Coupling of Laser Angular Momentum to Plasma for the Generation of Kilo-Tesla Magnetic Fields

High Energy Density Science Centre Seminar
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Andrew Longman*
University of Alberta, Edmonton, Canada

PhD Supervisor – Robert Fedosejevs

*longman@ualberta.ca

Outline

- **Motivation**
  - The need for strong magnetic fields
- Spin and Orbital Angular Momentum Beams
  - Brief review of Orbital Angular Momentum (OAM)
  - Diffraction of OAM beams and Laguerre-Gaussian (LG) modes
- The Inverse Faraday Effect
  - Analytic Models
  - Coupling of angular momentum to plasma and free electrons
- Numerical Modelling of the IFE
  - Modelling of Titan-like laser parameters
  - Asymmetric and realistic OAM beams
- Experimental Methods
  - Generating OAM beams at high intensity
  - Measuring magnetic fields

Motivation – The Need For Strong Magnetic Fields

Laboratory Astrophysics

- Magnetic Reconnection
- Pulsars, Magnetars
- Cosmic Radiation and Particle Acceleration

$\boldsymbol{B}\sim 100 - 10000T$

Particle Acceleration

- Laser Cyclotron Resonance
- Particle Guiding
- Enhancement of Laser Driven Light Sources

Fusion Plasmas

- Confinement of Plasmas
- Magnetically Assisted ICF
- Advanced Ignition Schemes – Fast Ignition

How We Currently Generate Strong *Longitudinal* Magnetic Fields

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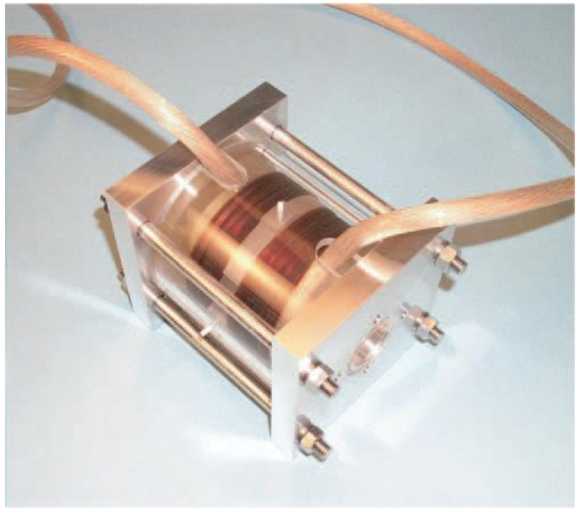
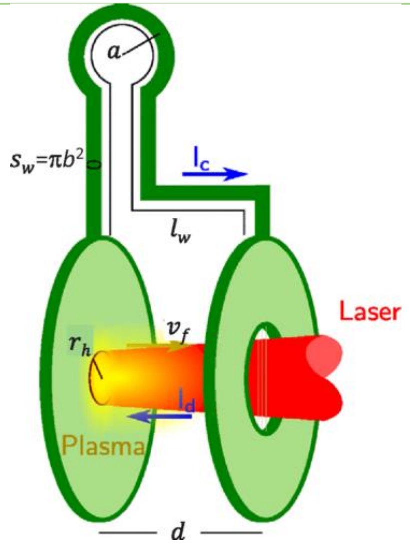


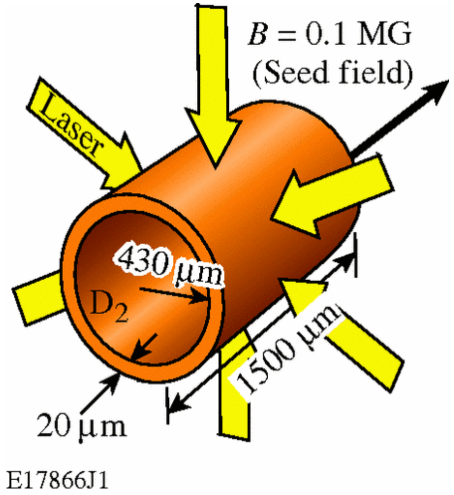
Pulsed power driven coils

- Field strengths can typically range from 10 - 100 Tesla
- Spatial scale can be on the order of cm
- Peak field can last for μs - ms
- Sometimes destroyed in process



Laser Driven Capacitor-Coil

- Field strengths can typically range from 100 - 1000 Tesla
- Spatial Scale can be on the order of mm
- Peak field can last for ps - ns
- Mostly destroyed in process

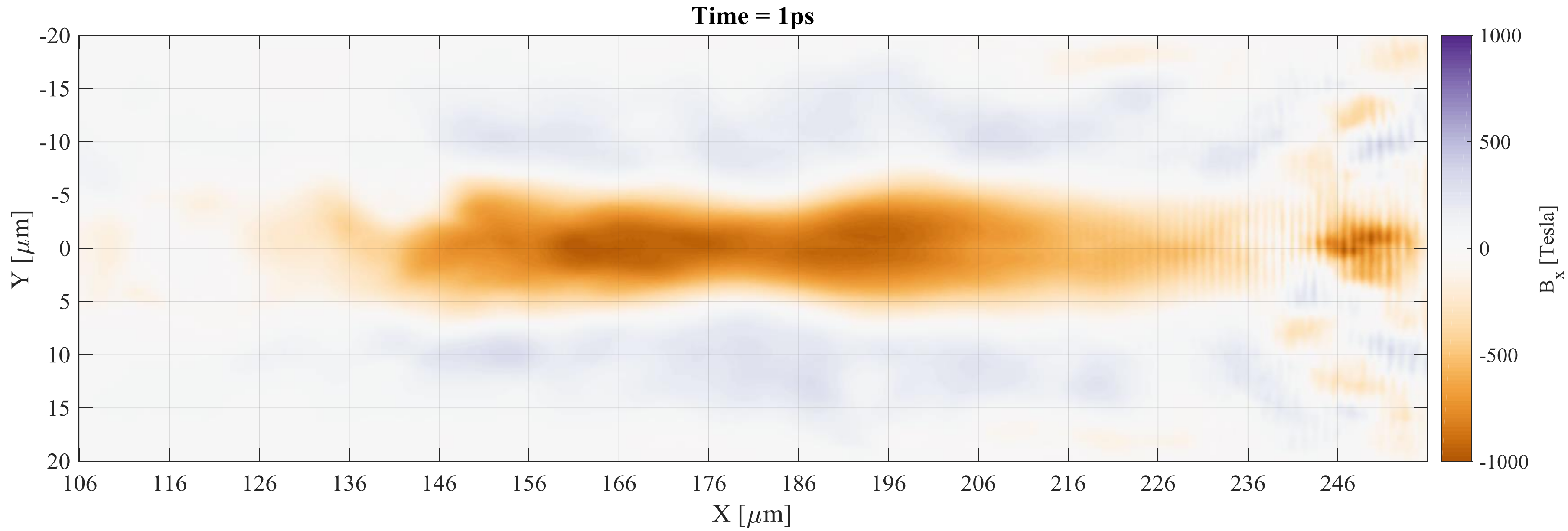


Flux Compression

- Field strengths can typically range from 100 - 1000 Tesla
- Spatial Scale can be on the order of cm
- Peak field can last for ns – μs
- Destroyed in process

Images: B. B. Pollock, et al, Rev. Sci. Inst. **77**, 114703 (2006), O. V. Gotchev, et al, Phys. Rev. Lett. **103**, 215004 (2009), V.T. Tikohonchuk, M. Bailly-Grandvaux, J. J. Santos, and A. Poye, Phys. Rev. E. 96, 023202 (2017)

New Technique - B Fields From Angular Momentum Of Light



Laser-Plasma Parameters For Above

- $0.03n_c$ He plasma
- $1 \times 10^{20} Wcm^{-2},\ \lambda = 1\mu m, w_0 = 8\mu m,$ 100fs, 10J
- Linearly Polarized Laguerre-Gaussian $l = 1$ mode

Inverse Faraday Effect (IFE)

- Field strengths can typically range from 100 - 10000 Tesla
- Spatial scale can be on the order of 100 μm+
- Peak field can last for ps's+
- Can be done at rep-rate of laser (no solid targets)
- Can be done with **linearly polarized** structured lasers

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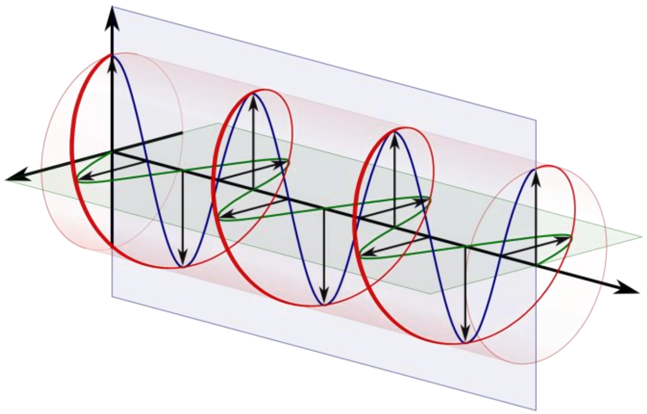
Structured Light Is Created By Modification Of Phase, Amplitude, And Polarization

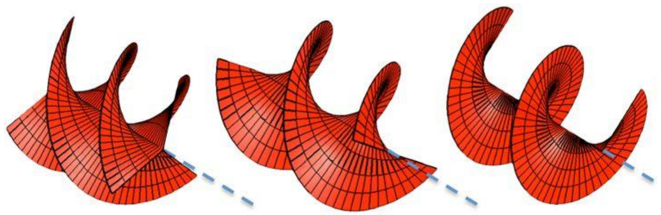
Polarization State



- Circular/elliptical polarization
- Radial/azimuthal polarization
- Carries spin angular momentum (SAM)

$$\boldsymbol{S} = \sigma_z \hbar \,, \qquad \sigma_z = \pm 1{,}0$$

Structured Phase

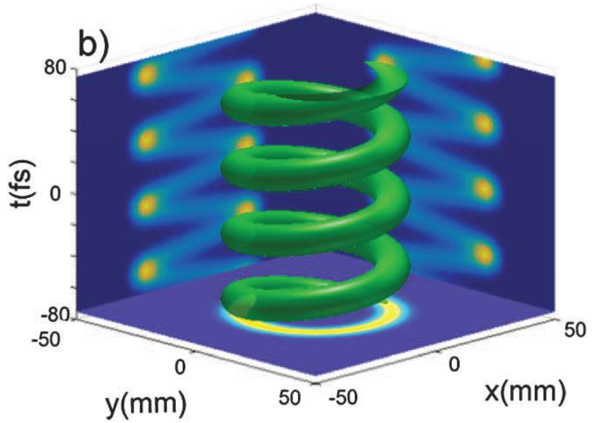


- Usually a helical phase $e^{i\ell\phi}$
- Carries a well defined orbital angular momentum (OAM)

$$\boldsymbol{L} = \ell\hbar$$

$$\ell = 0, \pm 1, \pm 2, \dots, \pm\infty$$

Beating Laser Beams

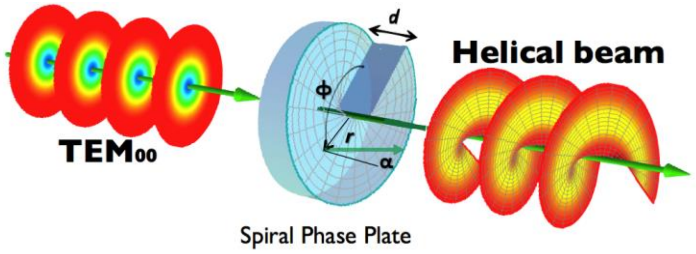


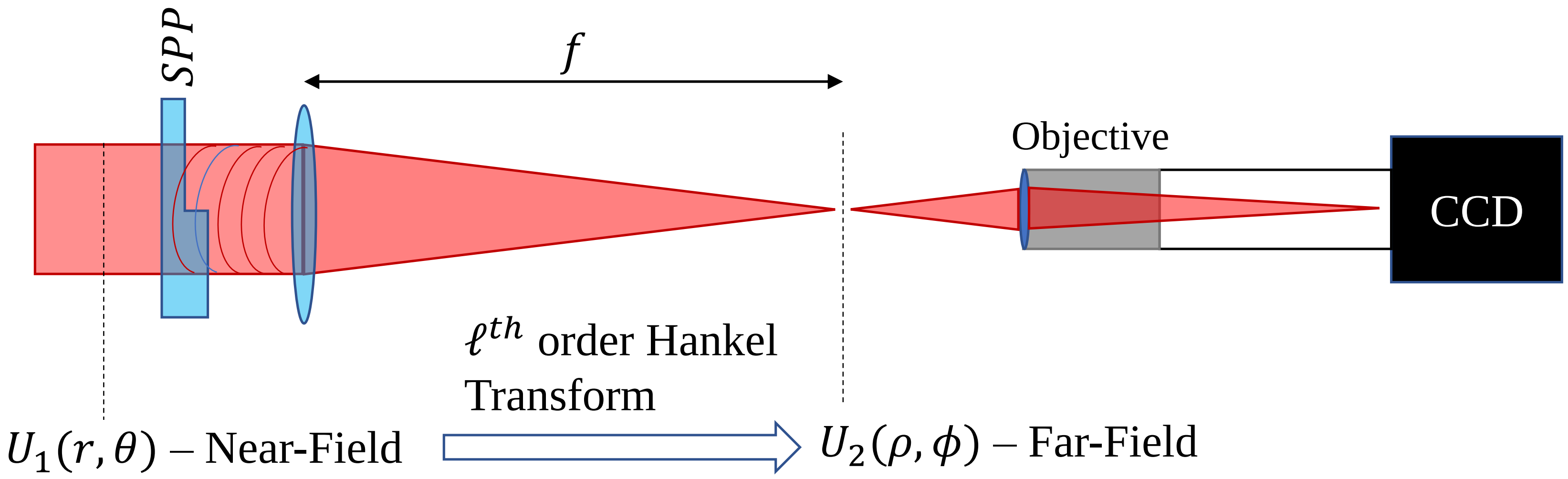
- Interference of structured beams
- Leads to spatio-temporal intensity profiles (light springs)
- Carry orbital angular momentum spectrum (wavelength dependant)

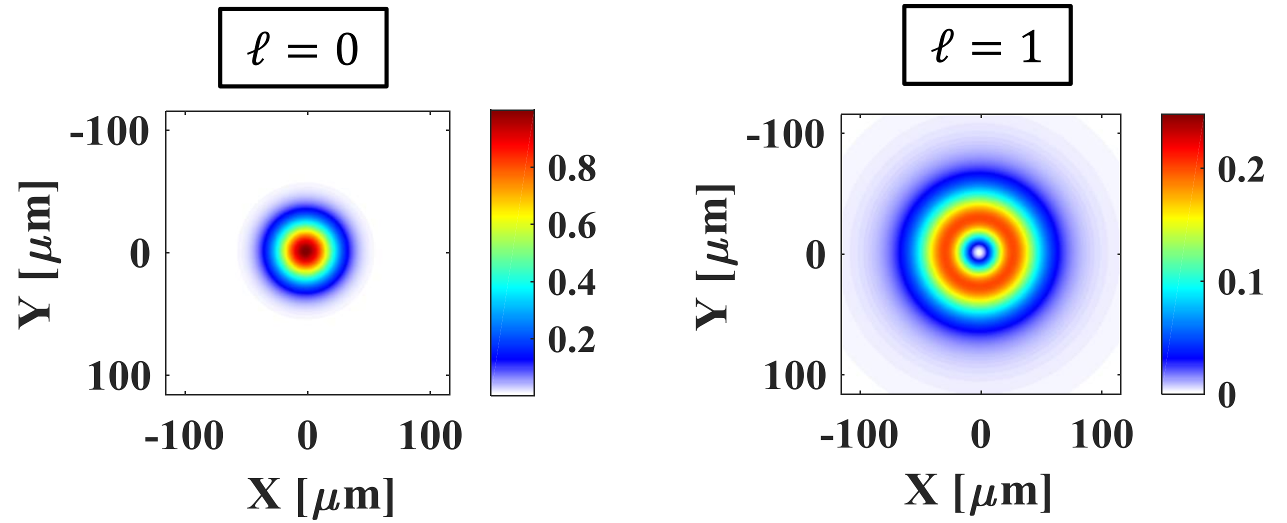
Images: https://en.wikipedia.org/wiki/Circular_polarization, M. Padgett, Proc. Royal Soc. A. **470**(2172), 2014, G. Pariente and F. Quere, Optics Letters, 40(9), 2037-2040 (2015)

Far-field Diffraction of OAM Beams Driven By Spiral Phase Plates

Spiral Phase Plates (SPP's)







A. Longman, C. Salgado, G. Zeraouli, J. I. Apinaniz, J. A. Perez-Hernandez, M. Khairy Eltahlawy, L. Volpe, and R. Fedosejevs, "*Off-axis spiral phase mirrors for generating high-intensity optical vortices*", Opt. Lett. **45**(8) (2020)

OAM Beam Diffraction From Gaussian Near-Fields

A. Longman, and R. Fedosejevs, *“Optimal Laguerre-Gaussian Modes For High-Intensity Optical Vortices”,* J. Opt. Soc. Am. A, **37**(4), 2020

Gaussian Near-Field Beam,

$$I_{nf}(r) \propto \exp\left(-2\frac{r^2}{R_0^2}\right)$$

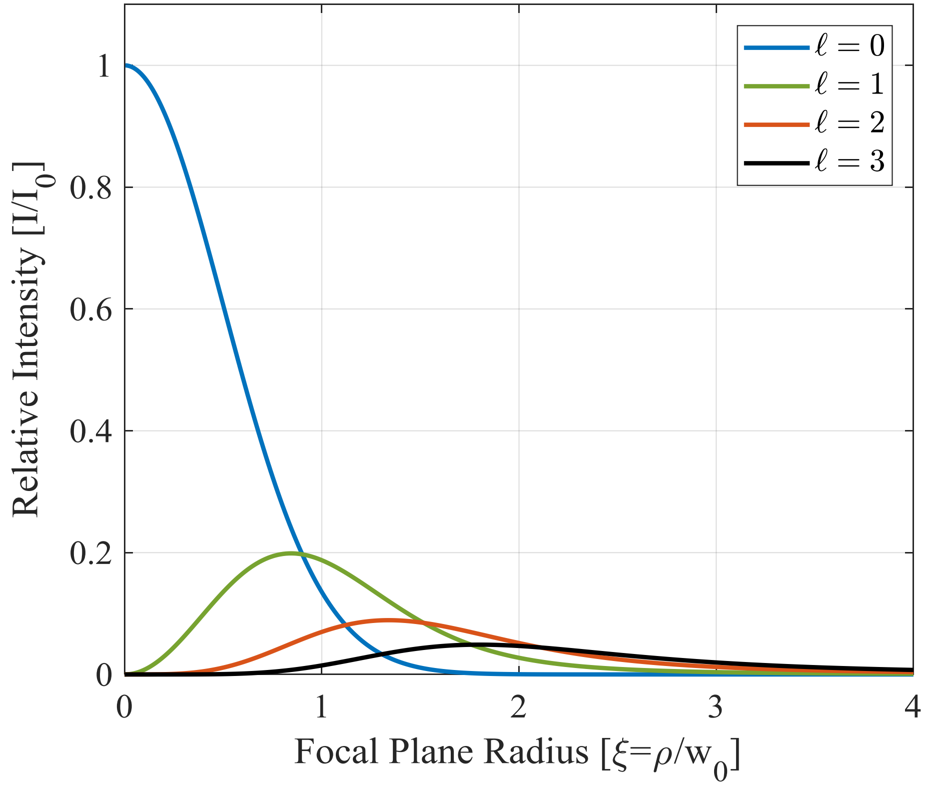
Hankel transforms to the far-field,

$$\boxed{I(\xi,\ell) = \frac{I_0\pi}{4}\xi^2 e^{-\xi^2}\left|I_{\frac{|\ell|-1}{2}}\left(\frac{\xi^2}{2}\right) - I_{\frac{|\ell|+1}{2}}\left(\frac{\xi^2}{2}\right)\right|^2}$$

