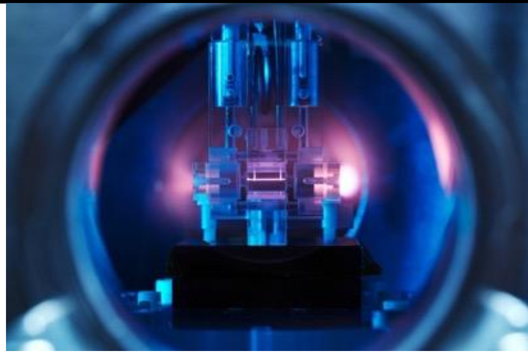
Plasma Accelerators / Compact Accelerators

Can we broaden accelerator impact with compact and cost-efficient accelerators?

African Conference on Fundamental Physics and Applications, or African Conference on Physics (ACP), June 28–July 4, 2018, Namibian University of Science and Technology (NUST), Windhoek Namibia



Ralph W. Assmann (DESY)
Coordinator EuPRAXIA
Lead Scientist DESY Accelerator R&D

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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

Particle Accelerators: Discovery Machines and Innovation Drivers

For Science, Industry and Society

- Today: world-wide operate about **30,000 particle accelerators** for science, medicine and industry
- Most accelerators are used for **industrial** applications
- Accelerators produced **data for dozens of discoveries that were rewarded with nobel prizes**.
- Accelerators help saving lifes and **curing people**.

Physics: Cyclotron

Physics: Stochastic Cooling

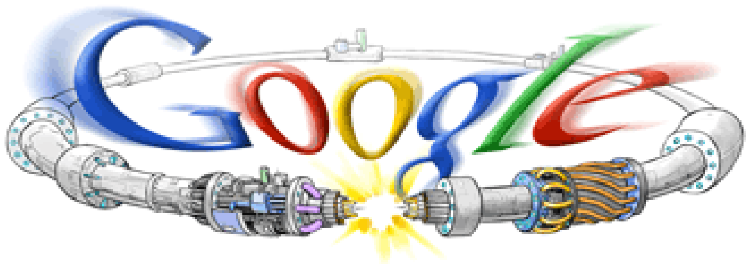
Physics: Higgs particle

Chemistry: ribosoms

Probing for New Particles and Forces

Fundamental Research Particle Physics

Higgs Seminar 4.7. 2012



THE TIMES

Higgs celebrates 'God particle' discovery

Tom Whipple, Science Correspondent, and Giles Whittell at Cern
Updated 35 minutes ago

Professor Peter Higgs has said he is chilling the champagne, and Geneva's bars are preparing to celebrate the scientific achievement of the decade, after Cern announced the discovery of a new "Higgs-like" boson, believed to be the fundamental particle known as the...

- How it unfolded
- Video blunder
- Bill Bryson at LHC
- Award for Higgs
- 5 Comments

LHC at CERN as a **Masterpiece of Accelerator Science**

Protons at ***6 thousand billion electron Volt***
→ ***27 km***

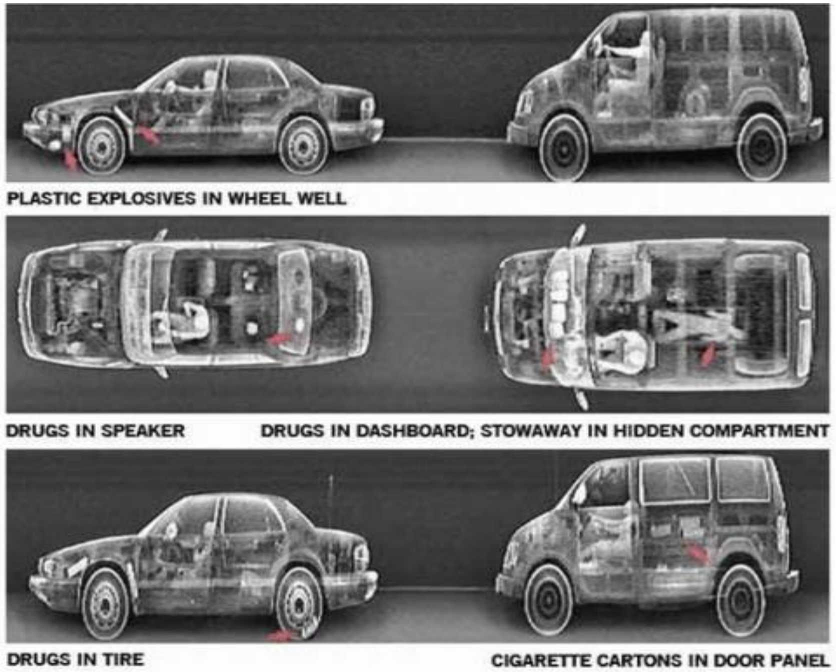
Understanding fundamental laws

Producing X Rays for Inspection

Industry and Security

Nuctech (China)

Varian (USA)



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

Electrons at 6 million Electron Volt

Protecting people

Irradiating and Destroying Tumor Cells

Medicine and Health

Heidelberg Ion-Beam Therapy Center (HIT)

Proton therapy

Varian TrueBeam STx Linac with BrailLab ExacTrac system at University Hospital Düsseldorf.

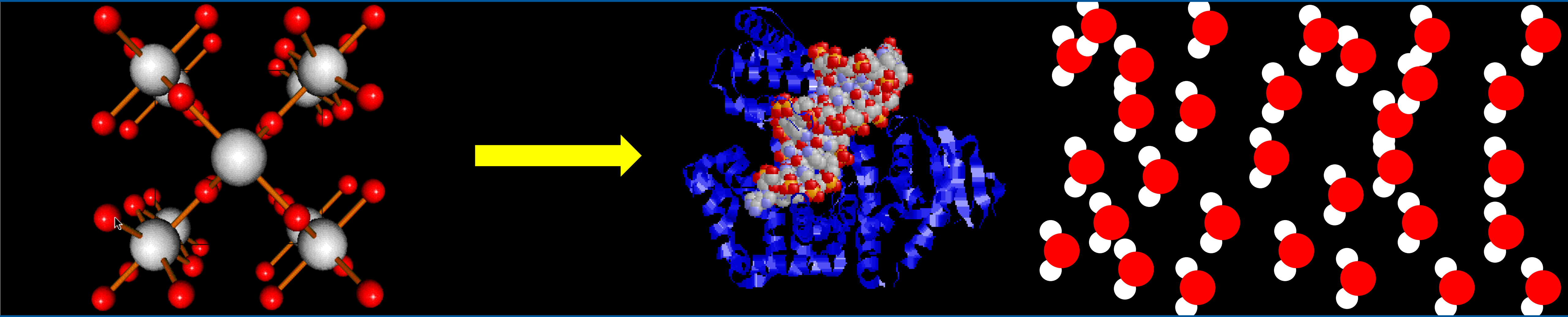
Electron therapy

up to 12 million electron Volt

Curing people

Producing Light and Filming Molecular Movies

Fundamental Research Physics, Structural Biology, Chemistry, Material Science



1900 2000 future

Era of Crystalline Matter

Ordered Structures, Equilibrium Phenomena, Phase Diagrams

you are here

Era of Complex Matter

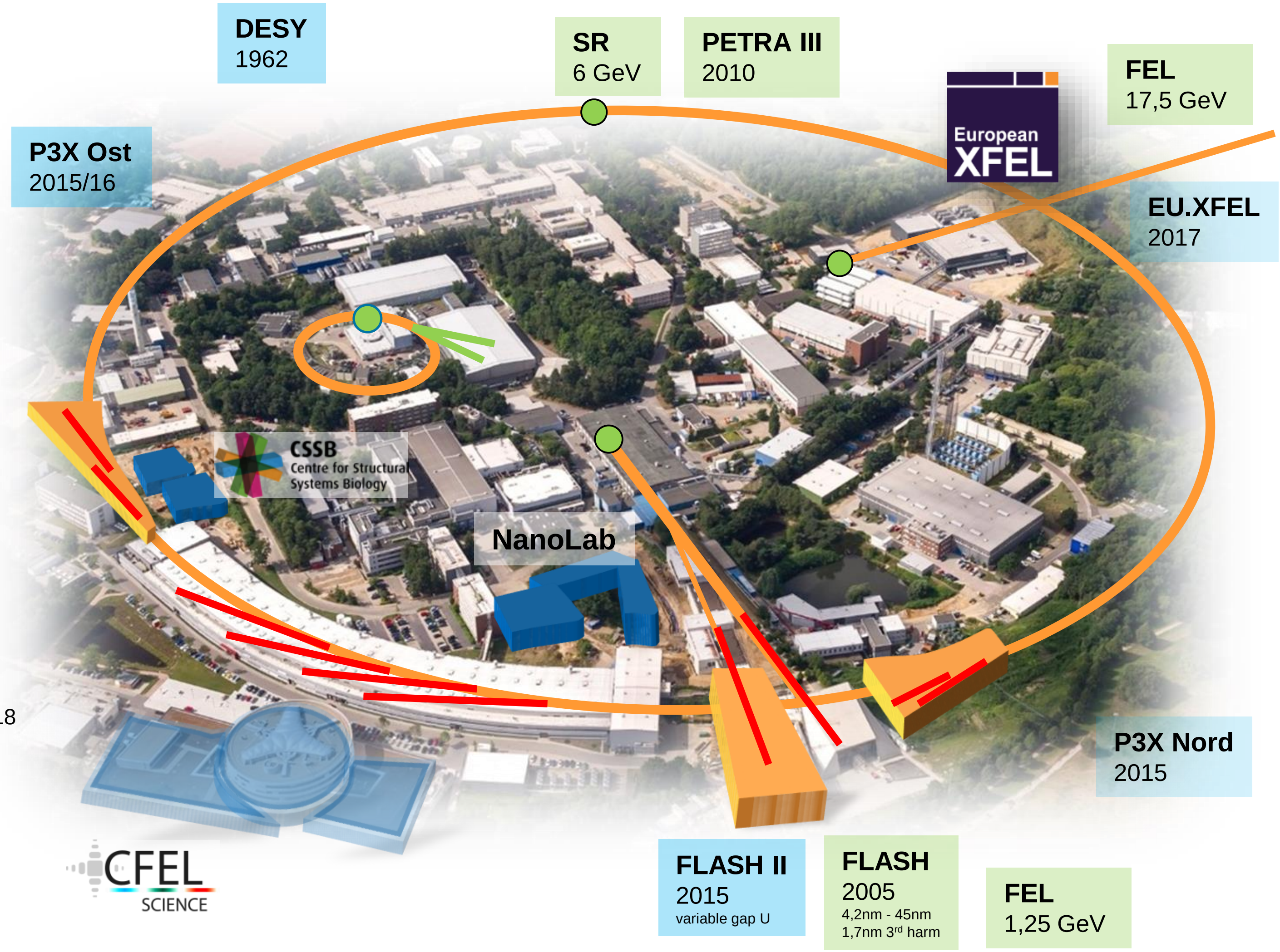
Locally Ordered Structures, Nonequilibrium Phenomena, Transient States

State of the art accelerators for the best light possible

Synchrotron radiation from accelerators	X-Ray Laser accelerators + High Brilliance SR accelerators

Particle Accelerators at DESY – Excellence in Photon Science

Hamburg (Germany): from 50 years ago to today (electrons up to 17 billion electron Volt)…



BUT:

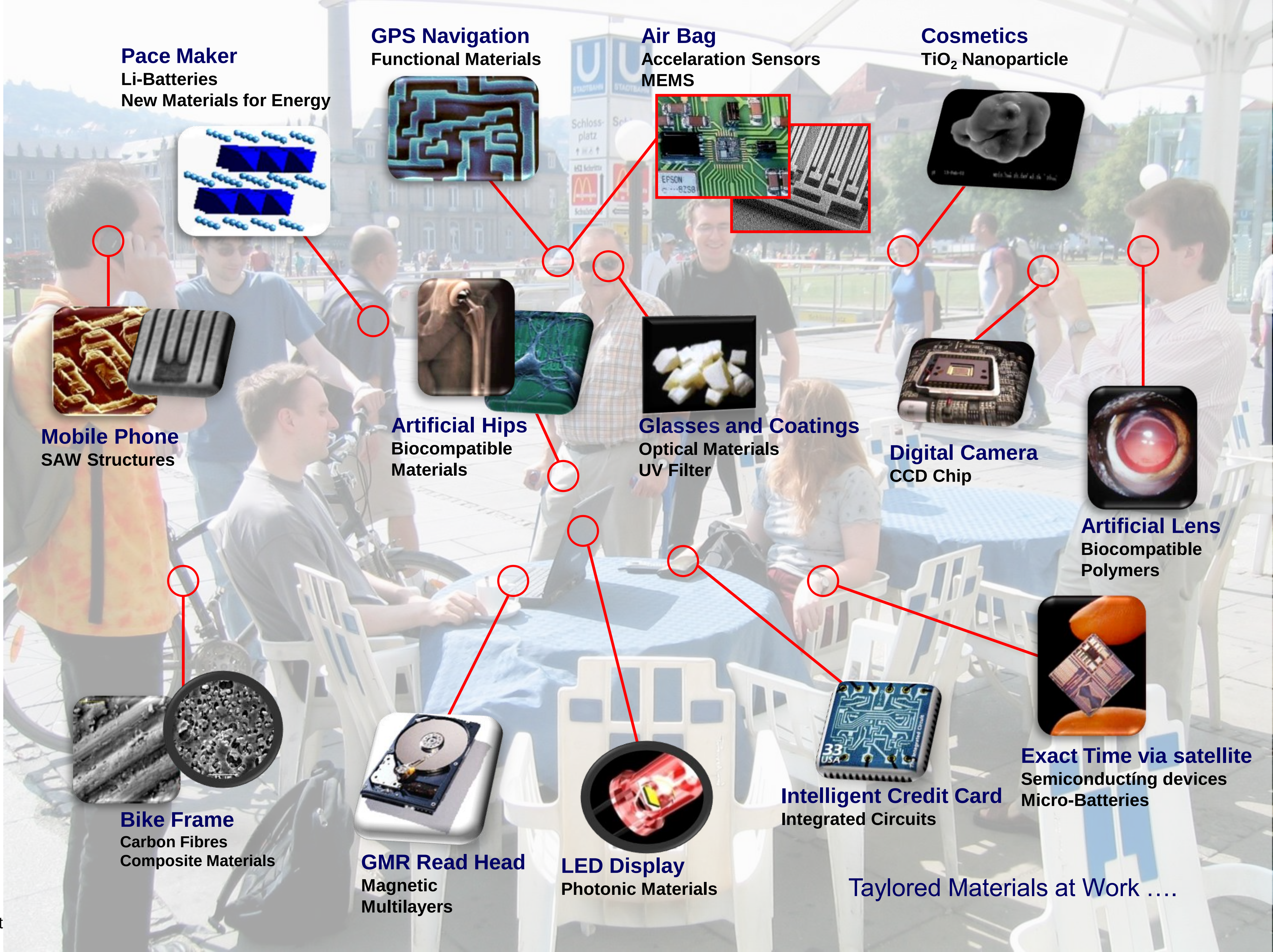
Progress in Hamburg-based colliders **limited by practical considerations on size and cost**.

