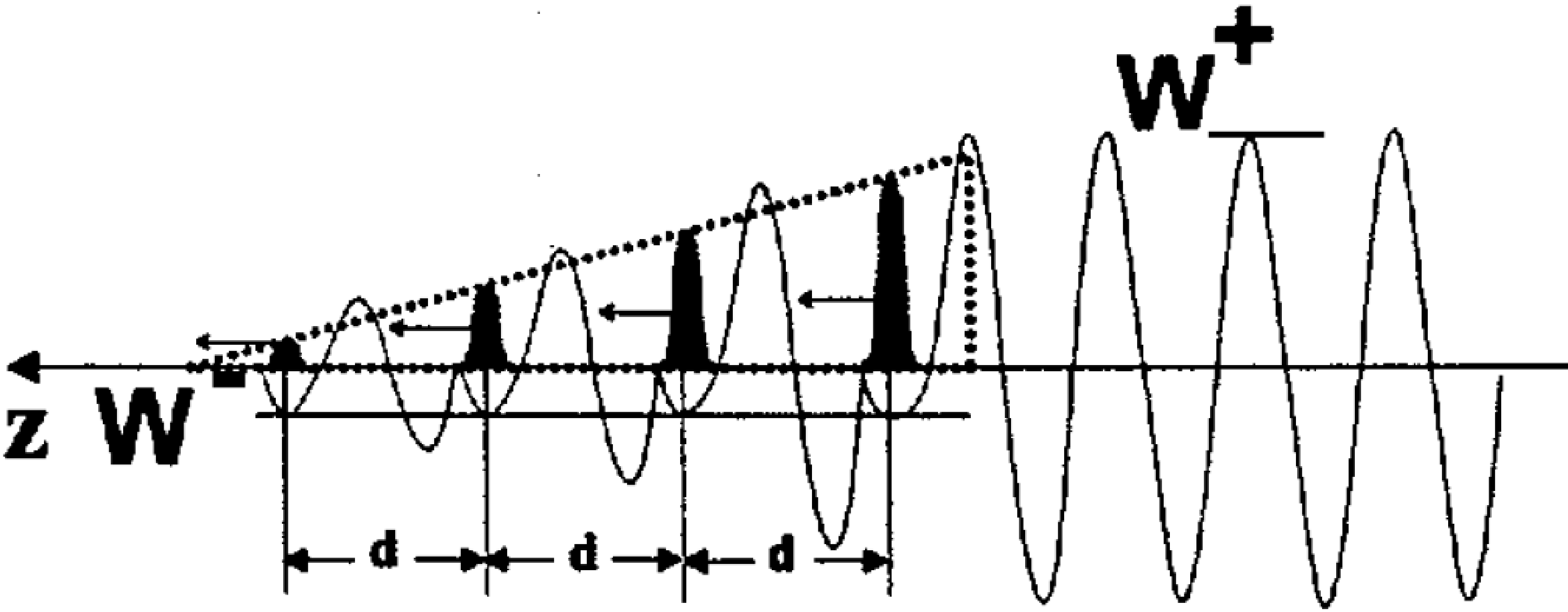
(2) **Long ramp component**:

- Charge neutrality is maintained. Same decelerating field maintained.

(3) **After driving bunch** (sharp edge):

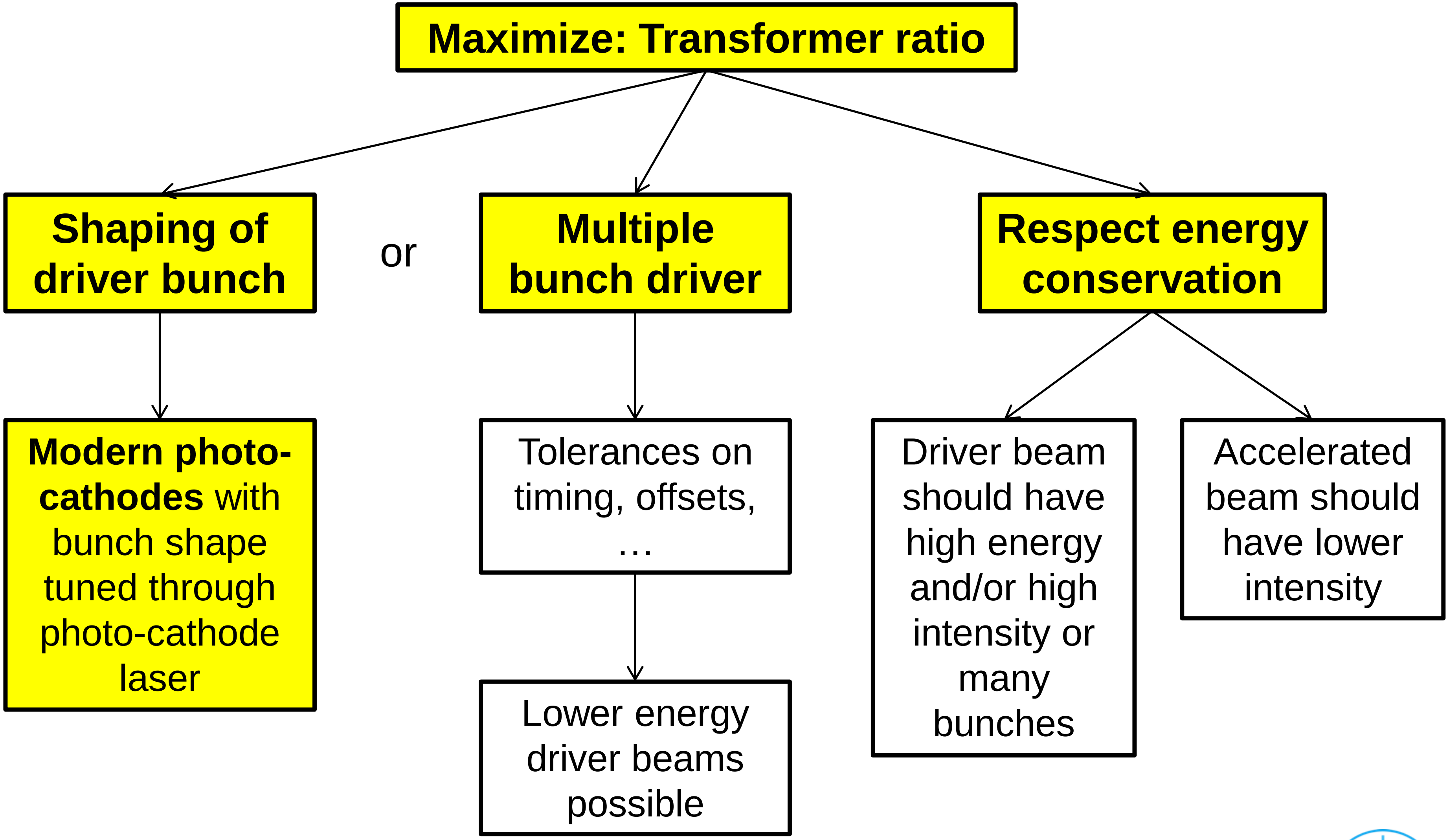
- Plasma channel becomes non-neutral.
- Plasma electrons are strongly attracted back to the ions and large scale plasma oscillations begin.

