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

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"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, 12.01.2017

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Accelerators: a long history…

89 years since the invention of the first modern accelerator

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

Rolf Wideröe's PhD thesis, 1928

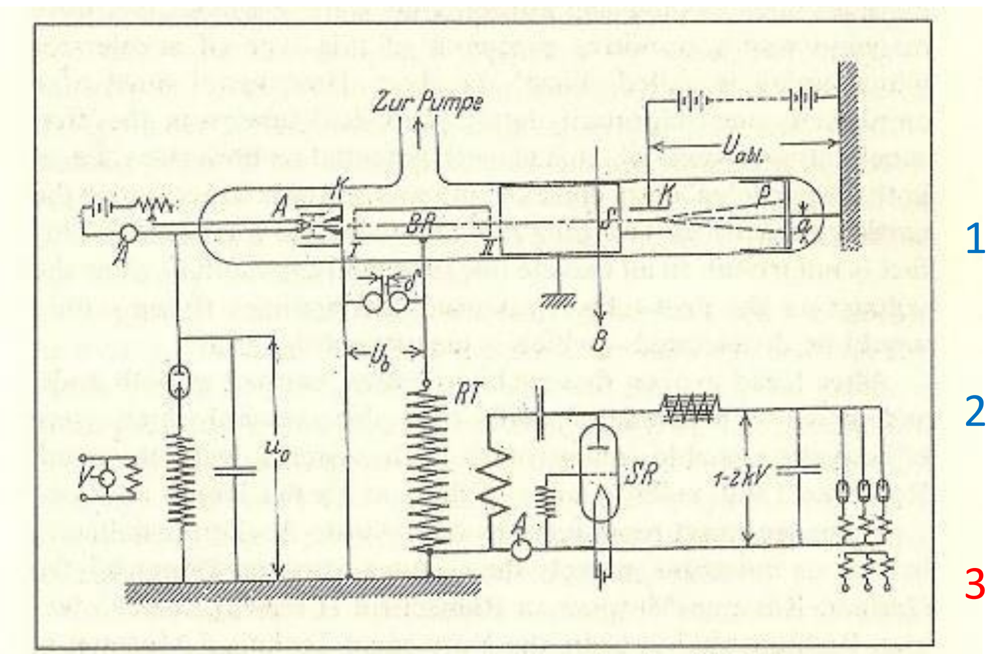


Fig. 3.6: Acceleration tube and switching circuits [Wi28].

Acceleration of potassium ions 1+ with 25kV of RF at 1 MHz → 50 keV acceleration ("at a cost of four to five hundred marks"…) in a 88 cm long glass tube.

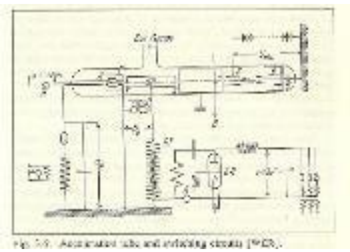
1. use of Radio-Frequency technology (at the time limited to 1-2 MHz) ⟶ marrying radio technology and accelerators.
2. Use of a drift tube separating 2 accelerating gaps → invention of periodic accelerators.
3. complete accelerator: ion source, RF accelerator, detector, all in vacuum

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)*

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)

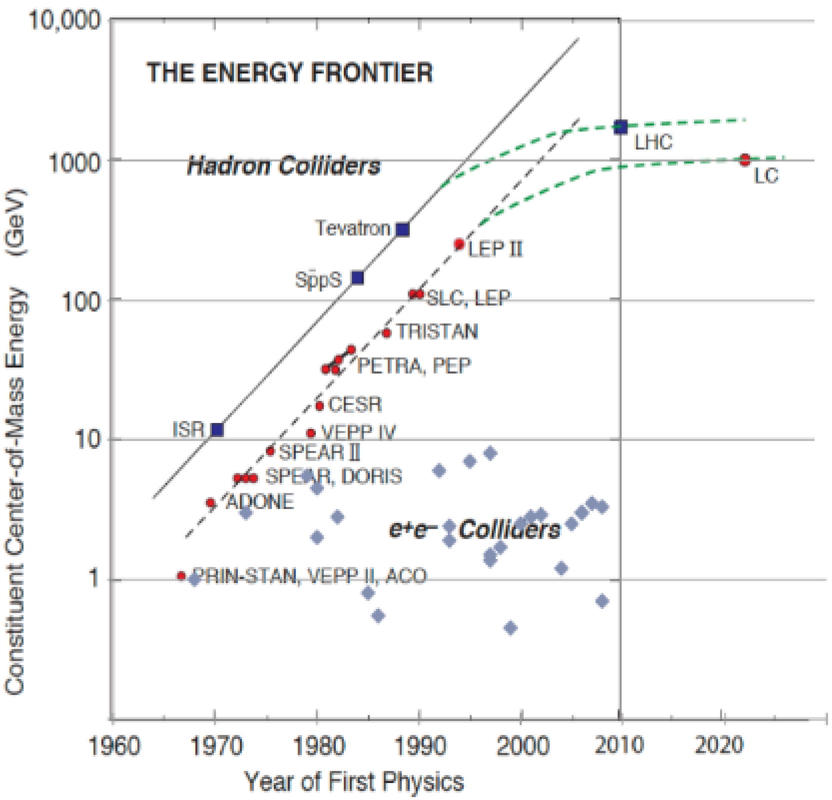
Strong focusing (Courant, Livingston, Snyder, Christofilos)

Superconductivity – magnets and cavities

2008
Start of the Large Hadron Collider

And now? The 2017 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…

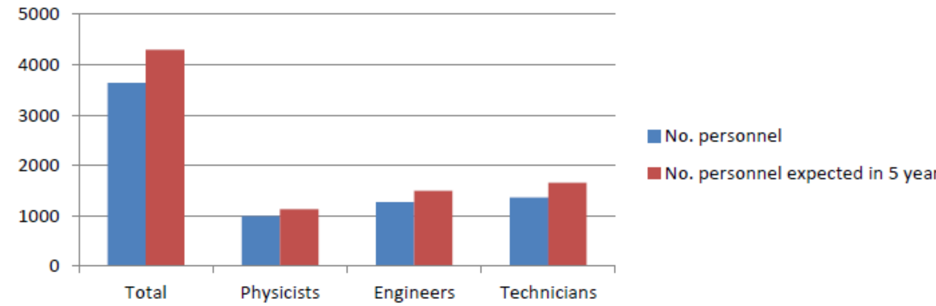
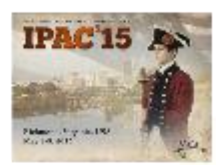
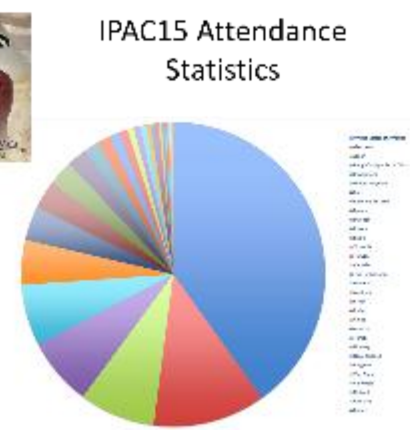


Figure 2.1: Total number of current personnel (blue) engaged in accelerator science activities a research institutes. The number of personnel expected in 5 years is shown in red.

