



Industrial and Societal Applications – WP3

Rob Edgecock on behalf of WP3

University of Huddersfield

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)
- Status: Almost complete, finishing at the end of April

Deliverables

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 ^{99m}Tc and therapeutic isotope production	HUD	M36	Done
D3.4	Design of a compact 140 MeV electron linear accelerator	CNRS	M40	Done

Milestones

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

Task 3.2 and 3.3: Main Achievements

- Many activities studying the use and development of electron beams
- 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
- Electron beams: 300 keV to 10 MeV
- High beam power for high dose rate
- Basic process:
$$\text{H}_2\text{O} \rightarrow [2.7] \text{OH}\bullet + [2.6] \text{e}^-_{\text{aq}} + [0.6] \text{H}\bullet + [2.6] \text{H}_3\text{O}^+ + [0.45] \text{H}_2 + [0.7] \text{H}_2\text{O}_2$$
 - G-value: molecules/100 eV
 - radicals react with biological, organic and inorganic matter

EB-technology against biohazards

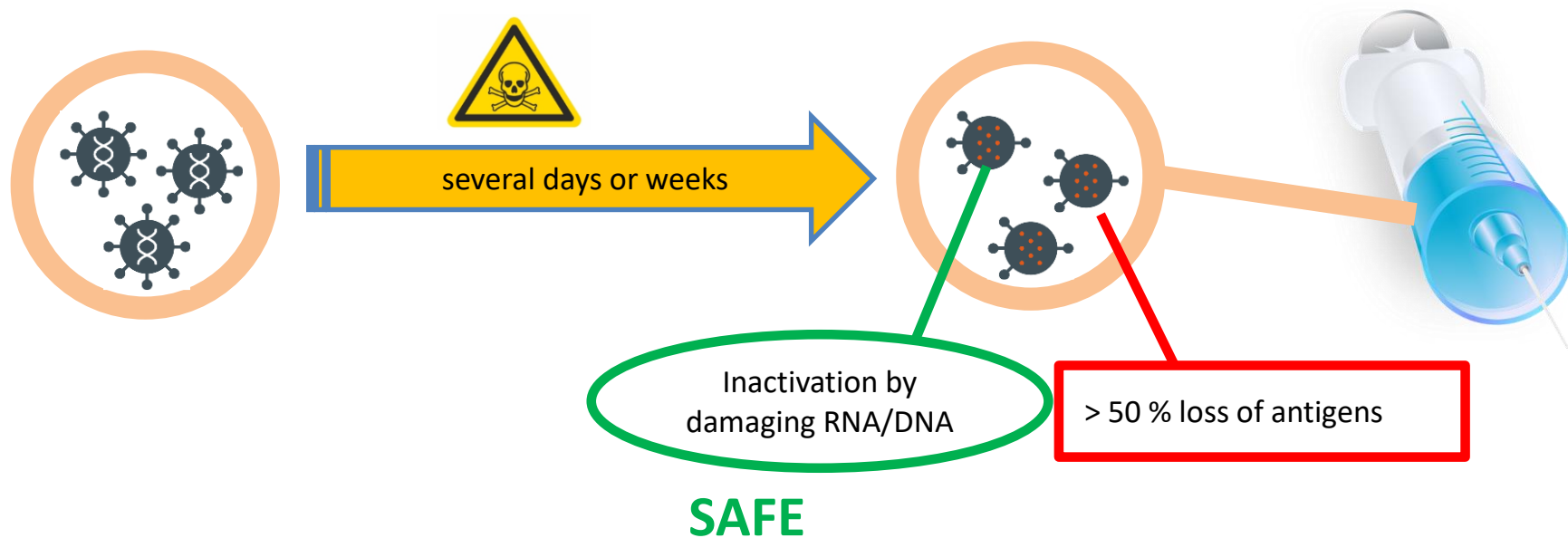
- Inactivation of viruses for vaccine production
 - First prototype machine, developed by Fraunhofer-consortium (FEP, IZI, IPA) works well and produces inactivated suspensions in the range of some liters per hour
 - Evaluated results for a lot of real types of vaccines
 - **First positive results on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



Inactivation of virus suspensions with low energy electron irradiation for vaccine production



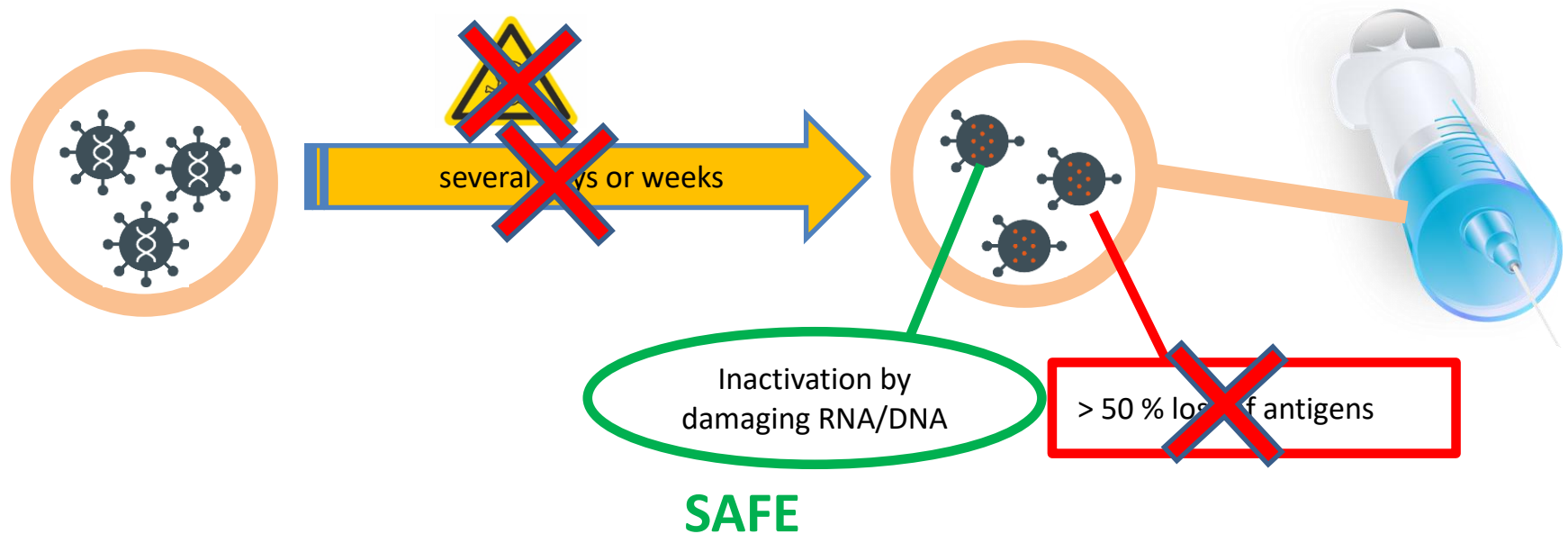
Current method: chemical inactivation



Inactivation of virus suspensions with low energy electron irradiation for vaccine production



