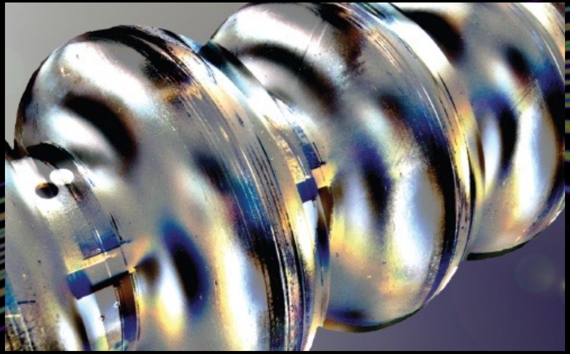
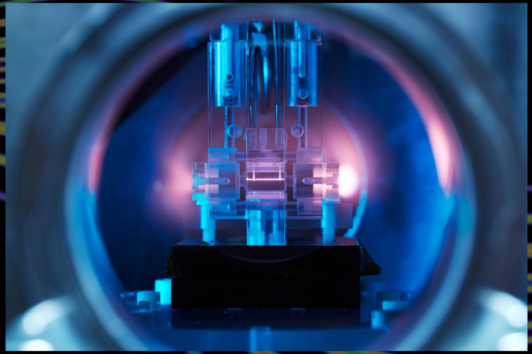
Novel High Gradient Particle Accelerators


Can we build smaller, less expensive accelerators?

JUAS 2023

Archamps, France

2 February 2023

Ralph W. Aßmann, DESY

This work is supported by funding from the European Union´s Horizon Europe research and innovation programme under grant agreement No. 101079773

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

MT
MATTER AND TECHNOLOGIES

DESY

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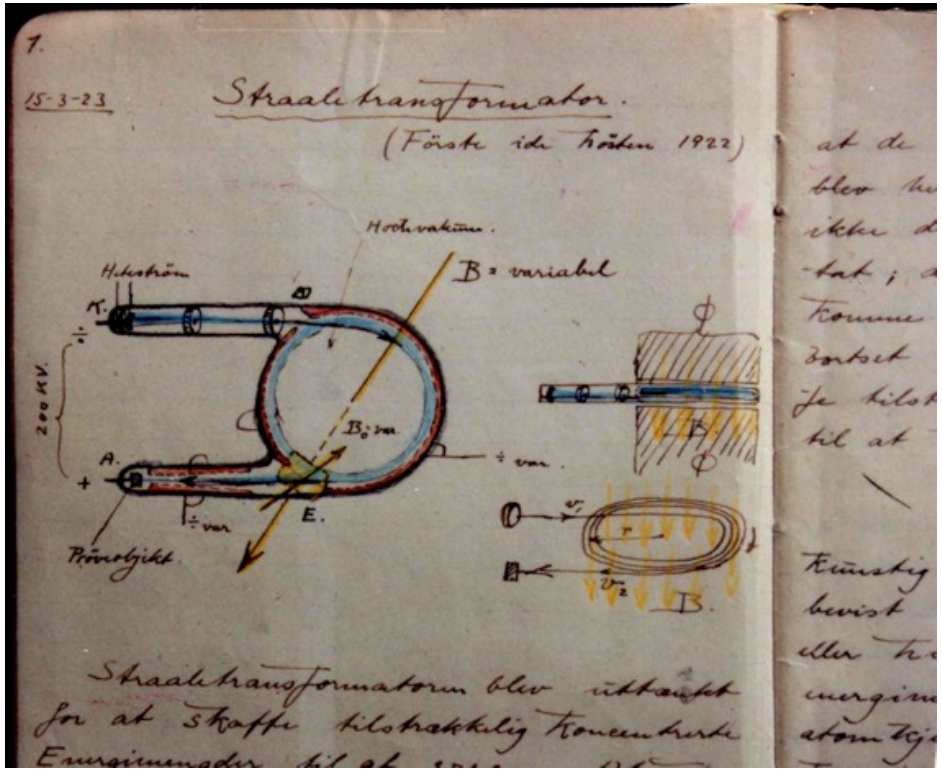
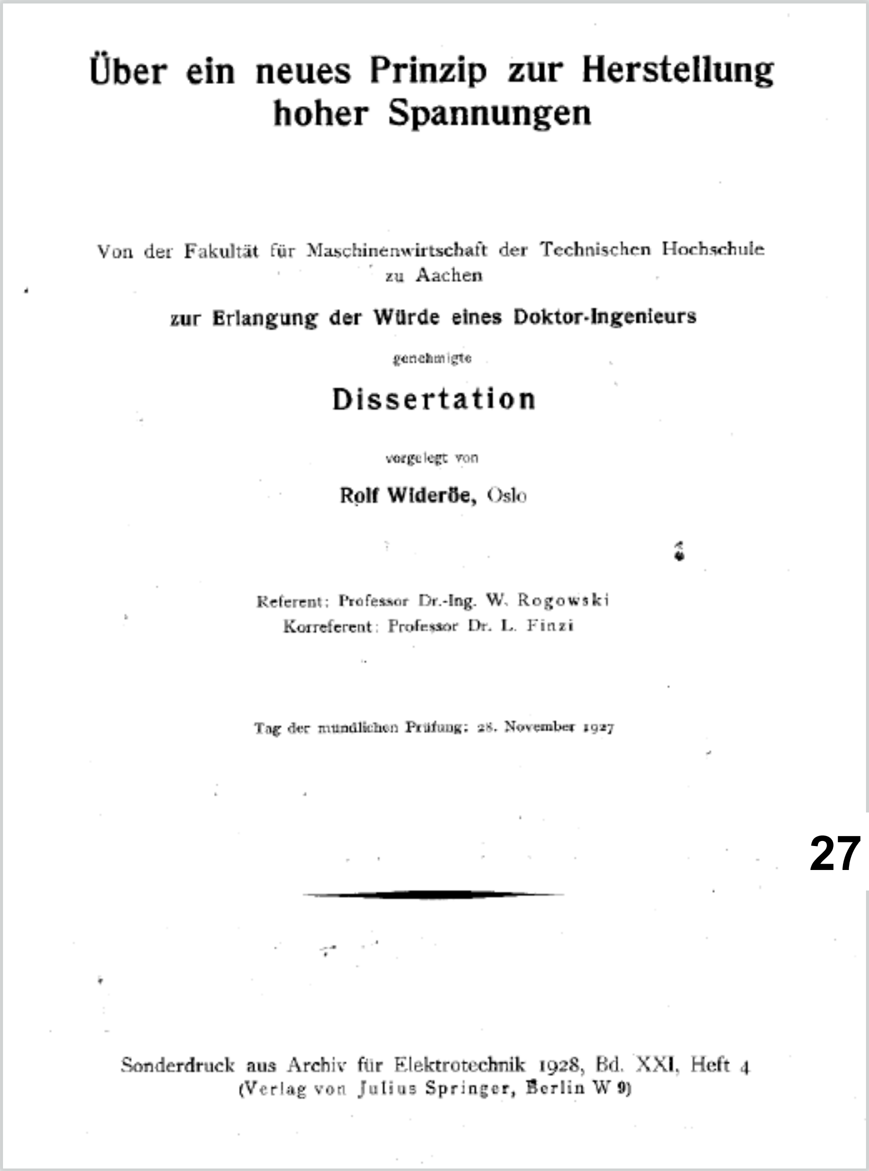




Über ein neues Prinzip zur Herstellung hoher Spannungen

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)

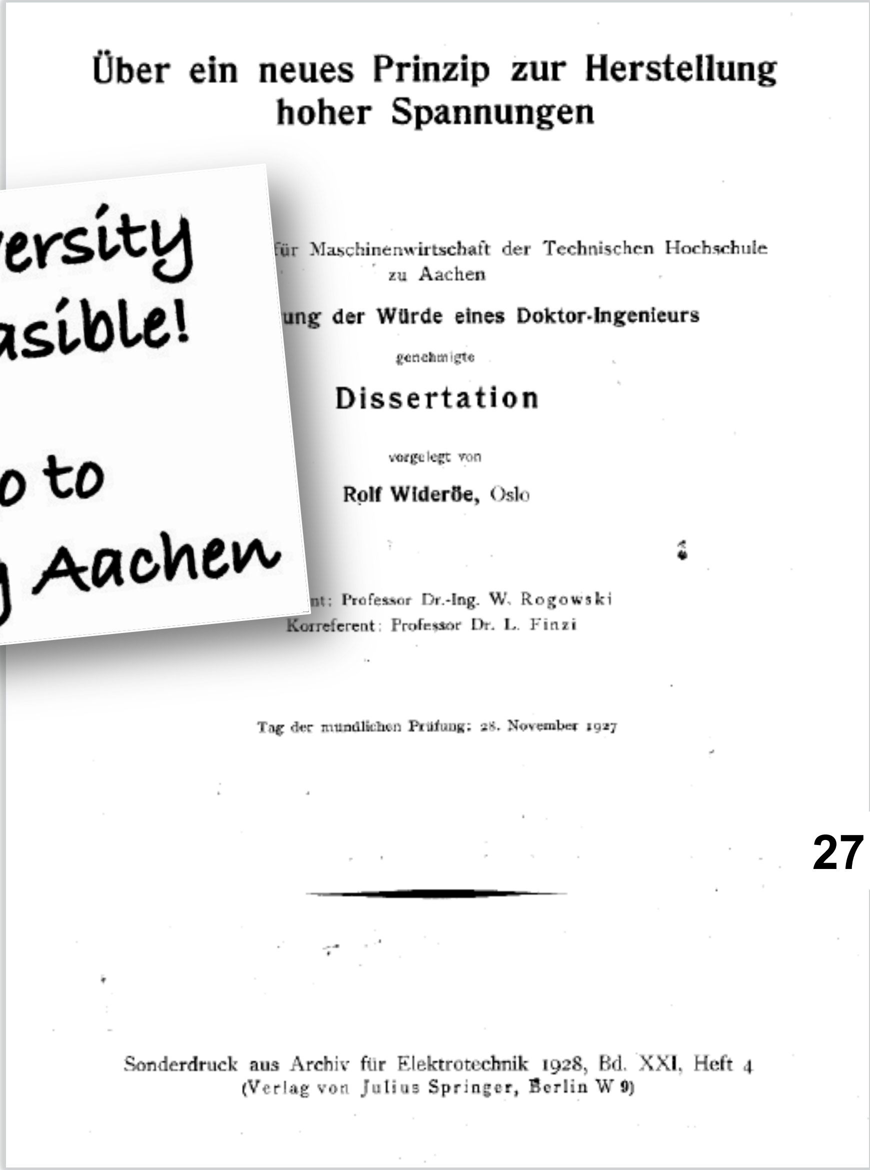
27 pages

First RF Linac Setup: PhD Wideröe 1927 in Aachen

Where RF accelerators started in practice

First refused at university Karlsruhe as not feasible!

Wideröe had to go to Technical University Aachen



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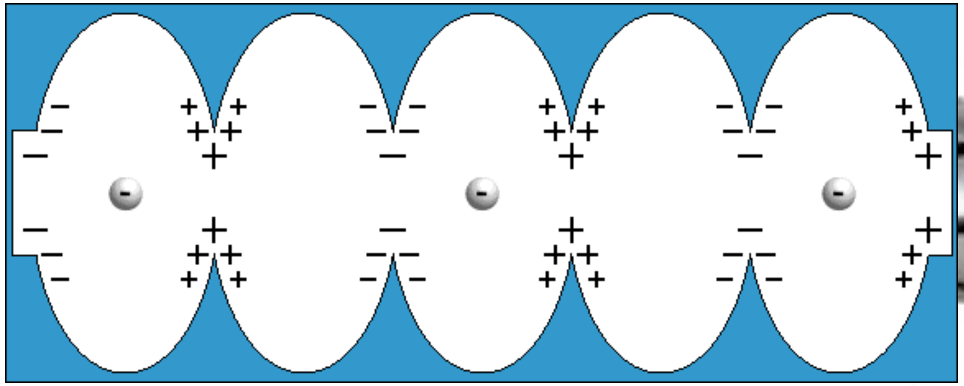
Electron Acceleration: The Success of RF

Alternating field (RF) synchronized to the particles

> 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.

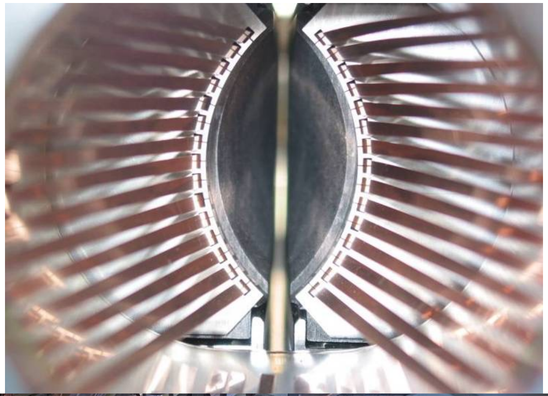
> Lesson: Never give up if up, if colleagues say it does not work – unless they can prove it to you by scientific means.

LHC as a Masterpiece of Accelerator Science

80 Years (and many inventions) later

First beam
10.9. 2008

Higgs Sem. 4.7. 2012



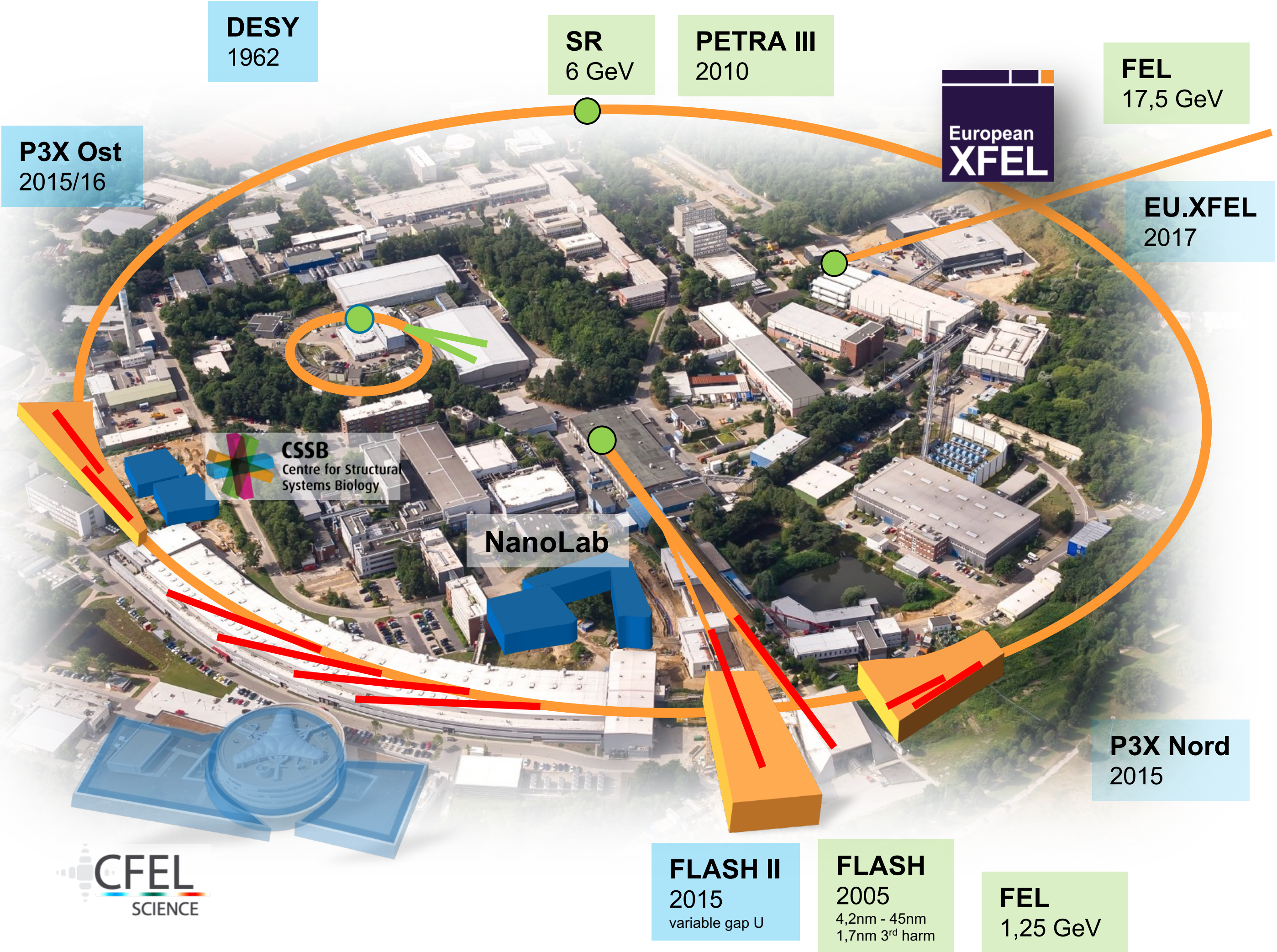
Particle accelerators have transformed DESY

From 50 years ago to today…

- DESY started as a particle physics laboratory
- Several flagship projects in the international race to discover new forces and particles.

Particle accelerators have transformed DESY

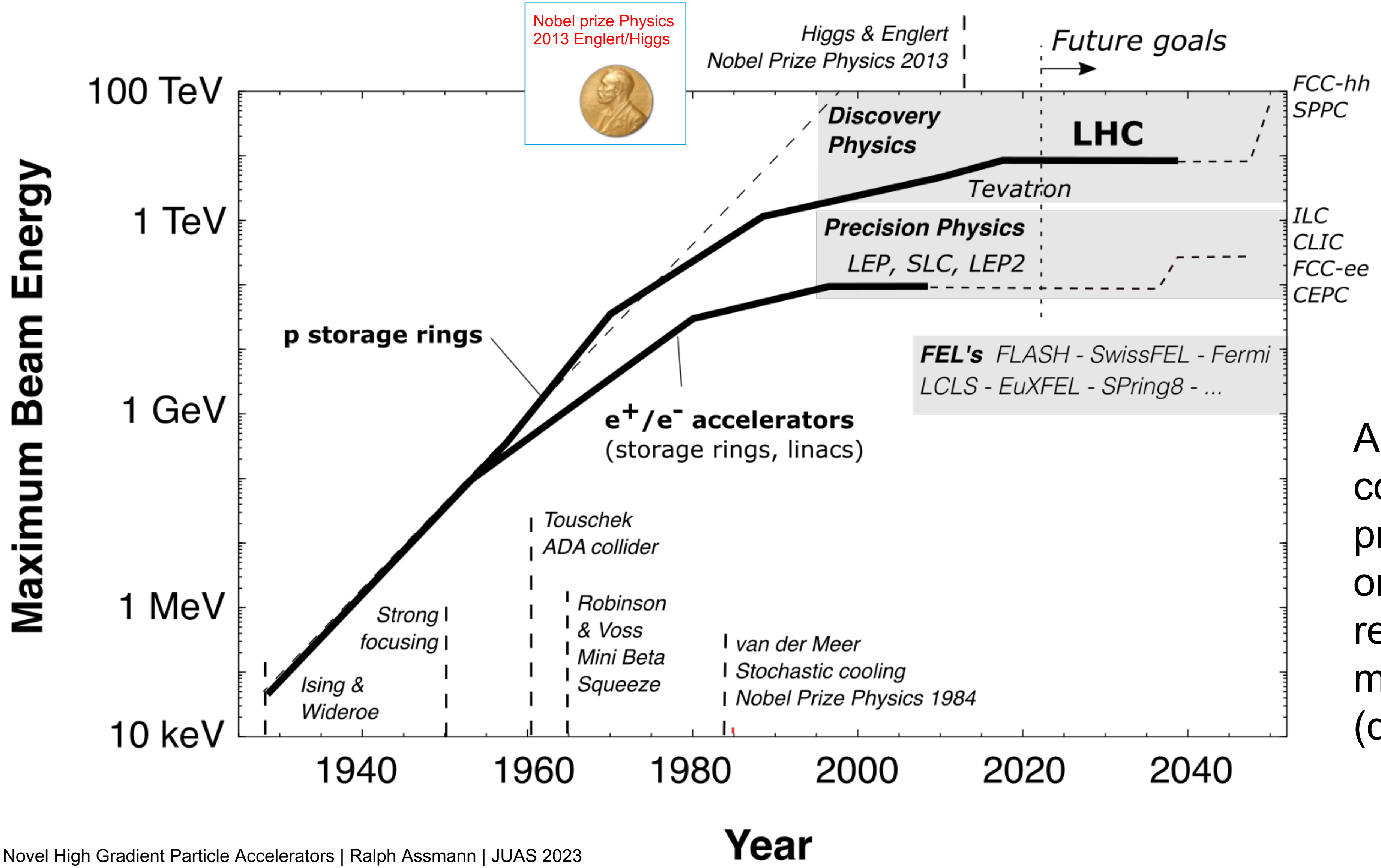
From 50 years ago to today…



BUT:
Progress in Hamburg-based colliders limited by practical considerations on size and cost.

Slow-down in Energy Increase of Frontier Accelerators

Livingston plot leveling off – here our version, giving beam energy versus time



Advance of new colliders limited by practical constraints on required resources (budget, manpower) and size (does it fit on site?)

Why this slow-down? Part 1

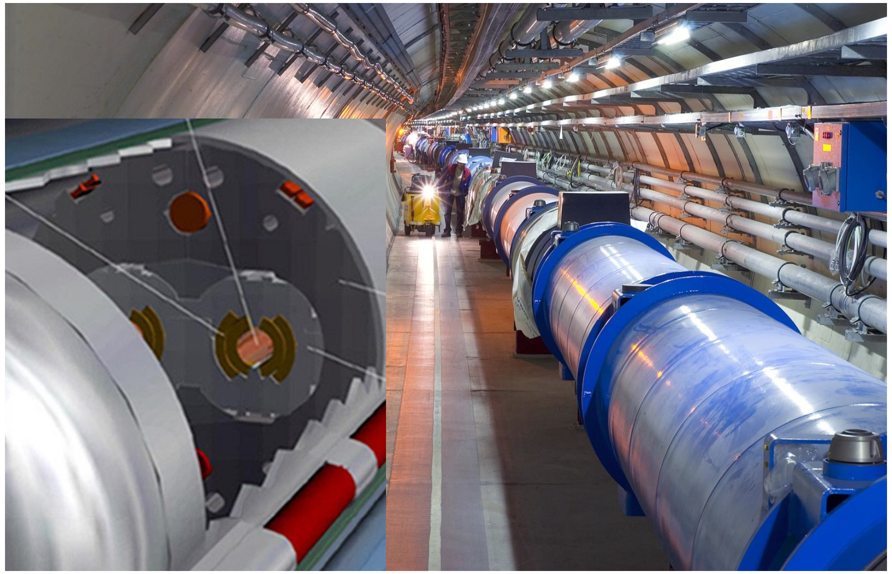
Technical limitations in highly advanced and mature technologies

Hadron (p) circular collider

- Limited by available bending field strength B_y (even super-conducting):

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

- Increase momentum p by increasing radius R times bending field B_y



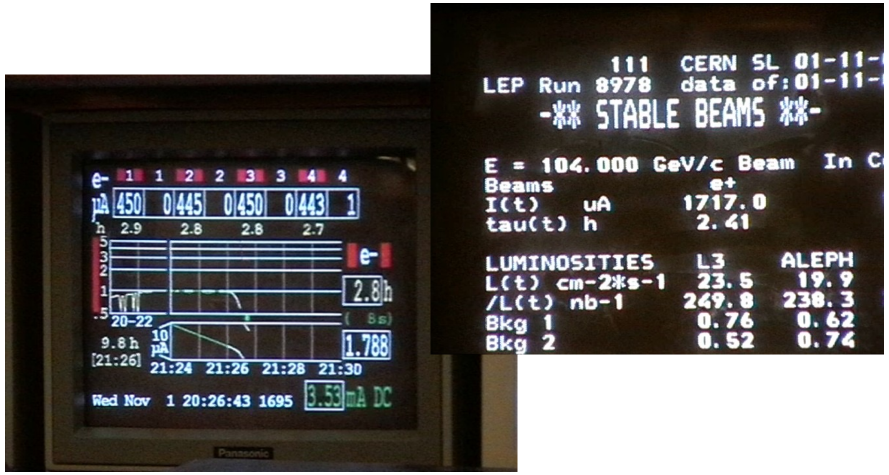
Lepton (e-,e+) circular collider

- Limited by synchrotron radiation losses U_0, to be fed back by RF voltage V_{RF}:

$$U_0 \propto \frac{E_b^4}{E_0^4} \frac{1}{\rho} = V_{RF} \sin \varphi_s$$

E.g. LEP2: 3% of energy lost per turn, 10,000 turns/second

- Increase momentum p by increasing radius R and lowering bending field B_y

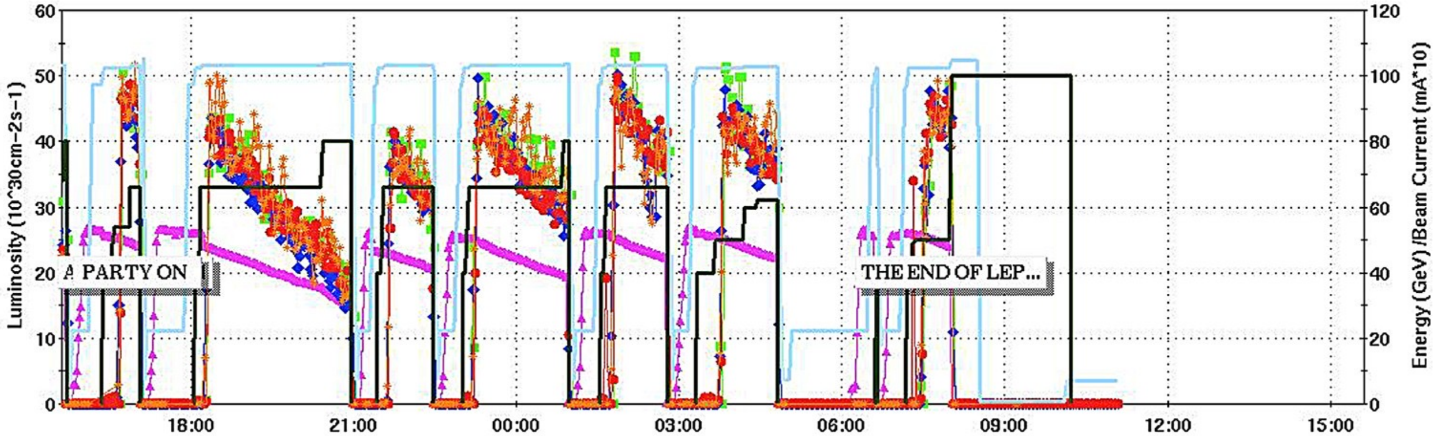


The End of LEP2

November 2nd, 2000, 7am

When we shut down LEP2 in 2000 we thought that it was the **last e+e- circular collider due to synchrotron radiation limit**!

But what about **going linear**? This avoids synchrotron radiation limitation! Why also slowing down?



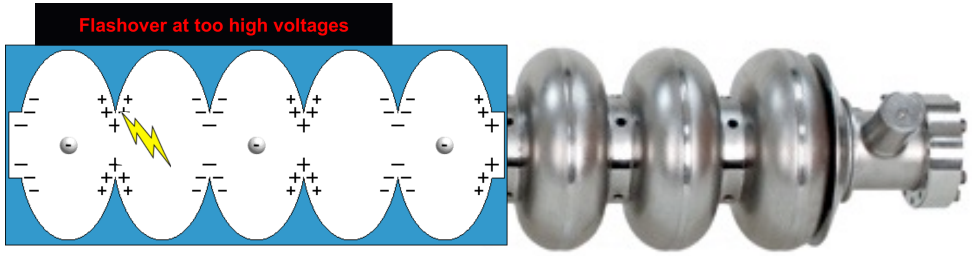
Why this slow-down? Part 2

Technical limitations in highly advanced and mature technologies

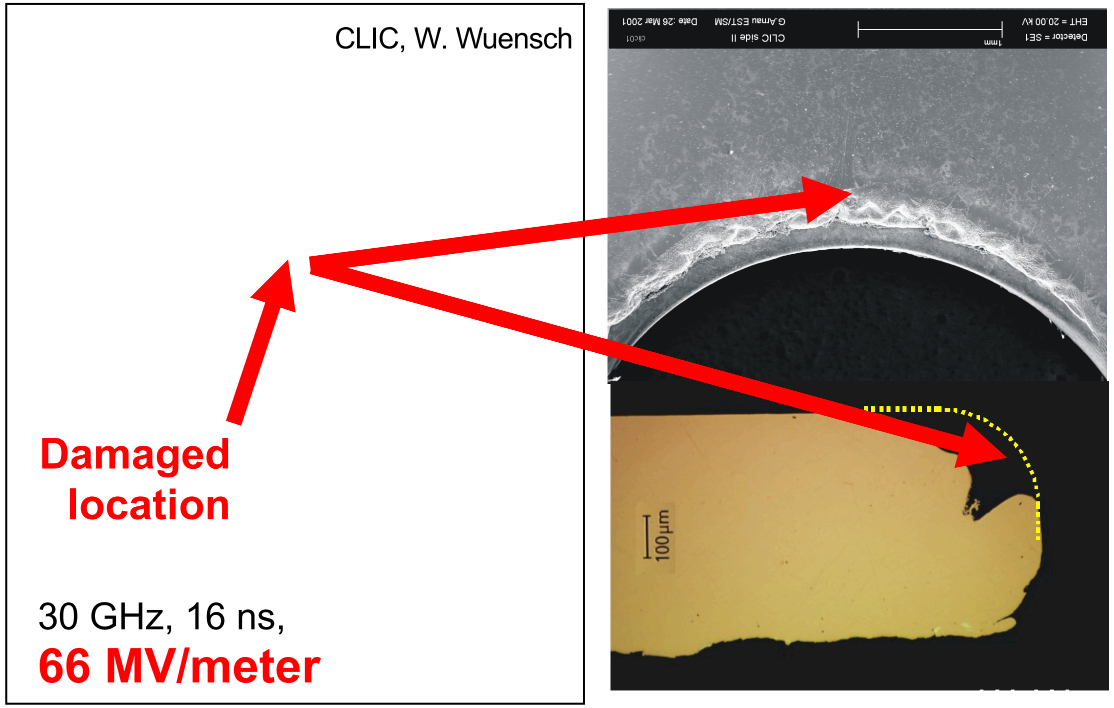
Lepton (e-,e+) linear collider

- Limited by achievable accelerating gradient (energy gain per length)
- Increase momentum p by increasing gradient G_{acc} or length L

$$p = L \cdot G_{acc}$$



- Achievable accelerating gradient limited by peak surface field, flashovers, surface damage and breakdown rate
- Example shows a result from CLIC at a high RF frequency of 30 GHz
- By now, some important progress made but gradients limited to 100 MV/m at max presently



How to advance?

Looking for solutions

Hadron (p) circular collider

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

Increase bending field
SC bend magnet work (FCC-hh)

Increase radius = size (FCC-hh)

Lepton (e-,e+) circular collider

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

Increase supplied RF voltage (FCC-ee)

Increase mass of acc. particle (muon)

Increase radius = size (FCC-ee)

Lepton (e-,e+) linear collider

$$p = L \cdot G_{acc}$$

Increase accelerating gradient
(a) Pushing existing technology (ILC, CLIC)
(b) New regime of ultra-high gradients (plasma, dielectric accelerators)

Increase length (ILC, CLIC)

How to advance?

Looking for solutions

If you look at it this way, you realize the **complementarity of various accelerator R&D efforts**, covering the whole space of possible solutions! We need to **look at all the options** to ensure the future!

Hadron (p) circular collider

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

Increase bending field
SC bend magnet work (FCC-hh)

Increase radius = size (FCC-hh)

Lepton (e-,e+) circular collider

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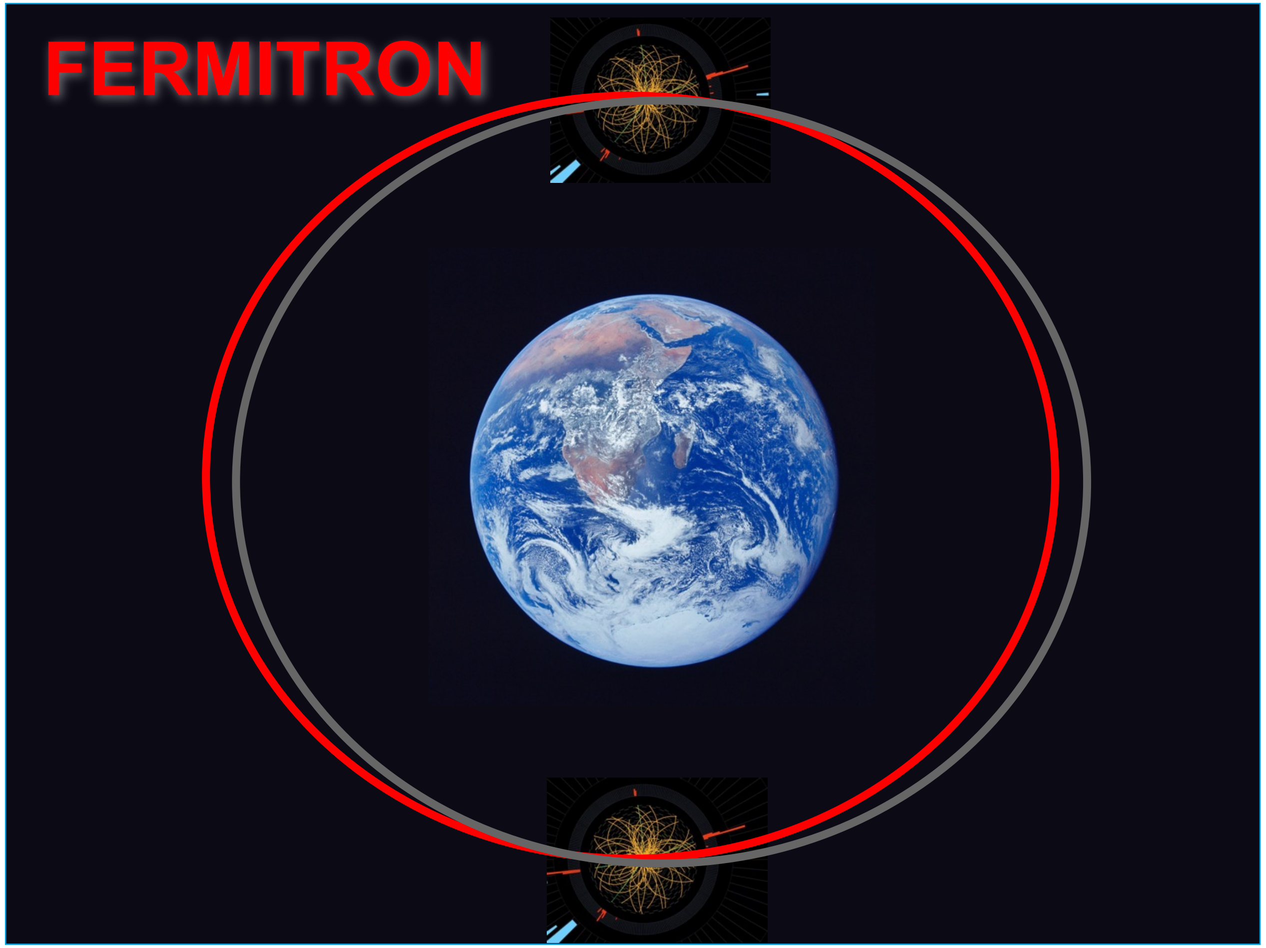
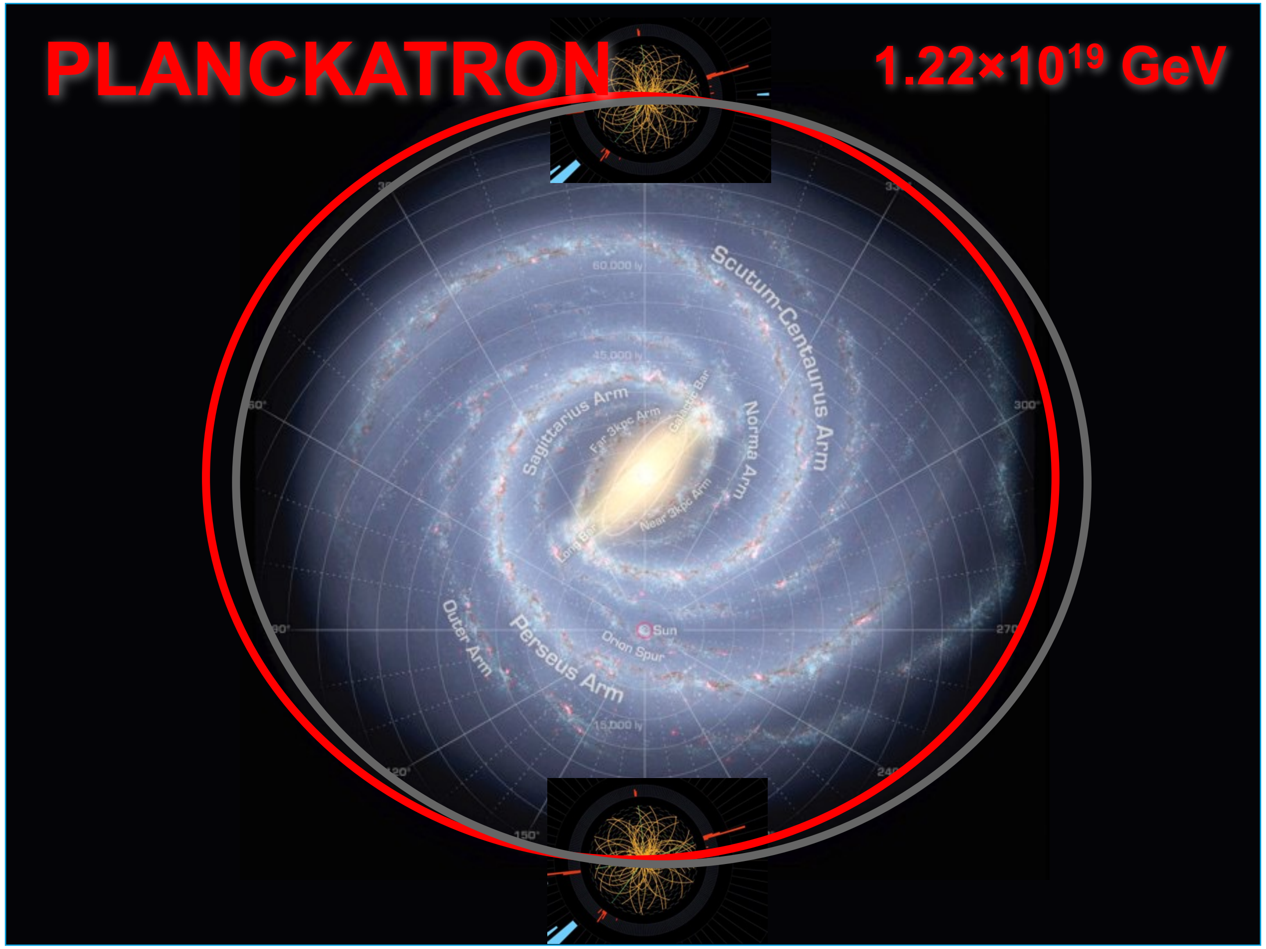
Increase accelerating gradient
(a) Pushing existing technology (ILC, CLIC)
(b) New regime of ultra-high gradients (plasma, dielectric accelerators)

Increase length (ILC, CLIC)

We can dream big ...

