European Projects for Collaborative Accelerator R&D

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A special seminar for the JUAS 2020 cycle

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Outline and motivation

Collaborative European R&D for particle accelerators

- Why R&D ?
- Why collaborative ?
- Why European ?

This is not a lecture, is a seminar that goes through:

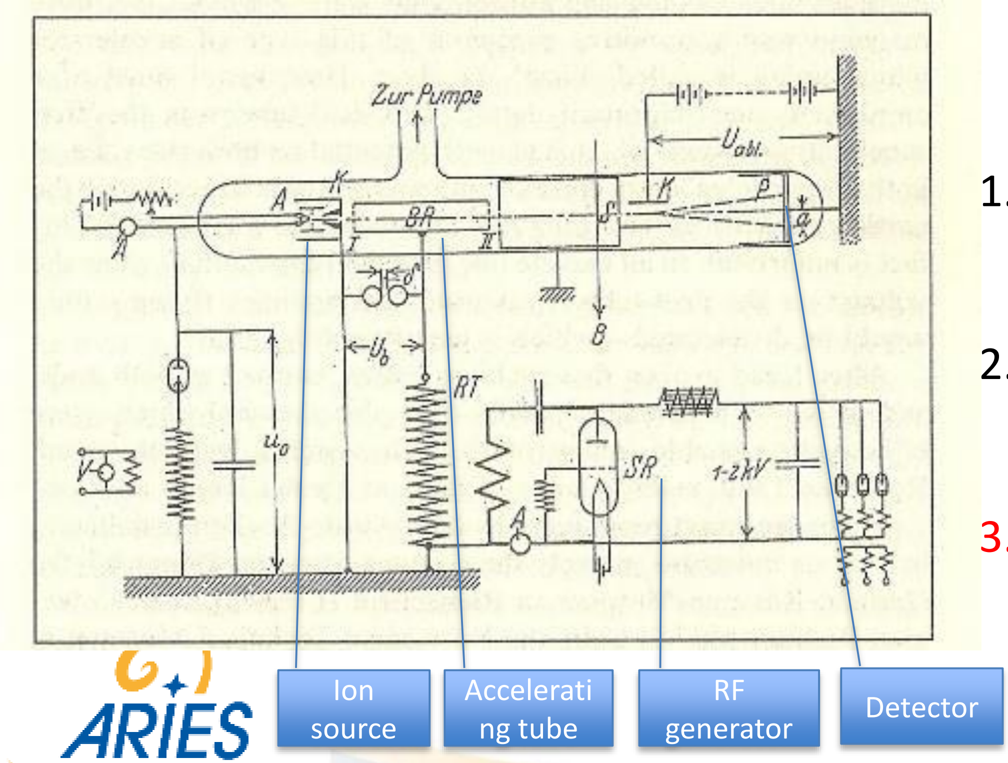
- 90 years of history of particle accelerators;
- The reasons and limitations of particle accelerator success;
- The need for innovation;
- Collaborations and the European perspective;
- The roadmaps to the future
- Some work for the new generations…

Particle accelerators: 92 years of history!

In 2018 was celebrated the **90th anniversary** of the invention of modern particle accelerators (using periodic acceleration provided by Radio-Frequency fields).

Rolf Wideröe's PhD thesis, 1928

Acceleration of potassium ions 1+ with 25kV of RF at 1 MHz → 50 keV acceleration in a 88 cm long glass tube) "at a cost of four to five hundred marks", less than 2'000 € today!



1. use of Radio-Frequency technology (at the time limited to 1-2 MHz) ⟶ marrying radio technology and accelerators.
2. Use of a drift tube separating 2 accelerating gaps → invention of periodic acceleration.
3. complete accelerator: ion source, RF accelerator, detector, all in vacuum

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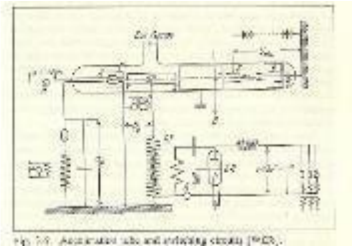
At the root of innovation

What were the ingredients of Rolf Wideröe's innovation?

- He was young (*PhD student, fresh ideas and time available*)
- He was under pressure to complete his thesis *(«necessity is the mother of invention»)*
- He was merging information and experience from different fields *(cross-fertilisation)*
- He was going all the way down to practical realisation (*to «innovate»*).

The Oslo Manual (OECD/Eurostat, 2005), defines innovation as "the implementation of a new or significantly improved product or process …"

Innovation in the particle accelerator field



1931…………1945/48….1952…………1965/90's…….

Cyclotron: cyclic acceleration with magnets (Lawrence)

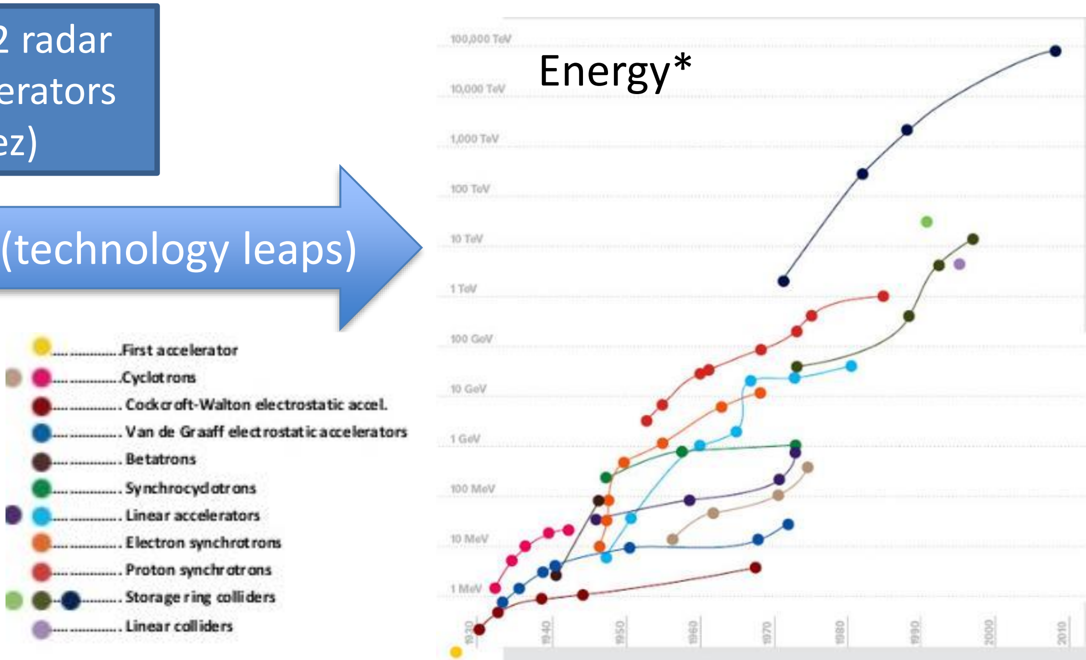
Application of WW2 radar technology to accelerators (Hansen, Alvarez)

Strong focusing (Courant, Livingston, Snyder, Christofilos)

Superconductivity – magnets and cavities

Succession of enabling technologies (technology leaps)

S. Livingston, 1959:
Accelerator energy increases by a factor of 10 every 6 years
(Moore's law of accelerators)



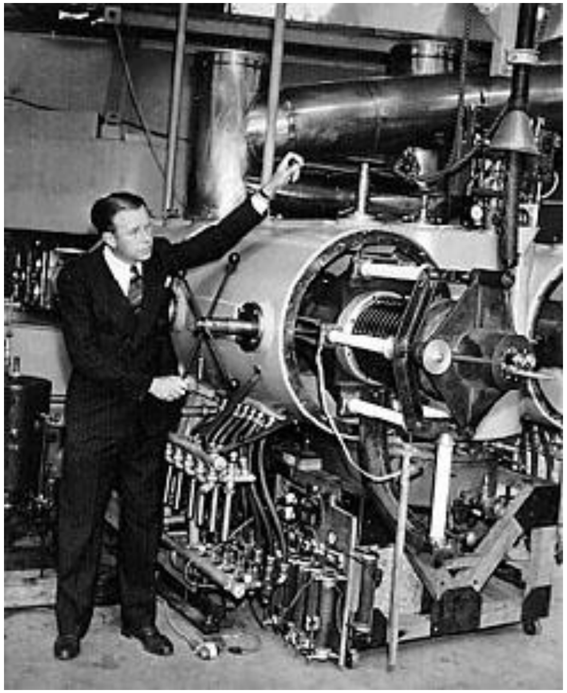
2009 Livingston plot, Symmetry magazine

**: for colliders, energy to reach same c.o.m. energy in collision with proton at rest*

Technology drivers

What were the **motivations** for all these innovations in accelerator technology? What were the «**technology drivers**»?

Basic science with its quest for new discoveries, coupled with some ambition to use the technologies for society (well-being).



Ernest Orlando Lawrence was the inventor of the cyclotron but also the inventor of «big science» as we know it (large scientific endeavours implying large budgets, with the support of industry and governments).

Physicists were striving to get more data from his first cyclotrons, but he reserved some 50% of beam time to production of medical isotopes and to the first cancer treatments with neutrons.

In a letter to Niels Bohr of 1935 he wrote: *«I must confess that one reason we have undertaken this biological work is that we thereby have been able to get financial support for all of the work in the laboratory. As you know, it is much easier to get funds for medical research.»*

In the WW2 years Lawrence moved to military research, and inaugurated a new «technology driver». Are we back to medicine as the main technology driver of the XXIst century?