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.





1302 attendees

- from 31 countries
- from 338 institutions
- 87 industrial exhibitors

Particle Accelerator Conferences are growing to a remarkable size: ~1’300 participants from countries as far as Vietnam, Colombia, Thailand, …

Accelerators in transition

We are moving from a paradigm where **basic science** (and energy) is the driving force for the development of new accelerators to a new paradigm where **applied science** (mainly 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?

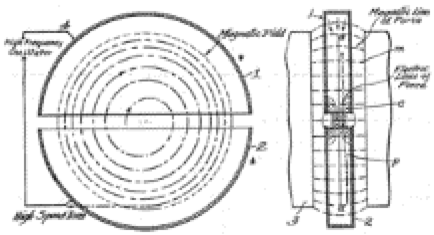
Research		**6%**
	Particle Physics	0,5%
	Nuclear Physics, solid state, materials	0,2 a 0,9%
	Biology	5%
Medical Applications		**35%**
	Diagnostics/treatment with X-ray or electrons	33%
	Radio-isotope production	2%
	Proton or ion treatment	0,1%
Industrial Applications		**60%**
	Ion implantation	34%
	Cutting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

Where are we going ?

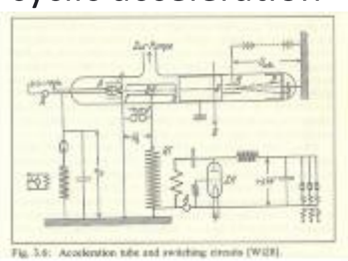
Collaborative R&D is needed for:

1 Push the gradients (B, E)
Improve efficiency

2 Push the limits:
Higher beam densities
and energies

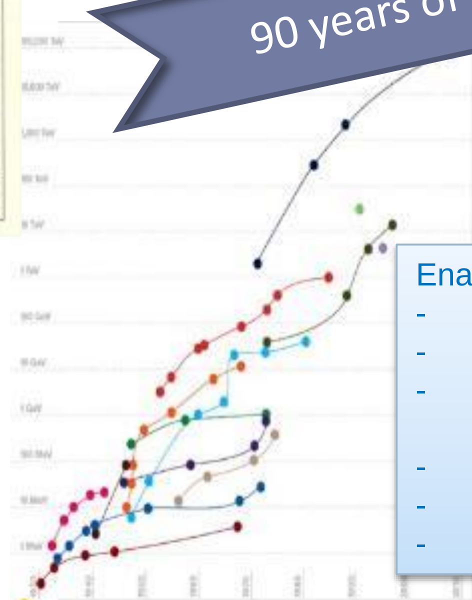


1931: Lawrence,
cyclic acceleration



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 and ARIES: the European highway to Accelerator R&D

Long tradition of European Union support to R&D for future particle accelerators: *Integrating Activities* under the *Capacity – Research infrastructure* Program
2013-17 **EuCARD-2** = European Coordinated Accelerator Research and Development,
2017-21 **ARIES** = Accelerator Research and Innovation for European Science and Society.

> 300 participants from 40 partners (Laboratories, Universities and Industries) across Europe (+ CERN)

Projects of 4 year duration

Workpackages covering different fields of advanced Accelerator R&D

EuCARD2: 23.5 M€ total cost, 8 M€ EC contribution (1/3)

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

Website: **http://eucard2.web.cern.ch/**

13 years of EU support to accelerators

EuCARD²

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

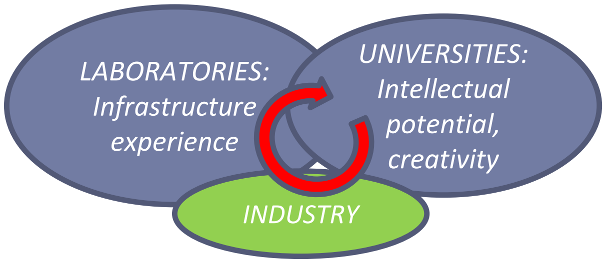
H2020

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

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€

The 4 ARIES Pillars


excellence


access


innovation


sustainability

Develop **key accelerator technologies** to make more performant, affordable, reliable and sustainable the present and future accelerators

Improve the European **accelerator infrastructure**

New scheme of Transnational Access opening **14 accelerator test facilities**

Enlarged consortium with **20 new partners** in accelerator projects and **6 new countries** in the East and South of Europe

Enhanced **industrial participation** (7 industries and 1 association)

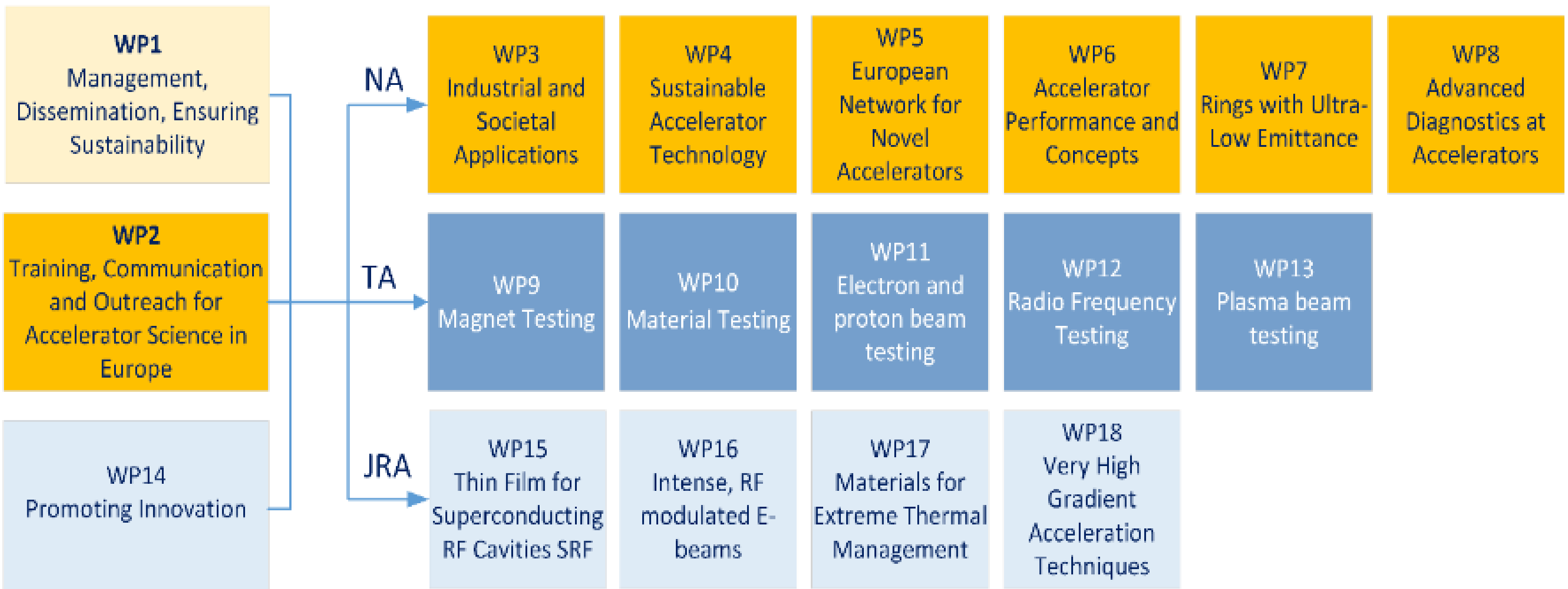
3 new **co-innovation programmes** with industry

