An Exploration of Proton and Electron Accelerator Business Opportunities

Moderator

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IPAC-17

Copenhagen, Denmark

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Session TUIA2

Program

- **Existing Commercial Accelerator Business and Opportunities – Robert W. Hamm, R&M Technical Enterprises, Inc., Pleasanton, CA**

- **Emerging Electron Beam Applications and Compact SRF-based Accelerators for Industry – Robert D. Kephart, Director Illinois Accelerator Research Center (IARC), Fermilab**

- **The Applications of Particle Accelerators in Europe – Dr. Angeles Faus-Golfe - Accelerator Department Laboratoire de l'Acceleratuer Lineaire (LAL), Orsay, FR**

- **Construction Projects and Upgrades of *Discovery Science* Particle Accelerators Worldwide – Søren Pape Møller, Aarhus University, DK**

The Beam Business

Well-established Commercial Applications

Electron and Photon Cancer Therapy (~$1,800 M)
Ion Implantation - semiconductors and materials (~$1,600 M)
Radioisotope Production (~$170 M)
Electron Beam Material Processing (~$180 M)
Electron Beam Materials Irradiators (~$160 M)

Developing Commercial Applications

Proton and Ion Cancer Therapy (~$800 M)
Neutron Generators (~$50 M)
Non-destructive Testing & Inspection Linacs (~$160 M)
Ion Beam Analysis (~$50 M)
Synchrotron Radiation (?)

- **Estimate > 100 commercial accelerator vendors worldwide**
- **Estimate > $5,000 M in sales/year**

Commercial Accelerator Opportunities

- Initial capital cost, operating cost, and reliability of the entire beam system play an important role in commercial applications, so new technologies to increase the user's return on investment (ROI) are always being sought.
- Existing manufacturers are always seeking new technology to improve and expand their product lines.
- New systems must be proven in a commercial application before they gain widespread acceptance; significant market penetration can take many years after the introduction of a new accelerator technology.
- The most important tool for commercial application is not the accelerator but the beam. Any new device must satisfy the beam specifications for a given application before it is a useful tool.

Emerging Electron Beam Applications and Compact SRF-based Accelerators for Industry

Dr Robert Kephart
Director,
Illinois Accelerator Research Center (IARC), Fermilab
May 16, 2017

Fermi National Accelerator Laboratory (DOE)

- Mission: Discovery Science High Energy Physics ➔
- Build & operate: High Energy & Power (MW) Accelerators
- 6800 acre site, ~$360M/yr, Staff of 1700, > 2200 users
- 650 Accelerator scientists, engineers + technical staff
- Broad skills in accel. design, simulation, fabrication, & test
- NEW: The Illinois Accelerator Research Center (IARC)
  - Mission: Exploit technology developed in pursuit of science to enable new industrial accelerator applications & businesses

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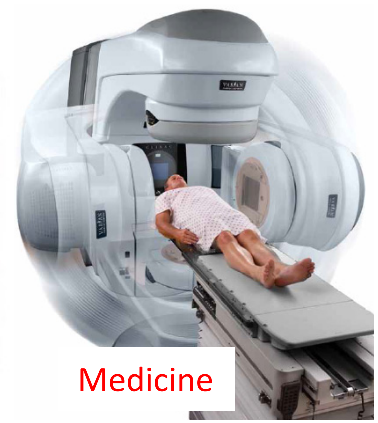
Accelerators in Industry and Medicine

- Created for science yet most accelerators are in industry
- About 30,000 accelerators are in use world wide
  - Sales of accelerators ~ $ 2-5 B/yr
  - Touch over $ 500B/yr in products

Crosslinked plastics & rubber

Digital Electronics



Medicine

Shrink wrapped food

Aircraft

Despite widespread use, many more new accelerator applications are envisioned

Future Accelerator Applications

Energy and Environment

- Treat Municipal Waste & Sludge
  - Eliminate pathogens in sludge
  - Destroy organics, pharmaceuticals in waste water
- In-situ environmental remediation
  - Contaminated soils
  - Spoils from dredging, etc
- Upgrade of heavy oil, flare gas

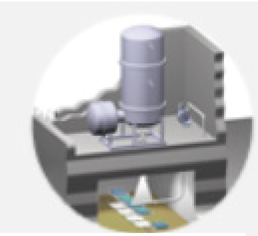
Industrial and Security

- Catalyze Chemical reactions to save time and energy
- In-situ cross-link of materials
  - Improve pavement lifetime
  - Instant cure coatings
- Medical sterilization without Co60
- Improved non-invasive inspection of cargo containers

These new applications need cost effective, energy efficient, high average power electron beams.

New technology can enable new applications (including mobile apps)

Current vs New Accelerator Technology



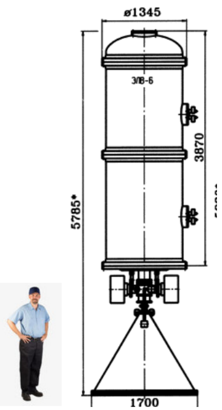
IBA Dynamitron

- Bulk materials processing applications require multi-Mev energy for penetration and 100's of kW (or even MW) of beam power
- > few MeV accelerators are typically copper and RF driven
  - Inherent losses limit efficiency (heat vs beam power) = ops cost
  - Heat removal limits duty factor, gradient and average power ➔ physically large "fixed" installations = CAPEX

IBA Rhodotron

New Technology: Superconducting Radio Frequency (SRF)

- High wall plug power efficiency (e.g. ~ 75%)
  - Large fraction of the input power goes into beam
  - High power & efficiency enables new $ 1 Billion class SRF-based science machines ➔ driving large R&D efforts at labs



Budker ELV-12

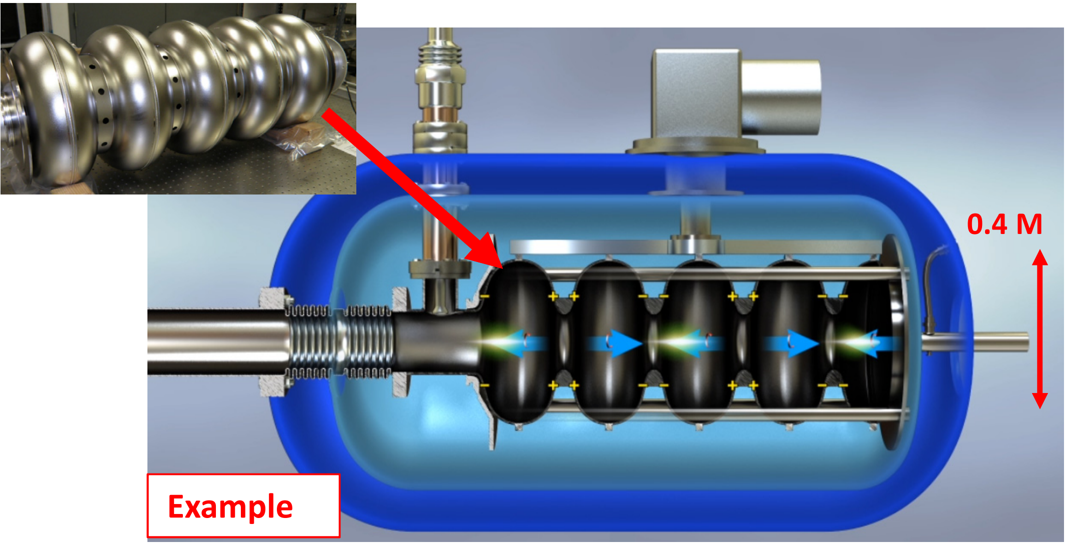
- Currently SRF-based science accelerators are huge with complex cryogenic refrigerators, cryomodules, etc. But this is changing!
- Recent SRF breakthroughs now enable a new class of compact, SRF-based industrial accelerators (lower CAPEX and OPS cost)

Recent SRF Technology Breakthroughs:

- Higher temperature superconductors: Nb_3Sn coated cavities dramatically lower cryogenic losses and allow higher operating temperatures (e.g. 4 K vs 1.8 K)
- Commercial Cryocoolers: new devices with higher capacity at 4 K enables turn-key cryogenic systems
- Conduction Cooling: possible with low cavity losses➔ dramatically simplifies cryostats (no Liquid Helium !)
- New RF Power technology: injection locked magnetrons allow phase/amplitude control at high efficiency and much lower cost per watt
- Integrated electron guns: reduce accelerator complexity

