ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-MOPOGE03

DESIGN OF A LINEAR ACCELERATOR FOR ISOTOPE PRODUCTION

A.Pisent, C.Baltador, L. Bellan, M. Comunian, J.Esposito, L.Ferrari, A.Galatà, F.Grespan
INFN/LNL, Legnaro, Italy
P. Mereu INFN/Torino, Italy
L. Celona INFN/LNS, Catania, Italy

Abstract

The recent accelerator developments allow the design of very efficient linear accelerators for various applications. The possible use of concepts, components and developments well established or recently achieved in larger projects will be illustrated, with some examples related to isotope production for medical applications.

INTRODUCTION

The accelerator driven production of radioisotope for medical applications (for diagnostics, therapy and combined, so called theranostic) is one of the most important applications of nuclear techniques. The focus of INFN in the field has grown up in the last years, also in connection with the possible use of the new cyclotron at LNL able to deliver 0.5 mA of protons with variable energy range (35-70 MeV). Novel as well as already established radionuclides of medical interest may alternatively be produced using alpha particle beams [1-3], having energy ranging between few and 40 MeV. This new approach may allow to yield radionuclides hard to be obtained with more traditional nuclear reactors or by proton accelerators by exploiting new reaction routes. This approach may lead to better radionuclidic impurity profile, simplifying the radiochemical separation/purification process.

Interesting cases are, e.g., the alternative supply of ^{99m}Tc through the ^{96}Zr(α,n)^{99}Mo reaction route, or the very important theranostic ^{67}Cu (under the spotlight at international level) by using the ^{64}Ni(α,p) route. Other interesting products are based upon the reaction routes^{209}Bi(α,2n)^{211}At., or ^{nat}Mo(α,x)^{97}Ru. The use of cyclotron for α particles has an intensity limitation (mainly related to the extraction system): the IBA cyclotron at Arronax is for example limited to about 35 μA.

THE ALPHA DTL LINAC DESIGN

With the project alpha-DTL, presently under evaluation by INFN as interdisciplinary accelerator research program (CSN5 call), we propose an alternative approach with a high duty cycle normal conducting linac (high frequency, i.e. 352 MHz), composed by an ECRIS (electron cyclotron resonance ion source), an RFQ (radio frequency quadrupole) and a DTL (drift tube linac), as sketched in Fig.1; an average of 0.5 mA of fully stripped He can be delivered to the target (one order of magnitude better than cyclotrons). Moreover, we intend to develop an original idea to allow in the DTL the energy regulation on a large range. This accelerator will represent a clear step forward in the field of accelerator driven isotope production.

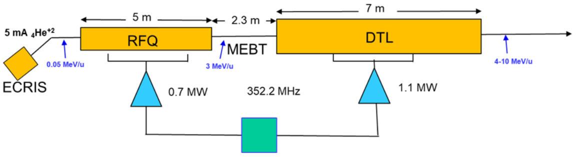

Figure 1: Block diagram of the alpha-DTL linac.

The design is based on the high power linac development by INFN in the last years. In particular, the RFQ uses the mechanics of TRASCO RFQ [4,5], 4 modules, and the tuning procedure developed for IFMIF-EVEDA [6]. The DTL uses the design developed for ESS [7, 8]. The RF system, two klystron and a single modulator, is the same of ESS normal conducting section.

The Background

Alpha-DTL project makes the best use of the unique competences and edge technologies developed by INFN, with application in a different field, new in terms of particle kind and applications. Moreover, the energy variation in a DTL is a substantial innovation in itself and opens to new applications; the DTL (well known for excellent efficiency in terms of beam dynamics and power consumption) can now be used as a flexible main linac to track energy dependent cross sections.

The implementation of the research program moves in four main directions, the beam dynamic design, the linac component development, the ion source and the solid target development. The first WP has the very important task to optimize the design (which for TRASCO RFQ and ESS DTL was though for high current protons) with A/q=2, with all the key performances, interfaces and limitations that characterize our system; moreover, the idea of energy variation is integrated in the design. A key ingredient of this optimization are the new algorithms developed for linac design based on genetic and AI techniques and heavy parallelization of the processes [9]. The second WP considers the design of the cavities and of the RF system, with a program of dedicated prototypes (actuated post-couplers for the DTL, new power couplers, new DT-tank interface…); also, 3D RF simulations allow unprecedented performances (for example a full DTL tank with all tuning and stabilizing devices). New milling machines allow substantial advantage with new geometry optimization. This WP has preeminent aspects in mechanics, rf design and control system. The third WP considers the ion source development, with a specific assessment of the reliable performances. The forth task is dedicated to assessing the solid target design for this specific application (10 kW beam power).

