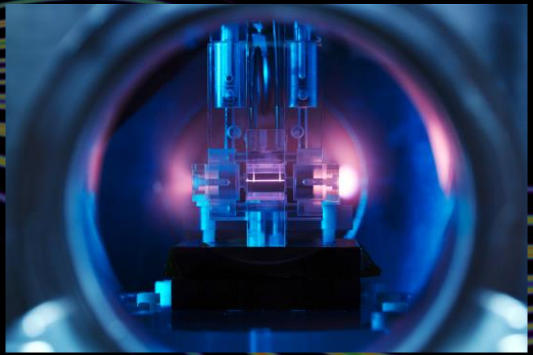
New Accelerator Physics and Technology Trends


An 18 Minute Glimpse at a Very Rich Topic

IHEP 2021

Virtual, Hongkong, China

20 January 2020

Ralph W. Aßmann, DESY

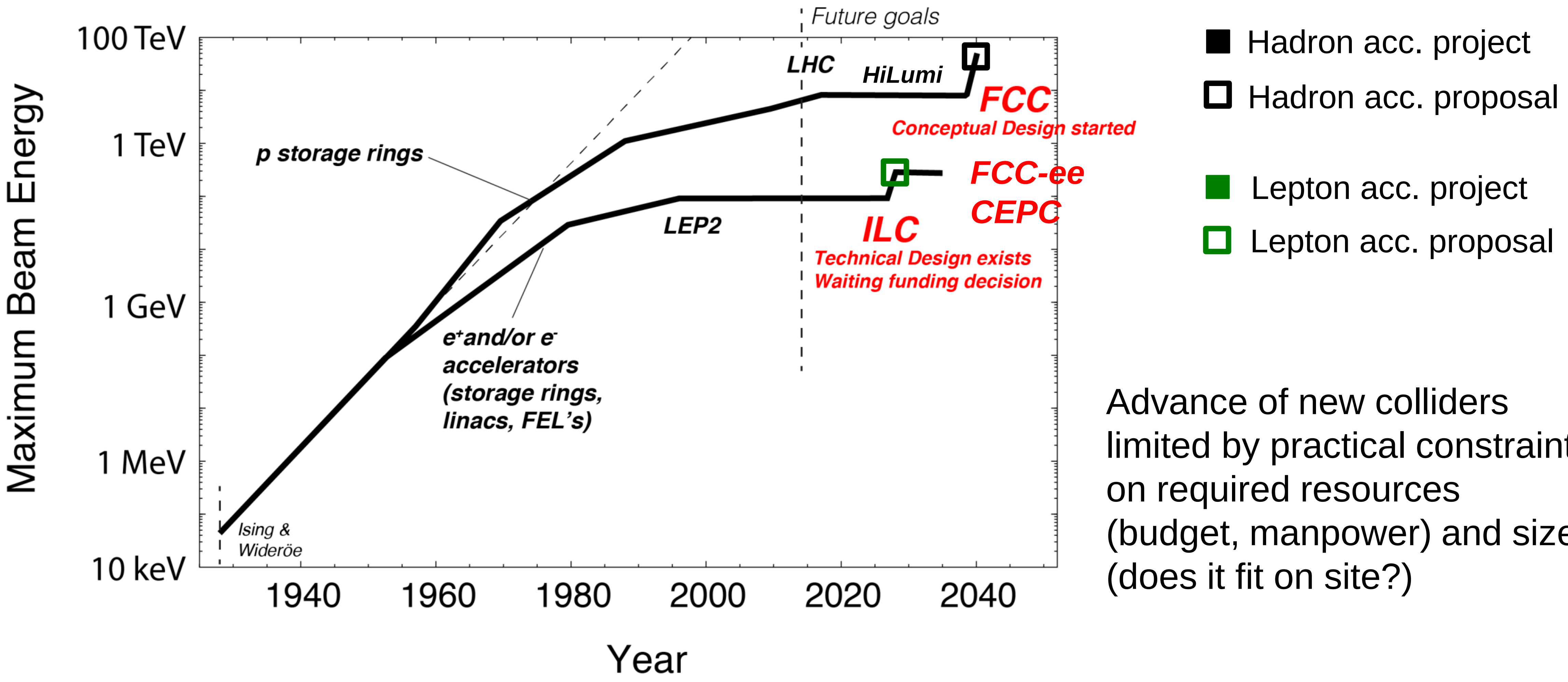
HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

MT
MATTER AND TECHNOLOGIES

DESY

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

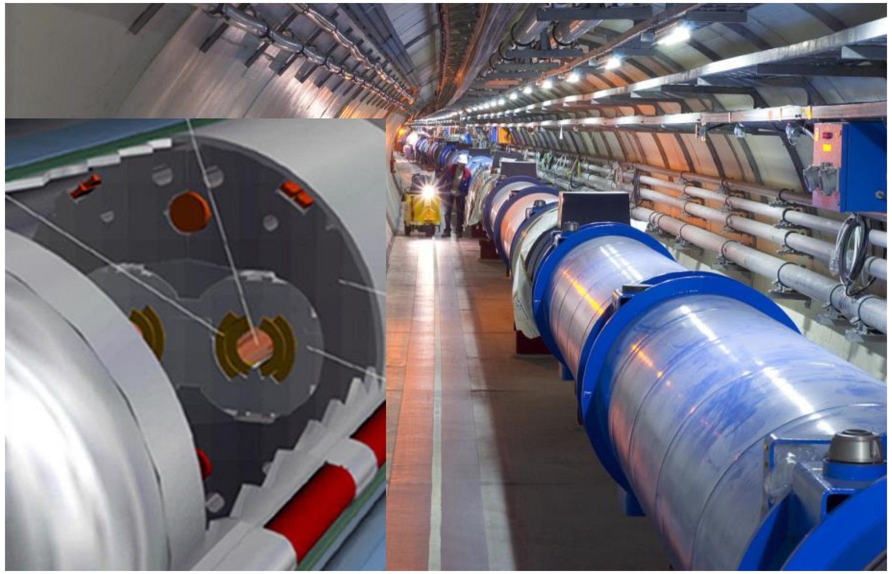
Technical limitations in highly advanced and mature technologies

