Laser Plasma Acceleration

R.W. Aßmann

Leading Scientist DESY

JUAS Seminar

Archamps, 1.2.2017

Accelerator Research and Development
ARD
A program by the Helmholtz association

HELMHOLTZ ASSOCIATION

European Network EuroNNAc for Novel Accelerators

EuCARD²

DESY

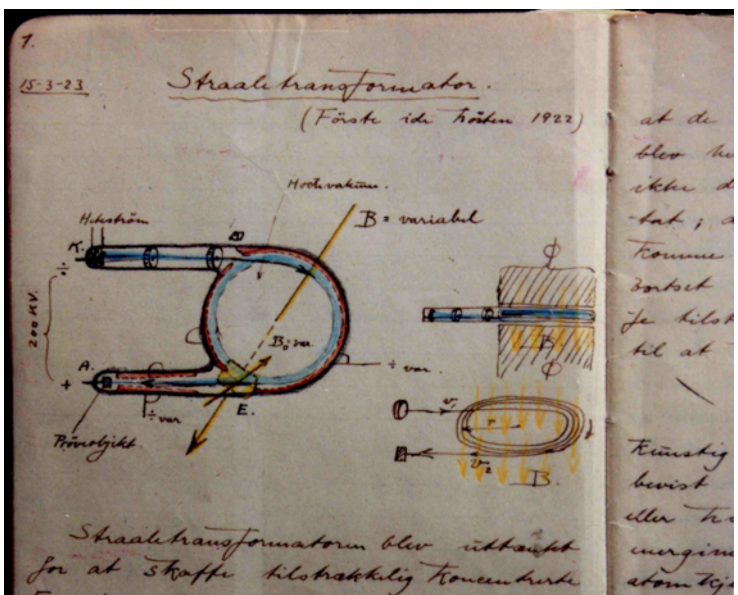
Content

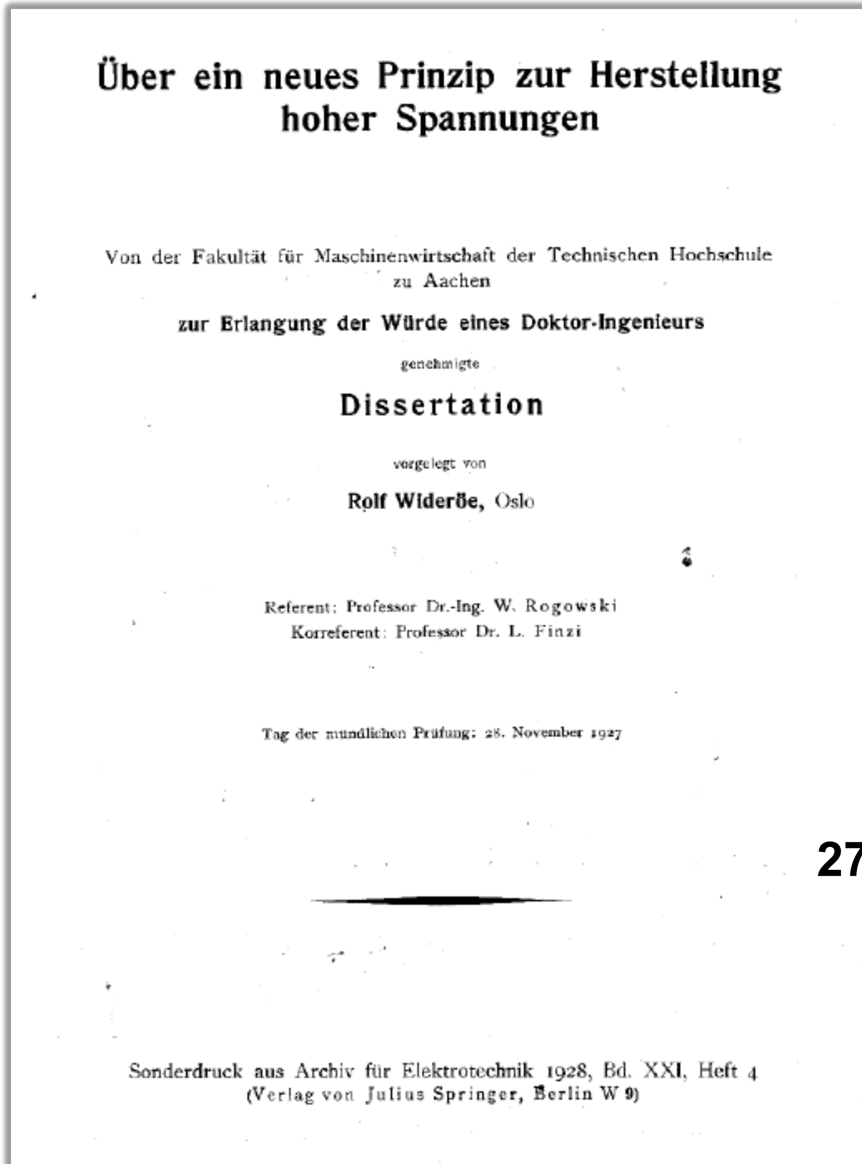
1. Accelerators – From Conventional Techniques to Plasmas
2. The Linear Regime
3. Tolerances
4. Outlook for Europe

Content

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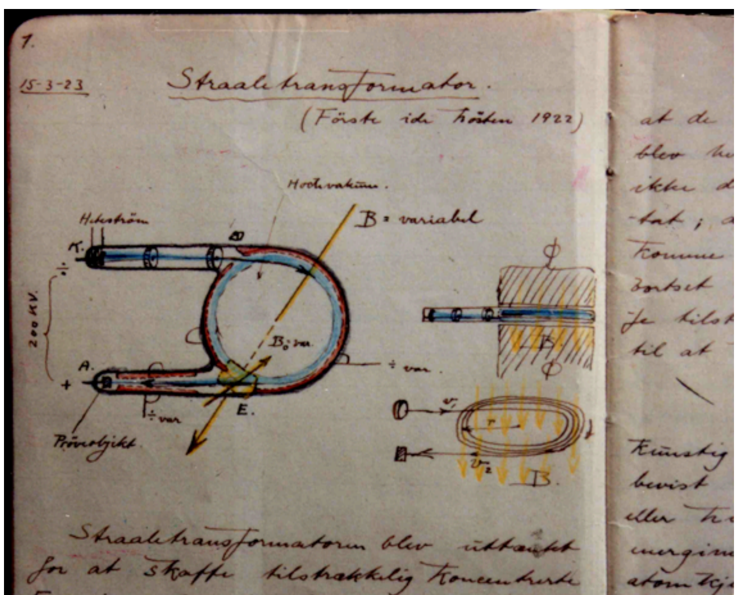

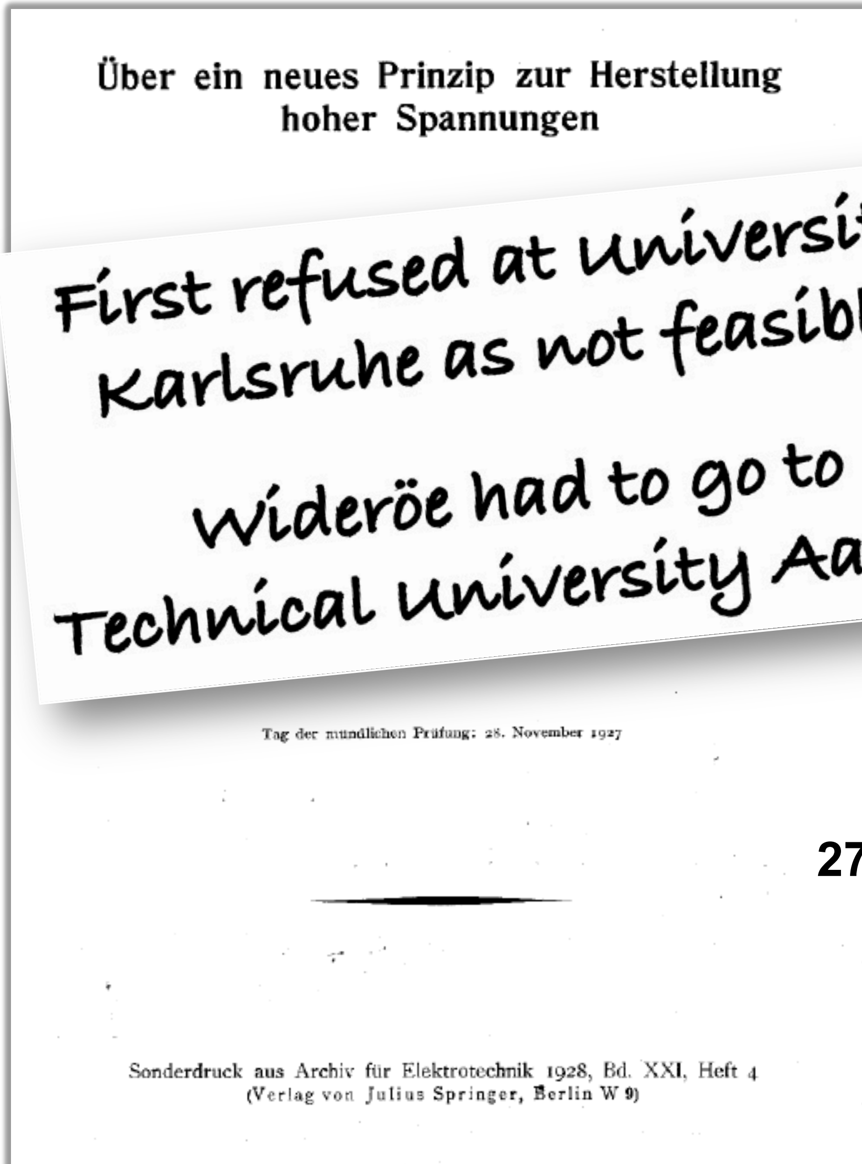

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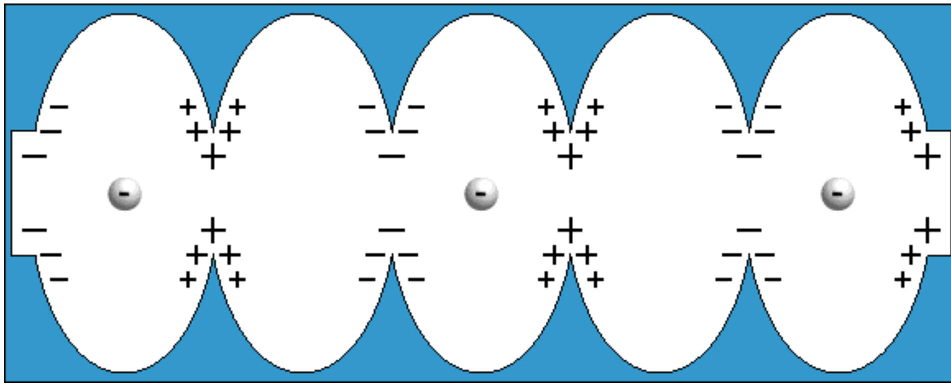
First refused at University Karlsruhe as not feasible!

Wideröe had to go to Technical University Aachen

27 pages

Electron Acceleration: The Success of RF

- Higher energies with **alternating voltage („RF“)**:



Sketch Padamse, Tigner

“Runzelröhre”

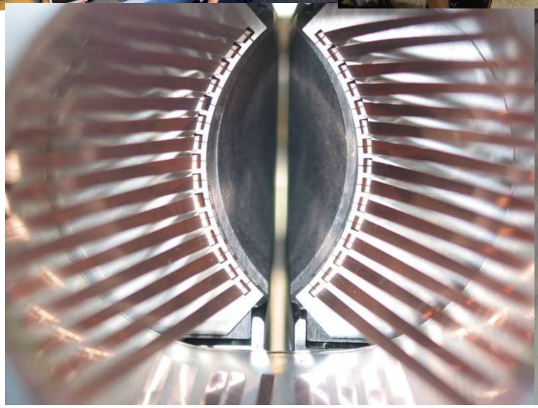
<u>20.000.000 Volt per Meter</u>

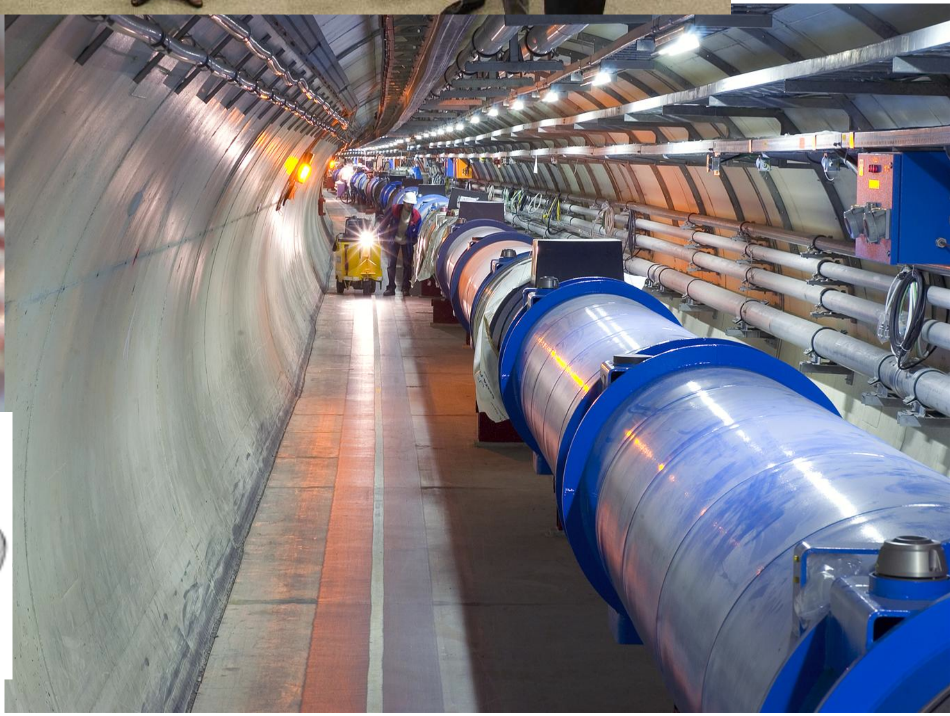
- **RF technology** (first shown by Wideröe 90 years ago) a tremendous success story.
- Lesson: Never give up if up, if colleagues say it does not work – unless they can prove it to you by scientific means.

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

Higgs Sem. 4.7. 2012

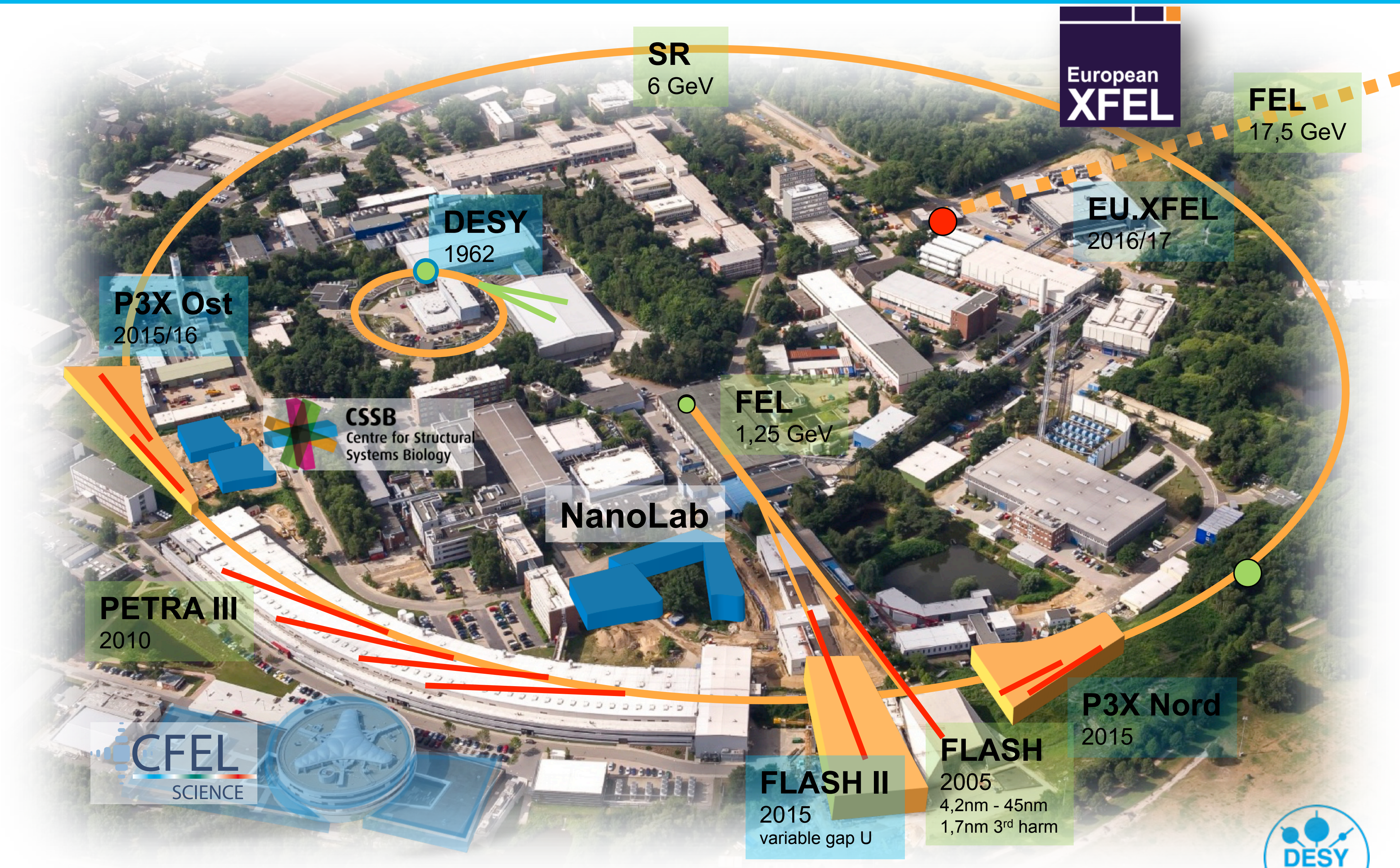
First beam 10.9. 2008





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

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

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

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

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

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

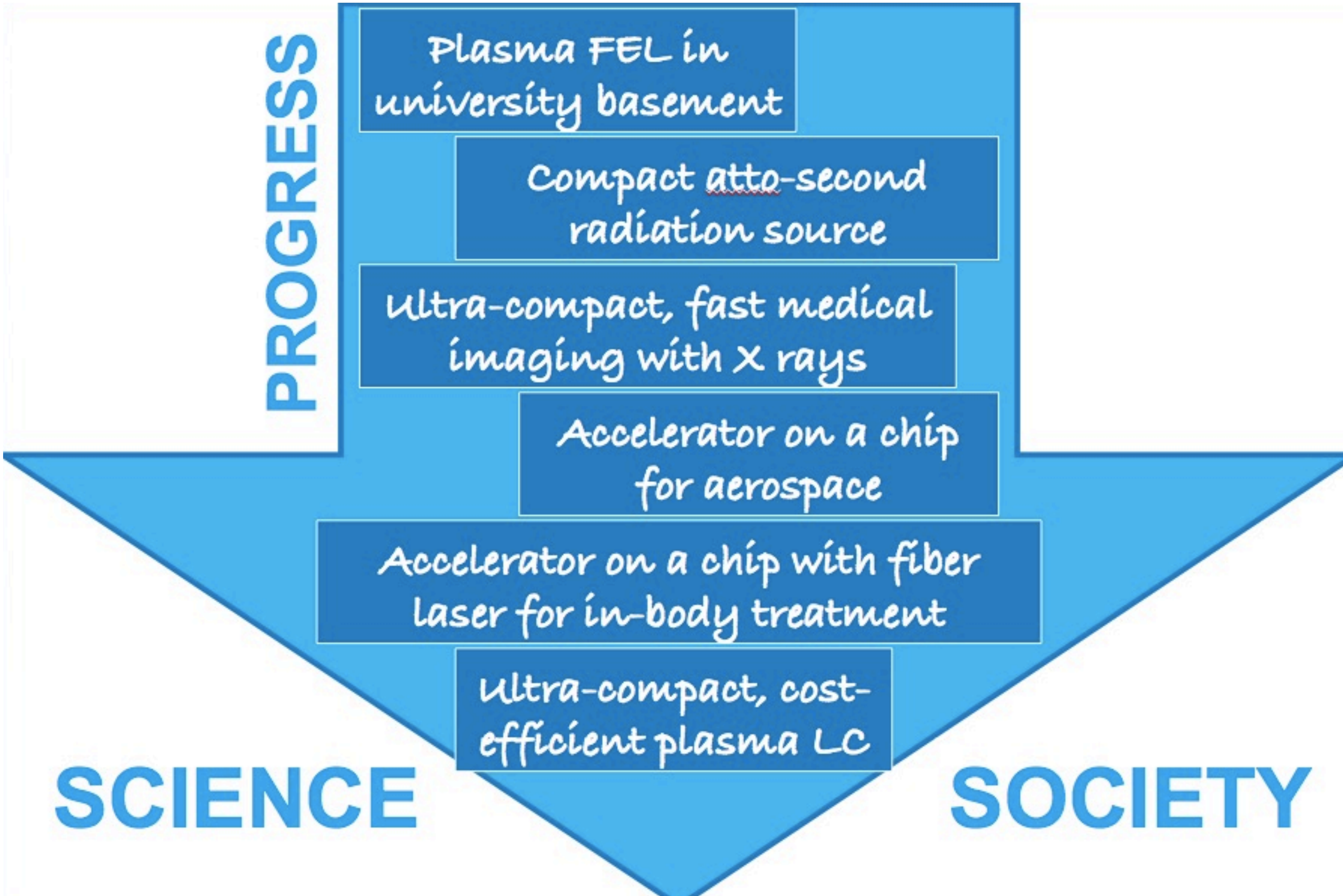
$$I_0 = 6.4 \cdot 10^{19}\,\text{W/cm}^2$$

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

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 Physiker Jens Osterhoff mit einer Plasmazelle. Sie könnte eines Tages ein 100 Meter langes Modul im Tunnel eines Röntgenlasers ersetzen

Der Mini-Teilchenbeschleuniger

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

Wir können bis zu 1000-mal stärkere elektrische Felder erzeugen als in existierenden Beschleunigern.
Ralph Aßmann

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

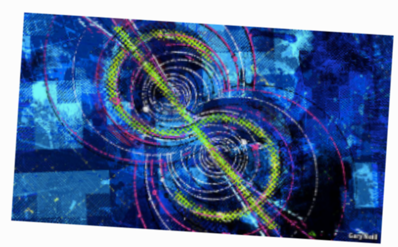
The Economist

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.

