Developing Accelerator Technologies for the Future - role of Technology at CERN

Brennan Goddard

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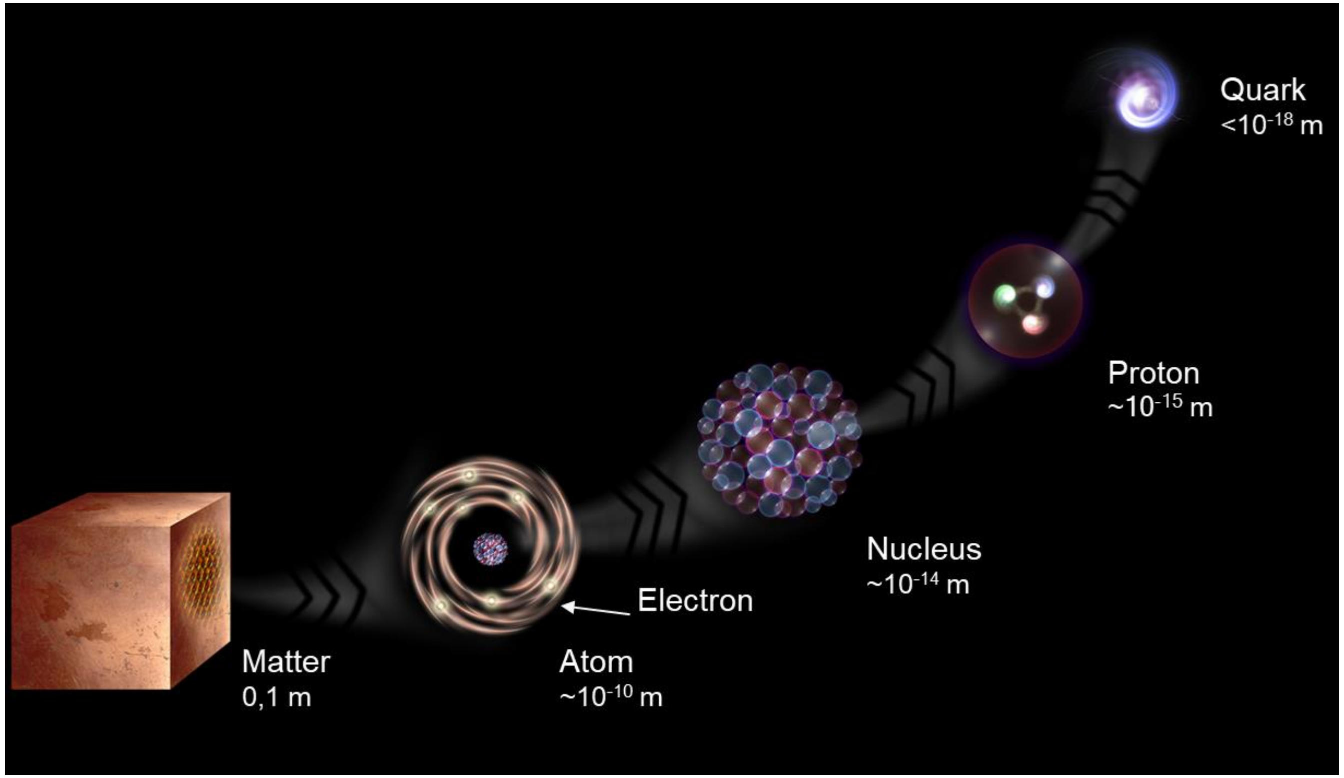
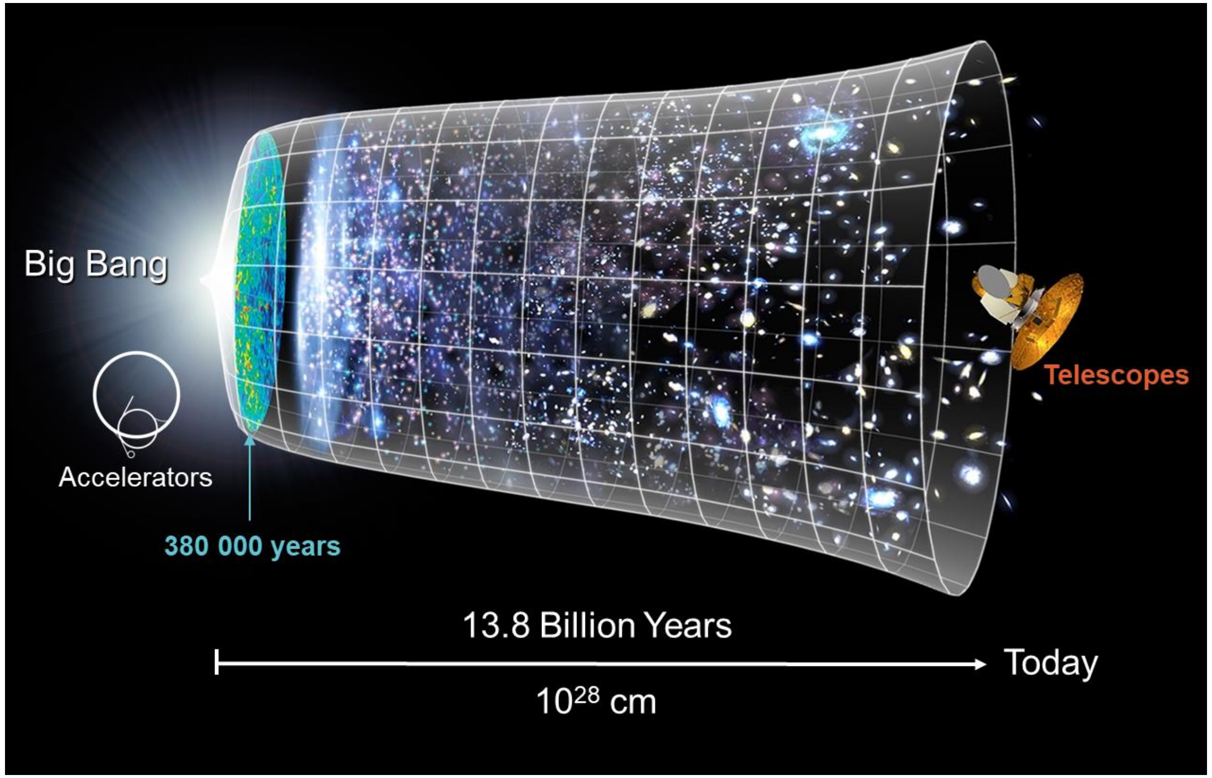
Visit of Foundation Future Leaders Program

CERN: Our Mission

- **To study the elementary building blocks of matter & forces that control their behaviour**
- **In so doing we reproduce the conditions a fraction of a second after the Big Bang, allowing us to gain insight into the structure and evolution of the universe**





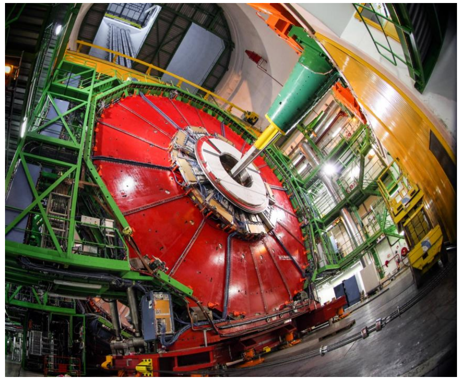
CERN:
Particle Physics, Innovation & Education

Innovation
Education
CERN
uniting people
Research

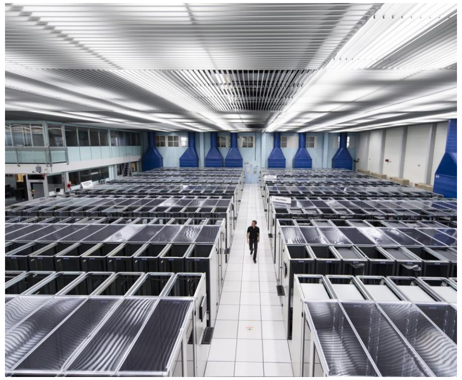
Interfacing between fundamental science and key technological developments

Driving technology innovation while educating the next generation of scientists & engineers

Particle Accelerators



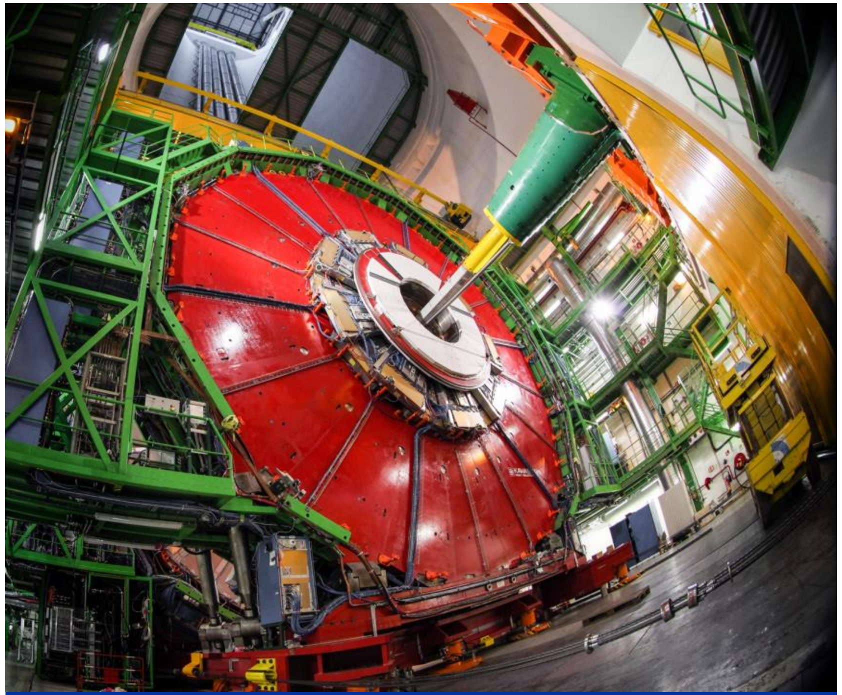
Particle Detectors

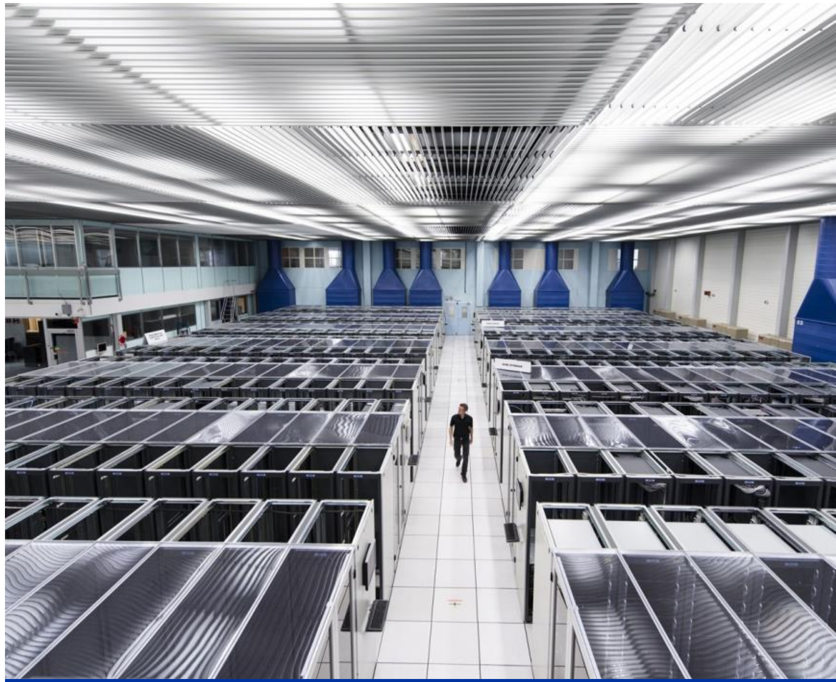


Large-scale computing (Grid)