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

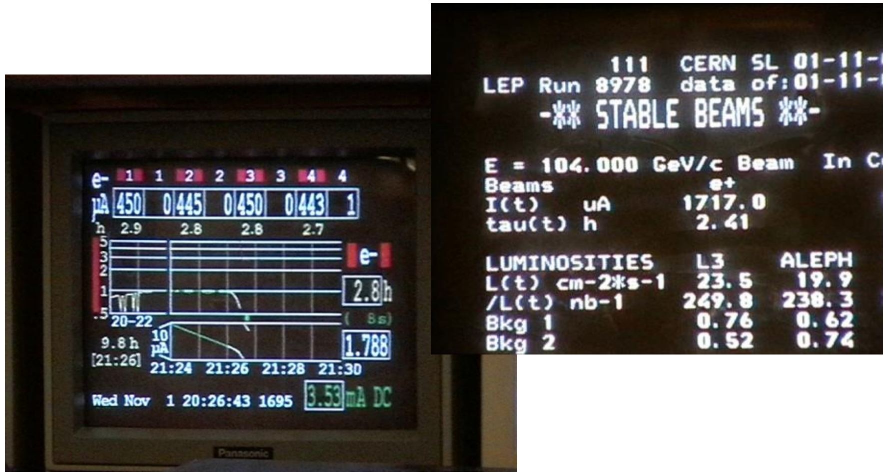


Lepton (e-,e+) circular collider

- 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

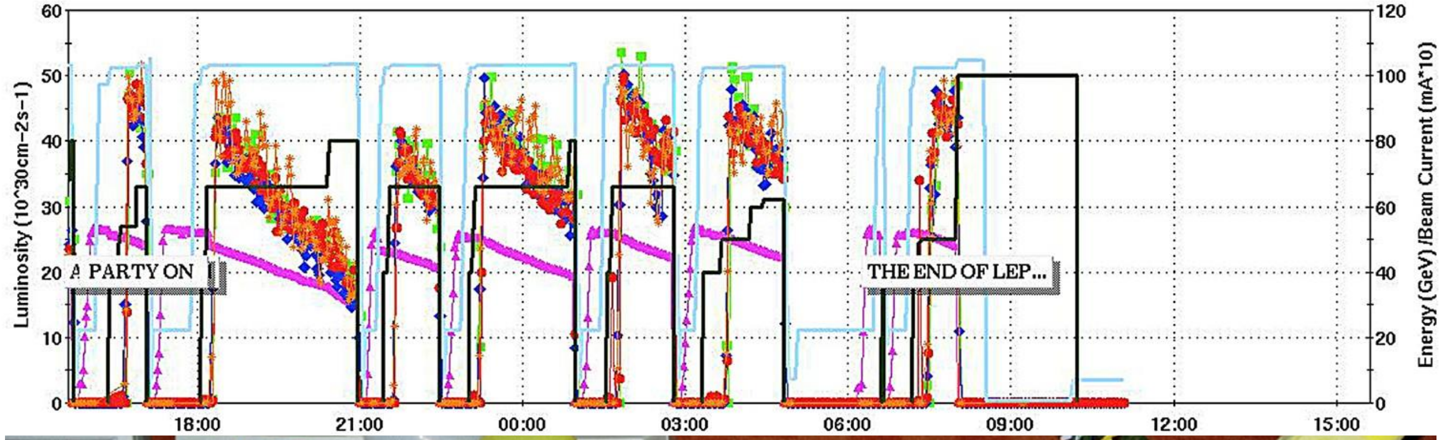
The End of LEP2

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**!

Larger facility with innovative high luminosity design (realizing new ideas) will allow pushing the e+e- energy frontier (**FCC-ee, CEPC**).

Alternatively: **going linear**. This avoids synchrotron radiation limitation! But comes with its own challenges.

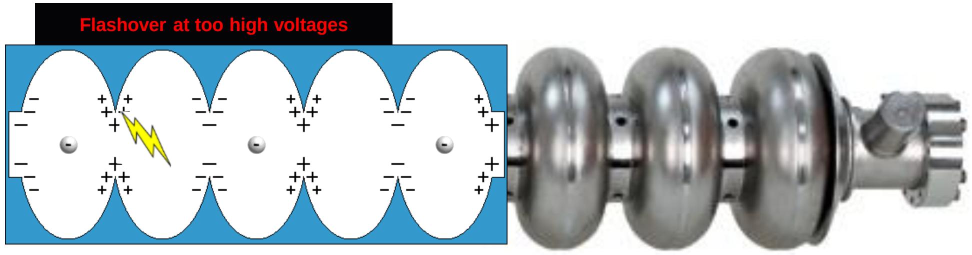


Why this slow-down? Part 2

Technical limitations in highly advanced and mature technologies

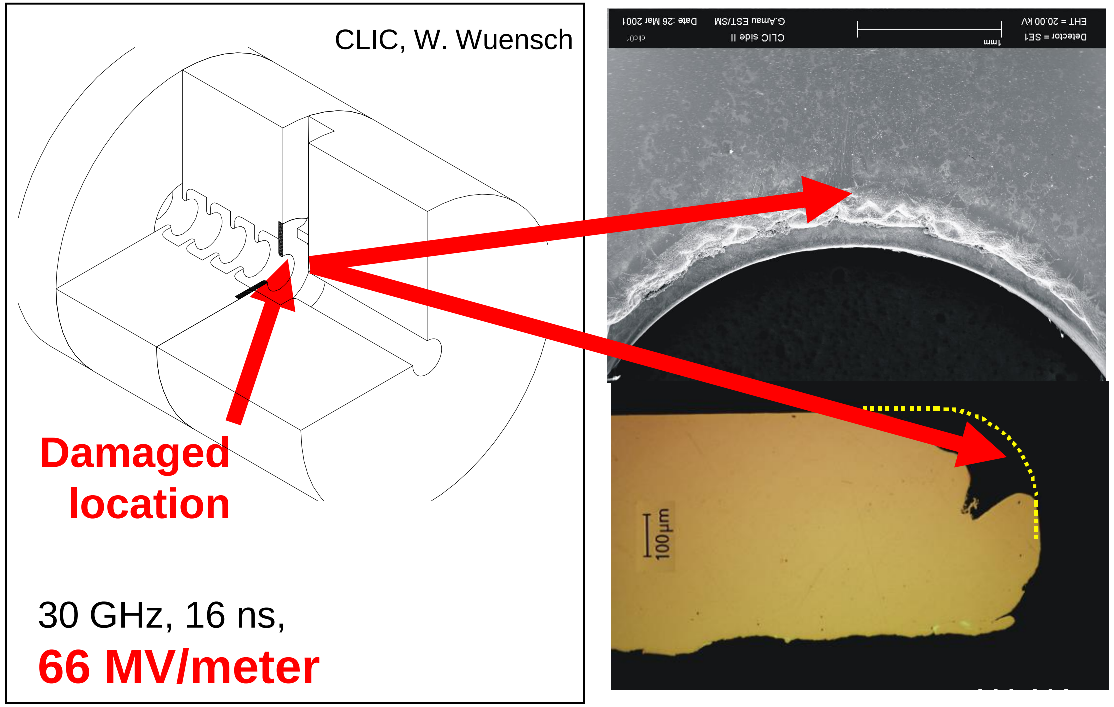
Lepton (e-,e+) linear collider

- 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

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

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

Increase radius = size (FCC-hh)

Lepton (e-,e+) circular collider

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

Increase supplied RF voltage (FCC-ee, CEPC)

Increase mass of acc. particle (muon)

Increase radius = size (FCC-ee, CEPC)

Lepton (e-,e+) linear collider

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

Increase accelerating gradient

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

Increase length (ILC, CLIC)

Many high tech activities ongoing in the big collider projects, pioneering new solutions, advancing technology and opening new possibilities!

No time to go through in detail. Apologies!

See the many talks on R&D and results presented at this conference!

Affordability is a critical issue: cost of components, energy efficiency, OP costs!

Here, just a few remarks on trends...

