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National Ignition Facility Dilation X-Ray Imager Diagnostic Instrumentation And Control System*

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NATIONAL IGNITION FACILITY DILATION X-RAY IMAGER DIAGNOSTIC INSTRUMENTATION AND CONTROL SYSTEM*

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Abstract

X-ray cameras on inertial confinement fusion facilities can determine the velocity and symmetry of target implosions by recording the x-ray emission of a back-lighter or the target itself gated as a function of time. To capture targets that undergo ignition and thermonuclear burn, however, cameras with less than 10ps shutter times are needed. Collaboration between Lawrence Livermore National Laboratory (LLNL), General Atomics and Kentech Instruments has resulted in the design and construction of an X-ray camera which converts an X-ray image to an electron image, which is stretched, and then coupled to a conventional shuttered electron camera to meet this criteria. This paper discusses diagnostic instrumentation and software used to control the DIXI diagnostic and seamlessly integrate it into the NIF Integrated Computer Control System (ICCS).

INTRODUCTION

In Inertial Confinement Fusion (ICF) experiments at the National Ignition Facility (NIF), lasers strike a hohlraum to generate an intense burst of x-rays. These x-rays ablate target capsule material, compressing the fuel inside to temperatures and pressures required for nuclear fusion [1]. To achieve ignition, the implosion must be symmetric as the target is compressed to the diameter of a human hair. To diagnose the symmetry of the implosion and understand how the reaction progresses, gated x-ray diagnostics measure and image the peak x-ray emission of the hot-spot. As yields increase, the duration of the peak x-ray emission is expected to shorten – as short as 20ps FWHM for ~7×10^{18} neutron yield [2]. Current gated x-ray imagers achieve temporal resolution ranging from 30-100ps. As neutron yields increase, current imaging designs are expected to fail. The Dilation X-Ray Imager (DIXI) allows for imaging of the x-ray emission at less than 10ps temporal resolution at yields up to 10^{17}.

Pulse Dilation Working Principle

The technology used to develop the short gate time for DIXI is Pulse-dilation [3], see Figure 1. When the x-ray signal strikes the photocathode, electrons are ejected and accelerated toward an anode mesh by a high-voltage pulse. The variation of the electric field gives the electrons an energy spectrum corresponding to the temporal shape of the high voltage pulse. The electrons are allowed to drift in space, with earlier high-energy electrons traveling faster than the later electrons, resulting in temporal dispersion of the electron pulse. A magnetic field through the drift space guides and de-magnifies the electron signal on the imaging electronics, countering the spatial dispersion as electrons travel through space. A 200ps gated micro-channel plate x-ray detector amplifies and converts the electrical signal to an optical signal which can be captured by film or CCD. The time-dilation of the electrical pulse through the drift space allows a short duration initial signal captured at the photocathode to be stretched in time by approximately 50× [4], giving the DIXI instrument its improved temporal resolution.

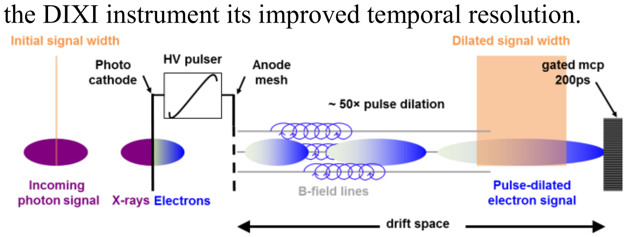

Figure 1: Pulse Dilation Working Principle

DIXI INSTRUMENTATION

The DIXI instrumentation has been described in detail [2,3,4,5,17]. Figure 2 shows the layout of the diagnostic in relation to the Target Chamber Center (TCC). At a distance of 10cm from TCC, the pinhole assembly is held on the Diagnostic Image Manipulator (DIM) to create multiple images of the target. The alignment follows the pattern used by the ARIANE diagnostic, also shown[6]. The pinhole image array is magnified approximately 64× onto the DIXI photocathode at 6.5m from TCC. The gated imager and CCD are located at 7.1m from TCC.

