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Measuring Pulsed Beams with a Slit-based Profiler

Pulse Rates, Power, and Damage Considerations

Although the NanoScan was designed originally to measure continuous wave (CW) laser beams, many lasers are operated in the pulsed mode. Measuring these pulsed beams has generally required the use of a CCD array profiler. This is a reasonable solution for low power lasers in the UV and visible wavelength range, but these will require external attenuation. Once the lasers leave the UV-VIS range, array cameras become extremely expensive. Although low frequency pulsed lasers operating in the 1Hz to 1000Hz range have no real alternative to the array profiler, the NanoScan can measure kHz frequency lasers. The NanoScan profiler incorporates the “peak connect” algorithm and software-controlled variable scan speed on all scanheads to enable the measurement of these pulsed lasers. The NanoScan is ideal for measuring Q-switched lasers and lasers operating with pulse width modulation power (PWM) control. In the past few years, lasers with pico- and femtosecond pulse durations have begun to be used in many applications. Although these lasers add some additional complication to the measurement techniques, the NanoScan is well suited to measure them, too. We will discuss the measurement of all these types of pulsed lasers below.

PWM Lasers

Many lasers, especially CO_2 lasers, use pulse width modulation (PWM) to control the power level of the laser. This is not true, pulsed operation, but rather a reduction of the duty cycle to lower the average power. The beam operates as if it were CW, and many operators do not even realize that the laser is pulsing. However, when attempting to measure a PWM laser with a scanning slit profiler, it must be treated as a pulsed laser source. To use the pulsed mode of the NanoScan the laser’s pulse frequency must be at least several kHz, and the combination of the frequency and beam size must provide a sufficient number of pulses across the beam to generate a meaningful profile. Eight to ten pulses are a reasonable minimum. PWM lasers usually operate around 10kHz. The relationship of the beam size and frequency is a fairly simple mathematical model. The NanoScan drum speed is software controlled from 1.25Hz to 20Hz. There are two available drum sizes for the NanoScan; the standard head has a drum diameter of 42mm and the large aperture and high power heads use a larger drum with 84mm diameter. On the 42mmdrum at the 1.25Hz rotation rate the slits travel at around 116.6mm per second or 116.6µm per millisecond. At a 10kHz laser repetition rate, a 175µm beam would have 15 pulses during the time that the slit was traversing it. This would provide enough data to generate a meaningful profile. A smaller beam would require a faster pulse rate, a larger one could perhaps run at a lower repetition rate. For example, a 1.0mm beam could be measured with a pulse rate as low as 2kHz and still provide a profile.

There is a table of minimum beam sizes and pulse frequencies for the large and small hubs and scan speeds at the end of this document. It is recommended that the 1.25Hz scan speed be used for pulsed beams, however, if the beam sizes are large enough, or the pulse rates fast enough, the measurement can be sped up by increasing the scan speed to 2.5Hz or above. The NanoScan software will generate a warning if the scan rate is set too high for the pulse rate or beam size. This warning algorithm is based on having at least 15 pulses across the beam to provide a minimum of 2% accuracy.

Q-Switched Lasers

Another type of pulsed laser, operating in the kHz pulse rate regime is the Q-Switched laser. These lasers use the pulsing to increase, rather than decrease, their effective power. By concentrating the laser power into a short pulse, the peak power of each pulse increases while maintaining a low average power. In order to measure these lasers the same mathematical relationship of pulse rate to beam diameter applies, but there is an additional complication; the peak power of the pulses may exceed the damage thresholds of the NanoScan even though the average power remains within the operating space. CW beams are measured as *power (P)* in Watts; pulsed beams as *energy (E)* in Joules. Therefore it is necessary to understand the beam's energy (E_{pulse}) to determine whether the unattenuated beam can be directly measured with the NanoScan.

$$E_{pulse} = \frac{P_{avg}}{f_{laser}}$$

Therefore a beam with an average power of 300 Watts with a pulse frequency of 8kHz will have energy as follows:

$$E_{pulse} = \frac{P_{avg}}{f_{laser}} = \frac{300W}{8\times10^{3}\,Hz} = 37.5mJ$$

The power density per pulse is also a function of the pulse duration τ. This is also important in understanding the potential damage to the profiler. Taking the above example, if the pulse duration is 1ms, then:

$$P_{pulse} = \frac{E_{pulse}}{\tau} \equiv \frac{37.5mJ}{1\times10^{-3}\,s} = 37.5W$$

Pico- and Femtosecond Lasers

When the pulse duration of the laser gets very short, such as with pico- and femtosecond lasers, the peak power of the pulses can become very large. This creates some added complications when determining the type of scanhead that can safely measure these beams. In addition to the average power of the beam, which is used to determine the proper operating space of a given scan head, it is important to know the energy density of the pulses. The energy density must be below the damage threshold for the aperture material, and the average power must fall within the operating space of the scan head for it to be possible to measure the beam without additional attenuation. To determine the energy density first use the above formula for the E_{pulse}:

$$E_{pulse} = \frac{P_{avg}}{f_{laser}}$$

Most pico- and femtosecond lasers have both a high repetition rate and a fairly low average power. They use the short pulse duration to amplify the effective power of the laser beam. A typical laser that one might encounter would have an average power of 1.0 watt and a repetition rate of 80kHz. For this laser the E_{pulse} would be:

$$E_{pulse} = \frac{P_{avg}}{f_{laser}} = \frac{1W}{80000\sec^{-1}} = 12.5\mu J$$

