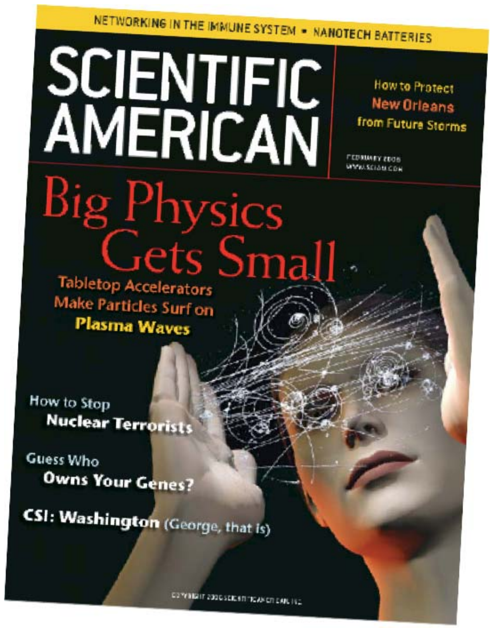
Beam Propagation

effects and parameters of the accelerated beam



R.W. Aßmann

Leading Scientist DESY

CAS

Plasma Acceleration

CERN, 27.11.2014

Accelerator Research and Development
ARD
A program by the Helmholtz association

HELMHOLTZ | ASSOCIATION

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

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!

Governed by Maxwell's Equations

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0} \qquad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \cdot \mathbf{B} = 0 \qquad \nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \epsilon_0 \mu_0 \frac{\partial \mathbf{E}}{\partial t}$$

$$\begin{aligned}
\mathbf{E} &= \text{Electrical field intensity} \\
\mathbf{B} &= \text{Magnetic flux density} \\
\mathbf{J} &= \text{Total current density} \\
\rho &= \text{Total charge density} \\
\mu_0 &= \text{Permeability of free space} \\
\epsilon_0 &= \text{Permittivity of free space}
\end{aligned}$$

Very few acceleration issues require quantum mechanics (e.g. spin polarization).

Lorentz Force F

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

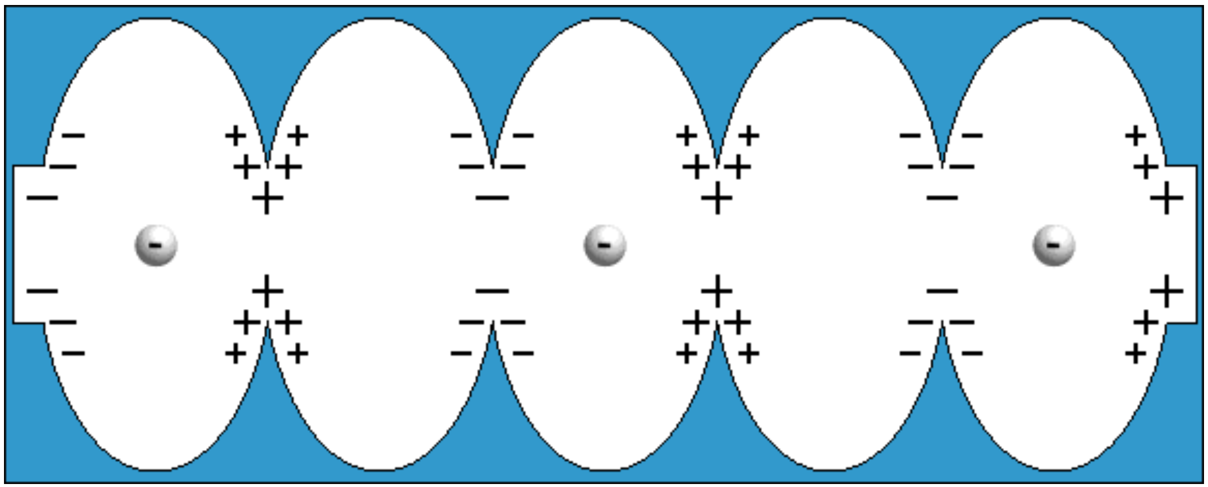
$$q = \text{Charge}$$
$$\mathbf{v} = \text{Velocity}$$

Longitudinal electrical field to accelerate a particle

Transverse magnetic field to guide a particle

RF Acceleration in Metallic Structures

Courtesy N. Walker



Courtesy Padamse, Tigner

From Ising's and Wideröe's start to 21st century RF technology.

"Runzelröhre"

- Ising's and Wideröe's scheme: Metallic structures are filled with oscillating, longit. e.m. fields.
- Charged **particles sit at the crest of the induced longitudinal voltage and are accelerated**. One passage → linac. Many passages → storage ring.
- Metallic walls can be super-conducting or room-temperature, RF fields can have different frequencies.

High Gradient – High Frequency – Small Dimensions

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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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

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W band	75 to 110	> 1000	0.2 – 0.1	Advanced acceleration schemes with ultra high gradients and very short cell lengths.

Plasma acceleration in the > W band

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.

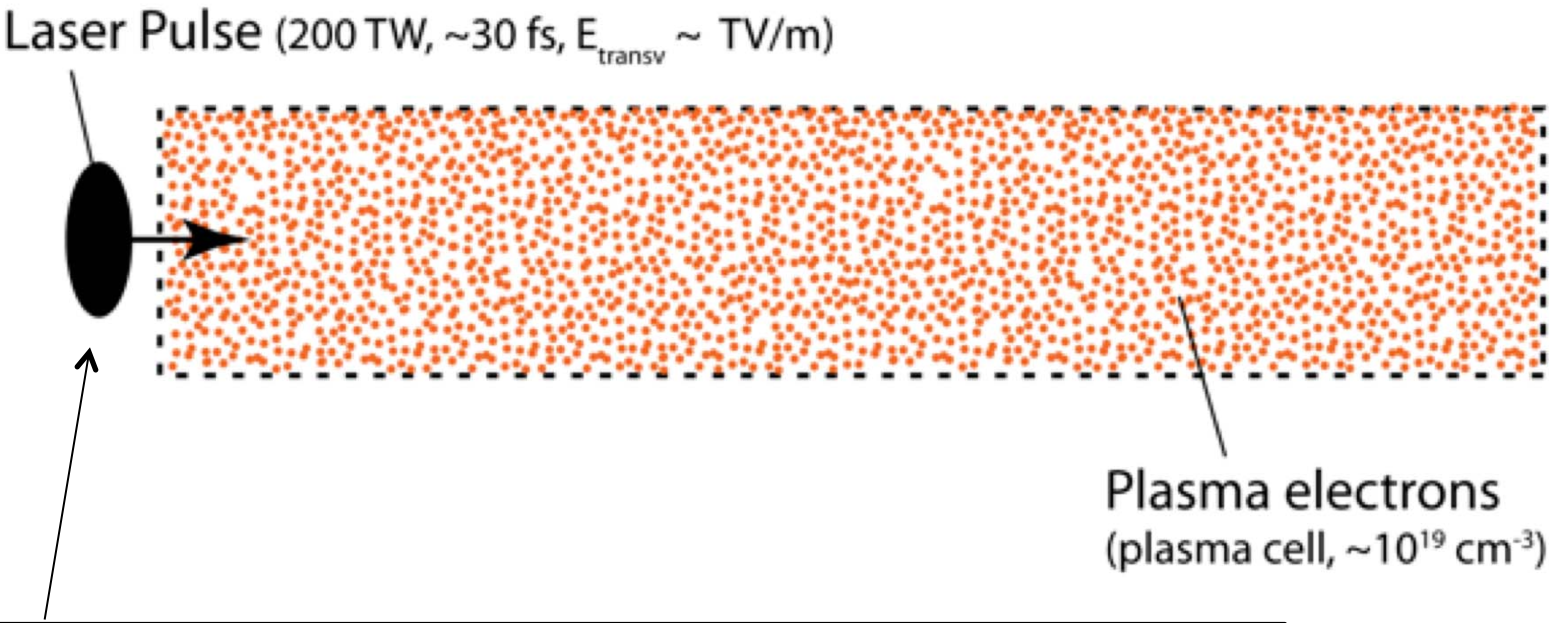
Collective plasma accelerators have recently received considerable theoretical and experimental investigation. Earlier Fermi[1] and McMillan[2] considered cosmic-ray particle acceleration by moving magnetic fields[1] or electromagnetic waves.[2] In terms of the realizable laboratory technology for collective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

the wavelength of the plasma waves in the wake:

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

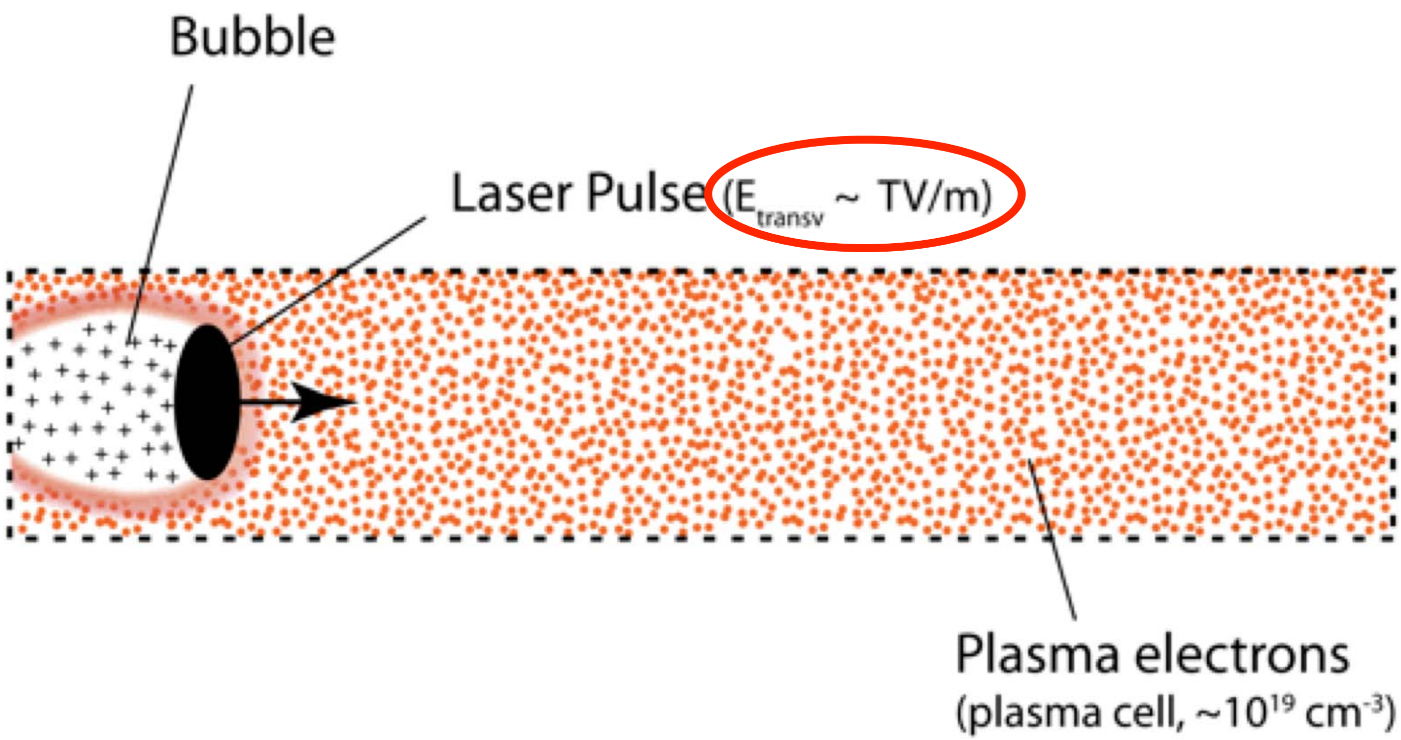
An alternative way of exciting the plasmon is to inject two laser beams with slightly different frequencies (with frequency difference $\Delta\omega \sim \omega_p$) so that the beat distance of the packet becomes

Reminder: 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).

Reminder: Plasma-Acceleration (Internal Injection)



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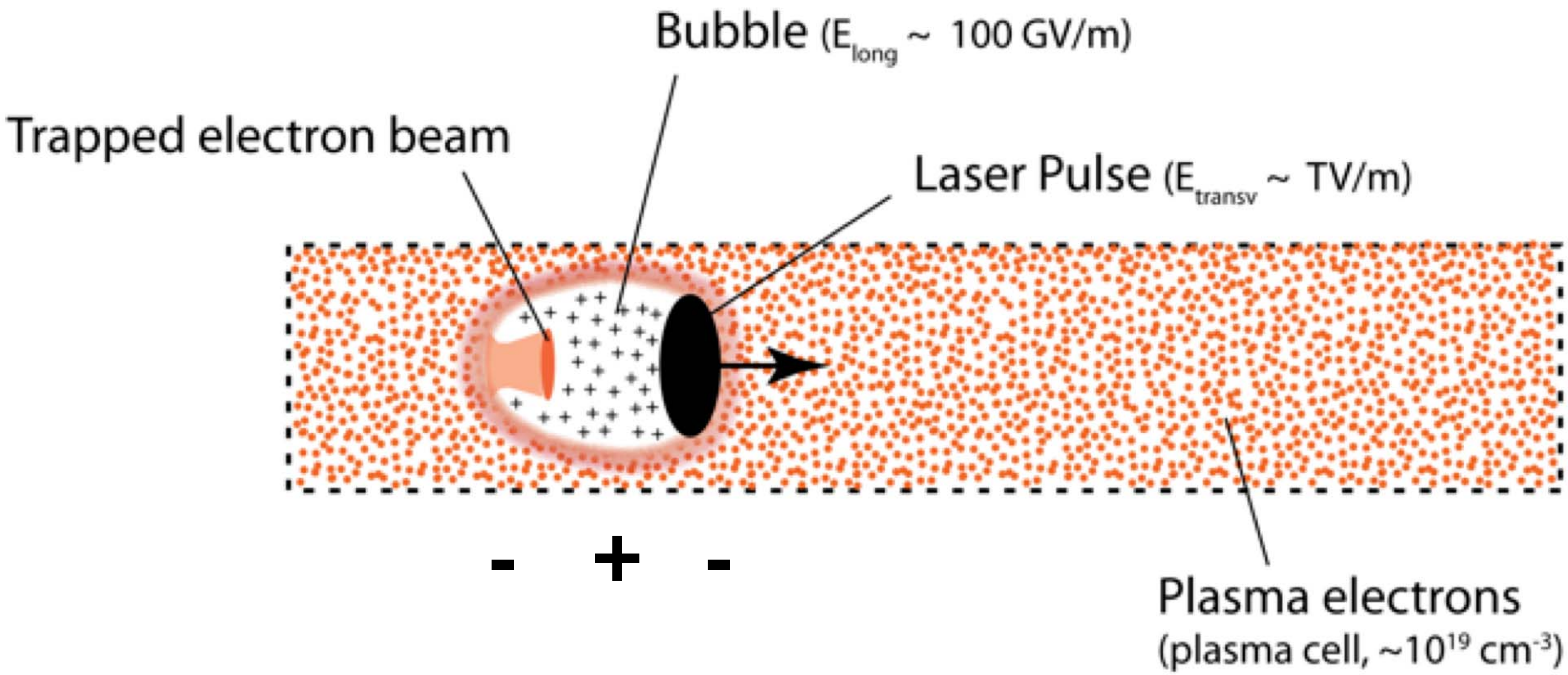

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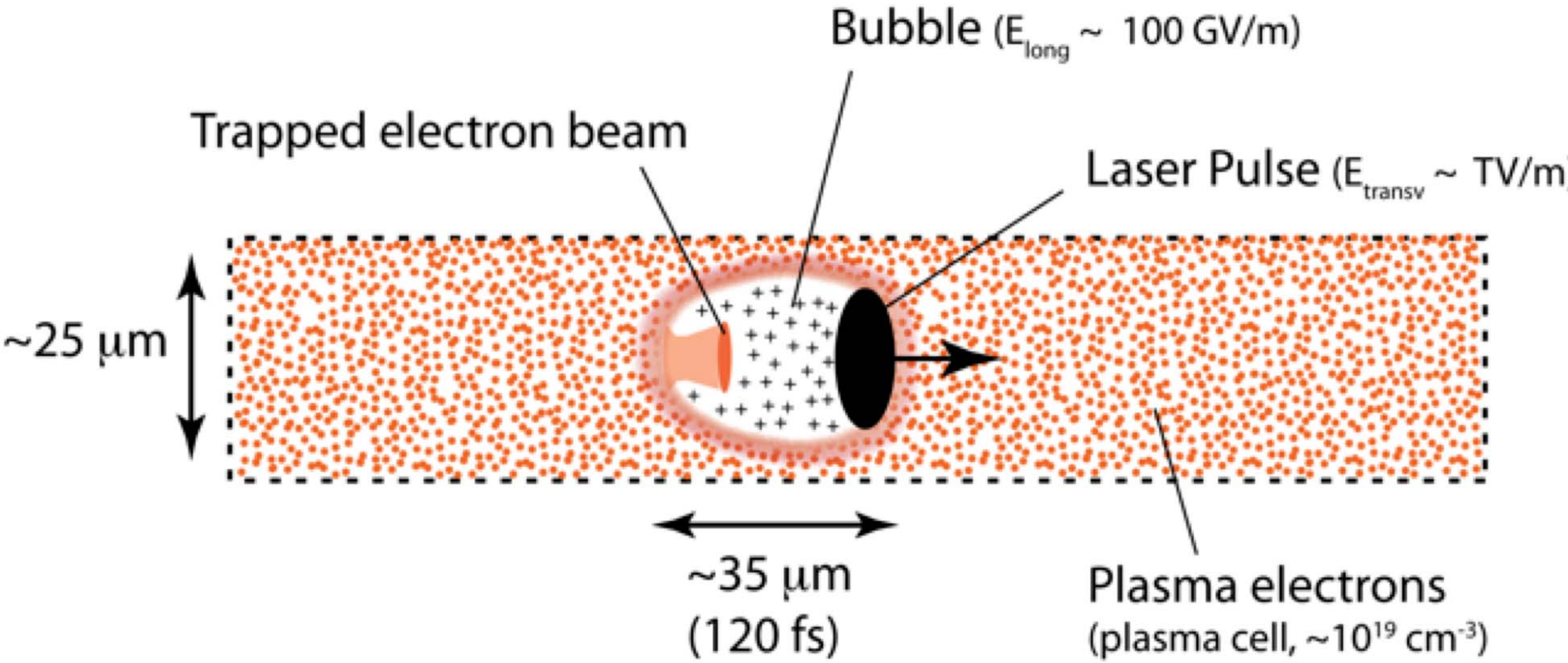
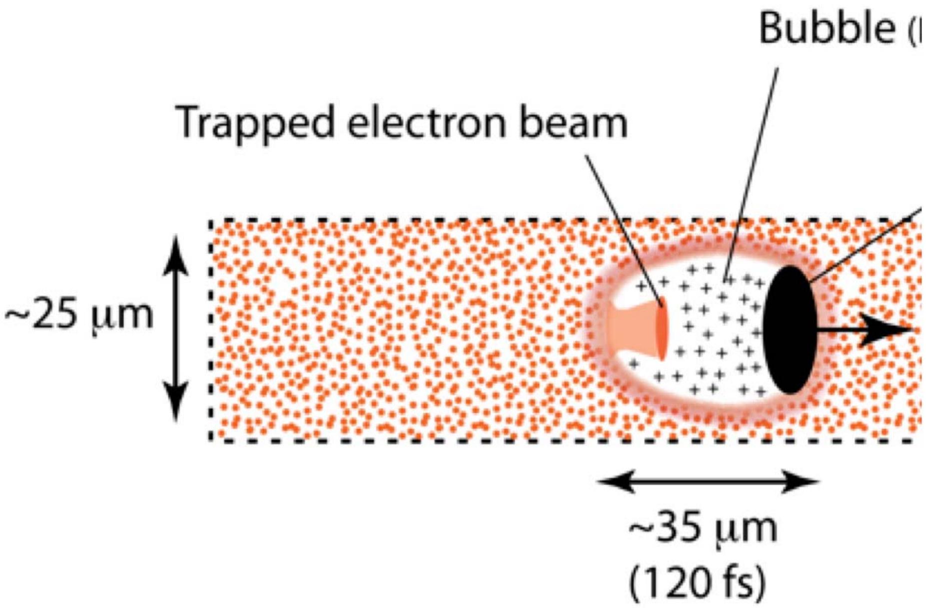


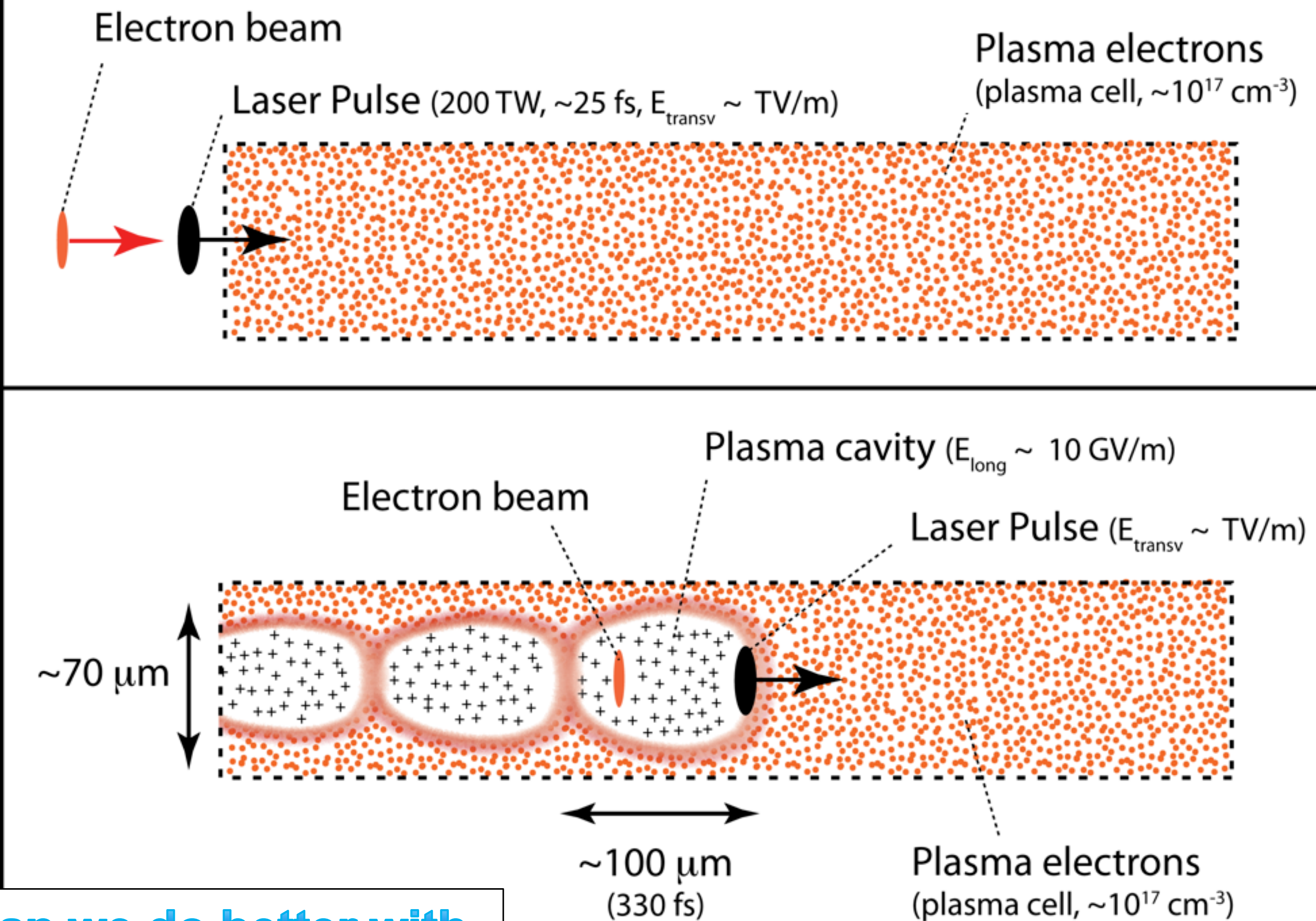
This accelerator fits into a human hair!

Reminder: 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.

External Injection…



Can we do better with external injection?

