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Authors

Murphy, TJ
Heidbrink, WW
Strachan, JD

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Application of coincidence techniques to fusion product measurements

T. J. Murphy, W. W. Heidbrink, and J. D. Strachan

Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08544

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Measurement of two products of a fusion reaction in coincidence is proposed. Possible detector arrays and sample count rates have been evaluated for reactions in the Fontenay-aux-Roses tokamak (TFR) and the Texas experimental tokamak (TEXT) and in the tokamak fusion test reactor (TFTR) neutral beam lines. The count rates indicate that this method is feasible on existing devices.

INTRODUCTION

In recent years, measurements of the properties of charged fusion products have become useful for the characterization of fusion plasmas. Most of the products of the important fusion reactions have now been detected and have been used to determine source rates,¹⁻⁴ reactant energies,^{3,5,6} source profiles,⁷⁻⁹ and current profiles.¹⁰ In these studies, the spatial sensitivity of the measurements was determined by the collimation of the detectors. Unconfined particles created anywhere along the orbits defined by the collimation were detected. Thus, the signal averaged the fusion emissivity over the particle orbit and spatial resolution relied on gradients in the fusion profile.

In this paper, the feasibility of measuring two fusion products in coincidence is examined. Coincidence measurements are attractive because they potentially afford more precise determination of the fusion emission profile, of the orbits of the charged fusion products (which can be related to the magnetic field structure), and of the velocities of the reacting particles than is possible with single-particle detection. The chief technical problem with this concept is the difficulty of obtaining adequate coincidence count rates with realistic detector geometries. In this paper, the coincidence count rates are explored for two possible tokamak experiments indicating that useful count rates are possible.

I. NEUTRAL DEUTERIUM BEAM

Charged fusion product diagnostics of high-power neutral deuterium beams have been shown to be effective in determining the relative amounts of D^+ , D_2^+ , and D_3^+ created in the beam line and, therefore, the relative fraction of the beam in the full-, half-, and third-energy components in the beam.^{11,12} In this type of beam-target reaction, the kinetics of the particles are determined by the conservation of energy and momentum.

These measurements were made by measuring the energy spectra of the reaction products and determining the yield of each energy component. The cross section for the reaction is well known,¹³⁻¹⁵ so the fraction of the deuterium beam in each energy component can be determined.

This method could potentially be improved by the use of coincidence techniques to specify the location of the reactions and by eliminating low-energy noise due to scattered

particles and x rays since they will not have an associated count in the other detector.

If the distance between the detectors is known and the energy of each product is measured, then the position of the reaction can be calculated from the difference in arrival time of the two particles at their respective detectors.

Table I lists the angles and energies of the products measured using a surface barrier detector (SBD) and a neutron detector (NE213) in coincidence for the $d(d,n)^3\text{He}$ reaction on a TFTR neutral beam line. The neutralizer pressure is 10^{-3} Torr, the accelerating voltage is 120 kV, and the current in each species is assumed to be 20 A. The neutron detector is located 30 cm from the beam axis just outside the bellows connecting the ion source to the neutralizer and has a radius of 1.0 cm. The SBD is located 22 cm from the beam axis just above a hole in the scraper, and 35 cm "downstream" from the neutron detector. It has an area of 0.73 cm². The neutralizer is 15 cm wide by 42 cm high. Assuming an intrinsic efficiency of 10% for the neutron detector and 100% for the charged particle detector, the total coincidence count rate is 64 s^{-1} .

If the neutron detector collimation is assumed to consist of a 30-cm-long channel 1.0 cm in radius, aligned to measure neutrons with $\phi_n \sim 120^\circ$, then the neutron detector will receive about 1.9×10^4 counts per second. If the $^3\text{He}^{++}$ detector collimation consists of 37 holes, 0.0794 cm in radius and 0.635 cm thick, looking at ^3He ions with $\phi_h \sim 50^\circ$, then the $^3\text{He}^{++}$ detector will measure 6.0×10^4 counts per second. If the coincidence gate time τ is set at 100 ns, then the random coincidence count rate will be $R_{\text{random}} = R_h \epsilon_h R_n \epsilon_n \tau = 11.4 \text{ s}^{-1}$. Thus, the true-to-random ratio is about 5.6 to 1.

TABLE I. Neutron and ^3He energies and angles for full-, half-, and third-energy components of the neutral deuterium beam for reactions occurring at the center of the beam line and Δt for reactions occurring at the top, middle, and bottom of the beam.

