



Radiofrequency (RF) Systems at CERN

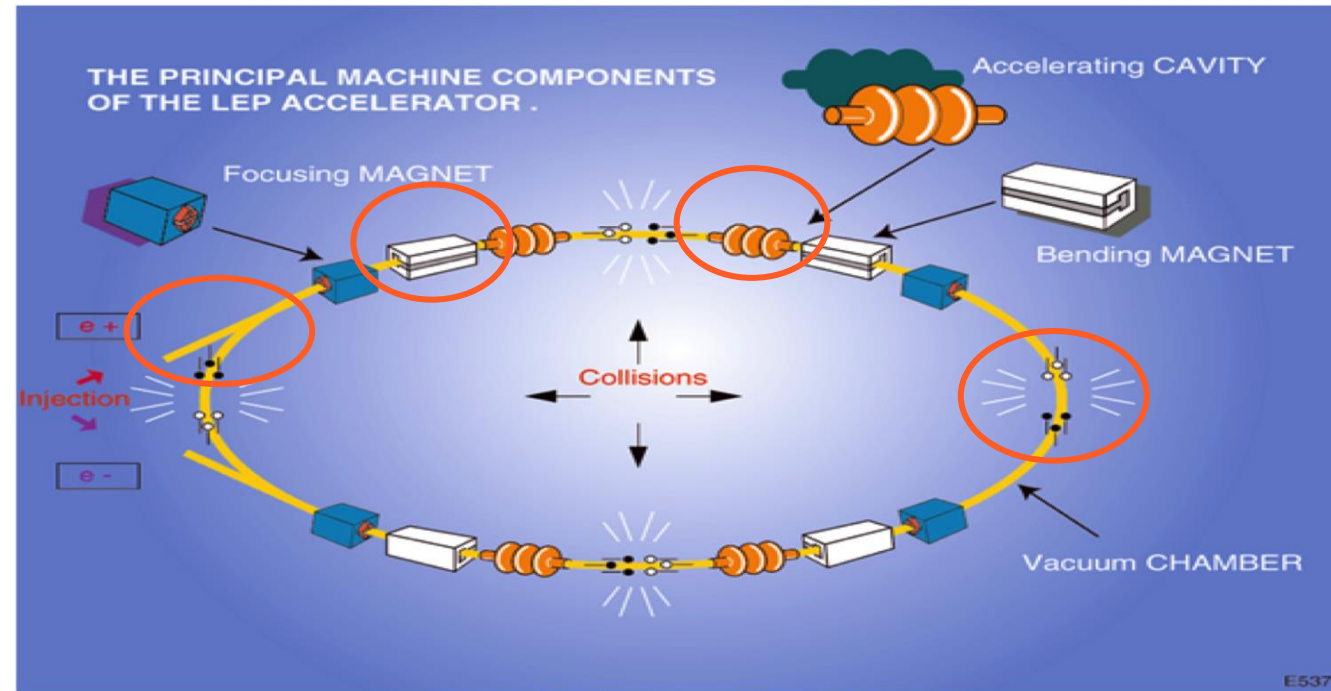
Olivier Brunner for the CERN RF Group
BSBF 4-7 October 2022, Granada

Content

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

What is a Particle Accelerator?

- Provides a beam of energetic particles to study the structure of matter
- 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

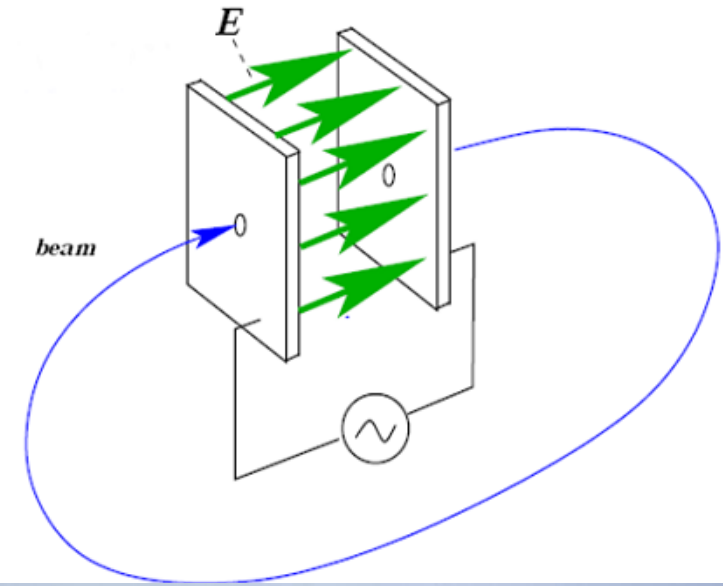
- There are more than 30,000 accelerators in operation around the world
- Multi-talented machines¹⁾:
 - particle physics research: “Particle accelerators are the closest things we have to time machines”, Stephen Hawking
 - creating tumour-destroying beams (e.g. FLASH therapy)
 - killing bacteria, sterilizing medical devices
 - developing better materials
 - helping scientists improve technologies (e.g. fuel injection systems)



