# Industrial and Societal Applications – WP3

A. Faus-Golfe on behalf of WP3

IJCLab – IN2P3 – CNRS



ARIES is co-funded by the European Commission Grant Agreement number 73087

# 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)

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# 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 $^{99m}Tc$ 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:

$$H_2O \rightarrow [2.7]\, OH\bullet + [2.6]\, e^-_{aq} + [0.6]\, H\bullet + [2.6]\, H_3O^+ + [0.45]\, H_2 + [0.7]\, H_2O_2$$

- G-value: molecules/100 eV
- radicals react with biological, organic and inorganic matter

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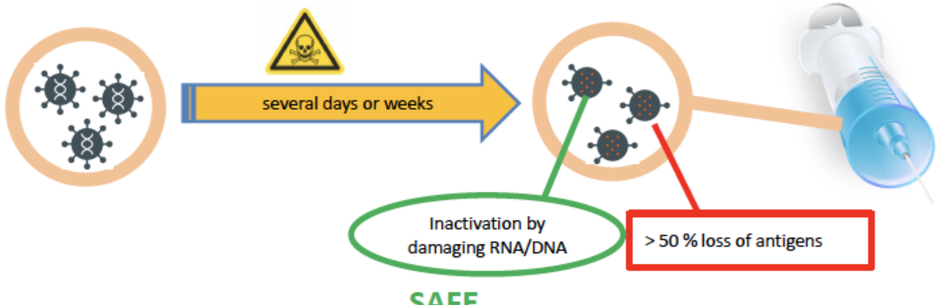
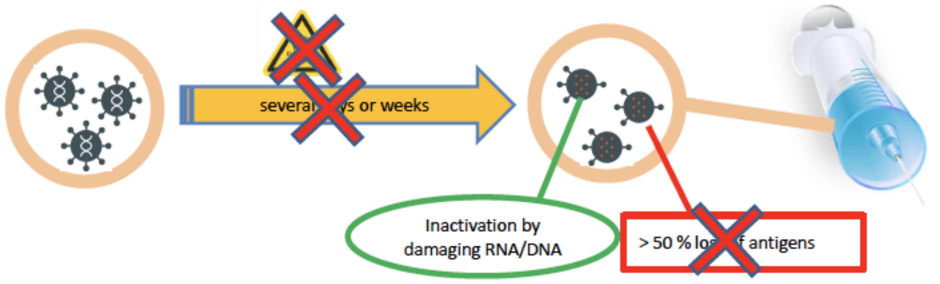
# EB-technology against biohazards

- **Inactivation of viruses for vaccine production**

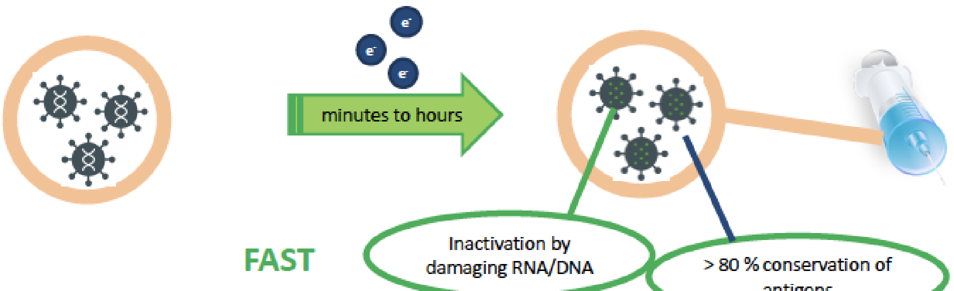
**Current method: Chemical inactivation**




**Aim: Elimination of drawbacks**




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

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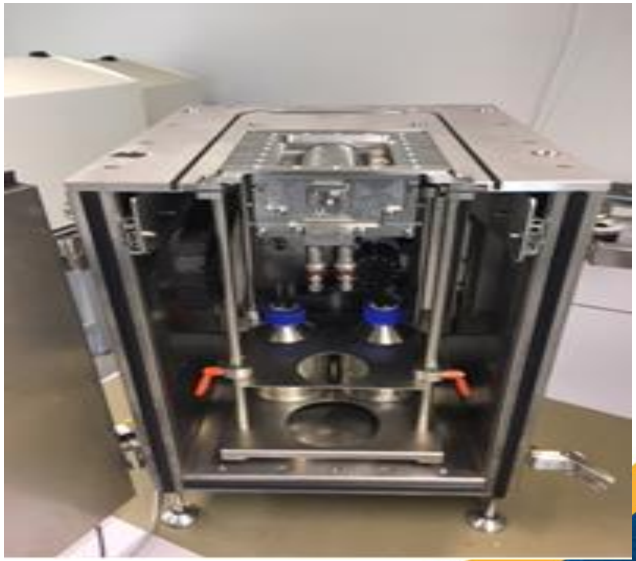
# EB-technology against biohazards

