



# Industrial and Societal Applications – WP3

A. Faus-Golfe on behalf of WP3

IJCLab – IN2P3 – CNRS

# Tasks

---

- Task 3.1. Coordination and Communication  
(Rob Edgecock - HUD)
- Task 3.2. Low energy electron beam applications: new technology development  
(Andrzej Chmielewski - INCT)
- Task 3.3. Low energy electron beam applications: new applications  
(Frank-Holm Roegner - FEP)
- Task 3.4. Medium energy electron beams  
(Angeles Faus-Golfe - CNRS)
- Task 3.5. Radioisotope production  
(Conchi Oliver - CIEMAT)

# Deliverables & Milestones

D3.1	Application of electron beams in the environmental area	INCT	M24	Done
D3.2	Evaluation of new technology for electron beam accelerators	INCT	M30	Done
D3.3	Comparison of different accelerator options for <sup>99m</sup> Tc and therapeutic isotope production	HUD	M36	Done
D3.4	Design of a compact 140 MeV electron linear accelerator	CNRS	M40	Done

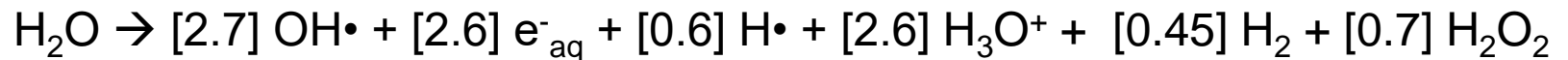
MS13	Current applications of e-beam accelerators up to 10 MeV	INCT	M12	Done
MS14	New industrial applications of electron beams	FEP	M18	Done
MS15	Medical applications of high energy electrons beams	CNRS	M24	Done
MS16	Study of different options for PET isotope production	CIEMAT	M30	Done

# Main Achievements T3.2 and T3.3

## Low-energy e-beam applications: new technology and applications

Many activities studying the use and development of e-beams  
(300 Kev to 10 MeV):

- New environmental applications:
  - Residual marine ballast water treatment
  - Sewage sludge treatment, biogas production, MPs, etc
  - Marine diesel exhaust treatment: PoC, Hertis
- Document preservation
- Food irradiation
- Virus inactivation
- High-beam power for high-dose rate
- Basic process:



- G-value: molecules/100 eV

- radicals react with biological, organic and inorganic matter

# EB-technology against biohazards

- Inactivation of viruses for vaccine production

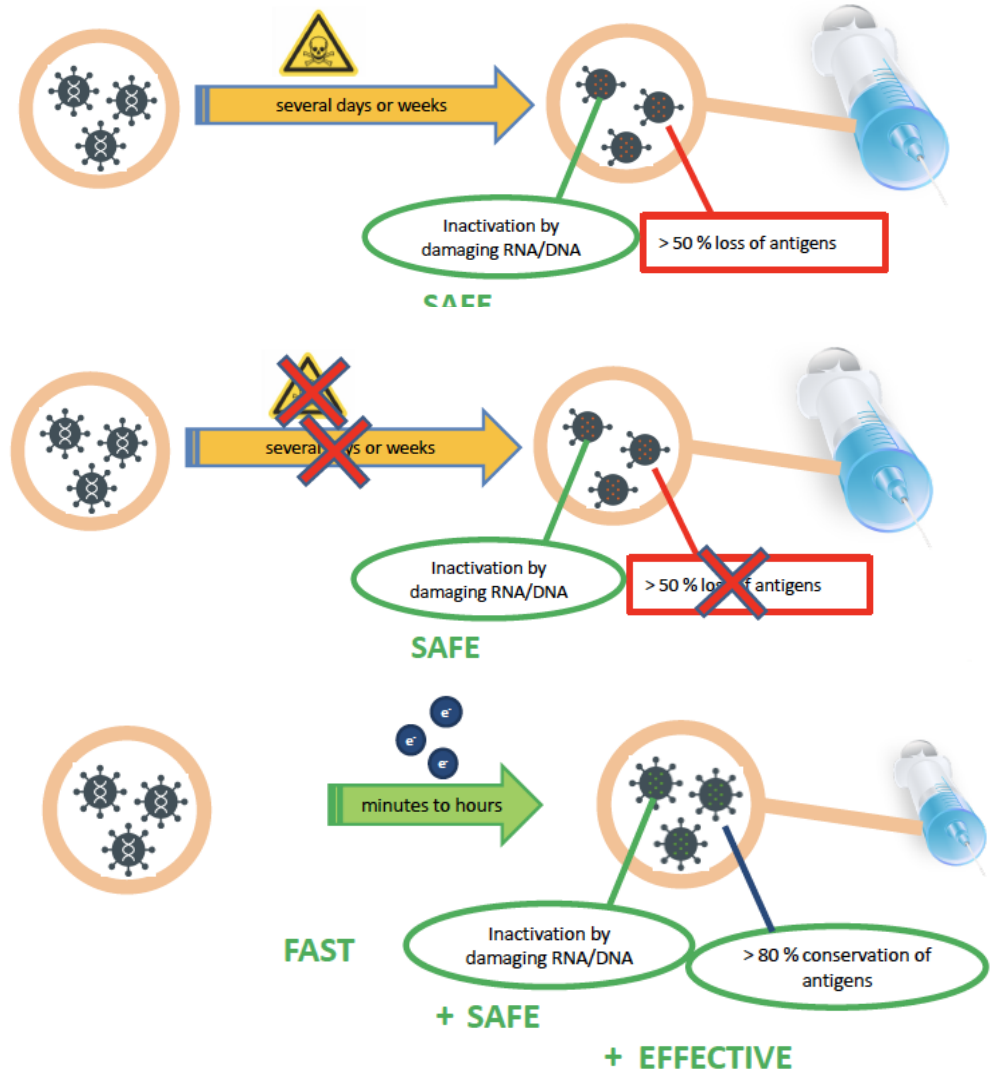
**Current method: Chemical inactivation**



