European projects for collaborative European R&D

M. Vretenar, CERN, ARIES Coordinator

A special seminar for the JUAS 2018 cycle

ESI, Archamps, 11.01.2018

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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 you…

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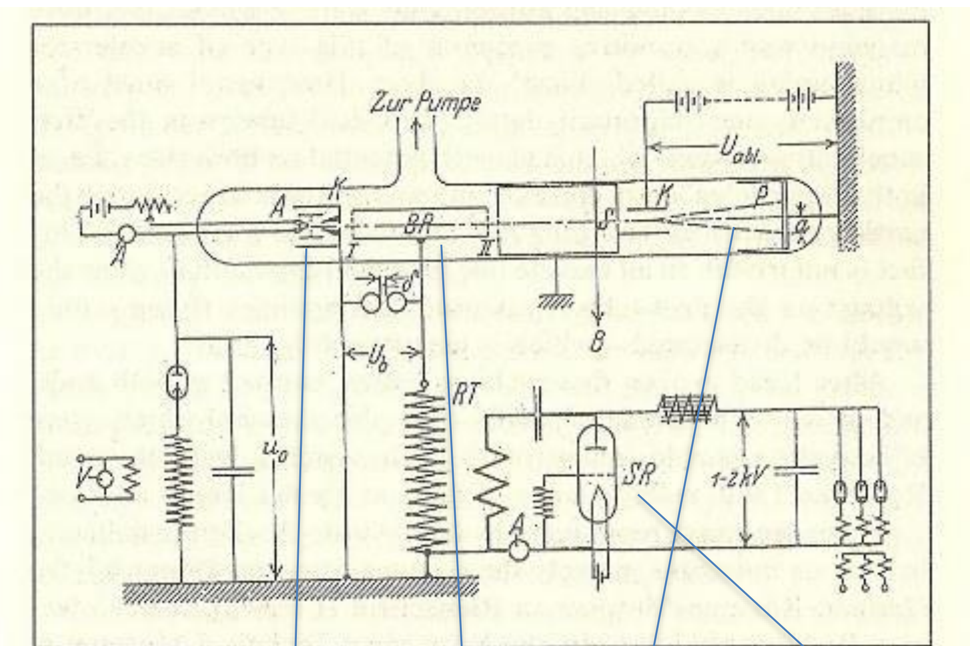
Particle accelerators: 90 years of history!

In 2018 we celebrate 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 ("at a cost of four to five hundred marks"…) in a 88 cm long glass tube.



Ion source | Accelerating tube | Detector | RF generator

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

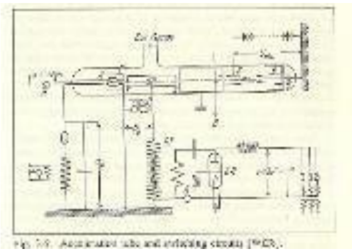
At the root of innovation

What were the ingredients of Rolf Wideröe's innovation?

- He was a PhD student *(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 …"

90 years, from infancy to maturity…



1931…………1945/48….1952…………..1965/90’s…….

1928
Wideröe builds the first modern accelerator

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

2018
End of Large Hadron Collider Run 2

Succession of enabling technologies (technology leaps)

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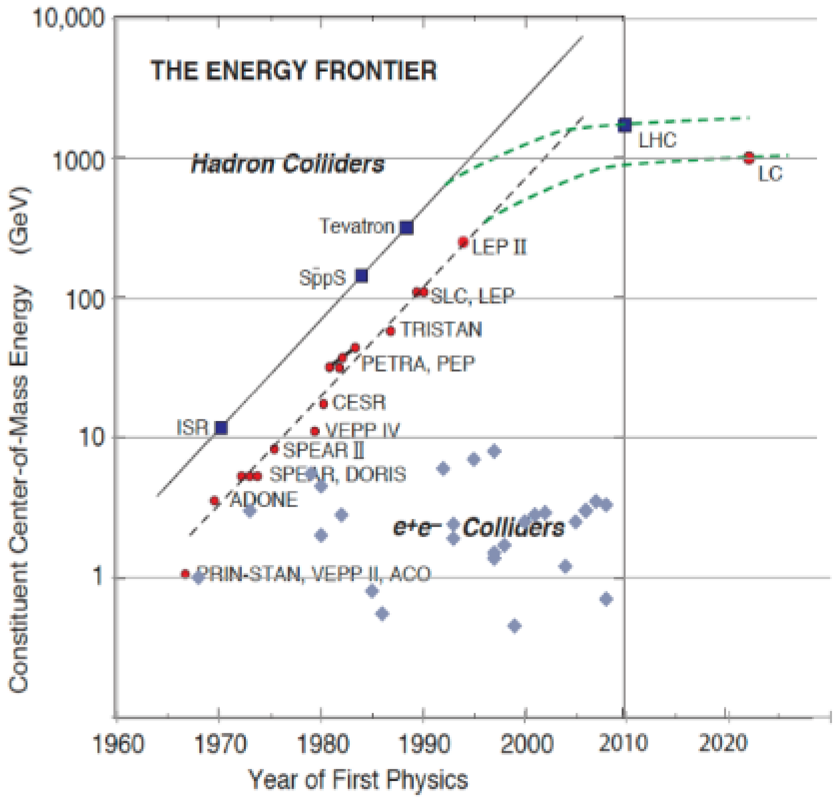
Particle Accelerators in 2018

Are we coming to a saturation?



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

But the field has never been so flourishing…

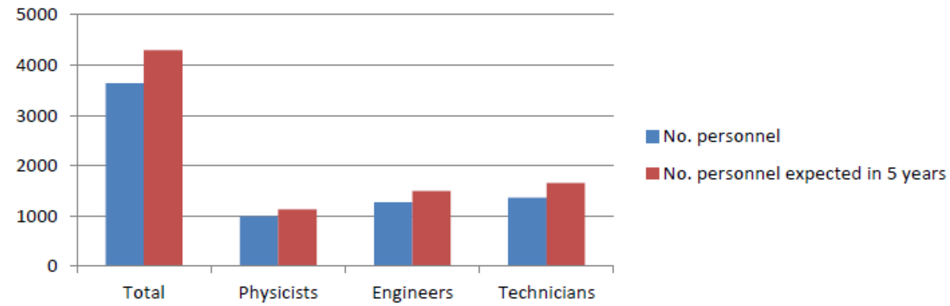
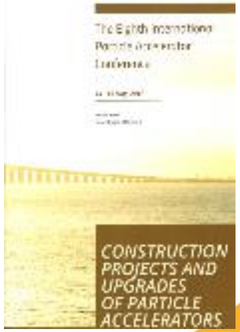


Figure 2.1: Total number of current personnel (blue) engaged in accelerator science activities a research institutes. The number of personnel expected in 5 years is shown in red.

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 introductory documentation to the 2017 IPAC Conference (13 America, 11 Asia, 26 Europe)

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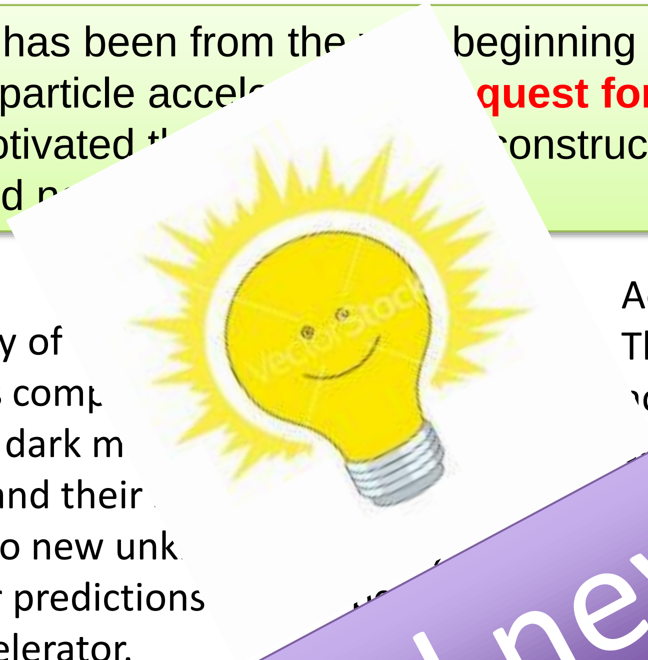
Sustainability of large accelerator facilities

Particle physics has been from the … beginning the **technology driver** for the development of particle accel… **quest for new particles** at increasingly higher energies has motivated t… construction and financing of increasingly large accelerators. And n…



Physics:
After the discovery of … Standard Model is comp… remain open (e.g. dark m… asymmetry, etc.) and their … probably related to new unk… but so far no clear predictions … verified by an accelerator.

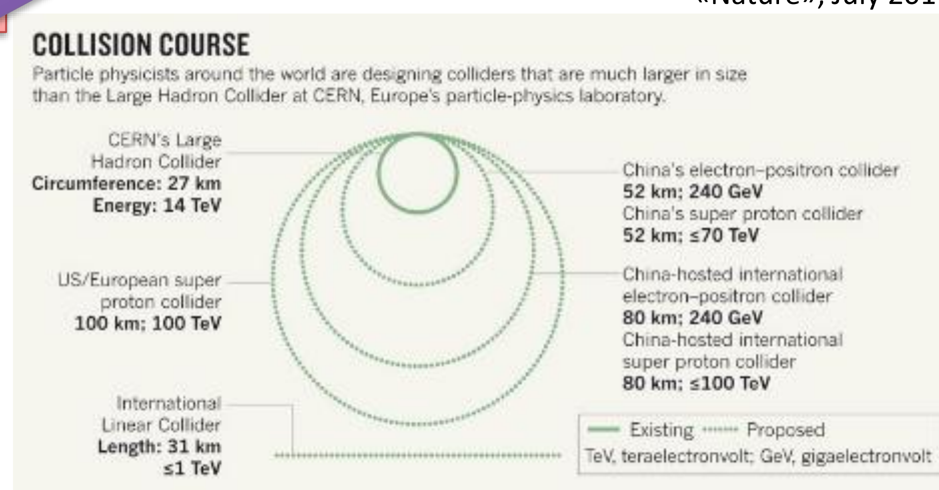
➡ Difficulty to financ…

Accelerators:
The **size, cost** … **nsumption** of the …ccelera… …eyond the … …ns on the long … …ccelerator-based

…ulty to implement new large projects

We need new ideas

«Nature», July 2014



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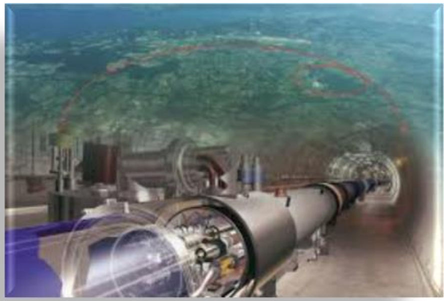
Accelerators in transition

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.)

