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Compact RF accelerators for nuclear waste characterization

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Summary. — Part of the management of radioactive waste produced by industrial, research or medical processes passes through their characterization with nuclear techniques using neutron sources (typically a D-T tube produces 10^6 n/pulse, 10 us 100 Hz). On the basis of what has been developed by INFN for other applications (IFMIF, ESS, BNCT...) it is possible to build a much more intense neutron source (10^9 n/pulse), based on a relatively compact 5 MeV RF linear accelerator and a thick beryllium target, exploiting ^{9}Be(p,n)^{9}B. This talk will recall what was discussed between SOGIN and INFN in recent years (MUNES project) in the light of the most recent results obtained by INFN in the field of linear accelerators.

1. – Introduction

INFN has a long expertise in the realization of linear accelerators for the production of neutron beams. Indeed with different groups (LNL, Torino, LNS, Padova) we have participated to the construction of various high power neutron sources, taking part to international collaboration with the mechanism of the Italian in-kind contribution. This approach has many advantages, since the international project can benefit of very specialized know how from national laboratories (particularly important for green field projects, but also for specific developments in well established labs), while the national laboratory gain an international challenge to develop new knowledges and know how. The in-kind contribution is generally in a sector where the national industry is well developed, so it can develop in close contact with national labs.

Two examples are INFN participation to IFMIF-EVEDA [3] (project started in 2008, beam in 2018) and ESS [2] (since 2015 in construction phase, beam on target in 2025). The first is the most powerful RFQ (radio frequency quadrupole) ever built, able to accelerate 125 mA of deuterons cw, while the second is a drift tube linac (DTL), a 40 m long structure with top performances in terms of beam power. The application field of the IFMIF neutron source is more specific, with the qualification of the structural materials for future fusion reactors with the high energy neutron spectrum, while ESS is more general application facility. In both case INFN participation opened the opportunity to apply the same approaches, technologies or even specific engineered components to different applications. We did a quite general survey of the possible applications of the developed technologies in a paper presented at the recent Linac conference in Liverpool [1]. A very interesting case was the alphaDTL, a high performance linac for medical isotope production.

The most relevant example in this our contest is instead MUNES. In the past years we developed RFQs for smaller neutron sources and interdisciplinary applications. This is the case of MUNES [4] (MUltidisciplinary Neutron Source); the short story starts from TRASCO RFQ, built at LNL for Nuclear Wastes Transmutation Research (1998-2004). Later in 2011 trilateral agreement between INFN, University of Pavia and SOGIN was signed for the study of a neutron source based on INFN high intensity linear accelerator to be installed in Pavia. In 2012 MUNES was granted as "progetto premiale" by Italian Ministry for a specific development of the accelerator components of this facility. Unfortunately the infrastructures for the facility in Pavia were not funded and the project was limited to the development of some critical neutron source component, mainly the RF source and the target.

At that time we started the collaboration with SOGIN considering a possible MUNES neutron source for nuclear waste characterization. Clearly there would have been logistic problems to have in the same site medical and nuclear applications. Moreover the RFQ needs to work cw (in continuous) for BNCT, and pulsed for PANWAS, so the double use makes the structure not completely optimized. Last year we won a PNRR initiative (Anthem) for the construction of a BNCT facility (30 mA 5 MeV) at Caserta Hospital University. At this point the application of the existing RFQ is not more available for PANWAS application, so with this workshop we took the opportunity to design a dedicated RFQ for a pulsed neutron source. As mentioned in the abstract part of the management of radioactive waste is the so called Passive/Active Waste Assay System (PANWAS). This method uses neutron differential die-away technique to quantify the fissile content (^{235}U, ^{239}Pu etc.). Present devices make use of a pulsed neutron sources (sealed D-T tube, 10^6 n/pulse in 10 us 100 Hz) and ^{3}He neutron detector. With an RFQ and a beryllium target it is possible to produce 10^9 n/pulse in 10 μs 100 Hz, neutron average energy 1.2 MeV and the sensitivity to Pu contamination can be dramatically improved.