Where,

$$\xi = \frac{\rho}{w_0}\,, \qquad w_0 = \frac{\lambda f}{\pi R_0}$$

R_0 is the near-field Gaussian beam radius, and $I_n(x)$ is the modified Bessel function of the 1st kind



OAM Beams From Flat Top Beams Previously Not Considered In Calculations

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A. Longman, and R. Fedosejevs, *"Optimal Laguerre-Gaussian Modes For High-Intensity Optical Vortices"*, J. Opt. Soc. Am. A, **37**(4), 2020

Flat-Top Near-Field Beam,

$$I_{nf}(r) \propto \left[circ\left(\frac{r}{R_F}\right)\right]^2$$

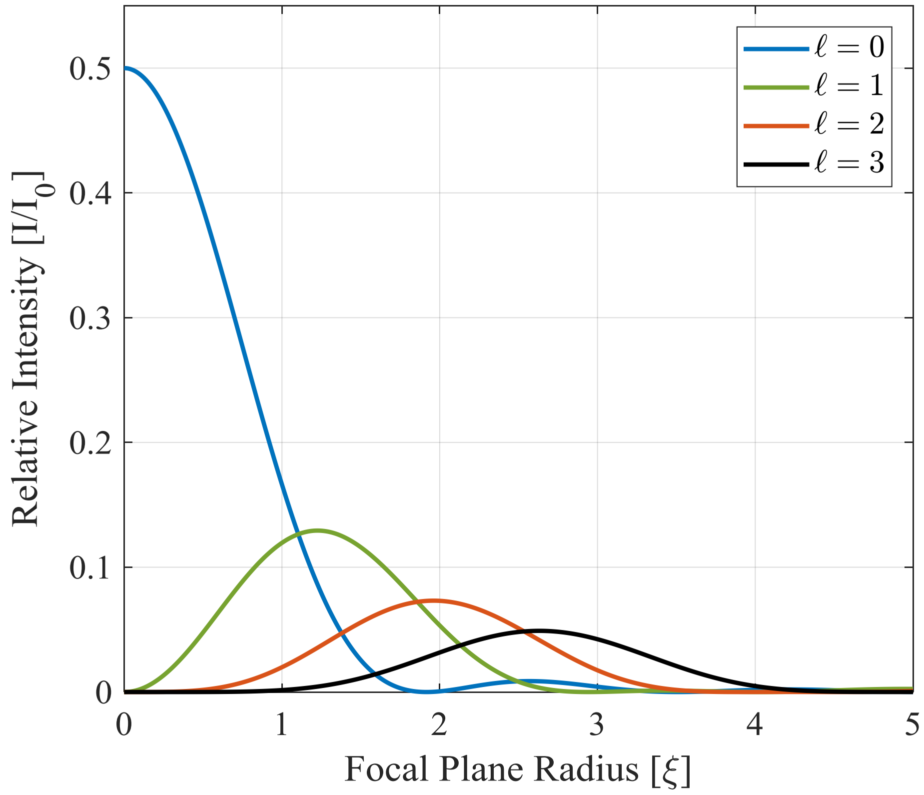
Hankel transforms to the far-field,

$$\boxed{I(\xi,\ell) = \frac{I_0}{2}\left|\frac{\xi^{|\ell|}}{|\ell|!\left(\frac{|\ell|}{2}+1\right)}\ {}_1F_2\left(\frac{|\ell|}{2}+1; |\ell|+1, \frac{|\ell|}{2}+2, -\xi^2\right)\right|^2}$$

Where,

$$\xi = \frac{\rho}{w_F}, \qquad w_F = \frac{\lambda f}{\pi R_F}$$

R_F is the near-field flat-top beam radius, and ${}_1F_2(\mathrm{a};\mathrm{b},\mathrm{c};\mathrm{d})$ is the generalized hyper-geometric function.



For Analytic/Numerical Modelling We Use Laguerre-Gaussian Modes

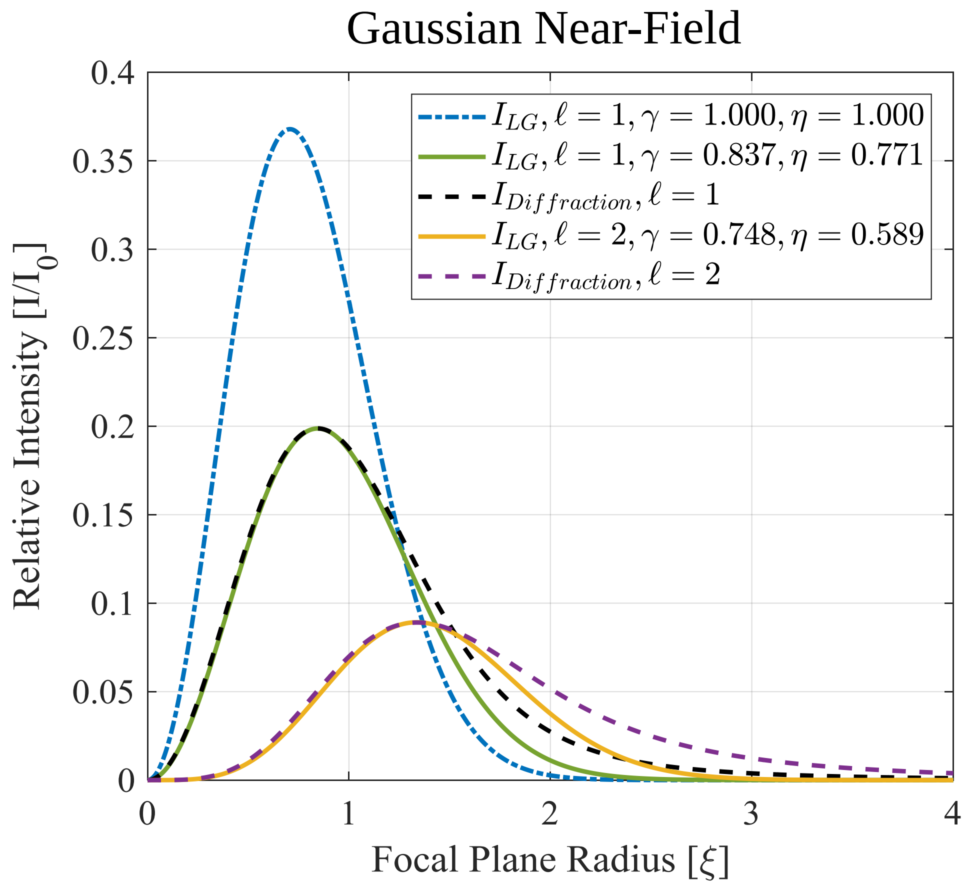
A. Longman, and R. Fedosejevs, *"Optimal Laguerre-Gaussian Modes For High-Intensity Optical Vortices"*, J. Opt. Soc. Am. A, **37**(4), 2020

- The far-field diffraction equations are not ideal for analytic or numerical modelling, so we instead use a modified Laguerre-Gaussian (LG) $p = 0$ basis set:

$$\boxed{\psi_{\ell,p}(\xi,\phi)\Big|_{z=0} = \sqrt{\frac{p!\,\eta\gamma^2}{|\ell|!}}\left(\xi\gamma\sqrt{2}\right)^{|\ell|} e^{-(\xi\gamma)^2} e^{i\ell\phi} L_p^{|\ell|}(2\xi^2)}$$

- The values of η and γ are optimally chosen such that the LG mode is a good fit to the diffraction theory.

- Values of η and γ have been tabulated in the reference above for Gaussian, Flat-top and super-Gaussian driver beams.



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Inverse Faraday Effect… On One Page

- Average rate of change of electron angular momentum in the presence of a beam carrying angular momentum [1,2]:

$$m_e n_e r\left(\frac{d}{dt}+\nu_{ei}\right)u_{e\theta}=-en_e r(E_\theta+u_{ez}B_r-u_{er}B_z)-\frac{dM_z}{dt}$$

- Allen (92) [3]:

$$M_z=\frac{\ell}{\omega c}I+\frac{\sigma_z r}{2\omega c}\left(\frac{\partial I}{\partial r}\right)$$

- Assuming $\nu_{ei}\sim 0$, $du_{e\theta}/dt=0, u_{ez,r}\ll c$:

$$en_e r E_\theta \sim -\frac{dM_z}{dt}$$

- Using Faraday's law:

$$\boxed{B_z=-\frac{f_{abs}}{ren_e\omega c}\left[\ell\frac{\partial I}{\partial r}+\frac{\sigma_z}{2}\frac{\partial}{\partial r}\left(r\frac{\partial I}{\partial r}\right)\right]}$$

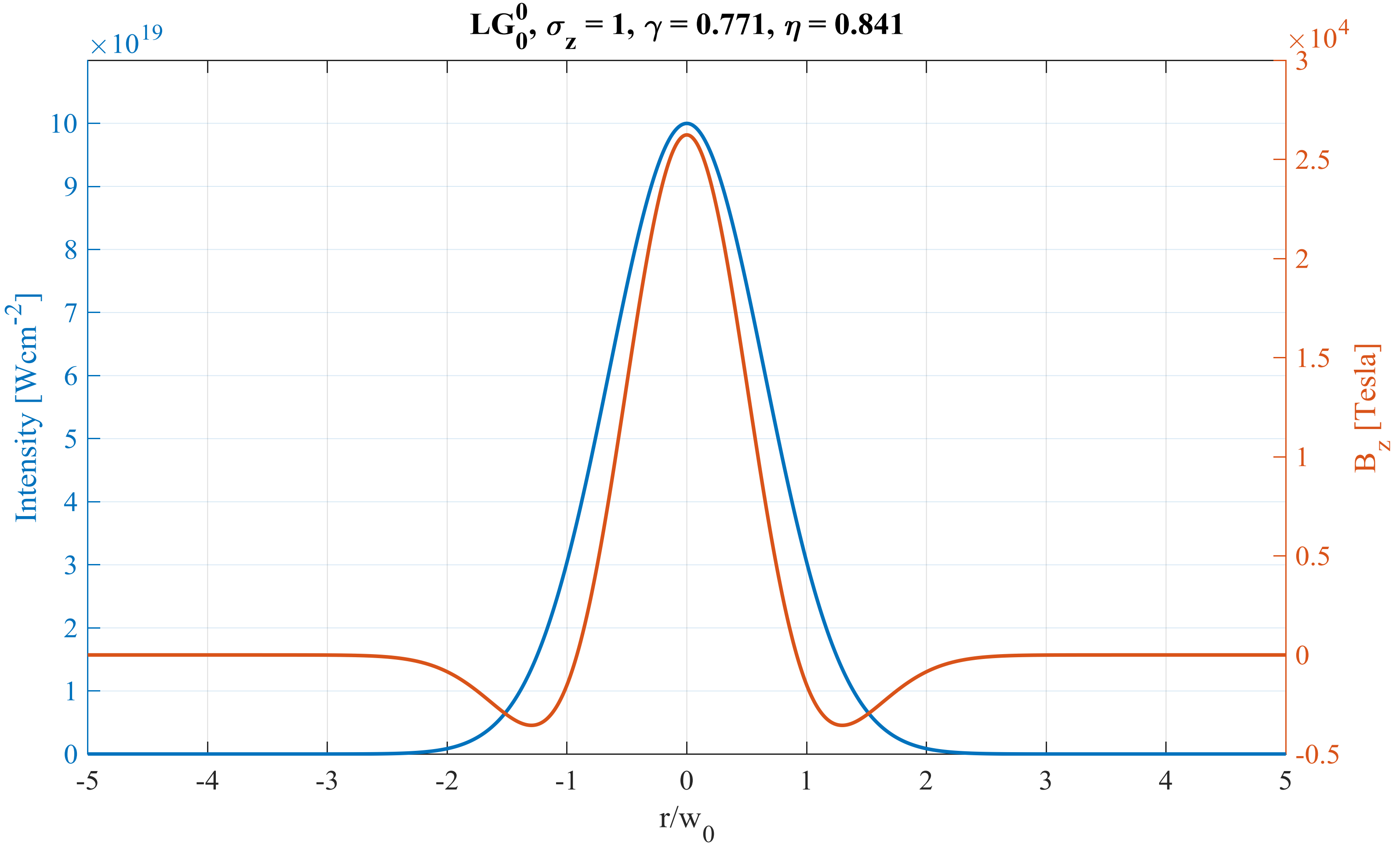
- f_{abs} is fraction of laser energy absorbed by plasma.

- Note dependence on σ_z - linearly polarized lasers can drive axial magnetic fields!

Refs: [1]. M. G. Haines, PRL 87(13), 2001, [2]. S. Ali, J. R. Davies, and J. T. Mendonca, PRL **105**, 035001, 2010 [3]. L. Allen, et al, Phys. Rev. A **45**, 8185, 1992

Inverse Faraday Effect Model – Circular Polarization

$$B_z = -\frac{2f_{abs}}{en_e\omega c w_0^2} I(r,\ell)\left[\ell\left(\frac{w_0^2|\ell|}{r^2} - 2\right) + \sigma_z\left(\frac{|\ell|^2 w_0^2}{r^2} - 2 - 4|\ell| + \frac{4r^2}{w_0^2}\right)\right]$$



Model Parameters

Near-field : Flat-top

$\ell = 0, \sigma_z = 1$

Peak Intensity: 1E20Wcm-2

$w_0 = 6\mu m, n_e = 3 \times 10^{19} cm^{-3}$

$f_{abs} = 1$

Peak axial B-field: ≈ **26000T**

Inverse Faraday Effect Model – Orbital Angular Momentum

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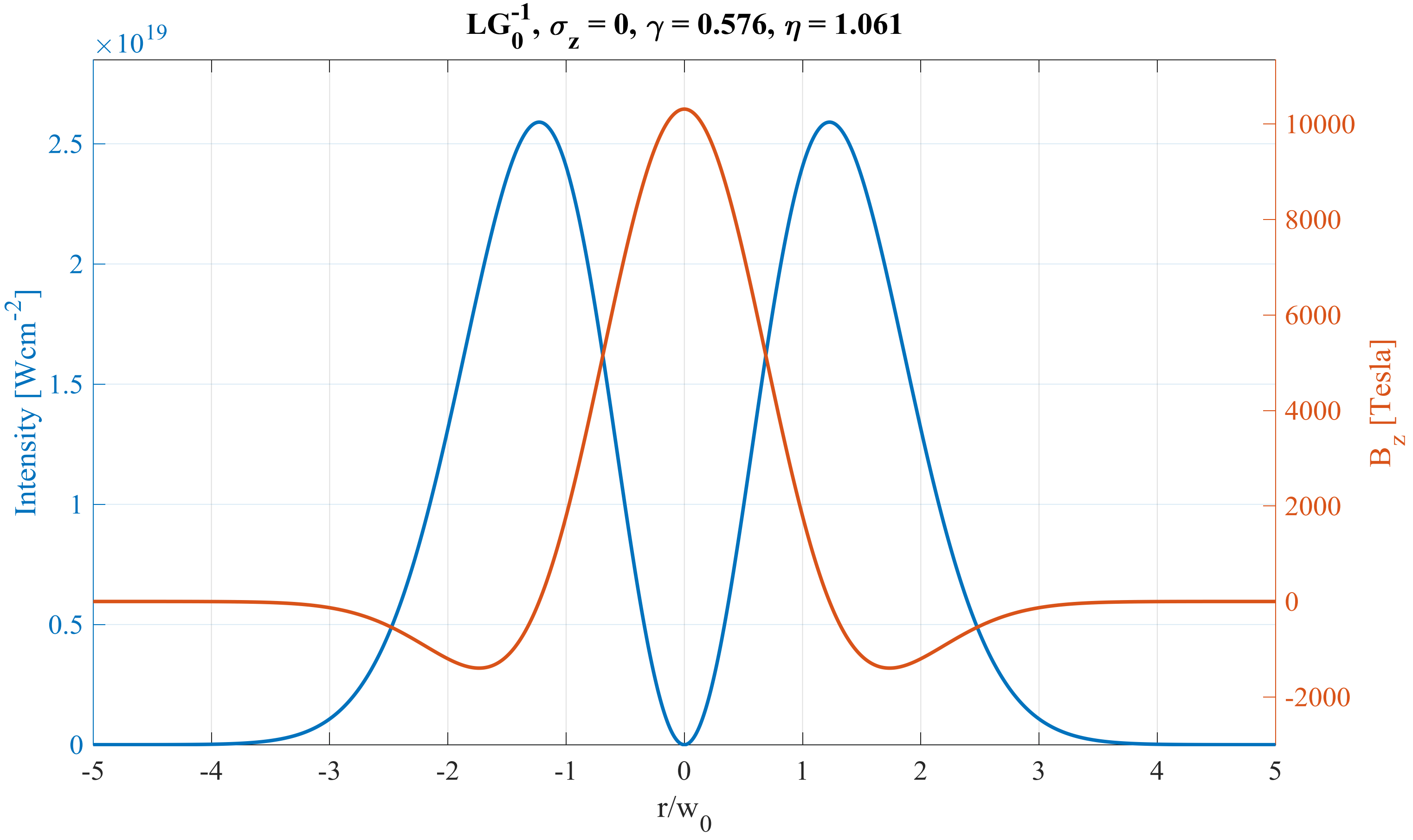
$$B_z = -\frac{2f_{abs}}{en_e\omega c w_0^2} I(r,\ell)\left[\ell\left(\frac{w_0^2|\ell|}{r^2} - 2\right) + \sigma_z\left(\frac{|\ell|^2 w_0^2}{r^2} - 2 - 4|\ell| + \frac{4r^2}{w_0^2}\right)\right]$$



<u>Model Parameters</u>

Near-field : Flat-top

$\ell = -1, \sigma_z = 0\ (LP)$

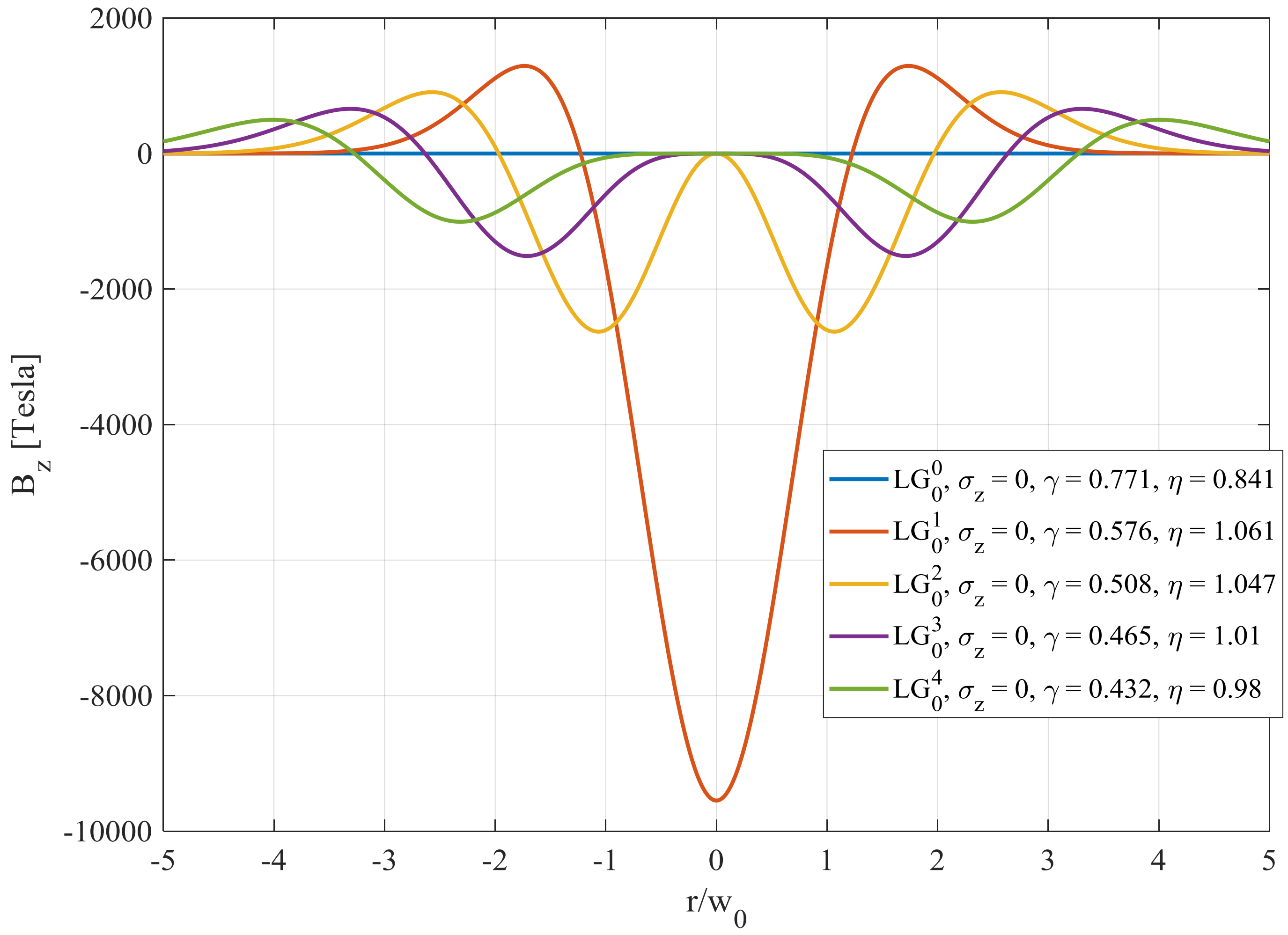
Peak Intensity: 2.5E19Wcm-2
(Energy is the same as previous)

