Laser intensity at nonlinear QED:
A realizable scheme

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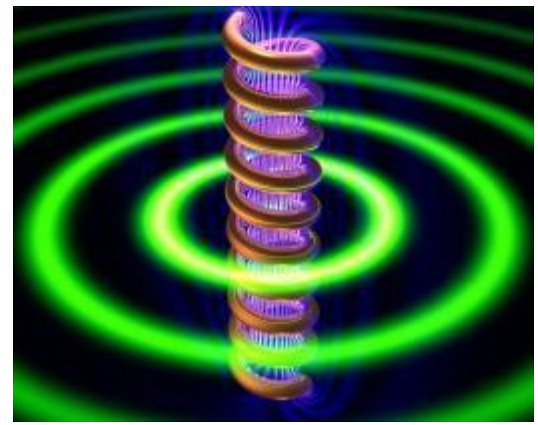
Motivation & Vision

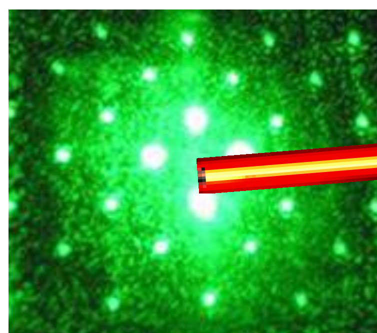
- **How to produce laser field with intensity that makes quantum vacuum nonlinear? Nonlinear QED: A New Science**

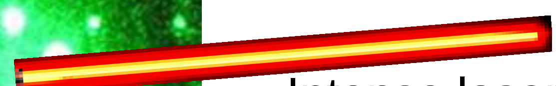
- **Gravitational force of light**

K S Ng and C H Raymond Ooi, (2013) “Gravitational Force of Bessel Light Beam”, Laser Physics 23, 035003.



- **Shield for Directed Energy**





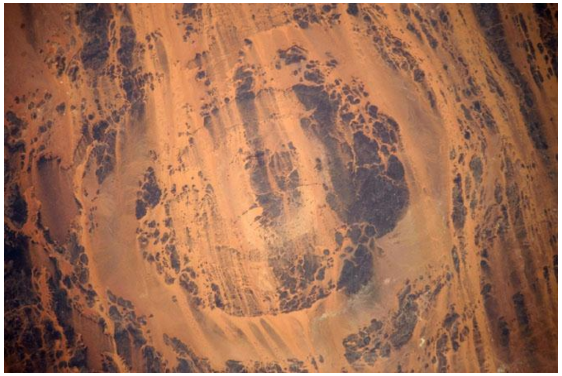
Intense laser or charged particles

- **A super laser that can destroy an asteriod and save mankind?**

"Dinosaur-Killer" Asteroid Crater Imaged for First Time
National Geographic News
March 7, 2003

A high-resolution map from NASA's Shuttle Radar Topography Mission (SRTM), released yesterday, has provided the most telling visible evidence to date of a 112-mile (180-kilometer) wide, 3,000-foot (900-meter) deep impact crater, the result of a collision with a giant comet or asteroid on one of Earth's all-time worst days.

Asteroid Impact Craters on Earth as Seen From Space



- **Laser stargate**

Consequences of Dirac's Theory of the Positron

Zeitschr. Phys. *98*, 714 (1936).

Folgerungen aus der Diracschen Theorie des Positrons.

Von **W. Heisenberg** und **H. Euler** in Leipzig.

Mit 2 Abbildungen. (Eingegangen am 22. Dezember 1935.)

$$\mathfrak{L}=\frac{1}{2}(\mathfrak{E}^2-\mathfrak{B}^2)+\frac{e^2}{\hbar c}\int_0^\infty e^{-\eta}\frac{d\eta}{\eta^3}\left\{i\eta^2(\mathfrak{E}\mathfrak{B})\cdot\frac{\cos\left(\frac{\eta}{|\mathfrak{E}_k|}\sqrt{\mathfrak{E}^2-\mathfrak{B}^2+2i(\mathfrak{E}\mathfrak{B})}\right)+\text{conj.}}{\cos\left(\frac{\eta}{|\mathfrak{E}_k|}\sqrt{\mathfrak{E}^2-\mathfrak{B}^2+2i(\mathfrak{E}\mathfrak{B})}\right)-\text{conj.}}+|\mathfrak{E}_k|^2+\frac{\eta^2}{3}(\mathfrak{B}^2-\mathfrak{E}^2)\right\}$$

VOLUME 91, NUMBER 8 — PHYSICAL REVIEW LETTERS — week ending 22 AUGUST 2003

Light Intensification towards the Schwinger Limit

Sergei V. Bulanov,* Timur Esirkepov,† and Toshiki Tajima

REVIEWS OF MODERN PHYSICS, VOLUME 78, APRIL–JUNE 2006

Nonlinear collective effects in photon-photon and photon-plasma interactions

Mattias Marklund* and Padma K. Shukla*

PHYSICAL REVIEW A **81**, 022122 (2010)

Nonperturbative multiphoton electron-positron–pair creation in laser fields

Guido R. Mocken,[*] Matthias Ruf,[†] Carsten Müller,[‡] and Christoph H. Keitel[§]

PRL **100,** 010403 (2008) PHYSICAL REVIEW LETTERS week ending 11 JANUARY 2008

Nonperturbative Vacuum-Polarization Effects in Proton-Laser Collisions

A. Di Piazza,[*] K. Z. Hatsagortsyan,[†] and C. H. Keitel[‡]

New Journal of Physics **14** (2012) 103002

Photon–photon scattering in collisions of intense laser pulses

B King[1,2] **and C H Keitel**[1]

VOLUME 79, NUMBER 9 PHYSICAL REVIEW LETTERS 1 SEPTEMBER 1997

Positron Production in Multiphoton Light-by-Light Scattering

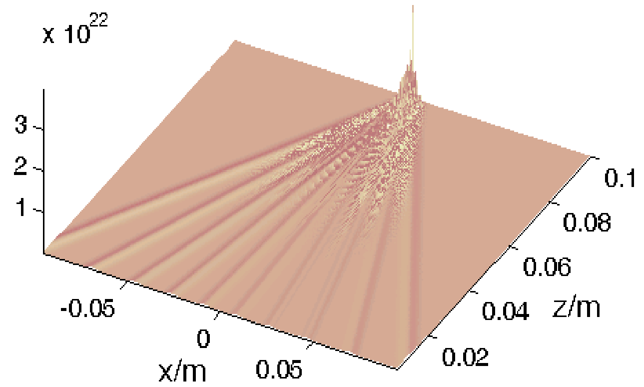
PRL **97,** 121302 (2006) PHYSICAL REVIEW LETTERS week ending 22 SEPTEMBER 2006

Signatures of the Unruh Effect from Electrons Accelerated by Ultrastrong Laser Fields

Ralf Schützhold,[1,*] Gernot Schaller,[1] and Dietrich Habs[2]

Outline

- Recent related works on nonlinear QED
- Scheme to generate superintense laser field
- Synchronization method
- Design constraints
- Theoretical justifications
- Simulated results of intensity distributions



Schwinger's limit

Schwinger field $E_S = m_0 c^2 / e \lambda\!\!\!^{-}_c$ 1.3233×10^{18} V/m

$\lambda\!\!\!^{-}_c = \hbar / mc \sim c\delta t$ ~0.386pm, Compton length

Schwinger intensity $I_S = 10^{29}$ W/cm^2 or 10^{33} W/m^2

The probability of spontaneous production of pair creation per unit time per unit volume

$$w = \frac{1}{\pi^2} \frac{\alpha}{\delta t} \frac{1}{\lambda\!\!\!^{-}_c{}^3} \left(\frac{E}{E_S}\right)^2 \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-n\pi \frac{E_S}{E}\right)$$

