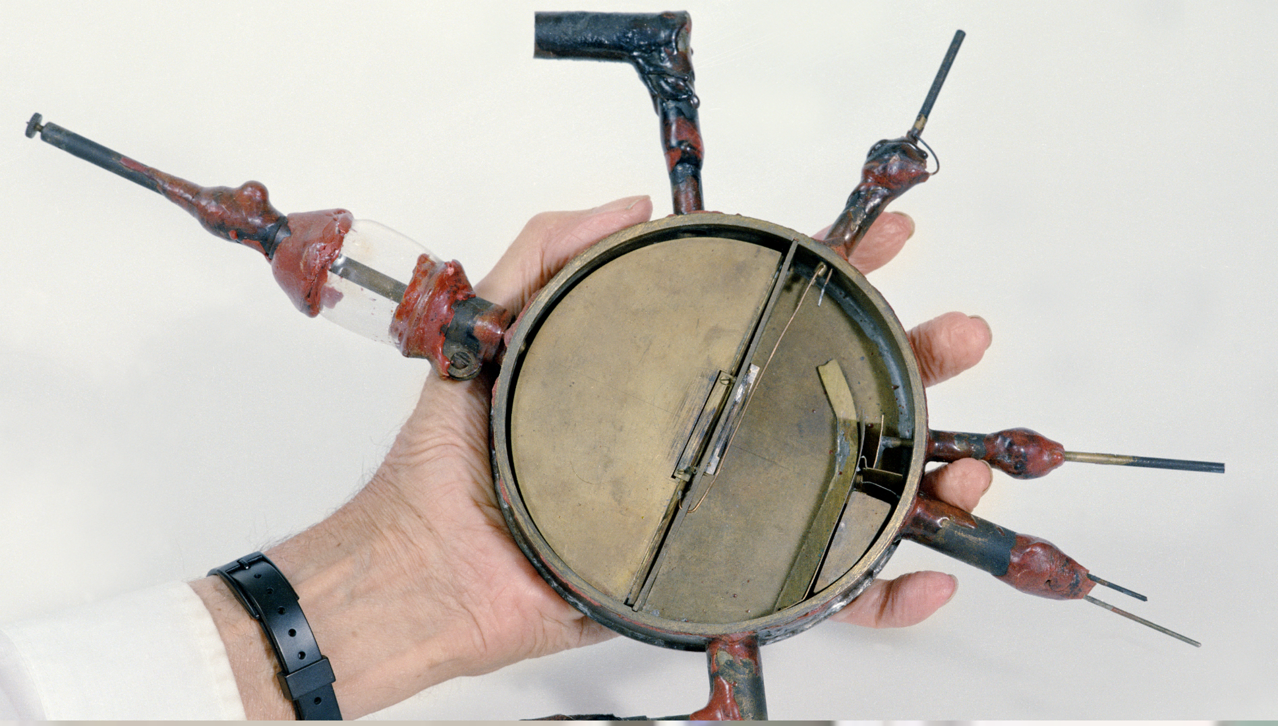
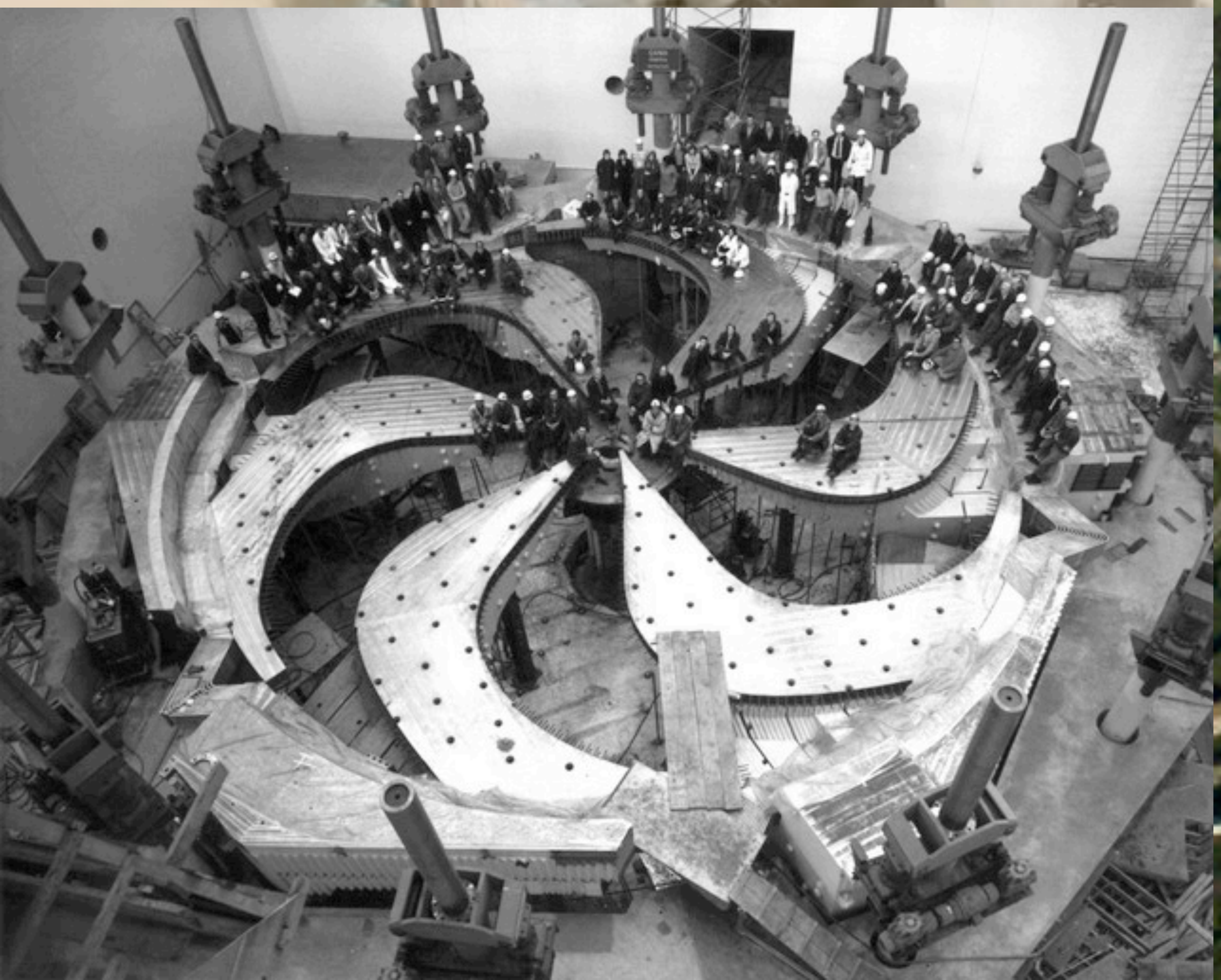




Accelerator Physics Overview

Prof. Brigitte Vachon
McGill University

What is a particle accelerator?

Device that uses electromagnetic fields to accelerate **charged** particles† to high speeds (energy).

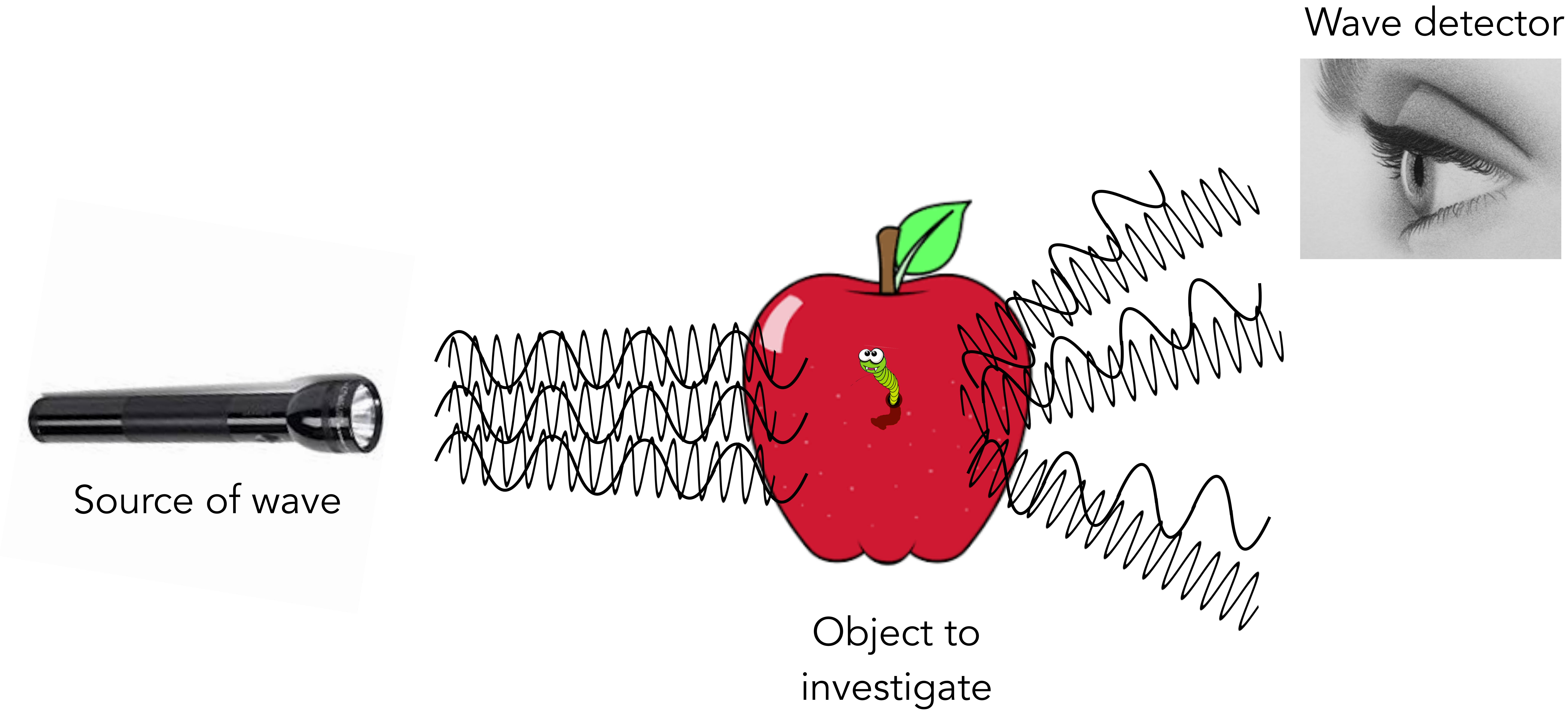
†e.g. elementary particles, hadrons, ions

What are accelerators used for?

"A beam of the right particles with the right energy at the right intensity can shrink a tumor, produce cleaner energy, spot suspicious cargo, make a better radial tire, cleanup dirty drinking water, map a protein, study a nuclear explosion, design a new drug, make a heat-resistant automotive cable, diagnose a disease, reduce nuclear waste, detect an art forgery, implant ions in a semiconductor, prospect for oil, date an archaeological find, package a Thanksgiving turkey or discover the secrets of the universe."

[B.L. Doyle, F.D. McDanniel, R.W. Hamm, SAND2018-5903B]

How do we “see” objects



Can resolve features of a size comparable to the wavelength used

Wave-like behaviour of matter

Wavelength of matter

$$\lambda = \frac{h}{p}$$

Planck constant

Momentum

Example: LHC
Proton momentum ~ 7 TeV/c
$\lambda \sim 10^{-18}$ m (attometers) !!!!

High momentum particles have a correspondingly small wavelength

Outline

(1) Brief historical introduction to particle acceleration

(2) Use of particle accelerator in physics research

(3) Current research facilities

(4) Future projects

Some basic concepts of accelerator physics along the way

Outline

(1) Brief historical introduction to particle acceleration

(2) Use of particle accelerator in physics research

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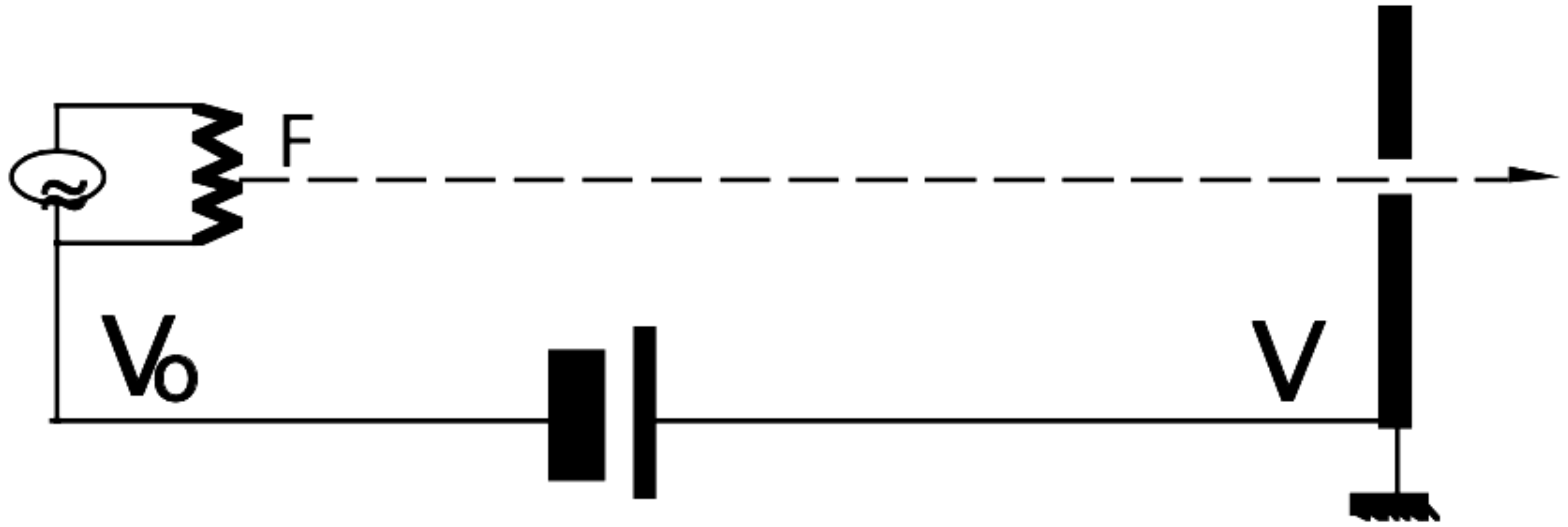
Electrostatic accelerators

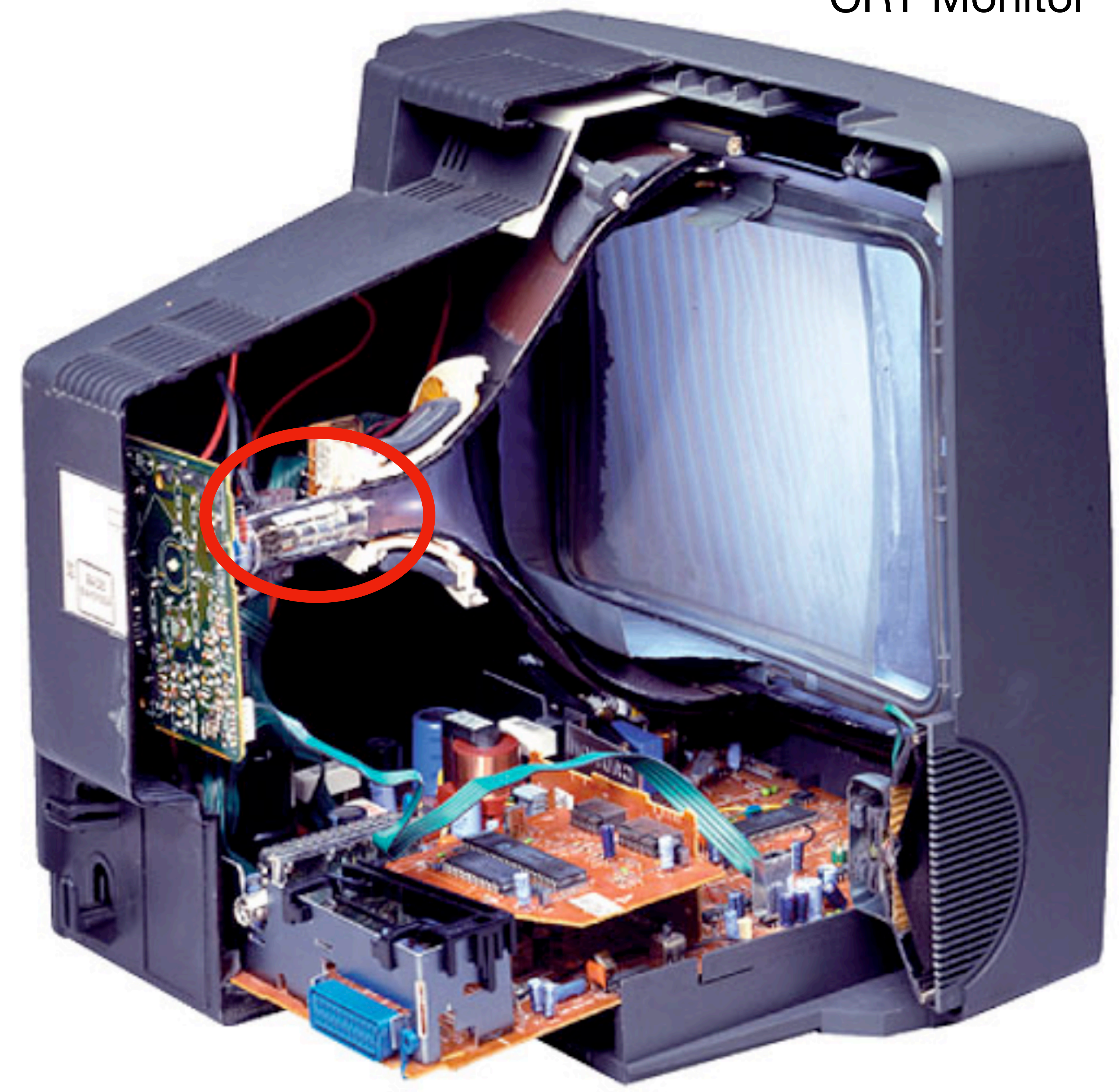


Credit: Tazzari, CAS-IC-2006

Particle Kinetic Energy gain:

$$\Delta K = q\ \Delta V$$

CRT Monitor



https://learnodo-newtonic.com/jj-thomson-contribution/cathode-ray-tube-in-a-tv

<u>Challenge</u>: Energy gain directly related to electric potential.

How to create a high voltage?

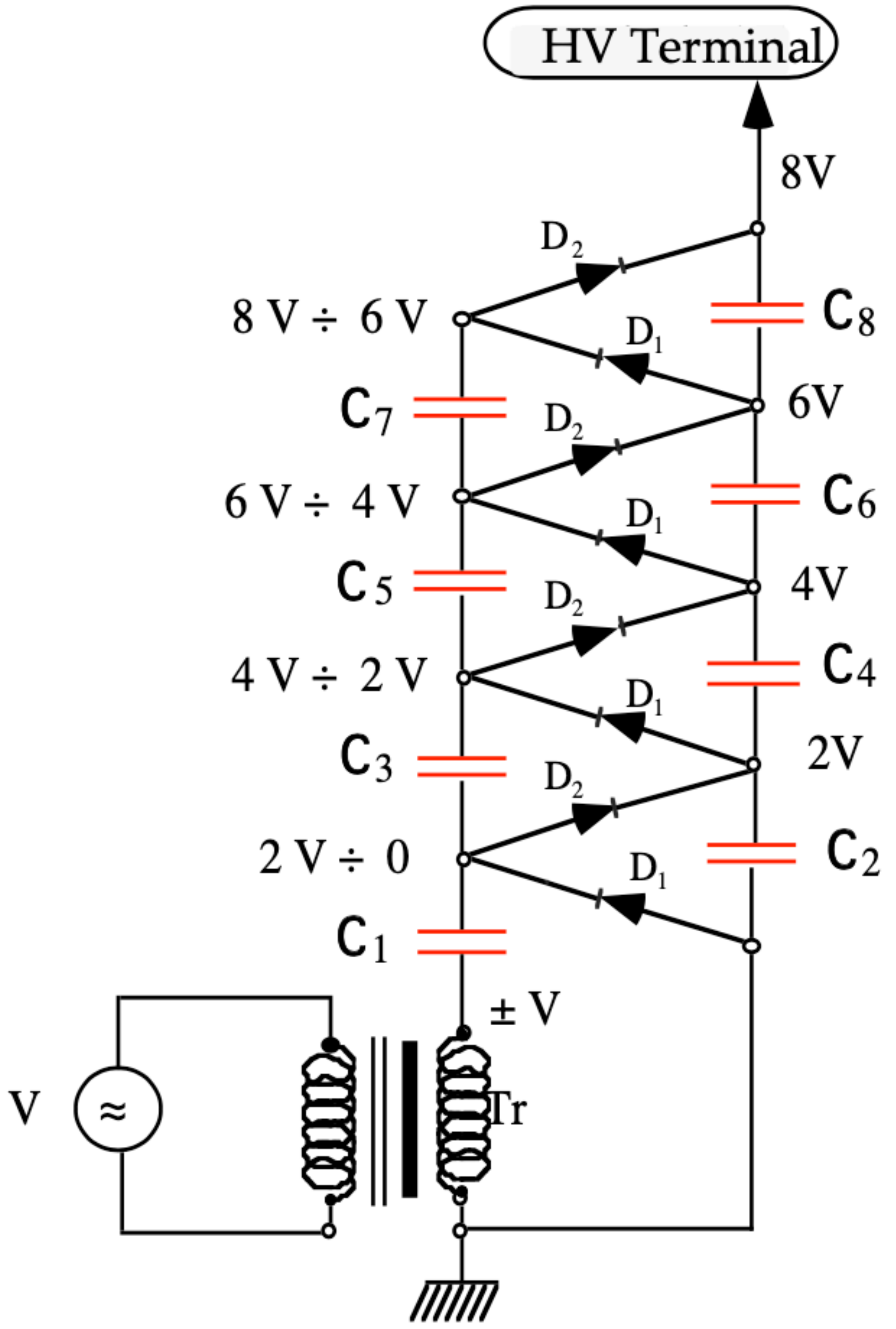
Electrostatic accelerators

Cockcroft-Walton

- First accelerator used in nuclear physics (1932).
- Nobel prize 1951

This Cockcroft-Walton accelerator was used at Fermilab until 2012!

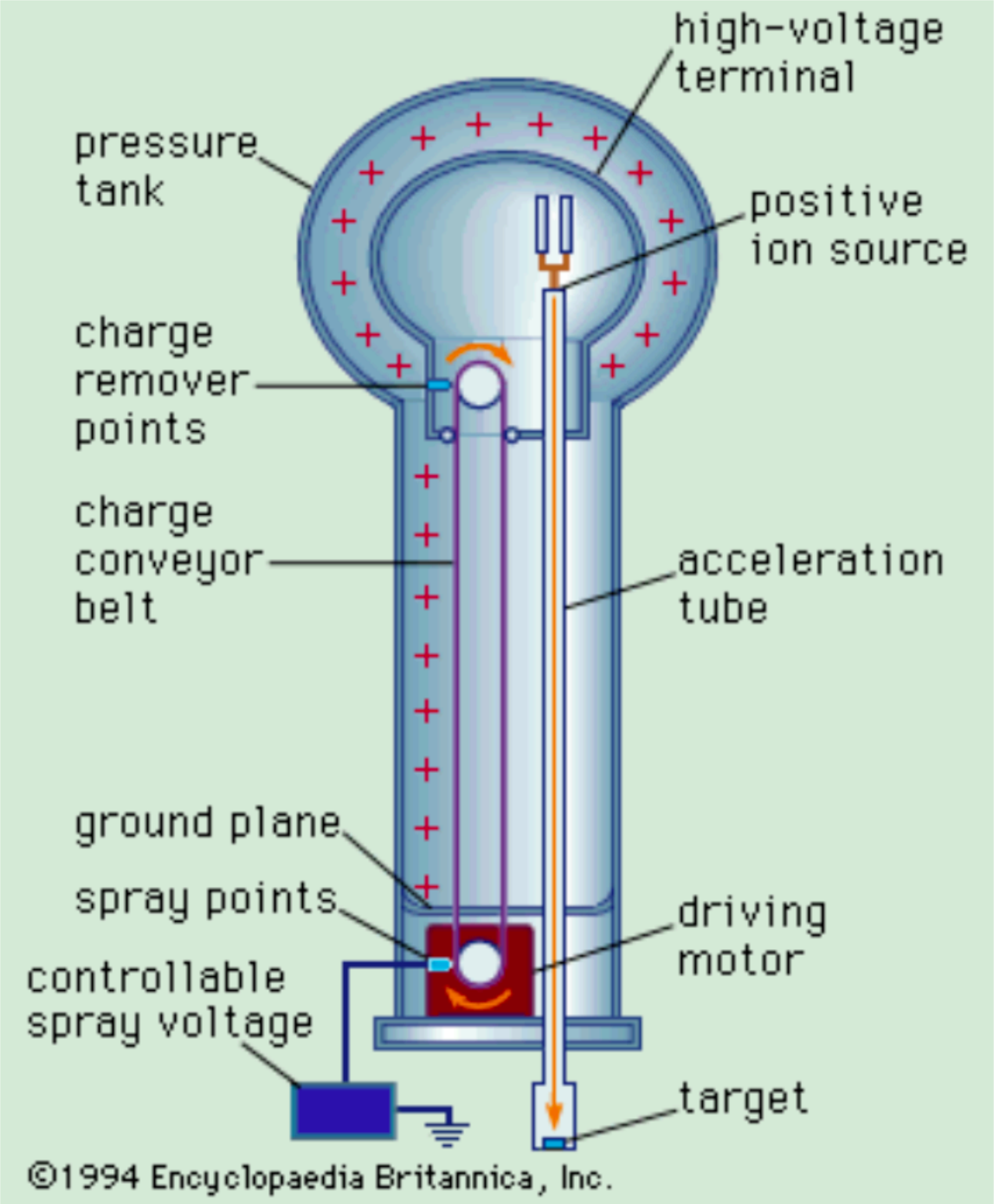
Voltage multiplier using capacitor/diode ladder



Electrostatic accelerators

Van de Graaff

- 1929: Uses a moving belt to accumulate electric charge on a hollow metal globe on the top of an insulated column,
- Capable of creating ~ 10 MV and DC current of 100 μA



AT ROUND HILL, FINAL STAGE OF CONSTRUCTION

Electrostatic accelerators

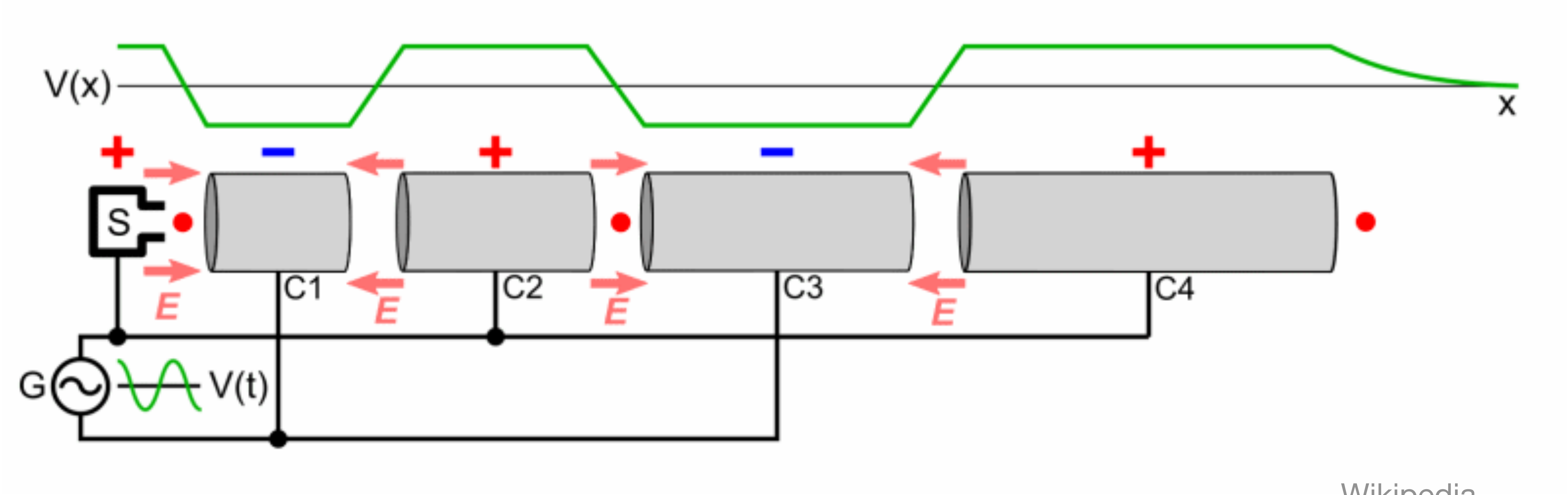
Limit: Electrostatic accelerator limited by achievable potential difference before discharge ($\sim O(1)\ MV/m$)

How to accelerate particles to higher energy?

