The Calliope Gamma Irradiation Facility

Director: A. Cemmi
Research staff: R. Carcione, I. Di Sarcina, J. Scifo, A. Verna*
Technician: G. Ferrara

ENEA FSN-FISS-SNI (Casaccia R.C. Rome, Italy)

*adriano.verna@enea.it
Gamma interaction with matter

High penetrating power

Sources of gamma rays
- Radioactive decays
- Secondary cosmic rays
- Astronomic objects (neutron stars, pulsars, supernovae, black holes)
- Lightning strikes
- Nuclear fission
- Nuclear fusion
- High-energy physics experiments
- .........
Gamma interaction with matter

Production: \( ^{59}_{27}\text{Co} + n \rightarrow ^{60}_{27}\text{Co} \)

Decay: \( ^{60}_{27}\text{Co} \rightarrow ^{60}_{28}\text{Ni}^* + e^- + \bar{\nu}_e \)
\[ ^{60}_{28}\text{Ni}^* \rightarrow 2^{60}_{28}\text{Ni} + 2\gamma \]

- Mean energy: 1.25 MeV
- Half life \( \approx 5 \) years

Gamma emission from **daughter nuclei** in **excited state** after alpha and beta decay or spontaneous fission.

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\[ \sigma_f \propto Z^5 \]
\[ \sigma_c \propto Z \]
\[ \sigma_p \propto Z^2 \]

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**Excitation**

**Ionization**

No radioactivity induced in the irradiated materials.
Gamma rays and matter: processing

1. Production/processing
   - Polymerization
   - Sterilization
   - Food irradiation

2. Exposition to radiation
   - Radiation hardness
   - Lifetime prevision
   - Reliability

Irradiation plant
Characterization laboratory

ENEAO
Italian National Agency for New Technologies, Energy and Sustainable Economic Development

ENEA overview

Energy efficiency

Environment and sustainability

Energy technologies and renewable energy sources

Nuclear technologies, safety and security

2600 employees
Calliope irradiation facility

@ ENEA Casaccia Research Center (Rome)

- Pool-type irradiation facility.
- 25 bars of $^{60}$Co (last recharge in 2018)
- Large volume irradiation cell (7.0 x 6.0 x 3.9 m$^3$)
- Maximum allowed activity: $3.7 \cdot 10^{15}$ Bq.
- Maximum dose rate: 6.3 kGy/h (Oct 2023)

- Irradiation and dosimetric certification.
- ISO 9001 (by 2023) and ISO 17025 (by 2024) quality management.
Calliope irradiation facility

Cherenkov radiation in the water. Active rack area: 41 cm x 75 cm.

Irradiation tests and procedures

- Different dose rates: distance from the source and use of lead shield and castles from 0 to 6.3 kGy/h.
- Different atmospheric and temperature conditions.
- Experimental dosimetric characterization.
- Simulation of the gamma field by Fluka/MCNP code.
Dosimetric laboratory

Dosimetric systems

❖ **Fricke dosimeter** (20-200 Gy)
  Optical transmittance
  Absolute dosimeter

❖ **Alanine - EPR dosimeter** (50 Gy-150 kGy)

❖ **Red-Perspex** (5-40 kGy), **radiochromic** (1 kGy-3 MGy)
❖ **Thermo Luminescent Dosimeter (TLD)** (1 mGy-100 Gy)
❖ **Real-time SiC diode** (0,1 – 10 kGy/h)
Lead castles

Low dose rate (LDR) irradiation tests

Modular lead castles:
- Variable thickness of the front wall (facing the gamma source)
- 1-cm thick Pb sheets composing the front wall
- The other walls are 3 cm thick Pb panels (fixed) to shield secondary radiation
- Opening on the rear wall for the use of cables and wires.

Internal dimensions: 45x35x33(H) cm³
On-line irradiations

Irradiation of biased devices and/or remote control
Characterization laboratory

Optical, spectroscopic and spectrometric characterization

- **Raman microscope**
  - 785 nm laser source.
  - + Confocal optical microscope

- **UV-VIS spectrophotometer**
  - Range: 190-2500 nm
  - Integrating sphere

- **Spectrofluorometer**
  - Excitation (230-1100 nm)
  - Emission (300-1100 nm)

- **FTIR/FTIR-ATR**
  - spectrophotometer
  - Range: 400-7000 nm
  - Integrating sphere

- **EPR spectrometer**
  - X band ~9 GHz

- **Colorimeter**
Processing laboratory

Thermal annealing and accelerated ageing test

- Climatic chamber:
  - temperature range: -75°C/+180°C
  - humidity range: 10 - 98 %
  - UV lamp (220 - 630 nm)

- Furnace
  - (T max = 1200°C)
  - Electronic components processed in biased conditions
Qualifications and research lines

Principal activities at $^{60}$Co Calliope facility

**Qualification tests**
- Materials, electronic devices, optical components in harsh radiation environments

**Applications:**
- Aerospace
- Nuclear plants (fission and fusion)
- High-energy-physics experiments.

**Experimental research**
- Chemical, physical and biological effects of ionizing radiation
- Materials' science
- Nuclear science
- Experimental particle physics (detectors)
- Cultural Heritage (elimination of biodeteriogens)
- Agriculture, control of pests
According to Waste form Technical Position (United States Nuclear Regulatory Commission) absorbed dose $10 \times 10^6$ Gy corresponding to a period of 300 years.
Qualification test: Nuclear application

Radiation damage for fusion components

ITER
International Thermonuclear Experimental Reactor Project

Fusion for Energy

piezo-motor

IVVS actuating components (dose = 4 MGy)

optical components

Radial Neutron Camera scintillators

Plastic (neutron and gamma)

Synthetic diamond
Irradiation tests on electronic components and devices for SPACE

- Ionization and displacement damage (surface/bulk)
- Dose rate effects
- T effects on damage mechanisms

The Calliope facility is part of the ASIF Programme (Italian Space Agency Supported Irradiation Facility) and indicated by the European Space Agency ESA for space irradiation tests.

