A Beam Quality Metric for High Energy Lasers

Prepared by Jack Slater on behalf of the High Energy
Laser Joint Technology Office
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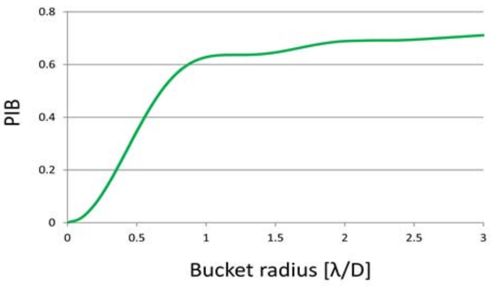
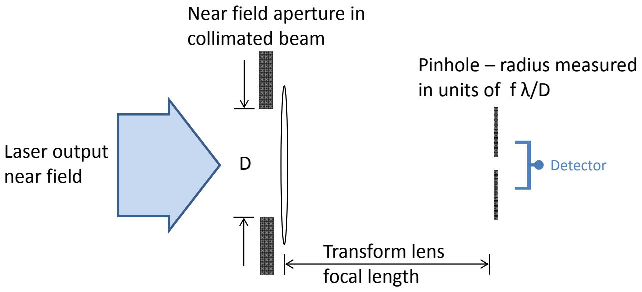
Executive Summary

A well defined beam quality (BQ) metric for high energy lasers can be developed based on a Power in the Bucket (PIB) concept already used in the laser community, but not well defined. PIB refers to the fraction of total power that can be delivered into a transmission cone measured in angular units, λ/D and called a "bucket," where λ is the laser wavelength and D is a characteristic size of the beam as launched. The PIB value has direct bearing on the ability to form a small and lethal spot on a target at range. Of course performance at range depends on many parameters including the diameter of the beam director and atmospheric transmission, but PIB measured at the laser exit is valuable for comparative purposes.



Conventional Power in Bucket Curve

A problem is that the community uses multiple definitions and measurement methods for this characteristic size D. This problem can be overcome by defining the PIB measurement in a particular geometry as shown here, called the Two Hard Aperture geometry, in which a near field aperture has diameter D and the far field pinhole aperture is varied to produce a curve similar to that above, but which we call a PIBM curve due to the presence of the near field aperture. Diameter D becomes a reliable measure of the beam size under the condition that the transmission through both apertures is maximized. This is a well defined measurement, but the question is whether it relates to potential performance of the laser in a weapon system. The answer is yes, because this near field aperture is optically equivalent to the constraint imposed by the beam director output diameter in a full scale system, and in such systems the fit of the beam to the beam director (or scraper upstream) is optimized just as in this metric. Of course in a weapon other system considerations are taken into account, such as pointing jitter and atmospheric beam aberration. But DEW systems do in principle perform a Two Hard Aperture measurement. The PIBM curve differs from the traditional PIB curve in that the height of the curve is reduced by the fractional power loss due to clipping at the near field aperture. The reported power consistent with the PIBM curve is that measured upstream of the near field aperture.



Laboratory Configuration for PIBM Measurement. The reported power is measured upstream of the near field aperture

With this metric, a laser beam with obscuration will necessarily score worse than an equivalent beam but without obscuration. Related to this, there is the question of comparing a laser with an unobscured beam, that will be cored later to fit an existing beam director, to a laser with intrinsic coring that will be used with the same beam director. The PIBM measurement can be made downstream of beam manipulations such as coring to produce meaningful comparisons.

The PIBM metric is a curve rather than a single number. With the curve, one can assess the utility of a given laser against both long and short range missions, as these are sensitive to different sections of the curve. Specific programs can emphasize specific points on the curve as appropriate.

In a laboratory setting it is useful to use a camera in the far field plane instead of pinholes because of pointing drift and jitter. That is permitted with this metric only if the camera can be calibrated to pinhole results. With this stipulation, it is comparatively easy for a laser vendor and independent test team to make equivalent measurements and to obtain equivalent results, or instead to find the cause of any disagreement.

In short form, the data to be provided for this metric are as follows (see report body for explanation).

Item	Data Item	Comments
1	System description	Provide basic information on the optical diagnostic layout
2	Near field parameters	Provide detail on placement of apertures, transform lens, etc
3	Power meter calibration	Identify calibration traceability of the power meter
4	PIBM and camera normalization	Provide detail on normalization procedures and calibration of camera to pinholes
5	Laser output power	Report power upstream of near field aperture
6	Laser PIBM curve	This is the primary beam quality characterization data
5’	Laser output power	If the laser output is not stable, report as in Items 5 and 6, but in time slices
6’	Laser PIBM curves	
7	Jitter PSD, σ_{rms} integrals	Report two-axis PSD and backward σ_{rms} integrals
8	Data as above, but following beam manipulation	Only needed if beam manipulation may significantly affect the above data

Section 1. Introduction and Overview

This document is prepared in response to guidance for High Energy Lasers found in the National Defense Authorization Act for Fiscal 2014. Specifically, it is a response to the Senate language under heading "High Energy Laser Weapons," and the House language under "Standardization of directed energy weapons systems characterization." Those two sections have in common the observation that Directed Energy Weapon (DEW) development is presently hampered by lack of common technical definitions and performance metrics, and that this situation should be rectified by development of such standards as needed. As explained, the problem with poorly defined metrics is that comparisons of various competing systems cannot be made effectively.

In this regard, the most compelling problem today relates to inconsistent metrics governing delivery of thermal energy to a target by a DEW system. Stepping back from any target-specific details, the underlying metric in question relates to the power that can be delivered to a designated spot in the atmosphere, i.e. an irradiance. This irradiance is obviously a function of many details, but in aggregate they relate to the "power" and "quality" of the launched beam, and to the "propagation efficiency" of that beam through the atmosphere. Here the term quality relates to the ability to focus the beam to a small spot at range. This document concentrates primarily on this beam quality (BQ), which is a term commonly used but poorly defined. Differences in BQ definitions within Department of Defense programs have led to the confusion that this document is intended to correct.

