Workshop on opportunities for Finnish Industry at CERN

- Radio Frequency Systems-

O. Brunner, SY-RF

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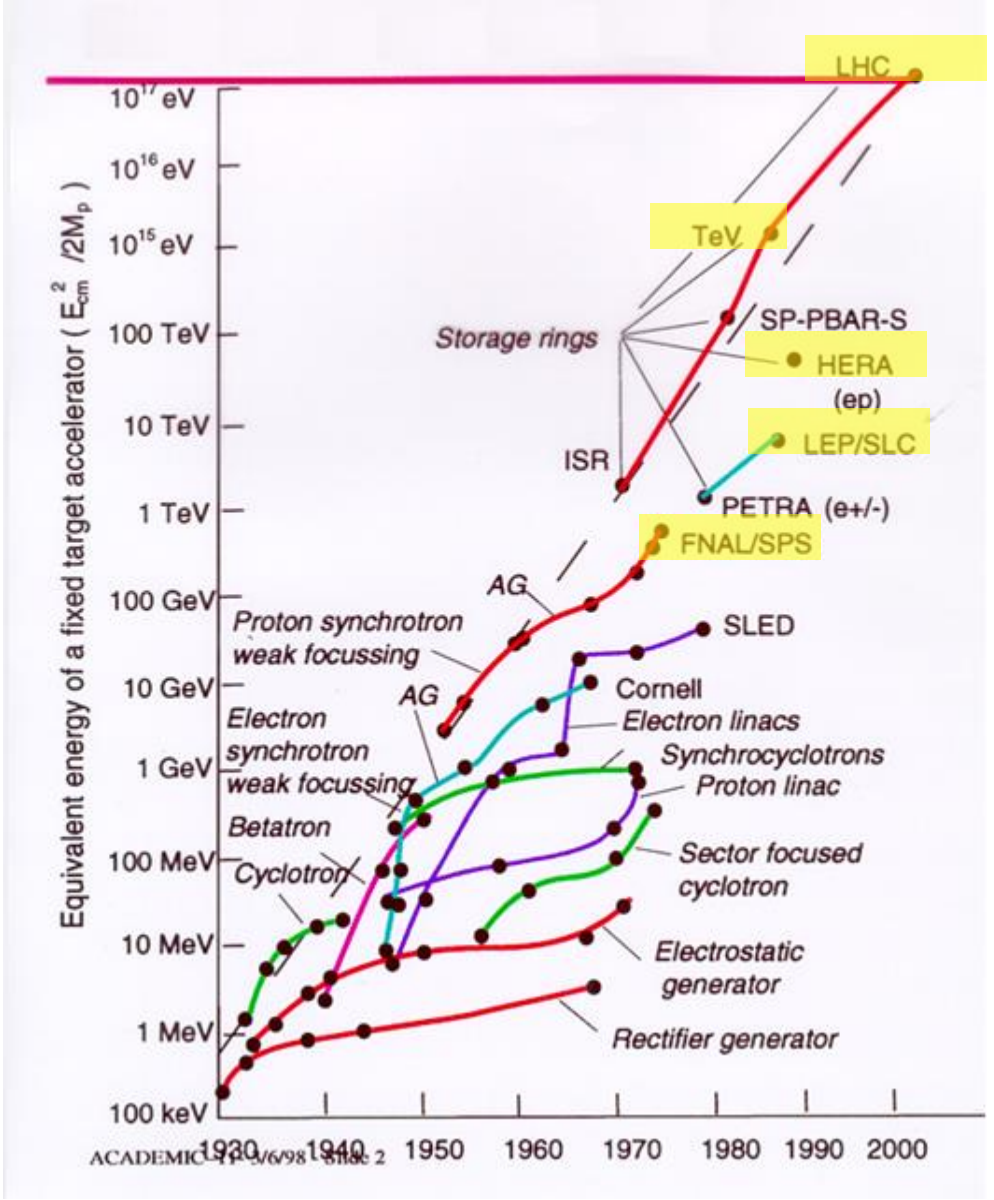
Content

