How innovation arises in science – a random walk through particle physics

Workshop for the Austrian Chamber of Commerce WKÖ / Terra Mater Mindcollider
26 – 27 September 2024

Edda Gschwendtner, CERN

“How innovation arises in science?”

ChatGPT:

Iteration

Open-mindedness

Interdisciplinary Approach

Risk-taking

Experimentation

Peer review

Curiosity

Collaboration

Tools and techniques

Data Analysis

insight

Creativity

Critical thinking

Funding

Observation

Prototype

Challenge asumptions

Problem indentification

Simulations

Adaption

Theoretical frameworks

Technology

Scientific Method

Alternative perspectives

Pattern recognition

Hypothesis

Knowledge transfer

Application

Vision

Failure

Breakthrough

Proof-of-concept

Serendipity

Trial and Error

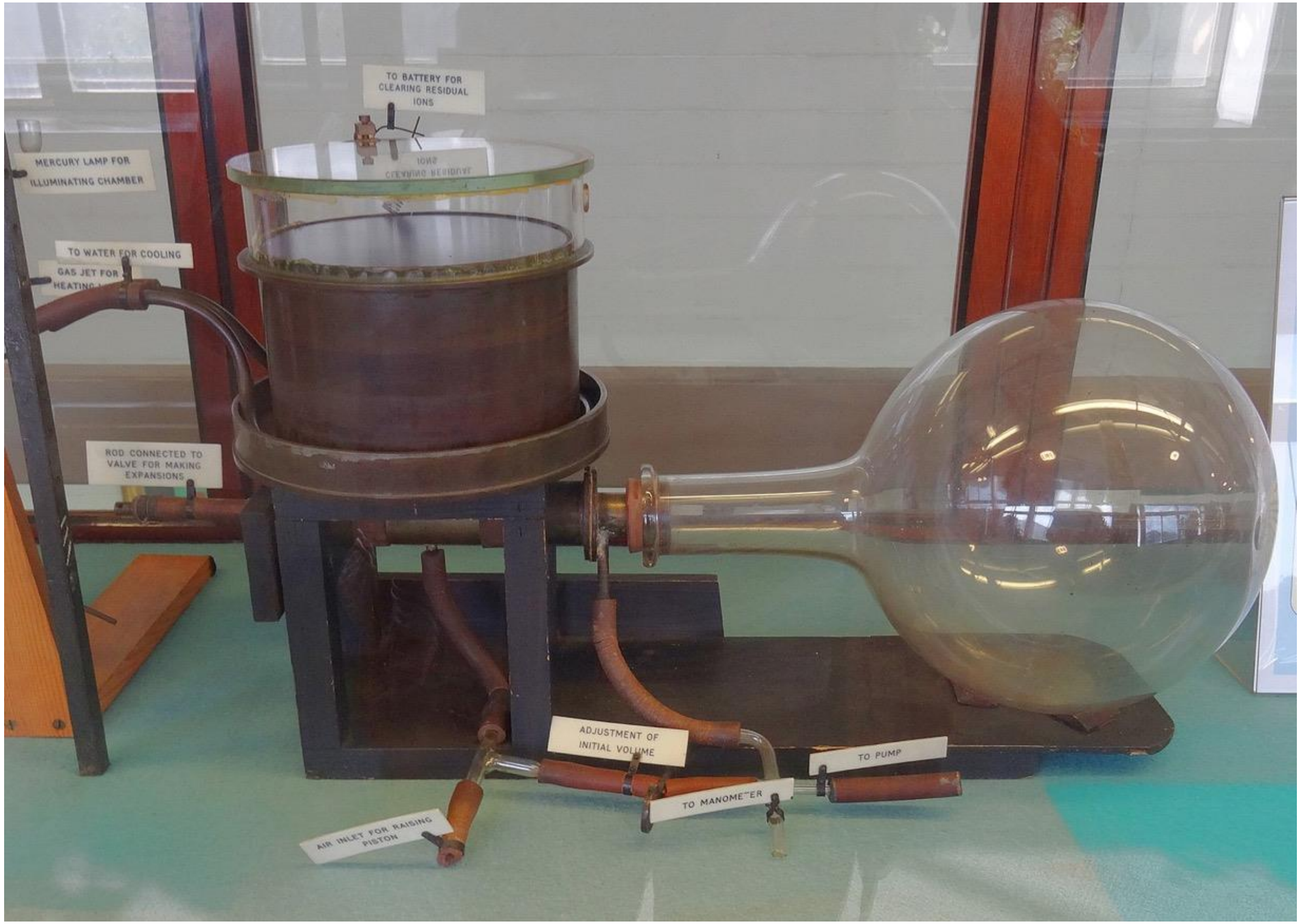
Impact

Disruption

Future-oriented

Regulation

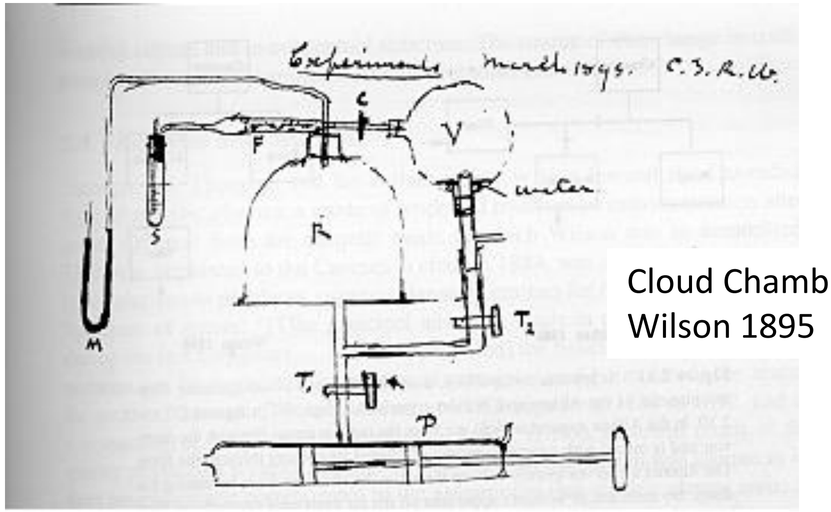
Cloud Chamber



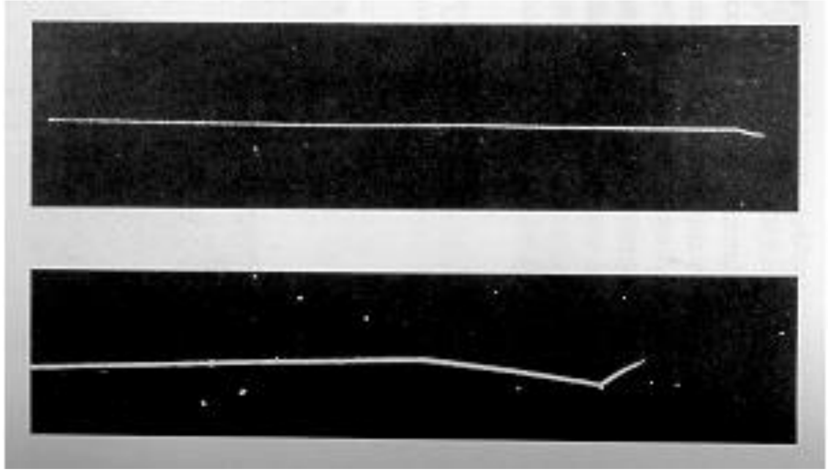
Wilson Cloud Chamber 1911

Cloud Chamber

Charles Thomson Rees Wilson, * 1869, Scotland:
Wilson was a **meteorologist** who was **interested in cloud formation** initiated by electricity.



Cloud Chamber, Wilson 1895



Early alpha-ray picture, Wilson 1912

1895 arrived at Cavendish Laboratory.

Wilson used a ‘dust free’ chamber filled with saturated water vapor to study the cloud formation caused by ions present in the chamber.

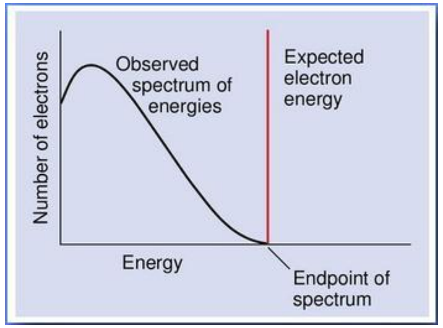
- C. Röntgen discovered X-rays in 1895.

Wilson used an X-Ray tube to irradiate his Chamber and found ‘a very great increase in the number of the drops’, confirming the hypothesis that ions are cloud formation nuclei.

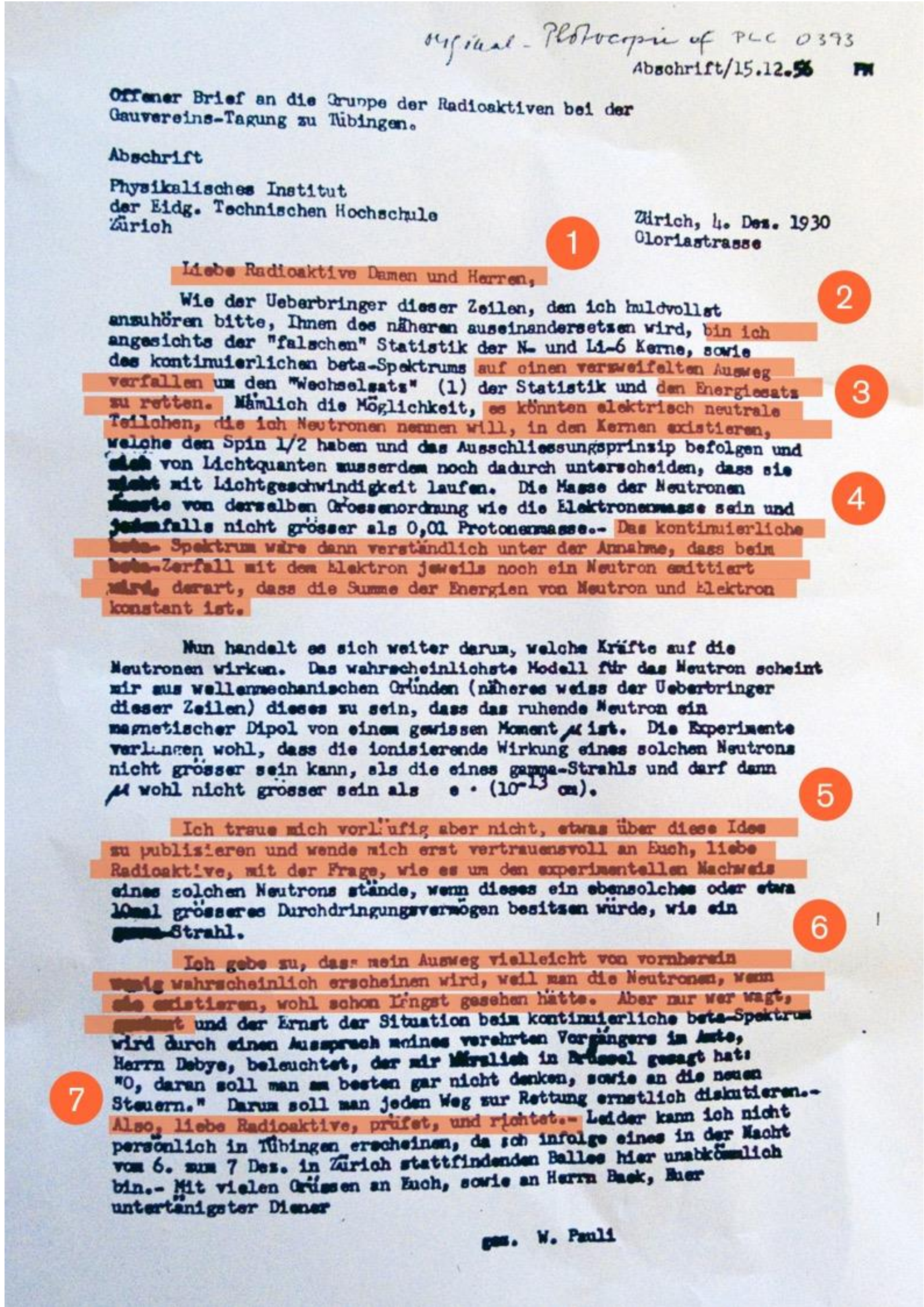
- H. Bequerel discovered Radioactivity in 1896. Produces same effect in cloud chamber.
- 1899 J.J. Thomson claimed that cathode rays are fundamental particles → electrons.
- Rays for radioactivity consist of alpha, beta and gamma particles (E. Rutherford).

1911: Wilson had track photographs from from alpha rays, X-Rays and gamma rays (high speed photography developed).

