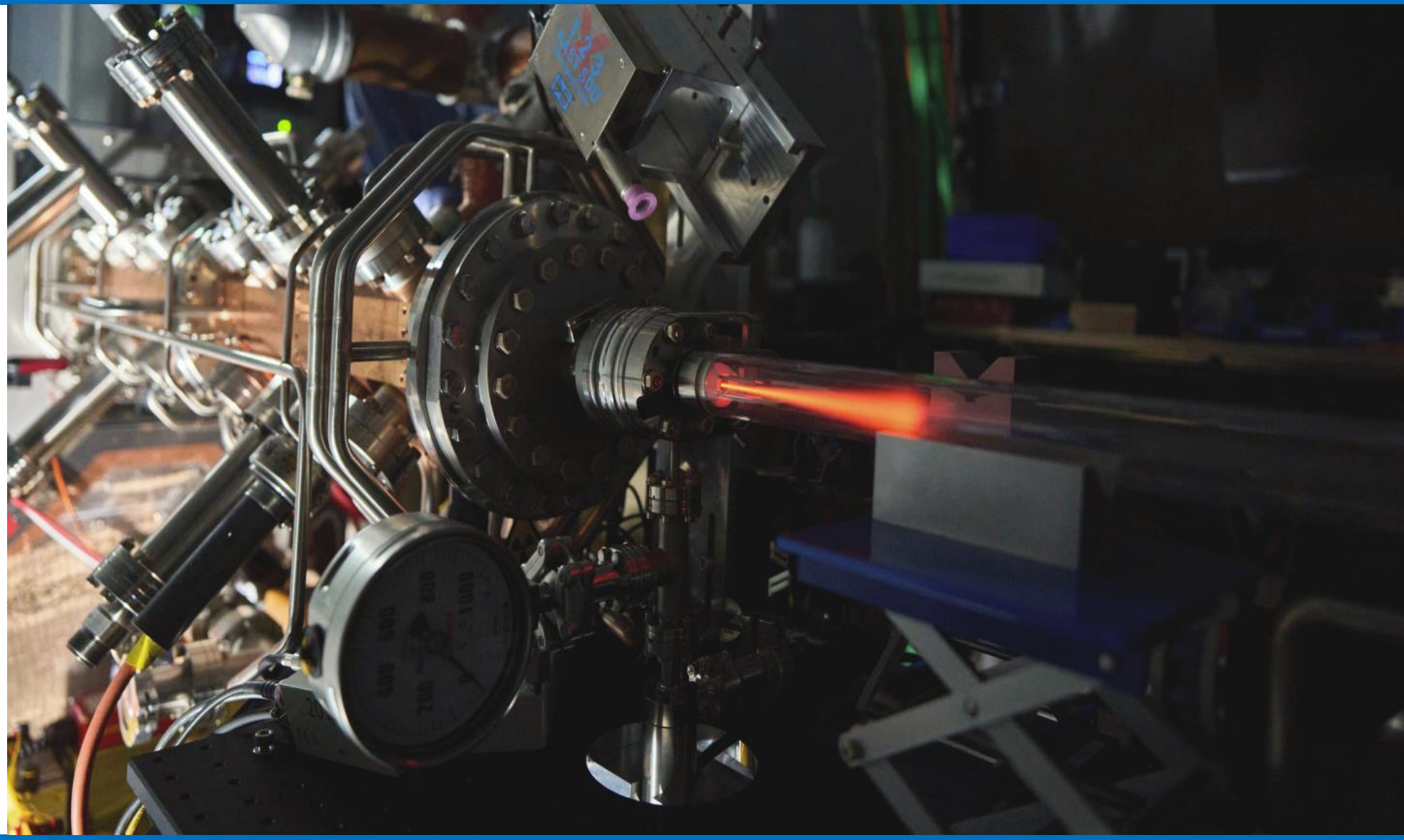
Maurizio Vretenar CERN Honorary

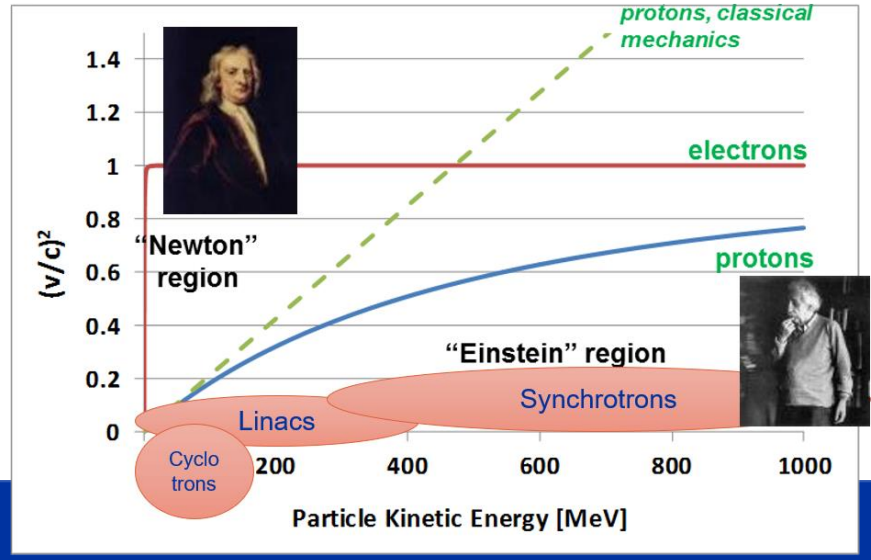


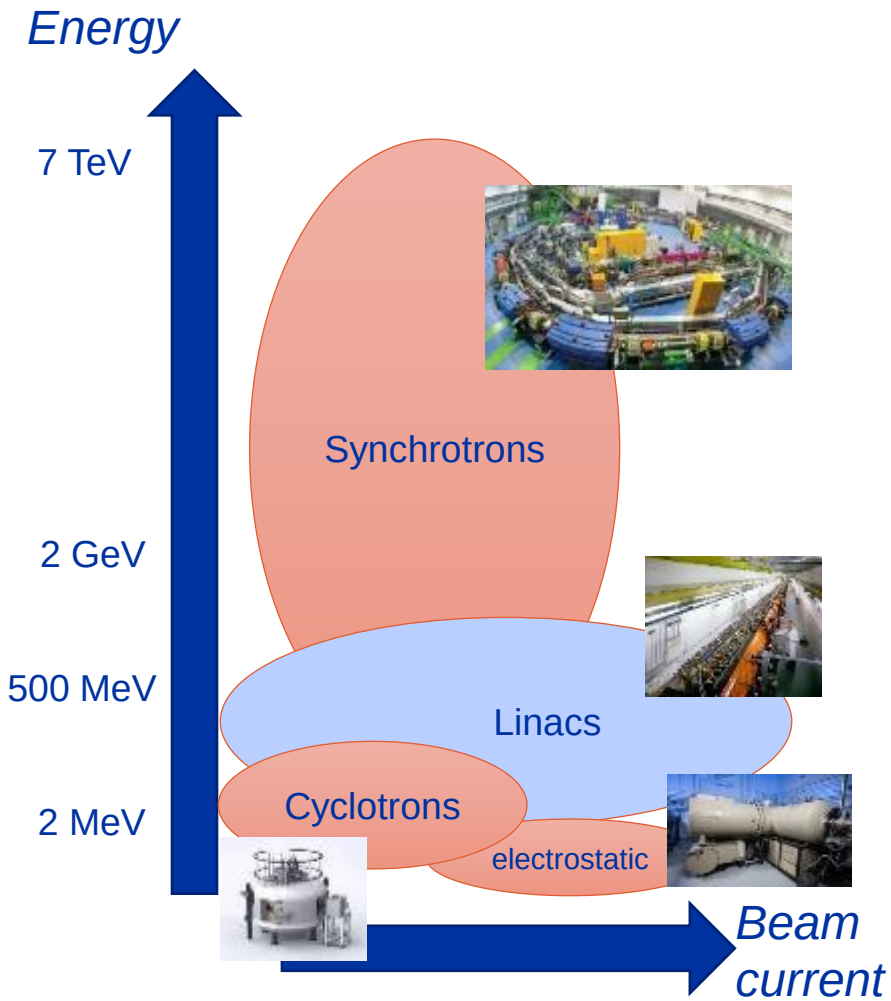
Linear accelerators: present technologies and future opportunities

Why linear accelerators ?

Linear Accelerators (**linacs**) for **protons and heavier ions** are used for:

- Low-Energy acceleration (injectors to synchrotrons or stand-alone): linacs can be **synchronous with the Radio Frequency (RF) fields** in the range where **velocity rapidly increases with energy**. When velocity increases slowly (≈100-200 MeV), synchrotrons are more efficient.
- High-Energy acceleration in the case of production of beams with **high intensity (=high average current)**: in comparison with synchrotrons, linacs can be pulsed at **high repetition frequency** (up to CW), are less affected by **resonances** and have more **distributed beam losses**.





Proton and ion particle accelerators
(energy refers to protons)

Compact low-energy accelerators for science and society

Low-energy: ? **<200-300 MeV** for protons, ions or electrons.

While particle physics is going to extreme energies,

- About **99.5%** of the 45,000 particle accelerators worldwide operate at energies between 0.1 and 100 MeV – notable examples radiotherapy electron linacs in hospitals (17,000, 10-20 MeV), ion implantation (12,000, <10 MeV), isotope production (1,800, 10-40 MeV).