Development of **societal applications** (medicine, industry, environment)

Joint programme with TIARA to develop a **model for sustainable accelerator science** in Europe

Training programme for the new generations of accelerator scientists and engineers

The structure



18 Workpackages:

8 **Networks** 5 **Transnational Access**, 5 **Joint Research Activities**.

New dimensions in ARIES

- ## Transnational Access:

Support to tests or experiments on 14 accelerator test facilities across Europe: can pay travels, subistance, technical support.

- Magnet testing: CERN SM18 and FREIA at Uppsala.
- Material testing: HiRadMat at CERN and M-branch at GSI.
- Beam testing: protons and RF at IPHI (CEA), high current electrons in ANKA (KIT), variable electron beams at VELA (CI), short electron bunches at FLUTE (KIT) and when operational at SINBAD (DESY).
- RF testing at FREIA (Uppsala) and at the XBOX at CERN.
- Plasma acceleration testing at the Apollon laser (CNRS), UHI100 laser (CEA-CNRS) and Lund Laser Centre.

- ## Education and Training :

New dimension in ARIES, pilot e-learning accelerator course and organization of training activities.

ARIES participants

	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

42 Participants

12 Laboratories, 22 Universities, 8 Industries

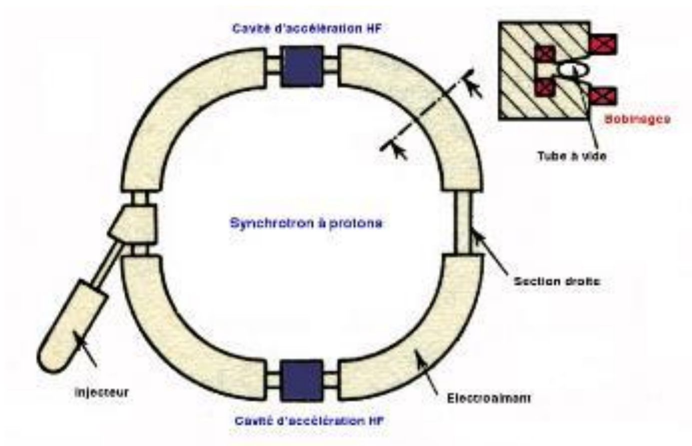
18 Countries (7 in the south and east of Europe!)

Dimensions of accelerator R&D

From The Economist, October 2013

EuCARD^2

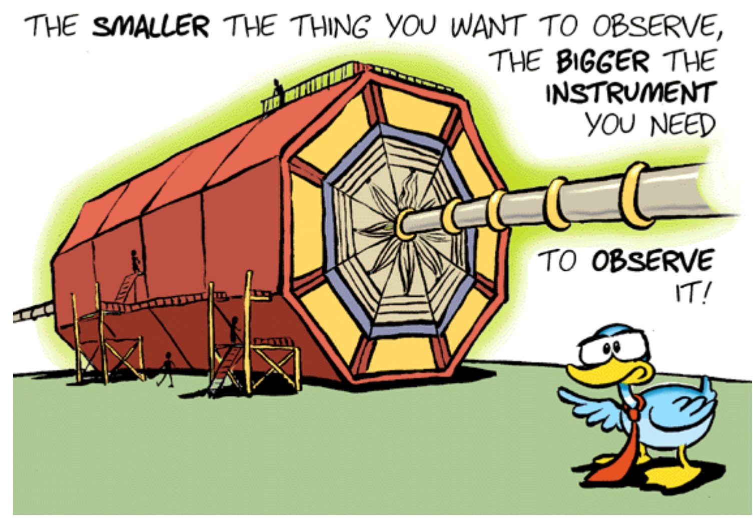
Smaller accelerators?

