The influence laser beams power imbalance on symmetry of absorbed energy in a corona of direct-driven targets

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Model of absorption laser radiation

One of the actual issue to obtain the successful ignition of thermonuclear targets on megajoule laser facilities is the providing of required symmetry of absorbed laser energy in the corona of direct-driven targets. In view of this, we calculated a propagation of a laser radiation in the isothermal corona with a power-law distribution of electron density on radius in the approximation of a geometrical optics taking into account of the refraction and inverse bremsstrahlung absorption of a laser radiation. The intensity in laser beams was set in the form of super-Gaussian spatial profile on a lens with a focal ratio of f/4. We considered two configurations of 48 clusters of laser beams located on a target chamber of a megajoule laser facility. A laser beam clusters arranged configuration 6×8 around of a directions passing through a centers of a cube faces give the configuration of (6 × 8) beams [1] and a symmetry axes of a laser beam clusters passed through a cube corners give another configuration of (8 × 6) beams.

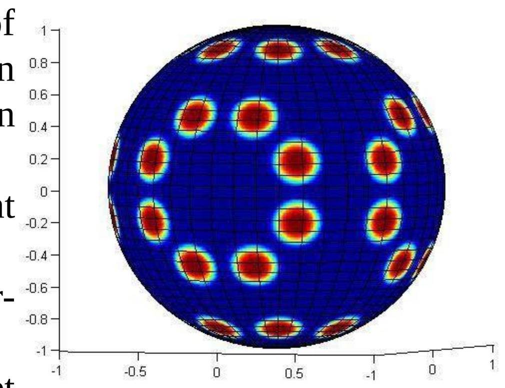
Fig. 1. Beams configuration 6×8

Calculation of the laser radiation absorption was carried out in the geometrical optics approximation for the electron density $n_e = n_c(r_c/r)^m$, where $n_c = (4\pi e^2)/(m_e\omega_0^2)$. Ray trajectory is given by formula[2]:

$$\theta(r) = \gamma + \int_r^R \frac{pdr'}{r'\sqrt{(nr')^2 - p^2}}$$

and optical thickness:

$$\tau(r) = \int_r^R \frac{kdr'}{\sqrt{1 - p^2/(nr')^2}}$$

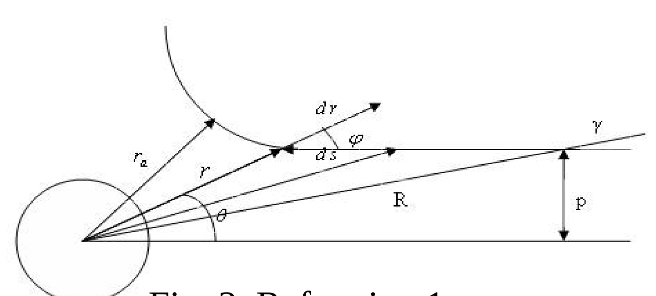
Fig. 2. Refraction 1 ray

Laser radiation is considered as a bundle of rays. From this bundle 3 successively selected. Two last of them form the ray tube, and the average beam power carries enclosed in this tube.

$$\frac{dE}{dtdV} = \frac{kI_0e^{-\tau(r)}}{\cos(\theta(r))}\frac{S_0}{S}$$

$$S_0 = 2\pi pdp$$

$$S = 2\pi\sin(\theta(r))d\theta$$

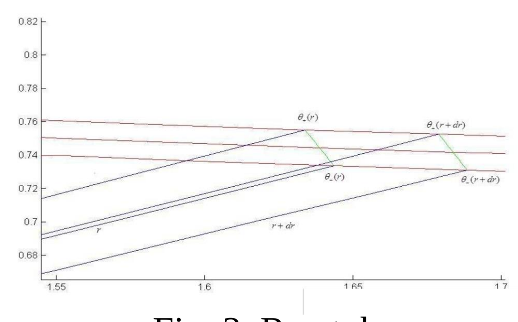
Fig. 3. Ray tube

Nonuniformity is characterized by asymmetry:

$$\eta = (F_{max} - F_{min})/\bar{F}$$

and roof-mean-square deviation

$$\Delta = \frac{1}{\bar{F}}\sqrt{\frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi}(F(\theta,\varphi) - \bar{F})^2\sin(\theta)\,d\theta d\varphi}$$

where $F(\theta,\varphi) = dE/dtd\Omega = \int_{r^*}^{R}(dE/dtdV)r^2dr$

Nonuniformity of energy absorption $dE/dtd\Omega$ for $n_e = n_c(r_c/r)^2$

The table below shows asymmetry and roof-mean-square deviation of $dE/dtd\Omega$ for $n_e = n_c(r_c/r)^2$in depending from defocusing d/r₀ for value k=2 и 4 in exponent of $I = I_0exp(-(\rho/R_L)^k)$.

d/r_0	$\eta_{k=2}$,%	$\Delta_{k=2}$,%	$\eta_{k=4}$,%	$\Delta_{k=4}$,%
4	10.40	2.21	16.44	3.21
6	3.62	0.73	11.69	1.91
8	4.44	0.81	7.91	1.58
10	6.90	1.10	9.22	1.74

And below (fig. 4) shows$dE/dtd\Omega$ and it harmonic composition for $n_e = n_c(r_c/r)^2$ for defocusingи d/r_0=6.

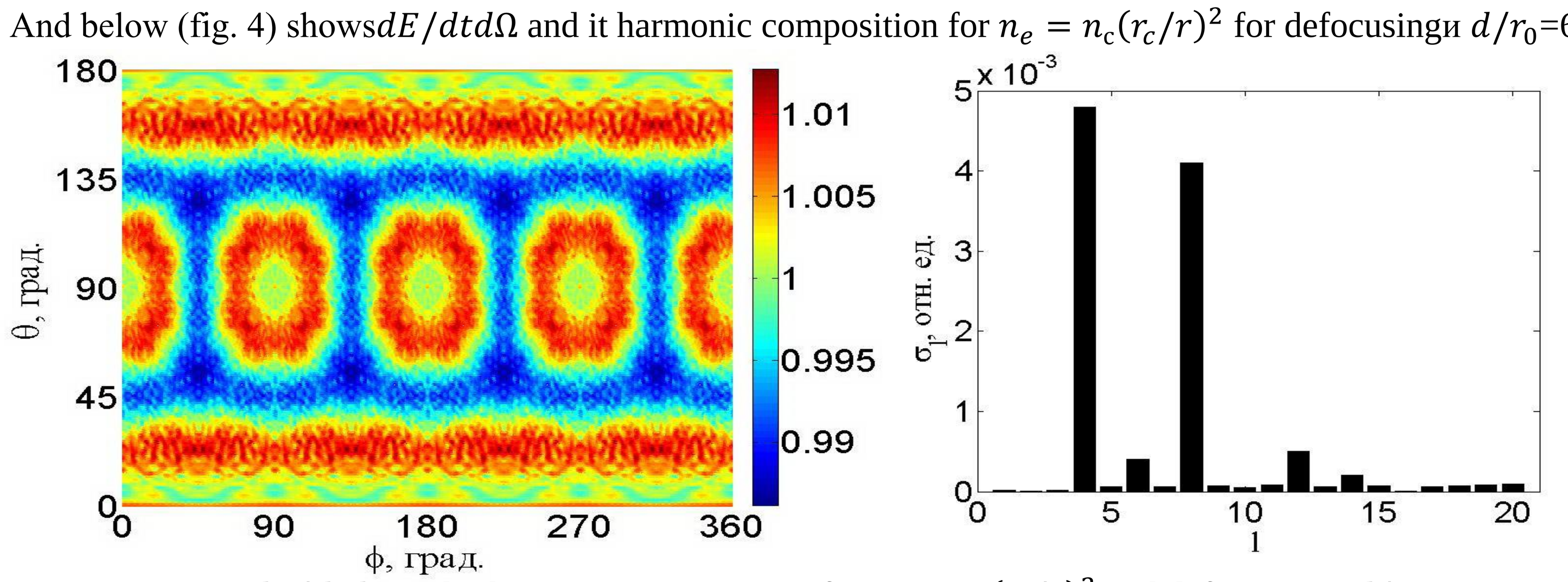
Fig. 4. $dE/dtd\Omega$ and it harmonic composition for $n_e = n_c(r_c/r)^2$ and defocusingи d/r_0=6