Electrodynamic accelerator

Standing wave linear accelerator ("Linac")

- Widerøe (1928): Apply acceleration voltage several times to particle beam.



Wikipedia

Energy gain after n^{th} step

Number of acceleration steps

Potential difference per gap

$$E_n = n \cdot q \cdot U_0 \cdot \sin(\phi)$$

Charge of the particle

Phase b/w particle and AC voltage

E.g Linac2 at CERN delivers protons to LHC at 50 MeV (relativistic $\beta = 0.31$)

Limit: Length of drift tubes for particle approaching relativistic speed and hence dimension of the whole accelerator will reach a size that may no longer be feasible.

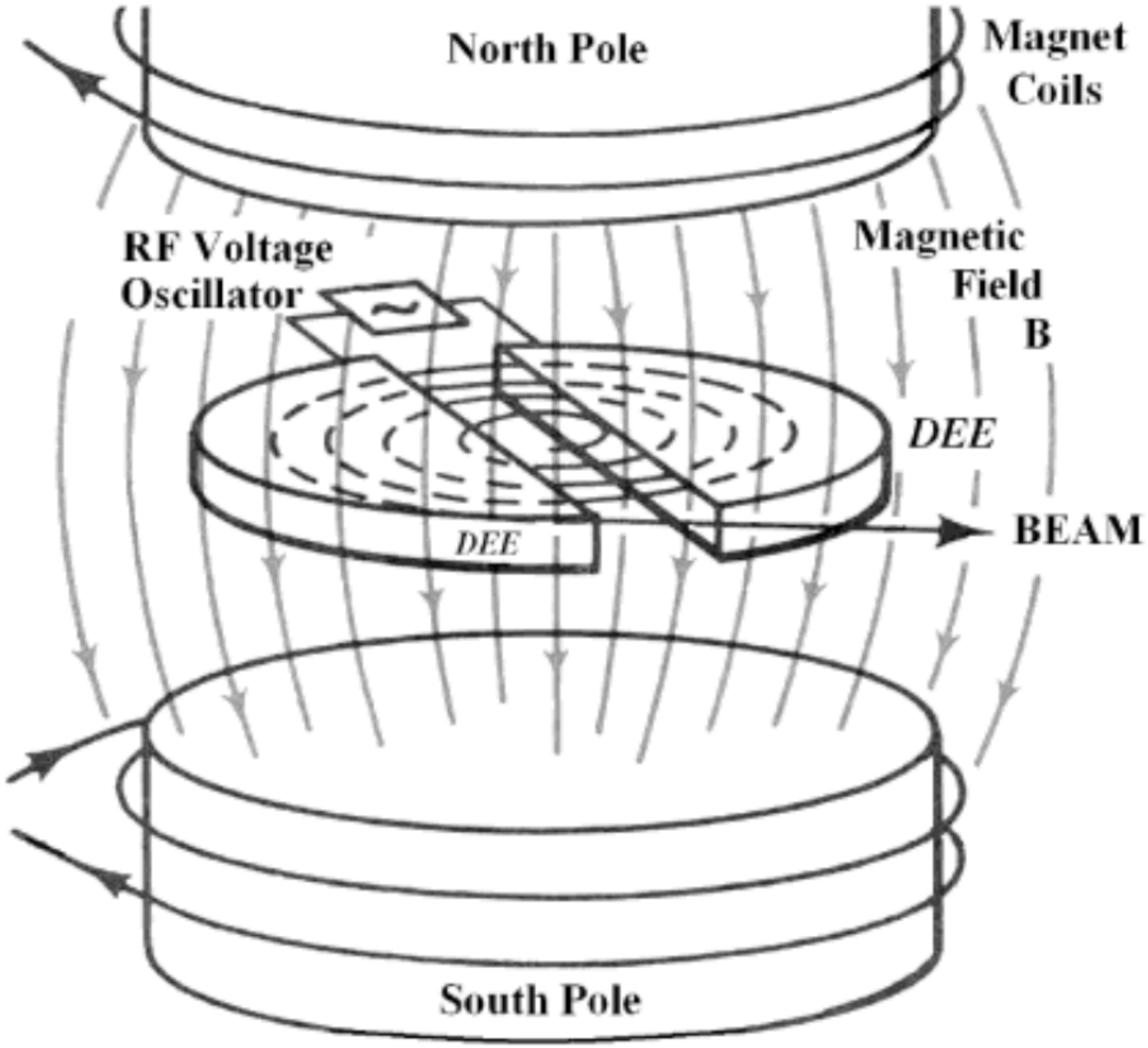
Circular acceleration with several pass through accelerating field!

Circular Accelerators: Cyclotron

- Invented by E.O. Lawrence (1930)

$$\vec{F} = q[\vec{E} + (\vec{v} \times \vec{B})]$$

Accelerated charged particles in a static magnetic field travel outwards from the center along a spiral path.



- Cyclotron frequency (non-relativistic):

$$\omega = \frac{v}{r} = \frac{eB}{m} = \text{constant}$$

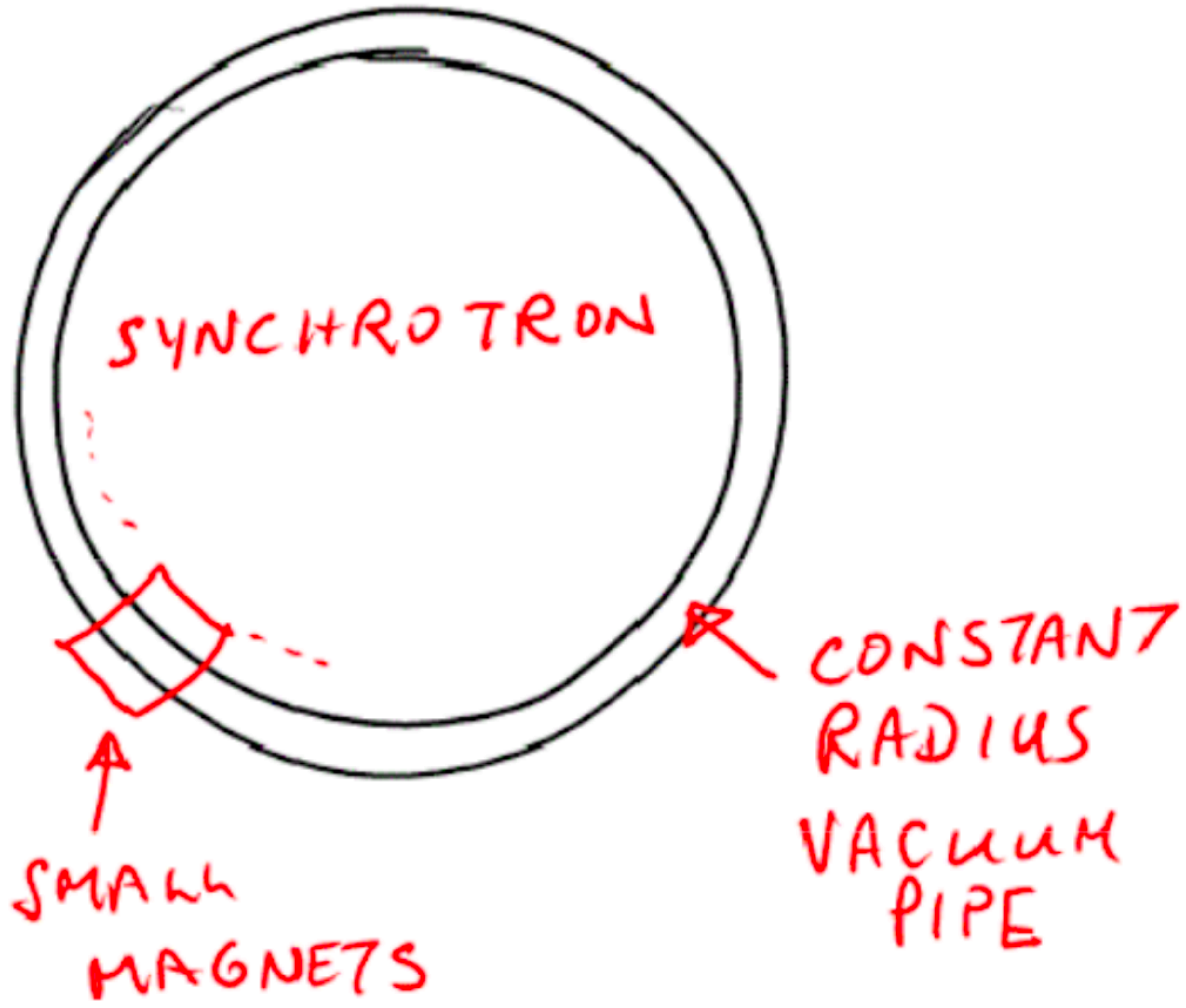
- Capable of producing DC current of order mA.

A. W. Chao, W. Chou, "Reviews of Accelerator Science and Technology - Volume 2: Medical Applications of Accelerators" (2010)

Circular accelerators

Limit: To reach high energy, size of magnet gets prohibitively expensive.

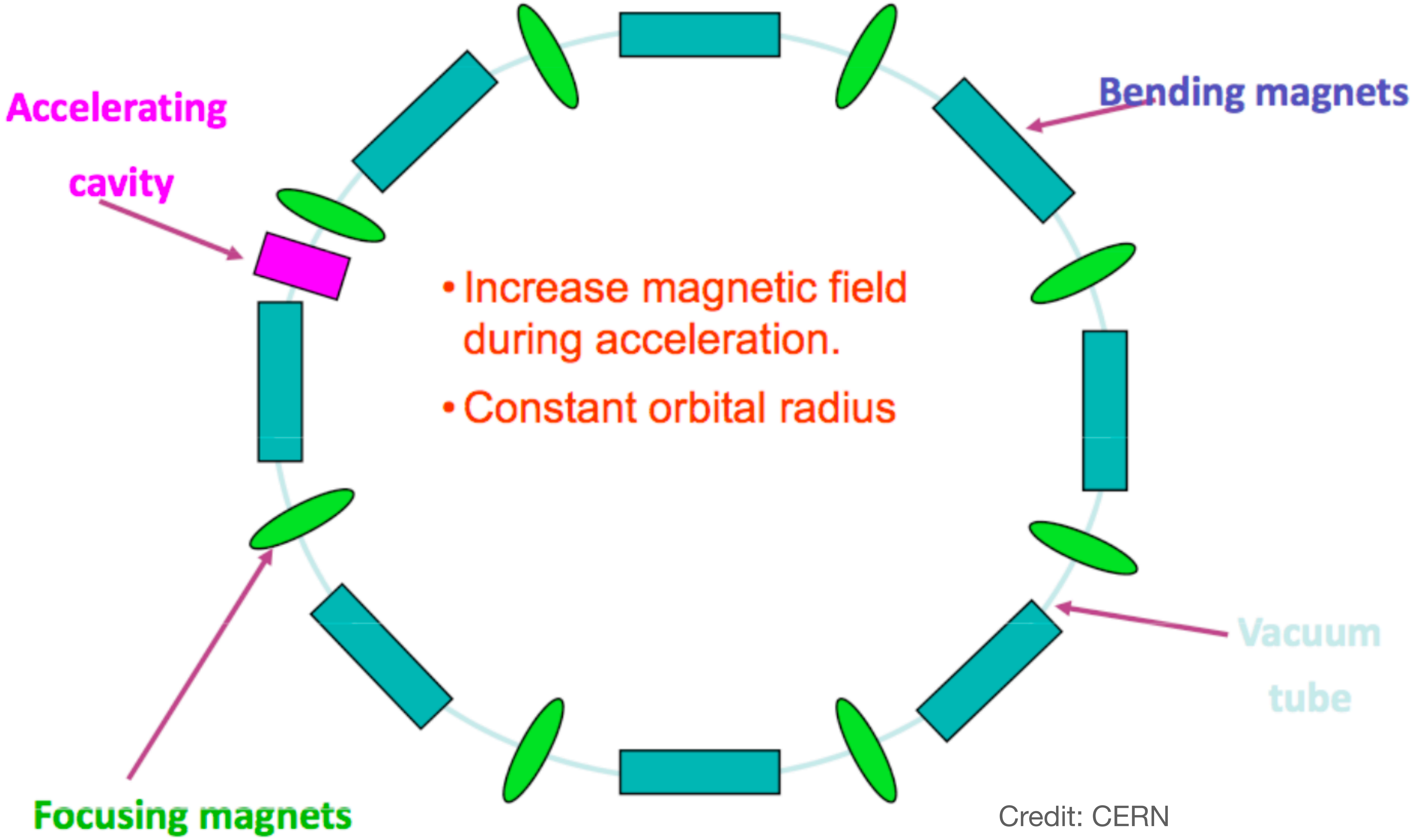
Design machine with constant orbit radius!



Credit: B. Orr, University of Toronto

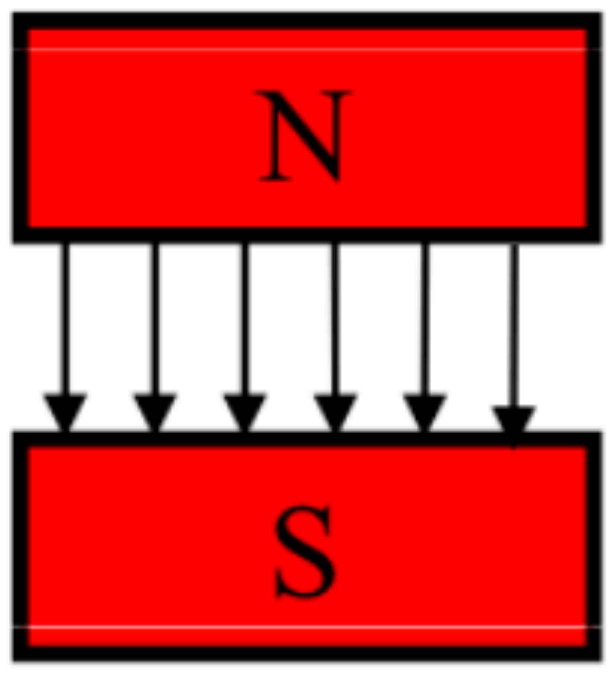
Circular accelerators: Synchrotron

- **Acceleration**: Provided by radio-frequency (RF) accelerating cavities.
- **Trajectory**: Particles kept in a constant radius orbit using dipole bending magnets with a time-dependent field!