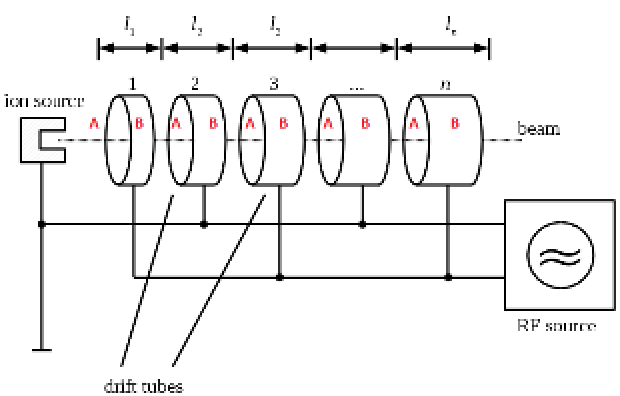


Synchrotrons: p/q=Bρ

Need to maximise magnetic field

Limitations: critical current density Jc for SC magnets



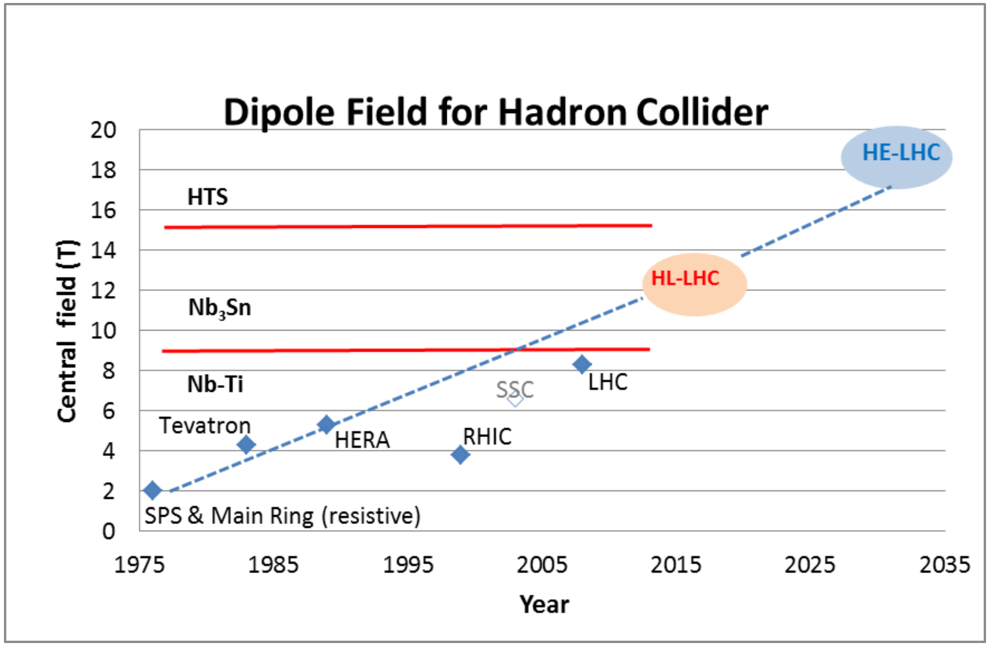


Linear accelerators: W=Eℓ

Need to maximise electric field

Limitations: sparking, field emission, etc.

The dipole field frontier



NbTi mature technology but limited to 9T

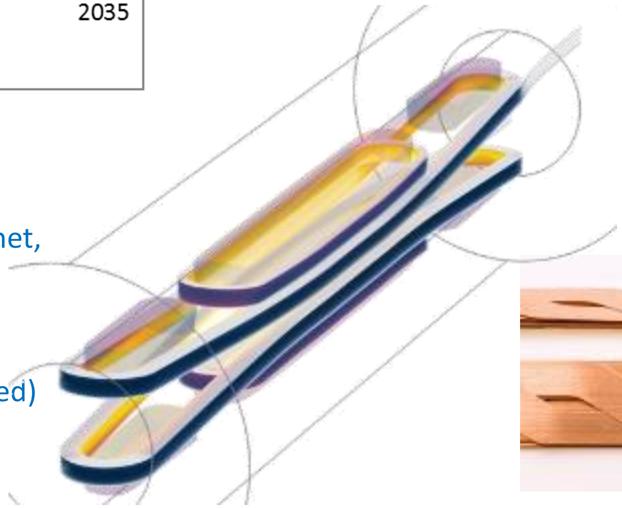
Nb_3Sn technology has seen a great boost in the past decade (factor 3 in J_C w/r to ITER) but was never used in an accelerator.

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

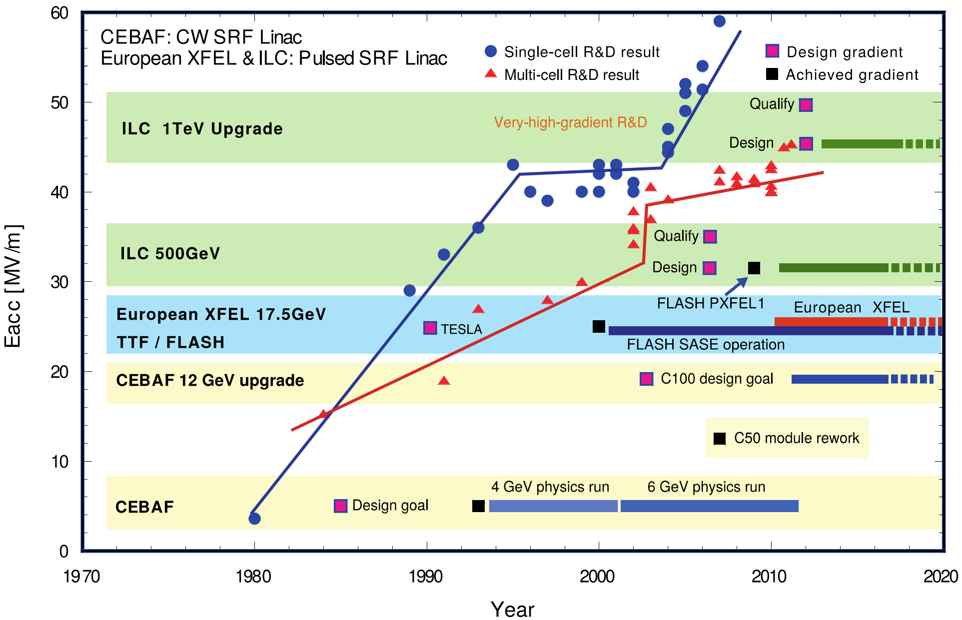
EuCARD-2 looks at HTS technology, the frontier of accelerator magnet technology.

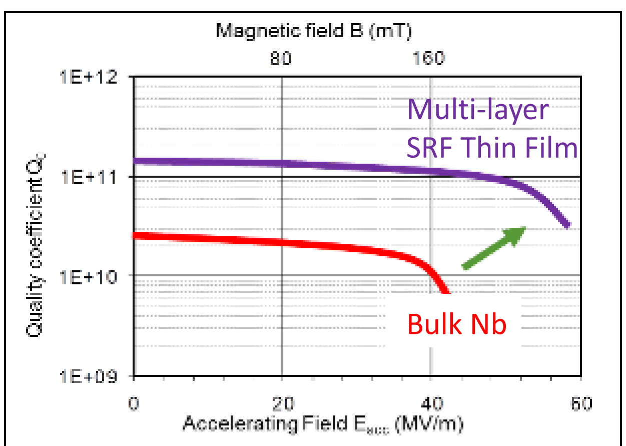
WP10 Future Magnets: R&D towards a 20 T HTS dipole magnet, develop 10 kA cable

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)