The purpose of this guidance document is to carefully define a metric and identify best measurement practices. The metric incorporates two important simplifications of the broad DEW development effort and mission sets. First, we consider only the most traditional DEW context in which thermal energy is delivered to the target, and the target fails due to thermal input. Second, the measurement methods presented here have been developed with emphasis on simplicity and repeatability. It is intended that for a given laser, two measurement teams each with their own equipment, can measure beam quality and obtain equivalent results. Although fairly simple, these measurements provide valuable, top-level, system performance information. They would be insufficient to fully optimize complex systems, or for example, to generate detailed interface specifications between a laser and a beam director.

Section 2 provides understanding of how the beam quality relates to the many system-level parameters that determine DEW performance. To provide context, consider that DEW *performance* refers to the ability of the DEW to provide irradiance at a given spot in the atmosphere, and DEW *effectiveness* refers to the probability that this irradiance will negate a particular target. This document deals only *with performance; effectiveness* is beyond the scope. The metric developed here is given in terms of a power-in-the-bucket (PIB) measurement. This section also provides the general argument that most of the laser parameters that determine performance are well understood in terms of definition and measurements, and that only a few need special attention.

Section 3 describes measurement of laser power. The power measurement is well understood by the community, but an example is included here to show how it can be measured consistently with the reported PIB data.

In Section 4 the basics of a PIB measurement are developed. PIB measurements are already well known to the DEW community, but with varying definitions. This section presents PIB utilizing a particular physical configuration that removes ambiguity. From this we also define a variation which we will call PIBM, which is the basic beam quality metric of this document. A required PIBM value is determined by analysis of a specific mission, or alternatively it may simply be a top-level program goal. There are no PIBM threshold or objective values provided in this document; only the definition and measurement methods are developed.

Section 5 expands the PIBM definition and measurement methods to include cases in which the beam has inadvertent temporal variation while lasing, e.g. the spot size or power at the target is changing. This is a common situation.

Section 6 contains best-practice guidelines pertaining to reporting of mutually consistent PIBM and laser power. Section 7 describes how camera-based data can be calibrated using pinholes. Section 8 identifies what laboratory data is required to properly report laser performance against this metric. Section 9 identifies the point of contact for questions or interpretations regarding this document, and Section 10 is a short summary.

Section 2. The PIBM Metric in the Context of Other System Metrics

The PIBM metric is a single but important part of any overall DEW system specification. Other top-level items include, for example, size weight and power (SWAP), reliability, maintainability, the ability to endure environmental factors, and cost. The focus of this document can be understood from Table 2.1, which follows the system from electrical input to photons on target, and indicates which factors are addressed here. All of the measurements describe here can be performed in the laboratory. Measurements downstream of the beam director or at the target are equally important but not addressed.

System Parameter	In this document?	Comment
Laser electrical efficiency	No	Is suitably measured with conventional engineering methods
Laser output power	Yes	Sec 3 shows a method of power measurement that is consistent with the measured PIBM
Laser PIBM curve	Yes	Is defined under steady state conditions in Sec 4 and non-steady conditions in Sec 5
Laser peak irradiance in far field	No	Is not directly measured, but can be estimated if PIBM curves extend to small buckets
Mission utility comparison of lasers at different wavelengths	No	Such comparison is straightforward (e.g. comparing 1 vrs 2 μm) and must include propagation effects, but is not part of this discussion
Laser PIBM including correction of laser aberrations by local-loop adaptive optics	Yes	In Sec 4.5
Laser PIBM including beam reshaping, such as coring for use with a Cassegrain telescope	Yes	In Sec 4.5
PIBM after adaptive optics for atmospheric compensation	No	Simulation of atmospheric effects and metrics for the degree of correction are not addressed
PIBM after telescope beam expander	No	Would require large diameter optics that are not commonly available in a laboratory setting
PIBM after atmospheric transmission	No	Would require instrumentation at the target location
Laser jitter and other temporal variations	Yes	In Sec 5

Table 2.1. Metrics described in the document as seen in the context of broader, system-level metrics.

Section 3. Measurement of Laser Power

A particular method of power measurement is described here as an example, not because power is difficult to measure or lacks suitable standards, but because it's important to use measurement configurations that assure that any reported power and PIBM will be mutually consistent. Figure 3.1 shows conceptually such a configuration. Use of the Near-Field Test Aperture is discussed in detail in Section 4. As will be explained, the PIBM curve is measured with the test aperture present, and the laser power consistent with that is measured with the aperture removed.

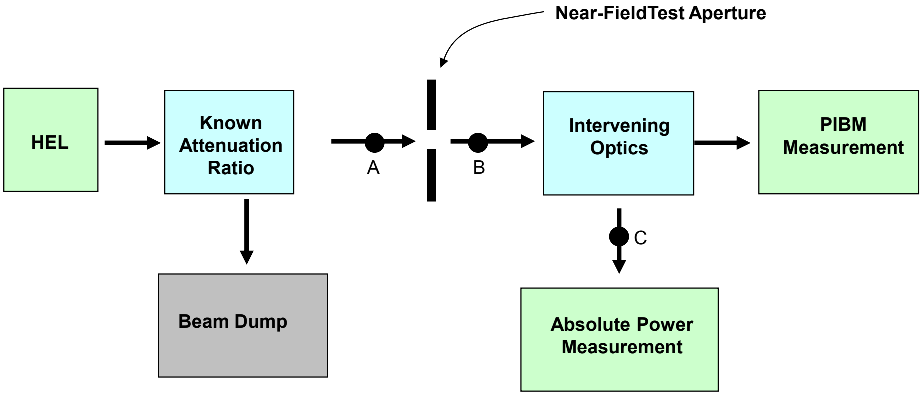


Figure 3.1. Conceptual implementation of a mutually consistent Power and PIBM measurement. The PIBM curve is measured with the test aperture present, and laser power consistent with that is measured with the aperture removed.

There are three primary pieces:

- A Known Attenuation, of order 30-40 dB attenuation (Sec 3.1) which provides a low-power sample while passing most of the beam to a dump that is not calibrated. The wavefront of the sampled beam must not be aberrated by the attenuator
- Some Intervening Optics (which generally exist by necessity) with modest loss, e.g. 3 dB, and this loss must be measured (Sec 3.3)
- A power sensor that has been absolutely calibrated (Sec 3.2).

