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Lenny Rivkin:: GFA:: Paul Scherrer Institute

PSI Accelerators

PSI Summer Students Lectures, July 13, 2016

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Large Research Facilities: accelerator based

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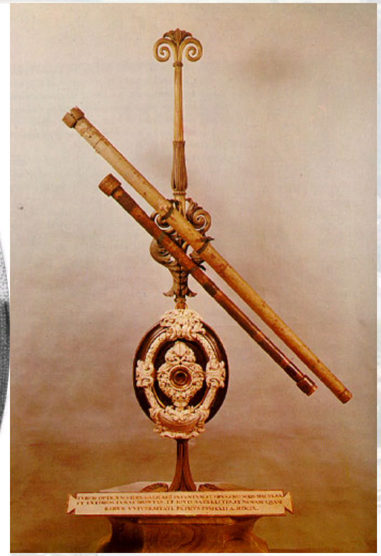
Instruments needed for human exploration

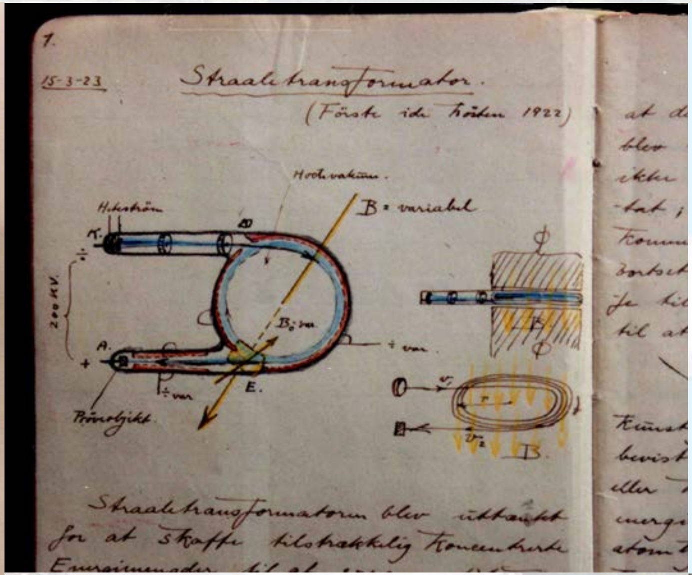
Galileo Galilei

400 years of discoveries

with «telescopes» «microscopes»

Zacharias Janssen

Accelerators are recent, modern instruments



Rolf Wideröe

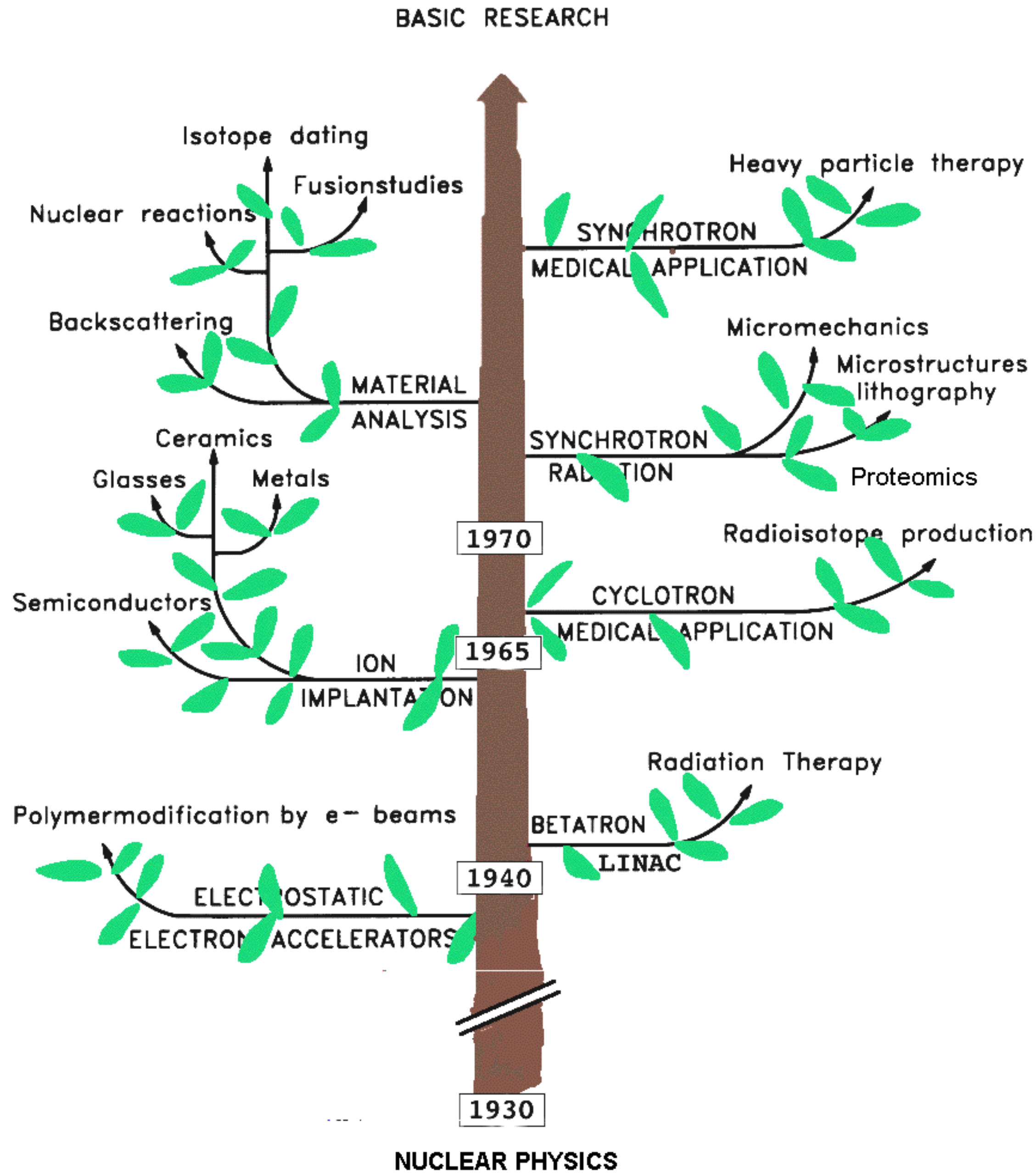
Ernest O. Lawrence

90 years Accelerators

The Role of Accelerators in Physical and Life Sciences

"It is an historical fact that scientific revolutions are more often driven by new tools than by new concepts"

Freeman Dyson



Particle beams: main uses

(protons, electrons, photons, neutrons, muons, neutrinos etc.)

Research in basic subatomic physics

Analysis of physical, chemical and biological samples

Modification of physical, chemical and biological properties of matter

ENGINES OF
DISCOVERY

A Century of Particle Accelerators

Andrew Sessler • Edmund Wilson

“Le véritable voyage de découverte ne consiste pas à chercher de nouveaux paysages, mais à avoir de nouveaux yeux”

Marcel Proust

The real voyage of discovery consists not in seeking new landscapes but in having new eyes

25 Nobel Prizes in Physics that had direct contribution from accelerators

Year	Name	Accelerator-Science Contribution to Nobel Prize-Winning Research
1939	Ernest O. Lawrence	Lawrence invented the cyclotron at the University of Californian at Berkeley in 1929 [12].
1951	John D. Cockcroft and Ernest T.S. Walton	Cockcroft and Walton invented their eponymous linear positive-ion accelerator at the Cavendish Laboratory in Cambridge, England, in 1932 [13].
1952	Felix Bloch	Bloch used a cyclotron at the Crocker Radiation Laboratory at the University of California at Berkeley in his discovery of the magnetic moment of the neutron in 1940 [14].
1957	Tsung-Dao Lee and Chen Ning Yang	Lee and Yang analyzed data on K mesons (θ and τ) from Bevatron experiments at the Lawrence Radiation Laboratory in 1955 [15], which supported their idea in 1956 that parity is not conserved in weak interactions [16].
1959	Emilio G. Segrè and Owen Chamberlain	Segrè and Chamberlain discovered the antiproton in 1955 using the Bevatron at the Lawrence Radiation Laboratory [17].
1960	Donald A. Glaser	Glaser tested his first experimental six-inch bubble chamber in 1955 with high-energy protons produced by the Brookhaven Cosmotron [18].
1961	Robert Hofstadter	Hofstadter carried out electron-scattering experiments on carbon-12 and oxygen-16 in 1959 using the SLAC linac and thereby made discoveries on the structure of nucleons [19].
1963	Maria Goeppert Mayer	Goeppert Mayer analyzed experiments using neutron beams produced by the University of Chicago cyclotron in 1947 to measure the nuclear binding energies of krypton and xenon [20], which led to her discoveries on high magic numbers in 1948 [21].
1967	Hans A. Bethe	Bethe analyzed nuclear reactions involving accelerated protons and other nuclei whereby he discovered in 1939 how energy is produced in stars [22].
1968	Luis W. Alvarez	Alvarez discovered a large number of resonance states using his fifteen-inch hydrogen bubble chamber and high-energy proton beams from the Bevatron at the Lawrence Radiation Laboratory [23].
1976	Burton Richter and Samuel C.C. Ting	Richter discovered the J/Ψ particle in 1974 using the SPEAR collider at Stanford [24], and Ting discovered the J/Ψ particle independently in 1974 using the Brookhaven Alternating Gradient Synchrotron [25].
1979	Sheldon L. Glashow, Abdus Salam, and Steven Weinberg	Glashow, Salam, and Weinberg cited experiments on the bombardment of nuclei with neutrinos at CERN in 1973 [26] as confirmation of their prediction of weak neutral currents [27].
1980	James W. Cronin and Val L. Fitch	Cronin and Fitch concluded in 1964 that CP (charge-parity) symmetry is violated in the decay of neutral K mesons based upon their experiments using the Brookhaven Alternating Gradient Synchrotron [28].
1981	Kai M. Siegbahn	Siegbahn invented a weak-focusing principle for betatrons in 1944 with which he made significant improvements in high-resolution electron spectroscopy [29].
1983	William A. Fowler	Fowler collaborated on and analyzed accelerator-based experiments in 1958 [30], which he used to support his hypothesis on stellar-fusion processes in 1957 [31].
1984	Carlo Rubbia and Simon van der Meer	Rubbia led a team of physicists who observed the intermediate vector bosons W and Z in 1983 using CERN's proton-antiproton collider [32], and van der Meer developed much of the instrumentation needed for these experiments [33].
1986	Ernst Ruska	Ruska built the first electron microscope in 1933 based upon a magnetic optical system that provided large magnification [34].
1988	Leon M. Lederman, Melvin Schwartz, and Jack Steinberger	Lederman, Schwartz, and Steinberger discovered the muon neutrino in 1962 using Brookhaven's Alternating Gradient Synchrotron [35].
1989	Wolfgang Paul	Paul's idea in the early 1950s of building ion traps grew out of accelerator physics [36].
1990	Jerome I. Friedman, Henry W. Kendall, and Richard E. Taylor	Friedman, Kendall, and Taylor's experiments in 1974 on deep inelastic scattering of electrons on protons and bound neutrons used the SLAC linac [37].
1992	Georges Charpak	Charpak's development of multiwire proportional chambers in 1970 were made possible by accelerator-based testing at CERN [38].
1995	Martin L. Perl	Perl discovered the tau lepton in 1975 using Stanford's SPEAR collider [39].
2004	David J. Gross, Frank Wilczek, and H. David Politzer	Gross, Wilczek, and Politzer discovered asymptotic freedom in the theory of strong interactions in 1973 based upon results from the SLAC linac on electron-proton scattering [40].
2008	Makoto Kobayashi and Toshihide Maskawa and Yoichro Nambu	Kobayashi and Maskawa's theory of quark mixing in 1973 was confirmed by results from the KEKB accelerator at KEK (High Energy Accelerator Research Organization) in Tsukuba, Ibaraki Prefecture, Japan, and the PEP II (Positron Electron Project II) at SLAC [41], which showed that quark mixing in the six-quark model is the dominant source of broken symmetry [42].

2013: François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at **CERN's Large Hadron Collider**"

20 Nobels with X-rays

Chemistry

1936: Peter Debye

1962: Max Perutz and Sir John Kendrew

1976 William Lipscomb

1985 Herbert Hauptman and Jerome Karle

1988 Johann Deisenhofer, Robert Huber and Hartmut Michel

1997 Paul D. Boyer and John E. Walker

2003 Peter Agre and Roderick Mackinnon

2006 Roger D. Kornberg

2009 V. Ramakrishnan, Th. A. Steitz, A. E. Yonath

2012 Robert J. Lefkowitz and Brian K. Kobilka

Physics

1901 Wilhelm Rontgen

1914 Max von Laue

1915 Sir William Bragg and son

1917 Charles Barkla

1924 Karl Siegbahn

1927 Arthur Compton

1981 Kai Siegbahn

Medicine

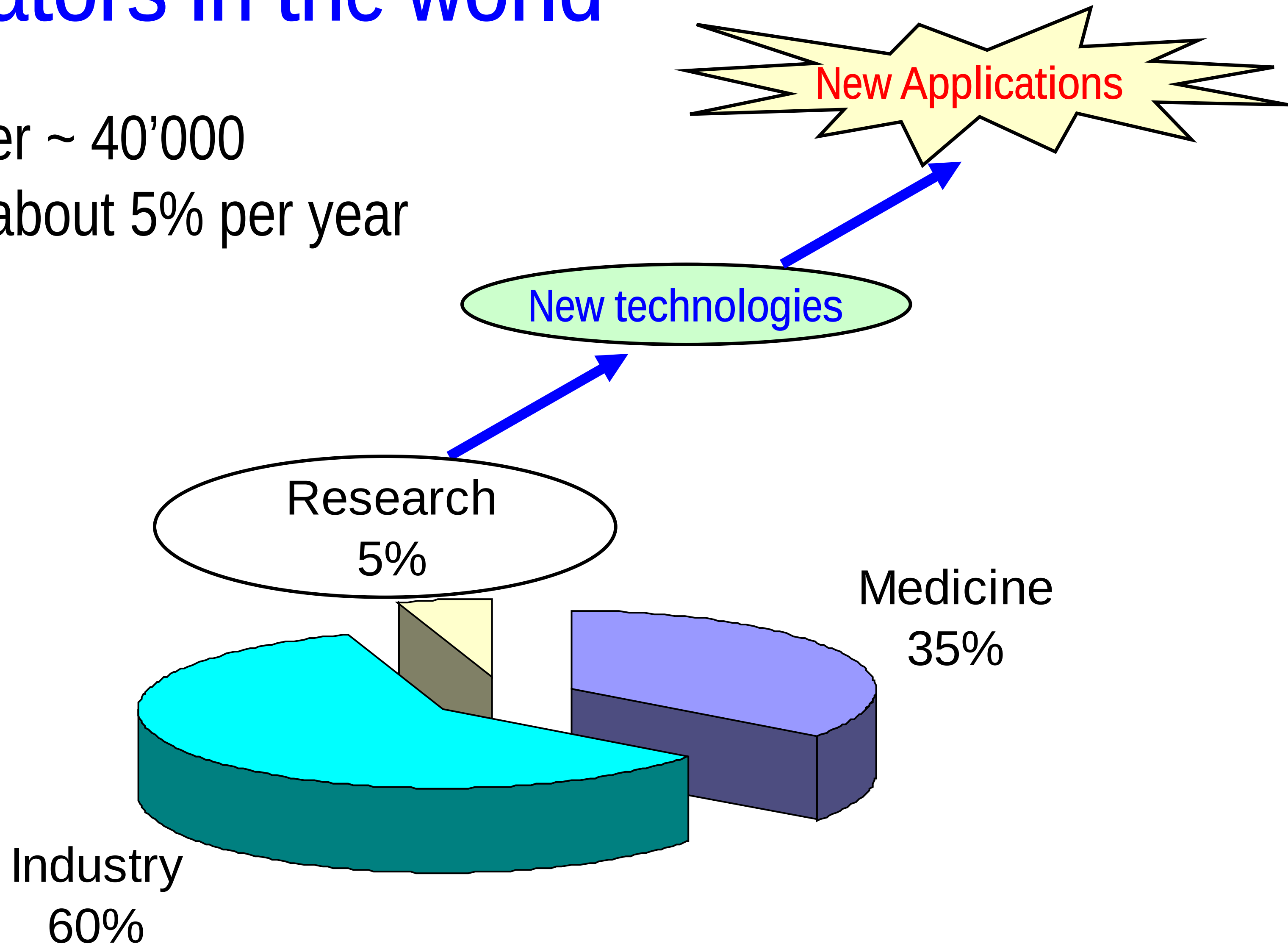
1946 Hermann Muller

1962 Frances Crick, James Watson and Maurice Wilkins

1979 Alan Cormack and Godfrey Hounsfield

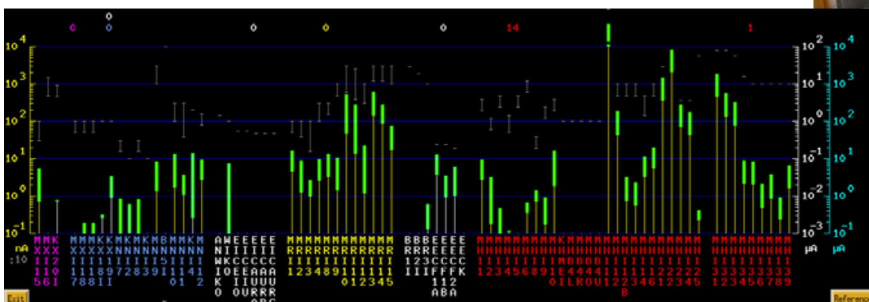
Accelerators in the world

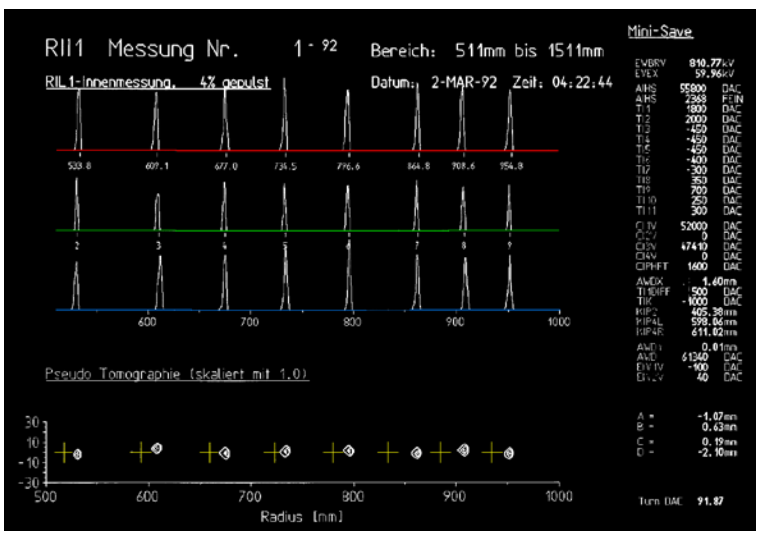
Total number ~ 40'000
growing at about 5% per year