J. Schwinger, Phys. Rev. ***82, 664 (1951).*** $\delta t = \hbar / m_0 c^2$

The number of pair creation $N = V \tau_p w$

1 pair at 10^{27} W/cm^2

Petawatt-class ultra-short quantum beam facility(UQBF) of the APRI, GIST

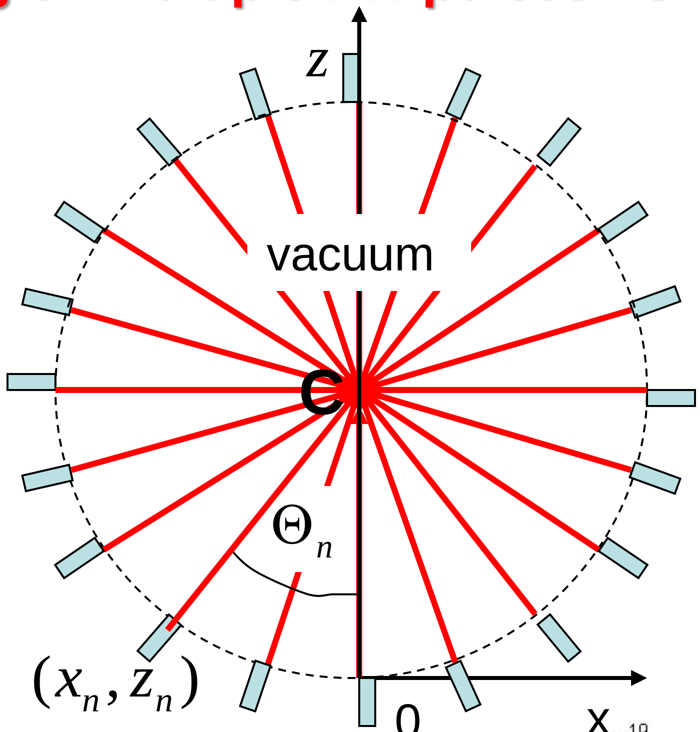
ASILS 4
2008

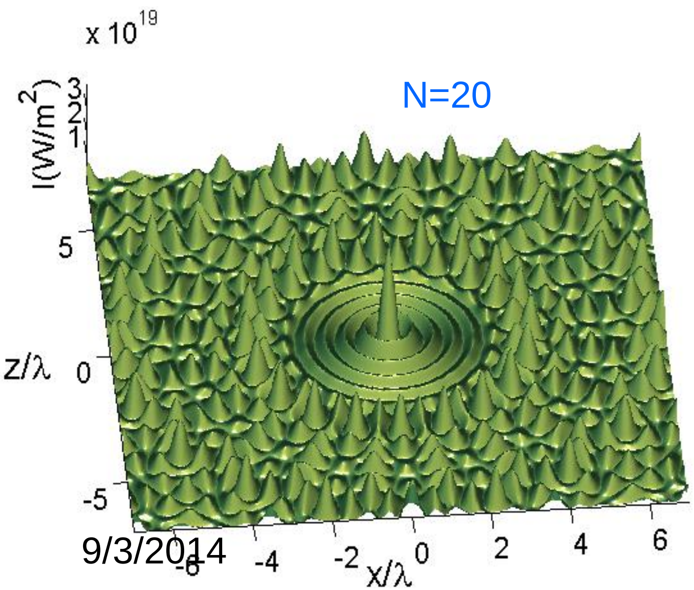
	Erg/J	Duration /fs	P/PW	I/W/cm2	waist	focus
LLNL	660	440	1.5	0.7^21	3.2cm 10^{14}	5mic
HERCULES	20	60	0.3	0.5^23	4inch or 10cm	1.3mic
UK/Vulcan						

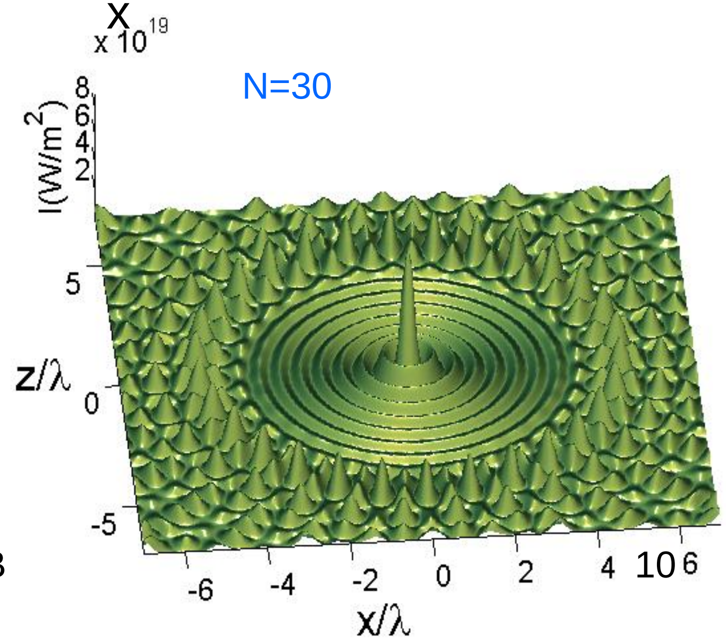
Table top max intensity 10^23 W/cm2
For higher intensity we need larger beam size and pump power

NIF & LMJ :
2MJ at 350nm in 3ns
5MJ at 530nm in 10-20ns => pump CPA giving 1 MJ in 10fs (1 micron^2) I~ P_{th} / λ^2
Fsat of amplifier = hv/sigma ~1 for Ti:Sap , ~40 for Yb:glass
Grating: 10m , Fd ~ 1 J/m^2
Phase controlled by deformable parabolic mirror

Merging of Multiple PW pulses - Unfocused

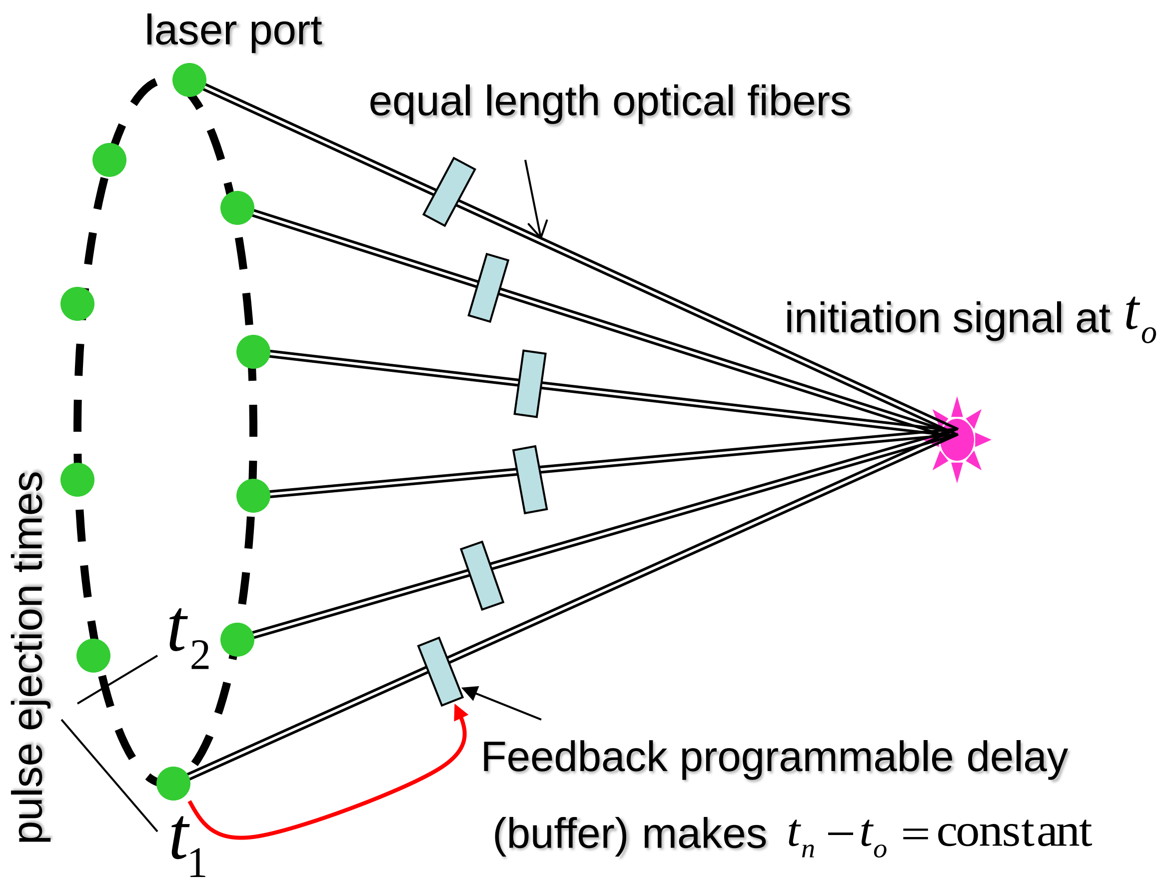






Pulse synchronization / initiation scheme

Superintense laser fields in circular array: effects of phase and pulse jitters,
C H Raymond Ooi & TY Tou, Appl Phys B (2010) 101: 825–833



Optical buffer compensates for the different amplification duration of each laser

Advanced Ti:Sa OPCPA can produce femtosecond laser pulse with

$$U_o = \frac{1}{2}\varepsilon_0 E_0^2 c\tau A_o = 200J$$

duration $\tau = 50fs$ and a waist of $w_0 = 3.6mm$ (cross section $A_o = \pi(w_0/2)^2 = 10^{-5}m^2$).

$$P_o = \frac{1}{2}\varepsilon_0 E_0^2 c A_o = 4PW,$$

$$I_o = \frac{1}{2}\varepsilon_0 E_0^2 c = 4\times 10^{20}\,W/m^2$$

$$E_0 = 5\times 10^{11}\,V/m$$

Below damage threshold $10^{22}\,W/m^2$ of optical surfaces, multiple beams can still be manipulated by optics.

For $N = 10$ beams directed from the edge of a circle to the center, intensity increases by 100 time to $4\times 10^{22}\,W/m^2$.

Intensity is still (10^4 times) lower than the current record $5\times 10^{26}\,Wm^{-2}$.

Output waist is not focused to diffraction limit in order to avoid strong energy spread upon propagation towards C.