Foto Laser-Plasmabeschleuniger

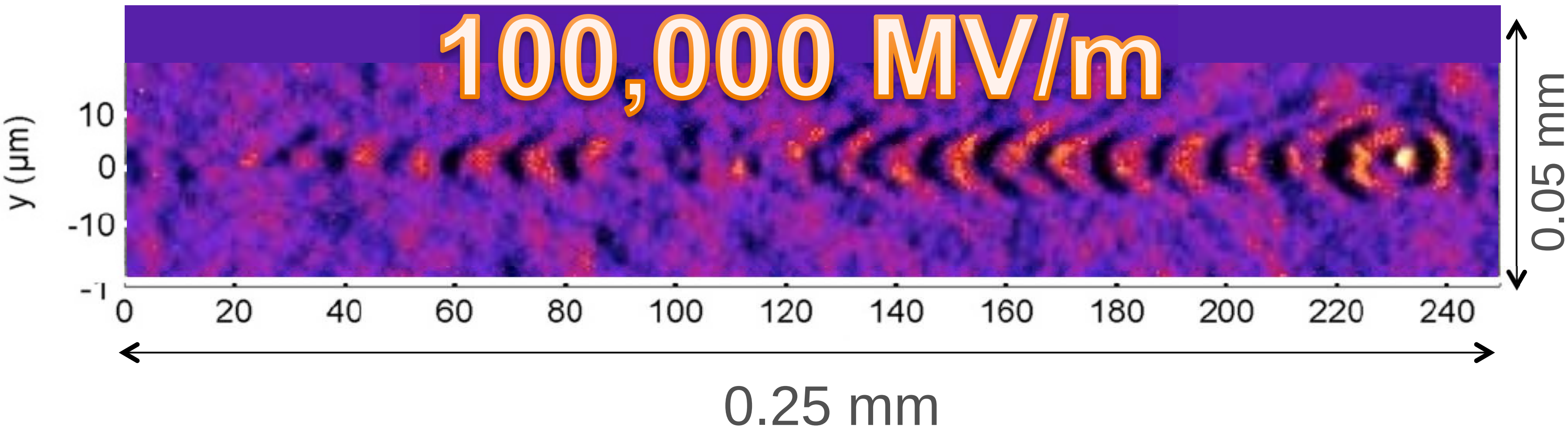
See lecture M. Kaluza

APPLIED PHYSICS LETTERS 103, 191118 (2013)

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

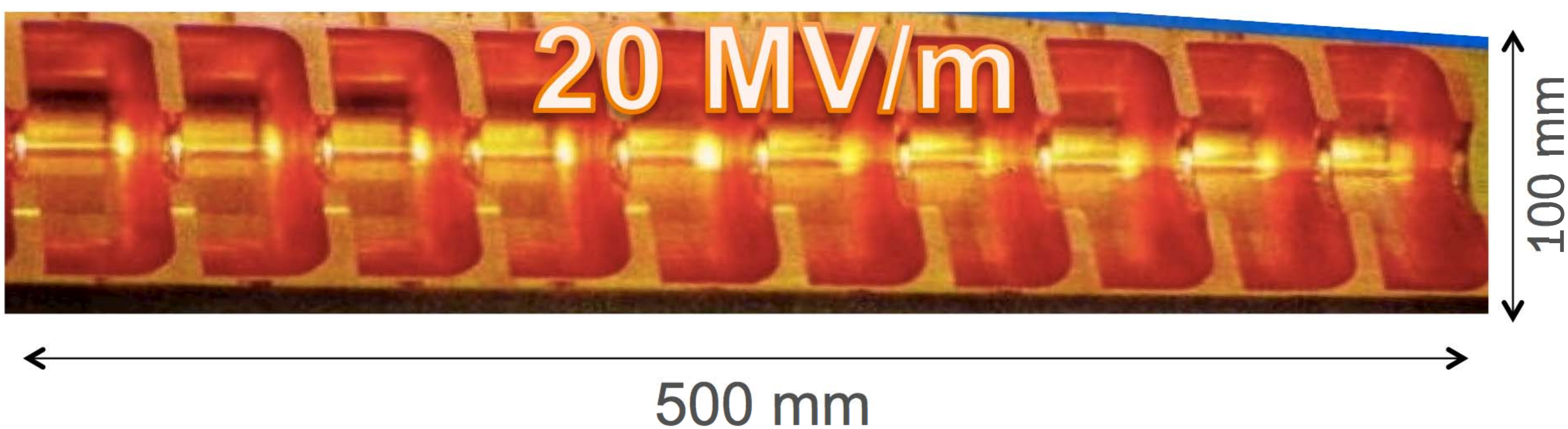
M. B. Schwab,[1,a)] A. Sävert,[1] O. Jäckel,[1,2] J. Polz,[1] M. Schnell,[1] T. Rinck,[1] L. Veisz,[3] M. Möller,[1] P. Hansinger,[1] G. G. Paulus,[1,2] and M. C. Kaluza[1,2]
[1]Insitut für Optik und Quantenelektronik, Max-Wien-Platz 1, 07743 Jena, Germany
[2]Helmholtz-Institut Jena, Fröbelstieg 3, 07743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



Wakefields a la Leonardo da Vinci in 1509…

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)

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

$$r \ll a$$

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

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

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

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

Depends on radial position r

The Useful Regime of Plasma Accelerators

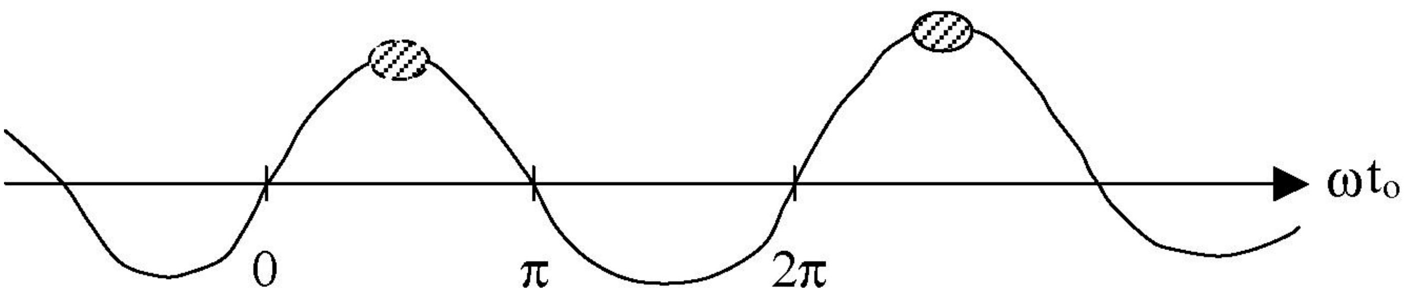
Two conditions for an accelerator:

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

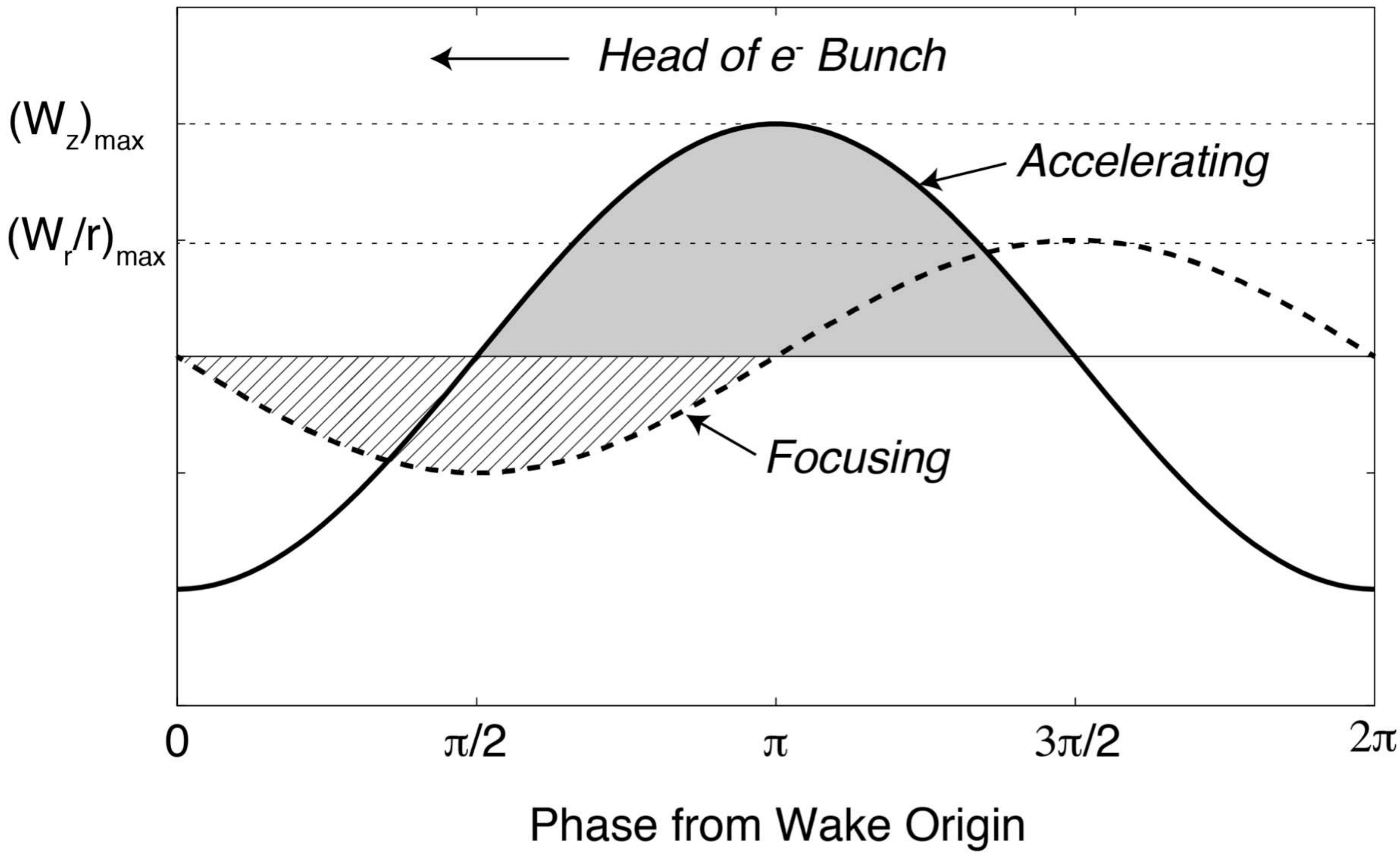
These two conditions define a useful range of acceleration!

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



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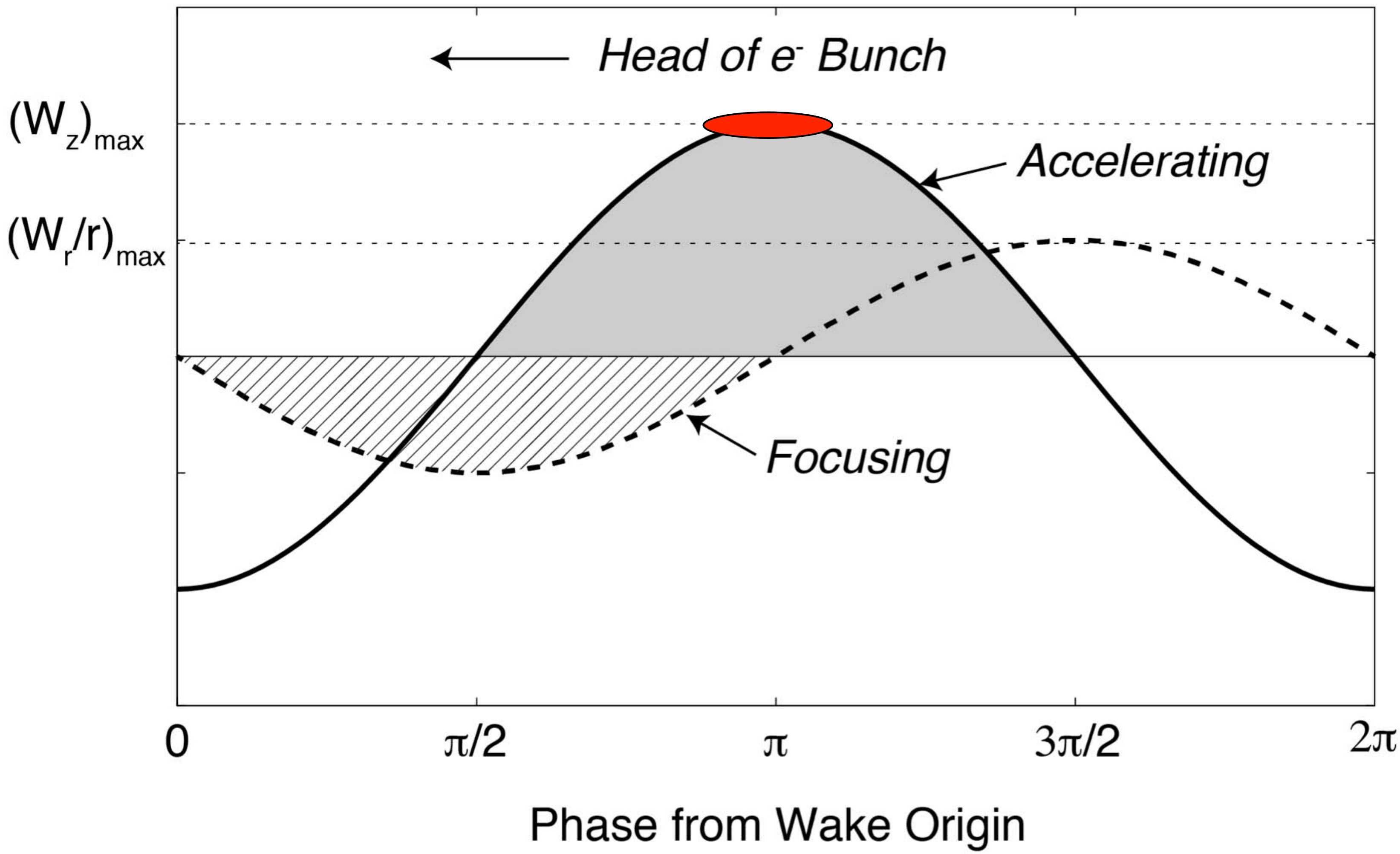
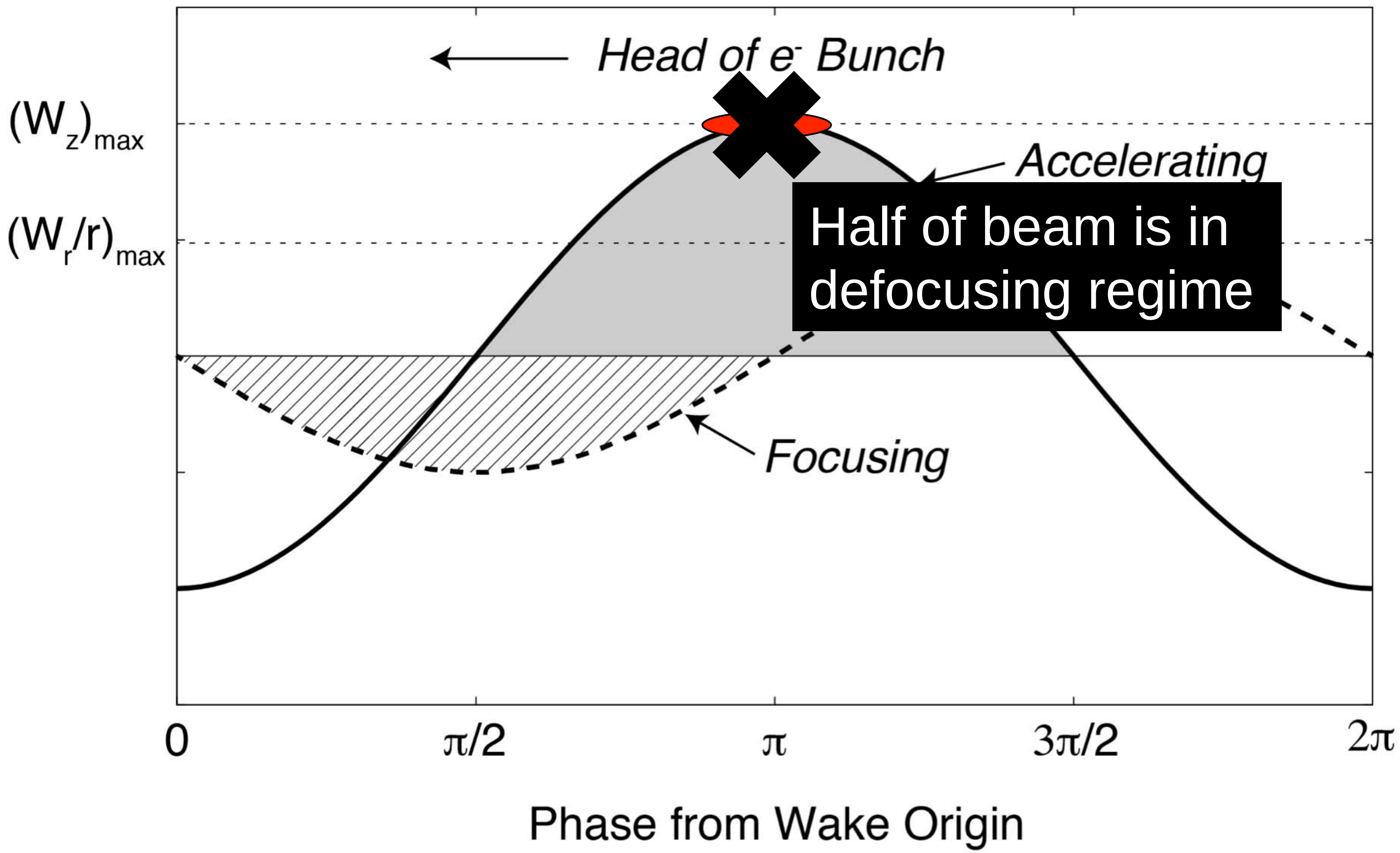


Plasma Accelerator



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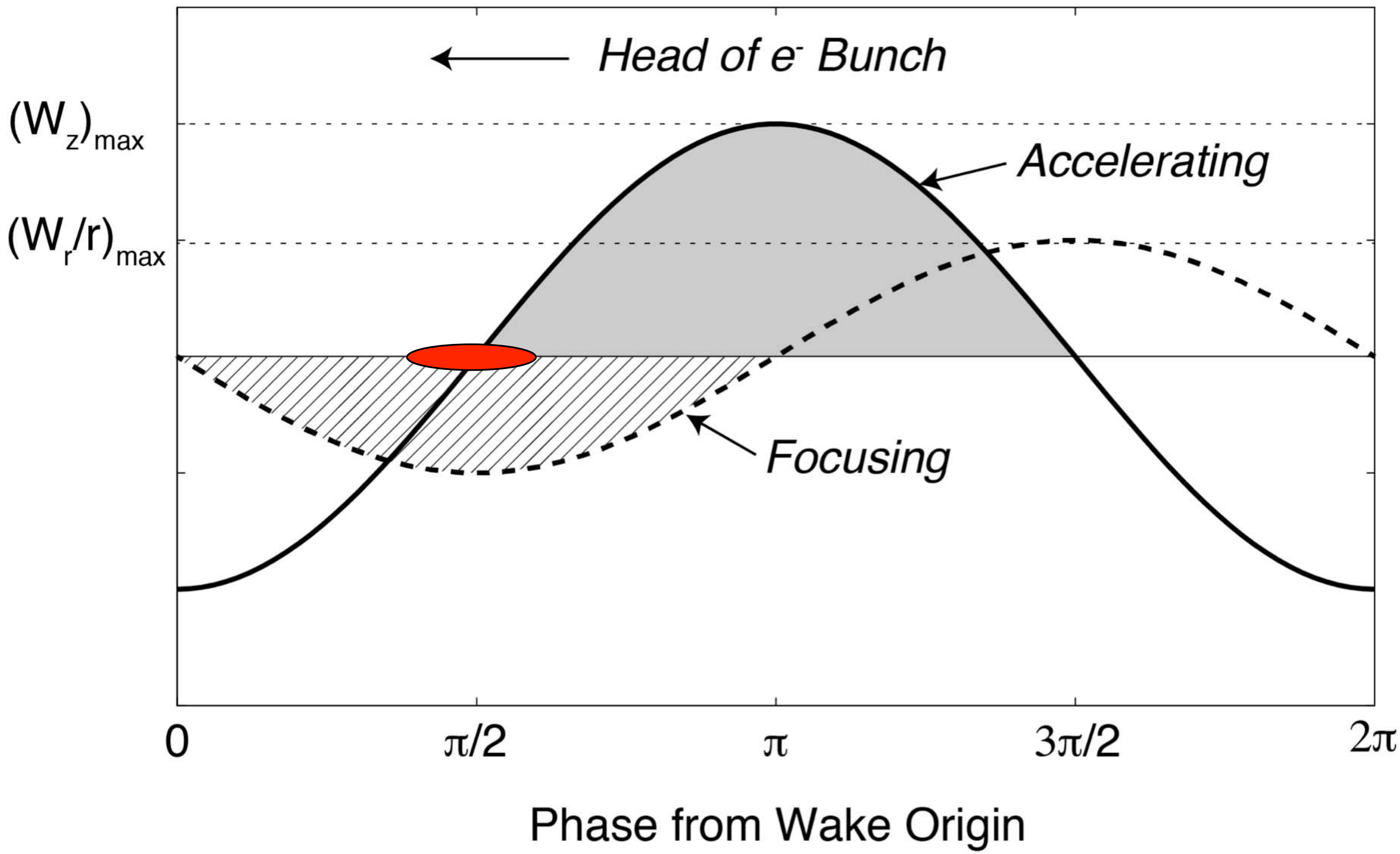
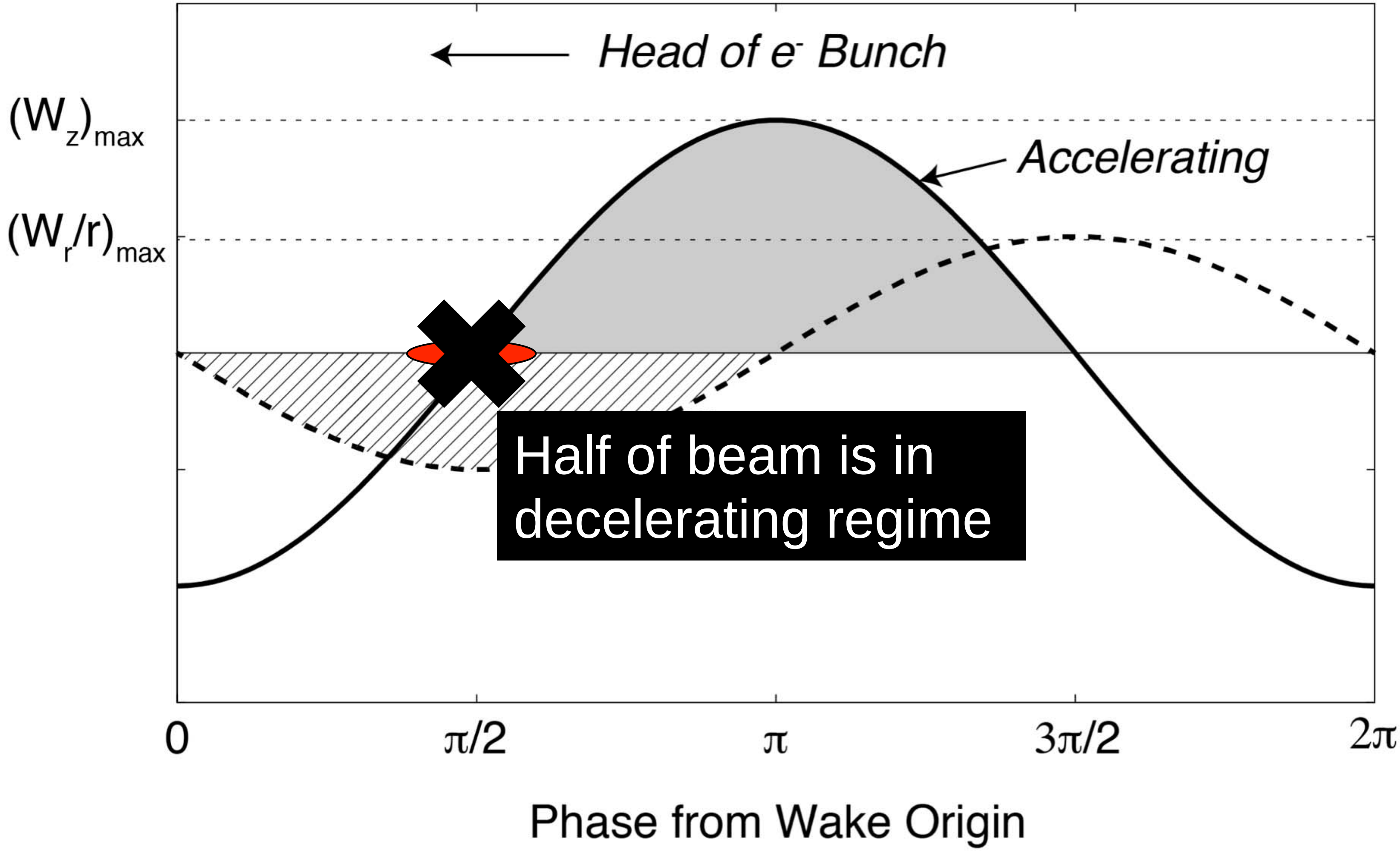


