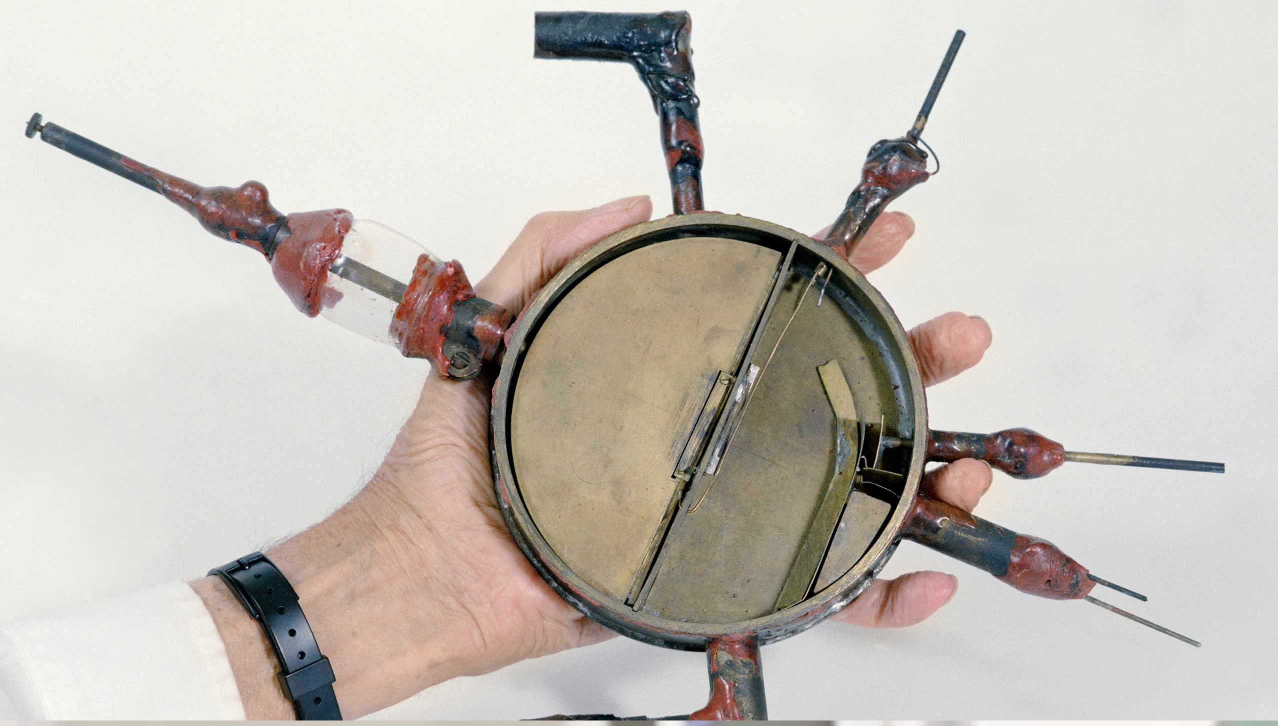
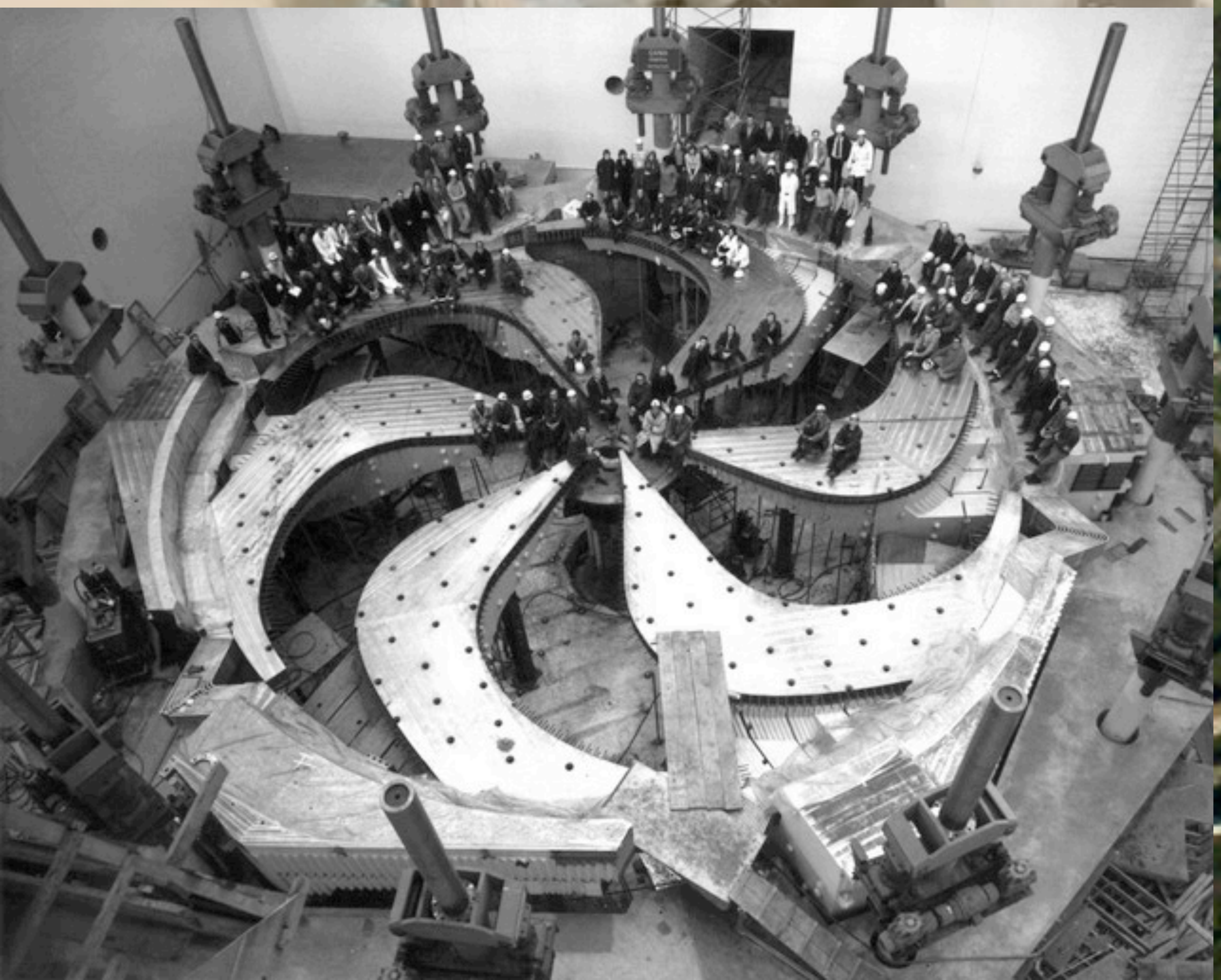
Accelerator Physics Overview





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

How many particle accelerators are there?

There are more than 30,000 particle accelerators in operation around the world!

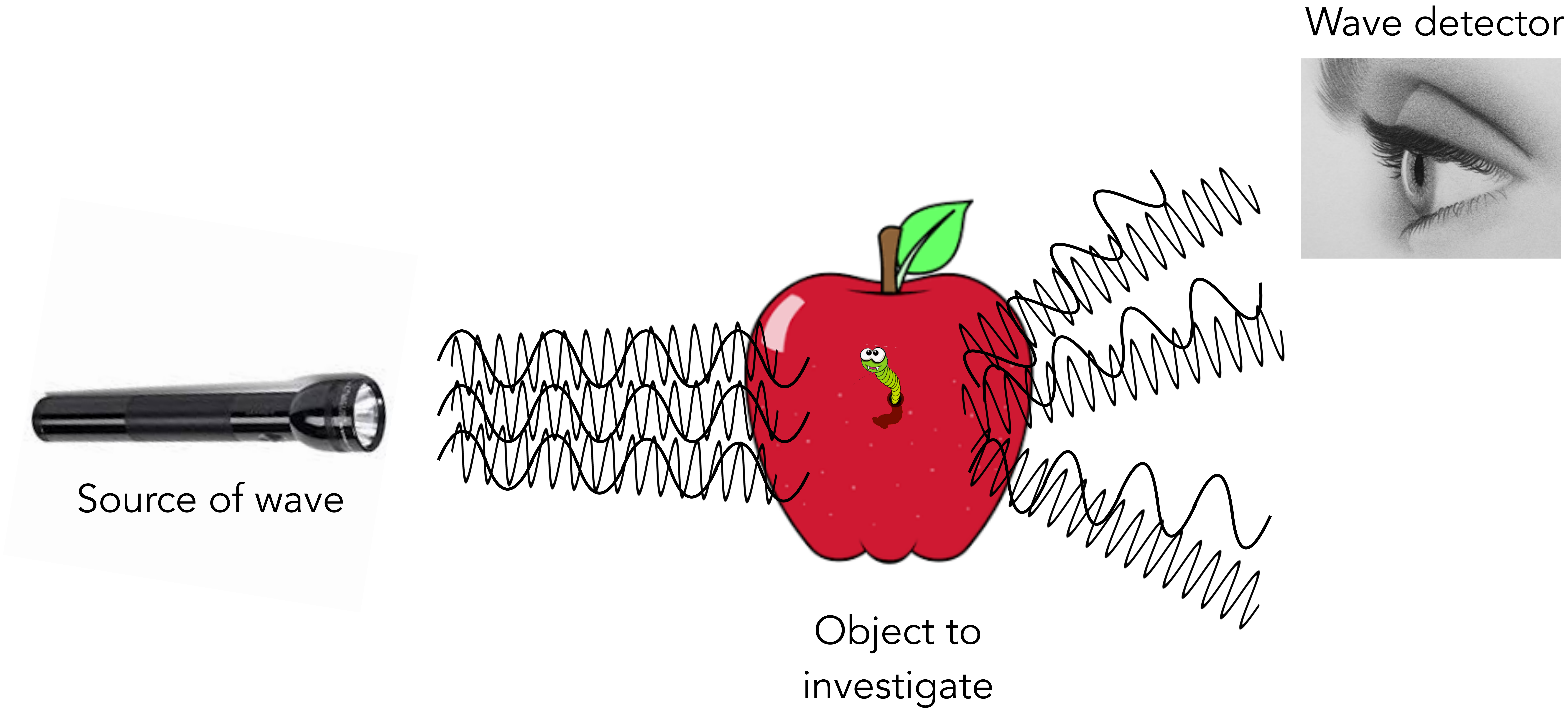
Witman, Sarah. "Ten things you might not know about particle accelerators". Symmetry Magazine. Fermi National Accelerator Laboratory. Retrieved 21 April 2014.

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) Current research facilities

(3) Future projects

Some basic concepts of accelerator physics along the way

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(1) Brief historical introduction to particle acceleration

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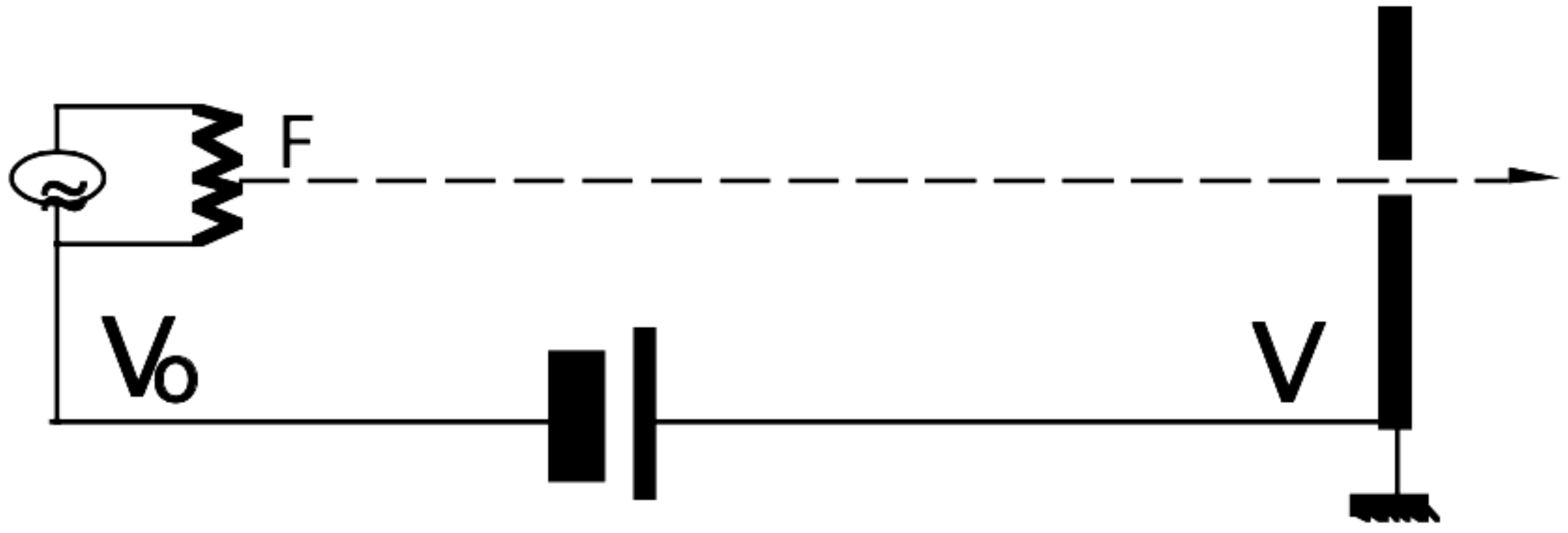
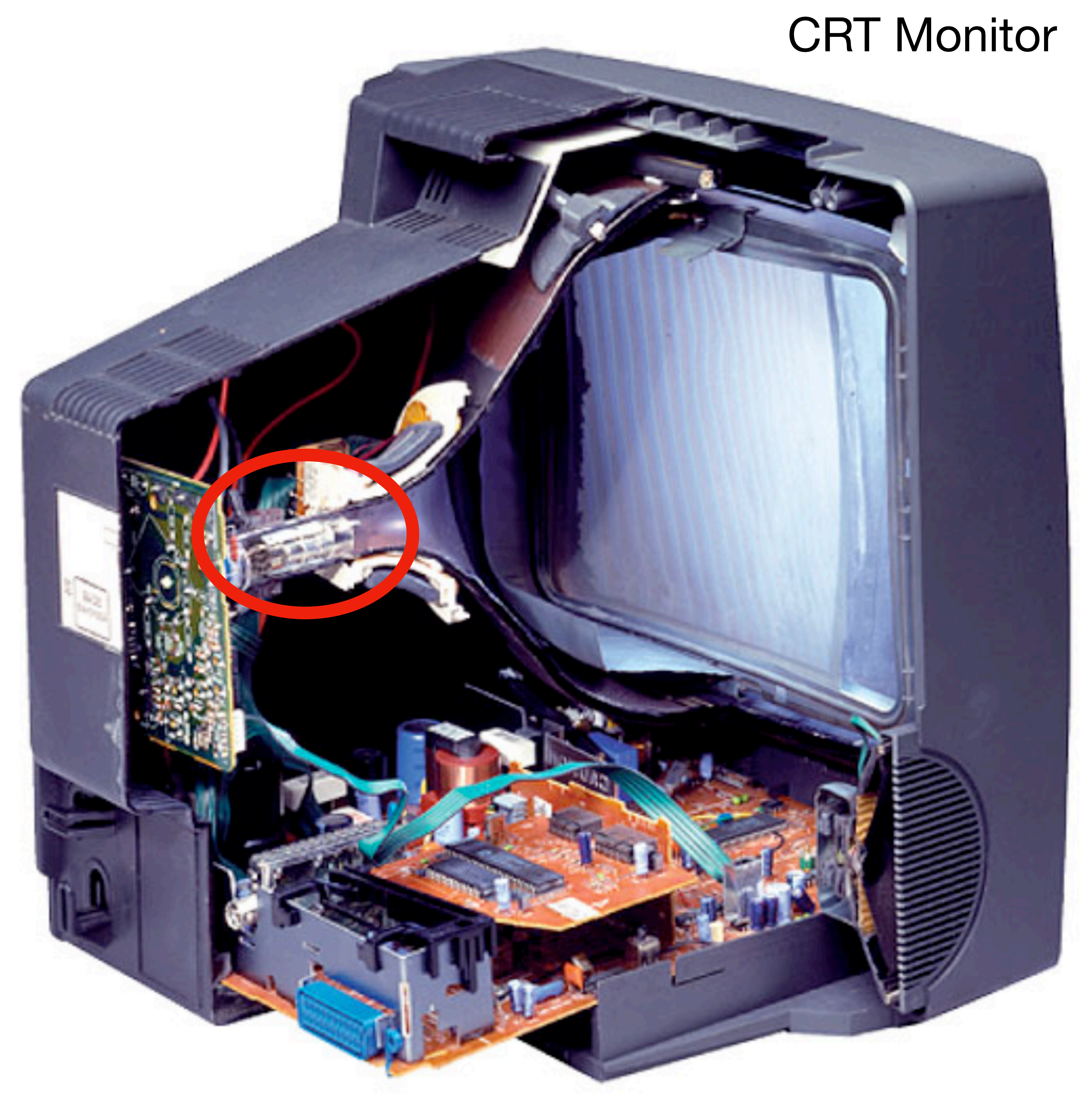
Some basic concepts of accelerator physics along the way

Electrostatic accelerators

Charged particles accelerated by a constant electric field produced by charged electrodes.



Credit: Tazzari, CAS-IC-2006



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

Particle Kinetic Energy gain:

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

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

How to create a high voltage?

