The ALTO facility for production of rare nuclei

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Abstract. The ALTO facility (Accélérateur Linéaire et Tandem d'Orsay) at Institut de Physique Nucléaire d'Orsay is under commissioning. The aim of this facility is to provide neutron rich isotope beams for both nuclear physics study (away from the valley of stability) and developments dedicated to next generation facilities such as SPIRAL2. The neutron rich isotopes are produced by photofission of ^{238}U induced by the 50 MeV electrons from the linear accelerator. The isotopes coming out of the fission target effuse towards an ion source to form a beam that is analyzed through the on-line separator PARRNe. Additional experimental beam lines are currently under construction.

1. Introduction

The last decade have seen a strong scientific interest in the production and the acceleration of radioactive nuclear beams (RNBs) and many RNB facilities are being constructed or are passing into advanced phases of design study throughout the world *e.g.* the SPIRAL2 project at GANIL [1] and the EURISOL project in Europe [2]. The production of intense beams of neutron-rich nuclei is particularly challenging. It would give access to the vast untouched field of potential discoveries still to be explored on the neutron-rich side of the β -valley. One of the most efficient way to produce intense beams of medium mass neutron-rich nuclides is to use fission of heavy elements like uranium. However it has been realized in the early stages of the SPIRAL2 design study that the production in ISOL-type conditions of fission rates order of magnitudes higher than those obtained in the previous generation facilities was a major technical issue and would necessitate a large R&D effort. Some of these R&D issues of the SPIRAL2 project could be studied in detail on the Orsay based fast-neutron fission induced ISOL setup named PARRNe (Production d'Atomes Radioactifs Riches en Neutrons) using the 14-MeV deuteron beam delivered by the Tandem [3, 4, 5, 6] (and Refs. therein). In the continuity of the R&D program realized using the PARRNe setup and after the success of an exploratory experiment performed at CERN using photofission [7] it has been decided to start a conceptual project for the installation at IPN-Orsay of a 50-MeV electron accelerator : the ALTO project (French acronym for **L**inear **A**ccelerator at the **O**rsay **T**andem). In our configuration, the $^{nat}UC_x$ pellets are exposed to the γ-flux generated by the interaction of the incident electron beam with the target container itself (*i.e.* part of the target serves as a converter). The first electron beam was extracted from the accelerating section in December 2005. In June 2006 a UC_x target-ion source ensemble was irradiated for the first time. The non-refractory fission products where extracted from the target, singly ionized and magnetically mass separated. The effective yields of the different fission-fragments were then measured by γ-spectrometry. An overview of the major points of the ALTO project is reported in the following sections as well as well an overview of the experimental results obtained.

2. The electron driver

It has been shown that the ratio of the number of fission of ^{238}U per incident electron tends to saturate from 30-MeV incident electron-beam energy and reaches saturation at 50-MeV [8]. This is due to the matching between the energy distribution of the Bremsstrahlung γ-spectrum and the energy shape of the ^{238}U giant dipole resonance (maximum cross section is 160 mb at 15 MeV). 50-MeV was then naturally chosen for the energy of the electron-driver. The main component of this driver consists in a linear accelerating section ceased to us by the CERN scientific authorities after the success of the experiment described in Ref. [7]. Other missing elements were given by the LAL (Orsay). The LINAC optimal working conditions for producing photofission are:

RF frequency	2998.55 MHz
Repetition rate	100 Hz
Output average current	10 μA
Output energy	50 MeV

The accelerator length is about 12 m. Fig. 1 shows a schematic view of the implantation of ALTO inside the Tandem beam areas. The driver is composed of the succession of an e-gun, a pre-buncher, a buncher, the accelerator section and an achromatic double deviation beam-line. This double-deviation curves the electron trajectory in order to join the former Tandem deuteron beam line. The target ion-source ensemble is placed at the *same* position as during the fast-neutron induced fission PARRNe experiments hence the mass-separator was maintained also at the same position.