E_d (keV)	E_n (keV)	ϕ_n (deg)	E_h (keV)	ϕ_h (deg)	Δt		
					top (ns)	middle (ns)	bottom (ns)
120	2308	117.5	1081	48.6	-25.3	19.2	58.7
60	2335	119.4	994	50.5	-25.1	19.4	60.3
40	2350	120.2	959	51.5	-25.0	19.5	61.0

TABLE II. Array for measuring orbits in TFR which exhibit drifts as well as cyclotron motion ($B_T = 2.0$ T, $I_p = 200$ kA).

Detector	R (cm)	Z (cm)	ϕ (deg)	rot (deg)	elev (deg)	ϵ_{single}	ϵ_{coin}
$^3\text{He}^{++}$	98	-23	0	0	0	9.3×10^{-9}	
n_1	95	-25	-29	90	63	1.7×10^{-5}	3.1×10^{-11}
n_2	101	-25	-46	90	63	1.4×10^{-5}	4.3×10^{-11}
n_3	101	-25	-57	90	63	1.4×10^{-5}	1.4×10^{-11}

Since the random coincidence count rate is quadratic in the reaction rate while the true coincidence rate is linear, reducing the count rates at the detectors increases the true-to-random ratio of coincidences. At $V_{\text{acc}} = 60$ kV, $I_{\text{full}} = I_{\text{half}} = I_{\text{third}} = 7$ A, the true coincidence rate drops to 5.6 s^{-1} , and the random coincidence rate to 0.088 s^{-1} , so that greater than 98% of the coincidences are "real." At higher voltages, the count rates can be reduced by lowering the neutralizer gas pressure. A factor-of-10 reduction in pressure reduces the random counts by a factor of 100, leading to an increase in the true-to-random ratio of a factor of 10. The random coincidences will be evenly distributed in Δt , but the true coincidences will lie only in the interval corresponding to reactions taking place within the neutralizer. Thus, the random coincidence level can be established and subtracted from the signal leaving only the true coincidences.

There will, of course, be other sources of noise, such as scattered neutrons and hard x rays, which will increase the random coincidence count rate, but potentially these sources can be controlled by increased shielding.

II. TOKAMAKS

Coincidence techniques can also be used in measuring the fusion products from reactions in magnetic fusion devices, such as tokamaks. Reactions of interest in tokamaks are $d(d,n)^3\text{He}$, $d(d,p)t$, $^3\text{He}(d,p)\alpha$, and $d(t,n)\alpha$. By measuring these reaction products in coincidence, more accurate knowledge of the reactions can be deduced.

When a reaction occurs in a fusion device, the reaction products start out in nearly opposite directions since the Q of

the reaction is much larger than the energies of the reacting ions. Neutrons travel in straight lines, but the charged particles travel in drifting orbits which can be (1) confined within the vessel, (2) lost promptly on unconfined orbits, or (3) born on confined orbits but, due to scattering or transport processes, eventually lost. If the orbits are of the second kind, then both particles could be detected and a coincidence measurement made.

The use of two detectors allows the detected region of the plasma to be localized. If two detectors are used in coincidence, only reactions occurring in a certain region can lead to particles reaching both detectors.

Tables II and III list the locations and collimation angles for possible coincidence arrays for the $d(t,n)\alpha$ reaction from the burnup of fusion-produced tritons and the $d(d,n)^3\text{He}$ reaction on TFR and the $^3\text{He}(d,p)\alpha$ reaction on TEXT. The efficiencies were calculated using an orbit code¹⁰ which numerically calculates the coincidence efficiency of a pair of detectors, counting only reactions which result in counts in both detectors.

A. TFR

The array described in Table II is designed to measure the neutron and $^3\text{He}^{++}$ ion produced from $d-d$ fusion reactions in TFR ($R = 98$ cm, $a = 18$ cm). Since charged particles born in tokamaks exhibit drifts and motion along field lines, particles which eventually enter the detector may have been born quite a distance from the detector. Thus, the detector can be sensitive to reactions which occur over a large region in the plasma. Because of this, only a small portion of the region detected by one detector will also be measured by a second detector.

This is demonstrated by the array described in Table II. A detector which measures $^3\text{He}^{++}$ ions is used in coincidence with three neutron detectors to measure the products of the $d(d,n)^3\text{He}$ reaction. At a reaction rate of 10^{11} s^{-1} , the $^3\text{He}^{++}$ detector measures a count rate of 930 s^{-1} , while neutron detector 2 measures a rate of $1.4 \times 10^5 \text{ s}^{-1}$, assuming an intrinsic efficiency of 10% for the neutron detector. This yields a random coincidence rate of 13 s^{-1} , using a coincidence resolution time of 100 ns, twice the period of the Larmor orbit for the $^3\text{He}^{++}$ ion in a 2-T magnetic field,

TABLE III. Location and efficiencies of the detectors in the TFR and TEXT coincidence arrays.

