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On the National Ignition Facility (NIF), the hot electrons generated in laser heated hohlraums are inferred from the >20 keV bremsstrahlung emission measured with the FFLEX broadband spectrometer. New high energy (>200 keV) time resolved channels were added to meet requirements for ignition and to infer the generated >170 keV hot electrons that can cause ignition capsule preheat. First hot electron measurements in near ignition scaled hohlraums heated by 96-192 NIF laser beams are presented.

1 Introduction

The National Ignition Campaign (NIC) that has begun recently on the National Ignition Facility (NIF) [1] will attempt to achieve fusion ignition and energy gain using a mega joule laser-driven hohlraums [2]. During the laser beams propagation inside the hohlraums hot electrons can be generated by laser-plasma instabilities [3]. For the current ignition design [1] the hot electrons with energies >170 keV can penetrate through the capsule ablator causing preheat of the deuterium-tritium (DT) fuel [4]. The preheat results in entropy increase and hence less fuel compression, resulting in less PdV work on the hotspot to initiate fusion. In the indirect drive ignition design on the NIF the high-Z hohlraums are heated by 192 laser beams with a shaped pulse shown in Figure 1a.
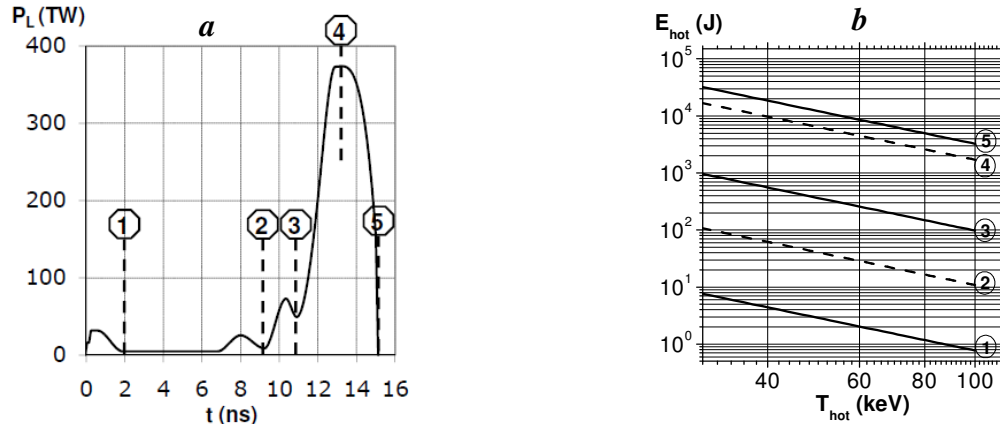

Figure 1 (a) Laser power for NIF ignition design and (b) hot electron thresholds for ignition as a function of T_{hot} integrated up to different times during the ignition pulse

Calculations show that in order to maintain fuel entropy to levels acceptable for ignition the hot electron thresholds are much more stringent at early times than at late times during the ignition pulse [4]. Under the assumption that the hot electrons are isotropic we calculated the acceptable total energy of hot electrons generated inside the ignition hohlraums at different times during the laser drive. Since only the >170 keV hot electrons can cause fuel preheat the calculated hot electron thresholds for ignition $E_{hot} \sim 1/T_{hot}^{1.8}$ assuming a maxwellian hot electron distribution. Figure 1b shows the acceptable thresholds for ignition up to different times during the laser drive. For T_{hot}=30 keV the allowable fraction of hot electrons out of the total laser energy ranges from 0.02% (E_{hot}=7.6 J) for the

first 2 ns to 2.5% (E_{hot}=30 kJ) at the end of the ignition laser pulse. Since most of the hot electrons are stopped inside the hohlraum, we infer them from the hard x-ray bremmstrahlung spectra they generate in the hohlraum walls. The thick target bremsstrahlung spectra generated by a maxwellian distribution of hot electrons is approximated by [3]:

$$I[keV/keV.sr] = \frac{e}{4\pi} \cdot 5 \times 10^{11} \cdot \frac{Z}{79} \cdot E_{hot}[J] \cdot e^{-h\nu / kT_{hot}[keV]} \quad [1]$$

On the NIF we measure the time integrated absolute >20 keV hard x-ray bremsstrahlung emission from laser heated targets using the Filter-Fluorescer diagnostic (FFLEX) [5].