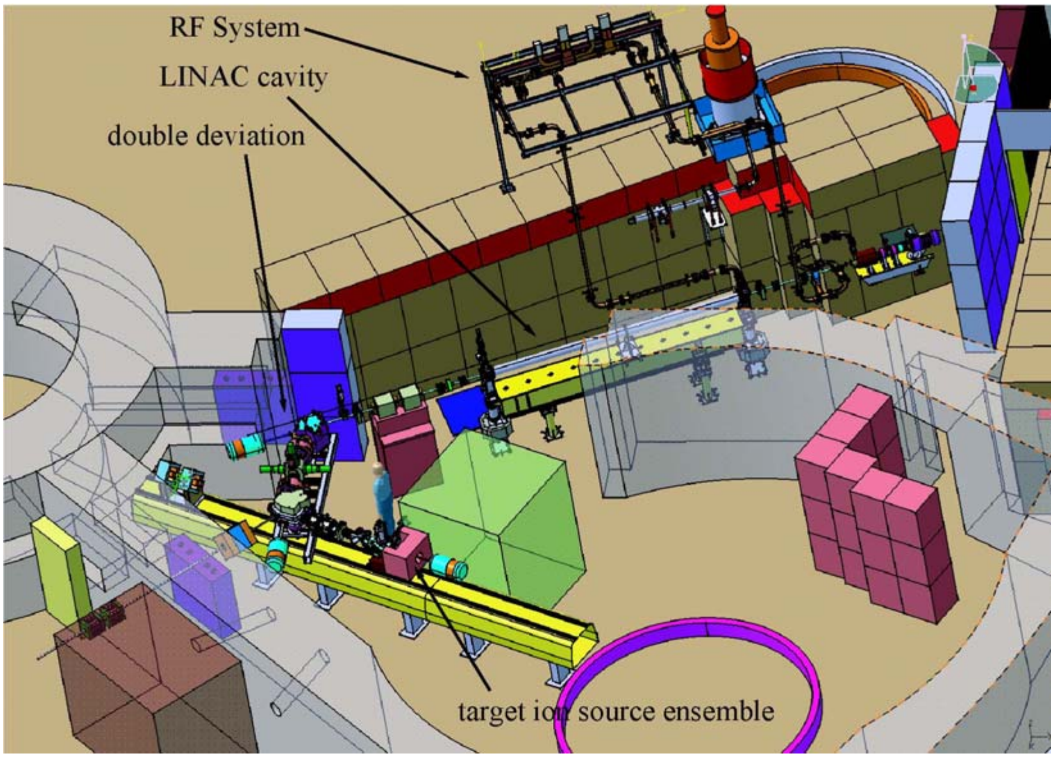

FIG. 1. Implantation scheme of the LINAC and double beam deviation in the Tandem building.

2.1. The LINAC and RF system

The RF system is based on the use of a THALES klystron (TH2100) and a modulator from LAL. The 3 GHz klystron delivers a 4.5 µs RF pulse and provides a peak power of 35 MW. The accelerating section works in the 2π/3 TW mode with quasi-constant field gradient. This section (which is the cavity recovered from the decommissioned LEP injector) provides an energy gain of 46 MeV for only 9 MW input RF power. The RF distribution allows to deliver the suitable power for a klystron power of 30 MW. The filling time of the section is 1.35 µs and the energy dispersion is 8% for a current pulse of 50 mA. The buncher is a tri-periodic structure working in standing wave mode at 3 GHz. An appropriate time allows to reduce the energy spread in the buncher. The pre-buncher allows to improve the time structure of the beam in the buncher. Simple calculations (confirmed by simulation) give optimal bunching for a power of 1 kW in the cavity. A classical triode thermionic gun operating between 80 kV and 90 kV produces variable pulses (0.2 µs to 3 µs). The peak current which is normally achieved is typically 3A but for our purpose the cathode is voluntarily under heated for delivering only 60 mA in order to minimize the current fluctuation during the pulse. To minimize the beam loading in the accelerating section, we choose to function at maximum pulse length. With 3 µs pulse at 100 Hz the beam loading is 4 MeV for energy of 50 MeV. During the first test-runs the intensity was maintained at 100 nA for safety reasons. Simulations showed that it should correspond to 10^9 fissions/s inside the target which was the rate routinely obtained during the PARRNe deuteron-induced fission experiments (details on the radiological conditions of the June 2006 test-run are give in a following section) . We have also reduced the repetition frequency at 10 Hz and operate with 250 ns pulse duration. The time structure of the electron beam is displayed in Fig. 2. Transmission between gun and entrance section is 77 % (81% theoretical), and transmission in the section is 96%. The bad transmission in the deviation was traced back to a perturbation in the magnetic field created by an ionic pump close to the line which has been removed since.

