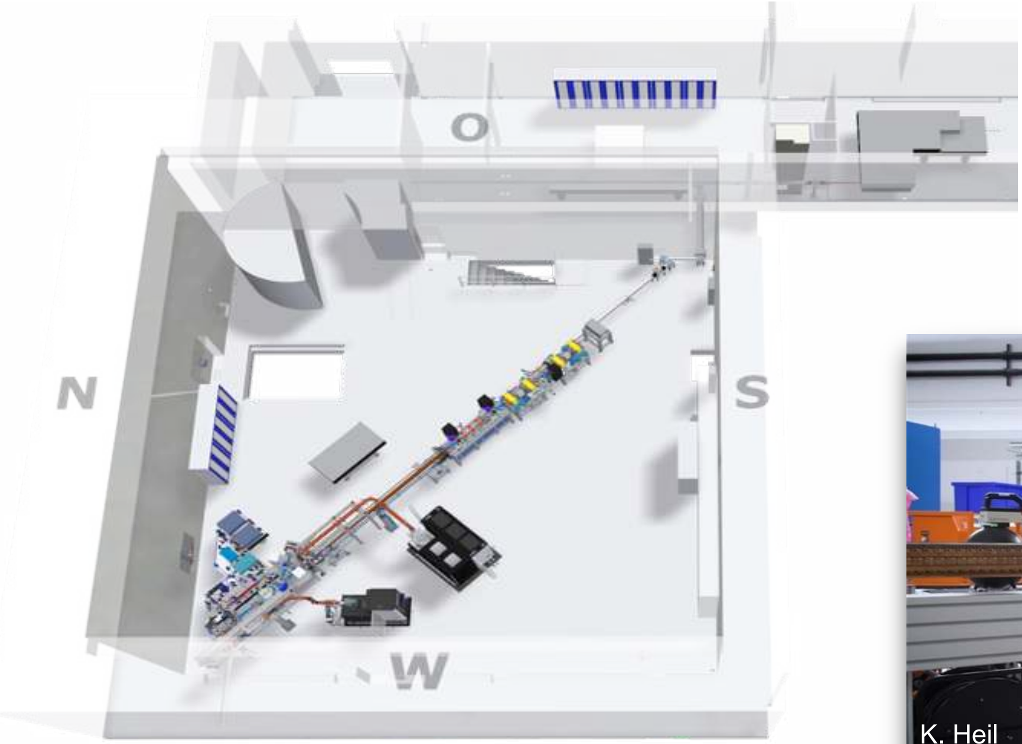
Karlsruhe Institute of Technology

Institute for Beam Physics and Technology

Particle Accelerator Physics

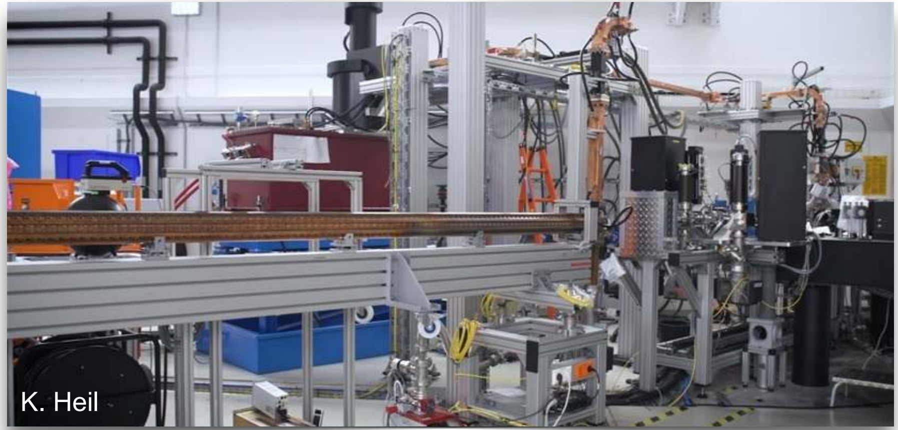
Anke-Susanne Müller, Axel Bernhard, Bastian Härer, Bennet Krasch, Nathan Ray

