Time-of-flight vs time-of-arrival in neutron spectroscopic measurements for high energy density plasmas

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The neutron time-of-flight (nToF) diagnostic technique has a lengthy history in Inertial Confinement Fusion (ICF) and High Energy Density (HED) Science experiments. Its initial utility resulted from the simple relationship between the full width half maximum of the fusion peak signal in a distant detector and the burn averaged conditions of an ideal plasma producing the flux [G. Lehner and F. Pohl, "Reaktionsneutronen als hilfsmittel der plasmadiagnostik," *Z. fur Physik,* **207** 83–104, 1967]. More recent precision measurements [M. Gatu-Johnson et al, "Indications of flow near maximum compression in layered deuterium-tritium implosions at the national ignition facility," *Phys. Rev. E,* **94**, 08 (2016),] and theoretical studies [D. H. Munro,"Interpreting inertial fusion neutron spectra," *Nuc. Fusion,* **56** 035001 (2016)] have shown the spectrum to be more subtle and complicated driving the desire for an absolute calibration of the spectrum to disambiguate plasma dynamics from the conditions producing thermonuclear reactions. In experiments where the neutron production history is not well measured, but the neutron signal is preceded by a concomitant flux of photons, the spectrum can be in-situ calibrated using a set of colinear detectors to obtain a true "time-of-flight" measurement. Presented is the motivation and overview of this technique along with estimates of the experimental precision needed to make useful measurements in existing and future nToF systems like the pulsed power Z-machine located in Albuquerque, NM at Sandia National Laboratories.

I. INTRODUCTION

Estimating burn averaged ion temperature, T_{ion}, has historically relied on measuring the spectral variance of fusion product neutrons[1–3]. This estimate typically used a single time resolved neutron detector sampling the flux some distance from the source. If the duration of the neutron production is short compared to the neutron flight time, the temperature has been estimated using either the FWHM, or the temporal variance of the fusion peak[3,4]. For fusion neutrons produced in a 4 keV plasma and sampled at a distance of 20 m, this corresponds to $\sim$ 31 ns for DD fusions, or 5 ns for DT fusions. Although the least demanding from a diagnostic and analysis perspective, detailed studies[5] have shown that plasma motion in high pressure ($p \geq 100$ Mbar) implosions confound the physical interpretation. To disambiguate the physics, more recent studies[6] have made independent estimates of apparent T_{ion} by measuring the isotropically distributed mean kinetic energy in excess of that attributable to the Q of the reaction. This approach relies on the relationship between the mean of the reactant pair kinetic energy distribution in the center-of-mass and the plasma temperature. This was initially calculated by Gamow[7] and more recently parameterized by Munro[8]. This excess kinetic energy, when boosted to the lab frame, produces an observable, albeit small, increase over that due to the mass defect in the reaction. Casting this excess in terms of momentum magnitude, Fig. 1a shows the temperature dependence for both DT and DD neutrons[9]. To estimate plasma temperature to a precision of 20% at 5 keV using DT neutrons requires a system capable of measuring absolute momentum to a precision of 5 km/s, or about 1 part in 10^4. This equates to a time-of-flight error budget of 40 ps for a 400 ns flight path. Using DD neutrons relaxes the precision requirement by five fold. Since most ICF facilities do not directly measure time-of-flight, but rather the arbitrary time-of-arrival, the absolute momentum is inferred by empirically cross timing the nToF instrument to a "bang time" detector, usually sampling photons assumed to be highly correlated with neutron production along a different flight path. In this schema, a fusion neutron's absolute velocity is given by:

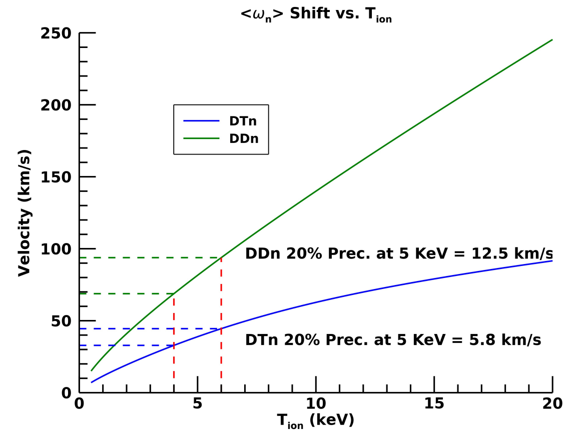
$$v_n = \frac{L_n}{\Delta T_{n-\gamma} + L_\gamma / c},$$