The aim of the alpha-DTL project during the 3 years of the call is to complete the R&D so to give a final answer to the few open questions and to prepare, possibly in a collaboration between INFN, European research institutes and industrial partners, the construction of this very performing instrument.

The Reference Design

A reference design for the RFQ, the MEBT and the DTL has been determined with the design code VERDE and the simulation codes of CEA. The parameters in Table 1 are the result of a quite vast exploration of the parameter space performed with AI methods. The results are illustrated in Fig. 2.

Table 1: Main Parameters of Alpha-DTL RFQ and DTL

Parameter	Symbol, unit	RFQ	DTL
Frequency	f [MHz]	352.21	352.21
Peak Current	I_p [mA]	5	5
Ion		${}^{4}He^{2+}$	${}^{4}He^{2+}$
Duty Cycle	D.C. [%]	10	10
Input / Output Energy	E_{in}/E_{out} [MeV/u]	0.05/3.0	3.0/10.125
Resonator length	L [m],L/λ	4.99, 5.874	7, 8.24
Maximum surface field	K_p	1.85	1.41
Transmission WB, Gaussian	[%]	92.5, 88.9	100, 100
Transverse Emittance in/out	$\varepsilon_{in,n,x,rms}/\varepsilon_{out,n,x,rms}$ [mm mrad]	0.2/0.17	0.35 /0.35
Longitudinal Emittance	$\varepsilon_{l,rms}$ [deg MeV/u]	0.129	0.17
Min and Max Voltage	V_{GB}, V_{acc} [kV]	68, 102.5	-
Average Acc. Field	E_0[MV/m]	-	2.6
Quadrupoles Gradient	G_{max}, G_{min} [T/m]	-	65, 45
Quadrupoles Length	[mm]	-	45
Average Aperture/ Quadrupoles Bore	$R_{0, GB}$ $R_{0, ACC}$ [mm]	2.55, 4.13	10
dissipated Power & beam loading (peak)	Pd, Pb [kW]	672, 29.5	794, 70

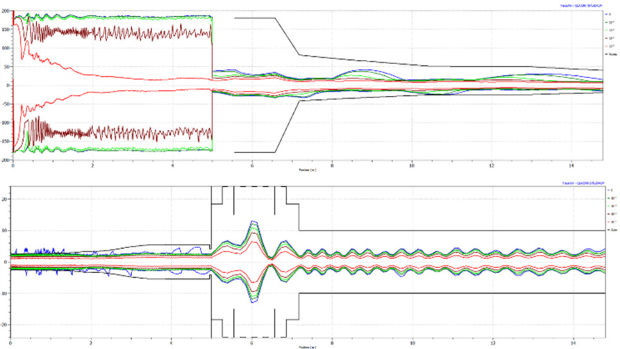

Figure 2: Start to end simulation from the begin of RFQ to the end of DTL.

The DTL Energy Variation

A distinctive feature of alpha-DTL is the final energy variation, obtained by acting on the RF system and on the actuators that mechanically rotate the post couplers.

In multicavity linacs (as ALPI), if the linac is set for the maximum energy, the energy decrease is achieved by switching off the last cavities; sometimes we readjust the transverse focusing strength. The DTL is a single cavity with permanent magnet quadrupoles (PMQ), so the final synchronous energy is determined by the geometry; if the field in the last part of the linac is decreased at 50-80% with respect to nominal one, the synchronous condition is lost (cos ϕ_s approx. 90%). Transversally the PMQ focusing channel can transport (with full transmission) the partially accelerated beam.

Alpha-DTL (as ESS DTL) is equipped with a set of post couplers terminated by stubs, to stabilize and flattten the accelerating field E_0 (Fig. 3). The key idea of the variable energy linac is the use of the post couplers to create a step in the field by means of rotation of the stubs (the reverse of what is done during tuning). Note that this new field configuration is still made stable against perturbation. The field step will terminate the acceleration process and will vary the beam output energy W_{out} (respect to the maximum energy, obtained with the flat field).

In Fig. 4 the steps obtained experimentally on ESS tank 3 by “detuning on purpose the post couplers are shown. In Fig. 5 an example of simulation at low energy, with full transmission.