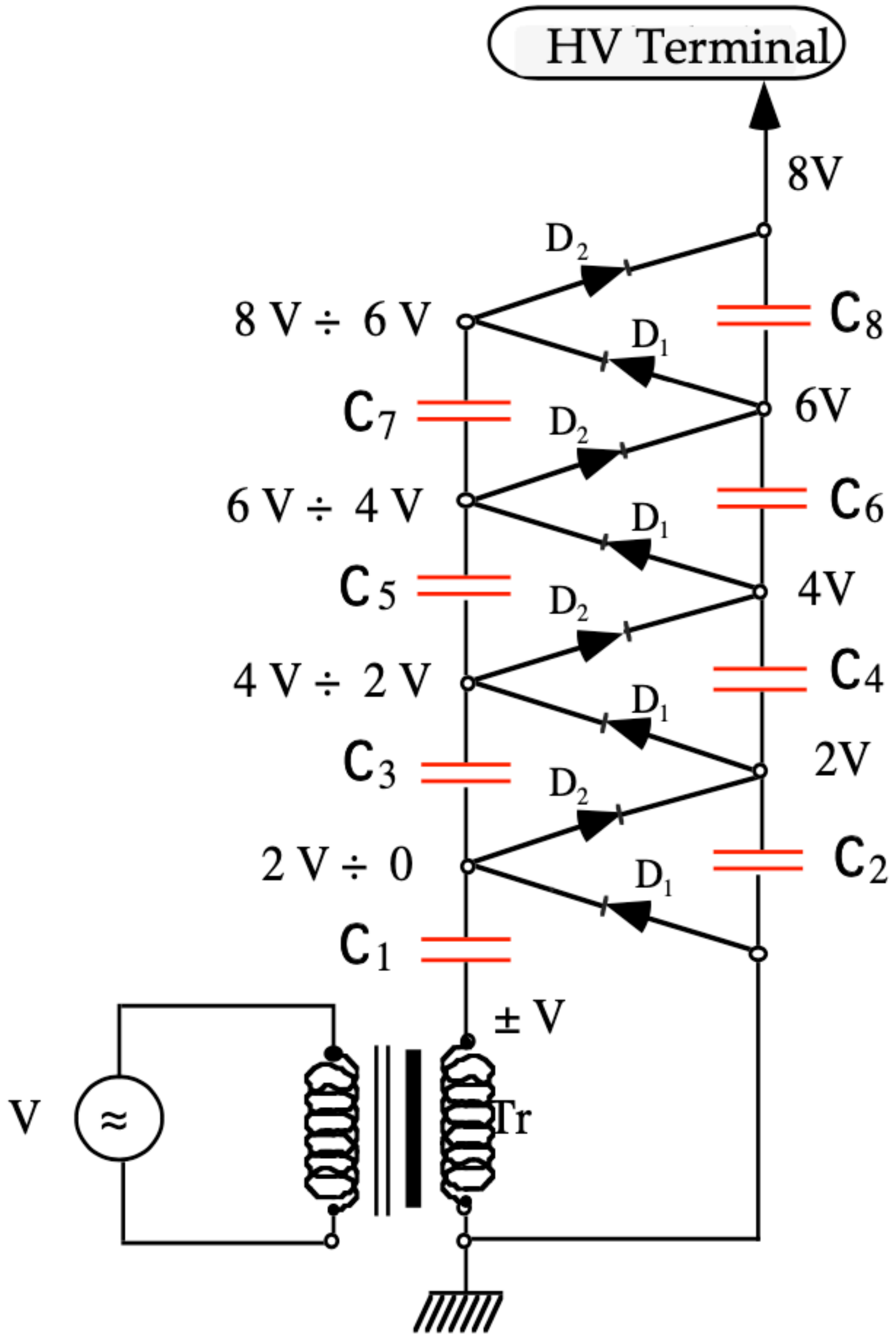
Electrostatic accelerators

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

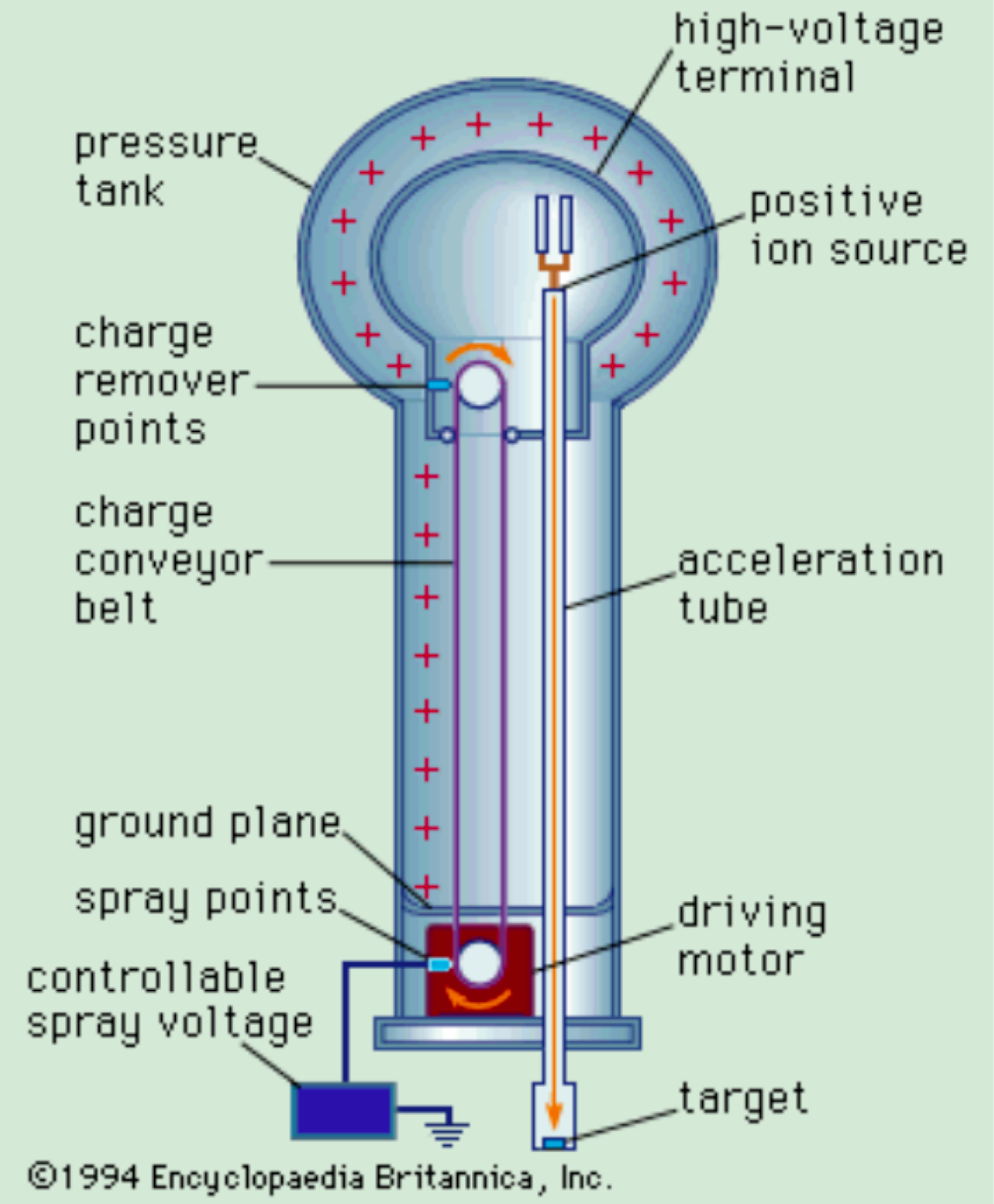


Electrostatic accelerators

Van de Graaff

- 1929: Electrostatic generator that uses a moving belt to accumulate electric charge on a hollow metal globe on the top of an insulated column, creating a high electric potential (~ 10 MV)

- Capable of producing DC current of 100 μA



AT ROUND HILL, FINAL STAGE OF CONSTRUCTION

Electrostatic accelerators

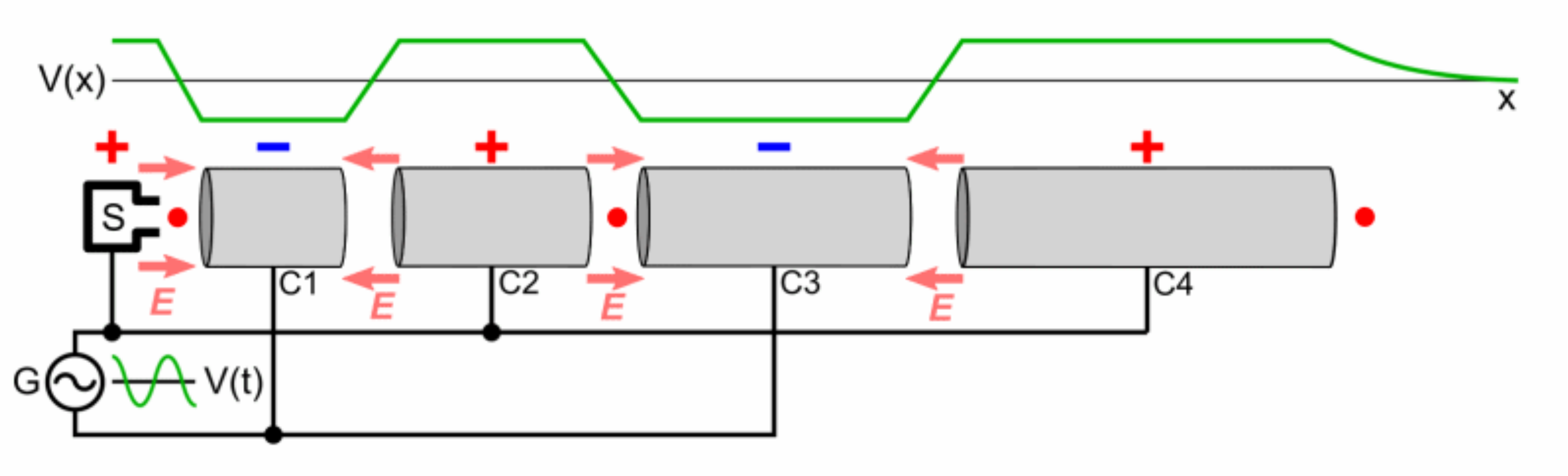
Limit: Electrostatic accelerator limited by achievable potential difference before discharge ($\sim O(1)\ MV/m$)

How to accelerate particles to higher energy?

Electrodynamic accelerator

Standing wave linear accelerator ("Linac")

- Widerøe (1928): Apply acceleration voltage several times to particle beam.
- Connect a series of acceleration electrodes to an AC supply.
- Electric field inside drift tubes is zero.
- Particles travel synchronous with RF cycles.



Wikipedia

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

- Energy gain after n^{th} step: E_n
- Number of acceleration steps: n
- Charge of the particle: q
- Potential difference per gap: U_0
- Phase b/w particle and AC voltage: ϕ

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.

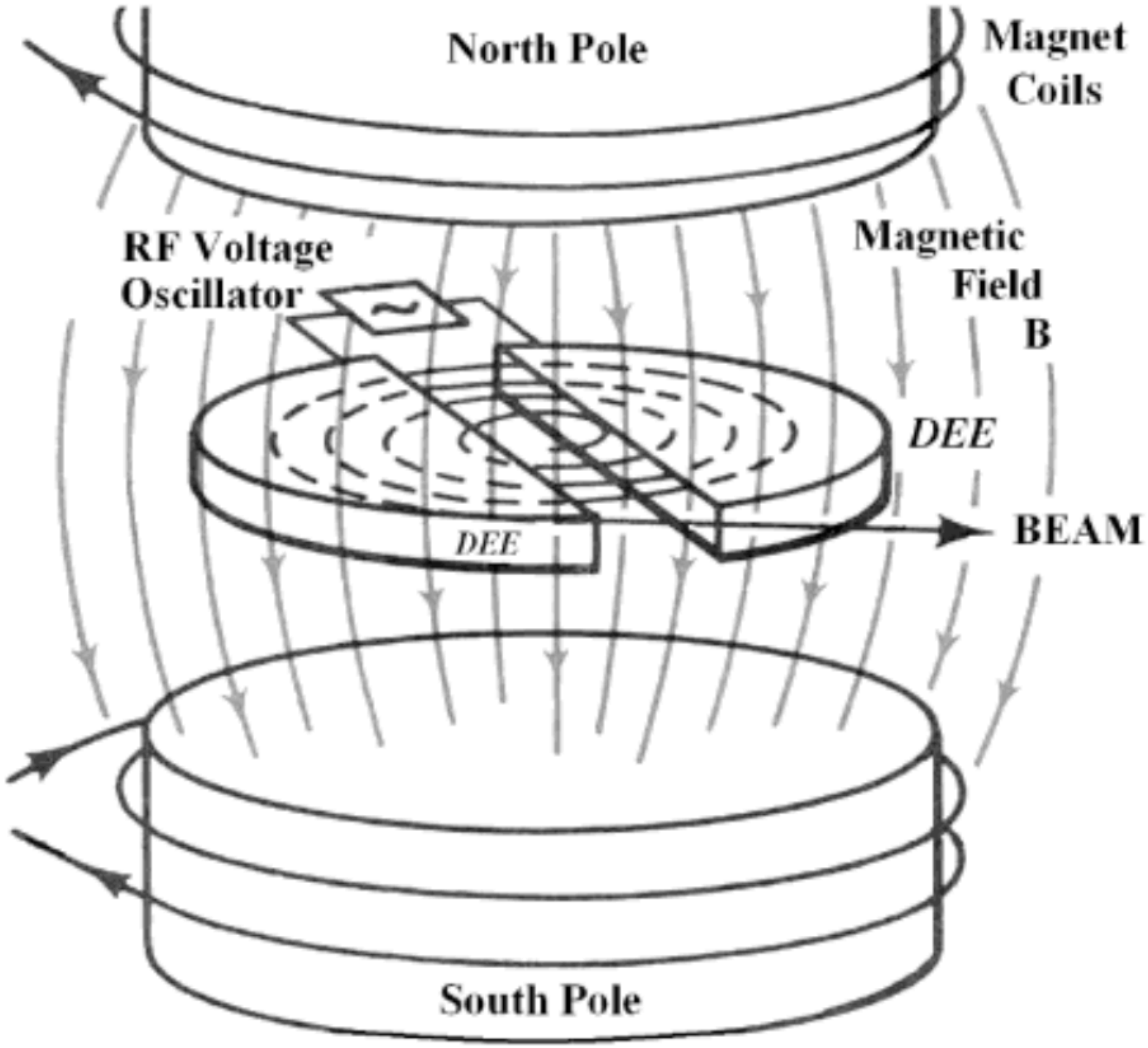
→ Circular acceleration with several pass through accelerating field!

Circular Accelerators: Cyclotron

- Invented by E.O. Lawrence (1930)
- Charged particles in a static magnetic field travel outwards from the center along a spiral path and get accelerated by radio frequency electromagnetic fields.
- Acceleration is supplied by instantaneous potential difference between two hollow D- shaped electrodes ("DEEs") that keep the E-field = 0 inside.
- Cyclotron frequency (non-relativistic):

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

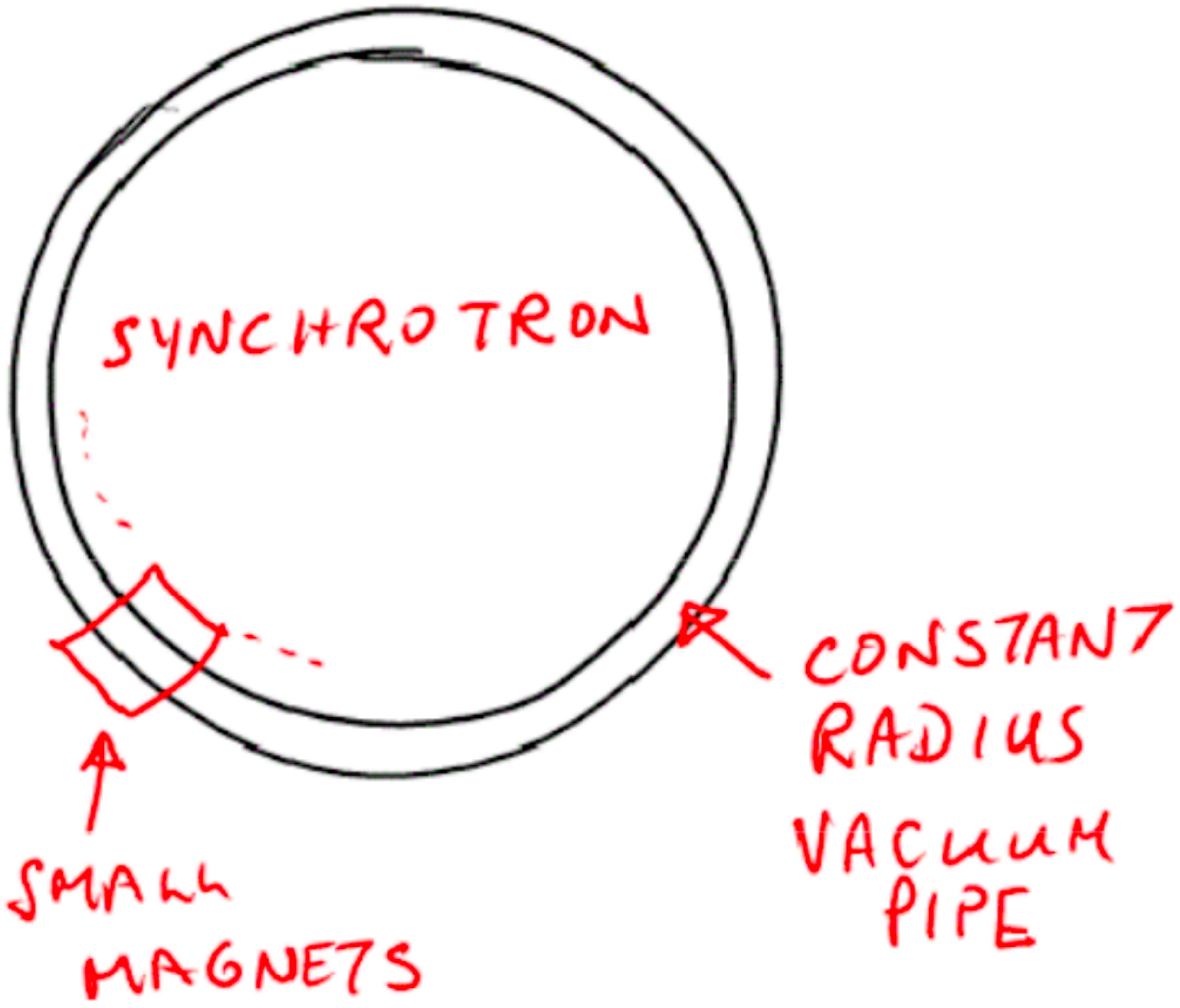
- Capable of producing DC current of order mA.



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

Circular accelerators

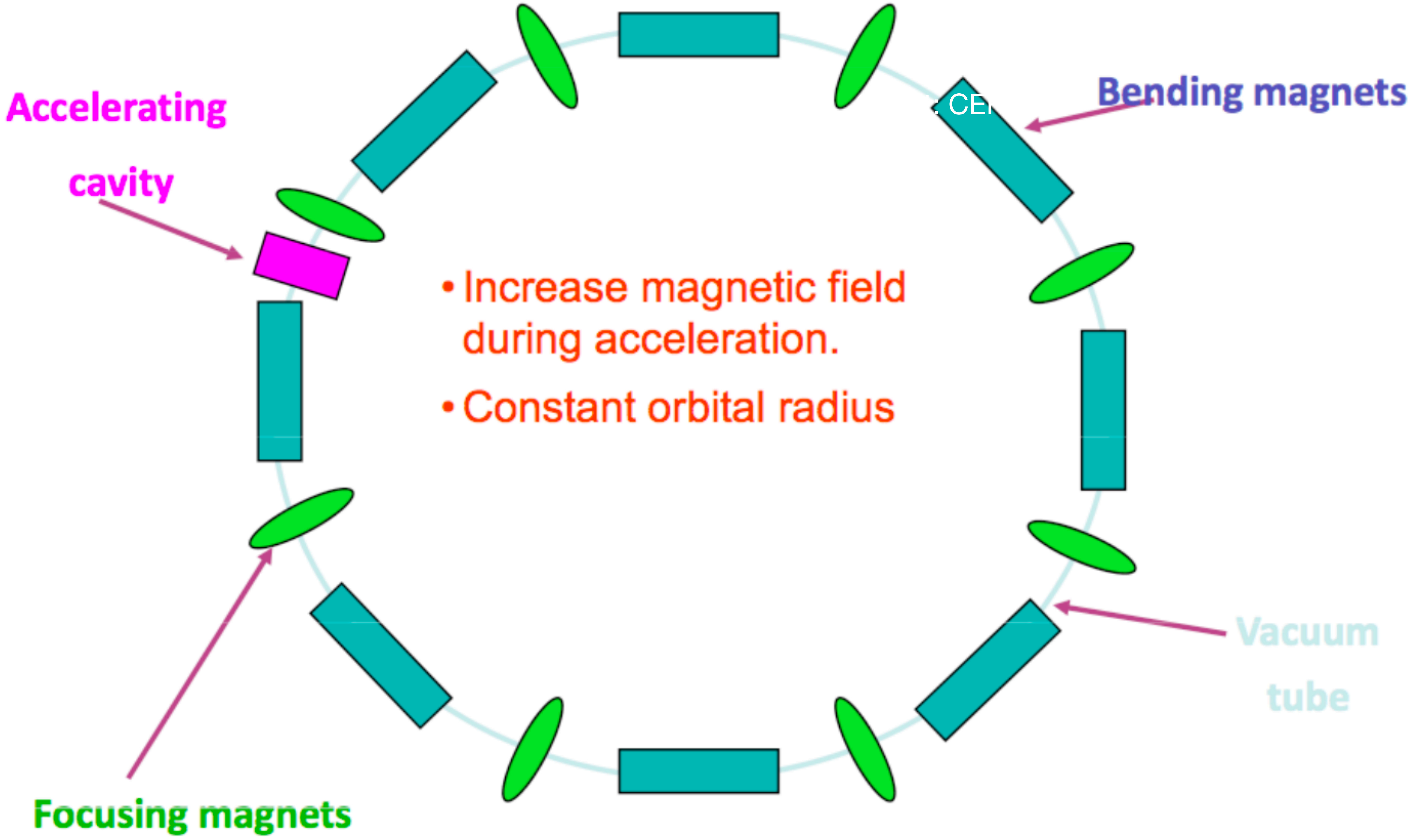
Limit: To reach high energy, size of magnet gets prohibitively expensive. → Design machine with constant orbit radius!