From basic science to 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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Driving and powering the transition

- Drive and favour this process
- Develop and test new ideas (innovation)
- In a collaborative environment (synergies and cross-fertilization)

Since more than 10 years the European Commission is supporting collaborative R&D actions for particle accelerators, in particular

EuCARD2 (European Coordinated Accelerator Research and Development), 2013-2017, http://eucard2.web.cern.ch/

ARIES (Accelerator Research and Innovation for European Science and Society), 2017-2021, https://aries.web.cern.ch/

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EU support to particle accelerator R&D

Integrating Activities

FP6
- **CARE** 01/2004 – 12/2008
  5 years, 15.2 M€ EU contribution

FP7
- **EuCARD** 04/2009 – 03/2013
  4 years, 10.0 M€ EU contribution
- **EuCARD-2** 05/2013 – 04/2017
  4 years, 8.0 M€ EU contribution

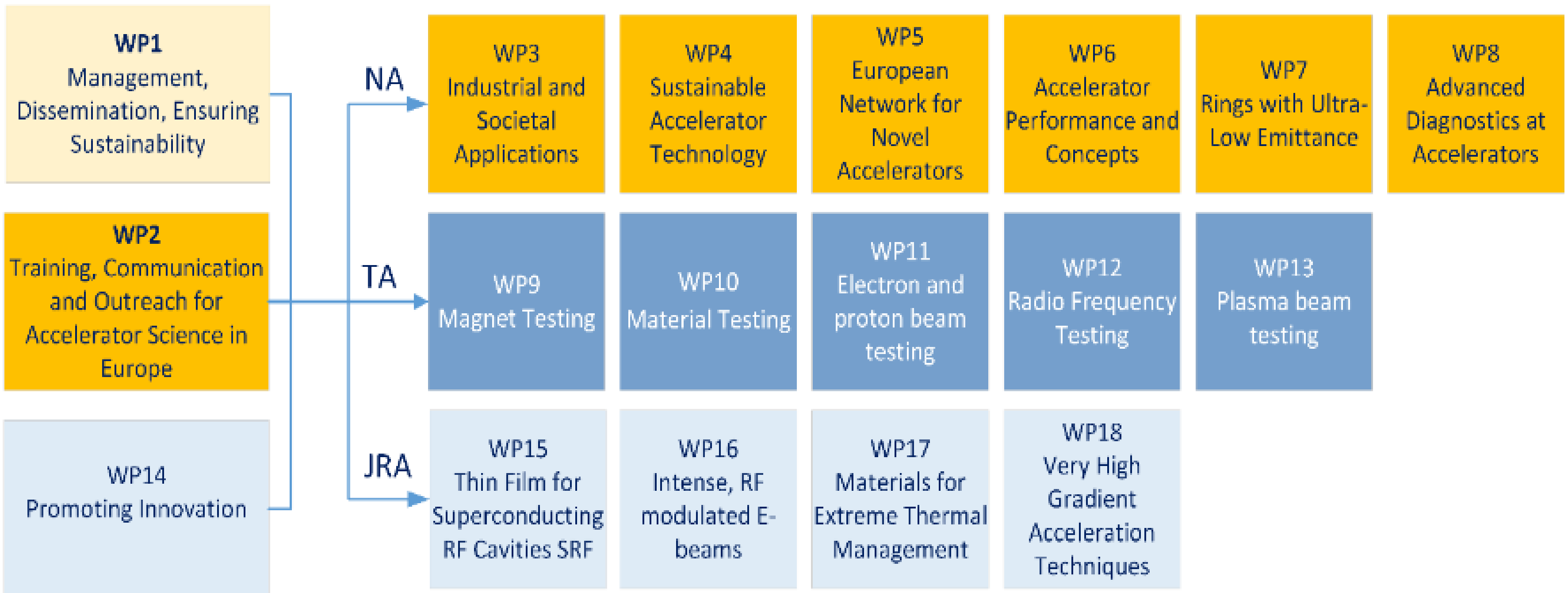
H2020
- **ARIES** 05/2017 – 04/2021
  4 years, 10.0 M€ EU contribution

Design Studies, Preparatory Phases

- EuroNu DS, 2008/12, 4M€
- SLHC-PP, 2008/11, 5.2M€
- ILC-HiGrade, 2008/12, 5M€
- TIARA-PP, 2011/13, 3.9M€
- HiLumi LHC, 2011/15, 4.9M€
- EuroCirCol, 2016/19
- EUPRAXIA, 2016/19

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

The ARIES Structure and Themes

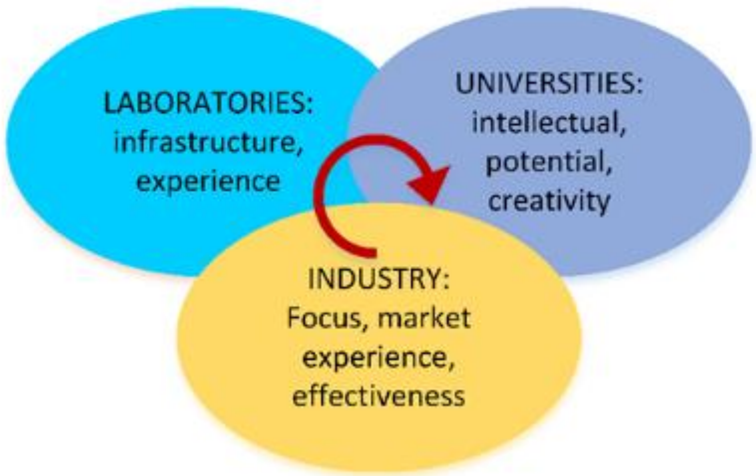


5 Networks on strategic themes: applications, sustainability, new concepts, extreme designs and instrumentation
5 Pools of testing facilities to prove new concepts
5 Joint Research Activities for experimental valiadation of selected technologies

Budget (4 years): 15 M€ from the partners, 10 M€ from the European Commission

The ARIES community

- 42 partners from 18 European countries (+CERN and ESS).
- Connecting the technological core of Europe with its dynamic periphery and large laboratories with universities, research centres and industries.



	Laboratories and research institutions hosting large accelerator infrastructures	Universities and research centres	Industries and industrial associations	Total
Based in the high-technology European hub: DE, UK, FR, IT, CH	PSI, DESY, GSI, KIT, CEA, CNRS, SOLEIL, CERN, INFN, STFC	UNIGE, JGU, SIEGEN, HZB, IAP, FAU, POLITO, POLIMI, UOXF, HUD	FEP, HIT, BRUKER, CNI, BREVETTI	25
Based in other EU-15 countries: BE, NL, PT, ES, AT, SE	ESS, ALBA	CIEMAT, UT, UU, UL, IST	RHP, IBA	9
Based in other EU countries: HU, LT, MT, PL, RO, SI, SK		WIGNER RCP, RTU, UM, WUT, INCT, ELI-NP, IEE/SAS	COSYLAB	8
Total	12	22	8	42

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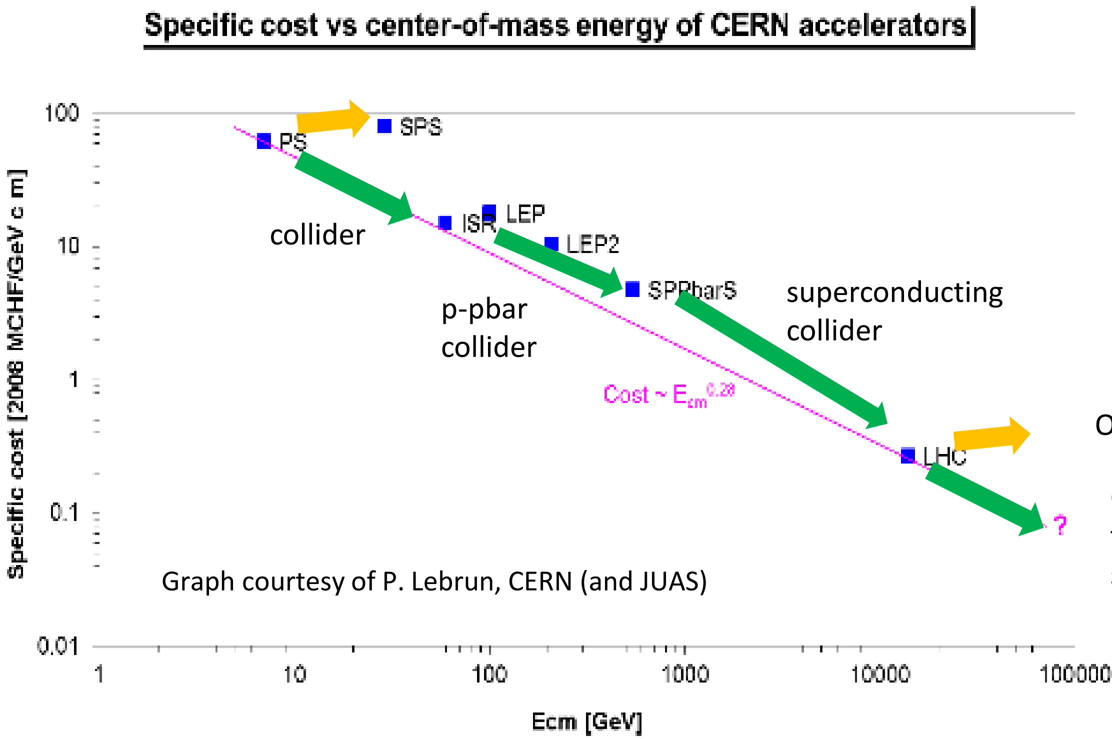
Multiple dimensions of accelerator R&D

The Economist, October 2013

Frontier accelerators



Option 1: scaling (Future Circular Collider)

Option 2: reduction in cost with new technologies (plasma colliders? low-cost superconductivity? pipeline tunnels?)

