Plasma Wake Driven FEL

R.W. Aßmann

Leading Scientist

Accelerator Development

DESY

CAS Lecture

DESY, 7.6.2016

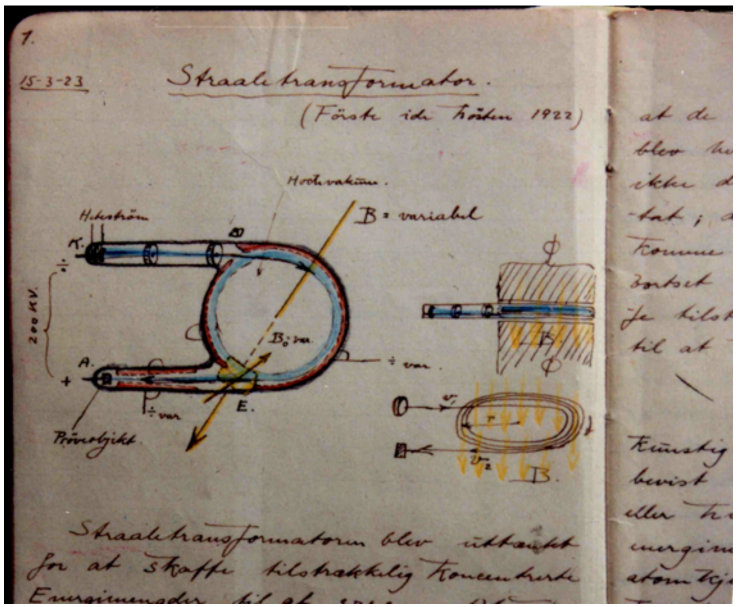
Content

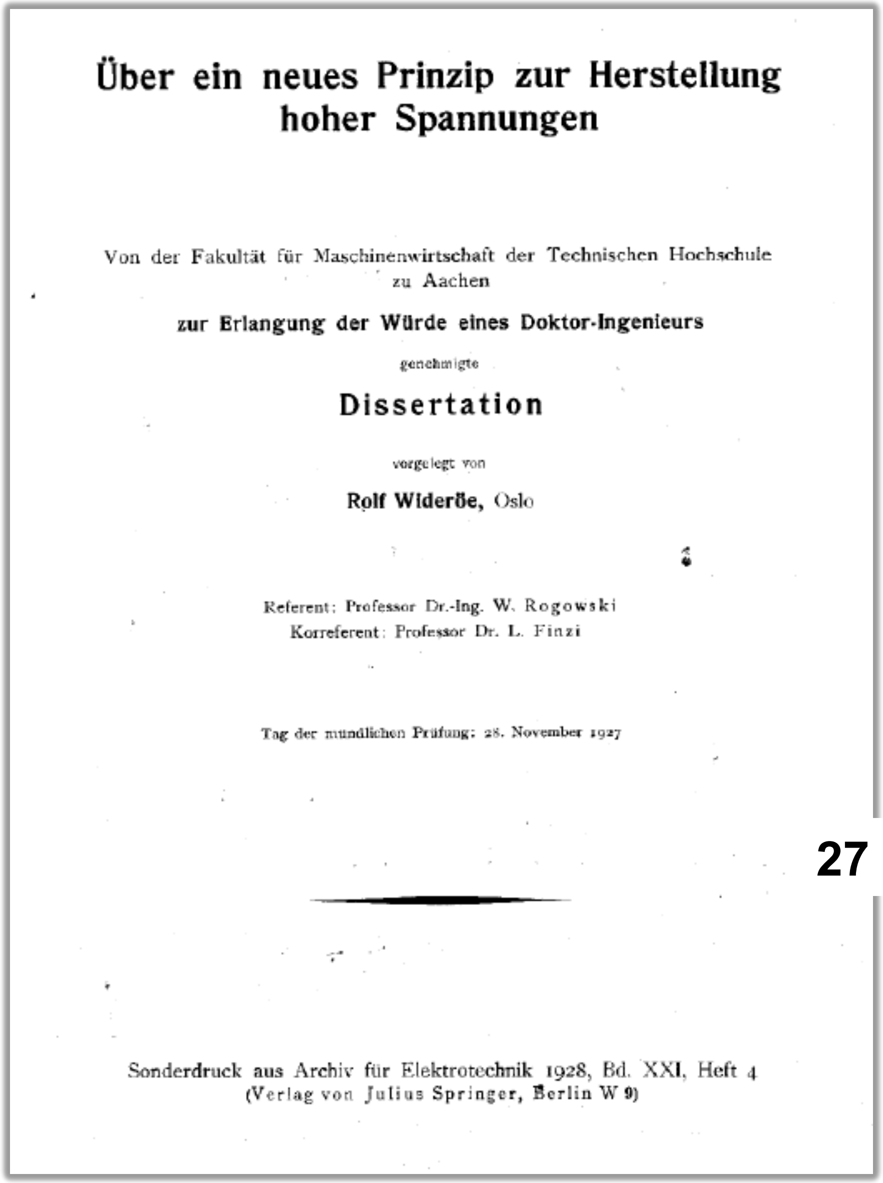
1. From Table-Top to Biggest Machines of Mankind
2. Towards 21st Century Table-Top: The Plasma Wakefield and the Plasma Accelerator
3. Building an FEL Based on Plasmas
4. Plasma FEL Projects in Europe

Content

1. **From Table-Top to Biggest Machines of Mankind**
2. Towards 21st Century Table-Top: The Plasma Wakefield and the Plasma Accelerator
3. Building an FEL Based on Plasmas
4. Plasma FEL Projects in Europe

First Demonstration: Wideröe's PhD 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 Widerõe, Oslo

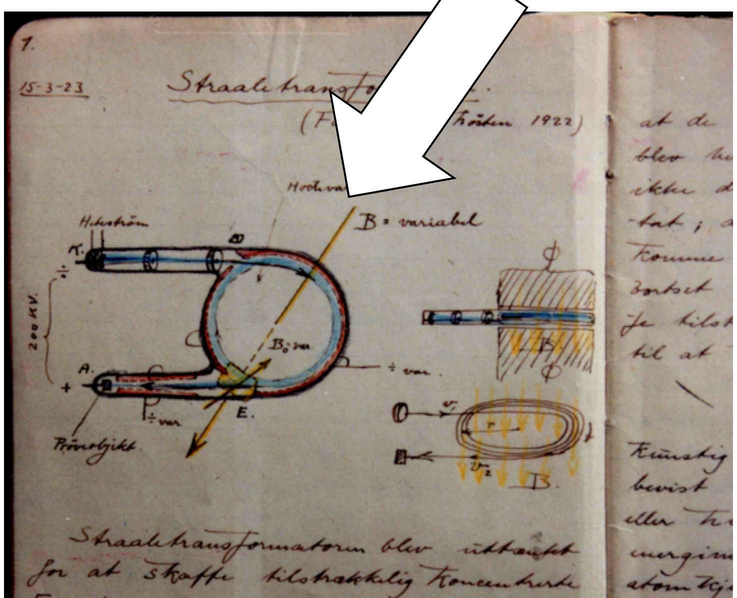
Referent: Professor Dr.-Ing. W. Rogowski
Korreferent: Professor Dr. L. Finzi

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

First Demonstration: Wideröe's PhD 1927 in Aachen



Über ein neues Prinzip zur Herstellung hoher Spannungen

First refused at university Karlsruhe as not feasible!

Wideröe had to go to Technical University Aachen

Tag der mündlichen Prüfung: 28. November 1927

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

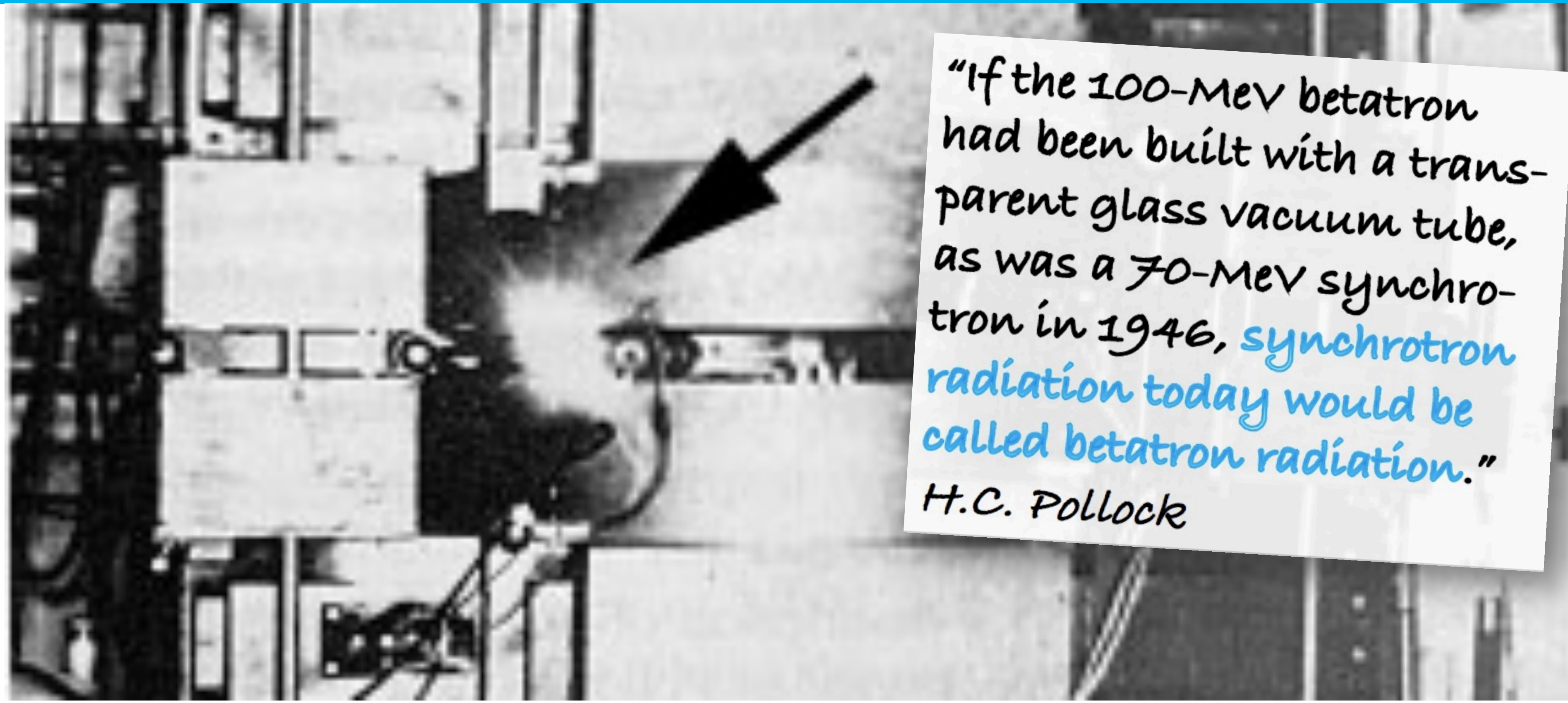
27 pages

The Situation in 1946 *(20 years after Wideröe's sketch)*…

A synchrotron can store a charged particle beam for many hours or even days ("storage ring")

Glass vacuum chamber of the 1947 General Electric Synchrotron Accelerator (70 MeV). Courtesy BNL and ESRF.

General Electric Synchrotron Accelerator 1946



"We had **some sparking** from one of the pulse transformers.

When **Haber looked around the comer** of the wall he noticed a very bright spot of light coming from the tube on the left hand side."

Herbert C. Pollock's Notebook from 1946

Nobel Prize Winners, a Spy, an Actor/Politician…

The discovery of synchrotron radiation

Herbert C. Pollock
2147 Union Street, Schenectady, New York 12309

(Received 12 April 1982; accepted for publication 29 April 1982)

"From the **academic community** there were many visitors between 1947 and 1949.

Among them we can count **six Nobel prize winners.**

With other visitors came Klaus Fuchs, the famous **Russian spy**, clearly capable since none of us in the synchrotron room could remember his visit until it was documented beyond question by the FBI.

Another visitor for 20 minutes was **Ronald Reagan**…"

Big impact on society obviously immediately expected

Nobel Prize Winners, a Spy, an Actor/Politician…

The discovery of synchrotron radiation

“Fro…
visit…

Am…

Wit…
Rus…
syn…
documented beyond…

It took another 25 years, until the 1970's, that synchrotron radiation was used for science and this big impact was realized

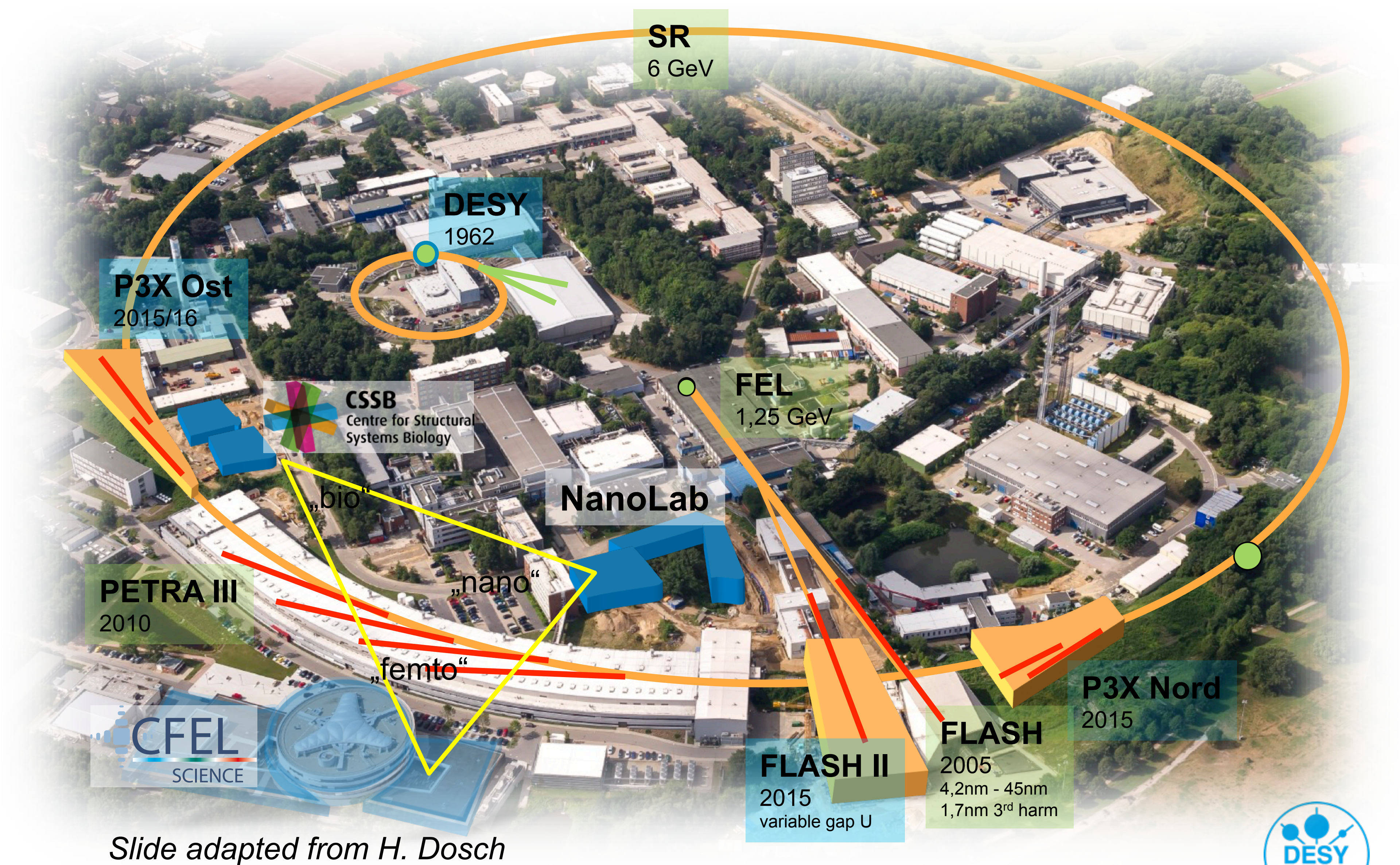
= 45 years after Wideröe's first sketch of a circular accelerator!

Another visitor for 20 minutes was **Ronald Reagan**…”

Big impact on society obviously immediately expected

DESY 50 Years ago...

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



Slide adapted from H. Dosch

Questions and Challenges Arise…

What is the next transformative step?

Where will accelerators be in 10 years?

Where will accelerators be in 80 years?

What will be the new ideas and technologies that make future accelerators possible?

Content

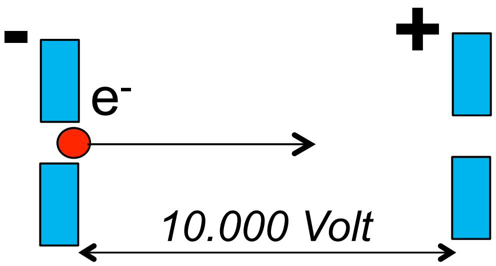
1. From Table-Top to Biggest Machines of Mankind
2. **Towards 21st Century Table-Top: The Plasma Wakefield and the Plasma Accelerator**
3. Building an FEL Based on Plasmas
4. Plasma FEL Projects in Europe

Can we build accelerators much smaller?

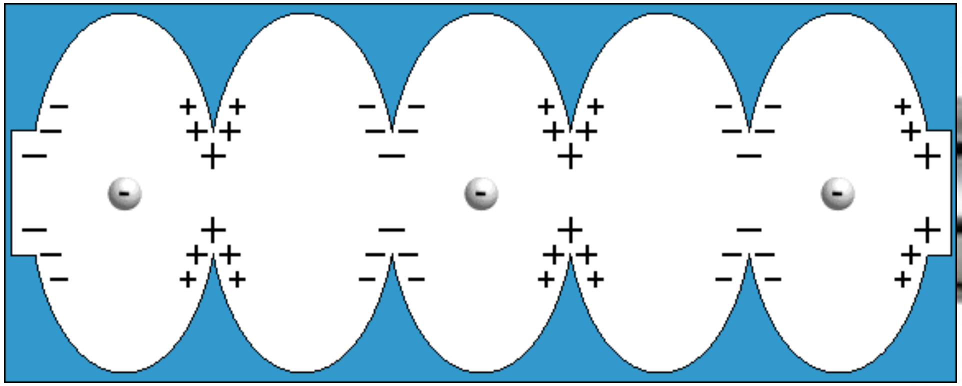
We miniaturized successfully phones, TV’s, computers, ...

Electron Acceleration: Reminder Basic Concept

- 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

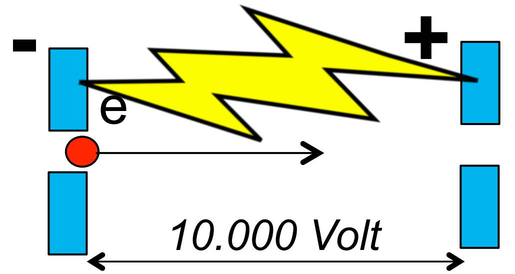
“Runzelröhre”

20.000.000 Volt per Meter

Electron Acceleration: Reminder Basic Concept

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

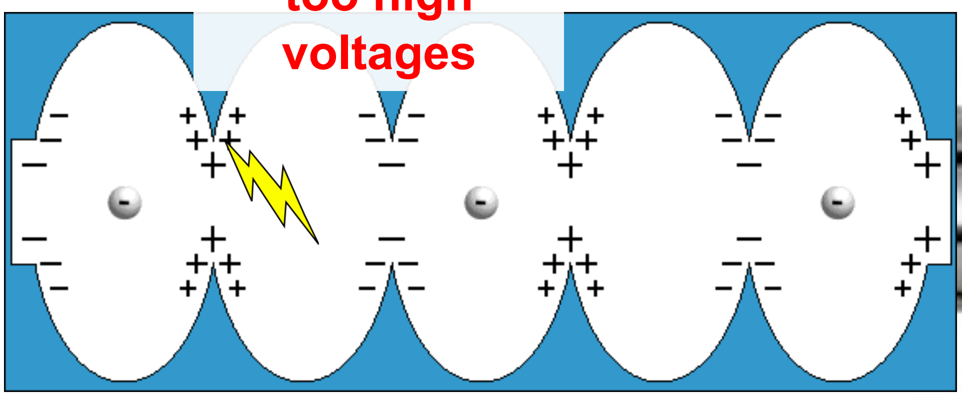
Can we increase the accelerating voltage? More powerful accelerators in same size with same technology?



Flashover at too high voltages

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

Flashover at too high voltages



Sketch Padamse, Tigner

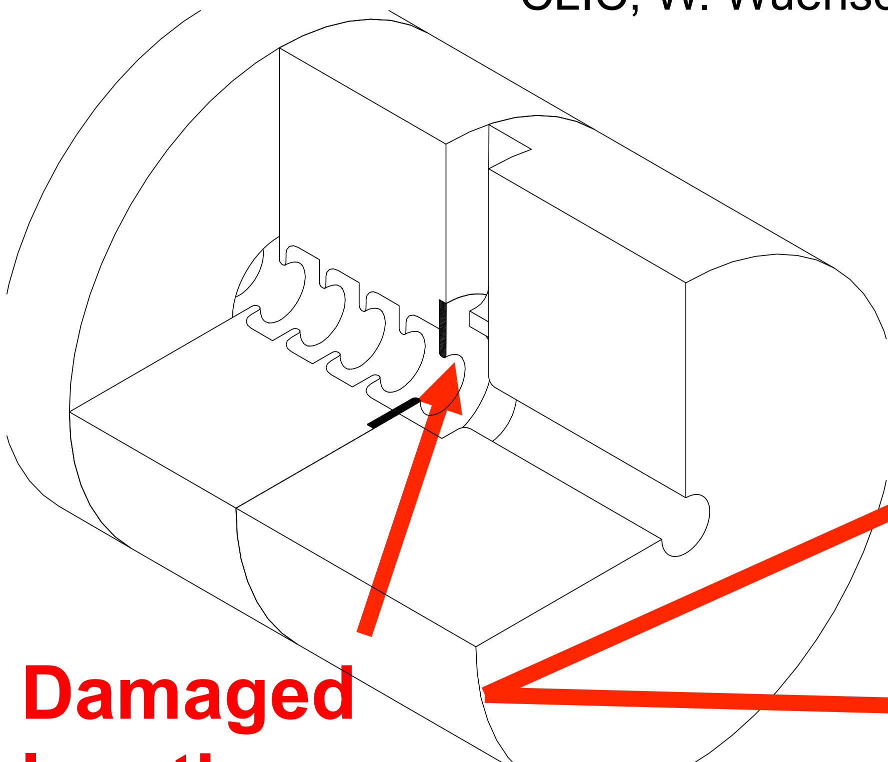
“Runzelröhre”

20.000.000 Volt per Meter

DESY

Flashovers Destroy the Metallic Structures

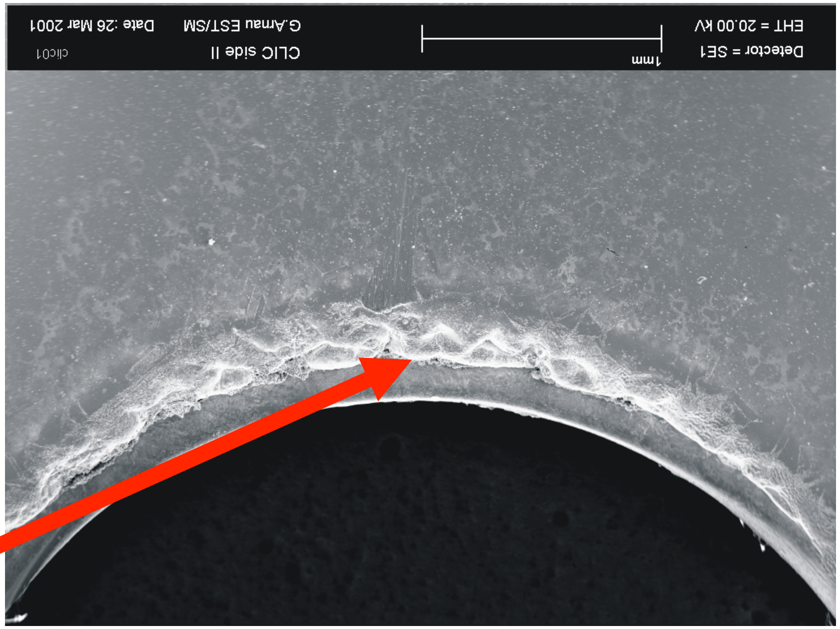
CLIC, W. Wuensch

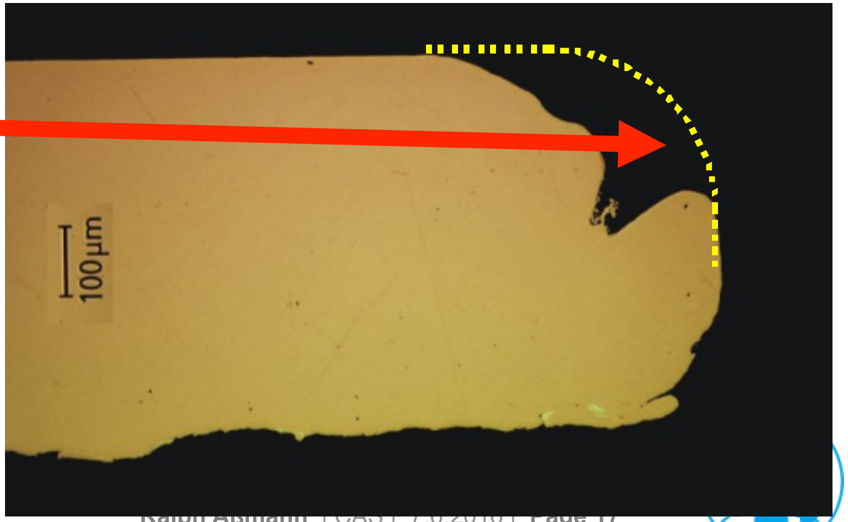


Damaged location

30 GHz, 16 ns,

66 MV/meter





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

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

The Laser Promise: Transverse Electrical Field

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

$$P = 100\,\text{TW}$$
$$r_0 = 10\,\mu\text{m}$$
$$I_0 = 6.4 \cdot 10^{19}\,\text{W/cm}^2$$

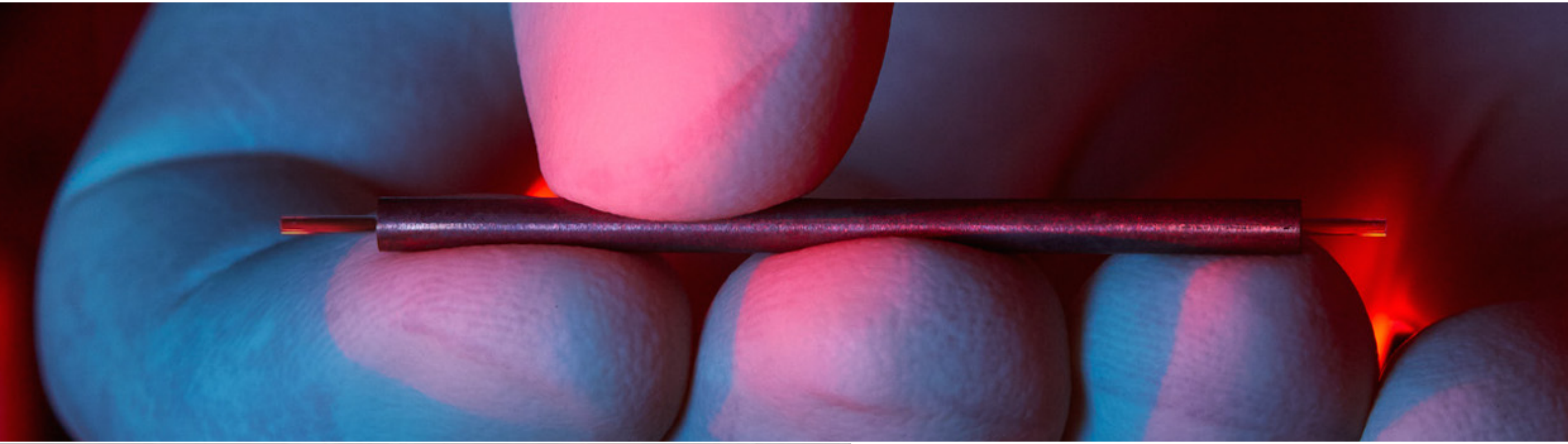
$$E_0 = 22\,\text{TV/m}$$

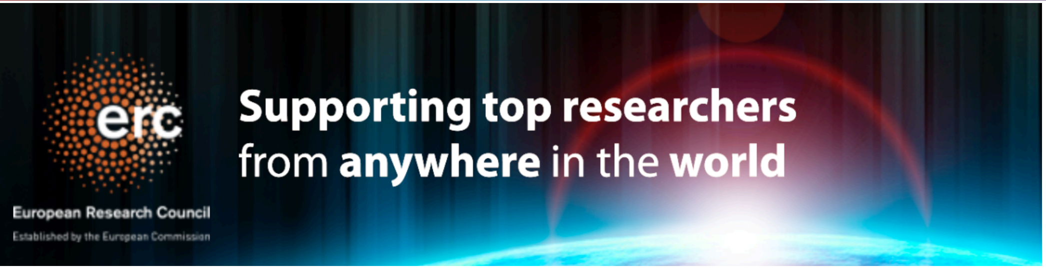
This is what we need!

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

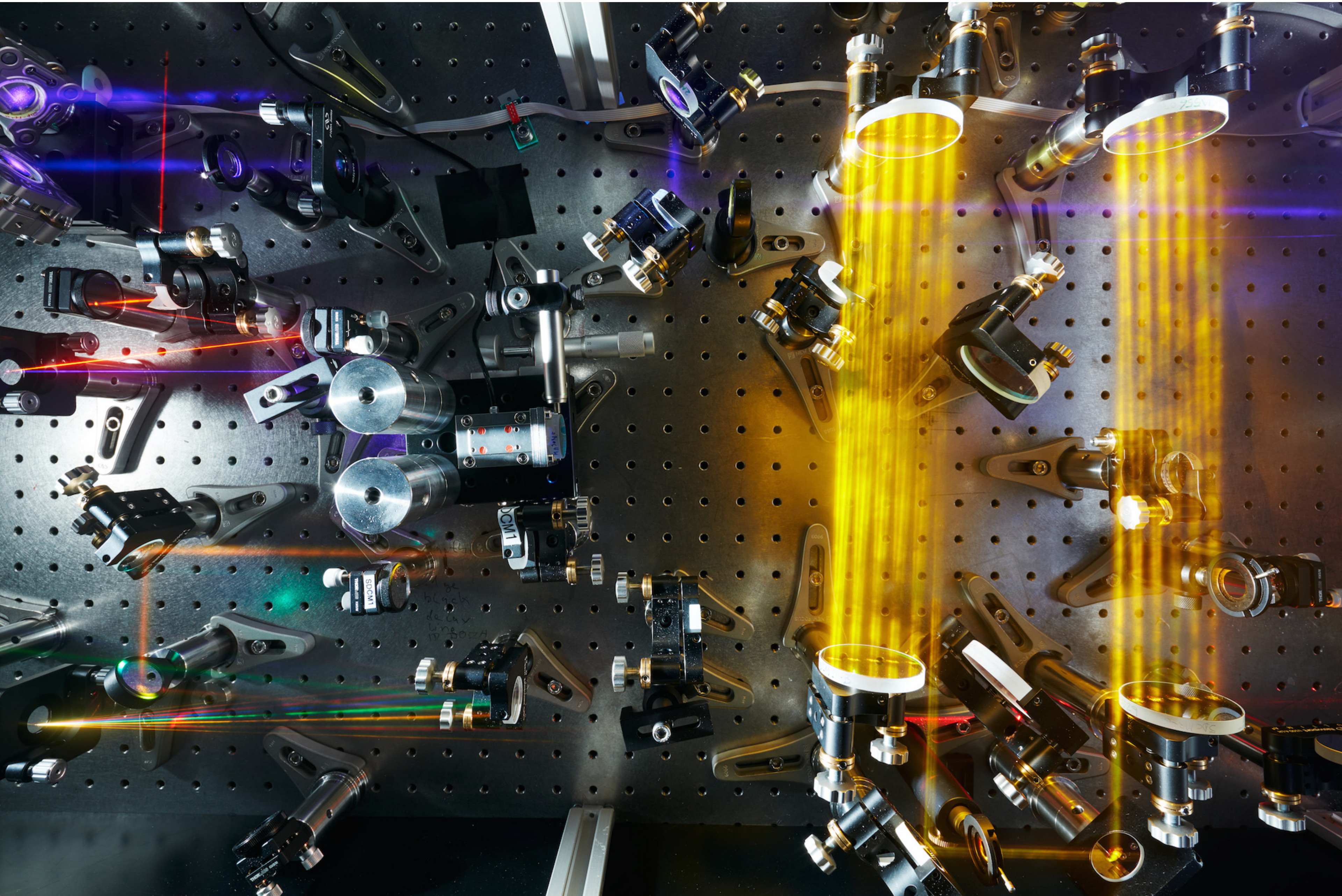
Laser-Driven Micro Structures (Vacuum) – 1

- 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*



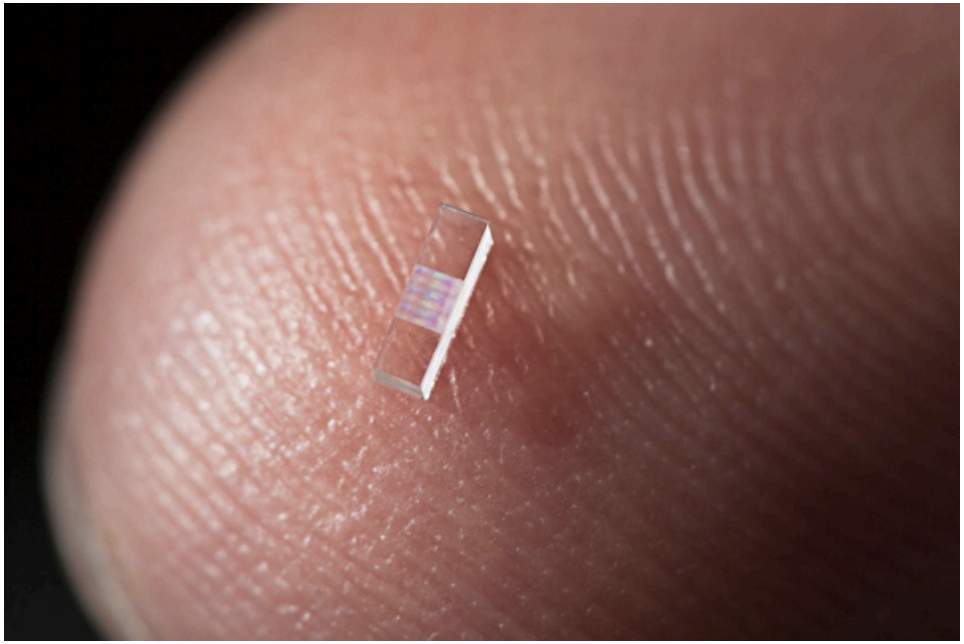


THz Laser Lab (DESY, CFEL, University Hamburg)



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 Foundation of Silicon Valley Billionaire...