- Introduction to accelerators
- Role of radio-frequency (RF) systems in accelerators?
- Components of a typical RF system
- Technologies, challenges and perspectives
- Summary

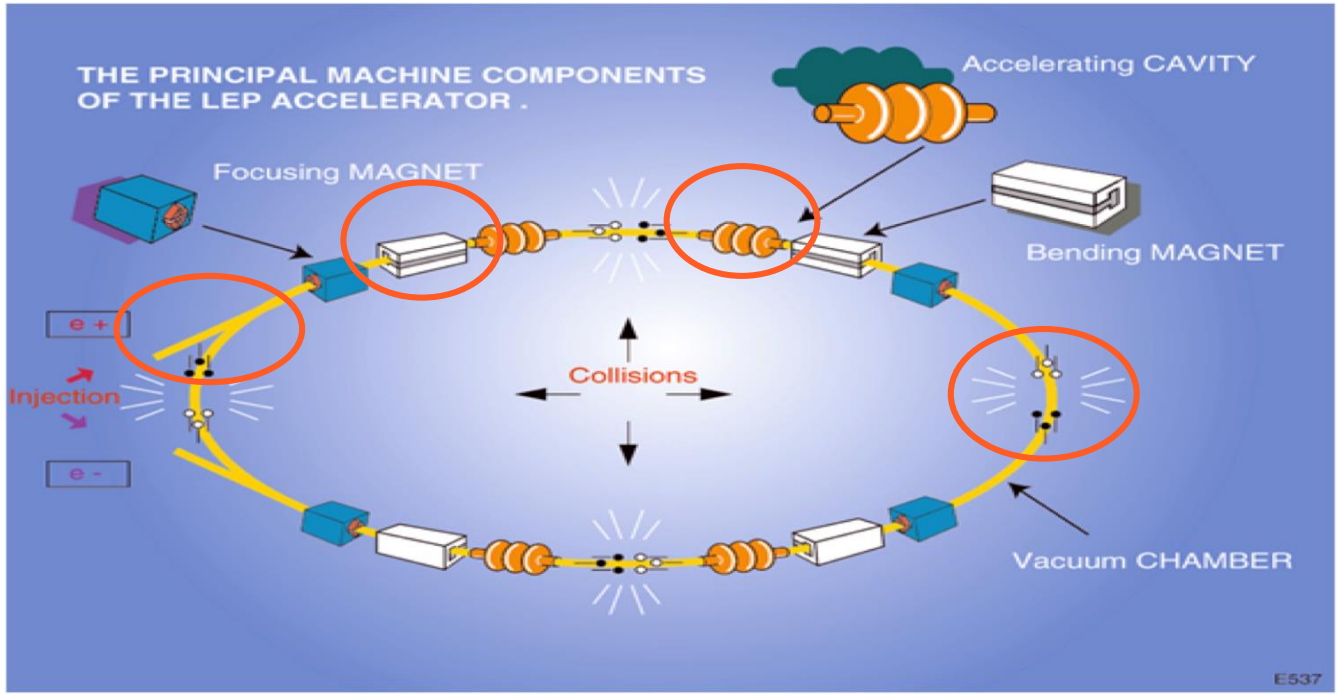
The history of accelerators

- Exponential development for almost 100 years
- In many cases accelerator needs have been the driving force behind new technologies
- Superconductivity, key technology of high-energy machines since the 1980s
- Accelerators are energy intensive: efficiency is a must to all future accelerator projects



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



Technologies needed for building and exploiting accelerators

- Civil engineering
- Survey, Geodesy
- Electrical distribution
- Cooling and Ventilation
- Cryogenics
- Magnets, room temperature and superconducting
- Power converters
- Ultra High Vacuum
- Radio Frequency, room temperature and superconducting
- Beam Diagnostics and Instrumentation
- Controls and Databases
- Beam feedback
- Injection, extraction… fast powerful kicker magnets
- Targets, dumps and collimators
- Electronics
- Large scale simulations
- Mechanical engineering
- Beam-materials science
- …