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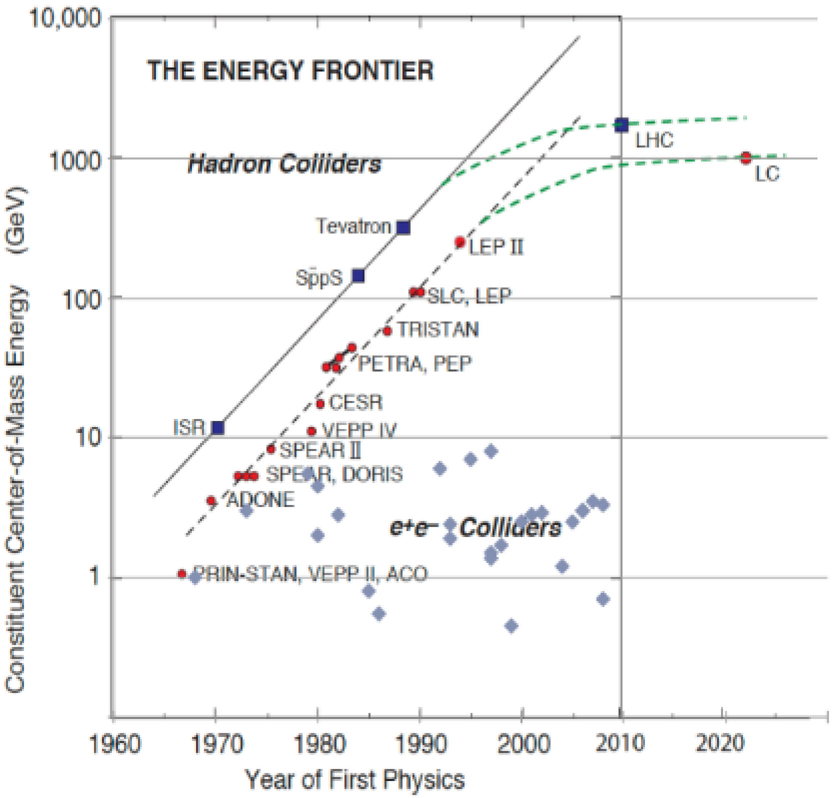
Particle Accelerators in 2020

we have reached the end of exponential energy growth



Updated Livingstone-type chart (Wikipedia 2014, uploaded by J.Nash, Imperial College)

But the field has never been so flourishing…

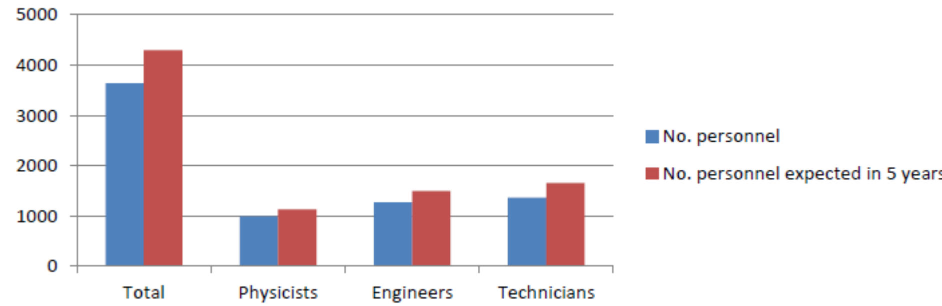
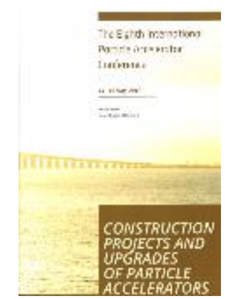


Figure 2.1: Total number of current personnel (blue) engaged in accelerator science activities a research institutes. The number of personnel expected in 5 years is shown in red.

TIARA, Need for Accelerator Scientists report, 2013: 3’700 people engaged in accelerator science in Europe, expected growth to **4’400** by 2018.



As many as **50** ongoing accelerator construction or upgrade projects listed in the 2017 IPAC Conference (13 America, 11 Asia, 26 Europe)

2’200 abstracts submitted at IPAC20

From basic science to applied science and society

We are moving from a paradigm where **basic science** is the driving force for the development of new accelerators to a new paradigm where **applied science** (photon and neutron science) and **health** appear as new driving forces for innovation in accelerator science. Medicine and materials are becoming the technology drivers of the XXIst century.

There are more than 30'000 particle accelerators in the world.

Where are they?

Research		**6%**
	Particle Physics	0,5%
	Nuclear Physics, solid state, materials	0,2 a 0,9%
	Biology	5%
Medical Applications		**35%**
	Diagnostics/treatment with X-ray or electrons	33%
	Radio-isotope production	2%
	Proton or ion treatment	0,1%
Industrial Applications		**60%**
	Ion implantation	34%
	Cutting and welding with electron beams	16%
	Polymerization	7%
	Neutron testing	3.5%
	Non destructive testing	2,3%

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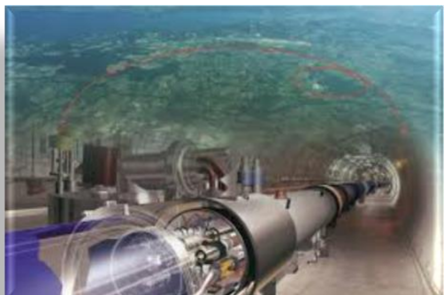
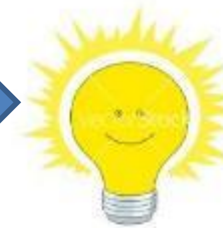
Accelerators in transition – not only particle physics!

1. Transition to new more affordable and sustainable technologies for basic science
2. Transition from basic science as main technology driver to a multiple system where applied science, medicine and industry can drive accelerator development.
3. Transition from a centralised configuration based on large laboratories to a distributed scheme (project clusters of small and large laboratories and industry)



Basic science

Limitations related to size, cost, energy.



New ideas, technologies

Applied science (photon and neutron sources)

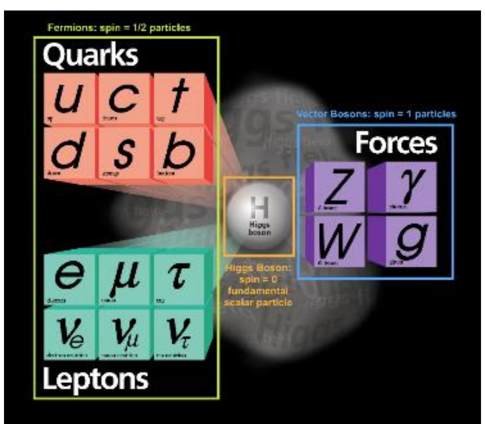
Societal applications (medicine, industry, environment, etc.)

Reaching the limits of sustainability ?

Particle physics has been from the very beginning the **technology driver** for the development of particle accelerators: the **quest for new particles** at increasingly higher energies has motivated the development, construction and financing of increasingly large accelerators. And now?

Physics:
After the discovery of the Higgs boson the Standard Model is complete – many questions remain open (dark matter, antimatter asymmetry, etc.) and their solutions are probably related to new unknown particles, but so far no clear predictions exist to be verified by an accelerator.

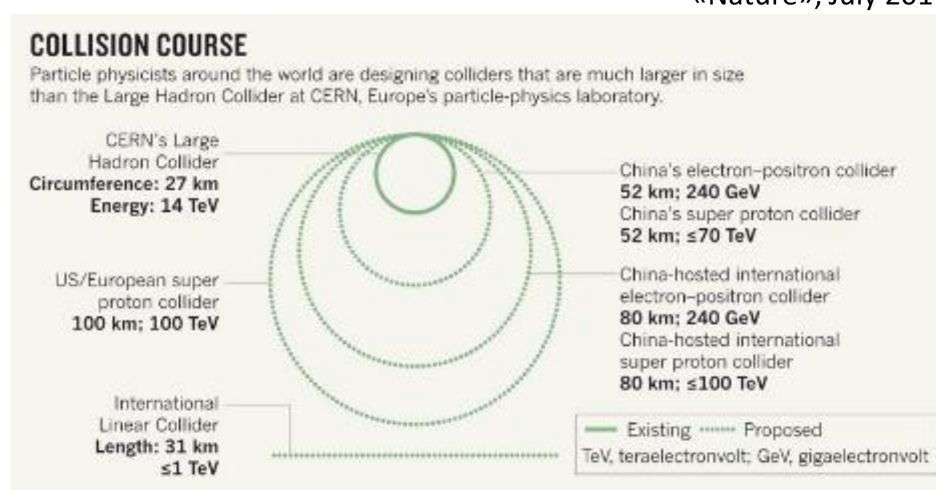
→ Difficulty to justify new large projects



Accelerators:
The **size, cost and energy consumption** of the accelerators required to go beyond the standard model rise questions on the long term sustainability of accelerator-based particle physics.

→ Difficulty to implement new large projects

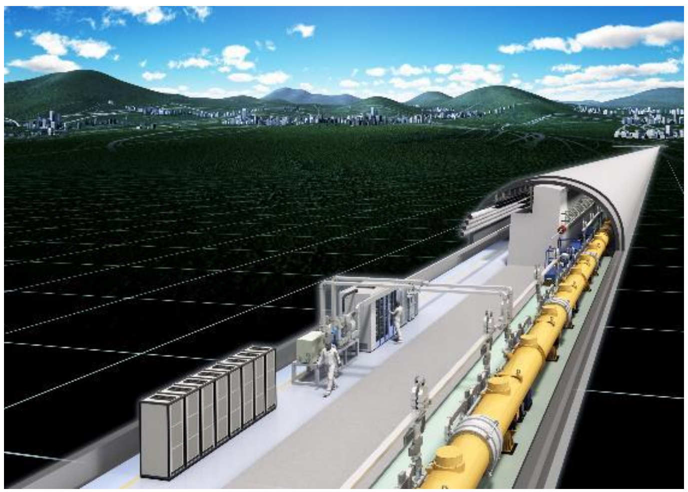
«Nature», July 2014

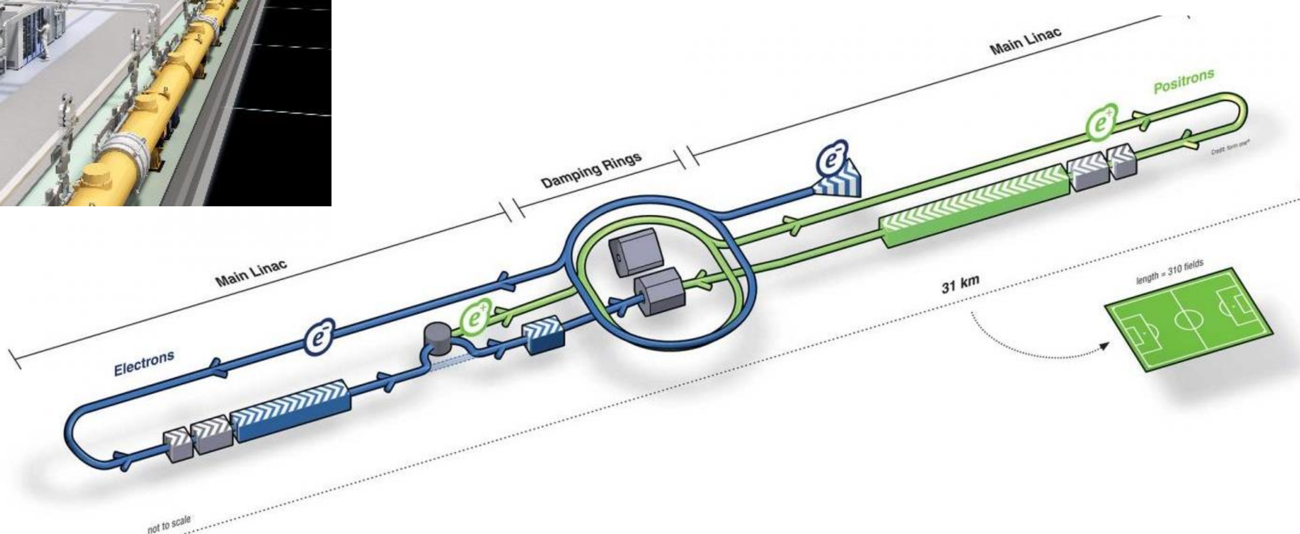


An example: the International Linear Collider

From the 19 December 2018 report of the Science Council of Japan on the construction of an International Linear Collider in Japan:

"In view of the finite resources available to humanity, the research style that presupposes an ever-growing scale-up of gigantic experimental facilities would eventually reach the limit of sustainability. The future way of "big science" is a theme to be deliberated by the whole academic community."



