# Optical Control of Laser-driven X-ray and XUV Radiation Sources

5TH EUROPEAN ADVANCED ACCELERATOR CONCEPTS WORKSHOP

LNF-INFN | 22 SEPTEMBER 2021 | ZAHRA M. CHITGAR - JÜLICH SUPERCOMPUTING CENTRE (JSC)

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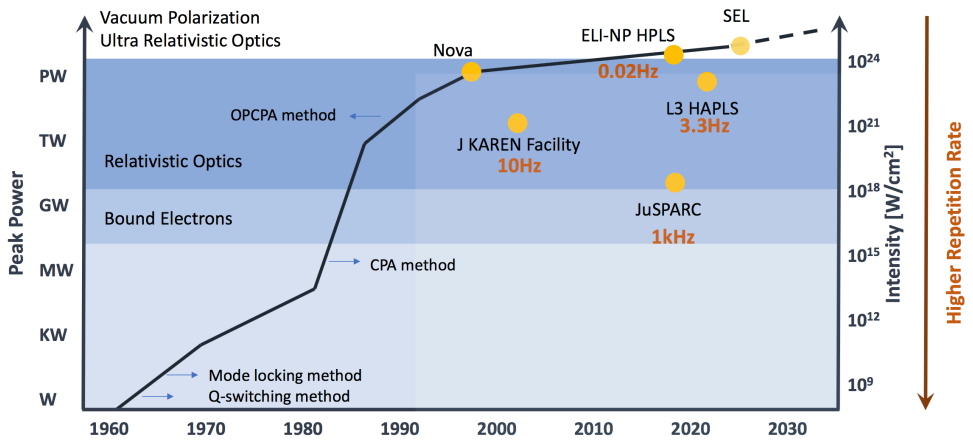
# INTRODUCTION AND MOTIVATION

## Ultra-short laser pulses

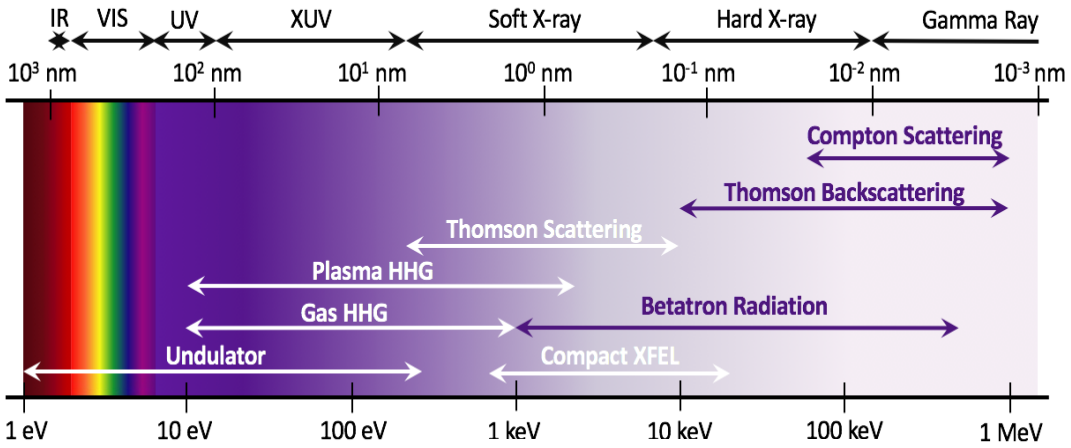
**Wish list characteristics of a laser-driven radiation source:**

- High flux
- Small energy bandwidth
- Low divergence
- Small emittance
- Short duration

Enhancement of laser intensities, high acceleration gradient (1GeV/m), high repetition rate




## Simulation of Laser-driven Radiation




Resolving a 10keV photon simulation resolution should be at least 0.01nm → Computationally very expensive

Existing Alternative: Calculating Far-field radiation based on the electron trajectory.

**Calculating near-field radiation by solving Maxwell's equation for electron trajectories.**

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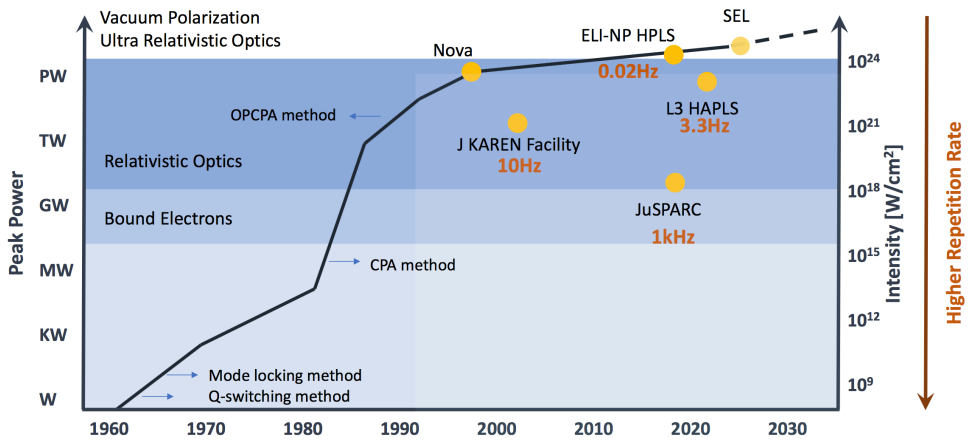


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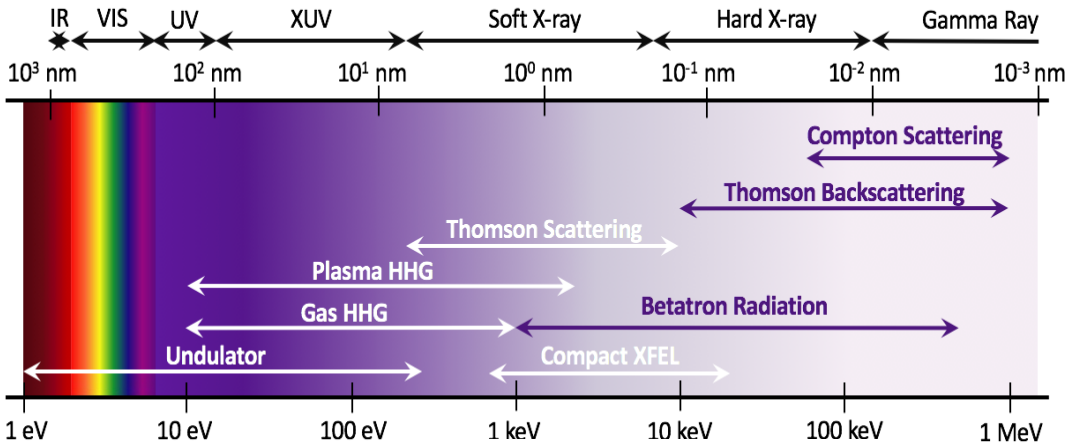