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,

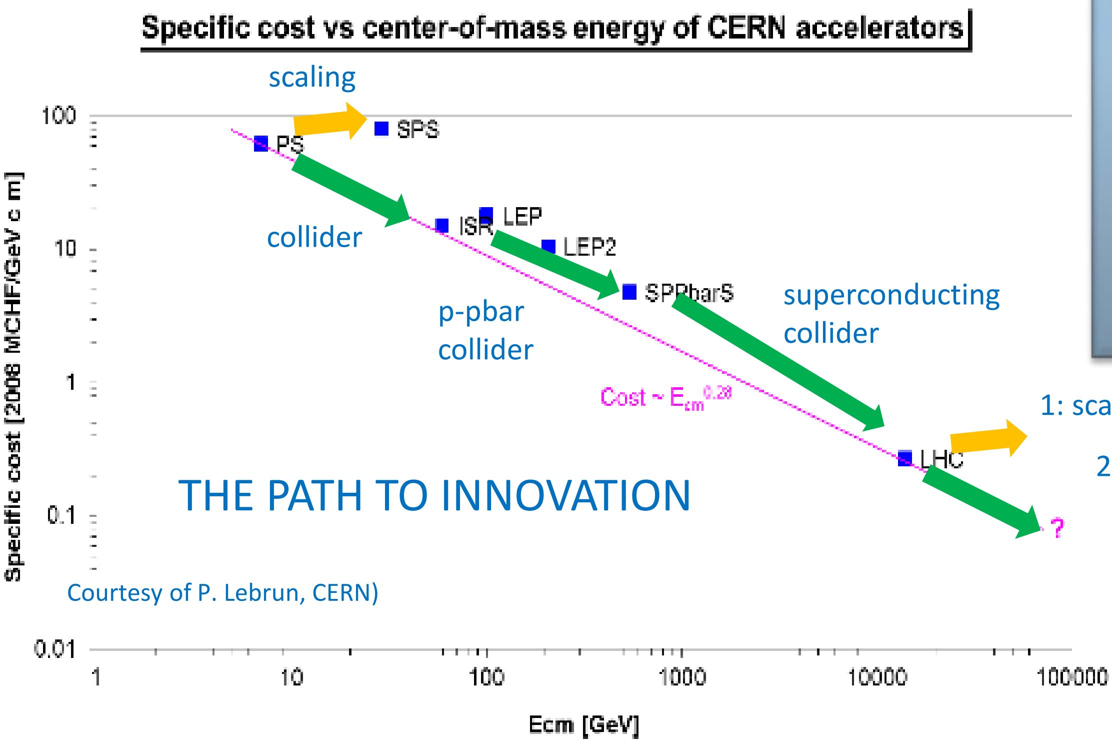
WP12 RF: R&D new higher-gradient superconductors: bulk Nb3Sn and nanometric multilayers of high Tc SC.

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

EuCARD² Accelerators at the frontier



Primary goal ⟶ reduce cost/energy

Traditional way → increase gradients (B, E)

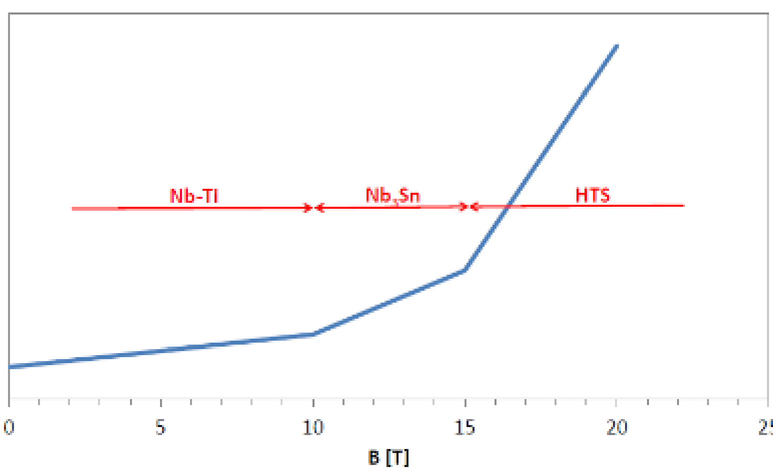
BUT: progress was possible only through innovation.

What is the cost/GeV that our society is ready to accept?

1: scaling, the Future Circular Collider

2: reduction in cost with new technologies:
plasmas, pipetron, low-cost HTS?

Cost of high-field magnets



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 aims at promoting innovation identifying and developing the technologies of the future.

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

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?

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.

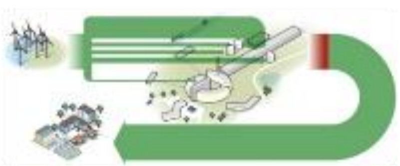
EuCARD-2 WP3: energy recovery from cooling, more efficient RF systems, energy storage, virtual power plant, low-power transport channels.

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

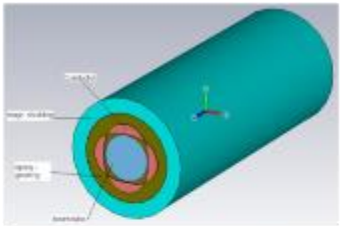
- Modelling of energy flows and optimisation in time
- How can heat distribution generate an income? Low temperature heat is the main issue: LTHD, greenhouses, fish farms (integrated?) , wastewater treatment,…
- Optimisation of normal/stand-by operation

New ideas towards a sustainable energy management

Plenty of ideas and initiatives appearing at the horizon:



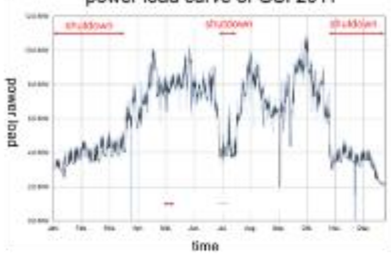
heat recovery at ESS



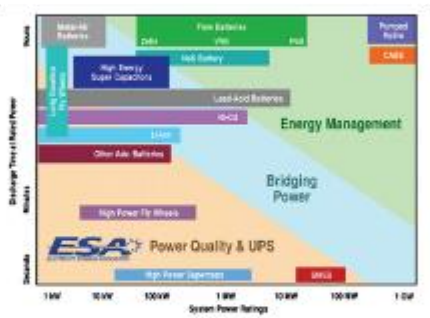
pulsed quads [GSI]

need for energy management

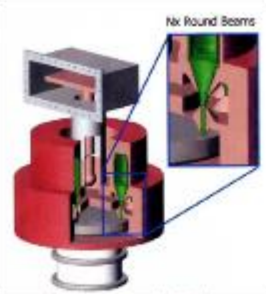
power load curve of GSI 2011



review of energy storage systems



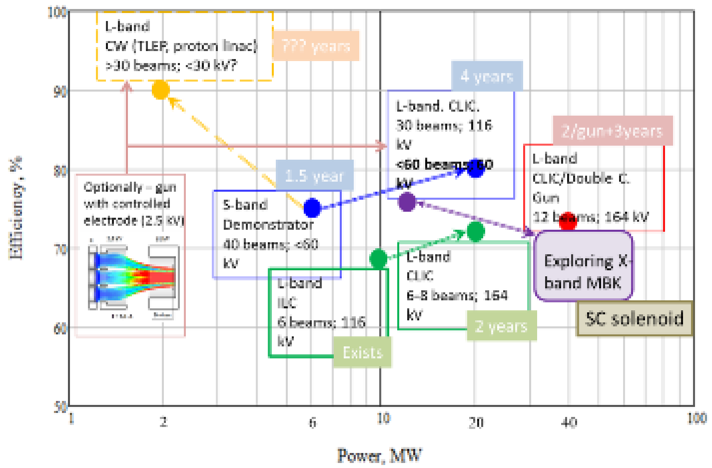
permanent magnet [CLIC]



