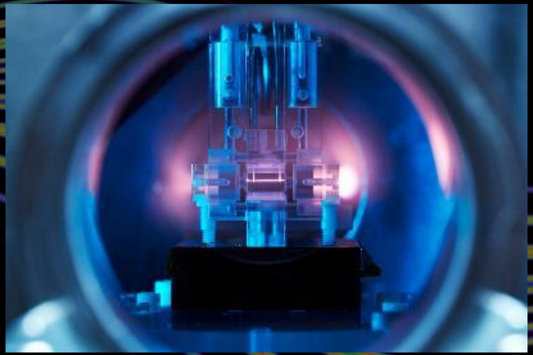
Novel High Gradient Particle Accelerators

Can we build smaller, less expensive accelerators?



JUAS 2019

Archamps, France

30 January 2019

Ralph W. Aßmann, DESY

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

MATTER AND TECHNOLOGIES

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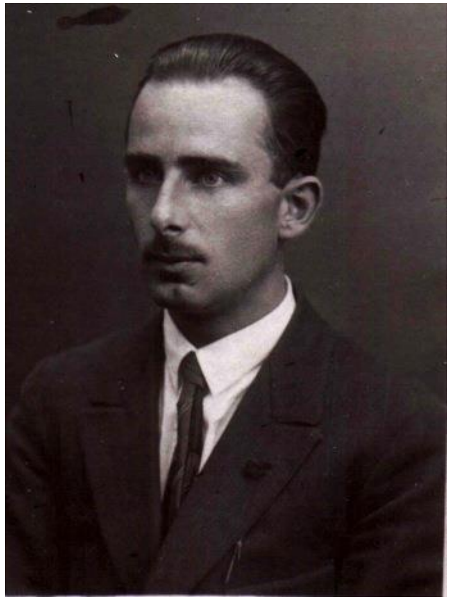
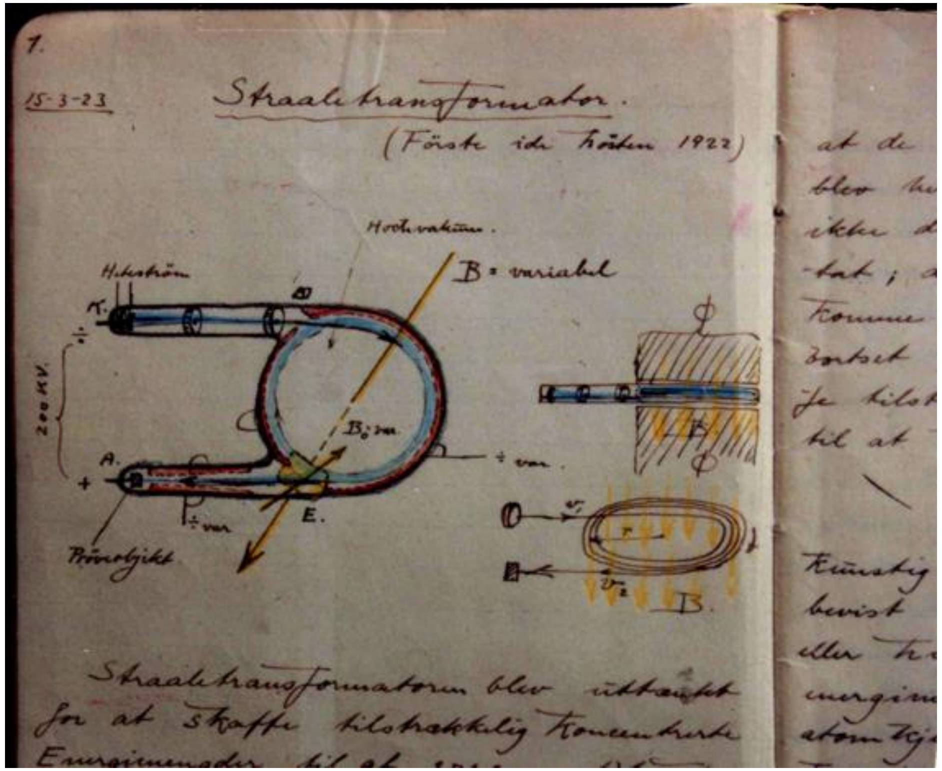
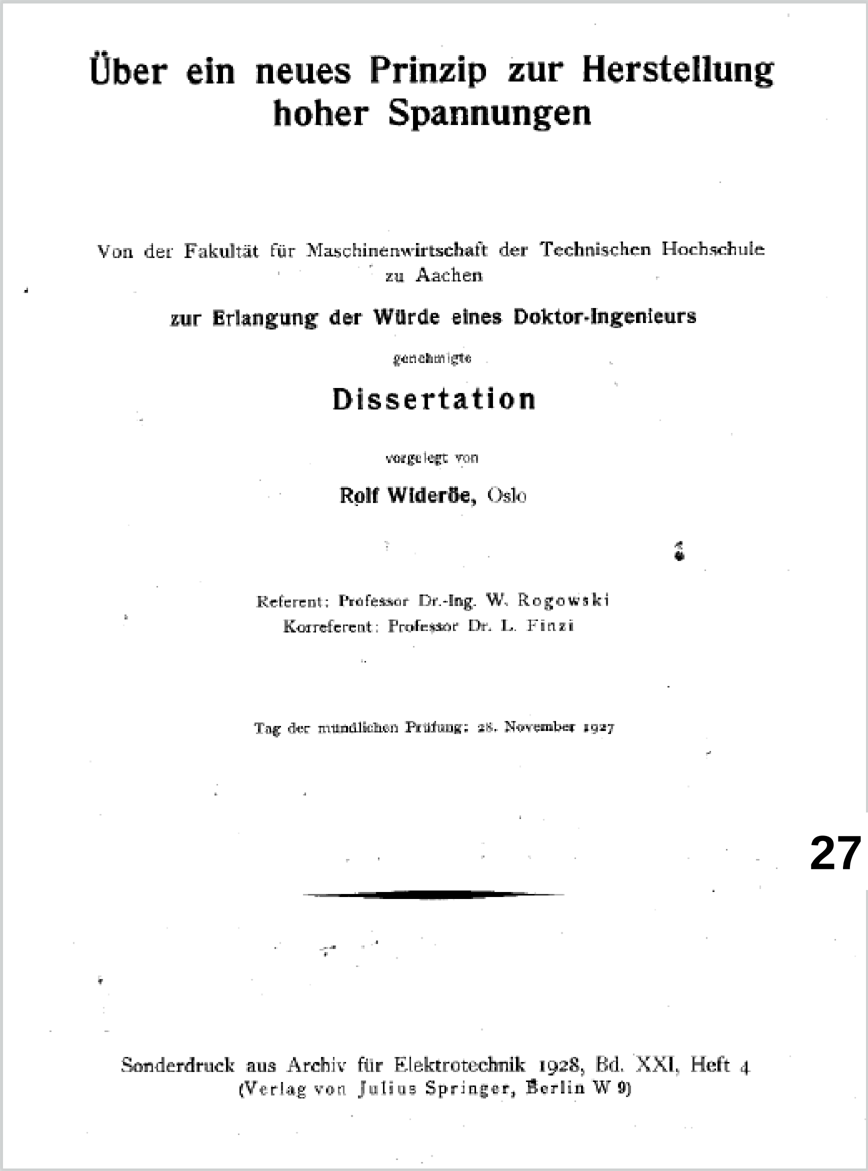
First RF Linac Setup: PhD Wideröe 1927 in Aachen

Where RF accelerators started in practice







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

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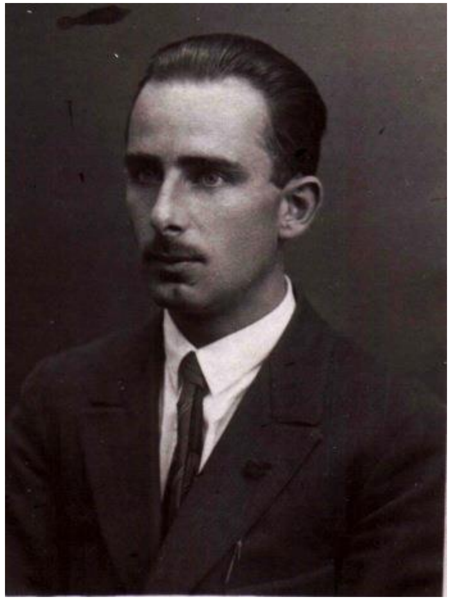
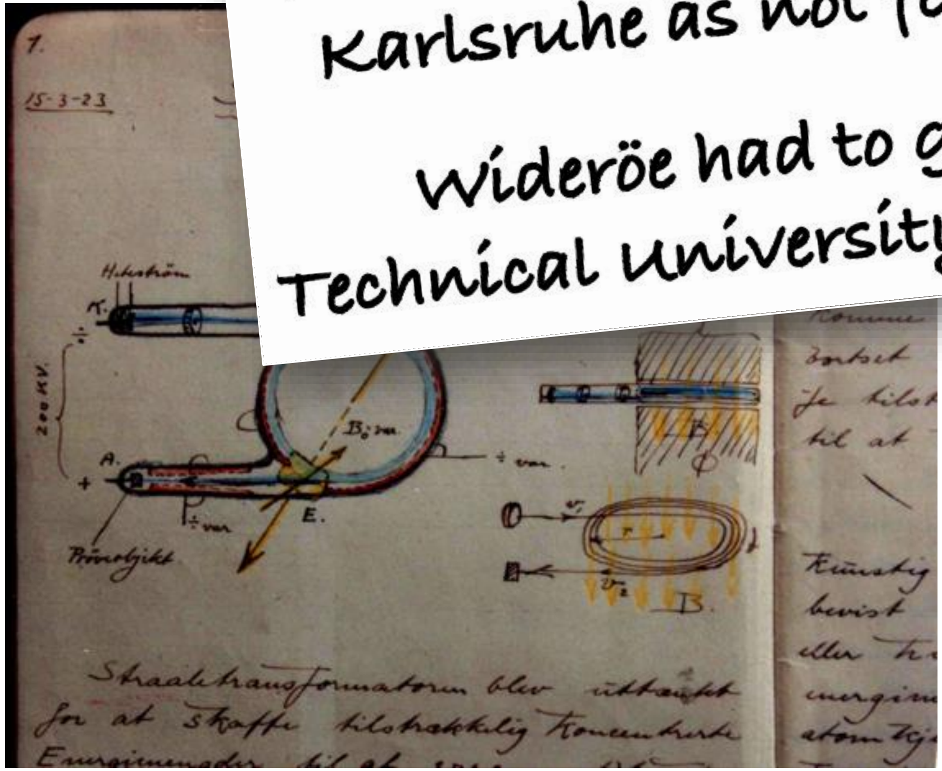
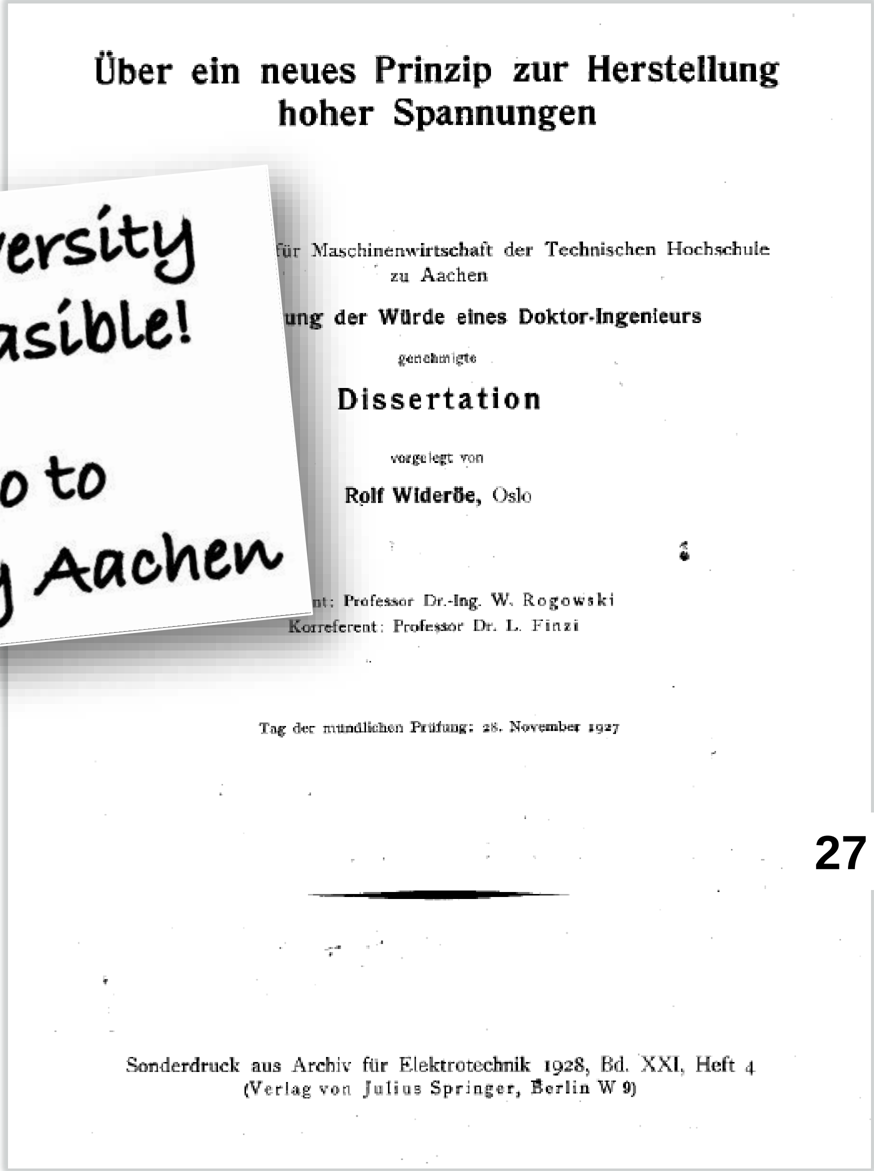




First refused at University Karlsruhe as not feasible!

Wideröe had to go to Technical University Aachen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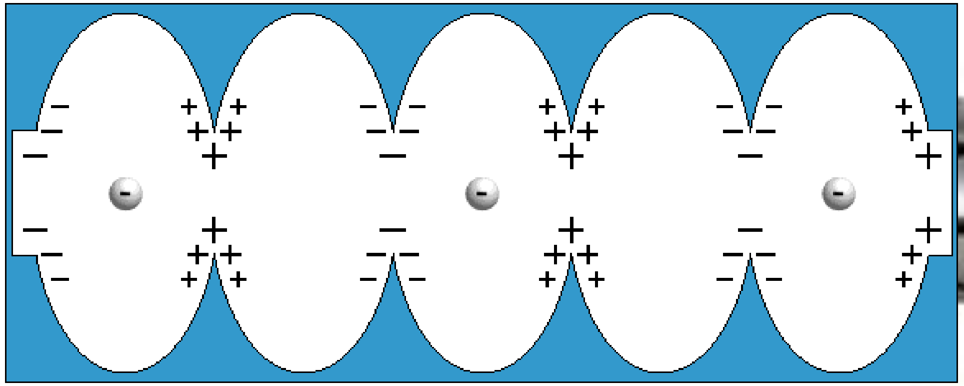
Electron Acceleration: The Success of RF

Alternating field (RF) synchronized to the particles

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



Sketch Padamse, Tigner

“Runzelröhre”

20.000.000 Volt per Meter

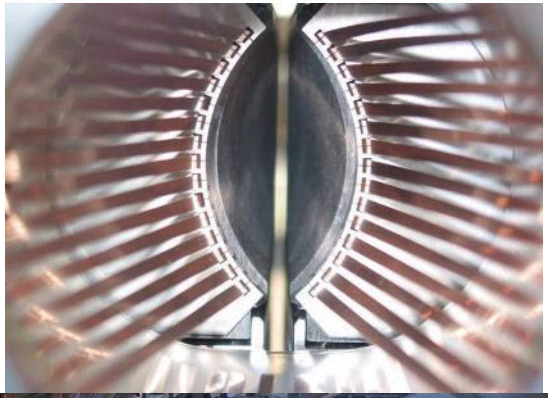
- **RF technology** (first shown by Wideröe 90 years ago) a tremendous success story.
- Lesson: Never give up if up, if colleagues say it does not work – unless they can prove it to you by scientific means.

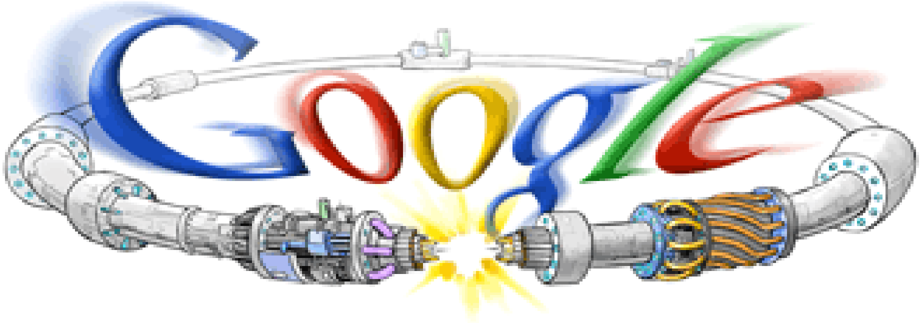
LHC as a Masterpiece of Accelerator Science

80 Years (and many inventions) later

First beam
10.9. 2008

Higgs
Sem.
4.7.
2012





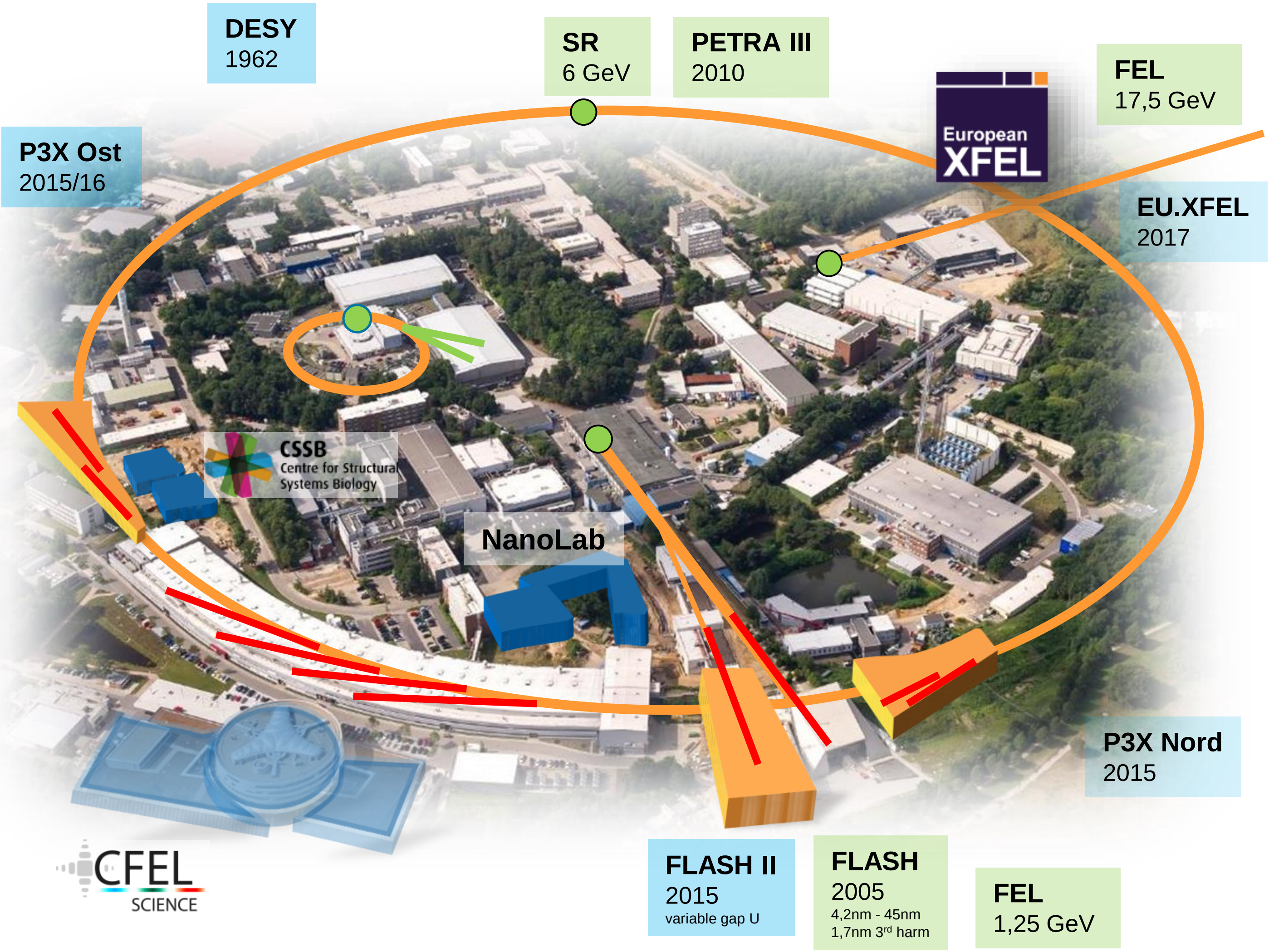
Particle accelerators have transformed DESY

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

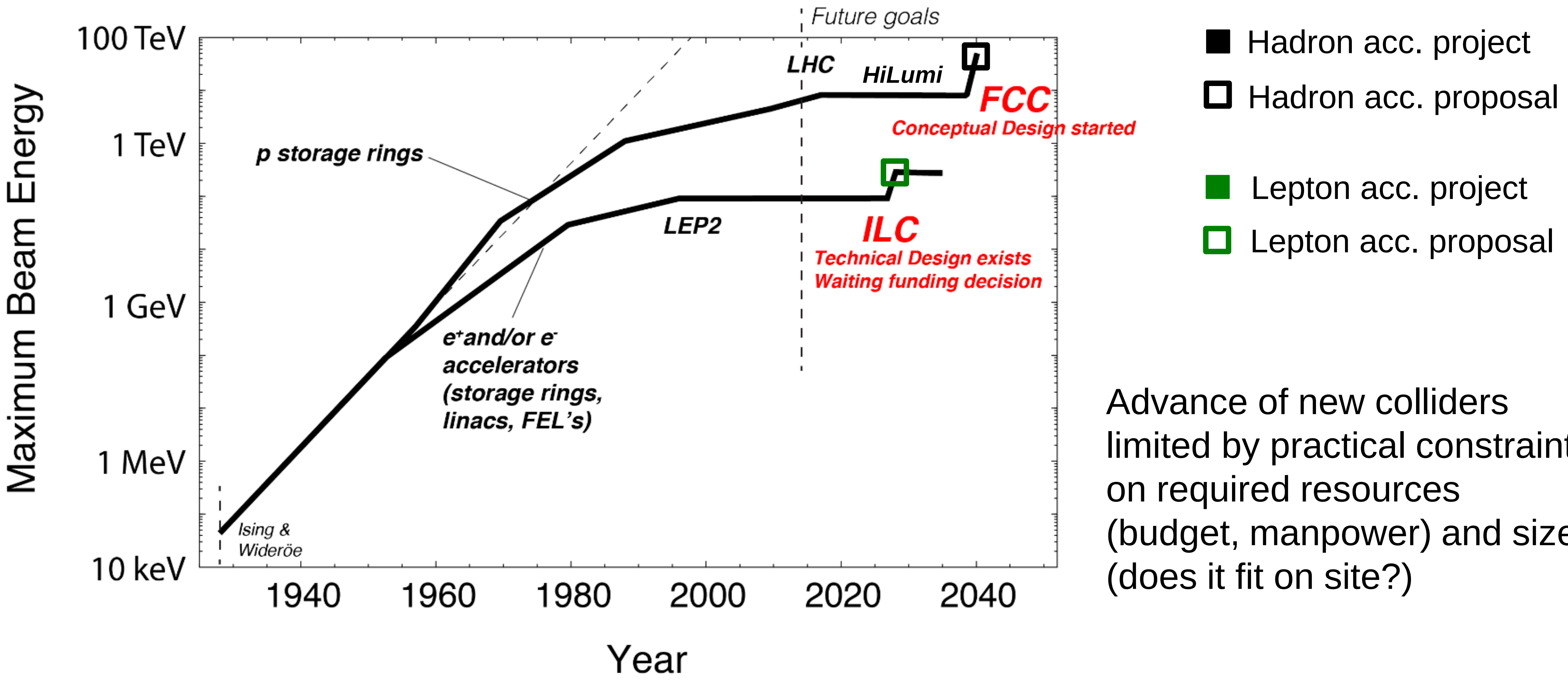
From 50 years ago to today…



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

Slow-down in Energy Increase of Frontier Accelerators

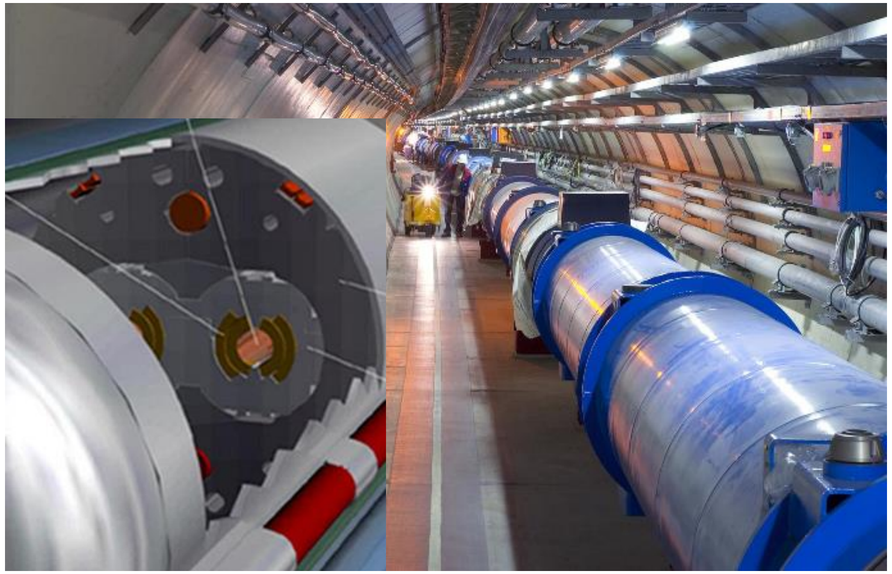
Livingston plot leveling off – here our version, giving beam energy versus time



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

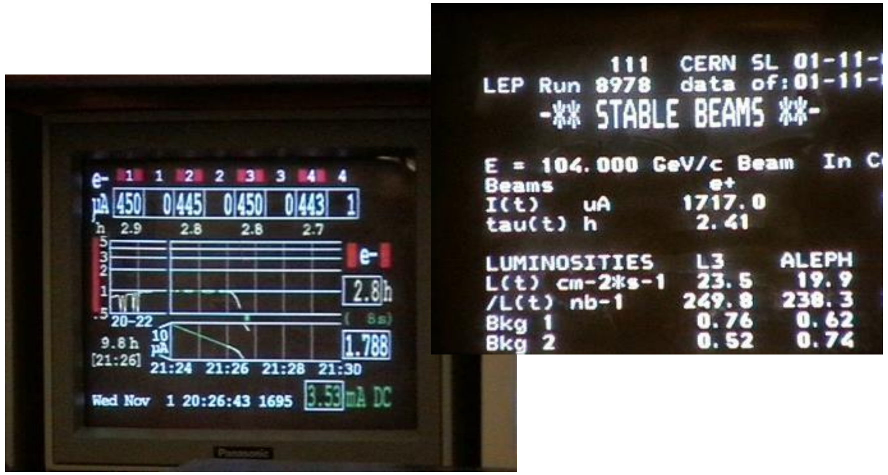


Hadron (p) circular collider

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

$$p = e \times R \times B_y$$

- 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

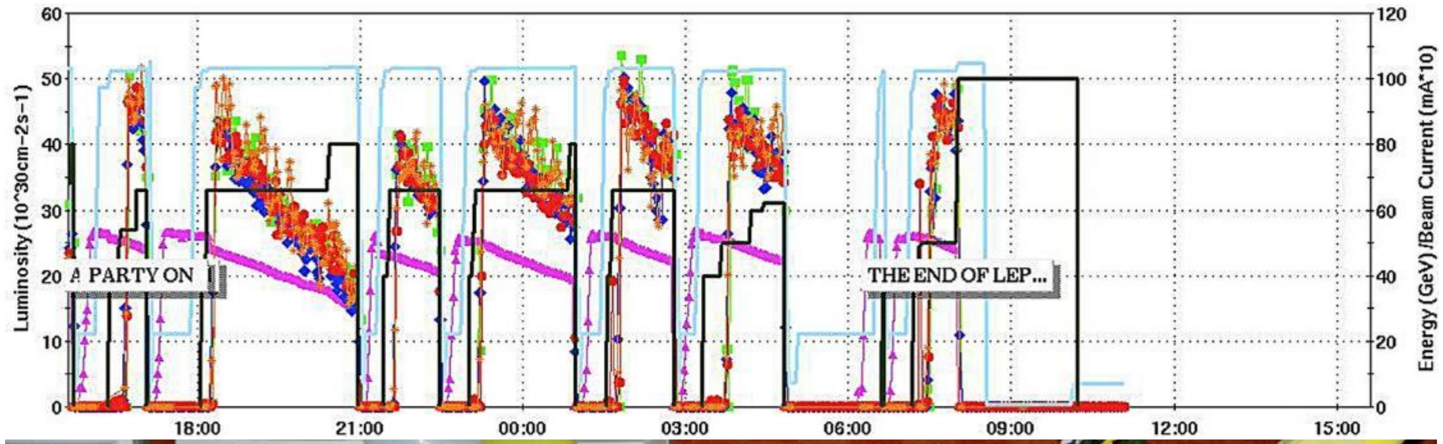
- Increase momentum p by increasing radius R and lowering bending field B_y

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?