All PSI accelerators operated from one control room

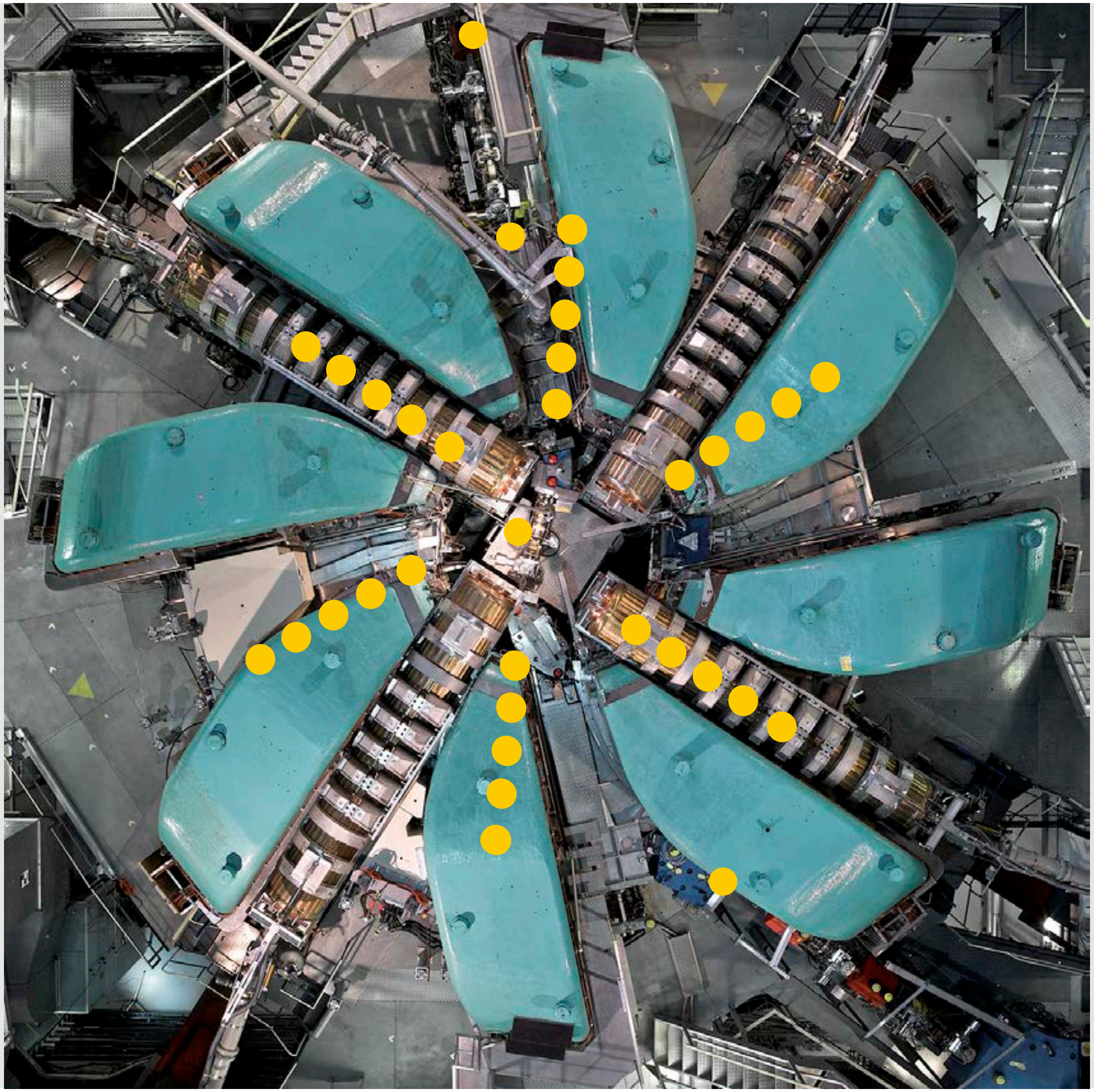
- 3 operators per 8 h shift for all PSI accelerators





590 MeV Ring Cyclotron at PSI

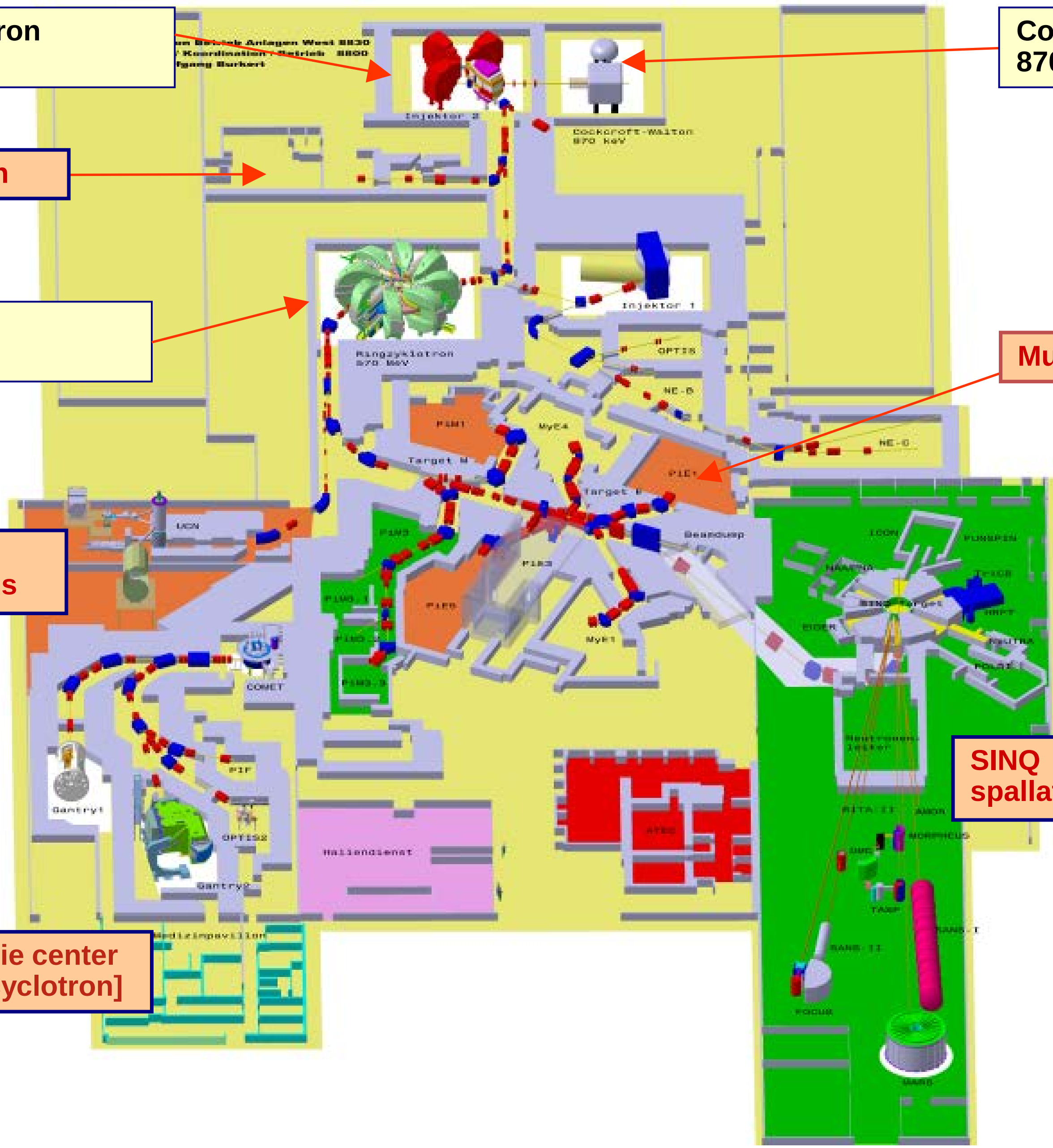
First beam on target: February 19th 1974




February 28, 2014 - 40 years PSI-Ringcyclotron
Proton Beam at Highest Intensity

The best expertise of many different professions is required to run the complex HIPA facility.

Overview HIPA



Injector II Cyclotron
72 MeV, 160kW

Cockcroft Walton
870keV, 10kW

Isotope Production

Ring Cyclotron
590 MeV, 1.3MW

Muon Beamlines

UCN
Ultra-Cold Neutrons

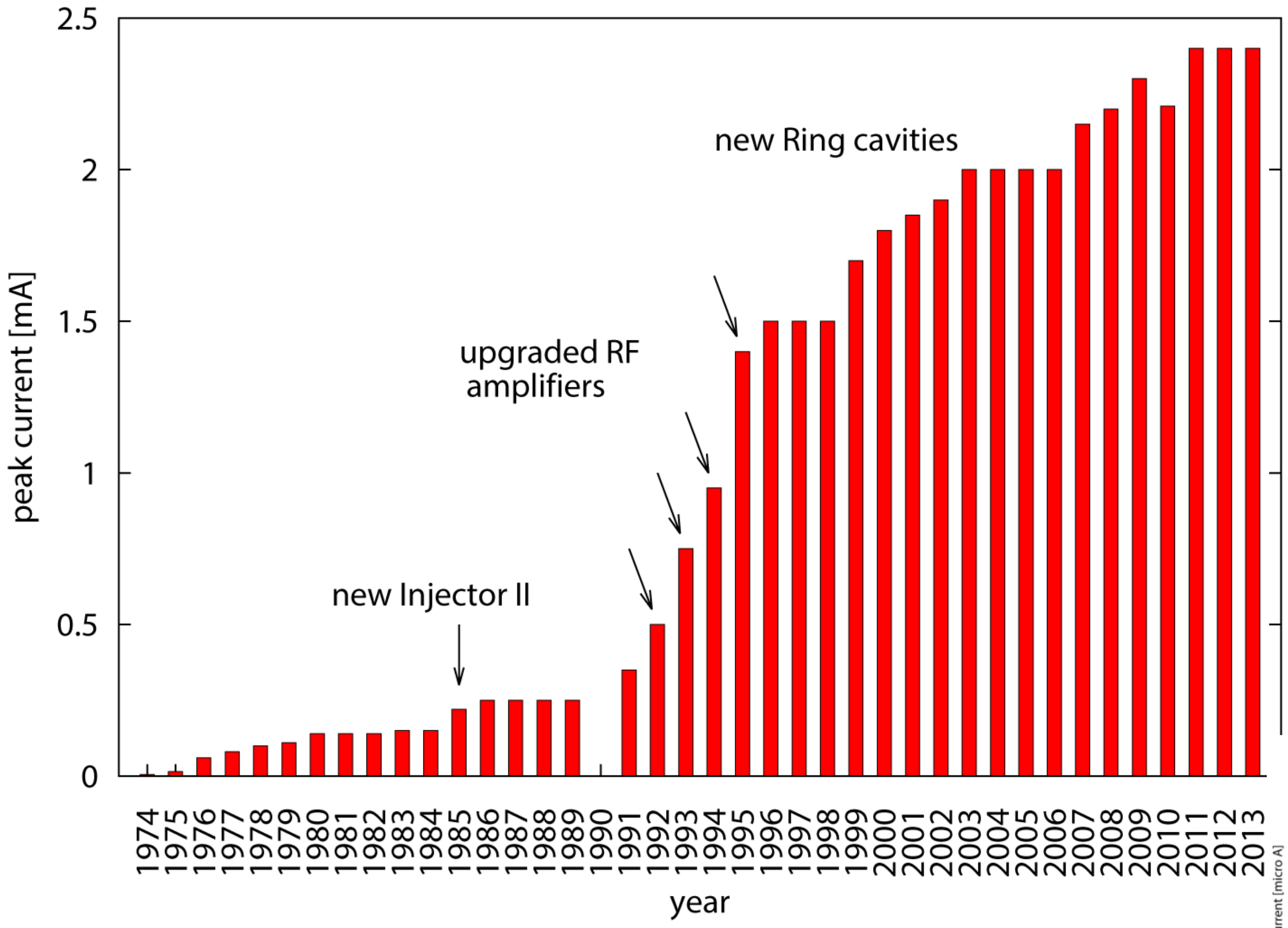
SINQ
spallation source

proton therapie center
[250MeV sc. cyclotron]

dimensions:
120 x 220m^2

Cockcroft-Walton 870 keV protons

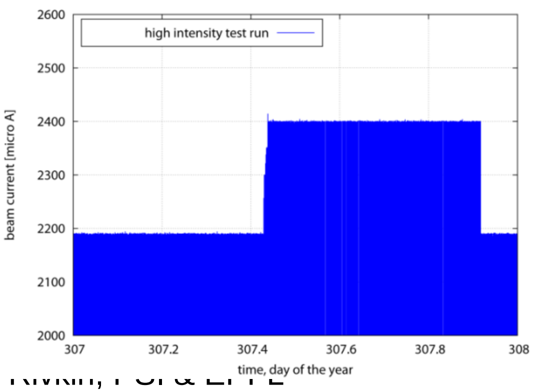
history of maximum beam power



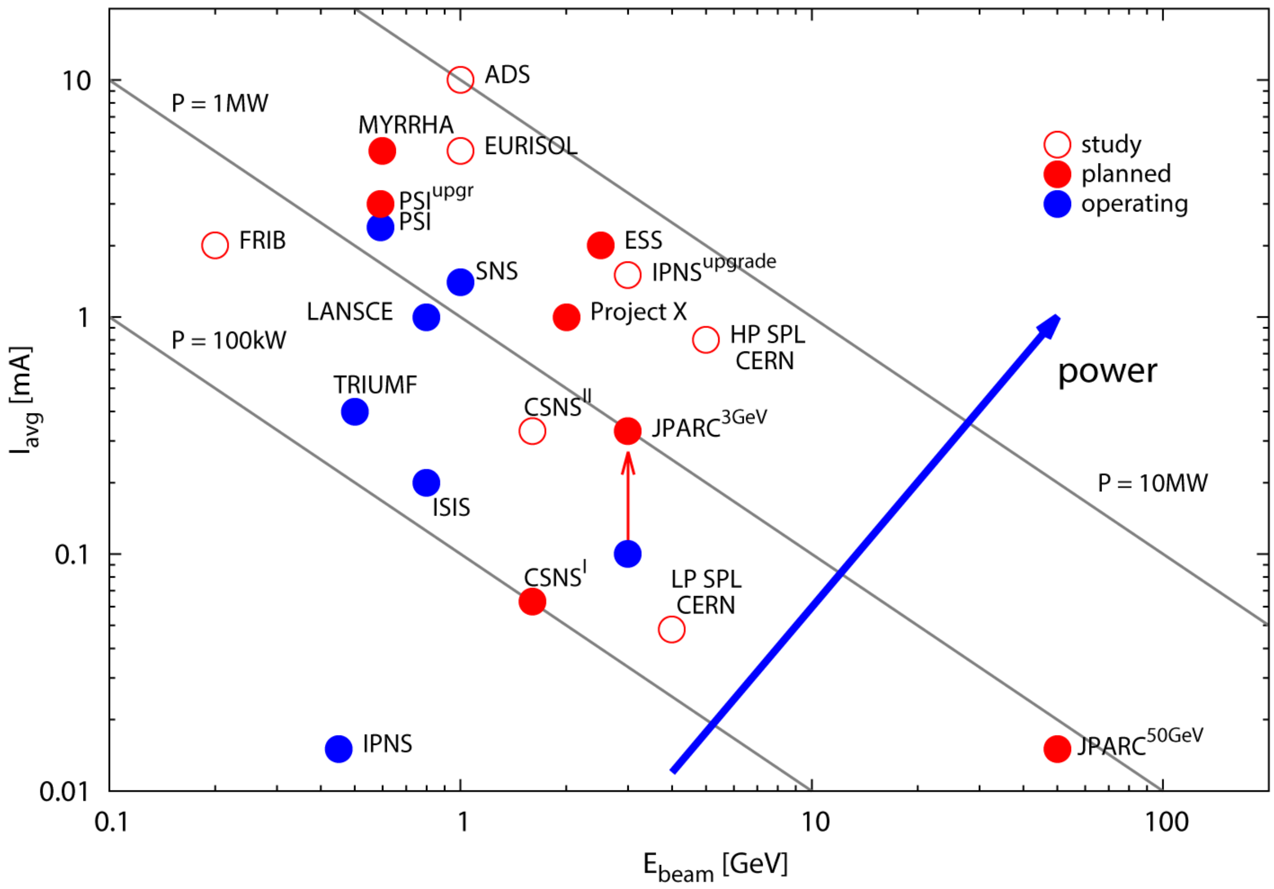
milestones:

- new injector cyclotron (84)
- upgrading Ring RF power
- replacing Ring cavities
- new ECR source

1974 planned: 100uA
today: 2.400uA
[routine: 2.200uA]



PSI HIPA in the international context



Neutron Sources

	Energy [GeV]	Power [MW]
ISIS	0.8	0.18
J-Parc	3.0	0.3 (1.0)
SNS	1.0	1.4
PSI	0.59	1.4
ESS	2.5	5.0
CSNS	1.6	0.1…0.5

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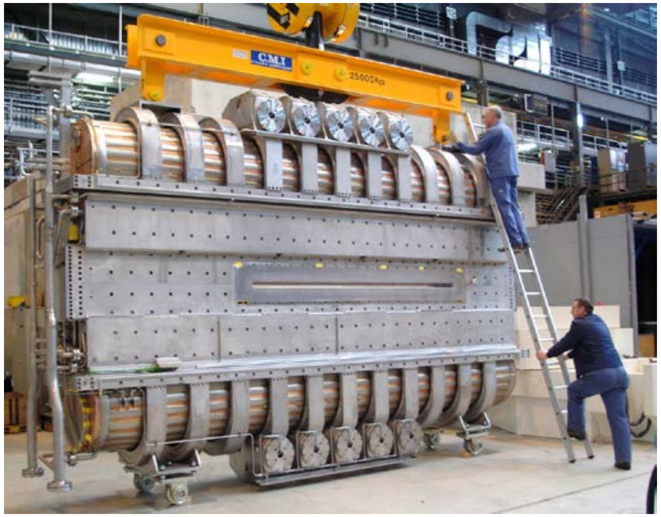
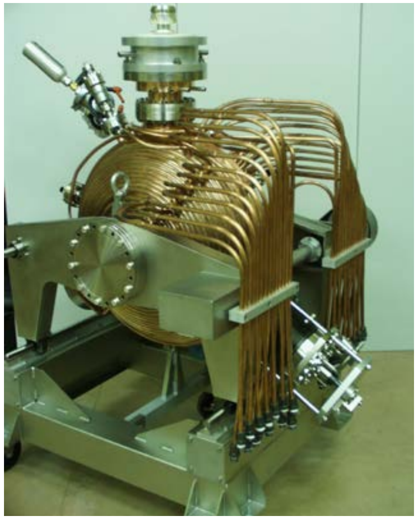
Radio Frequency Acceleration

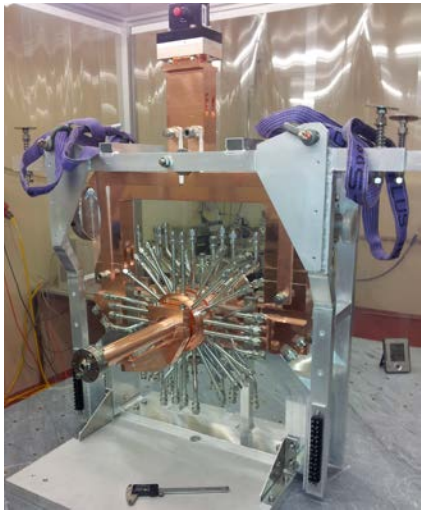
HF-Kavitäten 50 MHz (Ringzyklotron)



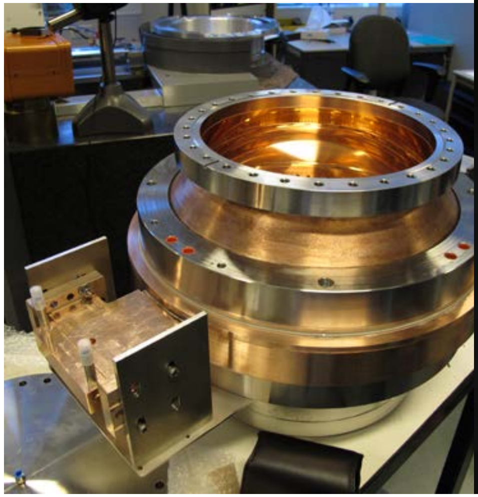
500 MHz (Swiss Light Source),

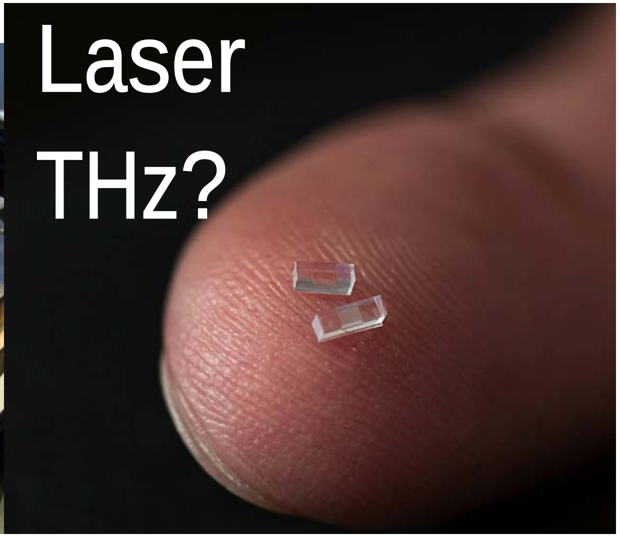


3 GHz (SwissFEL-Injektor),



6 GHz SwissFEL

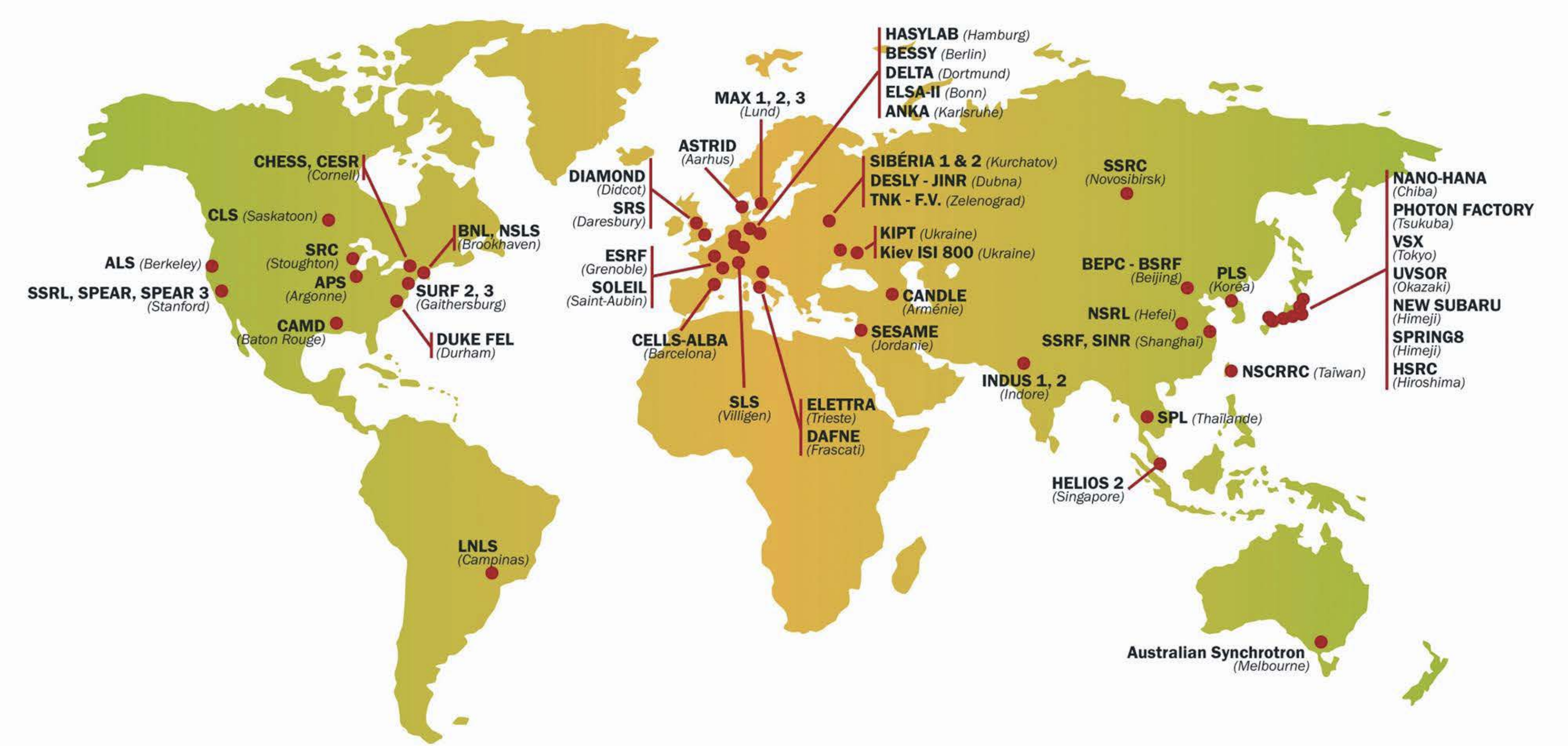




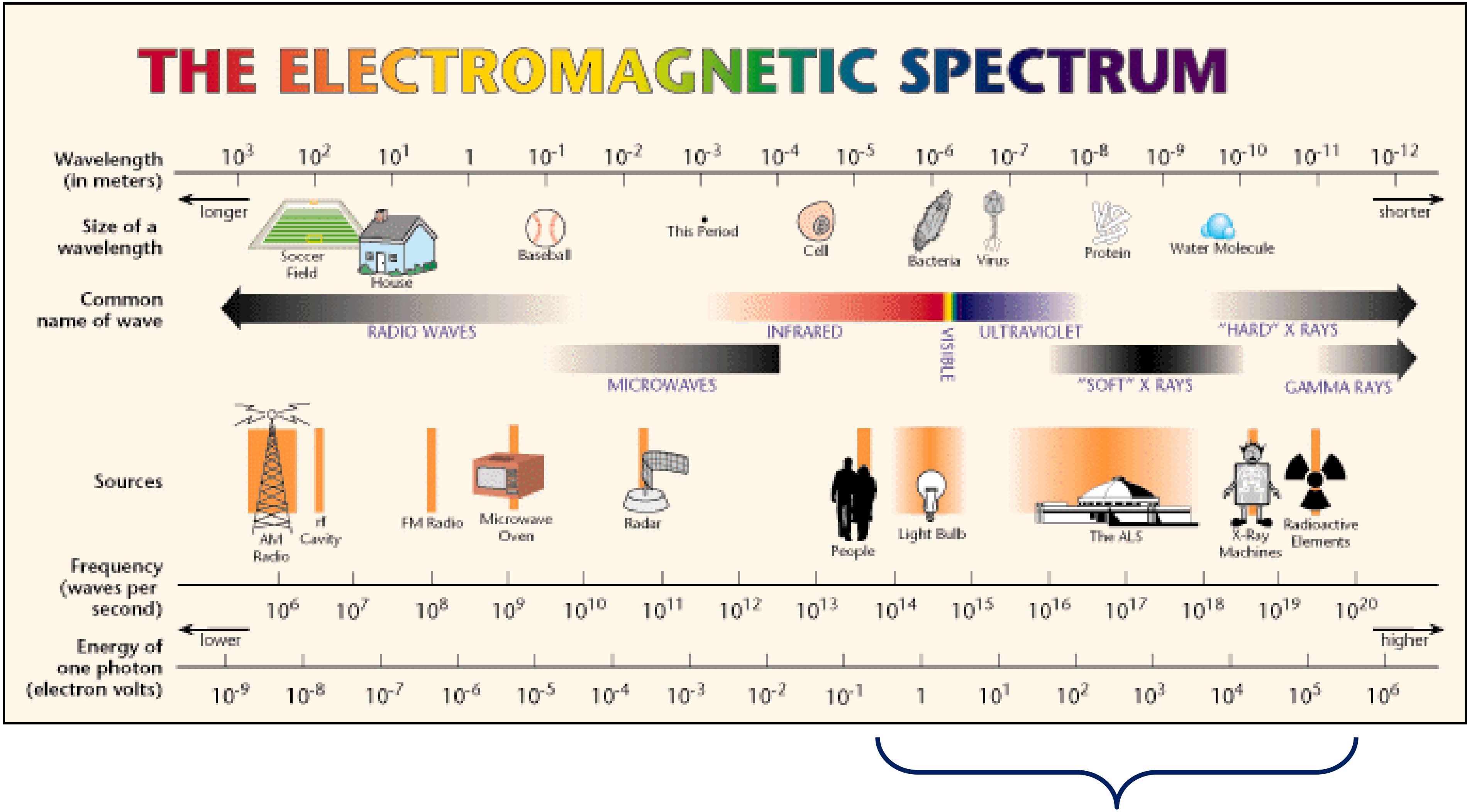
Light sources

Light sources: > 50 producing synchrotron light

60‘000 users world-wide

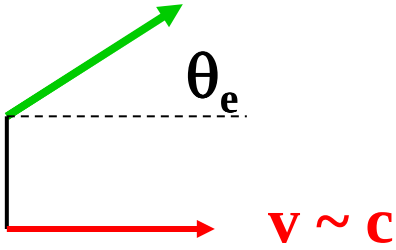


SLS Inaguration 2001: Twenty years after???

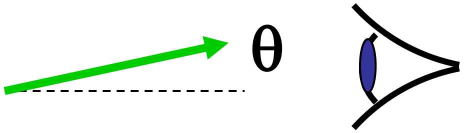


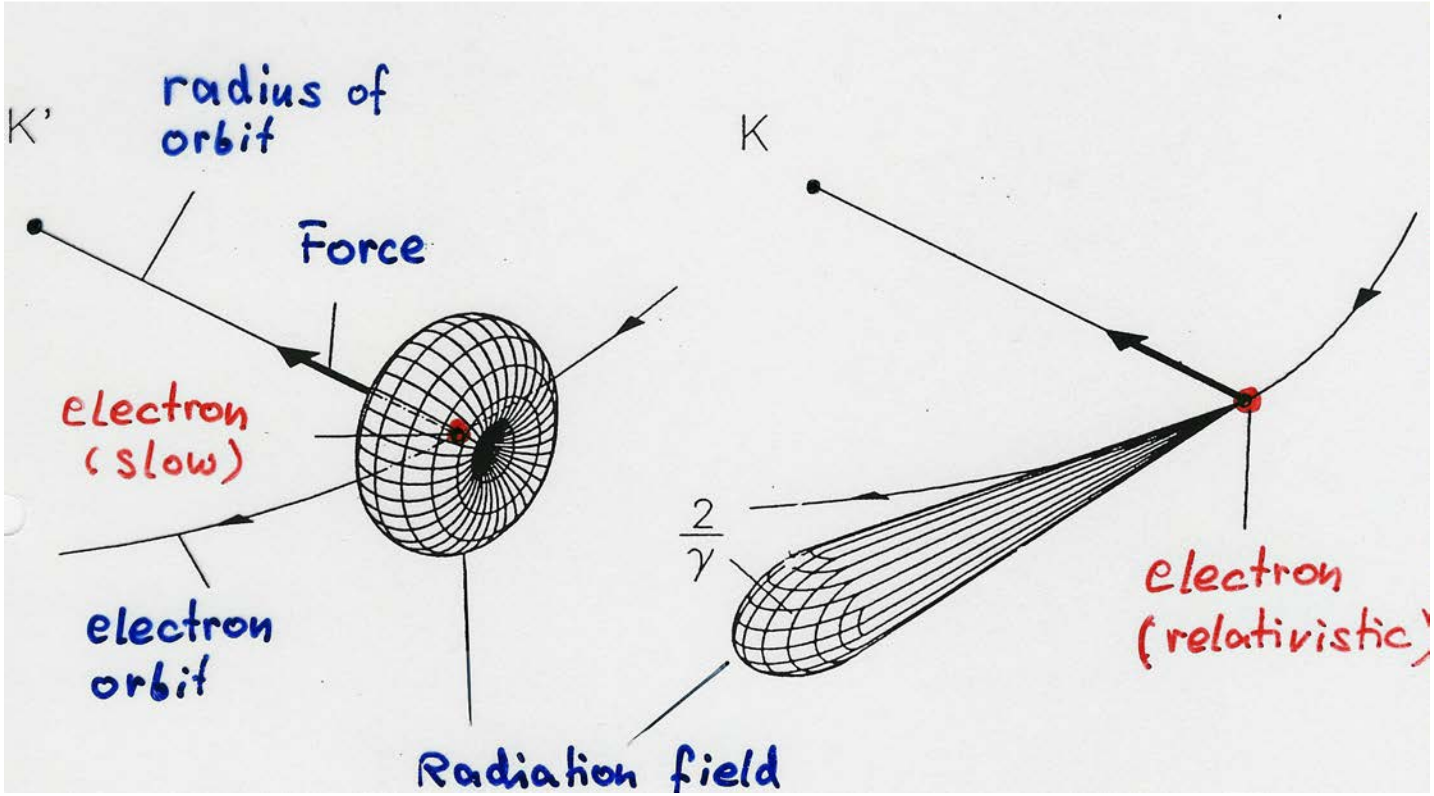
Wavelength continuously tunable !