Credit: B. Orr, University of Toronto

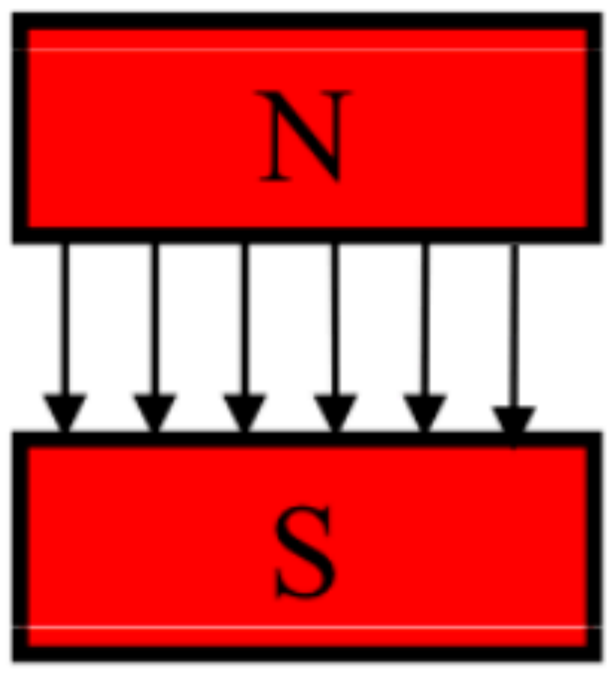
Circular accelerators: Synchrotron

- **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!
- As particles accelerate, the dipole magnetic field and the frequency of the RF accelerating cavities have to vary proportionally with particle energy.