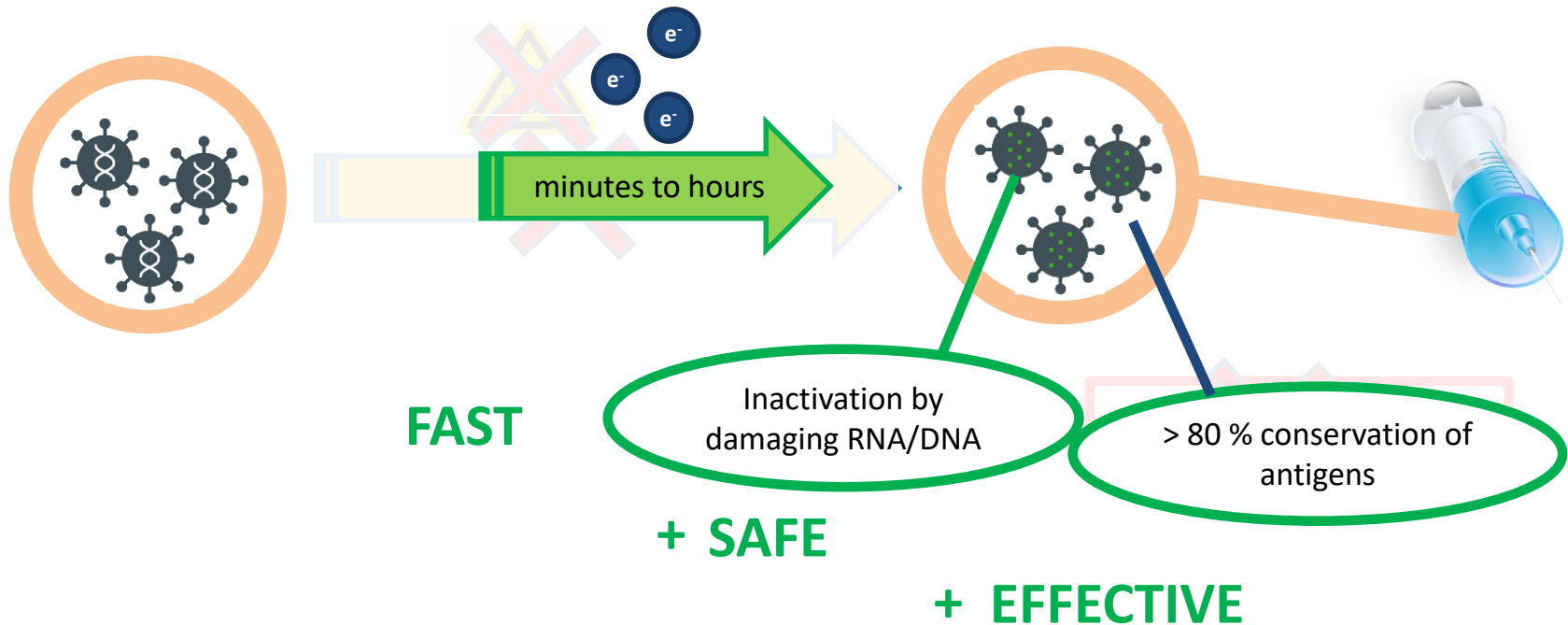
Aim: Elimination of drawbacks



Inactivation of virus suspensions with low energy electron irradiation for vaccine production



Novel method: low energy electron irradiation



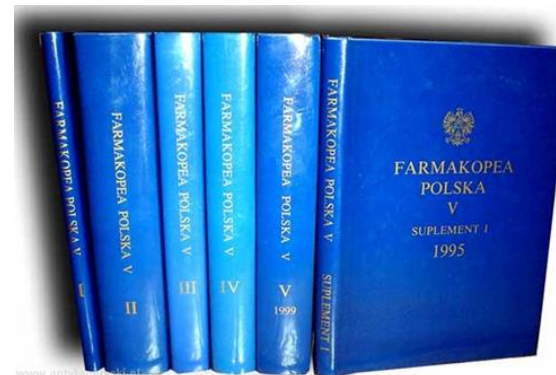
Preservation of Cultural Heritage



Project completed

It has been used for ~200m³ 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 Fryderyk Chopin University of Music Library)



