Title

Review of Lemons Et Al.

Author

Leary, Cameron

Publication Date

2024-12-12

Review of Lemons Et Al.

Cameron Leary[1,*]

[1] *UCLA Henry Samueli School of Engineering and Applied Science*

[*] *CameronLeary@g.ucla.edu*

Abstract: Lemons demonstrates that in good conditions a LG01 beam is an ideal choice for mitigating MBI. It is noted however that mechanical noise can lead to the overlap of the electron beam with the beam maxima. Other modes are not as susceptible to this problem, so there is a trade off between ideal heating performance and jitter mitigation. One alternative considered is a Hermite-Gaussian orthogonally polarized CV beam. The performance of an HG beam will be worse than that of an LG beam due to the wider beam waist and lower e-beam interaction for higher elevation angle magnitudes. Due to the lack of an E-field maxima in one plane the performance of an HG beam may be superior in an environment where transverse jitter is of major concern, particularly if the jitter is confined to the same plane as the null of the HG beam. Higher order beams with more sophisticated transverse distributions should also be considered.

INTRODUCTION

Microbunching is a significant problem in FEL's. As electrons in the beam collect into the troughs of the ponderomotive wave, they bunch together and in doing so exchange energy with the wave, either producing gain if they lose velocity to fall back into a trough, or loss of they gain velocity to roll down into a trough. Generally if the phase match condition is met they will be more likely to lose energy to the wave, as intended. In these bunches though, there can be additional substructure; extra bunching within each primary bunch. This is microbunching. The reason it happens is that the electrons in the electron beam never realistically have a perfectly uniform density distribution or energy distribution, and as they propagate through the continuum of an FEL these local differences become amplified. The presence of microbunches causes problems. This is because they both alter the bunches and cause them to radiate less coherently, and they themselves can radiate adding unwanted harmonics. The net effect is generally a spread in energy, which is bad if the goal is a narrow spectral width.

> “It turns out that transporting high-brightness electron beams through hundreds of meters of the accelerator and compressing it may lead to deterioration of its properties”- G. Stupakov[5]

Clearly this is a problem that needs to be mitigated. The key to doing is that an electron beam with greater spread in energy is less susceptible to MBI. A larger energy spread is good because the different energy levels help “smear out” the comparatively smaller density modulations in the beam, preventing them from amplifying as much. One way to produce this energy spread is with a laser heater. A laser heater is a laser shot into the beam while it is in the beginning of the FEL and interacting with an undulator. The beam adds random variation into the electron kinetic energies disrupting the non-random microbunching. This random variation gets averaged out as the electrons continue through the FEL but the overall effect is that there is no longer energy spread tied to a specific pattern caused by microbunching**1**. The laser heater has some important caveats: the spread in energies it adds must not exceed the spread in electron energies that can be tolerated by the FEL. If the spread were too large, phase matching would not work. Secondly, the laser heater should impart random energies. This second part is not actually possible- the energy modulation created is structured with a periodicity matching the lasers wavelength. The key is that this structure gets washed out as electrons propagate, so that by the time the beam makes it to the main wiggler the energy distribution is “random”. These are the basics, now on to the paper to be reviewed. The paper is about a laser heater. This laser heater is special in the energy distribution which is imparted on the transverse plane. It uses a Laguerre-Gaussian 01 beam shape allowing it to impart a gaussian shaped energy distribution to electrons in the transverse plane. The paper experimentally demonstrates that the energy distribution is indeed gaussian and that this is superior for MBI suppression when compared to other laser heaters that use Gaussian beam shapes.A non-ideality identified in the paper is that of transverse jitter effects. Transverse jitter leads to an offset between the center of the E-beam and the center of the laser. This can cause the electron beam to occasionally be centered not at the middle where the intensity is at a minimum, but along the ring of maximum intensity. This makes the LG01 no better than the gaussian mode, where the resulting energy distribution is a double horn. This demonstrates the importance of having the laser in its ideal position.