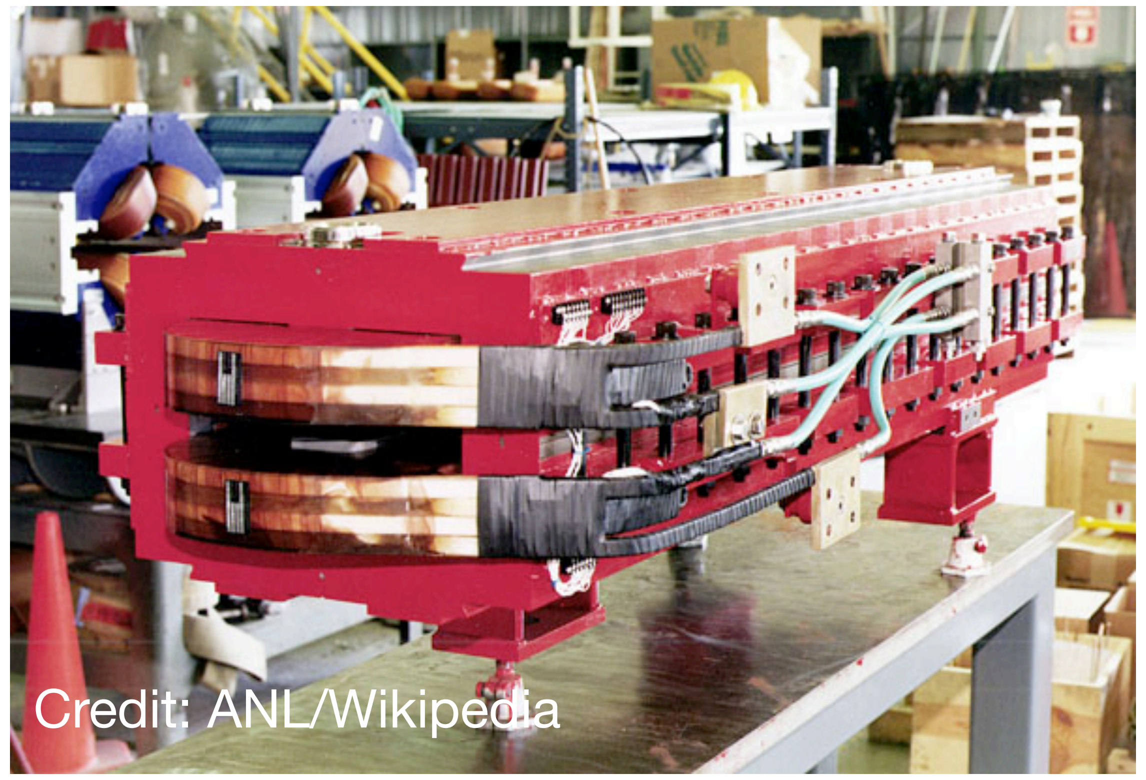


Synchrotron: trajectory

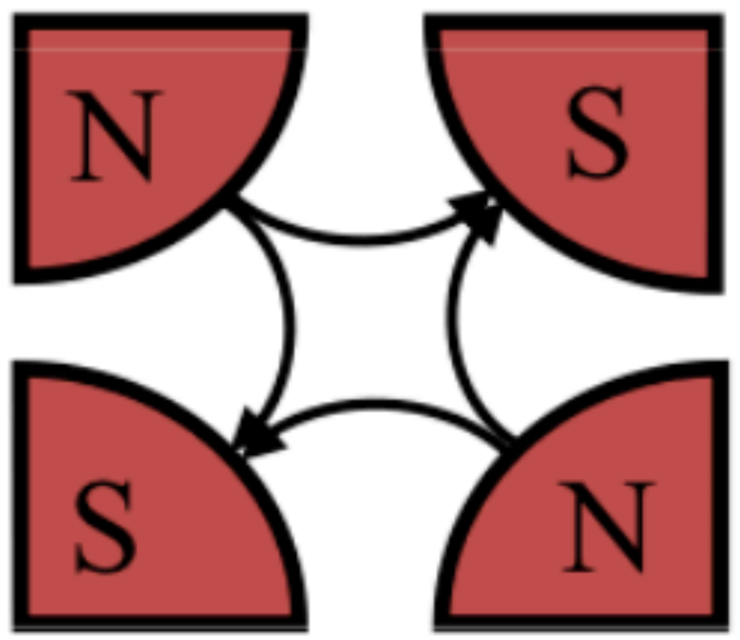
Dipole



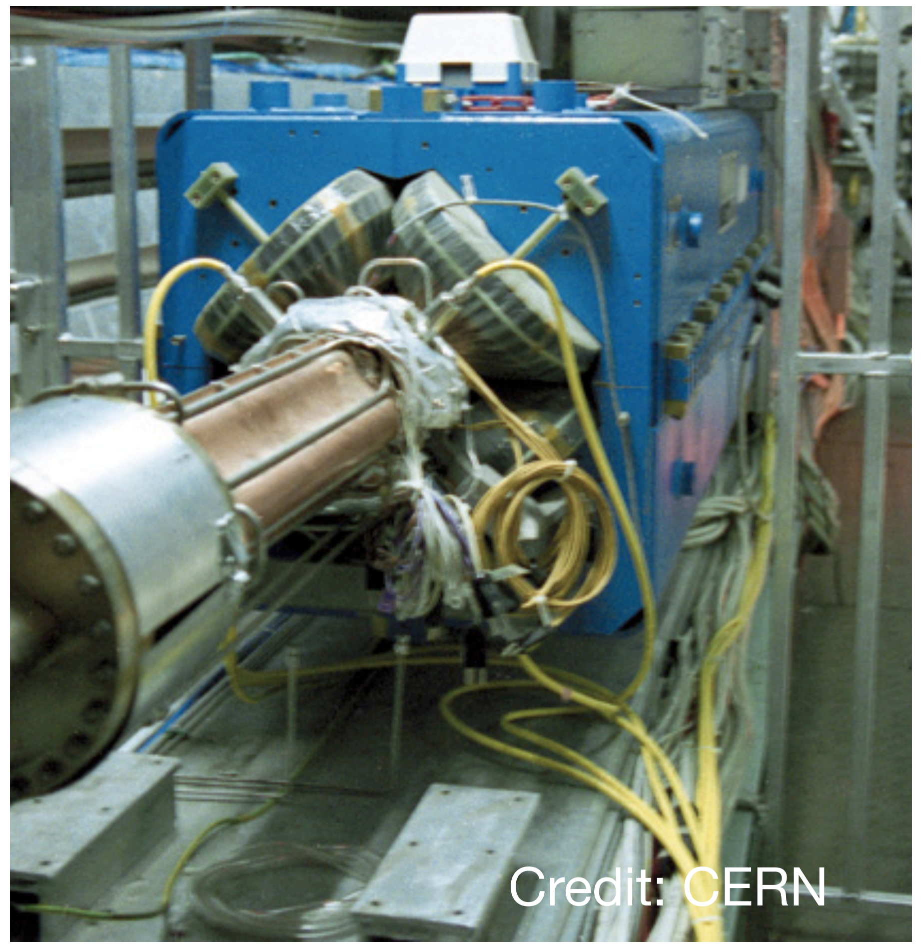
Bending



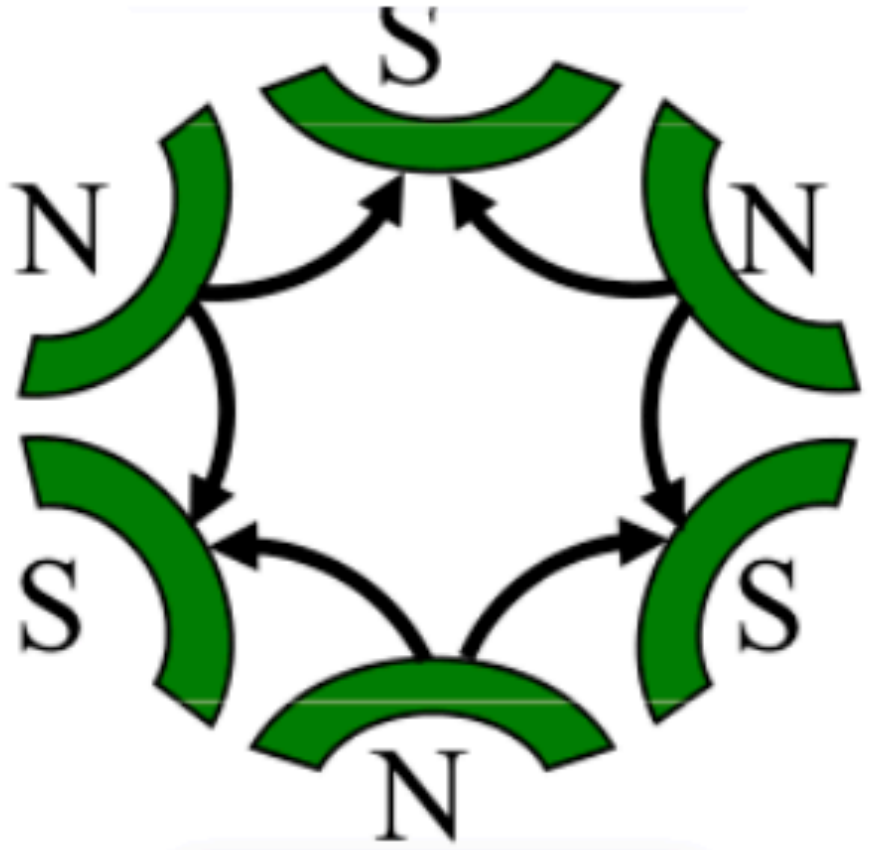
Quadrupole



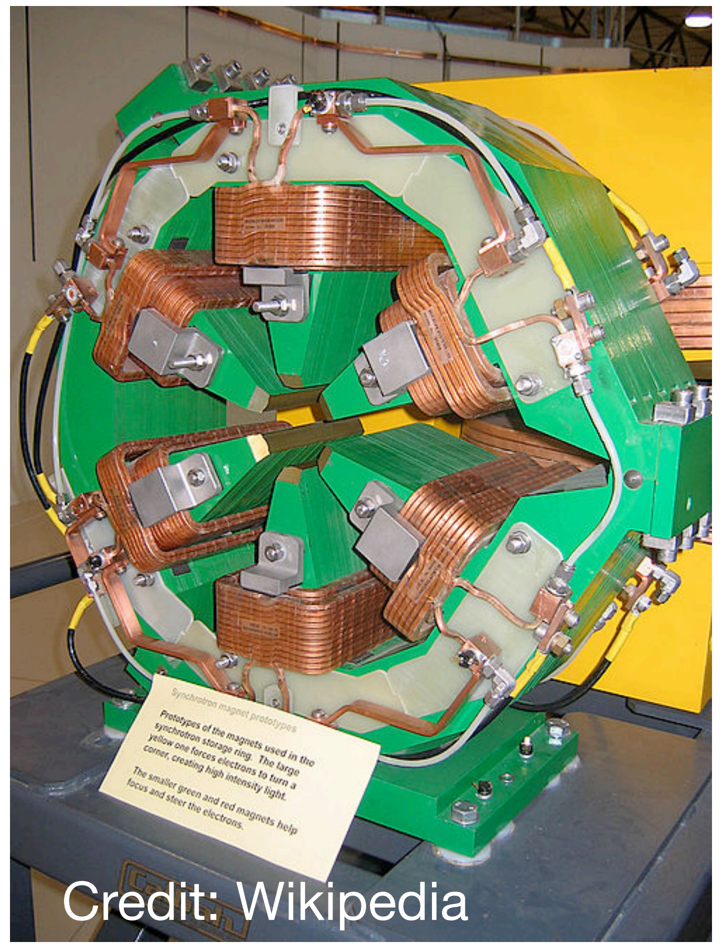
Focusing



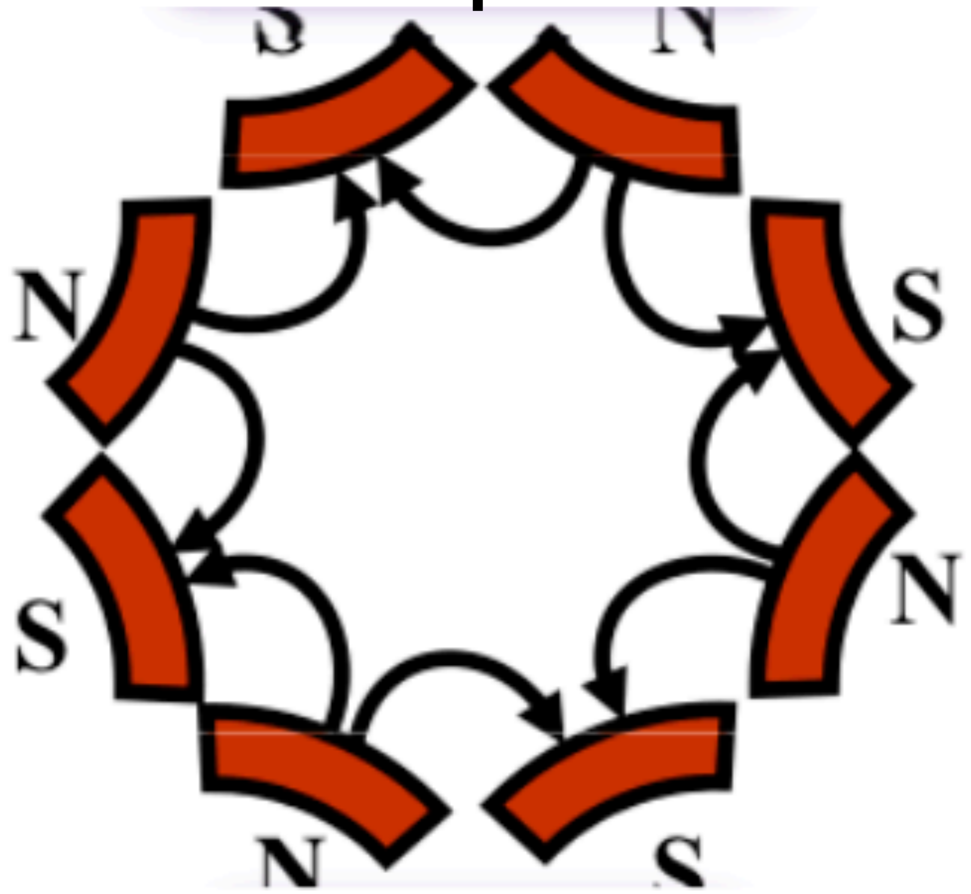
Sextupole



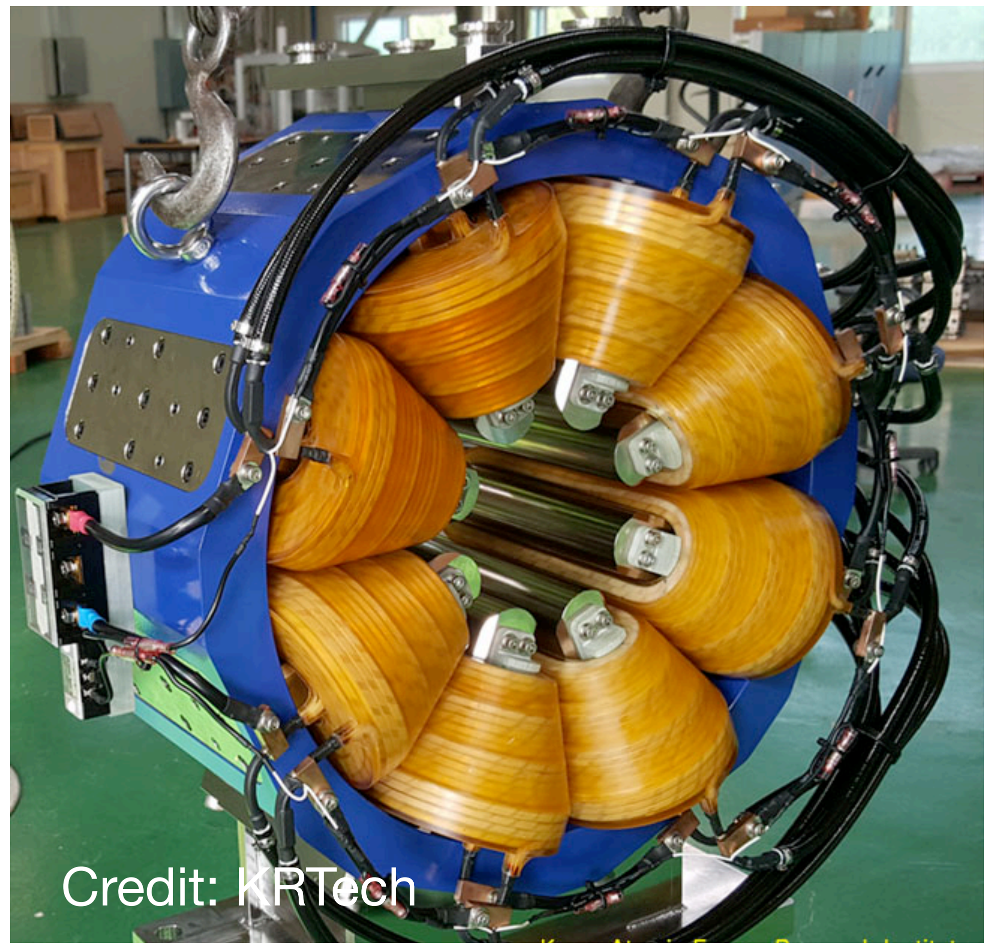
Chromaticity compensation



Octupole



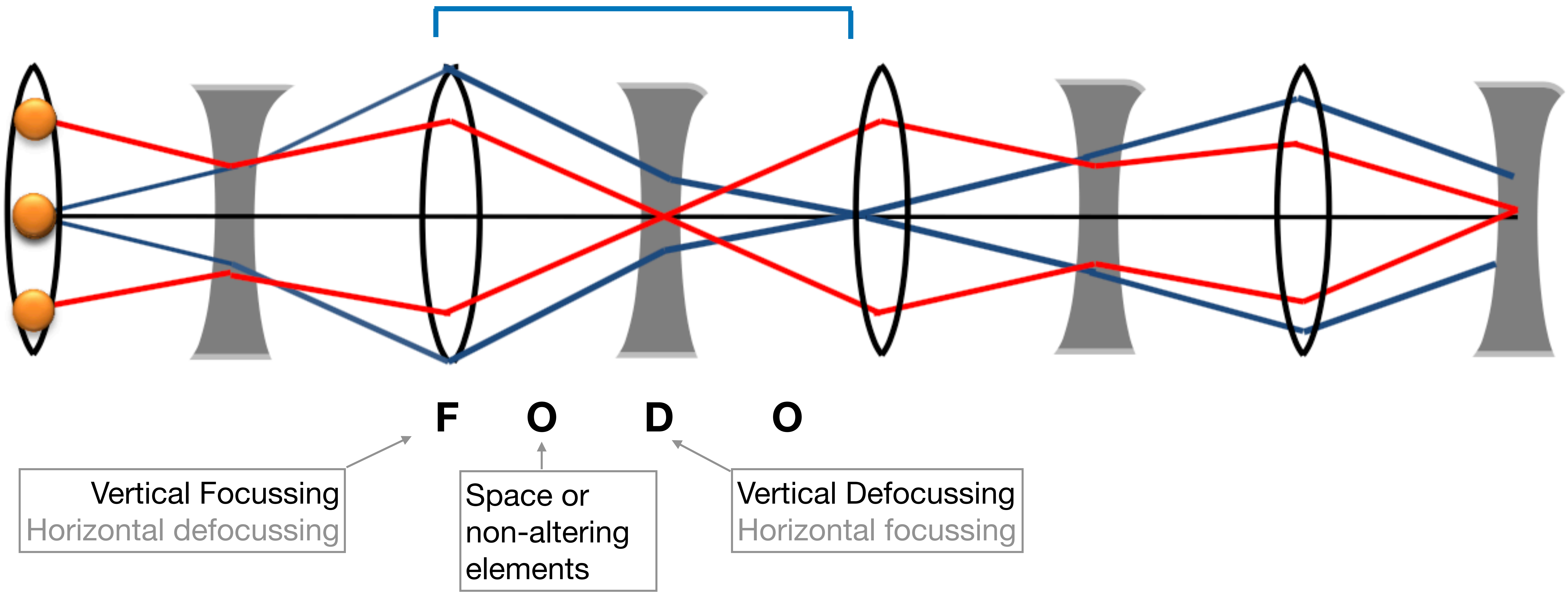
High-order corrections



Synchrotron: trajectory

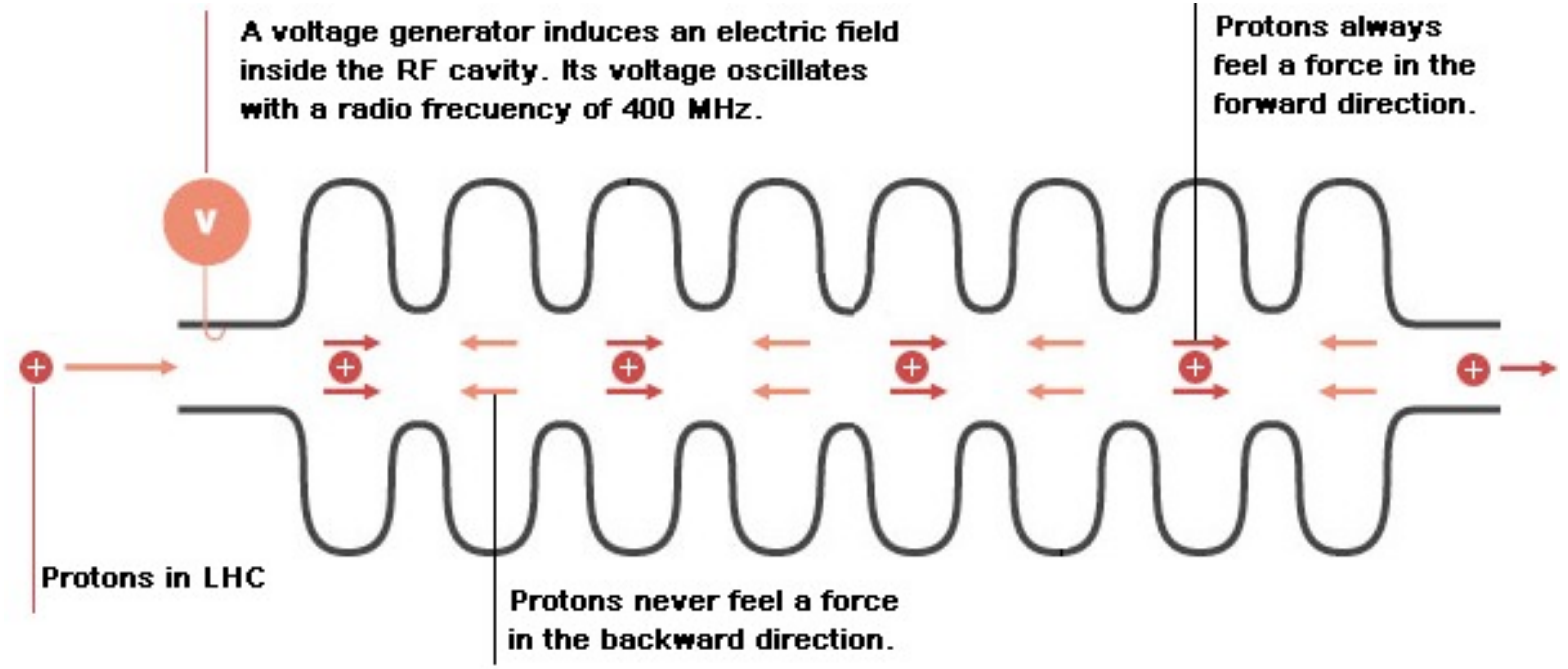
The (magnetic) "**lattice**" of an accelerator is the sequence of dipole, quadrupoles and other magnets which constitutes the accelerator.

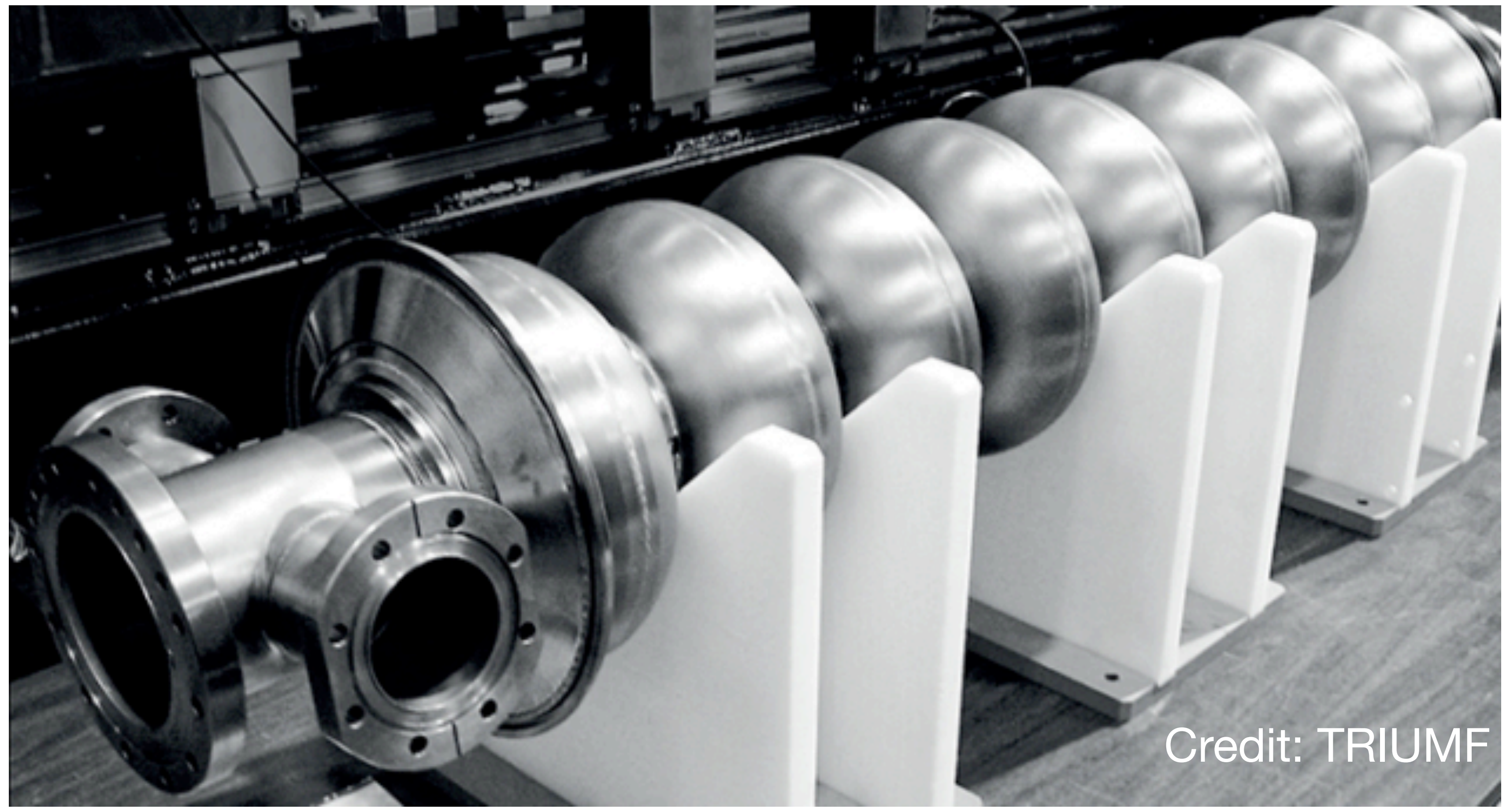
One of the most wide-spread lattice cell is called the **FODO cell**.

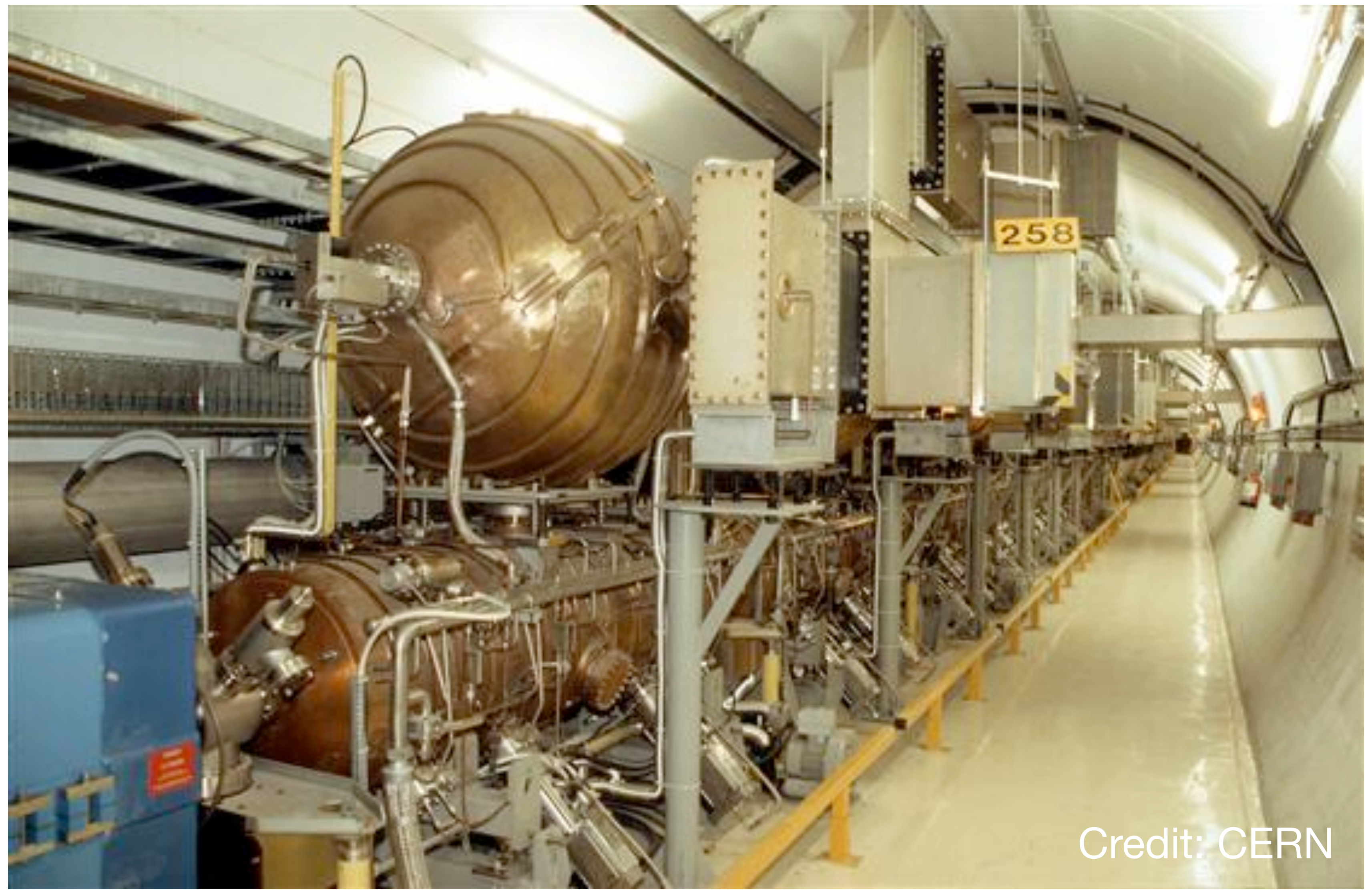


Beam particles trajectories through the focusing arrangement of several FODO cells show an oscillating pattern.

Resonant accelerating cavity




Credit: TRIUMF



Credit: CERN

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

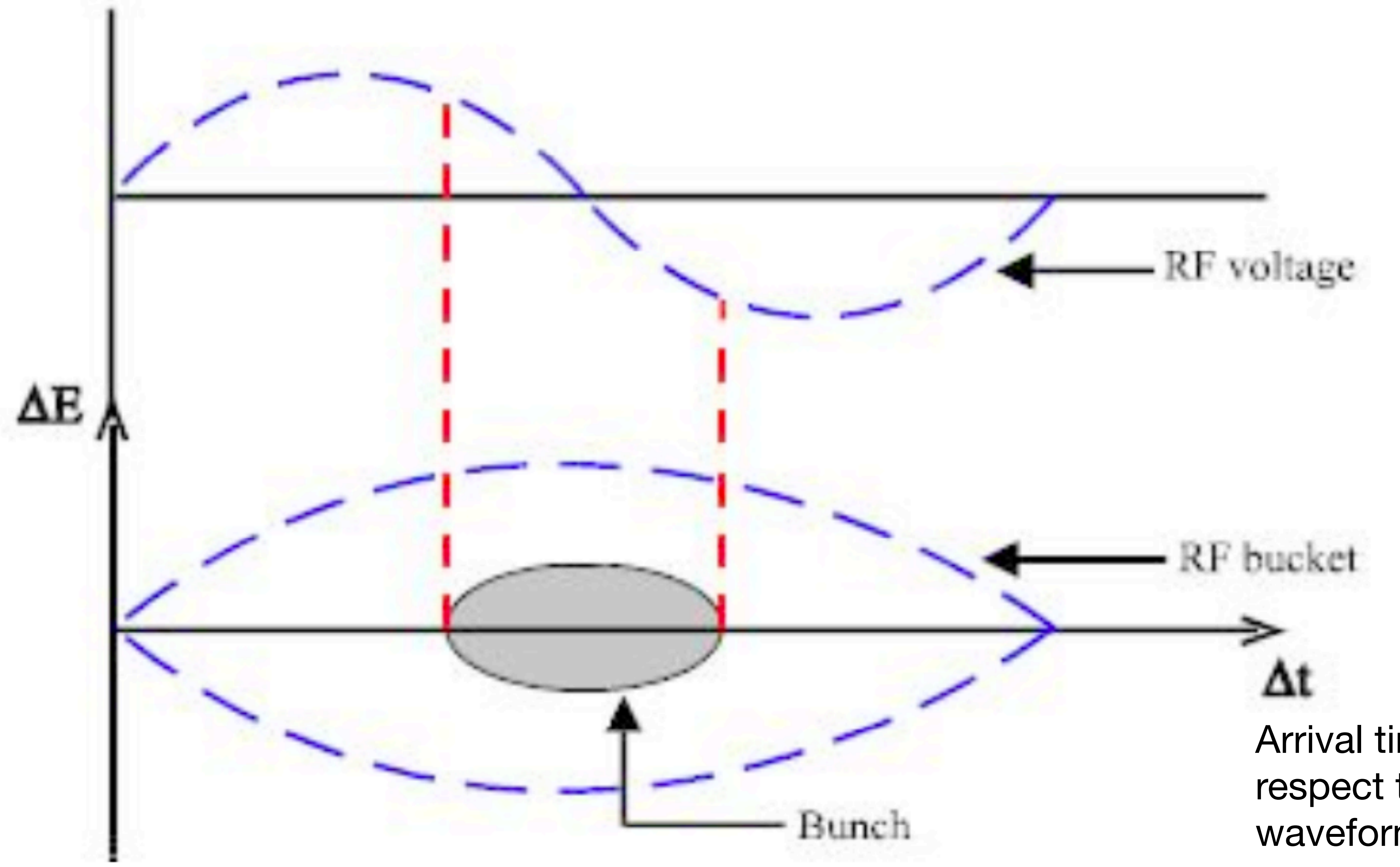
Synchrotron: Phase Stability

- To always see an accelerating voltage, the RF frequency must be an integer

  $f_{RF} = h\, f_{rev}$ [h = "harmonic number"]

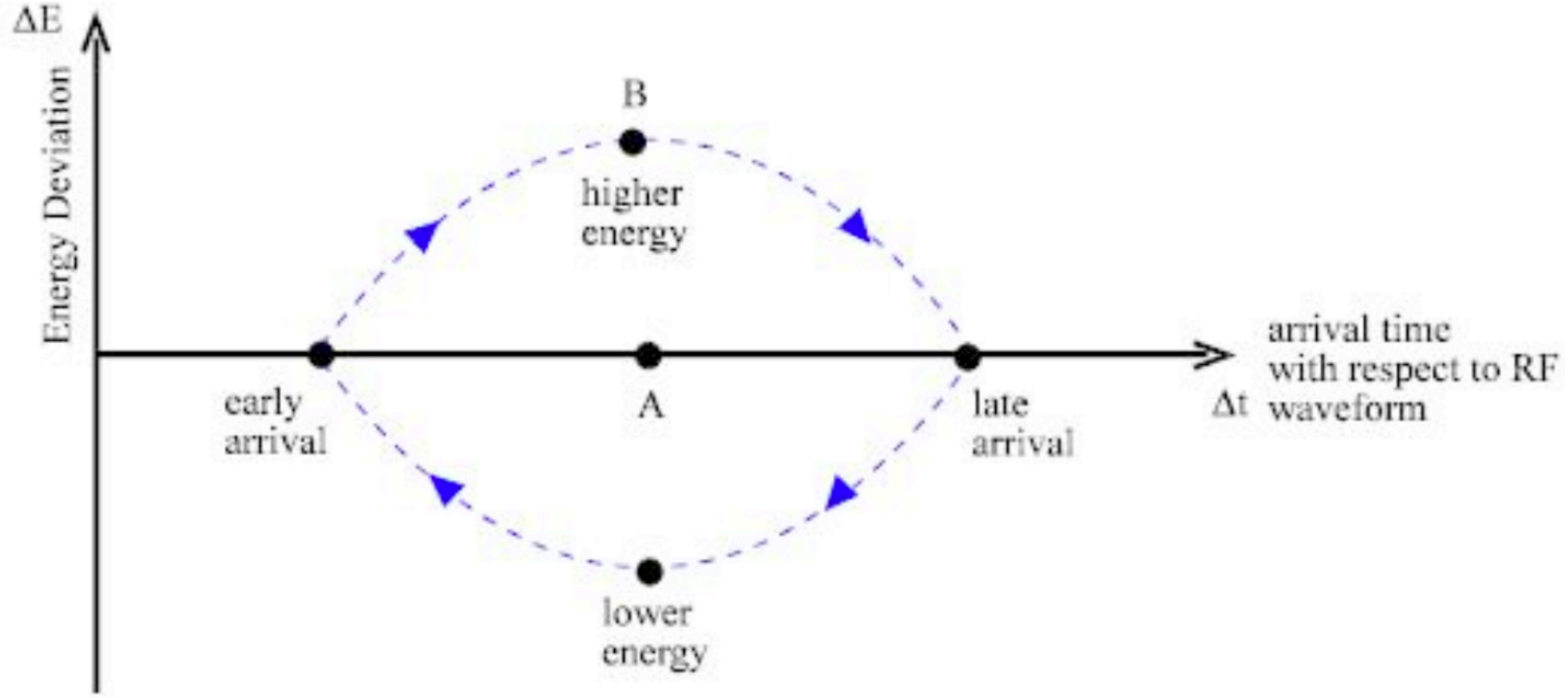
- The "h" segments of the circumference centred on these accelerating points
- Particles get "clumped" around the synchronous particle in a "bunch".
  This particle bunch is contained in an RF bucket.
- Not all buckets need to be filled with particle bunches.