- **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!**



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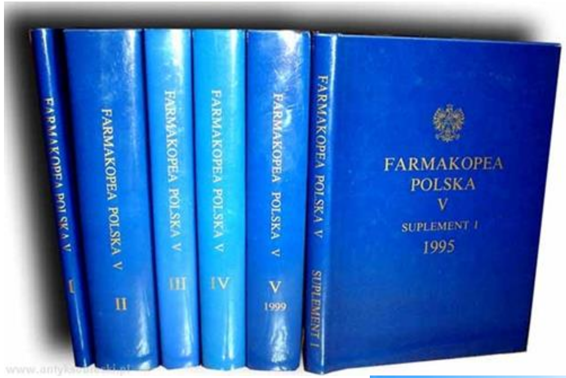
# EB for Preservation of Cultural Heritage

- **EB has been used for ~200m³ of archives, documents, books, etc**

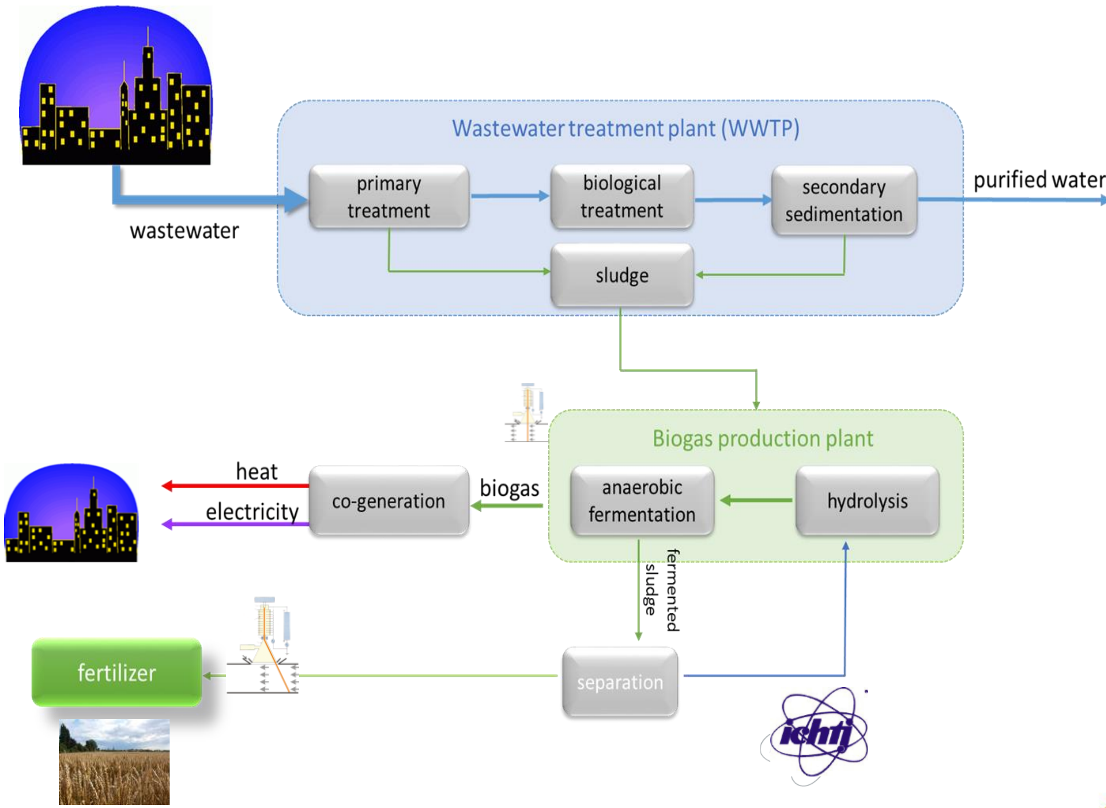



- Faculty of Modern Languages Library
- The Sejm (Polish Parliament) Library
- The Office for Registration of Medicinal Products, Medical Devices and Biocidal Products
- University of Warsaw – Library
- Valuable objects - *original music notation composed by Ignacy Paderewski* (stored in The Frederyk Chopin University of Music Library)

