Dr. A. Faus-Golfe
on behalf of the
APAE team

The brave new world of Accelerators Applications

PARTICLE
ACCELERATORS
AND PEOPLE

APAE

APPLICATIONS OF PARTICLES ACCELERATORS IN EUROPE

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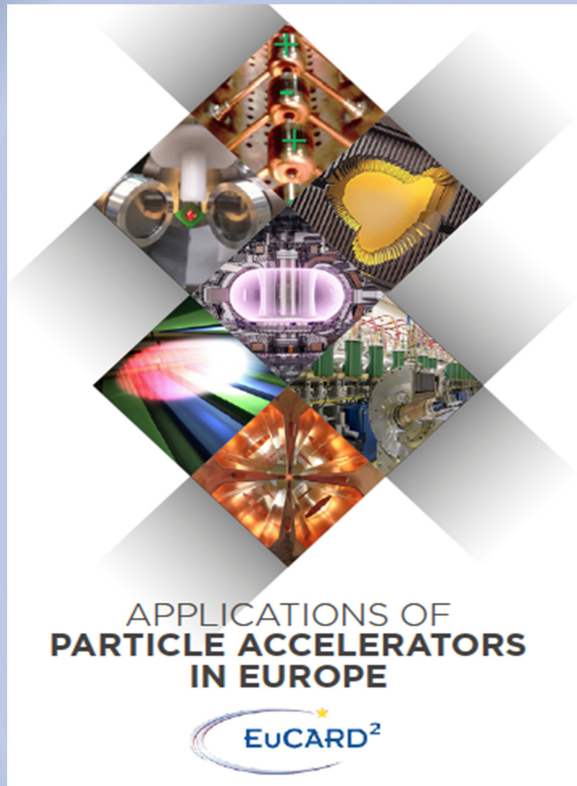
THE BRAVE APAE TEAM

- *EUCARD2:* M. Vretenar and R. Edgecock
- *APAE Committee:* S. Myers, R. Aleksan, O. Boine-Frankenheim, P. Burrows, G. Annelli, A. Pisent
- *Health: O. Lebeda, A. Mazal, H. Owen, O. Actis, J. Flanz*
- *Industry: M. Chiari, A. Chimielewski, F-H. Roegner, C. Jeynes, F. Lucarelli*
- *Energy: J.L. Biarrotte, A. Mosnier, E. Mund, G. Van den Eynde*
- *Security: G. Burt, J.O'Malley*
- *Photon sources: G. Garcia, T. Garvey, L. Rivkin*
- *Neutron sources: M. Lindroos, P. Mastinu, M.Seidel, E. Tanke, J. Thomason*

- *N. Hall and H_2O studies*



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DISCLAIMER

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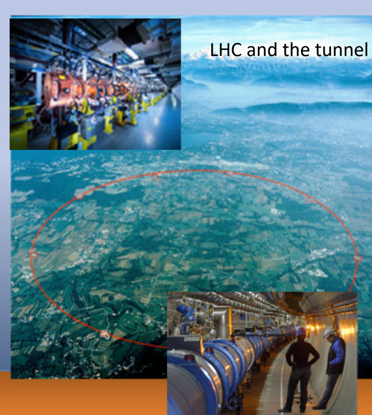
PARTICLE ACCELERATORS

During the past century **PHYSICS** and in particular **ACCELERATORS** and their **TECHNOLOGY** have played an essential role in delivering great **SCIENTIFIC** advances that have led to improved standards of **LIVING** and **WELLBEING.**

Today, accelerators (>40 000) are being increasingly applied as tools not only in **LABORATORY** but also in **HOSPITALS**, **BORDERS** and **INDUSTRY.** As accelerator technology develops, the potential for new applications is expanding, with Europe in a strong position to exploit them.


Thompson’s cathode-ray tube


Lawrence and Livingston cyclotron


LHC and the tunnel

ALBA


SINQ-PSI


IBA LABEC-INFN

MYRRHA RFQ


Desk-top e-beam

SCRF CEA

FFAG -EMMA

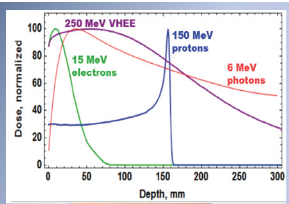
plasma cell - EuPRAXIA

terahertz accelerator module DESY

DEVELOPMENTS IN ACCELERATOR TECHNOLOGY

Current applications, especially in HEALTH and INDUSTRY, tend to use rather OLD TECHNOLOGY, and their performance, especially for NEWER applications, can be LIMITED by this. Much research is now going into developing more EFFICIENT, better PERFORMING and more COMPACT machines exploiting NEW APPROACHES to particle acceleration.

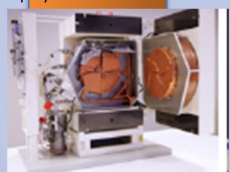
- **SUPERCONDUCTING (SC) magnets and RF cavities after 30 years of use in research start to be exploited in the commercial manufacture of accelerators.**
- **NEW COMPACT ACCELERATOR CONFIGURATIONS**
  - **Fixed Field Alternating Gradient Accelerator (FFAG).**
  - **Linear accelerator (linac).**
  - **Laser plasma acceleration (100 GeV/m).**
  - **Terahertz acceleration (400 GHz with 1.5 cm long, 1mm wide).**



Dose profile in water

X-ray IMRT

p-synchrotron HITACHI



16-MeV radionuclide cyclotron GE

ACCELERATORS AND HEALTH

The potential of accelerators in DIAGNOSTIC and THERAPY techniques has increased considerably over the past decades, playing a crucial role IDENTIFYING and CURING cancer, as well as in UNDERSTANDING the functioning of organs as brain.

PARTICLES (γ, e-, p, n, Ions, π, anti-p…)

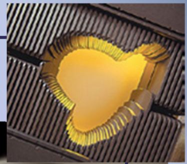
- **RADIOTHERAPY (RT) sculpted beams**
  - ***X rays*: 4-20 MeV e- linac (*bremsstrahlung*).**
  - ***Proton*: 230 MeV, 10 nA, 1Gy/l/min by Cyclotron/ Synchrotron.**
  - ***Ions:* 430 MeV/n C from Synchrotrons, He, O, Ar.**
  - ***Neutron*: fast n> 1 MeV from p 50 MeV in Be and BNCT.**
  - ***VHEE:* 100-300 e- linac.**

- **RADIONUCLIDES by radioactive isotopes, High- intensity p cyclotron**
  - ***Imaging: SPECT: (20-30 MeV) ^{67}Ga, ^{111}In…***
    PET: (7-19 MeV) ^{18}F, ^{11}C, ^{15}O, ^{13}N, novel as ^{64}Cu, ^{86}Y.
  - ***Therapy: ^{64}Cu, ^{67}Cu, ^{186}W, ^{211}At (α or high-energy β).***

HEALTH

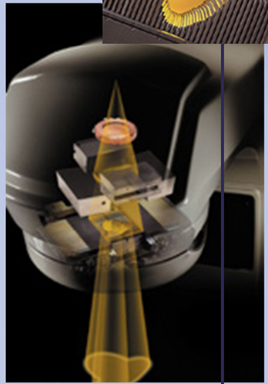
State of the Art I

multi-leaf collimator



Varian

X-ray beam

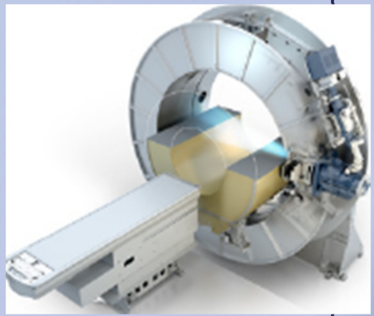


- ***X ray Radiation Therapy***
- ***Accurate delivery of X-rays to tumours***
  - **Intensity Modulated Radiotherapy (IMRT) and Volumetric Arc Therapy (VMAT) (several directions and fields).**
  - **Multi-leaf Collimators.**
- ***Combined Imaging and Therapy***

Axial Computed Tomography (CT), Nuclear Magnetic Resonance Imaging (NMRI) and Positron Emission tomography (PET) gives:

  - **Better definition in 3D and 4D (3D over time).**
  - **Distinguish volumes of functional biological significance (hypoxia, necrosis..).**
- ***Personalised planning***
  - **Robust treatment planning (less uncertainties).**
  - **Image Guided Radiation Therapy (IGRT).**
  - **Dosimetry *in-vivo* or transit.**
  - **Adaptive Radiotherapy (patient morphology changes).**

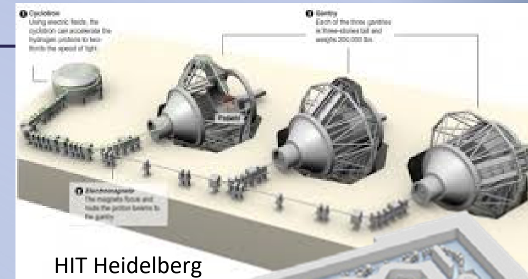
MR-linac Elekta



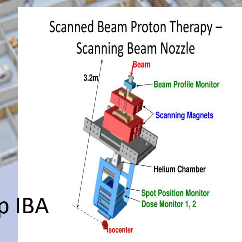
HEALTH

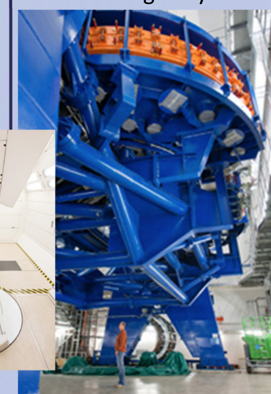
State of the Art II

- ***Particle Therapy***
- ***Proton Therapy***
  - More **cyclotrons** than synchrotrons (reversed tendency).
  - Beam-delivery systems (**gantries**) with **beam-scanning** rather than with passive scattering.
- ***Ions (Carbon) and exotic Particles Therapies***
  - For **C** mainly **synchrotrons** (greater ion-beam rigidity makes cyclotrons more difficult to employ).
  - Various ions (**He, O** and **Ar**) tested, renewed interest for He (lower transverse-scattering compared proton, intermediate step between protons and C ions).
  - More exotic candidates (π and **antiprotons**) studied. None is in routine clinical use today.