Neutrino



- 1930 postulated by Pauli to explain how beta decay can conserve energy, momentum, and angular momentum.
  - → first called it 'neutron' and considered that it was emitted from the nucleus.



Original - Photocopie of PLC 0393

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

① Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, ② bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. ③ Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- ④ Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

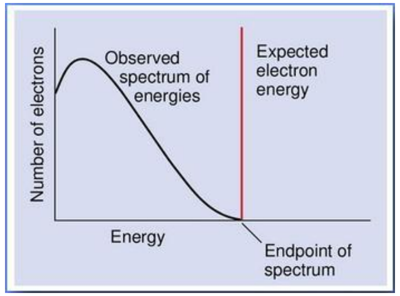
⑤ Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

⑥ Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir mündlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- ⑦ Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

Wolfgang Pauli,
Letter to the group of 'Radioaktiven', 1930

Neutrino



- 1930 postulated by Pauli to explain how beta decay can conserve energy, momentum, and angular momentum.
  → first called it 'neutron' and considered that it was emitted from the nucleus.

- 1932/33 Fermi called it now 'neutrino' in Paris and Solvay conferences. Edoardo Amaldi coined the word.

- **1934: Fermi's theory of beta decay** combines neutron and neutrino:
  - n → p + e +anti-neutrino_e

- **1938: indirect measurement: simultaneous cloud-chamber measurement of electron and recoil of the nucleus.**

- 1956: F. Reines and C. Cowan: first direct measurement in gold mine in South Africa:
  - beta capture: anti-neutrino_e +p → n +e+ ➔ measure 2 gammas (e+e- annilation and recoil gamma).

Motivation:

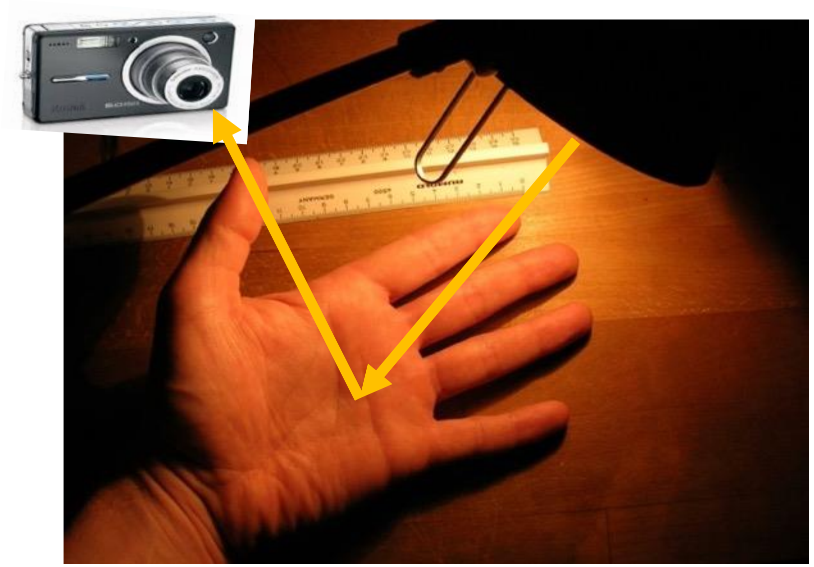
- Investigate the smallest building blocks of matter.
- Produce massive particles that are either unknown or predicted by theories.

How?

- Explore particle collisions at even higher energies.

Why Do We Need Particles at Even Higher Energies?

Pattern of the scattered light → structure of the hand.

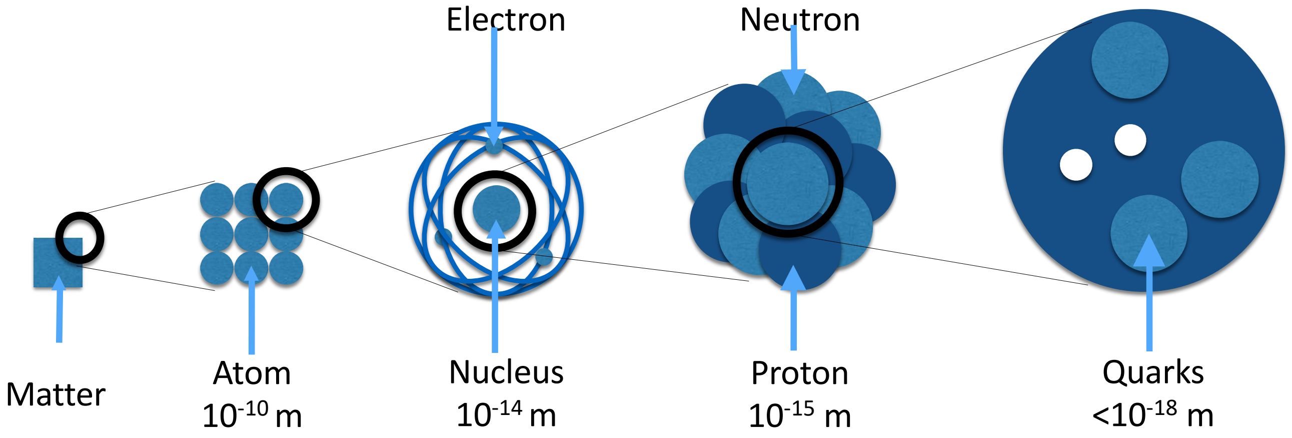


Visible light ~ 10^{-6} m = 1 micrometer = 0.001mm ~ size of a bacterium

Higher particle energy → smaller wavelength → smaller structures

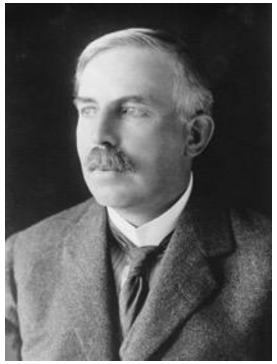
Accelerators are Super-Microscopes !

Why Do We Need Particles at Even Higher Energies?



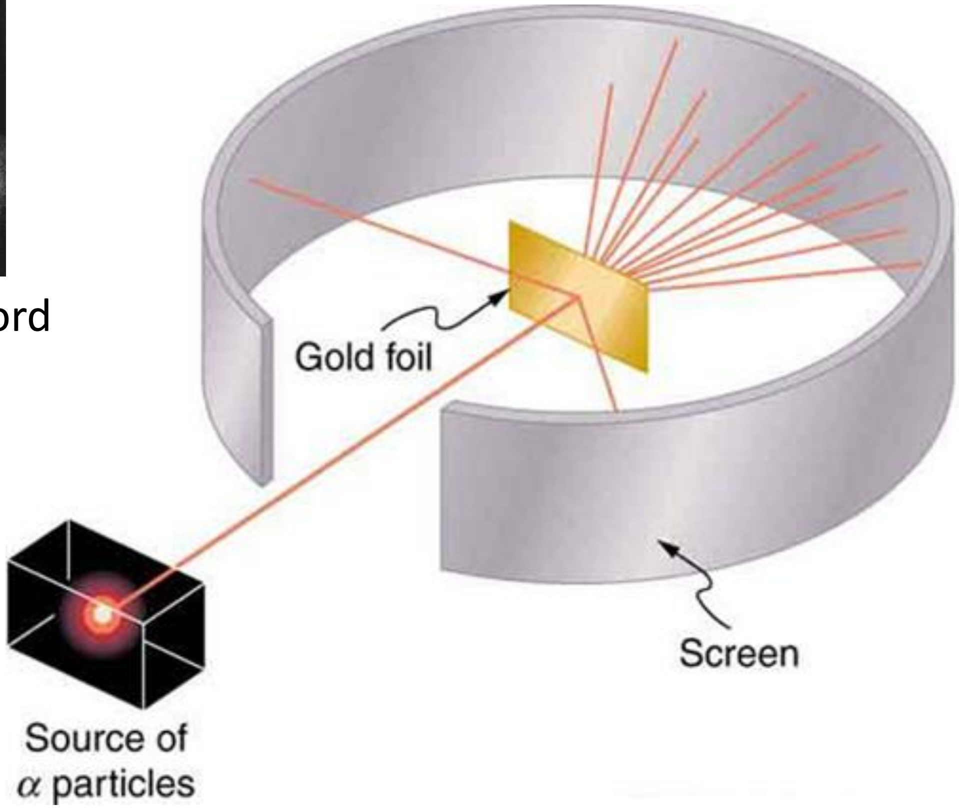
Optical Microscope:	10^{-6} m
Radioactive Source:	10^{-14} m
LHC:	$<10^{-21}$ m

Rutherford Experiment, 1910

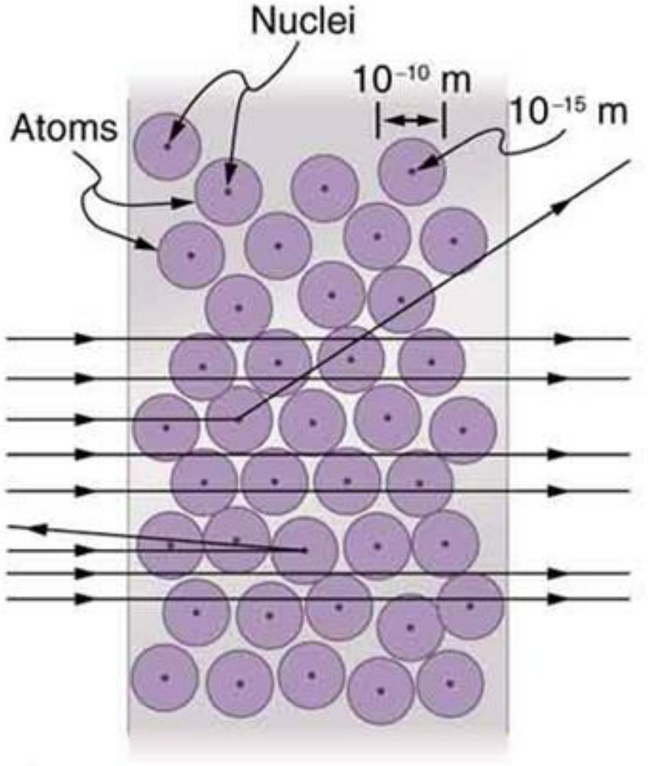


Ernest Rutherford

Alpha Particle Source



Pattern of scattered high energy particles
→ structure of the atom.



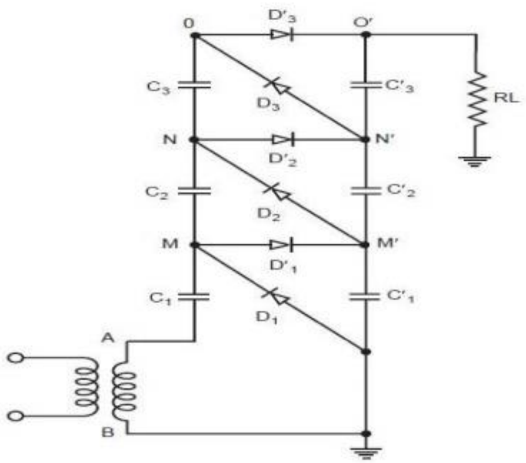
Atoms (10^{-10} m) consist of an extremely small Nucleus (10^{-15} m), electrons are moving around.