Plasma Accelerator



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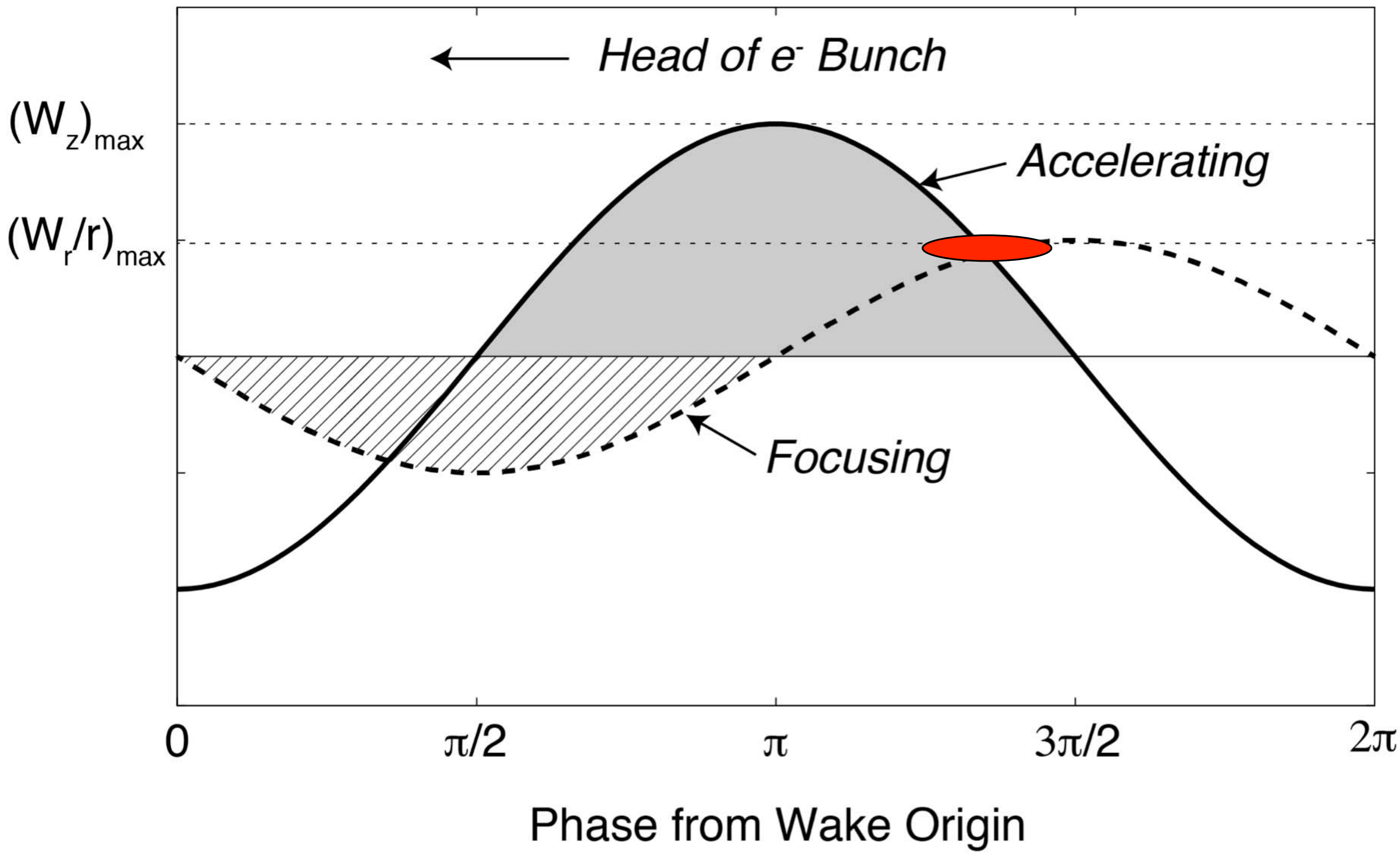
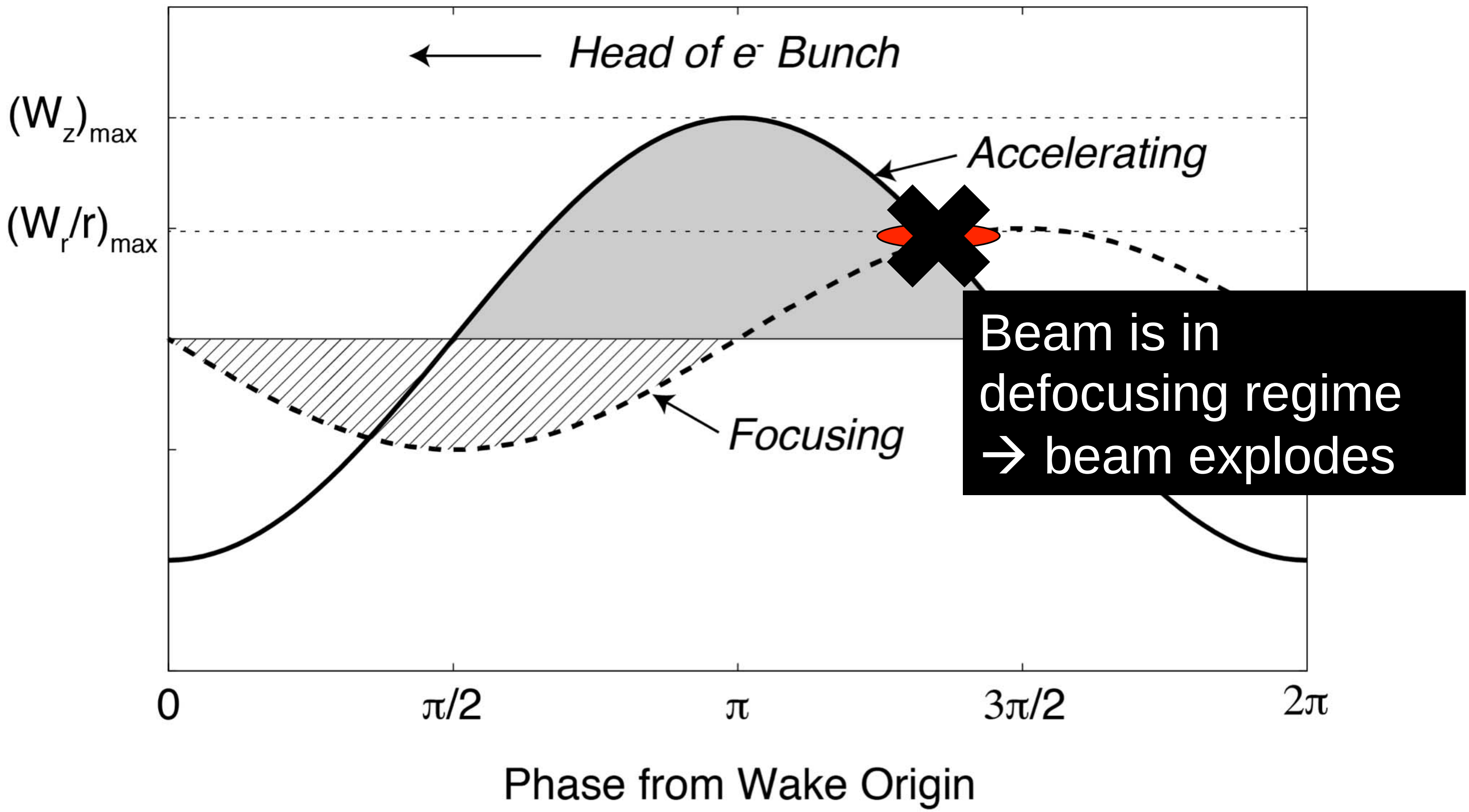
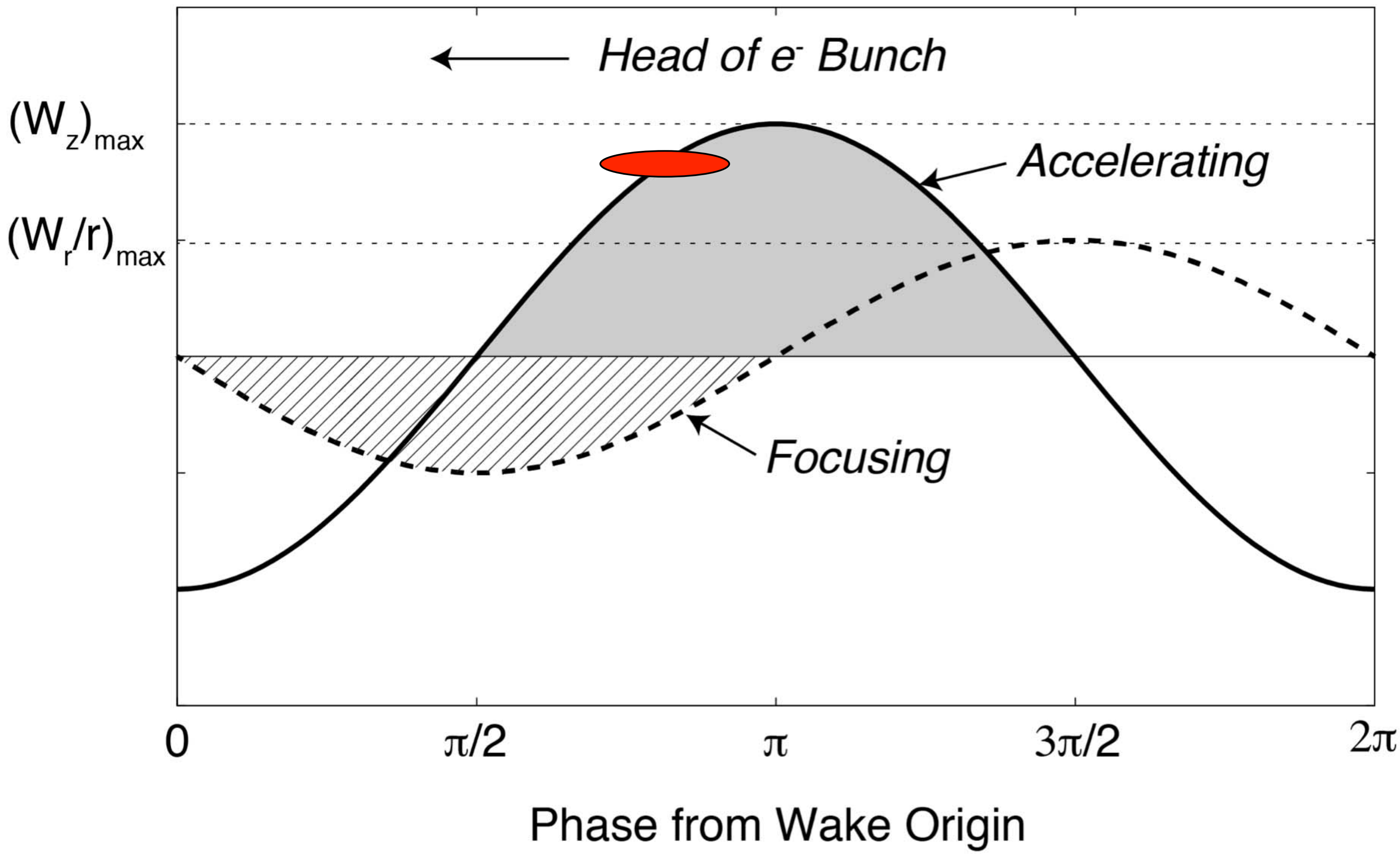


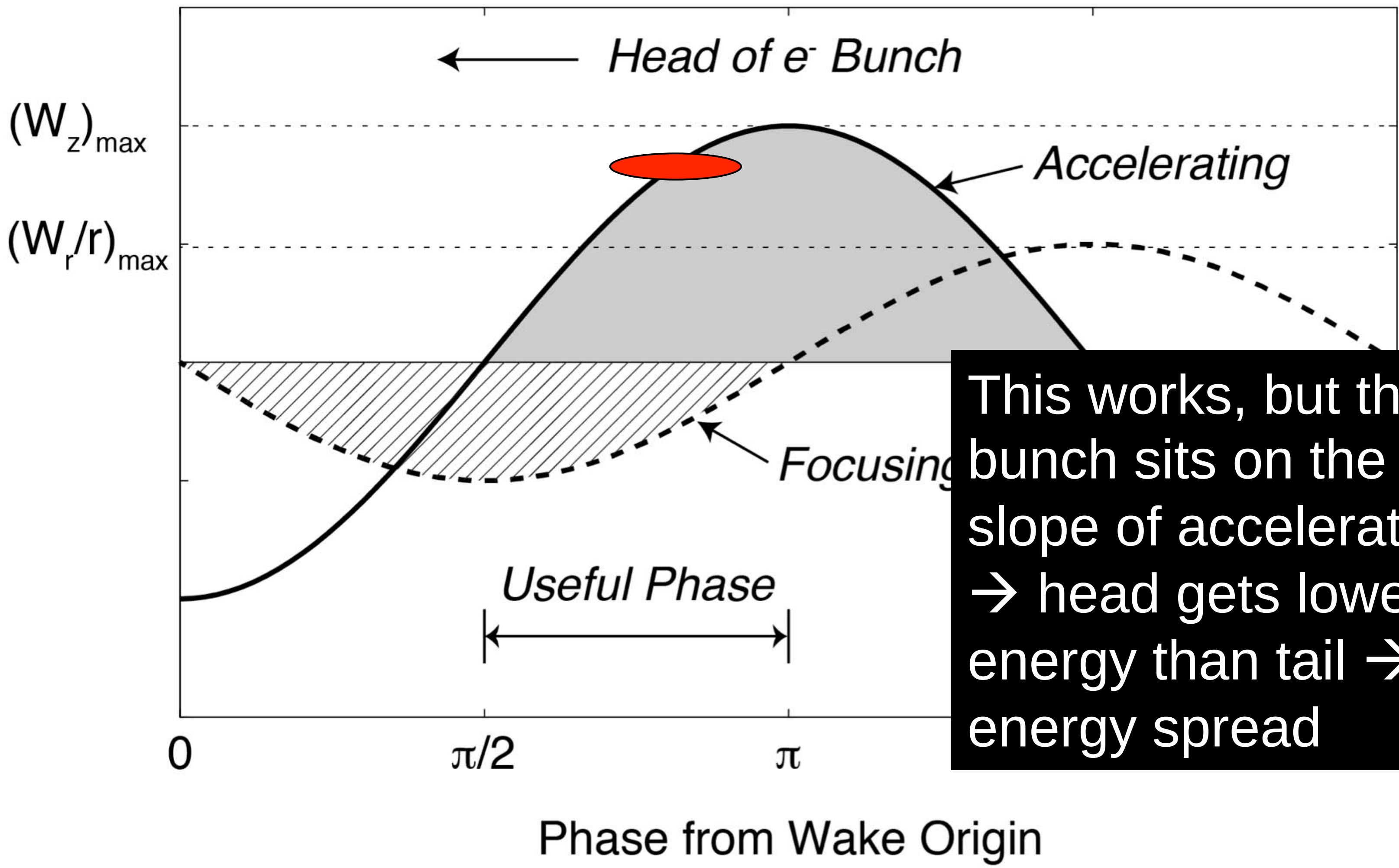
Plasma Accelerator



Plasma Accelerator

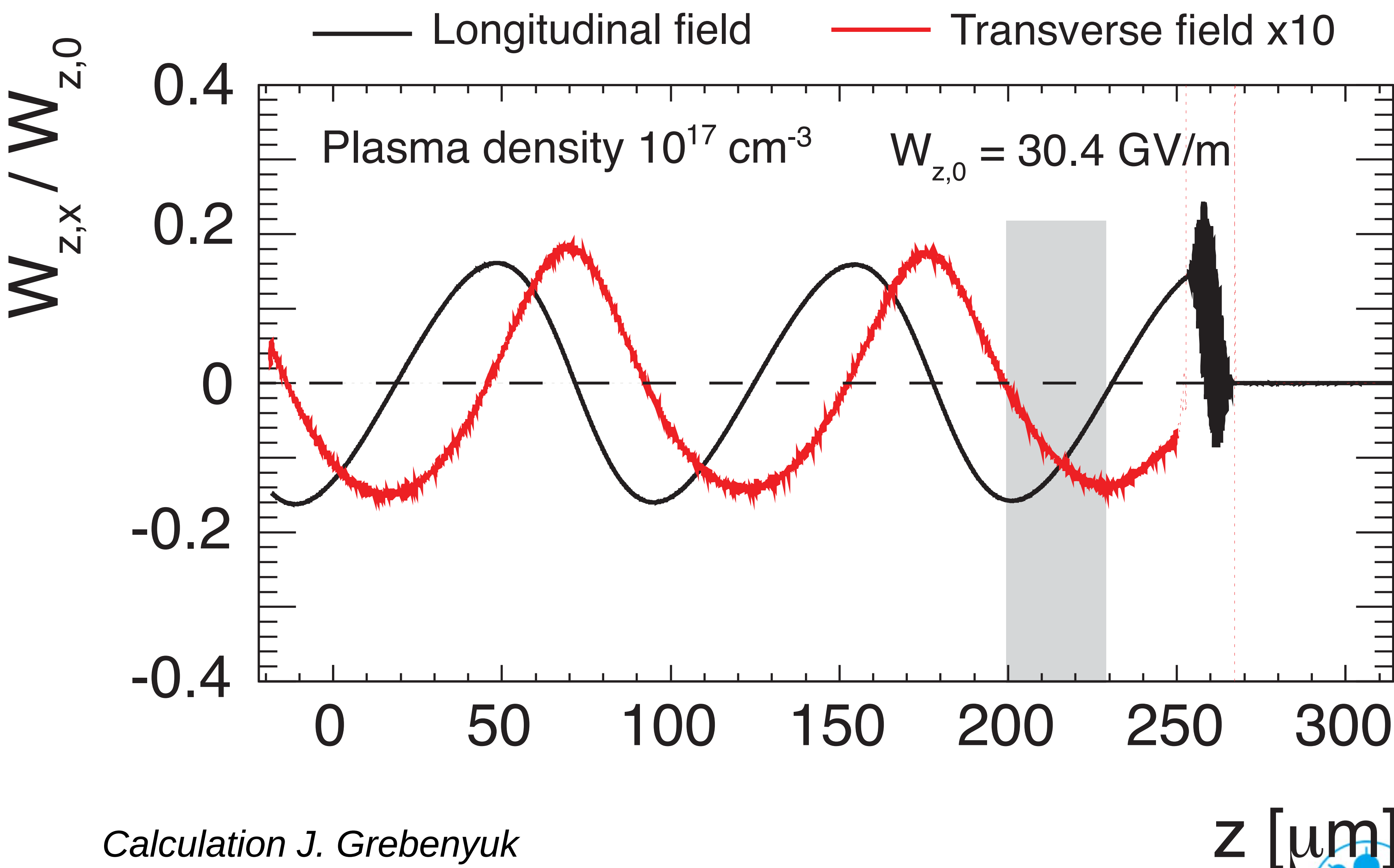


Plasma Accelerator



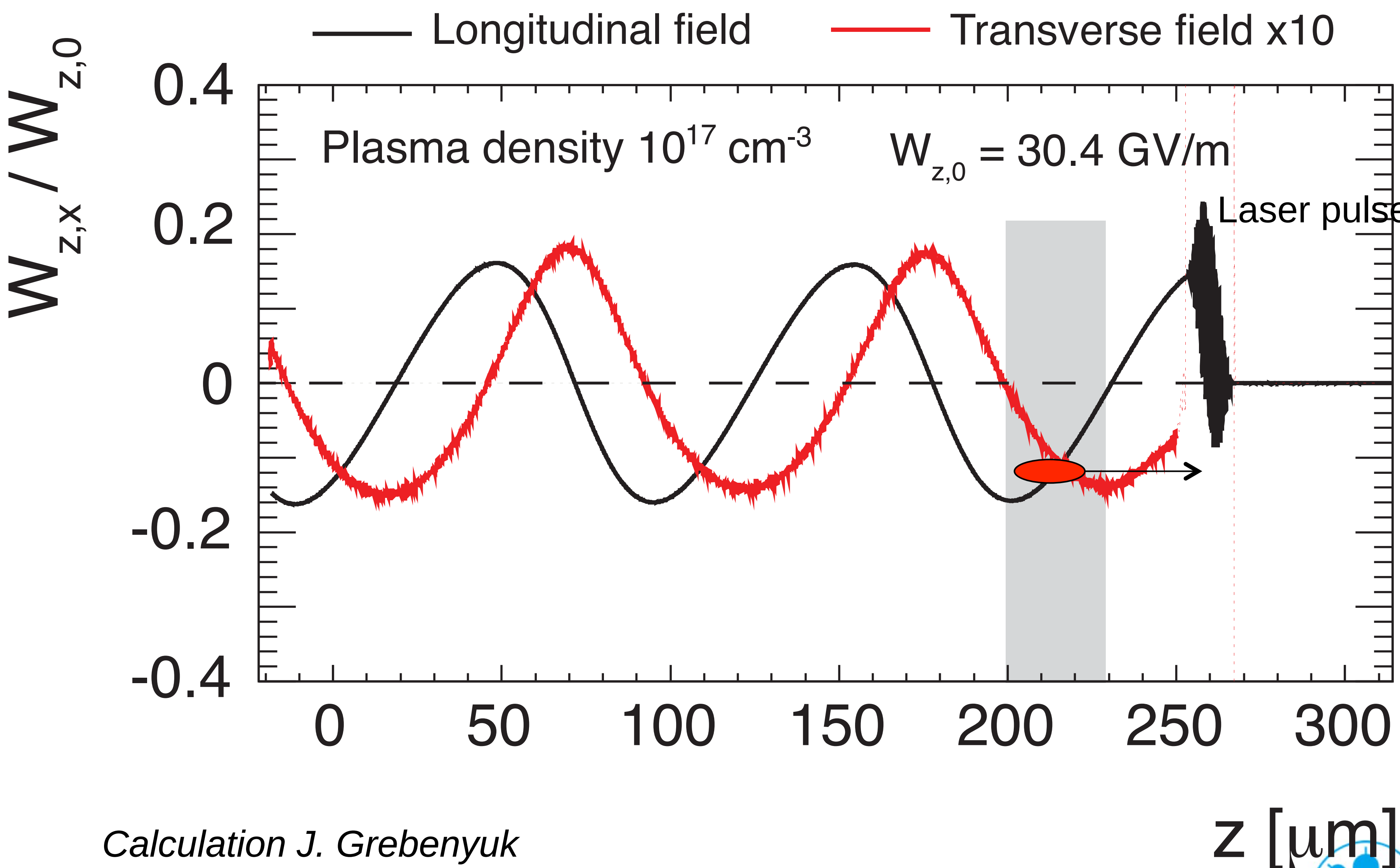
This works, but the bunch sits on the slope of acceleration → head gets lower energy than tail → energy spread

Comparison with OSIRIS simulation



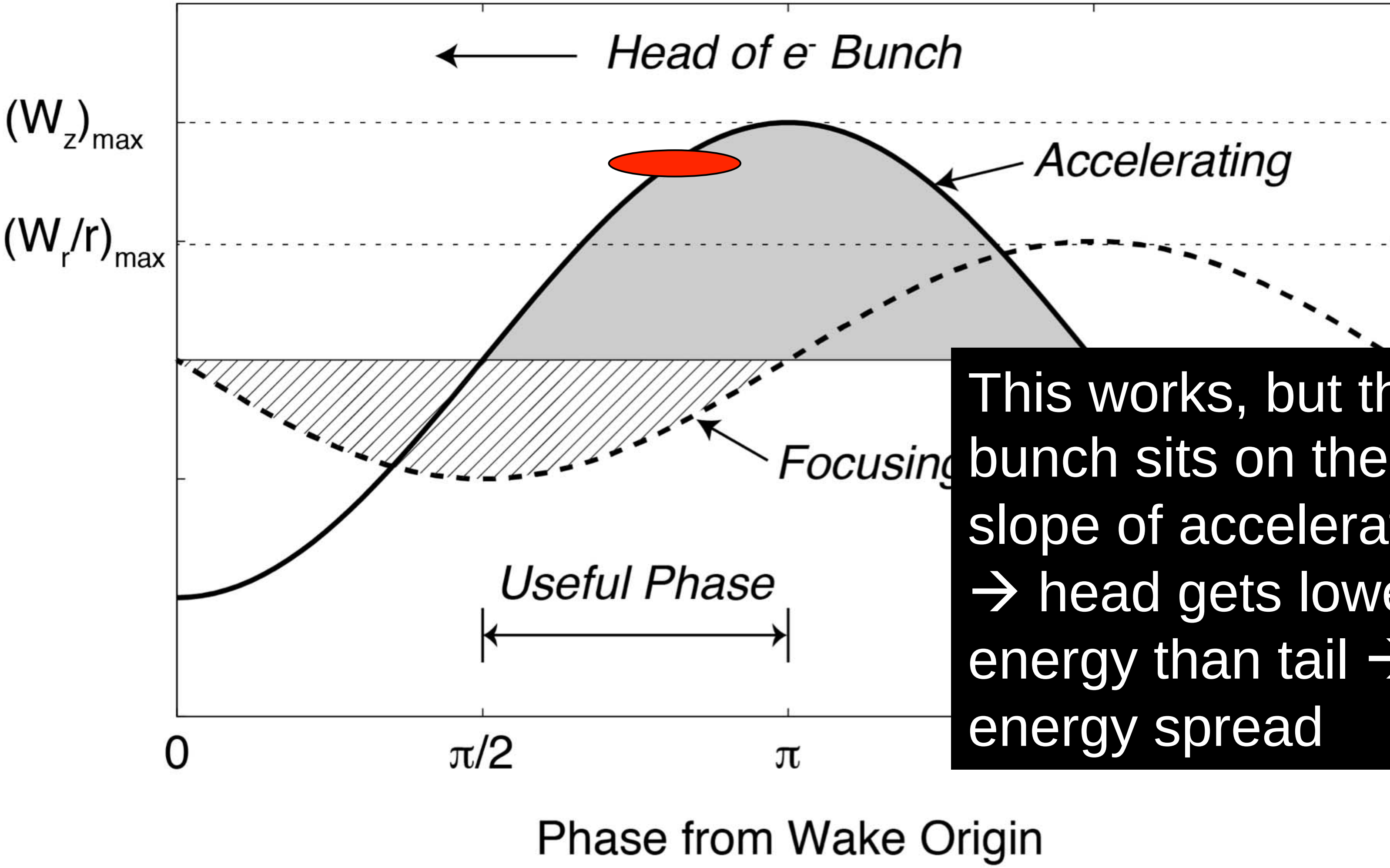
Calculation J. Grebenyuk

Comparison with OSIRIS simulation



Calculation J. Grebenyuk

Plasma Accelerator



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Optimization 1: Energy Spread

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

↓

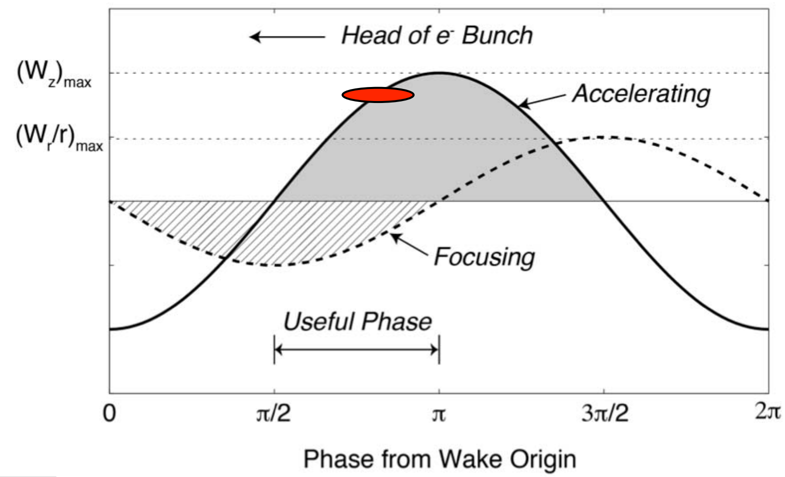
Minimize: Ratio of accelerated bunch length over ¼ plasma wavelength!