HIT Heidelberg
SIEMENS


multiroom p IBA

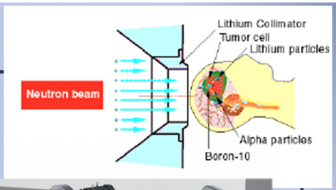


HIT C gantry


HEALTH

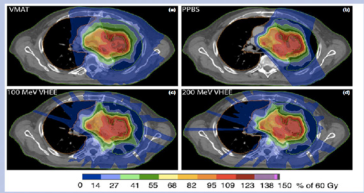
State of the Art III

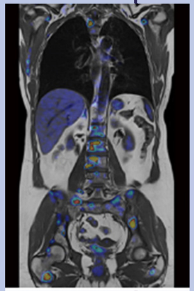
BNCT



- ***Particle Therapy***
- ***Neutrons Therapies***
  - **Fast Neutron Therapy: high RBE dose (radio-resistant tumours). Fewer patients treated.**
  - **Boron Neutron Capture Therapy (BNCT): $^{10}B + n \rightarrow [^{11}B]^* \rightarrow \alpha + {}^{7}Li + 2.31$ MeV**
- ***Very High-Energy Electron Therapy (VHEEE)***
  - **Renewed interest VHEE for 200-MeV (advantages as the flatter depth–dose profile, focused and steered, FLASH or mini-beams).**

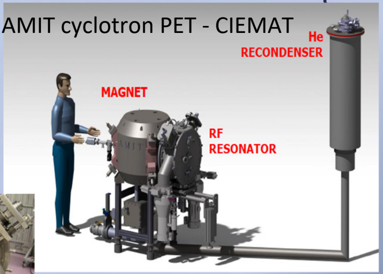
combined PET/MRI

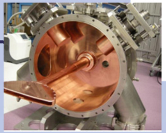




- ***Radionuclides***
- ***Imaging SPECT /PET***
  - **Improvement the surrounding by combining with CT/MRI.**
- ***Cancer therapy***
  - **Binding radionuclides to chemical compounds and to antibodies (radio-inmunotherapy)**

AMIT cyclotron PET - CIEMAT





HEALTH

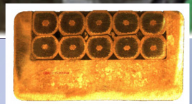
What are the R&D CHALLENGES? I

- ***X ray Radiation Therapy***
  - Image guided RT (including MRI and functional imaging).
  - Integration of measuring devices for dose reconstruction.
  - More precise and efficient 4D simulation (including biology).
  - New delivery system techniques (FLASH).
  - Use of "big data" as "smart data".
  - Reduction of cost and size.
  - Increase of reliability/availability for operation in challenging environments.

clinical prompt-gamma imaging

- ***Particle therapy***
  - Improved accelerator design (FFAG hybrid, linacs or laser).
  - SC technology (4T).
  - High-Intensity p.
  - Beam delivery and control (gantries).
  - Combined imaging and treatment (including MRI).
  - Other particles: VHEE, BNCT, He…

SC C gantry - NIRS



NbTi-Cu wire

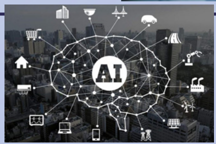
HEALTH

What are the R&D CHALLENGES? II

- ***Radionuclides***
  - **Targets: availability, cost, recycling, better yield and achievable radionuclide purity.**
  - **Versatile accelerators for wide range of energies and particles, higher intensities, reduced cost.**
  - **Novel diagnostic or therapeutic radionuclides.**
  - **Test of alternatives routes of established medical radionuclides (^{99}Tc- ^{99}Mo).**

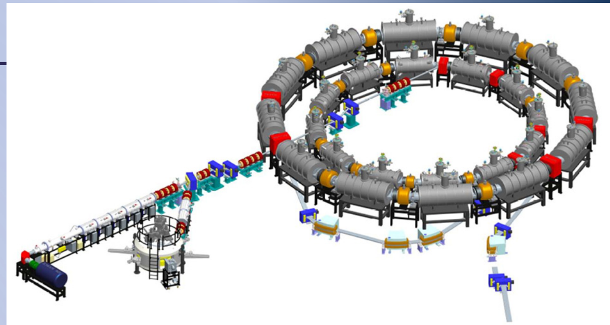
- ***Political and Societal***
  - **More Research/Industry collaboration.**
  - **Improved modelling, control and monitoring (AI).**
  - **Ensuring an adequate supply of medical isotopes in Europe.**
  - **Perception of the clinical use of radioactive isotopes.**

radionuclides purification PSI



HEALTH

What are the needed R&D?

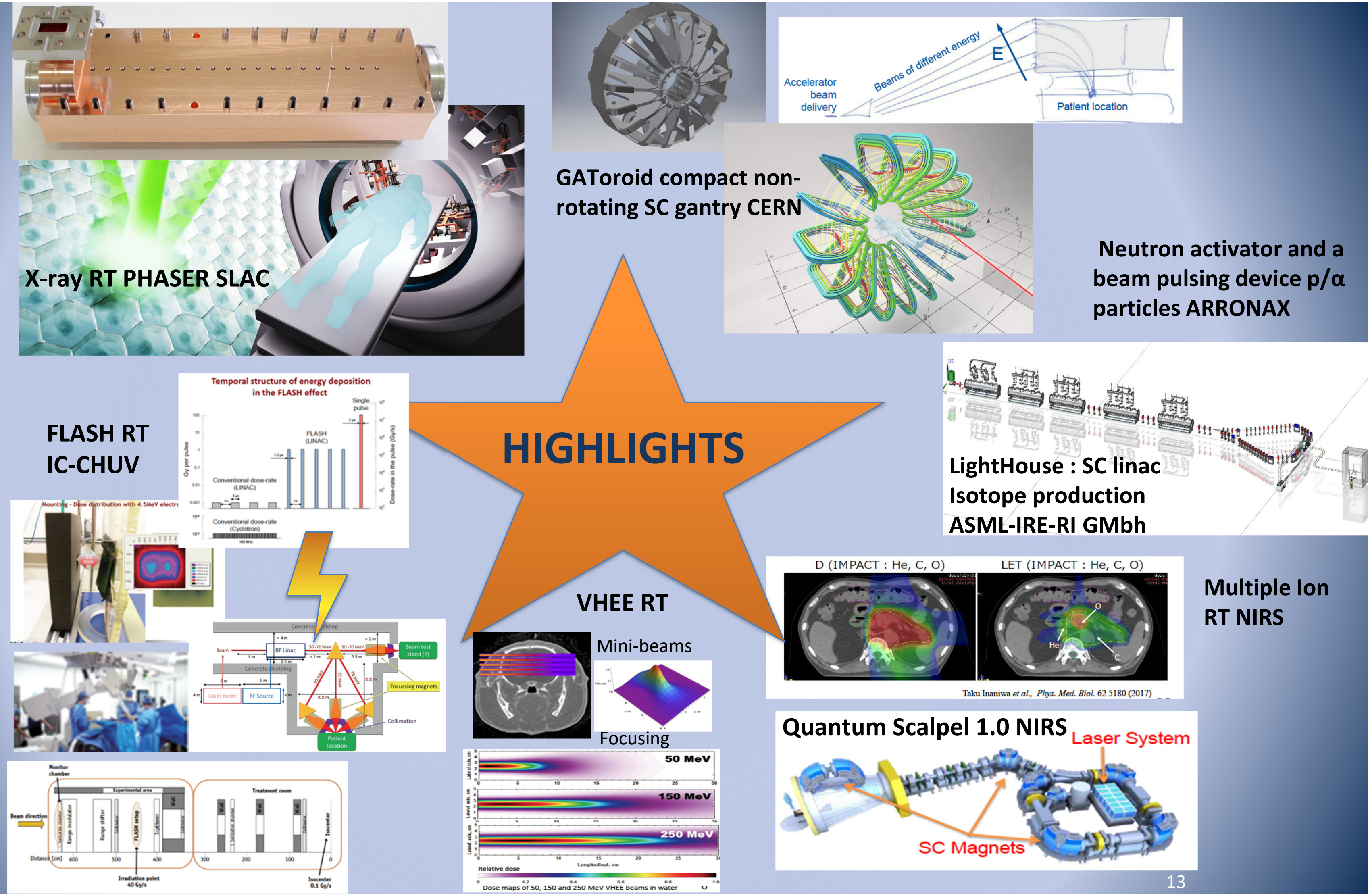


PAMELA combined p/C facility

TERA side-coupled HG linac

- ***Radiotherapy***
- **Multidisciplinary approach (biological info and immunological protocols personalised medicine).**
- **Multi-particle facility design, SC technology (gantries), high-gradient ions accelerators.**
- **Systematic RBE experiments (in-vivo animal and clinical studies for new therapies).**
- ***Radionuclides***
- **Alternative mechanisms for ^{99}Mo and ^{99m}Tc in Europe, novel radionuclides.**
- **Multi-particle facility, high-current, compact (production directly in hospitals).**