multi-beam IOT by con

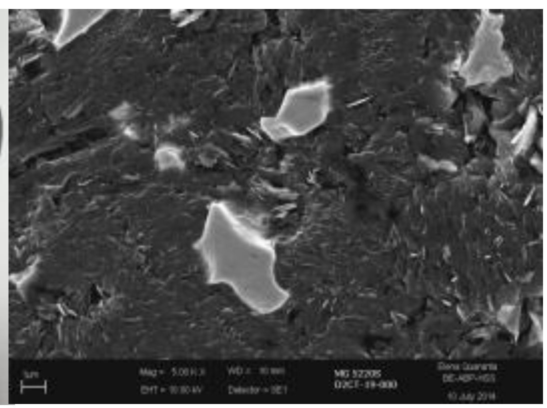
WP3
(Energy Efficiency)

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

EuCARD² Plasma Wakefield Acceleration

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

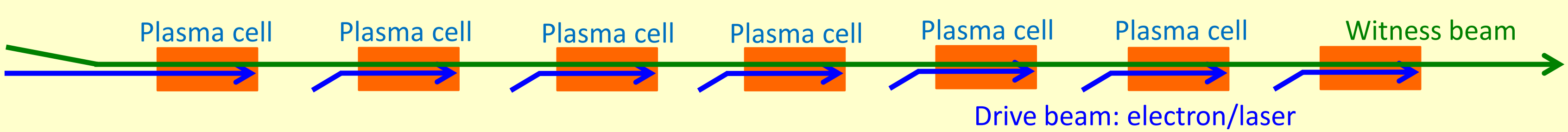
Several tens of kilometers for future linear colliders

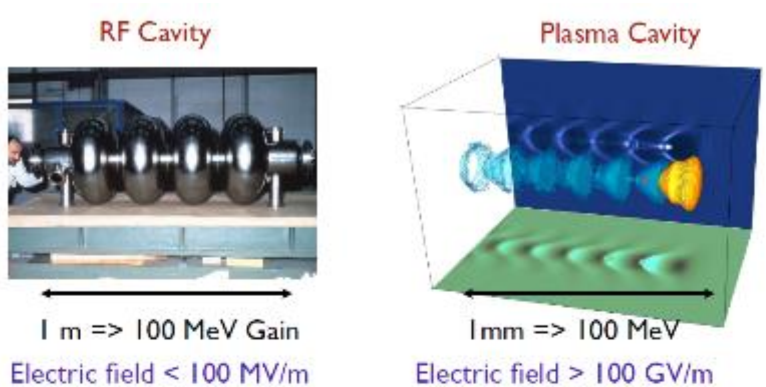
Plasma can sustain up to **three orders of magnitude much higher gradient**

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.





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)

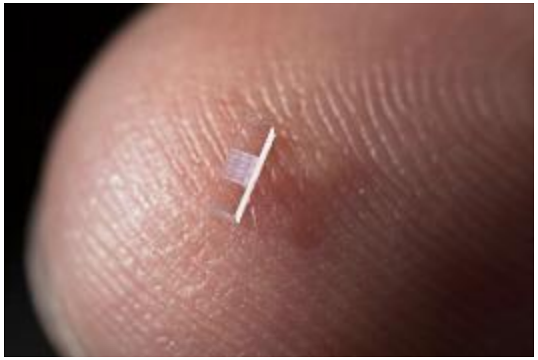
High efficiency laser driver : today in the best 1%