Trend: Smart Manufacturing and Assembly

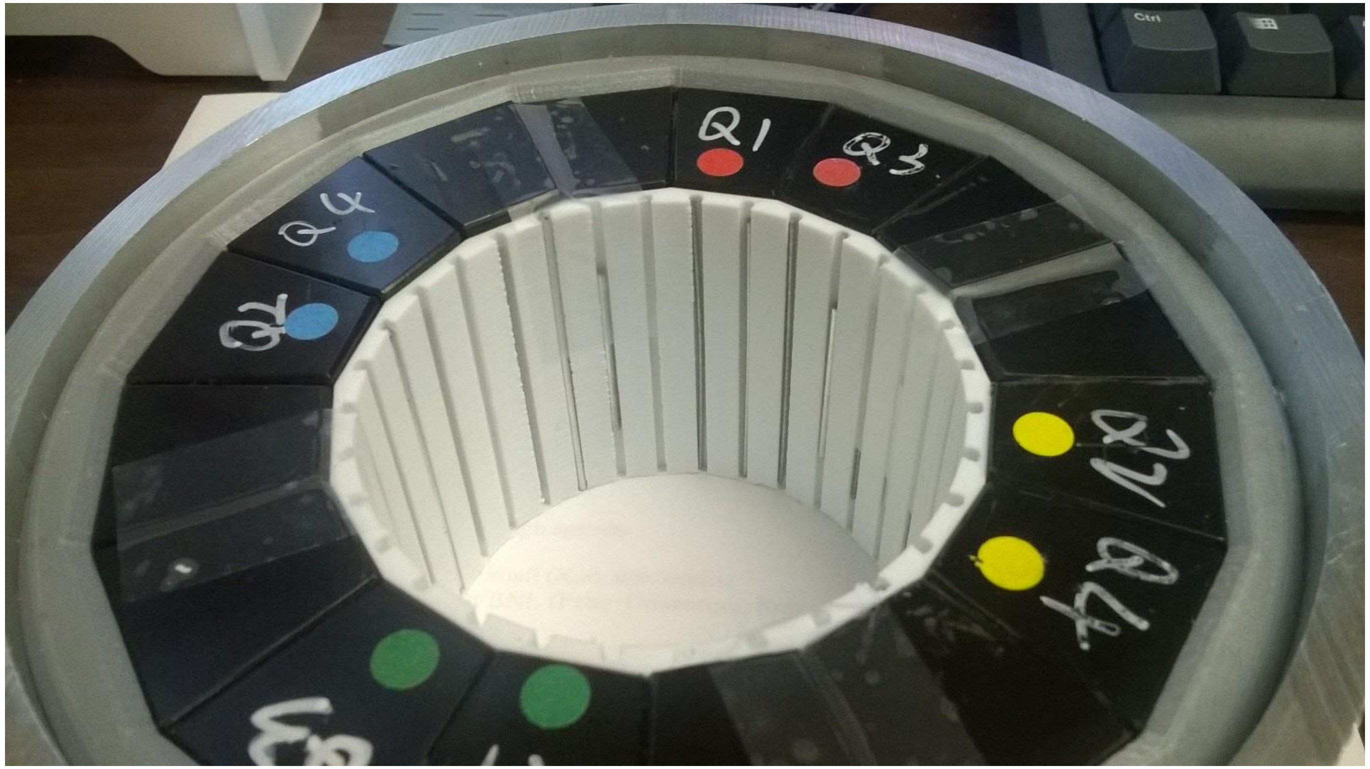
Can we bring down cost per meter of accelerator by a factor 2 – 10?

Picture courtesy S. Brooks, BNL

Smart manufacturing and assembly (optimized as industrial process):

- **Factory**: Instead of highly accurate pieces of permanent magnets (very expensive) accept non-perfect pieces with larger tolerances (*cheap*).
- **Measurement Lab**: Measure those pieces accurately.
- **Computer**: Solve for adequate positioning of pieces such required field on beam is achieved.
- **Computer**: Calculate required mechanical *custom support* for pieces.
- **Factory**: 3D print the optimized custom support.
- **Factory**: Assemble permanent magnet that provides required fields.

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



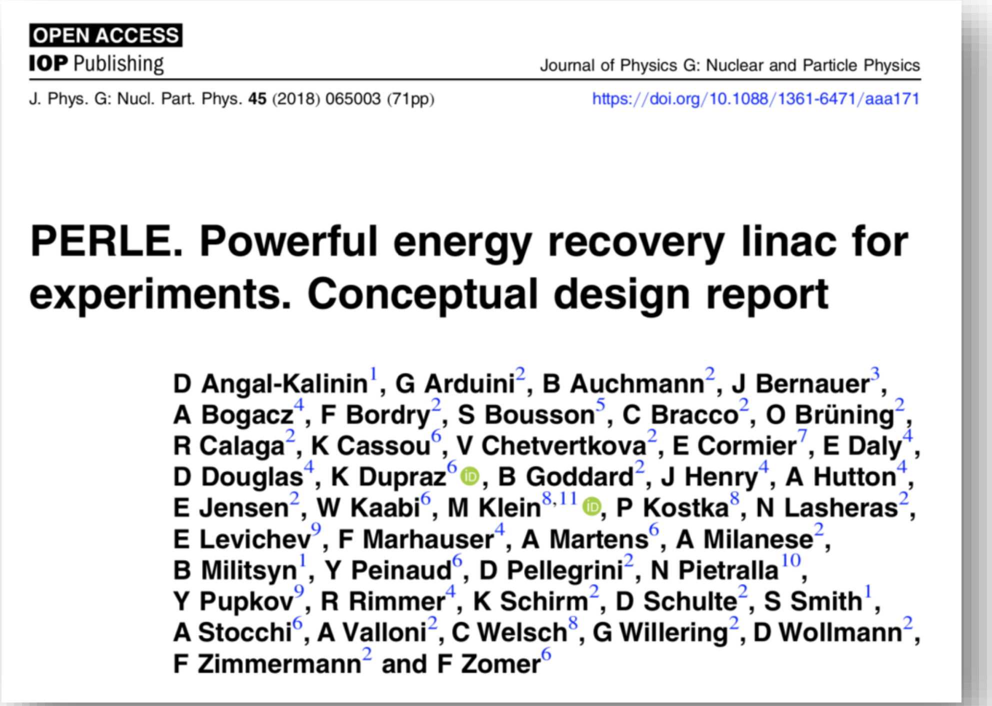
Material cost: **$1100**. No alignment better than 0.25 mm required anywhere. Assembled with mallet.

Trend: Energy Efficiency and Green Accelerators

Reduce energy consumption

For example, **ERL** (CBETA, PERLE, bERLinPro, ...), **permanent magnets, novel klystrons**:

- ERL concept proposed in 1965: M. Tigner, “A possible apparatus for electron clashing-beam experiments”. Nuovo Cim 37, 1228–1231 (1965).
- Re-use the energy stored in the beam – RF cavities for pumping energy into beam and for extracting it
- PERLE: 1 GeV energy recovery demonstration of a recirculating SC linear accelerator.



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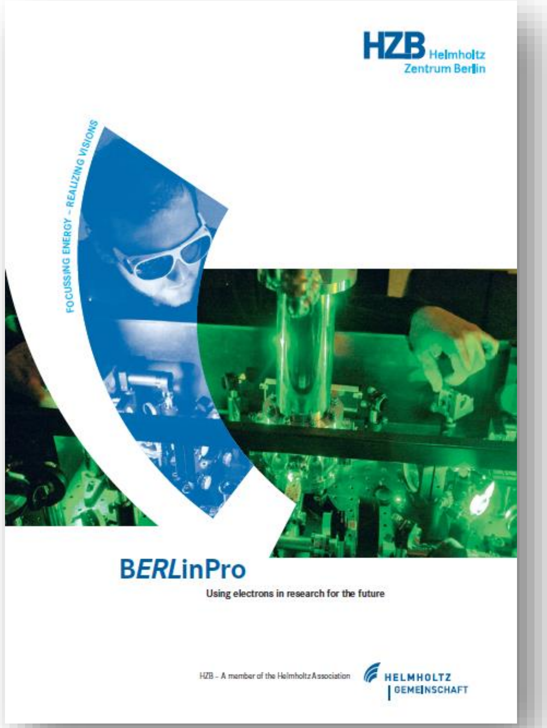
IOP Publishing — Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. **45** (2018) 065003 (71pp) https://doi.org/10.1088/1361-6471/aaa171