We develop technologies in three key areas


ACCELERATORS


DETECTORS


COMPUTING

Focus today on Accelerators

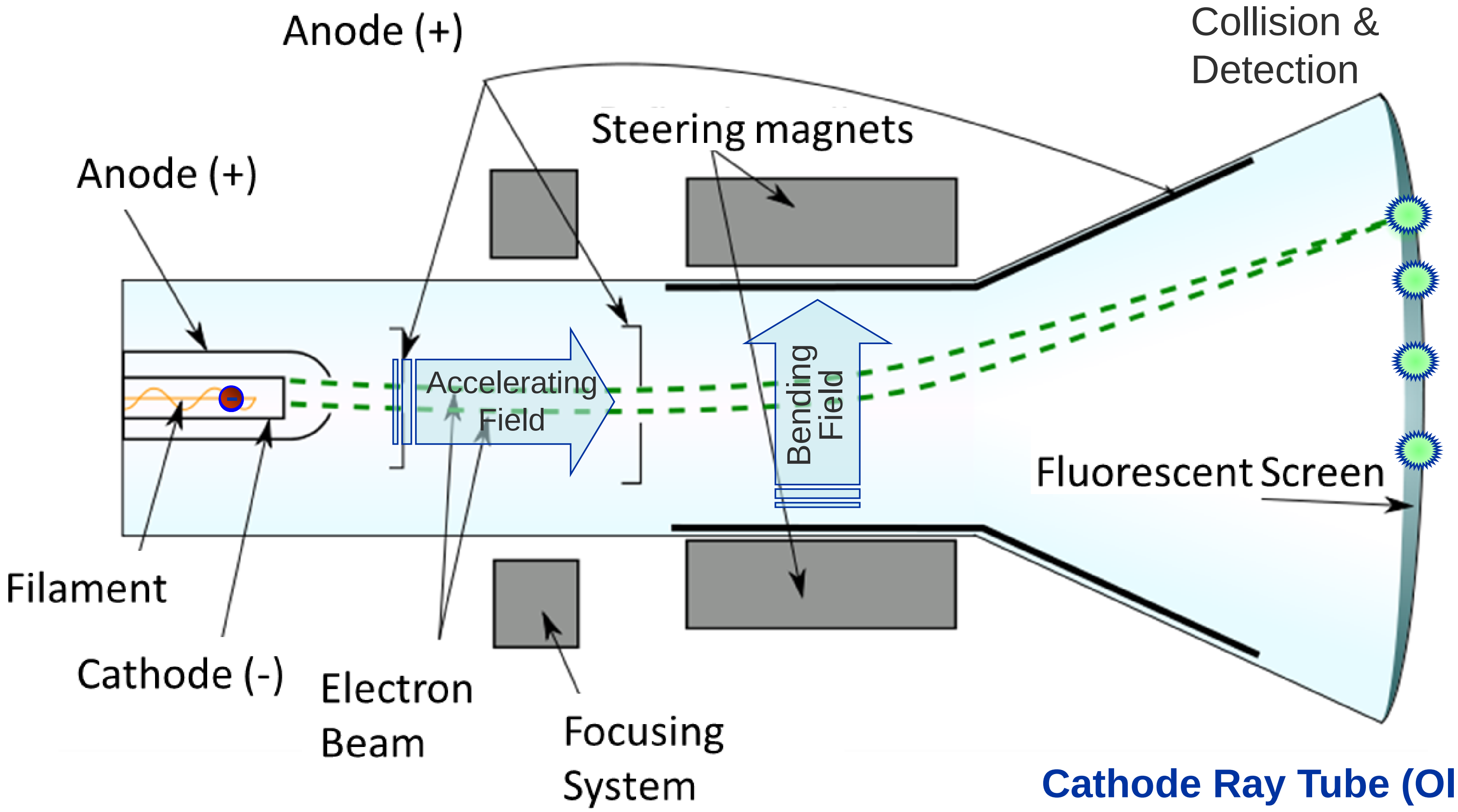

ACCELERATORS

DETECTORS

COMPUTING

Particle Accelerators
The tools of choice at CERN to explore these questions

How do accelerators work?

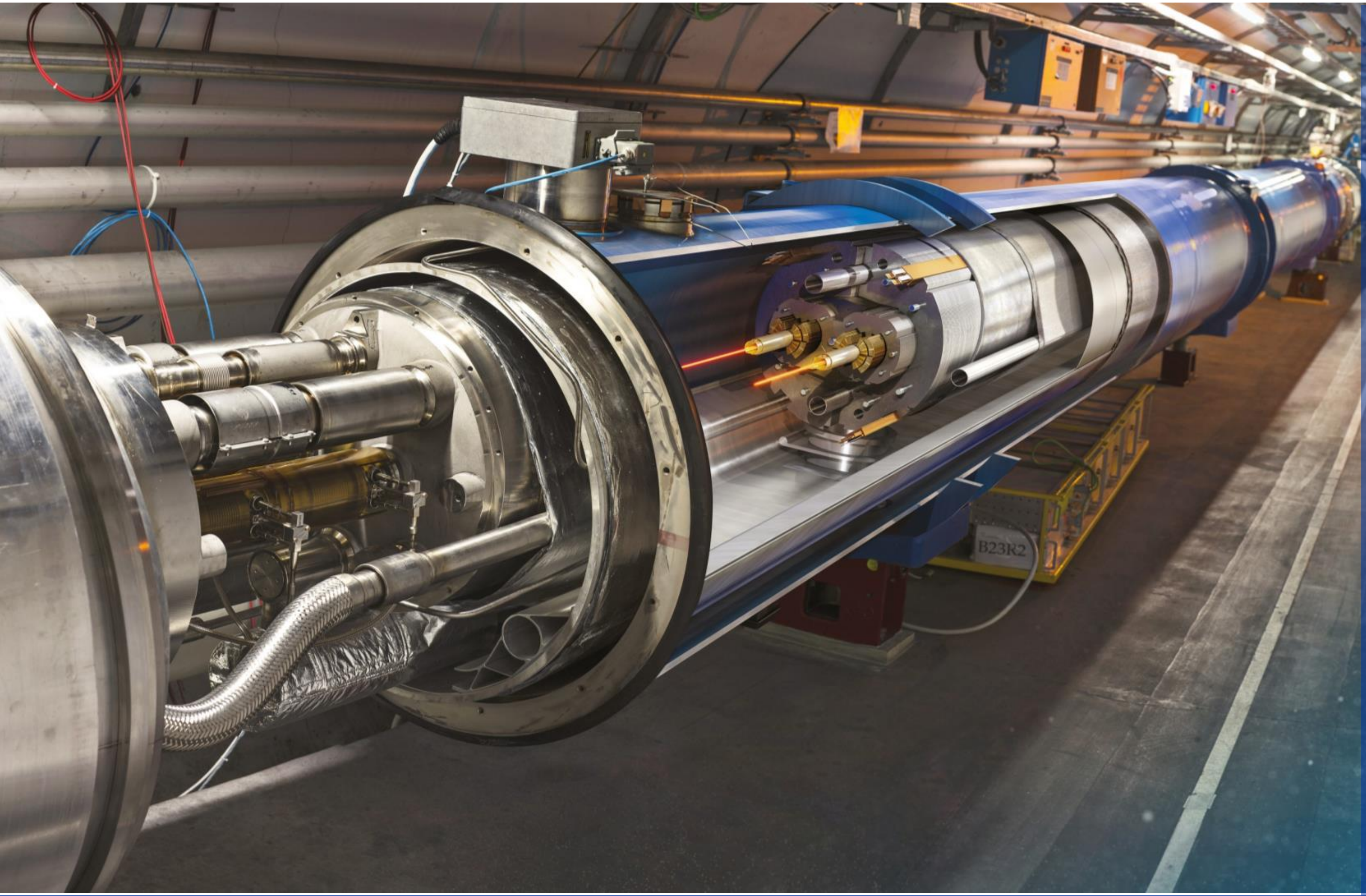


Cathode Ray Tube (Old TV set)

Essential Ingredients

- Accelerating gradients
- Magnetic fields
- Vacuum systems
- Powering systems
- Control systems
- Instrumentation

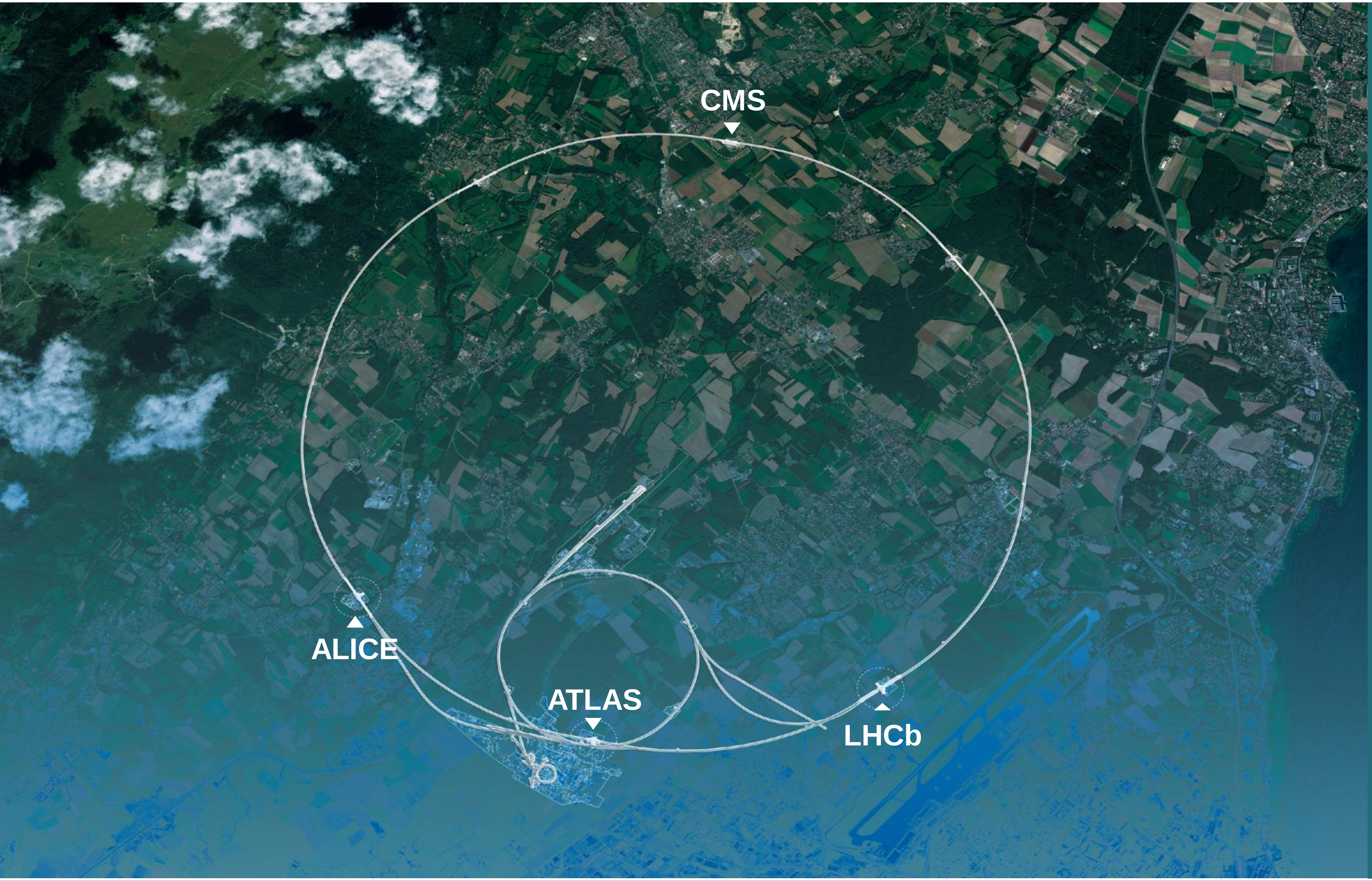
Particle Accelerators and their Detectors:
The tools of choice at CERN to explore these questions