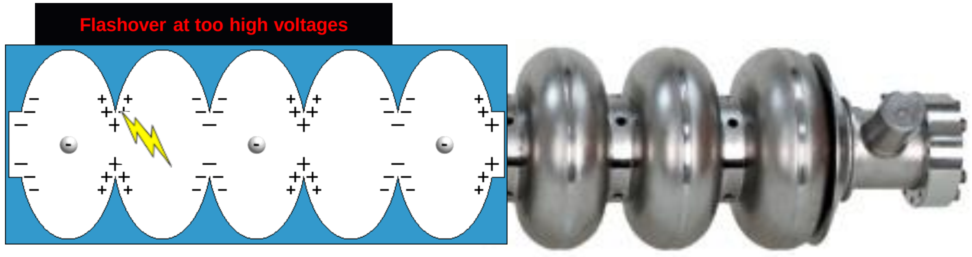


Why this slow-down? Part 2

Technical limitations in highly advanced and mature technologies

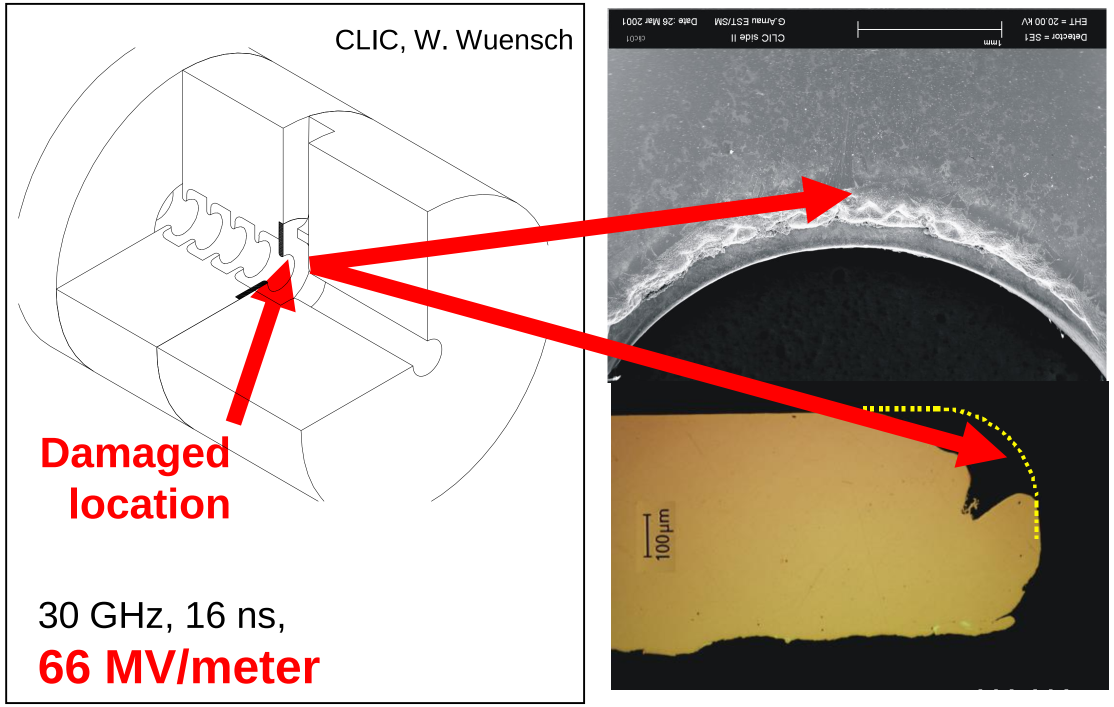
Lepton (e-,e+) linear collider

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



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

- 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

$$p = e \times R \times B_y$$

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

Increase radius = size (FCC-hh)

Lepton (e-,e+) circular collider

$$p \propto E_0 \times \sqrt[4]{r \times U_0}$$

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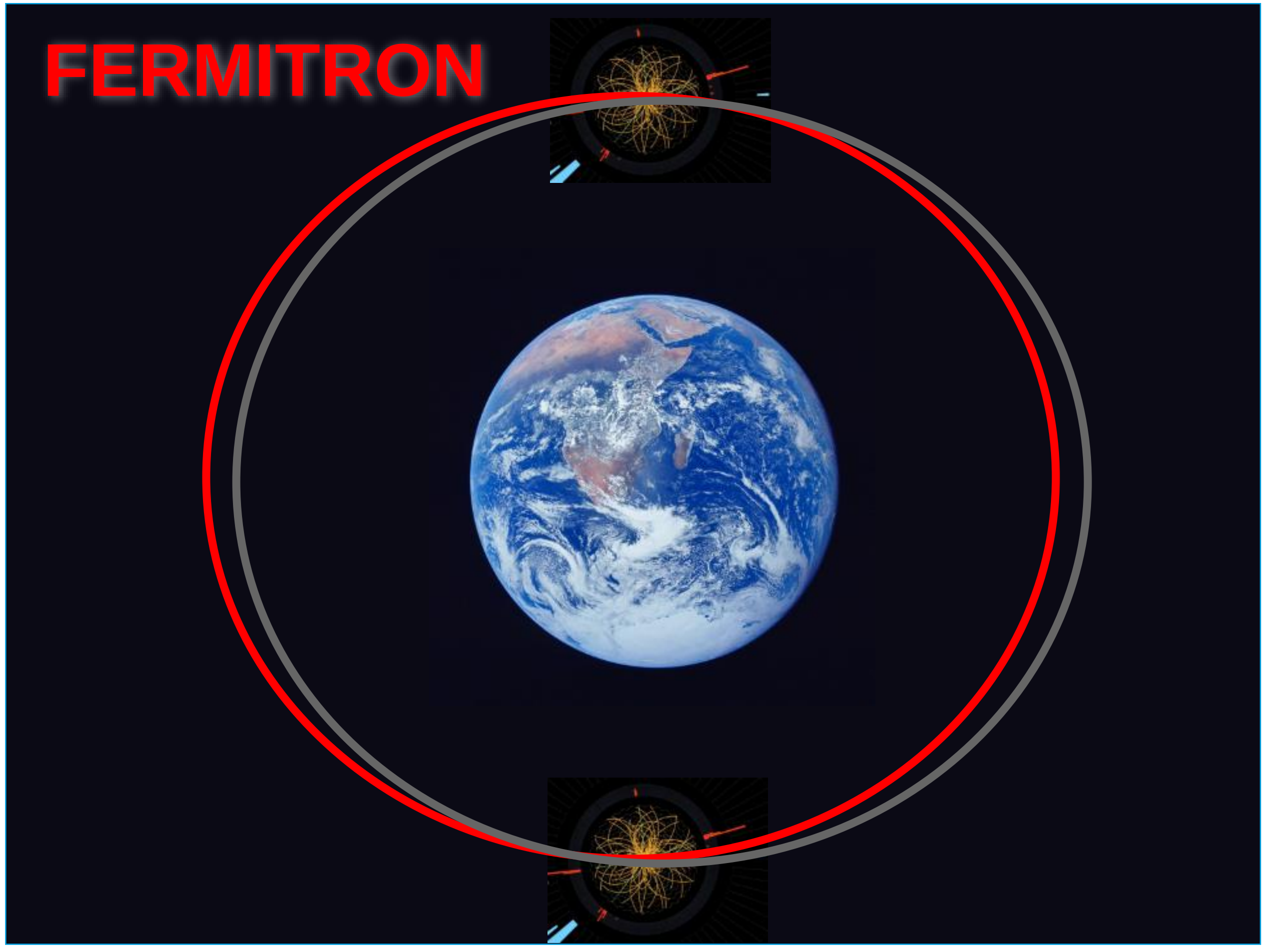
Increase accelerating gradient

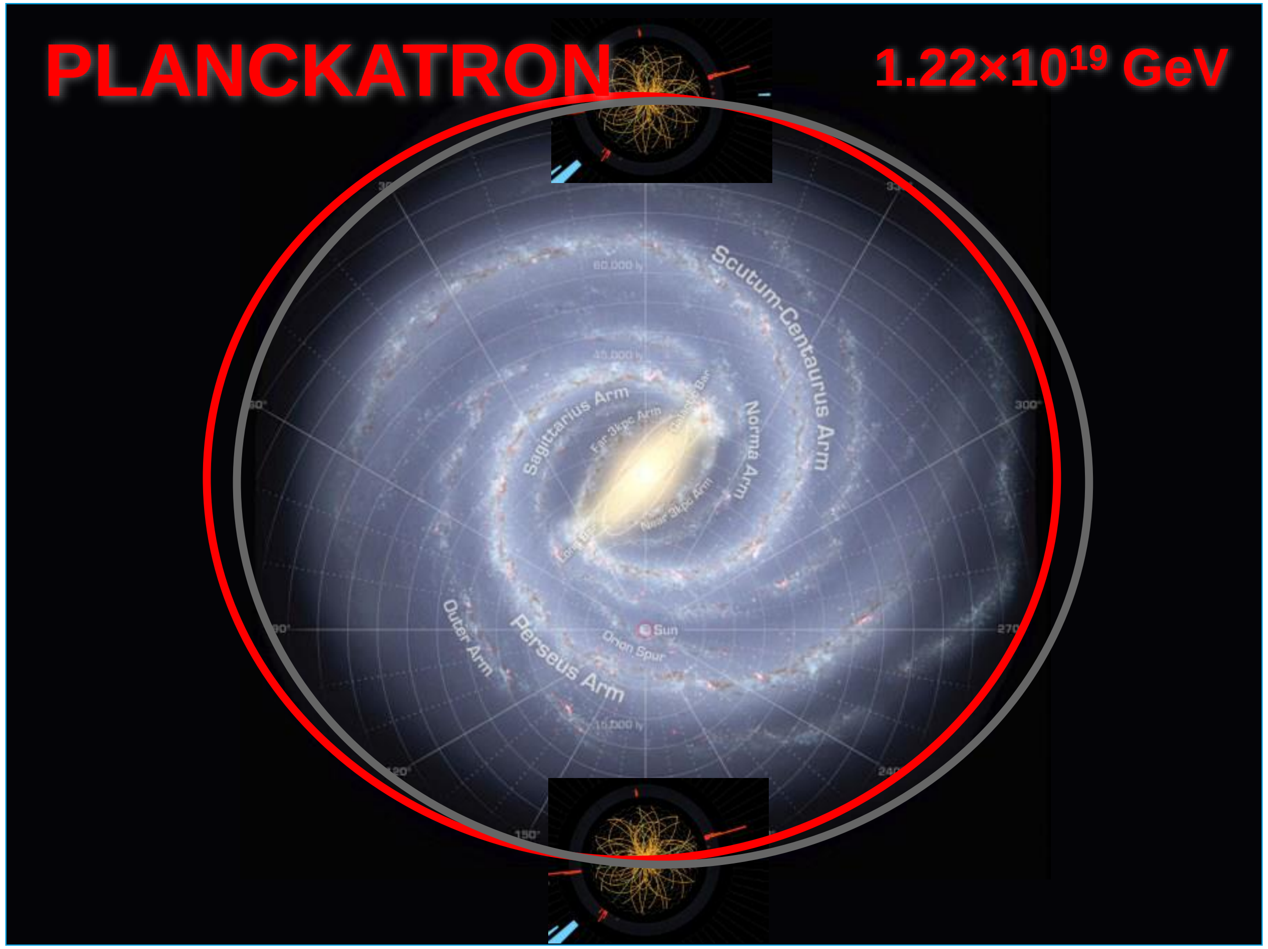
(a) Pushing existing technology (ILC, CLIC)
(b) New regime of ultra-high gradients (plasma, dielectric accelerators)

Increase length (ILC, CLIC)

We can dream big ...

The ultimate colliders





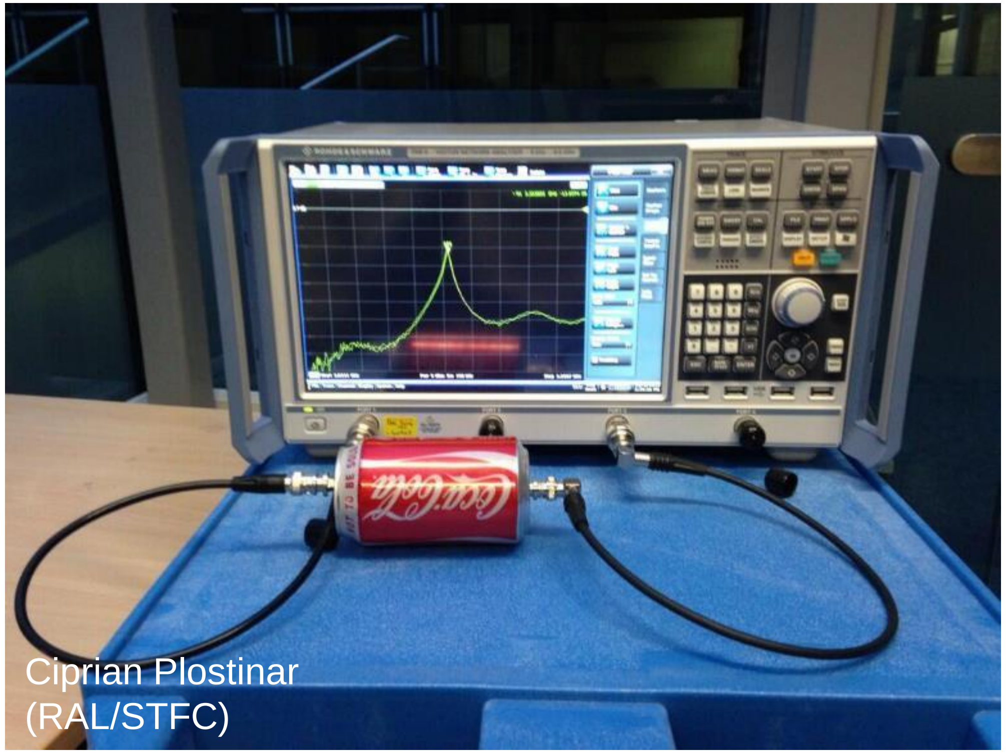
But: It is the cost not the size...

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 ...

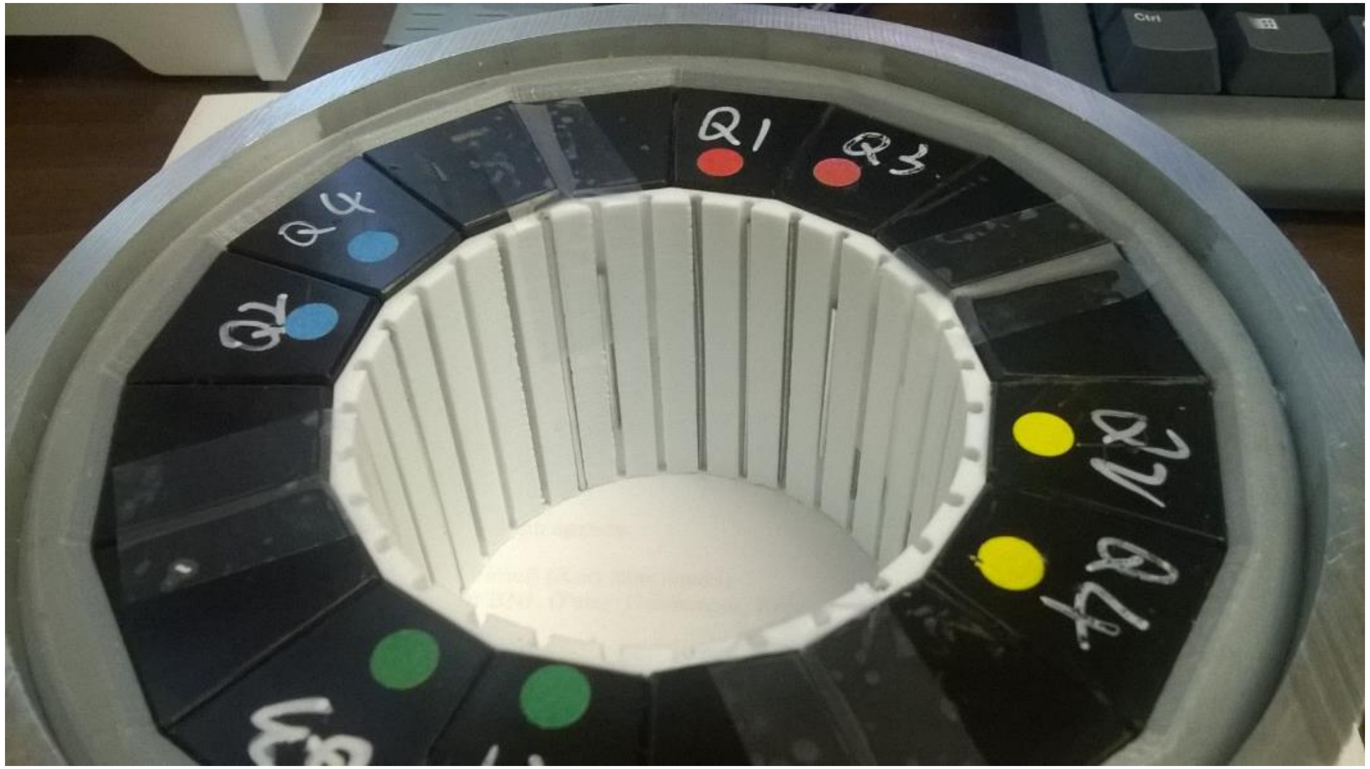
Can we bring down cost per meter of accelerator by a factor 2 – 10?



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*

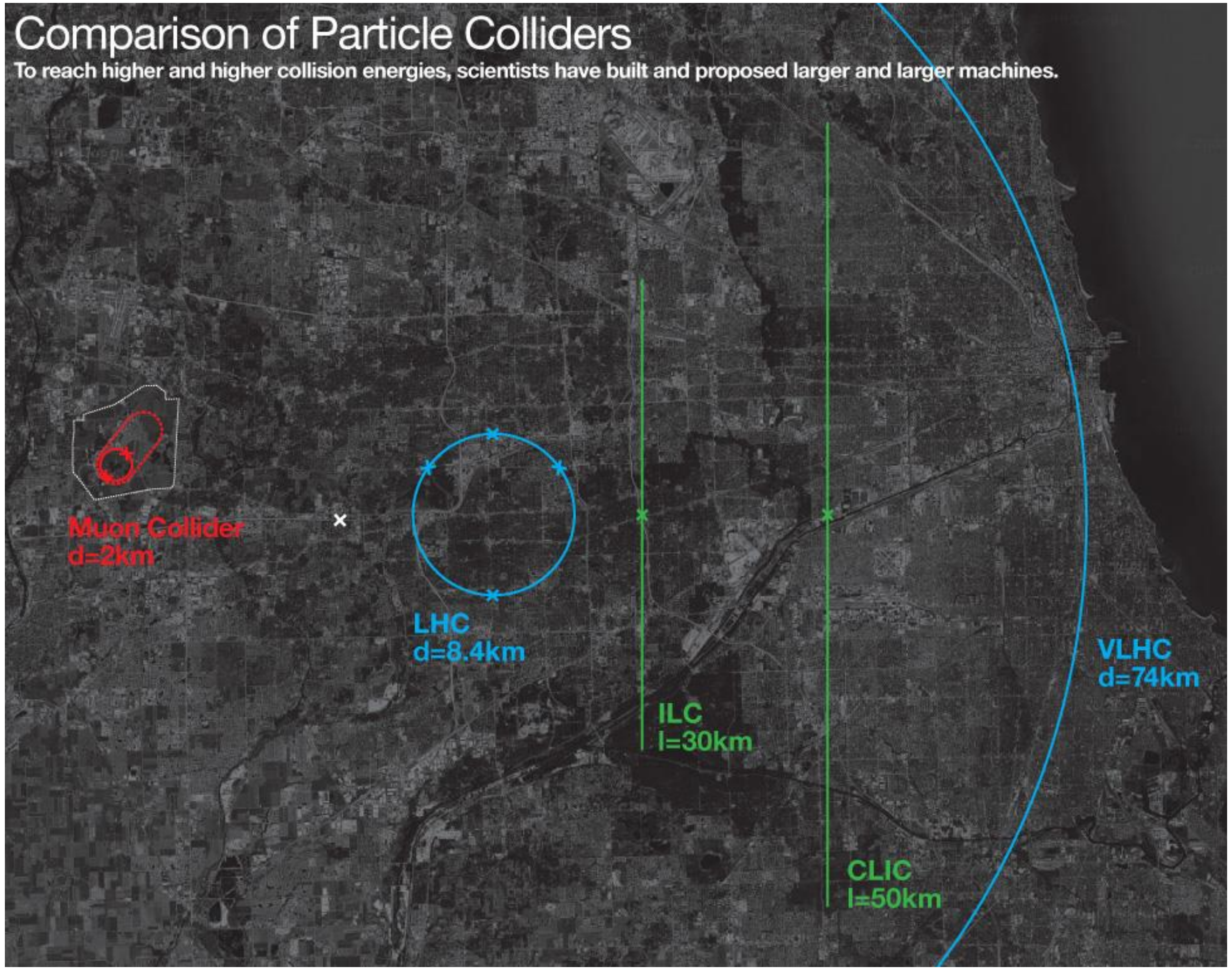
In the 1970s, use of mobile radio frequencies was expanding dramatically and existing antennas were becoming heavily overloaded. The engineering solution devised by Gerald David was to introduce multiple transmitter combiners onto a single antenna using band-pass filters. The use of a beer barrel in 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

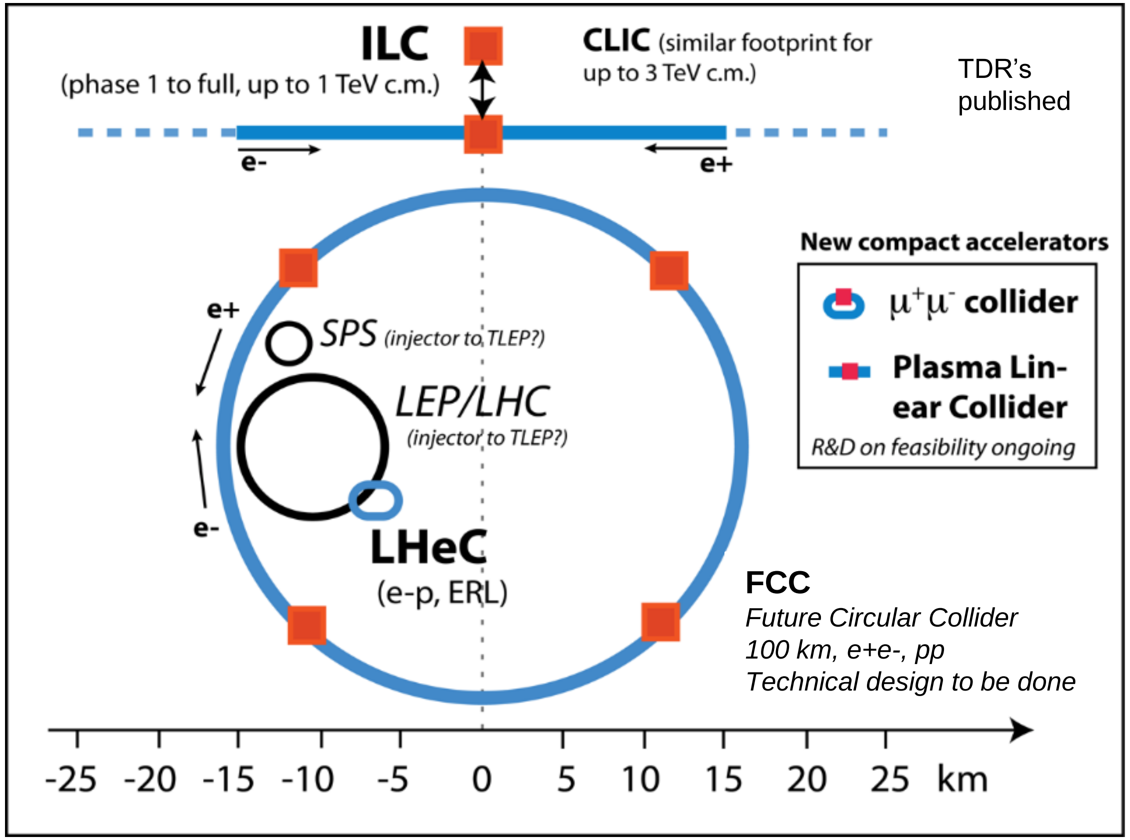
Material and pictures courtesy S. Brooks, BNL

…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

$$p = e \times R \times B_y$$

Increase b
SC bend m

Increase radius = size (FCC-hh)

Factor 206.8 higher mass muon versus electron

Lepto

$$p \propto E_0 \times \sqrt[4]{r \times U_0}$$

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

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

Increase length (ILC, CLIC)

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

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!

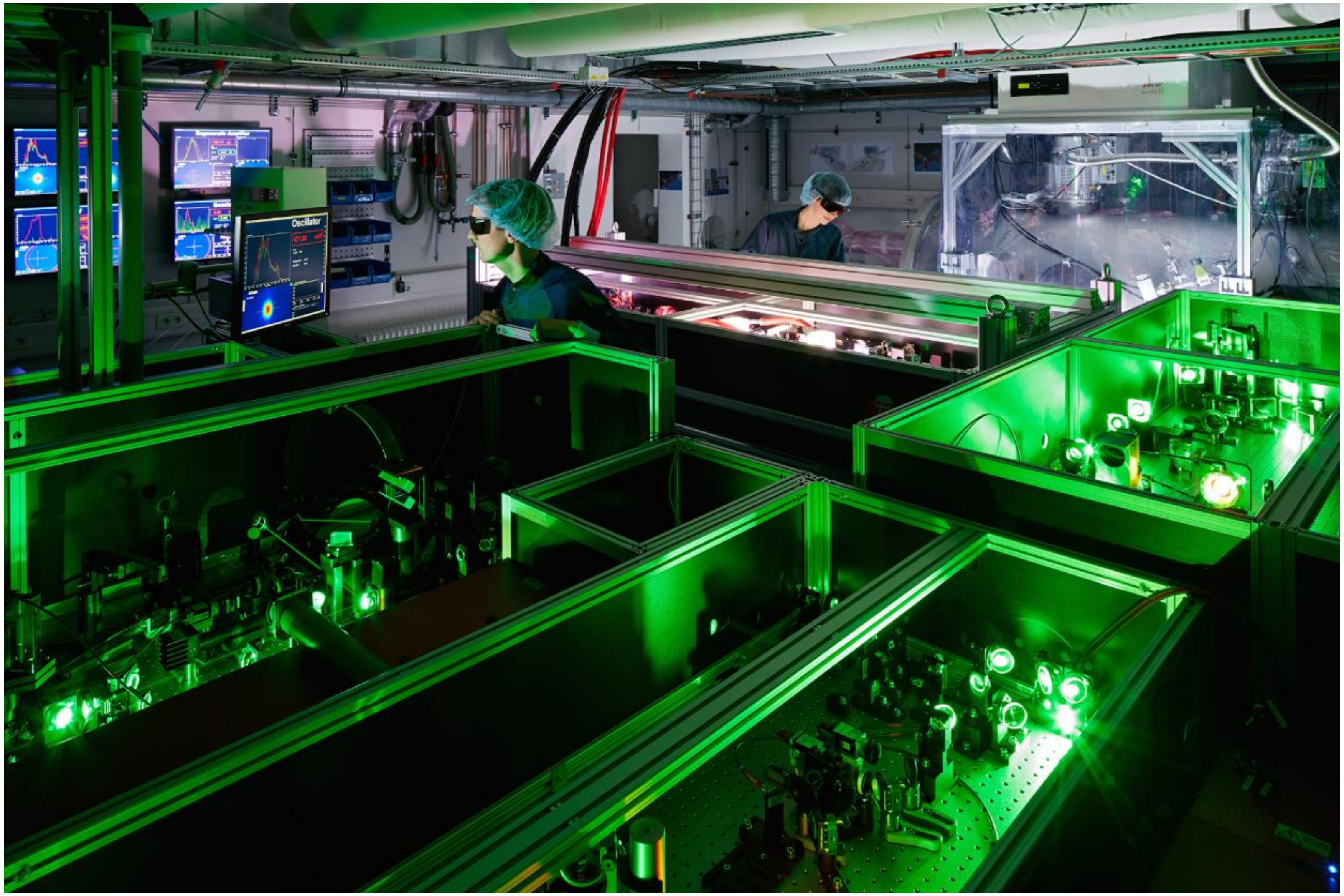
Modern lasers generate light pulses with very large transverse fields:

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

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

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

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

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

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

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

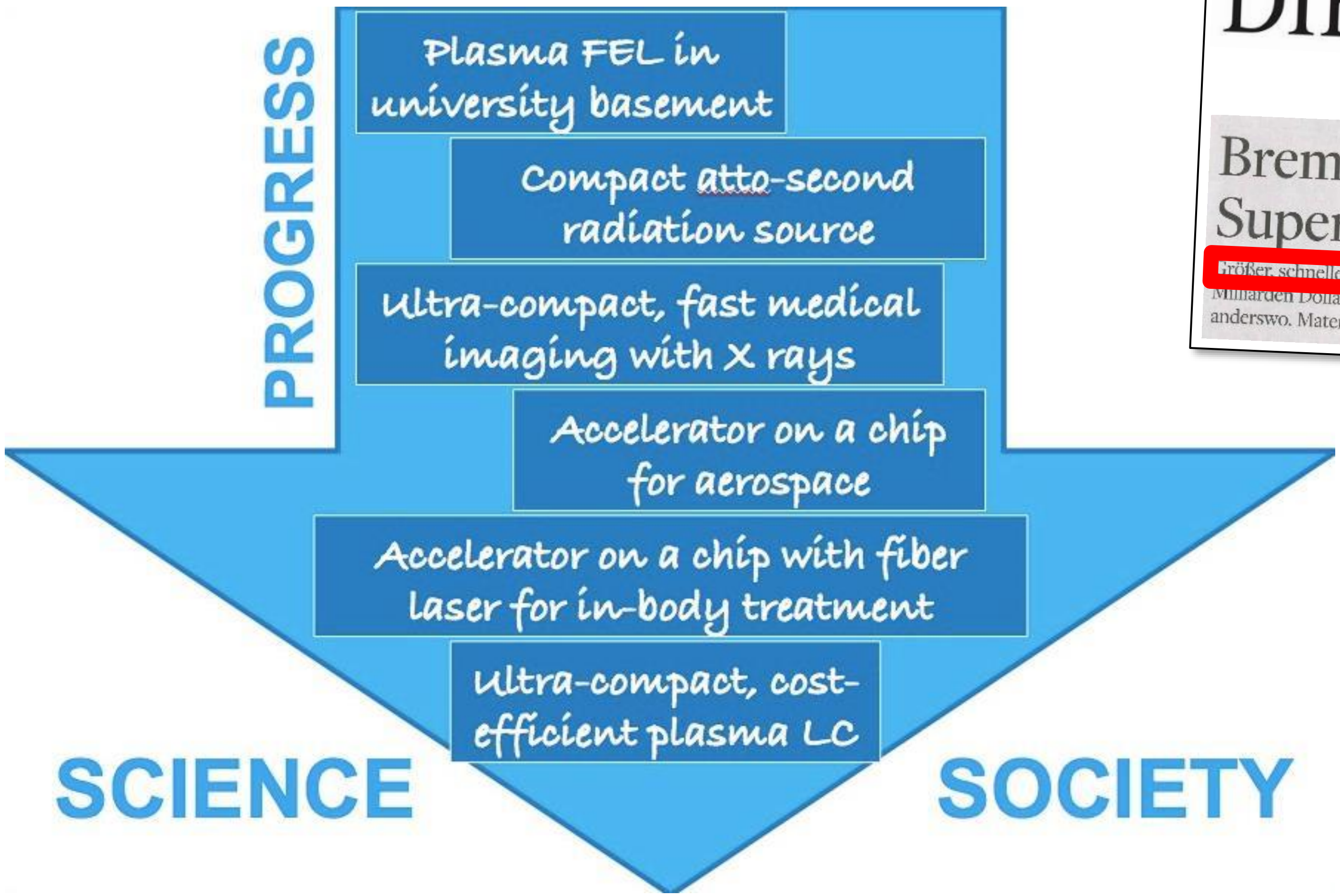
$$E_0 = 22\,\mathrm{TV/m}$$

This is what we need!

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

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

DER SPIEGEL

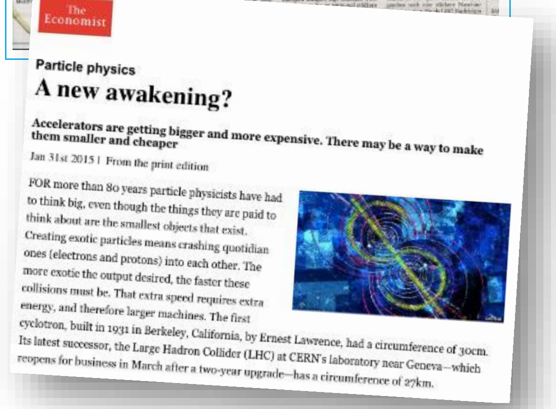
DER SPIEGEL 11/2015

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

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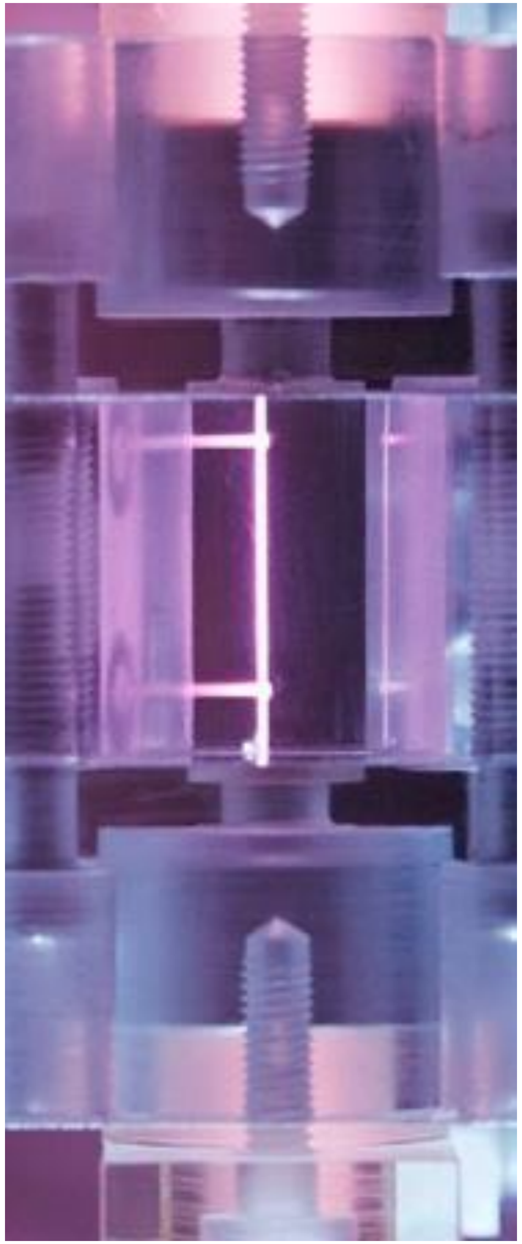
C band	4 to 8	35	3.8 – 1.9	Newer technology developed in Japan and used for the construction of the SACLA linac in Japan.