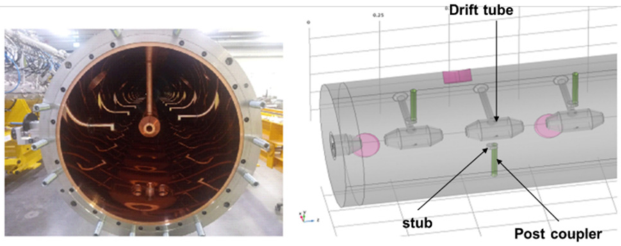

Figure 3: DTL cavity inner view and 3d simulation model. Post couplers with stubs are visible.

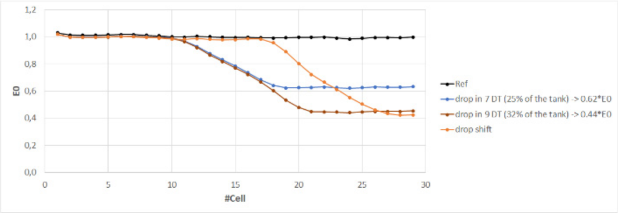

Figure 4: Field steps experimentally obtained by post coupler rotation in ESS-DTL3.

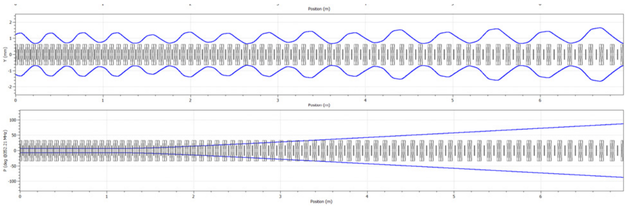

Figure 5: Only 1m out of 7 m of the alphaDTL accelerating (W_{out}=4 MeV/u).

The Source and the Injector

The required beam (5 mA He2+, 10% duty cycle) will be delivered by an ECRIS [10], where a plasma is created by microwave and magnetically confined to allow ionizations to high charge states. ECRISes presently in operation belong to the so-called second and third generation: the former, which were developed from the 90's, operate usually at 14-18 GHz and can produce Ar ions up to the charge state 16+. Confining magnetic fields are in the order of 1.5-2 T and are produced by room temperature coils coupled to permanent magnet sextupoles. Third generation ECRIS con produce fully stripped argon ions and are characterized by very high confining magnetic fields (up to 4T), normally obtained using superconducting magnets (for both solenoids and sextupole). They involve the use of a very expensive and complex technology, need an external cryogenic system and find their best application in the production of high intensity of very high charge states of heavy ions (e.g. 13 µA of U50+). The intensity is challenging, being, in fact, presently not available from 2nd generation ECRISes,. Two models could fill the gap between 2nd and 3rd generation, without involving the complexity of the latter, thus keeping low the costs and employing well-established technologies: the AISHA source [11], developed by INFN-LNS for hadrontherapy purposes, and the HIISI source [12], developed by JYFL. Both sources operate at 18 GHz but use different technologies to produce the confining magnetic field: in fact, AISHA employs High Temperature Superconducting (HTS) coils, while HIISI room temperature ones. Both are equipped with a permanent magnets sextupole. In particular, AISHA already obtained preliminary results of the production of the necessary intensity of He2+ beams and is available for a further investigation.

The LEBT will be magnetic, with a moderate resolution dipole system and an electrostatic chopping system before the large aperture solenoid to match the RFQ.

A FAMILY OF POSSIBLE LINACS

In the preparation of the proposal alpha-DTL a wider spectrum of possible applications was considered for the linac development available at INFN; ion sources, nc structures, RF sources (besides klystrons, SS amplifiers and tethrode systems). The most interesting cases are listed in Table 2.

In the first two lines the reference points, ESS DTL (with the CEA RFQ), and MUNES, the cw RFQ TRASCO to be used with Be target for BNCT application. These two elements (and the n production target) can be used for a compact neutron source (cansDTL).

Considering A/q=2, the main parameters of alpha-DTL (detailed in previous sections) are listed. The same linac could be extended to accelerate 80 kW d beam at 40 MeV for a competitive neutron source.

In the last two lines the possibility of a nc partial IFMIF facility is considered. In this case the high power 175 MHz realized by INFN is considered, with the empowered dynamics (150 mA) and frequency jump in the MEBT; nDTL* considers alpha-DTL field level (600 kW beam on target) and nDTL** half accelerating field (2400 kW on target). This last value is almost half of the nominal DONES [13] beam power (5MW).

CONCLUSION

The preliminary design of a linac able to accelerate 0.5 mA of alpha particles with 4-10 MeV/u energy variation is shown (alpha-DTL). This design, mainly based on the DTL realized by INFN for ESS, allows the realization of a very flexible and performant accelerator driven isotope source for medical application.