Germany Today

Accelerator-Based Photon Science Research Affecting Everyday Life

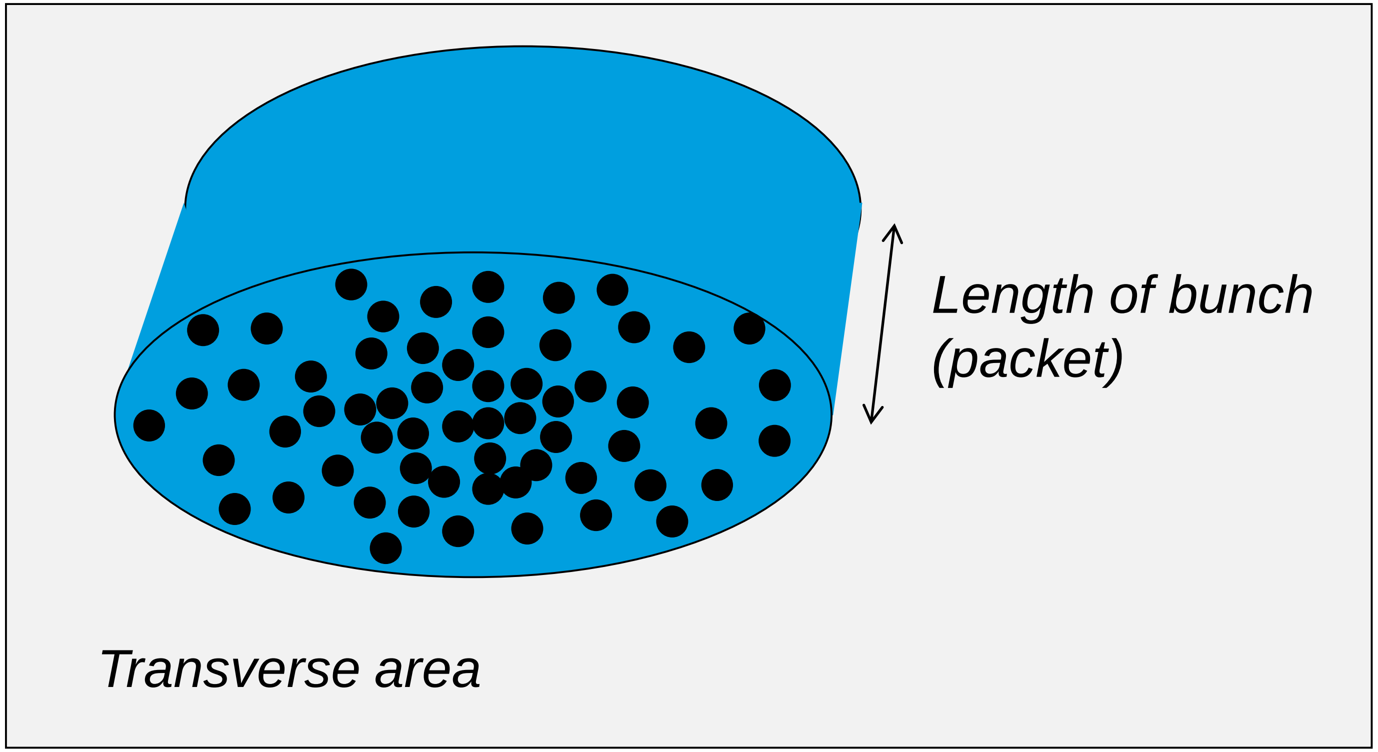
Germany Today

Accelerator-Based Photon Science Research Affecting Everyday Life



Frontier Electron Beams and Directions for New Beams

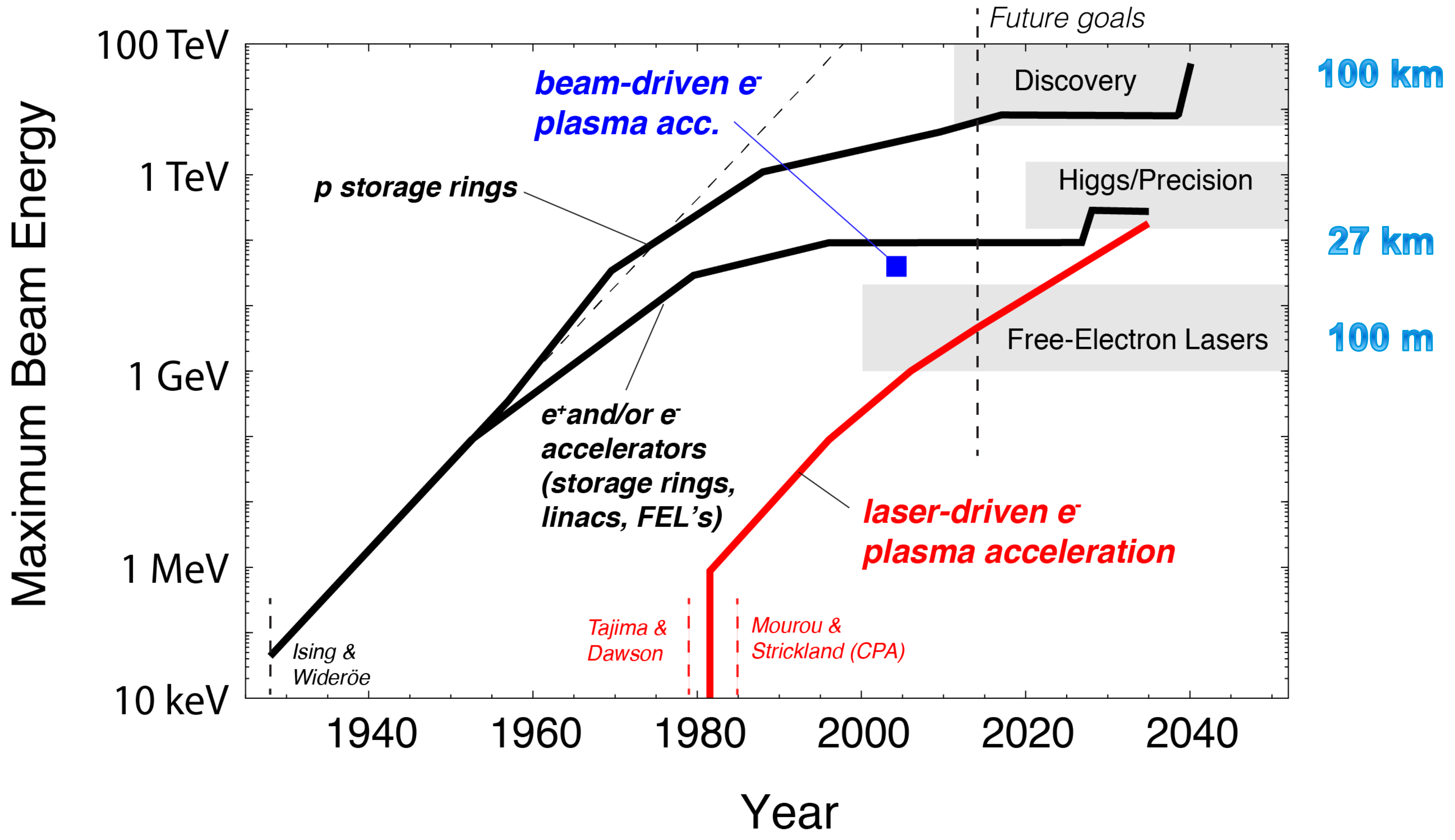
Towards ultra-dense, highest brightness electron beams



- **Increase kinetic energy** of particles (MeV – GeV – *TeV*)
- **More particles** per bunch (1 million – *100 billion*)
- **Smaller transverse area** (*1 nm* – 1 mm smallest diameter)
- **Shorter bunches** for access to ultra-fast science (*100 nm* – 100 μm)
- **More bunches** (1 – 1000)
- **MORE C O M P A C T TECH???**

Slow Down in RF and Invention of A New Technology

Complementing RF based Accelerators with Plasma Accelerators!?



Slow Down in RF and Invention of A New Technology

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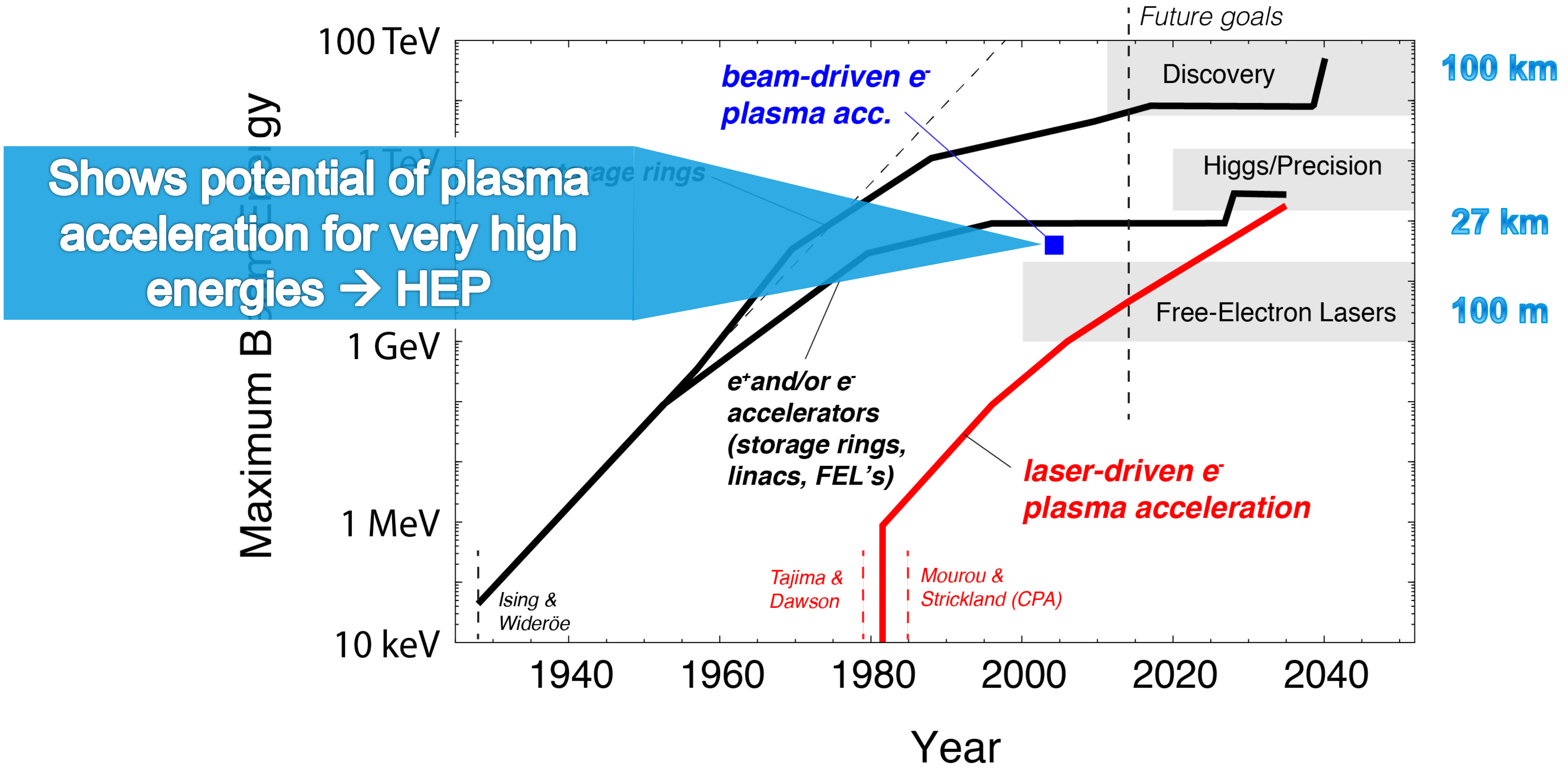