- Many **more applications** are emerging for low-energy hadron and lepton accelerators beyond their traditional use as injectors for high-energy machines:
  - Protons and ions: new radioisotopes, compact neutron sources, advanced particle therapy, …
  - Electrons: compact FEL's, FLASH radiotherapy, new radioisotopes, …



All these low-energy accelerators share similar challenges:

- **Compact** dimensions, to fit within small laboratories, hospitals, industry, etc.
- Affordable **cost**.
- Low **environmental impact**: reduced energy consumption, radioactivity, CO2,…
- Simplicity**, reliability**, easy maintenance, industrialisation.

Addressing these challenges requires a combination of **conventional** (stable and reliable) and **innovative** (high performance) technologies.

Proton and ion linacs – why chosing them

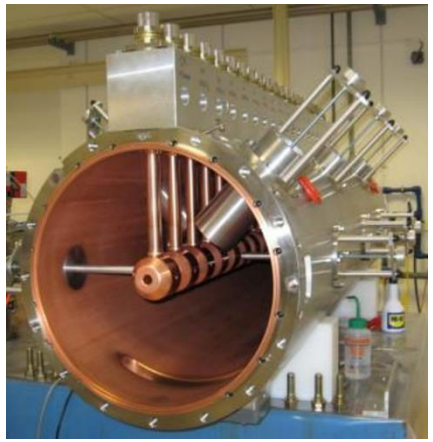
sequence of cells of **length βλ or βλ/2** *(λ = RF wavelength).*

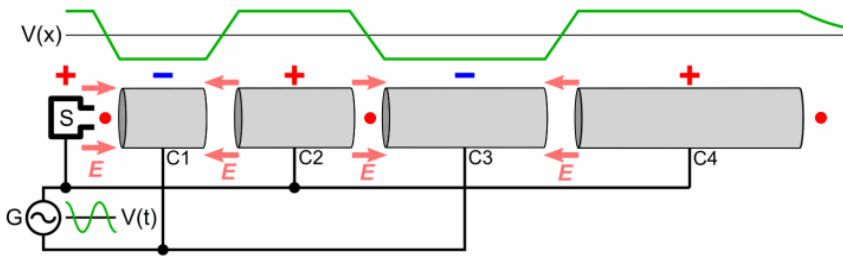
Advantages:

- Flexibility: can follow any particle velocity profile and provide any time structure for the beam.
- Controlled beam optics and no need for extraction, with minimum beam loss even for high beam currents.
- Modularity and upgradability: can be built in stages and are simple to upgrade.

Disadvantages:

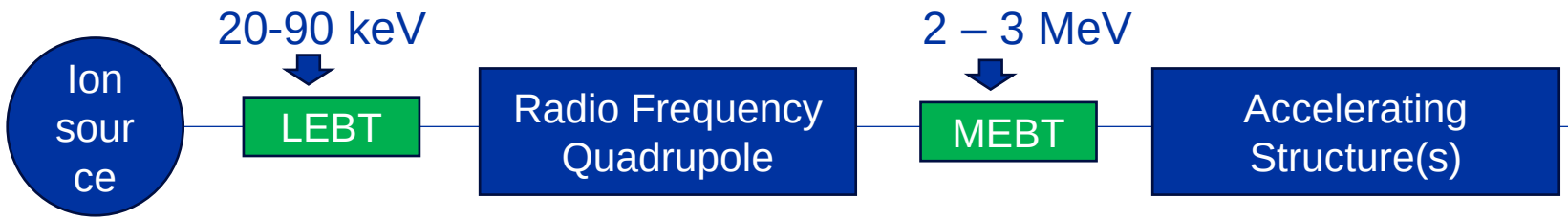
- Cost: particles cross only once each gap.
- Number of mechanical components.
- Superconductivity possible only from medium/high energies.