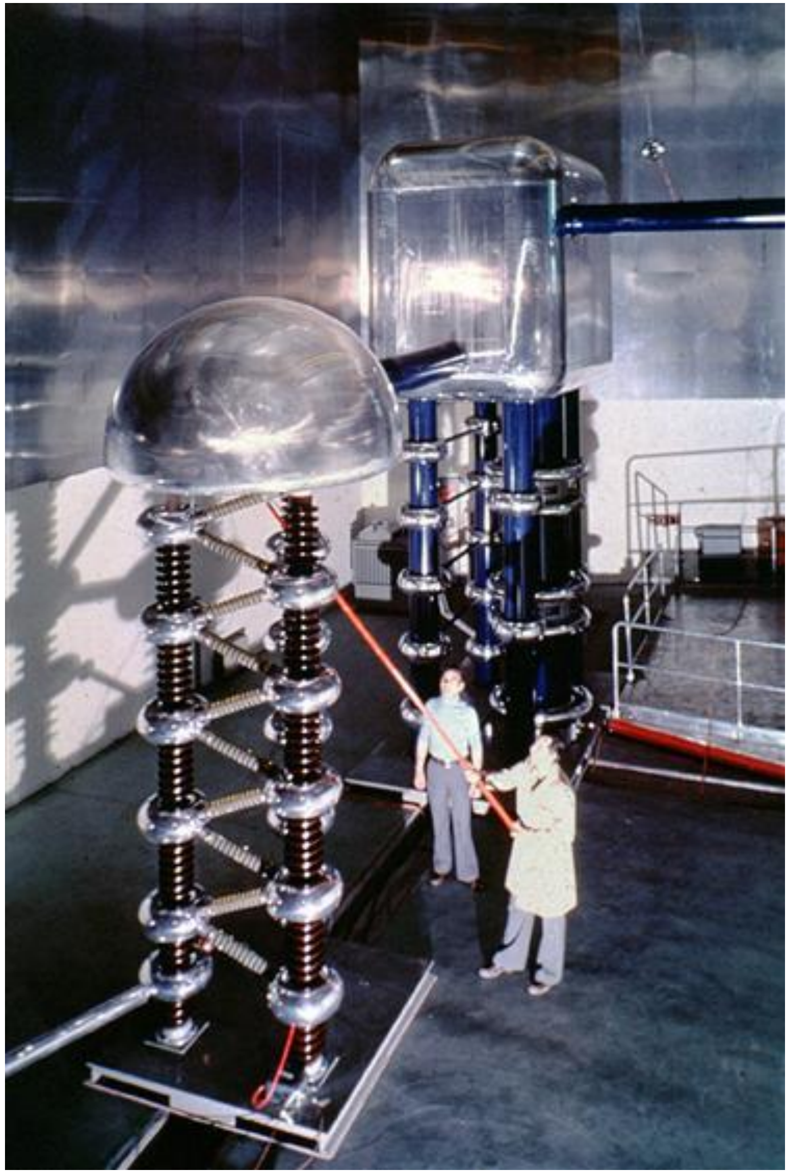
1927
E. Rutherford says, addressing the Royal Society:

*“… if it were possible in the laboratory to have a supply of electrons and atoms of matter in general, of which the individual energy of motion is greater even than that of the alfa particle, …. **This would open up an extraordinary new field of investigation**…”*

Cockcroft Walton – 1st Accelerator
Electrostatic Accelerators

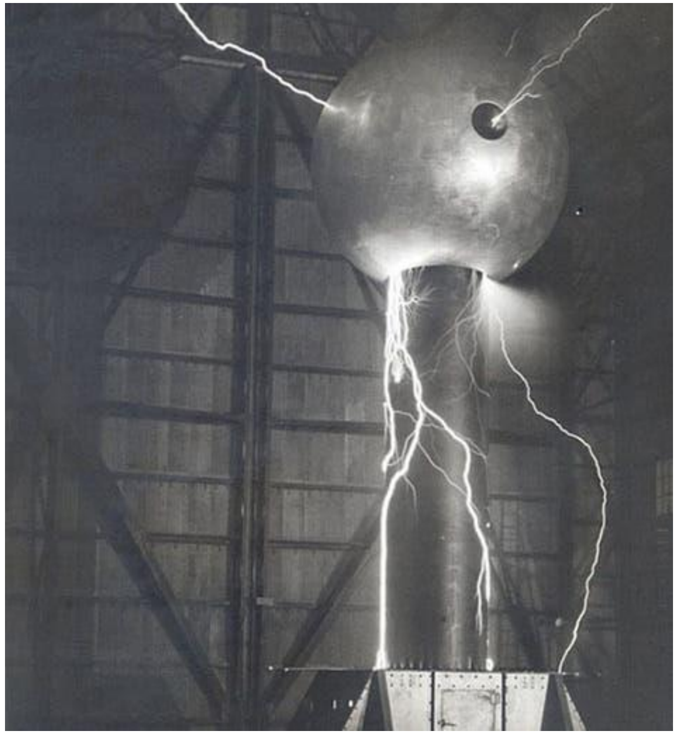
1932: First splitting of a nucleus (Lithium) by using a **400 keV proton beam**

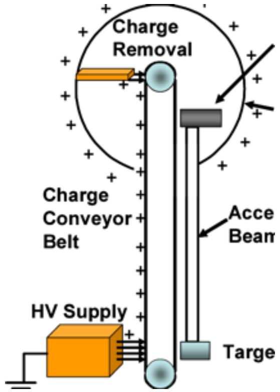




Van de Graaff Accelerator
Electrostatic Accelerators

1932 Possible thanks to further improvement of the charging system, insulation





R. J. VAN DE GRAAFF WITH FIRST GENERATOR

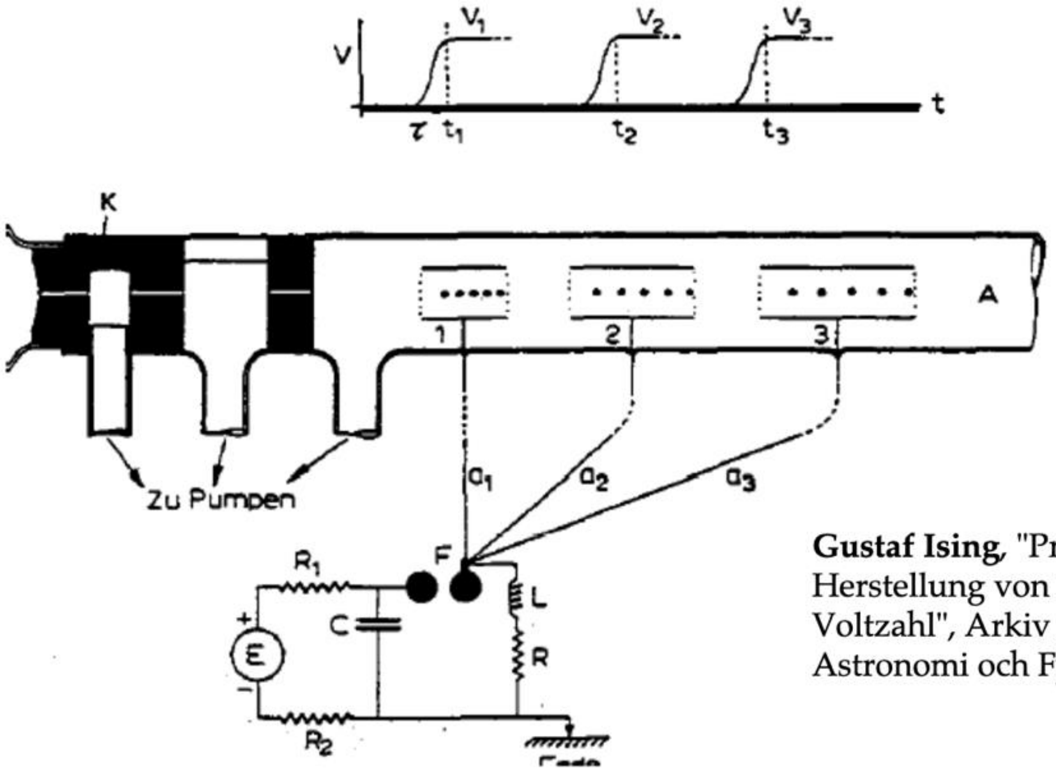
© MIT Museum all rights reserved

Go up to **~5 MeV = 5000 keV**

Based on static electricity

Linear Accelerator
Electrodynamic Accelerators

1924: G. Ising: instead of electrostatic use non-conservative electric fields.

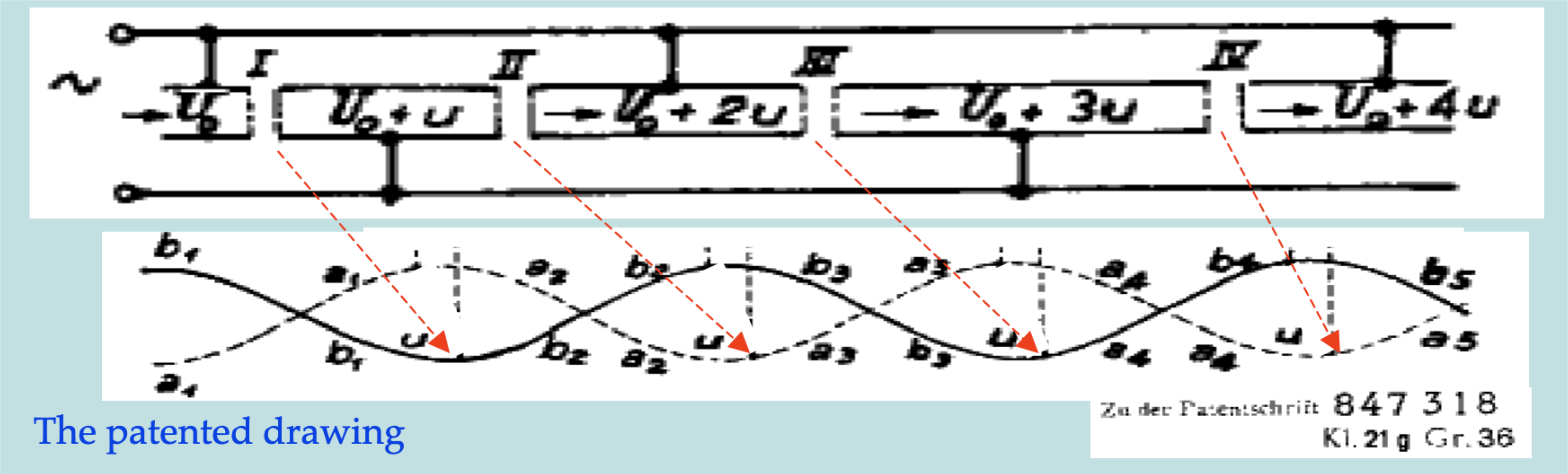


Gustaf Ising, "Prinzip einer Methode zur Herstellung von Kanalstrahlen Hoher Voltzahl", Arkiv för Matematik, Astronomi och Fysik, Band 18 (1924)

Fig. 1. Diagram of linear accelerator from Professor G. Ising's pioneer publication (1924) of the principle of multiple acceleration of ions.

Linear Accelerator
Electrodynamic Accelerators

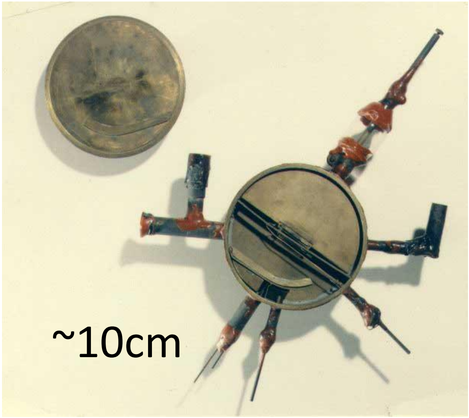
1927: Widerøe invents and builds a small, 2 section resonant linear accelerator with which he verifies the principle by accelerating ions to 50 KV using a 25 KV, 50 Hz generator.



The patented drawing

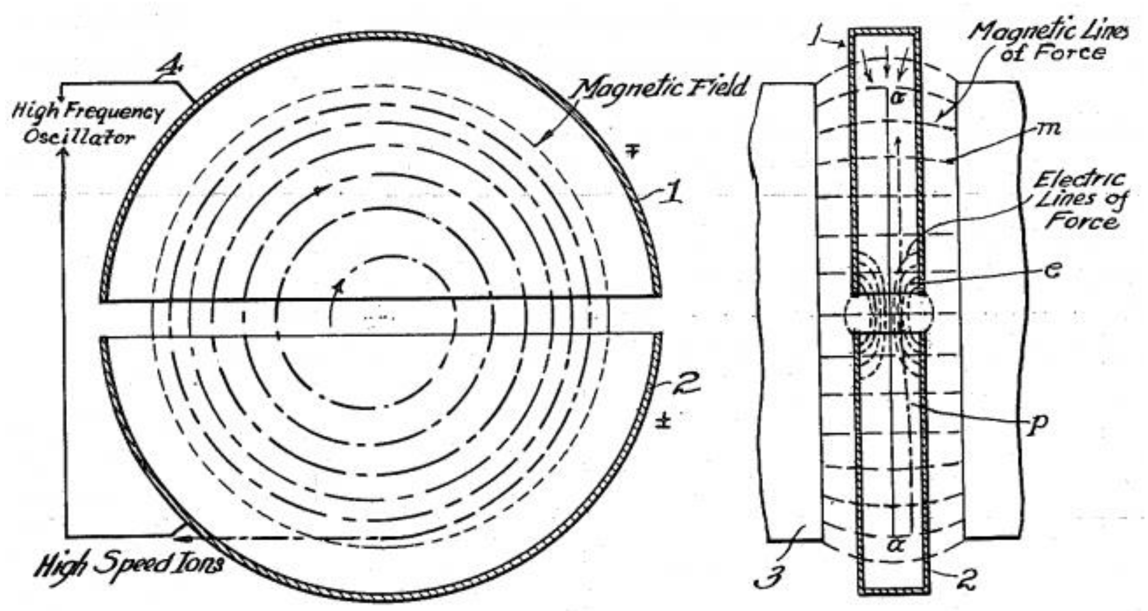
Widerøe: Instead of rectifying the AC voltage, he connected a series of acceleration electrodes in an alternating manner to the output of an AC supply. In principle, this device can produce step by step a multiple of the acceleration voltage, as long as for the negative half-wave of the AC voltage the particles are shielded from the decelerating field.