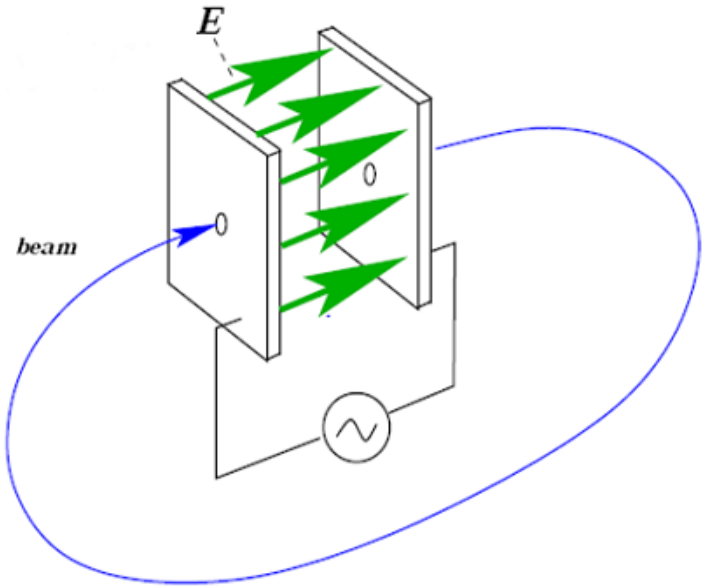
Particles accelerators around the world

- There are more than 30,000 accelerators in operation around the world [(1)]
- 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?



- Particle accelerators use <u>electric fields</u> to speed up and increase the energy of a beam of particles
- Electromagnetic resonators (RF cavities) allow to reach very high accelerating gradients (up to tens of megavolts per meter) at frequencies between ~10 kHz up to ~12 GHz
- RF cavities are located intermittently along the beam pipe
- 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

