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V. Rupert
D. Matthews
H. Ahlstrom
D. Attwood
R. Price
L. Coleman
K. Manes
V. Slivinsky

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Backlighting Prospects for Nova/Novette*

V. Rupert, D. Matthews, R. Price, H. Ahlstrom,
D. Attwood, K. Manes, W. Slivinsky

University of California
Lawrence Livermore National Laboratory

Abstract

High energy x-ray backlighters are necessary to diagnose the implosion symmetry and stability of intermediate and high density targets. Synchronization requirements betwen the target irradiating pulse and the radiograph place severe constraints on the type of x-ray sources which can be used and favors laser irradiated backlighters. Data gathered on line emitters as a function of laser pulselength, wavelength and intensity (ref. 1) in the 5 to 10keV region are used to determine which diagnostic instruments will be feasible for ICF target experiments, and the requirements for backlighter irradiation.

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Introduction

As ICF progresses towards higher density implosions, x-ray backlighting emerges as one of few diagnostic methods available to determine the dynamics, symmetry and stability of imploding shells and the compressed core size.

However, the very nature of the targets which we wish to diagnose, with their high Z pushers and large areal densities,[1] requires x-ray backlighting energies far in excess of any used in previously reported experiments.[2-4]

Viewgraph 1

When assessing the potential of backlighting for the next generation of laser fusion experiments using the Novette or Nova lasers, three main categories of requirements must be taken into account.

The target: Defines the x-ray energy required for backlighting. Indeed the transmission of various parts of the target (ablator, pusher, fuel) to a given wavelength x ray depends on the shell materials opacity and varies with time as its areal density. Hence, different energy x rays may be required to clearly identify the various target components at a given time, or even the same components at different times.

Moreover, self-emission of the target may be large enough at times to result in an unacceptable background level compared to the intensity of a given backlighting x-ray source.

The backlighter: Synchronization requirements (∿ 10 ps for some applications) between target irradiation pulses and backlighting flash are difficult to implement other than by using a laser generated x-ray pulse. In this case, the main target irradiating pulse and the backlighter irradiating pulse can be synchronized with the necessary accuracy. Hence, we are only considering at this time laser generated backlighting pulses. In particular, line emitters have been investigated,[5-6] principally because the large concentration of energy in a very narrow frequency window can be tuned to the particular part of the target under investigation by a proper choice of material. Since the opacities of the target components change rapidly with frequency, a source with a narrow bandwidth has the additional advantage of simplifying the data analysis.

Having selected the type of x-ray source which will be used, it is necessary to determine the relationship between the laser beam and x-ray source intensities. The extent and duration of the line emitter relative to the dimension of the laser irradiated spot and the laser duration also need to be known. This will help define the required optical pulse which will result in backlighter characteristics matched to a given imaging system.

The instruments: their bandwidth, sensitivity (acceptance angle), spatial and temporal resolution define the type of source which can be used for a specific application.

Viewgraph 2

Figure 2 shows the projected performance of a 9 keV backlighter used to diagnose a double shell target. On Fig. 2a, the outer pusher (TaCOH) accelerates inward while a slight preheat of the inner pusher (Au) results in a small increase in shell thickness. At approximately 4.8 ns, the two shells collide.

Figure 2b shows the transmitted backlighter intensity versus radius at four different times. The motion of the outer pusher should be easy to follow, and with sufficient spatial resolution, the preheat of the inner shell as witnessed by its early expansion could also be diagnosed with such a backlighter. Close to collision time, however, discrimination between the shells disappears. Some higher energy backlighter would be required to follow the inward motion of the shells any further.

Viewgraph 3

The preceeding figure was generated by determining the opacity and areal density of the various target components and generating a transmission curve for a specific energy backlighter. The calculated target self-emission for the same irradiation characteristics is shown in Fig. 3. The source of this self emission appears to be preduminately the outer pusher. Here we see that the background intensity (defined as the self-emission level) is a factor of 50 lower at 9 keV than at 4.5 keV. Data such as these are useful to compare with backlighter yields. As will be shown later, the decrease in backlighter yield with line energy is slight for similar laser parameters. Hence, in this case, the higher energy backlighter will result in a significant signal to noise improvement. Note that near peak compression the 9 keV self-emission increases dramatically. Near this time, however, areal densities have increased to the point that 9 keV backlighting has become useless in any case.