GORDON AND BETTY MOORE FOUNDATION

Search

PROGRAMS | GRANTS | NEWSROOM   Staff | About

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.

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?

Lorentz Force F

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

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

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,

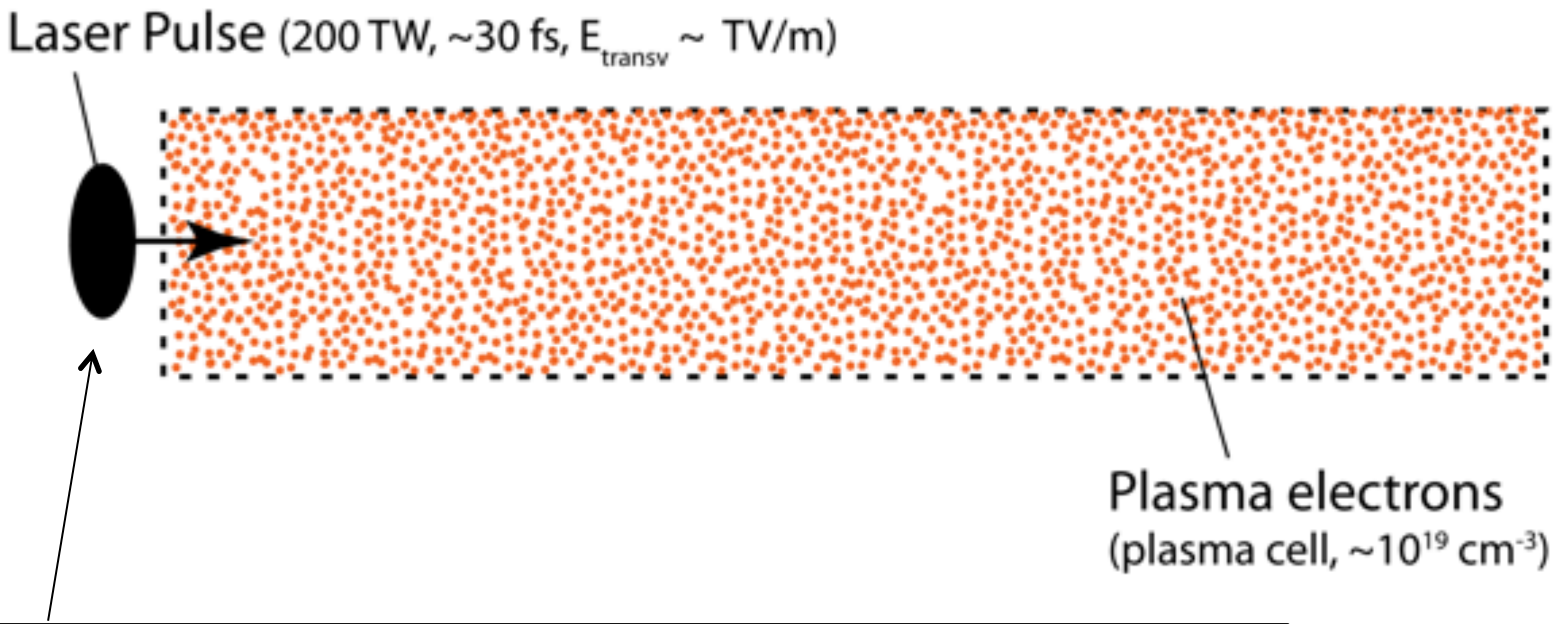
the wavelength of the plasma waves in the wake:

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

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

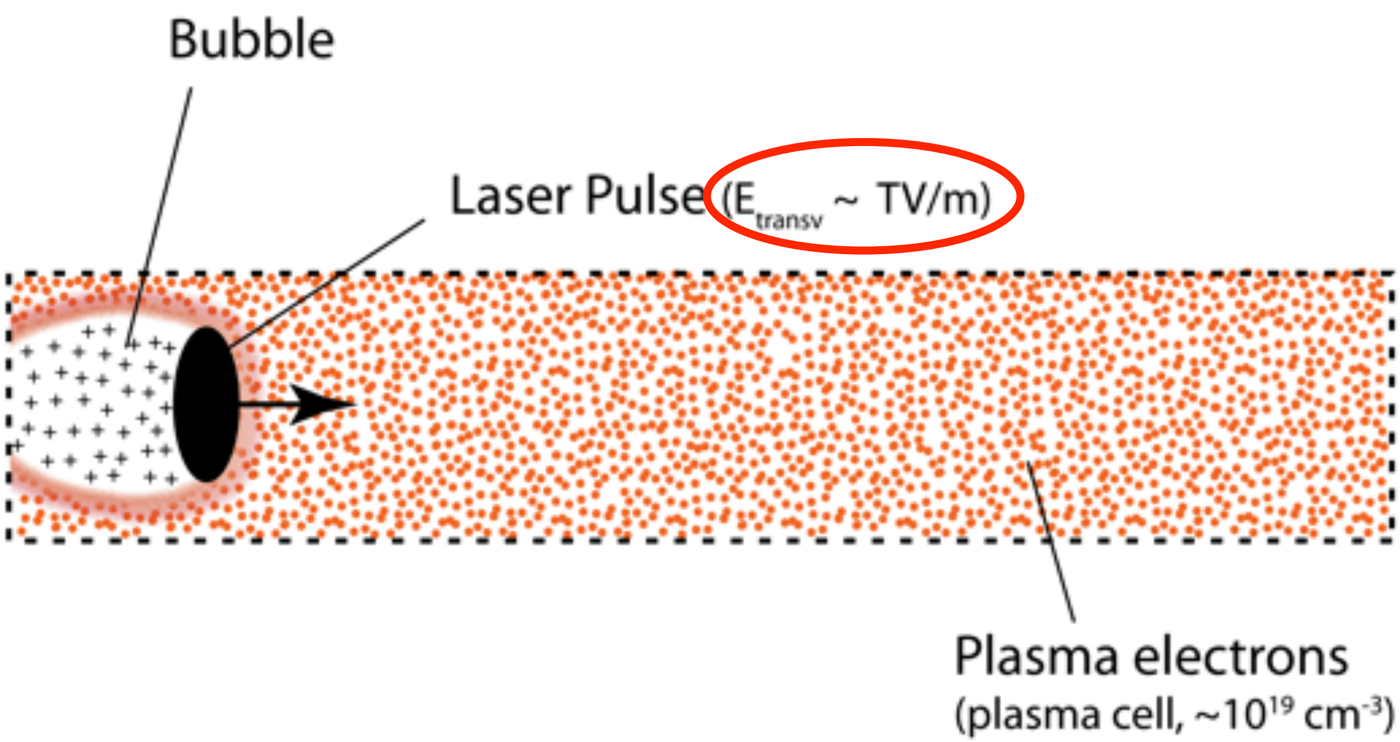
Laser Plasma-Acceleration (Internal Injection)

Plasma = same number of negative charges (low weight electrons) and positive charges (heavy weight ions)

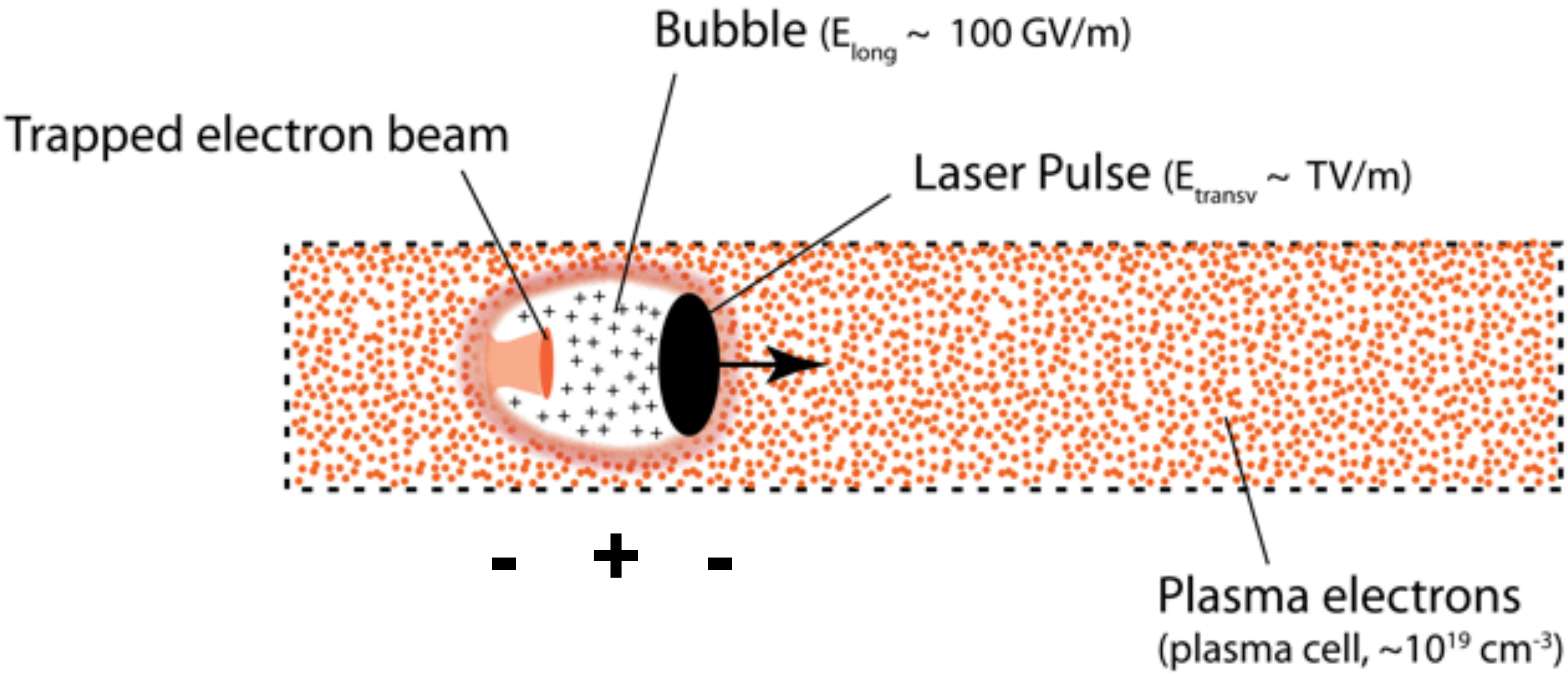


Works the same way with an **electron beam as wakefield driver**. But then usually lower plasma density. Ponderomotive force of laser is then replaced with space charge force of electrons on plasma electrons (repelling).

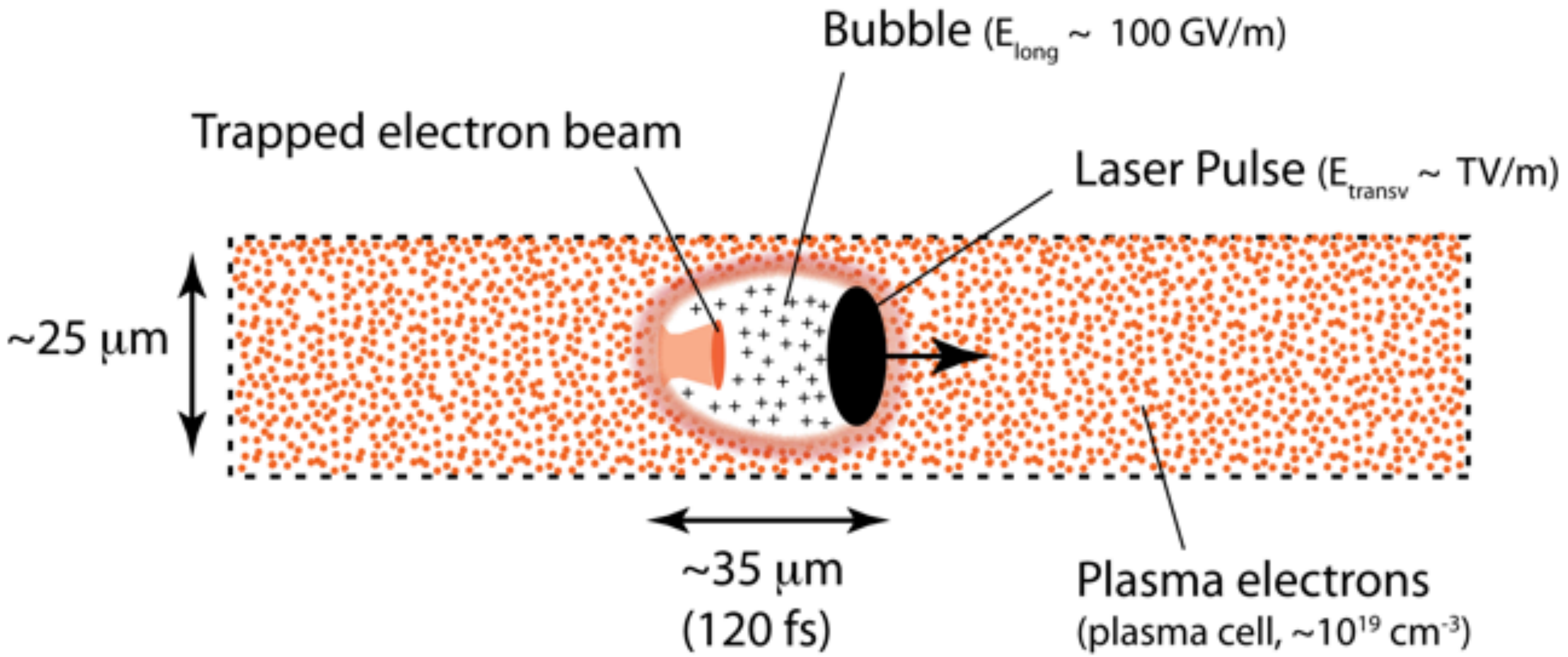
Laser Plasma-Acceleration (Internal Injection)



Laser Plasma-Acceleration (Internal Injection)

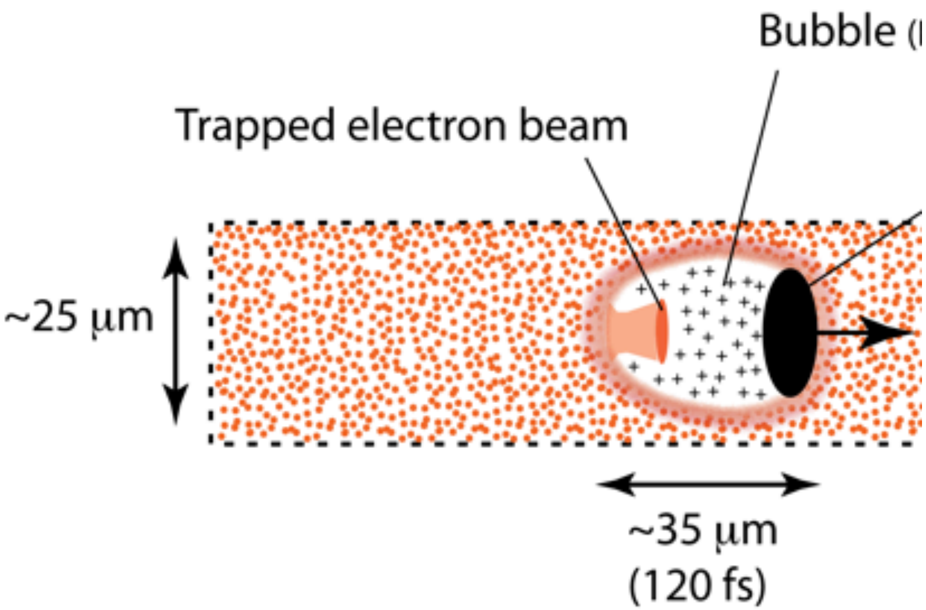


Laser Plasma-Acceleration (Internal Injection)



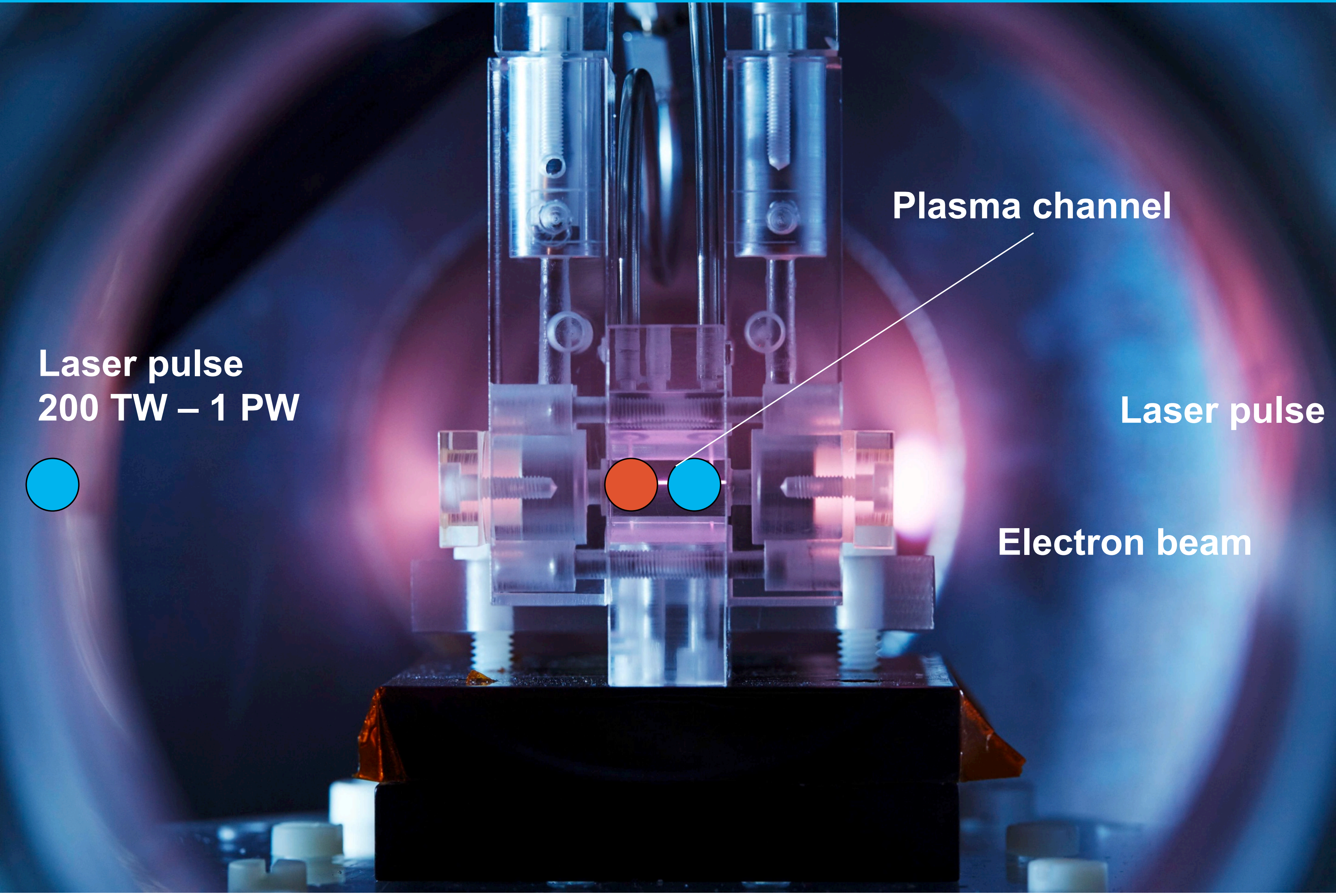
This accelerator fits into a human hair!

Laser Plasma-Acceleration (Internal Injection)



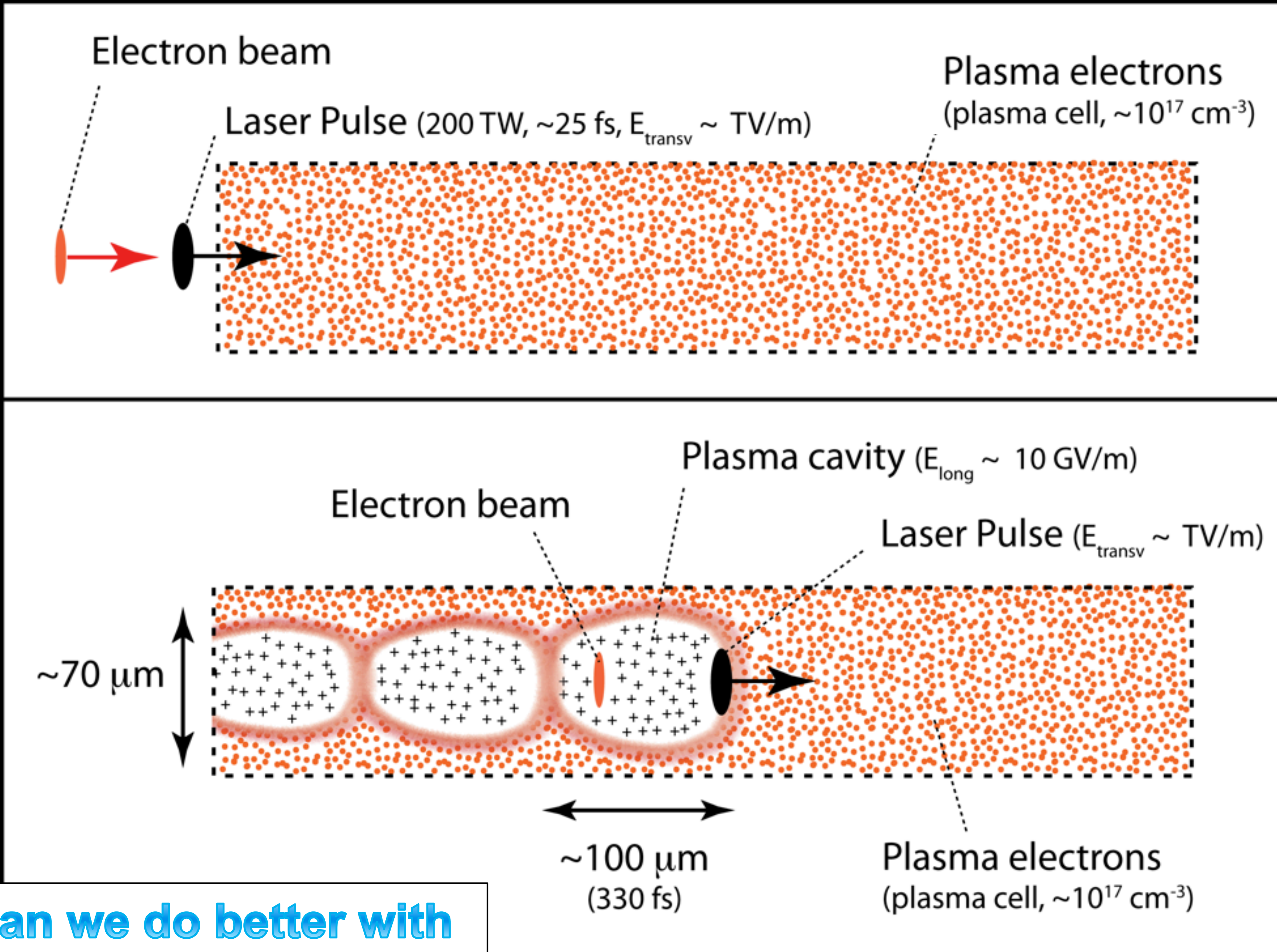
- This proved highly successful with electron bunches of **up to 4.25 GeV produced over a few cm**.
- Small dimensions involved → few **micron tolerances**!
- Highly compact but also **highly complex** accelerator: generation, bunching, focusing, acceleration, (wiggling) all in one small volume.
- Energy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

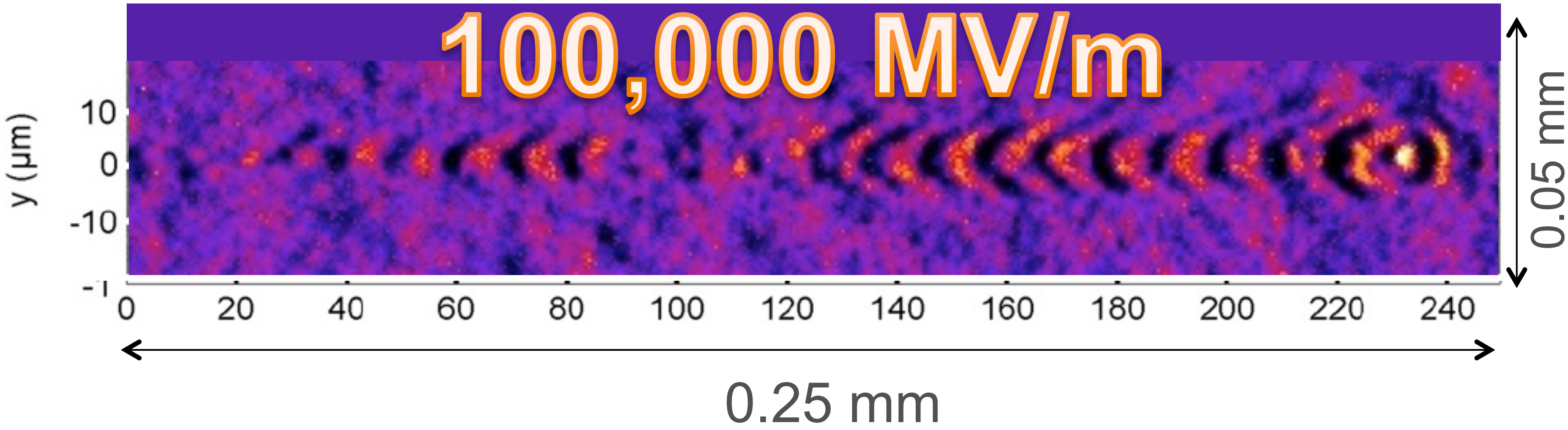
Foto Laser-Plasmabeschleuniger

APPLIED PHYSICS LETTERS 103, 191118 (2013)

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

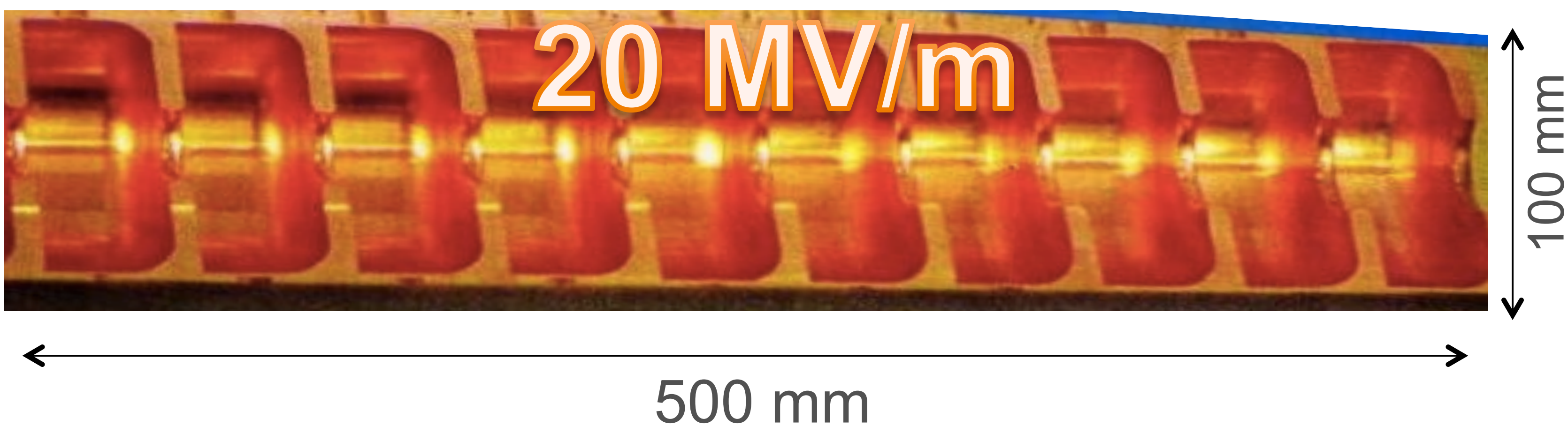
M. B. Schwab,[1,a)] A. Sävert,[1] O. Jäckel,[1,2] J. Polz,[1] M. Schnell,[1] T. Rinck,[1] L. Veisz,[3] M. Möller,[1] P. Hansinger,[1] G. G. Paulus,[1,2] and M. C. Kaluza[1,2]
[1]*Insitut für Optik und Quantenelektronik, Max-Wien-Platz 1, 07743 Jena, Germany*
[2]*Helmholtz-Institut Jena, Fröbelstieg 3,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