- **Enable compact industrial SRF accelerators at low cost**

Ideas integrated into a simple SRF accelerator*

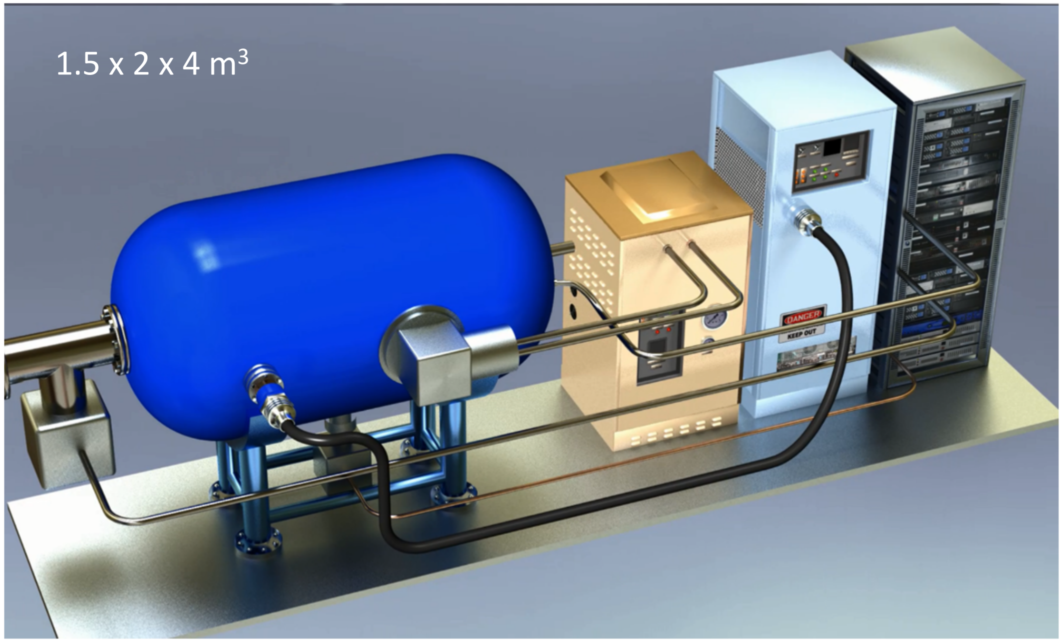


- Energy: ~ 10 MeV
- Power: 250 KW
- Compact
- Simple, reliable
- Affordable

- 650 MHz elliptical cavity (well understood from PIP-II)
- Magnetron RF source & commercial cryo-cooler
- Modular design scales to MW class industrial applications
- Accelerator system <3000 lbs ➔ mobile applications

* FNAL patents pending

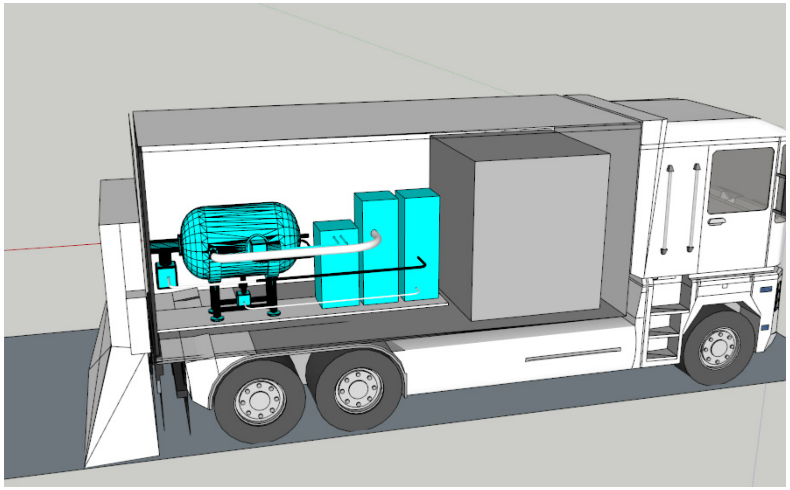
Developing a 250 KW skid mount Version



- Mobile high power accelerators enable new applications
- In-situ environmental or cross link applications
- DOE funds for conceptual design & key technologies
- Funding from DOD (USACE), interest from DHS, NNSA
- Goal: Create a new class of <u>industrial</u> SRF accelerators!

In-situ Environmental Remediation

- Since e-beams can disinfect or destroy organic compounds
- One can envision mobile SRF based accelerators for environmental remediation & decontamination.
- Examples
  - Clean soil contaminated by chemical spills
  - Remove hydrocarbons from soil
  - Destroy biohazards or toxins
  - Remove PCB's from dredge spoil
  - Provide an alternative to incineration

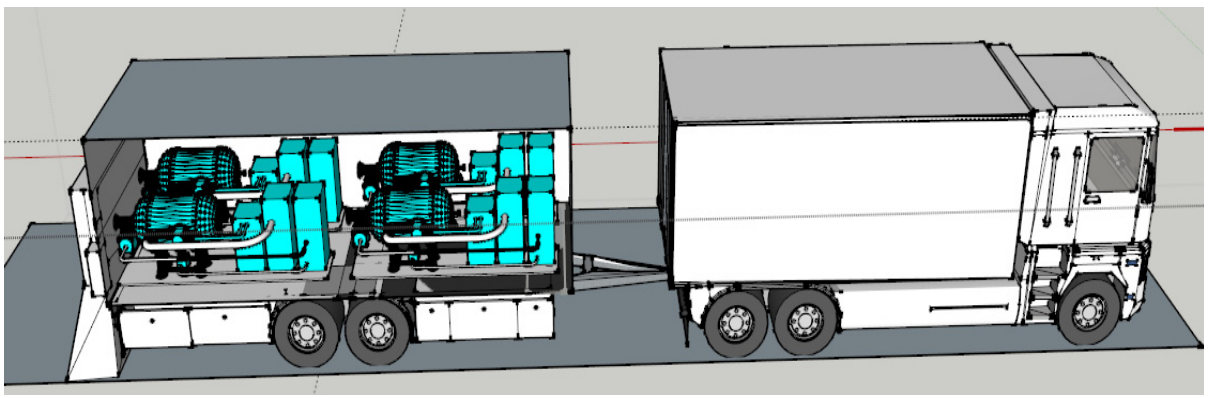


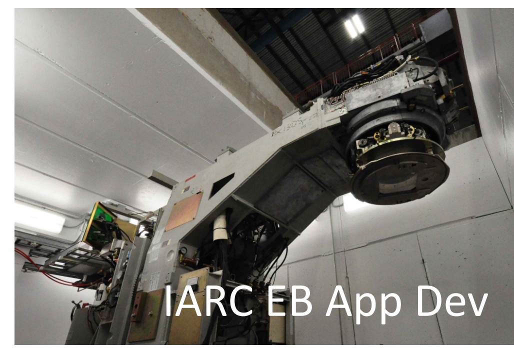
- Requires robust, reliable, compact, mobile accelerators that can be "brought to the problem"

In-Situ Cross-Link of Materials

Electron accelerators are widely used to cross link materials

- High power mobile accelerators enable entirely new construction techniques that can alter materials properties <u>after</u> placement
  - e.g. Improve the strength, toughness, and/or temperature range
- One applications: Improved Pavement
  - US Army Corps of Engineers partnership (FY17 ERDC funding)





- Collaborating to create a tough, strong binder with improved temperature performance vs bitumen to extend pavement lifetime
- U.S. spends > $ 50 B/yr to grind off and replace asphalt!

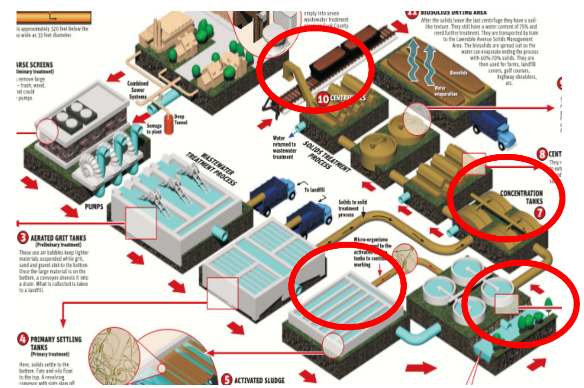
Conclusions

- Exploiting recent lab breakthroughs one can create high average power, CW, SRF-based electron linacs that are simple and cost effective for industrial applications
- The Illinois Accelerator Research Center at Fermilab is partnered with U.S. government agencies to create the first article of <u>an entirely new class of industrial SRF-based electron accelerators</u> that use no liquid cryogens
- Mobile, high energy, high power electron accelerators can enable a variety of entirely new industrial applications
- Several applications may have enormous market potential

Application: Waste Water/Sludge Treatment

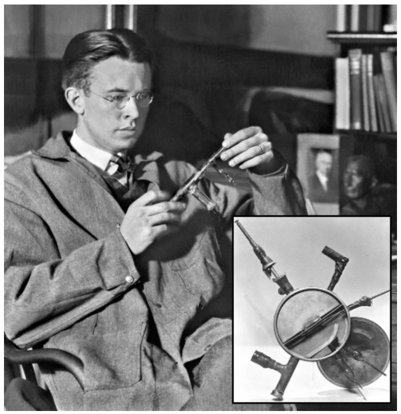
Accelerator above is 3 stories tall!