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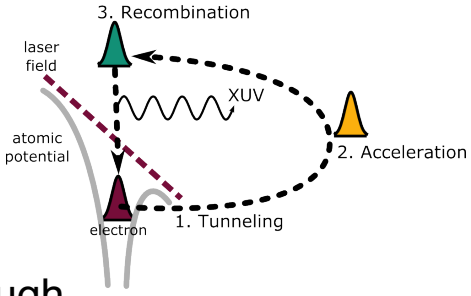
# BASICS OF LASER-DRIVEN RADIATION

## Compact Radiation Sources

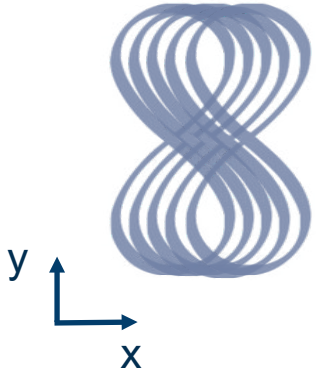
### Coherent High Harmonic Generation (HHG)

**HHG in Gas:** emission during a recombination process



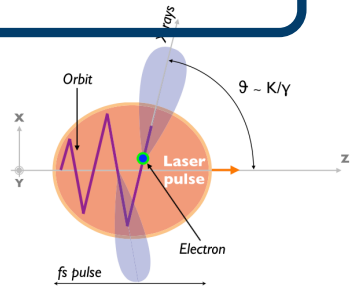

**HHG in Plasma:** emission through collective electron bunching and acceleration ⟶ nonlinear currents

Harmonic polarization depends on the incident laser polarization

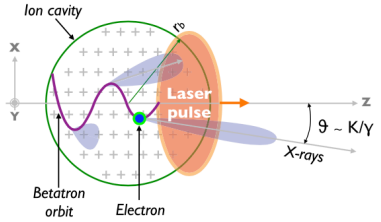



### Emission from Relativistic Electron Oscillation

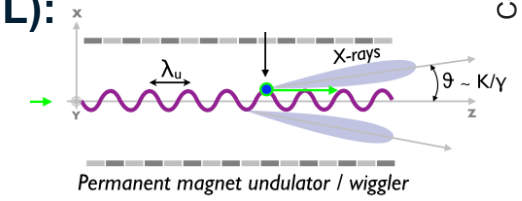
**Thomson scattering**
**Thomson backscattering:**
undulating electrons directly driven in EM field of a laser pulse




**Betatron Radiation:**
undulating electrons in plasma




**Coherent Free Electron Laser (FEL):**
undulating electrons in electromagnetic field of an undulator device




Corde, Sébastien, et al. "Femtosecond x rays from laser-plasma accelerators." *Reviews of Modern Physics* 85.1 (2013): 1.

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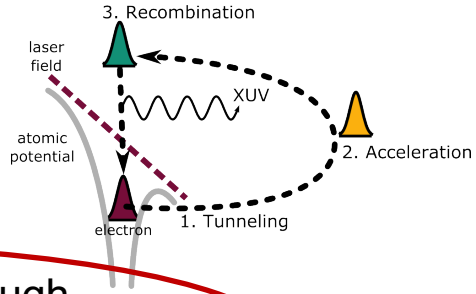


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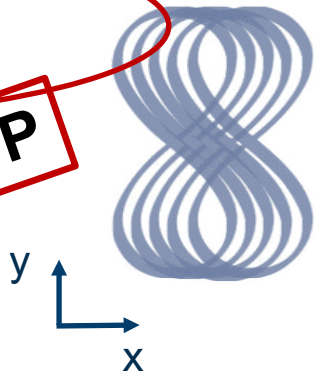
CP

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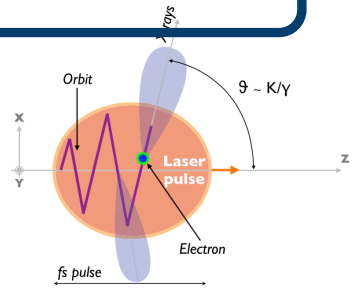


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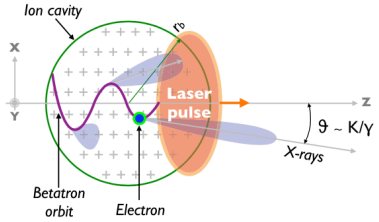


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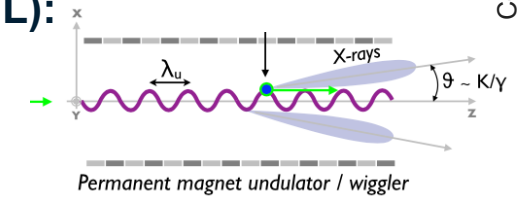


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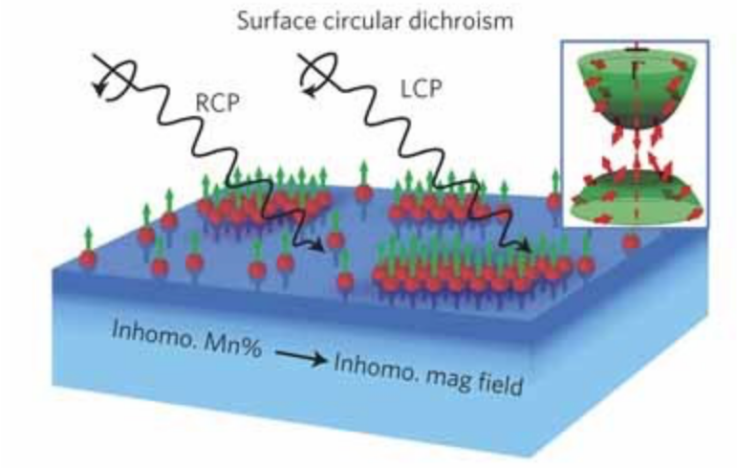
# CIRCULARLY POLARIZED (CP) HHG




Xu, S.-Y. et al. Hedgehog spin texture and Berry's phase tuning in a magnetic topological insulator. *Nature Phys.* **8**, 616–622 (2012).