Circular Accelerator
Electrodynamic Accelerators



1932: E.O. Lawrence, Berkeley

1.2MeV→ produced nuclear disintegration



Constant guiding magnetic field, constant-frequency electromagnetic field

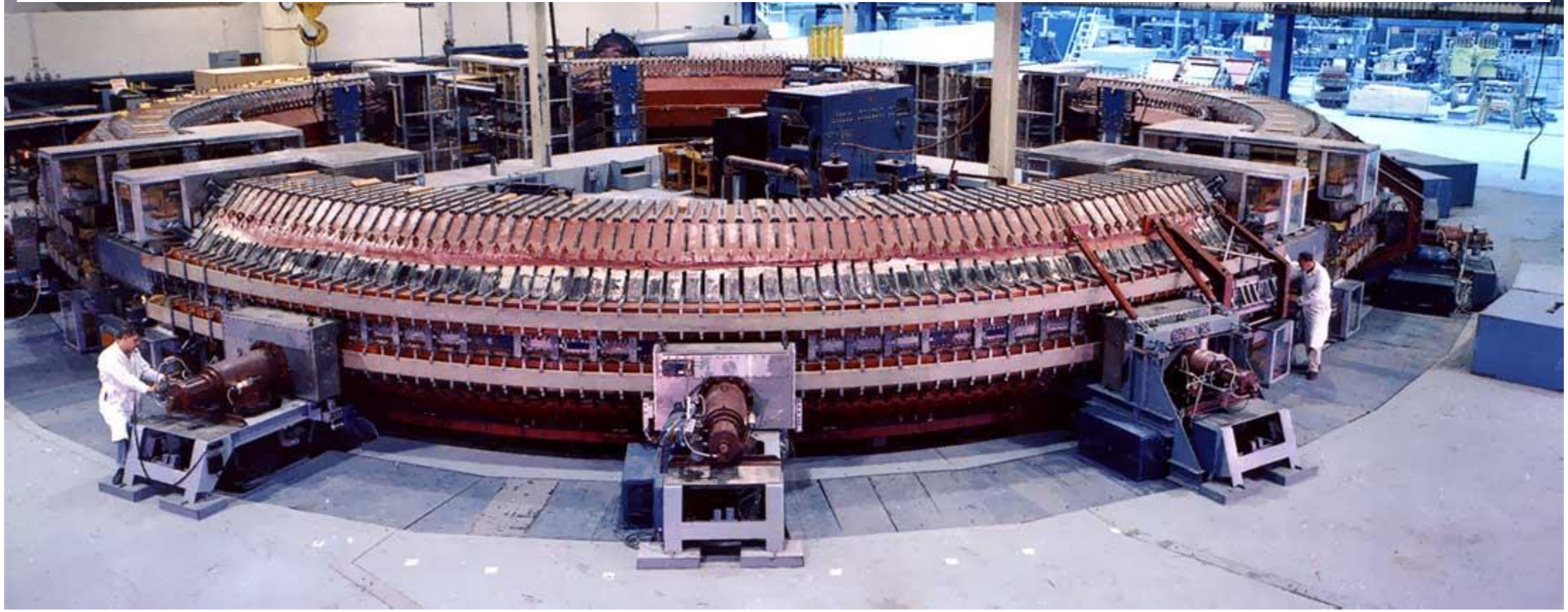
Limit is ~ **50 MeV = 50 000 keV**

Synchrotron Principle

1944 Vladimir Veksler
1945 Edwin McMillan (didn't know of Veksler's paper, was also in Russian) built first electron synchrotron

Principle: Varying magnetic field strength in time, synchronized to the increasing energy of the particles

Cosmotron, BNL Brookhaven Start building: 1948, 1952-66:, protons, **3.3 GeV = 3300 000 keV**



Courant-Snyder: have alternating focusing-defocusing magnets → make a net focusing!

→ meson production

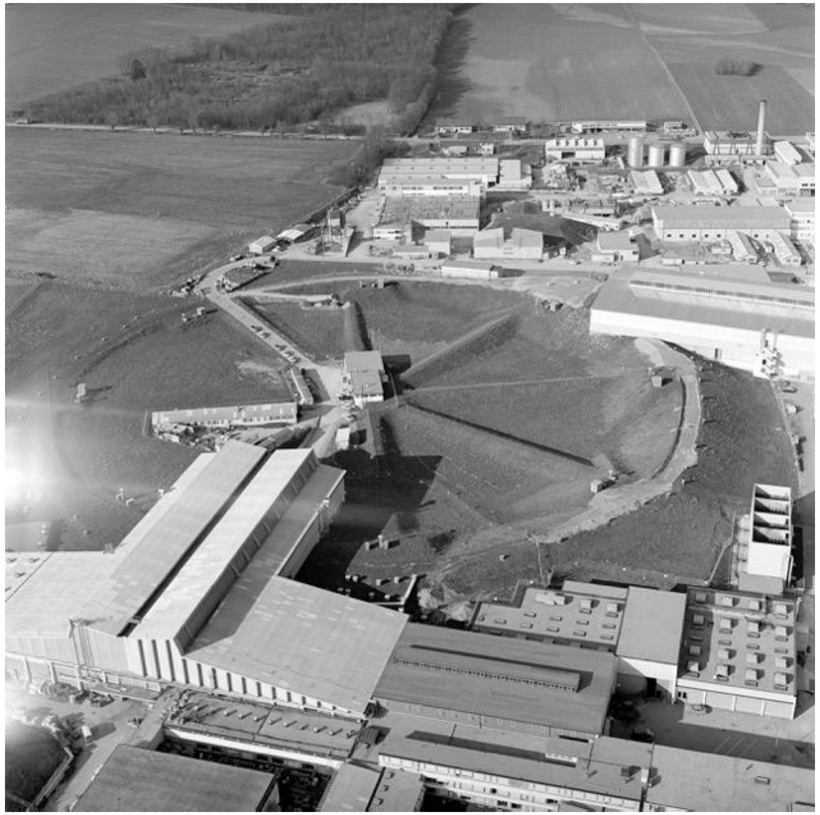
Proton Synchrotron

1959: CERN's first synchrotron

First time use of 'alternating-gradient focusing'

Protons up to **30 GeV = 30 000 000 keV**!

72 m radius, 628 m circumference.



Tools

New directions in science are launched by new tools much more often than by new concepts.

The effect of a concept-driven revolution is to explain old things in new ways.

The effect of a tool-driven revolution is to discover new things that have to be explained.

From Freeman Dyson ‘Imagined Worlds’

CERN's Accelerator Complex Today

LHC: 6.8 TeV = 6800 000 000 keV

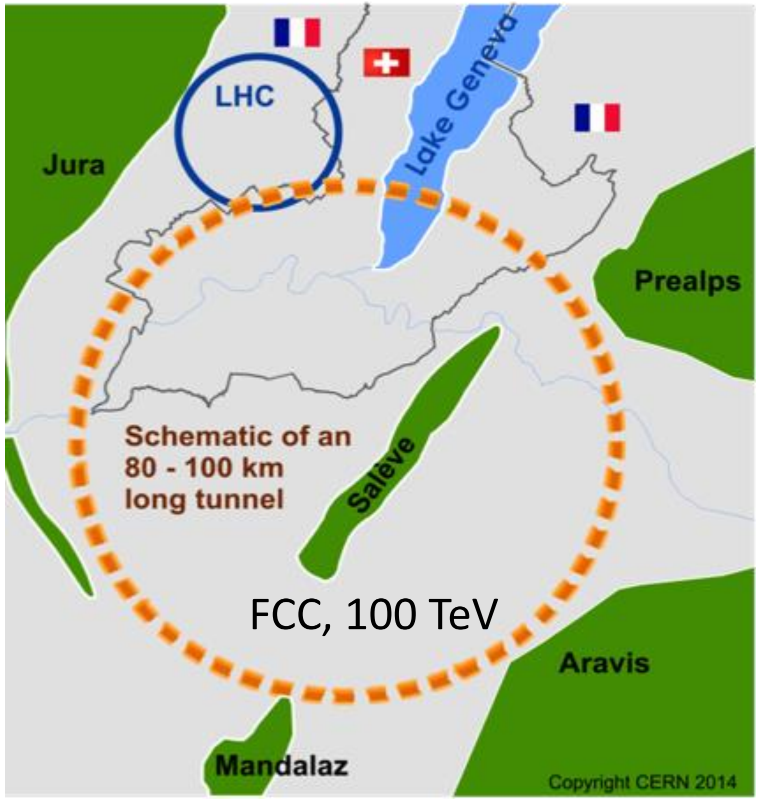
“Science never solves a problem without creating ten more”

George Bernard Shaw

Discover New Physics

Higher energies ➔ bigger accelerators

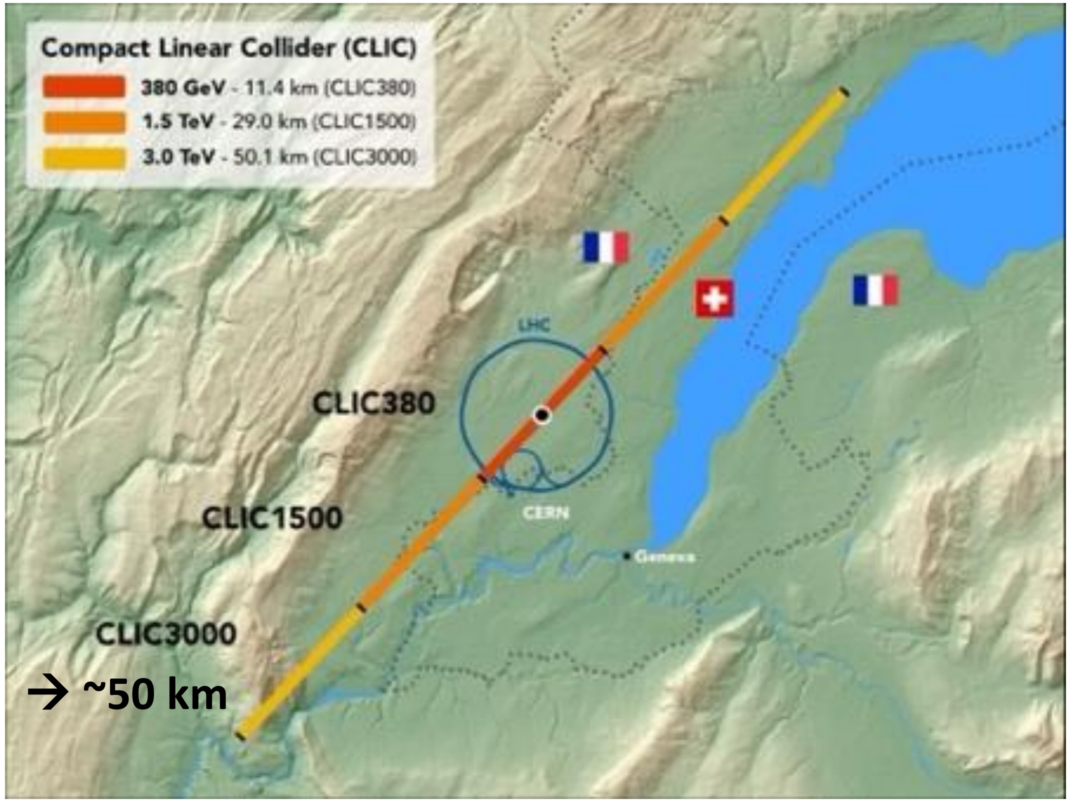
Circular Colliders



FCC, 100 TeV

Challenge: Magnets

Linear Colliders

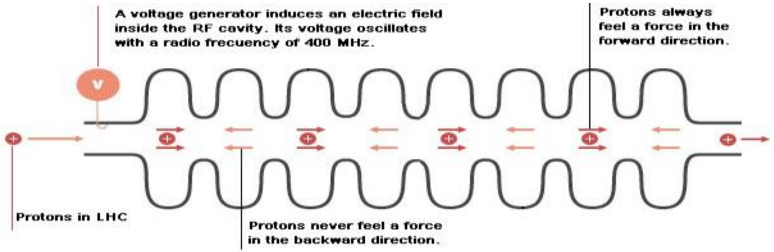


→ ~50 km

Challenge: Accelerating structure

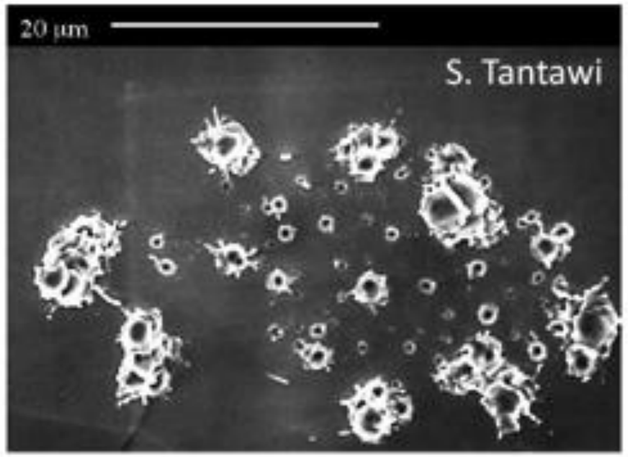
Accelerating Gradient

Conventional RF Cavities



(invention of Gustav Ising 1924 and Rolf Widerøe 1927)