Example:
Linac4 **Drift Tube Linac** at CERN
352 MHz RF frequency
Length 19 m
120 Drift Tubes
Energy 3 MeV to 50 MeV
Beta 0.08 to 0.31 →
cell length (βλ) 68mm to 264mm
→ factor 3.9 increase in cell length

Proton and ion linac architecture



Ion source
Critical for performance and reliability.
ECR sources now standard technology for protons and ions *(EU: produced by one vendor and one lab).*

Low Energy Beam Transport
Critical for emittance preservation.
Two-solenoid transport and matching (about 1 m length).
Possible with electrostatic lenses.

Radio Frequency Quadrupole (RFQ)
Focusing, bunching and (moderate) acceleration, critical for transmission and reliability.
Generation of RF quadrupole electric field with electrode modulation for longitudinal transport and focusing.

Medium Energy Beam Transport
Critical for matching to accelerating structure.
Quadrupoles and bunch rotation cavities.

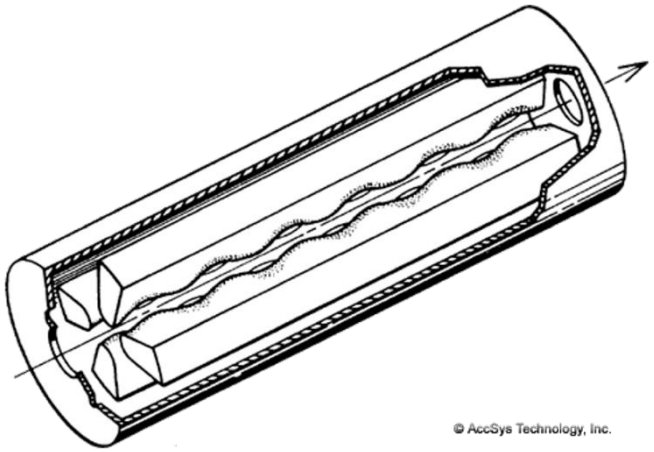
Main accelerating structures
Critical for cost and RF power consumption.
Multiple choices, with operating mode and geometry optimised for type of particle and energy.
Superconductivity is possible.

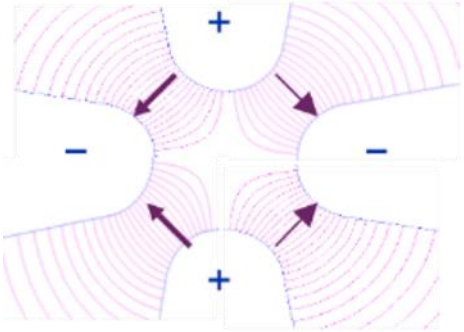
The choice of frequency:
- Cell dimensions ~ f^{-1}
- Maximum E field ~ $f^{1/2}$
- RF Power efficiency ~ $f^{1/2}$
- Machining tolerances ~ f^{-1}
- RF beam defocusing ~ f

Interest to go to the highest frequency permitted by mechanical tolerances and RF defocusing, selecting a range where high-power RF sources are available.
EU frequency: 352 MHz
US frequencies: 402.5 MHz
Asia frequencies: 325 MHz
(and multiples of basic frequency)

Radio Frequency Quadrupoles

RFQ = Electric quadrupole focusing channel + bunching + acceleration



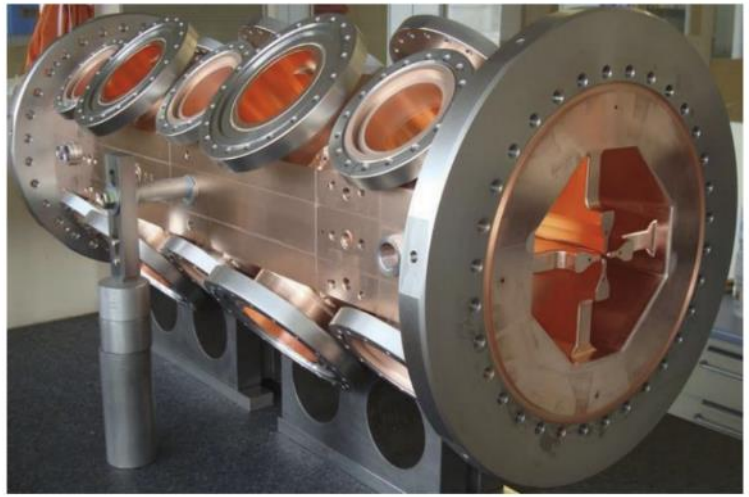


The RFQ is one of the most complex accelerating structures, invented only in 1980.

Modern RFQs are generally reliable and can reach high current and high duty cycle.

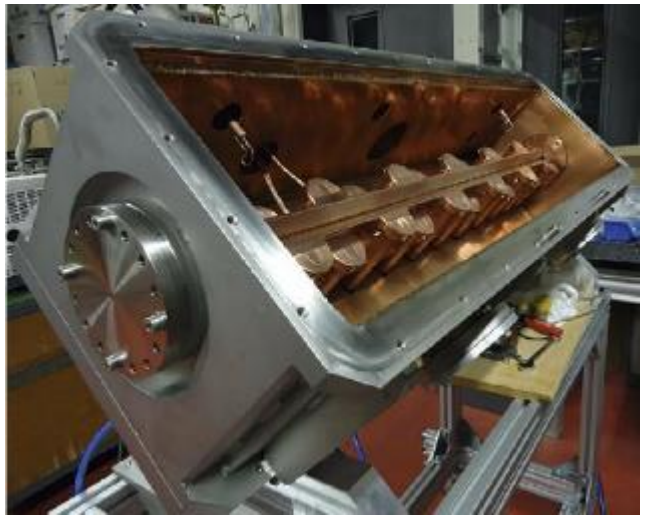
But concerns for long-term stability because of electrode erosion from bombardment of ion source particles

4-vane RFQ design (LANL, CERN, CEA, ESS-B, RAL, RI, … Brazed structure



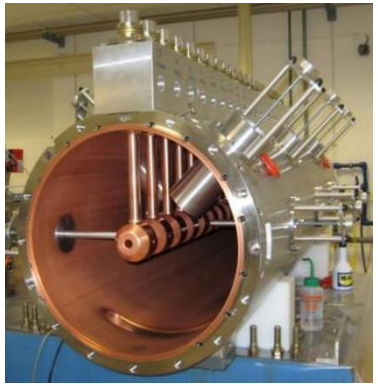
4-rod RFQ design (IAP Frankfurt, GSI, … Assembled structure on supports

