

Enhanced laser-driven radioisotope production using a helical coil target with tube

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(Received 10 January 2025; accepted 22 July 2025; published 9 September 2025)

We present a comprehensive study unveiling advancements in α particle spectra manipulation that can be achieved through the implementation of a helical coil target with tube (HCT). Leveraging particle-in-cell simulations, we demonstrate the ability to control the energy distribution of α particle bunches within a narrow range, down to a few MeV. This development marks the first instance of successful ion energy manipulation facilitated by the HCT configuration. Importantly, our investigations reveal a significant enhancement in radioisotope production, with yields ranging from 10 to 3000 times greater with an HCT than without. These findings underscore the transformative potential of the HCT approach in improving α particle production in the context of laser-plasma acceleration and its consequential impact on radioisotope production for diverse applications. We also investigate the production of radioisotopes using proton acceleration with the HCT configuration and demonstrate that the yield can be increased by a factor of 30.

DOI: [10.1103/fg53-l53v](https://doi.org/10.1103/fg53-l53v)

I. INTRODUCTION

Radioisotopes, natural or synthetic, are unstable nuclides because of an excess of nuclear energy. Around 90% of radioisotopes are used for medical diagnostic purposes, mainly β^+ (like ^{18}F , ^{43}Sc , or ^{44}Sc) and short-life emitters (like ^{123}I or $^{99\text{m}}\text{Tc}$) whereas β^- (^{47}Sc , ^{177}Lu , ^{131}I , or ^{90}Y) and alpha emitters (^{225}Ac , ^{211}At , ...) are exploited for medical therapy [1]. They are produced either with cyclotrons [2] by nuclear reactions induced by protons, alphas, or heavier ions or with nuclear reactors by reactions initiated by neutrons. The supply of medical radioisotopes is a sector in constant tension. The main problem is related to the cost of the necessary infrastructures and their aging. A compact and versatile laser-plasma accelerator able to produce protons or α particle beams of several tens of MeV in the same place could answer this issue.

One of the most widely used methods for laser-driven ion acceleration is the target normal sheath acceleration (TNSA) scheme [3,4]. In this regime, a high-intensity laser interacts with a solid target, inducing electron expulsion

from the target's front to its rear surface via the ponderomotive force. This process leads to charge separation within the target material and, when these electrons exit the back side of the target in vacuum, results in the generation of a static electric field reaching several TV/m. Consequently, protons from surface contaminants on the initially undisturbed rear surface are promptly accelerated to energies in the MeV range. However, for radioisotope production, the generated proton beam presents one major drawback: a broadband energy distribution that is exponentially decreasing with a cutoff energy increasing with the laser intensity. These features do not allow for efficient aiming of the maximums of the cross-section reaction. Moreover, the generation of protons at unsuitable energies might produce undesired radioisotopes.

Meanwhile, the concept of proton-boron (pB) fusion, envisioned as early as the 1930s [5], was realized through laser-induced fusion [6]. This fusion reaction, $p^+ + {}^{11}\text{B} \rightarrow 3\alpha + 8.7 \text{ MeV}$, offers distinct advantages, notably neutron-free production of α particles. The absence of neutrons simplifies system design and reduces radiation protection costs. Moreover, pB fusion holds promise for medical radioisotope production. However, a notable drawback of pB fusion for radioisotope production or any application relying on α particle beams, is the quasi-isotropic nature of the α particle flux. Another drawback is, as for TNSA, a broad energy spectrum of the α particle beam that does not allow efficient radioisotope production and might also produce undesired (harmful) radioisotopes.

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To address the limitations on proton beam, several improvements have been studied such as helical coils [7] or self-guiding through low density plasmas [8]. We propose to use a new design of helical coil targets with tubes (HCT) that we have developed [9] to overcome the limitations on α particle beams. The acceleration scheme using helical coil targets was first proposed by Kar *et al.* [7] to focus, postaccelerate, and bunch a proton beam generated by TNSA. During the laser-foil target interaction, the expulsion of hot electrons triggers a discharge current [10] that propagates through the helix connected to the target's rear side. In this configuration, an electromagnetic pulse is generated inside the helix, and the longitudinal component of the electric field postaccelerates and bunches the proton beam, whereas the radial component focuses it. This concept was demonstrated in several experiments [7,11–14], but the efficiency of this scheme in terms of energy bunching and postacceleration remains limited due to the current dispersion during its propagation through the helix [11]. To address this issue, Hirsch-Passicos *et al.* have recently proposed adding a conducting tube around the helix to mitigate dispersion and produce a bunching effect [9]. Furthermore, a previous experiment demonstrated for the first time, the effects of HC targets on carbon ions, while simulations suggested the possibility of bunching heavier ions such as carbon ions [15]. In this paper, we propose, for the first time, using HCT to shape not only the proton beam but also the α particle beam generated in the pB fusion reaction in a pitcher-catcher configuration. In that setup, protons and α particles are focused using HCT on a secondary calcium (Ca) target to produce scandium (Sc) isotopes (see Figs. 2 and 3). This paper presents preliminary simulation results for optimizing radioisotope production using HCT. The purpose of this study is to provide a comparative analysis of radioisotope production using HCT with protons versus HCT with α particles, with the objective of identifying the optimal approach to increase the number of produced radioisotopes and select the desired radioisotope.