Viewgraph 4

Before proceeding with a discussion of backlighter and instrument characteristics, we might note that different requirements result from the two types of backlighting experiments which can be considered.

BACKLIGHTING CAN PROVIDE TWO TYPES OF DATA WITH DIFFERENT REQUIREMENTS

o 1-D time resolved schemes provide velocity data and rough symmetry information

- Require long backlighting pulses — emission duration ∿2-5ns, resolution 10-100ps

- Radial velocities could be obtained by imaging only half the target — field of view ∿ 1mm, resolution ∿ 5-10μm or field of view < 200μm, resolution ∿ 2μm

- Symmetry data require imaging the full target diameter-------------------field of view 2mm

o 2-D snapshots provide information on symmetry and stability

- Require precise knowlege of flash time-----synchronization ∿ 10-20ps

- Are obtained with short backlighter flashes or fast shuttered systems----------exposure time ∿ 10-100ps

- Stability information can be obtained by imaging a sector of the target — field of view ∿1mm x 1mm, resolution ∿ 5-10μm or field of view 200μm x 200μm, resolution ∿2μm

It then appears that 1-D streaked radiography is less demanding of the backlighter than 2-D flash imaging since it requires a smaller source extent (the width of the field of view is determined by the streak camera slit width), and less stringent requirements on synchronization provided a long enough emission duration can be obtained.

Viewgraph 5

The results of backlighter characterization experiments were presented at a previous APS meeting[5], and will only be briefly summarized here with the addition of information gathered since at 0.35 μm laser irradiation.

The main features of the experiments run primarily with Ti, Ni and Zn are:

A threshold laser intensity must be exceeded to obtain a detectable line emission. This threshold

increases with increasing line energy.
increases as the laser pulse length decreases.
decreases with decreasing laser wavelength.

The conversion efficiency computed as photons (in the K_α helium and lithium-like resonance lines including nearby dielectronic satellites and intercombination lines as shown in Fig. 4) per incident joule of laser energy

decreases slowly with increasing laser intensity.
decreases with increasing line energy.
increases only slightly with decreasing laser wavelength.

Note: That whereas the first two results were confirmed by experiments at the University of Rochester,[7] the latter is in disagreement with LLE data. The reason for the discrepancy is not clearly understood at this time, although we note that a somewhat lower laser intensity was used in LLE experiments compared to ours (10^{15}W/cm^2 versus 3×10^{15}W/cm^2). Nonetheless, backlighting could clearly benefit from the increased yield quoted in Ref. 7.

Viewgraph 6

Sketchy data were accumulated on source extent and duration at 1.06 μm irradiation. On both accounts, the x-ray source characteristics seem to have exceeded the corresponding laser parameters. This is probably due to the fact that high energy lines are generated by suprathermal electrons in this case, and are thus particularly susceptible to space and time variation. At shorter wavelengths, the suprathermal electron production is greatly reduced so a better match of laser spot size and duration to corresponding x-ray source characteristics should occur for the thermally excited lines.

Viewgraph 7

The measured backlighter yield can be combined with the measured (or predicted) imaging system requirement to determine the laser intensity necessary to obtain a useful source. For streaked radiography, x-ray microscopes coupled with streak cameras are expected to be used extensively[8]. Table I shows that for 8 keV backlighting, the required laser intensity is barely sufficient to turn on the emitter lines at 1.06 μm when a Au cathode is used. With a CsI cathode the limiting intensity is defined by the threshold for line emission.

Viewgraph 8

For 2-D imaging, several options are being considered. To investigate outer shell symmetry and stability, frame times of the order of 50 to 100 ps should be useful. In this case, the short exposure time can be obtained either using streak camera framing techniques[9] or a microchannel plate gated with a fast Auston switch[10]. Either method can be used in conjunction with x-ray optics such as microscopes or Fresnel lenses.

In the case of the framing camera, the flux requirements at the target are identical to those needed for streaked radiography (Table I). For the gated microchannel plate, flux requirements are a factor of ten lower since tne integration time per image pixel is ten times longer. Hence, in the latter case, the minimum necessary laser intensity on the (8 keV) backlighter is the threshold intensity for line production.

Shorter frames are required to study the inner shell and the compressed core. It appears that the only method to obtain such images will be to generate an appropriately short x-ray flash. A regenerative amplifier[11], capable of producing 20 ps laser pulses, will be available at Novette and Nova. Experiments will be conducted to determine the duration of the x-ray emission which can be obtained with these laser pulses.

