ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-TUPWI026

A MONOCHROMATIC GAMMA SOURCE WITHOUT NEUTRONS*

R.W. Garnett#, S.S. Kurennoy, L.J. Rybarcyk, and T.N. Taddeucci, LANL, Los Alamos, NM 87545

Abstract

High-energy gamma rays can be efficiently produced using the direct excitation of the 15.1-MeV level in ^{12}C via the (*p*, *p*') reaction with the threshold energy of 16.38 MeV. The threshold for neutron production via ^{12}C (*p*, *n*) is 19.66 MeV, so there is an energy window of 3.28 MeV where the 15.1-MeV photons can be produced without any direct neutrons. Thick-target yield estimates indicate that just below the neutron production threshold, the photon output is about twice that of the more well-known ^{11}B (*d*, *n*) reaction requiring 4-MeV deuterons, with the expected 15.1-MeV photon flux to be approximately 1x10^{11} s^{-1}sr^{-1} per 1 mA of 19.6-MeV proton current on a carbon target. A compact pulsed proton accelerator capable of 10-mA or greater peak currents to drive such a gamma source will be presented. The accelerator concept is based on a 4-rod RFQ followed by compact H-mode structures with PMQ focusing.

INTRODUCTION

Conventional bremsstrahlung-based interrogation of special nuclear materials in cargo is not very efficient because its gamma energy spectrum is dominated by low-energy photons. On the contrary, 15-MeV photons are well matched to the peak of the photo-fission cross section for uranium. Such gamma rays can be efficiently produced using direct excitation of the 15.1-MeV level in the ^{12}C via (*p*, *p*') reaction that has the threshold energy of 16.38 MeV [1]. The threshold of neutron production via ^{12}C (*p*, *n*) is 19.66 MeV, so there is a window of 3.28 MeV where the 15.1-MeV photons can be produced without any direct neutrons. The thick-target yield estimates in [1] indicate that just below the neutron production threshold, the 15.1-MeV photon output is about twice that in the ^{11}B (*d*, *n*) reaction with 4-MeV deuterons (See Fig. 1).

For the latter, we estimated the 15.1-MeV photon flux as 5·10^{10} s^{-1}sr^{-1} per 1 mA of deuteron current [2]. Therefore, we expect a 15.1-MeV photon flux of 1·10^{11} s^{-1}sr^{-1} per 1 mA of 19.6-MeV protons on a carbon target – much higher than with conventional sources, and without the neutron background. Having such a monochromatic source of high-energy photons significantly reduces the total dose required for SNM interrogation in cargo. The detection efficiency also increases due to eliminated neutron background and shorter pulses.

ACCELERATOR SYSTEM

To implement the above promising approach, we need a compact system that accelerates protons with peak currents of 10s mA to 19.6 MeV. Based on our previous results [2, 3], one attractive option is a compact pulsed accelerator that consists of an RFQ followed by H-mode structures with PMQ focusing (H-PMQ). For preliminary estimates, we use results [3] where replacing the 201.25-MHz LANSCE drift-tube linac (DTL) by much more efficient H-PMQ accelerator structures [4] of the same frequency was studied. A 750-keV RFQ (~2 m) is followed by two inter-digital H-PMQ (IH-PMQ) tanks with the accelerating gradient 2.5 MV/m to bring protons to 5.4 MeV [3]. After that we switch to cross-bar H-PMQ structures (CH-PMQ); likely, three CH-PMQ tanks will be needed to accelerate protons to 19.6 MeV. The total accelerator length is estimated to be ~12 m, but can be reduced by increasing the gradient. The transverse size will be well within 1-m diameter. With peak currents below 50 mA, the highest values in designs [2, 3], the required maximum peak RF power should be less than 2.5 MW. The system is illustrated in Fig. 2 and looks feasible.