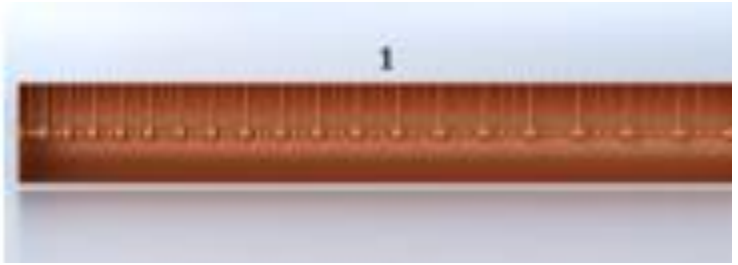




Linac accelerating structures – low/medium energy

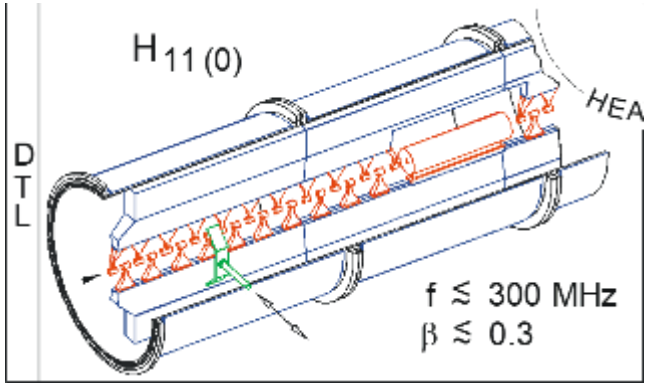
Drift Tube Linac (DTL) and derived (QA-DTL)

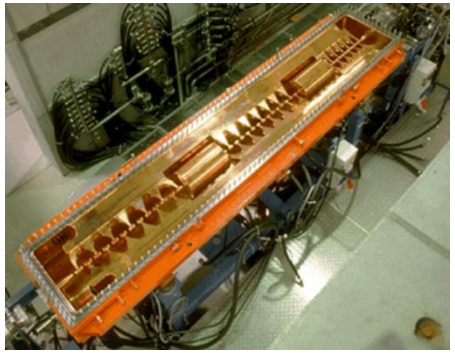




Reliable F0D0 beam optics with minimum emittance growth and beam loss

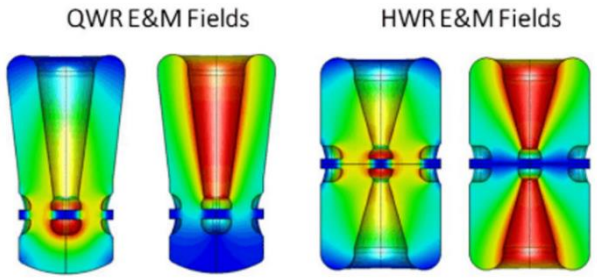
Interdigital H (IH) and derived (CH)

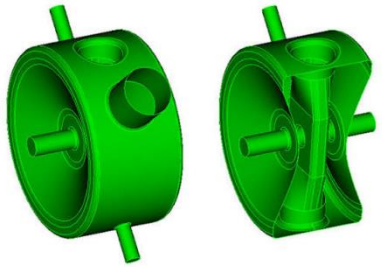




Higher shunt impedance (power efficiency) than DTL, more aggressive KONUS beam optics

Superconducting (QWR and HWR, Spoke, Elliptical)

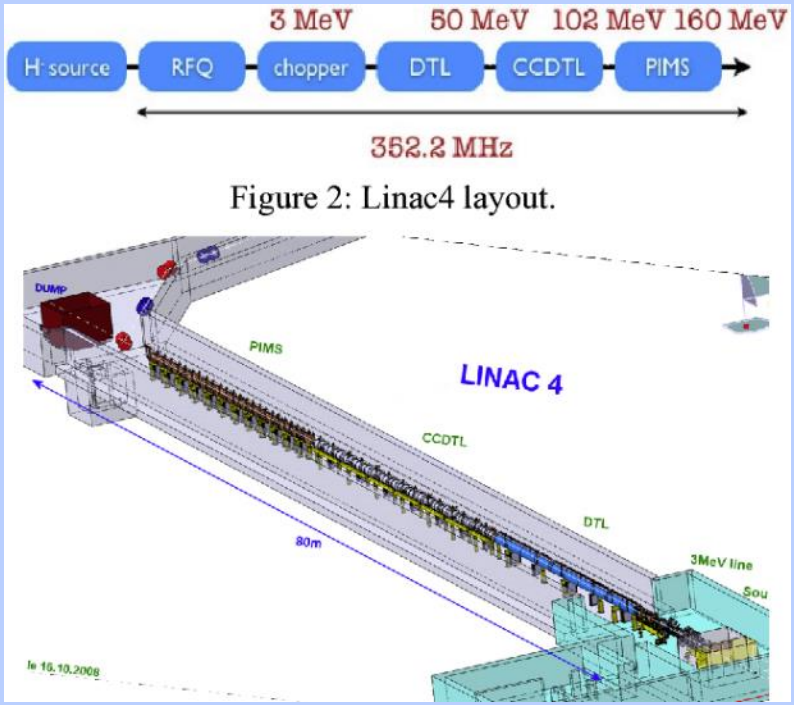






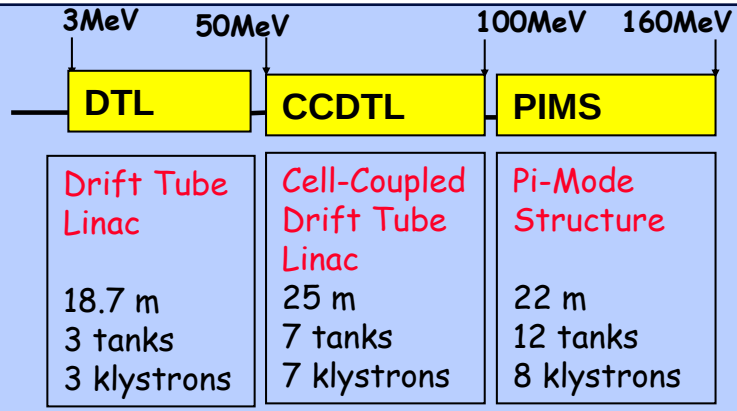
1-gap, 2-gap, multiple gasp superconducting cavities