PERLE. Powerful energy recovery linac for experiments. Conceptual design report

D Angal-Kalinin[1], G Arduini[2], B Auchmann[2], J Bernauer[3], A Bogacz[4], F Bordry[2], S Bousson[5], C Bracco[2], O Brüning[2], R Calaga[2], K Cassou[6], V Chetvertkova[2], E Cormier[7], E Daly[4], D Douglas[4], K Dupraz[6], B Goddard[2], J Henry[4], A Hutton[4], E Jensen[2], W Kaabi[6], M Klein[8,11], P Kostka[8], N Lasheras[2], E Levichev[9], F Marhauser[4], A Martens[6], A Milanese[2], B Militsyn[1], Y Peinaud[6], D Pellegrini[2], N Pietralla[10], Y Pupkov[9], R Rimmer[4], K Schirm[2], D Schulte[2], S Smith[1], A Stocchi[6], A Valloni[2], C Welsch[8], G Willering[2], D Wollmann[2], F Zimmermann[2] and F Zomer[6]



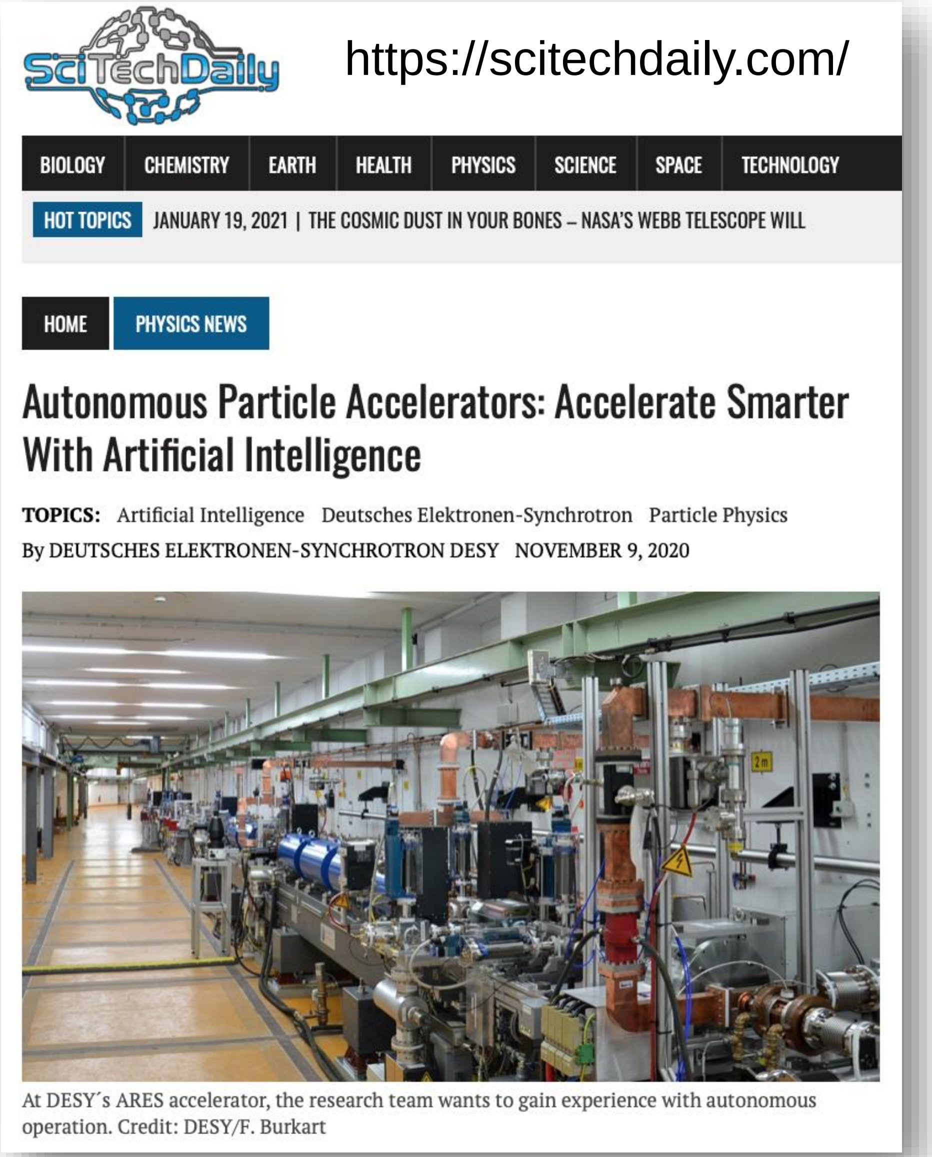
We heard about CEPC related work on **klystrons with improved efficiency**, see also impressive CERN-driven advances on klystron efficiency → mature technologies but still considerable room for improvement!

Trend: Machine Learning and Artificial Intelligence

Reduce energy consumption

Machine learning (SLAC, PSI, CERN), **automated commissioning** (ANL), and **autonomous accelerators** (DESY):

- At DESY in the SINBAD/ARES accelerator a team from DESY & KIT is testing methods towards an autonomous accelerator
- Exploits highly non-linear regime of ARES with limited number of degrees of freedom



Trend: Accelerators and Gravity

New territory for large colliders

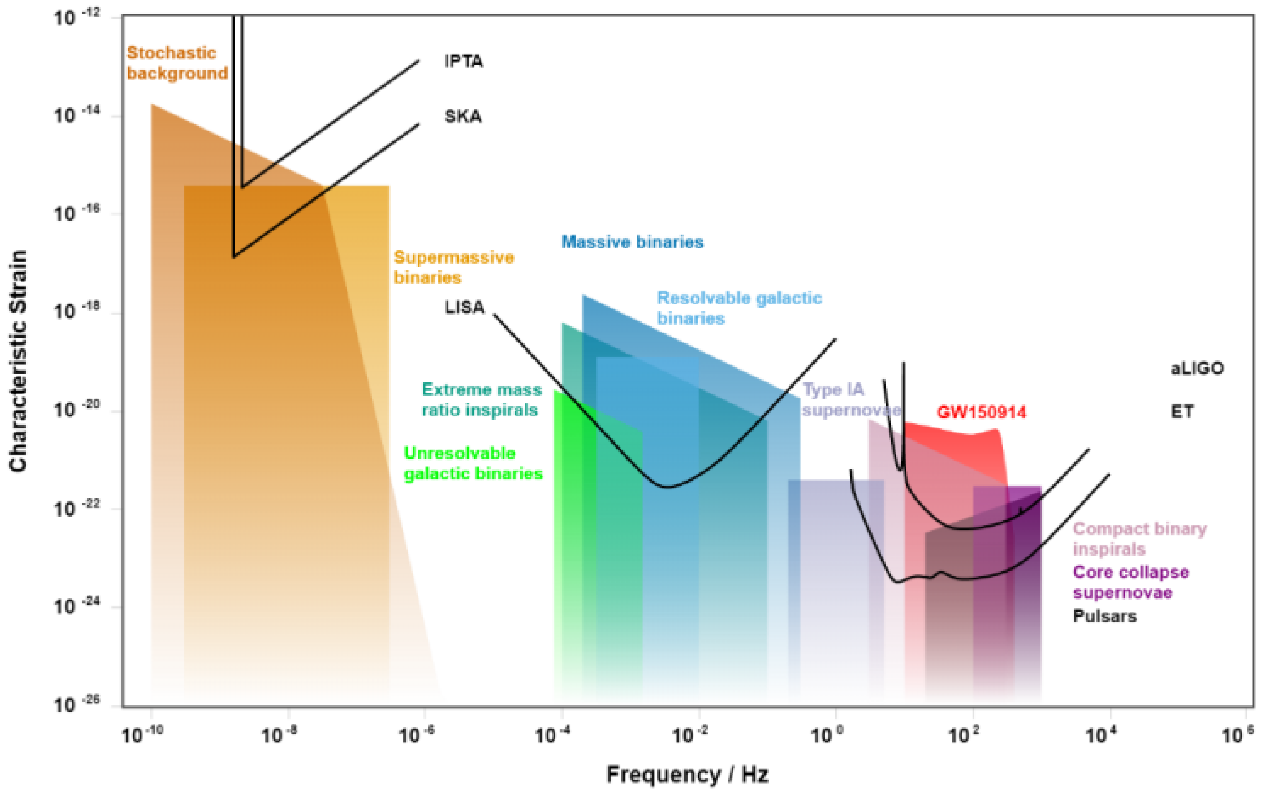
https://journals.aps.org/prd/abstract/10.1103/PhysRevD.102.122006