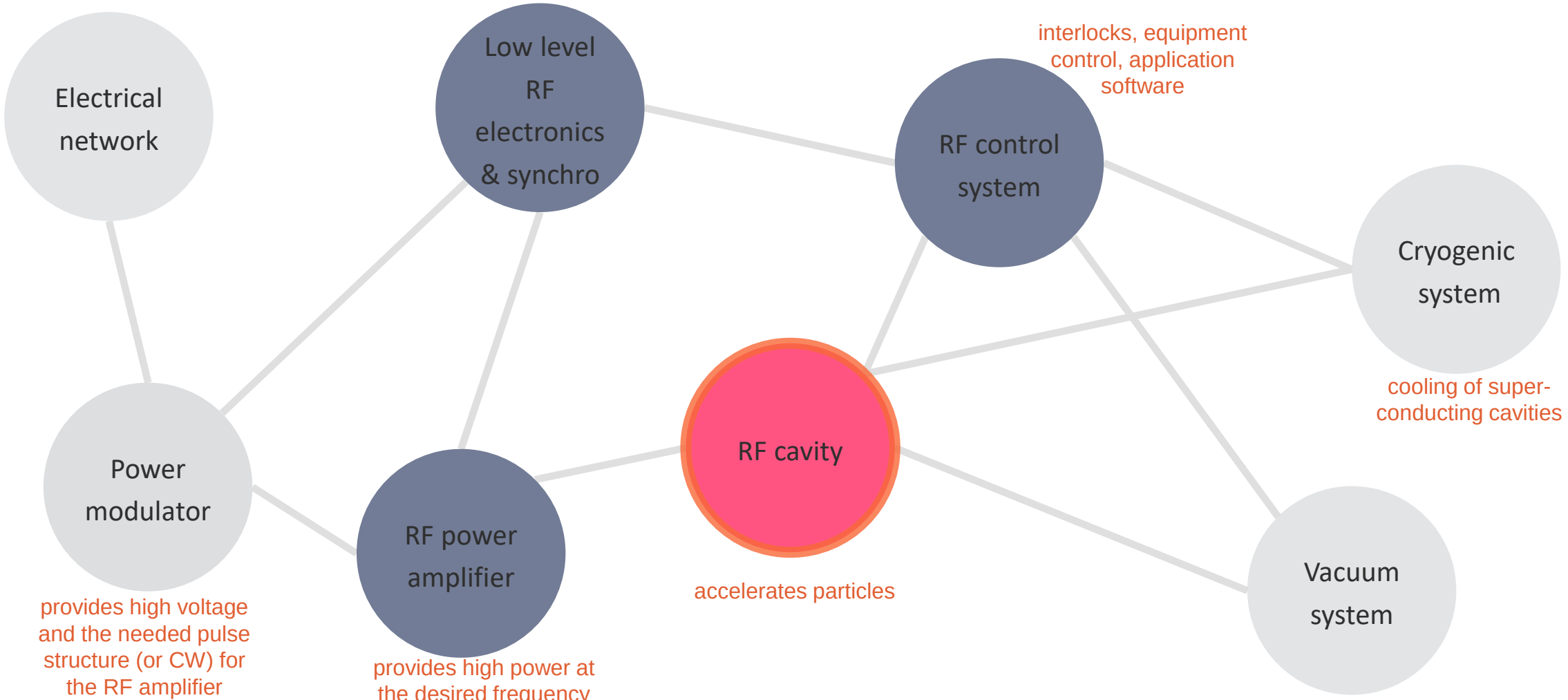
The synchronisation is crucial

Components of a typical RF system

accelerates particles

Courtesy: F. Gerigk

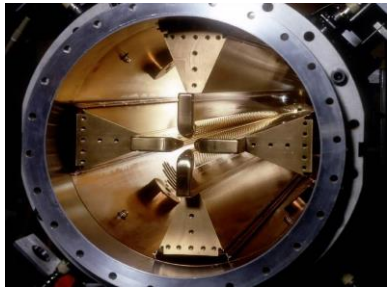
Components of a typical RF system



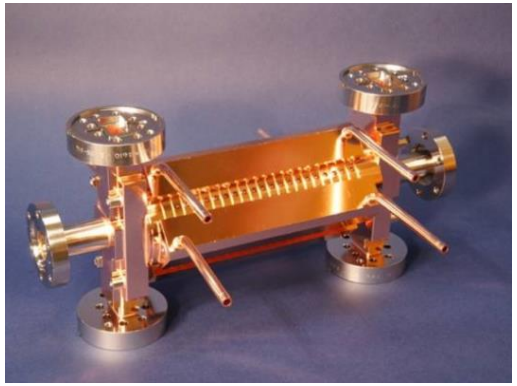
Courtesy: F. Gerigk

Example of RF cavities developed for (large) particle accelerators

Normal-conducting cavities



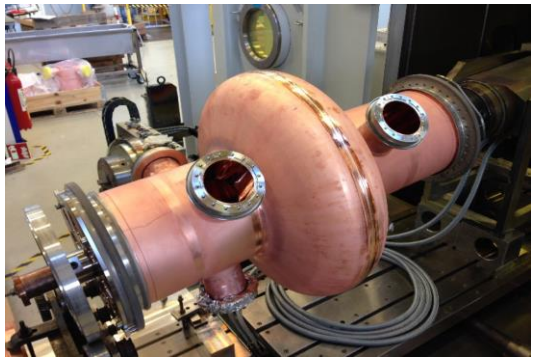

RF quadrupole
Drift tube linac



X-band high gradient accelerating structures

Also very promising for medical accelerators (FLASH therapy)

Superconducting cavities




Bulk Nb or Nb/Cu elliptical cavities


Exotic cavities: Bulk Nb crab cavities for LHC

Large scale projects (LHC, ILC, ESS, CERN FCC) need 100s or even 1000s accelerating cavities (http://cern.ch/fcc)

Technology challenges for superconducting cavities

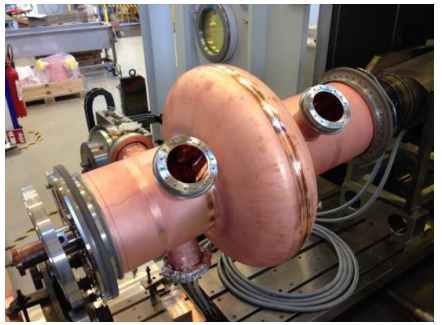
- Usually based either on copper with a Nb coating, or made out of bulk Niobium
- Prototyping is typically done at CERN, then the technology is exported to industry
- Today, there are only 2 companies in Europe, which can manufacture complete bulk Nb cavities, including surface chemistry and heat treatments. A few others can provide individual part only.