Examples of modern ion linacs – Linac4 and ESS



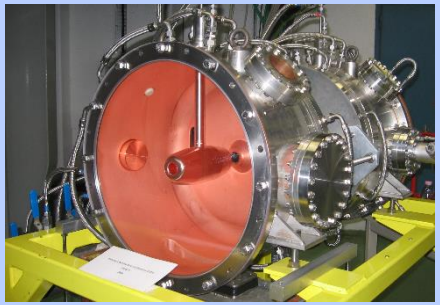
LINAC4 @CERN

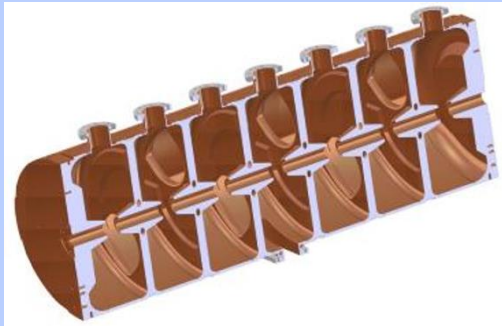
160 MeV
352 MHz



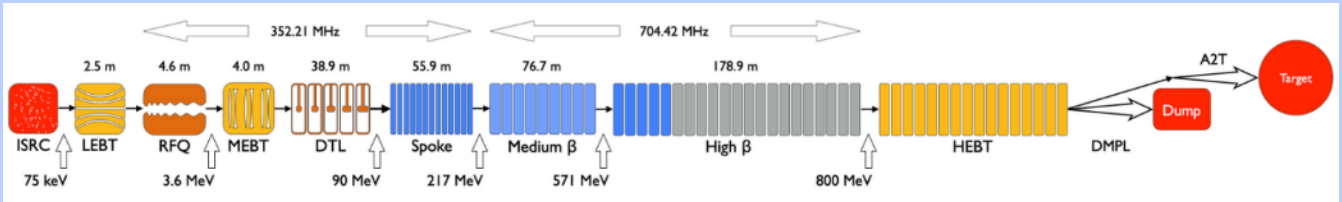
Both Linac4 and ESS accelerate only protons





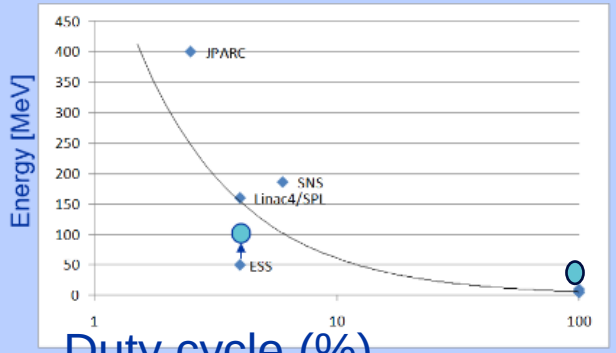


European Spallation Source 0.8-2 GeV 352 + 704 MHz



superconducting cavities (spoke and elliptical) at W>90 MeV.

At high energy and high duty cycle SC allows a reduction in overall cost



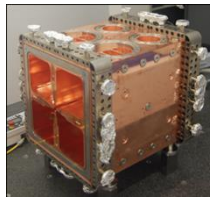
Examples of modern ion linacs – IFMIF-EVEDA



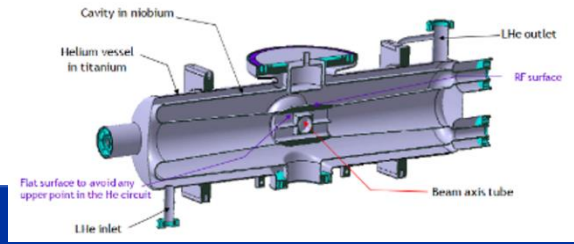
IFMIF-EVEDA in construction at Granada (Spain) for fusion material testing
Deuterons, 9 MeV, 125 mA, CW operation, 35 m

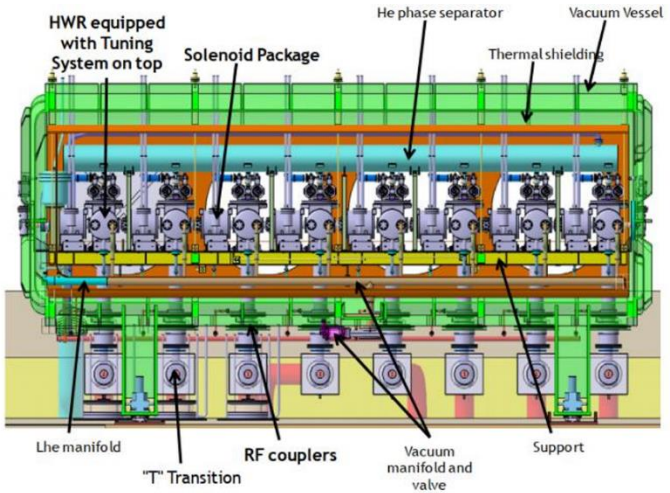
A deuteron source with the highest possible beam current

A Radio Frequency Quadrupole to bunch and accelerate the beam to 5 MeV



A series of cryostats containing independently phased half-wave cavities with solenoid focusing, bringing the beam energy to 40 MeV