**CP- sources Applications:**

- Photoelectron circular dichroism in chiral molecules
- Spin polarization of photoelectrons from topological insulators
- X-ray magnetic circular dichroism spectroscopy
- Magnetic microscopy
- Visualizing electric chirality and phase

**In gas:**

- There will be no recollision of electrons in case of CP laser pulse ⇒ no harmonics

**In Plasma:**

- Plasma Perturbation interacting with laser field

$$\frac{\partial^2 n}{\partial t^2} + \frac{\omega_p^2}{\gamma_0} n = \frac{c^2}{2\gamma_0^2}\frac{\partial A^2}{\partial x}$$

$$\mathbf{A} = (0, \delta A_0 \cos\varphi, (1-\delta^2)^{\frac{1}{2}} A_0 \sin\varphi)$$
$$\mathbf{A}_{CP} = (0, A_0 \cos\varphi, \ A_0 \sin\varphi)$$

Right hand side of the equation will be zero: no harmonic generation
Elliptically polarized harmonics could be generated by oblique incidence, **OR**

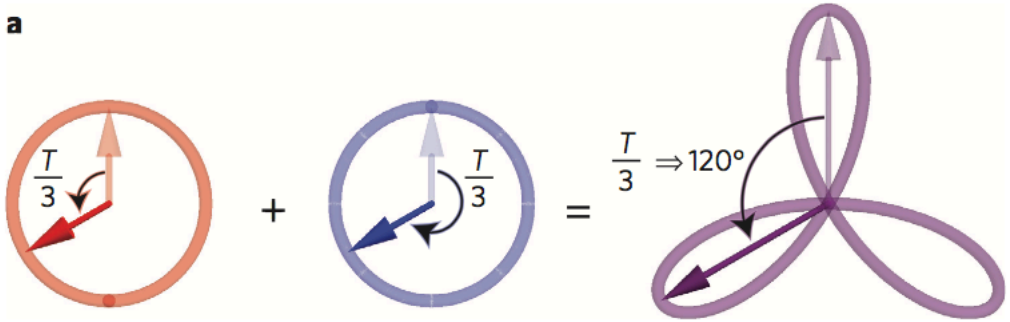
# CIRCULARLY POLARIZED (CP) HHG

## In Gas

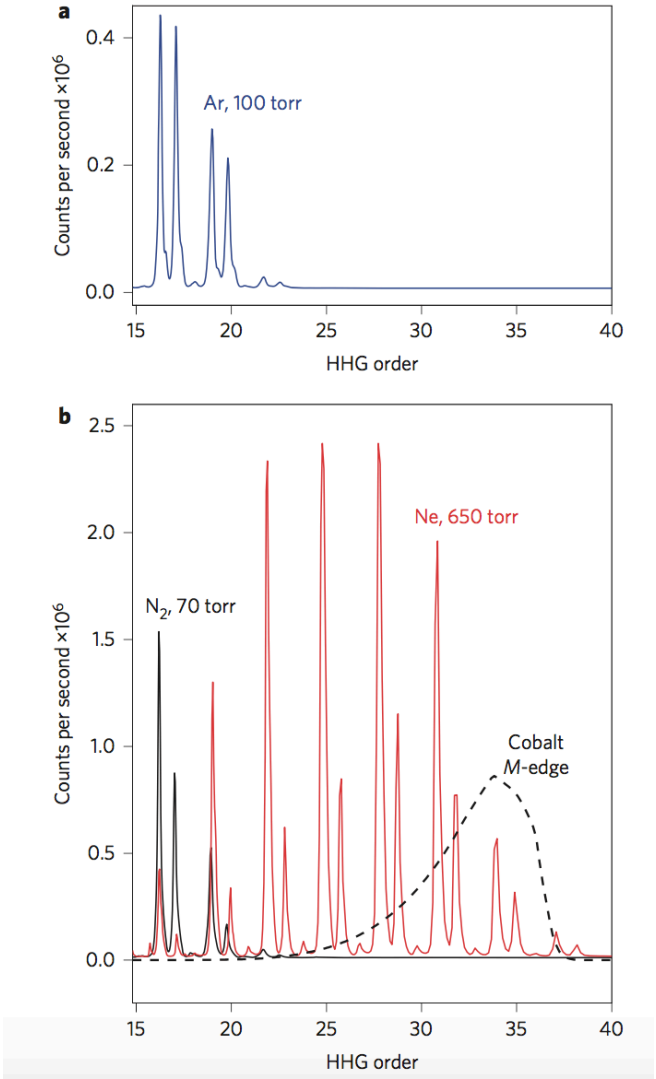
Bi-color: 2 pump pulses with different wavelength

$$\mathbf{A}_{CP} = (0, 0,\ A_0 \sin\varphi)$$

$$\mathbf{A'}_{CP} = (0, A'_0 \cos\varphi', 0)$$



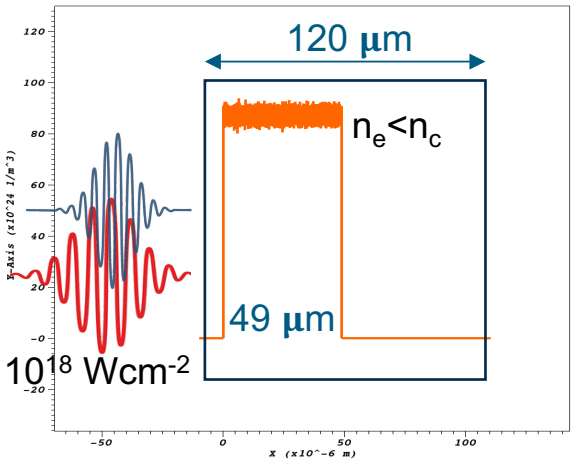

- Every third harmonic is suppressed (frequency ration q = 2)
- Harmonics efficiency limited by ionization
- LP Cutoff: $E_{max} = I_p + 3.17U_p$