- ***Ion secondary-particle imaging and dose-delivery instrumentation.***
- **Reduction of initial investment and functional costs.**
- **Cooperation between academics, industry, research centres and hospitals.**


HIGHLIGHTS
X-ray RT PHASER SLAC
GAToroid compact non-rotating SC gantry CERN
Accelerator beam delivery
Beams of different energy
E
Patient location
Neutron activator and a beam pulsing device p/α particles ARRONAX
LightHouse : SC linac
Isotope production
ASML-IRE-RI GMbh
FLASH RT
IC-CHUV
Temporal structure of energy deposition in the FLASH effect
Single pulse
FLASH (LINAC)
Conventional dose-rate (LINAC)
Conventional dose-rate (Cyclotron)
Concrete shielding
Beam
RF Linac
Beam test stand (?)
Laser room
RF Source
Focussing magnets
Collimation
Patient location
Monitor chamber
Experimental area
Treatment room
Beam direction
Distance [cm]
Irradiation point 40 Gy/s
Isocenter 0.1 Gy/s
VHEE RT
Mini-beams
Focusing
50 MeV
150 MeV
250 MeV
Relative dose
Dose maps of 50, 150 and 250 MeV VHEE beams in water
D (IMPACT : He, C, O)
LET (IMPACT : He, C, O)
Taku Inaniwa et al., Phys. Med. Biol. 62 5180 (2017)
Multiple Ion RT NIRS
Quantum Scalpel 1.0 NIRS
Laser System
SC Magnets

ACCELERATORS AND INDUSTRY

From **MANUFACTURING** and **PROCESSING** to **ENVIRONMENTAL** protection and **CONSERVATION** accelerated **PARTICLE BEAMS** offer a selective of **PRECISION** and **SENSITIVITY** not always available with other techniques, as chemical, and are often **NON-INVASIVE** and **NON-DESTRUCTIVE**.

PARTICLES (e- and Ions)

- **E-BEAMS**
  - ***Very-Low Energy***: 5-330 keV e-beam gun.
  - ***Low-Energy:*** 330 keV-10 MeV e-linacs.
- **IONS-BEAMS**
  - ***KeV-70 MeV Tandems.***

IBA LABEC INFN

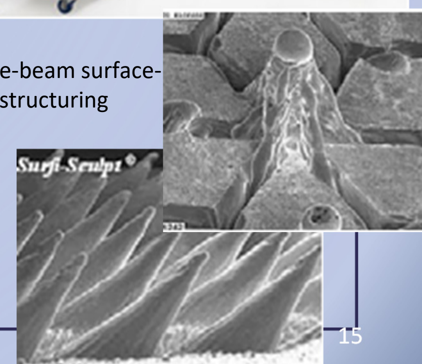
INDUSTRY

State of the Art I

E-beam re-melting furnace

desk-top e-beam

e-beam surface-structuring



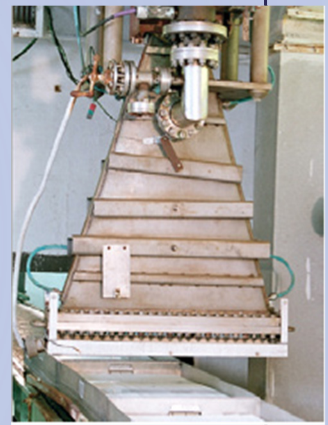
- ***Very low-energy e-beams (5-330 keV)***
- ***Non-thermal e-beam applications***
  - **Sterilisation (water fluids, and raw and webbings materials).**
  - **Seed treatment.**
  - **Disinfection of grains, nuts and spices.**
  - **2D-3D printing (cure ink printed and jetted material).**
  - **Lacquering and coating (cure and bond).**
  - **Grafting (non standard bonding: vitamins/polymers, enzymes/membranes).**
- ***Thermal e-beam applications***
  - **Melting (metals) and evaporation (layer deposition).**
  - **Welding (EBW) and joining.**
  - **Additive manufacturing (AM) by meltering (EBM) and structured sintering.**
  - **Surface machining (hardening, re-melting, alloying, embedding) and structuring.**
  - **E-beam drilling (ultra fine holes in high-strung materials).**

INDUSTRY

State of the Art II

- ***Low-energy e^- (330 keV-10 MeV)***
- ***Polymer modification (500 keV linacs)***
  - **Cross-linking polymers to insulate wires/cables.**
  - **Assemblies of wires for electronics.**
  - **Pre-vulcanise components of car tyres.**
- ***Material processing***
  - **Colouring gemstones (heat and radiation).**
  - **Semiconductor modification (optimise switching time).**
- ***Sterilisation (e/X systems linacs)***
  - **Medical and pharmaceutical material, wine corks, Tetra packs, food (10 kGy).**
- ***Environmental applications (1MW linacs)***
  - **Flue-gas treatment.**
  - **Waste water and sewage sludge treatment.**
- ***Biological hazards (10 MeV linacs)***
  - **Conservation (books, archives).**
  - **Security (letters and parcels).**

e-beams to sterilise packaging

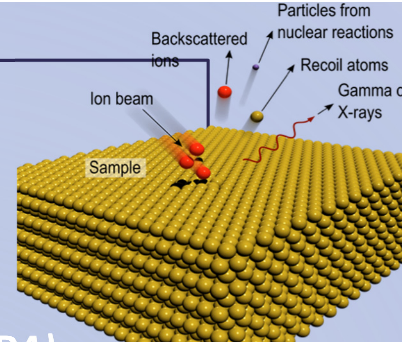


E-beam sterilising medical

E-beam pilot flue-gas treatment plant Poland

INDUSTRY

State of the Art III

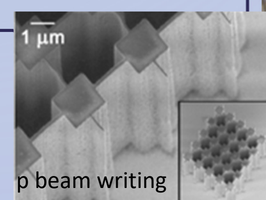


Ion Beam Analysis

- ***Ions (keV-70 MeV)***
- ***Ion Beam Analysis (EBS/RBS, NRA, PIXE, PIGE, ERDA)***
  - **Environmental:** air pollution (aerosols composition, source identity).
  - **Cultural heritage** (composition, age and conservation).
- ***Ion Beam Implantation***
  - **Semiconductor industry** (alter electronic properties, plasma implantation for quantum computing, novel optoelectronic devices).
  - **Proton-beam writing** (nano fluids devices, buried structures, 3D structures in Si).
  - **Nuclear industry** (emulate effect of neutrons in reactors).
  - **Nanomaterials** (buried nanostructures).
  - **Polymers** (deuteration analysis).

Particulate matter samples LABEC INFN

PIXE and PIGE at AGLAE LRMF



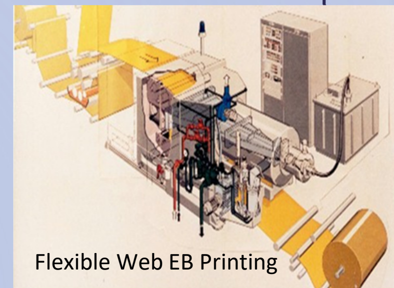
p beam writing

JANNuS triple-beam CEA

INDUSTRY

What are the R&D CHALLENGES? I

- ***Very low energy e-beams***
  - ***Non-thermal e-beams***
    - Novel high-voltage generator (compact).
    - New Insulation materials/technologies.
    - Exit windows (<80 keV).
    - Well-adapted for 3D applications (miniaturised).
    - Enlarged sealed (permanently evacuated).
    - New surfaces with lower X-ray-reflection (less shielding).
  - ***Thermal e-beams***
    - Self-diagnostic tools ('industry-4.0' automation, emission, guiding).
    - Structuring tools and technologies (1 to 10 mm).
    - New powder concepts (surface quality, additive manufacturing).


Flexible Web EB Printing

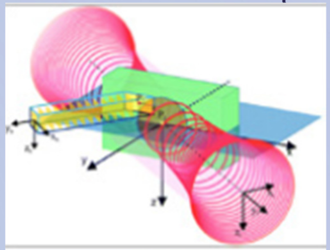
- ***Low energy e-beams***
  - Applications in nanotechnology and decontamination
  - Low-cost and compact.
  - Dual e/X systems high power.
  - Efficient/reliable (8500 hours/year, high current).