# EB-system for Hybrid Biogas

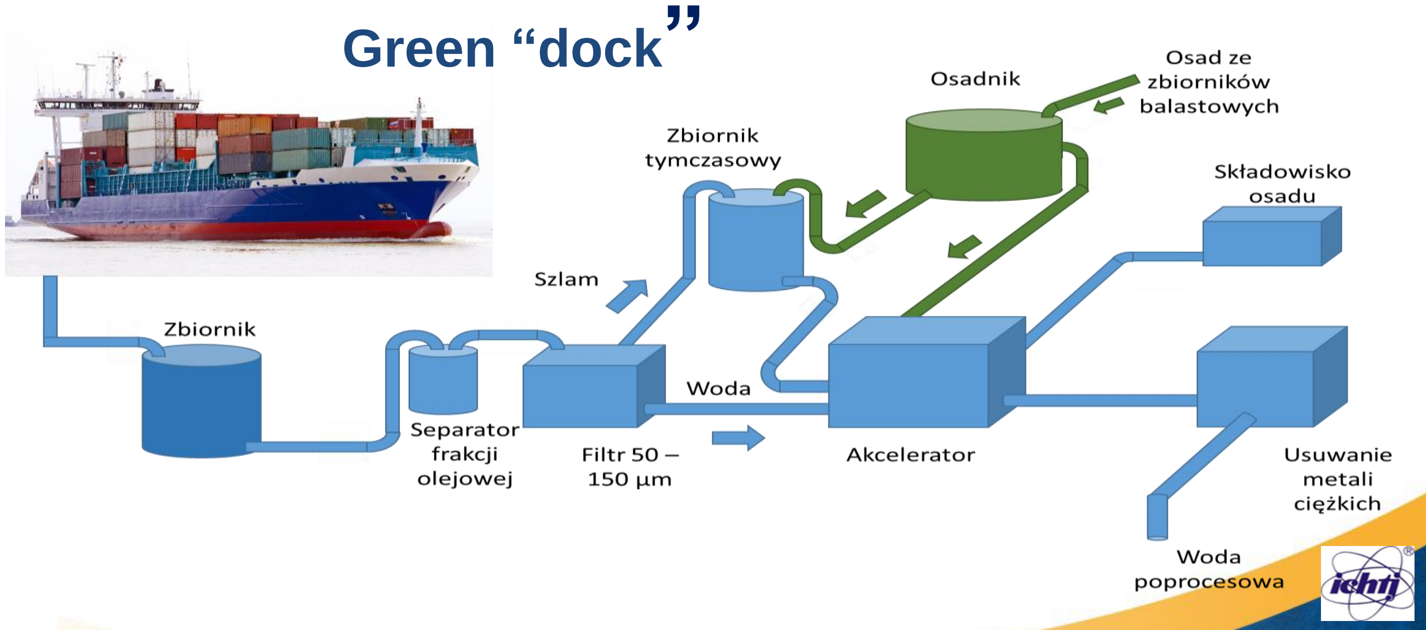
Advantage of proposed solution:

- **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:

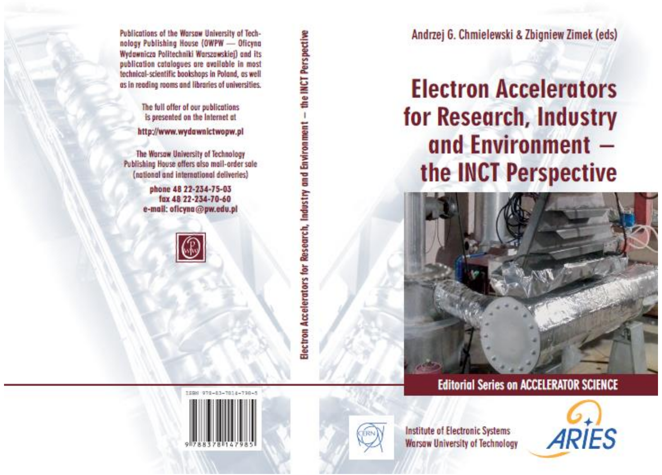
  - Urszula Gryczka ”Effect of ionizing radiation on polysaccharides” INCT, Warsaw, Defended March 23rd, 2021

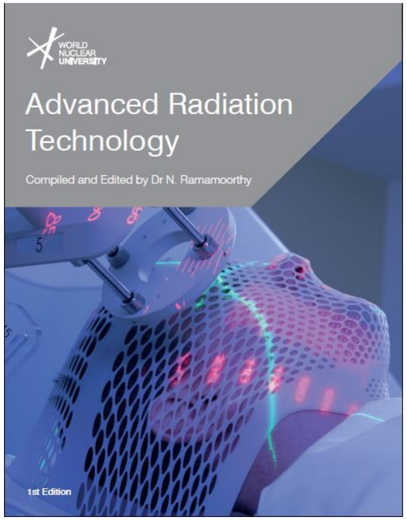
  - Dagmara Chmielewska-Śmietanko “Electron Beam for Preservation of Biodeteriorated Cultural Heritage Paper-Based Objects”, INCT

  - Malgorzata Siwek, “Study of Electron Beam Treatment for the Removal of Microplastics from Sewage Sludge”,HUD

# Some Outputs

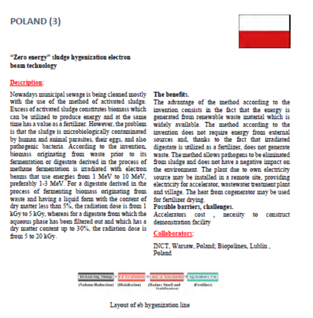
- Three books

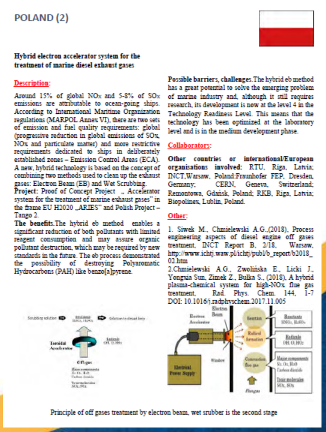








# Future in I.FAST WP12

***Strategy for Implementing new Societal Applications***
3rd May Wednesday   15:00 - 15:15 (CERN)
Andrea Sagatova - - Slovak Technical Univ.