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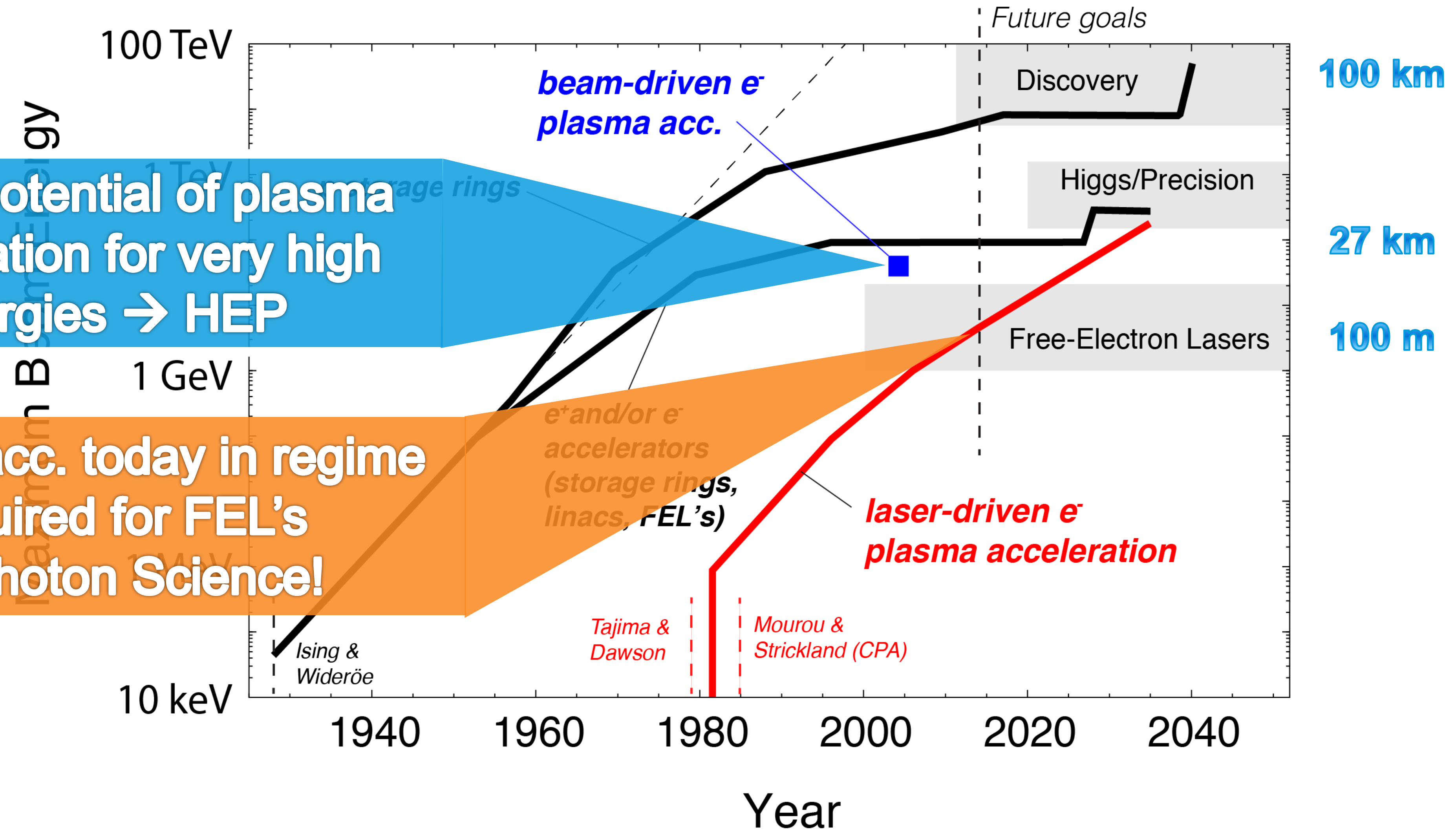

Shows potential of plasma acceleration for very high energies → HEP

Plasma acc. today in regime required for FEL's → Photon Science!

Slow Down in RF and Invention of A New Technology

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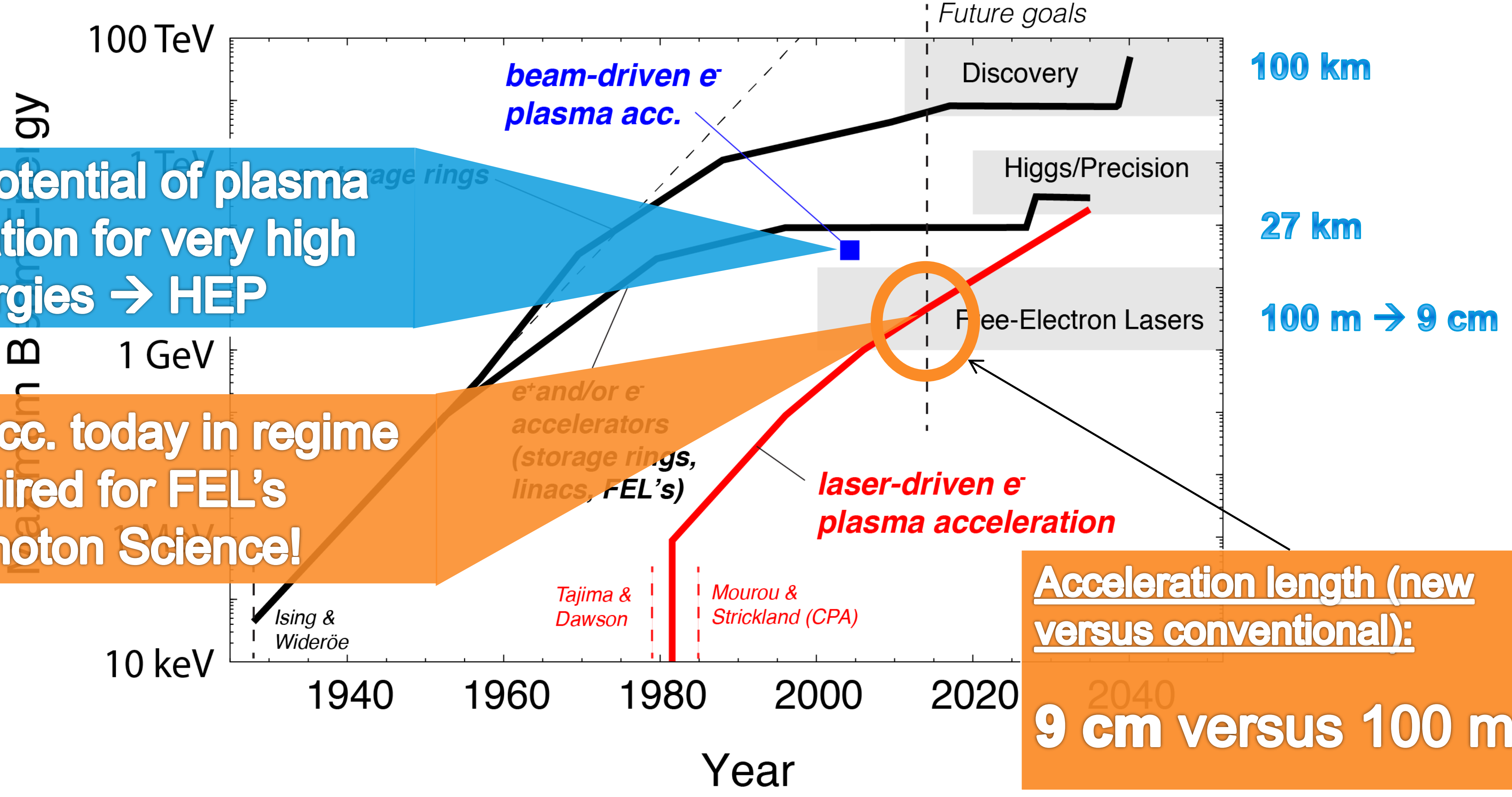


Shows potential of plasma acceleration for very high energies → HEP

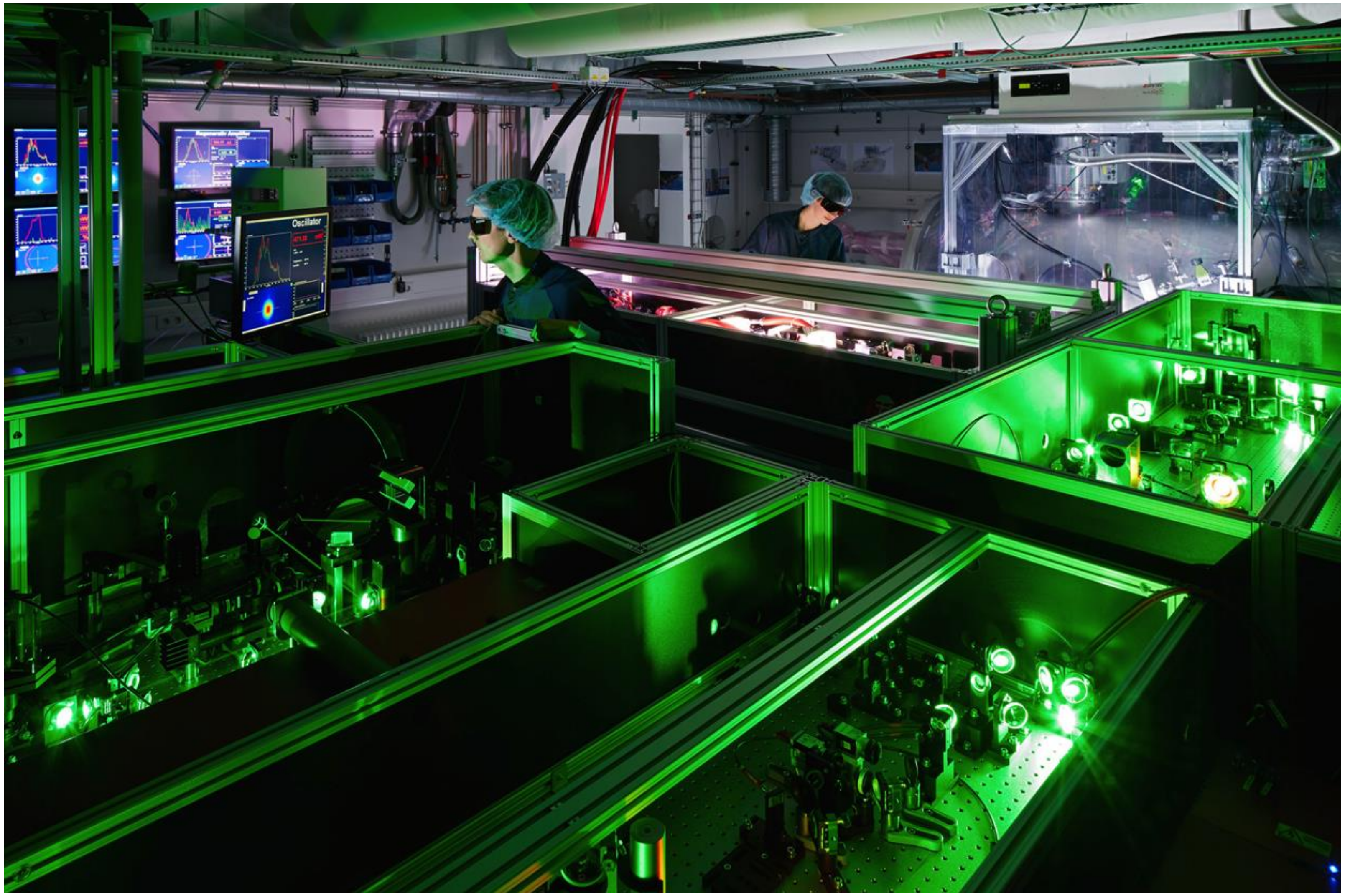
Plasma acc. today in regime required for FEL's → Photon Science!

Acceleration length (new versus conventional):

9 cm versus 100 m

Hamburg: ANGUS Laser Laboratory for Accelerator R&D

200 TW Ti-Sa laser from Thales, laboratory at DESY & University Hamburg



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

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

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

22 thousand billion Volt per meter

(“LHC energy in 30 cm instead of 27 km” → not really)

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

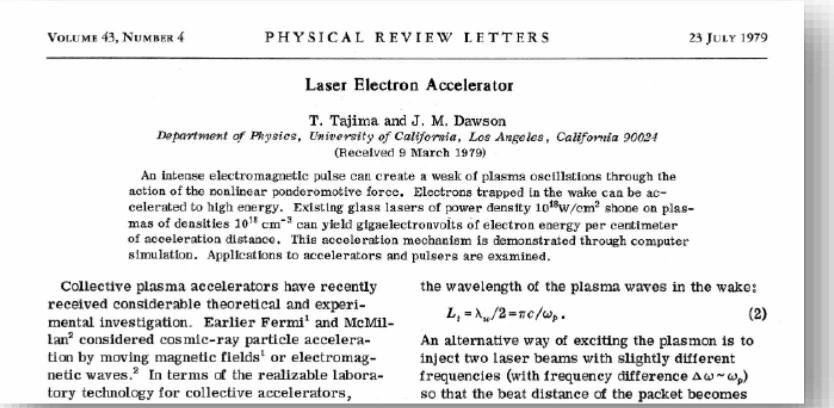
The Plasma Accelerator Concept

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



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)

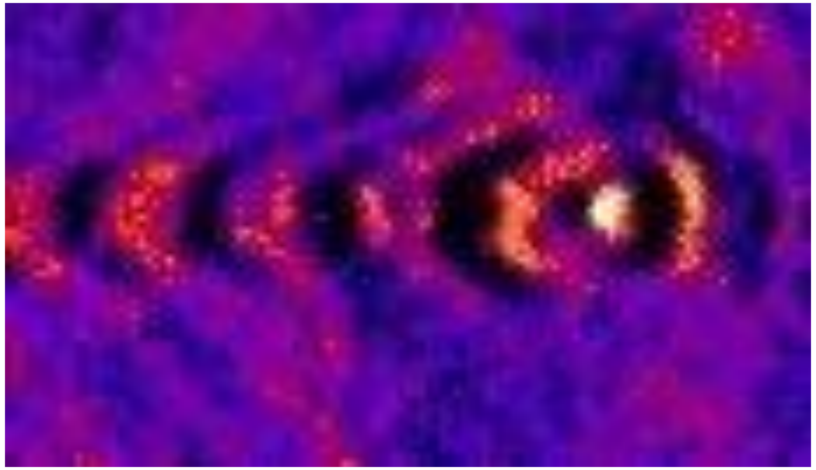
An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield 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