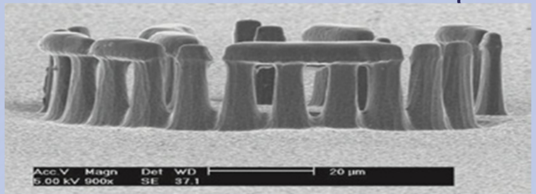

SteriHealth Process Machines FEP

INDUSTRY

What are the R&D CHALLENGES? II

- ***Ions beams***
  - ***IBA***
    - **Aerosol composition (Saharan dust).**
    - **Multilayer analysis in heritage.**
    - **Interior analysis of metal objects .**
  - ***Ion Implantation***
    - **Charge integration improvement (dosimetry, uniformity).**
    - **High-brightness micro-beams.**
    - **Integrated "holistic" and open design approach.**
    - **Small footprint and flexible.**
    - **Positive ions.**


confocal micro-PIXE geometry

micro-machined Stonehenge-like structure


- ***Political and Societal***
  - **Obsolete laws and regulations (food, medical).**
  - **Expanding the use and knowledge (environment, space, nanotechnology, decontamination,…).**
  - **Skills transfers and training across generational, institutional and geographical.**

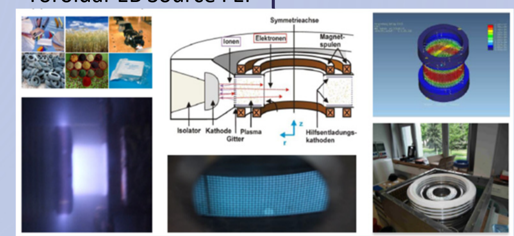
INDUSTRY

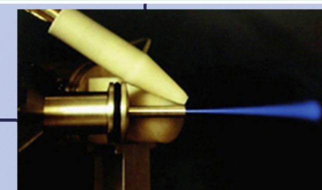
What are the needed R&D?

- ***Very-low energy e-beams***
  - **Next generation of accelerators with integrated peripheral components, high-power supplies, compact, robust, easy operation.**
- ***Low energy e-beams***
  - **Very high-power (MW) and high-energy (5-10 MeV).**
  - **Mobile facilities.**
  - **Use of SC techniques.**
- ***Ions beams***
  - ***IBA***
  - **Compact and portable for using in-situ.**
  - **Expand the use and the access to the facilities.**
  - **Standardisation of the IBA techniques.**
  - ***Ion Beam Implantation***
  - **Improve dosimetry and uniformity.**
  - **Micro-beams at high-brightness.**
  - **New types of accelerators as laser based (high-energy ions).**

EB Plant EPURA FEP

Toroidal-EB Source FEP

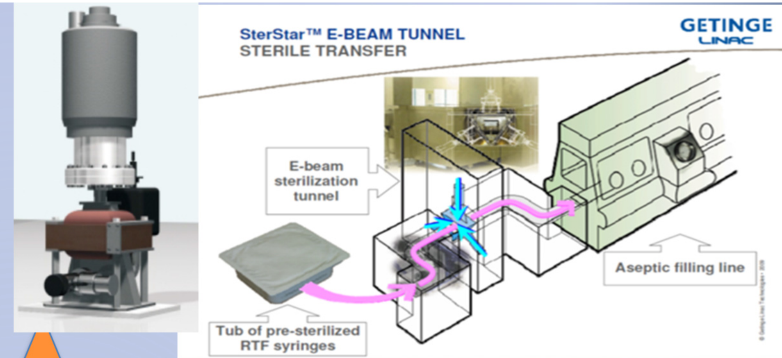




p beam in air

HIGHLIGHTS

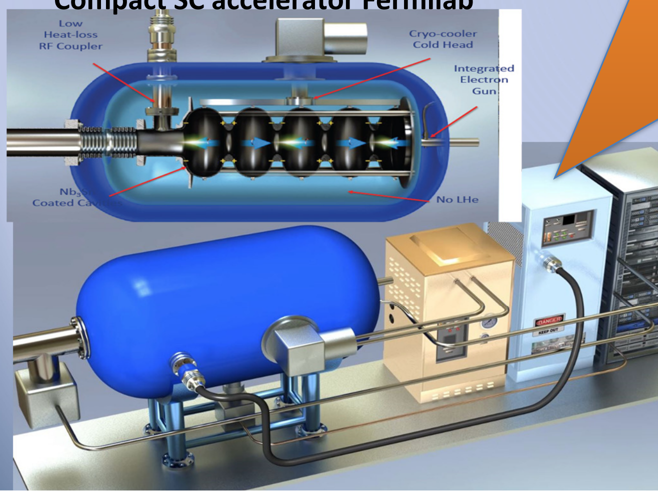
Sterilization of Bottles



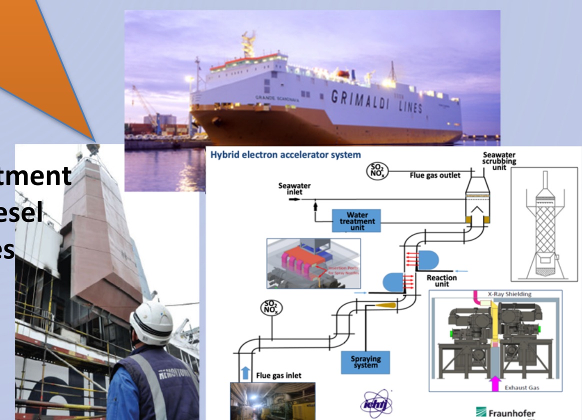
Sterilization Lines of Pharmaceutical Getinge

Mini-RFQ portable for medical and art

Compact SC accelerator Fermilab



E-beam treatment of marine diesel exhaust gases ARIES PoC

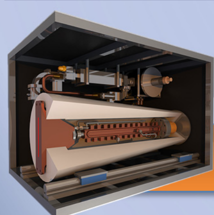


ACCELERATORS AND SECURITY

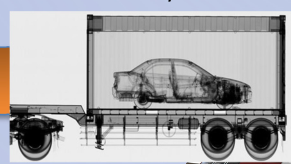
ACCELERATOR-BASED DIAGNOSTIC techniques are becoming increasingly useful in the demanding challenge of securing the **SAFETY OF CITIZENS**. Accelerators are deployed at national **BORDERS**, **AIRPORTS** as well as **NATIONAL LABS** to provide sources of **X-RAYS** or **NEUTRONS** to clear **GOODS** and **PASSENGERS**, to counter **TERRORISM** and to aid in the understanding and **STEWARDSHIP** of **NUCLEAR DETERRENTS**.

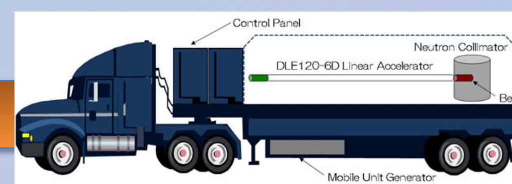
PARTICLES (e- and n)

- **E-BEAMS**
  - *X-rays*: 600 keV-10MeV e-beam linac.
  - *ϒ-rays:* bremsstrahlung source.
- **N-BEAMS**
  - *n:* $^{2}H/^{3}H$ *impinging* $^{2}H/^{3}H$.



Minituarized linac system from radiabeam



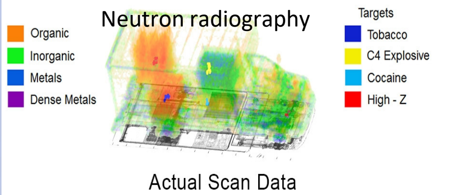


SECURITY

State of the Art I

Rapiscan's mobile high-energy X-ray system

- **Border Security /Counter Terrorism**
  - *X-ray Imaging*
    - **Marine freight: dual-energy systems to compare attenuation.**
    - **Air freight: low energy systems.**
    - **Rail cargo: energies 10 MeV, higher doses and faster repetition (high-speed).**
    - **People and Mail: energies 600 keV, low dose rate.**
    - **Explosives: energies few keV, low dose rate.**
  - *Gamma-rays*
    - **Nuclear Resonance Fluorescence (NRF)**
  - *Neutrons*
    - **Neutron radiography (detecting neutrons).**
    - **Neutron-induced gamma-spectroscopy.**



- **Nuclear security**
  - *X-ray imaging*
    - **Hydrodynamic testing nuclear stockpiles: 1-9 MeV condition and ageing.**
    - **Larger nuclear systems: 20 MeV, pulsed power sources, high current, <100 ns flash by a large pulse power generator (flash radiography).**

X-ray flash radiography CEA

SECURITY

What are the R&D CHALLENGES?

- *Border Security /Counter Terrorism*
  - More advance X-ray systems (2D-3D)
  - Simpler-to-use, universal screening systems.
  - More precise radiation dosage (people)
  - Better detection of nuclear material (NRF, protons).

Train cargo scanning

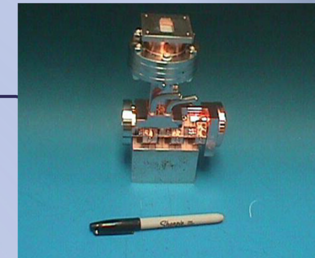
- *Nuclear Security*
  - Support to maintaining international treaties, safeguards and nuclear arms control inspection.
  - Support to stockpile stewardship.

Marine cargo scanning

- *Political and Societal*
  - Clearer EU policy on screening and irradiation regulation.
  - Optimising the radiation dose.
  - Ensuring public safety.
  - Safeguarding electronics goods.
  - Improve public understanding and perceptions.

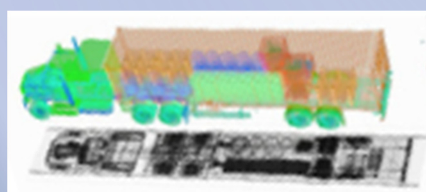
SECURITY

What are the needed R&D?