The ultimate colliders





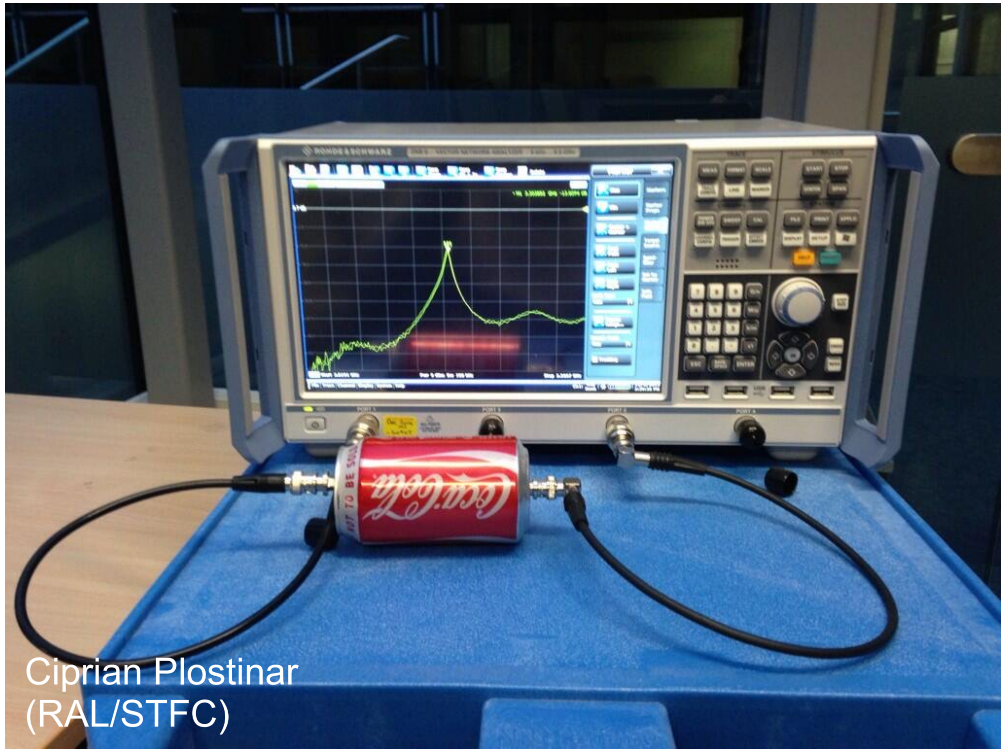
But: It is the cost not the size...

Gustav-Adolf Voss,
builder of PETRA, DESY
accelerator director
† 5. October 2013

“Of course, it should not be the size of an accelerator, but its costs which must be minimized.”

... we can dream affordable ...

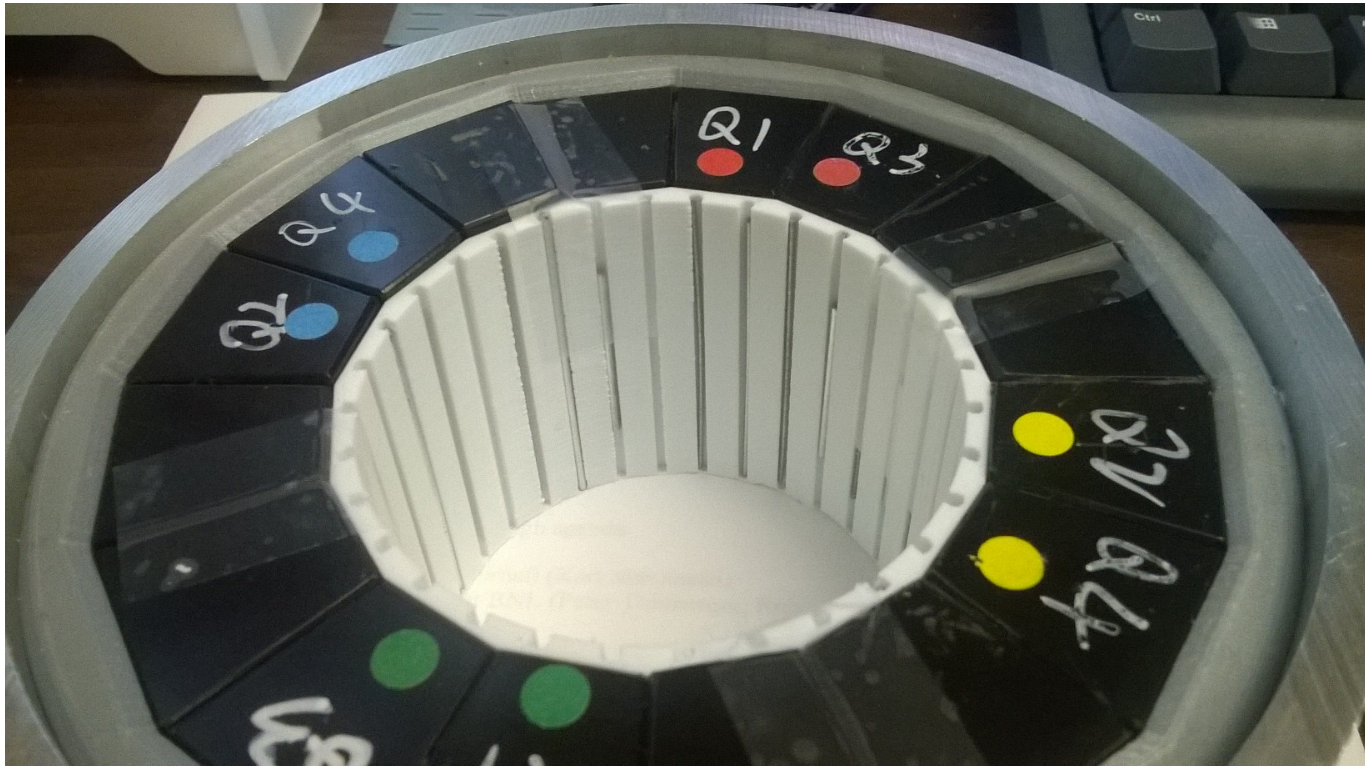
Can we bring down cost per meter of accelerator by a factor 2 – 10?



f = 3.3 GHz, Q = 50

Material and pictures courtesy S. Brooks, BNL

Halbach quadrupole using NdFeB, 3D printed, 23.6 T/m, R=34.7mm bore (0.82T max), 10^{-4} errors at R=10mm



Material cost: **$1100**. No alignment better than 0.25 mm required anywhere. Assembled with mallet.

... and even more affordable ...

Can we bring down cost per meter of accelerator by a factor 2 – 10?

GERALD DAVID OBE FREng
AERIAL FACILITIES LTD

DESIGN AND TECHNOLOGY

The beer barrel as a VHF cavity *resonator*

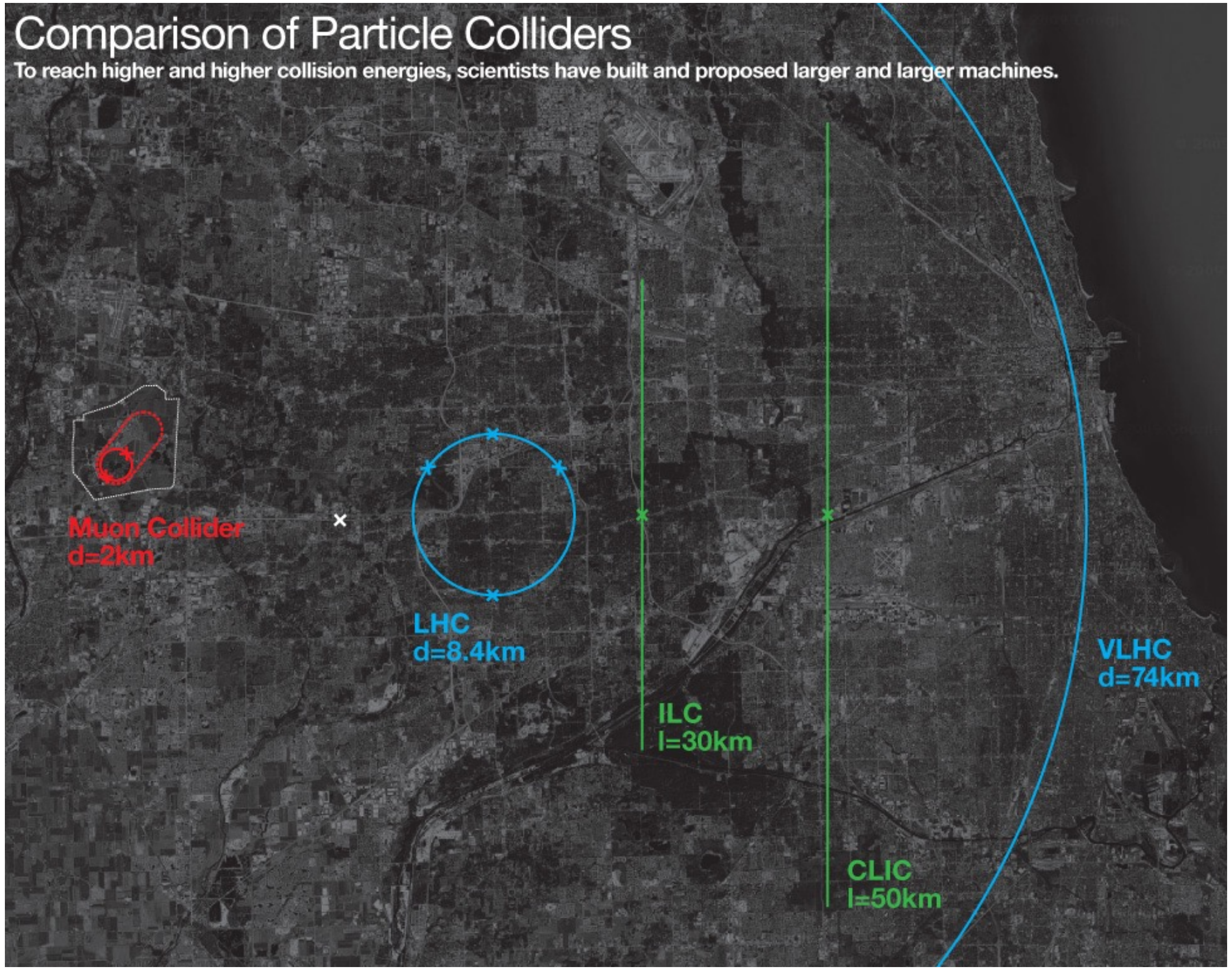
In the 1970s, use of mobile radio frequencies was expanding dramatically and existing antennas were becoming heavily overloaded. The engineering solution devised by Gerald David was to introduce multiple transmitter combiners onto a single antenna using band-pass filters. The use of a beer barrel in this context shows how existing structures can be adapted to new uses at a fraction of the cost of purposely designed components.

f = 150-165 MHz, Q = 9700

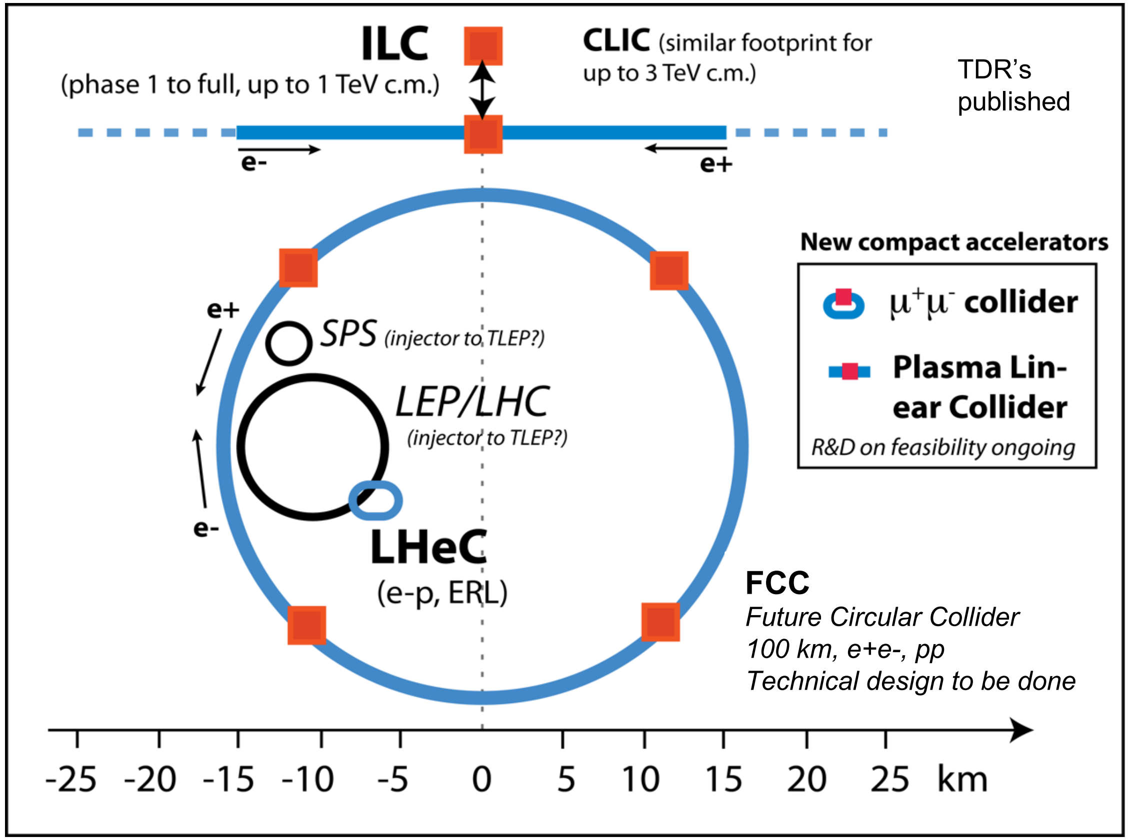
Material and pictures courtesy S. Brooks, BNL

…and we can dream small (and affordable)!

New generation(s) of particle physics colliders?



Courtesy Fermilab Website



The R&D on Compact Accelerators

Looking for solutions

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

Hadron (p) circular collider

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

Increase b
SC bend m

Increase radius = size (FCC-hh)

Factor 206.8 higher mass muon versus electron

Lept

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

Increase supplied RF voltage (FCC-ee)

Increase mass of acc. particle (muon)

Increase radius =

Factor 100 – 1000 higher accelerating gradient

Lepton (e-,e+) linear collider

$$p = L \cdot G_{acc}$$

Increase accelerating gradient
(a) Pushing existing technology (ILC, CLIC)
(b) New regime of ultra-high gradients (plasma, dielectric accelerators)

Increase length (ILC, CLIC)

Acceleration: Conventional and Advanced

How to get higher accelerating voltage?

Surfer gain velocity and energy by riding the water wave!

Charged particles gain energy by riding the electromagnetic wave!

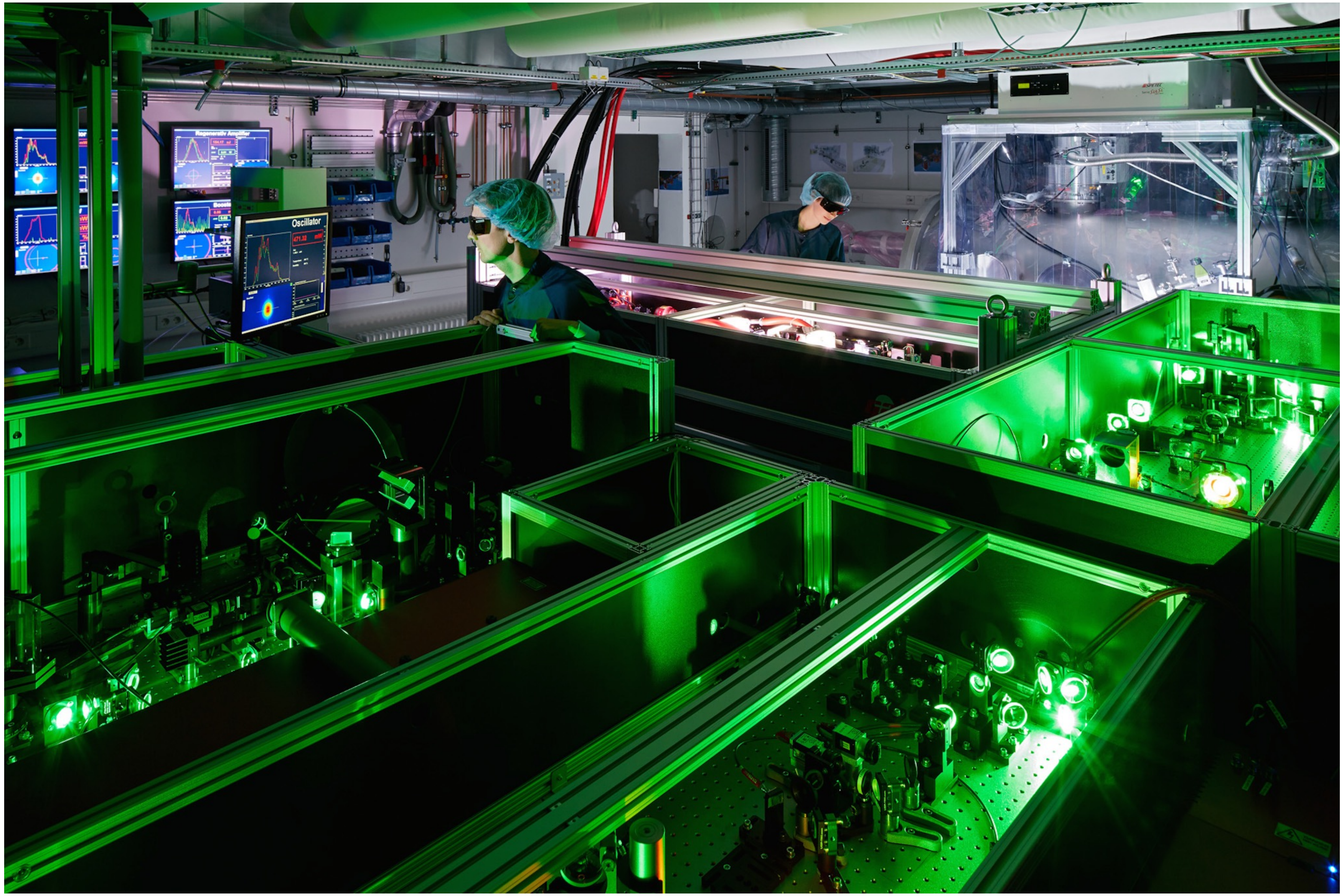
Modern lasers generate light pulses with very large transverse fields:

Many 1.000 billion volt per meter

Plasma or metallic structures couple fields to our particles!

ANGUS Laser Laboratory for Accelerator R&D

200 TW Ti-Sa laser, DESY & University Hamburg



The Laser Promise: Transverse Electrical Field

We can produce every day very high transverse electrical fields

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

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

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

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

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

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

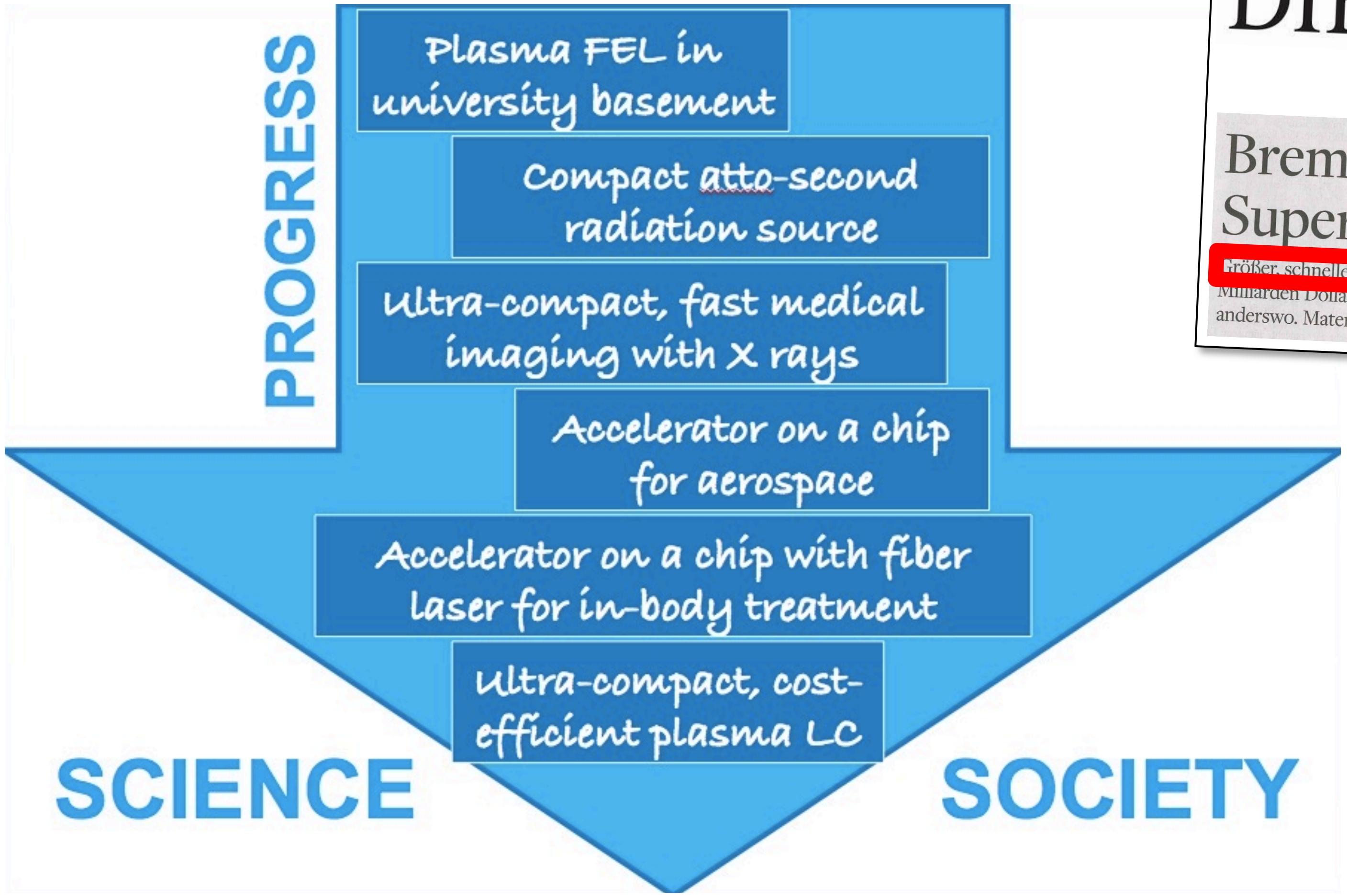
$$E_0 = 22\,\text{TV/m}$$

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…

New technology opens new possibilities



DIE WELT

SAMSTAG, 28. MÄRZ 2015

Bremse für Superbeschleuniger

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

Hamburger Abendblatt

WISSEN

Der Mini-Teilchenbeschleuniger

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

DER SPIEGEL

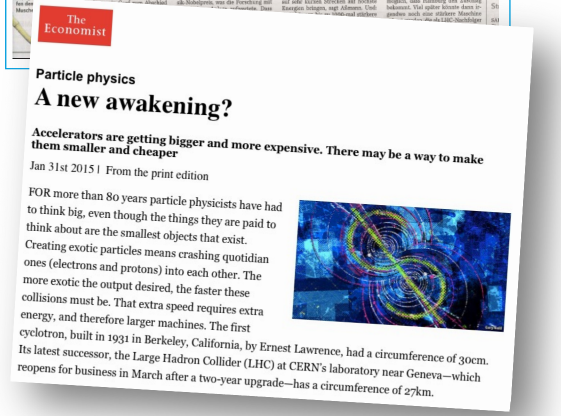
DER SPIEGEL 11/2015

Im Bann von Waxahachie

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

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

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



The Economist

Particle physics

A new awakening?

Accelerators are getting bigger and more expensive. There may be a way to make them smaller and cheaper

Jan 31st 2015 | From the print edition

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

High Gradient – High Frequency – Small Dimensions

Understanding frequency bands and its basic properties

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

Sketch Padamse, Tigner

"Runzelröhre"

20.000.000 Volt per Meter

High Gradient – High Frequency – Small Dimensions

Understanding frequency bands and its basic properties

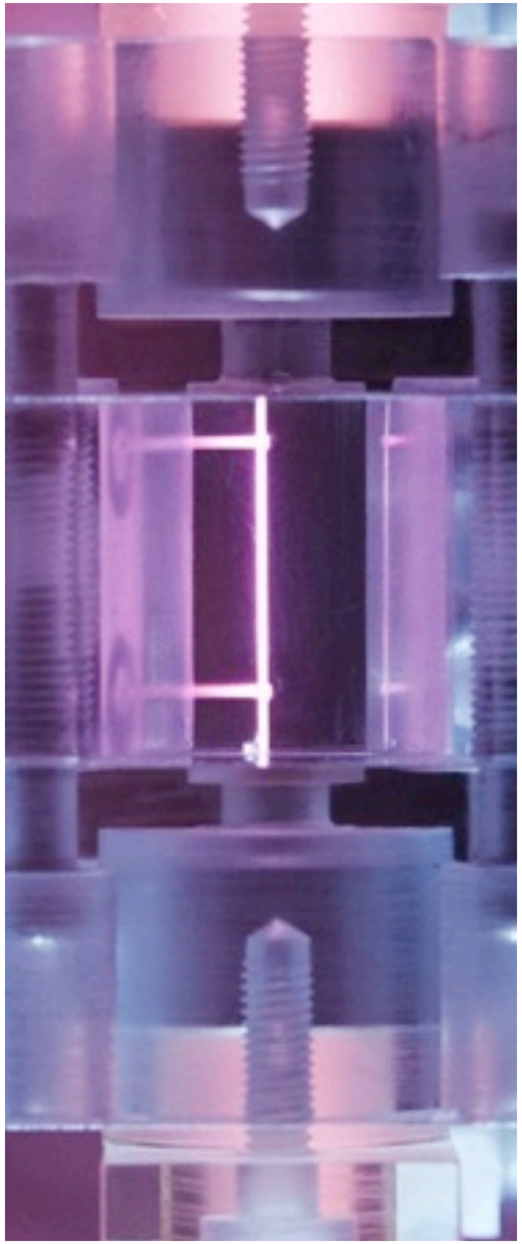
Band Designator	Frequency [GHz]	Gradient [MV/m]	Cell length [cm]	Comments
S band ↓	2 to 4	21	7.5 – 3.8	Technology of the SLAC linac that was completed in 1966. This is still the technology behind many accelerators.
C band	4 to 8	35	3.8 – 1.9	Newer technology developed in Japan and used for the construction of the SACLA linac in Japan.

High Gradient – High Frequency – Small Dimensions

Understanding frequency bands and its basic properties

Band Designator	Frequency [GHz]	Gradient [MV/m]	Cell length [cm]	Comments
C band	4 to 8	35	3.8 – 1.9	Newer technology developed in Japan and used for the construction of the SACLA linac in Japan.
X band	8 to 12	70 – 100	1.9 – 1.3	Technology developed from the 1990's onwards for linear collider designs, like NLC and CLIC. The cell length is up to a factor 10 shorter than in L band.

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

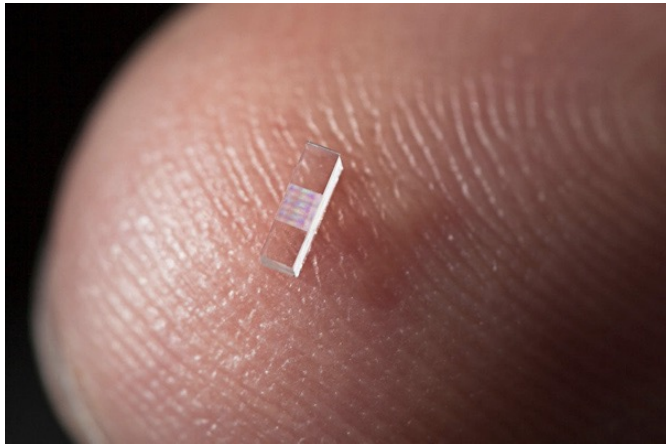


High Gradient – High Frequency – Small Dimensions

Powering novel accelerators

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

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



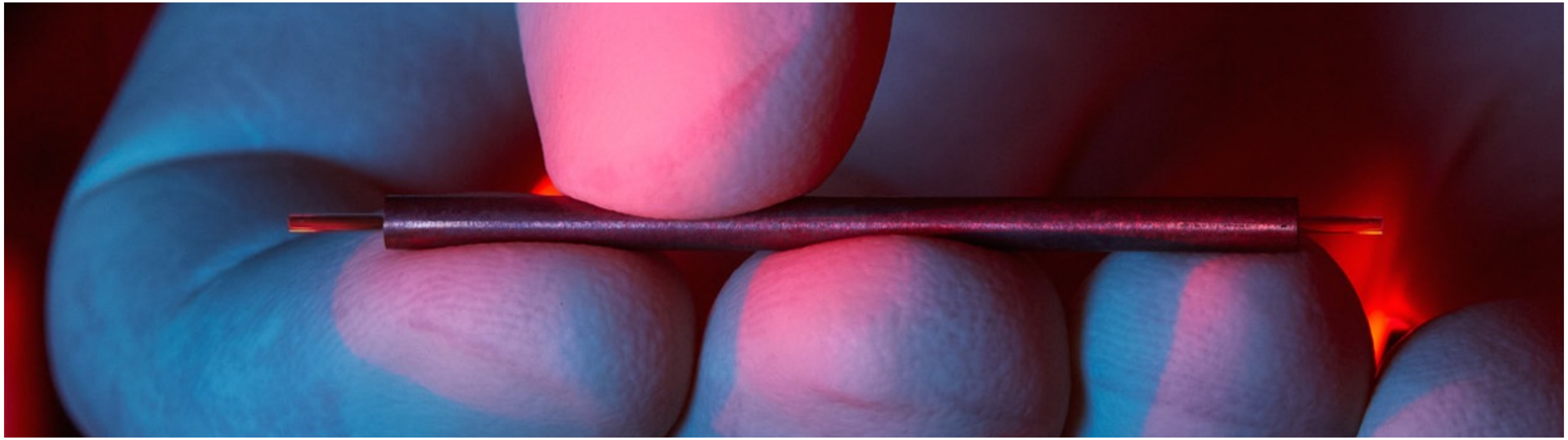
1 Microstructure Accelerator
Laser- or beam driven
Vacuum accelerators
Conventional field design

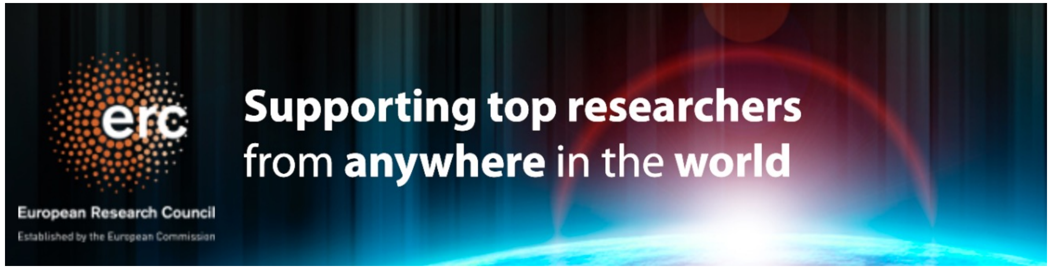
2 Plasma Accelerator
Laser- or beam driven
Dynamic Plasma Structure
Plasma field calculations

Laser-Driven Micro Structures (Vacuum) – 1

Vacuum dielectric accelerator

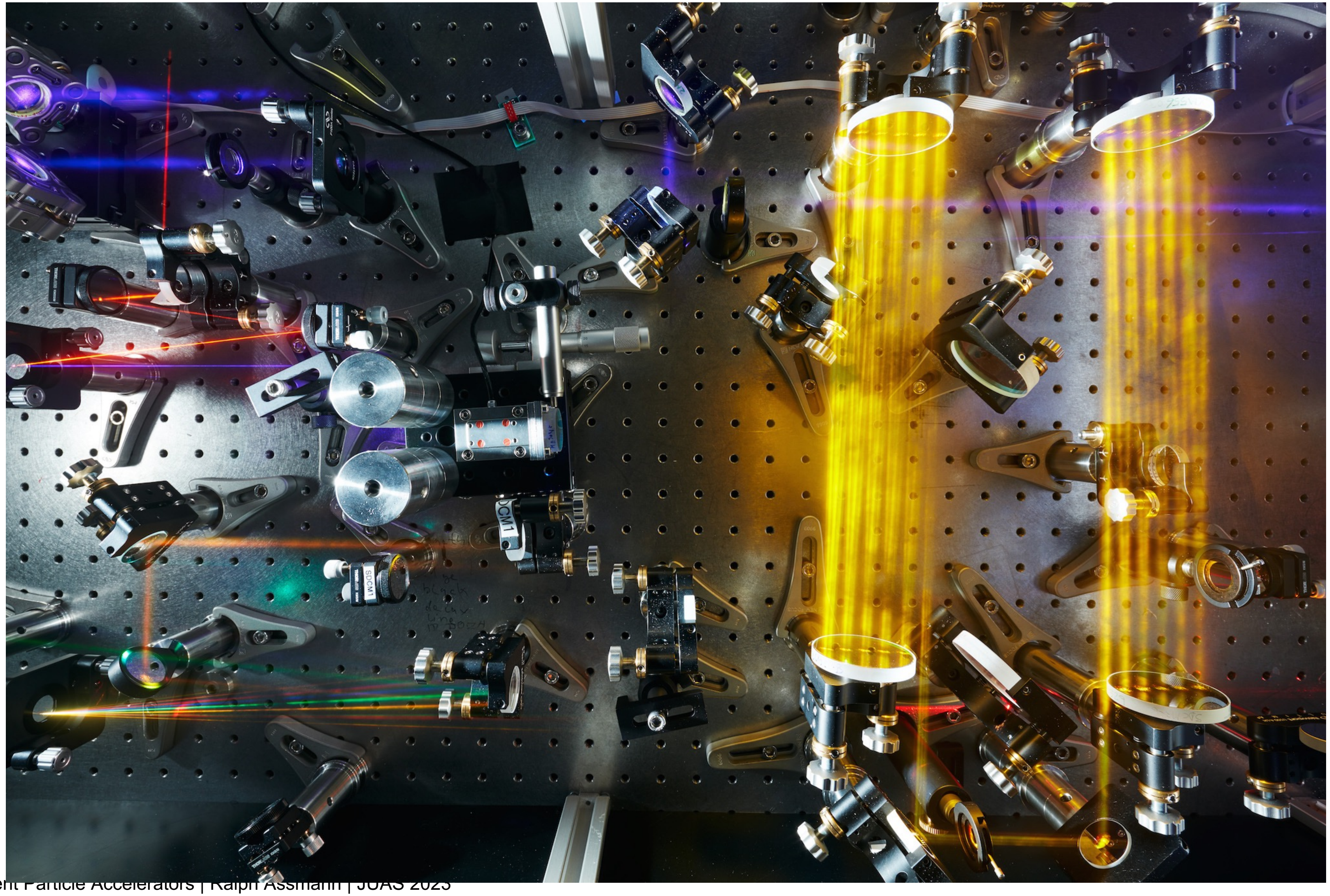
- 1 GeV/m possible but low absolute energies achieved so far
- **AXSIS project (ERC synergy grant)** at DESY/ Uni Hamburg: THz laser-driven accelerator with atto-second science → *Kärtner/Fromme/Chapman/Assmann*





THz Laser Lab (DESY, CFEL, University Hamburg)

Vacuum dielectric accelerator

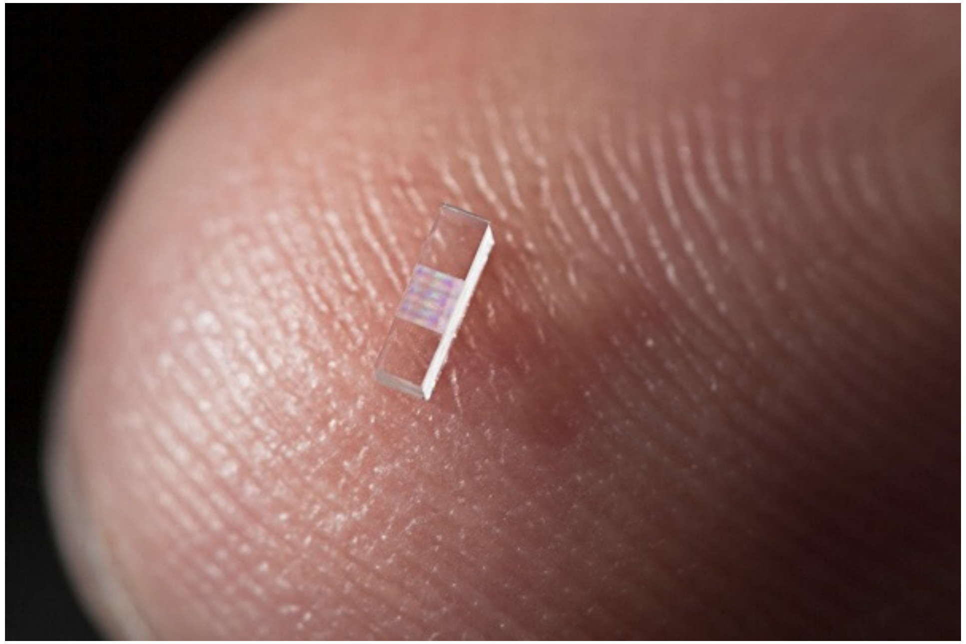


Laser-Driven Micro Structures (Vacuum) – 2

Vacuum dielectric accelerator

ACHIP
Accelerator on a Chip International Program

- **"Accelerator on a Chip"** grant from Moore foundation for work by/at Stanford, SLAC, University Erlangen, DESY, University Hamburg, PSI, EPFL, University Darmstadt, CST, UCLA
- Lasers drive **structures that are engraved on microchips** (e.g. Silicium)
- Major breakthroughs can be envisaged:
    - **Mass production**
    - **Implantable accelerators** for in-body irradiation of tumors
    - Accelerators for **outer space**



Financed by Silicon Valley billionaire...