$w_0 = 6\mu m, n_e = 3 \times 10^{19} cm^{-3}$

$f_{abs} = 1$

Peak axial B-field: ≈ **10000T**

As OAM In The Beam Increases, The B Field Decreases



Model Parameters

Near-field : Flat-top

$\ell = var, \sigma_z = 0$

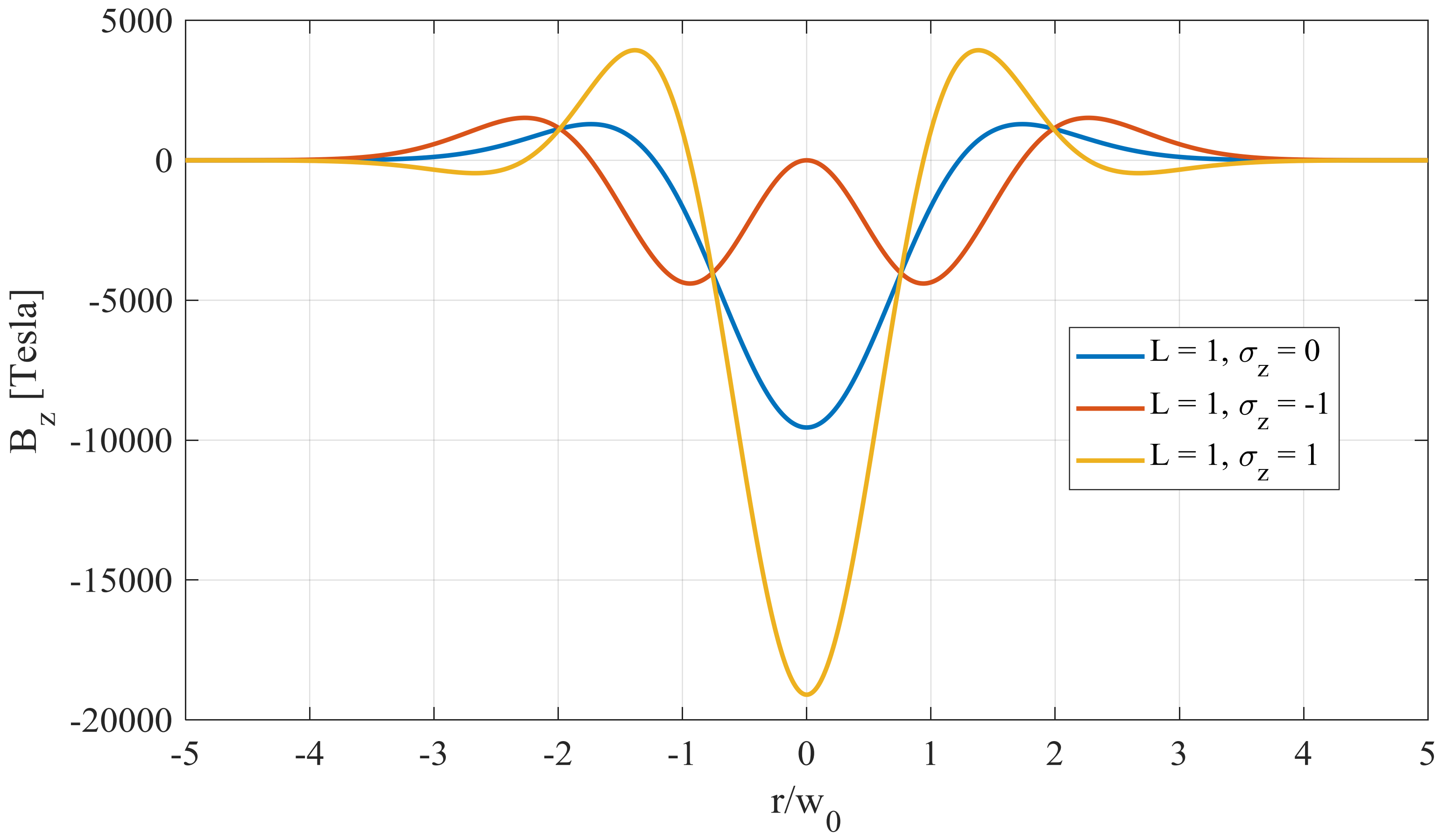
Peak Intensity: 1E20Wcm-2 ($\ell = 0$)
(Energy is the same for all)

$w_0 = 6\mu m$

$f_{abs} = 1$

ℓ	B_{max}
0	0
1	-9548
2	-2628
3	-1512
4	-1007

Spin Can Amplify OAM Driven B Fields



- Shown by Allen et al (1992):

$$\boxed{\boldsymbol{J} = (\sigma_z + \ell)N\hbar}$$

- Where, $\sigma_z = \pm 1{,}0$,
  $\ell = 0, \pm 1, \pm 2, \ldots, \pm\infty$

- Spin and orbital angular momentum can constructively or destructively interfere

- This is clear as the magnetic field generated can either be enhanced or dampened

Reference: L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, and J. P. Woerdman, Phys. Rev. A **45**, 8185 (1992)

Further Understanding is Needed On OAM/SAM Coupling Mechanisms

- A fundamental question concerning OAM and SAM beams is how they couple to the plasma, and if OAM/SAM can be transferred and by which mechanisms

- We started to look at this question from the fundamental point of view using single electrons in ultra-intense beams

- This however requires an accurate model of the E and B fields at focus in an LG mode

Laguerre-Gaussian Modes – Need paraxial forms exist for E and B fields

- To model the OAM beams, we opt to use the Erikson and Singh [1,2] model for modelling of the beams in the paraxial limit:

$$\boldsymbol{E} = E_0\left[\hat{x} + \frac{\hat{y}}{2k^2}\frac{\partial^2}{\partial x \partial y} + \frac{i\hat{z}}{k}\frac{\partial}{\partial x}\right]\psi(x,y,z)e^{i(kz-\omega t)}$$

$$\boldsymbol{B} = \frac{E_0}{c}\left[\frac{\hat{x}}{2k^2}\frac{\partial^2}{\partial x \partial y} + \hat{y} + \frac{i\hat{z}}{k}\frac{\partial}{\partial y}\right]\psi(x,y,z)e^{i(kz-\omega t)}$$

- We can utilize the elegant form of the LG modes given by,

$$\psi_{\ell,p}(r,\phi) = \sqrt{\frac{\eta p!\,\gamma^2}{(p+|l|)!}}\, e^{il\phi}\left(\frac{rkw_0}{\gamma\sqrt{2}Z}\right)^{|l|}\frac{z_0}{Z}\exp\left(-\frac{kr^2}{2Z}\right)L_p^{|\ell|}\left(\frac{kr^2}{Z}\right), \qquad Z = z_0 + iz$$

[1]. W. L. Erikson, and S. Singh, Phys. Rev. E. **49,** 5778-5786 (1994)

[2]. J. Peatross et al. Opt. Express **25**(13), 13990-14007, (2017)

Laguerre-Gaussian Modes – Analytic Forms Can Be Used For Calculations

- Deriving the Laguerre-Gaussian modes to second order paraxial has allowed the study of single electron dynamics in OAM beams to high accuracy

$$E = E_0 \begin{bmatrix} \hat{x} \\ \hat{y}\left[\frac{|\ell|\sin(2\theta)}{2} + \frac{i\ell\cos(2\theta)}{2}\right]\left[\frac{|\ell|-1}{k^2r^2} - \frac{(1+2L_1)}{kZ}\right] + \frac{xy[1+4(L_1+L_2)]}{2Z^2} \\ \hat{z}\left[\frac{\ell\sin(\theta)}{kr} + \frac{i|\ell|\cos(\theta)}{kr} - \frac{ix}{Z}(1+2L_1)\right] \end{bmatrix} \psi e^{i(kz-\omega t)}$$

$$L_1 = \frac{L_{p-1}^{|\ell|+1}\left(\frac{kr^2}{Z}\right)}{L_p^{|\ell|}\left(\frac{kr^2}{Z}\right)}$$

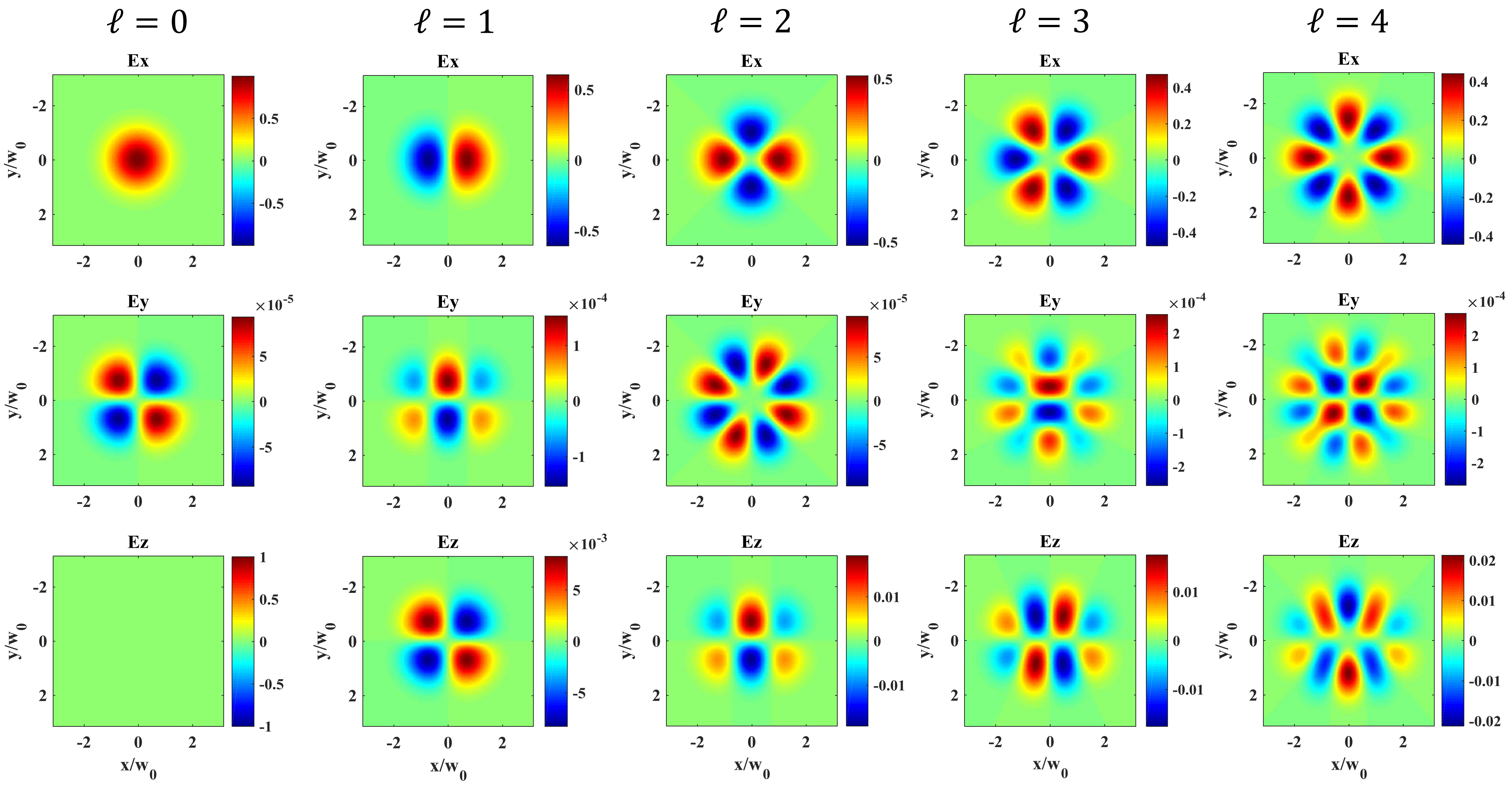
$$B = \frac{E_0}{c} \begin{bmatrix} \hat{x}\left[\frac{|\ell|\sin(2\theta)}{2} + \frac{i\ell\cos(2\theta)}{2}\right]\left[\frac{|\ell|-1}{k^2r^2} - \frac{(1+2L_1)}{kZ}\right] + \frac{xy[1+4(L_1+L_2)]}{2Z^2} \\ \hat{y} \\ \hat{z}\left[-\frac{\ell\cos(\theta)}{kr} + \frac{i|\ell|\sin(\theta)}{kr} - \frac{iy}{Z}(1+2L_1)\right] \end{bmatrix} \psi e^{i(kz-\omega t)}$$

$$L_2 = \frac{L_{p-2}^{|\ell|+2}\left(\frac{kr^2}{Z}\right)}{L_p^{|\ell|}\left(\frac{kr^2}{Z}\right)}$$

To be published – upcoming paper on nonlinear Thomson scattering in Laguerre-Gaussian beams

Laguerre-Gaussian Mode Field Distributions

For a beam linearly polarized in the x-direction @ z = 0:



Ponderomotive potential of OAM beam can trap and accelerate particles

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- Modified ponderomotive force due to donut mode

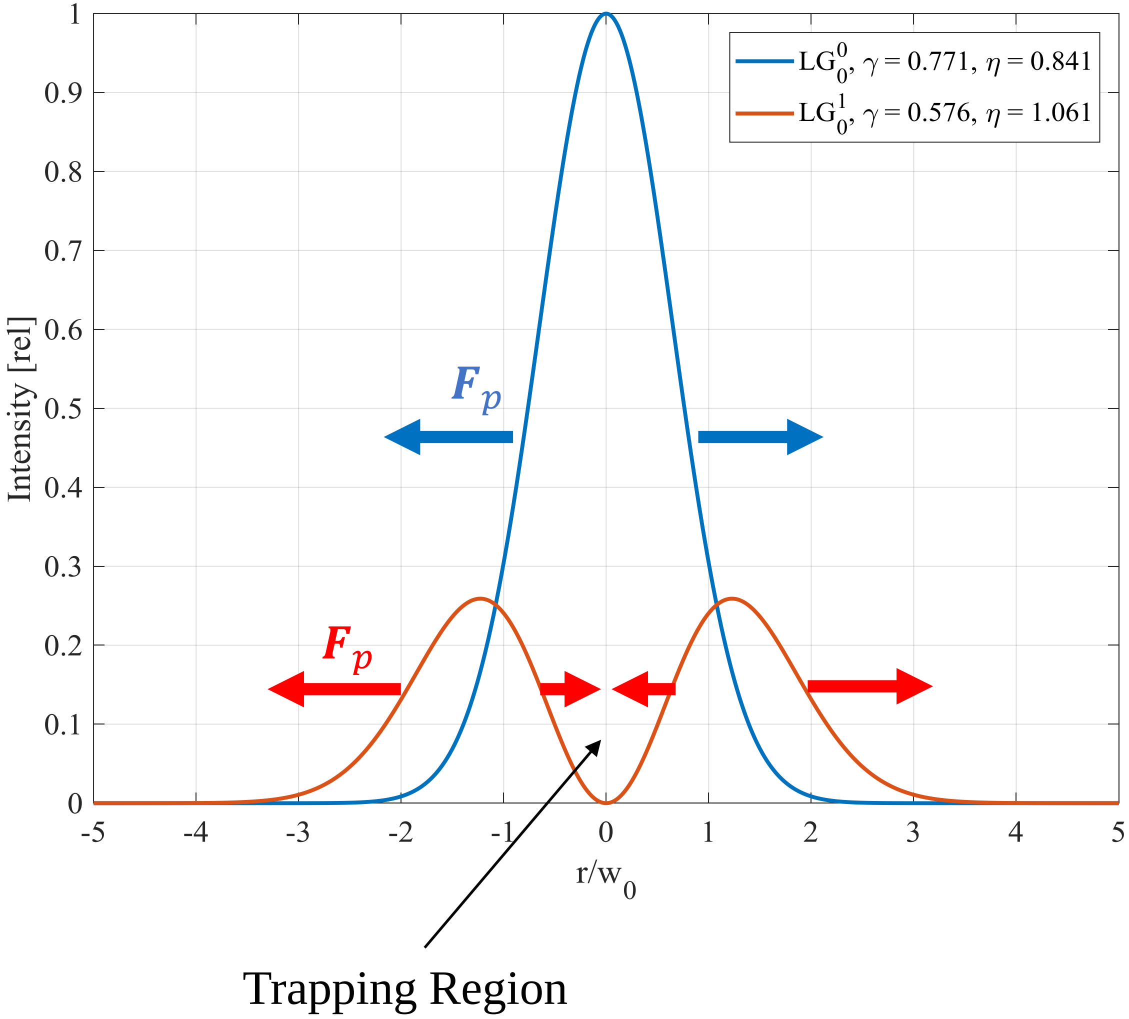
- Particle trapping/guiding due to ponderomotive well and wakefield focussing forces

$$\boldsymbol{F}_p(r,\ell) = -\frac{e^2}{4m_e\omega^2}|E(r)|^2\left(\frac{2|\ell|}{r} - \frac{4r}{w_{LG}^2}\right)$$

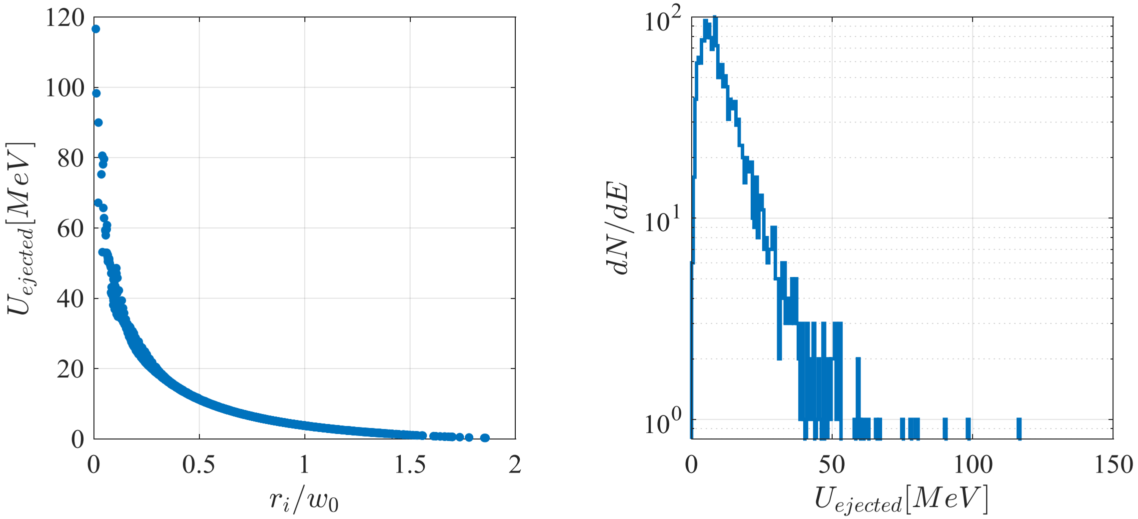
- Particles caught within the ponderomotive potential can be accelerated forward with a peak velocity as high as

$$\beta_z = \frac{a_0^2}{\sqrt{a_0^4 + 16}}$$

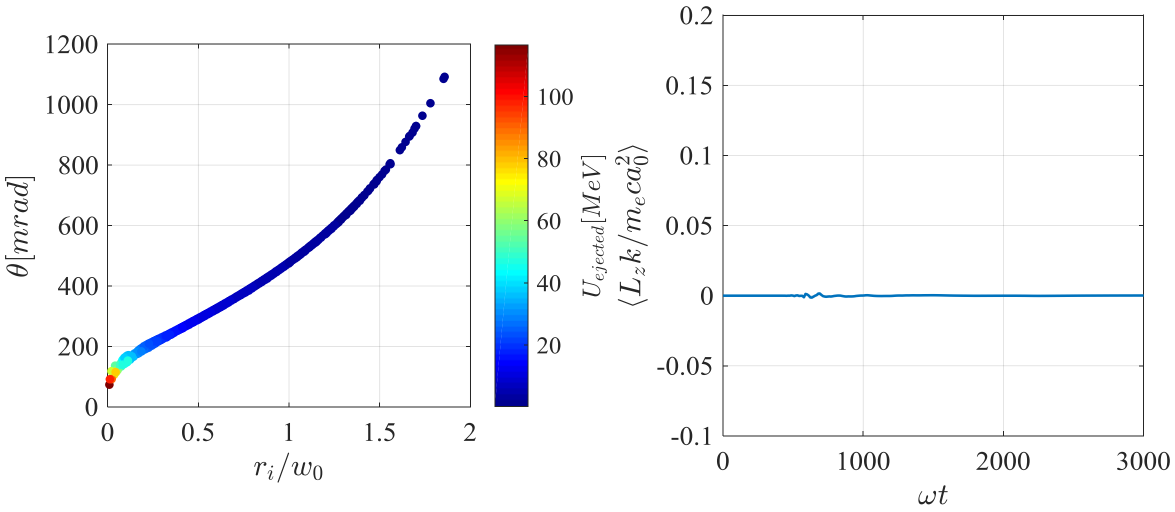
- No apparent AM transfer from ponderomotive force – no $\boldsymbol{F}_\theta$ component!



