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ELECTRON BEAM QUALIFICATION AT ENEA FRASCATI PARTICLE ACCELERATORS LABORATORY

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Abstract

The APAM Laboratory of the ENEA Frascati Research Centre hosts two electron beam S-Band standing wave linacs. The older one, named REX, produces a 5 MeV, 150 mA electron beam with maximum pulse repetition frequency (PRF) of 20 Hz. The second one, named TECHEA, was recently commissioned within a Research and Development program focused on breast radiotherapy applications: it produces a 3 MeV, 130 mA electron beam with maximum PRF of 100 Hz. Both plants can produce either electrons or X-rays through a conversion target. In this contribution we report qualification activities on the electron beam properties in air (flux, uniformity, and energy spectrum) at different source-target distances and at different extraction energies to assess the applicability of these facilities for multiple applications, such as sterilization, conservation of cultural heritage artifacts, material degradation, and space components testing.

INTRODUCTION

The ENEA Frascati Particle Accelerators and Medical Applications (APAM) Laboratory has a long standing in the development and prototyping of linear accelerators as radiation sources [1–3]. While mostly developed for radiation therapy research, these accelerators can also be employed in a wide range of technological applications. For electron linacs, this was demonstrated by the experience with the REX (Removable Electron to X-ray source) accelerator [4] in the fields of cultural heritage preservation [5,6], material characterization for nuclear fusion reactors [7] and space components testing [8].

Following this positive experience, we are planning to implement an X-ray/electron modality also on the newly commissioned X-ray source TECHEA (TEChnologies for HEAlth) accelerator [3].

In this contribution we report recent qualification activities on the REX and TECHEA plants operating in electron mode to further expand the range of applications of the REX plant and set-up the exploitation of the TECHEA accelerator in electron mode.

ENEA FRASCATI ELECTRON LINACS

The REX plant was commissioned at the end of the 80s and is based on old technologies: the linac is hosted into an external vacuum chamber and driven by a pulse-forming network limited to a PRF of 20 Hz. Conversely, the TECHEA accelerator, developed within a project which started in 2019, is based on current technologies and powered by a magnetron driven by a solid-state modulator with a maximum PRF of 100 Hz.

REX Irradiation Facility

The REX irradiation facility operating at ENEA Frascati Research Center is based on a 5 MeV S-band on-axis coupled electron linear accelerator and on its radiofrequency system. This machine can deliver either electrons or X-rays exploiting bremsstrahlung process, through a removable electron to photon head conversion made of high atomic number materials, such as tungsten, gold, platinum, and tantalum. REX is a RF pulsed standing wave LINAC driven by 2 MW peak power magnetron, which produces an accelerated electron beam of 3.4 µs FWHM pulse length and maximum beam current of 150 mA.

The electron beam is extracted through a 50 µm titanium exit window into a 40x40x80 cm^3 lead-shielded irradiation chamber.

TECHEA Prone Breast Radiotherapy Accelerator

The TECHEA accelerator was developed within the framework of the TECHEA project as a prototype of a device dedicated to the treatment of breast cancer with the patient in prone position [3]. It is based on a compact 3 MeV electron accelerator providing a 120 mA peak current in a 3.4 µs pulse. The linac is enclosed into a modular lead shielding which reduces stray X-rays from the accelerator structure. A tungsten converter, incapsulated into the lead shielding, produces bremsstrahlung X-rays with a beam quality very close to ^{60}Co gamma rays. The X-ray beam is shaped by a 13 degrees conical aperture into the lead shielding; additionally, a lead block (“dump”) is positioned behind the nominal irradiation position (isocenter) placed 60 cm from the accelerator. The maximum irradiation volume allowed by the accelerator lead shielding and dump is approximately $20×20×20$ cm^3.

ELECTRON BEAM QUALIFICATION

The beam parameters relevant to characterize an irradiation setup are the transverse uniformity on the target surface, the particle flux, the energy, and energy spec-

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trum. The electron beam from the REX and TECHEA accelerators is extracted in air and directed onto a target without further focusing. Expansion of the beam in free air determines a 2D gaussian transverse intensity profile, with standard deviation increasing with source-target distance. Particle flux and irradiation uniformity can be varied choosing different geometrical layout inside the irradiation chamber. The flux can be additionally varied acting on the pulse repetition frequency.