As a first step, the different reactions for radioisotope production and their cross sections, as well as the strategy to optimize the radioisotope production, are presented in Sec. II. The setup for protons is described in Sec. III A and the one for the α particles in Sec. III B. Section IV is dedicated to the description of the simulation chain. Finally, the results of simulation are presented in Sec. V. An evaluation of the number of produced radioisotopes, with or without HCT, is performed for proton and α configurations.

The objectives of this work are to demonstrate our ability to postaccelerate, focus, and select in energy (bunch) laser-produced proton and α particle beams using HCT and to identify the most effective way to produce radioisotopes by laser-plasma interaction.

II. RADIOISOTOPE PRODUCTION

This chapter focuses on the production of scandium isotopes, specifically ^{43}Sc , ^{44}Sc , and ^{47}Sc , due to their potential in various medical applications [1].

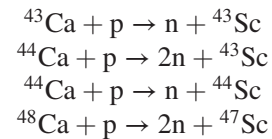
^{43}Sc and ^{44}Sc are positron-emitting radioisotopes that are highly suitable for use in positron emission tomography (PET) [16], a powerful diagnostic tool in oncology and other medical fields. Compared to conventional PET radioisotopes such as ^{18}F or ^{68}Ga , scandium isotopes offer advantages such as longer half-lives and more favorable decay properties, which allow extended imaging time windows and simplified logistics for radiopharmaceutical preparation and delivery [2,17,18].

^{47}Sc , on the other hand, is a particularly promising β^- emitter for targeted radiotherapy, where it can deliver therapeutic doses while also allowing real-time imaging through gamma emission [19,20]. This makes ^{47}Sc an excellent choice for radiation therapy applications, including radiolabeled drugs for treating tumors.

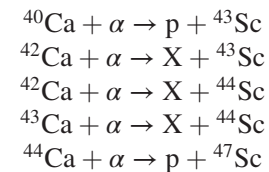
Furthermore, $^{43/44}\text{Sc}$ and ^{47}Sc being isotopes of the same atom, their chemical properties are identical: they can be incorporated within the same vector molecules. Thus, a macroscopical amount of the patient-injected radiopharmaceutical can be made such that it contains useful quantities of both types of isotopes. This allows for the theranostic technique [21] but using the same radiopharmaceutical for both diagnostic and treatment. This method of using pairs of matched isotopes allows for personalized medicine, i.e., more efficient patient-optimized deposition of dose [22].

A. Reactions

To produce scandium isotopes, we use incident protons or α particles to interact with a calcium target. For protons, the reactions of interest are as follows:



and for α particle, the reactions are as follows:



where X means other products, such as protons, neutrons, etc. The ^{40}Ca represents 97% of the natural Ca, ^{44}Ca represents 2%, ^{42}Ca represents 0.6%, ^{48}Ca represents 0.2%, and ^{43}Ca represents 0.1%. These ratios are important for interpreting the results presented in Sec. V.