Alternative: Multi-bunch driven PWFA



Power et al, 2000

Optimization 4: Maximum Energy Gain



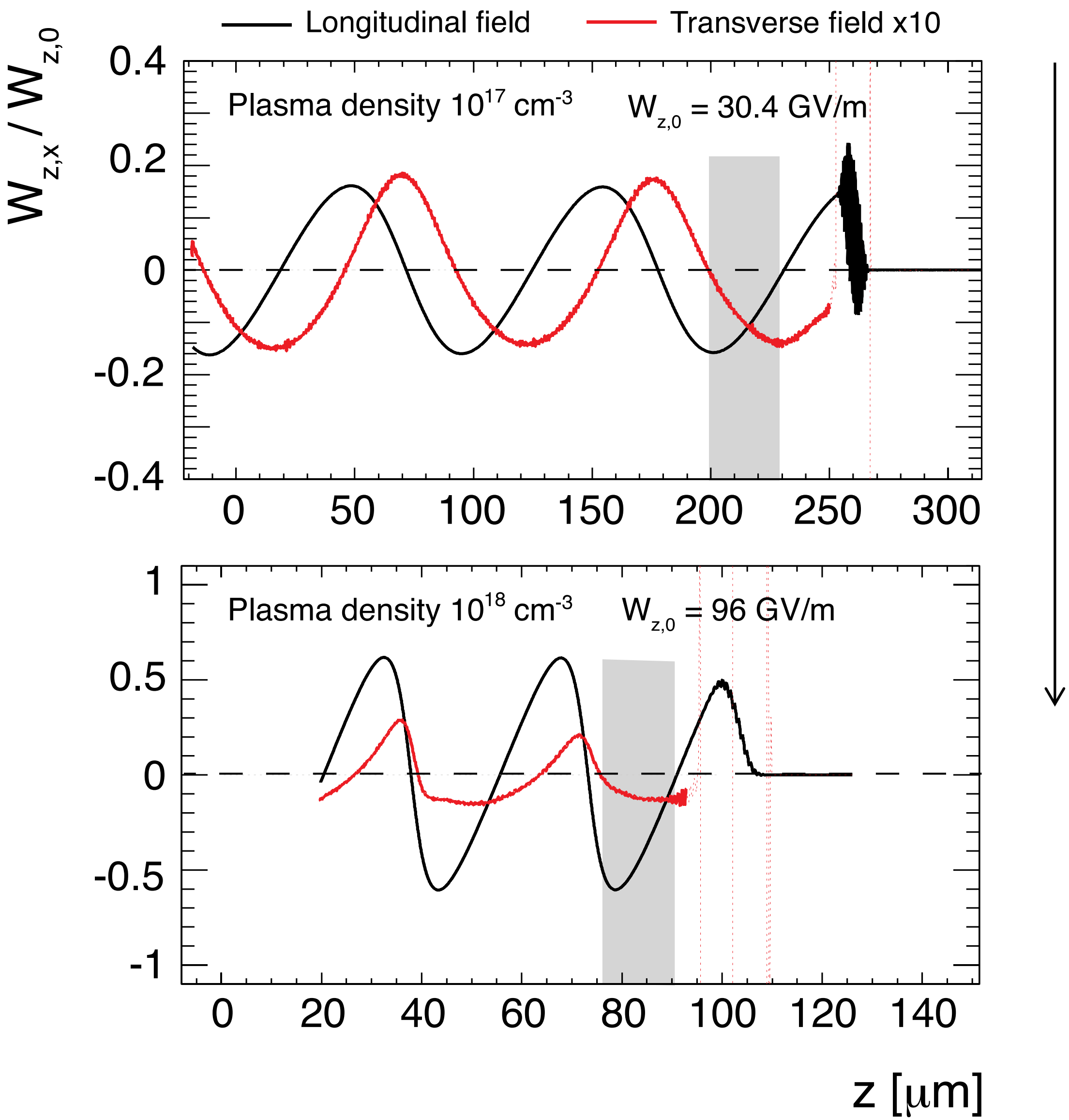
Content

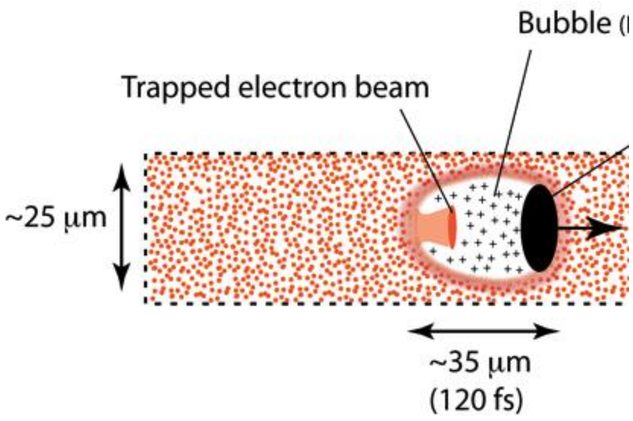
1. Accelerators – From Conventional Techniques to Plasmas
2. The Linear Regime
3. **The Non-Linear Regime**
4. Tolerances
5. Outlook for Europe

The Non-Linear Regime

- Blow-out and Non-Linear Regime
- Wave-Breaking as Limit to Maximum Energy Gain
- Self-injection in wave-breaking regime
- Hybrid Schemes → Trojan Horse

Fields Calculated with OSIRIS Code: Non-Linear Regime





Plasma Accelerator Physics I

- 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:

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

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

- 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 ω_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

- 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

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

$$\sigma_0 = \sqrt{\beta \varepsilon}$$

σ_0 = 1.3 μm for $\gamma\varepsilon$ = 0.3 μm

- 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 μm offset

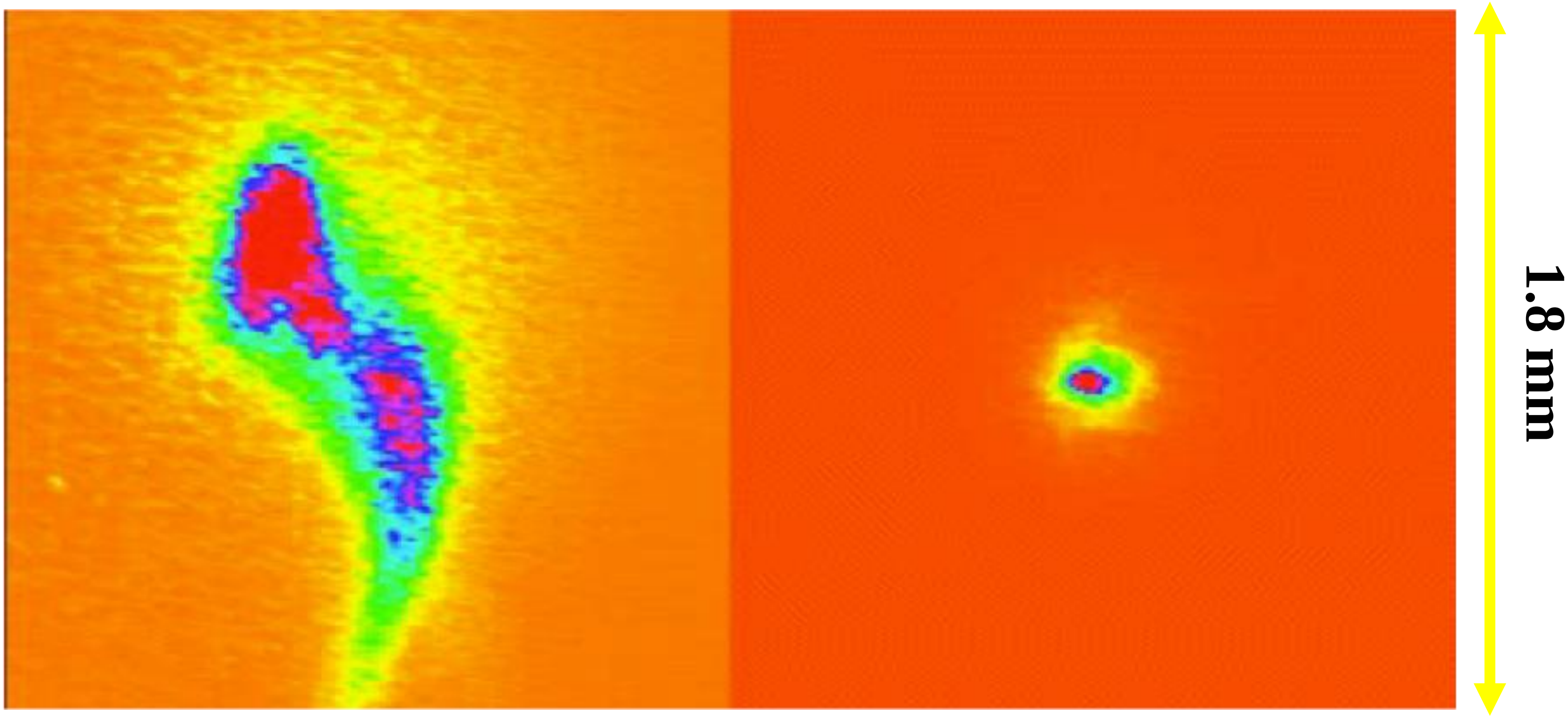
- Lower plasma density better: larger matched beam size, bigger tolerances.