2000 electrons scattering from LP Gaussian beam

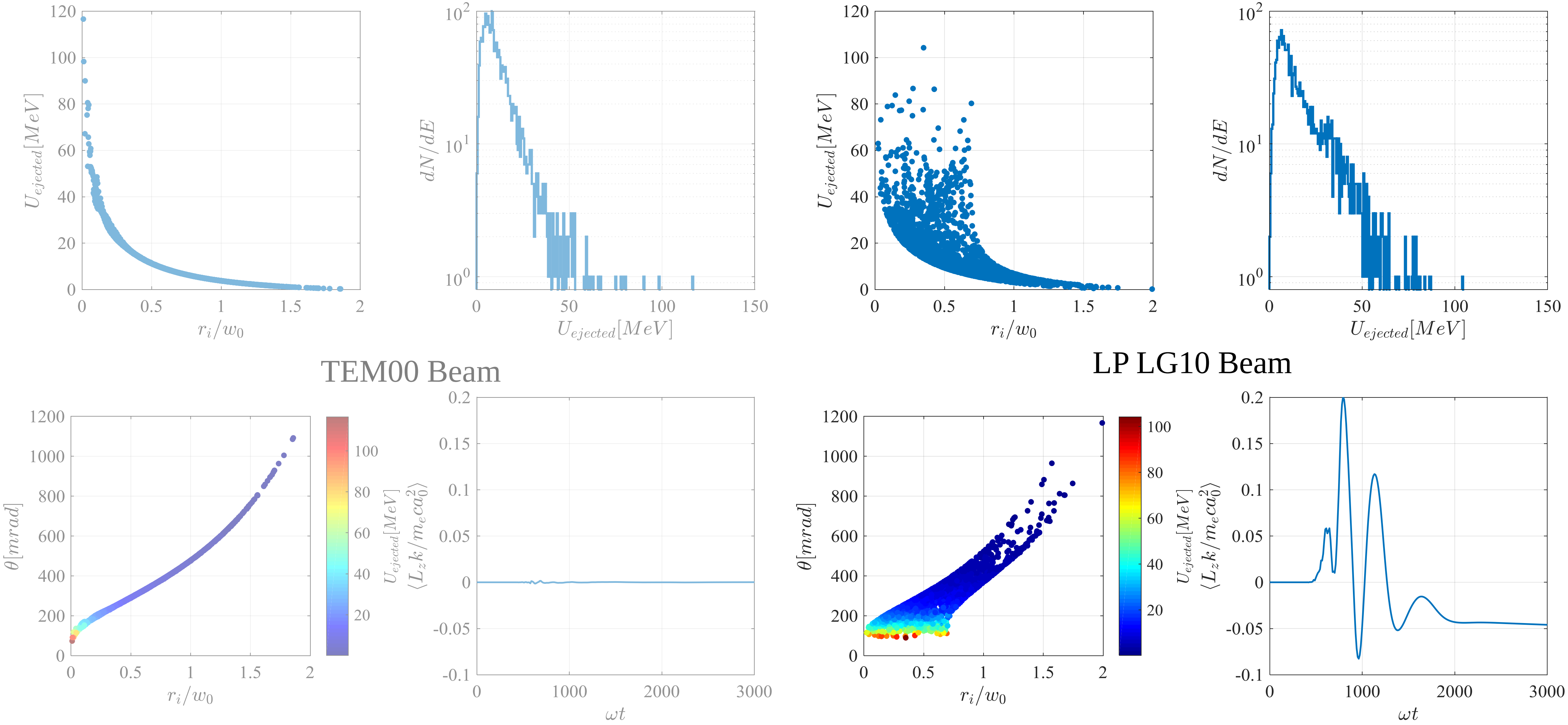


LP TEM00 Beam



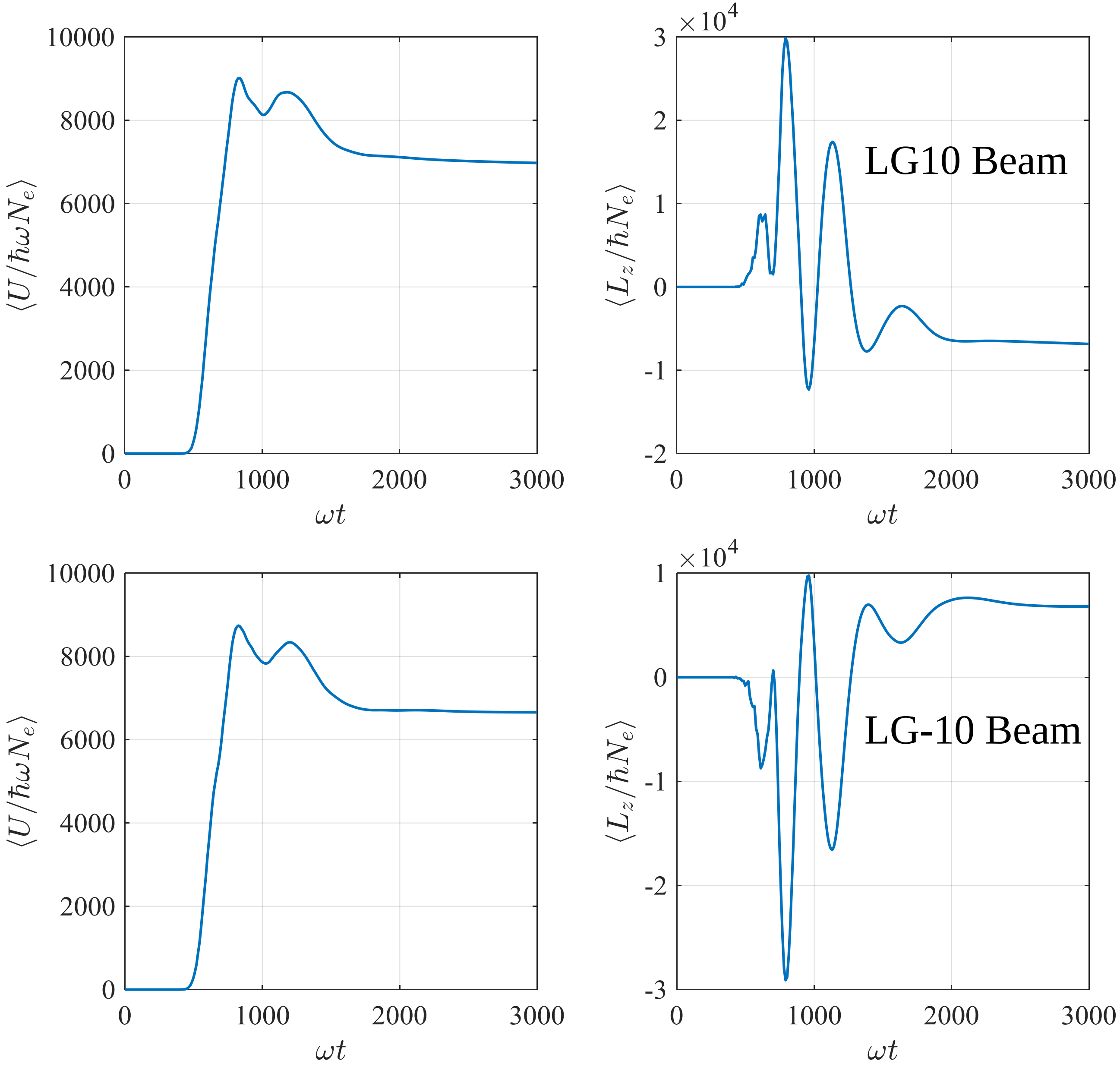
Parameter	Value
Intensity	$5 \times 10^{21} W cm^{-2}$
Beam waist	$10 \mu m$
Pulse duration	100fs

2000 electrons scattering from LP Laguerre-Gaussian beam



Beams have been normalized to contain same energy and focussed from same $f/\#$

Ponderomotive Scattering of Free Electrons can Transfer OAM



- Average number of photons absorbed per electron is ~7000 according to scattered energy
- Scattered electrons absorb ~7000$\hbar$ angular momentum from the photons
- Simple to understand using conservation of energy and angular momentum
- Direction of angular momentum absorbed changes with handedness of LG beam

OAM Coupling to single electrons scales with ponderomotive coupling:

$$L_z \propto \frac{a_0^2}{4}$$

Ponderomotive Scattering of Free Electrons can Transfer OAM

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- Average number of photons absorbed per electron is ~7000 according to scattered energy
- Scattered electrons absorb ~7000$\hbar$ angular momentum from the photons

OAM can be transferred to free electrons by ponderomotive-like mechanisms

Need high-intensity beams

OAM Coupling to single electrons scales with ponderomotive coupling:

$$L_z \propto \frac{a_0^2}{4}$$

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Self-focussing of LG modes in plasma is very different to Gaussian beams!

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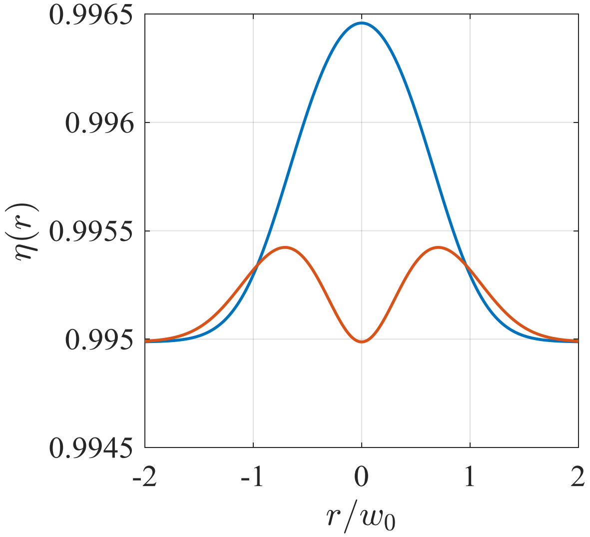
- To understand how a laser self focusses, we need to understand the refractive index of the plasma

$$\eta(r) \approx 1 - \frac{\omega_p^2}{\omega^2}\frac{n_e(r)}{n_0\gamma(r)}$$

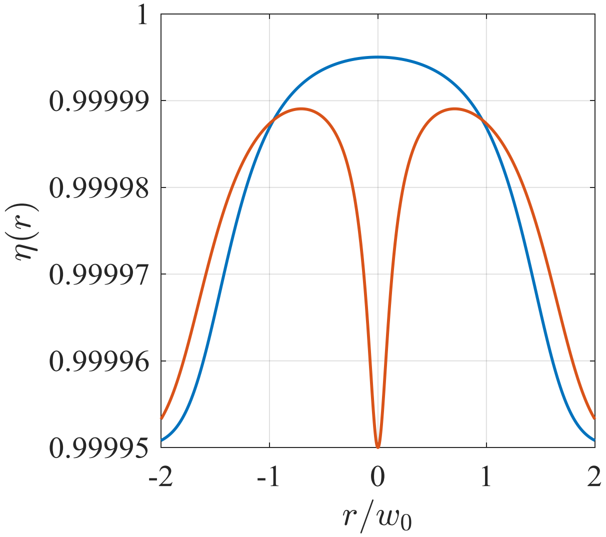
- Critical power for self focussing is modified for LG (p=0) beams to:

$$P_{c\ell}[GW] = 17.4\frac{n_c}{n_e}4^{|\ell|}\frac{|\ell|!\,(|\ell|+1)!}{(2|\ell|)!}$$

$$\frac{\omega_p}{\omega} = 0.1, a_0 = 1$$



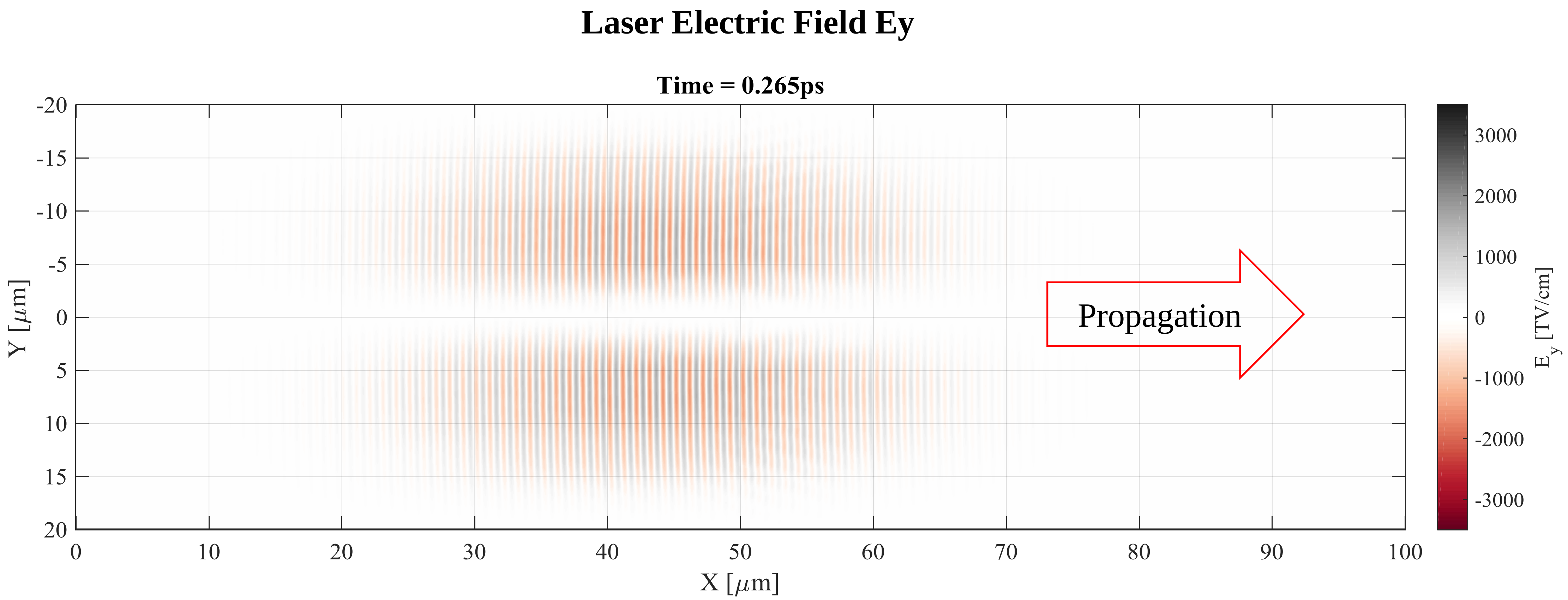
$$\frac{\omega_p}{\omega} = 0.1, a_0 = 10$$



Blue : TEM00 Beam

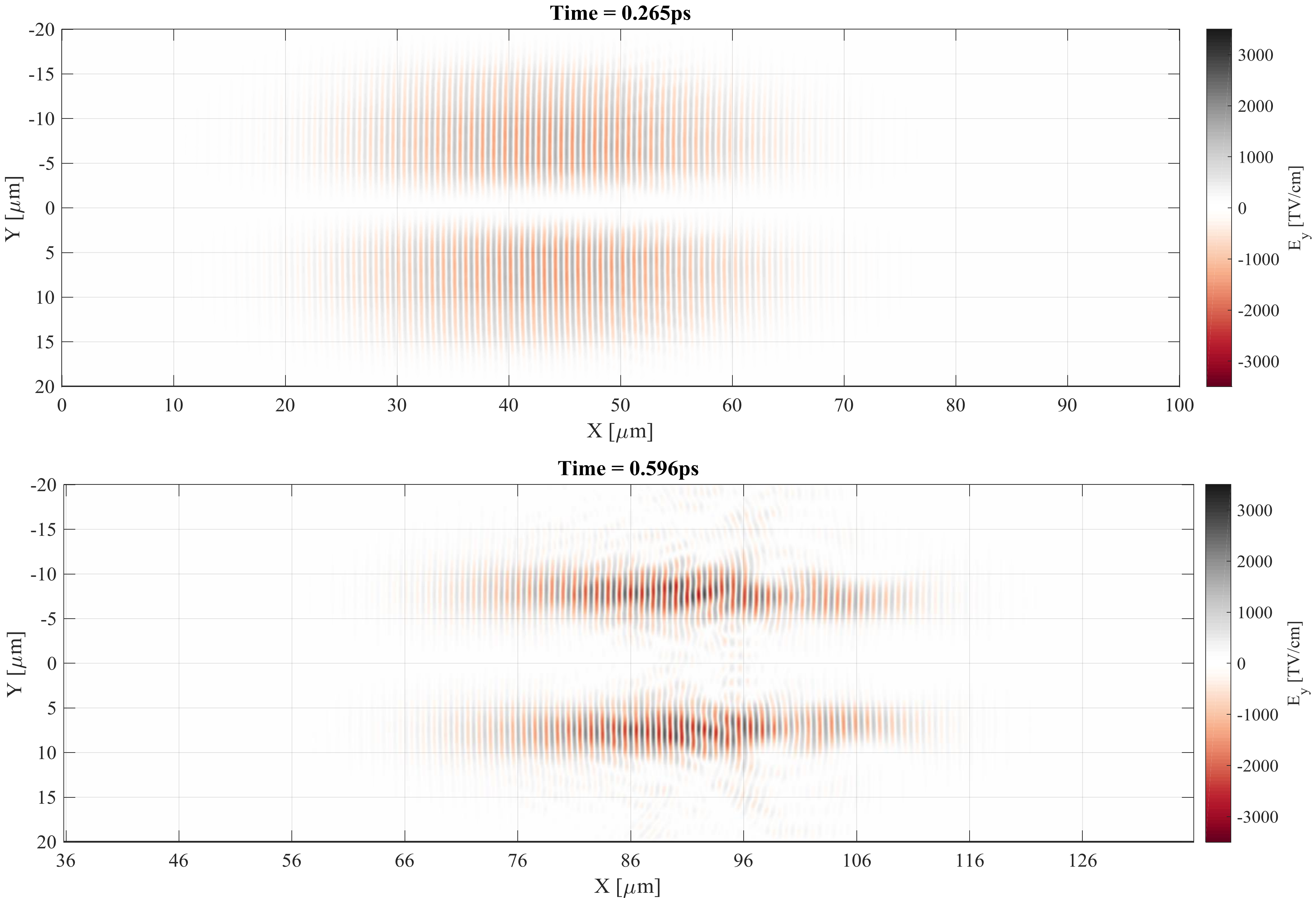
Red: LG10 Beam

OAM Modes Self Focus Differently To Gaussian Beams



$$n_e = 3 \times 10^{19} cm^{-3}, I = 2.5 \times 10^{19} W cm^{-2}, 100 fs, \ell = 1$$
$$P_{laser} > P_{sf}$$