DESY

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 Accelerators

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

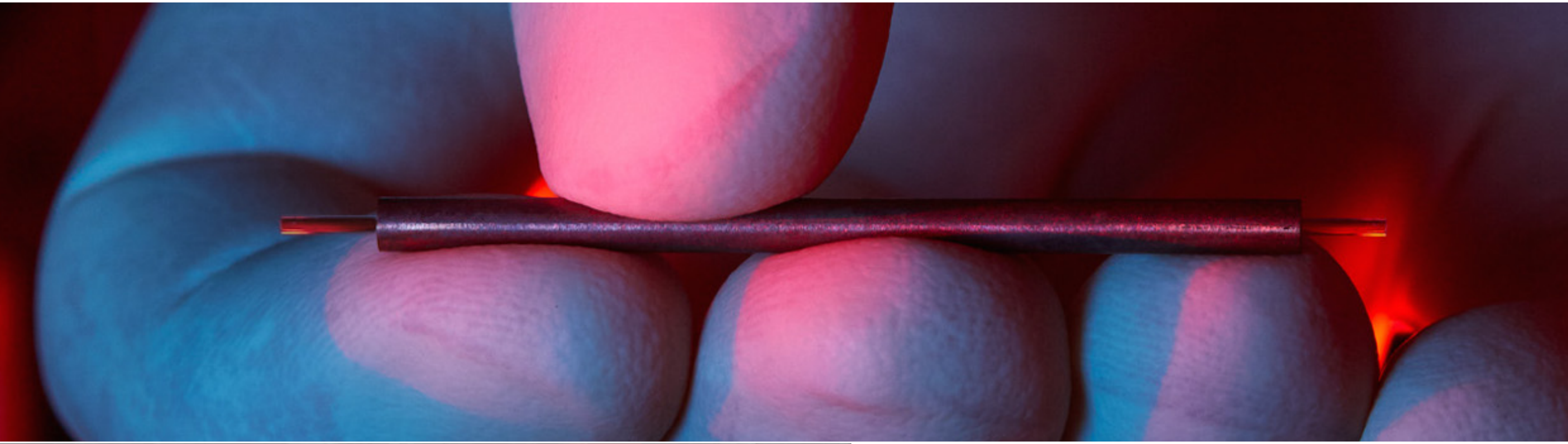
- No **klystrons** for high frequencies!
- Use particle bunches or laser pulses as drivers.
- Material limitations solved through "new cavities": dielectric materials, plasma cavities, …
- Two main directions:

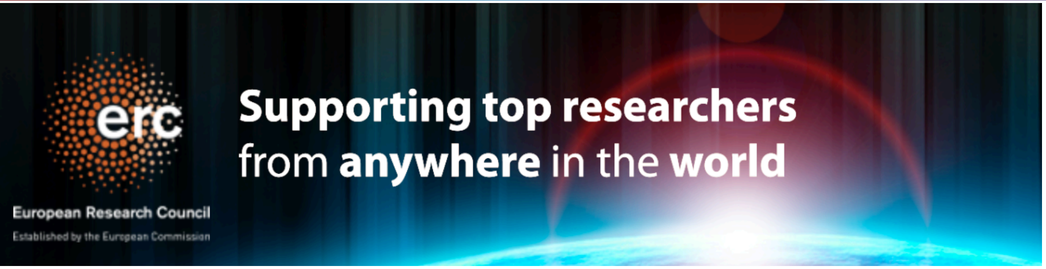
1 Microstructure Accelerator
Laser- or beam driven
Vacuum accelerators
Conventional field design

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

Laser-Driven Micro Structures (Vacuum) – 1

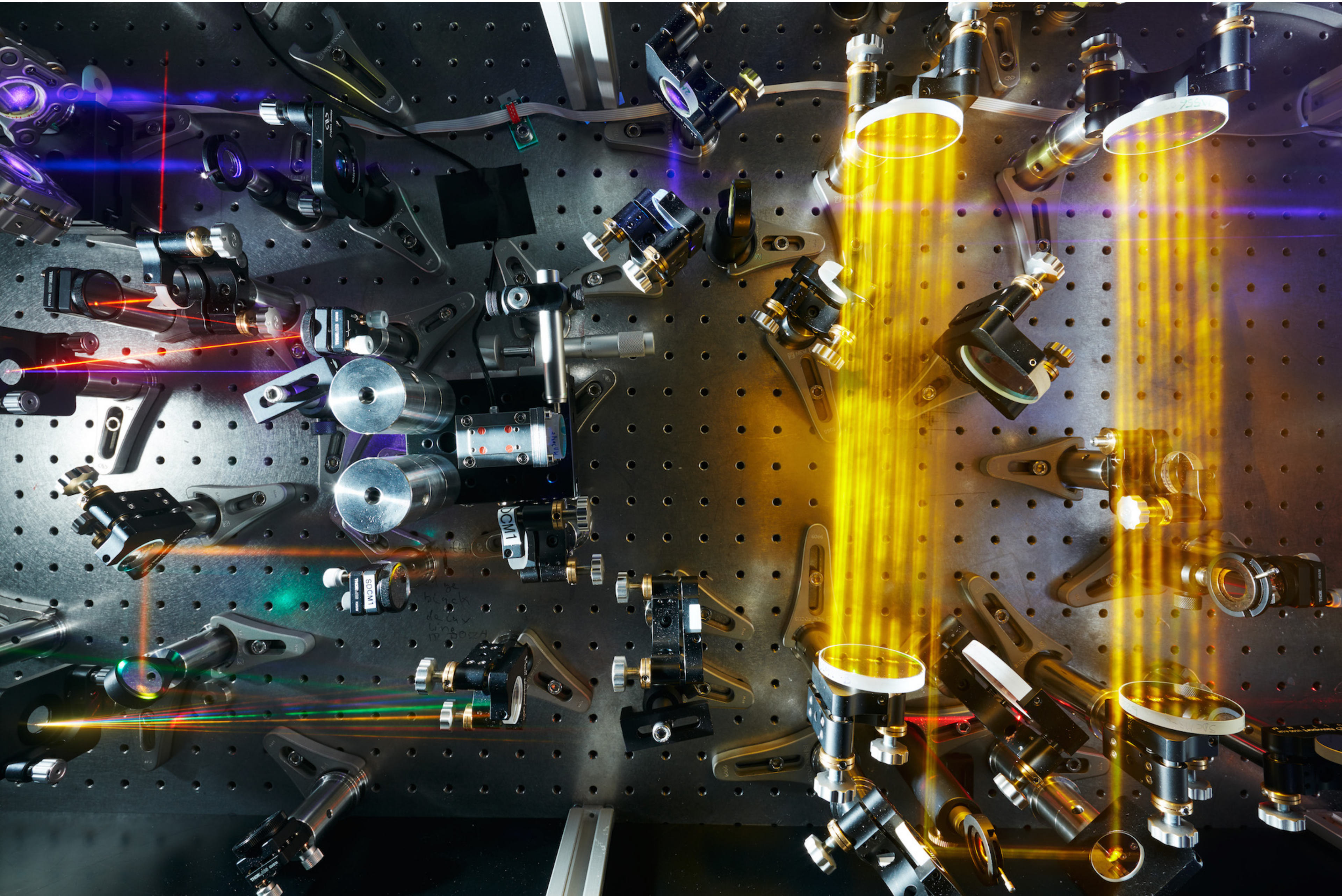
- 1 GeV/m possible but low absolute energies achieved so far
- **AXSIS project (ERC synergy grant)** at DESY/ Uni Hamburg: THz laser-driven accelerator with atto-second science → *Kärtner/Fromme/Chapman/Assmann*





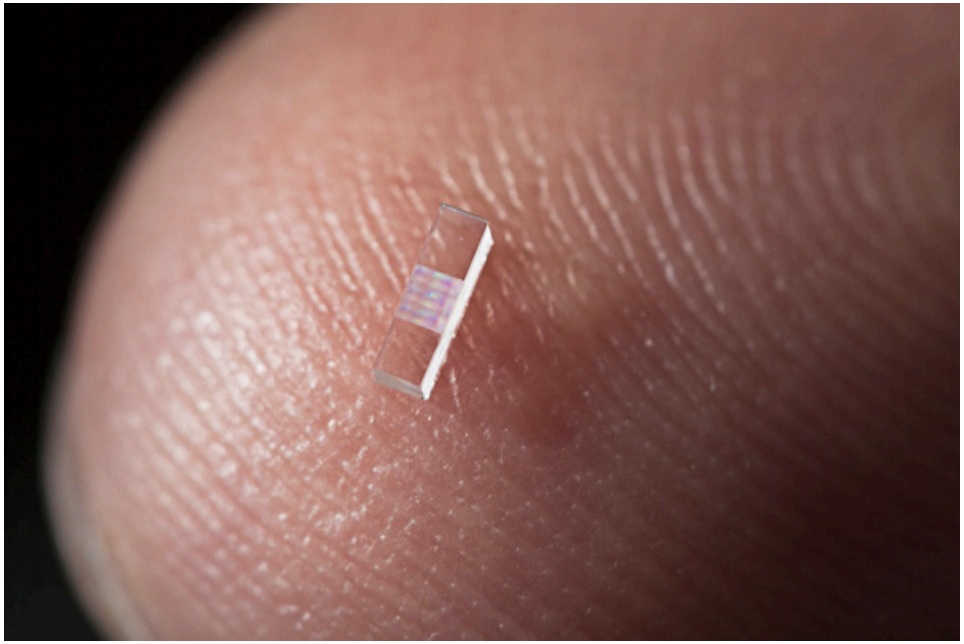
DESY

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.

Our Approach

The opportunity to create lasting, meaningful change drives our approach to our work. We establish specific strategies based on input from experts, identify partners who share our goals and measure results along the way–all while making adjustments as needed. We build relationships and fund work in areas where we hope to make a significant impact. We're okay with failing, as long as we learn from our mistakes. And we know that working together expands our ability to drive meaningful change.

Read More

Gordon & Betty Moore Foundation USA: Ansatz…

The Laser Promise: Transverse Electrical Field

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

ϵ_0 = Dielectric constant

c = Light velocity

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

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

This is what we need!

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

Lorentz Force F

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

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.

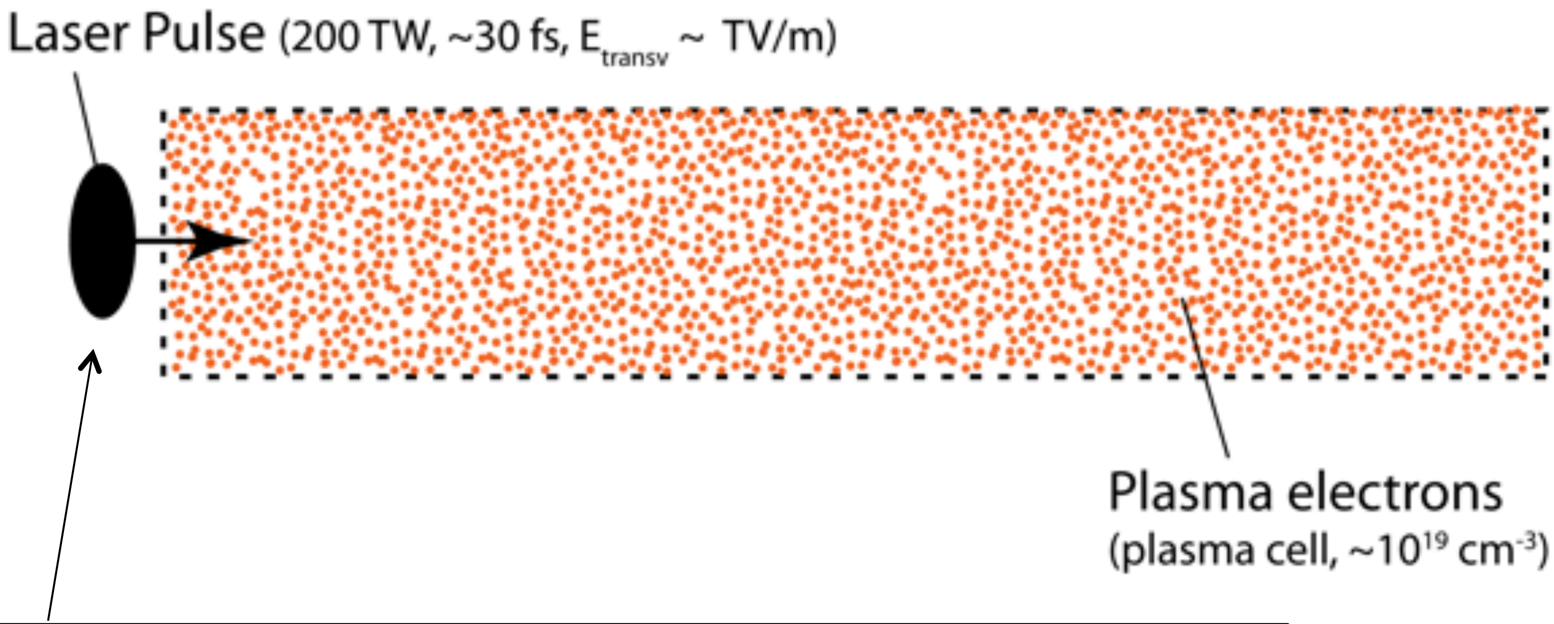
Collective plasma accelerators have recently received considerable theoretical and experimental investigation. Earlier Fermi[1] and McMillan[2] considered cosmic-ray particle acceleration by moving magnetic fields[1] or electromagnetic waves.[2] In terms of the realizable laboratory technology for collective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

the wavelength of the plasma waves in the wake:

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

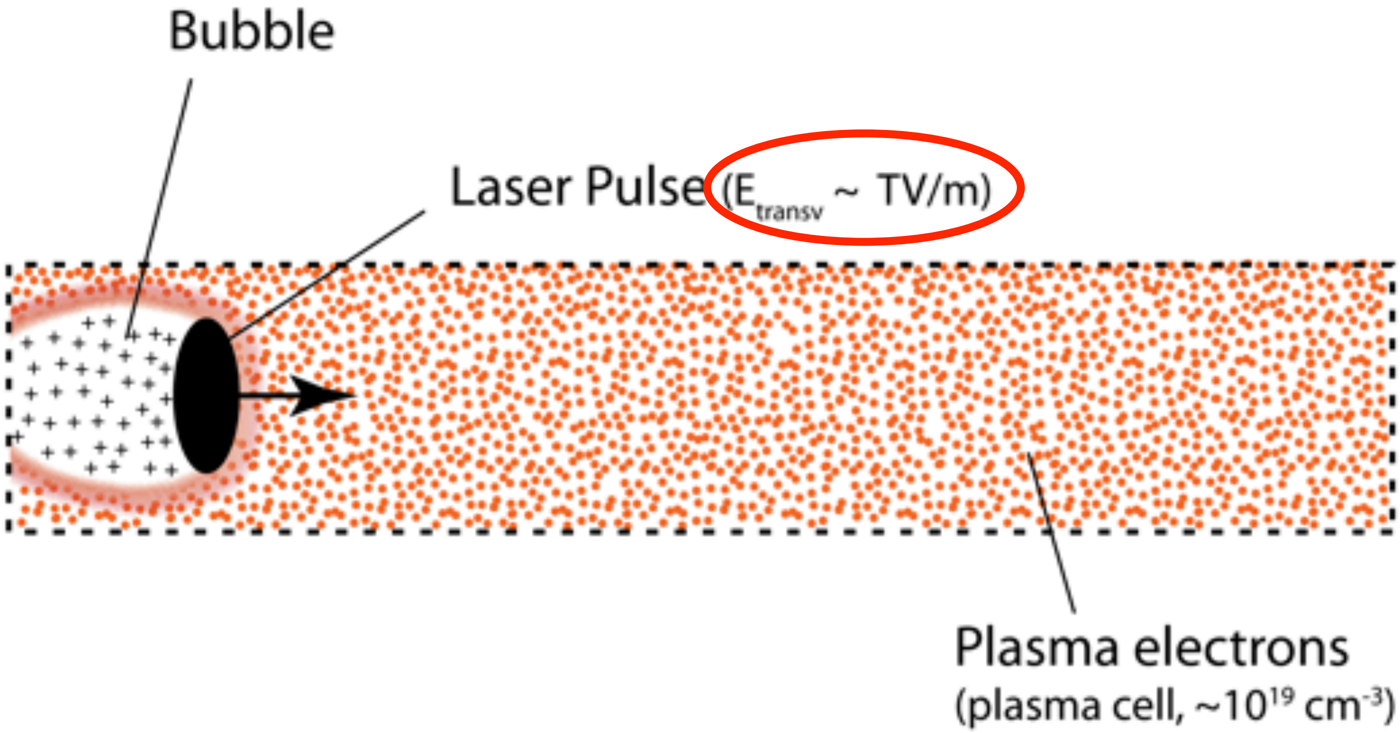
An alternative way of exciting the plasmon is to inject two laser beams with slightly different frequencies (with frequency difference $\Delta\omega \sim \omega_p$) so that the beat distance of the packet becomes

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)



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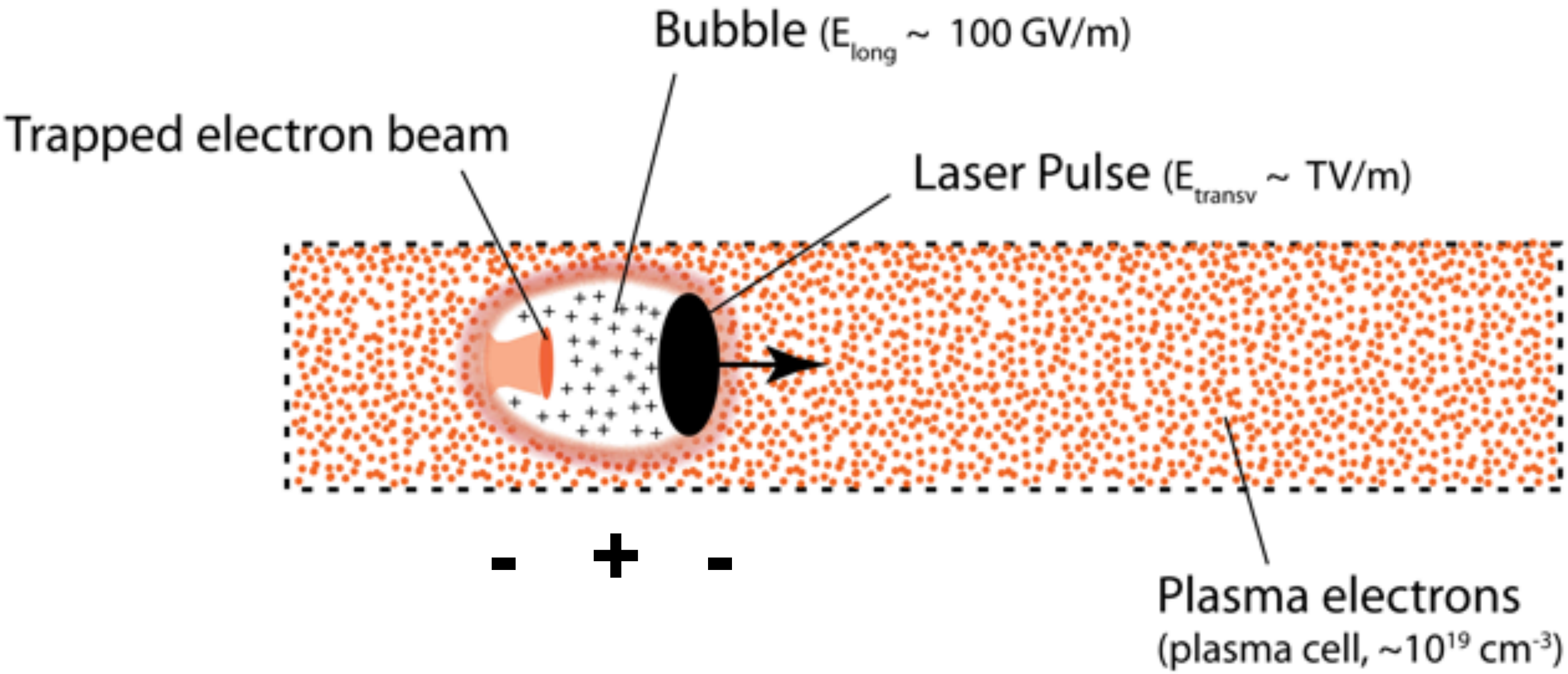
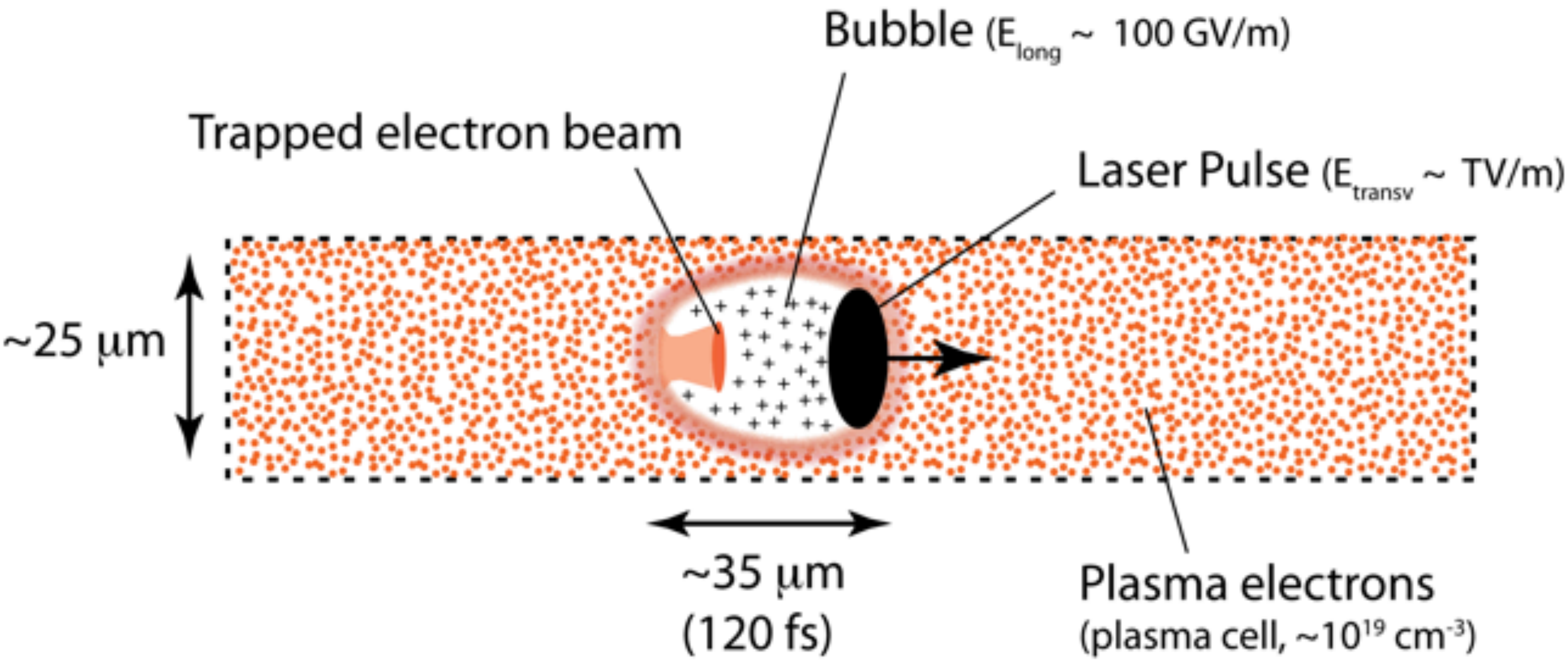
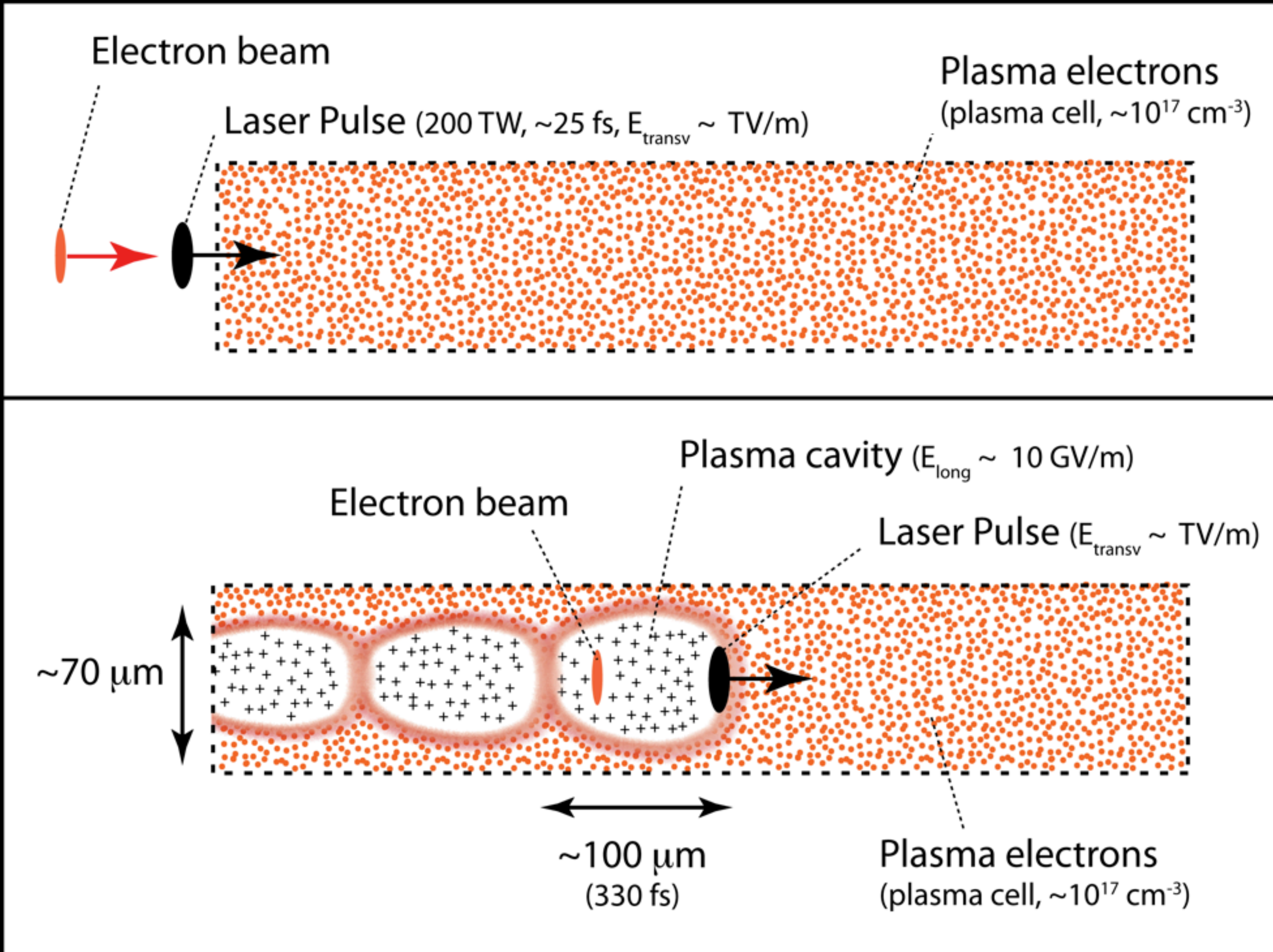