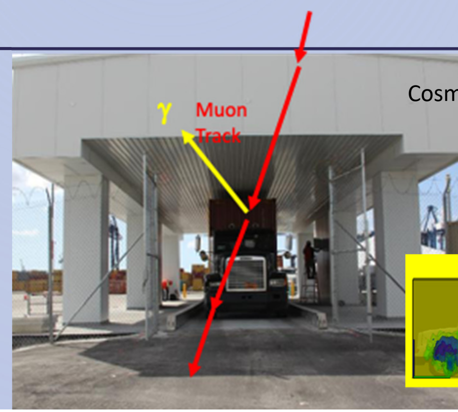


Ultra-compact 1 MeV linac

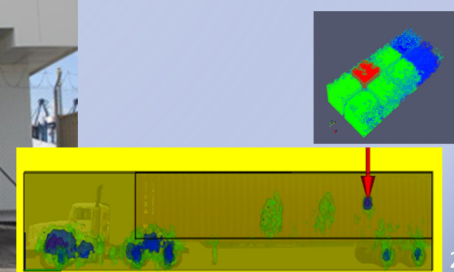
- Reducing **cost** and **size.**
- Development of **3D** imaging and **automated** image **recognition** (improve the throughput)
- Development of tuneable narrow X-ray sources to improve **NRF** (active fission detection).
- Development of **μ** accelerators for **μ**-scattering tomography.
- **More rugged, user-friendly**, autonomous technologies.
- Development of **compact multi-pulsed** source technology to support stockpile stewardship.



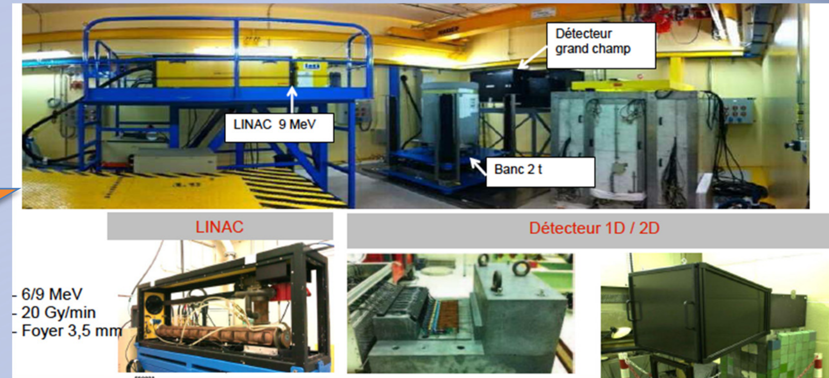
X-ray data from Passport System

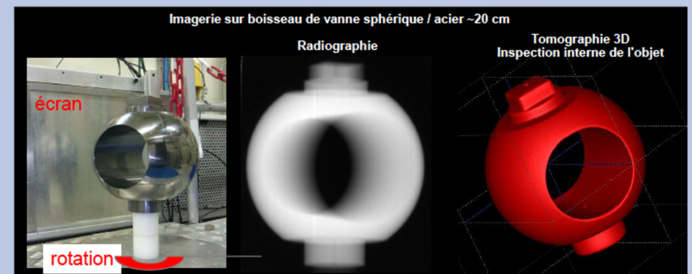


Cosmic Ray Muon and Electron Imaging



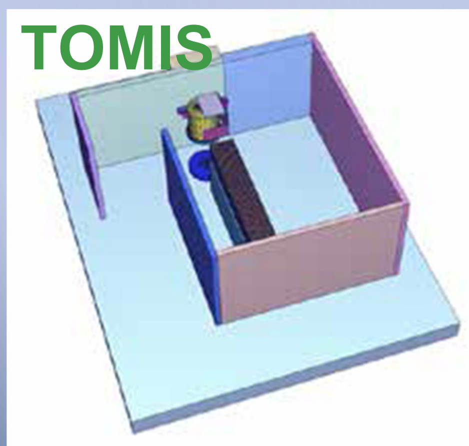
HIGHLIGHTS

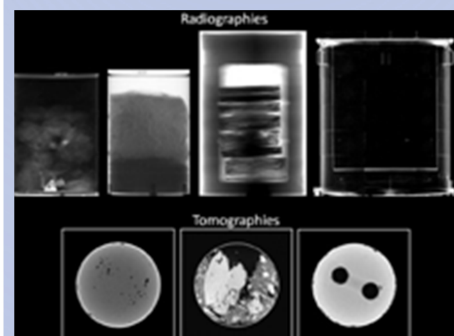




CINPHONIE 3D radiography/tomography CEA

TOMIS: In Situ Tomography multi-energy and low dose CEA-THALES



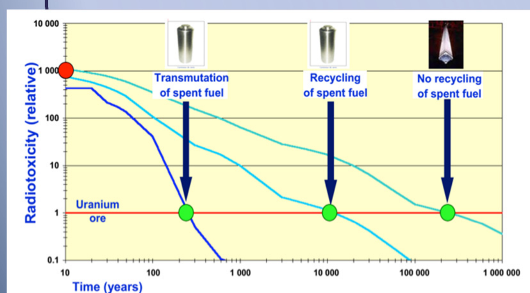


ACCELERATORS AND ENERGY

HIGH-POWER accelerators are essential to generate CLEANER and SUSTAINABLE energy but also to deal with LEGACY NUCLEAR WASTE.

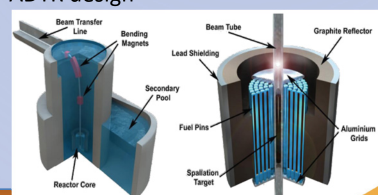
PARTICLES (p, $^{2}H/^{3}H$)

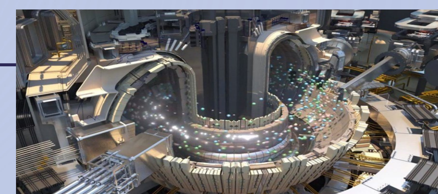
- **NUCLEAR FISSION**
  - **p: Accelerator Driven System (Subcritical rector core, spallation target and accelerator: 600 MeV, 4 mA, SC-CW linac high-power for fast n>1 MeV).**
- **NUCLEAR FUSION**
  - ***$^{2}H/^{3}H$: 1 MeV, 40 A, SC-CW linac high-power.***



Time evolution of the radiotoxicity of un-reprocessed and reprocessed spent fuel

ADTR design





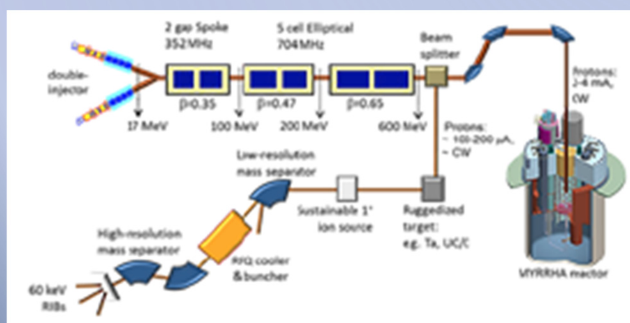
ITER in Cadarache

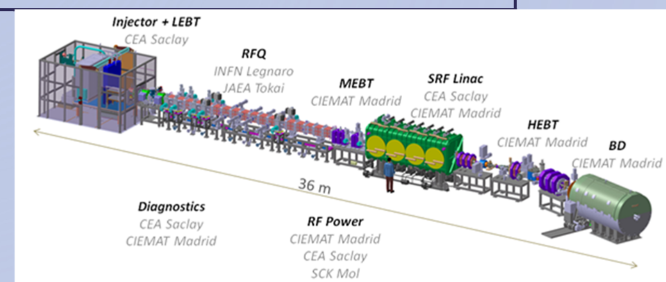
ENERGY

State of the Art

- ***Nuclear Fission***
  - **Destroying long lived radioactive waste (MAs) by transmutation with fast neutrons (1 MeV) giving medium mass-range MAs with with ADS (MYRRAH HPPAs SC-CW linac 600 MeV, 4mA, 2.4MW, <10 trip/3 s/month).**
  - **Power generation at sub-critical level driven by ADS (academic).**
- ***Nuclear Fusion***
  - **Magnetic confined nuclear reactor with plasma heated by a high-power accelerated $^2H/^3H$ beam (ITER 40 A of 1 MeV D^-).**
  - **Material qualification for fusion reactors (IFMIF-EVEDA for 14 MeV neutrons, LIPAc SC-CW linac, 9 MeV, 125mA, 1.125 MW, D^+ on target).**

MYRRHA system





LIPAc linac part of the IFMIF project in Rokkasho

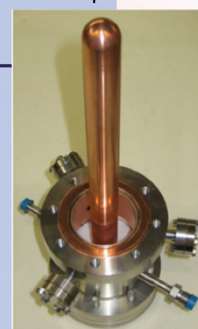
ENERGY

What are the R&D CHALLENGES?

- ***Nuclear Fission***
  - **Reactor core studies and its coupling with accelerator.**
  - **Powerful and exceptional reliable accelerators.**
  - **Design and safety analysis (ADS cooling by heavy liquid metal).**
- ***Nuclear Fusion***
  - **Material qualification (dpa damages).**
  - **High-power and high-intensity beams (beam halo control).**
- ***Political and Societal***
  - **Licensing aspect.**
  - **Exposure to radiation.**


GUINEVERE reactor SKCEN


MYRRHA 'spoke' SCRF IPNO

Power coupler LAL



High-energy SCRF


LIPAc - IFMIF in Rokkasho,

APAE

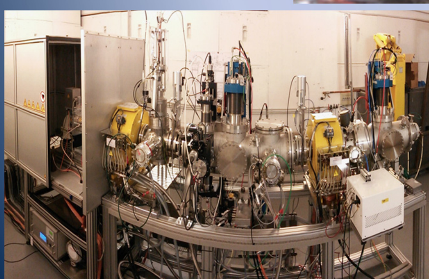
ENERGY

What are the needed R&D?

