Radiofrequency (RF) Systems at CERN

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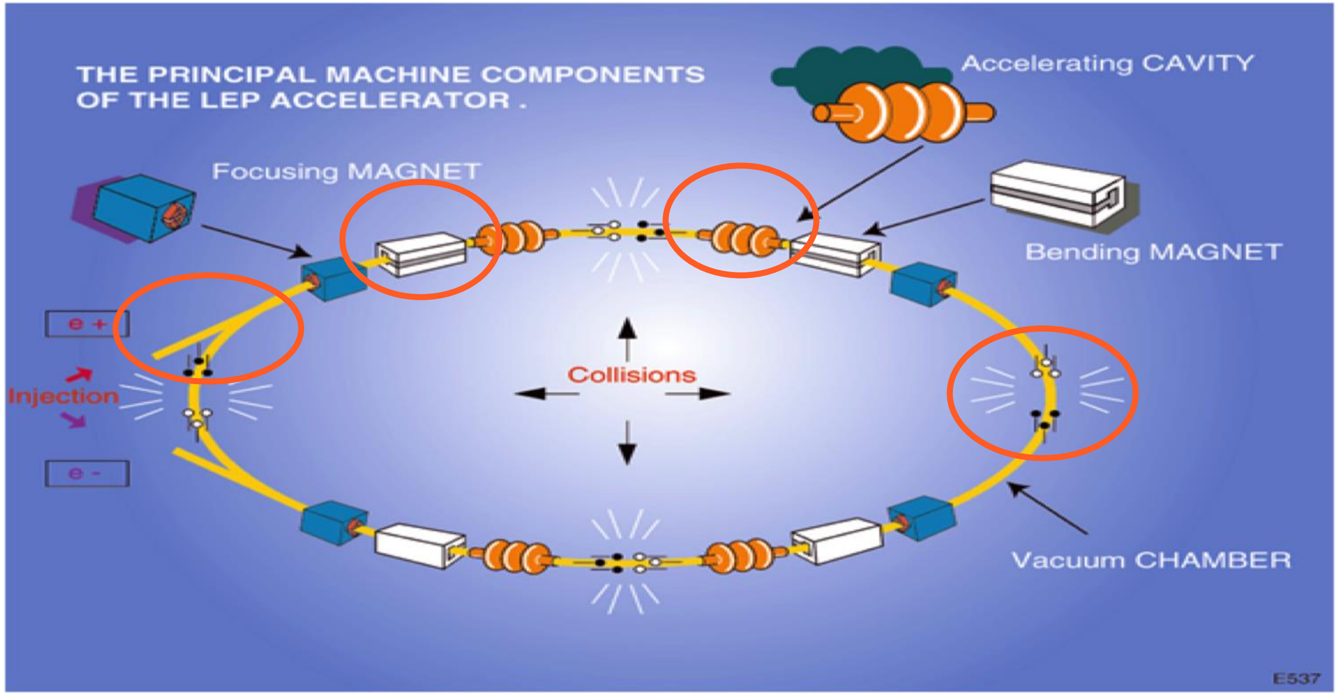
Content

- Introduction to accelerators
- Role of radio-frequency (RF) systems in accelerators?
- Specific technologies, challenges, needs and perspectives
- Summary

What is a Particle Accelerator?

- Provides a beam of energetic particles
- Employs a vacuum chamber in which the particles travel
- Employs magnetic fields to steer and focus the beam
- Employs electric fields to accelerate the particles – radio-frequency
- Makes collisions either against a fixed target, or between two beams of particles



Radio-frequency is a key technology needed for building and exploiting accelerators