KIT accelerators: FLUTE



Ferninfrarot-Linac-und-Test-Experiment

- Linac-based test facility
- Energy: 42 MeV



KIT accelerators: KARA

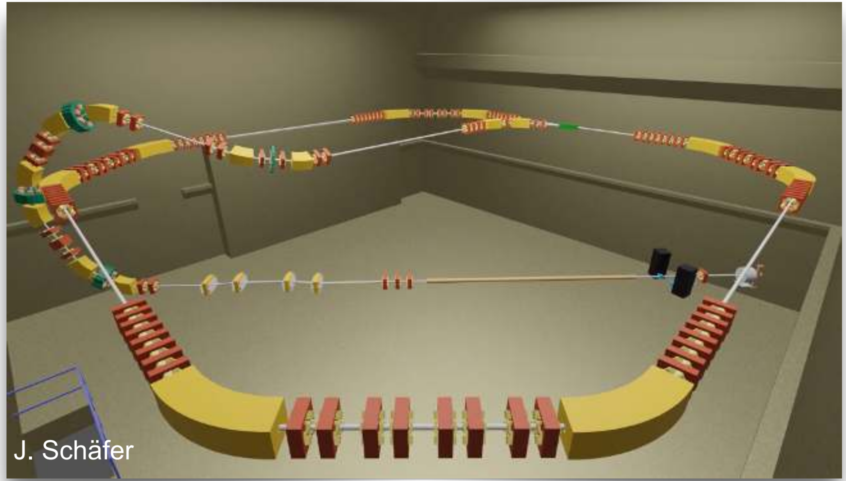

M. Breig

Karlsruhe Research Accelerator

- Synchrotron radiation source
- Accelerator test facility

- Energy: 2.5 GeV
- Circumference: 110 m

Future KIT accelerators

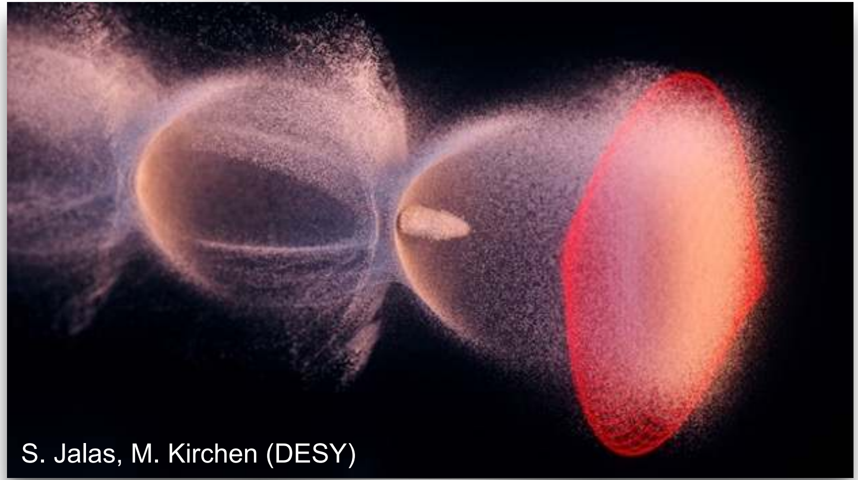

J. Schäfer

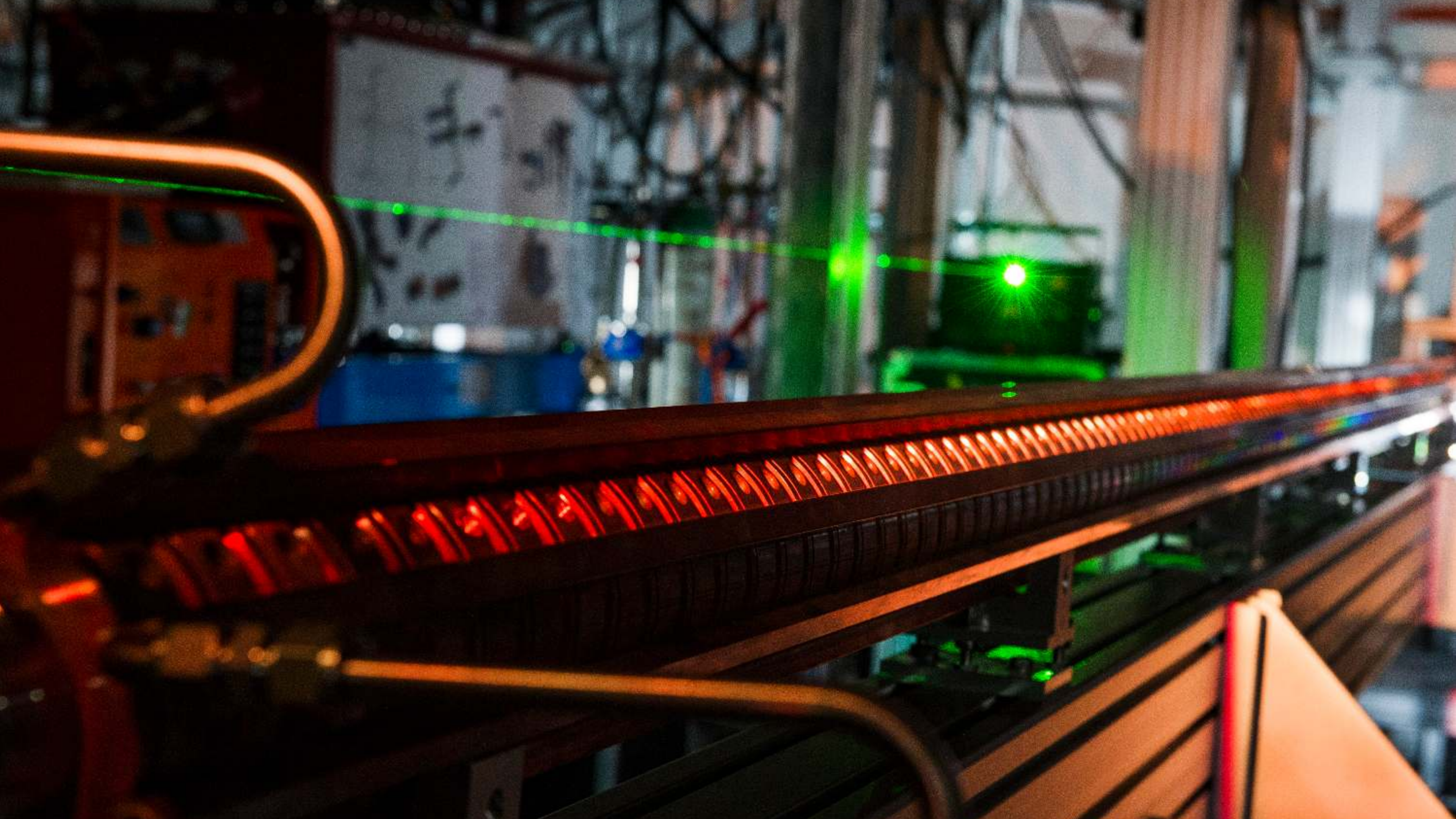
cSTART storage ring

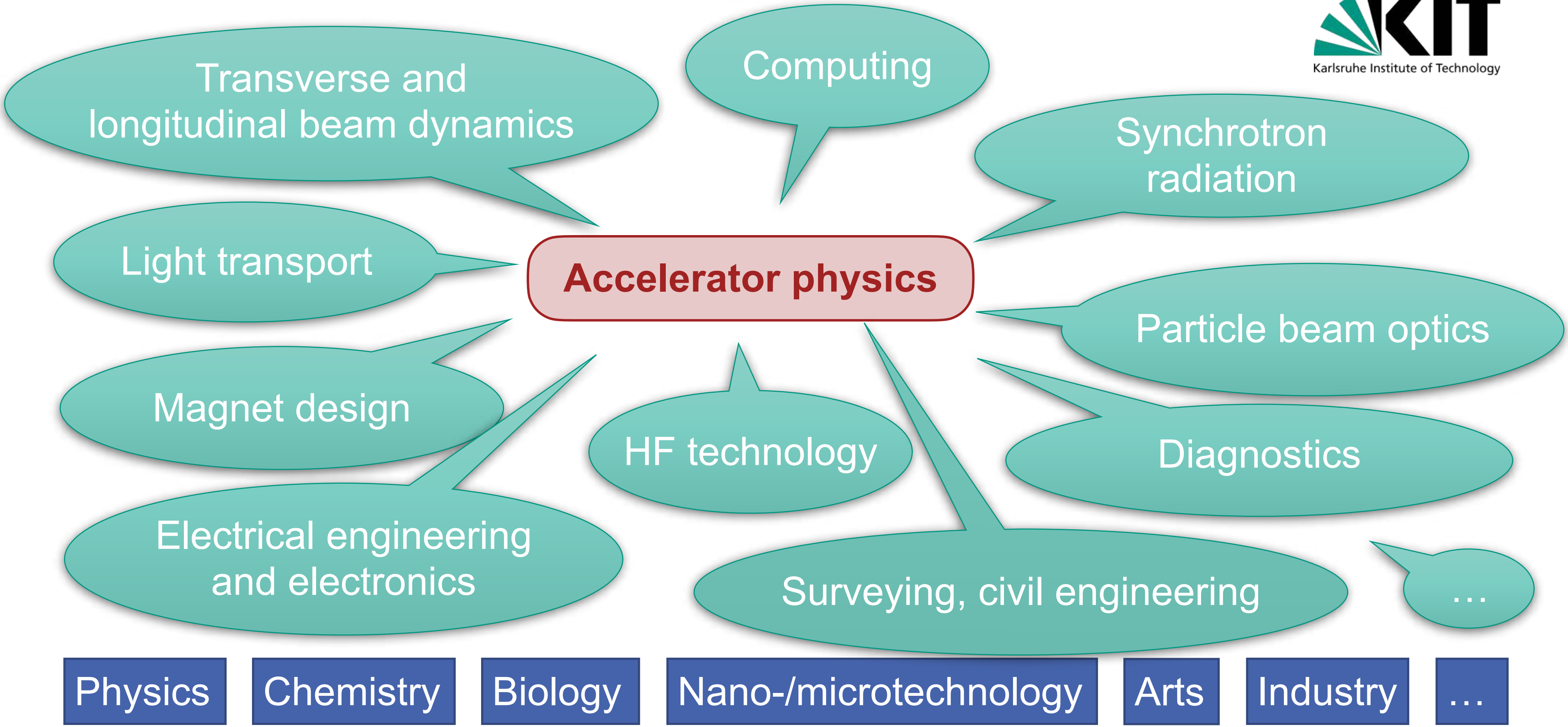
in procurement

laser in commissioning

laser plasma accelerator

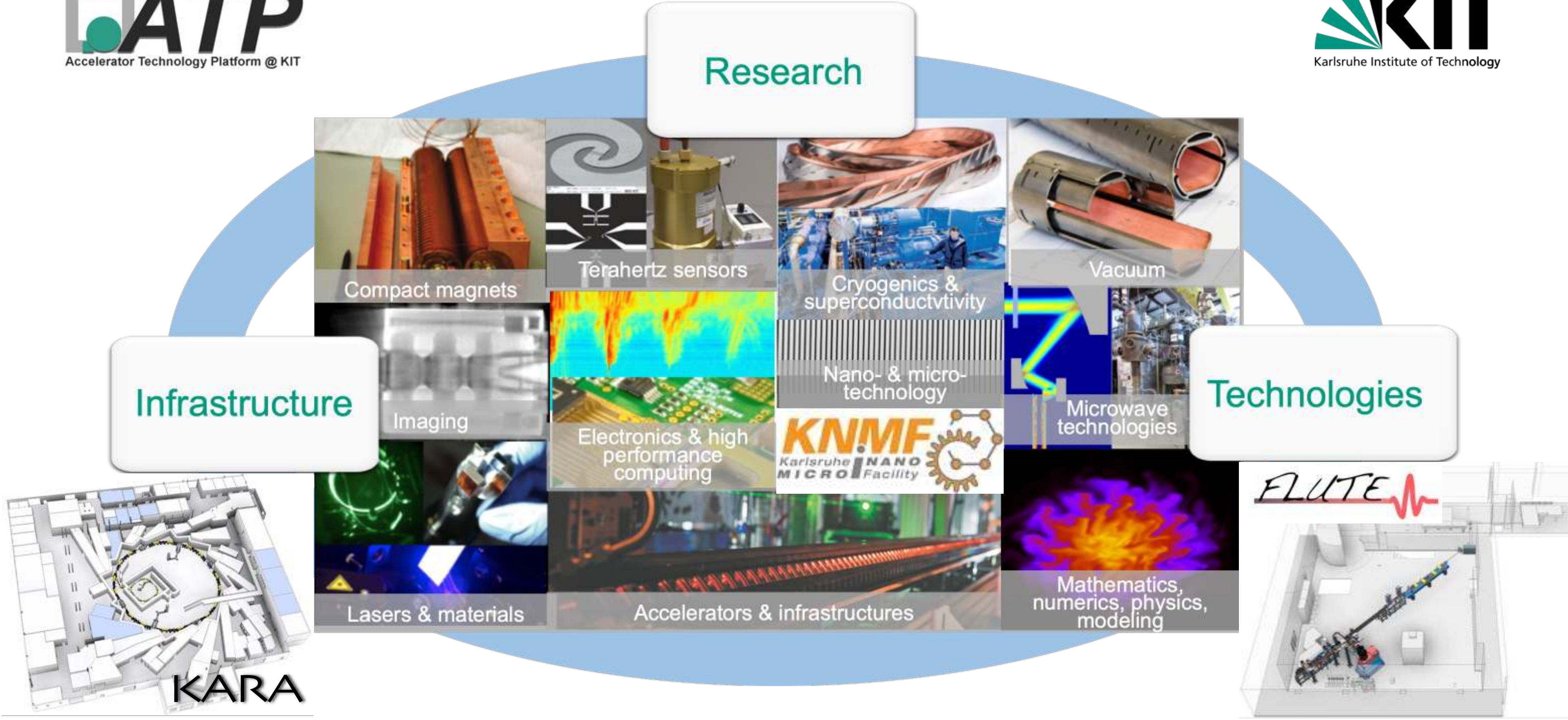

S. Jalas, M. Kirchen (DESY)

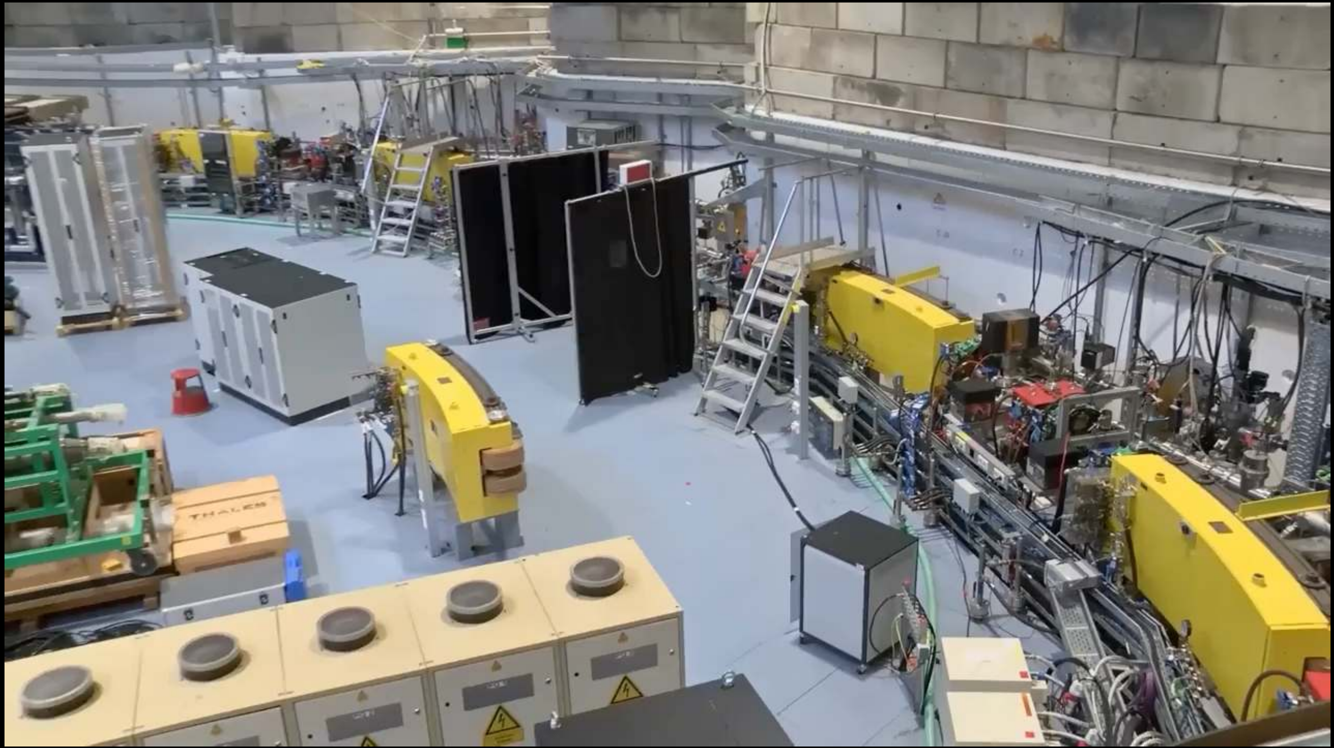



Accelerator physics
Transverse and longitudinal beam dynamics
Computing
Synchrotron radiation
Light transport
Particle beam optics
Magnet design
HF technology
Diagnostics
Electrical engineering and electronics
Surveying, civil engineering
…
Physics
Chemistry
Biology
Nano-/microtechnology
Arts
Industry
…