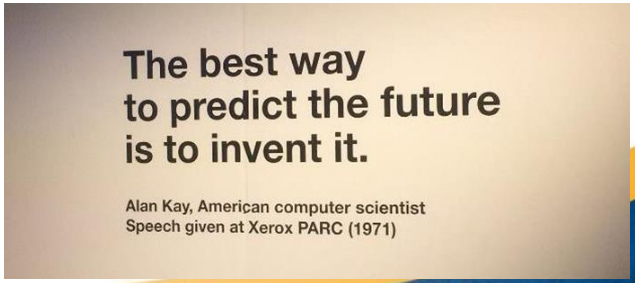


The big challenges for accelerator science

Making accelerator-based particle physics research more sustainable is going to be one of the main challenges to the accelerator community for this XXIst century.

At the same time, we need to work to bring accelerator technology outside of our traditional laboratories, to be used for applied science (materials, biology, etc.), medicine and industry.

We need new ideas
We need a collaborative and creative environment for these ideas to grow



Introducing ARIES

ARIES = Accelerator Research and innovation for European Science and Society

- Integrating Activity for Particle Accelerator R&D, co-funded by the European Commission under the Horizon 2020 programme, Grant Agreement 730871.
- Duration: 4 years, 1 May 2017 – 30 April 2021.
- EC contribution 10 M€, total cost 24.9 M€.
- 42 beneficiaries from 18 EU countries

https://aries.web.cern.ch/

ARIES mobilizes more than 400 physicists and engineers from 18 European countries

We are now preparing the successor project to ARIES that will cover the time frame 2021-25.

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EU support to particle accelerator R&D

FP6

CARE 01/2004 – 12/2008
5 years, 15.2 M€ EC contribution

FP7

EuCARD 04/2009 – 03/2013
4 years, 10.0 M€ EC contribution

EuCARD-2 05/2013 – 04/2017
4 years, 8.0 M€ EC contribution

H2020

ARIES 05/2017 – 04/2021
4 years, 10.0 M€ EC contribution

Integrating Activities

New Innovation Pilot (I.FAST)
05/2021 – 04/2025
4 years, 10.0 M€ EU contribution

Innovation Pilot

Long tradition of EC support to generic accelerator R&D: 4 successful Integrating Activities have raised 43 M€ EC funding over 16 years (2.7 M€/yr).

Cross-boundary subjects, not directly followed by large laboratories, with added value coming from collaboration and sharing of resources

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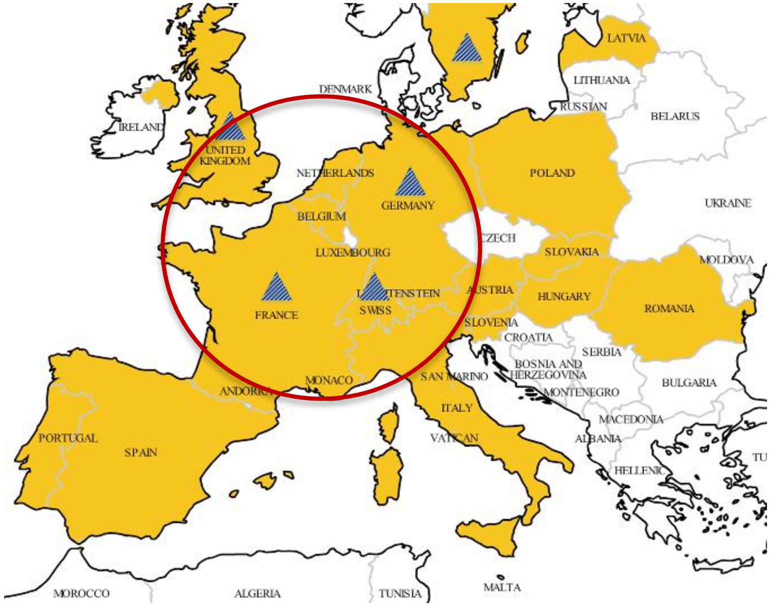
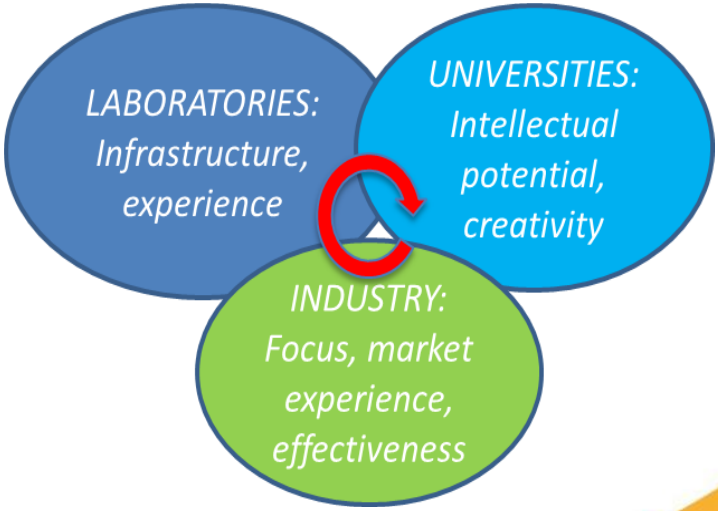
Connecting Europe, connecting academia with industry

- 42 partners from 18 European countries
- Goals: connect the technological core of Europe with its dynamic periphery, connect the large laboratories with universities, research centers and industries.
- 12 Laboratories and research institutions, 21 Universities and research centres, 8 industries.



80% of EU Research Infrastructure is based in only 4 countries



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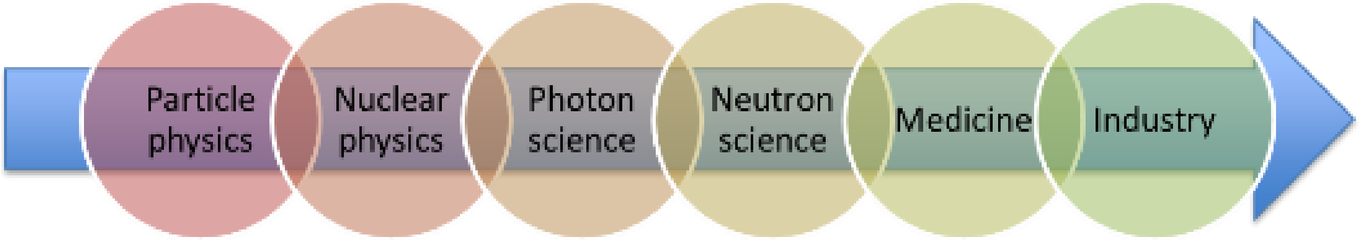
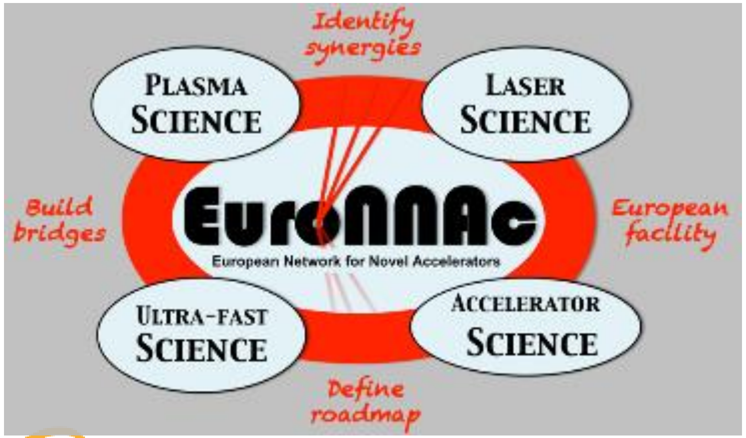
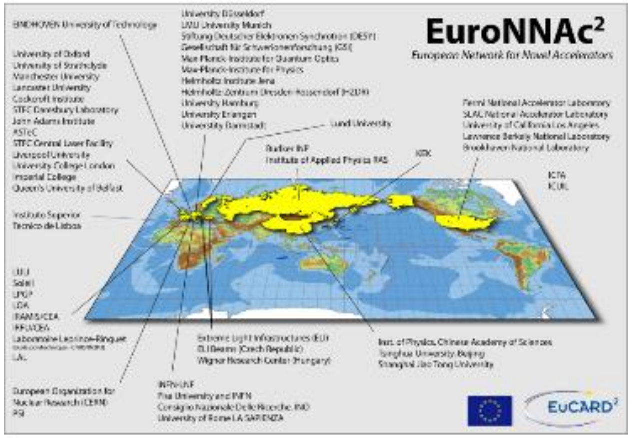
The goal: building bridges across communities



2 examples:

Convergence between synchrotron light ring facilities and electron rings for particle physics (factories and damping ring for colliders).





Plasma-based acceleration

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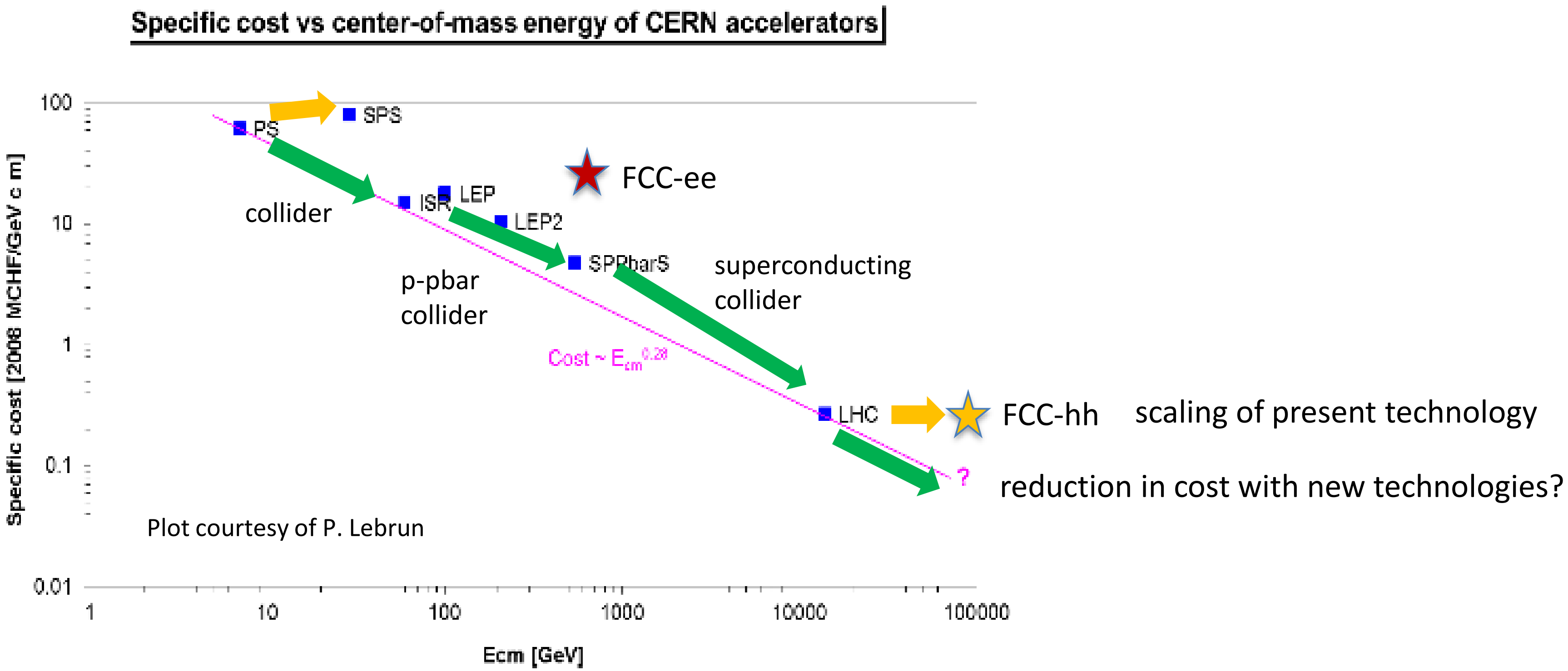
Multiple dimensions of accelerator R&D