Primary goal → reduce specific cost

Progress only through innovative technologies.

What is the overall cost that our (globalised) society is ready to accept?

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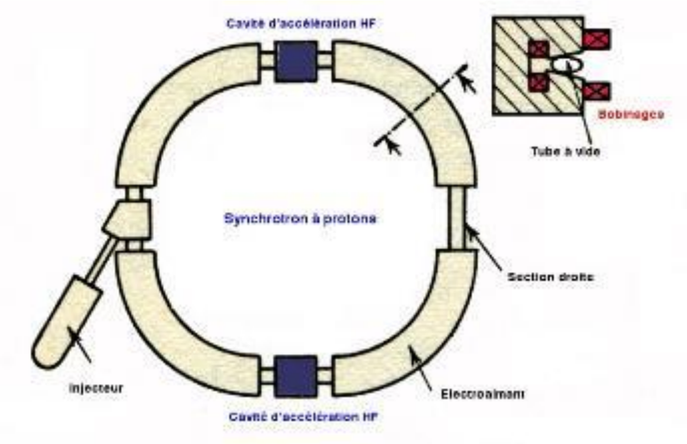
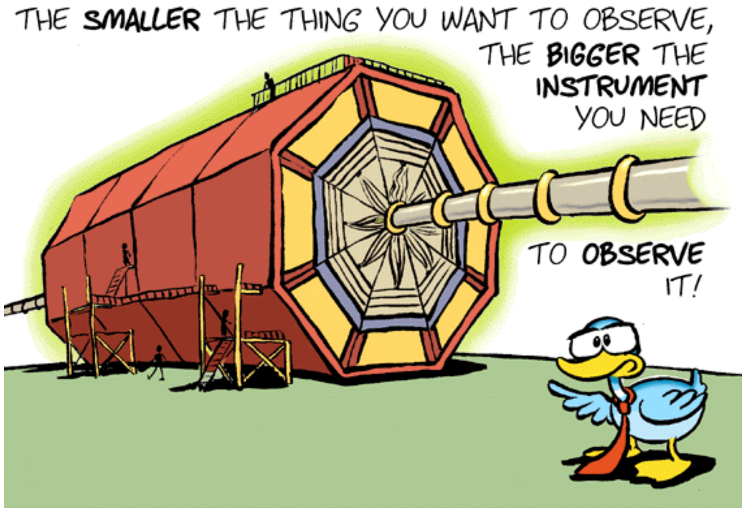
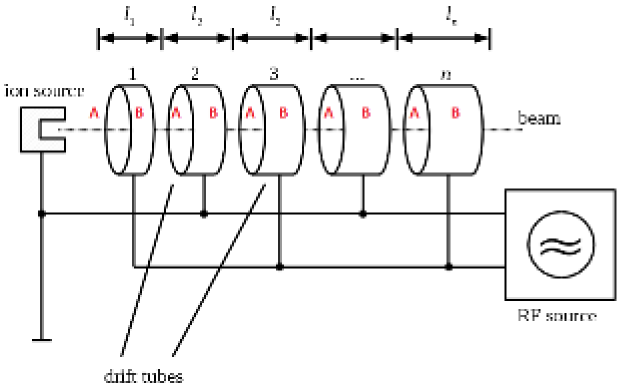
Smaller accelerators?



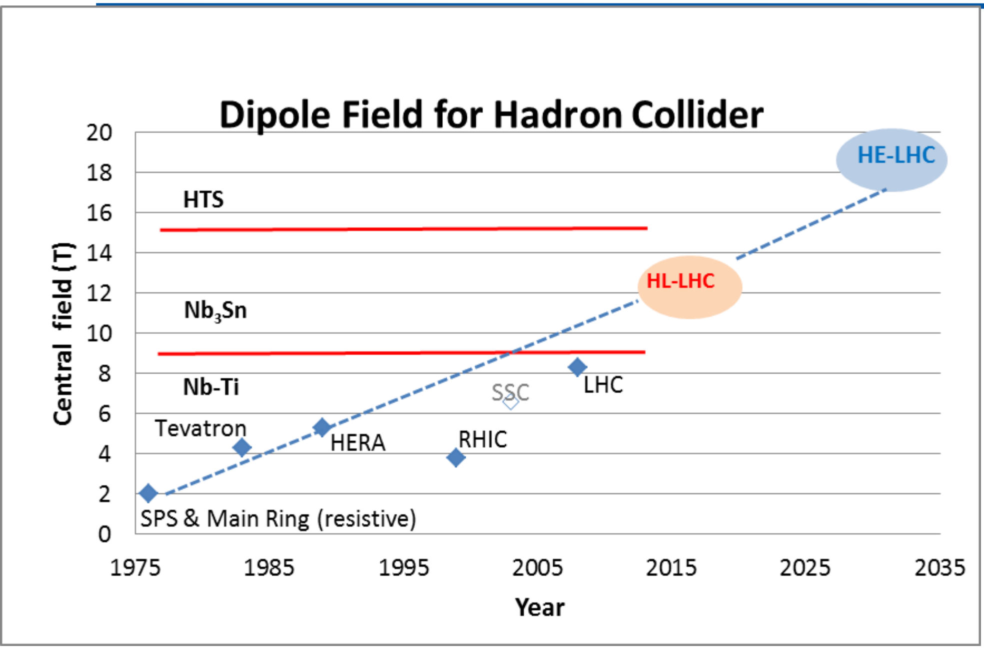
Synchrotrons: p/q=Bρ
Need to maximise magnetic field
Limitations: critical current density Jc for SC magnets





Linear accelerators: W=Eℓ
Need to maximise electric field
Limitations: sparking, field emission, etc.

The dipole field frontier



NbTi mature technology but limited to 9T

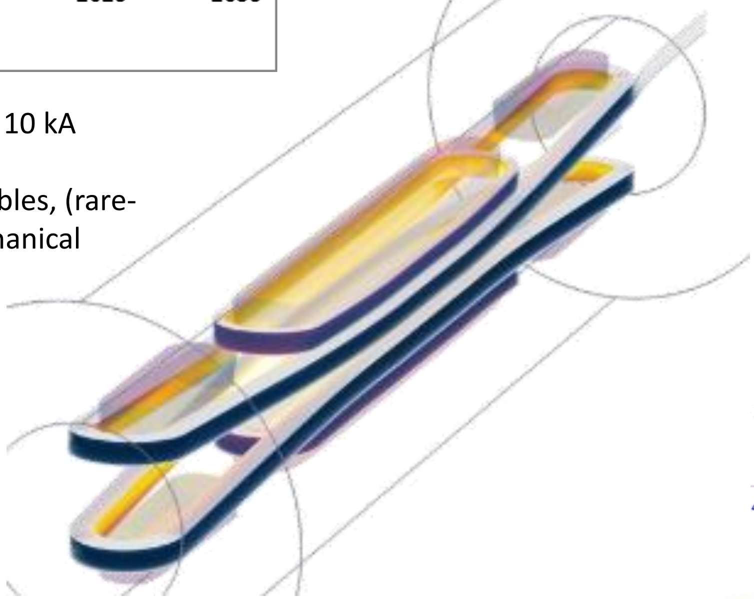
Nb_3Sn technology has seen a great boost in the past decade (factor 3 in J_C w/r to ITER) but is not yet used in an accelerator – HL-LHC as first step.

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

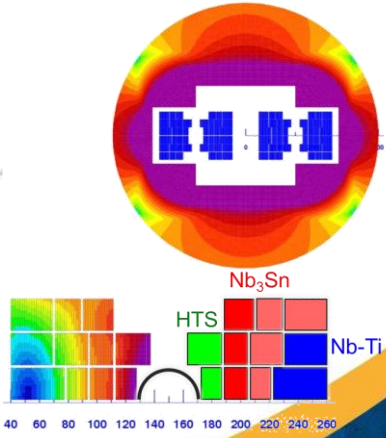
EuCARD-2 and ARIES are the European projects to push HTS magnet technology.