METHODS

There are other beams that are similar to LG01 in that they have a null at the center. An investigation of their effectiveness as an alternative is warranted. The first thought might be something like a cylindrical vector beam. These beams would perform worse than LG01 with no obvious benefits. This is because they have a larger beam area, and thus would need to be more powerful to impart the same energy as an LG01 beam. These CV beams are formed via the superposition of two orthogonally polarized Hermite-Gaussian beams. An individual HG10 beam has the same shape in E-field distribution in the transverse plane, only with diminishing amplitude for higher elevation angles. It has the same drawbacks as the CV beams, but unlike the CV beams, the drawbacks could be offset by a higher resistance to jitter. If we define non-catastrophic jitter as jitter in a direction where beam power is 3dB below its maximum, then it is determined that this angle is at a 45 degree elevation from the center in the direction of the null. From Fig. 3, see that the E-field maxima drops by $1/\sqrt{2}$ (red line) at this angle. Hypothetically the likelihood of jitter effects putting the electron beam at an intensity maximum would be reduced by a half over the LG beam due to the presence of nulls along one axis. Noting though this reduction would be if the power was 0 in these regions instead of a 3dB drop as approximated, but still this demonstrates the potential for this mode to handle jitter better. This warrants an investigation into if this beam could perform similarly, so the next task is to demonstrate that the energy distribution this beam would impart to the electron beam is gaussian just like the LG beam. Because the hermite-gaussian beam produces a similar shape E-field distribution as the laguerre-gaussian (see fig.4 for comparison), it can be inferred that the energy imparted would be of the same form as well. The difference is that the HG beam diminishes towards the nulls so looking at slices of E-field strength at different angles you would see the same shape but a changing maxima while the LG mode is the same at all angles. Considering the shape of the energy distribution, for the HG mode it would be nearly ideal in the x-z plane, and extremely non-ideal in the y-z plane, since energy distribution depends on E-field distribution**[5]**. A full treatment of the energy imparted to the electron beam by the HG beam is beyond the scope of this paper, but a comparison to the LG beam can be reasoned. In order for the spectral energy density encountered by the electron beam to be the same, the HG mode would need more energy since its beam width is wider. Even after this scaling, if one was to look at the $y = w_0/4$ plane for instance, the maximum intensity of the electric field would be the same in the LG mode, but will have dropped in the

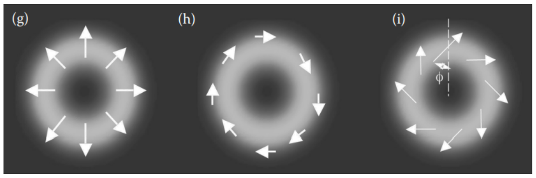

Fig. 1. CV Beams (Ref. [2])

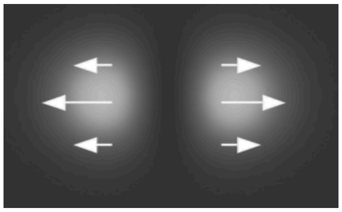

Fig. 2. OP HG Beam (Ref. [2])