The Economist, October 2013

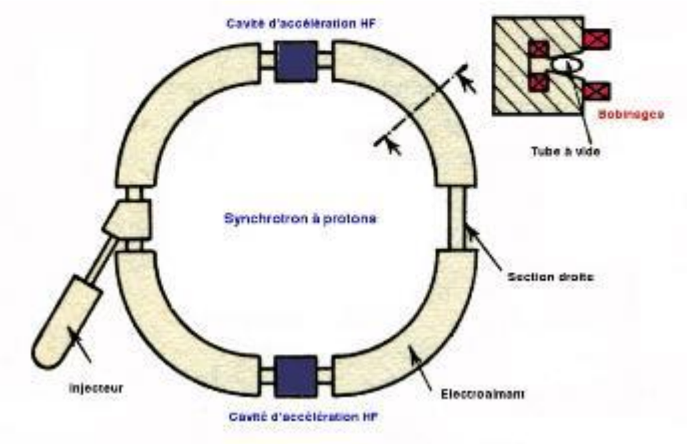
Frontier accelerators – economic sustainability



Where is the limit of sustainability? It depends on the economical environment and on the priorities of a given society.

To remain within the present limits we need innovative technologies.

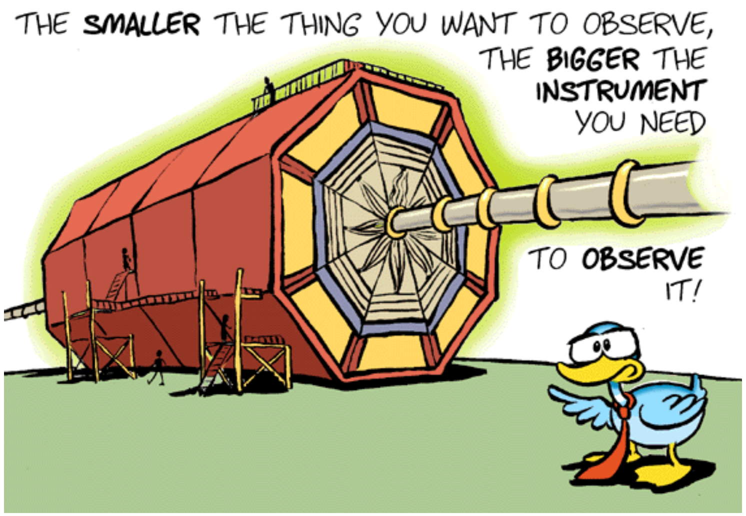
Smaller accelerators?

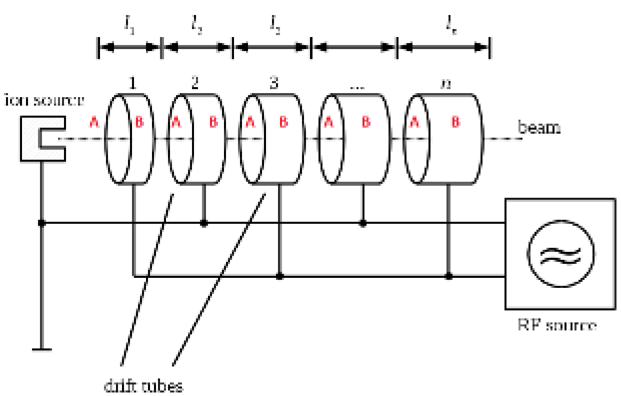


Synchrotrons: p/q=Bρ

Need to maximise magnetic field

Limitations: critical current density Jc for SC magnets





Linear accelerators: W=Eℓ

Need to maximise electric field

Limitations: sparking, field emission, etc.

(and RF power, proportional to V^2 !)

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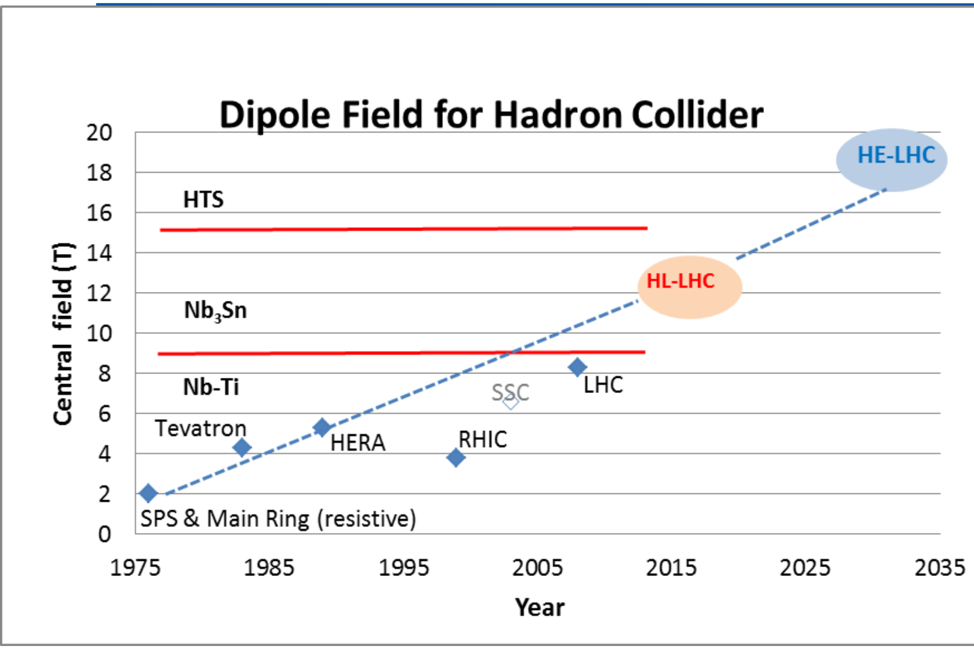
The dipole field frontier – ARIES for HTS

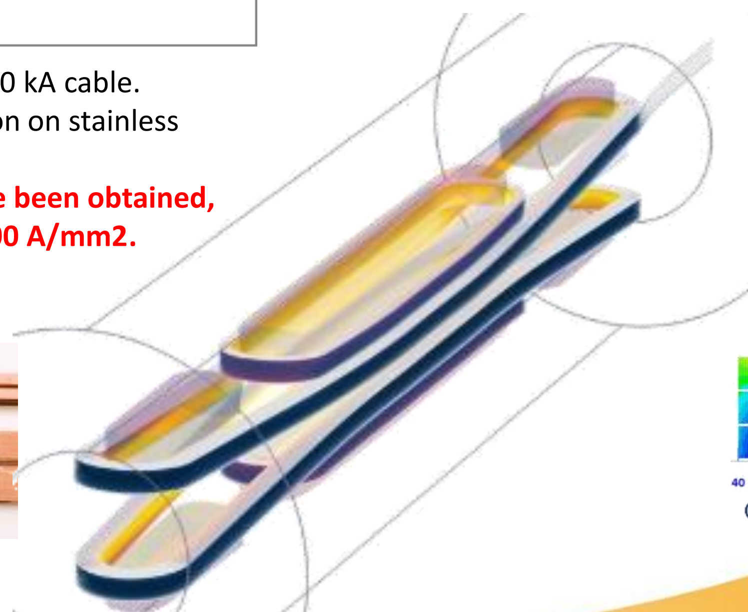


1. **NbTi** mature technology but limited to 9T
2. **Nb_3Sn** technology has seen a great boost in the past decade (factor 3 in J_C w/r to ITER) but is not yet used in an accelerator – HL-LHC as first step.
3. **HTS** High-Temperature Superconductor technology still in the experimental phase (Production quantities, homogeneity and cost need to evolve!) but can be the disruptive technology for future high-field magnets.

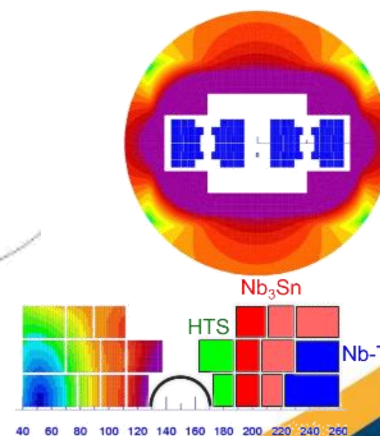
EuCARD-2 and ARIES are the place where HTS magnet technology is developed in Europe.

R&D towards a 20 T HTS dipole magnet, develop 10 kA cable.
REBCO (rare earth barium copper oxyde) deposition on stainless substrate, tape arranged in Roebel cables.
values of 900-1200 A/mm2 at 4.2 K , 18-20 T have been obtained, well above the ARIES minimum target value of 800 A/mm2.

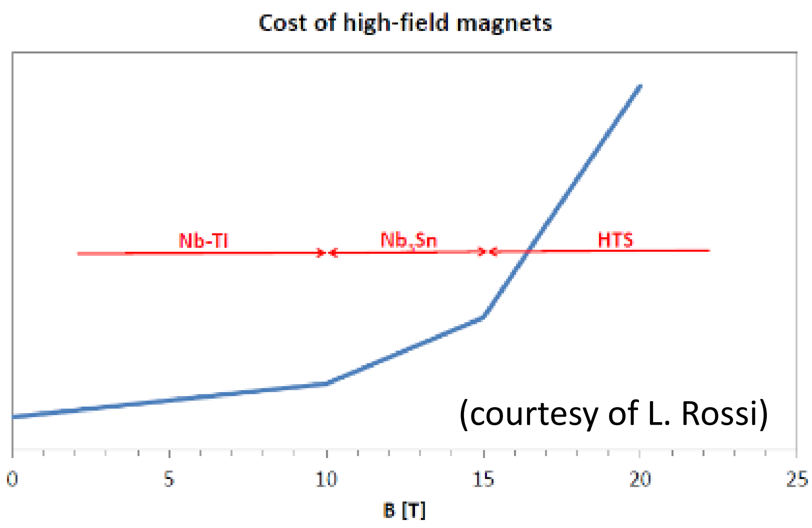
Fig. 1. A 12 mm tape produced by BHTS via ABAD and PLD method.