Using this value calculate the energy density for a given beam diameter by the following formula. Note that the energy density is presented as J/cm^2; therefore the beam area needs to be converted to cm in the formula. Unless the beam is wildly different from round, it is easiest to consider that the area will be that of a circle:

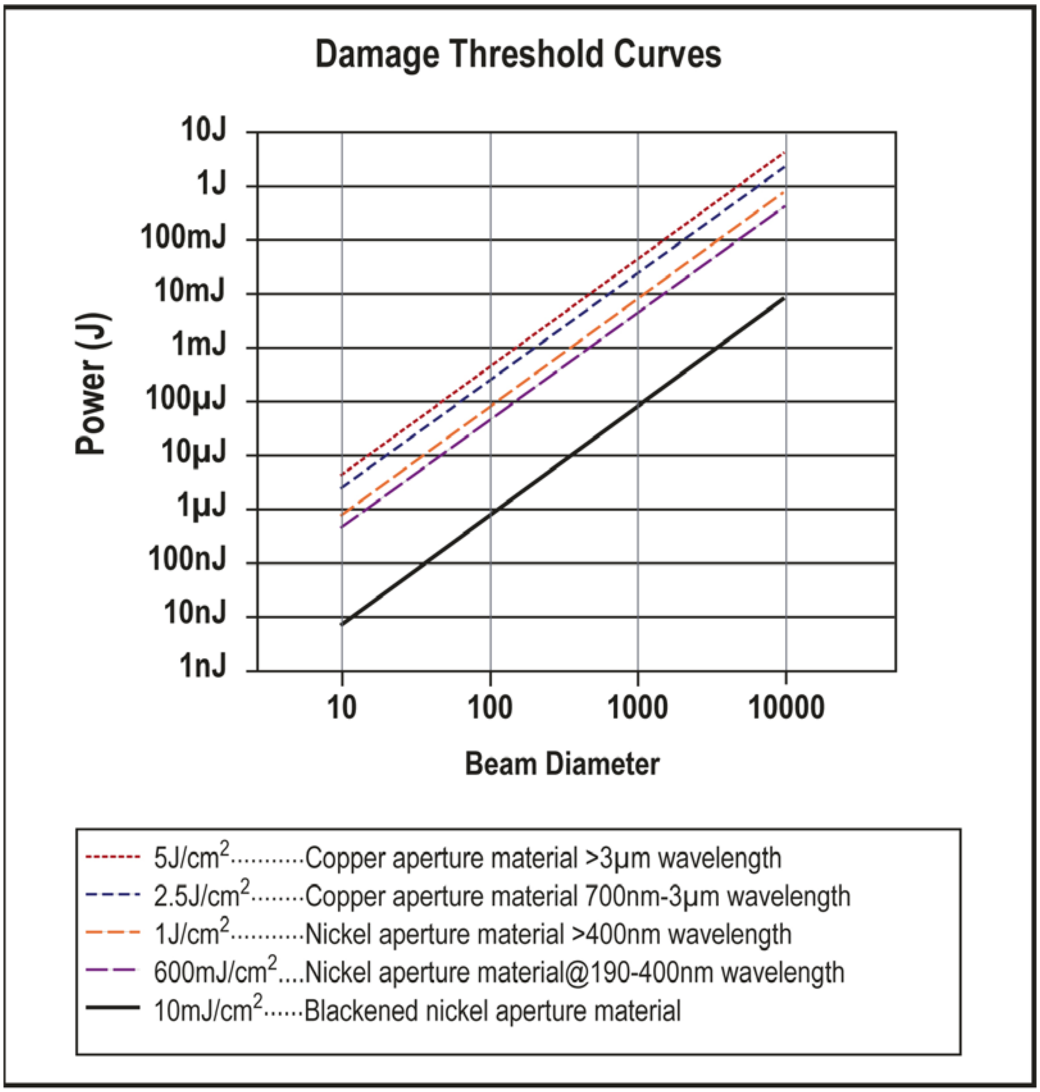
$$E_{density} = \frac{E_{pulse}}{\pi r^2}$$

For a 100μm beam at the 12.5μJ:

$$E_{density} = \frac{12.5\mu J}{\left(\frac{100\mu m \times 0.0001}{2}\right)^2 \pi} = 0.16 J/cm^2 = 160 mJ/cm^2$$

Once the energy density is calculated, it can be compared to the damage threshold for the aperture type and the wavelength range for the aperture material. The standard blackened slit material can only handle 10mJ/cm^2 before the blackening starts to ablate. For this reason, scan heads intended for use with these pico- and femtosecond lasers should have the reflective slits, regardless of the detector type or the average power of the lasers. The wavelength of the laser also influences the energy density that the aperture material can withstand. For the standard nickel alloy slits the maximum energy density is 600mJ/cm^2 for the range of 190nm to 400nm; for 400nm and above the value is 1.0J/cm^2. For the high power copper slits the values are 2.5J/cm^2 from 700nm to 3μm wavelength and 5J/cm^2 above 3μm. Copper slits are not recommended for use below 700nm, however in some experiments we have seen better performance in the UV (@355nm) from copper slits. This may be attributable to the better heat dissipation of the copper material or the fact that the copper aperture material is thicker than the nickel alloy.