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

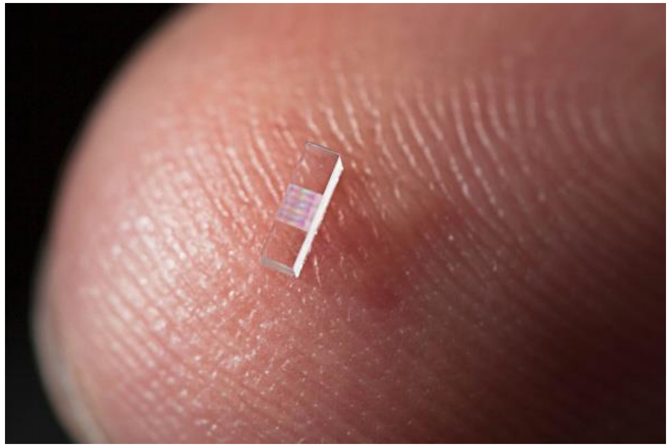


High Gradient – High Frequency – Small Dimensions

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**:



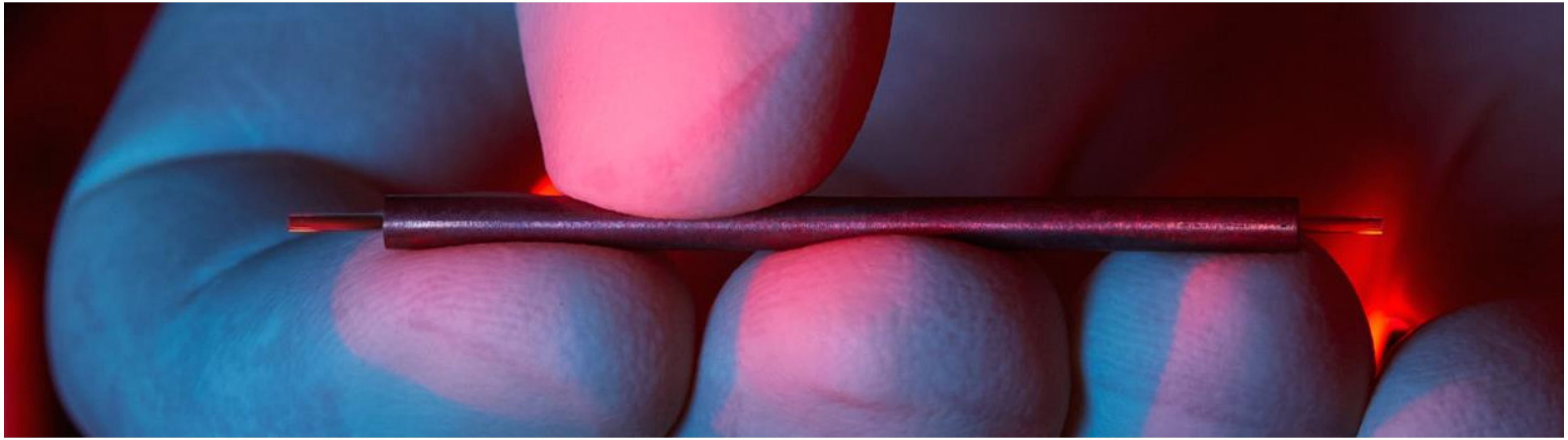
1 Microstructure Accelerator
Laser- or beam driven
Vacuum accelerators
Conventional field design

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

Laser-Driven Micro Structures (Vacuum) – 1

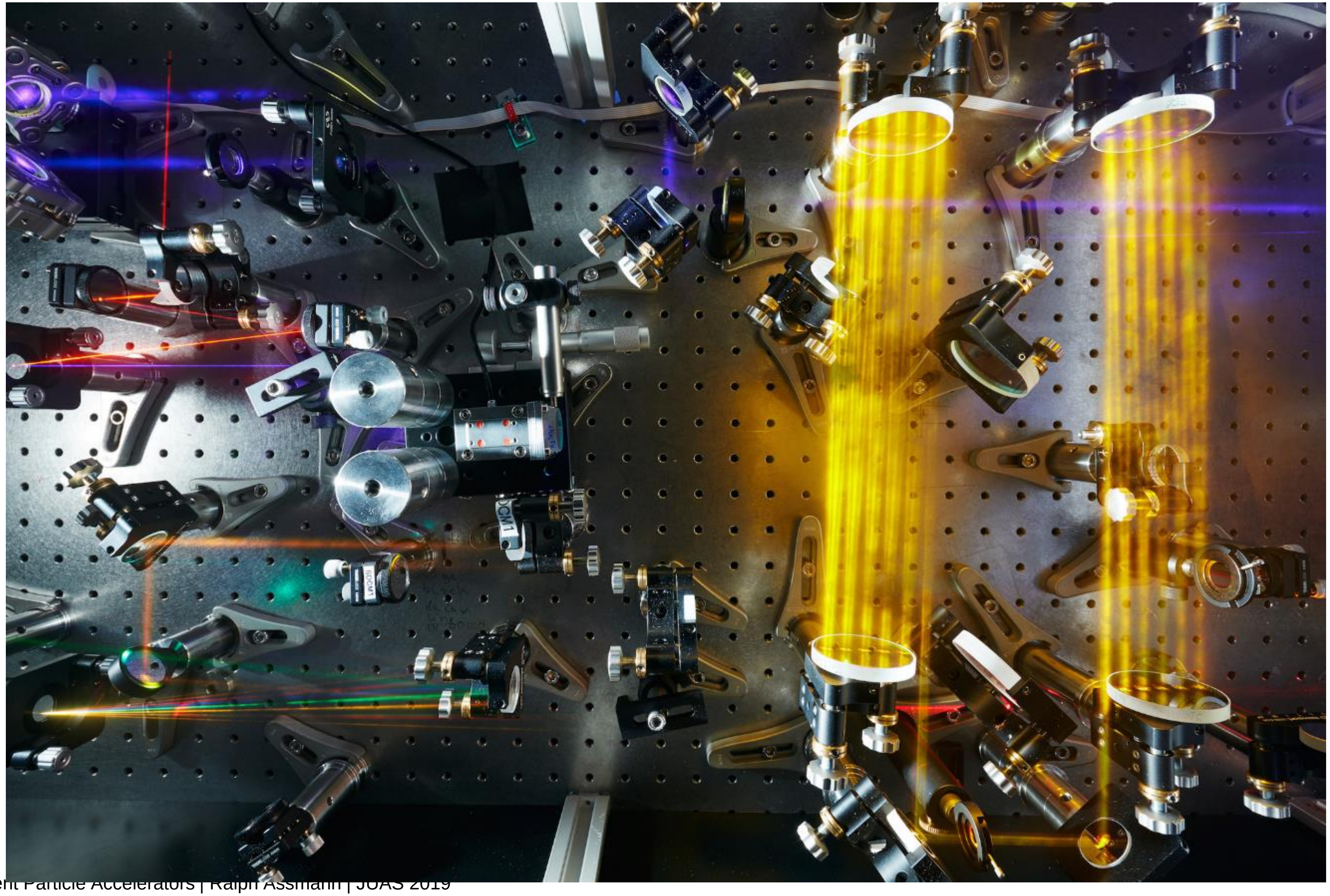
Vacuum dielectric accelerator

- 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

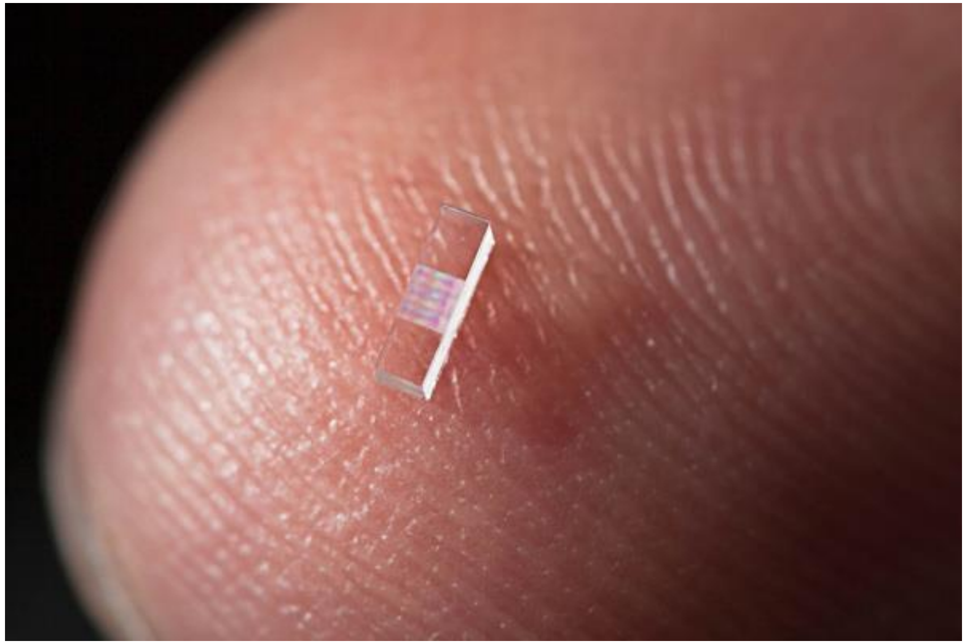


Laser-Driven Micro Structures (Vacuum) – 2

Vacuum dielectric accelerator

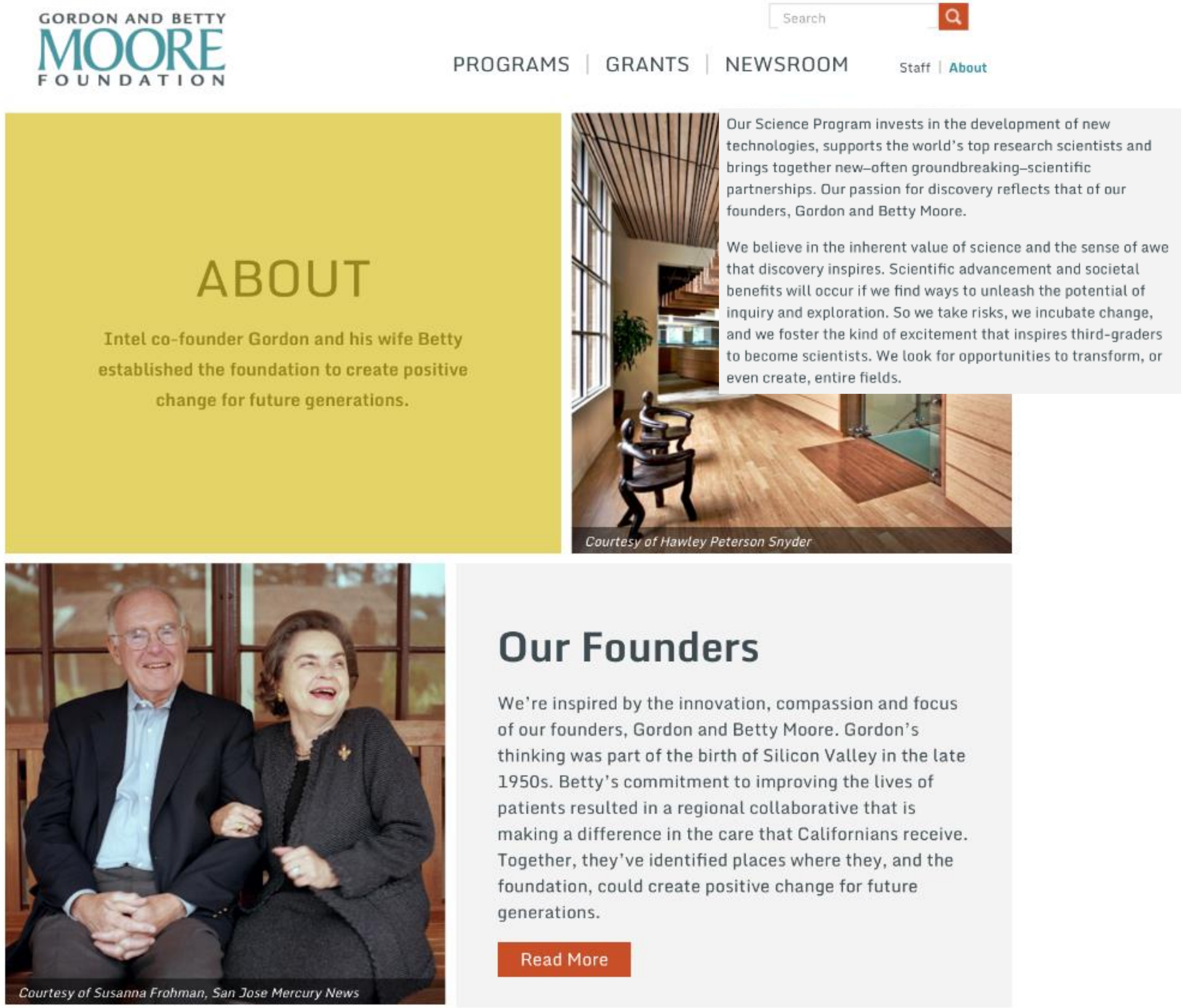
ACHIP
Accelerator on a Chip International Program

- **"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



The Laser Promise: Transverse Electrical Field

We can produce every day very high transverse electrical fields

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

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

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

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

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

This is what we need!

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

Lorentz Force F

The direction of the field matters

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

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

Longitudinal electrical field to accelerate a particle

Transverse magnetic field to guide a particle

Laser Plasma Accelerator: Transverse to Longitudinal

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:

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

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

The Plasma Accelerator Concept

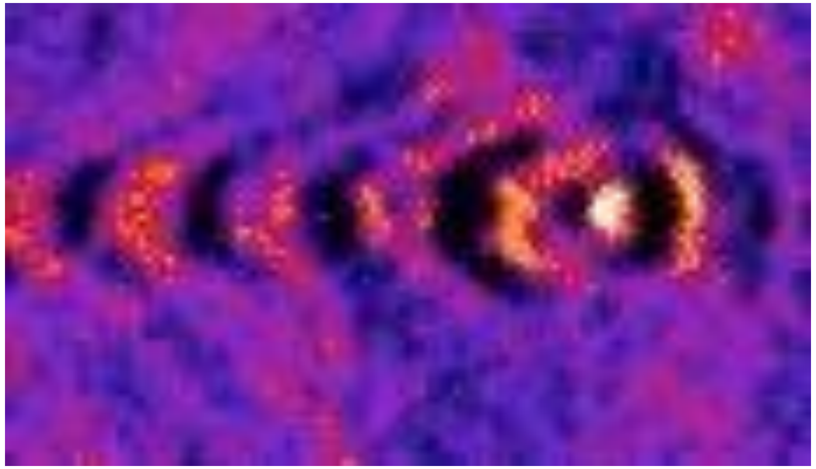
Overcome high-field limitations of metallic walls with dynamic plasma structures (undestructible)

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+) → transverse forces

longitudinal accelerating fields → Accelerating gradients of 10 GeV/m to 1,000 GeV/m



Courtesy M. Kaluza

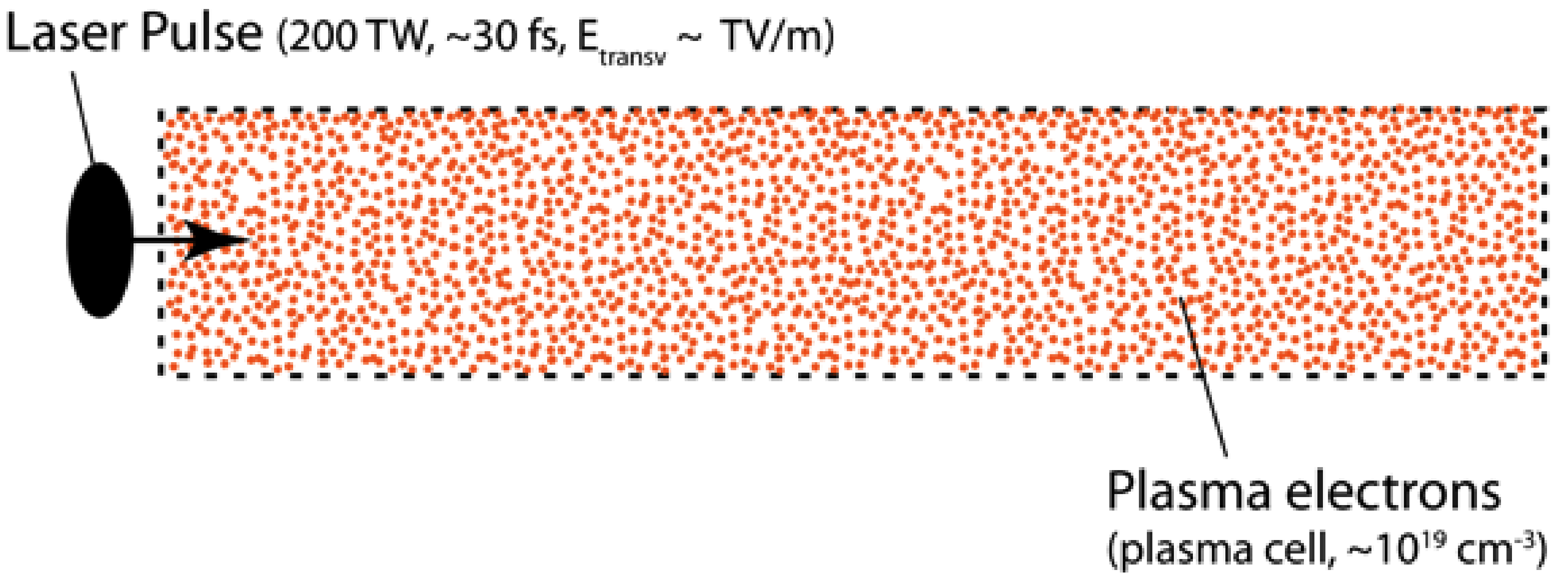
Options for driving wakefields:

- **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

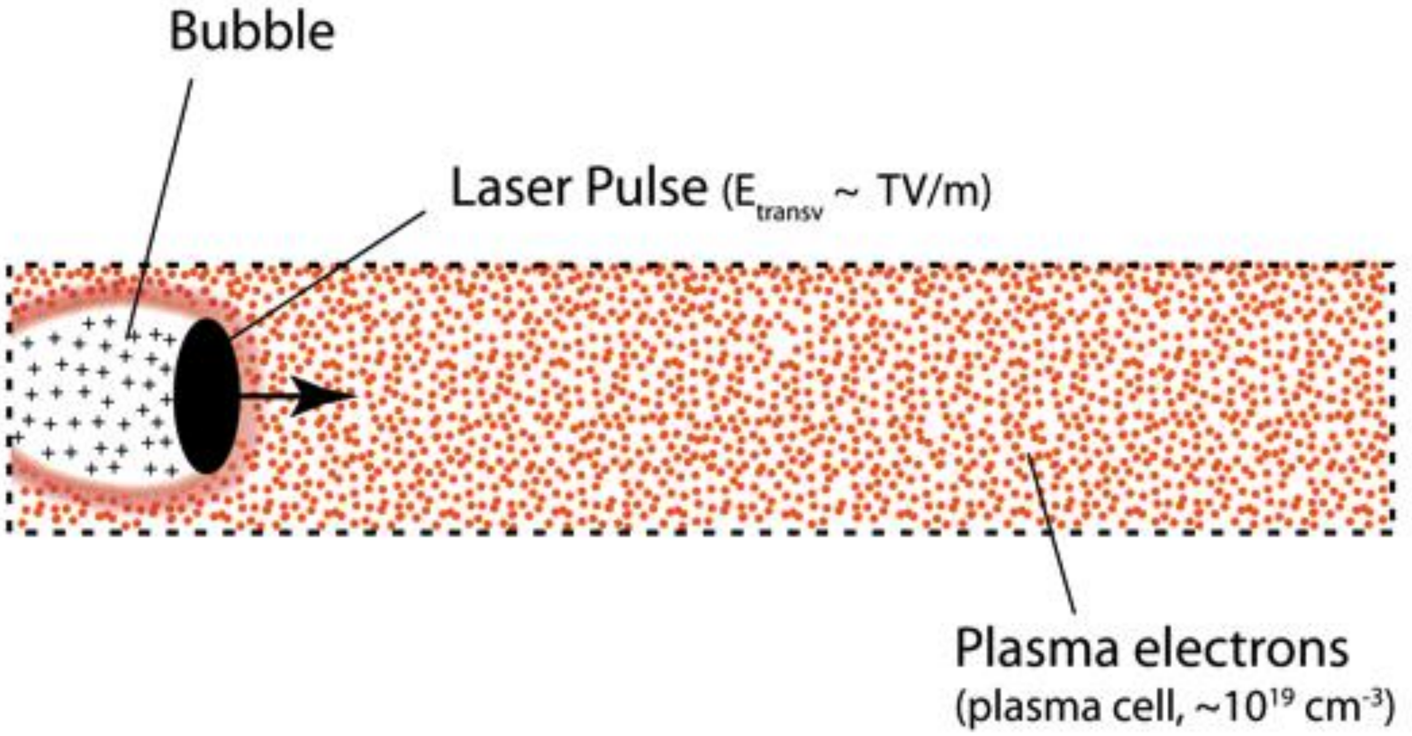
Internal injection

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).



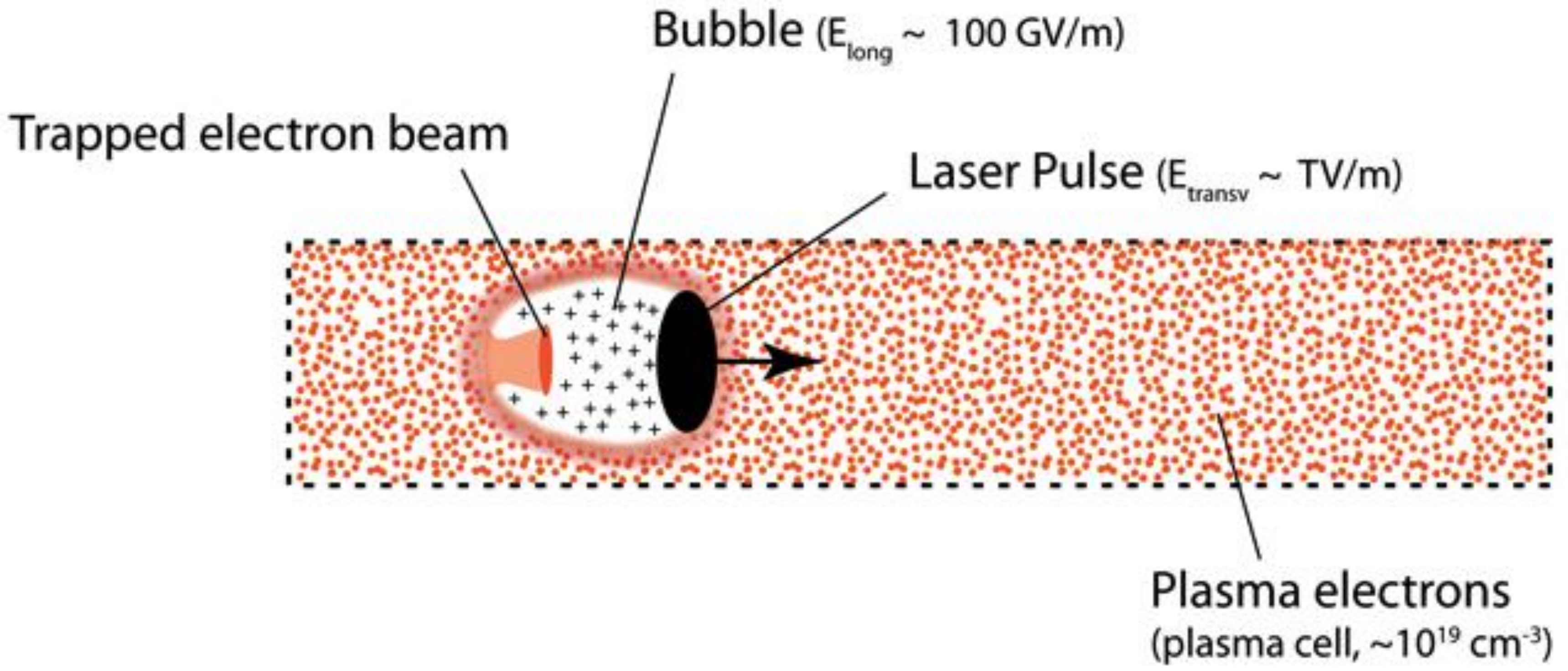
Laser Plasma-Acceleration

Internal injection



Laser Plasma-Acceleration

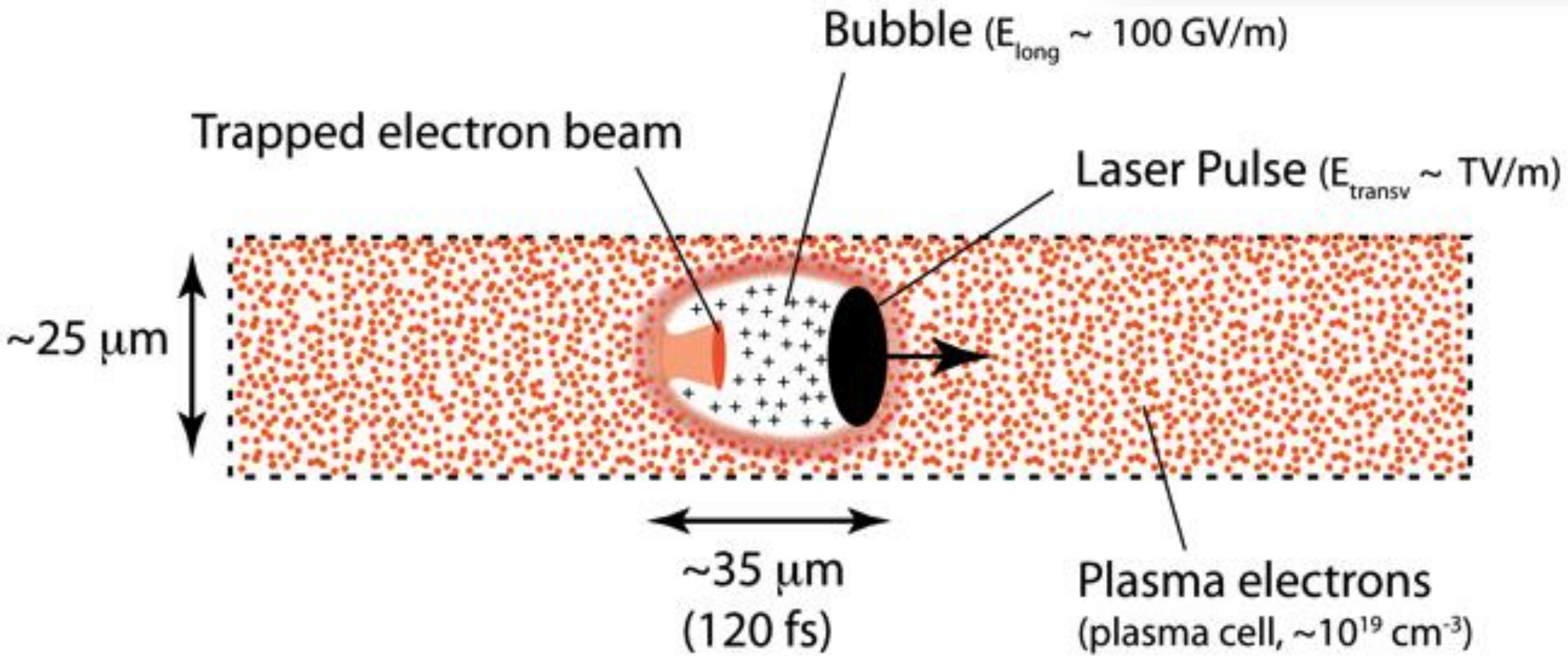
Internal injection → strong fields in the bubble suck in plasma electrons to form the electron beam



Laser Plasma-Acceleration

Internal injection

This accelerator fits into a human hair



Laser Plasma Acceleration

External injection

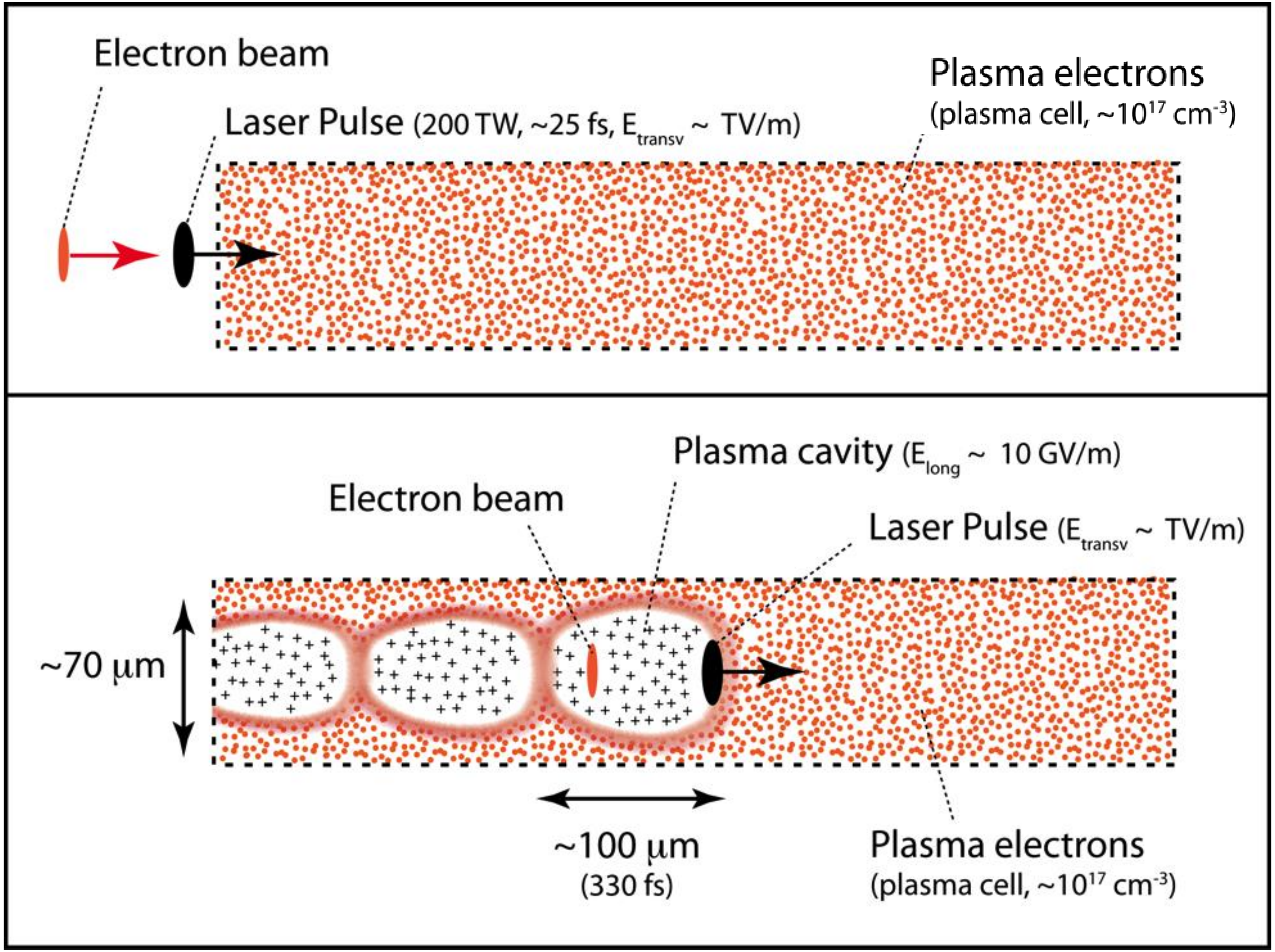


Photo Laser-Plasma Accelerator

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
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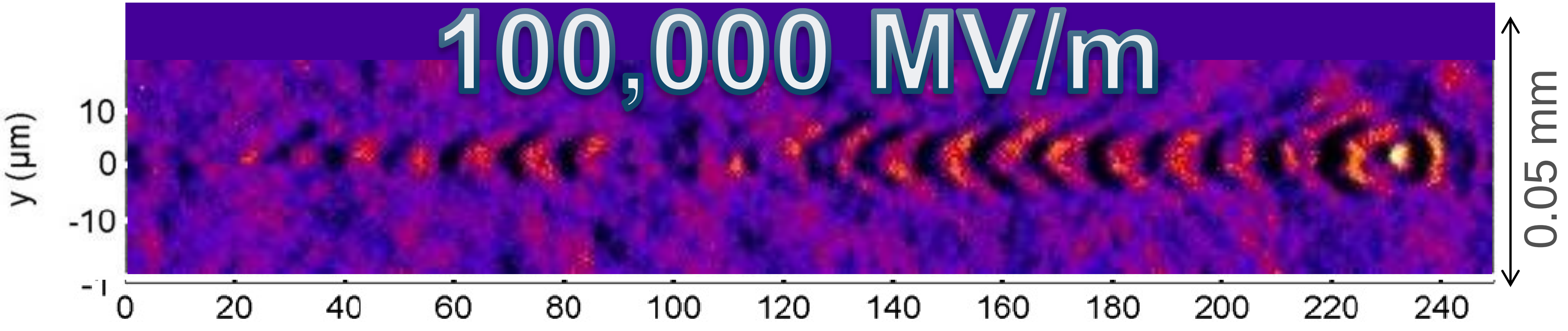
[3]Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany

2013



0.25 mm

Metal (Copper) S band linac structure

Microwaves for generation of RF waves

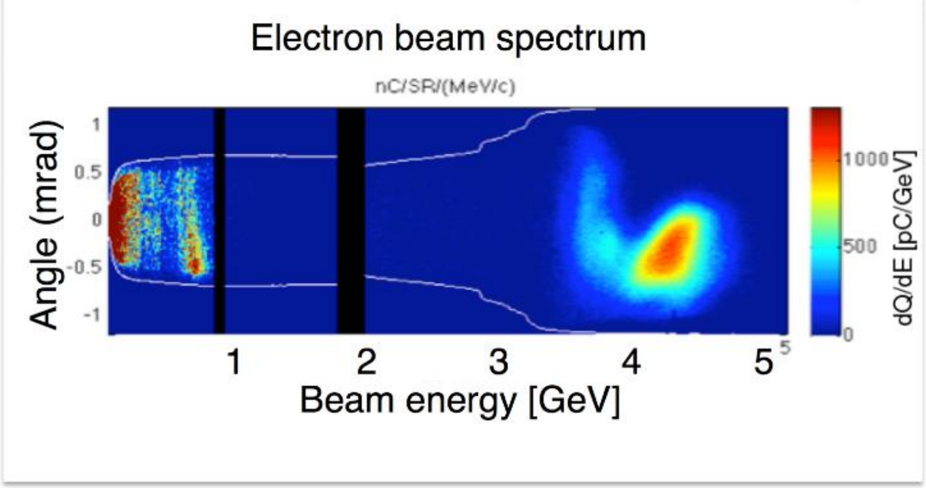
500 mm

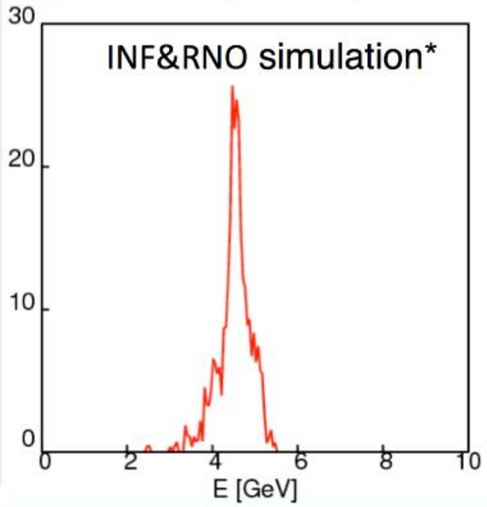
LBNL: 4.25 GeV beams have been obtained

from 9 cm plasma channel powered by 310 TW laser pulses (15 J)