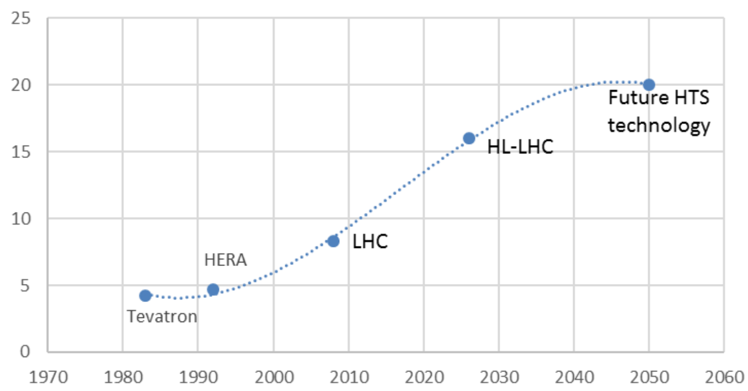


A 20 T HE-LHC dipole
L. Rossi & E. Todesco, (CERN)

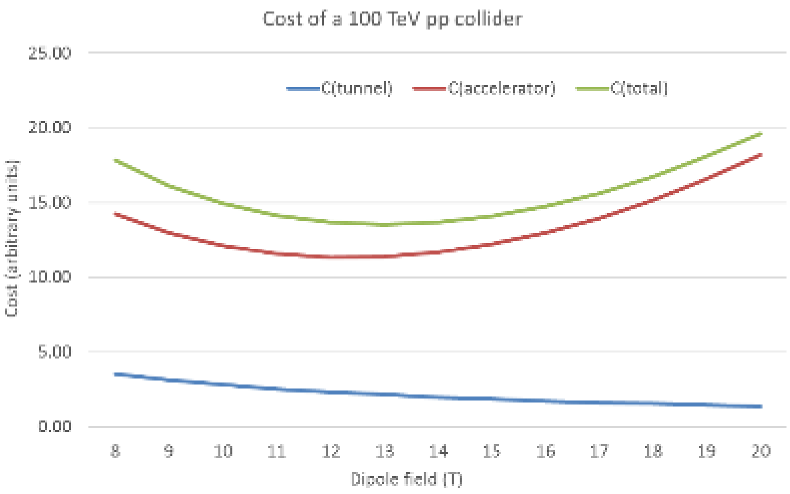


HTS magnets – reaching the limit?



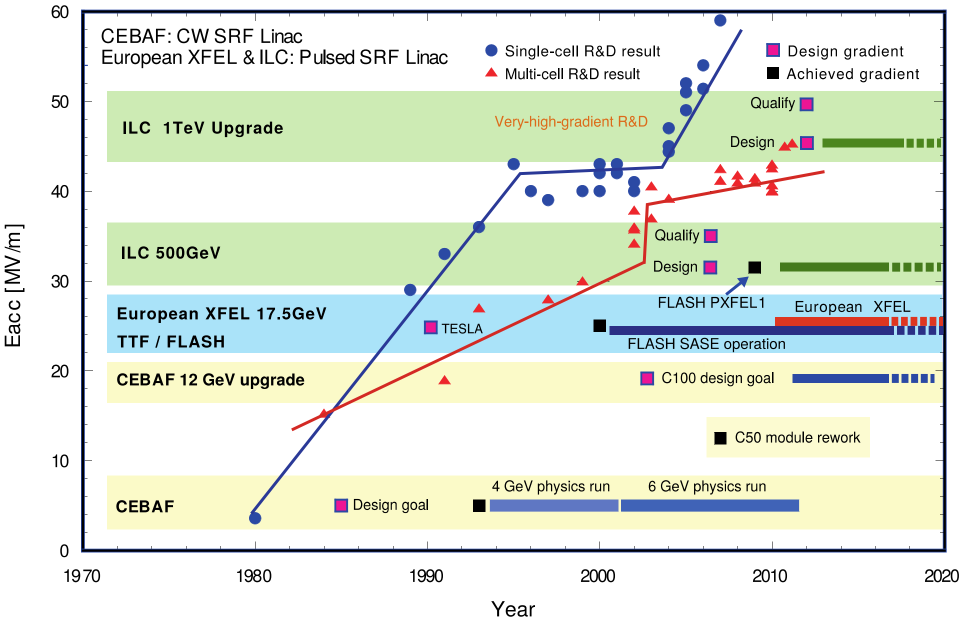


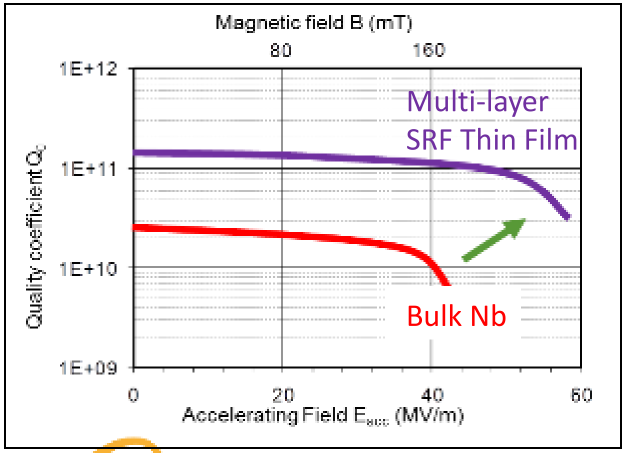
HTS allows reducing the size of the accelerator but not (yet) the cost



Superconducting magnet technology approaching saturation; increasing costs for minor performance improvements

The electric gradient frontier - superconducting





TRENDS:

- Coating of Nb with a thin layer of Nb_3Sn (allows operation at larger T, improved cryogenic efficiency)
- Coating of Cu cavites with Nb by HiPIMS (High Power Impulse Magnetron Sputtering,

EuCARD2 RF: R&D new higher-gradient superconductors: bulk Nb3Sn and nanometric multilayers of high Tc SC.

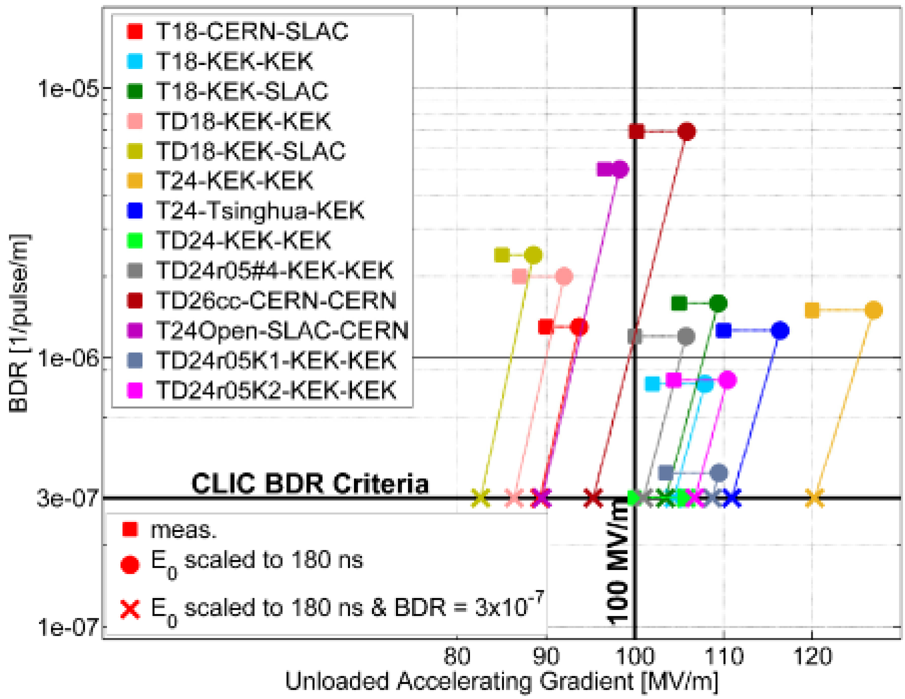
Support to the CLIC R&D for high-gradient NC.

(+ Nb sputtering, beam generation, beam diagnostics)

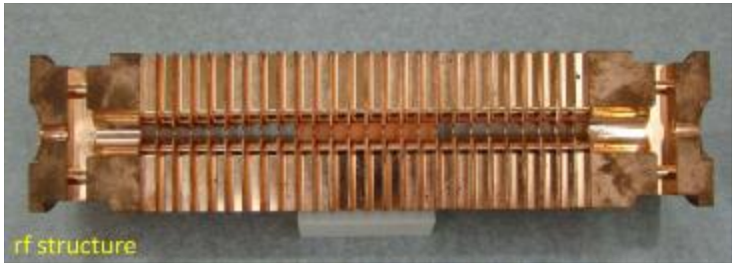
ARIES RF: new coating techniques (Nb and Nb3Sn on copper substrate)

Long-term goal: 60 → 90 MV/m

The electric gradient frontier – normal conducting



Most advanced results by the CLIC study at CERN
(some design supported by EuCARD2, testing supported by ARIES)



Pulsed systems, characterised by a BreakDown Rate (BDR), pulses lost because of vacuum arcing in the structure

100 MV/m gradient can be achieved (and exceeded)

… but the power scales as the square of the gradient!
High gradient means smaller dimensions but higher power consumption.