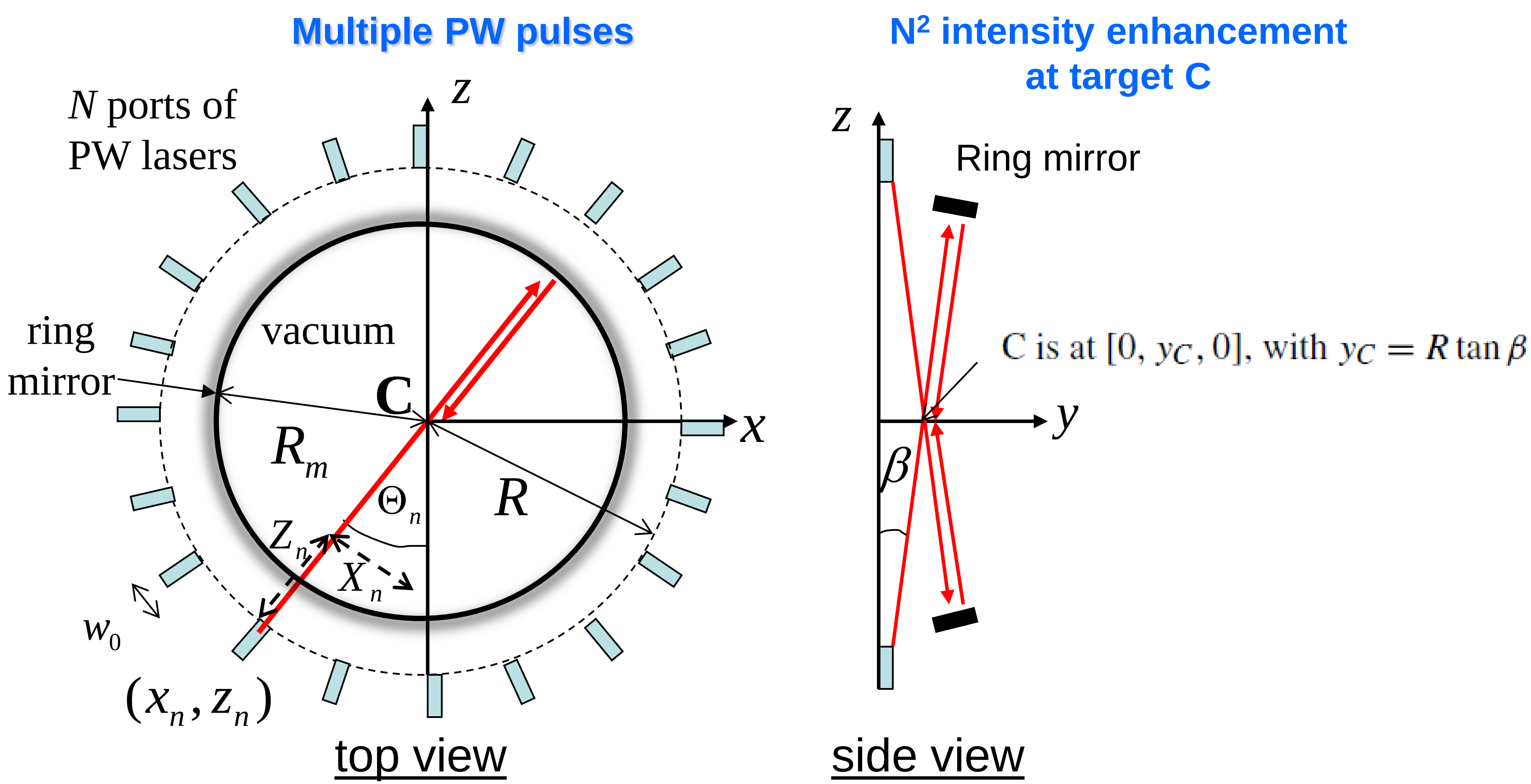
If PW lasers focused to the diffraction limit of $3.6\mu m$ intensity would increase 10^6 times, towards $4\times 10^{28}\,W/m^2$.

We don't stop at PW

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME **5**, 031301 (2002)

Zettawatt-exawatt lasers and their applications in ultrastrong-field physics

The Scheme: Multiple lasers in circular geometry

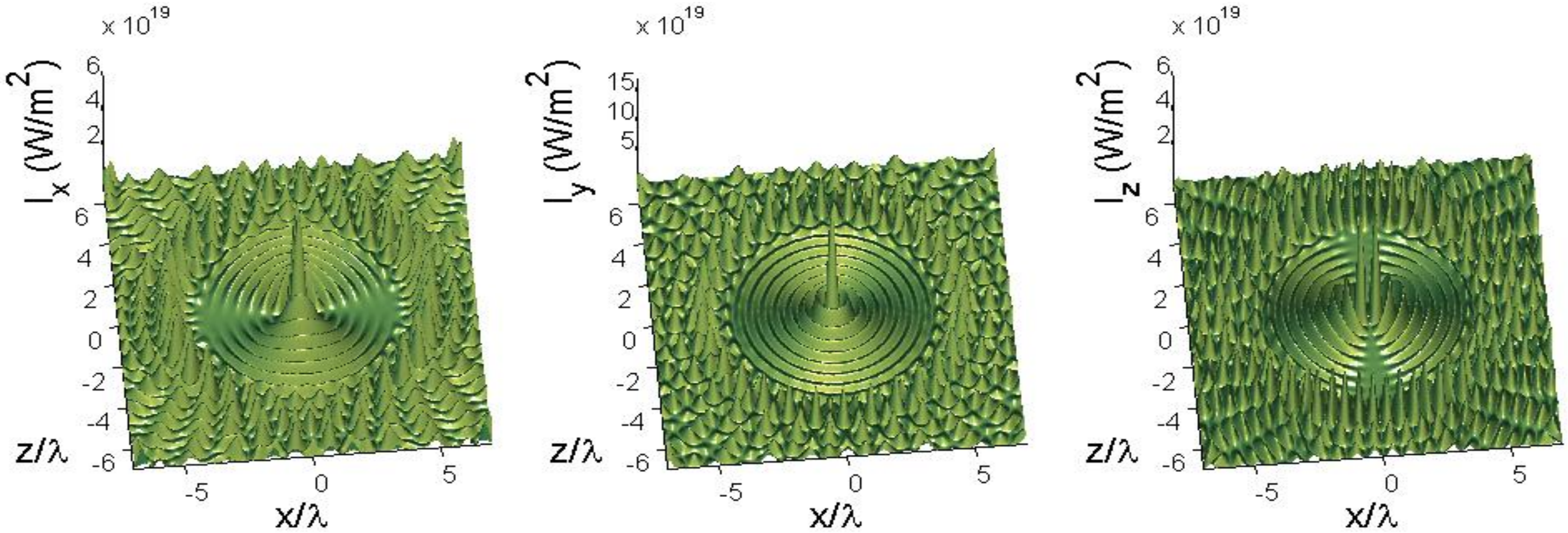


CH Raymond Ooi, JOURNAL OF APPLIED PHYSICS **107**, 043110 2010

The ring mirror does the "focusing" effect, replacing deformable mirror

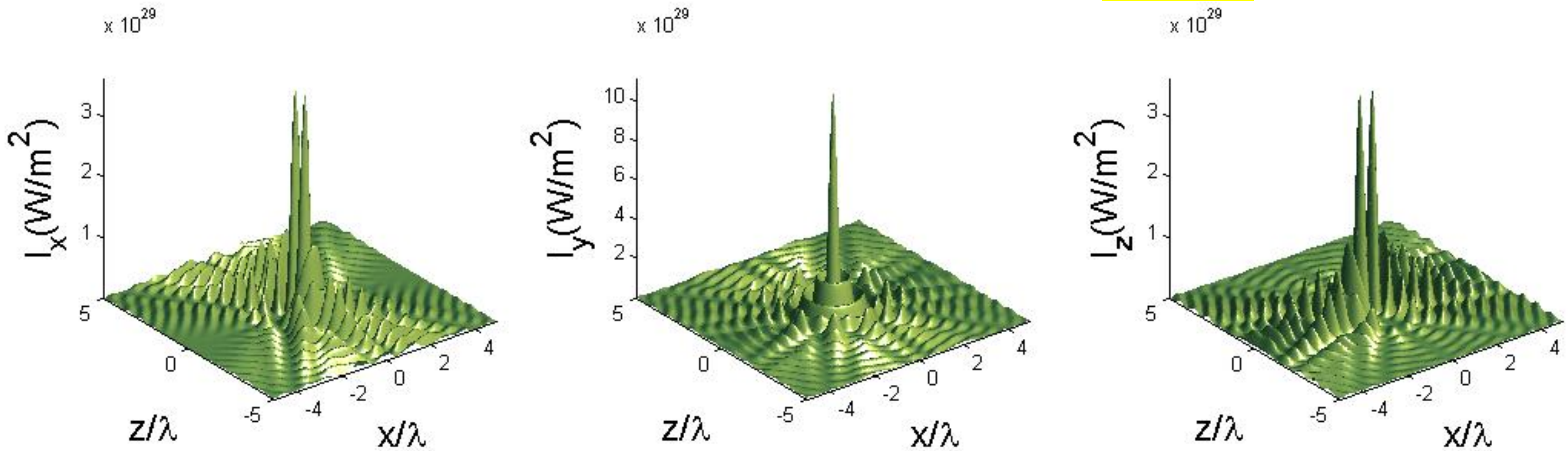
Unfocused: circular polarization, N=30

10^{19}

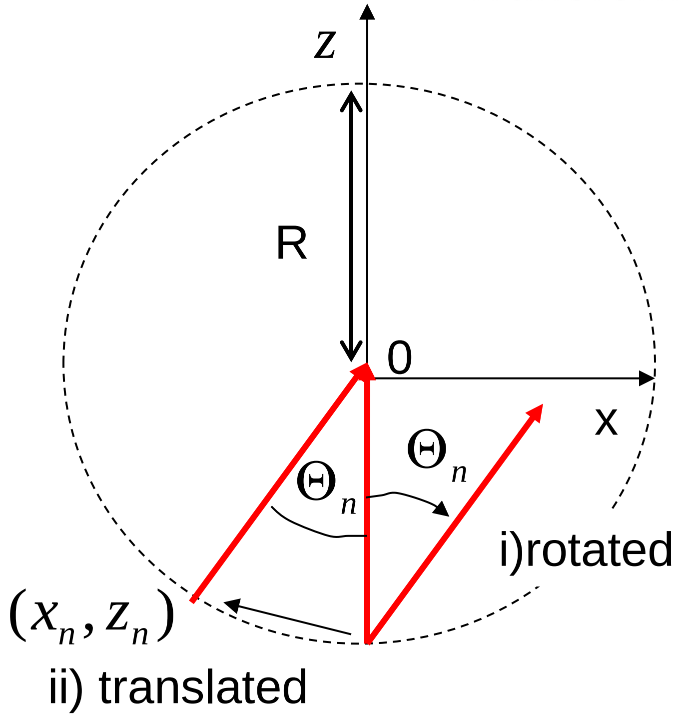


Focused: circular polarization, N=10

10^{29}



Transformation to circular geometry



$$X_n = (x - x_n)\cos\Theta_n - (z - z_n)\sin\Theta_n$$
$$Z_n = (x - x_n)\sin\Theta_n + (z - z_n)\cos\Theta_n$$

$$x_n = -R\sin\Theta_n,\ z_n = -R\cos\Theta_n$$

$$\mathbf{E}_n(x,y,z,t) = \hat{u}_n E_o e^{-i(\omega\tau_n + \varphi_n)} F(Z_n)\exp\{-F(Z_n)\rho_n^2\}\exp\{-(\frac{\tau_n + \delta_n}{T})^2\}$$

