Open call
"CLEAN"
Compact LinEar Accelerator for sterilizatioN

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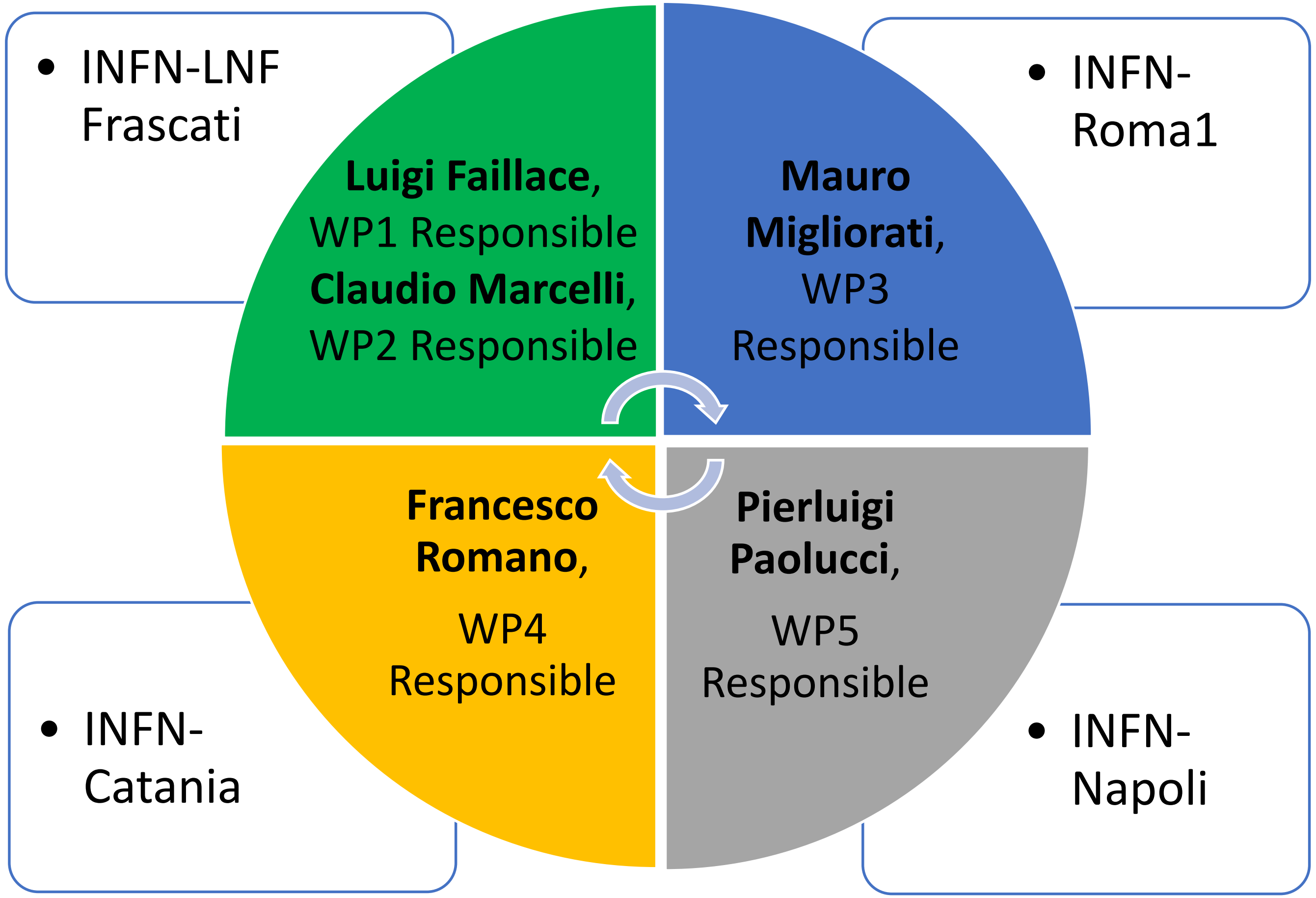
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Outline