Roof-mean-square deviation $\Delta = 0.73\%$. Harmonic with number 4 and 8 are leading.Calculation of harmonic composition performed by the formulas:

$$\sigma_l = \sqrt{\sum_{m=-n}^{m=n}(a_{lm}/a_{00})^2} \qquad a_{lm} = \frac{1}{4\pi}\int_0^{2\pi}d\varphi\int_0^{\pi}\frac{dE}{dtd\Omega}(\theta,\varphi)\overline{Y_l^m}(\theta,\varphi)\sin(\theta)d\theta$$

Nonuniformity of energy absorption $dE/dtd\Omega$ for $n_e = n_c(r_c/r)^3$

There are asymmetry and roof-mean-square deviation of $dE/dtd\Omega$ for $n_e = n_c(r_c/r)^3$in depending from defocusing d/r₀ for value k=2 и 4 in exponent of $I = I_0exp(-(\rho/R_L)^k)$ in the table.

d/r_0	$\eta_{k=2}$,%	$\Delta_{k=2}$,%	$\eta_{k=4}$,%	$\eta_{k=4}$,%
4	9.41	1.84	14.88	3.13
6	3.62	0.61	10.40	1.71
8	3.57	0.53	8.69	1.16
10	3.30	0.52	6.64	1.12

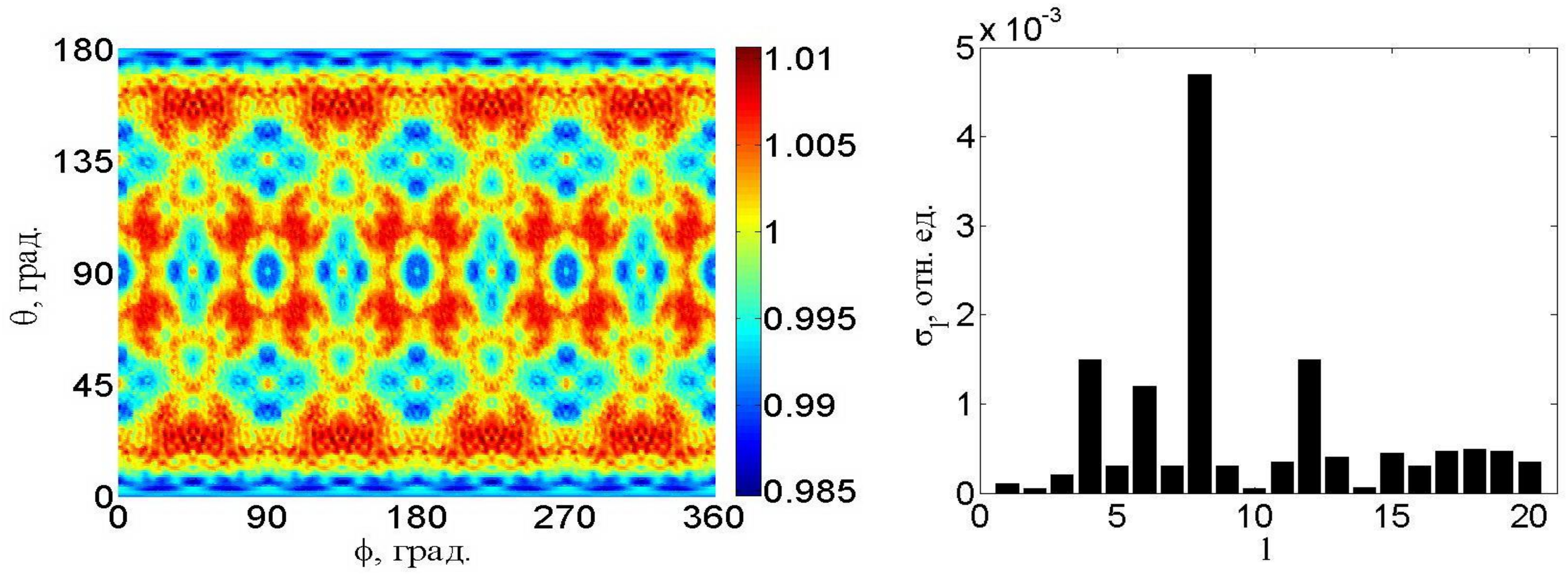
Fig. 5. $dE/dtd\Omega$ and it harmonic composition for $n_e = n_c(r_c/r)^3$ and defocusingи $d/r_0 = 10$