www.ariestech.com

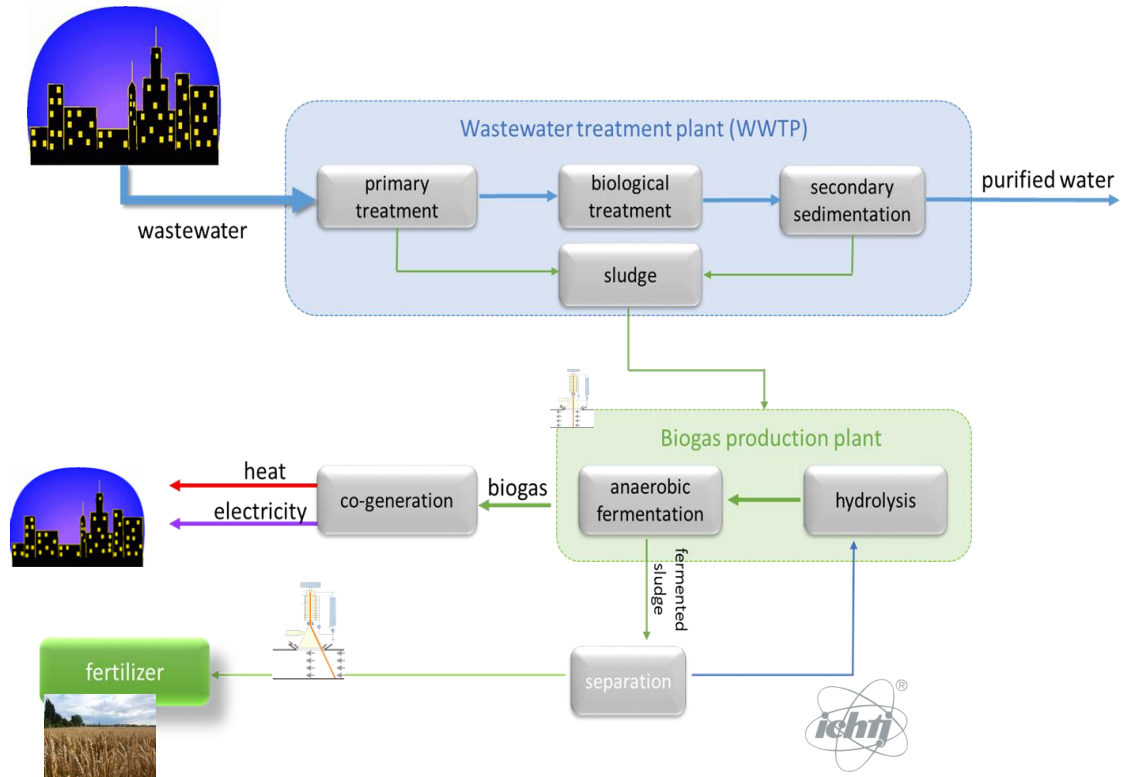


HYBRYD BIOGAS - EB SYSTEM



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

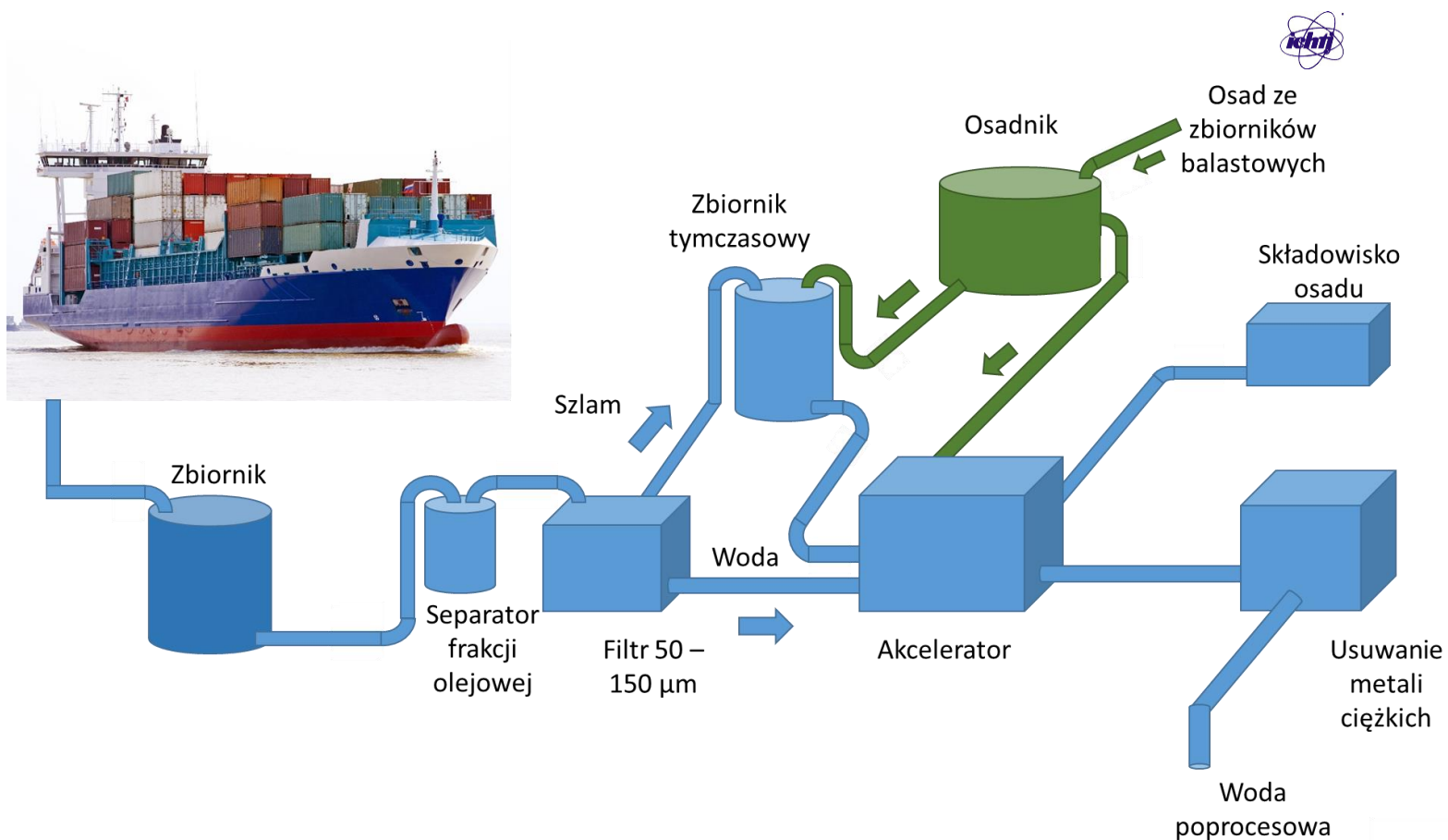


Ballast water discharge (IMO)



- 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.
- a) *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;
- b) *Escherichia coli* less than 250 CFU in 100 ml;
- c) *Enterococci* less than 100 CFU in 100 ml.