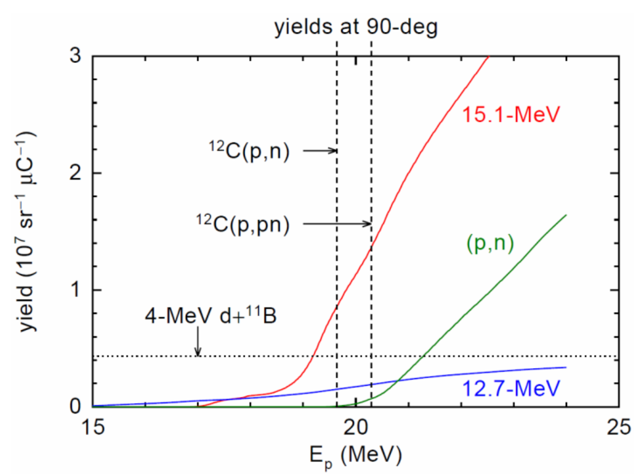

Figure 1: Thick-target yields for p+^{12}C photon and neutron production reactions.

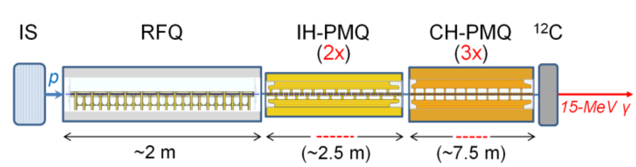

Figure 2: Accelerator scheme.

Ion Source and RFQ

Proton ion sources (IS) providing peak currents of 10s mA at duty factors up to 10-20% are readily available [5]. The IS will be connected to the RFQ entrance by a short electrostatic, low-energy beam transfer line (LEBT). The LEBT can also serve as the beam switch with on-off times ~50 ns as in the SNS front end. The 750-keV RFQ can be of either 4-vane or 4-rod type. Based on our recent

* Work supported by the United States Department of Energy, National Nuclear Security Agency, under contract DE-AC52-06NA25396.
# rgarnett@lanl.gov

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-TUPWI026

experience [6], the 4-rod RFQ is the preferable low-cost, simpler option at such duty factors. The typical peak RF power for such an RFQ is below 150 kW.

IH-PMQ

H-mode normal-conducting accelerating structures with PMQ focusing (H-PMQ) have been proposed and developed for proton or light-ion beams at relatively low beam velocities [4]. They employ efficient multi-gap resonators operating in the magnetic $TE_{m1(0)}$ mode: dipole one (m=1) in inter-digital-H (IH), quadrupole (m=2) in cross-bar-H (CH), or higher m. The new feature of the H-PMQ structures is that the transverse beam focusing is provided by permanent-magnet quadrupoles (PMQ) inserted inside the small drift tubes. H-PMQ cavities provide a very high accelerating efficiency, an order of magnitude better than in standard drift-tube linacs (DTL), while their transverse size is a few times smaller than for DTL resonators of the same frequency.

Many results of the study [3] are directly applicable here. We split IH-PMQ section into two relatively short IH tanks [3]. The first section starts at a beam energy of 0.75 MeV (velocity $\beta = v/c = 0.04$); the other continues from 2.5 MeV ($\beta = 0.073$). The layout of the first IH tank is illustrated in Fig. 3 from CST MicroWave Studio (MWS) [7]; it shows only the IH drift tubes (DTs), supporting stems, and vanes. The vane undercuts near the cavity end walls allow for the magnetic-flux return. The cut dimensions are adjusted to reduce the electric field drop near the tank ends. This tank contains 10 IH "periods," each consisting of two cells. The number of full DTs is 20, and two more half-DTs are located on the end walls. The DT lengths are from 2.1 to 4.4 cm, and DT outer radius is 1.8 cm; see also in Table 1. The cavity inner radius is 11.4 cm (cf. 47 cm for the LANSCE DTL tank 1). The field profile along the tank is tuned to keep the cell gradients nearly constant by adjusting the gap widths between DTs. The end gaps are made shorter to bring up the fields near the tank ends [1]. The gap lengths g are short in both IH tanks: the ratio g/L_c = 0.18-0.33 in IH T1 and 0.17-0.27 in T2, except for the end gaps. Here $L_c = \beta\lambda/2$ is the IH cell length (DT + gap), and λ is the RF wavelength. The frequency of the second mode in IH tank 1 is 16 MHz above 201.25 MHz. The calculated EM parameters are listed in Table 1. The Kilpatrick field E_K = 14.8 MV/m at 201.25 MHz [5].