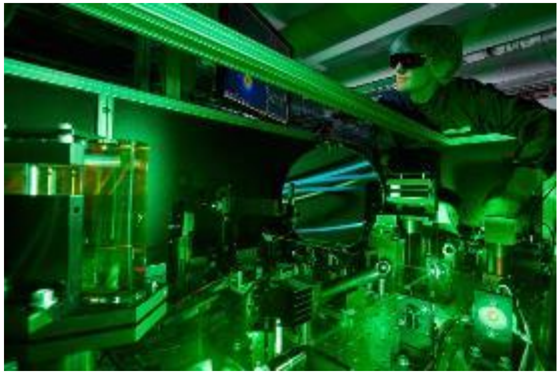
Courtesy of R. Assmann

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

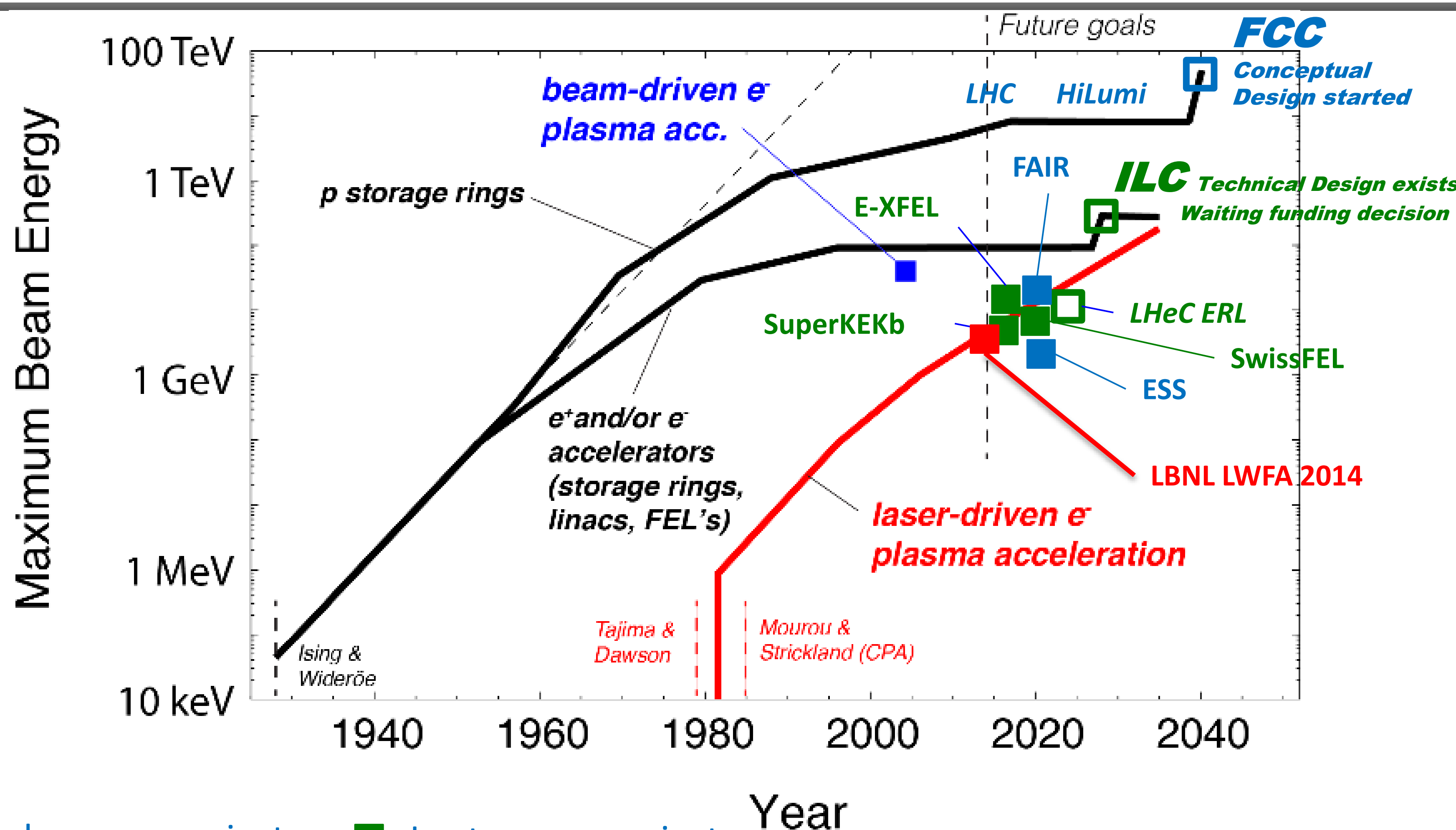
- Plasma-based electron and hadron accelerators:
  - Driven by lasers (for both e- and hadron), by e-beams (for e-: SPARC_LAB & FLASHForward in EU), by p-beams (AWAKE)
  - e-: Multi-GeV beams have been achieved → sufficient for applications
  - Hadrons: ion beams have been produced and transported
 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





courtesy of R. Assmann, DESY

Future of Accelerators

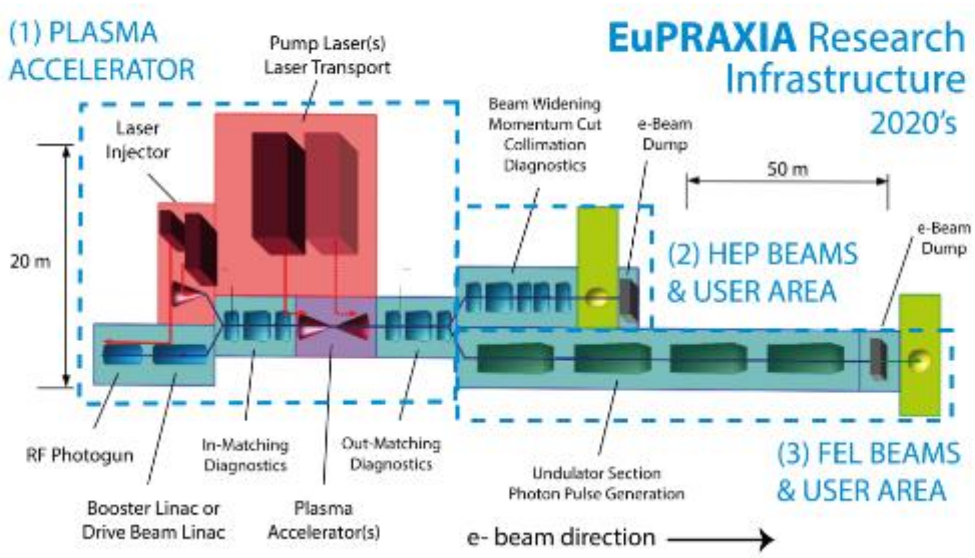


- ■ Hadron acc. project
- □ Hadron acc. proposal
- ■ Lepton acc. project
- □ Lepton acc. proposal

R. Assmann, EAAC 2015, 9/2015

EU supporting new Design Studies

2 projects submitted by our community have been accepted as Design Studies:
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…

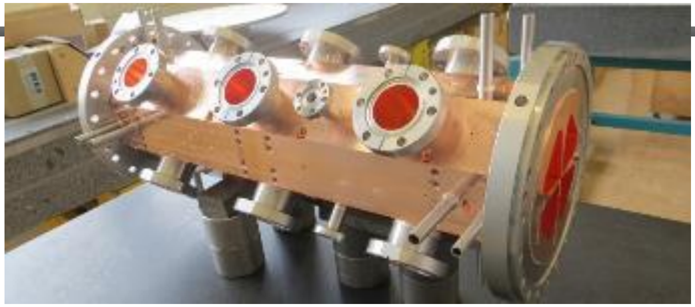
WP4 Accelerator applications

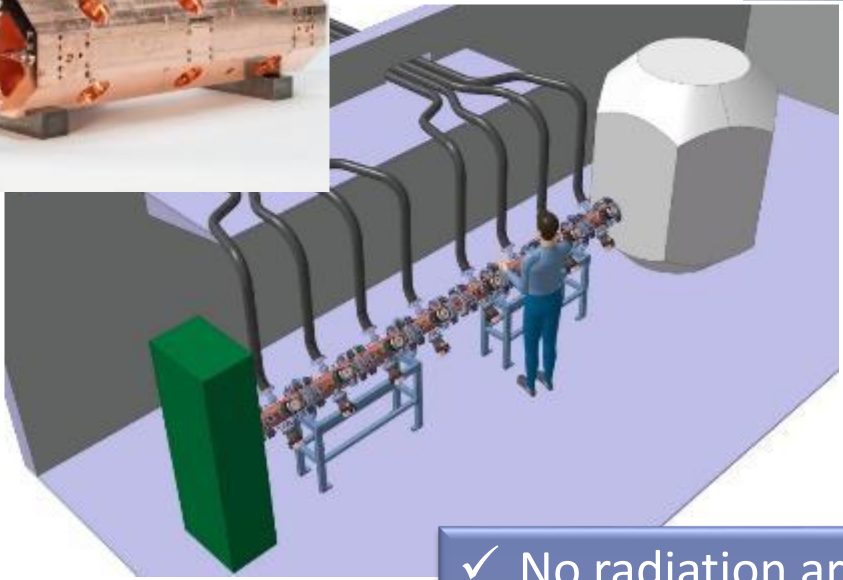
People in the street need the LHC (and now the FCC…) but need as well more and better medical isotopes, better materials, better semiconductors, improved security, etc.