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

Makes Things Difficult…

- Conventional acceleration structures:
  - Optimized to provide longitudinal acceleration and no transverse forces on the beam.
  - Due to imperfections, transverse forces can be induced. These "wakefields" caused major trouble to the first and only linear collider at SLAC.
- Plasma acceleration:
  - Ultra-strong longitudinal fields → high accelerating gradient.
  - Ultra-strong transverse fields → transverse forces cannot be avoided and must be controlled.
- For fun: A look at the SLAC linac beam before entering the plasma!

Seeing Electron Beam…



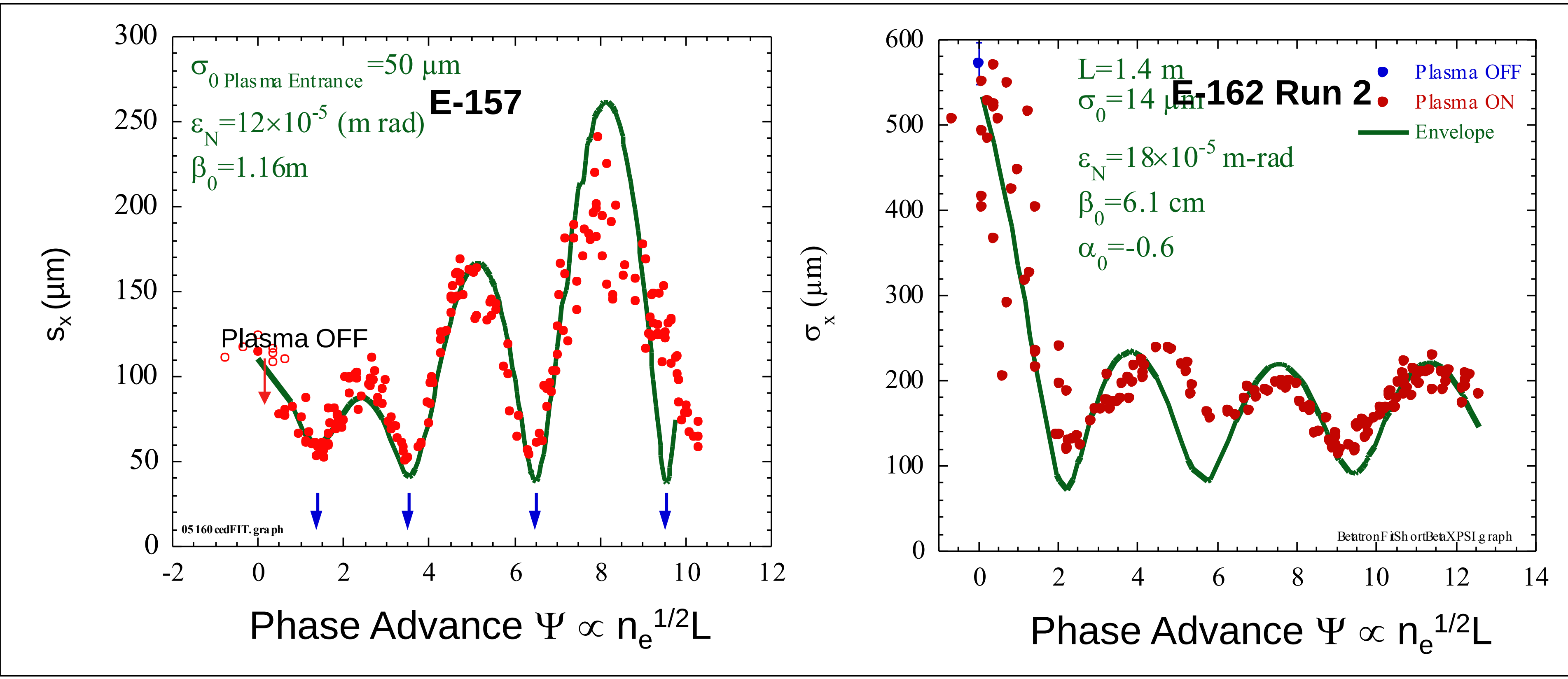
The transverse and longitudinally fields of the accelerator are set up to achieved small transverse beam sizes (right).

~ 2e10 electrons, 30 GeV

Beam Propagation Through A Long Plasma

• Smaller "matched" beam size at the plasma entrance reduces amplitude of the betatron oscillations measured at the OTR downstream of the plasma

• Allows stable propagation through long plasmas (> 1 meter)



C. E. Clayton et al., PRL 1/2002

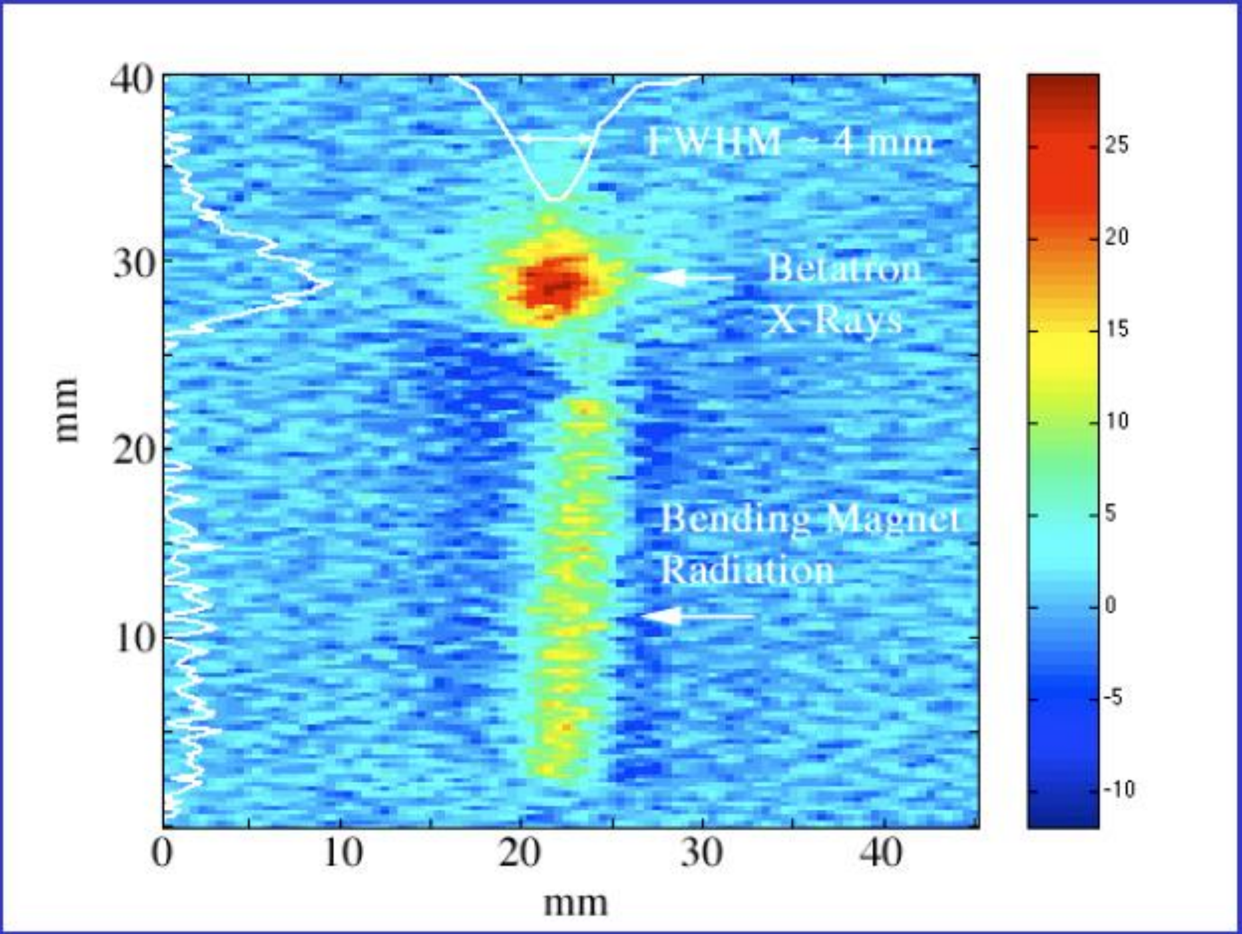
E-157/E-162 collaboration

Stanford Linear Accelerator Center

Betatron Radiation of X-rays

UCLA USC

Plasma focusing strength of 6000T/m acts as a strong undulator



- Peak brightness ~ 10^{19} photons/sec-mm^2-mrad^2-.1%bw!

Wave Breaking

Water velocity becomes larger than phase velocity of the wave

→ **Wave is breaking…**

Dawson 1959: if plasma modeled with one-dimensional sheets, then wave breaking equivalent to crossing of neighboring sheets.