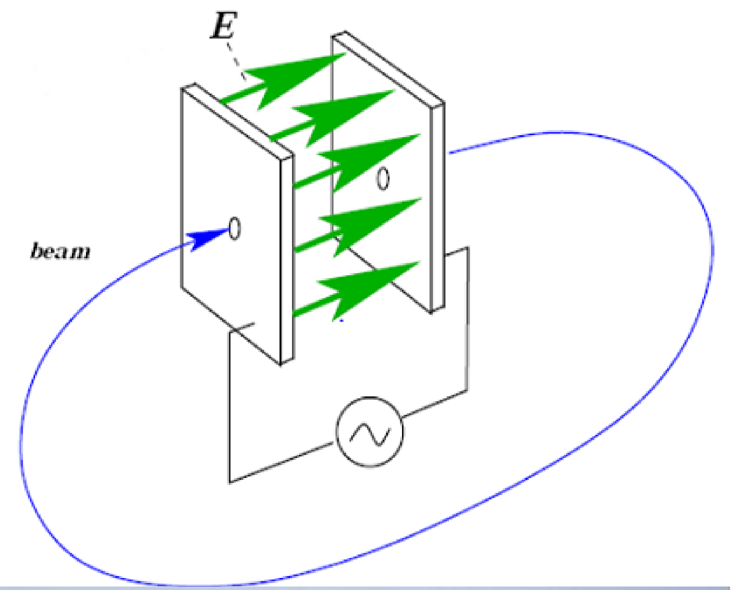
Particles accelerators around the world

- There are more than 30,000 accelerators in operation around the world
- Multi-talented machines[1]:
  - particle physics research: “Particle accelerators are the closest things we have to time machines”, Stephen Hawking
  - creating tumour-destroying beams
  - killing bacteria, sterilizing medical devices
  - developing better materials
  - helping scientists improve technologies (e.g. fuel injection systems)

Research accelerators is the place where the technology for all other accelerators is developed

[1] Witman, Sarah. "Ten things you might not know about particle accelerators". Symmetry Magazine. Fermi National Accelerator

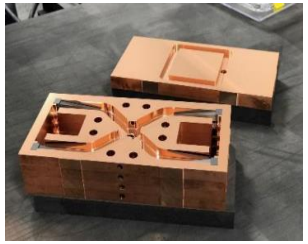
Why radio-frequency?

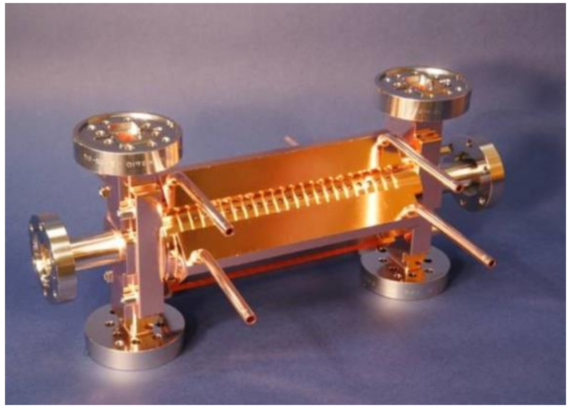


- Electric fields are used to speed up and increase the energy of a beam of particles
- Electromagnetic resonators (RF cavities) are used to reach very high accelerating gradients -> up to tens of megavolts per meter
- Each time a beam passes the electric field in an RF cavity, some of the energy from the radio wave is transferred to the particles (~10 kHz up to ~12 GHz)

  - RF Power
  - Gradient (cavities)
  - Control (timing & synchronisation)

Example of normal-conducting RF cavities:





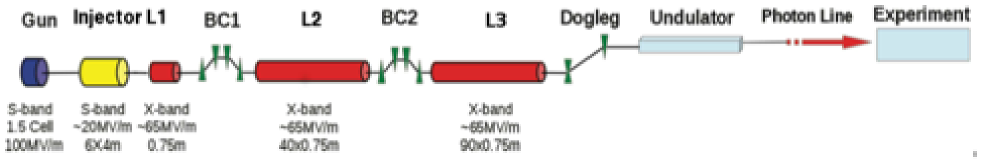
X-band high gradient accelerating structures

- **Developed for the Compact Linear Collider (CLIC) project - a proposed multi-km long accelerator (https://clic.cern/)**
- **The design and technologies are focused on increased acceleration and energy efficiency**
- **Key technology: 100 MV/m accelerating cavities, operating at 12 GHz**
  - **Ultra-precision machining (mechanical tolerances of < few µm)**
  - **Turning and milling**
  - **Strict qualification & CMM metrology (coordinate measuring machine)**
  - **Assembly: Cu diffusion bonding, brazing, EB welding**
  - **Micron-precision alignment discs (~10 µm with ~ 26 discs)**
- **Today, there are only few companies in Europe, which can produce disks/structures (VDL (NL), LT-ULTRA (D), Egile (SP))**