↓

Minimize length accelerated bunch → Ultra-short bunches (fs, as) → Ultra-fast science

and/or

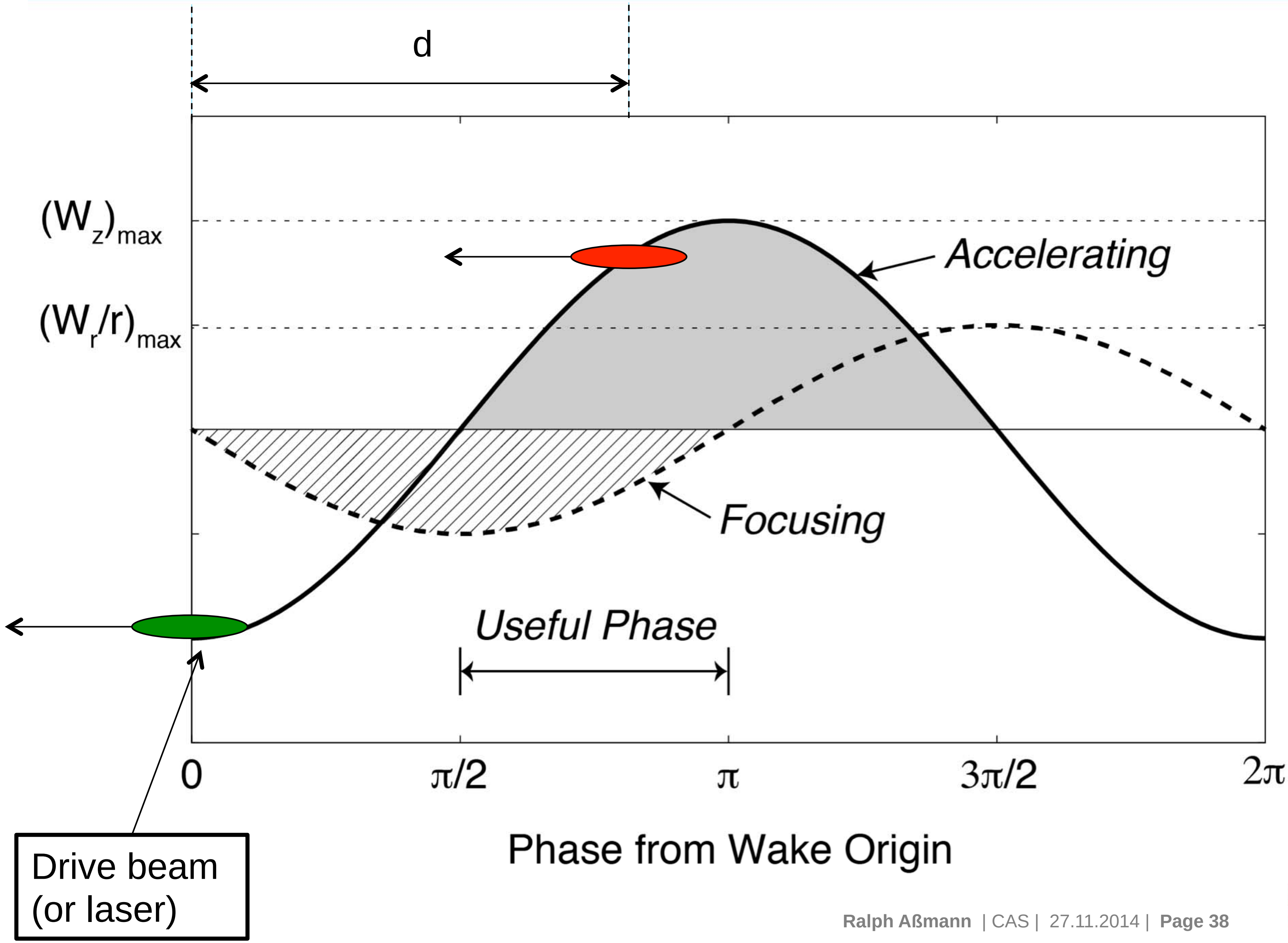
Increase plasma wavelength → Lower plasma density → Lower accelerating gradient



1 fs = 0.3 μm

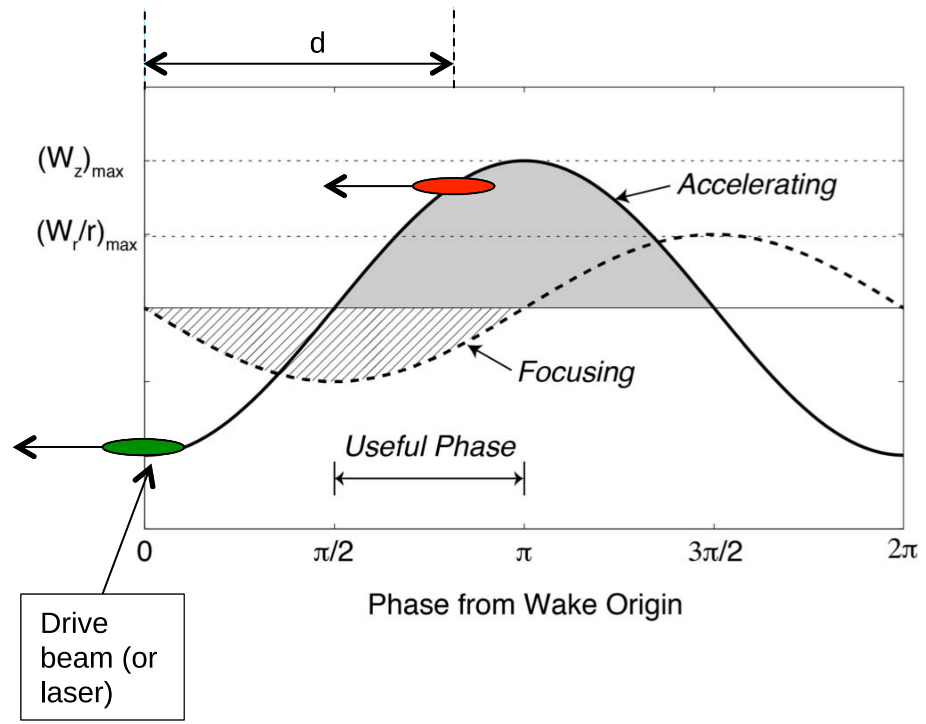
when travelling with light velocity c

Phase Slippage

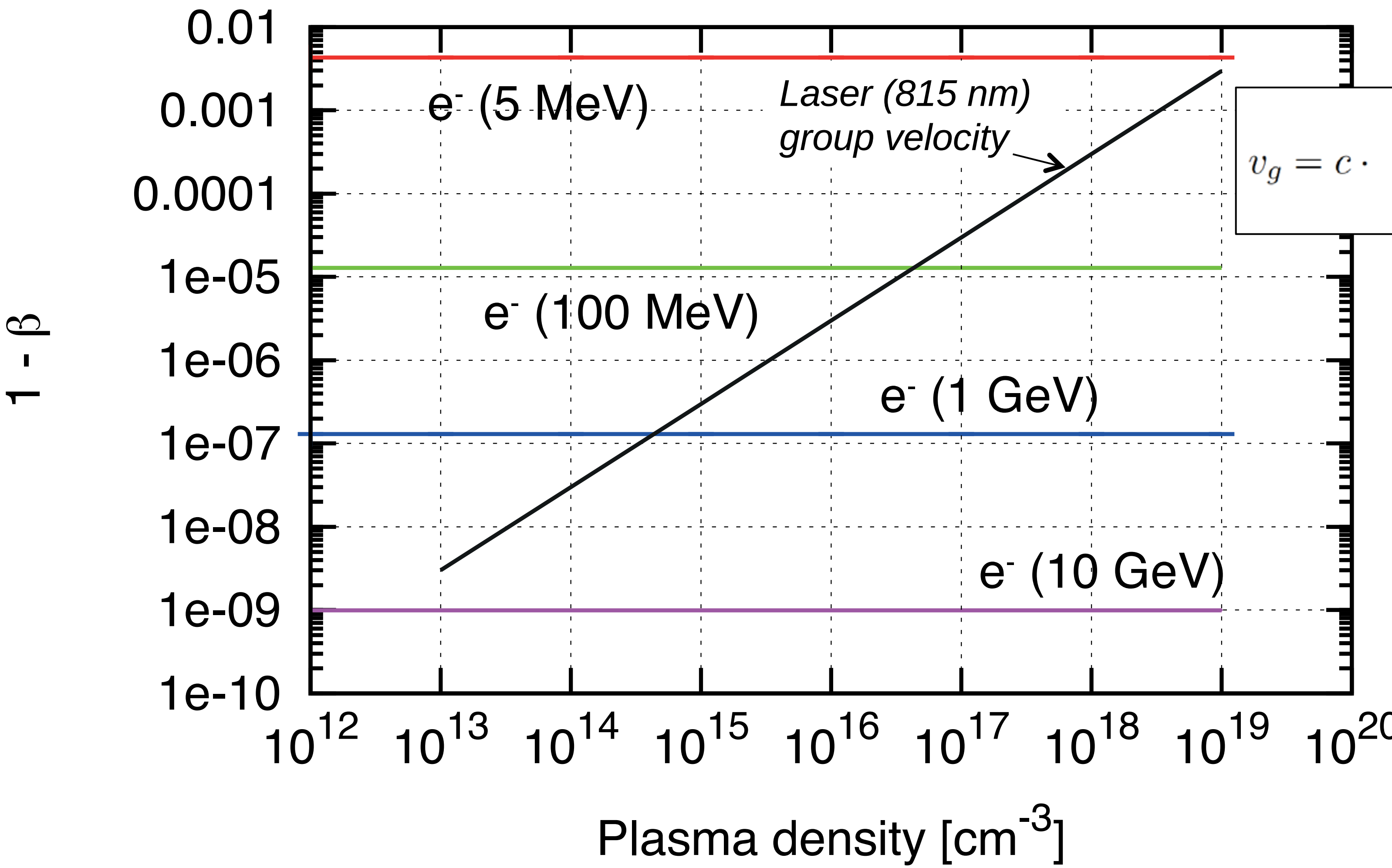


Phase Slippage

- 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.



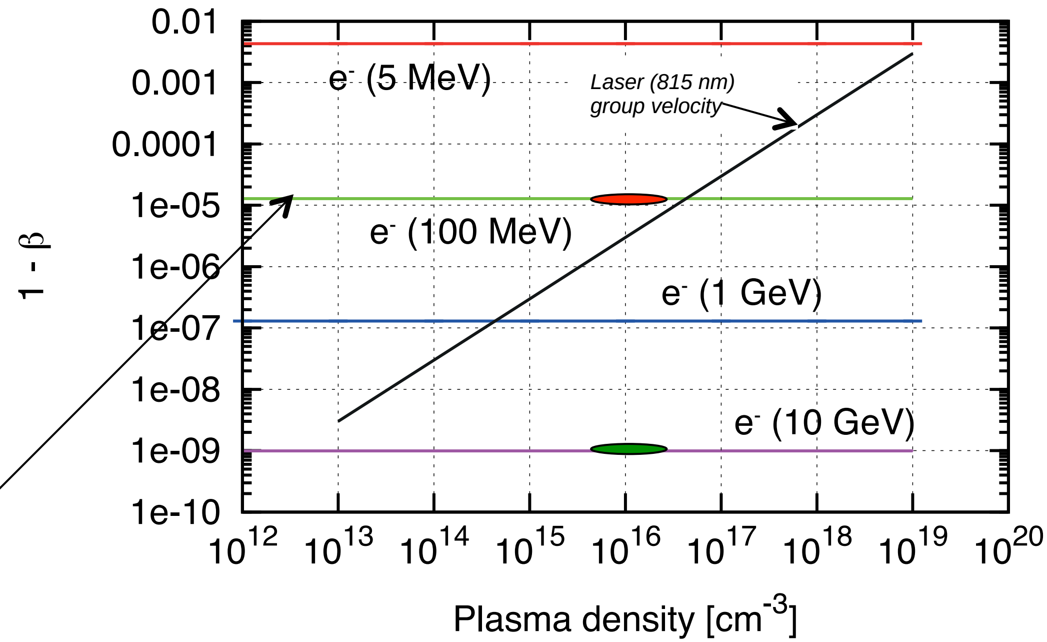
Dephasing (β = v/c, here consider relativistic beams)



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

Dephasing ($\beta = v/c$, 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:

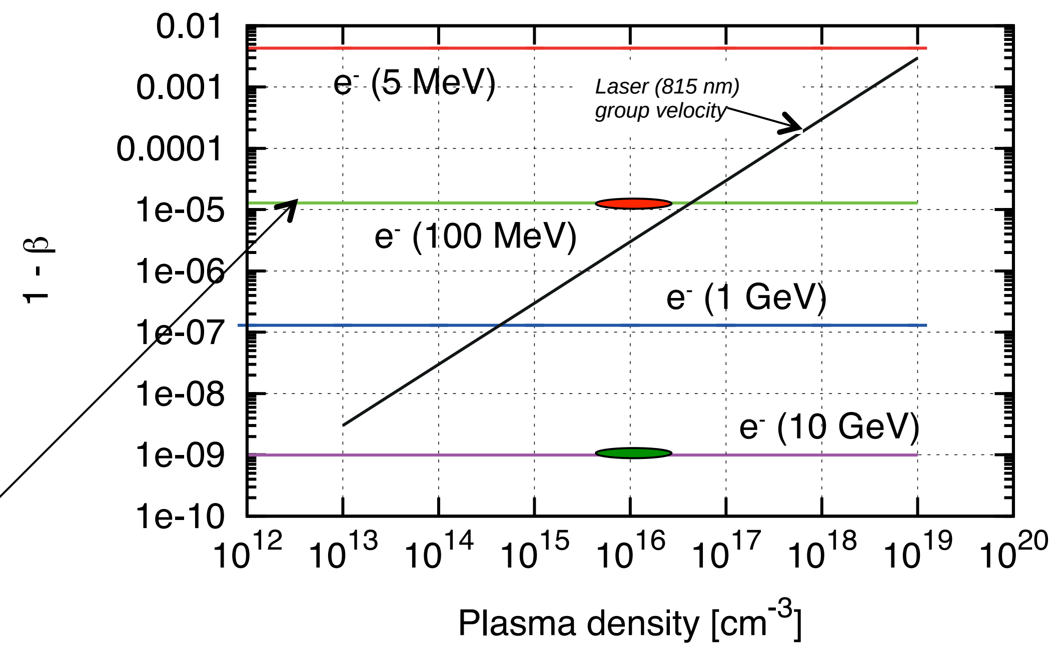
- Driver electrons are decelerated and slow down.
- Accelerated electrons speed up.

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

> Big advantage of beam-driven…

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

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



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> Plasma wavelength: **10 µm (n_0=1e19) – 1 mm (n_0=1e15)**

> However

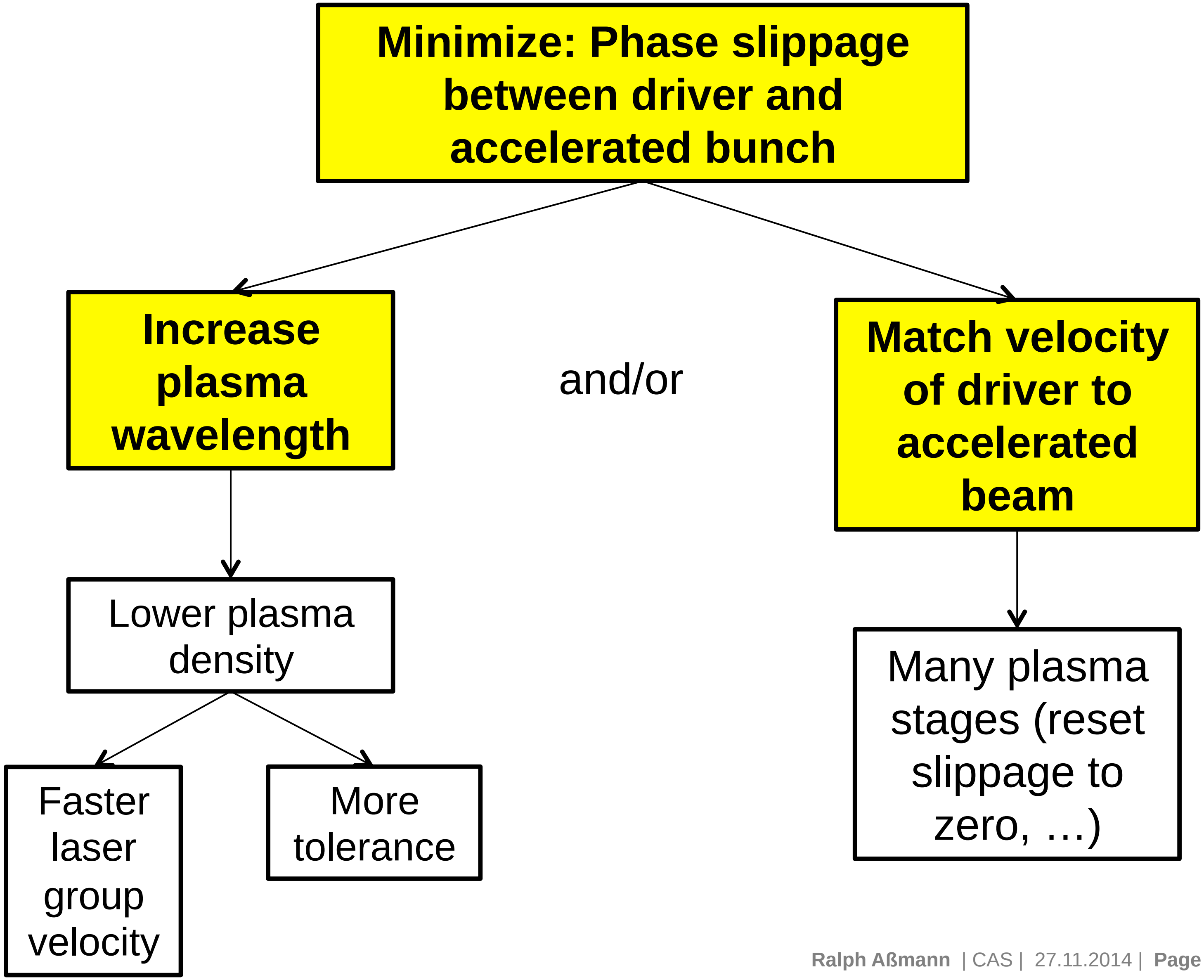
- Driver
- Acceler

3.6° - 360°

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

> Big advantage of beam-driven…

Optimization 2: Phase Slippage



Optimization 3: Stability / Reproducibility

Stabilize: Distance between driver and accelerated bunch.

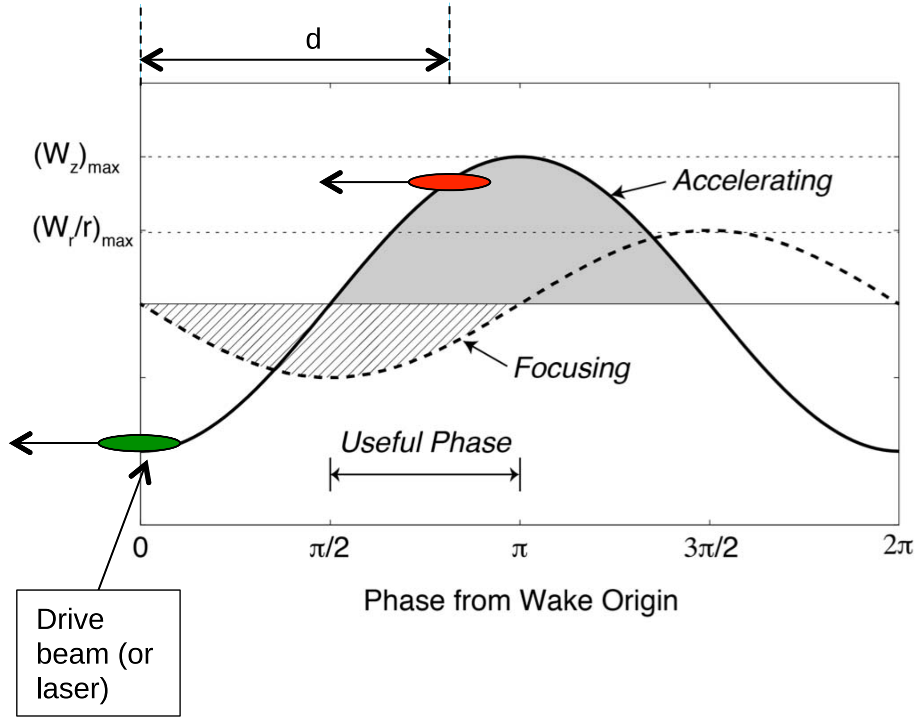
Internally generate accelerated electron bunch

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!

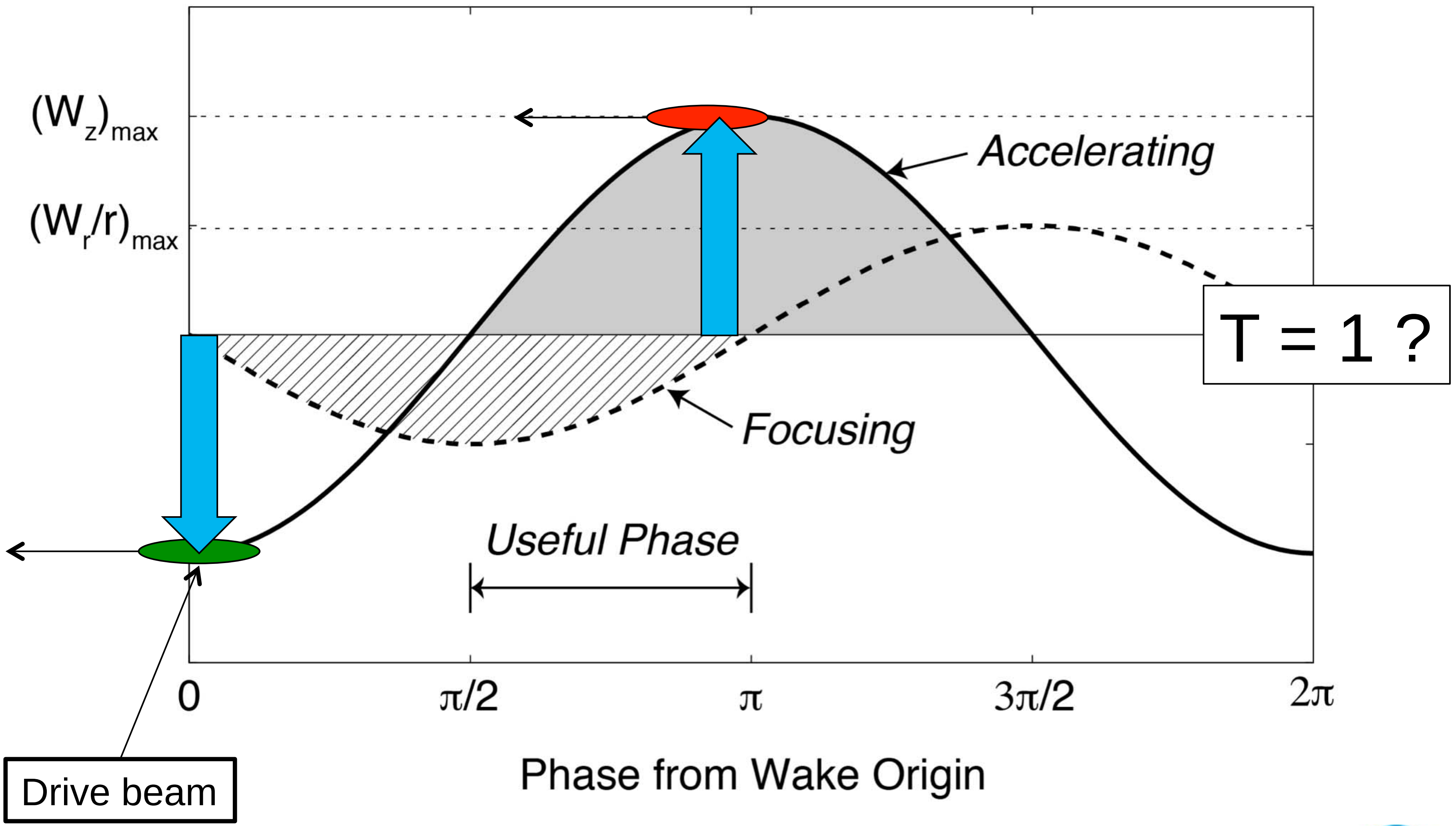
> This is, however, not possible in reality!