**Aim: Elimination of drawbacks**



**Novel method: low energy e-beam irradiation**



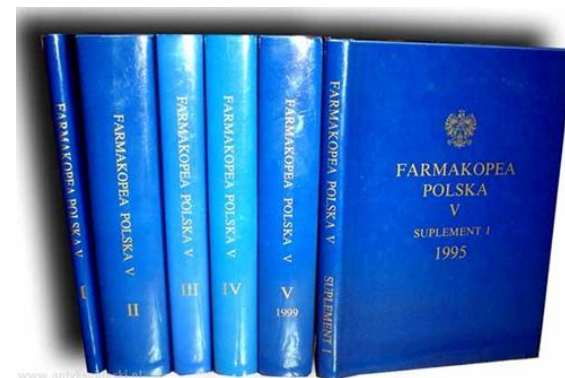
# EB-technology against biohazards

- **Inactivation of viruses for vaccine production**
  - First prototype machine, developed by Fraunhofer-consortium (FEP, IZI, IPA) works well and produces inactivated suspensions in the range of some liters per hour
  - Evaluated results for a lot of real types of vaccines
  - **First positive results on Corona-virus as well!**
  - High dose rate enables high preservation of important antigens
  - 300 keV accelerator for compact design
  - **First industrial licensing acquired!**



# EB for Preservation of Cultural Heritage

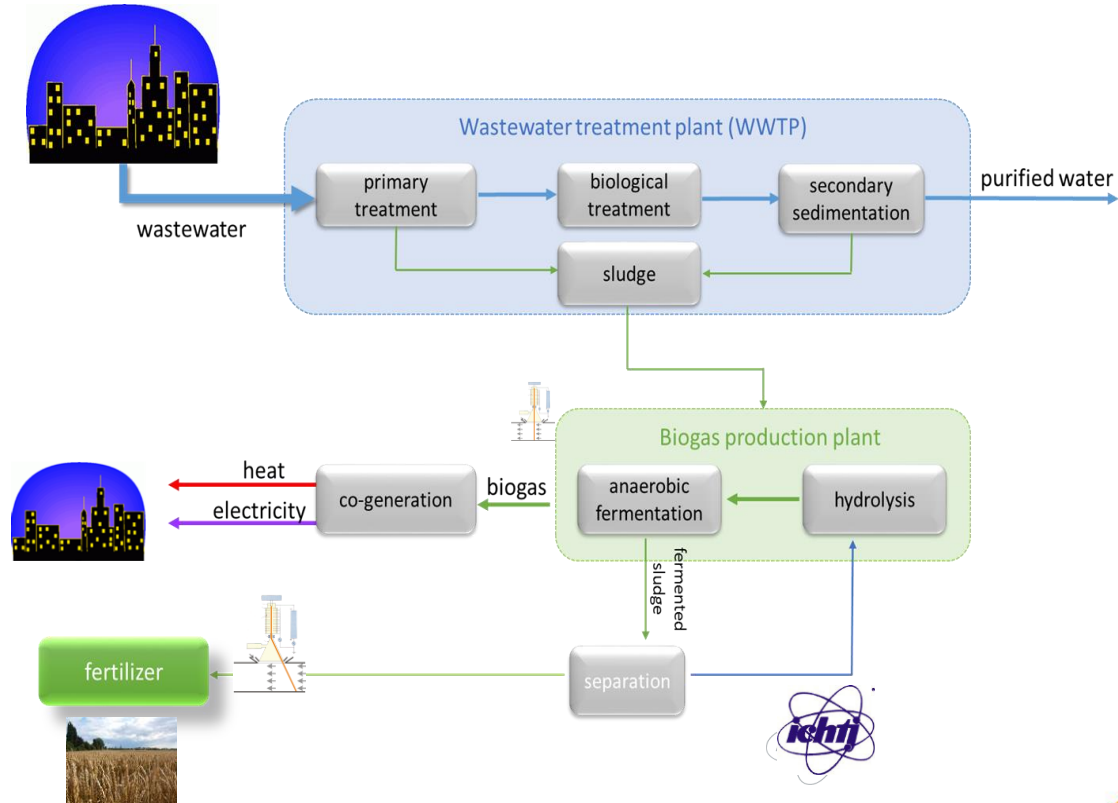
- **EB has been used for ~200m<sup>3</sup> of archives, documents, books, etc**
- Faculty of Modern Languages Library
- The Sejm (Polish Parliament) Library
- The Office for Registration of Medicinal Products, Medical Devices and Biocidal Products
- University of Warsaw – Library
- Valuable objects - *original music notation composed by Ignacy Paderewski* (stored in The Frederyk Chopin University of Music Library)



# EB-system for Hybrid Biogas

Advantage of proposed solution:

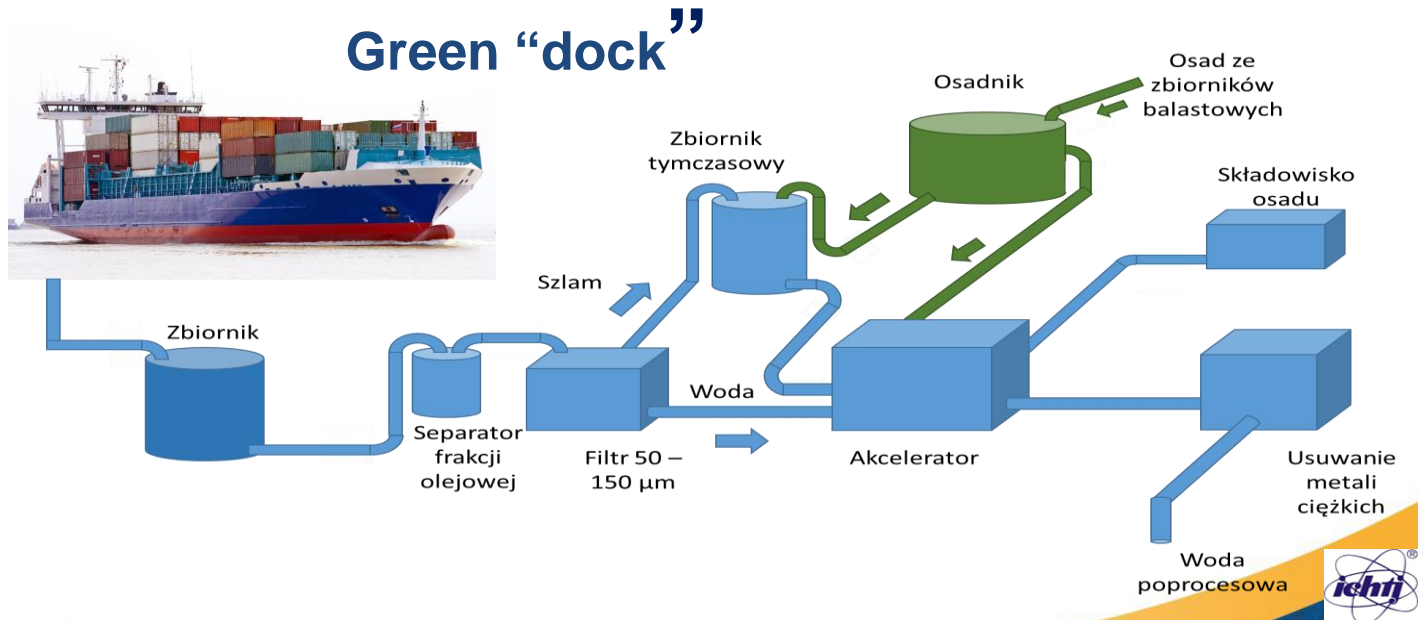
- **Environmental friendly technology**
- Biogas production is **disposal of problematic wastes**
- Production of **renewable power through combined heat and power cogeneration**
- Production of microbiologically safe organic fertilizer **due to electron beam hygenization**
- Technology can be applied in any place with sufficient biomass resources while there is **no need for external electric energy supply**
- **Also shows potential for modern contaminants:** microplastics, PPCP, POPs, AMR, etc