Laser Plasma-Acceleration (Internal Injection)

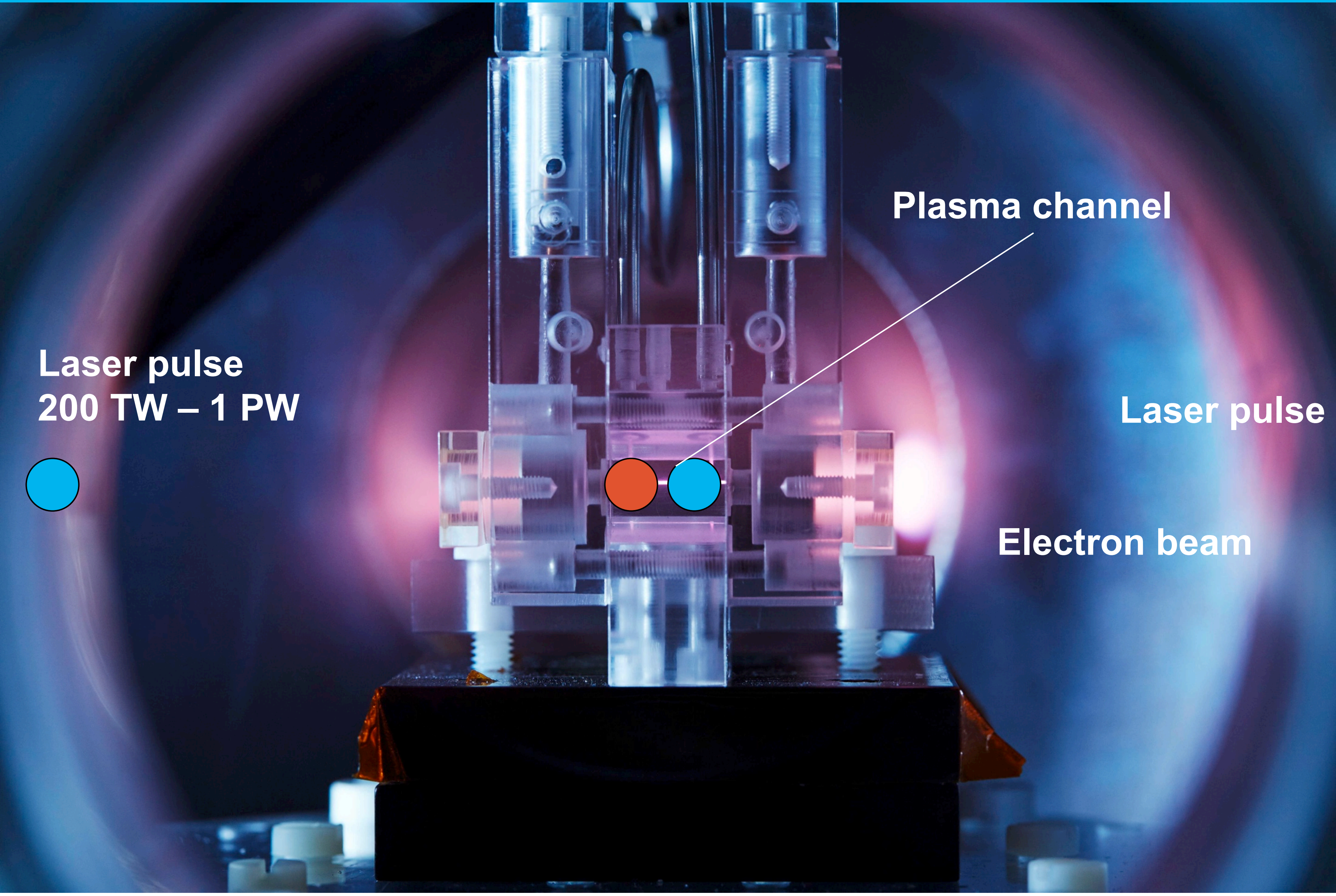


This accelerator fits into a human hair!

External Injection…



Laser Plasma Accelerators for Electron Beams



And the Plasma Accelerator is Compact…

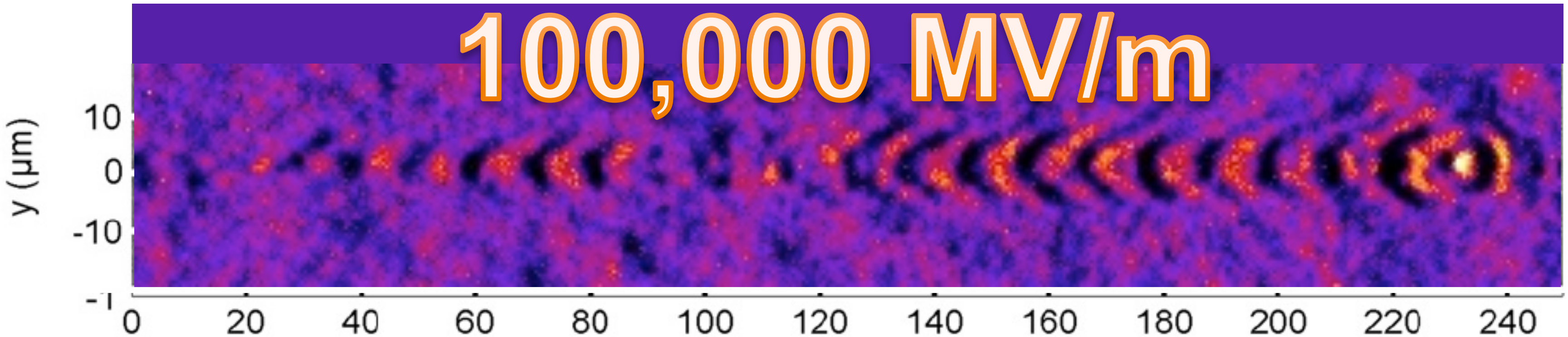
Foto Laser-Plasmabeschleuniger

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



0.05 mm

0.25 mm

Metall (Kupfer) S band Linac Struktur

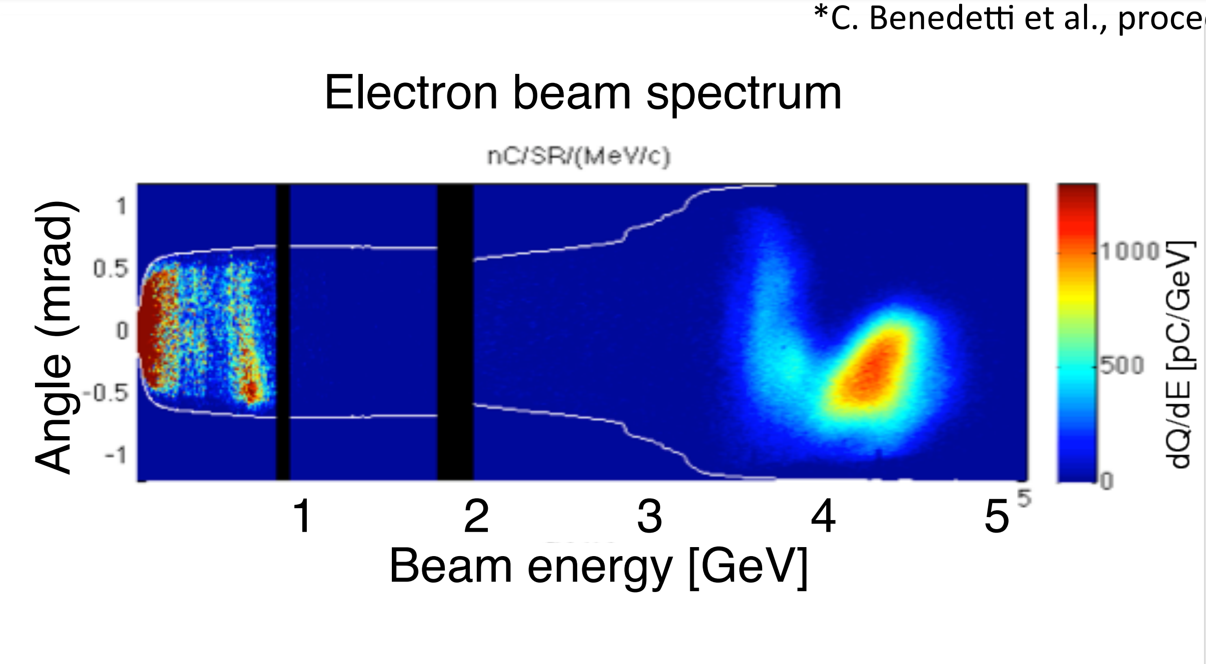
Mikro-Wellen zur Wellener-zeugung

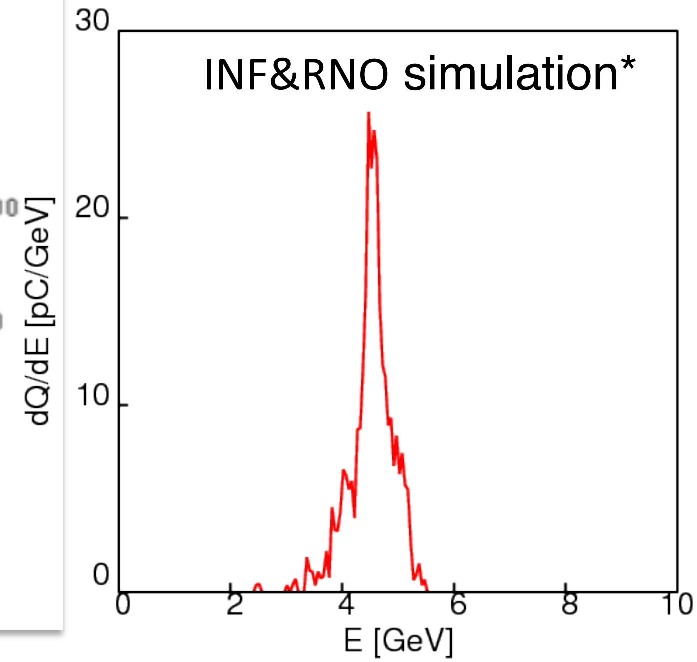
100 mm

500 mm

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}**)

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 m²
(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 m² (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. Tolerances

4. Outlook for Europe

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

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

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

Depends on radial position r

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

The Useful Regime of Plasma Accelerators

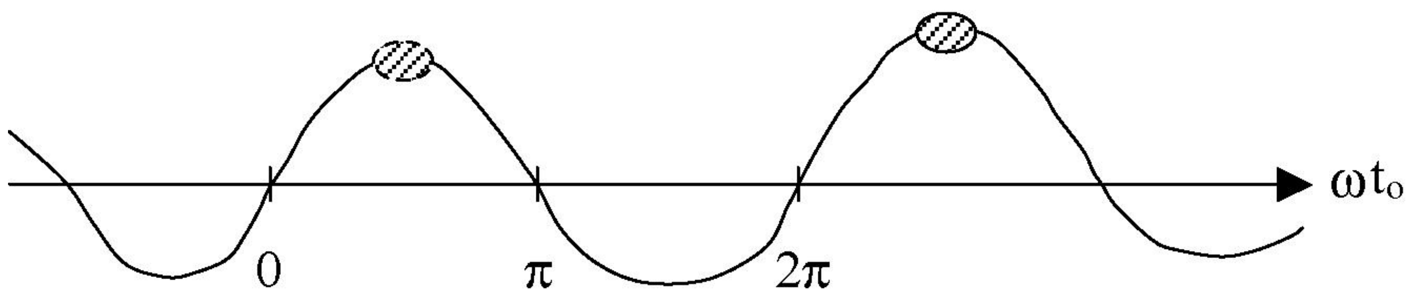
Two conditions for an accelerator:

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

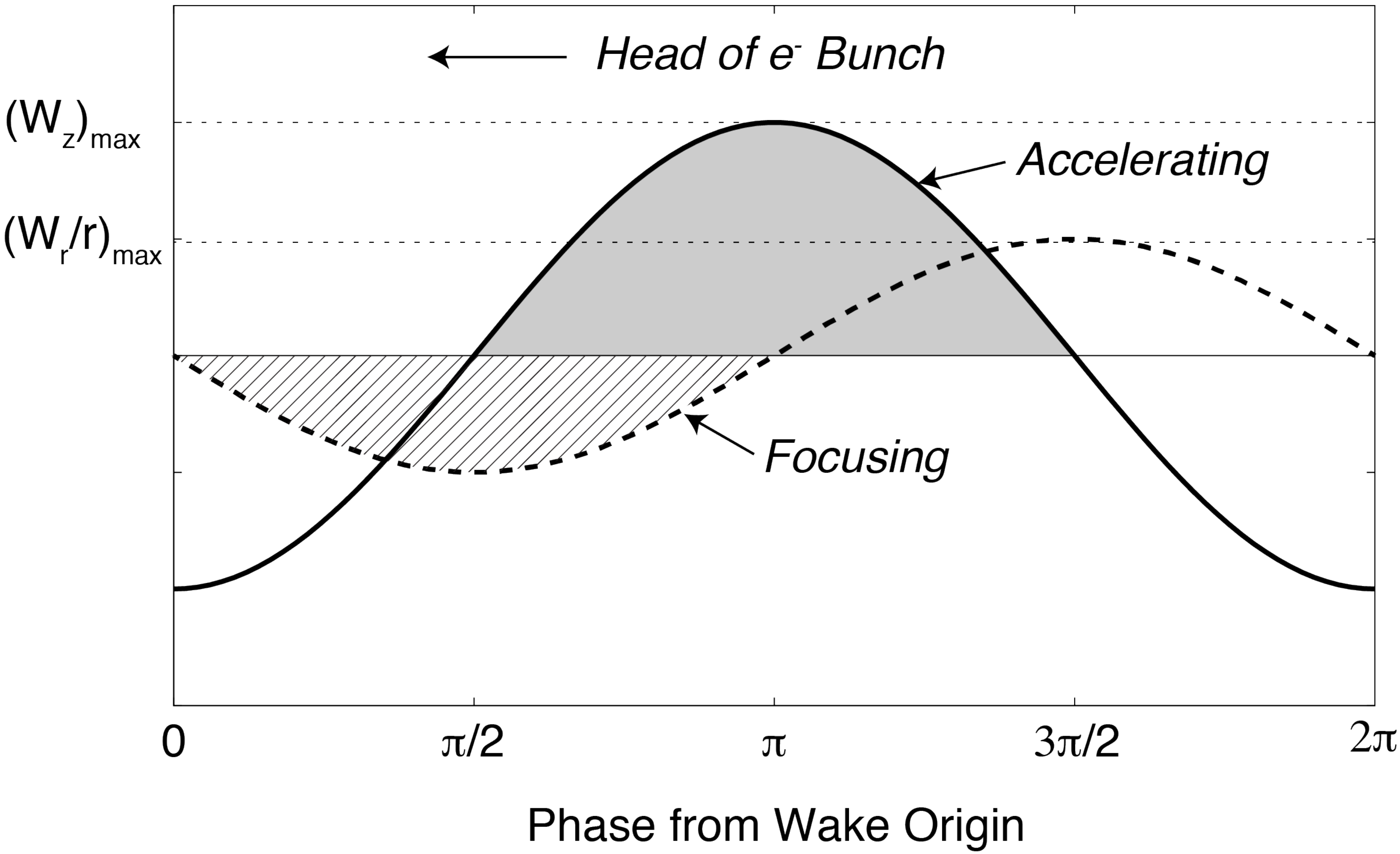
These two conditions define a useful range of acceleration!