where L_n is the flight path length of the neutron measurement, L_γ is the same for the bang time photons, and $\Delta T_{n-\gamma}$ is the time difference between the arrival of the neutron at L_n, and the photon at L_γ after the two systems have been cross timed. It is worth noting that the precision of this approach depends not only on the precision of the explicitly stated quantities, i.e. $\delta L/L$, but on a number of implied factors, such as, precise knowledge of signal path delays, instrument response functions, relative digitizer triggering, timing fiducial precision, and for laser based timing experiments, when photons are produced relative to the start of the laser pulse. For pragmatic purposes, all these uncertainties can be rolled into the timing uncertainty $\delta\Delta T_{n-\gamma}$. Now propagating uncertainties leads to a simple equation for the relative uncertainty in the neutron's absolute velocity via:

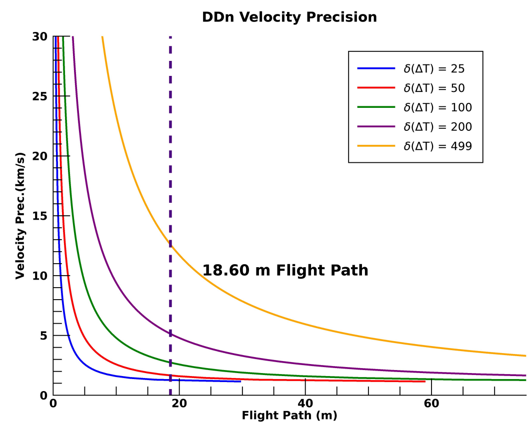
$$\frac{\delta v_n}{v_n} \approx \left(\left(\frac{\delta L_n}{L_n}\right)^2 + \left(\frac{v_{0n}}{L_n}\right)^2 \left(\left(\frac{\delta L_\gamma}{c}\right)^2 + \left(\delta\Delta T_{n-\gamma}\right)^2 \right) \right)^{1/2} \quad (1)$$

where v_{0n} is the magnitude of velocity due to the Q of the fusion reaction.

Fig. 1b shows the achievable DD neutron velocity precision as a function of flight path length for different arrival time precisions annotated in the legend. A detector positioned 18.6 m from the source could theoretically obtain an absolute velocity precision better than 5 km/s if the timing error budget were kept to a precision better than 100 ps. Since the investments required to achieve such a precision on this level are significant, and not all facilities are capable of performing high precision cross timing experiments, *i.e.* using the ARC laser at the National Ignition Facility, an alternative solution to this calibration is strongly desired. If, however, the experimental conditions include a sufficiently bright set of photons traveling along the same flight path as the neutrons, then by using two samples along the flight path of both fluxes would enable an in-situ calibration of the neutron momentum distribution. In addition to its conceptual simplicity, colinearity is essential to avoid systematic timing uncertainties of the neutron spectrum due to directional variations of the projected fluid motion. In the following, Sec. II provides a simple description of how such as system could be implemented and the different measurements that can be made, including absolute neutron momentum, and relative bang time, or burn history depending on the design choices. In Sec. III the theoretical measurement sensitivities of this system are described and the design choices that are needed to achieve these. Finally, in Sec. IV a brief overview of how such a system would be used in the new nToF suite being implemented on the Z-facility at Sandia National Laboratories in Albuquerque, NM, followed by a summary section in Sec. V.



(a) DTn and DDn Gamow shifts



(b) DDn Momentum Precision

FIG. 1: Fig. 1a shows the contribution to the excess neutron momentum, $\langle \omega_n \rangle$, from the reactant pair CoM kinetic energy distribution originally calculated by Gamow[7], but using the Padé approximant published by Munro[8]. The figure is annotated to illustrate the excess mean momentum precision required to make a 20% apparent T_{ion} estimate at 5 keV, *i.e.* 5.8 km/s and 12.5 km/s for DT and DD fusion neutron spectra respectively. Fig. 1b shows velocity precision as a function of flight path length per Eq. 1. The different colored curves reflect the different cross-timing assumptions between the nToF system and bang-time diagnostic as noted in the legend. The dashed black line represents the longest flight-path length of a new nToF suite at the Z-facility.