CEP **Imperfect sync**

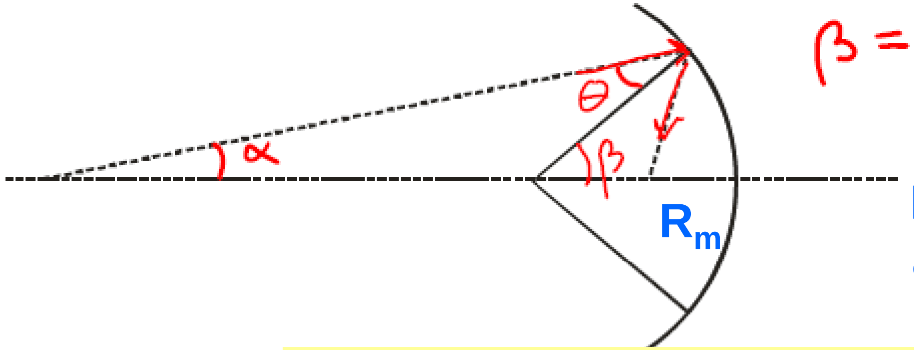
$$F(Z_n) = \frac{1}{1 - iZ_n^r / z_R} \qquad z_R = k_0 w_0^2/2 \qquad \rho_n = \sqrt{X_n^{2} + y_n^{r\,2}} / w_0 \qquad \tau_n = t - Z_n^r / c$$

$$\begin{pmatrix} Z_n^r \\ y_n^r \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} Z_n \\ y_n \end{pmatrix}$$

$$X_n = \Delta x_n \cos\Theta_n - \Delta z_n \sin\Theta_n \qquad \Delta x_n = x - x_n,\ x_n = -R\sin\Theta_n,$$
$$Z_n = \Delta x_n \sin\Theta_n + \Delta z_n \cos\Theta_n \qquad \Delta z_n = z - z_n,\ z_n = -R\cos\Theta_n$$

Reflection off mirror

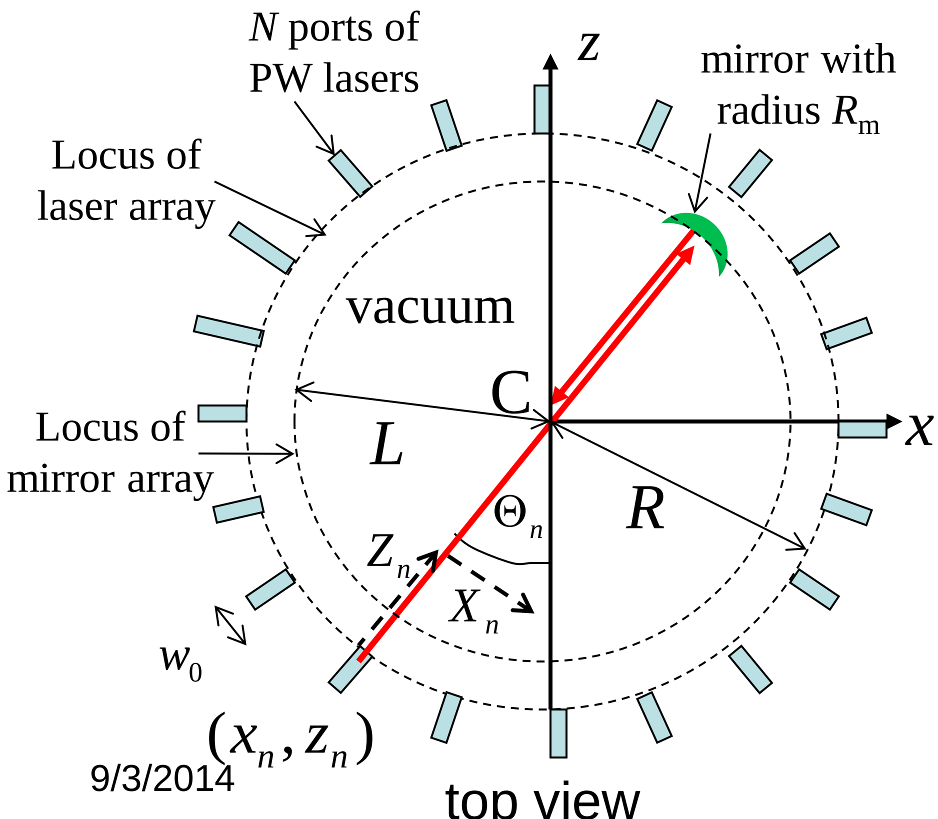
$\beta = \alpha + \theta$

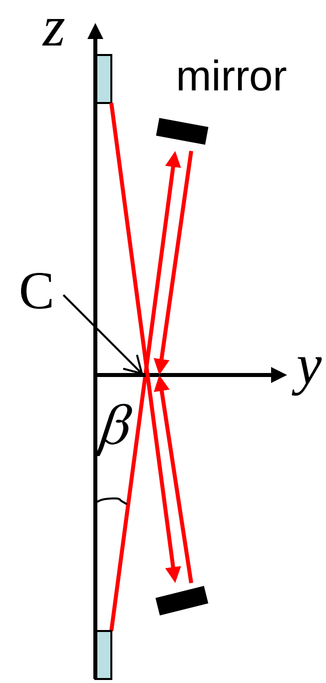


Ring mirror : L=R_m but focus will NOT be at C the center of the circle C but at R_m/2

C H Raymond Ooi & TY Tou, Appl Phys B (2010) 101: 825–833

Using piecewise mirrors with R_m=2L: Focus will be at C





$$\mathcal{R} = \frac{R}{\cos\beta} \text{ and } \mathcal{L} = \frac{L}{\cos\beta}$$

Electric field after reflection by mirror

$$\mathbf{E}'_n = \mathbf{E}'_{n,o} e^{-i(\omega\tau'_n + \varphi_n)} \mathcal{F}_n e^{-\mathcal{F}_n \rho'^2_n} e^{-(\frac{\tau'_n + \delta_n}{T})^2}$$

$$\mathcal{F}_n = \mathcal{F}(Z'_n) = i\frac{z_{Rm}}{q_m(Z'_n)} \qquad \rho'_n = \sqrt{X'^2_n + (y'^r_n)^2}/w_0$$

$$z_{Rm} = k_0 w_m^2/2, \; q_m(Z'_n) = Z'_n + i z_{Rm} \qquad w_m \simeq w_0 \mathcal{L}/z_R$$

$$X'_n = x\cos\Theta_n - z\sin\Theta_n$$

$$Z'_n = x\sin\Theta_n + z\cos\Theta_n$$

$$\tau'_n = t - (R + 2R_m)/c + Z'_n/c$$

$$w_m = w_0\sqrt{\Lambda^2\left(\frac{\mathcal{S}^2}{z_R^2} + 1\right) + \mathcal{L}\frac{(2\Lambda\mathcal{S} + \mathcal{L})}{z_R^2}} = w_0\xi \qquad (7$$

where $\mathcal{S} = \mathcal{L} + \mathcal{R}$, $\mathcal{L} = \frac{L}{\cos\beta}$, $\mathcal{R} = \frac{R}{\cos\beta}$ and $\Lambda = 1 - \frac{2\mathcal{L}}{R_m}$

Boundary condition: Matching the fields at Eo and Eo' at the mirror

$E_o F_n(\mathcal{L} + \mathcal{R}) = E'_o \mathcal{F}_n(\mathcal{L})$ at the reflection points $\mathbf{R}^m_n$

mirror position $\mathbf{R}^m_n = [-\frac{L}{R}x_n, (R + L)\tan\beta, -\frac{L}{R}z_n]$

Field enhancement factor

The boundary condition gives $E'_o = E_o \frac{1 - i\mathcal{L}/z_{Rm}}{1 - i(\mathcal{L}+\mathcal{R})/z_R}$

After reflection from the mirror, the intensity (at origin C) increases by a factor of

$$\epsilon = \frac{\mathcal{L}^2/z_{Rm}^2 + 1}{(\mathcal{L}+\mathcal{R})^2/z_R^2 + 1}$$

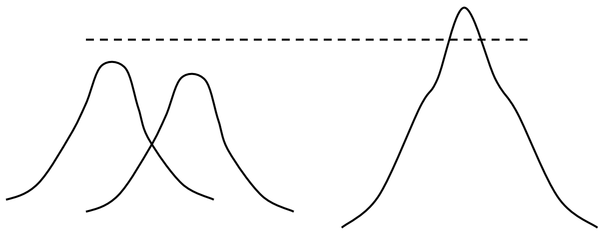
Intensity enhancement for *N* laser pulses at point C after reflection from the mirror

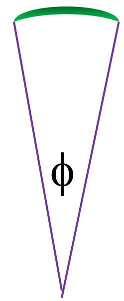
$$\eta = \frac{I_N}{I_o} = N^2\epsilon \simeq \frac{N^2\mathcal{L}^2}{z_{Rm}^2} = \frac{N^2\mathcal{L}^2\lambda^2}{\pi^2 w_m^4} = (N\frac{z_R}{\mathcal{L}})^2$$

boosted by a small L radius of mirror array?