2. The FFLEX diagnostic
2.1 Calibration and performance qualification
The FFLEX detectors consist of NaI(Tl) scintillators coupled to XP2008 photomultiplier tubes (PMT) that are connected to charge sensitive amplifiers (CSA). An early version of FFLEX with 8 filter-fluorescer channels in the 20-150 keV spectral range was activated in 2004 during the first hohlraum experiments during NIF Early Light (NEL) Campaign using the first four NIF beams [6,7] forming quad 31B. Recently, absolute response and PMT gain calibration measurements were performed in single photon counting mode using an Am241 radioactive source in preparation for the NIC. As expected, the measured PMT voltage gain exponents, in the 6.7-7.5 range, were consistent with 2004 calibrations. The scintillator-PMT absolute responses showed an average decrease of 5%. To qualify the performance of the FFLEX diagnostics for NIC we reproduced one of the NEL experiments [7] using 1.6 mm diameter, 1.5 mm long vacuum halfraum heated by a NIF quad with a 2 ns flattop laser pulse, 0.5 mm spot size at best focus and 13 kJ total energy. Figure 2 shows a comparison between the FFLEX spectra measured for the similar experiments during NEL and during the ongoing NIC.
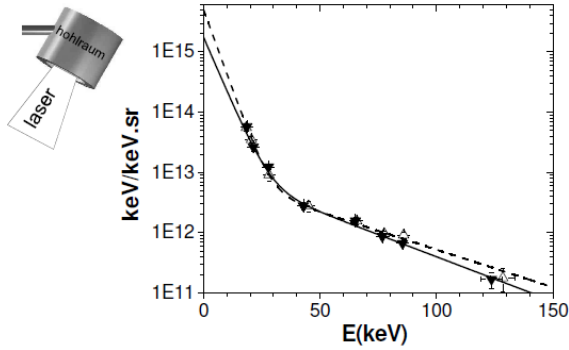

Figure 2 Experiment layout and corresponding FFLEX spectra measured on NEL [7] (empty points, dashed fit) and on a similar 2009 NIC experiment (solid points and fit)

The spectral points in the 8 FFLEX filter-fluorescer channels in 2004 and 2009 experiments are consistent with each other within 15% errors in the channel spectral and absolute responses. The measured spectra in these vacuum hohlraums are fitted by two-temperature distributions with a thermal electron component with T_1=4-5 keV temperatures characteristic for the laser spot plasma generated at the hohlraum wall and a hot electron component with T_{hot}=30 keV characteristic for hot electrons generated by stimulated Raman scattering (SRS) and $f_{hot} \leq 1\%$ (E_{hot}=100 J). The hot electron fraction scales with the laser intensity and is consistent with previous experiments [7], validating the FFLEX diagnostic.

2.2 FFLEX upgrade with high energy time resolved channels
For NIC, FFLEX must be able to measure minimum Ehot of ~1 J which was demonstrated during NEL [6,7]. Furthermore, early and late time hot electron thresholds (Fig.1b) that will be measured separately during experiments using truncated ignition laser pulses (Fig.1a) with the time integrated FFLEX require a shot-to-shot dynamic range of 10^5 which is satisfied by the broad gain range of the used PMT's and CSA's. The 8-channel FFLEX, however, cannot distinguish hard x-rays generated by >170 keV preheat hot electrons, nor can it measure a ~100 keV superhot electron component that