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

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



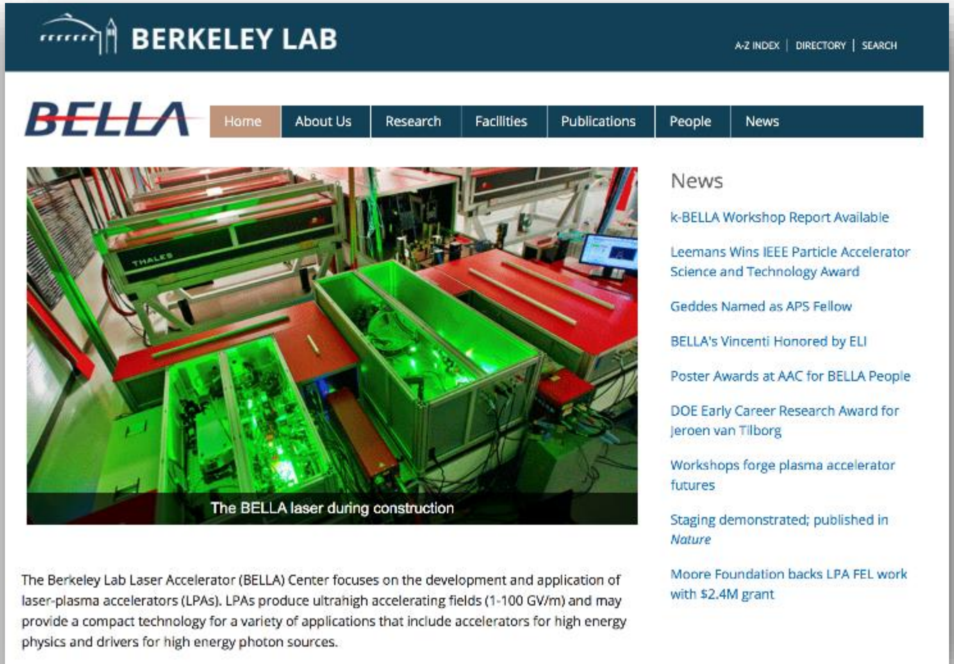


Slide: W. Leemans

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

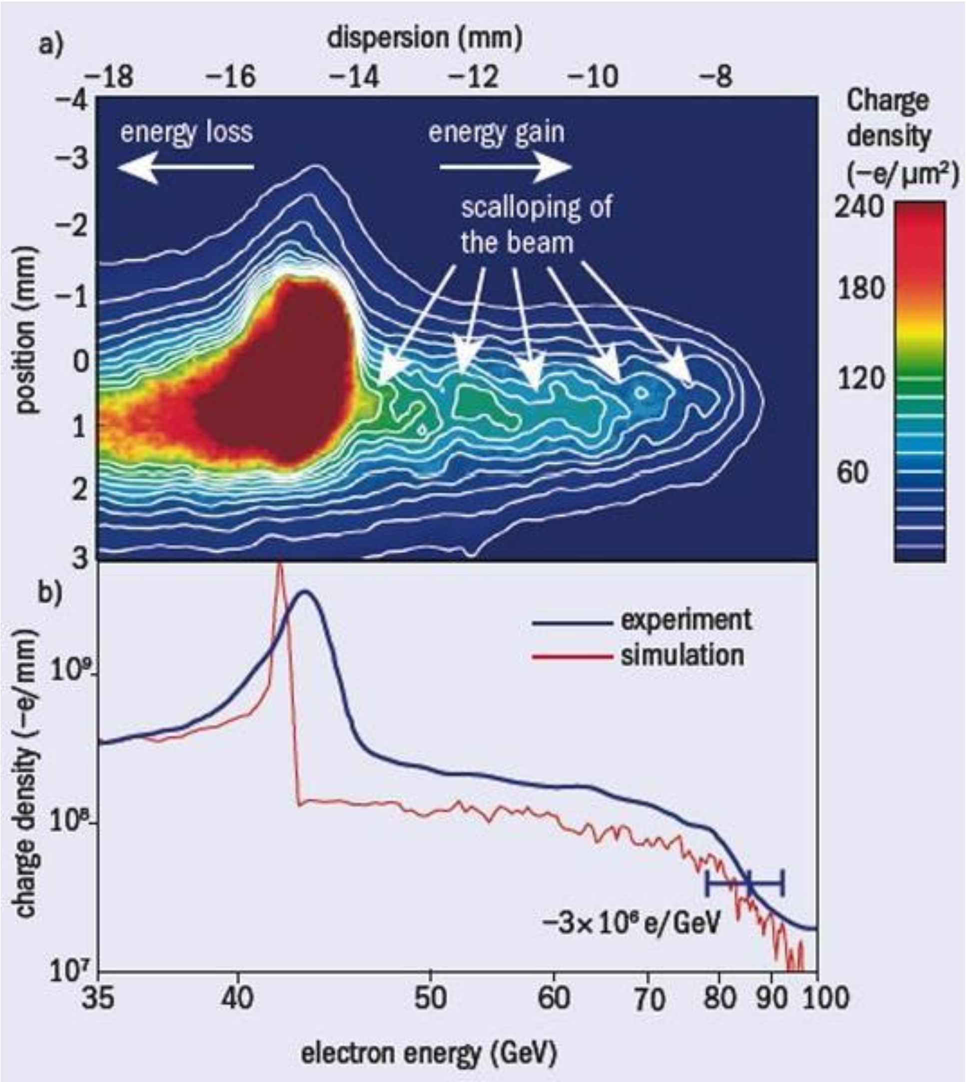
	Exp.	Sim.
Energy	**4.25 GeV**	4.5 GeV
ΔE/E	5%	3.2%
Charge	~20 pC	23 pC

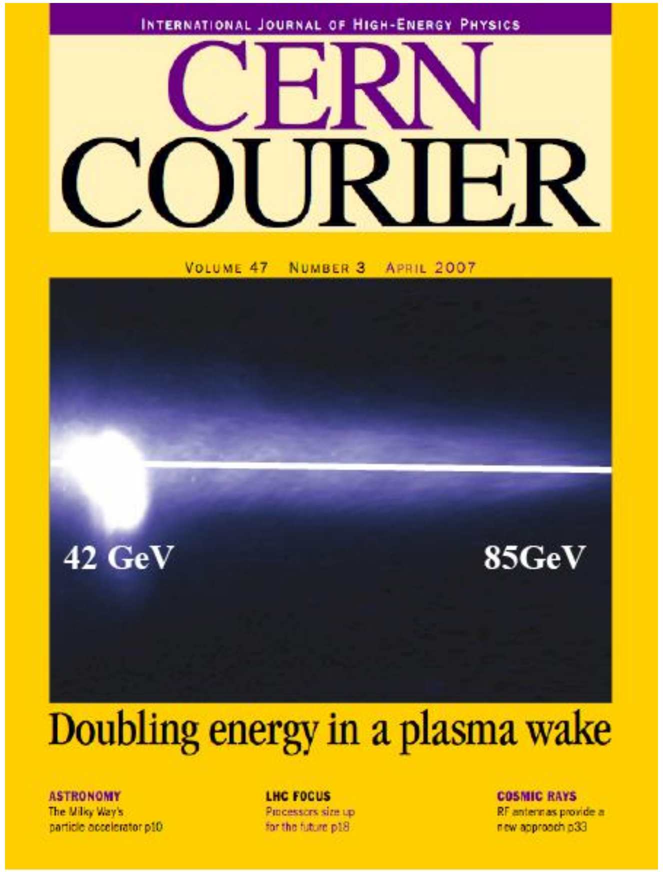
W.P. Leemans et al., PRL 2014



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)

Wait one moment… Compact and Cost-Effective?

Remember: It is not the size but the cost that matters

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

  Required space: 120 m²
  (can be visited)

- The laser size drives the size of such an accelerator facility. With such a 1 PW laser electrons of **4.25 GeV have been produced within 9 cm** (see LBNL result).
- The 1 PW laser should be sufficient for a **10 GeV accelerator within about 20 cm**. Total footprint: about 200-300 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.

$ ¥

¢ €

£

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)

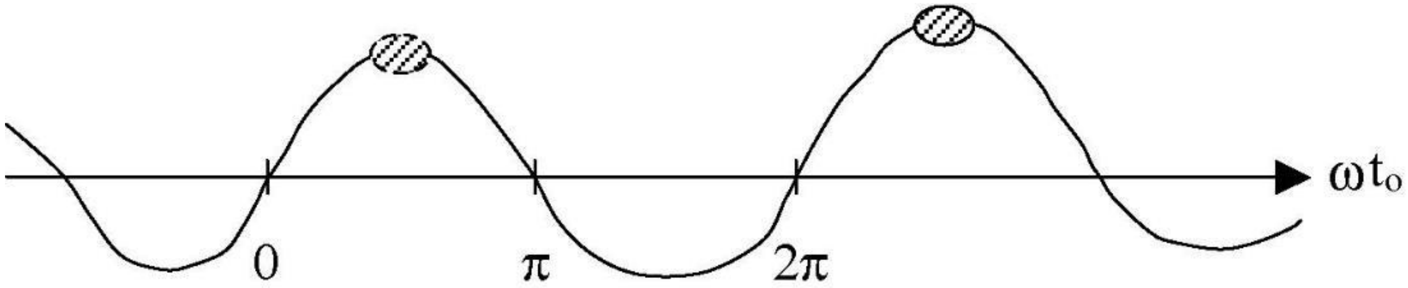
Two conditions for an accelerator:

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!

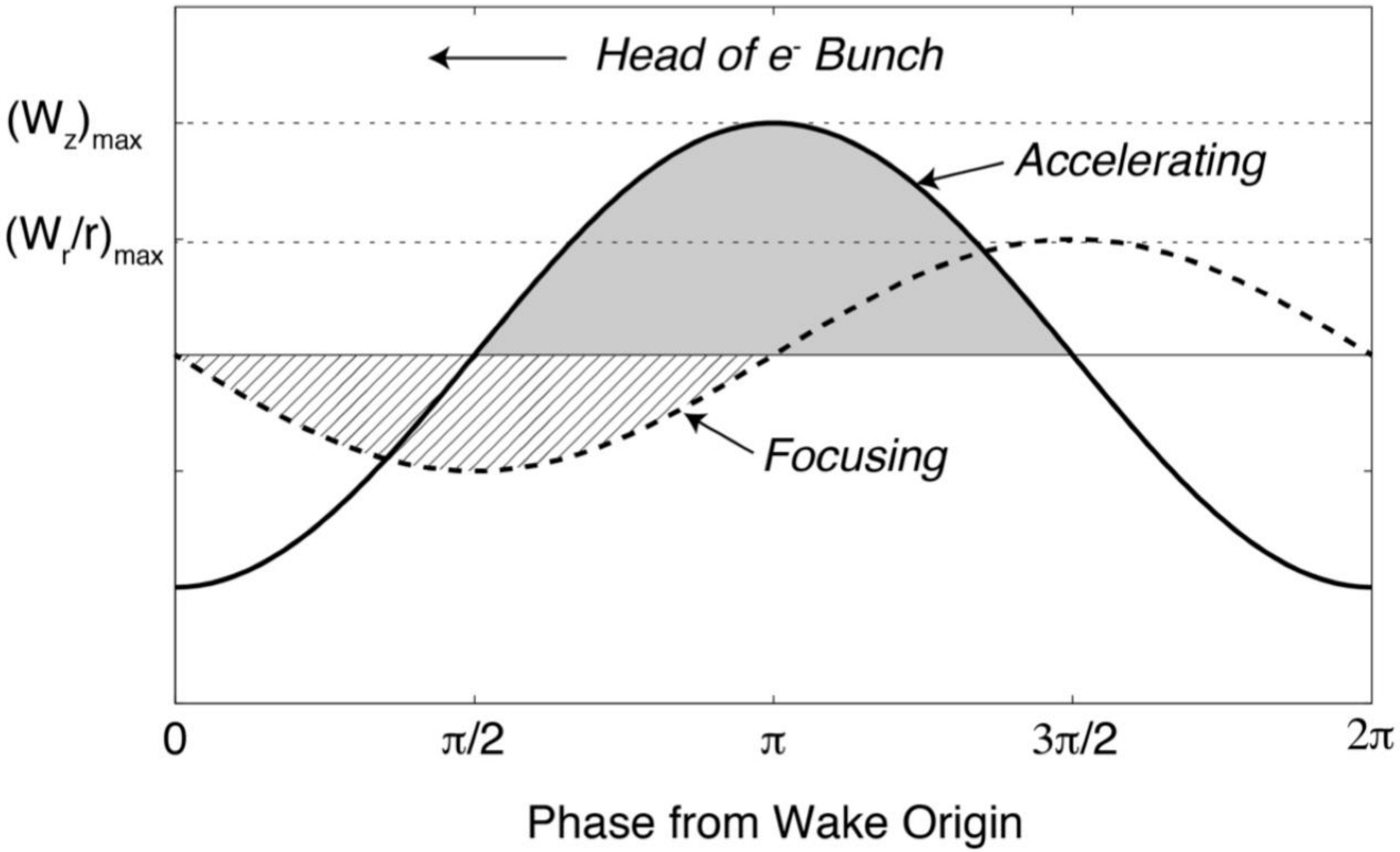
Reminder metallic RF accelerator structures:

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



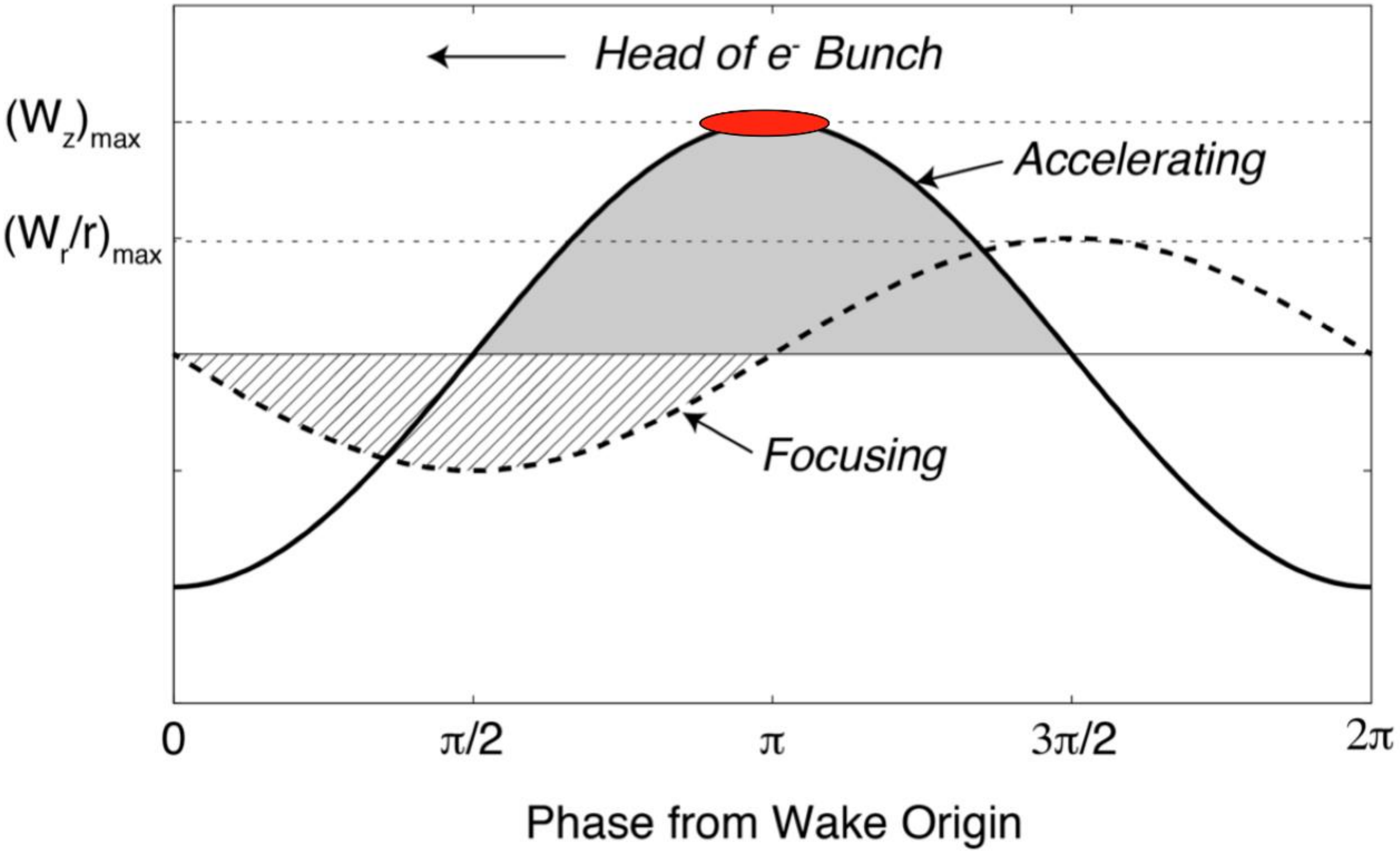
Plasma Accelerator Phasing

Finding the useful regime



Plasma Accelerator Phasing

Finding the useful regime



Plasma Accelerator Phasing

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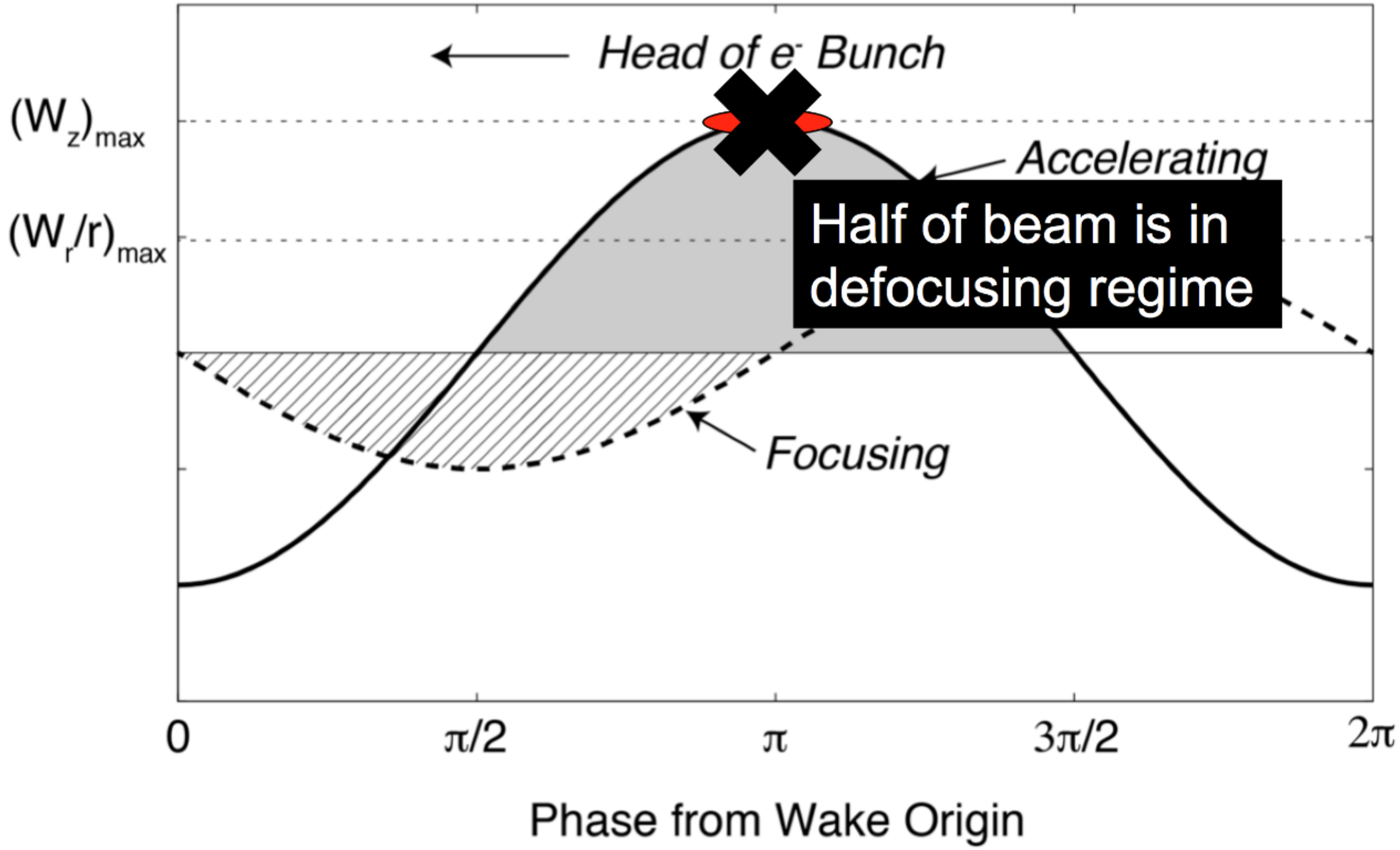

Plasma Accelerator Phasing

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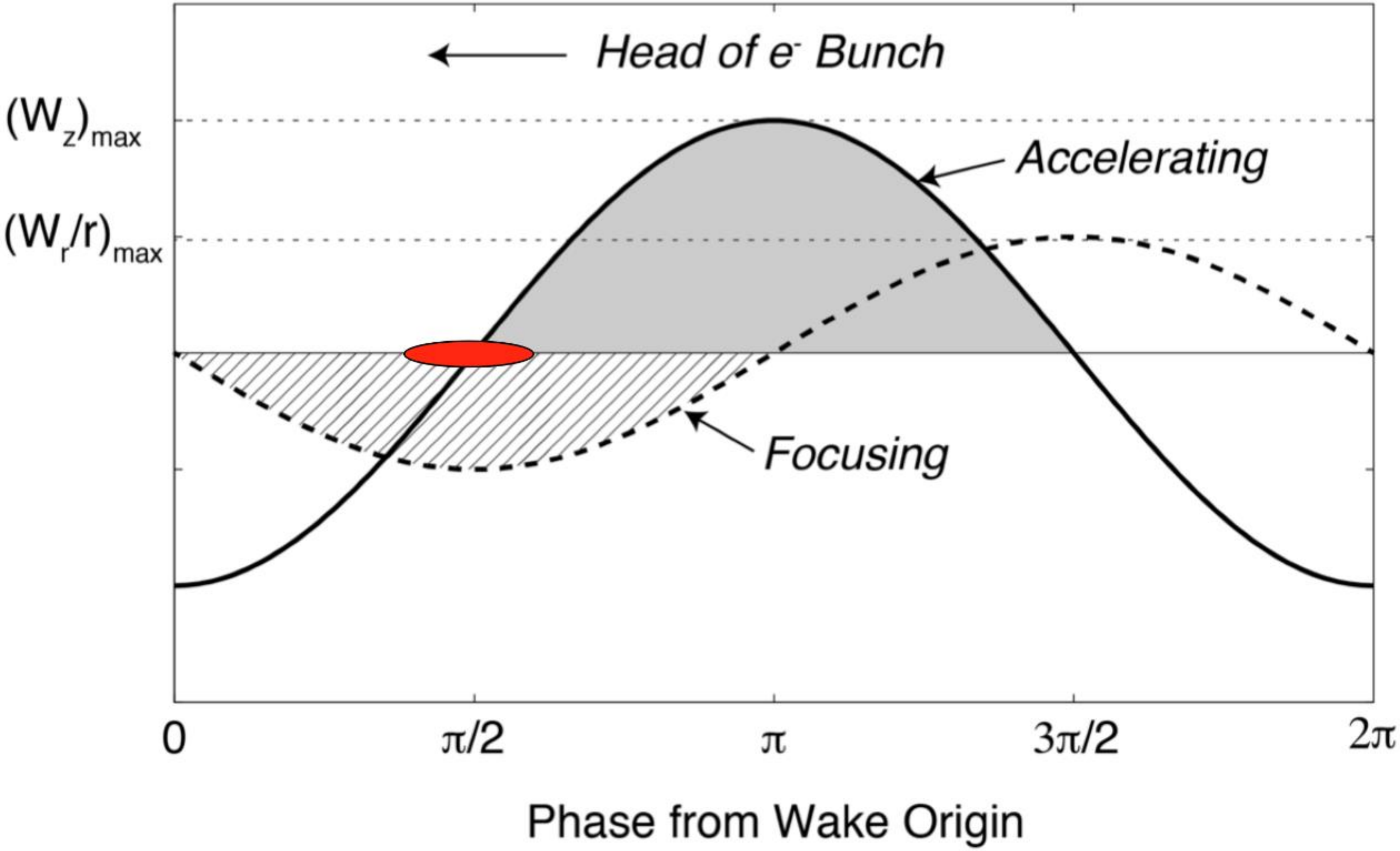
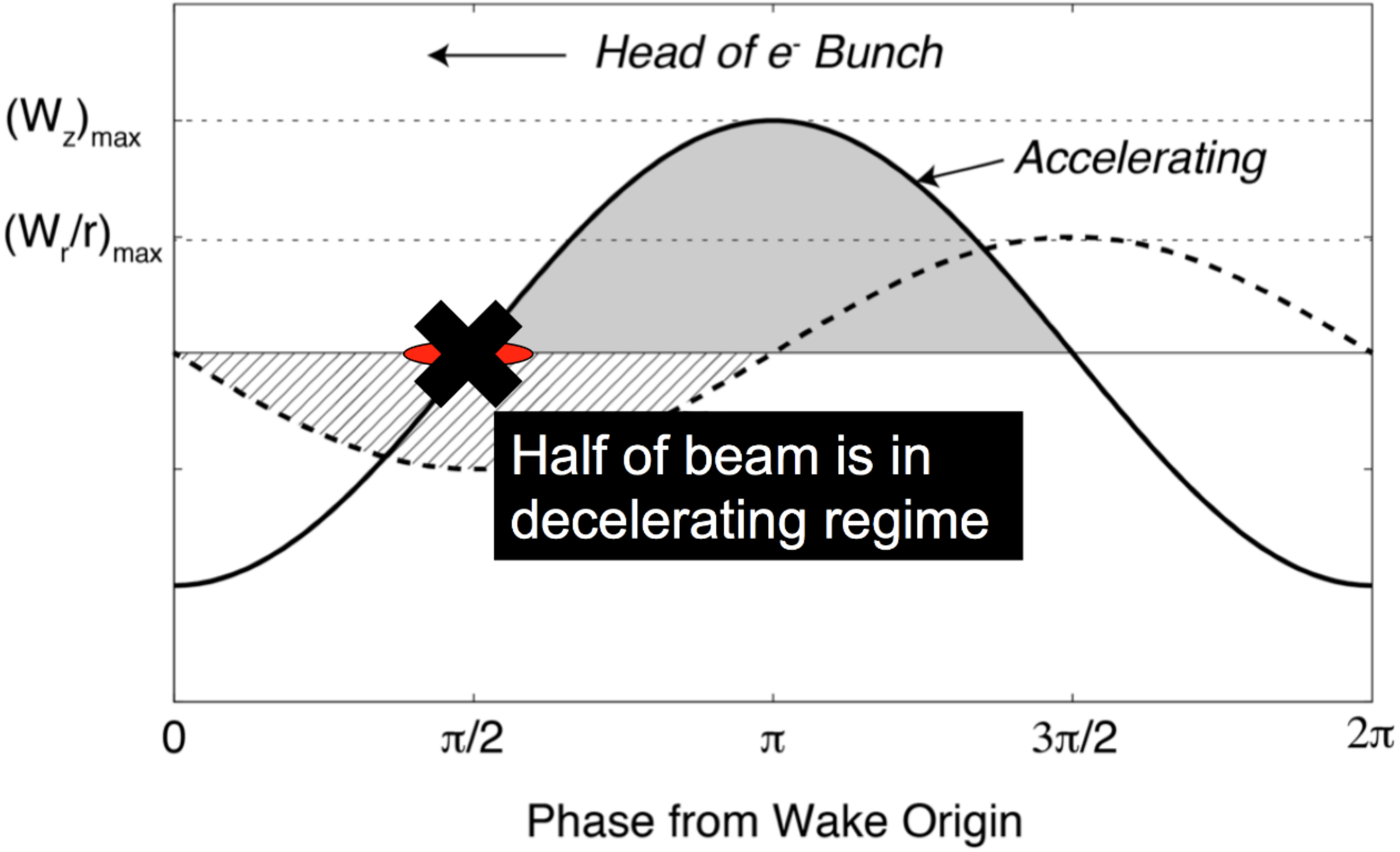


