The future of particle accelerators: the role of collaborative R&D in the European context

M. Vretenar, CERN
EuCARD-2 Coordinator & Linac4 Project Leader, CERN

"Prediction is very difficult, especially if it's about the future."
--Nils Bohr,

An introductory presentation for the JUAS 2016 cycle
European Scientific Institute, Archamps, 14.01.2016

EuCARD-2 is co-funded by the partners and the European Commission under Capacities 7th Framework Programme, Grant Agreement 312453

Accelerators: a long history…

88 years since the invention of the first modern accelerator

(i.e. using periodic acceleration provided by Radio-Frequency fields):

Rolf Wideröe's thesis, 1928

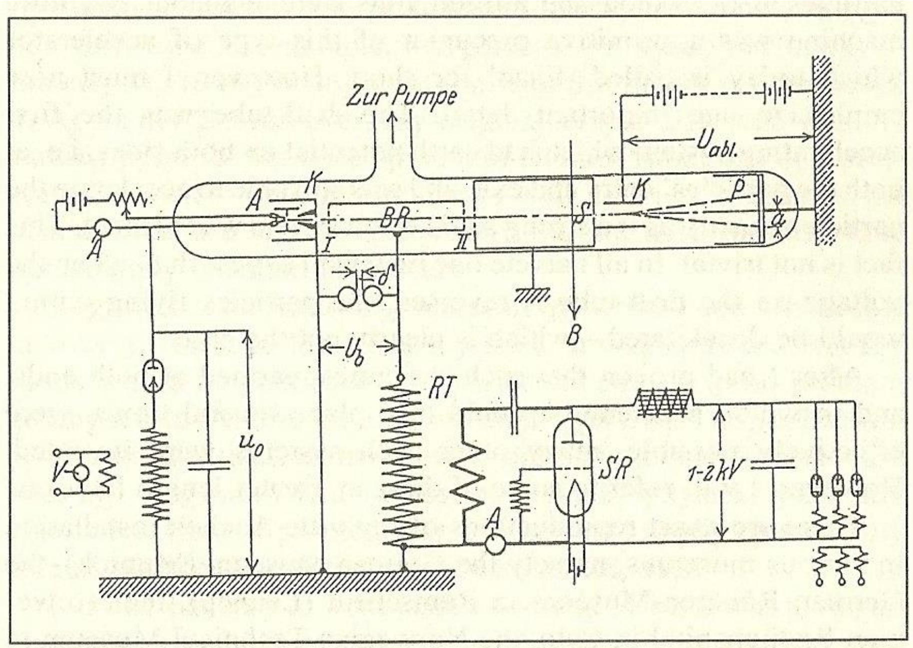


Fig. 3.6: Acceleration tube and switching circuits [Wi28].

Acceleration of potassium ions 1+ with 25kV of RF at 1 MHz → 50 keV acceleration ("at a cost of four to five hundred marks"…)

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 accelerators.
3. complete accelerator: ion source, RF accelerator, detector, all in vacuum

88 cm long glass tube – total cost less than 500 Marks

The ingredients

The ingredients of Rolf Wideröe's innovation:

- A PhD student *(fresh ideas and time available)*
- Under pressure to complete his thesis *(necessity is the mother of invention)*
- Merging information and experience from different fields *(cross-fertilisation)*

EuCARD² From infancy to maturity

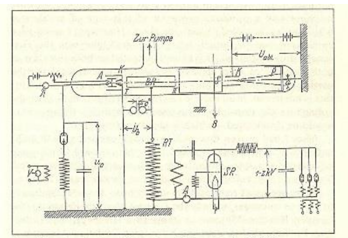


Fig. 3.6: Acceleration tube and switching circuits [Wi28].

1928
Wideröe builds the first modern accelerator

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

Cyclotron: cyclic acceleration with magnets (Lawrence)

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

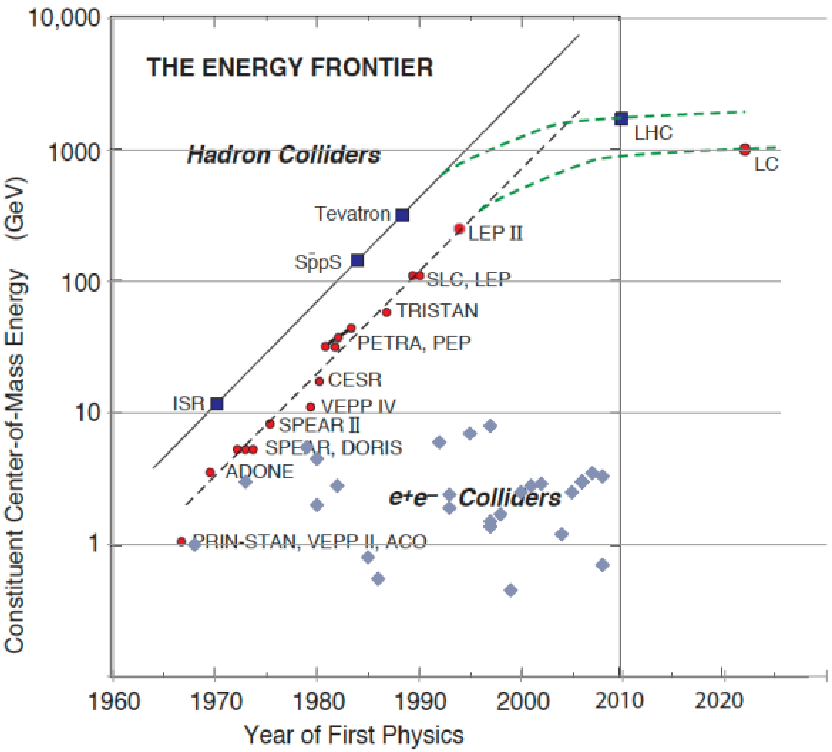
Strong focusing (Courant, Livingston, Snyder, Christofilos)

Superconductivity – magnets and cavities

2008
First beam in the Large Hadron Collider

And now? The 2016 accelerator landscape

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…

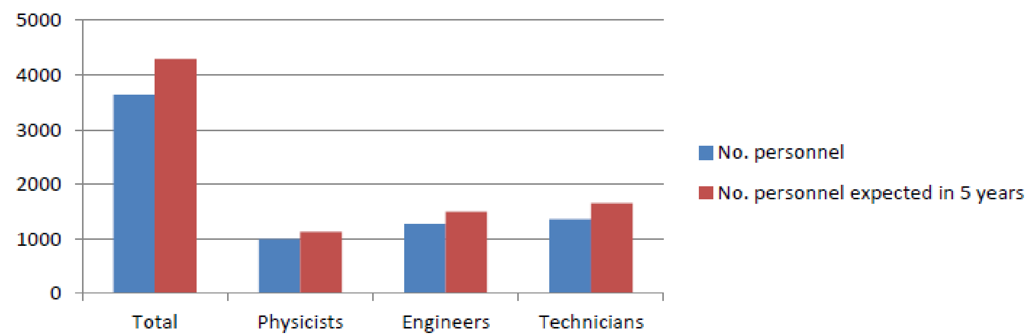


Figure 2.1: Total number of current personnel (blue) engaged in accelerator science activities a research institutes. The number of personnel expected in 5 years is shown in red.

TIARA, Need for Accelerator Scientists report, 2013: 3'700 people engaged in accelerator science in European research institutes, number expected to grow by 18% in 5 years.