Science for society

GORDON AND BETTY MOORE FOUNDATION

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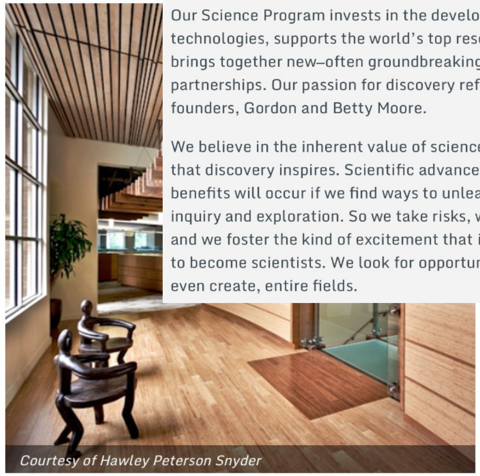
ABOUT

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



Courtesy of Hawley Peterson Snyder

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.

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

The Laser Promise: Transverse Electrical Field

We can produce every day very high transverse electrical fields

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

ϵ_0 = Dielectric constant

c = Light velocity

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

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

This is what we need!

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

Lorentz Force F

The direction of the field matters

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

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

Every accelerator is a transformator

Idea in 1979:

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

The Plasma Accelerator Concept

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

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

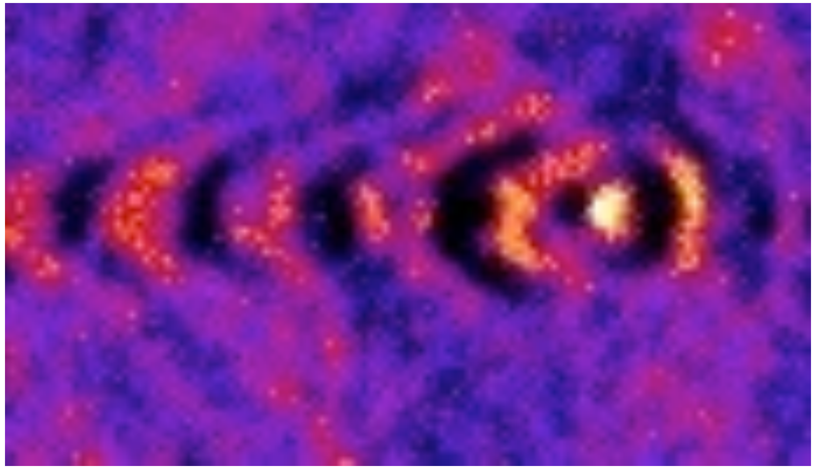
transverse forces into **longitudinal accelerating fields**

Pondero-motive force of a laser

or

Space charge force of a charged particle bunch (e-, p+)

Accelerating gradients of 10 GeV/m to 1,000 GeV/m



Courtesy M. Kaluza

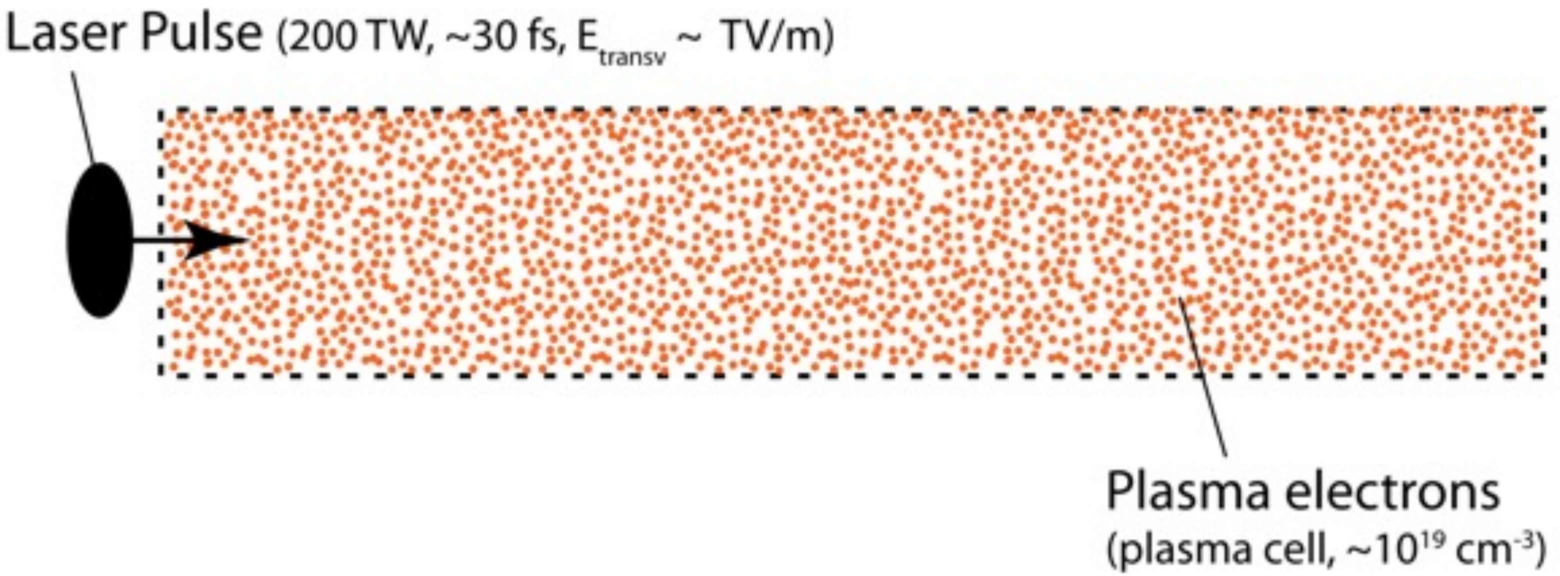
Options for driving wakefields:

- **Lasers**: Industrially available, steep progress, path to low cost
  Limited energy per drive pulse (up to **50 J**)
- **Electron bunch**: Short bunches (need μm) available, need long RF accelerator
  More energy per drive pulse (up to **500 J**)
- **Proton bunch**: Only long (inefficient) bunches, need very long RF accelerator
  Maximum energy per drive pulse (up to **100,000 J**)

Laser Plasma-Acceleration

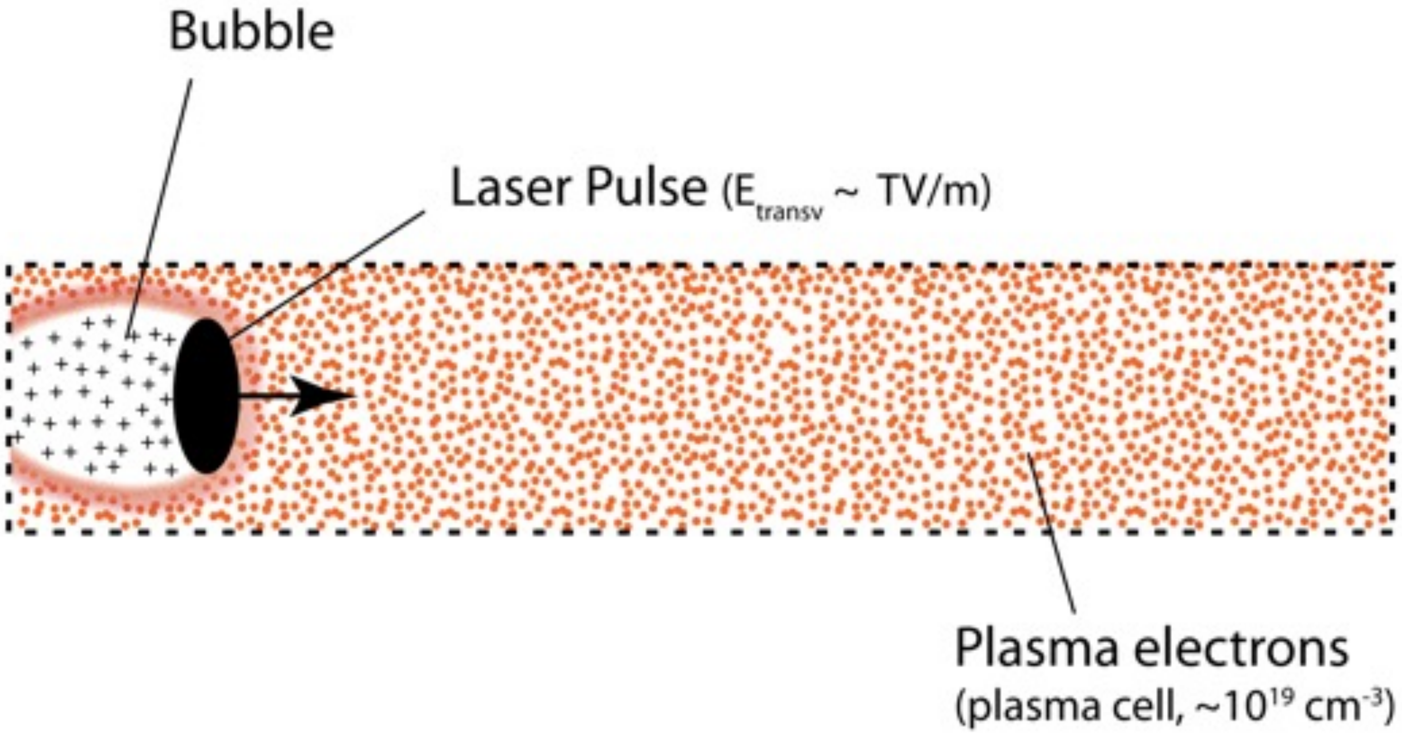
Internal injection

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



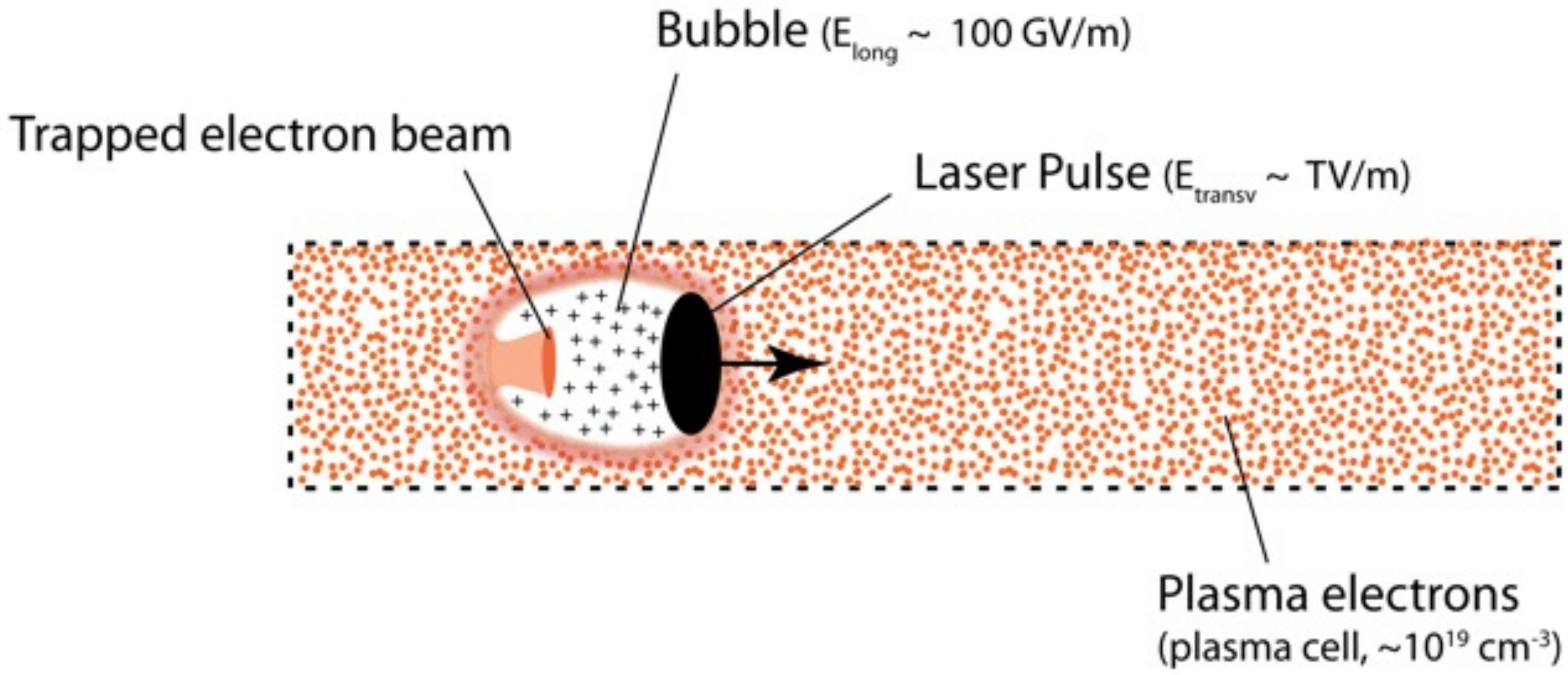
Laser Plasma-Acceleration

Internal injection



Laser Plasma-Acceleration

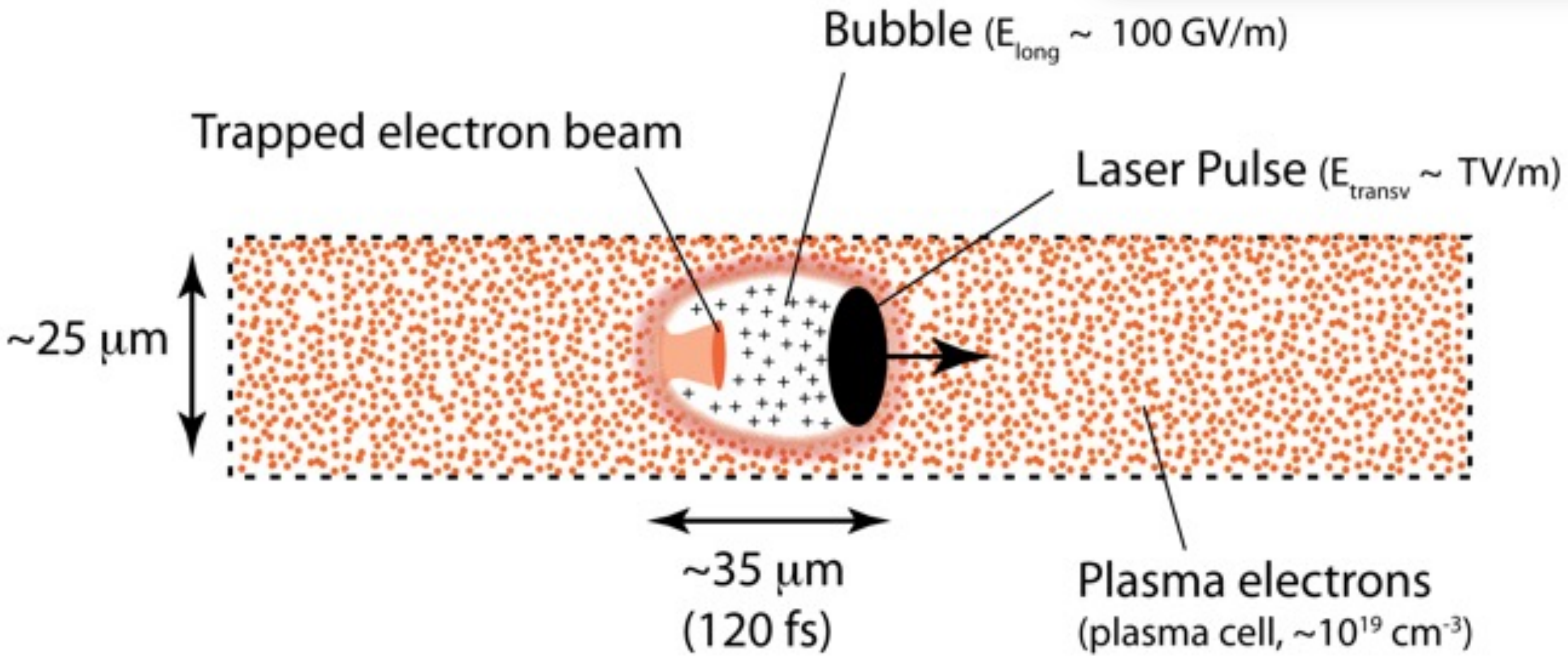
Internal injection → strong fields in the bubble suck in plasma electrons to form the electron beam



Laser Plasma-Acceleration

Internal injection

This accelerator fits into a human hair



Laser Plasma Acceleration

External injection

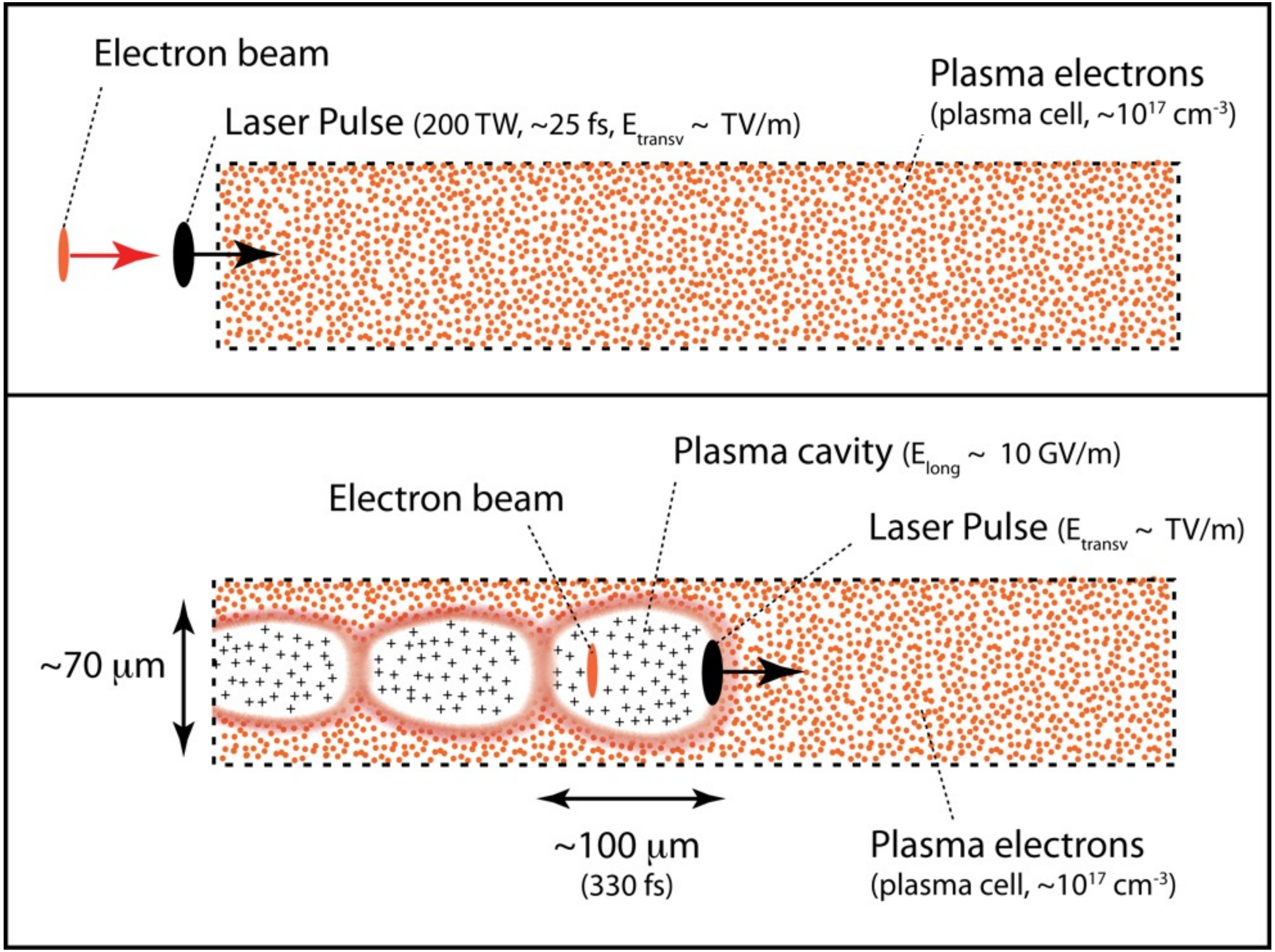


Photo Laser-Plasma Accelerator

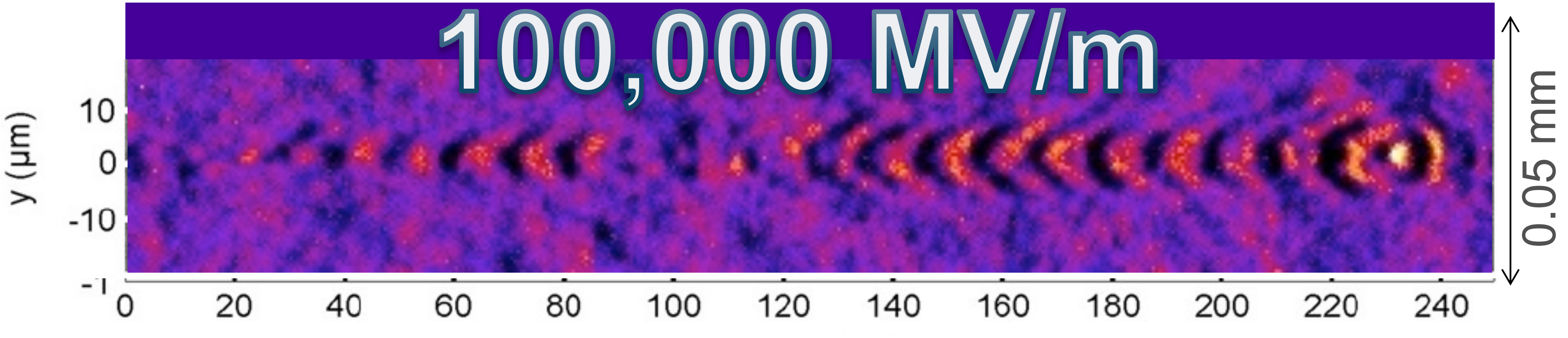
Small but can be photographed

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



0.25 mm

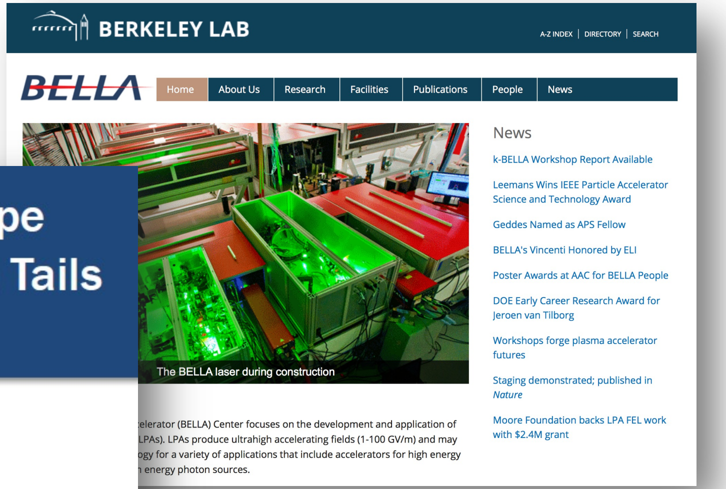
Metal (Copper)
S band
linac
structure

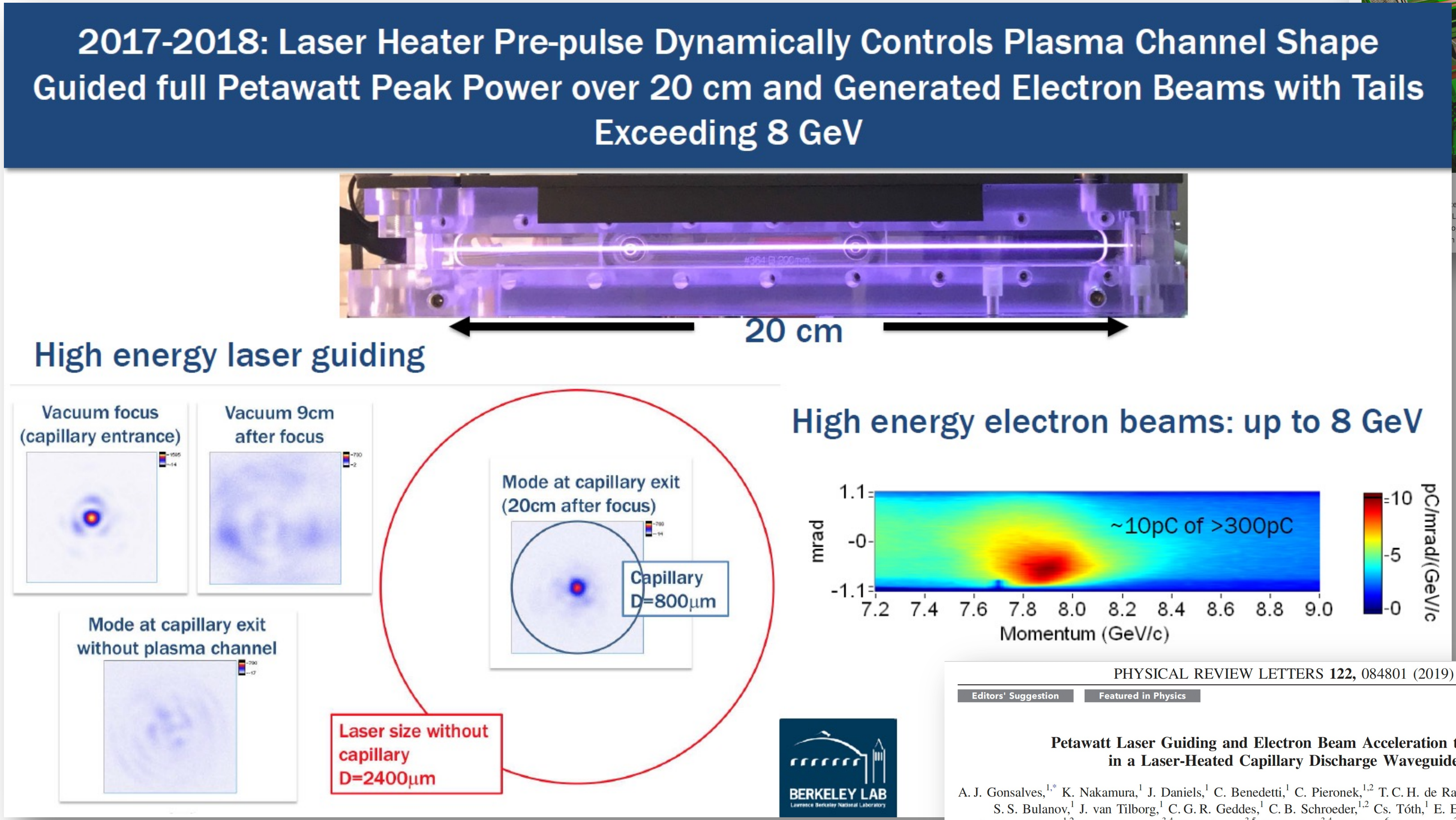
Microwaves for generation of RF waves

500 mm

LBNL: > 8 GeV beams have been obtained

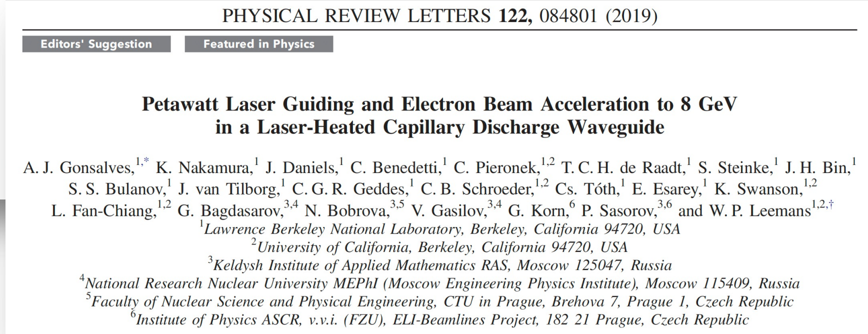
from 20 cm plasma channel powered by Peta-Watt laser pulses (15 J)





Laser
0.85 PW, 31 J, 1 Hz

Electrons
5 pC at 7.8 GeV
0.2 mrad divergence



PHYSICAL REVIEW LETTERS **122,** 084801 (2019)

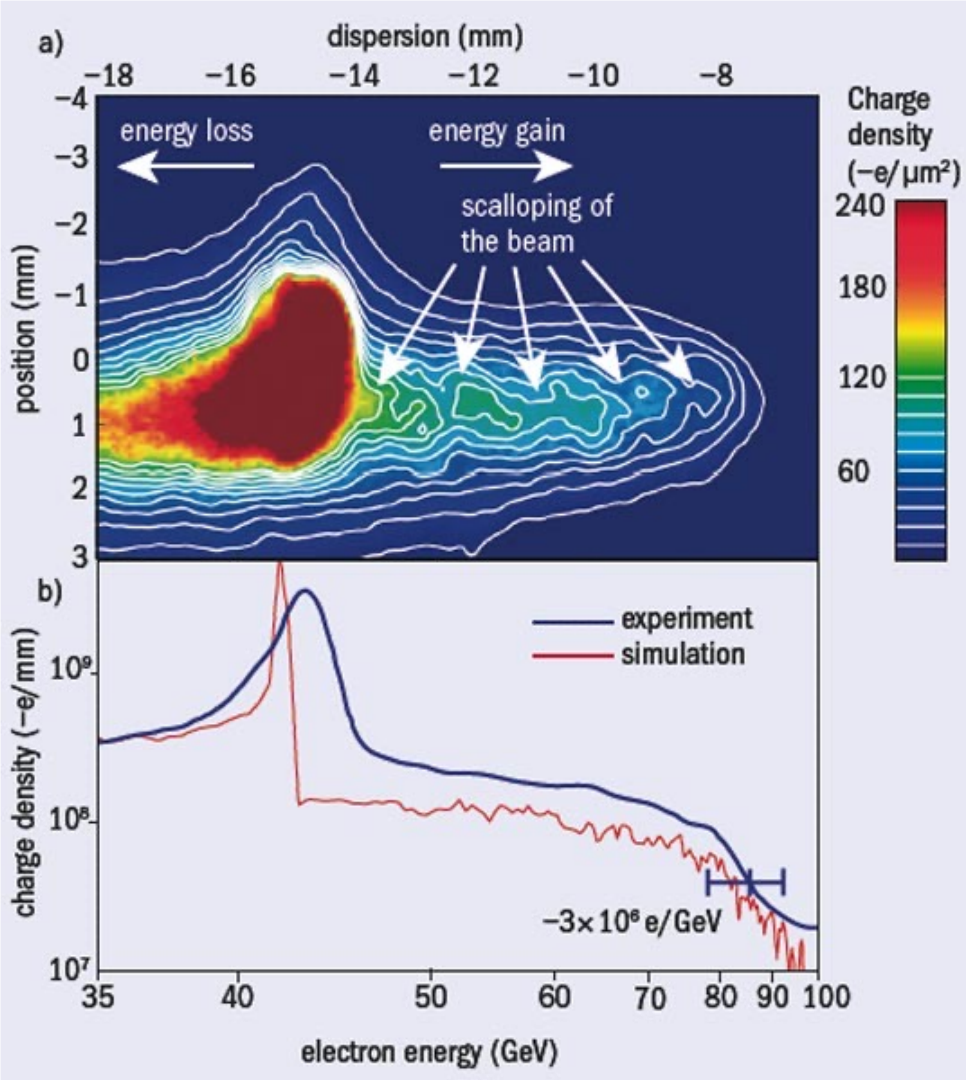
Editors' Suggestion | Featured in Physics

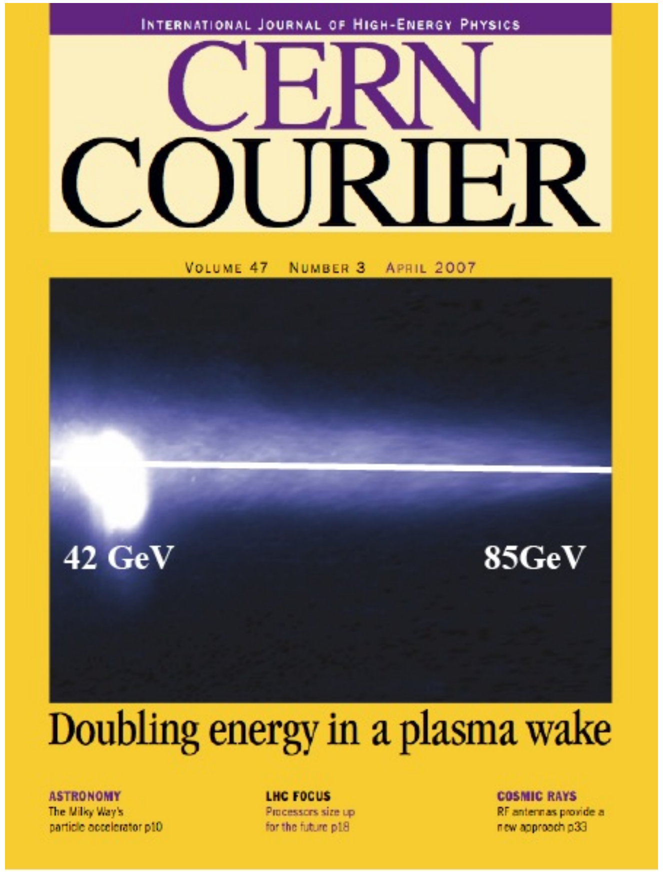
Petawatt Laser Guiding and Electron Beam Acceleration to 8 GeV in a Laser-Heated Capillary Discharge Waveguide