- Electron beams create highly reactive species
- Demonstrated effective for:
  - Disinfection of municipal bio-solids
  - Destruction of organics, pharmaceuticals
- Yet, despite demonstrations ~<u>no</u> market penetration
- Why? Municipalities are conservative; don't finance R&D
  - High power, cost effective, industrial accelerators have not been available to deploy* e.g. * http://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Energy_Environment_Report_Final.pdf
  - Compact SRF accelerators can change this situation
- IARC is partnered with the Chicago Metropolitan Water Reclamation District (MWRD)
  - Operate largest treatment plant in the world
  - Identified multiple areas to evaluate EB
  - Bio-solids, cell lysis, destroy pharmaceuticals



Fermilab

Introduction



During the past century, particle accelerators and their technology have played an essential role in delivering the scientific advances that have led to improved standards of living and wellbeing. Today, **accelerators** in various configurations are being increasingly applied as tools **not only in the laboratory** but also in **hospitals and industry**. As accelerator technology develops, the **potential for new applications** is expanding, with Europe in a strong position to exploit them.

The Working Group

International Organizing Committee:

- ✓ Angeles Faus-Golfe (APAE coordinator)
- ✓ Rob Edgecock (WP4 coordinator)
- ✓ Maurizio Vretenar (EuCARD2 coordinator)
- ✓ Roy Aleksan
- ✓ Oliver Boine-Frankenheim
- ✓ Phil Burrows
- ✓ G. Annelli
- ✓ Andrea Pisent
- ✓ Agnes Szeberenyi
- ✓ Jennifer Toes

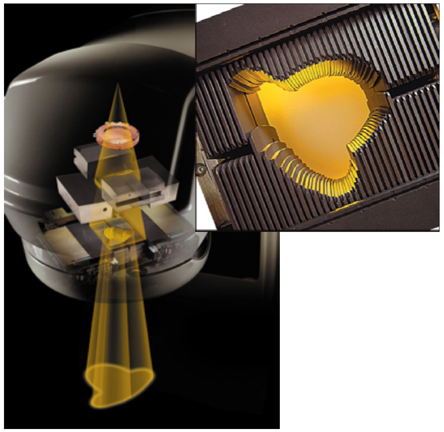
Areas and Conveners

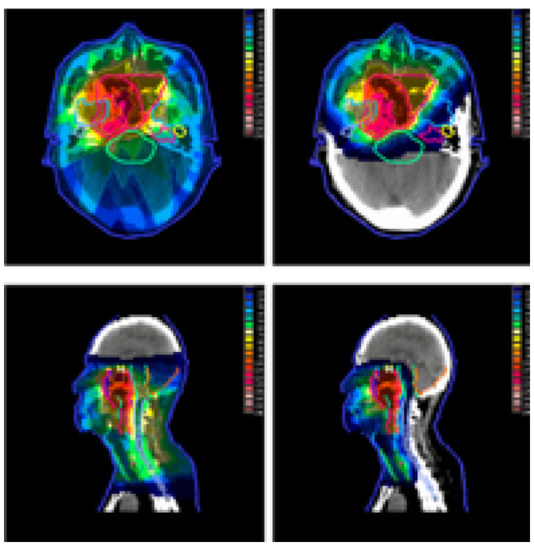
Health	**Radiotherapy:** A. Mazal **Radionuclides**: O. Lebeda **Accelerators:** H. Owen
Industry	**Ion implantation and beam analysis**: M. Chiari **Low energy e^- beams**: A. Chmielewski **Very-low energy e^- beams :** F. Roegner
Energy	**Fission:** E. Mund, G. Van den Eynde **Fusion:** A. Mosnier **Accelerators:** J.L. Biarrott
Security	G. Burt, J. O'Malley
Photon	L. Rivkin, T. Garvey
Neutron	M. Lindroos, E. Tanke, P. Mastinu , M. Seidel, J. Thomason

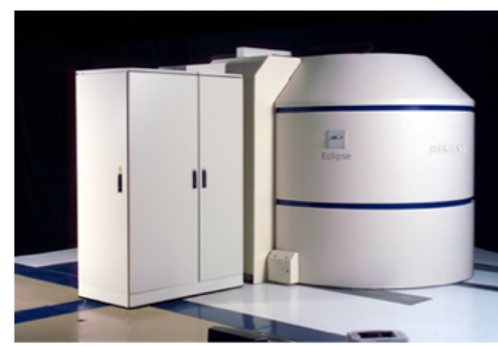
Summary of key recommendations

- ✓ Compact accelerators
- ✓ Improved designs and cost-effectiveness
- ✓ **Improved academia–industry interactions**
- ✓ **Improved student training and knowledge-transfer**
- ✓ Improved public understanding of accelerators and their science
- ✓ Improved R&D collaboration within the EU
- ✓ Further development of combined irradiation and imaging

Health: Highlights







Health: Impact on Industry

- ✓ **X-ray radiotherapy**: a better engagement in driving improvements to existing equipment designs may deliver cost savings (for example, in RF-structure designs) and thereby increased access to treatment, particularly in emerging economies;

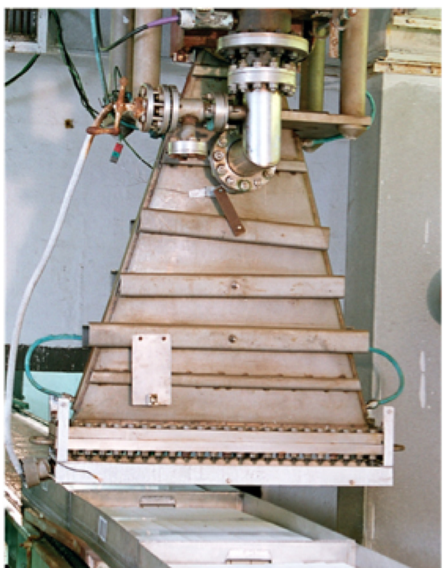
- ✓ **Proton therapy**: new technologies or imaging systems could enable new products to be offered; different technologies provide distinct IP that allow companies to enter the market;

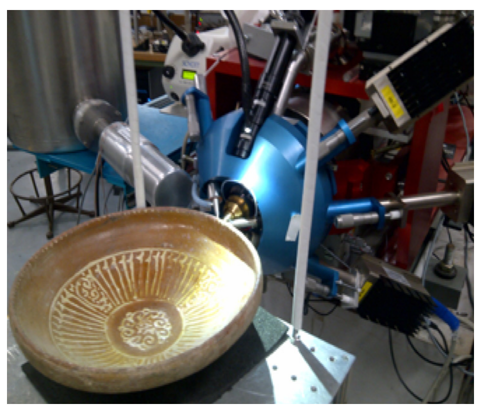
- ✓ **Ion therapy**: lower-cost designs may allow ion therapy to be adopted commercially in competition with proton therapy; systematic studies of RBE and related work can justify the greater cost of such treatment, leading to a commercial space for products;

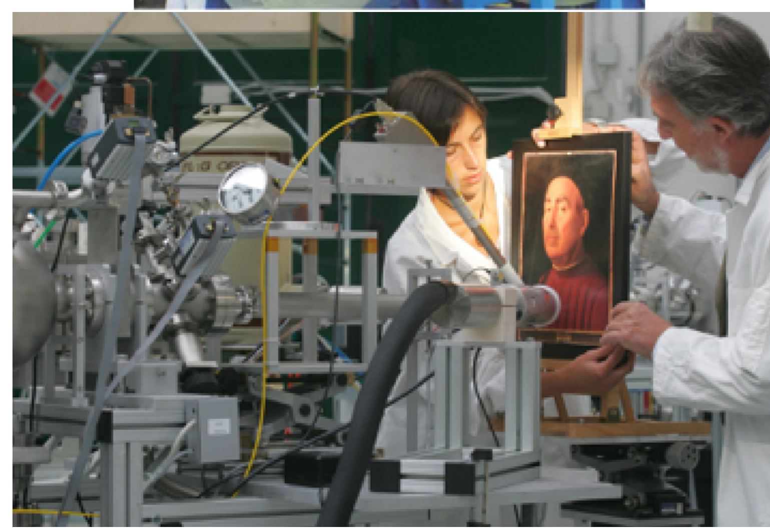
- ✓ **VHEET:** the demonstration of a new treatment method would first be in a clinic, then perhaps adopted more widely; it would need clinical justification in terms of improved dose at the equivalent cost to X-ray treatment;

- ✓ **Component development**: the development of technologies such as fast-ramping superconducting magnets and high-gradient X-band cavities provide new solutions for other research areas and for companies providing these components.