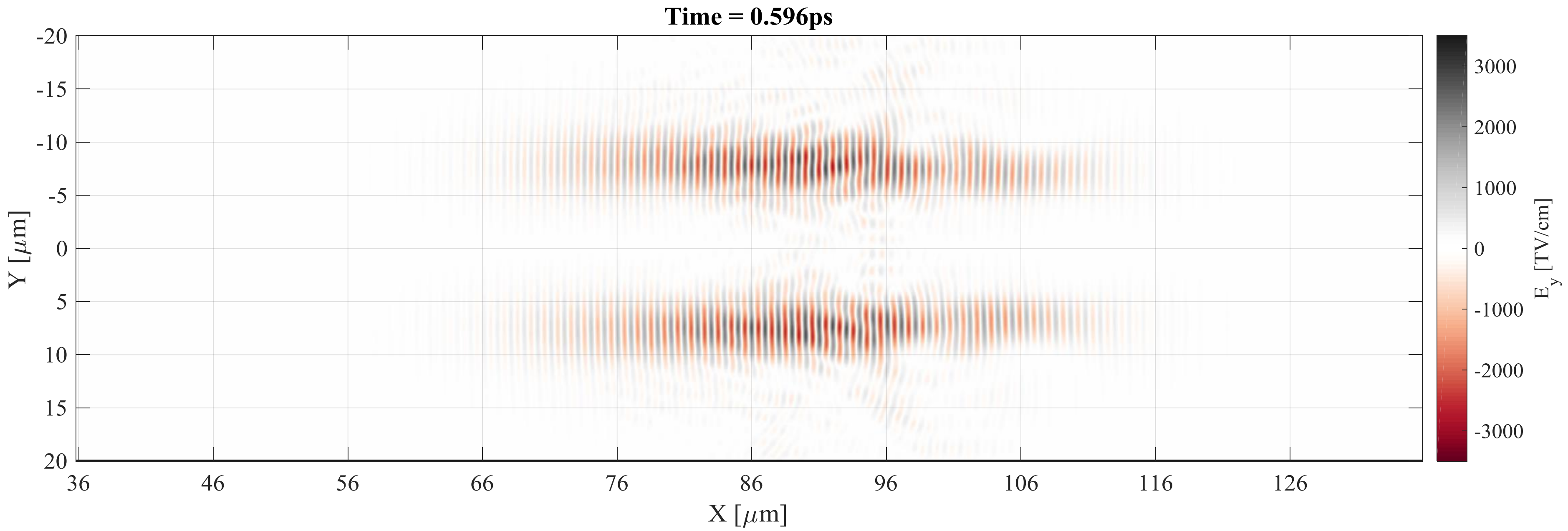
OAM Ring Initially Pinches

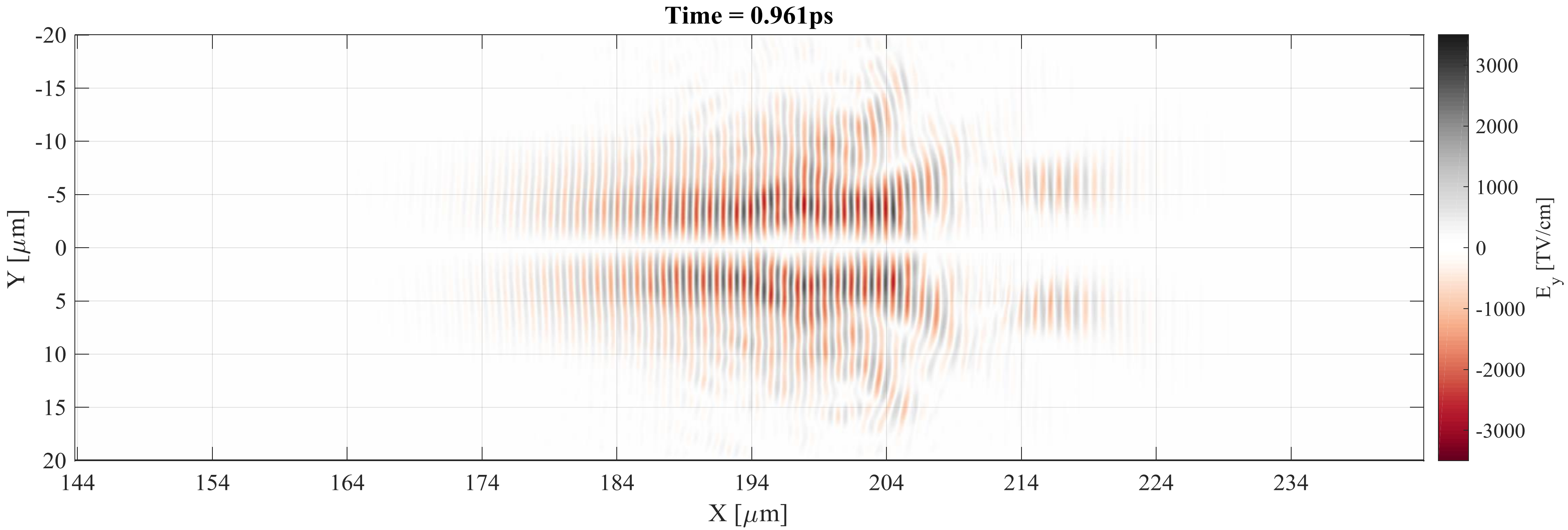


Self-focussing step 1

Ring Pinch

OAM Ring Then Collapses



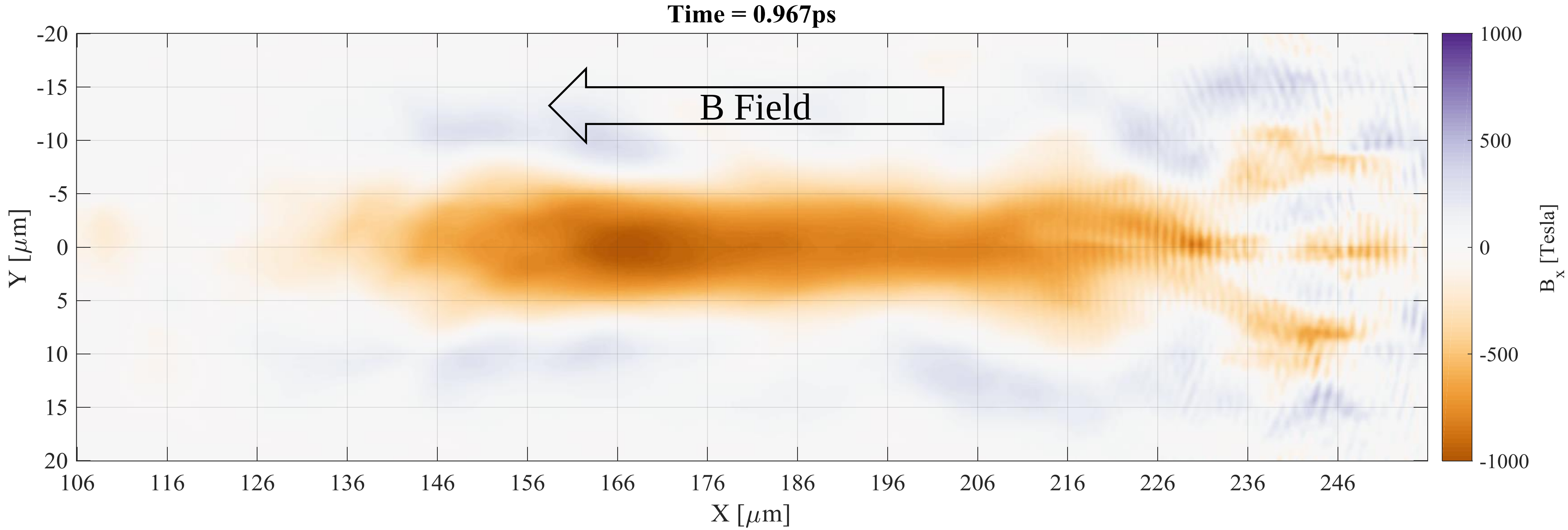


Self-focussing step 2

Ring Collapse

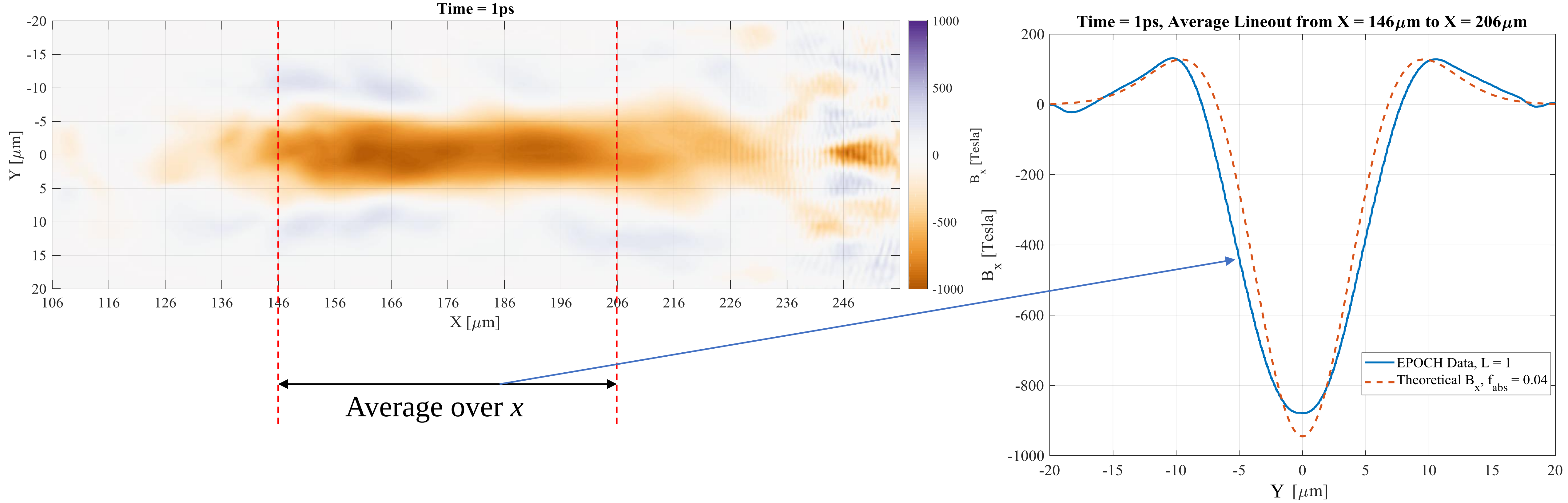
1000T B Fields are Created From 100fs, $2.5 \times 10^{19} Wcm^{-2}$ OAM Mode

- Axial Magnetic Field is averaged over 33fs output steps



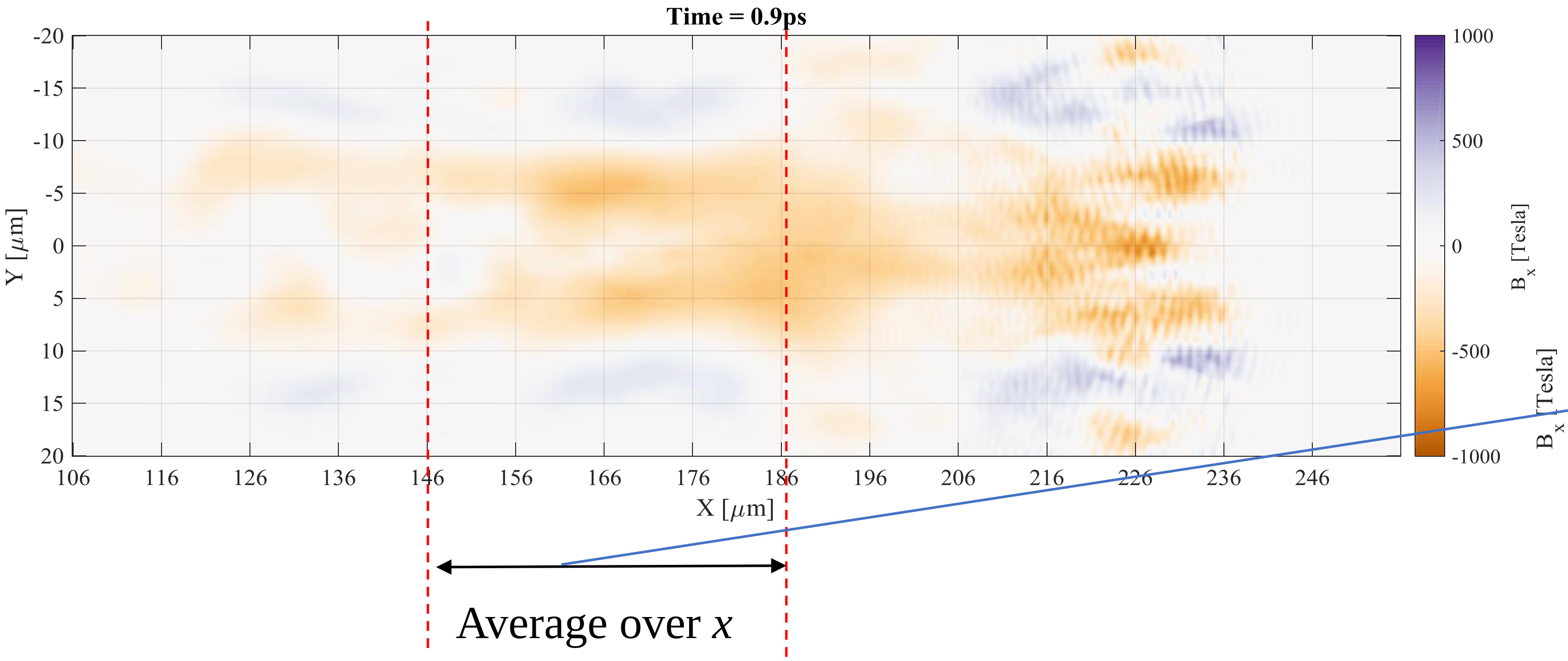
- About $100\mu m$ long from a 100fs laser pulse – magnetic field length may scale with pulse duration
- 10x **longer** than shown in previous publications
- B Field direction can be flipped by changing OAM mode: $\ell = 1 \rightarrow \ell = -1$

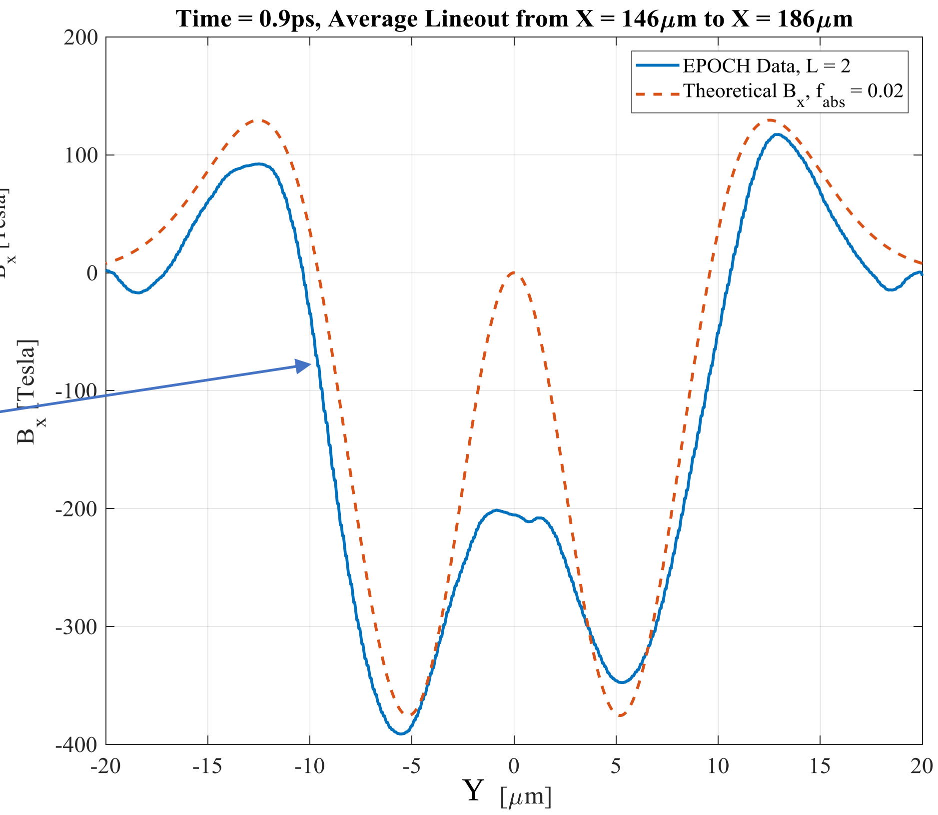
PIC Verifies Inverse Faraday Model For Linearly Polarized LG10 mode



- From the simulation we find the model parameters:
  - $f_{abs} \sim 4\% \quad @ \quad 1ps$
  - Peak intensity after ring pinch self focussing: $\sim 1.2 \times 10^{20} W cm^{-2}$
  - Electron density decreases by ~ 20%

Linearly Polarized LG_{20} Mode Agrees With Inverse Faraday Model

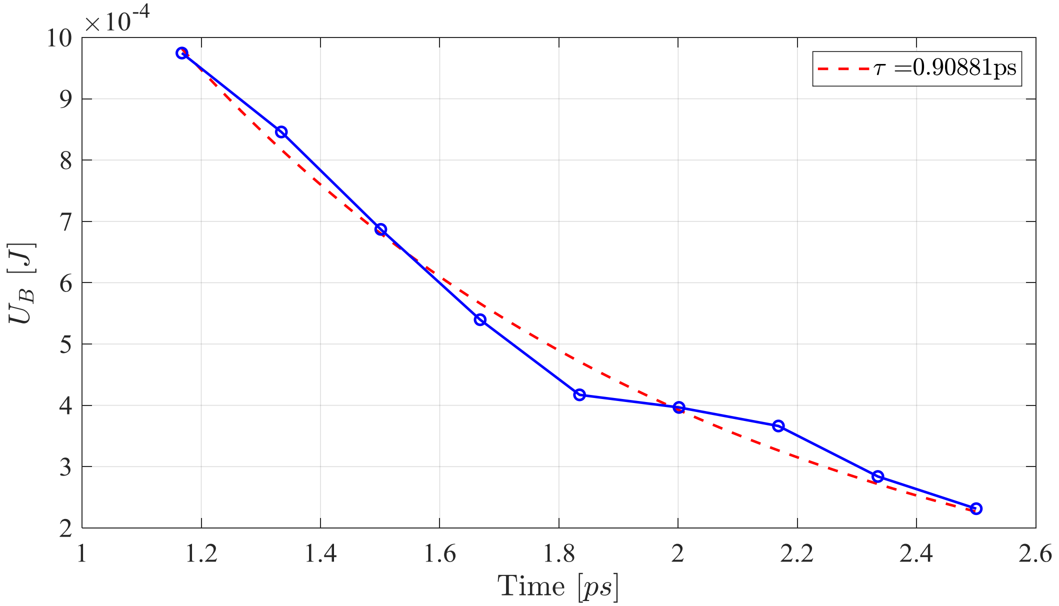




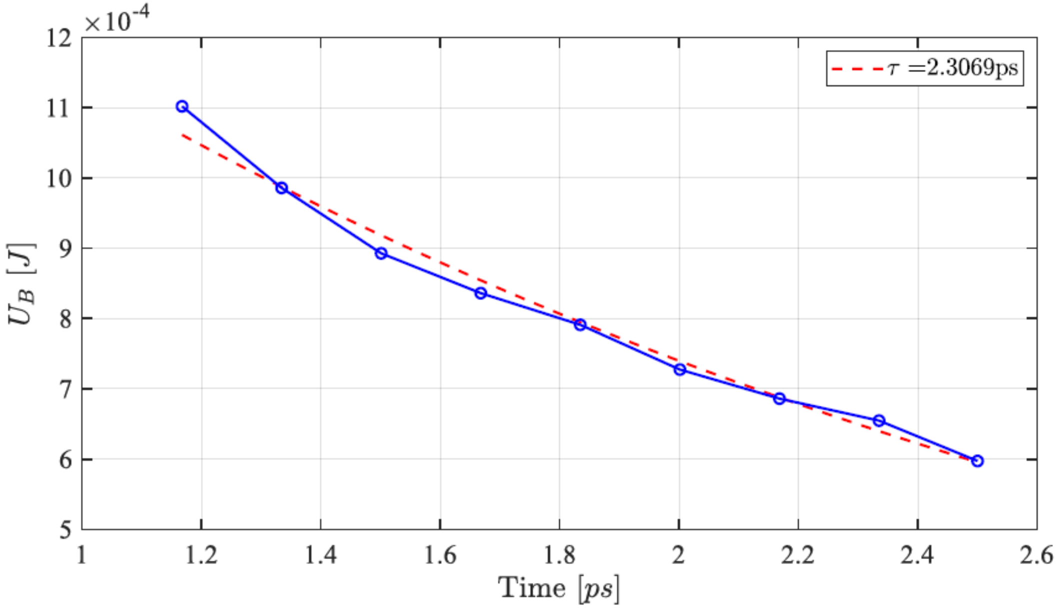
- B-field is weaker as expected
- The tube of magnetic field eventually collapses to a single solid rod of field.