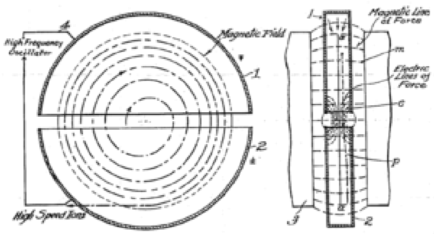
Accelerators are going through an impressive progress that at the moment more than by the quest for **energy** (basic science) is driven by aaplied science: x-ray or neutron sources, medical, etc.

Where are we going ?

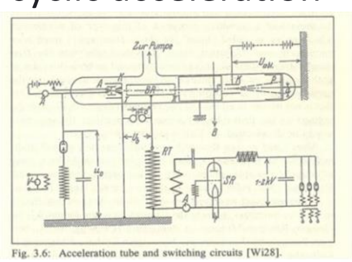
Collaborative R&D is needed for:

1 Push the gradients (B, E)
Improve efficiency

2 Push the limits:
Higher beam densities
and energies

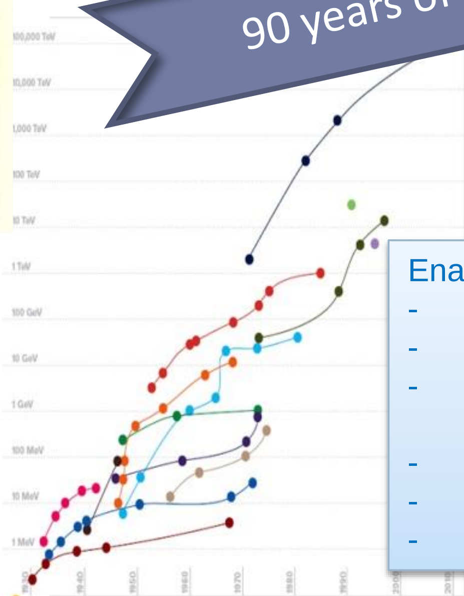


1931: Lawrence, cyclic acceleration

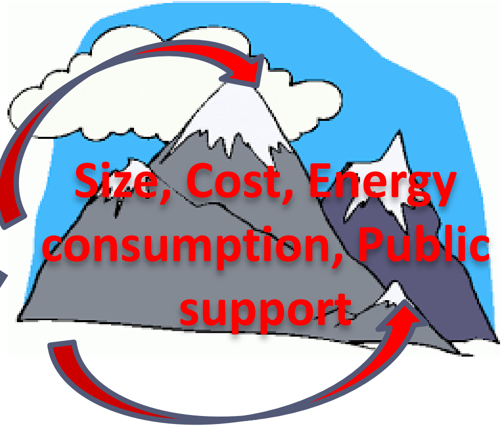


1928: Wideröe, periodic RF acceleration

90 years of particle accelerators



Enabling technologies
- RF acceleration
- Cyclic acceleration
- Strong focusing, phase stability
- Colliders
- Superconductivity
- (Plasmas ?)



3 A new paradigm:
Plasma wakefield
acceleration

Applied science
Medicine
Industry

4 Improve
applications and
technology
transfer

EuCARD-2: the European highway to Accelerator R&D

EuCARD-2 = European Coordinated Accelerator Research and Development, an *Integrating Activity* co-funded by the European Commission under the *Capacity – Research infrastructure* Program

> 300 participants from 40 partners (Laboratories, Universities and Industries) of 12 European Countries (+ CERN and Russia)

4 years duration (01.05.2013 - 30.04.2017)

13 Workpackages covering different fields of advanced Accelerator R&D

23.5 M€ total cost, 8 M€ EC contribution (1/3)

One website: **http://eucard2.web.cern.ch/**

One goal: **develop the technologies for tomorrow accelerators**

EuCARD-2 objectives

Scientific objectives:

1. Contributions to R&D topics of excellence (high risk, high pay-off) for research accelerators (HEP, nuclear physics, synchrotron lights, etc.).
2. Include new dimension of innovation, applications, relations with industry (healthcare, energy, environment, etc.).

Wider objectives:

- Join the efforts of large Laboratories (infrastructure, long-term strategies, experience) and Universities (intellectual potential, freedom and creativity).
- Strenghten European collaboration and foster synergies, create a network of complementary scientific infrastructures, enhance EU competitiveness.
- Promote public outreach of accelerator science, and education and training of the future generation of accelerator scientists.

EuCARD²

13 Workpackages

6 Networks

- **Extreme Beams** – F. Zimmermann (CERN)
  Frontier performance of accelerators. **2**
- **Low emittance rings** – Y.Papaphilippou (CERN), S.Guiducci (INFN), R.Bartolini (UOXF)
  Synergies synchrotron light sources, storage rings, damping rings, lepton colliders. **2**
- **Novel Accelerators** – R. Assmann (DESY)
  European roadmap for plasma-based accelerators. **3**
- **Energy Efficiency** – M. Seidel (PSI)
  Energy management in accelerators. **1**
- **Accelerator Applications** – R. Edgecock (HUD)
  Accelerator technology for industry, health care, energy, .. **4**
- **Catalysing Innovation** – G.Anelli (CERN), P.Woodman (STFC)
  Transfer to society of EuCARD-2 technologies. **4**

4 Research &Technology Developments

- **Future Magnets** – L. Rossi (CERN), P. Fazilleau (CEA)
  High Temperature Superconductors for 20 T magnets. **1**
- **Collimator Materials** – A. Rossi (CERN), J. Stadlmann (GSI)
  New materials for future collimators. **2**
- **Innovative RF Technologies** – P. Macintosh (STFC)
  High gradients for SC and NC accelerating cavities, RF diagnostics, photocathodes. **1**
- **Novel Acceleration Techniques** – V. Malka (CNRS)
  R&D topics on plasma wakefield acceleration. **3**

2 Access to Research Infrastructures

- **Ion Cooling Test Facility at STFC**
  R. Preece (STFC)
- **HighRadMat, MagNet at CERN**
  A. Fabich and M. Bajko (CERN)

The EuCARD-2 partners

40 partners from 15 European countries, including Russia

	#	Short names	Country	% of EC
Accelerator laboratories	10	CERN, CEA, CNRS, SOLEIL, DESY, GSI, INFN, ESS, PSI, STFC	Europe, France, Germany, Italy, Sweden, Switzerland, UK	63%
Technology Institutes and University departments in Applied Research	23	KUG, DTI, TUT, Grenoble INP, KIT, POLITO, WUT, UDUS, JGU, UROS, UM, UT, CSIC/VALENCIA, UU, UNIGE, HUD, RHUL, SOTON, STRATH, UCL, ULANC, UNIMAN, UOXF	Austria, Denmark, Finland, France, Germany, Italy, Malta, Netherland, Poland, Spain, Sweden, Switzerland, UK	27%
Scientific Research Institutes	5	HZB, HZDR, NCBJ, NRC KI, LUND	Germany, Poland, Russia, Sweden	7%
Industry	2	RHP, BHTS	Austria, Germany	3%

12 years of EU support to accelerators

ESGARD

*: only programs coordinated by the ESGARD committee, with particle physics as primary objective