would adversely preheat the fuel. Since at >170 keV photon energies no element absorption edges exist, the potential new high energy channels are high band-pass filter only ones [8]. With the estimated 15% calibration uncertainties per channel, calculations show that two new channels with typical filter only responses with >200 keV and >350 keV spectral band-passes are required to resolve two temperatures 30+100 keV hot-superhot electron distributions. They will also distinguish preheat hot electron signatures and, since experiments with a reduced number of truncated laser drives will be performed, the new channels are required to have <1 ns time resolution. Recently, in addition to the existing 8 filter-fluorescer channels, the required two high energy, time resolved channels were added to FFLEX. Figure 3 shows the layout and design of the upgraded FFLEX.
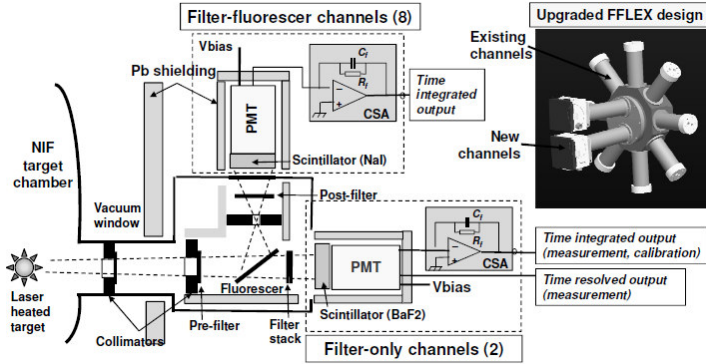

Figure 3 Layout and design of FFLEX upgraded with the two high energy, filter only channels
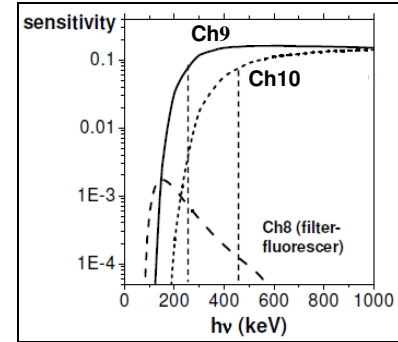
Figure 4 Spectral response of the new high energy channels

For the new channels fast Hamamatsu R5320 photomultipliers with a rise time of 0.7 ns are used, coupled to BaF_2 scintillators. The time response of the system that includes 50 m long signal cables measured with a Co60 source in single photon count mode revealed a 0.7 ns rise time and ~2 ns FWHM impulse response that depends slightly on the PMT voltage. Time resolved and time integrated signals via CSA are obtained for both experiments and absolute response measurements by tapping PMT signals off both anode and last dynode.

Figure 4 shows the spectral response of the new >200 keV and >350 keV channels, obtained by using filter stacks consisting of Au/Pt/Cu/Al (0.5/0.8/5/3 mm thick) coupled to a 10 mm thick scintillator and Pt/Cu/Al (4/5/3 mm thick) coupled to a 15 mm thick scintillator, respectively. Cu/Al filter combinations are used to suppress the K shell fluorescence of the high-Z filters. The absolute calibration of the high energy channels is ongoing in parallel to NIC experiments.

3. First hot electron measurements in multi-beam NIF hohlraum experiments
First 96-192 multi-beam hohlraum experiments were performed in scale 0.7-0.9 hohlraums of the full ignition targets to validate the hohlraum x-ray drive for ignition. Scale 0.7 (3.6 mm diameter x 6.5 mm long) vacuum hohlraums were heated by 96 laser beams with 2 ns square laser pulse with 150-310 kJ total energy. For corresponding average laser intensities per beam of 4, 6 and $8 \cdot 10^{14}$ W/cm^2 we measured 2-T distributions with f_{hot}/T_{hot} of 0.001%/17 keV, 0.0003%/38 keV and 0.2%/20 keV respectively. The results are consistent with previous experiments [6,7,9] which show that hot electron fractions start to be significant (~>1%) at laser intensities of ~10^{15} W/cm^2.
Scale 0.9 (4.6 mm diameter x 8.4 mm long) vacuum and gas filled hohlraums were heated by 192 laser beams and Figure 5 shows a summary of measured FFLEX spectra. Vacuum hohlraums at room and cryogenic temperatures heated by 600 kJ laser energy with 2 ns square laser pulses yielded 2-T spectra with T_1~10 keV and f_{hot}=0.2% at T_{hot}=30 keV. At similar $8 \cdot 10^{14}$ W/cm^2 laser intensity, this result is consistent with that measured the scale 0.7 NIF hohlraums and during NEL [6,7] in reduced scale hohlraums and lower than f_{hot}~>1% measured at 10^{15} W/cm^2 intensity (Fig. 2). In conclusion, for similar plasma filling conditions [6], the f_{hot} scaling with laser intensity in NIF multi-beam ignition

scale vacuum hohlraum experiments is consistent with previous data measured in reduced scale hohlraums heated by >40x less laser energy.