The fig. 5 shows $dE/dtd\Omega$ and it harmonic composition for $n_e = n_c(r_c/r)^3$ and defocusingи $d/r_0 = 10$. Roof-mean-square deviation $\Delta = 0.52$. Δ decreased in 1.5 times in comparison with the case for quadratic electron density profile. Harmonic with number 8 are leading.

The configuration of radiation through the corners of the cube. Asymmetry and roof-mean-square deviation in depending from defocusing d/r₀ for Gaussian intensity profile

The configuration of radiation through the corners of the cube is on fig. 6. Asymmetry and roof-mean-square deviation of $dE/dtd\Omega$ for $n_e = n_c(r_c/r)^2$ in depending from defocusing d/r₀ for Gaussian intensity profile shows below in the table.

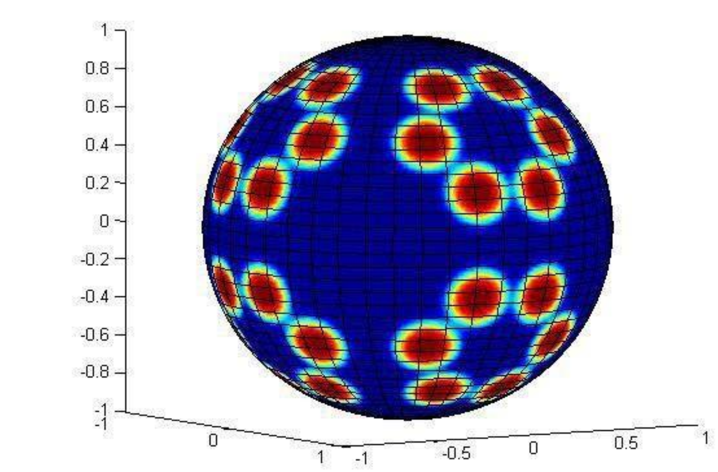
Fig. 6. Beams configuration 8×6

d/r_0	$\eta_{k=2}$,%	$\Delta_{k=2}$,%
4	15.78	3.78
6	4.33	0.50
8	4.79	0.86
10	10.56	1.44

On fig.7 you can see $dE/dtd\Omega$ and it harmonic composition in optimum, which corresponds to the red mark in the table above.