Integrating Activities

FP6

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

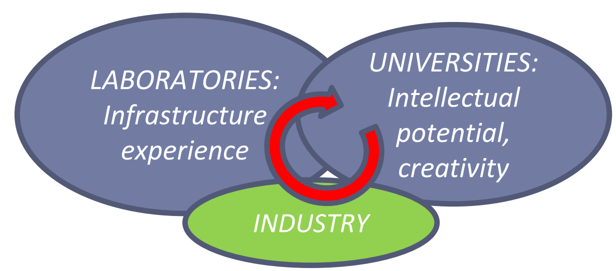
FP7

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

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€

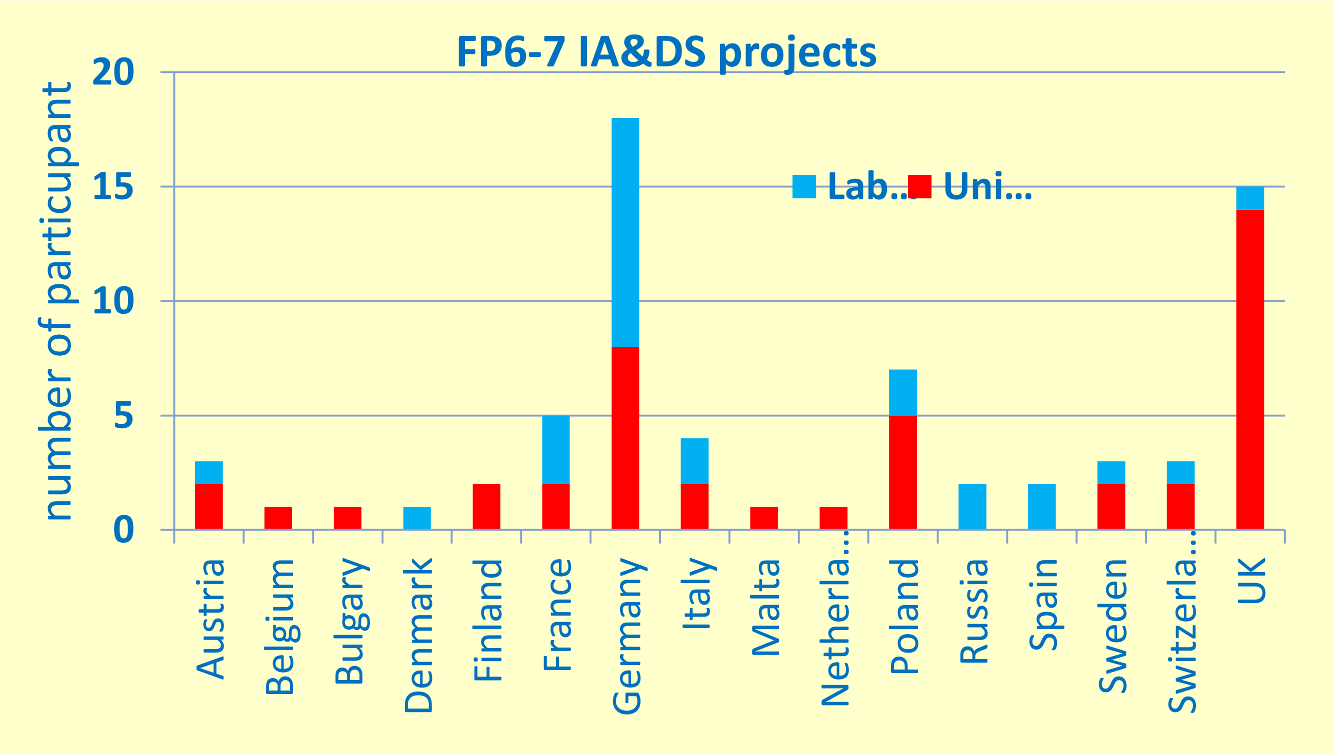


Low prioritiy of long-term R&D for large laboratories focused on short-term projects, while small institutions lack critical mass and the experience to be effective → a joint collaborative effort with the EU support is the most effective way to push the limits of our technologies.

The EC has contributed to accelerator projects in FP6 and FP7 with 68 M€ out of a total budget of ~228 M€

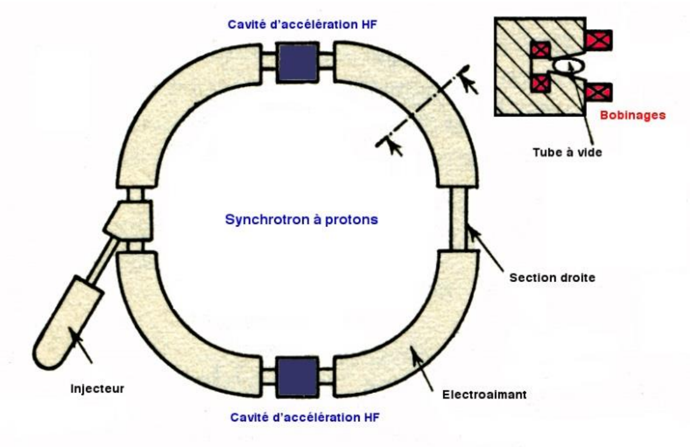
Participating institutes in FP 6&7

- In FP6-7 : 3 IA and 3 DS projects
- Total of 72 participants (number of participant in any of the 6 projects)

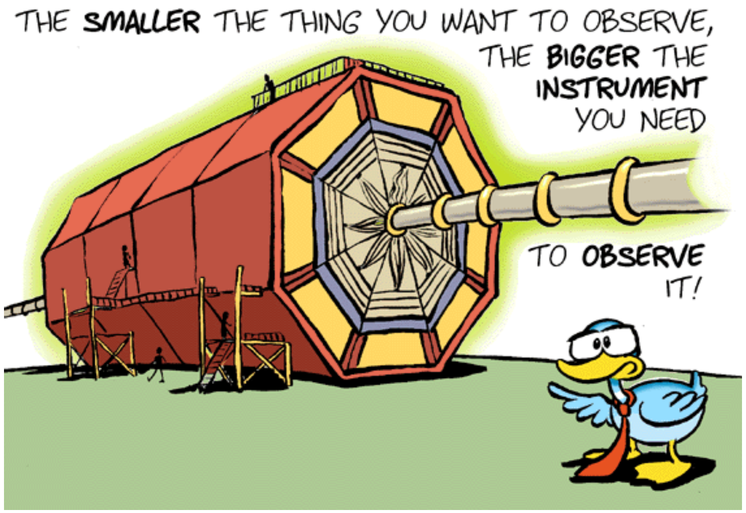


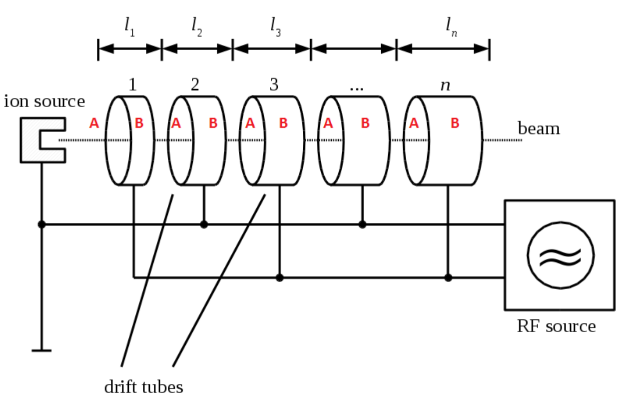
Data courtesy of R. Aleksan

Smaller accelerators?