Wavebreaking Limit

- Dawson 1959: if plasma modeled with one-dimensional sheets, then **wave breaking equivalent to crossing of neighboring sheets**.
- Non-relativistic wavebreaking field E_0:

$$W_z = 96 \ \frac{\mathrm{V}}{\mathrm{m}} \cdot \sqrt{\frac{n_0}{\mathrm{cm}^{-3}}}$$

Wave Breaking in Plasma Wakefields

- Relativistic wavebreaking: **capturing of electrons with velocity close to phase velocity of plasma wave → absorption of energy in plasma wave**.
- Relativistic wavebreaking field (**higher fields than E_0 are possible**):

$$E_{\mathrm{WB}} = \sqrt{2}(\gamma_p - 1)^{1/2} E_0$$

$$\gamma_p = (1 - v_p^2/c^2)^{-1/2}$$

- Thermal electron effects lead to reduction in wavebreaking field. Physics: A large fraction of the electron distribution will become trapped in the plasma wave → wave breaks.

Trapped in the Breaking Wave

Using the Trapped Electrons

Appl. Phys. B 74, 355–361 (2002)
DOI: 10.1007/s003400200795

Applied Physics B
Lasers and Optics

Laser wake field acceleration: the highly non-linear broken-wave regime

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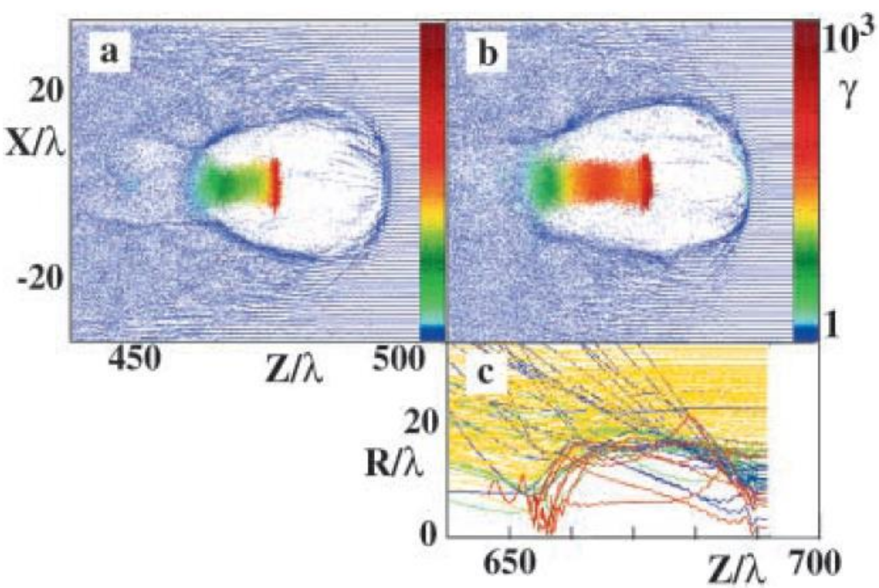
J. MEYER-TER-VEHN[2]

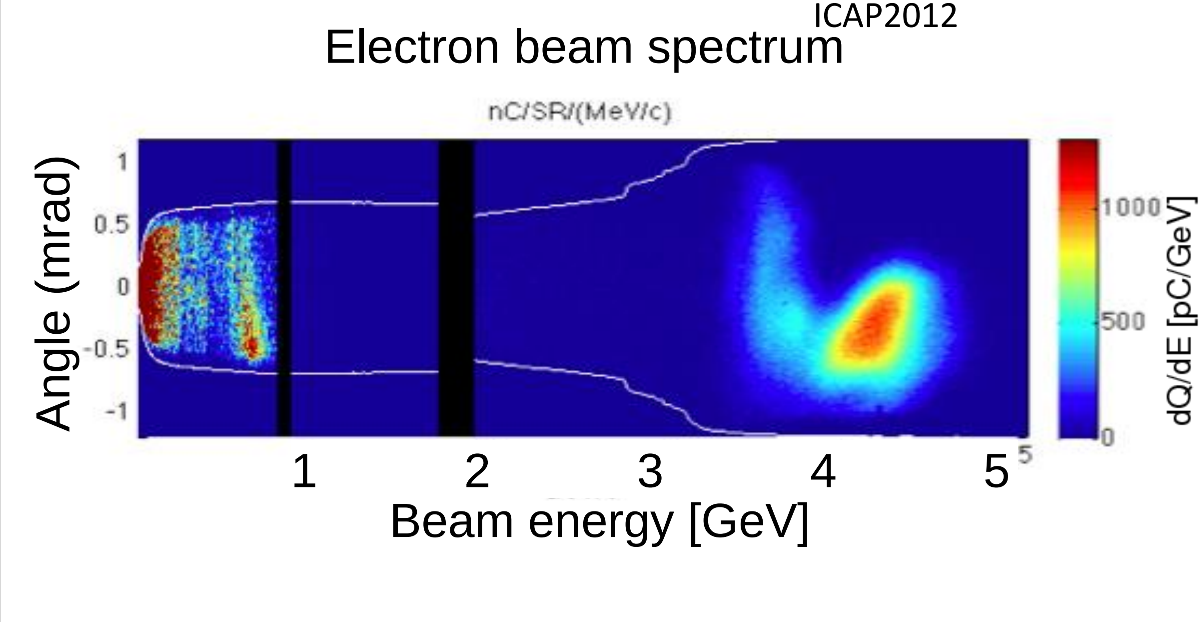
[1] Institut für Theoretische Physik I, Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany
[2] Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching, Germany

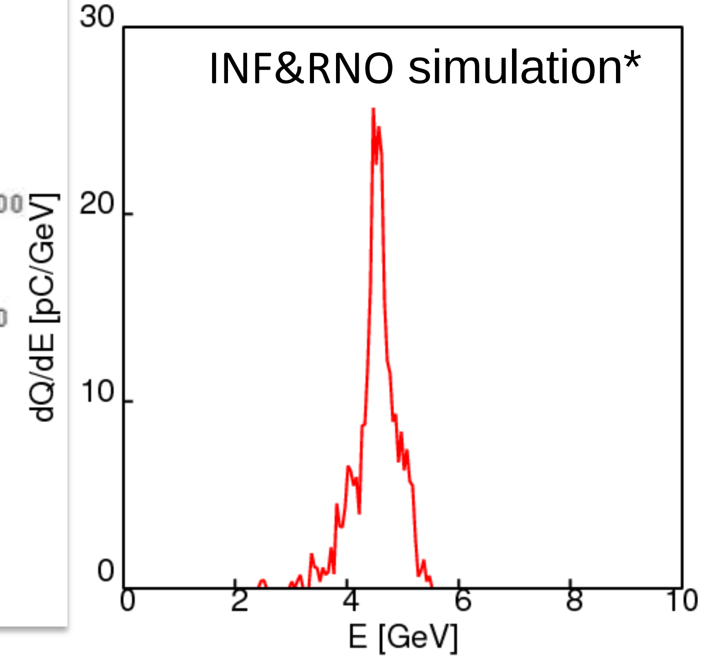


Pukhov, ter-Vehn 2002

4.25 GeV beams have been obtained from 9 cm plasma channel powered by 310 TW laser pulses **(15 J)**

*C. Benedetti et al., proceedings of AAC2010, proceedings of ICAP2012





Slide: W. Leemans

- **Laser** (E=15 J):
  - Measured longitudinal profile (T_0= 40 fs)
  - Measured far field mode (w_0=53 μm)
- **Plasma:** parabolic plasma channel (length 9 cm, n_0~6x10^{17} cm^{-3})

	Exp.	Sim.
Energy	4.25 GeV	4.5 GeV
ΔE/E	5%	3.2%
Charge	~20 pC	23 pC
Divergence	0.3 mrad	0.6 mrad

W.P. Leemans et al.,PRL 2014, in print

Bringing in the Trojan Horse

The Hybrid Scheme (Trojan Horse)

PRL **108,** 035001 (2012) PHYSICAL REVIEW LETTERS week ending 20 JANUARY 2012

Ultracold Electron Bunch Generation via Plasma Photocathode Emission and Acceleration in a Beam-Driven Plasma Blowout

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[2]*Institut für Laser- und Plasmaphysik, Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany*
[3]*Tech-X Corporation, Boulder, Colorado 80303, USA*