Constraints

Mirror radius cannot be reduced below a value such that the beams overlap, and constructive interference creates region of intensity beyond the damage threshold





$$2\pi R = \alpha' N R 2\phi' \ \text{ with } \alpha' \geq 1$$

$$L = \frac{w_0}{\sin\phi} = \frac{w_0}{\sin\frac{\pi}{\alpha N}} \simeq \frac{\alpha N w_0}{\pi}$$

Paraxial approximation $$\theta^2 = \left(\frac{\lambda}{\pi w_m}\right)^2 \simeq \left(\frac{w_0}{\mathcal{L}}\right)^2 \simeq \left(\frac{2w_0}{R_m}\cos\beta\right)^2 << 1$$

Combined constraint $$\theta = \cos\beta\,\sin(\pi/\alpha N) \ll 1$$

$$N_{\min} = \frac{\pi}{\alpha\sin^{-1}(\theta_{\max}/\cos\beta)}$$ θ_{max} =0.05 → 63

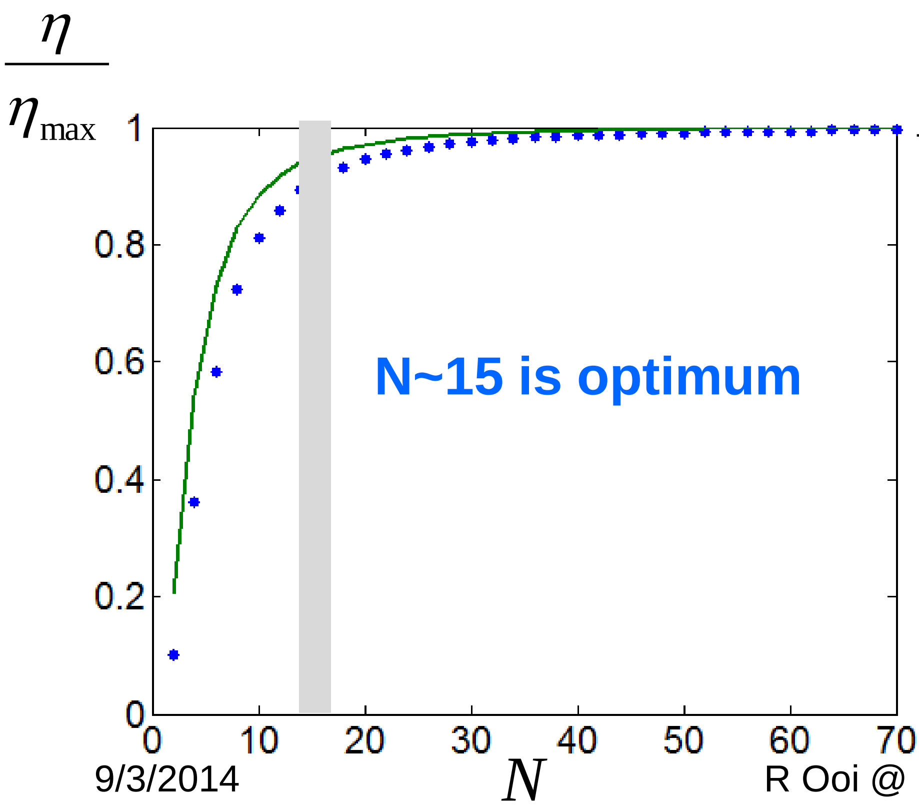
$$L_{\min} = \frac{w_0\cos\beta}{\theta_{\max}}$$ → 20 w_0

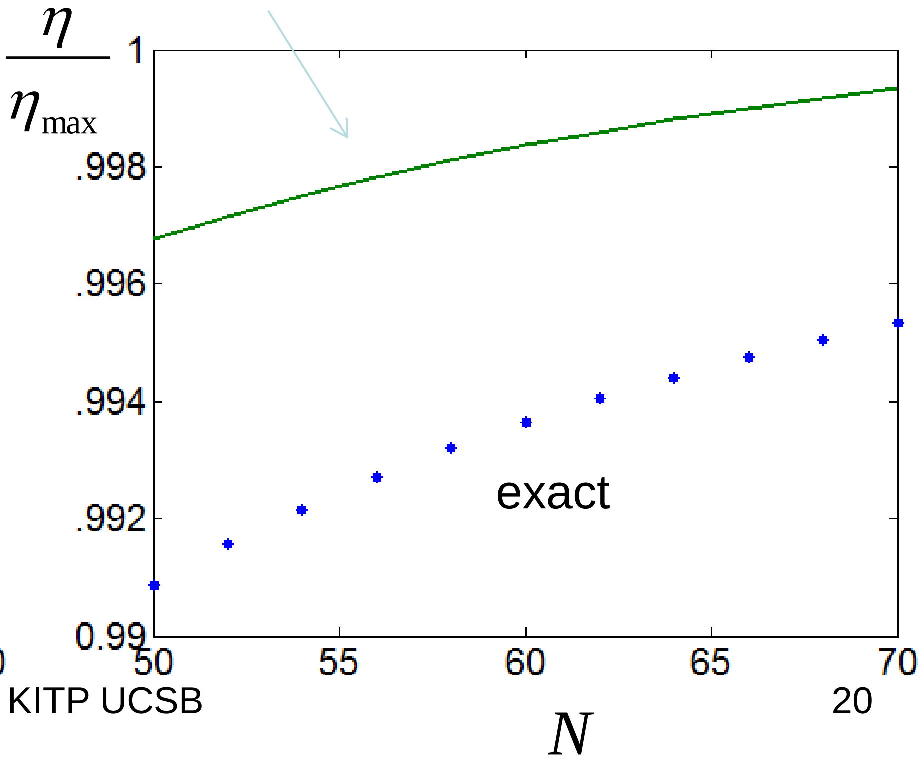
Optimum number of lasers

$$\eta \simeq \left(\frac{N z_R}{\mathcal{L}}\right)^2 = \left(\frac{N\pi w_0}{\lambda}\sin\frac{\pi}{\alpha N}\cos\beta\right)^2$$

Limit of very large N gives maximum enhancement

$$\eta_{\max} = \left(\frac{\pi^2 w_0}{\alpha\lambda}\cos\beta\right)^2$$





Ultimate Super- field

Laser fluence must be less than the mirror damage threshold

$$\frac{1}{2}\varepsilon_0 E(R_m)^2 cT < F_d \simeq 1J/cm^2$$

$T = 100$ fs

$$I_o^{\max} = F_d/T = 10^{17}\mathrm{Wm}^{-2}$$

Final expression for superintense field (scales with beam diameter), α=1. β=0

$$I^{\max} = I_o^{\max}\left(\frac{\pi w_0}{\lambda}\right)^2$$

$10^{27-28} Wcm^{-2}$

$10^{31-32} Wm^{-2}$

Nonlinear vacuum QED

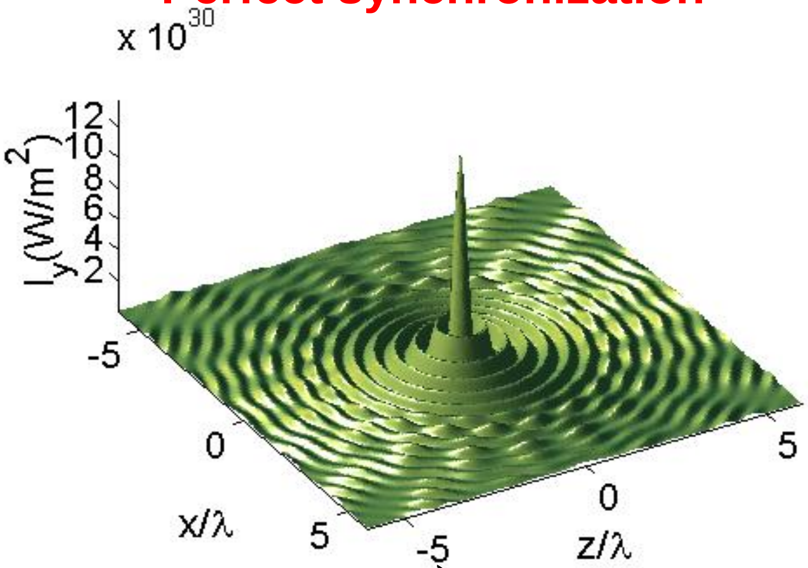
$$N = 63, w_0 = 1\mathrm{m},\ I_o^{\max} = 10^{17}\mathrm{Wm}^{-2} \text{ and } \lambda = 840\mathrm{nm},$$

OR shorter (atto) pulses 10fs with w_0=10cm

OR smaller laser near UV : w_0=30cm and λ=280nm

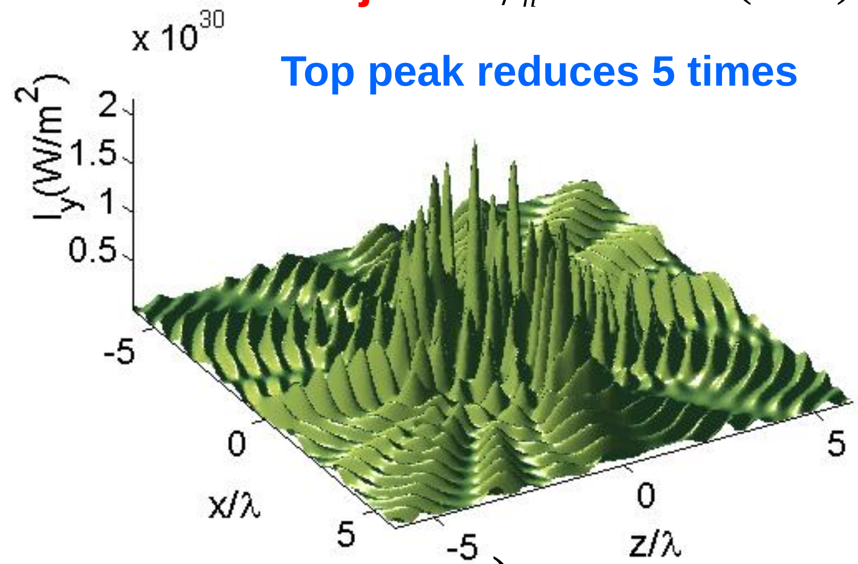
Intensity distribution for linearly polarized lasers, N=20