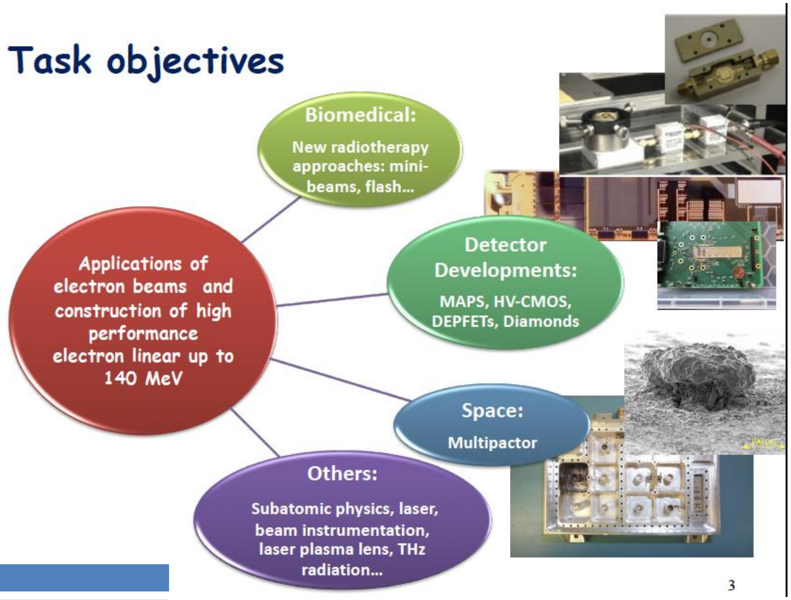
**Sub-task 12.3**: Environmental applications of electron beams
Toms Torims – RTU, Andrzej Chmielewski - INCT

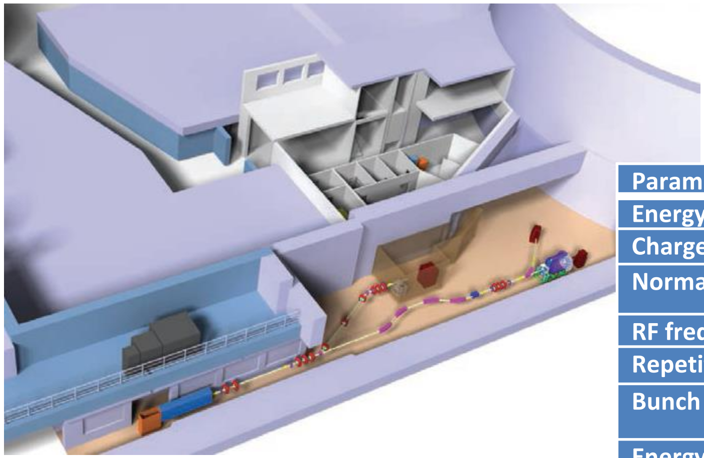
***Design of Advanced Electron Accelerator Plant for Biohazard Treatment***
4th May Wednesday 15:15 - 15:30 (CERN)
Andrzej Chmielewski - INCT

# Main Achievements T3.4

## Medium energy e-beam: new Radiotherapy applications

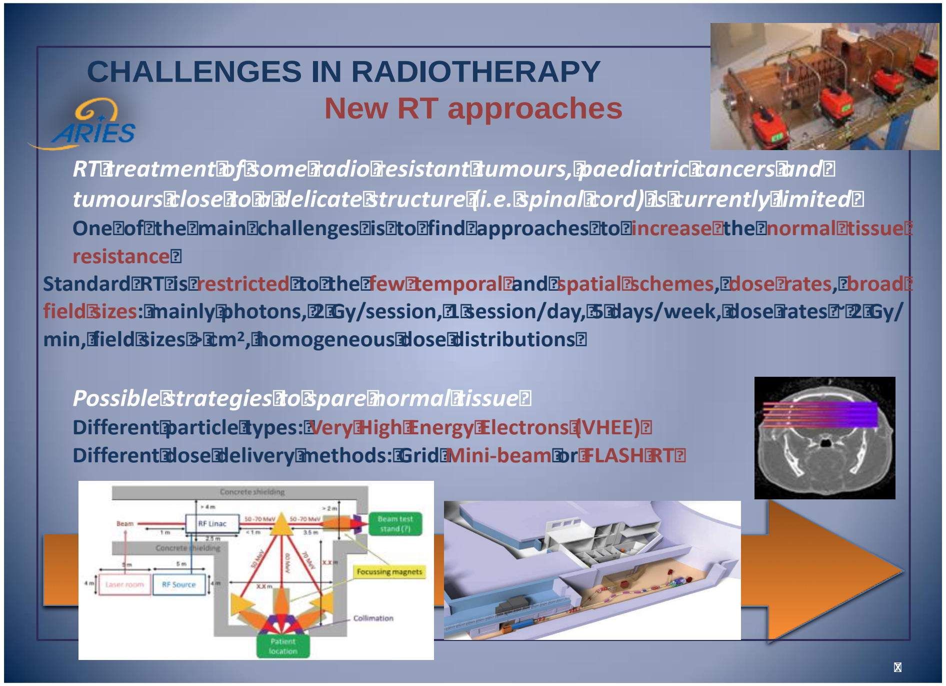
- Study of the applications of e-beams up to 140 MeV in the medical and other areas
- Study of the construction of high performance electron linear accelerator up to 140 MeV