(Received 30 March 2011; published 17 January 2012)

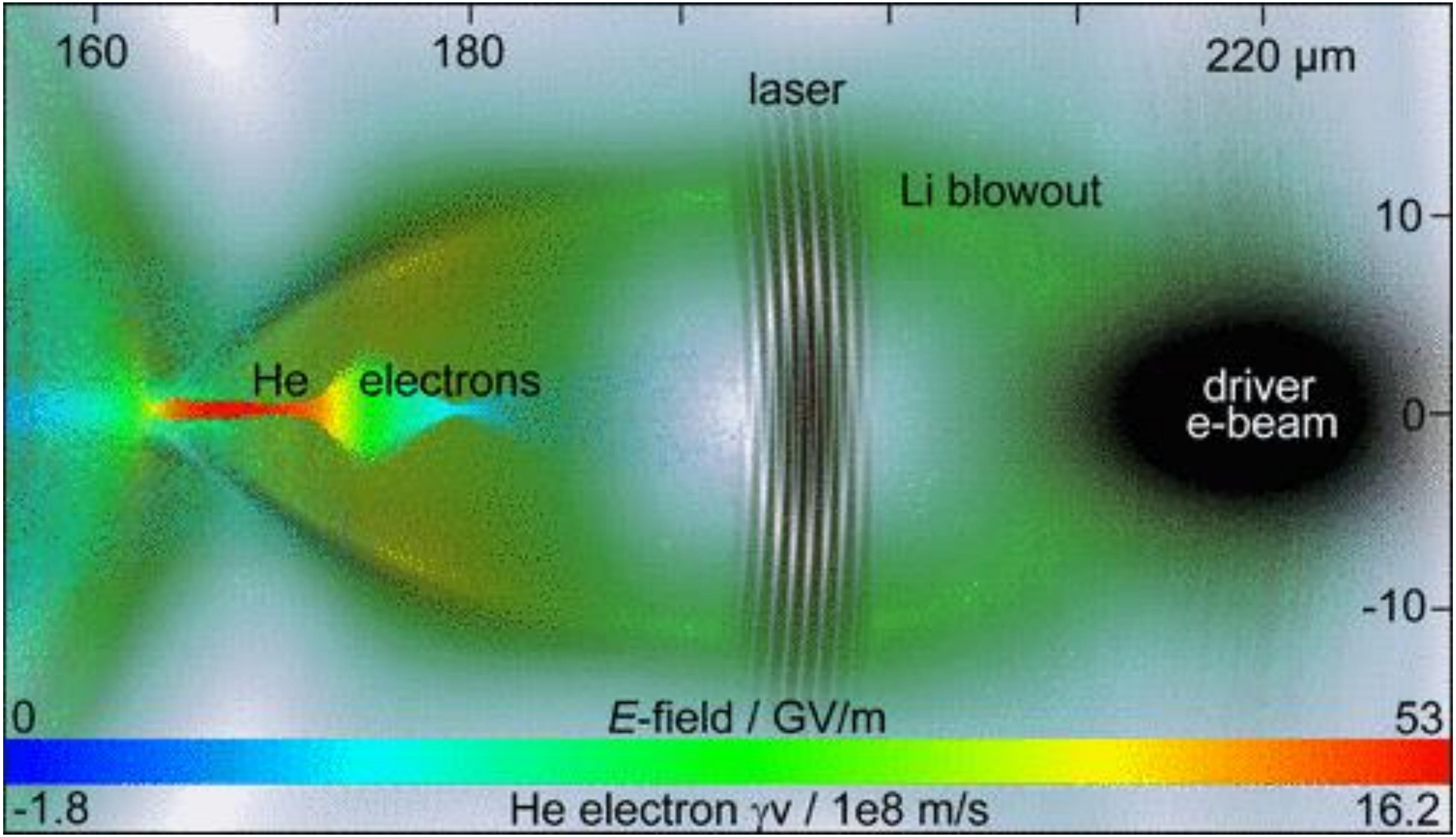
Beam-driven plasma wakefield acceleration using low-ionization-threshold gas such as Li

+

Laser-controlled electron injection via ionization of high-ionization-threshold gas such as He.

He electrons are released with low transverse momentum in the focus of the copropagating, non-relativistic intensity laser pulse directly inside the accelerating or focusing phase of the Li blowout → **generation of sub-μm-size, ultralow-emittance, highly tunable electron bunches**.

Sketch (Hidding et al, 2012)



Other approaches being studied, e.g. injection on the plasma density ramp

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Accelerator Builder’s Challenge *(simplified to typical values)*

- Match into/out of plasma with **beam size ≈1 μm** (about 1 mm beta function). Adiabatic matching (Whittum, 1989).
- Control **offsets** between the wakefield driver (laser or beam) and the accelerated electron bunch at **1 μm level**.
- Use **short bunches (few fs)** to minimize energy spread.
- Achieve **synchronization stability of few fs** from injected electron bunch to wakefield (energy stability and spread).
- Control the **charge and beam loading** to compensate energy spread (idea Simon van der Meer).
- Develop and demonstrate **user readiness of a 5 GeV plasma accelerated beam**.

Relax conditions…

- As low as possible plasma densities to start in most simple conditions. Larger matched beam size, relaxed tolerances, …
- The success will be all in accuracy, tolerances, precision! We mastered this in conventional accelerators.
- Do the same for plasma accelerators!

Content

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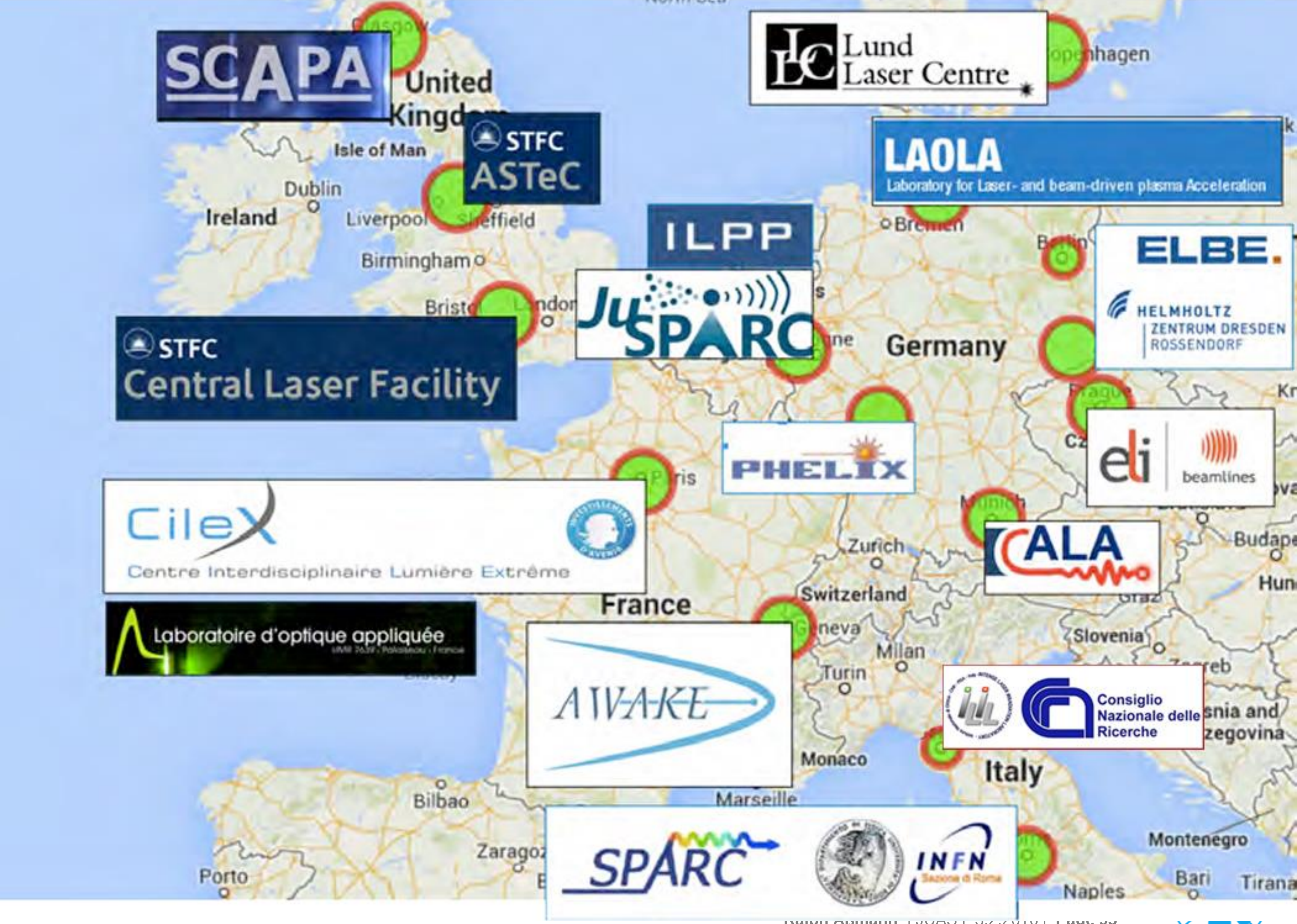
5. **Outlook for Europe**

Intensive work in Europe...