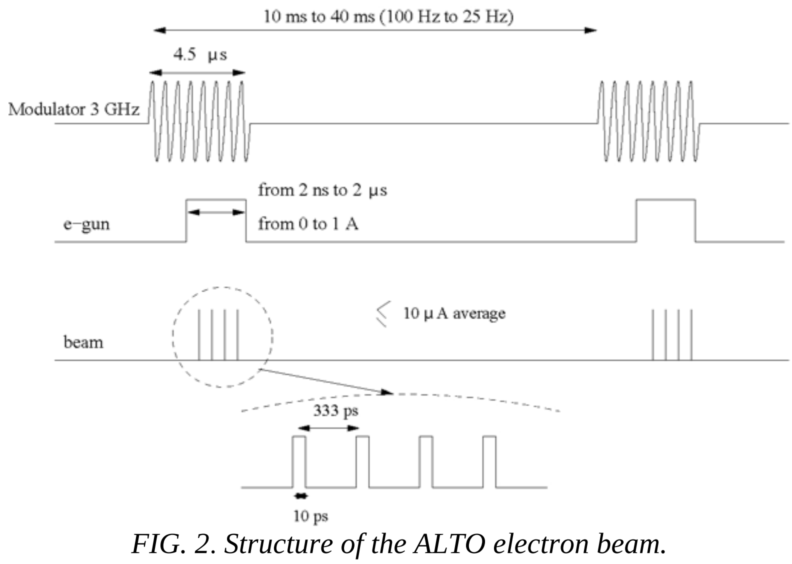

FIG. 2. Structure of the ALTO electron beam.

2.2. The double-deviation line and beam diagnostics

The achromatic double-deviation line following the linear accelerating section has three purposes:

- optimize the implantation of the LINAC in the Tandem experimental areas;
- insure a certain modularity in the use of the electron beam : after the first deviation the electron beam can be sent to a dedicated line, after the second deviation it regains the former path of the Tandem deuteron beam for irradiation of the UC*x* target ;

- place beam diagnostics.

The designed beam line consists of two 65° dipole magnets (R=0.4m) and six magnetic quadrupoles. The first quadrupole doublet at the output of the accelerating section allows the control of the beam envelope at the entrance of the first dipole. To achieve the achromaticity of the deviation, two quadrupoles are put between the two dipoles. Between these two quadrupoles a mobile slit which allows measuring the energy dispersion by position tuning. The beam dimension on the UC_x target container is adjusted using the last quadrupole doublet. There are three types of current diagnostics:

- two Wall Current Monitor (WCM) which are are resistive monitors
- three current transformers (TI)
- two beam stop (BS) with faraday cages and magnets in order to capture secondary electrons.

Three beam position monitors (BPM) have been taken from the Linac Injector of LEP/CERN. These BPM are the magnetic monitors. At last (and the most spectacular) we also use a system composed with a CCD monitoring the fluorescence light from a crystal when it is put into the beam path.