The chart below can be used in lieu of the calculation to compare the energy per pulse at a given beam diameter with the appropriate threshold line for the aperture material and wavelength of use. For the above case the 12.5μJ energy at 100μm would be below the 600mJ damage line, but would certainly be well above the damage level for blackened apertures.



These estimates of damage threshold are primarily based on the relative reflectivity of the slit material. There are many other factors that may influence interaction of the laser beam and the aperture. At some level of power and pulse duration this interaction may become non-linear. In addition surface finish, roughness, contamination, tarnish or oxidation can also affect the reflectivity of the materials. For this reason these damage threshold values can only serve as a guideline, not an absolute guarantee. Use caution when measuring any new or unfamiliar laser system.

Calculating the Minimum Beam Diameter per Pulse Frequency

The following table gives a list of calculated minimum beam diameters at a given pulse frequency for each of the drum sizes and for a desired number of pulses per profile. The more pulses per profile the more accurate the measurement is likely to be. The formula is fairly simple. Due to the 45^{o} angle of the slits to the direction of rotation, the actual speed of the slits is the drum speed divided by the square root of two.

$$\left(\frac{v}{\sqrt{2}} \Big/ f \right) N = D_{\min}$$

where:

- *v= drum velocity in µm per msec*
- *f = pulse frequency in kHz*
- *N = pulses per profile*
- *D_{min}= minimum beam diameter in µm*

The NanoScan pulsed operation can operate at any rotation rate, however it is recommended that the scan rate be 1.25 or 2.5Hz unless the laser repetition rate is above 50kHz. The larger drum used in the large aperture and High Power versions of the NanoScan cause the slits to move faster at any given rotation rate due to the larger circumference. For this reason the minimum beam sizes are larger for the large drum.

The peak connect algorithm finds the highest peak pulse, then using the frequency value entered by the operator it finds the other peaks and connects them to generate a smooth beam profile. It is important that the exact pulse frequency be entered into pulse acquisition parameters. The earlier BeamScan instruments only allowed the measurement of pulsed beams with the pyroelectric detector. NanoScan provides this capability with all scan heads and detectors. Beams with average powers that were too low to be measured with the pyroelectric detector can now be profiled using silicon or germanium scanheads. At high laser repetition rates it may be better to operate the NanoScan in CW mode and let the auto filter smooth the beam. When this is preferable is dependent on the individual laser's pulse performance. If inconsistent results are seen with a high rep rate laser (e.g., >80kHz), it would be advisable to try the measurement both ways.

Minimum Beam Size per Pulse Frequency

NanoScan	**Normal Drum**					**Large Drum (HP)**			
Rotation Rate (Hz)	1.25	2.50	5.00	10.00	20	1.25	2.50	5.00	10.00
slit speed (um/msec)	116.63	233.25	466.50	933.01	1866.01	233.25	466.50	933.01	1866.01
Data Points per Profile	15	15	15	15	15	15	15	15	15
Pulse Frequency (kHz)	**Minimum Beam diameter in µm**					**Minimum beam diameter in µm**			
1	1749	3499	6998	13995	27990	3499	6998	13995	27990
2	875	1749	3499	6998	13995	1749	3499	6998	13995
3	583	1166	2333	4665	9330	1166	2333	4665	9330
4	437	875	1749	3499	6998	875	1749	3499	6998
5	350	700	1400	2799	5598	700	1400	2799	5598
6	292	583	1166	2333	4665	583	1166	2333	4665
7	250	500	1000	1999	3999	500	1000	1999	3999
8	219	437	875	1749	3499	437	875	1749	3499
9	194	389	778	1555	3110	389	778	1555	3110
10	175	350	700	1400	2799	350	700	1400	2799
11	159	318	636	1272	2545	318	636	1272	2545
12	146	292	583	1166	2333	292	583	1166	2333
13	135	269	538	1077	2153	269	538	1077	2153
14	125	250	500	1000	1999	250	500	1000	1999
15	117	233	467	933	1866	233	467	933	1866
16	109	219	437	875	1749	219	437	875	1749
17	103	206	412	823	1646	206	412	823	1646
18	97	194	389	778	1555	194	389	778	1555
19	92	184	368	737	1473	184	368	737	1473
20	87	175	350	700	1400	175	350	700	1400
21	83	167	333	666	1333	167	333	666	1333
22	80	159	318	636	1272	159	318	636	1272
23	76	152	304	608	1217	152	304	608	1217
24	73	146	292	583	1166	146	292	583	1166
25	70	140	280	560	1120	140	280	560	1120
50	35	70	140	280	560	70	140	280	560
100	17	35	70	140	280	35	70	140	280
150	12	23	47	93	187	23	47	93	187