Green “dock”

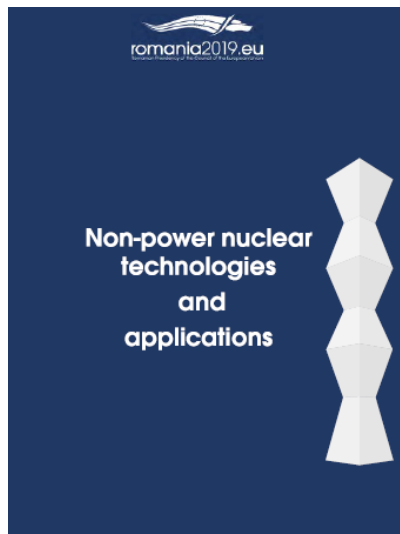
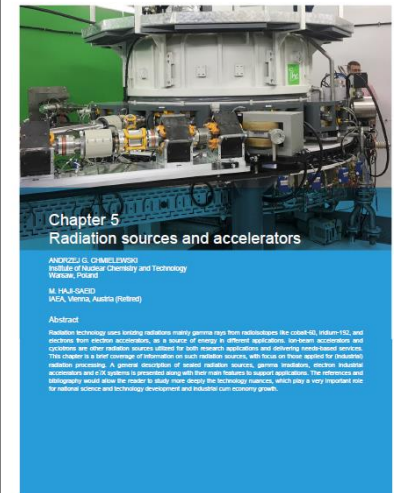
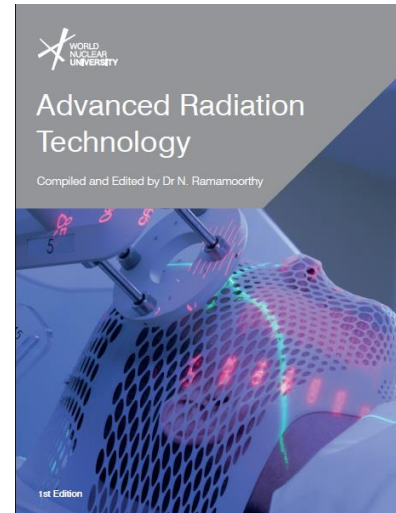
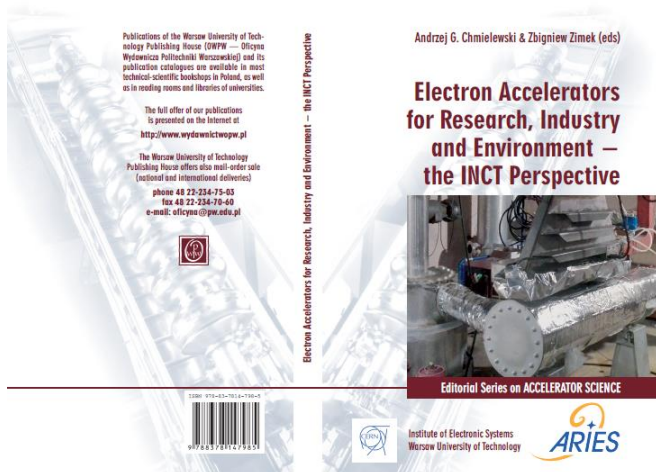


Some Outputs

- 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 theses:
 - 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



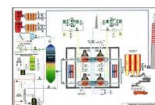
POLAND (1)



Electron beam free 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_x), nitrogen oxides (NO_x), VOCs, PAH, 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_x, NO_x and VOC removal was achieved. Additionally the hypothesis is a good fertilizer. A pilot test on industrial plant has been connected at coal fired power plant in northwest Poland. The next step in technology development was construction of pilot installation of heavy oil fired power plant in Amursk - Jastek Refinery.



Project: Industry based action, EU Horizon Project
The benefits: The technology enables a significant reduction of both pollutants (SO_x and NO_x) and good quality fertilizer is also produced. The electron beam demonstrated the possibility of destroying Polycyclic Aromatic Hydrocarbons (PAH) 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: ECED, Geneva, Switzerland; Bioplasma, Lublin, Poland; Kazimierz.



POLAND (3)



"Zero energy" ship hybridization electron beam technology

Description:

The benefits: The change of the method according to the previous version is the fact that the energy is generated from renewable waste material which is available. The method according to the previous one, but requires energy from external source and, thanks to the fact that produced electricity is utilized as a fertilizer, does not generate waste. The method allows pathways to be eliminated. The plant due to its own electricity source may be installed in a remote site, providing electricity for agriculture, wastewater treatment plant and villages. The last two components may be used for fertilizer storage.

Possible barriers, challenges: Accidents, and security to construct installations facility.

Collaborators:
INCT, Warsaw, Poland; Bioplasma, Lublin, Poland

Layer of 40 hybridization line

POLAND (2)



Hybrid electron accelerator system for the treatment of marine diesel exhaust gas

Description:

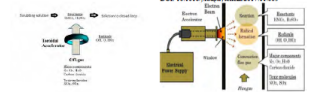
Annual 15% of global NO_x and 54% of SO_x emissions are attributable to ocean-going ships. According to International Maritime Organization regulations (MARPOL Annex VI), there are two sets of measures and that quality requirements: global sulphur reduction in global emissions of SO_x, NO_x and particulate matter and more restrictive requirements declared to ships in designated emission areas – Emission Control Areas (ECA). A new hybrid technology is based on the concept of combining the method used to clean up the exhaust gases: Electron Beam (EB) and Wet Scrubbing (WS). Project: Proof of Concept Project – Accelerator system for the treatment of marine exhaust gas" in the frame of ECED, ARIES and Polish Project – Trips.

The benefits: The hybrid electron method enables a significant reduction of both pollutants with limited impact on consumption and very minor organic pollutant destruction, which may be required by new standards in the future. The electron beam demonstrated the possibility of destroying Polycyclic Aromatic Hydrocarbons (PAH) like benzo(a)pyrene.

Possible barriers, challenges: The hybrid electron 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 4 in the Technology Readiness Level. This means that the technology has been optimized at the laboratory level and is in the final development phase.

Collaborators:
Other countries or international/European organizations involved: RTU, Riga, Latvia; INCT Warsaw, Poland; Fraunhofer, EFP, Dresden, Germany; ECED, Geneva, Switzerland; Bioplasma, Lublin, Poland; ECA, Riga, Latvia; Bioplasma, Lublin, Poland.