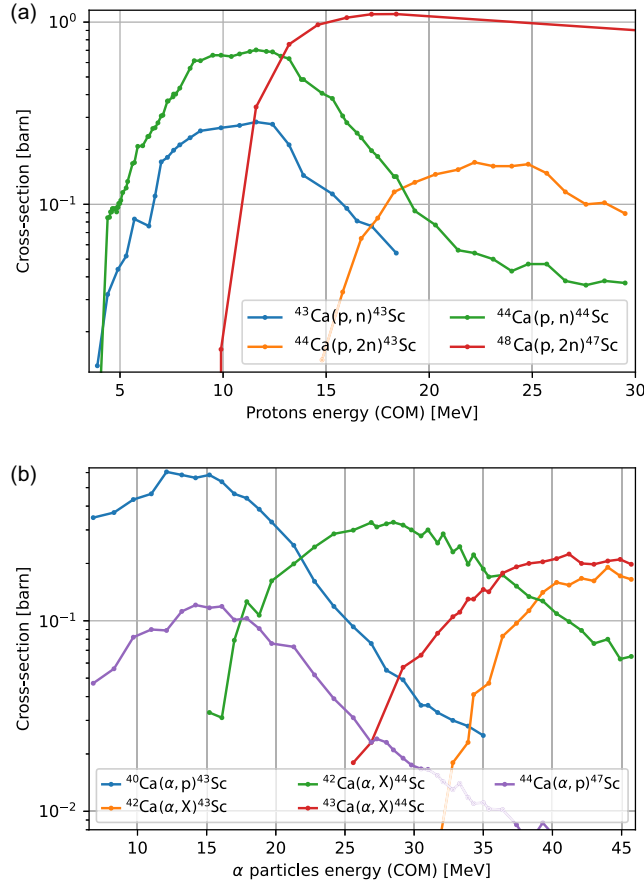


FIG. 1. Cross sections of the main reactions between calcium and (a) protons or (b) α to produce different scandium radioisotopes depending on the energy of the incident particles in the center of mass.

B. Cross sections

The proton-calcium cross section is shown in Fig. 1(a). A production of ^{43}Sc and ^{44}Sc starts at 5 MeV proton energy while ^{47}Sc needs 10 MeV. A cross section for ^{44}Sc starts at 15 MeV of proton energy. Also, because cross sections are quite narrow, energy bunching of particles is as important as postacceleration to select the desired cross section and produce the wanted radioisotope.

The cross sections presented in Fig. 1(b) for incident α particles show two points that must be taken into account. First, production of ^{47}Sc and ^{43}Sc only needs 10–25 MeV alphas energy while ^{44}Sc needs 20–40 MeV. Second, one can observe that the cross sections are also quite narrow. Therefore, energy bunching is mandatory.

C. Strategy

The growing interest in scandium-based isotopes has motivated efforts to develop efficient production methods using laser-driven ion acceleration. In this context, we explore how the implementation of advanced target technologies, such as the helical coil target, can optimize ion

acceleration to enhance radioisotope yields. This approach not only aims to validate simulation predictions but also paves the way for scalable production methods for medical radioisotopes.

The implementation of the HCT allows for the creation of a concordance between the energy range of bunched protons and the reaction cross section. For that, we use the capability of the HCT to postaccelerate and energy bunch proton spectra to increase the number of produced radioisotopes. The same principle can be applied to heavier ions. Indeed, the work performed by the electric field, defined as $W = \int_0^l qEdl$, is solely dependent on the charge and not on the particle's mass. Consequently, the energy gain of the α particles should exceed that of protons. Our challenge is to design, for the first time, an HCT geometry to postaccelerate and bunch α particles within the energy range of the nuclear reaction cross section (refer to Fig. 1). To do this, we focus on the production of protons and α above 10 MeV.

III. SETUP

A. Proton setup

We present the conventional HCT configuration in Fig. 2. This setup facilitates the generation of protons and discharge current. The discharge current propagates along the helical coil, inducing longitudinal and radial electric fields, which lead to proton bunching, acceleration, and focusing. The electromagnetic field is described in the previous publication [23]. In the final stage, these accelerated protons interact with the calcium target to produce scandium radioisotopes.

B. α setup

In the α configuration, a pitcher-catcher geometry is used as shown in Fig. 3. The laser-pitcher interaction triggers protons and a discharge current pulse. Protons interact with the catcher (boron target) and produce α particles in fusion reactions, while the current pulse propagates through a wire

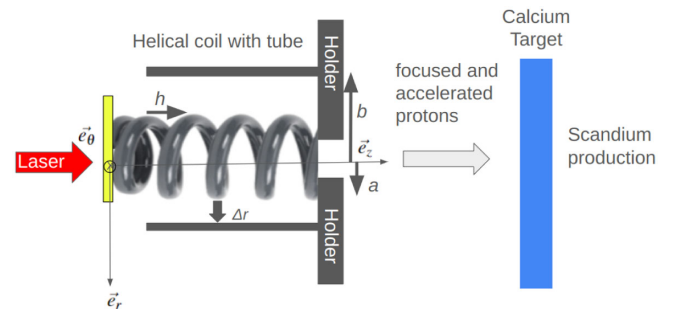


FIG. 2. Scheme of a helical coil with tube where the laser beam interacts with a foil target, accelerates protons, and creates a discharge current. The latter propagates in the HCT, postaccelerates, energy bunches, and focuses protons on a calcium target and produces radioisotopes. The helix is surrounded with a thin cylinder which is symmetric by rotation around the z axis.