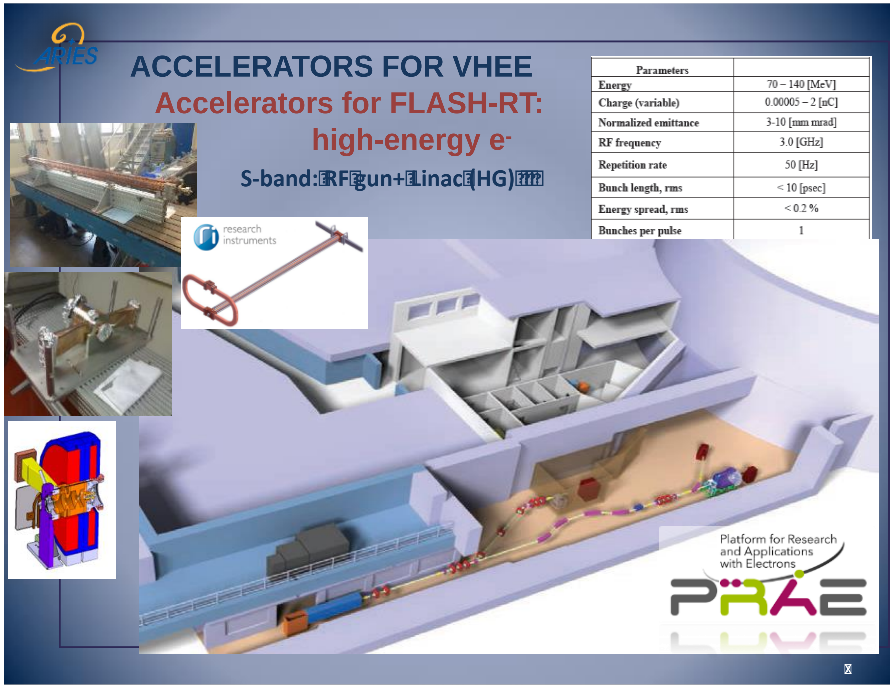


| Parameters | |
|---|---|
| Energy | 70 – 140 [MeV] |
| Charge (variable) | 0.00005 – 2 [nC] |
| Normalized emittance | 3-10 [mm mrad] |
| RF frequency | 3.0 [GHz] |
| Repetition rate | 50 [Hz] |
| Bunch length, rms | < 10 [psec] |
| Energy spread, rms | < 0.2 % |
| Bunches per pulse | 1 |

# New e- linac therapies and accelerator designs

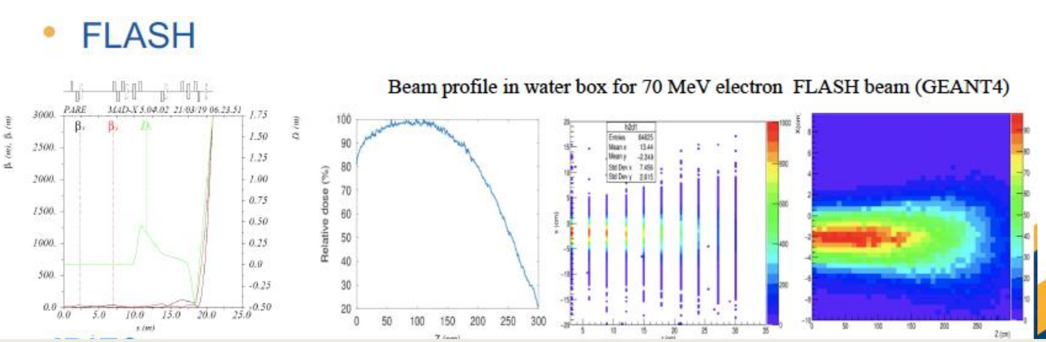



**Very High Energy Electrons (VHEE)** RT accelerator design, in particular for **Grid mini-beam** and **FLASH ultra-high dose rate** delivery modes:

- **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.