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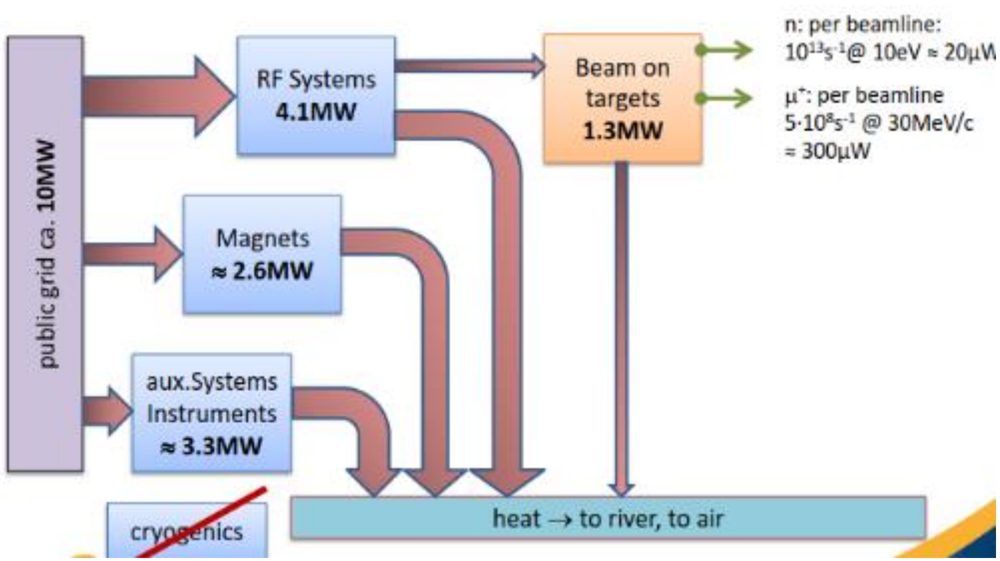
Efficient energy management

Total electricity consumption (GWh/y)	
PSI	125
ESRF	60
ISIS	70
KVI	4
INFN	25
ALBA-CELLS	20
GSI	60
CERN	1200
SOLEIL	37
ESS	317
MAX IV	66
DESY	150

Future large projects require huge amounts of electrical power.
Example: the ILC needs about 1/3 of a Fukushima-type nuclear reactor.
Going green? to supply CLIC500 or ILC would be needed 200 large windmills (80m diameter, 2.5 MW, 50% efficiency) covering a 100 km distance.

Electrical power consumption (MW) for LHC and future projects (estimated)		
	normal	Stand-by
LHC	122	89
HL-LHC	141	101
ILC	230	
CLIC 500 GeV	235	167
CLIC 1.5 TeV	364	190
FCC pp	250?	150?



Example: power flow in the PSI cyclotron facility (analysed in EuCARD2)

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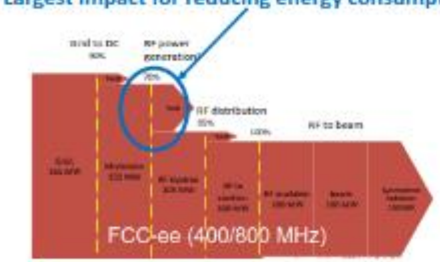
Some initiatives to improve power efficiency

EuCARD-2 WP3: energy recovery from cooling, more efficient RF systems, energy storage, virtual power plant, low-power transport channels.

Tunable high-gradient permanent magnet quadrupoles

Largest impact for reducing energy consumption of accelerators by RF power generation



Increase of 5% efficiency for RF generation
➔10 MW less electricity consumed
➔gain 50 GWh/year (2M€/year)

Increase of 5% efficiency of 12 GHz klystrons
➔10% less electricity consumed
➔gain 100 GWh (4 M€)

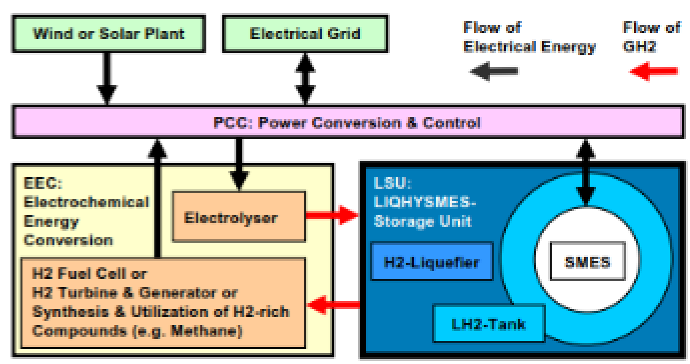
Photo: CLIC Xbox 12 GHz facility for cavities conditioning

Development of high-efficiency RF power sources

LIQuid HYdrogen & SMES

development by KIT for general purpose:
hybrid SMES/LH2
[M.Sander, R.Gehring, KIT]

- large power 10..100 MW
- capacity to ~70 GWh
- SMES to ~10 GJ
- synergy with existing cryogenics



Energy storage systems for accelerators

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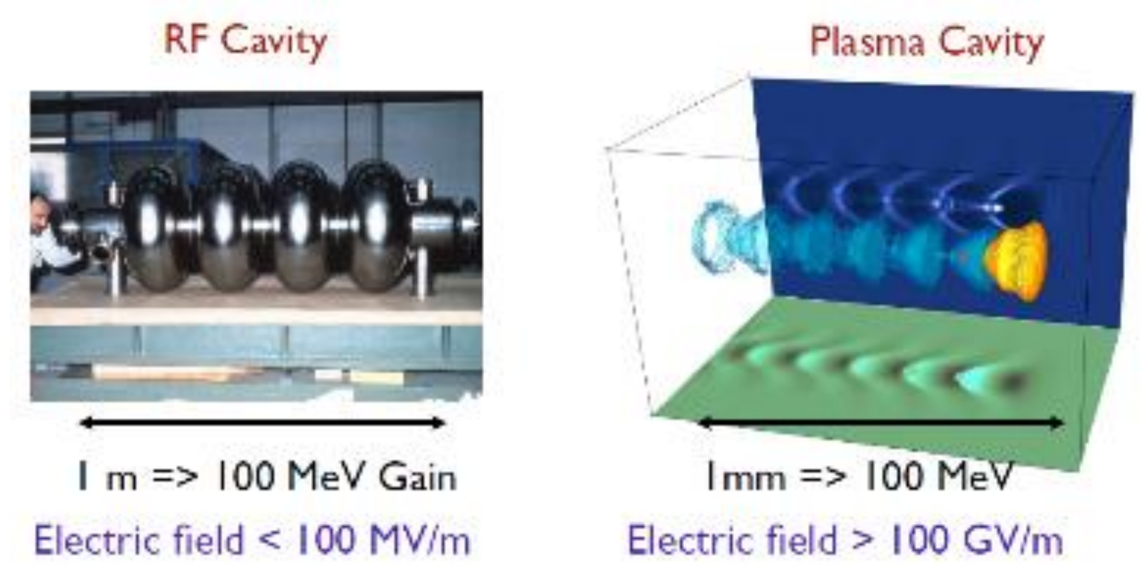
New acceleration techniques using lasers and plasmas

Accelerating field of today's RF cavities or microwave technology is **limited to <100 MV/m**

Several tens of kilometers for future linear colliders

Plasma can sustain up to **three orders of magnitude much higher gradient**

SLAC (2007): electron energy doubled from 42GeV to 85 GeV over 0.8 m → 52GV/m gradient



V. Malka et al., Science **298**, 1596 (2002)

An essential part of the EuCARD-2 and ARIES programmes

Two directions

Lasers can produce huge transverse electric fields (TV/m !)

Can we convert the transverse fields into longitudinal and use them for acceleration?

(1) Micro/Nano-Accelerators

Send THz Laser into Dielectric Waveguide (Micro-Accelerator)

(2) Plasma Accelerators

Use a plasma to convert the transverse electrical field of the laser (or the space charge force of a beam driver) into a longitudinal electrical field in the plasma.

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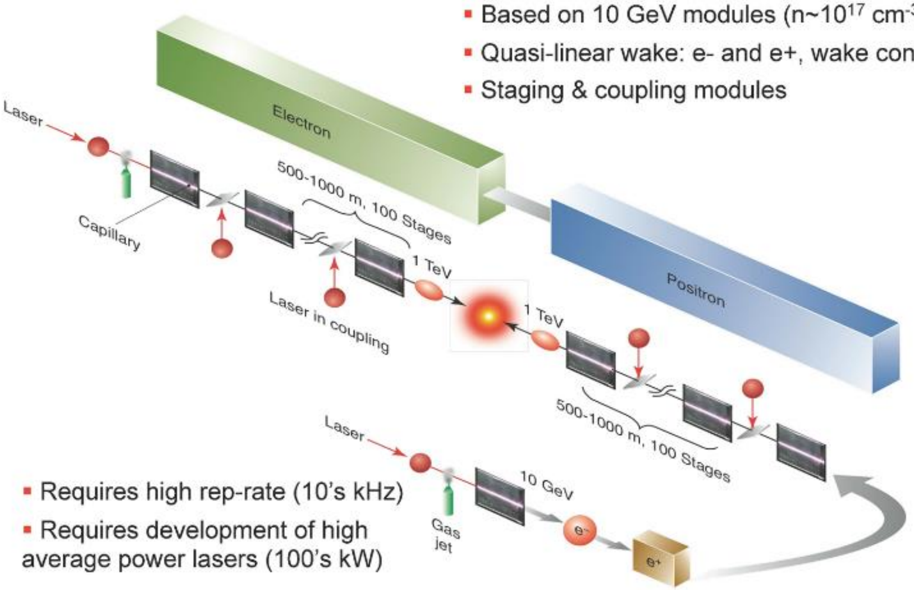
Towards a plasma-based linear collider?

- Based on 10 GeV modules (n~10^{17} cm^{-3})
- Quasi-linear wake: e- and e+, wake control
- Staging & coupling modules

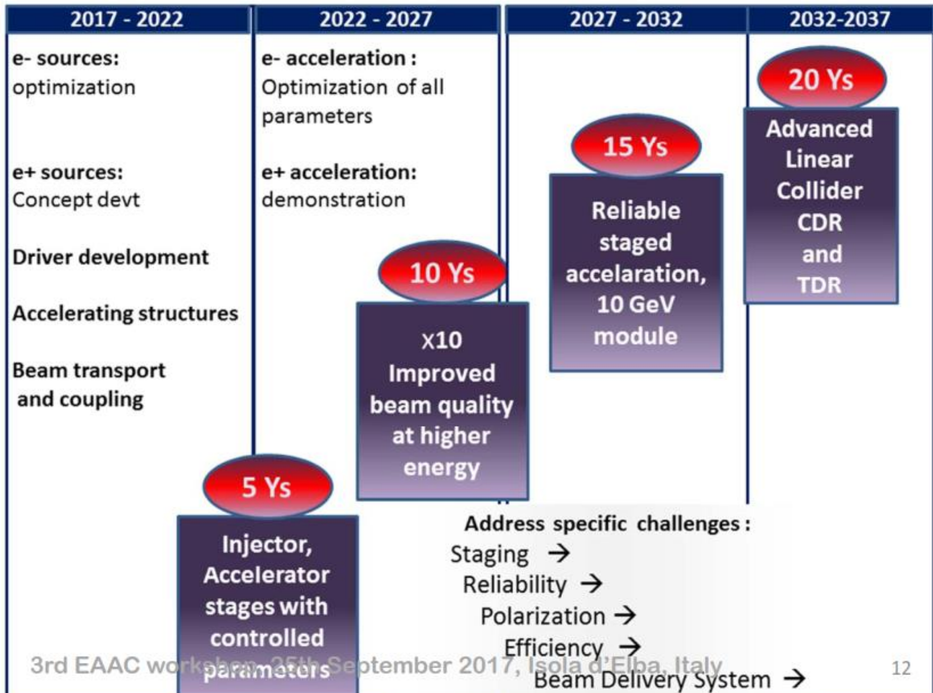


- Requires high rep-rate (10's kHz)
- Requires development of high average power lasers (100's kW)