R&D towards a 20 T HTS dipole magnet, develop 10 kA cable

First results: REBCO material in Roebel cables, (rare-earth based YBCO, high current density but mechanical issues still to be cleared)



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



Cost optimized, graded winding

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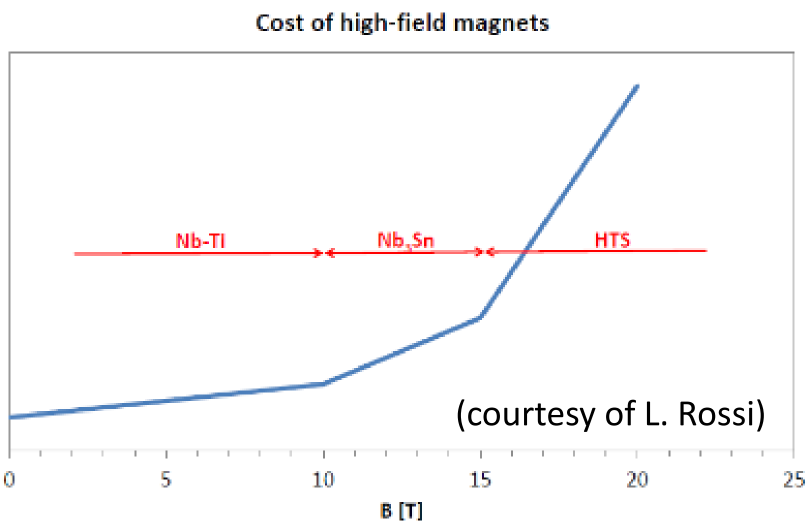
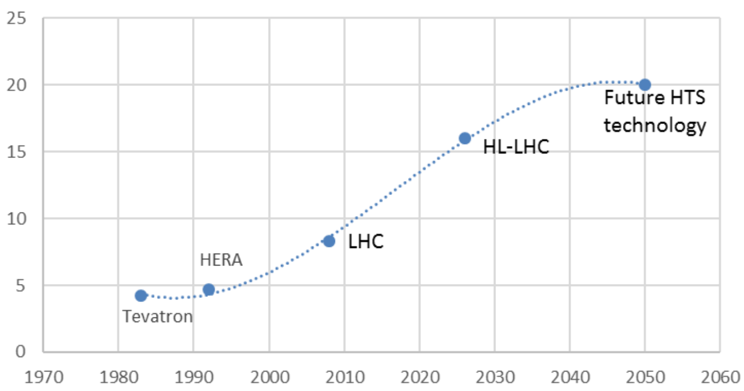
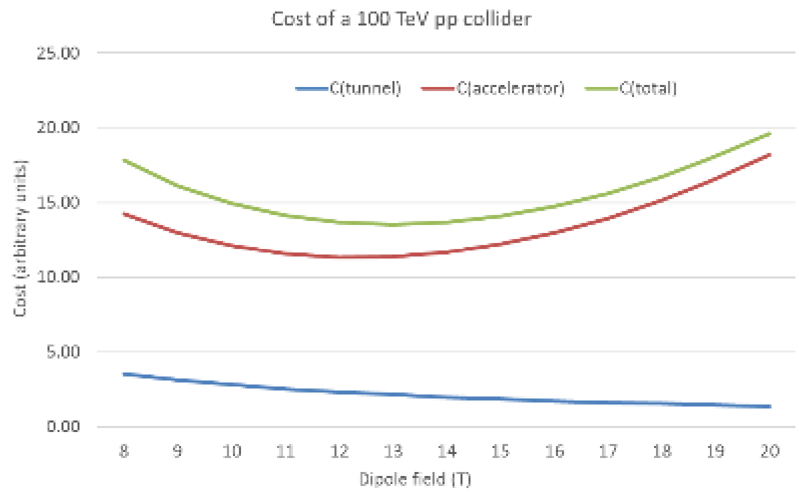
HTS magnets – reaching the limit?



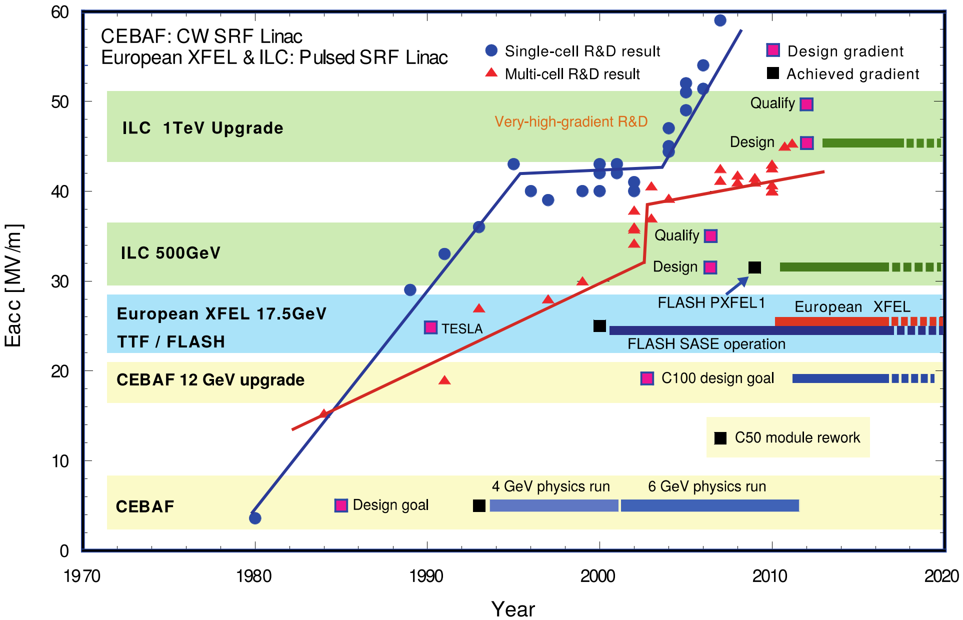
HTS allows reducing the size of the accelerator but not (yet) the cost

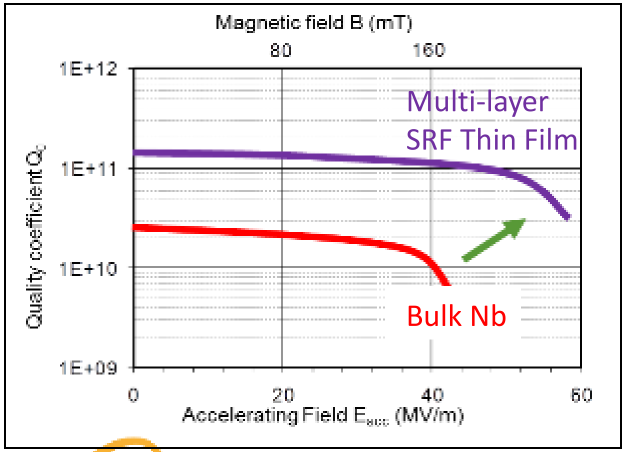




Superconducting magnet technology approaching saturation; increasing costs for minor performance improvements

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,

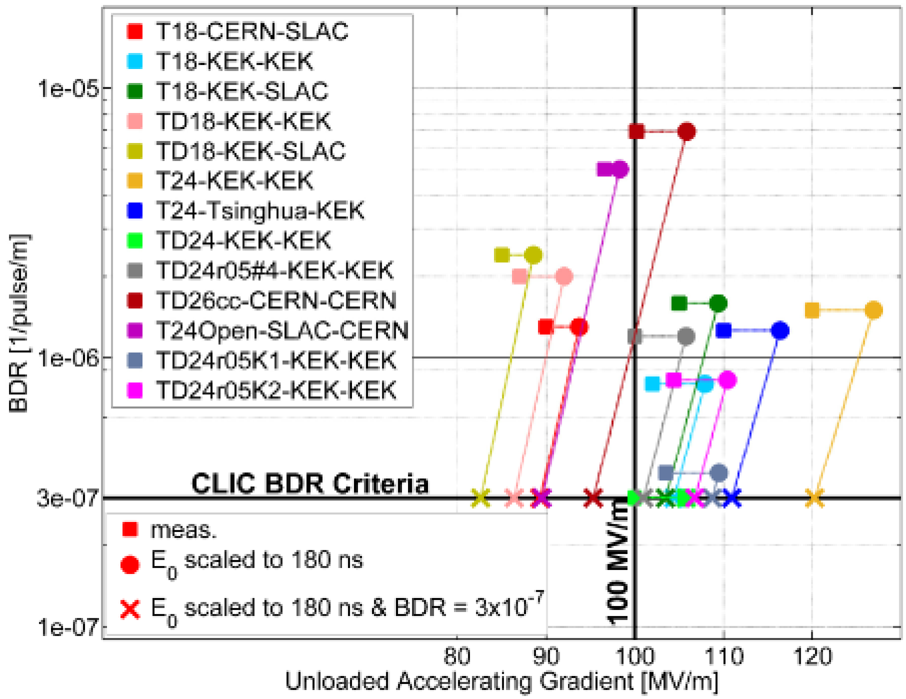
EuCARD2 RF: R&D new higher-gradient superconductors: bulk Nb3Sn and nanometric multilayers of high Tc SC.

Support to the CLIC R&D for high-gradient NC: wakefield management, RF sources.

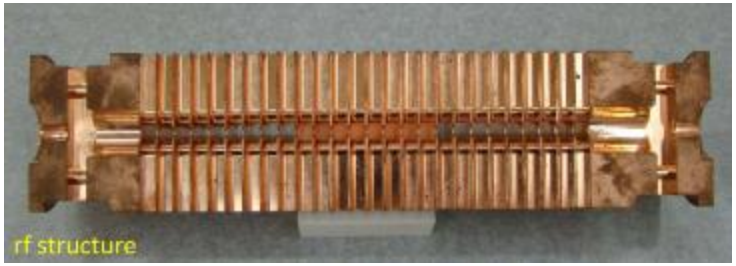
(+ Nb sputtering, beam generation, beam diagnostics)

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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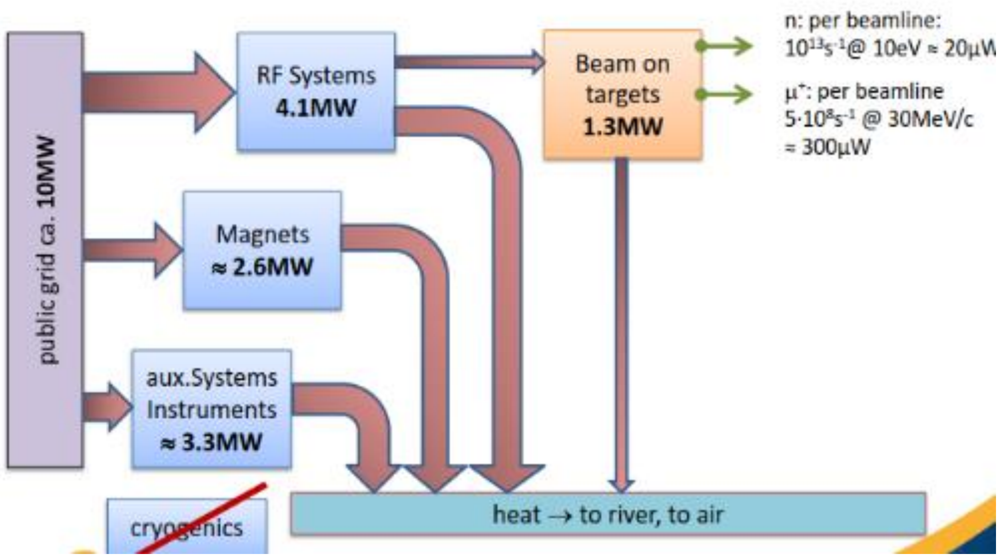
Efficient energy management