ATP
Accelerator Technology Platform @ KIT

KIT
Karlsruhe Institute of Technology

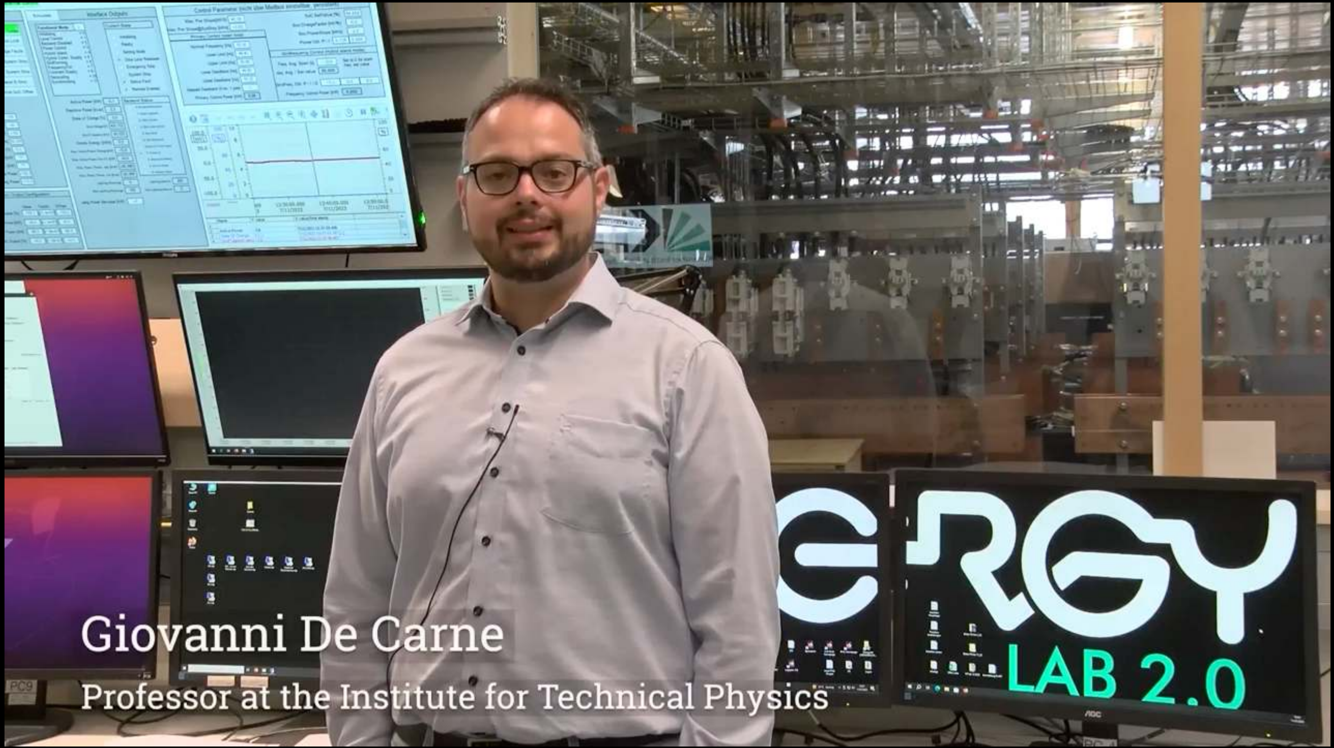




KARA
Karlsruhe Research Accelerators

KITTEN

https://publikationen.bibliothek.kit.edu/1000170555



KARA
Karlsruhe Research Accelerators

KITTEN

https://publikationen.bibliothek.kit.edu/1000170555

Source: home.cern/about/updates/2017/04/ancient-particle-accelerator-discovered-mars

Organizational information

- Modular course with integrated tutorials
  - 6 ECTS, Tue 8:00-9:30 h, Fr 9:45-11:15 h
- Certificate of achievement
  - Exercise sheets (6x): 50% in total, 30% of each sheet
  - Short presentation, case study
- Practical exercises (equivalent of 2 ECTS)
  - after the end of the semester
  - 1 day simulation practical
  - 1 day practical at the storage ring KARA
- Visit of the KIT accelerators (KARA, FLUTE): Date by arrangement
- Possible combinations for physics major and second major subject
  - Condensed Matter, Experimental Particle Physics and Astroparticle Physics, (Optics and Photonics)

Literature

- **Text books:**
  - K. Wille, *Physik der Teilchenbeschleuniger und Synchrotronstrahlungsquellen*, Teubner Studienbücher, 2. Auflage, 1996.
    bzw.: *The physics of particle accelerators*, Oxford University Press, 2005.
  - E.J.N. Wilson, *An Introduction to Particle Accelerators*, Oxford University Press, 2001.
  - H. Wiedemann, *Particle Accelerator Physics*, Springer-Verlag, 4th edition, 2015.
    directory of open access books: https://directory.doabooks.org/handle/20.500.12854/27959
  - P.J. Bryant, K. Johnsen, *The Principles of Circular Accelerators and Storage Rings*, Cambridge University Press, 1993.
  - J.D. Jackson, Klassische Elektrodynamik, De Gruyter Studium, 2014.

- **CERN Yellow Reports** & **CAS Proceedings:** https://cas.web.cern.ch/previous-schools
  - Introduction to Accelerator Physics, Jyvaskyla, Finland, 1992, CERN-94-01-V-1, CERN-94-01-V-2
  - Advanced Accelerator Physics, Zeuthen, Germany, 2003, CERN-2006-002
  - Advanced Accelerator Physics, Trondheim, Norway, 2013, CERN-2014-009

- **Image archives:**
  - CERN photo database: https://cds.cern.ch/collection/Photos?ln=de
  - KIT Bibliothek, former Forschungszentrum Karlsruhe

The illustrations in this lecture are mostly taken from the sources mentioned above.

Overview of this lecture

- Basic types of accelerators and their applications
- Physics of synchrotron radiation, wigglers and undulators
- Beam optics and beam dynamics
- Magnet technology for accelerators and synchrotron radiation sources
- Measurement and control of beam parameters
- Free-electron lasers
- Performance limits of accelerators
- New technologies, current & future projects

I - Types of particle accelerators

- Application of accelerators
- Electrostatic accelerators
  - Cockcroft-Walton, Van-de-Graaff, …
- Linear accelerators (linacs)
- Circular accelerators
  - Betatron
  - Cyclotron
  - Microtron
  - Synchrotron
  - Storage rings & colliders

CERN

Einsatzgebiete von Beschleunigern

Forschung

Kosmische Strahlen

Synchrotron-strahlung

Teilchenphysik

http://cds.cern.ch

Tumortherapie

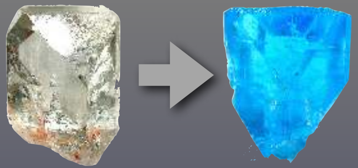
HIT, A. Peters, IPAC 2012

Bildgebung

T. van de Kamp et al., DOI: 10.1038/ s41467-018-05654-y

Lithographie

Strahlenvernetzung & farbl. Veränderung



Rob Lavinsky, iRocks.com CC-BY-SA-3.0

https://commons.wikimedia.org/w/index.php?curid=10127470

Medizin

Tiernahrung

Lebensmittel-bestrahlung

Schmuck

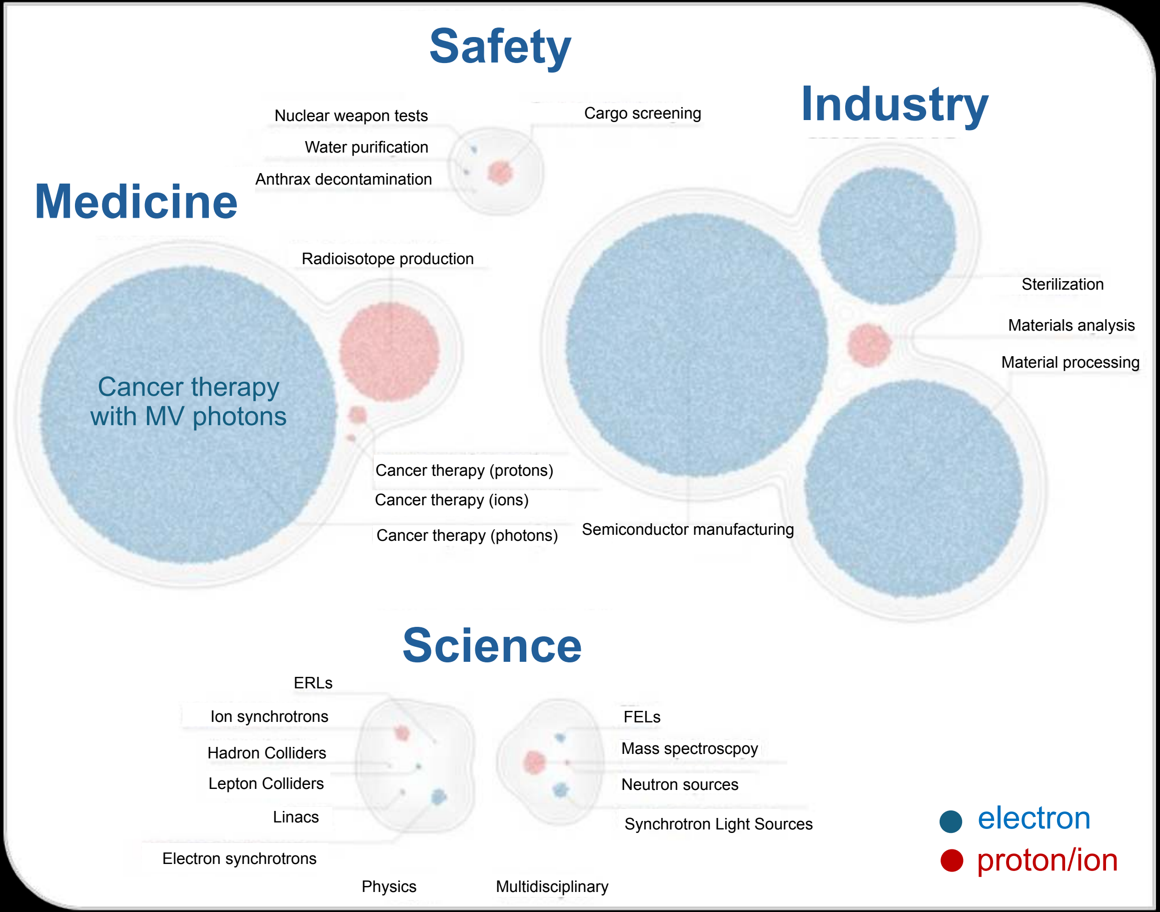
Kabel / Elektro-bauteile

Fahrzeug-industrie

Accelerators of the world

Only a small fraction of the world's accelerators serve solely science.

Most of the systems are used in industry and medicine.



D. Rathje / KfB

Karlsruher Institut für Technologie

https://videos.cern.ch/record/1611721

Nonlinear multi-particle dynamics in external fields

or

The other reasons we do accelerator physics

Why we study physics with an accelerator

…. apart from photon science and particle physics:

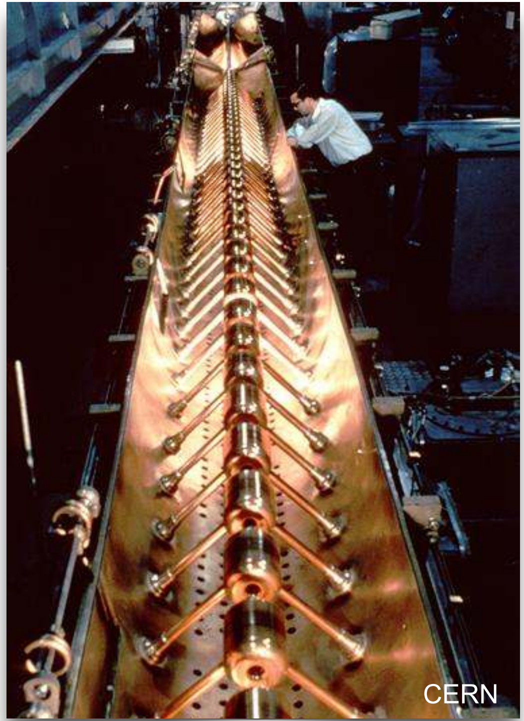
- Controlled test environment for fundamental physics offering
  - Extremely high electric fields (up to GV/m)
  - Short-duration excitiation with definable pulse shapes

- Multi-photon processes
- Nonlinear and ultrafast science
- Transient phenomena

→ ***non-equilibrium physics***

…from atomic to macrosopic scale.