2013

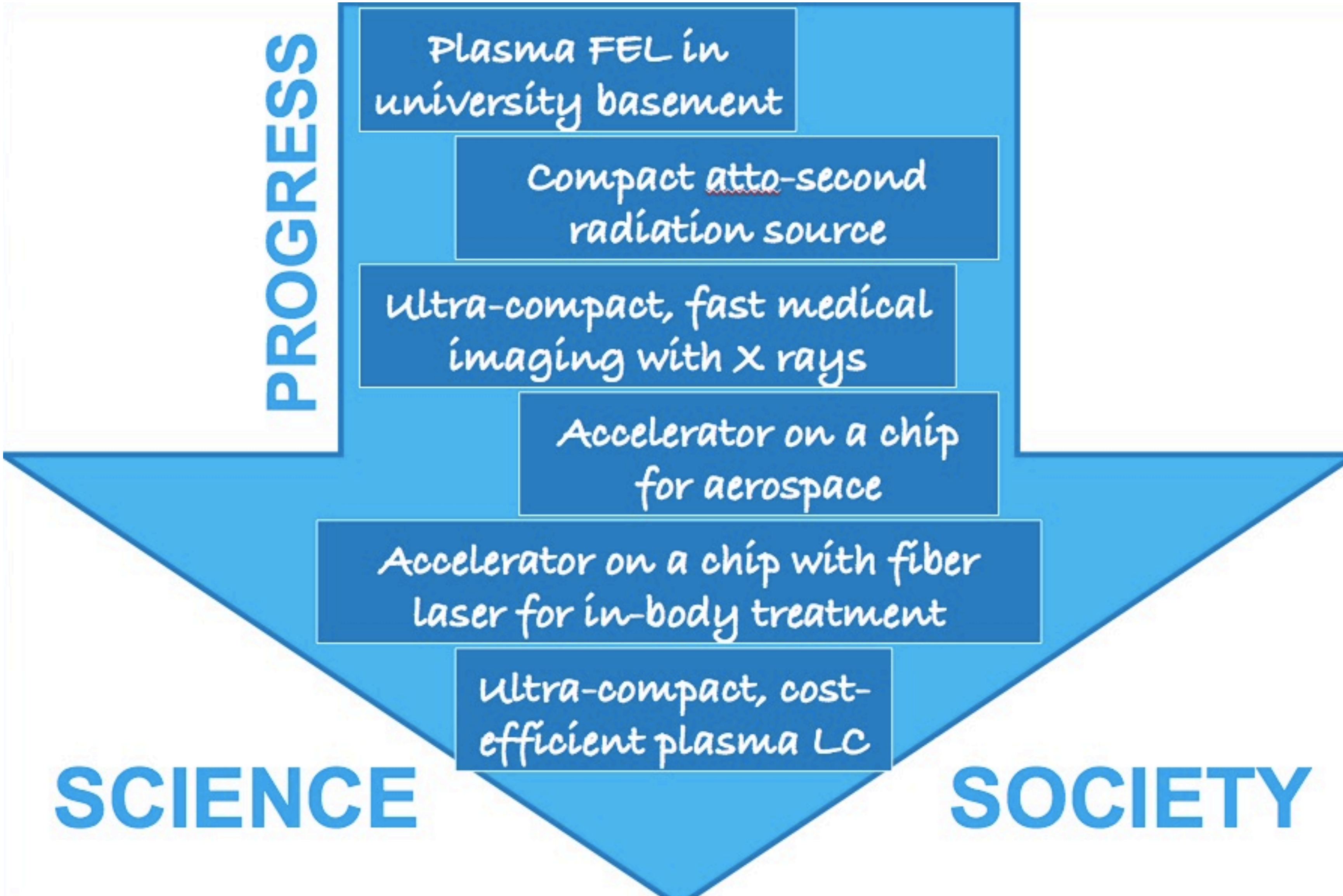


Metall (Kupfer) S band Linac Struktur

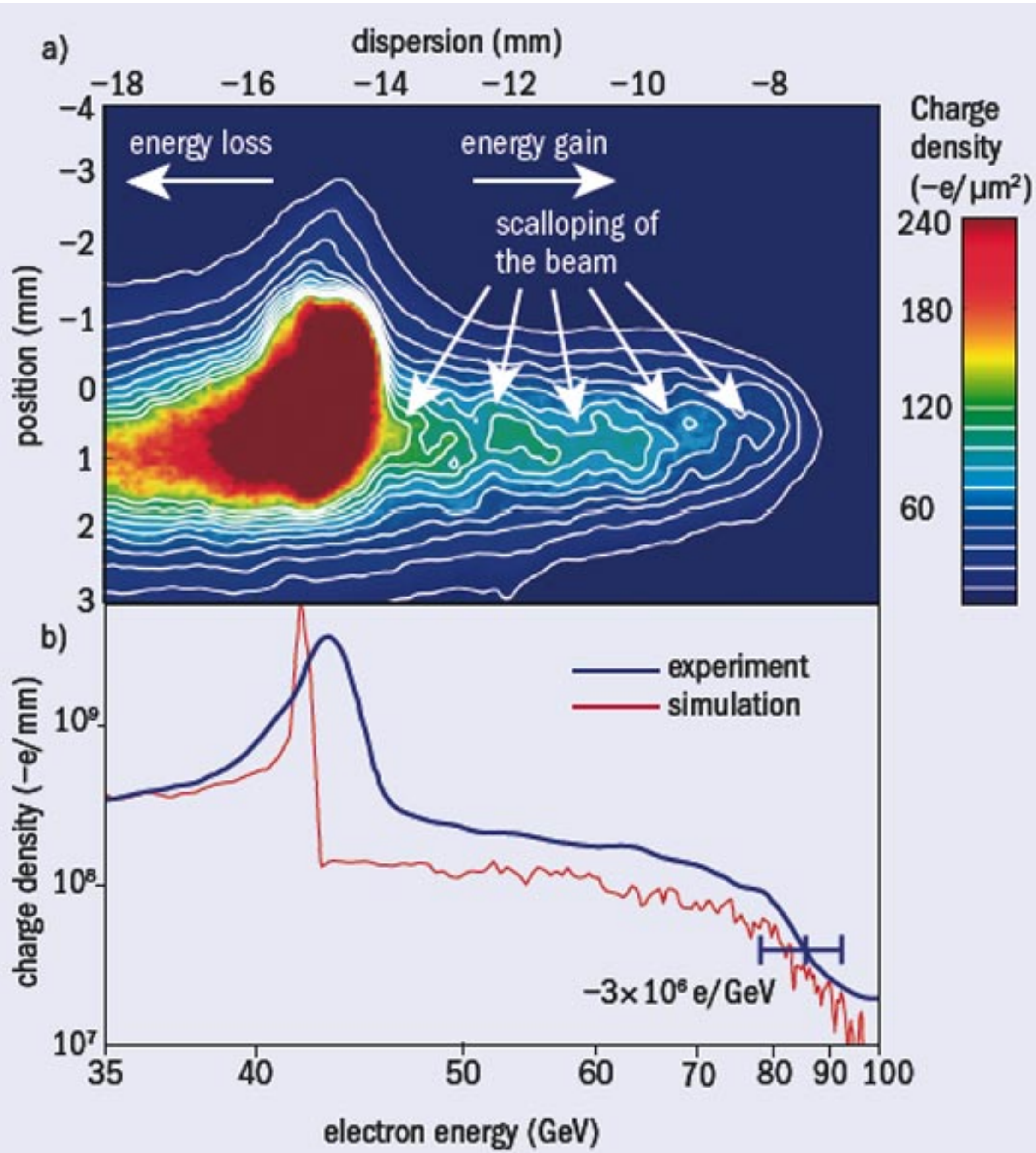
Mikro-Wellen zur Wellener-zeugung

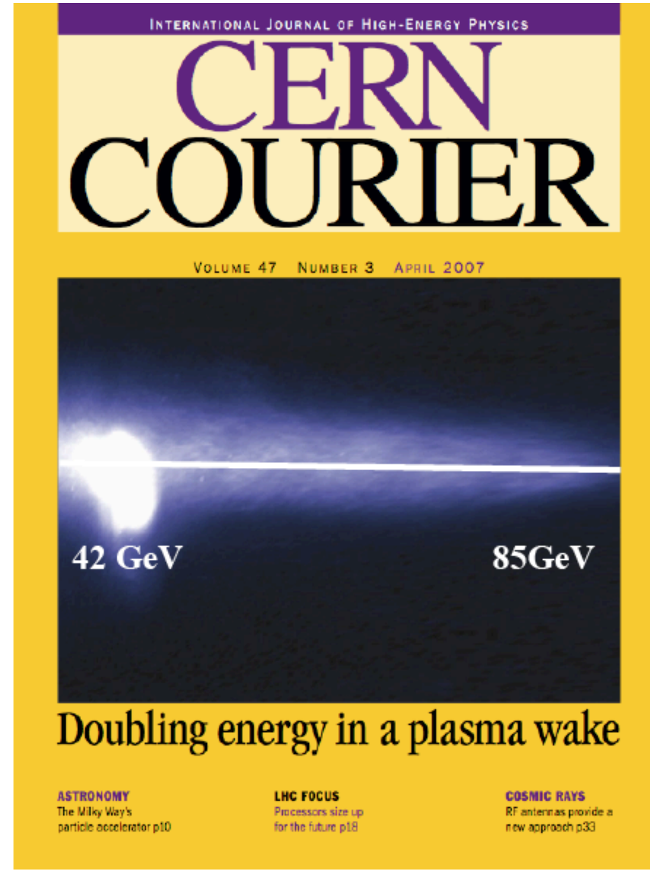


High fields trigger imagination of scientists and public…



Record Acceleration: 42 GeV (beam-driven)



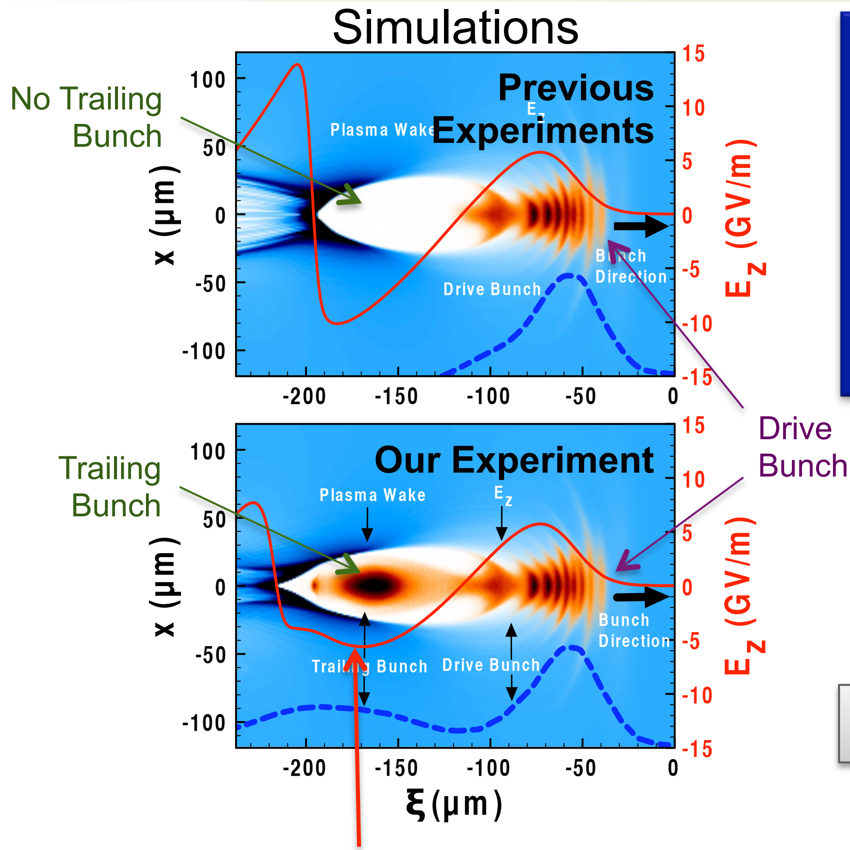


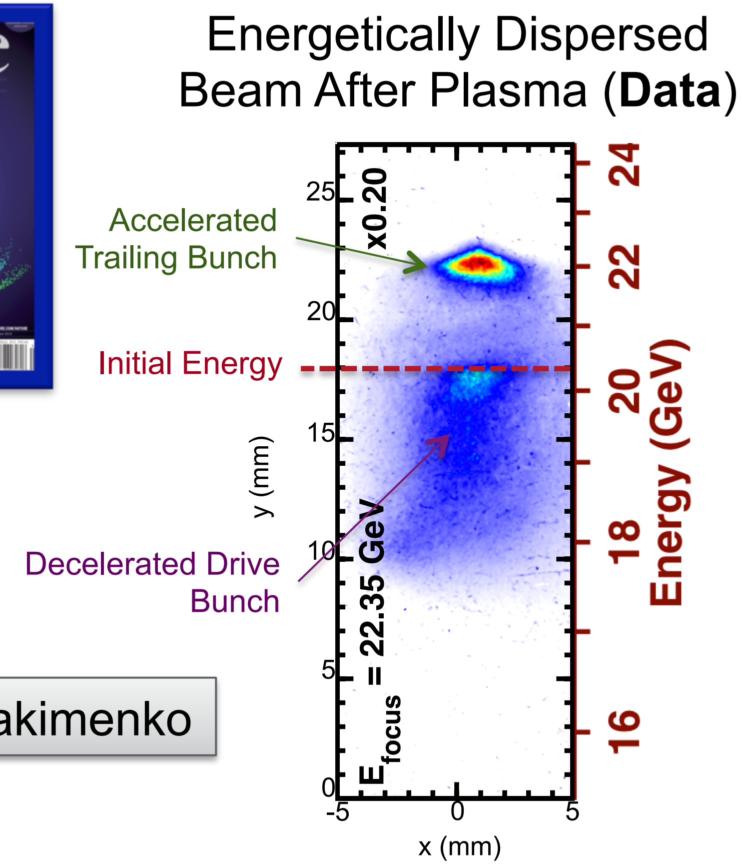
E167 collaboration
SLAC, UCLA, USC

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

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

UCLA SLAC





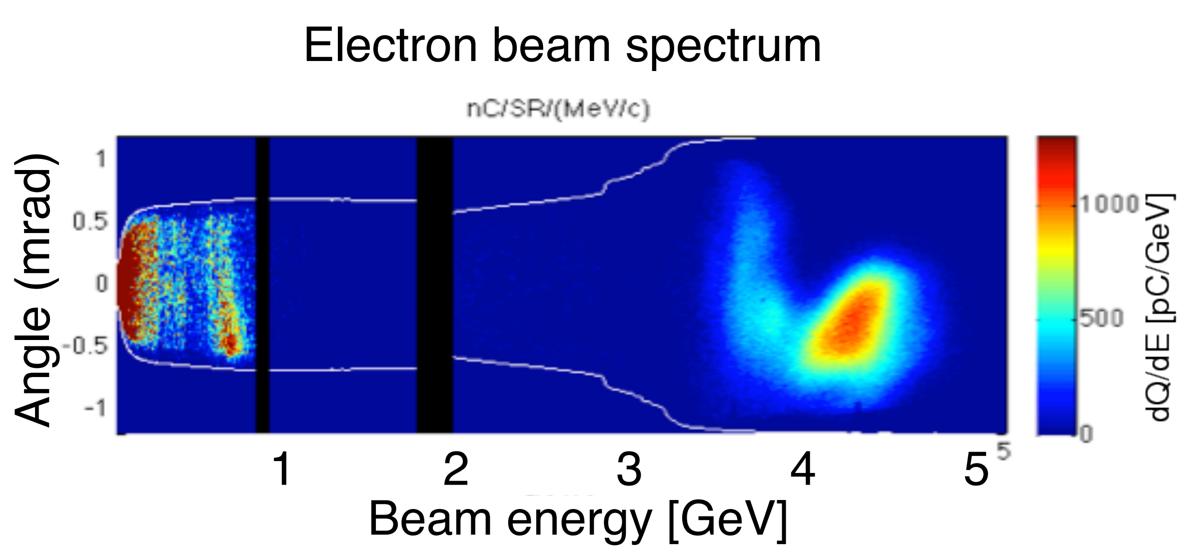
Slide: V. Yakimenko

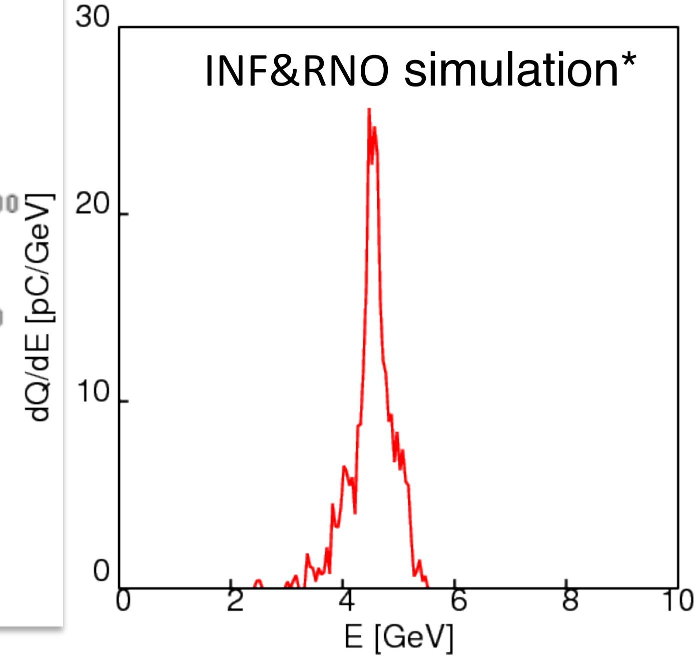
- Electric field in plasma wake is loaded by presence of trailing bunch
- Allows efficient energy extraction from the plasma wake

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

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





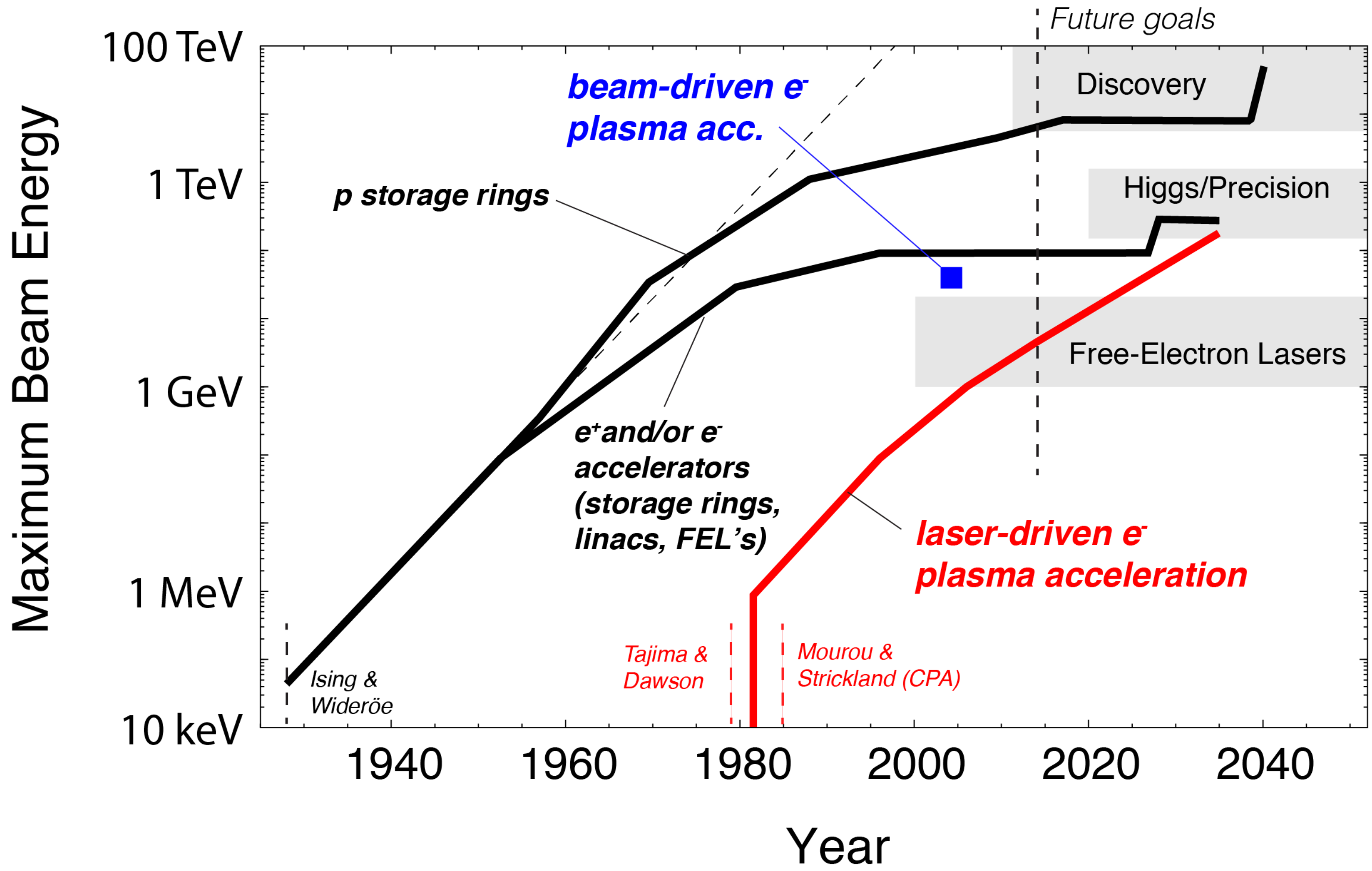
Slide: W. Leemans

- **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}**)

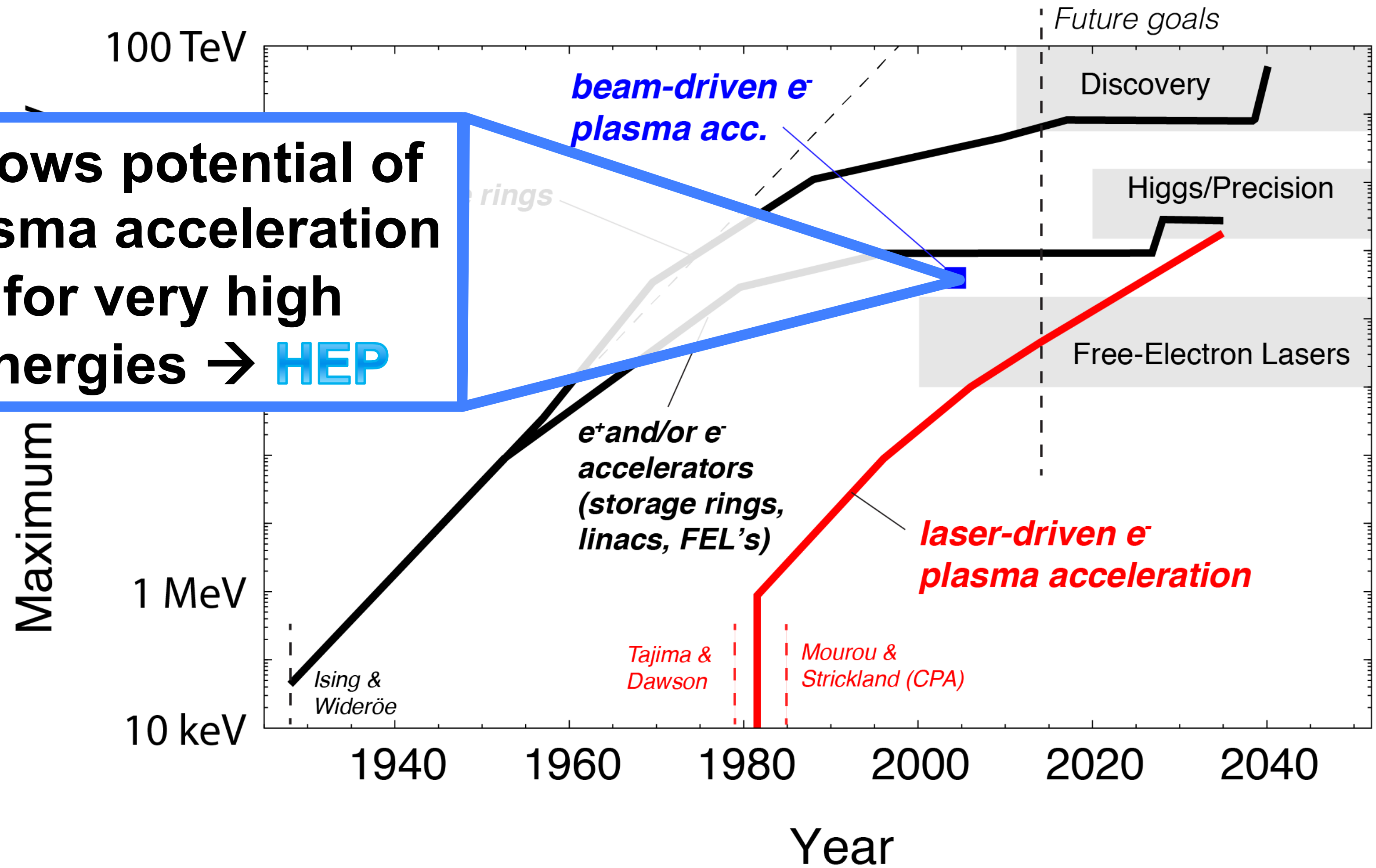
W.P. Leemans et al.,PRL 2014, in print

	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

Livingston and Accelerators at the Energy Frontier

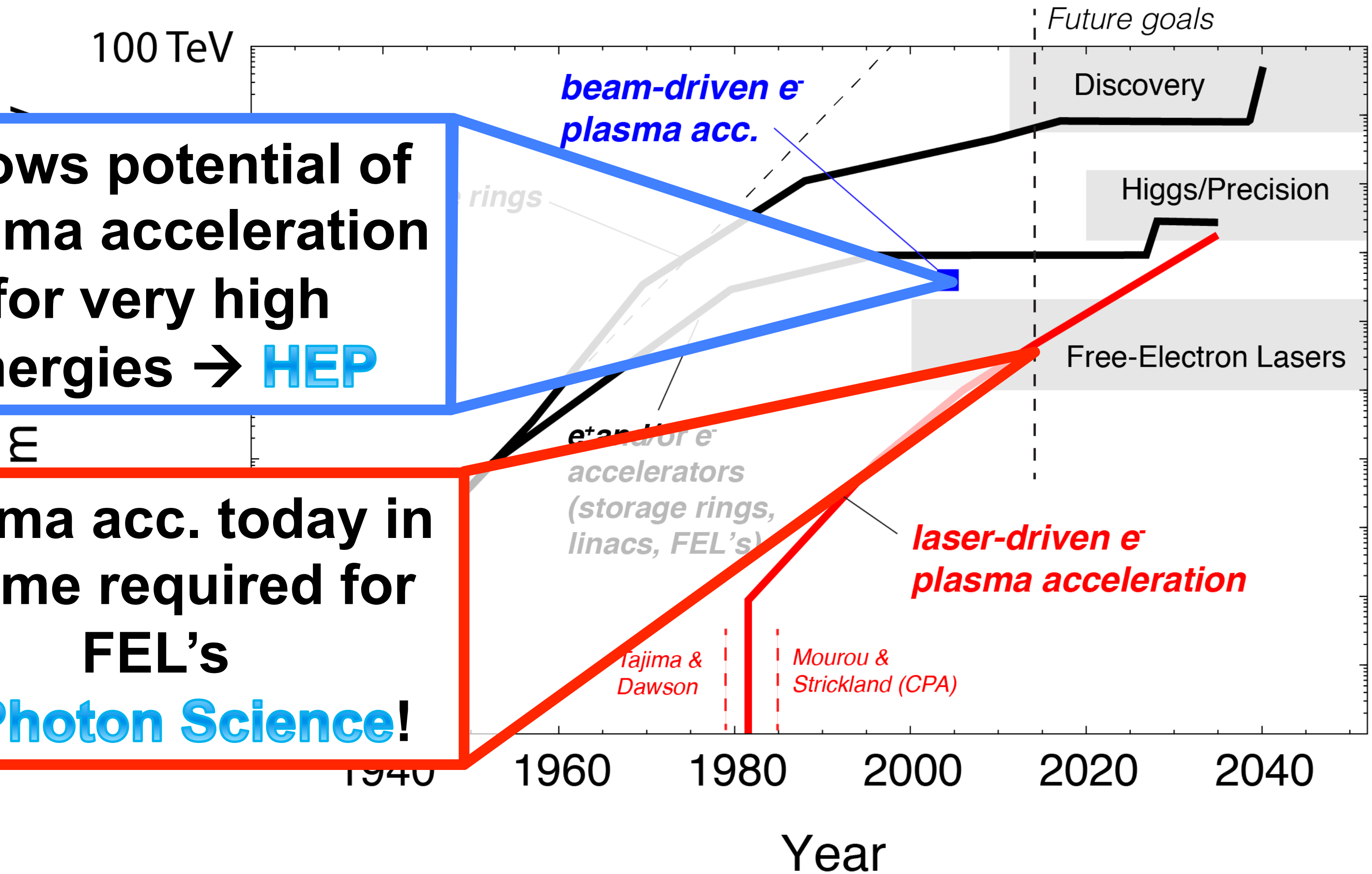


Livingston and Accelerators at the Energy Frontier



Shows potential of plasma acceleration for very high energies → HEP

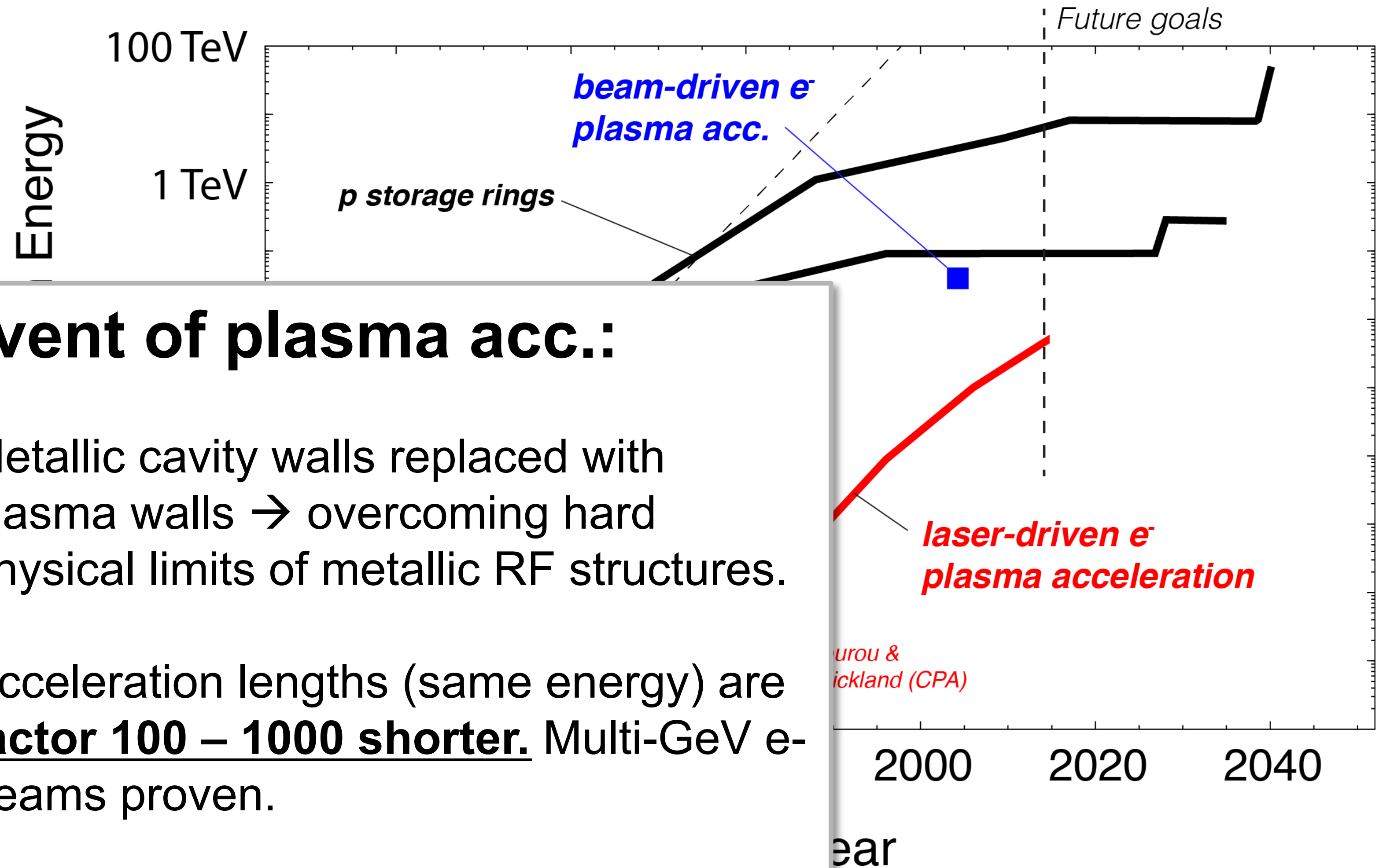
Livingston and Accelerators at the Energy Frontier



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 **<u>factor 100 – 1000 shorter.</u>** Multi-GeV e-beams proven.

3. Still short-comings but **<u>no fundamental limit</u>**.

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

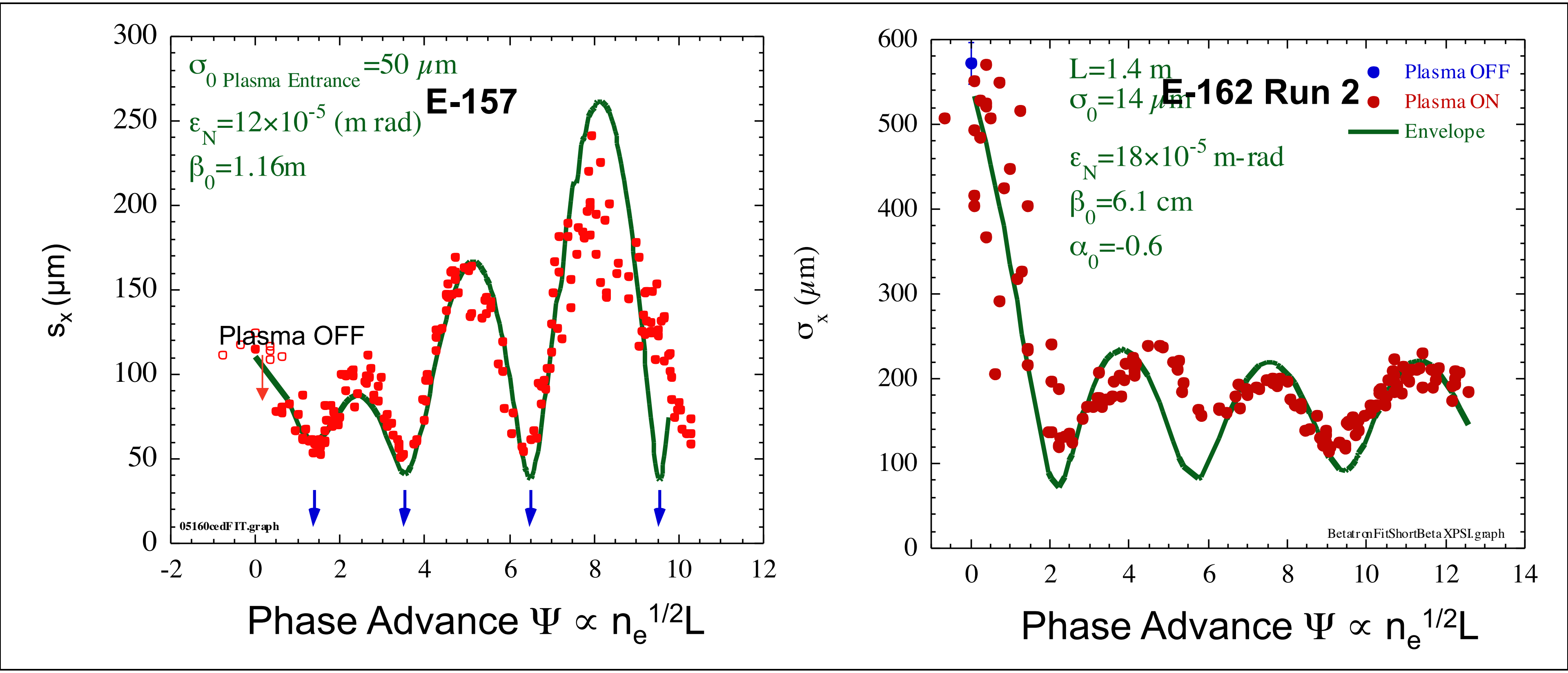
- Lower plasma density better: larger matched beam size, bigger tolerances.