Other:
1. Ułamek M., Chmielewski A.G. (2018), Process engineering aspects of diesel engine off gases treatment INCT Report B-218, Warsaw, http://www.inct.waw.pl/ict/pubs/papers/2018_0218.pdf
2. Chmielewski A.G., Zwiolicka E., Licki J., Wargala J., Zimek Z., Biala A. (2018), A hybrid plasma-chemical system for high-SO_x diesel gas treatment, Fuel, 218, 1044-1054, DOI: 10.1016/j.fuel.2017.11.005



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



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

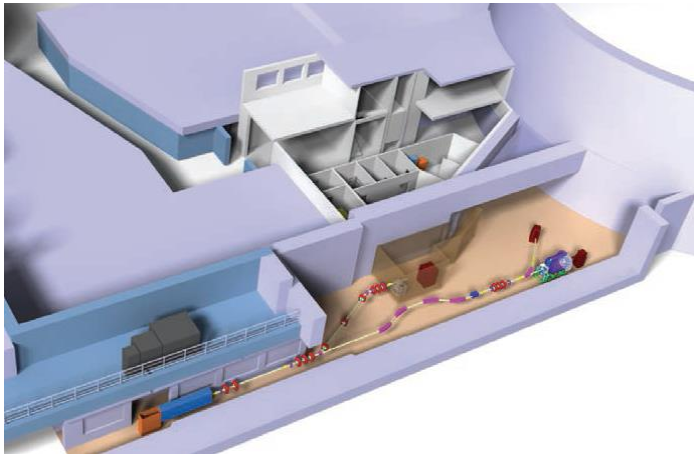
RADAGASS

- 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

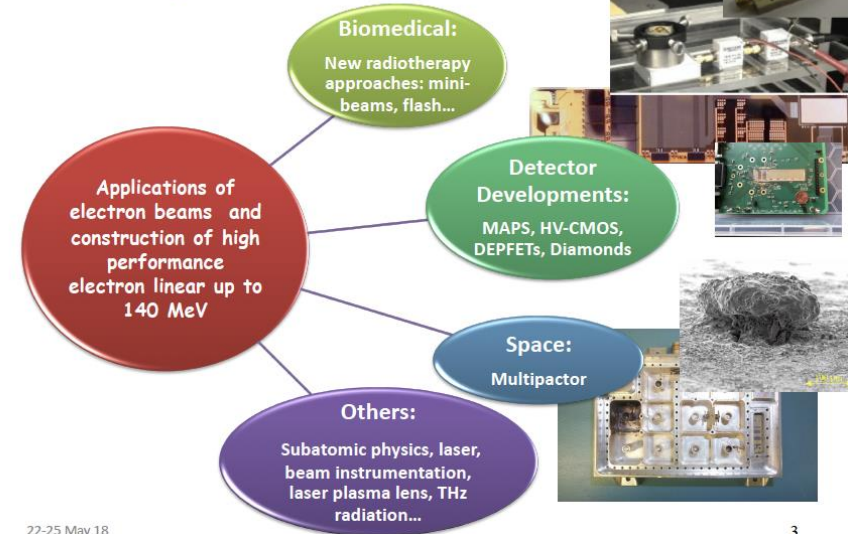
Task 3.4. Medium energy electron beams

Objectives:

- Study of the applications of electron 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



Task objectives



22-25 May 18

3

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

New e- linac therapies and accelerator designs

CHALLENGES IN RADIOTHERAPY

New RT approaches

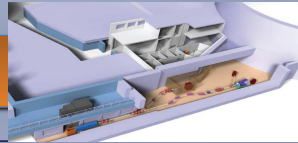
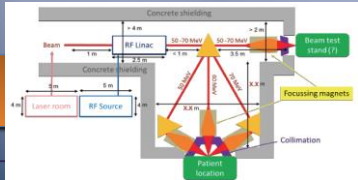
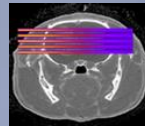
RT treatment of some radioresistant tumours, paediatric cancers and tumours close to delicate structure (i.e. spinal cord) is currently limited. One of the main challenges is to find approaches to increase the normal tissue resistance.

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 2 Gy/min, field sizes 10 cm², homogeneous dose distributions.

Possible strategies to spare normal tissue:

Different particle types: Very High Energy Electrons (VHEE)

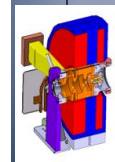
Different dose delivery methods: Grid Mini-beam or FLASH-RT



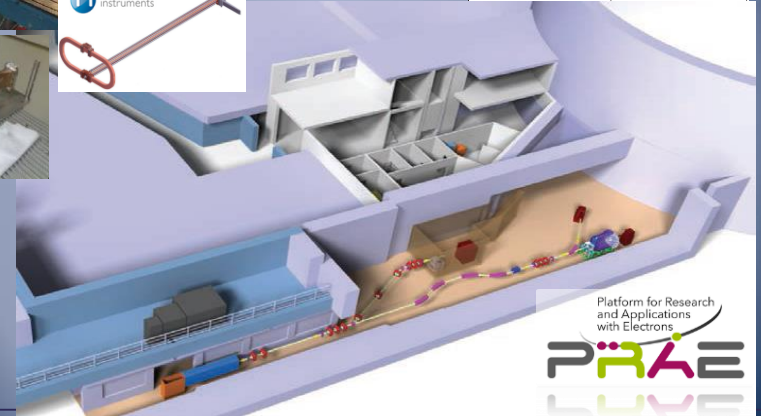
ACCELERATORS FOR VHEE

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



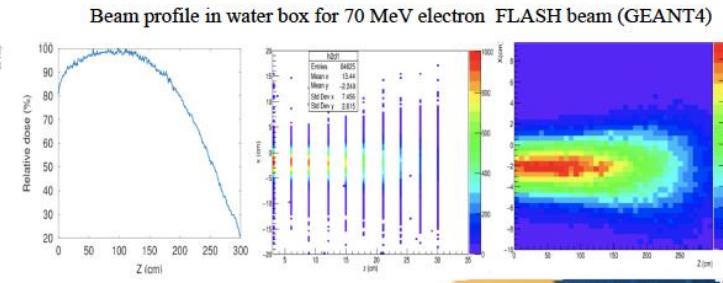
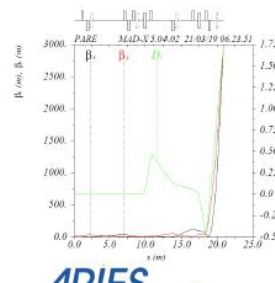
Platform for Research and Applications with Electrons
PRAE

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



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**



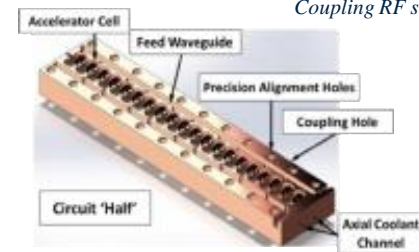
Built and tested structures to 230 MeV.