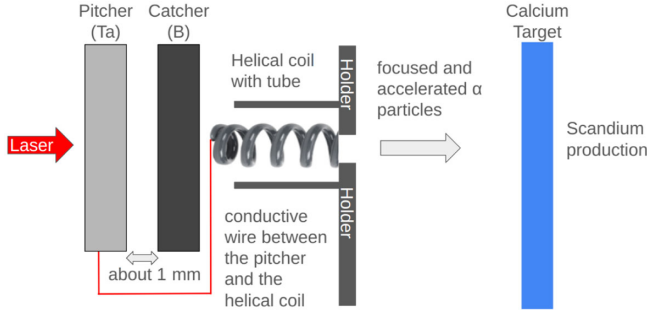


FIG. 3. Scheme of a pitcher-catcher configuration where the laser interacts with the pitcher to accelerate protons which in turn interact with the catcher and produce α particles. A wire conducts the discharge current produced by the pitcher and injects it on a HCT, to focus and postaccelerate α particles which interact a calcium target to produce scandium radioisotopes.

to the HCT. In the third stage, the discharge current propagates through the helical coil and bunches, accelerates, and focuses the α particles. In the final step, α particles interact with a calcium target to produce scandium radioisotopes (^{43}Sc , ^{44}Sc , or ^{47}Sc).

IV. SIMULATION CHAIN

A. Method

The simulation chain is composed of a three-dimensional (3D) particle-in-cell (PIC) code SOPHIE [24] to model the particle-wave interaction inside the HCT and a code FLUKA [25], a Monte Carlo transport code to evaluate the number of produced radioisotopes. In this study, TNSA proton spectra are derived from experimental measurements in two different facilities (INRS/ALLS and ILE/LFEX). They are used as input for SOPHIE simulations. These experimental data also serve as input in FLUKA to evaluate the reference case without HCT. The main SOPHIE output is the proton spectrum at the helix exit, which serves as input for FLUKA simulations.

Simulations in Sec. VA are performed using the ALLS ion acceleration beamline parameters. The Ti:Sapphire ALLS 150 TW laser, operates at a repetition rate of 2.5 Hz with a central wavelength of 800 nm. The system delivers laser pulses with an on-target energy of 3.3 J, duration of 22 fs, and peak intensity of about $1.3 \times 10^{20} \text{ W/cm}^2$. These simulations are directly linked with our previous publications [9,23] where we demonstrated the HCT capability to bunch protons around the energy of the maximum cross-section reaction with ^{43}Ca , ^{44}Ca , and ^{48}Ca [see Fig. 1(a)]. Other simulations are carried out with the data obtained at LFEX (Laser for Fast Ignition Experiment) laser [26]. The LFEX laser was engineered to achieve specific parameters: a pulse duration ranging from 1 to 10 ps with an output energy of 1 kJ. Operating at a wavelength of 1.05 μm , the laser achieves a cone-focused

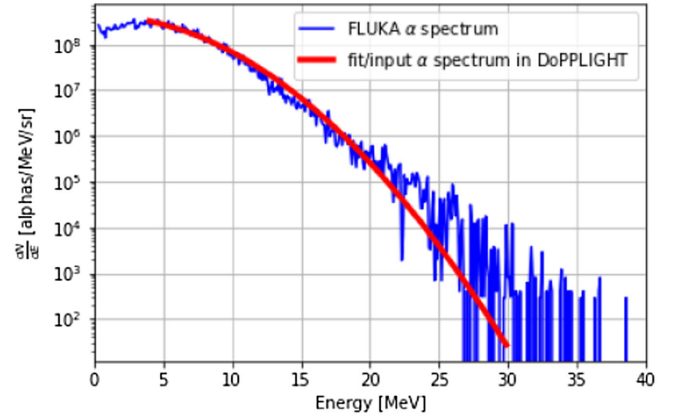


FIG. 4. α energy distribution obtained with FLUKA (blue curve) and the exponential fitting used for SOPHIE input (red curve).

spot diameter of 50 μm . In our simulations, we use 1 kJ and 1 ps for the energy and duration of the LFEX laser.

For α particles, we take as a starting point simulations of α particle production data from the LFEX campaign [27,28]. The baseline simulation of a 200 μm boron target irradiated with a TNSA proton beam is performed with FLUKA [28]. The α spectrum shown in Fig. 4 is taken at the rear side of the catcher target and used as input for SOPHIE simulations. This spectrum also serves as input in FLUKA to establish a reference case without HCT. The SOPHIE output spectrum is injected into FLUKA to model the interaction with the calcium target. Thanks to this simulation chain, the number of produced radioisotopes can be evaluated, with and without HCT, for proton and α configurations. The simulations for the α particles are conducted exclusively using LFEX parameters. Due to ALLS's lower energy, the α particles produced with it do not have sufficient energy to trigger the reactions whose cross sections are shown in Fig. 1. Additionally, the lower number of particles generated by ALLS means that there are not enough α particles to use the HCT effectively. As discussed in Sec. VA, HCT introduces significant particle losses, so a large initial number of particles is required before applying the HCT.