Perfect synchronization



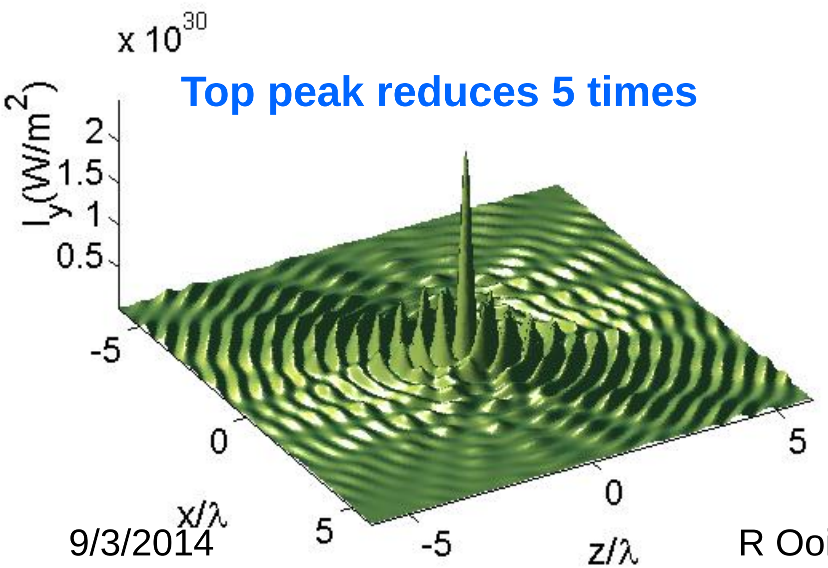
a)

CEP jitter $\varphi_n = 2\pi\,\mathrm{rand}(\pm 0.5)$



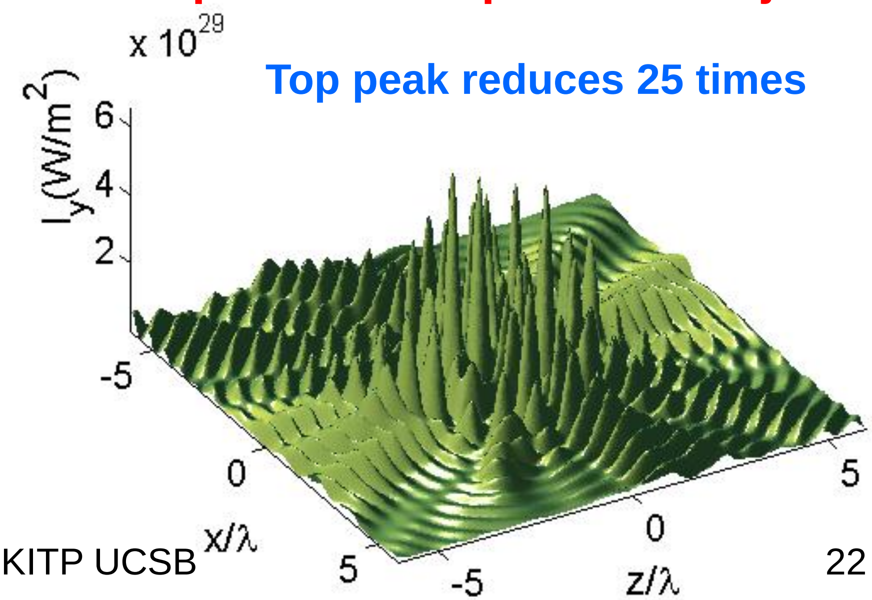
c)

pulse envelope jitter $\delta_n = 4T\,\mathrm{rand}(\pm 0.5)$



b)

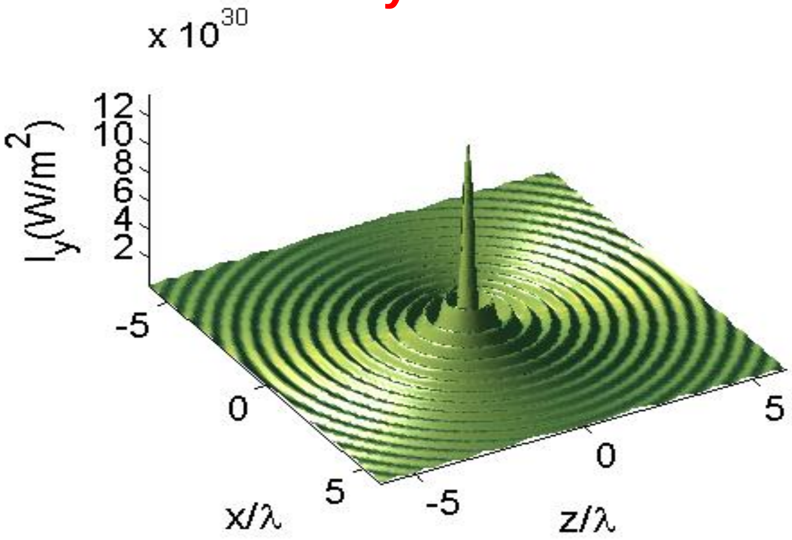
pulse envelope and CEP jitters



d)

Intensity distribution for linearly polarized lasers, N=63

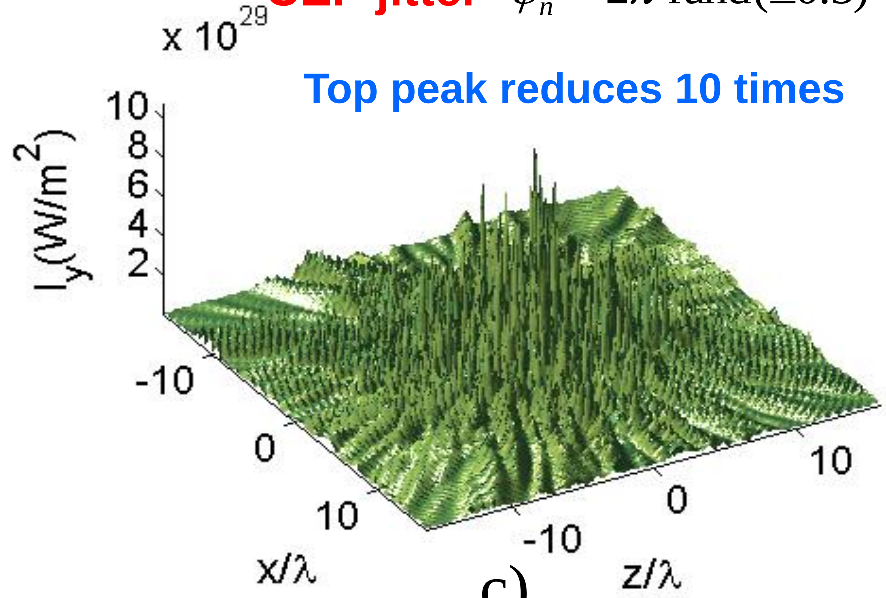
Perfect synchronization



a)

CEP jitter $\varphi_n = 2\pi\ \mathrm{rand}(\pm 0.5)$

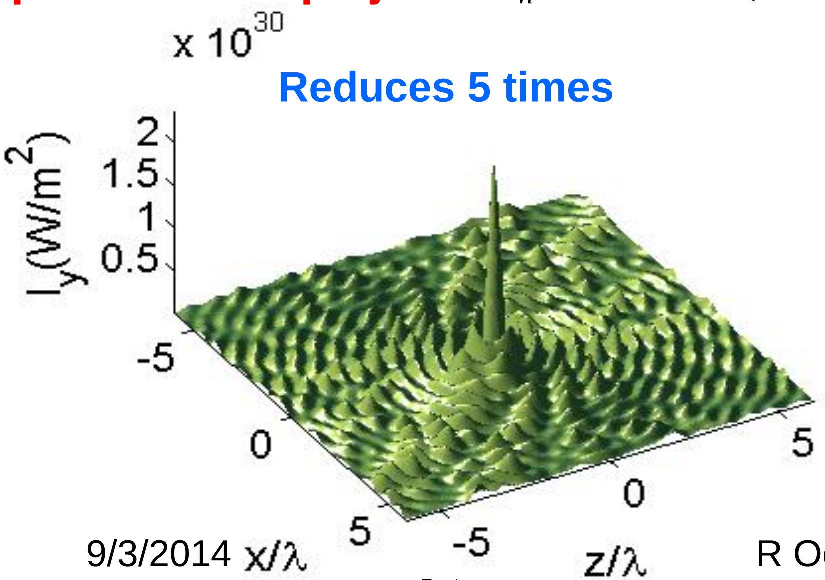
Top peak reduces 10 times



c)

pulse envelope jitter $\delta_n = 4T\ \mathrm{rand}(\pm 0.5)$

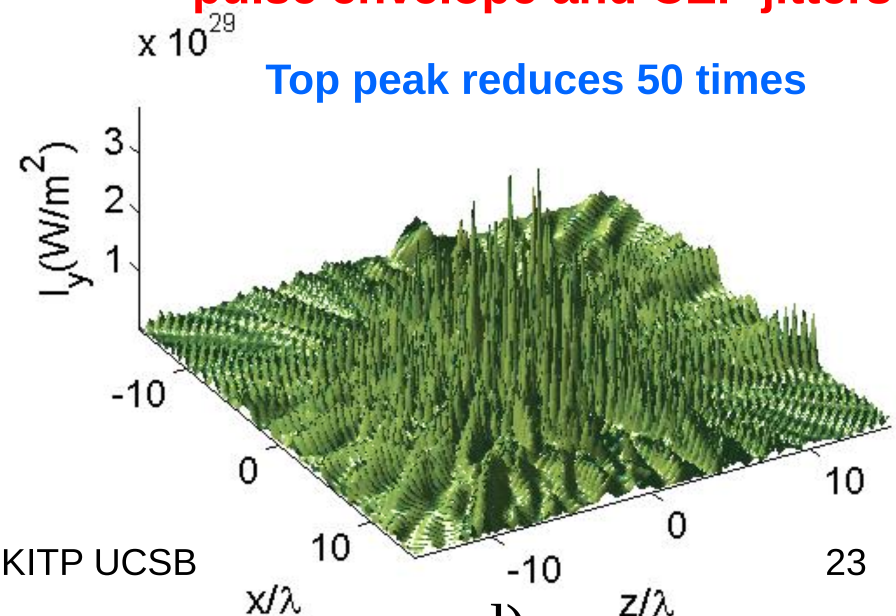
Reduces 5 times



b)