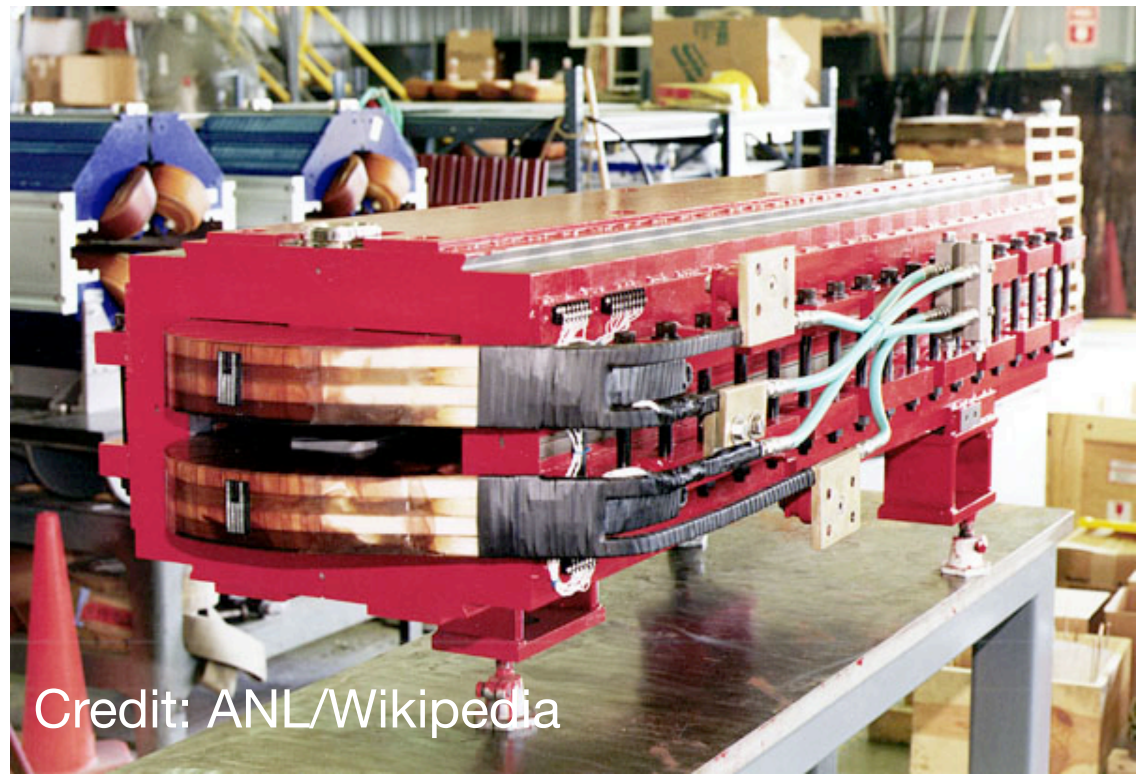


Synchrotron: trajectory

Dipole

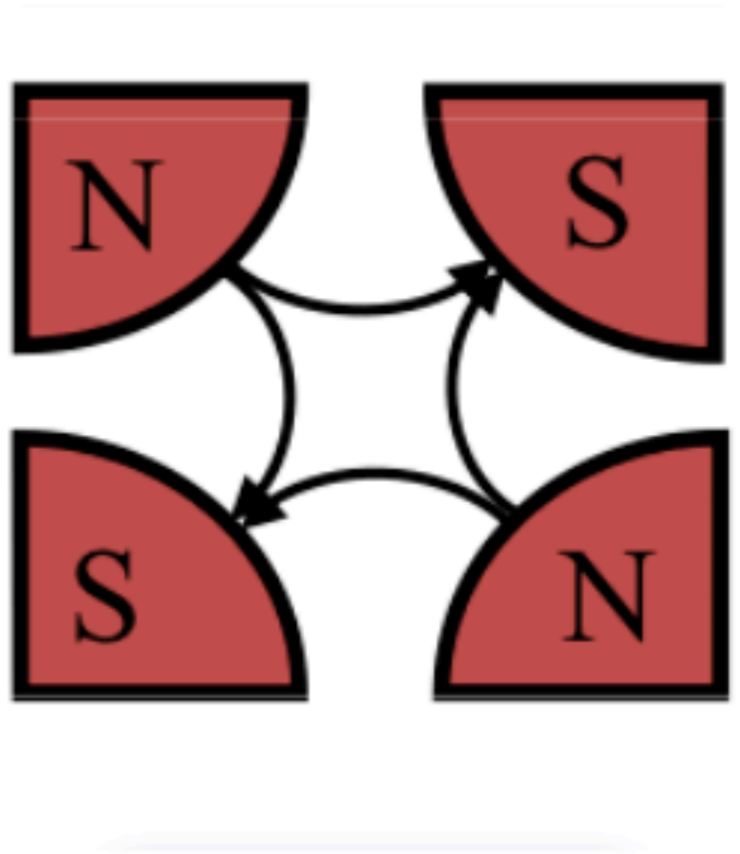


Bending

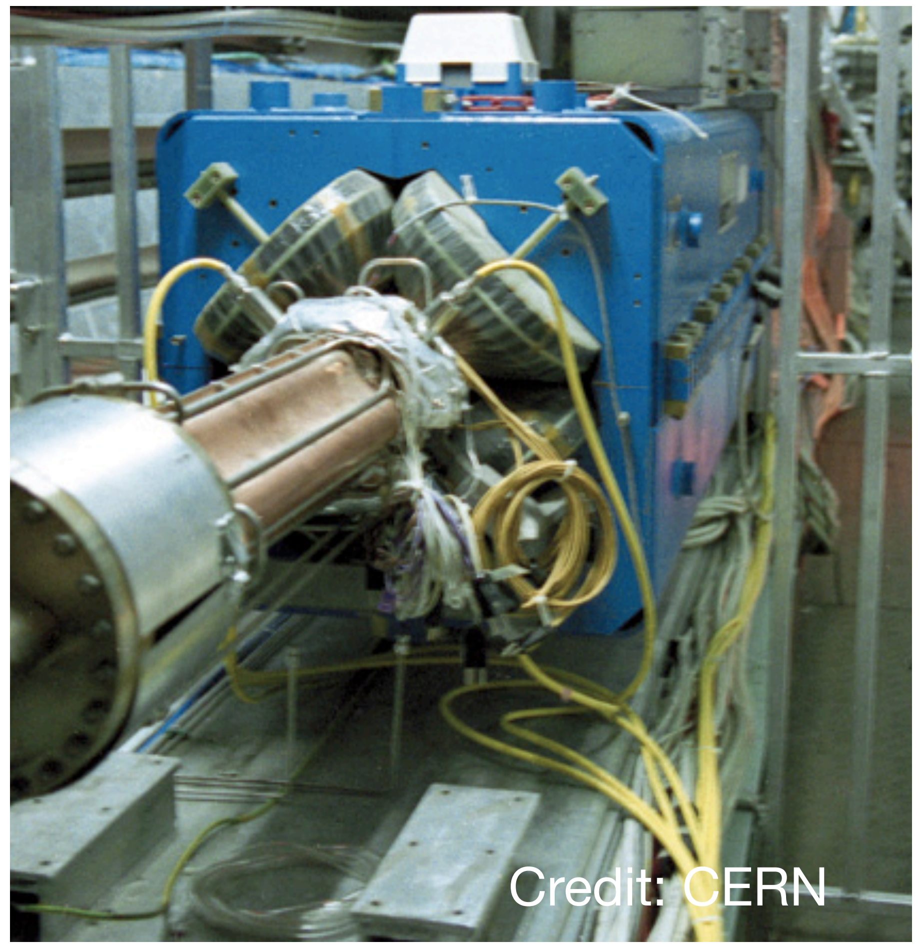


Credit: ANL/Wikipedia

Quadrupole

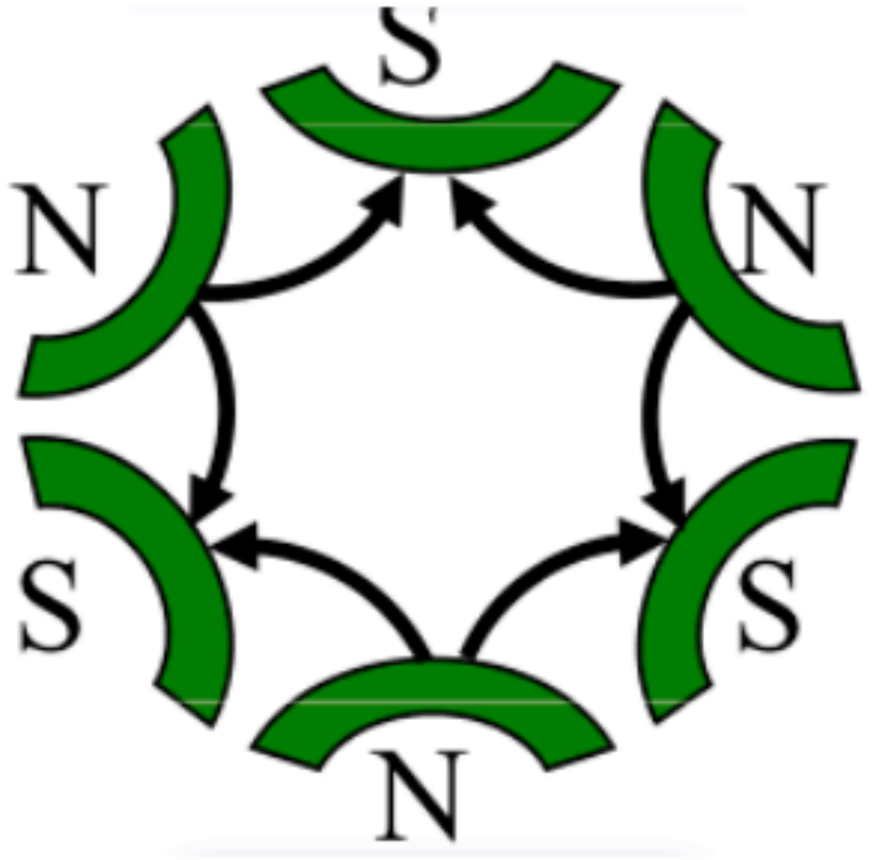


Focusing

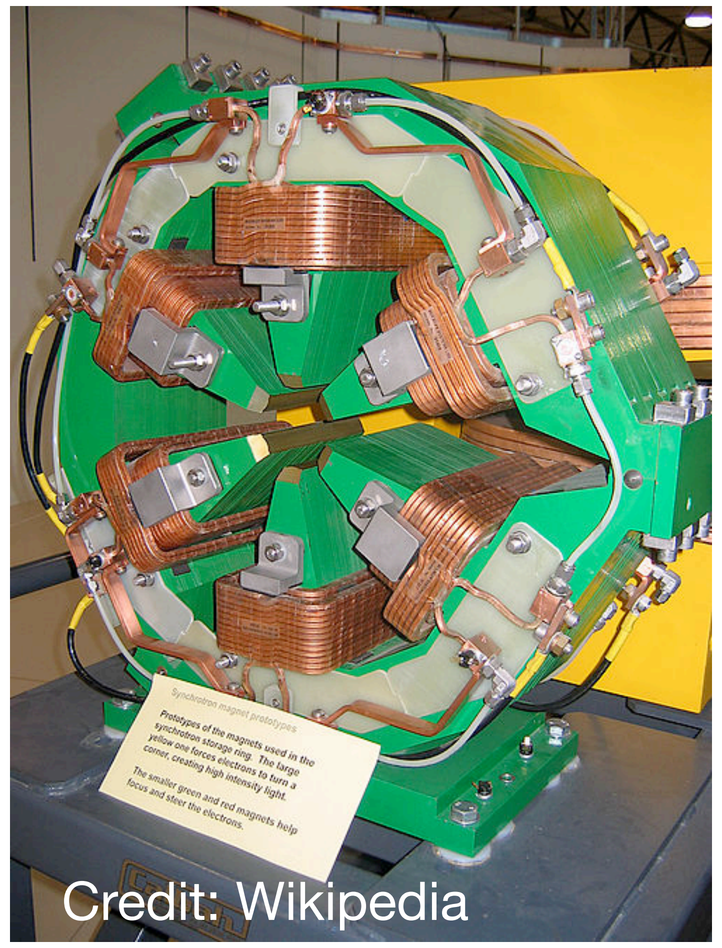


Credit: CERN

Sextupole

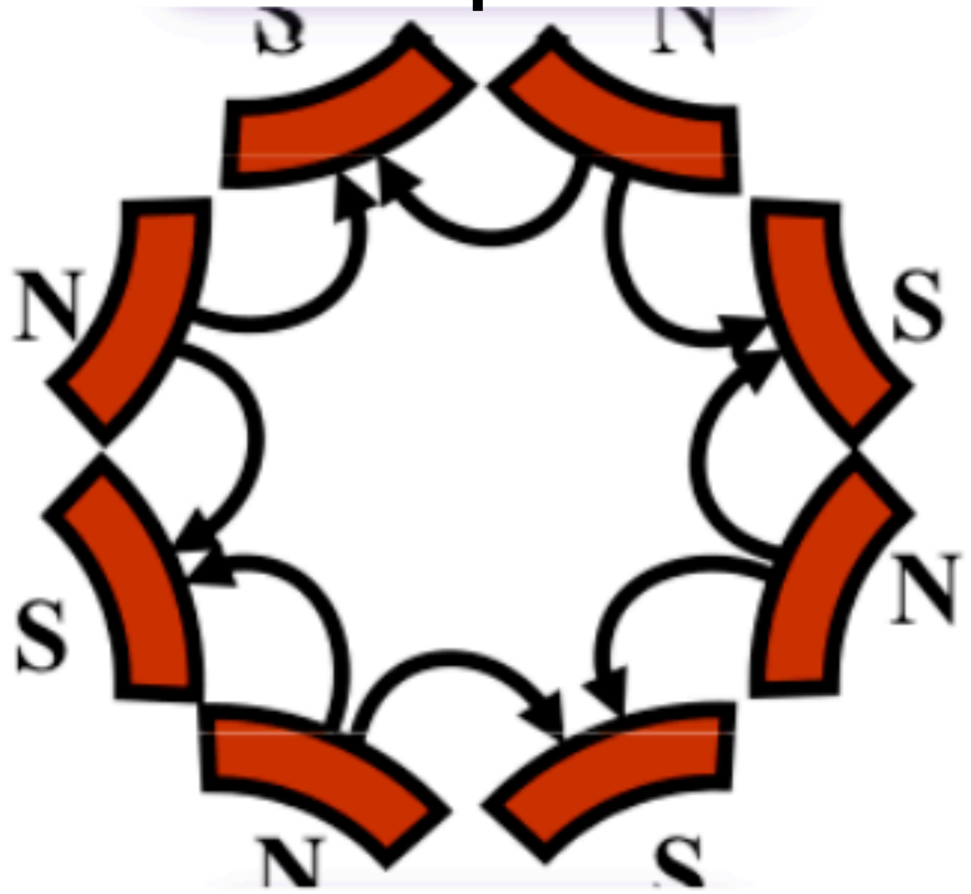


Chromaticity compensation

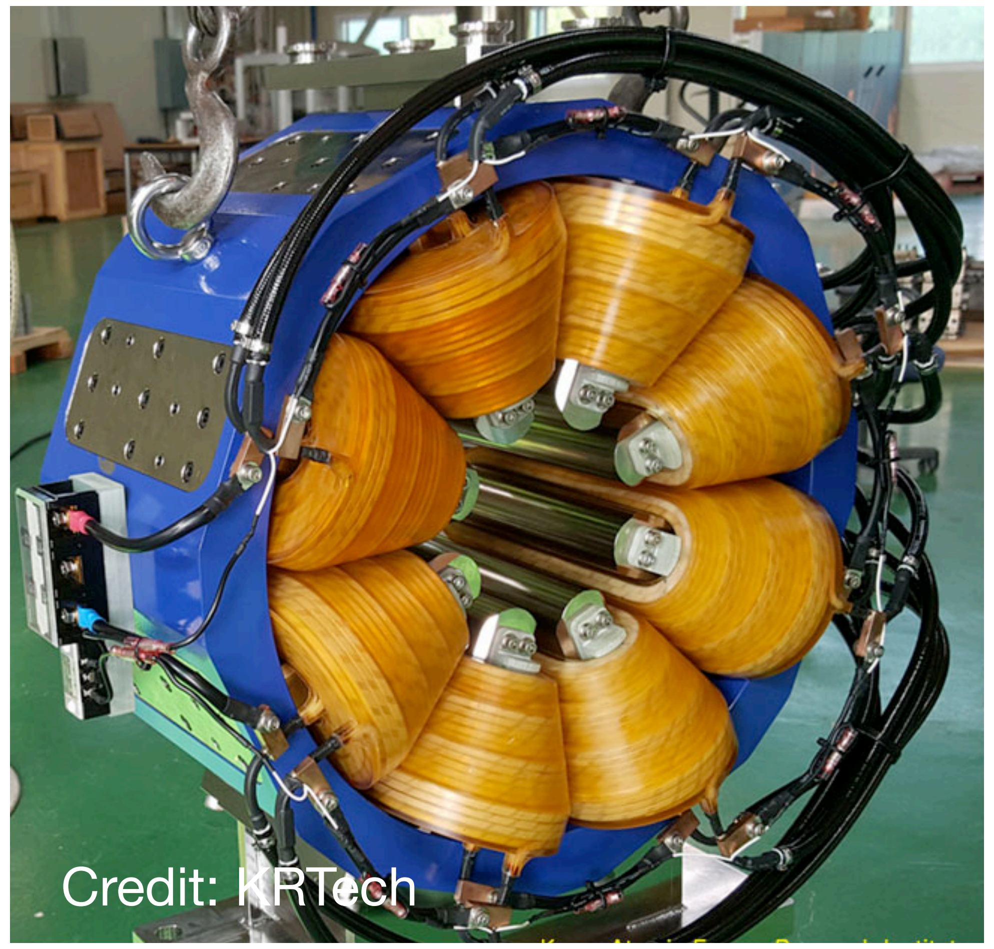


Credit: Wikipedia

Octupole



High-order corrections

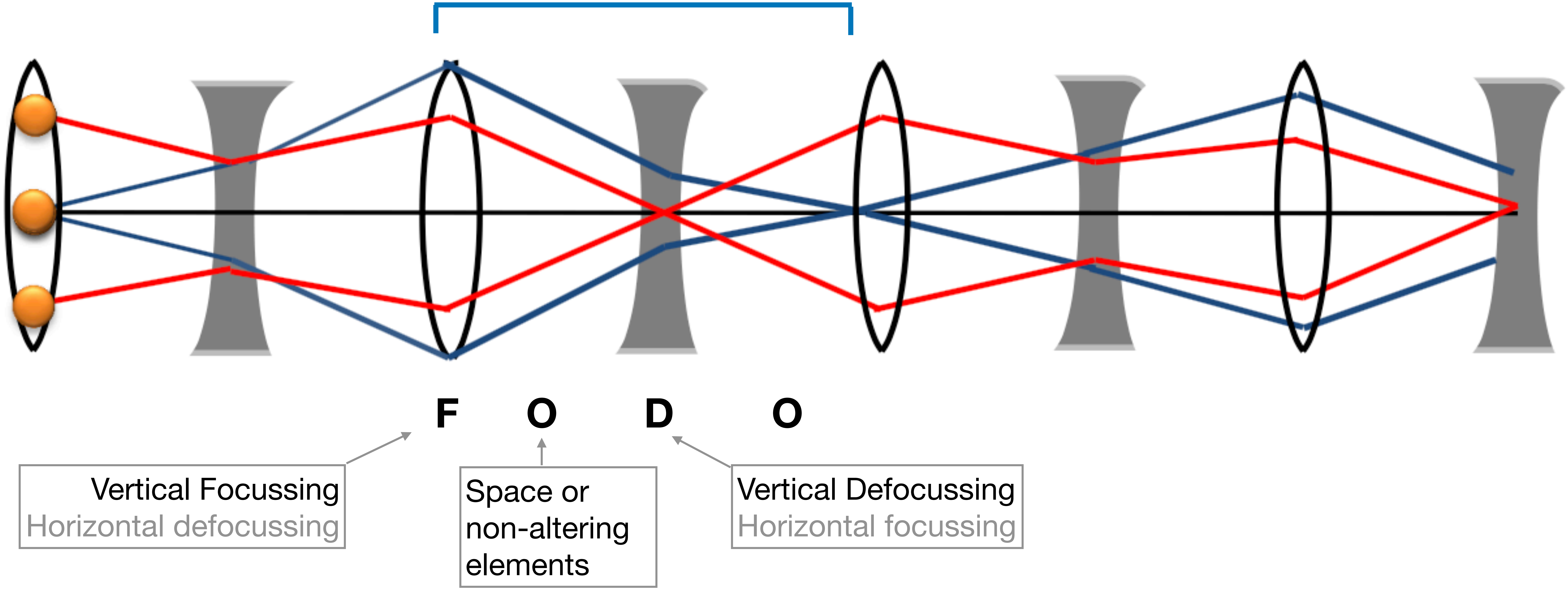


Credit: KRTech

Synchrotron: trajectory

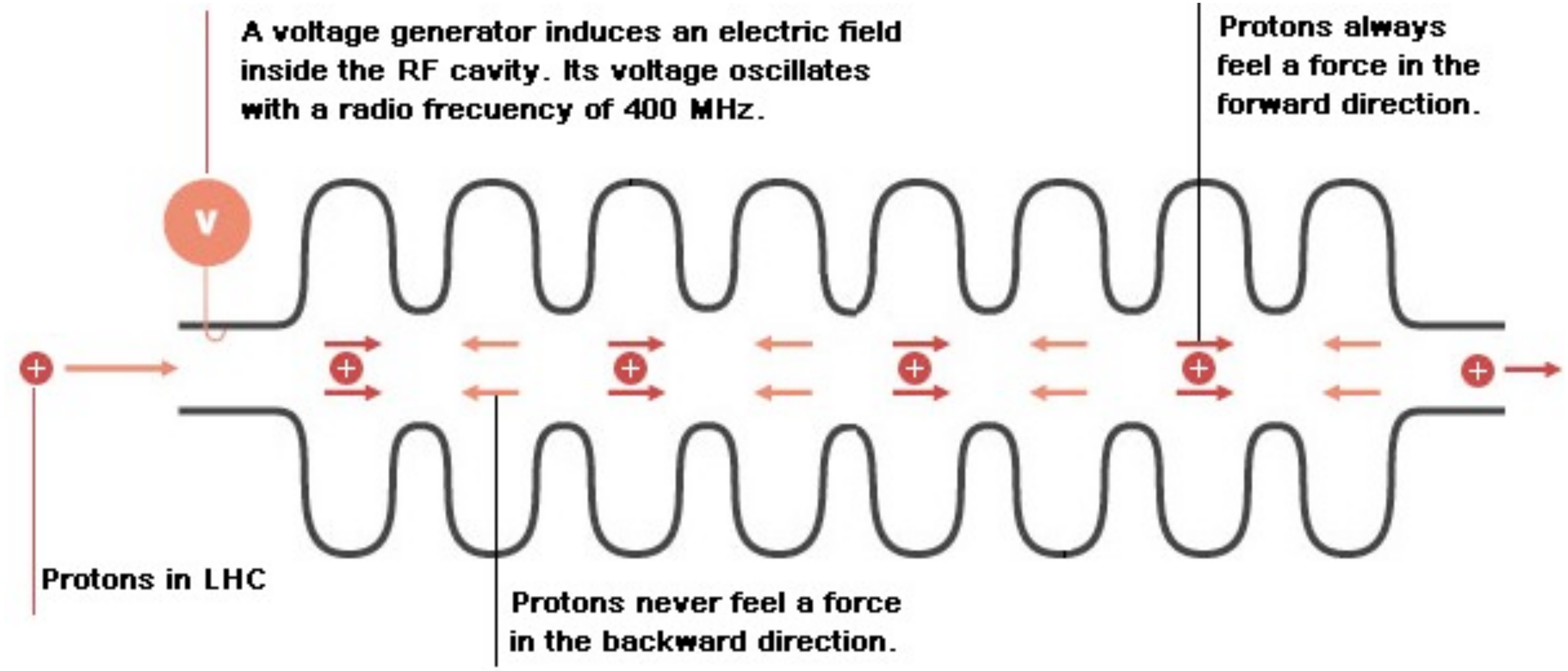
The (magnetic) "**lattice**" of an accelerator is the sequence of dipole, quadrupoles and other magnets which constitutes the accelerator.

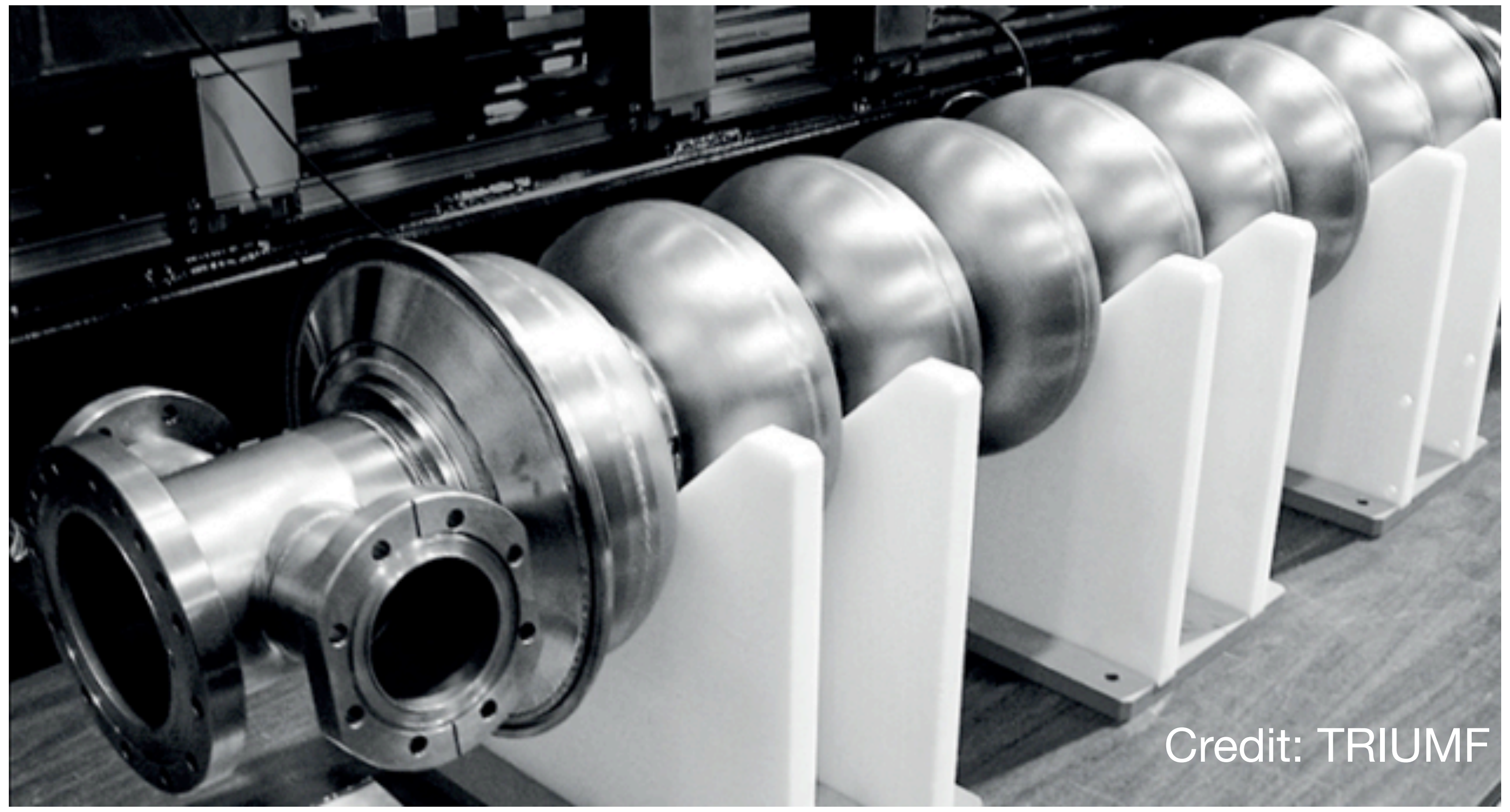
One of the most wide-spread lattice cell is called the **FODO cell**.

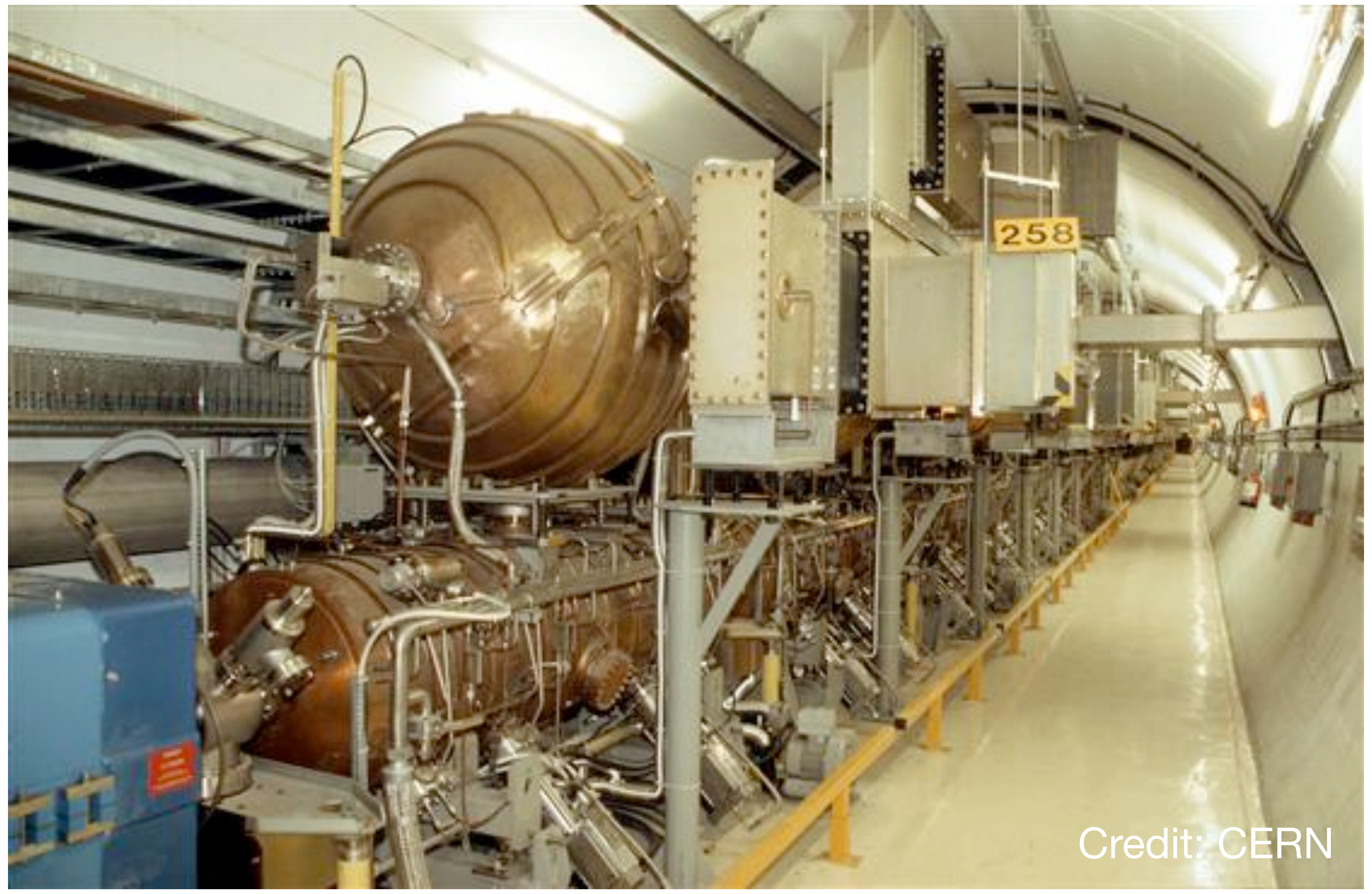


Beam particles trajectories through the focusing arrangement of several FODO cells show an oscillating pattern.

Resonant accelerating cavity





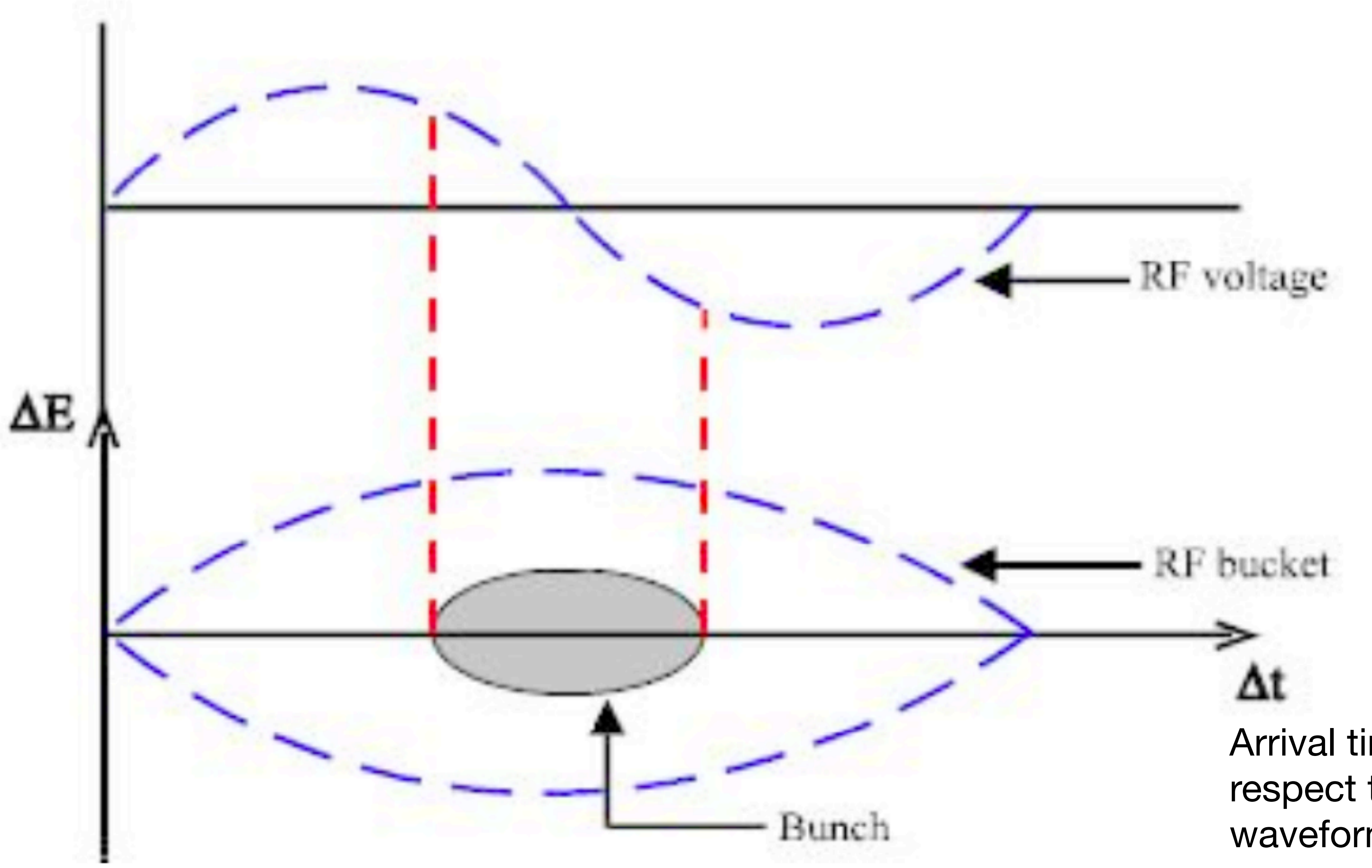


Superconducting cavities can achieve electric fields up to 50 MV/m.