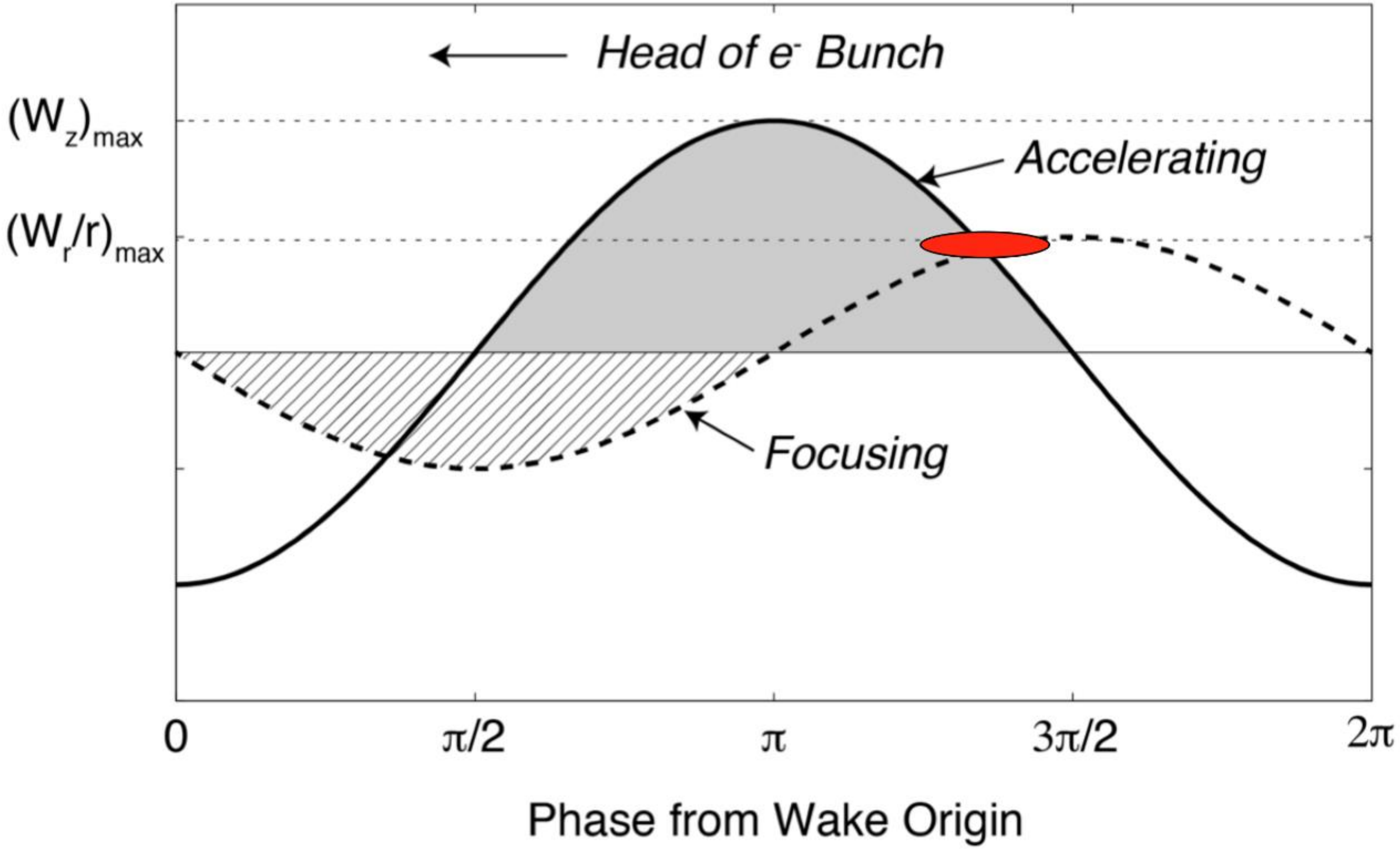
Plasma Accelerator Phasing

Finding the useful regime



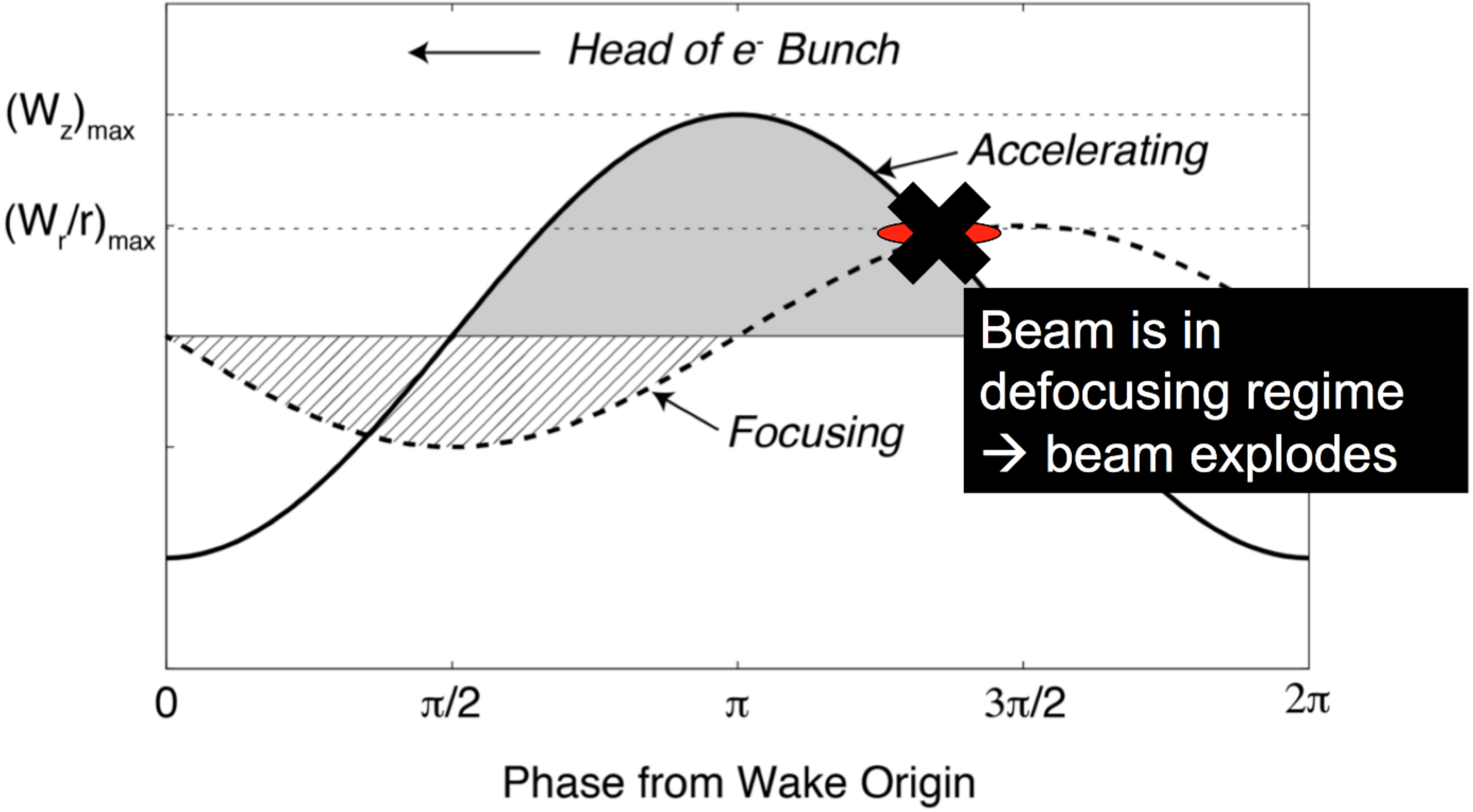
Plasma Accelerator Phasing

Finding the useful regime



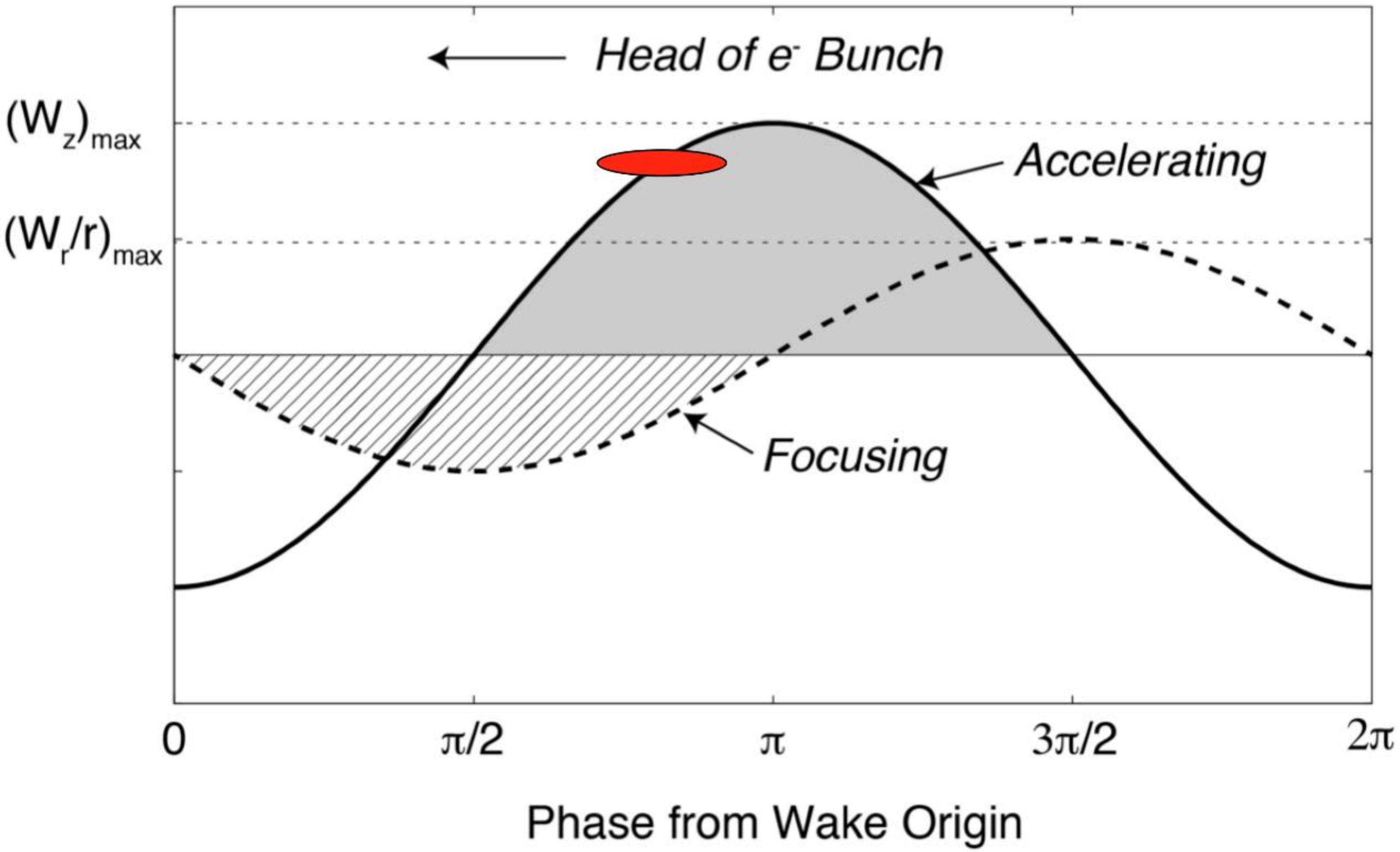
Plasma Accelerator Phasing

Finding the useful regime



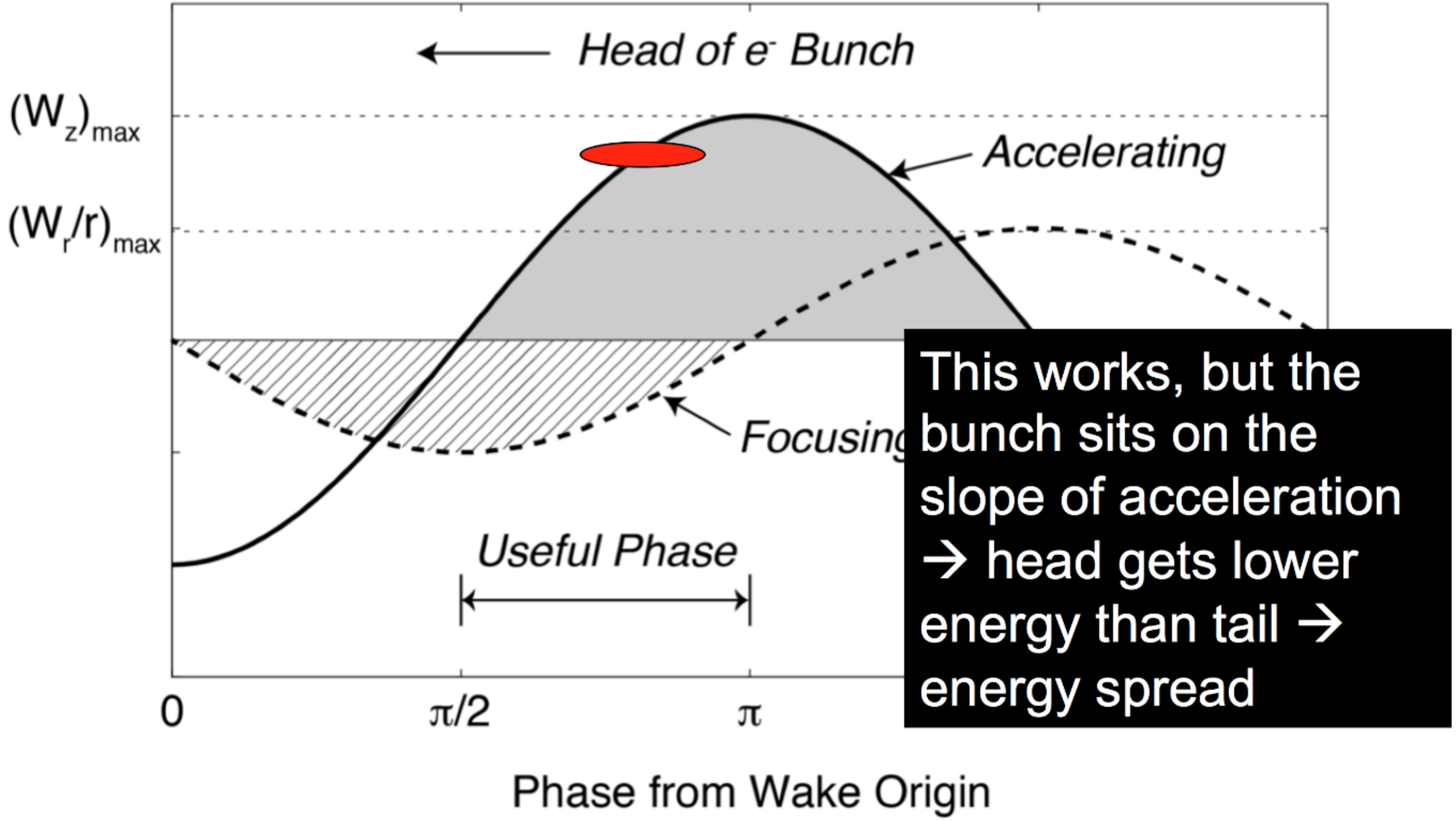
Plasma Accelerator Phasing

Finding the useful regime



Plasma Accelerator Phasing

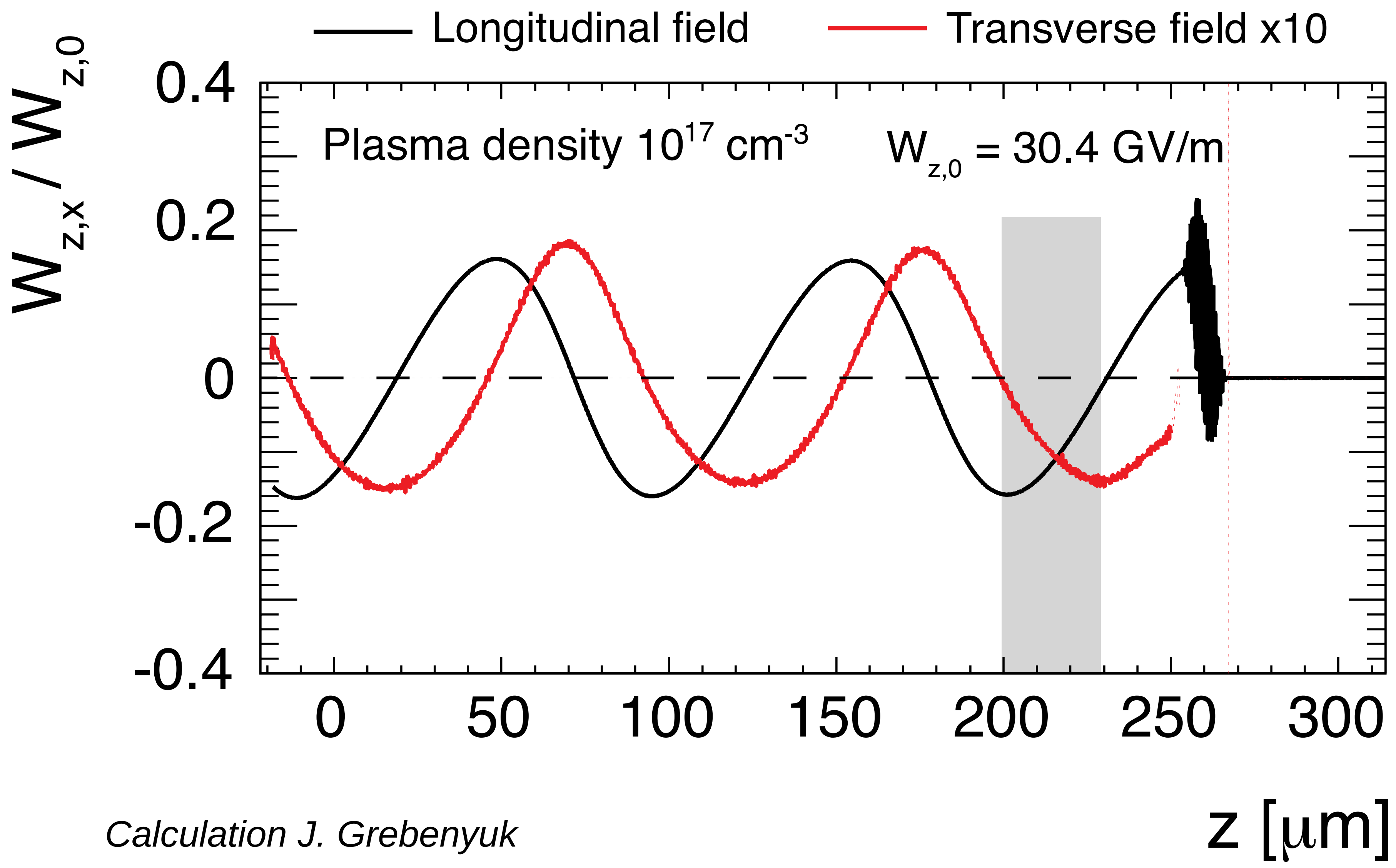
Finding the useful regime



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

Comparison with OSIRIS simulation

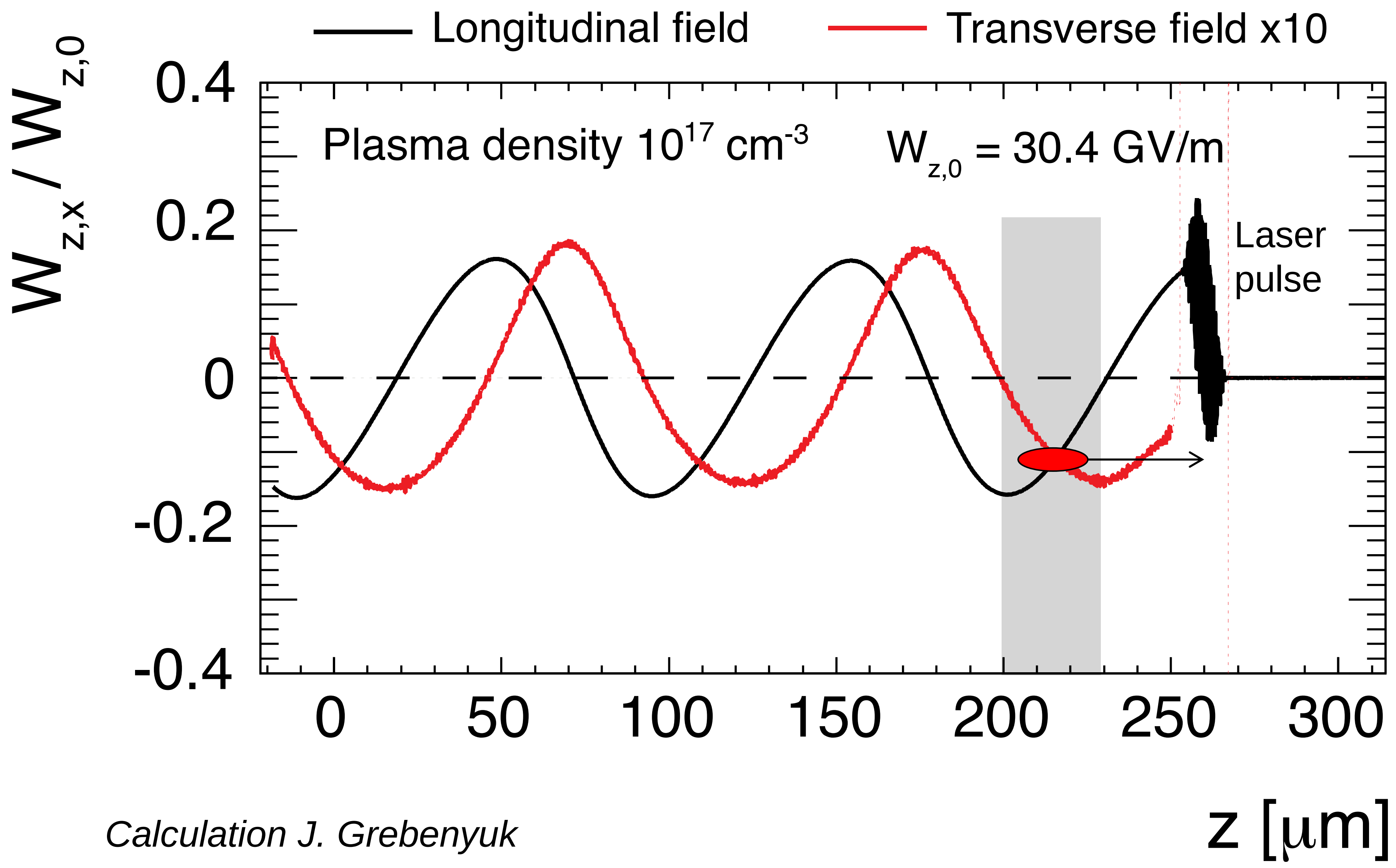
Finding the useful regime



Calculation J. Grebenyuk

Comparison with OSIRIS simulation

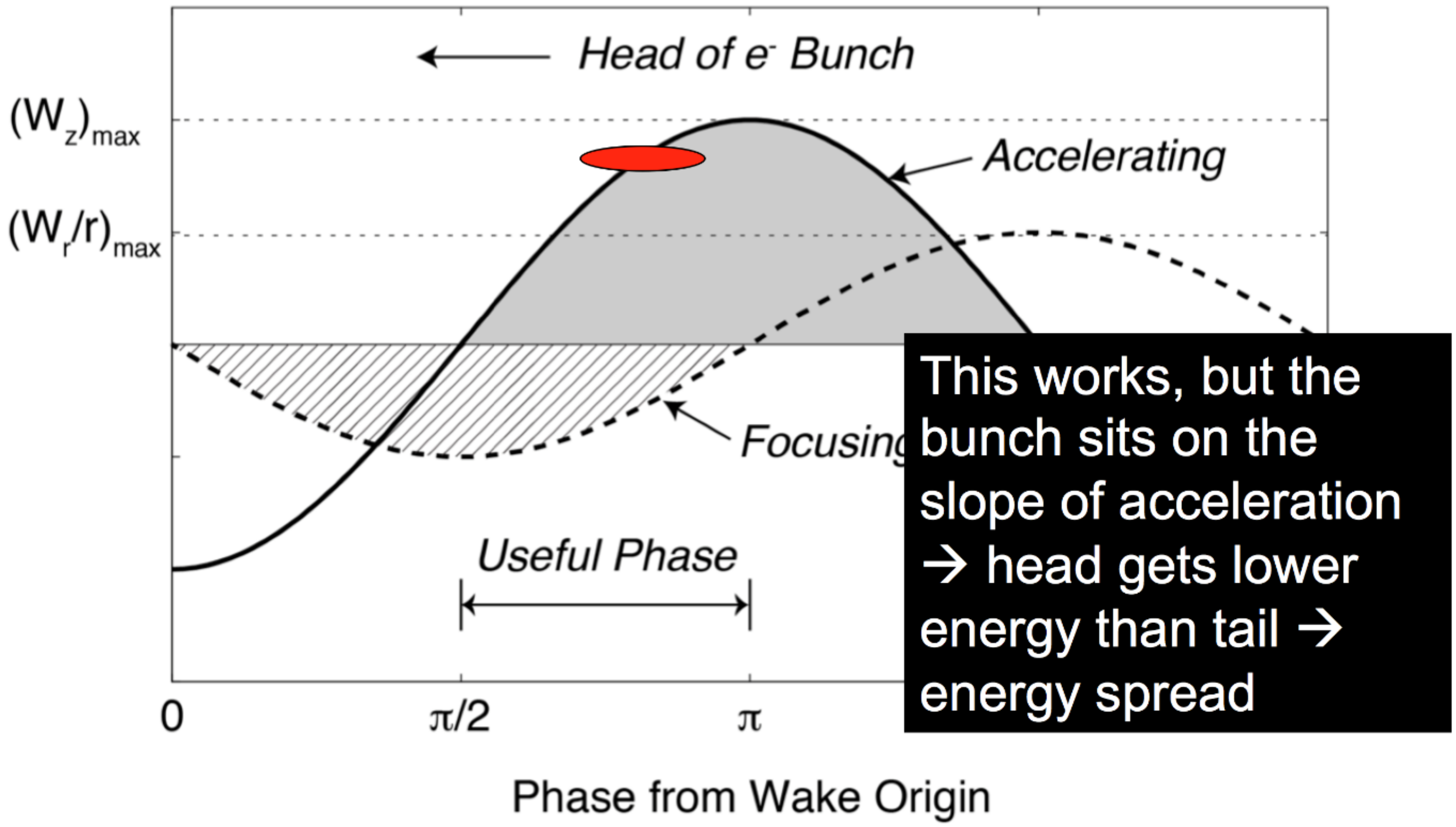
Finding the useful regime



Calculation J. Grebenyuk

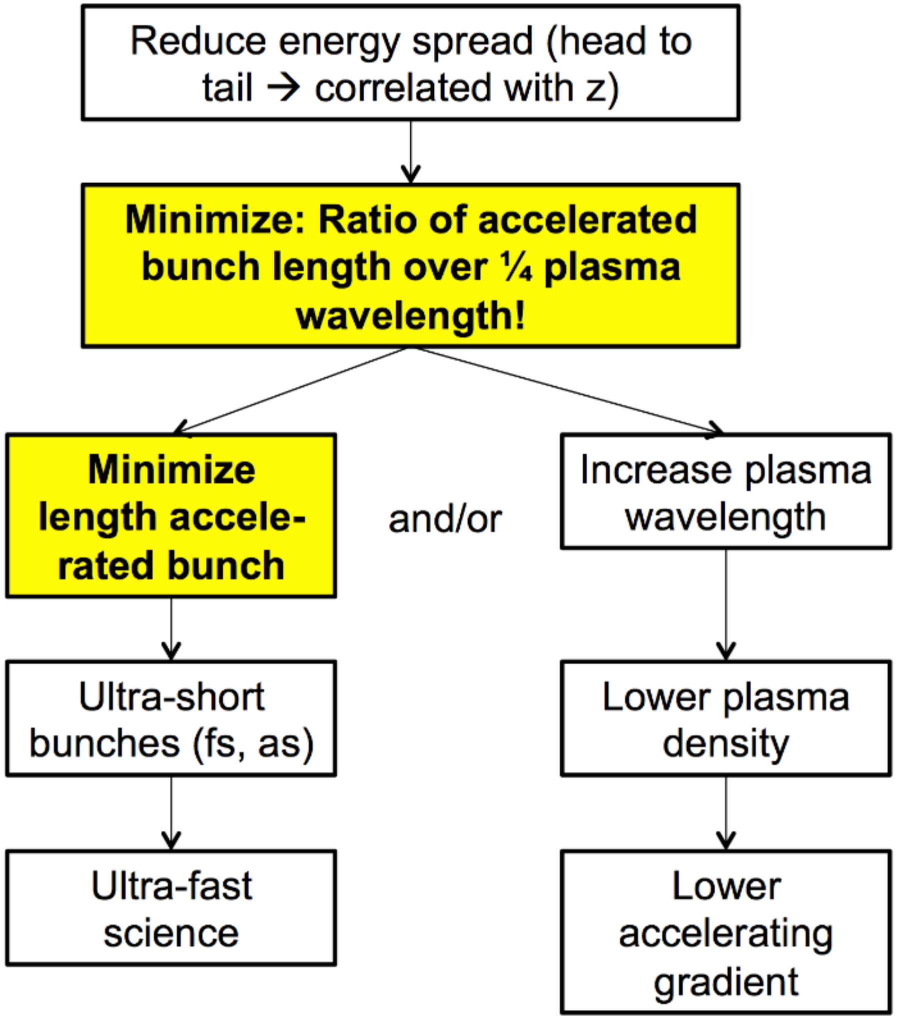
Plasma Accelerator Phasing

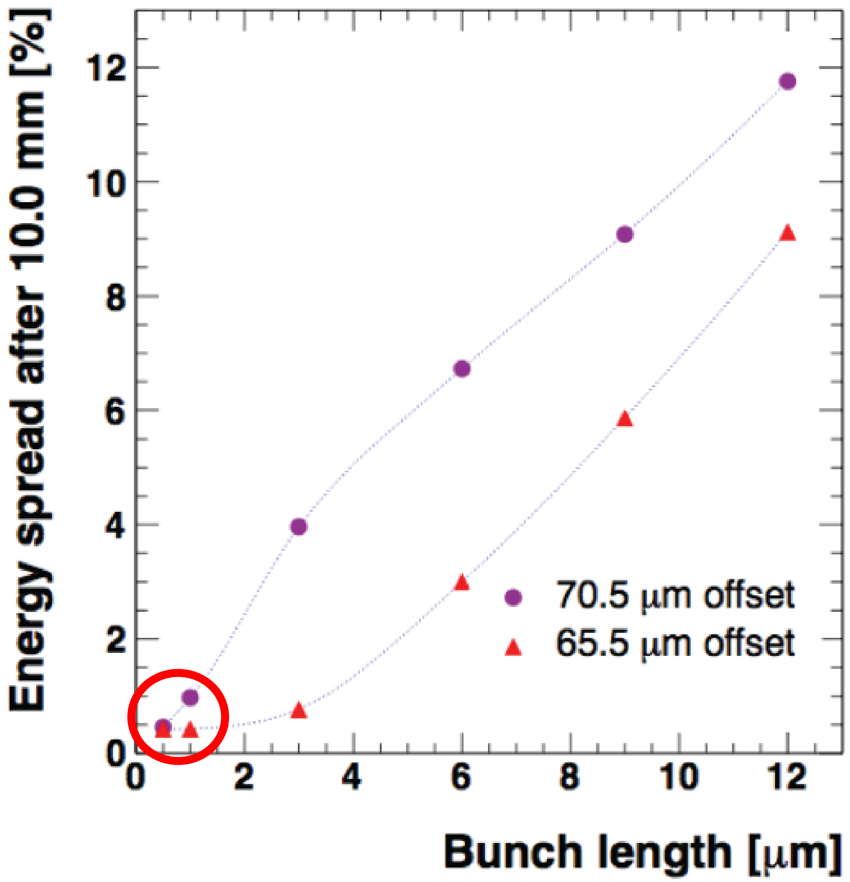
Finding the useful regime



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

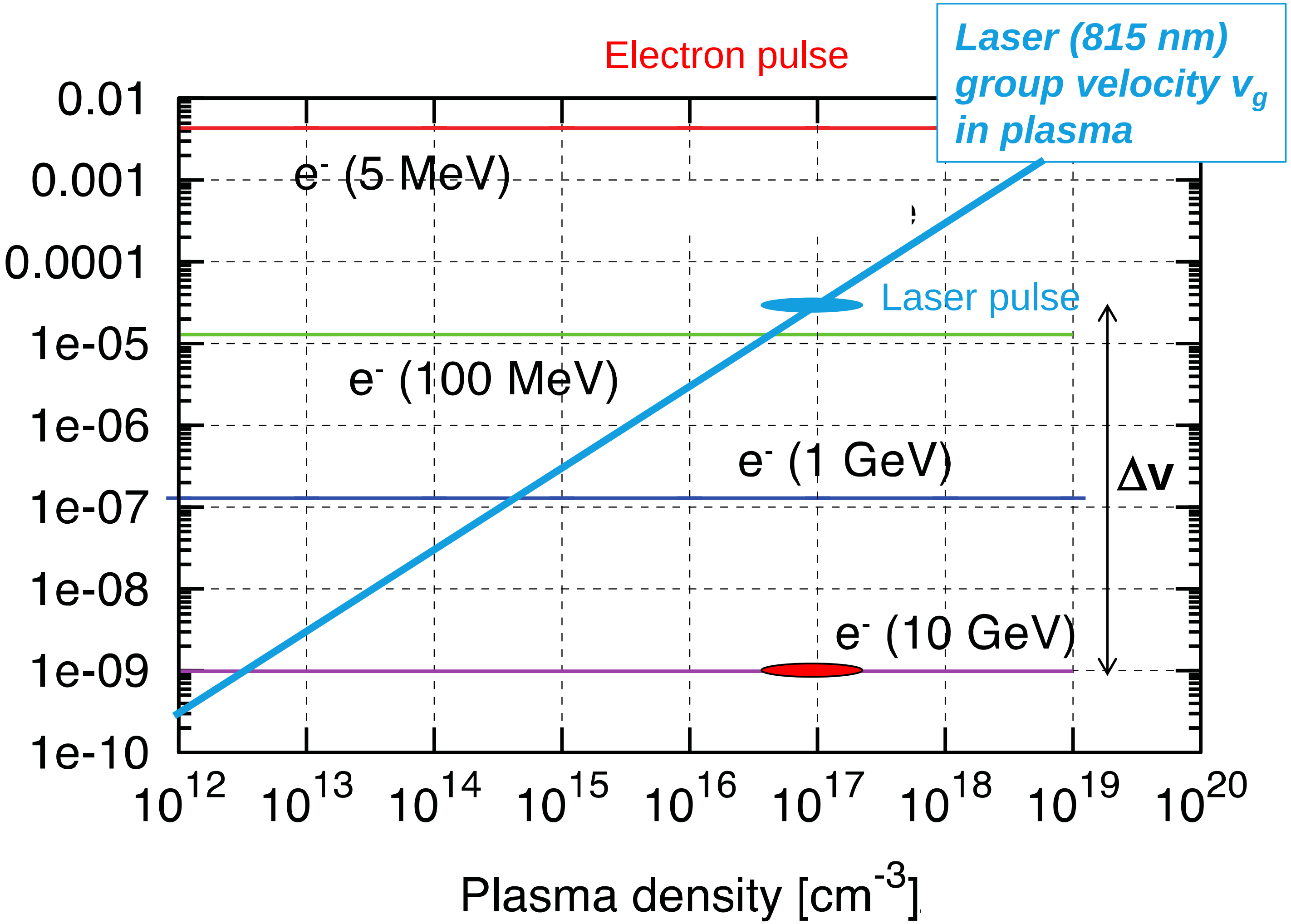
Dephasing

($\beta = v/c$, here consider relativistic beams)

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

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

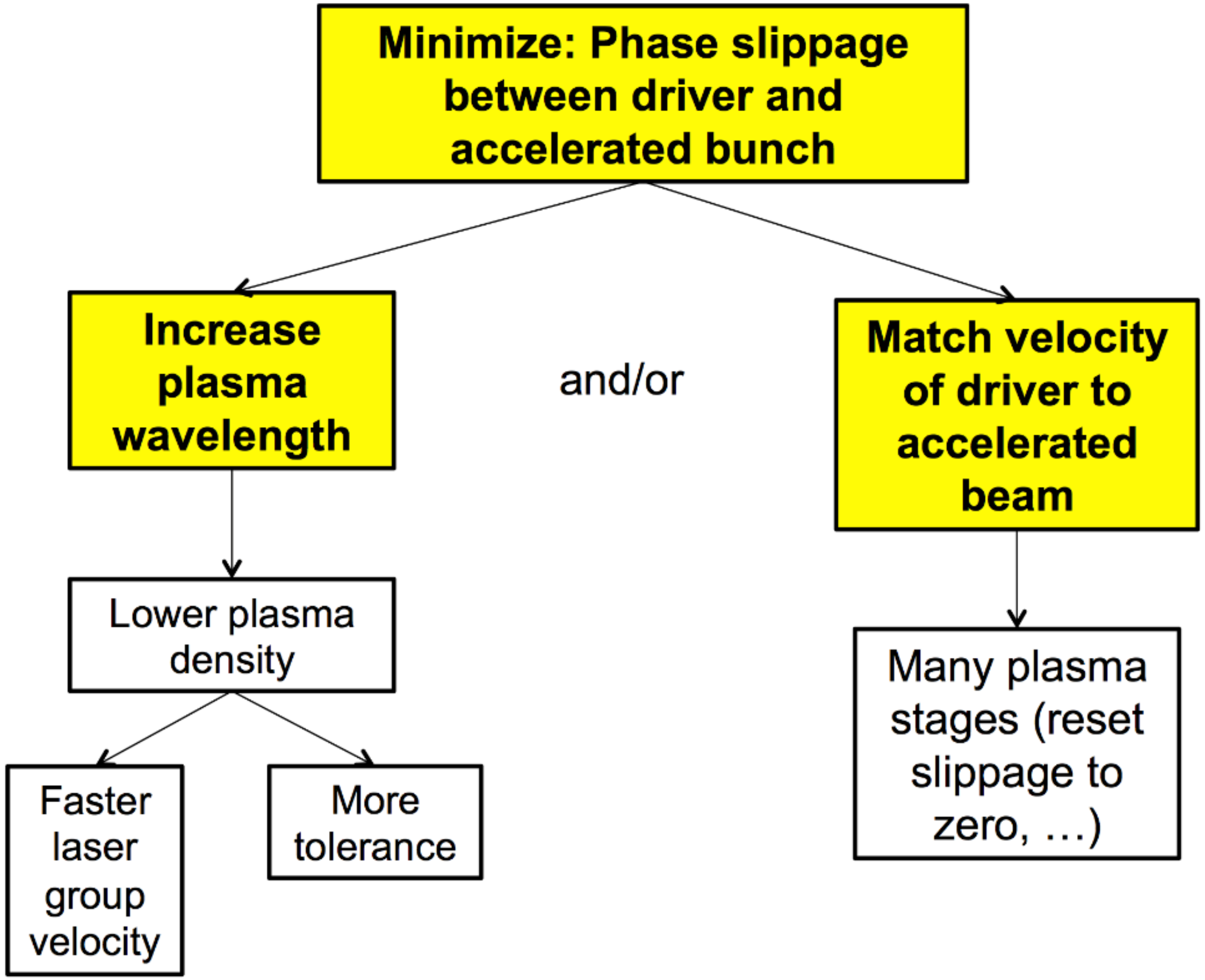
- Take **plasma density $n_0 = 10^{17}$ cm^{-3}** (electrons per cm^3). Therefore plasma wavelength **λ_p = 0.1 mm**.
- Assume drive pulse from a **laser with wavelength 815 nm**.
- Difference in velocities 1-β:
  $\Delta(1-\beta) \approx 3 \times 10^{-5}$
- Slippage: **30 μm per meter**
- = 30% of wavelength or 108° in "RF phase"!