Surface of Copper Cell After Breakdown Events

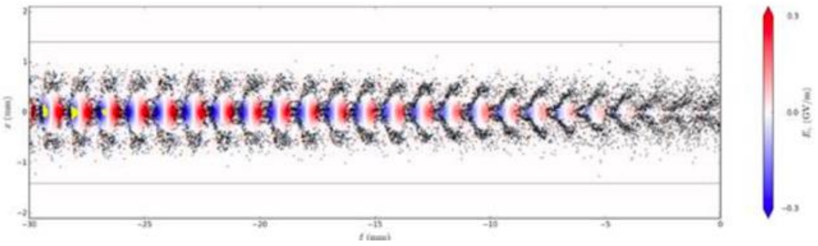


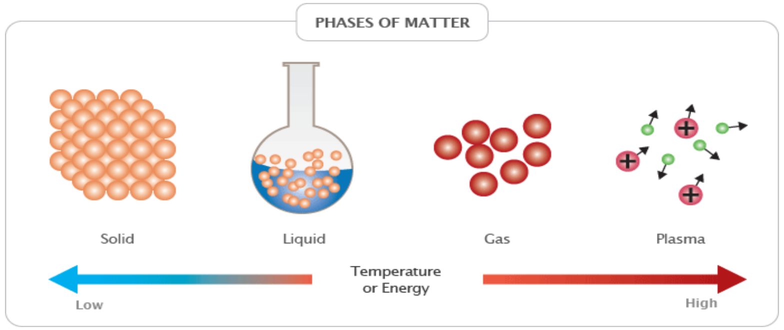
Typical gradients:

LHC: 5 MV/m
ILC: 35 MV/m
CLIC: 100 MV/m

Accelerating fields are **limited to <100 MV/m**

Plasma Acceleration



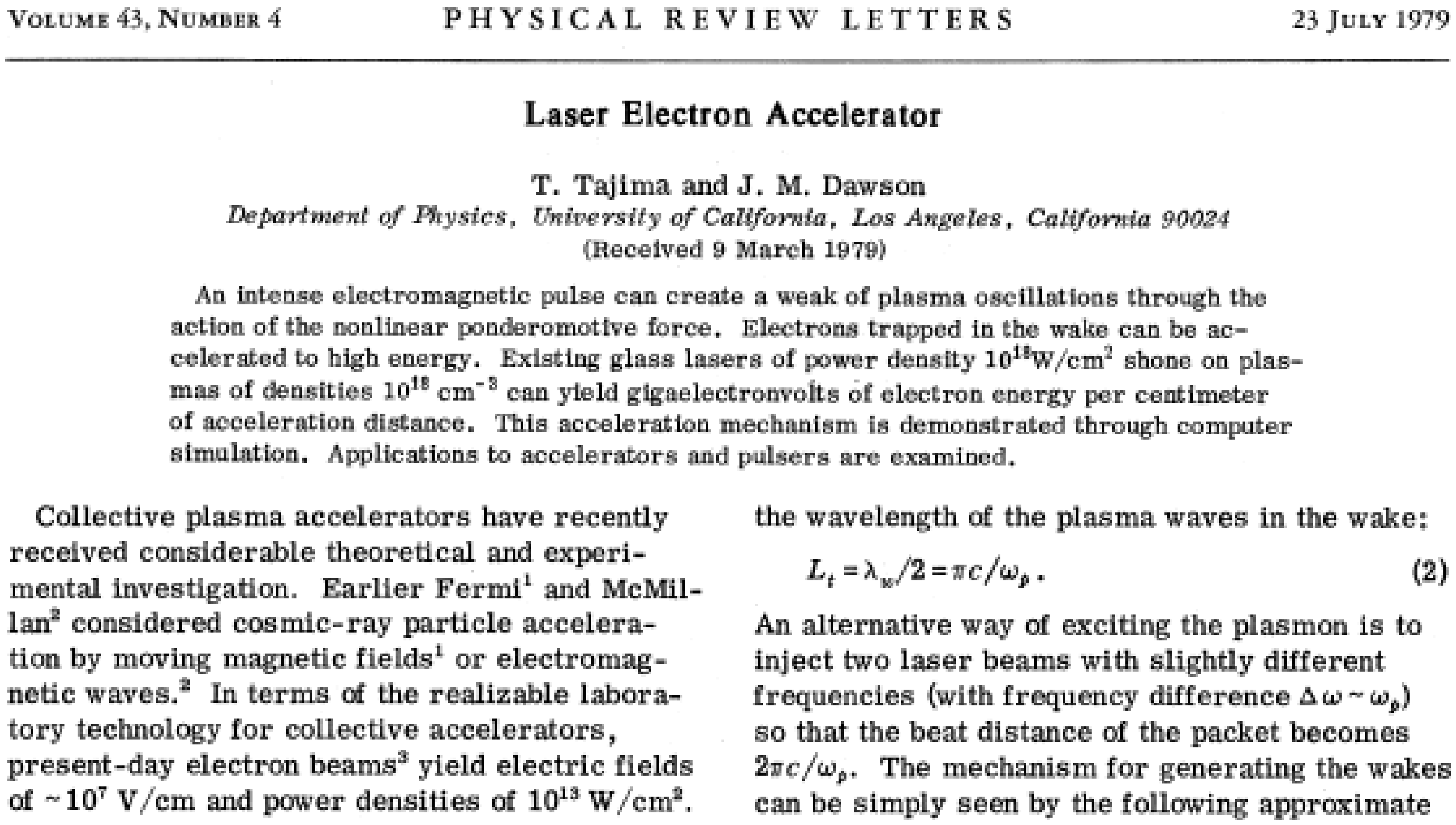


Plasma is already ionized or "broken-down" and can sustain **electric fields up to three orders of magnitude higher gradients**

→ order of 100 GV/m.

→ ~1000 factor stronger acceleration!

Seminal Paper 1979, T. Tajima, J. Dawson



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.

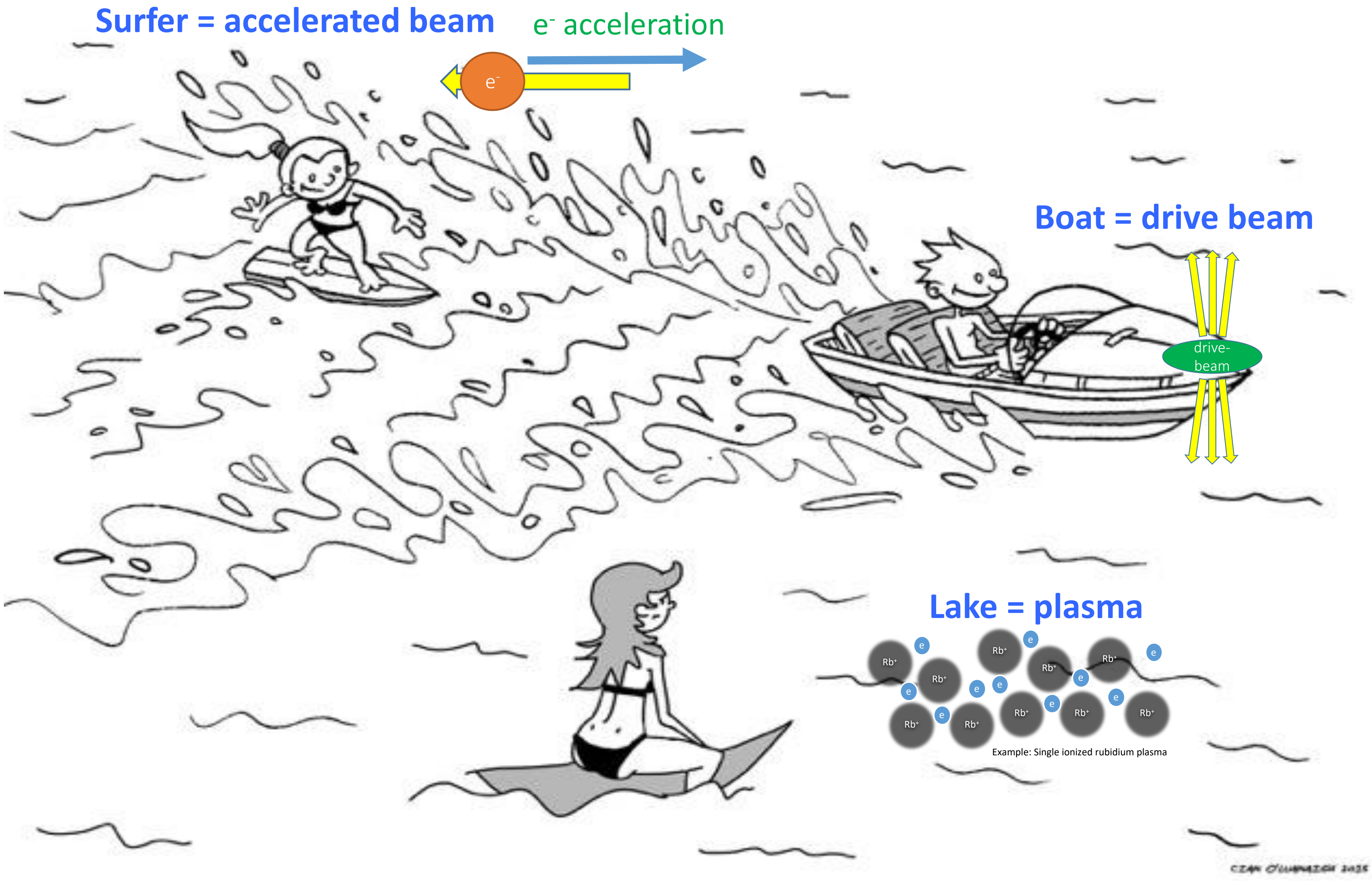
Collective plasma accelerators have recently received considerable theoretical and experimental investigation. Earlier Fermi[1] and McMillan[2] considered cosmic-ray particle acceleration by moving magnetic fields[1] or electromagnetic waves.[2] In terms of the realizable laboratory technology for collective accelerators, present-day electron beams[3] yield electric fields of $\sim 10^7$ V/cm and power densities of 10^{13} W/cm^2.

the wavelength of the plasma waves in the wake:

$$L_t = \lambda_w/2 = \pi c/\omega_p . \tag{2}$$

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 $2\pi c/\omega_p$. The mechanism for generating the wakes can be simply seen by the following approximate

How to Create a Plasma Wakefield?



Surfer = accelerated beam

e^- acceleration

Boat = drive beam

Lake = plasma

Example: Single ionized rubidium plasma

Many, Many Plasma Wakefield Experiments…!