> Limited by **transformer ratio T** (short, symmetric bunches):

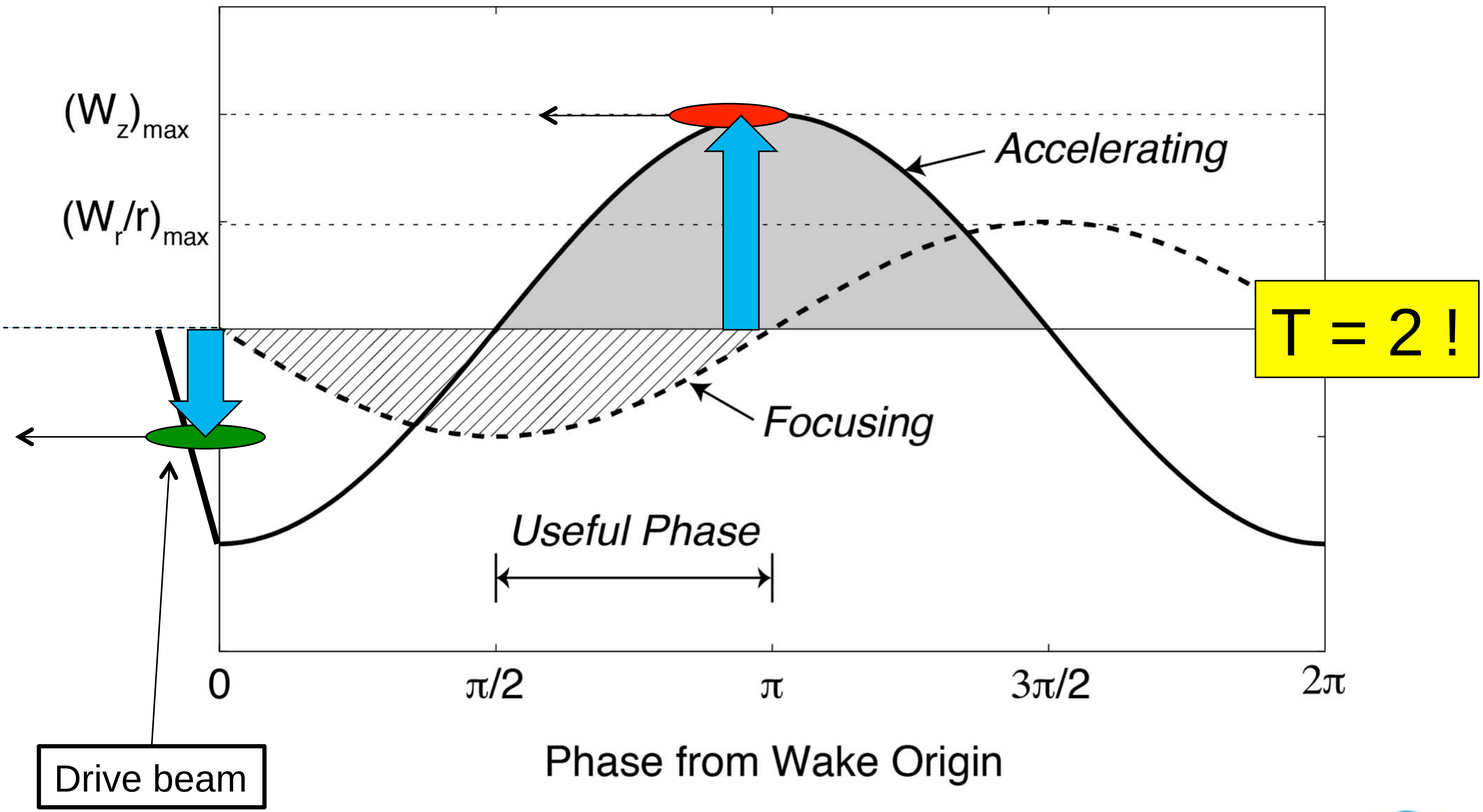
$$T = \left|\frac{\Delta E}{E_1}\right| = \left|\frac{\Delta E_{acc}}{\Delta E_{drive}}\right| \leq 2$$

Here it is assumed, drive beam looses all its energy

Transformer Ratio (Short Symmetric Bunches)

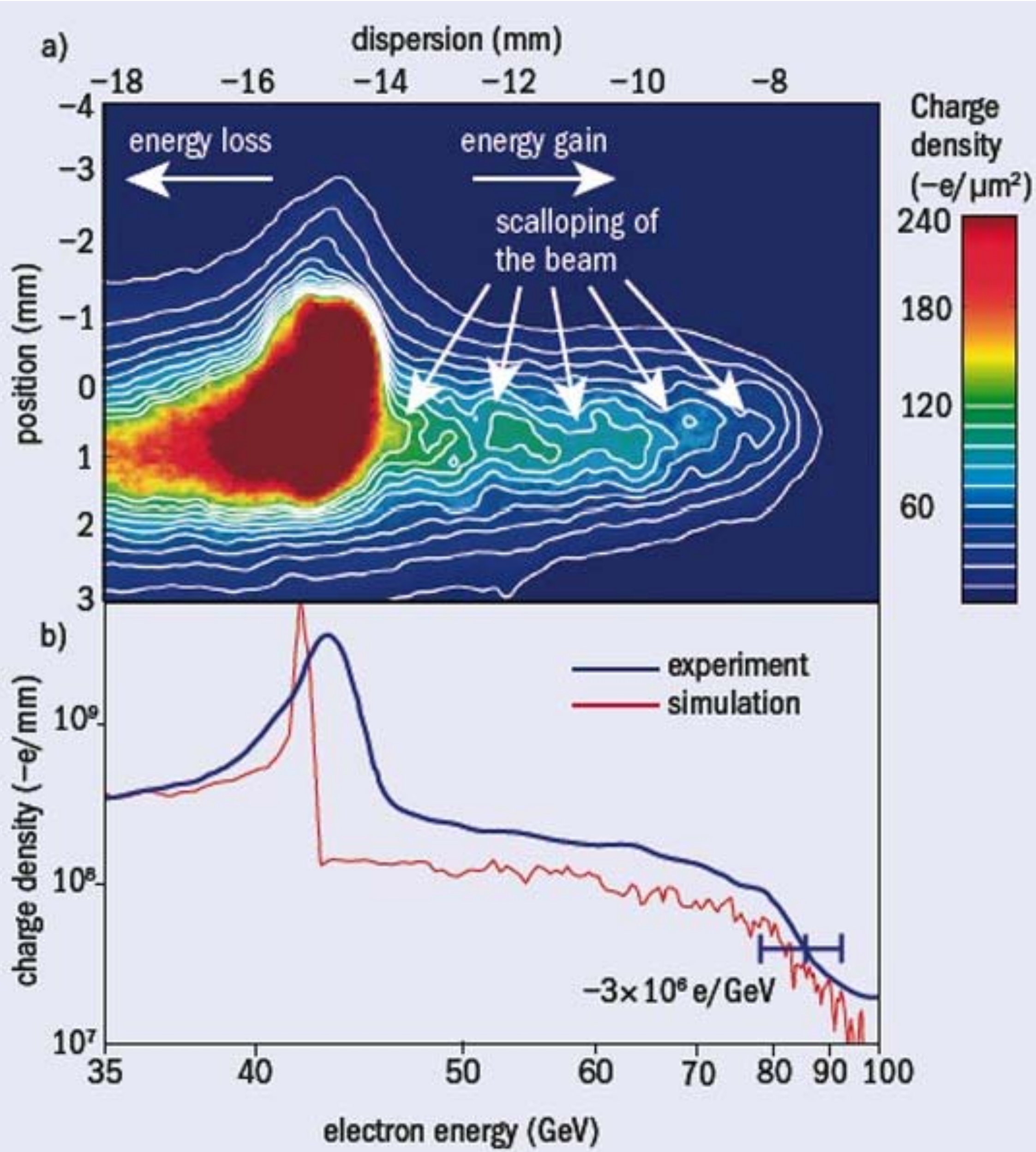


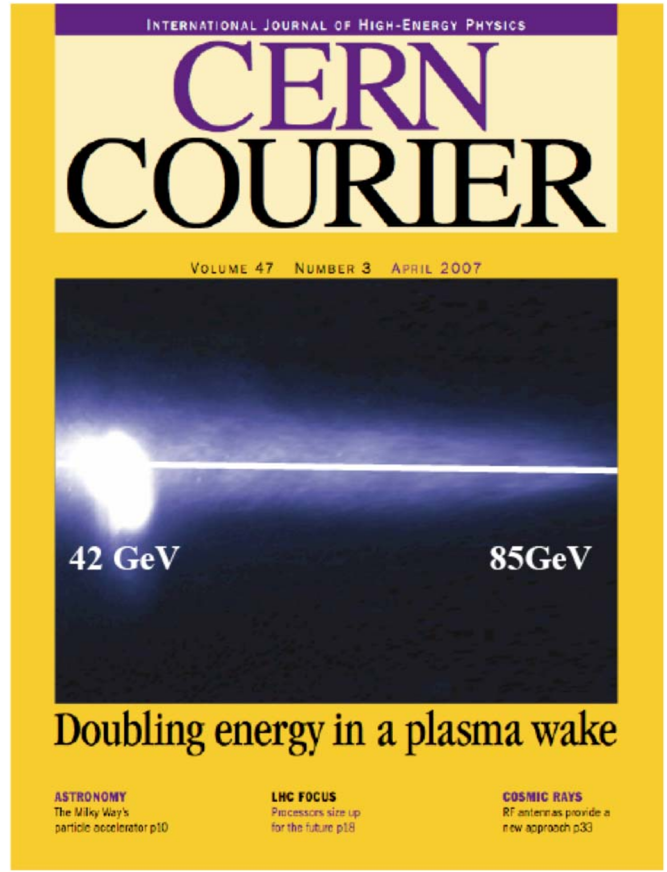
Transformer Ratio (Short Symmetric Bunches)



Head of driver sees no decelerating field

Record Acceleration: 42 GeV





E167 collaboration
SLAC, UCLA, USC

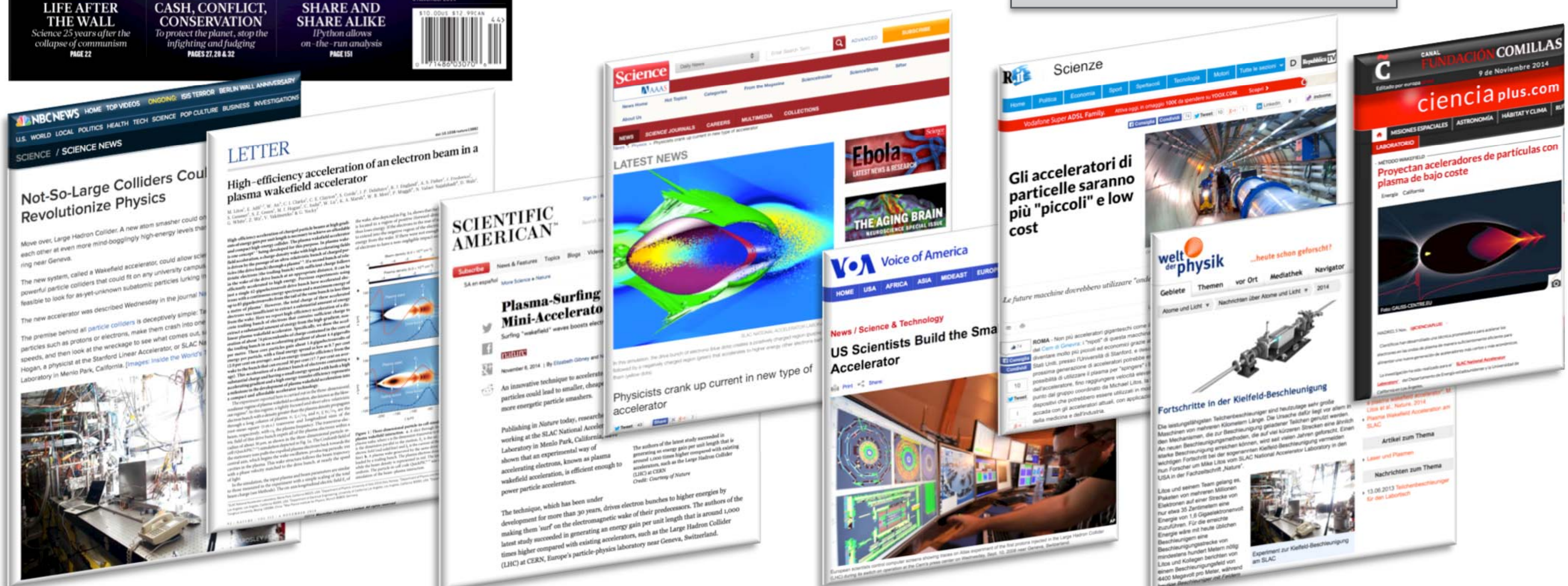
I. Blumenfeld et al, Nature 445, p. 741 (2007)

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

UCLA SLAC

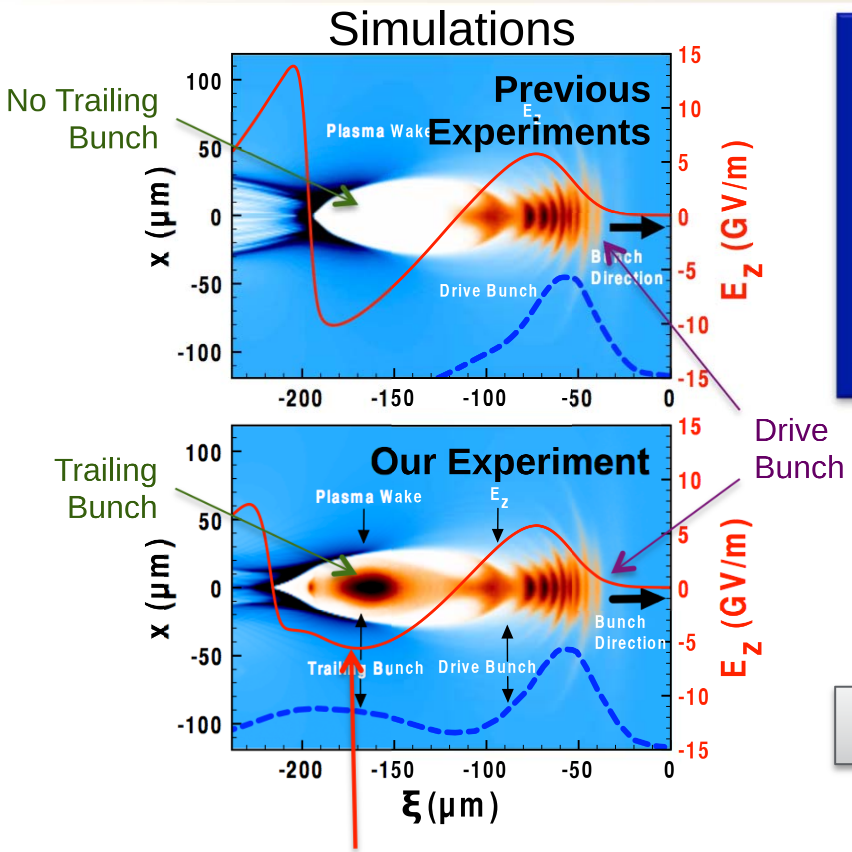
- Facility hosts more than 150 users, 25 experiments
- One high profile result a year
- Priorities balanced between focused plasma wakefield acceleration research and diverse user programs with ultra-high fields

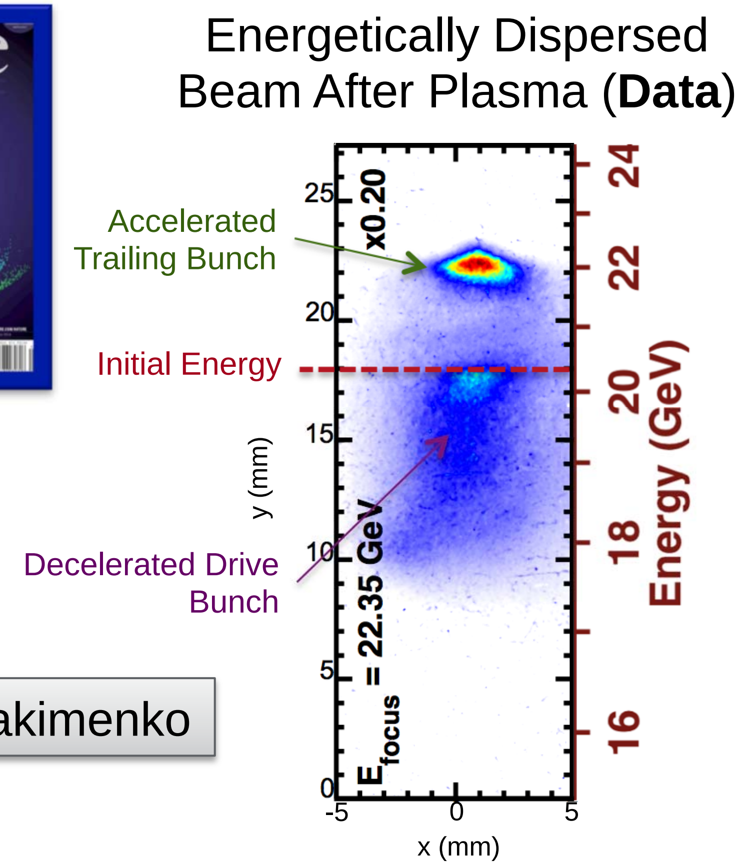
Slide: V. Yakimenko



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

UCLA SLAC



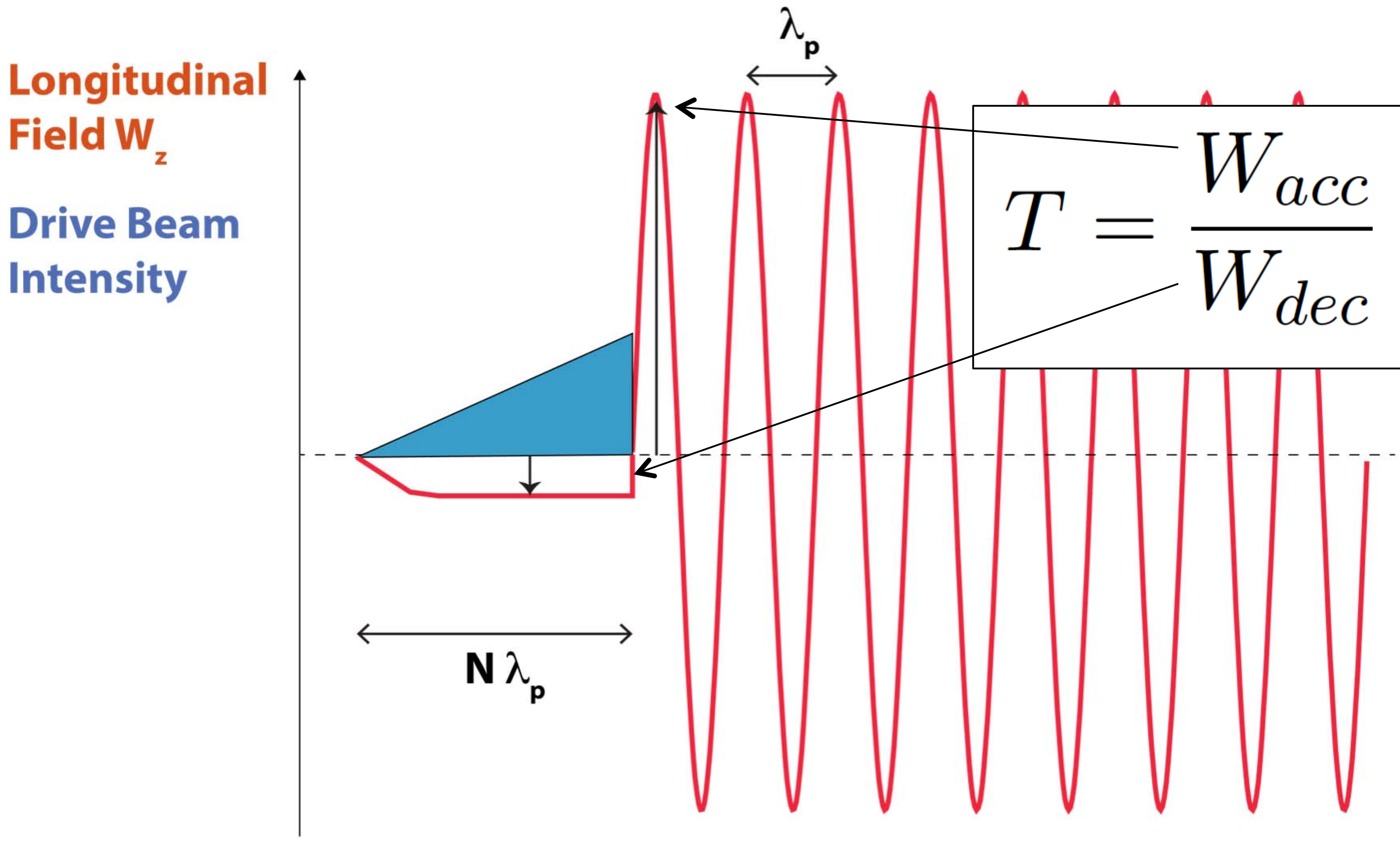


Slide: V. Yakimenko

- 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

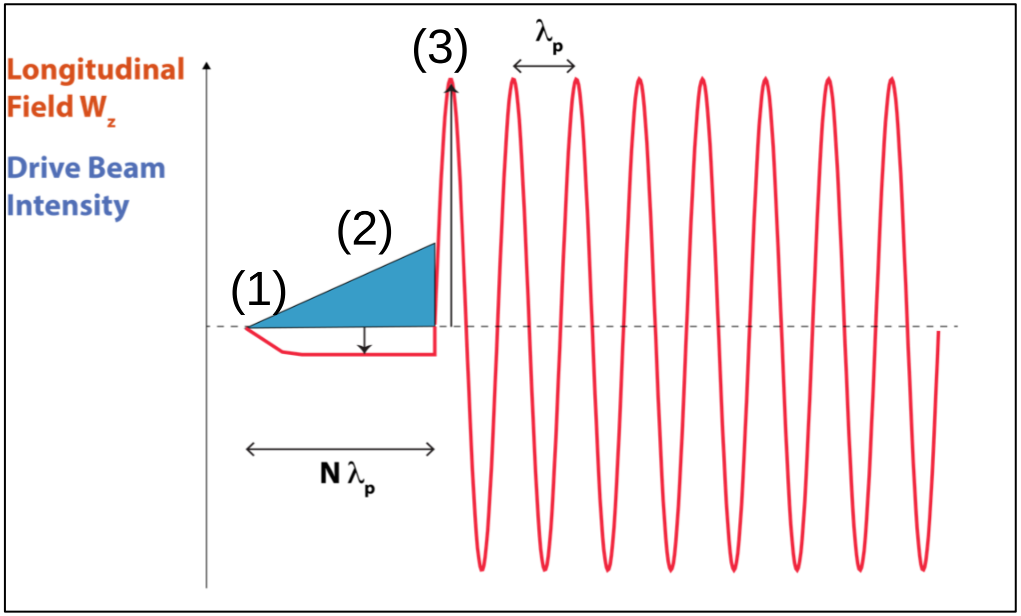


$$T = \frac{W_{acc}}{W_{dec}} = \pi N$$

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.



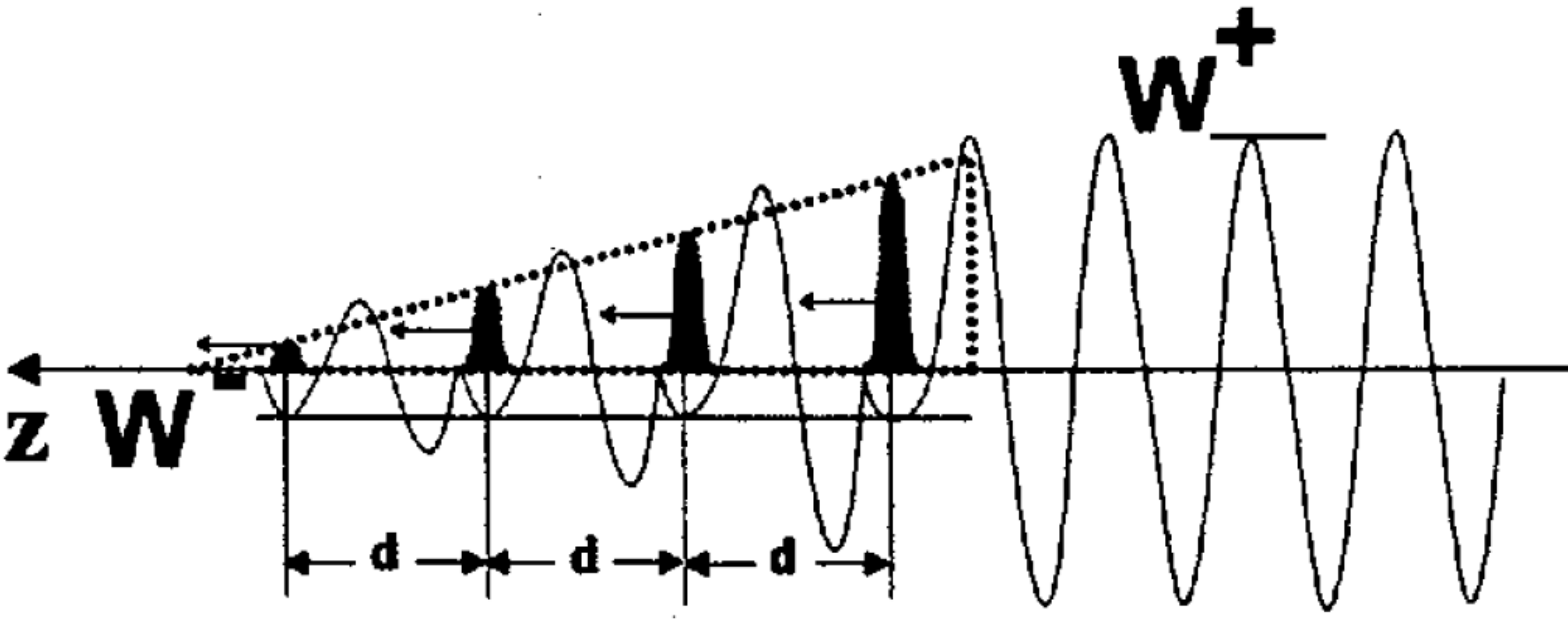
(2) **Long ramp component**:

- Charge neutrality is maintained. Same decelerating field maintained.

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

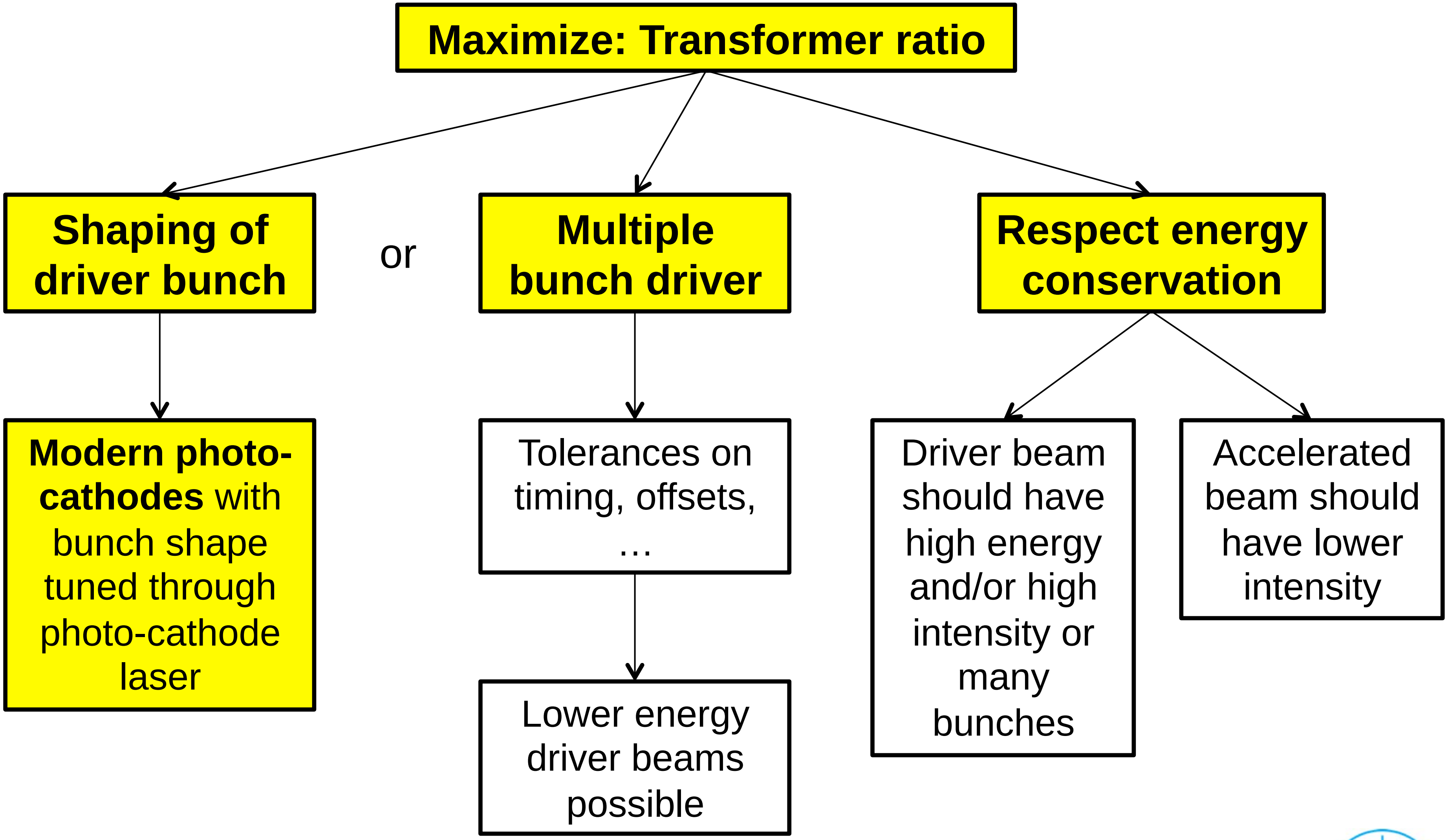
- Plasma channel becomes non-neutral.
- Plasma electrons are strongly attracted back to the ions and large scale plasma oscillations begin.