Synchrotron: Phase Stability

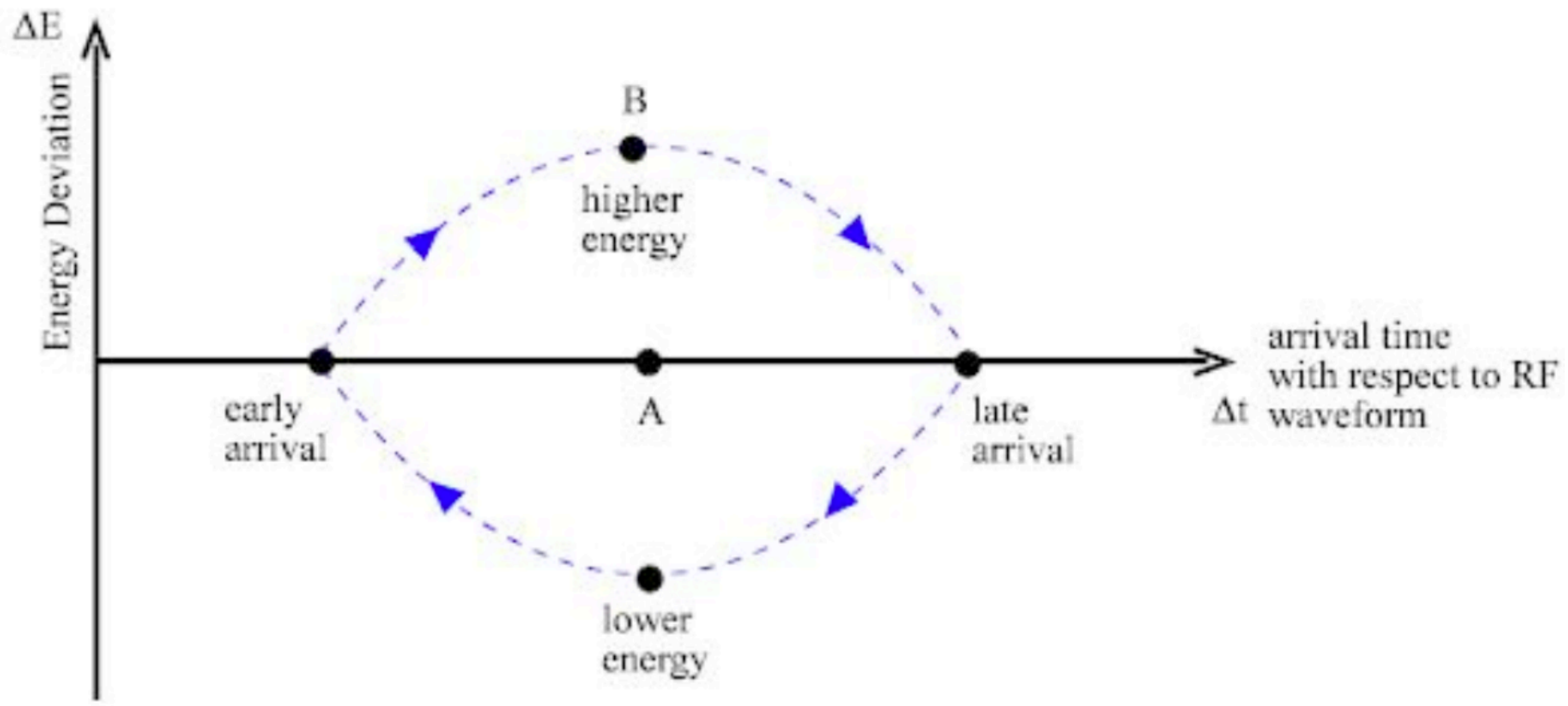
- To always see an accelerating voltage, the RF frequency must be an integer
  $f_{RF} = h\, f_{rev}$ [*h* = "harmonic number"]
- The "*h*" segments of the circumference centred on these accelerating points
- Particles get "clumped" around the synchronous particle in a "bunch".
  This particle bunch is contained in an RF bucket.
- Not all buckets need to be filled with particle bunches.

Example: LHC
f_{RF} = 400 MHz
Proton travelling at v ~ c
Circumference ~ 27 km
f_{rev} ~ 10 kHz
Harmonic number = 35,640.
occupied buckets = 2808



Arrival time with respect to RF waveform

Higher energy particles —> longer orbit and a lower revolution frequency —> delayed arrival at the accelerating cavity —> get more acceleration.



http://www.lhc-closer.es/php/index.php?i=1&s=4&p=19&e=0

Outline

(1) Brief historical introduction to particle acceleration

(2) Use of particle accelerator in physics research

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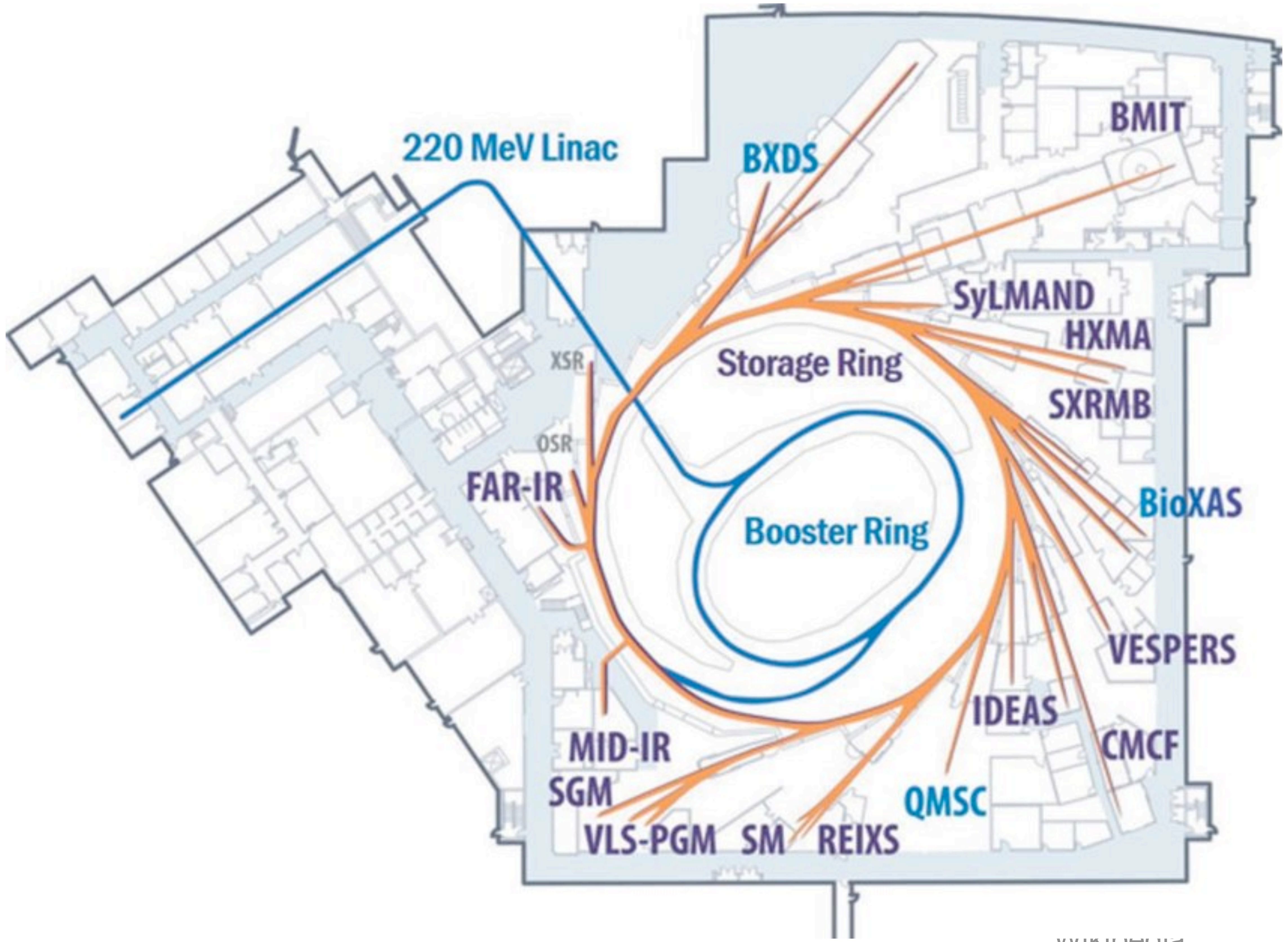
Accelerators in physics research

- **Light source**
  - **Synchrotron radiation**: Electromagnetic radiation emitted when charged particles are subjected to an acceleration perpendicular to their velocity.

$$P \sim \gamma^4$$

Canadian Light Source · Centre canadien de rayonnement synchrotron

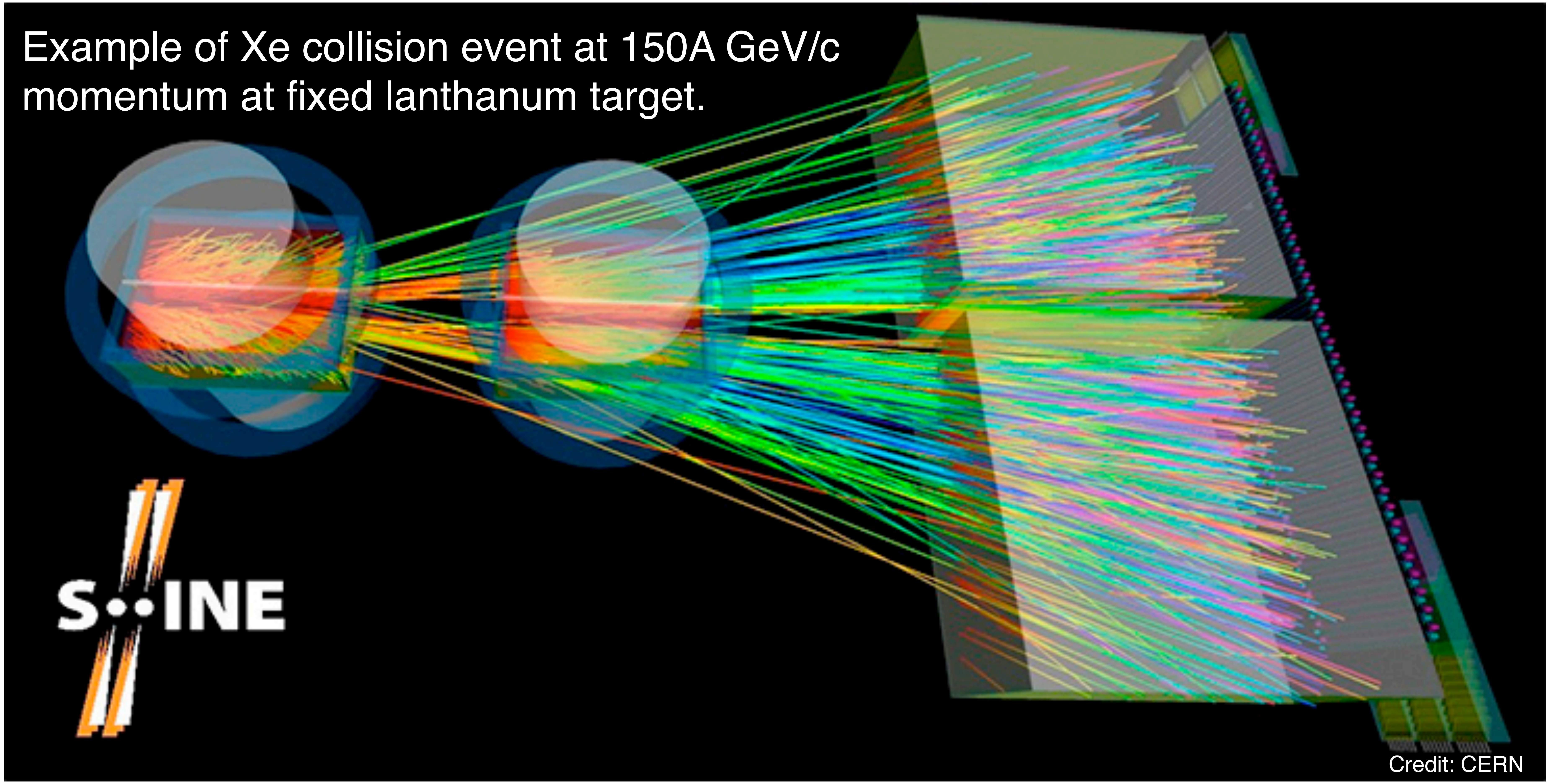


Wikipedia

Accelerators in physics research

- **Fixed-target experiments**

$$\sqrt{s} \approx \sqrt{2\ E_{\text{particle}} \cdot m_{\text{target}}}$$



Accelerators in physics research

- **Particle Collider**

$$\mathscr{L} = f \cdot \frac{n_1 n_2}{4\pi\sigma_x\sigma_y} \quad [\mathrm{cm}^{-2}s^{-1}]$$

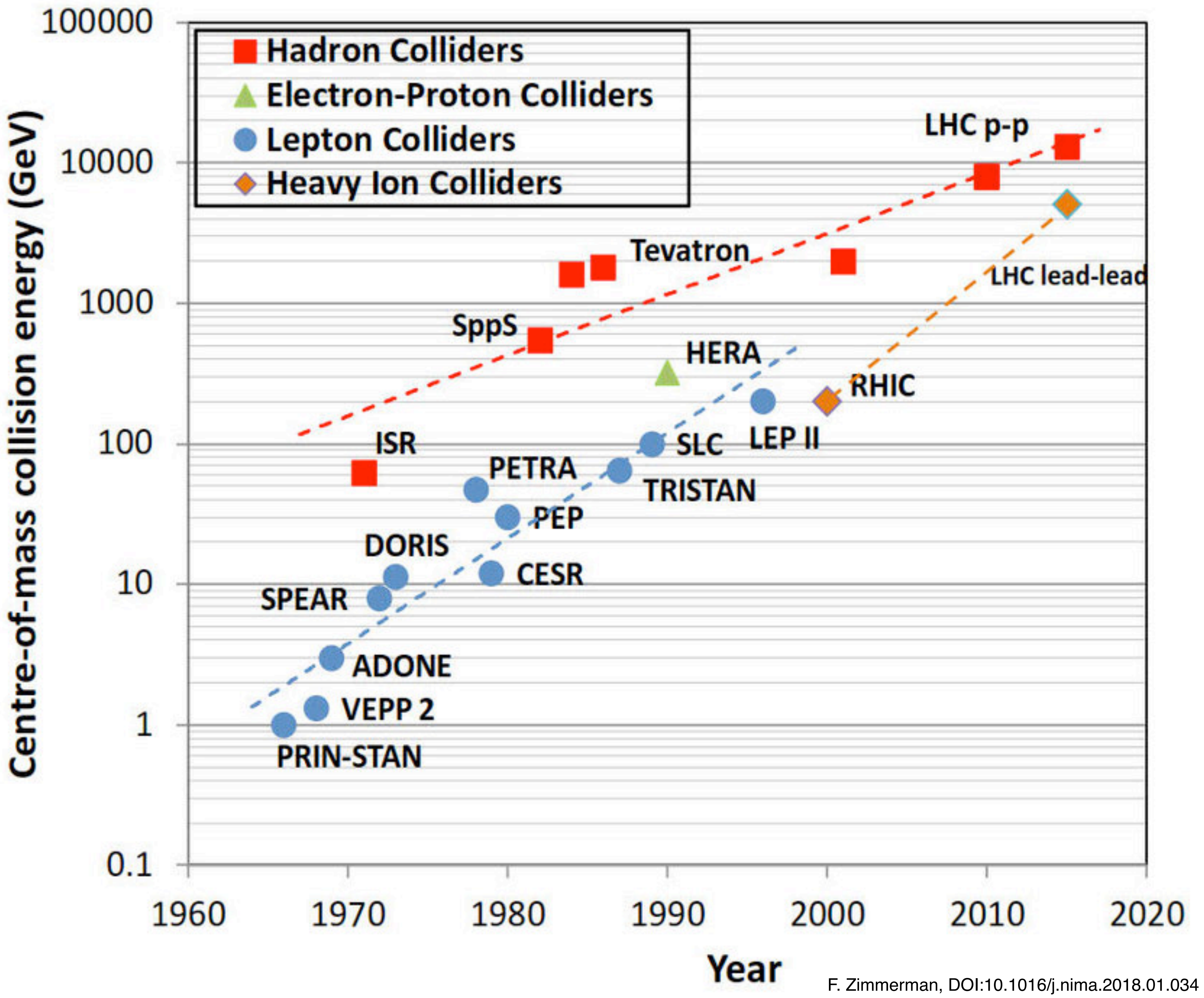
f: Bunch crossing frequency

n_1, n_2: number of particles per bunch

σ_x, σ_y: Bunch cross-section

$$\text{Rate} = \sigma\, \mathscr{L}$$

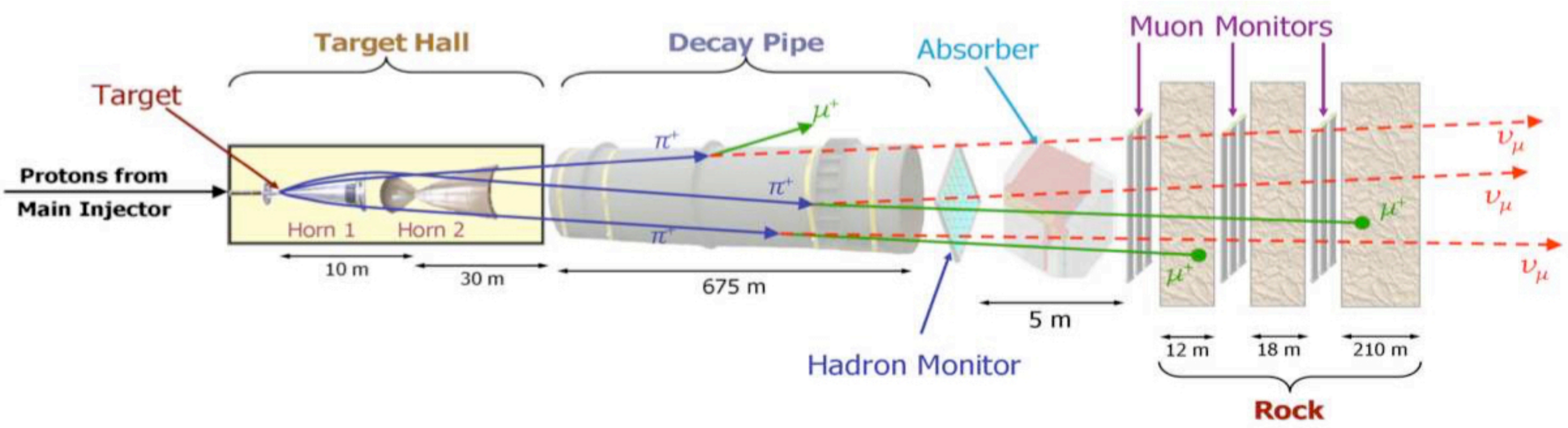
$$\sqrt{s} \approx 2\, E^{\text{lab}}_{\text{particle}}$$



F. Zimmerman, DOI:10.1016/j.nima.2018.01.034

Accelerators in physics research

- **Secondary beam production**
  - E.g. Neutrino beam



https://www.hep.ucl.ac.uk/nova/beam.shtml

Outline

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TRIUMF

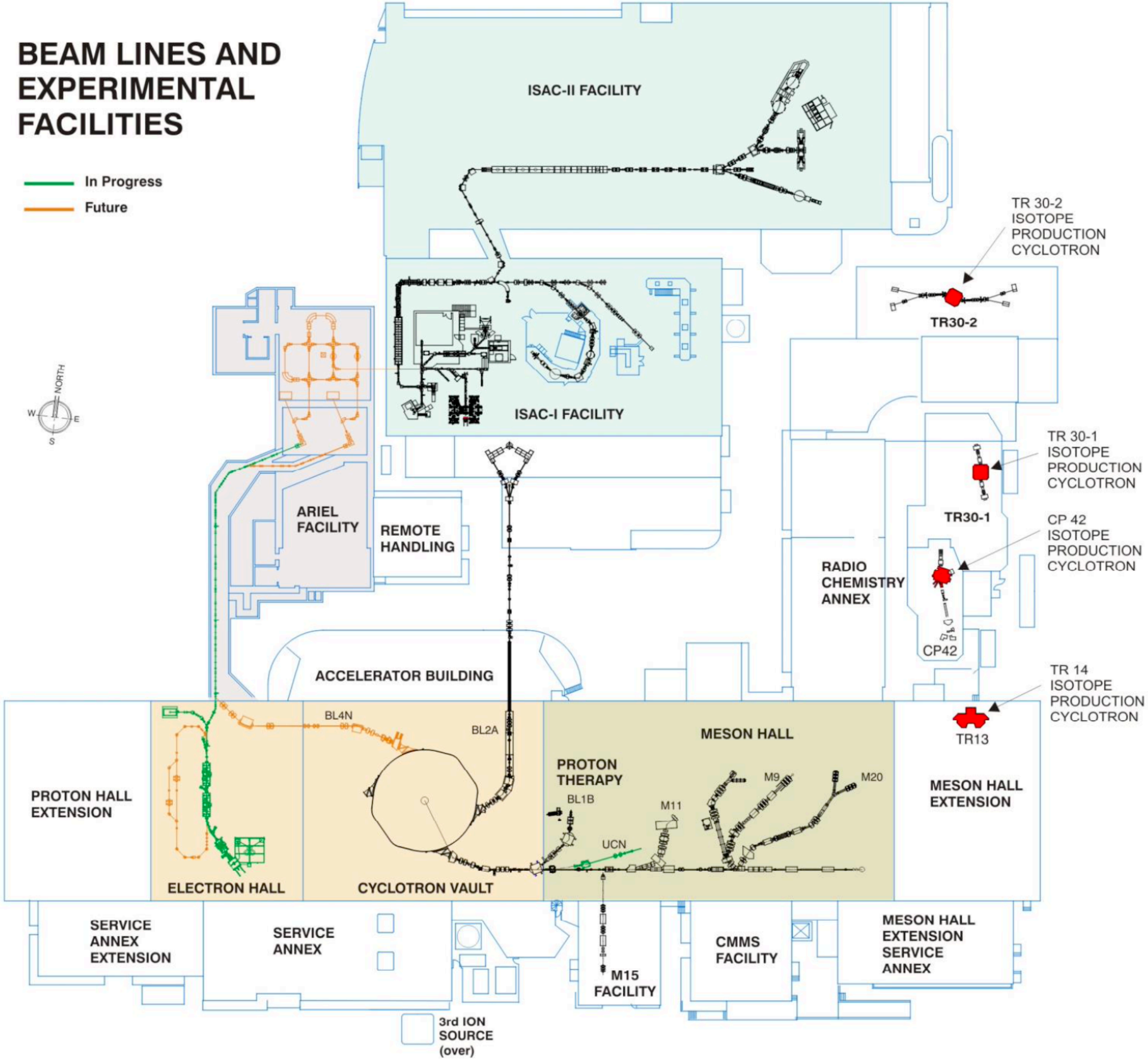
Primary beam driver:
Cyclotron, 500 MeV, 100 μA, H-
Produces rare isotopes, neutrons and muons!

Isotope Separator and Accelerator facility - ISAC
ISAC-I: Normal conducting-linac, 0.15-1.5 MeV/u
ISAC-II: Superconducting-linac, 5-15 MeV/u

Advanced Rare Isotope Laboratory - ARIEL
Superconducting electron linac 30 MeV, 10 mA

4 Cyclotrons for medical isotope production

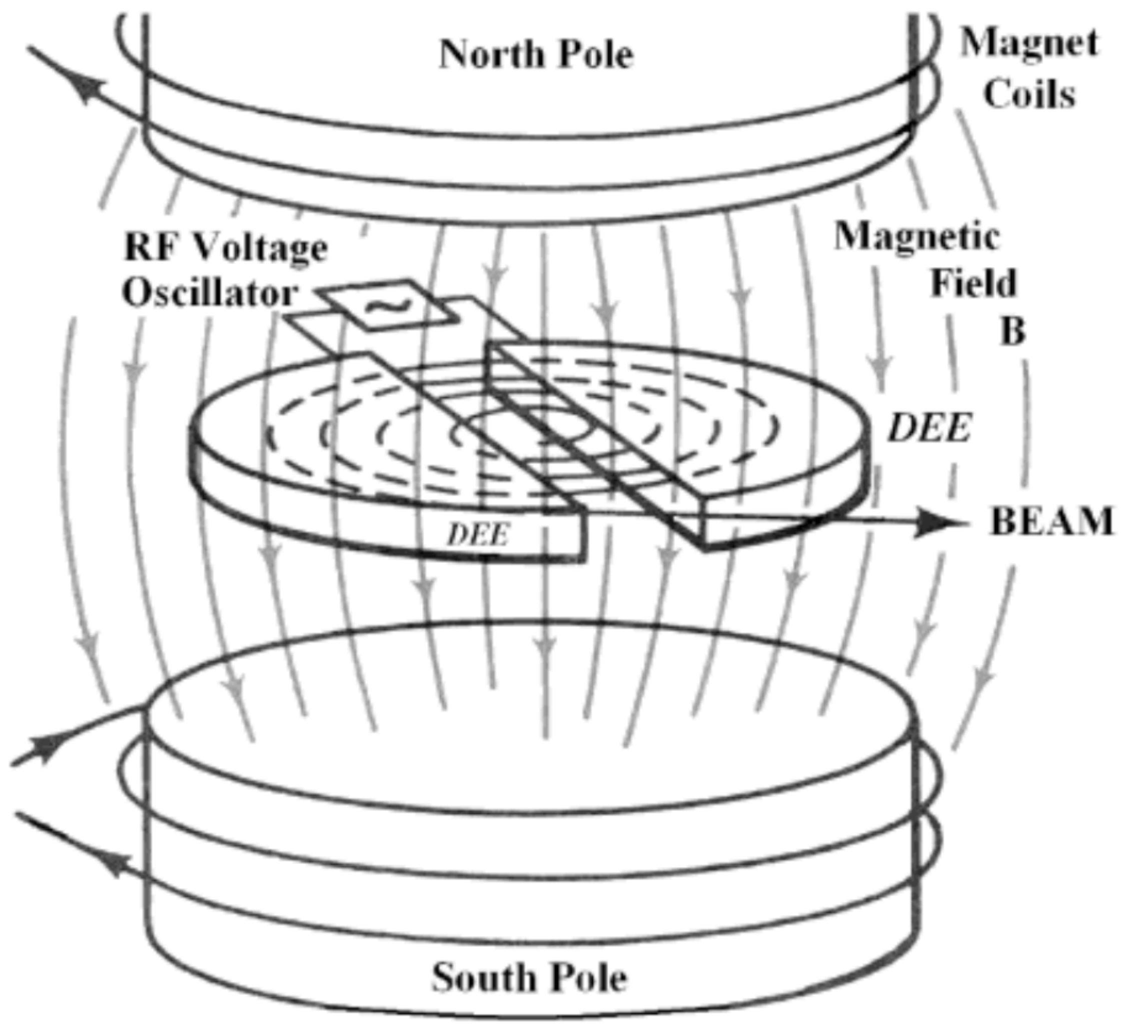
Physics Research:
- Accelerator Physics
- Nuclear structure
- Nuclear astrophysics
- Fundamental symmetries
- Particle Physics
- Nuclear medicine
- Molecular & Materials Science
- etc.