# EB for ballast water discharge

- Ballast water discharge typically contains a variety of biological materials, including plants, animals, viruses, and bacteria. These materials often include non-native, nuisance, exotic species that can cause extensive ecological and economic damage to aquatic ecosystems, along with serious human health issues including death.
  - *Vibrio cholerae* (O1 i O139) less than 1 CFU (colony forming unit - cfu) per 100 ml or less than 1 CFU per 1 gram (wet mass) zooplankton sample;
  - *Escherichia coli* less than 250 CFU in 100 ml;
  - *Enterococci* less than 100 CFU in 100 ml.



# Some Outputs

---

- Four H2020 and other multi-national proposals:
  - HERTIS - Hybrid Exhaust Gas Cleaning Retrofit Technology for International Shipping
  - PHOEBE - Production of High-Quality Organic Fertiliser using Electron Beams
  - ATChem - Advanced Technology as a Solution to Halogen-based Persistent and Mobile Chemicals
  - RADAGASS - Reduction in AMR Transmission by the Destruction of AMR Microorganisms, Genes and Antibiotics in Sewage Sludge and Animal Waste Using Electron Beams
- Three PhDs:
  - Urszula Gryczka "Effect of ionizing radiation on polysaccharides" INCT, Warsaw, Defended March 23rd, 2021
  - Dagmara Chmielewska-Śmietanko "Electron Beam for Preservation of Biodeteriorated Cultural Heritage Paper-Based Objects", INCT
  - Malgorzata Siwek, "Study of Electron Beam Treatment for the Removal of Microplastics from Sewage Sludge", HUD

# Some Outputs

- Three books



Publications of the Warsaw University of Technology Publishing House (WPH) — (Wydawnictwo Politechniki Warszawskiej) and its publication catalogues are available in most technical/scientific bookshops in Poland, as well as in reading rooms and libraries of universities.

The full offer of our publications is presented on the Internet at <http://www.wydawnictwopw.pl>

The Warsaw University of Technology Publishing House offers also mail-order sales (national and international deliveries)

phone 48 22 234 75-03  
fax 48 22 234 70-40  
e-mail: [oficya@pw.edu.pl](mailto:oficya@pw.edu.pl)

Electron Accelerators for Research, Industry and Environment – the INCT Perspective

Andrzej G. Chmielewski & Zbigniew Zimek (eds)

## Electron Accelerators for Research, Industry and Environment – the INCT Perspective

Editorial Series on ACCELERATOR SCIENCE



Institute of Electronic Systems  
Warsaw University of Technology



WORLD NUCLEAR UNIVERSITY

## Advanced Radiation Technology

Compiled and Edited by Dr N. Ramamoorthy

1st Edition

### Chapter 5 Radiation sources and accelerators

ANDRZEJ G. CHMIELEWSKI  
Institute of Nuclear Chemistry and Technology  
Warsaw, Poland

M. HA-J-SAEED  
NUA, Vienna, Austria (Poland)

**Abstract**  
Nuclear technology uses kinetic radiation mainly gamma rays from radionuclides like cobalt-60, cesium-137, and electron beam sources, as well as ion beams of various energies. Ion beams are produced and captured in other particle sources either for both research purposes and for other medical applications. This chapter is a brief overview of information on both radiation sources, with focus on those applied for industrial processes. A general description of several radiation sources, gamma irradiation, electron industrial accelerators and electron beams is presented along with their own features to support applications. The references and bibliography would allow the reader to study more deeply the technology, methods, which play a very important role for nuclear science and technology advancement and related industry growth.

romania2019.eu

## Non-power nuclear technologies and applications

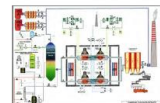
POLAND (1)



**Electron beam gas treatment**

**Description:**

The pollutants are emitted to the atmosphere with off-gases from industry, power stations, residential heating systems vehicles and ship engines. During the combustion process different pollutants as fly ash, sulfur oxides (SO<sub>2</sub>), nitrogen oxides (NO<sub>x</sub>), VOCs, PAHs, mercury are emitted. The air pollution control technologies have to be applied. Electron beam technology is among the most promising advanced technologies of a new generation, which allows simultaneous treatment of different pollutants. The high efficiency of SO<sub>2</sub>, NO<sub>x</sub> and VOC-treated was achieved. Additionally the hypothesis is a good fertilizer. A fertilizer test industrial plant has been constructed at coal-fired power plant in southwest Poland. The next step is technology development and construction of pilot installations of heavy oil-fired power plant in Aviano – Italian Refinery.



**Project:** Industry based action, EU Horizon ARIES Project  
**The benefits:** The technology enables a significant reduction of both pollutants (SO<sub>2</sub> and NO<sub>x</sub>) and good quality fertilizer is also produced. The e-b process demonstrated the possibility of destroying Polynuclear Aromatic Hydrocarbons (PAHs) like benzo(a)pyrene as well.

**Possible barriers, challenges:** The main barrier is related to the availability of high power electron accelerators.

**Collaborators:**  
**Other countries or international/European organizations involved:** CEZ, Germany; Swinerton; Bioplasma, Lublin, Poland; Kazuhiko.