Light is emitted into a narrow cone



$$\theta = \frac{1}{\gamma} \cdot \theta_e$$

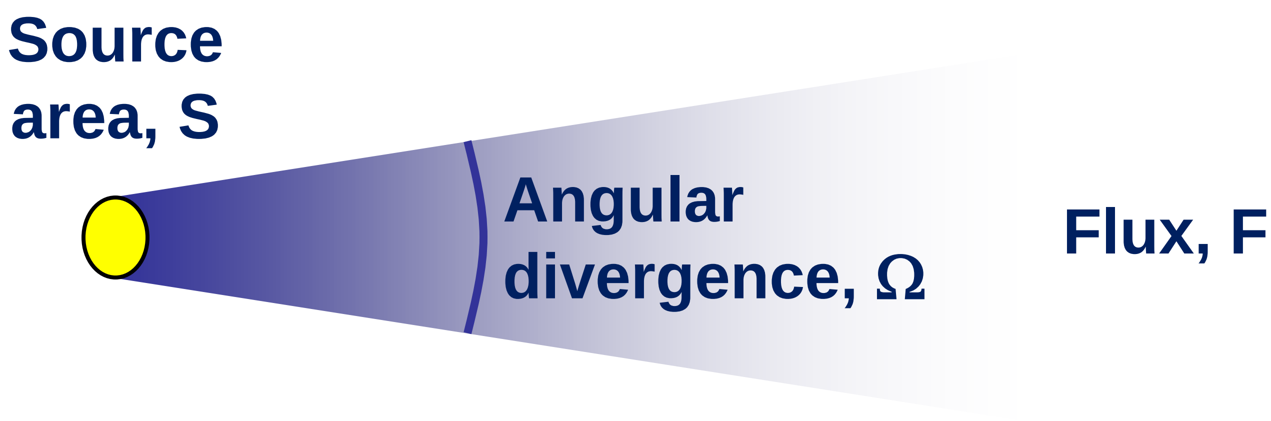




v << c

v ≈ c

The "brightness" of a light source:

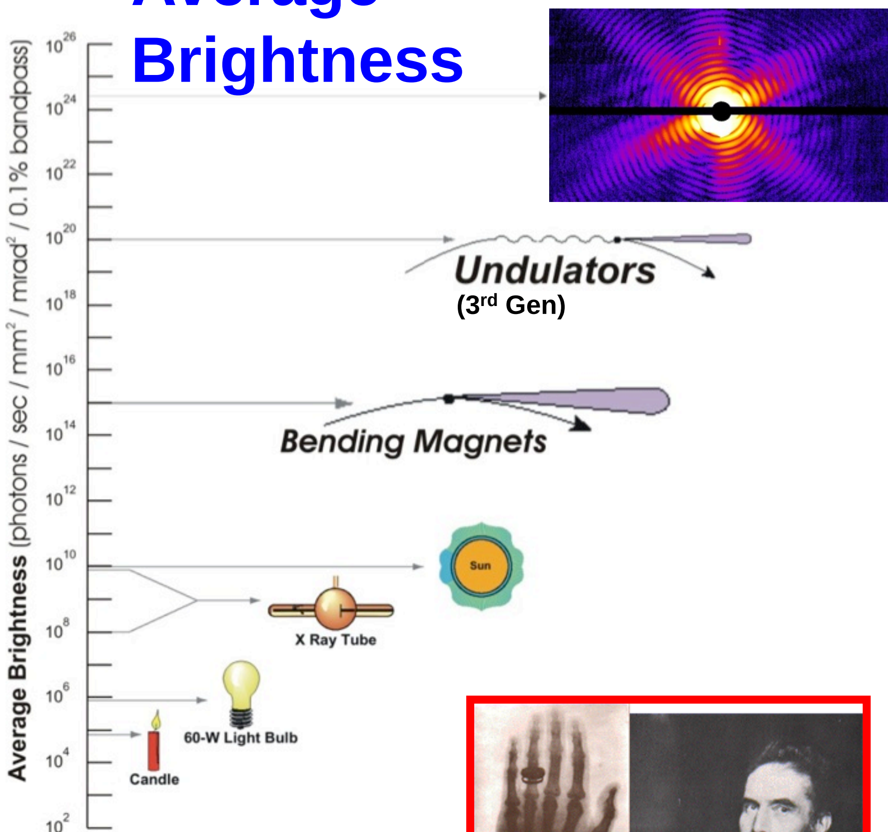


$$\text{Brightness} = \text{constant} \times \frac{F}{S \times \Omega}$$

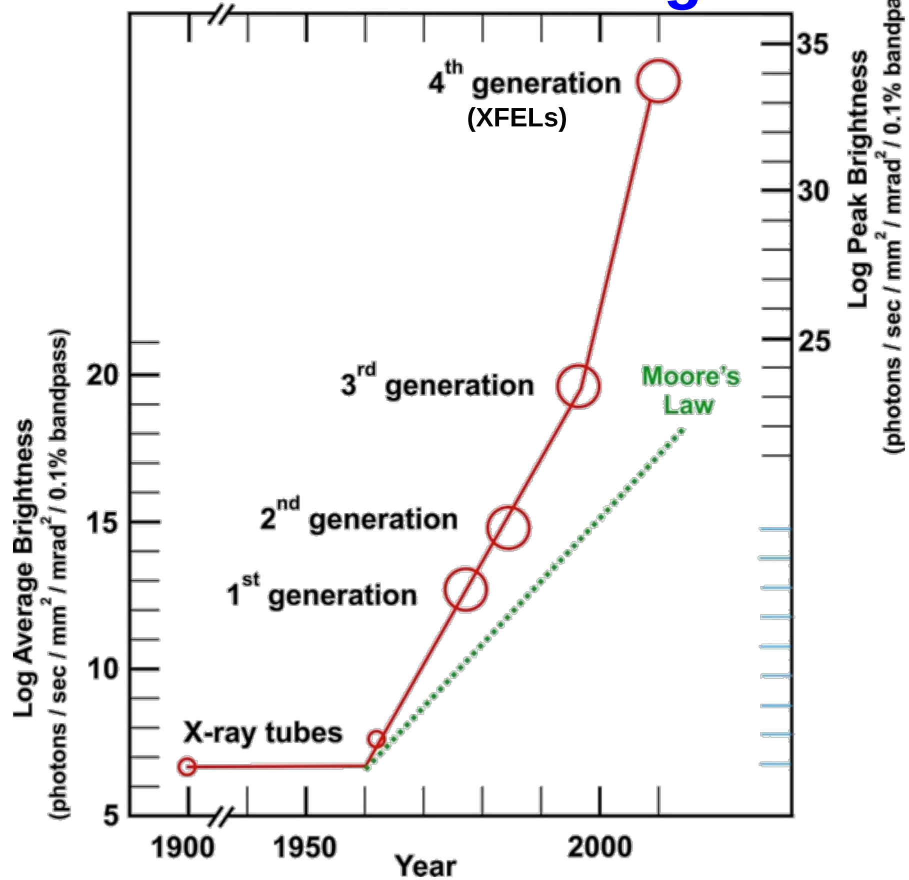
X-rays Brightness

Average Brightness

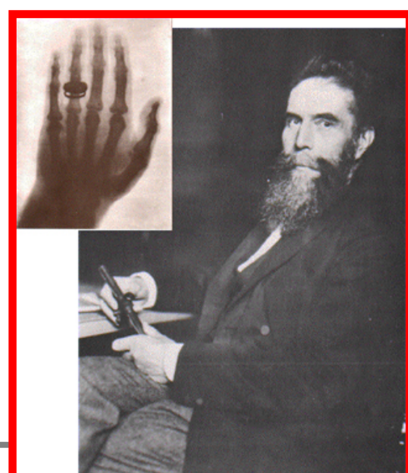
XFELs



Peak Brightness

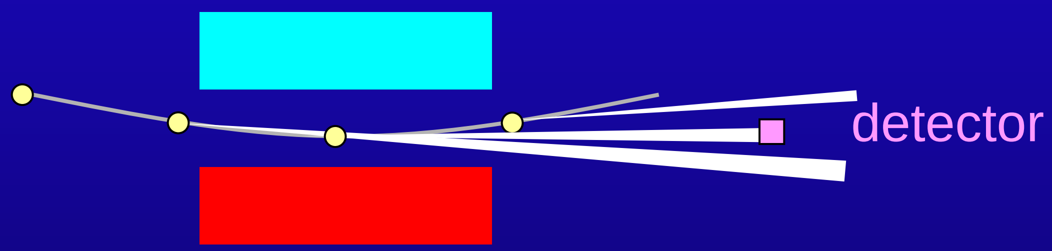


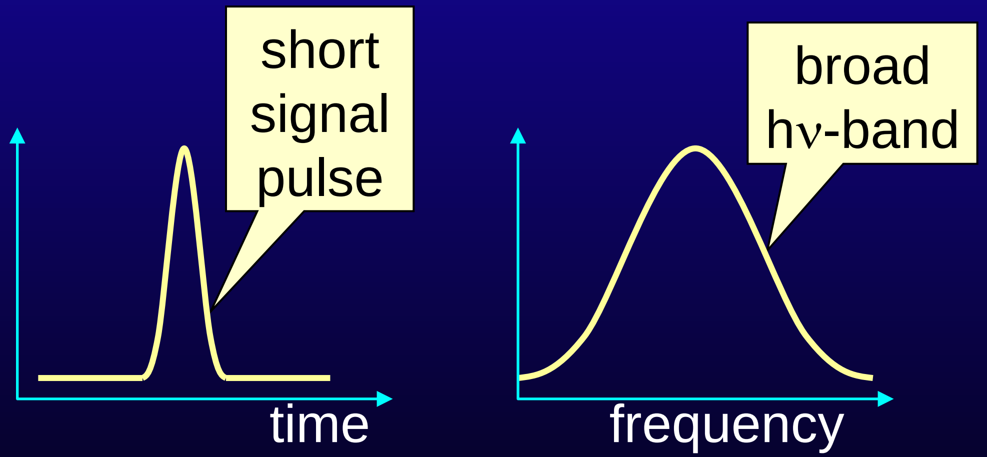
Bertha Roentgen's hand
(exposure: 20 min)



3 types of storage ring sources:

1. Bending magnets: $B \sim N_e$

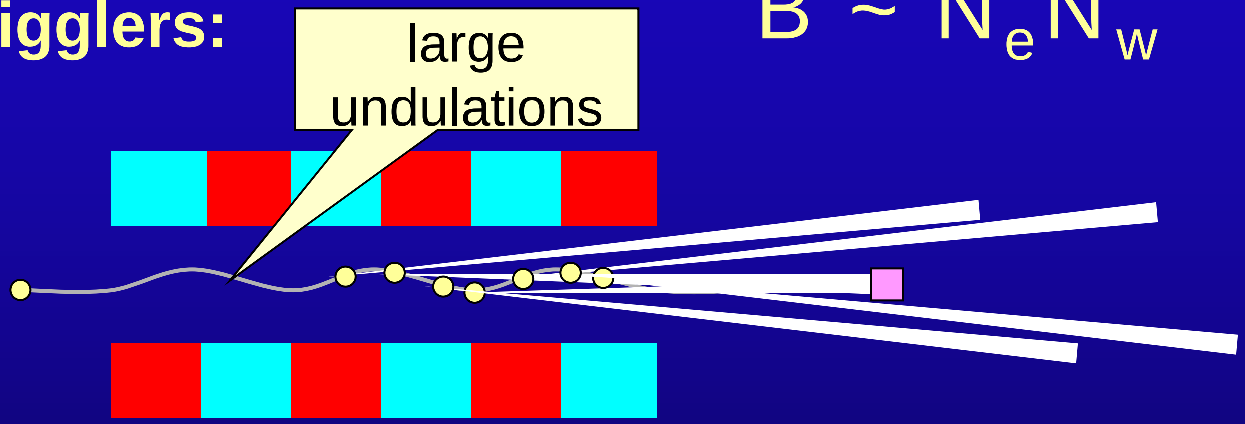


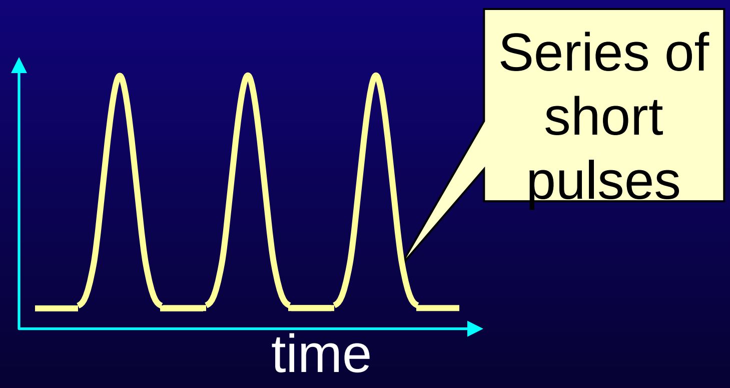


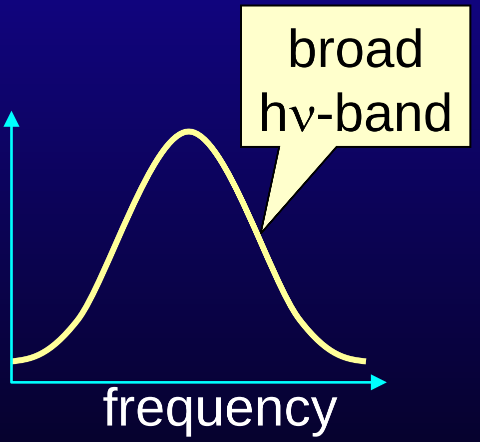
3 types of storage ring sources:

2. Wigglers:

$B \sim N_e N_w$ x10

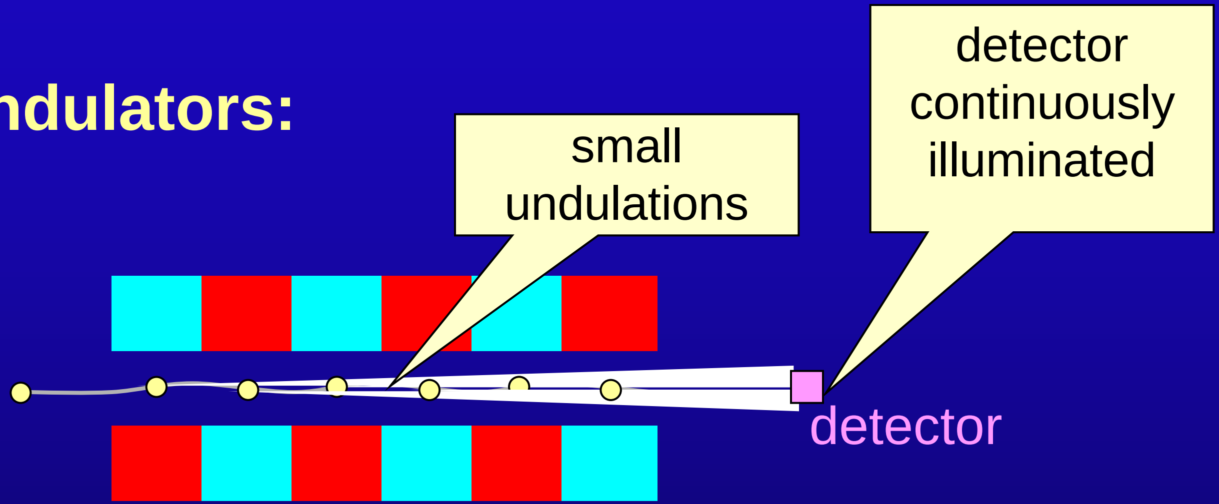




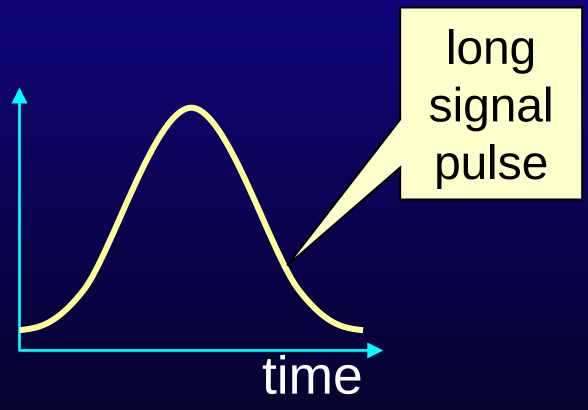


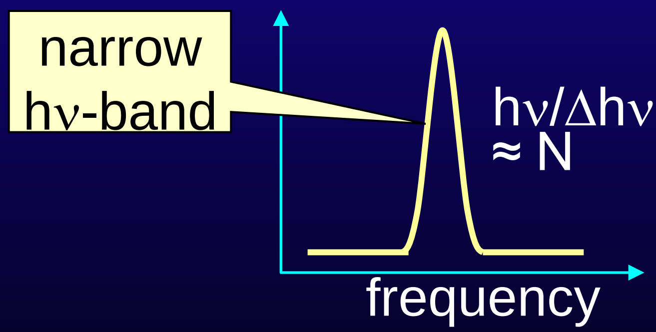
3 types of storage ring sources:

3. Undulators:

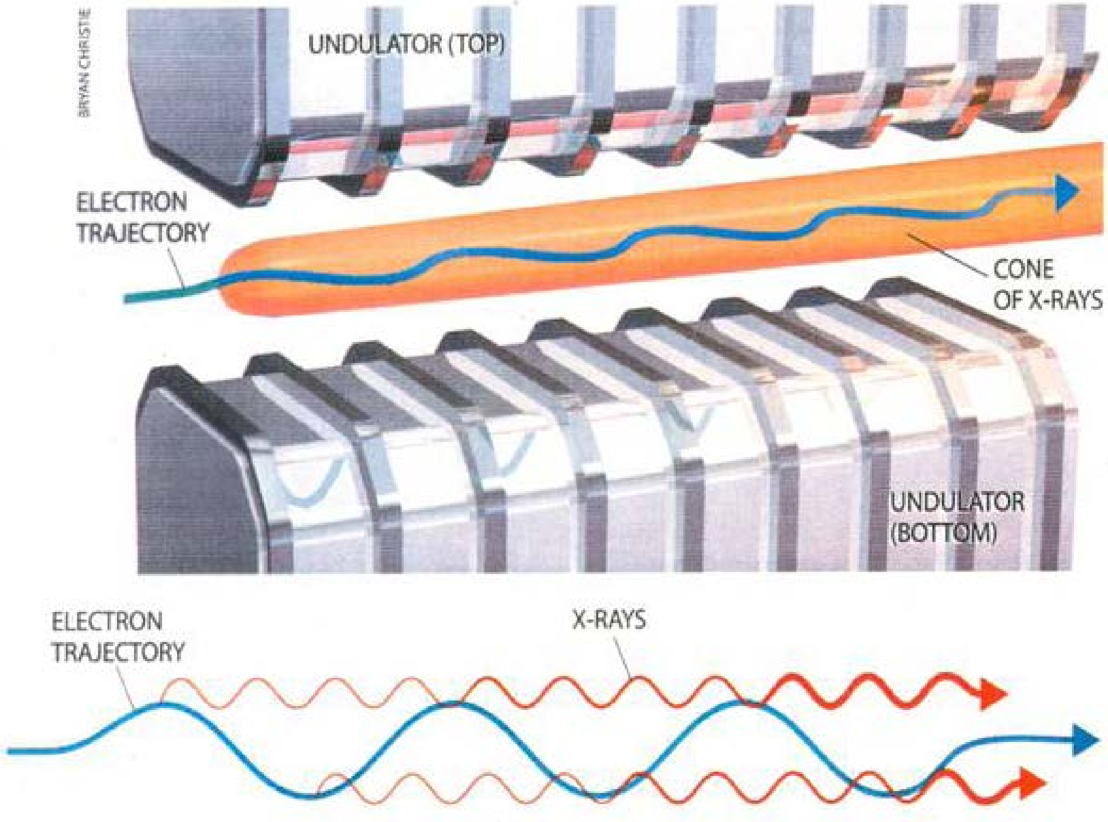


$$B \sim N_e N_u^2 \quad x10^3$$





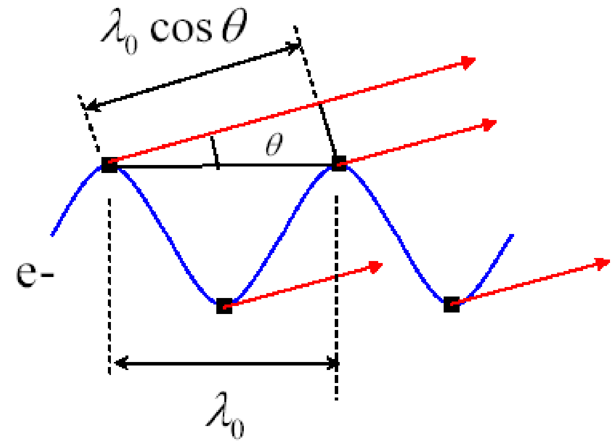
Undulators



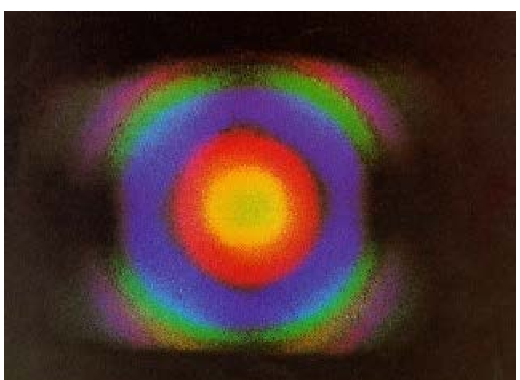
$$T_{obs} = T_{emit}(1 - \beta)$$

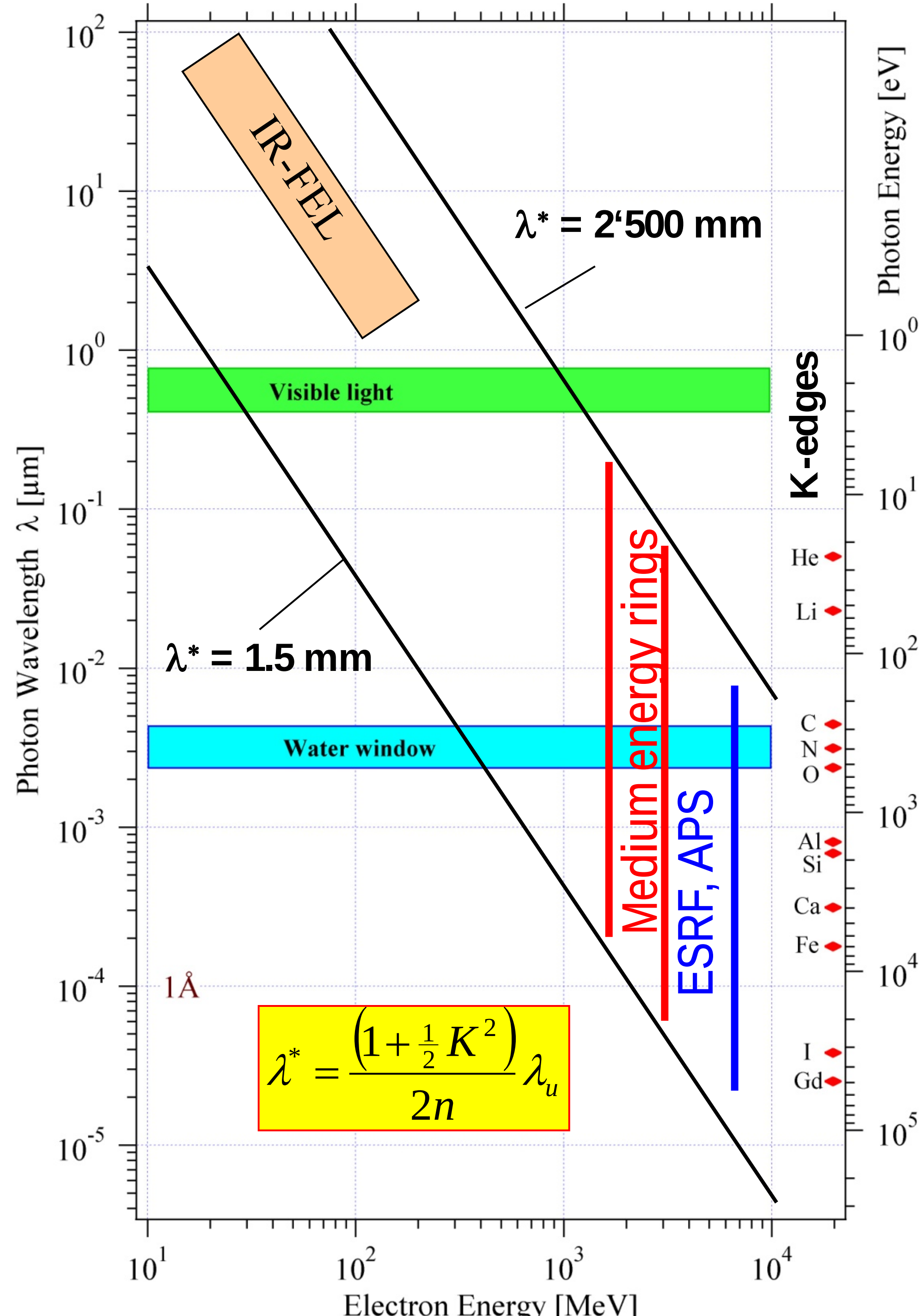
$$\lambda_{light} \approx \frac{\lambda_u}{2\gamma^2}$$

Undulator radiation

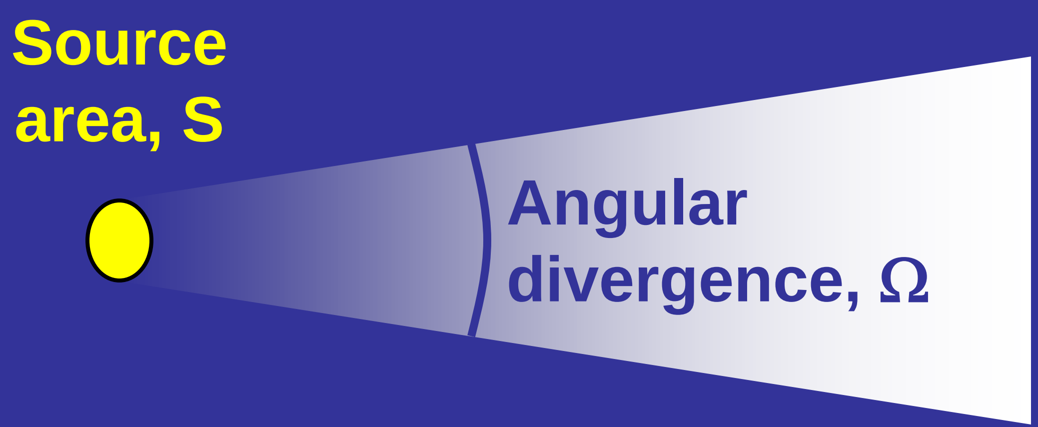


$$\lambda = \frac{\lambda_u}{2n\gamma^2}\left(1+\frac{K^2}{2}+\gamma^2\theta^2\right)$$





The electron beam “emittance”:

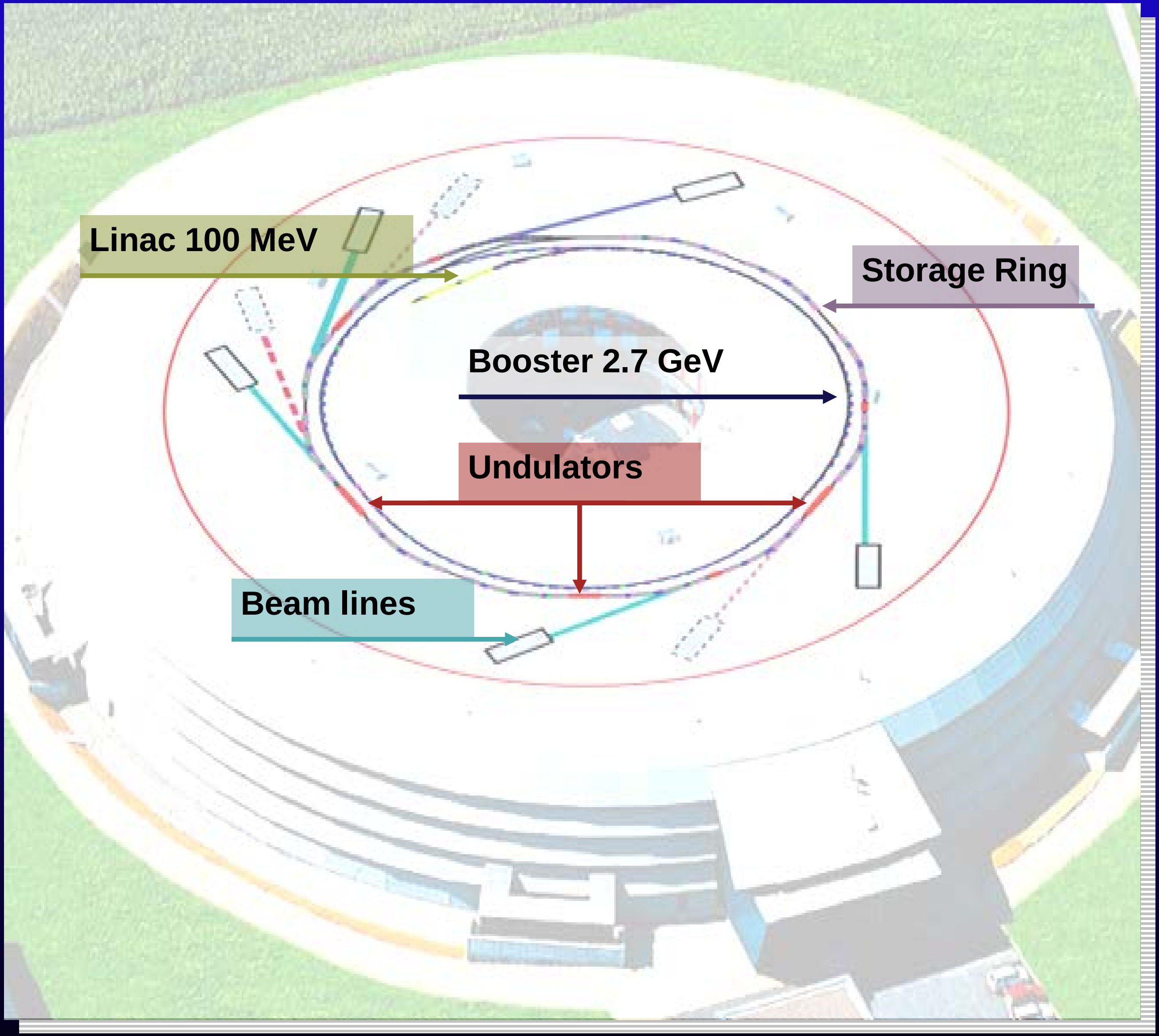


The brightness depends on the geometry of the source, i.e., on the electron beam emittance