Industry: Highlights







Industry very low energy e⁻ beams: Impact on Industry

A large fraction of the very low-energy e-beam accelerators used in the emerging, high-growth applications will be manufactured in Europe.

- ✓ **Additive manufacturing** technologies are expected to have a major impact on industry, as they expand the manufacturing possibilities dramatically (aerospace sector: GE, MTU, Airbus).
    - ✓ **E-beam melting** is expected to have a major share, alongside **laser-beam melting** and **laser metal deposition** technologies (highly reactive and/or high-melting-point materials: titanium and nickel-based alloys, inter-metallics, and refractories, sensible to thermal stresses, such as inter-metallics and high-performance steels).
    - ✓ **E-beam welding** has been utilized extremely successfully for decades. However, there is still huge potential in this area
- ✓ The **lack of knowledge** amongst designers is a particular obstacle in exploiting the potential offered by e-beam technologies. A knowledge of the benefits of e-beams must be spread amongst this group of specialists.

Industry low energy e^- beams: Impact on Industry

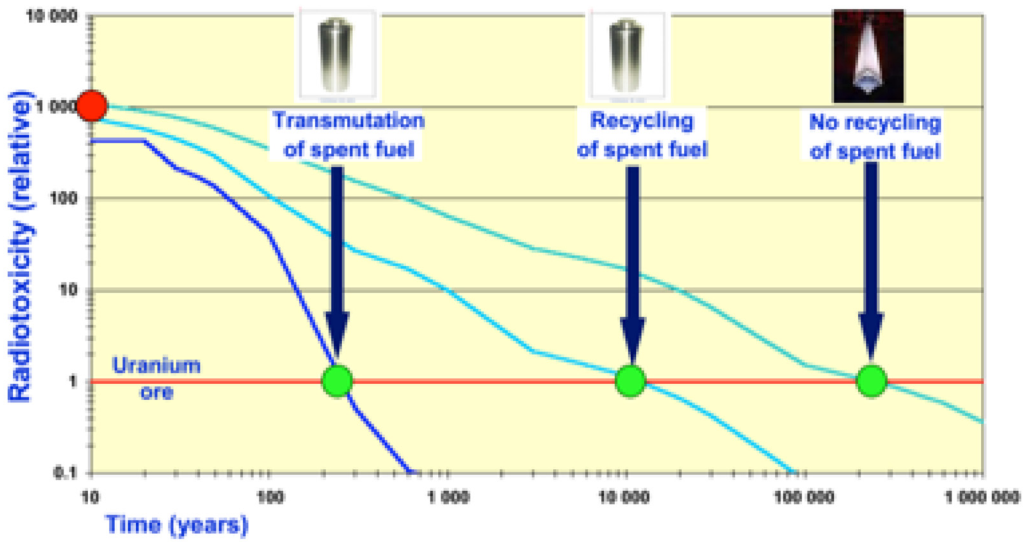
After 50 years of use of energetic electrons and X-rays for many applications, the field is still expanding.

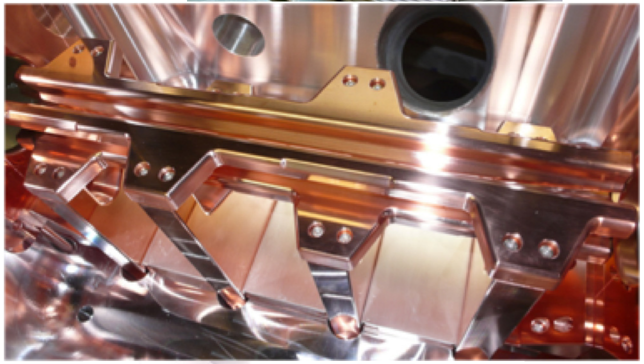
- ✓ The greatest industrial use of E-beams is in the **modification** of the **properties of polymers**, including rubber (wire and cable insulation, tyre manufacturing, the production of polymeric foams, heat-shrinkable films and tubes, the curing of coatings, adhesives and composites, printing..)
- ✓ Other applications could be the synthesis of hydrogels, the radiation-curing of polymeric composites, the production of fluoro-additives, and radiation-cured flexography, coatings, adhesives, paints, and printing inks.
- ✓ **Sterilisation of medical devices** with E-beams are the fastest-growing of the radiation processing methodologies, on a percentage basis.
- ✓ There are other important fields from social point of view: **environmental protection** (gas, liquid and solid wastes treatment) and **cultural heritage** preservation (disinfection of artefacts) have been developed.

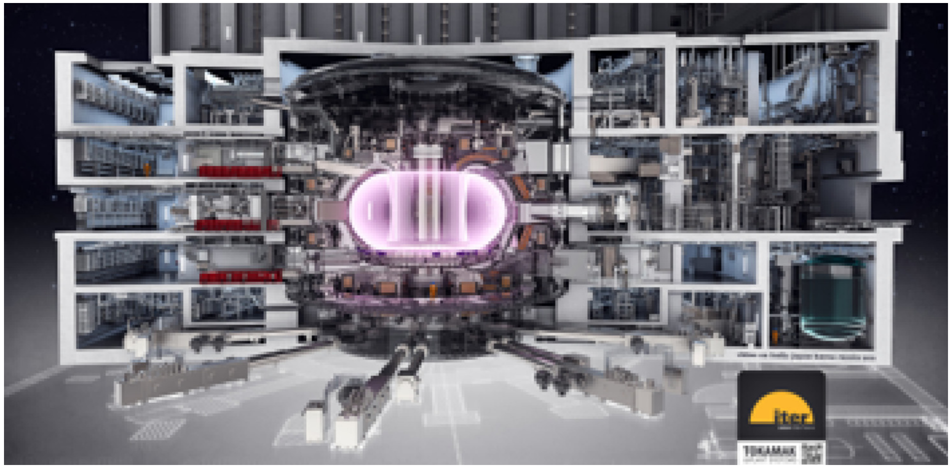
Industry Ion beams : Impact on Industry

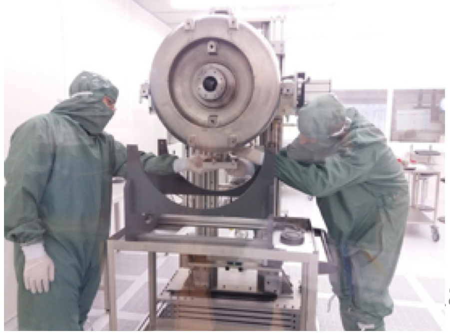
- ✓ Areas in which the potential of ion beams, apart from environmental and cultural heritage, for the **analysis and modification of materials** has not been fully exploited or promises to be further exploited should be identified. For ion beams to be exploited successfully, it is essential to have enough trained early-stage researchers capable of understanding the use of ion beams for both the analysis and modification of materials. Training should also aim at gaining ‘real-world’ experience and ‘business-facing skills’ with the private and public sectors.

Energy: Highlights









Energy: Impact on Industry

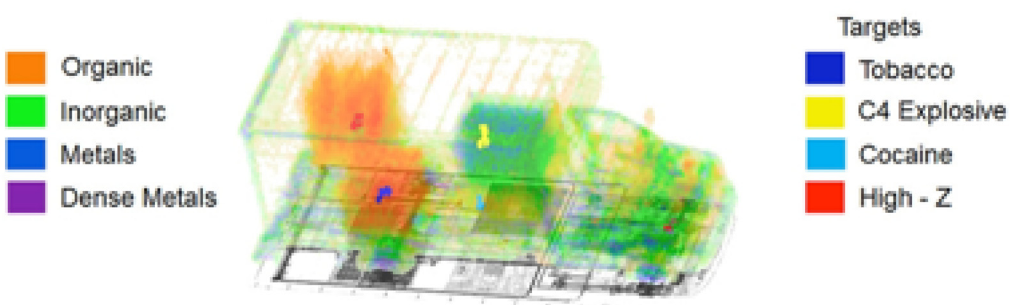
The R&D activities ongoing around the MYRRHA and the IFMIF projects are directly supporting the potential development of **novel nuclear energy generation**.

- ✓ On the **fission side**, the demonstration of the ADS concept, through MYRRHA, will allow the EURATOM community to extrapolate to the design of an industrial waste-burner and evaluate the viability of concentrated transmutation in a double-strata fuel-cycle approach. This extrapolation exercise will be especially valid for the accelerator, since its concept remains identical when going from demonstrator to industrial scales.

- ✓ On the **fusion side**, the IFMIF materials tests facility is also a crucial milestone on the pathway towards fusion-based nuclear energy.

- ✓ Significant outcomes are also expected in terms of **high-intensity beam mana**gement skills on the one hand, and in terms of **reliability and availability optimisation** on the other, particularly on companies that build accelerator components, as well as on companies that employ them for various applications (for example, the security screening technologies).