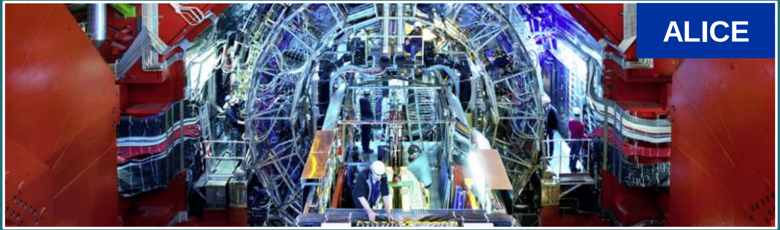


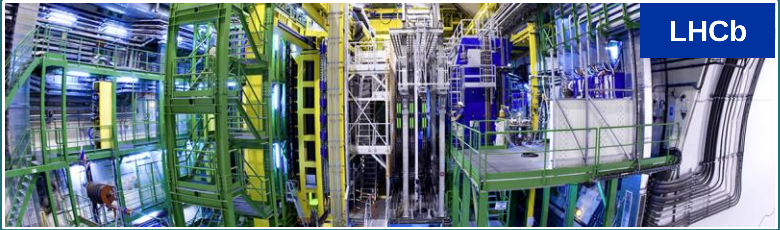
The Large Hadron Collider

- 27 km in circumference
- About 100 m underground
- 2 beams of trillions of protons travelling at 0.999999991 times the speed of light in opposite directions
- Superconducting radiofrequency system to accelerate the beams
- NbTi Superconducting magnets operating at - 271.3 °C to bend them in a circle
- Largest beam vacuum system worldwide
- Advanced powering, machine protection systems, beam diagnostics & control
- 4 Large experiments

The LHC and its Detectors





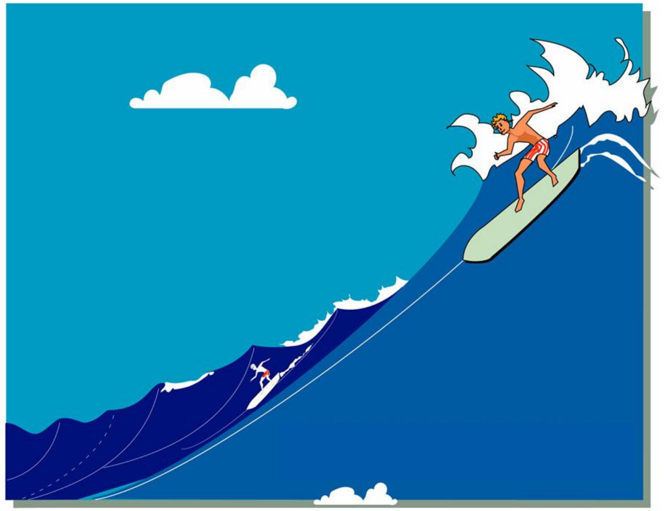


Key Accelerator Technologies

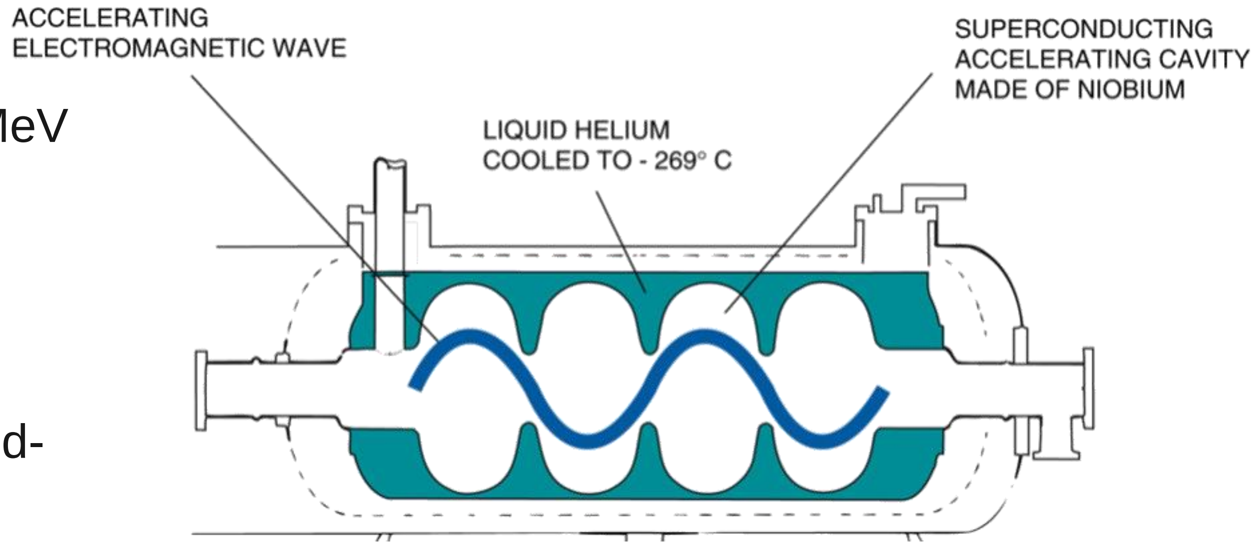
Radio-Frequency Systems

Radio Frequency Acceleration

- **In the same way that a wave pushes a surfer the electomagnetic wave gives energy to the particle**
  - In a circular accelerator the particle gains a small amount of energy each time it passes the accelerating structure
  - The magnets are used to steer the particle beam round the ring back to the acceleration point. The higher the energy the stronger the magnets need to be.

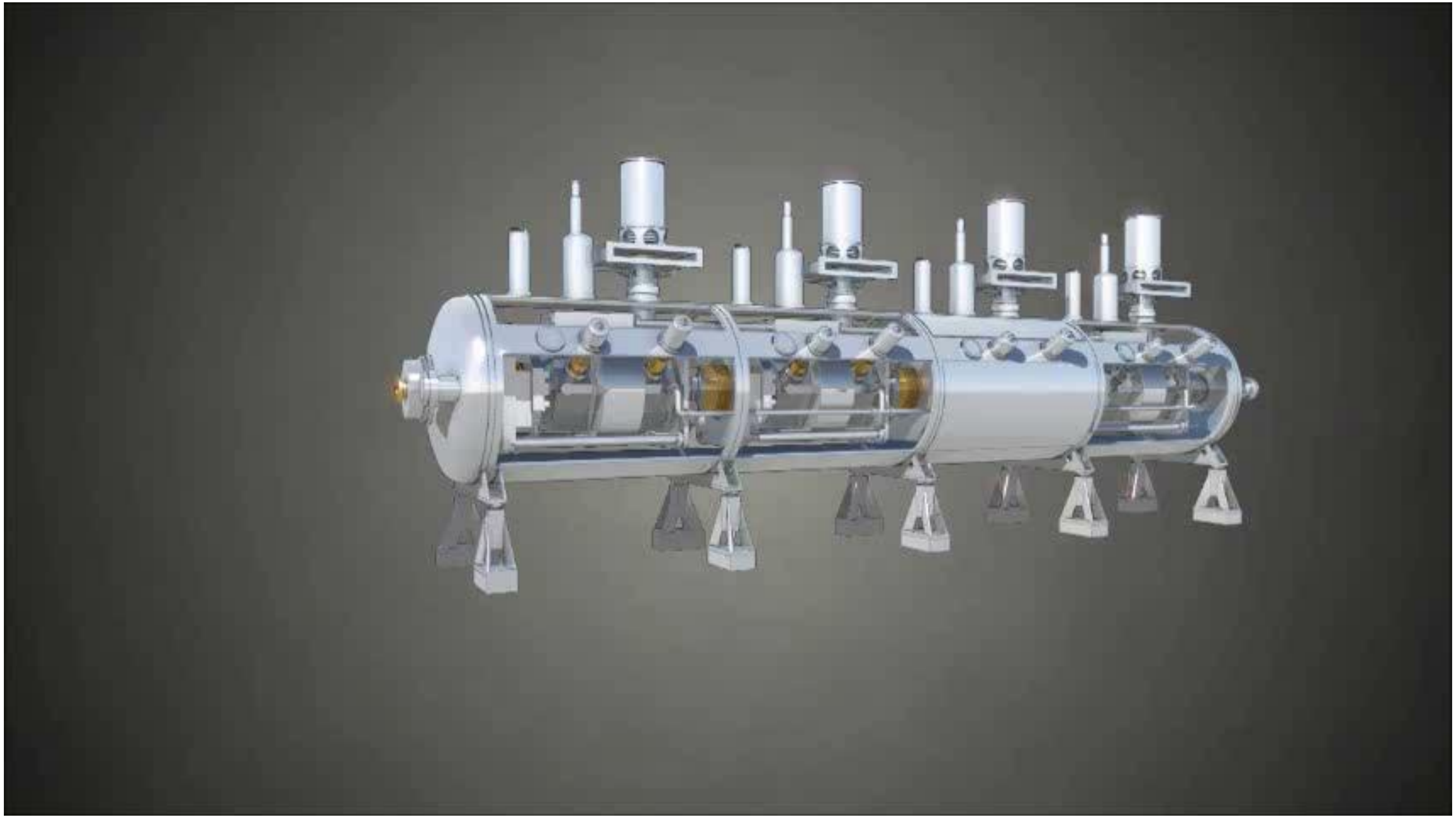


- **LHC has 2 modules of 4 cavities per beam**
  - 2 x 4 x 2 MV = 16 MV of accelerating gradient
  - On each turn particles can gain a maximum of 16 MeV of energy



- **It takes ~30 minutes to go from injection energy to top energy (~20 million turns)**
  - Driven by how fast the magnetic field can be ramped-up rather than how fast we can accelerate

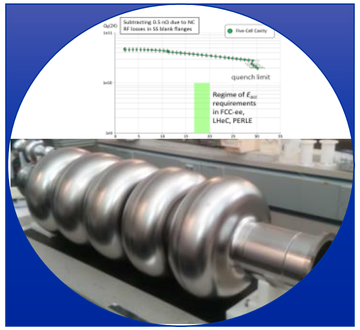
Radio Frequency Acceleration in the LHC



Superconducting Radio Frequency R&D

Cavity Studies

- Optimized Cavity Shape, Technology and Operating Temperature (complexity, power consumption, Q_o, E_{acc})
- Design 1- & 4-cell Cavities
- Beam-Cavity Interaction
- Cavity Control System (LLRF)



SRF & Substrate Technologies

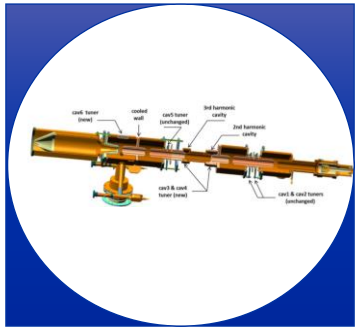
- Improved Cavity Engineering: New SC Materials, Novel Fabrication Methods, Substrate Surface Preparation, Coating Techniques
- Fabrication & Testing of 1-l & 4-cell cavities for new cryomodule
- Collaboration with international Partners