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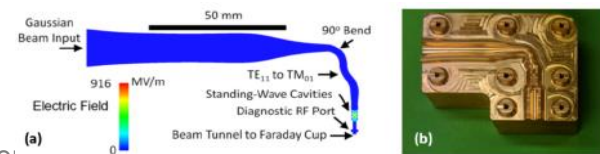
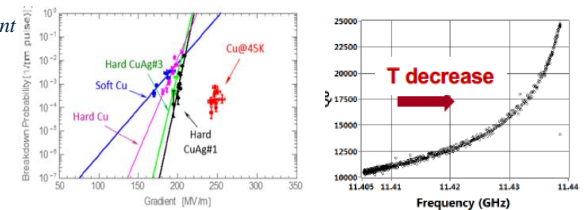
Accelerators for VHEE RT

- **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 π -mode Distributed Coupling RF structures



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

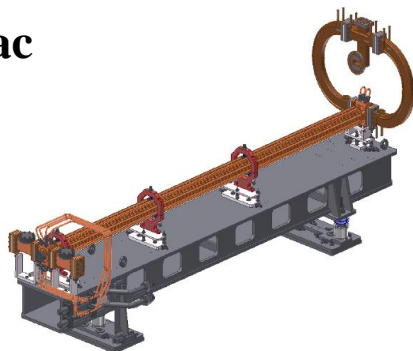


Possible designs for a compact e- linacs for VHEE applications

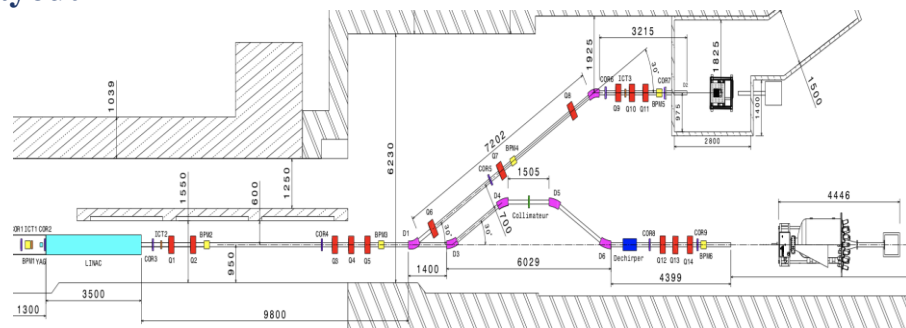
S-BAND LINACS

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]
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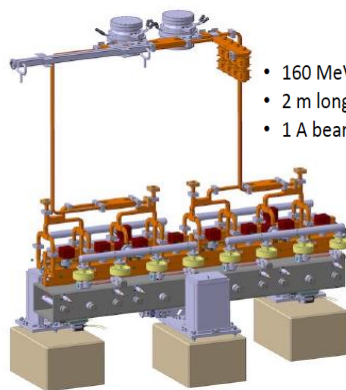


PRAE Accelerator Layout



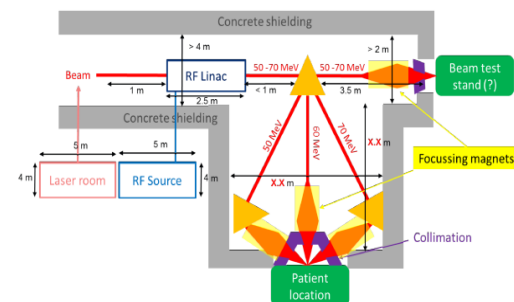
X-BAND LINACS

X-band HG CLIC unit

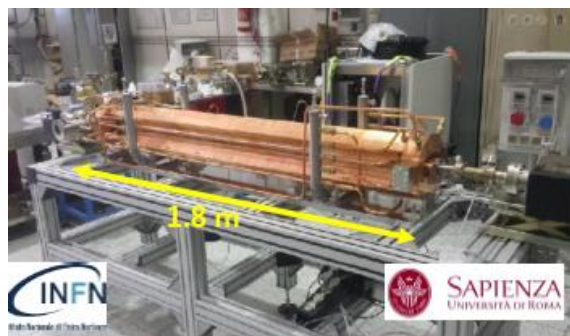
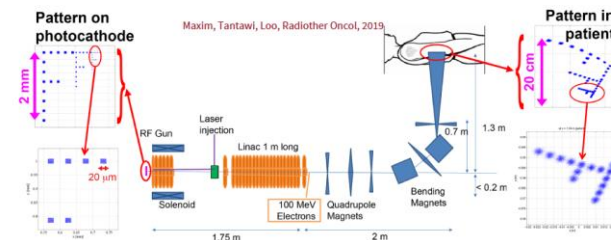


- 160 MeV energy gain
- 2 m long
- 1 A beam current

Preliminary design of FLASH facility for CHUV Laussane



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

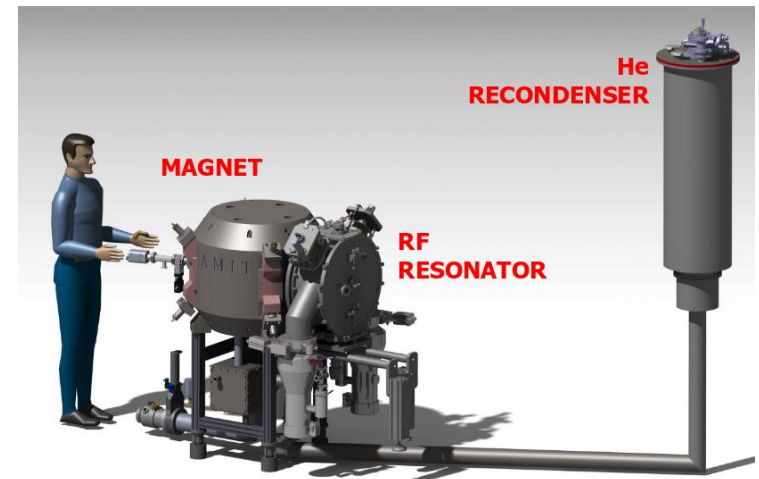


Task 3.5: AMIT cyclotron

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

Optimization of AMIT cyclotron (within ARIES project):