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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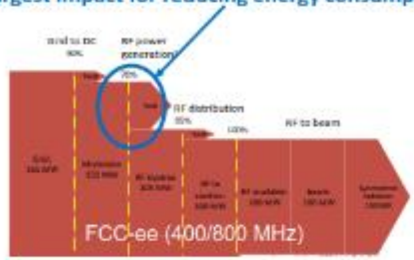
Some initiatives to improve power efficiency

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€)

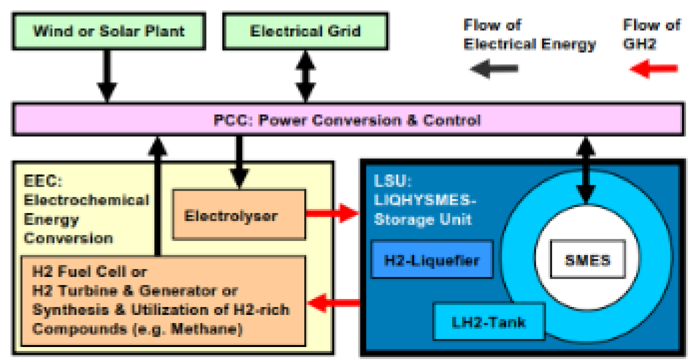
Photo: CLIC Xbox 12 GHz facility for cavities conditioning

Development of high-efficiency RF power sources

LIQuid HYdrogen & SMES

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

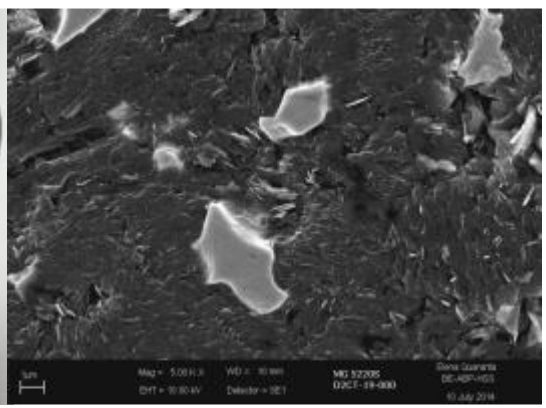
- large power 10..100 MW
- capacity to ~70 GWh
- SMES to ~10 GJ
- synergy with existing cryogenics



Energy storage systems for accelerators

Material challenges for future accelerators

- **Future machines** are set to reach unprecedented **Energy** and **Energy Density**.
- No existing material can meet extreme requirements for Beam Interacting Devices (Collimators, Absorbers, Windows …) as to **robustness** and **performance**.
- New materials are being developed to face such extreme challenges, namely **Metal-** and **Ceramic-Matrix Composites** with **Diamond** or **Graphite** reinforcements.
- **Molybdenum Carbide - Graphite** composite (**MoGr**) is the most promising candidate material with outstanding thermo-physical properties.



MoGr Key Properties	
Density [g/cm^3]	2.5
Melting Point T_m [°C]	~2500
CTE [10^{-6} K^{-1}]	~1
Thermal Conductivity [W/mK]	770
Electrical Conductivity [MS/m]	~1

- Understanding of **unexplored conditions** call for state-of-the-art numerical simulations completemented by advanced tests in dedicated facilities

Courtesy S. Redaelli

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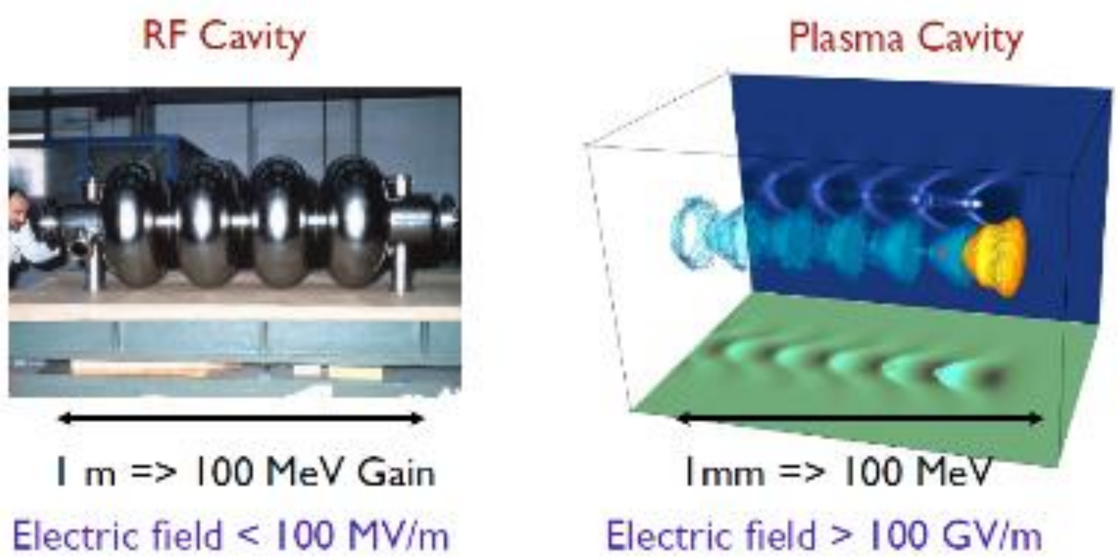
New acceleration techniques using lasers and plasmas

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

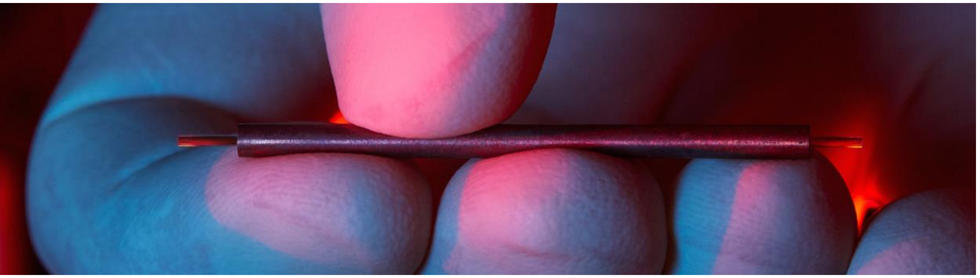
Two directions

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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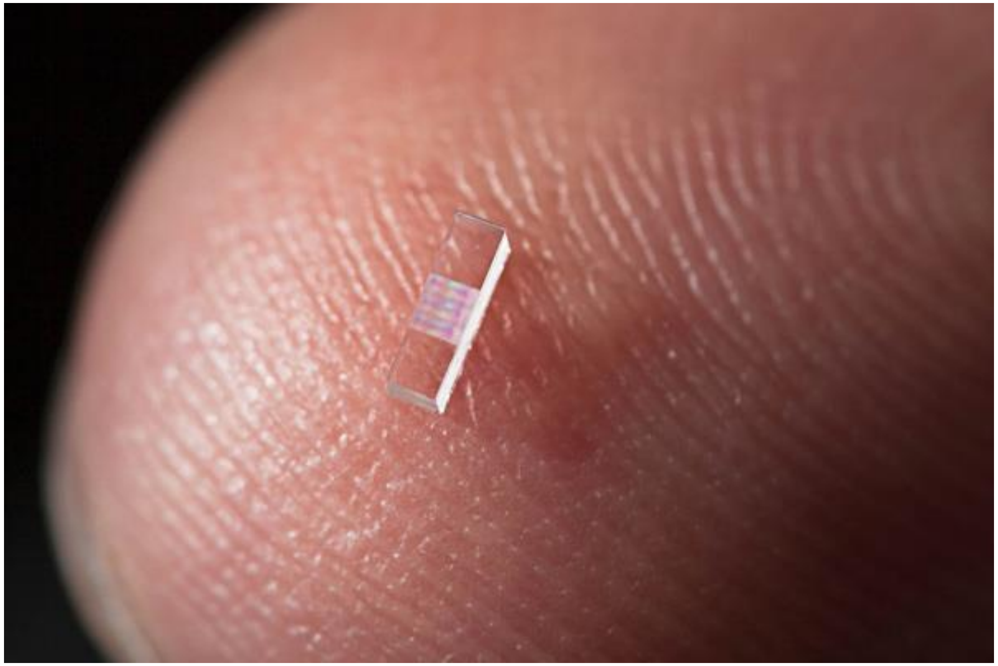
Accelerator on a chip

- "Accelerator on a Chip" grant from Gordon & Betty Moore foundation for work by/at Stanford, SLAC, University Erlangen, DESY, University Hamburg, PSI, EPFL, University Darmstadt, CST.