Table 1 also presents parameters of the IH tank 2, which is similar to tank 1 though the cavity is longer and its radius is 14.4 cm. The tank contains 22 full DTs with lengths from 4.2 to 6.8 cm. The second mode is ~7 MHz above the working one. Note that the effective shunt impedances are about 9 times higher than in the LANSCE DTL at the same beam energies [3]. The RF power surface losses in Table 1 are for ideal copper and should be increased by 20% for realistic estimates; still they are very low compared to the DTL. Simple water cooling using cooling channels only inside vanes will be sufficient, see [3] for details.

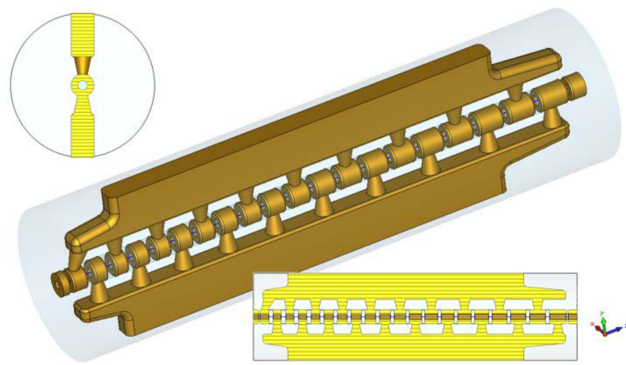

Figure 3: MWS model of IH tank 1 from 0.75 to 2.5 MeV. The resonator outer wall is removed; cavity inner volume is in light-blue. Two insets show the cavity transverse (top left) and longitudinal (bottom) cross sections.

Table 1: IH Tanks EM Parameters for E_0 = 2.5 MV/m

Parameter (* = 100% duty)	**IH tank 1**	**IH tank 2**
W_{in}, MeV (β_{in})	0.75 (0.04)	2.5 (0.073)
Quality factor Q	9815	12603
Tank length L, m	0.847	1.525
Beam aperture r_b, cm	0.75	0.75
Wall (Cu) RF power, P_w, kW*	34.6	72.8
Electric field E_{max}, MV/m (E_K)	26.2 (1.77)	24.5 (1.65)
T-factors	0.86-0.93	0.93-0.96
Shunt impedance ZT^2, MΩ/m	247.4	231.4

CH-PMQ

We switch to CH cavities at beam velocities above β = 0.1 as more efficient ones, see in [4]. We expect that 3 CH-PMQ tanks will be required to bring the proton beam energy to 19.6 MeV. The first CH tank (CH5.4, Fig. 4) brings the beam energy from 5.4 to 9.2 MeV. It contains 22 full DTs with lengths from 6.4 to 7.75 cm (23 gaps); the DT outer radius is 2 cm. The ratio g/L_c = 0.17-0.21.The cavity inner radius is 24.15 cm (cf. 45 cm for the LANSCE DTL tank 2). The frequency of the second mode is 5.8 MHz above 201.25 MHz.

The calculated EM parameters of the cavity are listed in Table 2. The last two columns in Table 2 give estimates for two CH tanks that follow CH5.4, from 9.2 and 14 MeV, respectively. The estimates are obtained by interpolating results between the CH5.4 and the CH tank from 20 MeV (CH20) in Ref. [3]. The CH9.2 tank will be similar to CH5.4 shown in Fig. 4, just longer. The 3-m long cavity for CH14 will contain 24 full DTs with an enlarged bore radius supported by longitudinally stretched stems. The CH20 tank [3] was 4.5-m long with 26 full DTs. Its stems were extended longitudinally (cut in the transverse plane and then stretched by 5 cm) to prevent

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-TUPWI026

the magnetic field from leaking between them. Even starting from 20 MeV ($\beta = 0.204$), the tank provided the effective shunt impedance of 67 MΩ/m, more than twice that of the LANSCE DTL at the same beam velocities.