3. The target-ion source ensemble

To produce neutron-rich nuclei by photofission, a thick target containing 72 g of uranium in a standard form of UC_x is used. The target is made of a series of UC_x pellets with a total length ≈ 19 cm. It is placed in a graphite container which is surrounded by a Ta oven with a thickness of 0.5 mm and heated up to about 2000 °C. Details of this target properties can be found in [9]. A picture of the target ion-source ensemble is shown in Fig. 3. The absolute density of the UC_x pellets is 3.5 g/cm^3, however, due to spacing between the pellets the effective overall density is reduced to 3.2 g/cm^3.

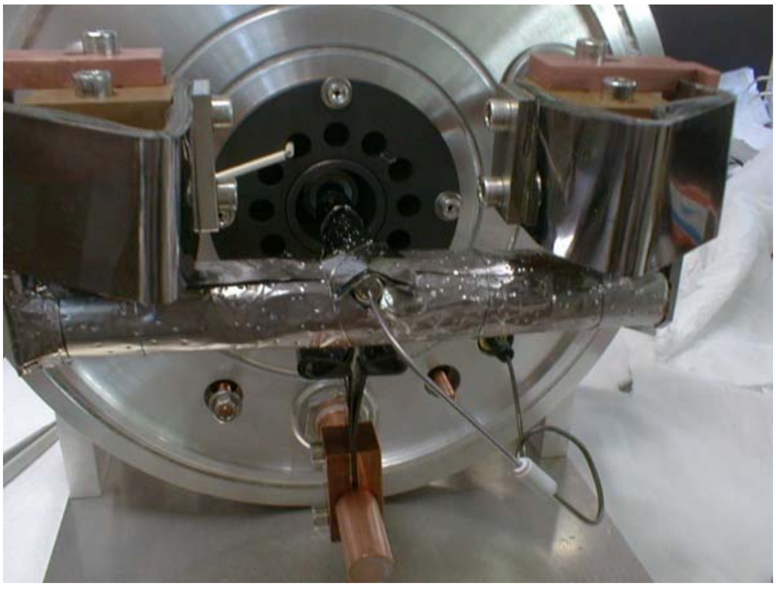

FIG. 3. The target-ion source ensemble.

A simulation using the FLUKA code [12, 13] shows that the 50-MeV incident electrons lose the major part of their energy after a mean path of 2.65 cm inside the target. One can see in Fig. 4 that the fission rate inside the targets tends to saturate with the target length. The saturation is reached for a target length of ≈ 7 cm.

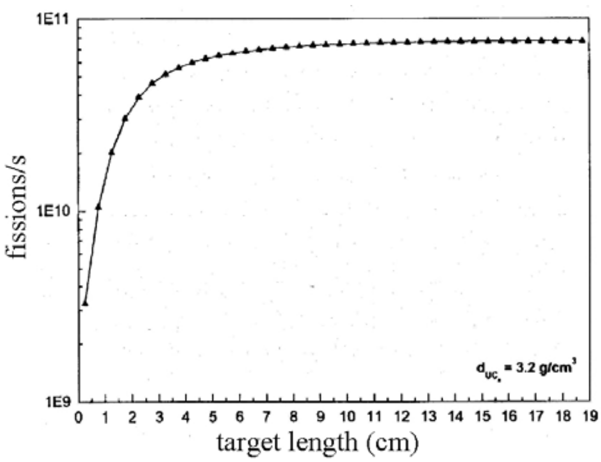

FIG. 4. Total number rate of fission inside the target as a function of the target length.

The results from the simulation for the spacial distribution of the fission rate inside the target are shown in Fig. 5: it is clear that the major part of the photofission events take place in the first few centimeters of the target. Since the hole which connects the target container to the ion source is pierced in the middle of the container (0 cm coordinate in Fig. 5) it is conceivable that this could have a significant influence on the effective release times for certain elements. A systematic comparison of the measured yields between the two experiments is presented and discussed in [9]. During the test-run of June 2006 the target was connected to a hot plasma ion-source of the MK5 ISOLDE type [11] in order to be in the closest conditions as possible with the equivalent test-run using the deuteron beam which was realized in December 2000 [10].