Boat = **laser** or **electron** beam


NBC NEWS

SCIENCE / SCIENCE NEWS

Not-So-Large Colliders Coul
Revolutionize Physics

LETTER

High-efficiency acceleration of an electron beam in a plasma wakefield accelerator

SCIENTIFIC AMERICAN

Plasma-Surfing Mini-Accelerato

Science

LATEST NEWS

Ebola

THE AGING BRAIN

Physicists crank up current in new type of accelerator

Voice of America

US Scientists Build the Sma
Accelerator

Scienze

Gli acceleratori di particelle saranno più "piccoli" e low cost

welt der physik

Fortschritte in der Kielfeld-Beschleunigung

COMILLAS

ciencia plus.com

Proyectan aceleradores de partículas con plasma de bajo coste


Monoenergetic beams of relativistic electrons from intense laser–plasma
ctions

uality electron beams from a
wakefield accelerator using
a-channel guiding

r–plasma accelerator
cing monoenergetic
on beams


CERN COURIER

Doubling energy in a plasma wake


nature

FULL SPEED AHEAD


nature

Dream beam

The dawn of compact particle accelerators

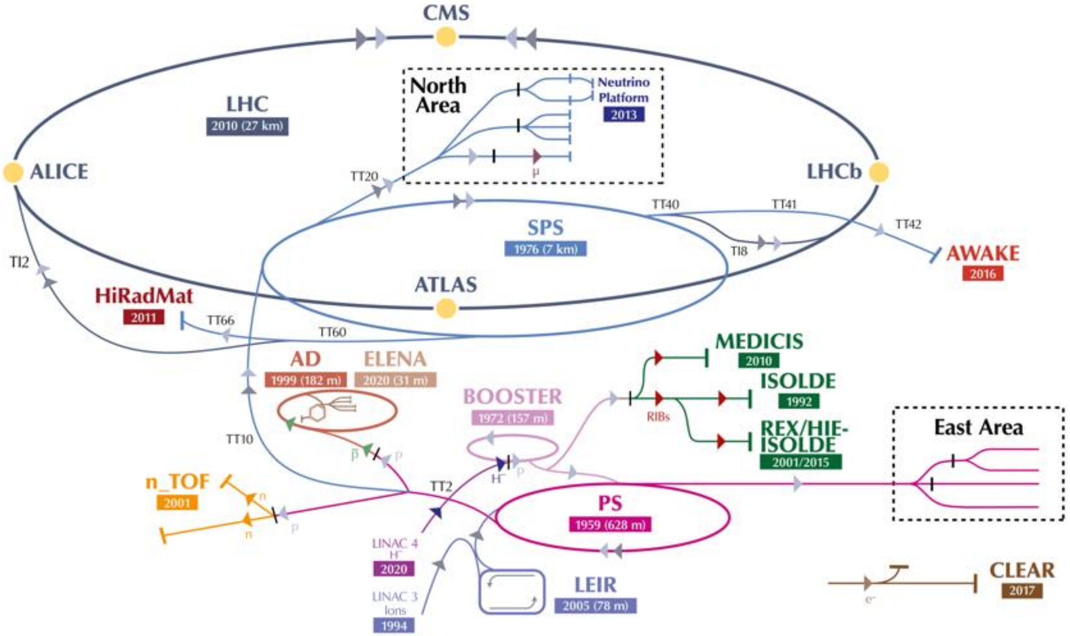

TEDxCERN

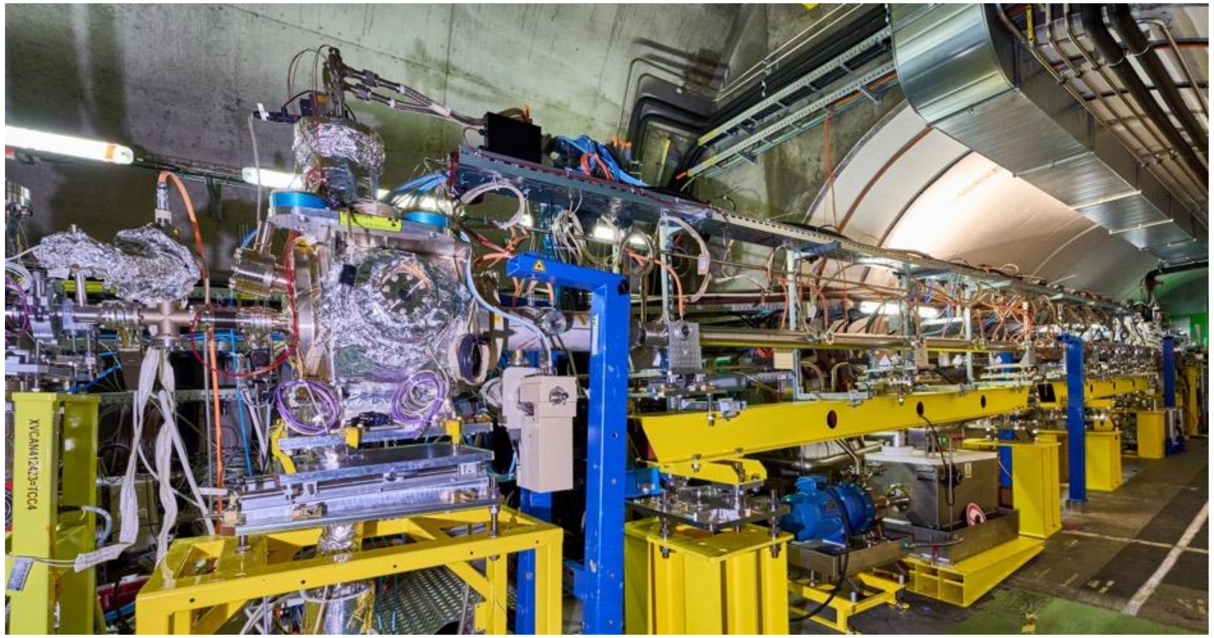
x = independently organized TED event

Surfing wakefields to create smaller accelerators

AWAKE

2009: Idea: use proton beam as drive beam (boat) → take advantage of the high energy of the protons!
Proposal in 2012
2013: AWAKE approval, first beam in 2016





AWAKE Stages of Innovation

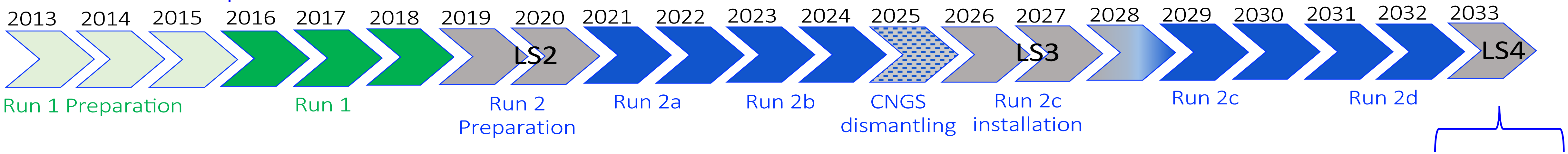
Proof-of-Concept:
RUN 1 (2016-2018)

p+ self-modulation

2 GeV e- acceleration

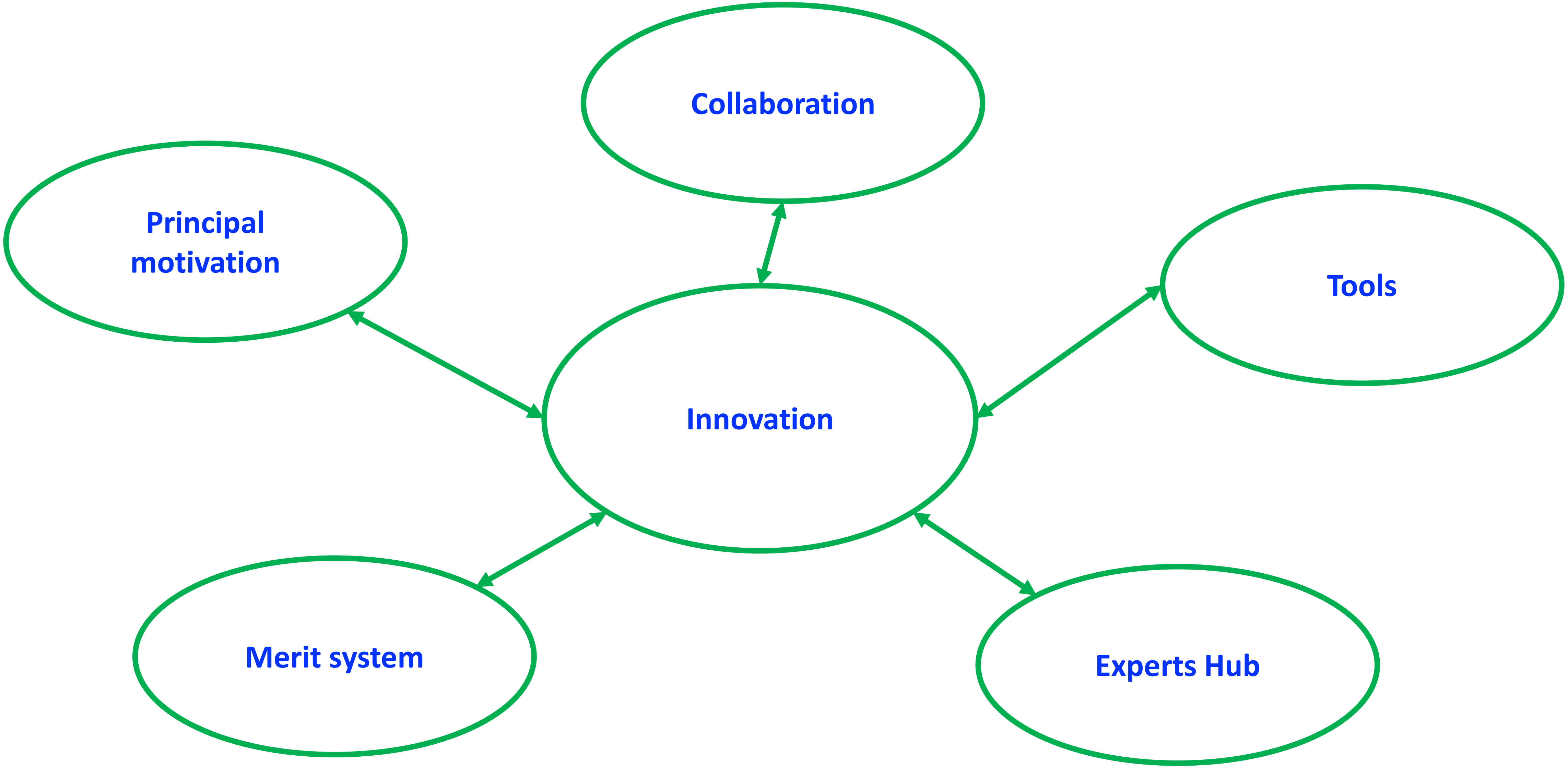
Quality:
RUN 2 (2021-2032)