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

The prototype has accelerated its first proton beam in December 2016!

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:

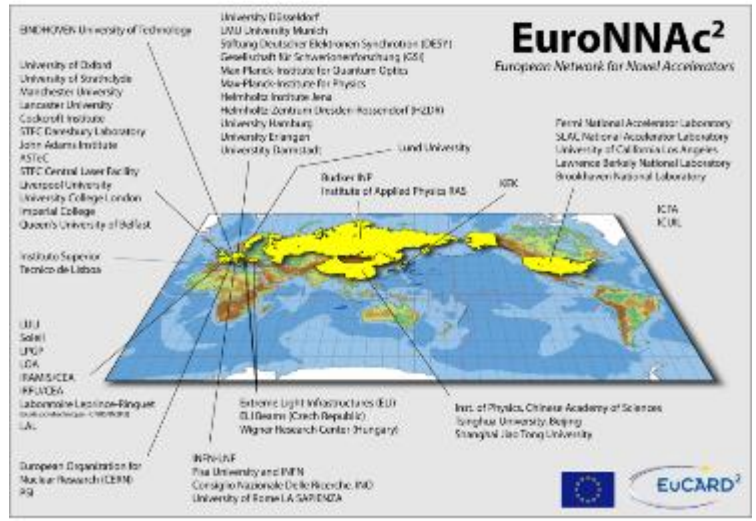
Universities and Laboratories: all consider collaboration essential, but have different evaluation criteria (=definitions of success): peer-reviewed publications for Universities and operational results are for Laboratories.

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

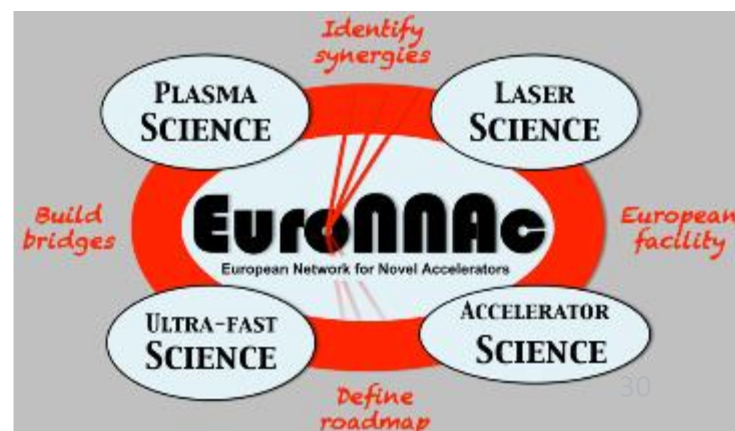
Building bridges across communities

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.



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.

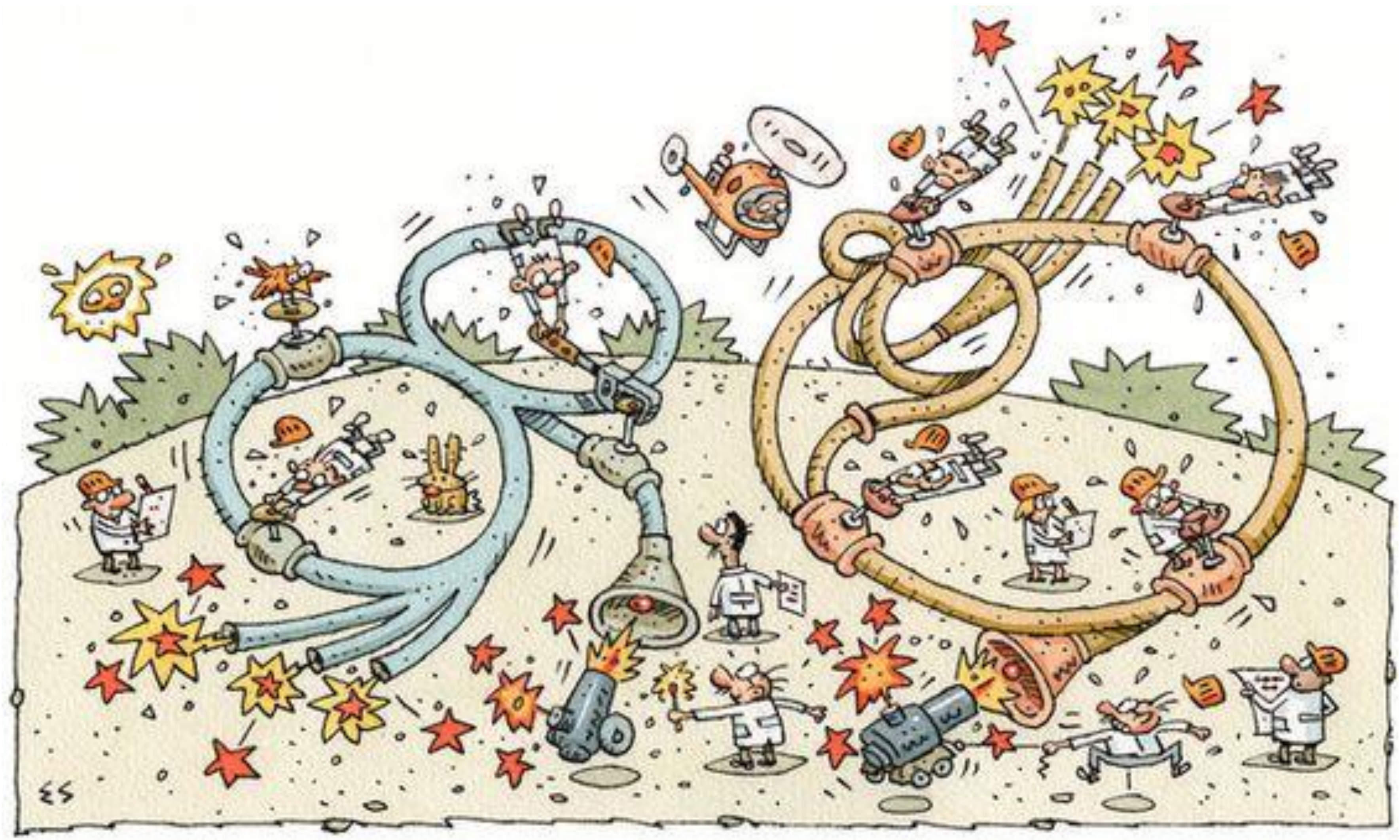
The final word…

Particle accelerators are a vivid and growing field, just starting the transition from
bas … ietal applications.

Bu … e frontiers of accelerators we need
fre … me change in paradigm…

Th … ng people developed in a
col … rs between different scientific fields.

We … jects like EuCARD-2 and ARIES, but
mo



Elwood Smith