Linear accelerators (Linacs)



Reference: https://cds.cern.ch/record/39283

Reference: https://cds.cern.ch/record/2260707

Large-scale synchrotrons

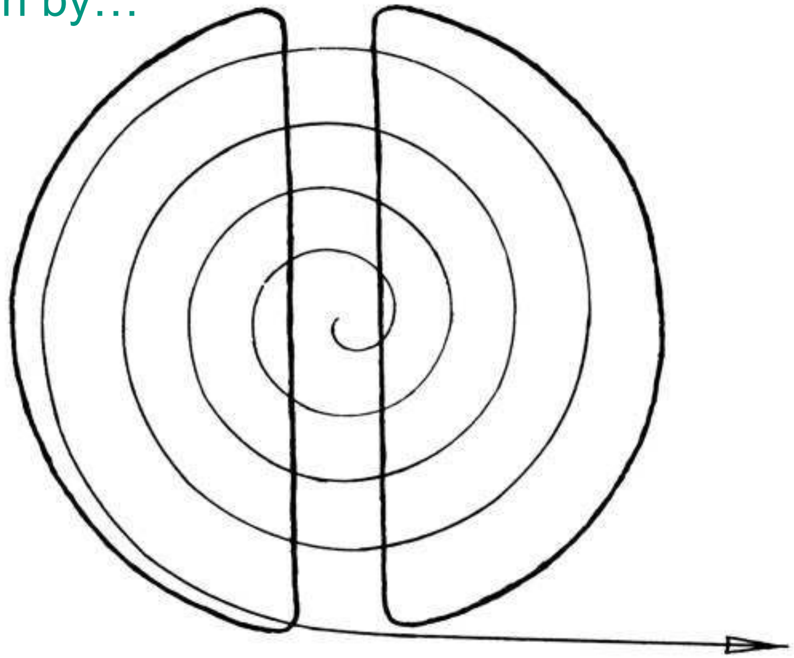
Maximilien Brice (CERN)


CERN

Reference: https://supernova.eso.org/exhibition/images/cern-aerial-cc/

Das Zyklotron humoristisch

The cyclotron, as seen by…

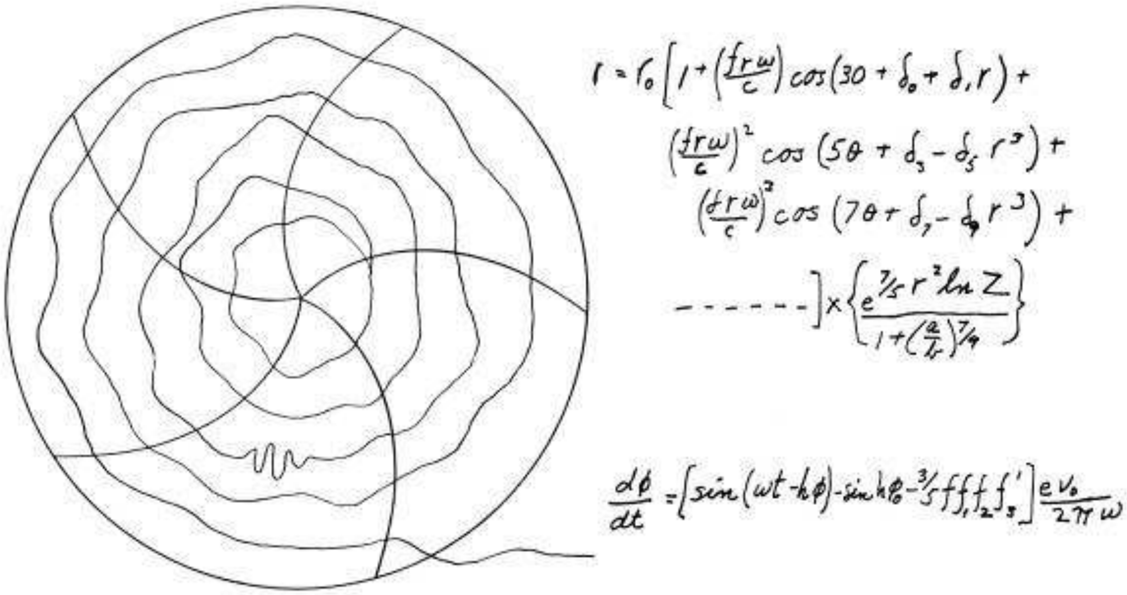


… the inventor.

David L. Judd and Ron MacKenzie: https://people.nscl.msu.edu/~lund/msu/phy905_2018/lec_lund/judd_cartoon.pdf,

Das Zyklotron humoristisch

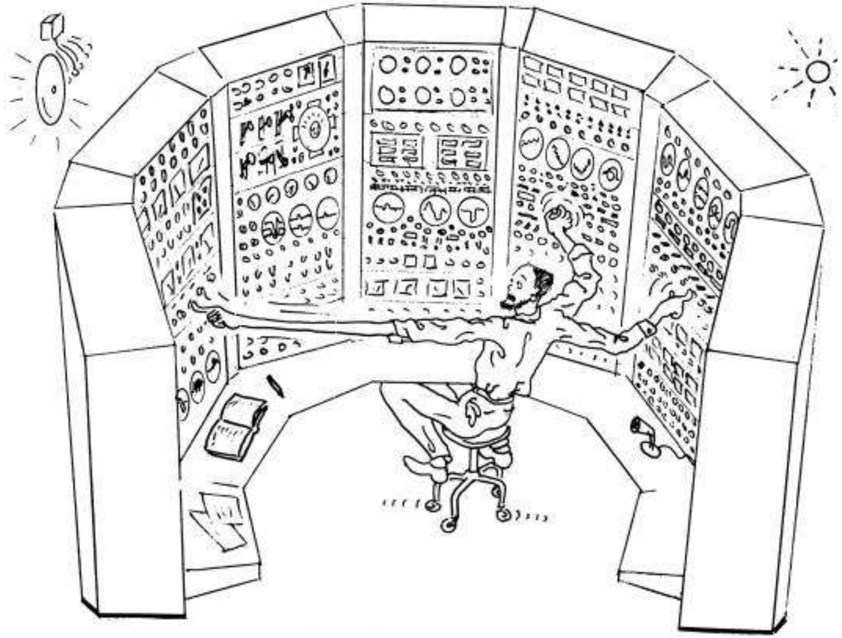
The cyclotron, as seen by…



… the theoretical physicist.

Das Zyklotron humoristisch

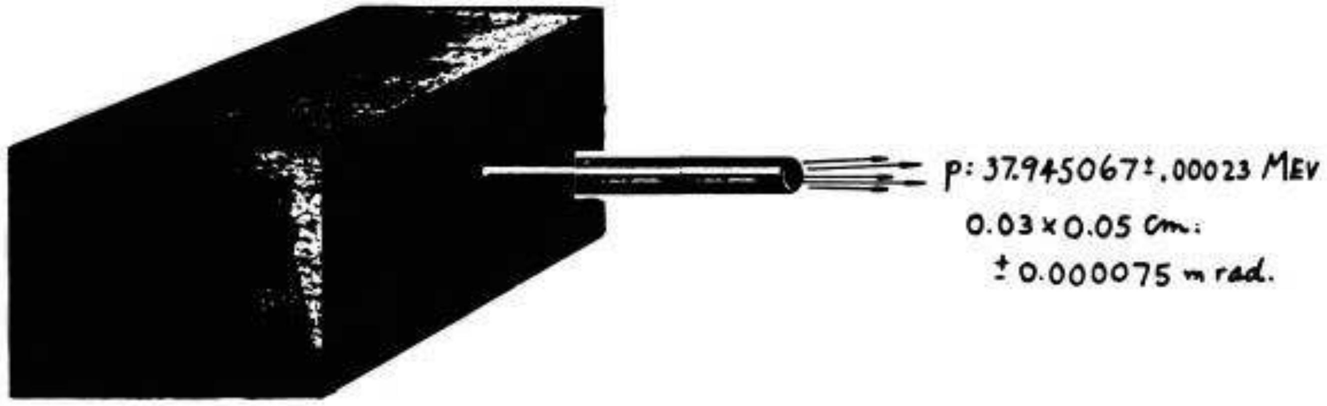
The cyclotron, as seen by…



… the operator.

Das Zyklotron humoristisch

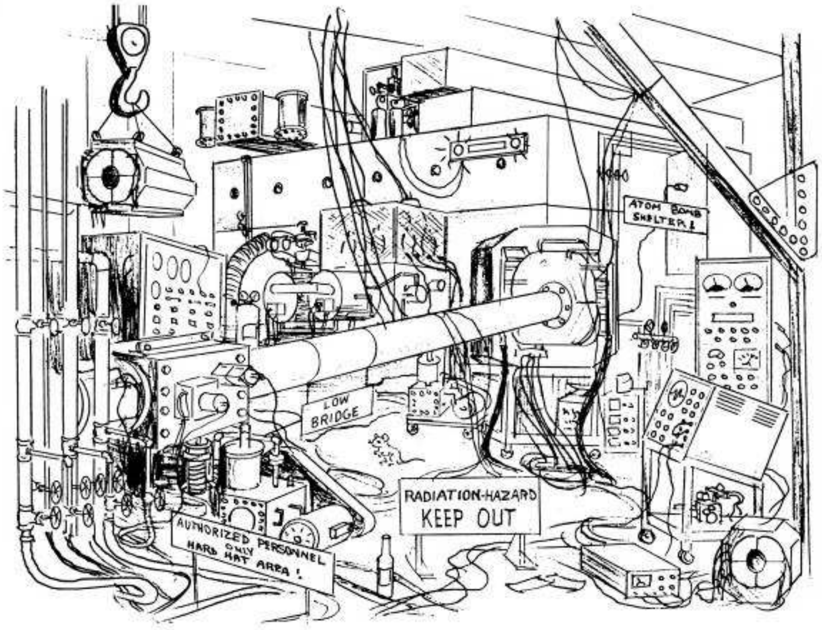
The cyclotron, as seen by…



… the experimental physicist.

Das Zyklotron humoristisch

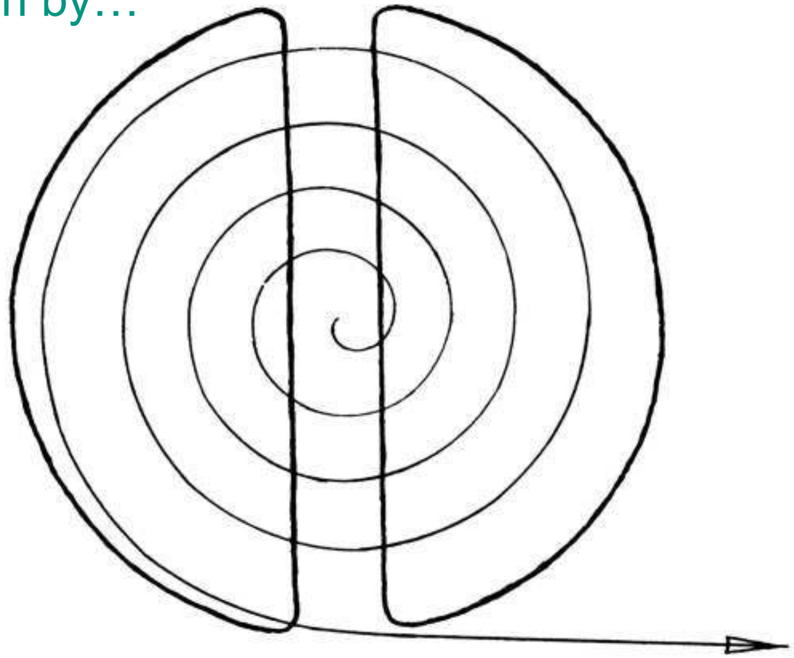
The cyclotron, as seen by…



… the visitor.