W.P. Leemans & E. Esarey, Physics Today, March 2009

Main challenges

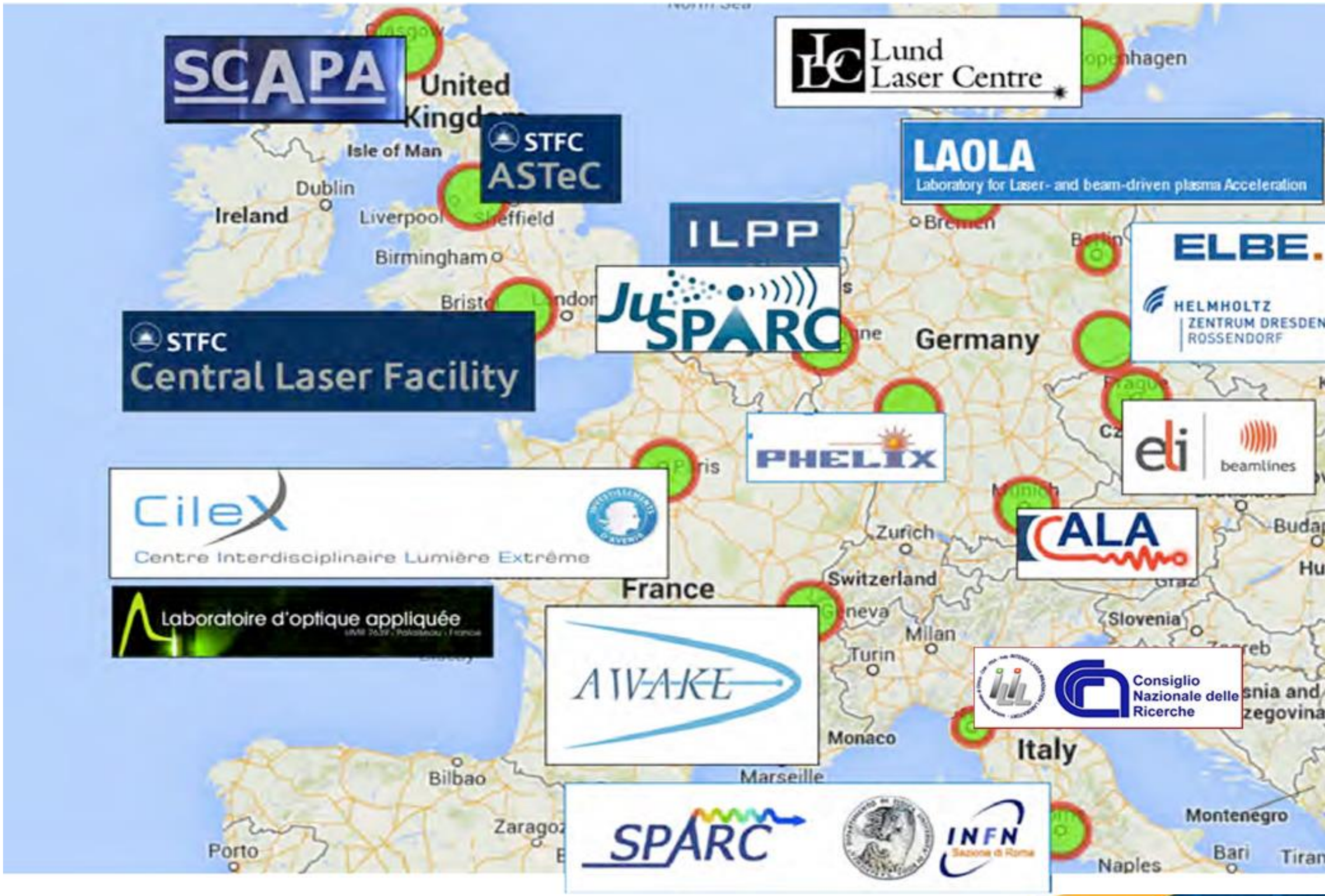
- Beam acceleration with small **energy spread**
- Preservation of small e-beam **emittance**
- Concepts for **positron acceleration** with high brightness
- **High efficiency** of acceleration for e$^-$ and e$^+$
- **Staging** required to reach very high energies
- **Repetition rates** averaging 10s of kHz
- Beam **stability and reproducibility**



Courtesy B. Cros

The European Network for Novel Accelerators

A wide European Network towards novel accelerators, supported by EuCARD2 and ARIES



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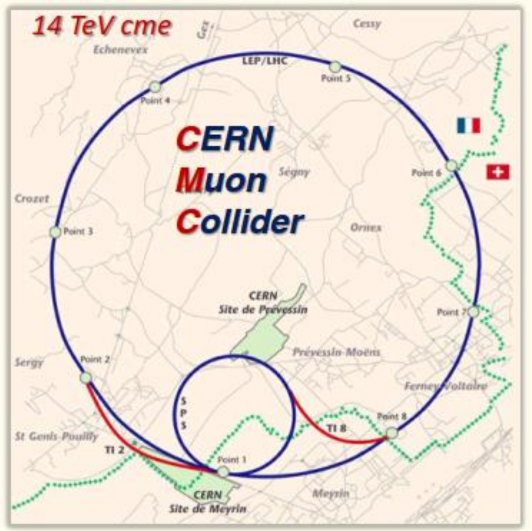
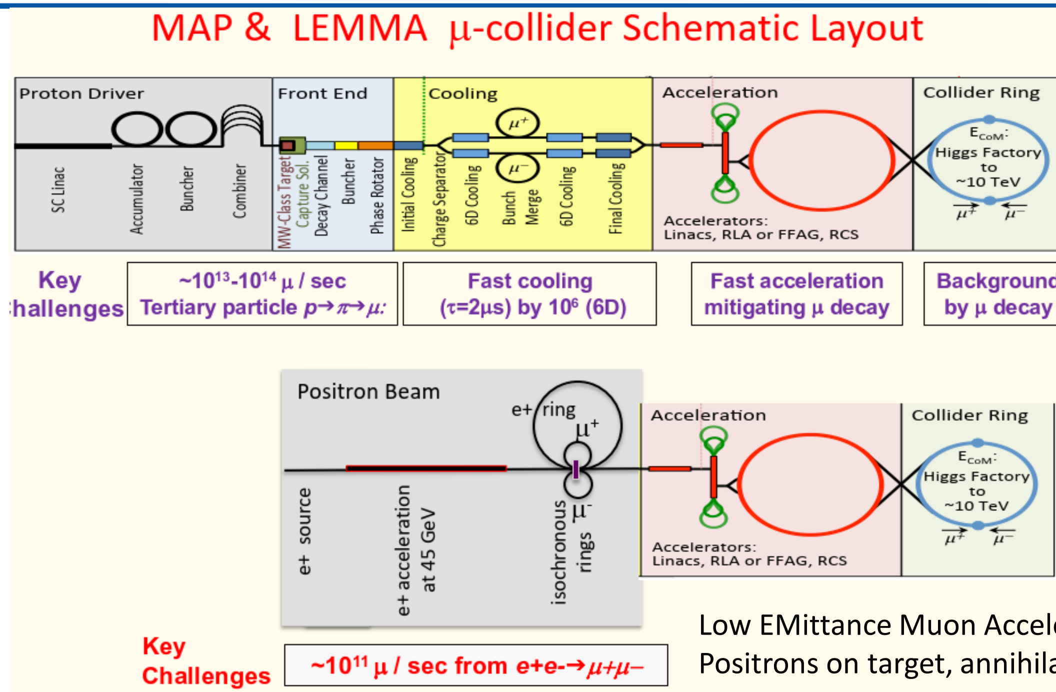
Other options for high energy: muon collider



MOPMF072, IPAC18, V. Shiltzev, D. Neuffer



Low EMittance Muon Accelerator
Positrons on target, annihilation

Colliding muons (for example in the LHC tunnel…):
Muons are leptons, similar to electrons but heavier (207 times), produced by pion decay or electron/positron annihilation, have a lifetime of only 2.2 μs.

- A $\mu^+\mu^-$ collider offers an ideal technology to extend lepton high energy frontier in the multi-TeV range:
  - No synchrotron radiation (limit of e^+e^- circular colliders)
  - No beamstrahlung (limit of e^+e^- linear colliders)
  - but muon lifetime is 2.2 μs (at rest)
- Best performances in terms of luminosity and power consumption

Critical components:
- Muon production complex (proton or positron beam, MAP or LEMMA)
- Muon acceleration complex

Excellent in term of power/luminosity, potential for cost savings
Many critical technical challenges requiring R&D

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Accelerators for medicine and industry

>30000 accelerators in use world-wide:

- **44% for radiotherapy** ← Treating cancer
- **41% for ion implantation** ← Making better semi-conductors
- **9% for industrial applications** ← "Curing" materials: sterilisation; carbon dating; treating flue gases or water; etc
- **4% low energy research** ← Microanalysis of materials, mass spectroscopy, PIXE, etc
- **1% medical isotope production** ← PET and SPECT medical imaging
- **<1% research**

WP4 Accelerator Applications: Workshops on

- Modern hadron therapy gantry developments
- Accelerators for accelerator driven systems
- Accelerator based neutron production
- Electron beams for industrial and environmental applications
- Compact accelerators for radioisotope production