II. MULTIPLE SAMPLE COLINEAR NTOF FOR IN-SITU CALIBRATION

As discussed in the introduction, the challenge with absolutely calibrating the neutron spectrum using a single nToF detector station results from precise determination of when the sampled neutrons were produced. Although the use of colinear nToFs is conceptually straight forward, and previously discussed for use on Z[10] and Omega[11], there are a number of practical issues that make cross-timing these detectors to bang-time a challenge. First and foremost is whether the facility is able to provide a precise cross timing experiment between the instruments that measure peak neutron production and the neutron flux at some distance. This generally requires a photon source that can be detected by both instruments, ideally in a configuration similar to what is used in neutron experiments. If this isn't readily available, then a surrogate experiment can be performed using instrumentation that is capable of providing the detailed relationship between the relative signal path delays, timing and triggering system jitter, etc, and whose systematic difference between the instruments may be characterized precisely[12]. In the absence of either of these approaches, a detailed accounting of each element in the two systems must be taken. This involves measuring the through delays of each passive element, the temporal response of the individual detectors as a function of configuration state, precise knowledge of the relationship between the timing and triggering systems used to record the data as well as any fiducial generators used to produce timing markers in the recorded data. This latter approach is a herculean task and generally produces data not precise enough to enable the desired measurement.

It is this latter circumstance that motivates the current work. In most fusion experiments, neutrons are generally accompanied by a concomitant flux of high energy photons. If these

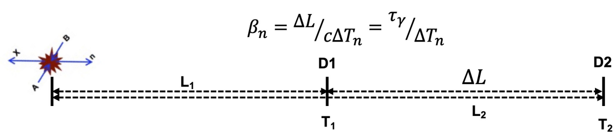


FIG. 2: Conceptual illustration of cross-timing colinear detectors along a single flight path to absolutely calibrate neutron velocity, by using the *known* flight time of photons between the two detector's at distances L_1 and L_2 from the source. This approach can reduce the systematic overheads associated with cross timing to bang time, or detectors along different flight paths.

photons are produced near the fusion reactions and travel to the nToF detector along the same flight path as the neutrons, then they may be used as an in-situ timing fiducial, assuming they induce a measurable signal. If now, as illustrated in Fig. 2, two colinear nToF detectors are located at distances, L_1 and L_2 from a fusion source, then the known flight time of photons between the detectors will necessarily be: $\tau_\gamma = (L_2 - L_1)/c = \Delta L/c$, where c is the speed of light in vacuum. From this knowledge, an individual neutron's velocity is $\beta_n = \tau_\gamma/\Delta T_n$, where ΔT_n is the measured neutron time of flight between detector stations D1 & D2, Heisenberg's uncertainty principle not withstanding. Since pulsed fusion experiments generate distributions in time and momentum of both photons and neutrons, the practical implementation of this concept is to generate a composite signal from the individual digitized signals from detectors D_1 and D_2, where the time difference in the gamma signals reflects their flight time difference τ_γ. This composite trace now has a physically meaningful time scale between the two neutron signals. Assuming a forward fit analysis akin to that of Hatarik[4] where a single source is used to fit both nToF signals simultaneously, then the neutron bang time and momentum distribution can be directly determined. Further, if the source model is augmented with few parameter burn history model it is also possible to estimate the burn width, assuming this is a substantial common mode of the signals measured by the two nToF detectors. Some of the the practical application of this approach is described in further detail in Sec. IV, however the sensitivity of this approach for estimating the mean of the neutron spectrum can be addressed using the simple algebraic relationship described in the next section.

