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PULSED NEUTRON SOURCE FROM THE INTENSE PARTICLE BEAM GENERATOR "THALIE"

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Abstract

High impedance generators have been proved efficient to produce, with suitable diodes, intense light ion beams. Using the pinch-reflex diode concept on the THALIE generator in operation at VALDUC, allows acceleration of deuteron or proton beams. By striking the beam with LiF thick targets (p(^{7}Li,n)^{7}Be or d(^{7}Li,n)^{8}Be reactions), neutron emission in the 10^{12} - 10^{13} range have been measured.

Introduction

High power generators recently developped for inertial confinement fusion research or radiation effects studies can accelerate, when coupled to suitable diodes, intense, multi-MeV, light ion beams. These beams, in turn, can be used to produce high field, pulsed fast neutron source.

Using a pinch-reflex diode concept[1] on the high impedance THALIE generator in operation at VALDUC, we have produced proton or deuteron beams. By striking the beam on a natural lithium target, we have obtained a pulsed fast neutron source in the 10^{12}- 10^{13} neutrons range in full space.

In this paper, we discuss the diode design to reach the optimal neutron emission and we describe the experimental conditions and the characteristics of the neutron source.

Principle of operation

The high impedance THALIE generator[2], primarily designed for flash X-ray production, includes a 500 kJ, 50 stages Marx generator driving a 32 Ω , 10 MV, asymetric oil Blumlein. An oil switch starts the Blumlein discharge, and the graded tube is powered through a 8 channels oil prepulse switch and a 32 Ω , 2 meters long oil transmission line. The tube is extended with a 120 Ω vacuum, magnetic insulation line.

The ion diode can be installed either at the end of this line, or in a 60 Ω , 0.5 m long line extension.

Up to now, only the normal negative polarity operation of the generator was tested, but positive polarity can be considered in the future.

Figure 1 shows the pinch-reflex (P.R.) diode adapted to the generator.

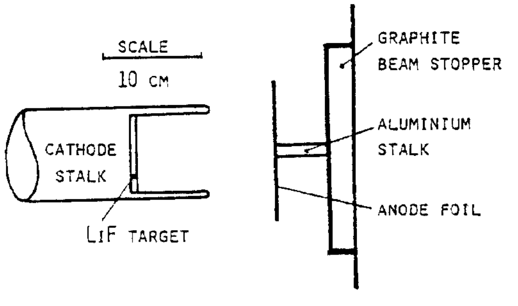

FIG. 1 - PINCH REFLEX DIODE GEOMETRY

A physical interpretation of P.R. diode experiments on high impedance generator has been presented by A.T. Drobot and all[3] . They have demonstrated that the prolonged electron lifetime is responsible for ion current density enhancement over the Child-Langmuir bipolar flow value given by :

$$\frac{J_i}{J_e} = \left(\frac{m_e}{m_i}\right)^{1/2} \left(1 + \frac{eV}{2\, m_e C^2}\right)^{1/2}$$

The protons extracted from the anode foil (or deuterons when coated with CD_2) are accelerated towards the hollow cathode and strike a LiF target in which neutrons are produced from the following reactions :

$$d + {}^7Li \longrightarrow {}^8Be + n \qquad Q = 15\ MeV$$

$$p + {}^7Li \longrightarrow {}^7Be + n \qquad Q = -1.88\ MeV$$

The first one is the most prolific, and can match the results of the (d,T) reaction when the particle energy is sufficiently high. Figure 2 shows the neutron yield Y_n from both reactions as a function of the ion energy E_i in the laboratory frame.