- Working Group Description
- Scientific Proposal
- State of the art
- Objectives and Methodology of the Proposal
- Project Organization in Working Packages
- Funding Requested

Working Group Description



Research Areas

1) **Particle Accelerators;**
2) **Detectors;**
3) **Interdisciplinary Applications of INFN technology.**

External Participants

Sapienza University
University of Palermo
University of Naples Federico II
Comeb srl
INAIL

Working Packages

- *WP 1* – Linac RF Design
- *WP 2* – Linac engineering, fabrication, installation and commissioning
- *WP 3* – Beam Dynamics and Optics Design
- *WP 4* – Development of new-generation of absolute and on-line Dosimetry
- *WP 5* – Experimental Setup and Case study

Introduction

- Inactivation of pathogenic agents like bacteria and viruses (including SARS-Cov-2) on materials, substances, clothes, protective devices, foods and waters, is posing high risks to community and is of great concern nowadays.
- Any failure in the inactivation process is likely to have dramatic consequences on health and safety, particularly whereby vaccines or effective treatments are not yet available.
- Extreme "exposures" are required to make sure that sterilization processes are effective and fast.

The CLEAN project aims at triggering the evolution of the radiation sterilization technique towards

***compact, cost-effective**, and **company-scale** solutions.*

Objectives:

- design, realization and demonstration of an innovative high average power C-Band linac, able to deliver both an **electron** beam (ultrashort pulses with high peak current) and **high-energy X-rays** via electron-target conversion
- obtain radiation doses **within seconds** up to **several kGy** → *Such sterilization doses are currently achieved in tens of minutes/hours in industrial gamma irradiators*.

Specific Targets

- water contaminants
- Personal Protective Equipment (PPE)
- other substances and small-to-large material volumes whereby other sterilization systems might have shown **no effectiveness** or **slow production rate** and/or the generation of **dangerous disposal**.