Plotting of Magnetic Field Energy in Simulation Finds Decay Time

$$U_B = \sum_{i,j,k} \frac{B_{i,j,k}^2}{2\mu_0} \Delta x_i \Delta y_j \Delta z_k \qquad U_B \propto e^{-\frac{t}{\tau}}$$



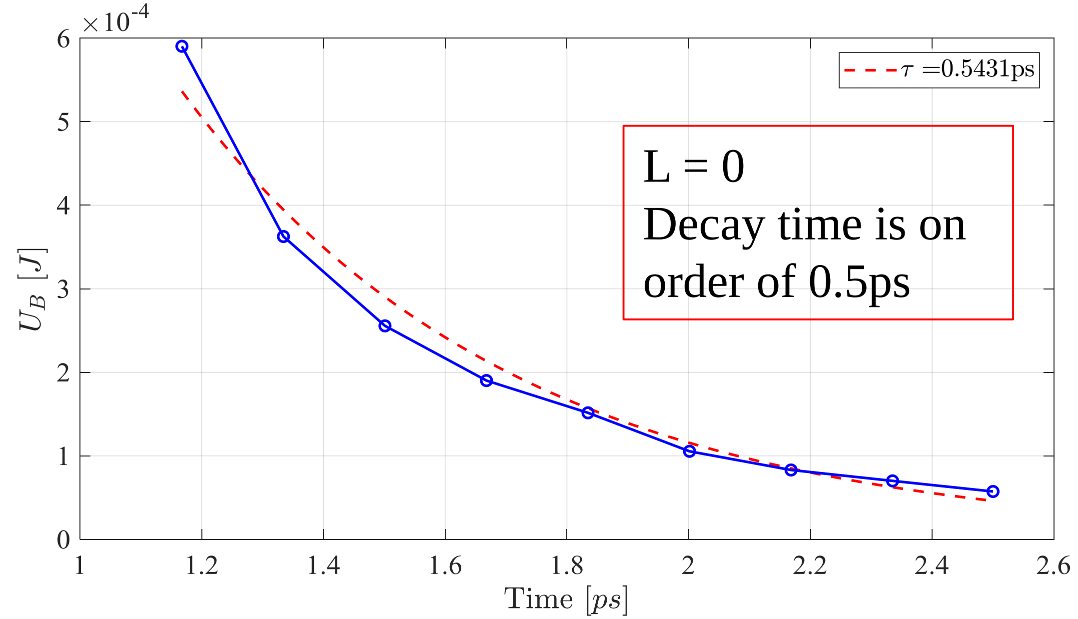
LG10 decay time ≈ $1ps$

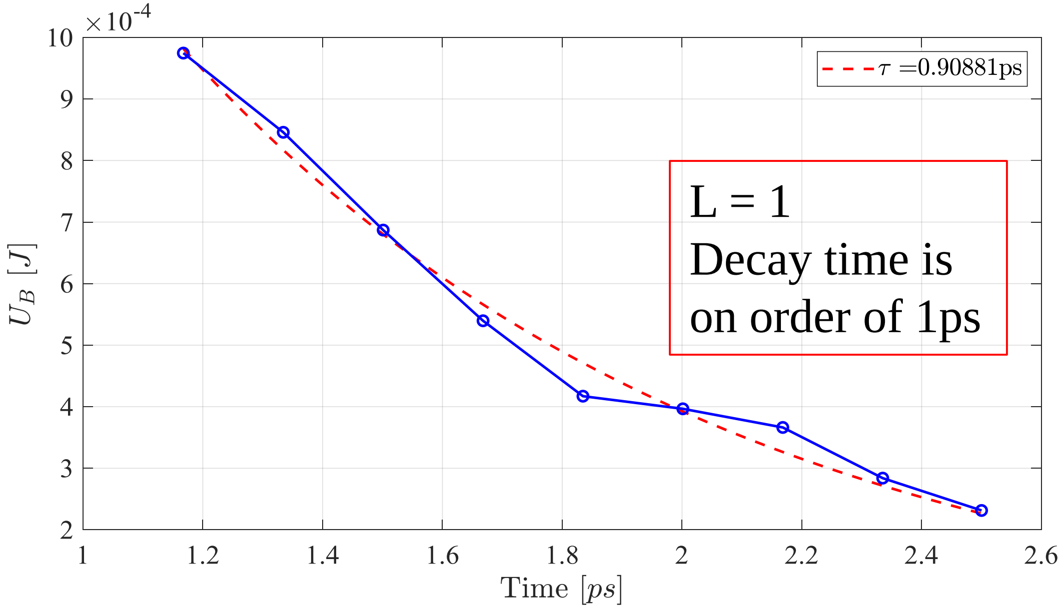


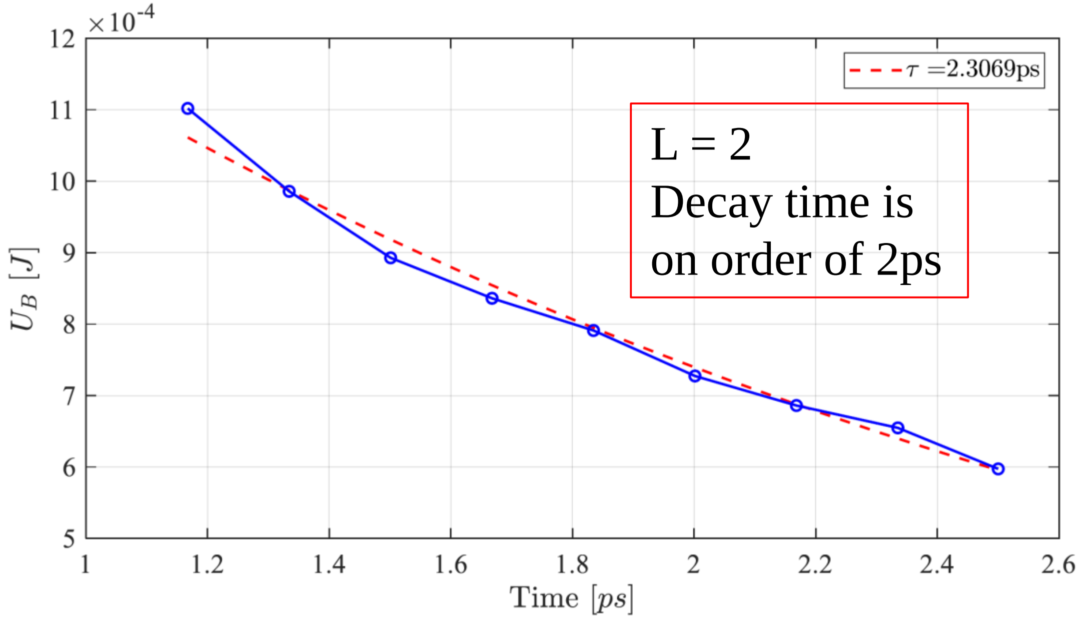
LG20 decay time ≈ $2ps$

- Increasing the laser OAM from $\ell = 1$ to $\ell = 2$ appears to double the decay time, at a cost of B field strength
- Decay time is much shorter than that assumed through magnetic diffusion in the plasma ~10ns assuming Spitzer resistivity

The B field Decay Time Seems To Be A Function of OAM Number





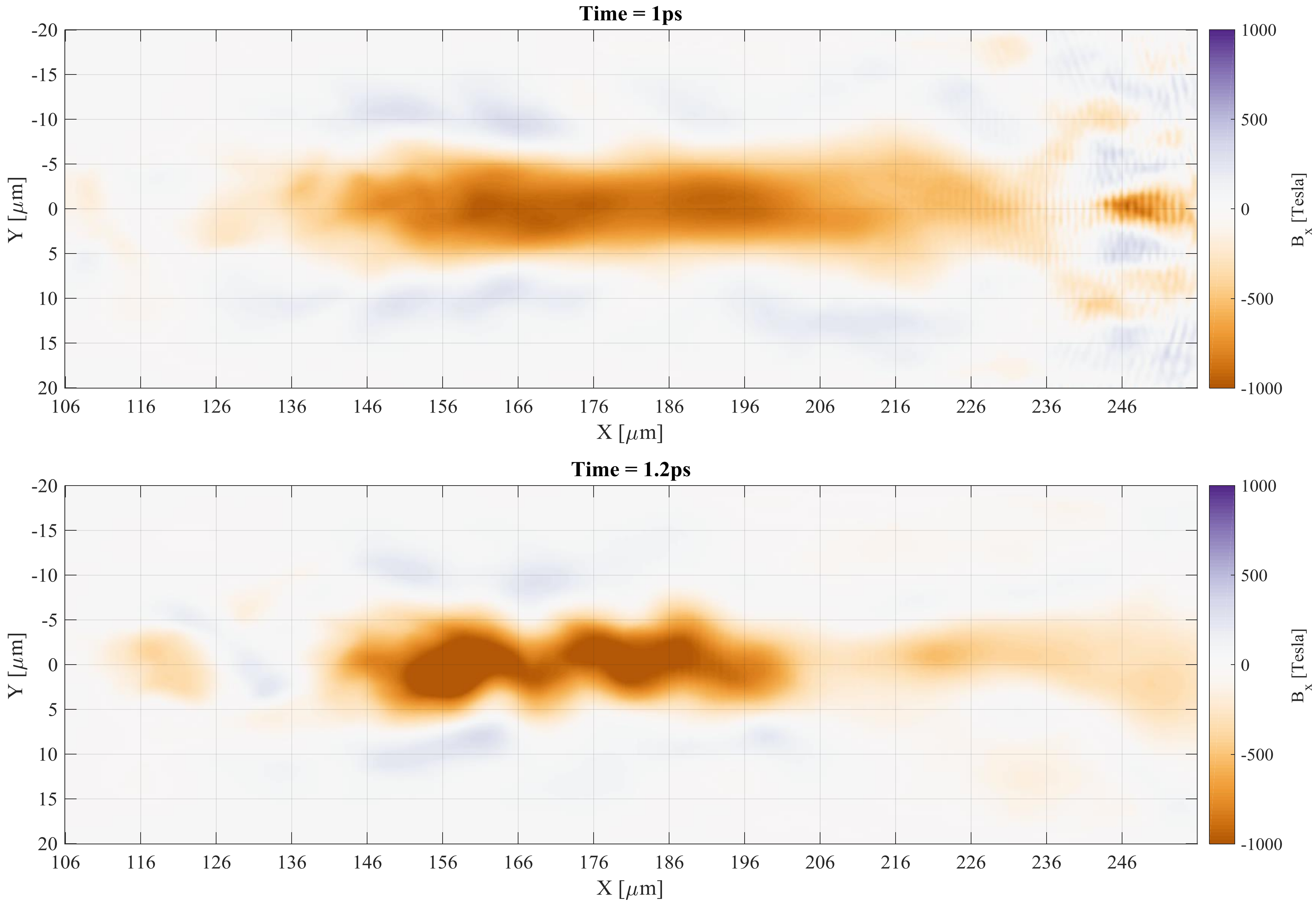


- Comparing the laser modes, we find an interesting result that increasing the OAM number in the beam looks to increase the B-field persistence

$$\tau \propto |\ell|$$

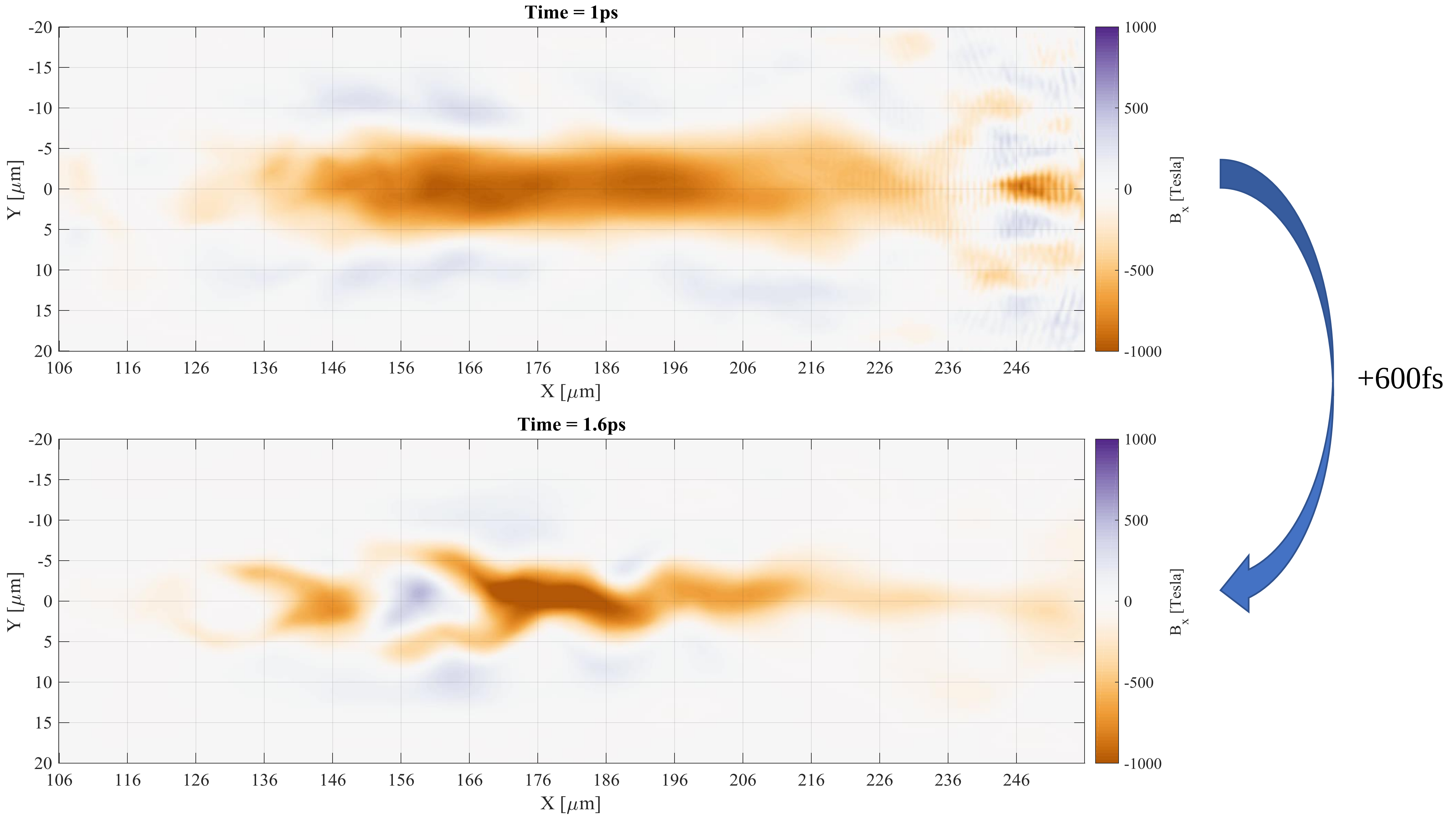
- Could be a result of radial electron energy and electrons leaving the grid