Courtesy M. Kaluza

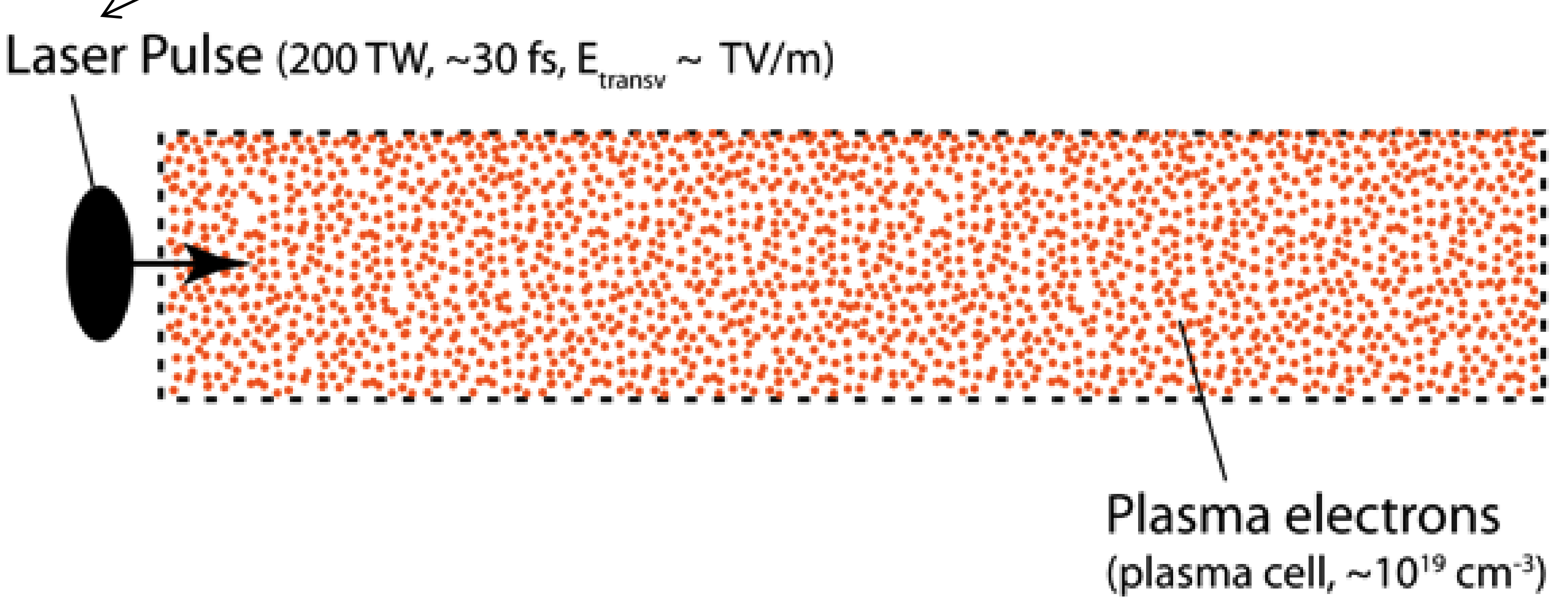
Options for driving wakefields:

- **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**)

Plasma Acceleration

Internal injection

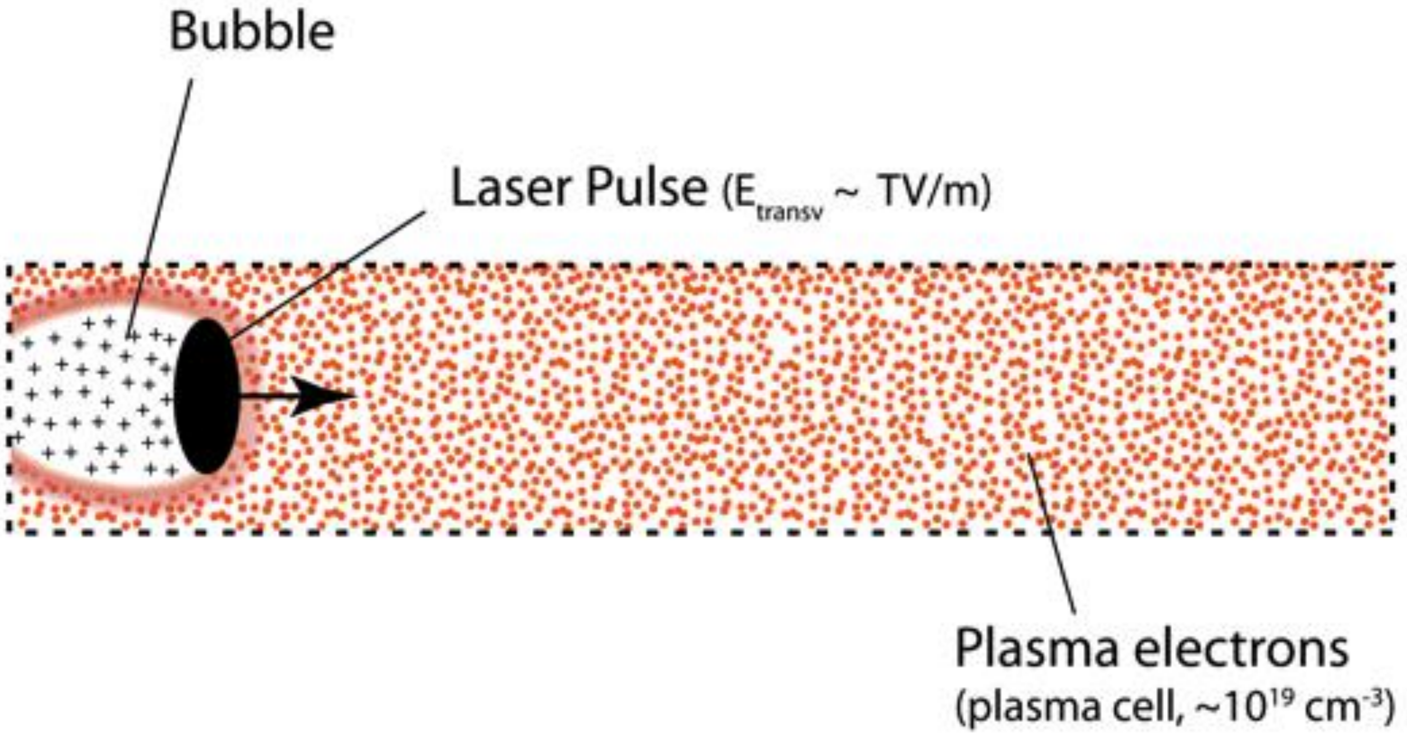
Works the same way with an **electron beam as wakefield driver**. But then usually lower plasma density. Ponderomotive force of laser is then replaced with space charge force of electrons on plasma electrons (repelling).



Like wakes left behind by a boat in water

Plasma Acceleration

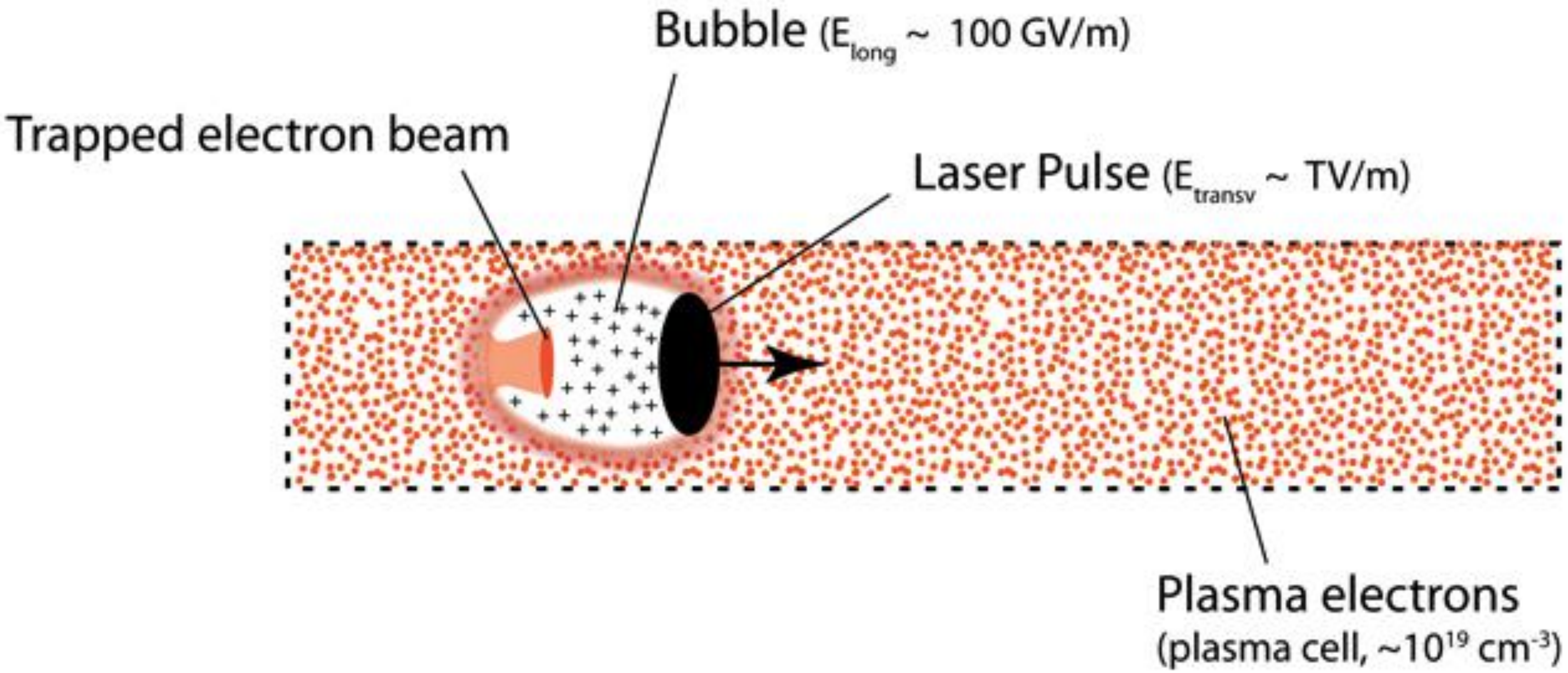
Internal injection



Like wakes left behind by a boat in water

Plasma Acceleration

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

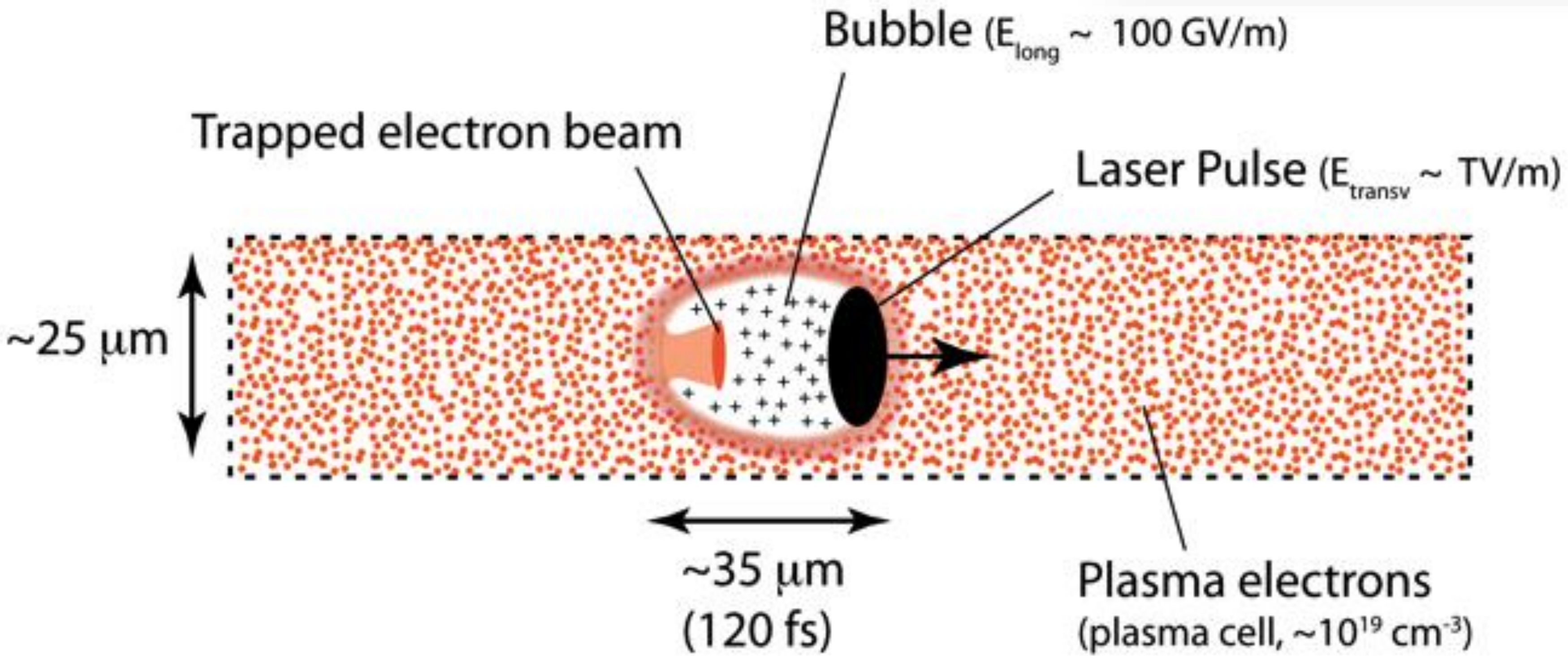


Like wakes left behind by a boat in water

Plasma Acceleration

Internal injection ("bubble regime")