Cryomodule Development

- Engineering design of 400 MHz cryomodule including ancillaries
- Building a 2 cavity CM which can host 1-/4-cell 400 MHz cavities
- R&D Collaboration with int'l Partners (e.g. JLAB)
- 800 MHz CM: Profit from Ongoing Development @ PERLE in Paris

FPC & HOM RF Couplers

- Improved design, fabrication and testing of 400 MHz Fundamental Power Coupler (FPC)
- FPC R&D towards 1MW CW fixed/movable FPC
- 'Adjustable' FPC (external large adaptation of Q_{ext})
- HOM coupler production

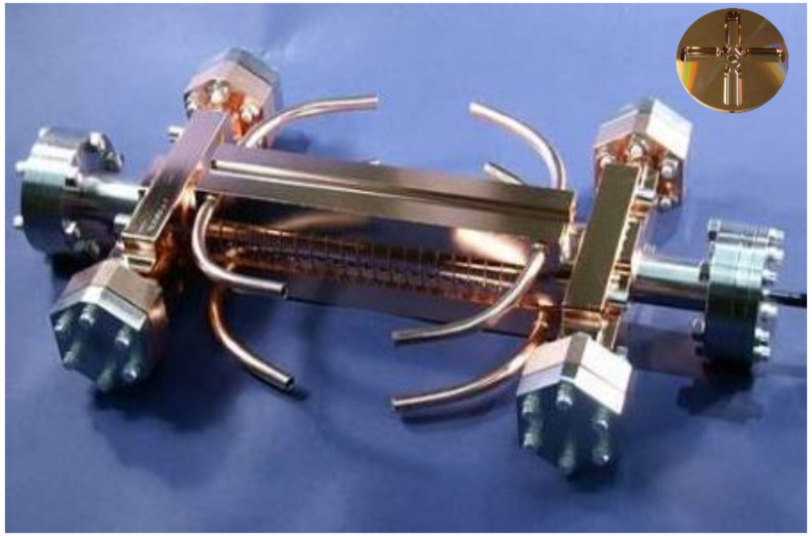


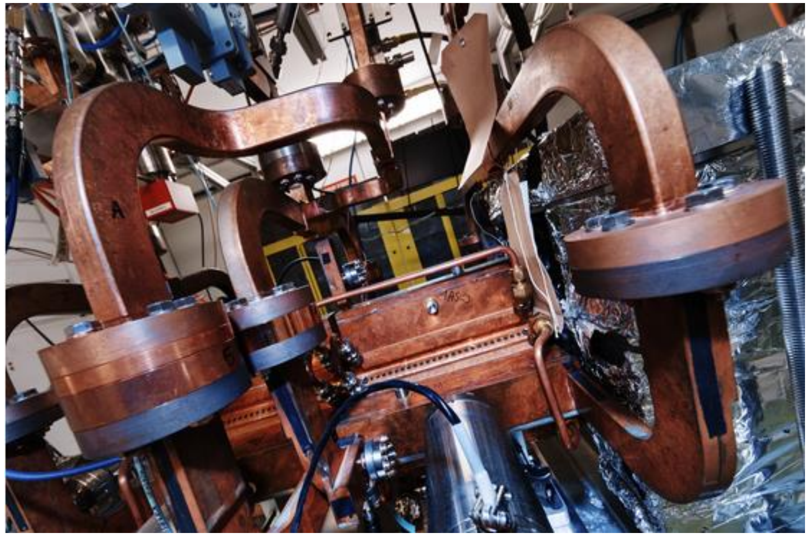
RF Power Sources

- novel klystron bunching methods
- LHC klystron retrofit as proof of principle
- prototype design, fabrication and testing

Radio Frequency Engineering at CERN

- Replacement of tubes with solid state amplifiers
- Production of seamless, high-precision copper cavities
- 12 GHz accelerating structures for CLIC
- X-band technology for FLASH radiation therapy





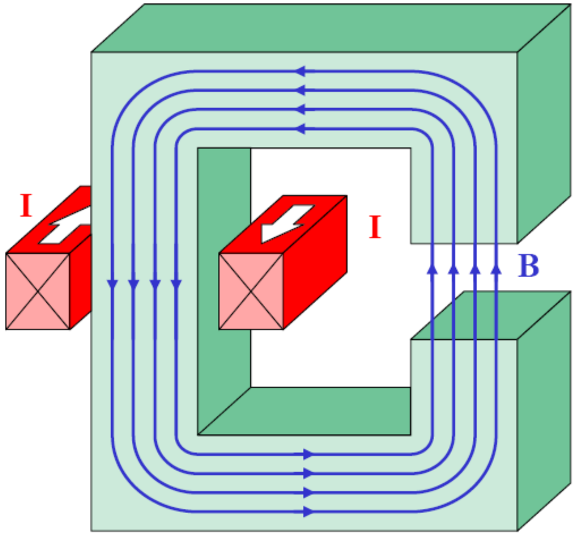
Key Accelerator Technologies

Magnet Systems

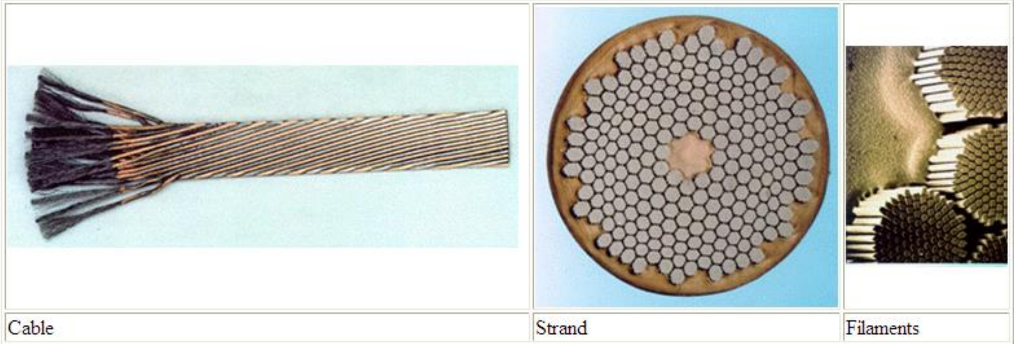
Why use Superconductivity?

- **Iron Yoke Magnets**
  - Good to reduce current required as iron guides magnetic field
  - But iron saturates at around 2T
    - For an accelerator with fixed magnetic field

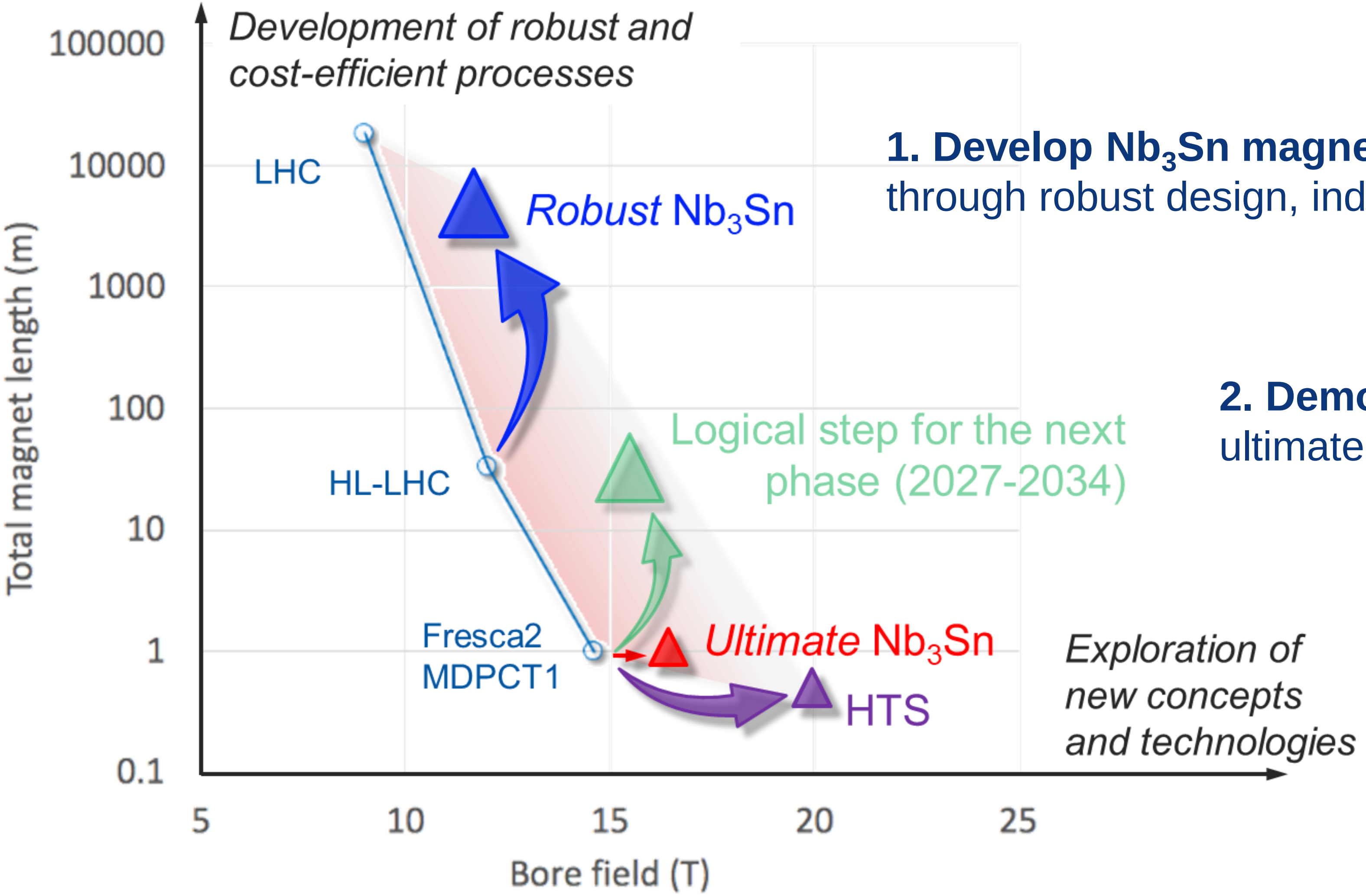
    Increasing the energy = increasing the size



- **Superconducting Magnets**
  - Virtually lossless (no resistance)
  - Can carry very high currents to create high magnetic fields
    - Up to 8T for the LHC magnets @ 13000 Amperes
  - BUT the wire needs to be cooled to near absolute zero
  - NbTi technology used for the LHC magnets