POLAND (3)



**"Zero energy" -ship hypersonic electron beam technology**

**Description:**

Developers' main goal is to bring closed energy with the use of the method of advanced ship-technology. The energy is used in the process of production and at the same time it is a source of fertilizer. However, the problem is that the ship is microscopically contaminated by human and animal particles, dust, and also pathogenic bacteria. According to the invention, humans equipped with their eyes and their detectors or detectors derived in the process of continuous decomposition is irradiated with electron beams that use energies from 1 MeV to 10 MeV, preferably 3-5 MeV. For a distance derived in the process of decomposing biomass originating from waste and being a liquid form with the content of dry matter of 80-90%, the radiation dose is 100-1.5 kGy-1.5 kGy, whereas for a distance from which the aqueous phase has been removed and which has a dry matter content up to 30%, the radiation dose is 500 to 10 kGy.

INCT, Warsaw, Poland; Bioplasma, Lublin, Poland



POLAND (2)



**Hybrid electron accelerator system for the treatment of marine diesel exhaust gases**

**Description:**

Around 15% of global NO<sub>x</sub> and 5-8% of SO<sub>2</sub> emissions are attributable to ocean-going ships. According to International Maritime Organization regulations MARPOL Annex VI, there are two sets of emission and fuel quality requirements: global (congressive reduction in global emissions of SO<sub>2</sub>, NO<sub>x</sub> and particulate matter) and more restrictive requirements declared to ships in delimitedly established zones – Emission Control Areas (ECA). A new hybrid technology is based on the concept of combining the method used to clean up the exhaust gases: Electro Beam (EB) and Wet Scrubbing (WS). Project: Proof of Concept Project – Accelerator system for the treatment of marine exhaust gas" in the frame of Horizon ARIES and Polish Project - Triaga 2.

**The benefits:** The hybrid e-b method enables a significant reduction of both pollutants with limited reagent consumption and very simple operation. The method allows pathogen to be destroyed, the possibility of destroying Polynuclear Aromatic Hydrocarbons (PAHs) has been proven.



**Possible barriers, challenges:** The hybrid e-b method has a great potential to solve the emerging problem of marine industry and, although it still requires research, its development is now at the level of a Technical Readiness Level. This means that the technology has been optimized at the laboratory level and is in the medium development phase.

**Collaborators:**  
**Other countries or international/European organizations involved:** RTU, Ulsan, Latvia; INCT, Warsaw, Poland; Fraunhofer, EFP, Dresden, Germany; CEZ, Gera, Switzerland; Roznoszenie, Gdansk, Poland; IZAR, Riga, Latvia; Bioplasma, Lublin, Poland.

**Other:**  
1. Uliasz M., Chmielewski A.G. (2019), Proof of concept engineering aspects of diesel engine off-gases treatment. INCT Report B-318. [https://www.ictj.org/publications/2019\\_0318](https://www.ictj.org/publications/2019_0318)

2. Chmielewski A.G., Zwiolicka E., Lich J., Uliasz M., Uliasz B., Szala A. (2018), A hybrid plasma-chemical system for high-NO<sub>x</sub> diesel gas treatment. Fuel, Fuel Cells, 184, 1-7. DOI: 10.1016/j.fuel.2017.11.005

Principle of off-gases treatment by electron beam, wet scrubber in the second stage



# Future in I.FAST WP12

---

## ***Strategy for Implementing new Societal Applications***

3rd May Wednesday 15:00 - 15:15 (CERN)

Andrea Sagatova - - Slovak Technical Univ.

**Sub-task 12.3:** Environmental applications of electron beams

Toms Torims – RTU, Andrzej Chmielewski - INCT

## ***Design of Advanced Electron Accelerator Plant for Biohazard Treatment***

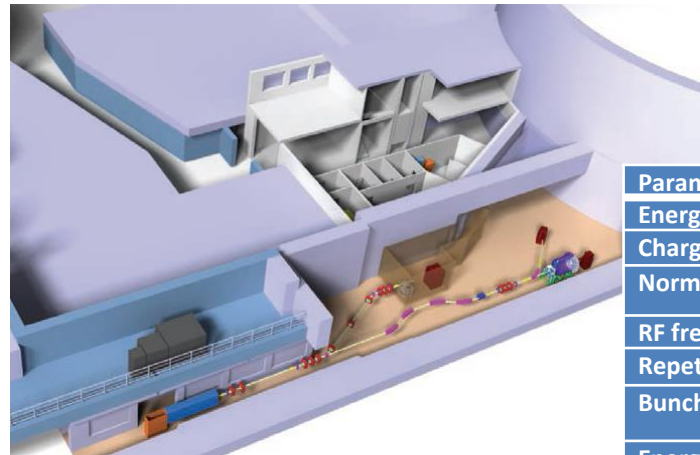
4th May Wednesday 15:15 - 15:30 (CERN)

Andrzej Chmielewski - INCT

# Main Achievements T3.4

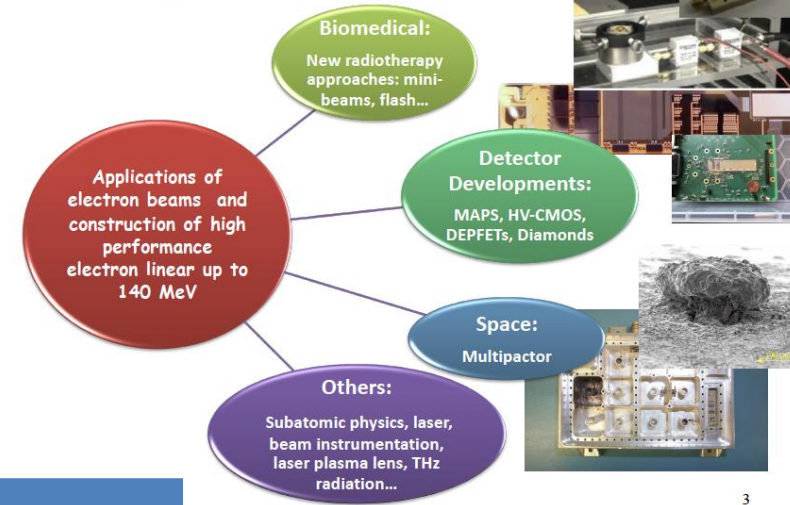
## Medium energy e-beam: new Radiotherapy applications