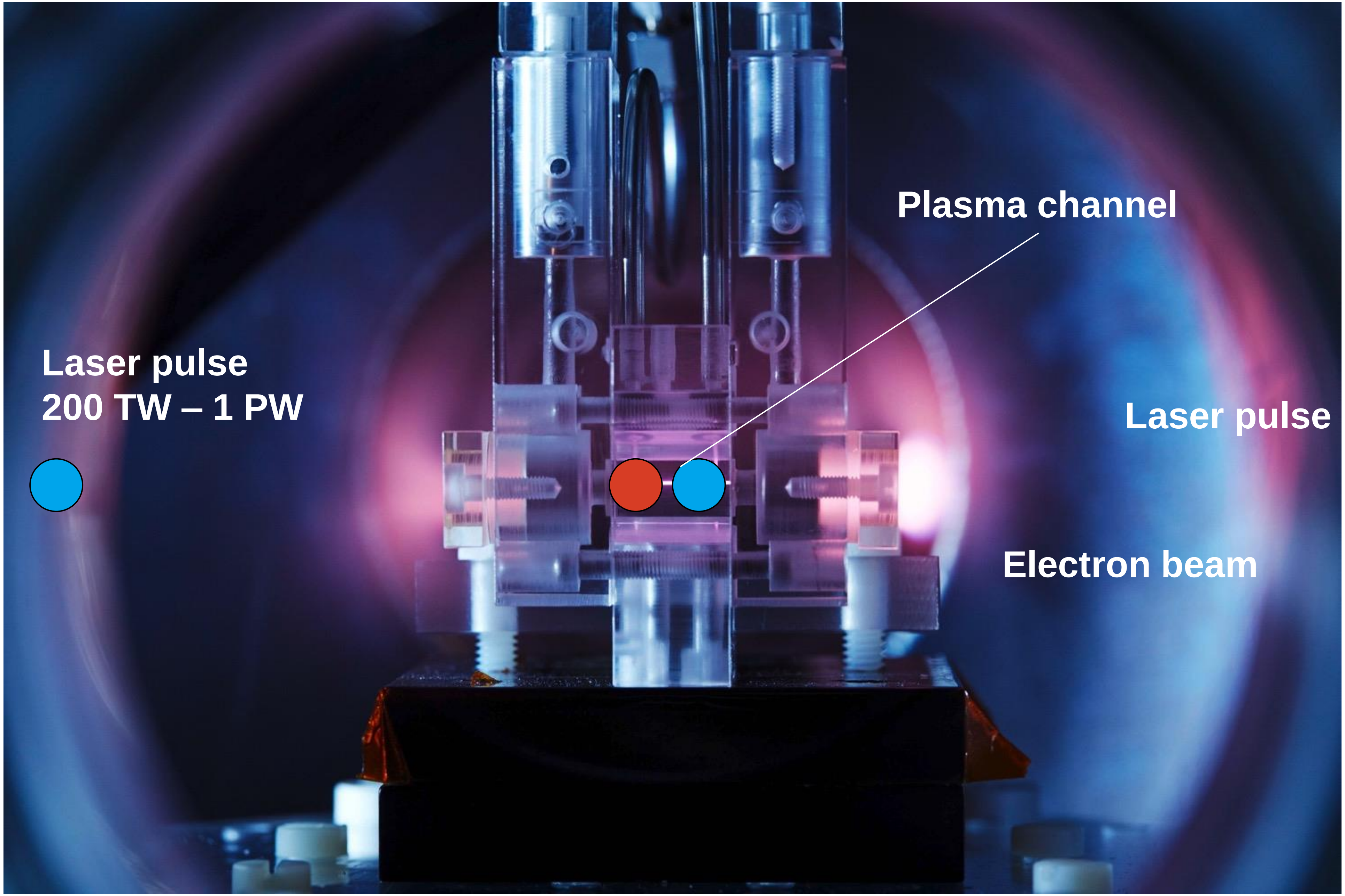
This accelerator fits into a human hair



Like wakes left behind by a boat in water

Laser Plasma Accelerator for Electron Beams

“Bubble regime”, invented in Europe



...and it is really much smaller!

A few cm's of plasma create as much energy as the 100 m long S.C. FLASH linac

Accelerator size becomes almost negligible!

Do not forget the **size of the laser**, which is the dominant size here:

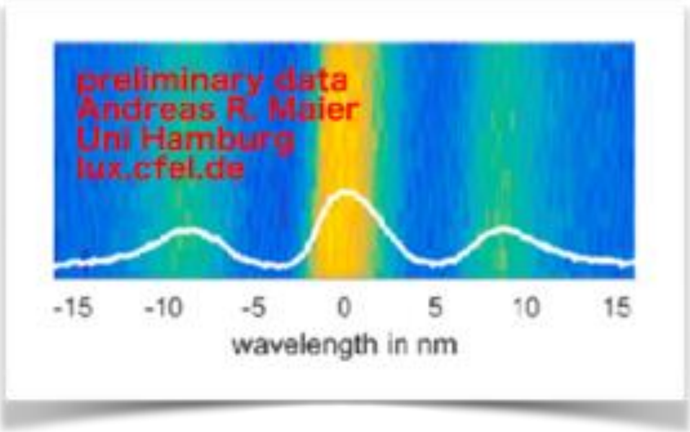
Fit a **10 billion electron Volt accelerator in 300 square-meter** laboratory instead of 500 meter long accelerator tunnel!

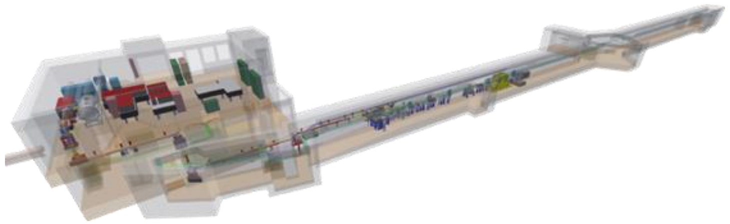
€ $ ¥ £

University Hamburg / DESY: LUX (A. Maier et al)

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

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG





About **400 MeV 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)**, first **24h operation**. Latest: 1 GeV electron beam.

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

The European Opportunity

The European Opportunity

DESIGNING THE FUTURE

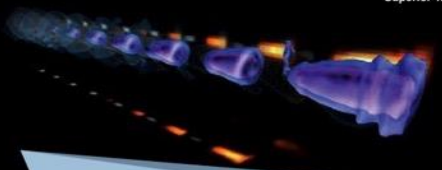
The EuPRAXIA Consortium is preparing a conceptual design for the world's first multi-GeV plasma-based accelerator with industrial beam quality and dedicated user areas.

© DESY, Heiner Müller-Elsner

INTERNATIONAL COLLABORATION

EuPRAXIA brings together a consortium of 16 laboratories and universities from 5 EU member states. The project, coordinated by DESY, is funded by the EU's Horizon 2020 programme. The consortium has been joined by 18 associated partners to make additional in-kind contributions.

The consortium holds open international events to strengthen collaborations, to connect to interested users from FEL's, high-energy physics, medicine and industry, and to assess the development of the project.



Computer simulation of a laser wakefield

© Dr Jorge Vieira, Instituto Superior Tecnico, Lisbon

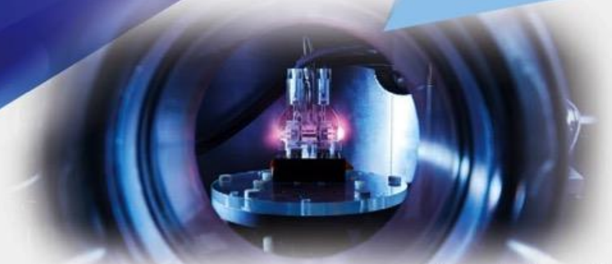


Image of a plasma cell.

© DESY, Heiner Müller-Elsner

Particle accelerators have become powerful and widely used tools for industry, medicine and science. Today there are some 30,000 particle accelerators worldwide, all of them relying on well-established technologies.

The achievable energy of particles is often limited by practical boundaries on size and cost, for example, in hospitals and university laboratories, or available funding for very large scientific instruments at the energy frontier.

A new type of accelerator that uses plasma wakefields promises accelerating gradients as much as 1,000 times higher than conventional accelerators! This would allow much smaller machines for fundamental and applied research.

The goal of this project is to produce a conceptual design for the world's first multi-GeV plasma-based accelerator that can provide industrial beam quality into dedicated user areas.

ADVANCED TECHNOLOGIES

The project is structured into 14 working groups dealing with simulations of high gradient laser plasma accelerator structures, design and optimization of lasers and electron beams, research into alternative and hybrid techniques, Free Electron Lasers (FEL), high-energy physics, and radiation source applications.

EuPRAXIA joins novel acceleration schemes with modern lasers, the latest correction technologies and large-scale user areas. The consortium offers unique training opportunities for researchers in a multidisciplinary field.

OPENING NEW HORIZONS

The project will bridge the gap between successful proof-of-principle experiments and ground-breaking, ultra-compact accelerators.

With a smaller size and improved efficiency, plasma-based technologies have the potential to revolutionize the world of particle accelerators multiplying their applications to medicine, industry and fundamental science.

Participants in the EuPRAXIA Steering Committee Meeting. Paris, February 2016

© Sylvaine Pieyre, LLR

EuPRAXIA

EuPRAXIA Horizon2020 Design Study

European Plasma Accelerator Infrastructure with Pilot Users

- **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
- **125 scientists** in our work list

Start: 1 Nov 2015
End: 31 Oct 2019

Deliverable: Conceptual Design Report

www.eupraxia-project.eu

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

Collaboration of 40 institutes

From Europe, Asia and United States

16 EU laboratories are beneficiaries. **24 associated partners** from EU, Europe, Asia and US contribute in-kind.

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

EuPRAXIA

Where is Africa in EuPRAXIA?

Missing an African Collaborator while we have Asian and US institutes involved

- **Inviting African groups to collaborate with us.**
- Compact, laser-based accelerators are a **medium term way to build up scientific infrastructure and research in additional countries.**
- **We will look for resources to fund such a work.**
- **Examples for possibilities:**
  - **Doctors interested in** medical applications (defining your needs with us)
  - Groups interested in **3D design of facilities and technical components** (students can work in Africa on PC's and software that we organize, addressing our problems)
  - Groups interested **to send young scientist for participating in our experimental work** in Germany, then analyzing data in Africa.
  - Groups interested in **lasers** and their operation.

Email to: ralph.assmann@desy.de

Management Structure

Heads of Project and of Supervisory Boards

Collaboration board

Scientific advisory board

Project coordinator

Management support team

Steering committee

WP1: Project management and technical coordination

WP2: Physics and simulation

WP3: High-gradient laser-plasma accelerating structures

WP4: Laser design and optimization

WP5: Electron beam design and optimization

WP6: FEL pilot application

WP7: High-energy physics and other pilot applications

WP8: Outreach and liaison

WP9: Alternative e-beam driven plasma structures

WP10: Use of other novel technologies

WP11: FEL application prototyping

WP12: Accel. prototyping and experiments at test facilities

WP13: Alternative radiation generation

WP14: Hybrid laser-electron-beam driven acceleration

Steering Committee

EuPRAXIA

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A European Strategy for Accelerator Innovation

Required intermediate step between proof of principle and production facility
One accelerator 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

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EuPRAXIA Objectives

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

1. Address **quality**. Show **plasma accelerator technology is usable**

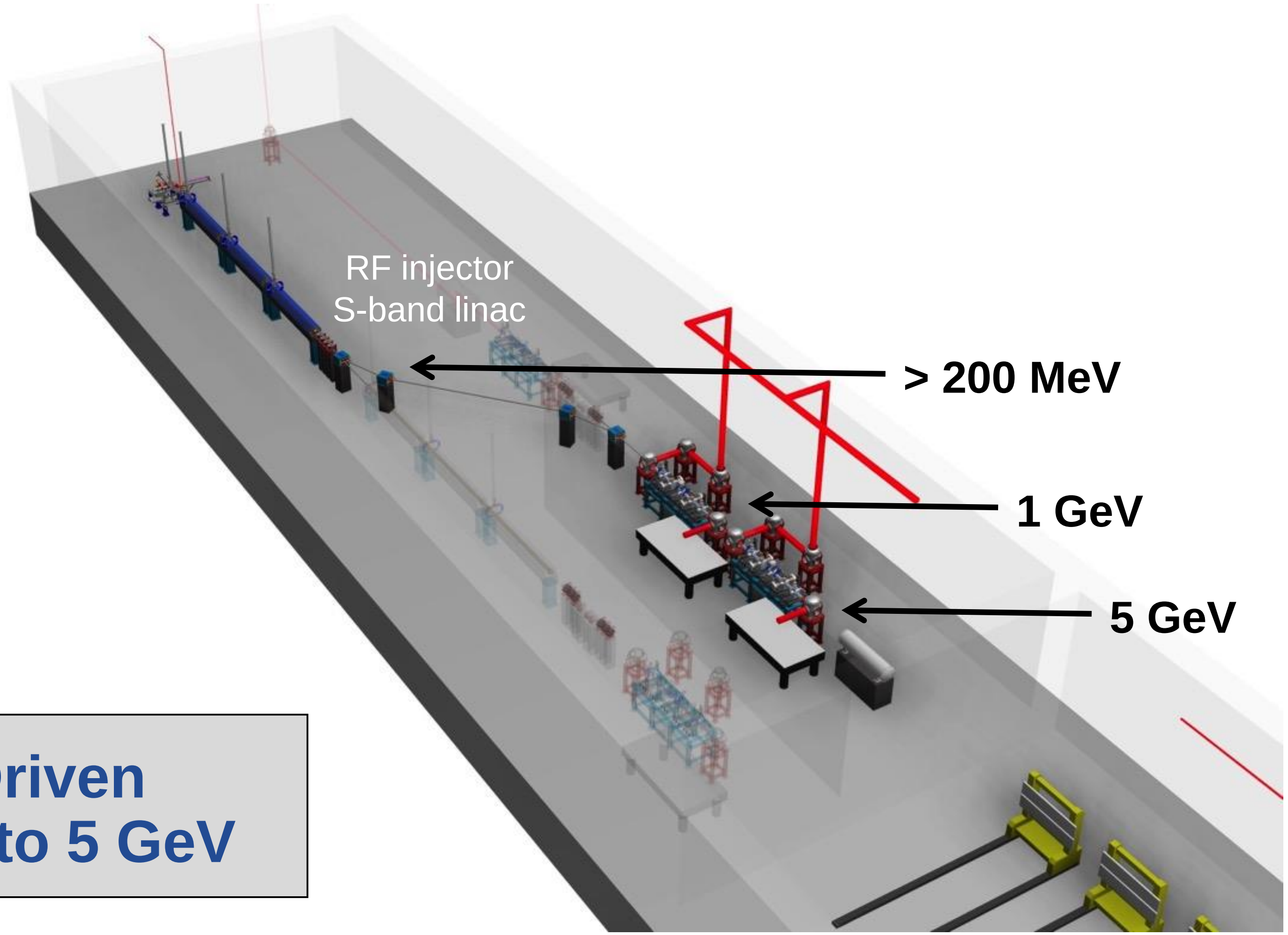
2. Show **benefit in size and cost** versus established RF technology

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)