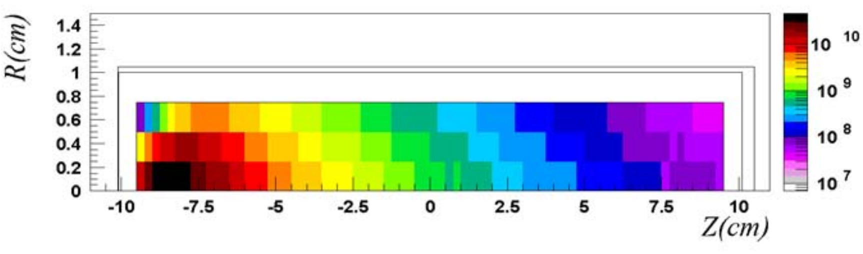

FIG. 5. Simulation of the distribution of the fission rate in the UCx target in number of fission/cm^3/s for an incident electron beam of 10 µA at 50 MeV (the assumed target density is 3.2g/cm^3).

4. Safety aspects

For safety reasons, the test-run of June 2006 had to be realized in radiological conditions similar to those encountered during the preceding fast neutron experiments *i.e.* similar dose rates inside the Tandem experimental rooms (and actually similar fission rate inside the target). These running conditions were then carefully simulated before the experiment [14]. Using the FLUKA code, *efficient* dose rates induced by γ-rays were simulated for the regions inside and in the close vicinity of the cave 210 of the Orsay Tandem induced by a 100 nA electron beam hitting the UC_x target and the subsequent photofissions. In Fig. 6 are represented mean values of the simulated *efficient* dose rates. These values correspond to an average of the *efficient* dose rate over 1 m in vertical direction around the beam position. During the experiment the *equivalent* dose rates were measured at the high of the beam in four positions immediately situated behind the cave 210 shielding points are indicated by the numbered dots in Fig. 6.