A new campaign of measurements was recently conducted on this plant to widen the range of applications. In particular, we investigated the beam properties after reduction of the nominal beam energy with either active or passive means. The methods here reported will be applied to the TECHEA electron beam once commissioning of the machine as an X-ray source is completed. In the meantime, the TECHEA accelerator operation in electron mode was investigated with a FLUKA simulation.

Measurements on REX

Here we report results of energy characterization and transverse uniformity at different energies after passive and active degradation of the REX 5 MeV beam. Active variation of the electron beam energy was obtained acting on the beam injection energy (at the e-gun level), and on the accelerating field amplitude at the RF generator level (varying the magnetron power and frequency tune). Passive variation was obtained with aluminum degraders of variable thickness.

Since a spectrometer magnet is not available in the REX plant, the energy of the electron beam was characterized with two experimental techniques already described in literature. The first technique relies on the analysis of beam transmission fraction through different aluminum thickness [9]. This measurement is performed at the accelerator exit, as shown in Figure 1: the aluminum foils are placed between the current transformer, at the linac exit, and the Faraday cup measuring the attenuated current. With this technique, the most probable beam energy is calculated from the transmission curve:

$$E_p(MeV) = \frac{0.27R_{ex} + 0.165}{0.536}$$

where R_{ex} is the extrapolated range.

The first method was used only to investigate active energy variation. Stable operation was obtained in the range from 5.5 to 4.3 MeV. The corresponding measured transmission curves are reported in Figure 2 for two accelerator settings: nominal power (setting A) and reduced power (setting B).

The second technique relies on energy deposition in water, which is measured with GAFchromic films of EBT3 and HD-V2 types in a water phantom. Acquisition of Percentage Depth Dose (PDD) curves allows evaluating not only the most probable energy E_p, but also the energy spectrum with an analysis method which is described in detail in another contribution to this conference [10]. This is therefore a significant improvement with respect to the first technique. Furthermore, these measurements can be performed also at different distances from the accelerator exit. A sample of energy distribution measurements obtained with EBT3 films is reported in Table 1: they combine active modulation (the already described power settings A and B) and use of aluminum degraders (0 and 4.6 mm thickness), and are acquired at different distances D from the linac exit.

Figure 1: Energy measurement set-up: aluminum transmission curve method.

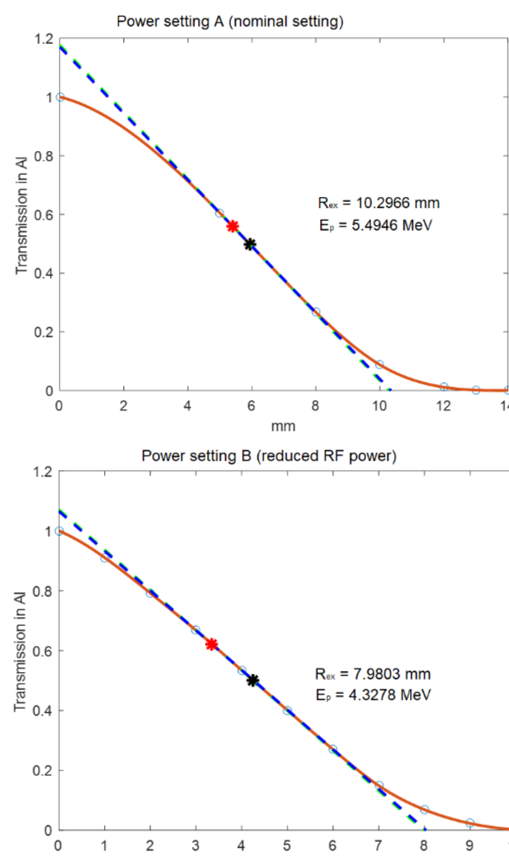

Figure 2: Transmission measurement through aluminum: nominal power (top) and reduced power (bottom) settings.