This arrangement will not damage the near-field aperture, and can be used with a low-power calibrated power meter that has sufficient bandwidth to follow the laser pulse train and measure turn-on time. Important points in this design are now discussed.

Section 3.1 Attenuation of the HEL Beam by a Known Factor

One well tested method for providing a known attenuation factor is the use of front-surface reflection from an uncoated dielectric, as in Fig 3.2. The uncoated surface permits the reflection coefficient to be reliably calculated using the known index of refraction, assuming no unusual circumstances due to surface preparation. Wavelength, polarization, and angle of incidence are important. With fused silica and for near-normal incidence, the front surface reflection is attenuated roughly 14 dB, so that for example, only four stages are needed to reduce a 100 kW beam to levels at which the beam is easily manipulated. An AR (antireflection) coating on the rear surface of this wedge is useful to reduce the power contained in secondary beam(s).

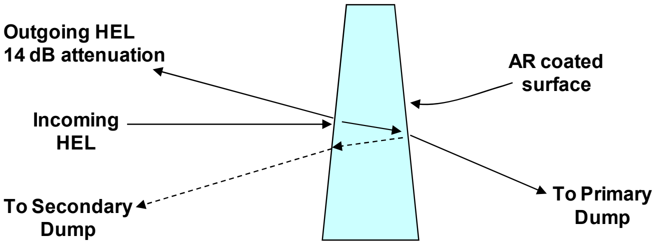


Figure 3.2. Example of known attenuation via reflection. Shown is one stage of front-surface attenuation based on a known Fresnel reflection coefficient. One secondary reflection is shown as dashed line; others exist.

The angle of incidence will generally be at least a few degrees off normal, hence reflectivity will differ for S and P polarization. A compensation for this which also allows large offsets from normal incidence, is to use an even number of attenuation wedges, say two, and use an out-of-plane geometry such that the S-polarized photons on one wedge become the P-polarized photons on the other.

Section 3.2 Absolutely-Calibrated Power Meter

Referring again to Fig 3.1 and the absolutely calibrated power meter, this meter should have calibration traceable to the National Institute of Standards and Technology. Temporal bandwidth is important; generally 10 Hz or better will be needed for DEW characterization, and detectors based on thermal response may be too slow. A calibrated photodiode in an integrating sphere is one solution, and this configuration facilitates the measurement identified in Sec 3.3.

Section 3.3 Measuring Loss of Intervening Optics

In Fig 3.1 the Intervening Optics provide functions such as beam size manipulation, and as these are in the path to the absolutely calibrated power meter, their loss must be known. If a power meter of known linearity is available, these losses can be measured directly by using this single meter at positions B and then C while a probe beam is inserted at position A. When using a probe, one must take into account how probe properties, e.g. wavelength, polarization state, and collimation, might vary from those of the HEL under testing.

Section 4. Power in the Bucket Measurement, PIBM

Section 4.1 Overview

This section describes a PIB metric that includes a near-field aperture which is part of the measurement geometry, but not necessarily part of a DEW system. With that aperture, we call this the PIBM metric. Optically, this aperture represents a de-magnified version of the beam director output aperture. The use of this test aperture permits a well defined performance metric. As will be seen, maximizing the metric generally leads to some intercepted power by this aperture, and since interception of any HEL beam is potentially problematic, use of such a metric must be carefully considered. As a historical comment, beam directors have always been a limiting aperture and hence could intercept power, or equivalently they were protected by a guard aperture with the same result. Beam interception was a power degradation to be minimized, but today the HEL community is considering beams with poorly defined edges, e.g. from fiber lasers, and in this case some interception will be intentional. This point is examined in detail in Sec 4.4.

Section 4.2 Basics of PIBM Measurement

We now develop a well-defined PIBM definition. Consider the concept drawing of Figure 4.1. This shows a configuration of two circular apertures, one in the collimated laser near field and the other in the far field. This is the “Two Hard Aperture” configuration of PIB, which we will call PIBM when the measurements are normalized in a particular way. Various PIB configurations found in the literature may not include the near-field aperture, and in these cases the near field beam size, which is crucial to the PIB concept, must be determined in some other way.

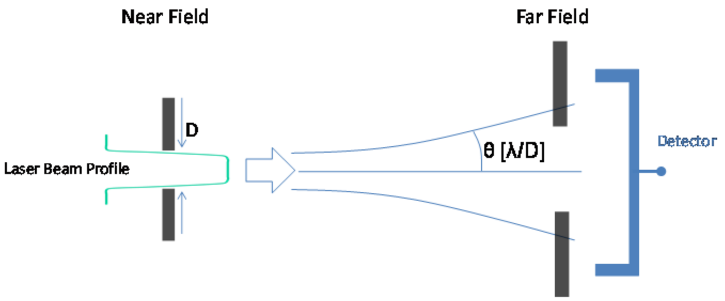


Figure 4.1.   Conceptual configuration of “Two Hard Aperture” configuration for the PIBM measurement. The PIBM curve, i.e. fraction of laser power versus bucket size passing through both apertures, is generated by varying the diameter of the far field aperture while the near field aperture is fixed.

The typical laboratory implementation of the concept is shown in Fig 4.2.

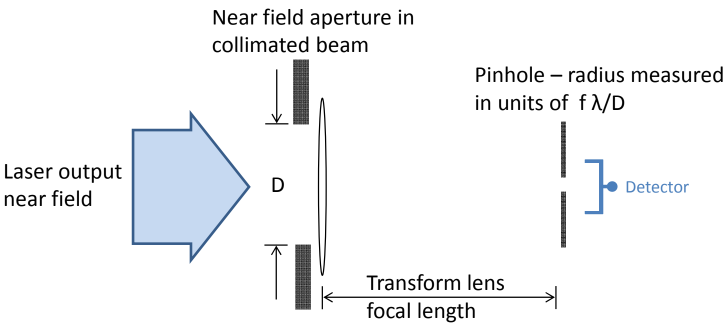


Figure 4.2.   Implementation of concept from Fig 4.1 in a laboratory setting. Use of a camera in the far field is discussed in Sec 7.