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

Optimization: Phase Slippage

Maximize distances over which we can accelerate



Optimization: Phase Slippage

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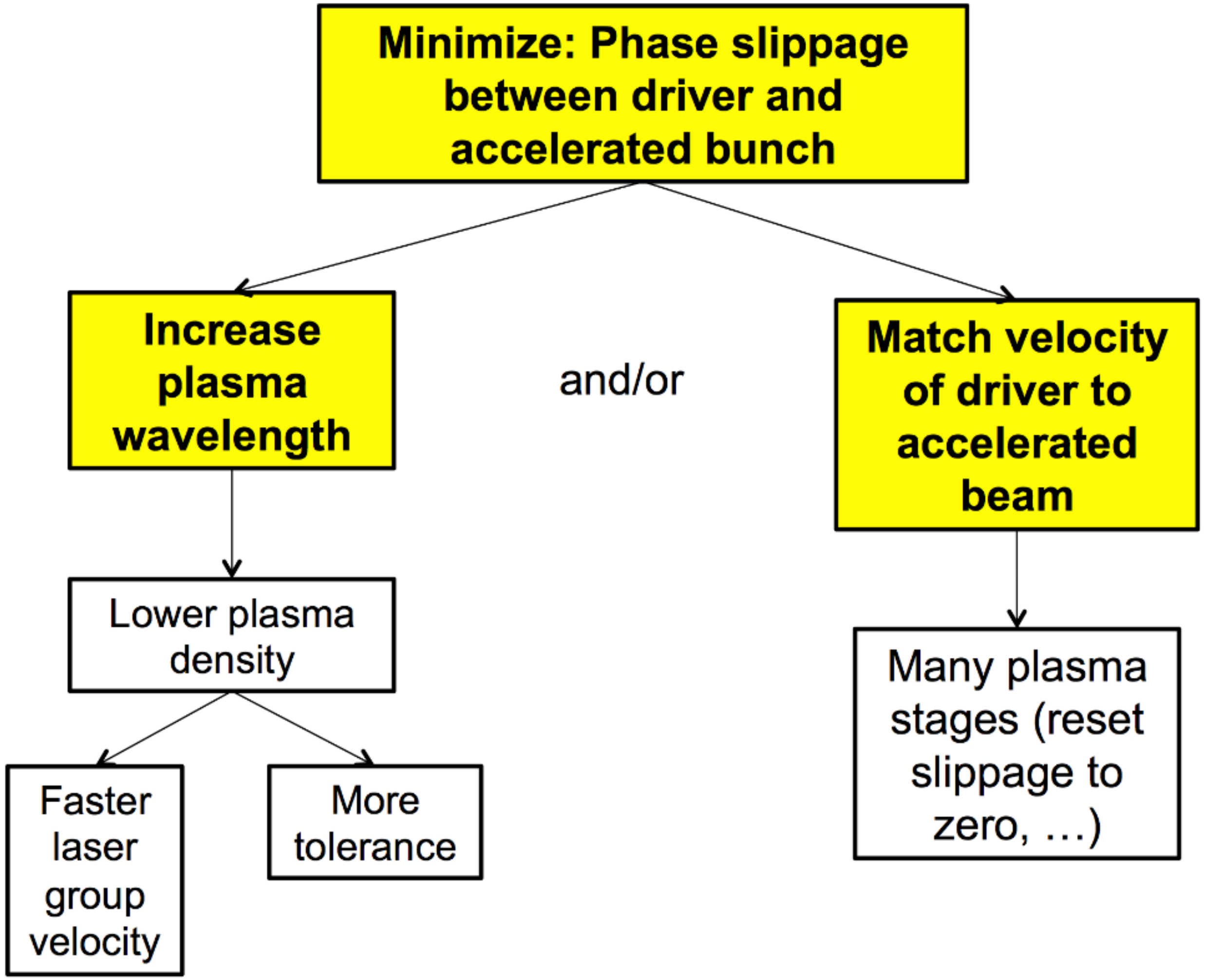
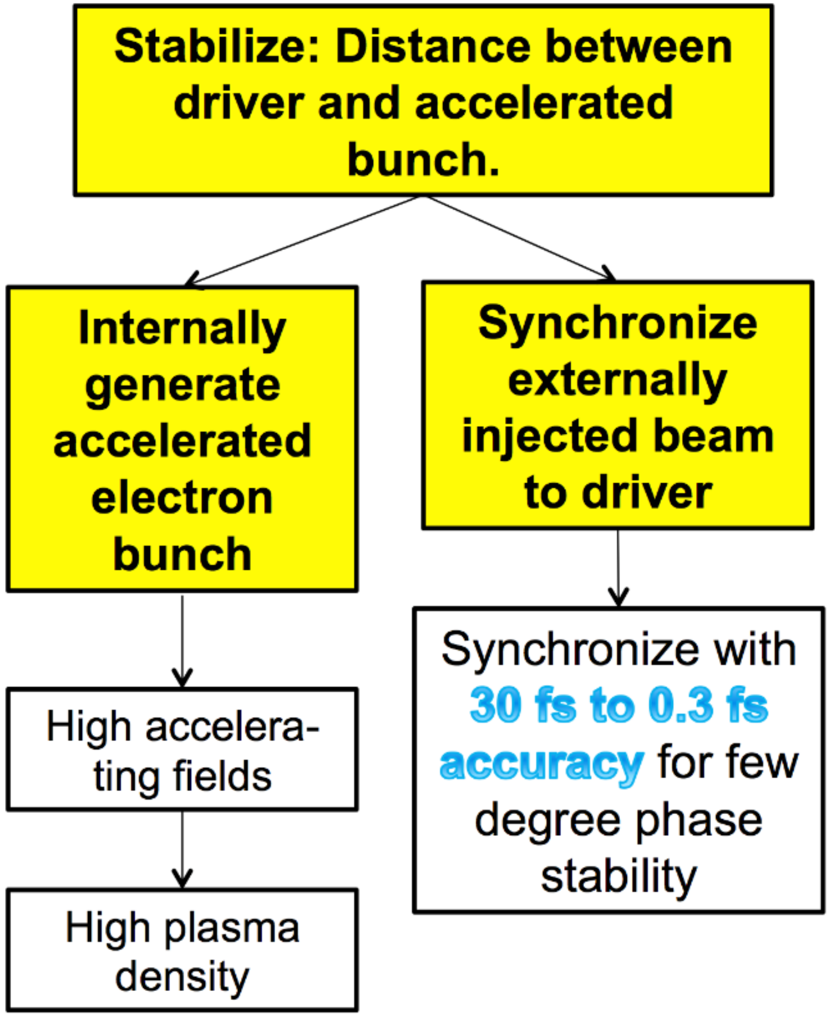


Stability/Reproducibility

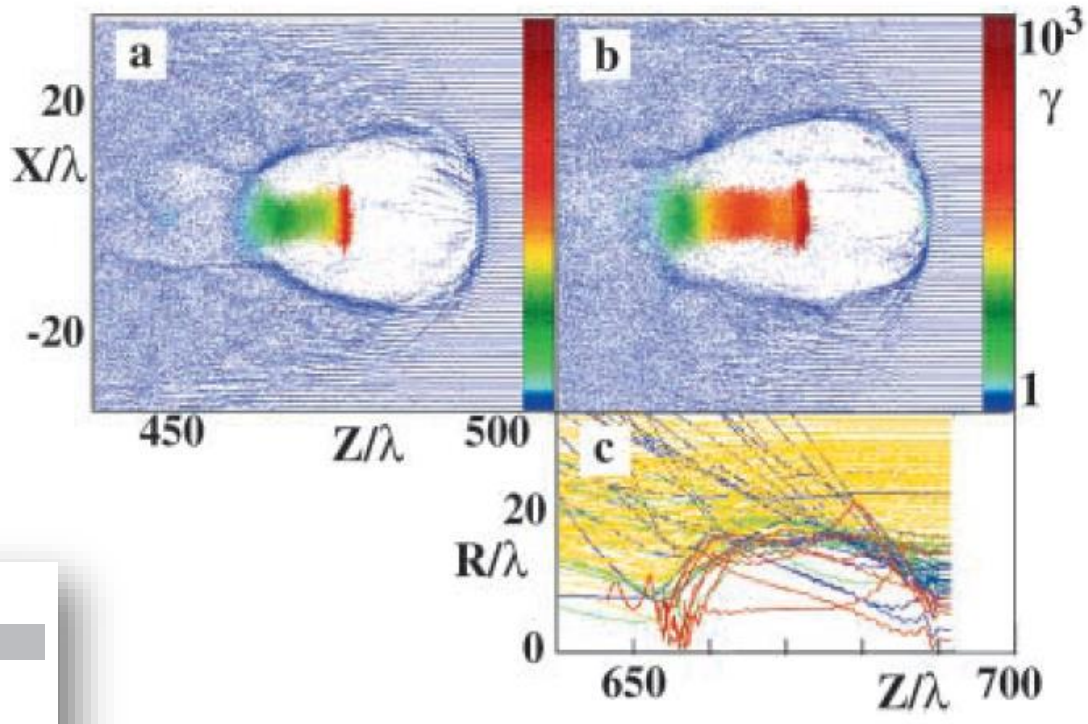
Hit the same phase every time



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:

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

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 $\gamma\varepsilon$ = 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

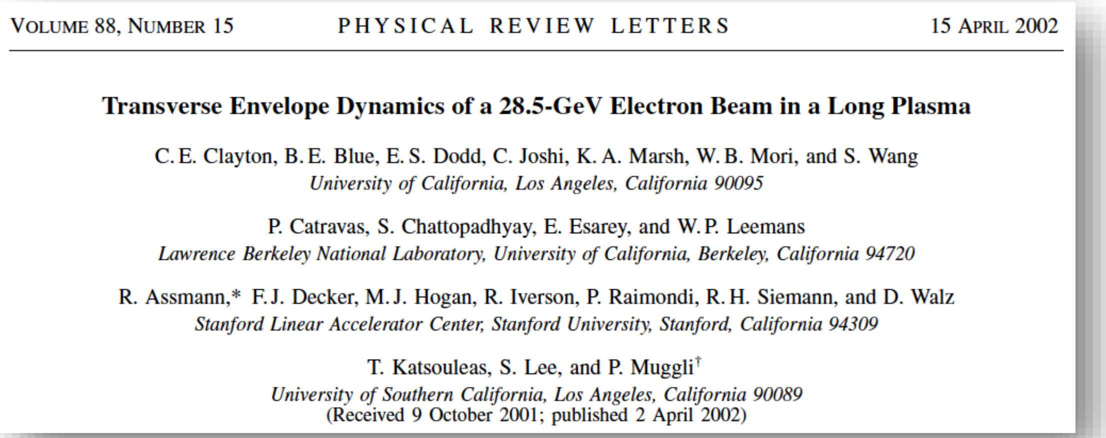
- Lower plasma density better: larger matched beam size, bigger tolerances.

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

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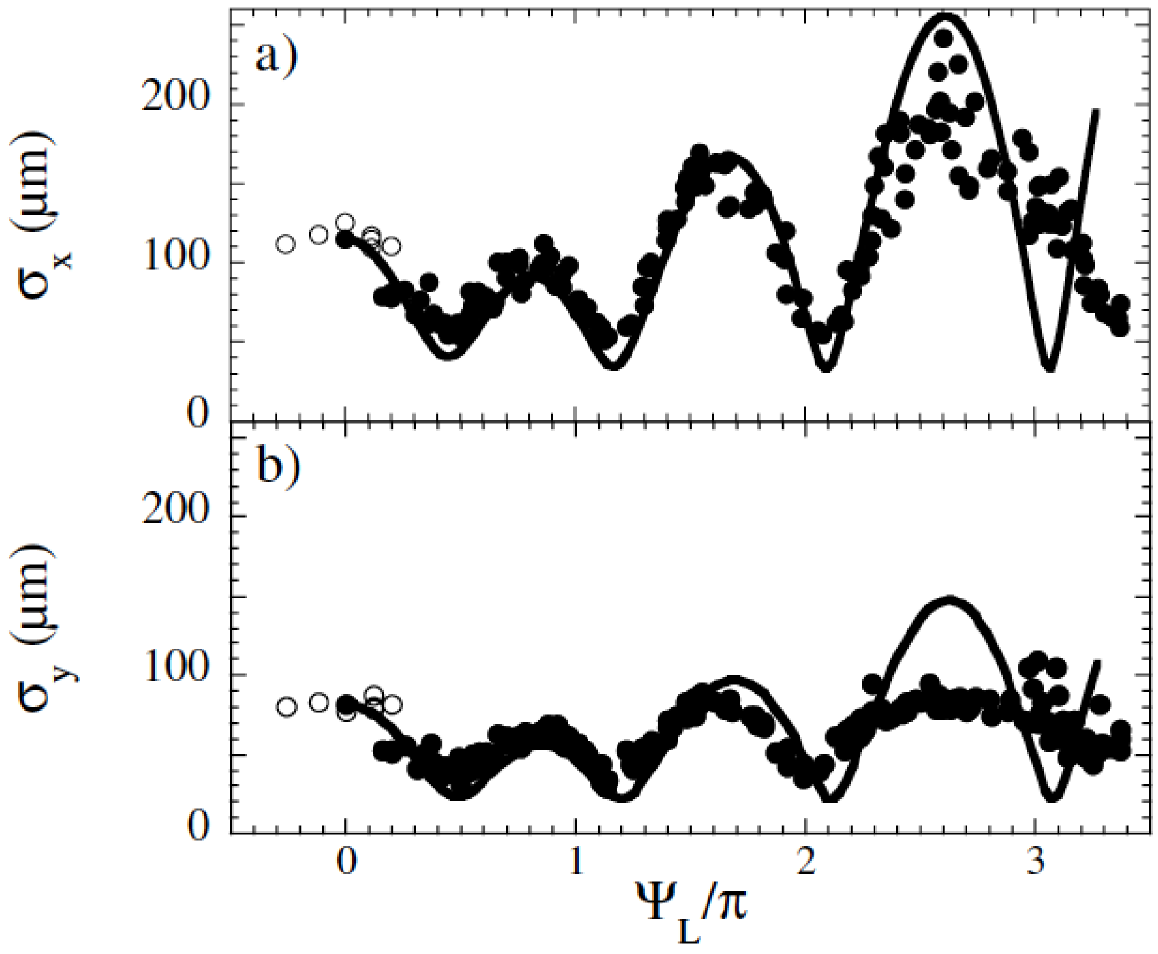
R. Assmann,* F. J. Decker, M. J. Hogan, R. Iverson, P. Raimondi, R. H. Siemann, and D. Walz
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

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



Strong plasma focusing: 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]

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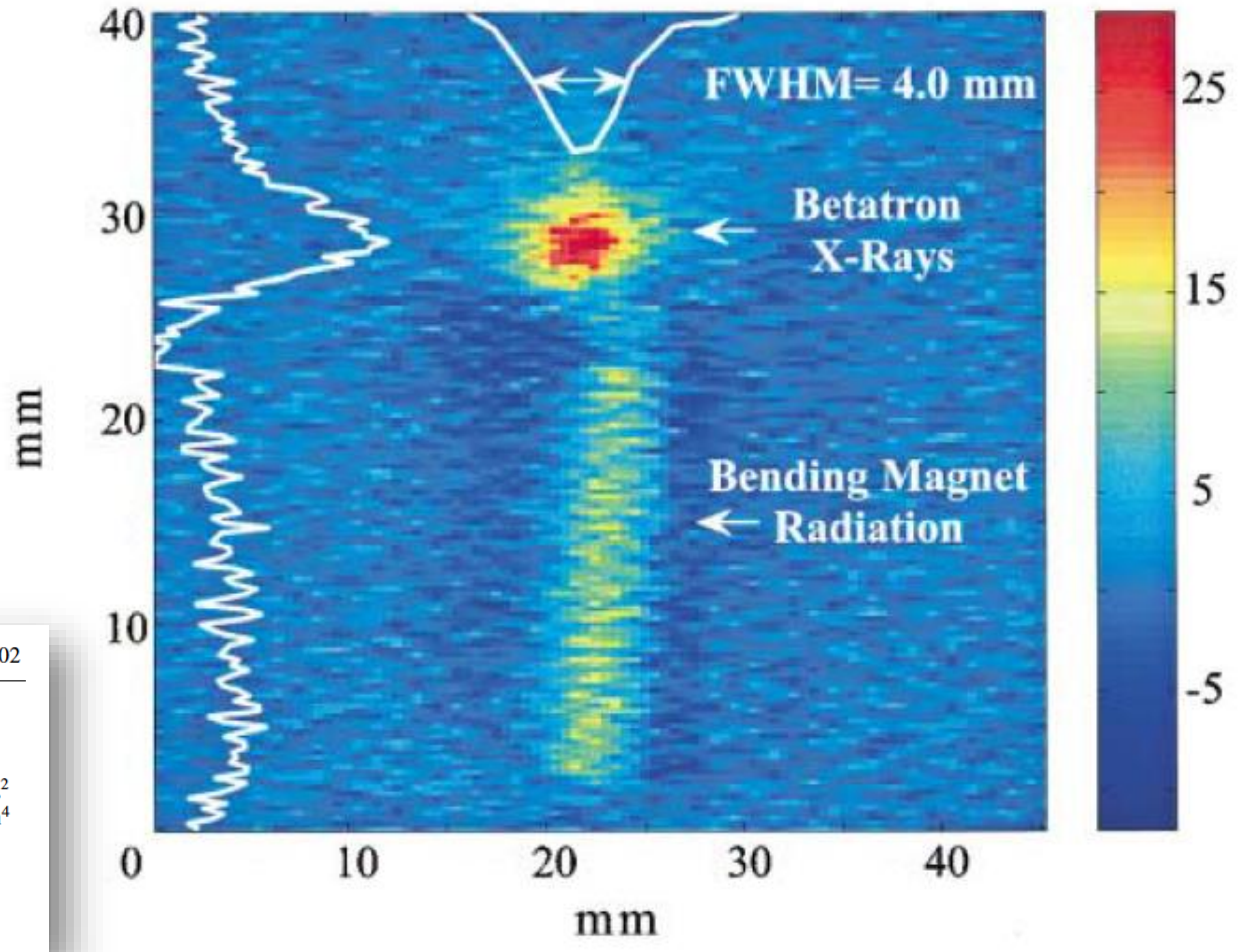
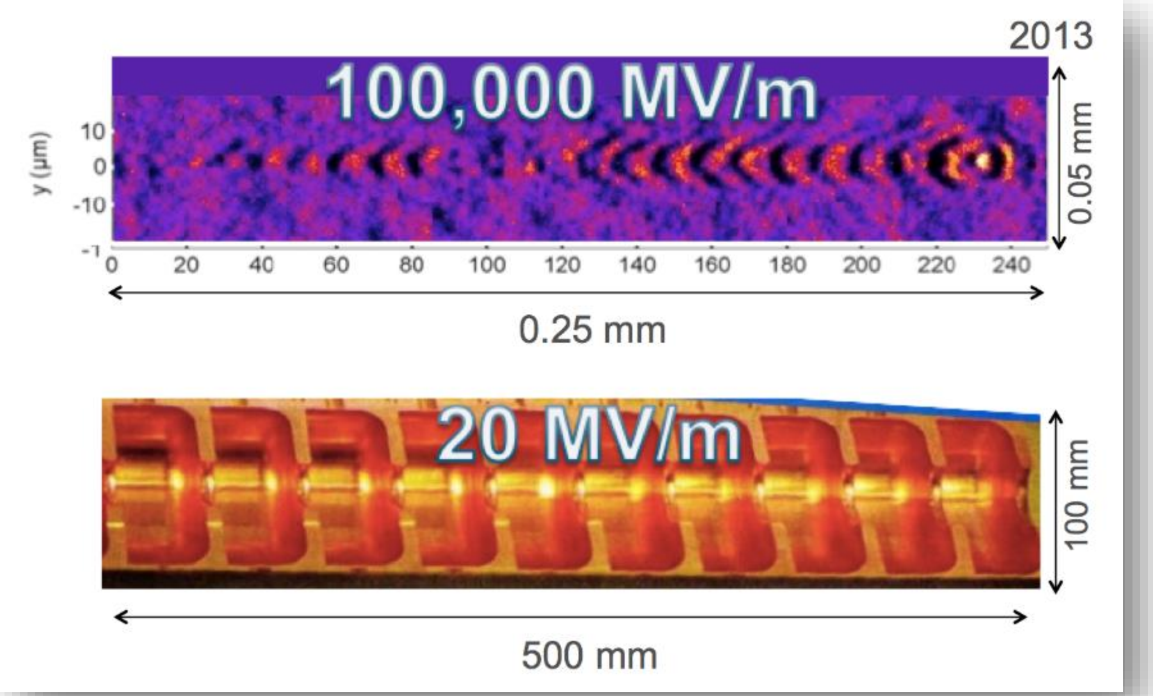
[2]*University of Southern California, Los Angeles, California 90089*
[3]*Stanford Linear Accelerator Center, Stanford, California 94309*
[4]*CERN, Switzerland*
(Received 8 October 2001; published 19 March 2002)



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.
- For fun: A look at the SLAC linac beam before entering the plasma!



Seeing Electron Beam…

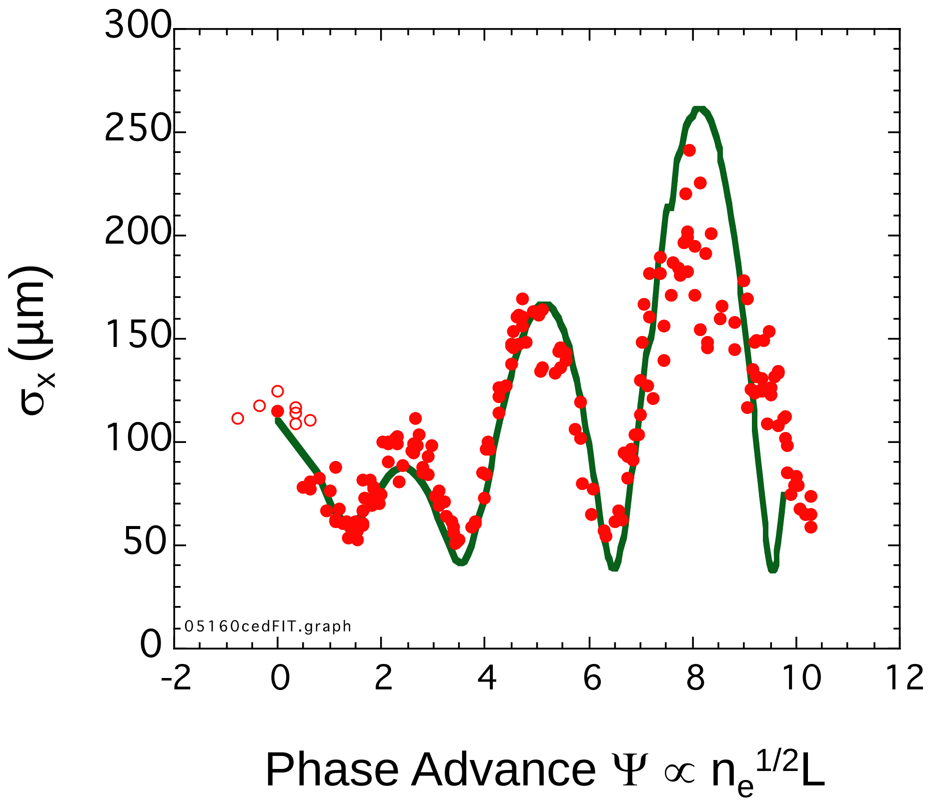
~ 2e10 electrons, 30 GeV

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

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**.

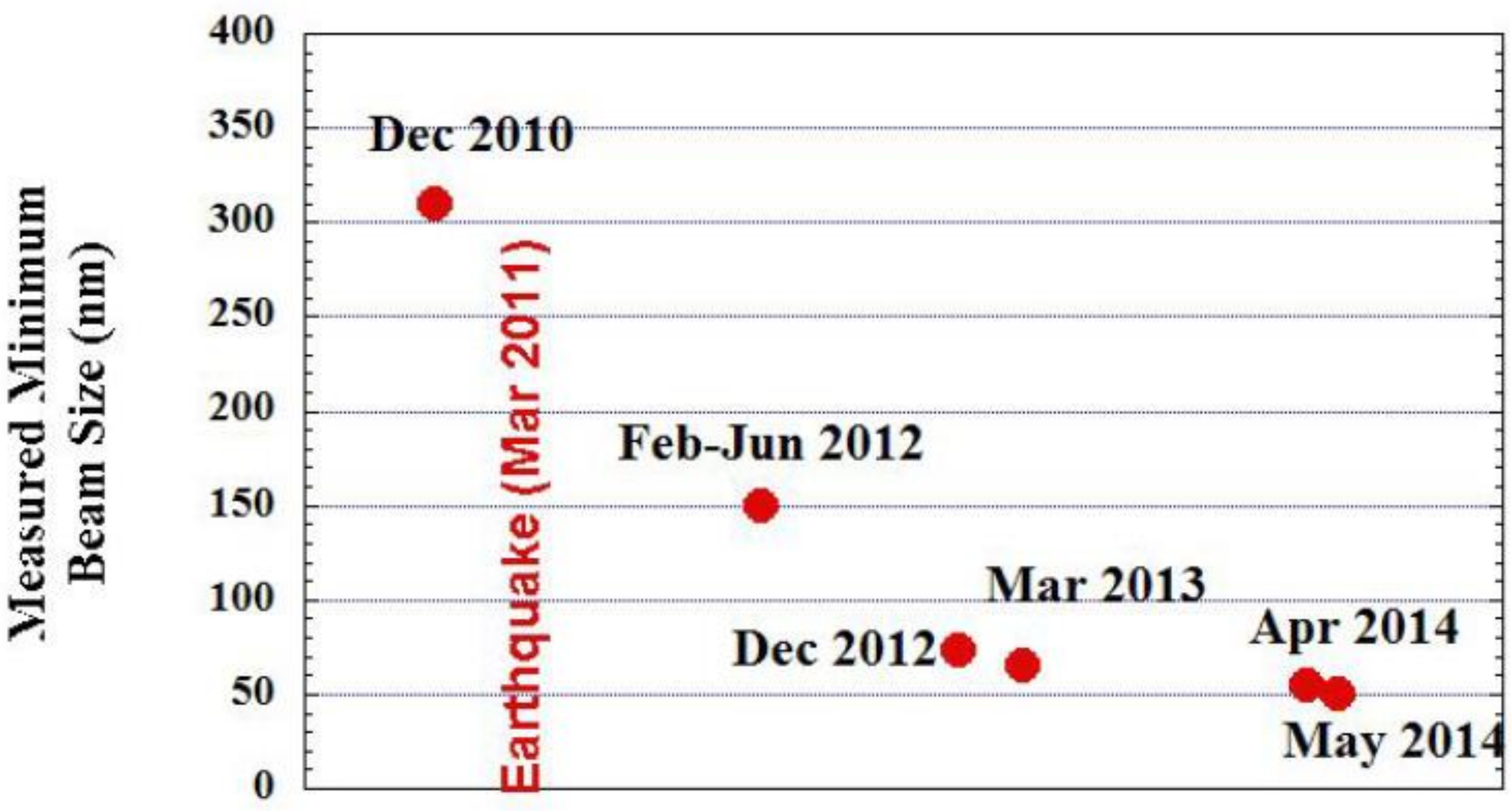


PRL 2002, C. E. Clayton, B. E. Blue, E. S. Dodd, C. Joshi, K. A. Marsh, W. B. Mori, and S. Wang, P. Catravas, S. Chattopadhyay, E. Esarey, and W. P. Leemans, R. Assmann, F. J. Decker, M. J. Hogan, R. Iverson, P. Raimondi, R. H. Siemann, and D. Walz, T. Katsouleas, S. Lee, and P. Muggli

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…

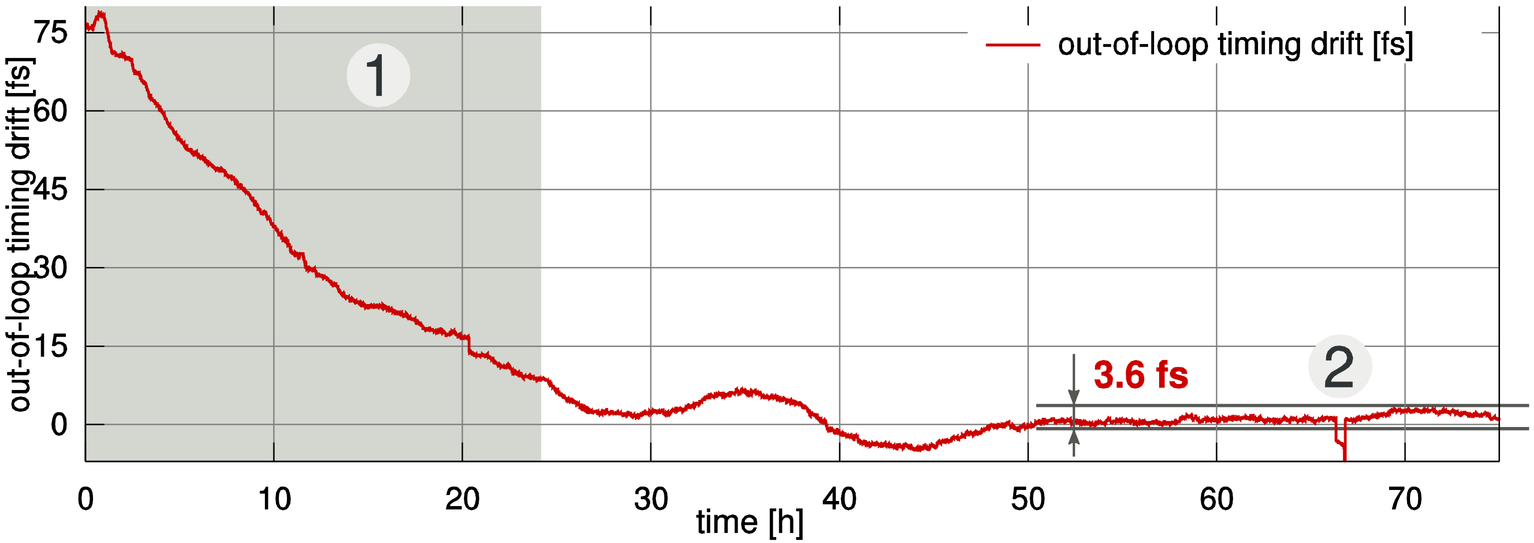


50 nm with a 1.3 GeV electron beam
(from K. Kubo et al. Proc. IPAC 2014)

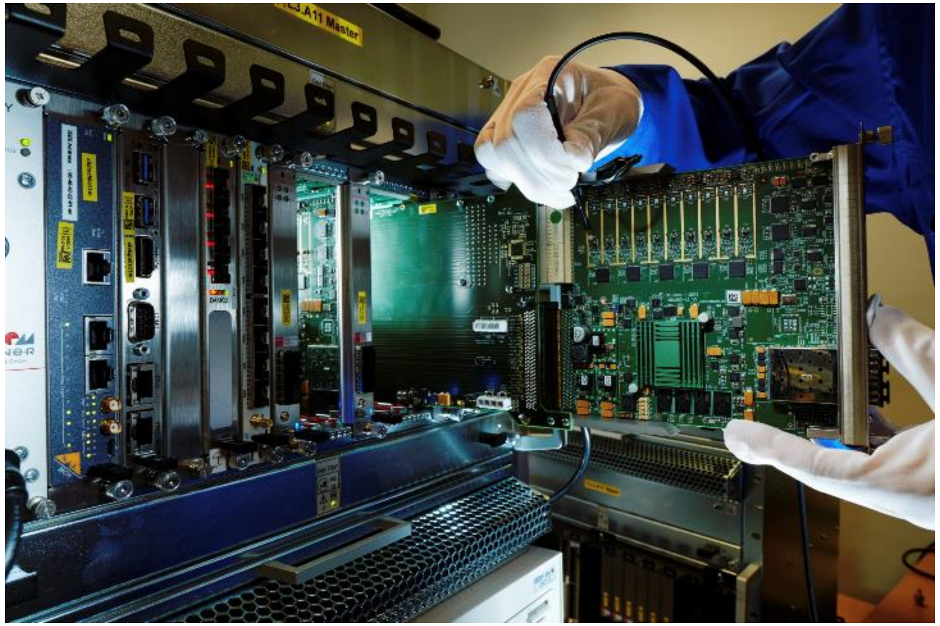
Accelerator Builder’s Challenge – Feasible?

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).



Contents

Novel Acceleration R&D in Europe

How can we develop plasma accelerators towards usability?

Independent national projects*, funded by national states. About 16 major facilities for novel plasma acceleration R&D.

European Network EuroNNAc for Novel Accelerators

European novel accelerator projects with international involvement

AWAKE

CERN experiment collaboration under leadership of MPI (A. Caldwell)

AXSIS

ERC Synergy Grant

EuPRAXIA

Funded by EU Horizon2020 as EU Design Study

** See note on ELI*

Helmholtz Support for Compact Accelerators

The agenda of the president of the Helmholtz Association (largest science organization in Germany)

HELMHOLTZ GEMEINSCHAFT

Stand: 26. September 2016

AGENDA des Präsidenten der Helmholtz-Gemeinschaft

Zu den inhaltlichen Herausforderungen zählen aus heutiger Sicht:

From today's perspective the following challenges are identified

- Energiesysteme der Zukunft — ***energy systems***
- Information und Data Science — ***information and data science***
- Integrierte Erforschung des Erdsystems — ***research earth system***
- Neuartige Materialien und Wirkstoffe — ***new materials and agents***
- Entwicklung neuer Mobilitätskonzepte — ***new mobility concepts***
- Psychische Erkrankungen und Translation für eine individualisierte Medizin — ***psych. disease indiv. medicine***
- Neue Generationen von kompakten Beschleunigersystemen. — ***New generations of compact accelerators.***

In den nächsten Jahren werden wir diese und andere Themen auf vielfältige Weise unterstützen.

Support programs:

Accelerator R&D
ARD research topic in Matter&Technology (MT)

Independent **research activity**: same hierarchical level as HEP and photon science

IuVF funding
"Plasma Accelerator"

Strategic investment
30M€ ATHENA soon? (same funding pot as Helmholtz LHC detector lab)

(A) EuPRAXIA Horizon2020 Design Study *(DESY coordinated)*

European Plasma Accelerator Infrastructure with Pilot Users, site-independent (now mid-term)

- Collaboration of **40 institutes**
  - **16 EU laboratories** are beneficiaries
  - **24 associated partners** from EU, Europe, Asia and US contribute in-kind, 4 joined after 1st year:
    KIT (Germany), FZJ (Germany),
    University Jerusalem (Israel), IAP (Russia)
  - 2 additional associate partners just joined: University Belfast, Ferdinand-Braun-Institute, Leibniz Association, Berlin
- Collaboration brings together:
  - Big science labs: photon science, particle physics
  - Laser laboratories: high power lasers
  - International laboratories: CERN, ELI (associated)
  - Universities: accelerator research, plasma, laser
- Organized in **8 EU-funded work packages** and **6 in-kind work packages**
- **125 scientists** in our work list

It is a relatively small infrastructure so several bids for hosting it are being prepared in Italy, Germany, …

EuPRAXIA: A European Strategy for Accelerator Innovation

Do the required intermediate step between proof of principle and production facility – make one acc. unit!

PRESENT EXPERIMENTS

Demonstrating
100 GV/m routinely

Demonstrating **GeV** electron beams

Demonstrating basic **quality**

EuPRAXIA INFRASTRUCTURE

Engineering a high quality, compact plasma accelerator

5 GeV electron beam for the 2020's

Demonstrating user readiness

Pilot users from FEL, HEP, medicine, ...