CERN High Field Magnet Program

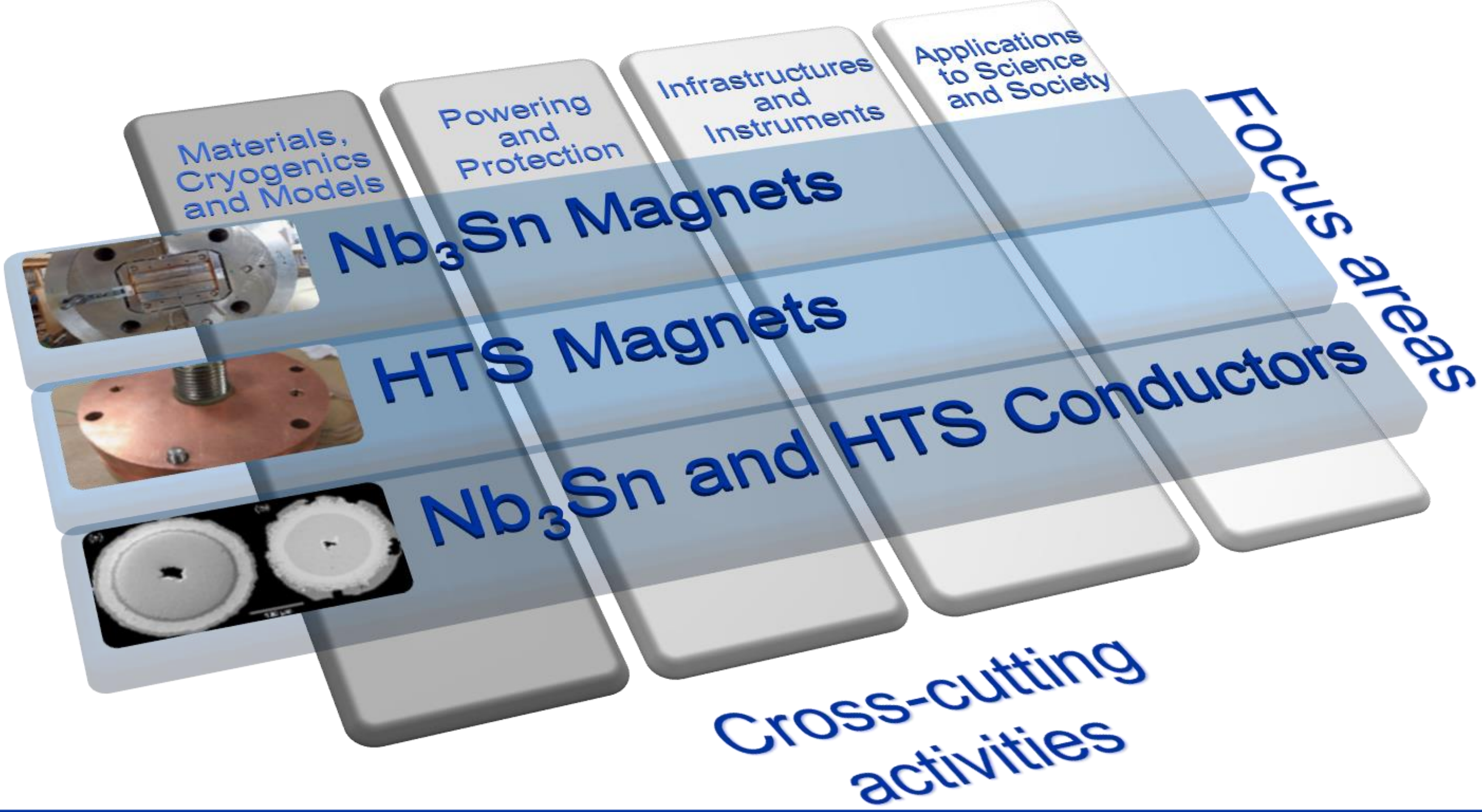


1. Develop Nb_3Sn magnets for collider-scale production, through robust design, industrial processes and cost reduction

2. Demonstrate Nb_3Sn full potential in terms of ultimate performance (short model programs)

3. Provide a proof-of-principle for HTS magnet technology

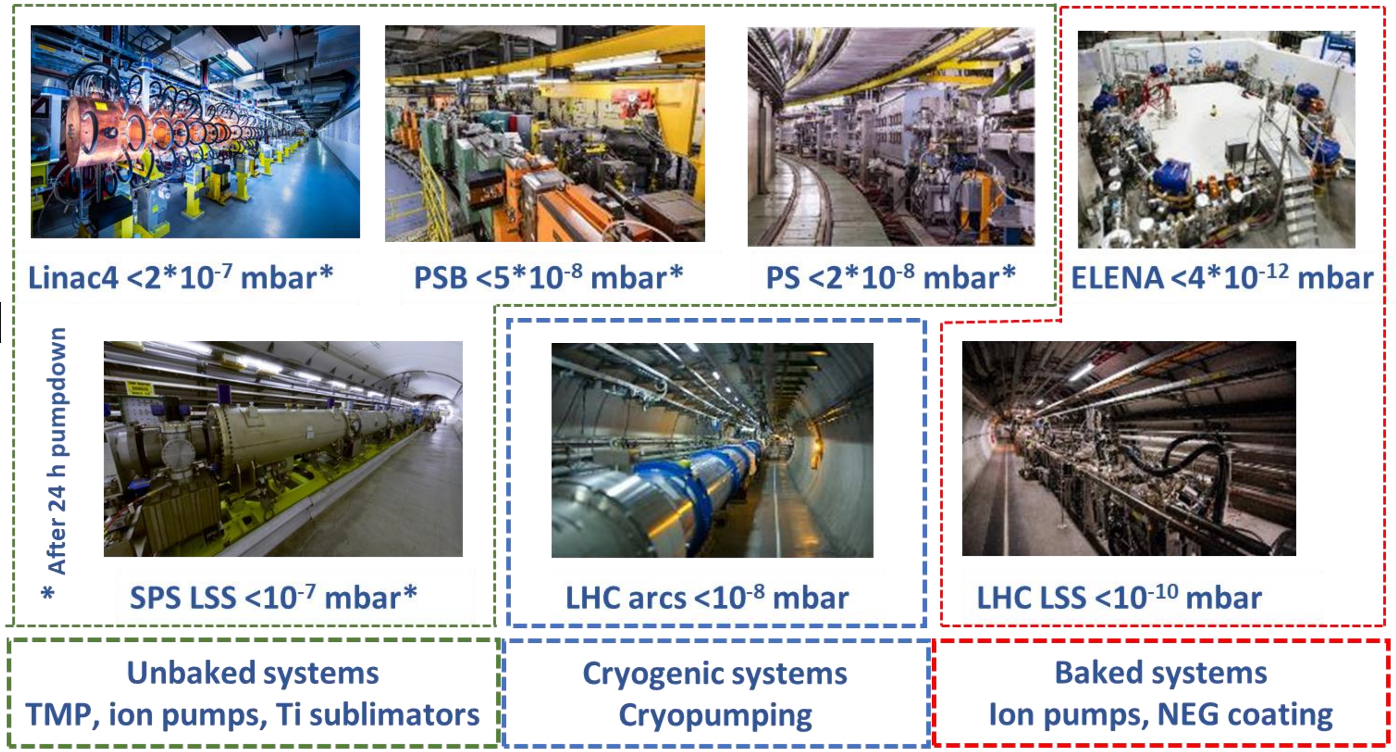
Main Technological Challenges, Studies and R&D

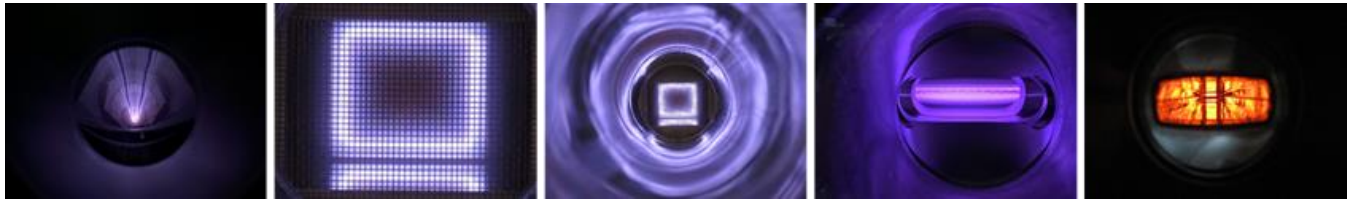


Other Enabling Technologies

Largest Beam Vacuum system Worldwide

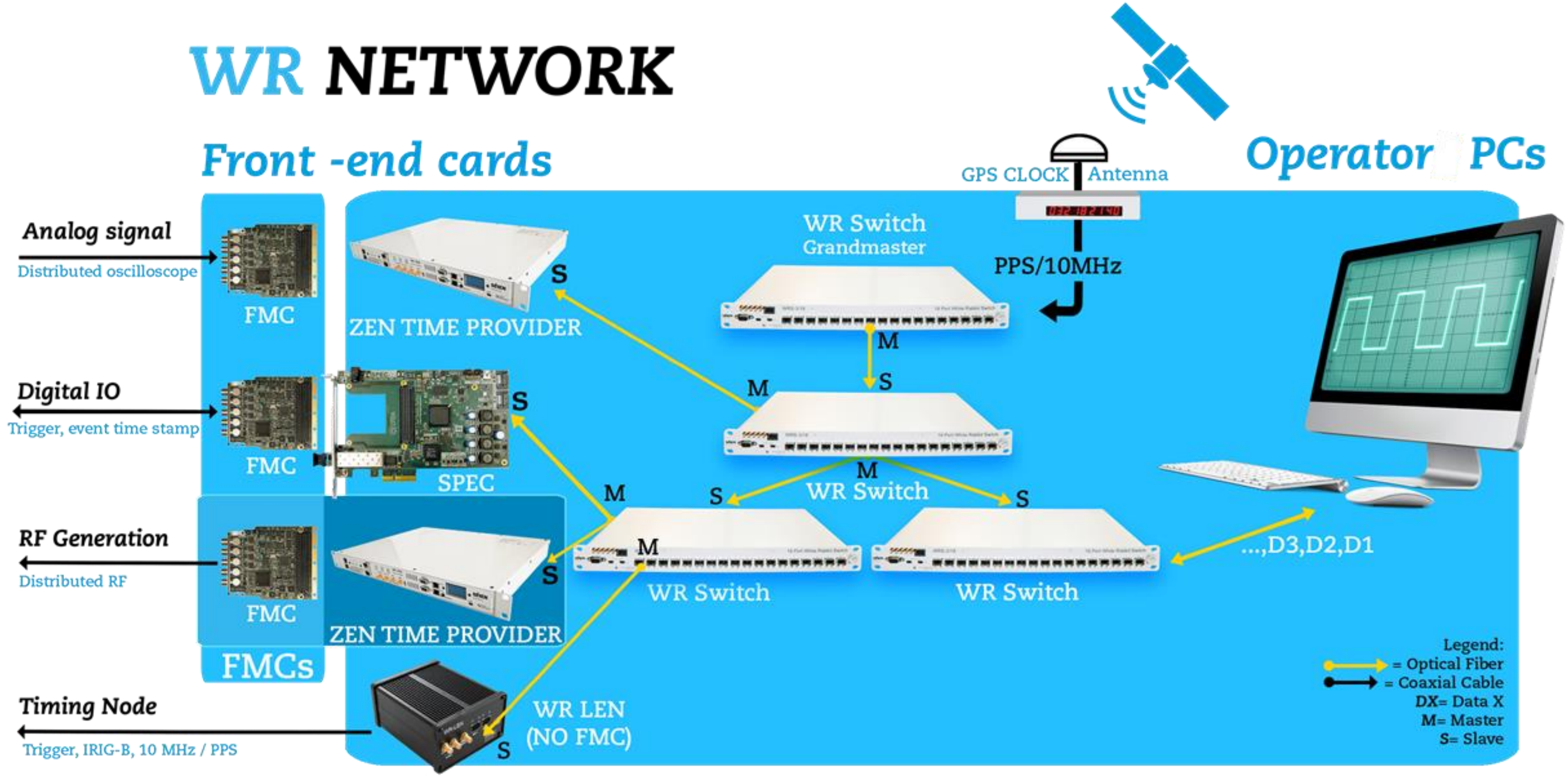
- **65km UHV/XHV lines**
  - Multiple technologies used
- **Coatings and Plasma Processing an integral technology to obtain required vacuum with high intensity particle beams**
  - Thin film coating: evaporation, diode and magnetron sputtering
  - All types of materials including Nb, A15, amorphous-Carbon and Non-Evaporable Getter (NEG) coatings
  - Plasma and laser processing of surfaces
  - Removal of hydrocarbon contamination
  - Numerical simulations