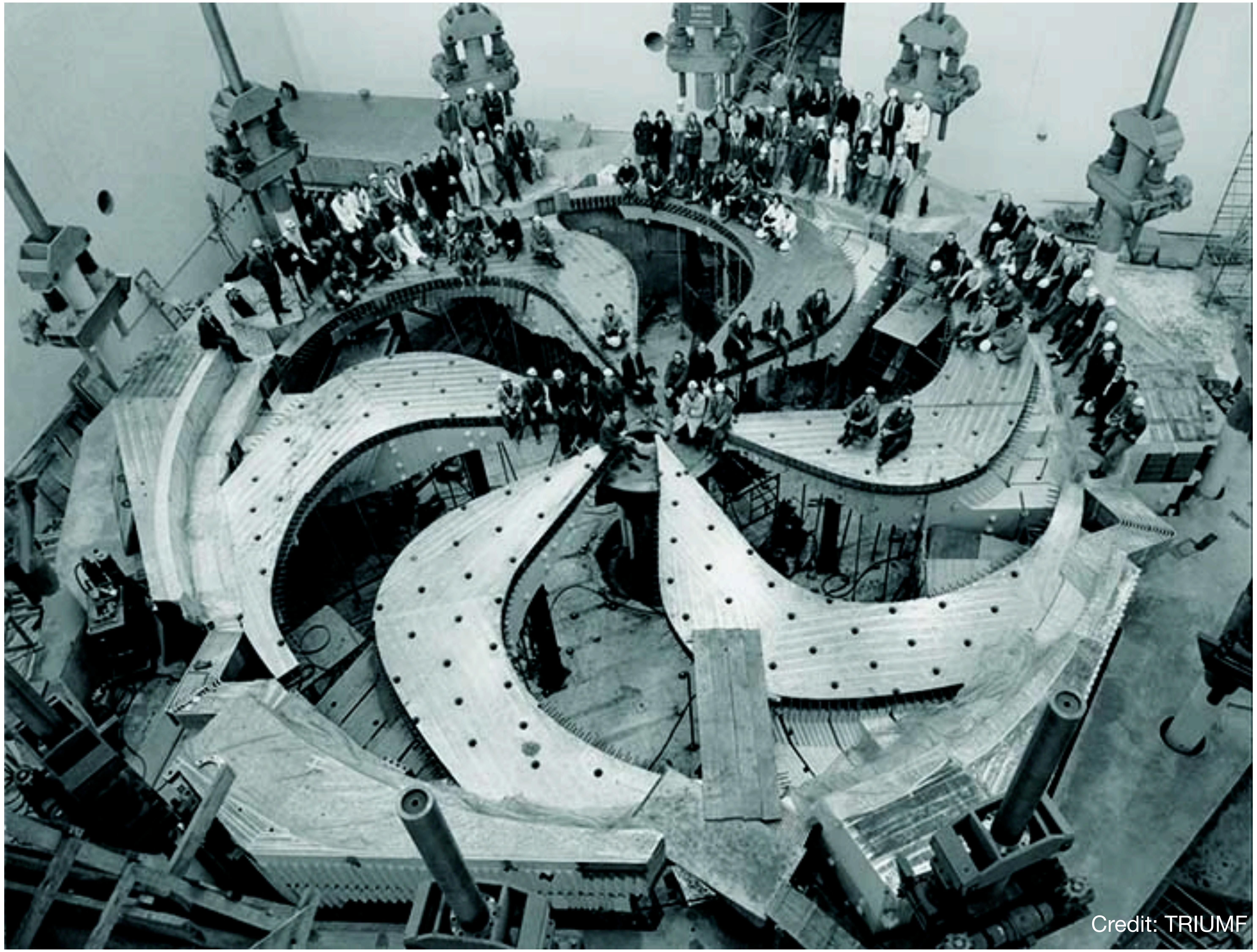


TRIUMF

- **World's largest cyclotron!**
- Recall cyclotron frequency: $\omega = \dfrac{eB}{m}$

  but for relativistic particle $m = \gamma m_0$
- Need to make a B field that increases with radius.
  - But this de-focusses the beam.
  - Solution: Make B field vary in azimuth so that the net effect is to focus beam.

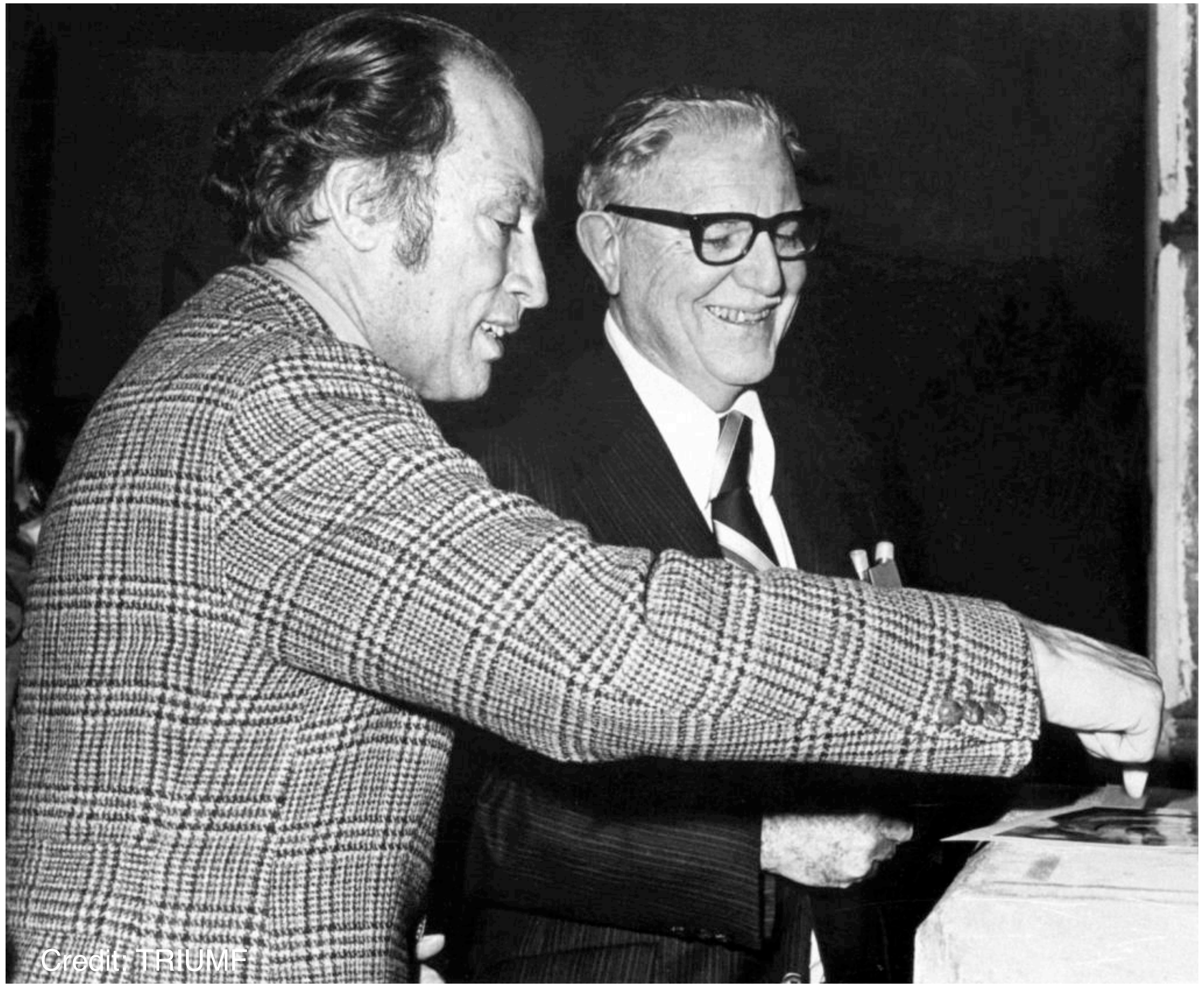




Credit: TRIUMF

TRIUMF

Pierre Elliott Trudeau, 1976

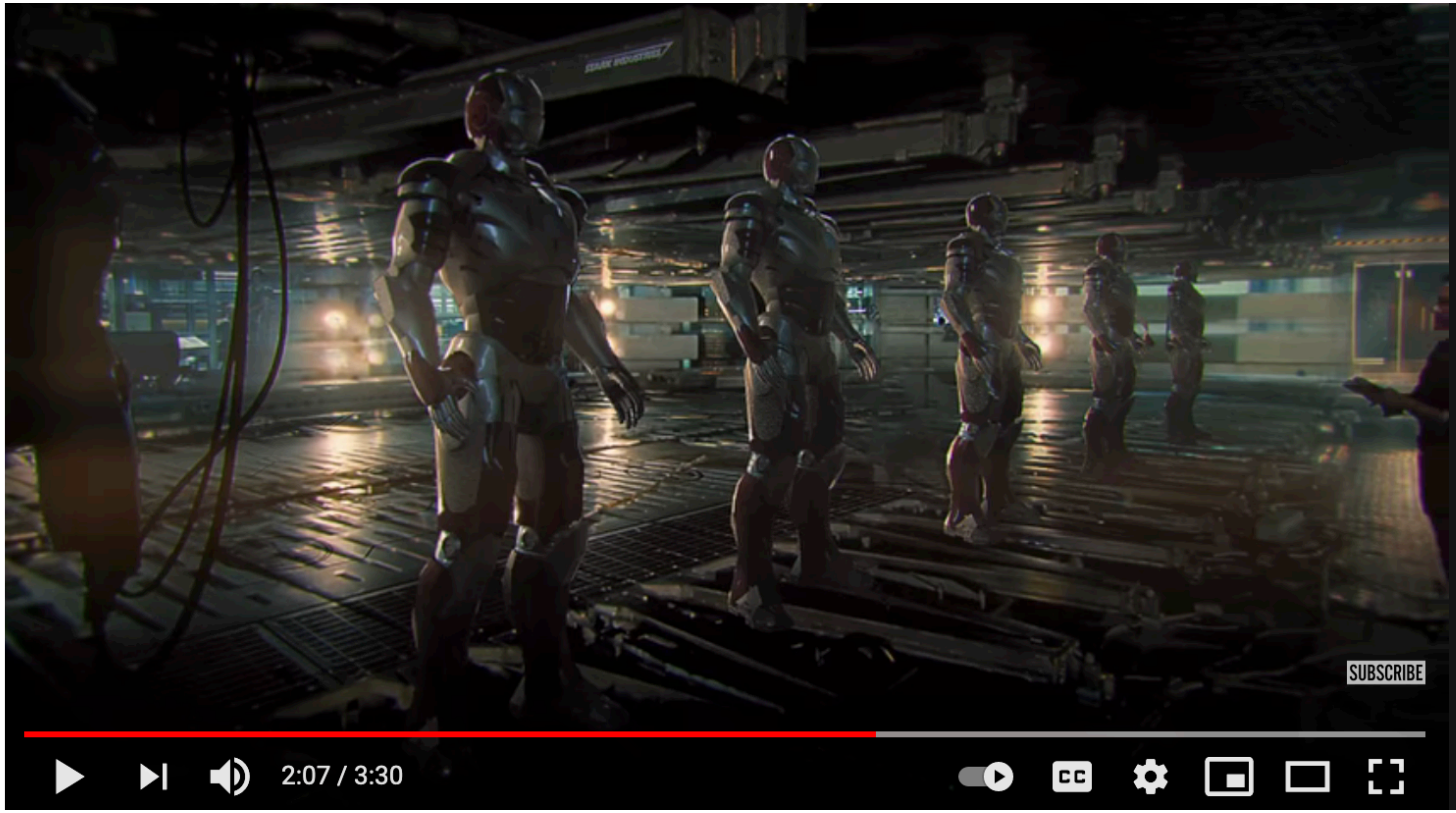


Credit: TRIUMF

Justin Trudeau, 2018

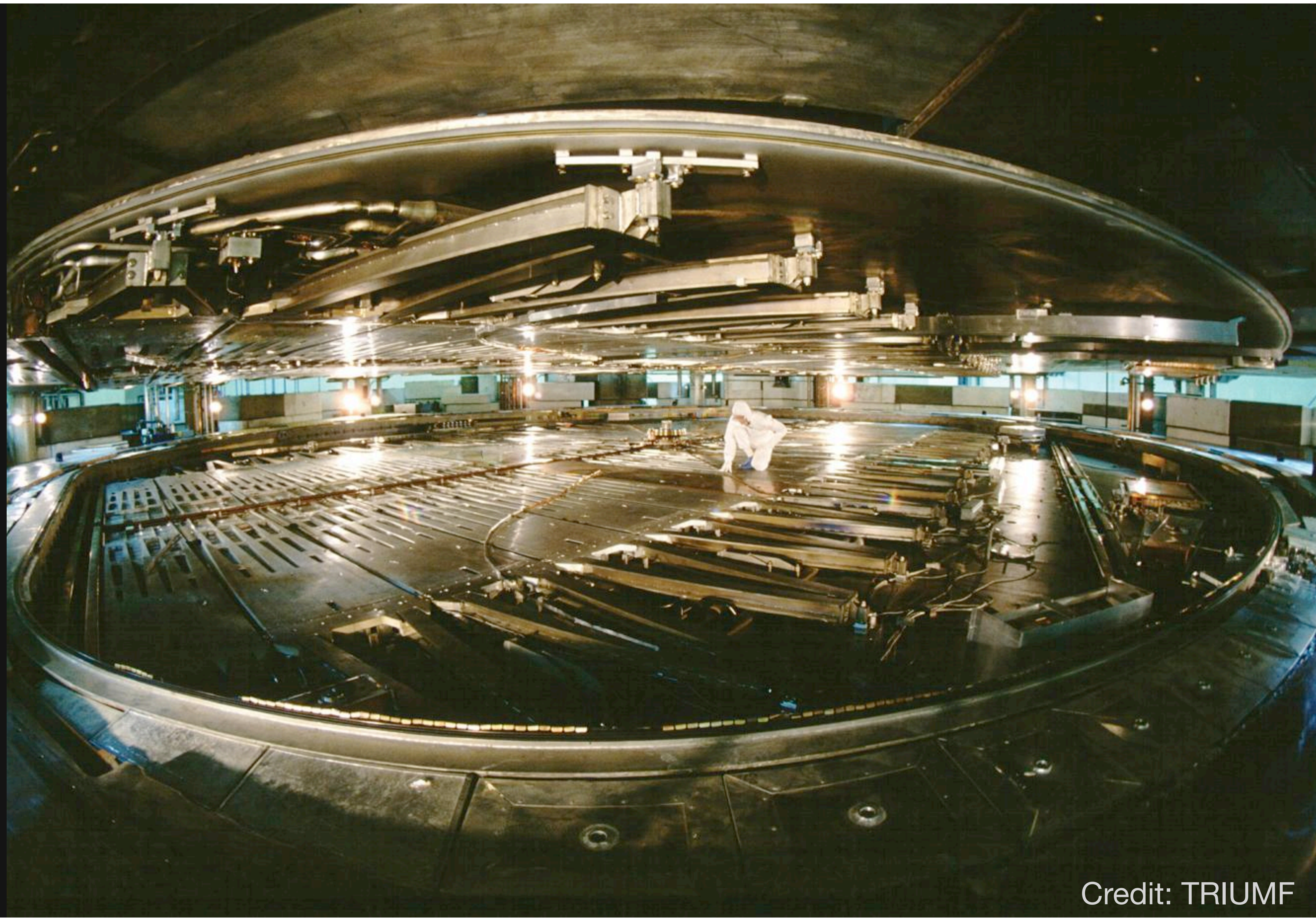
Credit: TRIUMF

TRIUMF



Avengers: Infinity War First Look (2018):: Movieclips Trailers

Inside the TRIUMF Cyclotron vacuum chamber



Credit: TRIUMF

Stanford Linear Accelerator (USA)

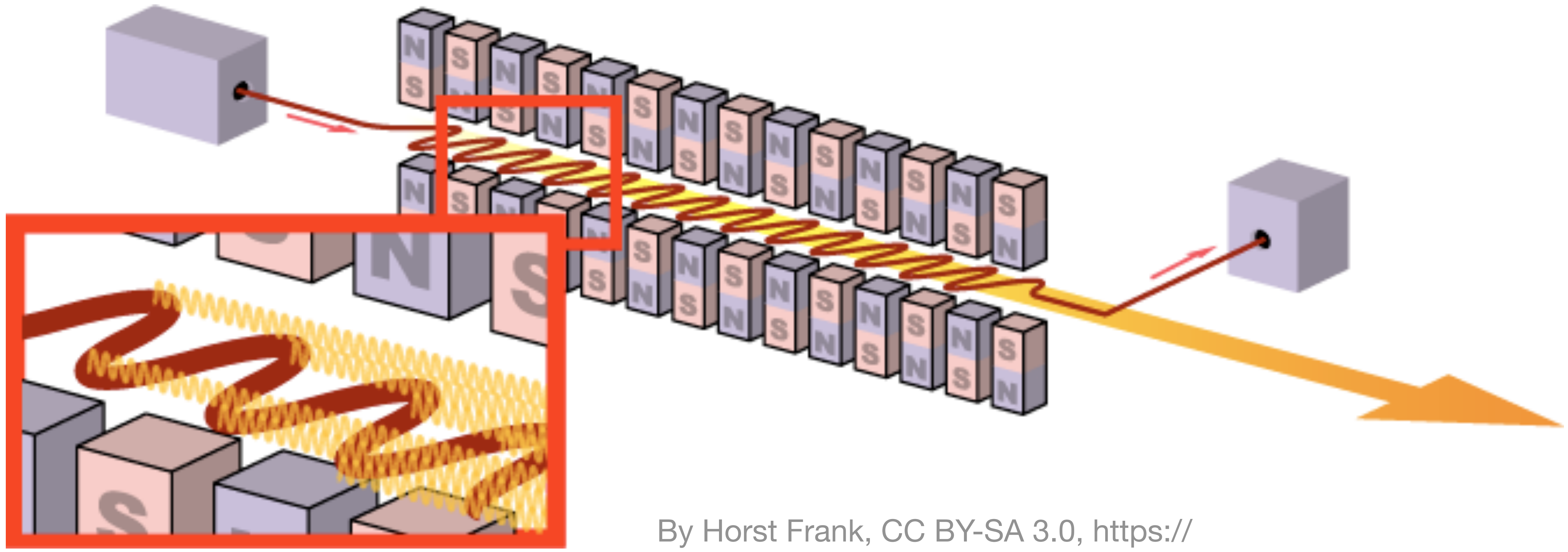
- 3 km linac with top energy of 50 GeV
- Klystron gallery was the longest building in the world!
  (…until LIGO interferometers was completed in 1999)
- **Physics research**:
- Materials science, Biology, Chemistry.
- Accelerator physics
- Particle physics
- Astrophysics/cosmology
- etc.


Credit: SLAC

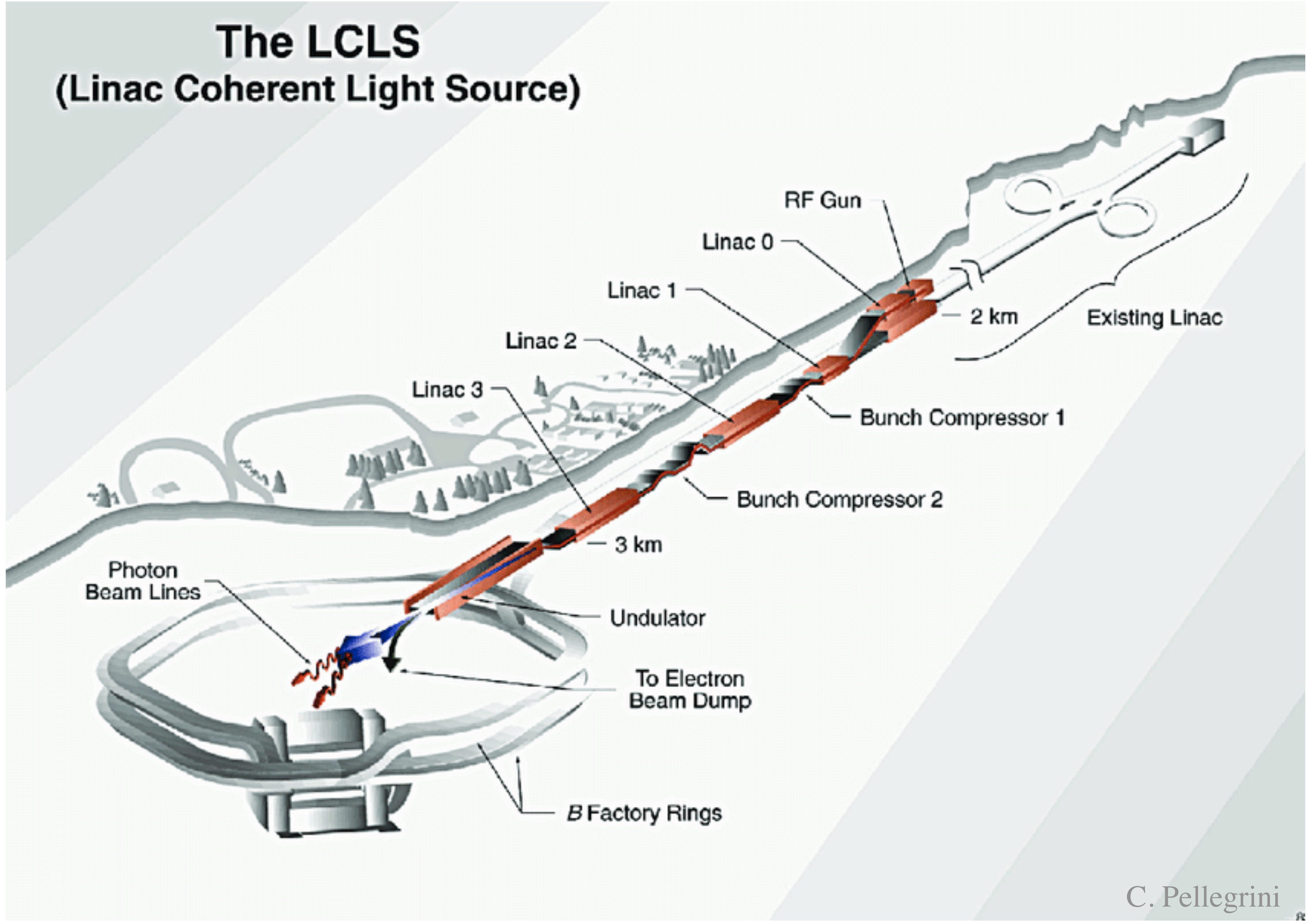

By Peter Kaminski - United States Geological Survey, Public Domain, https://commons.wikimedia.org/w/index.php?curid=134012

Stanford Linear Accelerator (USA)

- **> 2009**: The Linac Coherent Light Source (LCLS) is a free electron laser facility: extremely brilliant and short pulses of synchrotron radiation.
- **Synchrotron radiation**: Electromagnetic radiation emitted when charged particles are accelerated radially.