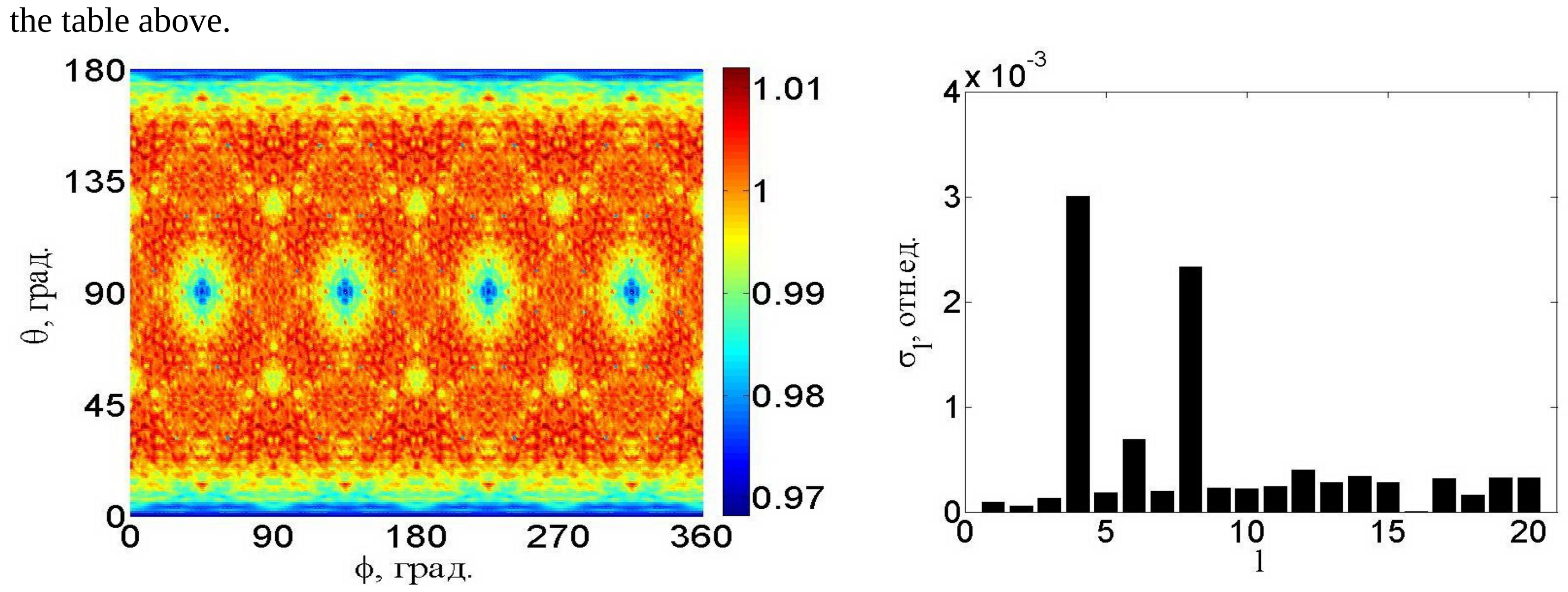
Fig. 7. $dE/dtd\Omega$ and it harmonic composition for $n_e = n_c(r_c/r)^3$ and defocusingи $d/r_0 = 6$

Radial profile $dE/dtdV$ and amplitude 4 harmonic for $n_e = n_c(r_c/r)^2$ and defocusing d/r_0=6