A. J. Gonsalves,[1,*] K. Nakamura,[1] J. Daniels,[1] C. Benedetti,[1] C. Pieronek,[1,2] T. C. H. de Raadt,[1] S. Steinke,[1] J. H. Bin,[1] S. S. Bulanov,[1] J. van Tilborg,[1] C. G. R. Geddes,[1] C. B. Schroeder,[1,2] Cs. Tóth,[1] E. Esarey,[1] K. Swanson,[1,2] L. Fan-Chiang,[1,2] G. Bagdasarov,[3,4] N. Bobrova,[3,5] V. Gasilov,[3,4] G. Korn,[6] P. Sasorov,[3,6] and W. P. Leemans[1,2,†]
[1]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[2]*University of California, Berkeley, California 94720, USA*
[3]*Keldysh Institute of Applied Mathematics RAS, Moscow 125047, Russia*
[4]*National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow 115409, Russia*
[5]*Faculty of Nuclear Science and Physical Engineering, CTU in Prague, Brehova 7, Prague 1, Czech Republic*
[6]*Institute of Physics ASCR, v.v.i. (FZU), ELI-Beamlines Project, 182 21 Prague, Czech Republic*

SLAC: 42 GeV acceleration has been shown

85 cm plasma driven by a 42 GeV electron beam, tail of bunch accelerated





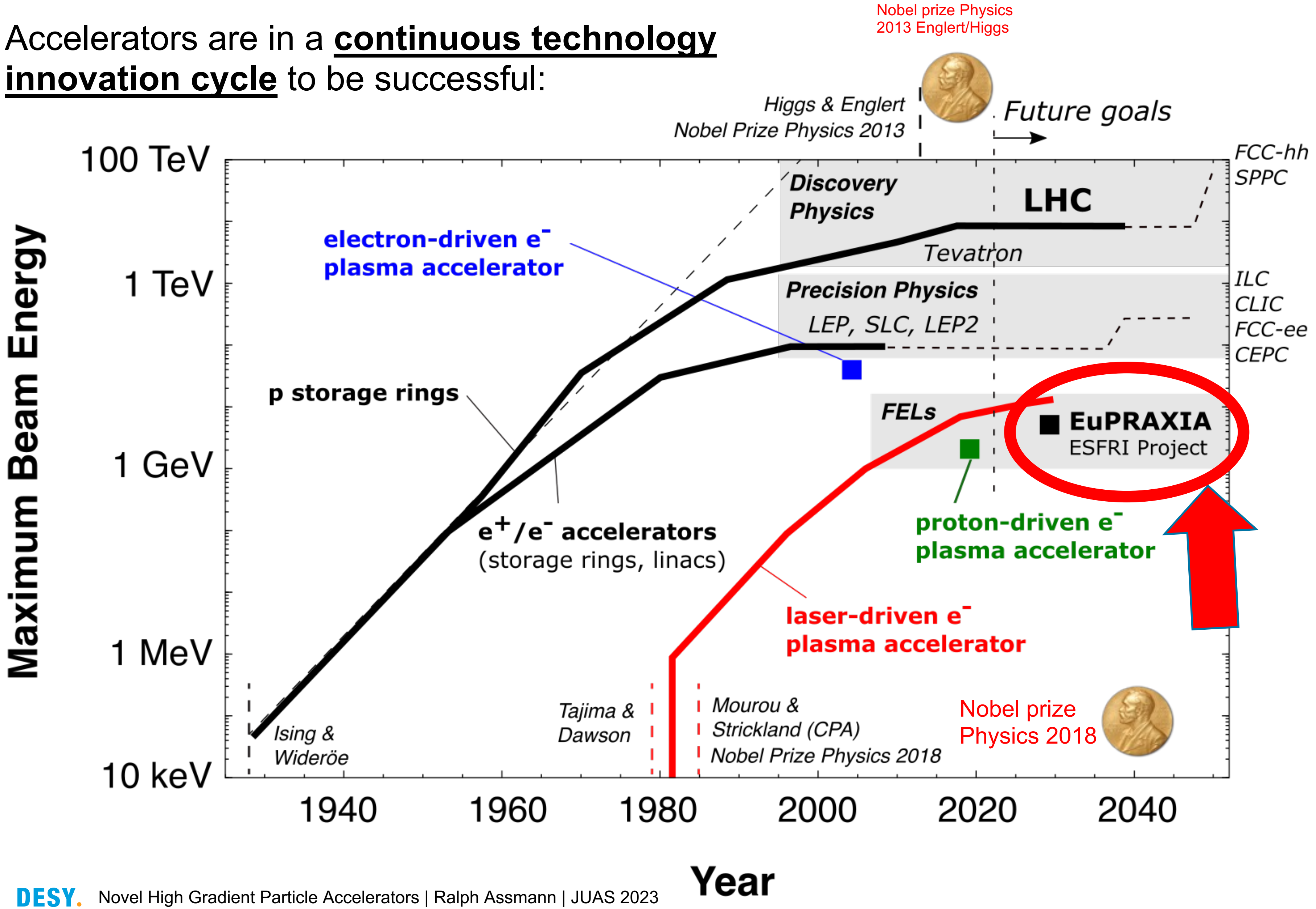
Bob Siemann, SLAC

E167 collaboration
SLAC, UCLA, USC

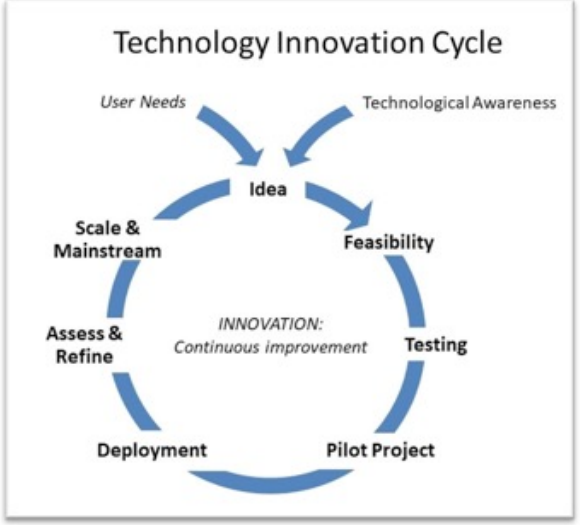
I. Blumenfeld et al, Nature 445, p. 741 (2007)

Progress in Particle Accelerators: New Technology

Accelerators are in a **continuous technology innovation cycle** to be successful:



- Examples of **new ideas and solutions**: RF, AG focusing, beta squeeze, stochastic cooling, polarized beams, superconducting magnets/RF, advanced materials for vacuum/collimators, plasma / laser accelerators,
- **Particle physics in the driver seat** for most of those developments



A. Walter Dorn, Unite Paper 2021(1)
https://walterdorn.net/home/295-tech-innovation-model-for-un-2

Contents

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

The formulae behind it all

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

$$r \ll a$$

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

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

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

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

The formulae behind it all

Accelerating field

Depends on radial position r

Changes between accelerating and decelerating as function of longitudinal position z

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

π/2 out of phase

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

Transverse field

Depends on radial position r

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

The Useful Regime of Plasma Accelerators

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

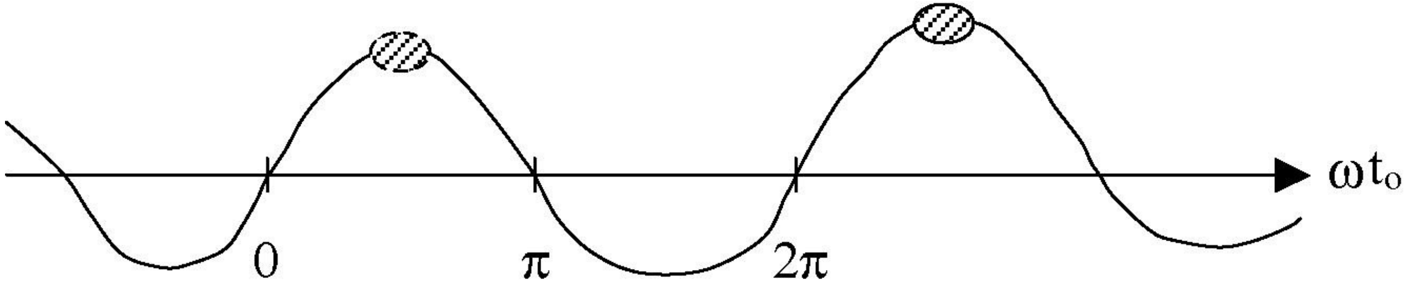
Two conditions for an accelerator:

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

These two conditions define a useful range of acceleration!

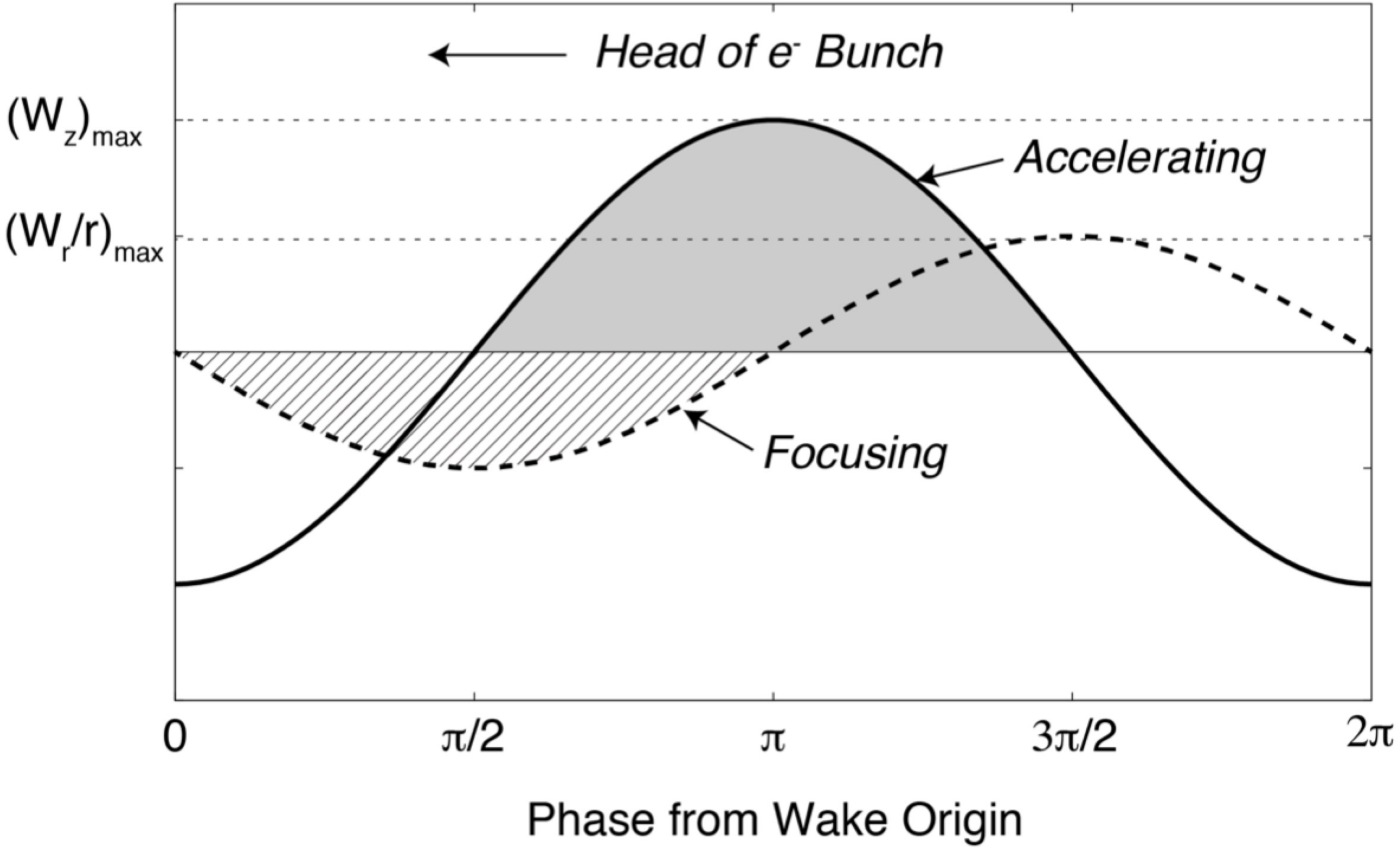
Reminder metallic RF accelerator structures:

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



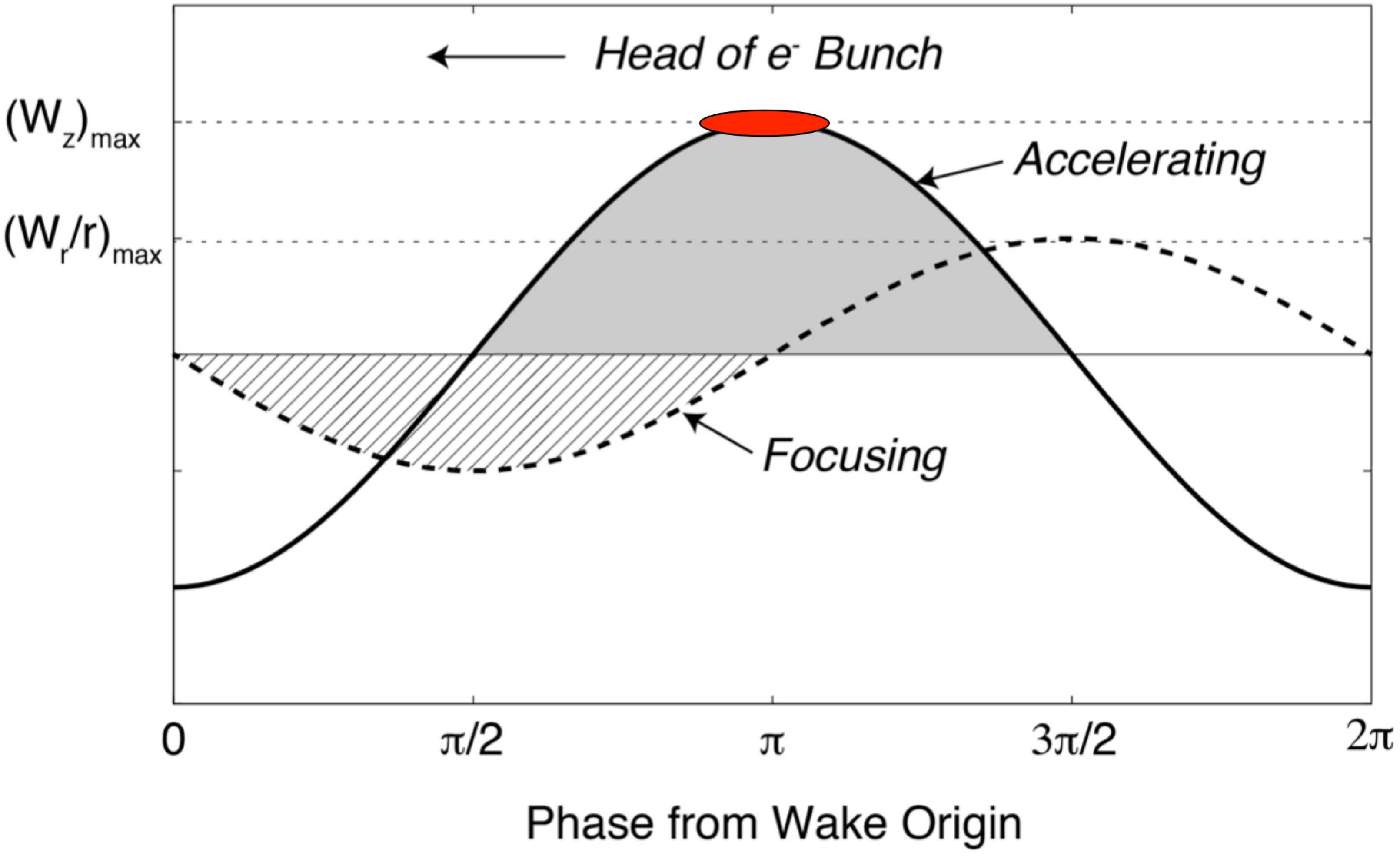
Plasma Accelerator Phasing

Finding the useful regime



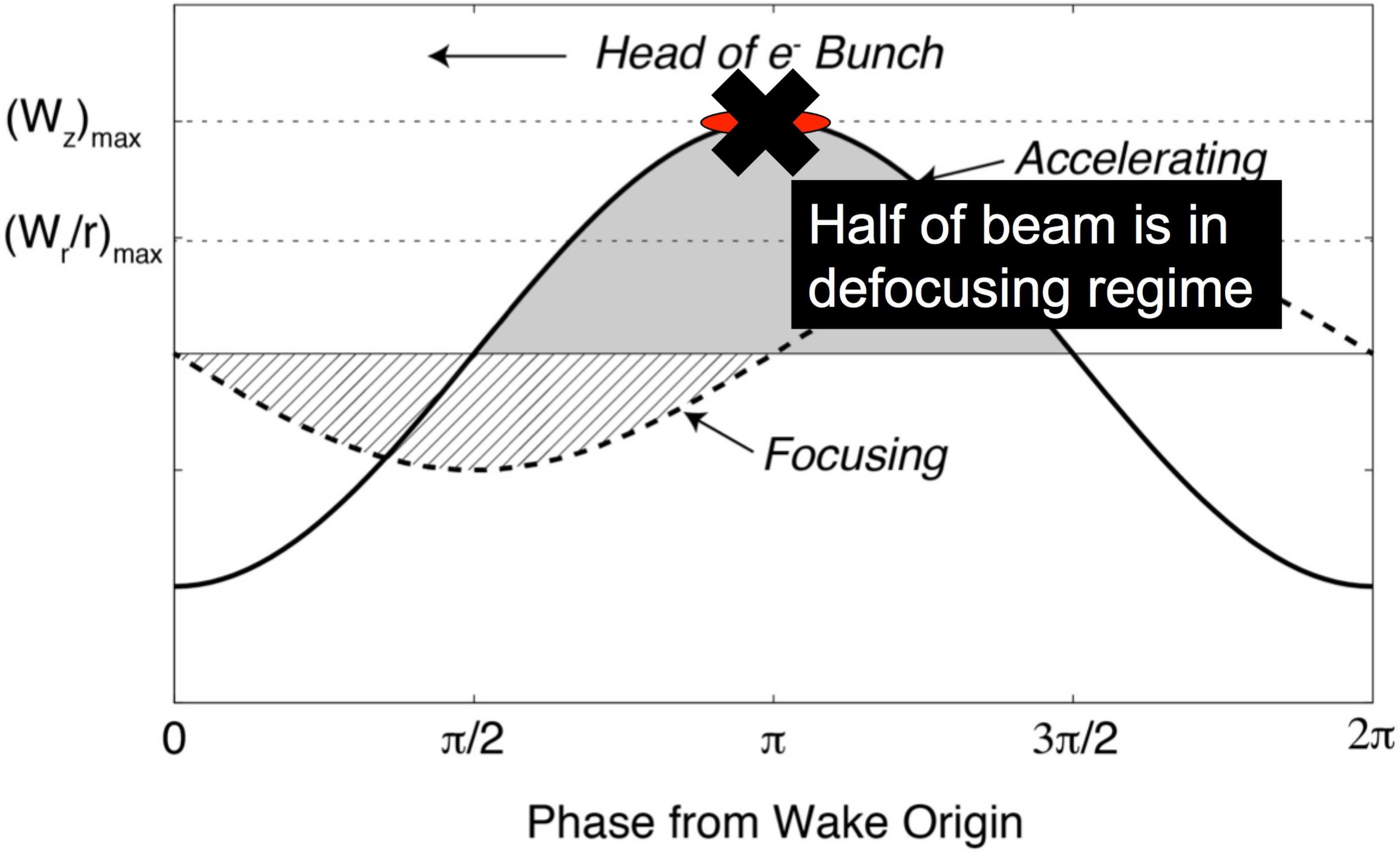
Plasma Accelerator Phasing

Finding the useful regime



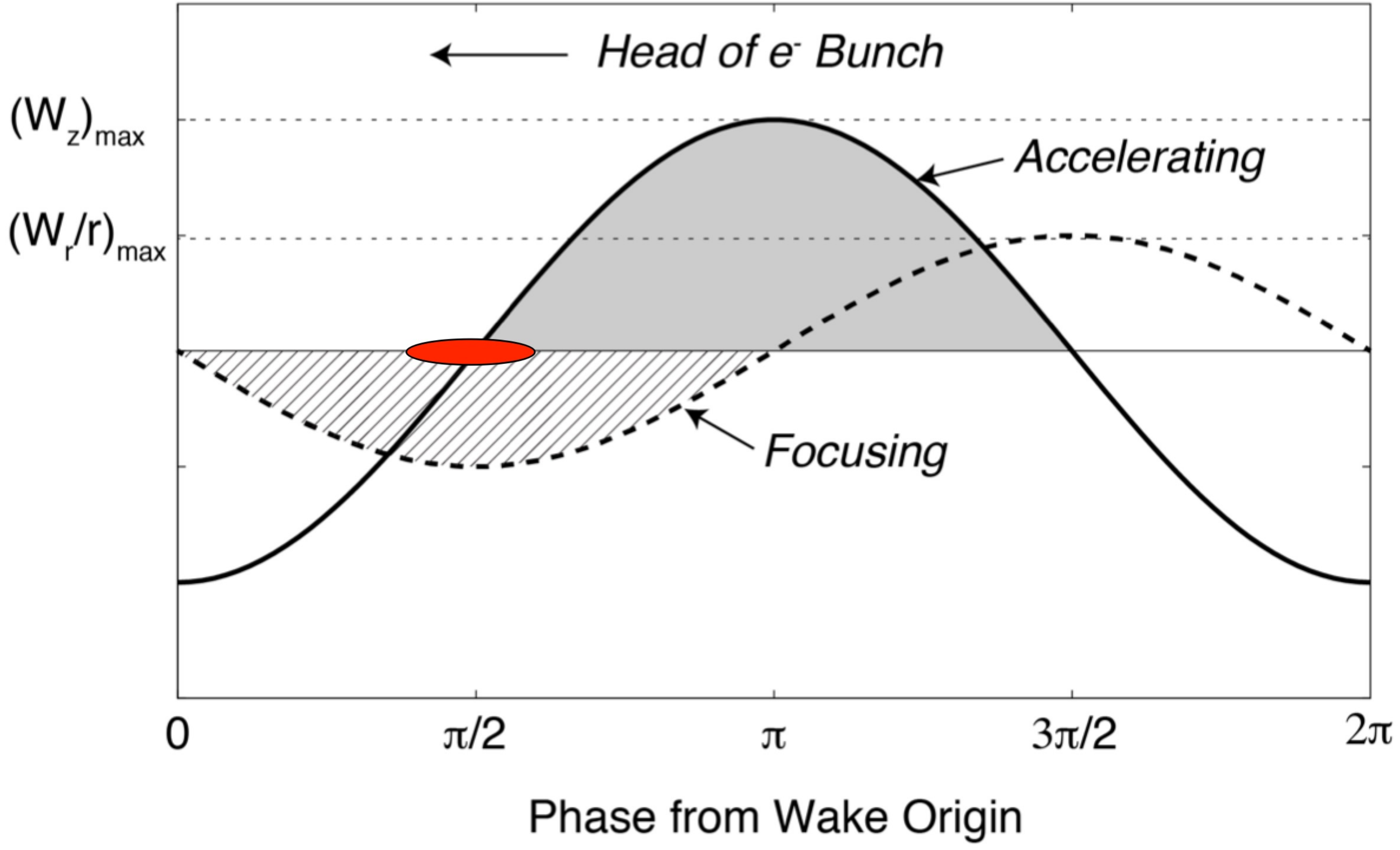
Plasma Accelerator Phasing

Finding the useful regime



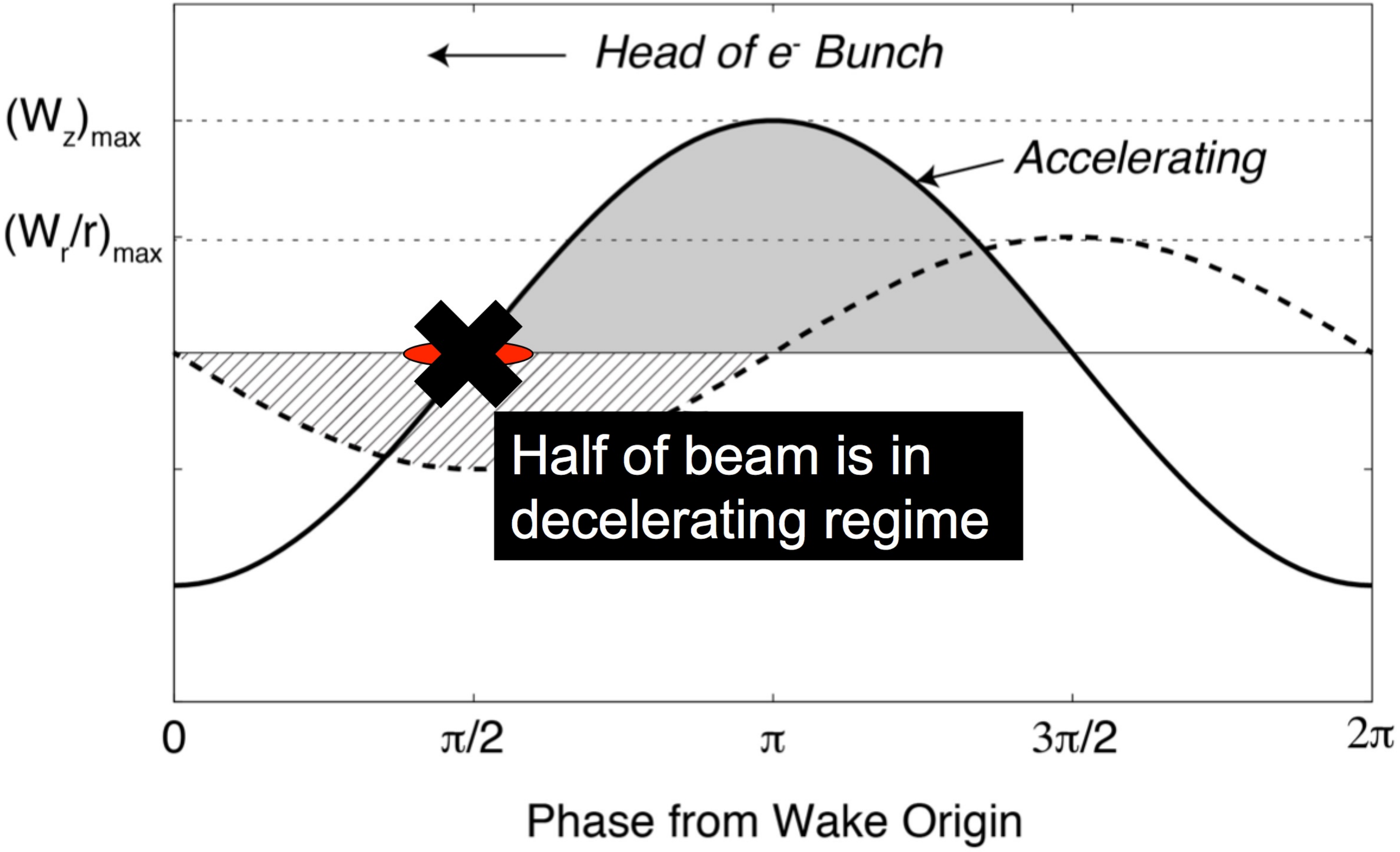
Plasma Accelerator Phasing

Finding the useful regime



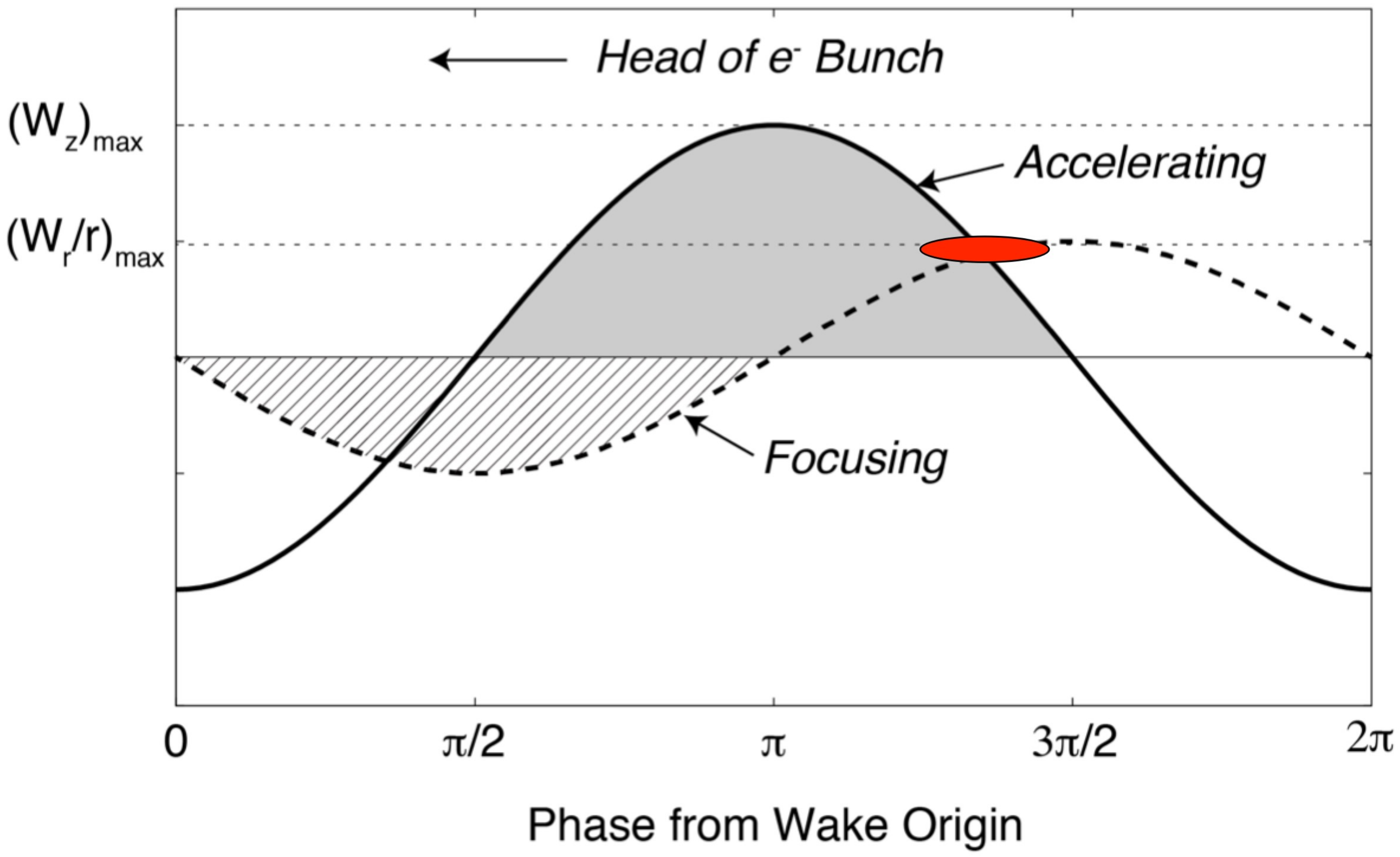
Plasma Accelerator Phasing

Finding the useful regime



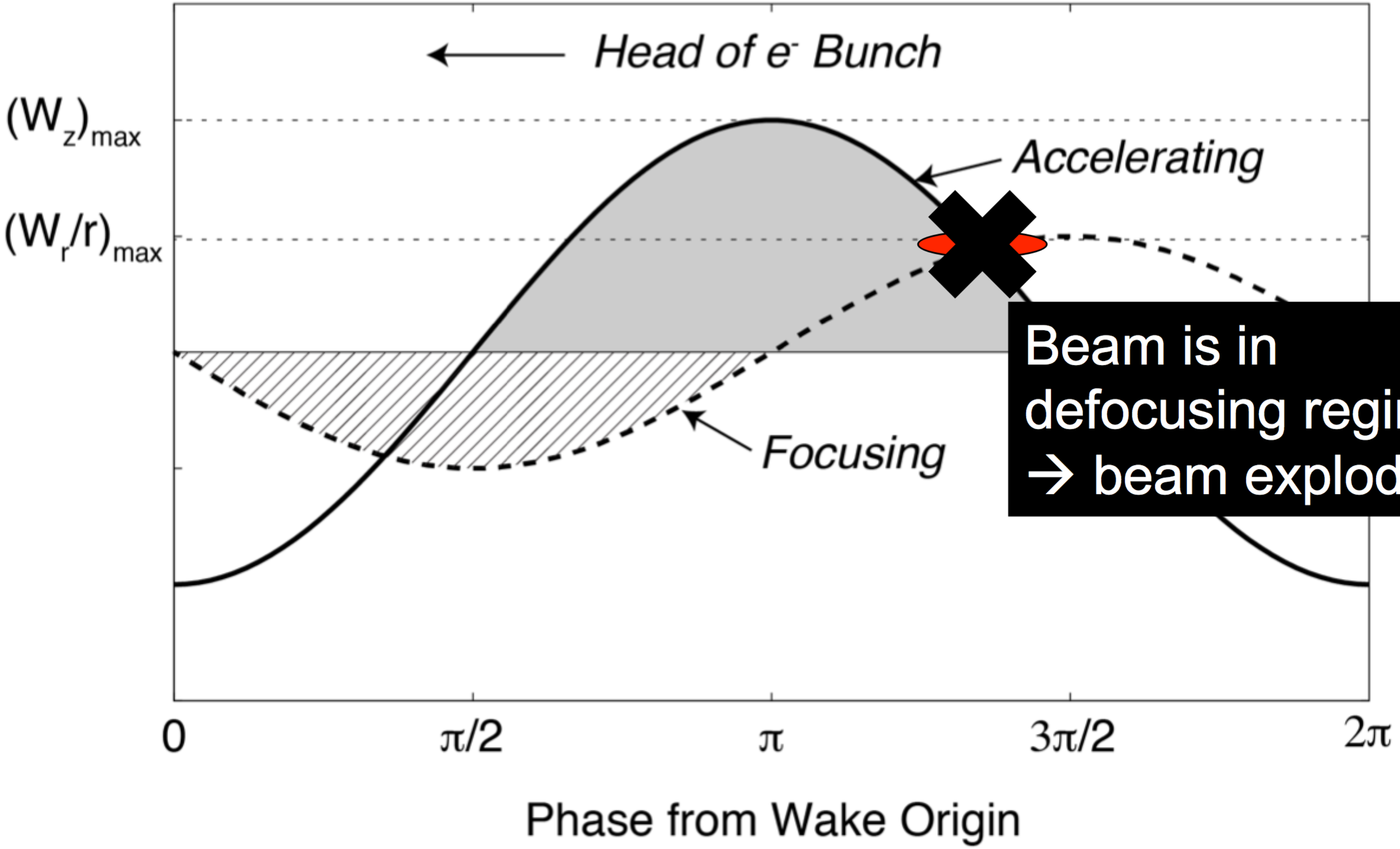
Plasma Accelerator Phasing

Finding the useful regime



Plasma Accelerator Phasing

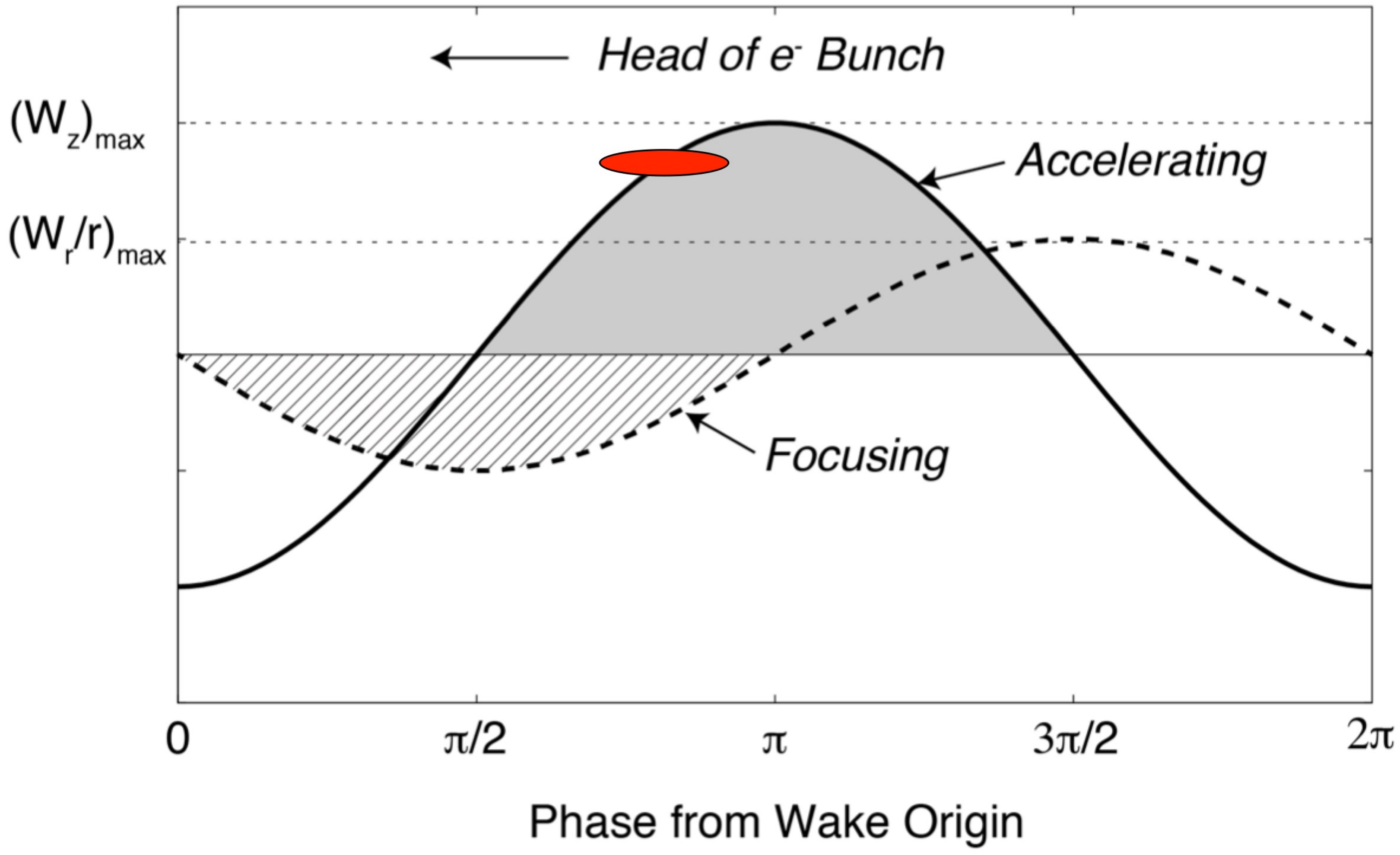
Finding the useful regime



Beam is in defocusing regime
→ beam explodes

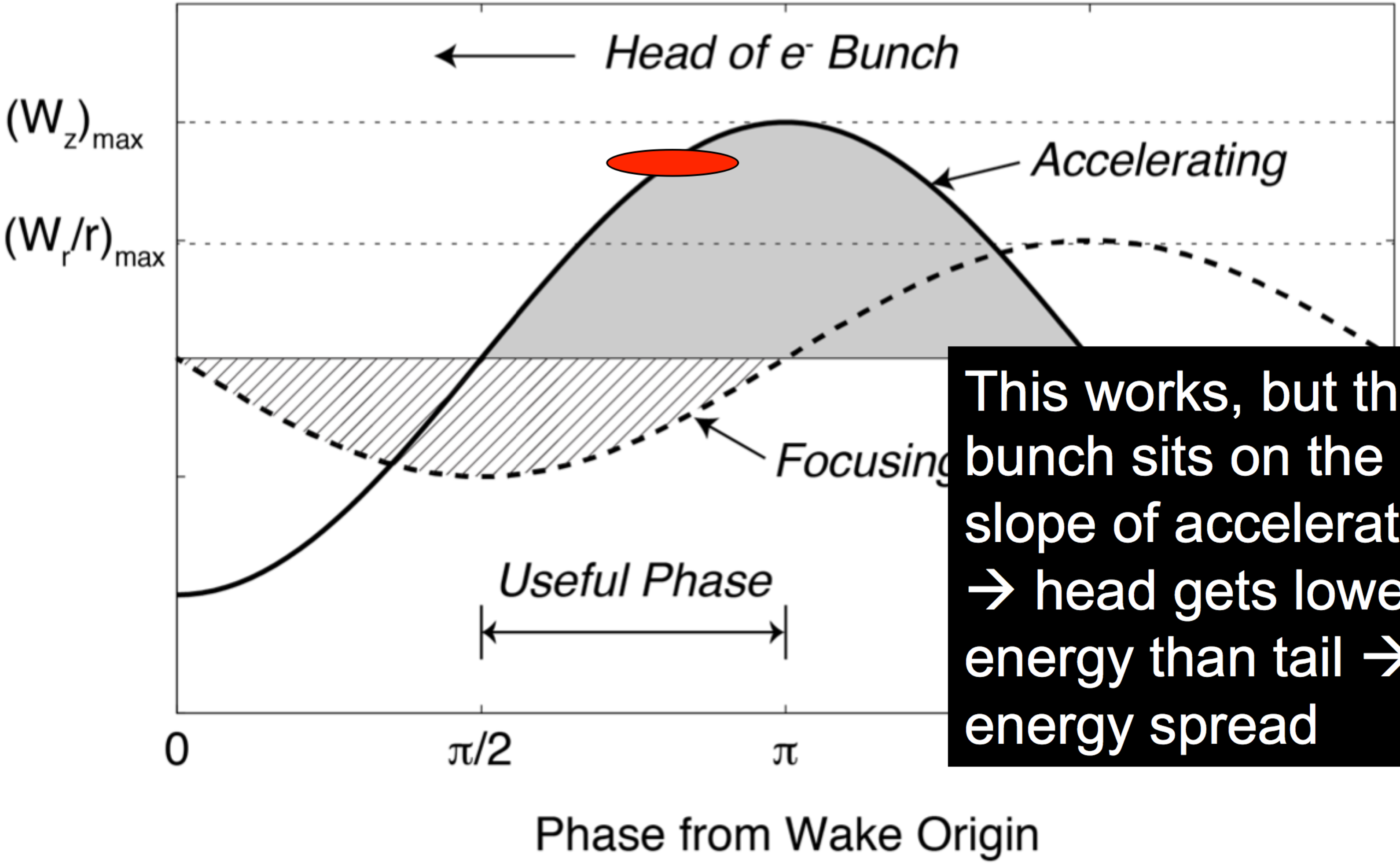
Plasma Accelerator Phasing

Finding the useful regime



Plasma Accelerator Phasing

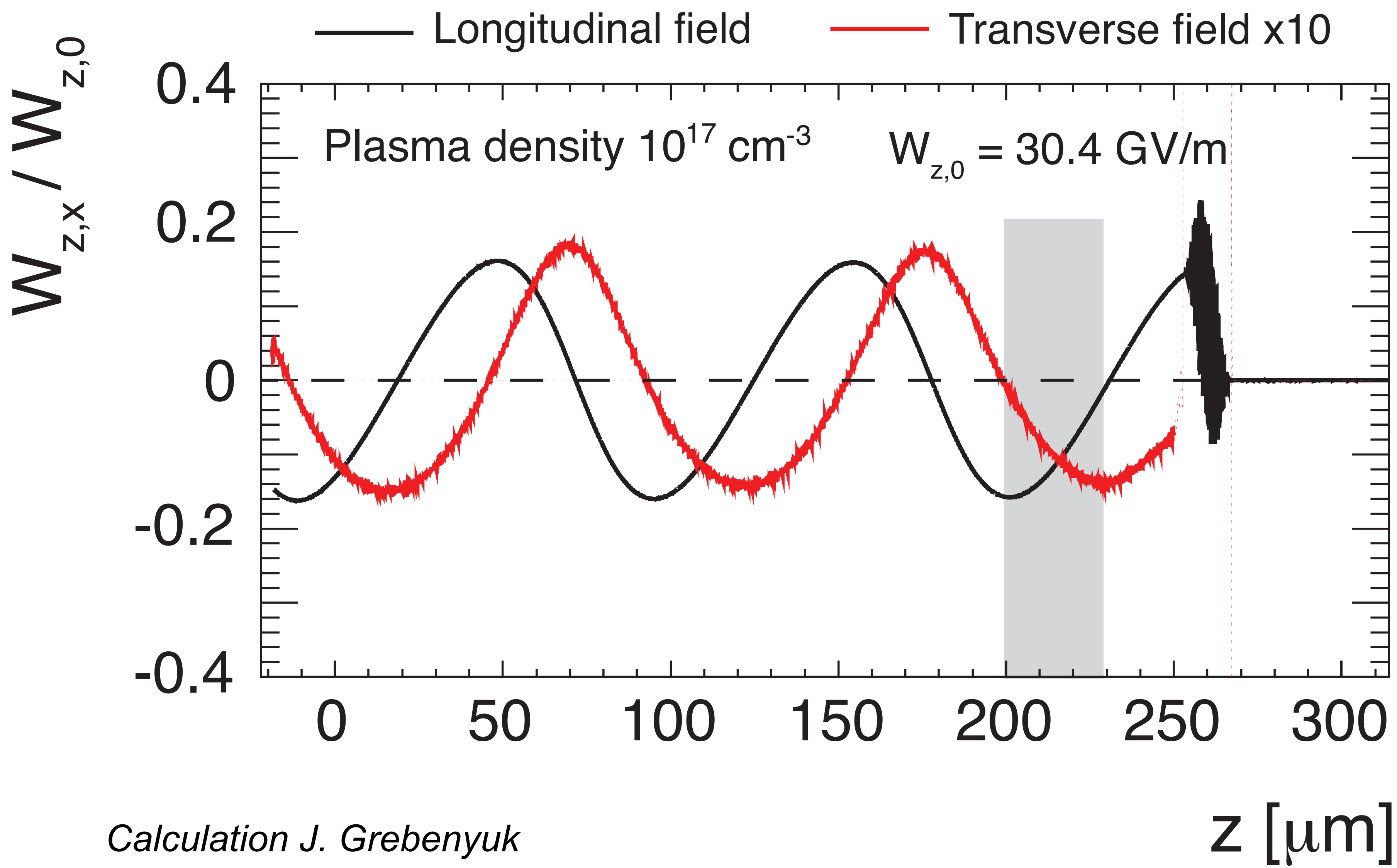
Finding the useful regime



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

Comparison with OSIRIS simulation

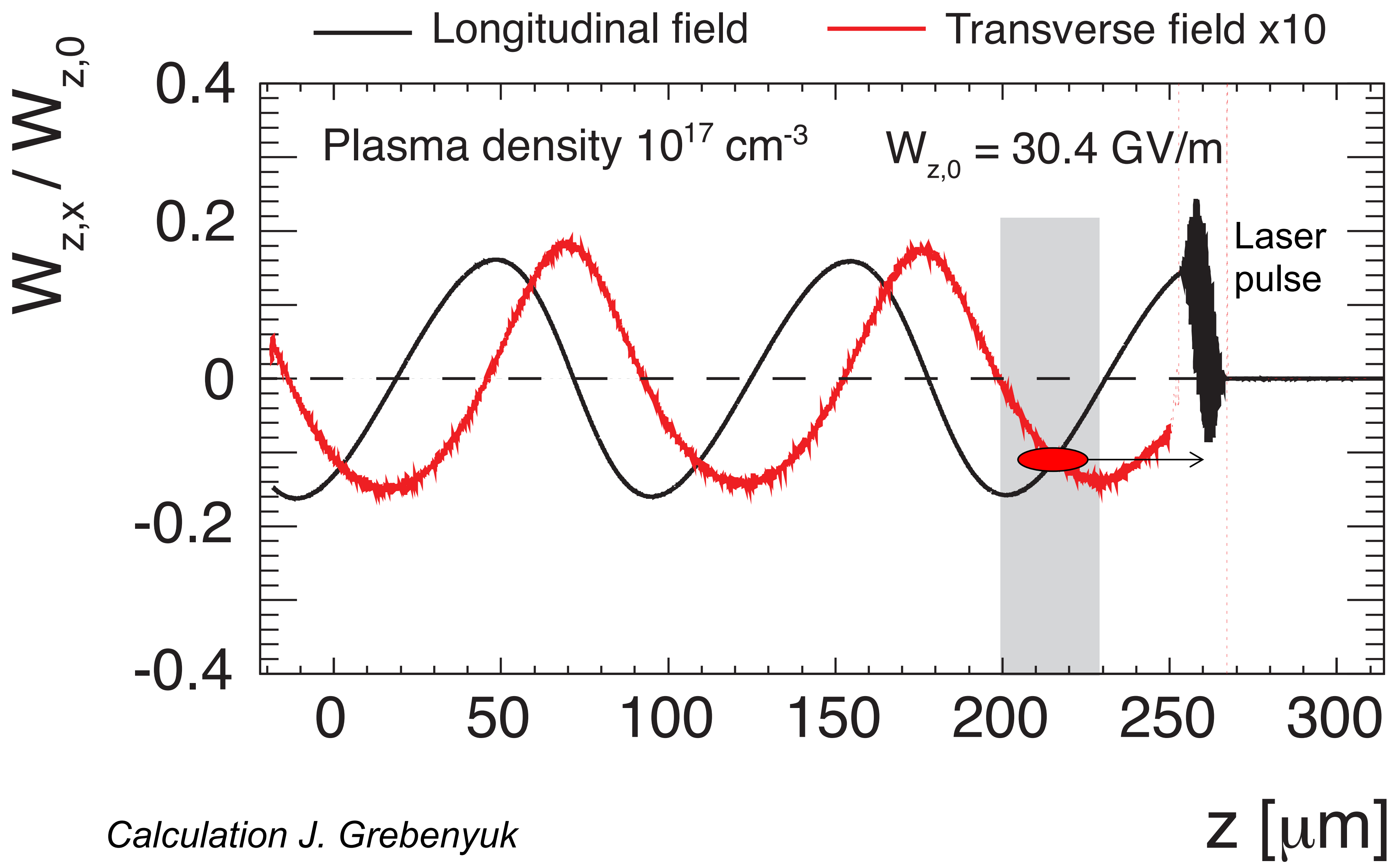
Finding the useful regime



Calculation J. Grebenyuk

Comparison with OSIRIS simulation

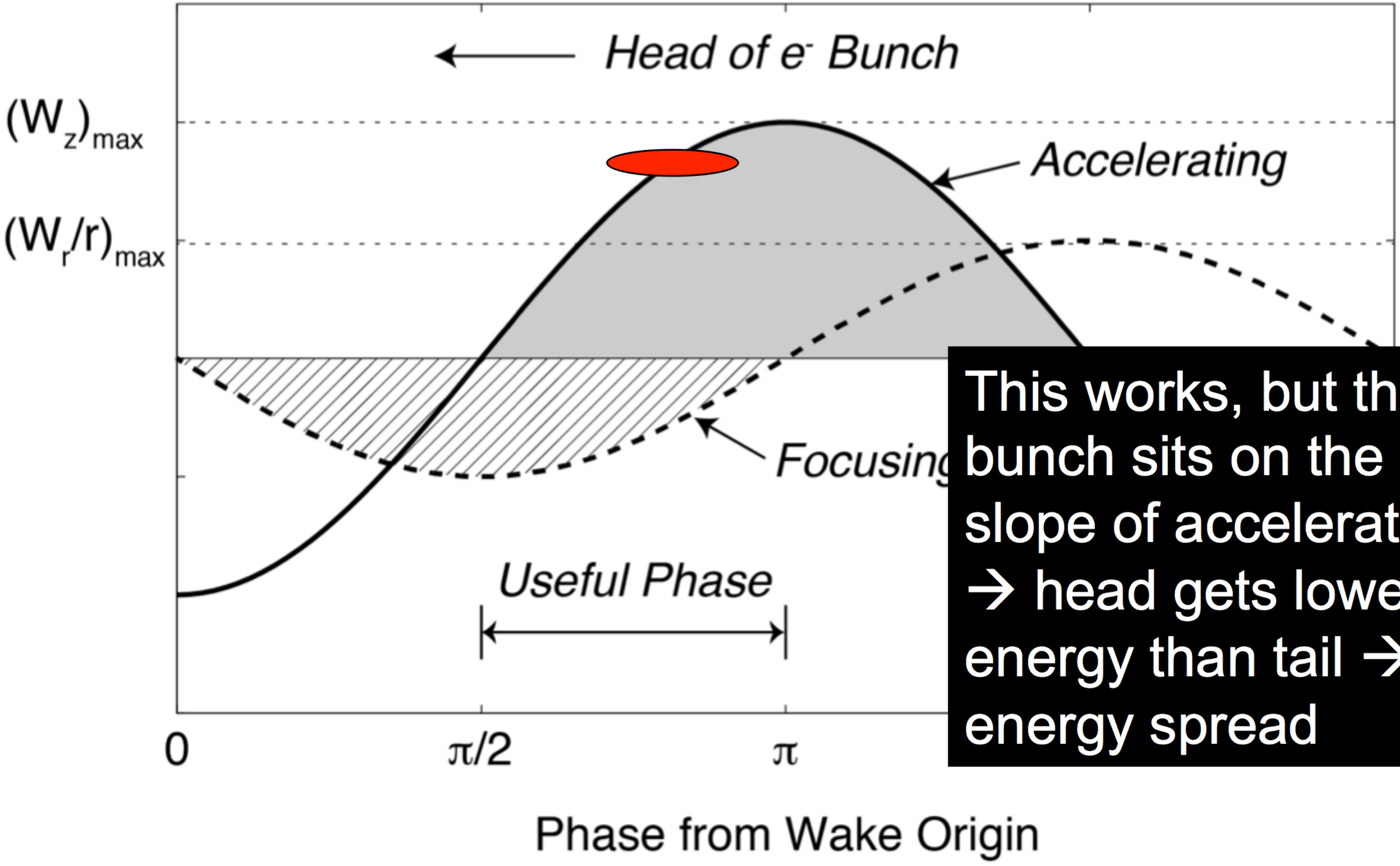
Finding the useful regime



Calculation J. Grebenyuk

Plasma Accelerator Phasing

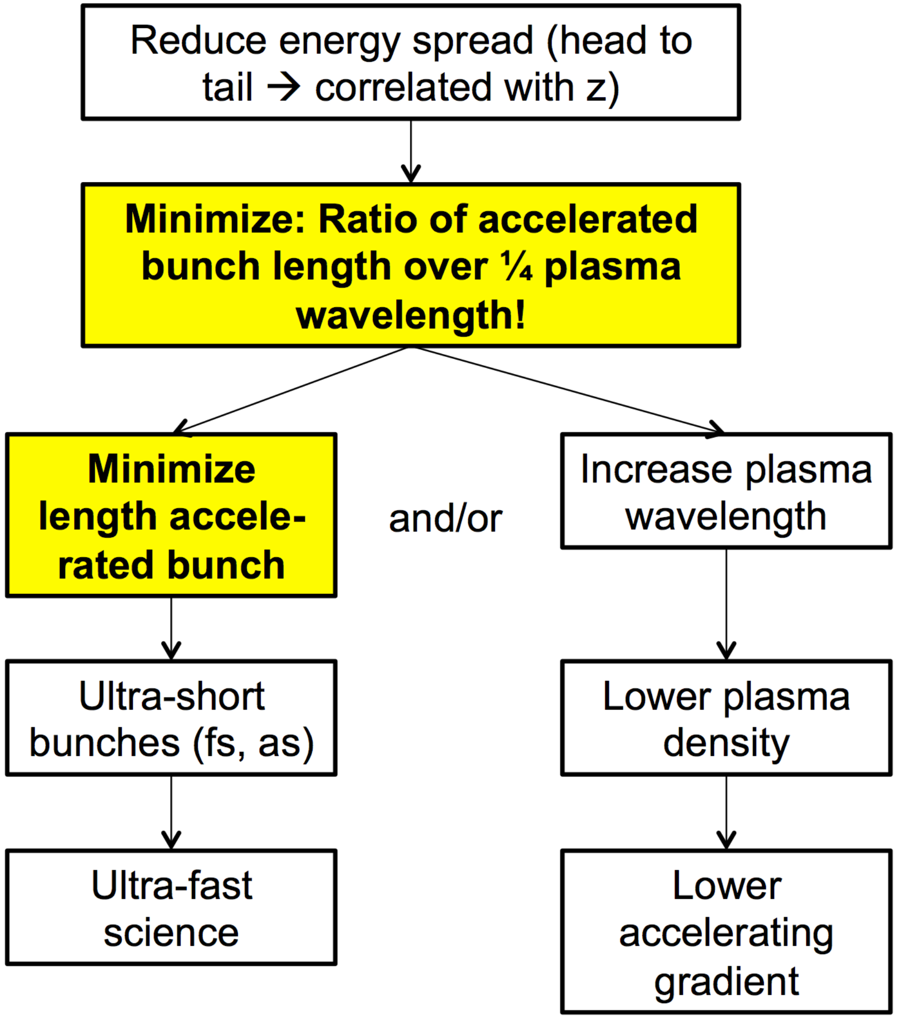
Finding the useful regime

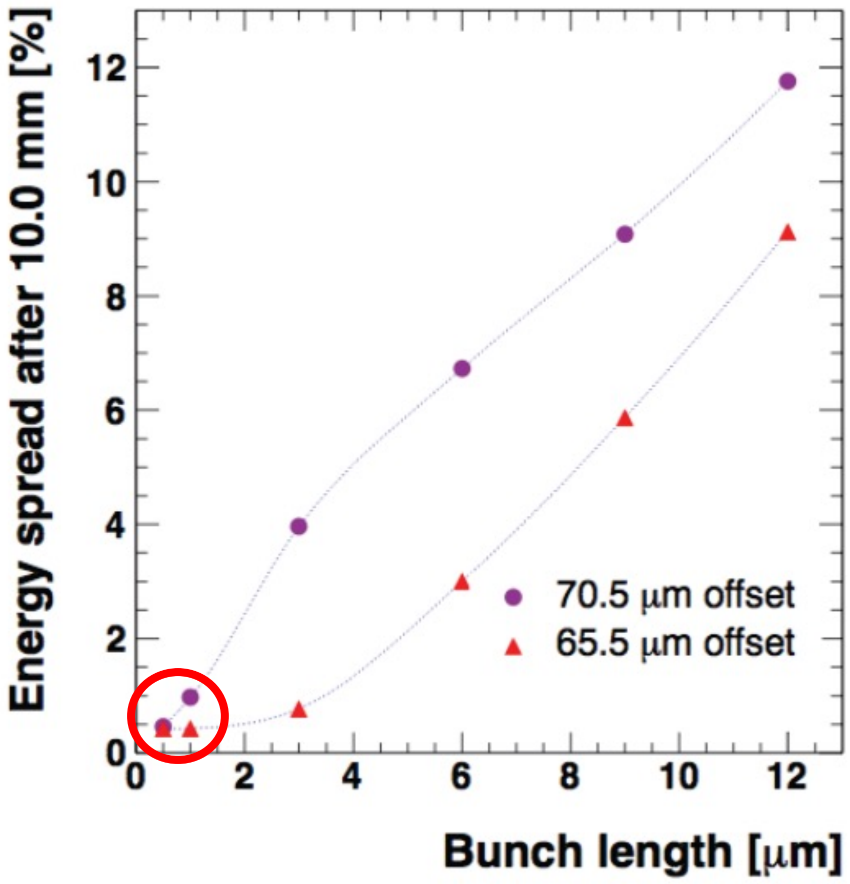


This works, but the bunch sits on the slope of acceleration → head gets lower energy than tail → energy spread

Optimization: Minimal Energy Spread

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





R. Assmann
J. Grebenyuk
IPAC 2014

1 fs = 0.3 μm when travelling with light velocity c

Dephasing

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

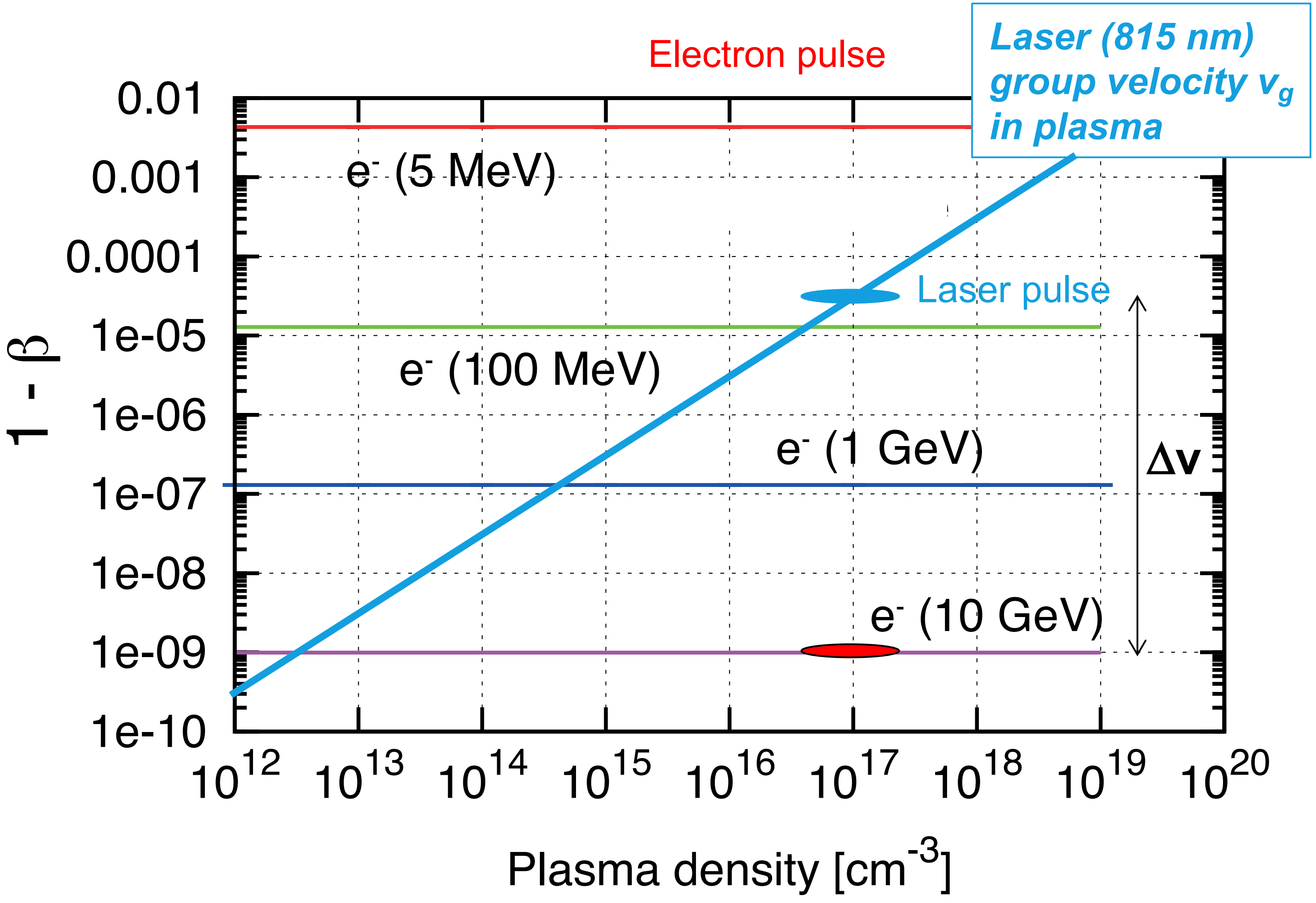
- Velocity difference **Δv** creates **slippage ΔL**:

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

- Take **plasma density $n_0 = 10^{17}$ cm^{-3}** (electrons per cm^3). Therefore plasma wavelength **λ_p = 0.1 mm**.
- Assume drive pulse from a **laser with wavelength 815 nm**.
- Difference in velocities 1-β:

  $\Delta(1-\beta) \approx 3 \times 10^{-5}$

- Slippage: **30 µm per meter**
- = 30% of wavelength or 108° in "RF phase"!

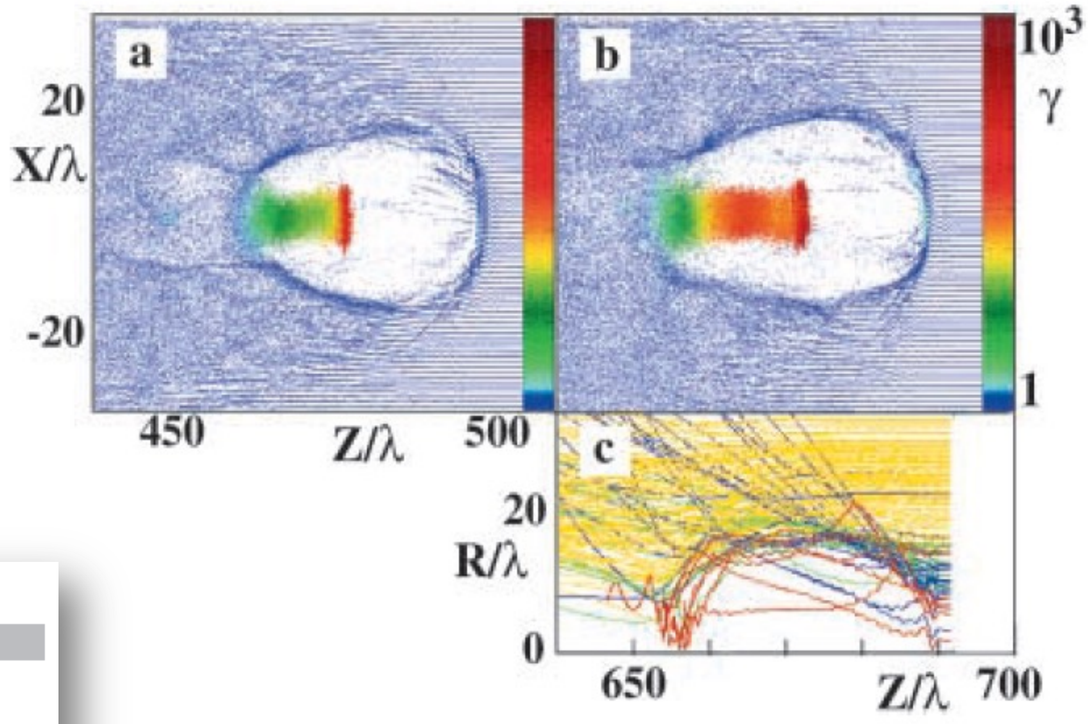


$$\lambda_p \approx 1\mathrm{mm} \cdot \sqrt{\frac{10^{15}\mathrm{cm}^{-3}}{n_0}}\,. \qquad v_g = c \cdot \sqrt{1 - \frac{\omega_p^2}{\omega_l^2}}$$

Warning: Non-Linearities are Important

Linear regime nice to get an understanding – Quasi-linear and non-linear regimes most often used

- 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

*Paper by Pukhov and Meyer-Ter-Vehn one of most cited papers in accelerators: **refused at higher impact journals as irrelevant** ("would never work")*

Contents

Plasma Accelerator Physics I

Small accelerators exhibit also very small tolerances – here is the difficulty

- A plasma of density n_0 (same density electrons - ions) is characterized by the **plasma frequency**:

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

- This translates into a **wavelength** of the plasma oscillation:

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

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

Small accelerators exhibit also very small tolerances – here is the difficulty

- The plasma oscillation leads to **longitudinal accelerating fields** with a gradient of (higher plasma densities are better):

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

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

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

Small accelerators exhibit also very small tolerances – here is the difficulty

- The ion channel left on axis, where the beam passes, induces an **ultra-strong focusing field**. In the simplest case:

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

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

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

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

β = 1.1 mm for 100 MeV

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

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

Plasma Accelerator Physics IV

Small accelerators exhibit also very small tolerances – here is the difficulty

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

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

σ_0 = 1.3 μm for γε = 0.3 μm

DIFFICULTY

- Offsets between laser and beam centres will induce betatron oscillations. Assume: full dilution into emittance growth (energy spread and high phase advance).
- Tolerances for **emittance growth** due to offsets $\Delta x = \sigma_x$:

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

100% for 1.3 μm offset

DIFFICULTY

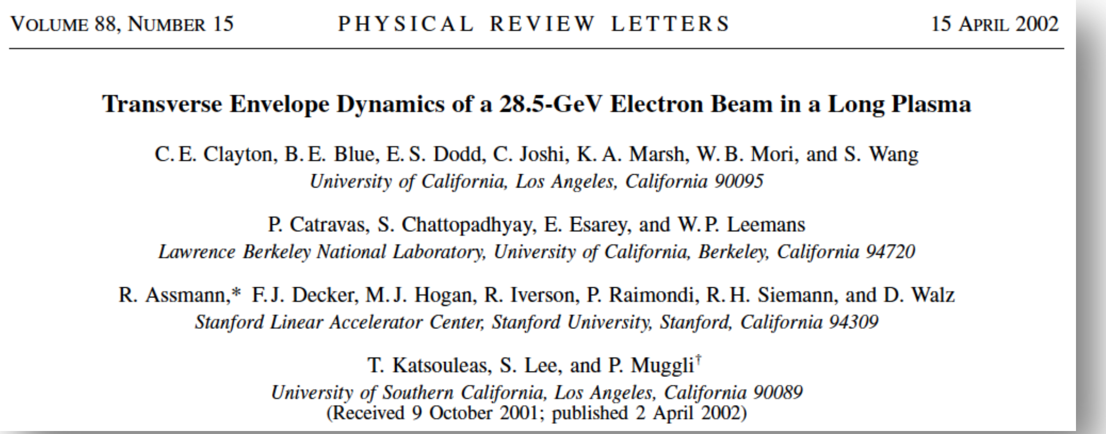
- Lower plasma density better: larger matched beam size, bigger tolerances.

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

Experiment – Strong plasma focusing: Betatron motion

Plasma works as a focusing quadrupole

- A plasma has a very strong focusing field in both planes.
- Focusing strength and phase advance depends on plasma density.
- Experiment with a beam-driven plasma at SLAC in 2001: Send an electron beam into a plasma and measure beam sizes at exit point.