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

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

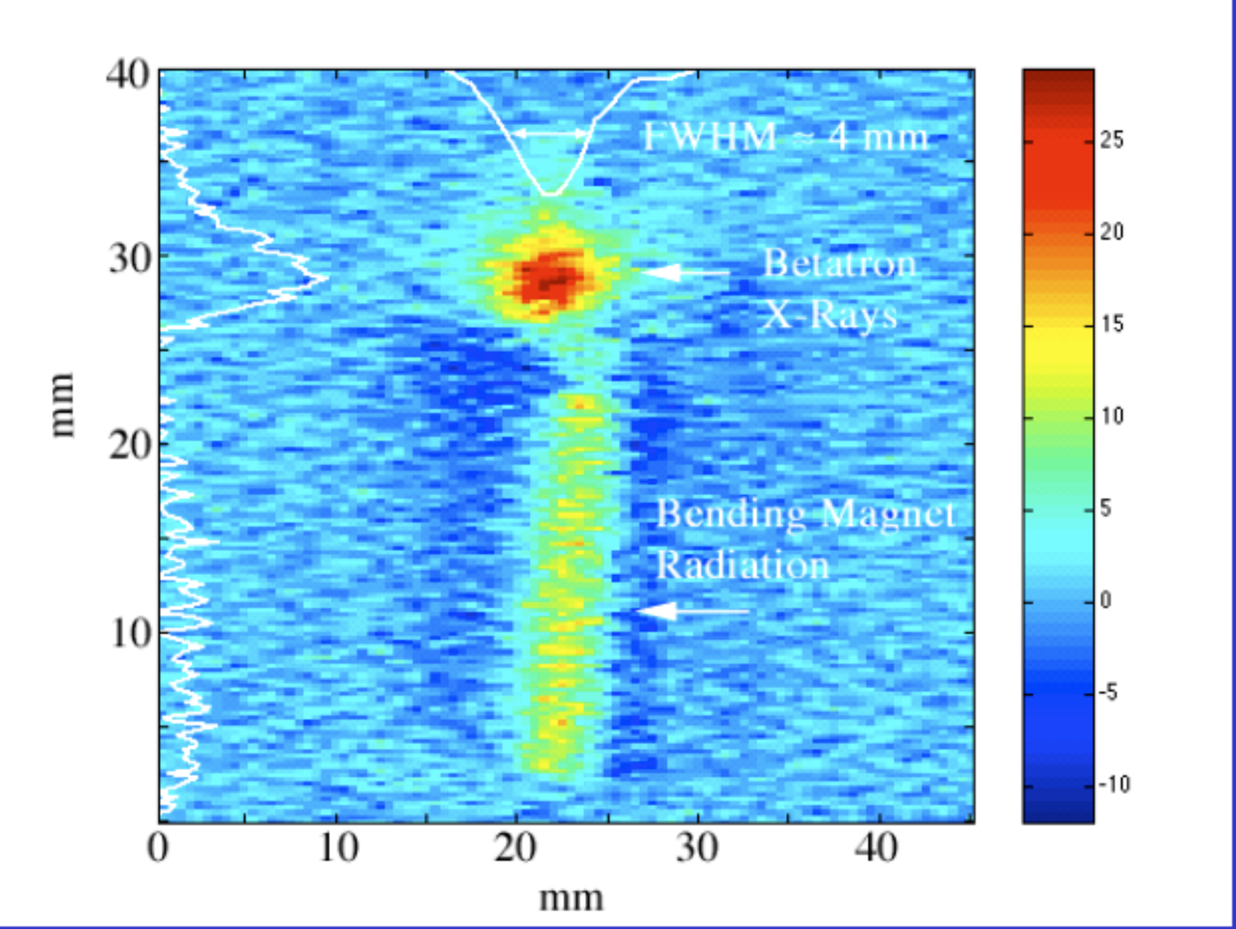
• Allows stable propagation through long plasmas (> 1 meter)



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!

Lasers or plasmas as undulators...

- See lecture by J. Rosenzweig: Path to shrinking down undulator sections!
- In this lecture: focus on accelerator part of an FEL

Content

1. From Table-Top to Biggest Machines of Mankind
2. Towards 21st Century Table-Top: The Plasma Wakefield and the Plasma Accelerator
3. **Building an FEL Based on Plasmas**
4. Plasma FEL Projects in Europe

FEL Needs High Quality Beam (Learnt at this CAS)

Plasma accelerators have small dimensions and they have/should have small dimensions beams! Possible FEL parameters that are being considered (example):

λ = 4 nm, K = 1, λ_u = 15mm, slice energy spread 0.025%, E about 1 GeV

Possible beam parameter sets have been worked out. For example:

- Energy: 1 – 5 GeV
- Charge: 10 – 30 pC
- Bunch length rms: 1 μm (about 3 fs)
- Peak current: 2 – 3 kA
- Norm. emittance: 0.2 μm
- **Energy spread: 0.2 %**

FEL = The Power of Coherence

Adapted from P. Schmüser

Can plasma accelerators produce the required quality?

Yes, B U T ...

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

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

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 defocusing as function of longitudinal position z

The Useful Regime of Plasma Accelerators

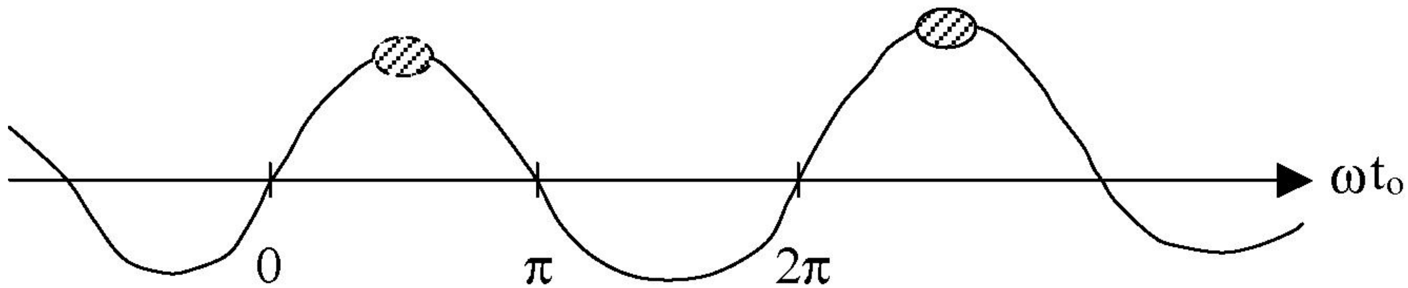
Two conditions for an accelerator:

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

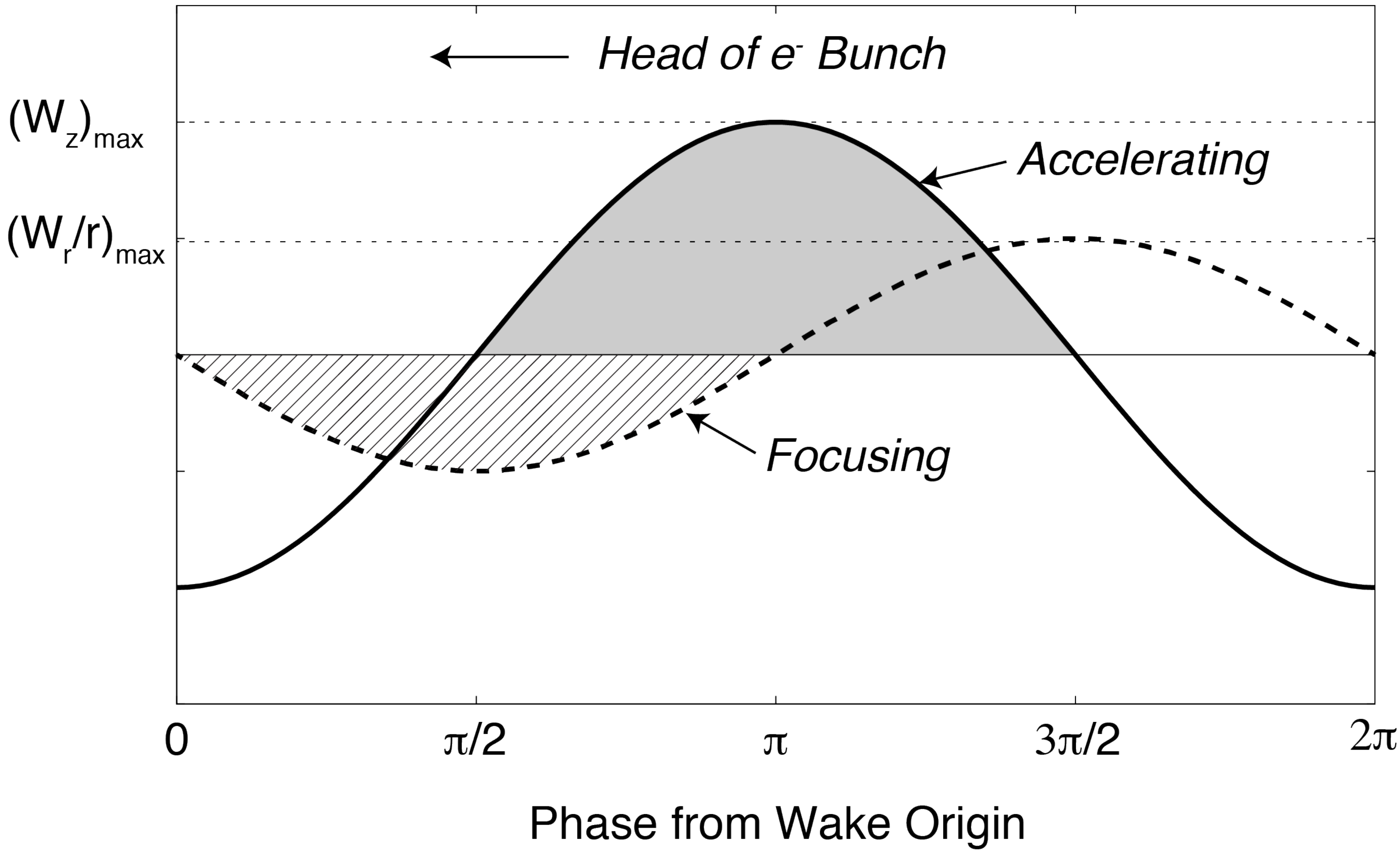
These two conditions define a useful range of acceleration!

Reminder metallic RF accelerator structures:

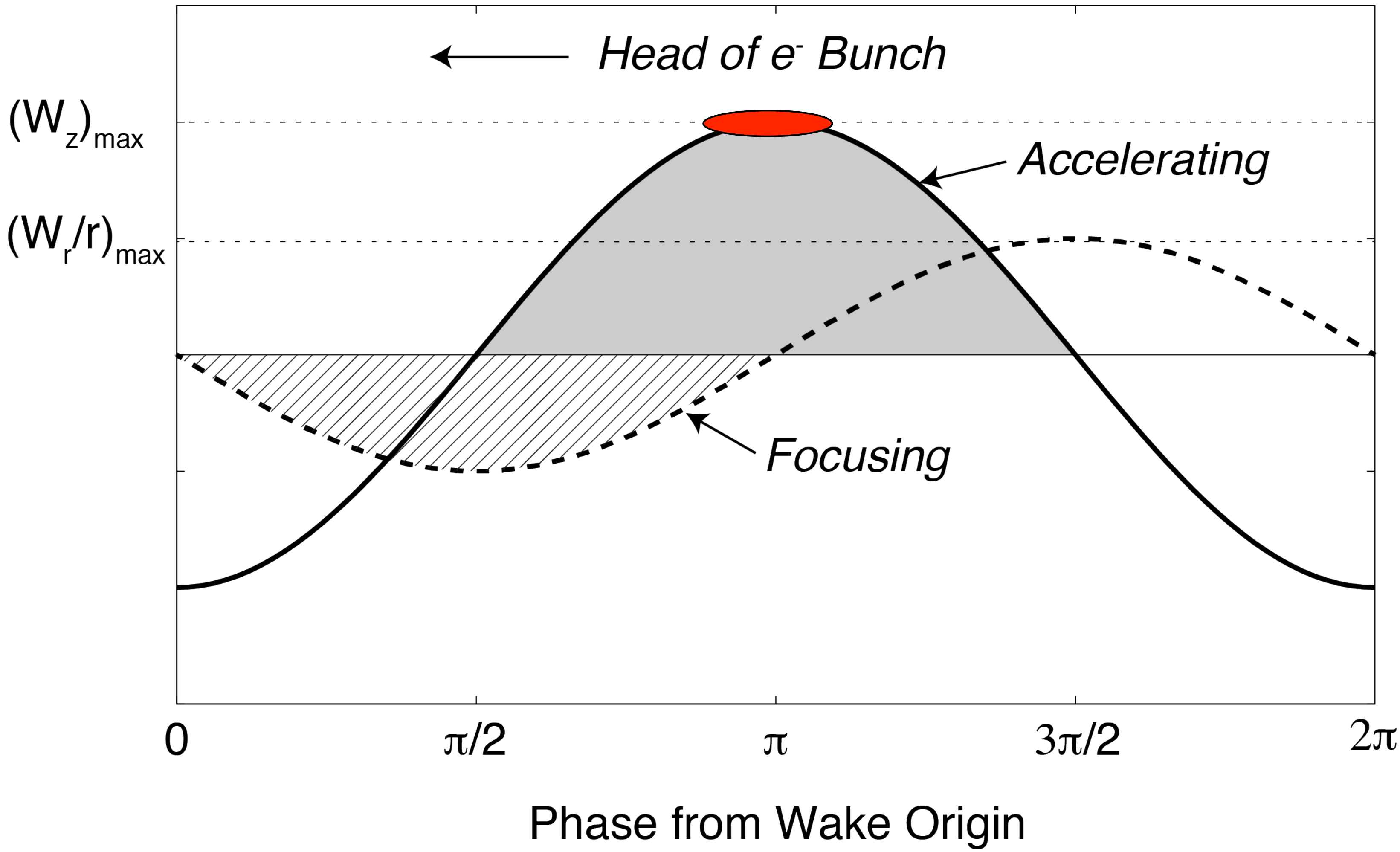
no net transverse fields for beam particles → full accelerating range is available for beam → usually place the beam on the crest of the accelerating voltage