We develop here a conceptual design of such a compact and powerful neutron source.

2. – The RFQ

The RFQ (Radio Frequency Quadrupole) is a RF linear accelerator particularly suited for the acceleration of a high intensity low energy beam. The beam follows a straight path on the axis of an electric quadrupole, the polarity is alternating with RF and this allows to condition of stability of both the vertical and horizontal motion, even in presence of strong space charge (reciprocal repulsion of the accelerated particles, protons in this case). Moreover the electrodes are modulated (fig. 1), in such a way to create a (small) longitudinal electric field component that can be made synchronous with the accelerated

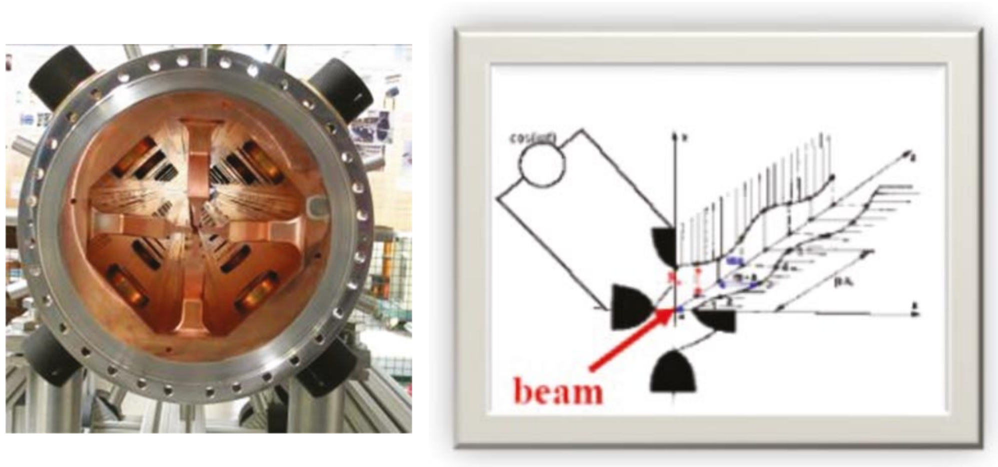

Fig. 1. – Inner view of TRASCO RFQ and schetch of a the RFQ modulation.

particles, following the phase stability principles like in higher energy accelerators. The very interesting characteristics of RFQs is the possibility to have many periods in a short space and with a simple geometry, so to realize quite complex beam dynamics strategies in a compact system. The machining of the electrodes (where the modulation is produced) determine the quality of the accelerated beam. We considered here the design of a dedicated pulsed RFQ for nuclear waste characterization (30 mA, 10 μs, 100 Hz). In fig. 2 we have a schematic view.

The main features of this design of the system are the use of four RFQ modules (TRASCO mechanics and 3d modulation), four solid state amplifiers modules (MUNES design, the power is upgraded form 125 to 150 kW thanks to pulsed operation) and a thick Be target (three layers, Be-V-Cu), with moderate power density (150 W). The beam from a pulsed ion source is matched into the RFQ using an electrostatic transport

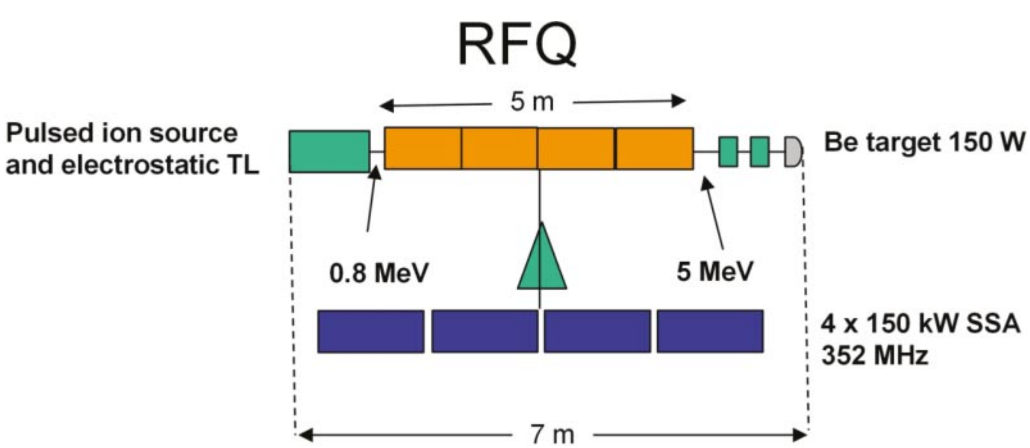

Fig. 2. – Schematic lay out of the proposed accelerator.