VOLUME 88, NUMBER 15 PHYSICAL REVIEW LETTERS 15 APRIL 2002

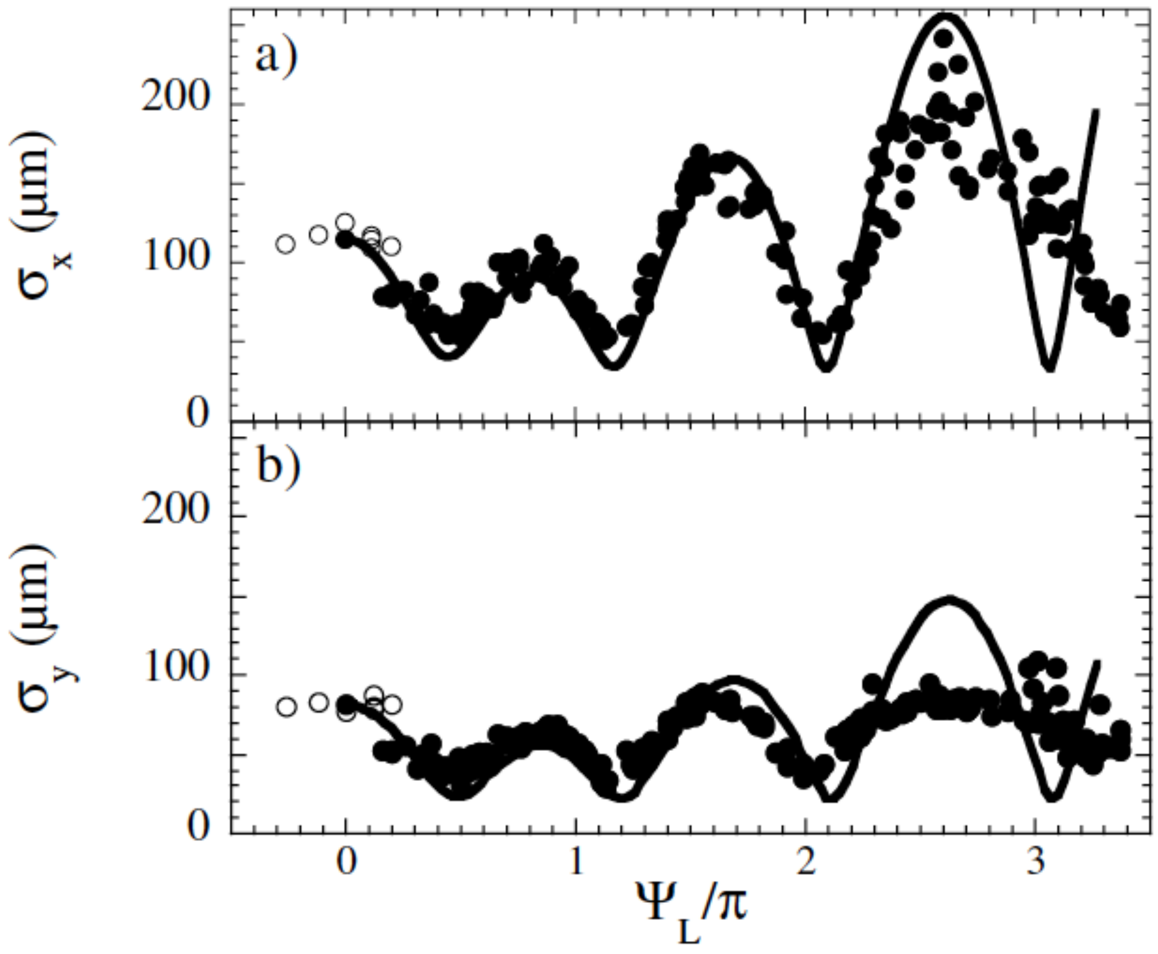
Transverse Envelope Dynamics of a 28.5-GeV Electron Beam in a Long Plasma

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

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

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

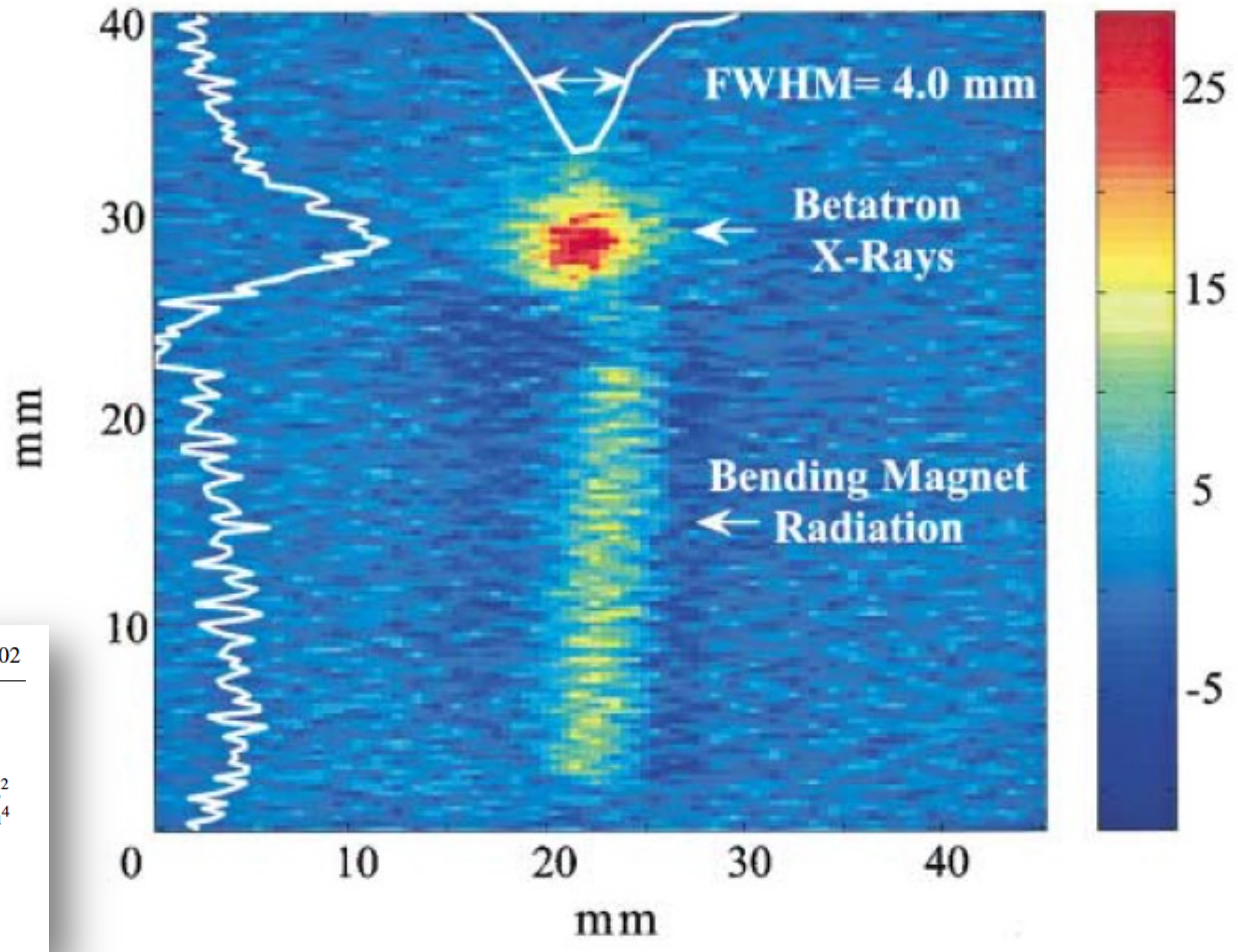
T. Katsouleas, S. Lee, and P. Muggli†
University of Southern California, Los Angeles, California 90089
(Received 9 October 2001; published 2 April 2002)



Experiment –Betatron motion and X rays

Wiggling electrons emit X rays → a plasma accelerator as accelerator and undulator at once

- If an electron beam is injected mis-matched into a plasma, we expect strong beta mismatch oscillations of the beam size.
- The oscillating electrons should radiate X rays.
- This was seen in a SLAC experiment in 2001.
- Plasma acts as undulator!



VOLUME 88, NUMBER 13 PHYSICAL REVIEW LETTERS 1 APRIL 2002

X-Ray Emission from Betatron Motion in a Plasma Wiggler

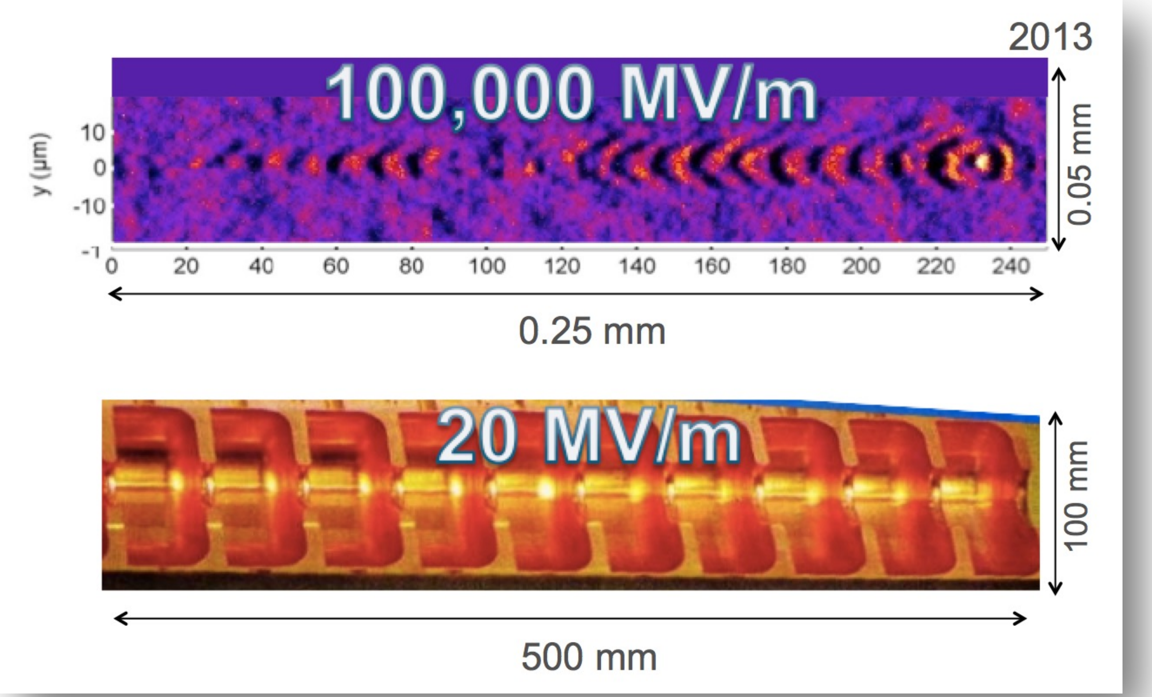
Shuoqin Wang,[1] C. E. Clayton,[1] B. E. Blue,[1] E. S. Dodd,[1] K. A. Marsh,[1] W. B. Mori,[1] C. Joshi,[1] S. Lee,[2] P. Muggli,[2] T. Katsouleas,[2] F. J. Decker,[3] M. J. Hogan,[3] R. H. Iverson,[3] P. Raimondi,[3] D. Walz,[3] R. Siemann,[3] and R. Assmann[4]

[1]*University of California, Los Angeles, California 90095*
[2]*University of Southern California, Los Angeles, California 90089*
[3]*Stanford Linear Accelerator Center, Stanford, California 94309*
[4]*CERN, Switzerland*
(Received 8 October 2001; published 19 March 2002)

Plasma opens new reach but also difficulties…

Comparing plama to conventional accelerators

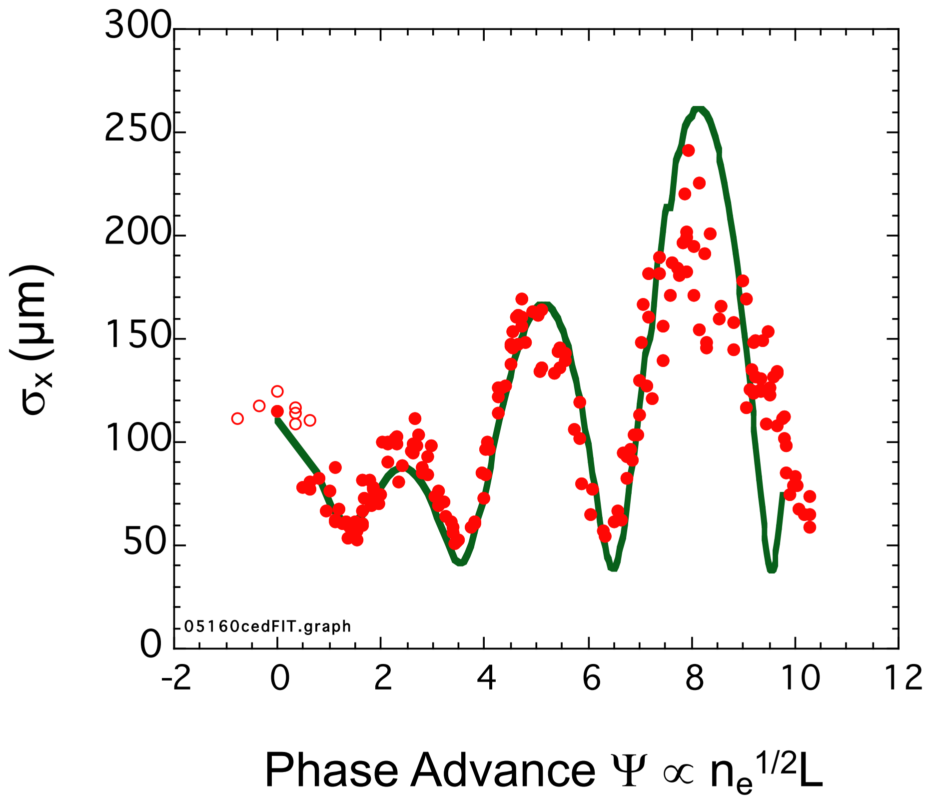
- **Conventional acceleration structures:**
  - Optimized to provide longitudinal acceleration and no transverse forces on the beam.
  - Due to imperfections, transverse forces can be induced. These "wakefields" caused major trouble to the first and only linear collider at SLAC.
- **Plasma acceleration:**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



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**.

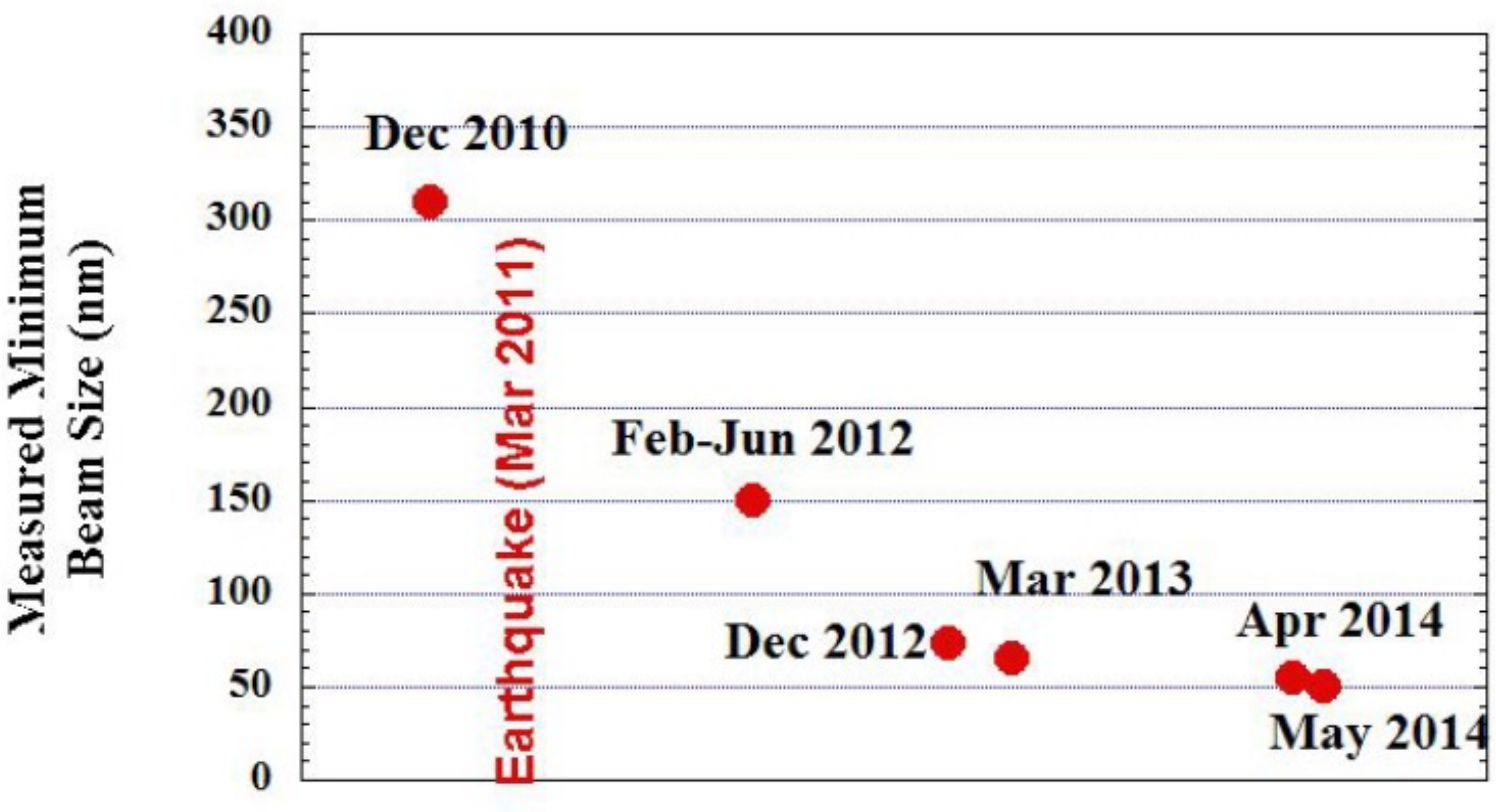


PRL 2002, C. E. Clayton, B. E. Blue, E. S. Dodd, C. Joshi, K. A. Marsh, W. B. Mori, and S. Wang, P. Catravas, S. Chattopadhyay, E. Esarey, and W. P. Leemans, R. Assmann, F. J. Decker, M. J. Hogan, R. Iverson, P. Raimondi, R. H. Siemann, and D. Walz, T. Katsouleas, S. Lee, and P. Muggli

Accelerator Builder’s Challenge – Feasible?

We can generate nanometer beams – so we can inject

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



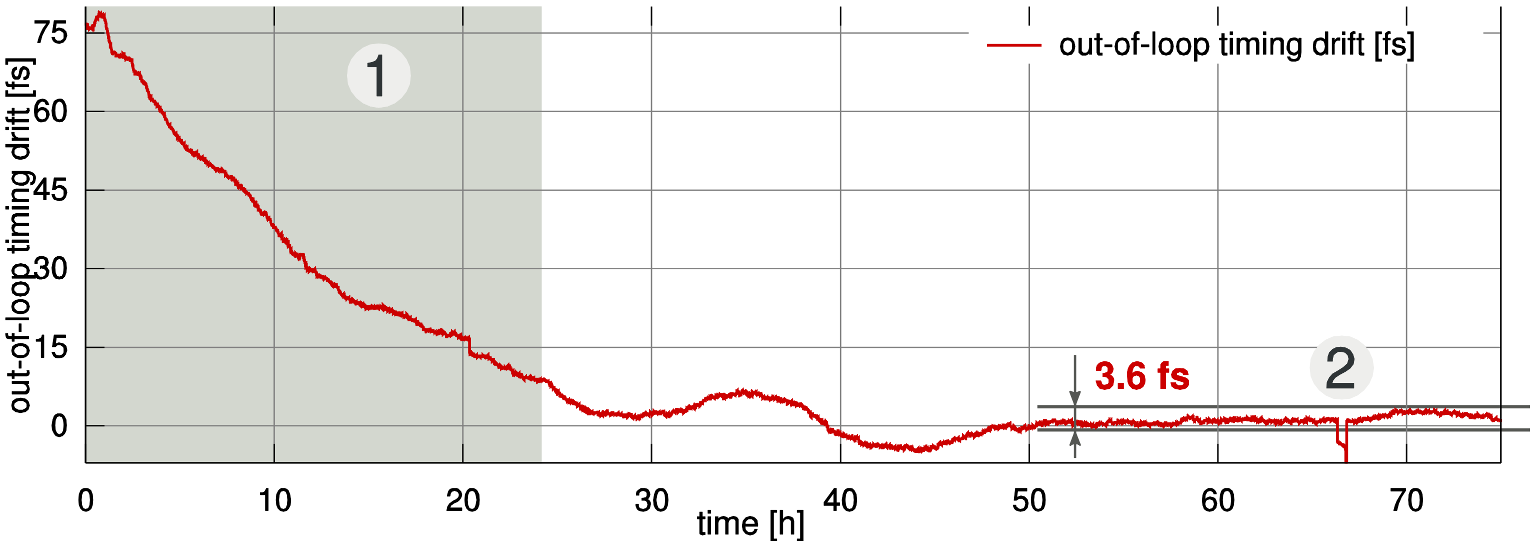
50 nm with a 1.3 GeV electron beam

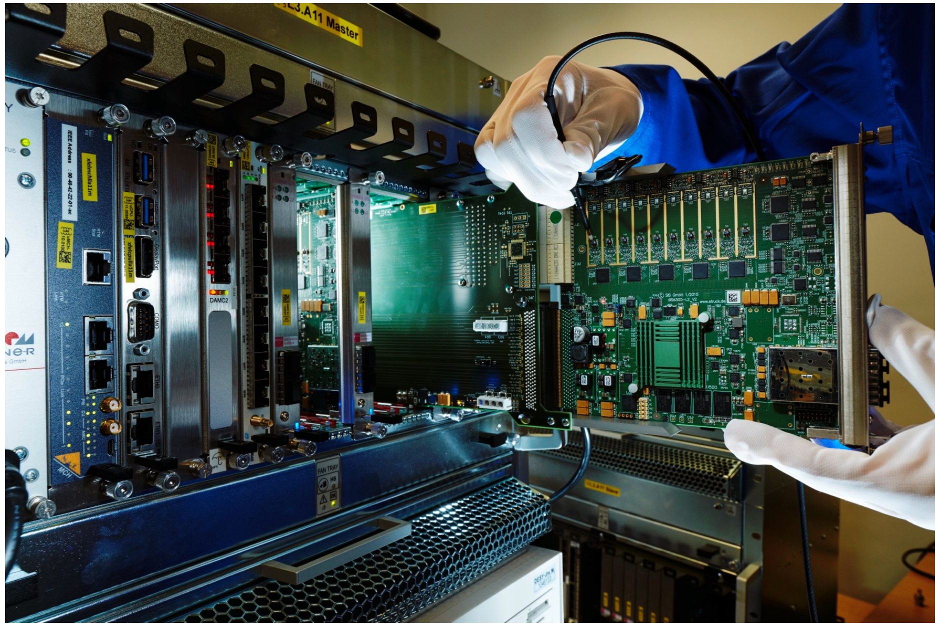
(from K. Kubo et al. Proc. IPAC 2014)

Accelerator Builder's Challenge – Feasible?

Modern technology approaching atto-second regime

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).

One of the Holy Grails: Reaching FEL Quality

Adapted from P. Schmüser

FEL
=
The Power of Coherence

FEL Needs High Quality Beam

Plasma accelerators have small dimensions and they have/should have small dimensions beams! 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 %**	(whole bunch)

First Laser-Driven FEL Lasing at SIOM

27 nm FEL radiation from a laser-driven plasma accelerator

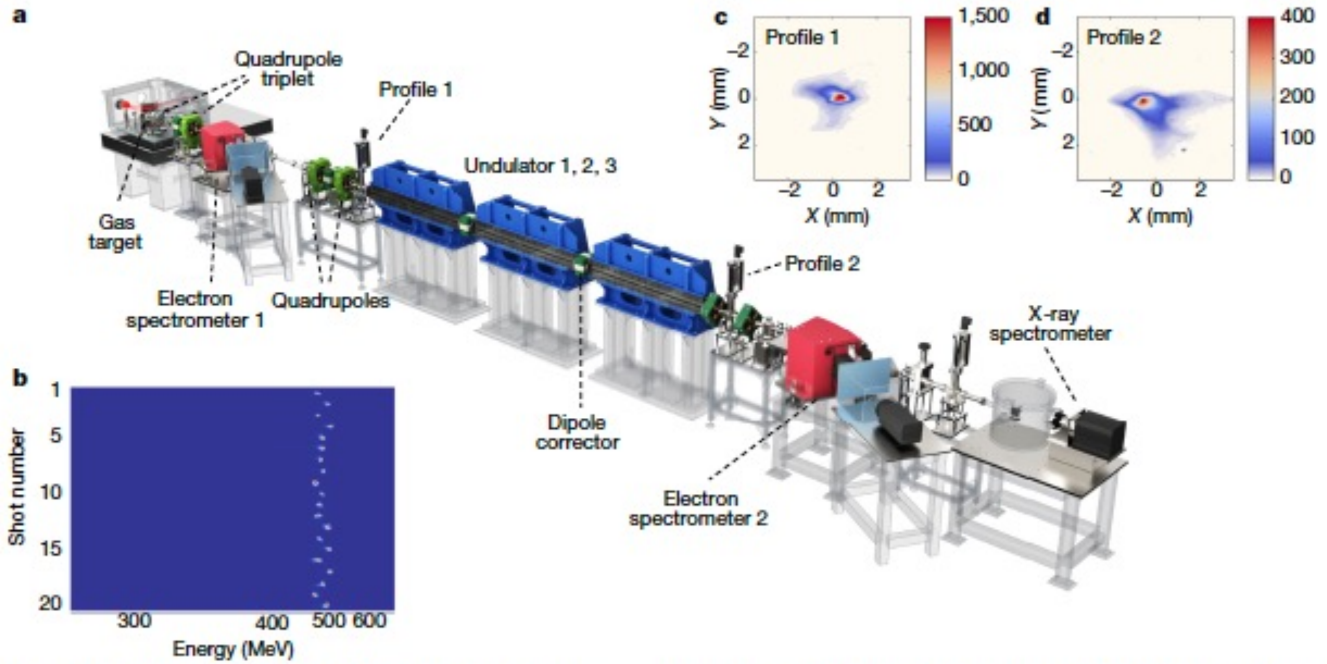


Fig. 1 | Schematic layout of LWFA-based free electron laser experiment. **a**, Undulator beamline with a total length of approximately 12 m from the gas target for the LWFA to the X-ray spectrometer. **b**, Typical spectra of electron beams from the LWFA for 20 consecutive shots. **c**, **d**, Measured transverse profiles of the electron beam at the entrance (**c**) and exit (**d**) of the undulators. The scale bars are normalized.

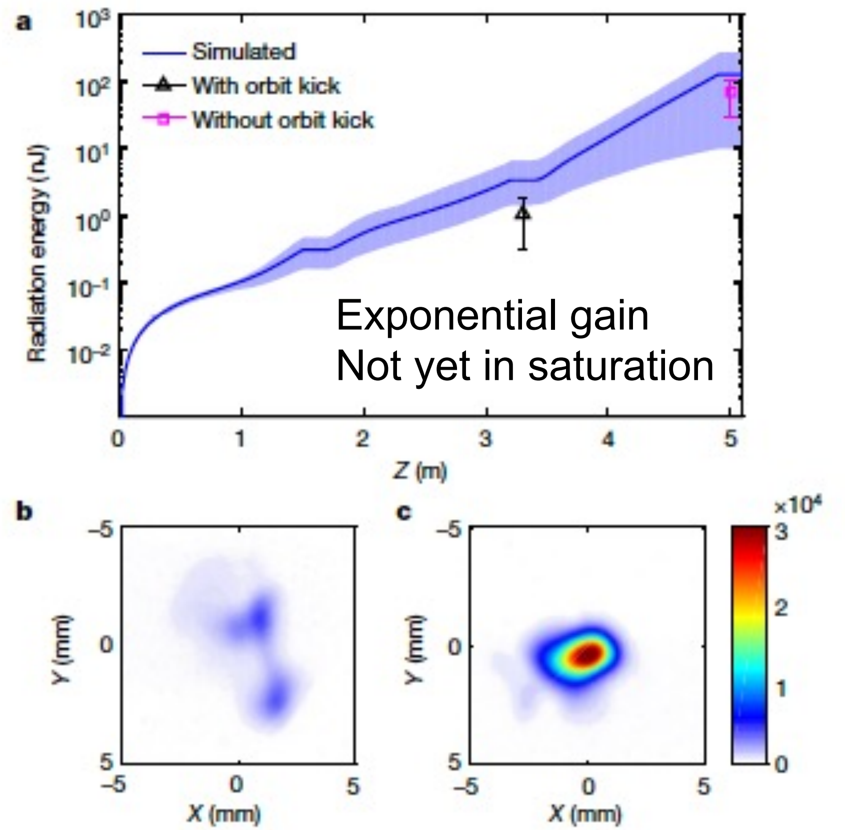
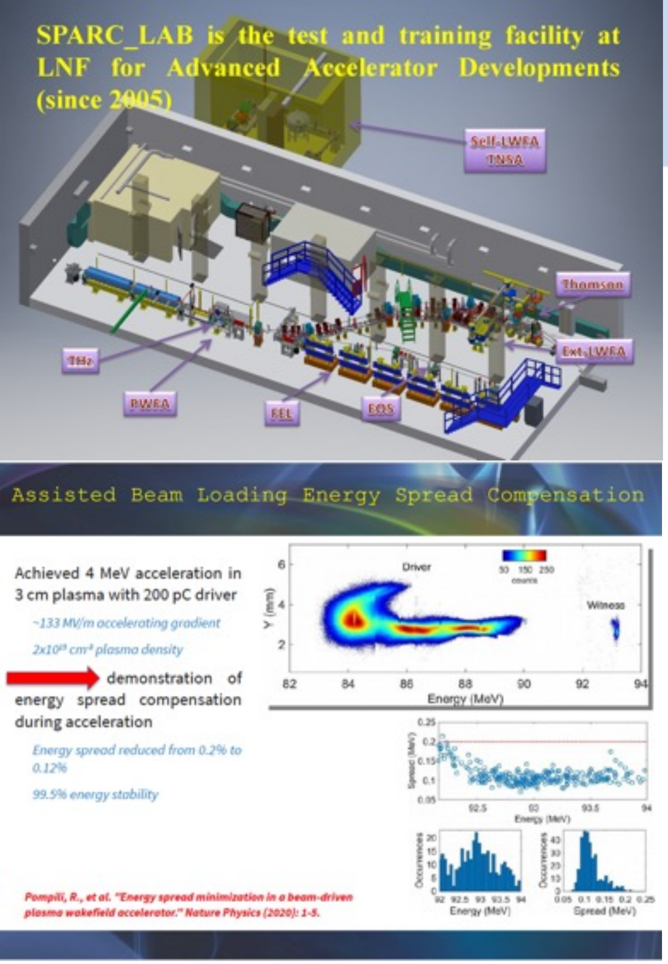


Fig. 3 | Undulator radiation measurement at 27 nm. **a**, Measured radiation energy with (black) and without (magenta) the orbit kick and the simulated energy along the undulator. Error bars represent the r.m.s. statistical uncertainty in the measured energy averaged over 20 shots. **b**, **c**, Corresponding transverse-beam patterns of the radiation measured with (**b**) and without (**c**) the orbit kick. The scale bar is normalized.

Figures from: Wang, W., Feng, K., Ke, L. *et al.* Free-electron lasing at 27 nanometres based on a laser wakefield accelerator. *Nature* **595,** 516–520 (2021). https://doi.org/10.1038/s41586-021-03678-x



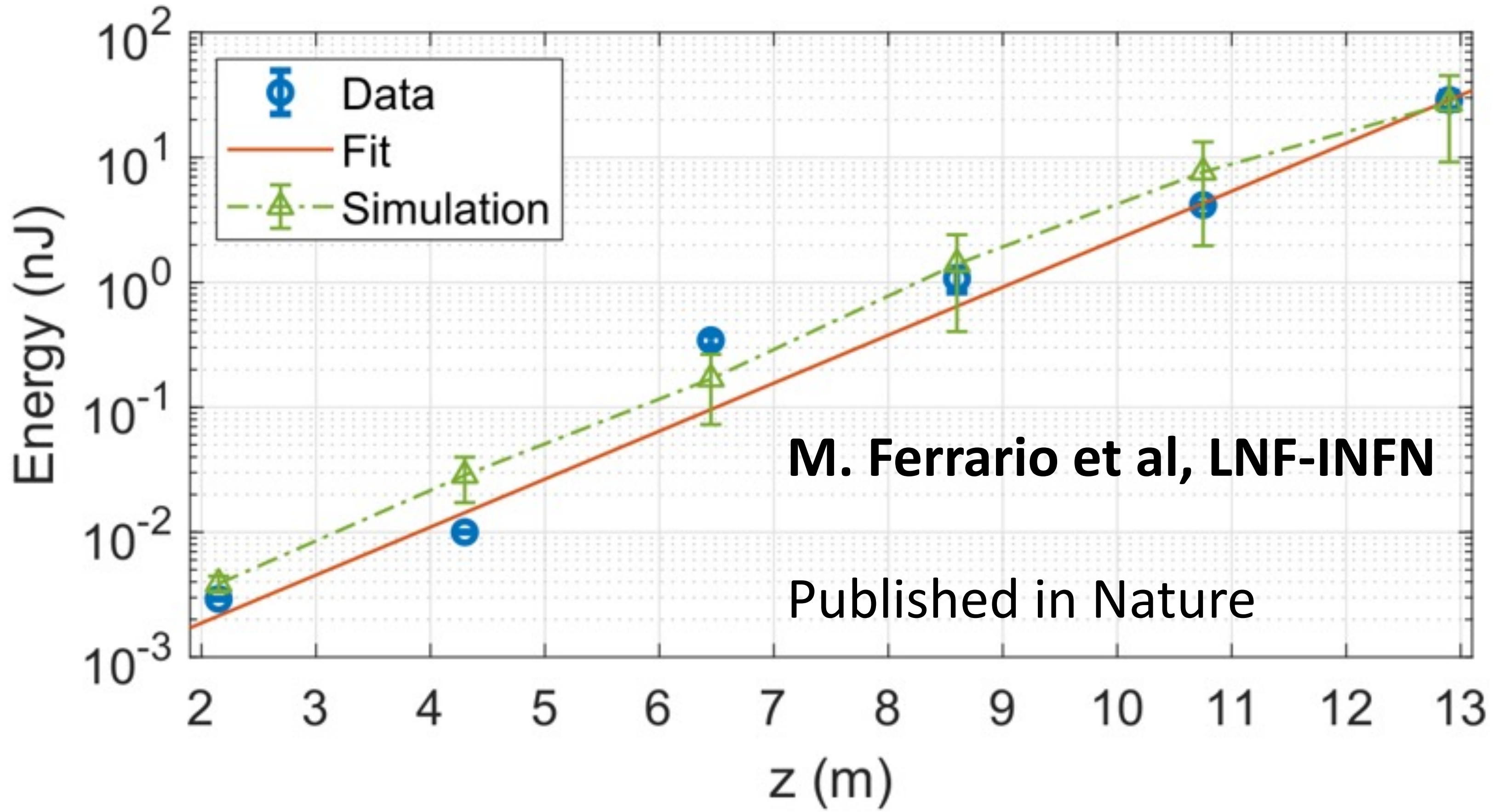
M. Ferrario et al

Submitted to Nature

First SASE-FEL Lasing at SPARC_LAB

in a beam-driven plasma wakefield accelerator

FEL Energy gain along the undulators:



M. Ferrario et al, LNF-INFN

Published in Nature

Breakthrough LNF, SIOM: Experimental proof that plasma accelerated electron beams are good enough for free-electron lasers (and colliders?)

Contents

EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA = A New European Research Infrastructure Based on Plasma Accelerators

This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement No. 101079773

The EuPRAXIA Project

http://www.eupraxia-project.eu/

Funded by the European Union

- First ever design of a **plasma accelerator facility**.
- **Conceptual Design Report for a distributed research infrastructure** funded by EU Horizon2020 program. Completed by 16+25 institutes.
- Challenges addressed by EuPRAXIA since 2015:
  - **Can plasma accelerators produce usable electron beams**?
  - **For what can we use those beams** while we increase the beam energy towards HEP and collider usages?
- Next phase consortium: **> 50 institutes**
- Preparatory Phase project: **2022 – 2026** (approved)
- Start of 1st operation: **2028**

600+ page CDR, 240 scientists contributed

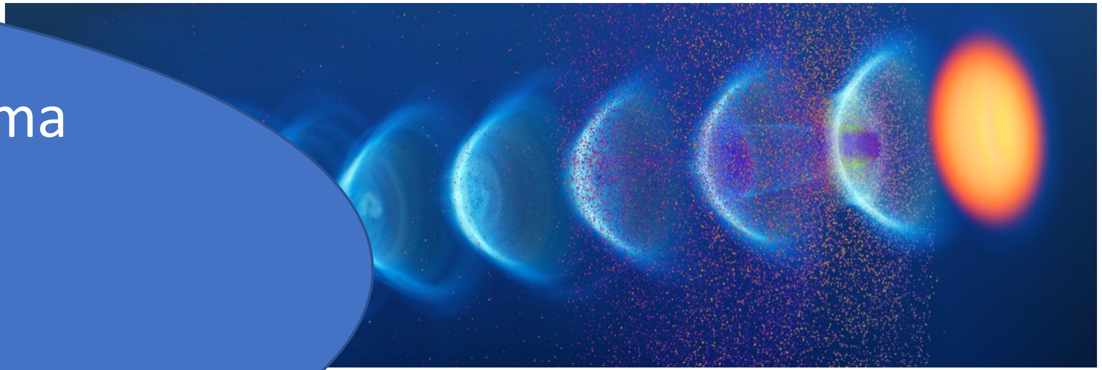
A New European High-Tech Research Facility Delivering Frontier Science

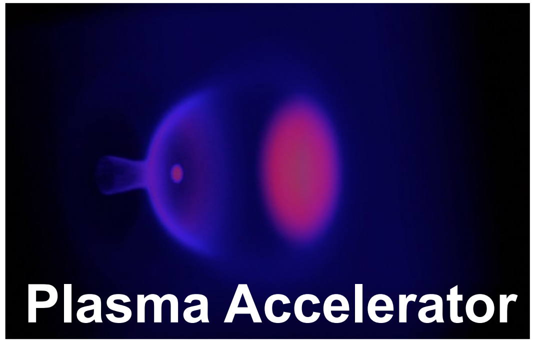
Funded by the European Union

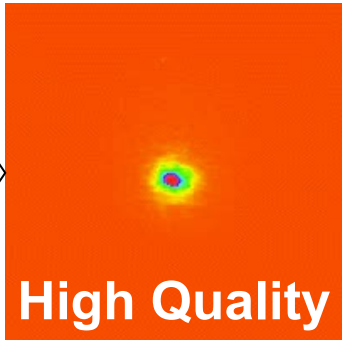
1

Building a facility with very high field plasma accelerators, driven by lasers or beams
1 – 100 GV/m accelerating field

Shrink down the facility size







http://www.eupraxia-project.eu/

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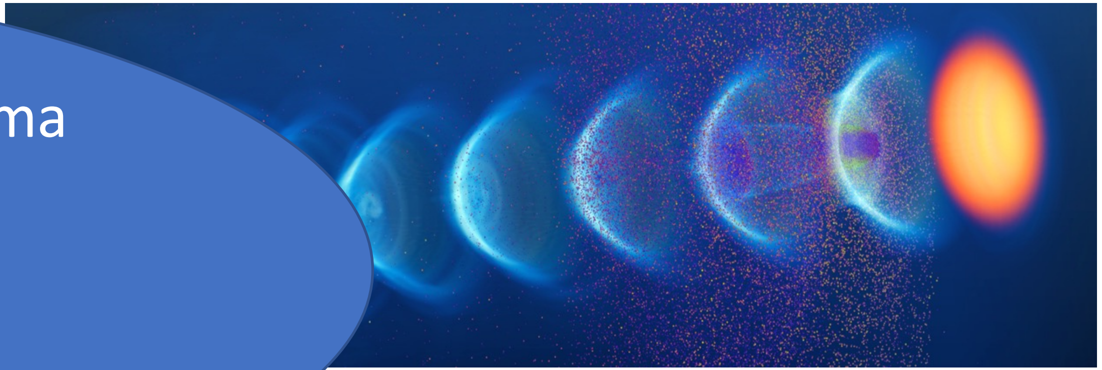
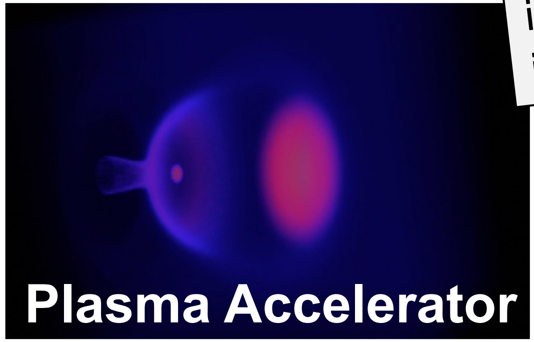
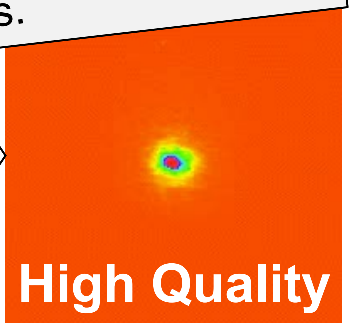


Added value
new RI's due to compactness and cost-efficiency – ultra-fast science bringing new capabilities to institutes, hospitals, universities, industry, countries.