High Accuracy Synchronised Timing Solutions

- **Sub-nanosecond synchronisation through ethernet – White Rabbit**
  - Developed at CERN and now standardised under IEEE1588

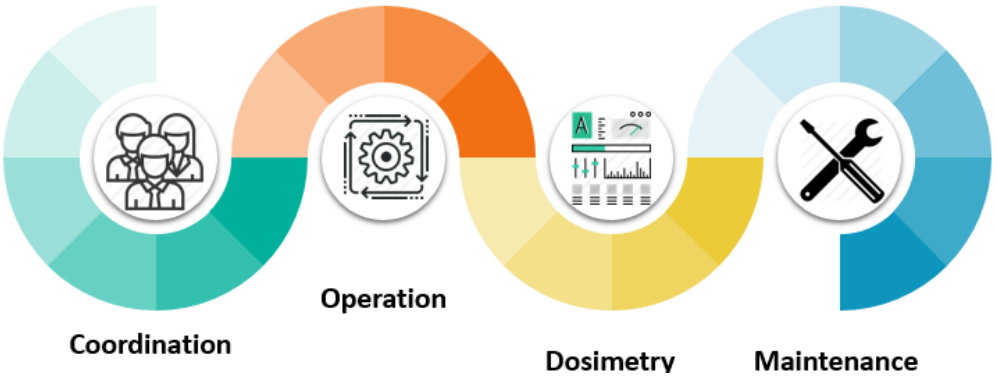


- **Fully open-source**
  - Hardware, gateware & software with many users
- **Many applications both within & outside the accelerator community**
  - General synchronisation
  - RF signal distribution
  - Trigger Distribution
- **Current Development**
  - new WR switch (v4)

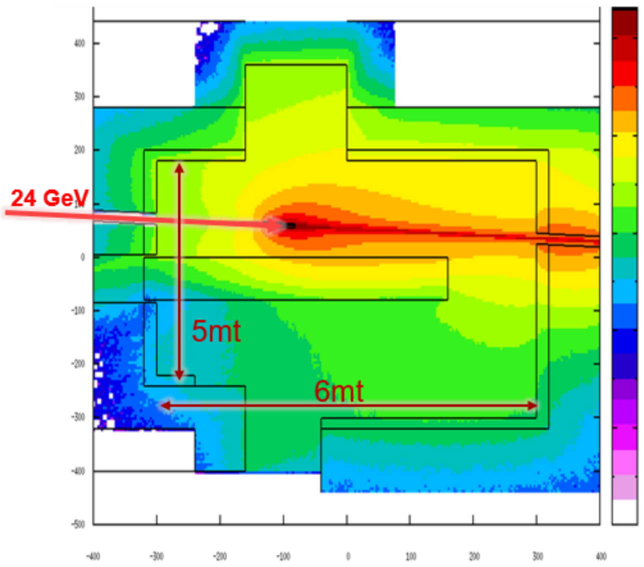
Designing & Testing Radiation Tolerant Electronics

CERN Irradiation Facilities

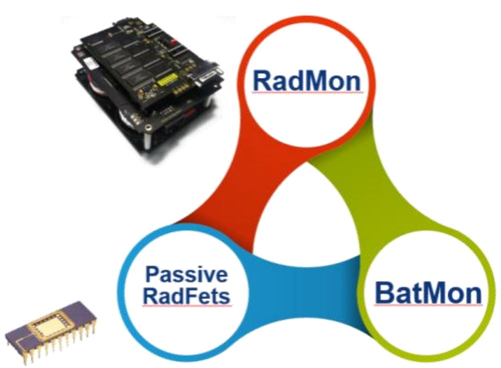
- CERN High Energy Accelerator Mixed field (**CHARM**) & **Cobalt 60** facilities
  - Testing both total dose and single event effects
  - Identifying suitable off-the-shelf (COTS) solutions

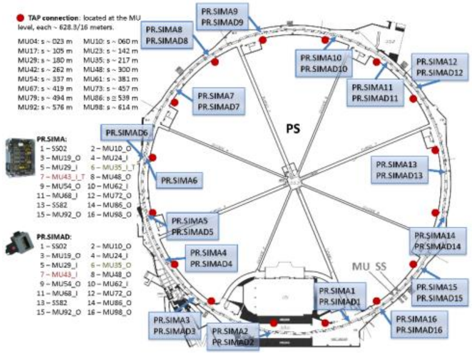


CC60 CHARM



RADMON monitoring system for in-situ measurement of radiation levels on electronics

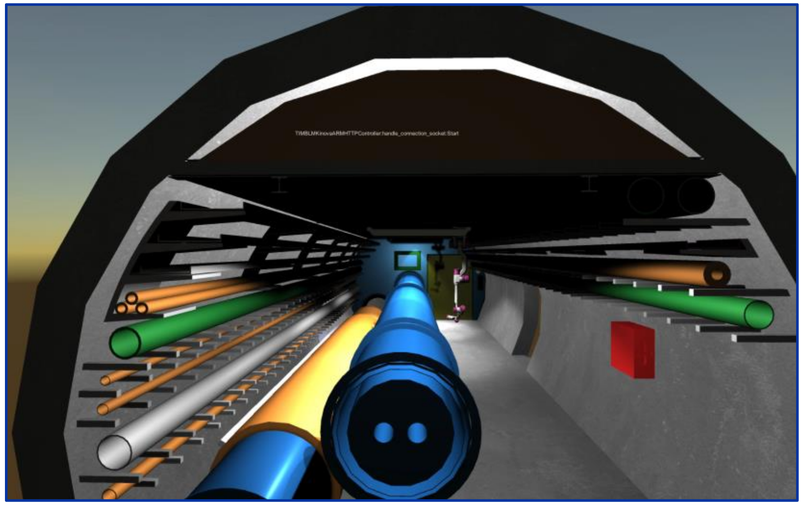




Robotics Technologies at CERN

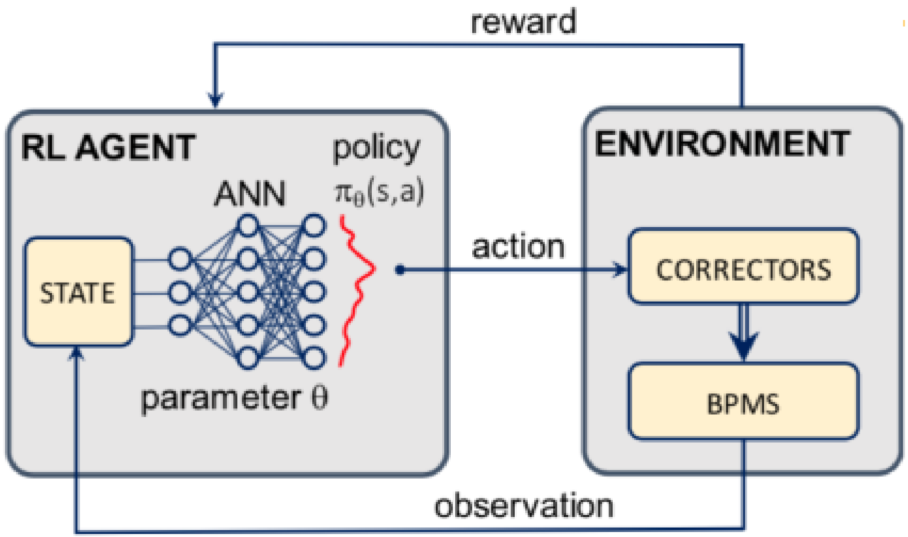
- **Robotics in Harsh Environments**
  - Preparation for human intervention
  - Environmental measurements, maintenance & inspection in radioactive areas
  - Inspection of radioactive devices
  - Reconnaissance & search and rescue

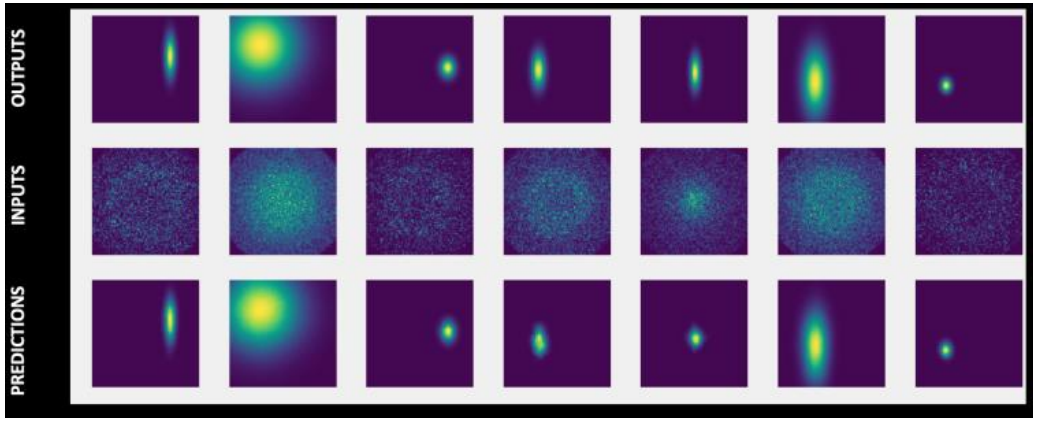
- **Robotics for Remote Installation & Maintenance**
  - Essential for future large machines
  - Concepts to be included at design stage
  - Improvement of autonomy required
  - AI for full automation



Machine Learning for Accelerator Operation

- Use of Generic optimisers
- Use of reinforcement/supervised learning
- Model-predictive control
- Deep Learning
- Quantum reinforcement learning





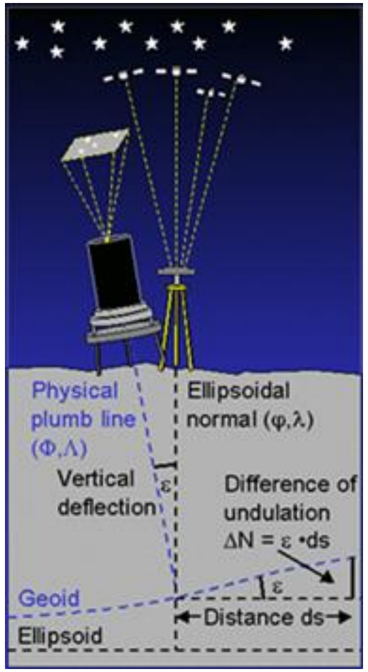
- **Applications**
  - Reduction in time required to find optimal settings in multi-parameter environment
    - Efficient steering of beams
    - Improving system performance
  - Interpreting images

Geodetic Metrology

- **Challenges**
  - Scale from nm to 100km
  - Range in size of components
  - Environment - radiation, cryogenic, limited access,..
  - Accuracy & Precision required

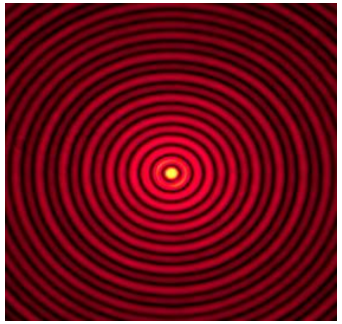
- **Position Monitoring & Adjustment**
  - **HL-LHC**
    - Monitoring of magnet inside cryostat at micrometer level
    - Alignment over all components over 200m better than ~250μm
  - **CLIC**
    - Component alignment at ~10μm
    - Stabilisation of critical components at nanometre level