- Study of the applications of e-beams up to 140 MeV in the medical and other areas
- Study of the construction of high performance electron linear accelerator up to 140 MeV



Parameters	
Energy	70 – 140 [MeV]
Charge (variable)	0.00005 – 2 [nC]
Normalized emittance	3-10 [mm mrad]
RF frequency	3.0 [GHz]
Repetition rate	50 [Hz]
Bunch length, rms	< 10 [psec]
Energy spread, rms	< 0.2 %
Bunches per pulse	1

### Task objectives



# New e- linac therapies and accelerator designs

## CHALLENGES IN RADIOTHERAPY New RT approaches

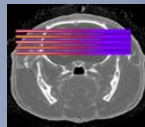
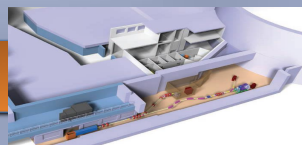
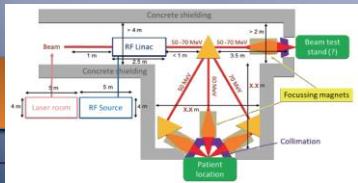
RT treatment of some radioresistant tumours, paediatric cancers and tumours close to delicate structure (i.e. spinal cord) is currently limited. One of the main challenges is to find approaches to increase the normal tissue resistance.

Standard RT is restricted to the few temporal and spatial schemes, dose rates, broad field sizes: mainly photons, 2 Gy/session, 1 session/day, 5 days/week, dose rates of 2 Gy/min, field sizes of 1 m<sup>2</sup>, homogeneous dose distributions.

Possible strategies to spare normal tissue

Different particle types: Very High Energy Electrons (VHEE)

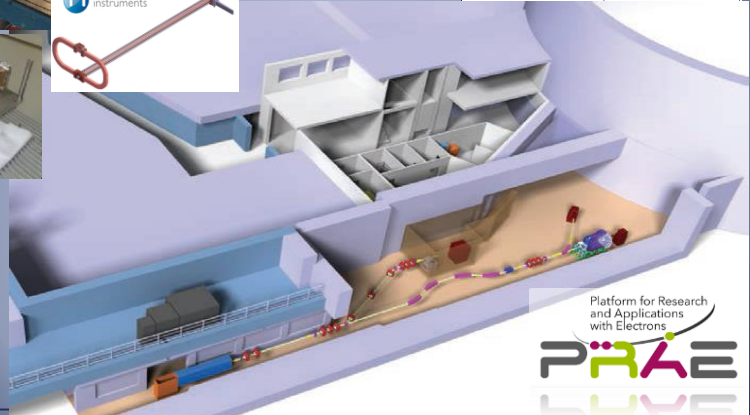
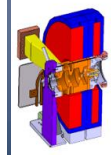
Different dose delivery methods: Grid Mini-beam or FLASH RT



## ACCELERATORS FOR VHEE Accelerators for FLASH-RT: high-energy e-

S-band: RF gun + Linac (HG)

Parameters	
Energy	70 - 140 [MeV]
Charge (variable)	0.00005 - 2 [nC]
Normalized emittance	3-10 [mm mrad]
RF frequency	3.0 [GHz]
Repetition rate	50 [Hz]
Bunch length, rms	< 10 [ps]
Energy spread, rms	< 0.2 %
Bunches per pulse	1



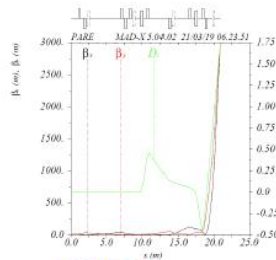
Platform for Research and Applications with Electrons  
**PRAE**

Very High Energy Electrons (VHEE) RT accelerator design, in particular for **Grid mini-beam** and **FLASH ultra-high dose rate** delivery modes:

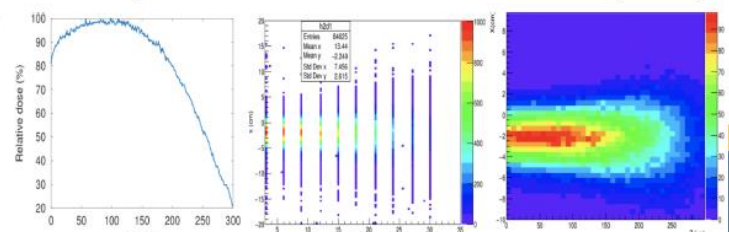
- **Dose rates:** 2 Gy/min - 100 Gy/sec
- **Beam sizes:** 0.5 mm - 10 cm
- **Homogeneous beam:** +/- 2-3%

for single or multiple beams and single or multiple fractions in biological and preclinical applications.

## FLASH



Beam profile in water box for 70 MeV electron FLASH beam (GEANT4)



PhD: B. Bai, Injector linac optimizations for FCCee and applications for PRAE, University: Paris-Saclay / University Chinese Academy of Sciences, 2021.



# Very High Energy Electrons RT: VHEE'20 workshop



<https://indico.cern.ch/event/939012/>

## Accelerator technologies for VHEE RT

High-gradient RF structures where more than 100 MeV/m are now achievable.

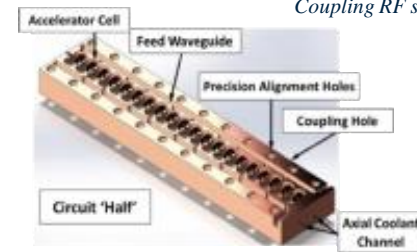
Some promising R&D are:

- distributed coupling accelerator
- use of cryogenic copper
- higher frequencies millimetric waves (~100 GHz) and higher repetition rates using THz sources

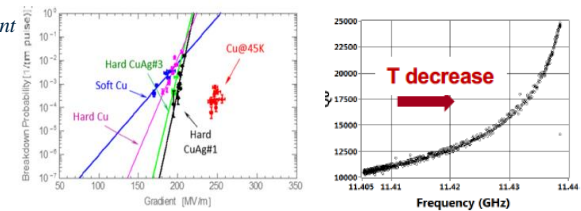
## Accelerators for VHEE RT

- Normal Conducting RF linacs: eRT6-Oriatron at CHUV, ElectronFlash at IC, CLEAR at CERN, CLARA at Daresbury and AWA at ANL
- Super Conducting RF linacs: ELBE Center of High Power Radiation Sources at HZDR and PITZ at DESY in Zeuthen
- Laser Plasma Facilities: DRACO at ELBE LOA at IPP