Security: Highlights



Actual Scan Data

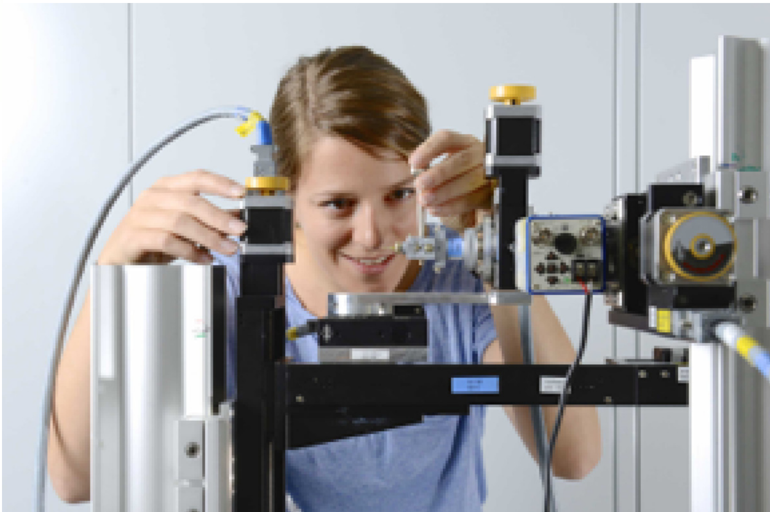
Security: Impact on Industry

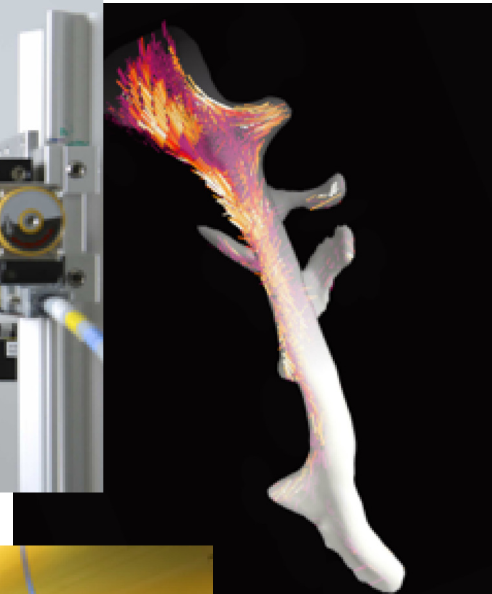
The potential application of advanced accelerator technologies to security offers significant commercial opportunities for EU industry, both within Europe and across the world.

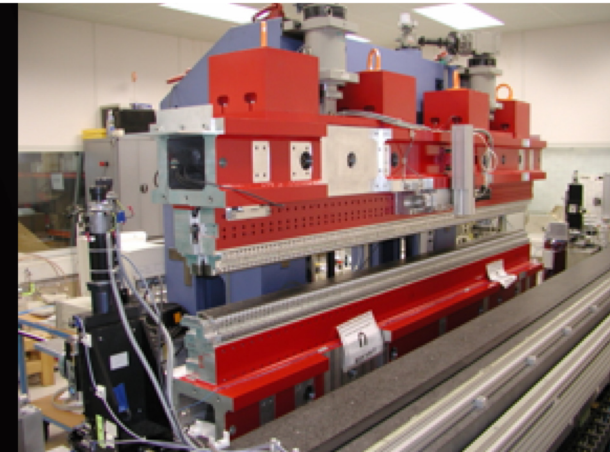
Most commercial accelerator-based systems for security rely on **traditional RF-driven linac** technology for **radiographic applications**, with some niche development of **pulsed-power technology** (mainly in the US) for stockpile stewardship.

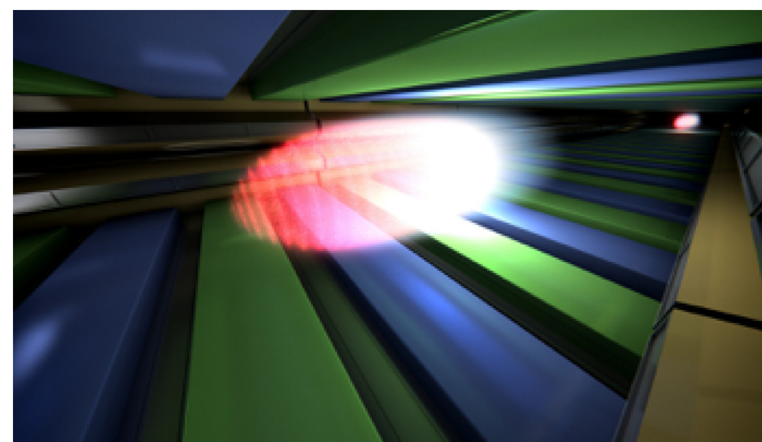
Industry could partner with the EU and with national governments to develop new, robust accelerator technologies for these applications, and new product lines for novel source applications. Industry could also work with regulatory bodies to promote their sensible and safe implementation and anticipate regulatory changes in this area. There is often a public fear of radiation at any dose level, even if well below allowed limits. In particular, a greater public understanding of the radiological hazards that the public may be subject to, and the radiation effects on electronic goods and equipment, could help steer the output of accelerators utilised in border inspection.

Photon sources: Highlights









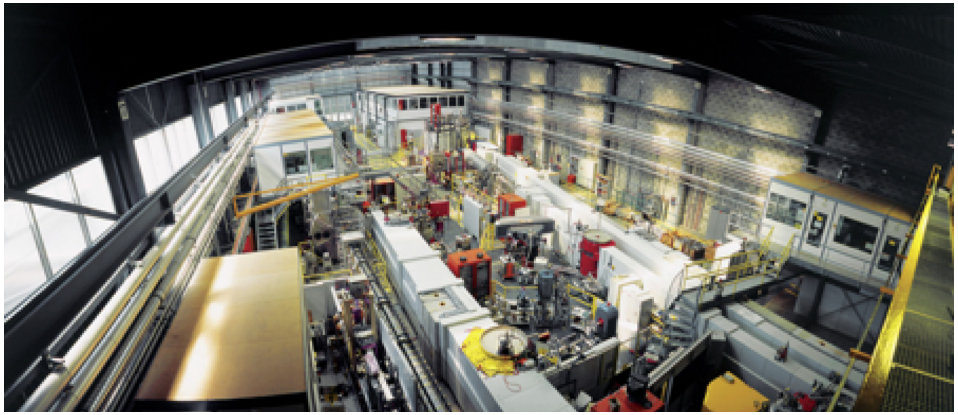
Photons Sources: Impact on Industry

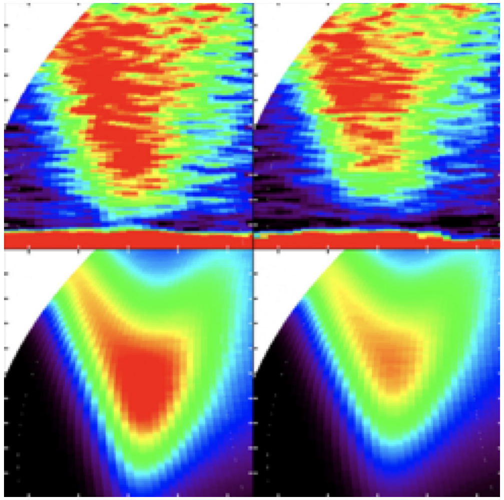
- ✓ The construction and operation of high-brightness light sources have a significant impact on industry. Many of the required products are not readily commercially available, a strong **collaboration with industry** is required in the development and production of these **components**.