Gas filled (CH_4) hohlraums at room temperature were heated with ignition-like laser pulses (Fig. 1) with pulse lengths of 11 ns and ~500 kJ total laser energy. For a laser intensity of $5 \cdot 10^{14}$ W/cm^2, i.e. lower than in vacuum hohlraums (Fig 5), the measured FFLEX spectra are also fitted by 2-T distributions with T_1~10 keV and T_{hot}~30 keV, but with 10x less spectral flux, yielding lower f_{hot}=0.02% as expected.
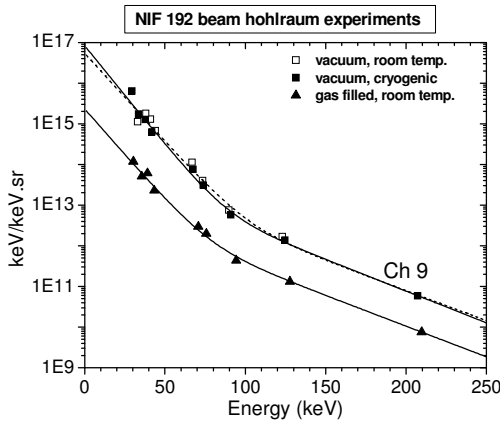

Figure 5 FFLEX spectra in room temperature and cryogenic vacuum hohlraums and in gas filled hohlraums at room temperature
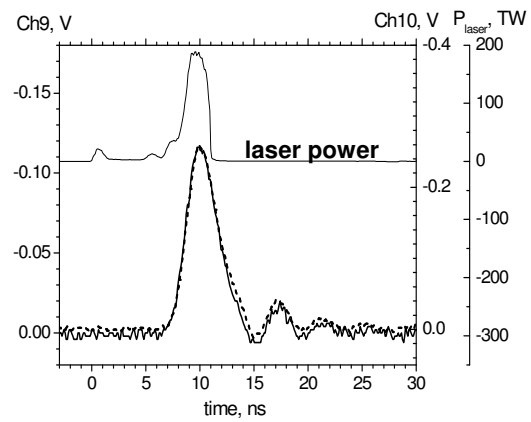
Figure 6 Total laser power, Ch9 (dashed line) and Ch10 (solid line) hard x-ray signals

In the NIF experiments the new >200 keV Channel 9 gives spectral points consistent with the first 8 channels (Fig. 5), showing that there is no high energy cutoff of the hot electron distribution at $h\nu$~$4kT_{hot}$, as suggested by some physics models [3]. Channels 9 and 10 provide also the time history of the hard x-ray signals corresponding to hot electrons. For vacuum hohlraums, hard x-ray signals with 6 ns FWHM were measured for 2 ns square laser pulses. The longer duration of the x-ray signals compared to the laser pulses is attributed to the high-Z wall plasma stagnation on the hohlraum axis. Figure 6 shows the total laser power and the time resolved x-ray signals measured in channels 9 and 10 for scale 0.9 gas filled hohlraums at room temperature. X-ray signals were generated only during the peak of the laser power, with no measurable early time emission within the single shot dynamic range of the scopes of 200. Furthermore, since the gas fill suppresses the wall plasma stagnation, their FWHM of 3 ns is comparable to the main laser pulse.

In the ongoing NIC FFLEX will be employed in cryogenic gas filled (He-H mix, pure He) hohlraum experiments, similar to ignition hohlraums [2]. Furthermore, Channel 10 will provide data that will probe the existence of a superhot electron component [3].

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