Shown in Figure 3, the DIXI instrument includes an EMI-shielded Filter Image Plate (FIP) enclosure to simplify change-out of filter packs and alignment image plates. Surrounding the DIXI are the vacuum utilities and electrical support infrastructure, along with a substantial shielding enclosure to protect the imaging electronics or film pack. The DIXI is tilted off-axis by 20° from the diagnostic port line-of-sight for additional shielding from

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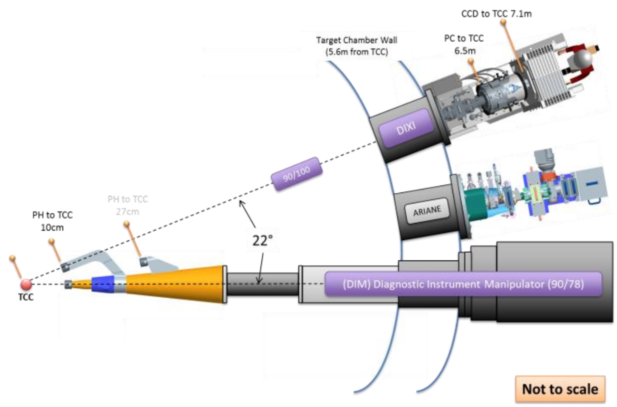

Figure 2: System layout of DIXI Diagnostic in NIF

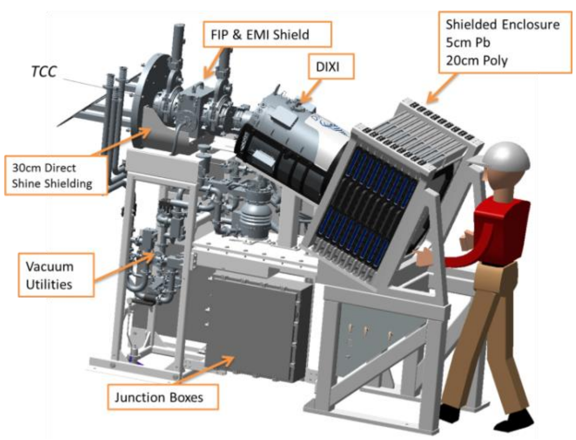

Figure 3: DIXI instrument installation and shielding

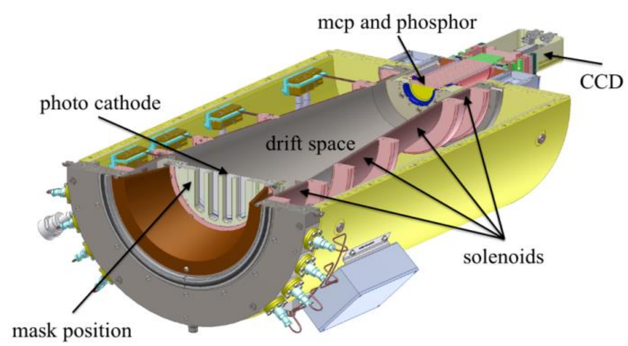

Figure 4: Cutaway detail of DIXI instrument

the target chamber wall. These considerations allow for the DIXI instrument to be used in a neutron yield up to 10^{17}.

As described above and shown in Figure 4, the DIXI instrument uses a photocathode at the front end to generate the electrical impulse in response to the x-ray signal from the target. The photocathode consists of four individual strips, allowing for independent strip timing. The strips are further separated by a tantalum mask. Four pulsed solenoid magnets surrounding the drift space generate a longitudinal magnetic field, which guides the electron signal and de-magnifies the image by 2.5×. A single-strip MCP and phosphor convert the electrical signal to an optical image which is recorded using either a CCD or film.

DIXI Control and Data Acquisition Equipment

The equipment to control the DIXI diagnostic and to capture the data from the detector is located in the diagnostic mezzanine, tens of meters in distance from the target chamber, including by two meters of concrete. The DIXI instrument is controlled via several high-voltage pulse generators for the photocathode strips, the four solenoid magnets, the MCP and the phosphor. Three high-bandwidth oscilloscopes measure the pulse monitor outputs of the several pulsers as well as a fiducial signal to allow cross-timing with the NIF timing system [7]. Other diagnostic control equipment includes the vacuum utilities, power supplies, and Programmable Logic Controllers for the vacuum system and the CCD readout computer.