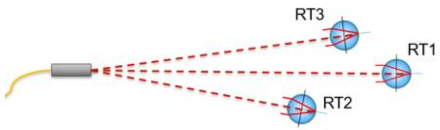
Permanent monitoring



Geodetic aspects

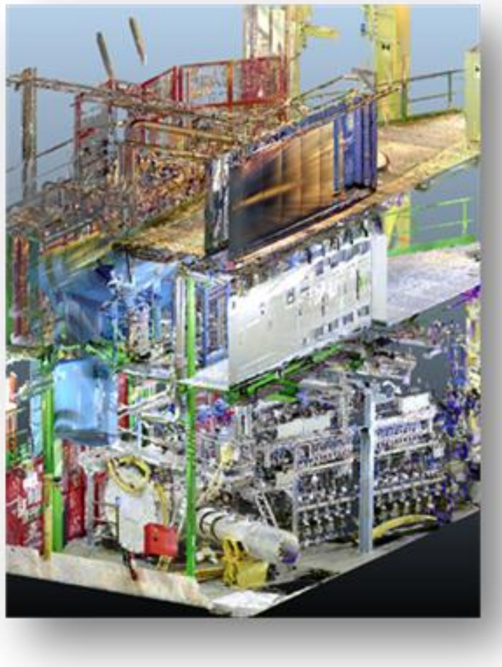
Structured laser beam





Frequency Scanning Interferometry (FSI)

R&D



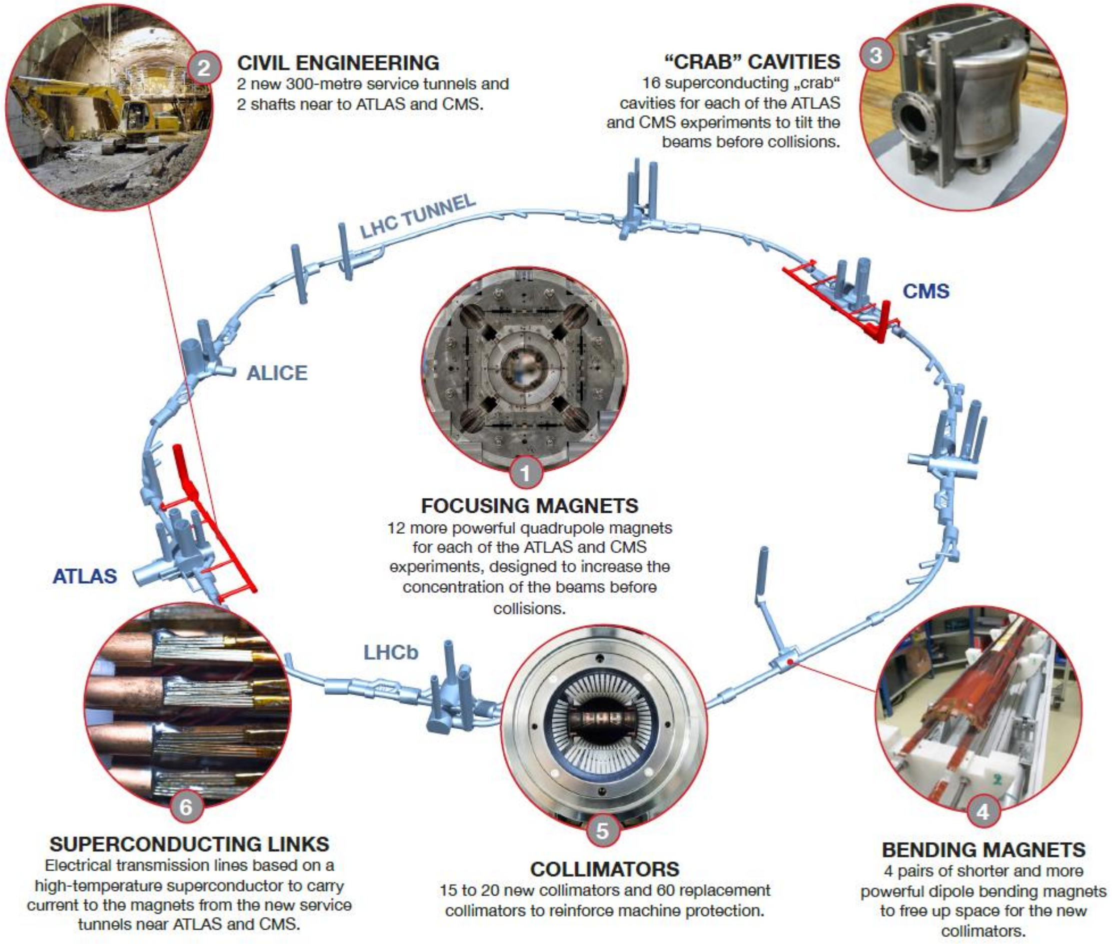
Georeferenced scans

Accelerator Technologies and the Future

Beyond LHC – Already Underway

The High Luminosity Large Hadron Collider (HL-LHC) – to be completed in 2028

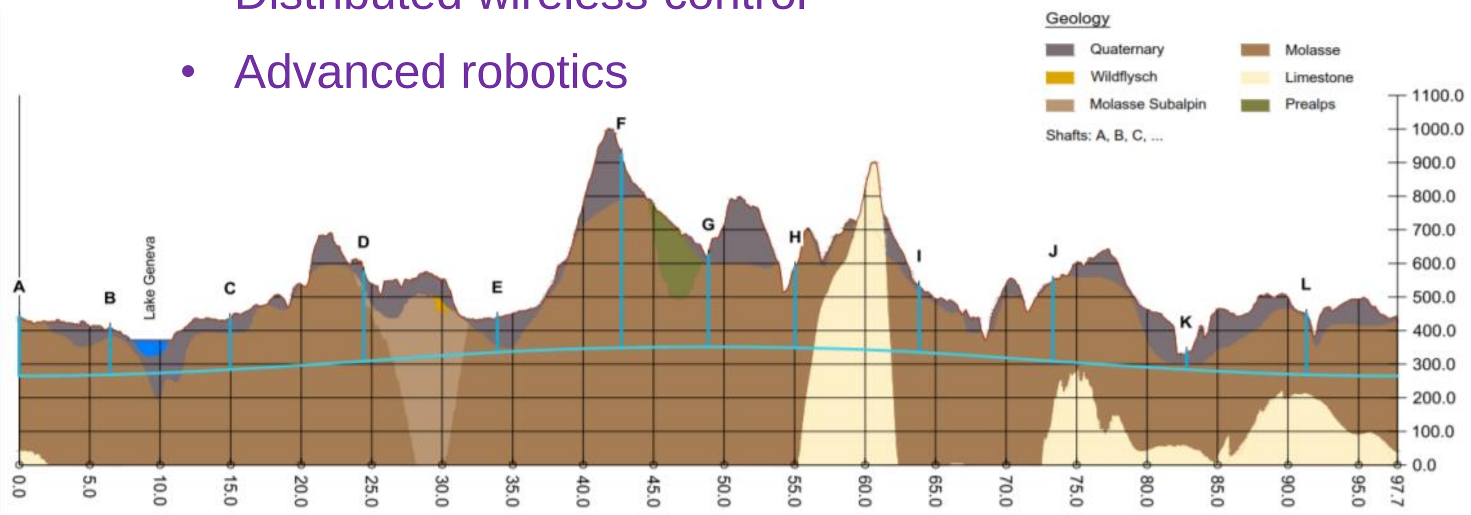
- A 1 billion CHF upgrade of the LHC to achieve a five-fold increase in the number of instantaneous collisions, enabling the experiments to enlarge their data sample by an order of magnitude compared with the LHC baseline programme
- **Key innovative technologies include:**
  - Nb_3Sn superconducting magnets
  - High-power, loss-less superconducting links
  - Compact superconducting radiofrequency cavities with ultra-precise phase control
  - New materials and coatings for beam intercepting devices
  - New dual phase CO_2 cooling technology for the experiments

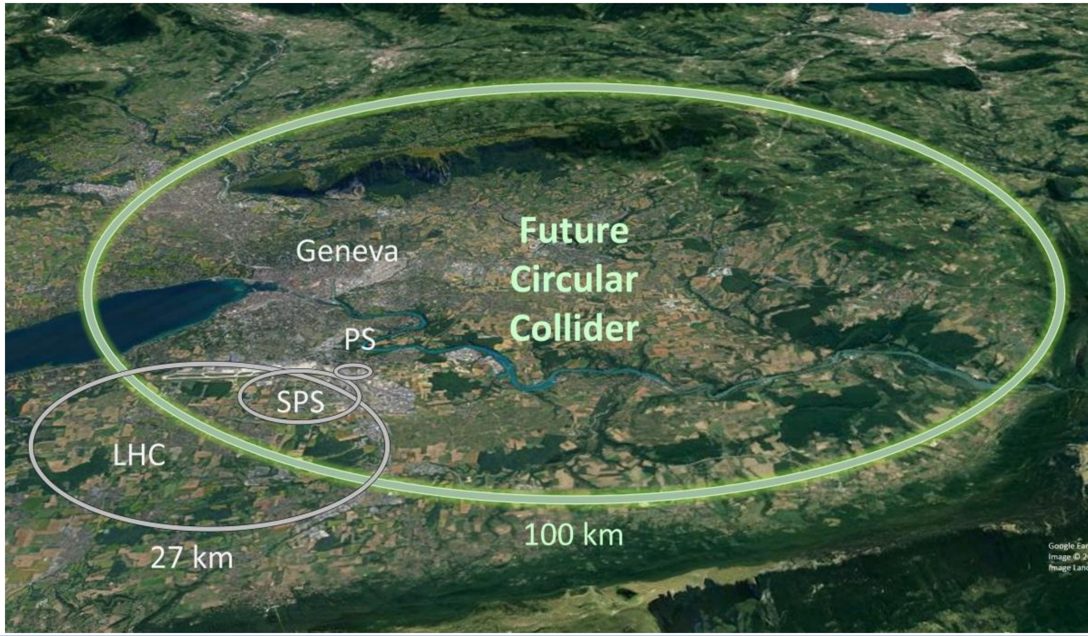


Beyond LHC – Future Possibilities

A Future Circular Collider – feasibility study underway

- Goal: to push the energy frontier of particle colliders to reach 100 TeV (LHC at 13.6 TeV)
- A ~100km ring linking to the existing CERN accelerator complex
- Key technology challenges include:
  - Energy efficient designs for acceleration and magnet powering
  - Nb_3Sn Magnet technology to reach much higher field
  - Higher gradient superconducting RF
  - Distributed wireless control
  - Advanced robotics