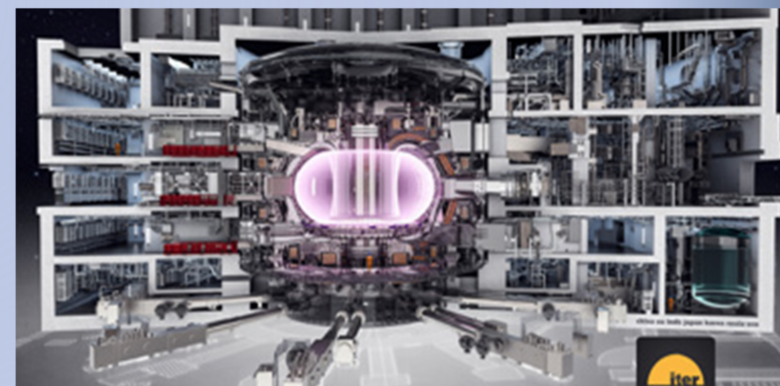
- ➢ **Development high-intensity high-reliability p/D injectors.**
- ➢ **Development SC RF-cavity technology, high-power, high-reliability .**
- ➢ **Investigation of high-current beam dynamics and beam halos.**
- ➢ **Innovative beam instrumentation.**
- ➢ **Modelling of the reliability (AI).**
- ➢ **Safety for high-energy, high-current accelerators coupled to a spallation target.**

MYRRHA RFQ
Frankfurt Univ.

MYRRHA LEBT LPSC



Furnace at IPNO



ITER experimental fusion plan

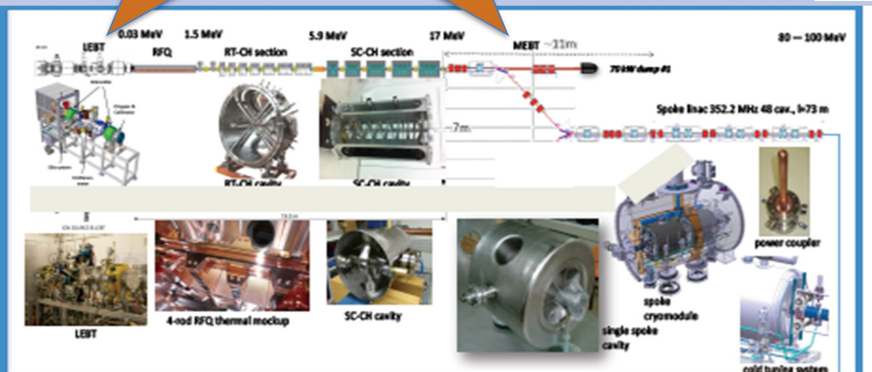
HIGHLIGHTS

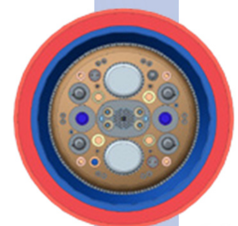
MINERVA (100MeV)

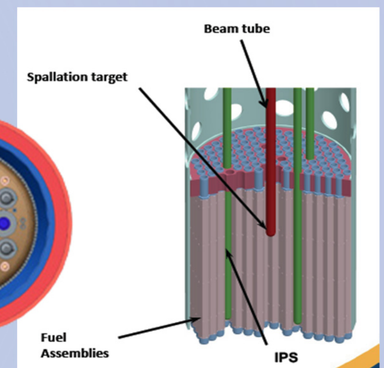
MYRRHA

SCK•CEN

Phase 1 – 100 MeV

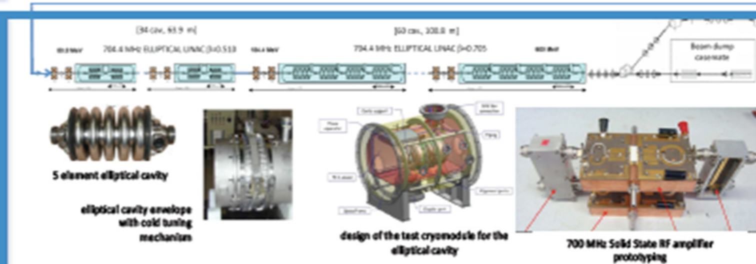


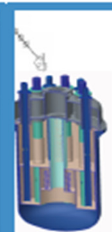




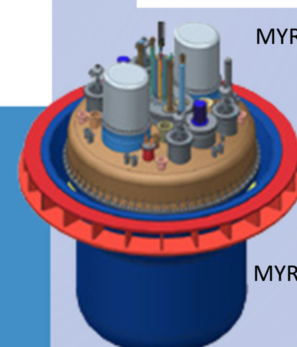
MYRRHA Core and fuel

Phase 2 – 600 MeV





Phase 3 – Reactor



MYRRHA reactor vessel

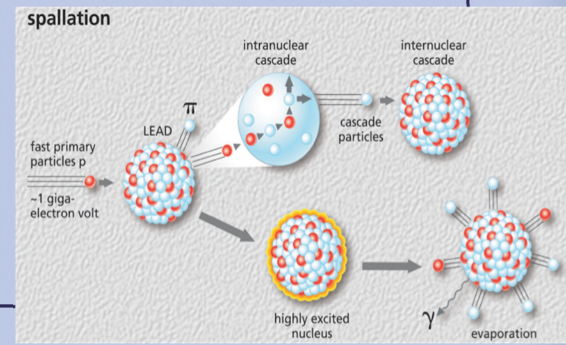
ACCELERATORS AND NEUTRONS SOURCES

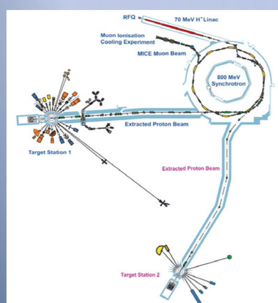
NEUTRONS beams are a key tool in both **BASIC** and **INDUSTRIAL** research: engineering, chemistry, IT and computing, material science, polymers and soft matter, biology, medical, environment and cultural heritage.

PARTICLES (p)

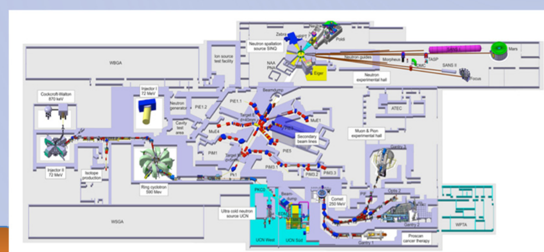
Spallation sources 0.5-3 GeV p:

- **SHORT PULSES (μs): Synchrotrons.**
- **LONG PULSES (ms): linac.**
- ***CONTINUOUS: cyclotrons.***

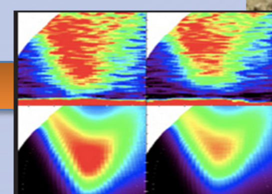


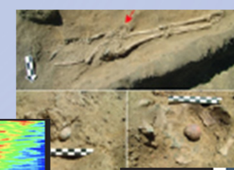


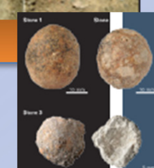
ISIS spallation neutron source Oxford



Swiss neutron source SINQ PSI

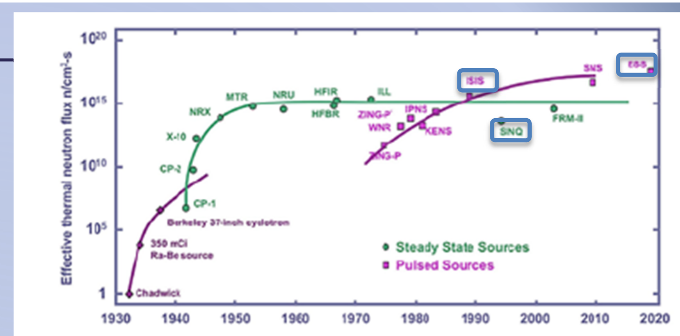






Neutron inelastic scattering measurements

NEUTRON SOURCES
State of the Art



instantaneous neutron flux as function of year

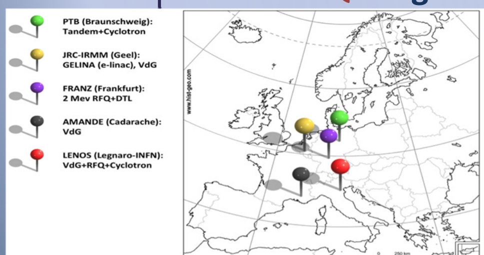
- ***Spallation Sources***

  Higher brightness/flux:
  - **Steady state (SINQ-PSI cyclotron).**
  - **Pulsed sources (ISIS Synchrotron and ESS linac 62.5 mA, 2GeV, 5MW).**


SINQ PSI

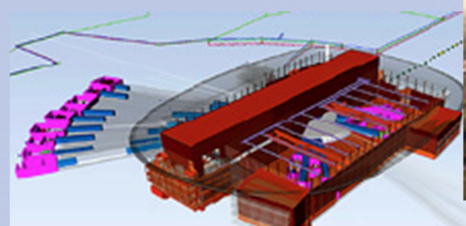
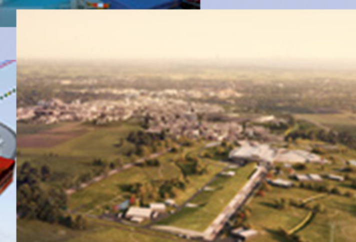
- ***Compact Neutron Sources (CNSs)***

  Low-energy reactions (p/^{2}H impinging Be/Li target):
  - **RFQs: high-current (tens mA).**



CNNs existing and in construction in Europe


CNNs Typical scheme

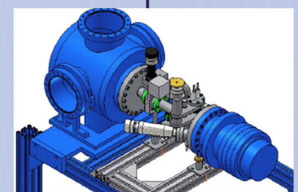
ESS facility in Lund

NEUTRON SOURCES

What are the R&D CHALLENGES?