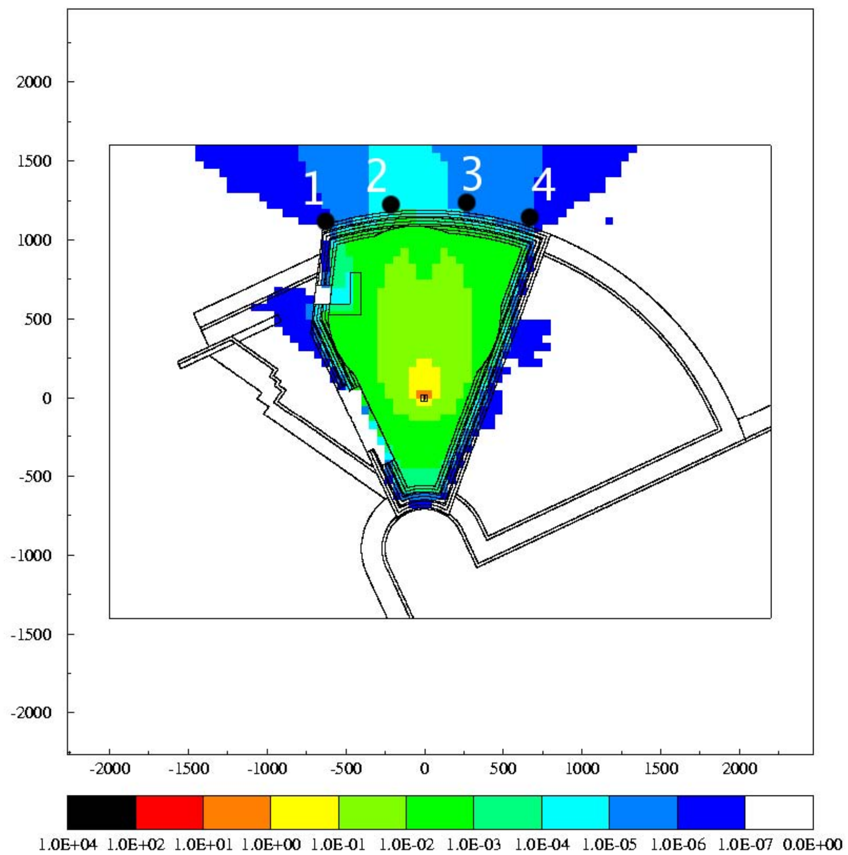

FIG. 6. Simulation of the distribution of the efficient dose rates in and around cave 210, dose rates on the scale are given in Sv/hour (taken from [14]). Vertical and horizontal scales on the map are in cm.

The measured values are reported in Tab 2. One can see that the agreement with the prediction from simulation is excellent. This good agreement gives us confidence in the shielding as it has been dimensioned and designed for the 10µA nominal electron beam.

1	4
2	200
3	34
4	6

Table 2 Equivalent dose rates due to γ ray measured during the test-run of june 2006 (μSv/h).

4. measured beam intensity at ALTO

The intensities of the different mass-separated fission-product beams were characterized on the PARRNe beam line. The beam was collected on a mylar tape and the activities of the different collected isotopes were quantified by detection and identification of the characteristic γ-rays. Details of the experimental setup and the measurement procedures are found in [10]. Masses from A=78 to 95 and A=117 to 144 (plus A=160) were systematically

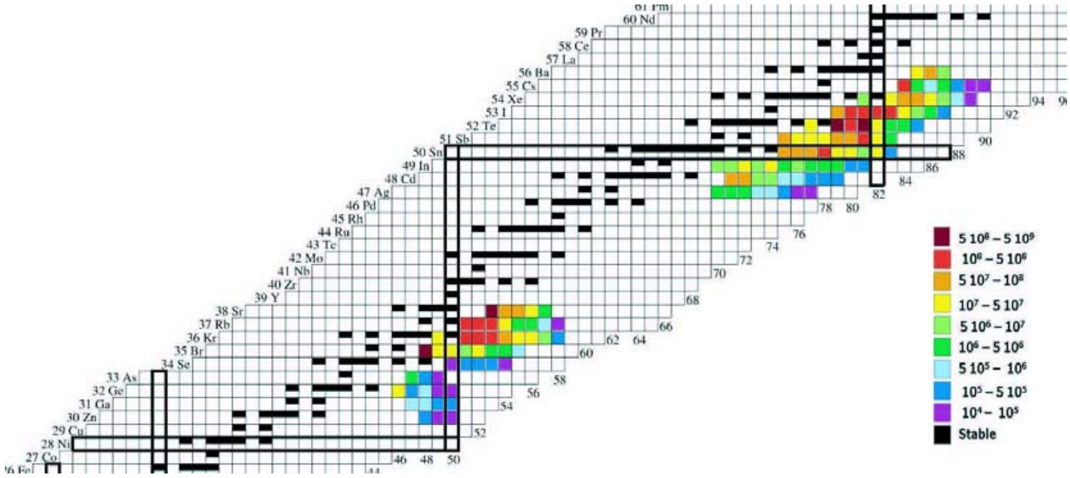

FIG. 7. Yields of fission-fragments in number of ion/s after extraction and mass separation measured at ALTO with an e-beam intensity reduced to 100 nA (instead of the nominal 10 μA).

studied. Comparison with the intensities previously measured in the fast-neutron induced experiment of December 2000 shows that the order of magnitude is the same as with primary beam of 14-MeV deuterons of 1μA and a primary beam of 50-MeV electrons of 100 nA. These measured yields happen to be in good agreement with both numerical simulations and empirical estimates [10]. Hence we expect from now on to reach yields of mass-separated fragments 10 to 100 times higher by simply increasing the electron beam intensity of a factor 100 and *without* special efforts on the source efficiency and target release times. The intensities measured in the test-run of June 2006 are summarized in Fig 7.

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