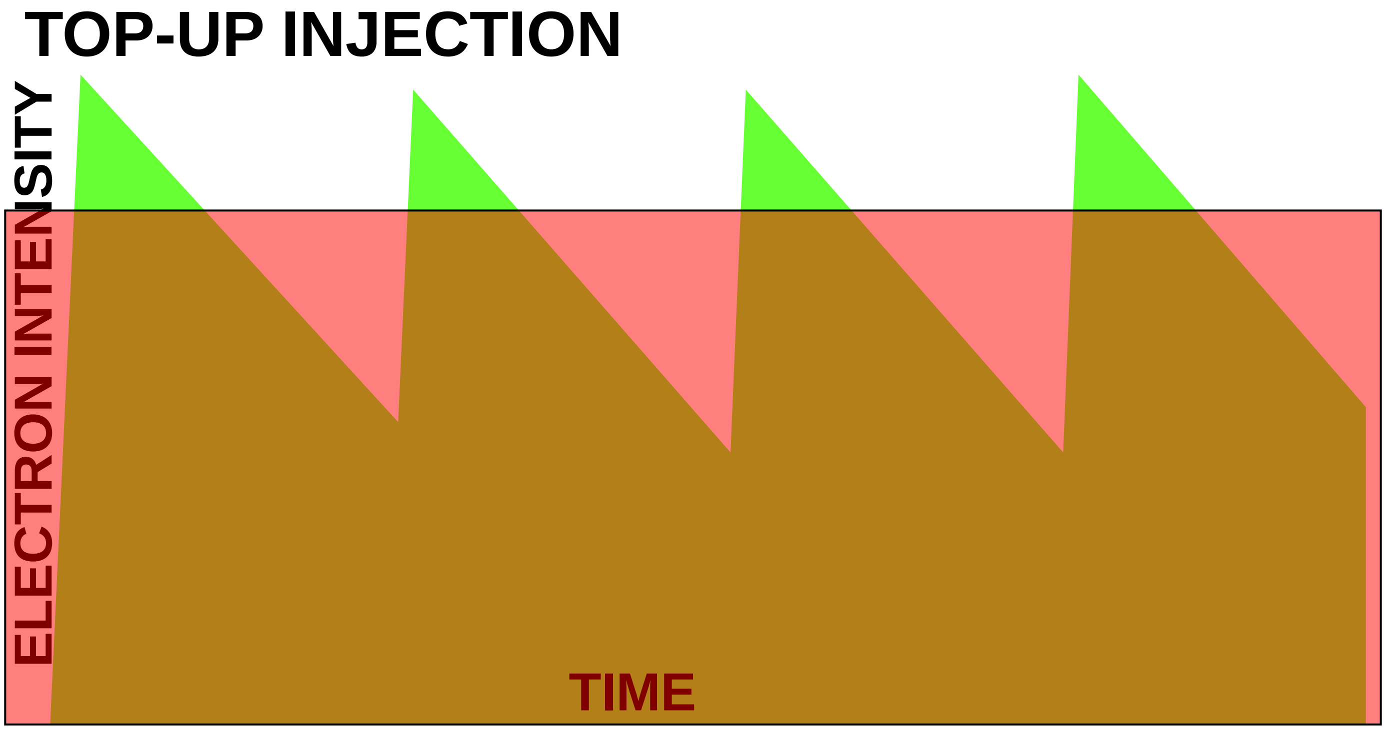
Emittance = S x Ω

Large Research Facilities: accelerator based

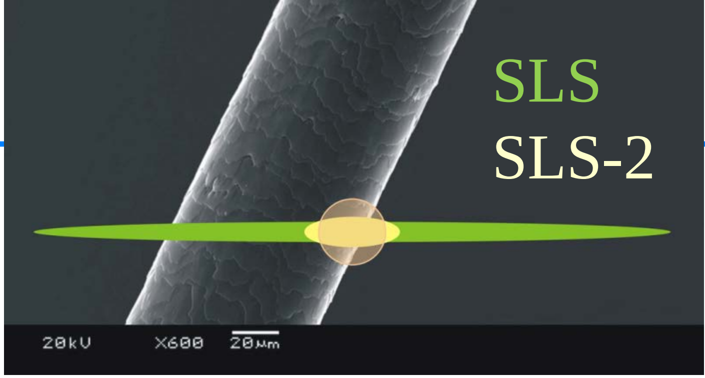
Anatomy of a light source



Top-up injection: key to stability



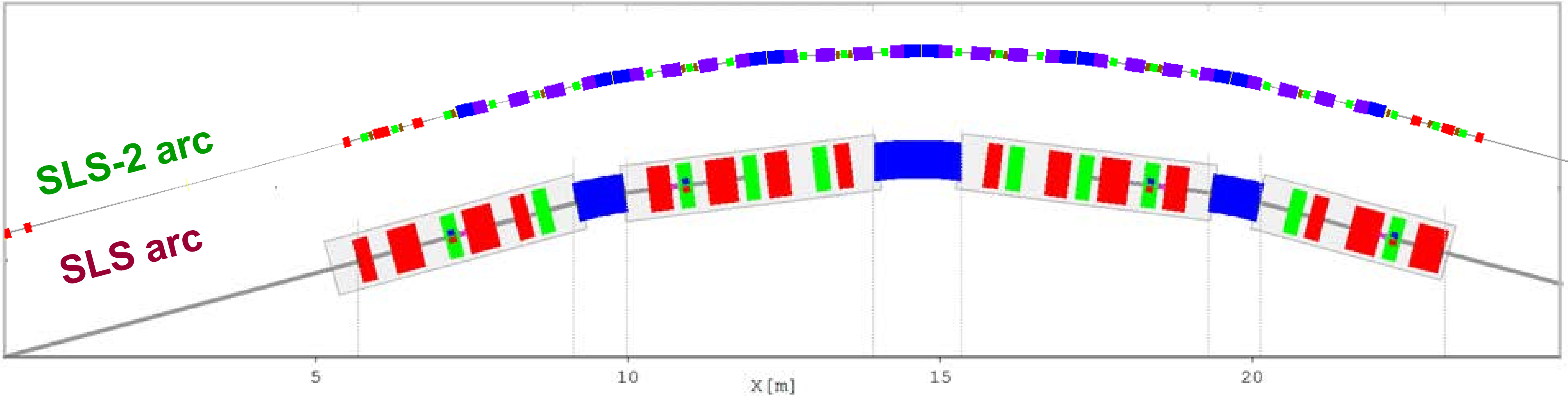
SLS2 upgrade



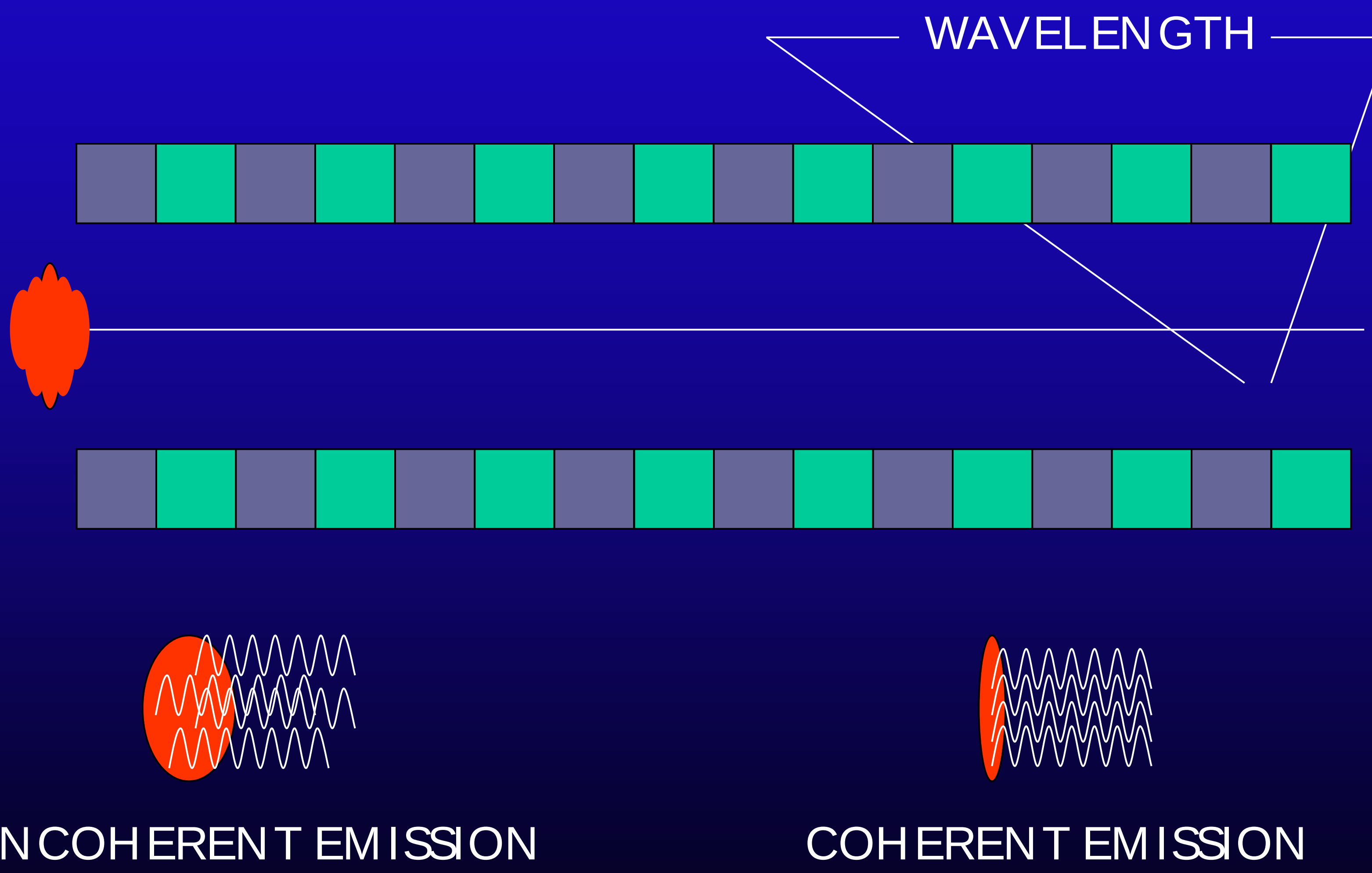
- Dramatic increase in SLS brilliance, making the facility internationally competitive for another two decades (by a factor of **20 – 50**)

- Using multibend achromat magnet lattice to replace the existing ring and upgrading all the key components necessary to maintain the stability and reliability

- Beamlines upgrade to push the envelope, utilising the increased source brilliance and coherence



MUCH HIGHER BRIGHTNESS CAN BE REACHED WHEN THE ELECTRONS COOPERATE



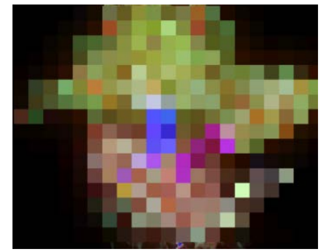
SwissFEL – a new accelerator based RI

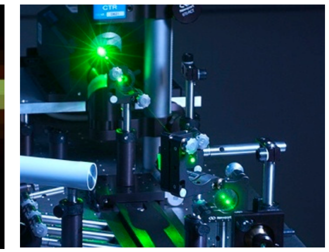
3rd gen. synchrotron

fine, slow

optical lasers

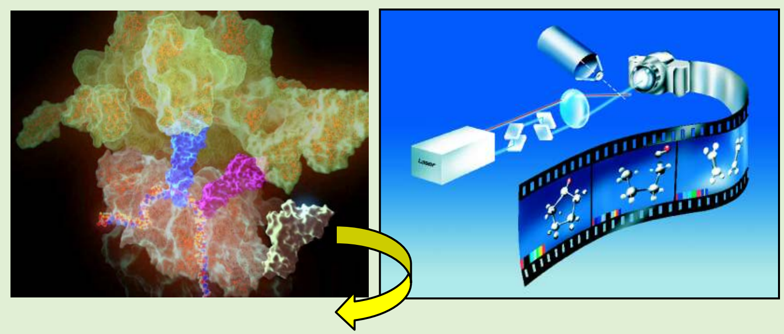
fast, coarse





SwissFEL fine **and** fast

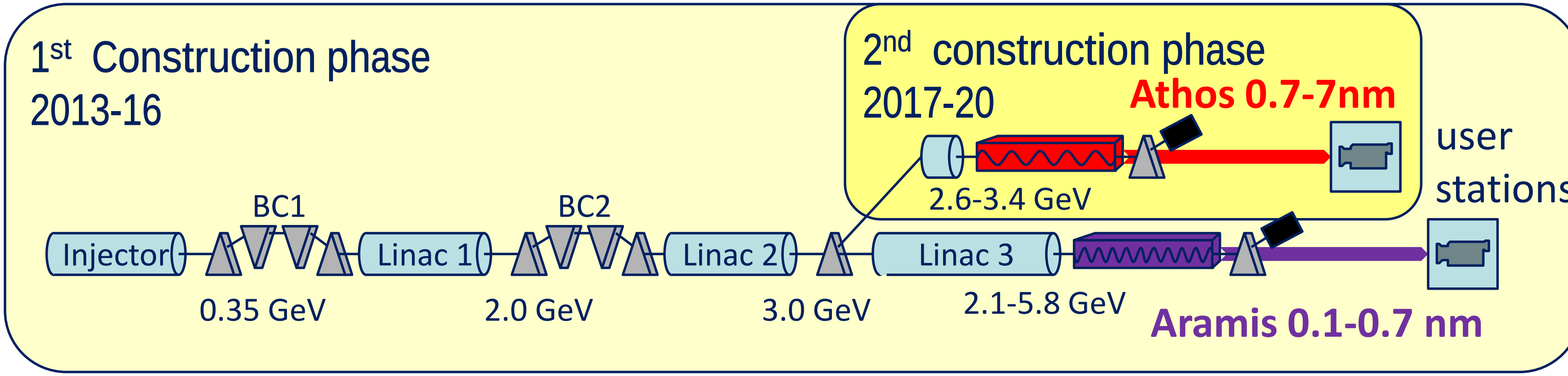
at extreme high intensity



new direct insights into chemical, physical, biological mechanisms governing our daily-life

a national free electron X-ray laser for Switzerland

SwissFEL in a nutshell



Aramis

Hard X-ray FEL, λ=0.1-0.7 nm
Variable gap, in-vacuum Undulators
First users 2017
Operation modes: SASE & self seeded

Athos

Soft X-ray FEL, λ=0.7-7.0 nm
Variable polarization, Apple II undulators
First users 2019 ?
Operation modes: SASE & self seeded

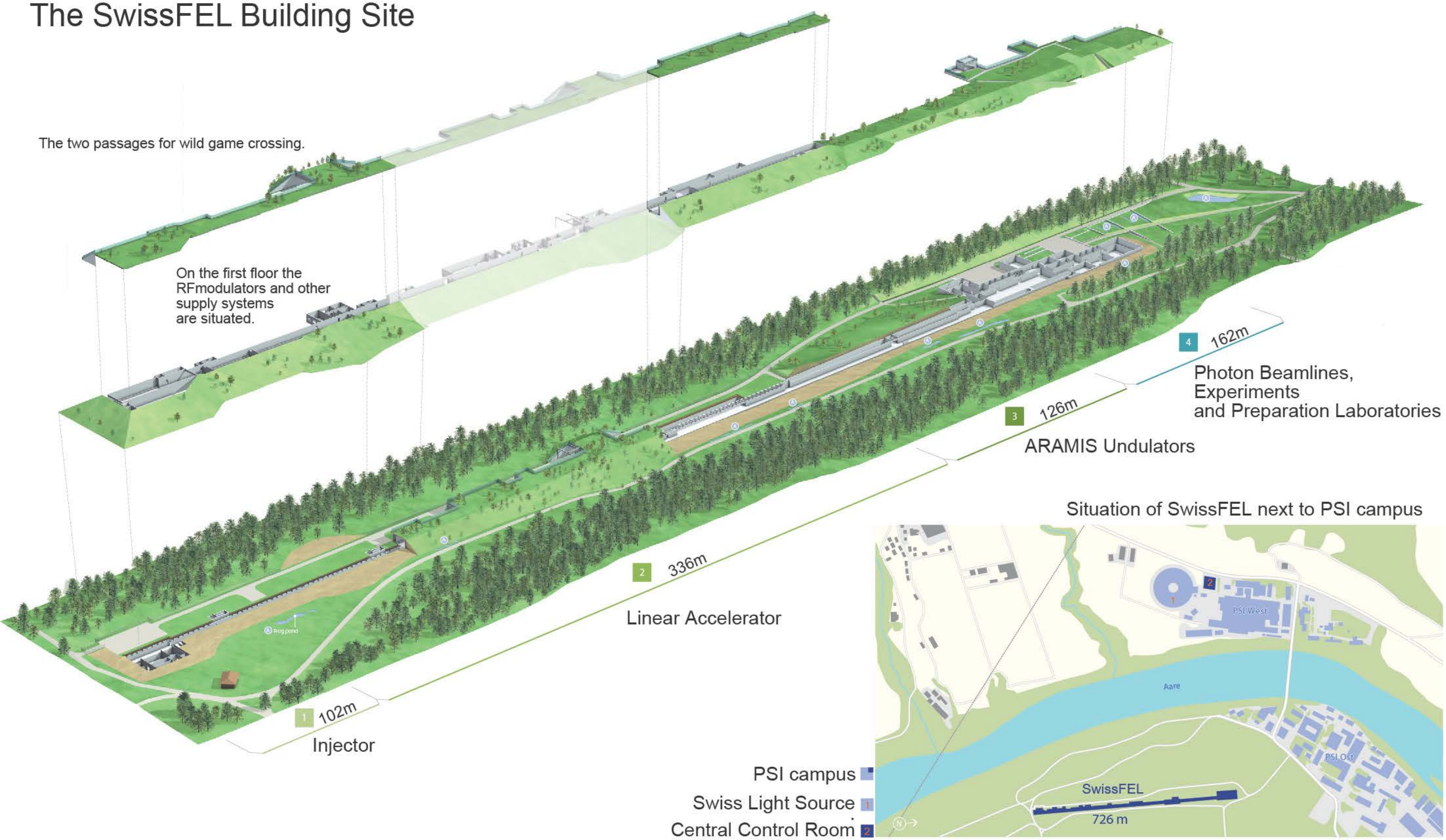
Main parameters

Wavelength from	1 Å - 70 Å
Photon energy	0.2 - 12 keV
Pulse duration	1 fs - 20 fs
e^- Energy	5.8 GeV
e^- Bunch charge	10 - 200 pC
Repetition rate	100 Hz