PRODUCTION FACILITIES

Plasma-based **linear collider** in 2040's

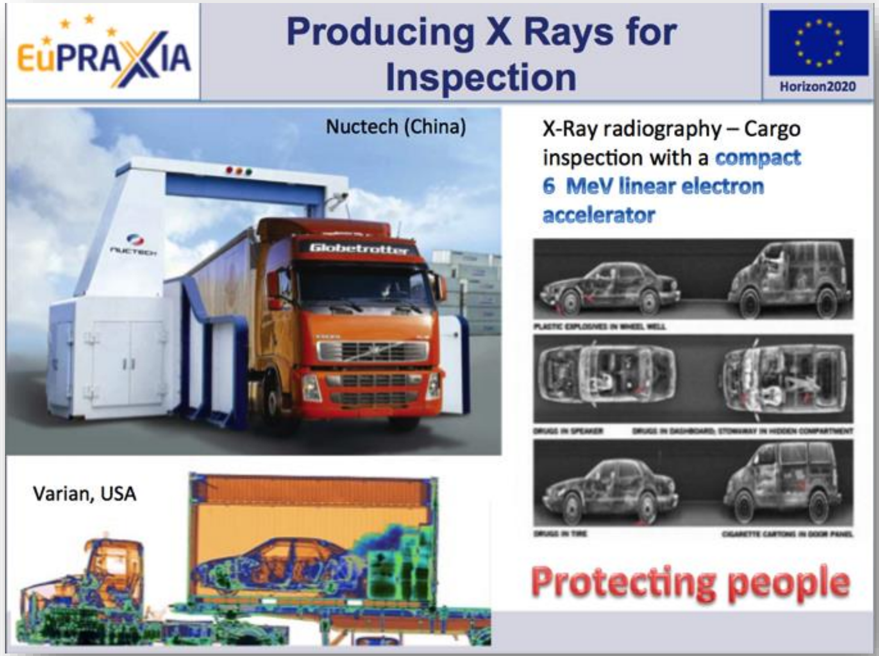
Plasma-based **FEL** in 2030's

Medical, industrial applications soon

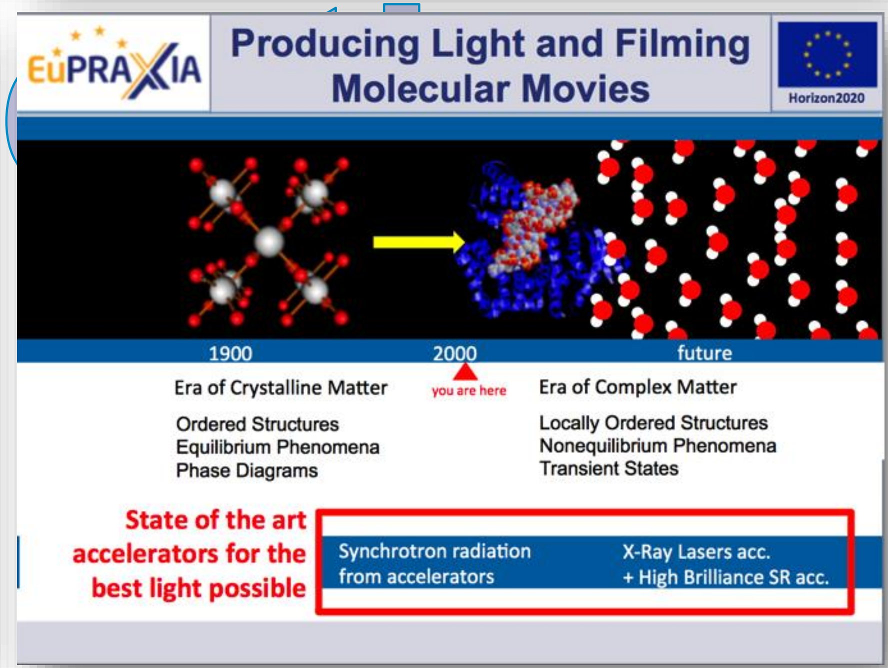





EuPRAXIA
Probing for New Particles and Forces
Horizon2020
Higgs Seminar 4.7. 2012
Google
THE TIMES
Higgs celebrates 'God particle' discovery
27 km LHC at CERN
Understanding fundamental laws


EuPRAXIA
Producing X Rays for Inspection
Horizon2020
Nuctech (China)
X-Ray radiography – Cargo inspection with a compact 6 MeV linear electron accelerator
Varian, USA
Protecting people


EuPRAXIA
Irradiating and Destroying Tumor Cells
Horizon2020
Heidelberg Ion-Beam Therapy Center (HIT)
Curing people


EuPRAXIA
Producing Light and Filming Molecular Movies
Horizon2020
1900
2000
future
Era of Crystalline Matter
you are here
Era of Complex Matter
Ordered Structures
Equilibrium Phenomena
Phase Diagrams
Locally Ordered Structures
Nonequilibrium Phenomena
Transient States
State of the art accelerators for the best light possible
Synchrotron radiation from accelerators
X-Ray Lasers acc. + High Brilliance SR acc.

Already working today: Medical Imaging

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

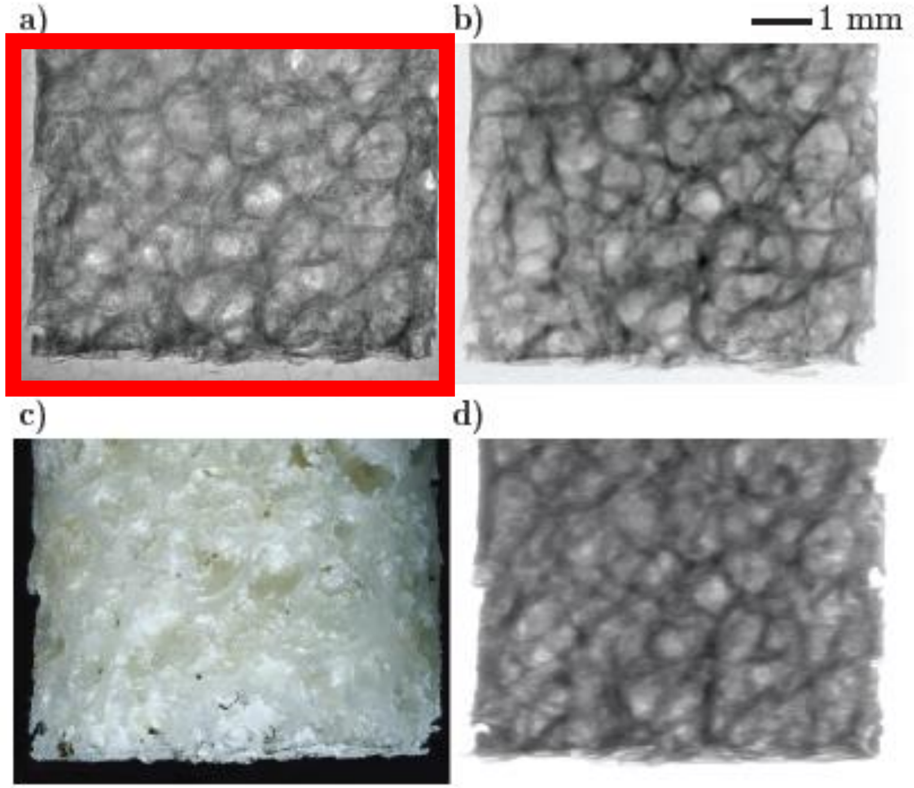
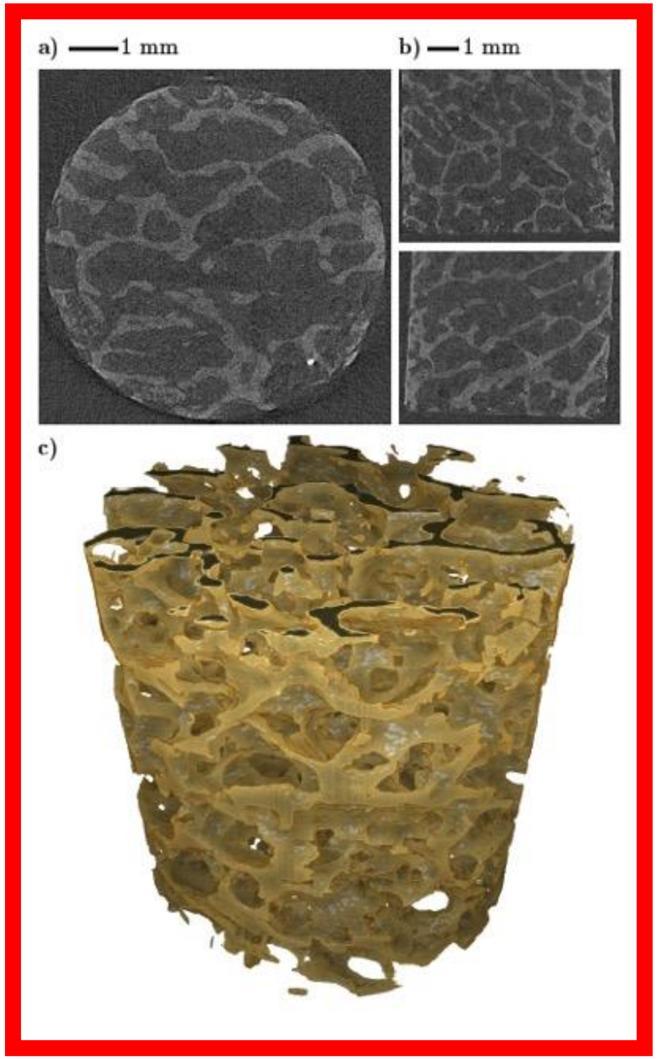


Figure 3. Images of the bone sample recorded with a) the betatron x-ray source b) conventional μCT scanning c) composite macro photography d) virtual illumination of the 3D reconstruction by a source of $E_{crit} = 33\,\text{keV}$.



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

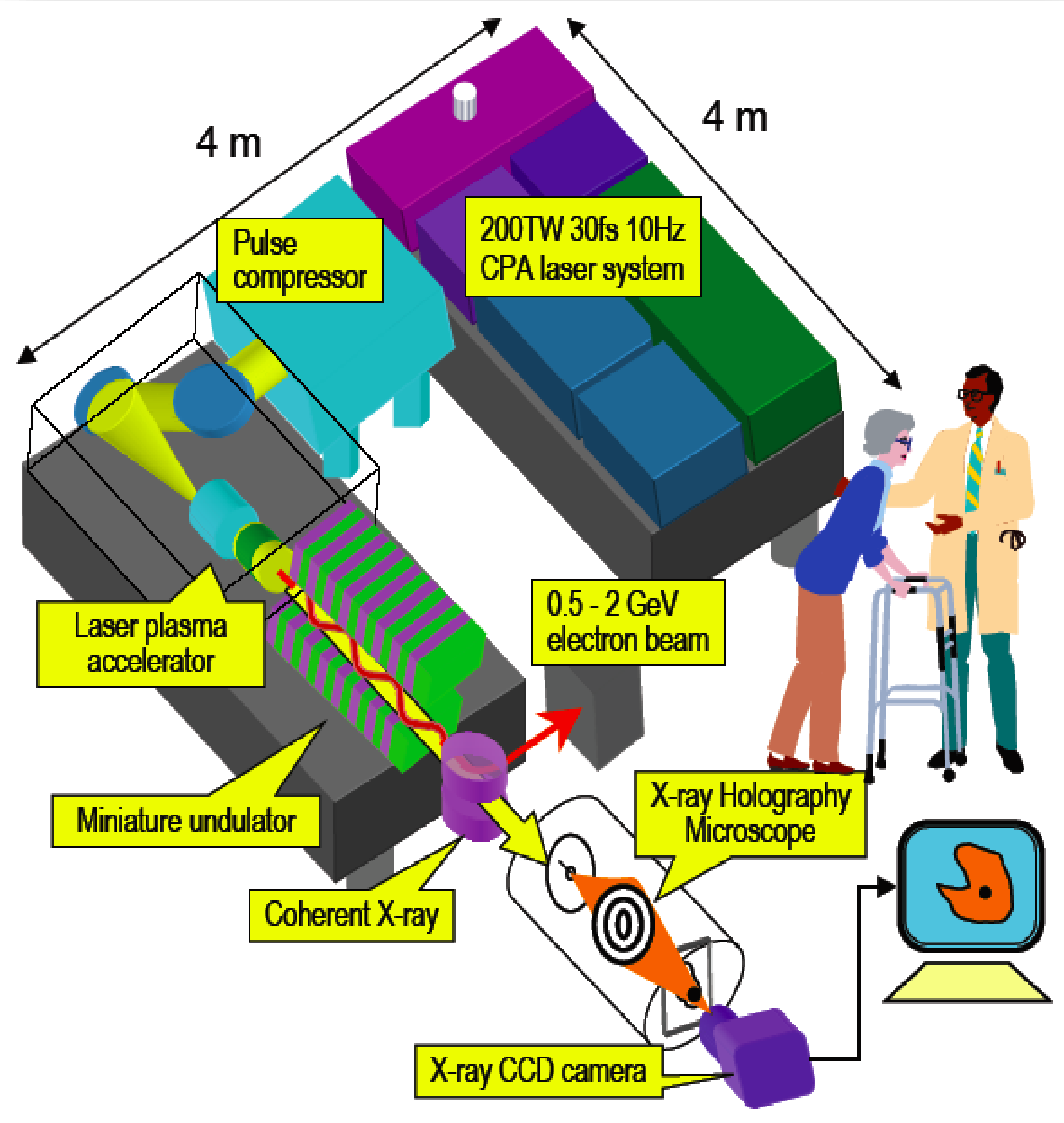
Scientific Reports **5**,
Article number: 13244 (2015)
doi:10.1038/srep13244

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

Laser plasma based betatron X ray source

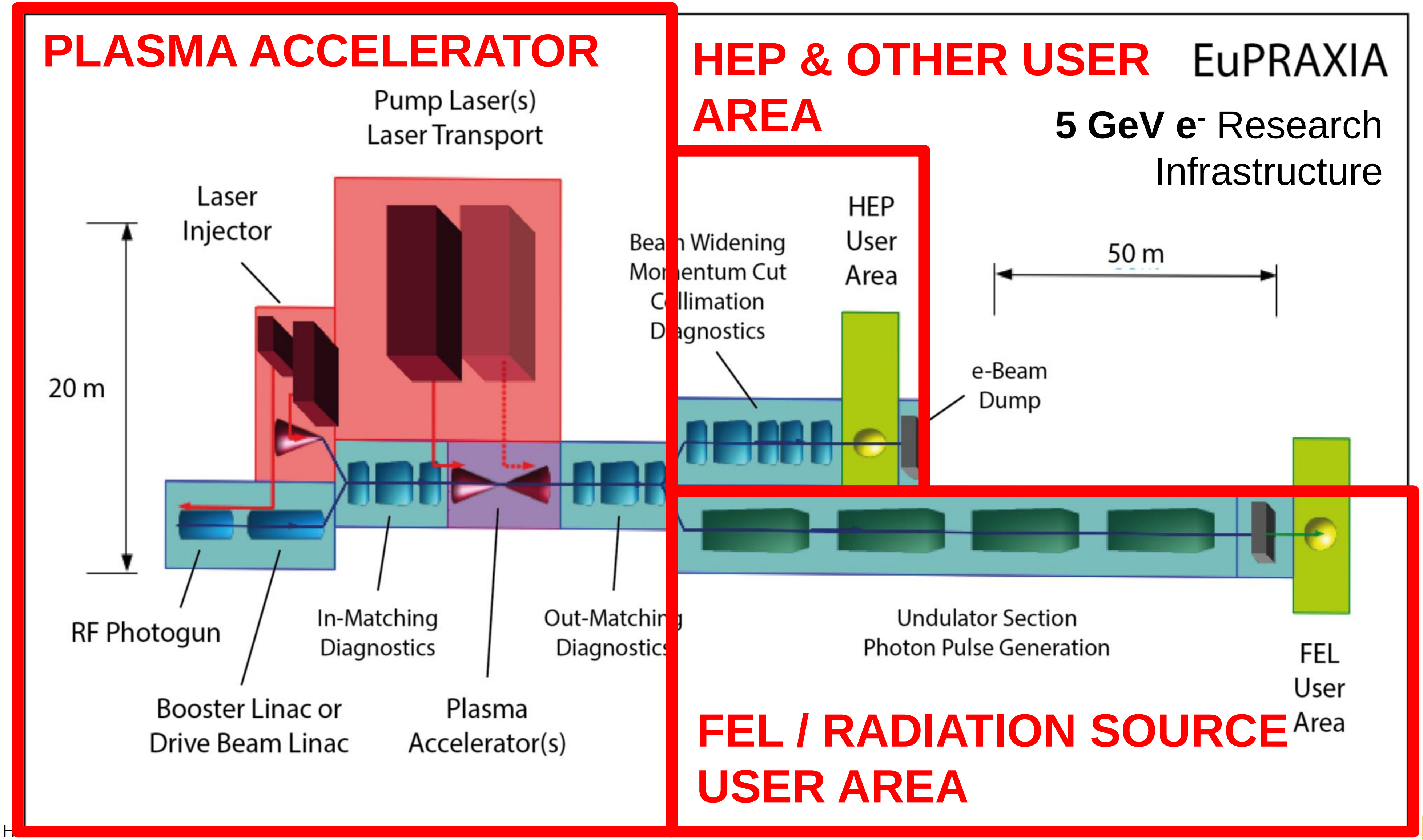
The Vision

Toshi Tajima 2010



EuPRAXIA: Pilot users will have dedicated areas

Targeted up to 5 GeV: FEL application, table-top HEP test beam, medical applications



EuPRAXIA Objectives

EuPRAXIA is a conceptual design study for a 5 GeV electron plasma accelerator

1. Address **quality**. Show **plasma accelerator technology is usable**:
   - Incorporate established accelerator technology for optimal quality
   - Combine expertise from accelerator, laser labs, industry, international partners
   - Develop new technical solutions and a few use cases
2. Show **benefit in size and cost** versus established RF technology:
   - Proposed solutions must offer a significant benefit, e.g. fitting constrained spaces (small labs, hospitals) and/or must be less effective.
   - Cost benefits must include low operational costs (turn-key, industrial lasers at high repetition rate, cost-effective RF components, ...): small team, remote OP, …

*Note: EuPRAXIA will initially be **low power** and **low wall-plug power efficiency***

- *Baseline (10 Hz): 10s of Watt with ~ 1 mJ/photon pulse energy*
- *Efforts with **industry and laser institutes** to improve rep. rate & efficiency (incorporate fiber-based lasers with 30 % efficiency)*

Try to finally realize low energy spread…

Old proposal from Simon van der Meer

CERN/PS/85-65 (AA)

CLIC Note No. 3

IMPROVING THE POWER EFFICIENCY

OF THE

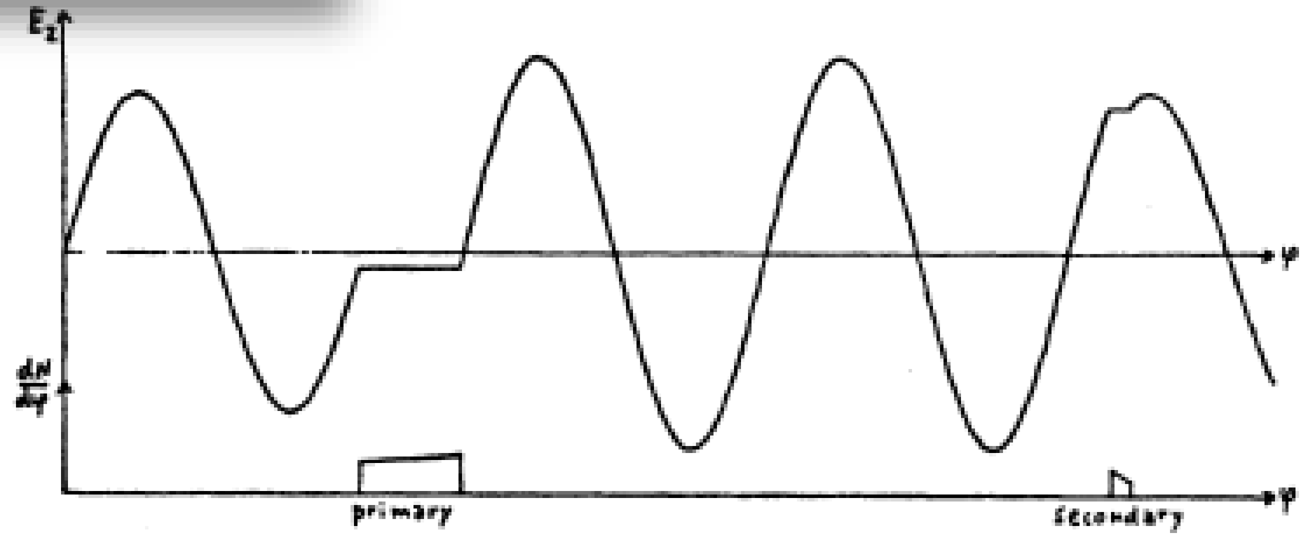
PLASMA WAKEFIELD ACCELERATOR

S. van der Meer

Beam loading, energy spread and efficiency

1985 van der Meer

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



Solve external timing for laser-driven plasma accelerators

Achieve required sub-femtosecond timing and accuracy…

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

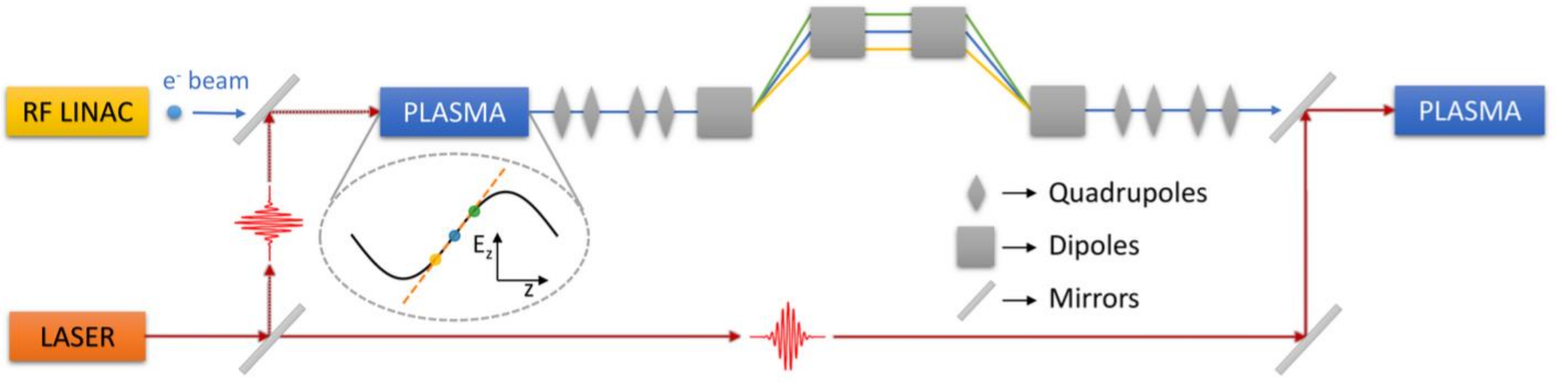
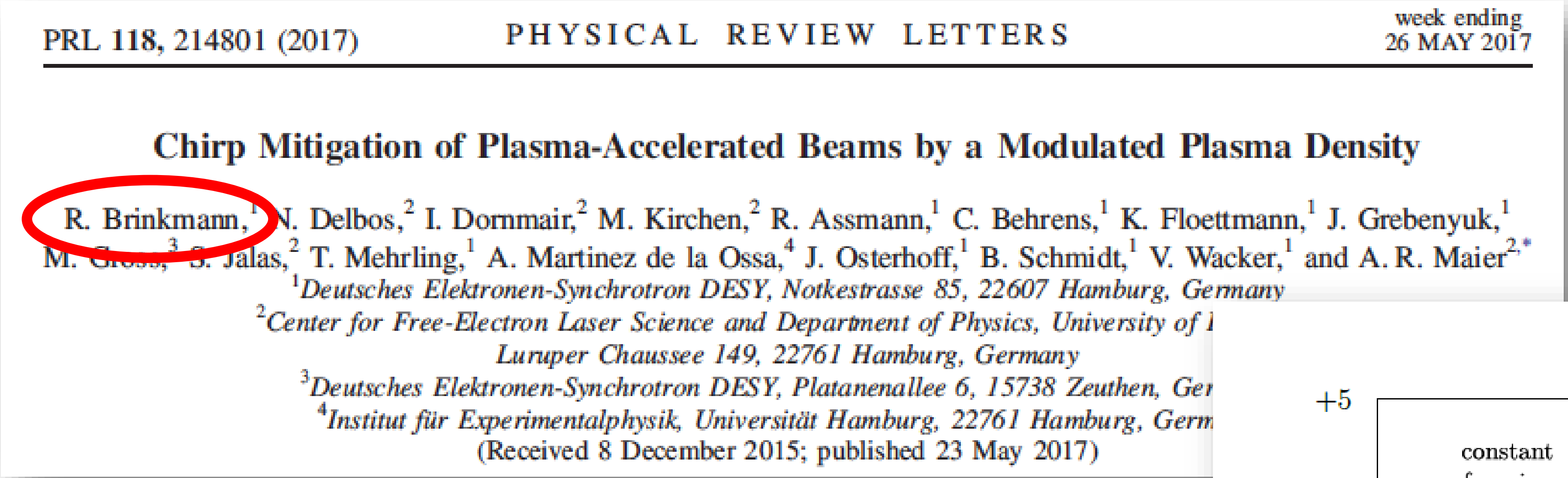


Figure 1. Schematic view of the synchronizing stage.

Reduce energy spread by a novel scheme

Jump from positive (focusing) to negative phase (defocusing) of plasma accelerator → kind of FODO scheme



PRL 118, 214801 (2017) PHYSICAL REVIEW LETTERS week ending 26 MAY 2017

Chirp Mitigation of Plasma-Accelerated Beams by a Modulated Plasma Density

R. Brinkmann,[1] N. Delbos,[2] I. Dornmair,[2] M. Kirchen,[2] R. Assmann,[1] C. Behrens,[1] K. Floettmann,[1] J. Grebenyuk,[1] M. Gross,[3] S. Jalas,[2] T. Mehrling,[1] A. Martinez de la Ossa,[4] J. Osterhoff,[1] B. Schmidt,[1] V. Wacker,[1] and A. R. Maier[2,*]

[1]*Deutsches Elektronen-Synchrotron DESY, Notkestrasse 85, 22607 Hamburg, Germany*

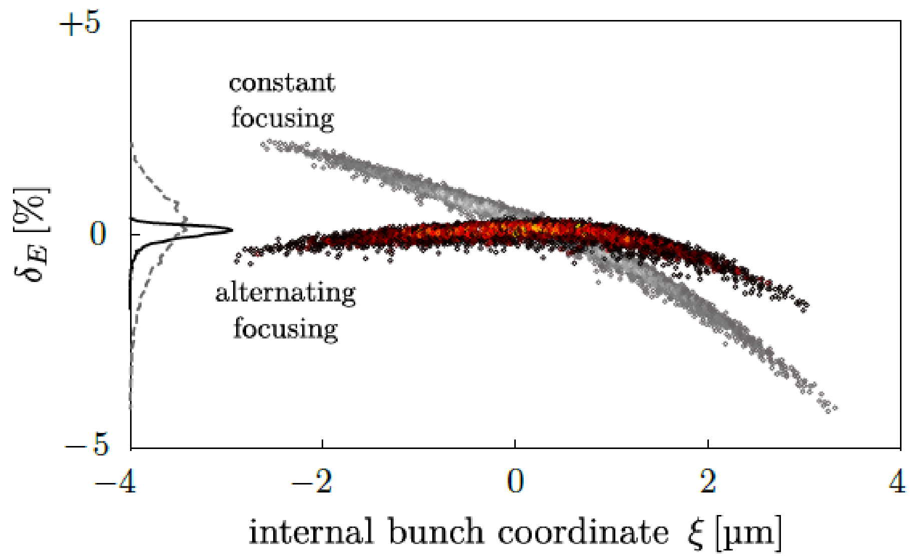
[2]*Center for Free-Electron Laser Science and Department of Physics, University of I*

Luruper Chaussee 149, 22761 Hamburg, Germany

[3]*Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, 15738 Zeuthen, Ger*

[4]*Institut für Experimentalphysik, Universität Hamburg, 22761 Hamburg, Germ*

(Received 8 December 2015; published 23 May 2017)

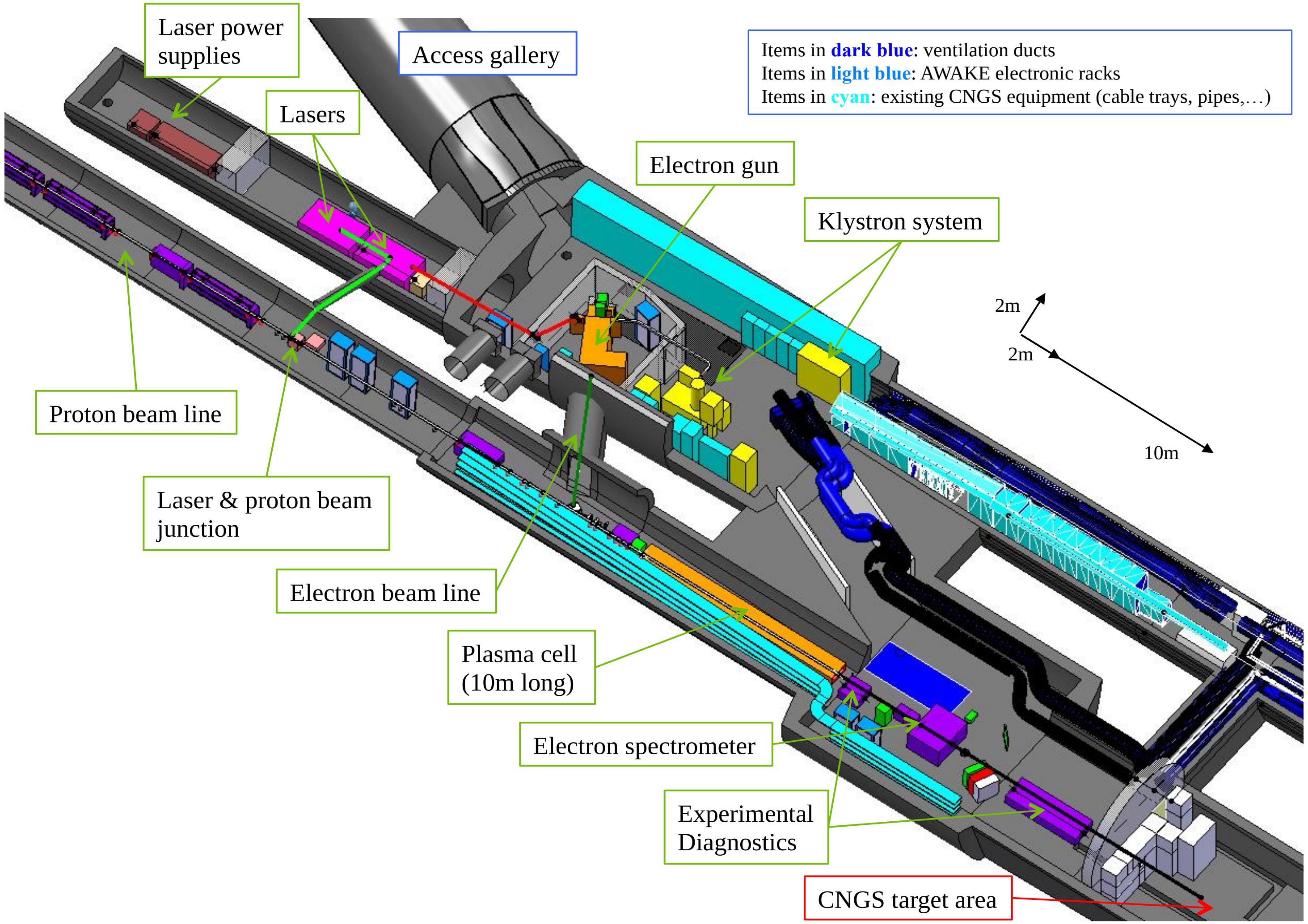


... and many more good ideas and concepts in- and outside of EuPRAXIA

kHz beams, long guiding, plasma lenses, high charge, improved quality, hybrid nano-emittance guns, application development, undulator radiation, novel undulators, theory advances, better and faster simulations, hollow plasmas, ...

(B) AWAKE Experiment at CERN

Aim: Demonstrate proton-driven plasma acceleration. 1 GeV electron acceleration in 10 meters



Thanks for AWAKE slides and information to A. Caldwell, P. Muggli, G. Xia

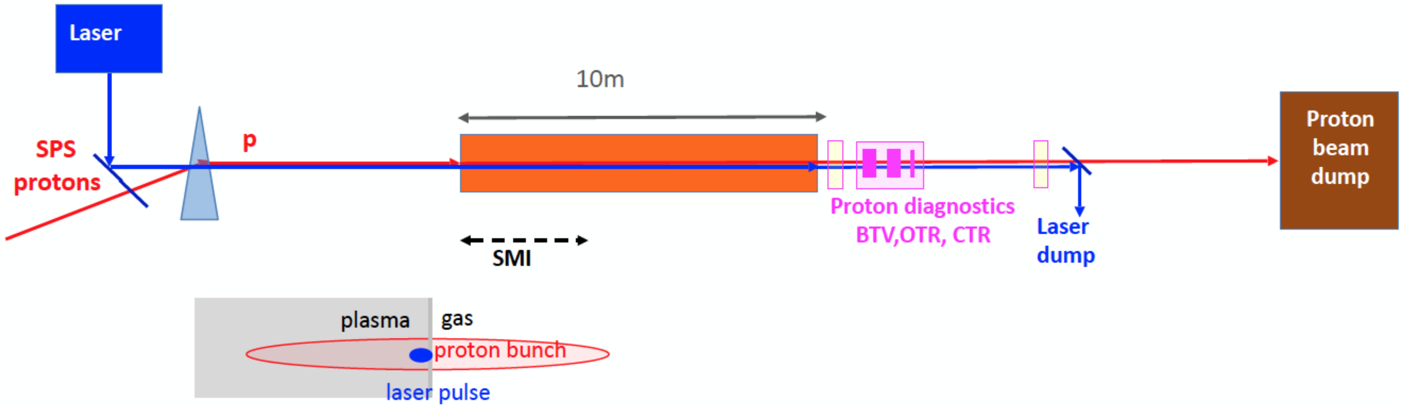
All results preliminary and under detailed analysis!

AWAKE: Experimental Program and Results

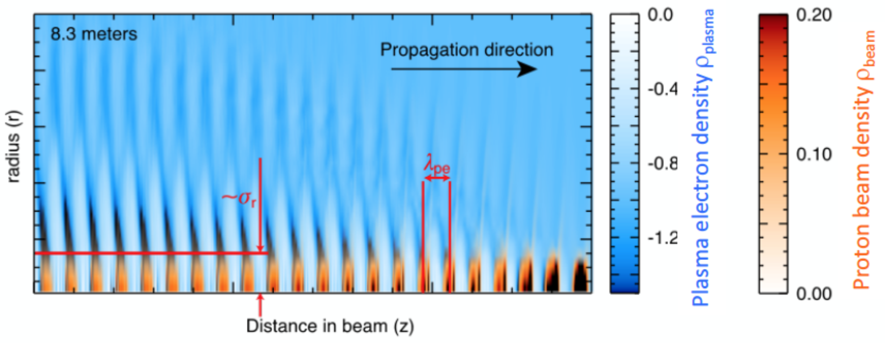
The long proton bunch is modulated by plasma wakefield

Clearly see the transverse blow-up of the proton beam. Only possible with very strong electric fields !