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/

## 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**

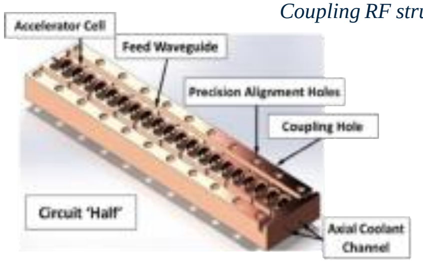
- **Super Conducting RF linacs:**

**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*



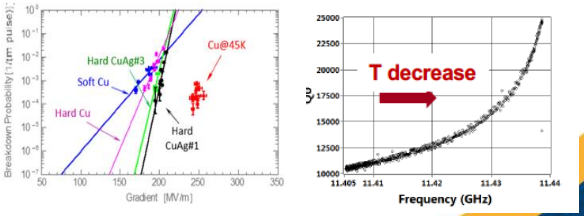

## Accelerator technologies for VHEE RT

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

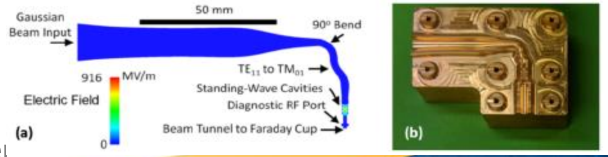
Some promising R&D are:

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

*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.*



# 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] |
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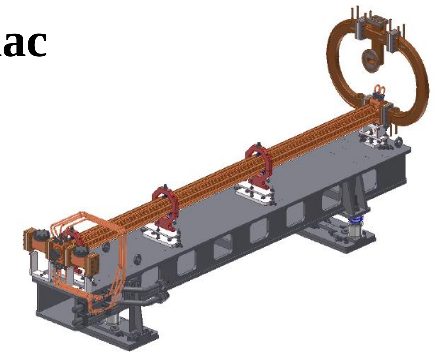
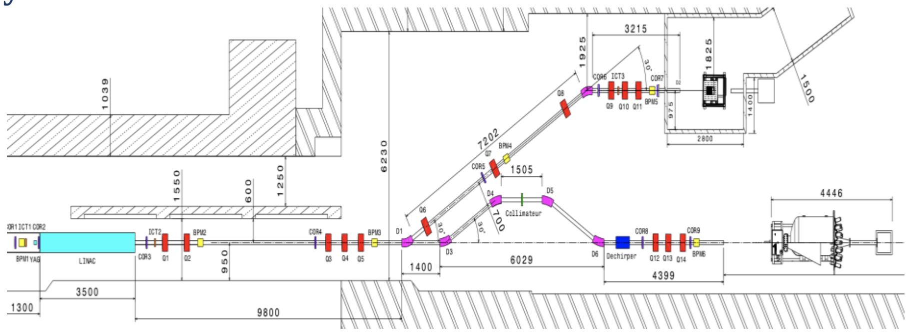
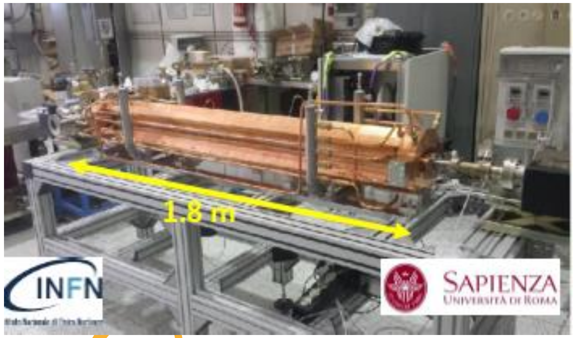