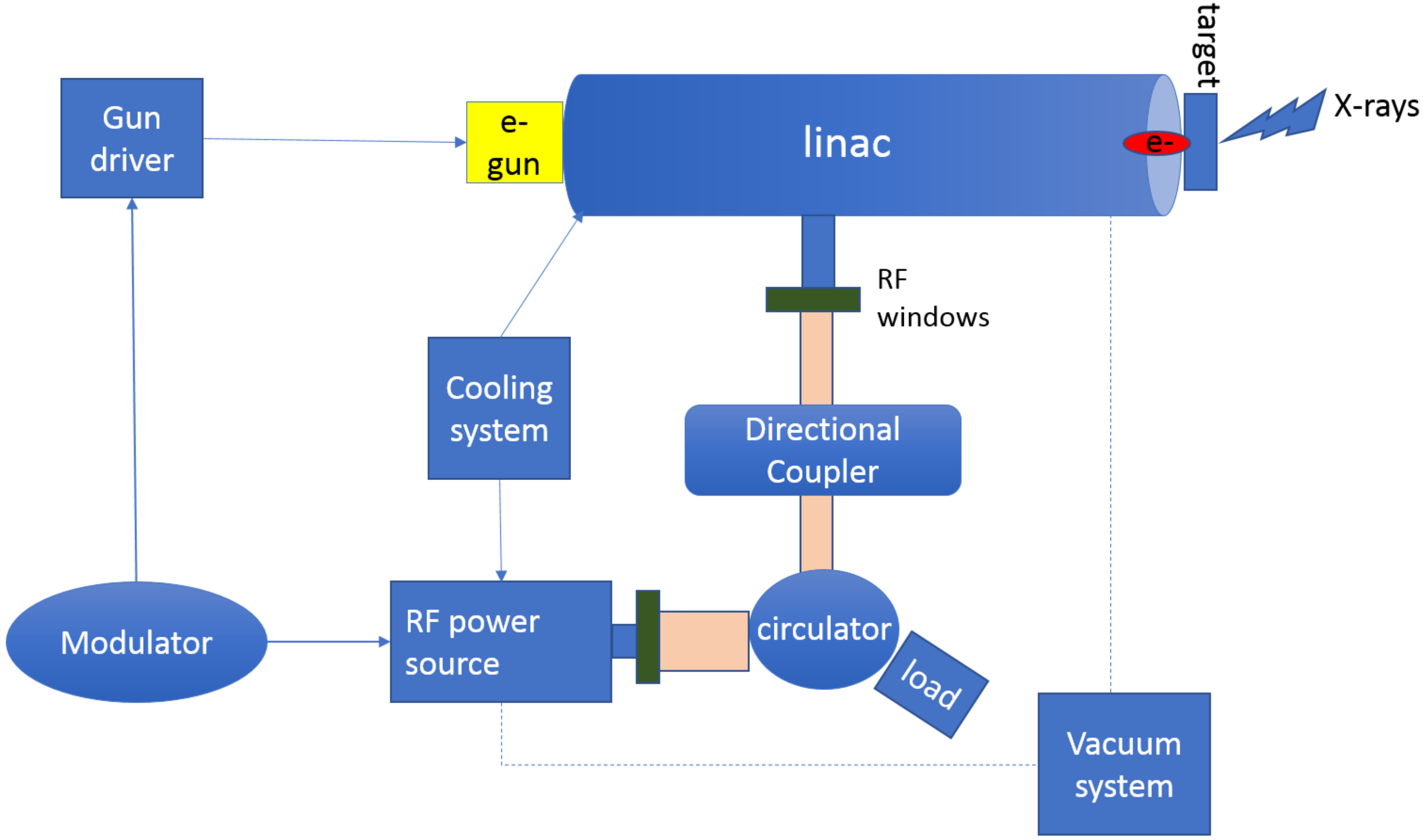
State of the art

	Application	Beam energy	Average Current
Research	High-Energy Physics	>1GeV	10's µA - 10's mA
Medical Area	Diagnostics		> 1 µA
	Radiotherapy	4-25 MeV	10 nA – 1 µA (X-rays of 200-500 cGy/min@1m, flux of 10^{7-8} photons/s/mm^2)
	Radioisotopes Production	Up to 70-90 MeV	Up to 10 mA
	FLAH therapy	Up to 7 MeV	>10's µA
	Blood Irradiation	1-2 MeV	>10's µA
Industry	Material Processing	< 10 MeV	10-150 mA
	Sterilization	< 10 MeV	Up to 10 mA
	Non-Destructive Testing (NDT)		> 1 mA
Security	Cargo Scanning	< 10 MeV	0.1 mA – 1 mA
Environmental Area	Water, flue gas treatment, etc.	0.7-5 MeV	5-10 mA

Current approach for sterilization:

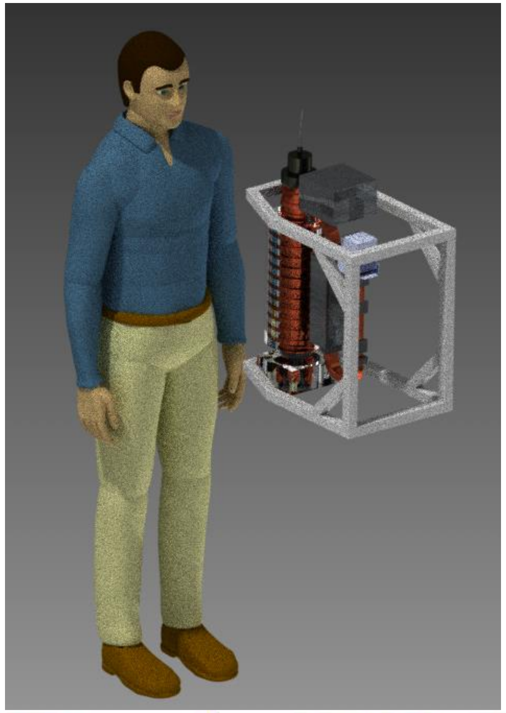
- RF accelerators such as the IBA Rhodotron are large machines, not transportable;
- gamma ray sources: 137Cs and 60Co → half-life time of these sources allows operation up to about a few years before they are replenished but the storage of these sources represents a safety threat;
- ethylene oxide (EtO) → lengthy cycle time, a high-cost, and its potential hazards to patients and staff who work on the sterilization process line;