H. Braun

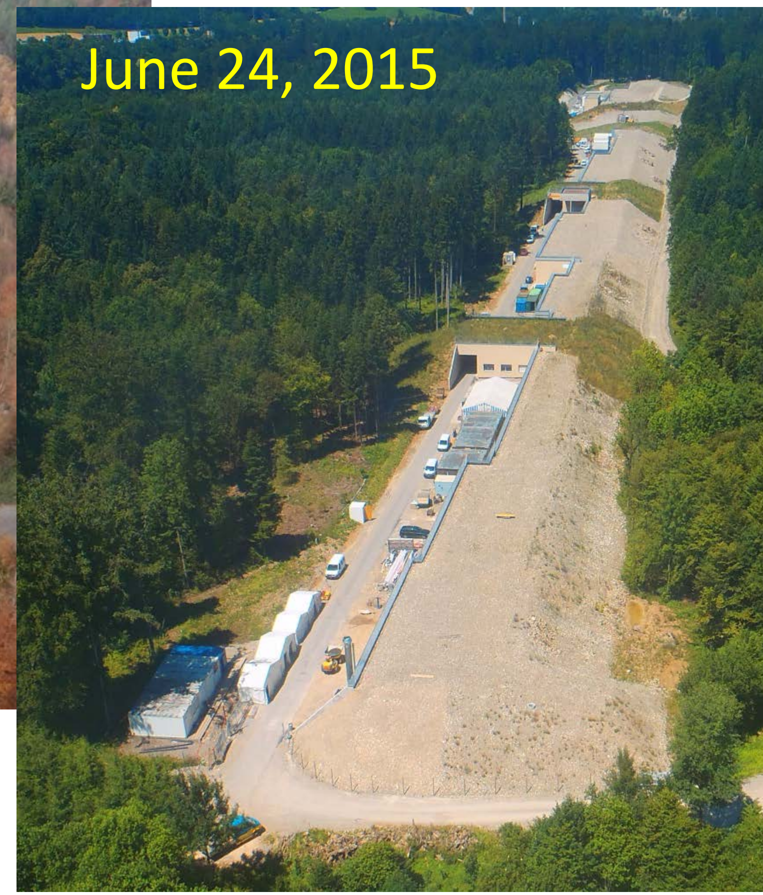
SwissFEL Building

The SwissFEL Building Site



H. Braun

SwissFEL Building progress



Building key figures

overall length: 740 m

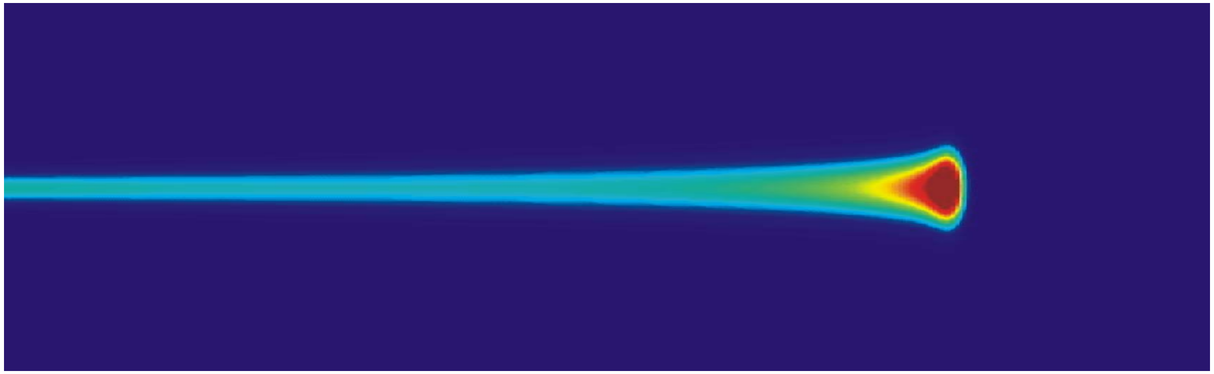
soil movements: 95’000 m3

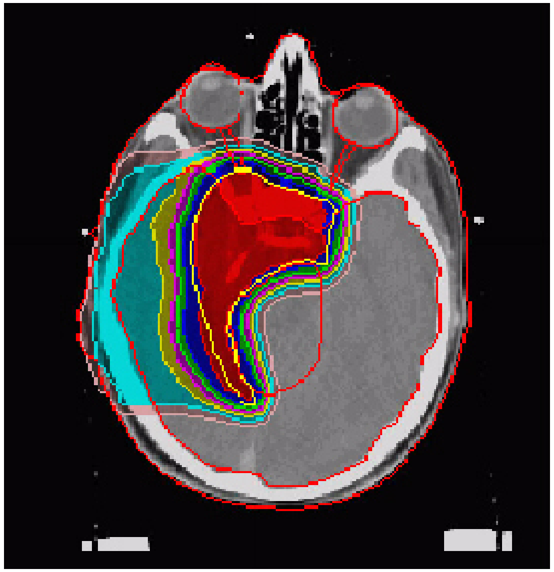
casted concrete: 21’000 m3 or 50’000 t

H. Braun

Medical applications

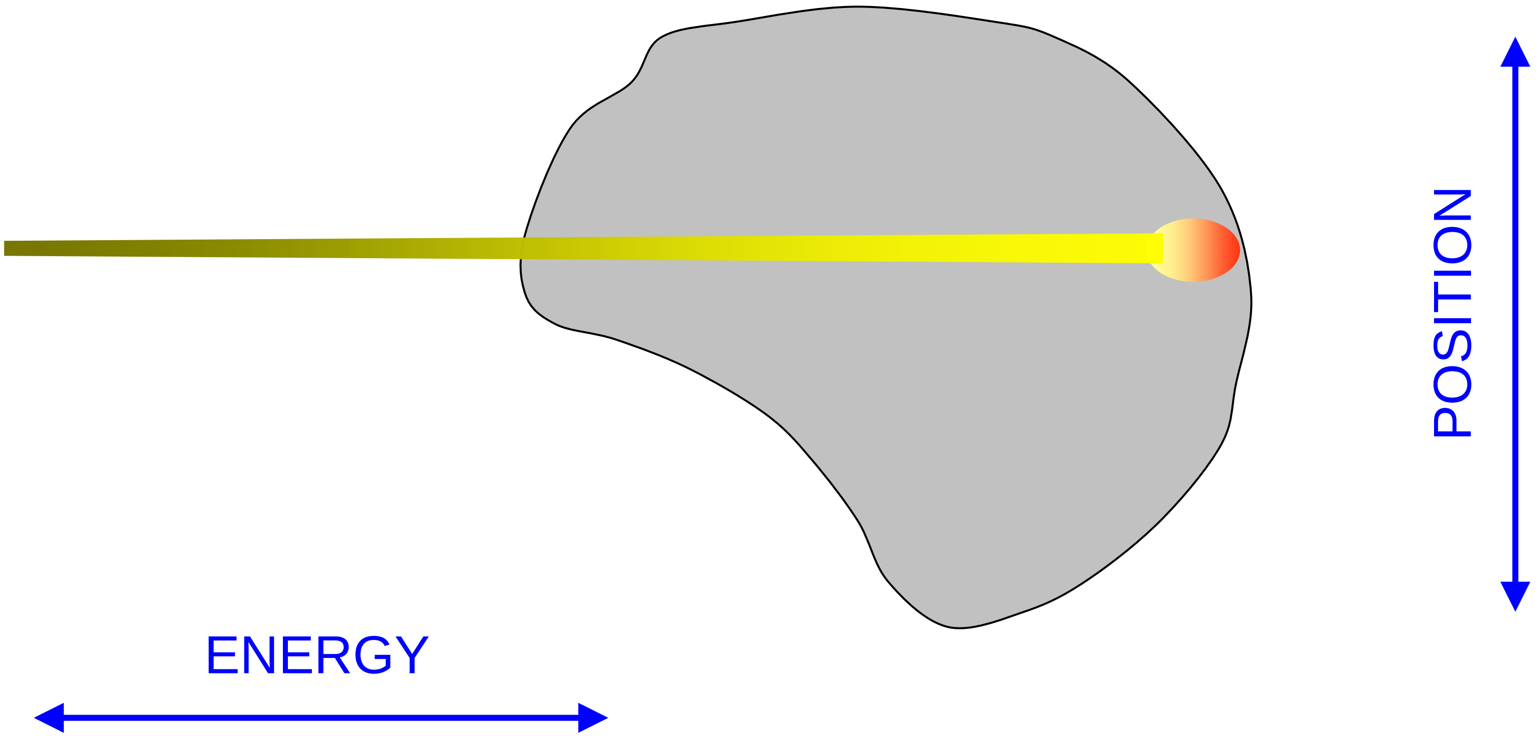
BRAGG PEAK





... ALLOWS THE TREATMENT OF DEEP INSIDE LYING TUMORS WITH BEST PROTECTION OF THE SURROUNDING

SPOT SCANNING



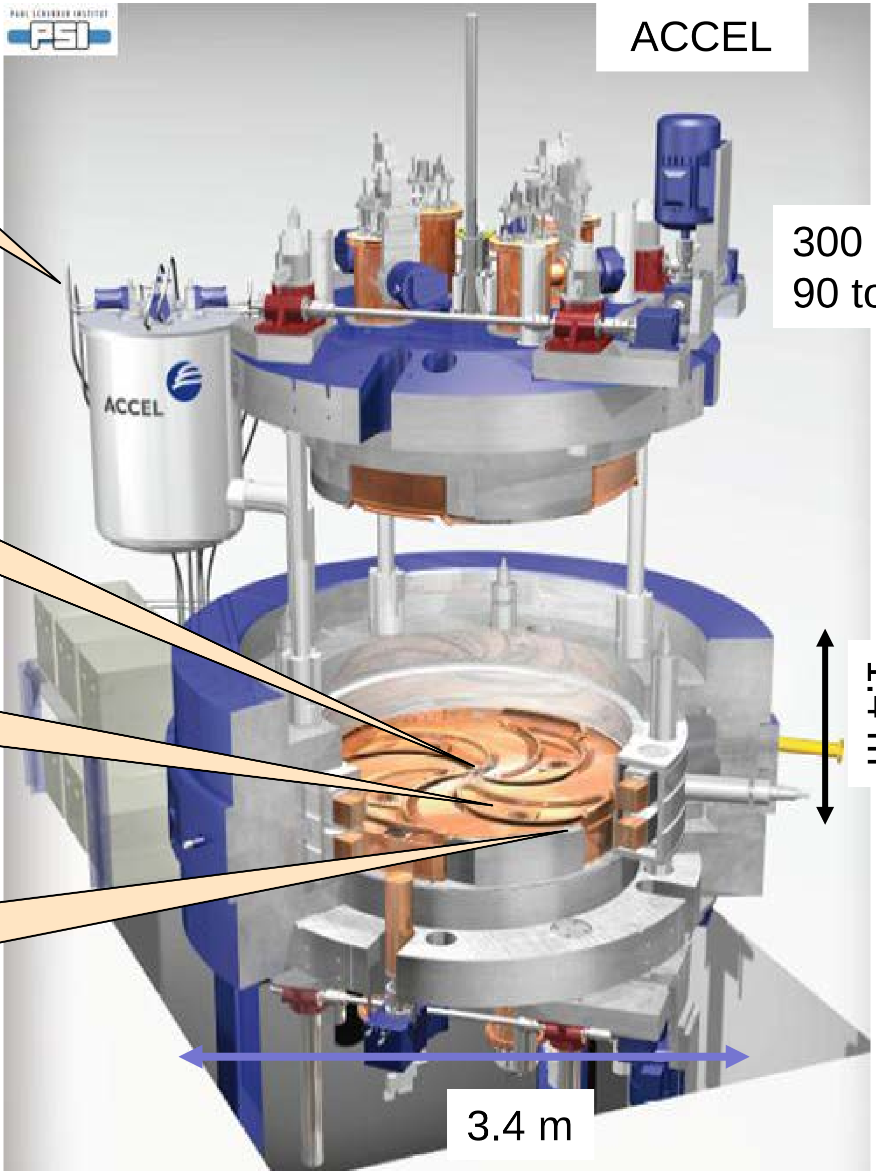
250 MeV proton cyclotron (ACCEL/Varian)

Closed He system
4 x 1.5 W @4K

Proton source

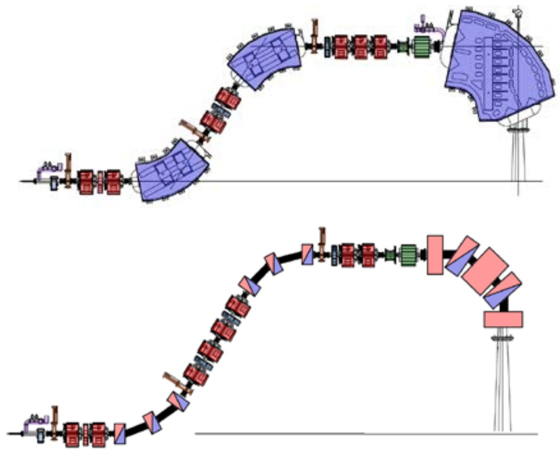
superconducting coils
=> 2.4 – 3.8 T

4 RF-cavities
≈100 kV on 4 Dees



PROSCAN: very high availability (≈ 98 %!)

Design study of:
Gantry with Superconducting magnets



Gantry 2

superconducting Gantry

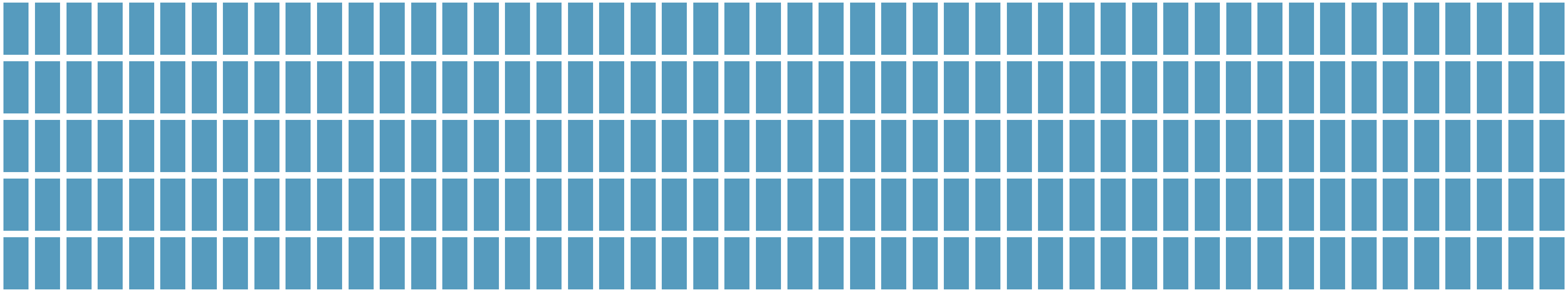
EXPECTED IMPROVEMENTS:

⇒ NOT much smaller, but:

⇒ Weight: 200 tons → 50 tons
⇒ Field size: 12 x 20 cm^2 → 20 x 20 cm^2
⇒ Energy acceptance 1.5% → 20 %

Hadron Market

Patients Treated Worldwide



50,000,000 patients treated with **photons**

100,000 patients treated with **hadrons**


To make the benefits of Hadrontherapy available to more people:
Reduce cost of systems
Reduce footprint
Simplify systems
Simplify operation
VARIAN medical systems

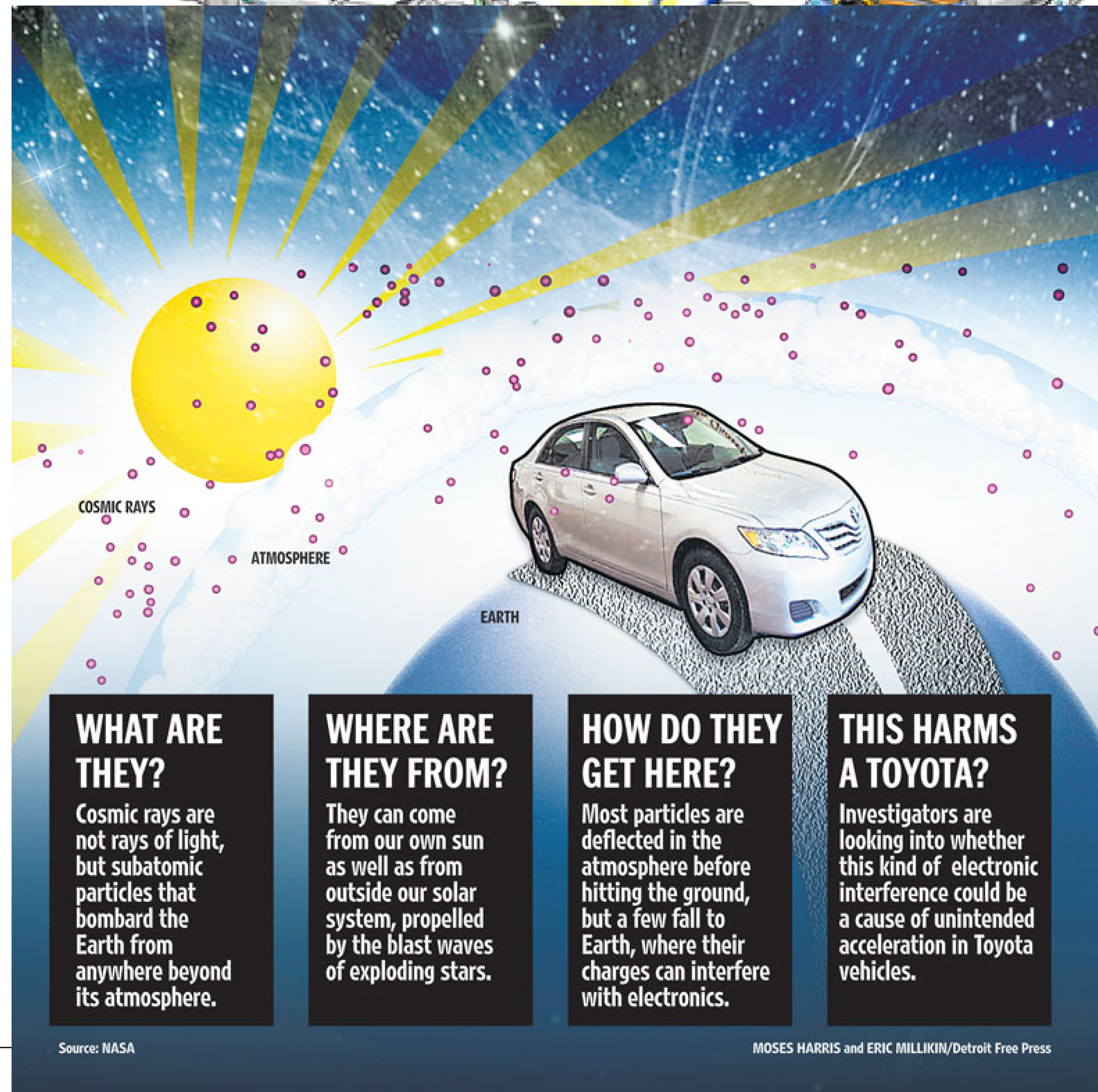
Google News

'Accelerator'

⇛ many Toyota links!