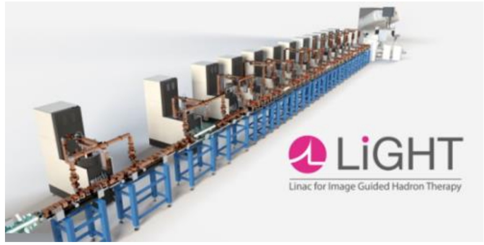
CLIC would need ~200'000 cavities

CLIC technology: a wide range of application

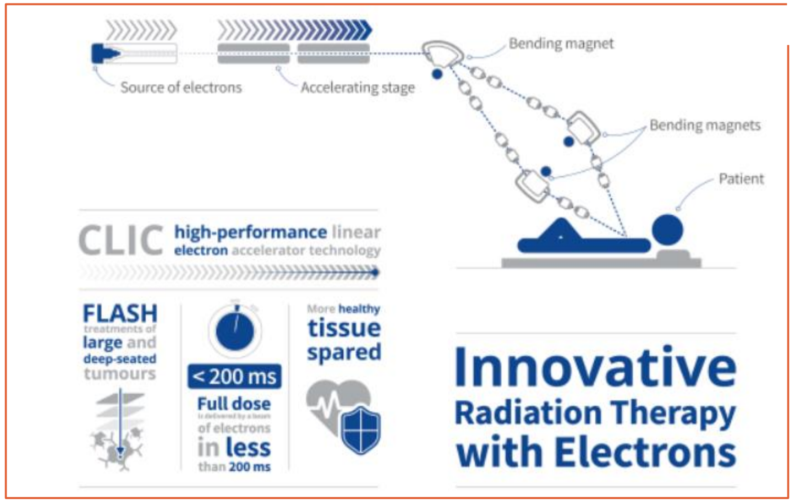
Inverse Compton Scattering Sources



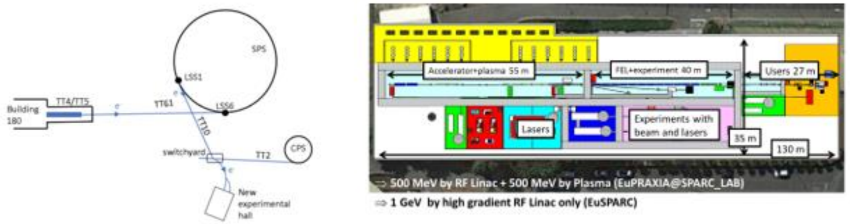
X-Ray Free-Electron Lasers (XFEL)



Proton Beam Therapy



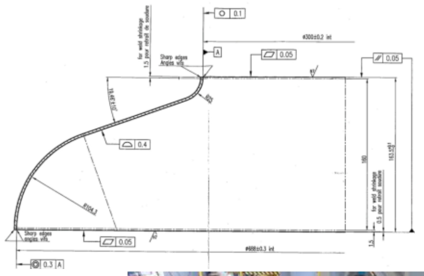
FLASH Radiotherapy

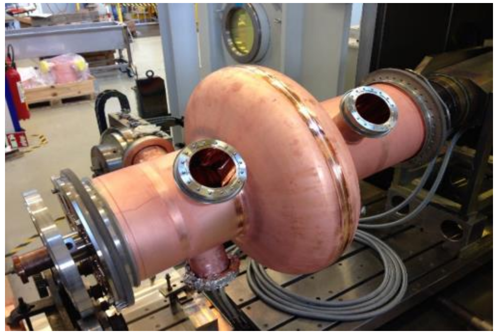


GEV-Range Research Linacs

Very promising for medical accelerators

Example of superconducting RF cavities:





Bulk Nb or Nb/Cu
elliptical cavities

- Based either on copper with a Nb coating, or made out of bulk Niobium
  - High purity base material: 3D-forged OFE copper, high-purity Nb
  - Production of copper “half cells”, ⌀ ~700 mm with tight tolerances (e.g.: parallelism =50 µm, shape accuracy =0.4 mm)
    - Deep drawing, spinning, hydro-forming, + internal electron-beam welding
  - Removal of surface damage layer (100-200 µm) by chemistry (electro-polishing)
    - Final surface roughness ~0.1 - 0.2 µm.
  - Need VERY HIGH quality Nb coating (few µm)
- Prototyping is typically done at CERN, then the technology is exported to industry
- Today, there are only 2 companies in Europe, which can manufacture complete bulk Nb cavities (Zanon (I), RI (D))