e- acceleration to several GeV,
beam quality control, scalability



➔First applications: >2033

Environment for Innovation in AWAKE and …



Collaboration

Principal motivation

Tools

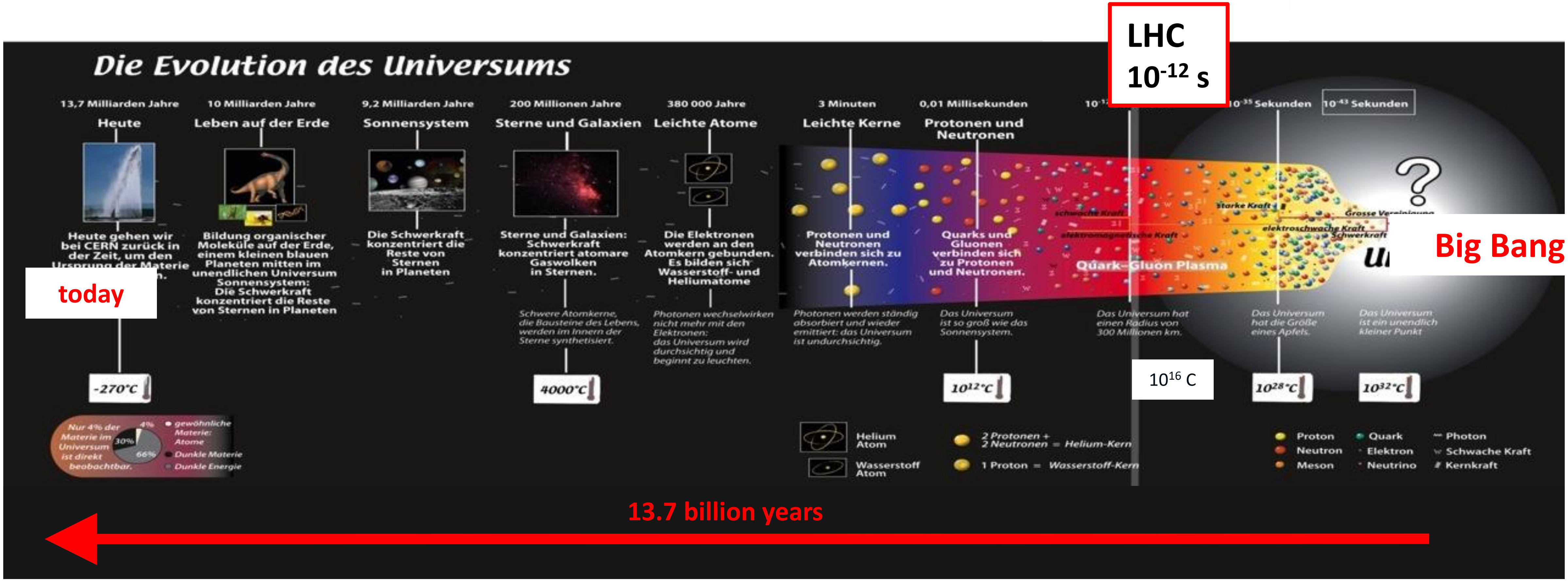
Innovation

Merit system

Experts Hub

Principal motivation

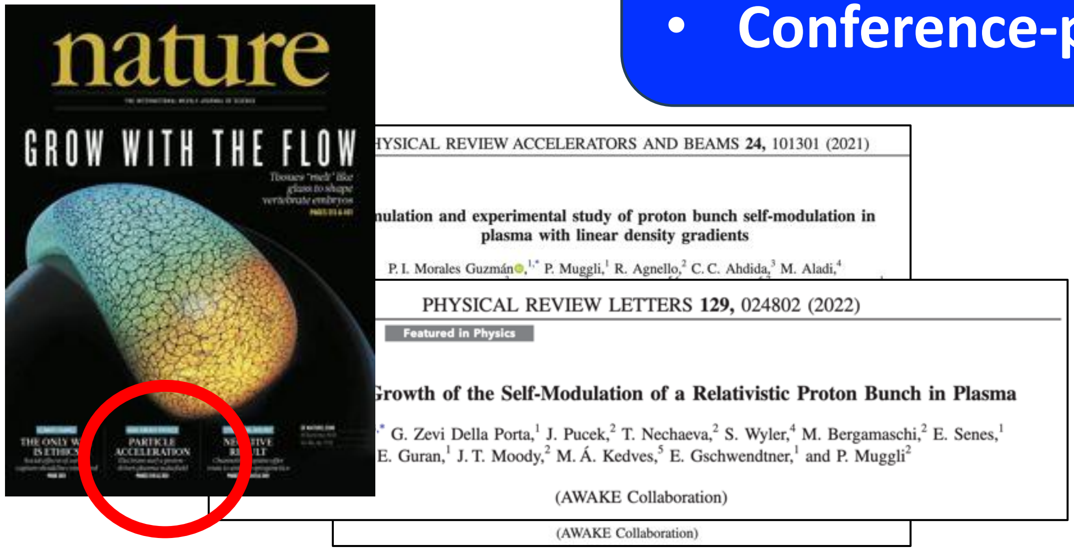
Increase particle energies
→ understanding the building blocks of matter and the origin of the universe.



Merit system

- PhD thesis
- Publications
- Conference-presentations

Young scientists



HYSICAL REVIEW ACCELERATORS AND BEAMS **24,** 101301 (2021)

mulation and experimental study of proton bunch self-modulation in plasma with linear density gradients

P. I. Morales Guzmán,[1,*] P. Muggli,[1] R. Agnello,[2] C. C. Ahdida,[3] M. Aladi,[4]

(AWAKE Collaboration)

PHYSICAL REVIEW LETTERS **129,** 024802 (2022)

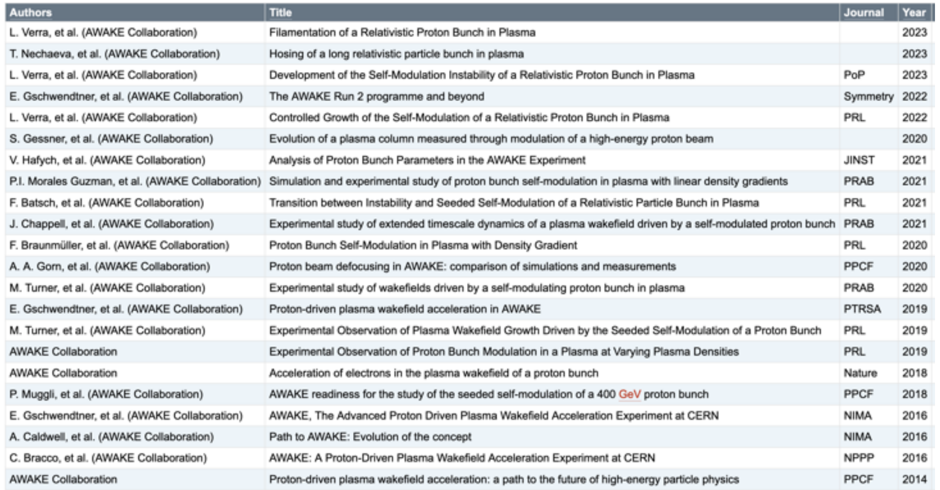
Featured in Physics

rowth of the Self-Modulation of a Relativistic Proton Bunch in Plasma

[*] G. Zevi Della Porta,[1] J. Pucek,[2] T. Nechaeva,[2] S. Wyler,[4] M. Bergamaschi,[2] E. Senes,[1] E. Guran,[1] J. T. Moody,[2] M. Á. Kedves,[5] E. Gschwendtner,[1] and P. Muggli[2]

(AWAKE Collaboration)

Collaboration papers in high-level journals



Authors	Title	Journal	Year
L. Verra, et al. (AWAKE Collaboration)	Filamentation of a Relativistic Proton Bunch in Plasma		2023
T. Nechaeva, et al. (AWAKE Collaboration)	Hosing of a long relativistic particle bunch in plasma		2023
L. Verra, et al. (AWAKE Collaboration)	Development of the Self-Modulation Instability of a Relativistic Proton Bunch in Plasma	PoP	2023
E. Gschwendtner, et al. (AWAKE Collaboration)	The AWAKE Run 2 programme and beyond	Symmetry	2022
L. Verra, et al. (AWAKE Collaboration)	Controlled Growth of the Self-Modulation of a Relativistic Proton Bunch in Plasma	PRL	2022
S. Gessner, et al. (AWAKE Collaboration)	Evolution of a plasma column measured through modulation of a high-energy proton beam		2020
V. Hafych, et al. (AWAKE Collaboration)	Analysis of Proton Bunch Parameters in the AWAKE Experiment	JINST	2021
P.I. Morales Guzman, et al. (AWAKE Collaboration)	Simulation and experimental study of proton bunch self-modulation in plasma with linear density gradients	PRAB	2021
F. Batsch, et al. (AWAKE Collaboration)	Transition between Instability and Seeded Self-Modulation of a Relativistic Particle Bunch in Plasma	PRL	2021
J. Chappell, et al. (AWAKE Collaboration)	Experimental study of extended timescale dynamics of a plasma wakefield driven by a self-modulated proton bunch	PRAB	2021
F. Braunmüller, et al. (AWAKE Collaboration)	Proton Bunch Self-Modulation in Plasma with Density Gradient	PRL	2020
A. A. Gorn, et al. (AWAKE Collaboration)	Proton beam defocusing in AWAKE: comparison of simulations and measurements	PPCF	2020
M. Turner, et al. (AWAKE Collaboration)	Experimental study of wakefields driven by a self-modulating proton bunch in plasma	PRAB	2020
E. Gschwendtner, et al. (AWAKE Collaboration)	Proton-driven plasma wakefield acceleration in AWAKE	PTRSA	2019
M. Turner, et al. (AWAKE Collaboration)	Experimental Observation of Plasma Wakefield Growth Driven by the Seeded Self-Modulation of a Proton Bunch	PRL	2019
AWAKE Collaboration	Experimental Observation of Proton Bunch Modulation in a Plasma at Varying Plasma Densities	PRL	2019
AWAKE Collaboration	Acceleration of electrons in the plasma wakefield of a proton bunch	Nature	2018
P. Muggli, et al. (AWAKE Collaboration)	AWAKE readiness for the study of the seeded self-modulation of a 400 GeV proton bunch	PPCF	2018
E. Gschwendtner, et al. (AWAKE Collaboration)	AWAKE, The Advanced Proton Driven Plasma Wakefield Acceleration Experiment at CERN	NIMA	2016
A. Caldwell, et al. (AWAKE Collaboration)	Path to AWAKE: Evolution of the concept	NIMA	2016
C. Bracco, et al. (AWAKE Collaboration)	AWAKE: A Proton-Driven Plasma Wakefield Acceleration Experiment at CERN	NPPP	2016
AWAKE Collaboration	Proton-driven plasma wakefield acceleration: a path to the future of high-energy particle physics	PPCF	2014

PhD/master thesis

Author	Title	Year	Type/Link
Karl Rieger	Direct detection of the self-modulation instability of a long relativistic proton bunch in the AWAKE Experiment	2023	PhD Thesis
Pablo Israel Morales Guzman	Particle-in-Cell Simulations of Plasma Density Variations in a Proton-Driven Wakefield Accelerator	2023	PhD Thesis
Can Davut	Design and Experimental Verification Study of Non-invasive Short Electron Bunch Length Monitor for AWAKE Run 2	2023	PhD Thesis
Linbo Liang	Beam-driven plasma wakefield acceleration in AWAKE.	2023	PhD Thesis
Samuel Wyler	Control of Proton Beam Self-Modulation for AWAKE via Initial Beam Parameters	2022	Master's Thesis
Vasyl Hafych	Development of Advanced Statistical Algorithms and Application to the AWAKE Experiment at CERN	2022	PhD Thesis
Livio Verra	Electron Bunch Seeding of the Self-Modulation Instability in Plasma	2022	PhD Thesis
Alexander Gorn	Properties of wakefield acceleration with a proton driver in a radially confined plasma	2022	PhD Thesis
James Chappell	Experimental study of long timescale plasma wakefield evolution	2021	PhD Thesis
Fabian Batsch	Instability and Seeded Self-Modulation of a Relativistic Proton Bunch in Plasma	2021	PhD Thesis
Anna-Maria Bachmann	Self-Modulation Development of a Proton Bunch in Plasma	2021	PhD Thesis
Barney Williamson	Electron Beam Dynamics in a Proton-driven Plasma Wakefield	2021	PhD Thesis
Vladimir Minakov	Properties of beam acceleration in the plasma wakefield of a long modulated driver	2021	PhD Thesis
Mathias Hüther	Direct Observation of the Hosing Instability of a Long Relativistic Proton Bunch in the AWAKE Experiment	2020	PhD Thesis
Fearghus Robert Keeble	Measurement of the electron energy distribution at AWAKE	2019	PhD Thesis
Felipe Peña	Predicting the Trajectories of Relativistic Particle Beams for External Injection in Plasma Wakefield Acceleration	2019	Master's Thesis
Veronica Berglyd Olsen	Beam Loading in a Proton Driven Plasma Wakefield Accelerator	2018	PhD Thesis
Marlene Turner	First Observation of the Seeded Proton Bunch Self-Modulation in Plasma	2017	PhD Thesis
Mariana Moreira	Influence of proton bunch and plasma parameters on the AWAKE experiment	2017	Master's Thesis
Gabriel Fior	Study of impact ionization by a proton bunch	2017	Master's Thesis
Fabian Batsch	Interferometer-based white light measurement of neutral rubidium density and gradient for the AWAKE experiment at CERN	2016	Master's Thesis
Anna-Maria Bachmann	Measurement of the Plasma Radius in a Vapor Cell using Schlieren Imaging	2016	PhD Thesis
Karl Rieger	Streak cameras and optical transition radiation as a diagnostic for self-modulation of charged particle beams in plasmas	2014	Master's Thesis