Kfir, O., Grychtol, P., Turgut, E. *et al. Nature Photon* **9**, 99–105 (2015)c

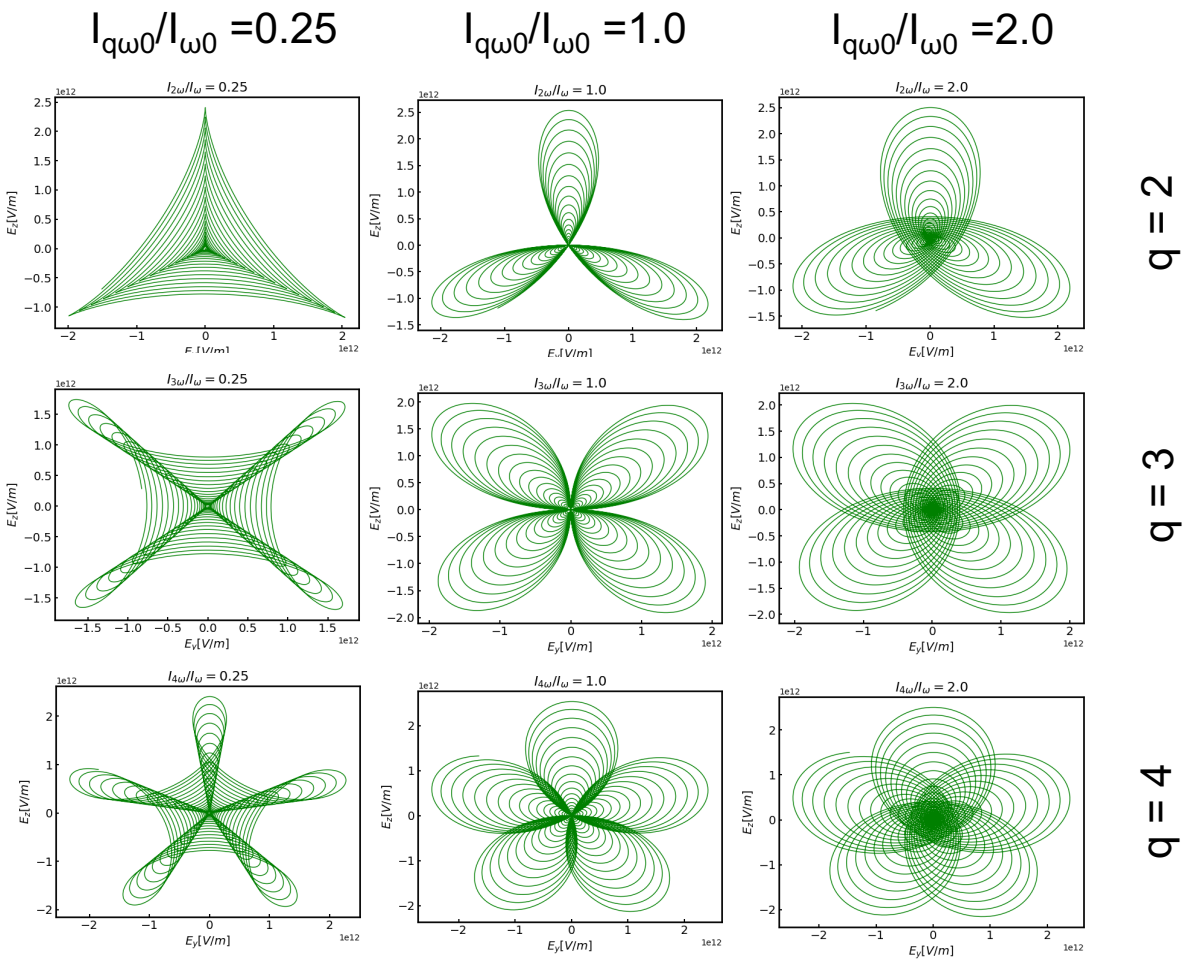
# BI-COLOR CP HARMONIC GENERATION IN PLASMA

## (1D PIC Simulation results)




- $n_x$ = 60000 (400 grid per wavelength)
- underdense preionized helium plasma
- 10 μm from the left boundary
- 100 particles per cell
- Laser pulse wavelength 0.8 μm
- Pulse duration 30 fs: intensity
- 2 pulses of $\omega_0$ and $q\omega_0$: phase ratio q
- Counter- or co-polarized

**Incident Laser Profile: $I_{\omega 0} + I_{q\omega 0}$**



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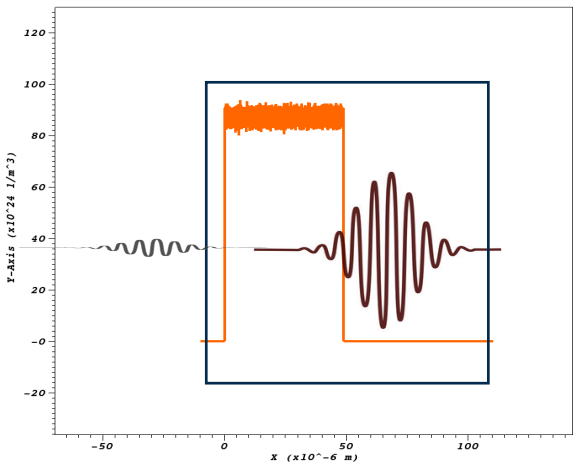
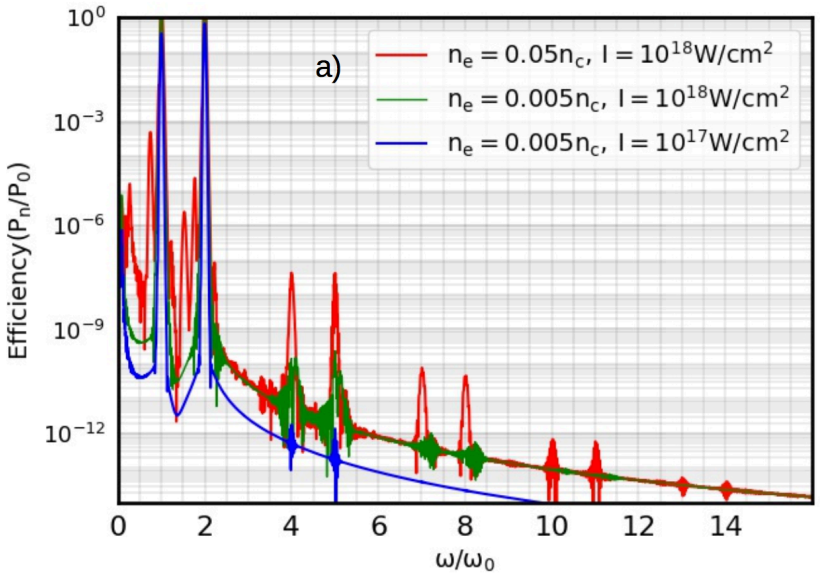
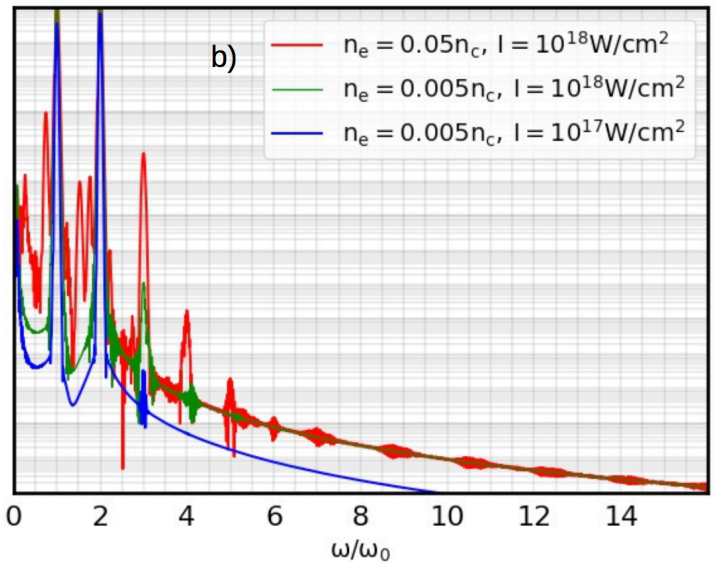



**frequency ration q = 2**

Counter-polarized pulses




Co-polarized pulses




harmonics efficiency increases with:

- Laser intensity
- Plasma desnity



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# SIMULATION TOOLS

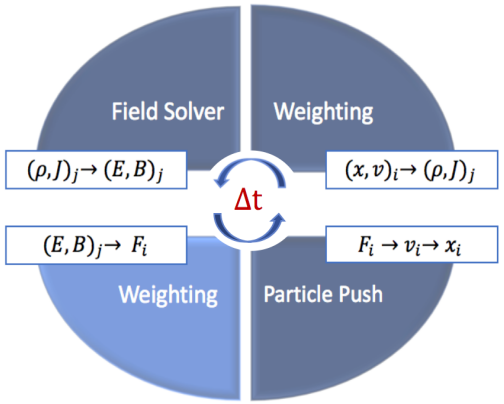
## Fully Kinetic Particle in Cell (PIC) Code

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v}\times\mathbf{B})$$

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

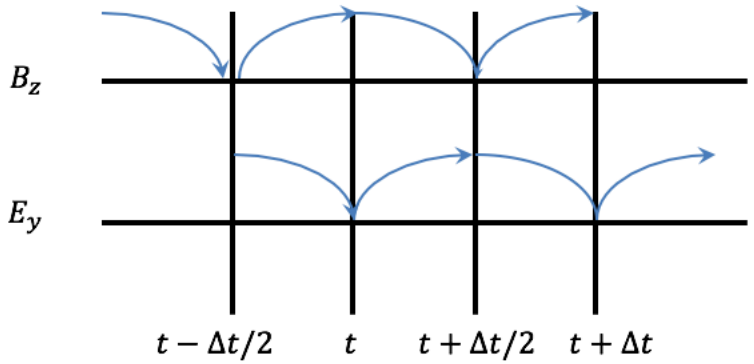
$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t}$$




### Yee Scheme

$$\frac{E^{n+1} - E^{n}}{\Delta t} = c\nabla\times B^{n+1/2} - 4\pi J^{n+1/2}$$

$$\frac{B^{n+1/2} - B^{n-1/2}}{\Delta t} = -c\nabla\times E^{n}$$




- ✓ Fully kinetic models like PIC codes: solve the Maxwell's equations for a velocity distribution of particles on each grid point
- ✓ Fluid models use the first moment of the velocity distribution on each grid point
- ➢ Fluid models are faster

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# FLUID MODEL VS. FULLY KINETIC PIC CODE

## 1D3v Fluid Model – DS Field Solver

$$\frac{\boldsymbol{B}^{n+1/2}-\boldsymbol{B}^{n-1/2}}{\Delta t}=-c\nabla\times\boldsymbol{E}^{n},$$

$$\frac{\boldsymbol{E}^{n+1}-\boldsymbol{E}^{n}}{\Delta t}=c\nabla\times\boldsymbol{B}^{n+1/2}-\boldsymbol{J}^{n+1/2}$$

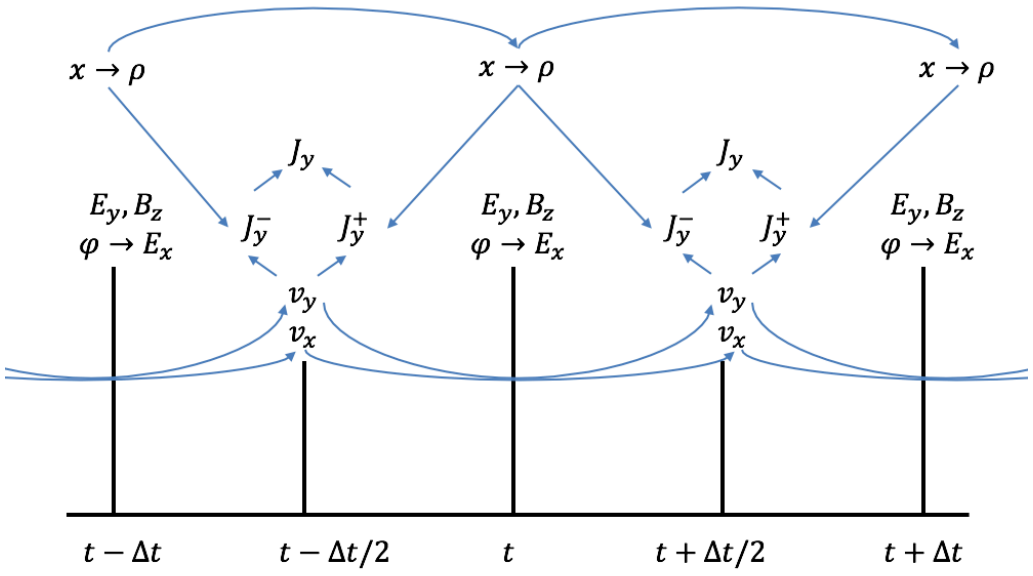
$$\left(\frac{\partial}{\partial t}\pm c\frac{\partial}{\partial x}\right)\,{}^{\pm}F_y=\mp\frac{1}{2}J_y$$

$$\left(\frac{\partial}{\partial t}\pm c\frac{\partial}{\partial x}\right)\,{}^{\mp}F_z=\mp\frac{1}{2}J_z$$

$$E_y={}^{+}F_y-{}^{-}F_y,$$
$$-E_z={}^{+}F_z-{}^{-}F_z,$$
$$B_y={}^{+}F_z+{}^{-}F_z,$$
$$B_z={}^{+}F_y+{}^{-}F_y.$$

$$\left(F^{+}_{y,z}\right)^{n+1}_{i+1}=\left(F^{+}_{y,z}\right)^{n}_{i}-\frac{\Delta t}{2}\left(J_{y,z}\right)^{n+1/2}_{i+1/2},$$

$$\left(F^{-}_{y,z}\right)^{n+1}_{i}=\left(F^{-}_{y,z}\right)^{n}_{i+1}+\frac{\Delta t}{2}\left(J_{y,z}\right)^{n+1/2}_{i+1/2},$$




$$\left(A_{y,z}\right)^{n+1}_{i}=\left(A_{y,z}\right)^{n}_{i+1}-2\Delta t\left(F^{+}_{y,z}\right)^{n+1/2}_{i+1/2}$$

$$\left(J_{y,z}\right)^{n}_{i}=\left(v_{y,z}\right)^{n}_{i}\left(n_e\right)^{n}_{i}=\frac{\left(p_{y,z}\right)^{n}_{i}\left(n_e\right)^{n}_{i}}{\gamma^{n}_{i}}$$

# BI-COLOR CP HARMONIC GENERATION IN PLASMA

## (Fluid Model)

$$\mathbf{A_1} = \left(0, \frac{A_0}{\sqrt{2}}\cos\theta, \frac{A_0}{\sqrt{2}}\sin\theta\right), \quad \theta = \omega_0 t - k_0 x,$$

$$\mathbf{A_2} = \left(0, \frac{A_0'}{\sqrt{2}}\cos\theta', \frac{A_0'}{\sqrt{2}}\sin\theta'\right), \quad \theta' = q\omega_0 t - k_q x$$