By Horst Frank, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=3977203



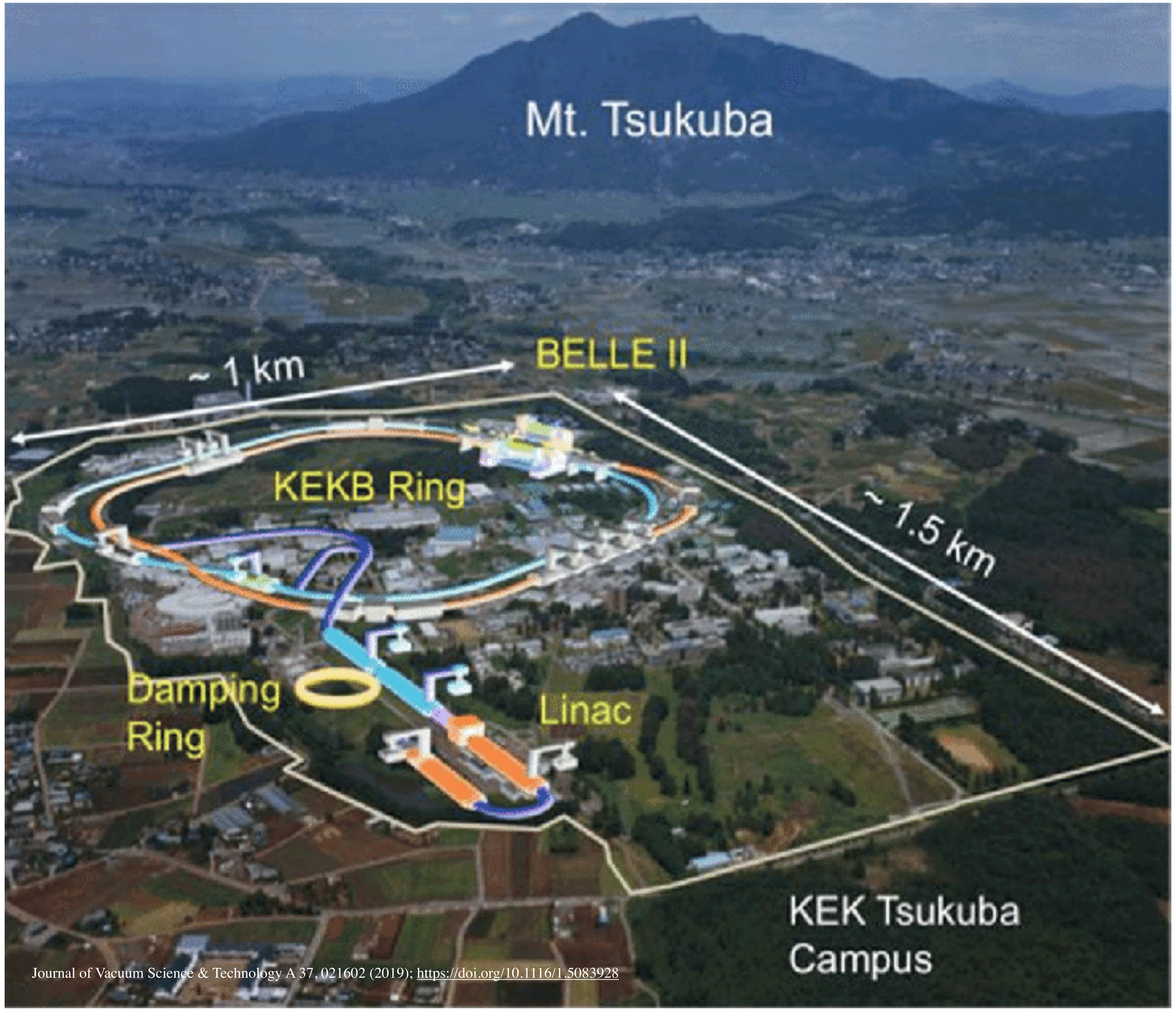
KEK (Japan)

- **> 2016**: SuperKEKB asymmetric electron-positron collider.
- Circumference of 3 km.
- Beam energies: $E_+ = 4\ GeV,\ E_- = 7\ GeV$
- Center-of-mass energy: $10.57\ GeV/c^2$
- Beam currents: $I_+ = 9.4\ A,\ \ I_- = 4.1\ A$
- World's highest luminosity: $8 \times 10^{35}\ cm^{-2}s^{-1}$ (target)

- **Experiment**: Belle-2

- **Physics research**:

- Flavor physics
- CP violation
- Search for new physics
- etc.



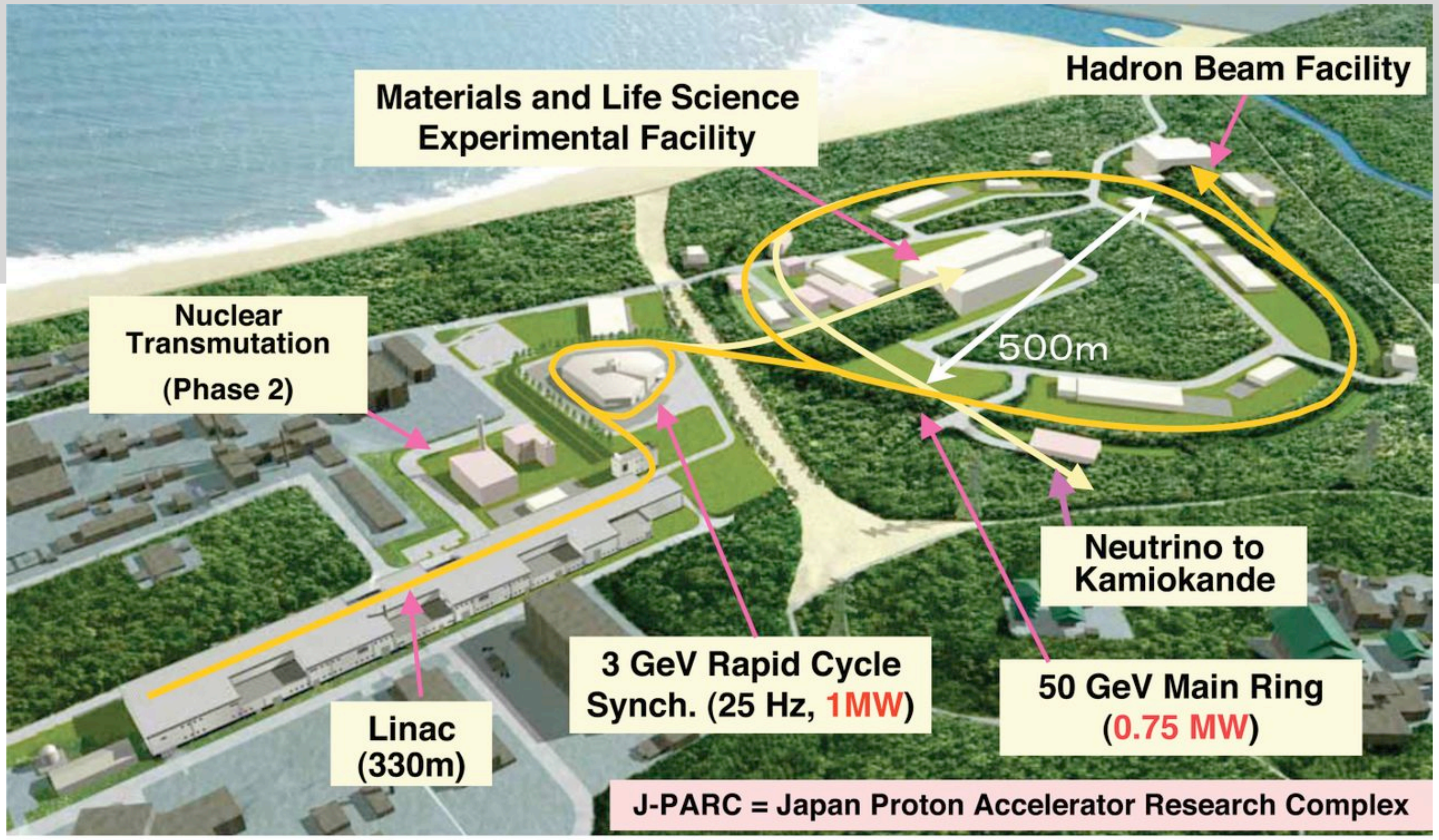
Journal of Vacuum Science & Technology A 37, 021602 (2019); https://doi.org/10.1116/1.5083928

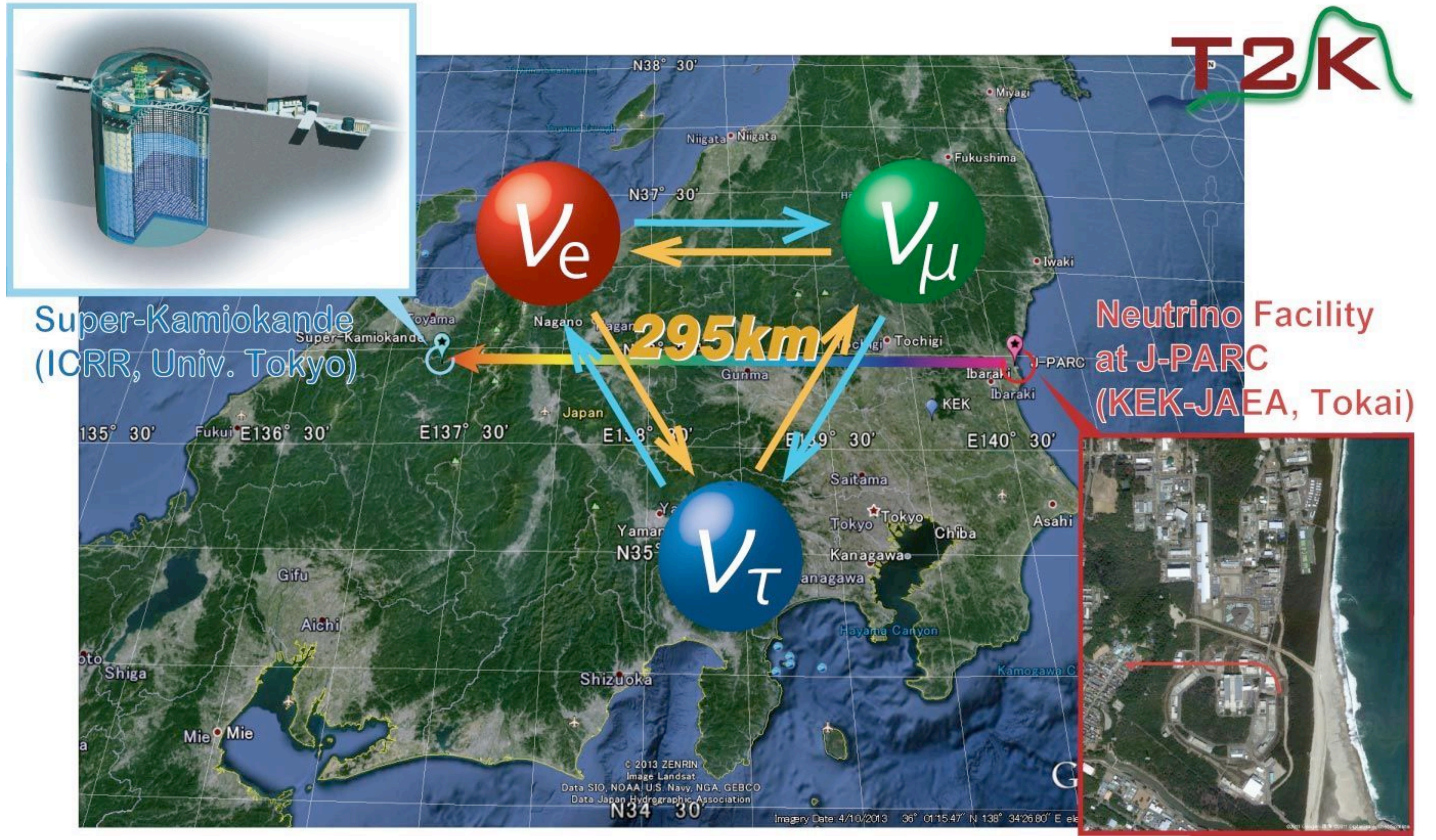
J-PARC (Japan)

- Main Ring accelerates protons to 50 GeV.
- World's-highest Intensity Neutrino Beam
- Beam current ~ $20\ \mu A$

- **Experiments**:
  - Super-Kamiokande
  - Hyper-Kamiokande (future)

- **Physics research**:
  - Neutrino properties
  - etc.





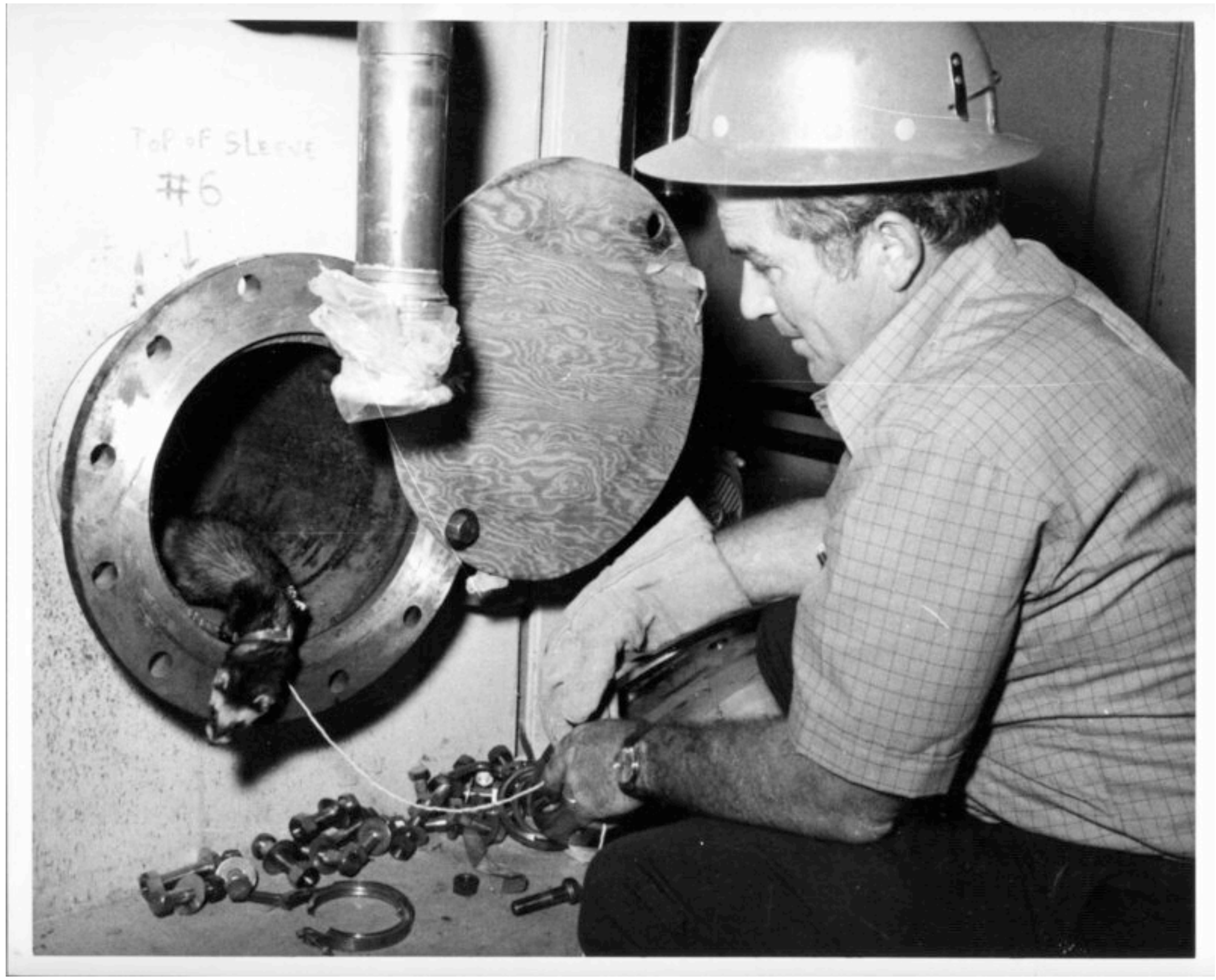
Fermilab (USA)

- **1983-2011**: Tevatron collider
- Collision centre-of-mass energy: $1.96\ TeV$
- World's highest-energy proton-antiproton collider.
- Circumference: 6.3 km

- **CDF and D0 experiments**:
  - Discovery and study of top quark
  - Search for new physics
  - Hadron physics
  - Flavour physics
  - + Wide range of particle physics topics

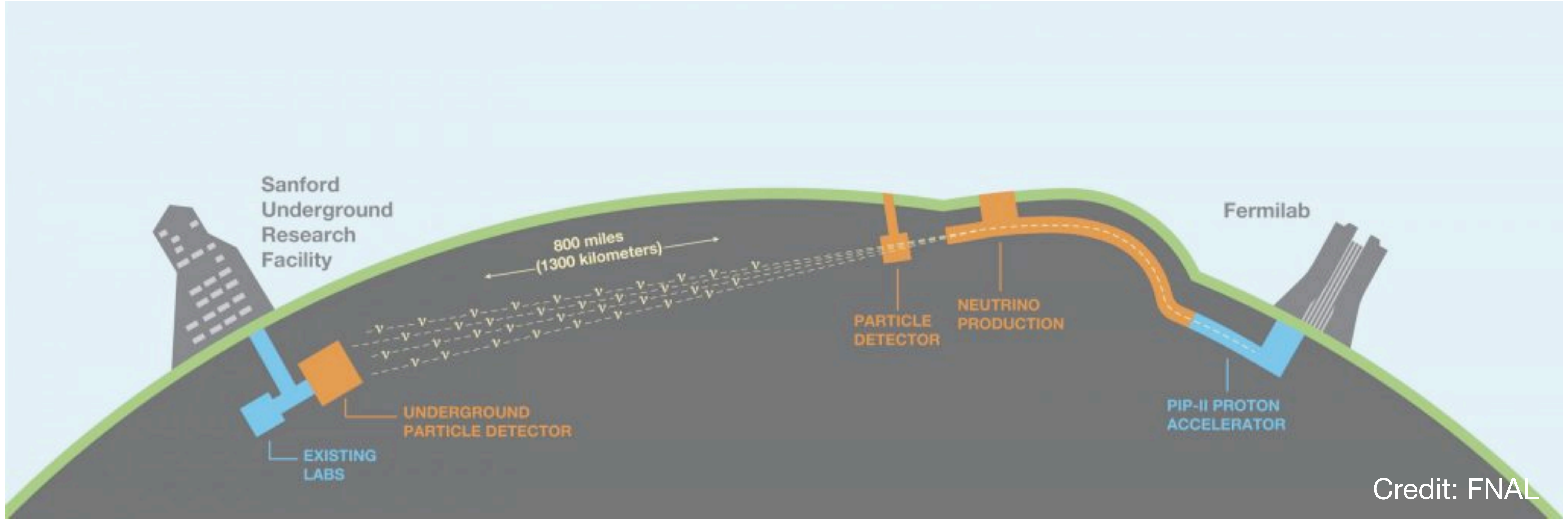
Fermilab (USA)

Felicia the Ferret

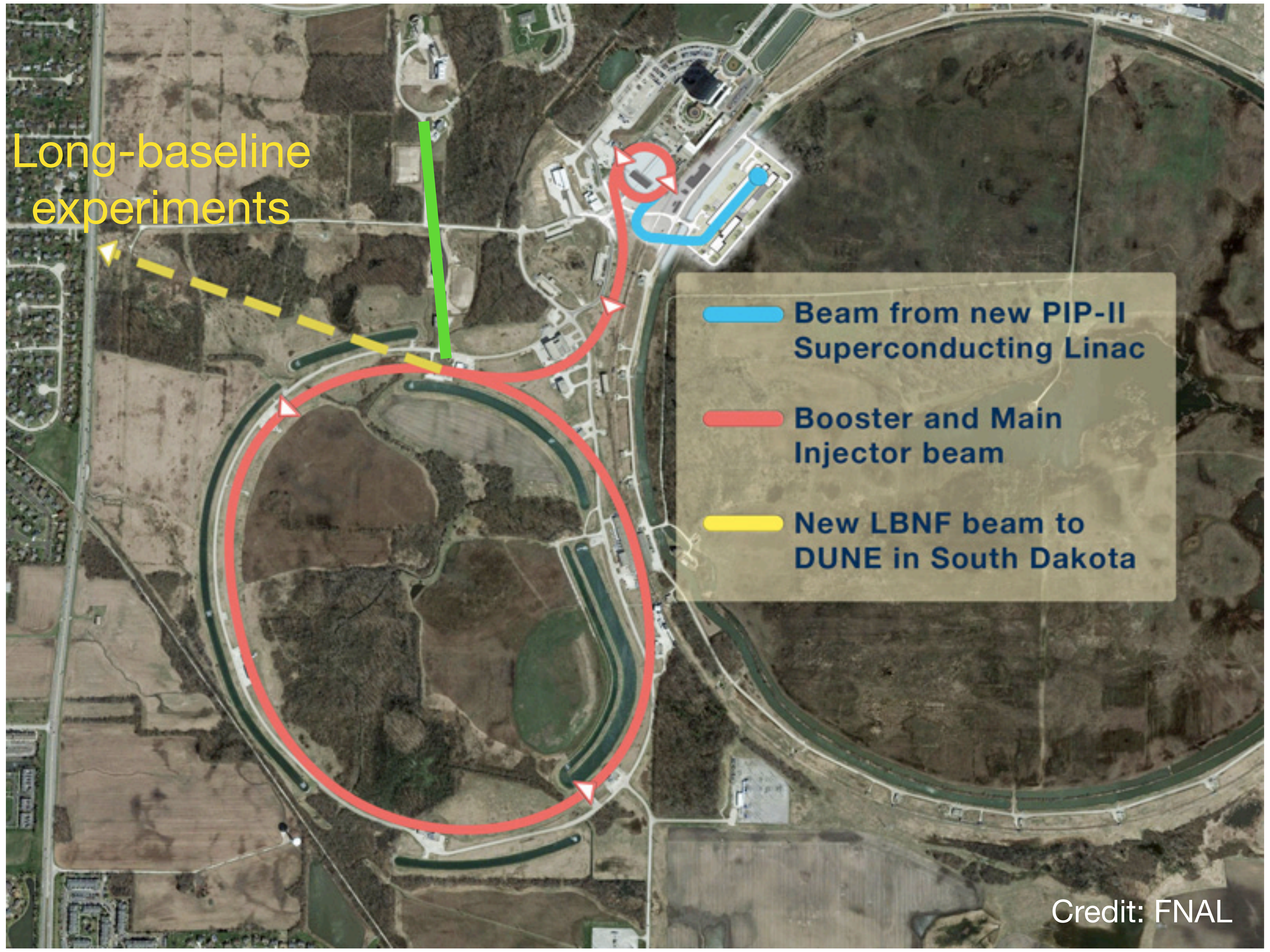


Fermilab (USA)

- **> 1999**: Fermilab has become the "Neutrino capital of the world"
  - Short-baseline experiments
  - Long-baseline experiments
- **Experiments:**
  - NOvA
  - ANNIE
  - MicroBooNE
  - SBND
  - DUNE
  - etc…



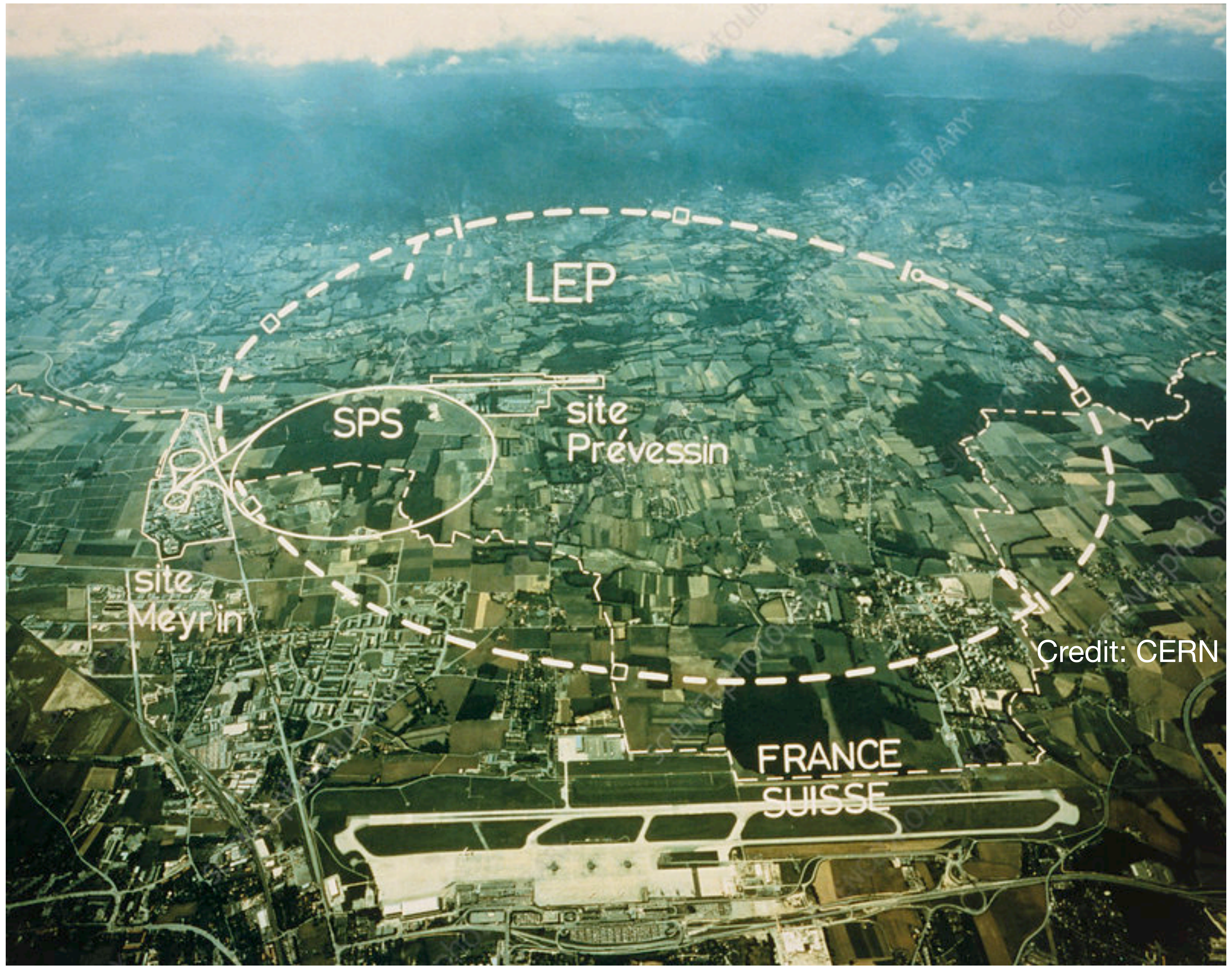
Short-baseline experiments



CERN (Switzerland/France)

- Founded in 1954: CERN unites scientists from around the world in the pursuit of knowledge

- **1989-2000**: Large Electron-Positron (LEP) collider
  - 1989-1994: $\sqrt{s} = 90\ GeV$
  - 1996-2000: $\sqrt{s} = 130 - 209\ GeV$
- Circumference: 27 km
- **Experiments**: ALEPH, DELPHI, L3, OPAL
  - Z bosons
  - W bosons
  - Flavour physics
  - Search for new physics
  - etc.