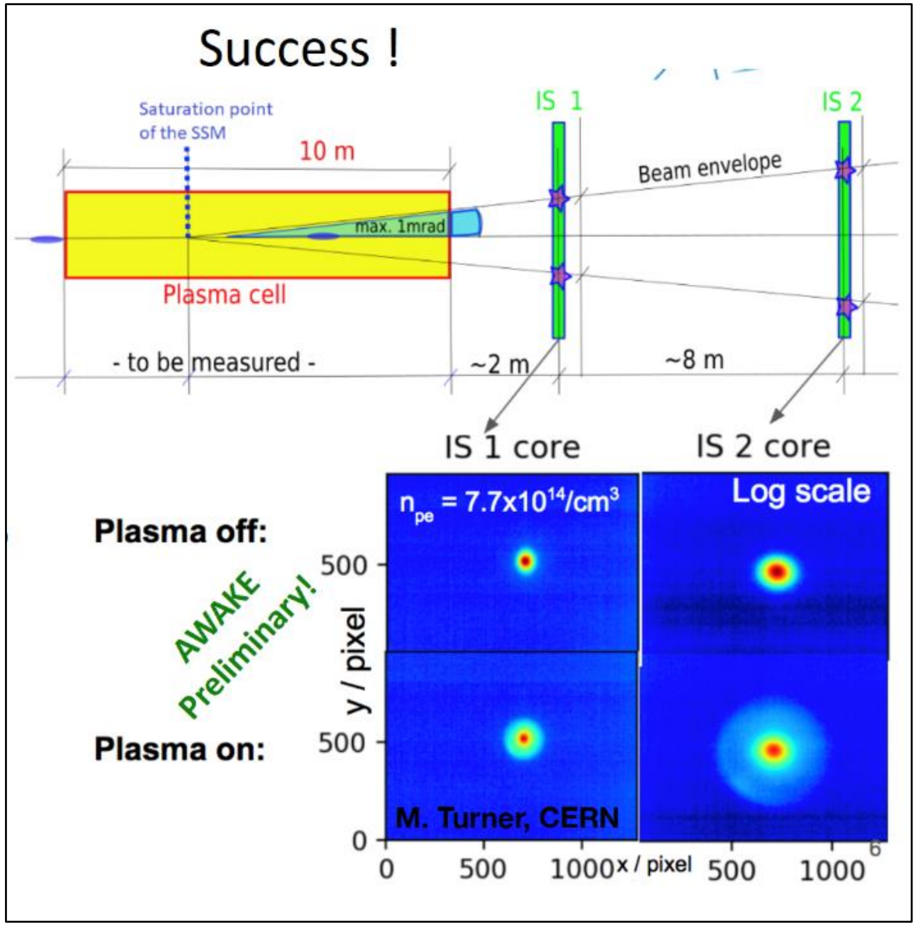
Phase 1: Understand **the physics of self-modulation instability.**



J. Viera, IST



Self-modulated proton bunch resonantly driving plasma wakefields.

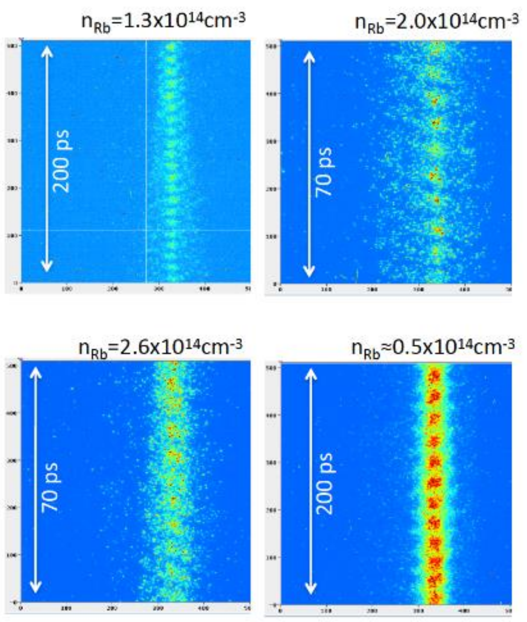


AWAKE: Seeded SMI, e- Acceleration

Modulation pattern follows plasma wavelength, accelerates injected e-

We observe strong, persistent microbunching for a range of densities.

Seeding is a critical ingredient for producing many periods of microbunches along the beam.



K. Rieger, MPP

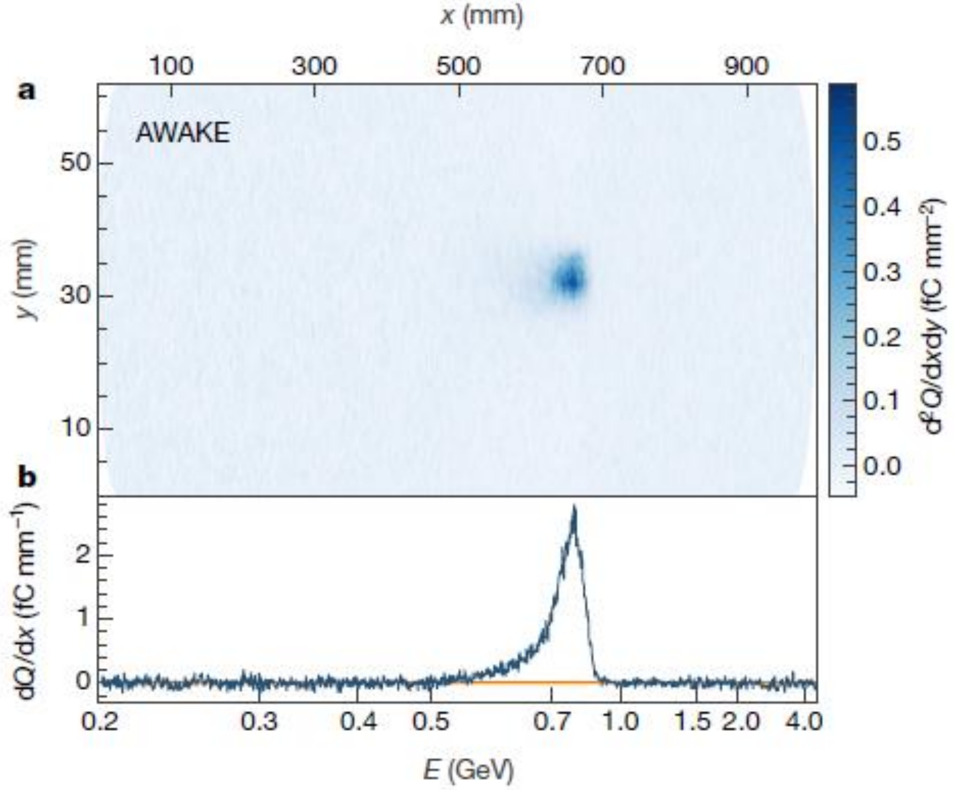
LETTER

OPEN

https://doi.org/10.1038/s41586-018-0485-4

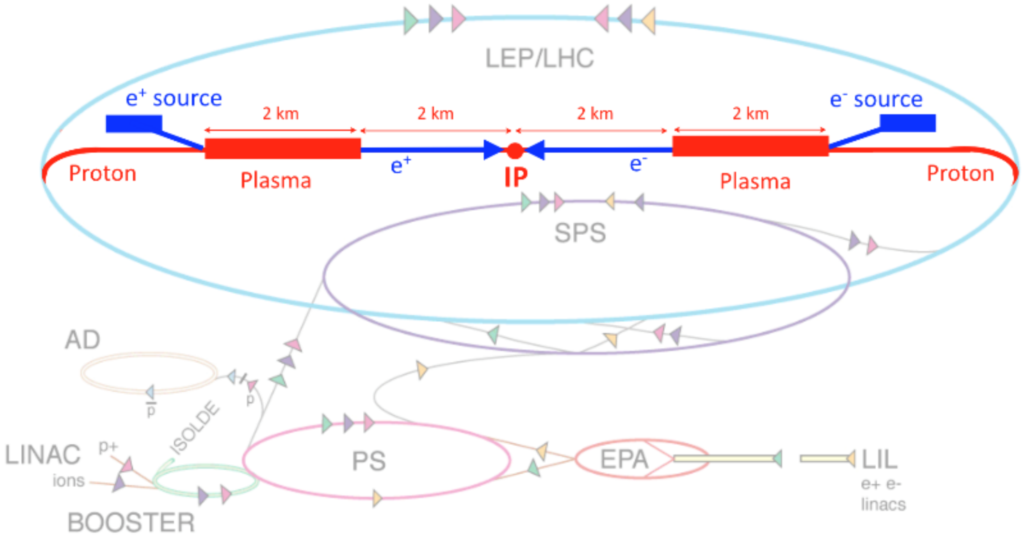
Acceleration of electrons in the plasma wakefield of a proton bunch

E. Adli[1], A. Ahuja[2], O. Apsimon[3,4], R. Apsimon[4,5], A.-M. Bachmann[2,6,7], D. Barrientos[2], F. Batsch[2,6,7], J. Bauche[2], V. K. Berglyd Olsen[1], M. Bernardini[2], T. Bohl[2], C. Bracco[2], F. Braunmüller[6], G. Burt[4,5], B. Buttenschön[8], A. Caldwell[6], M. Cascella[9], J. Chappell[9], E. Chevallay[2], M. Chung[10], D. Cooke[9], H. Damerau[2], L. Deacon[9], L. H. Deubner[11], A. Dexter[4,5], S. Doebert[2], J. Farmer[12], V. N. Fedosseev[2], R. Fiorito[4,13], R. A. Fonseca[14], F. Friebel[2], L. Garolfi[2], S. Gessner[2], I. Gorgisyan[2], A. A. Gorn[15,16], E. Granados[2], O. Grulke[8,17], E. Gschwendtner[2], J. Hansen[2], A. Helm[18], J. R. Henderson[4,5], M. Hüther[6], M. Ibison[4,13], L. Jensen[2], S. Jolly[9], F. Keeble[9], S.-Y. Kim[10], F. Kraus[11], Y. Li[3,4], S. Liu[19], N. Lopes[18], K. V. Lotov[15,16], L. Maricalva Brun[2], M. Martyanov[6], S. Mazzoni[2], D. Medina Godoy[2], V. A. Minakov[15,16], J. Mitchell[4,5], J. C. Molendijk[2], J. T. Moody[6], M. Moreira[2,18], P. Muggli[2,6], E. Öz[6], C. Pasquino[2], A. Pardons[2], F. Peña Asmus[6,7], K. Pepitone[2], A. Perera[4,13], A. Petrenko[2,15], S. Pitman[4,5], A. Pukhov[12], S. Rey[2], K. Rieger[6], H. Ruhl[20], J. S. Schmidt[2], I. A. Shalimova[16,21], P. Sherwood[9], L. O. Silva[18], L. Soby[2], A. P. Sosedkin[15,16], R. Speroni[2], R. I. Spitsyn[15,16], P. V. Tuev[15,16], M. Turner[2], F. Velotti[2], L. Verra[2,22], V. A. Verzilov[19], J. Vieira[18], C. P. Welsch[4,13], B. Williamson[3,4], M. Wing[9*], B. Woolley[2] & G. Xia[3,4]



AWAKE: Possible Long-Term Future HEP Applications

LHC providing drive bunch → low luminosity



e+ e- collider

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

ELSEVIER

Collider design issues based on proton-driven plasma wakefield acceleration

G. Xia [a,b,*], O. Mete [a,b], A. Aimidula [b,c], C.P. Welsch [b,c], S. Chattopadhyay [a,b,c], S. Mandry [d], M. Wing [d,e]

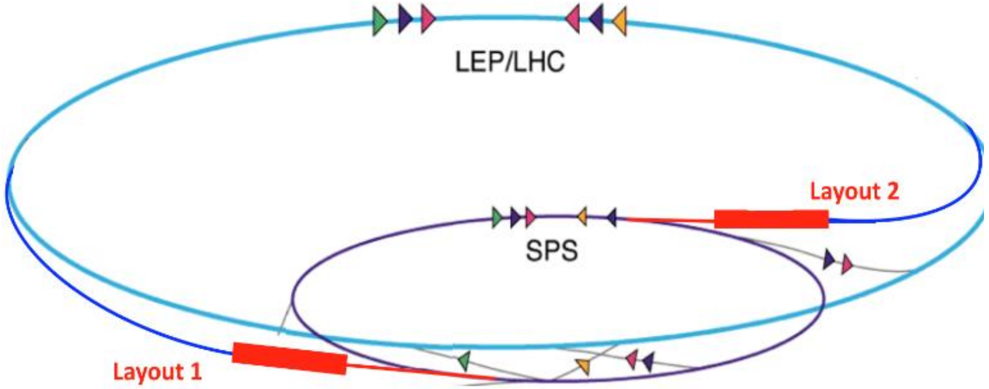
[a] School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
[b] The Cockcroft Institute, Sci-Tech Daresbury, Daresbury, Warrington, United Kingdom
[c] The University of Liverpool, Liverpool, United Kingdom
[d] Department of Physics and Astronomy, University College London, London, United Kingdom
[e] Deutsche Elektronen-Synchrotron DESY, Hamburg, Germany

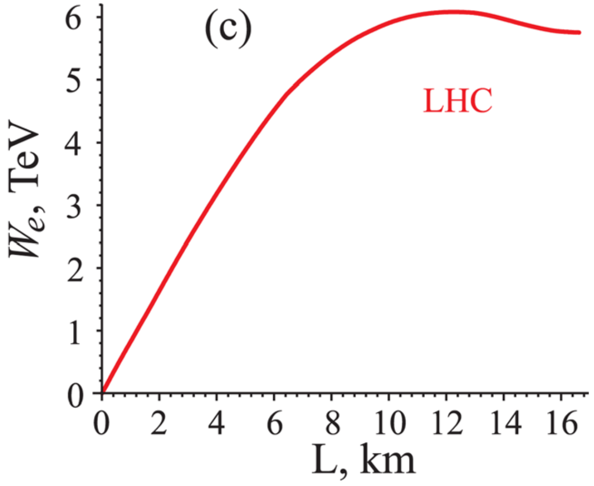
ARTICLE INFO

Keywords:
PDPWA
Colliders
Self-modulation instability
Dephasing

ABSTRACT

Recent simulations have shown that a high-energy proton bunch can excite strong plasma wakefields and accelerate a bunch of electrons to the energy frontier in a single stage of acceleration. It therefore paves the way towards a compact future collider design using the proton beams from existing high-energy proton machines, e.g. Tevatron or the LHC. This paper addresses some key issues in designing a compact electron–positron linear collider and an electron–proton collider based on the existing CERN accelerator infrastructure.

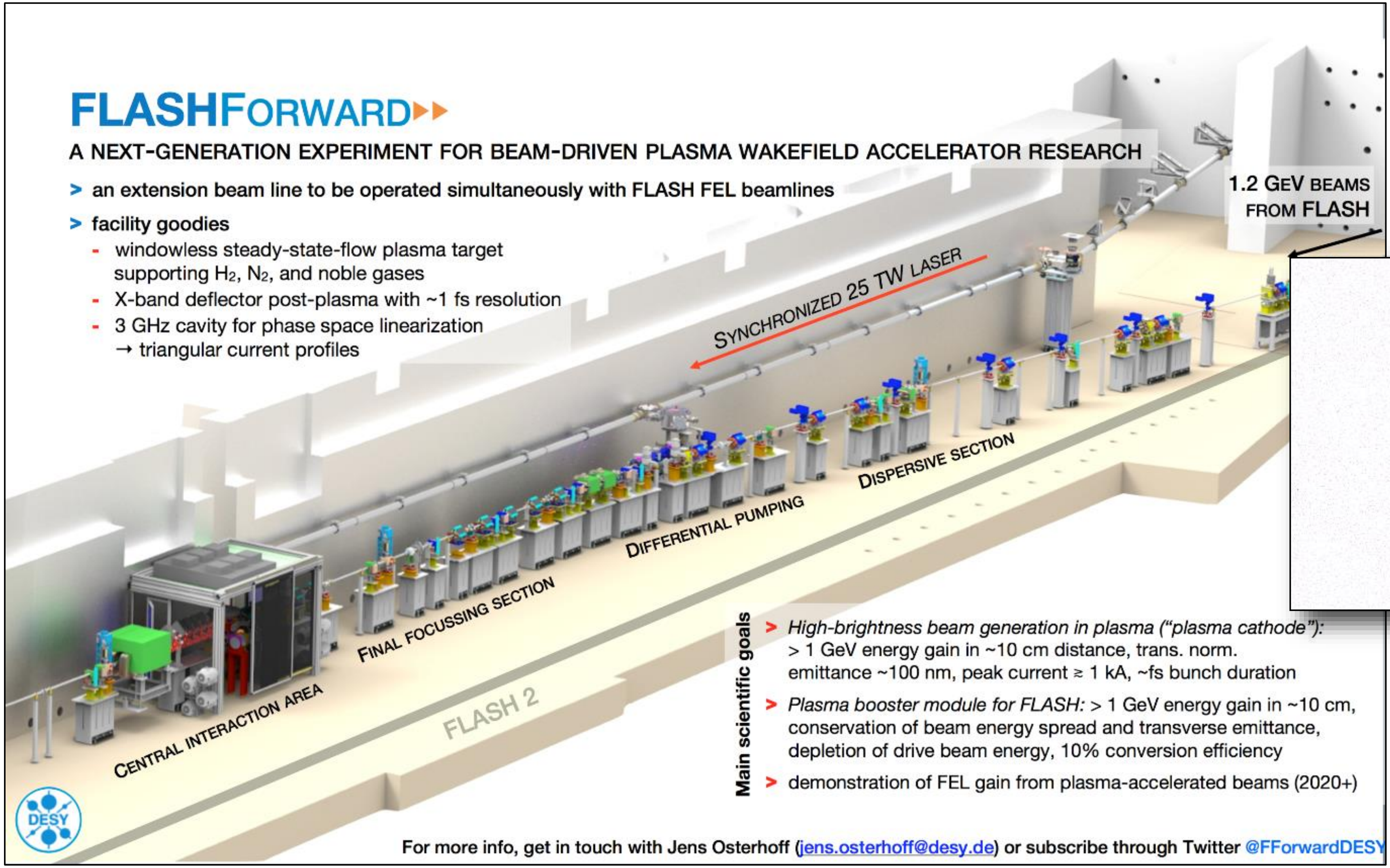


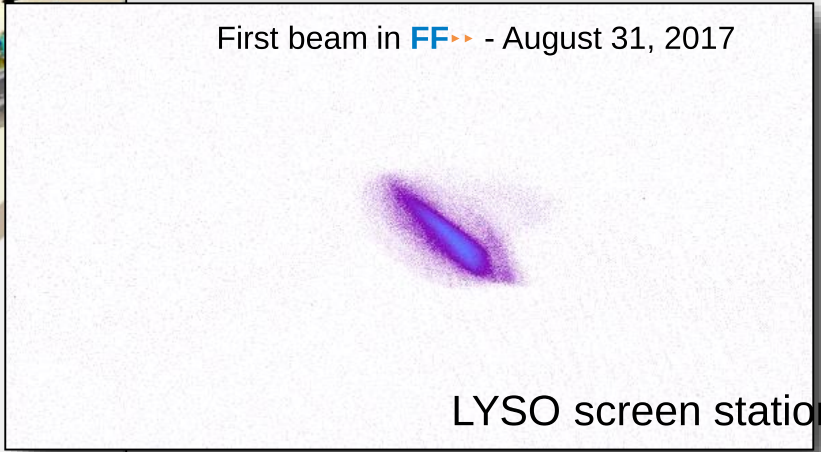


e-p collider

(C1) Hamburg Infrastructure – FLASHForward

An electron beam-driven plasma accelerator R&D approach → towards HEP applications





(C1) Hamburg Infrastructure – FLASHForward

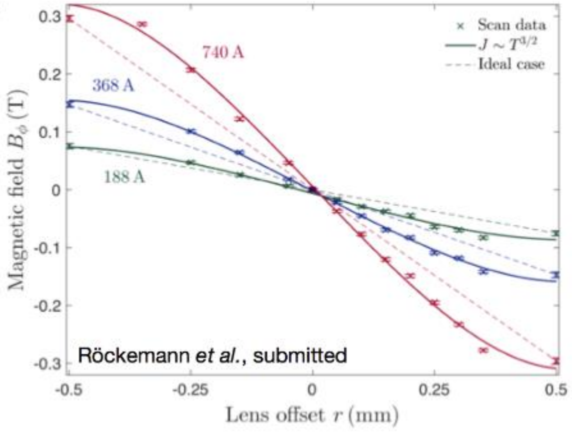
An electron beam-driven plasma accelerator R&D approach → towards HEP applications

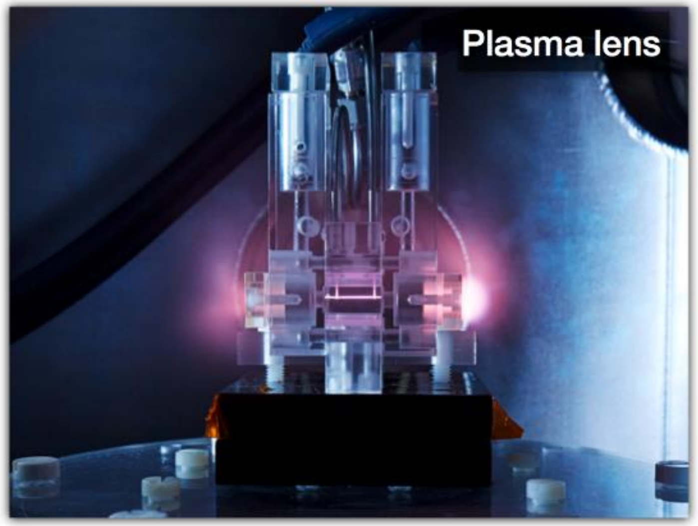
Field characterization of kT/m active plasma lenses

RECENT FF▸▸ SCIENTIFIC HIGHLIGHTS

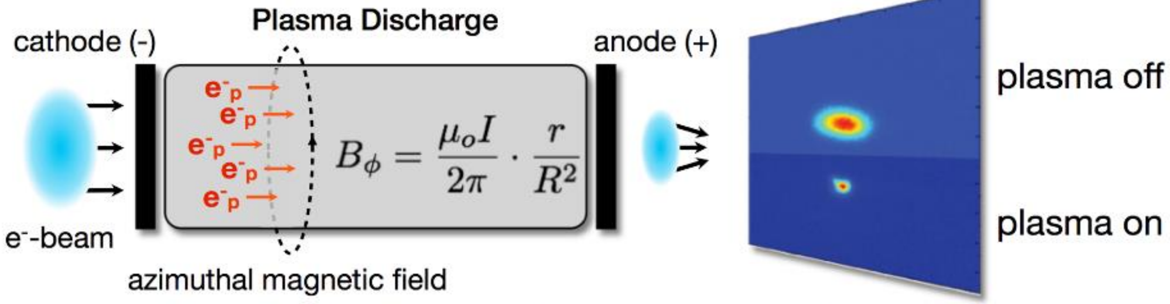
in collaboration between

- **direct field measurements** with 855 MeV beam at Mainz Microtron
- **7 mm long lens, 1 mm ⌀**
- **transverse offset scan**
- **100 shots per data point**
- **no effect on pointing / position stability**
- measured **linear, symmetric field gradients ≤ 879 ± 1 T/m**



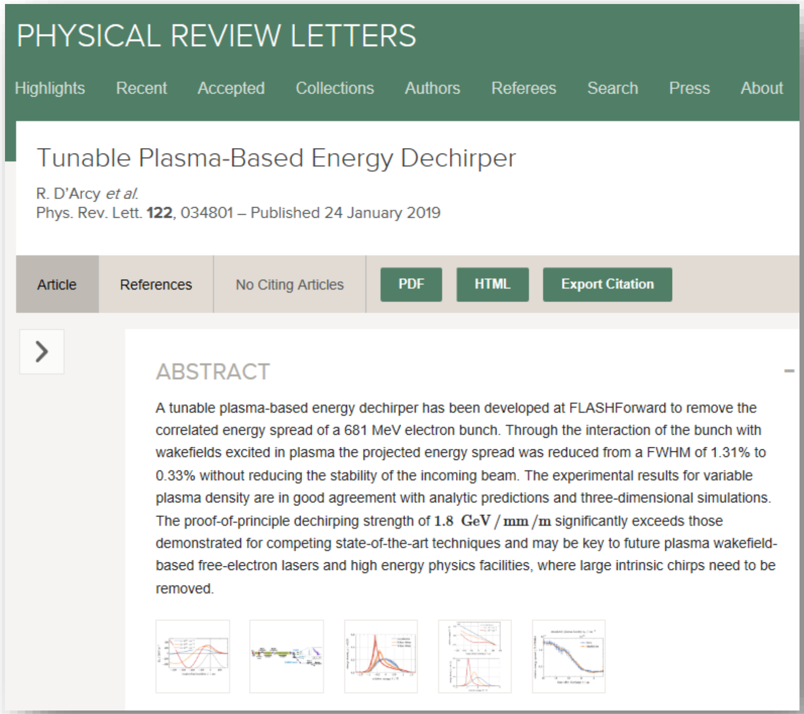


- **applications**
  - beam matching into plasma, high-field generation
  - beam capturing from plasma, emittance conservation
- gradient scalable to multi-kT/m



→ F = I x B, tunable and symmetric focussing force for e⁻-beam

J. van Tilborg et al., Phys. Rev. Lett. 115, 184802 (2015)



PHYSICAL REVIEW LETTERS

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Tunable Plasma-Based Energy Dechirper

R. D'Arcy *et al.*
Phys. Rev. Lett. **122**, 034801 – Published 24 January 2019

Article | References | No Citing Articles | PDF | HTML | Export Citation

ABSTRACT

A tunable plasma-based energy dechirper has been developed at FLASHForward to remove the correlated energy spread of a 681 MeV electron bunch. Through the interaction of the bunch with wakefields excited in plasma the projected energy spread was reduced from a FWHM of 1.31% to 0.33% without reducing the stability of the incoming beam. The experimental results for variable plasma density are in good agreement with analytic predictions and three-dimensional simulations. The proof-of-principle dechirping strength of 1.8 GeV / mm /m significantly exceeds those demonstrated for competing state-of-the-art techniques and may be key to future plasma wakefield-based free-electron lasers and high energy physics facilities, where large intrinsic chirps need to be removed.

(C2) Hamburg Infrastructure – LUX

An laser-driven plasma R&D approach → towards FEL applications

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

A. Maier et al

About 1 GeV electrons from plasma accelerator, guide beam out of plasma, transport to undulator, generate X rays in undulator, dump electron beam, measure X rays (8 nm)

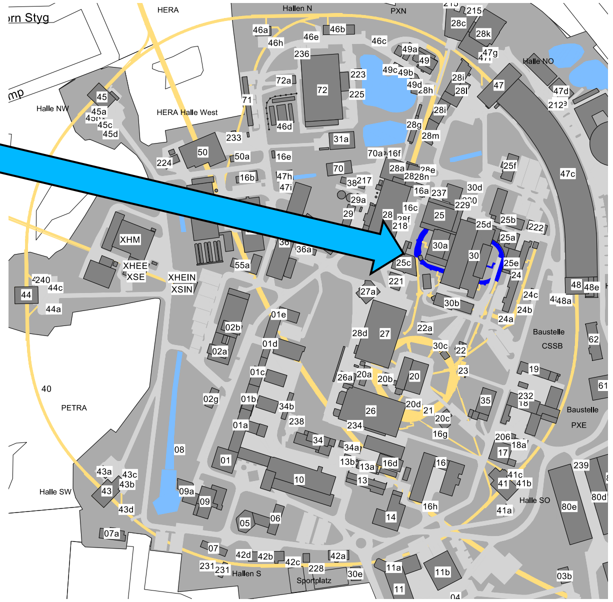
Next steps: towards harder X rays, lasing (saturation not possible in available length of undulator)

(C3) Hamburg Infrastructure – SINBAD

Several plasma experiments ongoing or under setup

SINBAD

Ex-DORIS



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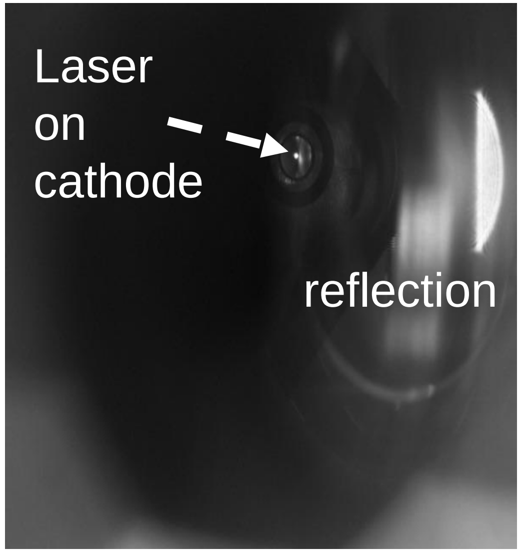
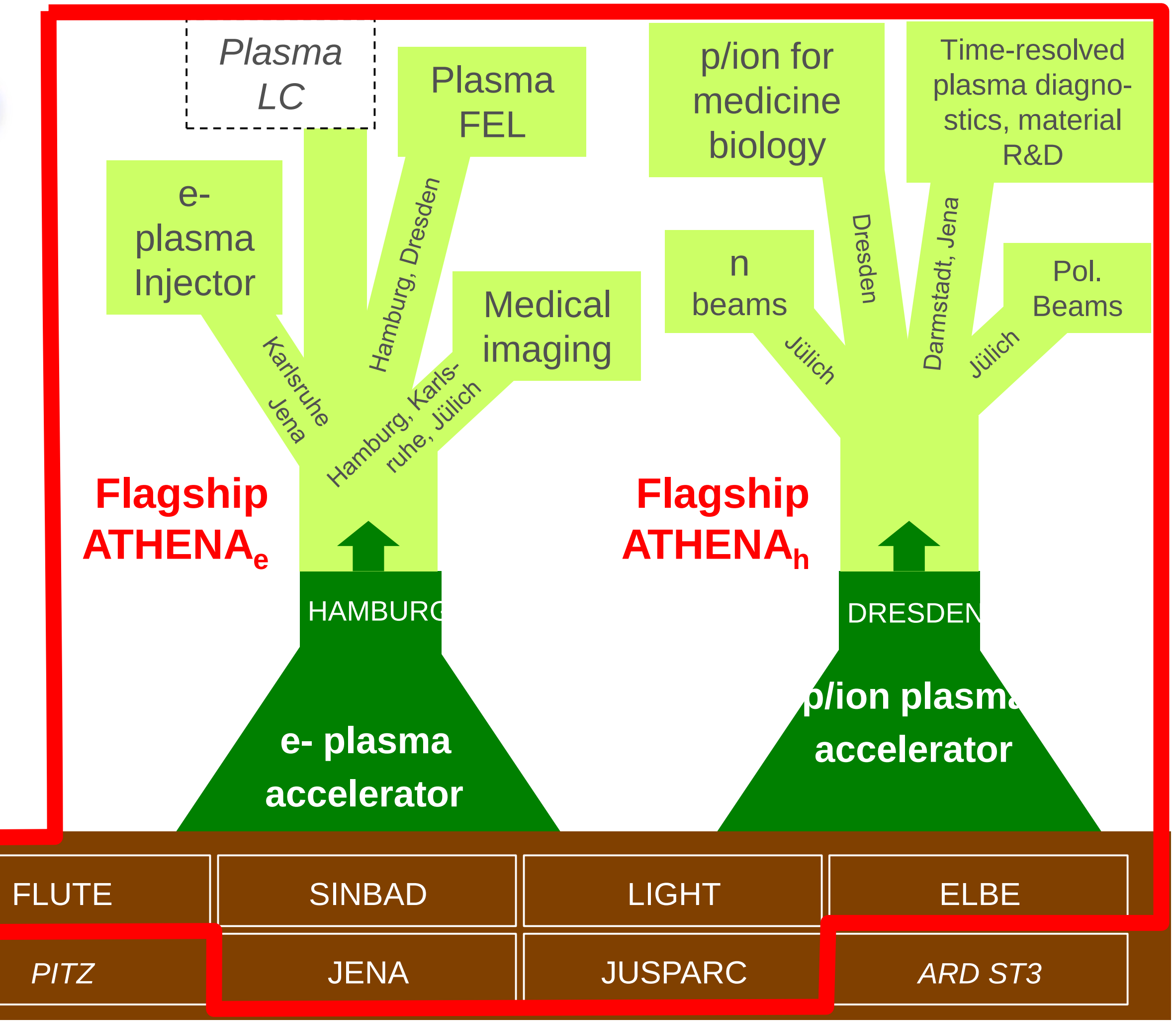


Image courtesy Lutz Winkelmann.

(C3) SINBAD will host one of the two ATHENA flagship projects

Under final approval, 2018 – 2021, 30 M€ all centers, 2 future technologies for the Helmholtz strategy



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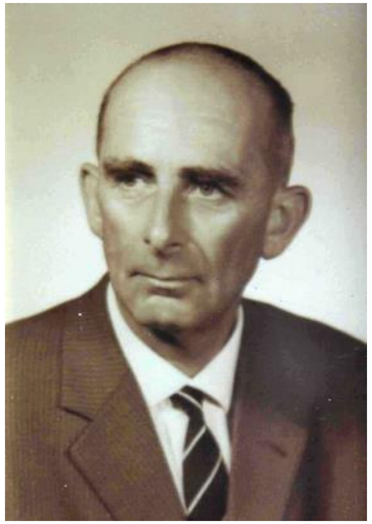
Conclusions

Long-term future

- The **long-term future is bright**: there will be plenty of opportunities as technology advances!
- **Plasma colliders** are another possible game changer. Energy very promising but beam quality insufficient:
  - 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. Please follow up.
- A long-term future with novel colliders does not come by itself: **We (you) must work towards this goal and support it as required, continuing long tradition**.

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**.“

Thank you for your attention - enjoy your drink...

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.

Courtesy S. Brooks, BNL