Novelty of the proposed system



- Novel approach with the CLEAN project:
  - Portability;
  - Tunable output energy, at (very) fast rate, e.g. as low as some ms from pulse to pulse;
  - Long life cycle and modularity;
  - Linac-based machines have lower costs compared with DC machines;
  - development and adoption of new cost-effective methods for the fabrication of RF accelerating structures in order to be conceived for future in-series production in small facilities ;
  - development of a novel on-line dose measurement systems, to avoid saturation phenomena which preclude the use of current state of the art dosimeters.

Objectives and Methodology of the Proposal



Energy (MeV)	6 MeV (Variable 1-9 MeV)
RF Frequency	5.712 GHz
Peak/Average Current (mA)	200/0.2
Duty Cycle	0.1%
Pulse duration (μsec)	3 - 4
Peak Power (MW)	2.6 MW
Linac length (cm)	~ 40 cm
Average Beam Power (kW)	1.2 kW
Linac Weight (kg)	< 30 kg
Average Dose Rate	25 Gy in 4.5 us (electrons) 25 Gy in few seconds (X-rays) 25 Gy in tens of minutes γ-sources

The main research activities that will be performed in order to achieve our target are summarized in the following:

1. Development of an **optimized RF and beam dynamics design** in order to achieve the proposed C-band linac features: compactness, low-cost, variable output beam current;

2. The development of **self-shielding** is an important task. This machine is designed to be utilized by hospitals, private companies and any sterilization facilities where self-shielding is mandatory;

3. The development of a **dual-mode operation** scheme: electron beams for high-dose requirements in short amount of time for low-depth materials (up to 10 kGy integrated dose in a few seconds and penetration depth up to at least 5 cm) and X-rays (for the sterilization of thick materials);

4. The development of a **new-generation of accurate high-flux dosimeters** and of real-time dose monitoring.

WP1 - Linac RF Design

Local Coordinator: Luigi Faillace – INFN-LNF

INFN-LNF, which has a long experience in particle accelerators, is to provide the RF, beam dynamics design of the linac as well as its commissioning. INFN-LNF will lead WP1.

The main features which will have to be provided for the proposed linac are summarized, but not exhaustively, in the following:

1. **Compactness.** RF simulations will be carried out in order to obtain a compact geometry for the C-band linac operating at 5.712 GHz. Novel geometries will be optimized in order to reduce the costs for linac machining and to avoid high-cost temperature bonding processes, such as brazing and diffusion bonding.
2. **High Average current.** The C-Band technology allows to achieve very high gradients and higher shunt impedance, which, properly optimized, will allow for reduction of the total length around half a meter with peak RF power consumption of few MW's. An ad-hoc cooling system will be engineered to handle average power in the kW range.
3. **Low-cost.** Different fabrication scenarios will be investigated in order to achieve a cost-effective solution. As an example, the machining of the linac in two halves made out of hard copper and welded together on the outer surfaces (using TIG or EBW techniques) will noticeably reduce the production time and overall the costs, compared with vacuum or hydrogen brazing.

WP2 - Linac engineering, fabrication, installation and commissioning

Local Coordinator: Augusto Claudio Marcelli – INFN-LNF

INFN-LNF (WP2 together with WP1) will supervise this task.