The near field aperture represents a de-magnified version of the beam director output aperture, or a scraper that is protecting the beam director, and the far field aperture represents interrogation of the spot at the target. In this sense any DEW system performs a Two Hard Aperture PIBM measurement.

There is the question of where the near field aperture and transform lens are located relative to the laser. The metric (Fig 4.1) assumes that the laser near field is the Fourier transform plane of the DEW target. So the transform lens (Fig 4.2) must also be in the laser near field, hence we require that the laser and lens be separated by no more than about $r^2/100\lambda$ (i.e. we require a Fresnel number > 100), assuming a collimated laser beam of characteristic radius r. The near field aperture can be anywhere between the laser and lens, but it must be assured that the beam size exiting the aperture matches the beam size at the lens. If significant high angle emission is present in the near field, not all near field aperture positions will produce identical results. Laser developers should consider this if an independent measurement team will be visiting, and it is desired that both groups would make the same measurement.

Excursions from the preceding paragraph may be needed in special circumstances. If for some reason there is beam size magnification between the near field aperture and lens, then the diameter at the lens would be used in the PIBM abscissa label. In that case the allowable laser-lens separation is calculated as $r_1r_2/100\lambda$ where r_1 and r_2 are the beam radii at the laser and lens. In another excursion, an image relay may be required from the laser to the near field aperture, or from the near field aperture to the transform lens.

If the opening of the far field aperture is varied to produce a curve of detected power versus the aperture angular radius in units of λ/D, and the curve is normalized in a particular way as described below, then this is the traditional “PIB curve” and an example is found in Fig. 4.3.

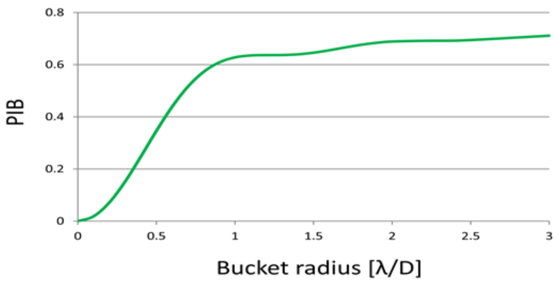


Figure 4.3 Example Power in Bucket curve.

When the curve of Fig 4.3 is normalized to power downsteam of the near field aperture, we will refer to it as a PIB curve. It asymptotes to unity at large buckets, as is the community practice. When it is instead normalized to the power upstream of the near field aperture, it becomes a PIBM curve. The PIBM curve asymptotes to whatever fraction of power is transmitted by the near field aperture. Best measurement practices for normalization are discussed in Sec 6.

Section 4.3 Statement of the PIBM Metric

We are now in position to state the performance metric, which is a curve called PIBM and defined as follows:

$$\text{PIBM} = \text{PIB} * \text{TE} \tag{1}$$

where PIB is the power-in-the-bucket (encircled energy) curve for photons downstream of a circular, unobscured near-field aperture and TE is the transmission efficiency through that aperture. The near field aperture is present when the PIB curve is generated. See text just below Fig 4.3 regarding normalization. The laser power consistent with the PIBM curve is that measured upstream of the near field aperture. Units of the abscissa are the far field bucket angular radius in units of λ/D, where D is the diameter of the near-field aperture in the Two-Hard-Aperture configuration. The abscissa should be extended to include at least 80 percent of the total power downstream of the near-field aperture.

Both apertures are circular in keeping with the common shape of beam directors and common lethality considerations. The near field aperture has no obscuration, but the situation of beams that will be manipulated downstream by coring, for example, is considered in Sec 4.5. The fit of the laser beam into the near field aperture, hence the degree of beam interception, is determined by the laser provider. That transmission efficiency can in principle be optimized for each value of the far field bucket size, but it is intended that all reported PIBM curves have a fixed near field aperture diameter for a given curve. If only a single PIBM curve is provided, then the fit of the beam into the near field aperture should be that which maximizes the height of the PIBM curve at a far field bucket radius of 2λ/D.

Use of a curve as the metric, rather than a single point, is necessary because of the large difference in relevant bucket sizes (when expressed in λ/D units) between short range and long range missions. It should also be appreciated that different lasers have substantially different shapes of PIBM curves, so that knowledge of one point does not imply knowledge of the whole curve.

Use of a far field camera as a substitute for the pinhole is discussed in Sec 7.

If a particular laser development program stipulates that noncircular or obscured apertures are to be used in either the near or far field for beam characterization, care should be taken to avoid any possible confusion of those measurement results with the metric of this document**.** *Measurements made with such deviations, or other significant deviation from the definition of this Section, shall not use the PIBM label.*

Section 4.4 Justification of a Metric that Involves Beam Clipping

We now examine the issue of whether a metric that involves beam clipping can be relevant to a fielded DEW system. As mentioned above, the community is presently considering lasers without well defined beam edges in the near field, and this can lead to intentional near field clipping. We'll call these *soft-edge* beams, and fiber lasers with their Gaussian-like near field intensity pattern are an example.

In sizing the soft edge beam to the beam director telescope (or equivalently our near-field test aperture), there is an optimization to be performed. Consider that the telescope output diameter D is fixed, and that a desired bucket on the target, yλ/D, is fixed at some value of y. Then this is the Two-Hard-Aperture situation, and the adjustable parameter is the size of the input beam (as seen at the primary mirror) relative to D. The optimization is to adjust that size to maximize the power passing though both apertures. When the input beam is small compared to D, all of the beam is transmitted through the telescope, but the beam then expands rapidly and hence only a small portion falls in the already-specified far-field bucket. When the input beam size is comparable to or exceeds D, more power is clipped by the telescope, but transmitted photons will have a smaller diffraction spread. The PIBM for a specified bucket radius will have a maximum value somewhere between the limiting cases of highly underfilling or highly overfilling the near field aperture.