Example: LHC
f_{RF} = 400 MHz
Proton travelling at v ~ c
Circumference ~ 27 km
f_{rev} ~ 0.01 MHz
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) Current research facilities

(3) Future projects

Accelerators in physics research

- **Light source**
  - Synchrotron radiation: Electromagnetic radiation emitted when charged particles are accelerated radially.
- **Fixed-target experiments**
  - Energy available in centre-of-mass system: $\sqrt{s} \approx \sqrt{2\ E_a^{lab} \cdot m_{target}}$
- **Secondary beam production**
  - E.g. Neutrino beam
- **Collider**
  - Energy available in centre-of-mass system: $\sqrt{s} \approx 2\ E_a^{lab}$
  - Luminosity: $\mathscr{L} = f \cdot \frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$

f: Bunch crossing frequency
n_1, n_2: number of particles per bunch
σ_x, σ_y: Bunch cross-section

TRIUMF

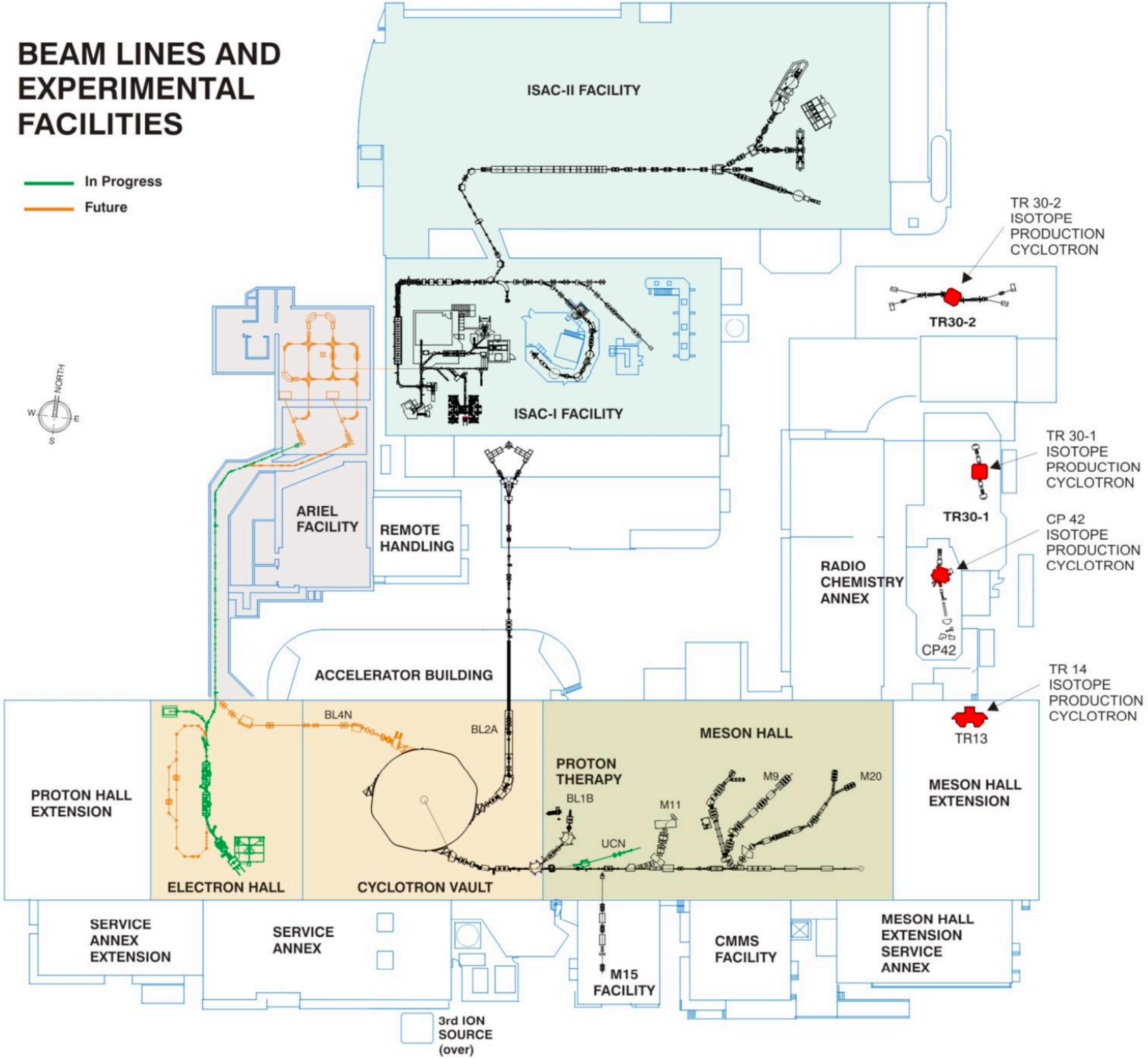
Primary beam driver:
Cyclotron, 500 MeV, 100 μA, H-
Produces rare isotopes, neutrons and muons!

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

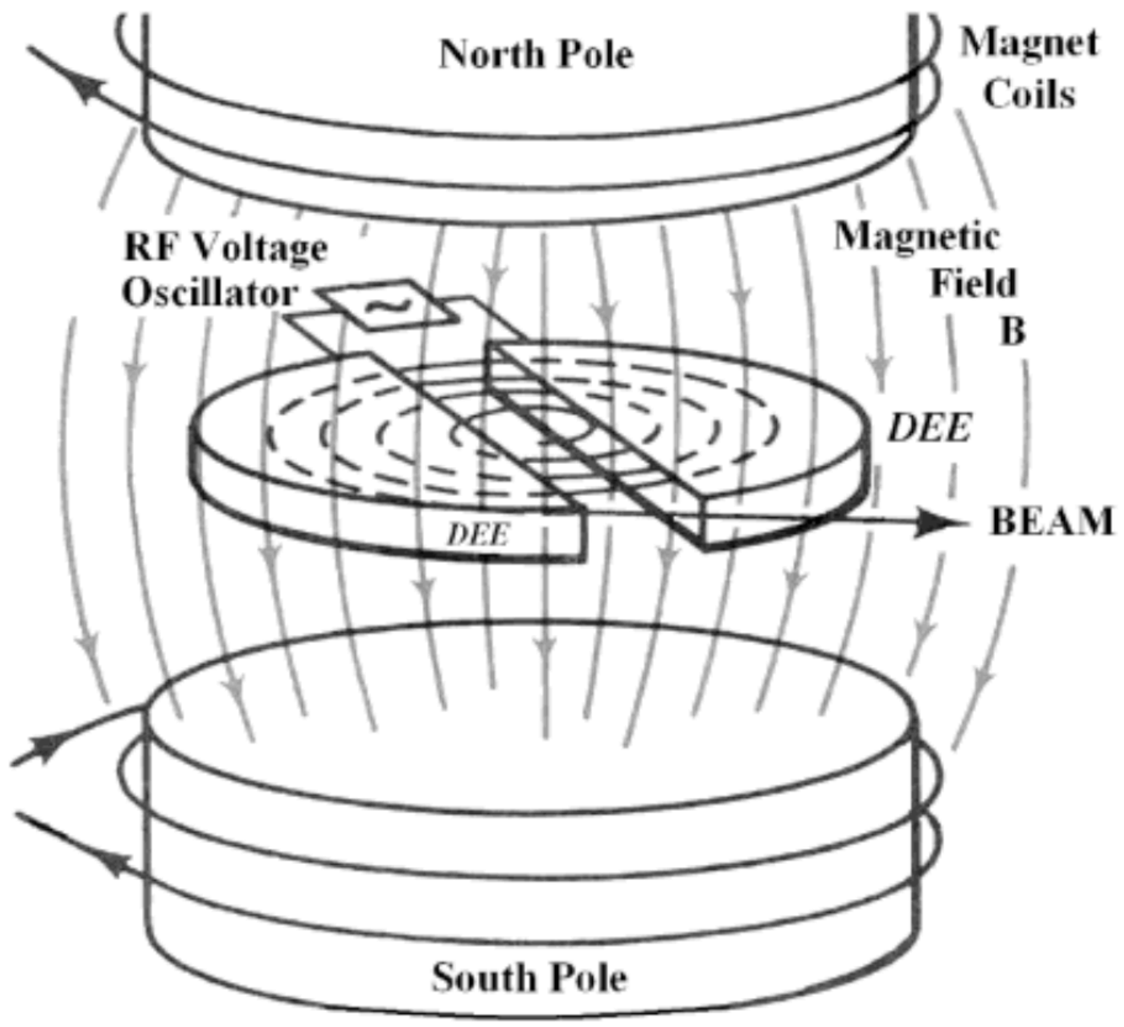
Physics Research:
- Accelerator Physics
- Nuclear structure
- Nuclear astrophysics
- Fundamental symmetries
- Particle Physics
- Nuclear medicine
- Molecular & Materials Science
- etc.

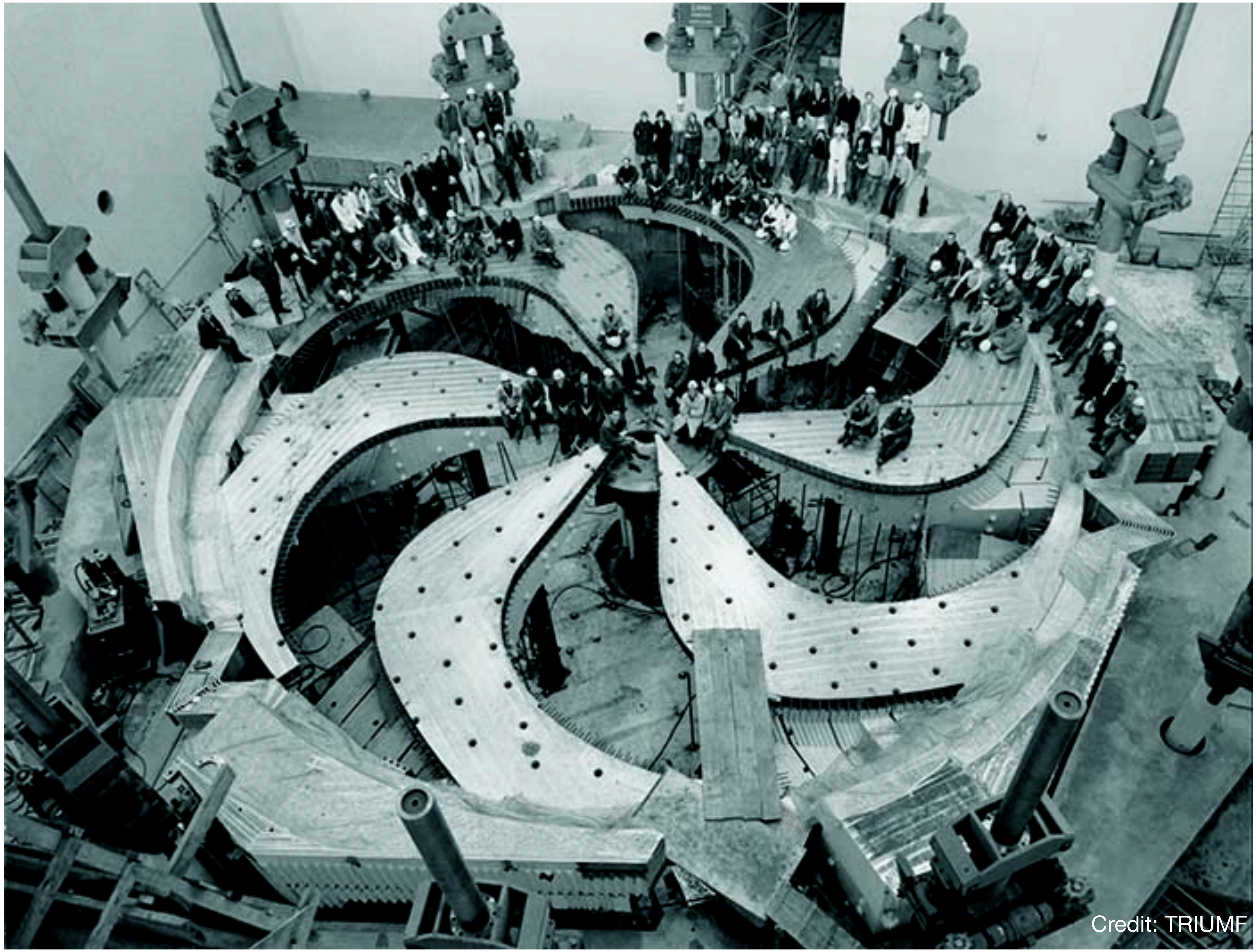


TRIUMF

- **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.

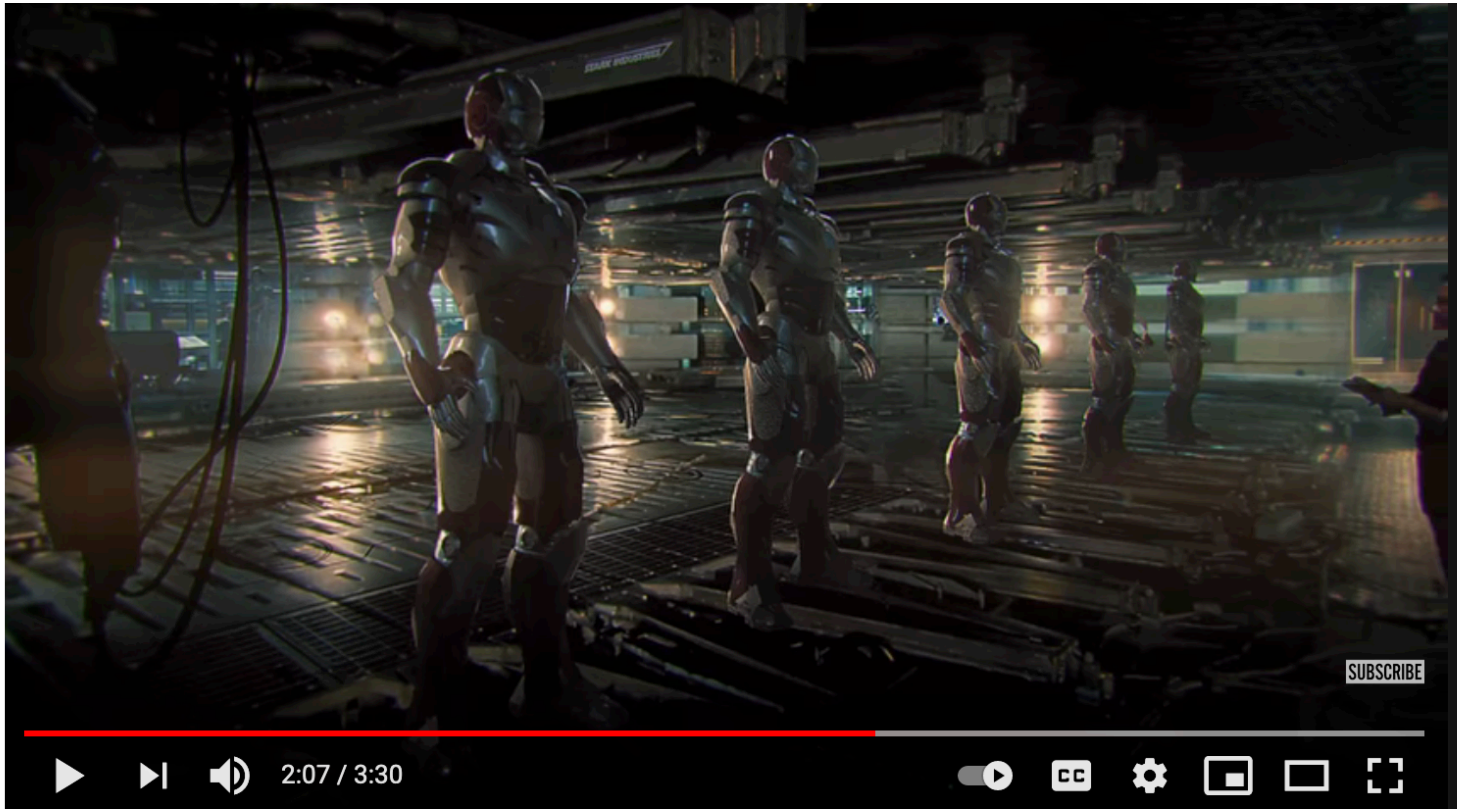


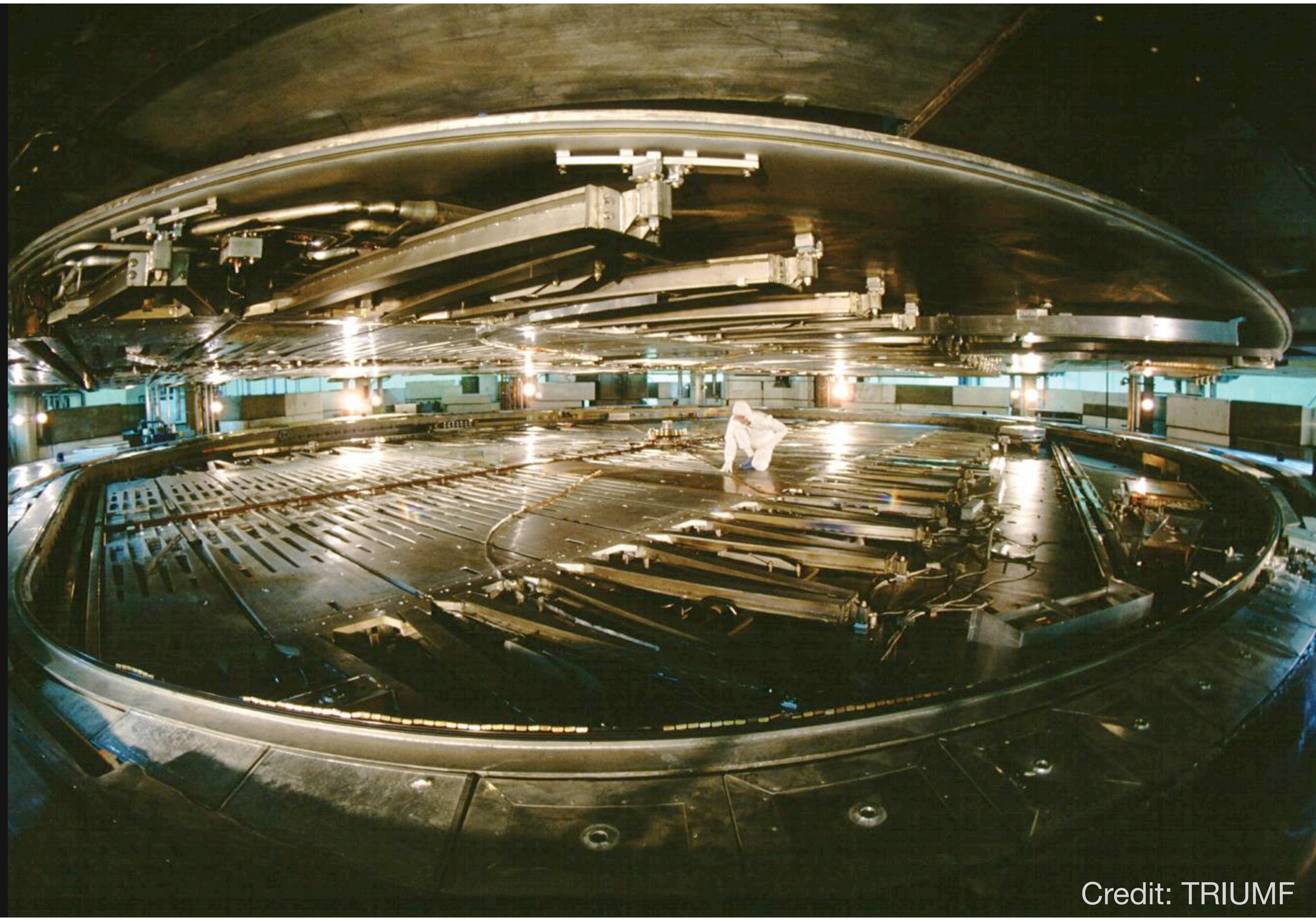


Credit: TRIUMF

TRIUMF

Inside the TRIUMF Cyclotron vacuum chamber





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

Stanford Linear Accelerator (USA)

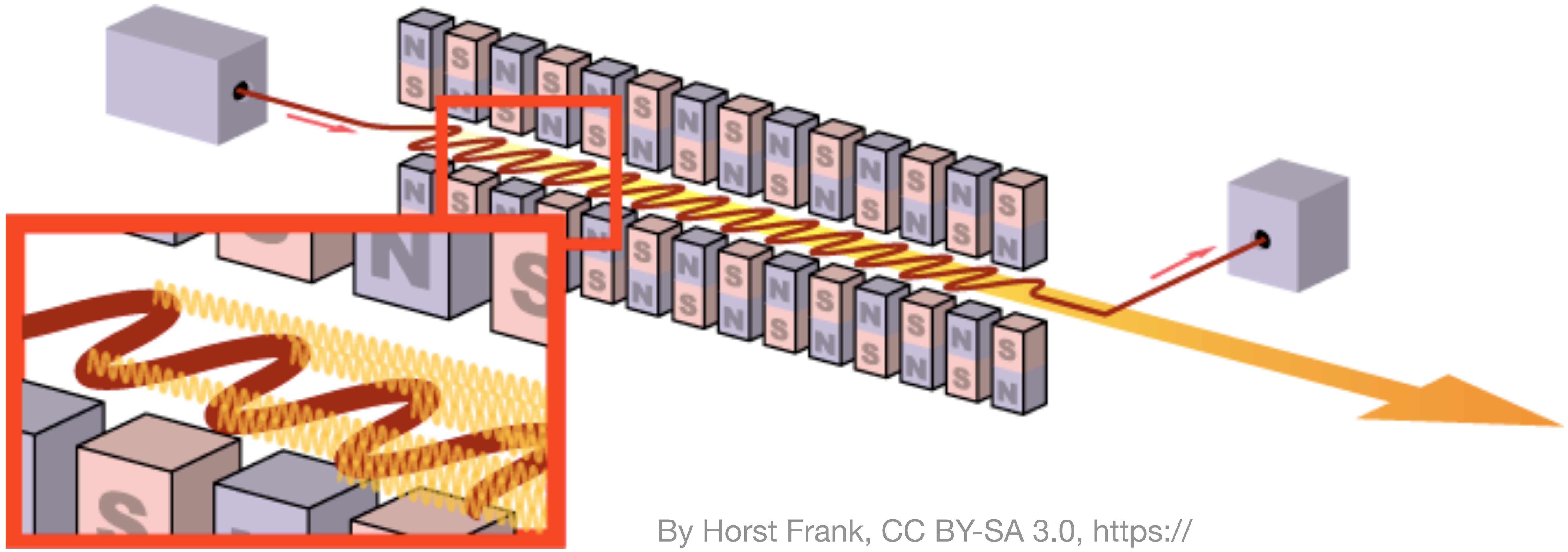
- 3 km linac with top energy of 50 GeV
- Klystron gallery was the longest building in the world!
  (…until LIGO interferometers was completed in 1999)
- **Physics research**:
- Materials science, Biology, Chemistry.
- Accelerator physics
- Particle physics
- Astrophysics/cosmology
- etc.