Reminder metallic RF accelerator structures:

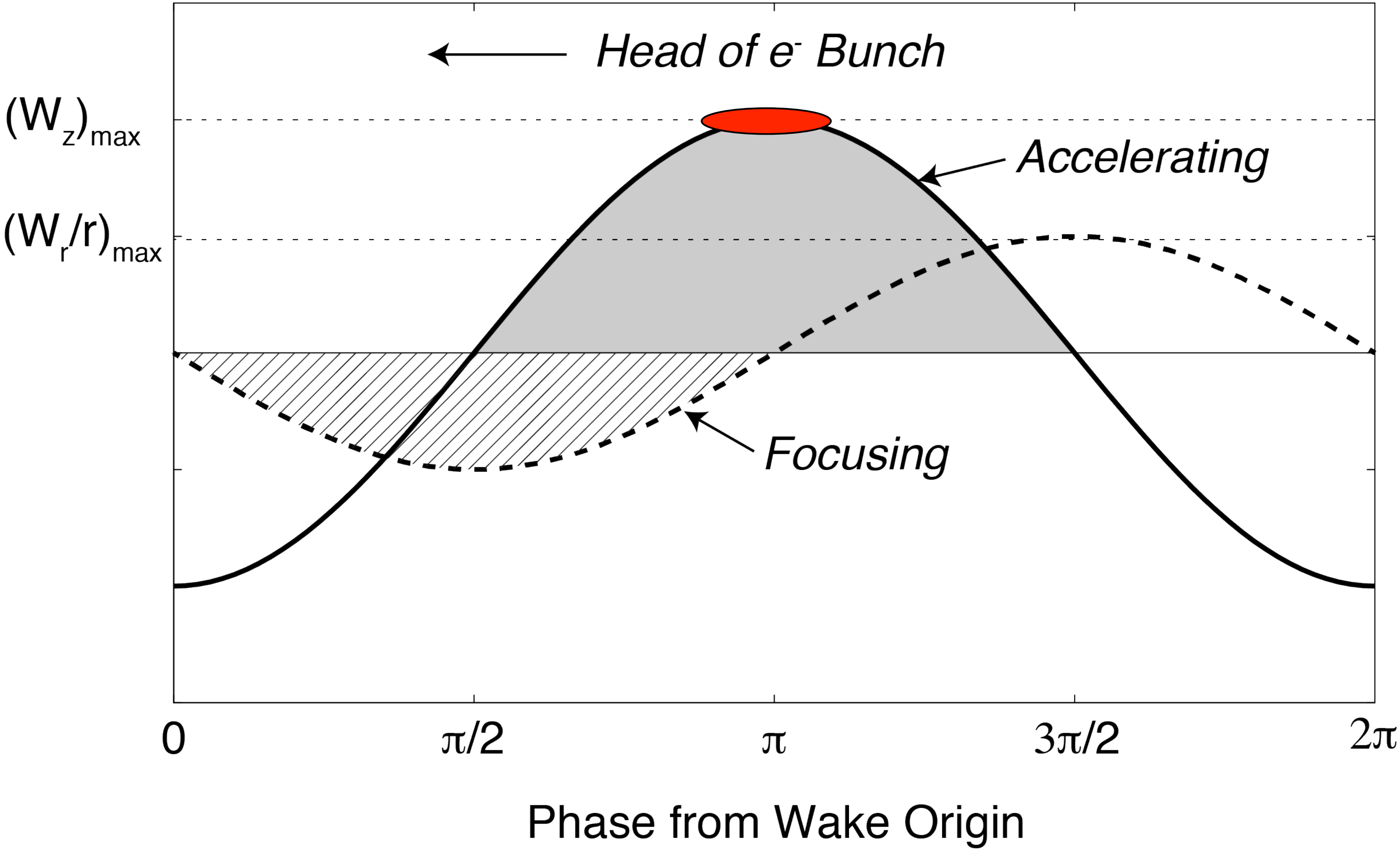
no net transverse fields for beam particles → full accelerating range is available for beam → usually place the beam on the crest of the accelerating voltage



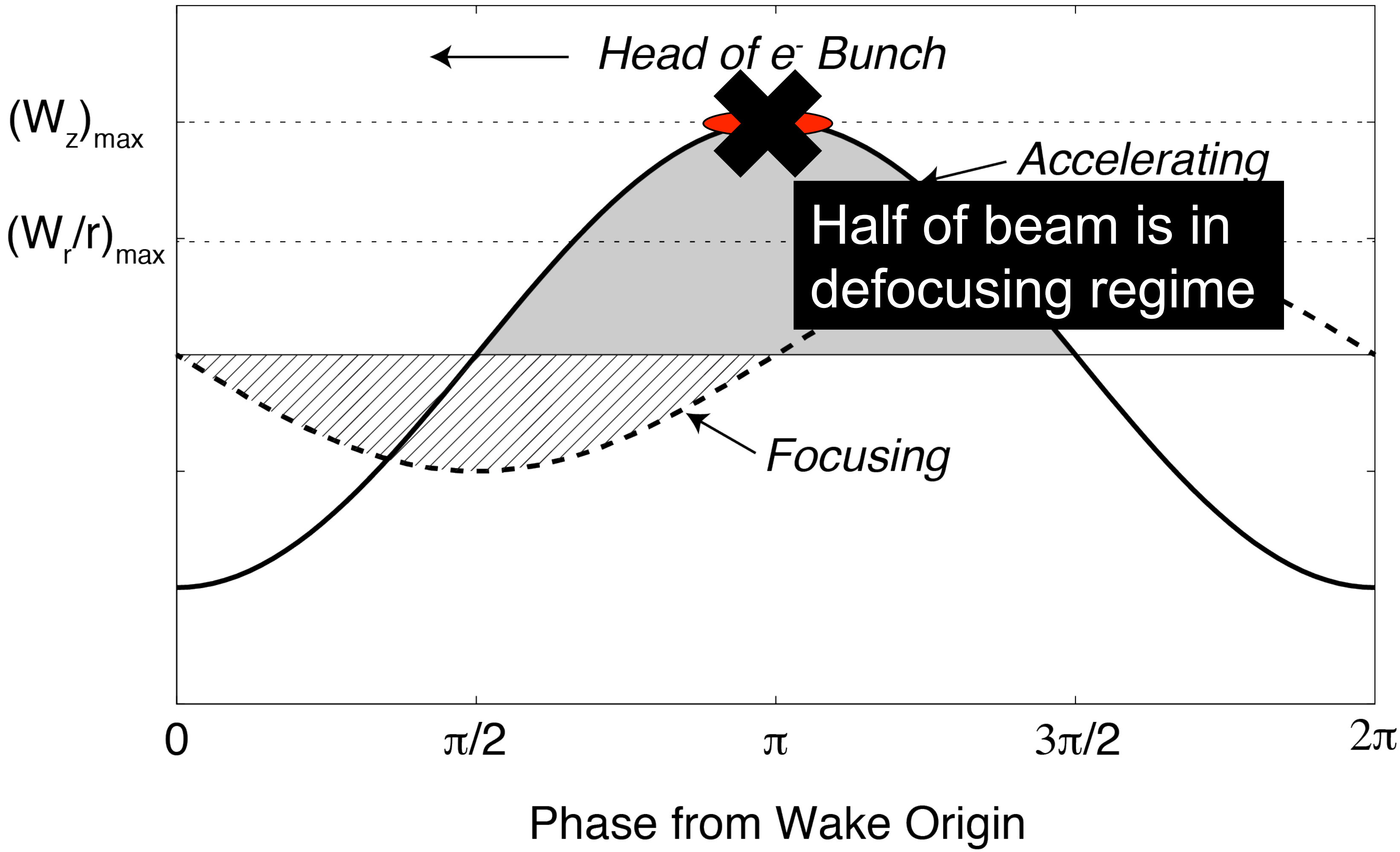
Plasma Accelerator



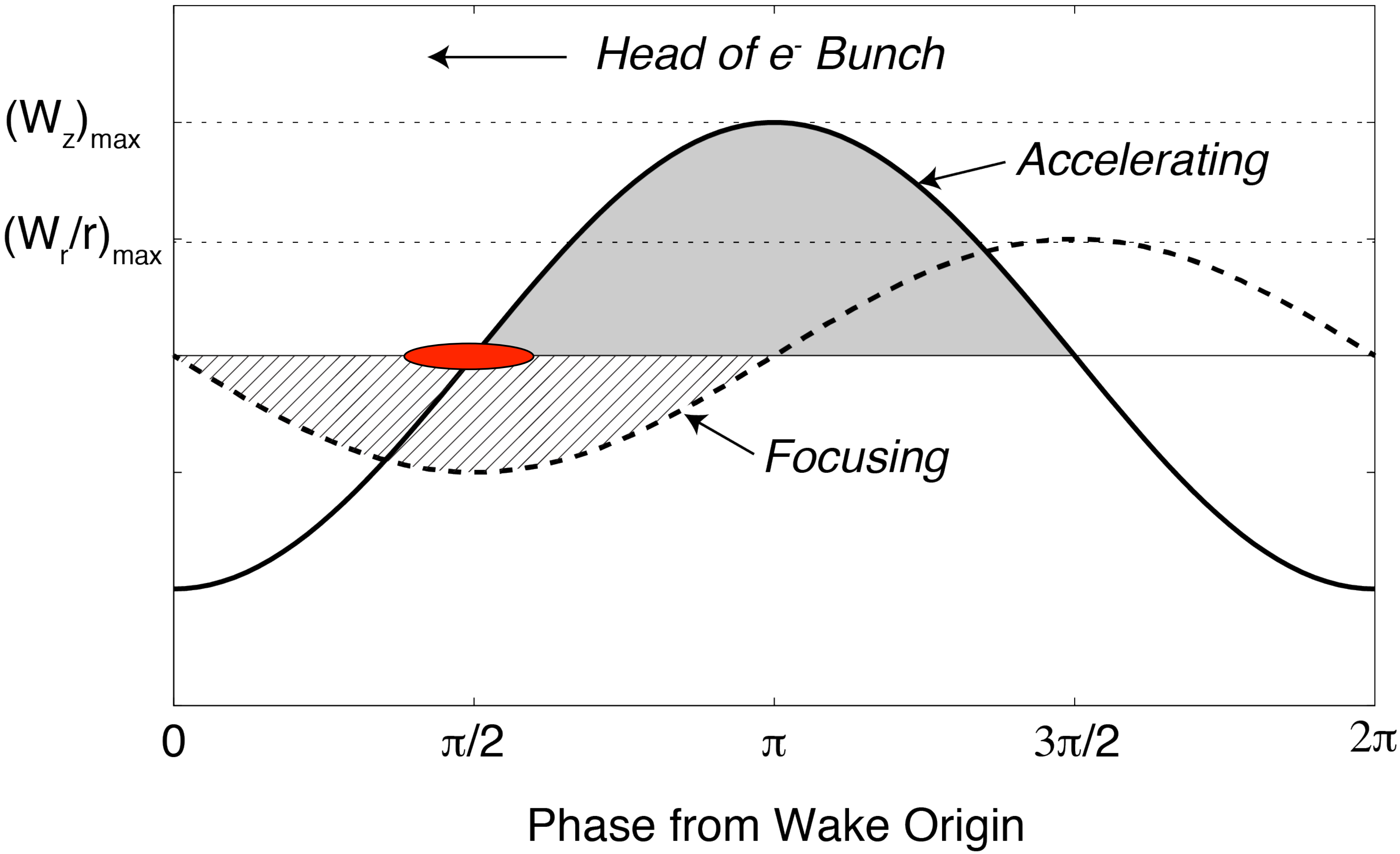
Plasma Accelerator



Plasma Accelerator



Plasma Accelerator



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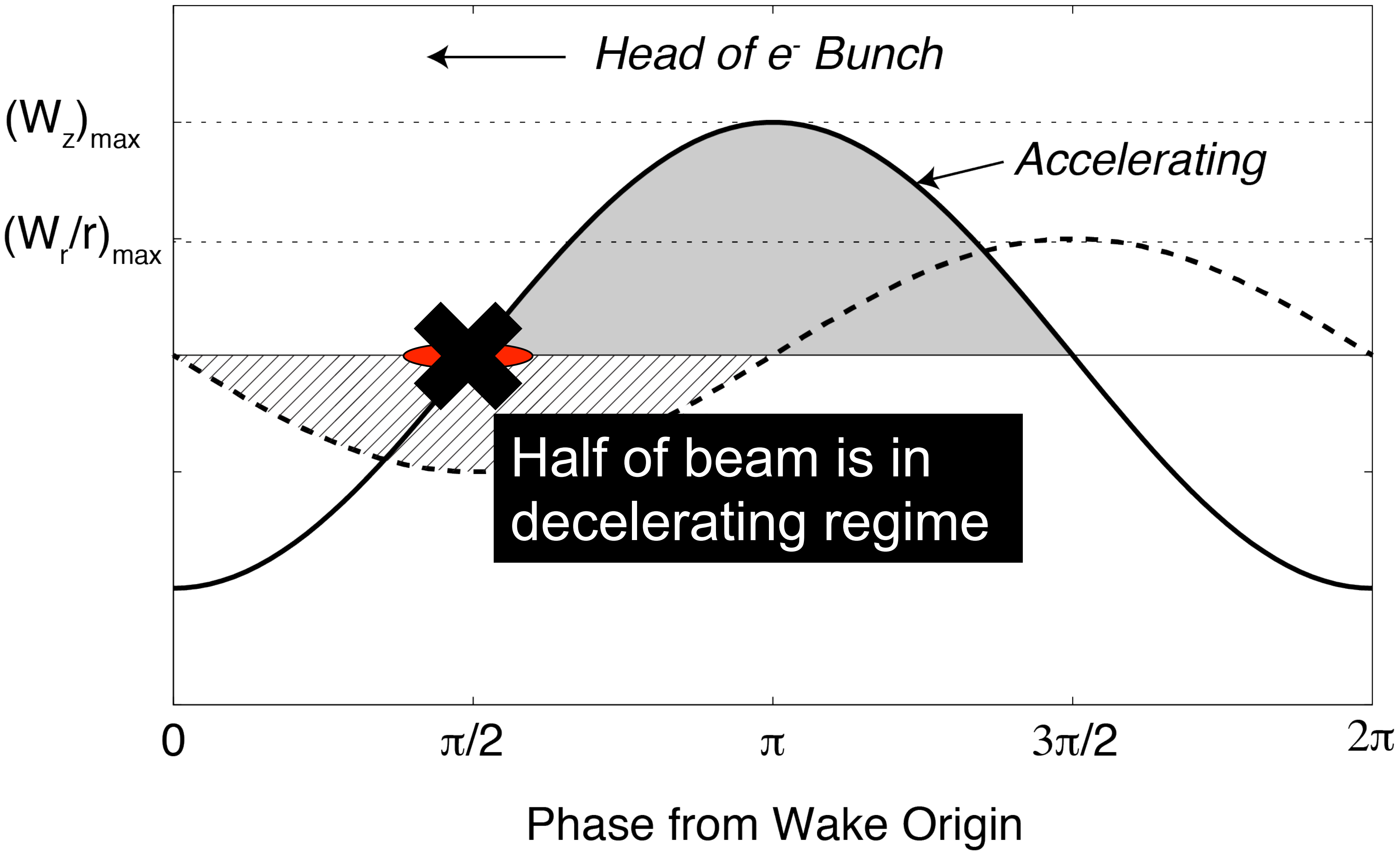
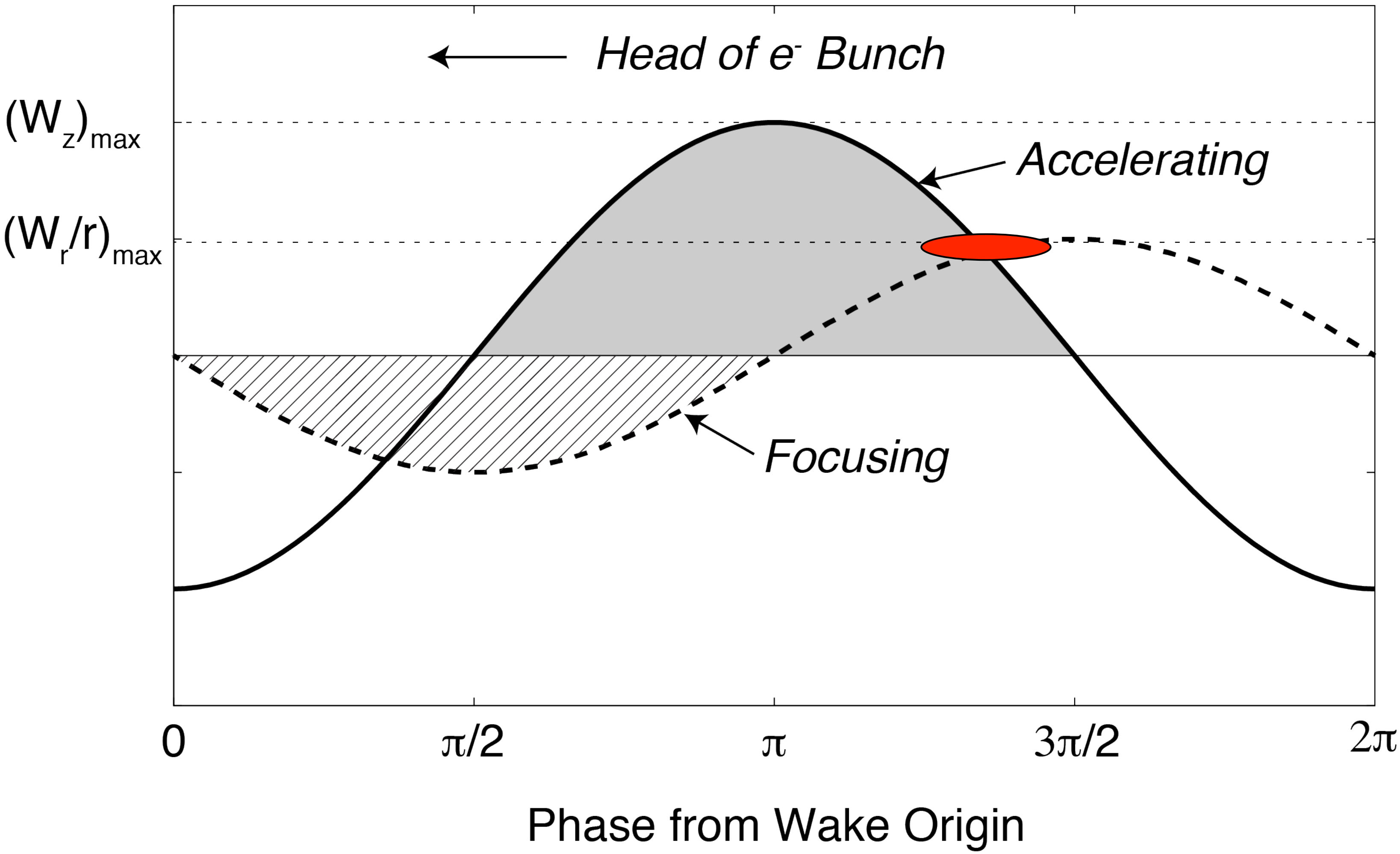
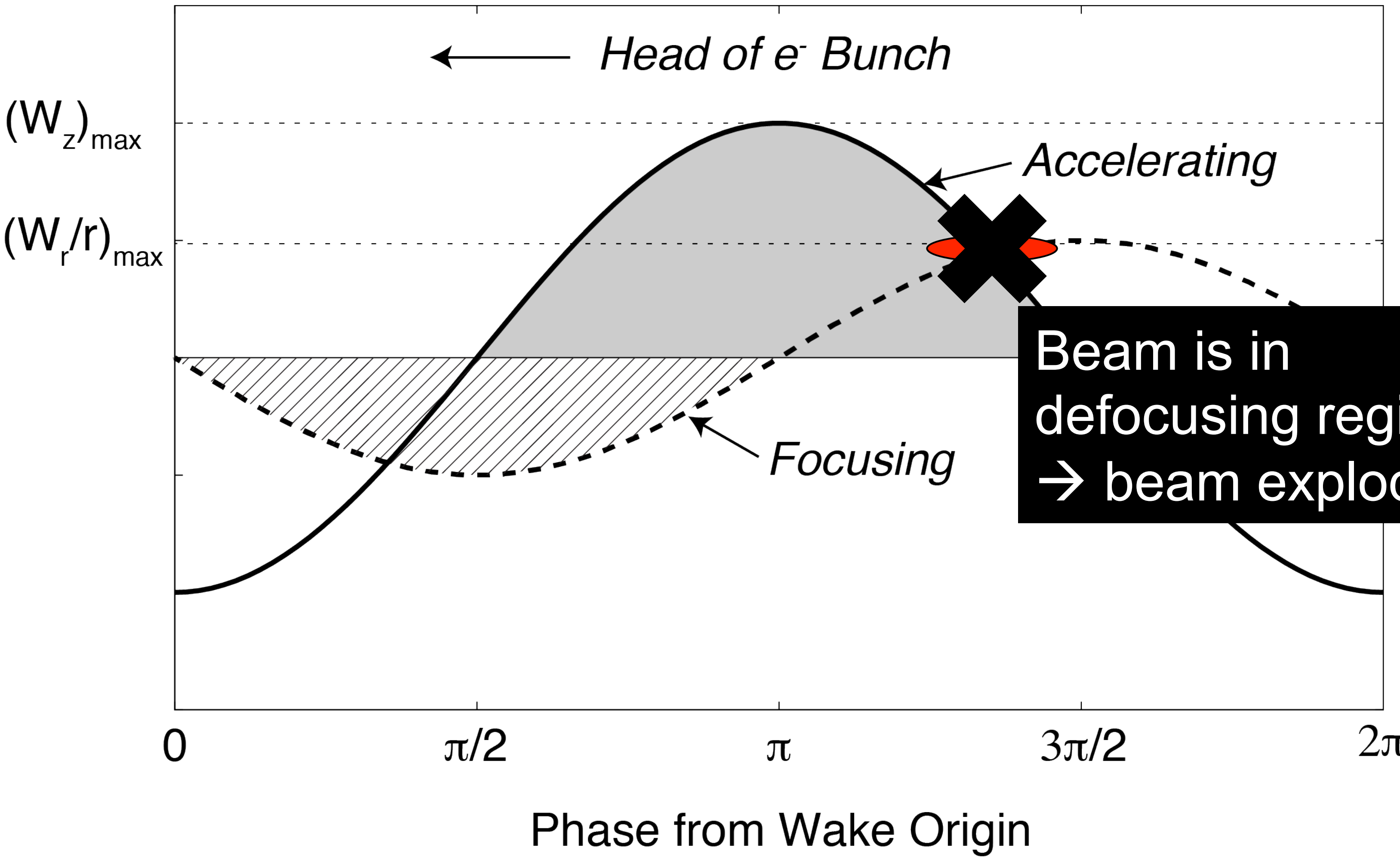