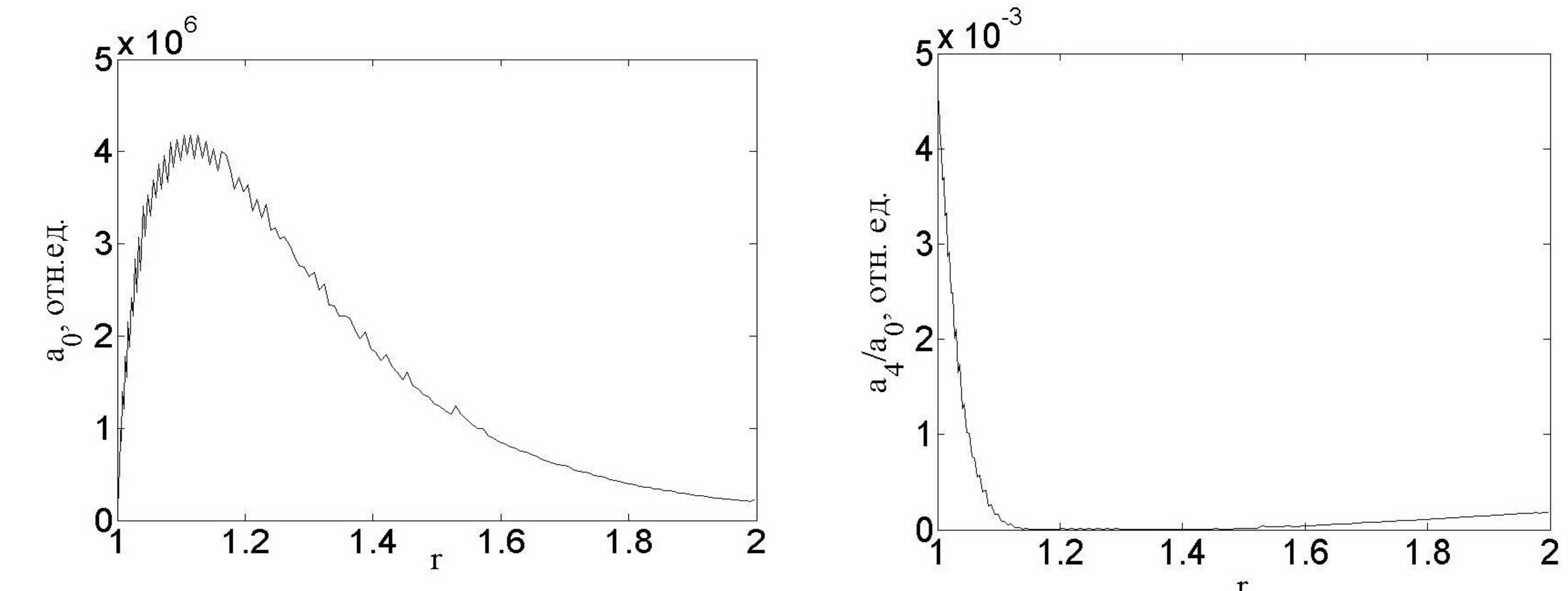
Fig. 8. Radial profile $dE/dtdV$ and amplitude 4 harmonic for $n_e = n_c(r_c/r)^2$ and defocusing d/r_0=6