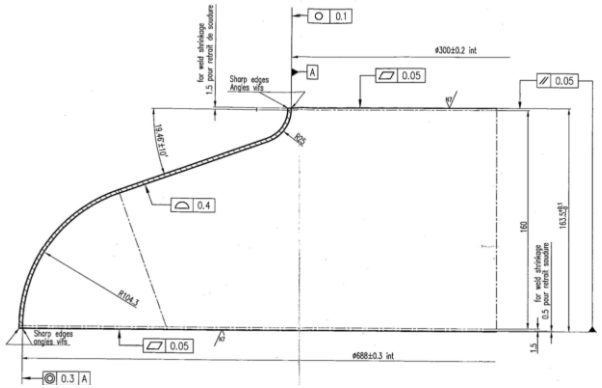
<u>Challenges:</u>

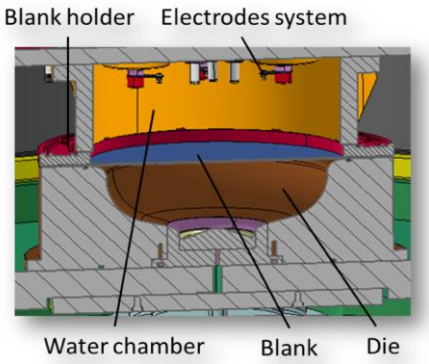
- Need VERY GOOD quality substrates:
  - Highly pure base material, 3D-forged OFE copper (tight specifications), high-purity Nb with RRR >=300.
  - No grinding on internal surfaces (exposed to RF fields). Tolerances ~10 - 100 µm.
  - Removal of surface damage layer (100-200 µm) by chemistry (buffered chemical polishing BCP, Electro-polishing EP)
  - Final surface roughness ~0.1 - 0.2 µm.
  - Full penetration electron-beam welds…
- Need VERY HIGH quality Nb coating (few µm)

Production of superconducting cavities

- Production of copper “half cells”, ⌀ ~700 mm with tight tolerances (e.g.: parallelism =50 µm, shape accuracy =0.4 mm)
  - Deep drawing (in the past)
  - Spinning (difficult but understood)
  - Electro-Hydro Forming : successful collaboration with BMAX (France)







Courtesy: BMAX

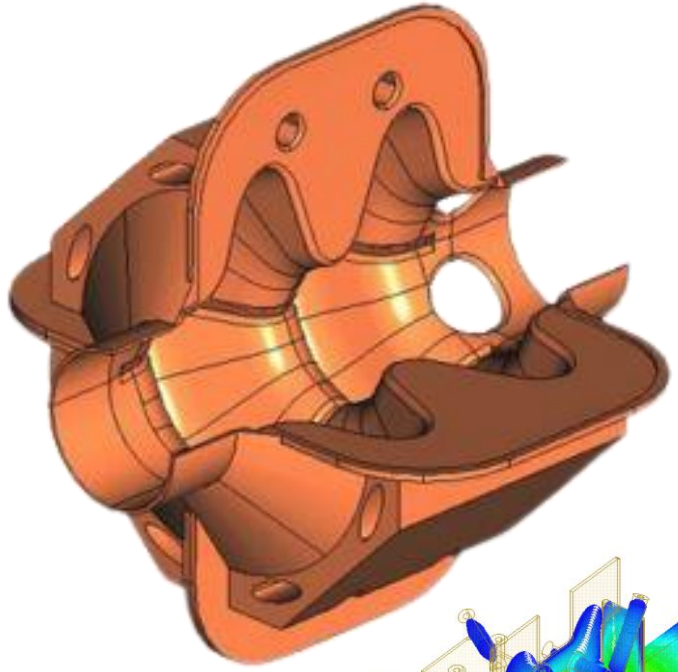
- Electron-Beam welding of half cells
- Smooth inner surface needed (in the past we welded from the inside, now full penetration from outside)
- Rolling and EB-welding of tubes, extrusion of ports, flanges…