ACHIP
Accelerator on a Chip International Program

GORDON AND BETTY MOORE FOUNDATION

Courtesy R. Assmann

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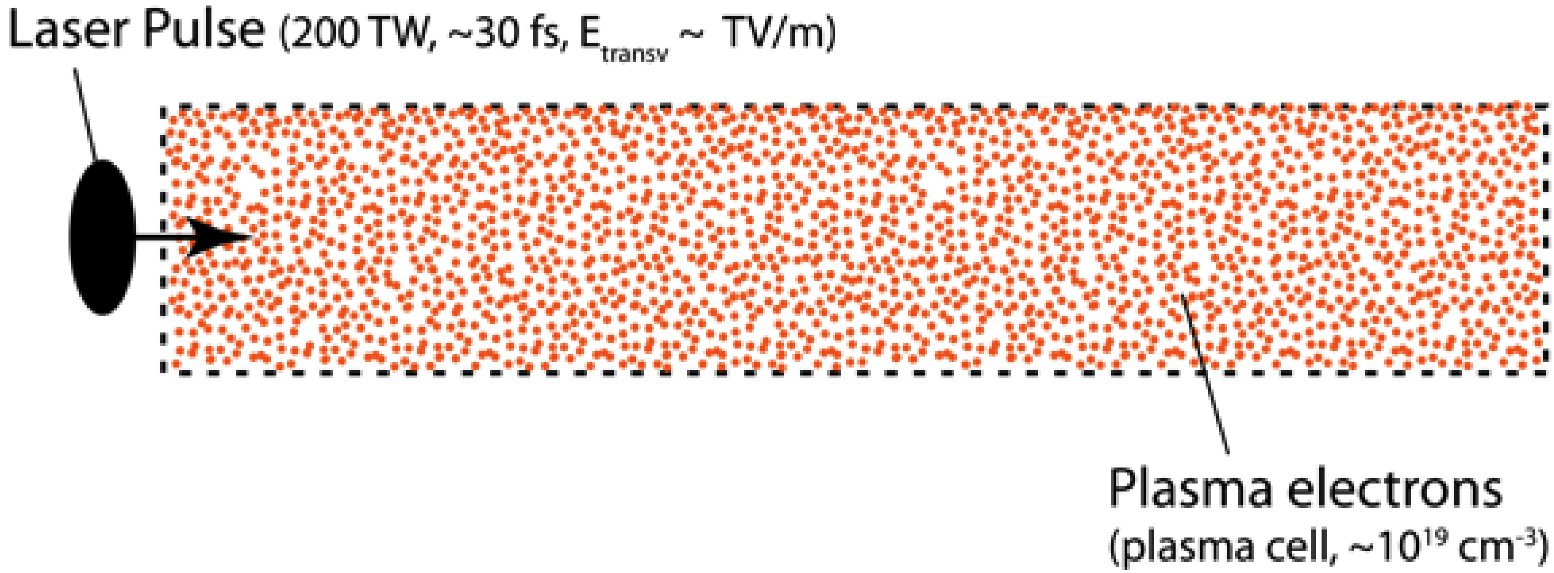
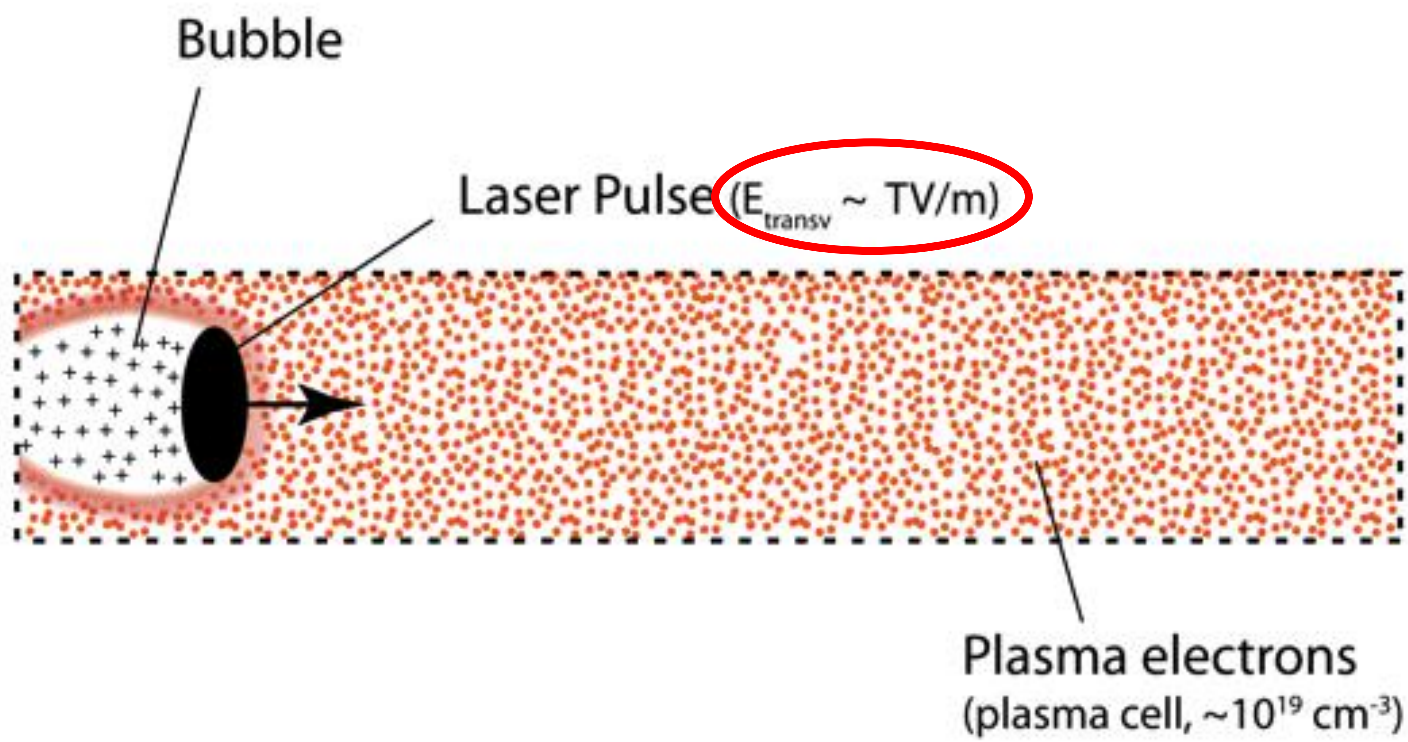
Laser Plasma-Acceleration (Internal Injection)



Laser Plasma-Acceleration (Internal Injection)