B. SOPHIE

SOPHIE [24] is a 3D FDTD-PIC code, that solves Maxwell's equations both in vacuum and within materials. The code handles boundary conditions encompassing perfect electric conductors, dielectrics, and magnetic materials. In tandem, Newton's second law of dynamics governs the relativistic particle propagation in vacuum, employing Boris' solver [29]. The attainment of self-consistency is realized through the implementation of Buneman current collectors. Of particular note is the use of boundary conditions, such as perfect electric conductors, which obviate the necessity of macroparticles for current propagation through the helix. This strategic design alleviates constraints on problem size while facilitating simulations.

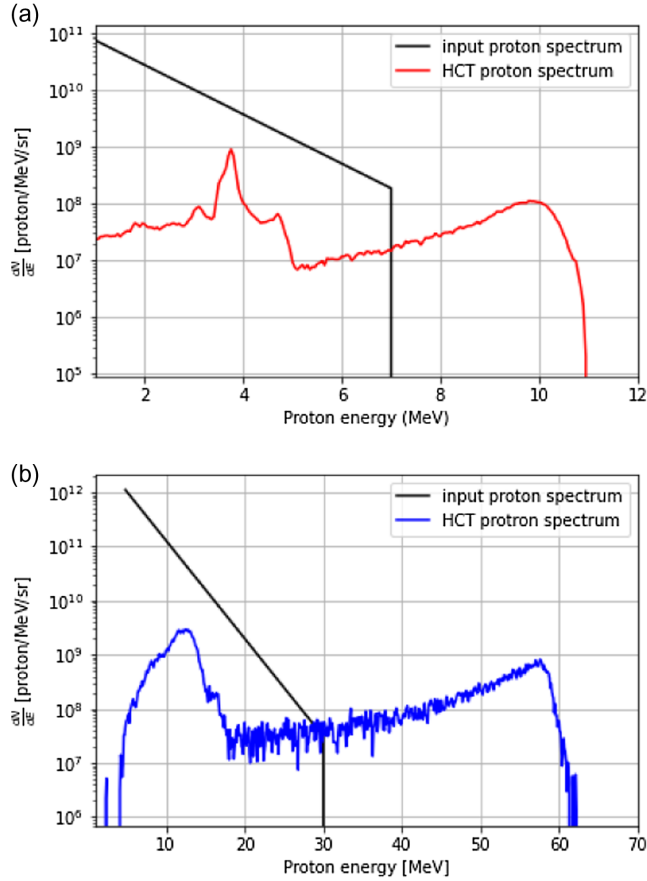


FIG. 5. Energy distribution of the accelerated protons at the HCT exit for INRS (a) and LFEX (b) calculated with the SOPHIE code. Black lines show the input proton spectrum at the HCT entrance. HCT parameters are as follows: a radius $a = 0.5$ mm, a pitch $h = 0.35$ mm, a tube of radius $b = 0.7$ mm, and a length $L = 15$ mm for the ALLS facility, and a radius $a = 0.6$ mm, a pitch $h = 0.864$ mm, a tube of radius $b = 1$ mm, and a length $L = 15$ mm for the LFEX facility.

SOPHIE can operate on large scales as it does not resolve the laser wavelength, simulating grids spanning several centimeters and extensive time intervals of the order of nanoseconds. This capability renders SOPHIE indispensable for modeling the physics of HCT.

In the simulations, we consider a helical coil attached to the rear side of a foil target. The target, coil, and holder are modeled as perfect conductors and meshed at real scale with a cell size of $\Delta x = \Delta y = \Delta z = 20$ μm , resulting in 2×10^9 cells distributed over a volume of 72 cm^3 . Electrons, protons, and α -particles are represented using 10 million macroparticles.

The energy and angular distributions of the injected protons are based on experimental measurements with TNSA without a helical coil. The energy distribution corresponds to the black curve in Figs. 5(a) and 5(b), respectively, for the ALLS and LFEX facilities, while the α particle energy distribution is shown in red in Fig. 4.

The angular distribution follows a super-Gaussian function $dN_p/d\theta \propto \exp[-(\theta/\theta_p)^{10}/2]$, with $\theta_p = 19^\circ$ for protons and $\theta_p = 90^\circ$ for α particles. The temporal profile of the particle emission dN_p/dt is modeled as a Gaussian function with a full width at half maximum duration τ of a few ps. Although its exact value is unknown, it remains negligible compared to the proton transit time (> 100 ps) through the coil and their final bunch duration caused by time-of-flight dispersion. The transverse size of the particle emission zone is set to $200 \mu\text{m}$.

The proton and α -particle dynamics inside the helical coil are governed solely by the electromagnetic fields generated by the discharge current. To model this discharge current, isotropically emitted electrons are introduced with an energy distribution similar to that of the protons. The electron emission zone matches the protons' transverse size of $200 \mu\text{m}$.