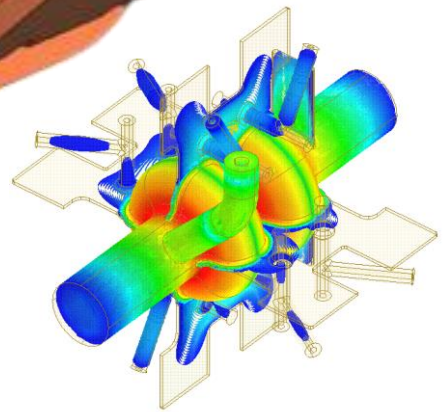
Seamless & cost-efficient technique would be used for thousands of cavities in institutes all over the world…

New CERN development for FCC

SWELL: Slotted Waveguide ELLiptical Cavity

- A 600 MHz elliptical cavity with 4 slots for strong higher order mode damping
  - Very attractive for all high current accelerators
- Fabrication & assembly:
  - Machining 4 quadrants out of bulk Copper
  - Nb coating of quadrants
- Engineering challenges: assembly (clamping), vacuum, tuning..
- Cooling: He channels are drilled into the bulk material: no more Helium tank!
- All around cavity that could replace most of the other cavities presently foreseen for the FCC-ee
- Prototyping at 1.3 GHz started



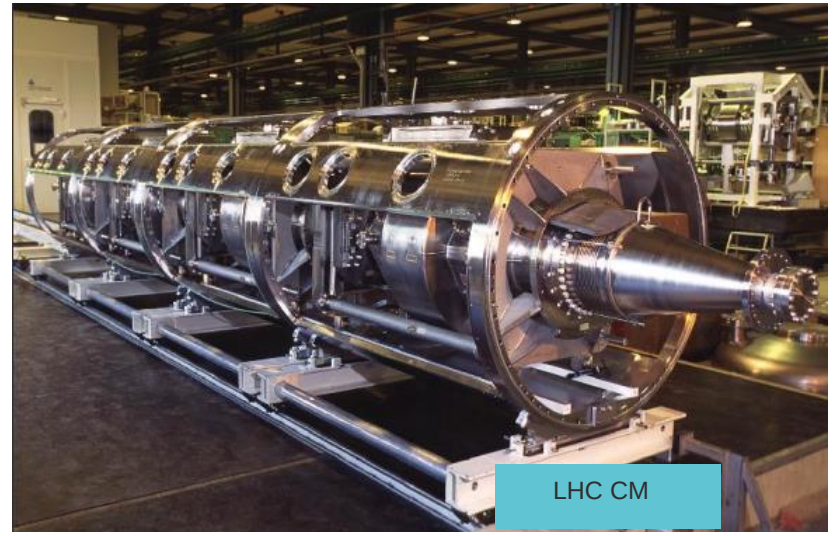


If successful the SWELL cavity would be used in many accelerators all over the world…

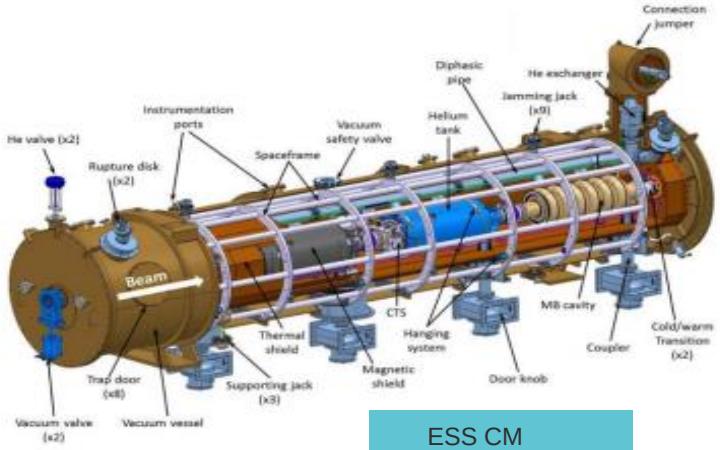
Courtesy: I. Syratchev, F. Peauger

Production of cryomodules (CM)