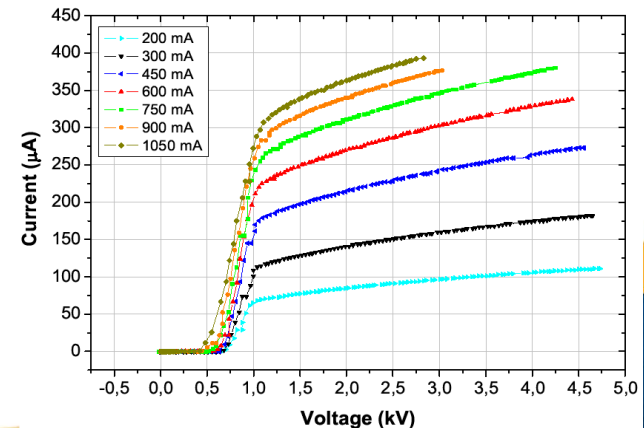
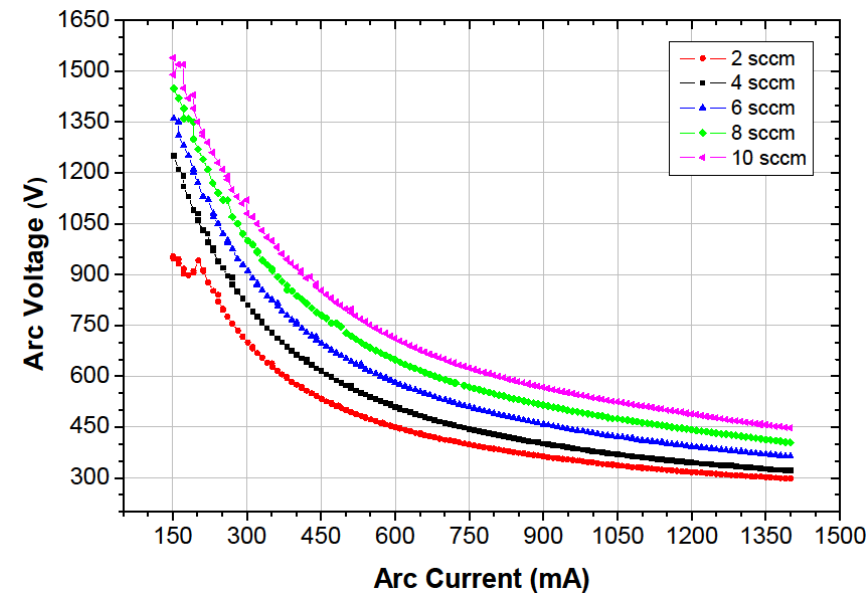
- Ion Source Validation and characterization
- Beam Dynamics
- Optimization of the autonomous Cooling Supply system



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

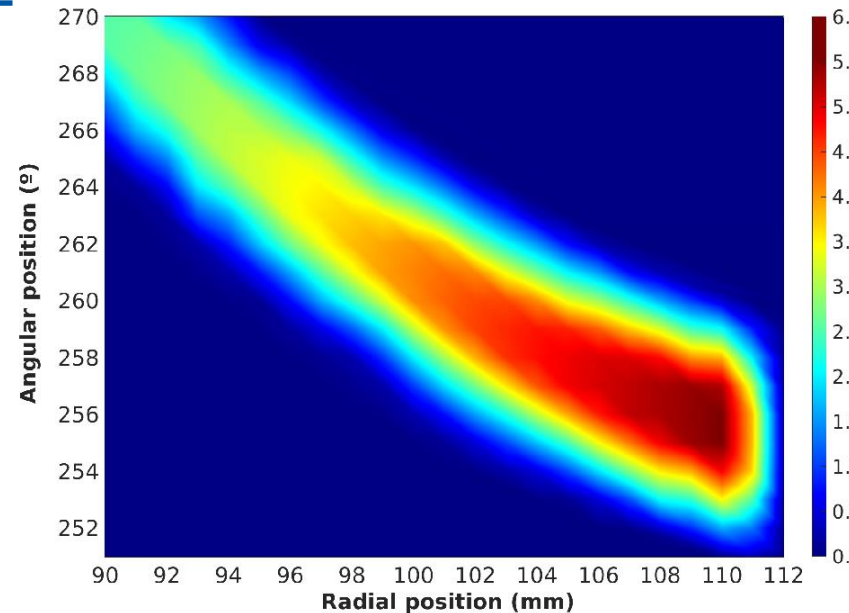


AMIT Beam dynamics

- ❑ 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.

Thesis: P. Calvo, *Optimizing the radioisotope production of the novel AMIT superconducting weak focusing cyclotron*, 2020