The external and co-financing private company, Comeb srl, will perform the following:

- Linac **engineering, fabrication, installation** and support to the testing and commissioning of the whole linac-plus-irradiation
- Engineering of the whole linac **assembly structure** which will include all the subsystems, including the RF power source (magnetron), the waveguide system for RF power distribution, vacuum pumps, the monitoring system, the electronics rack with gun driver and modulator for the magnetron, the cooling system and control units for the mechanical, electrical control of the linac.
- Engineering of the **architecture** that can host the whole linac assembly, including the focusing solenoid and the self-shield apparatus →At first, we will design the structural support system for the high-power tests inside a bunker*.
- The first prototype that will be installed and tested will be high-capital as it applies to all innovative machines built for the first time.
- The aim of this proposal is also to market strategy in order to develop following linacs which have a cost of about 1/3 or less than the prototype for the **production in series**. Therefore, we will also proceed to the engineering of an architecture which is more suitable and compatible with hospitals, private company and other sterilization facilities.

*In the case of unavailability of the bunker for the linac commissiong at INFN-LNF, one option is foreseen in order to mitigate this risk: INFN- LNS (Laboratori Nazionali del Sud).

WP3 - Beam Dynamics and Optics Design

Local Coordinator: Prof. Mauro Migliorati – INFN-Roma1

INFN-Roma 1 will lead WP3. In order to meet the challenging specifications of the linac main features, an extensive program of beam dynamics simulation will address the following tasks, in parallel with WP1:

1. Large output beam energy range. Unlike accelerators for high-energy physics, the variability of the output energy range is very limited for industrial and medical linacs. We propose a C-band linac which will be able to have not only to operate in the same range but also the possibility for operating at a lower energy value.

2. Determination of maximum beam current. We estimate that our proposed linac will be able to operate at a maximum current of 200 mA. This option will be investigated and supported by accurate beam dynamics simulations, including beam break-up and higher order modes estimations.

3. Beam Focusing. The focusing system, typically a solenoid, will be designed and optimized for compact transverse dimensions. The focusing system will have to be compatible with the self-shielding apparatus that will be installed around the linac.

4. Self-Shielding. Collaborating with WP1 and WP4, Montecarlo simulations of the self-shielding apparatus will be carried out. The challenge is to integrate the shielding itself with focusing system in the same assembly. Monte Carlo calculations will be needed to "shape" the shielding by: (1) concentrating it in leaking points, and (2) avoiding unnecessary weight. Tungsten-based materials and alloys will be evaluated in view of reducing weights and sizes.

The beam dynamics simulations will also involve the dimensioning of the required magnet spectrometer for beam energy measurements. This task (WP3) will be performed in collaboration with WP1, WP2 and WP4.

WP4 Dosimetry

Local Coordinator: Francesco Romano, INFN-CT

Development of detectors for relative, absolute and on-line dosimetry of high-flux beams, implementing novel approaches with both and passive and active dosimeters.

Objectives:

- Novel approach utilizing a prototype of **small portable calorimeter**. Calorimeters are accurate dose rate independent real time dosimeters typically developed and used at National Metrology Institutes, but new portable prototypes are being recently developed. (INFN-CT)
- To complement and cross compare the calorimetry measurements, a set of irradiations at the same conditions will be done using **alanine detectors**. (INFN-CT)
- A novel approach for real-time in-transmission monitor using in-transmission non-destructive technique, based on the fiber optic technology, scintillating fibers, at the exit of the accelerator. Real-time determination of optical changes of the radiochromic films induced by radiation (INFN-NA)
- Development of miniaturized SiC-based sensors. (INFN-LNF)

WP5 - Experimental Setup and Case Study

Local Coordinator: Pierluigi Paolucci – INFN-Napoli

A sterilization experiment with electron beams is different than an experiment with gamma sources, as the beam may vary in intensity during the irradiation. For such a reason the high-current irradiator will be provided with a **real-time beam monitor**, that should be as transparent as possible.

Silicon carbides or scintillating fiber are intended to operate, possibly in combination, as beam monitors.

The sterilization experiment will be subdivided in *three phases*:

- **Beam monitor calibration**. Using well-established high-dose techniques, such as the calorimeter or the alanine, the beam monitor will be calibrated in terms of absorbed dose in water at a given position (typically the build-up in water equivalent material). A kGy/Monitor units coefficient will be derived.