Our p evious backlighter experiments show, however, that very high intensities on target will be required to exceed the line production threshold. Even at 0.35 μm irradiation, it is probable that some 10^{17} W/cm^2 will be needed*. Any extended source would then require inordinately high laser energies on the backlighter. Therefore, we are primarily concerned with point source imaging techniques.

Viewgraph 9

Since the required laser intensities on the backlighter are determined by the instruments and backlighter yield, the laser pulse energy and duration can be determined knowing the size and characteristic velocity of the target shells which are to be studied.

* LLE results might imply somewhat lower intensities.

Based on a characteristic target size of 250 μm, the times of interest for streak radiography of the outer shell is of the order of 2 ns and two to three 100 ps frames would be desirable over a 2 ns duration. The denser inner shell which might require the higher energy backlighter is assumed to have a 1 ns characteristic time. Table 2 (Viewgraph 9) shows that even where a streak camera with a gold photocathode is used, the required energy on target remains lower than the design energy (10-15 kJ @ 1.06 μm, 7-10 kJ @ 0.53 μm). Hence, one sided irradiation of targets, with a second arm used for backlighting, is possible and might be useful for specially designed "physics" or "code normalization" experiments.

However, when a CsI photocathode is used for streaked radiography or a microchannel plate for 2-D imaging, much can be accomplished with a 1 kJ, 300 GW separate backlighting arm although some reduction of dynamic range must be accepted for the higher energy backlighters. With such a separate backlighting arm, full irradiation of nominal targets will be possible.

Point source imaging schemes are not proposed at this time. However, study of the relationship between x ray and laser pulse duration is necessary to develop flash backlighting for Nova.

Viewgraph 10

Predictions for Nova are based on larger targets which are being considered and the higher compressions expected.

While backlighting below 8 keV may be used for special experiments, a Nova target will require backlighting at 9 keV at least.

Using our current knowledge of Ni and Zn line emitters, and assuming the optimum configuration of the imaging system (CsI cathode or microchannel plate), the laser intensity required to obtain three orders of magnitude dynamic range is below the line emission threshold for 1.06 or 0.53 μm irradiation and slightly above at 0.35 μm irradiation. Using 0.53 μm as a baseline, a threshold laser intensity on target of 4×10^{15} W/cm^2 can be used.

For streaked radiography where dynamics of an outer shell are to be investigated, a 1000 x 50 μm backlighting source is appropriate. Then it is necesary to provide 2 TW of 0.53 μm light. For a 5 ns pulse duration, one of the Nova beams (10 kJ) will be used.

Since 2-D imaging requires a much larger source (2 x 2 mm^2), it is apparent that schemes other than point source imaging will be prohibitive in energy within our current capabilities. For point source imaging, limitations are due to the minimum x-ray flux required for the instrument. Initial estimates based on LLNL data show that 2.5 TW of 1.06 μm radiation would be needed for a 10 μm source (alternately 10 TW are needed for 5 μm resolution). This again should be possible using a Nova beam and corresponds to 2.5×10^{18} W/cm^2 on target. Note that should LLE's results prevail, a significant reduction of the required power could occur. If 0.35 μm light is used for irradiation, this reduction could be as much as an order of magnitude.

The high intensity on target possible with point-source-flash-radiography may allow backlighting with x-ray energies higher than 9 keV. This is possible since the total line yield decreases slowly with line energy. More experiments remain to be done to determine how high an energy this technique will allow. At the highest energies considered thus far (hν ∿80-100 keV), filtering techniques will be used to select an appropriate bandwidth out of continuum emission of a high Z source.