For the ALLS facility, the electron emission is set to 160 nC , while proton emission is 12 nC , both with an emission duration of 7 ps [9,30]. For the LFEX facility, the electron emission is 1600 nC , the proton emission is 1200 nC [27,31], and the α -particle emission is 4.5 nC , all with an emission duration of 14 ps .

The radial electric field, generated by the current pulse propagation through the coil, focuses protons and defocuses electrons. Therefore, inside the helical coil, the TNSA particle beam is deneutralized. If the proton ejected charge is lower, it decreases the space charge (Coulomb repulsion) and, therefore, the cut-off energy, but increases the retrieved number of protons at the exit. If the number of ejected electrons is lower, it reduces the discharge current intensity and therefore the number of protons retrieved at the exit, due to the lower focussing and the angular aperture of the helical coil, and decreases the cut-off energy due to the lower longitudinal electric field, responsible for the acceleration [9,23,32].

C. FLUKA

The FLUKA code [25,33] stands as a versatile Monte Carlo simulation tool designed to comprehensively model the interaction and transport of particles across various mediums. Its development is rooted in the aspiration to incorporate the most robust and precise physics models, ensuring a microscopic approach where each computational step is underpinned by sound physical principles.

This code exists in two versions: one from CERN and one from INFN. Here, the version from INFN [34] was used with 200 million particles per simulation. The target size is $5 \times 5 \times 2 \text{ mm}$ of $^{\text{nat}}\text{Ca}$ inside a very large void region, with 2 mm being in the beam direction. This length is sufficient because the most energetic α particles of up to 60 MeV only go through two-thirds of the target. The input used is the proton and alpha spectrum sampled in bins of 0.1 MeV , which is then used for Monte Carlo type calculation.

The 2021 version of the code was used because special Fortran routines were developed that used MGDRAW results as SOURCE for FLUKA simulations. These are here needed when using α particle simulation results as input. The evaporation, coalescence, and peanut model modules are activated along with heavy ions transport. Radioactive decay uses the semianalog model for Monte Carlo sampling of the physical distribution. Results are then obtained using the RESNUCLE, or residual nuclei module, which gives a number of each isotope per code unit. We present in Sec. VB the total number of radioisotopes obtained.

V. RESULTS

A. SOPHIE simulations

To determine the helix parameters, radius a and pitch h , we compute the phase speed V_{HC} , corresponding to the longitudinal speed of a current pulse going at the speed c along the helical coil such that $V_{HC} = hc/\sqrt{h^2 + 4\pi^2 a^2}$. This phase speed determines the population of particles synchronized with the electromagnetic pulse having an initial energy $E_{HC} = \frac{1}{2}m_i V_{HC}^2$, where m_i is the ion mass. To determine the final energy of the bunch, one can then use the scaling law given in our previous publication [9].

1. Proton setup

To synchronize the phase speed V_{HC} with the proton velocities, two distinct geometries are required for ALLS and LFEX. For the ALLS facility, the geometry needs to be optimized for lower energy protons (with a maximum energy of 7 MeV), so we must decrease the pitch h or increase the radius a to reduce V_{HC} . In contrast, for the LFEX facility, due to the higher proton energies, we need to increase V_{HC} , which can be achieved by reducing the radius or increasing the pitch. SOPHIE simulations showcase the capability to achieve energy bunching around 3.5 and 10 MeV [refer to Fig. 5(a)]. The input of this SOPHIE simulation is the classical TNSA spectrum obtained from this facility (black curve). In the same way, for the LFEX facility, using the classical TNSA spectrum obtained from this facility (black curve) as input of the SOPHIE simulation, and adding a helical coil yields a first bunch at 12 MeV and a second one at 57 MeV [see Fig. 5(b)]. For both cases, the number of protons at the HCT exit is low (yield of about 1%) compared to those at the entrance (black curves). This HCT limit is discussed in previous publications [9,23,32]. However, what is not shown in these graphics is the number of protons/MeV/sr which has increased due to the focusing effect of the HCT. These HCT proton spectra are used as input data for FLUKA simulations.

2. α setup

With SOPHIE, we can simulate the propagation and acceleration of α particles in the HCT. Figure 6