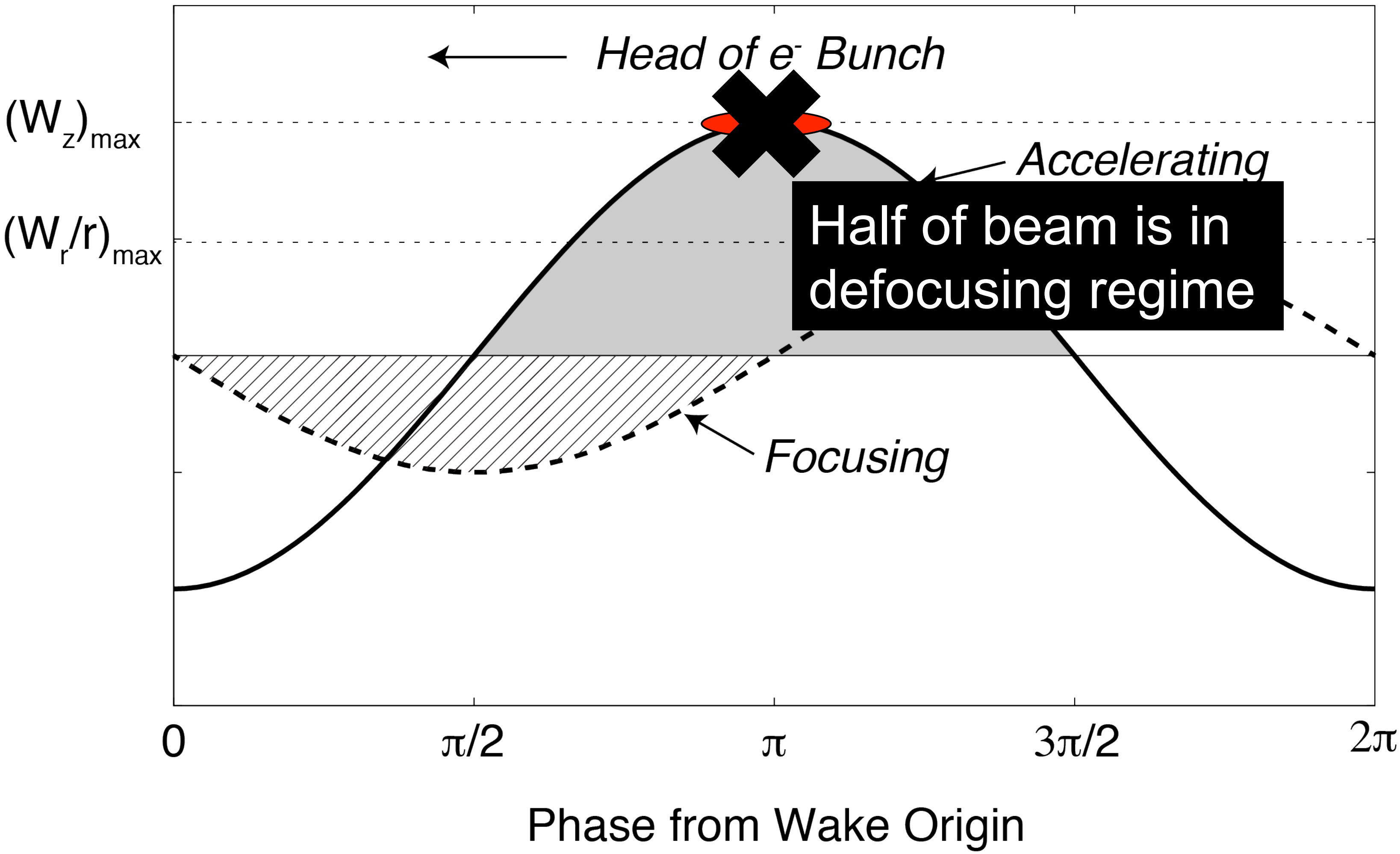
Plasma Accelerator



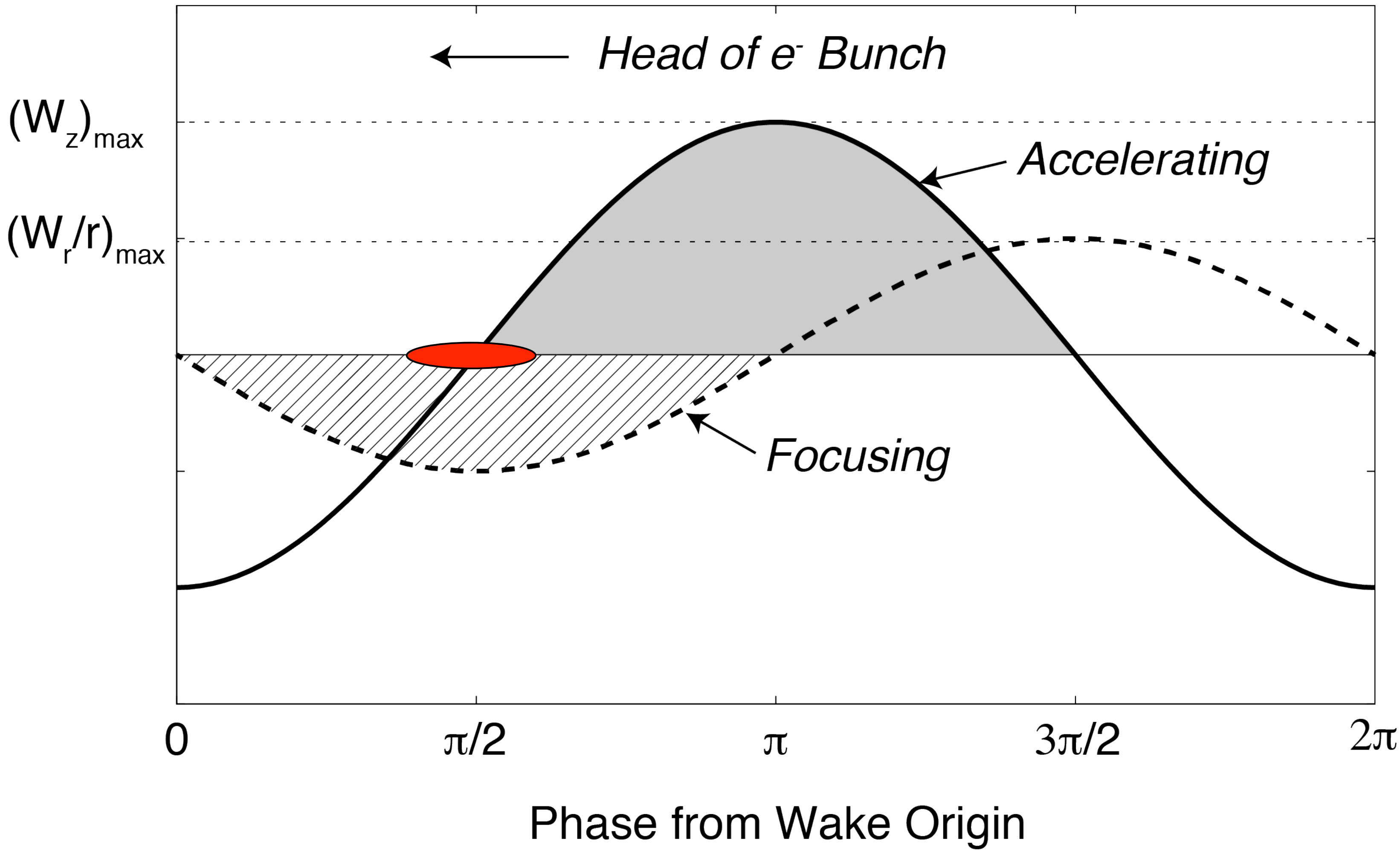
Plasma Accelerator



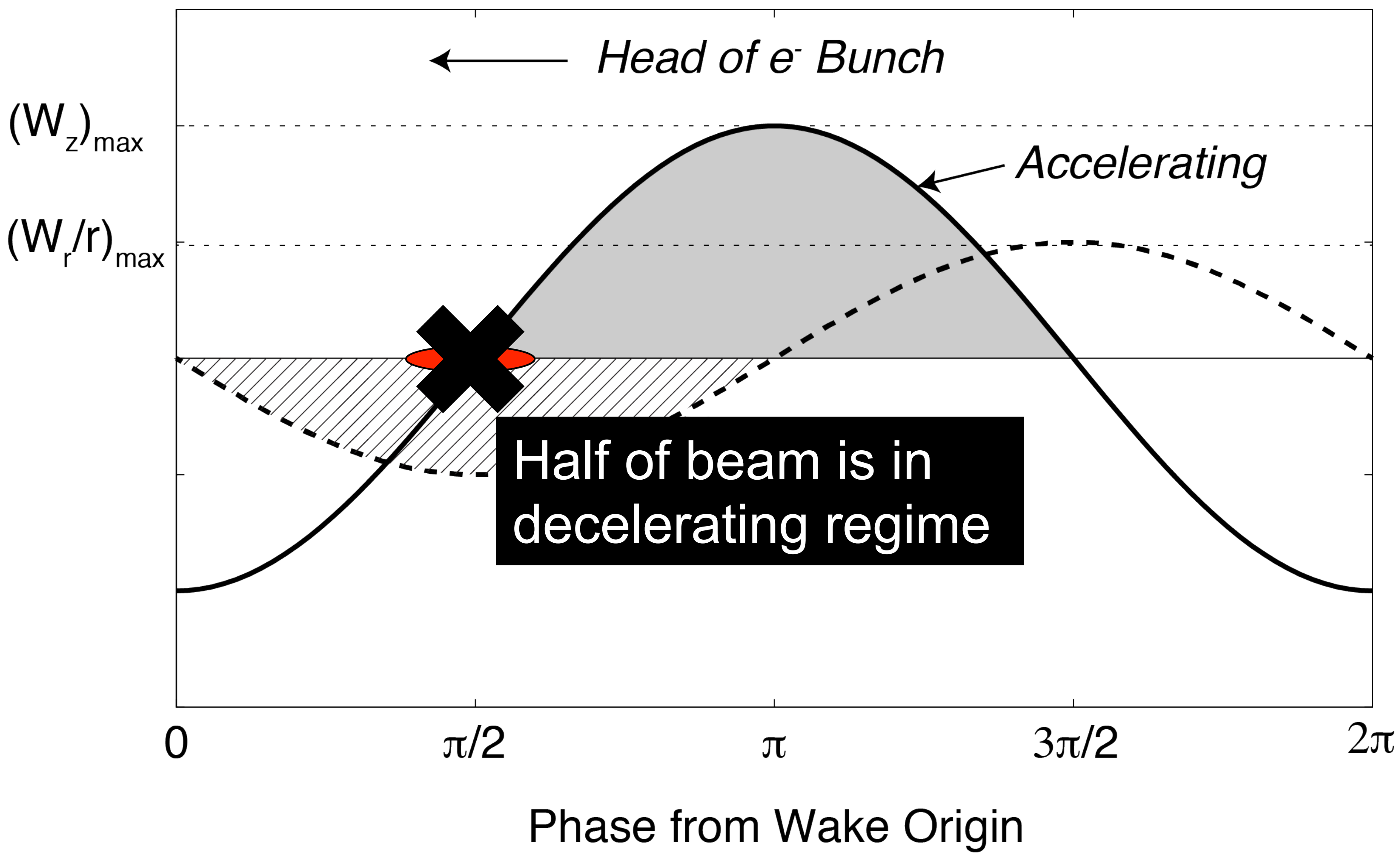
Plasma Accelerator



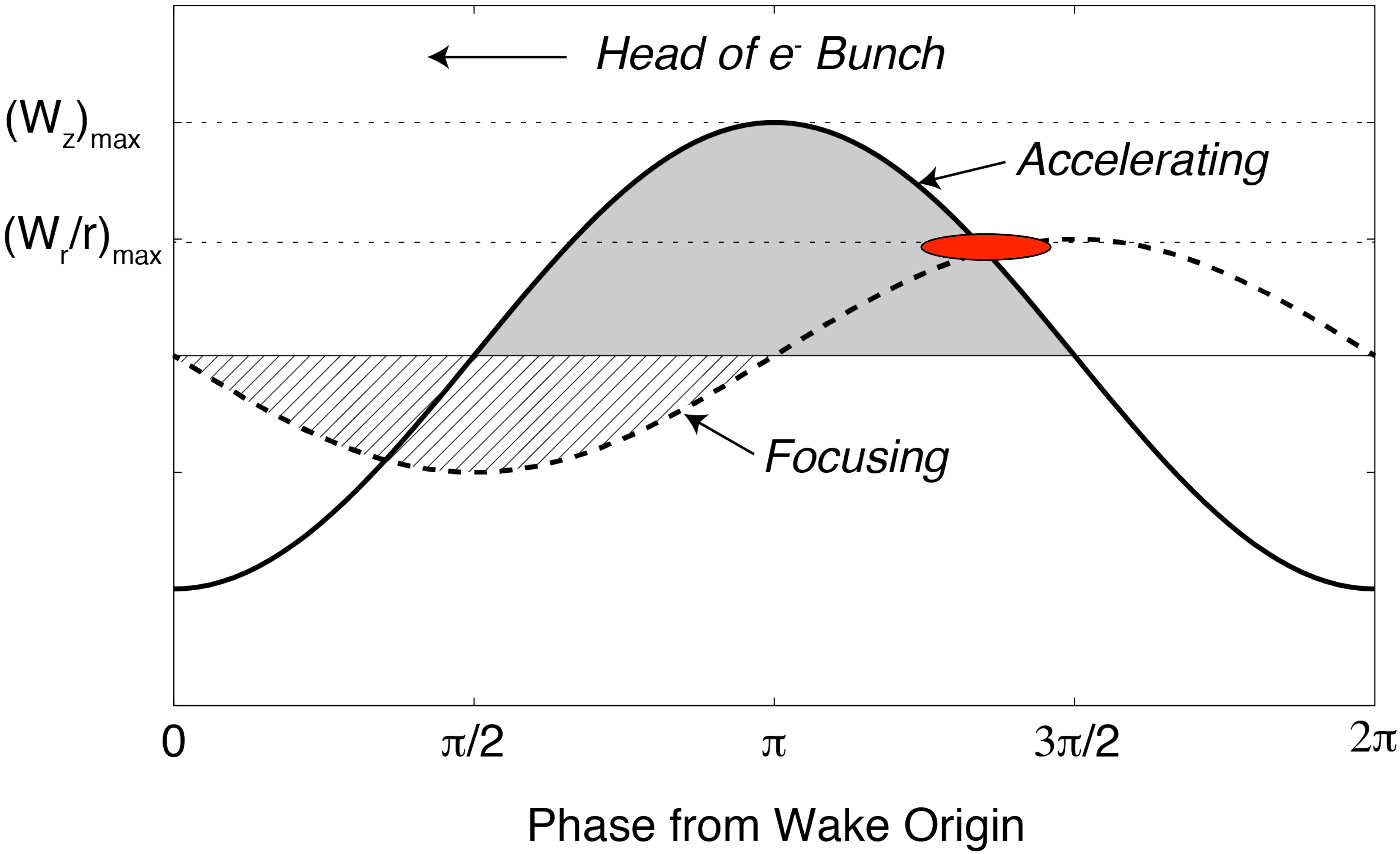
Plasma Accelerator



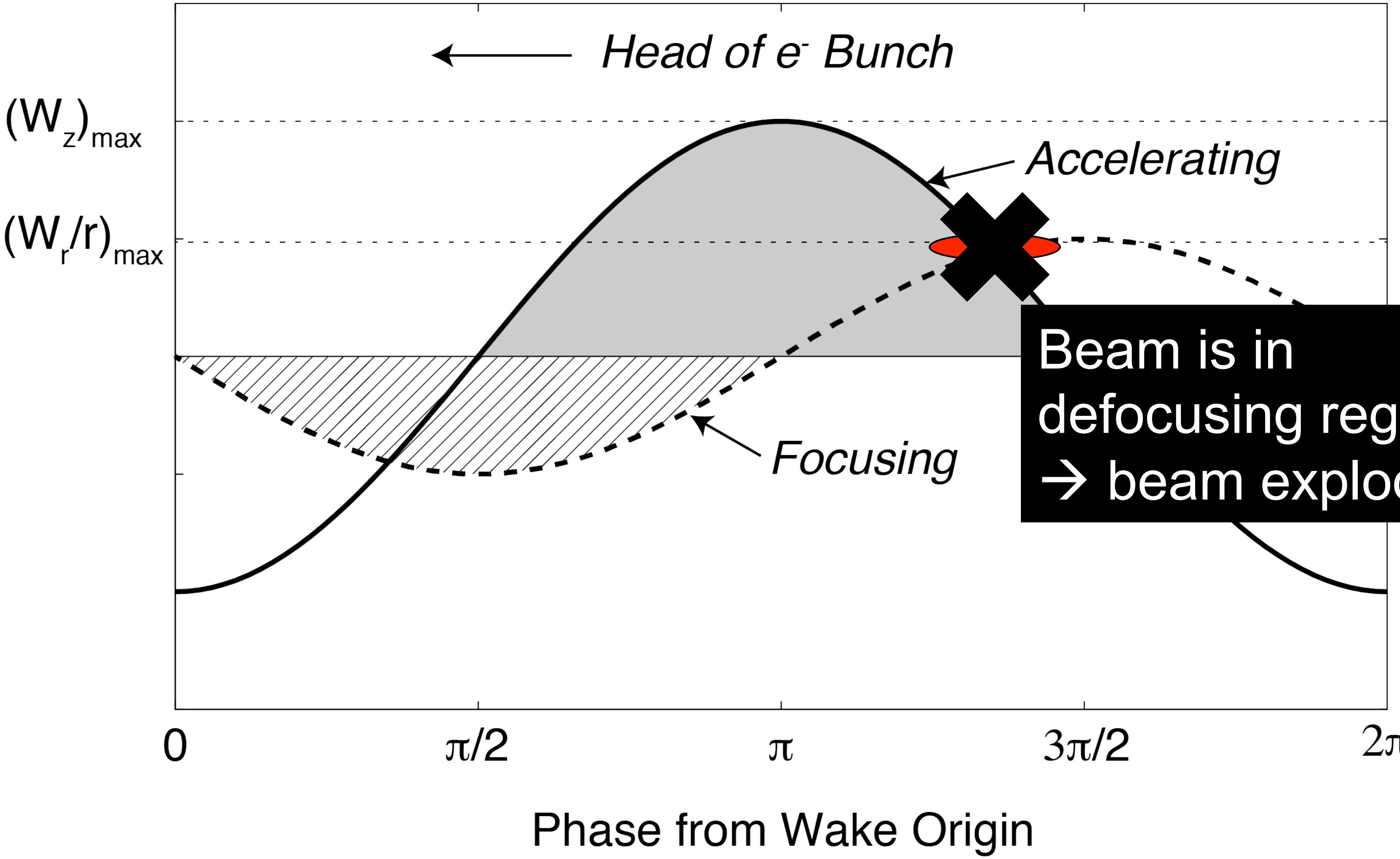
Plasma Accelerator



Plasma Accelerator

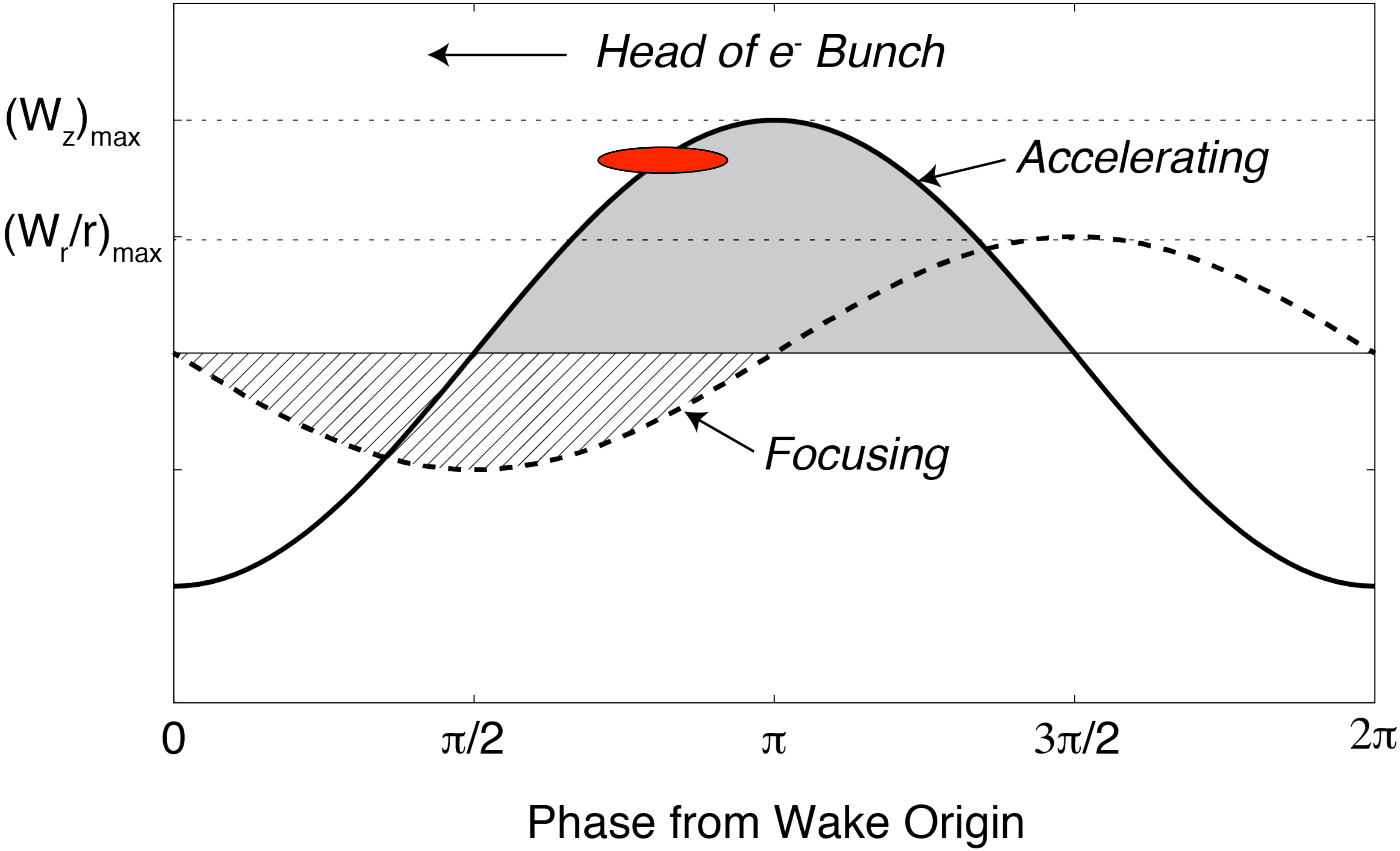


Plasma Accelerator

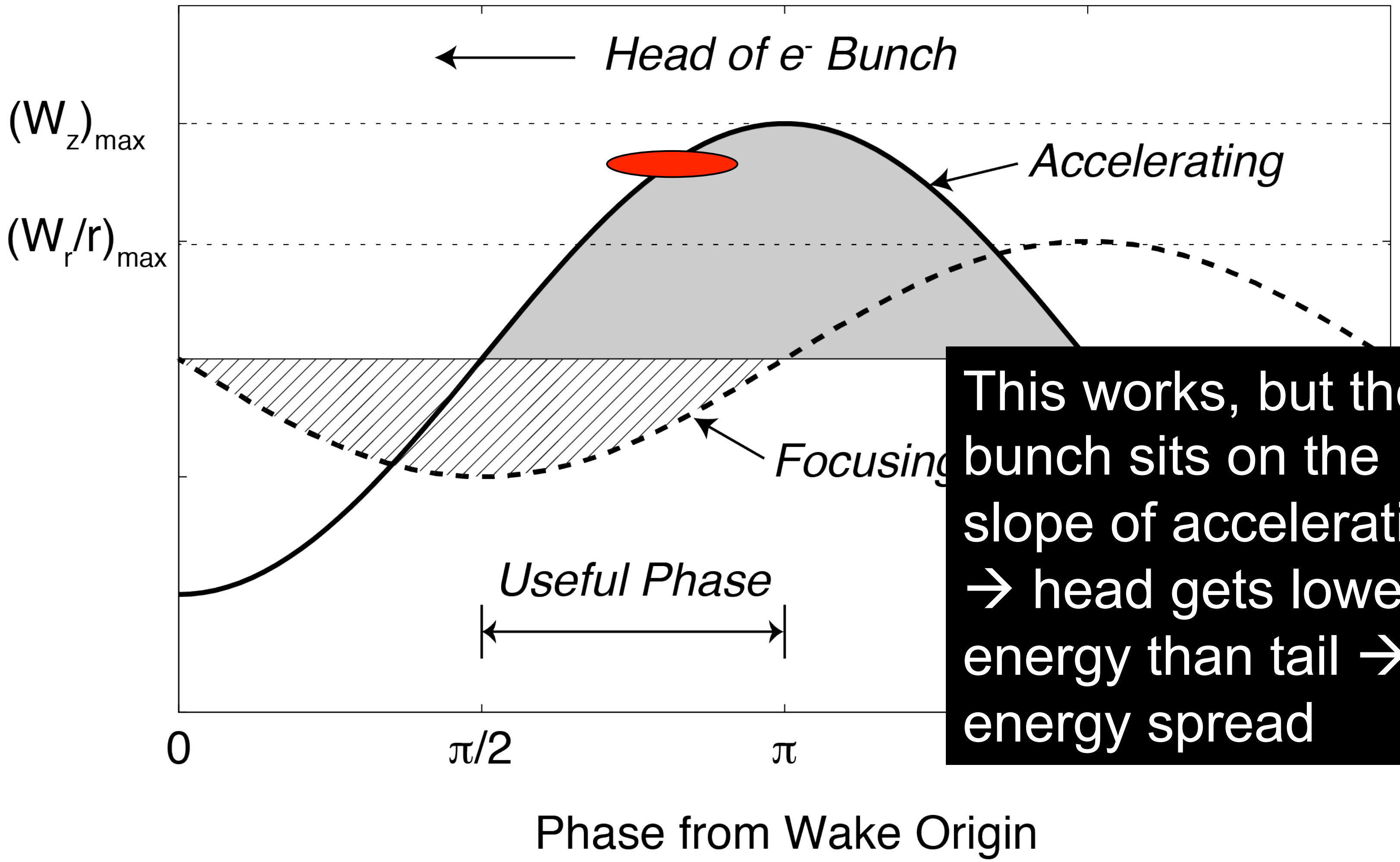


Beam is in defocusing regime → beam explodes

Plasma Accelerator

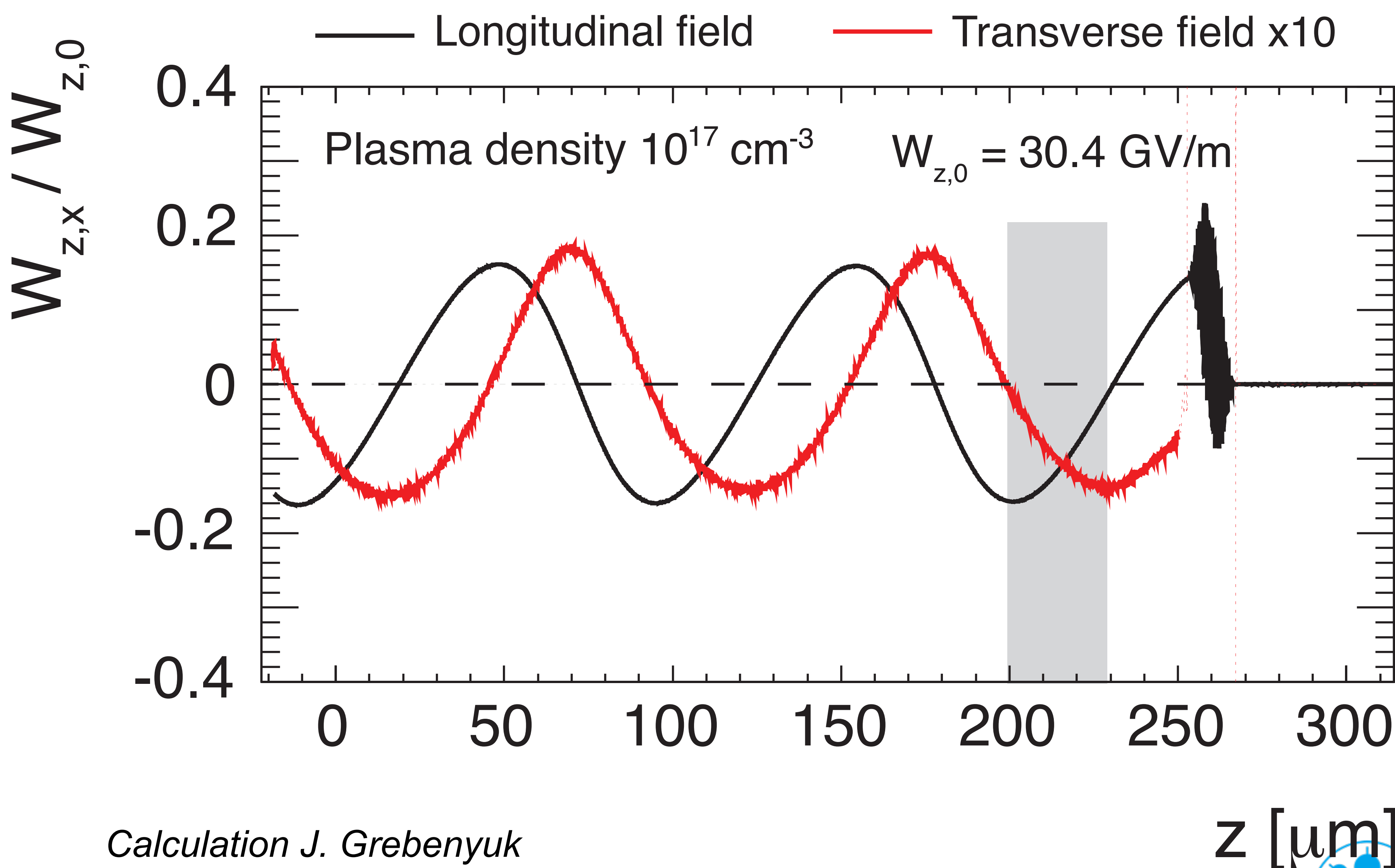


Plasma Accelerator



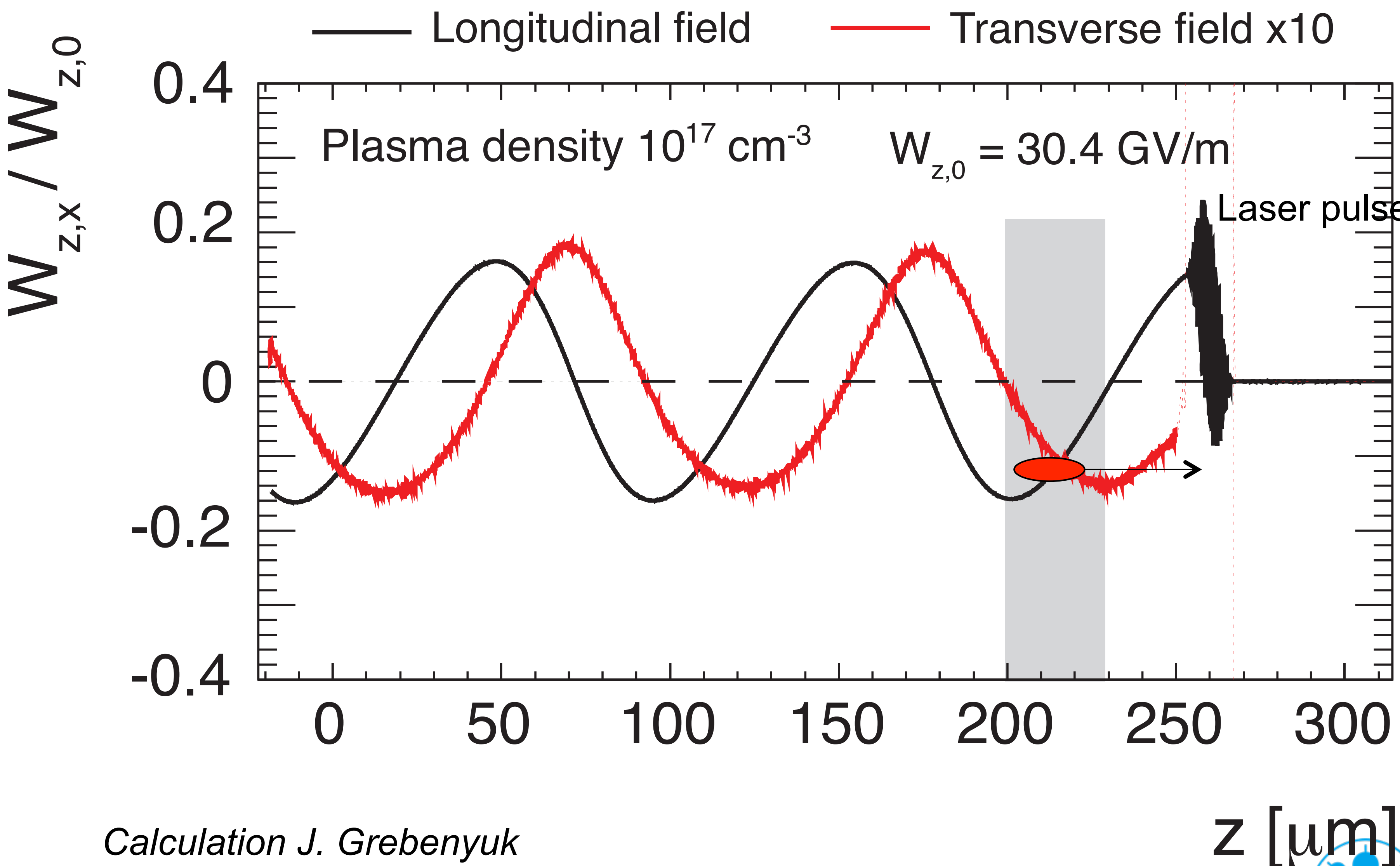
This works, but the bunch sits on the slope of acceleration → head gets lower energy than tail → energy spread

Comparison with OSIRIS simulation



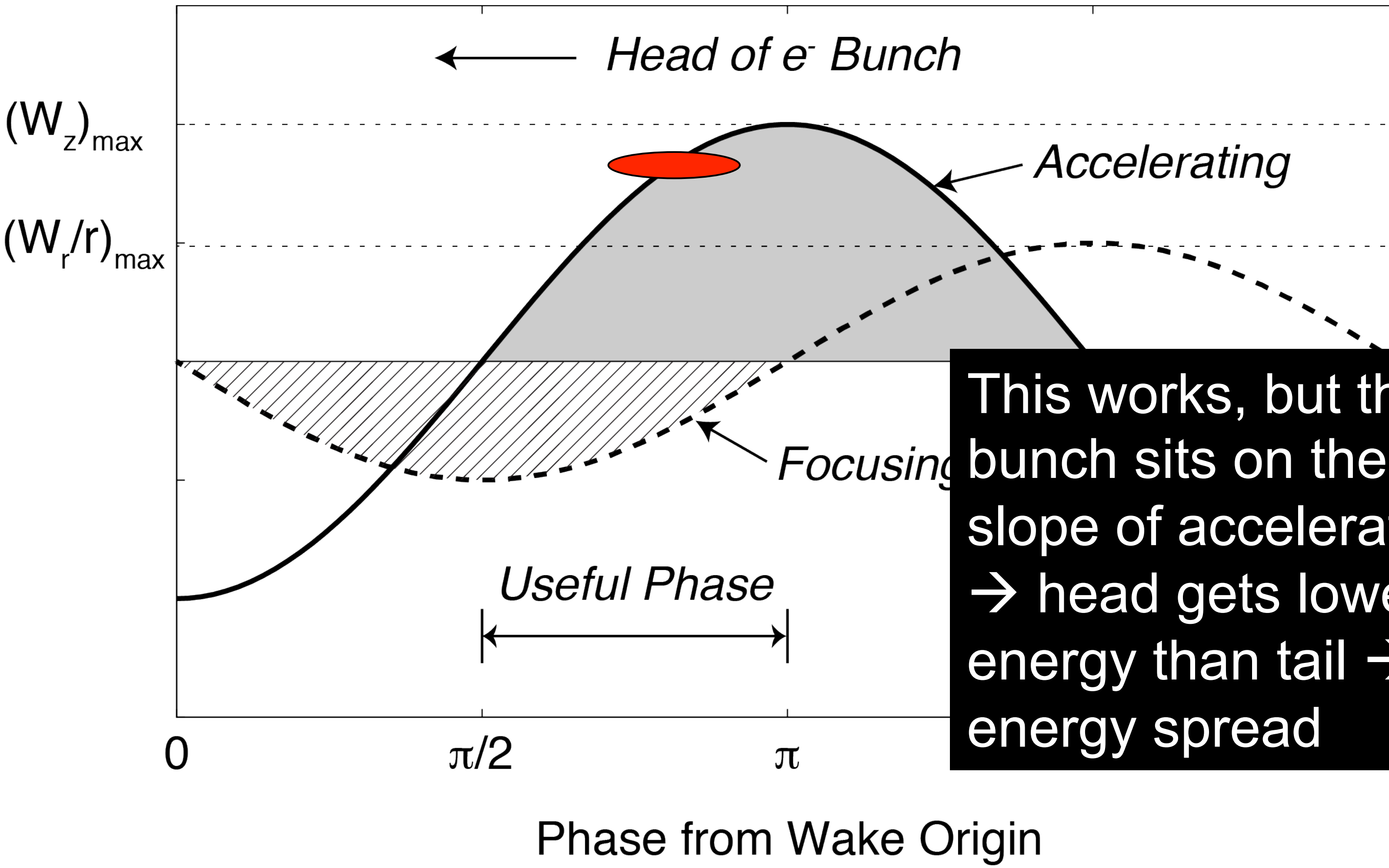
Calculation J. Grebenyuk

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

B U T …

Energy spread is a physics feature and a serious problem!

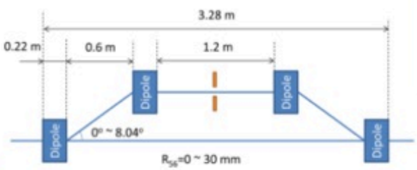
Accelerator Builder's Challenge *(simplified to typical values)*

- 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 1 – 5 GeV plasma accelerated beam**.

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

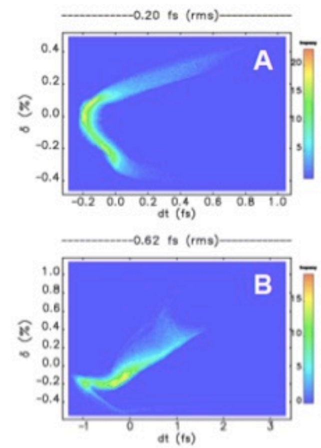
- Match into and out of plasma with **beam size around 1 µm** (about 1 mm beta function).
- Control **offsets** between the wakefield driver (laser or beam) and the accelerated electron bunch at **1 µm level**.
- Use **short bunches (few fs)** to minimize energy spread.

Bunch Compressor



→ 200 atto-s Working point A	
Initial charge (pC)	10
Gun gradient (MV/m)	110.0
Gun phase (deg)	0.0
Laser pulse duration (ps)	3.0
TW1 gradient (MV/m)	23.9
TW1 phase (deg)	-59.2
TW1 gradient (MV/m)	23.9
TW1 phase (deg)	-59.2
R56 (mm)	10.0
Slit width (mm)	0.4
Final charge (pC)	0.38
ε_x (µm)	0.05
ε_y (µm)	0.05
Energy spread	0.0019
Current (A)	650

→ 620 atto-s Working point B	
Initial charge (pC)	100
Gun gradient (MV/m)	110.0
Gun phase (deg)	0.0
Laser pulse duration (ps)	3.0
TW1 gradient (MV/m)	23.9
TW1 phase (deg)	-60.0
TW1 gradient (MV/m)	23.9
TW1 phase (deg)	-60.0
R56 (mm)	10.0
Slit width (mm)	0.4
Final charge (pC)	2.77
ε_x (µm)	0.24
ε_y (µm)	0.18
Energy spread	0.0022
Current (A)	1528



Study and simulations: J. Zhu

References:
P. Emma, Phys. Rev. Lett. 92, 074801(2004)
S. Di Mitri, PRSTAB 16, 042801 (2013)

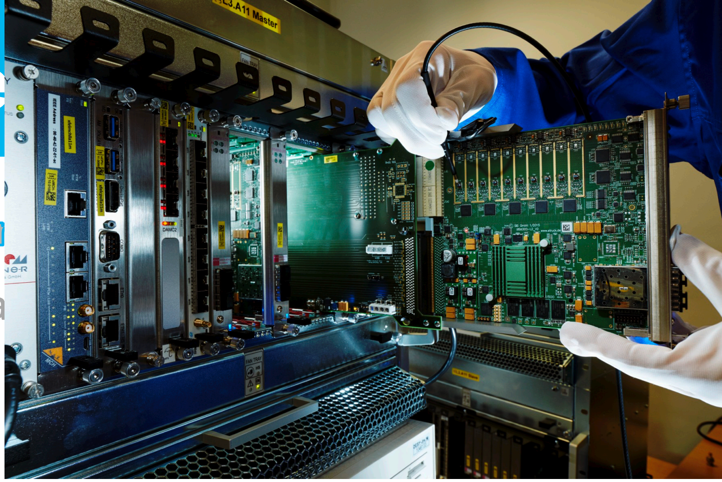
ARD HELMHOLTZ GEMEINSCHAFT

SEITE 13

Planned SINBAD Linac at DESY:

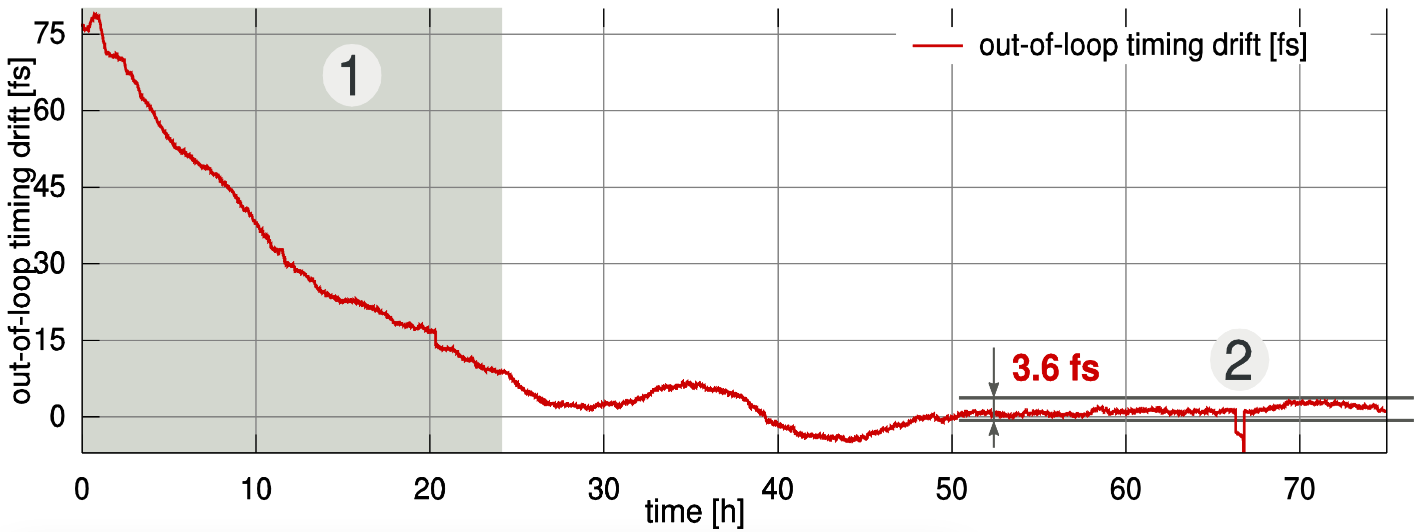
200 atto-second start-to-end simulation

Accelerator Builder's Challenge



- Match into and out of plasma with **beam size around 1 µ**
- Control **offsets** between the wakefield driver (laser or bea 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).



Femtosecond Precision in Laser-to-RF Phase Detection

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

1 femto-second = 0.0003 mm

*at light velocity

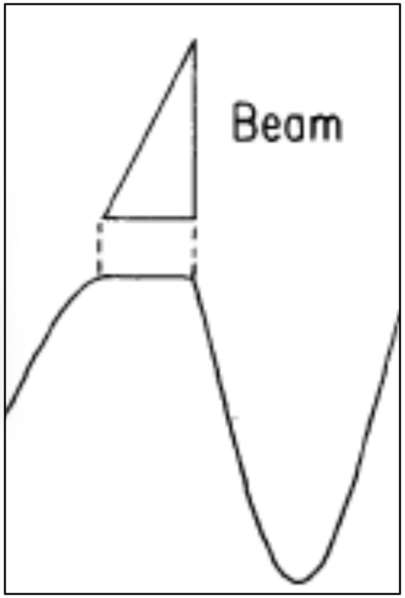
DESY

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

- Match into and out of plasma with **beam size around 1 μm** (about 1 mm beta function).
- 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.

We need to generate and accelerate the triangular beam!

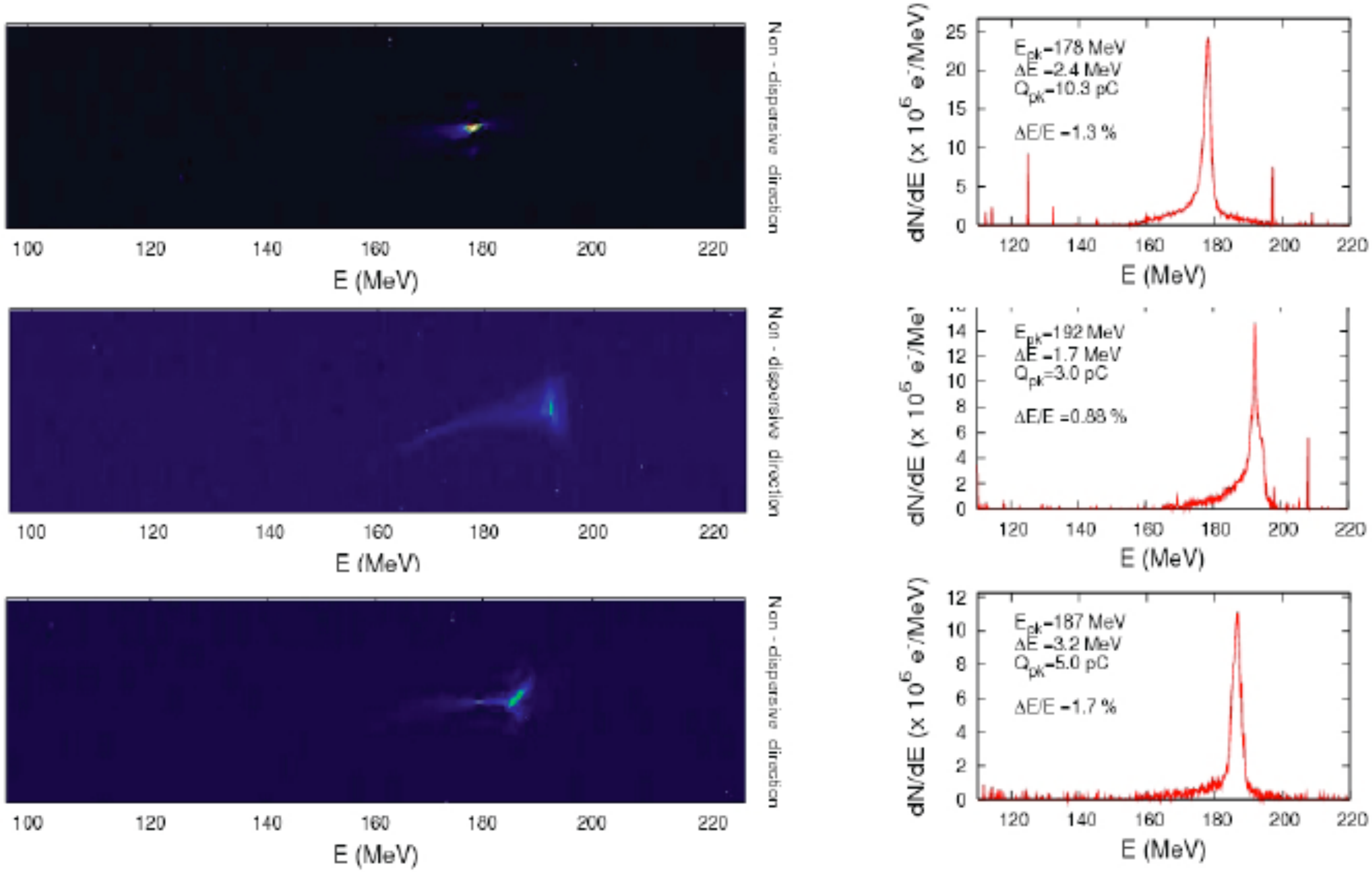


Ralph A

- Idea: Beam Loading to Flatten Wakefield
- Author: **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. *Particle Accelerators, 1987, Vol. 22, pp. 81-99.*

1% relative energy spread

Slide by V. Malka



C. Rechatin *et al.*, Phys. Rev. Lett. **102**, 194804 (2009)

Alternative: Coping with Large Energy Spread

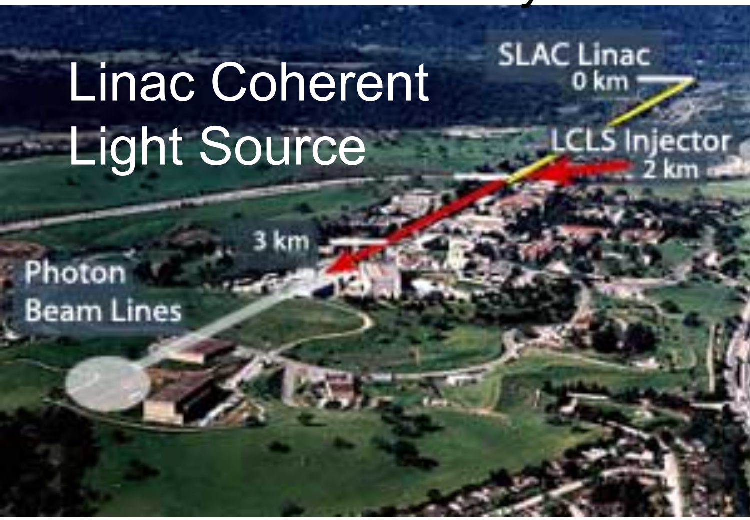
- Focus is presently on **accelerating small energy spread beams** in plasma accelerators:
  - Beneficial for extracting beams from plasmas (**chromatic emittance growth**)
  - Beneficial for matching in/out of plasma (**chromaticity**)
  - Beneficial for lasing in an FEL (**coherence**)
- In case **low energy spread is not possible, alternatives have been proposed**:
  1. **Lengthening the outcoming bunch to reduce energy spread over the slice that lases.** A. Maier et al, PRX
  2. **Transverse gradient undulators** with a dispersive chicane
- Interesting directions with many possible applications.