Table 2: General Parameters for Possible Linacs of the Same Family for Various Applications

			RFQ			DTL			whole linac			RF power (approx)	
Linac	A/q	specie	wout	Length	freq	wout	#of tanks approx	focusing	duty cycle	peak curr.	**beam power**	peak	average
			MeV/u	m	MHz	MeV/u	8m each	structure	%	mA	**kW**	MW	MW
ESS DTL	1	p	3.6	5	352	90	5	F0D0	4	65	**234**	12.05	0.48
BNCT MUNES	1	p	5	7.3	352	na	na		100	40	**200**	1.00	1.00
cansDTL	1	p	3	4	352	20	1	F0D0	10	40	**80**	2.60	0.26
alphaDTL	2	4He+2	3	5	352	10	1	FF0DD0	10	5	**10**	1.90	0.19
nDTL	2	d	3	5	352	20	2	FF0DD0	10	20	**80**	3.70	0.37
nDTL*	2	d	2.5	10	176	20	2	TBD	10	150	**600**	8.90	0.89
nDTL**	2	d	2.5	10	176	20	4	TBD	40	150	**2400**	7.80	3.12

REFERENCES

[1] G. Pupillo, L. Mou, S. Manenti, F. Groppi, J. Esposito and F. Haddad, "Nuclear data for light charged particle induced production of emerging medical radionuclides", *Radiochim. Acta*, vol. 110, pp. 689-706, 2022. `doi:10.1515/ract-2022-0011`

[2] G. Pupillo, J. Esposito, F. Haddad, *et al*., "Accelerator-based production of 99Mo: a comparison between the 100Mo(p,x) and 96Zr(α,n) reactions", *J. Radioanal. Nucl. Chem.*, vol. 305, pp. 3–78, 2015. `doi:10.1007/s10967-015-4091-8`

[3] G.B. Rosenthal and H.C. Lewin, "Production of 99Mo Using High-Current Alpha Beams", in *Proc. 2014 topical meeting on Molybdenum-99 technological development*, June 24-27, 2014, Washington D.C., USA

[4] A.Pisent, M. Comunian, A. Palmieri, G.V. Lamanna, D. Barni, "TRASCO RFQ", in *Proc. LINAC 2000,* Aug. 2000, Monterey, CA, USA, paper THD02, p.902.

[5] A. Pisent, E. Fagotti, P. Colautti "MUNES a Compact Neutron Source for BNCT and Radioactive Wastes Characterization", in *Proc. LINAC'14*, Geneva, 2014, Switzerland, paper MOPP088, p. 261.

[6] A. Pisent *et al*., "IFMIF-EVEDA RFQ Design", in *Proc. 11th European Particle Accelerator Conf. (EPAC'08)*, Genoa, Italy, Jun. 2008, paper THPP078, pp. 3542–3544.

[7] F. Grespan *et al.,* "IFMIF/EVEDA beam commissioning at nominal 125 mA deuteron beam in pulsed mode" in *Proc. IPAC'20*, Caen, France, May 2020, pp. 21-25. `doi:10.18429/JACoW-IPAC2020-TUVIR11`

[8] F. Grespan *et al.*, "ESS Drift Tube Linac manufacturing, assembly and tuning", in *Proc. IPAC'21*, Campinas, SP, Brazil, May 2021, pp. 1797-1800. `doi:10.18429/JACoW-IPAC2021-TUPAB173`

[9] L. Bellan *et al.,* "Updates on VeRDe, beam dynamics optimization toolkit for RFQ design" LNL Annual Report 2021, p.137-138, ISSN 1828-8561

[10] R. Geller, Electron Cyclotron Resonance Ion Sources and ECR Plasmas (Taylor & Francis), 1996.

[11] G. Castro *et al., "* The AISHa ion source at INFN-LNS", *J. Phys.: Conf. Ser.,* vol. 2244, p. 012025, 2022. `doi:10.1088/1742-6596/2244/1/012025`

[12] H. Koivisto *et al.*, "A new 18 GHz room temperature electron cyclotron resonance ion source for highly charged ion beams", *Rev. Sci. Instrum.*, vol. 91, p. 023303, 2020. `doi:10.1063/1.5128860`

[13] I. Podadera *et al.,* "Commissioning plan for IFMIF DONES Accelerator", presented at LINAC'22, Liverpool, UK, Aug.-Sep. 2022, paper TUPOJO01, this conference.