It is instructive to examine this optimization as studied by Yura [JOSA-A, 1995, Vol 12, pg 375]. He considered the case of an input beam with Gaussian intensity profile and no phase error. We will examine that specific case for the remainder of this subsection; other cases, i.e. non-Gaussian profiles and with phase errors, will be conceptually similar. Figure 4.4 shows the result of maximizing the transmission through both apertures in the Two-Hard-Aperture geometry. The collimated input beam radius at $1/e^2$ intensity is ω_o. For these curves the near-field-aperture fill ratio, $2\omega_o/D$, is re-optimized for power in the bucket *at each far field bucket size*, and this done by holding D fixed while ω_o varies. The top curve shows the fractional transmission through the near field aperture, and the lower curve shows $2\omega_o/D$.

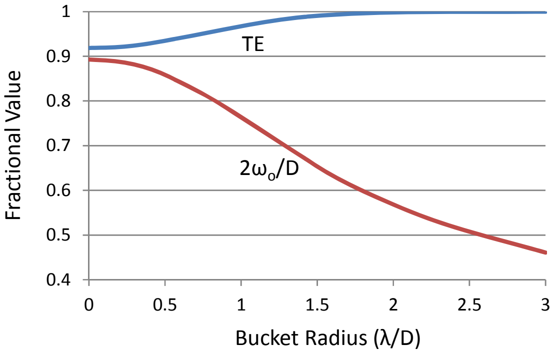


Figure 4.4. Optimization of Gaussian input beam in Two-Hard-Aperture configuration as a function of bucket radius. The top curve is fractional power transmitted through the near field aperture, TE, and the bottom curve is the optimum near-field-aperture fill ratio, $2\omega_o/D$.

If the system is optimized for centerline intensity at the target (i.e. for small buckets), the near field filling is such that $2\omega_0/D \approx 0.89$, corresponding to clipping of 8.1 percent of the power incident on that aperture.

We can anticipate that such clipping is potentially problematic in a DEW system. So we ask the following question: if laser performance is predicted according to this metric (i.e. with optimum near field clipping as per Fig 4.4), but the laser is intended for use in a DEW system in which this much clipping in not permitted for whatever reason, is this metric a useful indicator of DEW performance?

Fig 4.5 shows three special case PIBM curves that address this question. These curves are special in that they are for a system with a variable fill ratio, $2\omega_o/D$, whereas a real system may have a fixed fill that has been optimized for some particular far field bucket size. But these curves show what is possible. The blue curve is the PIBM optimized for total transmission through both apertures at each bucket size and hence follows Fig 4.4. That is, the interception at the near field aperture is varying from zero to 8.1 percent when moving from right to left along this Fig 4.5 curve. The red and green curves also have continually optimized $2\omega_o/D$, but with the clip constrained to a maximum value. The red curve has near-field clipping constrained to 1.0 percent or less. So starting from the far right on the graph, this means that the blue and red curves are identical until the clipping reaches 1 percent. At about 1.8 λ/D and less, the blue curve experiences ever larger clips (to a maximum of 8.1 percent), while the clipping of the red curve is capped at 1 percent. Similarly, the green curve has near- field clipping constrained to the range 0.1 percent or less. All three curves asymptote to unity because the near field aperture, when continuously optimized for each bucket size as done here, clips power only for small buckets (see blue curve of Fig 4.4).

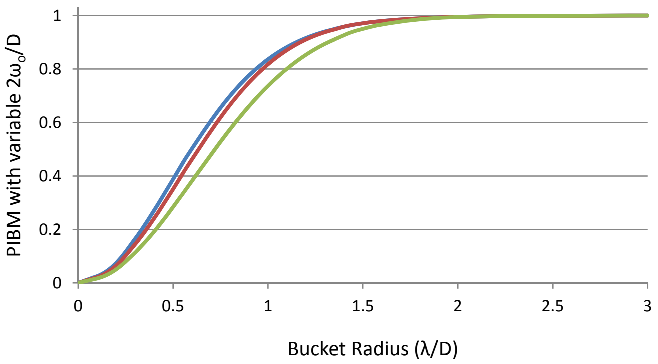


Figure 4.5. PIBM for special case of optimizing the near-field-aperture fill for each far field bucket size. The blue curve has no restriction on the near field clip and hence follows Fig 4.4. The red and green curves correspond to clips constrained to a maximum value of 1.0 and 0.1 percent respectively.

In Fig 4.6 the same information as in Fig 4.5 is presented, but plotted to directly address this question: if the laser PIBM metric is reported without clip limitation, and a DEW system using that laser is then fielded, but with a clip limitation, what is the performance difference between the reported PIBM metric and actual performance (ignoring jitter, the atmosphere, etc)? Plotted are the clip-limited PIBM values divided by the unconstrained PIBM values. The red curve compares the case of 1.0 percent clip limit to the unconstrained case, and the green curve compares the case of the 0.1 percent clip limit to the unconstrained clip. We note again that these cases with variable fill ratio show what is possible, whereas a real system would likely have fixed fill ratio that has been optimized for some particular far field bucket.

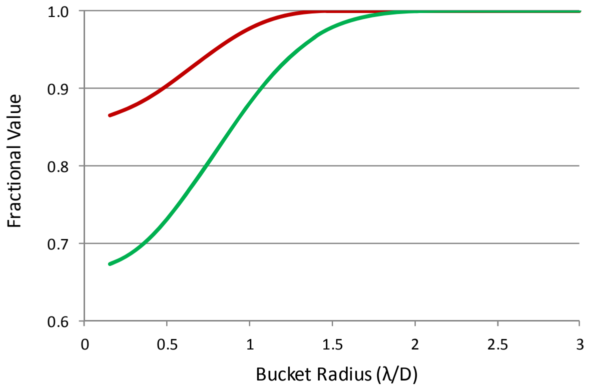


Figure 4.6. Ratio of continuously optimized PIBM values (i.e. near-field-aperture fill ratio is variable) with clip limitation to the PIBM value without clip limitation. The red curve is the case of 1.0 percent maximum power clip and the green curve is for 0.1 percent.