- Main challenge is the increase of the **neutron flux** at **target level**
- **Higher** beam **powers** and **currents** (halo control).
- Improved **RF power sources** (availability and efficiency).
- **Efficient injection** for Synchrotrons and **space charge** effect.
- **Extraction** scheme for **long pulses.**
- Development of **high-intensity cyclotrons.**
- Higher-energy, high-current **CNNs.**
- **Further Technical challenges** and **Integration:** target, moderator, chopper, neutron guides, instrumentation, detectors,..

target assembly for LENOS



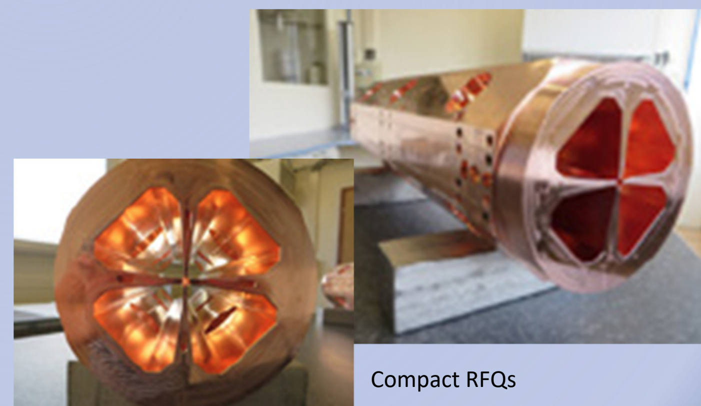
- ***Political and Societal***
  - **Retaining skills and training** (across generational, institutional and geographical).
  - **Organisational** and **financial.**
  - **Impact** on **environment** (high degree of sustainability).

NEUTRON SOURCES

What are the needed R&D?

- ➢ **Optimized target/moderator to maximize neutrons/beam power.**
- ➢ **Energy-efficient RF sources (cost drivers).**
- ➢ **Low-loss injection and longer-pulse extraction schemes for synchrotrons.**
- ➢ **High-quality SCRF cavities.**
- ➢ **Compact CNNs (compact high-power RFQs).**
- ➢ **Alternative accelerators types (FFAGs).**

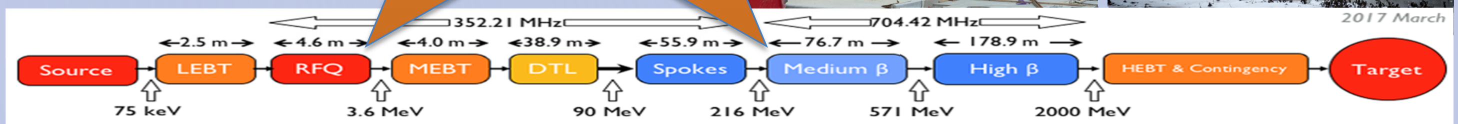
Test stand two klystron ESS



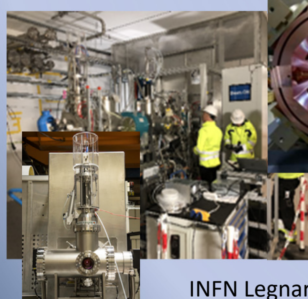
Compact RFQs

HIGHLIGHTS

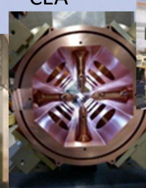
EUROPEAN SPALLATION SOURCE

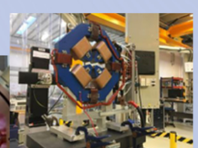


LNS



CEA





ESS-Bilbao

IPN-Orsay Uppsala Univ.

Elettra, STFC Daresbury and Aarhus Univ.

INFN Legnaro

CEA, INFN Milano and STFC Daresbury.

ESS-Bilbao

ACCELERATORS AND PHOTON SOURCES

Accelerators offers the **MOST INTENSE** source of **HIGH-ENERGY PHOTONS** (soft and hard X rays, VUV) used in the analysis of a wide range of **SCIENTIFIC** and **INDUSTRIAL R&D**: chemistry, biomedicine, material science, nanotechnology, condensed matter, environmental, cultural heritage, manufacturing, engineering…

PARTICLES (e-)

- **SYNCHROTRONS:** wide spectrum, multiple lines, ps pulse length.
- **LINACS:**
  - FREE ELECTRONS LASERS (FELS) brighter and shorter pulse (fs).
  - ENERGY RECOVERY LINACS (ERLs) complex extension of FELs.
- **COMPTON SOURCES:** compact, tunable, intense and monochromatic.

PHOTON SOURCES

State of the Art

- ➢ ***SR Sources based***
  - ➢ **3rd generation with wigglers and undulators (brighter light at higher energy).**
  - ➢ **Diffraction limit SR with Multi-Bends-Achromats (MBA) (one-two orders reduced emittance).**

(ALBA, ANKA, BESSY2, DELTA, DIAMOND, ELETTRA, ESRF, MAX IV, PETRAIII, SLS, SOLARIS, SOLEIL…in Europe) - LEAPS

- ➢ ***Linacs Based***
  - ➢ **Self-amplified spontaneous emission (SASE) FELs**

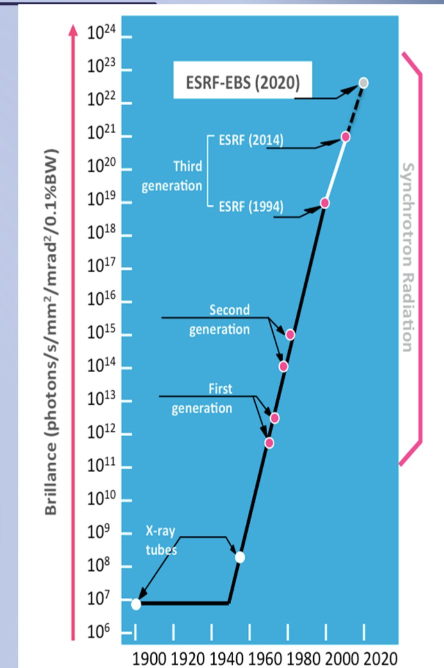
(E-XFEL, Swiss FEL, PAL-XFEL, FERMI, LCLSII, SACLA, SHINE XFEL).

  - ➢ **ERLs combines SR with SASE-FELS**

(BerlinPro, ALICE, Novosibirsk, C-beta).

- ➢ ***Compton Sources***
  - ➢ **Laser backscattering with an e-beam (50 MeV e- from ring or linac producing 40 KeV photons).**

(Munich Compact light source-TUM, ThomX, Eli-NP).

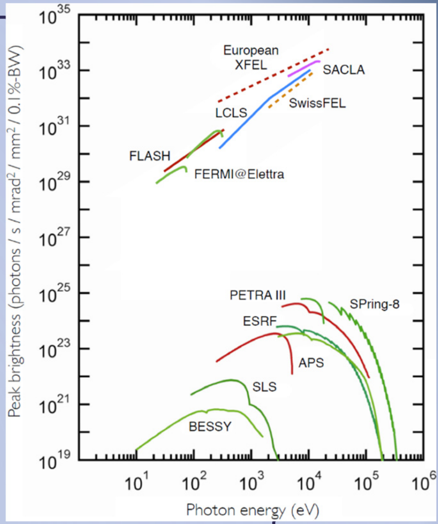


evolution of peak brilliance of electron storage rings

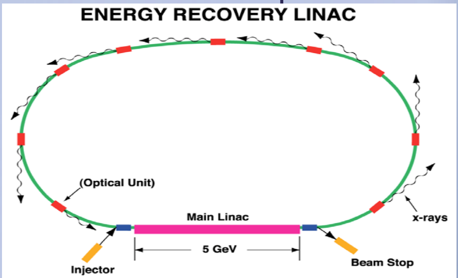
PHOTON SOURCES

What are the R&D CHALLENGES?