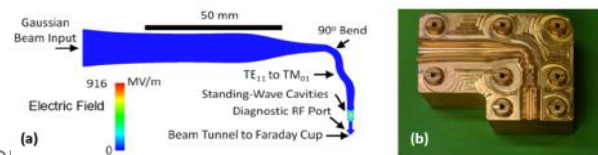
*X-band  $\pi$ -mode Distributed Coupling RF structures*



*Left: Breakdown probability measurement in a single cell cryogenic test. Right: Quality factor for cryogenic copper accelerator structures*



*Built and tested structures to 230 MeV.*



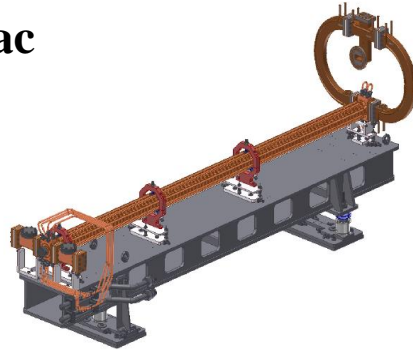
To edit footer: Insert -> Header & Footer

# Possible designs for a compact e- linacs for VHEE applications

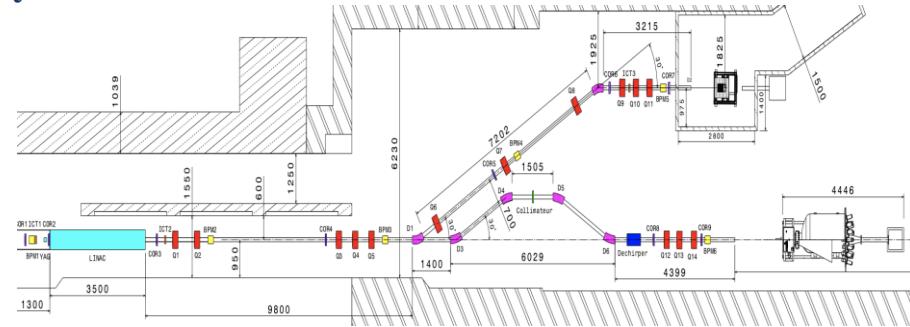
## S-BAND LINACS

### S-band HG TW linac

Parameters	
Energy	70 – 140 [MeV]
Charge (variable)	0.00005 – 2 [nC]
Normalized emittance	3-10 [mm mrad]
RF frequency	3.0 [GHz]
Repetition rate	50 [Hz]
Bunch length, rms	< 10 [psec]
Energy spread, rms	< 0.2 %
Bunches per pulse	1



### PRAE Accelerator Layout



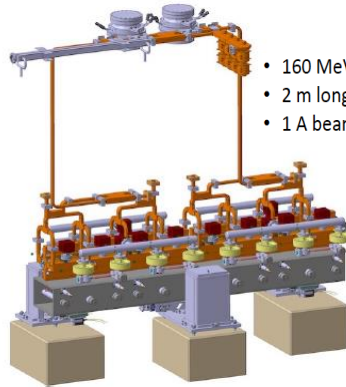
## X-BAND LINACS

### C-BAND LINACS

### C-band linacs HG SW wave

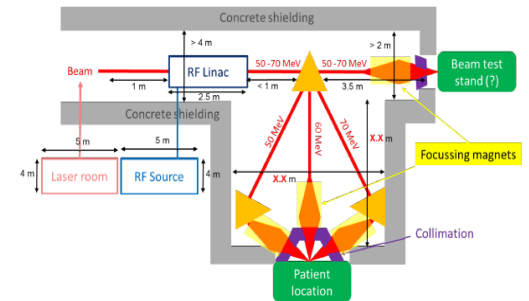


### X-band HG CLIC unit

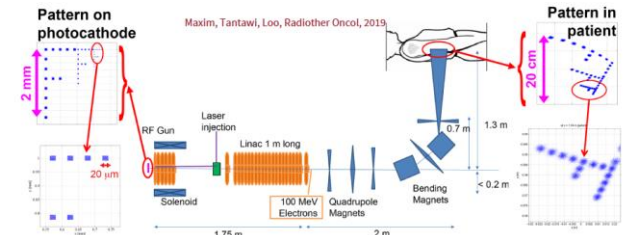


- 160 MeV energy gain
- 2 m long
- 1 A beam current

### Preliminary design of FLASH facility for CHUV Lausanne



### PHASER facility sketch for 80-150 MeV high-energy electrons





# Future in I.FAST WP12

---

## *Strategy for Implementing new Societal Applications*

3rd May Wednesday 15:00 - 15:15 (CERN)

Andrea Sagatova - Slovak Technical Univ.

**Sub-task 12.2:** Novel forms of radiotherapy

Angeles Faus-Golfe - CNRS

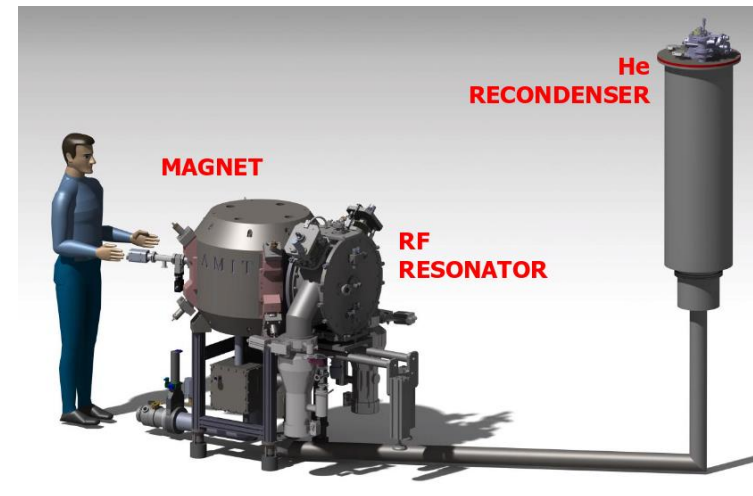
# Main Achievements T3.5

## Radioisotope production: AMIT cyclotron

- Advance Molecular Imaging Technology (AMIT) Cyclotron
- Development of a **compact mini-cyclotron for  $^{11}\text{C}$  and  $^{18}\text{F}$  single doses production**
- Cyclotron to be installed in (or near) the hospitals
  - Compactness requirement  $\rightarrow$  high magnetic field
  - Low maintenance and power consumption