EAAC 2015

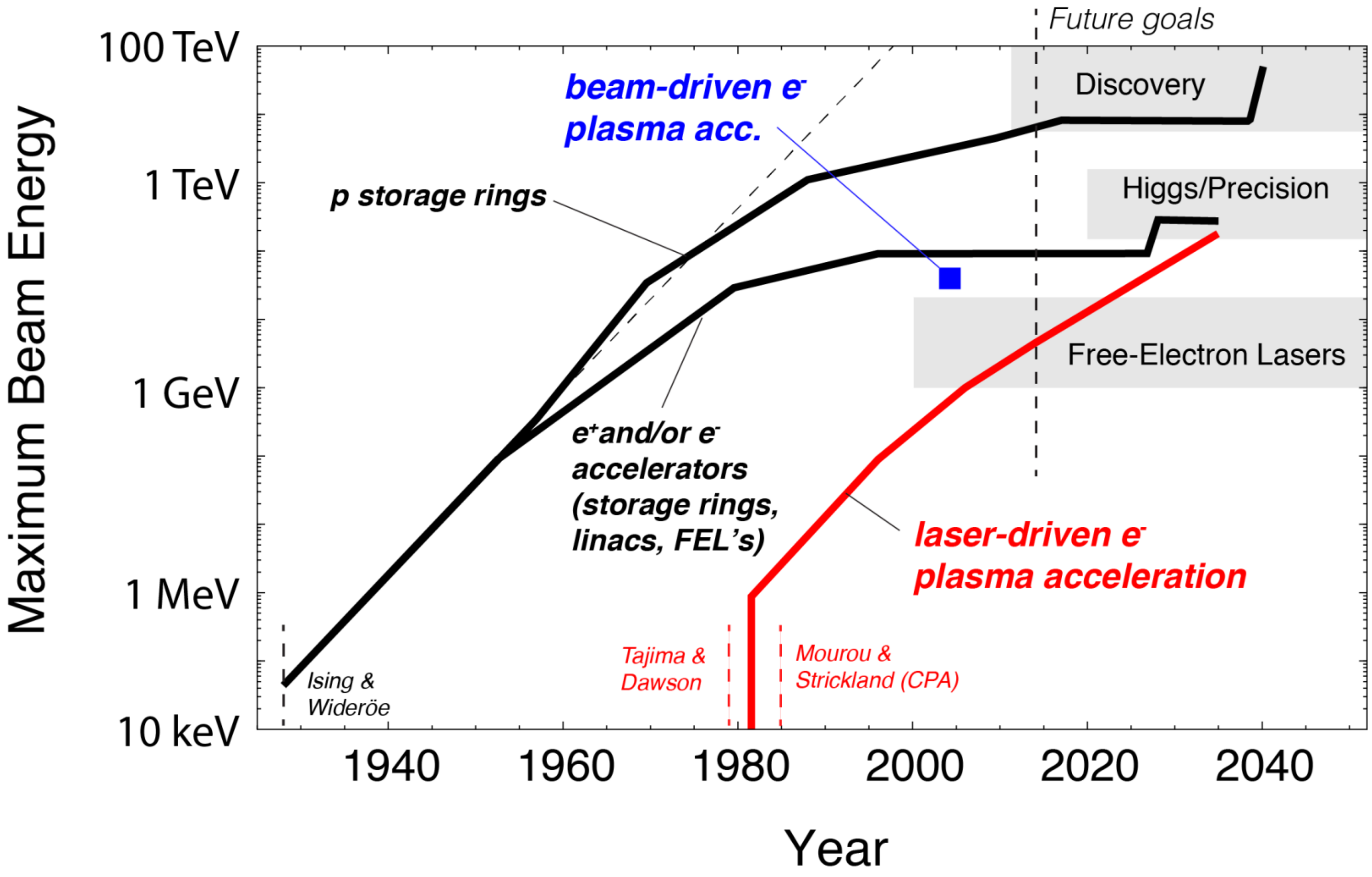
2nd EUROPEAN ADVANCED ACCELERATOR CONCEPTS WORKSHOP
13-19 SEPTEMBER 2015 *LA BIODOLA - ISOLA D'ELBA - ITALY*

- 258 registered participants + about 50 accompanying persons.
- 45 sponsored students.
- Participants from 23 countries in 4 continents (11 EU member states).
- 16 % female participation.