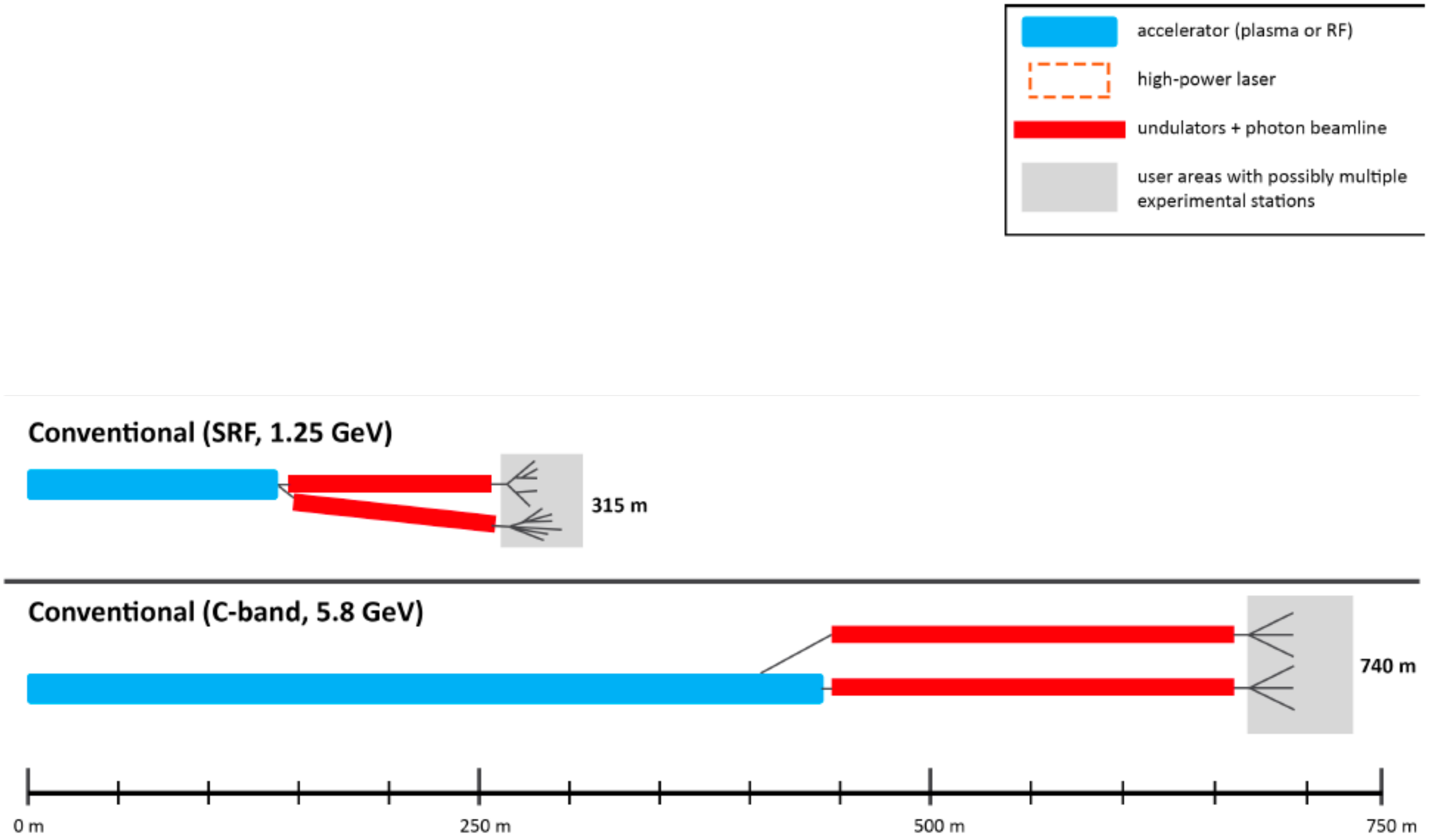


EUROPEAN PLASMA RESEARCH ACCELERATOR WITH EXCELLENCE IN APPLICATIONS

http://www.eupraxia-project.eu/

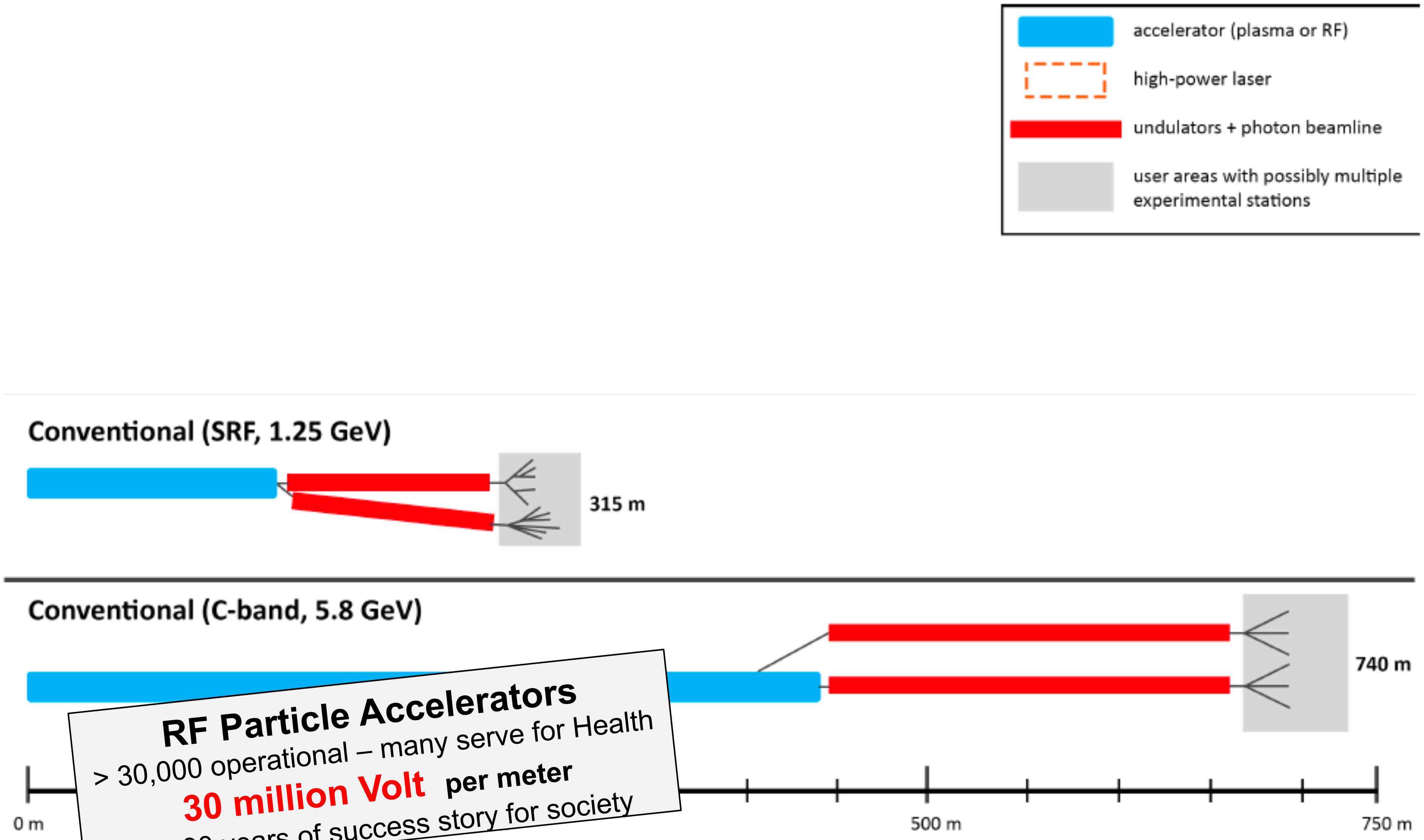
EuPRAXIA Facility Size: C O M P A C T

Funded by the European Union



EuPRAXIA Facility Size: C O M P A C T

Funded by the European Union



RF Particle Accelerators

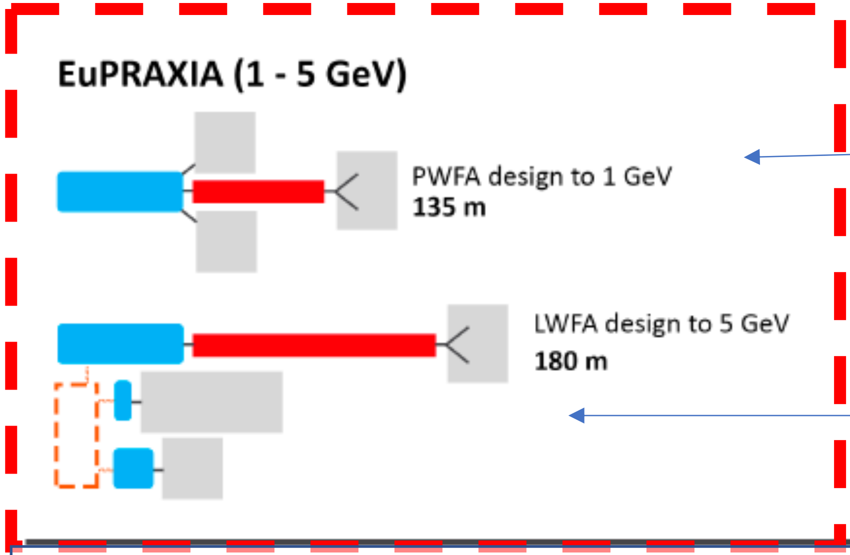
> 30,000 operational – many serve for Health

30 million Volt per meter

RF: 90 years of success story for society

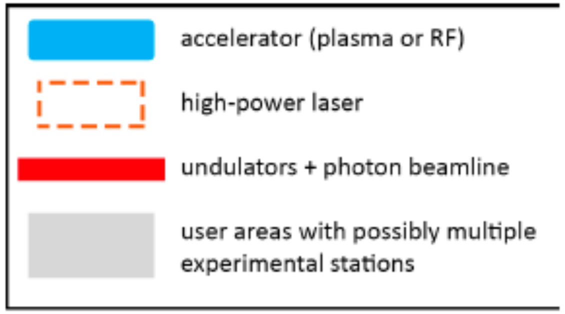
EuPRAXIA Facility Size: C O M P A C T

Funded by the European Union



EuPRAXIA at Frascati

EuPRAXIA at ***ELI-Beamlines or EPAC or Pisa or ???***



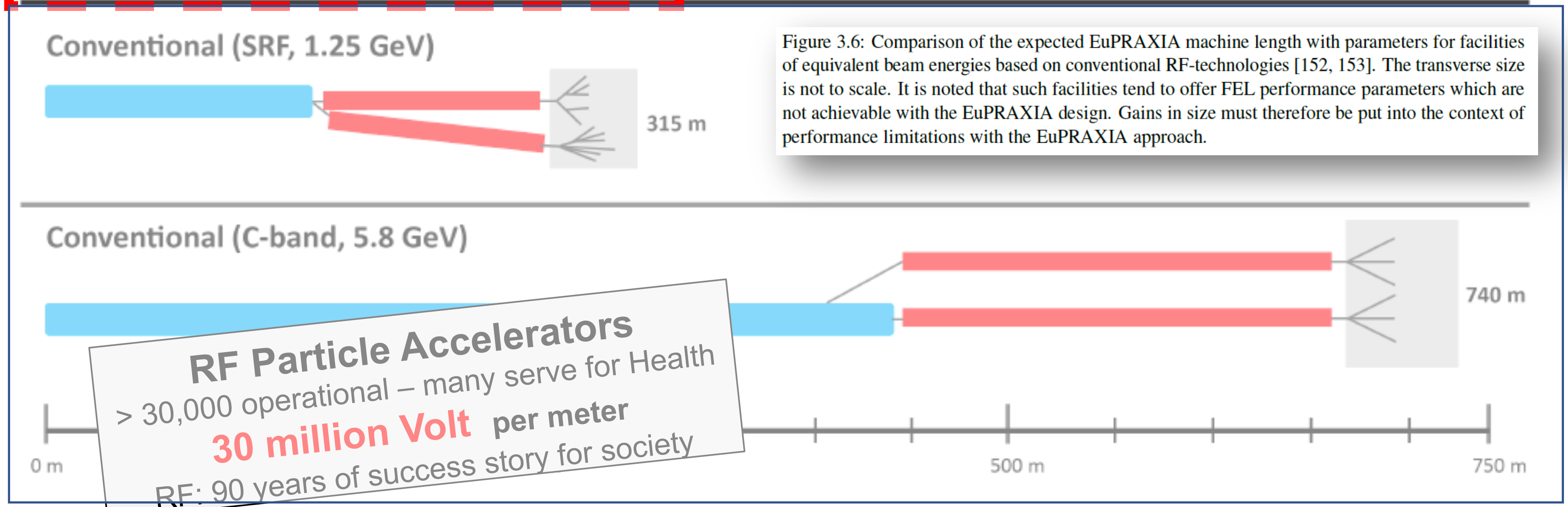


Figure 3.6: Comparison of the expected EuPRAXIA machine length with parameters for facilities of equivalent beam energies based on conventional RF-technologies [152, 153]. The transverse size is not to scale. It is noted that such facilities tend to offer FEL performance parameters which are not achievable with the EuPRAXIA design. Gains in size must therefore be put into the context of performance limitations with the EuPRAXIA approach.

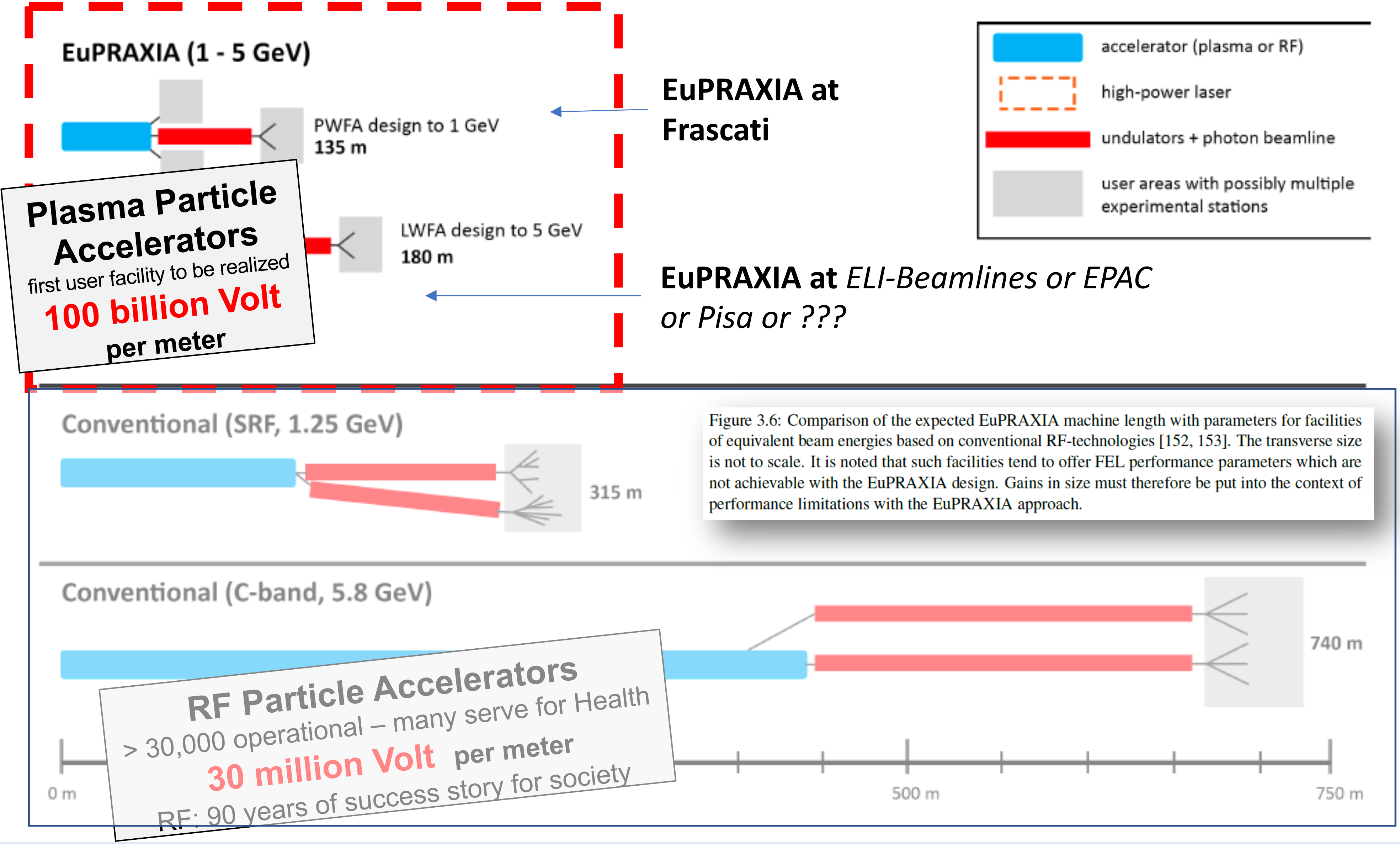
RF Particle Accelerators
> 30,000 operational – many serve for Health
30 million Volt per meter
RF: 90 years of success story for society

- Distributed
- **2 Construction Sites**
- Several Excellence Centers

IMPORTANT:
EuPRAXIA design includes **innovative concepts & solutions** but also lab space, RF injectors, transfer lines, undulator lines, shielding, ... (the **real space** needed)

EuPRAXIA Facility Size: C O M P A C T

Funded by the European Union



EuPRAXIA at Frascati

EuPRAXIA at ***ELI-Beamlines or EPAC or Pisa or ???***

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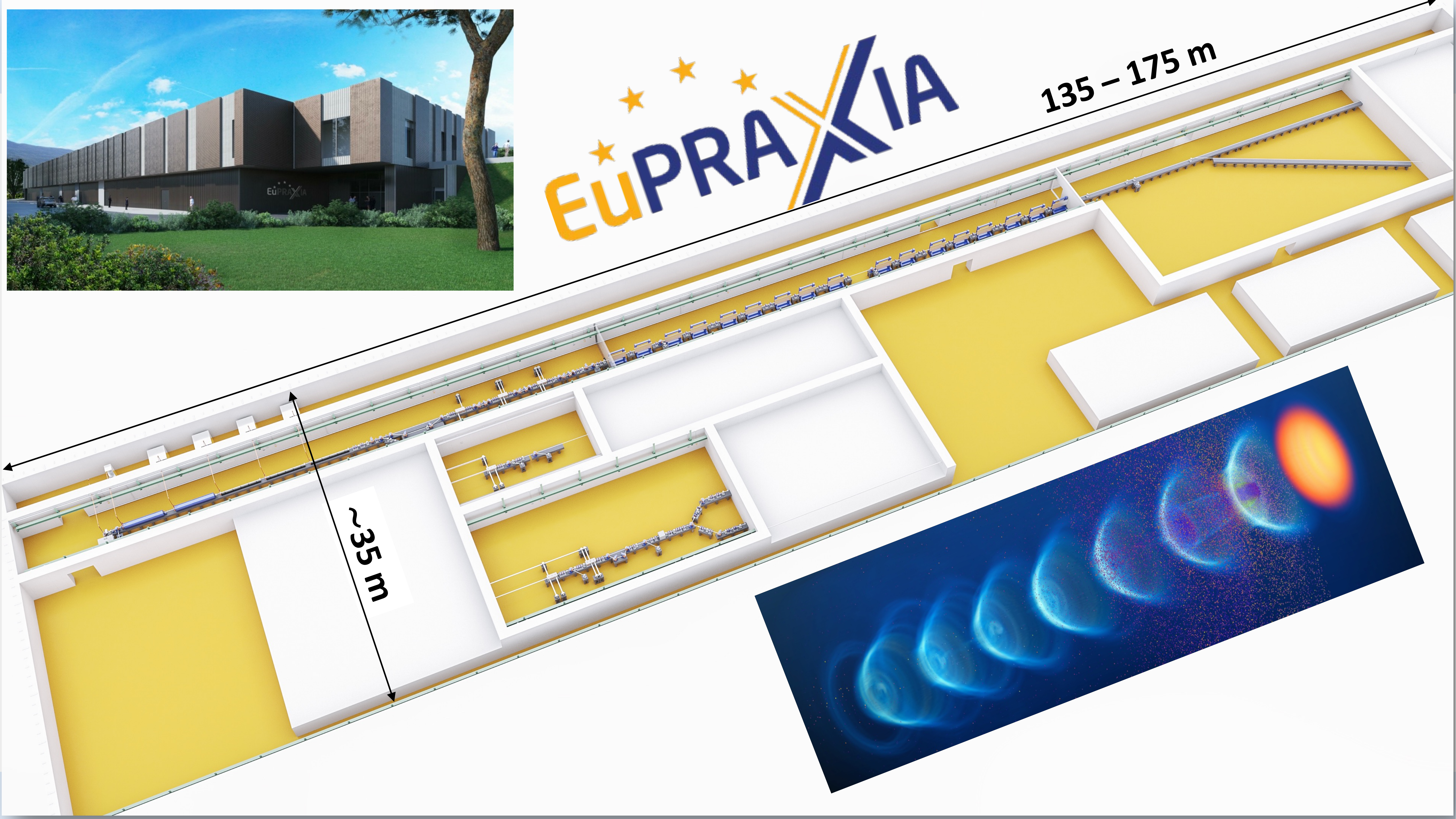
EuPRAXIA
135 – 175 m
~35 m

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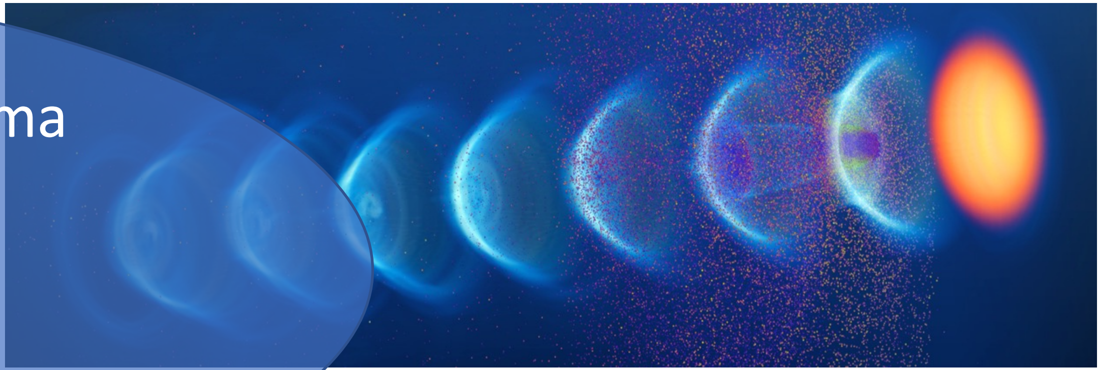
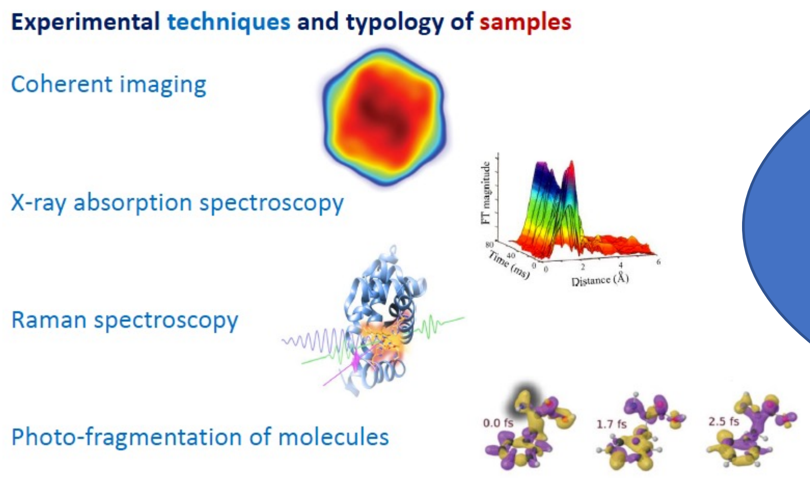
Shrink down the facility size





2

Producing particle and photon pulses to support several urgent and timely science cases

Enable frontier science in new regions and parameter regimes

Probing for New Particles and Forces

Horizon2020

Higgs Seminar 4.7. 2012

Understanding fundamental laws

Producing X Rays for Inspection

Horizon2020

X-Ray radiography – Cargo inspection with a **compact 6 MeV linear electron accelerator**

Protecting people

Irradiating and Destroying Tumor Cells

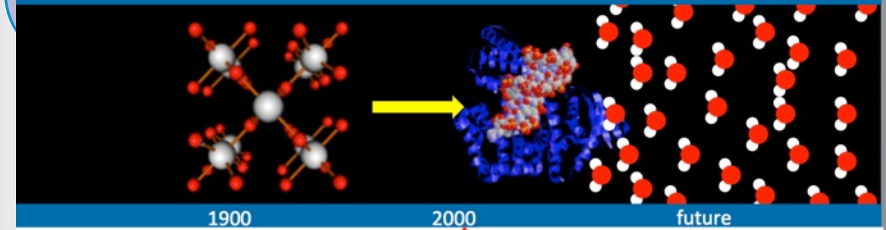
Horizon2020

Heidelberg Ion-Beam Therapy Center (HIT)

Curing people

Producing Light and Filming Molecular Movies

Horizon2020



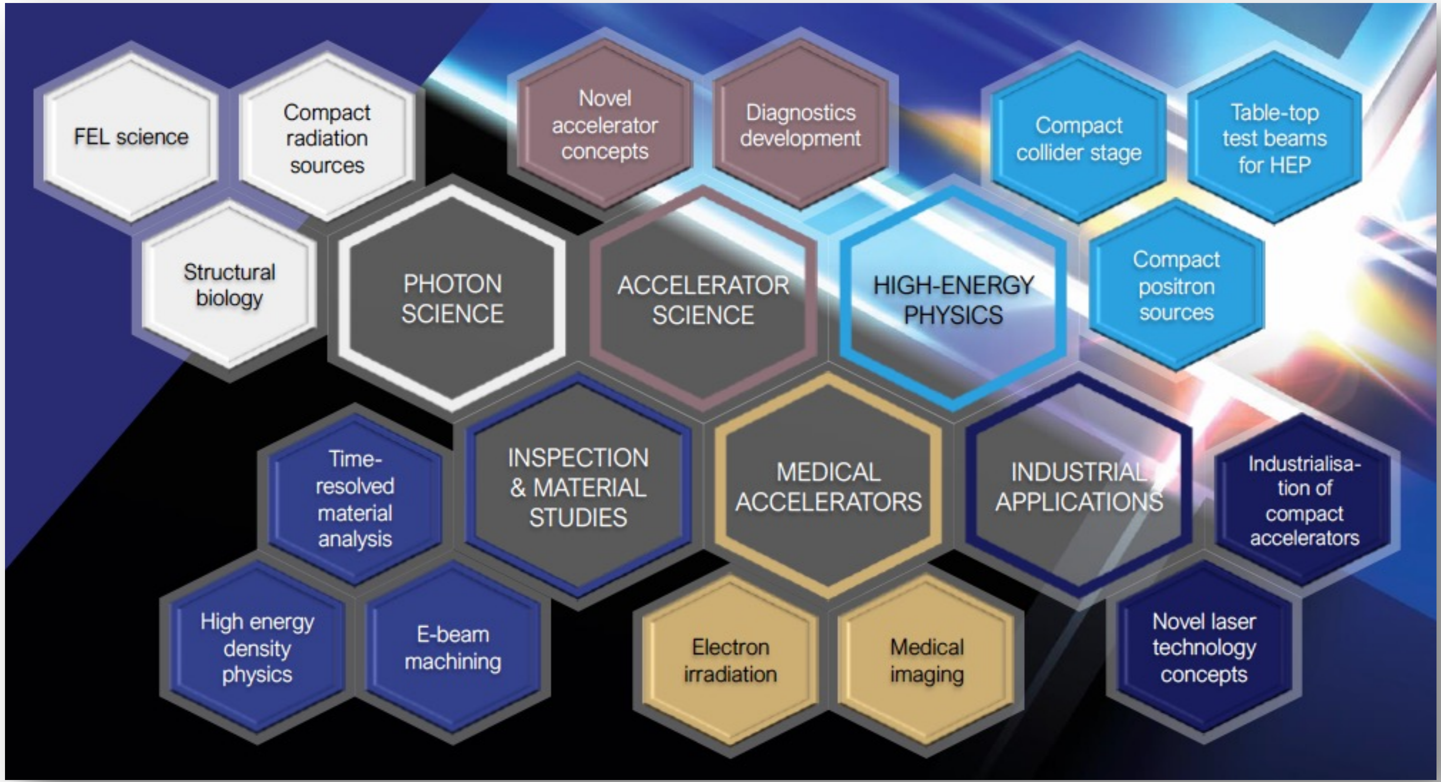
you are here

Era of Crystalline Matter	Era of Complex Matter
Ordered Structures	Locally Ordered Structures
Equilibrium Phenomena	Nonequilibrium Phenomena
Phase Diagrams	Transient States

State of the art accelerators for the best light possible

Synchrotron radiation from accelerators	X-Ray Lasers acc. + High Brilliance SR acc.

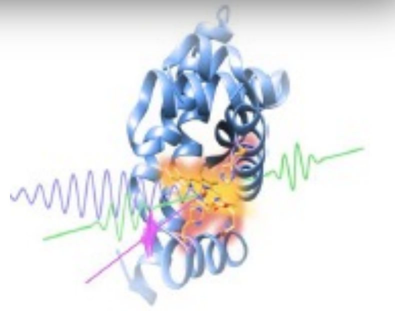
Versatile – Designed for Users in Multiple Science Fields



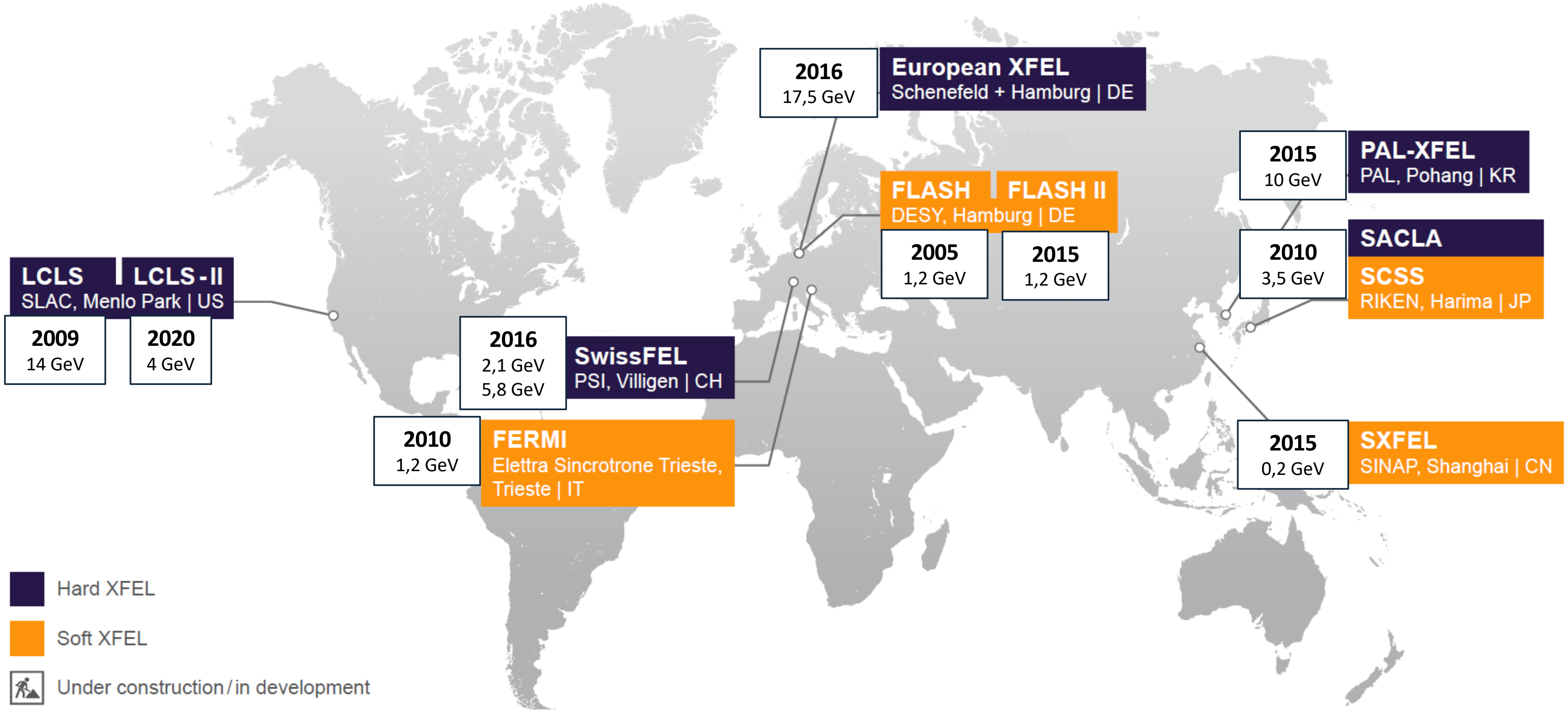
*Delivers 10-100 Hz **ultra-short** pulses*

- **Electrons**
  (0.1-5 GeV, 30 pC)
- **Positrons**
  (0.5-10 MeV, 10^6)
- **Positrons** (GeV source)
- **Lasers**
  (100 J, 50 fs, 10-100 Hz)
- **Betatron X rays**
  (1-110 keV, 10^{10})
- **FEL light**
  (0.2-36 nm, 10^9-10^{13})

Topics of research: proteins, viruses, bacteria, cells, metals, semiconductors, superconductors, magnetic materials, organic molecules



X Ray FEL User Facilities World-Wide



2005: **1** → 2015: **5** → 2022: **8** → 2029: **10** (?) → 2036: **???**

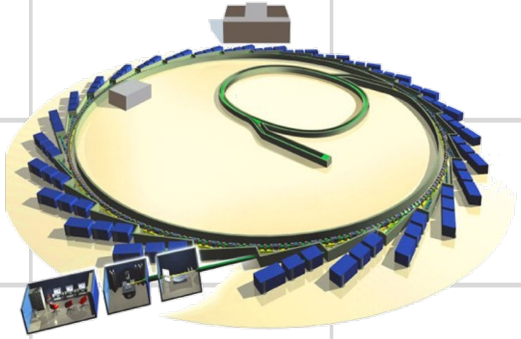
- **Tremendous success story**
- New facilities and strong upgrade program
- **New projects**:
  - MAX IV FEL (CDR)
  - EuPRAXIA (TDR, ESFRI Project)
  - POLFEL
  - UK FEL

Human-made Sources of Light

Funded by the European Union

Visible light

Ultraviolet light



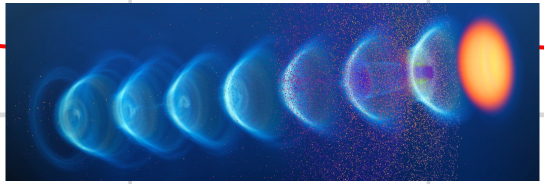
Soft X Rays

FELs OF EUROPE

Hard X Rays

Gamma Rays

Compact plasma-based source



1 µm | 100 nm | 10 nm | 1 nm | 100 pm | 10 pm | 1 pm | 100 fm | 10 fm

New capabilities with light sources based on circular (1970) and linear (2005) particle accelerators

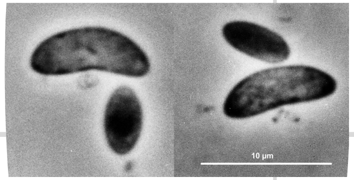
X rays with extremely high brilliance and time resolution capabilities

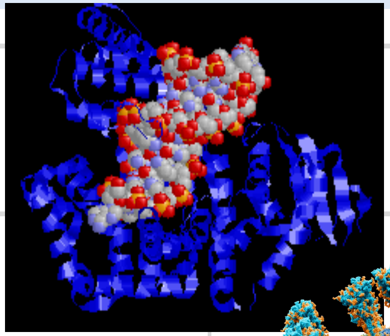
*Problem: **BIG** and expensive*

Why Additional Compact *(Less Powerful)* FEL`s?