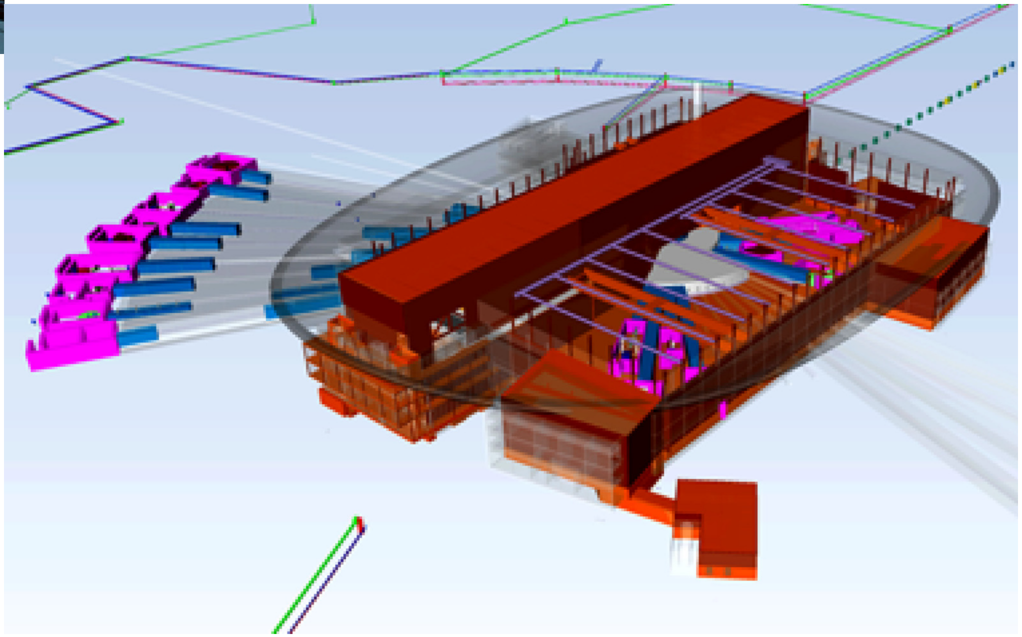
- ✓ Laboratories that operate SRs have in recent years become increasingly aware of the concepts of **technology-transfer and knowledge-exchange**, and so often seek **industrial partners to commercialise** their ideas and enable new products to appear on the market as: Research Instruments in Bergisch Gladbach, Germany (injector linacs), Libera in Solkan, Slovenia (beam-position monitors), Dectris in Baden-Dättwil, Switzerland (photon detectors), and Cosylab in Ljubljana, Slovenia (accelerator control systems)...

- ✓ Another example of the importance of light sources to industry is the provision of beam-time on a commercial basis to companies that can benefit from the unique characteristics of synchrotron radiation but which could not justify the investment of building their own sources. An important development for industry would be the **commercialisation of compact SRs.**

Neutron sources: Highlights







Neutron Sources: Impact on Industry

Neutron research has many industrial applications, for example, stress and fatigue studies, quality studies for manufacturing processes, and structural and dynamical studies of pharmaceutical products. CNSs are easy to operate, versatile and are relatively inexpensive to build and operate. This could make them available at many locations in Europe, which would greatly benefit industrial users, and help maintain a European industrial neutron-user community. Furthermore, simple and easy access to CNSs is important for R&D on the larger, high-flux neutron facilities.

The high-flux neutron sources such as ISIS, the ILL and SINQ all have industrial users, both those who buy time at the facilities for studies where the result is proprietorial, and users who sponsor open research of general interest to industry.

APAE docs

- ✓ **APAE full document and brochure** in the printing process
- ✓ **APAE web page** http://apae.ific.uv.es/apae/
  Under construction

APAE

Thanks to all the IOC and the conveners for their collaboration

Contact: Angeles.Faus-Golfe@uv.es

Construction Projects and Upgrades of ***Discovery Science*** Particle Accelerators Worldwide

Søren Pape Møller, Aarhus University, DK

- Based on the latest Accelerator Projects booklet now available from IPAC.
- I have grouped the projects, but there may be others not submitted to the new booklet.
- I apologize for any wrong interpretations, priorities and selection of the material presented.

Construction Projects and Upgrades of ***Discovery Science*** Particle Accelerators Worldwide

Five Categories

- Light Sources
- High-energy particle accelerators
- Nuclear physics accelerators
- Device/test accelerators
- Others:
  - ✓ Medical accelerator
  - ✓ Spallation neutron sources
  - ✓ Accelerator driven systems
  - ✓ Fusion-materials testing

Light Sources

Project	Country	Laboratory	Energy	Current	Description	Cost	Start	Compl.
Sirius	Brazil		3 GeV		Synch MBA	100	2012	2018
APS Upgrade	USA	ANL	6 GeV	200 mA	Synch MBA	770	2019	2025
LCLS II	USA	SLAC	4 GeV		CW SC linac	1045	2016	2020
AUS SYNCH	Australia	Austral Synch	3 GeV		Upgrades	50	2016	2026
SPring-8-II	Japan	SPring-8	8 GeV	200 mA	0.100 nm-rad			5 years
HEPS-TF	China	IHEP			R/D	50	2016	2019
ThomX	France	LAL			Compton BS	10	2014	2018
FLUTE	Germany	KIT	41 MeV e		FIR and THz	4		2019
ERL	Germany	UNI-Mainz			recirculating e	15	2015	2021
ILSF	Iran		3 GeV		3rd Gen LS	300	2015	2025
SOLARIS	Poland	Solaris NSRC	1.5 GeV	6 nm	Light Source	50	2011	2016
ALBA	Spain	CELLS			upgrade og ALBA			

2,400 M€

- Large variation in electron-energy, cost and size.
- Synchrotron radiation has become *hot* again!
- More LS upgrades can be expected due to the revival with the ”new” **Multi-Bend-Achromat** lattices first used at **MAX IV** in Lund in Sweden.

Light Sources

MAX IV, Sweden

7 BA; 0.20-0.33 nm-rad, Ø 548 m, 3 (1.5) GeV

Another 5-10 facilities are contemplating similar or even much lower emittances

Light Sources

SIRIUS, Brazil
5 BA; 0.27 nm-rad,
Ø 518 m, 3 GeV

MAX IV, Sweden
7 BA; 0.20-0.33 nm-rad, Ø 548 m, 3 (1.5) GeV

Another 5-10 facilities are contemplating similar or even much lower emittances

High-Energy Particle Accelerators

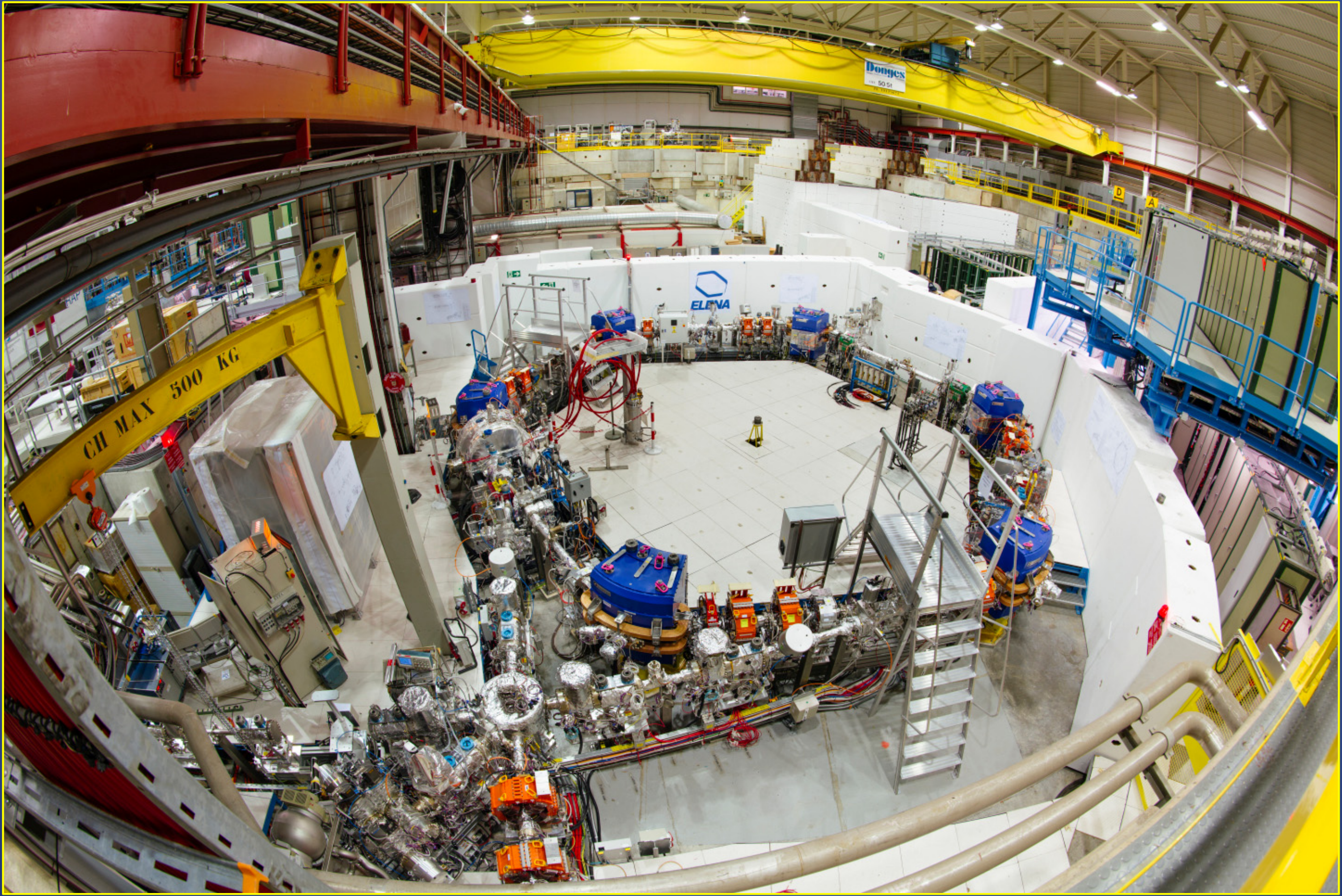
Project	Country	Lab	Energy	Part	Description	Cost	Start	Compl.
LBNF	USA	Fermilab		v	FNAL beam towards S Dakota		2020	2026
PIP (proton im-provement plan)	USA	Fermilab		p	FNAL upgrade	78	2011	2019
PIP-II	USA	Fermilab	800 MeV	p	SC linac	650	2019	2025
Super t-Charm Factory	Russia	Budker INP	1-2.5 GeV	e	e^+e^- collider 10^{35}	450		5 years
HiLUMI/HL-LHC	Switzerland	CERN				950	2016	2026
LIU	Switzerland	CERN			LHC injector upgrade	200	2010	2021
ELENA	Switzerland	CERN	0.1-5 MeV	pbar	Low-energy antiprotons	25	2014	2019
FCC	Switzerland	CERN			100 km collider	?	2028	~2040