Alternative: Multi-bunch driven PWFA



Power et al, 2000

Optimization 4: Maximum Energy Gain



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

Blow-Out Regime

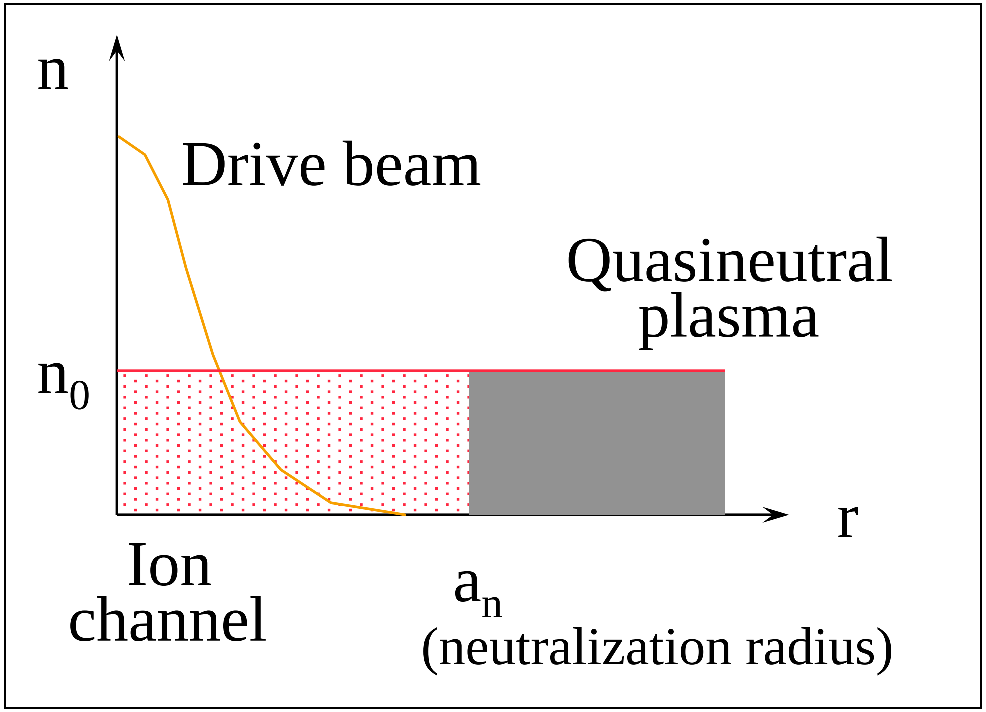
Equilibrium condition:

Ion charge neutralizes beam charge:

$$a_n = \sigma_r \cdot \sqrt{\frac{n_b}{n_0}}$$

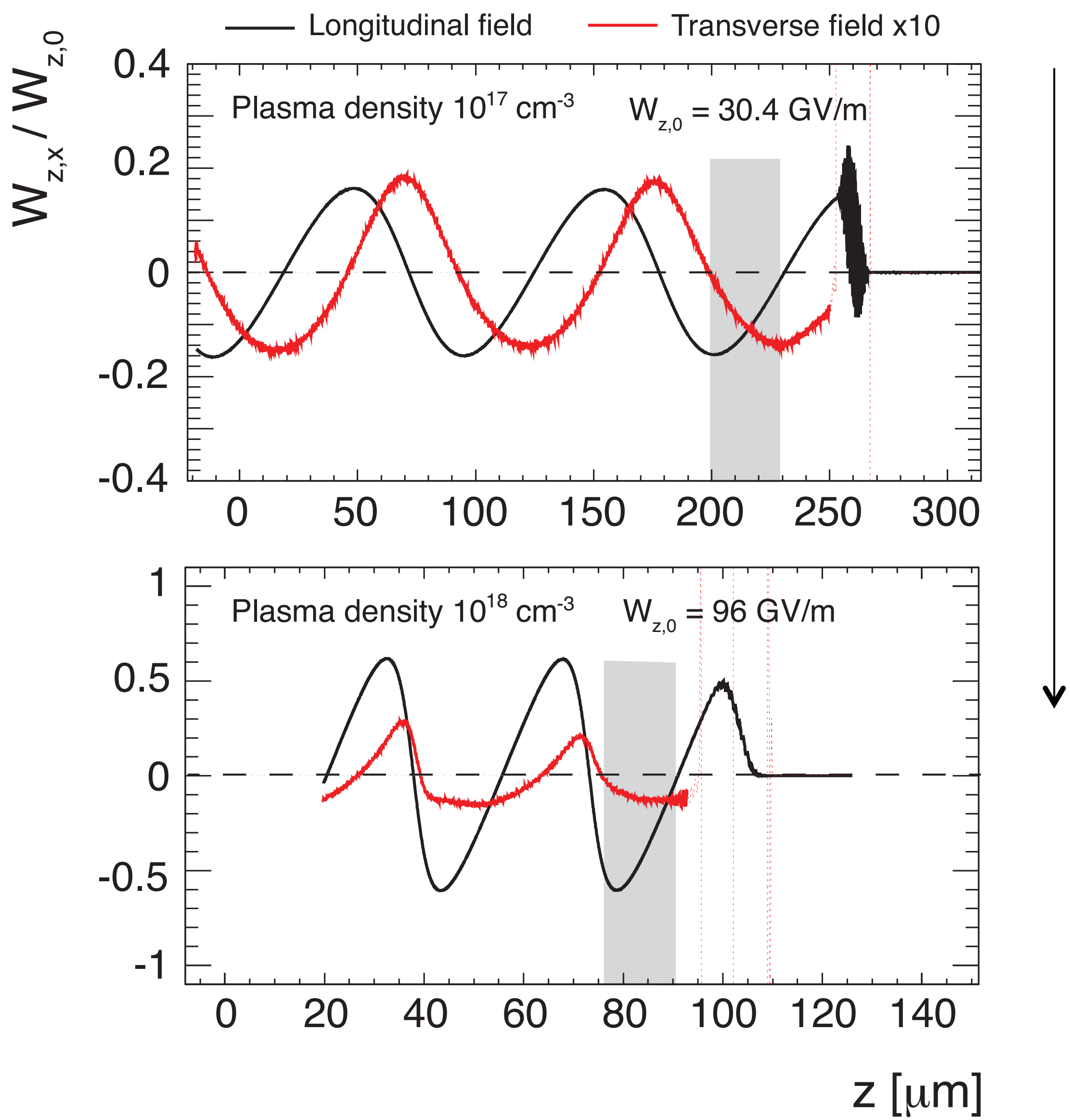
Beam size

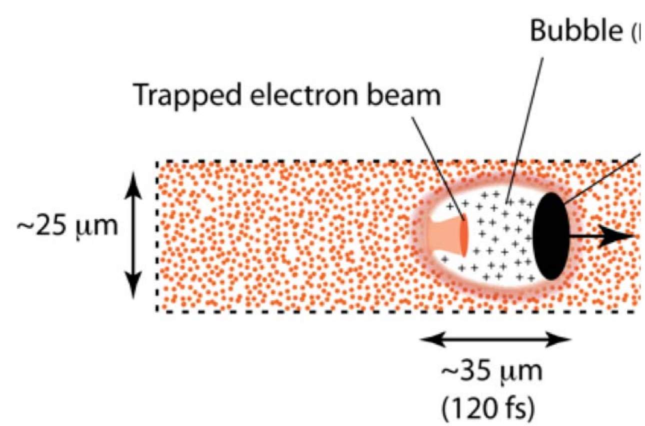
SLC:
$n_b/n_0 = 10$



Beam and plasma densities determine most characteristics of plasma wakefields!

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):

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

9.6 GV/m for 10^{16} cm^{-3}

- The **group velocity of the laser in a plasma** is as follows for $\omega_p \ll \omega_l$: (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.

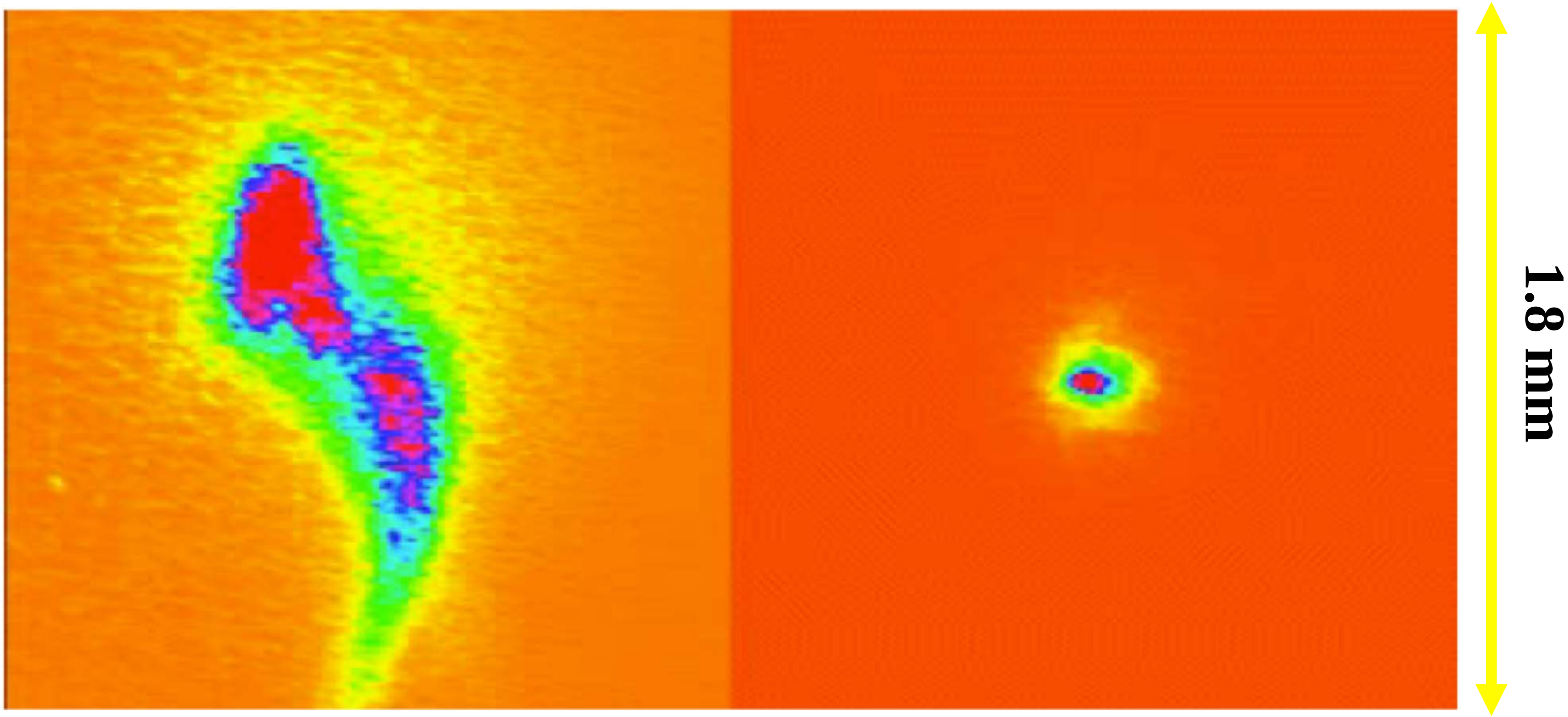
Makes Things Difficult…

> 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…

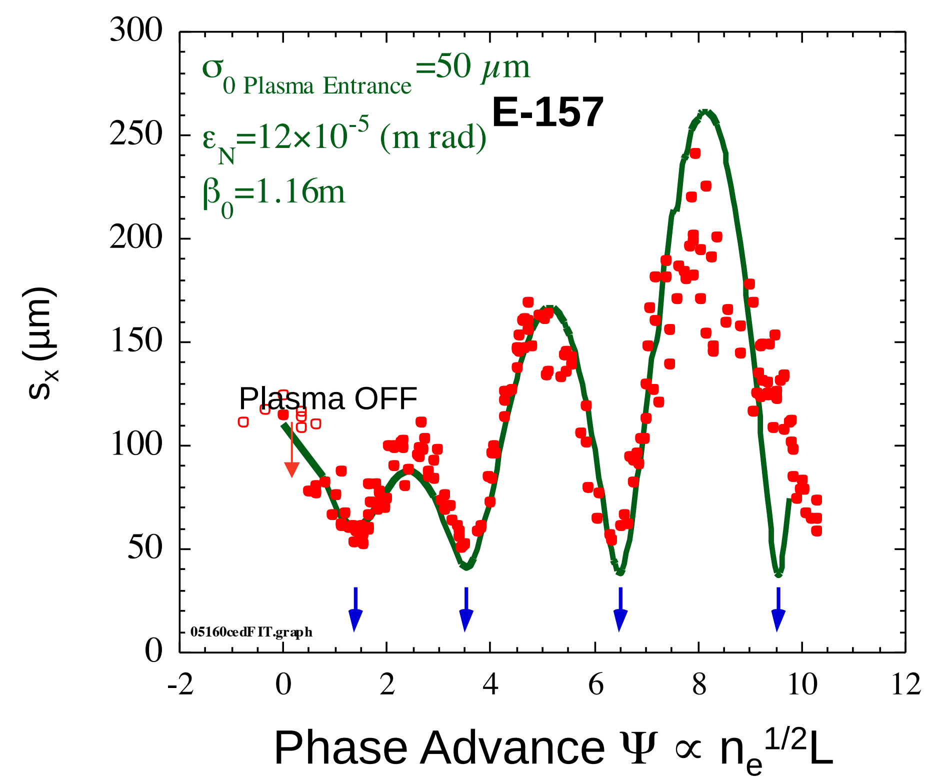


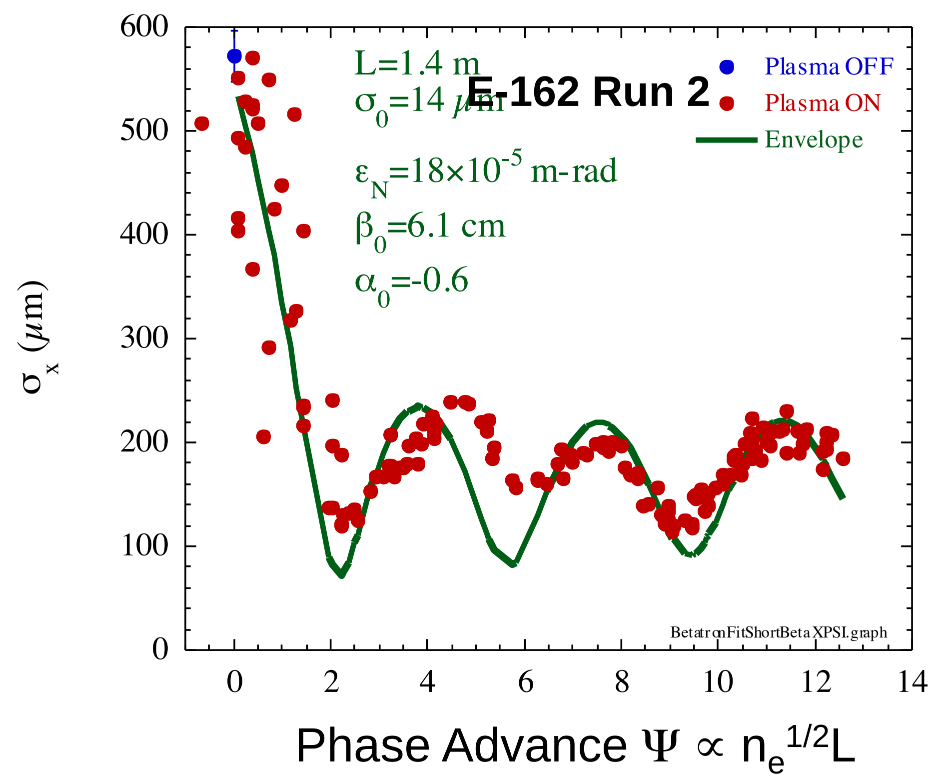
The transverse and longitudinally fields of the accelerator are set up to achieved small transverse beam sizes (right).

~ 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)



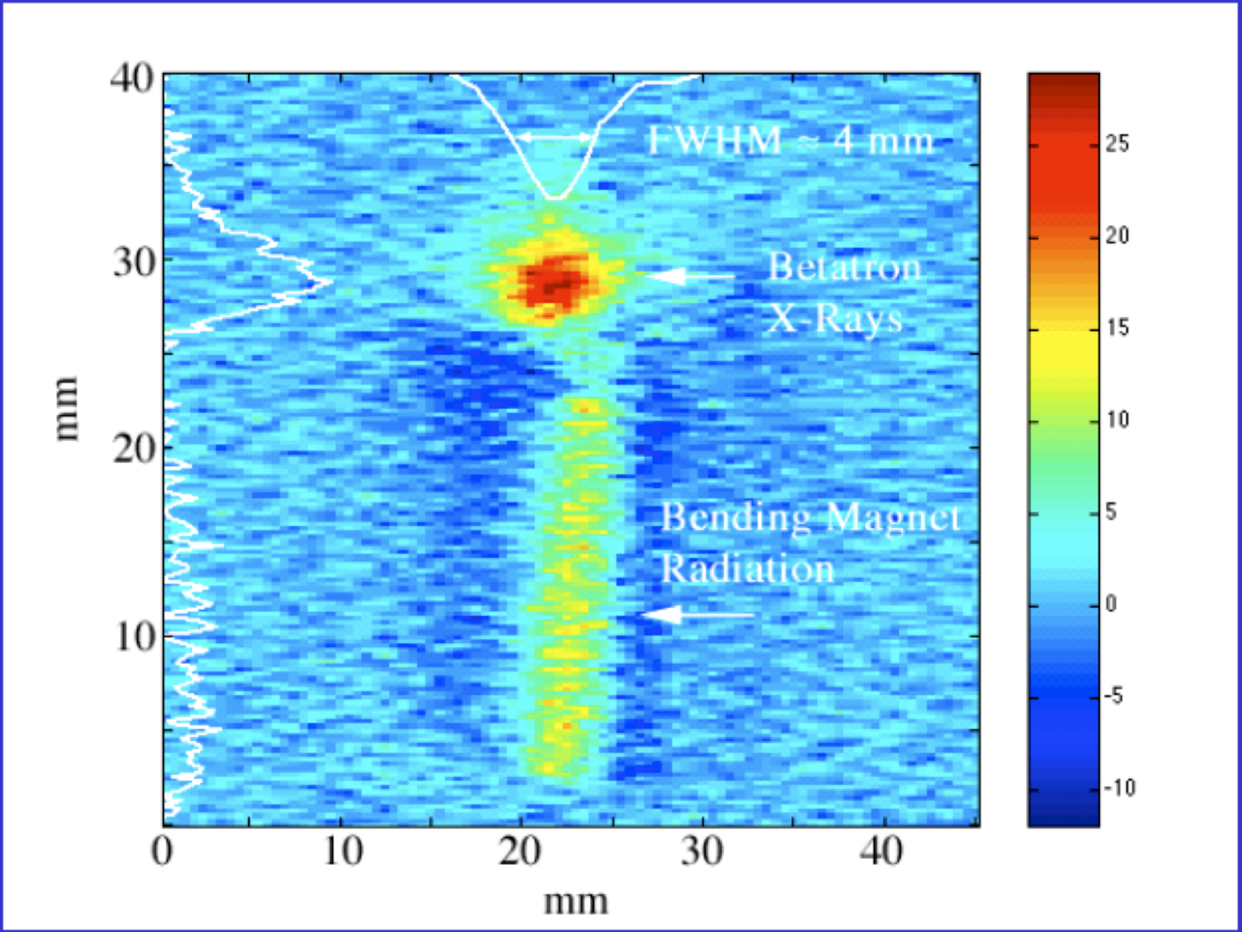


C. E. Clayton et al., PRL 1/2002

E-157/E-162 collaboration

Betatron Radiation of X-rays

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



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

E-157 collaboration

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

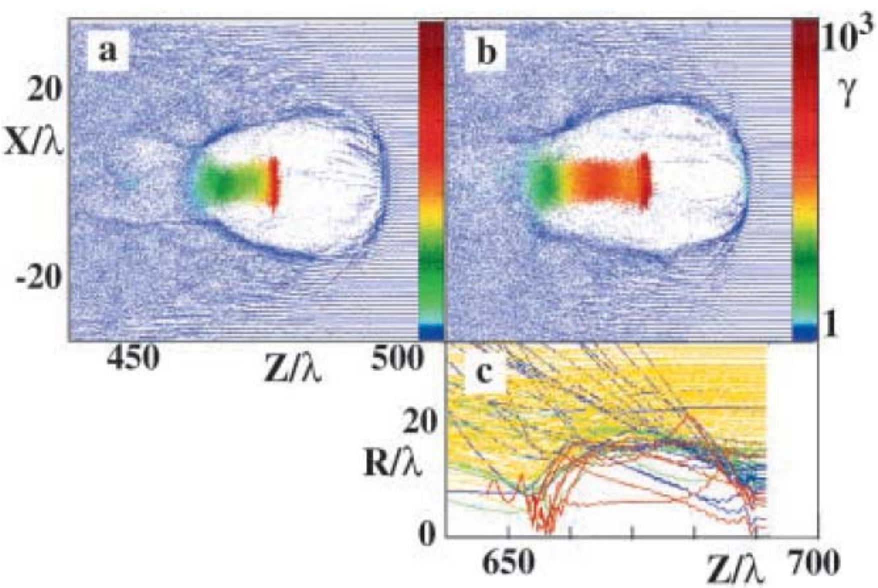
Using the Trapped Electrons

Appl. Phys. B 74, 355–361 (2002)
DOI: 10.1007/s003400200795
Applied Physics B
Lasers and Optics

A. PUKHOV[1,✉]
J. MEYER-TER-VEHN[2]

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

[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

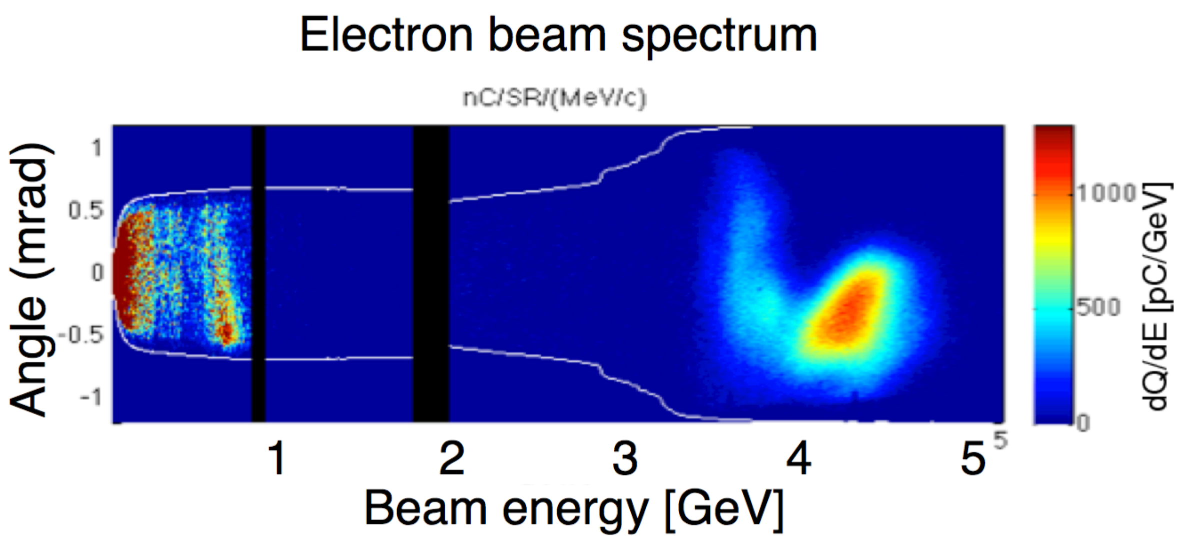


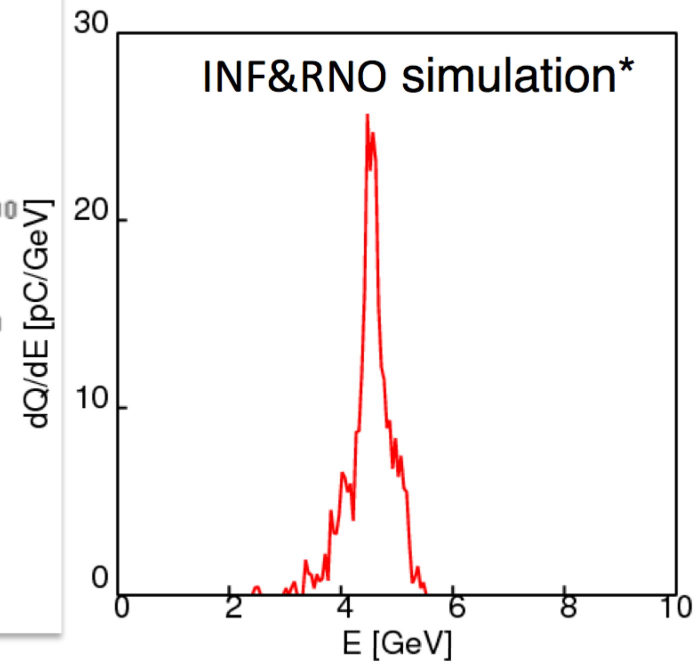
→ See lecture of Alexander Pukhov

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_0~6×10^{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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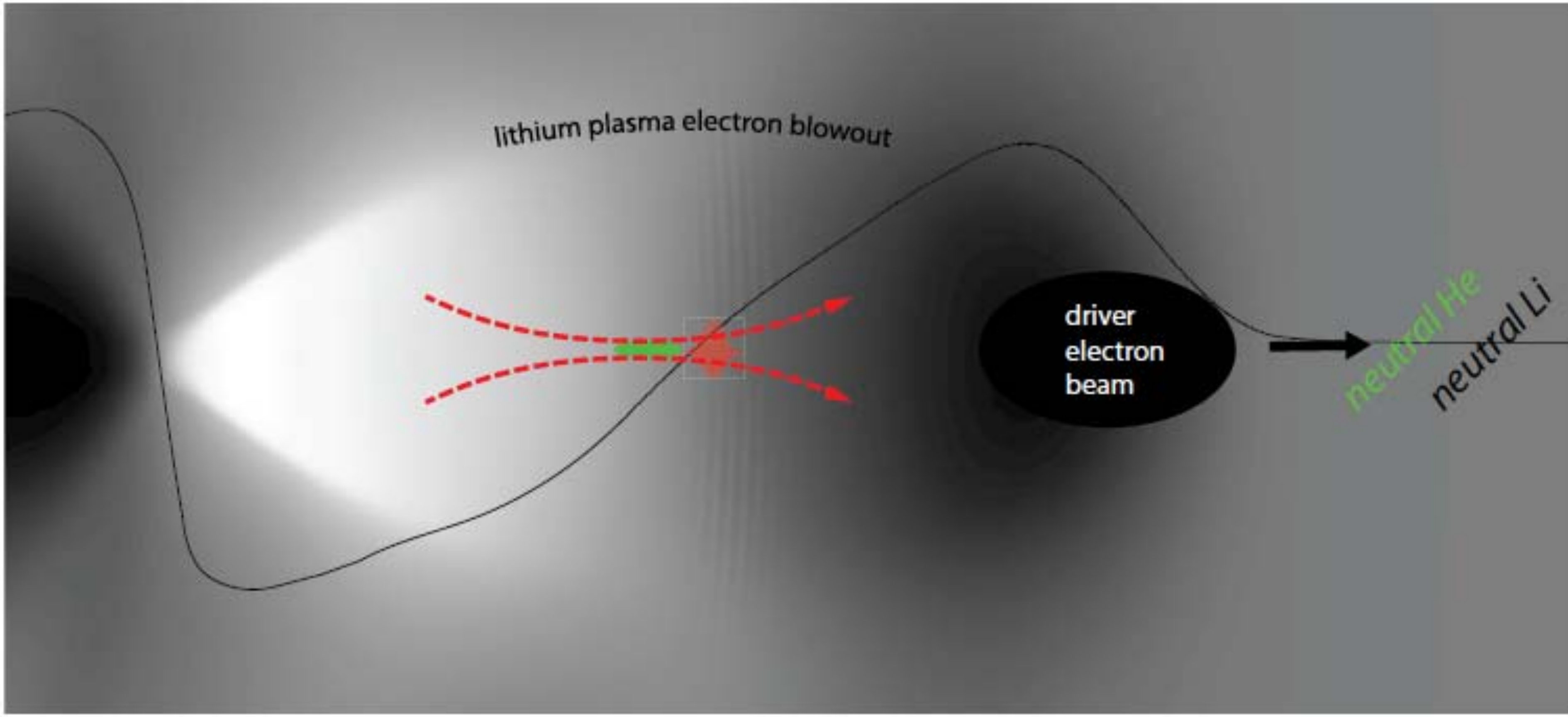
[3]*Tech-X Corporation, Boulder, Colorado 80303, USA*
(Received 30 March 2011; published 17 January 2012)