Our conclusion for this perfect (no phase error) Gaussian example is: a) for optimization to far field buckets > 2λ/D, there is no reason to clip the beam in the near field; and b) for buckets < 1.5λ/D, one needs to consider carefully how any reported PIBM curve was generated, i.e. what clip was made and what clip is intended for the fielded system.

Whether the near field beam is clipped or not, the presence of the near field aperture is required by this metric. It should be emphasized that this discussion did not include pointing jitter, track errors, or atmospheric effects, all of which tend to wash out sensitivity to the laser performance for small buckets. Hence there is little incentive to optimize the PIBM curve for the smallest buckets unless that is part of an overall system consideration.

Section 4.5 Accounting for Beam Reshaping and Other Beam Manipulations

A PIBM curve measured at the laser exit plane becomes less useful for performance prediction if the beam is manipulated en route to the beam expander telescope (other than magnification). If, for example, the laser has no inherent central obscuration but its beam will be cored for use with a Cassegrain telescope, then a PIBM measured at the laser exit is not representative of a PIBM measured after the coring. This section addresses such issues.

As a detail, we will not be concerned with specialized information that would be contained in interface documents between beam line components. For example, an interface document may place restrictions on scattered power to avoid damage.

Fig 4.7 is a block diagram beam line that includes potential beam manipulations.

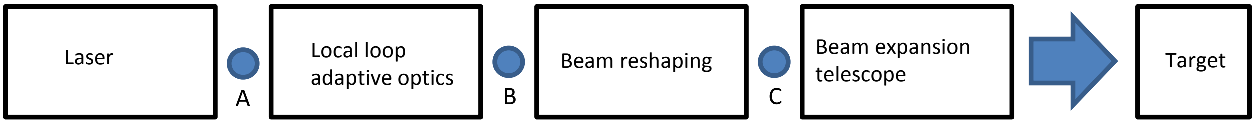


Figure 4.7. Potential beam manipulations between the laser and beam expanding telescope. PIBM curves can be generated at positions A, B, or C. Adaptive optics for atmospheric compensation may also be present but are not germane to this discussion.

We assume as a starting point that a PIBM curve exists for the laser itself, i.e. measured at position A using a low power sample in accordance with Fig 3.1 or equivalent, and that the goal would be to get a PIBM representative of point B or C.

Basically, there are two ways to proceed. PIBM information from point A can be advanced to B or C by calculation (which typically requires knowledge of the intensity and phase on the plane at A), or the PIBM measurement can be made at B or C. Adaptive optics and beam reshaping (e.g. via axicon lens pair) represent substantial changes to the wavefront phase and amplitude, and these changes are adversely affected by surface-figure and alignment tolerance requirements that are not easily satisfied. Given this and the difficulty of accurately knowing the amplitude and phase to begin with, the PIBM cannot generally be calculated with confidence.

When the PIBM differences from one point to another on the beam line are important, downstream PIBM measurements should be made.

Section 5. Temporal Variations

Temporal variation of the laser beam requires special consideration in the Two Hard Aperture configuration. We assume that a weapon system will output a train of pulses, each of several seconds duration and separated by a second or more. The interest here is characterization of a single pulse. (No specific pulse train is identified in this document. If successive pulses in a train are not essentially identical, e.g. there is a power droop or decay in PIBM, then some means of characterizing that variation should be devised.)

Thinking of Fig 4.1, there are possibilities of centration and beam size/shape variation, both in the near and far fields. Considering both apertures to be fixed in size and location, then in Eq (1) both PIB and TE are time variable.

The general approach to characterization of temporal variation within a pulse is (with details in Sec 5.1 and 5.2):

a) Separate variations according to fast and slow time scales. We assume that pointing jitter is fast and can be characterized for the whole pulse by a single power spectral density (PSD) curve. We assume that power and PIBM variations are slow and can be characterized by reporting them at intervals through the pulse. We ignore slow pointing drift all together, assuming that it will be real-time corrected in a weapon system.

b) Any reported PIBM curve will take into account the expectation that active jitter correction (separate from any correction internal to the laser) would be provided downstream in a weapon system.

c) Slow variations in power and PIBM should be reported if they exceed 10 percent of average values within the main body of the pulse. PIBM includes both near and far field behavior. At the near field aperture, centration drift or shape change is captured as a variable TE ratio. The far field bucket size to monitor for the 10 percent criteria can be the 2λ/D radius as called out in Sec 4.3. As a rough guideline, power and PIBM curves should be reported at half-second intervals within the main body of the pulse until the beam stabilizes or terminates. If snapshots at half second intervals do not reasonably characterize the pulse, then either shorter intervals must be considered or some form of averaging must be devised.

Sec 5.1 Reporting PIBM with Anticipation that Active Jitter Correction will be Added Later

To enact Item (b) above, it is convenient to use a camera measurement in place of the far field pinhole, allowing the camera to freeze out some portion of the pointing jitter. (*Any use of a camera must be consistent with the camera validation via pinholes as described in Sec 7.*)

To see how this can work, consider as an example a single-frame far field camera image made with an integration period of 10 milliseconds. This image has the property that: a) the offset of the centroid (from some average position established from many frames) is the cumulative effect of all frequency components < 100 Hz (roughly) and varies from shot to shot; and b) the smearing of the spot size is indicative of frequency components > 100 Hz and will be relatively repeatable from shot to shot. Therefore, if a PIBM curve is calculated by centering the calculation on the spot of a single image, that curve will be roughly equivalent to the curve that would result from the presence of a physical jitter correction loop with 100 Hz bandwidth.

Since we are considering the bandwidth of a jitter control loop that may be built at a later time, and with bandwidth to be determined later, a set of PIBM's (for a single time slice) can be generated from a set of single-frame camera images, each with different integration times. The integration time mimics the inverse bandwidth of the jitter rejection loop that is not yet present. A typical PIBM data set would include integration times of 100, 10, and 1 milliseconds, corresponding roughly to jitter rejection bandwidths of 10, 100, and 1000 Hz, respectively. Of course the use of single-frame images makes sense only if shot to shot variation is small.