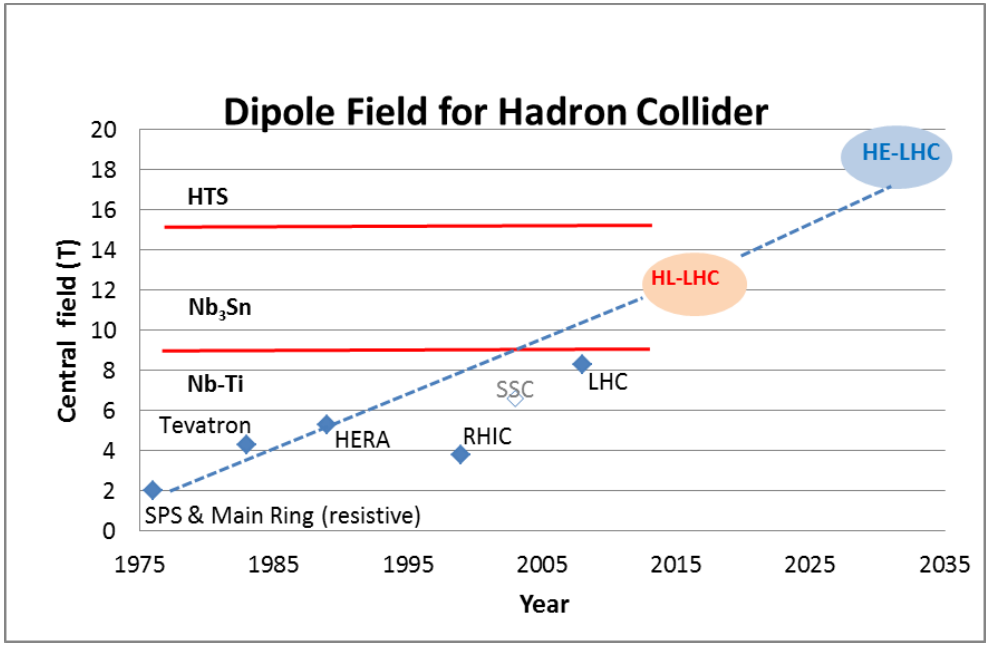
Synchrotrons: p/q=Bρ
Need to maximise magnetic field
Limitations: critical current density Jc for SC magnets





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

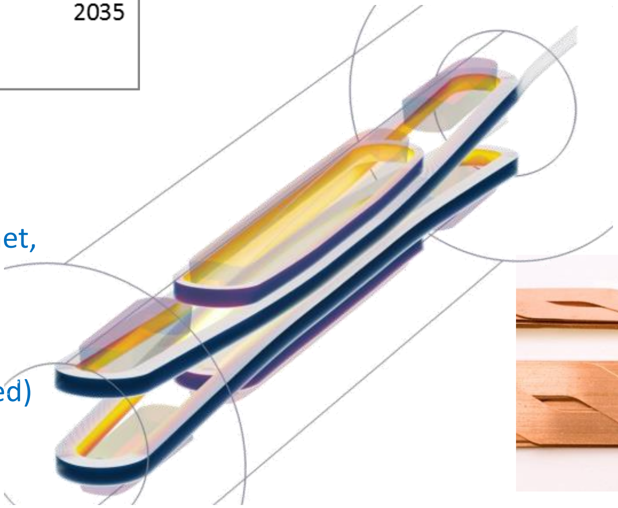
Nb_3Sn technology has seen a great boost in the past decade (factor 3 in J_C w/r to ITER) but was never used in an accelerator.

High-Temperature Superconductor technology still in the experimental phase (Production quantities, homogeneity and cost need to evolve!)

EuCARD-2 looks at HTS technology, the frontier of accelerator magnet technology.

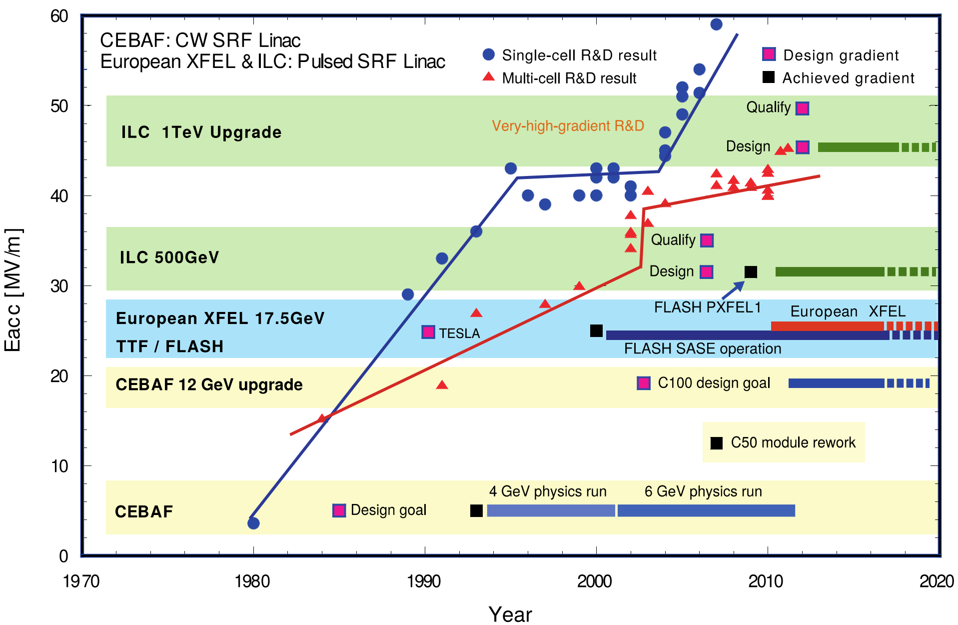
WP10 Future Magnets: R&D towards a 20 T HTS dipole magnet, develop 10 kA cable

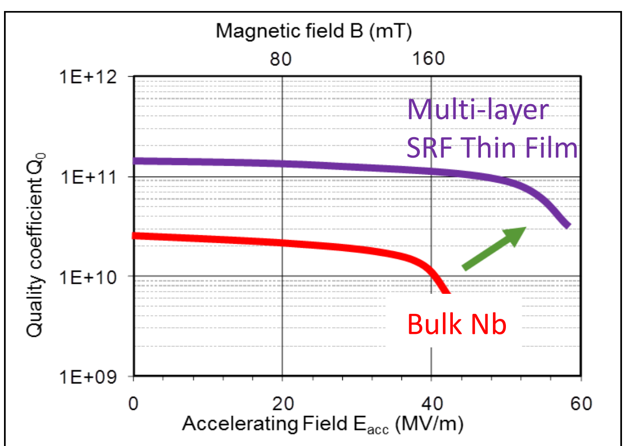
First results: focus R&D on REBCO material in Roebel cables, (rare-earth based YBCO, high current densitiy but mechanical issues still to be cleared)



EuCARD^2

The electric gradient frontier





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,

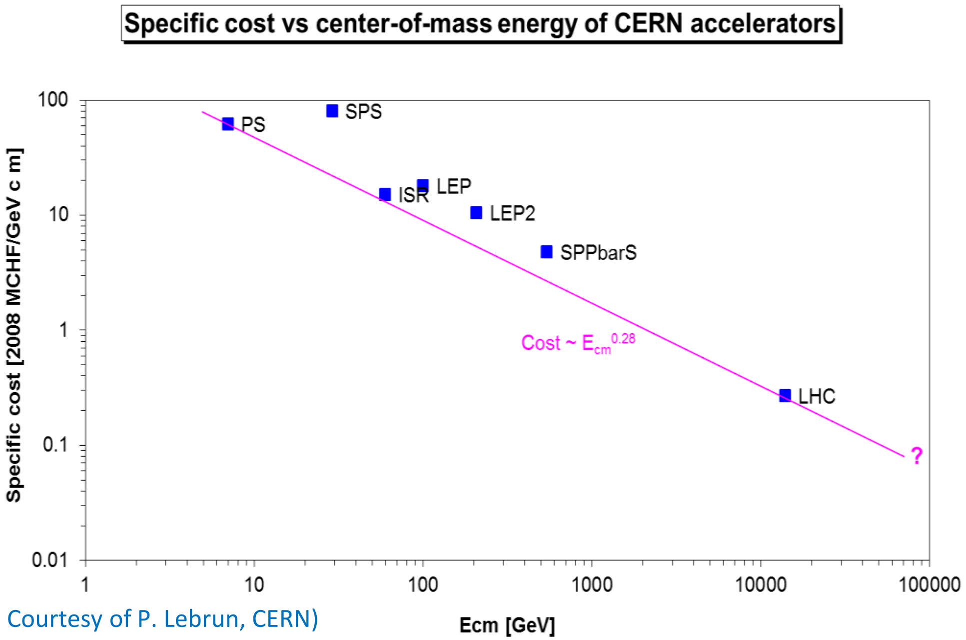
WP12 RF: R&D new higher-gradient superconductors: bulk Nb3Sn and nanometric multilayers of high Tc SC.