Das Zyklotron humoristisch

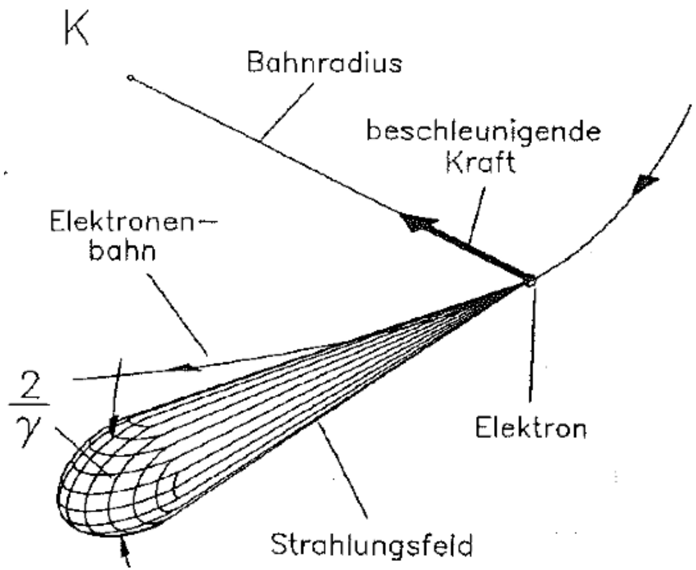
The cyclotron, as seen by…



… the student.

II - Synchrotron radiation, wigglers & undulators

- Electrodynamics of moving point charges
  - Radiant charges
  - Energy loss
- Properties of normal synchrotron and undulator radiation
  - Synchrotron radiation spectrum
  - Angular distribution



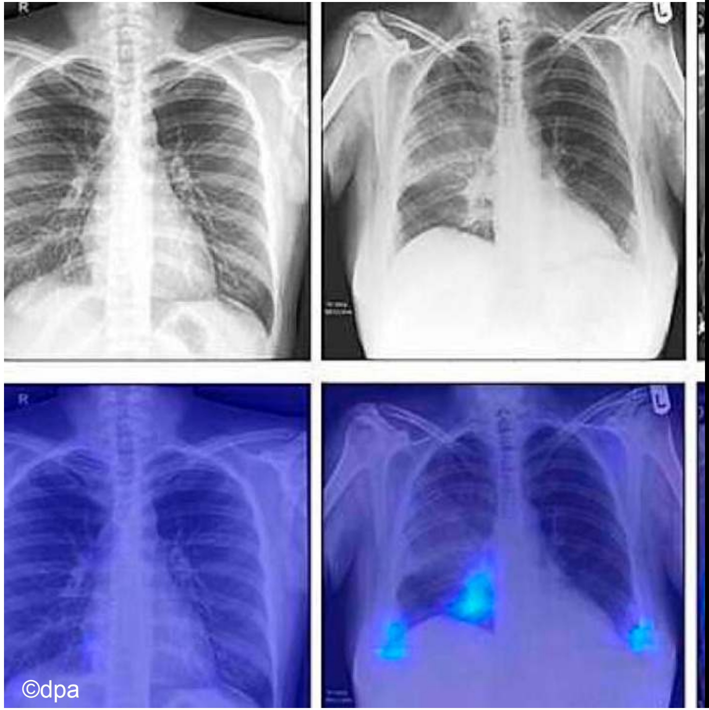
Impact of Brilliance

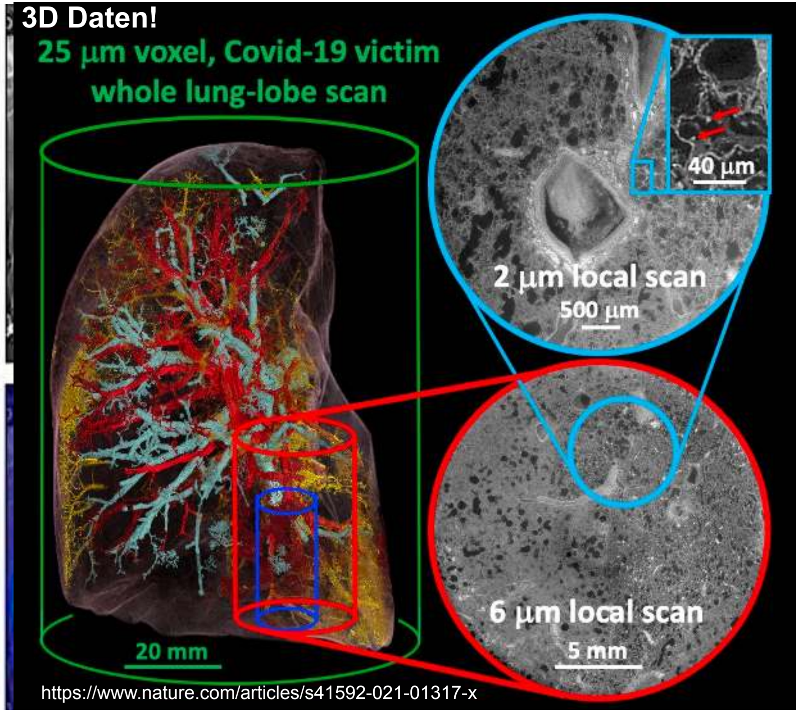
Healthy | state of the art X-ray image | Covid19

X-ray tomography at a synchrotron (ESRF)

Raw data: Only intensity (single frequency)

Computer analysis



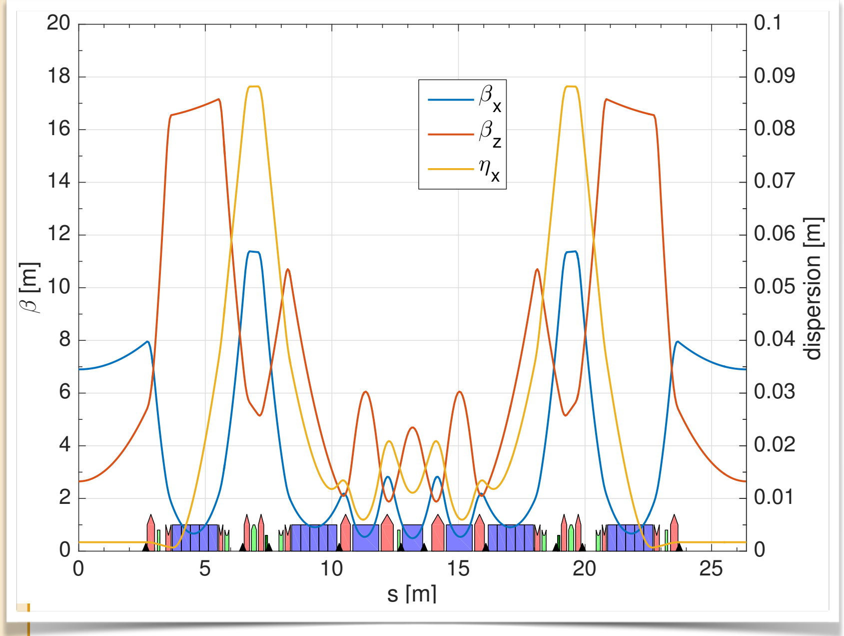


III - Beam optics & beam dynamics

- Basics of transverse beam optics
  - Magnetic lenses
  - Equations of motion and transfer matrices
  - Optic functions and emittance
  - Tune, chromaticity and resonances
  - Dispersion and beam size

- Basics of longitudinal beam dynamics
  - Longitudinal oscillations
  - RF buckets and stable phase

- Oscillations and damping
- Many-particle systems



Accelerators are precision instruments

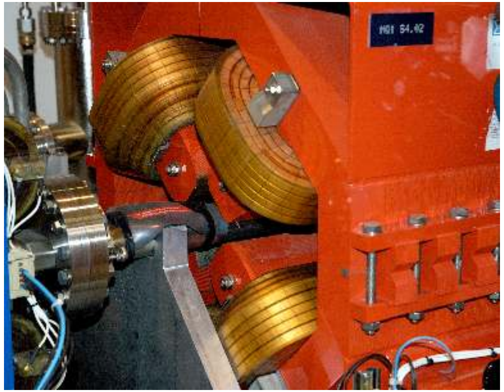
They are tuned

IV - Magnet technology

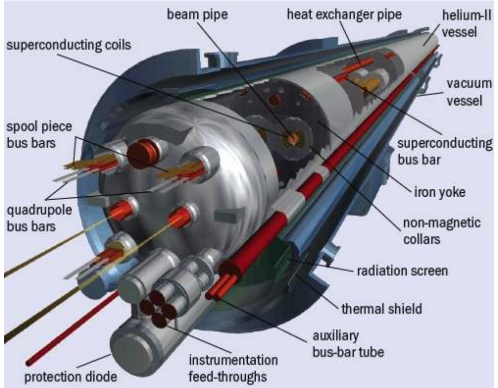
- Accelerator magnets
  - Requirements and specification
  - Higher orders
    - Errors and corrections
  - …

- Special magnets for synchrotron radiation sources
  - Wigglers
  - Undulators
  - …