Beyond LHC – Future Possibilities

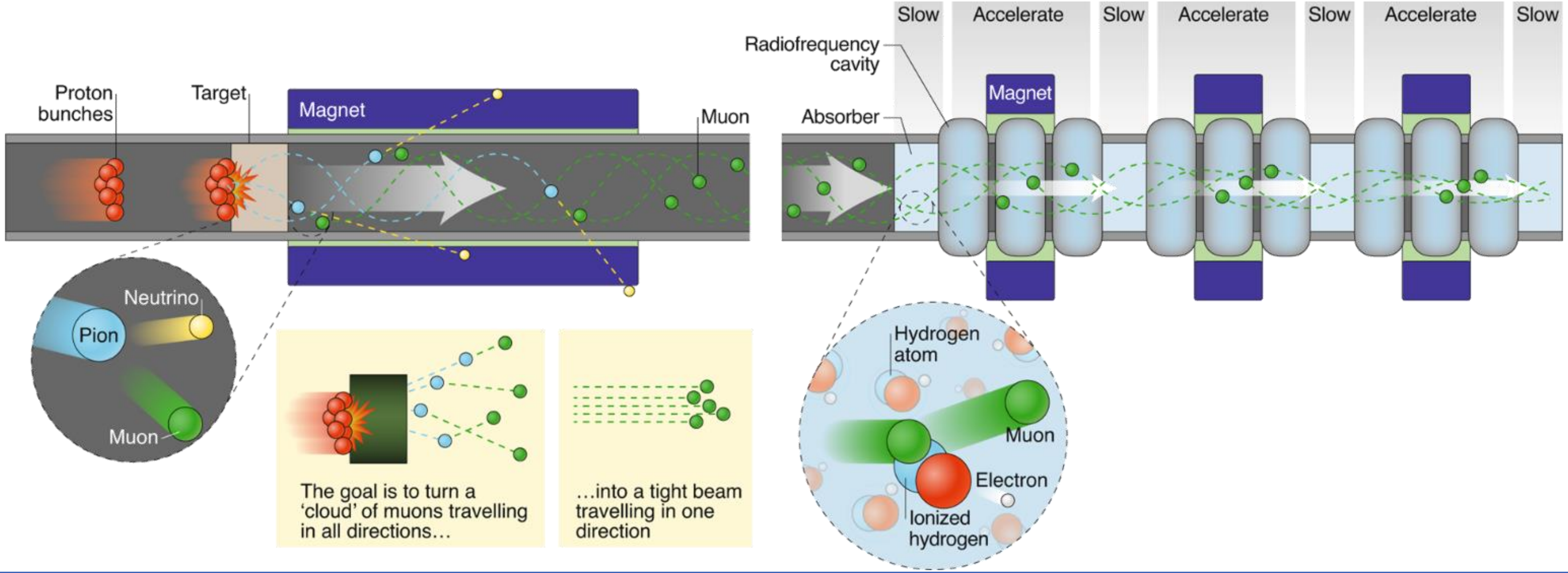
A Compact Linear Collider – technical design report under preparation

- For the era beyond HL-LHC – horizon of 2040
- Novel two-beam accelerating technique using high-gradient, room temperature, X-band RF cavities
- Expandable, staged programme (11 – 50 km) with collision energies up to the energy frontier
- Technology challenges include:
  - Avoiding high-voltage breakdown in any of the 140’000 accelerating structures
  - High precision alignment & stability
  - Minimising power consumption

Looking even further – R&D Concepts

A Muon Collider – study underway

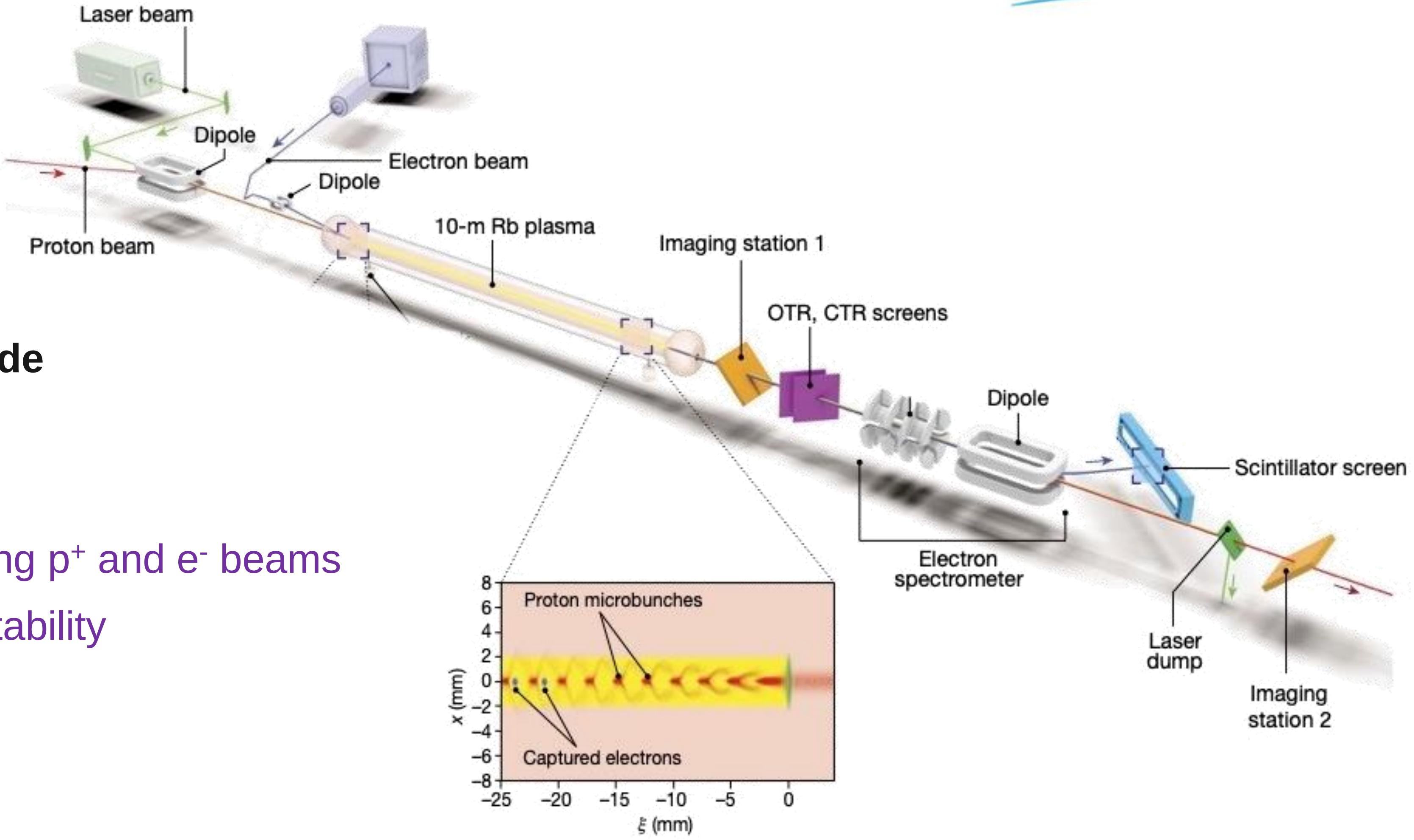
- Promises to reach higher energy and luminosity than linear colliders
- **Global Challenges:**
  - Muons are not stable (lifetime only 2.2 μs at rest) so acceleration needs to be very fast
    - At relativistic speeds their lifetime is much longer : time slows down for the muon!
    - Muons decay to produce neutrinos leading to radiation issues at the surface
- **Technology challenges include**
  - Very high-field magnets
  - Efficient radiofrequency
  - Robust beam targets



Looking even further – R&D Concepts

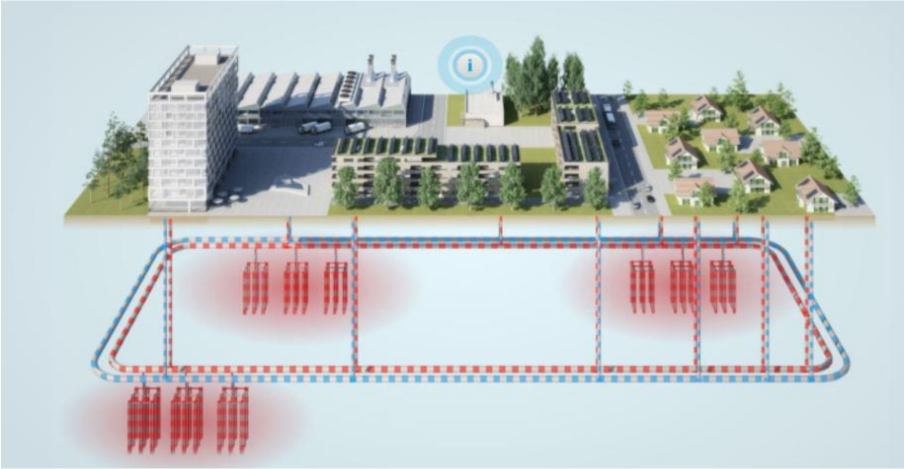
Plasma Wakefield Acceleration – Experimental studies underway

- Novel acceleration concept being studied by the AWAKE experiment at CERN
- Replaces traditional radiofrequency cavities with a plasma cell for acceleration
- **Technology challenges include**
  - Long plasma cells
  - Powerful laser systems
  - Instrumentation of overlapping p^+ and e^- beams
  - Power supply and magnet stability



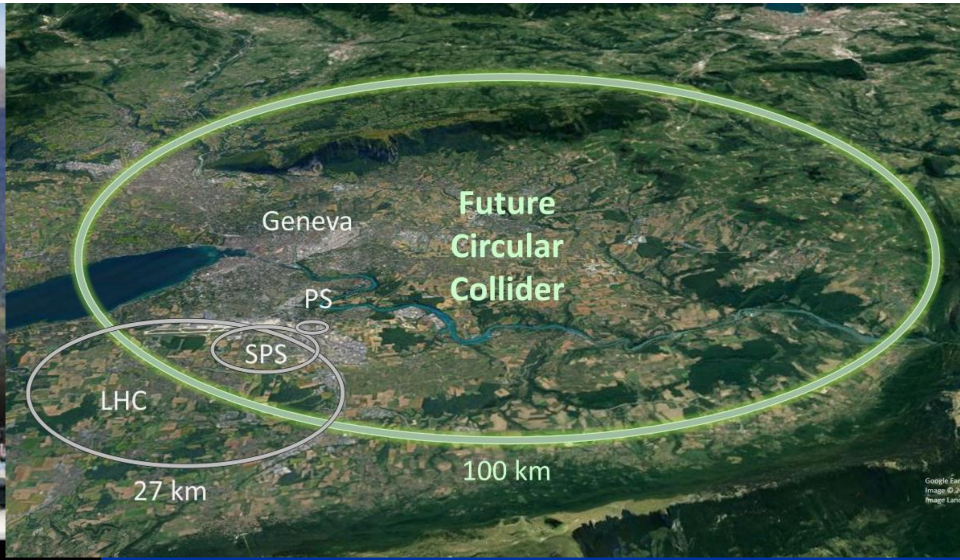
A Challenge of Today - Sustainability

- **Any future large scale accelerator needs to consider sustainability at the design stage**
- **Significant effort ongoing to address this**
  - **Reducing waste energy**
    - Heat recuperation from cooling systems
    - Adaptive control systems for energy efficiency in accelerator operation and infrastructure management
    - Energy recovery and load-levelling
  - **Lowering the carbon footprint**
    - Replacing high-global-warming-potential gases with more environment-friendly ones
      - Move from traditional gases (Global Warming Potential of ~8,000) to CO_2 (Global Warming Potential 1) for the High Luminosity LHC upgrade
  - **Improving existing technology:**
    - High efficiency klystrons for radiofrequency powering
    - Use of high field permanent magnets



Closing remarks

- The next generation particle accelerator for High Energy Physics is not yet decided, but will depend fully on new technologies to extend the energy, intensity and sustainability frontiers
- CERN has ambitious R&D programmes under way to develop technology for the future
- The spectrum of activities is broad, multi-disciplinary and depends on global collaborations
- Priorities and objectives will evolve, including the key theme of energy sustainability
- Technology is at heart of today's accelerator operation and development for the future



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