DIXI CONTROL SOFTWARE

The layered architecture of the software environment at NIF allows several teams of developers the freedom to develop independently, while coupled at well-defined interface points. The layers of software involved in the development of the DIXI include the Target Diagnostic Systems (TDS), Integrated Computer Control System (ICCS), Campaign Management Tools (CMT), Location Component and State (LoCoS), and Shot Analysis and Visualization (SAVI). As each of these systems is described at length elsewhere, this paper will focus on the portion of these systems relating to the DIXI diagnostic.

Target Diagnostic Systems

The control of the Target Diagnostic Systems (TDS) subsystem is achieved through the Instrument-Based Control (IBC) software framework [8]. The IBC framework is designed to allow reusable instrument code to be bundled together to build complex control for larger diagnostic systems using a common set of diagnostic hardware. The framework is also designed to operate stand-alone, to allow the same control software to be used outside of the NIF environment. The other layers of the software environment interface with the IBC software to direct commands to the diagnostic equipment.

The control of the DIXI instrument was developed based on similar X-Ray imaging systems deployed at NIF [9]. The software interface available to the user is designed to ensure that the instrument not be configured outside the specifications and to ensure that data taken is consistent with known calibrated configurations. The user-selectable parameters are the gain, gate width, and strip timing. All other parameters are configured carefully by DIXI engineering team according to the known working configurations and calibrations.

The gain is set through the MCP bias voltage, ranging from -300V to 300V, with each 50 V step corresponding to a 3× increase in signal, close to other MCP based detectors [10,11]. The instrument gate width can be selected partially through the photocathode bias voltage, but also requires a hardware timing configuration change in the MCP pulser.

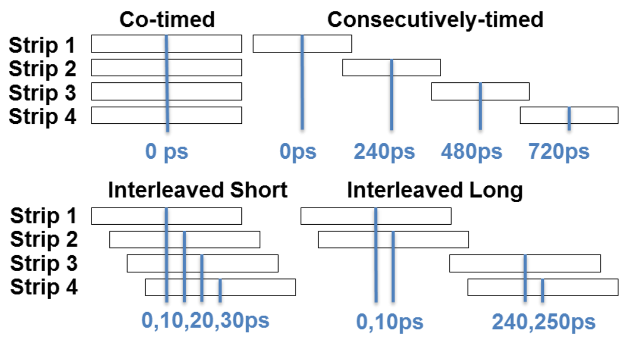

Figure 5: Proposed DIXI timing setups for NIF

Because of the high temporal resolution of the DIXI instrument, configuring the instrument timing correctly is challenging. The timing setup has been simplified to make available four configurations, shown in Figure 5. The co-timed configuration is primarily for verification of the strip-to-strip timing, and the timing relative to the arrival of the x-ray signal from the target. The consecutively timed configuration allows for the maximum total gate width of the instrument.

The interleaved timing configurations allow pairs of strips to be timed closely, so that by observing two sets of images with a slight offset, the diagnostic can sustain its high temporal resolution. Due to the high magnification, a field of view of 150μm will be magnified to a diameter of almost 1cm at the photocathode. The lower part of the pinhole images will arrive at the photocathode slightly after the top of the image. Taking into account the speed of the voltage pulse on the PC as well as the 20° tilt, this causes a time difference of approximately 24ps for a 1cm pinhole image [12]. By timing two strips offset from each other, the pairs of pinholes can be used to reconstruct the correct image. A long and short interleaved configuration allows for either two or four sets of images to be used for this correction, with a trade-off of the gate width to observation length.

Campaign Management Tool Suite

The Campaign Management Tool (CMT) [13] is the interface an experiment designer will use to specify the NIF laser power, pulse shape, pointing, and timing of each beam-line, as well as configuring the diagnostics to be used to acquire data from the target implosion. In the context of the DIXI diagnostic, CMT allows the experiment designer to specify the construction of the pinhole assembly, the filters to be inserted in the FIP, the MCP gain and gate width, and the timing configuration of the photocathode strips. CMT facilitates the review and approval of the laser and diagnostic configuration and generates reports, work orders, and database entries needed to prepare the facility for the shot.