Device	Detector	R (cm)	Z (cm)	rot (deg)	elev (deg)	ϵ_{single}	ϵ_{coin}
TFR $B_T = 3.0$ T $I_p = 300$ kA	n	102	-25	0	90	1.1×10^{-5}	
	α_1	120	-5	163	52	2.1×10^{-9}	2.8×10^{-11}
	α_2	121	0	163	46	3.0×10^{-9}	1.0×10^{-10}
	α_3	120	5	166	40	6.2×10^{-9}	1.4×10^{-10}
	α_4	118	10	166	29	9.1×10^{-9}	2.1×10^{-10}
	α_5	115	15	169	11	5.2×10^{-9}	1.2×10^{-10}
TEXT $B_T = 2.0$ T $I_p = 200$ kA	p	100	-29	0	40	1.2×10^{-7}	
	α_1	128	-7	175	16	5.1×10^{-10}	4.8×10^{-11}
	α_2	128	7	172	7	2.6×10^{-9}	1.5×10^{-10}
	α_3	120	21	172	-13	4.6×10^{-9}	2.1×10^{-10}
	α_4	107	28	172	-45	2.6×10^{-9}	9.6×10^{-11}

representing an uncertainty of ± 1 in the number of orbits the ion makes before entering the detector. These detectors measure a "true" coincidence rate of 0.43 s^{-1} , for a true-to-random ratio of 1 to 30. Using several identical detectors simultaneously will increase the count rates, but will not improve the ratio of true and random coincidences. Lowering the reaction rate will improve this ratio, but prevent the accumulation of a useful number of counts in a reasonable amount of time.

This problem can be overcome by using a different class of orbits. If the charged particles are energetic enough, their Larmor orbits will have diameters equal to or larger than the minor radius of the tokamak. In this case, charged particles strike the vessel wall (or detector) before they have time to drift or exhibit much toroidal motion. Thus, a detector will only be sensitive to particles born in a relatively localized area. Thus, a second detector can be placed in such a way that a significant fraction of the reactions leading to counts in the first detector will also result in counts in the second. Also, much shorter coincidence resolution times can be used, since the particles leave the plasma in less than one Larmor period. This is the strategy used in designing the arrays in Table III.

The array described for the TFR tokamak in Table III consists of a 14-MeV neutron detector located below the vessel at a major radius of 102 cm and five 3.5-MeV α particle detectors located at a single toroidal location but distributed in poloidal angle. In each case, the elevation of the alpha collimation was chosen to maximize the coincidence count rate with the neutron detector.

The alpha particle detector was collimated with a 1-by-4 mm collimator separated by 1 cm from a 1-by-4 mm detector with the longer side oriented vertically. The neutron collimation had a radius of 2 cm and a length of 10 cm. For a 14-MeV neutron production rate of $3 \times 10^{10} \text{ s}^{-1}$, as from the burnup of fusion produced tritons, alpha particle detector 4 will measure 273 s^{-1} and the neutron detector will receive $3.3 \times 10^4 \text{ s}^{-1}$. This leads to a random coincidence rate of 0.09 s^{-1} and a true coincidence rate of 0.63 s^{-1} , for a true-to-random ratio of 7 to 1, assuming a coincidence resolution time of 10 ns. By simultaneously using several closely spaced collimators, the count rate can be multiplied. For instance, 20 collimators of the size described could fit into an area of 1 cm^2 , multiplying the count rates by a factor of 20, but leaving the true-to-random ratio unaffected. Several similar neutron detectors could be used in the same way.

B. TEXT

The TEXT ($R = 100 \text{ cm}$, $a = 28 \text{ cm}$) array consists of one 14.7-MeV proton and four 3.7-MeV alpha particle de-

tectors located inside the vacuum vessel at one toroidal angle. The alpha particle detectors are collimated with 1-by-4 mm collimators separated by 1 cm from a 1-by-4 mm detector oriented with the longer side vertical. The proton detector collimation consists of a 2.26-cm-radius hole 5 cm long.

At a $^3\text{He}(d,p)\alpha$ reaction rate of 10^{11} s^{-1} , the proton detector will count 1.2×10^6 protons per second, while alpha particle detector 2 will count 260 s^{-1} . The two used in coincidence yield 15.3 s^{-1} , while the random coincidences are 3.1 s^{-1} , assuming a coincidence resolution time of 10 ns. This is a true-to-random ratio of 5 to 1.

III. CONCLUSION

Coincidence techniques can improve current methods of fusion product diagnostics by allowing better spatial resolution of the reactions being measured and more accurate knowledge of the orbit of charged fusion products. Using Δt measurements, the profile of a neutral deuterium beam may be deduced.

Calculated count rates indicate that coincidence techniques are feasible on several present devices.

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