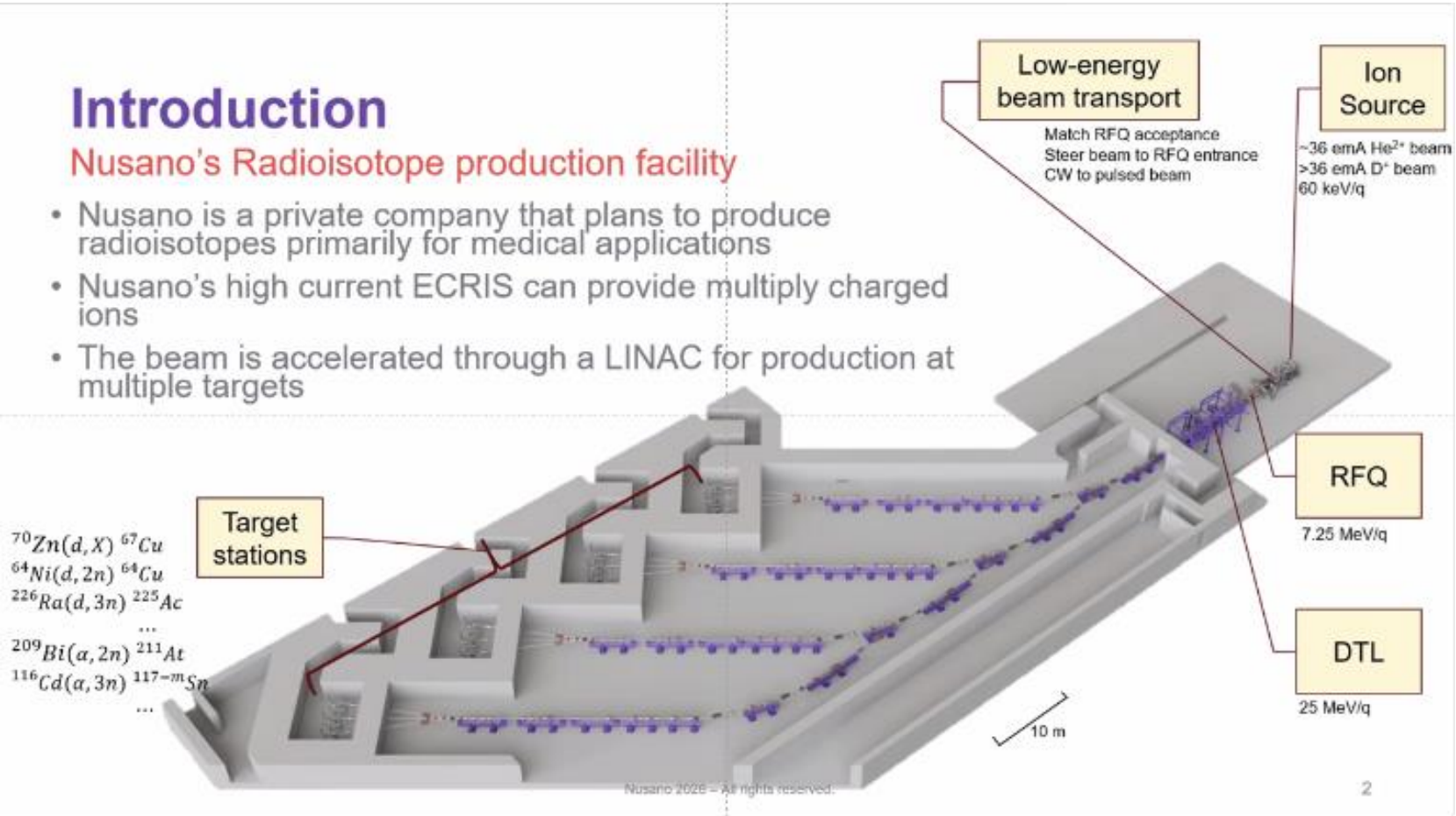
Modern ion linacs – MYRRHA - MINERVA



ECR ion source
4-rod RFQ
CH cavities to 16.6 MeV
Superconducting spoke to 100 MeV
352 MHz

MINERVA: MYRRHA ADS prototype phase 1 in construction at Mol (Belgium)
Protons, 100 MeV, 4 mA, CW operation

Modern ion linacs – NUSANO



from NUSANO presentation at ECRIS26

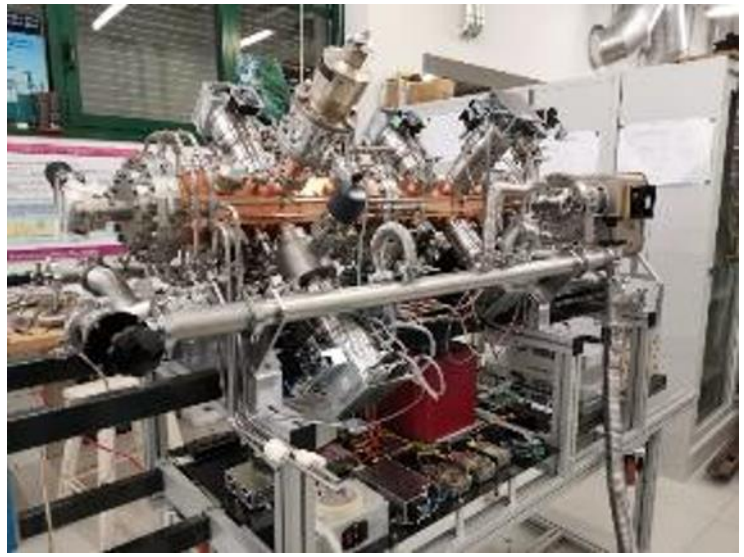
Private company building in Salt lake City (Utah) a facility for large-scale production of medical radioisotopes.

Deuterons and helium (alpha) ions 4He2+
energy 50 MeV
3-5 mA current (average)
Special ECR source design for 40 mA peak He2+ current *(tbc)*
10% duty cycle?
RFQ and DTL produced by RI?

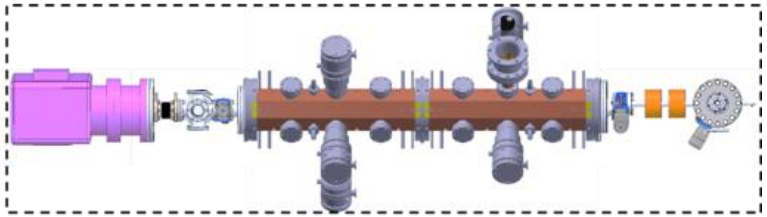
12 targets for production of 211At and 211Rn (with Li beam, as 211At generator) plus other 25 radionuclides used for therapy, diagnostics, theragnostics, and as generators for other radionuclides.

Initial commissioning goal was early 2025, present target end 2026.

New linac technologies: compact high-frequency RFQs



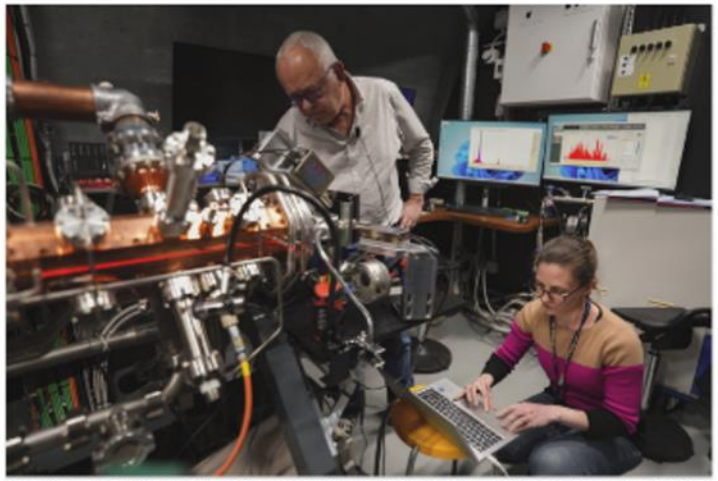
Transportable RFQ for Ion Beam Analysis (PIXE) built by CERN and LABEC for the Florence art restoration centre (Opificio)



Science Gateway's mini accelerator is now taking data

The mini proton accelerator ELISA, situated in CERN's Science Gateway exhibition centre, has started analysing archaeological samples

22 NOVEMBER, 2024 | By Naomi Dinmore



A particle accelerator on display in a museum exhibition is rare. But a functioning particle accelerator conducting real scientific research in a museum exhibition? That's unprecedented. After years of development, the proton accelerator ELISA (Experimental Linac for Surface Analysis) is now being used for archaeological research at Science Gateway, CERN's education and outreach centre. This marks the first time a proton accelerator of this kind has been used for research as a part of a museum exhibition.