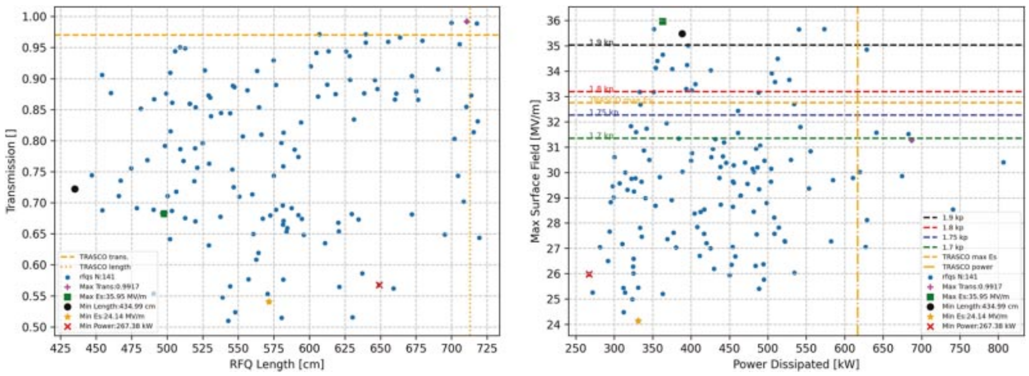

Fig. 3. – Optimization of the RFQ geometry.

line. The RFQ Design Study was performed exploring different configurations; each dot in fig. 3 is a full 10^5 multiparticles simulation of a complete RFQ. The exploration of the multiparameter space is optimized with an intense intense use of AI algorithms. The scope of the optimization is to determine period by period the length, the quadrupole aperture and the modulation amplitude.

The resulting machine as said can be made very compact. The resulted geometry parameters and beam dynamics of the selected RFQ is reported in fig. 4. The pulsed ion source can be an ECR or a more duoplasmatron; in any case we plan to use a short electrostatic line. The estimate is to have source and line in less than one meter. The RFQ as shown can have a length of about 5 m, and corresponds to the use of four brazed copper modules of TRASCO kind. This means that the mechanics, and the procedure for machining, brazing and qualify the structures are already developed. Respect to the existing RFQ the power efficiency can be improved thanks to the modern milling machines that allow the so called 3d modulation. The beam can then be delivered to a beryllium target with a short magnetic quadrupole line, or possibly directly leaving the RFQ beam expansion. For the beryllium target we are developing high power targets at the same energy. Even if in this case both the cooling and the blistering (surface damage due to H deposit) are much less critical than for BNCT, we plan to use the same technique of a three strata target to improve target durability: the Be layer for neutron production, V to withstand the Bragg pick and master H deposit, copper to dissipate the power. In this case the beam can be a spot of about 1 cm diameter.

Al together the beam line can be approximately 7 m long, and could in principle be made part of a container of standard dimensions (Container 40′ high cube, internal dimensions $12\times2.43\times2.34$ m^3), together with the barrel irradiation chamber.

The problem for the design of a system really easy to transport is the RF. We plan to use solid state amplifiers. This choice looks simpler then the more traditional klystron system, since we avoid a large vacuum structure, with high voltage and the oil modulator. The entire RF system consists in four structures of 150 kW peak power each, that should be assembled in 2.5 m units (five racks for each amplifier). The sum of the length of those racks is approximately equal to the linac length, but we do not have yet a very compact solution for the RF distribution. The integration of the system will be a very interesting challenge.