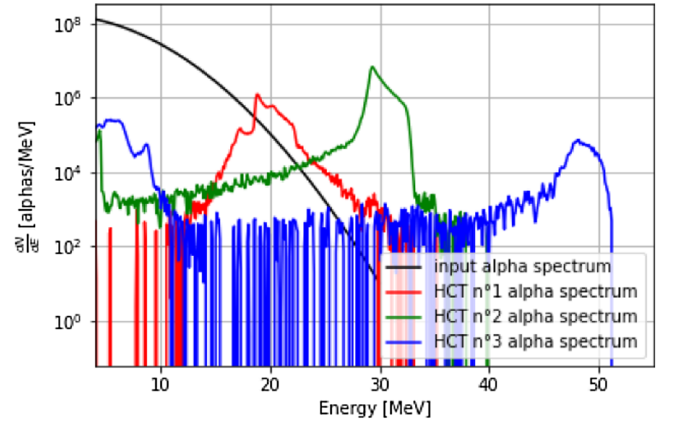


FIG. 6. Energy distribution of the α particles accelerated in different HCT geometries. The black line shows the input α spectrum at the HCT entrance. In this figure, we show three different HCT geometries $a = 0.9$ mm, $h = 0.3$ mm, and $b = 1.3$ mm (red curve, HCT n°1); $a = 0.8$ mm, $h = 0.4$ mm, and $b = 1$ mm (green curve, HCT n°2); $a = 0.5$ mm, $h = 0.35$ mm, and $b = 0.9$ mm (blue curve, HCT n°3) and a length $L = 15$ mm.

demonstrates that, even if the number of exiting α particles remain low, the HCT facilitates significant energy bunching within the range of 20–50 MeV, dependent on parameters such as the radius a and pitch h . What this figure does not show is the increase in the number of α per solid angle (decreasing the angular dispersion from 45° to 1°), in the energy range of the bunch, compared to the input α spectrum. These findings represent a pivotal contribution of this paper: they demonstrate, for the first time, our ability to manipulate heavy ion energies using the HCT configuration (it was already demonstrated for protons). These HCT α spectra are used as input data for FLUKA simulations.

B. FLUKA simulations

1. Proton setup

Radioisotope production of scandium from natural calcium has been looked at for two distinct proton acceleration laser systems: INRS and LFEX. The two regimes give varying proton spectra ranging from 10 to 50 MeV. As such, we numerically study the radioisotope production, with and without HCT, comparing the results to the number of protons per shot.

As seen in Table I, for both facilities, the yield is significantly increased with the HCT configuration. In the case of the LFEX laser, the number of radioisotopes is increased by a factor of 2 to 14 (2 for ^{44}Sc , 8 for ^{47}Sc , and 14 for ^{43}Sc). For the INRS case, we get an increase factor of 30 for the two isotopes: ^{43}Sc and ^{44}Sc . Due to the low energy range of protons, no ^{47}Sc is produced—either with or without HCT—in the INRS case.

TABLE I. Number of radioisotope atoms per shot, obtained using our simulation chain for each facility, with and without HCT, using the proton setup.

N/shot	^{43}Sc	^{44}Sc	^{47}Sc
No coil LFEX	44	1144	36
Coil LFEX	634	2400	288
No coil INRS	5	31	None
Coil INRS	170	962	None

These increases come from the fact that with the helical coil on INRS setup, we increase the proton cut-off energy up to 10 MeV. Thanks to this, one can reach the peak of the cross sections for $^{43}\text{Ca}(p,n)^{43}\text{Sc}$ and $^{44}\text{Ca}(p,n)^{44}\text{Sc}$ reactions [see, respectively blue and green curves on Fig. 1(a)] which were unattainable without helical coil. Concerning LFEX setup, we trigger $^{44}\text{Ca}(p,2n)^{43}\text{Sc}$, $^{44}\text{Ca}(p,n)^{44}\text{Sc}$, and $^{48}\text{Ca}(p,2n)^{47}\text{Sc}$ reactions [see the green, orange and red curves, respectively, in Fig. 1(a)]. The high-energy protons lose energy propagating inside the calcium target and increase their probability of interaction, enhancing the yield even more. Additionally, the use of helical coil increases the number of protons with energies above 20 MeV, which corresponds approximately to the cross-section peaks of $^{44}\text{Ca}(p,n)^{44}\text{Sc}$ and $^{48}\text{Ca}(p,2n)^{47}\text{Sc}$ reactions.

2. α setup

Cross sections for the production of different calcium isotopes are shown Fig. 1; these indicate which energy ranges should be aimed for with the α particles spectrum. SOPHIE simulations have showcased great advance for α particles bunching and acceleration which can greatly increase the yield of radioisotopes.

As shown in Table II for ^{43}Sc and ^{44}Sc , we have obtained, respectively, a multiplication by 50 and 3000 using HCT. ^{47}Sc yields have also been improved by factors 100 for the HCT n°2 and n°3. One can, therefore, conclude that the energy bunching effect compensates for the reduction in the number of incident particles, and that, thanks to the helical coil, the number of produced radioisotopes can be greatly increased.

Indeed, with the HCT n°1, one can increase the number of particles with energy above 15 MeV which correspond to the maximum of the $^{40}\text{Ca}(\alpha,p)^{43}\text{Sc}$ and $^{44}\text{Ca}(\alpha,p)^{47}\text{Sc}$

 TABLE II. Number of radioisotope atoms per shot, obtained using our simulation chain for each facility, with and without HCT, using the α setup.