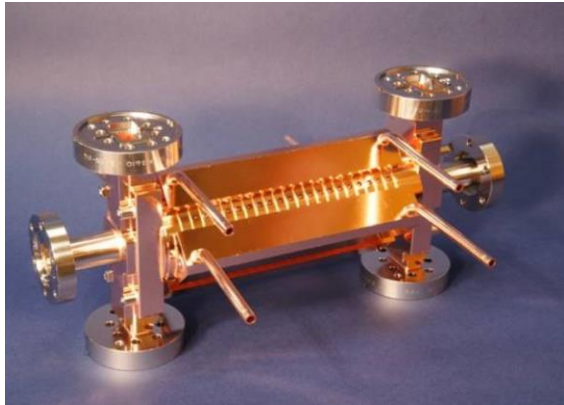
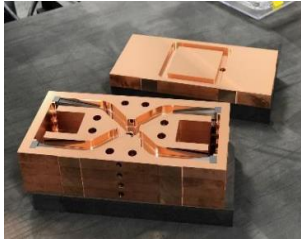
Research accelerators is the place where the technology for all other accelerators is developed

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) at frequencies between ~ 10 kHz up to ~ 12 GHz
- 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
 - **RF Power**
 - **Gradient (cavities)**
 - **Control (timing & synchronisation)**



Example of normal-conducting RF cavities developed for large accelerators (CLIC)



X-band high gradient accelerating structures

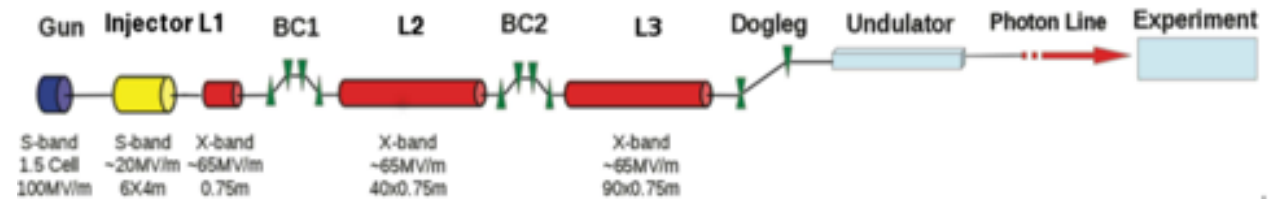
- The Compact Linear Collider (CLIC) is a proposed multi-km long accelerator that is being designed as an addition to CERN's accelerator complex (<https://clic.cern/>)
- The design and technology developments are focused on reduced cost, and increased acceleration and energy efficiency
- Key technology: 100 MV/m accelerating gradients cavities, operating at 12 GHz
 - Diamond tool 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 ($\sim 10 \mu\text{m}$ with ~ 26 discs)

Very promising for medical accelerators (FLASH therapy)

X-band and high gradient applications overview



Inverse Compton Scattering Sources



X-Ray Free-Electron Lasers (XFEL)

CLIC high-performance linear electron accelerator technology

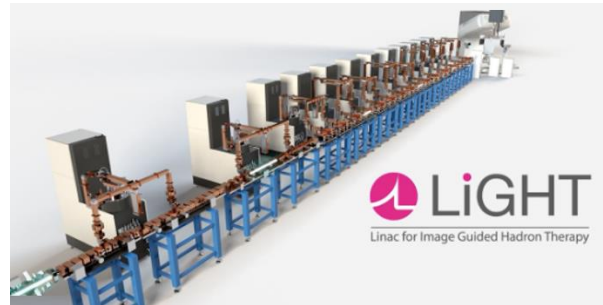
FLASH treatments of large and deep-seated tumours

More healthy tissue spared

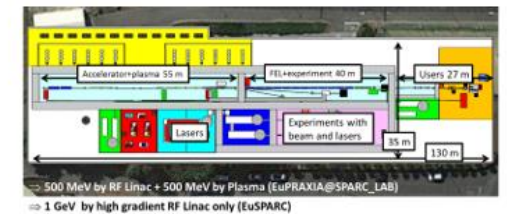
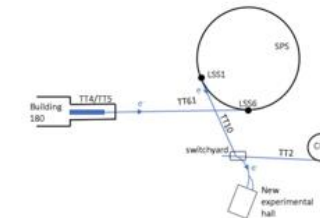
Innovative Radiation Therapy with Electrons

Full dose of electrons in less than 200 ms

FLASH Radiotherapy



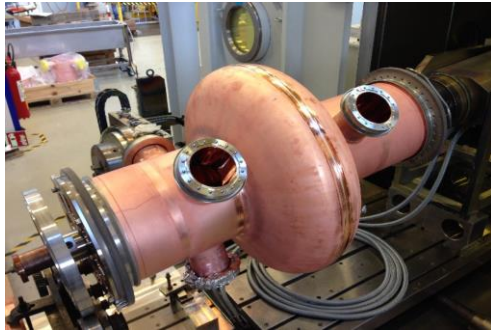
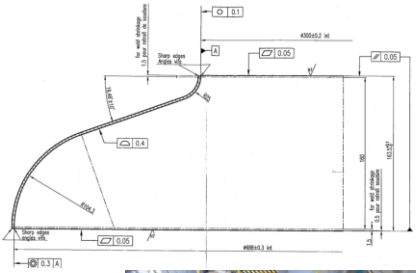
Proton Beam Therapy