- According to the sterilization need, **the medium to be sterilized will be prepared**. For example, to sterilize very thin DPI such as wearable masks, these should be sandwiched between plastic sheets to ensure the charged particle equilibrium at their position.

- The irradiation will be stopped when the **monitor unit indicator (MU) will equalize the desired sterilization dose**.

Case-study: drinking water sterilization.

The main goals in the drinking water, wastewater, groundwater and sewer disinfection is to remove recalcitrant compounds and the residual waterborne bacteria and viruses (vibrio cholera, cryptosporidium, shigella, Escherichia coli, and enteric viruses). Previous studies demonstrated that a dose of few kGy could be sufficient to effectively reduce many of these chemicals.

This technology is becoming a concrete alternative method to disinfection processes, such as chlorine, UV, and ozone. The main advantages are:

- stability of the disinfection efficiency during the time.
- a very low bacterial regrowth after disinfection.
- large saving in cost of power consumption.

INFN-LNF activities in WP1

Luigi Faillace	80%
Alessandro Gallo	20%
David Alesini	10%
Roberto Bedogni	20%
Bruno Spataro	0%
Augusto Marcelli	30%
Luca Piersanti	20%
Marco Bellaveglia	10%
Antonio Falone	10%
Marco Diomede	20%
Mostafa Behtouei	30%
Giancarlo Della Ventura	20%
Paola De Padova	20%
Sergio Quaglia	20%
Michele Scampati	20%
Giorgio Scarselletta	20%

INFN-LNF
Total FTE: 3.5

Milestones:
2021
Linac RF final design
1st semester 2022
Linac self-shielding design
2nd semester 2022
Control unit design report
2023
Supervision of the linac installation and commissioning, assigned to WP2
Deliverables:
1. Accelerating RF structure design
2. Design of the radiation safety shielding
3. Cooling system design

INFN-LNF activities in WP2

Luigi Faillace	80%
Alessandro Gallo	20%
David Alesini	10%
Roberto Bedogni	20%
Bruno Spataro	0%
Augusto Marcelli	30%
Luca Piersanti	20%
Marco Bellaveglia	10%
Antonio Falone	10%
Marco Diomede	20%
Mostafa Behtouei	30%
Giancarlo Della Ventura	20%
Paola De Padova	20%
Sergio Quaglia	20%
Michele Scampati	20%
Giorgio Scarselletta	20%

INFN-LNF
Total FTE: 3.5

Milestones:
1st semester 2021
Acquisition of the magnetron with electromagnet, modulator, diagnostics, ancillary components (waveguides, RF windows, circulator and/or 90° hybrid, etc…)
2nd semester 2021
Engineering-ready Linac final design
Procurement of the electron-X-ray conversion target.
1st semester 2022
Linac Fabrication
Procurement of the solenoid and shielding apparatus.
2nd semester 2022
Low-power RF characterization
1st semester 2023
Linac Assembly with all subsystems
2nd semester 2023
Linac testing and commissioning.
Beam characterization.

Deliverables:
1. Accelerating RF structure engineering and fabrication
2. Cooling system procurement
3. Procurement of the radiation safety shielding
4. Procurement of electron-X-ray target
5. Support system

INFN-Roma1 activities in WP3

INFN-Roma1
Total FTE: 2.5

Prof. Mauro Migliorati	20%
Prof. Luigi Palumbo	30%
Prof. Andrea Mostacci	20%
Paolo Valente	20%
Lucia Giuliano	60%
Luca Ficcadenti	20%
Roberto Li Voti	30%
Fabio Bosco	50%

Milestones:
1st semester 2021
Preliminary Beam Dynamics linac design report, including specifications for the beam focusing system requirements.
2nd semester 2021
Final beam dynamics linac design report
1st semester 2022
Specifications report for beam diagnostics and spectrometer.
2nd semester 2022
Testing of focusing system and diagnostics.
2023
Collaboration to the installation, together with WP1, of the beam focusing system, diagnostics, spectrometer and shielding in the linac system.