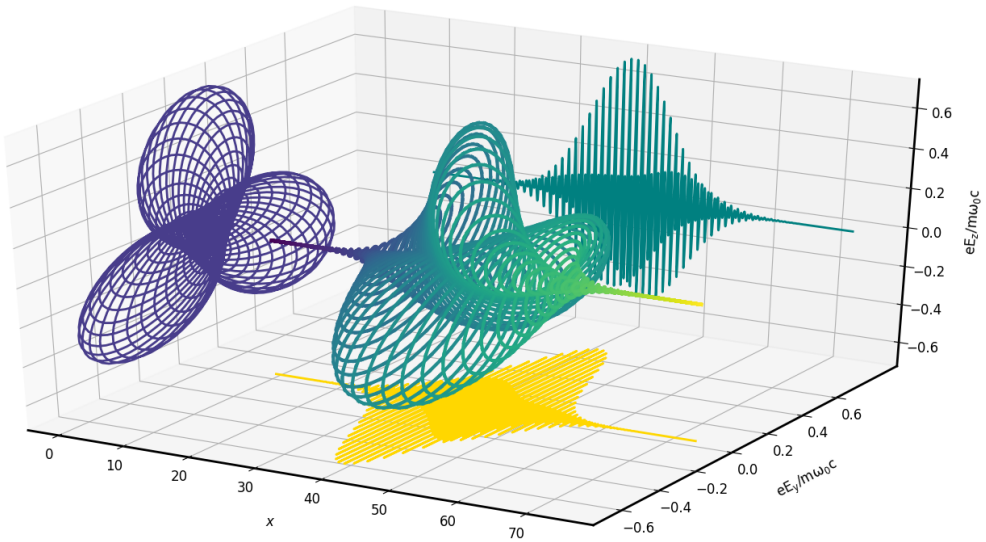
$$\nabla^2 \boldsymbol{A} - \frac{1}{c^2}\frac{\partial^2 \boldsymbol{A}}{\partial t^2} = -\mu_0 \boldsymbol{J}$$

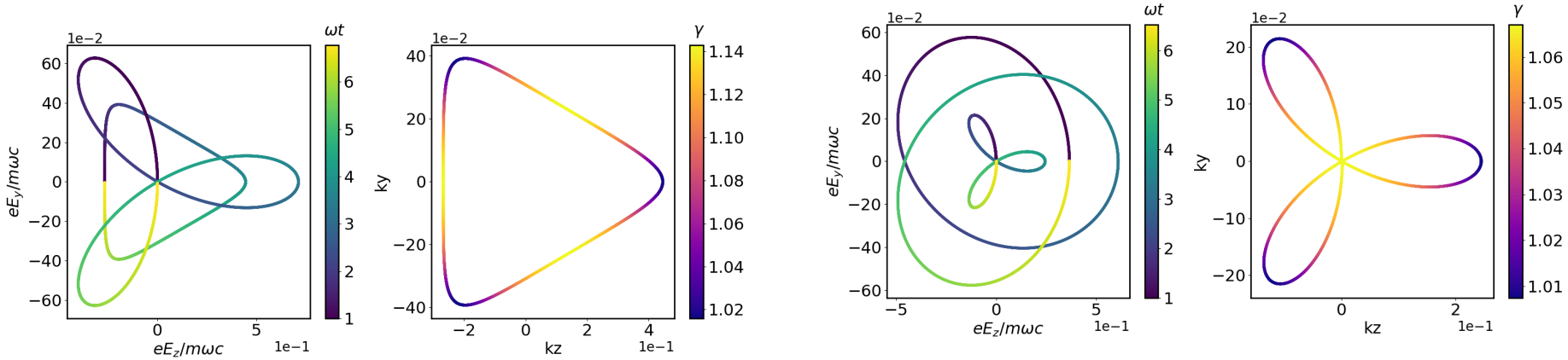
$$\frac{\partial n_e}{\partial t} = -\frac{c\partial(n_e u)}{\partial x}$$

$$\frac{\partial^2 \varphi}{\partial x^2} = k_p^2(n_e - 1)$$

$$\frac{\partial p_x}{\partial t} + cu\frac{\partial p_x}{\partial x} = c\frac{\partial \varphi}{\partial x} - \frac{c}{2\gamma}\frac{\partial A_\perp^2}{\partial x}$$

Esarey, Eric, et al. "Nonlinear analysis of relativistic harmonic generation by intense lasers in plasmas." *IEEE transactions on plasma science* 21.1 (1993): 95-104.



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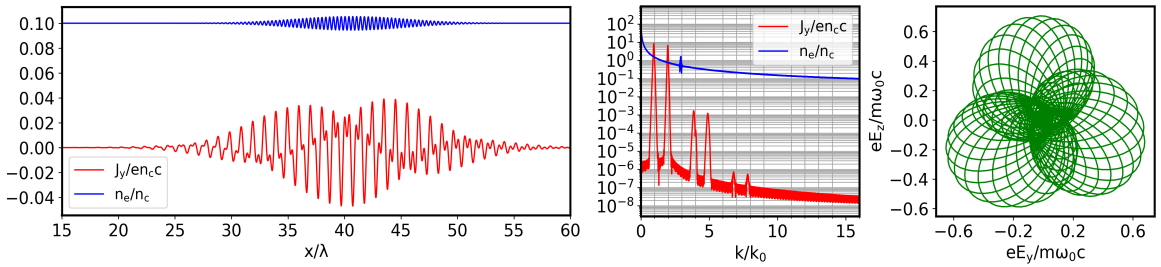
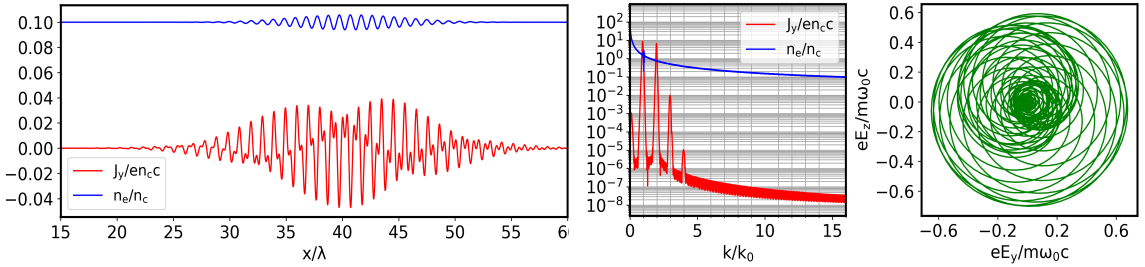
# BI-COLOR CP HARMONIC GENERATION IN PLASMA