Sec 5.2 Reporting Jitter Power Spectral Density (PSD)

A two-axis PSD should be reported that reflects behavior of the laser without downstream active correction. This can be measured with a fast lateral position sensor (LPS) or equivalent that detects the centroid of the far field spot. The bandwidth of that detector would nominally be ≥ 1 kHz, and this measurement is made without active jitter correction other than any that is internal to the laser. Such measurements may inadvertently convolve the actual laser jitter with jitter caused by relative movement of optical benches in the laboratory, for example, but nevertheless these data can provide a useful indication of system behavior and a checkpoint on the time-integrated camera images. Backward integrals (starting from high frequency) to give two-axis σ_{rms} values as a function of frequency should also be provided. Effects such as table motion will presumably affect only the low frequency portion of these integrals.

Although we recognize that low frequency jitter and drift are generally correctable and hence allowable without penalty, no quantitative guidance regarding an allowance is provided here; that is a system-specific issue.

Section 6. Laboratory practice for normalization of PIB, PIBM

Section 6.1 Normalization of PIB

A pinhole based PIB curve is made with a series of far field pinholes, the largest of which is intended to capture all of the far field power. If this condition is satisfied, then the curve can be *self normalized* with ordinate values given as fractions of total far field power. Use of such a *fractional PIB* is the general practice of the community. (See normalization concept defined in Sec 4.2.) One requirement for self normalization is a linear detector, and that is easily accomplished with a photodiode in an integrating sphere behind the pinhole. But the requirement to view all far field power can be problematic. Laser developers often don't look for high-angle emission, which may occur due to beam misalignment, beam strikes on clean-up apertures, or when the edges of the gain media (parallel to the beam line) have large spatial gradients in temperature. Two ways to look for this potential problem are: 1) examine the input face of the largest pinhole with a camera and look for beam strikes; and 2) confirm that the self normalized PIB curve is not sensitive to variation in the size of the largest pinhole.

Section 6.2 Normalization of PIBM to PIB

Recall Fig 3.1 and Eq 1. The PIBM and PIB curves differ only by the transmission ratio of the near field aperture, TE. This ratio is easily measured if the near field aperture is removable, and if the transmitted power is measured with and without the aperture.

But there is potential mischief. Consider that when the near field aperture is removed, the field of view of the absolute power meter is insufficient to collect all the laser power. In this case the laser power will be under reported. Generally, this problem does not arise if the absolute power meter is in the near field. (Fig 3.1 does not indicate if the meter is in the near or far field.)

Now consider a deviation from the configuration of Fig 3.1 in which the absolute power meter is located upstream of the near field aperture and has very large collection in space and angle. Consider further that the TE ratio will now be determined using a *far field* detector, e.g. the PIB photodiode. In the self normalization procedure (Sec 6.1) it would have already been determined that this detector views all far field power *when the near field aperture is present*. But now we are making a ratio measurement with and without the near field aperture. So in this case it is easily possible that the measured TE ratio will be based on only a subset (in space and angle) of what is captured by the absolute power meter. If so, the reported TE ratio will be too close to unity. Equivalently the reported PIBM is too optimistic for the reported power, and vice versa. Best practice is to locate the absolute power meter downstream of the near field aperture while remaining in the near field, and use that same meter to measure TE.

Section 7. Use of a Far Field Camera

In practice, a far field camera is essentially indispensable due to alignment drift, pointing jitter, variable laser modal properties, and movement between tables in the laboratory. In Fig 4.2 a typical pinhole positioning requirement can be as small as 10 µm lateral to the beam, and this stability may not be available in a passively aligned system. A far field camera with short exposure time can alleviate this problem, and in a field application it is alleviated by active tracking.

The pinhole measurement is the gold standard, and a camera should be used only when its results can be calibrated to pinhole data as describe below. When calibration can be accomplished, then the camera data is preferred since with camera data one can generate continuous PIB and PIBM curves suitable for input to simulation software. Under some circumstances, a tracking loop (i.e. active alignment) may be required to achieve stability sufficient for pinhole-to-camera calibration. Experience in the JTO JHPSSL program (the 100 kW Joint High Power Solid State Laser) shows that cameras can be problematic and must be used with care.

The spectral bandwidth of the camera must be suitable. There is a potential problem when using silicon-based cameras with spectrally-combined fiber lasers operating in the one micron region.

Section 7.1 Camera Calibration to Pinholes

We assume in this section that a camera is being used for one or both of two purposes: a) providing a continuous PIB curve over some desired range of bucket sizes, or b) alleviating the problem of pointing drift and/or jitter in a passively aligned system.

When the camera is used to generate PIB's in a self-normalized mode (see Sec 6.1), there is a potential difficulty due to limited linearity and dynamic range. The problem occurs when the camera field of view is made large in order that all the far field power can be collected. If some far field power is at large angles from the centroid, e.g. ≥ 50 λ/D, then for self normalization the image must span this large area, but most of the power may be found in a small spot of order 2 λ/D. Since the camera will be adjusted so that the hot spot doesn't saturate, most of the other pixels will receive little signal and hence noise becomes a problem.

Figure 6.1 illustrates the general strategy for calibration of camera data to pinhole data. In this example, *calibration* refers to multiplication of the camera-based PIB curve by a single normalization factor that makes the camera curve pass through a pinhole-measured data point. Bear in mind that one must calibrate the camera with all settings that will be used, e.g. various single-frame integration times (short integration times can exacerbate camera problems). The overall strategy is to use pinhole data to calibrate camera data, and then to use pinholes for larger buckets and to use the camera for smaller buckets. With this arrangement, the pinholes are tolerant of modest alignment drift and jitter, and the camera can be used to freeze out jitter and drift. Specifically, short-integration-time camera images can be re-centered on each frame. Re-centering is generally desired (See Sec 5).

Referring to Fig 6.1, assume for example that we desire a measurement at point A, or over a range including point A, and that there is insufficient alignment stability to make a direct pinhole measurement at A.