Plasma Accelerator

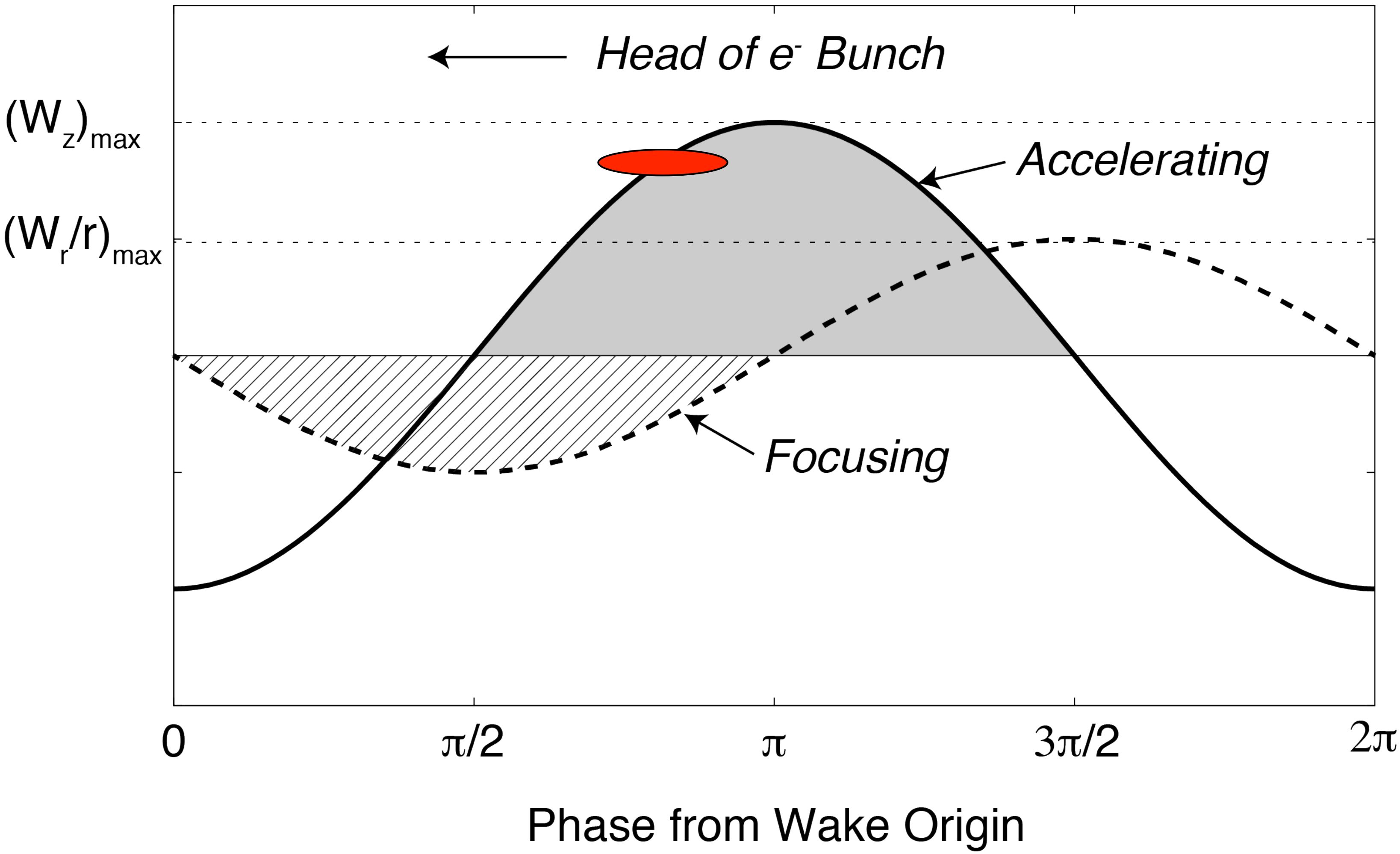


Plasma Accelerator

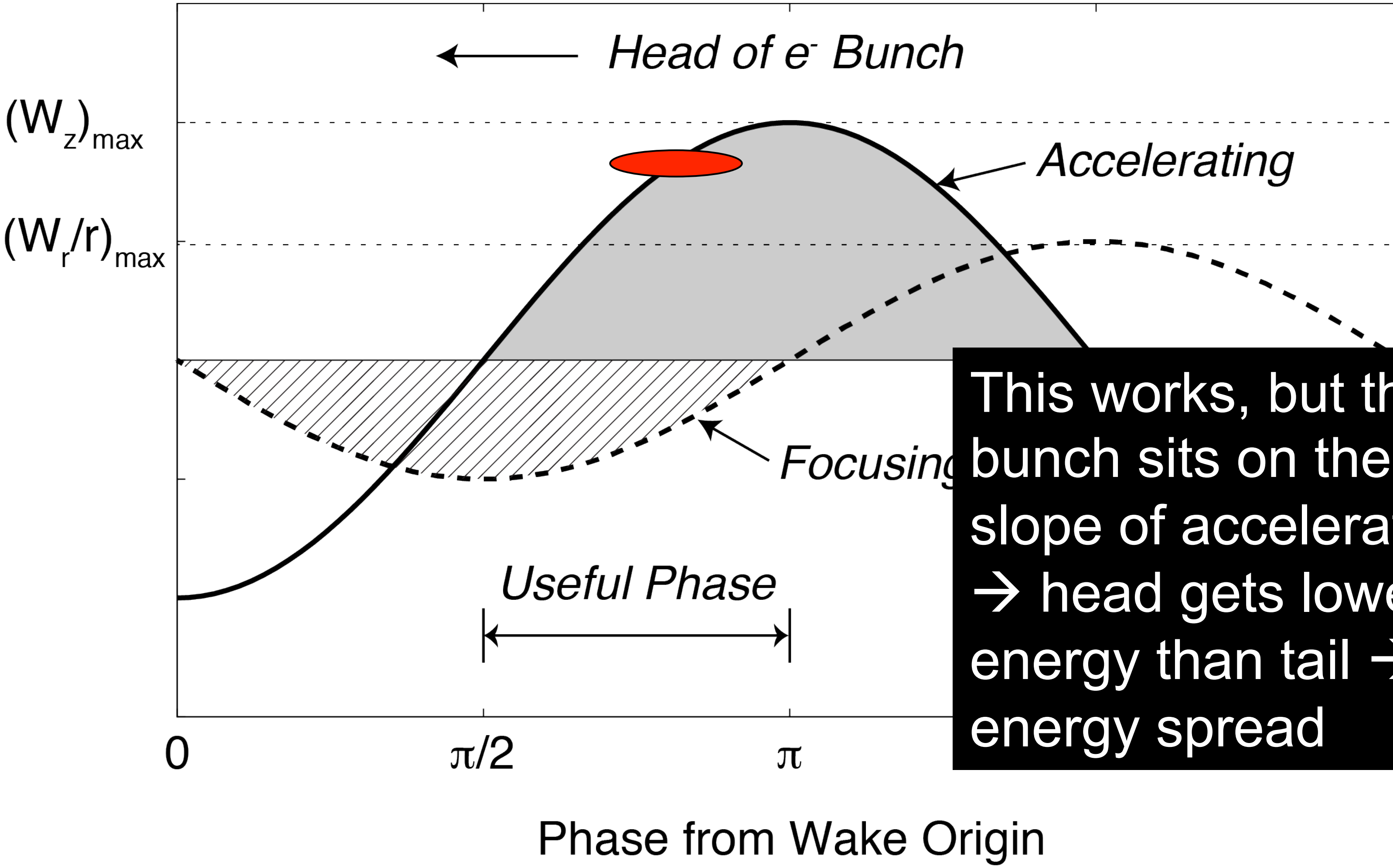


Beam is in defocusing regime → beam explodes

Plasma Accelerator

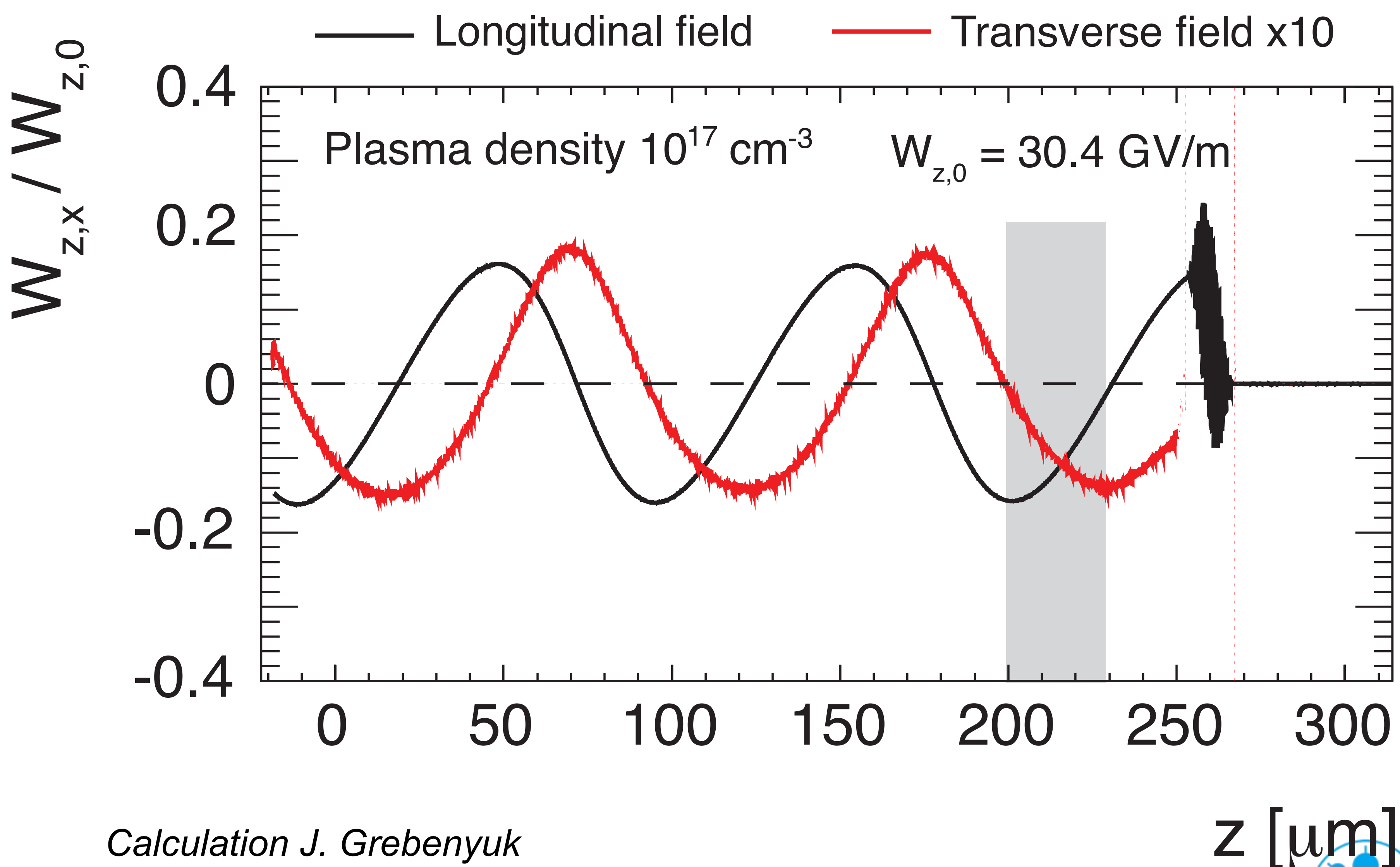


Plasma Accelerator



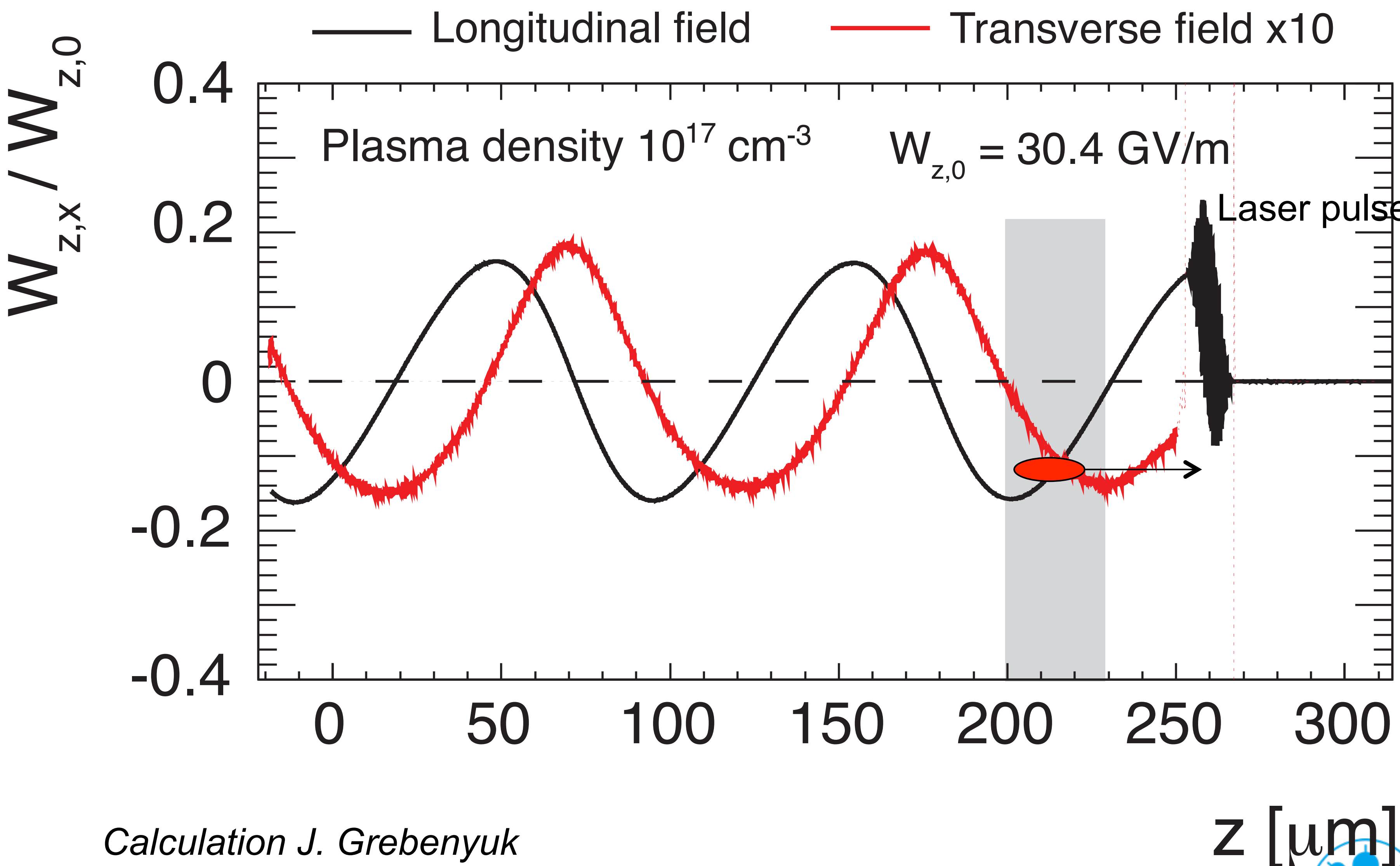
This works, but the bunch sits on the slope of acceleration → head gets lower energy than tail → energy spread

Comparison with OSIRIS simulation



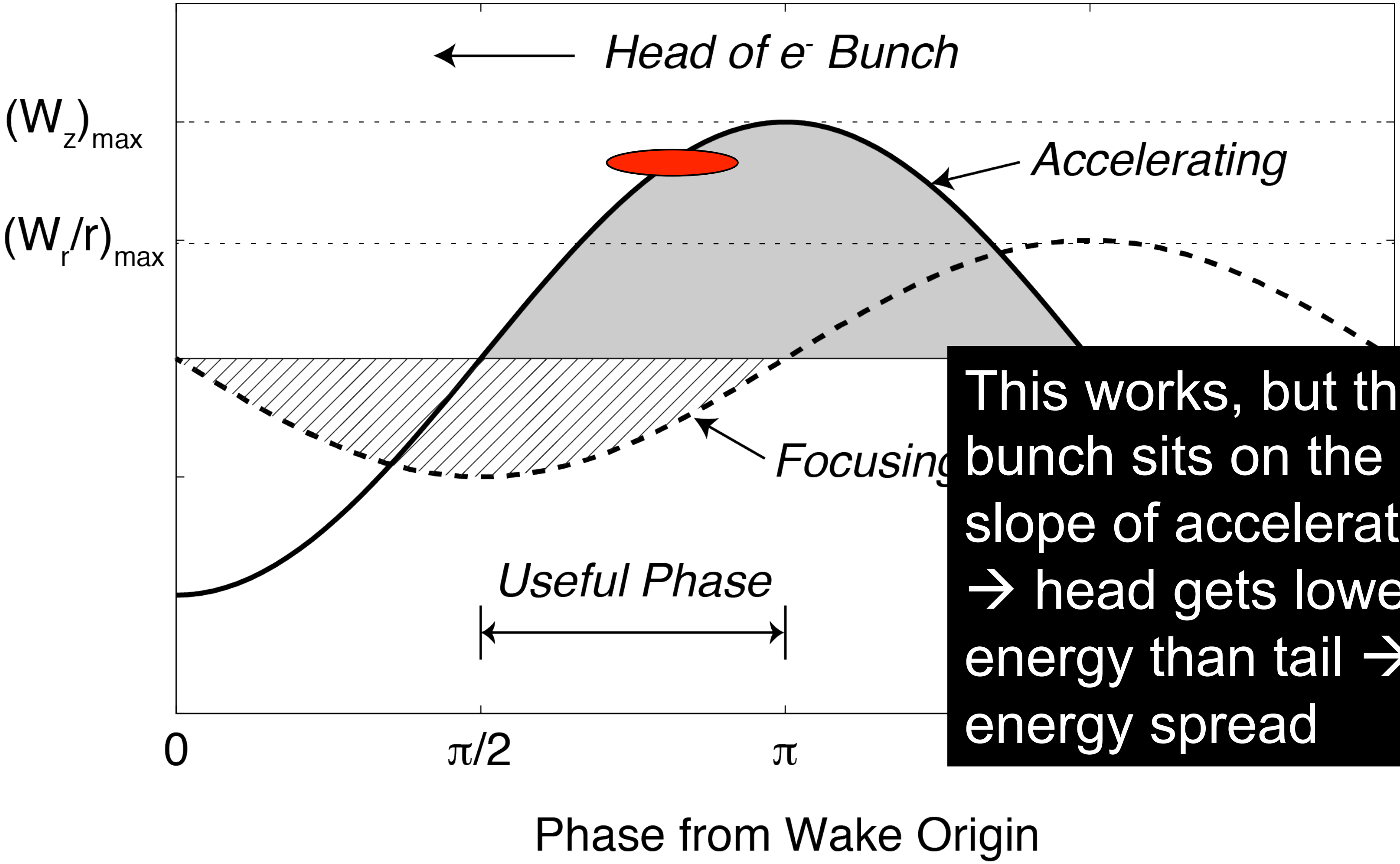
Calculation J. Grebenyuk

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

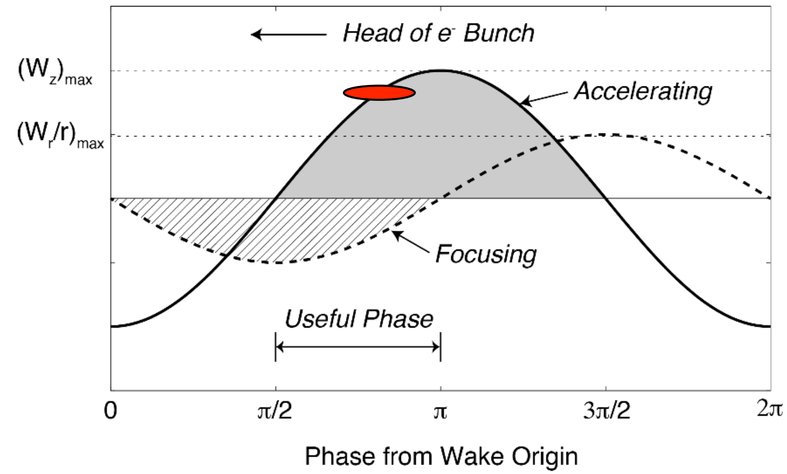
Reduce energy spread (head to tail → correlated with z)

↓

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

Minimize length accelerated bunch and/or Increase plasma wavelength

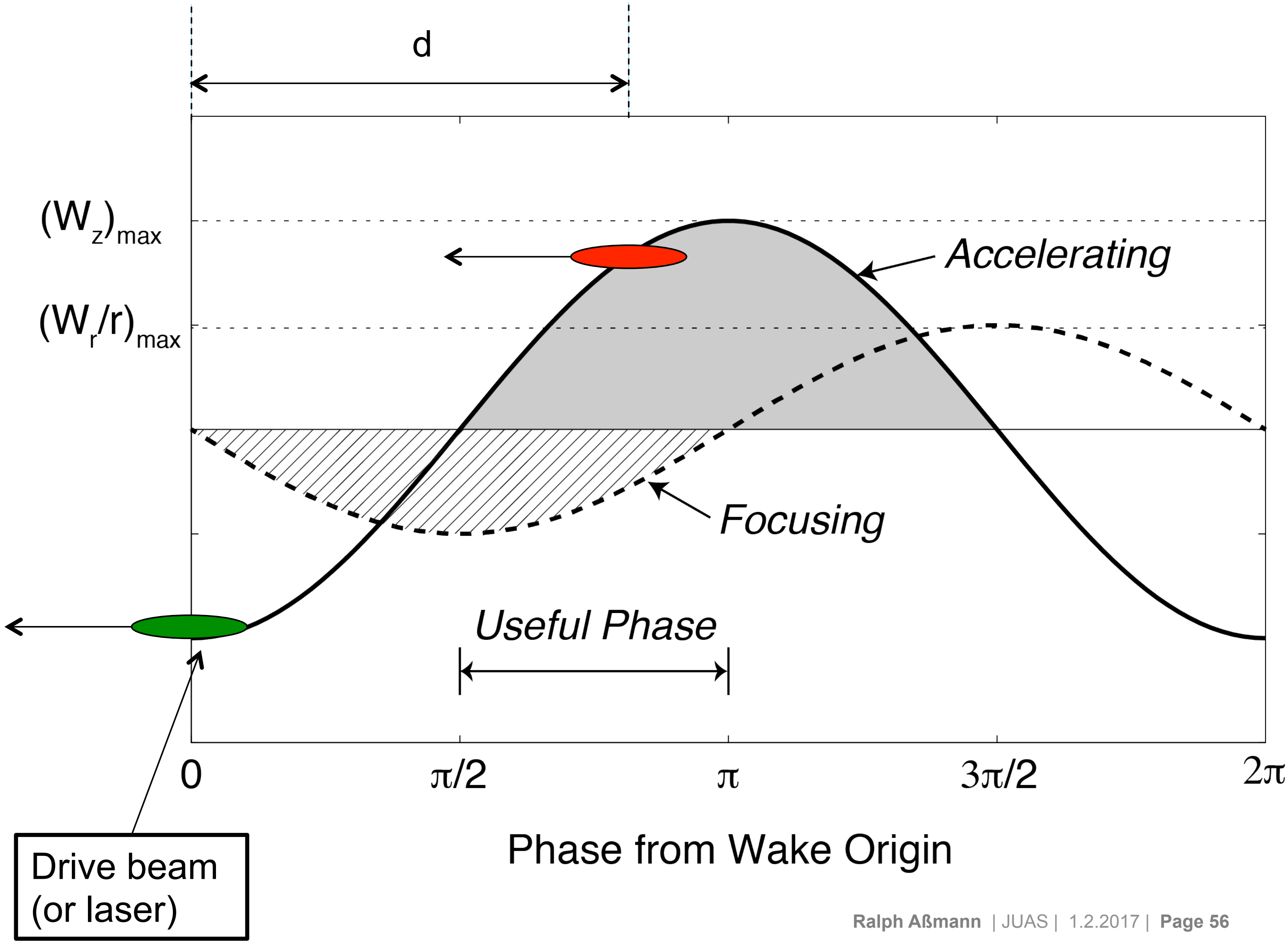
Minimize length accele-rated bunch	Increase plasma wavelength
↓	↓
Ultra-short bunches (fs, as)	Lower plasma density
↓	↓
Ultra-fast science	Lower accelerating gradient