Deliverables:
1) Beam dynamics simulations report
2) Beam optics for beam manipulation design
3) Beam optics for beam manipulation specifications
4) Beam diagnostics, focusing system and Spectrometer specifications

INFN-CT activities in WP4

Francesco Romano	60%
Maurizio Marrale	40%
Antonio Bartolotta	40%
Elio Tomarchio	40%
Maria Cristina D'Oca	40%

INFN-Catania
Total FTE: 2.2

Deliverables:
1) Report on calorimeter features and usage
2) Assessment of the fiber optic real time dose monitoring
3) Protocol for dosimetry
4) Verification of the calibration chain and characterization of the accelerator output

Milestones:
1st semester 2021
Proof of principle with existing small calorimeter with high flux beams
Calibration of the alanine dosimeters with 60Co beams
Calibration of radiochromic films with 60Co beams
2nd semester 2021
Study and design of the final calorimeter prototype using Monte Carlo simulations
Design optimization of the innovative fiber optic real time dose monitoring with radiochromic films
1st semester 2022
Realization of the calorimeter prototype
Characterization of alanine response at different dose rates
Characterization of the fiber optic real time dose monitoring
2nd semester 2022
First test of the prototype with conventional electron beams and cross-comparisons with alanine dosimeters and fiber optic real time dose monitoring with radiochromic films
1st semester 2023
Test of the prototype with high flux beams at a test facility and comparison with alanine
Test of the innovative fiber optic dose monitoring device with high flux beams at a test facility
2nd semester 2023
Final measurements with the CLEAN accelerator

INFN-Napoli activities in WP5

INFN-Napoli Total FTE: 2.4

Pierluigi Paolucci	30%
Biagio Rossi	20%
Orso Maria Iorio	10%
Francesco Fienga	30%
Salvatore Buontempo	10%
Francesco Fabozzi	10%
Nicola Cavallo	20%
Marco Guida	20%
Giovanni Libralato	20%
Marco Trifuoggi	20%
Donatella Caniani	20%
Giovanni Breglio	20%
Antonello Cutolo	10%

Milestones:
1st semester 2021
Calibration and test in Napoli laboratory of the COD and TOC analyser
2nd semester 2021
Design and preparation of the first set of wastwater sample.
Characterization of the sample in Napoli laboratory
1st semester 2022
Matrix of test tubes and handling support construction
2nd semester 2022
Test beam and data analisys of the first samples
1st semester 2023
Design and preparation of the second set of wastewater sample. Simulation results
2nd semester 2023
Test beam at CLEAN accelerator.
Decontamination results versus energy beam and dose.

Deliverables:
1) Test tubes Matrix (5x5 max)
2) Automatic handling of Matrix
3) Protocol for the wastewater characterization pre and post irradiation.
4) Test beam equipments.

Financial requests – WP1

Activity N.	Description	2021 [k€]	2022 [k€]	2023 [k€]
WP1.1	Messa a punto del beam monitor rad-tolerant	13		
WP1.2	validazione del beam monitor rad-tolerant and studio di radioprotezione		13	
WP1.3	Messa in opera su macchina del beam monitor e validazione del self-shielding			5
	Post Doc	25	25+25	25
	Missions	10	10	13
	TOT	**48**	**73**	**43**

WP1 TOT = 164 k€

Financial requests – WP2 INFN-LNF

Activity N.	Description	2021 [k€]	2022 [k€]	2023 [k€]
WP1.1	Magnetron + Electromagnet	77		
WP1.2	Modulator		58	
WP1.3	E-gun	7		
WP1.4	Circulator	13		
WP1.5	Gun Driver		13	
WP1.6	Vacuum System and Mechanical Structure		36	
WP1.7	Cooling Sytem		6	
WP1.8	Waveguides+windows	9		
WP1.9	Water Load	10		
WP1.10	Solenoid		7	
WP1.11	Ancillary		88	
WP1.12	Mechanical engineering design, fabrication assembling and support for testing	20	20	30
WP1.13	Ancillary services (documentation, configuration control, management)	20	20	30
	Materials Costs and handling	24	42	
	SUB-TOT	180	290	60
	Comeb srl co-financing	20	20	20
	TOT	**160**	**270**	**40**