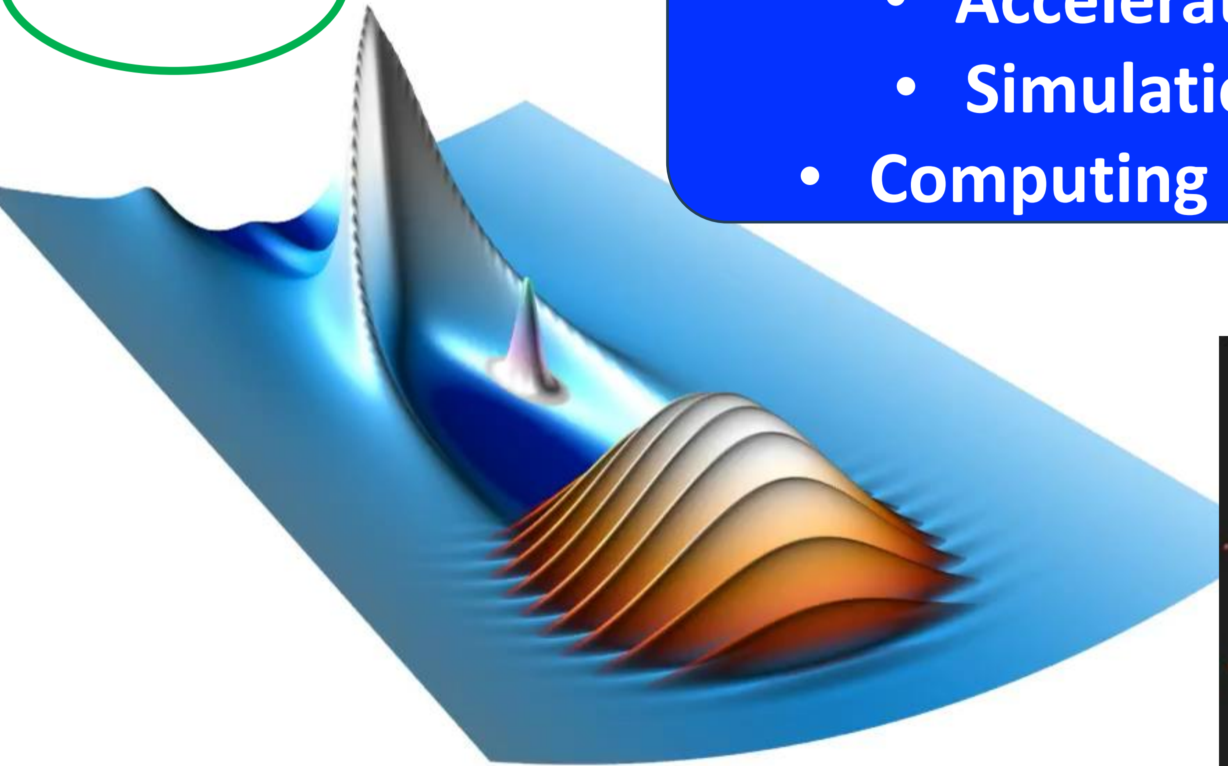
Collaboration

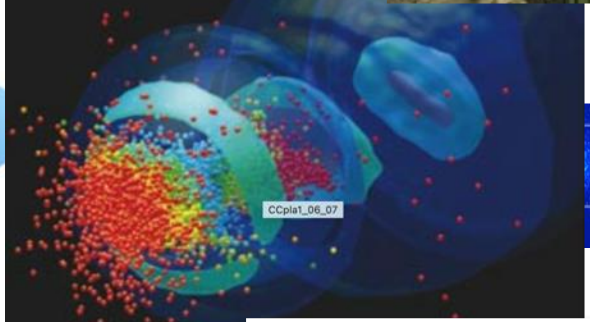
- International Collaboration
- 22 institutes worldwide, 100 authors
- Broad and diverse expertise

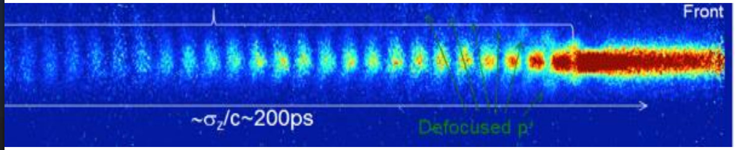
"In science, we must be interested in things, not in persons."
Marie Curie

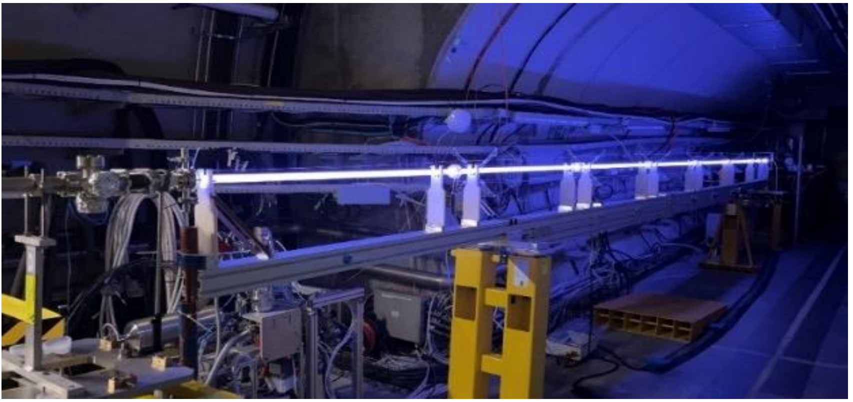
Tools

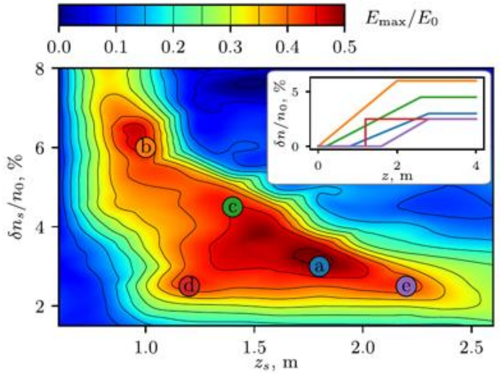
- Instrumentation
- Accelerators
- Simulations
- Computing Power

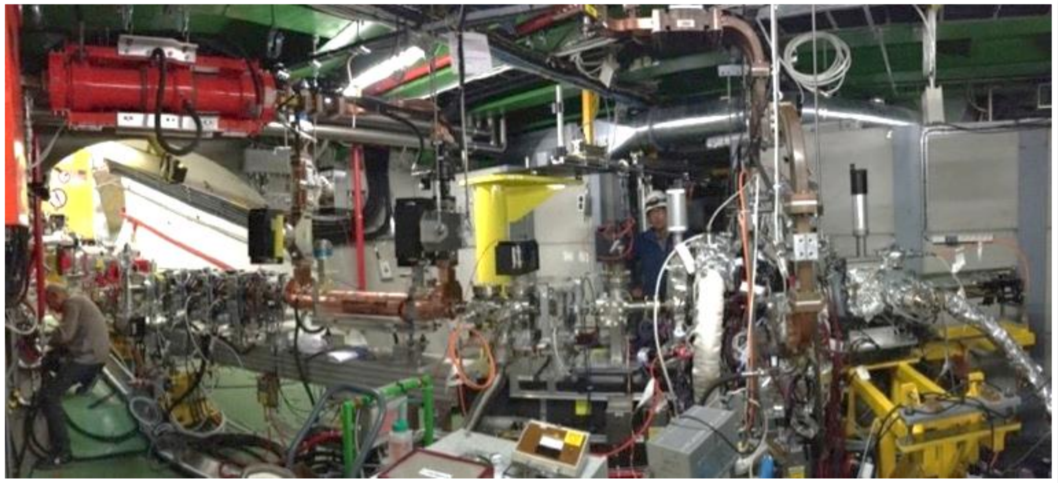












Experts Hub

Hub of experts at CERN







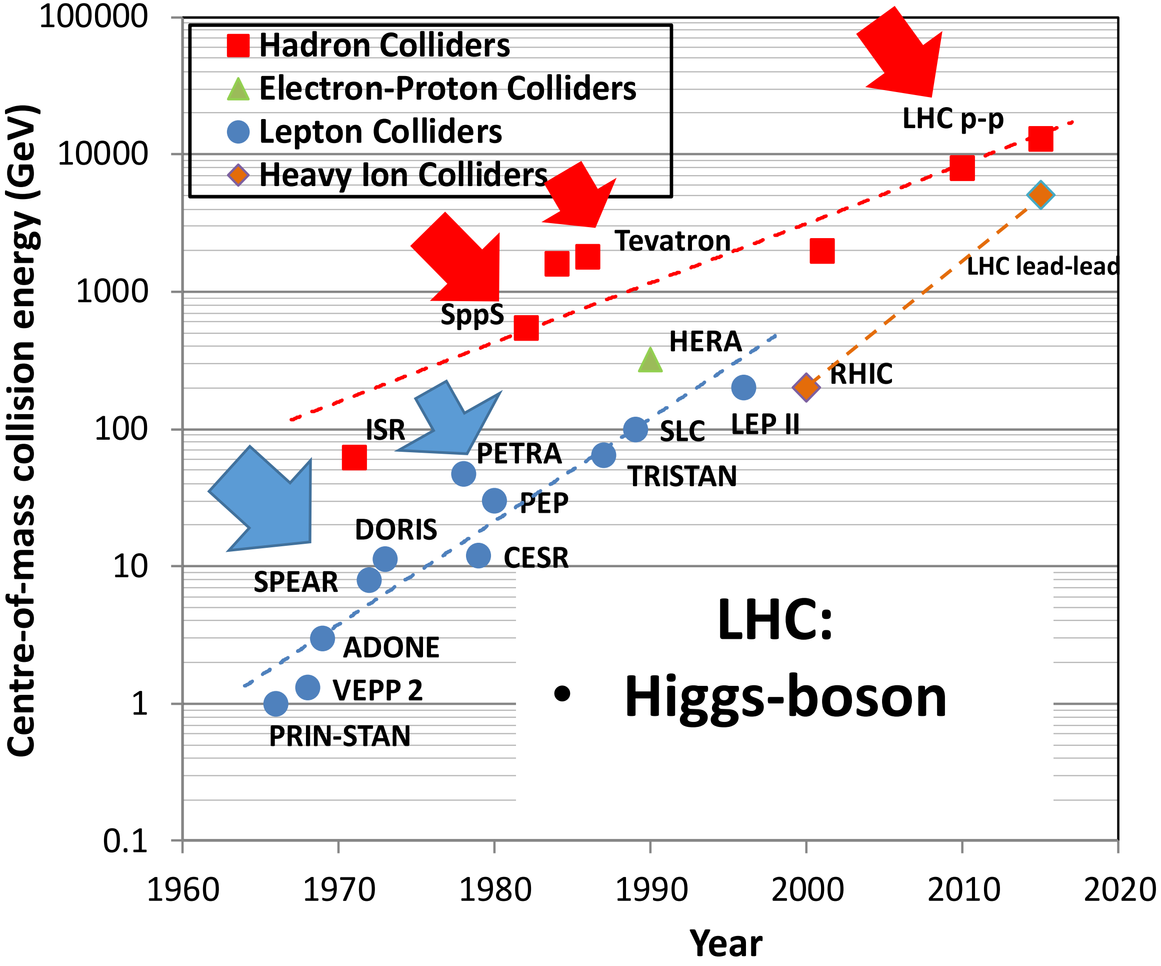


“The good thing about science is that it’s true whether or not you believe in it.”

Neil deGrasse Tyson

Thank You!

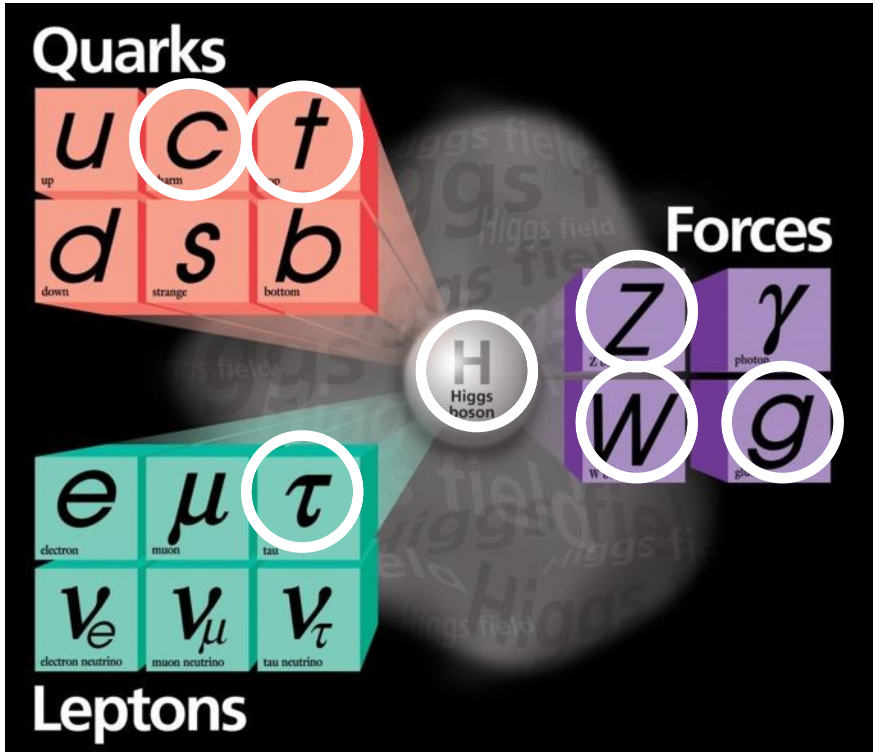
Discoveries with Colliders



LHC:

- **Higgs-boson**

Standard Model
Particles and forces



Open Questions

Despite of impressive progress and discoveries in the past decades several fundamental question remain open

Is there only a single type of Higgs boson and does it behave exactly as predicted?

Why is the universe composed only of matter? Where has the anti-matter gone that was produced simultaneously in the big bang?

Today 80 % of the mass of the universe is unknown.
What is the universe made of?

Why is the gravitation so much smaller than the other forces?
How to reconcile gravitation with quantum mechanics?