B Field Persists For ~1ps After Genesis

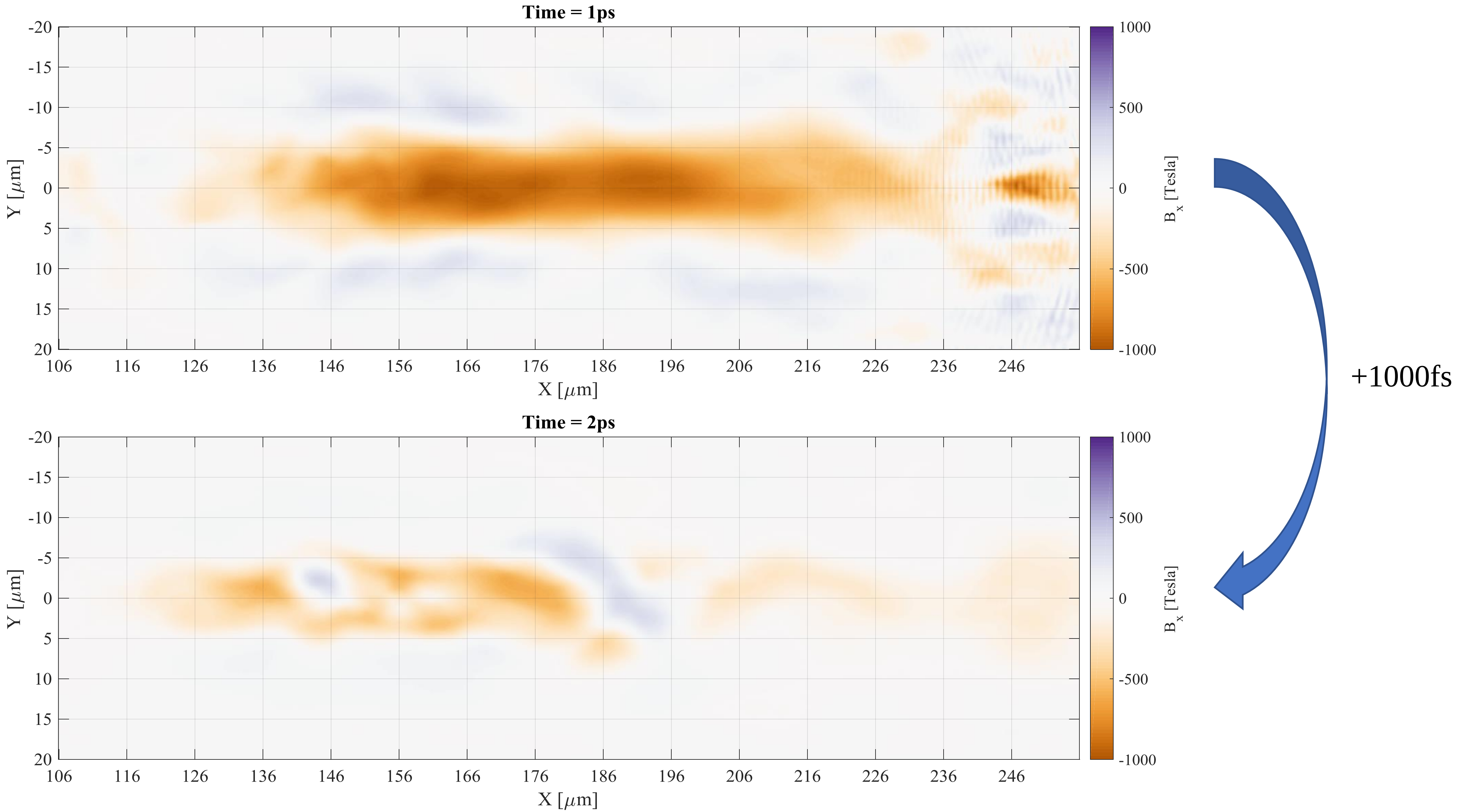


+200fs
B field starts to kink

B Field Persists For ~1ps After Genesis

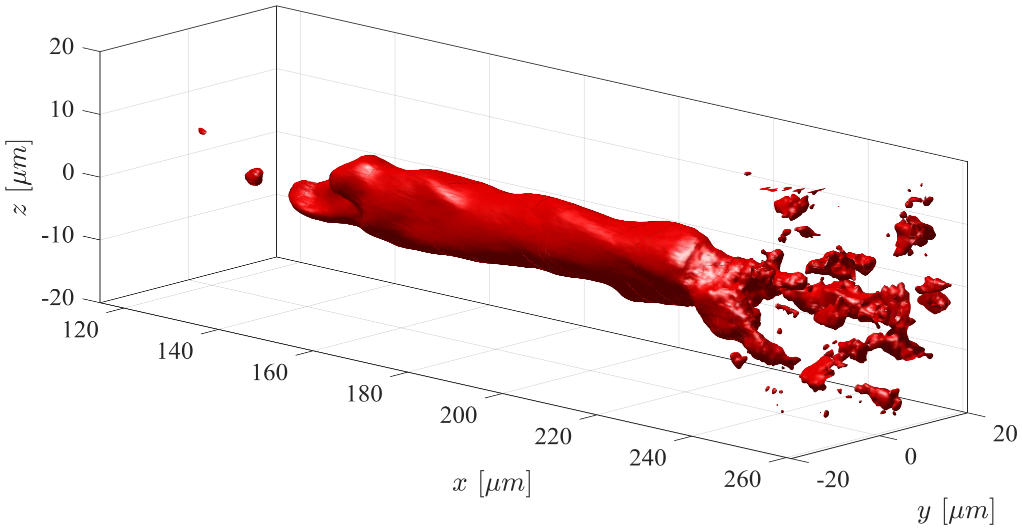


B Field Persists For ~1ps After Genesis

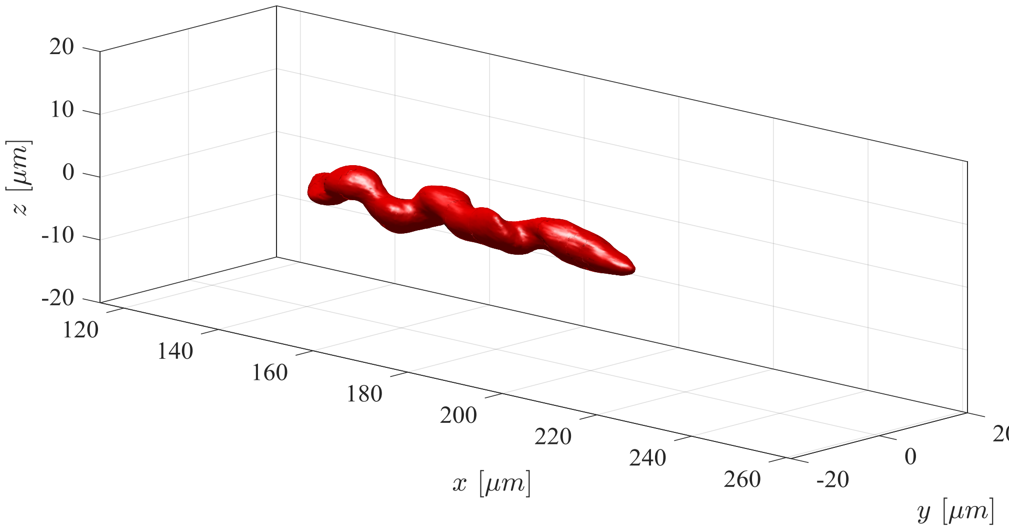


Change in decay time maybe related to the wobble corkscrew instability

-100T Magnetic Field Isosurface



LG10 Simulation time ≈ $1ps$



LG10 Simulation time ≈ $2.34ps$

- Through previous theta pinch instability work, it has been shown that the wobble instability can be suppressed by increasing azimuthal mode number [1].

[1] J. P. Friedberg, L. D. Pearlstein, “*Rotational Instabilities in a theta pinch*,” Phys. Fluids **21**(7) 1978

Using a Perturbative Approach – We Can Model Asymmetric Beams

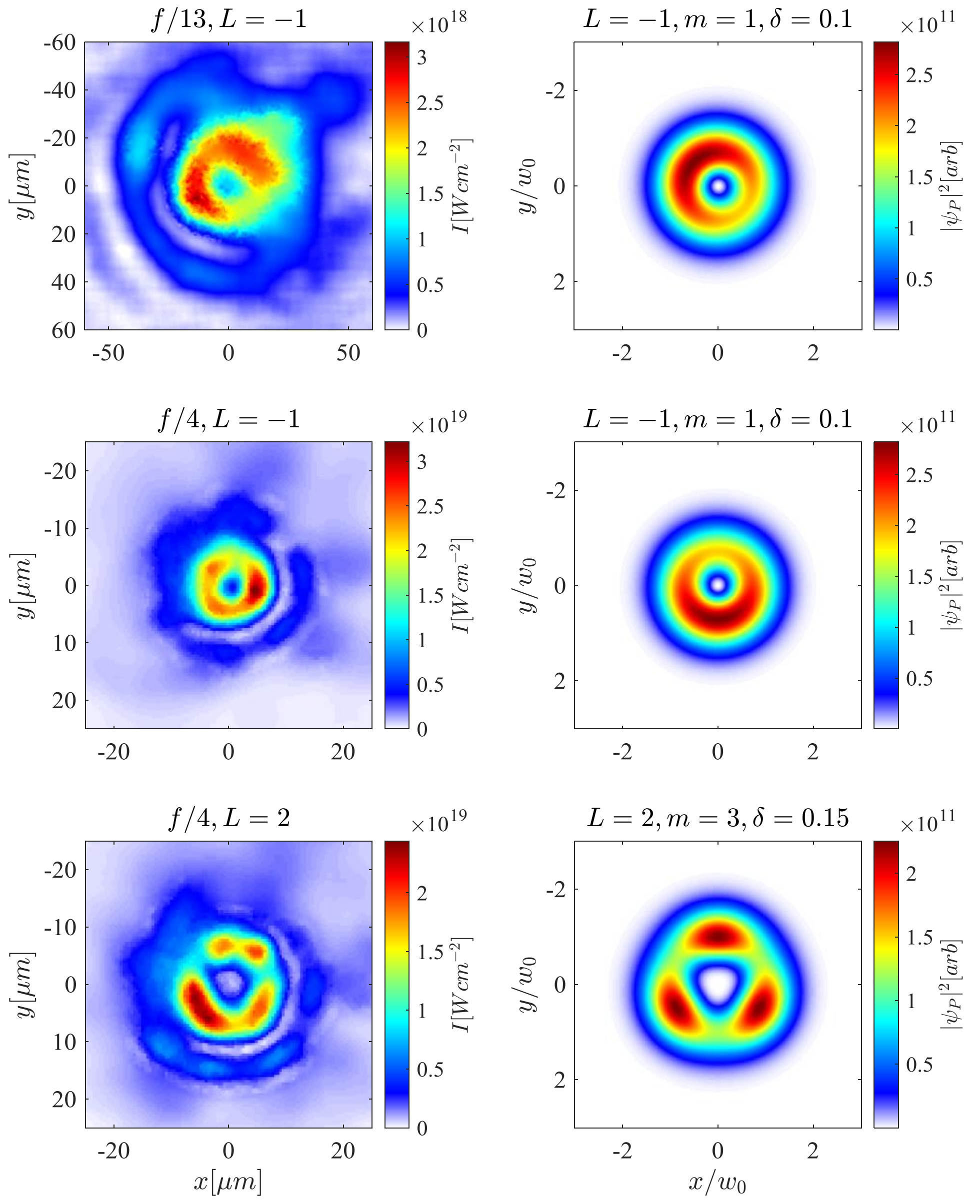
- Perturbing the LG (L) mode with the function allows us to model the beams more realistically

$$\boxed{\lambda = 1 + \delta \cos(m\theta)}$$

- Decomposing the perturbed wavefunction into 3 orthogonal LG (ℓ) modes:

$$\eta_{L-\ell=0} = \left(1 + \frac{\delta^2}{2}\right)^{-1}$$

$$\eta_{|L-\ell|=|m|} = \frac{\Gamma^2\left(\frac{|\ell|}{2} + \frac{|L|}{2} + 1\right)}{2|L|!\,|\ell|!}\left(1 + \frac{2}{\delta^2}\right)^{-1}$$



Experiment

Theory

An Asymmetric Beam has Little Effect On B Field Generation

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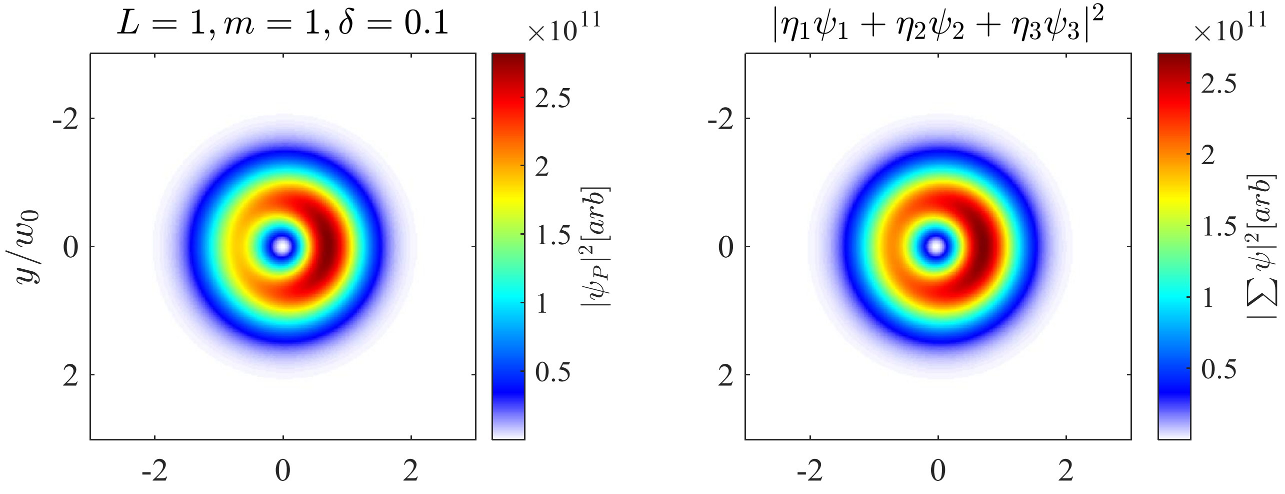
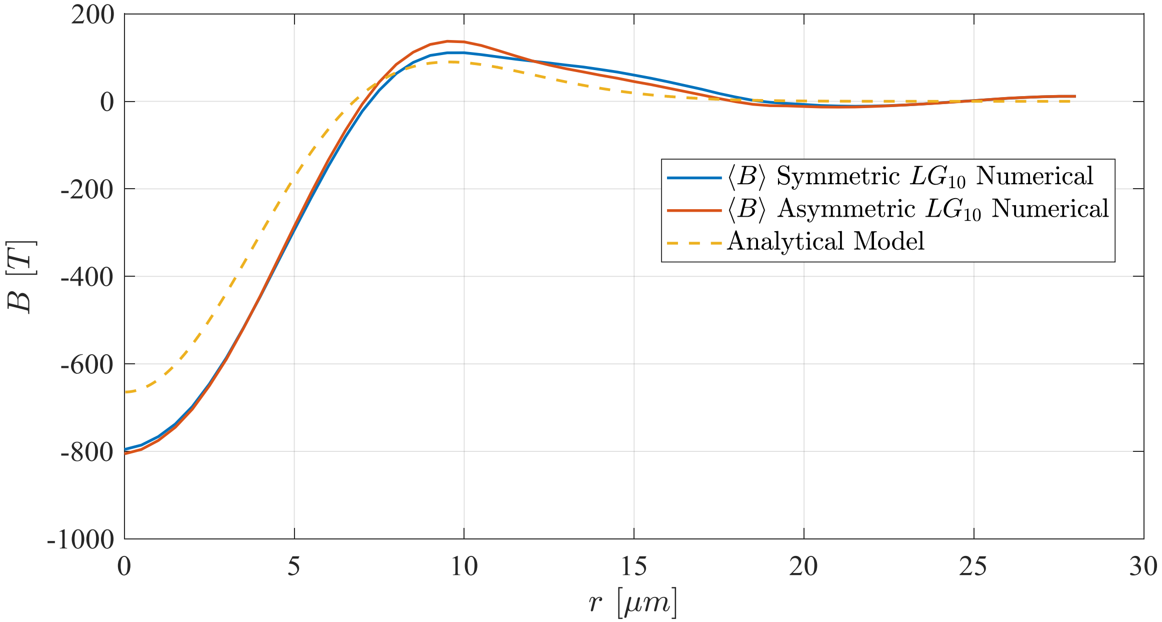
- Considering a 10% perturbation on the beam
- We can decompose the perturbed beam into 3 modes:

$$L = 1, m = 1, \delta = 0.1$$

Decomposes to:

$$99.5\%\ \ell = 1, \qquad 0.2\%\ \ell = 0, \qquad 0.2\%\ \ell = 2$$





Outline

- Motivation
  - The need for strong magnetic fields

- Spin and Orbital Angular Momentum Beams
  - Brief review of Orbital Angular Momentum (OAM)
  - Diffraction of OAM beams and Laguerre-Gaussian (LG) modes

- The Inverse Faraday Effect
  - Analytic Models
  - Coupling of angular momentum to plasma and free electrons

- Numerical Modelling of the IFE
  - Modelling of Titan-like laser parameters
  - Asymmetric and realistic OAM beams

- **Experimental Methods**
  - Generating OAM beams at high intensity
  - Measuring magnetic fields

The Need For New High Intensity OAM Optics

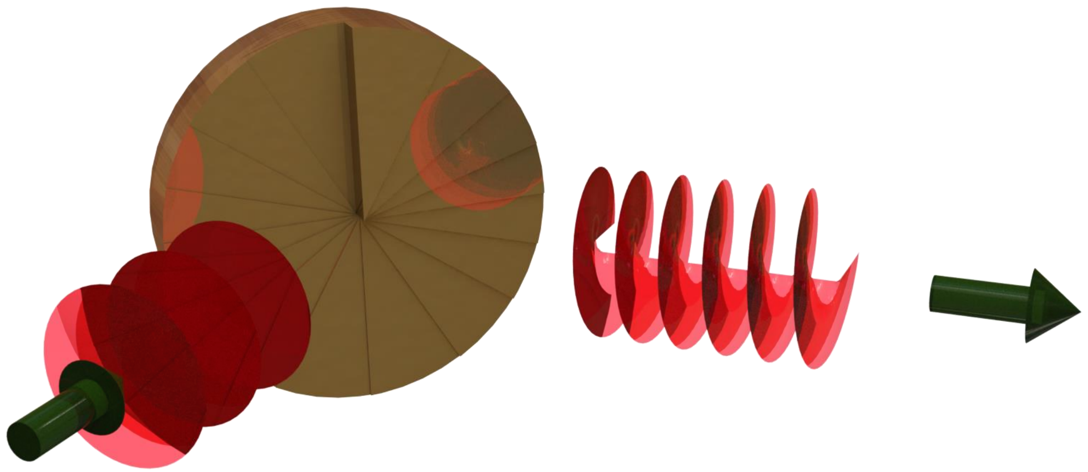
- Currently it is difficult to generate optical vortices at ultra high intensities:
  - Issues with nonlinear effects on beam temporal and spatial profiles if transmitted through glass
  - Issues with retro-reflections and mode separation with spiral phase mirrors
  - Expensive to etch a spiral into a large diameter (>100mm) glass substrate
  - Damage threshold of optics is typically too low for high-power laser facilities

We Have Analyzed Alternate Methods Of OAM Generation

Design Parameters

- Needed to be scalable to any size (diameter)
- Needed to be compatible with ultra-short pulses
- Cost effective – manufactured on campus
- Flexibility for use in any laser system (after amplifier)
- High damage threshold

Off-Axis Spiral Phase Mirror (OASPM)

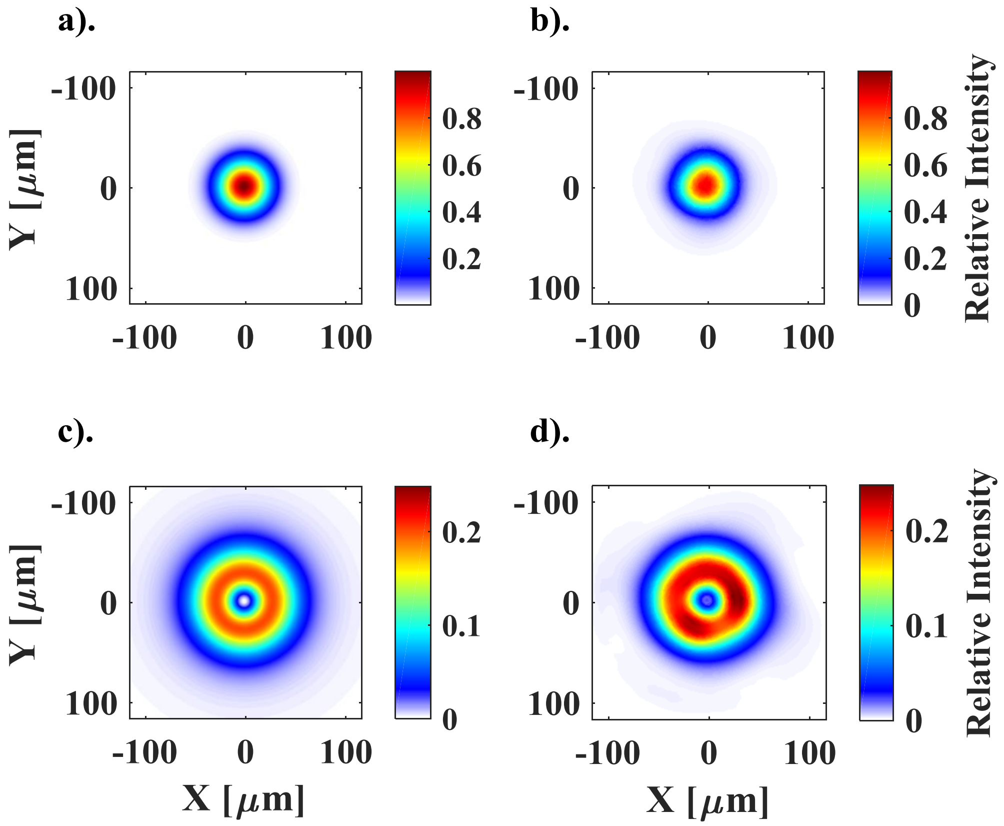


A. Longman, and R. Fedosejevs, "Off Axis Spiral Phase Mirror," U.S. Provisional Patent #62/508,222 (2017-2019)

A. Longman, C. Salgado, G. Zeraouli, J. I. Apinaniz, J. A. Perez-Hernandez, M. Khairy Eltahlawy, L. Volpe, and R. Fedosejevs, "*Off-axis spiral phase mirrors for generating high-intensity optical vortices*", Opt. Lett. **45**(8) (2020)

Performance Was Tested With A 2 inch Prototype

- Initial tests with a lab HeNe laser beam
- OASPM was used at a 45deg incidence angle and was manufactured to a 2inch diameter.
- High symmetry focal spots, almost perfect agreement with diffraction theory using an f/30 lens