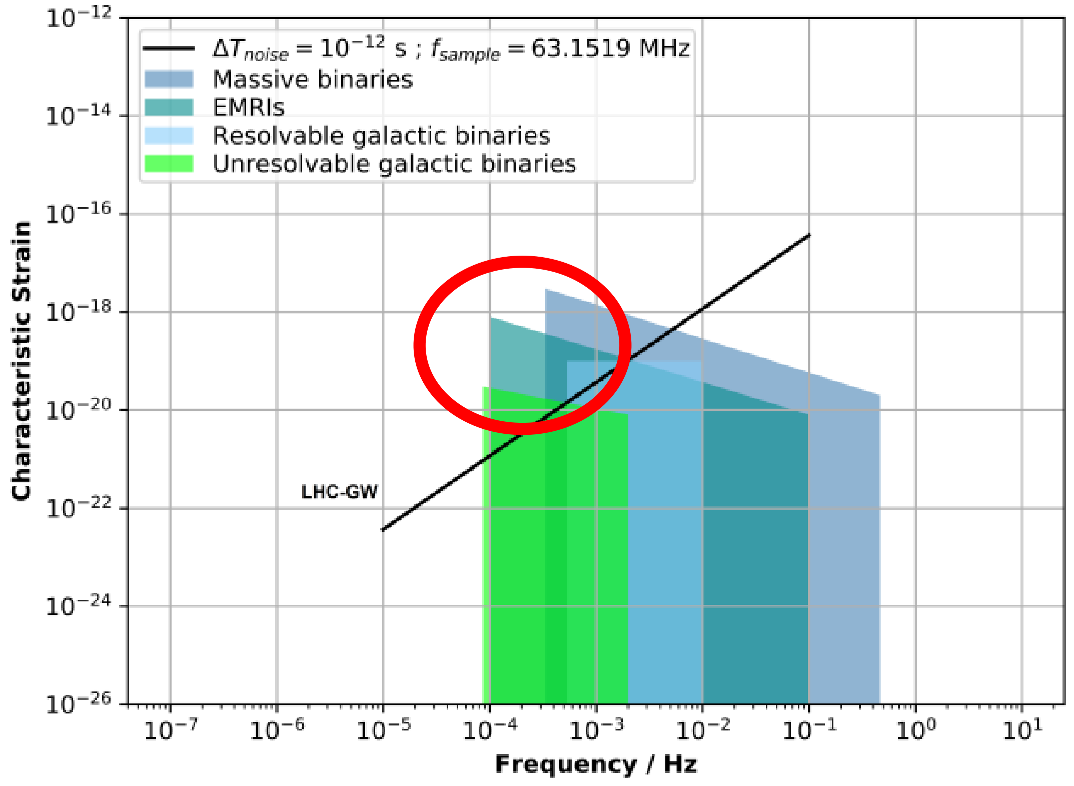
https://arxiv.org/pdf/2012.00529.pdf

Can a large storage ring like LHC detect gravitational waves?

Thanks to Frank Zimmermann

Rao et al, PRD 2020

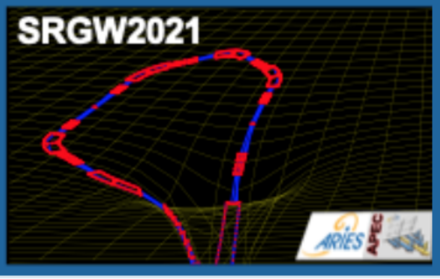




Trend: Accelerators and Gravity

New territory for large colliders

https://indico.cern.ch/event/982987/



SRGW2021 - ARIES WP6 Workshop: Storage Rings as Gravitational Wave Detectors

26 January 2021 to 31 March 2021
Europe/Zurich timezone

Search...

- Overview
- International Committee
- Registration
- Participant List
- Poster

ARIES WP6 Workshop: Storage Rings as Gravitational Wave Detectors "SRGW2021"

Starts 26 Jan 2021, 08:00
Ends 31 Mar 2021, 23:00
Europe/Zurich

Virtual Space

Frank Zimmermann
Giuliano Franchetti
Marco Zanetti

SRGW2021_resized.pdf
Zoom Link for SRGW2021 Sessions

Thanks to Frank Zimmermann

Trend: 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 = size (FCC-ee)

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)

Trend:

Muon Collider R&D

(material and input from Nadia Pastrone, Daniel Schulte, Mark Palmer)

- The recent update of the European strategy has pointed out muon colliders as subject of interest and R&D for the future of particle physics.
- This will likely result in the future proposal and implementation of an **international test or demonstrator facility for muon collider R&D**, too early to be defined now in detail.
- A working group has been formed to scientifically justify the investment into a demonstration programme before the next strategy process and to define what this programme should contain.
- The core test facility might be a cooling facility. There will certainly be prototype development and most likely beam tests.
- Full tests for both the proton and the positron-based sources for a muon collider might be excluded due to limited resources.
- Beam tests will be relevant since for example the LEMMA design currently uses collision beta-functions of 0.2 mm in both planes, which I only saw in the plasma collider proposals.

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

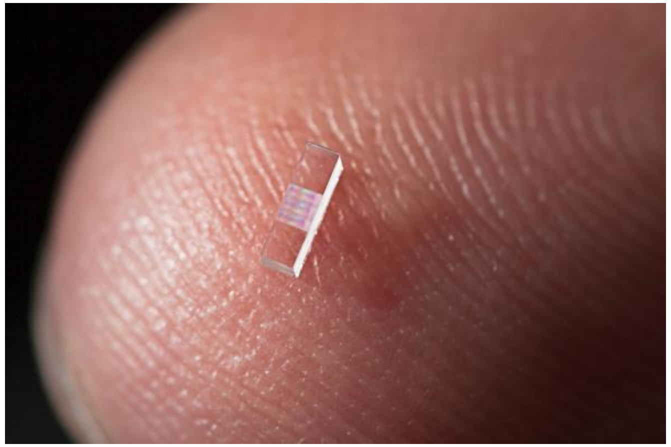
Increase length (ILC, CLIC)

Trend: 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**:



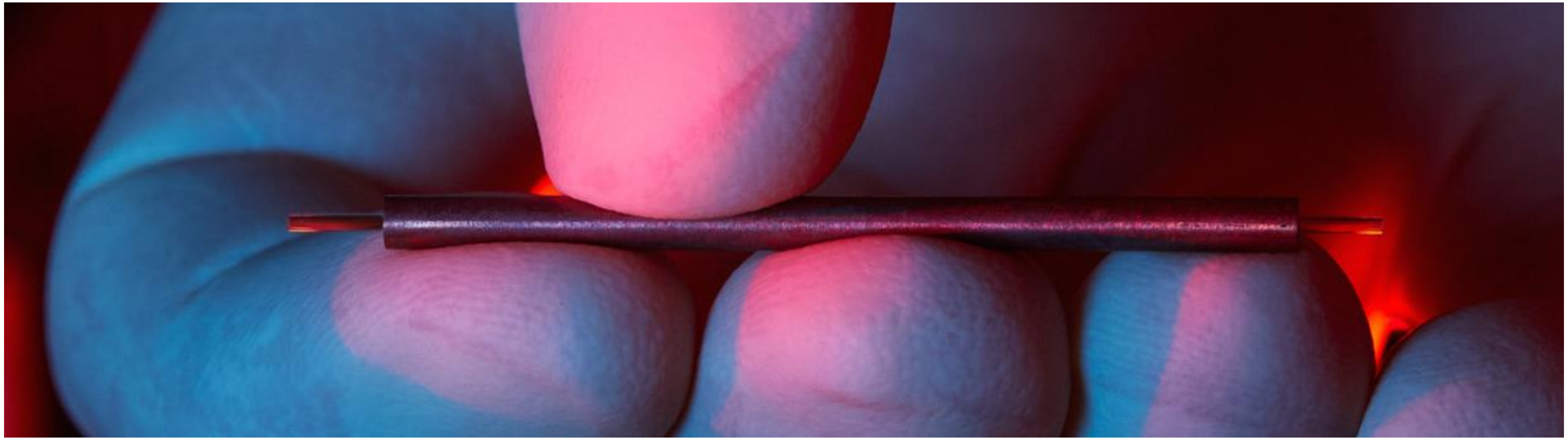
1 Microstructure Accelerator
Laser- or beam driven
Vacuum accelerators
Conventional field design

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*

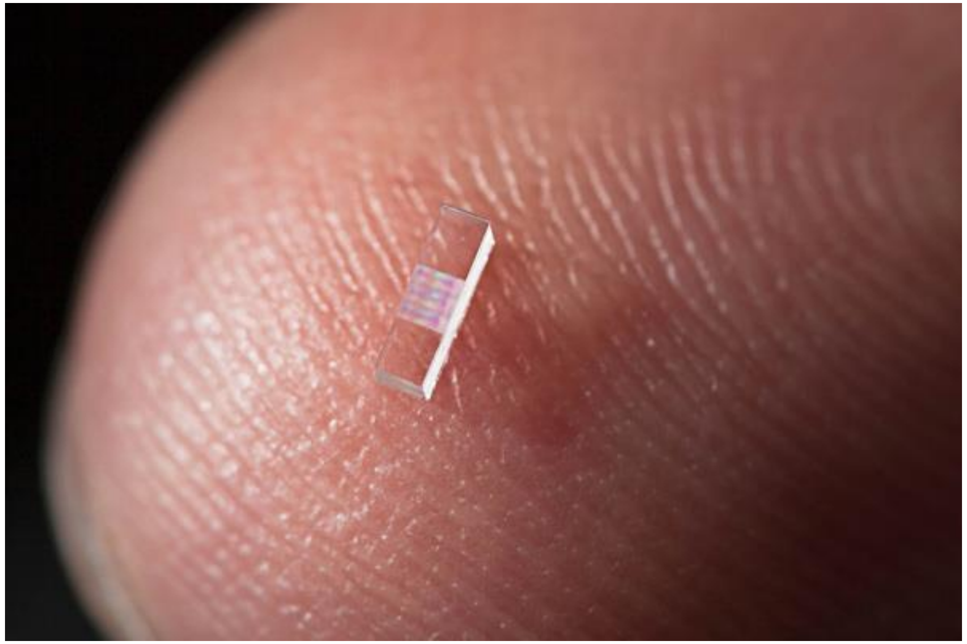


Laser-Driven Micro Structures (Vacuum) – 2

Vacuum dielectric accelerator

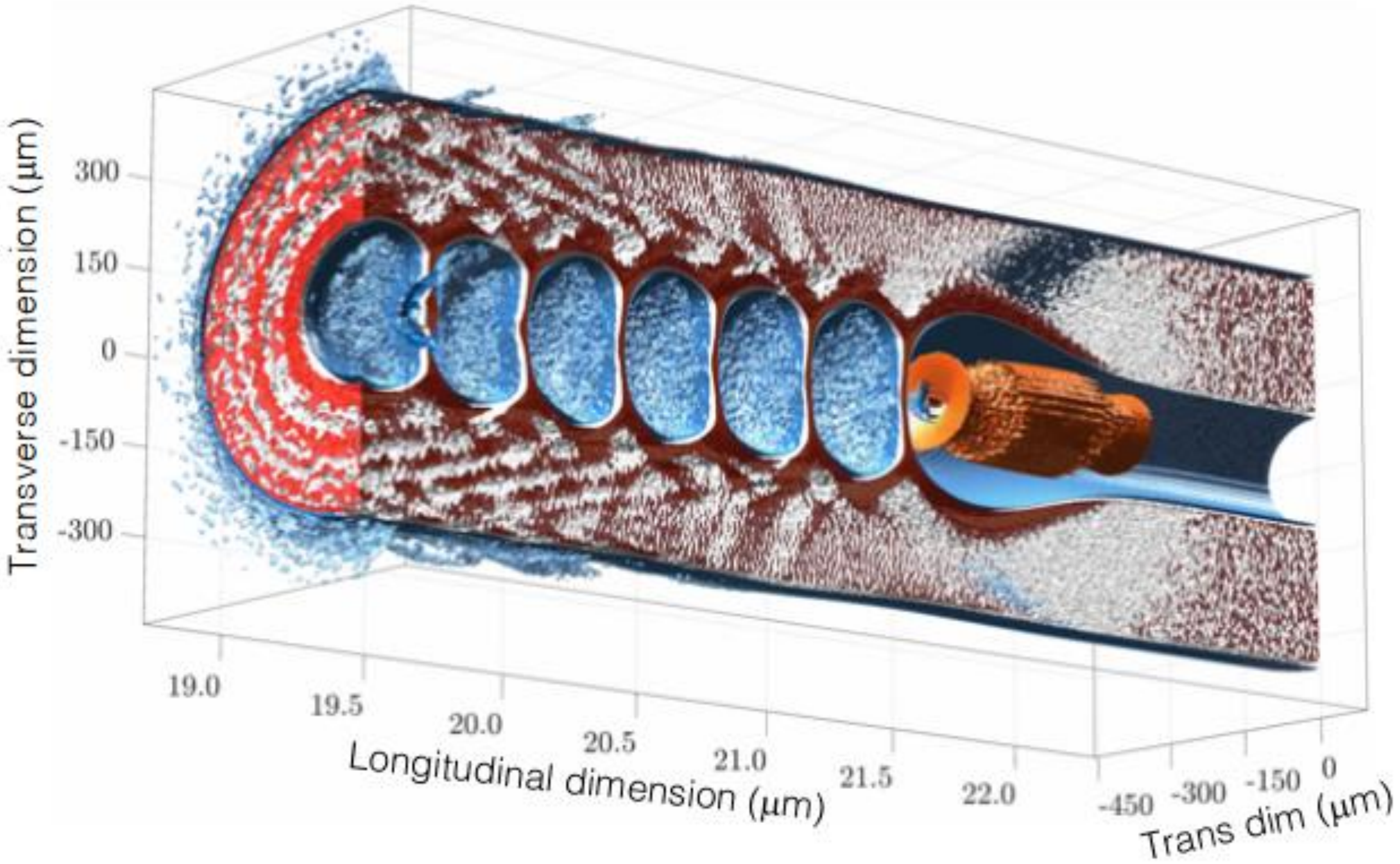
ACHIP
Accelerator on a Chip International Program

- **"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**



Nano Structures...