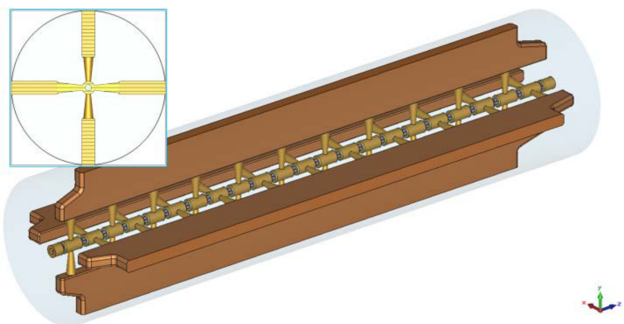

Figure 4: MWS model of CH tank from 5.4 MeV. The resonator outer wall is removed; cavity inner volume is in light-blue. The inset shows the transverse cross section of the cavity.

Table 2: CH Tanks EM Parameters for E_0 = 2.5 MV/m

Parameter (*100%)	CH5.4	CH9.2	CH14
β_{in}	0.107	0.14	0.17
Quality factor Q	15847	17500	19000
Tank length L, m	2.019	2.5	3.0
Beam aperture r_b, cm	1.0	1.0	1.25
Wall power, P_w, kW*	178.2	275	400
E_{max}, MV/m (E_K)	24.3 (1.64)	23	22
T-factors	0.94 - 0.97 for all		
ZT^2, MΩ/m	129.1	108	87

The power values in Tables 1 and 2 plus in the RFQ, increased by 20% for realistic surfaces, give an estimate of 1.4 MW for the peak RF power in the accelerator. Adding the beam power of 1 MW (50 mA * 20 MeV) brings the total required peak RF power to about 2.5 MW.

DISCUSSION

Details of the beam pulse structure depend on detectors and are not discussed here. From general considerations, we assumed a regular pattern of short beam pulses. Optimal accelerator parameters will be defined based on the detector requirements.

One should mention alternative accelerator options. The RFQ can be followed by H-cavities with KONUS beam dynamics [8] or with alternating phase focusing [9]. However, both options will lead to longer structures than the H-PMQ. Additionally, the alternating phase focusing structure has lower current limits. Of course, a standard DTL is also possible but its size would be significantly larger and the efficiency much lower than for the proposed H-PMQ solution.

CONCLUSIONS

We propose a compact pulsed proton accelerator providing peak currents up to 50 mA to drive an intense monochromatic source of 15-MeV photons. The accelerator is based on a 4-rod RFQ followed by efficient H-mode structures with PMQ focusing. The main application of such a source is efficient interrogation of SNM in cargo, which becomes possible due to a significantly reduced total radiation dose, shorter pulses, and eliminated neutron background.

The accelerator system itself can also be used for other industrial and medical applications. For example, intense 20-MeV proton beams are useful for PET isotope production.

REFERENCES

[1] T.N. Taddeucci, "High-energy gamma rays and low-energy neutrons from p+^{12}C reactions," Los Alamos, 2011, unpublished.
[2] S.S. Kurennoy, R.W. Garnett, and L.J. Rybarcyk, "Intense Combined Source of Neutrons and Photons for Interrogation Based on Compact Deuteron RF Accelerator," report LA-UR-14-25961; CAARI, San Antonio, TX, 2014.
[3] S.S. Kurennoy, L.J. Rybarcyk, and T. P. Wangler, "An H-mode Accelerator with PMQ Focusing as a LANL DTL Replacement," IPAC11, San Sebastian, Spain, p. 2655 (2011); http://www.JACoW.org
[4] S.S. Kurennoy et al., Phys. Rev. ST Accel. Beams 15, 090101 (2012).
[5] I.G. Brown, *Physics and Technology of Ion Sources*, (2nd ed., Weinheim: Wiley-VCH, 2004).
[6] R.W. Garnett et al., "Status of the LANSCE Front-End Upgrade," PAC13, Pasadena, CA, p. 327 (2013).
[7] CST Studio Suite, www.cst.com
[8] U. Ratzinger and R. Tiede, NIM A415, 229 (1998).
[9] Y. Iwata et al., "IH-DTL as a Compact Injector for a Heavy-Ion Medical Synchrotron," Linac08, Victoria, BC, Canada, p. 715 (2008); http://www.JACoW.org