- SC 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



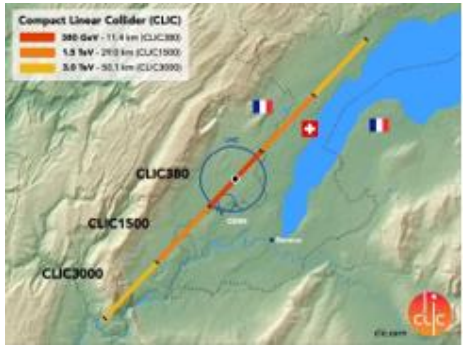
LHC CM



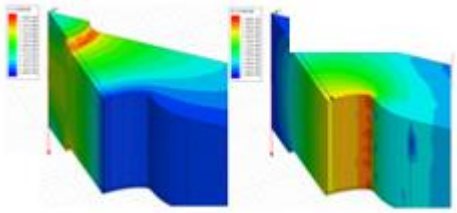
ESS CM

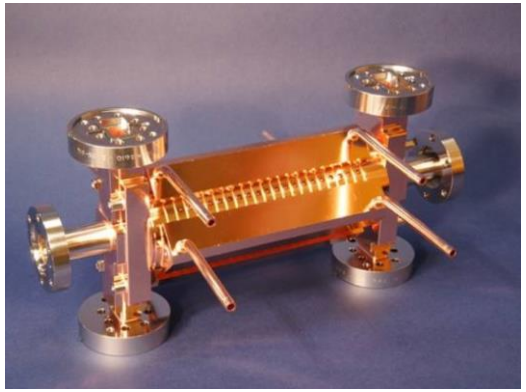
All major scientific projects require tens or even hundreds of cryomodules

X-band normal-conducting high gradient accelerating structures



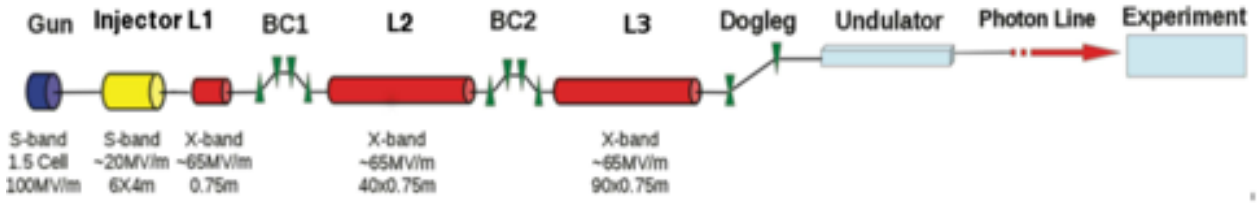
- The Compact Linear Collider (CLIC) is a proposed multi-km long accelerator that is being designed as an addition to CERN's accelerator complex (https://clic.cern/)
- The design and technology developments for CLIC focused on reduced cost, and increased acceleration and energy efficiency
- Contributed to the progress of highly accurate design simulation tools & competences
- Incorporates accelerating structures to produce accelerating gradients as high as 100 MV per metre, 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 (~10 µm with ~ 26 discs)