2,400 M€

High Energy Physics is performed at a few very large facilities

ELENA@CERN

A low-energy (5->0.1 MeV, Ø 30 m) antiproton ring for ”high-energy” physics
Fundamental symmetries: charge, mass, gravitation etc. on $\bar{p}$ and $\overline{H}^0$



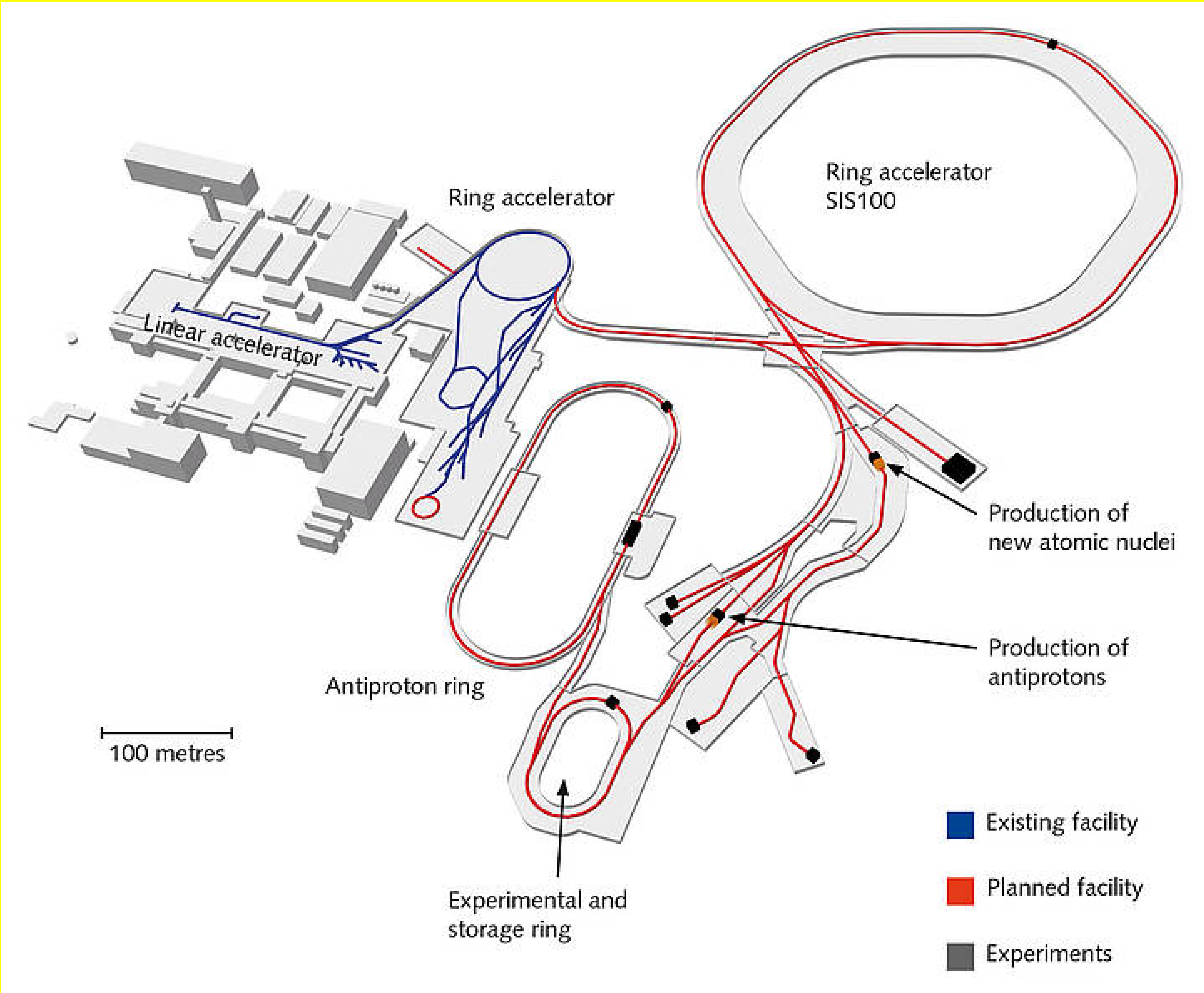
Nuclear Physics Accelerators

Project	Country	Lab	Energy	Power	Description	Cost	Start	Compl.
ARIEL-II	Canada	TRIUMF			sc cw linac - RIB	45	2016	2023
eRHIC	USA	BNL	18/275 GeV e/p		E-Ion collider		?	?
JLEIC	USA	JLAB				1500	2022	2029
FRIB	USA	MSU	200 MeV/u	400 kW	Linac	730	2014	2021
HIAF	China	Chinese Academy of Sciences			Linac, ring	500	2017	2024
RIBF upg	Japan	RIKEN Nishina Center			radioactive isotope beams			
RAON	Korea	Institute for Basic Science	200 MeV/u	400 kW	RI - SC linac + cyclotron	946	2011	2021
FAIR	Germany	GSI			Ion synchrotrons +	1200	2017	2025
LNS SC cyclotron	Italy	INFN LNS	40 amu	10 kW	SC cyclotron upgrade	11	2017	2020
ELI-NP	Romania	IFIN-HH/ELI-NP	20 MeV gamma		inverse compton scattering	67	2014	2019
NICA	Russia	JINR	SC magnets		heavy ion collider	500	2015	2020