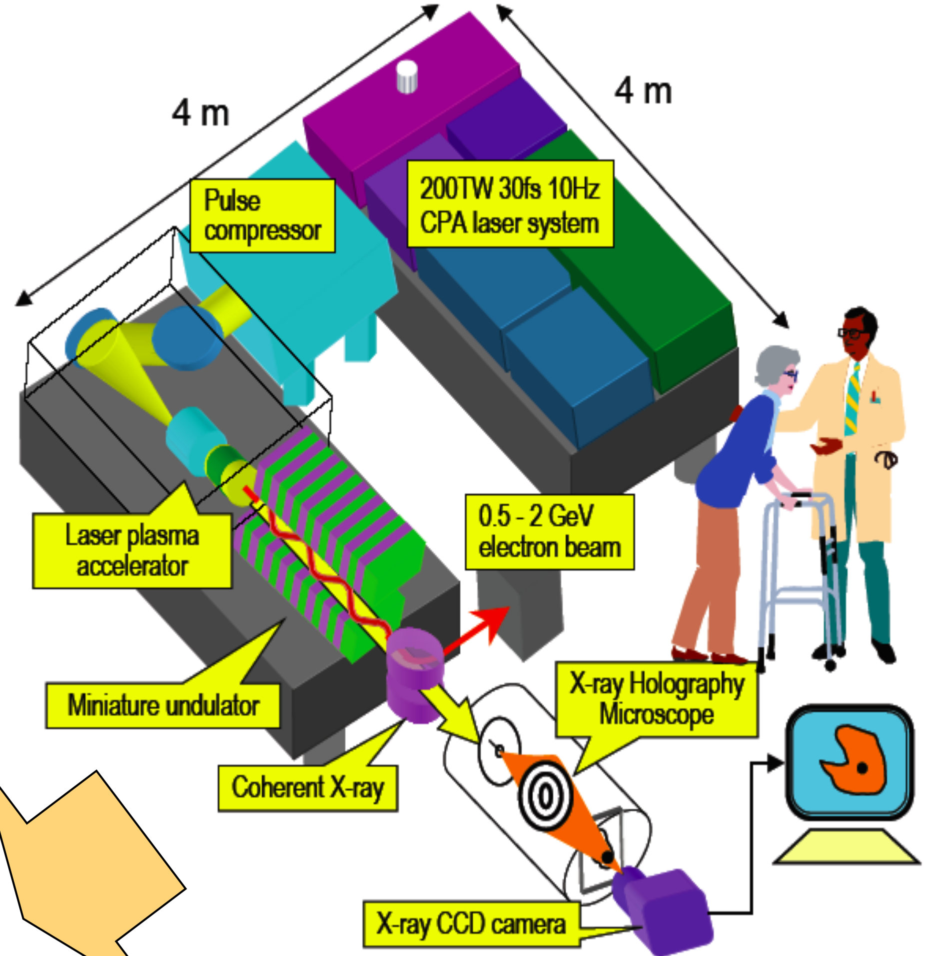
Content

1. From Table-Top to Biggest Machines of Mankind
2. Towards 21st Century Table-Top: The Plasma Wakefield and the Plasma Accelerator
3. Building an FEL Based on Plasmas
4. **Plasma FEL Projects in Europe**

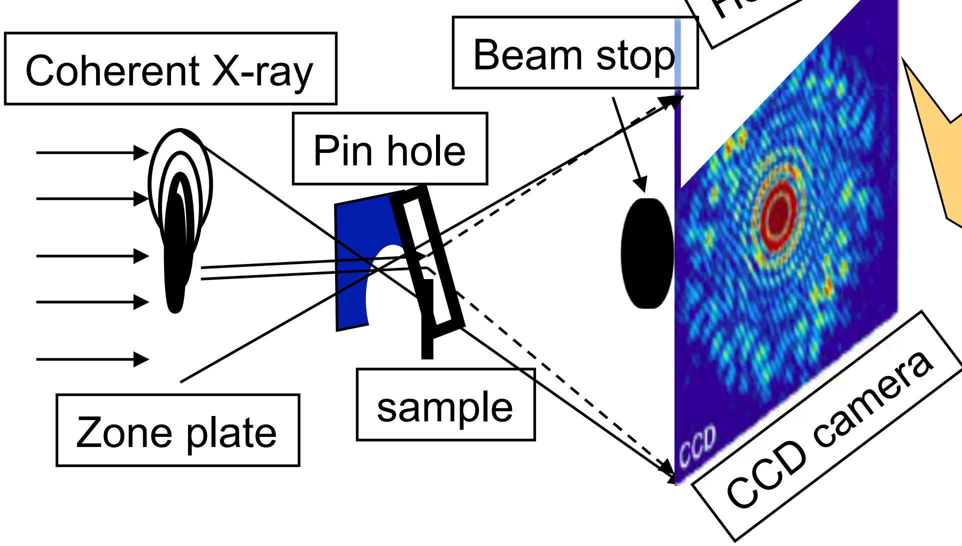
The DREAM: Laser-driven table-top X-ray Free Electron Laser

Kilometer-scale X-ray FEL



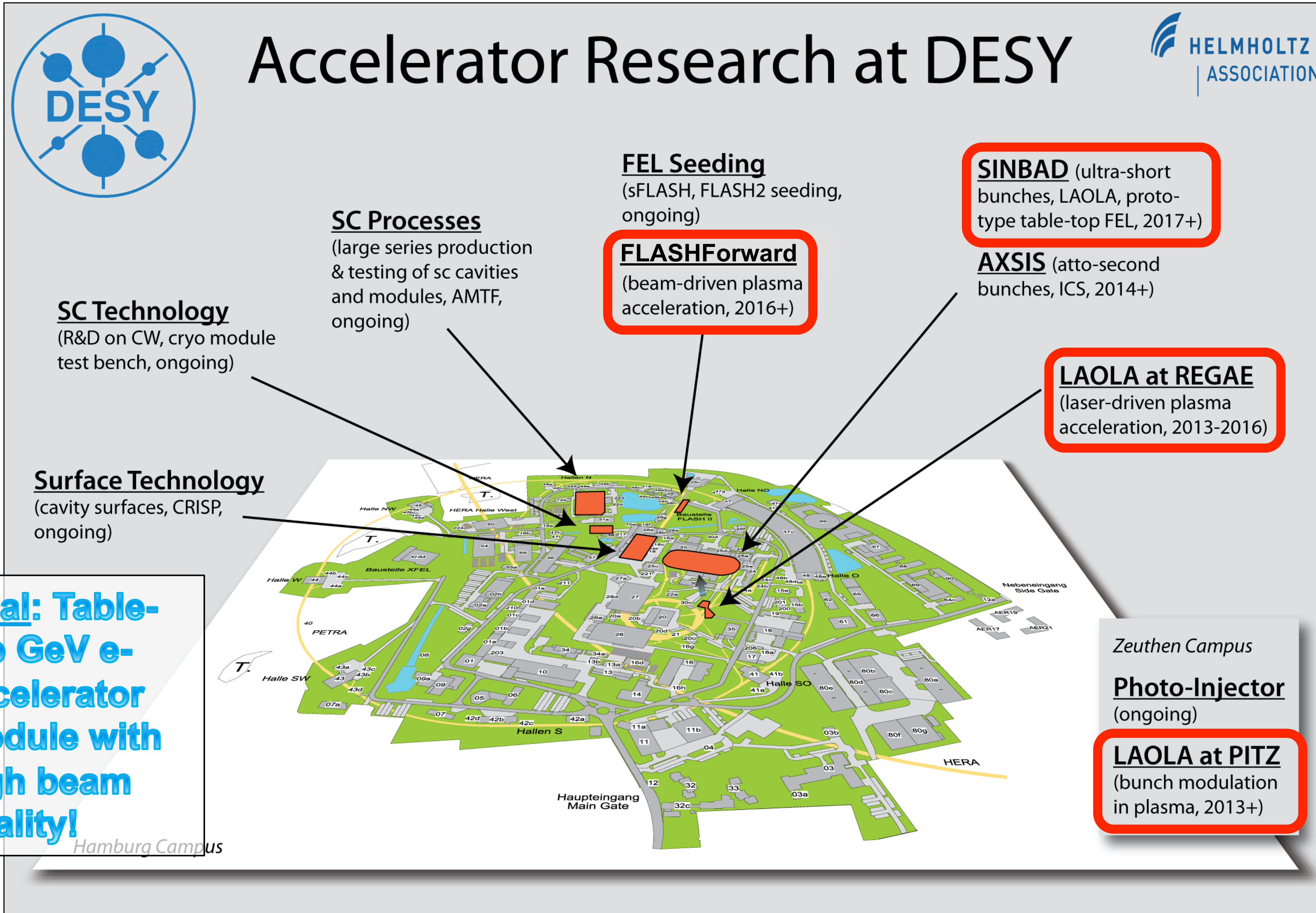


X-ray Holography Microscope



Visualization by T. Tajima, 2010

HEP and photon science lab: DESY Accelerator R&D



Goal: Table-top GeV e- accelerator module with high beam quality!

LAOLA Collaboration Hamburg

Laser: Ti:Sa 200 TW, 25 fs pulse length, 5 Hz repetition rate

- *Initially: Laser-driven wakefields in REGAE. LUX exp. towards FEL*
- *Later: Move to SINBAD facility.*

F. Grüner

A. Maier

Beams:

- **REGAE**: *5 MeV, fC, 7 fs bunch length, 50 Hz*

- **FLASH**: *1.25 GeV, 20 – 500 pC, 20 - 200 fs bunch length, 10 Hz.*
  Beam-driven plasma wakefields. Beam-driven plasma wakefields with shaped beams and innovative injection methods. Helmholtz VI with UK collaboration.

FLASHForward▸▸

J. Osterhoff

- **PITZ**: *25 MeV, 100 pC, 20 ps bunch length, 10 Hz.*
  Beam modulation experiment in a plasma cell, preparation to CERN experiment AWAKE

F. Stephan

- **SINBAD**: dedicated R&D, multi purpose, *150 MeV, 0.01 – 3 pC, down to < 1 fs bunch length, pulse rate 10 – 1000 Hz*
  → **Home of AXSIS ERC Synergy Grant**
  → **Home of ATHENA$_e$**

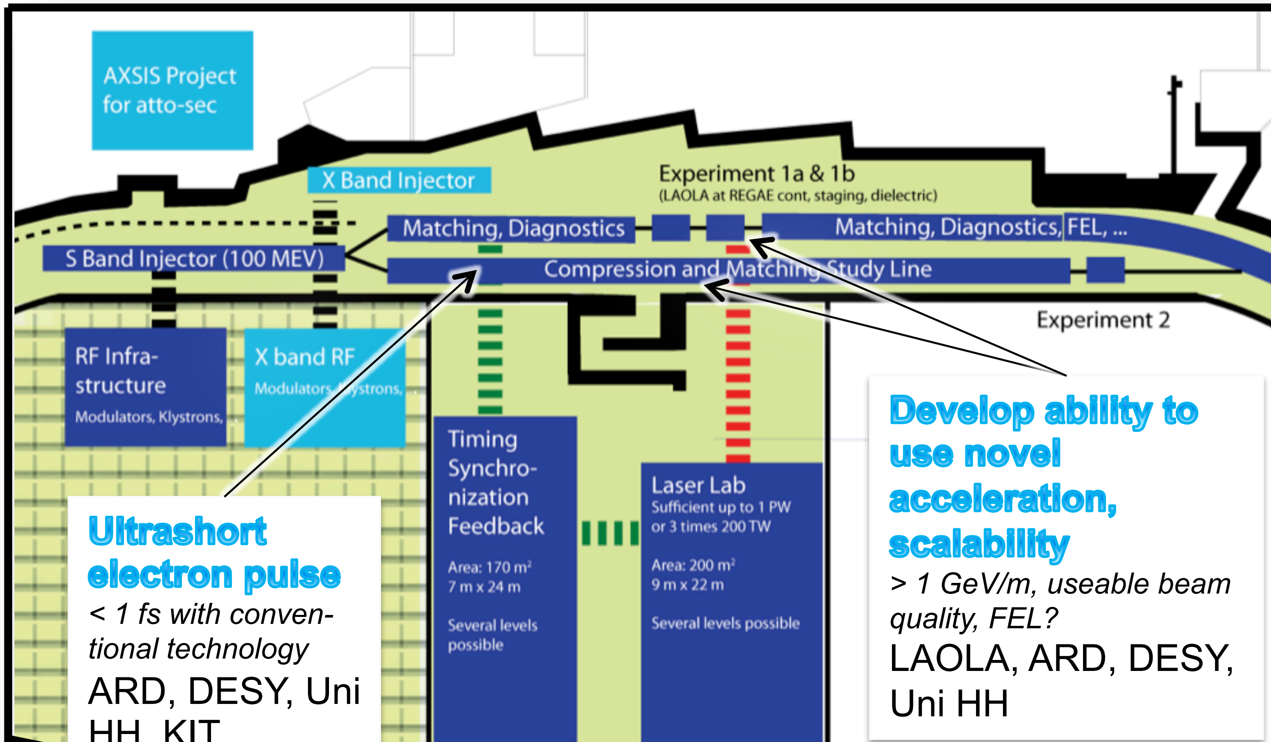
U. Dorda

B. Marchetti

Similarly strong teams in other Helmholtz centers!

S hort IN novative B unches & A ccelerators at D esy

ARD top class research in existing infrastructure



Ultrashort electron pulse

< 1 fs with conventional technology

ARD, DESY, Uni HH, KIT

Develop ability to use novel acceleration, scalability

> 1 GeV/m, useable beam quality, FEL?

LAOLA, ARD, DESY, Uni HH

Compact Atto-Second Light Source

50 as, ICS

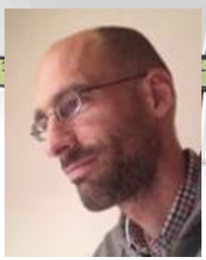
ERC Synergy Grant 14 M€, DESY, Uni HH, Arizona

European Research Council
Established by the European Commission

P. Fromme F. Kärtner

R. Assmann H. Chapman

Footprint: 90 m x 50 m



Room for further phases and users

Third party funding, interest from ELI, …

Projects for Plasma FEL (100 Billion Volt Machine)

1. <u>The Helmholtz Project ATHENA in Germany</u>
   1. Outstanding review results & resonance
   2. Funding presently being decided
2. The Horizon2020 Project EuPRAXIA
   1. Only 2nd EU design study in H2020 on accelerators (after CERN 100 km project)
   2. Initiated and led by Helmholtz/DESY
   3. Fully funded by EU

Common proposal of all Accelerator Centers in the Helmholtz Association

ATHENA Project

***A**ccelerator **T**echnology **HE**lmholtz i**N**fr**A**structure*

Electron energy goal: 1 GeV – the step before EuPRAXIA with 5 GeV

Development of ultra-compact* accelerators and radiation facilities for science and medicine

**and highly cost-efficient*

SINBAD Short INnovative Bunches & Accelerators at DESY
ARD Spitzenforschung im alten DORIS Komplex
durch optimale Nutzung der Infrastruktur
Kompakte Atto-Sekunden Lichtquelle
50 as, ICS
ERC Synergy Grant, DESY, Uni HH, Arizona
Ultrakurzer Elektronenpuls
< 1 fs mit konventioneller Technologie
ARD, DESY, Uni HH, KIT
Nutzbarkeitsstudien Plasmabeschleuniger, Skalierbarkeit
> 1 GeV/m, nutzbare Strahlqualität, FEL?
LAOLA, ARD, DESY, Uni HH
Raum für weitere Phasen und Nutzer
Drittmittel Interessensbekundung ELI
PIER
Coordinating PI
bERLinPro centre for high power cw beams in sc accelerators
bERLinPro = Berlin Energy Recovery Linac Project
100 mA / low emittance technology demonstrator
bERLinPro Helmholtz-Zentrum Berlin
beam dump
6.5 MeV, 100 mA = 650 kW
booster
4.5 MeV
linac module
44 MeV
srf-gun
1.5-2 MeV
merger
dogleg
igh virtual beam power zone
microwave instability driven radiation generation)
50MeV, 100mA, 2ps (5 MW of virtual beam power)
50MeV, 10mA, <100fs (500kw of virtual beam power)
both modes normalized emittance < 1mm mrad
Jülich Short-Pulse Particle and Radiation Centre
JÜLICH
Particle physics
Synchrotron radiation
JuSPARC
Material researcl
Markus Büscher
ELBE center for high power radiation sources
Dual beam Petawatt / 150 TW ultrashort pulse laser facility
Diode pumped Petawatt laser development
Synchronized operation with ELBE accelerator
Dedicated shielded target areas (~1000m² laser lab space)
Beam driven sources (THz, FEL, ...) at ELBE
ELBE
150TW
Draco PW
HZDR
Kiel
Rostock
Lübeck
Stade
Hamburg
Bremerhaven
Bremen
Pasewalk
Elbdeichvorland
Berlin
Hanover
Steglitz-Zehlendorf
Bielefeld
Brunswick
Magdeburg
Büren
Halle
Essen
Dusseldorf
Riesa
Leipzig
Germany
Chemnitz
Dresden
Zentrum
Horn mit Kahlköpfchen
Zwickau
Frankfurt
Nuremberg
Mitte
Donauauen bei Stadldorf
Stuttgart
Passau
Tübingen
Augsburg
Ulm
Munich
Salz
The LIGHT test-stand at GSI: coupling of laser-accelerated ions into conventional accelerators
Principle: manipulation of laser-accelerated ions
HI Jena
GSI
HZDR
ion source (TNSA)
solenoid/ quadrupols
spiral resonator
1. Laser-driven ion acceleration
2. beam conditioning (collimation)
3. drift line and phase-space rotation
Current results:
initial experimental proof of principle done
diagnostics done
tinues in POF III
t towards 100 MeV
ions
to GSI's SIS accelerator
nents (repetition rate and
proton spectrum
proton beam
FLUTE: ARD-Forschung am KIT
KIT
Ultrakurze Elektronenpulse (1 fs bis 300 fs)
Grosser Bereich an Ladungen (1 pC bis 3 nC)
Kohärente Strahlung für Materialwissenschaften und biologische Anwendungen
Entwicklung/Tests von Kurzpuls-Strahldiagnose und Instrumentierung
Kooperation KIT, PSI, DESY
Ferninfrarot Linac- U
FLUTE
FLUTE, a Linac-Based THz Source at KIT
Helmholtz-Institute Jena
of diode-
ser systems
f broad-band
: 16.6 J @
40 mm
relative z-position (µm)
Development and application of novel plasma diagnostics:
few-fs and 1-µm resolution,
first direct visualization of the laser-driven plasma wave in a laser-electron accelerator.
M. Schwab et al., Applied Phys. Lett (2013)
A. Sävert et al., submitted (2013)

Universities and External Partners

Friedrich-Schiller-Universität Jena

TECHNISCHE UNIVERSITÄT DRESDEN

TECHNISCHE UNIVERSITÄT DARMSTADT

KIT Karlsruher Institut für Technologie

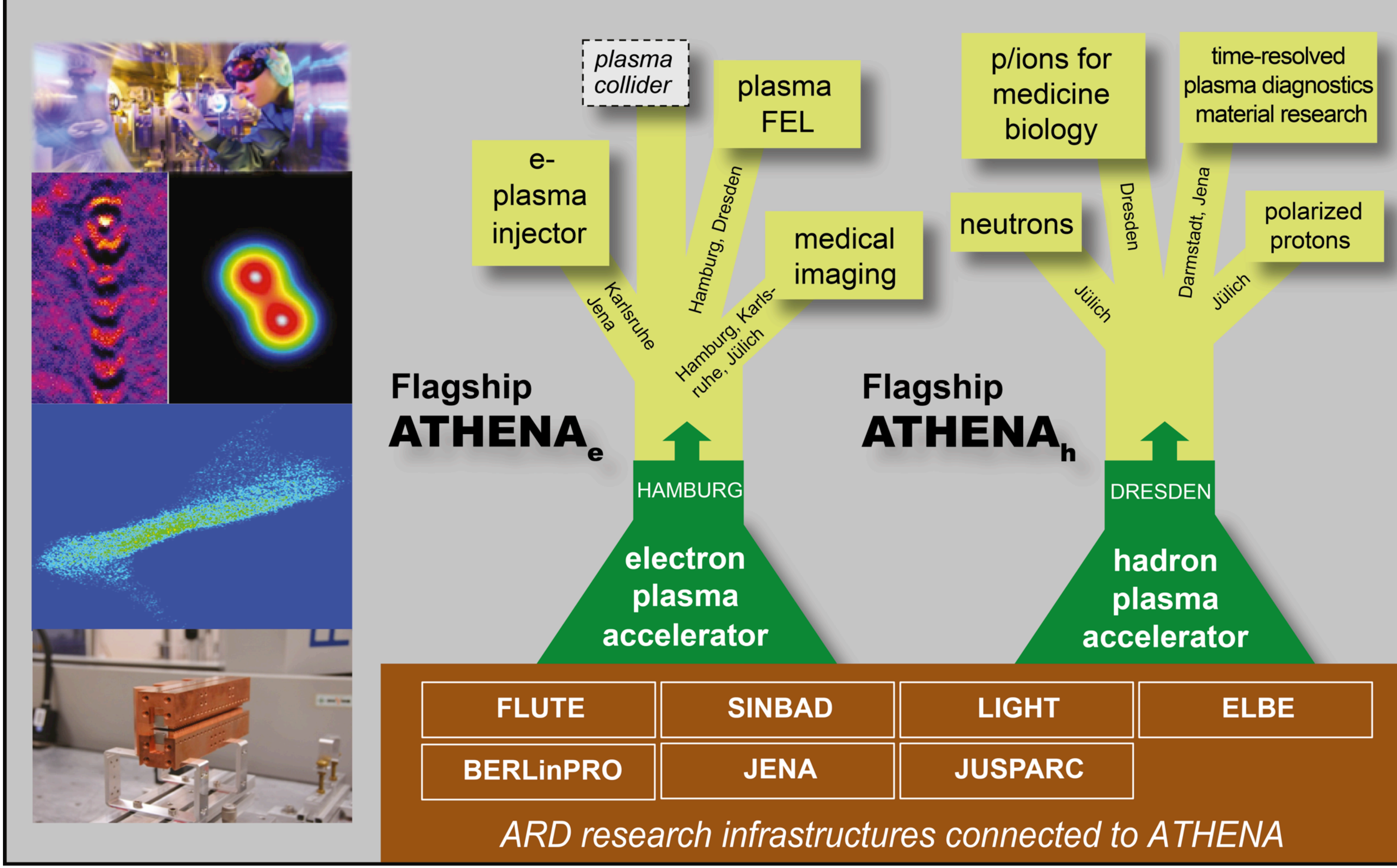
University of Strathclyde Glasgow

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

WESTFÄLISCHE WILHELMS-UNIVERSITÄT MÜNSTER

*In the following the partner universities and external partners are not explicitly indicated on each WP, except UHH. Contributions will be discussed in more detail in the upcoming review talks.

Accelerator Research and Development ARD
HELMHOLTZ | GEMEINSCHAFT



ATHENA: construction 2018 – 2021, total invest 93 M€ (if 30 M€ grant from Helmholtz awarded), proposal submitted June 30th, 6 Helmholtz centers + 1 institute + universities + 1 international collaborator, using infrastructures together, 2 future technologies for the Helmholtz strategy, high relevance for applications in many centers.

ATHENA Potential of New Acc. Technology

- **Reduced size (and cost) particle accelerators**. More science for the same budget!

- Due to short acceleration wavelength: **Ultra-short pulses of particles → ultra-fast science applications**
(*also pump-probe exp. = exciting and measuring fast processes*)

- Strong transverse magnetic fields → ultra-strong wiggling/undulating → **point-like photon emission → better than conventional resolution.**

- Possibility of phase space manipulation with beams and lasers → **ultra-small emittance beams** (*“nano emittance”*)

- Compact footprint → **additional accelerator applications comple-menting “big science”:**
compact hospital light source for imaging, compact FEL in universities, compact proton/ion therapy for cancer, compact radiation source for cargo inspection (ions and e-), compact plasma LC, …

New Accelerators towards Users

ATHENA-h

- First medical user area
- High repetition rate laser (higher dose)
- High stability laser front end (reliability)
- Heavy ion applications
- Polarized protons
- Neutrons

ATHENA-e

- Quality e- beam from plasma to delivery point
- First science user area
- Conventional and novel accelerator technology
- Plasma FEL
- Medical imaging
- Injection into storage ring
- Towards staging → LC

ATHENA Vision

Decision PENDING

- Timescale of ATHENA is into the 2030's:
  - **Construction: 2018 – 2021**
  - **Operation: 2022 – 2032+**
- ATHENA provides **infrastructure to optimize usability of beams from novel accelerators** during its operational phase.
- ATHENA will involve pilot users in dedicated areas:
  - have **users learn about new beams**
  - expose the novel accelerator technologies to **constructive criticism from users**
- ATHENA is not a user facility but the step before.

Projects for Plasma FEL (100 Billion Volt Machine)

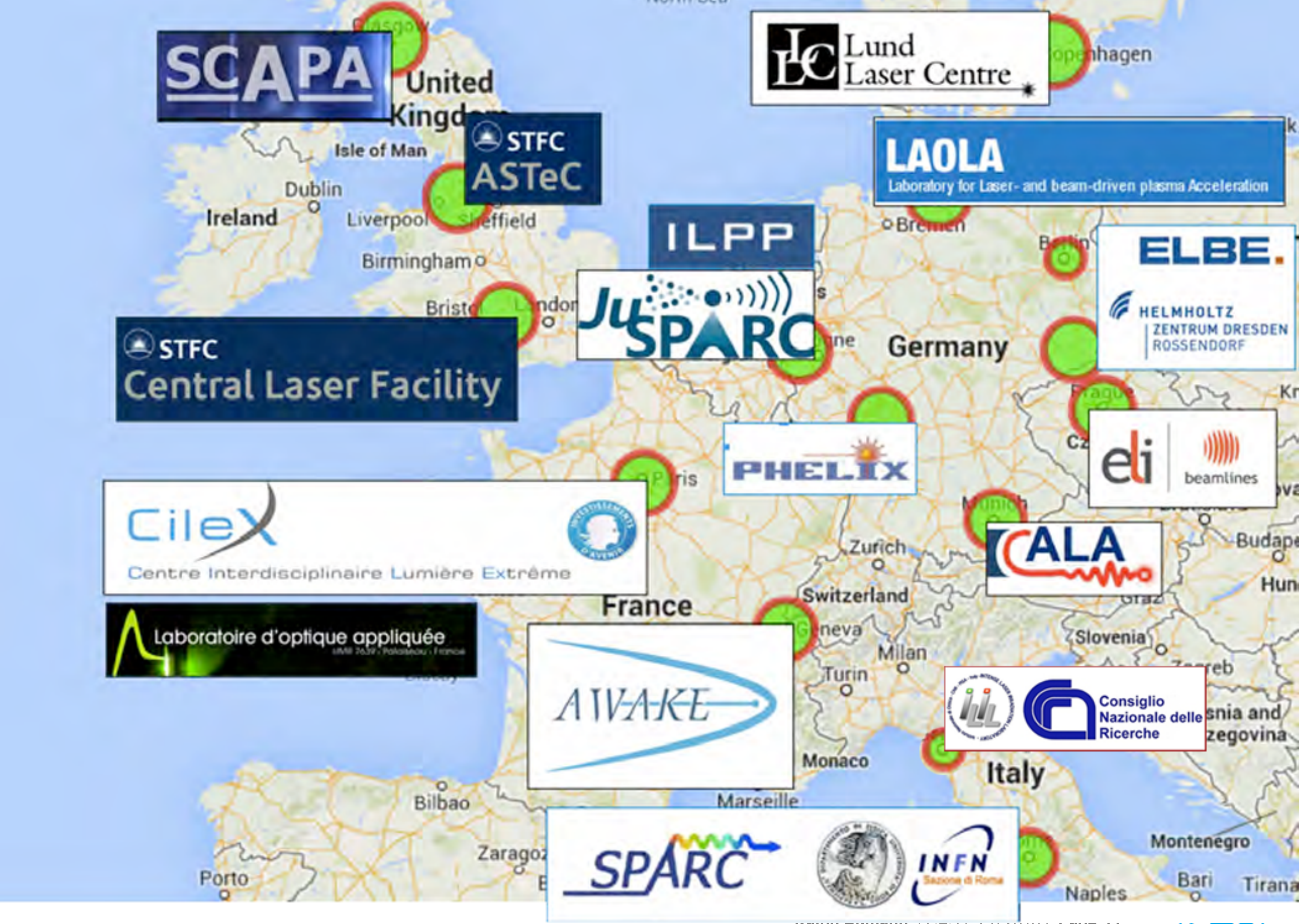
1. The Helmholtz Project ATHENA in Germany
    1. Outstanding review results & resonance
    2. Funding presently being decided
2. <u>The Horizon2020 Project EuPRAXIA</u>
    1. Only 2nd EU design study in H2020 on accelerators (after CERN 100 km project)
    2. Initiated and led by Helmholtz/DESY
    3. Fully funded by EU

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

The Horizon2020 EuPRAXIA Project

Towards a Groundbreaking European Plasma Accelerator

EuPRAXIA Consortium

Plus 16 Associated Partners

Plasma Accelerators: The Future?

- **Believers:** Believing that we can build GeV/TeV/PeV particle accelerators for a lower price tag and can open many new applications and scientific discoveries.
- **Non-believers:** Believing that the many short-comings of the plasma accelerator technology (efficiency, positrons, stability, energy spread, ...) cannot be solved in reasonable time.
- **The EuPRAXIA approach:**
  - Focus on facts and physics. Take short-coming serious.
  - However, if not proven impossible we assume solutions can be found and we work on these solutions.
  - Use the **laser and plasma accelerator technology to design a full blown particle accelerator and estimate the achievable performance**.

Reminder: A Particle Accelerator is More than the Accelerating System

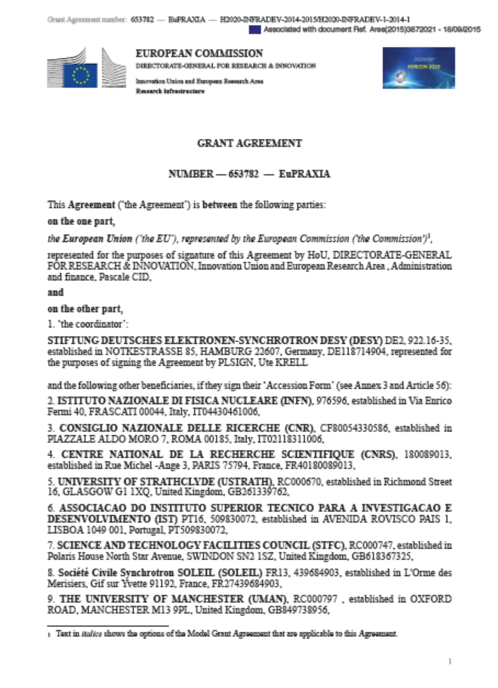
- In a circular accelerator facility:
  Accelerating systems < 10% of total investment
- In a linear accelerator facility:
  Accelerating systems < 30% of total investment

- 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 a real accelerator for pilot users**

EuPRAXIA is a Horizon2020 Design Study

- EuPRAXIA is a so-called **EU design study**.
  - FP7 (2007 – 2013): EU funded 16 such studies, of which 7 were in physical science. Only 2 were accelerator-related.
  - Horizon2020 (2014 – 2020): EuPRAXIA project is **one of two accelerator-related design studies** funded so far, other is EuroCirCol (FCC from CERN).
- Already great success to have been selected! A great chance for promoting novel accelerators.
- Study is legally governed by
  - **grant agreement (269 pages)**, defining the work plan, milestones and deliverables.
  - **consortium agreement (48 pages)**, defining project rules.
- **Partners** have signed contracts, **associated partners** have sent signed letters, accepting consortium rules (governance, IP, ...).


Grant Agreement number: 653782 — EuPRAXIA — H2020-INFRADEV-2014-2015/H2020-INFRADEV-1-2014-1
Associated with document Ref. Ares(2015)3872021 - 18/09/2015

EUROPEAN COMMISSION
DIRECTORATE-GENERAL FOR RESEARCH & INNOVATION
Innovation Union and European Research Area
Research Infrastructure

GRANT AGREEMENT

NUMBER — 653782 — EuPRAXIA

This **Agreement** ('the Agreement') is **between** the following parties:

on the one part,

the European Union ('the EU'), represented by the European Commission ('the Commission')[1],

represented for the purposes of signature of this Agreement by HoU, DIRECTORATE-GENERAL FOR RESEARCH & INNOVATION, Innovation Union and European Research Area , Administration and finance, Pascale CID,

and

on the other part,

1. 'the coordinator':

STIFTUNG DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY (DESY) DE2, 922.16-35, established in NOTKESTRASSE 85, HAMBURG 22607, Germany, DE118714904, represented for the purposes of signing the Agreement by PLSIGN, Ute KRELL

and the following other beneficiaries, if they sign their 'Accession Form' (see Annex 3 and Article 56):

2. **ISTITUTO NAZIONALE DI FISICA NUCLEARE (INFN)**, 976596, established in Via Enrico Fermi 40, FRASCATI 00044, Italy, IT04430461006,

3. **CONSIGLIO NAZIONALE DELLE RICERCHE (CNR)**, CF80054330586, established in PIAZZALE ALDO MORO 7, ROMA 00185, Italy, IT02118311006,

4. **CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE (CNRS)**, 180089013, established in Rue Michel -Ange 3, PARIS 75794, France, FR40180089013,

5. **UNIVERSITY OF STRATHCLYDE (USTRATH)**, RC000670, established in Richmond Street 16, GLASGOW G1 1XQ, United Kingdom, GB261339762,

6. **ASSOCIACAO DO INSTITUTO SUPERIOR TECNICO PARA A INVESTIGACAO E DESENVOLVIMENTO (IST)** PT16, 509830072, established in AVENIDA ROVISCO PAIS 1, LISBOA 1049 001, Portugal, PT509830072,

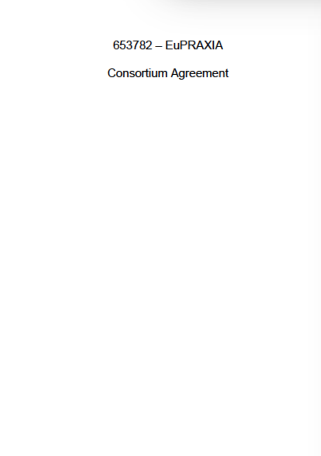
7. **SCIENCE AND TECHNOLOGY FACILITIES COUNCIL (STFC)**, RC000747, established in Polaris House North Star Avenue, SWINDON SN2 1SZ, United Kingdom, GB618367325,

8. **Société Civile Synchrotron SOLEIL (SOLEIL)** FR13, 439684903, established in L'Orme des Merisiers, Gif sur Yvette 91192, France, FR27439684903,

9. **THE UNIVERSITY OF MANCHESTER (UMAN)**, RC000797 , established in OXFORD ROAD, MANCHESTER M13 9PL, United Kingdom, GB849738956,

[1] Text in *italics* shows the options of the Model Grant Agreement that are applicable to this Agreement.