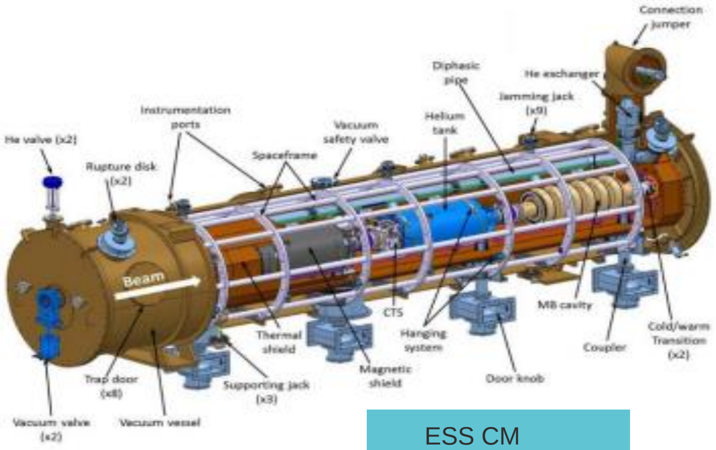
Seamless & cost-efficient technique would be used for thousands of cavities in institutes all over the world (LHC, ILC, ESS, CERN FCC)

(http://cern.ch/fcc)

Production of cryomodules (CM)

- **Superconducting cavities must be housed in complex, state-of-the-art helium-cooled CM (operating temperatures 1.6 K to 4.5 K)**
- **Large variety of CM designs, many common features:**
  - **Integration and simulations studies**
  - **Vacuum vessel with thermal and magnetic shielding**
  - **Cold mass supporting system, alignment, tuning system, cryostat & piping**
  - **Beam vacuum gate valves, pressure relief devices**
  - **Instrumentation and cables (RF, temperature, pressure)**
  - **RF power couplers, HOM couplers**
- **Manufacturing of mechanical parts and assembly (mostly done in clean rooms) are usually subcontracted to external companies**

LHC CM

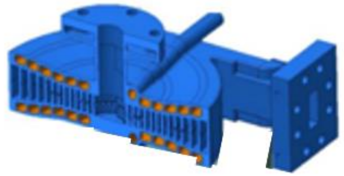


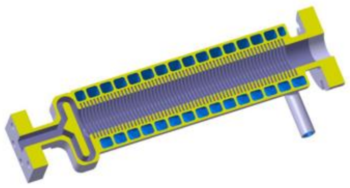
ESS CM

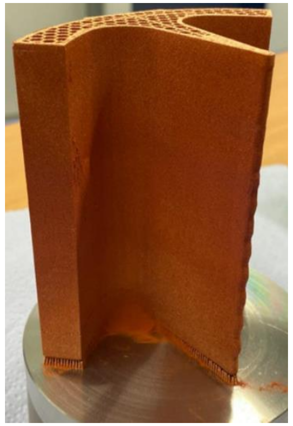
All major scientific projects require tens or even hundreds of cryomodules

Metal additive manufacturing

- Part of the European IFAST project (Innovation Fostering in Accelerator Science and Technology) (https://indico.cern.ch/event/1133254/)
- Covers all domains:
  - Vacuum, diagnostics, cooling, cryogenics,…
  - RF (some examples):
    - CLIC RF spiral & compact load (titanium)
    - Higher order mode couplers (niobium)
    - OFE-Cu RFQ ¼ sector (Fraunhofer IWS, Rosler IT, Riga TU)
- Important efforts are aimed at:
  - Optimizing the metal powder production/quality
  - Improving the material density, roughness, and accuracy
  - Improving the surface finishing (micro-mechanical polishing)