1 fs = 0.3 μm

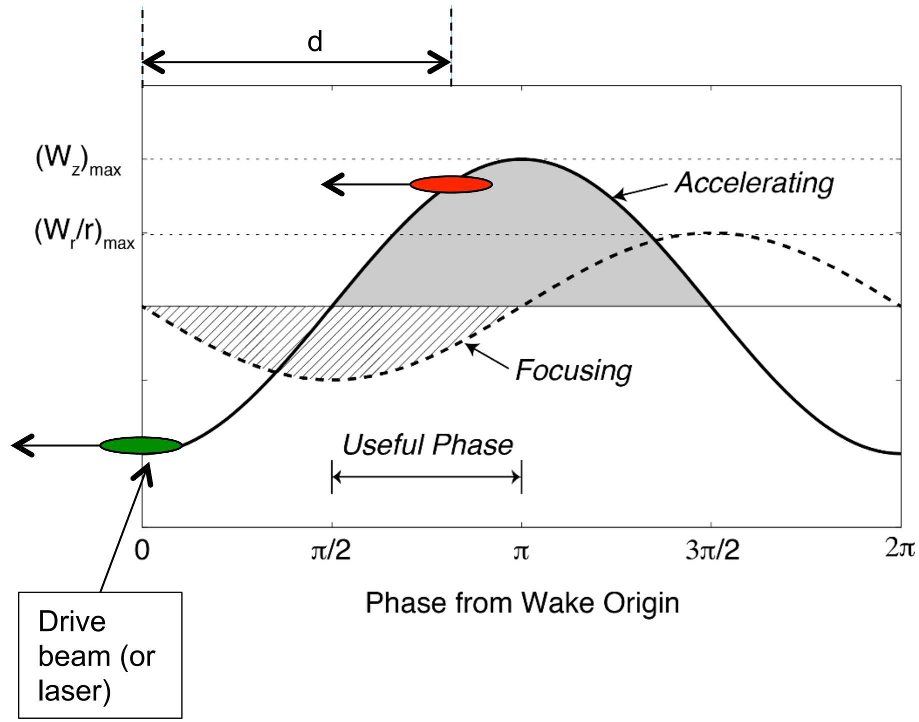
when travelling with light velocity c

Phase Slippage

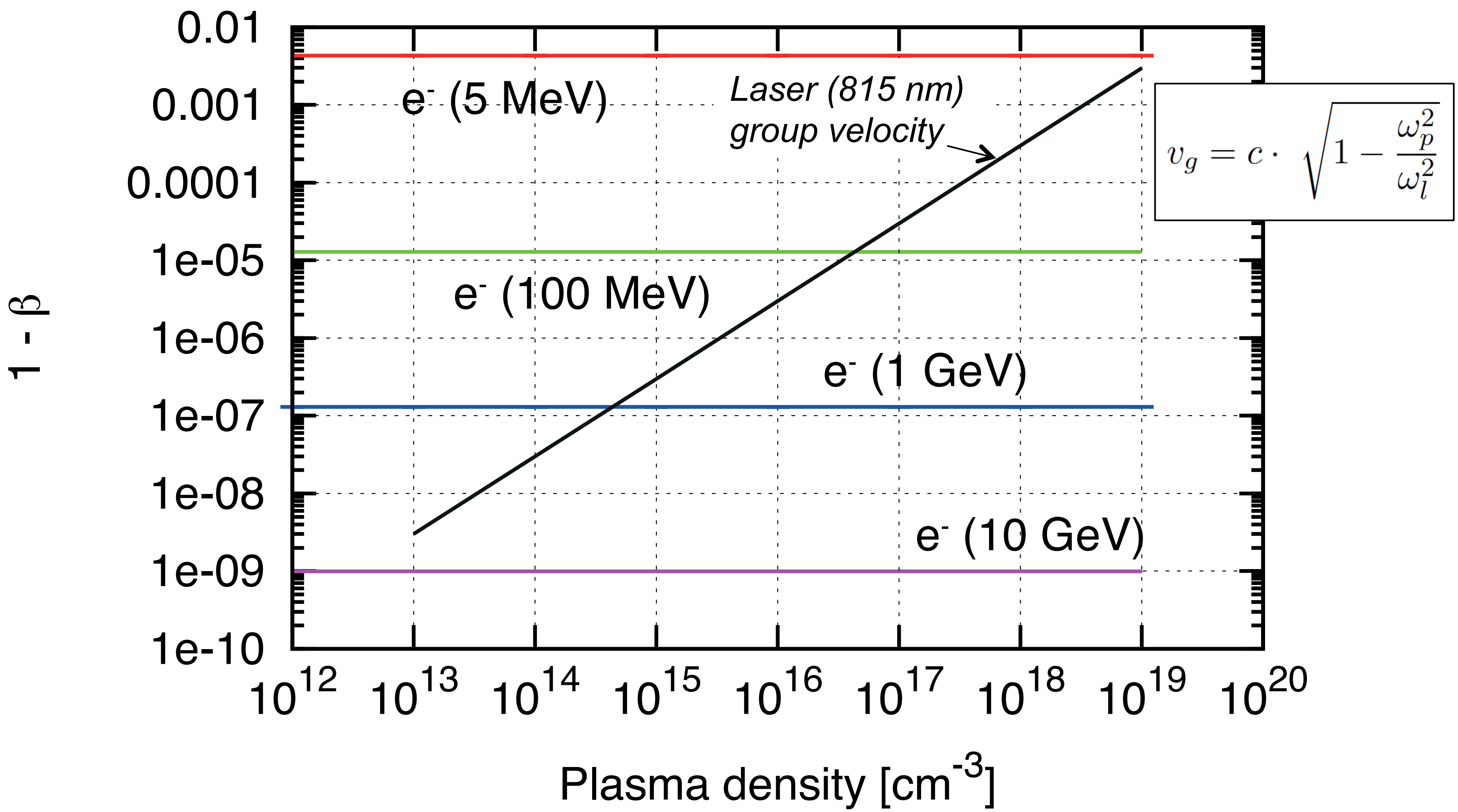


Phase Slippage

- 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.

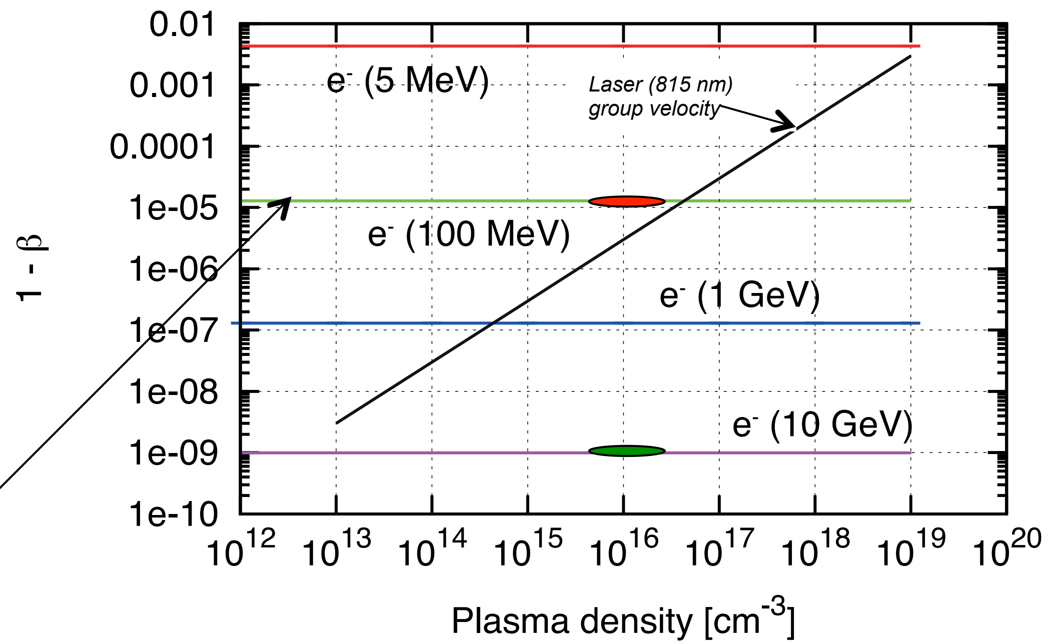


Dephasing (β = v/c, here consider relativistic beams)



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

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

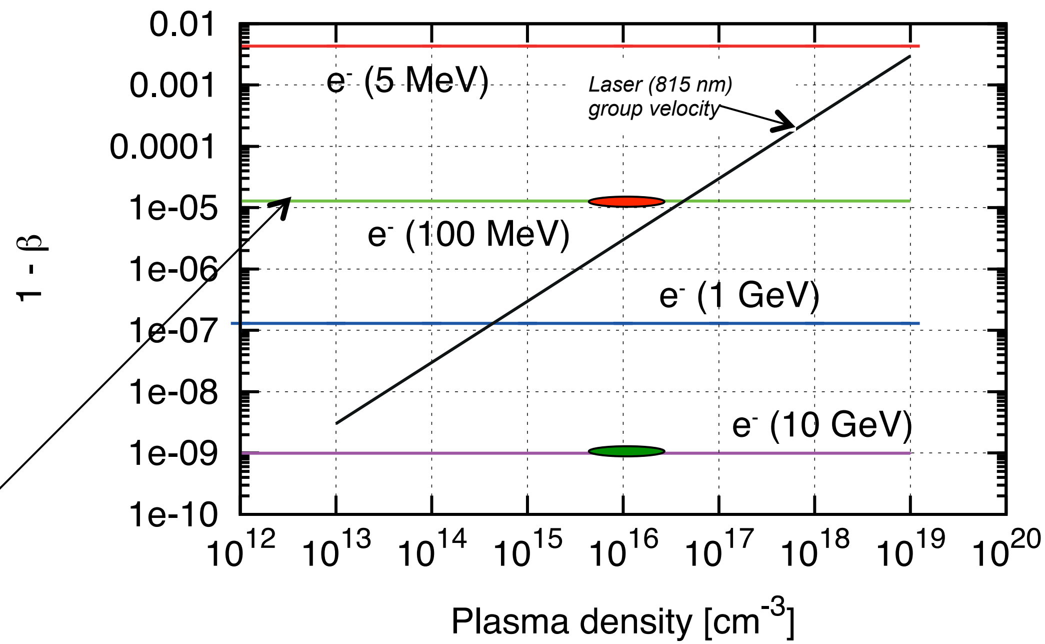


- Imagine **10 GeV beam driver**.
- Imagine **initial energy of accelerated electrons to be 100 MeV**.
- After 1 m slippage by ≈10^{-5} m = **10 μm**.
- Plasma wavelength: **10 μm (n_0=1e19) – 1 mm (n_0=1e15)**
- However:
  - Driver electrons are decelerated and slow down.
  - Accelerated electrons speed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

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



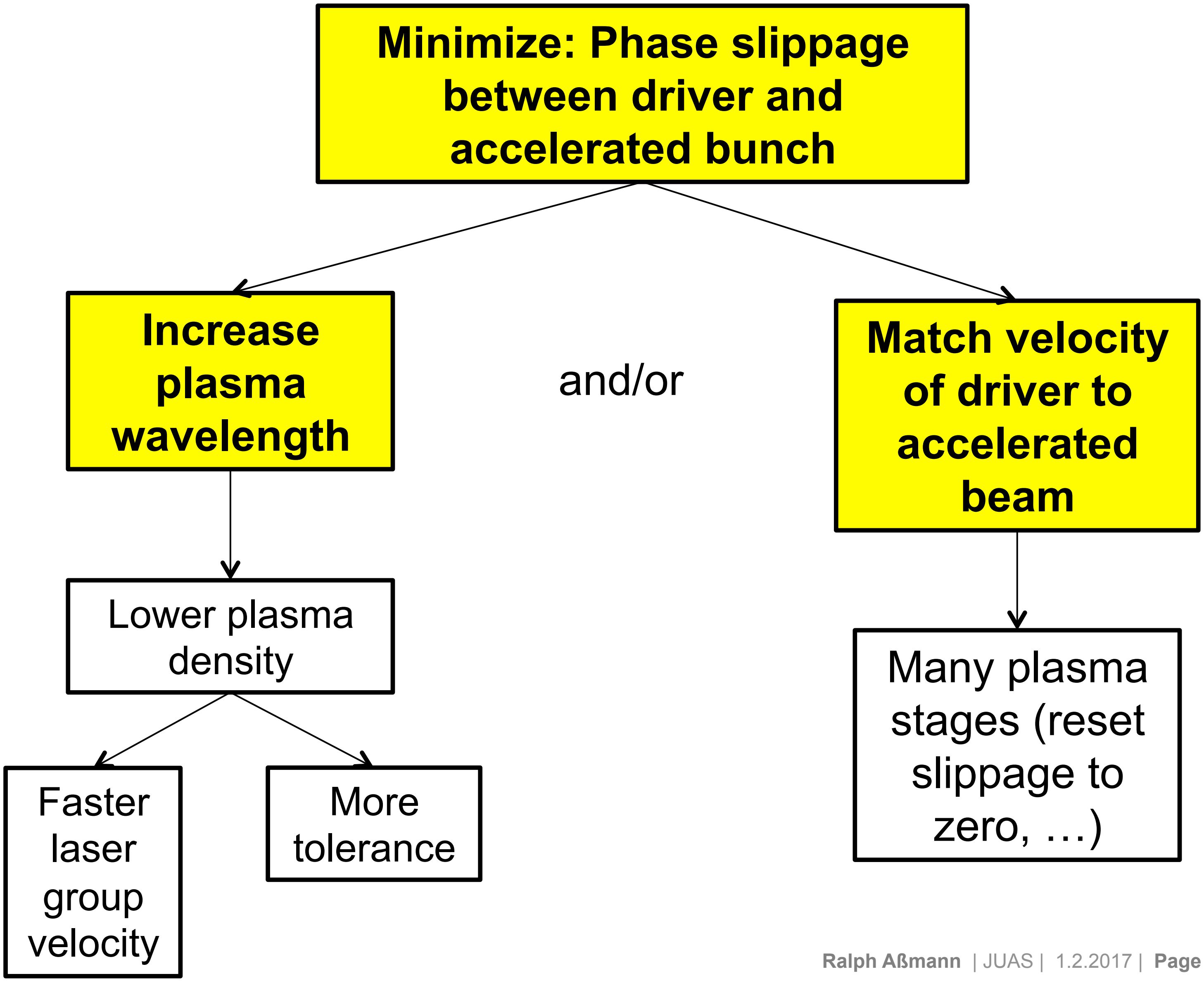
- Imagine **10 GeV beam driver**.
- Imagine **initial energy of accelerated electrons to be 100 MeV**.
- After 1 m slippage by ≈10^{-5} m = **10 μm**.
- Plasma wavelength: **10 μm (n_0=1e19) – 1 mm (n_0=1e15)**
- However
  - Driver e
  - Acceler

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.

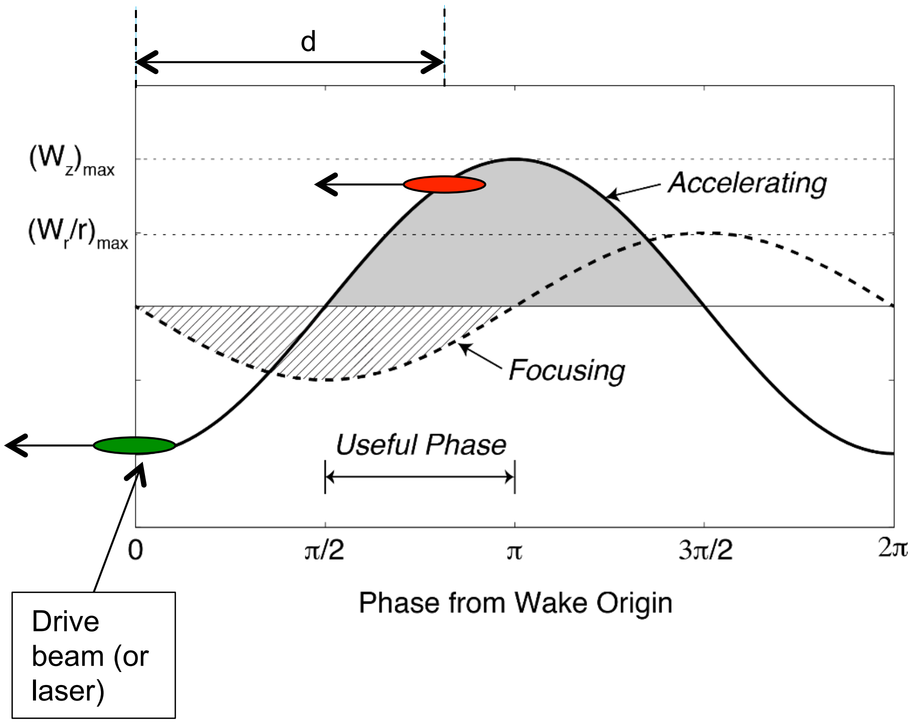
Internally generate accelerated electron bunch

High accelera-ting fields

High plasma density

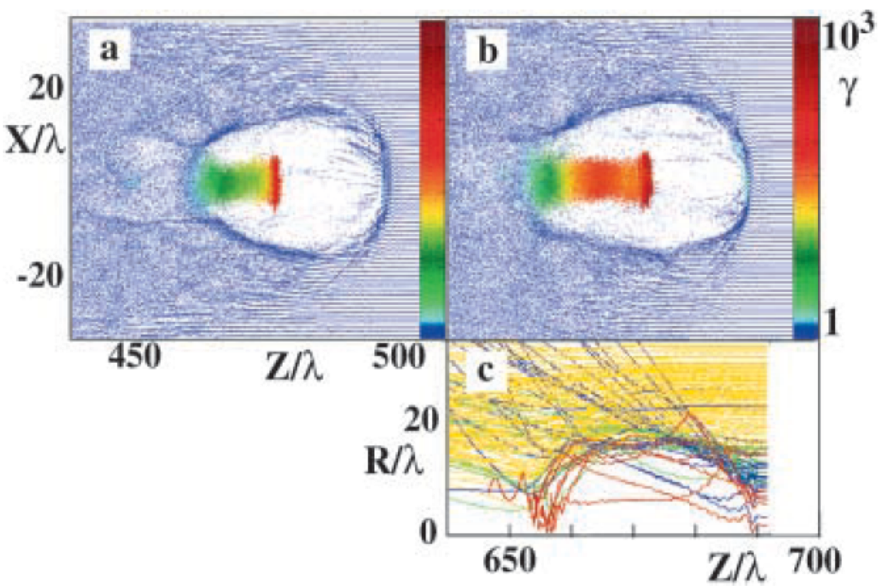
Synchronize externally injected beam to driver

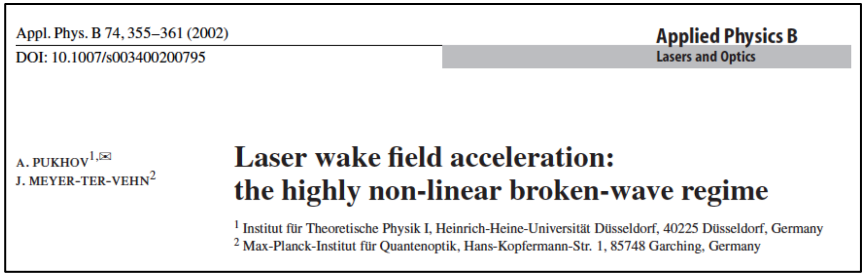
Synchronize with **30 fs to 0.3 fs accuracy** for few degree phase stability



Warning: Non-Linearities are Important

- Plasma wakefield acceleration is most often operated in the so-called **non-linear regime**.
- No time to discuss here – would require more time.
- Accelerating field approaches triangular shape and focusing field is constant with radius → easier regime in many aspects.
- Electron trapping (beam forming) occurs here.





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

Content

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

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):

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

$$\propto N_b / \sigma_z^2$$

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 γε = 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.