Theory

Experiment

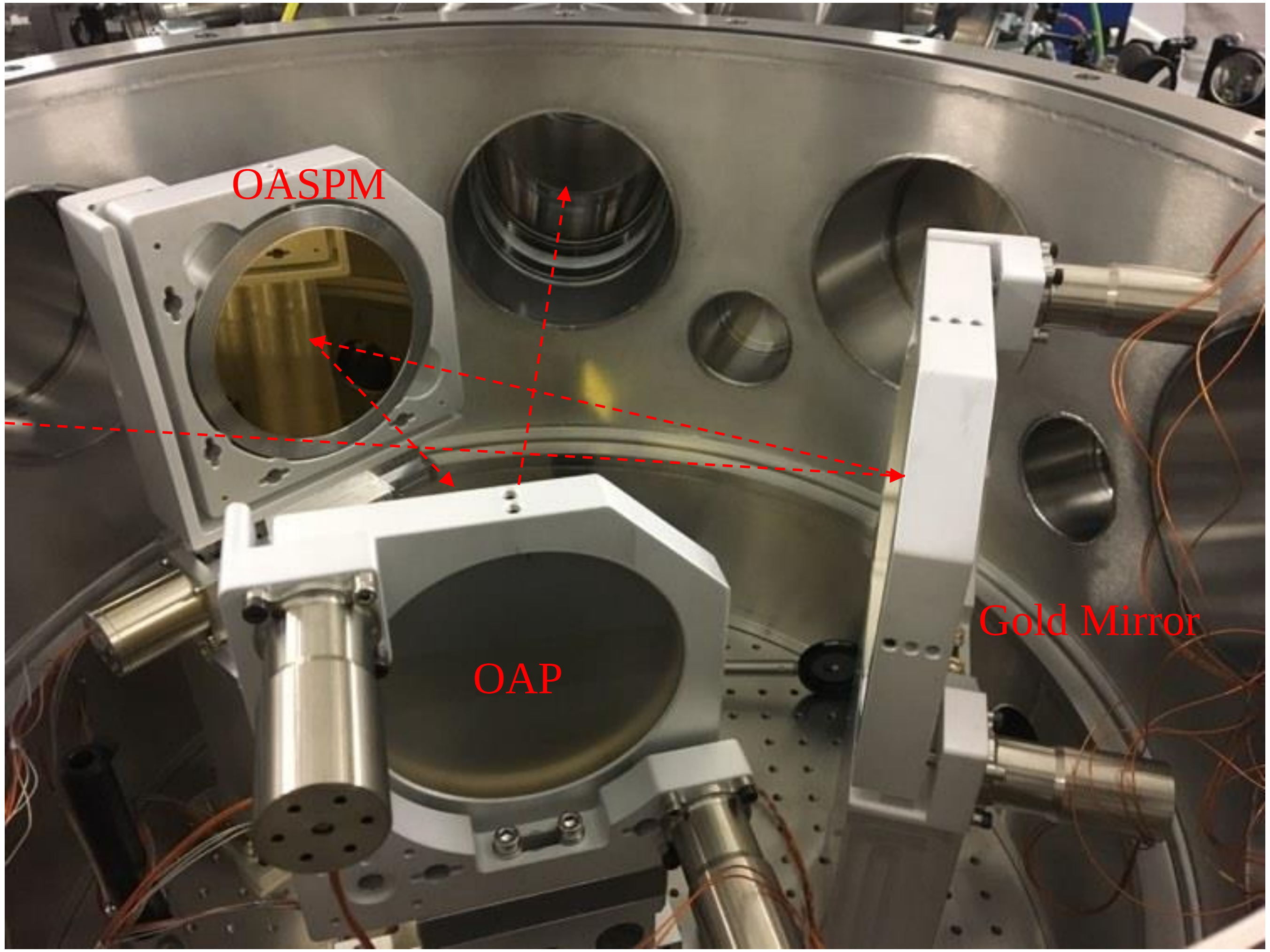
A. Longman, C. Salgado, G. Zeraouli, J. I. Apinaniz, J. A. Perez-Hernandez, M. Khairy Eltahlawy, L. Volpe, and R. Fedosejevs, Opt. Lett. **45**(8) (2020)

Tested At High Power Using CLPU 200TW VEGA Laser

- Testing with the Centros Laseres Pulsados Ultraintenses (CLPU) in Salamanca, Spain

<u>CLPU VEGA 2 Beam Characteristics</u>

- 3J, 30fs at focus using an f/4 or f/13 OAP
- 10Hz
- $\lambda = 800nm,\ \Delta\lambda = 80nm$
- 5” OASPM inserted at 17.8deg AOI

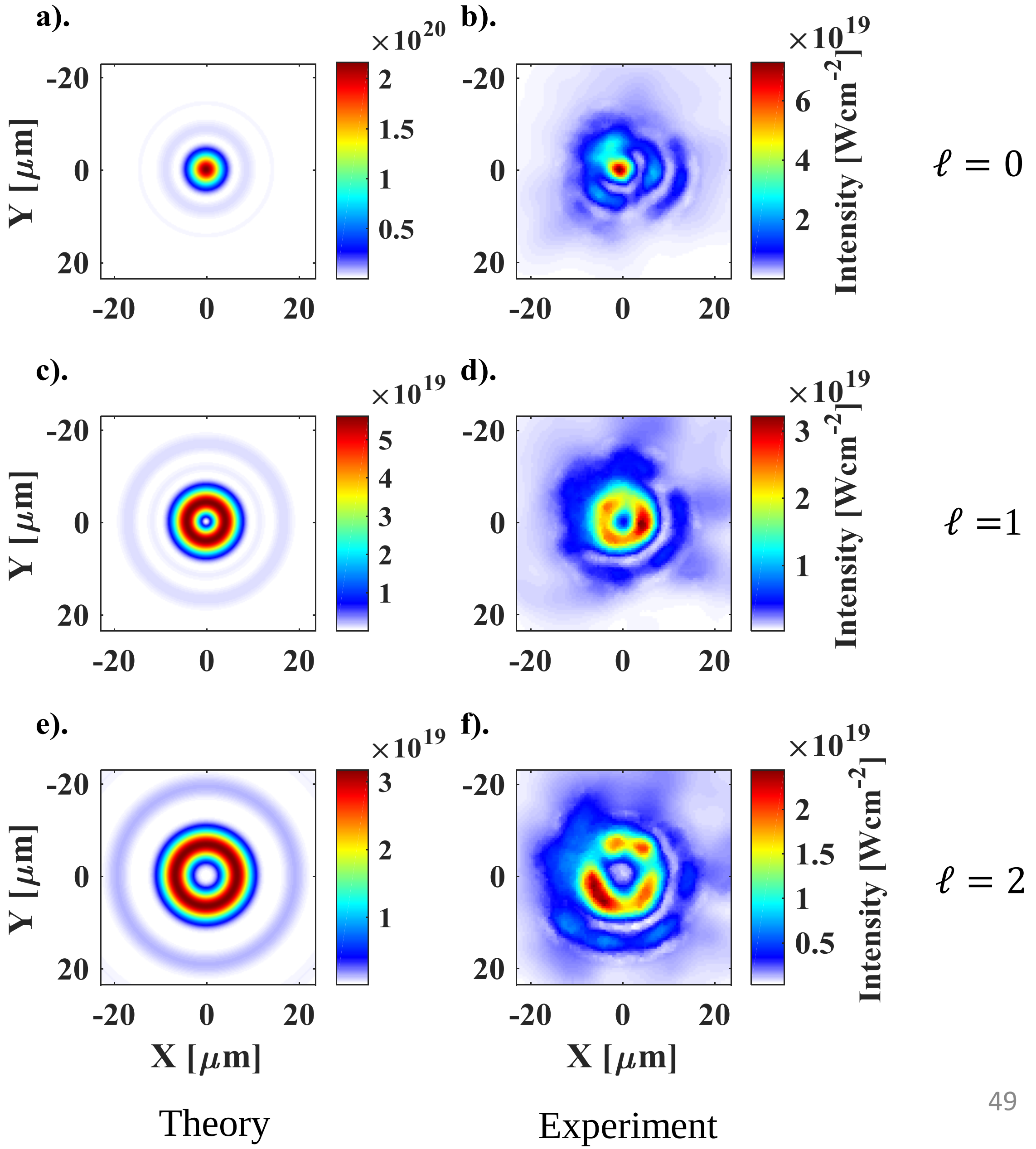


Our Experiments Yielded Highest OAM Intensity To Date

- Spatial inhomogeneities in the laser near-field seem to be the main limiting factor in the focal spot symmetry.
- Aberrations in the focus such as trefoil, astigmatism, and coma also reduced spot symmetry.

<u>OAM Beam Characteristics</u>

- $\ell = 0, 7 \times 10^{19} Wcm^{-2}$
- $\ell = 1\,, 3.2 \times 10^{19} Wcm^{-2}$
- $\ell = 2\,, 2.4 \times 10^{19} Wcm^{-2}$



A. Longman, C. Salgado, G. Zeraouli, J. I. Apinaniz, J. A. Perez-Hernandez, M. Khairy Eltahlawy, L. Volpe, and R. Fedosejevs, Opt. Lett. **45**(8) (2020)

Two Suitable Methods To Diagnose Strong Axial Magnetic Fields

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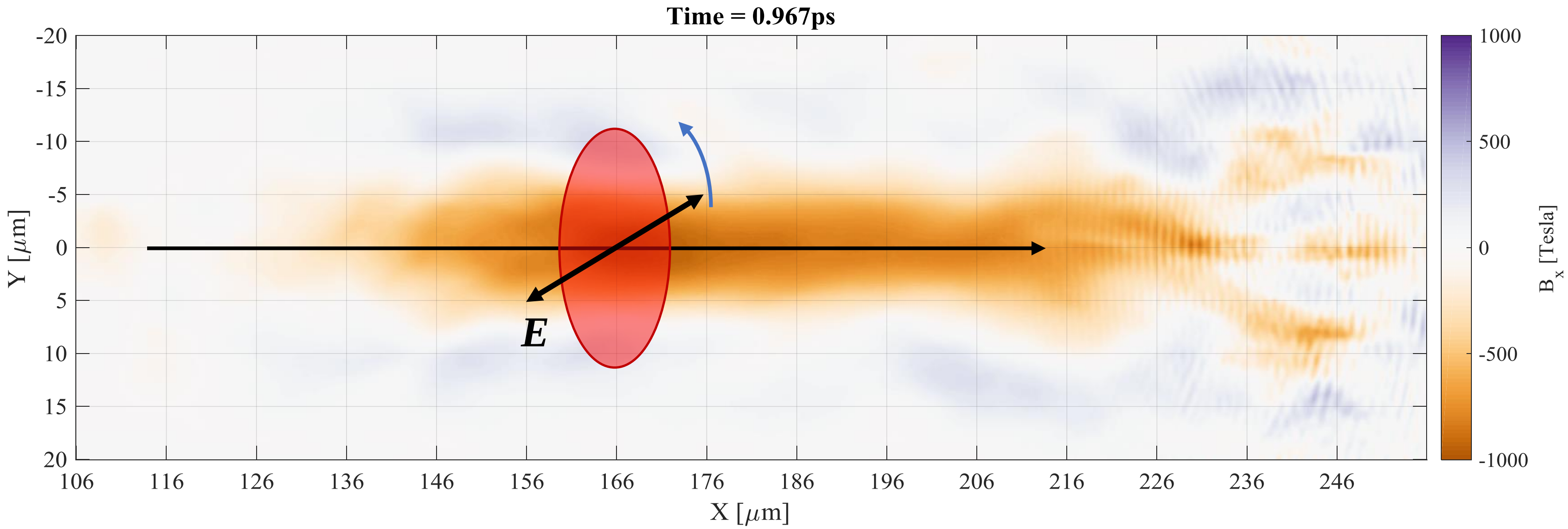
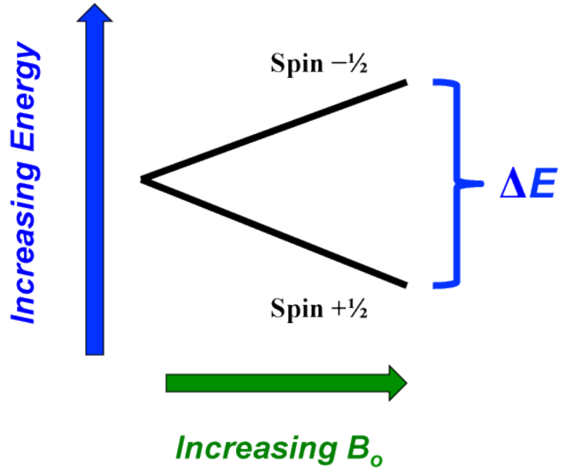
- Faraday Rotation – Probe pulse is polarization rotated

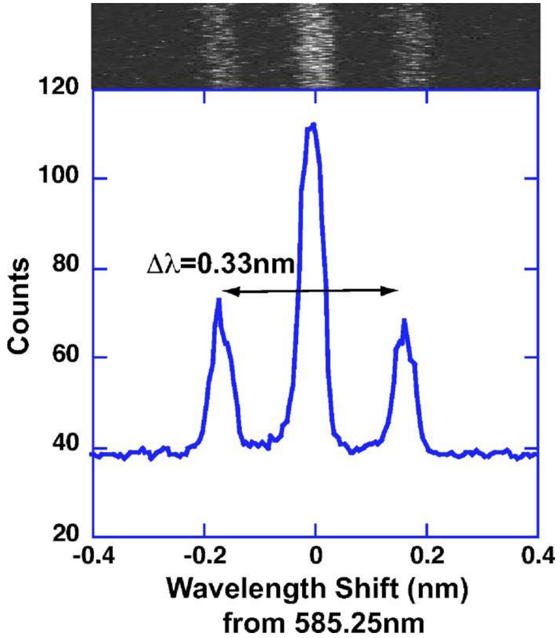


- Zeeman splitting of spectral lines

For spin ½ electrons:

$$\Delta\lambda = \frac{\lambda_0^2 eB}{2\pi c m_e}$$





Zeeman splitting of neon line

Images: http://mriquestions.com/energy-splitting.html , B. B. Pollock, et al, Rev. Sci. Inst. **77**, 114703 (2006),

New Methods For B field Measurement are Being Considered

- While the two previous methods of B-field measurement are being suitable for the fields we intend to measure, we are also exploring alternatives:
  - Proton radiography
  - Cyclotron emission ($\approx 10\mu m$)
  - SRS backscatter
  - Thomson scattering

Conclusions

- Diffraction models of high-power OAM beams were developed allowing for the first time accurate modelling of high intensity OAM beams
  - An additional perturbation model has been developed for modelling of asymmetric OAM beams
- Determined that OAM can be transferred to free electrons through ponderomotive-like forces – OAM coupling scales as a_0^2
  - Derived symmetric paraxial E and B fields of generalized Laguerre Gaussian modes
- Using EPOCH PIC code we were able to identify two new self focussing modes – ring pinch and ring collapse
- Modelling of inverse Faraday effect using EPOCH confirms previous analytic models
  - In addition, we showed the magnetic field persistence (~1ps) decay time, and also typical length scales of 100μm
  - Magnetic field persistence may be inhibited by wobble instabilities, can increase time by increasing OAM mode
- The off-axis spiral phase mirror has been introduced and now allows for the generation of ultra-high intensity OAM beams in almost any laser system – already collaborating with two groups on implementation on other lasers
  - The highest intensity OAM beams to date were generated

Acknowledgements

I would like to thank and acknowledge the following people;

Robert Fedosejevs

CLPU Scientific, Technical, and Laser Teams

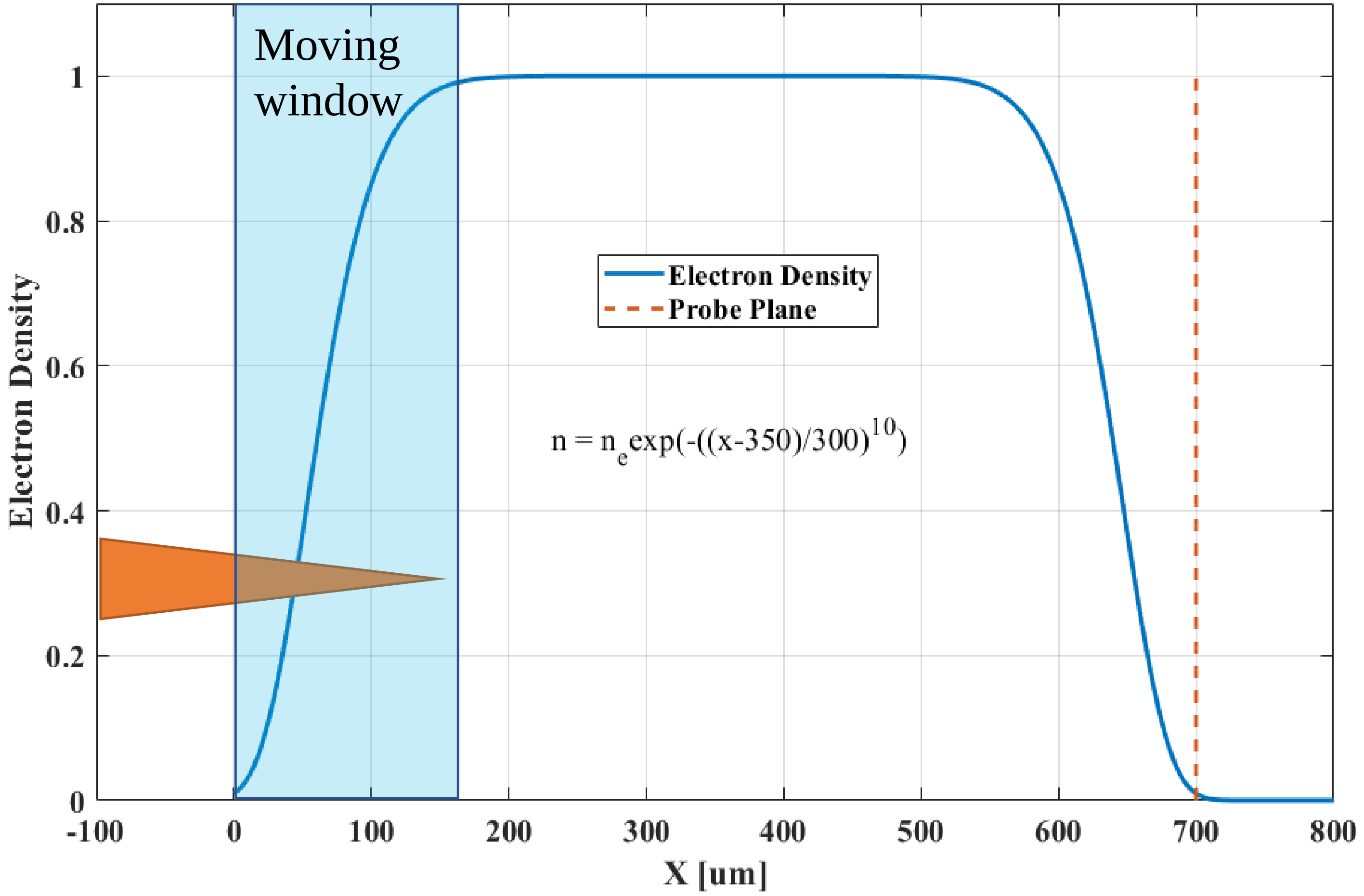
University of Alberta machine shop and nanoFAB centre – OASPM and diagnostic fabrication

Jason Myatt

EPOCH development team

And funding from;

PIC Simulations Were Performed Using EPOCH and Compute Canada



- 4000 x 500 x 500 cells
- 150μm x 40μm x 40μm
- 2 billion particles
- He + Ionizable Nitrogen Plasma (2.7keV)
- $3 \times 10^{19} cm^{-3} = 0.03 n_c$
- $2.5 \times 10^{19} W cm^{-2}$, $100 fs$
- Linearly Polarized LG_{10}
- ~15CPU years / run