III. SYSTEM DESIGN AND SENSITIVITIES

To implement a "neutron speed-trap" requires some practical considerations to ensure the physics goals are met. As mentioned, a first moment estimate of apparent T_{ion} near 5 keV requires a momentum precision better than $\sim 0.05\%$ when using DD fusion neutrons. Writing the velocity equation in terms of the first moment gives: $\langle v_n \rangle = \Delta L/(T_2(\langle v_n \rangle) - T_1(\langle v_n \rangle)) = \Delta L/\Delta T(\langle v_n \rangle)$, where the quantities, $T_1(\langle v_n \rangle)$, and $T_2(\langle v_n \rangle)$ are the flight times to detector stations D_1 and D_2 of a neutron traveling at the mean velocity of the distribution. The requisite precision translates to a system precision through the relation:

$\delta L(\mu m)$	Min. $\Delta L(cm)$
250	141
500	283
1000	565

TABLE I: Minimum separation of detectors D_1 and D_2 in centimeters for a measurement precision δL in units of microns and assuming $\delta\Delta L/\Delta L = 0.05\%/\sqrt{2}$.

$$\left(\frac{\delta \langle v_n \rangle}{\langle v_n \rangle}\right)^2 = \left(\frac{\delta\Delta L}{\Delta L}\right)^2 + \left(\frac{\delta\Delta T(\langle v_n \rangle)}{\Delta T(\langle v_n \rangle)}\right)^2 \leq (0.05\%)^2$$

It is up to the system designer how to allocate the error budget among the independent components, for the present purposes it will be split equally between the two. This leads to a constraint on the spacing between detectors D_1 and D_2 such that $\Delta L(cm) \geq 2\sqrt{2} \cdot \delta L(\mu m)/5$, where the distance between the detectors is measured in centimeters and the precision to which they are measured is in units of microns. Tab. I illustrates the minimum separation between to D_1 and D_2 for three putative measurement precisions using DD fusion neutrons.

The temporal precision will result from the accuracy at which the gamma signals are properly located on the composite trace. Ignoring detector systematics, we can express this uncertainty as $\delta\Delta T(\langle v_n \rangle)/\Delta T(\langle v_n \rangle) = c \cdot \delta t/\lambda$, where λ is the effective flight path length, $L_1 \cdot L_2/\sqrt{L_1^2 + L_2^2}$. Under the assumption that $\Delta L/L_1 \approx 1/2$ and the equal partition assumption above, the temporal error budget results in a constraint in the timing system of $\delta t \leq 1.4 \times 10^{-4} \cdot L_2\ /c$, or ≈ 9.3 *ps* for a 20 meter flight path. Since this is the precision required on the time separation of the gamma signals in the detectors, the precision required for locating the mean of each signal is decreased by a factor of $\sqrt{2}$, resulting in a 6.8 ps mean precision requirement in the 20 m example above.

If the gamma signal has a width that is much narrower than the sampling period, Δ_s, then the sampling period must satisfy the requirement that $\Delta_s \approx \sqrt{12} \cdot 6.8$ ps, or 24 ps. If, on the other hand, the gamma signals have a finite width such that it can be well sampled over the full-width half maximum, then an analytic model may be employed to co-register the means of the two signals. For illustration purposes a Gaussian model is assumed and Cramer-Rao bound theory will be employed to estimate the variance of $\hat{\tau}_i$, the mean of the gamma arrival times. Cramer-Rao bound theory states that the covariance matrix $\mathbf{K}$ must be bounded by the inverse of the Fisher information matrix[13], *i.e.* $\mathbf{K} \geq \mathbf{F}^{-1}$. Further, if the total number of samples in the record is large compared to the number of fit parameters then $\mathbf{K} \approx \mathbf{F}^{-1}$ and the variance on the fit parameters can be directly estimated. For the case of a well sampled

Gaussian voltage signal, the variance of the mean estimate, $\hat{\tau}$, is given by[14]:

$$var(\hat{\tau}) = \frac{2}{\sqrt{\pi}} \left(\frac{\sigma_n}{V_\gamma \cdot \Delta_s} \right)^2 \Delta_s \sigma_G$$

where $V_\gamma \Delta_s$, $\hat{\tau}$, and σ_G are the Gaussian amplitude, mean, and width. Δ_s is the sample period, and σ_n the Gaussian distributed noise on each signal sample, assumed to be independent. Eqn. 2 illustrates that precision improves linearly with reduced bit noise, while only to the $1/2$ power with increasing sampling rate. For example at the NIF, a 3 ns Gaussian width signal, sampled at 10 GS/s with 0.5% noise results in a precision of ∼13 ps on fit estimates of $\hat{\tau}$. Decreasing the noise by a factor of 2 improves the precision by a factor of 2, whereas increasing the sampling to 20 GS/s only improves the precision by $\sqrt{2}$, or 9 ps. Regardless, the desired precision is within reach of modern technology and can be implemented if some care is taken.