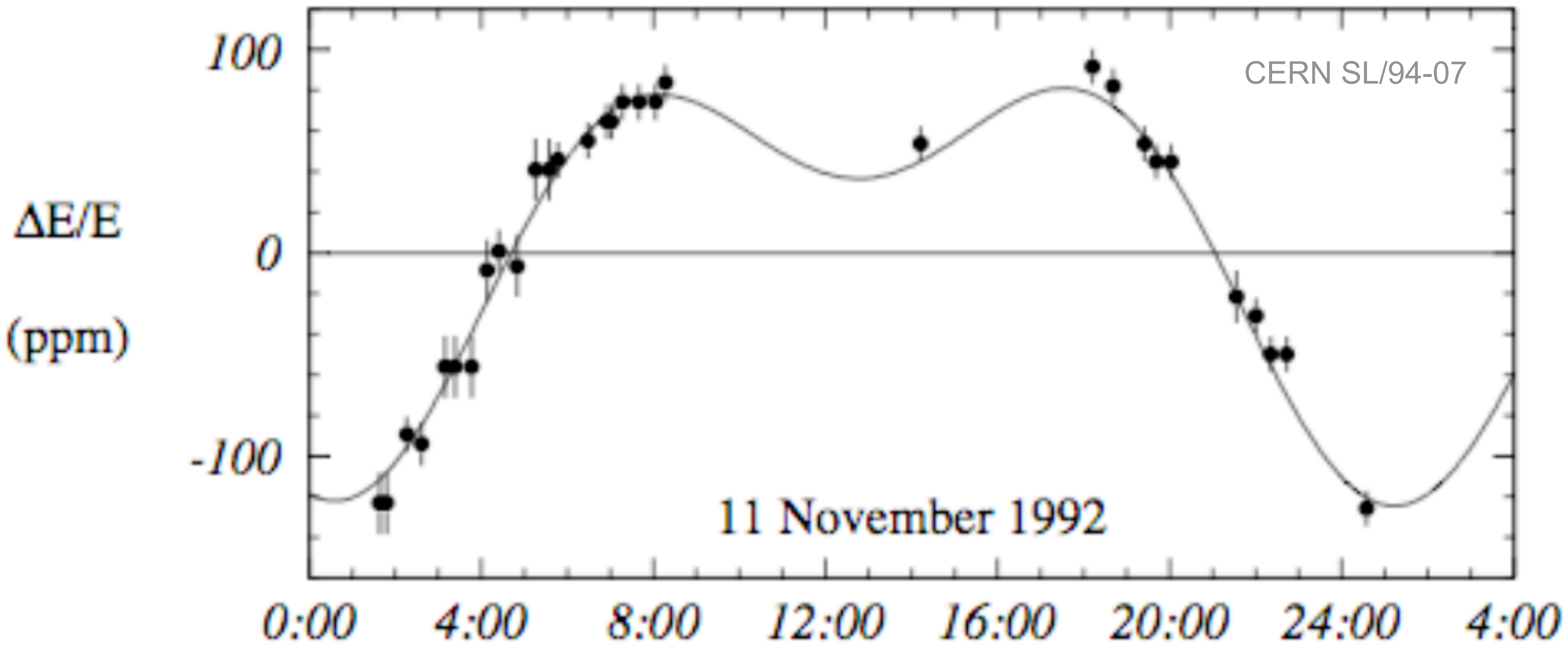


Credit: CERN

CERN (Switzerland/France)

- **1989-2000**: Large Electron-Positron (LEP) collider

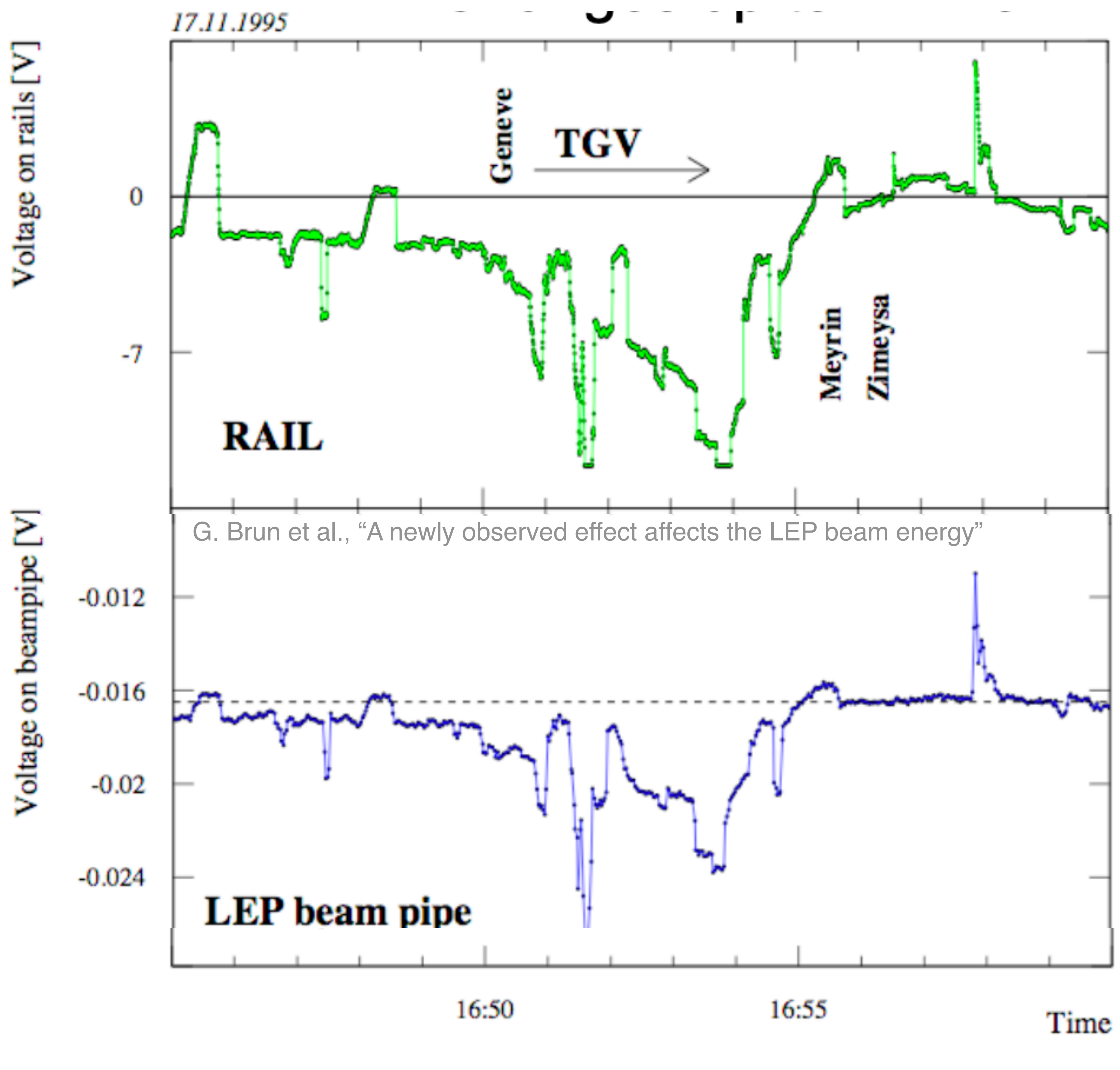
LEP energy changes due to tidal effects



1996 “beer bottle” incident….

Mysterious periodic changes in energy observed for many years….

The Paris-Geneva TGV!!

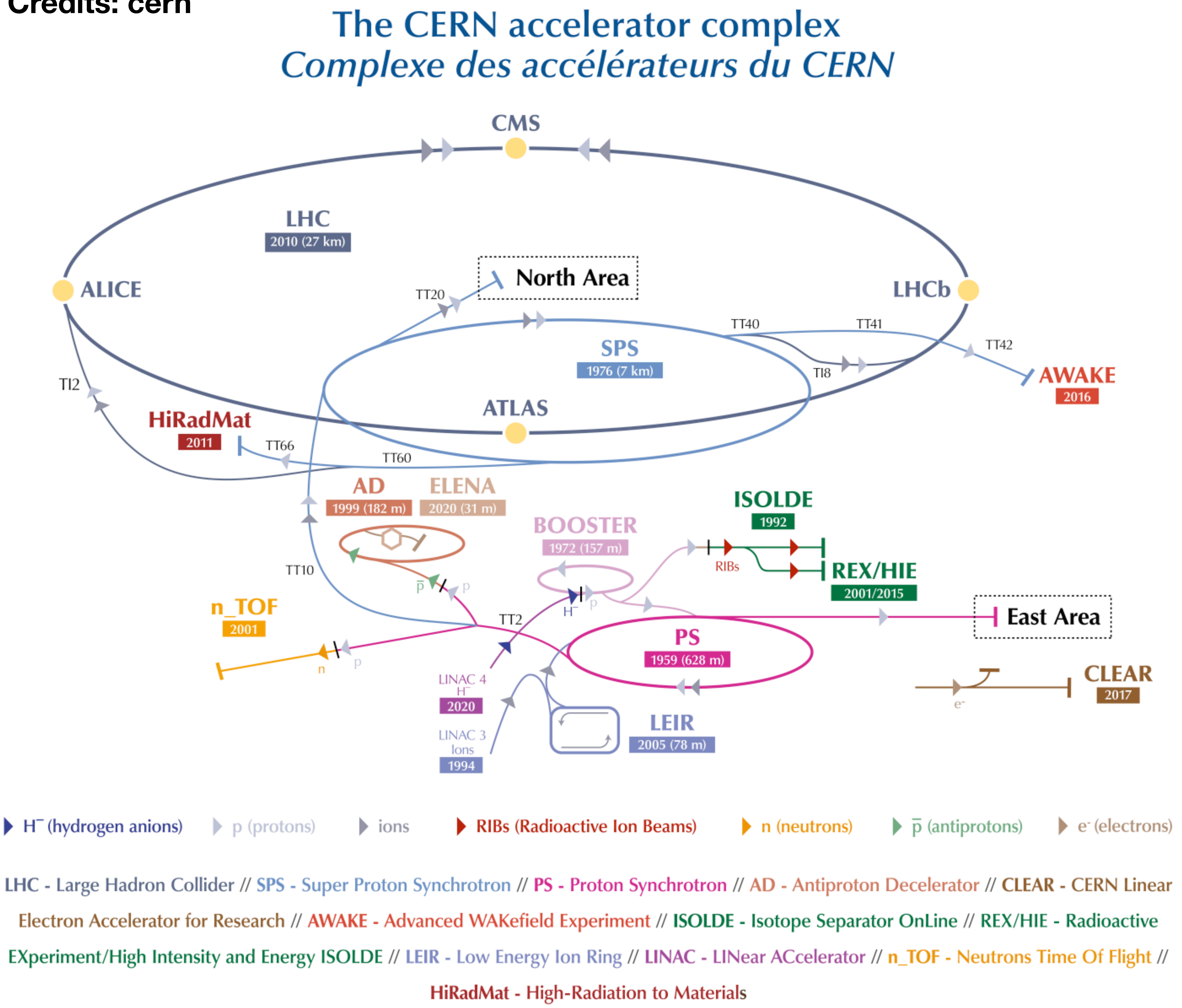


CERN

Some highlights

- LHC experiments
  - ALICE, ATLAS, CMS, LHCb
- Fixed-target experiments
  - COMPASS, NA61/SHINE, NA62, etc.
- Antimatter experiments
  - ALPHA, AEGIS, ASACUSA, GBAR, etc.
- Testbeam and radiation facilities

Credits: cern

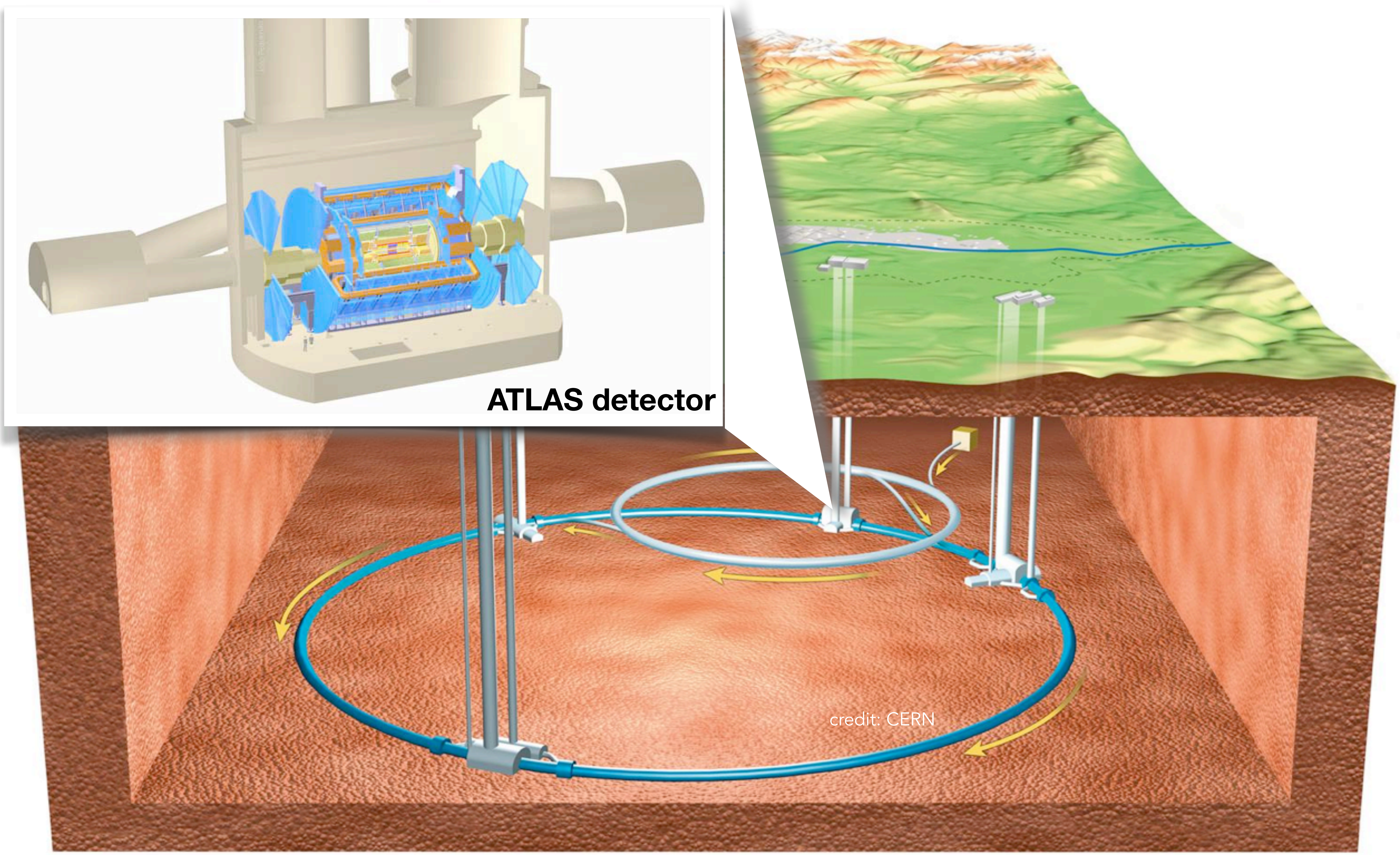


The Large Hadron Collider at the CERN laboratory

- Highest energy collider in the world!
- Proton-proton collisions at center-of-mass energy of 14 TeV
- Began operation in 2010
- > 1 billion collisions per second

Courtesy CERN

CERN: Large Hadron Collider



The Large Hadron Collider at the CERN laboratory

- 1232 dipole magnets
- 392 quadrupole magnets

The inside of the LHC is colder than outer space!