Location Component and State

The Location Component and State (LoCoS) application [13] is used to track the configuration of the facility, from large complex systems down to individual attenuators. The information from LoCoS is used, for example, to configure the correct trigger timing offsets, to link to the correct calibration for a diagnostic on a particular date, which target is used for a specific shot, and which components were used in a pinhole assembly. With the DIXI, when the instrument is installed, the serial number for each sub-component of the diagnostic is entered into LoCoS. As filter packs are loaded into the FIP, or as the pinhole assembly is built and attached to the DIM nose cone, the serial numbers are tracked, and linked to the calibration data for each component. When the system is configured for a shot, a configuration check within the CMT suite compares the part numbers requested in the experiment in CMT against the installed parts in LoCoS to ensure that all diagnostics are configured as requested for the shot.

Integrated Computer Control System

NIF's Integrated Computer Control System (ICCS) is designed to precisely align and amplify the NIF laser. It is divided into many subsystems which control the timing, power level, pulse shape, alignment, and the multi-stage amplification of the laser [14]. ICCS also directs other subsystems, such as the timing system and Target Diagnostics, to coordinate the setup, triggering, and data acquisition of the diagnostics with the sequencing of the laser shot.

When an experiment is loaded by the ICCS shot software, the settings for the Target Diagnostics Software specified by CMT are loaded from the shot setup database and made available to the Target Diagnostic Software through XML files. The ICCS software allows the operator to direct the diagnostic through dry-run sequences to validate the requested shot settings, diagnostic operation, and to make adjustments to timing if necessary. In coordination with the setup of the NIF laser, the ICCS shot software then directs the diagnostic equipment through rod shots and finally the system shot. At the end of the each dry run, rod shot and system shot cycle, the shot archive location is specified, and the Target Diagnostic Software writes out the archive data in Hierarchical Data Files (HDF) [15].

Shot Analysis and Visualization

After the data is acquired from a shot, the Shot Analysis and Visualization (SAVI) suite of tools [13] allows the experimenter to see analysed results and performance metrics from the shot. The HDF files are read and saved in the analysis database. As each file is loaded, the name of the instrument that generated the file triggers the type of correction and analysis to be performed on the data. In order to determine the correct calibration to use for the analysis, the SAVI application queries the LoCoS application for the installed part for the shot date and the current calibration data as of that date.

The analysis of DIXI data within SAVI is under development, but will follow the pattern of other framing cameras developed at NIF. The monitor pulses from the oscilloscope waveforms will be analysed to determine the strip-to-strip timing for the four DIXI photocathode strips,

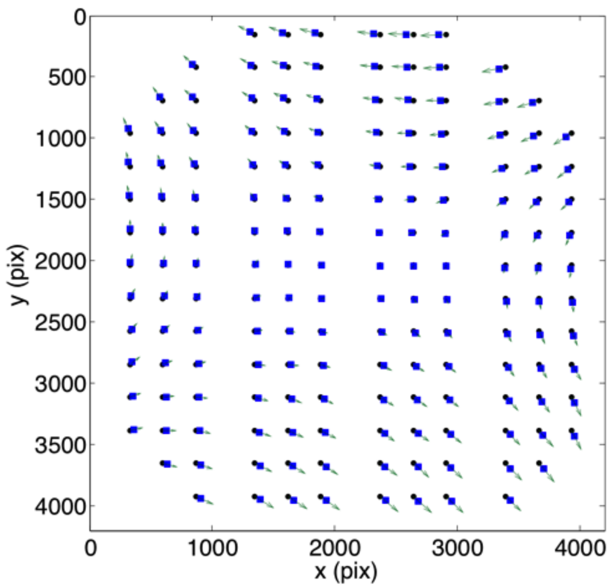

Figure 6: Plot of warp correction generated using an artificial pinhole mask

as well as the timing of the MCP and photocathode relative to the NIF laser pulse at the target. The images from the CCD will be corrected to remove the warping effects of the magnetic field in the drift space, as shown in Figure 6 [16], as well as other corrections, such as flat-field and background subtraction. The data are also made available to scientists and experiment designers for customized analysis, such as extracting the individual pinhole images into a time-history view of the x-ray emission of the target implosion.

CONCLUSIONS

This document was prepared as an account of work The DIXI instrument has been developed to provide a high temporal resolution x-ray imaging diagnostic in the increasing neutron yields of ICF targets. DIXI will allow scientists a better understanding of the physics of nuclear fusion, the performance of ICF targets, and the behaviour of matter at temperatures and densities only available at NIF.

DISCLAIMER

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