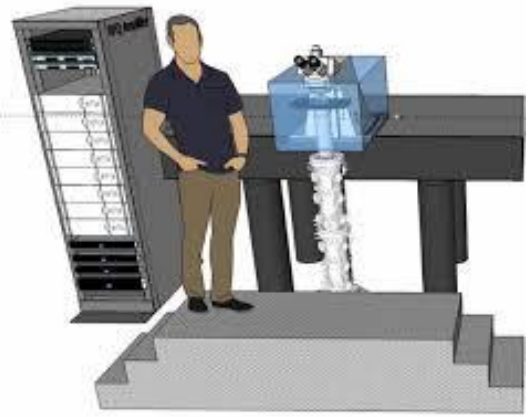
A high-frequency RFQ at 2 MeV is now installed at the CERN visitors centre (Science Gateway).

Another step in the quest for higher frequencies and compact dimensions.

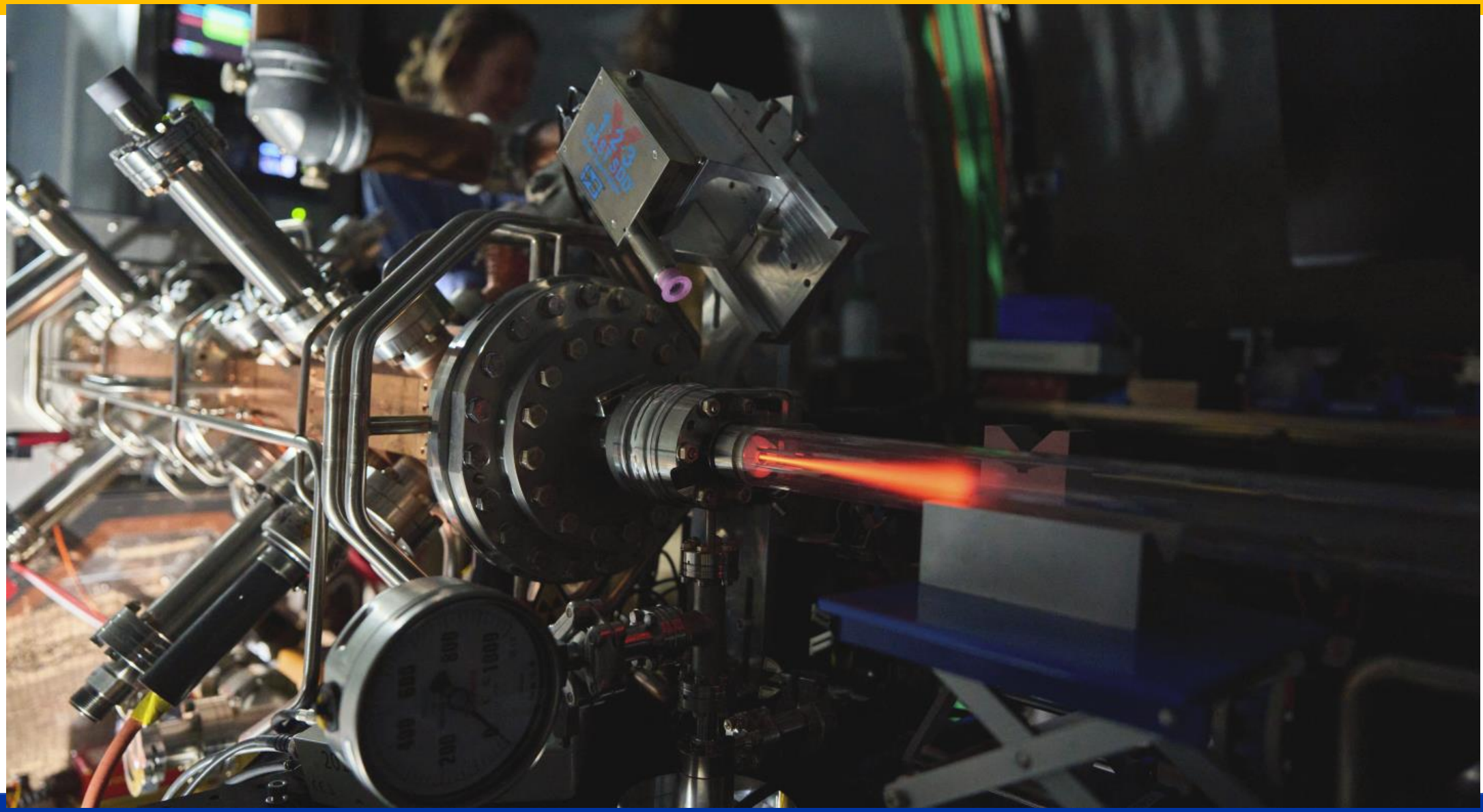
750 MHz RFQ (highest frequency in the world) developed originally for proton therapy of cancer (3 MeV, 2 m), now reproduced in several versions for Ion Beam Analysis (2 MeV, 1 m) in research centres and universities.

Protons or helium ions, low current (small aperture): < 1 mA.

Proposal for cell irradiation system in a biological research lab fed by a compact RFQ.



The Bragg peak – 2 MeV p-beam in air, out of the ELISA RFQ



New linac technologies: additive manufacturing

Additive manufacturing of copper or niobium (and multimaterial!) structures by LPBF is making remarkable progress.

Advantages: Complex geometries without assembly, welding or brazing (simplified process, reduced risk at transitions)
Complete freedom in optimising geometry for power efficiency and for cooling. Option of multimaterial.

Challenges: Surface quality, post-processing required to obtain smooth surfaces. Material removal to compensate.
Dimensions, present 3D printers limit size to about 30x30x30 (cm) – constantly improving.