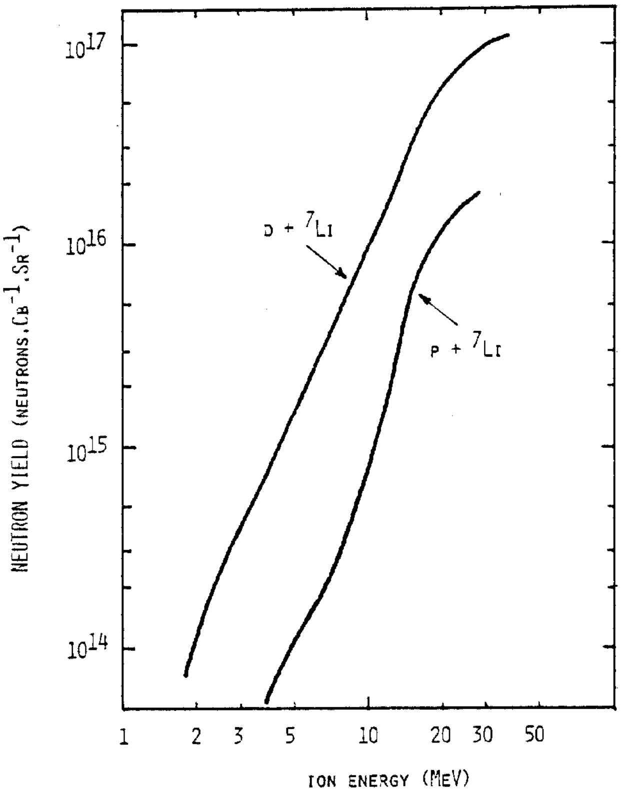

FIG. 2 - NEUTRON YIELD

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This yield is calculated for thick target interaction of the beam :

$$Y_n(E_i) = \int_0^{E_i} \frac{\sigma_t(E)}{\frac{1}{n}\left|\frac{dE}{dx}\right|}\, dE$$

n is the number of atoms of ^{7}Li per cm^3 of LiF target, σ_t is the total cross section for the reaction.

Consequently, the number of neutrons N_n emitted in full space is given by :

$$N_n = \int_{\substack{\text{voltage}\\ \text{pulse}}} \frac{I_i(V)}{e}\, Y_n(V)\, dt$$

where I_i is the ion current and V the acceleration voltage.

For a square pulse voltage and current , we can roughly estimate that the number of emitted neutrons is :

$$N_n \simeq \alpha V^k I_i \tau \qquad (1)$$

with τ : current duration,

and α : a coefficient.

k is equal to 2.8 for (d + ^{7}Li) and 3 for (p + ^{7}Li) when V is about 5 MeV.

The ion diode current and acceleration voltage are function:1) of electrical characteristics of the generator and :2) of the diode behavior.

Introducing Z_B as the Blumlein impedance of the THALIE generator and Z the diode impedance, we have :

$$V = 2\eta V_B \frac{Z}{Z + Z_B} \qquad (2)$$

where η is the efficiency and V_B is the peak charging voltage of the line. The impedance Z is given by :

$$Z = \frac{V}{I_e + I_i}$$

or :

$$Z = \frac{V}{I_e} \qquad (3)$$

when $I_i \ll I_e$.

This last condition is usually observed on high impedance particle generators. In the pinch-reflex diode, Lee and Goldstein have previously established that[1] :

$$I_i = I_e \frac{R}{D} \left(\frac{2\,e\,V}{m\,c^2}\right)^{1/2}$$

In the pinch-reflex diode as well as in the classical diode, when the voltage is sufficiently high (V>2 MV), we can notice that I_i increases with the total current I multiplied by $V^{1/2}$.

$$I_i = \beta\, I\, V^{1/2} \qquad (4)$$

where β is a factor characteristic of the flow regime in the diode.

By combining the set of equations (1), (2), (3) and (4) we obtain N_n versus Z and Z_B :

$$N_n = \alpha\beta(2\eta V_B)^{k+3/2} . \tau . \frac{Z^{k+1/2}}{(Z + Z_B)^{k+3/2}}$$

The optimal value of Z maximizing the neutron emission is :

$$Z = (k + 1/2)\, Z_B \qquad (5)$$

For the THALIE generator (Z_B = 32 Ω), this condition leads to Z $\sim$100 Ω. Unfortunately, the pinch condition of the beam necessitates that the current in the diode exceeds the critical current I_c :

$$I_i + I_e > I_c = 8500\beta\gamma\frac{R}{D}$$

where $\frac{R}{D}$ is the cathode aspect ratio.