1


653782 – EuPRAXIA

Consortium Agreement

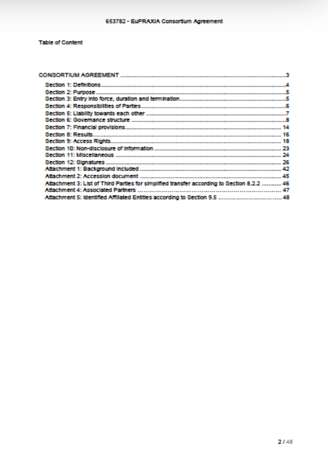

653782 - EuPRAXIA Consortium Agreement

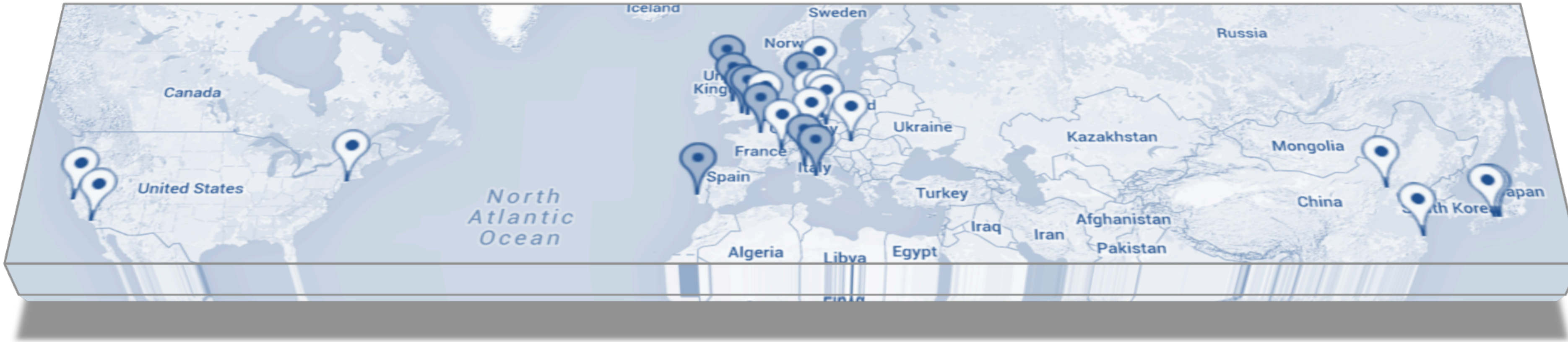
Table of Content

CONSORTIUM AGREEMENT 3
Section 1: Definitions 4
Section 2: Purpose 5
Section 3: Entry into force, duration and termination 5
Section 4: Responsibilities of Parties 6
Section 5: Liability towards each other 7
Section 6: Governance structure 8
Section 7: Financial provisions 14
Section 8: Results 16
Section 9: Access Rights 18
Section 10: Non-disclosure of information 23
Section 11: Miscellaneous 24
Section 12: Signatures 26
Attachment 1: Background included 42
Attachment 2: Accession document 45
Attachment 3: List of Third Parties for simplified transfer according to Section 8.2.2 46
Attachment 4: Associated Partners 47
Attachment 5: Identified Affiliated Entities according to Section 9.5 48

2 / 48

EuPRAXIA = 16 Partners plus 16* Associated Partners

Horizon2020



United States

- CENTER FOR ACCELERATOR SCIENCE AND EDUCATION AT STONY BROOK UNIVERSITY & BROOKHAVEN NATIONAL LABORATORY (BNL)
- LAWRENCE BERKELEY NATIONAL LABORATORY (LBNL)
- UNIVERSITY OF CALIFORNIA AT LOS ANGELES (UCLA)

Europe

- **STIFTUNG DEUTSCHES ELEKTRONEN-SYNCHROTRON (DESY)**
- **ISTITUTO NAZIONALE DI FISICA NUCLEARE (INFN)**
- **CONSIGLIO NAZIONALE DELLE RICERCHE (CNR)**
- **CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE (CNRS)**
- **UNIVERSITY OF STRATHCLYDE (USTRATH)**
- **ASSOCIAÇÃO DO INSTITUTO SUPERIOR TÉCNICO PARA A INVESTIGAÇÃO E DESENVOLVIMENTO (IST-ID)**
- **SCIENCE AND TECHNOLOGY FACILITIES COUNCIL (STFC)**
- **SOCIÉTÉ CIVILE SYNCHROTRON SOLEIL (SOLEIL)**
- **THE UNIVERSITY OF MANCHESTER (UMAN)**
- **THE UNIVERSITY OF LIVERPOOL (ULIV)**
- **AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE (ENEA)**
- **COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES (CEA)**
- **UNIVERSITA DEGLI STUDI DI ROMA LA SAPIENZA (UROM)**
- **UNIVERSITAET HAMBURG (UHH)**
- **IMPERIAL COLLEGE OF SCIENCE, TECHNOLOGY AND MEDICIN (ICL)**
- **THE CHANCELLOR, MASTERS AND SCHOLARS OF THE UNIVERSITY OF OXFORD (UOXF)**

- HELMHOLTZ-INSTITUT JENA
- HELMHOLTZ-ZENTRUM DRESDEN-ROSSENDORF
- LUDWIG-MAXIMILLIANS-UNIVERSITÄT MÜNCHEN
- UNIVERSITY LILLE
- UNIVERSITY LUND

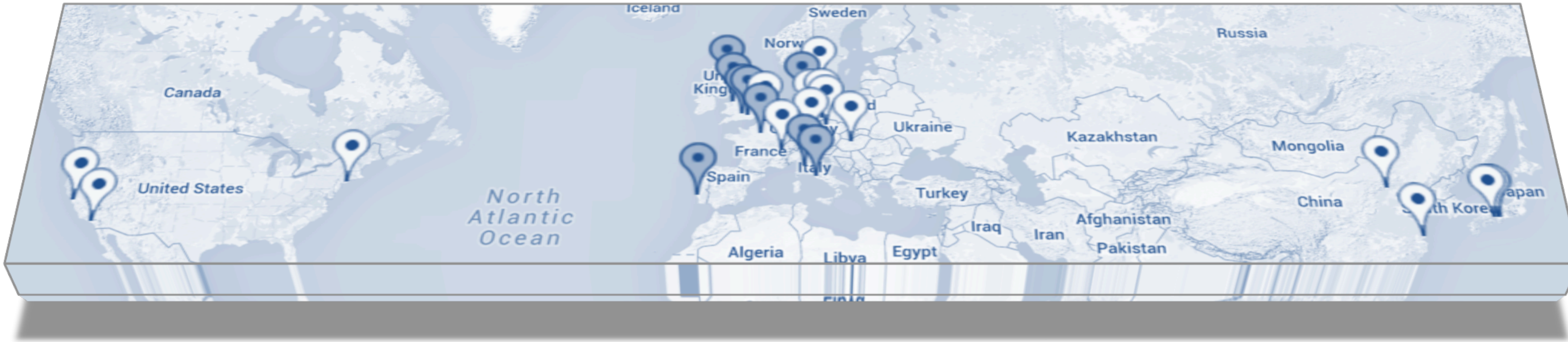
- EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)
- ORGANISATION EXTREME LIGHT INFRASTRUCTURES - BEAMS (ELI-B)
- WIGNER RESEARCH CENTER OF THE HUNGARIAN ACADEMY OF SCIENCE IN UNGARN

China / Japan

- JIAOTONG UNIVERSITY SHANGHAI
- TSINGUA UNIVERSITY BEIJING
- KANSAI PHOTON SCIENCE INSTITUTE, JAPAN ATOMIC ENERGY AGENCY
- OSAKA UNIVERSITY
- RIKEN SPRING-8 CENTER

**KEK could not sign to consortium agreement. Legal discussions with SLAC ongoing. Other candidates contacted us: Russia, Turkey.*

EuPRAXIA = 16 Partners plus 16 Associated Partners



All required expertise on board:

- **HEP labs** (operating world's energy frontier accelerators)
- **Photon science labs** (operating XFEL's, synchrotron rad.)
- **Laser labs** (operating 1 – 5 Peta-Watt frontier lasers)
- **Plasma accelerator labs** (operating plasma accelerators with record stability)
- **Theory labs** (operating advanced plasma acc. simulations)

HOME | EUPRAXIA FOR BEGINNERS | DISSEMINATION | EVENTS | CONTACT US | INTRANET

EuPRAXIA

http://eupraxia-project.eu

Horizon2020

Project Web Site

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

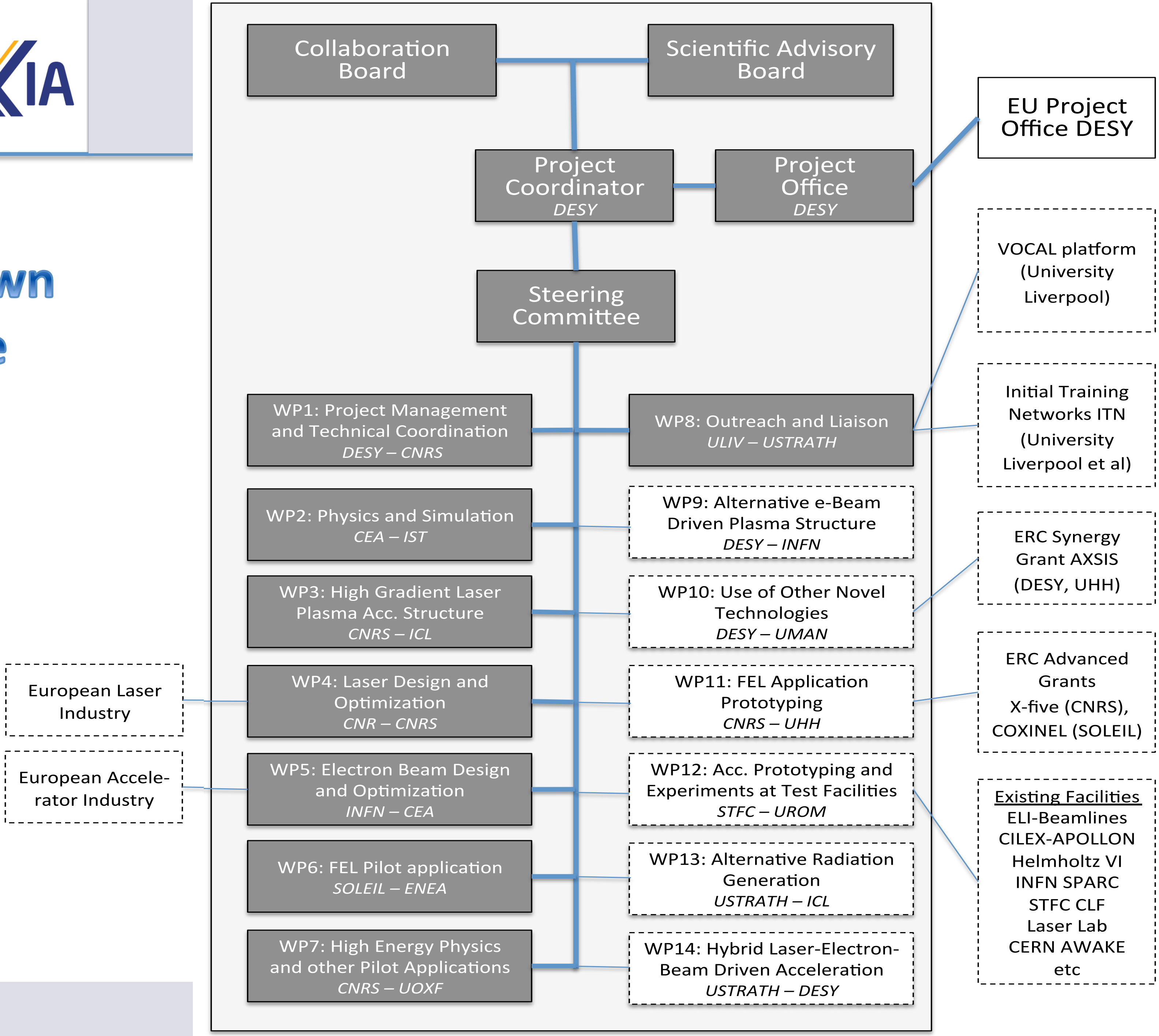
The management bodies will organise, lead and control the project's activities and make sure that objectives are met

LEARN MORE

OPENING NEW HORIZONS

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

Work Breakdown Structure



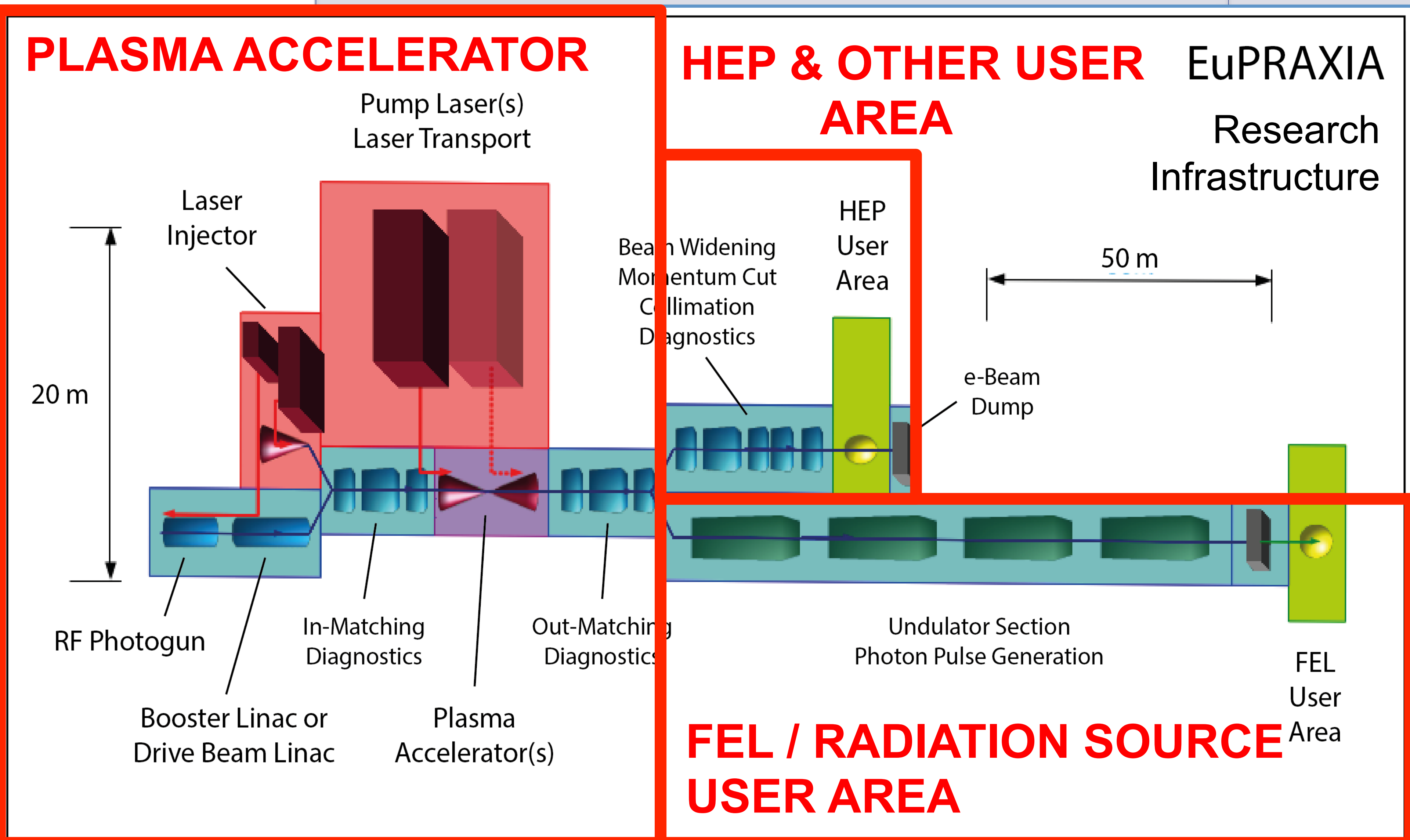
EuPRAXIA General Goals

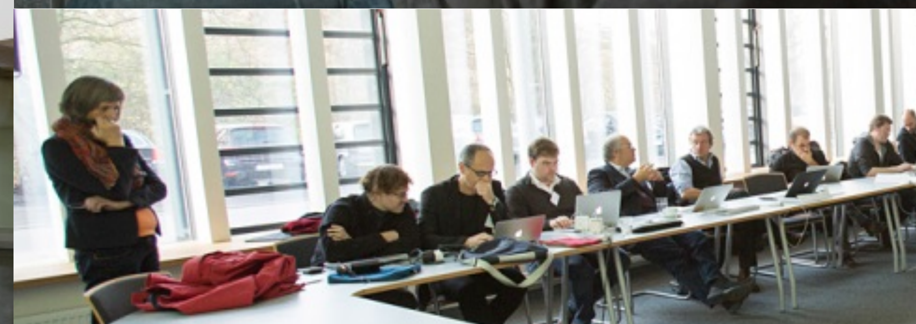
- **Technical focus**:
  - designing accelerator and laser systems for improving the quality of plasma-accelerated beams, similar to the methods used in conventional accelerators.
  - These methods require significant space and investment.
- **Scientific focus**:
  - developing beam parameters, two user areas and the use cases for a femto-second Free Electron Laser (FEL), High Energy Physics (HEP) detector science and other applications.
- **Managerial focus**:
  - developing an implementation model for a common European plasma accelerator.
  - this includes a comparative study of possible sites in Europe, a cost estimate and a model for distributed construction in Europe and installation at one central site.

EuPRAXIA Research Infrastructure for the 2020's

5 GeV electron beam

Horizon2020





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


EuPRAXIA
Ecole polytechnique
2016 02 19
Andreas Walker
DESY

EuPRAXIA Work Progress

Example WP4 "Laser Design and Optimization"

Horizon2020

- On **May 18, 2016** at SOLEIL - France.
- **Leading international laboratories were represented** including:
  - Intense Laser Irradiation Laboratoy (INO - Italy),
  - the Laboratoire d'Utilisations des Lasers Intenses (CNRS - France),
  - the Lawrence Livermore National Laboratory (USA),
  - the Centro de Láseres Pulsados Ultracortos Ultraintensos (University of Salamanca, Spain),
  - the Central Laser Facility (Science and Technology Facilities Council, UK),
  - The Petawatt Laser Facility (University of Texas at Austin, USA)
- and **international laser manufacturers** such as
  - Thales (France),
  - National Energetics (USA),
  - Amplitude Technologies (France),
  - Amplitude Systèmes (France) and
  - Proton Laser (Spain).

100cube Laser Challenge

- "Brainstorming" session starting basic specifications of the EUPRAXIA laser from EUPRAXIA steering committee, the so-called "**100 cube**": **100 J, 100 fs, 100 Hz**, contrast 10^{10} at 10ps → 1PW @ 100Hz
- Detailed report is in preparation for Pisa meeting in June 29, 2016. **Participants agreed to meet regularly every 6 months.**

EUROPEAN
PLASMA RESEARCH
ACCELERATOR WIT
EXCELLENCE IN
APPLICATIONS

Cutting edge lasers

Collimation

Modern accelerator technology

24/7 operation

Next-gen facility

Feedbacks and corrections

HQ electron beams

FEL facility

Other apps

100 – 250 m footprint

Competition for best EU site

HEP appli-cations

EuPRAXIA Implementation Model

Horizon2020

- Goal is to **design one operational facility at one location.**
- **Resources will be distributed** to partners:
  - Model of big particle physics detector: Many institutes team up to build one detector at one place, each contributing a part.
- Open **site study** with the goal to propose the best site. To be considered:
  - Existing infrastructure, host lab support, scientific user community, support from funding agency, …
- Facility will be **devoted to provide for pilot users**:
  - Ultra-compact X-ray FEL
  - Ultra-compact GeV electron source for HEP detector development
  - Other applications (industry, medicine, ...)

Supported by EU Horizon 2020

European Network for Novel Accelerators

EuroNNAc2

supported by EU via EuCARD2

EuroNNAc and EuPRAXIA Workshop on a European Plasma Accelerator

We are organizing a workshop in Pisa inviting the communities of conventional facilities, lasers and novel accelerators, discussing the unique opportunities for our fields from such a design study. We will bring together the initial EuPRAXIA project team, EuroNNAc network participants and interested scientists to collect input from all parties and to base this effort deeply into the interests of our communities.

The EuroNNAc and EuPRAXIA Workshop on a European Plasma Accelerator will take place June 29 to July, 1, 2016 at INO-CNR/INFN, Pisa, Italy.

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…

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.

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 $\Delta x = \sigma_x$:

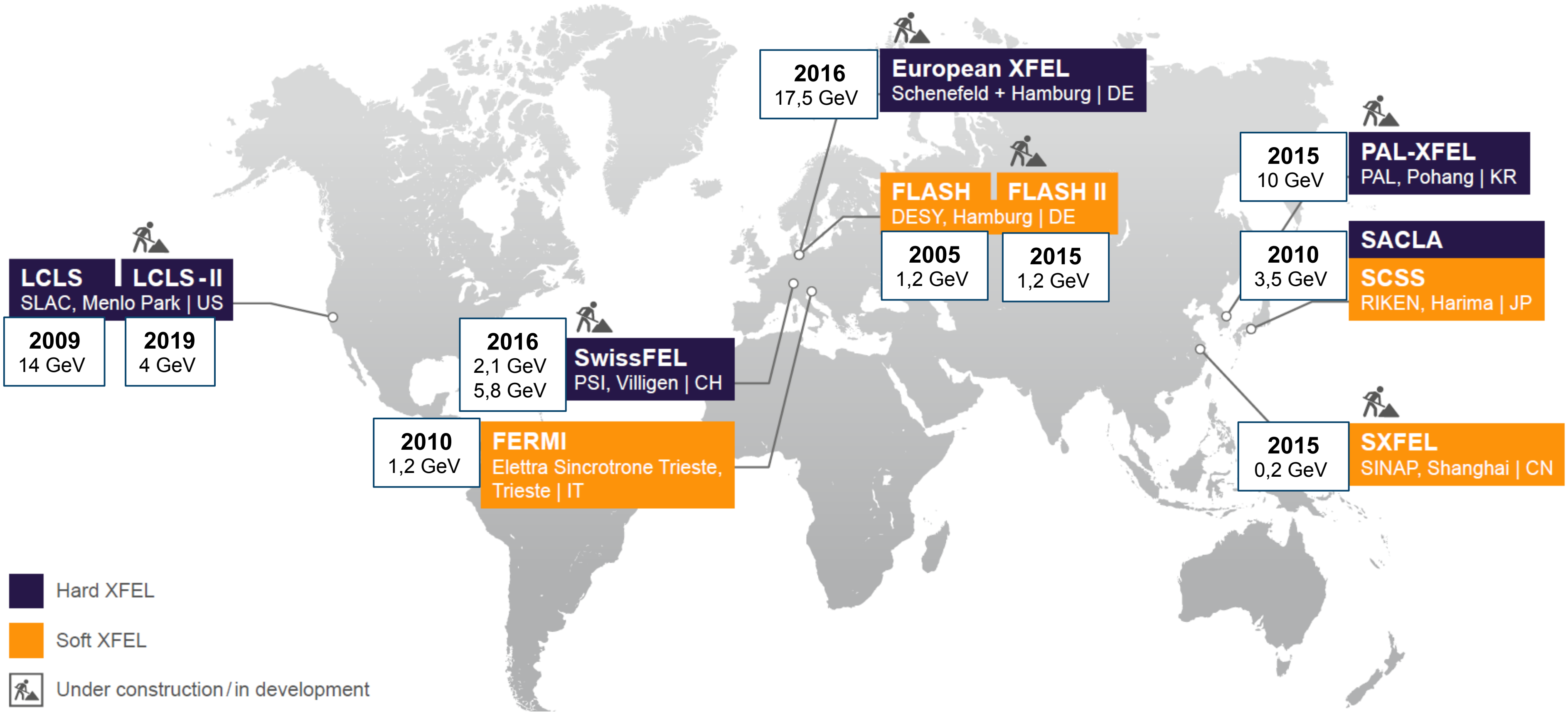
$$\frac{\Delta\varepsilon}{\varepsilon_0} = \left(\frac{\sigma_x}{\sigma_0}\right)^2$$

100% for 1.3 μm offset

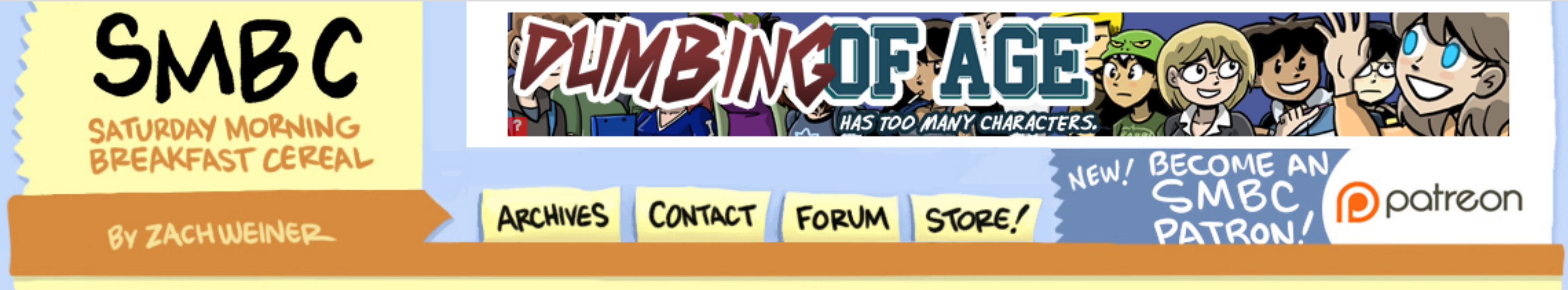
- Lower plasma density better: larger matched beam size, bigger tolerances.

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

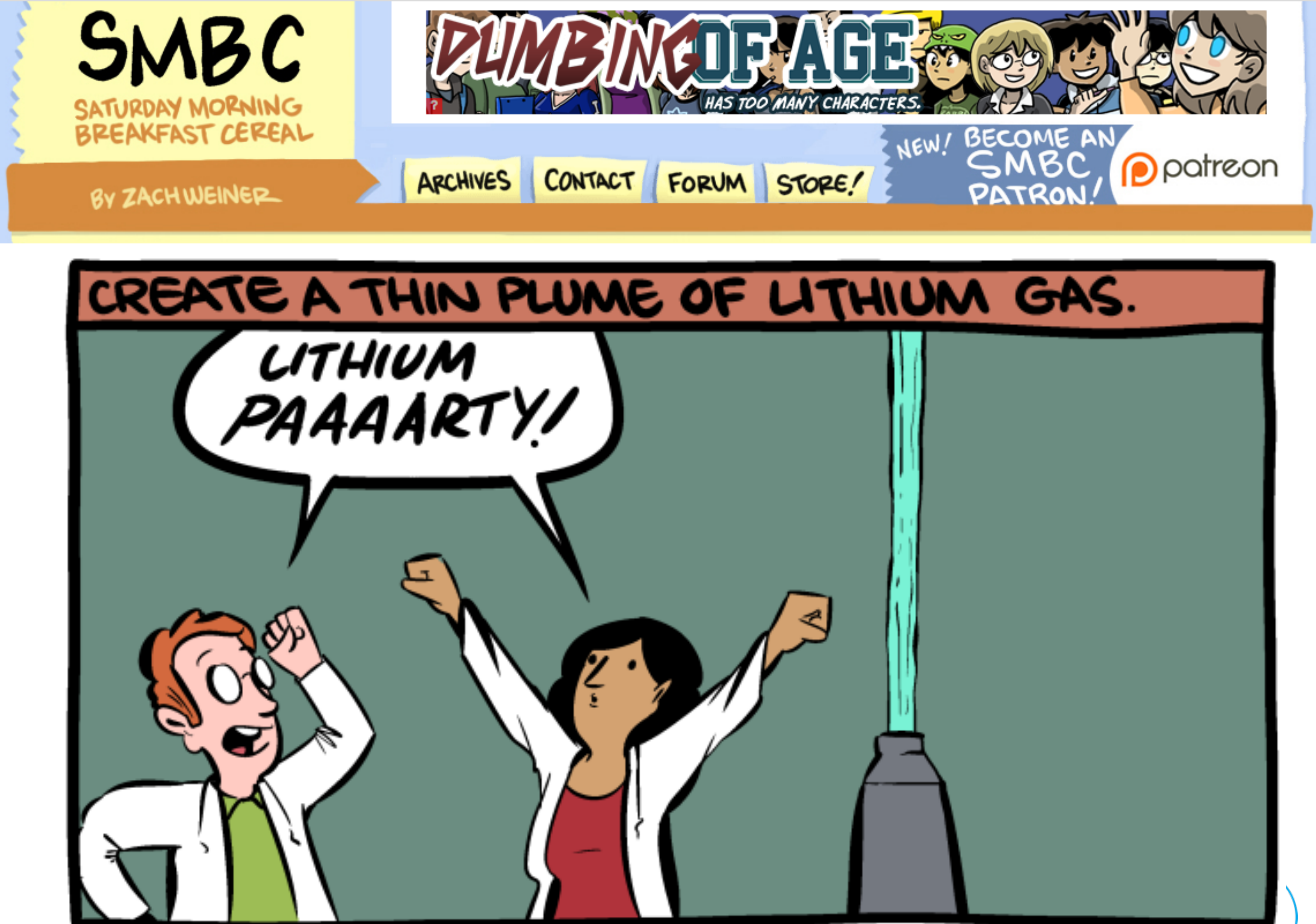
Great Progress: X-RAY FEL Map of the World.