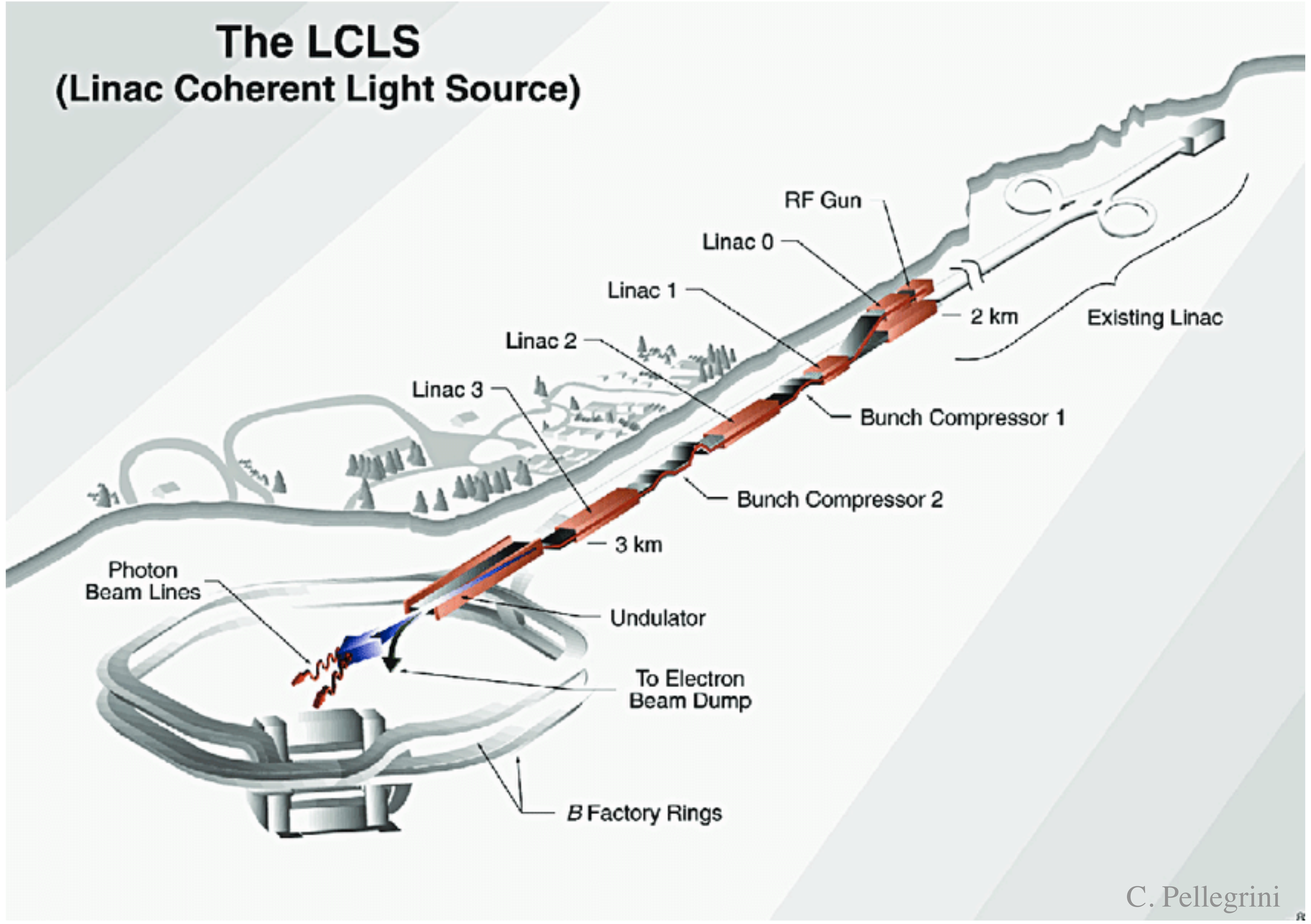

Credit: SLAC


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.



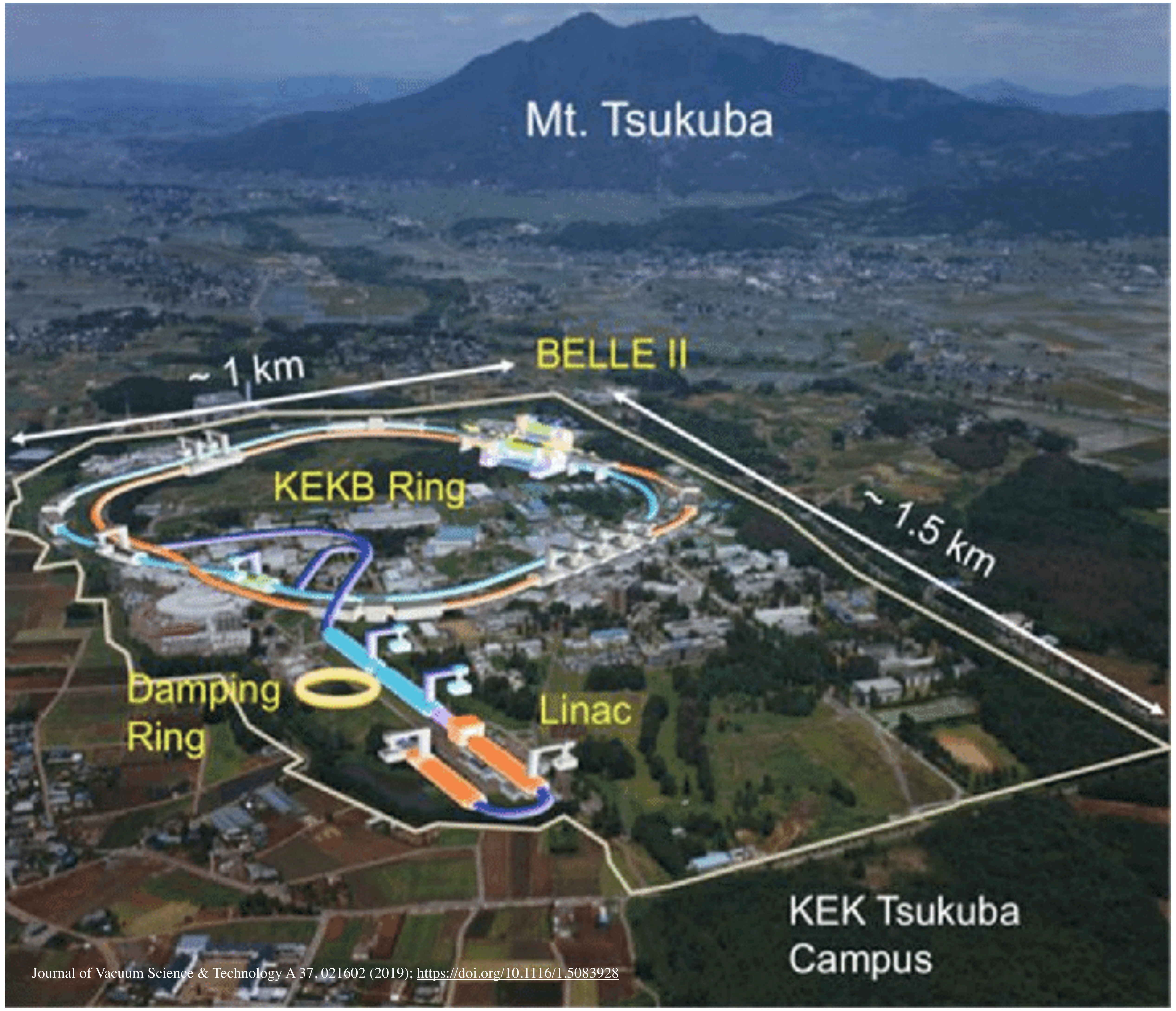


KEK (Japan)

- **> 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.



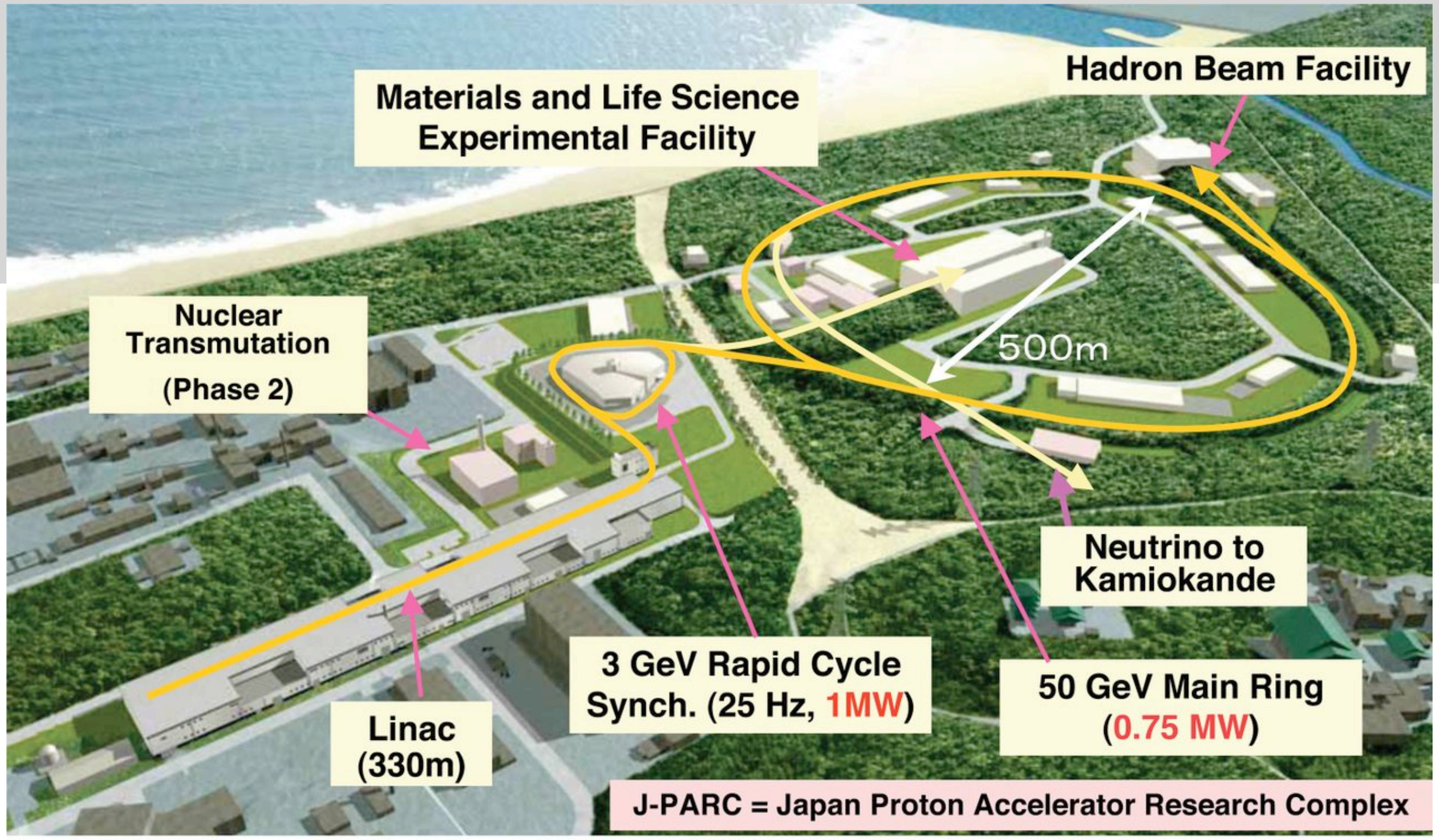
Journal of Vacuum Science & Technology A 37, 021602 (2019); https://doi.org/10.1116/1.5083928

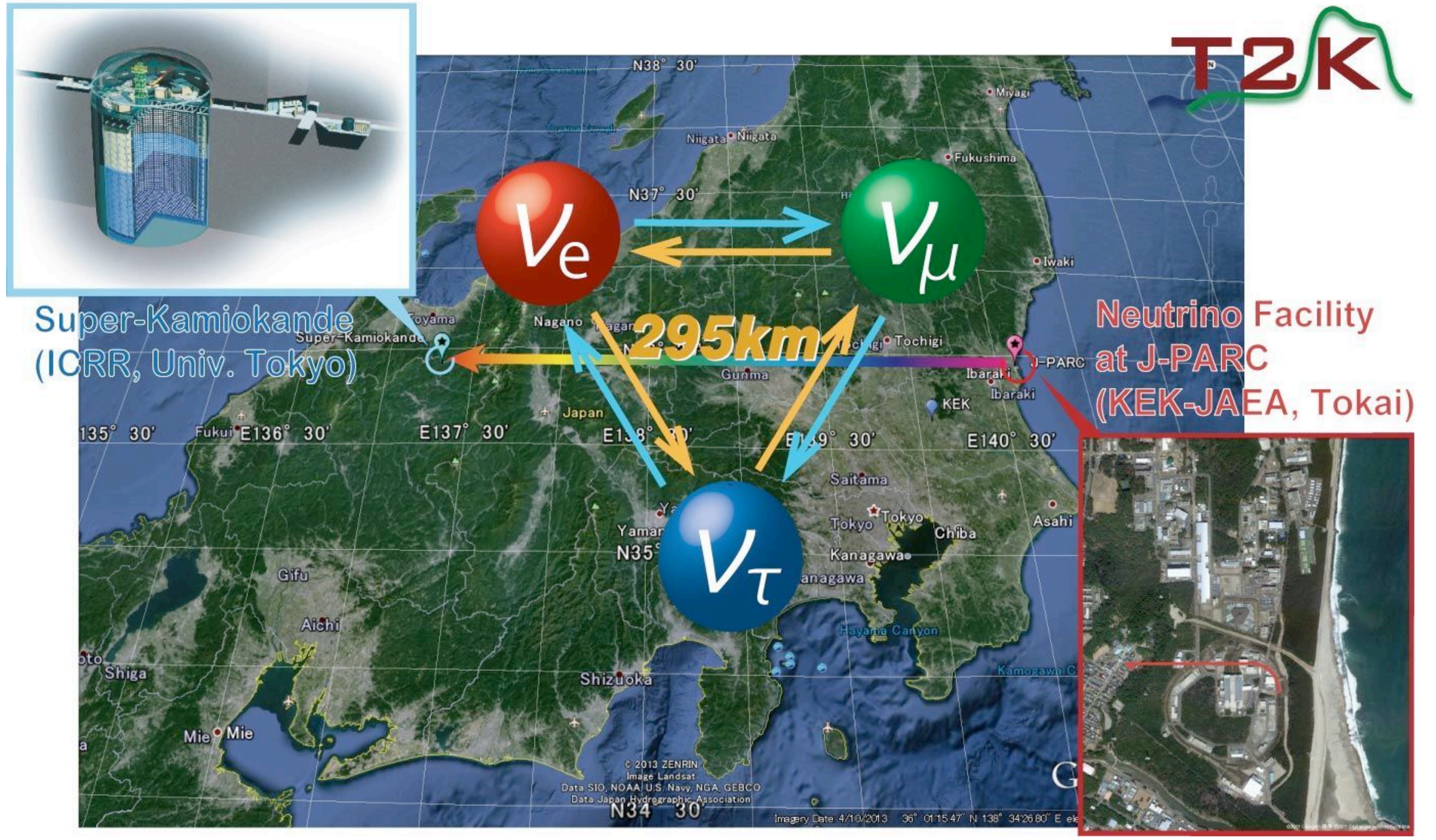
J-PARC (Japan)

- Main Ring accelerates protons to 50 GeV.
- Protons made to hit a graphite target, producing many different types of secondary particles, among which many are π-mesons. Then these π-mesons decays produce neutrinos.
- 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

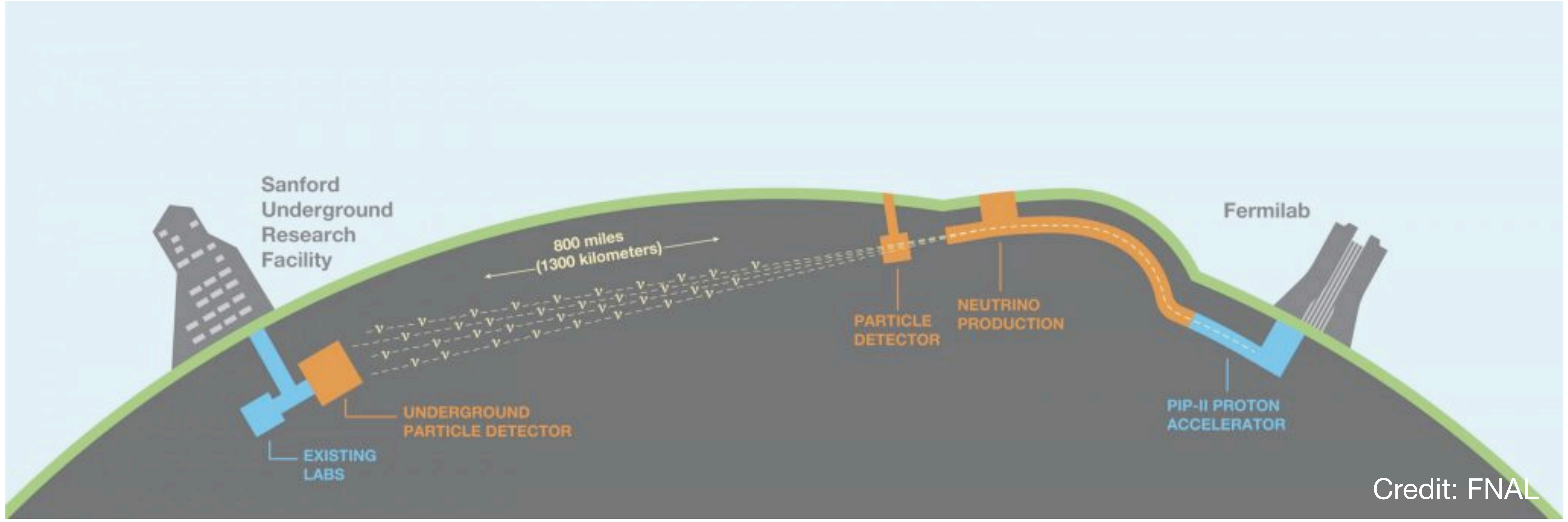
- **CDF and D0 experiments**:
  - Discovery and study of top quark
  - Search for new physics
  - Hadron physics
  - Flavour physics
  - + Wide range of particle physics topics