Courtesy CERN

Outline

(1) Brief historical introduction to particle acceleration

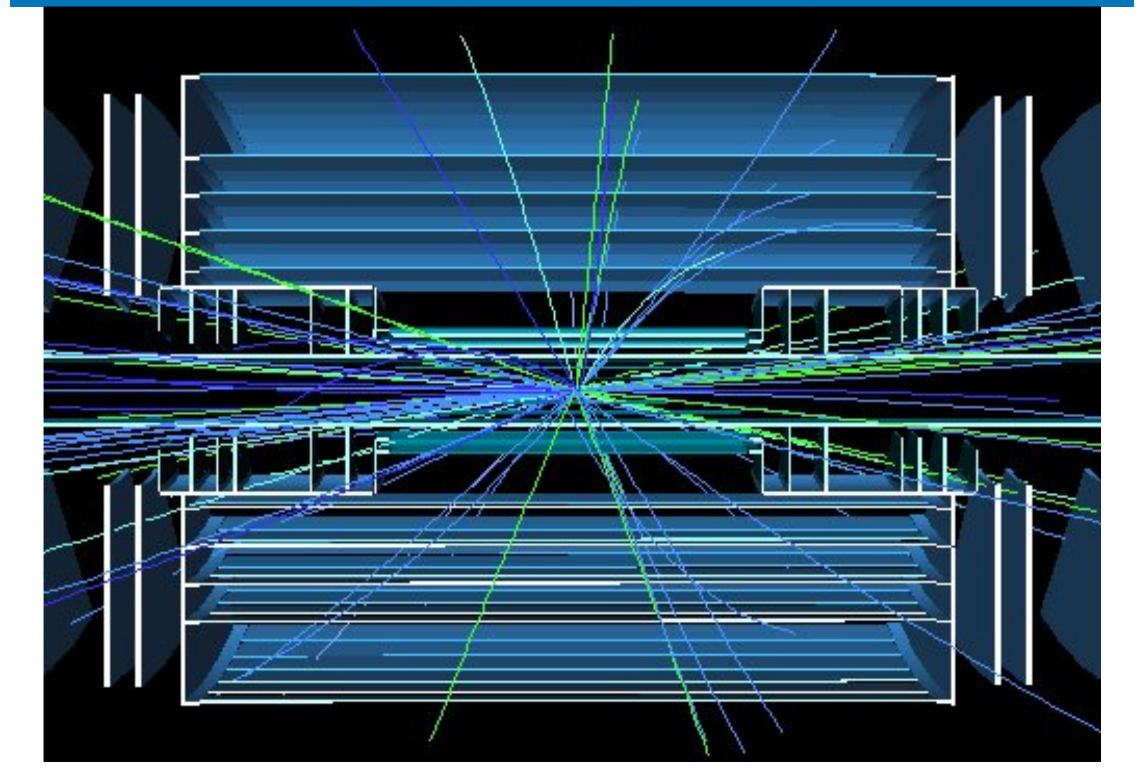
(2) Current research facilities

(3) Future projects

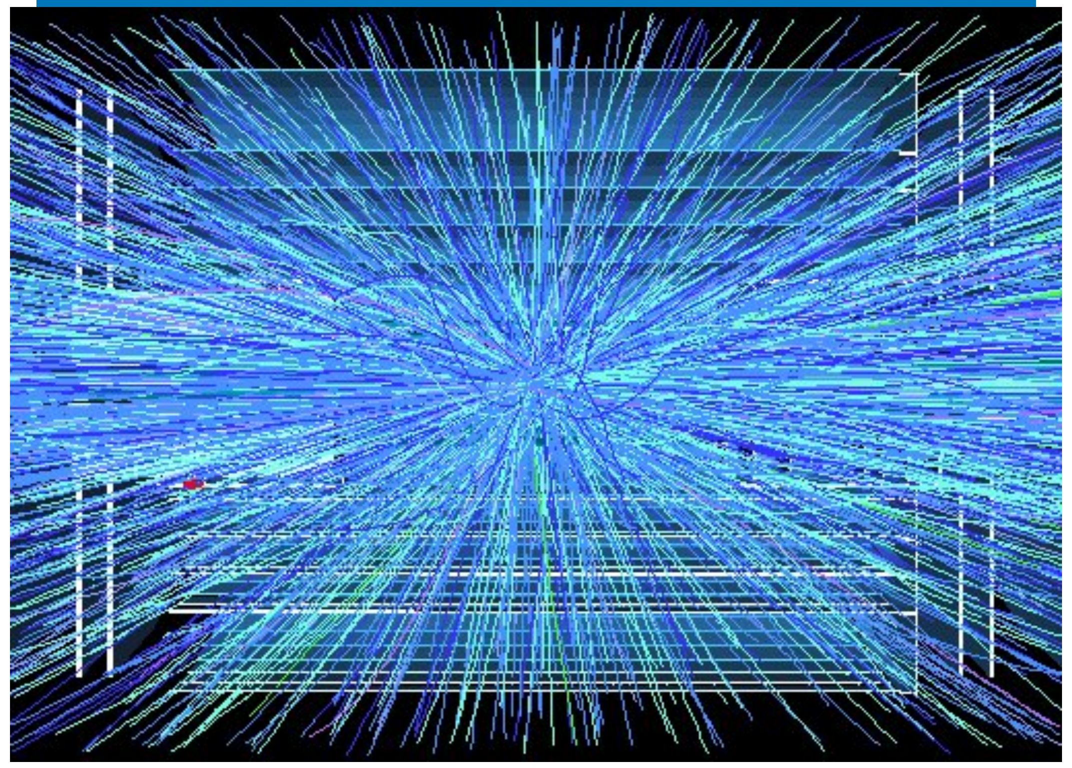
You are here

2010 2020 2030 2040 2050 2060 2070

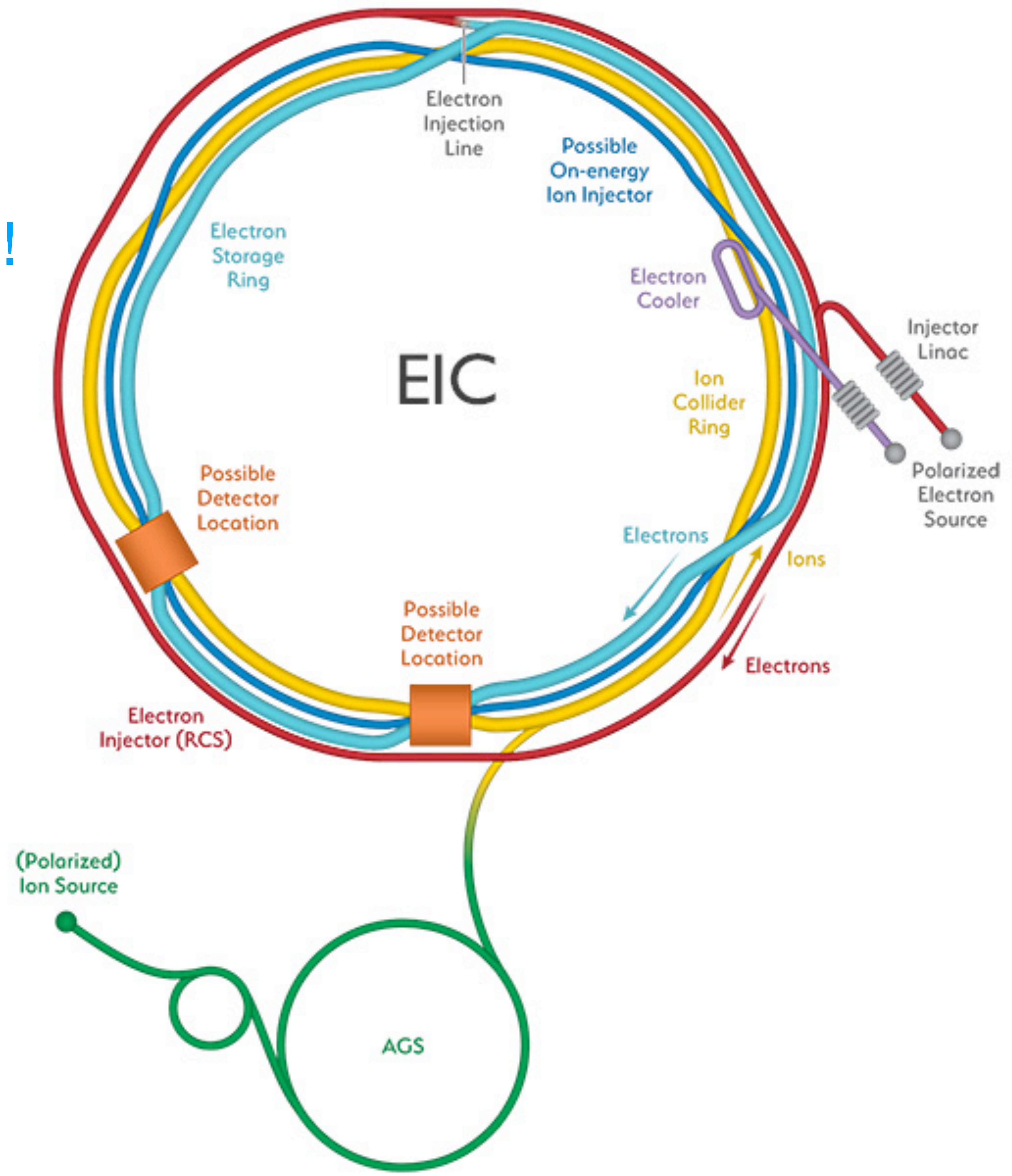
LHC



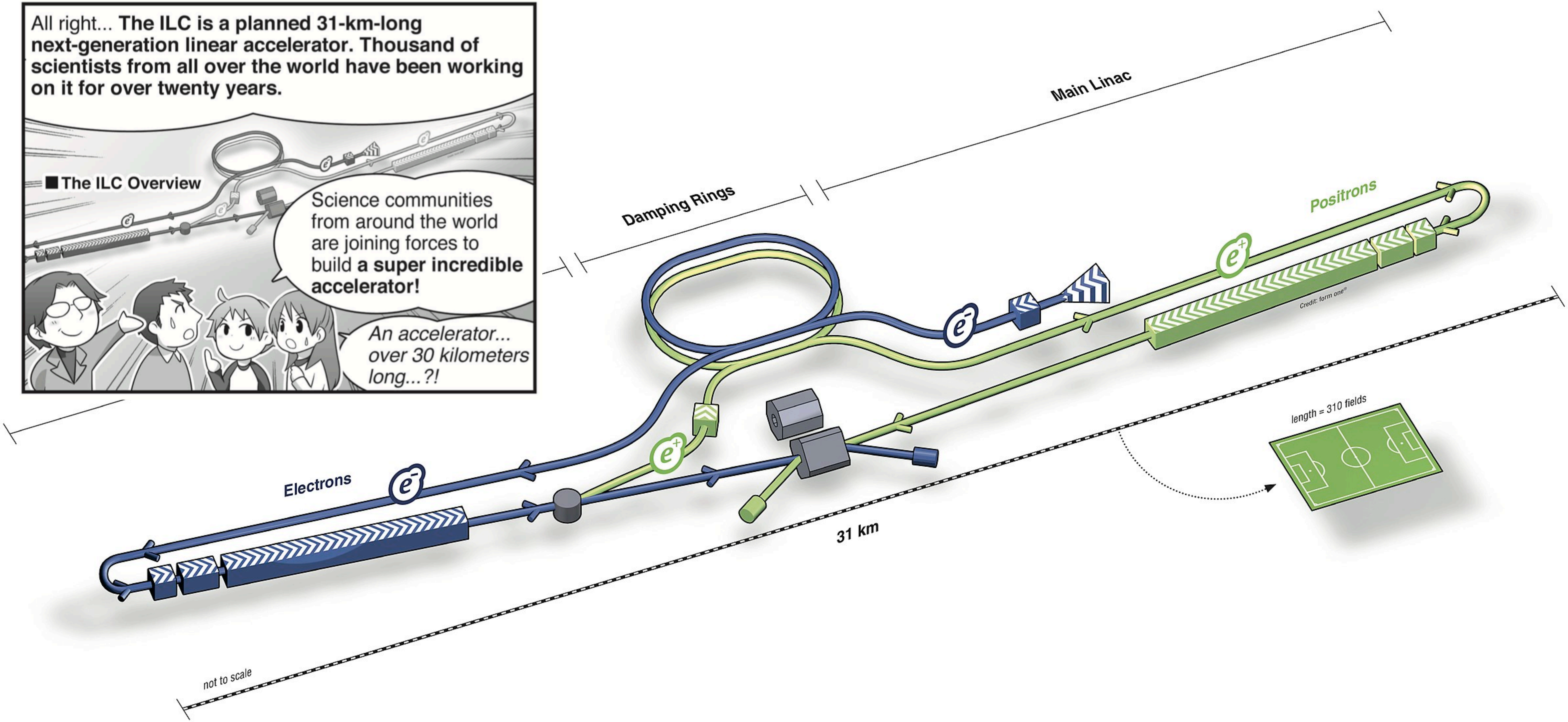
High Luminosity - LHC



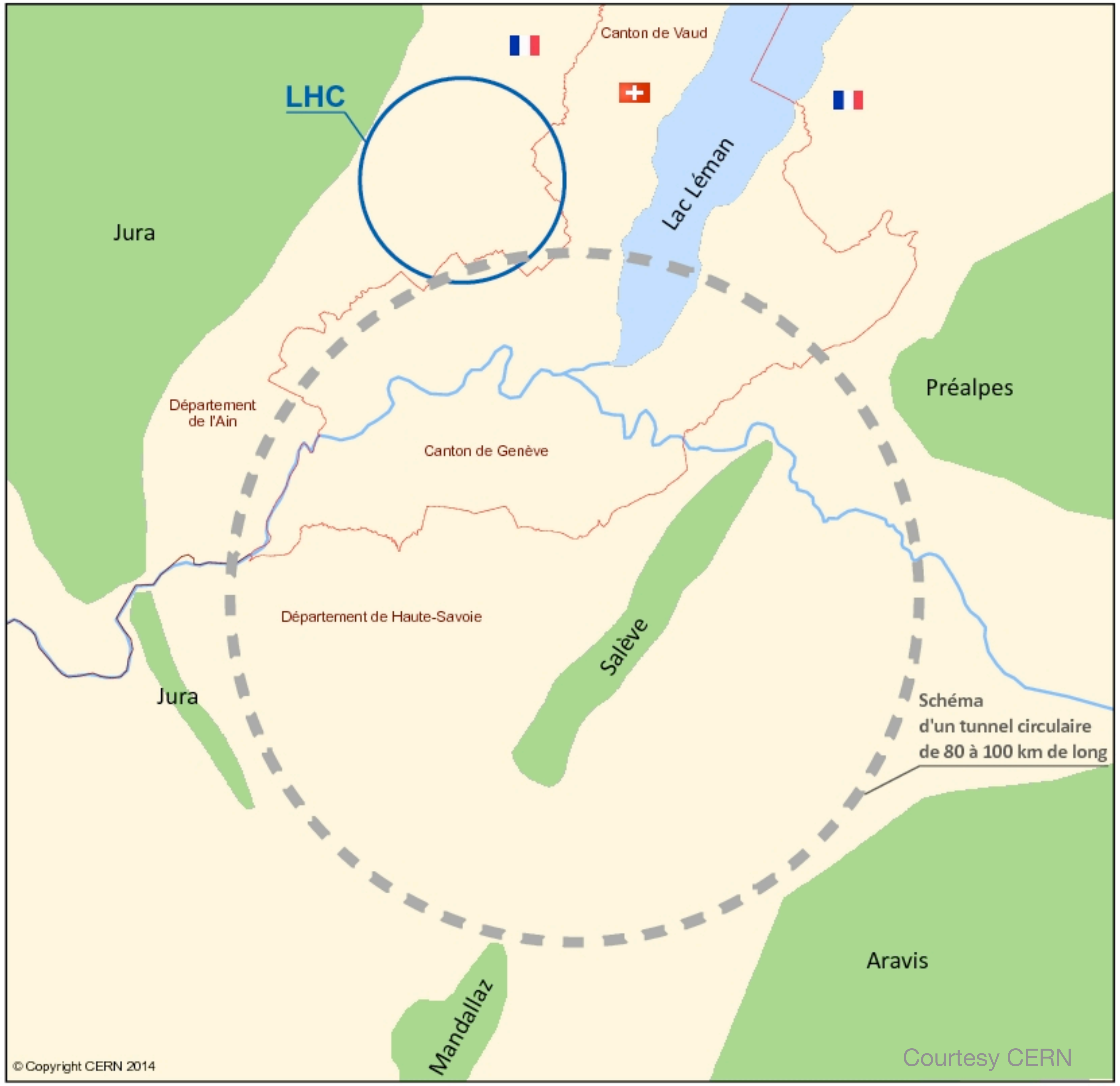
- The EIC will be the only electron-nucleus collider operating in the world!
- High luminosity: $10^{33} - 10^{34}\ cm^{-2}s^{-1}$
- Large centre-of-mass energy range: $20 - 140\ GeV$
- Polarized beams
- Large range of ion species
- Physics:
  - 3D structure of protons and nuclei
  - Proton spin
  - Quark and gluon confinement



International Linear Collider (ILC)

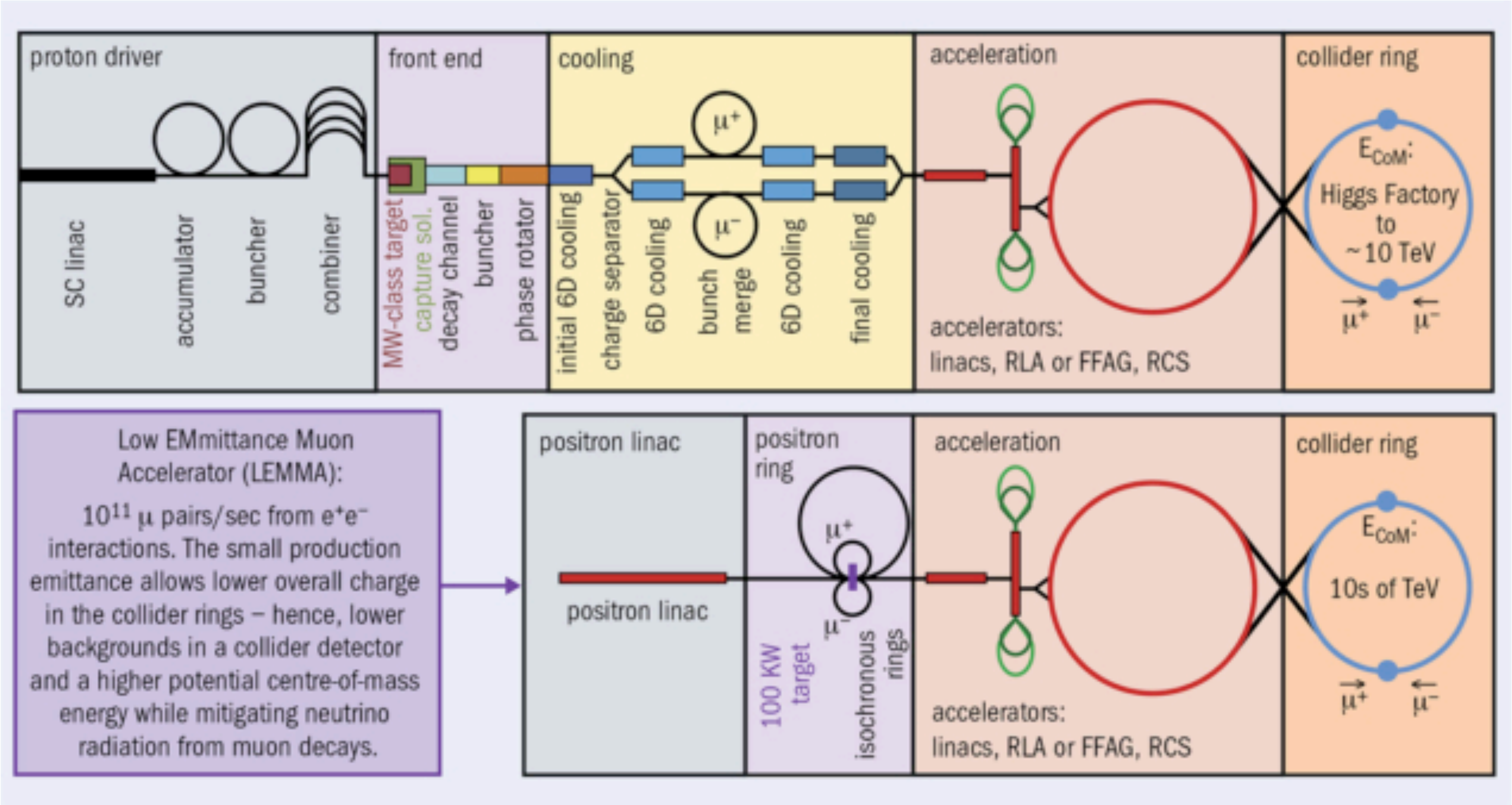


Future Circular Collider (FCC)

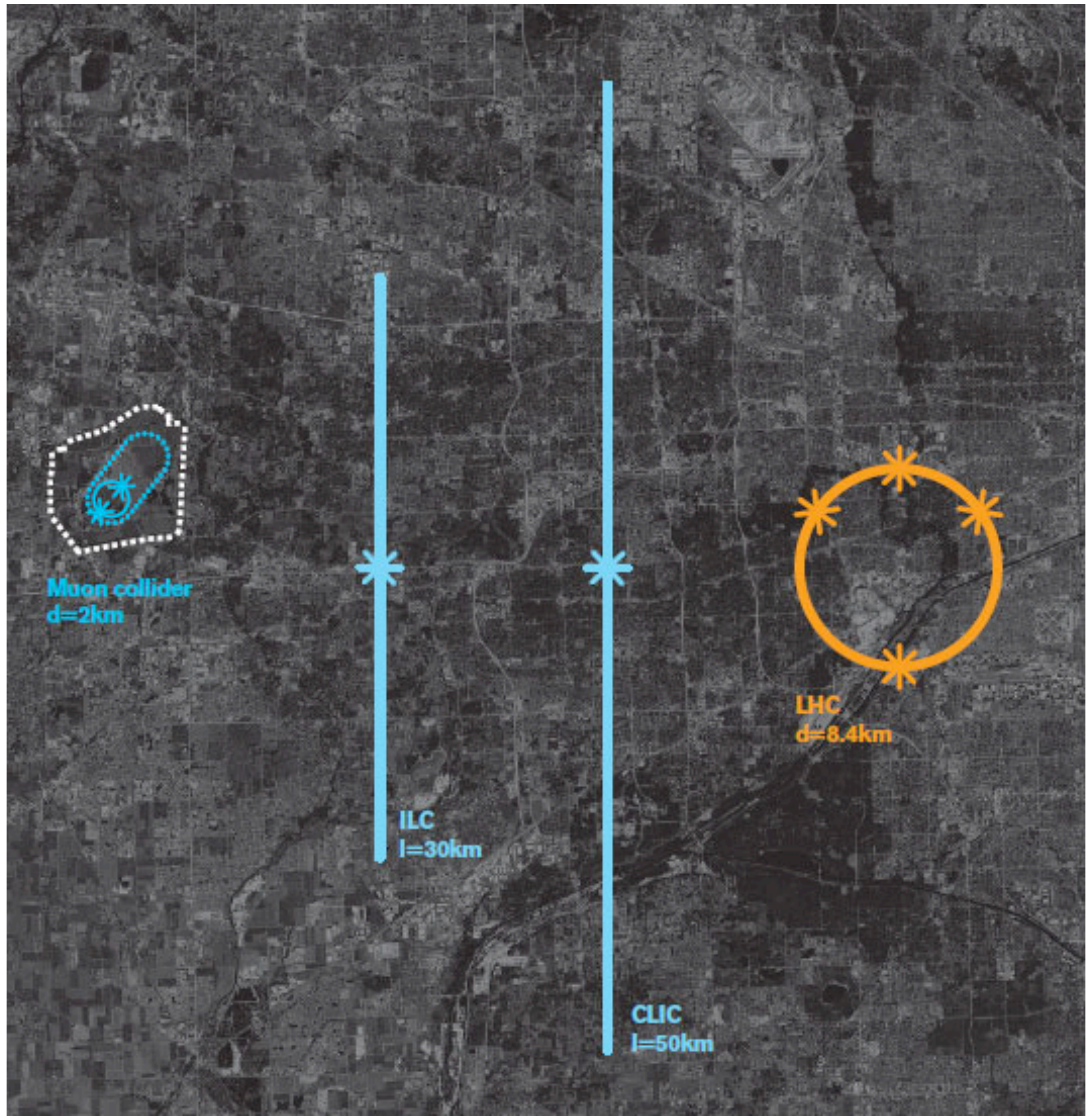


- Collider circumference of 100 km
- Proton-proton collisions at 100 TeV

Muon Collider



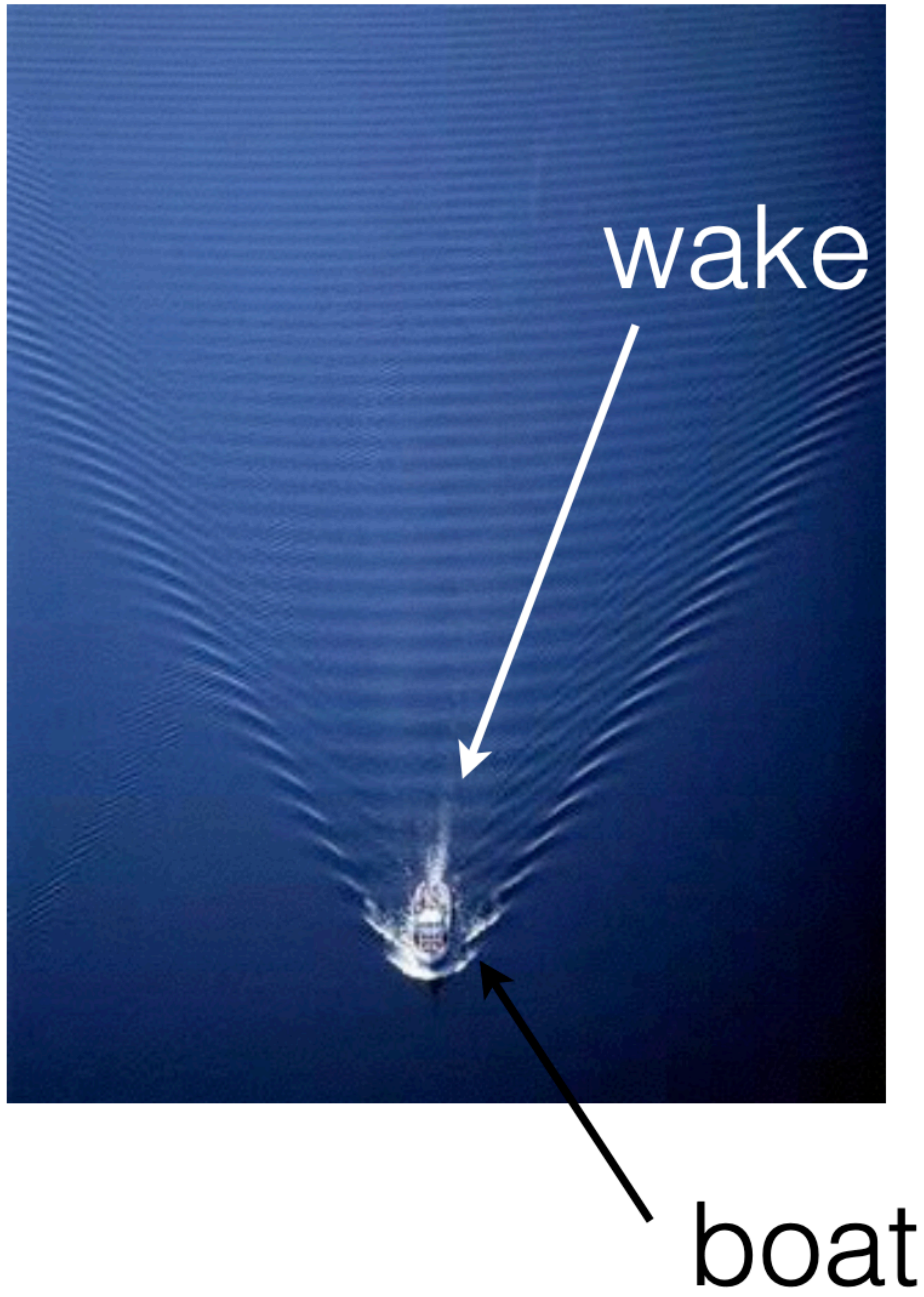
J P Delahaye *et al*. 2019 arXiv:1901.06150.

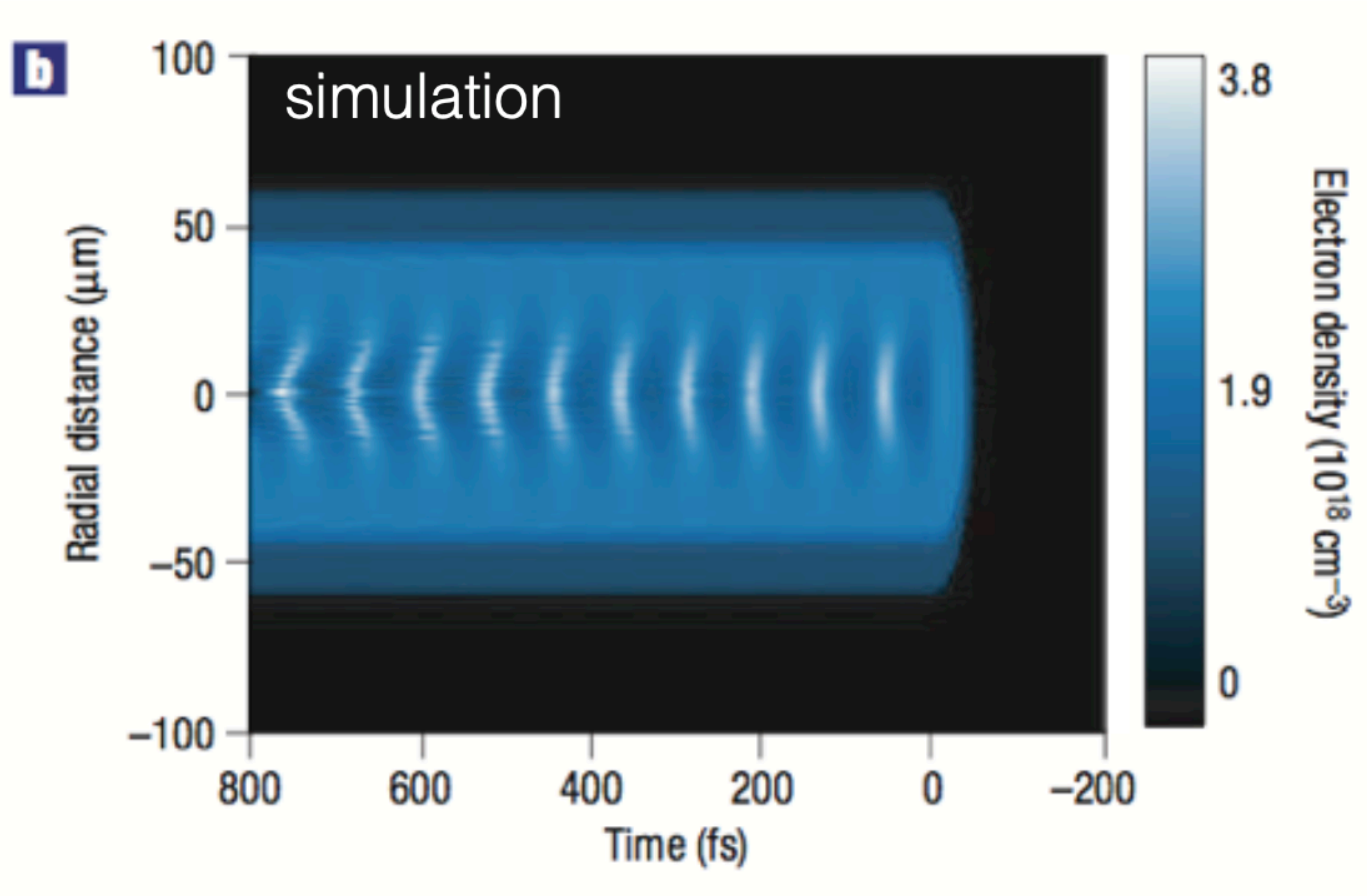


Credit: Symmetry Magazine

Plasma Wakefield Acceleration

Can achieve field gradient ~ 100 GV/m!
X100 times higher than the gradient of a RF accelerating cavity!

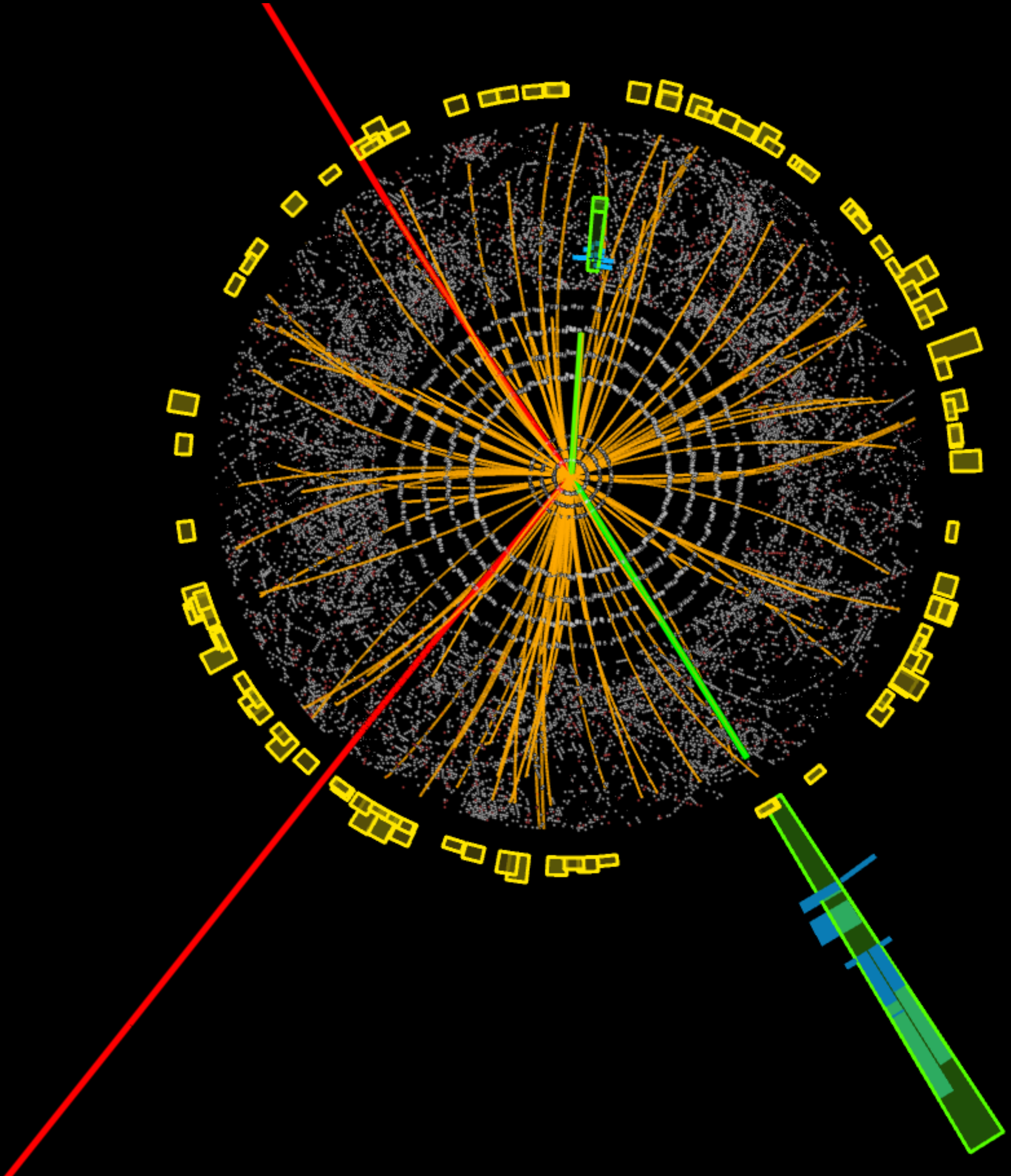




Summary

- Particle accelerators are everywhere!
- Rich history of technological breakthroughs.
- Major accelerator facilities exist all around the world.
- Several future projects under development that will open up the door to new discoveries.

Questions?



Want to learn more:
http://cdsweb.cern.ch/record/1017689