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

The 50 Billion Volt per Meter Linear Accelerator

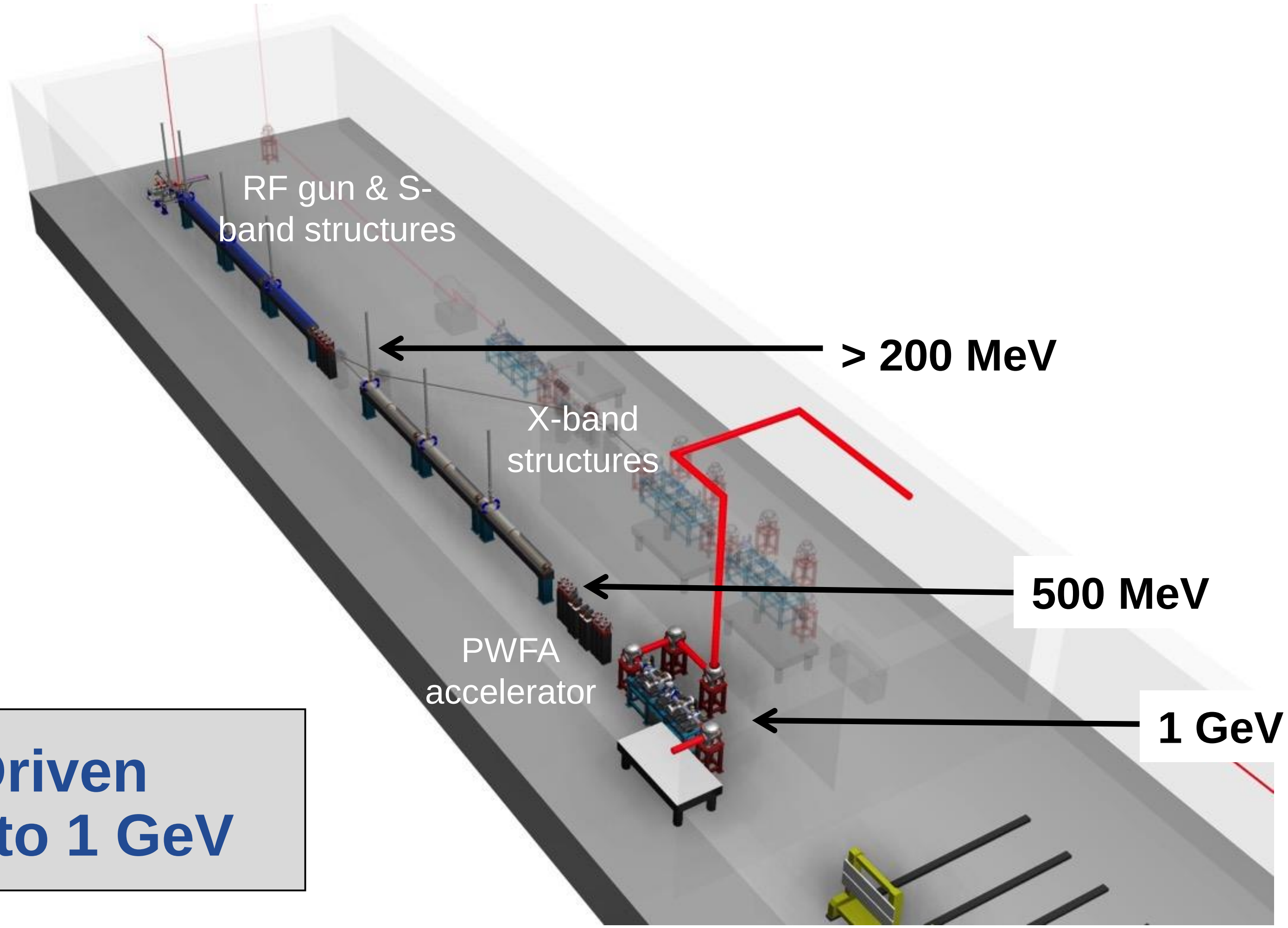


A Laser-Driven Stages to 5 GeV

EuPRAXIA

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

The 50 Billion Volt per Meter Linear Accelerator



B **Beam-Driven Stages to 1 GeV**

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

Targets in Facility Parameters

Overview of EuPRAXIA technical goals. Not self-consistent cases. Detailed and self-consistent parameter tables are available upon request.

High-energy, ultrashort electron beams		
Energy	[GeV]	1 – 5
Energy spread	[%]	0.1 – 5
Beam duration	[fs]	3 – 20
Beam charge / no. of electrons	[pC / -]	5 – 50 / 3×10^7 – 3×10^8
Typical transverse beam size*	[µm]	2 – 100
Repetition rate	[Hz]	1 – 100
Ultrashort Free-Electron Laser radiation pulses		
Wavelength	[nm]	0.05 – 10
No. of photons per pulse	[-]	10^{10} – 10^{12}
Pulse duration	[fs]	3 – 35
Bandwidth	[%]	0.1 – 0.5
Three main high power laser systems		
Wavelength	[nm]	800
Energy on target	[J]	5 – 100
Pulse duration	[fs]	20 – 60
Repetition rate	[Hz]	20 – 100

* *with a normalised transverse beam emittance of 0.5 – 1.5 µm*

EuPRAXIA

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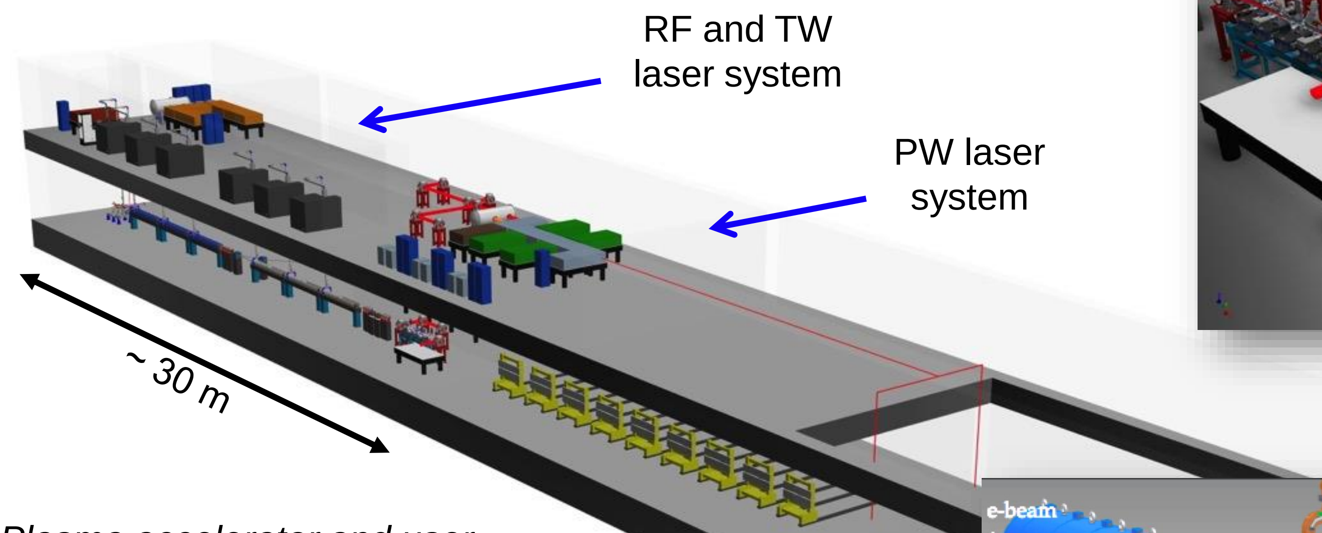
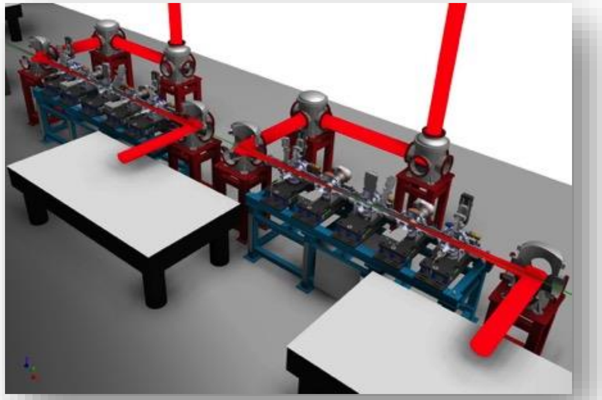
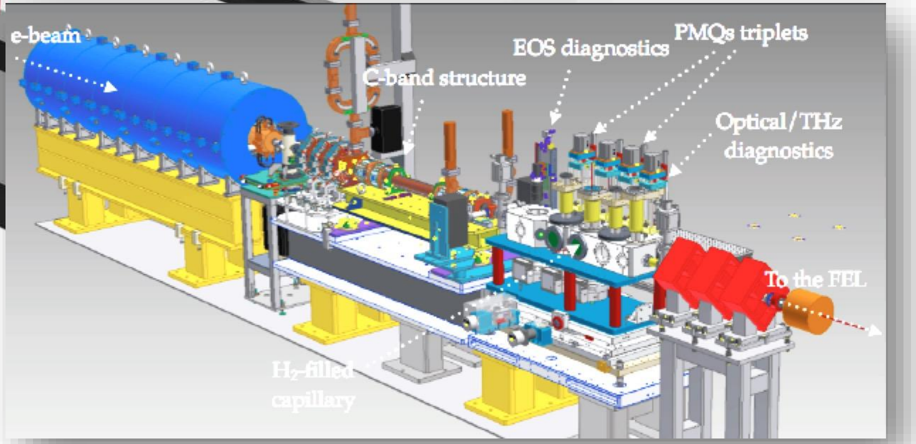
The EuPRAXIA Facility (Under Design)

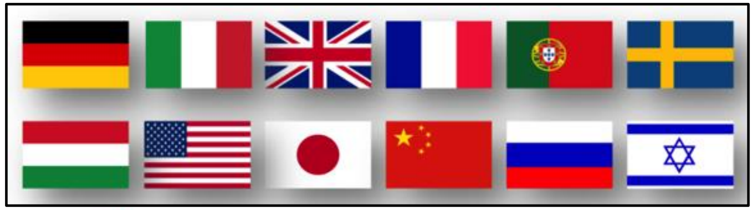




Plasma accelerator and user lines are on 1st level

RF and laser infrastructure are on 2nd level





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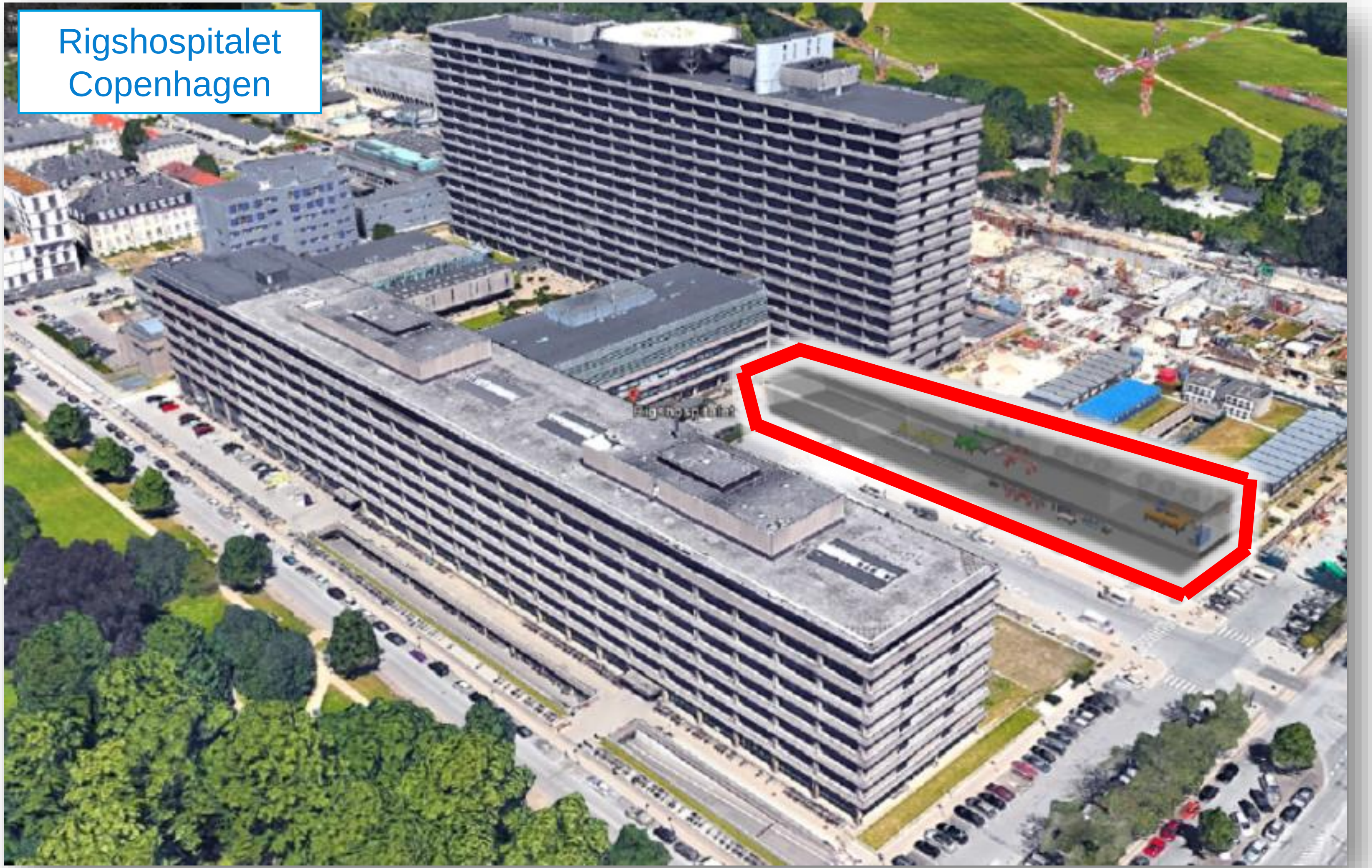
Fits on the Parking Lot of the Hospital Copenhagen