WP2 TOT = 470 k€

Financial requests – WP3 INFN-Roma1

Activity N.	Description	2021 [k€]	2022 [k€]	2023 [k€]
WP1.1	Hardware and Software for Beam dynamics simulations	10		
WP1.2	Consumables (self-shielding,…)		10	
	Post Doc		25	
	Missions	5	5	5
	TOT	**15**	**40**	**5**

WP3 TOT = 60 k€

Financial requests – WP4 INFN-Catania and Napoli

Activity N.	**Description**	**2021 [k€]**	**2022 [k€]**	**2023 [k€]**
WP4.1 CT	Portable calorimeter		40	
WP4.2 CT	Alanine pellets	2	2	2
WP4.3 CT	Maintenance EPR spectrometer for alanine analysis	1	1	1
WP4.4 CT	Alanine calibration with 60Co source	3		
WP4.5 CT	Laboratory consumables for alanine measurements	2	2	2
WP4.6 CT	Phantom for cross-comparison of alanine and calorimeter measurements		3	
WP4.7 CT	GafChromic for relative dose distributions	2	2	2
WP4.6 NA	Consumables (Silicon carbides or scintillating fiber, radiochromic films…)	10	10	10
WP4.7 NA	Instrumentation	5	5	5
	Post Doc	25	25	
	Missions	5	10	10
	TOT	**55**	**100**	**32**

WP4 TOT = 187 k€

Financial requests – WP5 INFN-Napoli

Activity N.	Description	2021 [k€]	2022 [k€]	2023 [k€]
WP5.1	Chemical oxygen demand (COD) COD analyzer	10		
WP5.2	Total organic carbon (TOC) analyzer	10		
WP5.3	Matrix of Test tubes	2		
WP5.4	Automatic handling system for Matrix		4	
WP5.5	Reagents for toxicity analyses, reagents for chemical analyses, reagents for microbiological analyses	10	10	10
	Post Doc		25	
	Missions	5	5	5
	TOT	**37**	**44**	**15**

WP5 TOT = 96 k€

Total financial requests

Working Packages	Year 1	Year 2	Year 3	WP Total
WP1 **LNF**	13 k€ Cons 10 k€ Missions 25 k€ Post-Doc	13 k€ Cons 10 k€ Missions 25 k€ Post-Doc 25 k€ Post-Doc	5 k€ Cons 13 k€ Missions 25 k€ Post-Doc	31 k€ 33k € 100k € **WP1 TOT 164 k€**
WP2 **LNF**	160 k€ Cons	270 k€ Cons	40 k€ Cons	470 k€ * **WP2 TOT 470 k€**
WP3 **Roma1**	10 k€ Cons 5k€ Missions	10 k€ Cons 5k€ Missions 25 k€ Post-Doc	5k€ Missions	20 k€ 15 k€ 25 k€ **WP3 TOT 60k €**
WP4 **Catania** **and** **Napoli**	15 k€ Cons 15 k€ Missions 25 k€ Post-Doc	65 k€ Cons 15 k€ Missions 25 k€ Post-Doc	12 k€ Cons 15 k€ Missions	92k€ Cons 45 k€ miss 50 k€ **WP4 TOT 187k€**
WP5 **Napoli**	32k€ Cons 5 k€ Missions	14k € Cons 5 k€ Missions 25 k€ Post-Doc	10k€ Cons 5 k€ Missions	56 k€ 15k€ 25k€ **WP5 TOT** **96k€**
Year TOT	**315**	**532**	**130**	**Grand TOT: 977 k€**

* (net costs, assuming procurement from Comeb SrL co-financing 60 k€ tot)