Magnet technology

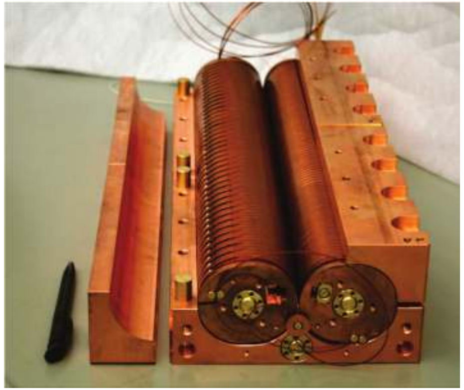


Bildquelle: KIT-IBPT



Bildquelle: CERN

Bildquelle: APS



Bildquelle: V. Afonso Rodríquez

V - Measurement and control of beam parameters

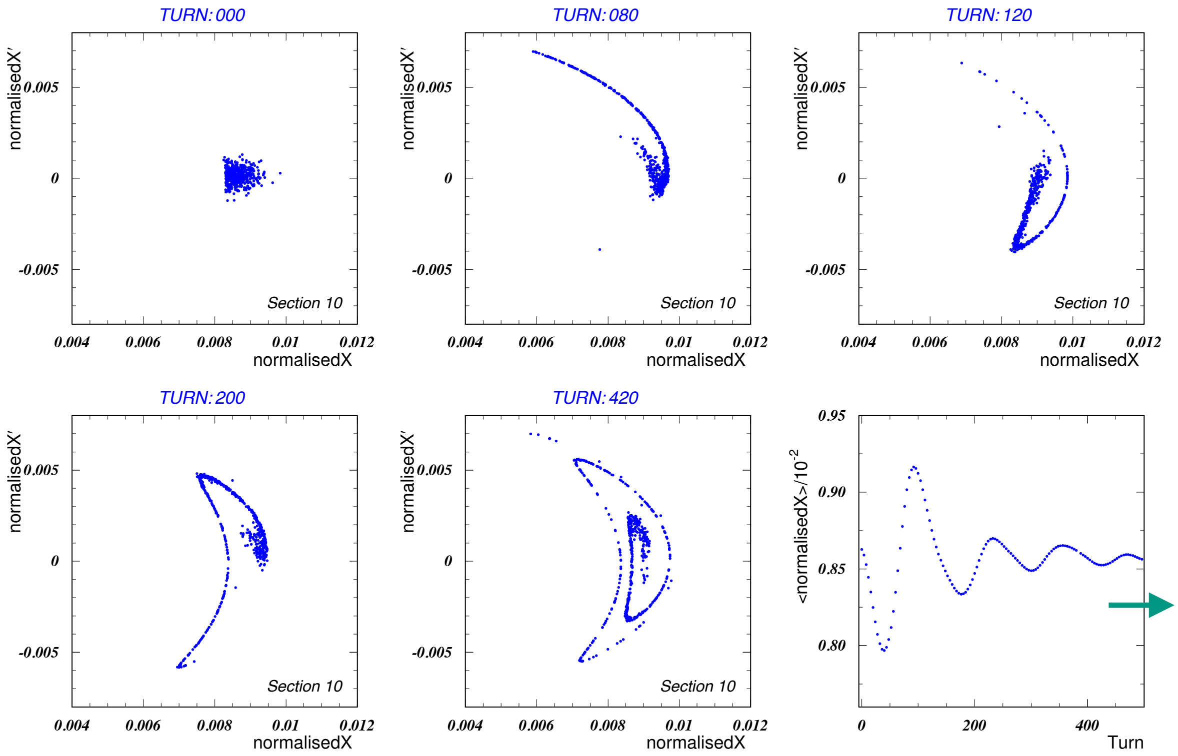
Karlsruhe Institute of Technology

- Beta functions and dispersion
  - Gradient variation / response matrix

- All around the betatron tune
  - FFT & LNP
  - Results from multi-turn measurements
  - Phasen space reconstruction

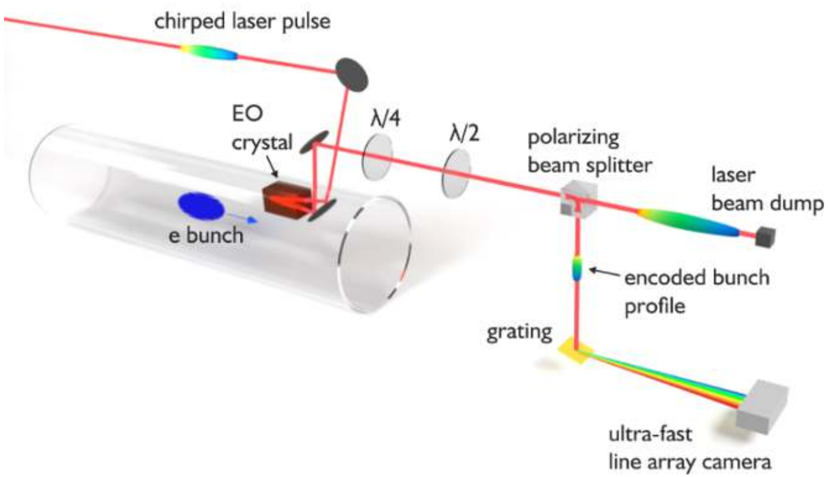
- Beam energy
  - Transverse polarisation
  - Resonant spin depolarisation
  - LEP and external effects

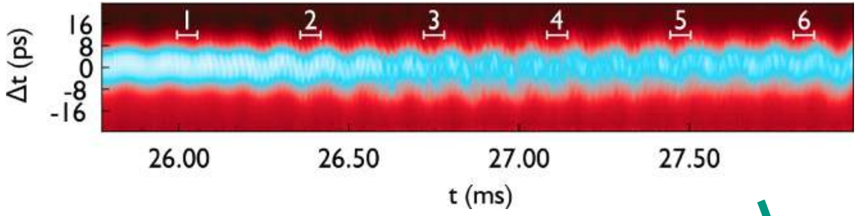
Measurements in phase space



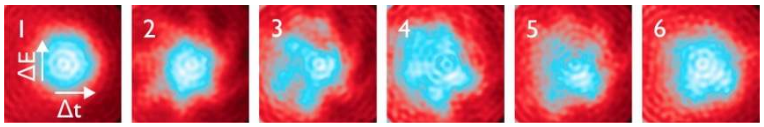
Only mean values are actually observed!

Phase space tomography



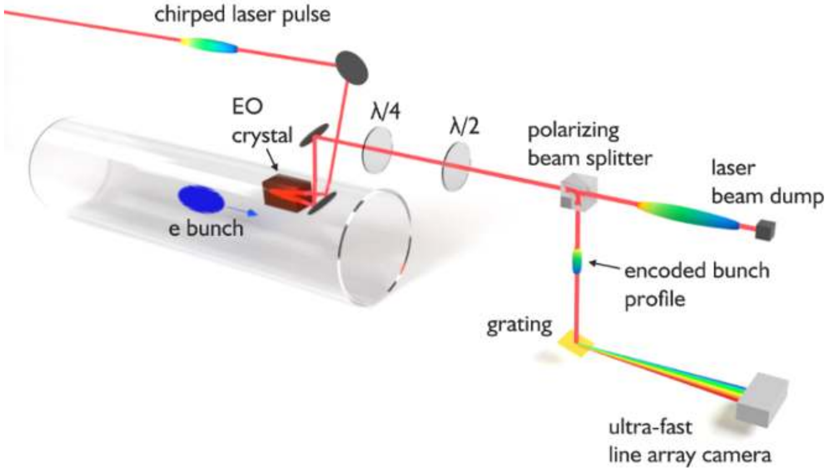


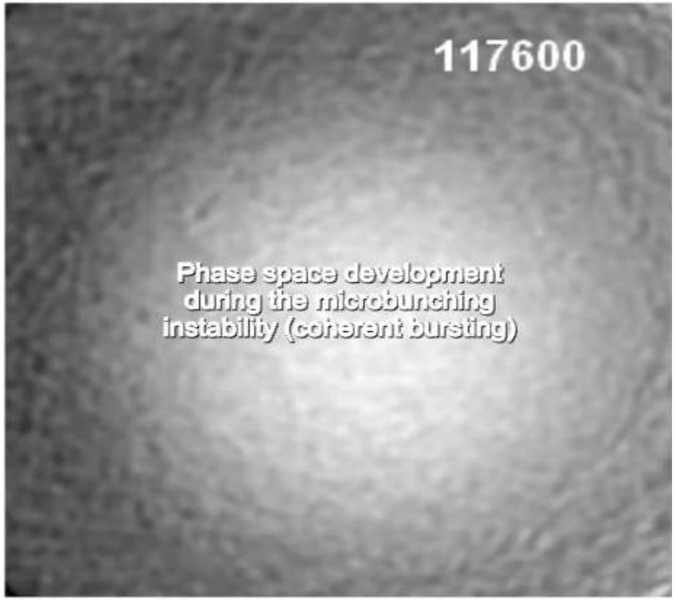
Complete phase space image reconstructed from time interval of 61 μm



- electro-optic spectral decoding
- bunch profile measurement
- single-bunch @ 2.7 MHz

Phase space tomography

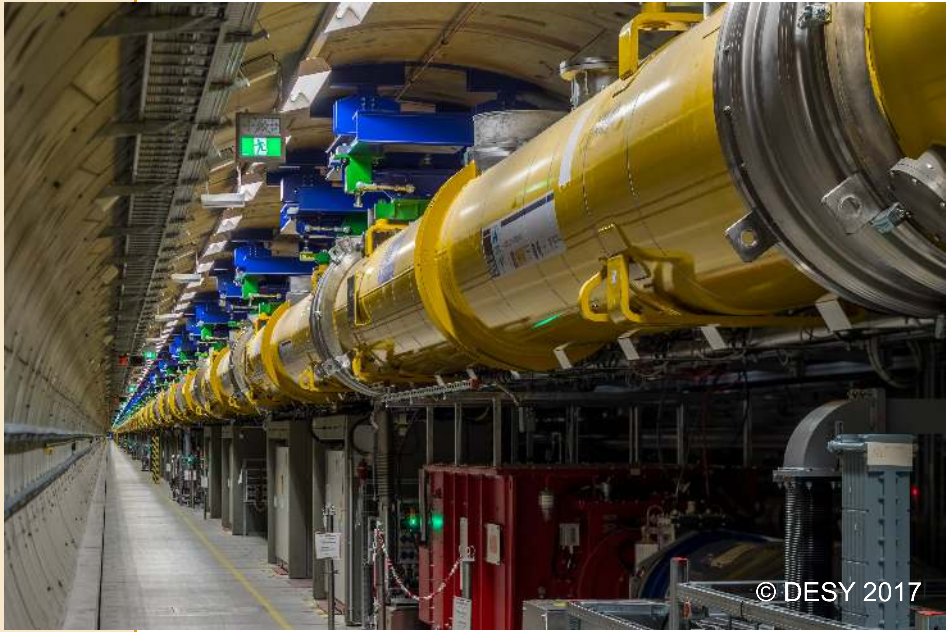




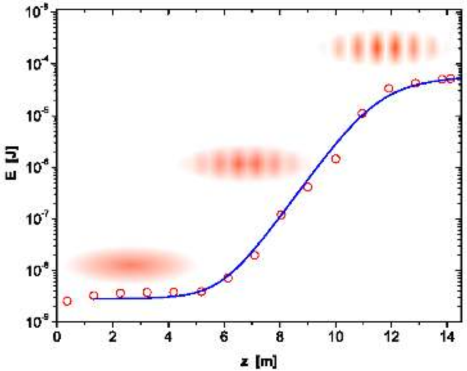
- electro-optic spectral decoding
- bunch profile measurement
- single-bunch @ 2.7 MHz

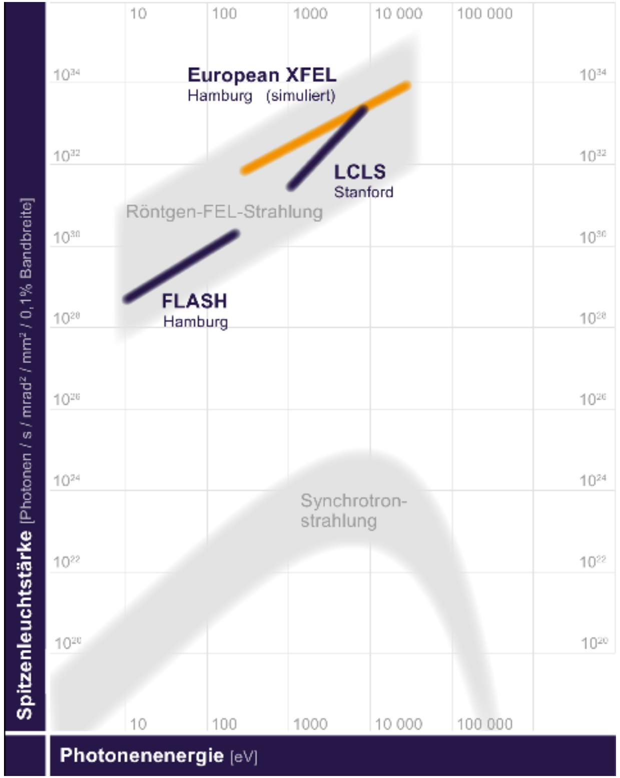
VI - Free-electron lasers (FELs)

- FEL: Application of
  - longitudinal beam dynamics
  - undulators
  - synchrotron radiation
- Examples
  - European XFEL
  - SwissFEL