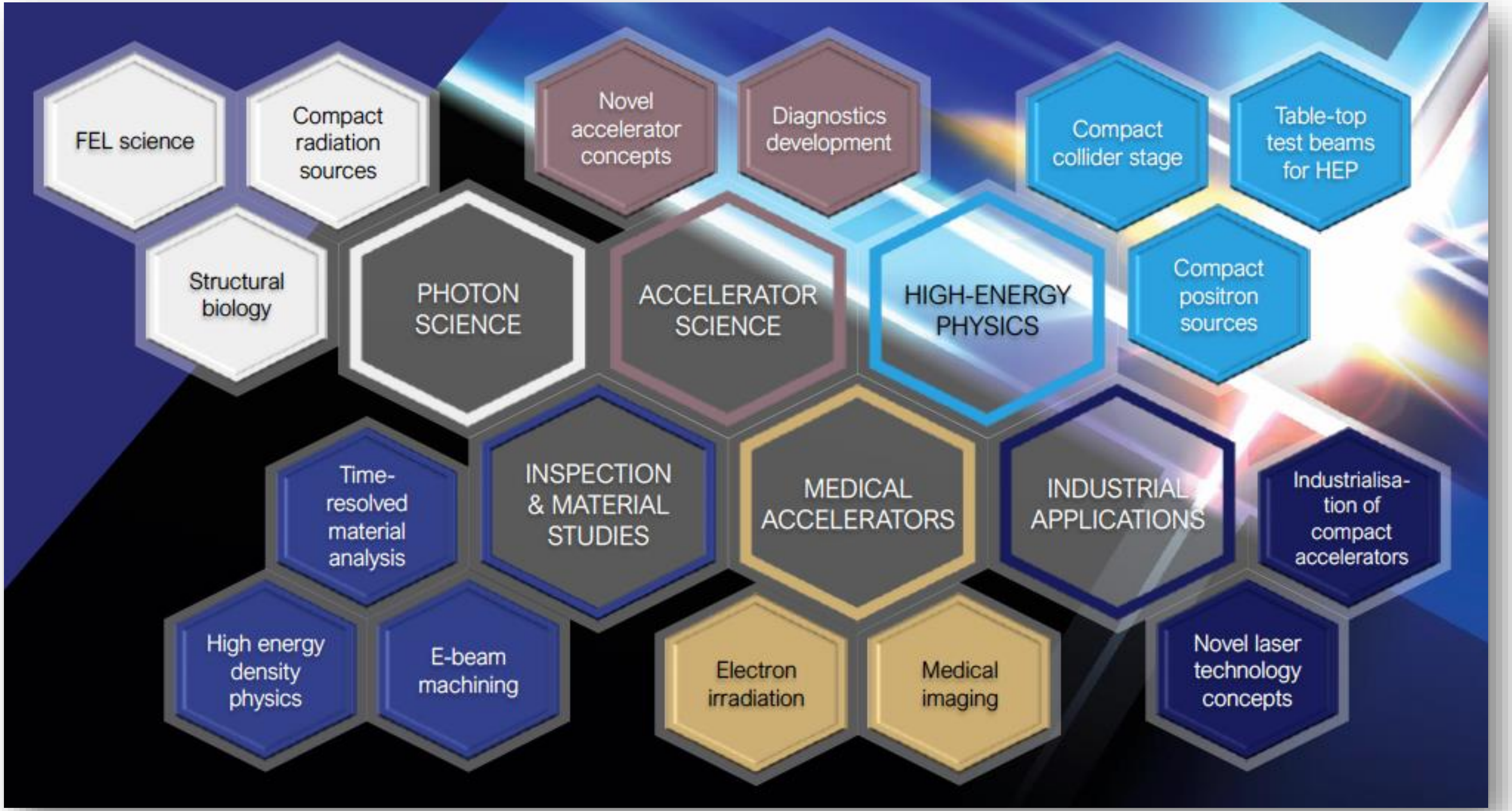


Illustrative example prepared for IPAC17 talk in Copenhagen

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

Versatile – Designed for Multiple Applications

High Energy – Accelerator R&D – Photon Science – Material – Medical – Industrial



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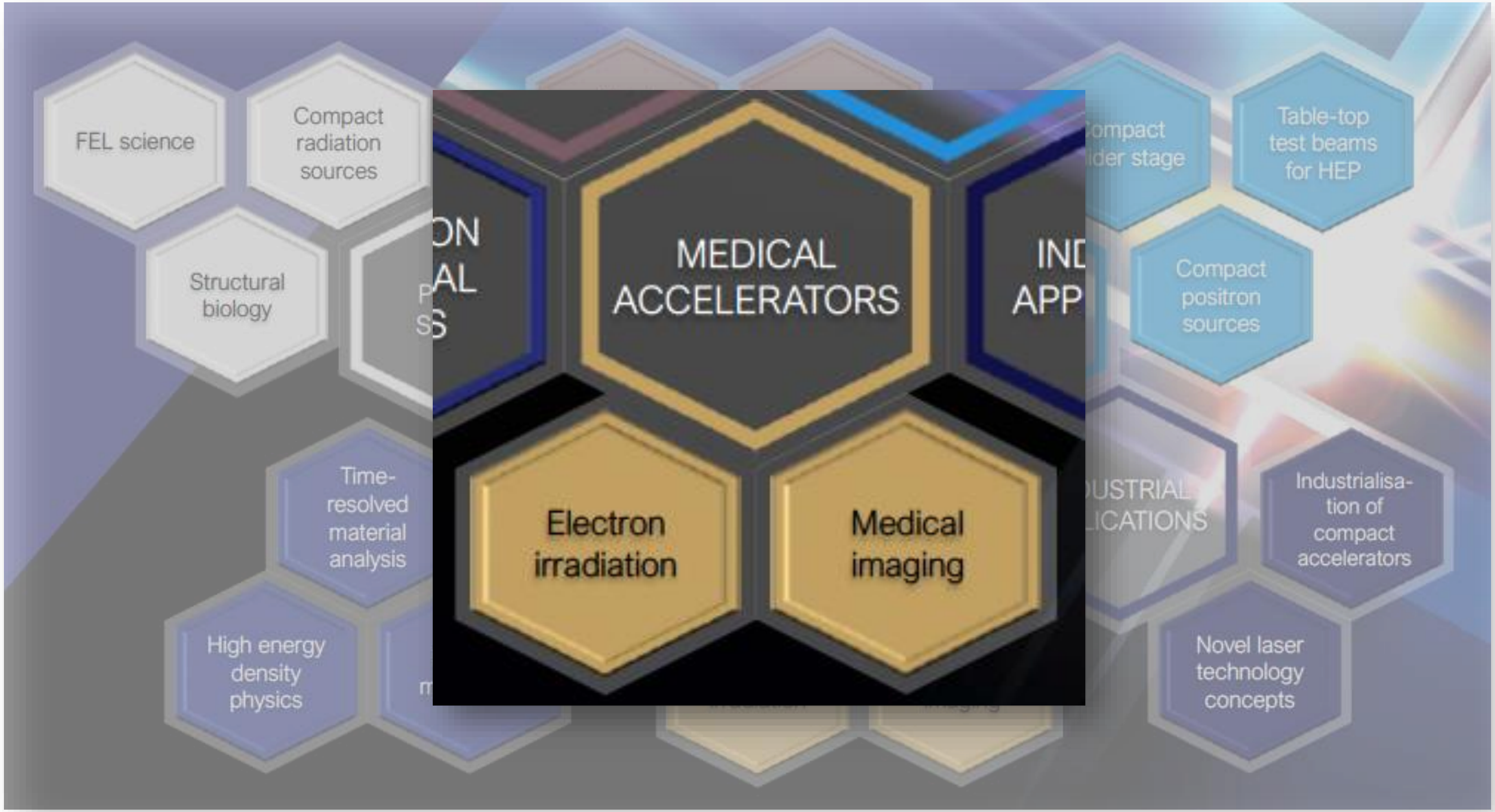

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Medical Imaging with Plasma Accelerators

Some Unique Advantages – Already Working Today – Too Slow at the Moment

2015 publication from J.M. Cole et al., John-Adams-Institute, UK: “Laser-wakefield accelerators as hard x-ray sources for 3D medical imaging of human bone”. Nature Scientific Reports 5, 13244 (2015)

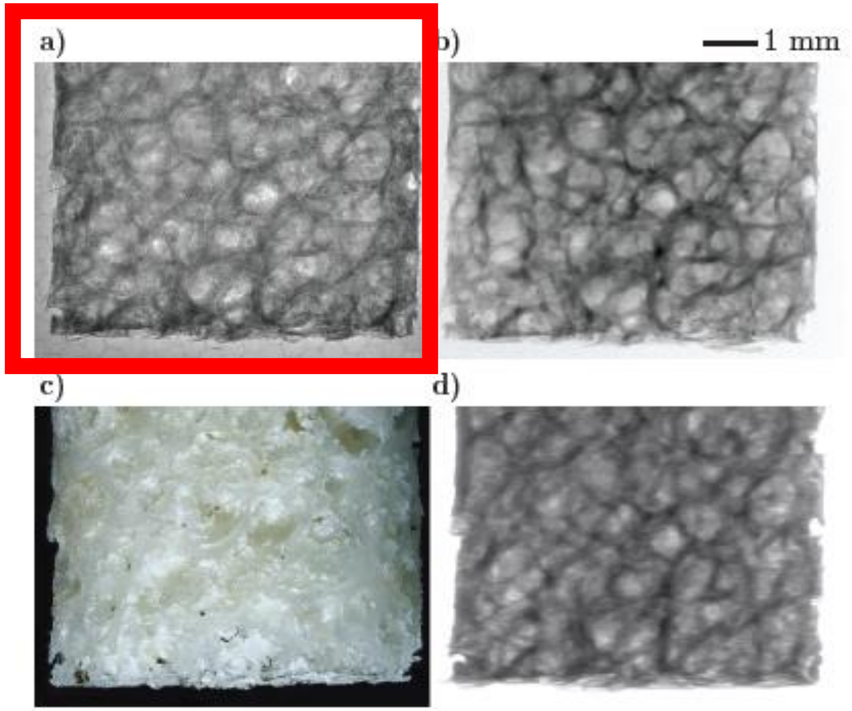
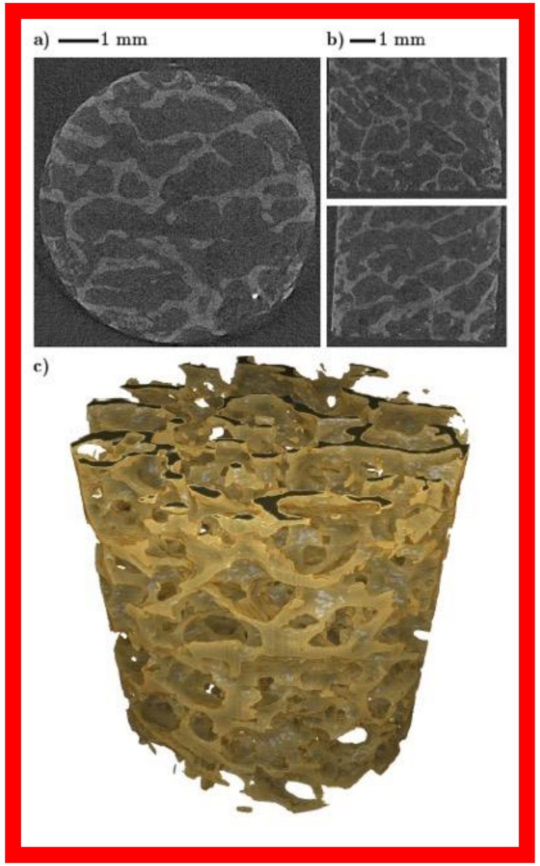
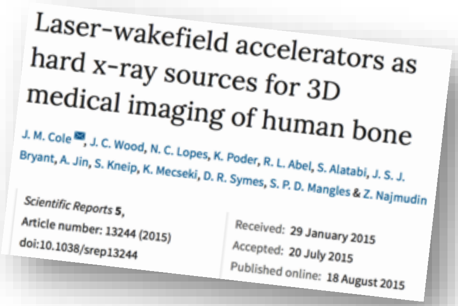


Figure 3. Images of the bone sample recorded with a) the betatron x-ray source b) conventional μCT scanning c) composite macro photography d) virtual illumination of the 3D reconstruction by a source of $E_{crit} = 33\,\mathrm{keV}$.





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

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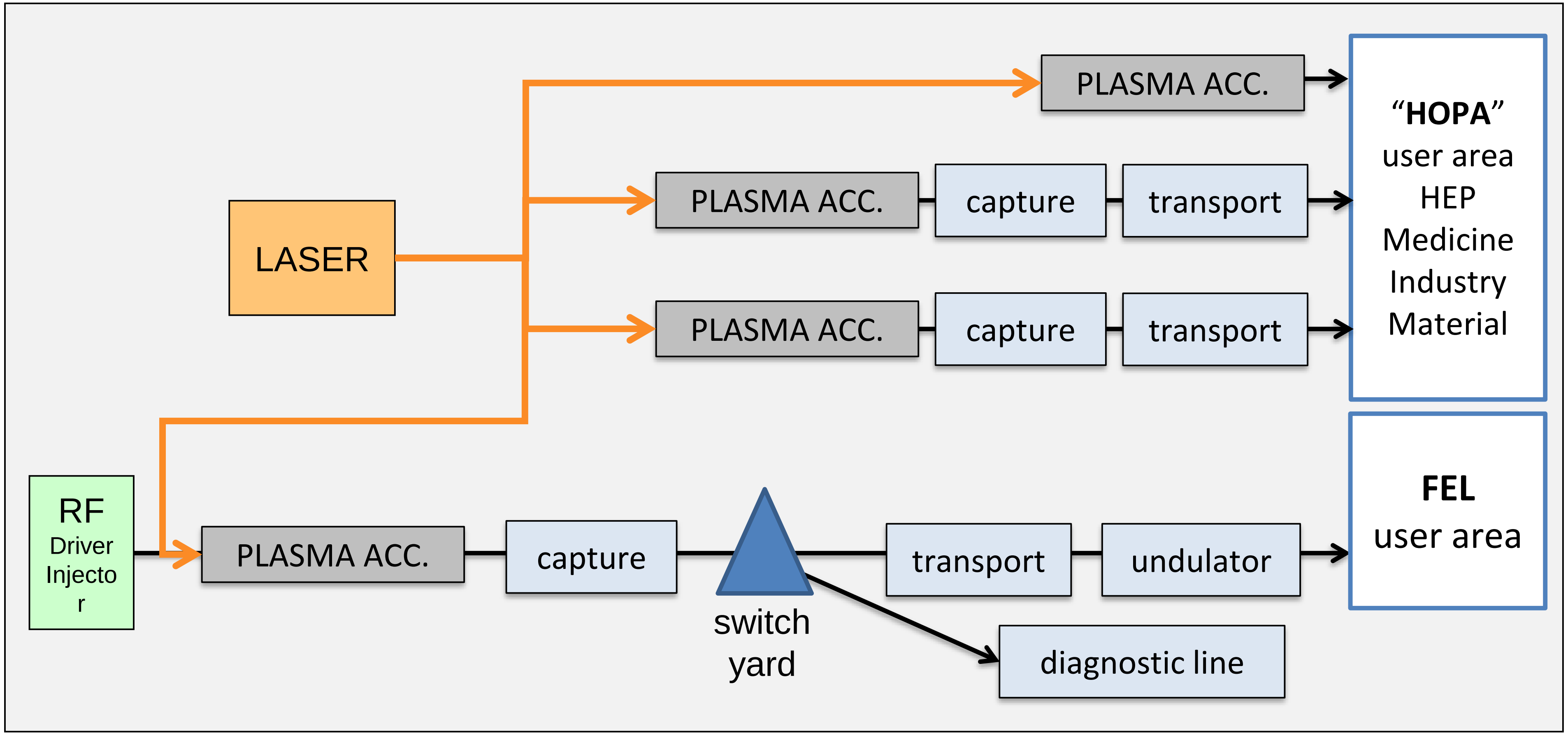
Published online: 18 August 2015

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.