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

(+ Nb sputtering, beam generation, beam diagnostics)

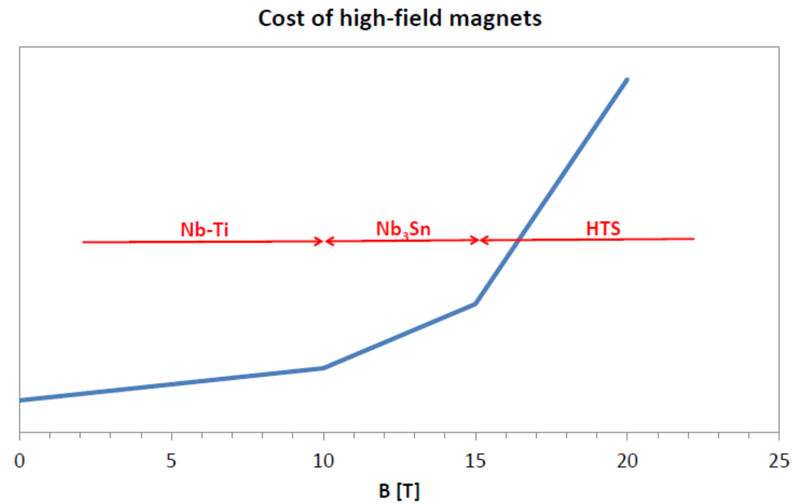
Long-term goal: 60 → 90 MV/m for superconducting cavities

Frontiers of accelerators



Courtesy of P. Lebrun, CERN)

- Primary goal → reduce cost/energy
- *Traditional way* → increase gradients (B, E)
- BUT: cost and power do not scale linearly with the gradient.
- Up to the final frontier: public acceptance



Complex system of "frontiers" that become more and more interrelated and/or overlapping, common to many different types of accelerators.

The EuCARD-2 collaborative effort becomes essential to optimize and develop the new technologies.

Efficient accelerators

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

Efficient energy management is the key to survival in the XXIst century.
(even when price of oil is decreasing…)
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?

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

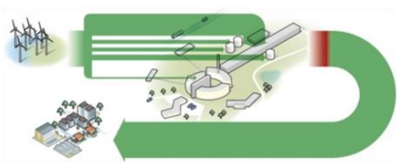
Need new techniques for efficient energy utilisation and heat recovery → impact on accelerators and on public opinion (key to public acceptance!).

- Modelling of energy flows and optimisation in time
- How can heat distribution generate an income? Low temperature heat is the main issue: LTHD, greenhouses, fish farms (integrated?) , wastewater treatment,…
- Optimisation of normal/stand-by operation

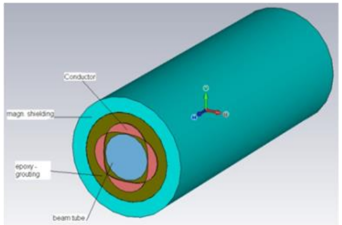
New ideas towards a sustainable energy management

Plenty of ideas and initiatives appearing at the horizon:

WP3
(Energy Efficiency)

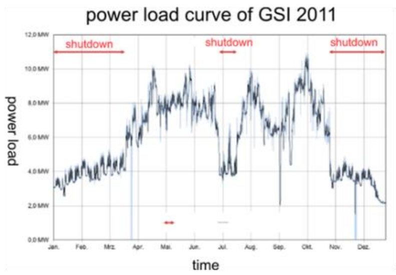


heat recovery at ESS

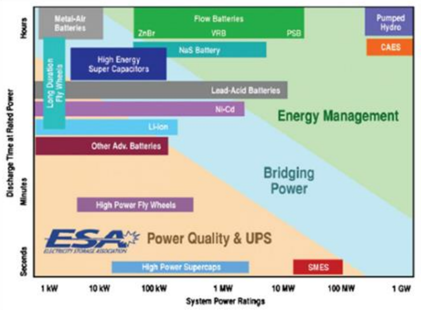


pulsed quads [GSI]

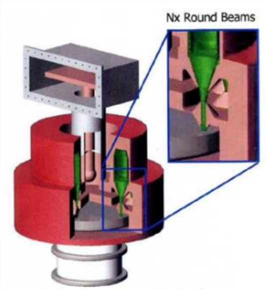
need for energy management



review of energy storage systems

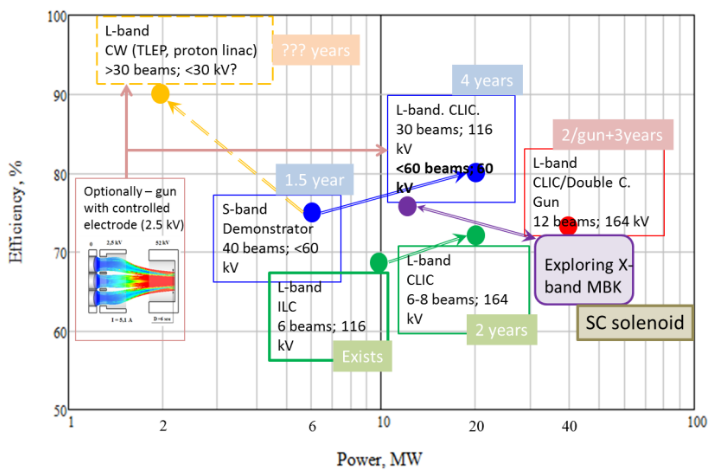


permanent magnet [CLIC]



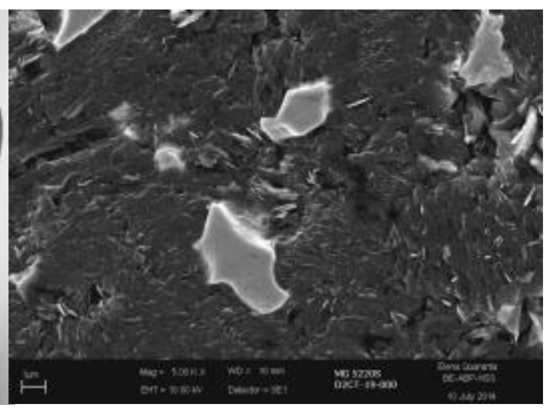
multi-beam IOT by con

New high-efficiency RF power sources



Material challenges in 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 Stefano Redaelli

Plasma Wakefield Acceleration

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

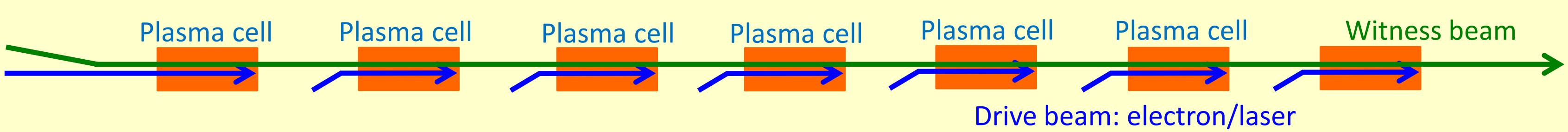
Several tens of kilometers for future linear colliders

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

Laser or electron drive beam: limitation of the energy carried by the drive beam (< 100J) and the propagation length of the driver in the plasma (<1m).