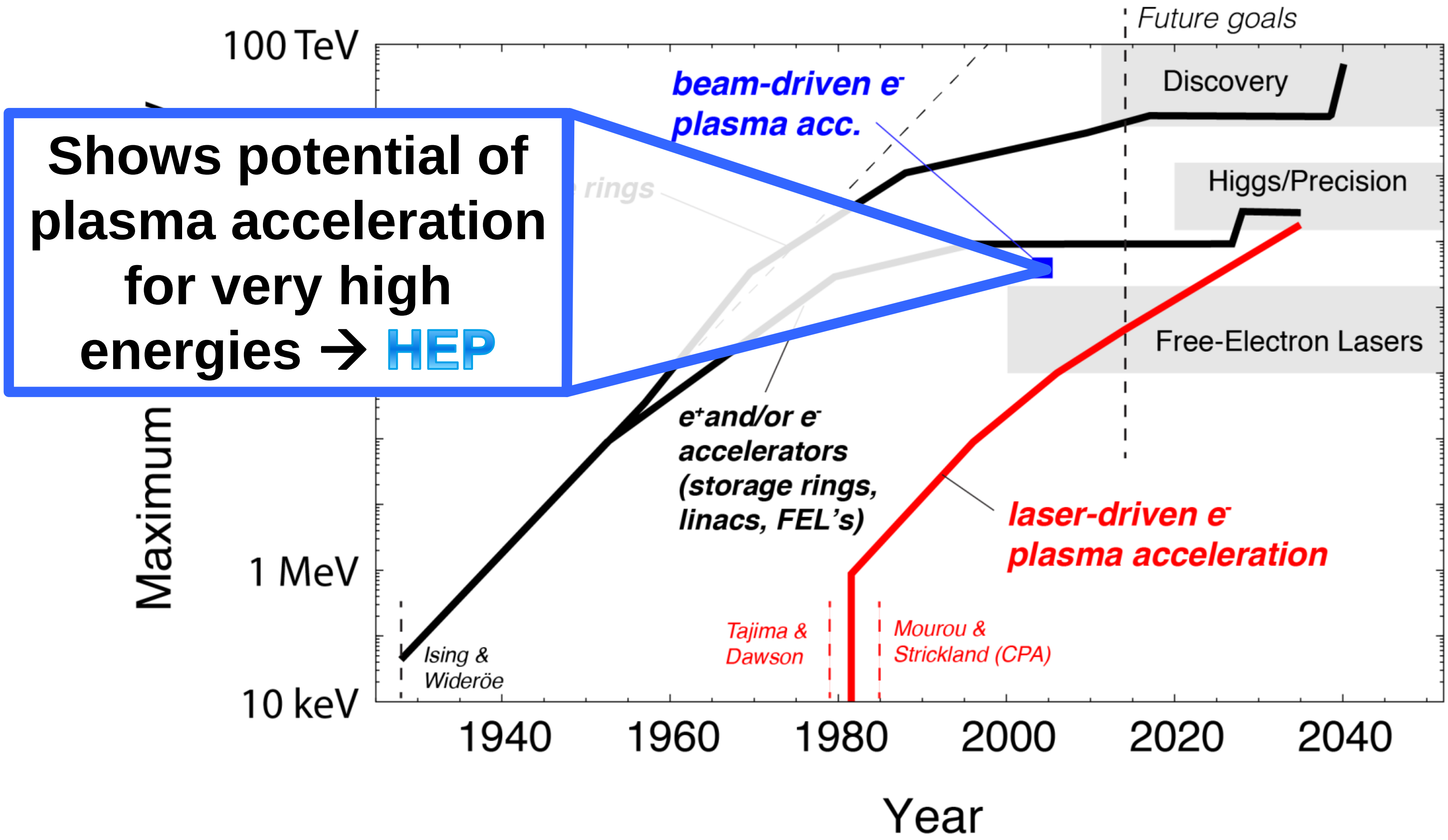


SCAPA
United Kingdom
Isle of Man
Dublin
Ireland
Liverpool
Sheffield
Birmingham
Bristol
STFC ASTeC
STFC Central Laser Facility
Lund Laser Centre
LAOLA
Laboratory for Laser- and beam-driven plasma Acceleration
ILPP
JuSPARC
Germany
ELBE.
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF
eli beamlines
PHELIX
CALA
CileX
Centre Interdisciplinaire Lumière Extrême
Laboratoire d'optique appliquée
France
Zurich
Switzerland
Milan
Turin
Slovenia
AWAKE
Consiglio Nazionale delle Ricerche
Monaco
Italy
Bilbao
Marseille
Zaragoza
Porto
SPARC
INFN
Montenegro
Bari
Naples

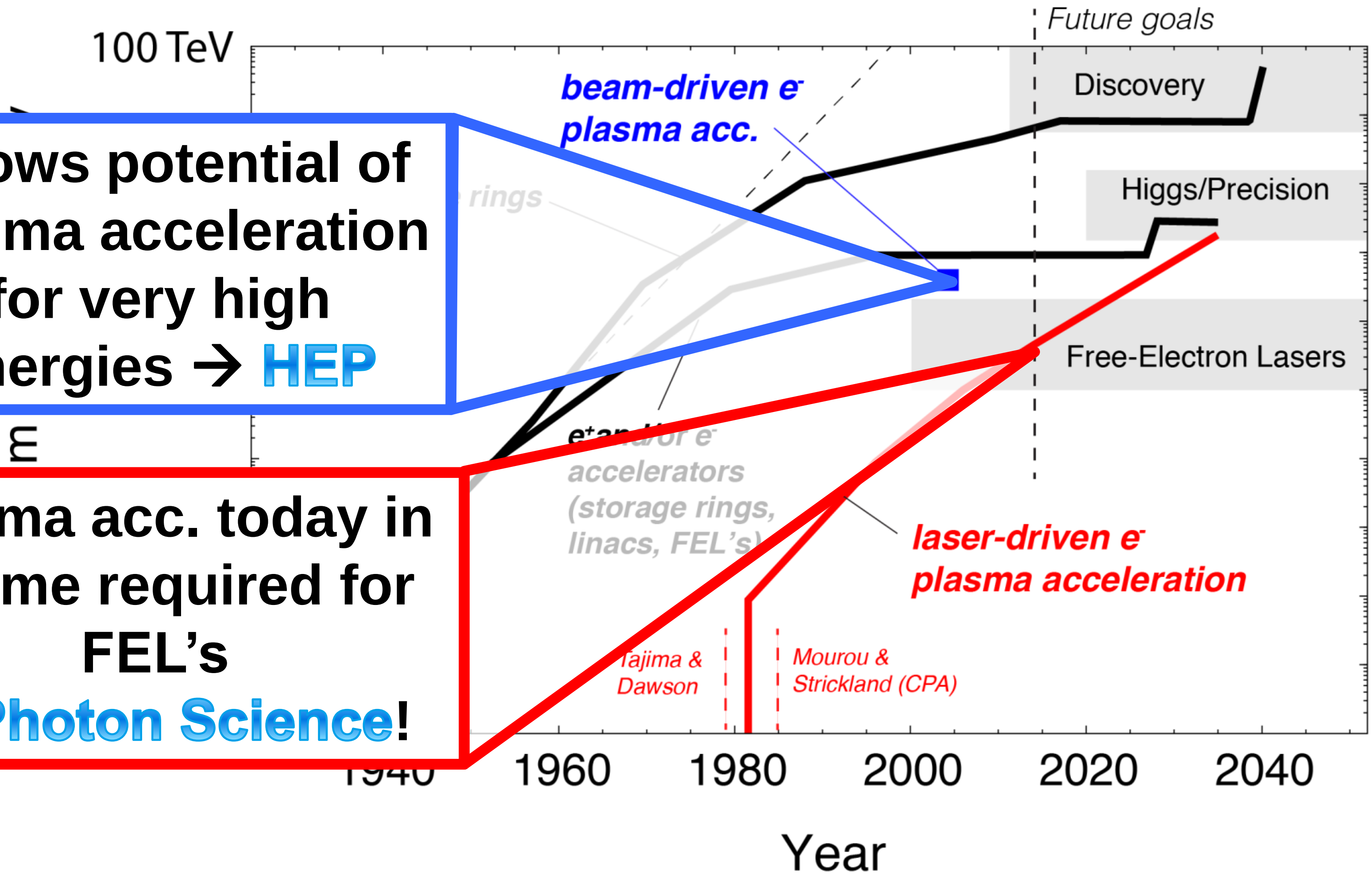
Livingston and Accelerators at the Energy Frontier



Livingston and Accelerators at the Energy Frontier



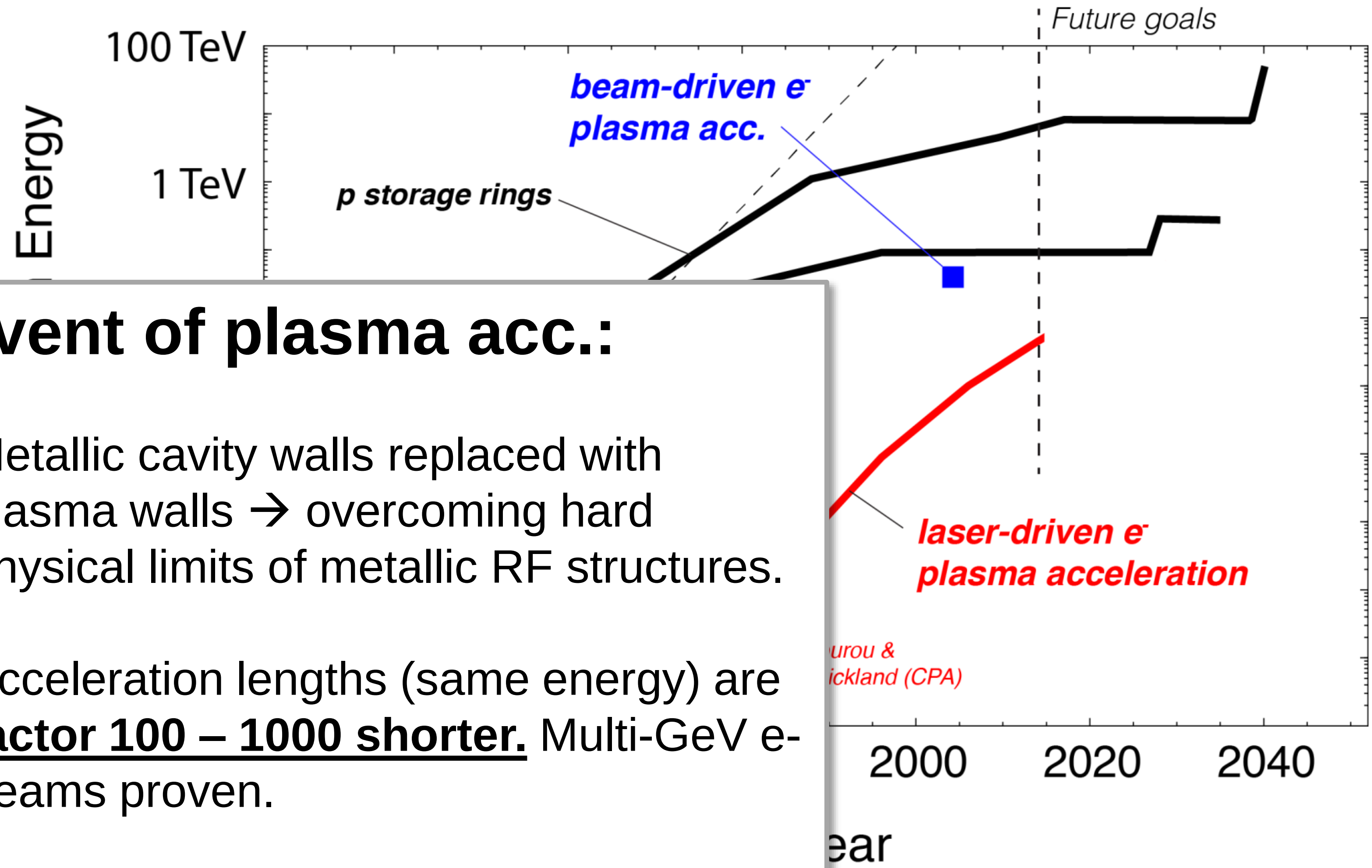
Livingston and Accelerators at the Energy Frontier



Shows potential of plasma acceleration for very high energies → HEP

Plasma acc. today in regime required for FEL's → Photon Science!