pulse envelope and CEP jitters

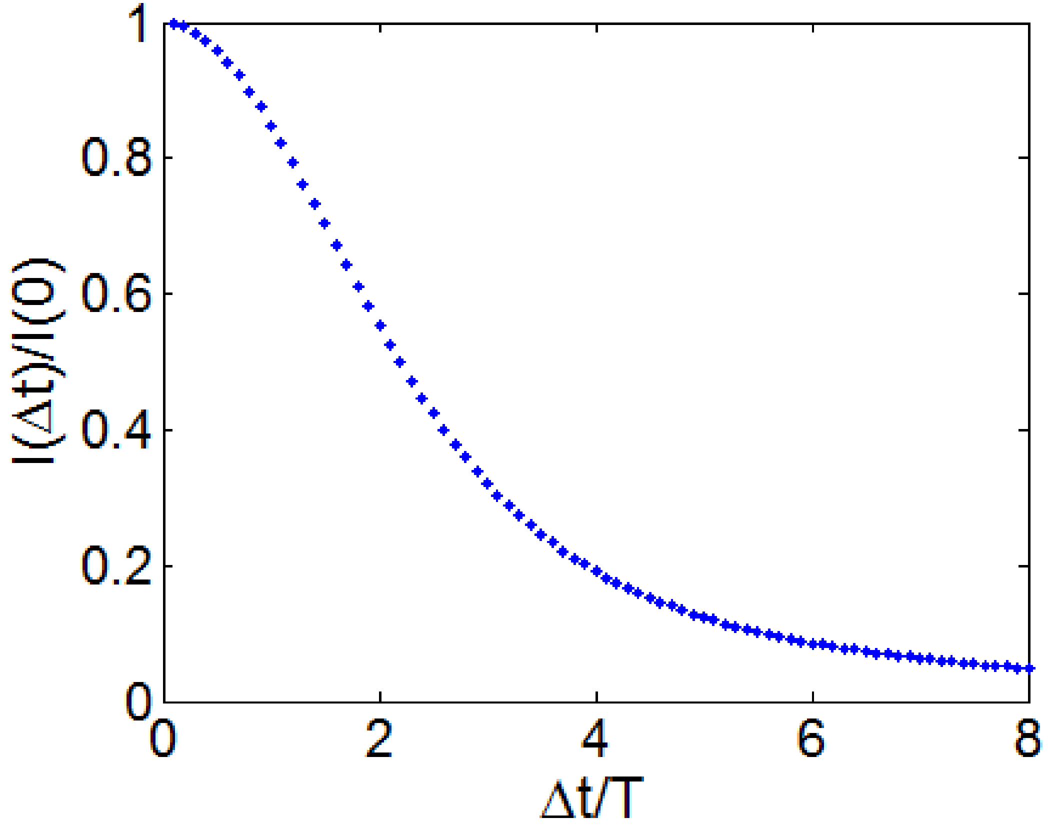
Top peak reduces 50 times



d)

Envelope Jitters

$$\frac{I(\Delta t)}{I(0)} = \frac{1}{(2N+1)^2}\left(2\sum_{n=1}^{N} e^{-(n\Delta t/N2T)^2} + 1\right)^2$$

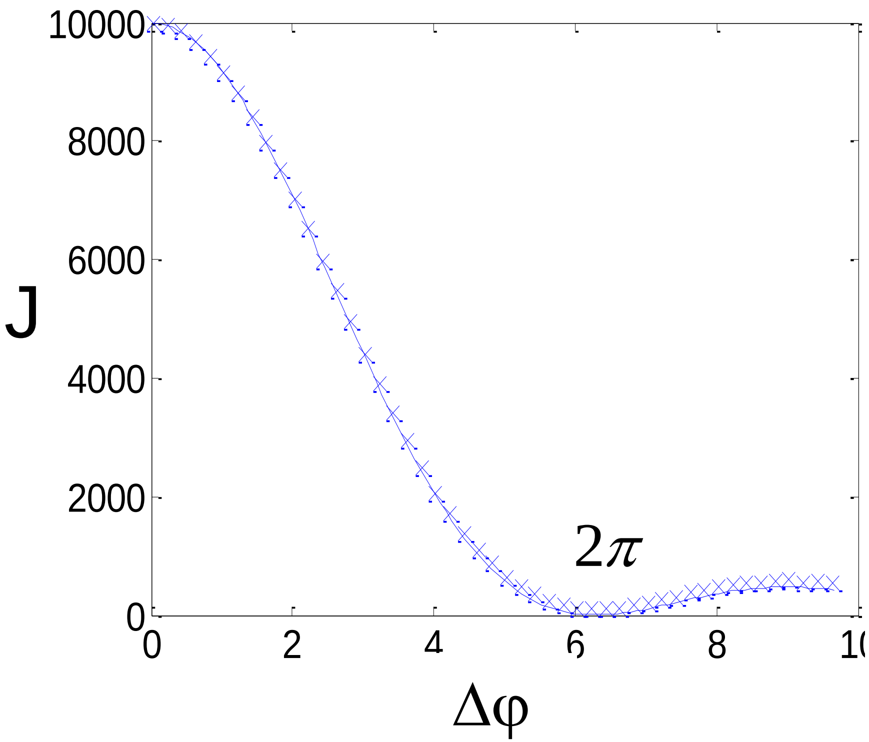


b)

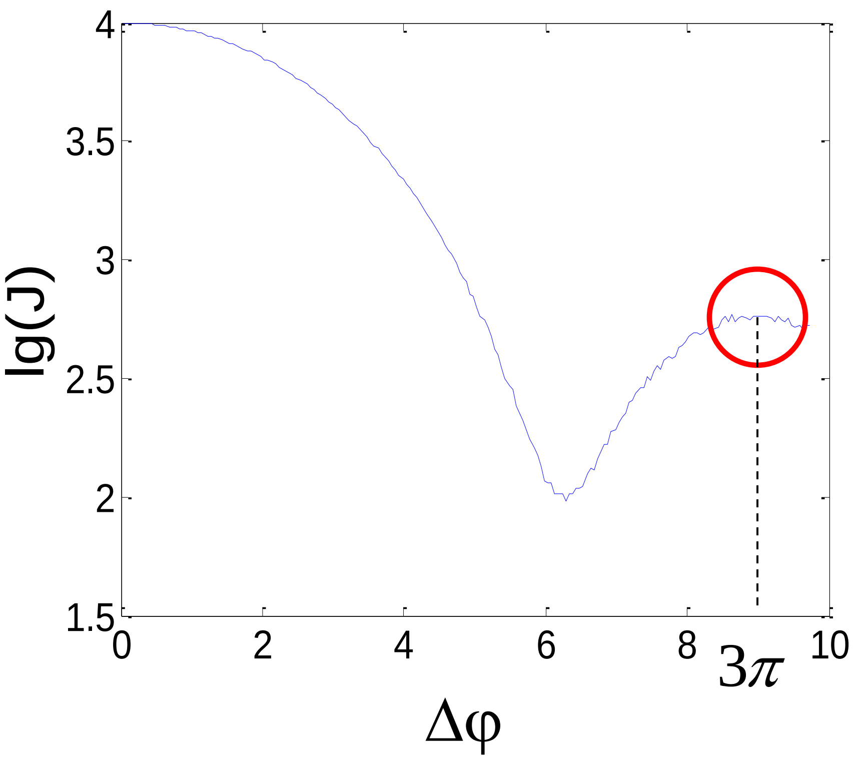
CEP Jitters

$$J(\Delta\varphi) = \frac{1}{M}\sum_{k=1}^{M}\left|\sum_{n=1}^{N} e^{i\phi_n}\right|^2 \underset{N\ \text{large}}{\simeq} N^2 \frac{\sin^2(\frac{\Delta\varphi}{2})}{(\frac{\Delta\varphi}{2})^2}$$