IV. IMPLEMENTATION ON THE Z-MACHINE

The benefit of this approach can be seen on the Z-facility where precision cross timing experiments between neutron and bang time detectors are currently a challenge. Most ICF experiments produce a significant gamma flux with a typical FWHM of ∼ 7 ns. Fig. 3 illustrates typical signals from two Z-nToF detectors located along the LoS270 flight path at distances of ∼9.5 and 11.5 m from the source[15,16]. These data were produced by the MagLIF platform where the neutron production history makes a significant contribution to the temporal width of the nToF signals at these distances. Nonetheless these data can be used to illustrate what may be possible for future experiments and other platforms. The precision of the ∼2 m separation is 1 mm. Each station samples the signal at 2 GS/s with a Gaussian noise after stitching of ≈ 0.1% of full scale. Using the approach outlined in Sec. III, the velocity precision of the neutron signal after cross timing the two Gammas signals is given by $\delta v_n / v_n = 0.05\%$, or 11 km/s when measuring DD fusion neutrons. This can be improved by increasing the sampling rate of the digitizers to say 10 GS/s and improving the spatial precision of the detector locations.

The Z-facility is currently in the process of upgrading their nToF suite with plans to implement three new horizontal, *i.e.* $z = 0$, flight paths. Given the 9-fold rotational symmetry about the $r = 0$ axis, the azimuthal separation between each flight path will be 120° enabling a tripodal geometry that will be used to estimate the isotropic mean excess momentum in the $z = 0$ plane. The current plans will implement a long flight path station 18.6 m from the $r = 0$ axis. If a second station were to be added at 11.6 m with a ΔL precision of 700 μm and both systems sampling at 20 GS/s with 0.1% full scale noise, then the theoretical mean neutron velocity precision of this system, assuming the gamma signals described above

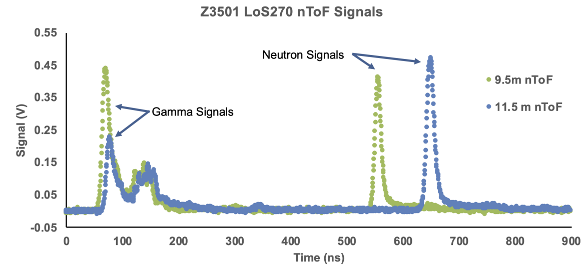


FIG. 3: Illustration of the signals collected by two Z-facility nToF detectors positioned along the same flight path at distances of ∼ 9.5 *m* and ∼ 11.5 *m* from the source. These data were collected on Z-shot Z3501 using the MagLIF platform.

would be 0.01% or ∼2.1 km/s for DD fusion neutrons. Further, this second station would only need to measure the early time gamma and DD fusion neutron signals, as the spectral calibration is most precise for the slower DD fusion neutrons.

V. SUMMARY

The ability to absolutely calibrate the fusion neutron spectrum produced at HED facilities can be a challenge when cross timing experiments between bang time and nToF diagnostics are not readily available. This can be an even more daunting task when detailed accounting of signal path through delays, triggering, and jitter are factored into the effort. In facilities where the fusion neutron signal is also accompanied by a measurable photon signal it is possible, with some care, to calibrate the neutron spectrum via use of two colinear nToF detectors positioned at different distances along the neutron flight path. This requires precise knowledge of the separation between the two detectors, as well as their reduced flight path length, the amount of noise present in the recorded data, as well as the speed at which it is sampled. This approach has initially been developed at the Z-facility on the existing nToF systems, and will be documented in a future paper. Its greatest impact, though, will be when utilized on the new tripodal nToF system currently under construction. The theoretically possible mean DD fusion neutron velocity precision of a pair of colinear nToF detectors in this new system is ∼2 km/s enabling a ∼ 5% estimate of apparent T_{ion} at 5 keV when exploiting the tripodal configuration to determine v_{iso}. This precision is currently better than current systems that require dedicated cross timing experiments relative to bang time. These estimates are based on ideal conditions, and will be impacted by the typical real world and facility implementation considerations, such as non-ideal photon signals, scattered radiation, signal reflections, radio-frequency noise, etc. These latter issues will be addressed in forthcoming work as the initial phases of the new diagnostic suite at Z is implemented.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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