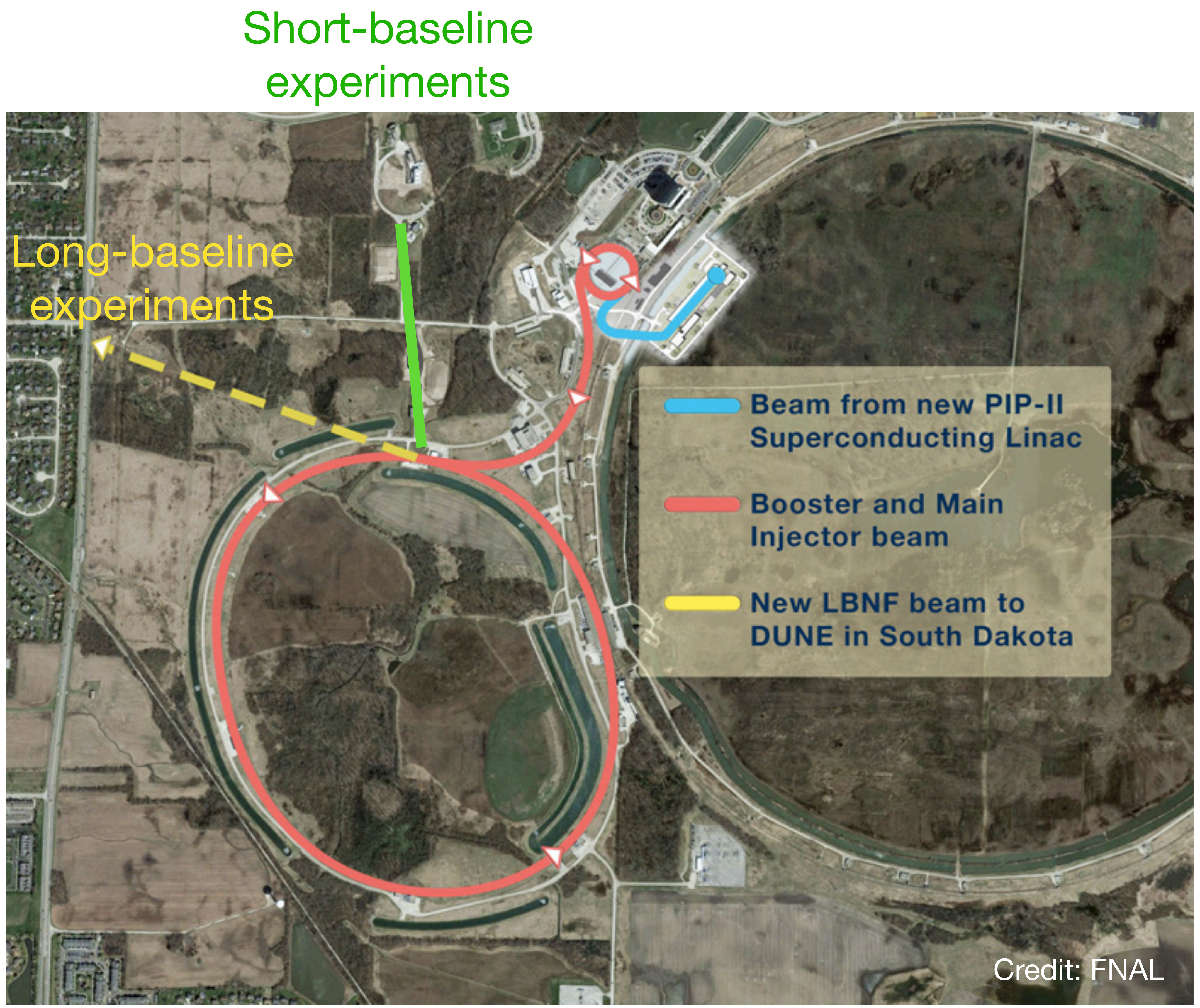
Fermilab (USA)

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…

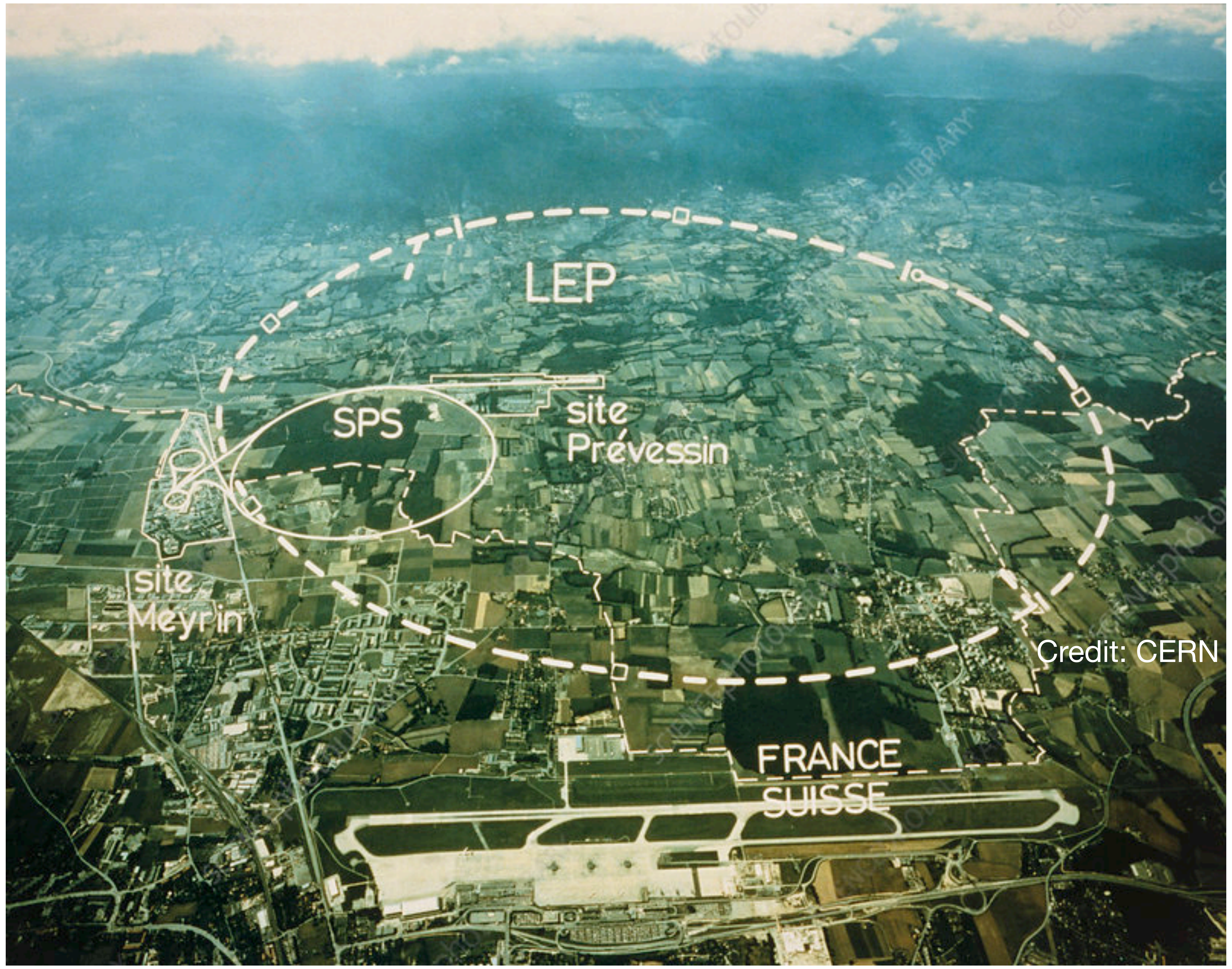




CERN (Switzerland/France)

- 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.

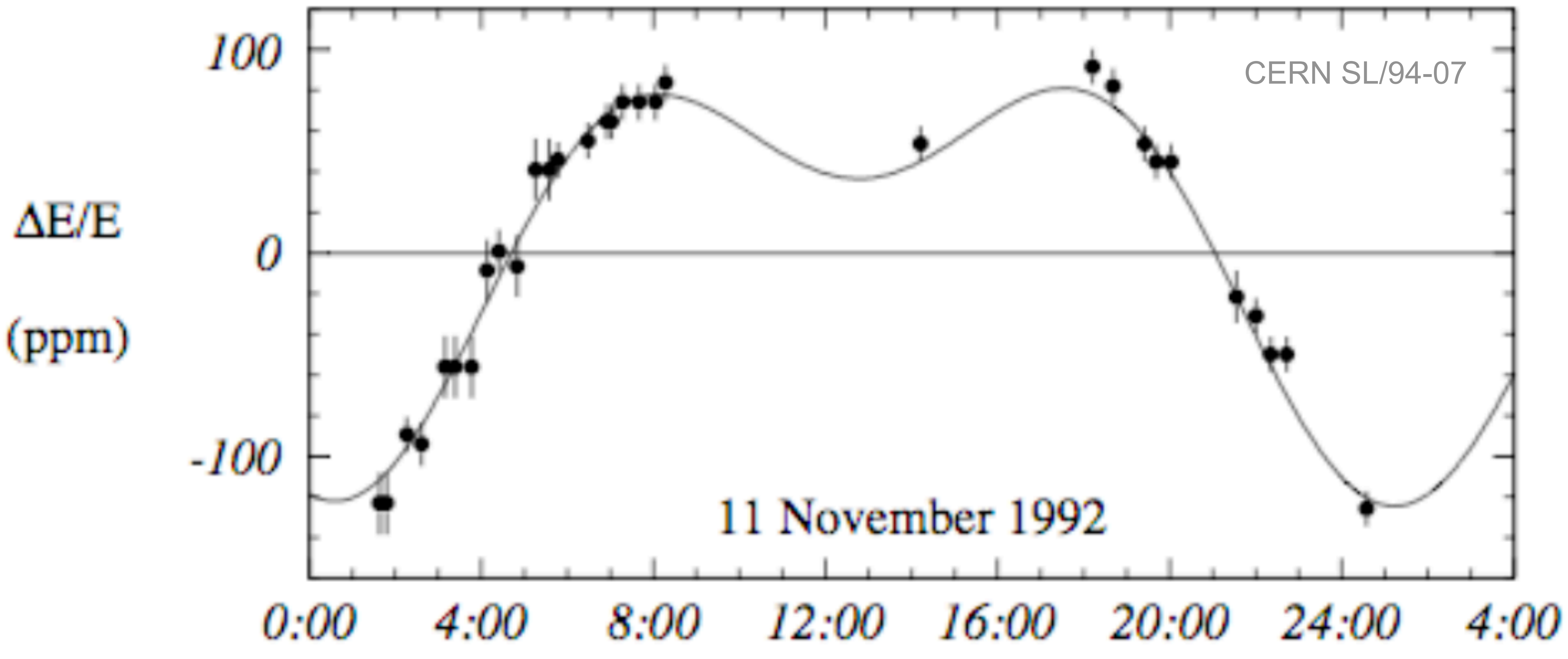


Credit: CERN

CERN (Switzerland/France)

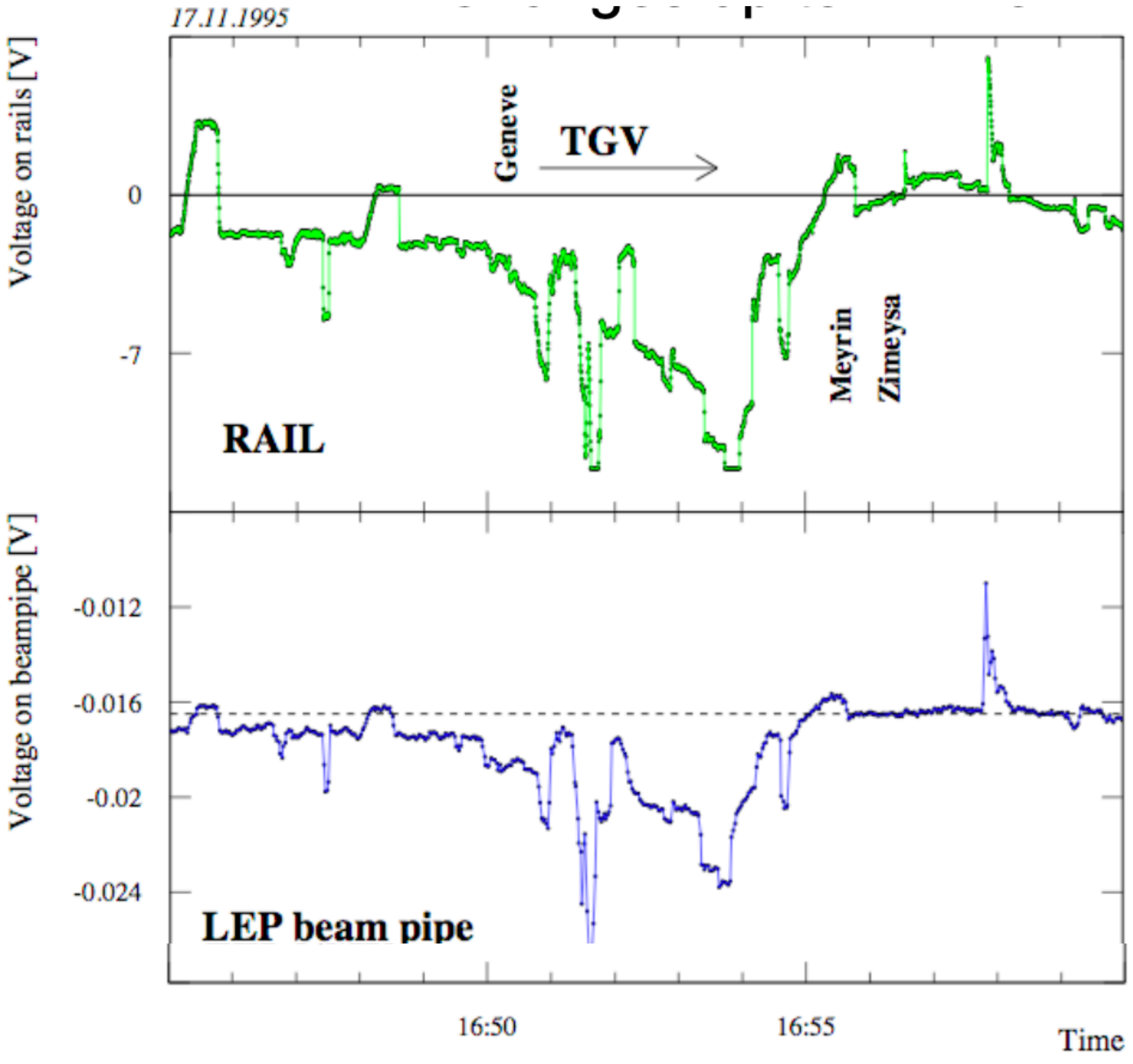
- **1989-2000**: Large Electron-Positron (LEP) collider

LEP energy changes due to tidal effects



Mysterious periodic changes in energy observed for many years….

The Paris-Geneva TGV!!



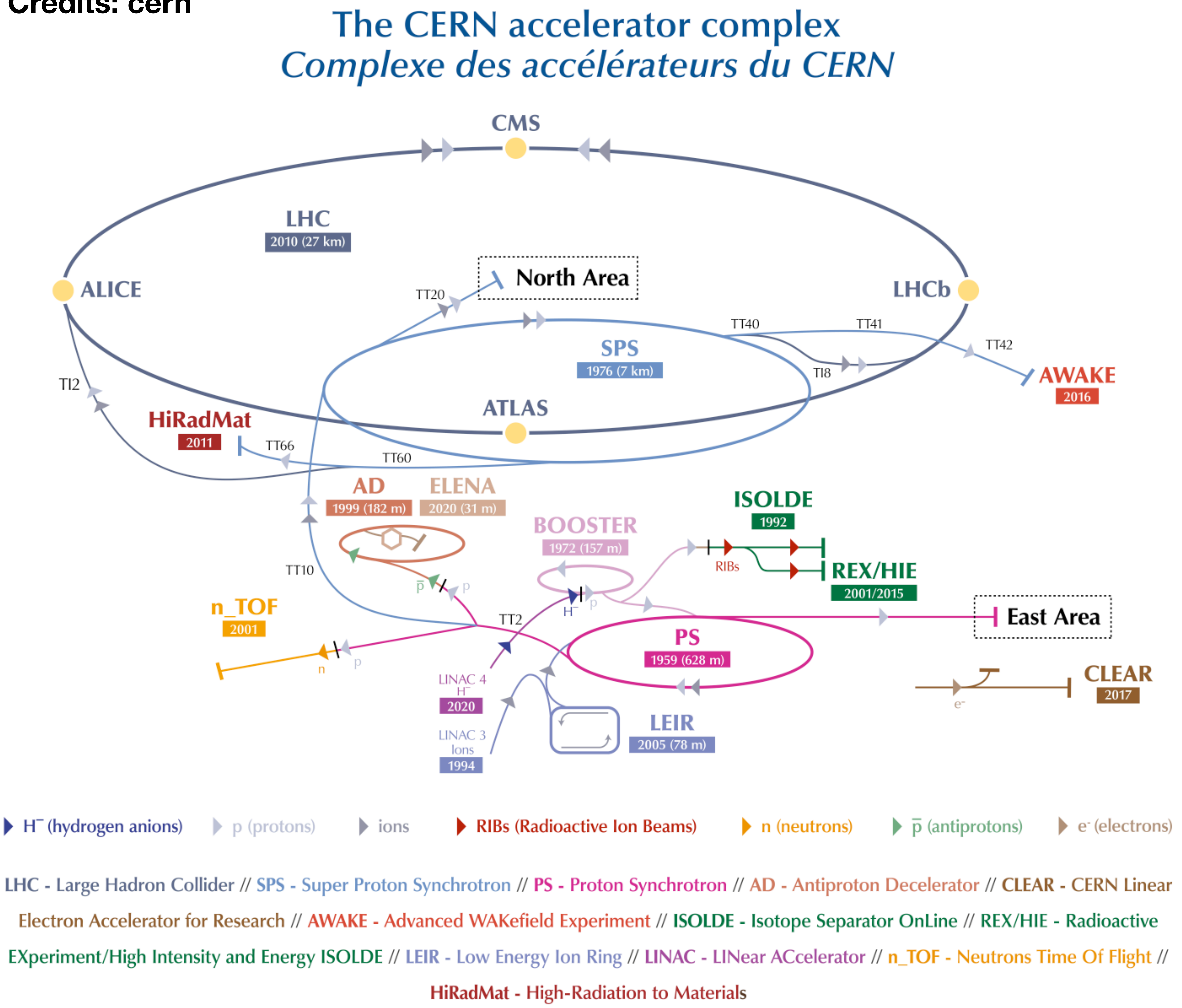
1996 "beer bottle" incident….