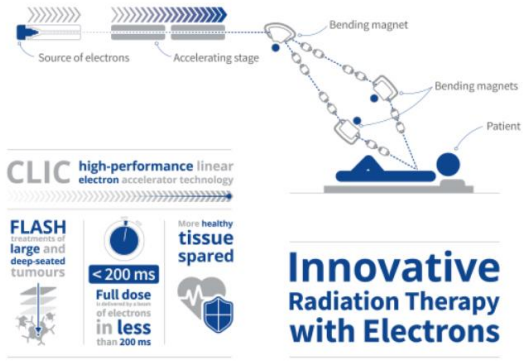


X-band and high gradient applications overview

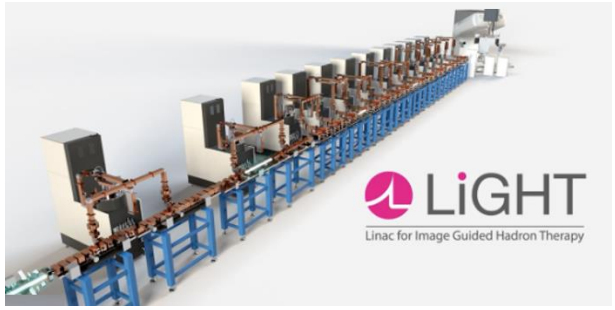
Inverse Compton Scattering Sources



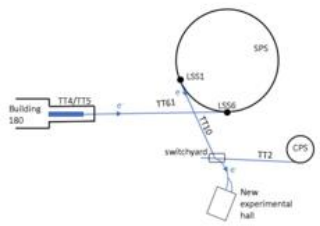
X-Ray Free-Electron Lasers (XFEL)

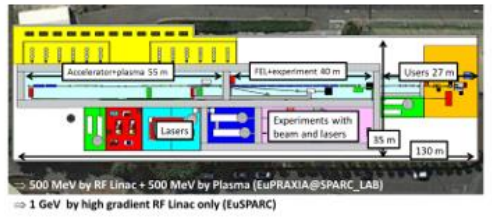


FLASH Radiotherapy



Proton Beam Therapy



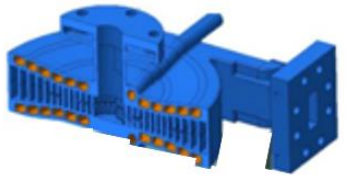


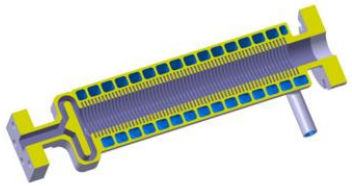
GEV-Range Research Linacs

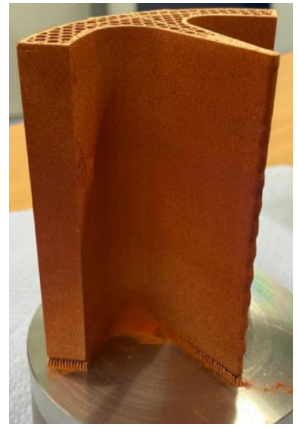
Courtesy: W.Wuensch

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)



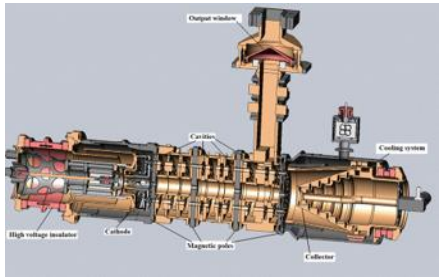


The activity for accelerator components ~ doubles every year

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)



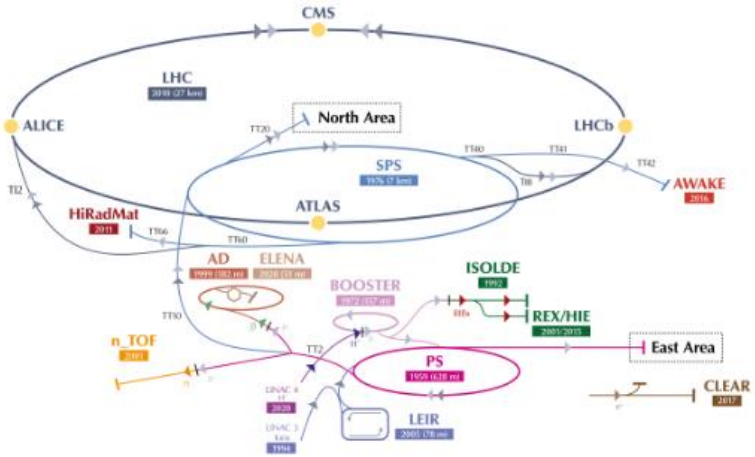
- Strong demand for solid-state high-power pulse modulators and RF systems
  - ScandiNova Systems AB (Sweden) is by its break-through technology a world leader

- 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
  - 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



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