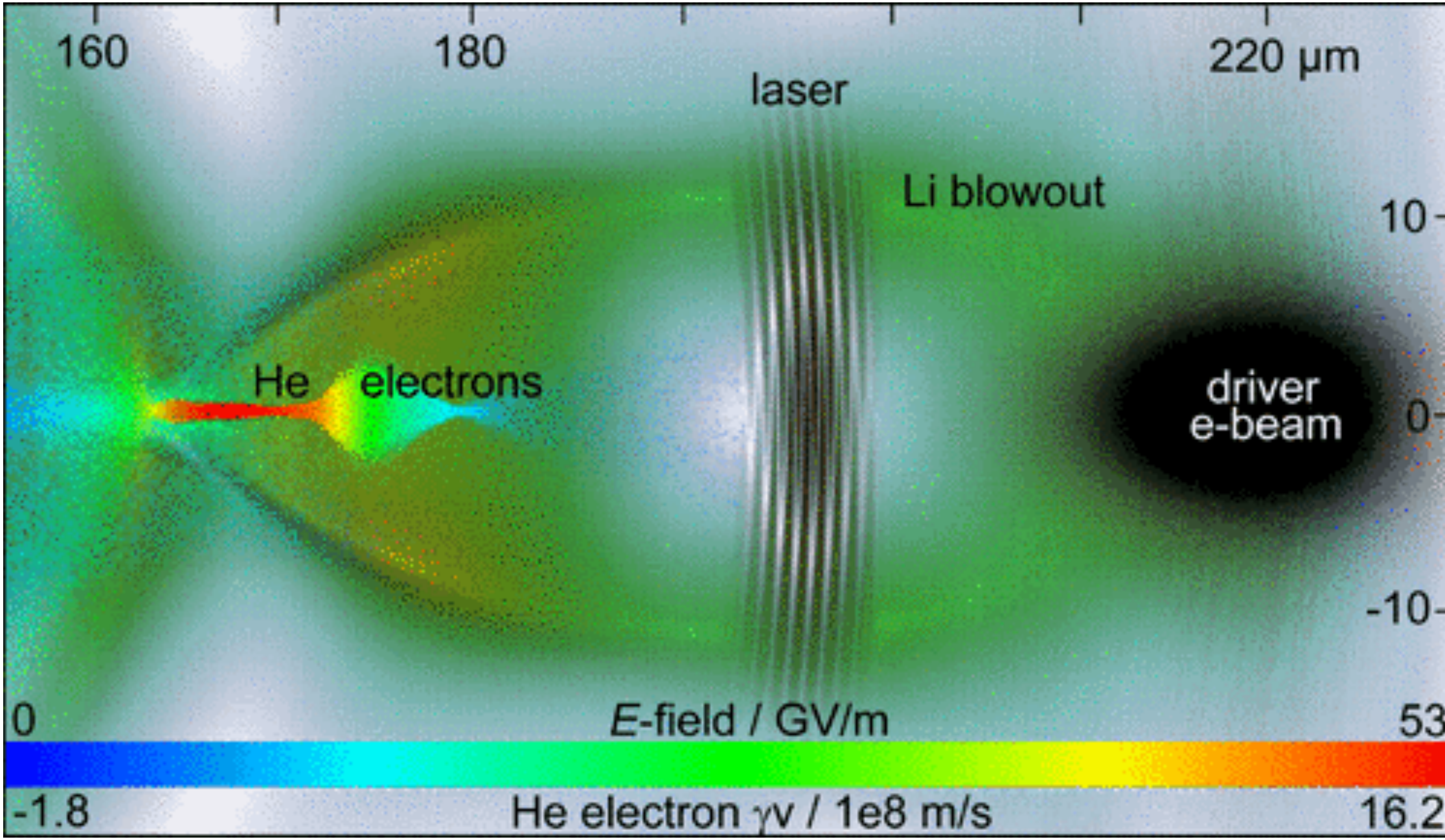
Beam-driven plasma wakefield acceleration using low-ionization-threshold gas such as Li	+	Laser-controlled electron injection via ionization of high-ionization-threshold gas such as He.

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)



Sketch (Hidding et al, 2012)



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

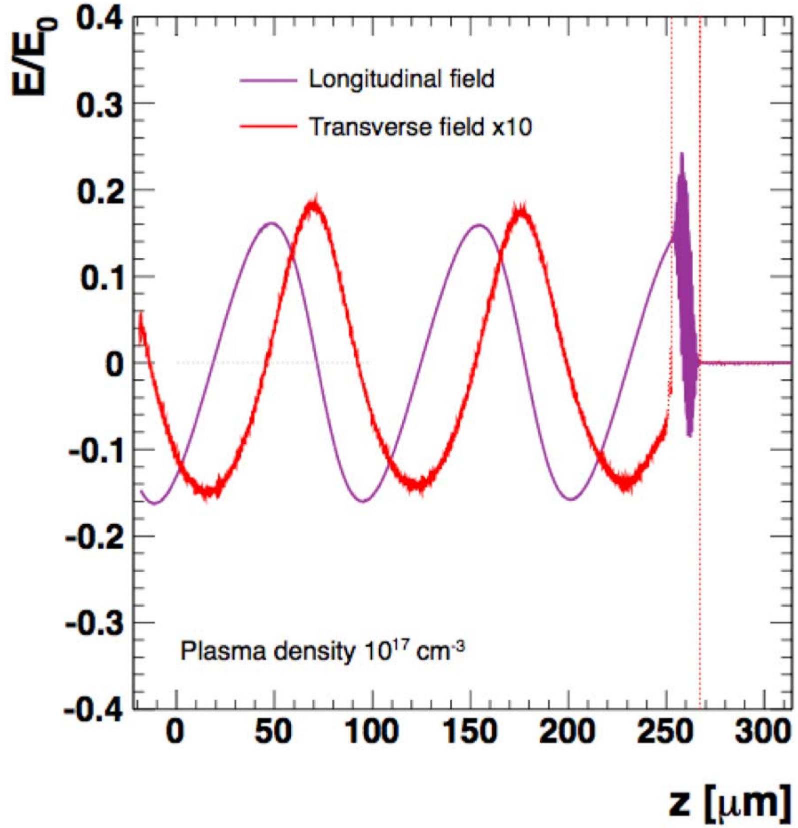
Tolerances and Towards Plasma Accelerators

Beam Dynamics in Plasma Acceleration (J. Grebenyuk, RA)

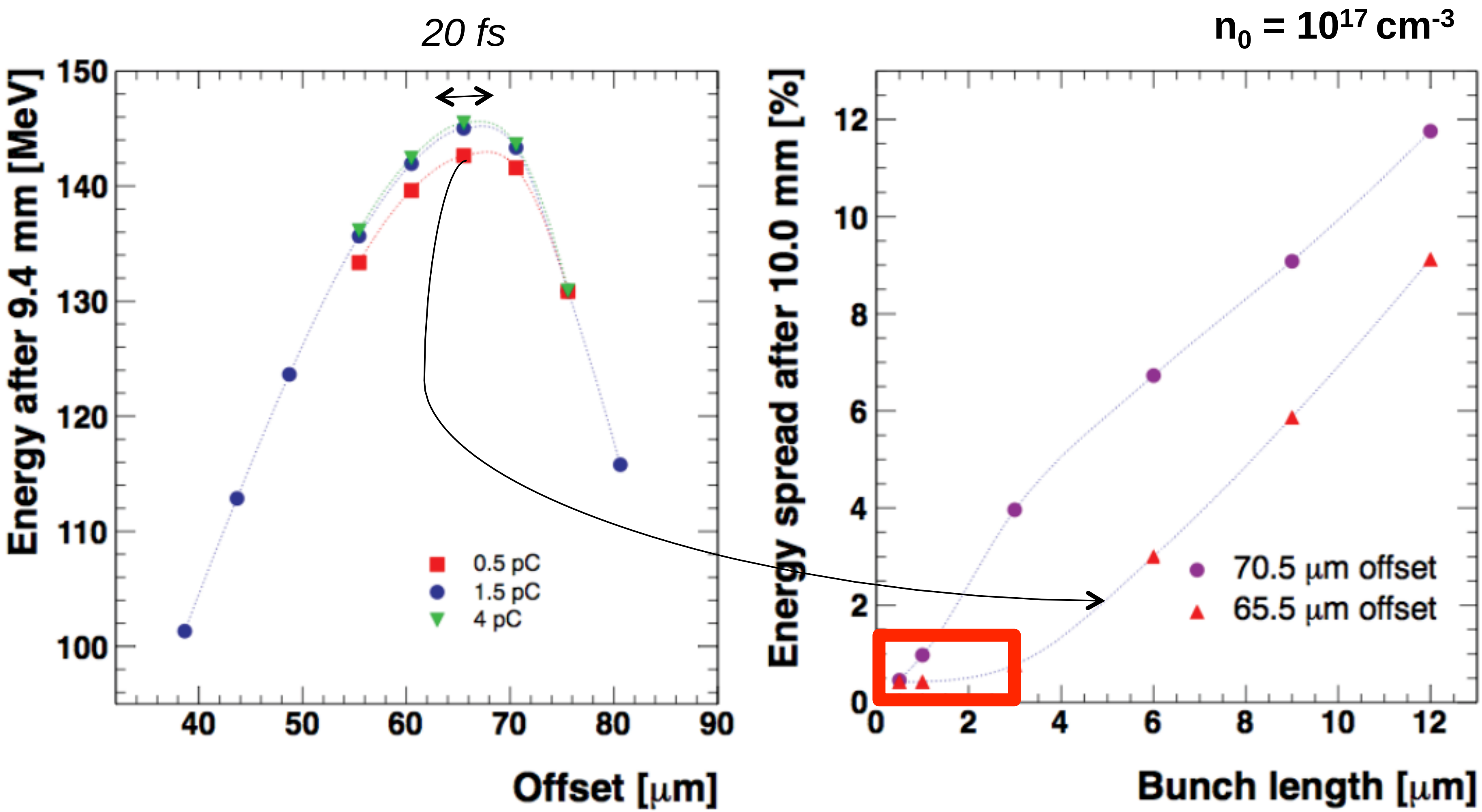
- Energy-spread growth
  - Reason: slope in the accelerating field in the focusing part of the plasma cavity
  - Solution: accelerate bunches which occupy only a small fraction of the plasma wavelength

- Emittance growth (inside plasma)
  - Reason: mismatch of the bunch Twiss parameters to the intrinsic plasma beta
  - Solution: precise transport and matching of the bunch inside plasma

- Emittance growth (after plasma)
  - Reason: chromatic effects due to the energy spread
  - Solution: minimise energy spread



Energy + Energy Spread after ≈ 1 cm Plasma



Beam Loading to Flatten Wakefield *S. van der Meer – T. Katsouleas*

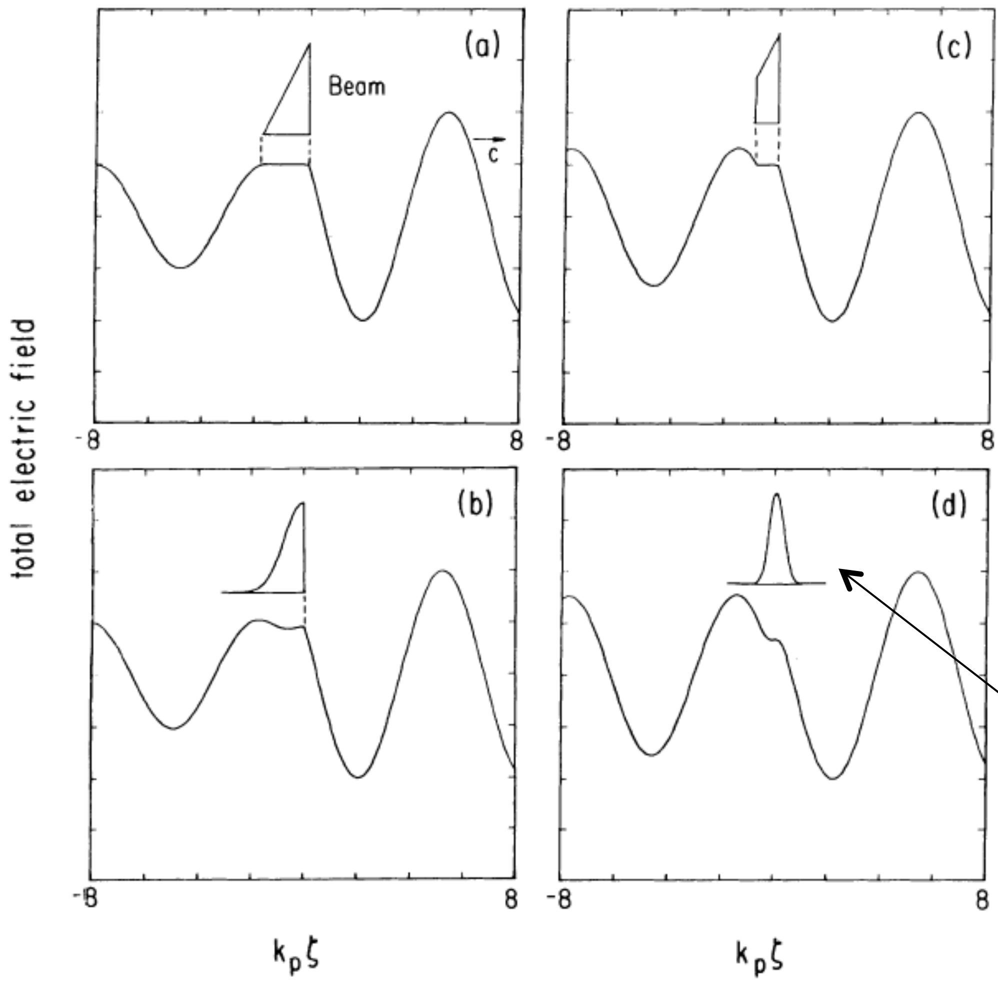


FIGURE 4 Total electric field for various beam shapes: (a) triangle [Eq. (22), $N = 3N_0/4$, $k_p\zeta_0 = \pi/3$), (b) half-Gaussian of same number of particles, (c) truncated triangle ($N = 9N_0/16$), and (d) Gaussian of same number as (c).

- Idea: Simon van der Meer – CLIC Note No. 3, CERN/PS/85-65 (AA) (1985).
- Shape the electron beam to get optimized fields in the plasma, e.g. minimize energy spread.
- Study: Tom Katsouleas.

This case we simulated.
Other cases to come.

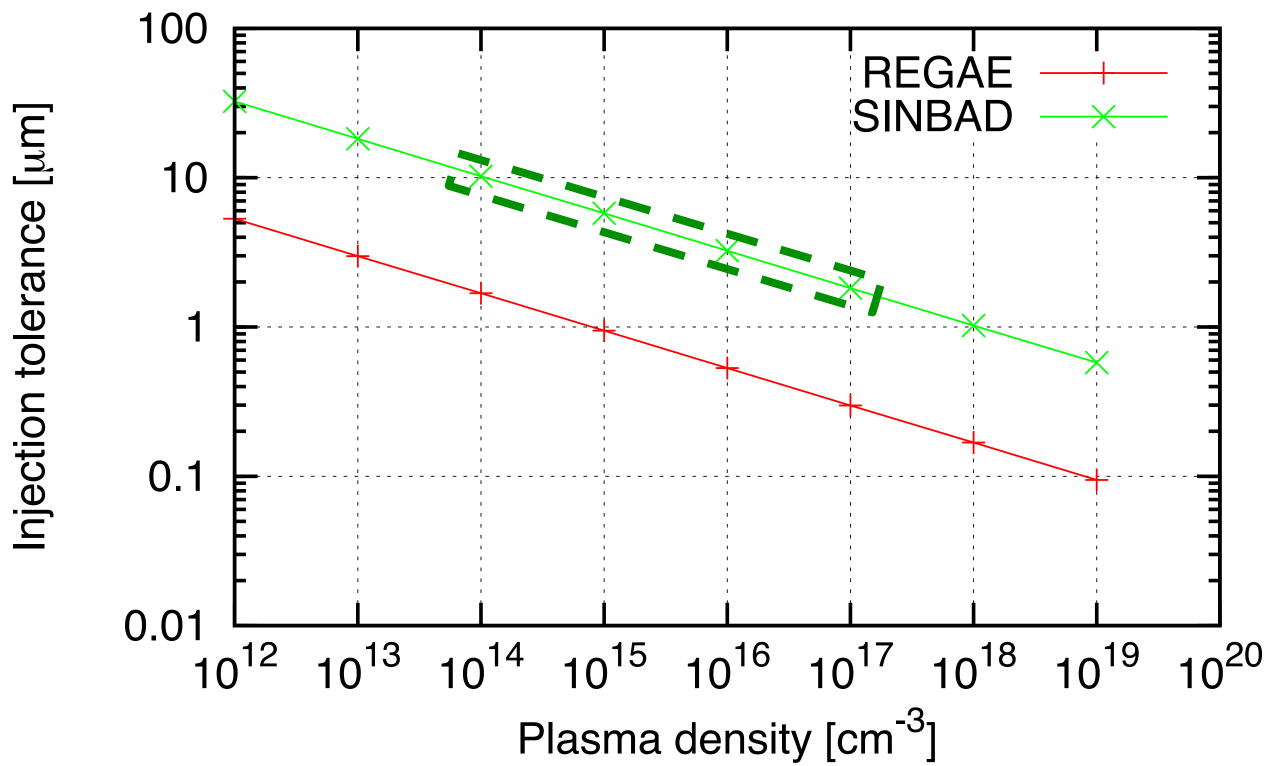
Katsouleas, T., et al. Beam Loading in Plasma Accelerators. Particle Accelerators, 1987, Vol. 22, pp. 81-99 (1987)

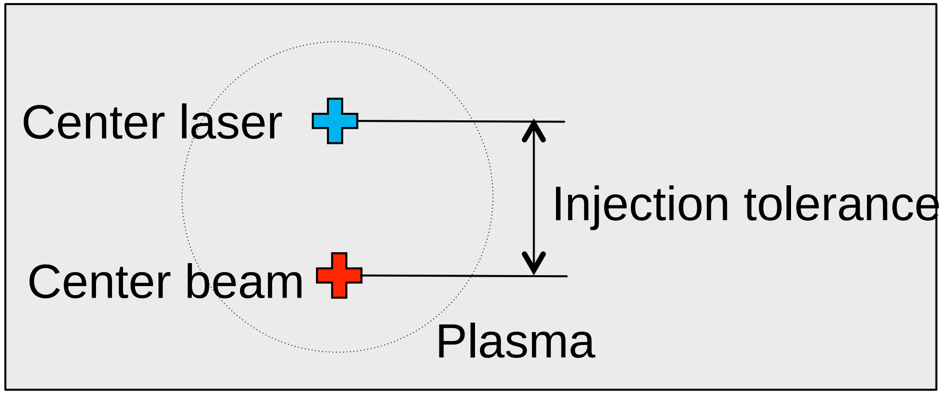
Injection Tolerance: Beam to Plasma Wakefield

- A tolerance for doubling of the initial emittance is calculated.
- Assumptions:
  - δ = 0.1%
  - Full dilution
- Injection tolerances for the considered SINBAD case (100 MeV):

10 µm → 1 µm

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





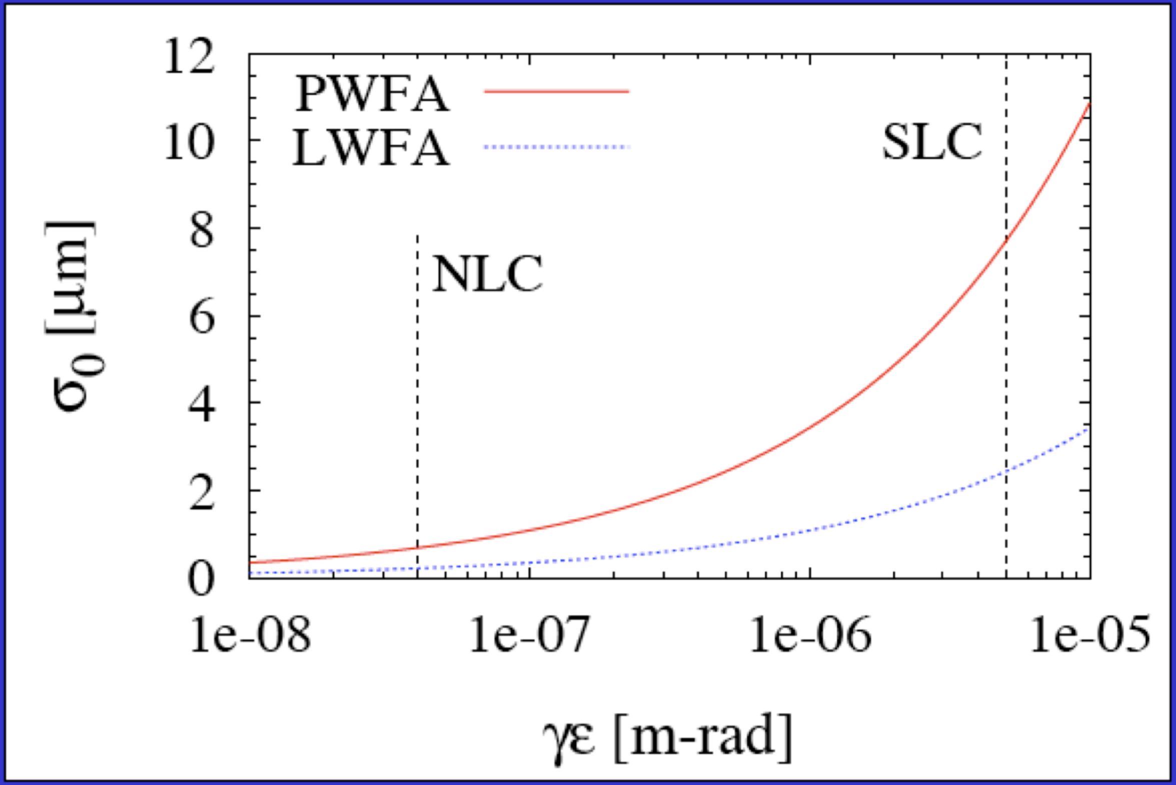
Short accelerator, but what about emittance?

R. Assmann, K. Yokoya, NIM 1997

Parameter	PWFA	LWFA
Acceleration	1 GeV/m	30 GeV/m
Wavelength	2 mm	100 μm
Focusing field	6,000 T/m	600,000 T/m
Module length	6 m	1 m
Injection energy	1 GeV	1 GeV
Final energy	1 TeV	1 TeV
Acc. length	1 km	33 m

Emittance Growth II

Matched beam size at injection energy:



NLC type emittance requires sub-micron spot size!

$4\ 10^{-8}$ m rad

Emittance Growth III

Tolerance for alignment beam - plasma wakefield:

- emittance 4 10^{-8} m rad with **200%** emittance growth
- Number of plasma cells: 167 or 33 (LWFA)

RMS alignment tolerance: < **300 nm** (PWFA) **30 nm** (LWFA)

High energy plasma-wakefield accelerator will have difficult alignment problems, but...

New ideas: Hollow plasma channels

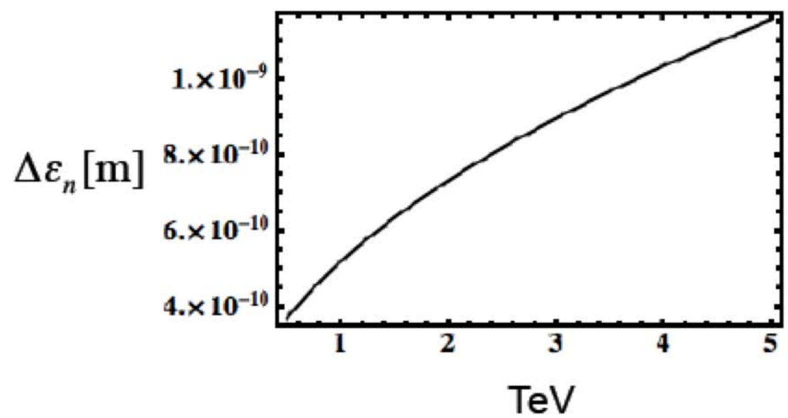
No ions on axis, no focusing!
Acceleration still works...