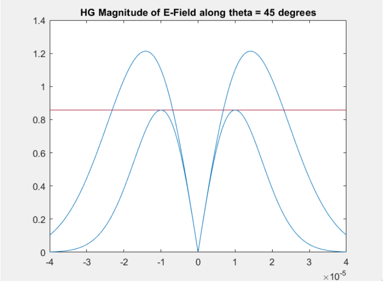

Fig. 3. Null Angle

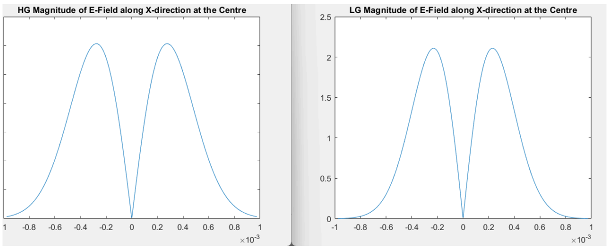

Fig. 4. E-Field Distribution Shapes

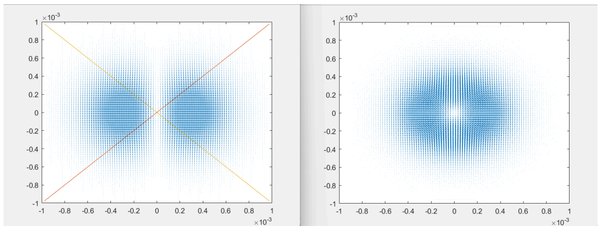

Fig. 5. HG and LG Beam Transverse E

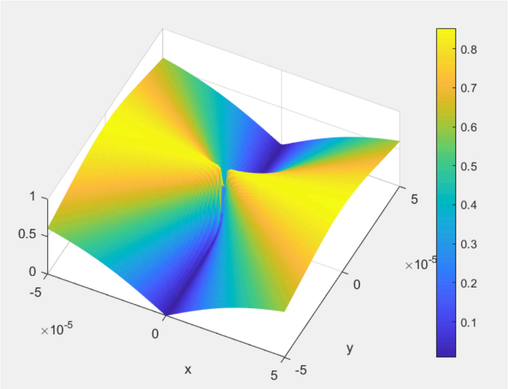

Fig. 6. Relative Field Strengths

HG mode (w_0 being the beam width of the electron beam). To quantify this, I will treat the electron beam as a bivariate normal distribution since it is mentioned in the paper that it is Gaussian. The electrons in the y=0 plane see nearly the same field for both LG and HG modes, which is good since this is the peak of electron population. The electrons at $(w_0/4, w_0/4)$ see a forty percent drop in the field intensity in the HG mode as in the LG mode, but this location also has a population of seventy percent the maximum. Weighting the x% drop in electric field by the y% drop in electron population, the HG mode will impart an amount proportional to xy% the energy as the LG mode in this location. Because E-field strength is proportional to energy imparted, this is a good metric for comparing. It is worth noting that the amount of energy imparted is less important than the distribution, but the total energy imparted for equivalently intense beams is still a valuable comparison. Fig(6) is the relative E-field strength plotted within one e-beam width from the center. The shape makes sense: they are almost equal (yellow color) everywhere except for close to the hourglass-shaped null of the HG beam (blue/green color).

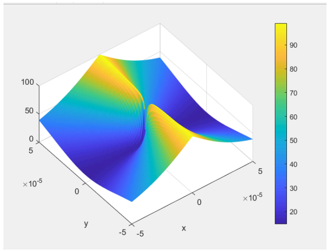

Fig. 7. Percent Drop

The percent drop is shown in fig(7). The next figure (8) is the percent difference between HG and LG modes weighted by the electron distribution within one beam width from 0. This is the weighted percent drop within the range of the electron beam. Taking its sum and averaging by total electron density, we find that the average electron feels 2.8 percent less E-field in the HG mode than in the LG mode. If energy imparted to electrons is directly proportional to energy in the field, which is proportional to the E-field squared, then the energy imparted by the HG beam would be 7.8% lower in total compared to the LG beam of equivalent adjusted magnitude.

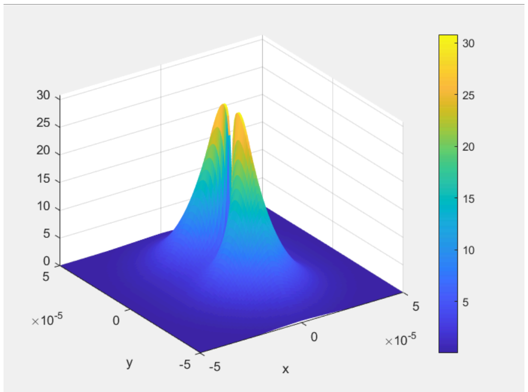

Fig. 8. Weighted Percent Drop

Table 1. Supplementary Materials

Matlab Code	**Matlab Code for 170A Paper**

CONCLUSIONS

A 7.8% drop in total energy imparted and a less ideal energy distribution is not worth having a less than 50% decrease in jitter effects. Even in a noisy environment with an idealized view of the performance of HG10 beams against transverse jitter, it is still unlikely that an HG10 beam will perform better than a LG01 beam. Potentially if a system were to be intentionally designed to have jitter in the direction of the HG null it would perform better, but there is no obvious reason to do this. However, higher order beam modes and superpositions of modes with complex beam fronts potentially could perform better than an LG01 mode in noisy environments, but these scenarios are difficult to treat mathematically. The best course for laser heater technology I believe would be to continue using the Laguerre-Gaussian modes and to mitigate jitter with mechanical methods rather than complex beam manipulations.

REFERENCES

1. Freund, H. P., & Antonsen, T. M. (2018). *Principles of Free Electron Lasers*. Springer.
2. Forbes, A. (Ed.). (2014). *Laser beam propagation: Generation and propagation of Customized Light*. CRC PRESS.
3. Di Mitri, S., & Spampinati, S. (2017). Microbunching instability study in a linac-driven free electron laser spreader beam line. *Physical Review Accelerators and Beams, 20*(12), 120701
4. Zhan, Q. (2009). Cylindrical vector beams: From mathematical concepts to applications. *Advances in Optics and Photonics, 1*(1), 1–57.
5. Stupakov, G. (2014). Control and application of beam microbunching in high brightness linac-driven free electron lasers. In *Proceedings of the 5th International Particle Accelerator Conference (IPAC2014)*, Dresden, Germany. JACoW Publishing.
6. Huang, Z., & Kim, K.-J. (2002). Formulas for coherent synchrotron radiation microbunching in a bunch compressor chicane. *Physical Review Special Topics - Accelerators and Beams, 5*(7), 074401.
7. Tang, J., & Lemons, R. (2020). Laguerre-Gaussian mode laser heater for microbunching instability suppression in free-electron lasers. *Physical Review Letters, 124*(13), 134801.