Free electron lasers





Bildquelle: European XFEL

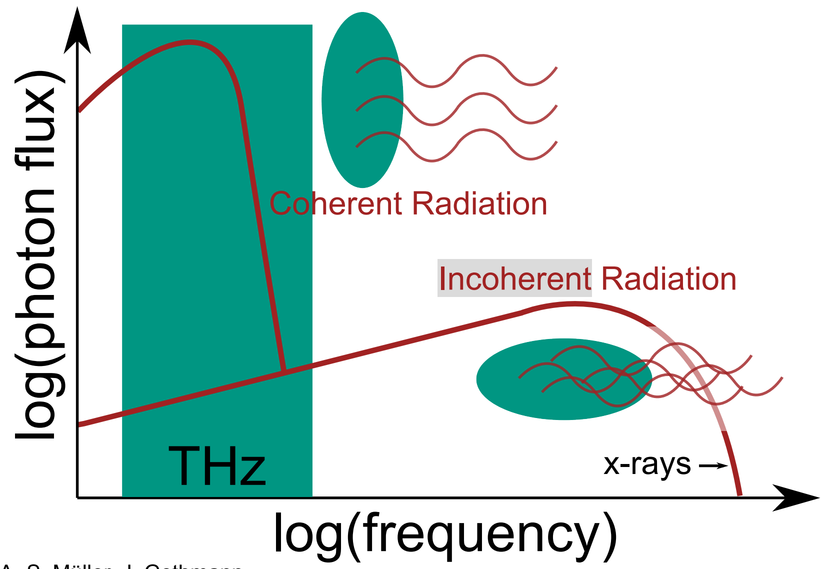
VII - Performance limits of accelerators

- Circular accelerators
  - Impedance
  - Tune and beam current
  - Synchrotron tune in extreme cases
  - Head-tail effects

- Electrons
  - Ultra-short pulses & CSR

- Protons
  - high-intense beams
  - Beam-beam effects (in case of colliders)

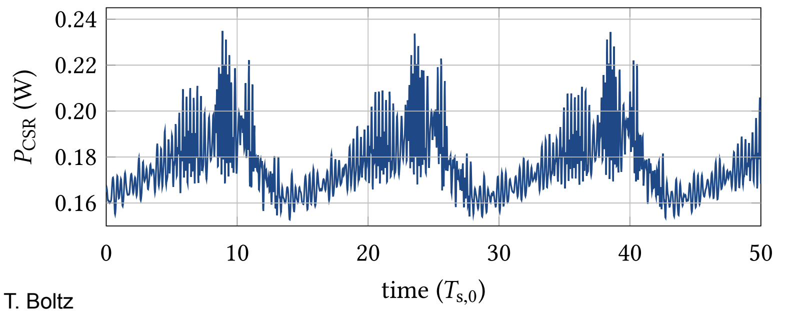
THz radiation in a storage ring



A.-S. Müller, J. Gethmann

Short electron bunches emit coherent radiation

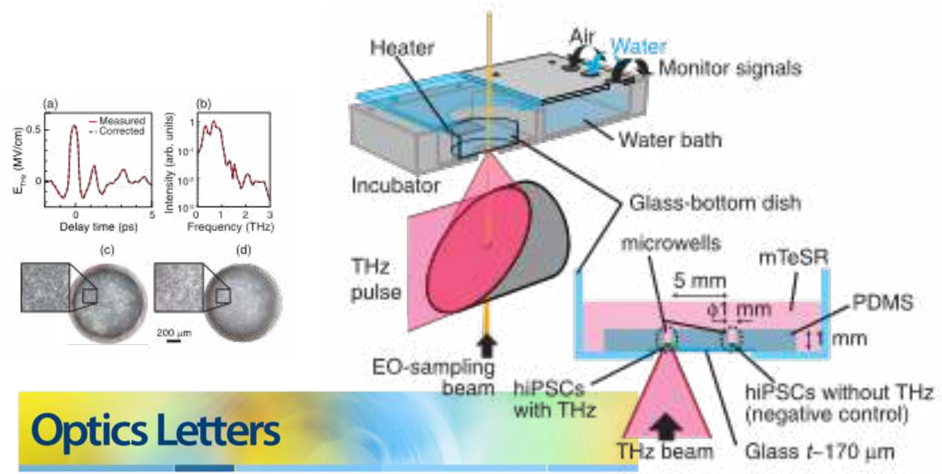
- Broadband emission
- Enormous increase of radiation in the THz range
- High brilliance



T. Boltz

THz pulses in material

Human stem cell manipulation

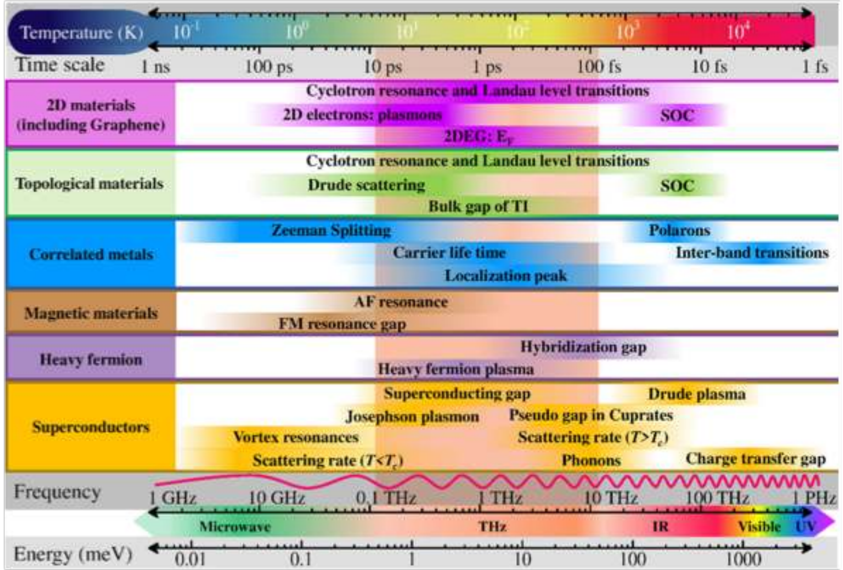


Terahertz pulse-altered gene networks in human induced pluripotent stem cells

Takehiro Tachizaki,[1,2] Reiko Sakaguchi,[2,3] Shiho Terada,[2] Ken-Ichiro Kamei,[2,*] AND Hideki Hirori[2,4]

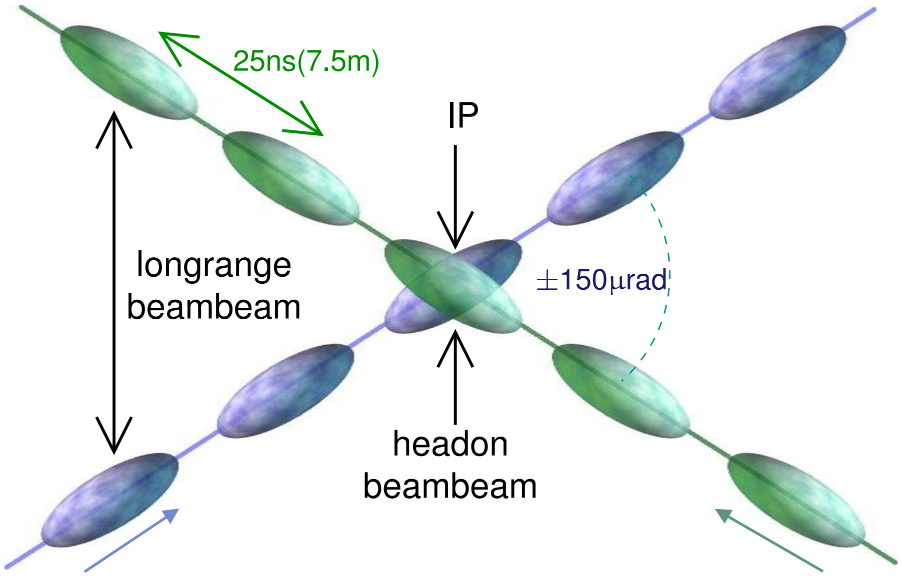
[1] Department of Optical and Imaging Science & Technology, School of Engineering, Tokai University, Kanagawa 259-1292, Japan
[2] Institute for Integrated Cell-Material Sciences, Kyoto University, Kyoto 606-8501, Japan
[3] Department of Synthetic Chemistry and Biological Chemistry, Graduate School of Engineering, Kyoto University, Kyoto 615-8510, Japan
[4] Institute for Chemical Research, Kyoto University, Kyoto 611-0011, Japan
*Corresponding author: kamei.kenichiro.7r@kyoto-u.ac.jp

Spectroscopy of quantum materials



THz spectroscopy of quantum materials
Eur. Phys. J. Spec. Top. (2021) 230:4113–4139

Collision of two beams



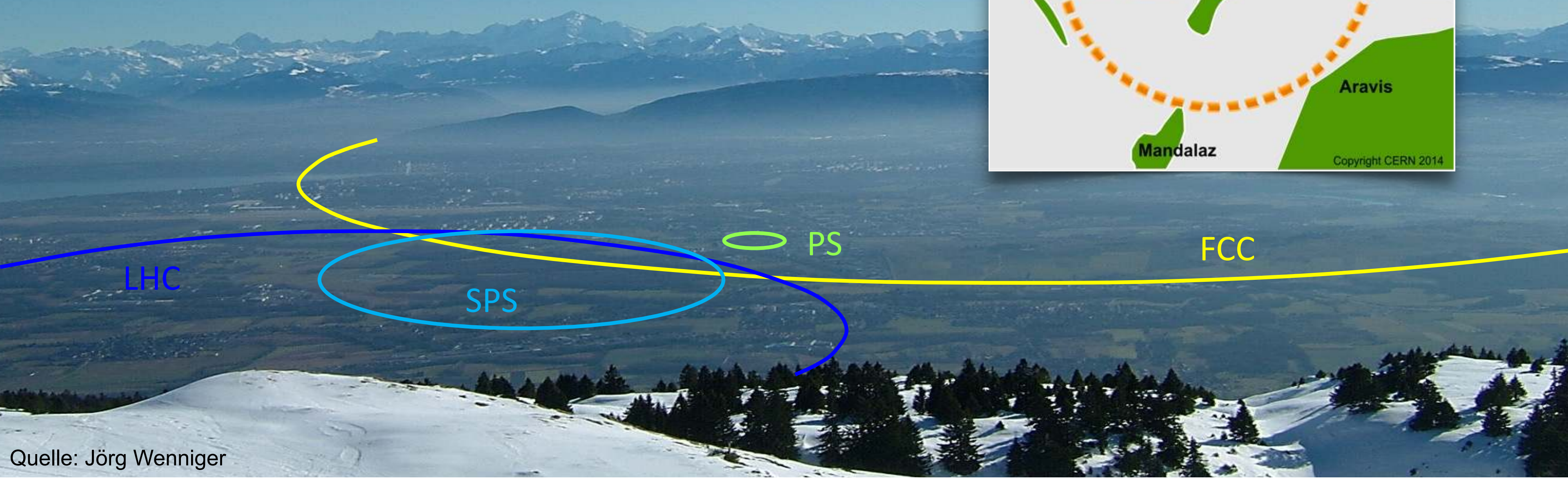
Two beams in the collider must always be separated except in IP.