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

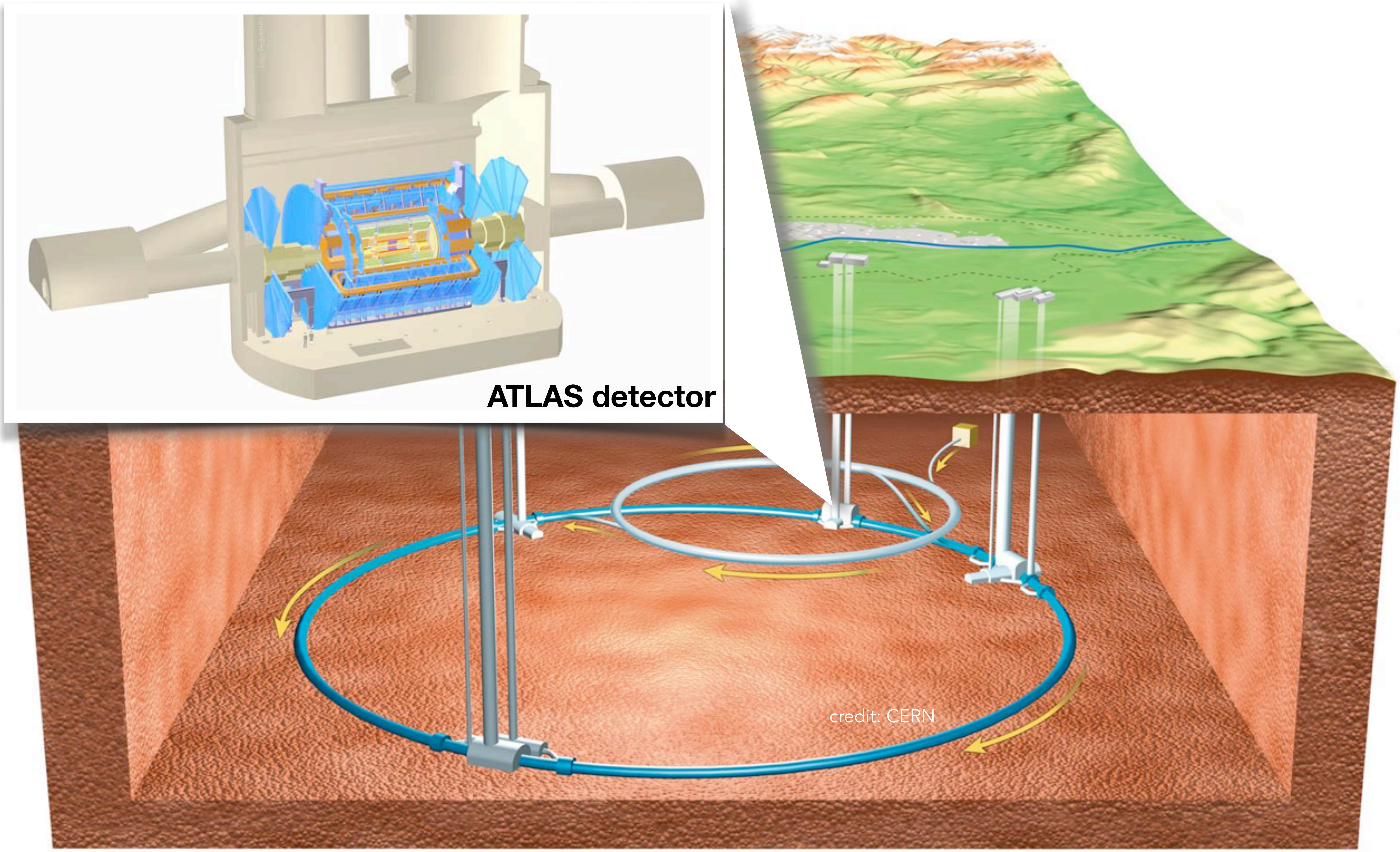


The Large Hadron Collider at the CERN laboratory

- Highest energy collider in the world!
- Proton-proton collisions at center-of-mass energy of 14 TeV
- Began operation in 2010
- 2800 bunches per beam, 150 billions protons per bunch
- > 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

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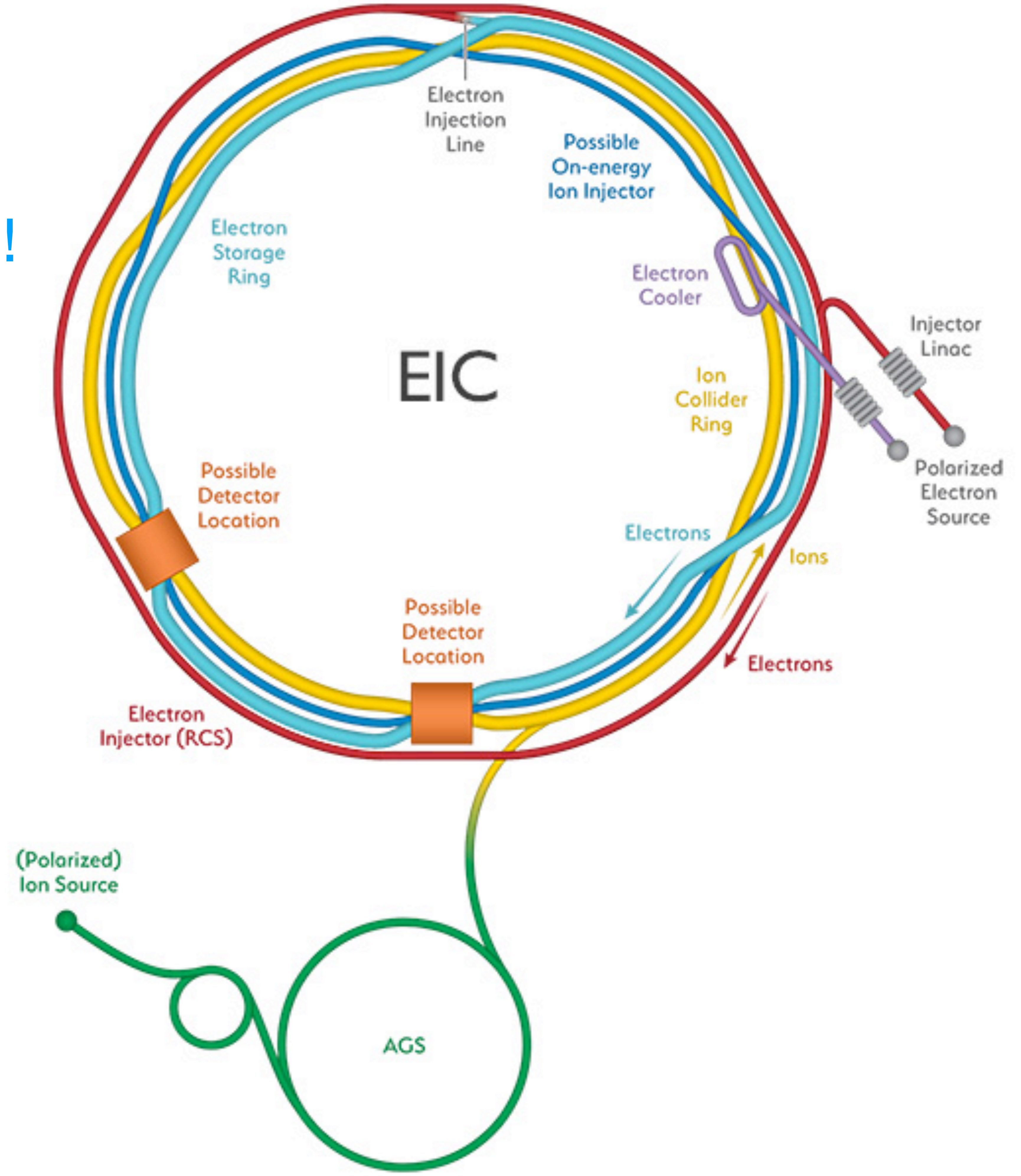
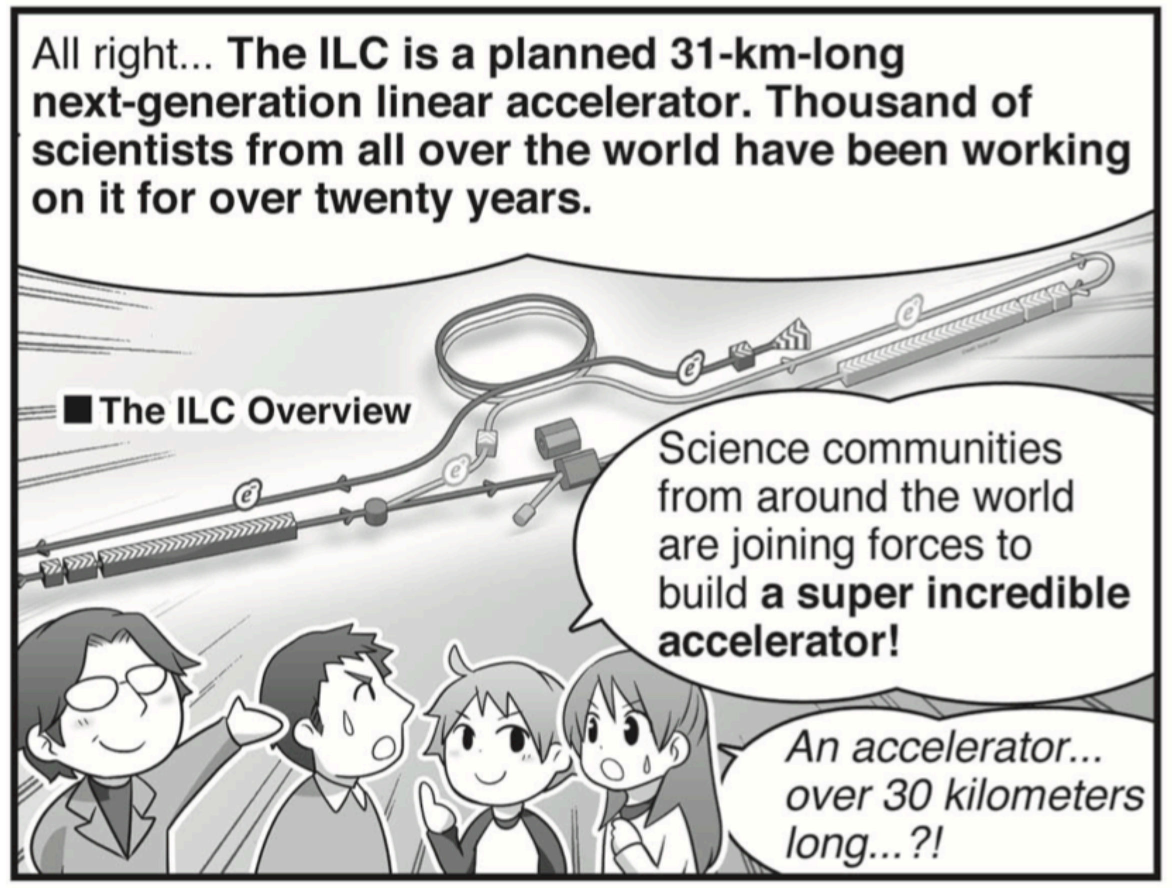
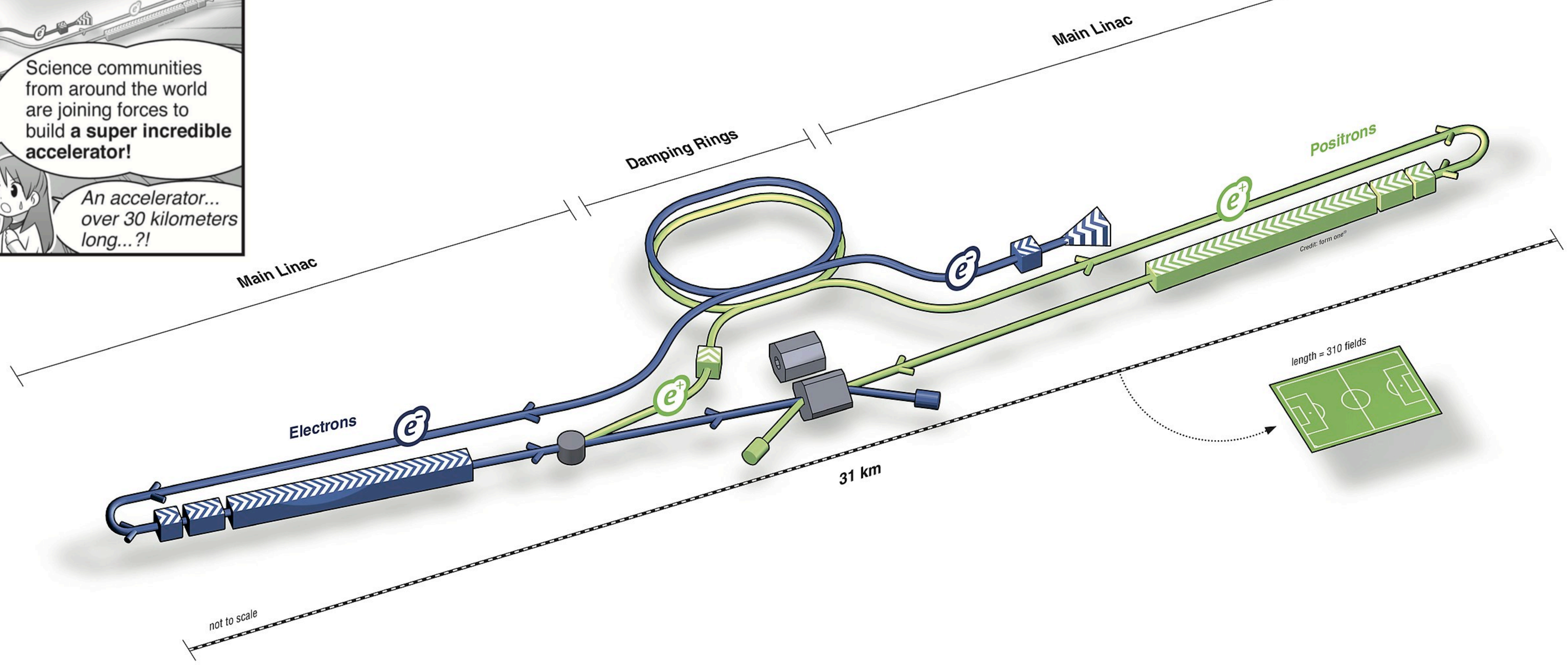
You are here
2010
2020
2030
2040
2050
2060
2070
LHC
High Luminosity - LHC

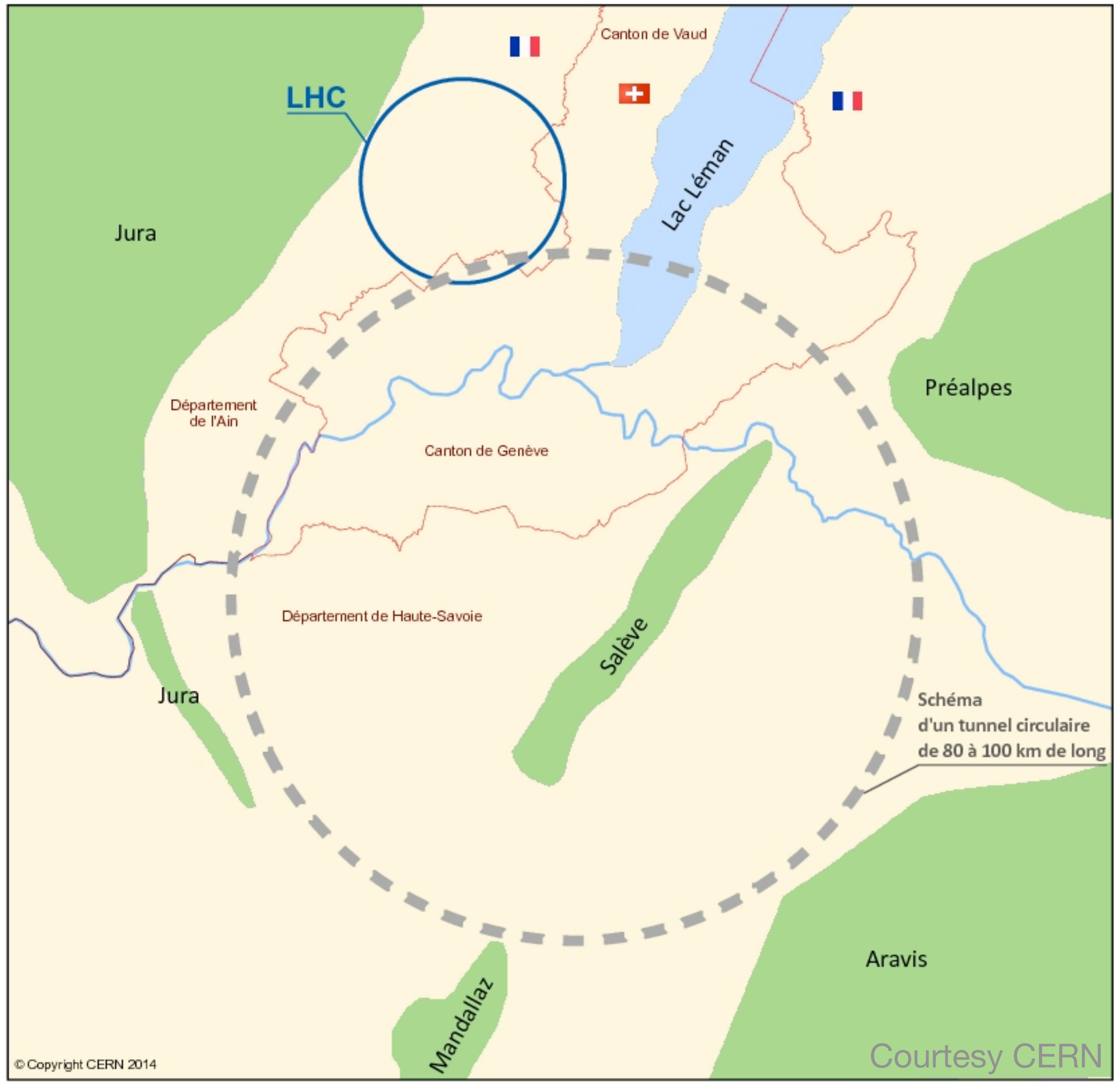
- The EIC will be the only electron-nucleus collider operating in the world!
- High luminosity: $10^{33} - 10^{34}\ cm^{-2}s^{-1}$
- Large centre-of-mass energy range: $20 - 140\ GeV$
- Polarized beams
- Large range of ion species
- Physics:
  - 3D structure of protons and nuclei
  - Proton spin
  -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







Courtesy KEK



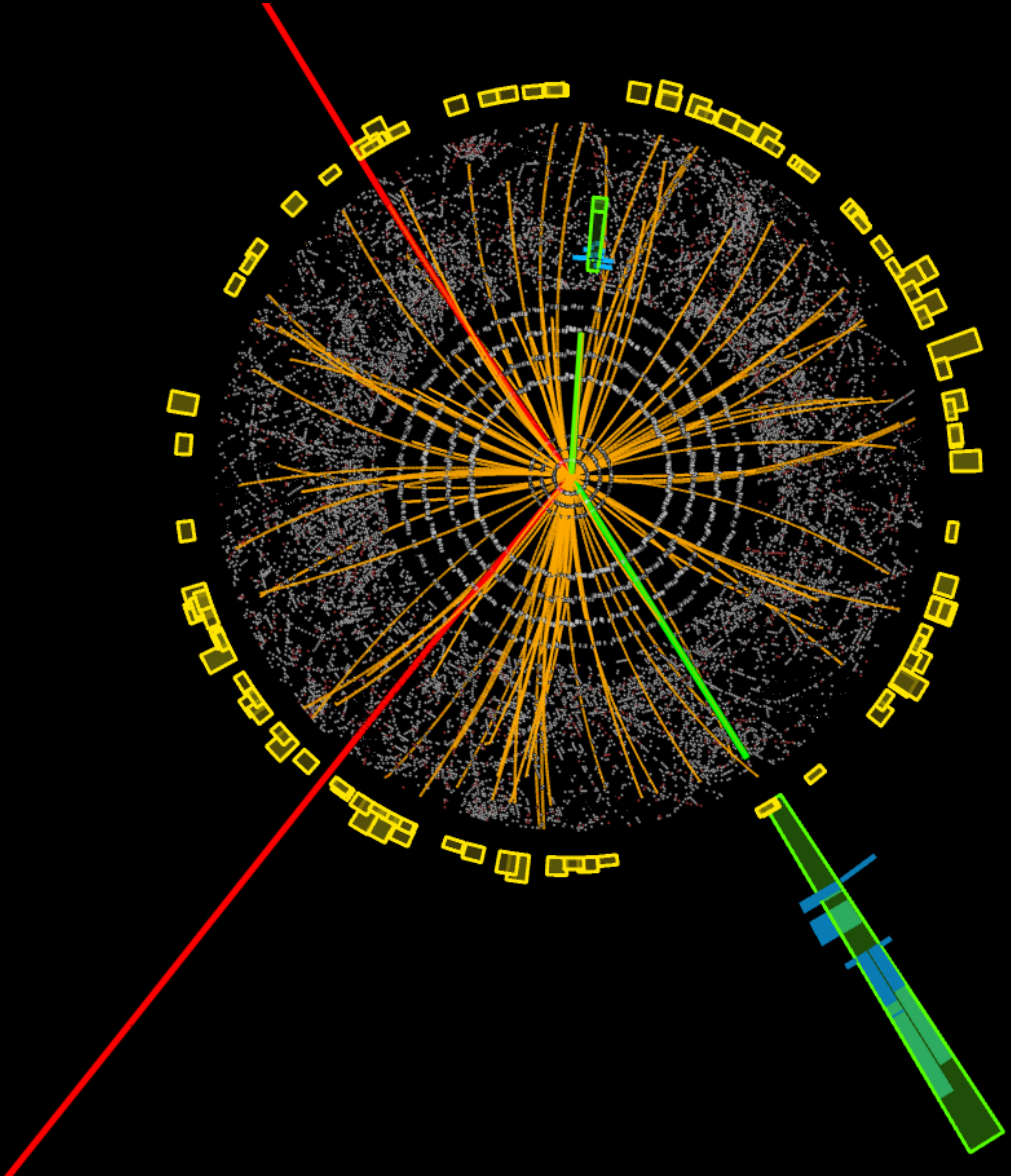
- Collider circumference of 100 km
- Proton-proton collisions at 100 TeV

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.

Come and join us!

Questions?



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