Specifications:
- ESA/SCC 22900 (5)
- MIL-STD 883

Ionization damage due to space radiation
Total ionizing dose

Standard and low dose rate windows
ENEA ASIF Facilities:

**REX**
Removable Electron to X-ray

- Electron and X-ray
- 5 MeV electron linac
- Electron to photon conversion unit

**Top Implant**
Intensity Modulated Proton Linear Accelerator for Radiotherapy

- Low energy proton (2.6 MeV - 7 MeV)
- High energy proton (35 MeV - 71 MeV)

**Calliope**
Gamma Irradiation Facility

- 2γ emitted in coincidence with 1.25 MeV mean energy
- Activity: 1.6 x 10^{15} Bq (May 2022)
- Max dose rate (May 2022): 7.4 kGy/h

**FNG – Frascati Neutron Generator**

- 14 MeV neutron (reaction T(d,n)^4He);
- 2.5 MeV neutron (reaction D(d,n)^3He)

**Triga RC-1**

- Maximum thermal power: 1 MW;
- Maximum neutron flux: 2.7 x 10^{13} n/cm^2 s

**Tapiro**

- Maximum power: 5 kW;
- Maximum neutron flux: 4 x 10^{12} n/cm^2 s
Experimental research: High energy physics experiments

Cherenkov and scintillator detectors

- Fermilab
- INFN

Neutrinoless decay of muon

Calorimeters with Cherenkov crystals

- Scintillator crystals @ Calliope
  - CMS @LHC CERN
  - BELLE II @SuperKBK (JAP)

Graphs showing transmittance (%)

- **PbF$_2$**
  - non-irradiated
  - 0.723 kGy
  - 7.20 kGy
  - 73.7 kGy
  - 259.7 kGy

- **PbWO$_4$**
  - non-irradiated
  - 0.723 kGy
  - 7.20 kGy
  - 73.7 kGy
  - 259.7 kGy
  - 370.1 kGy
  - 549.1 kGy
  - 795.2 kGy
  - 1515 kGy
Experimental research: Glassy matrices and optical devices

1) Lenses and optical coating substrate for Space and Nuclear Plant

2) Transition metal doped glassy matrices with photoluminescence properties

For production of different colored LEDs (white)

CIE chromaticity is tuned from yellow and green to white by adjusting glassy matrix composition and/or Cu⁺/Mn²⁺ dopant concentration ratio.

3) Radiochromic and photochromic glassy matrices as dosimetric systems, data memories and optical lenses

Manganese doped phosphate glasses

Glass matrix: P₂O₅, Dopant: MnO, 4 mol%

Reversible thermal bleaching

14.3 kGy after bleaching
14.3 kGy after bleaching

Mn²⁺ uncolored Oxidation by γ irradiation Mn³⁺ colored
Experimental research: Polymeric materials

Effects of gamma radiation on polymeric materials

Low dose → Cross-linking

High dose → Degradation

Influence of:
- atmospheric conditions
- irradiation parameters
- temperature

Hughes et al. Material Horizons (2019)

Remmel, c&en (2020)

Embrittlement, fragmentation, change of color

Free radicals

Very active species
Post-irradiation chemical reactions with free radicals

- Cultural heritage (paper, wood, cellulose).
- Biopolymers, proteins
- Polymers of technological interest, resins
Experimental research:
Adhesive epoxy resins

Investigation of the gamma irradiation effects (0-500 kGy)

- Mechanical properties
- Chemical bonds (FTIR)
- Formation and recombination of free radicals (EPR)

3M Scotch-WeldTM EC-2216 B/A Gray (3M2216)

EPR analysis

![EPR analysis graph](image-url)
Experimental research: 
Gamma irradiation of superconductors

Irradiation of SC tapes and thin films for space applications

Collaboration with ENEA FRASCATI 
Superconductivity Laboratory

- YBCO thin films grown on LAO and STO by metalorganic decomposition (MOD).
- Commercial REBCO tapes (SuNAM, SuperOx, Shanghai ST)

See oral contributions from Valentina Pinto this morning and Antonio Pietropaolo in this session.
Experimental research:
Gamma irradiation of superconductors

- Effects of the gamma irradiation on HTS are strongly controversial. See presentation by Simon Chislett-McDonald yesterday.

Future perspectives

- Irradiation at higher absorbed dose and dose rate: simulation of the gamma radiation field in a fusion nuclear reactor.
- Irradiation in operating conditions (below $T_C$)
  ALERT: explosion of liquid nitrogen in gamma field

- Comparison with neutron irradiation @ Frascati Neutron Generator (FNG)
Calliope: the research staff

Alessia Cemmi
Director of Calliope Facility

Ilaria Di Sarcina

Jessica Scifo

Giuseppe Ferrara

Adriano Verna

Rocco Carcione
Thank you for your attention!