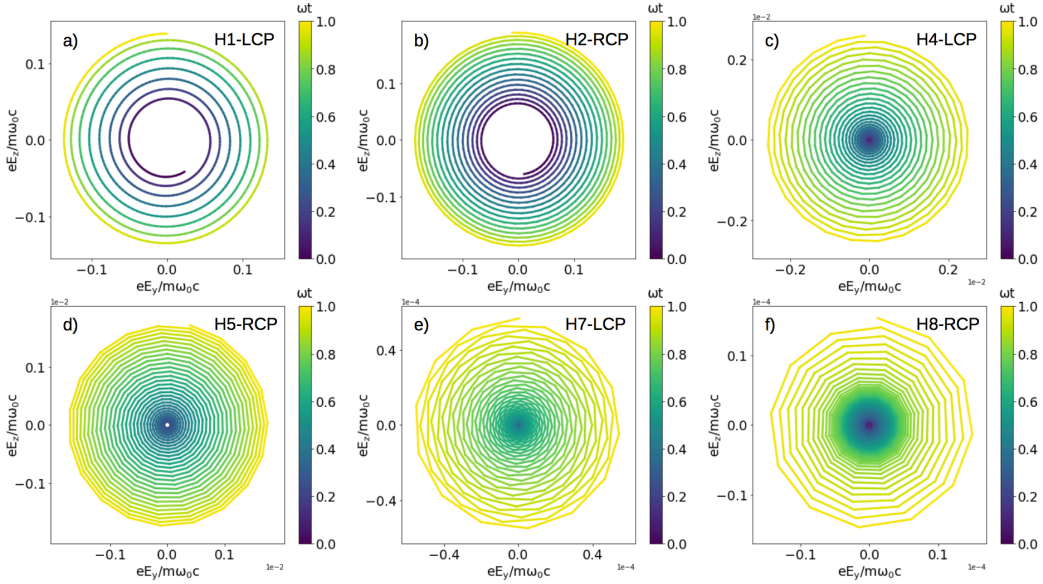
## (Selection rules + Chirality/handedness)

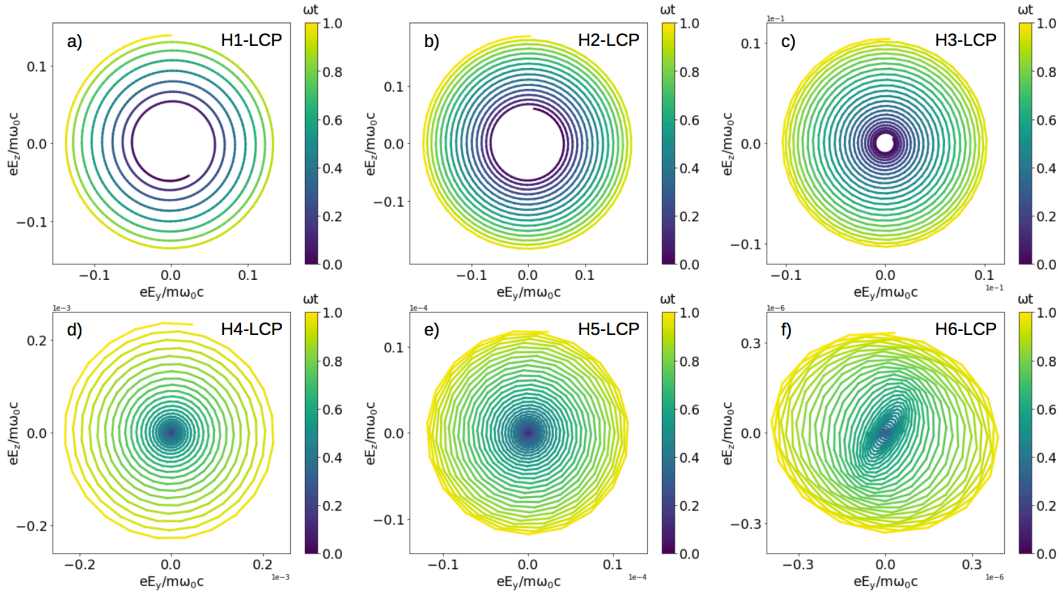
Counter-Polarized: $I_{2\omega}/I_{\omega}=2$




Co-Polarized: $I_{2\omega}/I_{\omega}=2$



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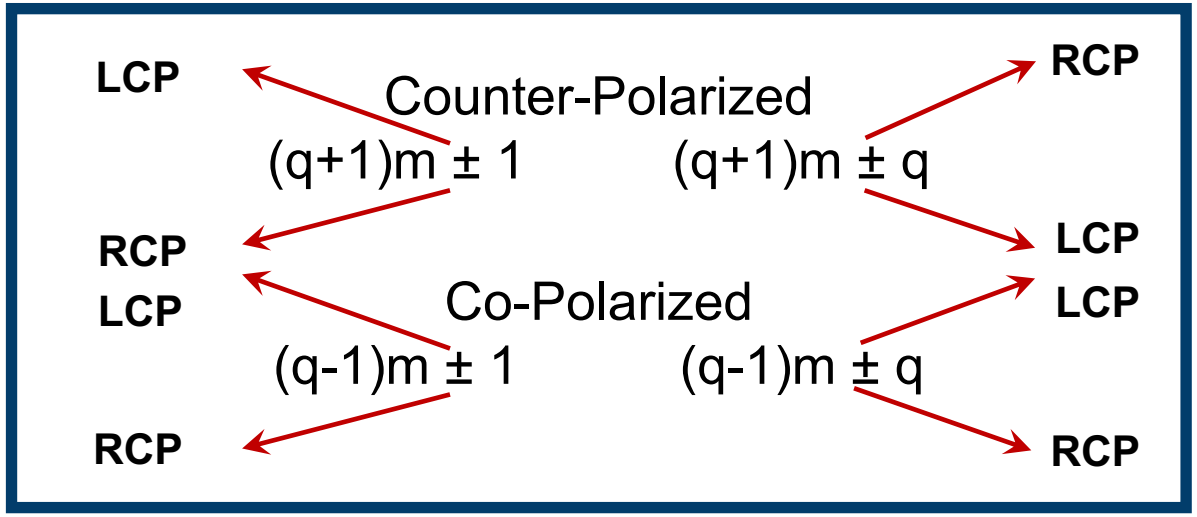
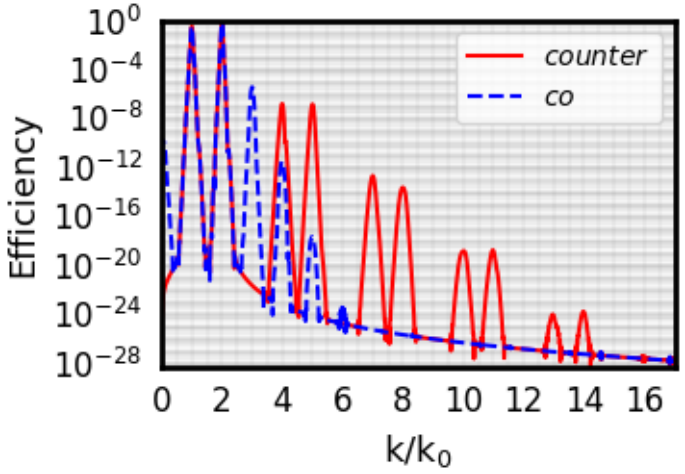
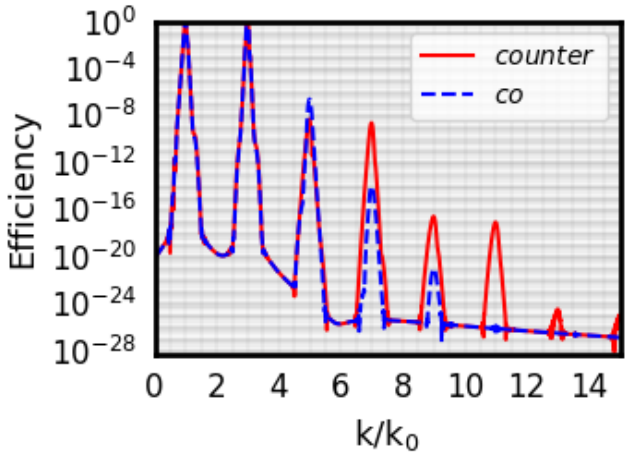
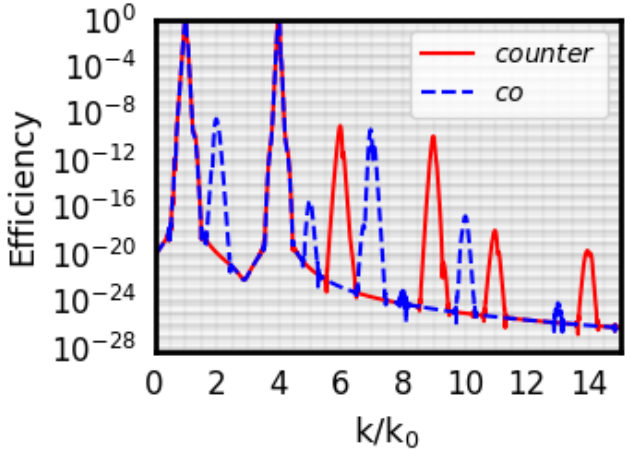