Staging of large number of acceleration sections required to reach 1 TeV region.

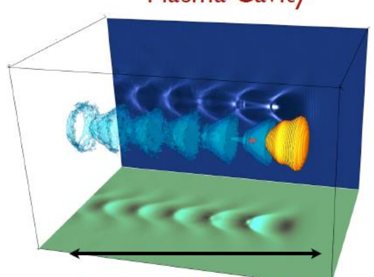


RF Cavity

1 m => 100 MeV Gain

Electric field < 100 MV/m

Plasma Cavity



1mm => 100 MeV

Electric field > 100 GV/m

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

Concept of Laser-Driven Plasma Linac : Challenges

1 PW laser at high rep rate (>100Hz): today in the best 1 Hz

Plasma and vacuum chambers

Transport between stages

Thermal effects on the guiding structure wall

External guiding/self-guiding

Collimation and beam filtering

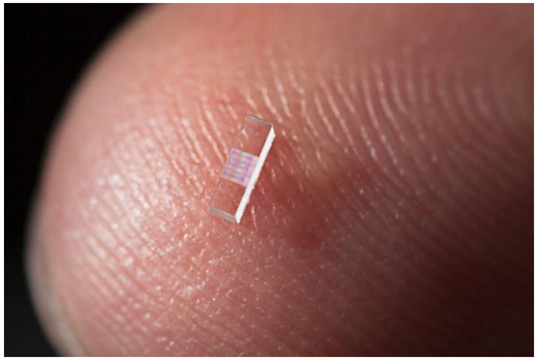
Accelerating plasma structure: linear (<1GV/m) or non-linear (>few GV/m to 100s GV/m)

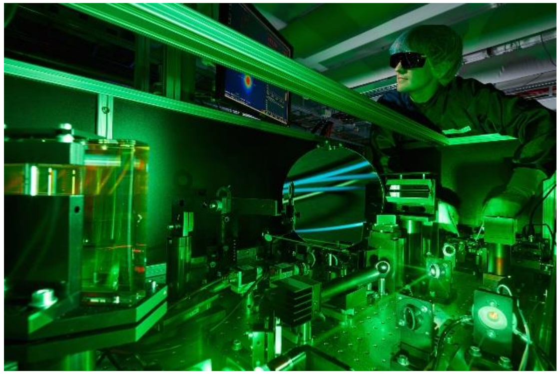
High efficiency laser driver : today in the best 1%

Courtesy of R. Assmann

A very vivid field !

- Laser-driven dielectric structures or waveguides:
  - 1 GeV/m possible but low absolute energies achieved so far
  - AXSIS project (ERC synergy grant) at DESY/U. Hamburg for THz laser-driven accelerator with atto-second science
  - “Accelerator on a Chip” grant from Moore foundation for work by/at Stanford, SLAC, University Erlangen, DESY, University Hamburg, PSI, EPFL, University Darmstadt, CST





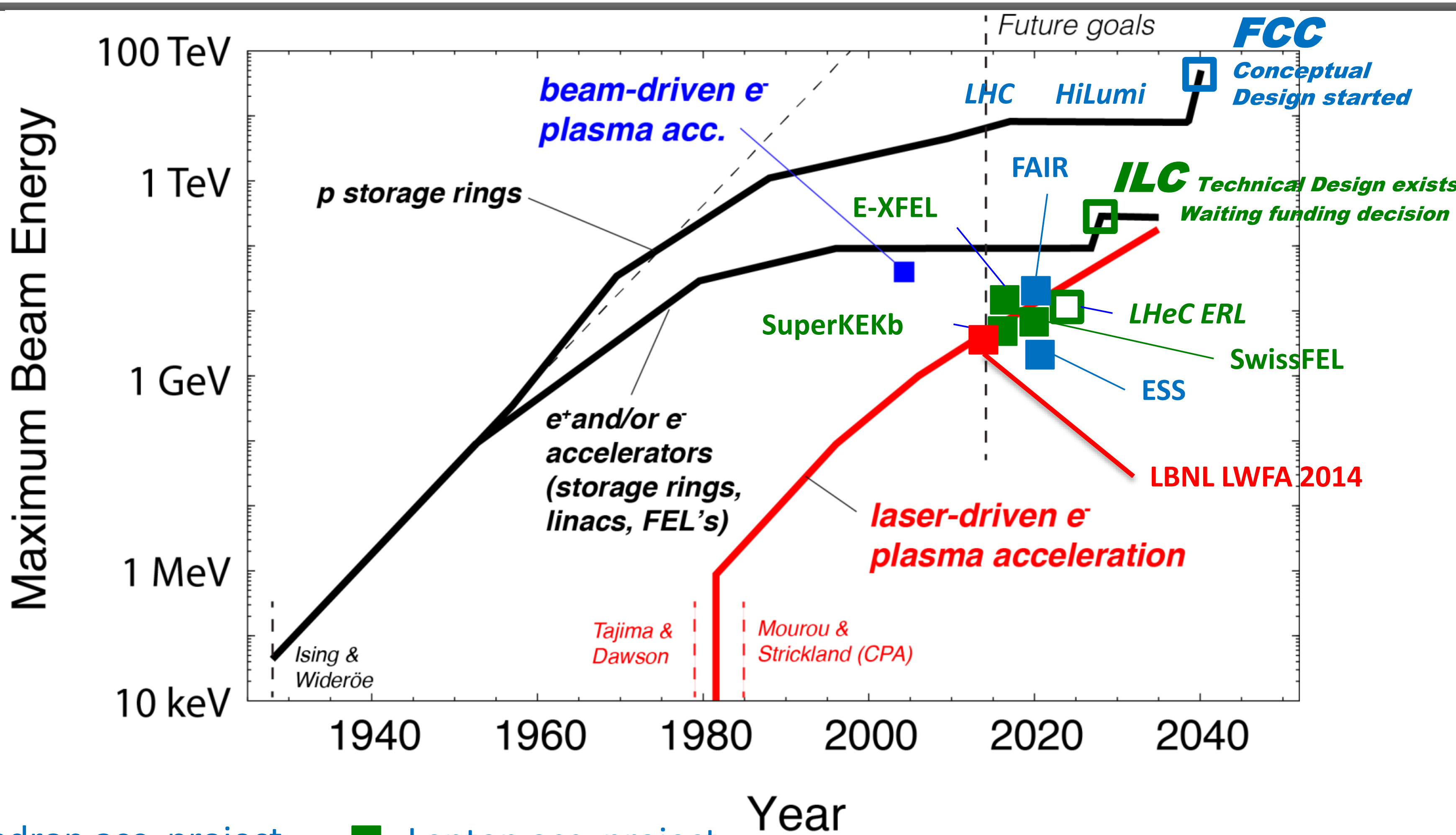
- Plasma-based electron and hadron accelerators:
  - Driven by lasers (for both e- and hadron), by e-beams (for e-: SPARC_LAB & FLASHForward in EU), by p-beams (AWAKE)
  - e-: Multi-GeV beams have been achieved → sufficient for applications
  - Hadrons: ion beams have been produced and transported
  - Activities at many centers in Europe (as well as US and Asia)

courtesy of R. Assmann, DESY

EuCARD²


SCAPA
STFC ASTeC
Lund Laser Centre
LAOLA
Laboratory for Laser- and beam-driven plasma Acceleration
ILPP
JuSPARC
ELBE.
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF
STFC
Central Laser Facility
PHELIX
eli beamlines
CileX
Centre Interdisciplinaire Lumière Extrême
CALA
Laboratoire d'optique appliquée
AWAKE
Consiglio Nazionale delle Ricerche
SPARC
INFN
United Kingdom
Isle of Man
Dublin
Ireland
Liverpool
Birmingham
Germany
France
Zurich
Switzerland
Slovenia
Milan
Turin
Monaco
Italy
Marseille
Bilbao
Porto
Montenegro
Bari
Tirana
Naples