This is unconsistent with equation (5), and a compromise must be found.

In addition, the electron stagnation time in the anode-cathode gap, responsible after reference 3 for the ion current enhancement, varies with time in the pulse. Being short at the beginning of the pulse because of the paraxial trajectories of the electrons at low current, it increases till the collapse time and depends on several parameters as prepulse or voltage rise time.

In order to take into consideration the previous remarks on the diode impedance and behavior, we have modified the pinch-reflex geometry. Our goal is to create at early time in the pulse an electrostatic field reflexing the electrons when their trajectories are assumed to be paraxial. Figure 3 gives the geometrical design of the modified P.R. diode, called pinch-reflex hybrid (PRH) diode.

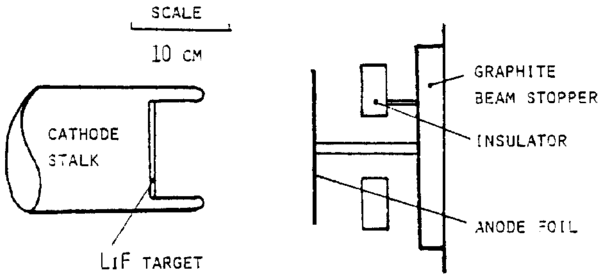

FIG. 3 - PINCH REFLEX-HYBRID GEOMETRY

Behind the anode foil baked with a thin conductor (5 μ tantalum) which is grounded by the conducting hollow anode stalk, we dispose a 3 cm thick dielectric ring (lucite) supported at the back plate by dielectric rods We assume that the first electrons crossing the anode foil are stopped in the insulator and form a real cathode, as long as electrical breakdown does not occur. We compare later the results obtained with and without reflexing structures.

Diagnostics

In addition to the usual current and voltage monitors of the beam, nuclear diagnostics were used to measure the neutron source characteristics :

- a silver activation counter,
- two plastic scintillators and P.M. tubes as time-of-flight detectors.

The silver activation counter, located 3.4 meters away from the target at an angle of 135° apart from the ion direction, gives the source strength. The results take into account the reaction anisotropy, and a possible correction for different neutrons energy.

Two plastic scintillators were located at 8 meters and 11 meters away from the target in the 180° direction. A shield including 40 cm thick lead protected the scintillators against X-rays from electron bremsstrahlung. The delivered signal gives the time-of-flight spectrum. Finally, a X-ray pinhole camera was installed about 1 meter away from the anode, and viewed the electron beam interaction with the anode foil.

Results

Table I summarizes the results obtained from the different experiments conducted with the P.R. or PRH diode configuration and $p+{}^7Li$ or $d+{}^7Li$ reaction.

Table I

DIODE GEOMETRY	REACTION	TOTAL PEAK CURRENT (kA)	MEAN ION ENERGY (MeV) (1)	ION CURRENT (kA) (2)	NEUTRON IN 4 π
PR	$p + {}^7Li$	116	4.1	12	$0.42.10^{12}$
PR	$d + {}^7Li$	132	(4)	(9.6)	3.10^{12}
PRH	$p + {}^7Li$	110	4.3	12	$0.45.10^{12}$
PRH	$d + {}^7Li$	108	(4.5)	(7)	3.10^{12}

(1) DEDUCED FROM TOF SIGNAL

(2) ION CURRENT PULSE DURATION IS DEDUCED FROM BREMSSTRAHLUNG SIGNAL F W H M

As expected after neutron yield calculation, the $d+{}^7Li$ reaction is about a factor of 6 most prolific than the $p+{}^7Li$ reaction. The maximum neutron energies are respectively in the 15 MeV and 2 MeV range when observed in the 180° direction. Figure 4 gives the time-of-flight spectrum (TOF) from both reactions.