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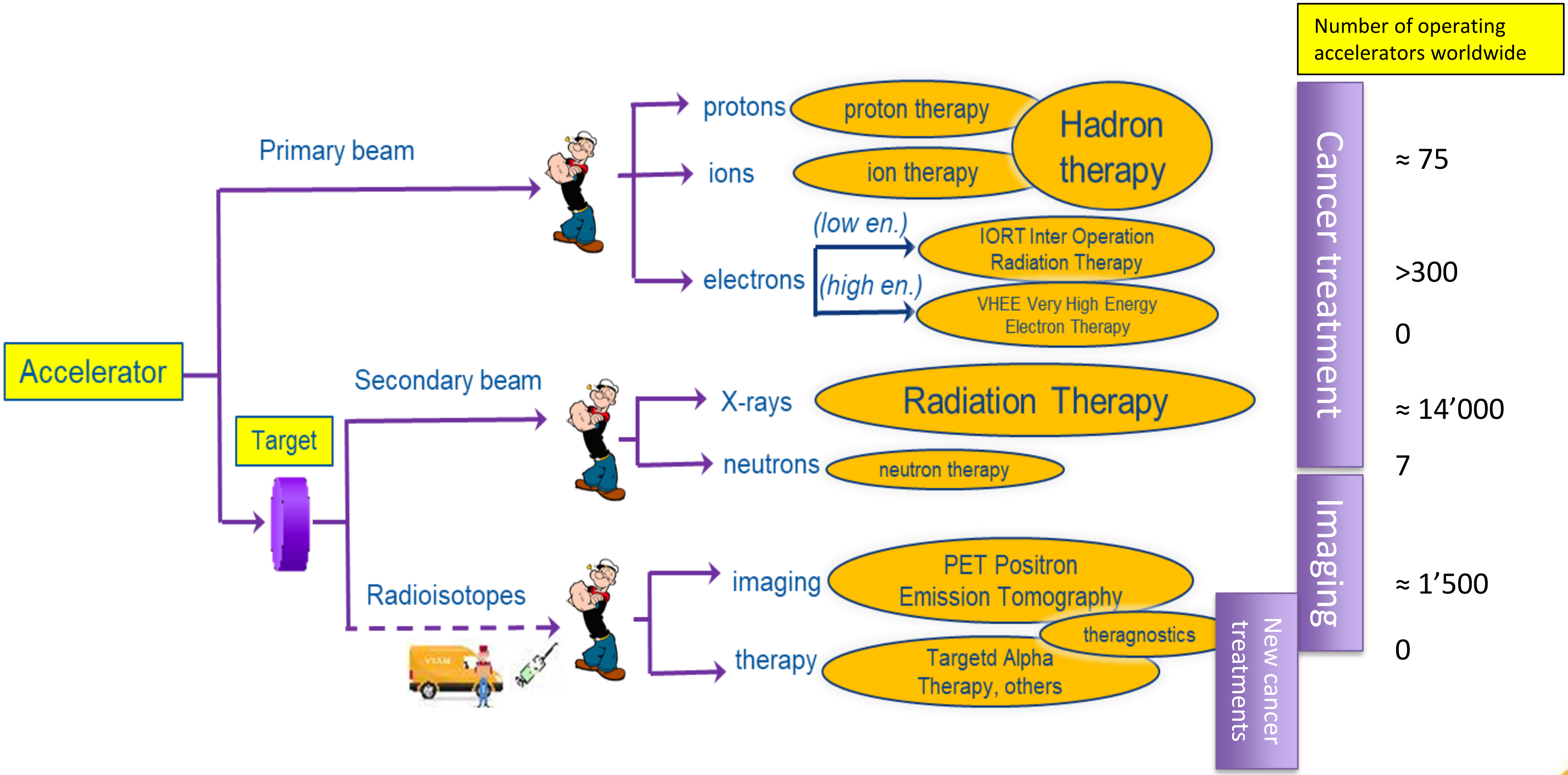
Particle Accelerators for medicine



> 16’000 particle accelerators operating for medicine worldwide, from imaging to cancer therapy

Accelerator production of radioisotopes

- Used for imaging:
  - Positron Emission Tomography (PET)
  - Single Particle Emission Computed Tomography (SPECT)
- Therapy:
  - brachytherapy

Commonly used for PET:

18F – 2*511 keV photons, 2 hour half-life

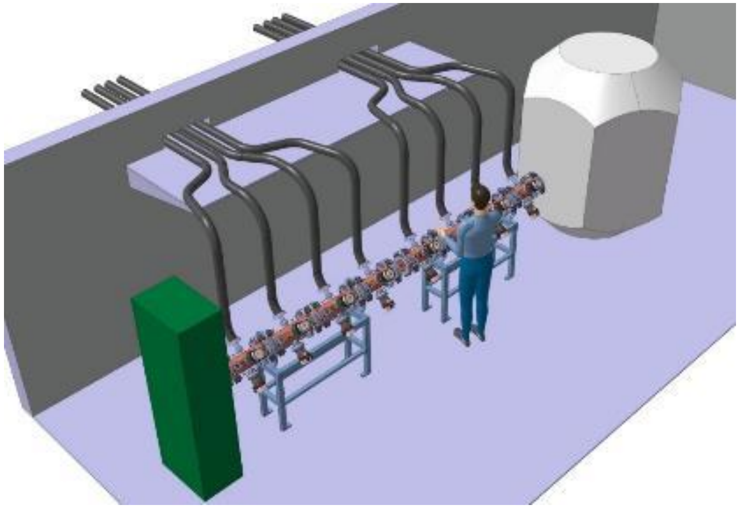
Produced in large cyclotron-based production centres and shipped overnight to hospitals

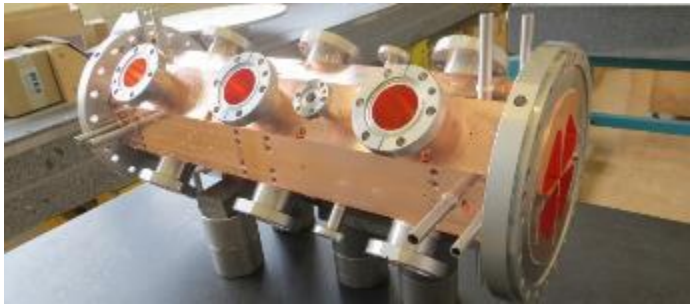
Interest in compact accelerators that can produce the isotopes directly in the hospitals:

- Shorter supply chain, easier availability
- Lower dose to patient
- Allows shorter lifetime isotopes with better resolution:
  - 11C: ~20 min
  - 13N: ~10 min
  - 15O: ~2 min

Compact accelerators for radioisotope production

AMIT superconducting cyclotron for isotope production in hospitals (CIEMAT, Spain)





Radio Frequency Quadrupole linac system for isotope production in hospitals (CERN)

Environmental applications of accelerators

Low-energy electrons can break molecular bonds and be used for:

- Flue gas treatment (cleaning of SOx and NOx from smokes of fossil fuel power plants)
- Waste water and sewage treatment
- Treatment of marine diesel exhaust gases.

- Maritime transport is the largest contributor to air pollution: a cruise ship emits as much sulphur oxydes as 1 million cars!
- Ships burn Heavy Fuel Oil, cheap but rich in Sulphur. Diesels (high efficiency) emit Nitrogen oxydes and particulate matter.
- New legislation is going to drastically limit SOx and NOx emissions from shipping, with priority to critical areas near coasts.
- So far, technical solutions exist to reduce SOx or NOx, but there is no economically viable solution for both.

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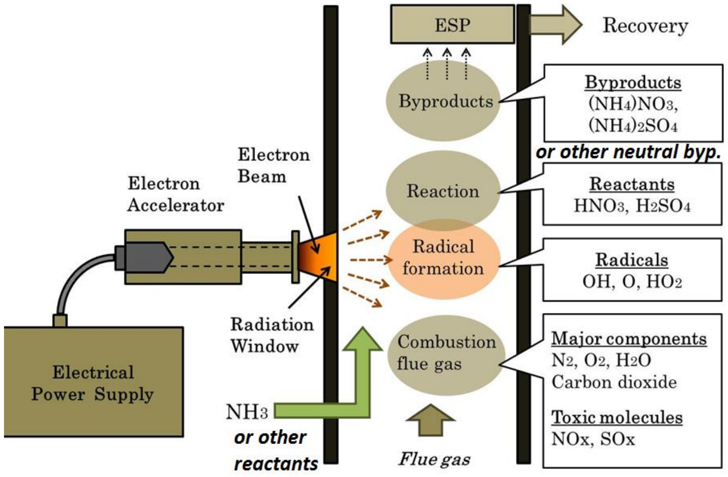
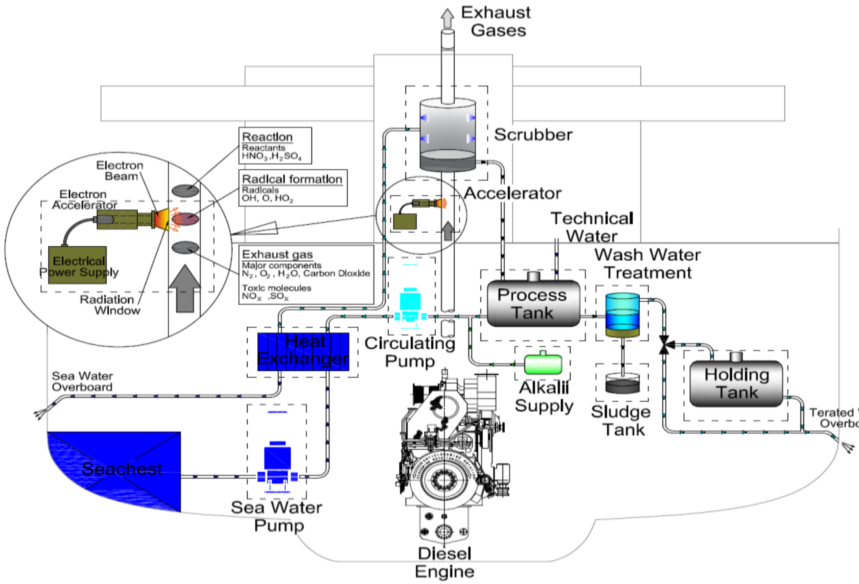
Hybrid Exhaust Gas Cleaning Retrofit Technology for International Shipping (HERTIS)

An ARIES activity, based on a patent from INCT Warsaw

Wide collaboration of research institutions (including CERN), accelerator industry, shipyards, maritime companies, maritime associations spreading through Germany, UK, Switzerland, Poland, Latvia, Italy.

100 kV electron accelerator to break the high order molecules that are then cleaned by a water jet (scrubber)





Next steps:

1. test and validate the system on a real diesel engine, first on shore and then onboard.
2. Submit a proposal for EU support for testing on a real ship.

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Test at Riga Shipyard, 5 July 2019

Installation used an electron accelerator system on truck from Fraunhofer Dresden commonly used to treat crops – it had to be back in Germany at mid-July for the start of the harvesting season. The funnel of an old Latvian tugboat (the ”Orkāns”) was connected via a long pipe to the electron accelerator. The fumes then passed through a small scrubber before being released in the air.

The tests confirmed the laboratory measurements and the overall effectiveness of the system.

Measured **NOx removal rate 45%** at full engine power with available scrubber and accelerator. Estimated removal with optimised scrubber and homogeneous e-beam 98%.
SOx removal only measured in laboratory (no Sulphur allowed in port) with similar removal rates.

Some final words - at the roots of innovation

We need innovative ideas, but what are the ingredients of innovation? Remember the first slide on Wideröe's invention!

1. Merge inputs from different science and technology fields (look around you!)
2. Challenge the established traditions (but respect experience!)
3. Take risks (but foresee mitigations!)

*An **innovation** is the **implementation** of a new or significantly improved product (good or service), or process, a new marketing method, or a new organizational method. (from the Oslo Manual, Guidelines for collecting and interpreting innovation data, OECD, 2005)*

Innovation is the process of translating an idea or invention into something (object or service) that creates value.

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The final word…

Particle accelerators are a vibrant and growing field, in full transition from basic science to applied science and to wider societal applications.

But to drive this transition and to push further the frontiers of accelerators we need fresh ideas, technology jumps, and (why not!), some change in paradigm…

The secret for the success are novel ideas by young people developed in a collaborative environment, jumping across borders between different scientific fields.

To achieve this we need multinational supporting bodies like the European scientific programmes, but above all…

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Thank you for your attention

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