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BACKLIGHTING PROSPECTS FOR ICF TARGETS

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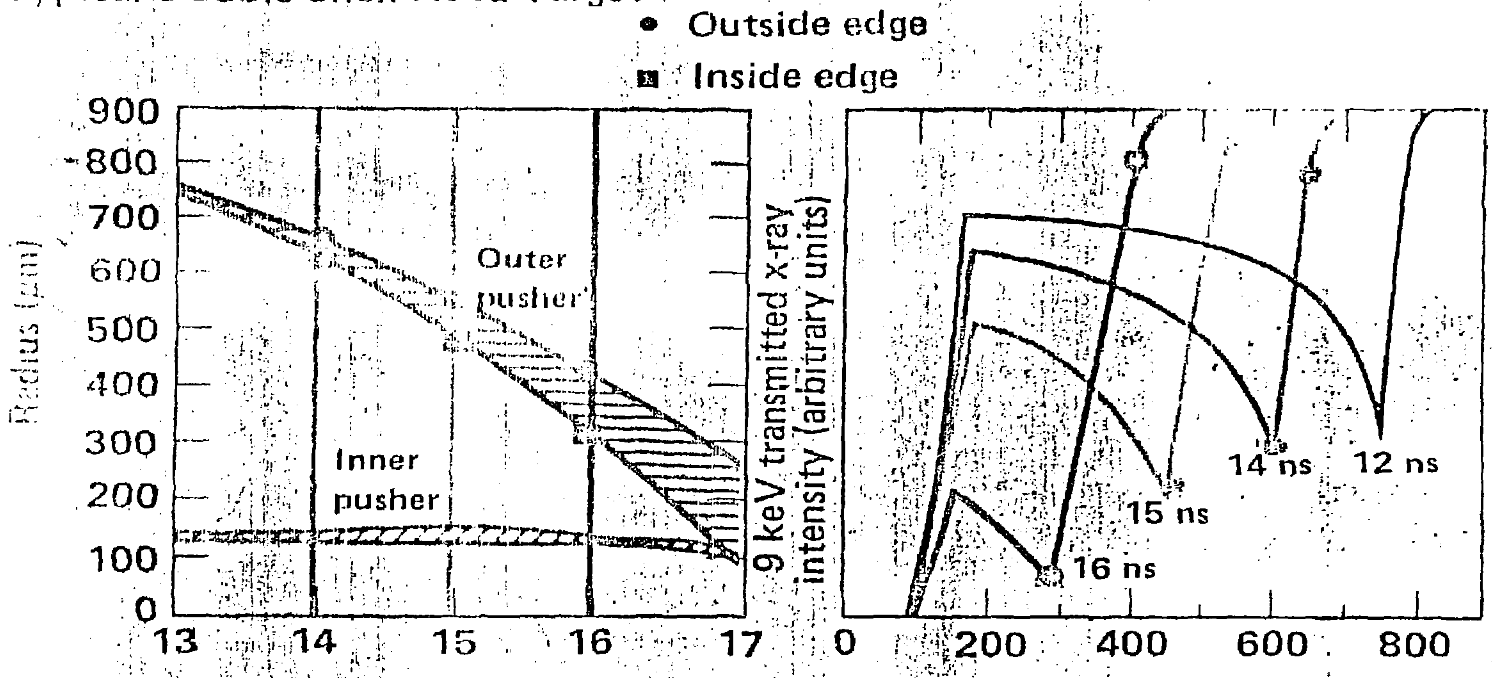
BACKLIGHTING ISSUES

The Target:	Areal density of various components
	Self emission
The Backlighter:	Energy (wavelength)
	Intensity
	Extent
	Duration
The Instruments:	Bandwidth
	Sensitivity and acceptance angle
	Spatial resolution
	Temporal resolution