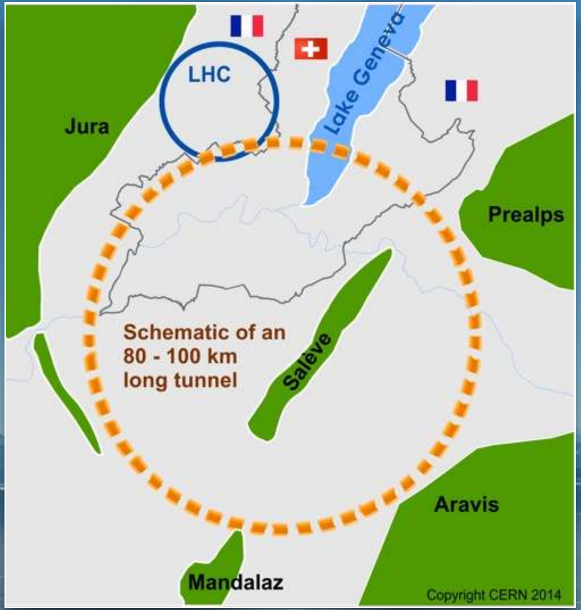
- collision angle
- additional tune shift
- larger aperture required
- coupling
- resonances
- reduced cross section

VIII - New technologies, current & future projects

- Examples of current and future projects
  - LHC and HL-LHC
  - Linear colliders: CLIC & ILC
  - European XFEL
  - FCC
  - Muon Collider
  - (FFAGs)
- New technologies
  - Plasma-based acceleration
  - Dielectric accelerators

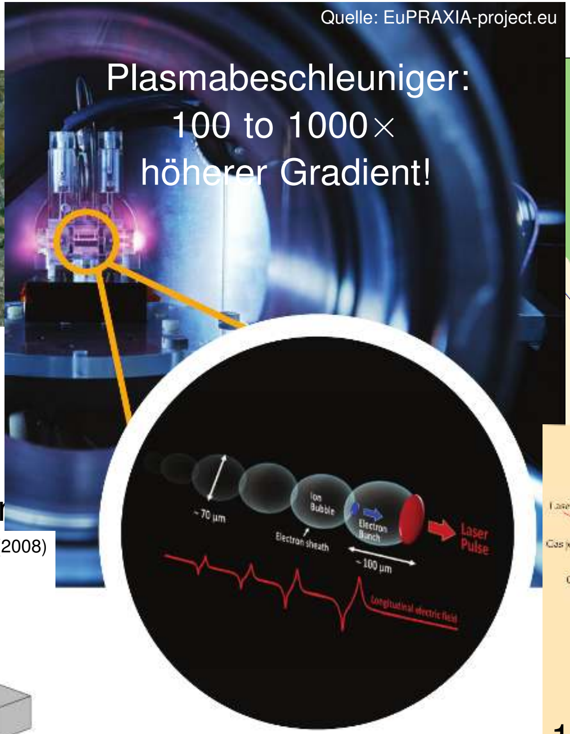
Future Circular Collider (FCC)



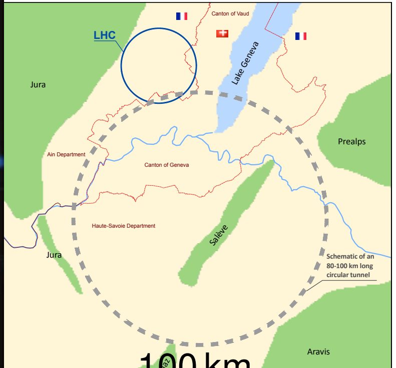


Quelle: Jörg Wenniger

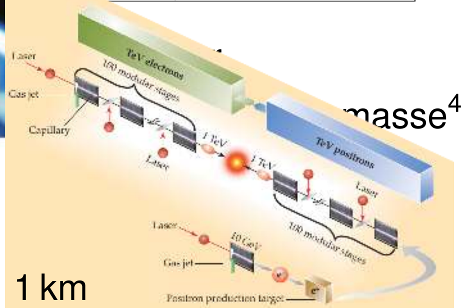
Future projects, new technologies



FCC



Esarey&Leemans, Physics Today 03/2009

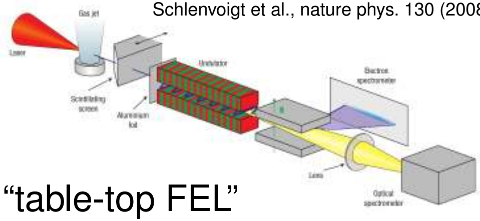


Lineare Hf-Beschleuniger

- Länge $\propto$ Energie
- Beschleunigungsgradien

masse[4]

Schlenvoigt et al., nature phys. 130 (2008)

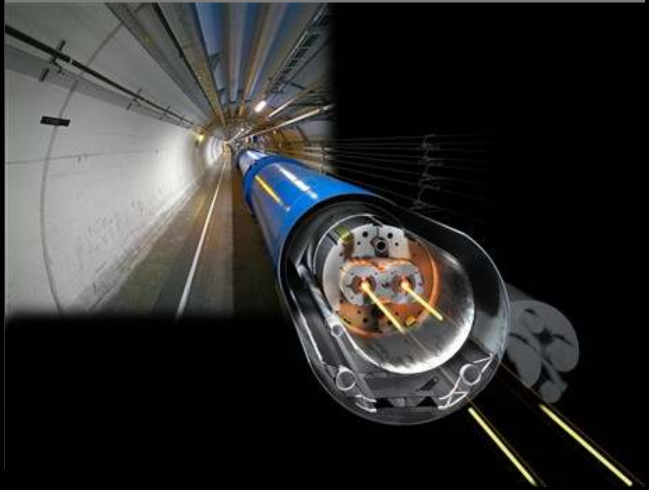


"table-top FEL"

New technologies and more

KIT
Karlsruher Institut für Technologie

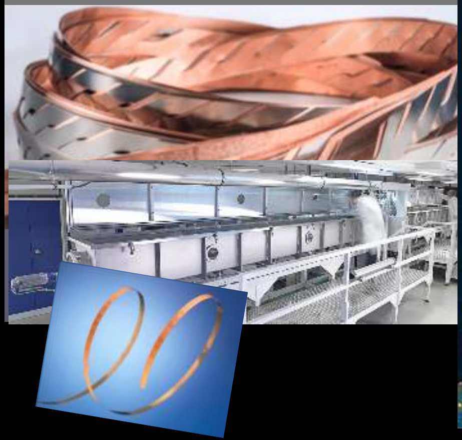
LHC: 1232 8 T dipoles



https://cds.cern.ch; CERN-AC-1107167-02

FCC needs 4 x more dipoles with twice the field than LHC.

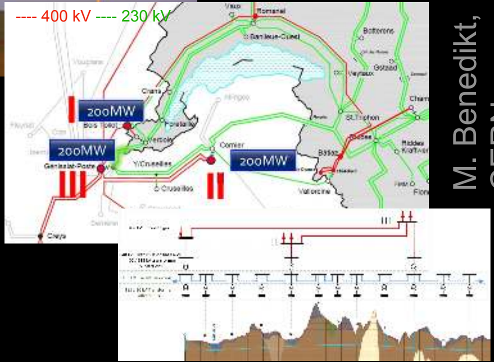
KIT conductors, magnets & cryogenics



THE CODE OF THE UNIVERSE

High temperature superconductors for ever higher beam energies and for the energy transition.

More challenges



M. Benedikt, CERN

THE CODE OF THE UNIVERSE

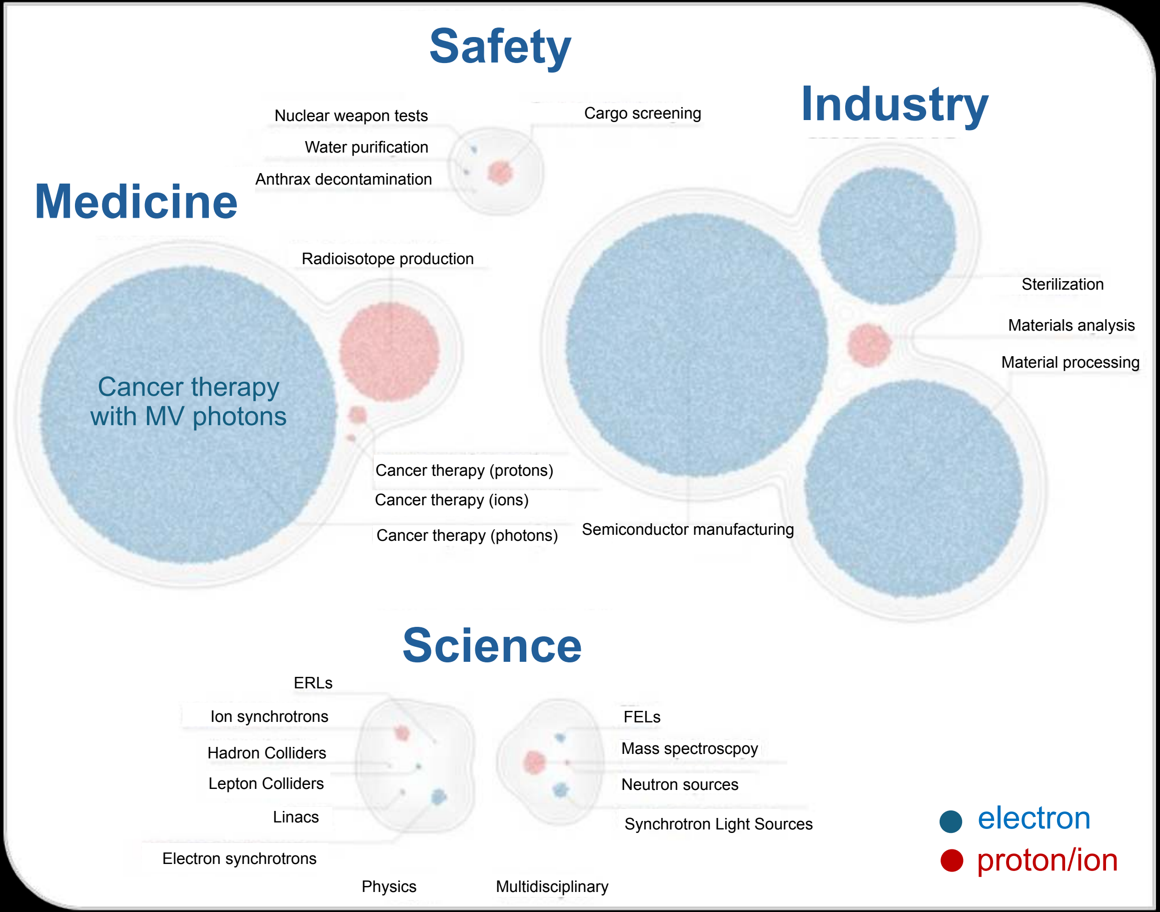
The energy within the beam is only a small fraction of the total power going into the accelerators system.

Increasingly complex grid requires new approaches.

Accelerators of the world

A large fraction of the world's accelerators serves a medical purpose.

Most of those systems enable MV photon therapy to treat cancer.



D. Rathje / KfB

Accelerators enable radiotherapy

Data from https://dirac.iaea.org

Radiotherapy is a cornerstone of cancer treatment.

The availability is insufficient.

Today's machines are costly, not scalable and cannot meet the future demand.


Vision
Shrinking particle accelerators…
…to treat tumors from inside the human body
Benefits
Affordable, accessible, and gentle radiotherapy
Approach
Novel sub-millimeter light-driven accelerators…
accelerator
tumor
fiber
light driver
localized irradiation
…instead of collateral tissue damage
external irradiation through body tissue