Future of Accelerators



■ Hadron acc. project ■ Lepton acc. project

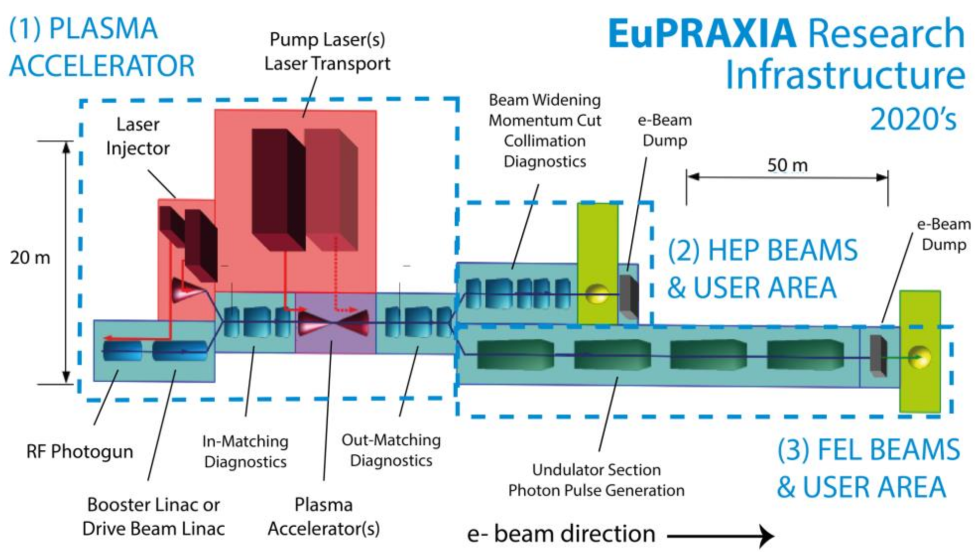
□ Hadron acc. proposal □ Lepton acc. proposal

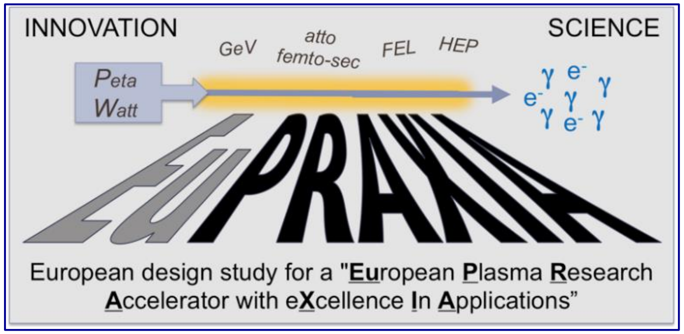
R. Assmann, EAAC 2015, 9/2015

The new EU Design Studies

2 projects submitted by our community to the 2014 EC call for Design Studies have been selected for funding (although this call was extremely competitive!)

1. EuroCIRCOL: FCC-hh 100km Circular collider (Core part of FCC)
2. EuPRAXIA: European Plasma Accelerator with High Beam Quality and Pilot Applications





EuPRAXIA: Design of a Plasma Accelerator Center (5 GeV and 250 m length) for 2 pilot users:

- compact femto-second FEL
- HEP detector science.

Beam Parameter	Unit	Value
Particle type	-	Electrons
Energy	GeV	1 – 5
Charge per bunch	pC	1 – 50
Repetition rate	Hz	10
Bunch duration	fs	0.01 - 10
Peak current	kA	1 – 100
Energy spread	%	0.1 – 5
Norm. emittance	mm	0.01 – 1

Towards medicine and industry

Courtesy R. Edgecock

>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**

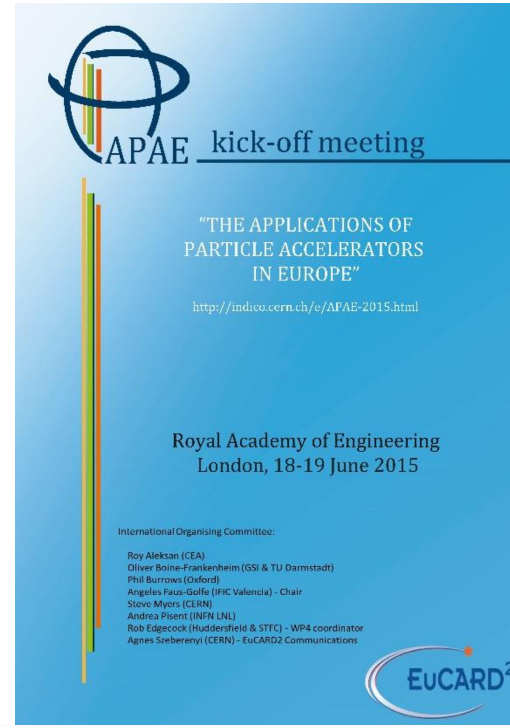
WP4 Accelerator Applications: Workshops on

- 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

Key questions: what does the man in the street need?

More and better science – we all agree!
More and better life – we all agree, too…

WP4 Accelerator applications

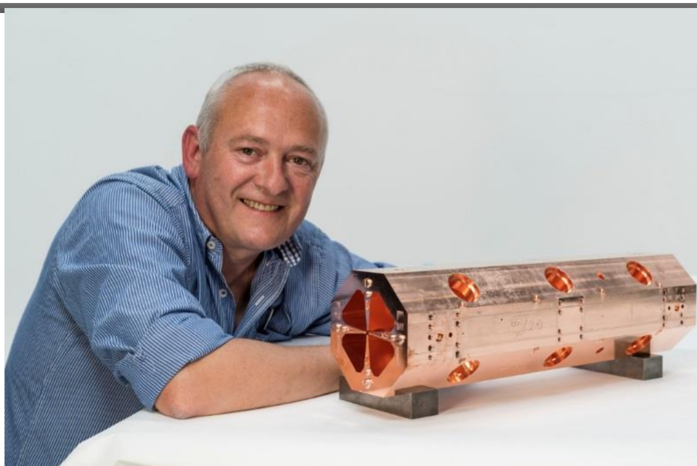


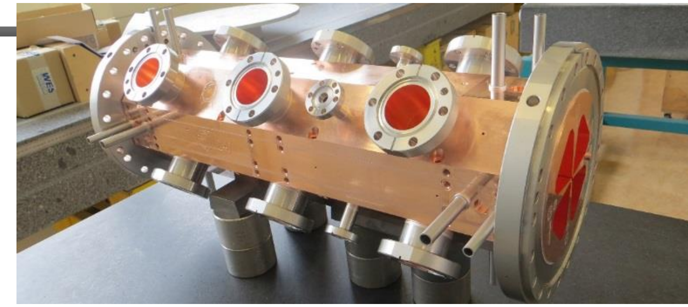
People in the street need the LHC (and now the FCC…) but need as well more and better medical isotopes, better materials, better semiconductors, improved security, etc.