The influence of beams power imbalance on uniformity

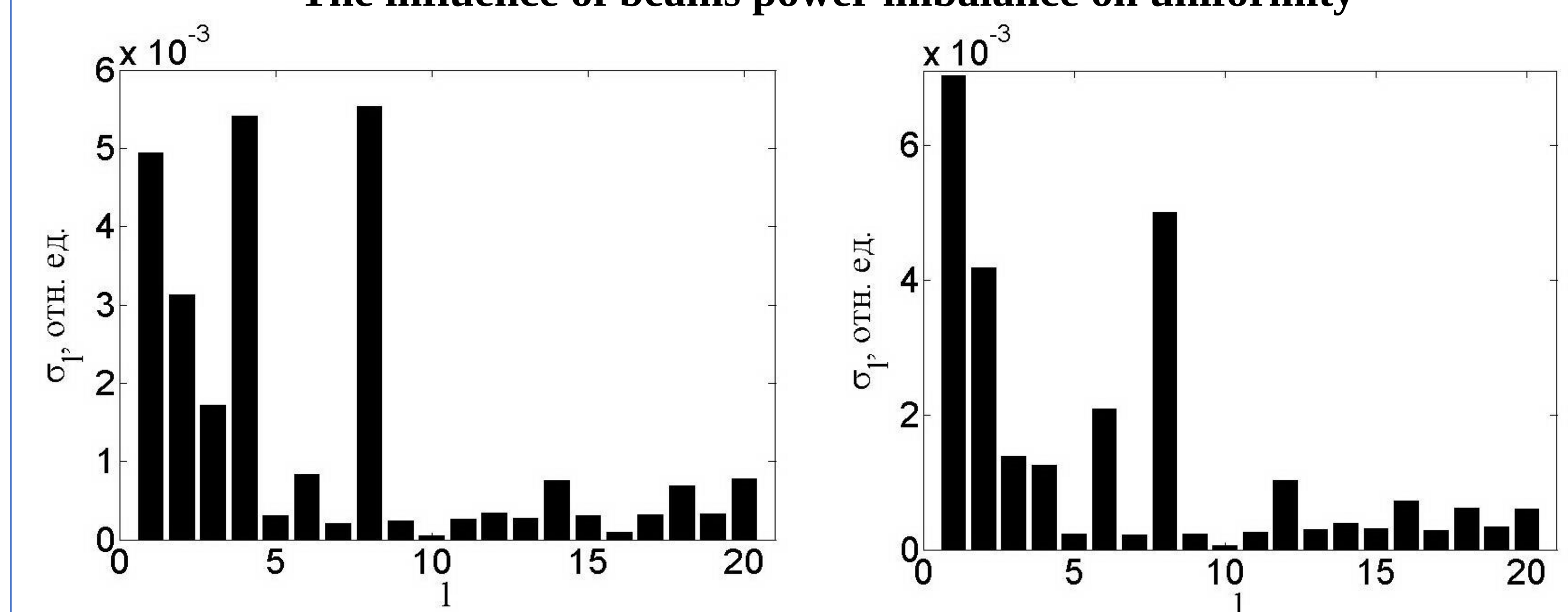
Fig. 9. Averaged harmonic composition by defocusing d/r_0=6 with dispersion in power $\sigma_p = 3\%$ for $n_e = n_c(r_c/r)^2$ (left) and defocusing d/r_0=10 with dispersion in power $\sigma_p = 5\%$ for $n_e = n_c(r_c/r)^3$ (right)

The accounting of power imbalance in laser beams cause a degradation of absorbed energy uniformity and the appearance of lower harmonics regardless of the configuration of the beams, and amplitude of the harmonics 4 and 8 has not changed.

Comparison uniformity of the absorbed energy to 6 and 8 directions of irradiation cube geometry

The first table shows the calculations of roof-mean-square deviation without taking into account refraction Δ_o and with it Δ_a for the configuration 6×8 and 8×6.

N	Δ_o,%	Δ_a%,
6×8	0.35	0.73
8×6	0.2	0.53

And in the second table you can see the average roof-mean-square deviation for the specified disbalance in power beams.

	Δ_8,%, m=2	Δ_6 ,%,m=2	Δ_6 ,%, m=3
$\sigma_p = 3\%$	0.78	0.98	0.73
$\sigma_p = 5\%$	0.98	1.31	0.96

Calculations show that value of Δ would be less than 1% under optimum conditions, assuming that the standard deviation of laser beams power will be provided as $\sigma_P \leq 3\%$ for the configuration 6 × 8 beams and $\sigma_P \leq 5\%$ for the configuration 8 × 6 beams.

Conclusion

- Accounting laser refraction leads to a deterioration of uniformity of the energy absorbed in two times.
- The optimal conditions of focus and profile of the laser intensity at which the standard deviation of the energy absorbed is less than 0.55%.
- Imbalance of power between the 48th quadras laser beams must not exceed 3% for the standard deviation of the absorbed energy is not more than 1%.
- The transition from 6-and 8-m main directions of irradiation cube geometry improves the uniformity of the absorbed energy and the allowable power imbalance in ~ 1.5 times.

1. Bel'kov S. A. et al. Thermonuclear targets for direct-drive ignition by a megajoule laser pulse. JETP, 2015. Vol. 121, Issue 4, pp 686-698.
2. Ginzburg V. L., Propagation of Electromagnetic Waves in Plasma. Fizmatlit, Moscow, 1960.