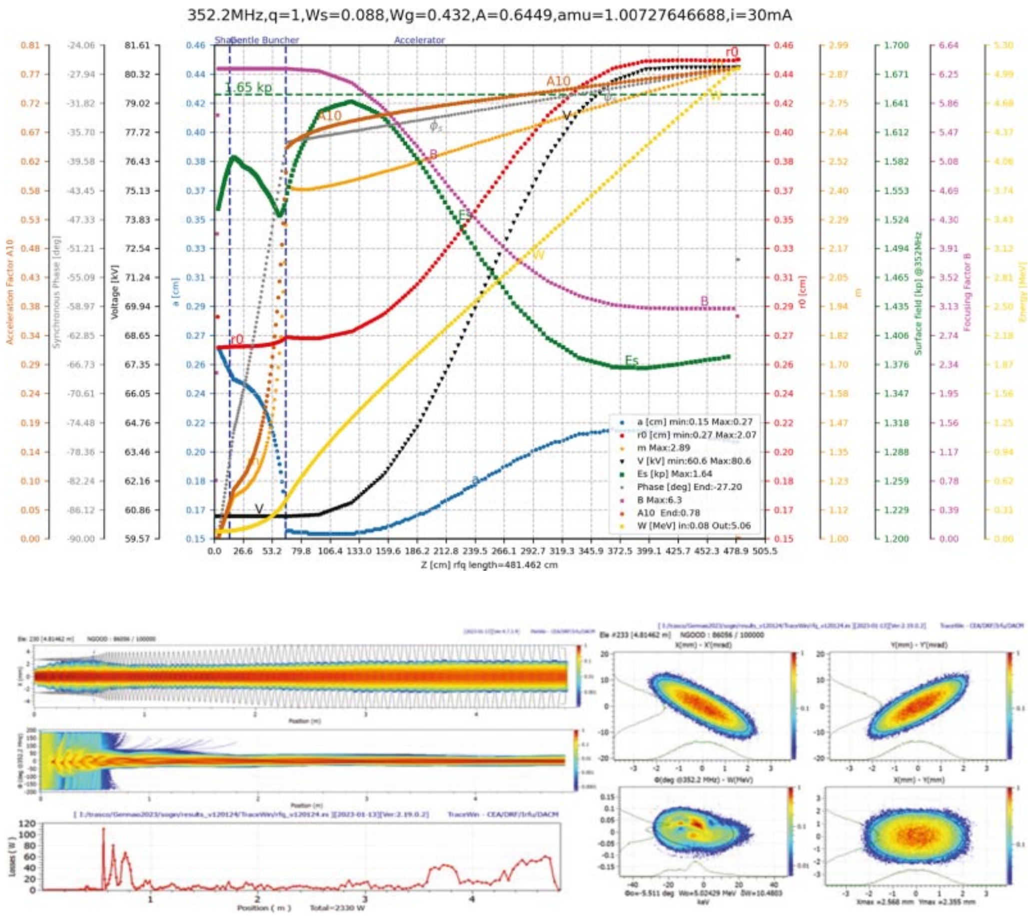

Fig. 4. – Selected modulation and resulting beam dynamics.

TABLE I. – *Comparison of TRASCO RFQ and RFQ for Nuclear Waste.*

	TRASCO	Selected RFQ
Particle	Proton	Proton
Final Energy (MeV)	5.0	5.0
Current (mA)	30.0	30.0
Frequency (MHz)	352.2	352.2
Length (cm)	713	481.5
Voltage min/Max (kV)	68/68	60.6/80.6
Max Surface field (MV/m)	32.8	30.3
Transmission (%)	97	85
rms Longitudinal emittance (MeVdeg)	0.18	0.33
RF Power dissipation (kW)	617	456

3. – Conclusion

We have a preliminary design for a dedicated pulsed RFQ for nuclear waste characterization (30 mA, 10 μs, 100 Hz). This design uses elements already developed and tested (RFQ, RF, production target), so schedule and budget guess can be reliable. There is for sure space for cost optimization in case of industrial application.

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