Emittance Growth IV

Emittance Growth via scattering < nm

Total emittance growth over accelerator: $\Delta\varepsilon_n \approx Z r_e \Phi \ln\left(\frac{\lambda_D}{R_a}\right)\left[\sqrt{\gamma_f} - \sqrt{\gamma_i}\right]$

H (fully-ionized)
$k_B T_e$=10 eV
a_0=1
n=10^{17} cm^{-3}
r_L= 63 micron
Ψ = 10°



- Strong focusing yields tighter alignment tolerances
  - May require new techniques and advanced beam-based alignment methods
- In principle, hollow plasma channel may be used to eliminate scattering

Schroeder et al., AAC08 Proceedings (2009)

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

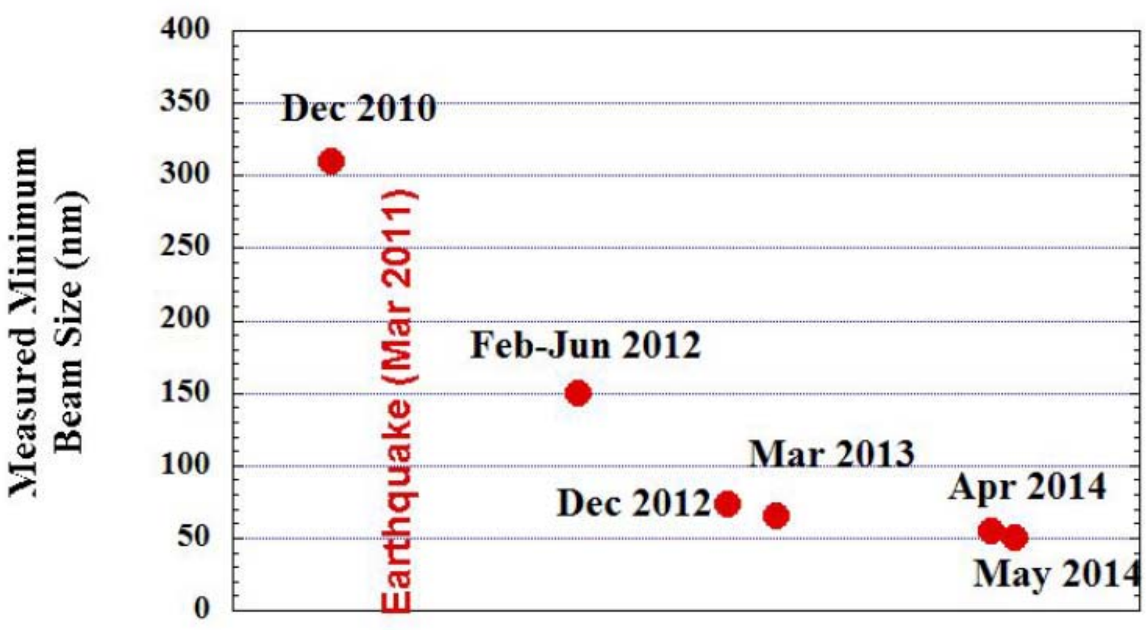
- Match into/out of plasma with **beam size ≈1 μm** (about 1 mm beta function). Adiabatic matching (Whittum, 1989).
- Control **offsets** between the wakefield driver (laser or beam) and the accelerated electron bunch at **1 μm level**.
- Use **short bunches (few fs)** to minimize energy spread.
- Achieve **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 <u>low as possible plasma densities</u> to start in most simple conditions. Larger matched beam size, relaxed tolerances, …
- The success will be all in <u>accuracy, tolerances, precision</u>! We mastered this in conventional accelerators.
- Do the same for plasma accelerators!

Accelerator Builder's Challenge – Feasible?

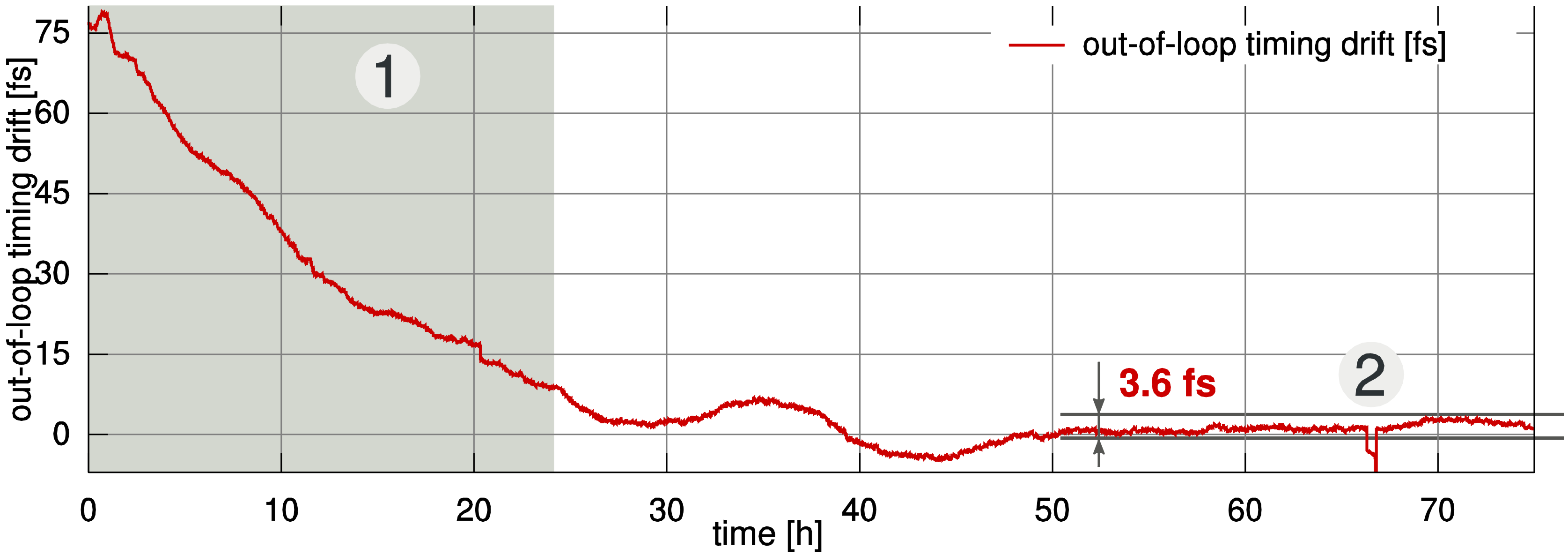
> Difficult but we believe solutions can be found. Will not come for free…



50 nm with a 1.3 GeV electron beam
(from K. Kubo et al. Proc. IPAC 2014)

Accelerator Builder's Challenge – Feasible?

> Difficult but we believe solutions can be found. Will not come for free…

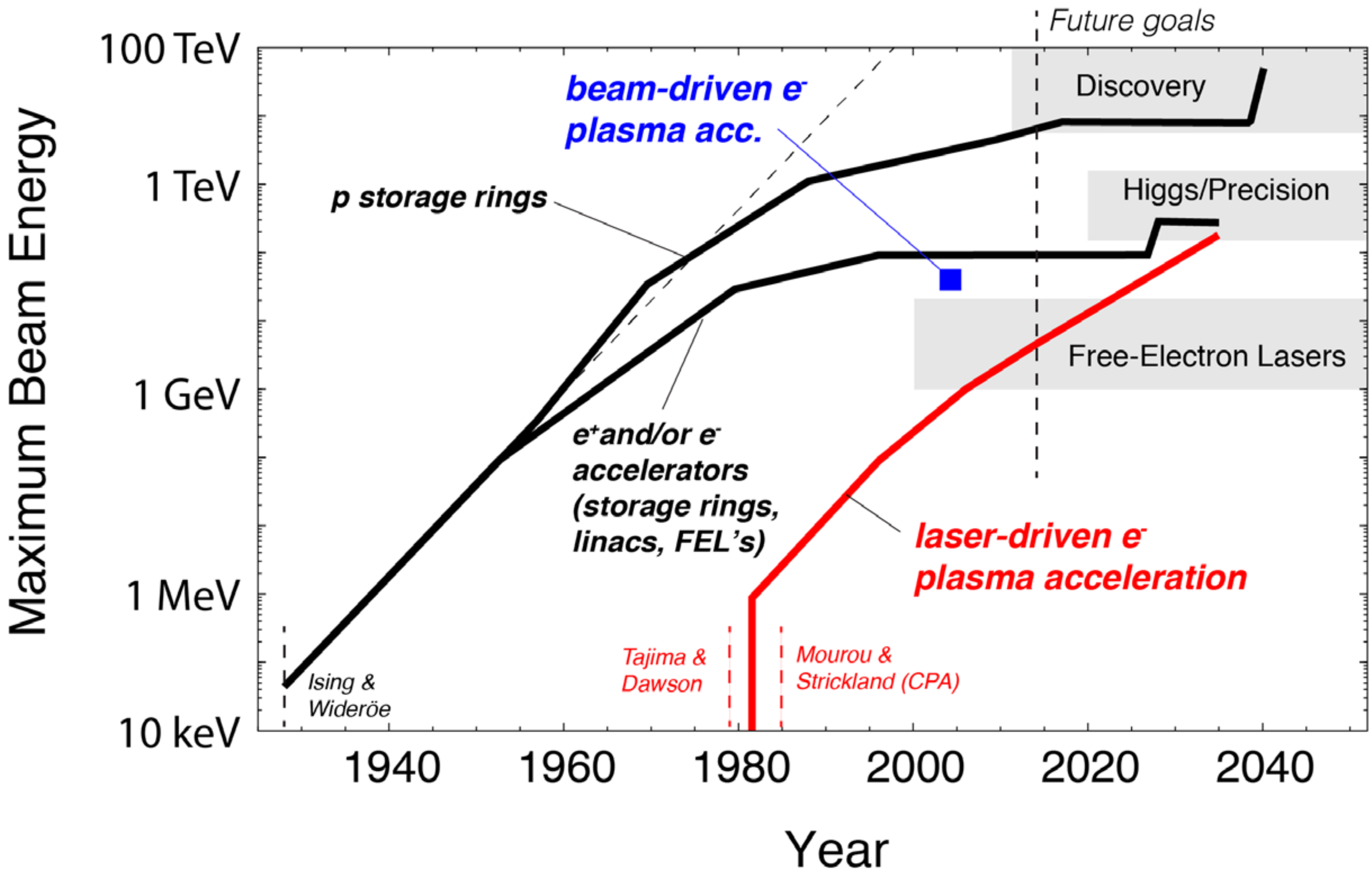


Femtosecond Precision in Laser-to-RF Phase Detection

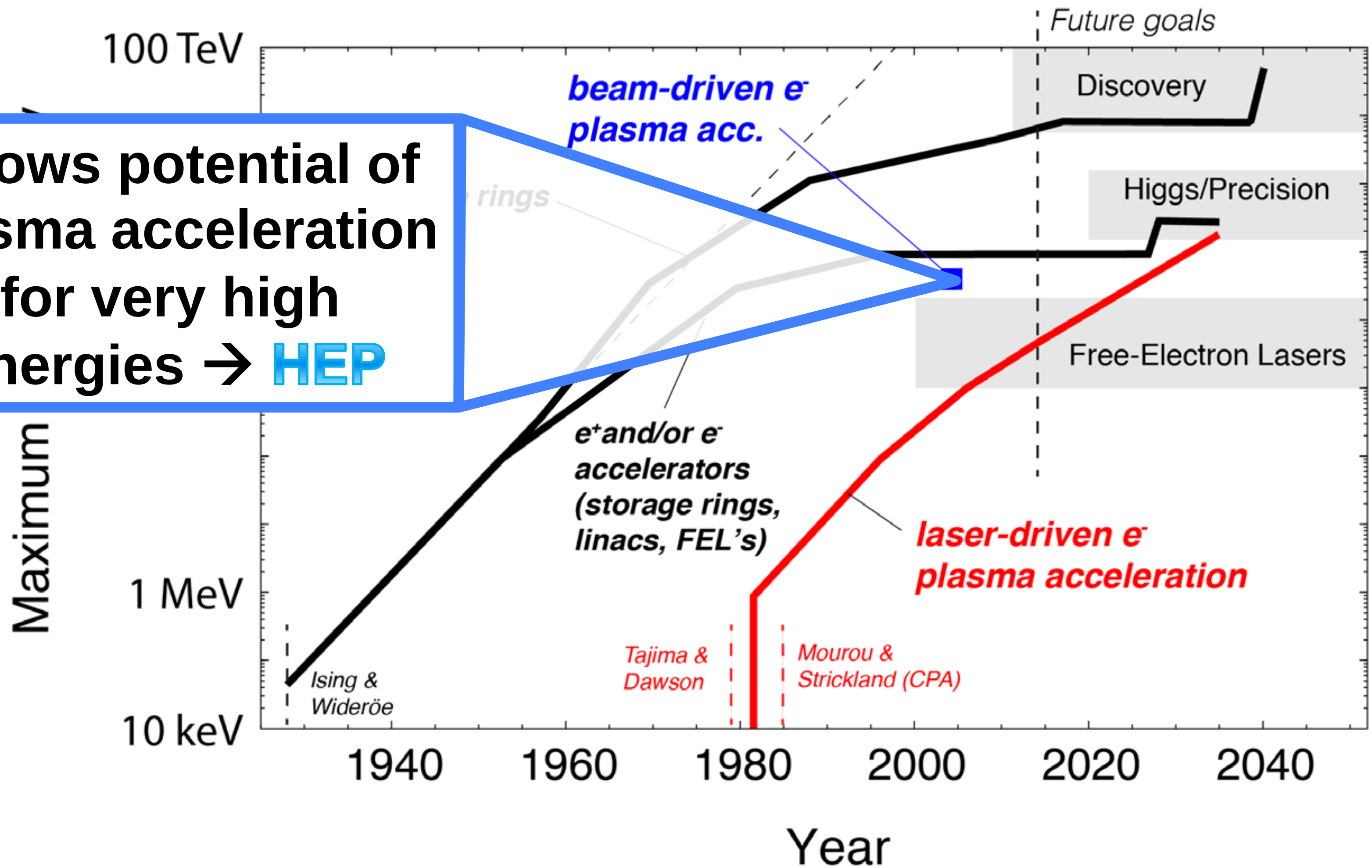
(from H. Schlarb, T. Lamb, E. Janas et al. Report on DESY Highlights 2013).

> Again: **No fundamental limit here, but strong technical challenges!**

Livingston and Accelerators at the Energy Frontier

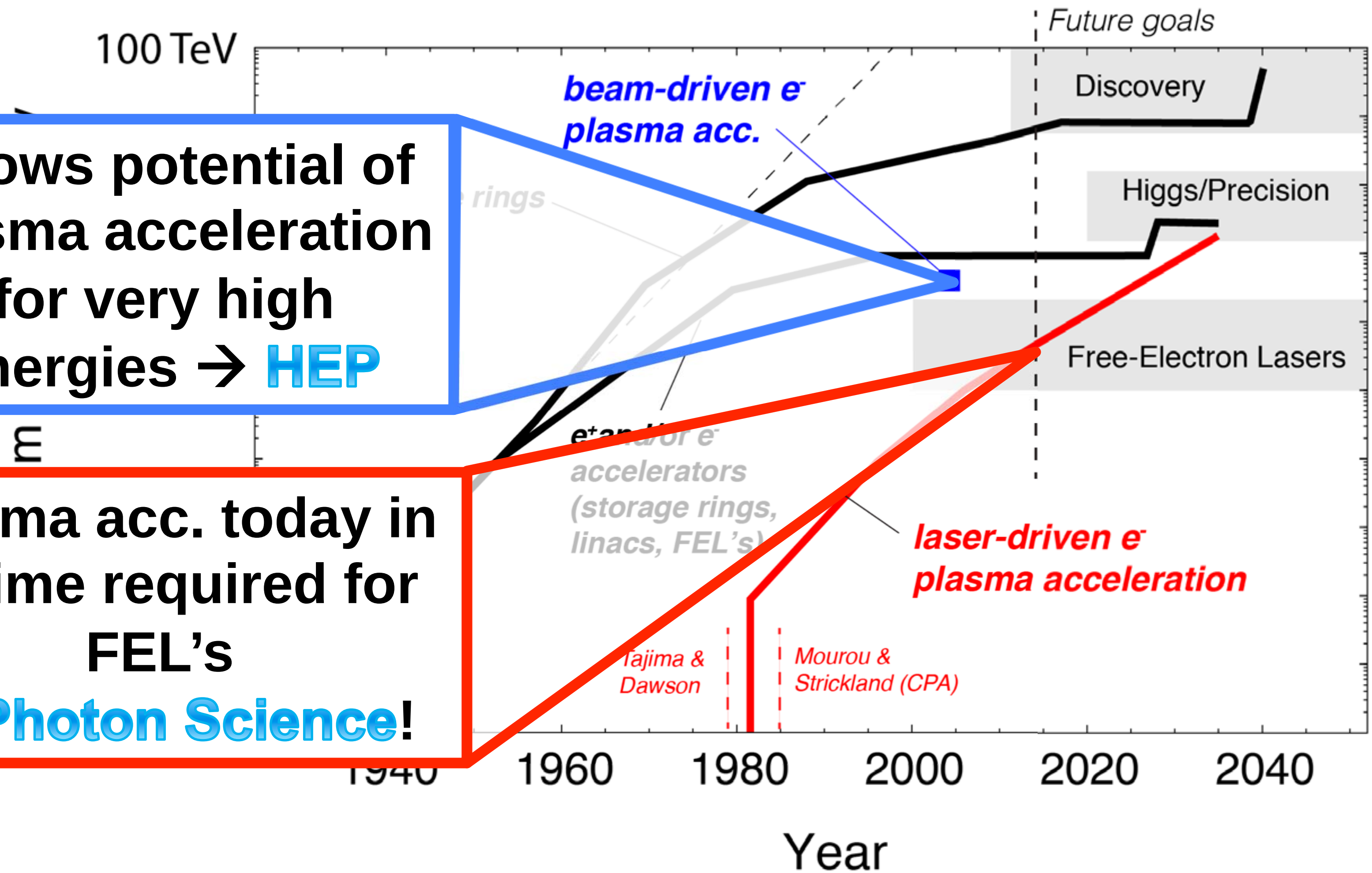


Livingston and Accelerators at the Energy Frontier



Shows potential of plasma acceleration for very high energies → HEP

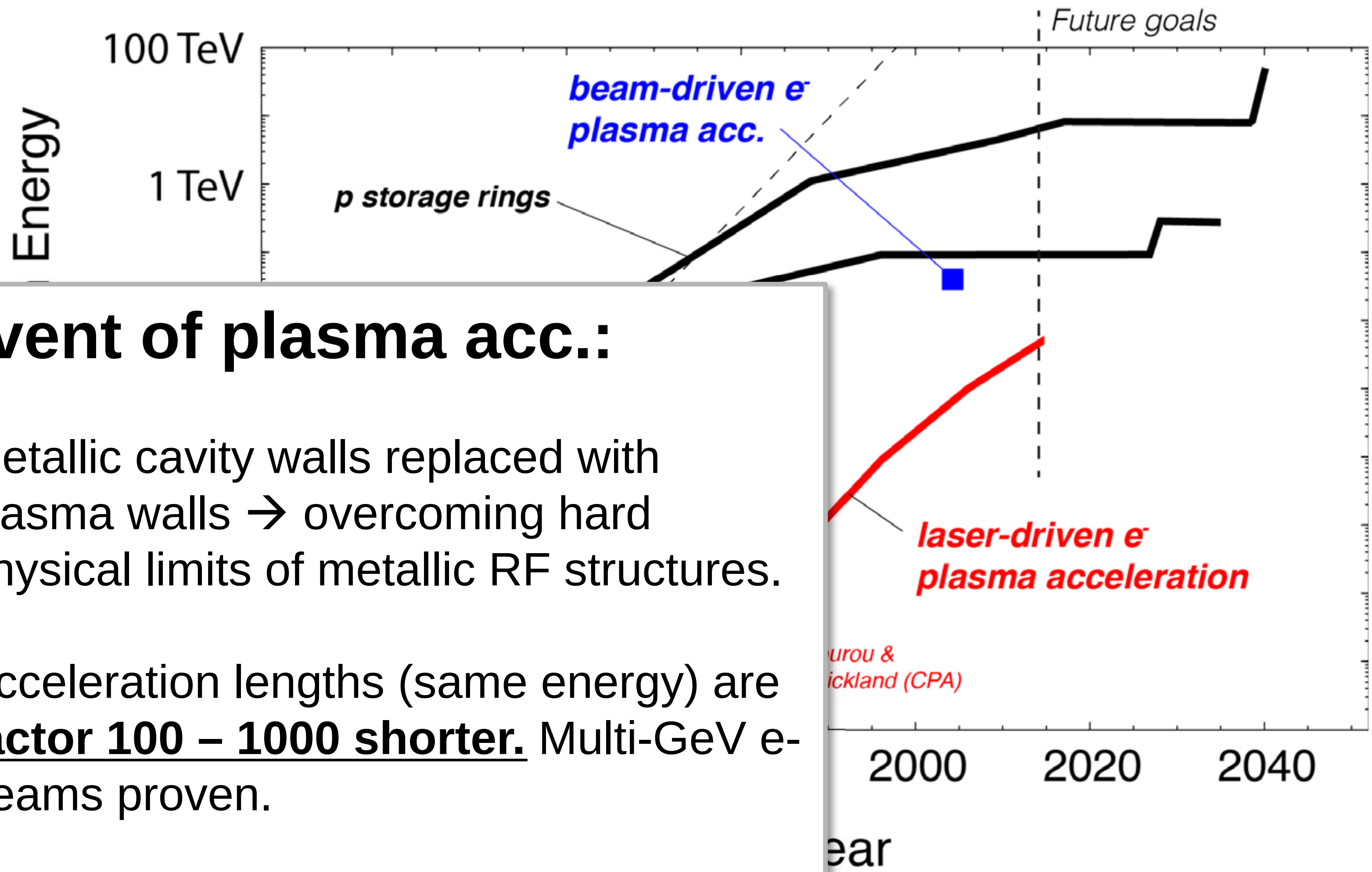
Livingston and Accelerators at the Energy Frontier



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



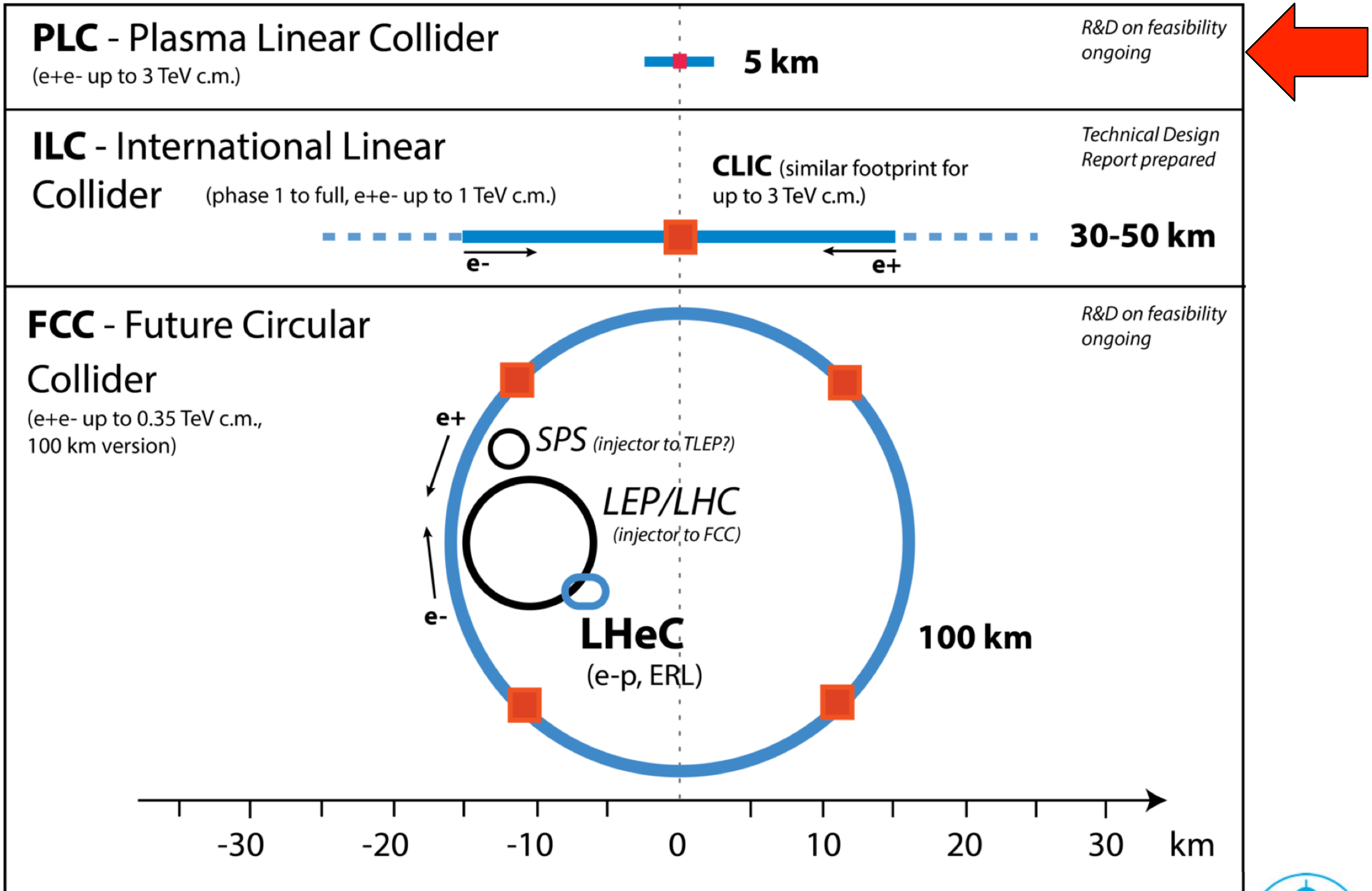
Advent of plasma acc.:

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?



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…