Livingston and Accelerators at the Energy Frontier



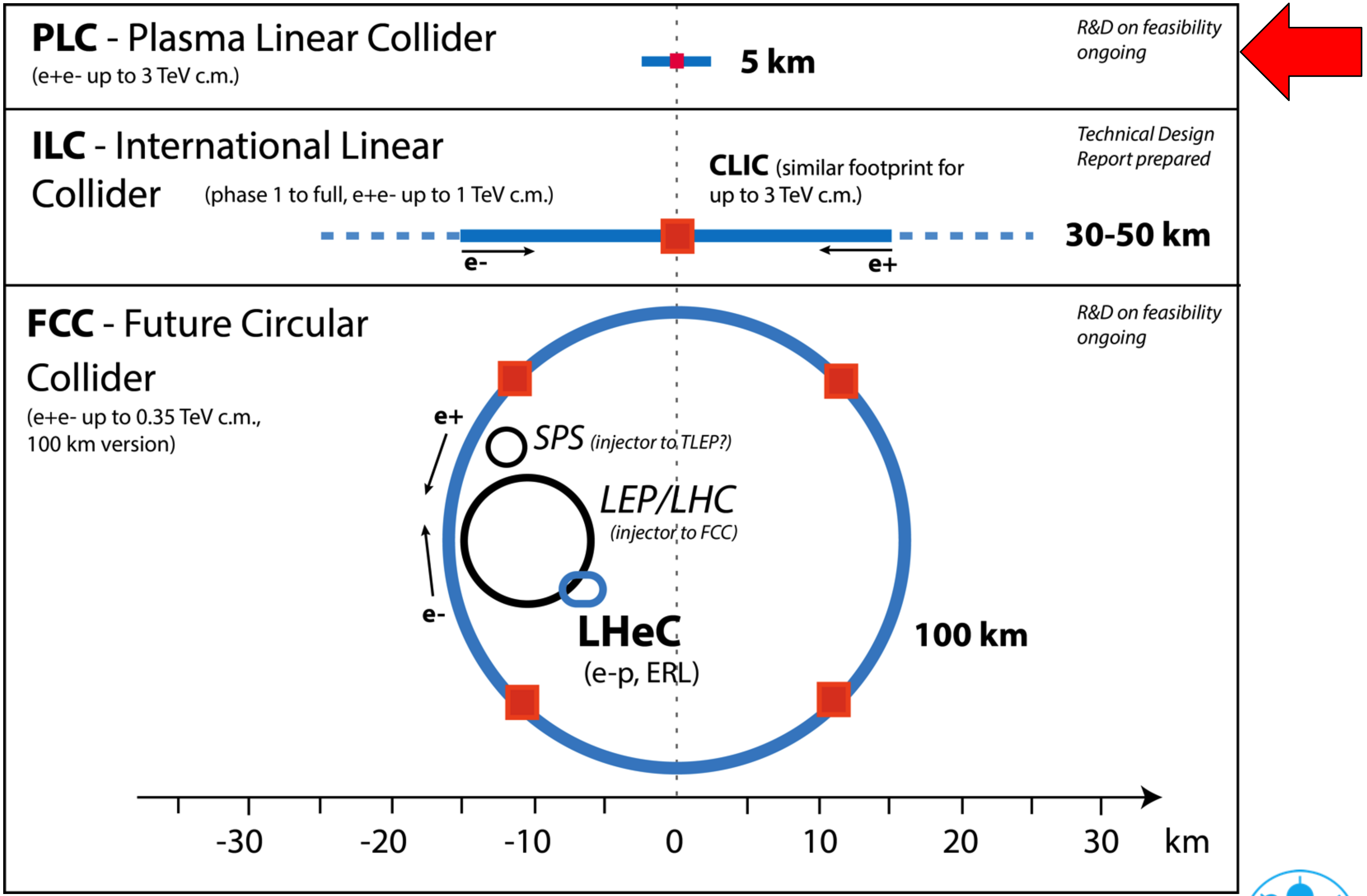
Advent of plasma acc.:

1. Metallic cavity walls replaced with plasma walls → overcoming hard physical limits of metallic RF structures.

2. Acceleration lengths (same energy) are **factor 100 – 1000 shorter.** Multi-GeV e-beams proven.

3. Still short-comings but **no fundamental limit**.

Small is Beautiful!? Is it?



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http://eupraxia-project.eu

NOVEL FUNDAMENTAL RESEARCH

COMPACT EUROPEAN PLASMA ACCELERATOR WITH SUPERIOR BEAM QUALITY

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OUR TECHNOLOGY

EuPRAXIA brings together novel acceleration schemes, modern lasers, the latest correction technologies and large-scale user areas.

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PARTICIPANTS

A consortium of 16 laboratories and universities from 5 EU member states has formed to produce a conceptual design report.

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WORK PACKAGES

The project is structured into 14 work packages of which 8 are included into the EU design study.

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MANAGEMENT

The management bodies will organise, lead and control the project's activities and make sure that objectives are met

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OPENING NEW HORIZONS

EUPRAXIA IS A LARGE RESEARCH INFRASTRUCTURE BEYOND THE CAPABILITIES OF A SINGLE LAB

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IST-ID Associação do Instituto Superior Técnico para a Investigação e Desenvolvimento

MANCHESTER 1824 The University of Manchester

INFN

UNIVERSITY OF LIVERPOOL

ENEA Italian National Agency for New Technologies, Energy and Sustainable Economic Development

UNIVERSITY OF OXFORD

SAPIENZA UNIVERSITÀ DI ROMA

University of Strathclyde Glasgow

Imperial College London

UHH Universität Hamburg

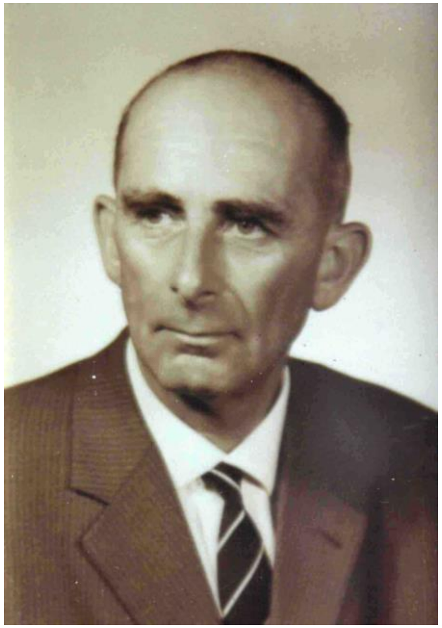
Science & Technology Facilities Council

plus 18 associated partner institutes

COMPACT EUROPEAN PLASMA ACCELERATOR WITH SUPERIOR BEAM QUALITY

Design report for a 5 GeV facility by end of 2019, including science case for pilot users, cost and site study. Second design study ("plan B") after FCC/EuroCirCol.

Wideröe 1992 at age 90



After all, **plans can only be made for those accelerators which can realistically be built with the means available, and obviously, these means are limited**.

Ideas are not subject to any such considerations. The **limitations are set only by the intellect of human beings themselves**.

The **theoretical possibilities** with regard to accelerating particles by electromagnetic means (i.e. within the scope of the Maxwell equations which have been known since the 19th century), **are nowhere near being exhausted**, and technology surprises us almost daily with innovations which in turn allow us to broach new trains of thought.

…there are yet **more fundamental breakthroughs** to be made. They could allow us to advance to **energies unimaginable today**.

Thank you for your attention…