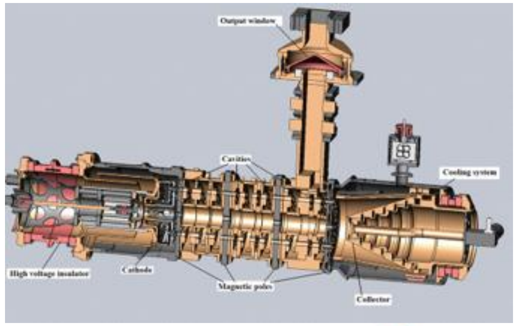


The activity for accelerator components ~ doubles every year

Courtesy: A. Grudiev, P.Trubacova, R. Gerard, T. Torims (TU/CERN)

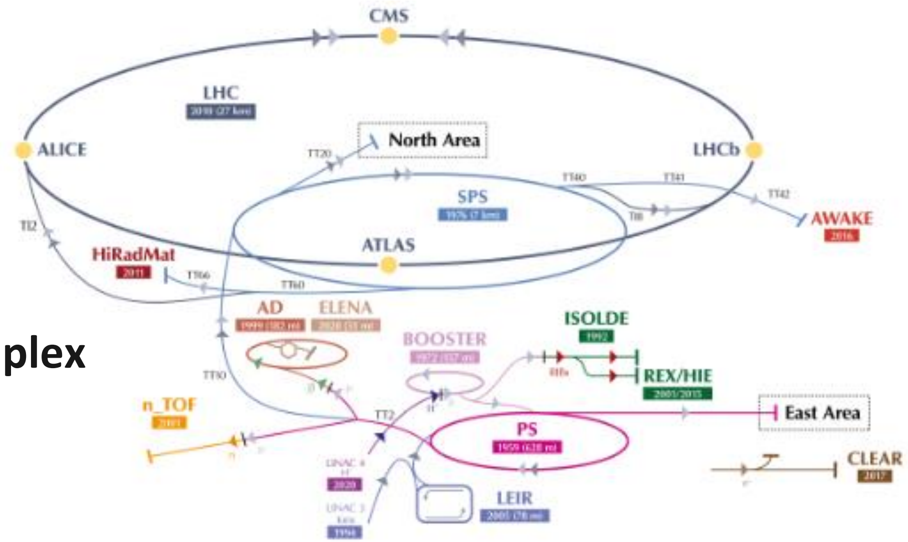
RF power amplifiers

- Higher energy efficiency (HE) power systems is a must for all machines
- Impressive CERN-driven progress in High Efficiency Klystron technologies in recent years
  - Large efforts to demonstrate > 80% efficiency (~20% improvement)
  - Klystrons are needed for ‘all’ high RF power & high frequency systems
  - Thales (France) is the only European supplier for high-power klystrons (not yet in x-band)
- Strong demand for solid-state high-power pulse modulators and RF systems
  - Europe is by its break-through technology a world leader
- Solid state amplifiers are the go-to for many accelerator power systems, incl. FCC
  - Examples: SOLEIL 4×190kW 352 MHz, SPS 32×135kW 200 MHz



Continuous demand for new HE RF power sources (incl. replacement of obsolete technologies)

Controls systems



- Continuous need for upgrades or new developments for the accelerator complex
- "Industrial" solutions:
  - VMEbus Crates + power supplies + remote management
  - Industrial PCs: ~ 750 operational IPCs for the on-line control of the complex
  - High-performance server platforms (Quads) and storage devices for the Data Center
  - µTCA based developments

- "CERN-born" technologies (mostly open-source design - see https://www.ohwr.org)
  - White Rabbit: high performance timing system provides sub-nanosecond synchronization -> used worldwide

Dynamic adaptation and customization of fast-changing technologies

Typical Low-level RF board for LHC

Summary

- **Accelerator technology typically demands (very) long R&D phases**
- **The technology advances are then often used for industrial/medical applications**
  - **Example: Deep Electron FLASH Therapy market could represent tens of machines per year (> ½ billion €)**
- **Experience show that companies involved on prototyping or small series, are often in a prime place once technologies go industrial**
- **The maintenance and upgrade of the existing CERN accelerator complex requires continuous contact with leading-edge industries of many types**
- **The future CERN project (FCC) would need respectively ~1000 cavities and hundreds of RF power systems over a 20 year period, <u>starting ~2030</u>**
- **CERN is actively promoting technology transfer to industry with its Knowledge Transfer (KT) group**

Many thanks for your attention