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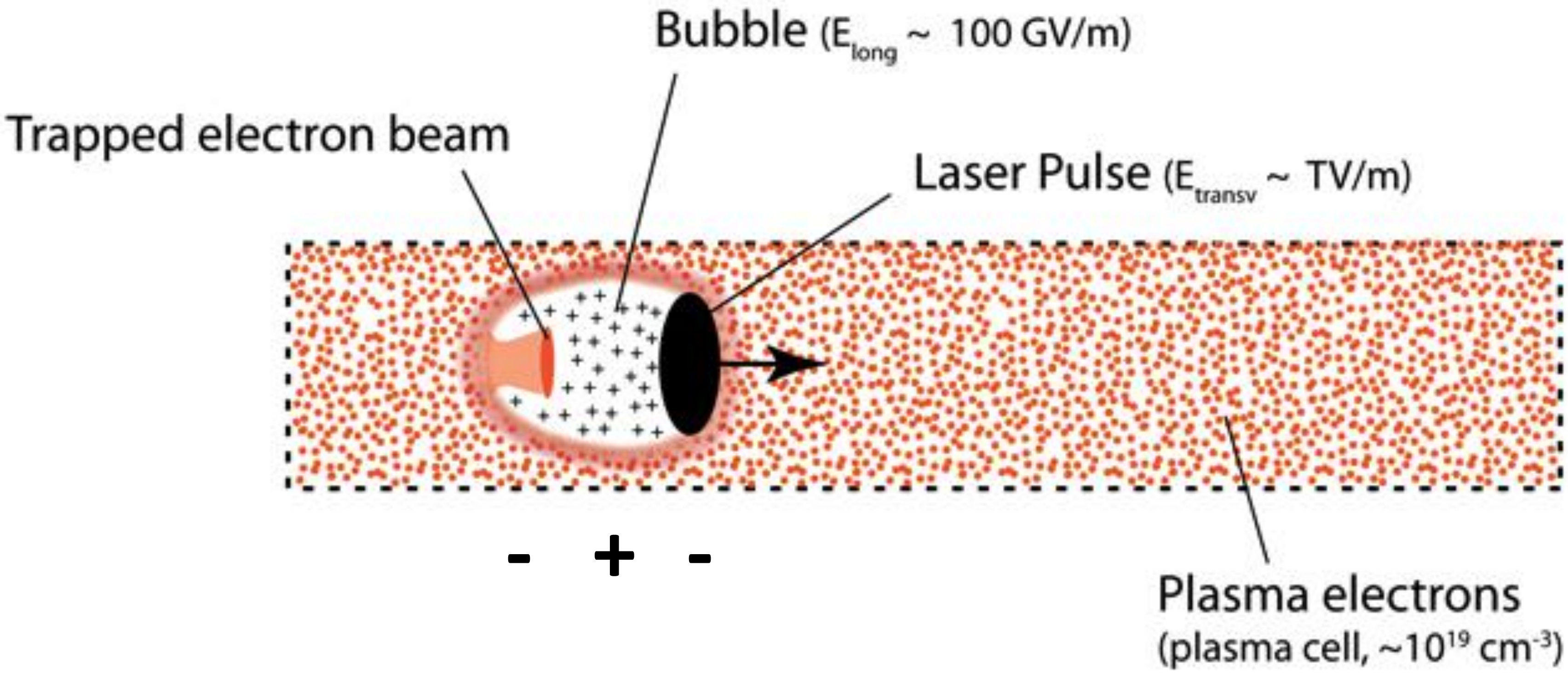
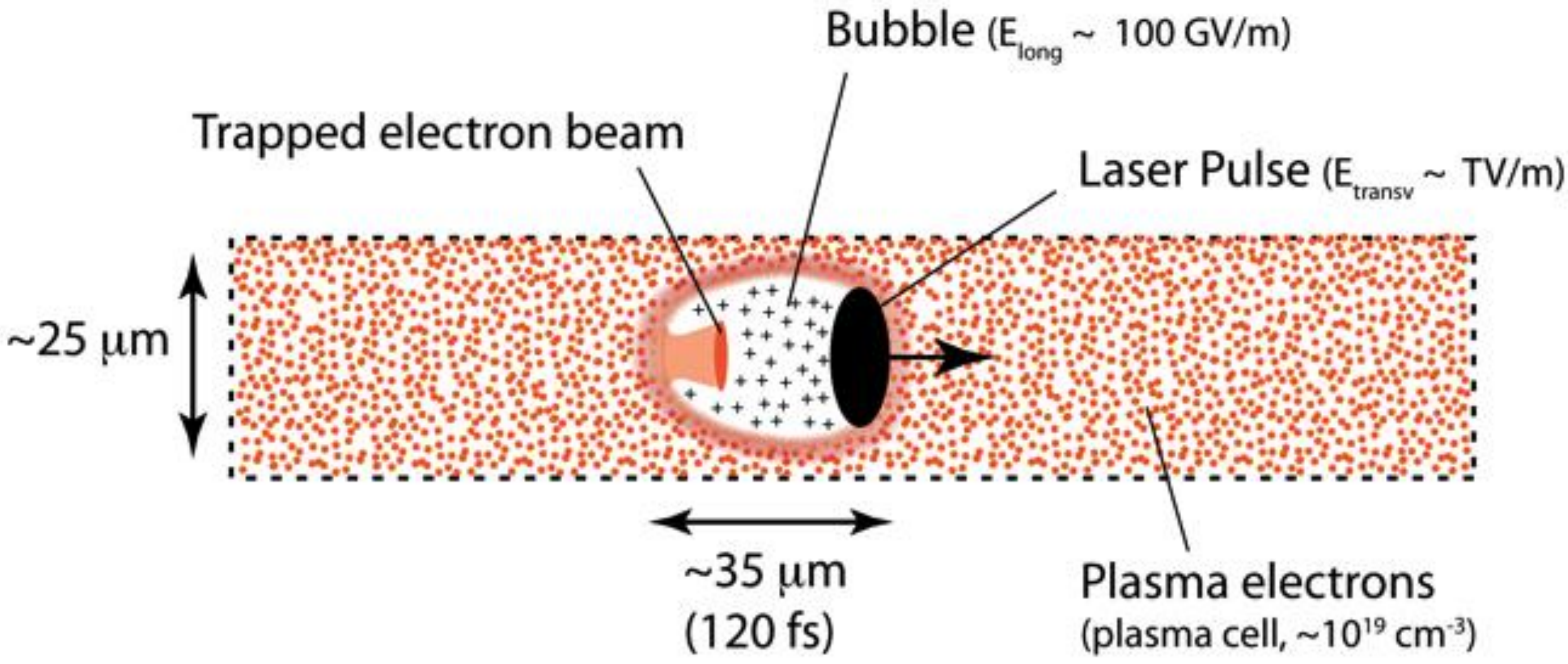
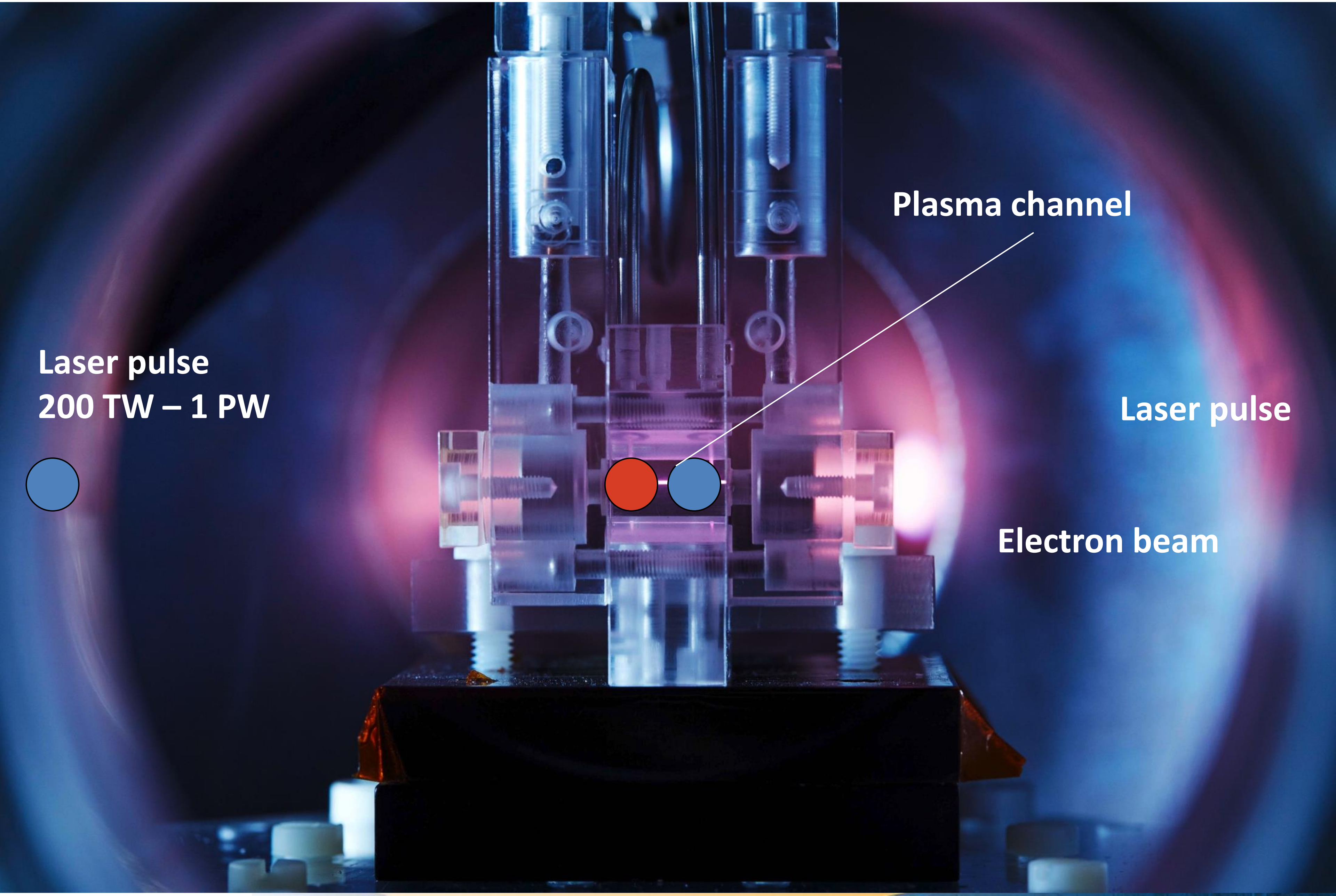


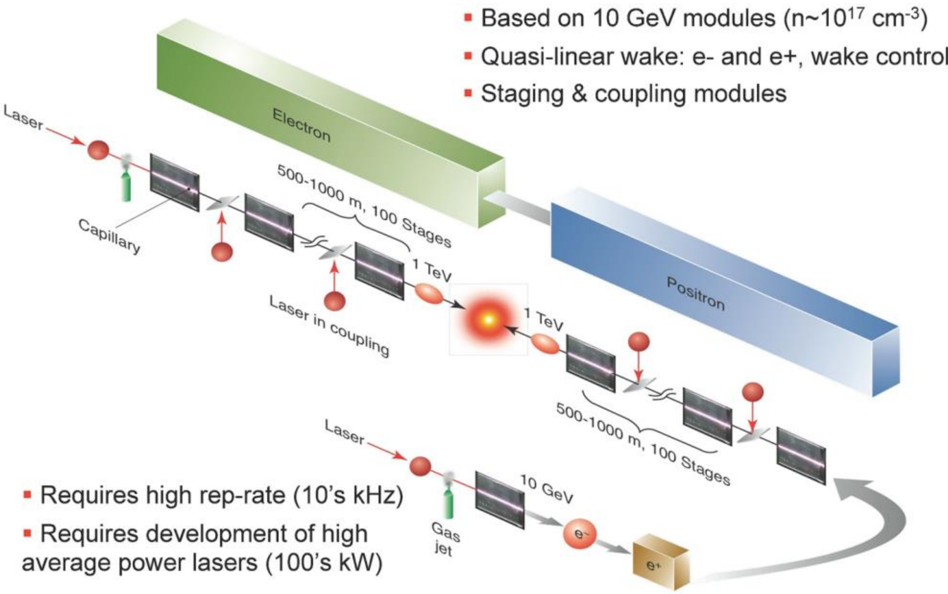
Laser Plasma-Acceleration (Internal Injection)



Laser Plasma Accelerators for Electron Beams



Towards a plasma-based linear collider?