Can the Facility REALLY Do ALL of This?

Another Advantage of Plasma Accelerators



Laser pulses distributed to "small" plasma accelerators to drive many applications!

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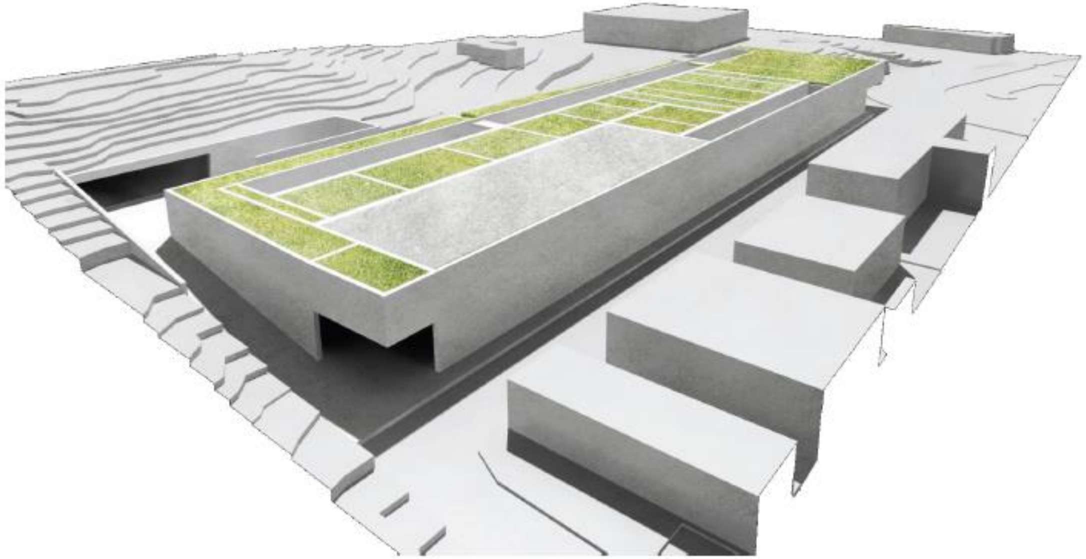
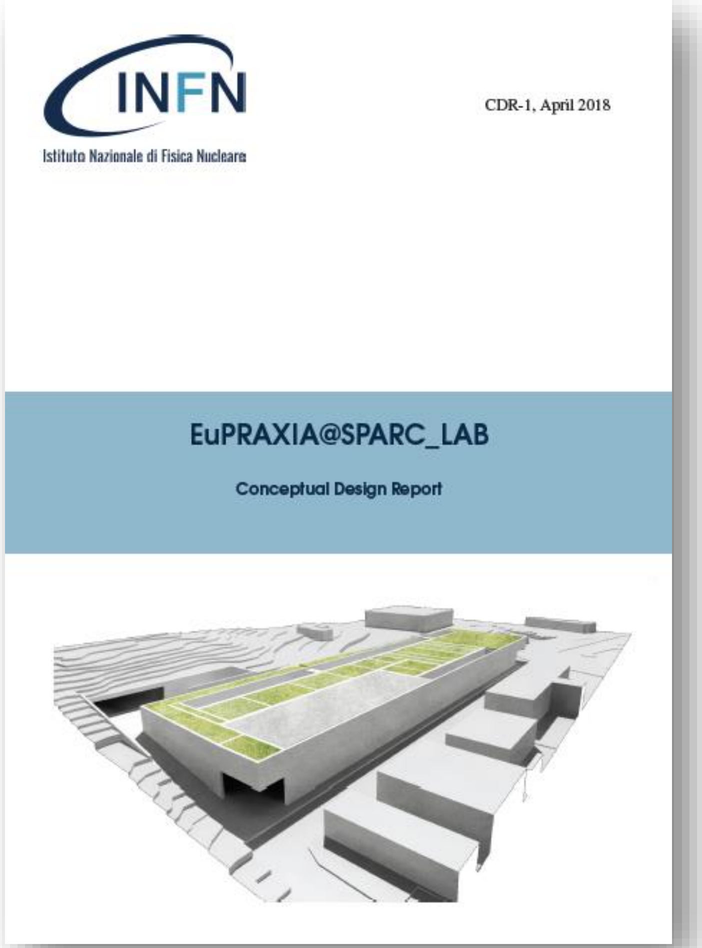
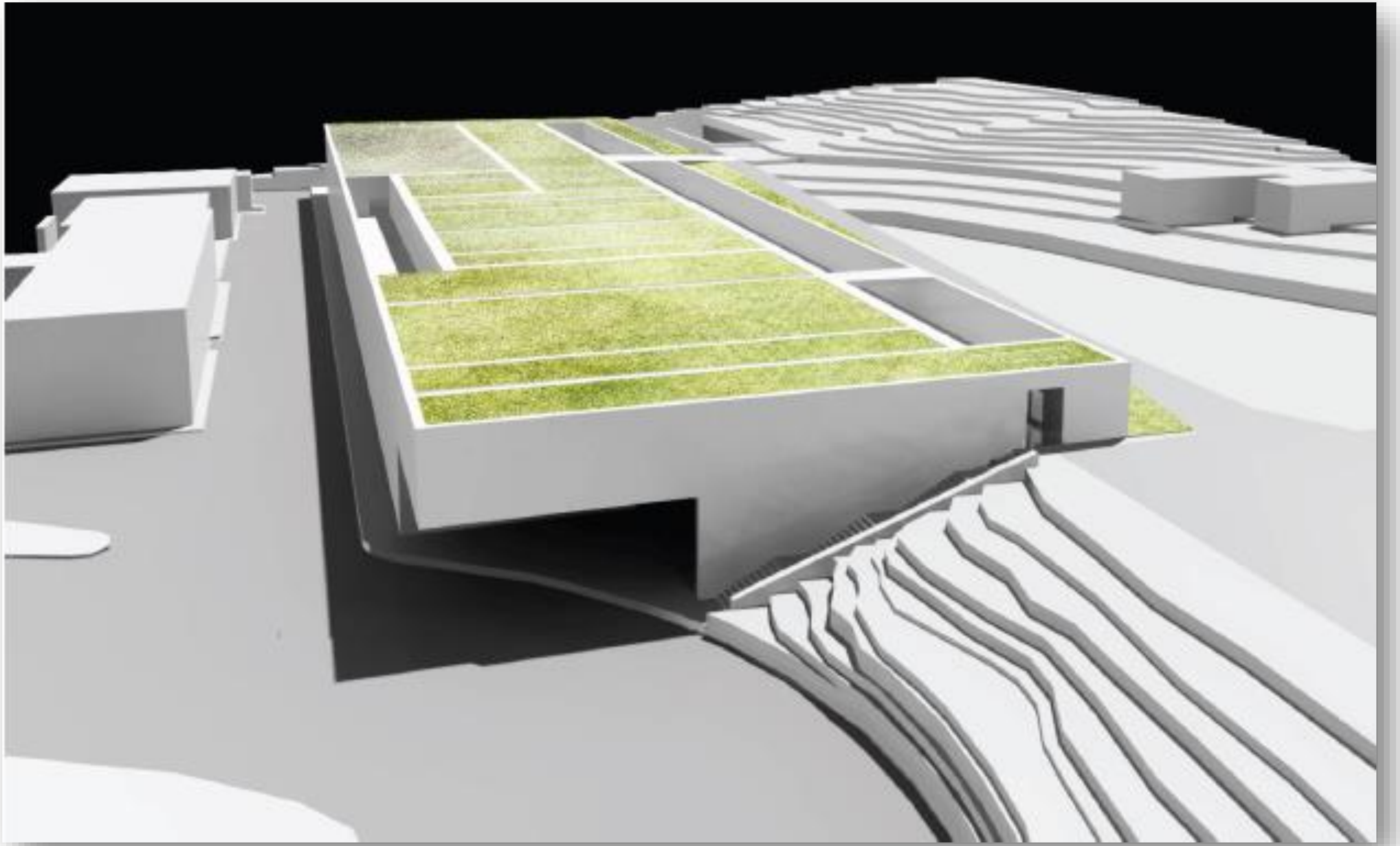
EuPRAXIA at SPARClab in Frascati




INFN
Istituto Nazionale di Fisica Nucleare
CDR-1, April 2018
EuPRAXIA@SPARC_LAB
Conceptual Design Report

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

Impression of EuPRAXIA@SPARC_LAB at LNF



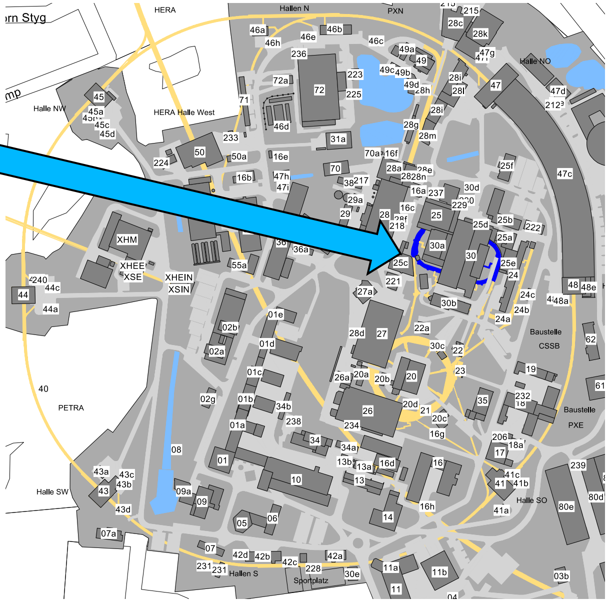
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

Hamburg Infrastructure – SINBAD

Under construction – will house laser-driven novel accelerators at DESY → ATHENA$_e$ project at DESY

SINBAD

Ex-DORIS



ACCELERATORS | PHOTON SCIENCE | PARTICLE PHYSICS

Deutsches Elektronen-Synchrotron
A Research Centre of the Helmholtz Association

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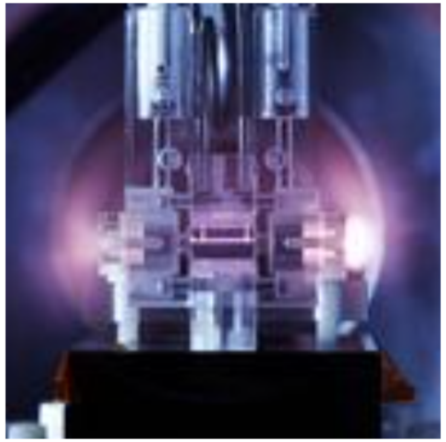

18/06/14 · Press-Release

Helmholtz Association supports ATHENA with 29.99m euro grant

ATHENA ("Accelerator Technology HElmholtz iNfrAstructure") is a new research and development platform focusing on accelerator technologies and drawing on the resources of all six Helmholtz accelerator...

- Latest news: ATHENA project approved for 29.99 M€ investment.
- Funded by Helmholtz strategic funding and BMBF "Pakt für Forschung"

The work on ATHENA is closely embedded in the wider context of European research through the EU-sponsored design study EuPRAXIA, with its 40 partner institutes, which is also coordinated by DESY. Hence the top German research project ATHENA has had a clear European perspective and orientation right from the start.

Press and Public Understand the Huge Potential

Examples from Germany


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

"Bigger, faster, more expensive: no way!"


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

"Can we have smaller machines?"

"Yes, we can!"


Hamburger Abendblatt

WISSEN

Der Mini-Teilchenbeschleuniger

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

"The tiny particle accelerator"

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

Conclusions

Europe developing new high tech and compact accelerators

- The **long-term future is bright**: there will be plenty of opportunities as technology advances!
- **EuPRAXIA Goals on 10-15 year time-scale:**
  - Demonstrate plasma-wakefield accelerated multi-GeV-scale electron beams with stability and quality sufficient for first pilot user experiments
  - Contribute to the conception of new European accelerator facility
- Compact accelerators **broaden the use and benefits of accelerators for our societies**, also opening new possibilities for Africa
- We **look for African collaborators** and will try to find funds for supporting this...

Thank you for your attention

Looking for African collaborators

Email to: ralph.assmann@desy.de

- Compact accelerators are a chance for everybody.
- Plenty of things to do – we need your help!
- Inviting African groups to collaborate with us.
- We will look for resources to fund such a work.

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