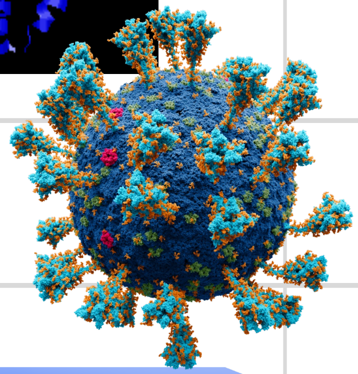
Visible light

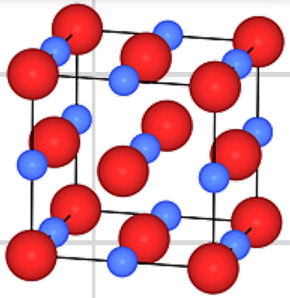
Ultraviolet light





Soft X Rays





Hard X Rays

Gamma Rays

EuPRAXIA

1 µm | 100 nm | 10 nm | 1 nm | 100 pm | 10 pm | 1 pm | 100 fm | 10 fm

Practically unlimited number of study objects with potentially high impact on our lives:

- About 320,000 unknown viruses that infect mammals
- There may be a million bacterial species in 30 grams of rich soil in Norway
- Need for access and screening time – work for students at many universities

Funded by the European Union

Already working today: Medical Imaging

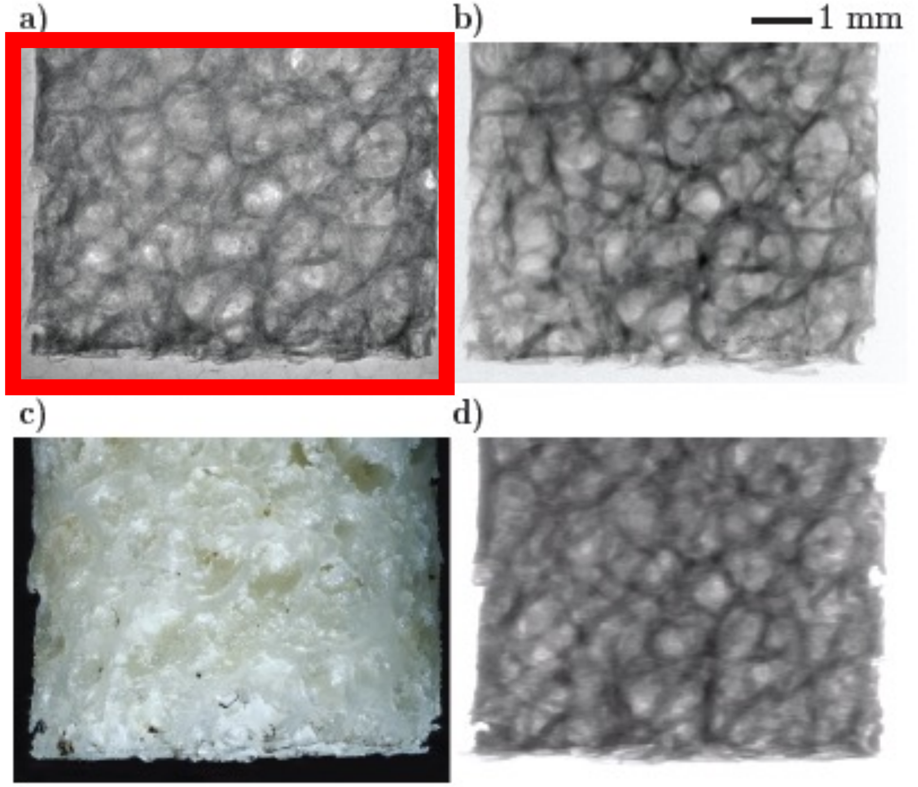
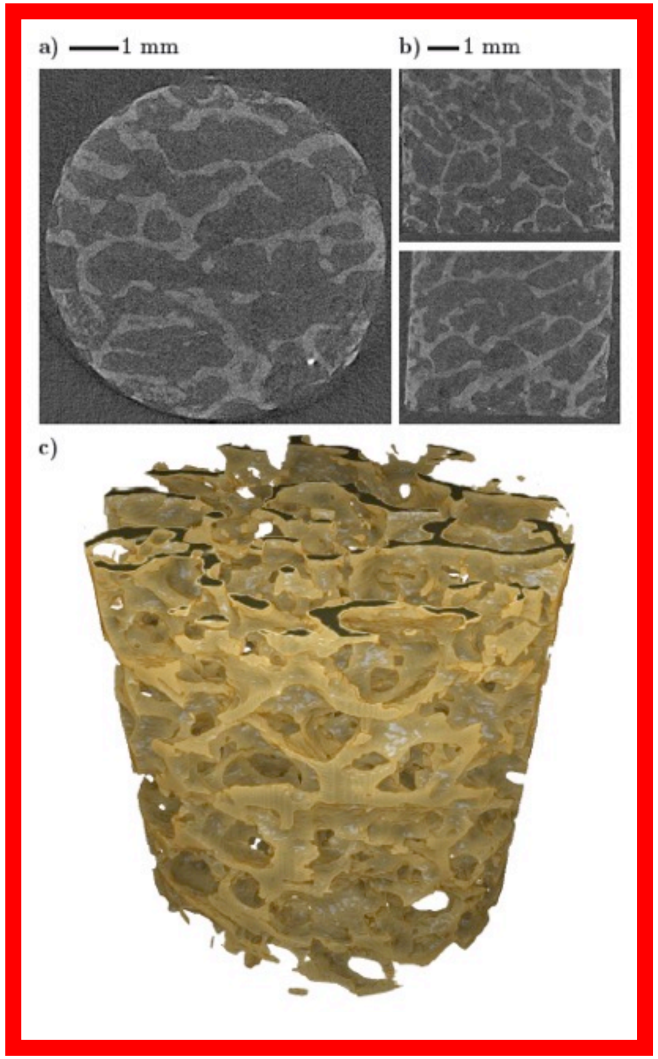


Figure 3. Images of the bone sample recorded with a) the betatron x-ray source b) conventional μCT scanning c) composite macro photography d) virtual illumination of the 3D reconstruction by a source of $E_{crit} = 33\,\text{keV}$.



Laser-wakefield accelerators as hard x-ray sources for 3D medical imaging of human bone

J. M. Cole, J. C. Wood, N. C. Lopes, K. Poder, R. L. Abel, S. Alatabi, J. S. J. Bryant, A. Jin, S. Kneip, K. Mecseki, D. R. Symes, S. P. D. Mangles & Z. Najmudin

Scientific Reports **5**, Article number: 13244 (2015)
doi:10.1038/srep13244

Received: 29 January 2015
Accepted: 20 July 2015
Published online: 18 August 2015

from J.M. Cole et al, John-Adams-Institute, UK

Laser plasma based betatron X ray source

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

EuPRAXIA

*Fully plasma-based beamline for generating betatron radiation as a **compact X-ray source for medical imaging and material analysis**. The user area is behind the wall on the right.*

EuPRAXIA facility rendering picture

European Plasma Research Accelerator with eXcellence In Applications

Press Release ESFRI 30.6.21

https://www.esfri.eu/latest-esfri-news/new-ris-roadmap-2021

ESFRI

ABOUT

HOME > NEWS > LATEST ESFRI NEWS

ESFRI announces new RIs for R

- There is a **new level of ambition** to develop globally unique, complex facilities for frontier science: Einstein Telescope – highest value project ever on the Roadmap - EUR 1.900 million, and EuPRAXIA – innovative accelerator based on plasma technology - EUR 569 million.

30.06.2021

PRESS RELEASE

ESFRI announces the 11 new Research Infrastructures to be included in its Roadmap 2021

€4.1 billion investment in excellent science contributing to address European challenges

After two years of hard work, following a thorough evaluation and selection procedure, ESFRI proudly announces the **11 proposals** that have been scored high for their science case and maturity for implementation and will be included as new Projects in the **ESFRI 2021 Roadmap Update**.

neuroscience, computing and technology, offering scientists and developers advanced tools and services for brain research.

- **EIRENE RI** - Research Infrastructure for EnvIRonmental Exposure assessment in Europe, the first EU infrastructure on human exposome (environmental determinants of health).
- **ET** - Einstein Telescope, the first and most advanced third-generation gravitational-wave observatory, with unprecedented sensitivity that will put Europe at the forefront of the Gravitation Waves research.
- **EuPRAXIA** - European Plasma Research Accelerator with Excellence in Applications, a distributed, compact and innovative accelerator facility based on plasma technology, set to construct an electron-beam-driven plasma accelerator in the metropolitan area of Rome, followed by a laser-driven plasma accelerator in European territory.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

EuPRAXIA-Preparatory Phase Consortium

34 Institutes from 12 Countries → to be merged with ESFRI Consortium

Funded by the European Union

EuPRAXIA Preparatory Phase

Coordinator

Università di Roma Tor Vergata
Consiglio Nazionale delle Ricerche
SAPIENZA Università di Roma
ENEA Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile
INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati
Elettra Sincrotrone Trieste

TÉCNICO LISBOA
eli beamlines

IASA

FBH Leibniz Ferdinand Braun Institut
Fraunhofer ILT

Wigner
SZTE University of Szeged
Pécsi Tudományegyetem University of Pécs

cnrs
cea
THALES

DESY.
HZDR Helmholtz Zentrum Dresden Rossendorf
JÜLICH Forschungszentrum
LMU Ludwig-Maximilians-Universität München

EPFL
Empa Materials Science and Technology

ALBA
CLPU Centro de Láseres Pulsados

UK Research and Innovation
University of Liverpool
University of Oxford
Queen's University Belfast
University of Strathclyde Glasgow
Imperial College London

CERN

The Hebrew University of Jerusalem
UCLA

Complemented by institutes in **EuPRAXIA ESFRI consortium: additional 17 institutes** from France, Germany, Poland, Sweden, United Kingdom, China, Japan, United States. Russian institutes presently suspended.

PP Steering Committee: Leaders Behind EuPRAXIA

Funded by the European Union

- Governing Board (Decision-making body)
- Steering Committee
- Scientific Advisory Board
- Technical & Industrial Advisory Board
- Board of Financial Sponsors

WP1 - Coordination & Project Management
R. Assmann, INFN & DESY
M. Ferrario, INFN

WP2 - Dissemination and Public Relations
C. Welsch, U Liverpool
S. Bertellii, INFN

WP3 - Organization and Rules
A. Specka, CNRS
A. Ghigo, INFN

WP4 - Financial & Legal Model. Economic Impact
A. Falone, INFN

WP5 - User Strategy and Services
F. Stellato, U Tor Vergata
E. Principi, ELETTRA

WP6 - Membership Extension Strategy
B. Cros, CNRS
A. Mostacci, U Sapienza

WP's on coordination & implementation as ESFRI RI (organization, legal model, financing, users)

WP7 - E-Needs and Data Policy
R. Fonseca, IST
S. Pioli, INFN

WP8 - Theory & Simulation
J. Vieria, IST
H. Vincenti, CEA

WP9 - RF, Magnets & Beamline Components
S. Antipov, DESY
F. Nguyen, ENEA

WP10 - Plasma Components & Systems
K. Cassou, CNRS
J. Osterhoff, DESY

WP11 - Applications
G. Sarri, U Belfast
E. Chiadroni,U Sapienza

WP12 - Laser Technology, Liaison to Industry
L. Gizzi, CNR
P. Crump, FBH

WP13 - Diagnostics
A. Cianchi, U Tor Vergata
R. Ischebeck, EPFL

WP14 - Transformative Innovation Paths
B. Hidding, U Strathclyde
S. Karsch, LMU

WP15 - TDR EuPRAXIA @SPARC-lab
C. Vaccarezza, INFN
R. Pompili, INFN

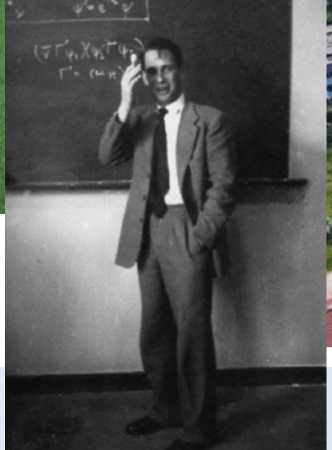
WP16 - TDR EuPRAXIA Site 2
A. Molodozhentsev, ELI-Beamlines
R. Pattahil, STFC

WPs on technical implementation and sites

Headquarter and Site 1: EuPRAXIA@SPARClab

Funded by the European Union

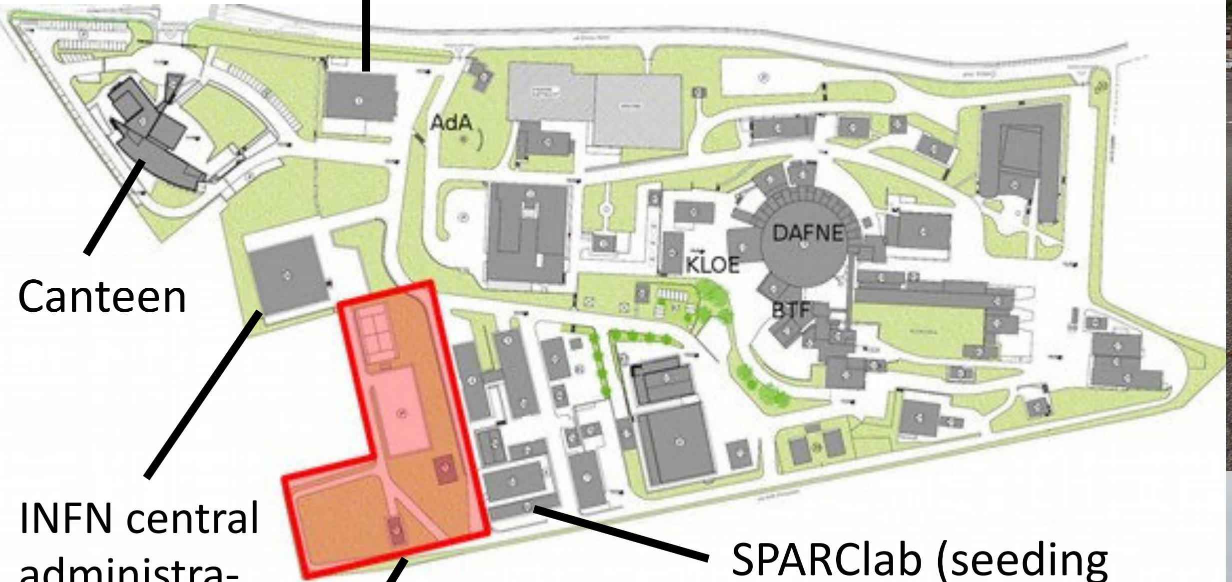
- Frascati`s future facility
- > 130 M€ invest funding
- Beam-driven plasma accelerator
- Europe`s most compact and most southern FEL
- The world`s most compact RF accelerator (X band with CERN)



It Fits the Frascati Site

(also fits sites at a large university, hospital, company, …)

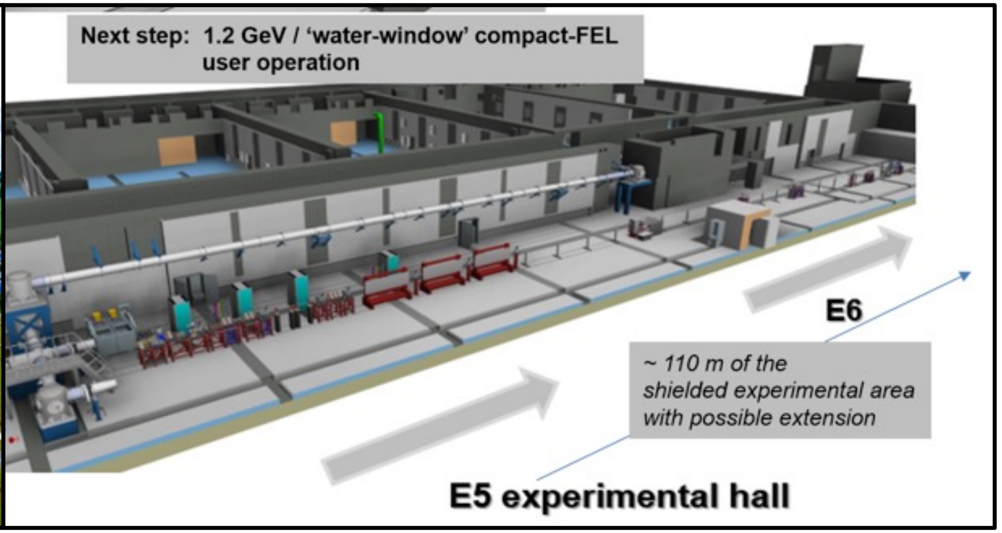
Funded by the European Union

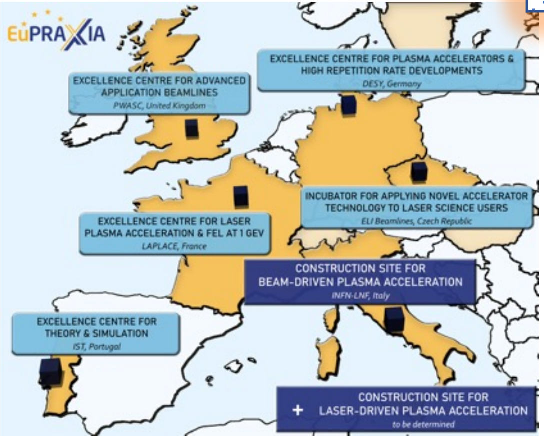


EuPRAXIA @ SPARClab

(European site 1)

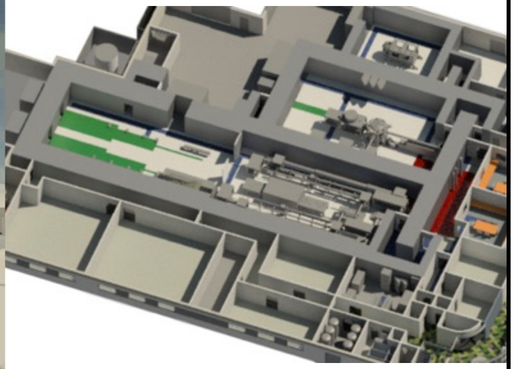
Candidate 2nd Sites from CDR





EuPRAXIA @ EPAC

Rutherford, STFC, UK



CNR Campus Pisa

Solve external timing for laser-driven plasma acc.

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

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

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

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

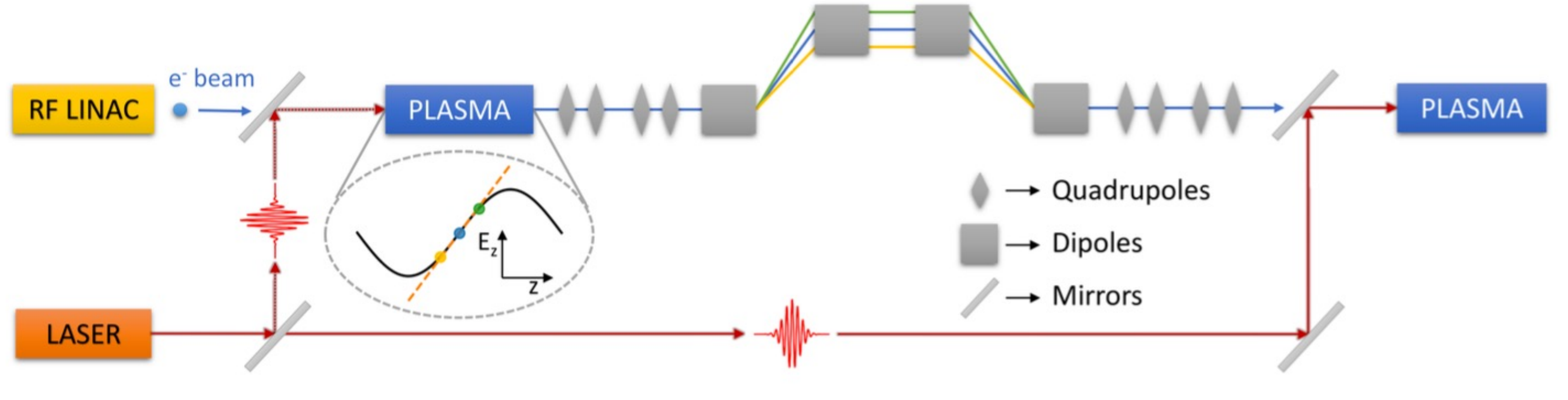


Figure 1. Schematic view of the synchronizing stage.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

Try to finally realize low energy spread…

Old proposal from Simon van der Meer

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

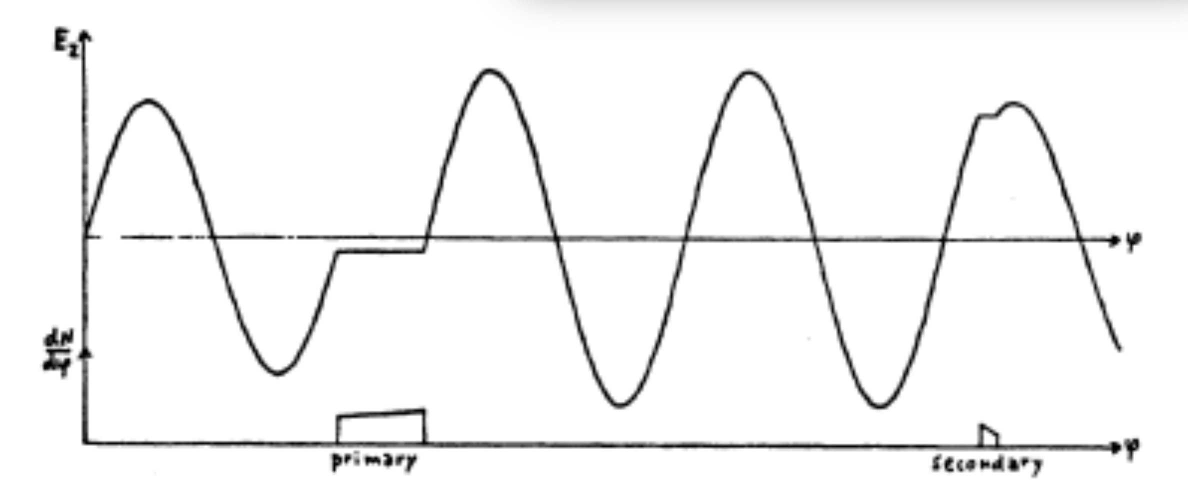
1985 van der Meer

Beam loading, energy spread and efficiency

IMPROVING THE POWER EFFICIENCY
OF THE
PLASMA WAKEFIELD ACCELERATOR

S. van der Meer

van der Meer: Nobel Prize Physics for invention of stochastic cooling → SppS collider at CERN



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

Compact Multi-Stage Plasma-Based Accelerator

PHYSICAL REVIEW LETTERS **123,** 054801 (2019)

Compact Multistage Plasma-Based Accelerator Design for Correlated Energy Spread Compensation

A. Ferran Pousa,[1,2,*] A. Martinez de la Ossa,[1] R. Brinkmann,[1] and R. W. Assmann[1]
[1]*Deutsches Elektronen-Synchrotron DESY, 22607 Hamburg, Germany*
[2]*Institut für Experimentalphysik, Universität Hamburg, 22761 Hamburg, Germany*

(Received 20 November 2018; revised manuscript received 10 June 2019; published 31 July 2019)

The extreme electromagnetic fields sustained by plasma-based accelerators could drastically reduce the size and cost of future accelerator facilities. However, they are also an inherent source of correlated energy spread in the produced beams, which severely limits the usability of these devices. We propose here to split the acceleration process into two plasma stages joined by a magnetic chicane in which the energy correlation induced in the first stage is inverted such that it can be naturally compensated in the second. Simulations of a particular 1.5-m-long setup show that 5.5 GeV beams with relative energy spreads of 1.2×10^{-3} (total) and 2.8×10^{-4} (slice) could be achieved while preserving a submicron emittance. This is at least one order of magnitude below the current state of the art and would enable applications such as compact free-electron lasers.

DOI: 10.1103/PhysRevLett.123.054801

Combined RF plus optical scheme

- 1.5 m long
- 5.5 GeV
- **0.03%** slice energy spread
- **0.12 %** total energy spread
- sub-micron emittance

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

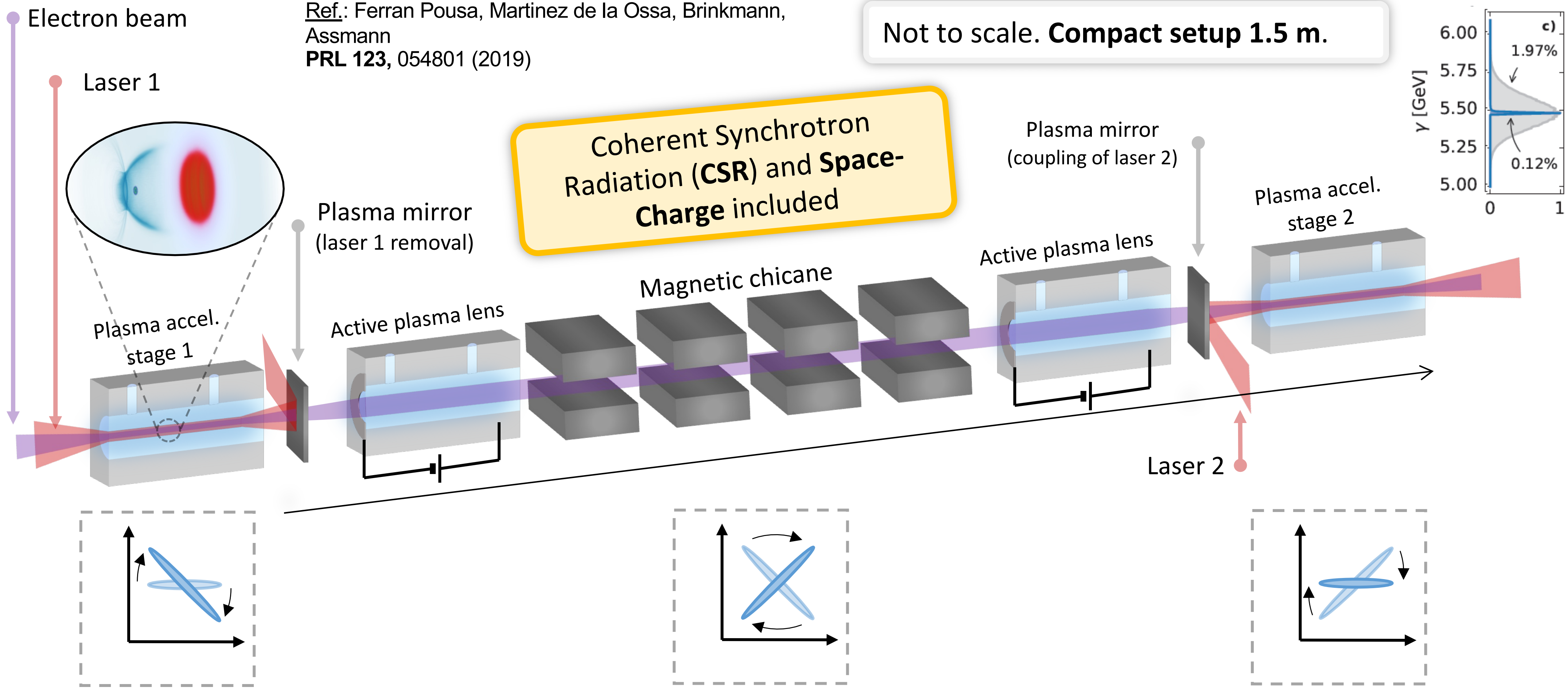
EuPRAXIA

European Plasma Research Accelerator with eXcellence In Applications

Compact Multi-Stage Plasma-Based Accelerator

Ref.: Ferran Pousa, Martinez de la Ossa, Brinkmann, Assmann
PRL 123, 054801 (2019)

Not to scale. **Compact setup 1.5 m.**



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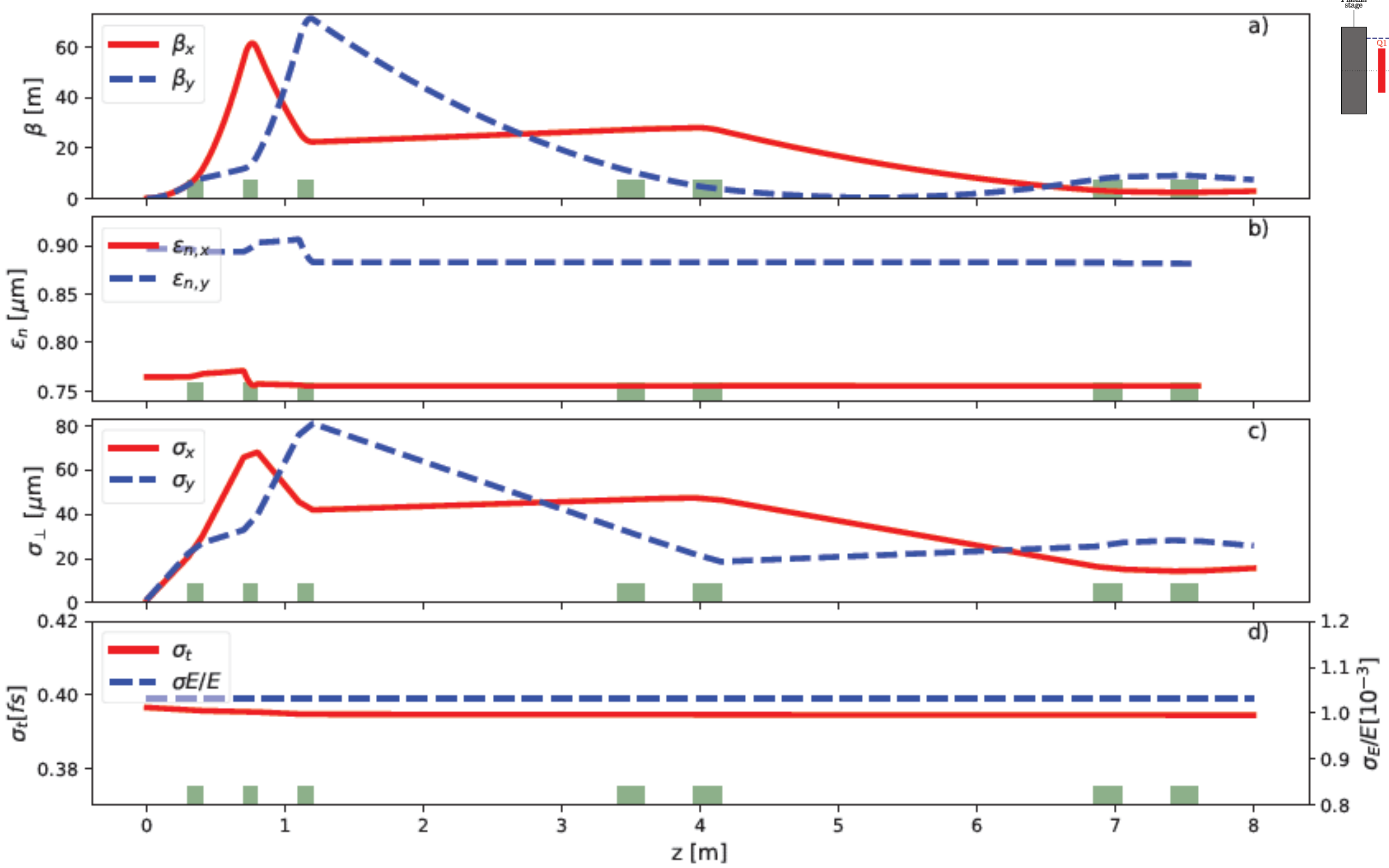
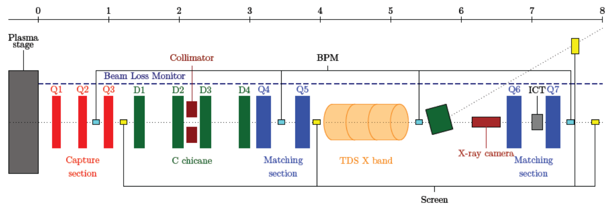
EuPRAXIA

Beam Transport Design





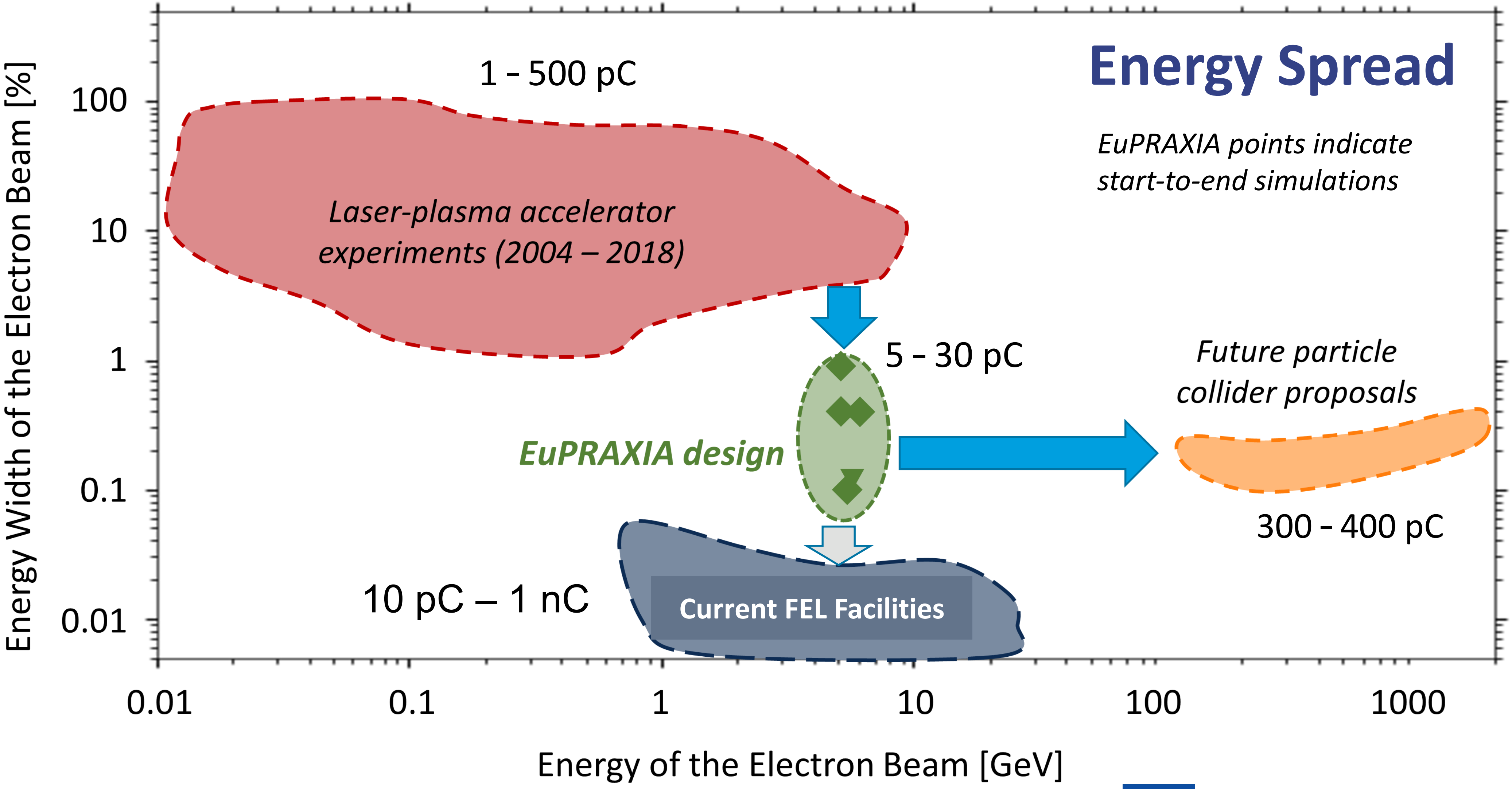
- Here: high energy **beam transport over 8 meters**
- Preserved beam quality is achieved in the design
- Space has important benefits

A. Chance et al

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

European Plasma Research Accelerator with eXcellence In Applications

EuPRAXIA: Progressing on the Quality Problem



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

Conclusions

Long-term future

- The **long-term future is bright**: there will be plenty of opportunities as technology advances!
- **Plasma accelerators** are another possible game changer. Energy very promising and beam quality still difficult but making rapid progress:
  - There are **now near future science applications outside HEP, e.g. FEL**. This can be the stepstone towards a plasma linear collider.
  - Major projects going on, all including HEP aspects.
  - The European plasma accelerator project EuPRAXIA selected for ESFRI roadmap with government support (only accelerator project since HighLumi LHC, first ever plasma accelerator project) – will build two FEL facilities!
- A long-term future with novel FEL`s and colliders does not come by itself: **We (you) must work towards this goal and support it as required**.

Wideröe at age 90

A visionary and optimist from young to old age

"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**."