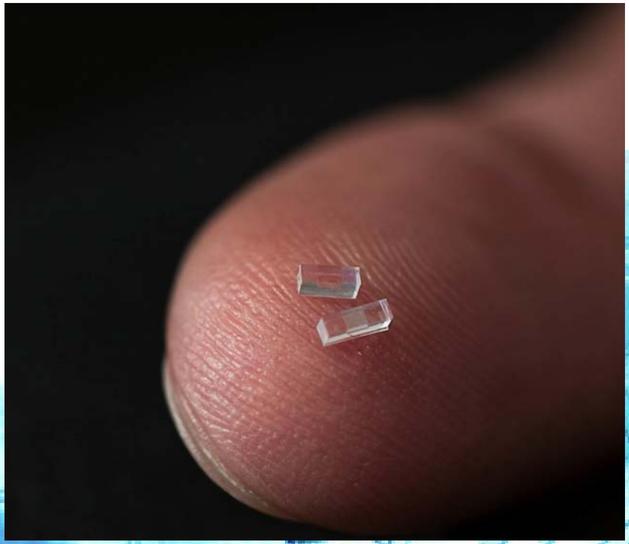
'Particle accelerator'

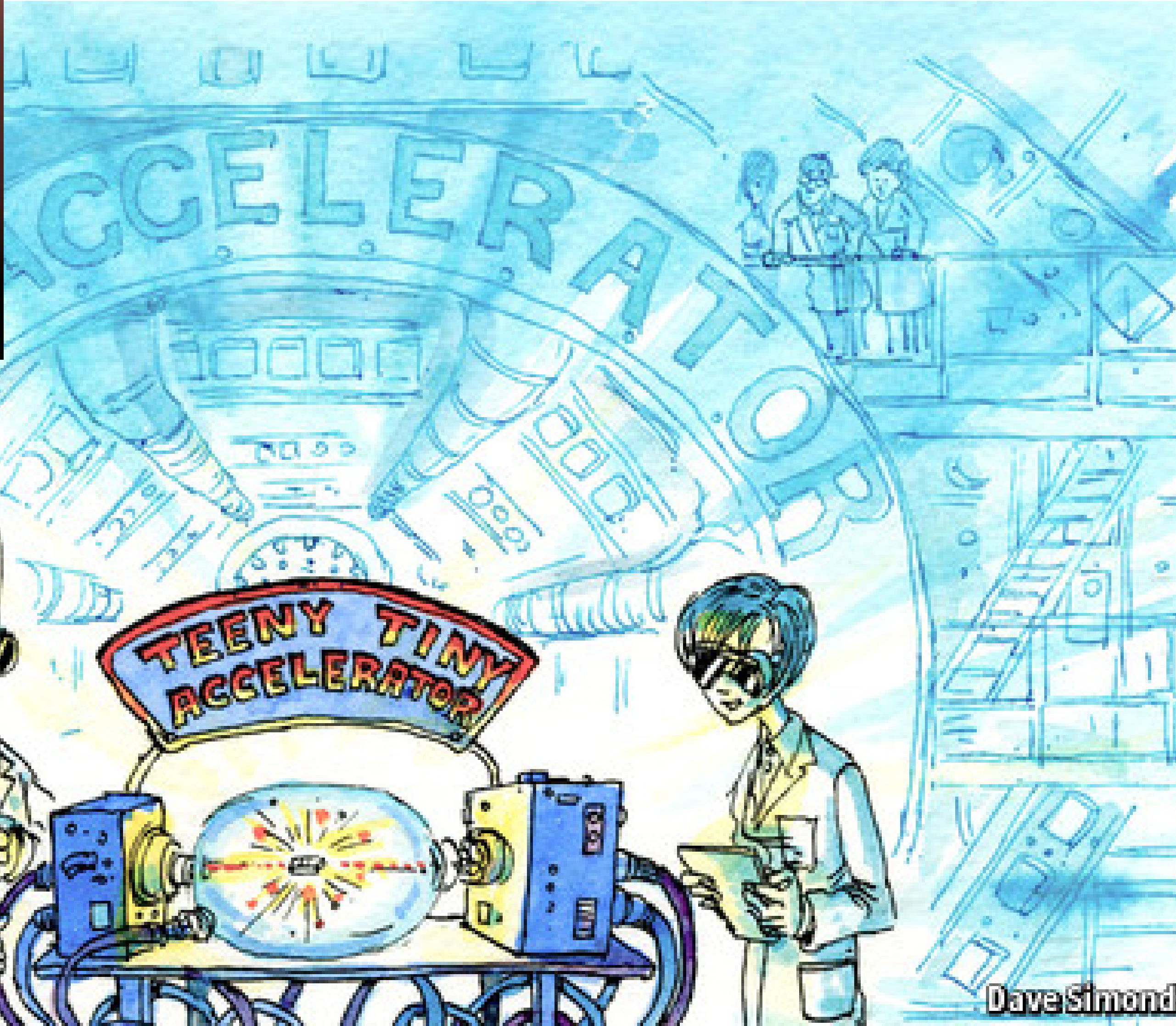
⇛ gave this link:



Accelerator on a chip

The Economist





The future

SwissFEL

Aramis 2017 ⇒

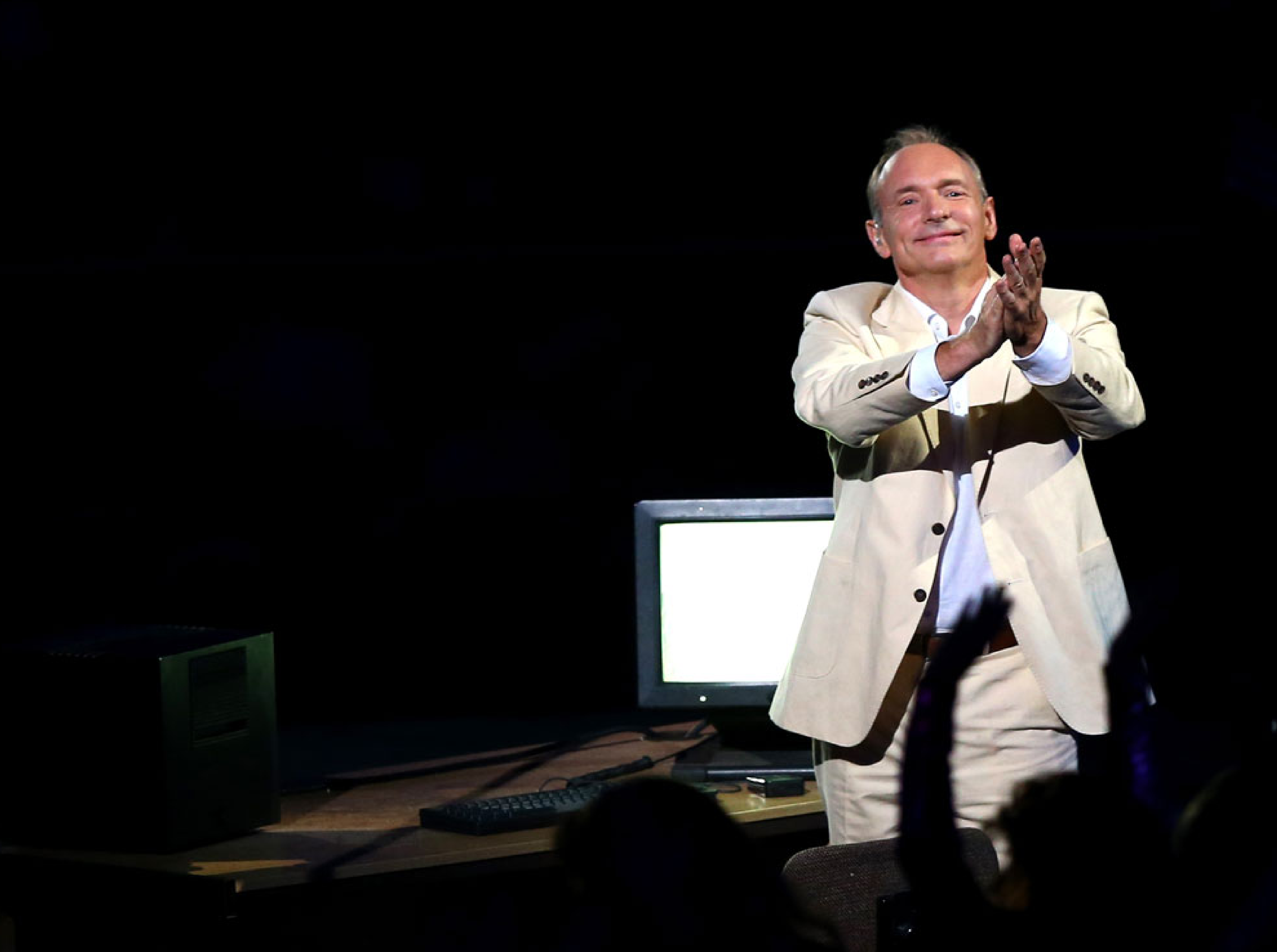
Athos 2020 ⇒

SLS2

2023 ⇒

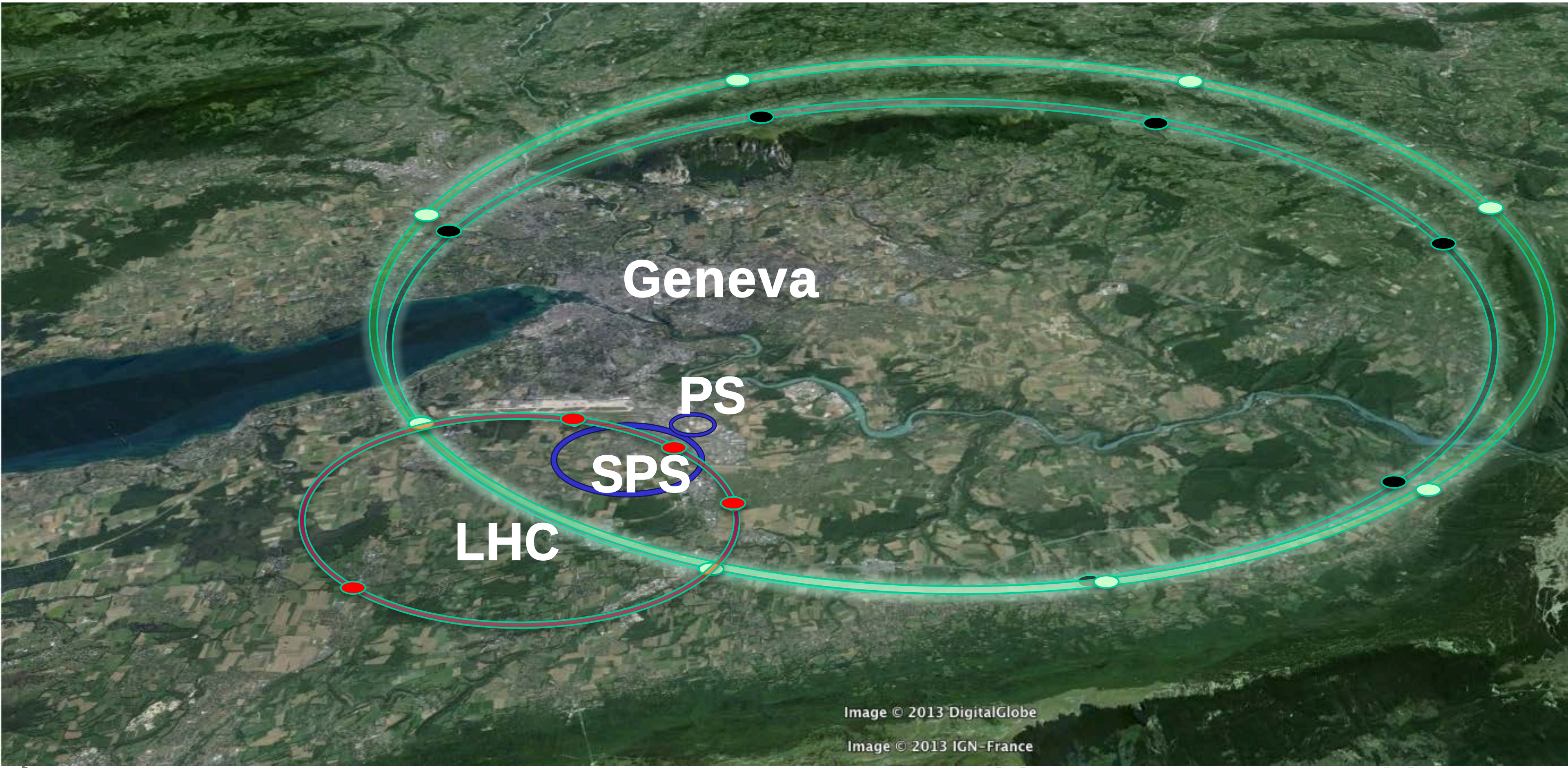
Engines of Discovery

Le Matin
CERN
Le boson de Higgs fêté comme une rock-star
The Economist
July 7th-13th 2012
Economist.com
In praise of charter schools
Britain's banking scandal spreads
Volkswagen overtakes the rest
A power struggle at the Vatican
When Lonesome George met Nora
A giant leap for science
the guardian
Stuart Jeffries Lucy Mangan Martin Kettle Zoe Williams Richard Sennett
Picture that changes the way we see the universe for ever
Osborne accuses Labour
EUREKA! BOFFINS
ND 'GOD'S GLU
HIGGS BOSON
HOMOPHOBIA, HIP-HOP AND THE STAR WHO CAME OUT
EUR
OH
It may sound nuts, but it's like a bolt..
COMMENT
One of the greatest discoveries in history of science



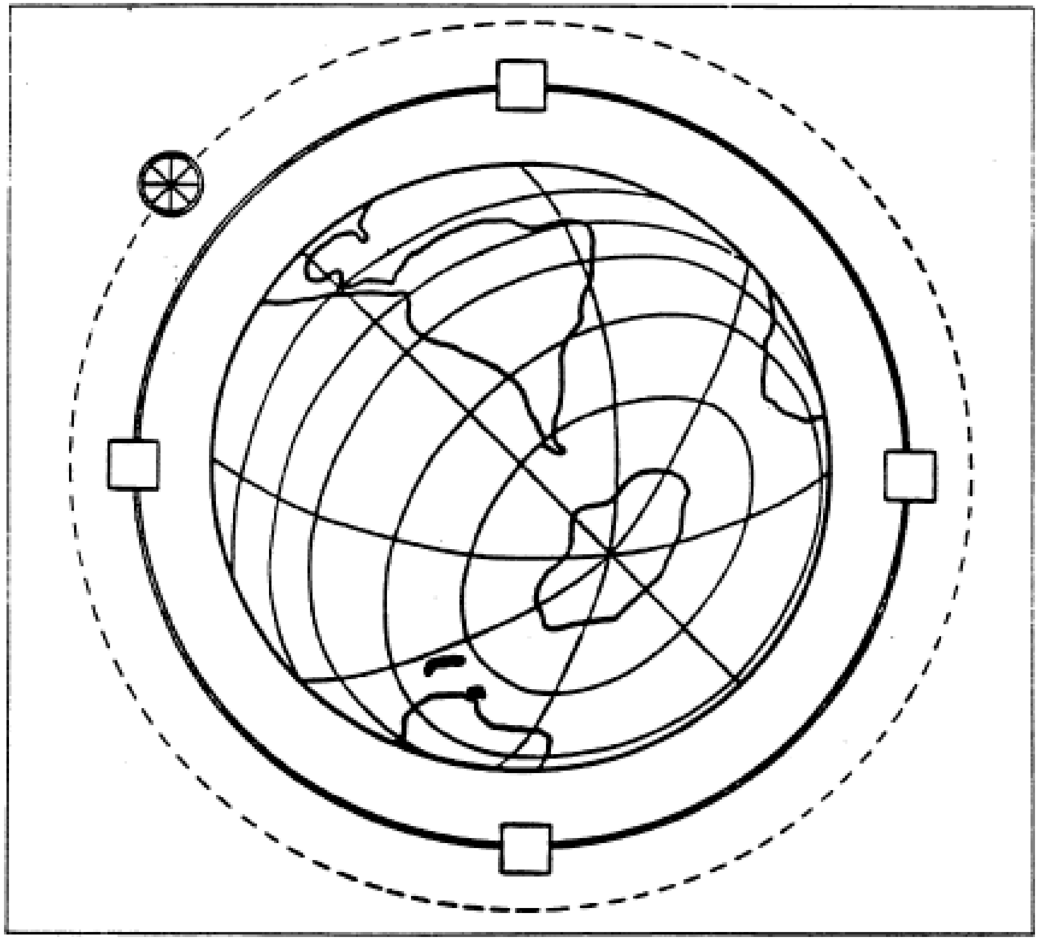
Credit: CERN

FCC development: High Energy LHC Phase0 ?



LHC	HE-LHC	FCC-hh	FCC-hh
27 km, 8.33 T	27 km, 20 T	80 km, 20 T	100 km, 16 T
14 TeV (c.o.m.)	33 TeV (c.o.m.)	100 TeV (c.o.m.)	100 TeV (c.o.m.)

Enrico Fermi’s (1954) Space-Based World Machine



From a 1954 Slide by Enrico Fermi, University of Chicago Special Collections.

Cosmic accelerators

Constellation Pictor: Pictor A X-ray image

- X-ray jet originating near a giant black hole