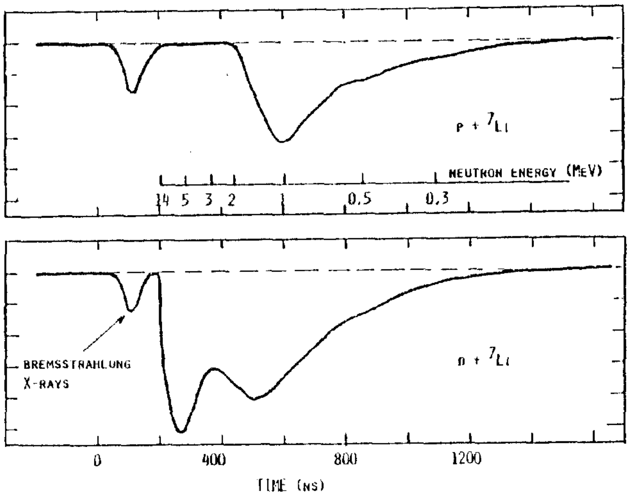

FIG. 4 - TIME OF FLIGHT SIGNAL

From the neutron time-of-flight spectrum given by the $p+{}^7Li$ reaction, it is possible to infer the ion maximum energy, which is :

$$E_{i\ max} = E_{n\ max} + 1.92 \text{ MeV}$$

The neutron maximum energy is measured by the TOF difference between the bremsstrahlung X-rays peak and the fastest neutrons. Due to the lesser sensitivity of the neutron energy to the deuteron energy, the same calculation is not possible in the case of $d+{}^7Li$ reaction. The maximum proton current is derived from the neutron calculated yield and energy, assuming a ion pulsed current duration typically of the order of 40-50 ns, which is the measured width of the bremsstrahlung signal recorded by a photodiode. The best results show a ion (proton) current of about 15 kA and a total ion energy of about 4 kJ.[4]

Due to larger anode-cathode gaps (100 mm versus 50 mm), the hybrid PRH diode operates at higher impedance (30 % higher) than the classical P.R. diode.

The neutron yield data for the same anode material are in the same range for the two configurations. For the classical P.R. diode, this is consistent with a weak pinch flow regime, intermediate between a Child-Langmuir and a tight pinch flow, since the total current in the diode does not exceed the Alfven-Lawson value.[3,4]

Combining equations (1) and (4), we express the neutron yield in terms of the electrical characteristics and of the flow regime coefficient β as :

$$N_n = \alpha . V^{k+1/2} . \tau . \beta . I \qquad (6)$$

The measured variations of V and I in the two configurations (hybrid and classical) do not explain alone the similar neutron yields. A modification in the flow regime, that is in the β factor, could account for it. In any case, the proton current (maximum value $\leqslant$ 15 kA) exceeds the Child-Langmuir relativistic flow value only by a factor of atmost 2.

Conclusion

Experiments have been conducted on the multi-MeV THALIE generator for acceleration of protons and deuterons with pinch-reflex diodes of simple or more complicated configurations. The ion beams are then used to produce a pulsed neutron source, from the $p+{}^7Li$ or $d+{}^7Li$ reactions. The main conclusions derived from the observed results are :

1- The neutron yield range about 0.5×10^{12} for $p+{}^7Li$ with 2 MeV neutron maximum energy and $3 .10^{12}$ MeV for $d+{}^7Li$ with 14 MeV neutron maximum energy.

2- The classical (P.R.) and hybrid (PRH) diodes give neutron yields in the same range.

3- The maximum ion (proton) current reaches 15 kA, that is a factor of 2 over Child-Langmuir bipolar flow limit.

Due to negative polarity operation of the generator, the maximum available neutron fluence is limited by the anisotropy of the neutron emission and the distance between the lithium target and the outside of the diode. Positive operation could allow in the future higher fluences, the target being fixed on the diode outside wall and taking advantage of the 0° neutron emission angle.

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