Number of random trials M=50, N=100, $\Delta\varphi = 2\pi$



c) i

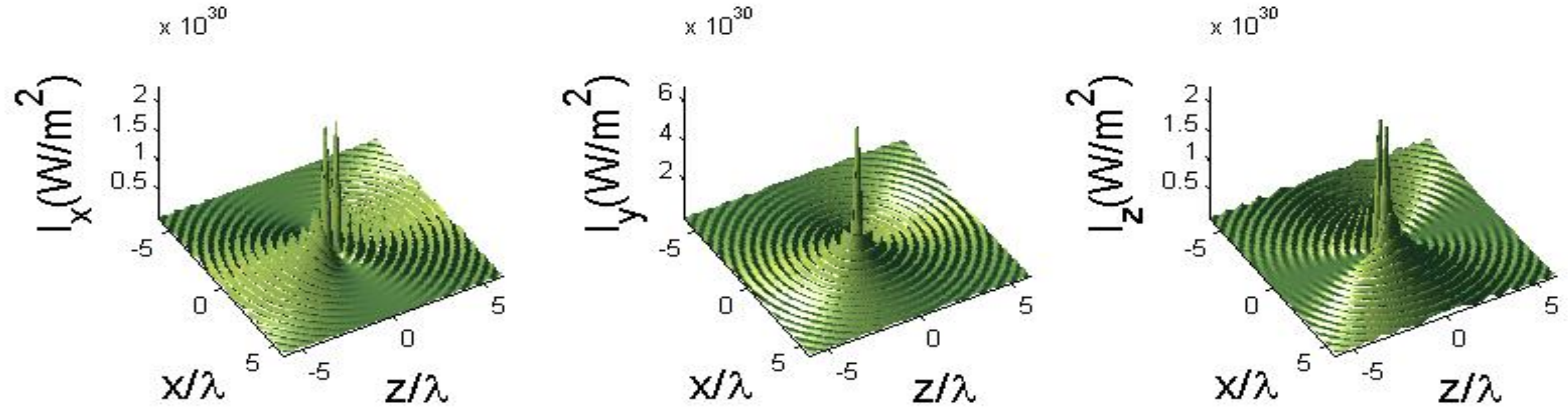


c) ii

Intensity distribution for circularly polarized lasers

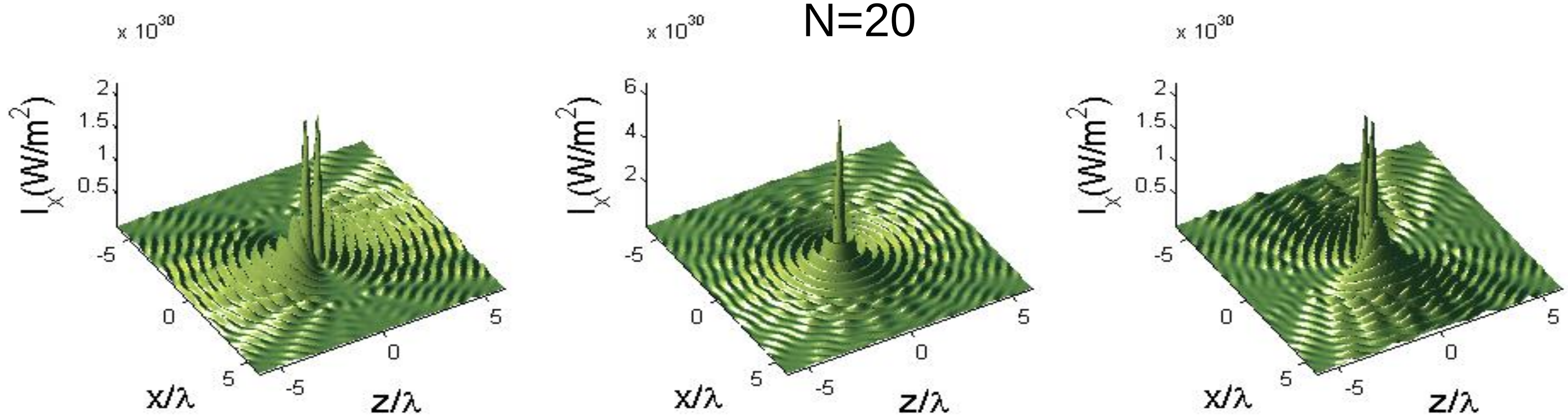
$$I^{lin} \approx I_y^{cir} + \sqrt{2}(I_x^{cir} + I_z^{cir}).$$

N=63

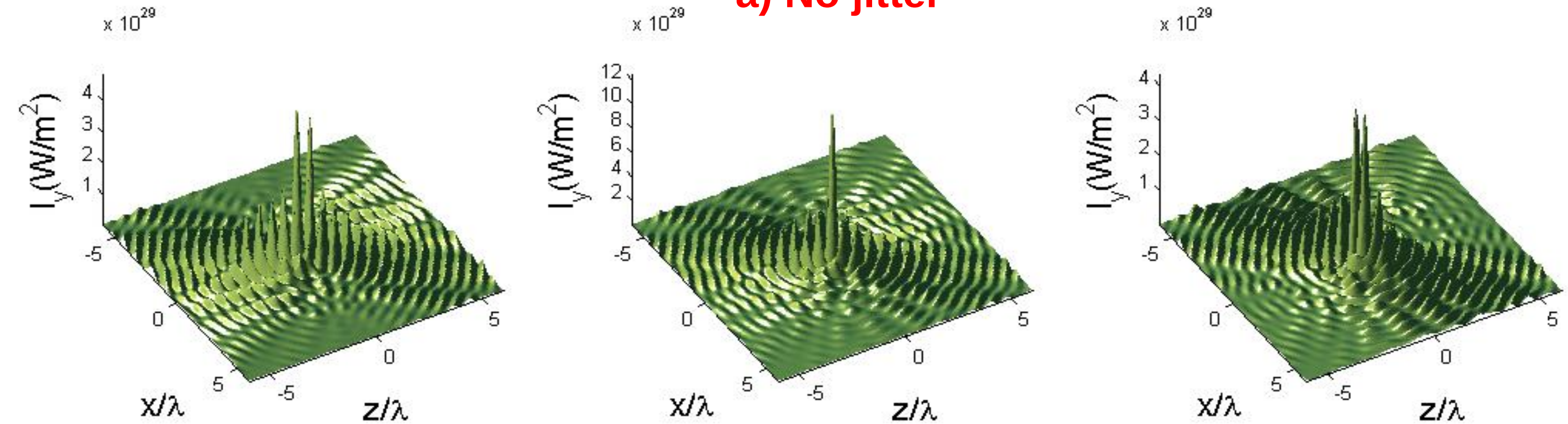


a) No jitter

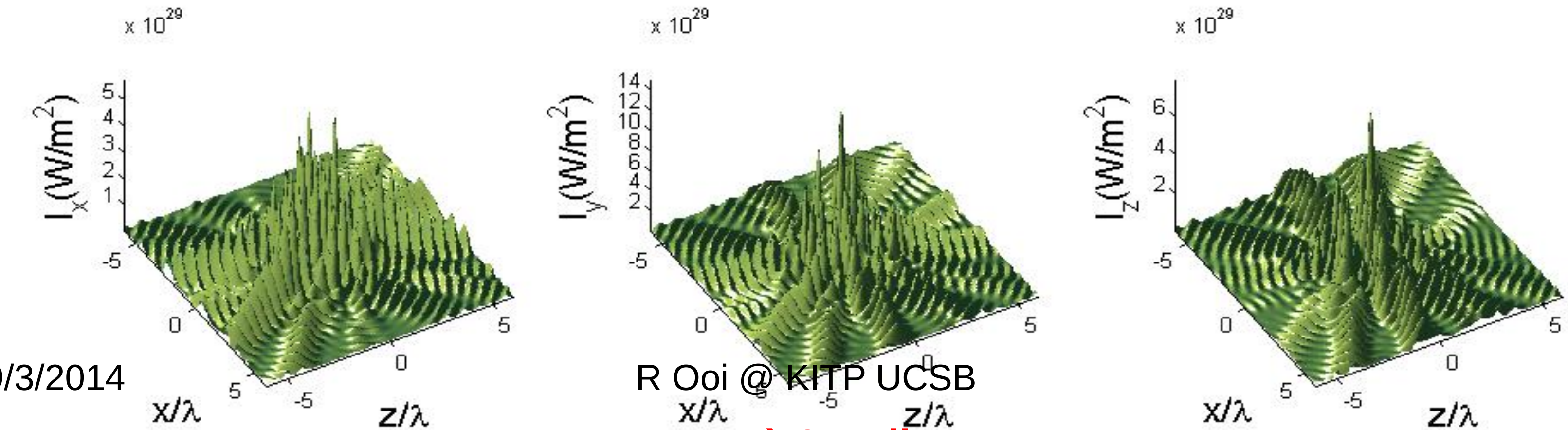
N=20



a) No jitter



b) Pulse envelope jitter



c) CEP jitter

Conclusion

- **Multiple pulses in circular geometry can be scaled up to produce intensity beyond the nonlinear vacuum QED.**
- **Unexpectedly, the enhancement does not scale with N^2 but with area of beam.**
- **In the (worst) case without synchronizations of the CEP and the pulse timing, the intensity is sacrificed by a factor of 50 only.**
- **Superintense laser is possible and should be developed to safeguard the future of mankind.**

Future research

- Super laser to destroy/deflect massive objects in space

Quantum & Laser Science group

Postdoc

Shailendra Singh (India)

PhDs

F Mathkoor (Yemen) - quantum correlation

Davoud Ghodsi (Iran) - nanophotonics

KS Ng (M'sia) - relativistic optics

PhD

C. Y. Lee (M'sia) - nonlinear photonics

Nor H (M'sia) - quantum optics

Ho Wai Loon (M'sia) - intense laser interactions

MSc

P C Seow (M'sia) - nonlinear scattering

KS Tan(M'sia) - quantum plasmonics

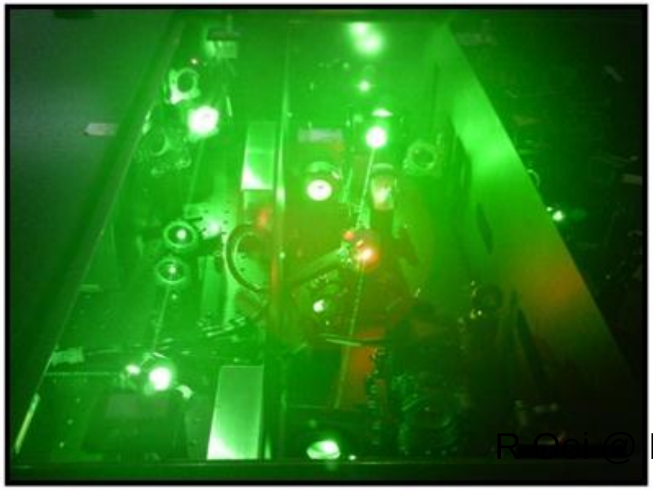
S. Ainisyahida (M'sia) - quantum information

KC Low (M'sia) - micro-nanophotonics

YY Khoo (M'sia) - qtm vacuum

Quantum and Laser Science, Femtosecond Laser Lab
HIR Building, Universiti Malaya

The Femtosecond Laser.



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Thank You