GEV-Range Research Linacs

Courtesy: W. Wuensch

Example of superconducting RF cavities developed for (large) particle accelerators



Bulk Nb or Nb/Cu
elliptical cavities

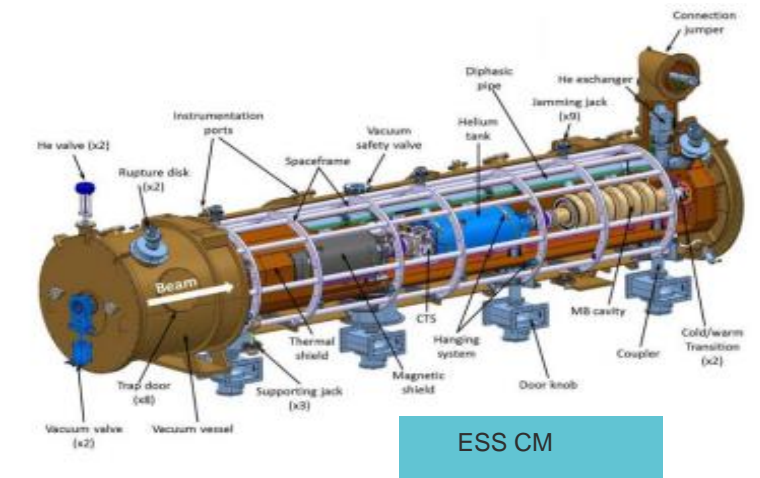
- Based either on copper with a Nb coating, or made out of bulk Niobium
 - Highly pure base material: 3D-forged OFE copper, high-purity Nb with RRR ≥ 300
 - Production of copper “half cells”, $\varnothing \sim 700$ mm with tight tolerances (e.g.: parallelism = 50 μm , shape accuracy = 0.4 mm)
 - Deep drawing, spinning, hydro-forming, + internal electron-beam welding
 - Removal of surface damage layer (100-200 μm) by chemistry (electro-polishing)
 - Final surface roughness $\sim 0.1 - 0.2 \mu\text{m}$.
 - 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, including surface chemistry and heat treatments.

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



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)



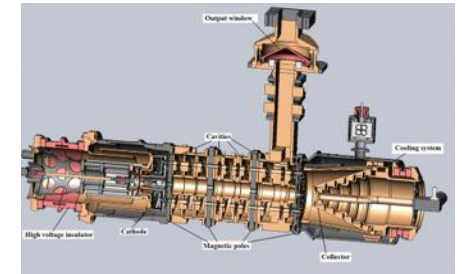
The activity for accelerator components ~ doubles every year

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

RF power amplifiers

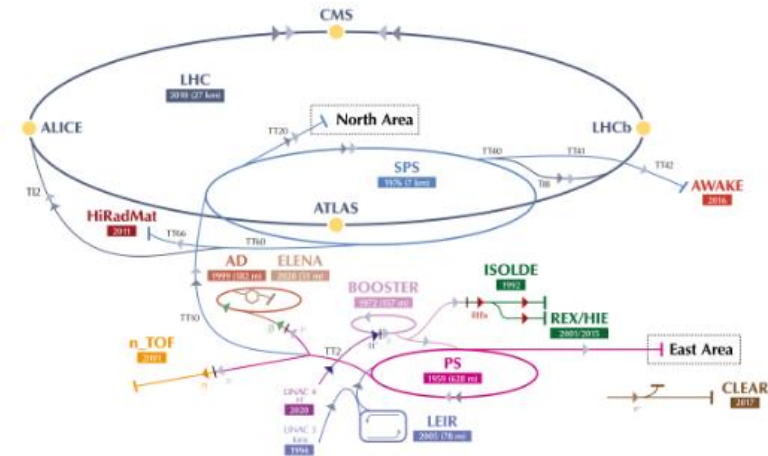
- Higher energy efficiency (HE) power systems is a must for all machines
- Impressive CERN-driven progress in High Efficiency Klystron technologies in recent years
 - Sustained efforts to demonstrate > 80% efficiency (~20% improvement)
 - Klystrons are needed for ‘all’ high RF power & high frequency 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
 - ScandiNova Systems AB (Sweden) is by its break-through technology a world leader
- Solid state amplifiers are the go-to for many accelerator power systems:
 - Examples: SOLEIL 4×190kW 352 MHz, SPS 32×135kW 200 MHz (w. Thales Gérac)

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
 - μ TCA 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



Typical Low-level RF board for LHC

Dynamic adaptation and customization of fast-changing technologies

Summary

- Accelerator technology typically demands (very) long R&D phases
- The technology advances are then often used for industrial/medical machines
 - 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 or CLIC) would need respectively ~1000 or ~200'000 cavities and hundreds of RF power systems over a 20 year period, starting ~2030
- CERN is actively promoting technology transfer to industry with its Knowledge Transfer (KT) group



Many thanks for your attention