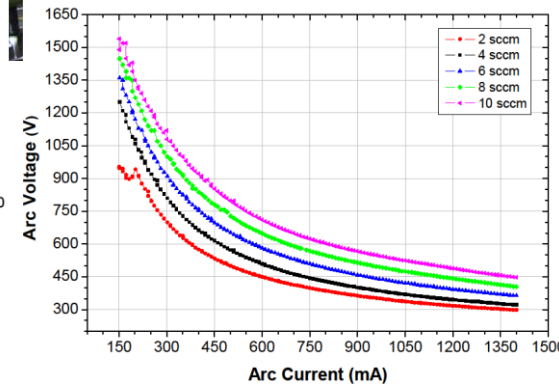
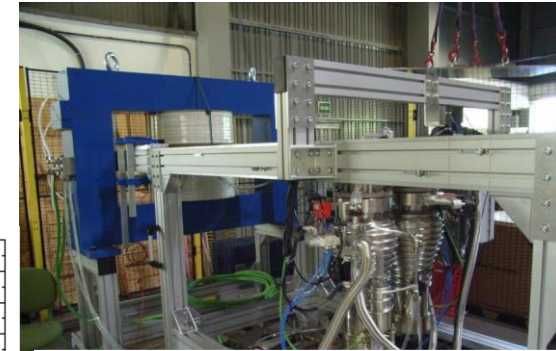
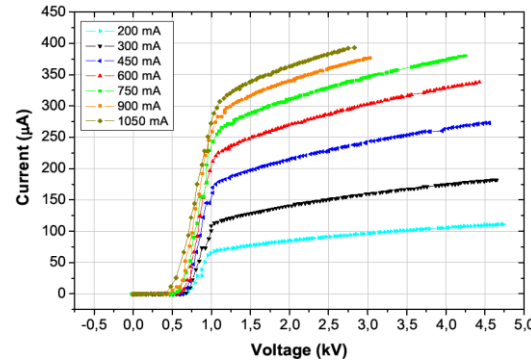
### Optimization of AMIT cyclotron:

- Ion Source Validation and characterization
- Beam Dynamics
- Optimization of the autonomous Cooling Supply system



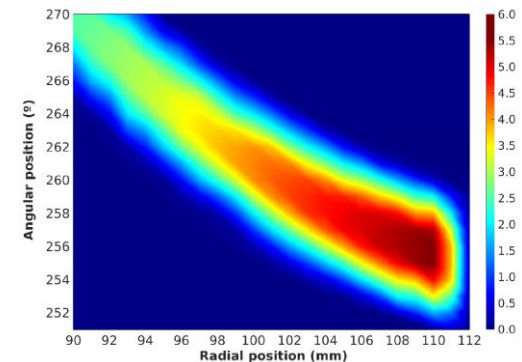
# Ion source characterization in a devoted Ion Source Test Bench

- Devoted Ion Source Test Bench at CIEMAT
- The measurements of the discharge characteristics and extracted ion current have provided relevant information for the final operation of the cyclotron:
  - Discharge characteristics curves
  - Beam extraction regimes
  - Influence of different plasma conditions → Optimizing IS input parameters
  - Cathode lifetime
  - Plasma expansion gap studies



## AMIT Beam dynamics

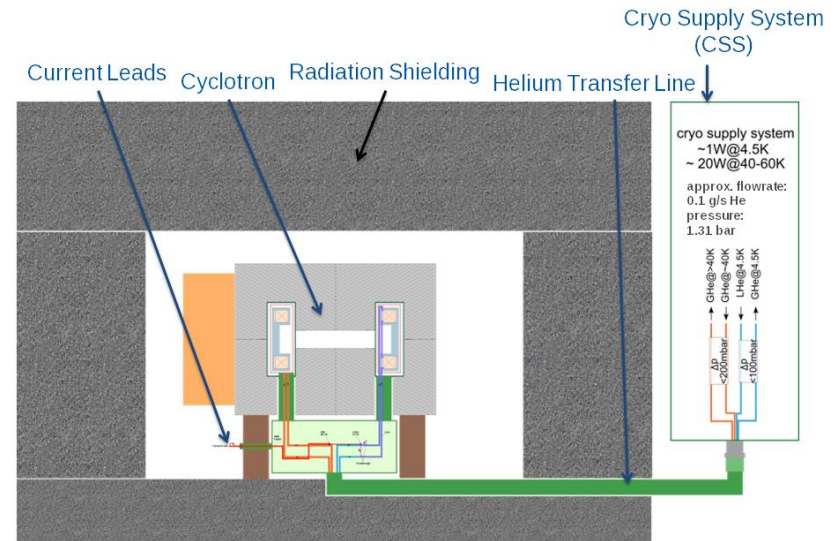
- Fine tune analysis of the different cyclotron configuration parameters
- Determination of the adequate **beam extraction positions** for a suitable beam transportation to the target
- Assessment of the **beam residual stripping interactions** in AMIT cyclotron, optimizing the beam injection conditions to control the pressure level and minimize the stripping losses.



# AMIT SC magnet

## Main goals:

- Very compact design of the whole magnet
- Stable operation of a superconducting magnet.
- Minimized thermal losses for superconducting operation. **Cryogenic supply out of high radioactive environment.**
- Easy accessibility for particle chamber, target and ion source. Removable poles for magnetic shimming

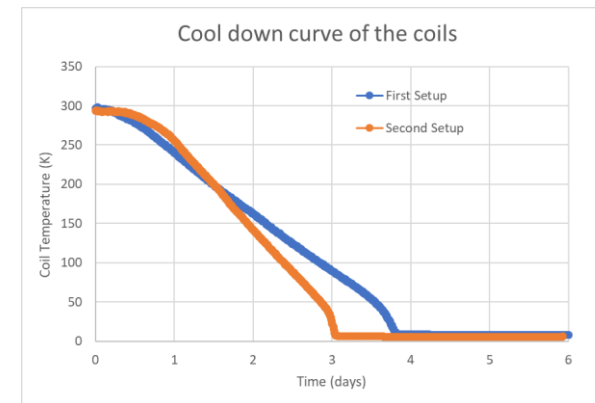


The optimization of the autonomous Cryogenic Supply System, originally designed by CERN, has been performed in the ARIES framework, including among other modifications:

- Added injection line for hybrid usage (closed and/or open circuit): Helium will be cooled down by cryocooler inside CSS, but additional liquid can be injected from external Dewar
- Pipes modified to match the cyclotron
- Additional by-pass valve to reduce the cool down time
- Filter for particles coming from coils given the required high purity He for an efficient liquefaction

# Test of adapted CSS + cyclotron

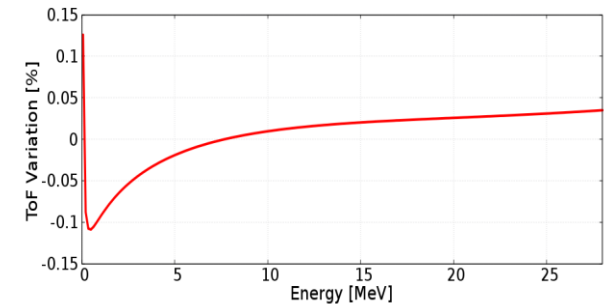
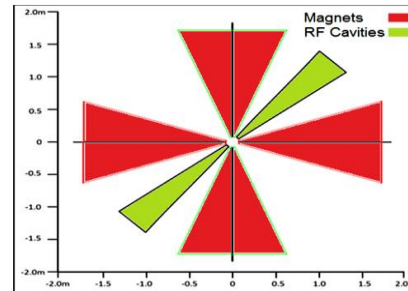
- First test of cyclotron using adapted CSS and original Transfer line (TFL)
- Coils were cooled up to 11 K (not enough)
- Heat from the transfer line was measured: 0.7 W (too much)
  - A new transfer line was designed and developed at CIEMAT
  - Some minor modifications were also included in current leads to minimize heat
- A set of operational parameters was tested
- Superconducting state of the coils was reached by means of the CSS (<6.1 K)
- Pressure values of 2.1 bar or more are needed
- It took about 5 days to reach steady-state conditions from ambient with no cryogenics used
- Additionally, a new helium compressor was installed for higher mass flow for speed up the cool down time. It was reduced about 20%
- Also the warm up time was reduced in about 25%
- The cryogenic development is considered completed



Thesis: *Development of a Novel Concept of Efficient Superconducting Magnet for Radioisotope Production Cyclotron*, J. Munilla, 2020

# FFAG optics design - HUD

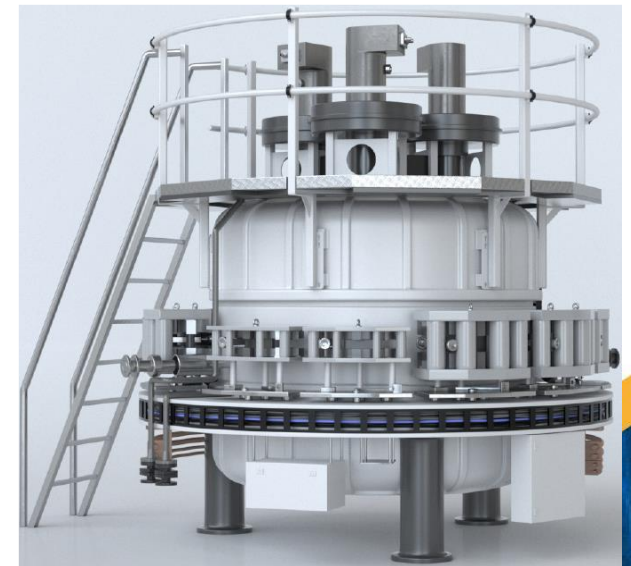
- 75 keV to 28 MeV
- Protons and alphas
- High current: 4mA protons, 800μA alphas
- $^{99m}\text{Tc}$  production with internal target looks feasible



PhD: David Bruton - UoH

# Rhodotron for $^{99m}\text{Tc}$ production - IBA

- Photo-production of  $^{99}\text{Mo}$  via  $^{100}\text{Mo}(\gamma, n)^{99}\text{Mo}$
- Direct replacement of reactor produced  $^{99}\text{Mo}$
- Uses new version of Rhodatron: TT300-HE
- 125kW of electrons at 40 MeV
- North Star Medical (US) buying 8, first 2 operational 2021



# Future in I.FAST WP12

---

## *Strategy for Implementing new Societal Applications*

3rd May Wednesday 15:00 - 15:15 (CERN)

Andrea Sagatova - Slovak Technical Univ.

**Sub-task 12.5:** Accelerator production of radioisotopes for imaging and therapy

Diego Obradors, Conchi Oliver – CIEMAT

# Conclusions

---

- WP3 has done all
  - Milestones
  - Deliverables
  - Objectives
- A lot has been achieved
- It has had significant impacts in health, industry and the environment
- Collaborations have been created with new partners
- Funding proposals have been submitted to other sources



# ATChem

---

- H2020 Green Deal Area 8.1 – persistent and mobile chemicals
- ATChem: 19 partners, 9 MEUR
- Removal and destruction of PFAs and MPs as carriers from waste water
- PFAs: - perfluoroalkyl and polyfluoroalkyls, >300 chemicals  
one of the strongest bonds in nature  
many are toxic and they bioaccumulate  
most Europeans exceed TWI level
- Structure:
  - WP2: Novel detection techniques
  - WP3: Toxicity measurements (using worms)
  - WP4: Removal techniques (foam fractionation, membranes, gels)
  - WP5: Destruction techniques (e-beam, ultra-sound, plasma)
  - WP6: Pilot plant tests
  - WP7: Dissemination, outreach, policy-making
- Result: June/July

# RADAGASS

---

- JPIAMR-ACTION Joint Transnational Call for Proposals 2021
- RADAGASS: 4 partners, 3 countries, 610 kEUR
- Sewage sludge and animal waste: important sources of AMR growth
- Use of electron beams for destruction of AMR and antibiotics
- Structure:
  - WP2: Destruction of AMR bacteria, genes, antibiotics in sludge
  - WP3: Destruction of antibiotics in animal slurry in Brazil
  - WP4: Impact and implementation
- Result: Outline proposal stage: May