**PRAE Accelerator Layout**



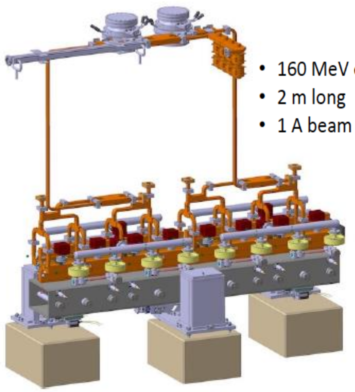

## C-BAND LINACS

### C-band linacs HG SW wave



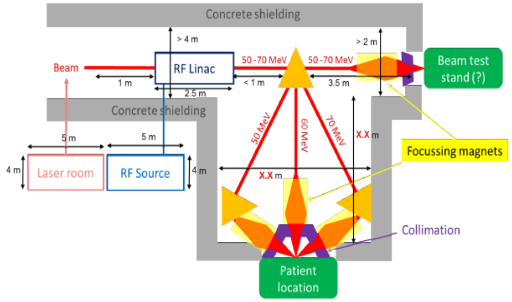

## X-BAND LINACS

### X-band HG CLIC unit

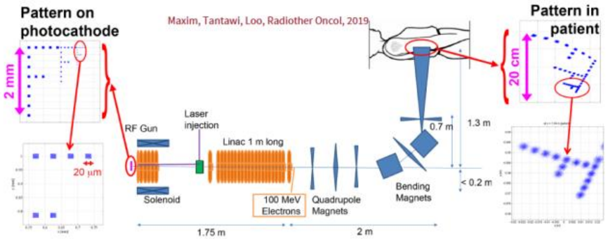


- 160 MeV energy gain
- 2 m long
- 1 A beam current

Preliminary design of FLASH facility for CHUV Laussane




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



# 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

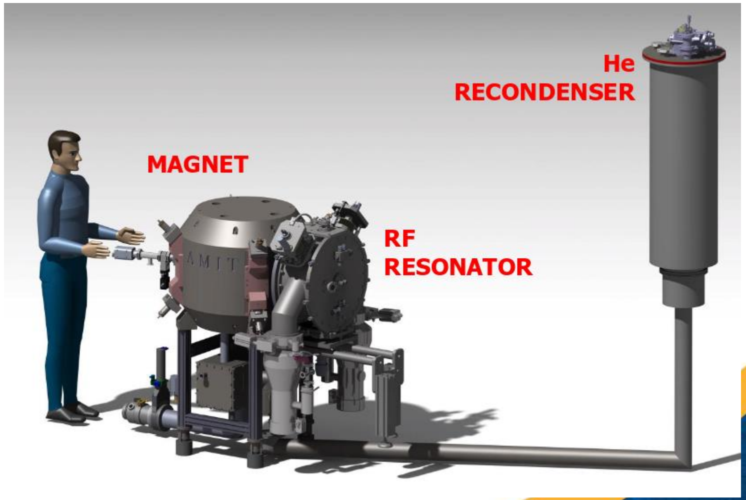
# Main Achievements T3.5

**Radioisotope production: AMIT cyclotron**

- Advance Molecular Imaging Technology (AMIT) Cyclotron
- Development of a **compact mini-cyclotron for $^{11}C$ 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

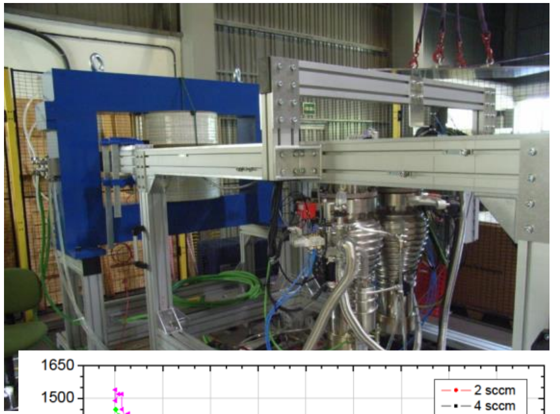
**Optimization of AMIT cyclotron:**

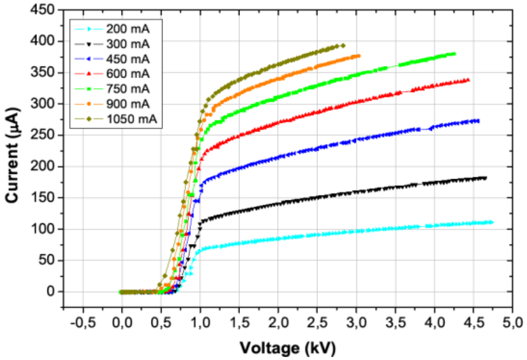
- Ion Source Validation and characterization
- Beam Dynamics
- Optimization of the autonomous Cooling Supply system

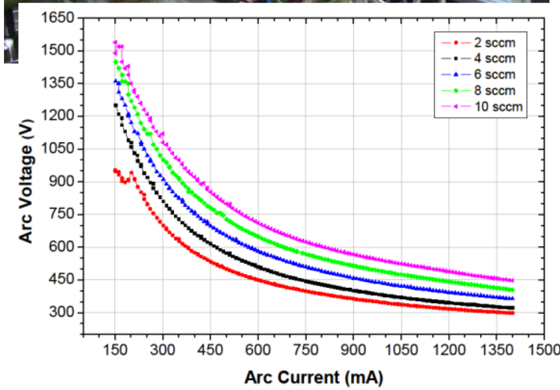


# Ion source characterization in a devoted Ion Source Test Bench

- 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 expansión gap studies

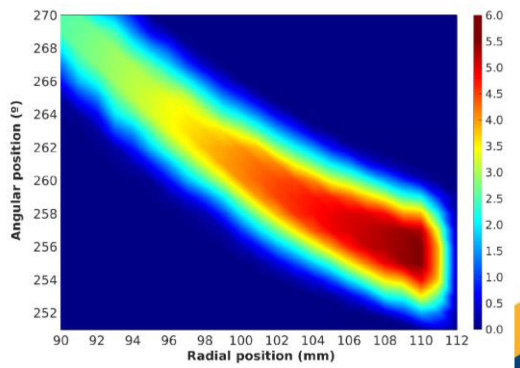





## AMIT Beam dynamics

- 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.