- *SRS*
  - Reduction of emittance (increase coherent radiation).
  - Narrow apertures, coating techniques.
  - Injection schemes.
  - Controlling the beam position (orbit correction).
  - Extending to harder X-rays.
    (SC high-field longitudinal gradients bending magnets).
- *SASE FELS*
  - Extending to faster processes (fs to as).
  - Measuring the arrival time/pulse length (TDS?).
  - Tunable seeding source.
- *ERLs*
  - Low-emittance conservation
  - SC RF (power couplers, resonant modes control)
  - Improved photocades materials.



photon energy and brightness



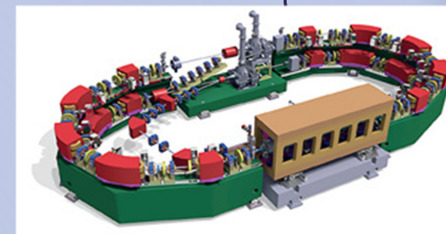
ERL principle

- Adequate capacity for research (allocation of beam time/competition).
- Improving reliability (98-99 %, 200 days per year, <150 h meantime failures).
- Improving data acquisition and processing.

PHOTON SOURCES

What are the needed R&D?

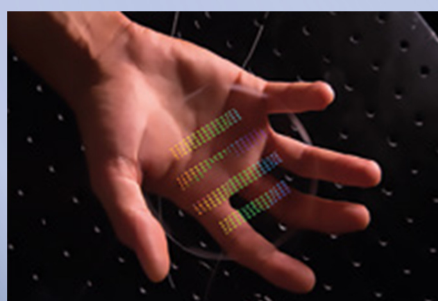
- **Traditional technologies**
  - **High-brightness, high-repetition rate guns for FELs.**
  - **SCRF HOM damping for ERLs.**
  - **Low- Emittance modelling and simulation.**
  - **Undulators in vacuum, SC (shorter period lengths).**
  - **New RF power sources.**



Compact light source to be commercialised by Advanced Accelerator Technologies

- **Compact FELs using plasma-wave accelerators (DESY-FLASH).**

- **Accelerators on a chip (miniature dielectric structures).**



Nano-fabricated silica chips can be used to accelerate e- (SLAC)

FLASH accelerator project at DESY


Phase I
180 million € during the period 2009 to 2015
• The constuction of 19 new generation experimental stations to explore the nanoworld
• The creation of a new ultra-stable experimental hall of 8000 m²
• The improvement and refurbishment of most of the cutting-edge scientific equipment and accelerator infrastructure
Phase II
150 million € during the period 2015 to 2022
• The construction of a new storage ring, inside the existing structure, with performance increased by a factor of 100
• The construction of new state-of-the-art beamlines
• An ambitious instrumentation programme (optics, high-performance detectors)
• An intensified big data strategy, designed in order to exploit the enhanced brilliance, coherent flux and performances of the new X-ray synchrotron source
ESRF
The European Synchrotron
MAX IV
beta X/m
beta Y/m
10* disp X/m
machine function (m)
s/m
HIGHLIGHTS
TU Delft
TU/e Technische Universiteit Eindhoven University of Technology
Universiteit Antwerpen
TUM
TECHNISCHE UNIVERSITÄT MÜNCHEN
Smart*Light
LAL
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE
European XFEL
LCLS

IMPACT ON INDUSTRY AND EDUCATION I

This R&D can be performed only via close and efficient collaboration of research institutes with industrial partners.

- ***Health***

RT equipment represents an annual market of nearly 6B$ with a growth rate close to 7%. New approaches not only to improve the results, but also to open new indications:

  - **X-ray radiotherapy: cost saving, access to treatment in emerging economies.**
  - **Proton Therapy: new technologies or imaging systems giving new products.**
  - **Ion therapy: lower cost designs leading to a commercial space for products.**
  - **VHEE therapy: demonstration of a new treatment method in clinic.**
  - ***Component development: fast ramp magnets, SC magnets, X-band technology,..***
  - **Radionuclides: collaboration research/industry for cyclotron/linacs developments.**

- ***Industry***

Europe is very strong in e-beam technology accelerator technology, the applications in industry will add more than 1B€ to GNP on EU. High-potential in:

  - **Very-low energy e-:beam: E-beam melting, E-beam welding, AM.**
  - **Low energy e-beam: polymers, sterilisation of medical, environmental…**

- ***Energy***
  - **Potential of novel nuclear energy generation and Industrial waste-burner.**

IMPACT ON INDUSTRY AND EDUCATION II

➢ ***Security***

Significant opportunities for industry for advance accelerator technologies:

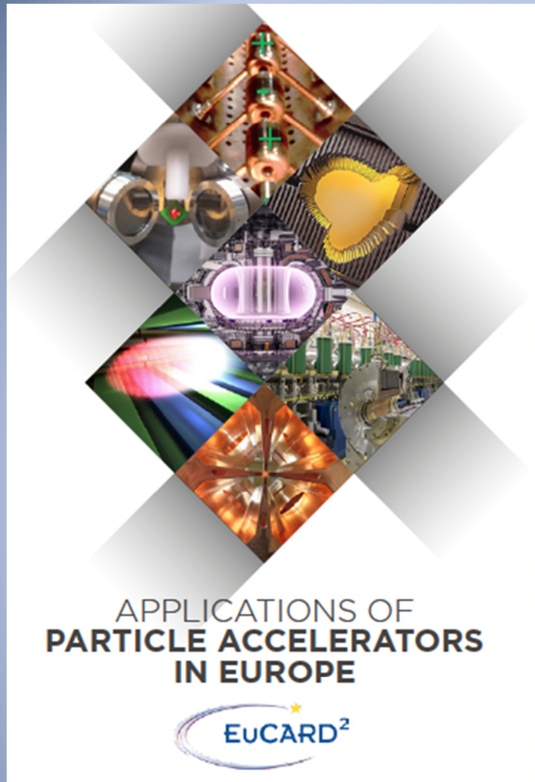
- ➢ **Work with regulatory bodies to promote and anticipate regulatory changes.**
- ➢ **Greater public understanding of the radiological hazards.**

➢ ***Photon and Neutron Sources***

- ➢ **Use of SR and Neutrons.**
- ➢ **New SR projects has a large impact on industry (custom-build components specified by SR experts in collaboration with industry).**
- ➢ **Development of CNNs could be very important for industry.**

➢ ***Education***

- ➢ **Development of staff skilled in technological and clinical/security and industrial areas to better tying-together both areas.**
- ➢ **Training of scientists, technicians and engineers in the use of Photon and Neutrons and in the related technology.**
- ➢ **Networking and ITN EU activities as ENLIGHT, PARTNER, LEAPS, EUCARD2, DITANET, ARIES, AMICI, OMA, COMPACT-LIGHT… are crucial, new projects are in preparation: ARIES2.**

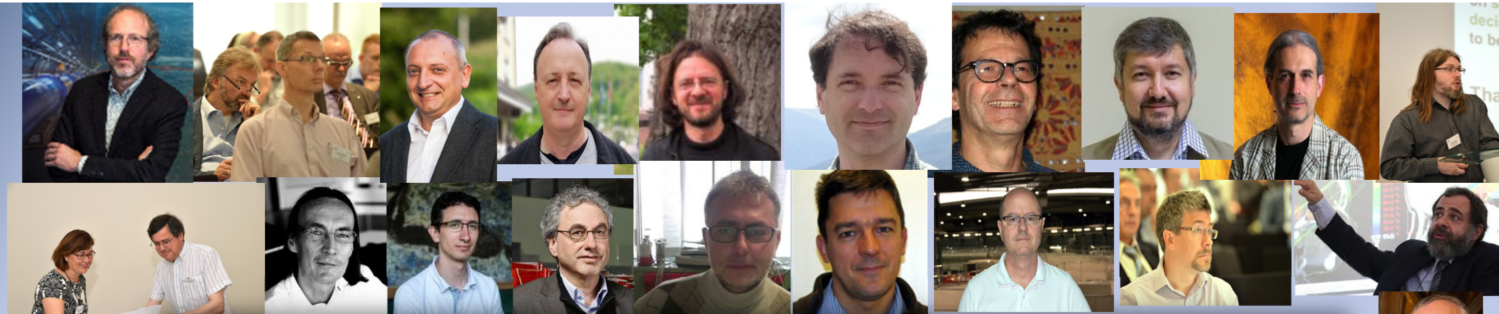


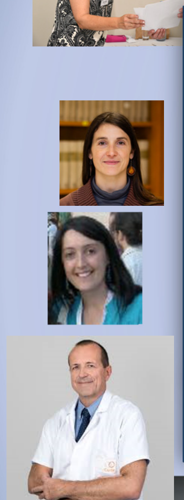
http://eucard2.web.cern.ch/

APAE

SUMMARY OF KEY RECOMMENDATIONS

- ***More COMPACT accelerators, using SC and NOVEL acceleration Techniques***
- **SIMPLER cost-effective designs, more EFFICIENT, ROBUST and RELIABLE, CHEAPER to run and more MOBILE**
- **Further development of combined IRRADIATION and IMAGING**
- **Improved ACADEMIA-INDUSTRY interactions**
- **Improved STUDENT TRAINING and KNOWLEDGE TRANSFER**
- **Improved R&D COLLABORATION within EU**
- **Improved PUBLIC UNDERSTANDING of accelerators and their science**





THE BRAVE COLLABORATORS
APAE team

Health: P. Poortmans, V. Favaudon, M. Dosanjh, L. Bottura, T. Shirai,
R. Delorme, Y. Prezado, A. Patriarca
Industry: C.J. Thangaraj, T. Torins
Security: S. Chel, E. Simon, N.Estre
Energy: H. Danared
M.T. Andreu, Y. Papaphilippou, N. Catalan Lasheras, A. Vnuchenko, Y. Han,
B. Bai, A. Pastushenko, A. Hrybok, W. Kaabi