V.G.2

TRANSMITTED X RAY FLUX FOR A 9 keV BACKLIGHTER — COMPUTED

Typical Double Shell Nova Target



Time history of shell boundaries

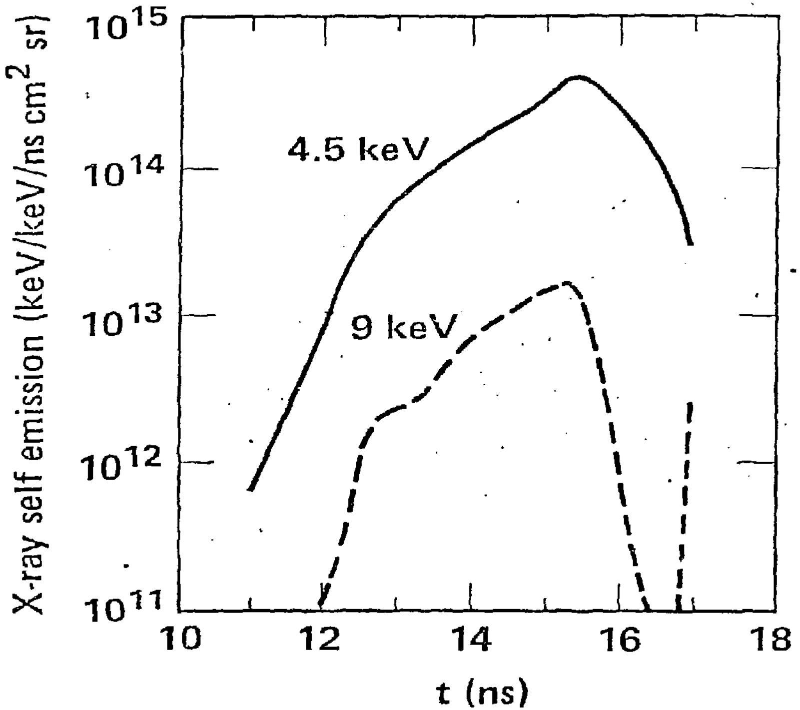
Transmitted backlighter intensity

0-50-0481-0854

V.G.3

SELF EMISSION OF THE TARGET CAN BE SIGNIFICANT

Except at ignition the background due to self emission is more favorable to 9 keV backlighting



20-90-0481-0851

VG4

BACKLIGHTING CAN PROVIDE TWO TYPES OF DATA WITH DIFFERENT REQUIREMENTS

- 1-D time resolved schemes provide velocity data and rough symmetry information
  - Require long backlighting pulses — { emission duration ~2-5 ns; resolution 10-100 ps }
  - Radial velocities could be obtained by imaging only half the target — { field of view ~ 1 mm; resolution ~ 5-10 μm } or { field of view $\lesssim$ 200 μm; resolution ~ 2 μm }
  - Symmetry data require imaging the full target diameter – – – – – – – – – – – – – field of view 2 mm
- 2-D snapshots provide information on symmetry and stability
  - Require precise knowledge of flash time – – – – – synchronization ~ 10-20 ps
  - Are obtained with short backlighter flashes or fast shuttered systems – – – – – – – – exposure time ~ 10-100 ps
  - Stability information can be obtained by imaging a sector of the target — { field of view ~ 1 mm X 1 mm; resolution ~ 5-10 μm } or { field of view $\lesssim$ 200 μm X 200 μm; resolution ~ 2 μm }

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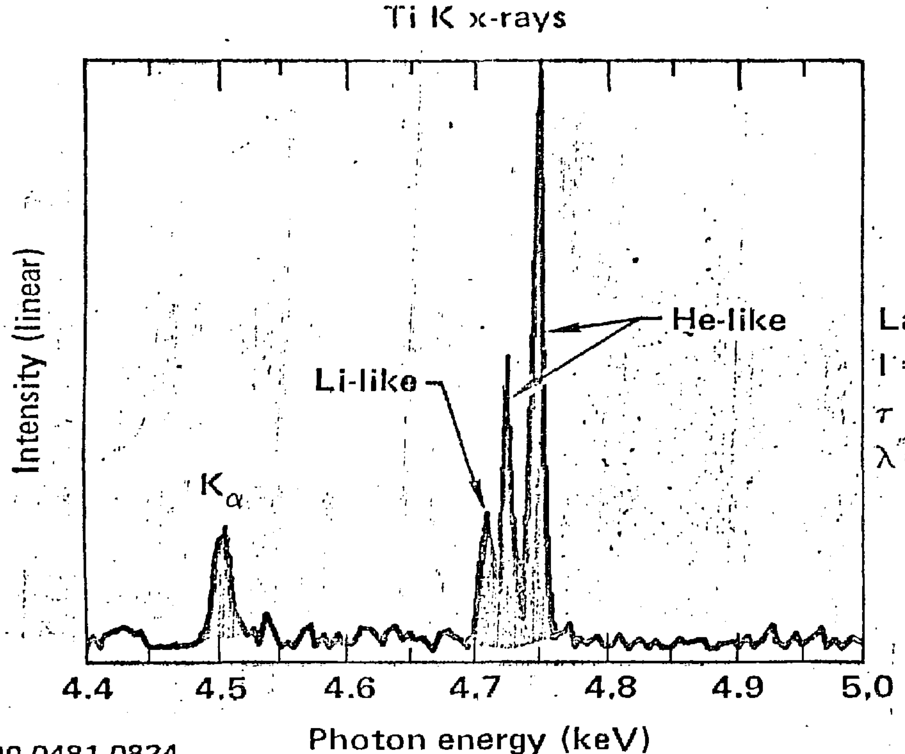
VG 4a (backup)