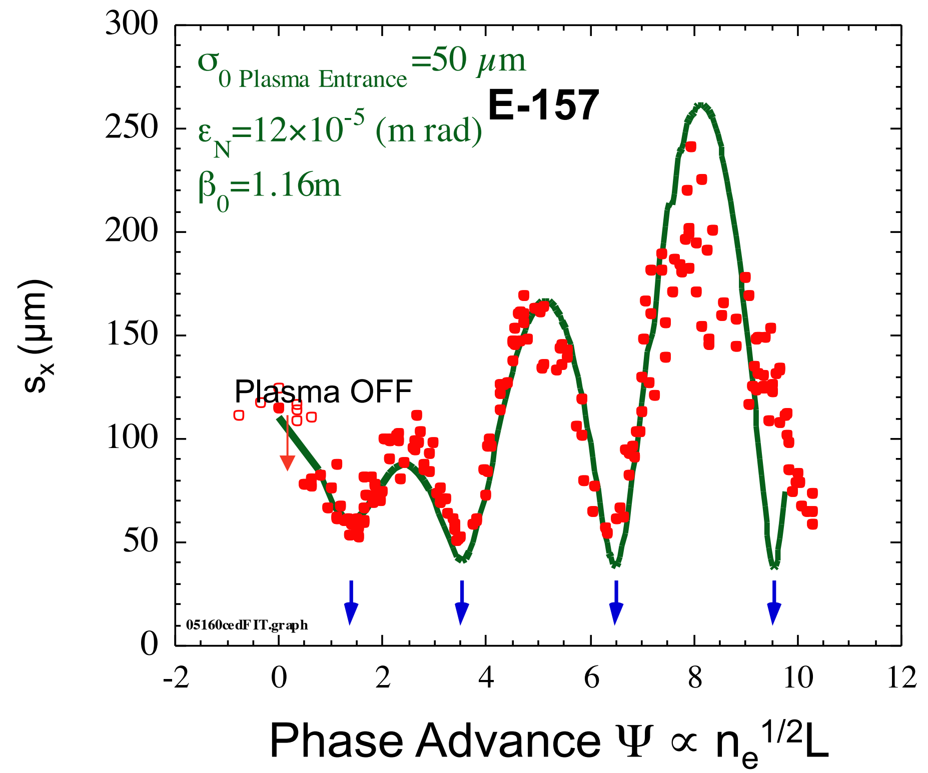
Beam Propagation Through A Long Plasma

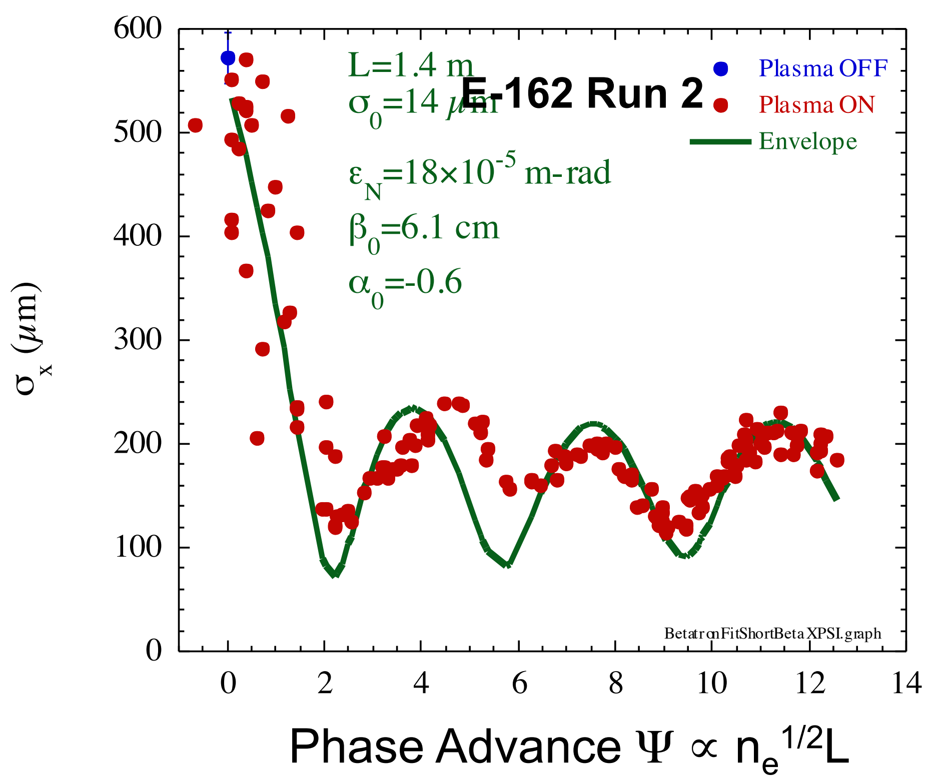
Stanford Linear Accelerator Center

UCLA

USC

- 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)



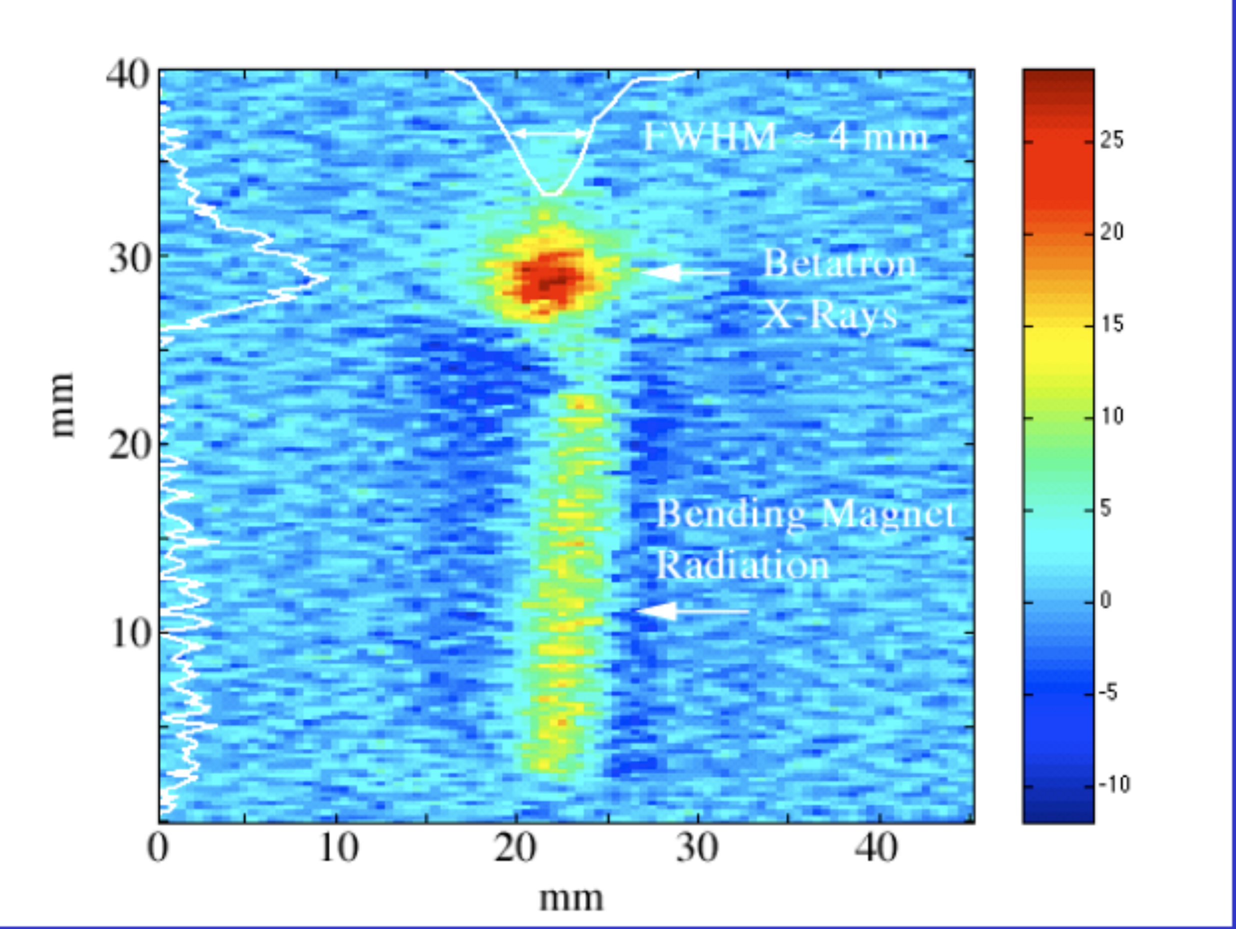


C. E. Clayton et al., PRL 1/2002

E-157/E-162 collaboration

Betatron Radiation of X-rays

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



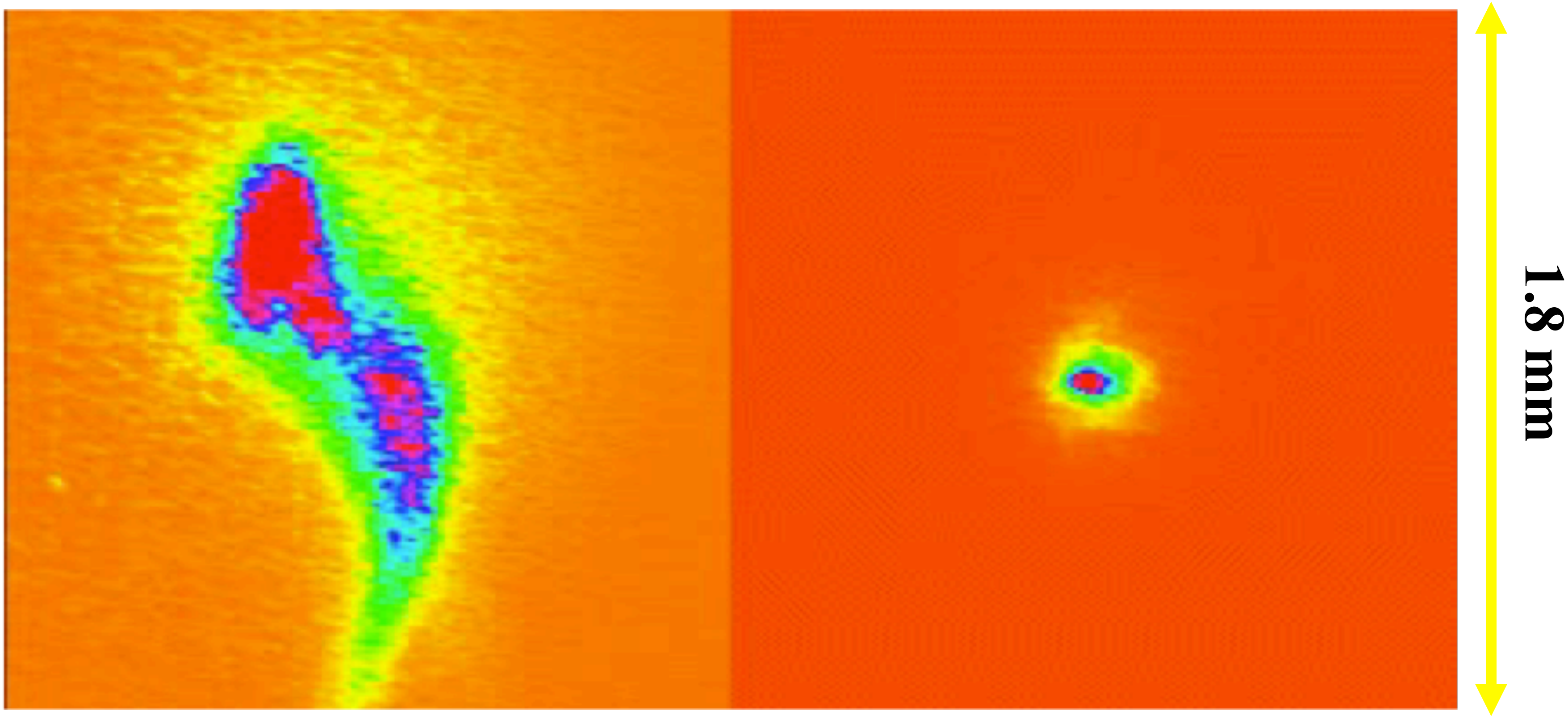
- Peak brightness ~ 10^{19} photons/sec-mm^2-mrad^2-.1%bw!

E-157 collaboration

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).

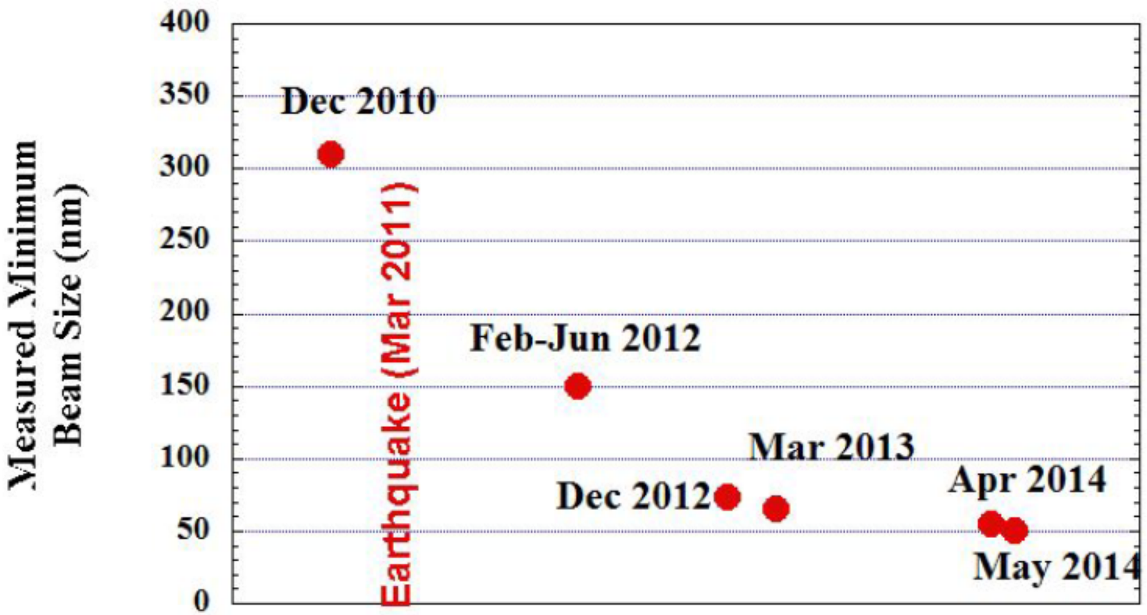
~ 2e10 electrons, 30 GeV

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**.

Accelerator Builder's Challenge – Feasible?

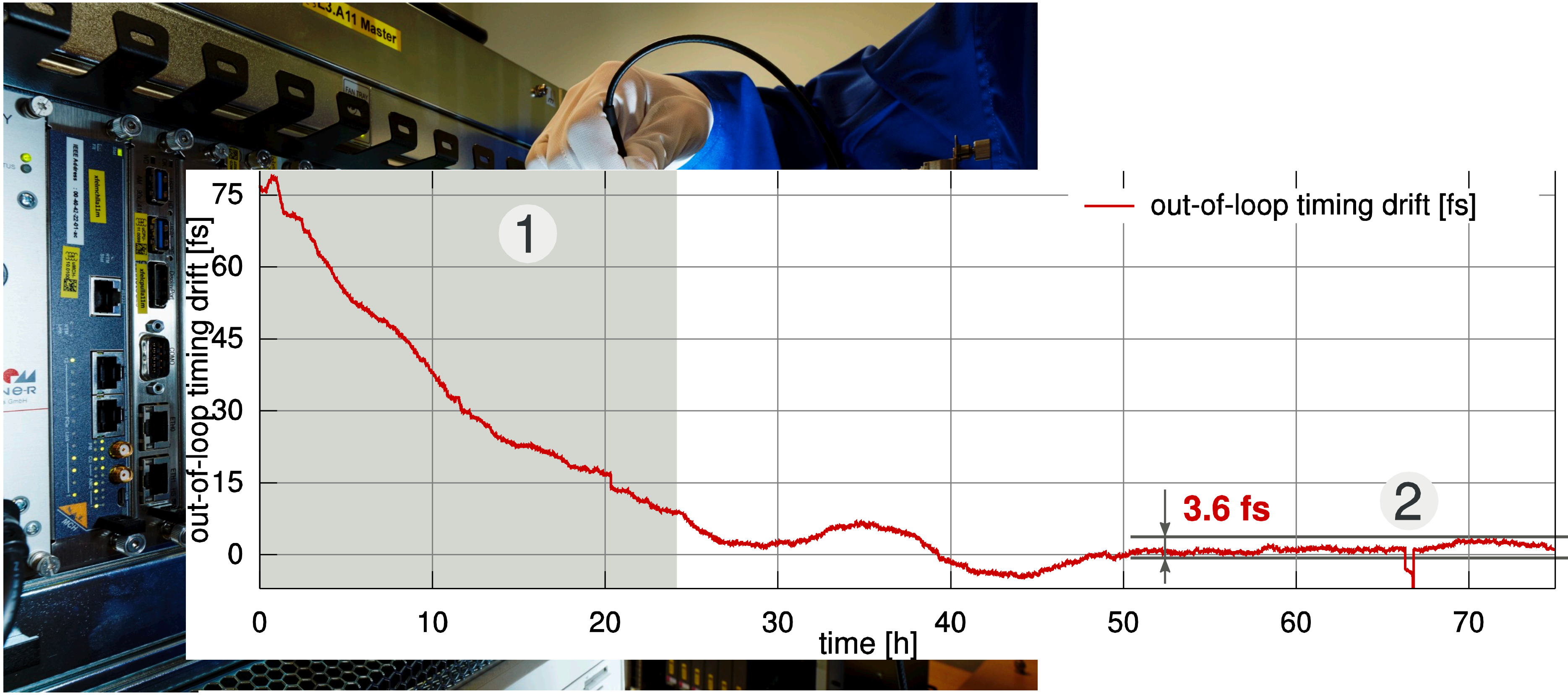
> Difficult but we believe solutions can be found. Will not come for free…



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

Accelerator Builder's Challenge – Feasible?

DESY Ultra-Fast Electronics and Synchronization



Femtosecond Precision in Laser-to-RF Phase Detection

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

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

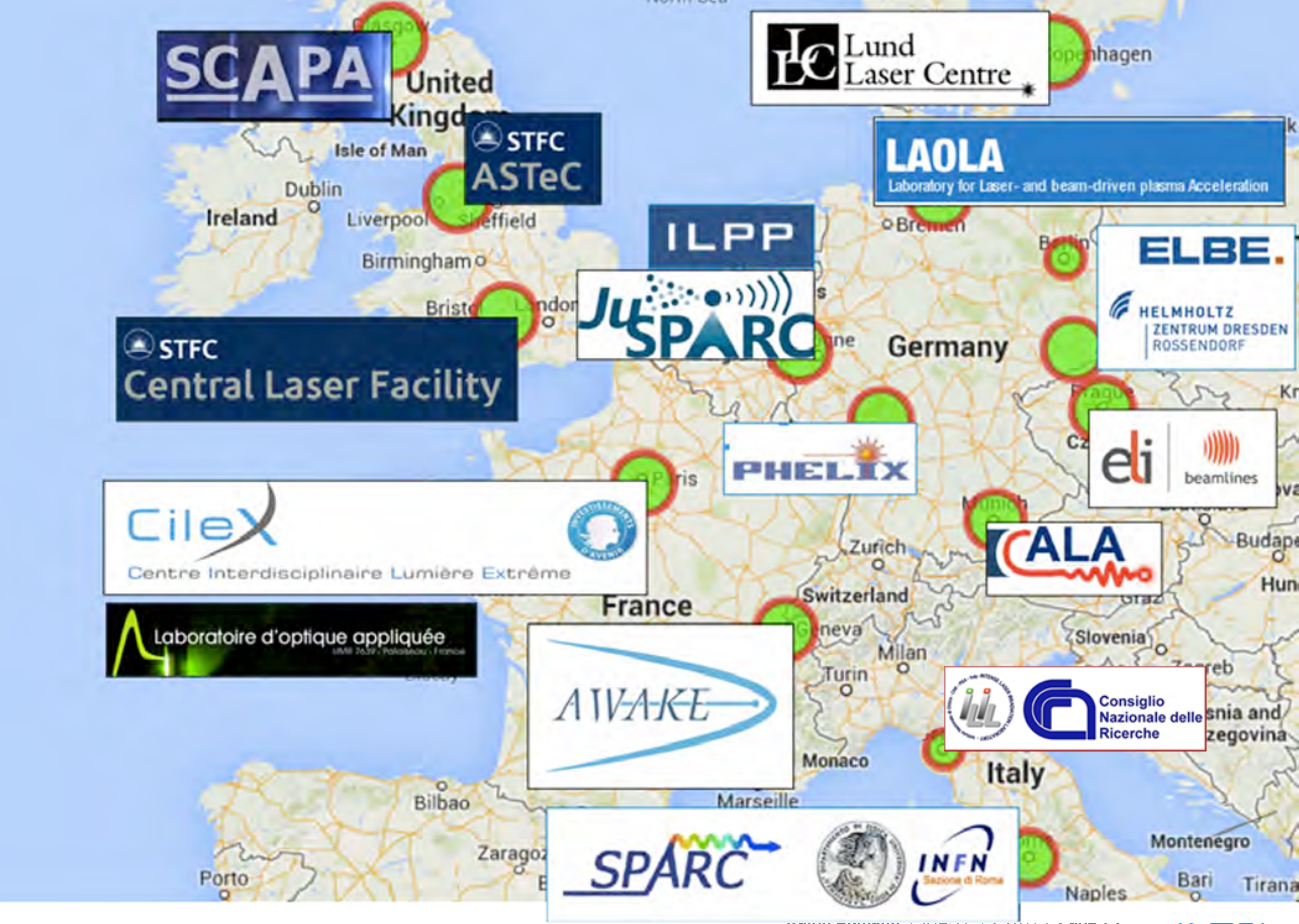
1. Accelerators – From Conventional Techniques to Plasmas
2. The Linear Regime
3. The Non-Linear Regime
4. Tolerances
5. **Outlook for Europe**