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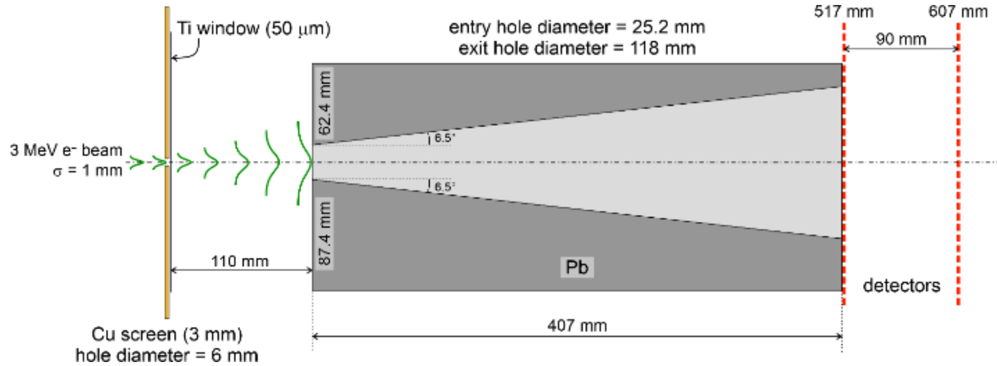

Figure 3: Electron beam transport geometry for FLUKA simulation of the TECHEA accelerator.

Table 1: Energy Measurements with EBT3 Films

setting		D	E_p	E_{aver}	FWHM
mm Al	power	cm	MeV	MeV	MeV
0	A	10	5.24	4.57	1.16
0	B	30	4.22	3.95	0.94
4.6	A	20	2.92	2.21	0.48
4.6	A	30	2.76	2.12	0.59

Energy measurements with GAFchromic films additionally enable measurements of the beam intensity distribution on a plane perpendicular to the beam propagation direction. Examples of the impact of aluminum foils, used for passive energy degradation, on the transverse homogeneity and fluence are reported in Table 2 for the case of a target size of 2×2 cm^2 and an aluminum thickness of 4 mm for two distances (10 and 20 cm) from the linac exit. Fluences calculation takes into account the transmission reduction caused by the degrader.

Table 2: Uniformity and Fluence on a 2×2 cm^2 Target with and without Aluminum Degrader

Degrader (mm Al)	Distance (cm)	Uniformity (± %)	Fluence delivered in 30 min (e- cm^{-2})
0	10	30	6.4E+15
0	20	17.5	3.7E+15
4	10	4.6	6.9E+14
4	20	2.2	3.1E+14

FLUKA Simulation of the TECHEA Electron Beam

A preliminary Monte Carlo simulation with FLUKA [11-13] of a monochromatic 3 MeV electron beam was conducted to investigate the effect of the lead shielding on the electron beam transport to the isocenter position and evaluate the transverse uniformity of the beam. The simulated, simplified geometry is shown in Figure 3. The isocenter position is placed at 607 mm from the linac Ti window. Results of the electron beam transport to the isocenter are shown in Figure 4 as the 1D section of the intensity distribution. Summary of the resulting uniformity and fluence calculations for three reference target geometry are given in Table 3.

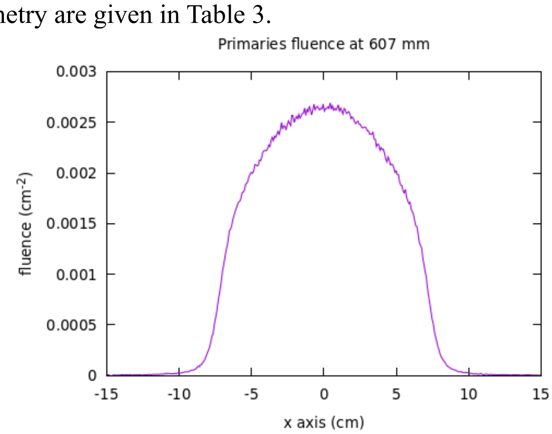

Figure 4: Simulation results of electrons (primaries) transport at the isocenter position

Table 3: Uniformity and Fluence Calculations for Target at the Isocenter

Target size (cm^2)	Uniformity (± %)	Fluence delivered in 30 min (e^- cm^{-2})
2 x 2	1	7.0E+14
5 x 5	5	7.7E+14
10 x 10	17	6.7E+14

CONCLUSIONS

We have reported the results of the recent measurement campaign on the electron beam produced by the REX facility at ENEA-Frascati focused on assessing the beam characteristics at different energies obtained by active and passive means. We verified that energy reduction is feasible, but not advantageous for applications below 3 MeV, where passive degradation strongly reduces the fluence and increases the energy spectrum FWHM. For such applications, the TECHEA accelerator in electron mode seems a promising solution according to the preliminary FLUKA simulation.

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