5,500 M€

Many funded projects both small and very large

FAIR and GSI



Land has been prepared, civil works starting in 2017

Large RCS
Storage rings
Beamlines
Separators
………

Devices/Test Accelerator

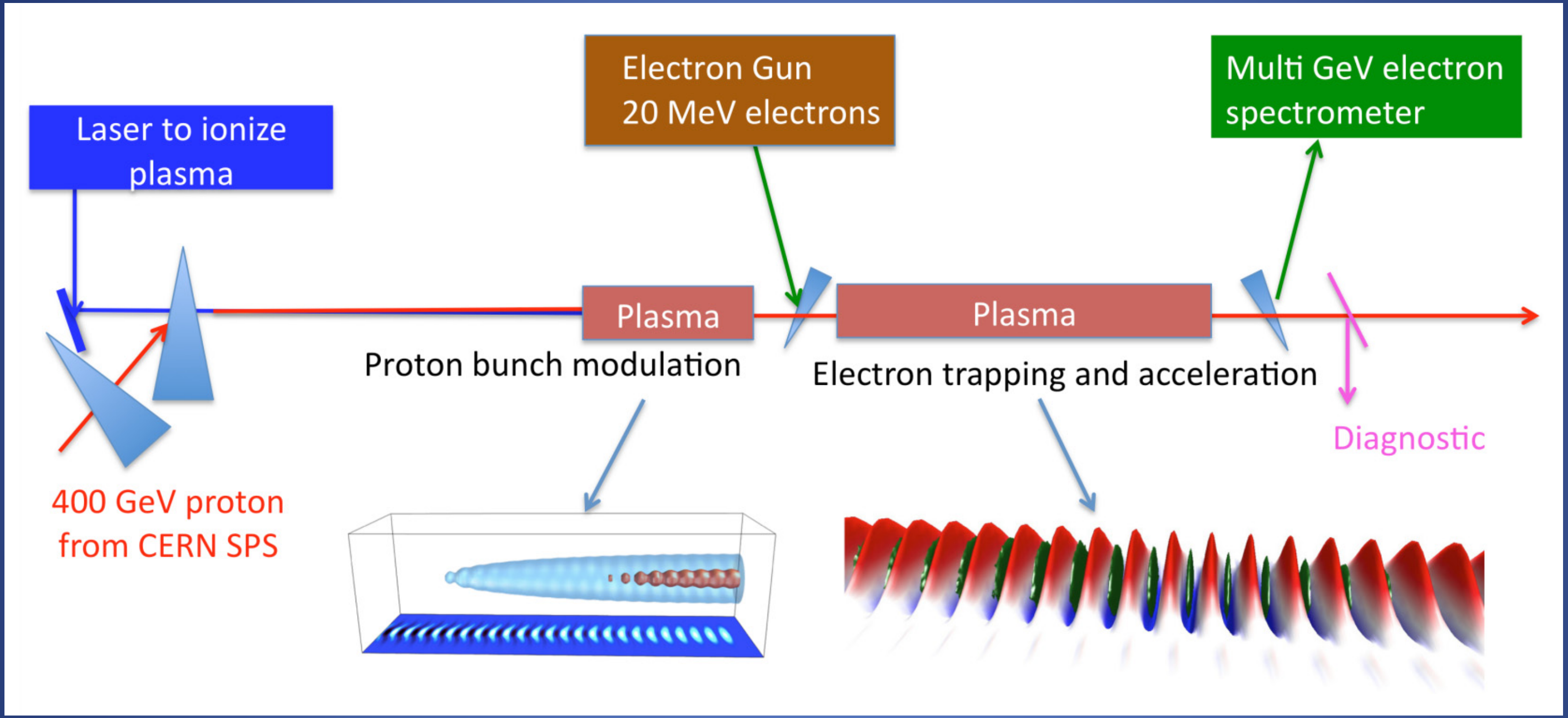
Project	Country	Lab	Energy	Description	Cost	Start	Compl.
Cornell-BNL ERL Test Accelerator	USA	BNL		ERL	25	2017	2021
FACET-II	USA	SLAC	> 10 GeV	Plasma wakefield accelerator	46	2017	2020
IOTA/FAST	USA	FERMILAB	150 MeV e - 70 MeV p	e/p Accelerator R/D IOTA ring	20	2014	2020
bERLinPro	Germany		50 MeV/100 mA	SC ERL	40	2013	2018
MESA	Germany	Mainz	155 MeV e	SC ERL	15	2015	2021
SINBAD	Germany	DESY	10-100 MeV	THz, acceleration etc	20	2017	2019
SPARC_LAB	Italy	INFN-LNF	200 MeV e	Laser acceleration	3	2017	2020
ELIMED	Italy	INFN		laser-driven ion acceleration	3	2014	2017
AWAKE	Switzerland	CERN		proton driven plasma wakefield experiment	20	2013	2017
FCC	Switzerland	CERN	100 TeV	hadron collider		2027	2037
CLARA	UK	STFC	250 MeV	Single pass FEL	50	2015	2020
RF transmitter	Taiwan	NSRRC	60 kW	Solid-state transmitter	0,4	2014	2019
ESS Bilbao	Spain	ESS Bilbao		systems for ESS	92	2014	2025

334 M€

- Many accelerator developments, including ”new” acceleration methods.
- Lots of interesting physics and a large potential.

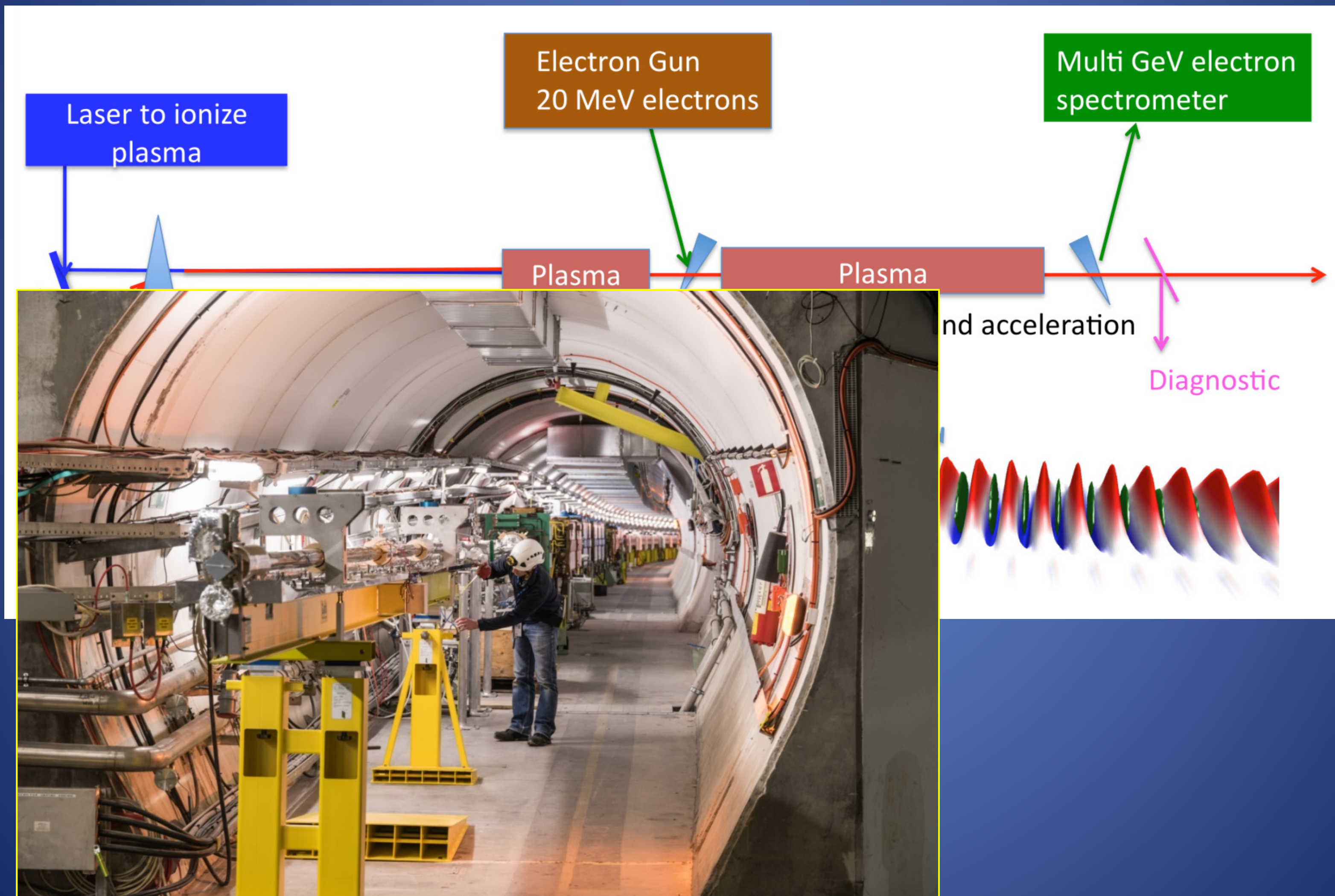
AWAKE@CERN

Proton-driven Wakefield Acceleration Experiment



AWAKE@CERN

Proton-driven Wakefield Acceleration Experiment



Medical

Project	Country	Lab	Energy	Current	Description	Cost	Start	Compl.
iBNCT	Japan	Tsukuba	8 MeV p	5 mA	medical BNCT	25	2011	2017
KHIMA	Korea	KIRAMS		p/ion	RFQ, synch	195	2010	2020
SPES	Italy	INFN-Legnaro	40 MeV p		radioisotopes	53	2012	2021

273 M€

Materials for Fusion

IFMIF-A-FNS	Japan		40 MeV d	125 mA	40 MeV (125 mA)	?	?	?
IFMIF-DONES	Europe	Ciemat	40 MeV d	125 mA	CW SC d linac	500	2020	2028

500 M€

Accelerator Driven System (transmutation)

MYRRHA	Belgium	SCK.CEN	100/600 MeV p	4 mA CW	ADS	320	2018	2024

320 M€

Spallation Neutron Sources

China SNS	IHEP	IHEP	1.6 GeV		RCS	251	2011	2018
ESS	Sweden	ESS	2 GeV	5 MW	linac	1840	2014	2025

2,091 M€

ESS

- 2 GeV, 5 MW
- Prototypes complete or being finished and series production is commencing.
- Still opportunities.
- Schedule for accelerator: first beam in 2019, finished early 2020s.

Conclusions

- Research accelerator construction is still a very active field, with a large number of small, medium and very large projects spread all over the world.

- These are still large investments/procurements:
  - ✓ 13,764 M€/5 years ≈ **275 M€/year**.
  - ✓ Hamm: ~**5,000 M€/year** for commercial accelerators.

- Numerous opportunities available in the research accelerator field for existing and new companies.