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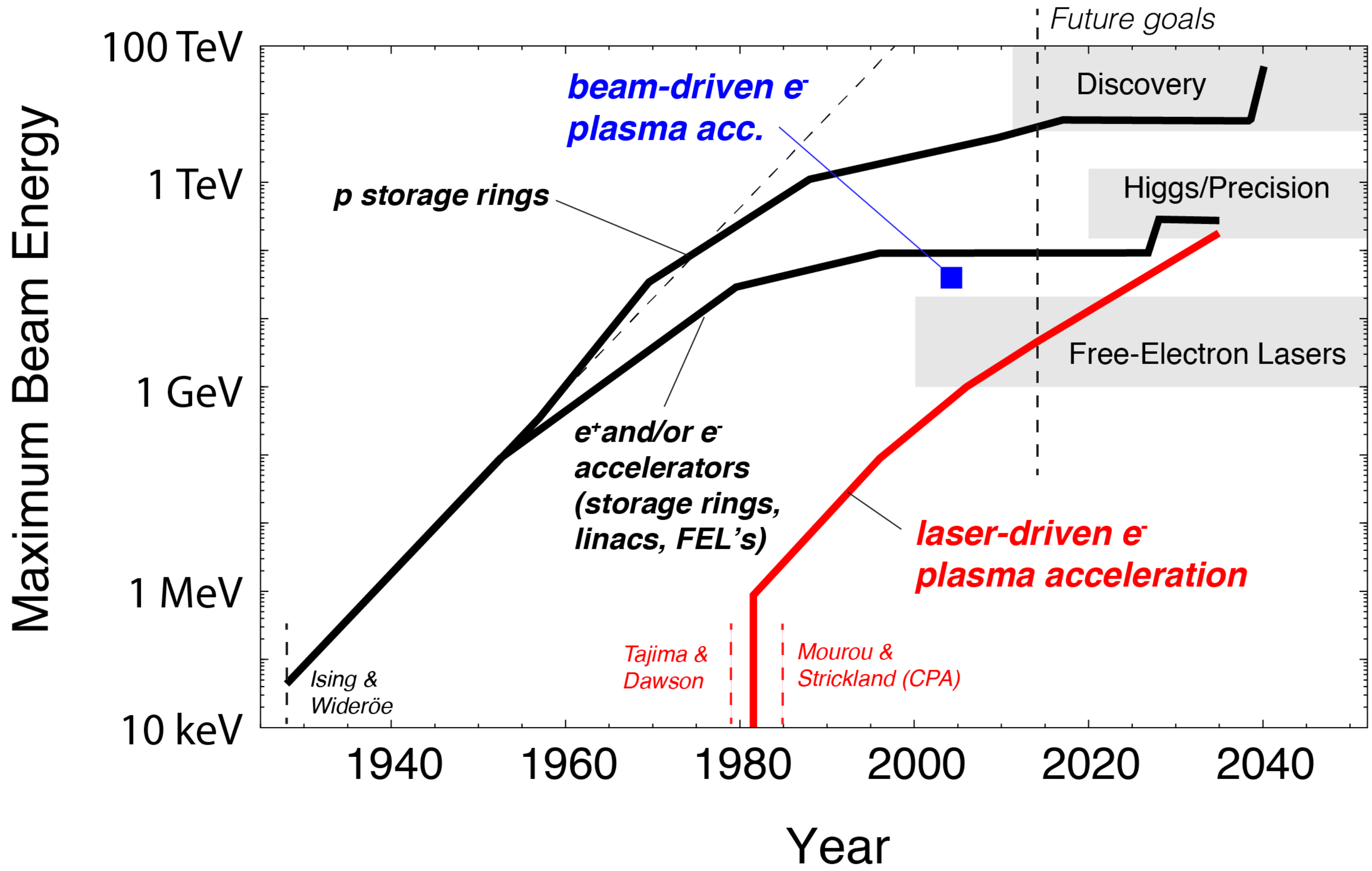
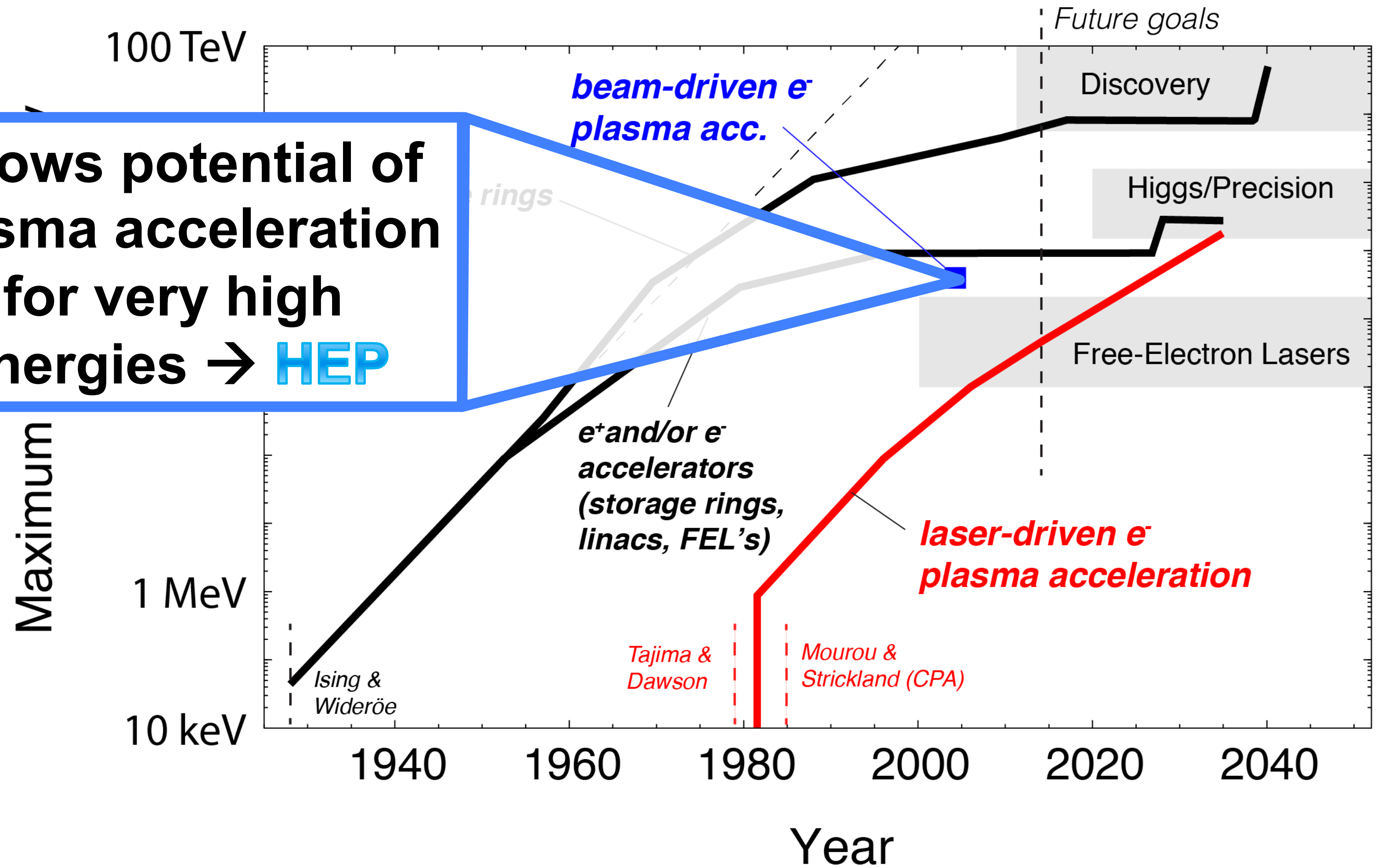
Bilbao
Marseille
Zaragoza
SPARC
INFN
Montenegro
Porto
Bari
Naples

Livingston and Accelerators at the Energy Frontier

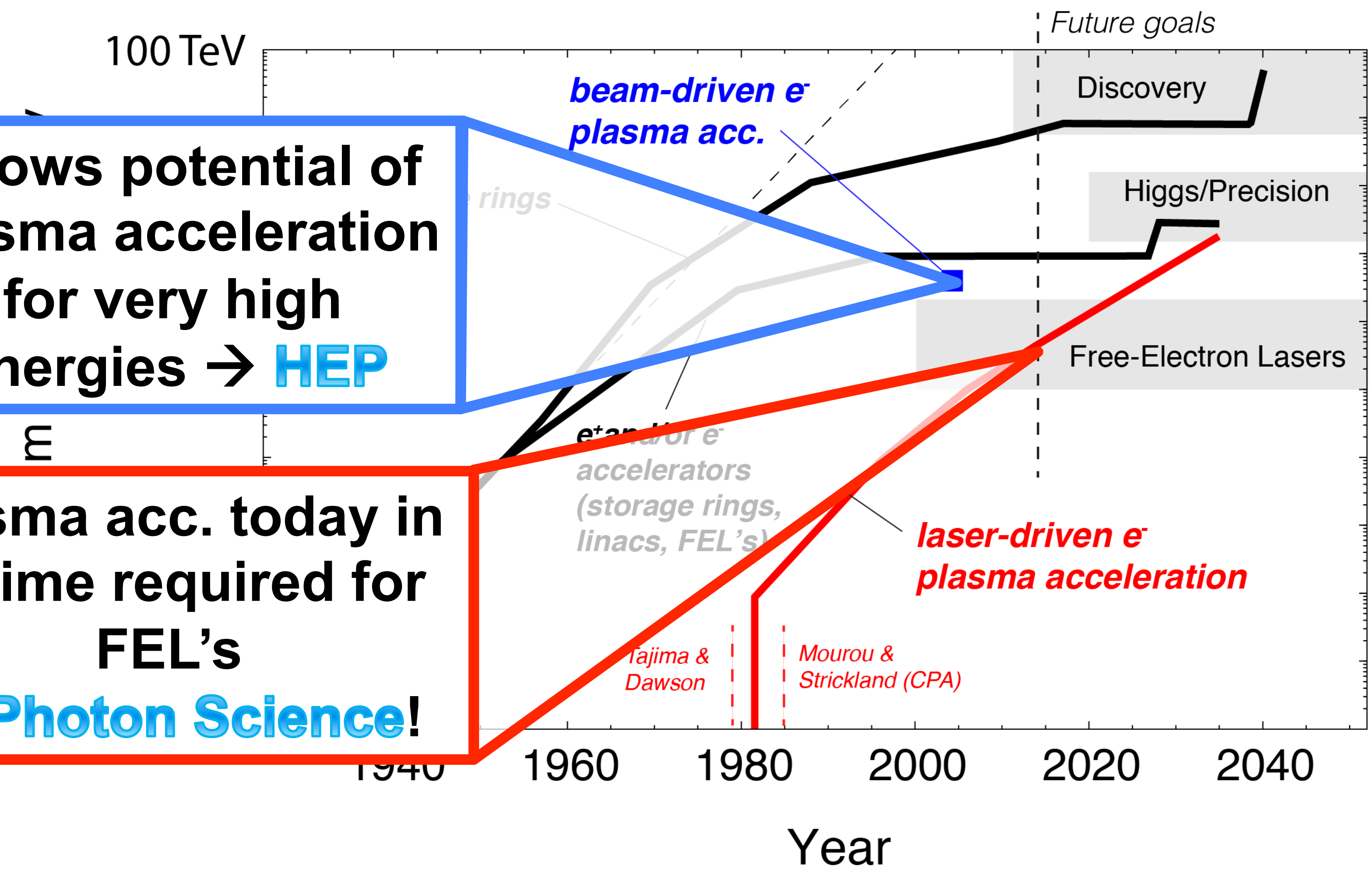


Livingston and Accelerators at the Energy Frontier



Shows potential of plasma acceleration for very high energies → HEP

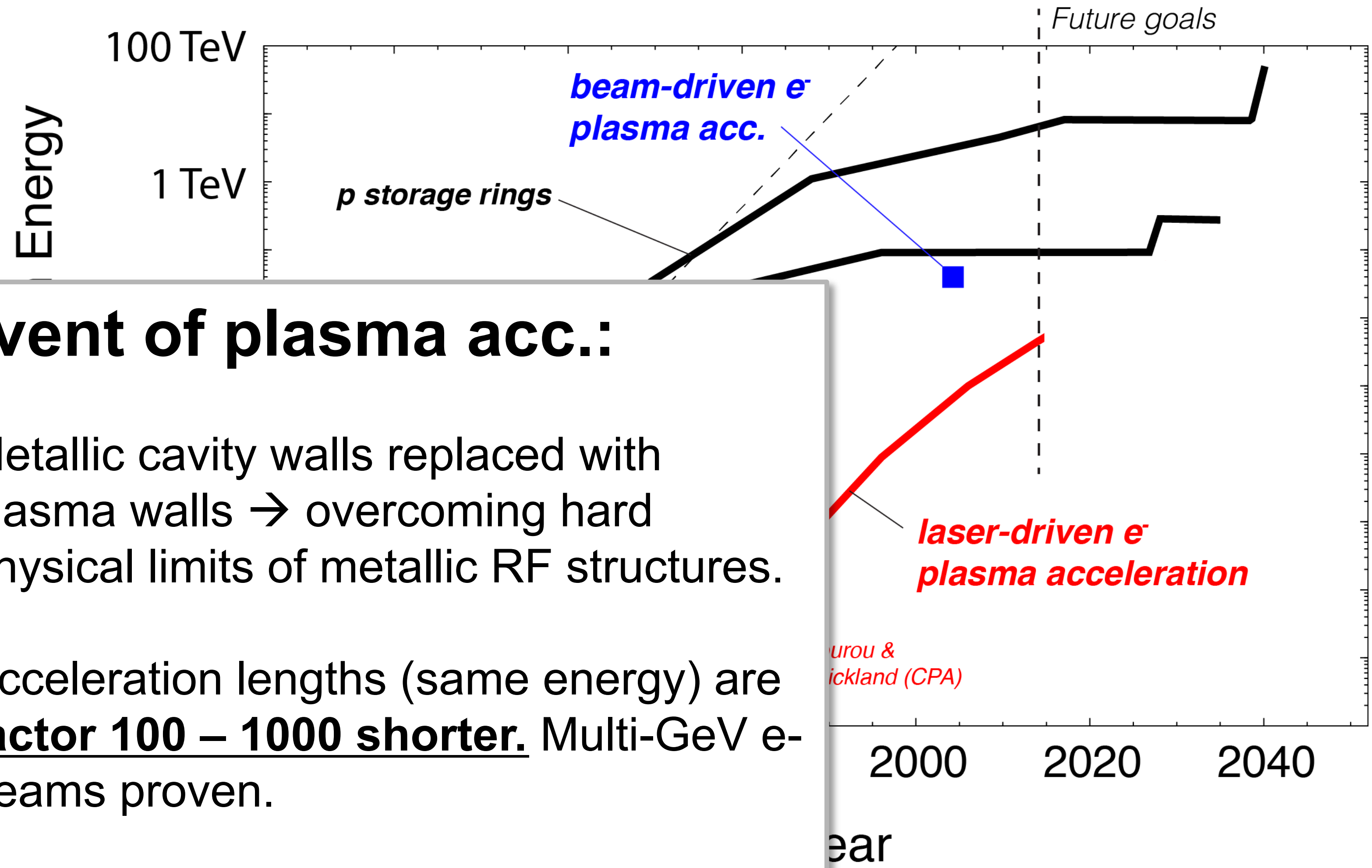
Livingston and Accelerators at the Energy Frontier



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**.

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EuPRAXIA

http://eupraxia-project.eu

NOVEL FUNDAMENTAL RESEARCH

COMPACT EUROPEAN PLASMA ACCELERATOR WITH SUPERIOR BEAM QUALITY

Find Out More

OUR TECHNOLOGY

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

LEARN MORE

PARTICIPANTS

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

LEARN MORE

WORK PACKAGES

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

LEARN MORE

MANAGEMENT

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

LEARN MORE

OPENING NEW HORIZONS

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

DESY

cnrs

cea

Consiglio Nazionale delle Ricerche

SOLEIL SYNCHROTRON

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

UH 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.


Kick-off meeting at DESY on Nov 26th – 27th

EuPRAXIA Ambition and Schedule

Horizon2020

Basic research (R): Proving theoretical principles – discovering new schemes

Engineering (D): Improve and optimize acceleration devices, industrialize

Prototyping: Build a prototype accelerator unit to demonstrate performance

User operation: Build user facilities delivering beam for applications

Many sites.
Typically 30 M€ investment per site.
Tremendous progress in 35 years.
Effort will continue the next decades.
Focus on research: users outside scope.

one needs the other

EuPRAXIA

One or few sites.
Larger investment:
30 M€ < X << 1 B€
ESFRI roadmap in 2018 or 2020
CDR for 2020
Operation 2025 to 2035

More than the Plasma Accelerator

- In a circular accelerator facility:
  Accelerating systems < 10% of total investment
- In a linear accelerator facility:
  Accelerating systems < 30% of total investment

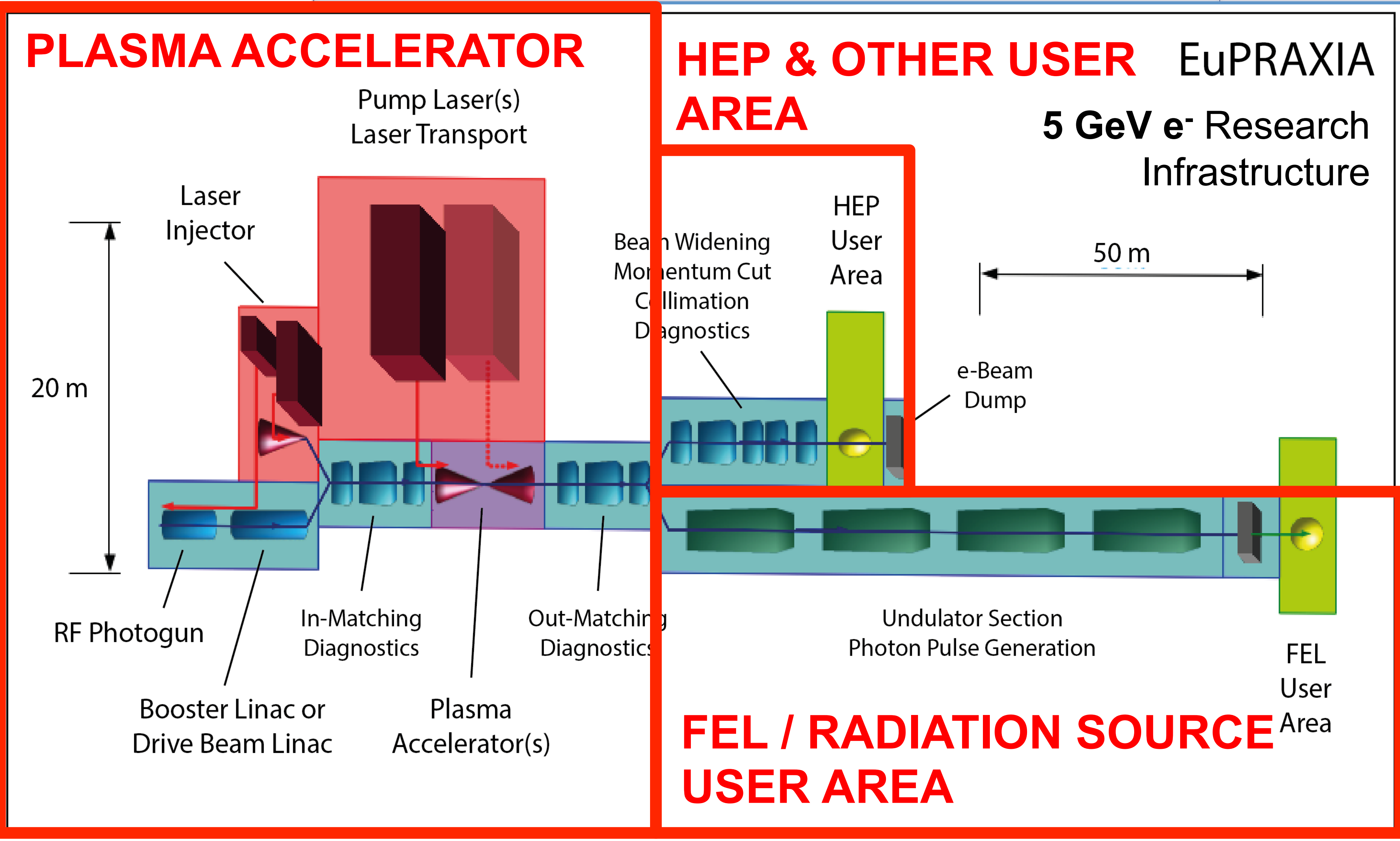
- Highly developed (and expensive) systems for generation/ bending/focusing/diagnostics/correction/collimation/control of particle beams:
  - Accelerator facilities would not provide interesting performance without these systems.
  - **For plasma accelerators not at addressed yet, due to focus on acceleration highlights and lack of budget**

→ EuPRAXIA to address this: build an accelerator research infrastructure for pilot users

EuPRAXIA Research Infrastructure for the 2020's

5 GeV electron beam

Horizon2020

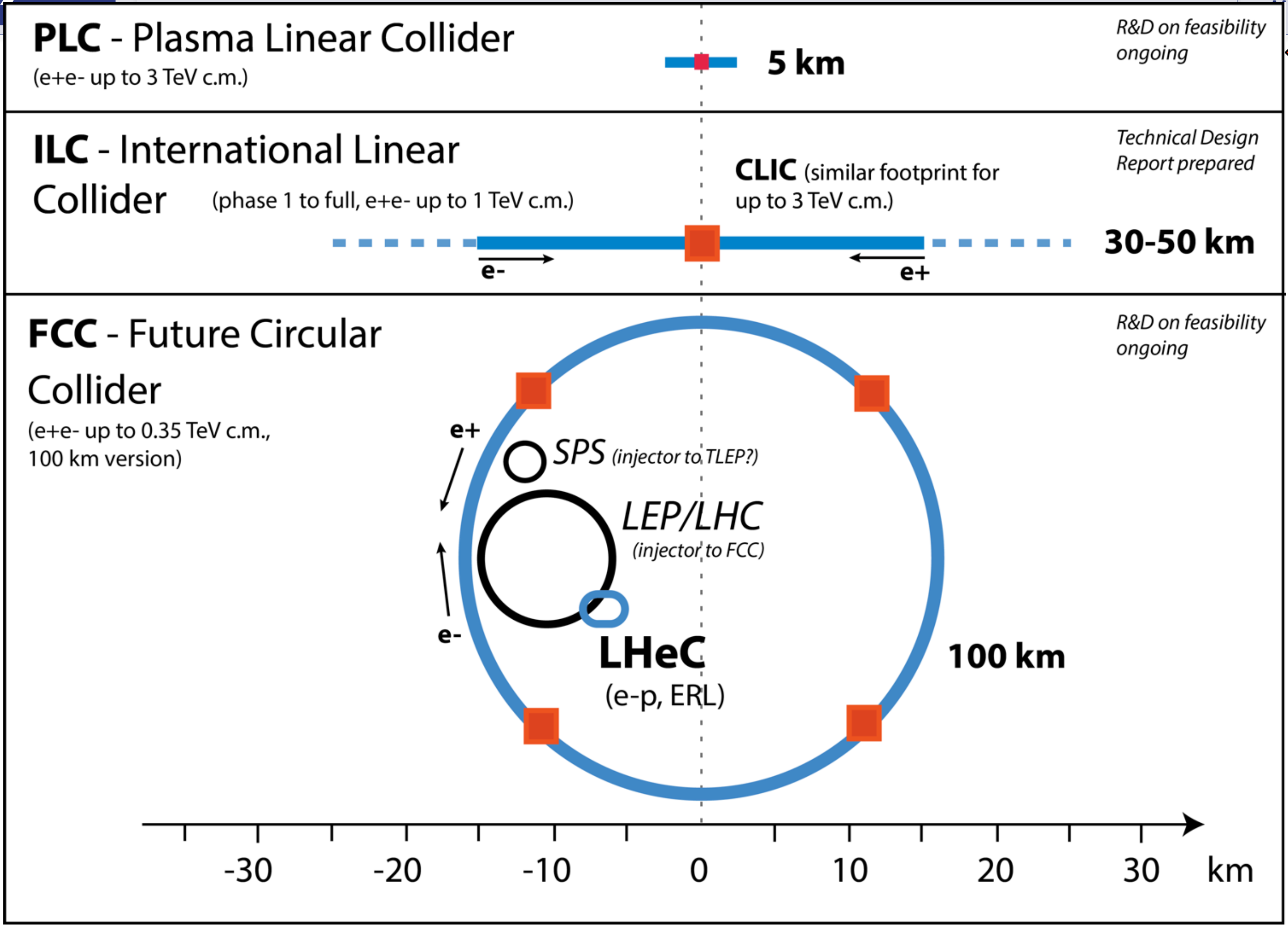


Pisa Science Meeting

June/July 2016, 120 participants

Horizon2020

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…