<https://iopscience.iop.org/article/10.1088/1748-0221/16/03/T03008>

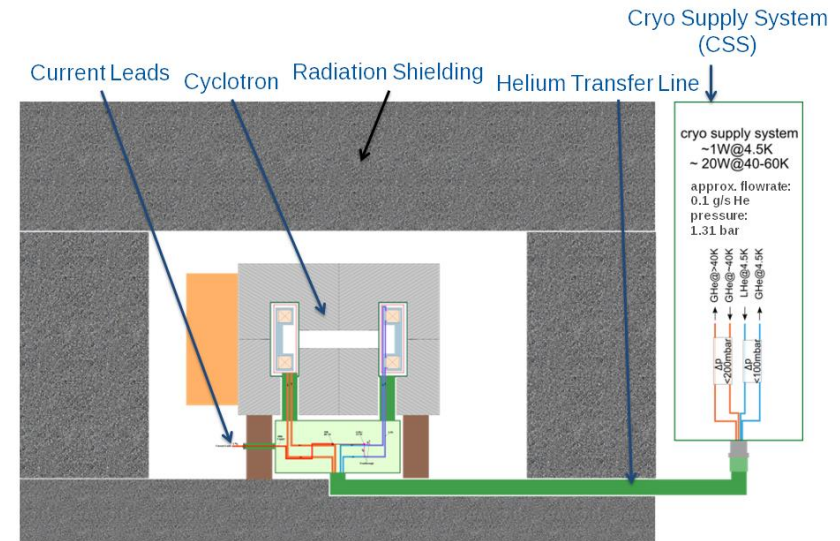


Relative ^{18}F production for stripping foil position

AMIT Superconducting 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

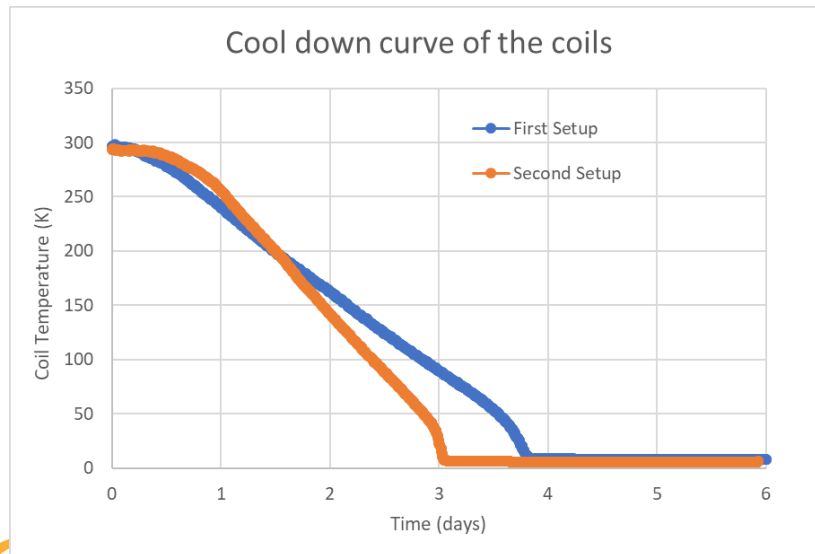
Test of adapted CSS + cyclotron

- ❑ 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



Test of adapted CSS + Cyclotron+ New TFL

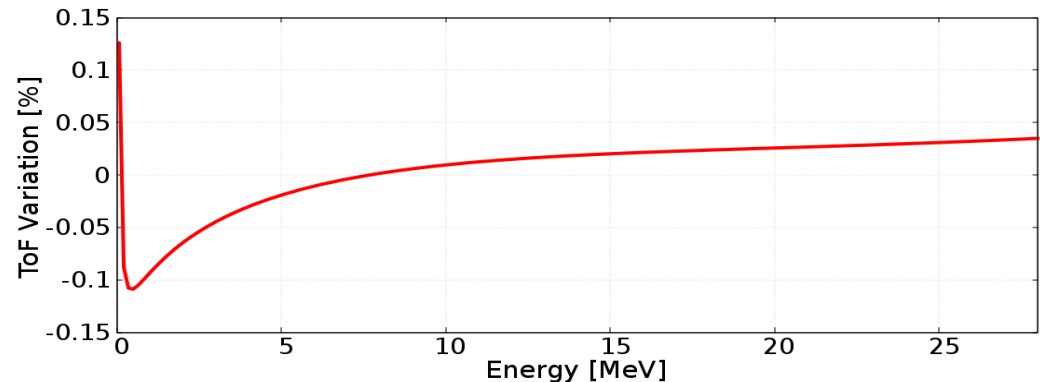
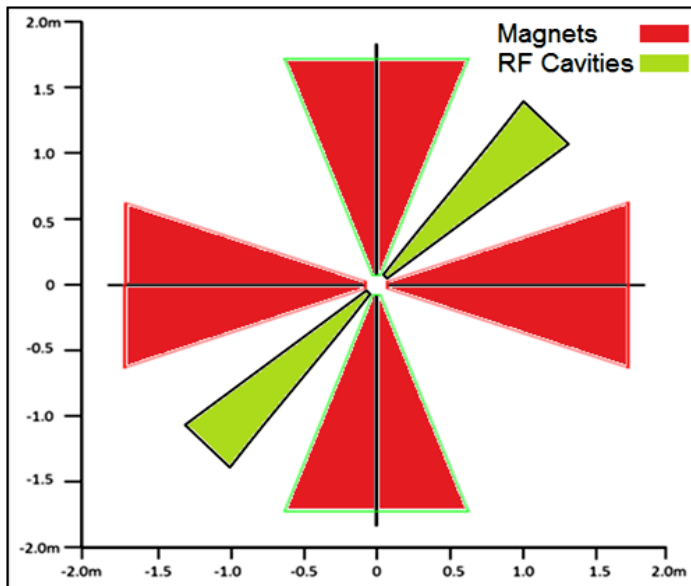
- ❑ A set of operational parameters was tested
- ❑ Superconducting state of the coils was reached by means of the CSS (<6.1 K)
- ❑ Pressure values of 2.1 bar or more are needed
- ❑ It took about 5 days to reach steady-state conditions from ambient with no cryogenics used
- ❑ Additionally, a new helium 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

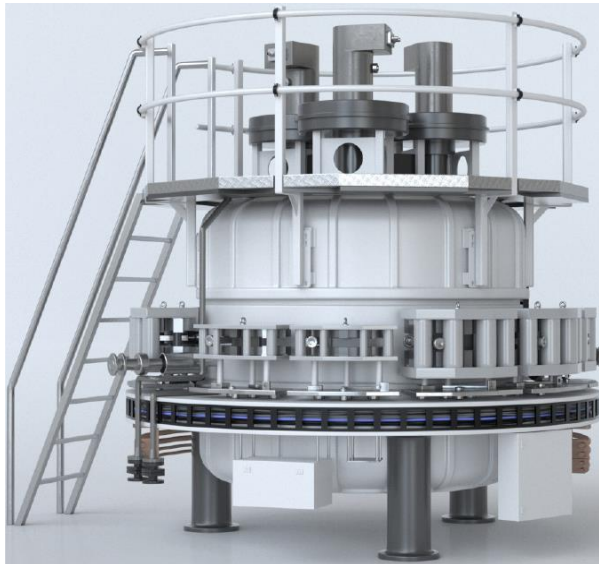
FFAG optics design - HUD

- 75 keV to 28 MeV
- Protons and alphas
- High current: 4mA protons, 800 μ A alphas
- ^{99m}Tc production with internal target looks feasible
- David Bruton thesis available from UoH repository



Rhodatron for ^{99m}Tc production - IBA

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



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