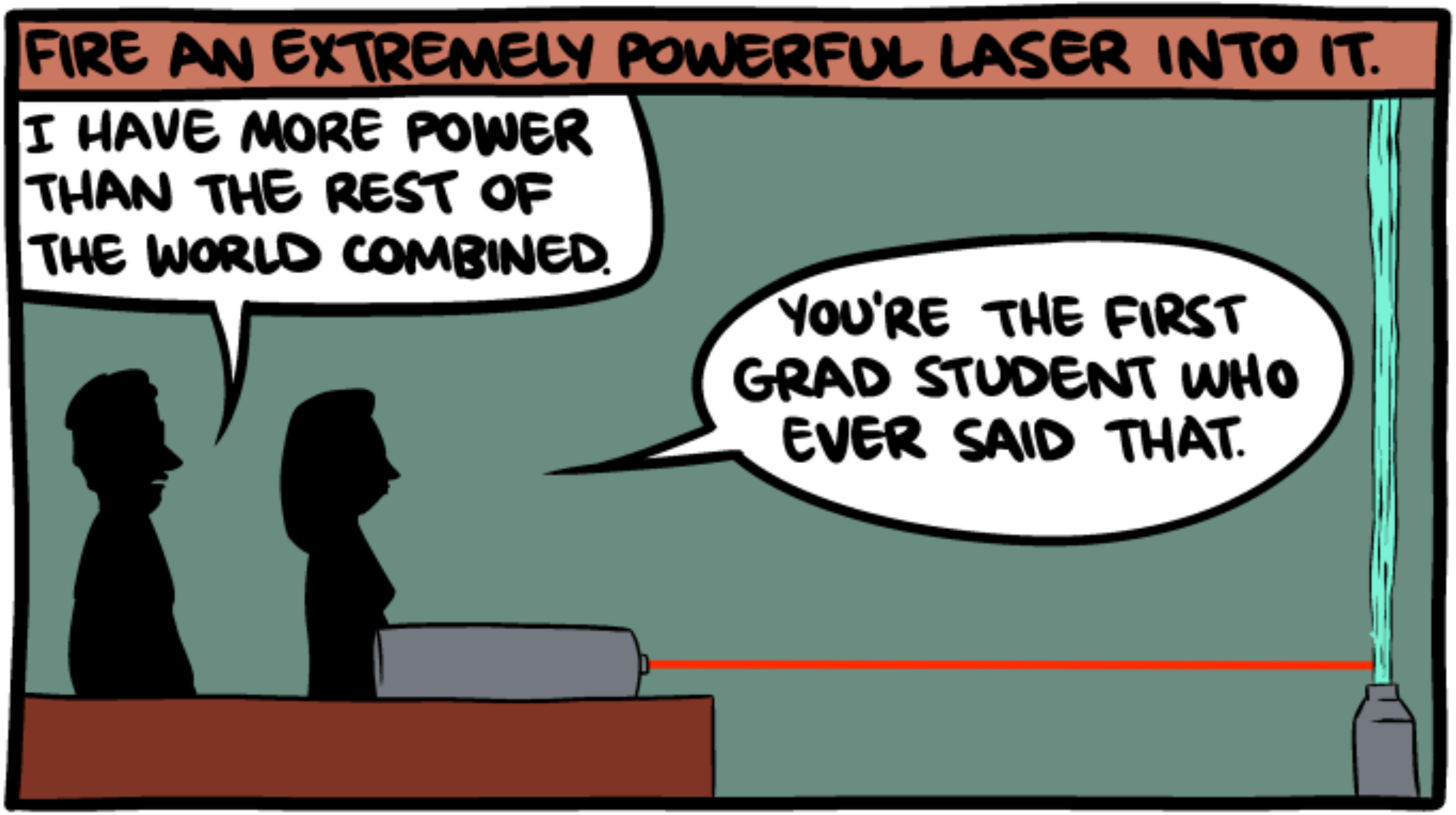


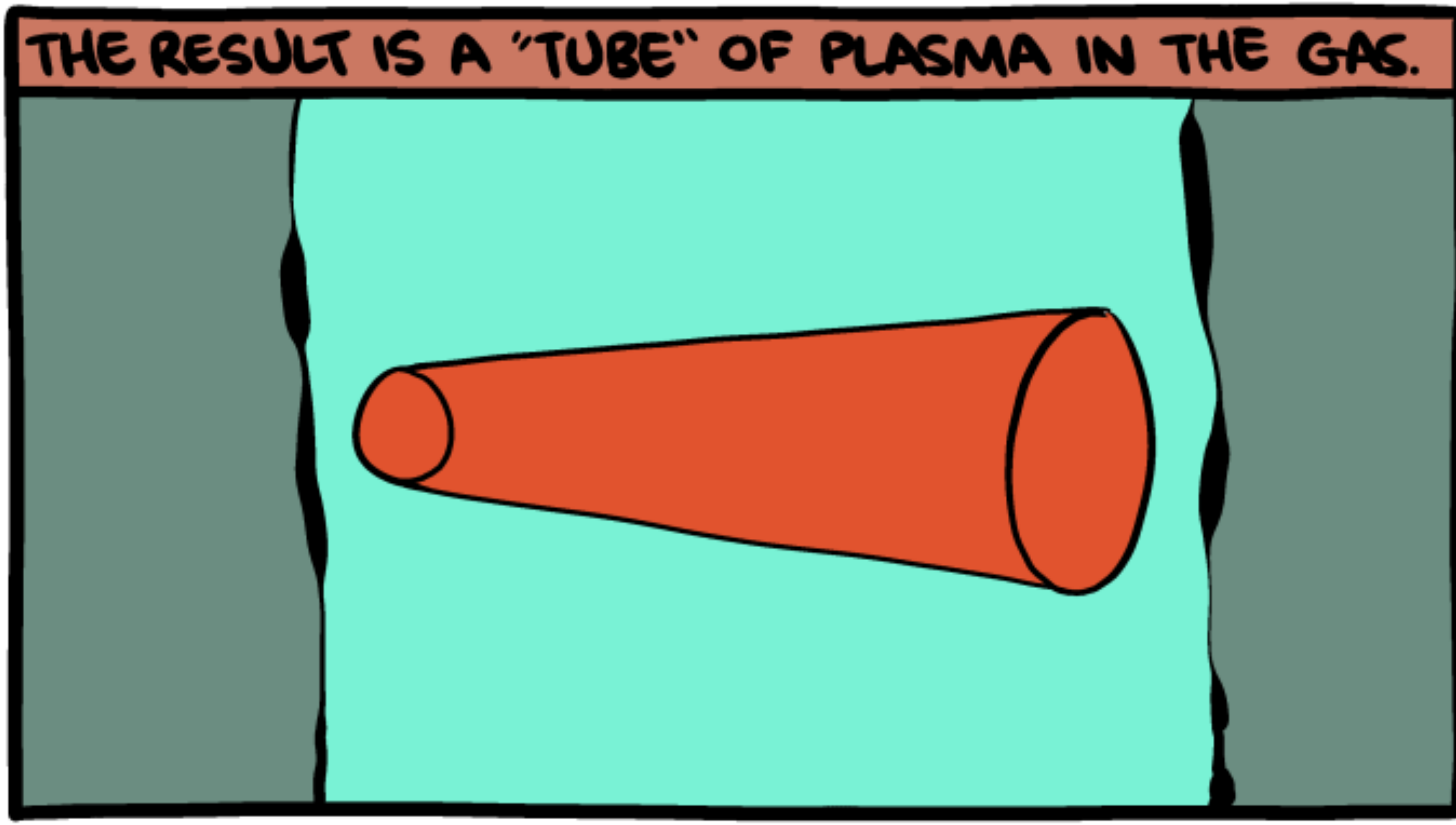
2005: 1 → 2015 (today): 5 → 2025: 10+



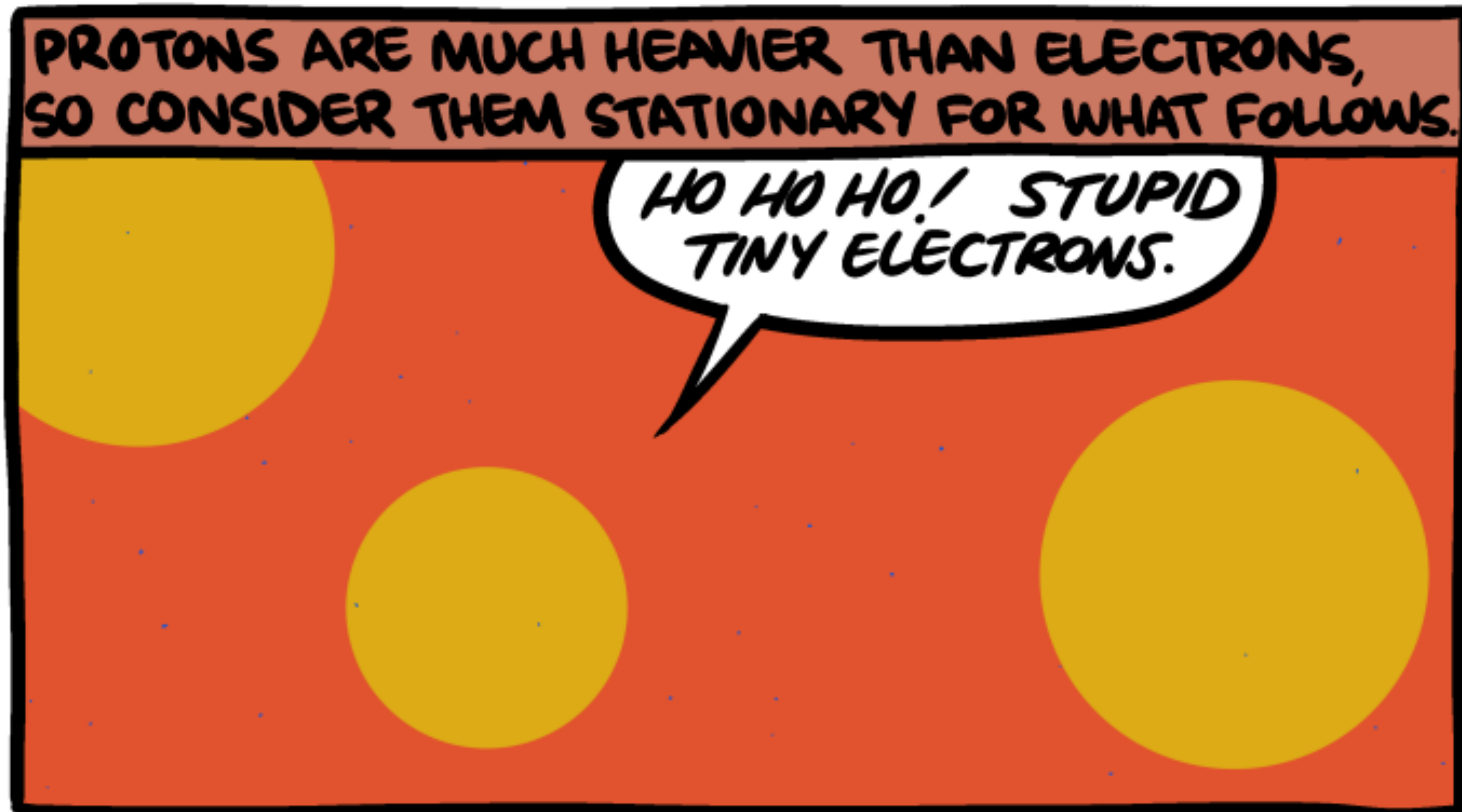
PLASMA WAKEFIELD ACCELERATION
A GUIDE

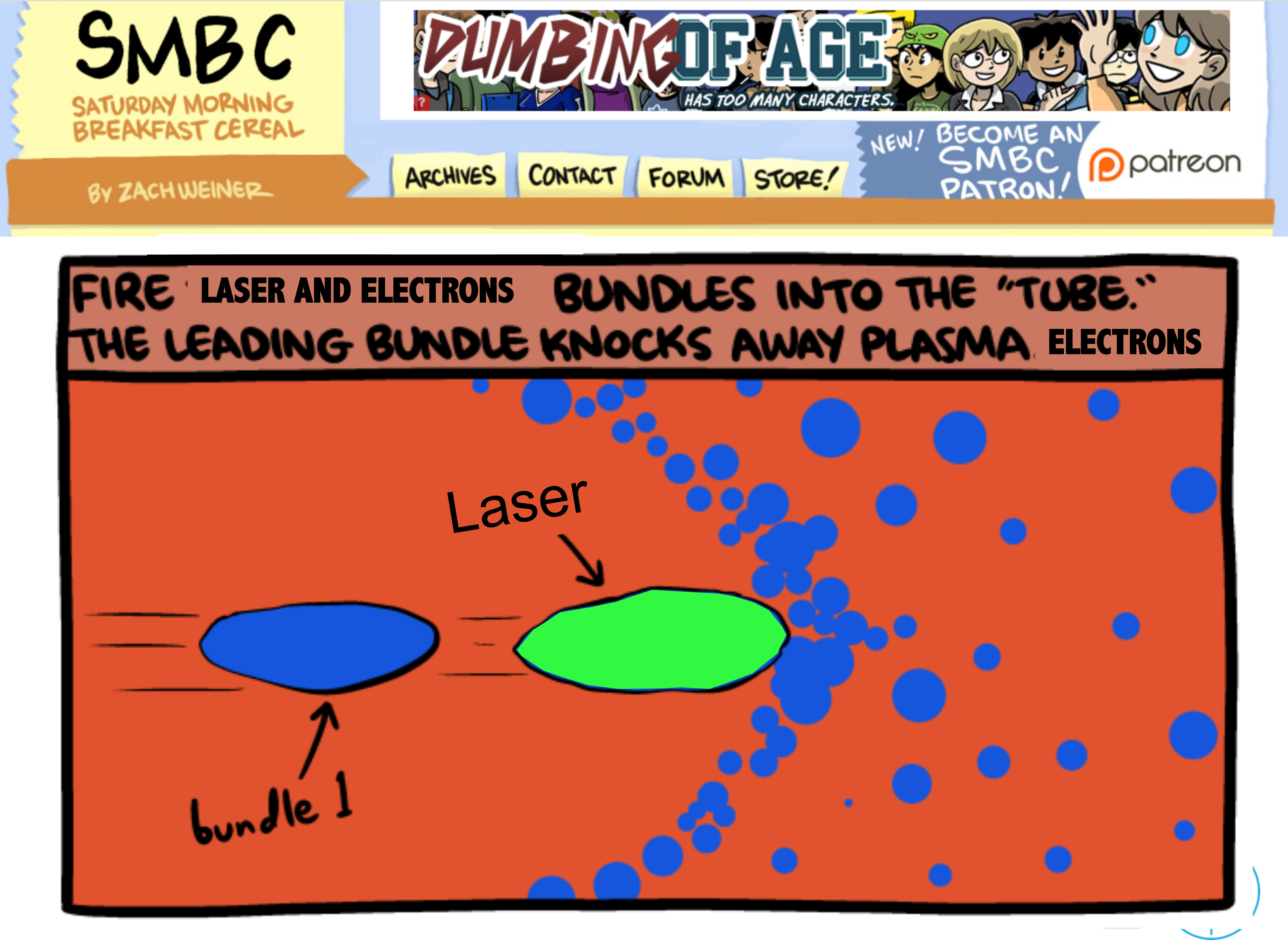

SMBC
SATURDAY MORNING BREAKFAST CEREAL
BY ZACH WEINER
DUMBING OF AGE
HAS TOO MANY CHARACTERS.
ARCHIVES
CONTACT
FORUM
STORE!
NEW! BECOME AN SMBC PATRON!
patreon
CREATE A THIN PLUME OF LITHIUM GAS.
LITHIUM PAAAARTY!


FIRE AN EXTREMELY POWERFUL LASER INTO IT.
I HAVE MORE POWER THAN THE REST OF THE WORLD COMBINED.
YOU'RE THE FIRST GRAD STUDENT WHO EVER SAID THAT.

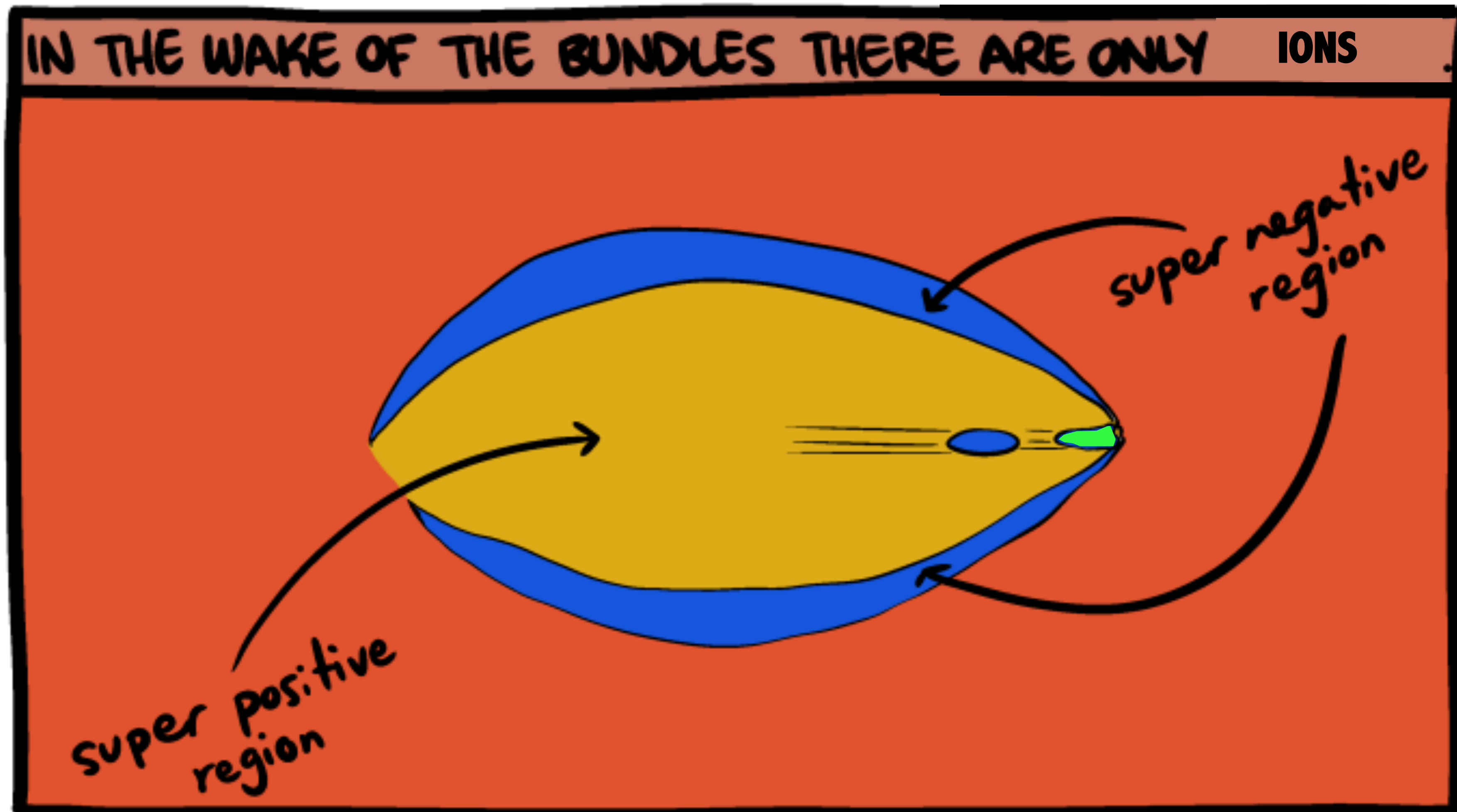

THE RESULT IS A "TUBE" OF PLASMA IN THE GAS.


DUMBING OF AGE
HAS TOO MANY CHARACTERS.

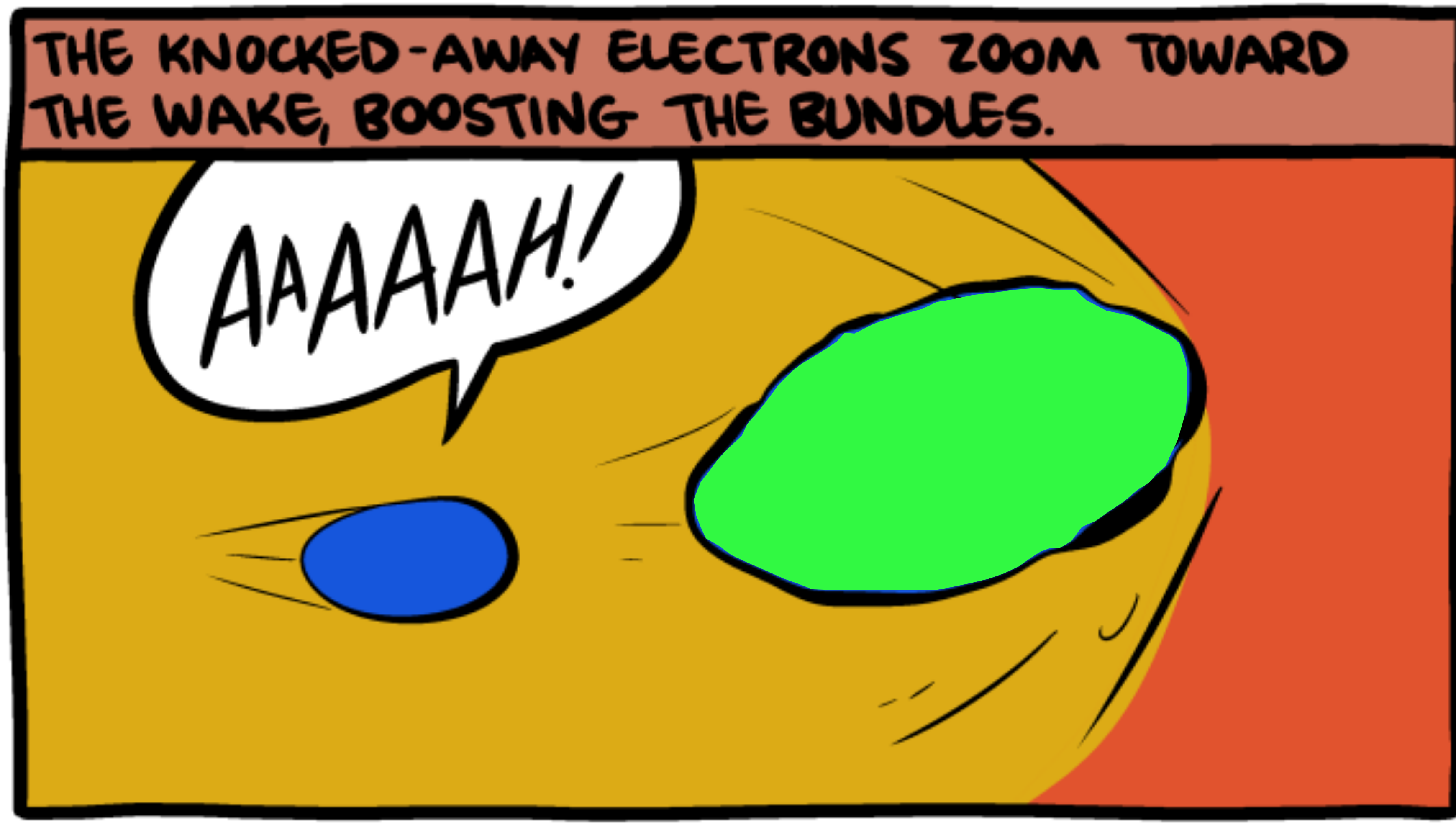

PROTONS ARE MUCH HEAVIER THAN ELECTRONS, SO CONSIDER THEM STATIONARY FOR WHAT FOLLOWS.
HO HO HO! STUPID TINY ELECTRONS.

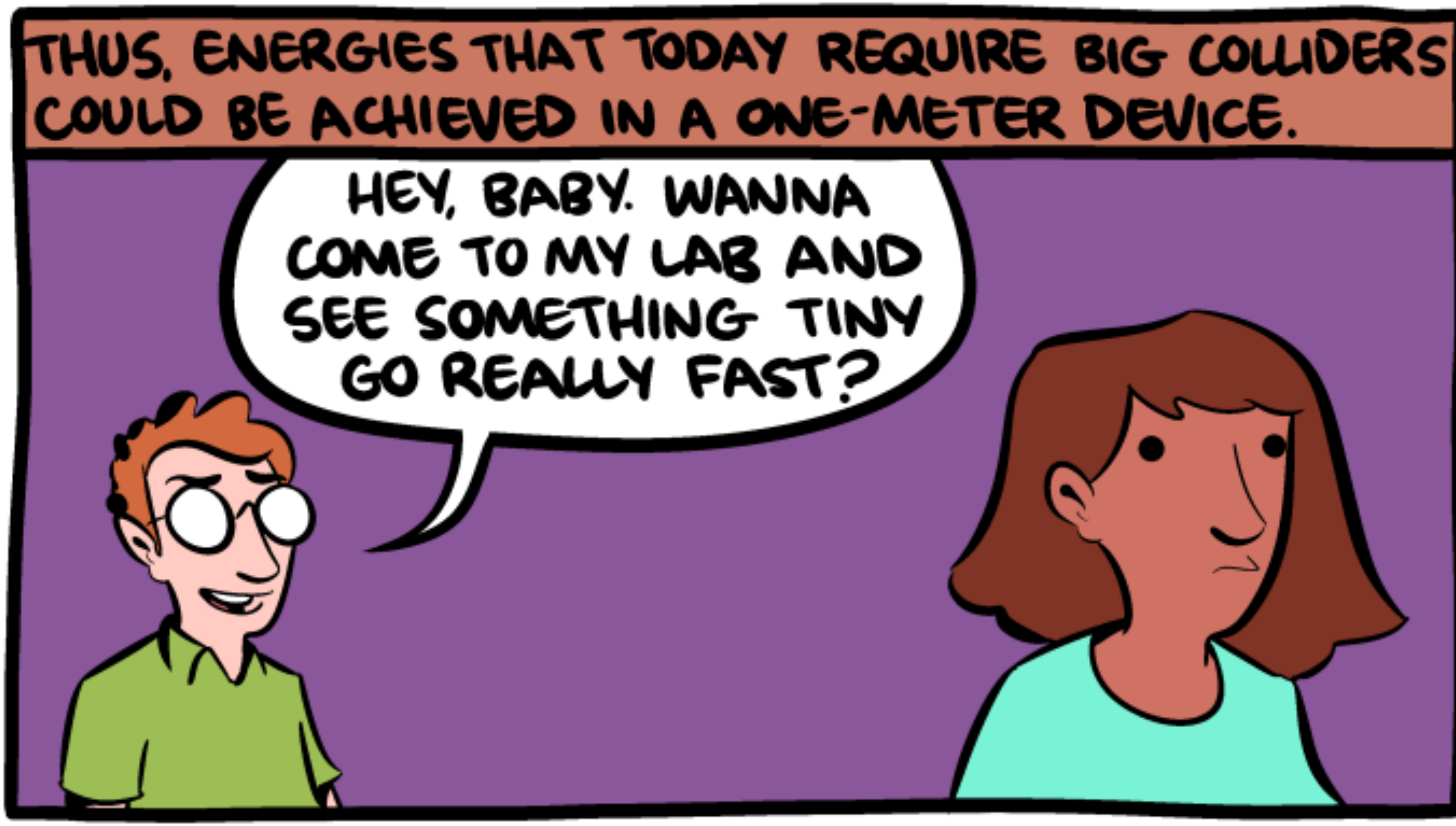

SMBC
SATURDAY MORNING BREAKFAST CEREAL
BY ZACH WEINER
DUMBING OF AGE
HAS TOO MANY CHARACTERS.
ARCHIVES
CONTACT
FORUM
STORE!
NEW! BECOME AN SMBC PATRON!
patreon
FIRE LASER AND ELECTRONS BUNDLES INTO THE "TUBE."
THE LEADING BUNDLE KNOCKS AWAY PLASMA ELECTRONS
Laser
bundle 1


SMBC
SATURDAY MORNING BREAKFAST CEREAL
BY ZACH WEINER
DUMBING OF AGE
HAS TOO MANY CHARACTERS.
ARCHIVES
CONTACT
FORUM
STORE!
NEW! BECOME AN SMBC PATRON!
patreon


IN THE WAKE OF THE BUNDLES THERE ARE ONLY IONS.
super negative region
super positive region


SMBC
SATURDAY MORNING BREAKFAST CEREAL
BY ZACH WEINER
DUMBING OF AGE
HAS TOO MANY CHARACTERS.
ARCHIVES
CONTACT
FORUM
STORE!
NEW! BECOME AN SMBC PATRON!
patreon


THE KNOCKED-AWAY ELECTRONS ZOOM TOWARD THE WAKE, BOOSTING THE BUNDLES.
AAAAAH!


THUS, ENERGIES THAT TODAY REQUIRE BIG COLLIDERS COULD BE ACHIEVED IN A ONE-METER DEVICE.
HEY, BABY. WANNA COME TO MY LAB AND SEE SOMETHING TINY GO REALLY FAST?


SMBC
SATURDAY MORNING BREAKFAST CEREAL
BY ZACH WEINER
DUMBING OF AGE
HAS TOO MANY CHARACTERS.
ARCHIVES
CONTACT
FORUM
STORE!
NEW! BECOME AN SMBC PATRON!
patreon
WE DON'T YET KNOW IF THIS METHOD WILL YIELD LHC-LEVEL ENERGIES.
SO FAST.


SMBC
SATURDAY MORNING BREAKFAST CEREAL
BY ZACH WEINER
DUMBING OF AGE
HAS TOO MANY CHARACTERS.
ARCHIVES
CONTACT
FORUM
STORE!
NEW! BECOME AN SMBC PATRON!
patreon
BUT, I GUESS WHAT I'M SAYING IS, IF IT DOES, CAN WE PLEASE DO THIS?
OH, YOU WORK AT THE LHC? NEATO! I HAVE TWO OF THOSE ON MY LAWN.
smbc-comics.com

Optimization 1: Energy Spread

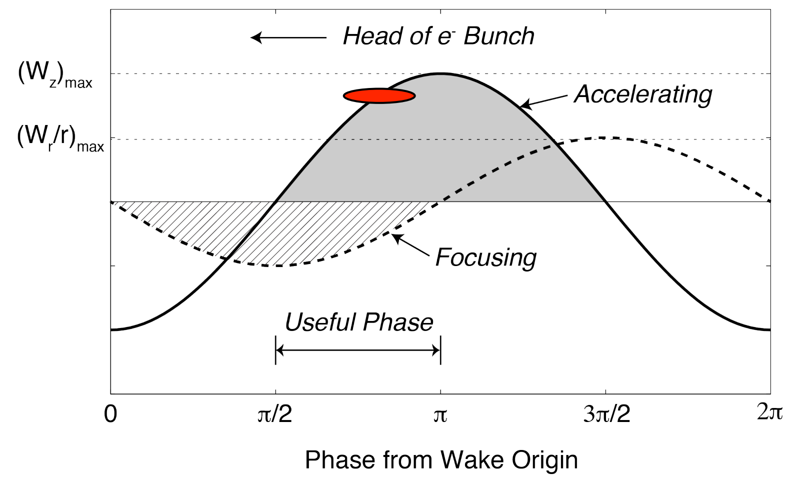
Reduce energy spread (head to tail → correlated with z)

↓

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

Minimize length accelerated bunch and/or Increase plasma wavelength

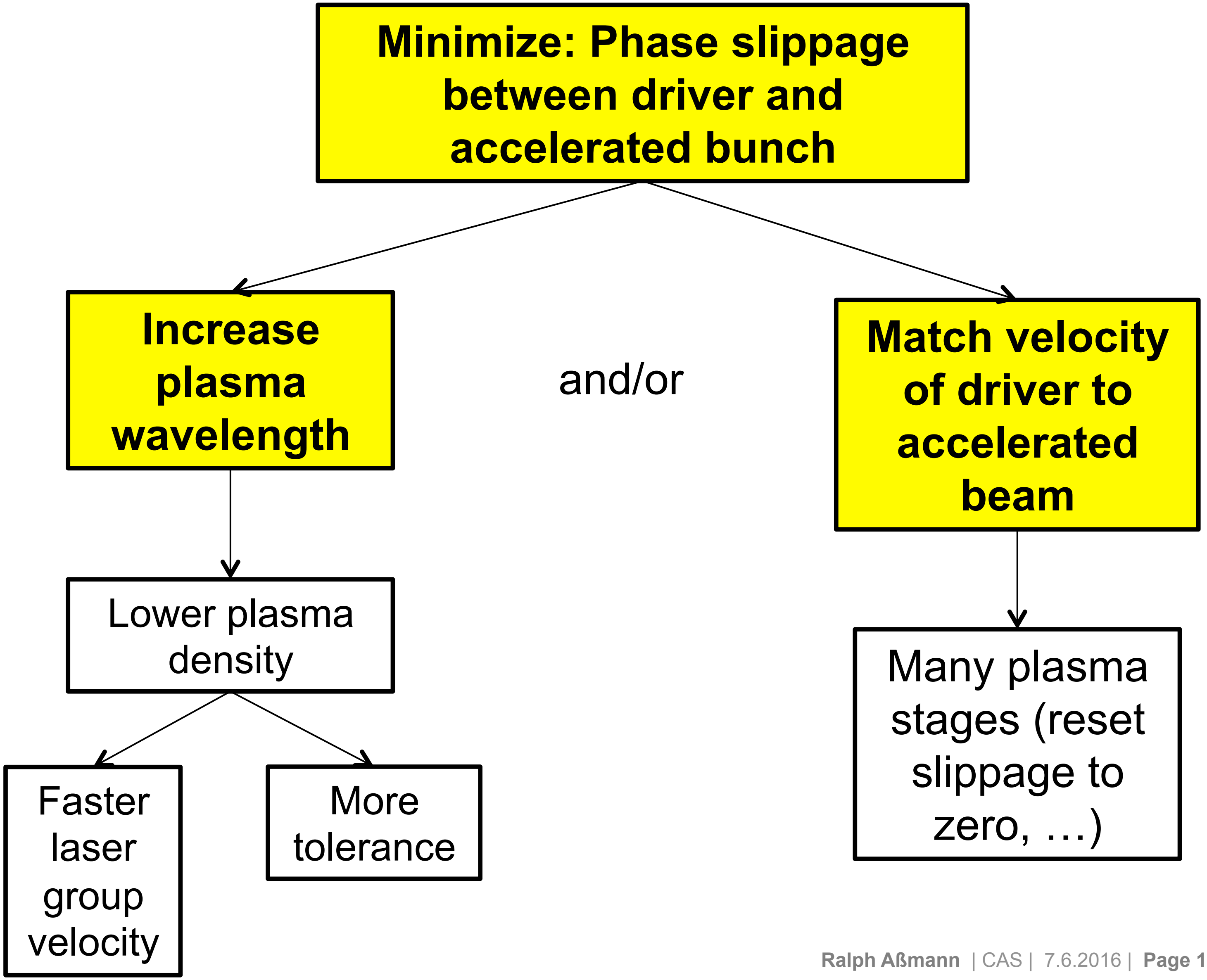
Minimize length accele-rated bunch	Increase plasma wavelength
↓	↓
Ultra-short bunches (fs, as)	Lower plasma density
↓	↓
Ultra-fast science	Lower accelerating gradient



1 fs = 0.3 μm

when travelling with light velocity c

Optimization 2: Phase Slippage



Optimization 3: Stability / Reproducibility

Stabilize: Distance between driver and accelerated bunch.

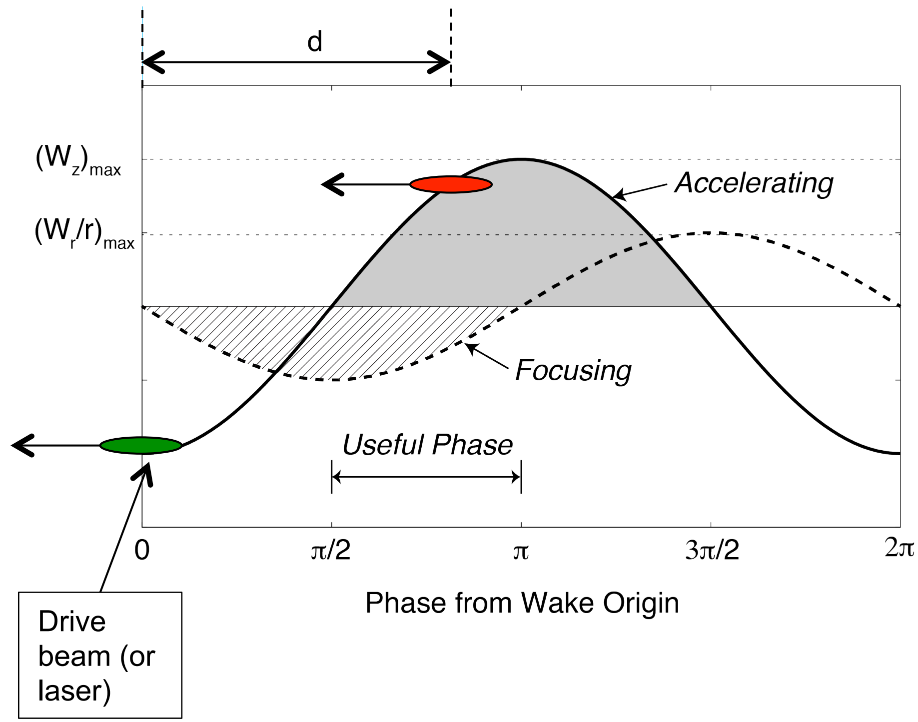
Internally generate accelerated electron bunch

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



Optimization 4: Maximum Energy Gain

Maximize: Transformer ratio

- **Shaping of driver bunch**
  - **Modern photo-cathodes** with bunch shape tuned through photo-cathode laser

or

- **Multiple bunch driver**
  - Tolerances on timing, offsets, …
    - Lower energy driver beams possible
- **Respect energy conservation**
  - Driver beam should have high energy and/or high intensity or many bunches
  - Accelerated beam should have lower intensity