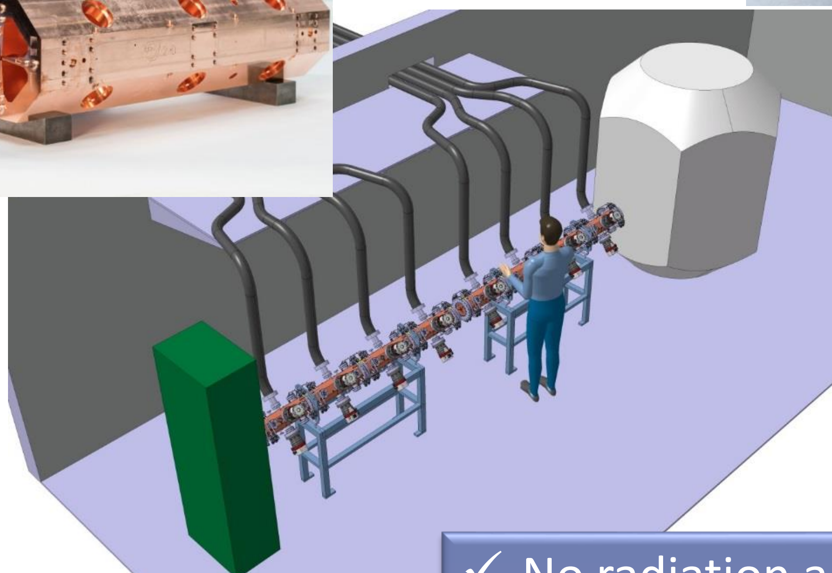
June 2015: Kick-off meeting of APAE: document for policy-makers on applications of interest in Europe and for which technology developed for research can have an impact.

Recent industrial workshop on accelerators for production of medical isotopes

Example: compact RFQ accelerator for radioisotope production in hospitals







Input energy = 40 KeV
Total Length = 4.0 m
Output Energy = 10 MeV
Frequency 750 MHz
Average current = 20 μA
Peak current = 500 μA
Duty cycle = 4 %
Peak RF power < 800 kW
Total weight (RFQ): 500 kg

Production for PET scans of ^{18}F and ^{11}C

- ✓ No radiation around accelerator and target.
- ✓ Easy operation (one button machine).
- ✓ High reliability.
- ✓ Minimum footprint (15 m2).

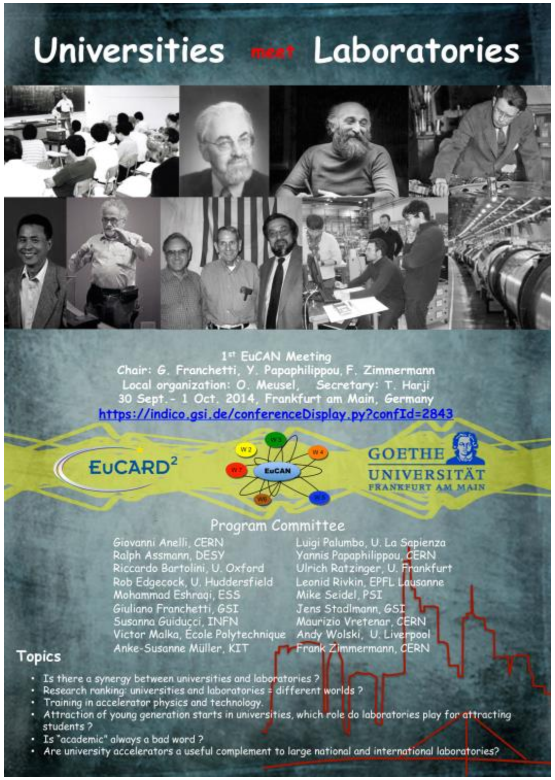
EuCARD-2 key questions: what do we need to work together?

European projects are all about collaborations, but collaborations are not straightforward because we often speak different languages depending from our originating environment (university, laboratory, industry).

EuCARD-2 is approaching the **Sociology of Accelerator R&D Collaborations**:

- Recent dedicated Workshop on «Universities meet Laboratories
- Session on collaboration between Industry and Academia at a recent Workshop «EC2 meets industry»

We need to work together because our discipline is at the boundary between science and technology… but:



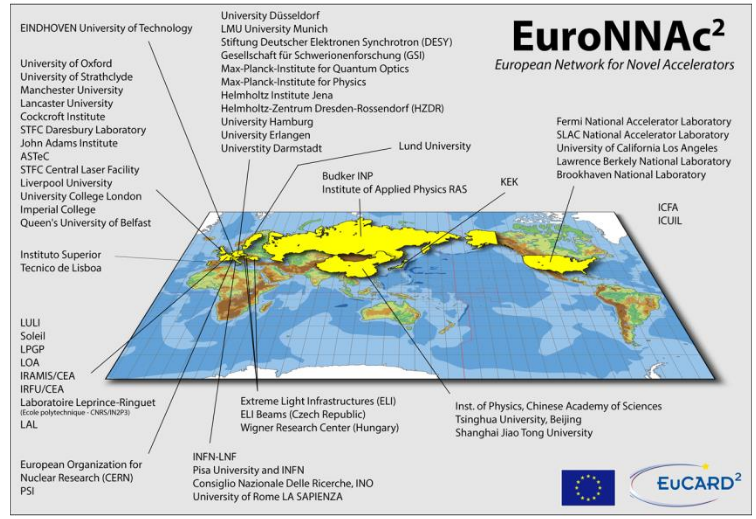
Universities and Laboratories: all consider collaboration essential, but have different evaluation criteria (=definitions of success): peer-reviewed publications for Universities and operational results are for Laboratories.

Industries and academic/scientific world: all consider collaboration essential, but have to face problems of sharing of IP, confidentiality, way of working.

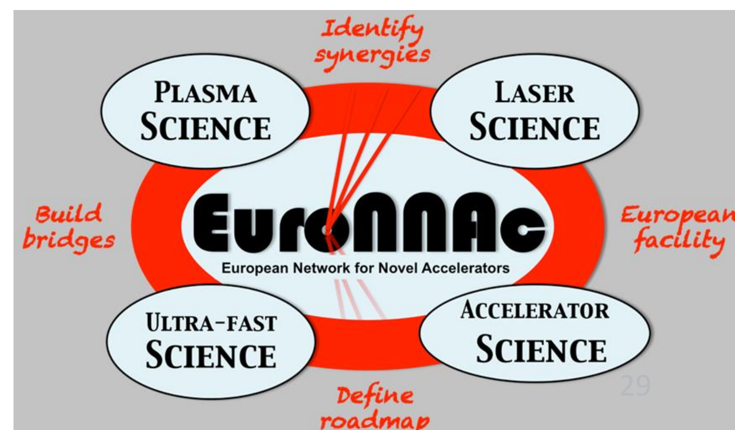
EuCARD-2 bulding bridges across communities

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.



EuCARD^2

The new ARIES Project

After EuCARD-2 we are now preparing a proposal for the next Integrating Activity for Accelerators that if approved will take over from EuCARD-2 in 2017 for a duration of 4 years.

Not a continuation, but a completely new project:

ARIES

Accelerator
Research and
Innovation for
European
Science and Society

New features:

- 6 new countries (18 total).
- More industrial partners (7 total).
- New innovation programmes with industry.
- More focused on fewer strategic R&D topics.
- Accent on accelerator applications.
- Opening key accelerator test infrastructures to external users.
- Education and training content.

Isotope production – Environmental applications – High efficiency RF sources – Advanced instrumentation – HTS magnet technologies – Materials for extreme thermal management – Multistage LWFA – Dielectric laser accelerators - …

Many PhD grants are expected to be cofinanced by ARIES. If interested, stay tuned!

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 or for which customers will pay.

The final word…

ld, just starting the transition from
ocietal applications.

the frontiers of accelerators we need
some change in paradigm…

ung people developed in a
ders between different scientific fields.

rojects like EuCARD-2, but most of