N/shot	^{43}Sc	^{44}Sc	^{47}Sc
No coil	1181	0.1	1
HCT n°1	53,000	0.4	6
HCT n°2	46,000	342	114
HCT n°3	8260	242	159

cross sections (see blue and purple curves, respectively, in Fig. 1(b)). With the HCT n°2 and 3 one can trigger the $^{42}\text{Ca}(\alpha,X)^{43}\text{Sc}$, $^{42}\text{Ca}(\alpha,X)^{44}\text{Sc}$, and $^{43}\text{Ca}(\alpha,X)^{44}\text{Sc}$ reactions (see the orange, green, and red curves, respectively, in Fig. 1), which was unattainable without helical coil. Similarly to protons in the previous paragraph, α particles of energies higher than those near the peak of the cross sections (above 30 MeV) slow down propagating inside the calcium target: their energy is reduced to more optimal values and thus their probability of reaction is increased. This also allows the trigger the $^{44}\text{Ca}(\alpha,p)^{47}\text{Sc}$ reaction whose cross-section peak is at lower energies.

α particles are more efficient than protons at producing ^{43}Sc , primarily due to the natural proportion of calcium isotopes. Protons react with ^{43}Ca , which constitutes only 0.1% of natural calcium, whereas α particles react with ^{40}Ca , which makes up 97%. Additionally, to fully understand these results, it is crucial to consider the differences in reaction cross sections for the respective processes such as been done in this work.

VI. CONCLUSION

Nuclear reactions require specific energies to take place, and it is sometimes necessary to have bunches of particles at the maximum of the cross-section reaction in order to obtain the highest number of products. HCT gives the opportunity to correct that aspect in laser-accelerated proton and α spectra as these are usually too broad to aim for a specific nuclear reaction.

Our numerical study unveils a potential advancement in α particle manipulation enabled by the innovative helical coil target configuration. Through particle-in-cell simulations using SOPHIE, we have demonstrated the possibility of controlling the energy distribution of α particle bunches. Moreover, our findings underscore the potential of the HCT for radioisotope production, with yields exhibiting a significant enhancement ranging from 50 to 3000 times greater compared to conventional laser plasma acceleration methods.

Furthermore, we have shown the interest of different setups such as the HCT configuration with protons to produce ^{44}Sc and the HCT configuration with α to produce ^{43}Sc . To produce ^{47}Sc , both α and protons with HCT are interesting, multiplying the number of produced radioisotope by a factor of 100 and 10, respectively.

This enhancement holds promise for various fields reliant on radioisotopes, including medicine, industry, and scientific research. Moving forward, the HCT presents a transformative avenue for advancing α particle acceleration techniques with high-intensity lasers, offering opportunities for further exploration and application in diverse scientific and technological domains.

Currently, radioisotopes are produced using high-energy proton or alpha beams generated by large cyclotrons, such

as ARRONAX in Nantes (France), which can deliver proton currents of approximately 10^{15} protons per second. In contrast, large-scale laser facilities can produce up to 10^{14} protons per shot via laser-driven acceleration, although the repetition rate is limited to a few shots per day. To achieve comparable production rates, a promising alternative is to use medium-intensity lasers operating at higher repetition rates. For instance, at INRS with ALLS laser facility, more than 10^{12} protons per shots can be produced at 2.5 Hz. Continuous advancements are being made in both laser intensity and repetition rate, driven by numerous companies active in the development of laser technologies. Additionally, parallel efforts are focused on increasing the proton yield per shot through optimization of laser parameters and target design. Indeed, the primary target could be optimized to yield more protons and the secondary target could be enriched in relevant isotopes for more reactions.

Eventually, to implement the helical coil in a high repetition rate setup, its setup will be adapted, and its multishot capabilities will be assessed in a future experiment.

ACKNOWLEDGMENTS

This work is supported by the CEA/Direction des Applications Militaires (DAM) laser plasma experiments validation project and the CEA/DAM basic technical and scientific studies project. This work is also supported by the National Sciences and Engineering Research Council of Canada (NSERC) (Grant-RGPIN-2023-05459, ALLRP 556340-20), Compute Canada (Job: pve-323-ac) as well as the Canada Foundation for Innovation (CFI). This work was granted access to the HPC resources of IRENE under the allocation No. A0170512899 made by GENCI. We acknowledge the financial support of the IdEx University of Bordeaux/Grand Research Program “GPR LIGHT,” and of the Graduate Program on Light Sciences and Technologies of the University of Bordeaux. The authors are grateful to V. Tikhonchuk and O. Cessenat for their help and useful discussions.

The authors have no conflicts of interest to disclose.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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