QUOTED CONVERSION EFFICIENCIES INCLUDE THE FULL CLUSTER OF K LINES



Laser irradiation conditions

$I = 3 \times 10^{16}$ W/cm^2

$\tau = 100$ ps

$\lambda = 1.06\ \mu m$

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THE BACKLIGHTERS IN A NUTSHELL: PART I

- The threshold laser intensity required to obtain an x-ray line
  - Increases with increasing line energy
  - Increases as the laser pulse length decreases
  - Appears to decrease with decreasing laser wavelength
  - Is the limiting factor for backlighting
- The conversion efficiency in photons/joule
  - Ranges from 10^{11} to 10^{12} for all backlighters tested (Ti, Ni, Zn)
  - Decreases slowly with increasing laser intensity
  - Decreases with line energy
  - Is sufficient for most imaging schemes available or conceived

For 1.06 μm Irradiation:

- The extent of the line emitting region appears to exceed the laser spot size. This presents a problem for point source imaging schemes
- The time of emission appears to exceed the irradiation time. This may preclude the use of short bursts of line emission for flash radiography

Both issues need to be addressed more systematically. Since high energy lines are predominantly generated by superthermal electrons at 1.06 μm, they are particularly susceptible to space and time dilation. At shorter wavelengths better match of x-ray and laser characteristics can be expected.

LASER INTENSITY REQUIRED FOR STREAKED RADIOGRAPHY

For 3 orders of magnitude dynamic range – Figure of merit of microscope same as that of 22X system

Backlighter energy keV	X-ray optics	Streak camera photocathode	Flux required at target keV/cm^2 sec sr	Backlighter conversion efficiency I_X/I_L keV/J sr	Laser intensity required I_L w/cm^2
3.5 ⩽	Wölter	Au CsI	10^{26} 4×10^{25}	$\sim 2 \times 10^{12}$	5×10^{13} 2×10^{13}
4.7	Barbee/KB*	Au CsI	8×10^{26} 6×10^{25}	$\sim 3 \times 10^{11}$	3×10^{15} 2×10^{14}
8.0	Barbee/KB*	Au CsI	3×10^{27} 1.3×10^{26}	$\sim 2.4 \times 10^{11}$	2×10^{16} (9×10^{14})

*Estimated

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OPTIONS FOR 2-D RADIOGRAPHY

- Short exposure time is an instrumental function
  - Framing camera
  - Gated microchannel plate estimated frame time ~100 ps
- Flash x-ray source
  - Very short laser irradiation of the backlighter may provide short x-ray pulses/~20 ps
  - High intensities on target are needed to obtain the desired x-ray lines: a point source imaging scheme must be used

LASER REQUIREMENTS FOR BACKLIGHTING

- Typical target size 250 μm
  - Streaked backlighting source area $400 \times 100\ \mu m^2$
  - 2D imaging source area $300 \times 300\ \mu m^2$
- 3 orders of magnitude dynamic range width

Line energy hν keV	Laser requirements Streak* $E_{kJ} = P_{Tw} \times \tau_{ns}$			2D** $E_{kJ} = P_{TW} \times \tau_{ns}$		
≤ 3.5	0.4	0.2	2	0.08	0.04	2
~ 4.7	2.4	1.2	2	0.54	0.27	2
~ 8	8.0	8.0	1	1.8	1.8	1

*Au photocathode

**Microchannel plate or framing camera with CsI photocathode

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7 TO 9 keV BACKLIGHTING APPEARS POSSIBLE FOR NOVA SIZE TARGETS

- Long pulse backlighting is limited by the high threshold intensity required to turn on appropriate lines: this requires a high energy or a small backlighting area.

  Lower thresholds at shorter wavelengths imply that diverting one out of ten of the NOVA phase I beams will allow backlighting with as much as 3 orders of magnitude dynamic range for 10 kJ of 0.53 μm light in 5 ns.

- Short pulse backlighting is only viable for point source projection systems. The same limitation as above prevails but here the backlighting area needed for extended source schemes lead to prohibitive power requirements even at 0.53 μm.

  PIX will allow backlighting at 100 ps with 10 μm spatial resolution with 2.5 TW of 1.06 μm light.

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