Figure from Akash Sahai

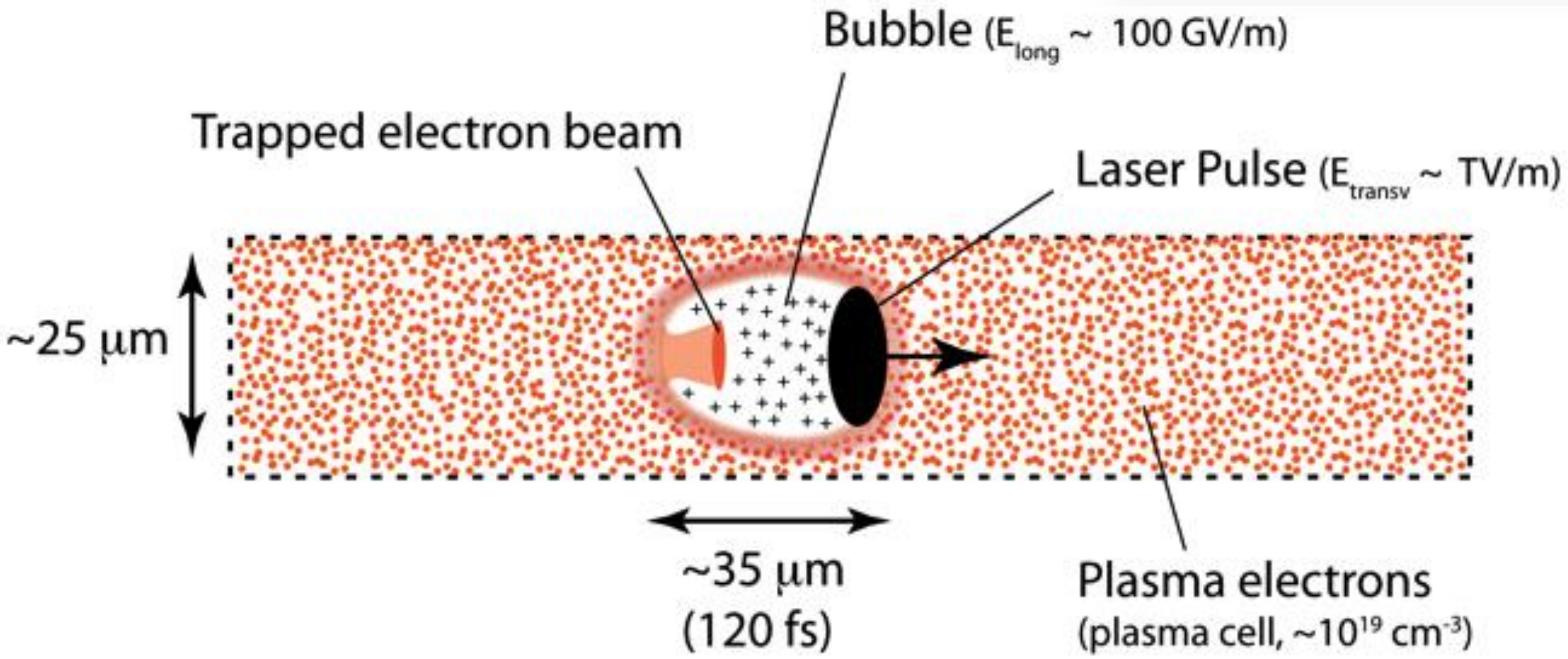


Small dimensions with particular promises and challenges

Trend: Laser Plasma-Acceleration

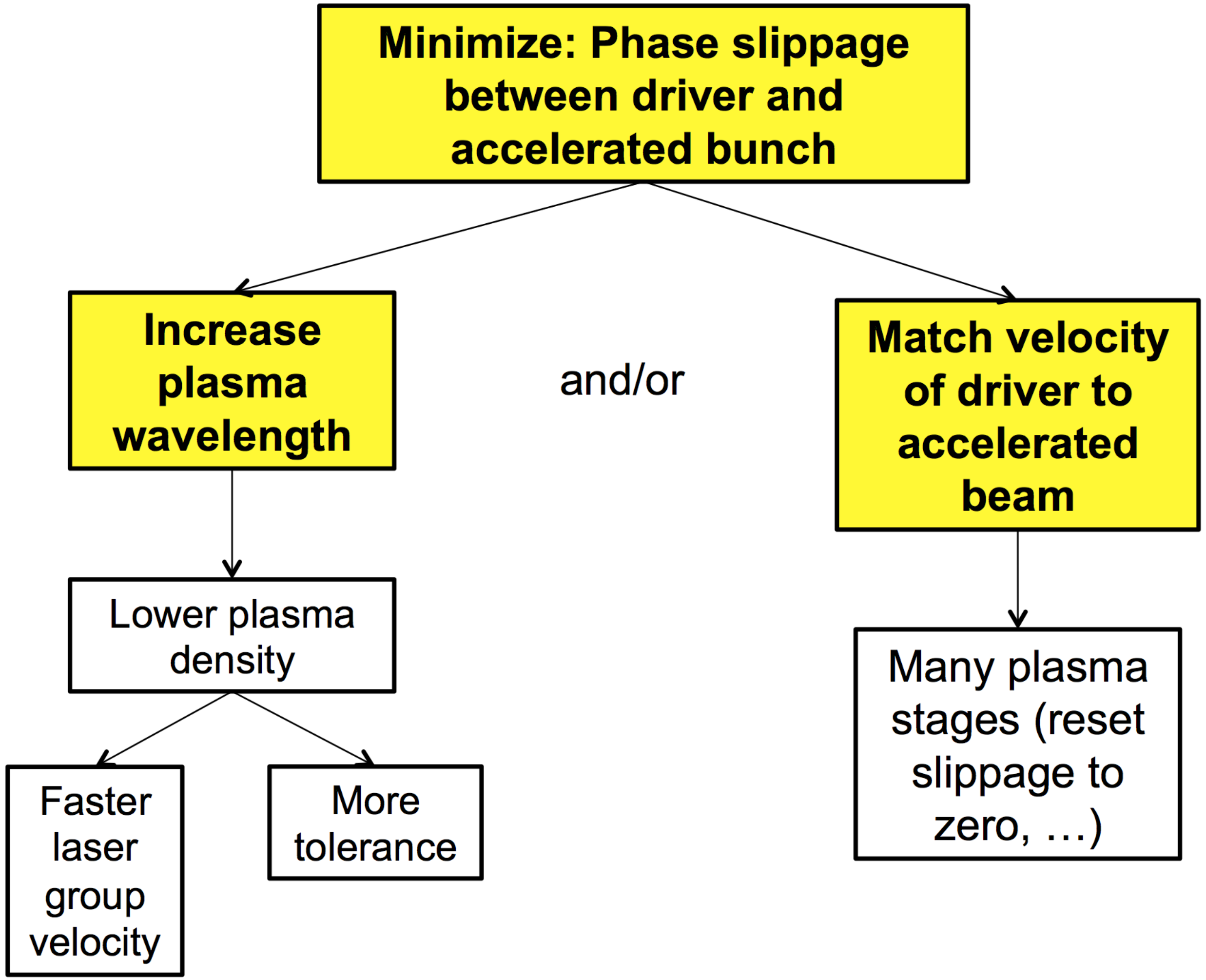
Internal injection

This accelerator fits into a human hair



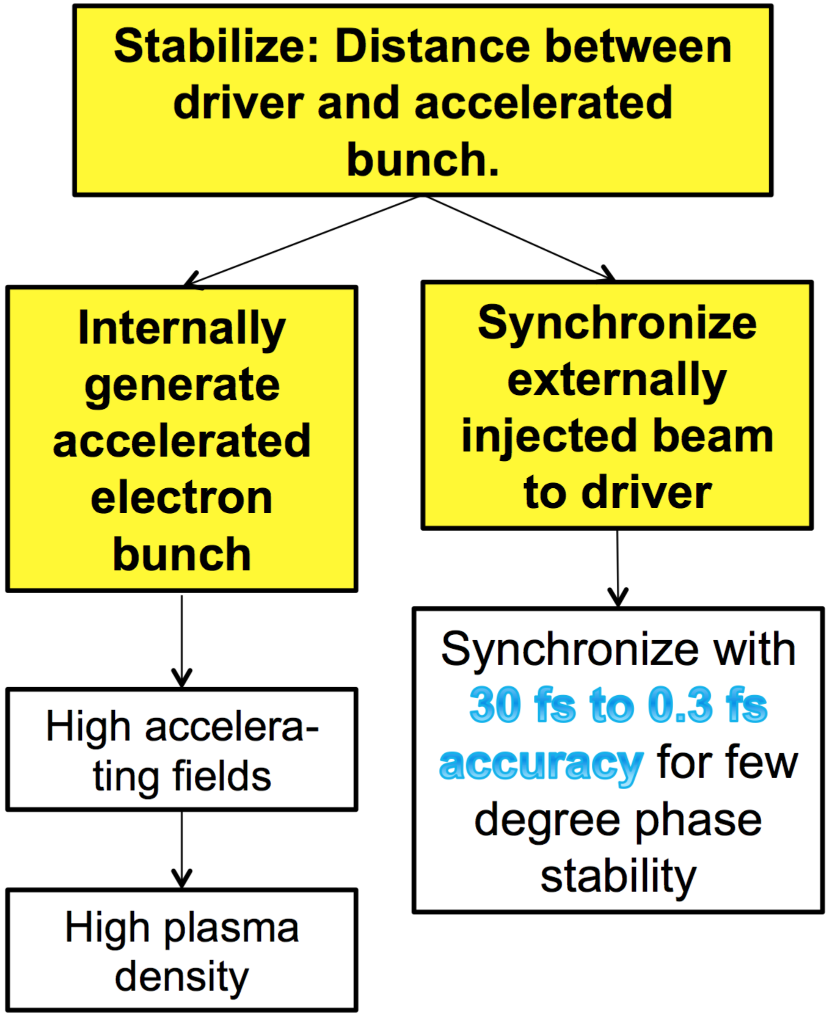
Optimization: Phase Slippage

Maximize distances over which we can accelerate



Stability/Reproducibility

Hit the same phase every time



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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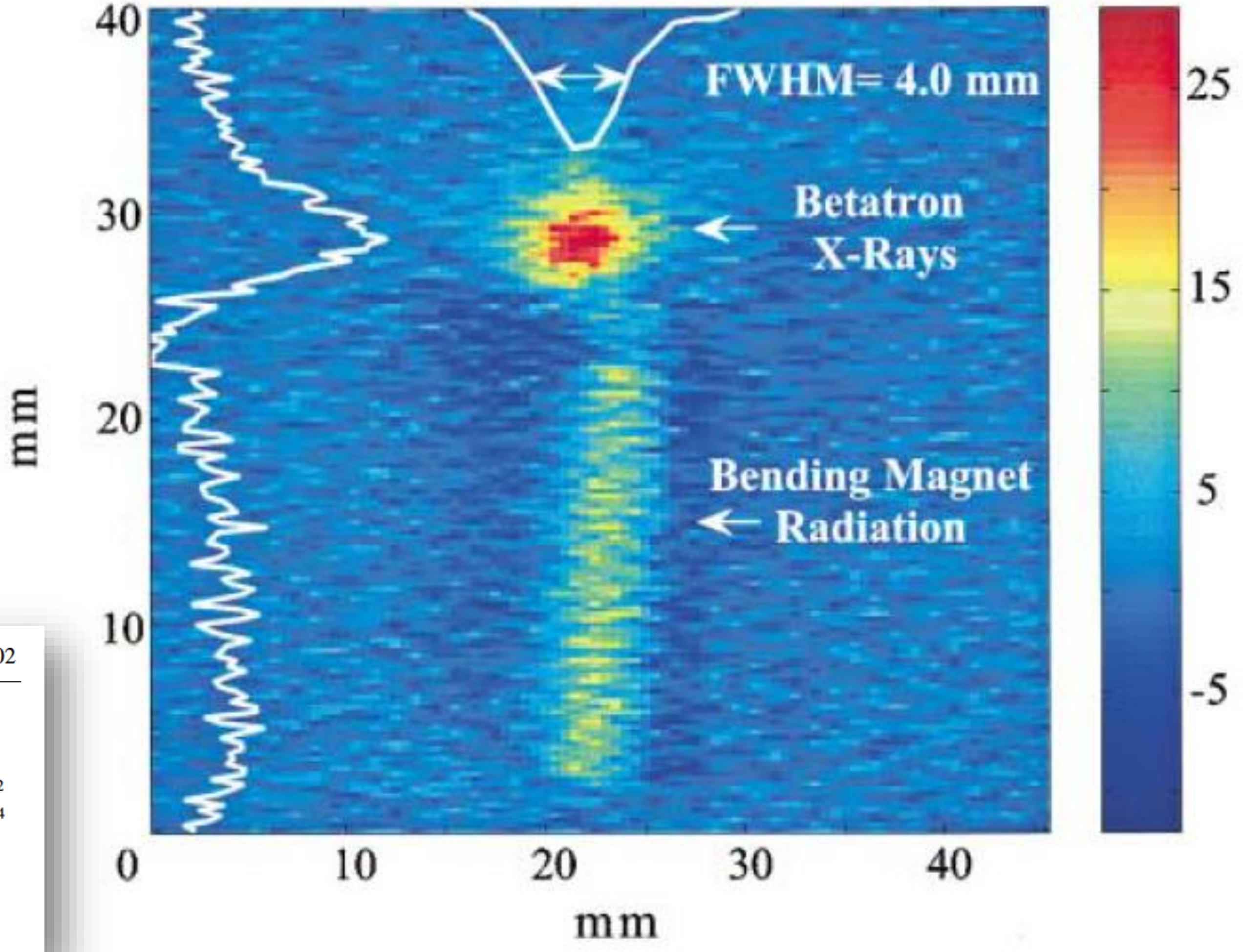
(Received 8 October 2001; published 19 March 2002)



Novel Acceleration R&D in Europe → Towards International Projects

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 in Europe.

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*

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

Conclusions

Long-term future

- The **long-term future is bright**: there will be plenty of opportunities as technology advances!
- Larger e+e- colliders are a future path, requiring **affordable technology** and **good energy efficiency**, both if circular or linear.
- **Advanced e+e- colliders** (plasma/dielectric/laser) are another possible path forward. Energy very promising but beam quality insufficient:
  - There are **now near future science applications outside HEP, e.g. FEL**. This can be the stepping stone towards a plasma linear collider.
  - Major projects going on, all including HEP aspects.
- **Muon colliders** and **future ep** machines are subject of intensifying R&D.
- In Europe **experts panels** are being set up to **propose accelerator R&D roadmaps** in follow-up to European strategy of particle physics. Stay tuned...

Thank you for your attention