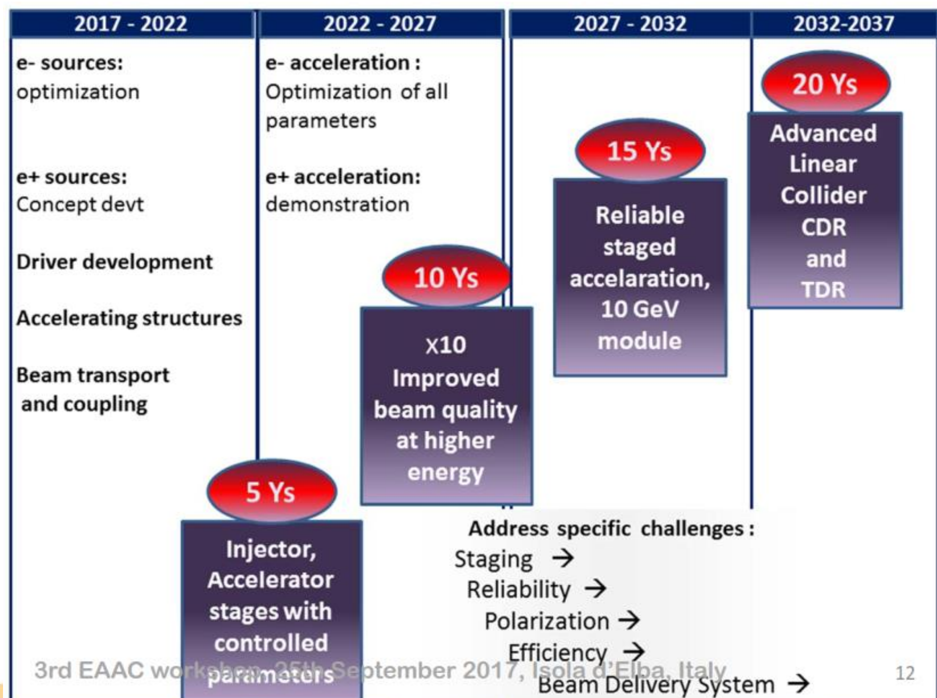


W.P. Leemans & E. Esarey, Physics Today, March 2009

Courtesy B. Cros

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**



The European Network for Novel Accelerators

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

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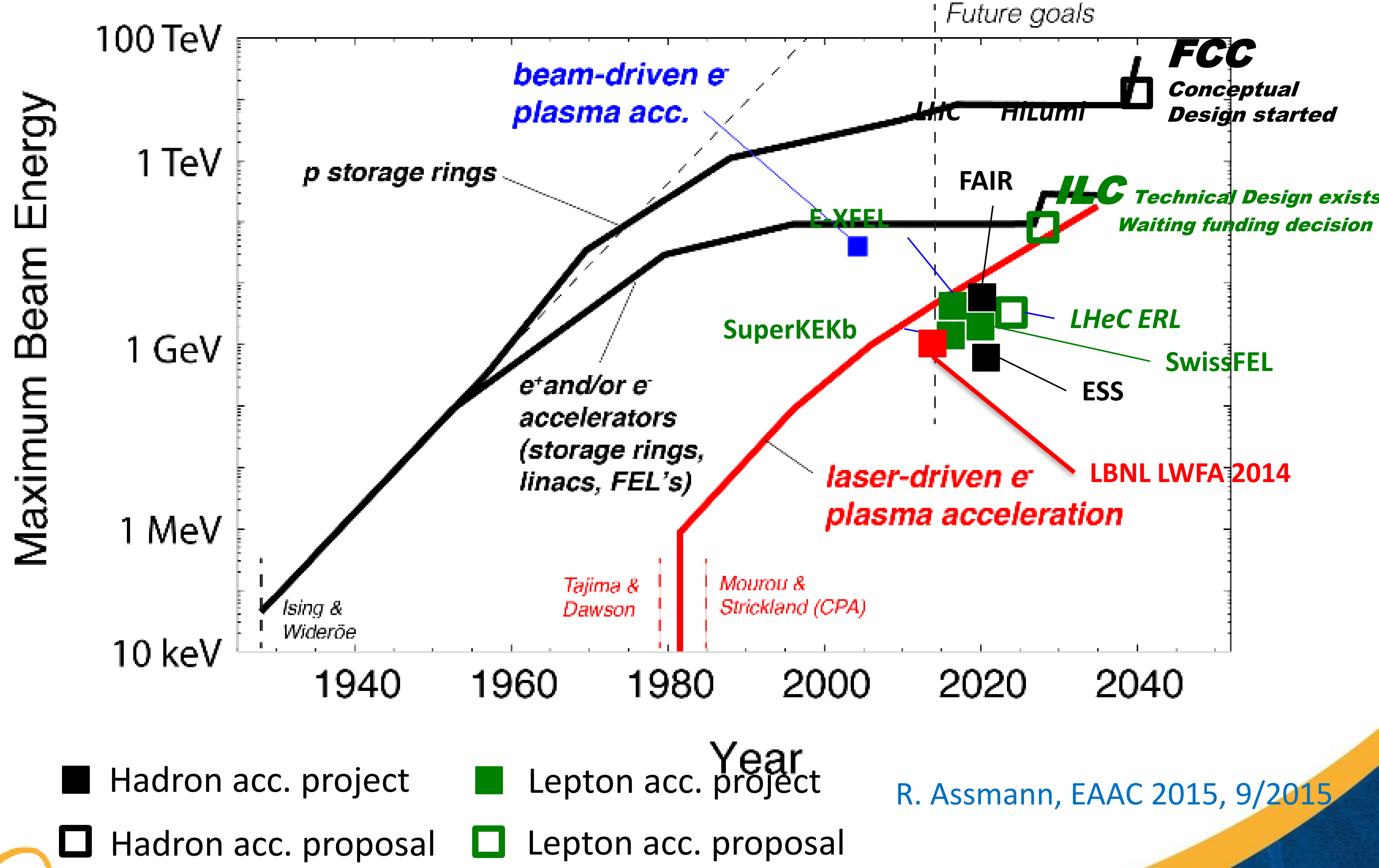
The future of accelerators ?



R. Assmann, EAAC 2015, 9/2015

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/cheap muon sources
- Compact accelerators for radioisotope production

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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

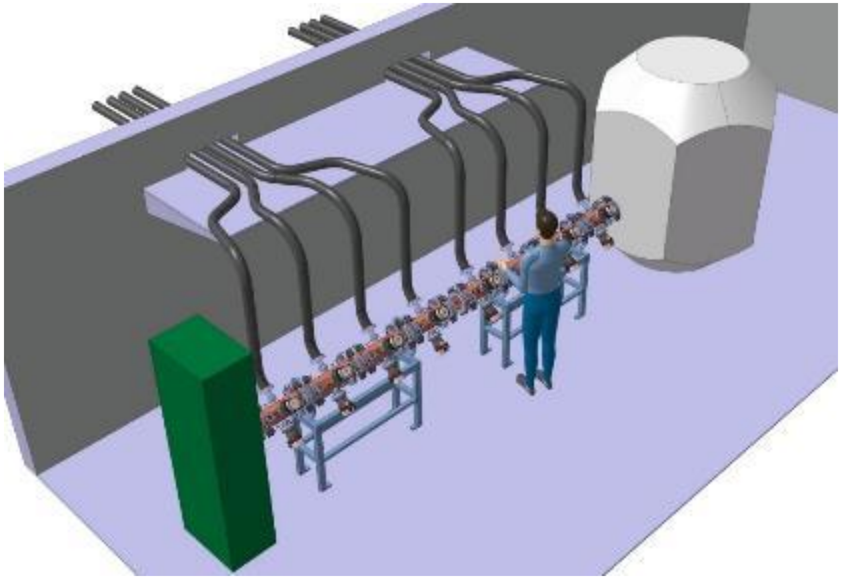
Produced in large cyclotron-based production centres and shipped overnight to hospitals

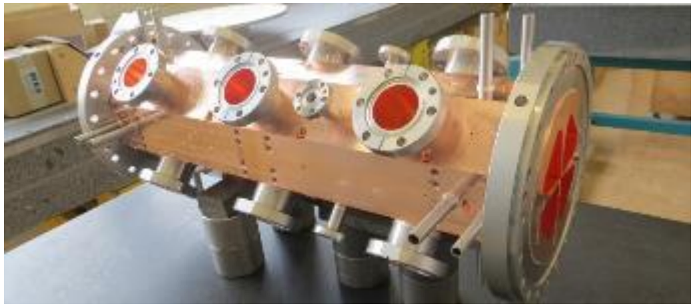
Interest in compact accelerators that can produce the isotopes directly in the hospitals:

- Shorter supply chain, easier availability
- Allows using shorter lifetime isotopes that can provide 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)

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Environmental applications of accelerators

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

- Flue gas treatment (cleaning of SOx and NOx from smokes of fossil fuel power plants)
- Waste water and sewage treatment

A recent example:
Workshop organized by ARIES on ship exhaust cleaning by an electron beam (100-300 keV).
Maritime transport is nowadays the largest contributor to air pollution and strict limitations are going to be introduced over the next years.
ARIES plans to start the development of an accelerator-based system that could be used to retrofit existing ship diesel engines.

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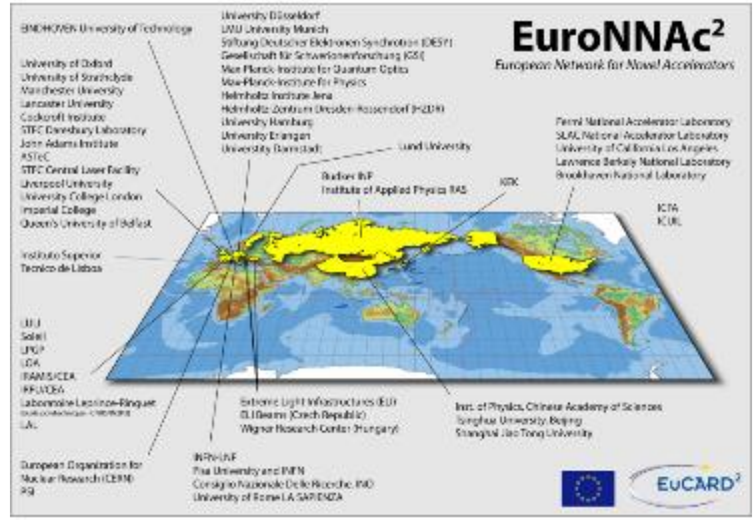
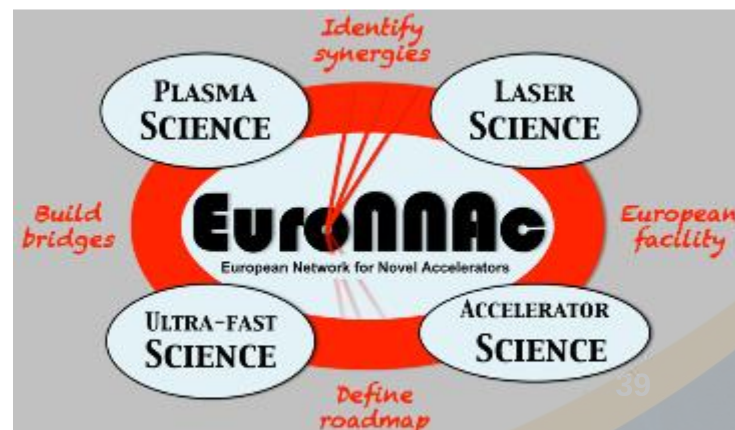
The goal: building bridges across communities

Convergence between synchrotron light ring facilities and electron rings for particle physics pioneered by EuCARD-2 WP6.

The goal is to expand this collaboration in the next Integrating Activity



EuroNNAC2 (WP7) is a global collaboration with precise objectives, as defined in the EuPRAXIA Design Study proposal.



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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.

The final word…

Particle accelerators are a vibrant and growing field, just starting the 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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