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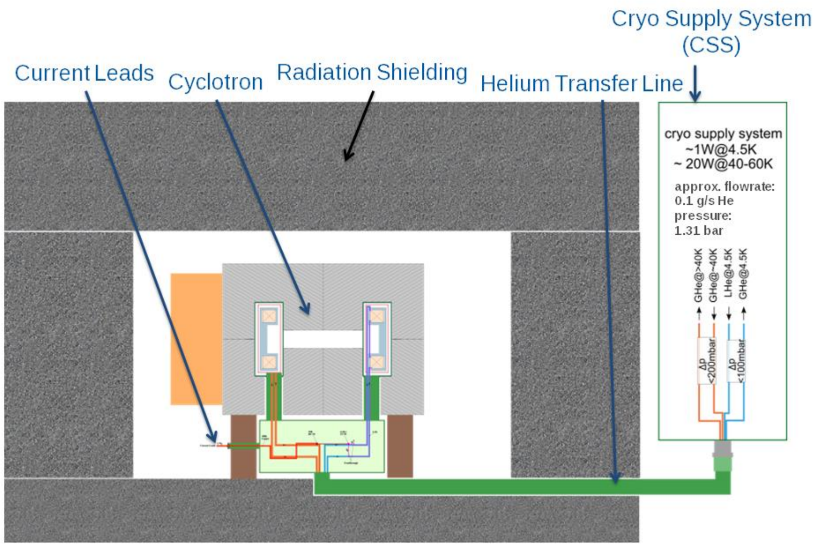
PhD: P. Calvo, *Optimizing the radioisotope production of the novel AMIT superconducting weak focusing cyclotron*, 2020 https://iopscience.iop.org/article/10.1088/1748-0221/16/03/T03008

# 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

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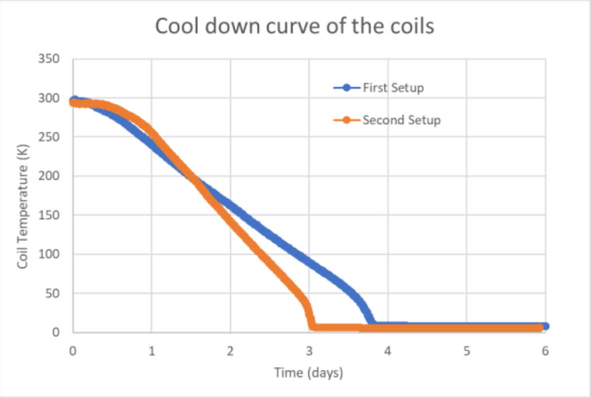
# Test of adapted CSS + cyclotron

- 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 mini mize 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 to 5 days to reach steady-state conditions from ambient with no cryogens 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

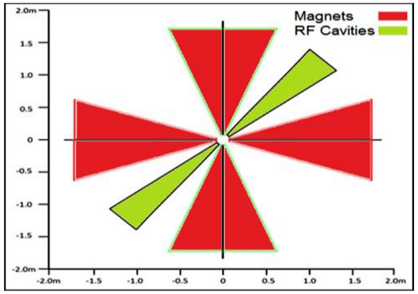


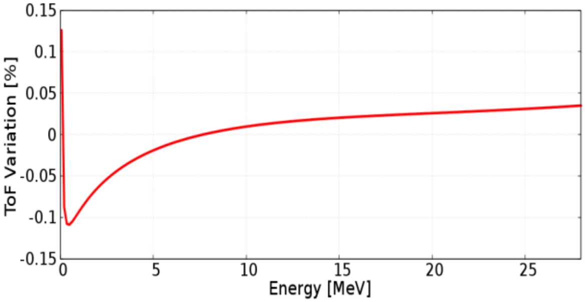

Thesis: *Development of a Novel Concept of Efficient Superconducting Magnet for Radioisotope Production Cyclotron*, J. Munilla, 2020

ARIES

# FFAG optics design - HUD

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

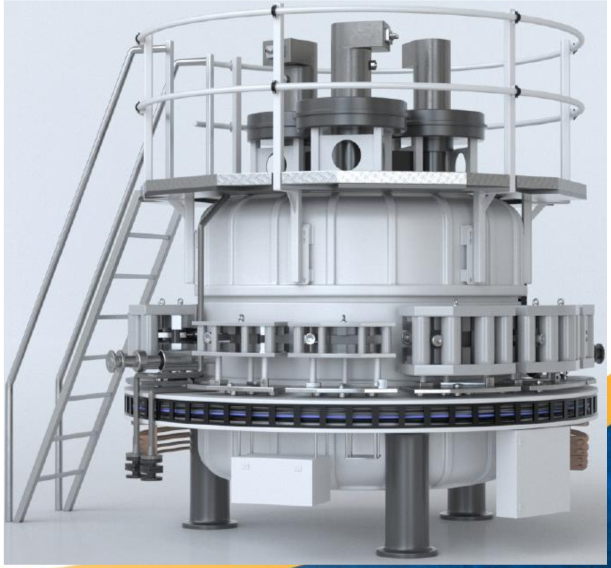



PhD: David Bruton - UoH

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

- Photo-production of $^{99}$Mo via $^{100}$Mo(γ,n)$^{99}$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



# 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

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# 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

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# 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