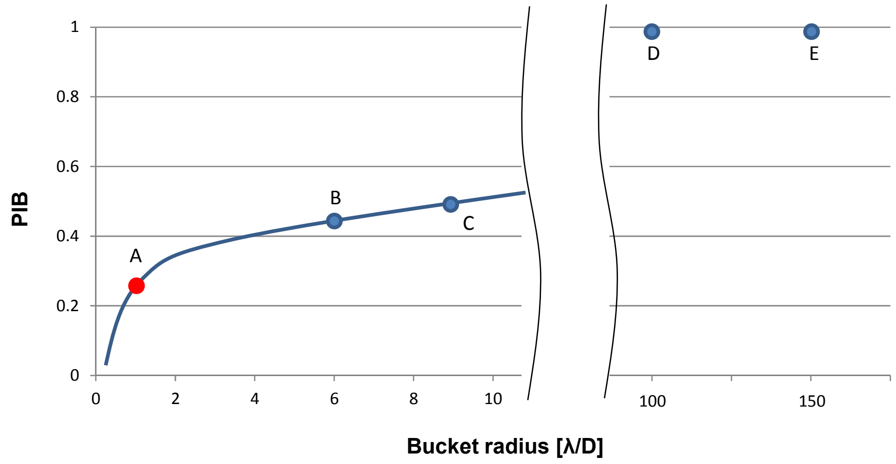


Figure 6.1. Example use of camera and pinholes together to provide a correctly normalized PIB curve. A camera-based measurement at point A is desired, and pinhole measurements at points B, C, D, and E are used to properly normalize the camera PIB curve (blue line). The blue curve then provides the correct PIB value for bucked size A. See text.

The first step is to validate that the large pinhole E is collecting all the far field energy. That involves the large pinhole D, and the idea is to show that for these large pinholes the power detected is independent of pinhole size. This, plus verifying that there is no beam strike on the input side of the pinholes (e.g. by camera observation) shows that they do likely capture all the far field power. These two apertures, independent of their size (values in the figure are only examples), should have a radius ratio ≥ 1.4, and the two detected signals should be identical to within a few percent. Given this, we'll assume that pinhole E represents 100 percent power.

As a detail, a useful detection geometry is to place the pinhole in front of an integrating sphere with a photodiode in the sphere's detector port. Careful baffling and spectral filtering will likely be required to avoid confusion from ambient light, which can include scattered light from pump diodes in the case of solid state lasers.

With pinhole E confirmed as the 100 percent power point, the second step is to calibrate the small-field-of-view camera-based PIB curve (blue line), taken in the example to extend to about 10 λ/D, and we choose 9 λ/D as the point of normalization. Then the ordinate value plotted for point C is the ratio

(power through pinhole C) / (power through pinhole E)

and we normalize the camera-based PIB to pass through that point.

Finally, validate that the normalization of the camera-based PIB curve is insensitive to the normalization radius by changing that radius and recalculating the camera-based curve. The two normalization points should have radii ratio of ≥ 1.4, so the points placed in this example at 6 and 9 λ/D are suitable. If insensitivity to the normalization radius cannot be demonstrated, the problem may be that: a) the normalization radius was too small given the alignment instability, or b) the normalization radius was too large given the linearity and dynamic range of the camera. In either case, active tracking (a servo loop) may be needed to stabilize the far field spot on the pinholes and hence permit a verifiable calibration. An active tracking loop is used in the Government Diagnostic System that resides at MIT Lincoln Laboratory. When the calibration is successful, the desired PIB value at bucket size A is read from the blue curve.

Section 8. Reportable Data

A summary of the data to be reported per these guidelines is captured in Tables 8.1 and 8.2.

Item	Data Item	In this Doc.	Comments
1	Top level system description	Sec 3	Provide a simple block diagram and layout diagram for the diagnostic system. For sensors, indicate which are in the near field and which are in the far field.
2	Near field parameters	Sec 4.2, 4.3	What are the relative placements of the laser exit plane, near field aperture, and transform lens? How is collimation in this region validated? How is the laser exit plane defined? What is the near field aperture diameter? How is the near field aperture transmission determined? What is the transform lens focal length? Is an image relay used?
3	Power meter calibration	Sec 3	Identify calibration traceability of the power meter. If attenuation is used, how is it calibrated/calculated? What is the spectral and temporal bandwidth?
4	PIB, PIBM, and camera normalization	Sec 6, 7	If a camera is used, document normalization of pinhole and camera data. What is the maximum field of view of the largest pinhole (radius in λ/D)? How is it determined that this field of view captures all of the far field power? How are camera-based PIB integrals calibrated to pinhole data? What is the camera spectral bandwidth?

Table 8.1. System Setup and Calibration Report

Item	Data Item	In this Doc.	Comments
If beam is stable			
5	Laser output power	Sec 3, 6, 7	Reported power is upstream of near field aperture
6	Laser PIBM curve	Sec 4.2, 4.3, 6, 7	PIBM curve extends to ≥ 80% of power transmitted through the near field aperture. What is the near field aperture transmission (TE)? If multiple near field apertures are used, provide curve for each aperture. PIB curve can be reported optionally, but TE parameter must be included
If beam is not stable			
5’	Laser output power	Sec 3, 5, 6, 7	As in Items 5, 6, but in ½ sec time slices until pulse is stable or terminates
6’	Laser PIB, PIBM curves	Sec 4.2, 4.3, 5.1, 6, 7	
7	Jitter PSD, σ_{rms} integrals	Sec 5.2	Report two-axis PSD and backward integrals. These data can include jitter from table movement, which presumably affects the PSD at low frequency
If measurements are made downstream of beam manipulations			
8	Data as above, but following beam manipulation	Sec 4.5	Only needed if beam manipulation may significantly affect the above data

Table 8.2. Beam Characterization Data

Section 9. Technical Interaction with the Government Regarding This Beam Quality Metric

The High Energy Laser Joint Technology Office will maintain this document and interact with the community regarding questions and comments. Contact the HEL-JTO Director.

Section 10. Summary

A systematic approach has been presented for a comparatively simple measurement of beam quality based on a carefully defined modification of the common PIB metric. This metric is a curve, rather than a point, and is thus relevant to both long and short range DEW missions. The metric can be evaluated at the laser exit, or at points further along the beam line. It is intended for use as a component in top-level, end-to-end system performance predictions and laser comparisons.

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