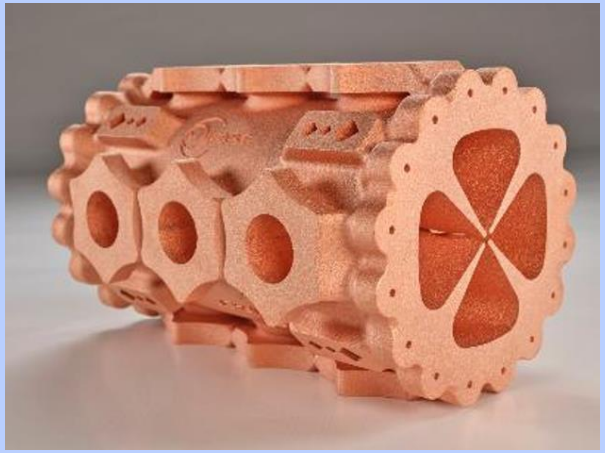

INNOVATION / SCIENCE

First ever prototype particle accelerator made using additive manufacturing technology

6. December, 2022
Author: Anda Asere

Publicity photo

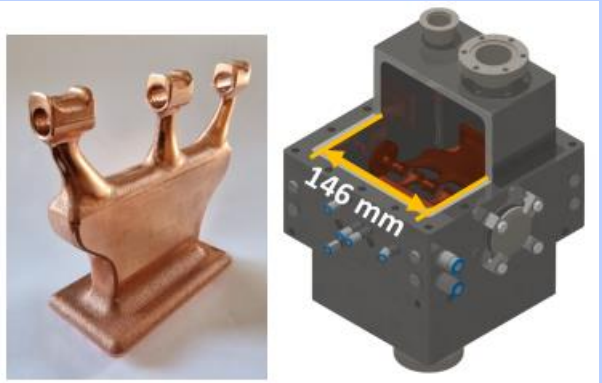
Collaboration CERN-Milano-Riga (and others) in the EU projects I.FAST-EPITA is building 750 MHz copper RFQ's.



Successful vacuum, HV, post-processing test. Building new prototype for RF and beam test.

Frankfurt University is building 400 MHz Interdigital-H structures (in stainless steel, machined and copper plated).



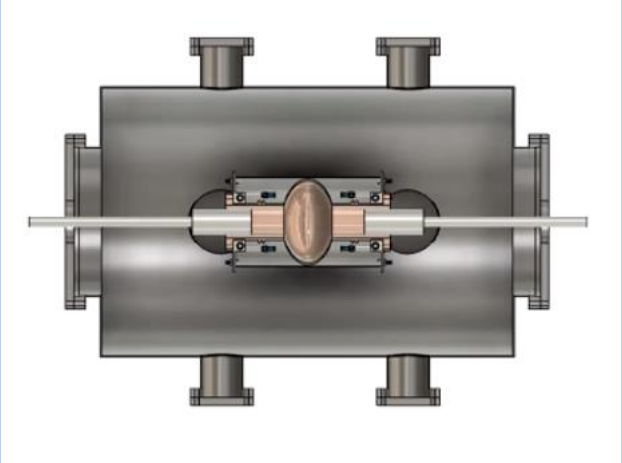


Successfully tested with RF power (25 kW).

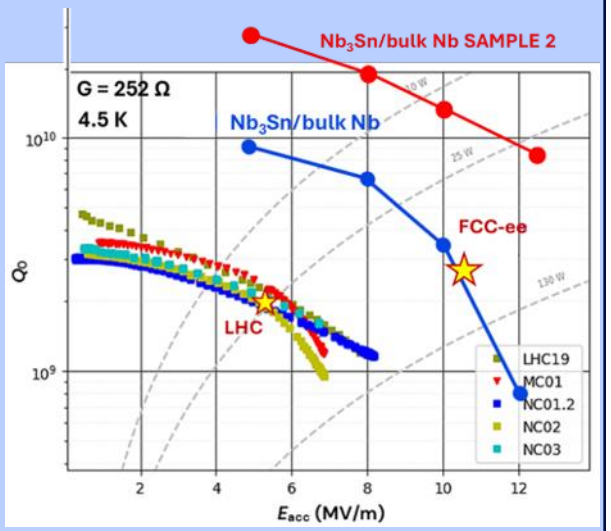
New linac technologies: superconducting coatings

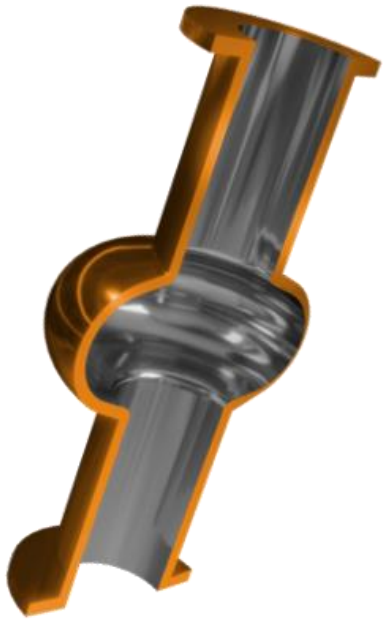
Thin-film coatings for superconducting cavities are making remarkable progress, with the goal of replacing bulk niobium.
In particular, many opportunities with **Nb3Sn**, higher Tc and Bsh than niobium (about factor 2).

Advantages:	high RF efficiency (Q-value) at 4.2 K, reducing cryogenic-system complexity and operating costs.
	lower material cost, less uncertainties on Nb delivery and cost.
	thick copper substrate, higher thermal conductivity reducing microphonics and vibrations.
	potential for higher gradients at low temperature
Challenges:	Difficult coating process, still being optimised. Need multi-layers.
	Control of surface defects.



Wide collaboration in I.FAST EU project (UKRI, INFN, PICCOLI, USI, CEA, IEE, HZB, HZDR, RTU).
Built, coated (ALD) and successfully RF tested a 1.3 GHz cavity. 4 coating techniques compared.
Being continued in EPITA – but Europe is dramatically behind US and China!





The road towards the miniature accelerator…

To increase the diffusion of particle accelerators, one of the main challenges for accelerator designers is to conceive "**miniature accelerators**", providing the required beam parameters with minimum footprint, accessible cost, and low power consumption and environmental impact.



Exploiting new incremental and disruptive particle accelerator technologies

Category	Particle	Configuration	Energy/Footprint	Main limitations
Incremental technologies (RF-based)	protons	mini-RFQ	~ 2 MeV/m^2	RF power density, beam acceptance
	protons	mini-cyclotron	~ 5 MeV/m^2	Shielding, magnet weight
	protons, electrons	High-frequency NC and SC linacs	~ 20 MeV/m^2	Cryogenics, reliability
Disruptive technologies (laser-based)	p, ions	laser accelerator	~ 10 MeV/m^2	Energy dispersion, beam emittance, efficiency
	electrons	dielectric laser (DLA), plasma	~ GeV/m^2	Beam optics, thermal loading, radiation damage, efficiency

Many directions to explore and exciting R&D:

- Additive manufacturing (integrated systems)
- Superconducting RF coatings
- HTS for compact magnets with low consumption (synchrotrons and cyclotrons)
- AI and ML for automatised operation
- Use of lasers as power sources

Thank you for your attention



Picture credit: Elwood Smith