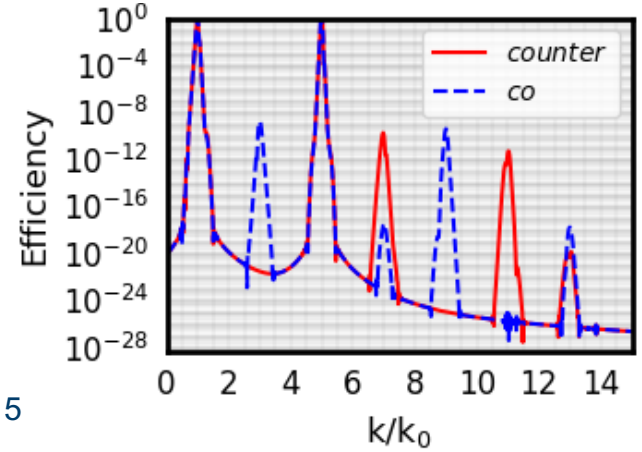

q = 2
counter: 3m ± 1, 3m ± 2
co: m ± 1, m ± 2




q = 3
counter: 4m ± 1, 4m ± 3
co: 2m ± 1, 2m ± 3




q = 4
counter: 5m ± 1, 5m ± 4
co: 3m ± 1, 3m ± 4




q = 5
counter: 6m ± 1, 6m ± 5
co: 4m ± 1, 4m ± 5

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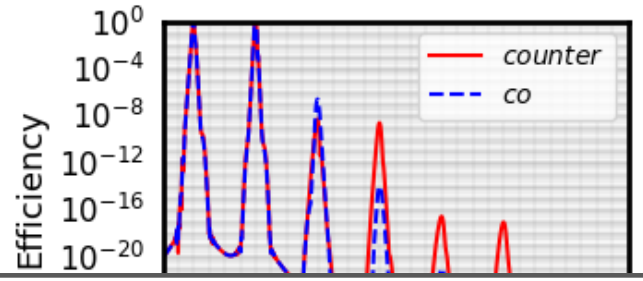


q = 3
counter: 4m ± 1, 4m ± 3
co: 2m ± 1, 2m ± 3

LCP

RCP

LCP

RCP

± 4

± 5


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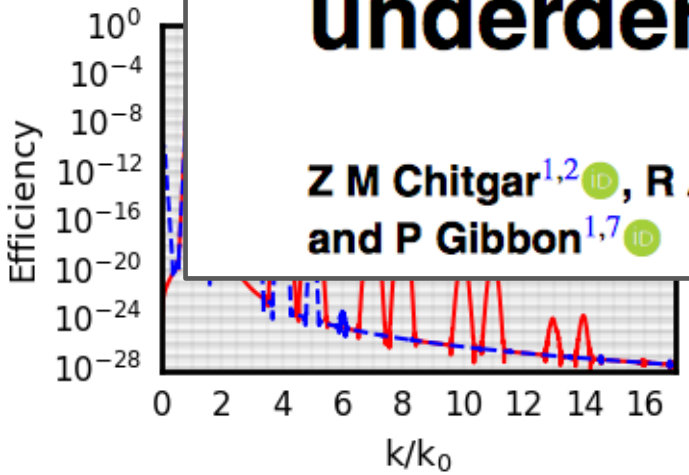
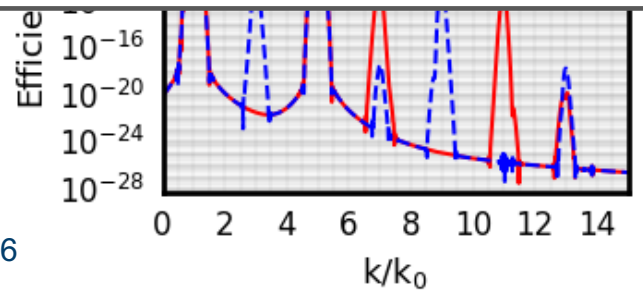
Plasma Phys. Control. Fusion **63** (2021) 035023 (12pp)
https://doi.org/10.1088/1361-6587/abd9e1


## Theory of circularly polarized harmonic generation using bi-colour lasers in underdense plasmas


Z M Chitgar[1,2], R Adam[3], C Greb[3], A Lehrach[2,4,5], M Büscher[3,6] and P Gibbon[1,7]

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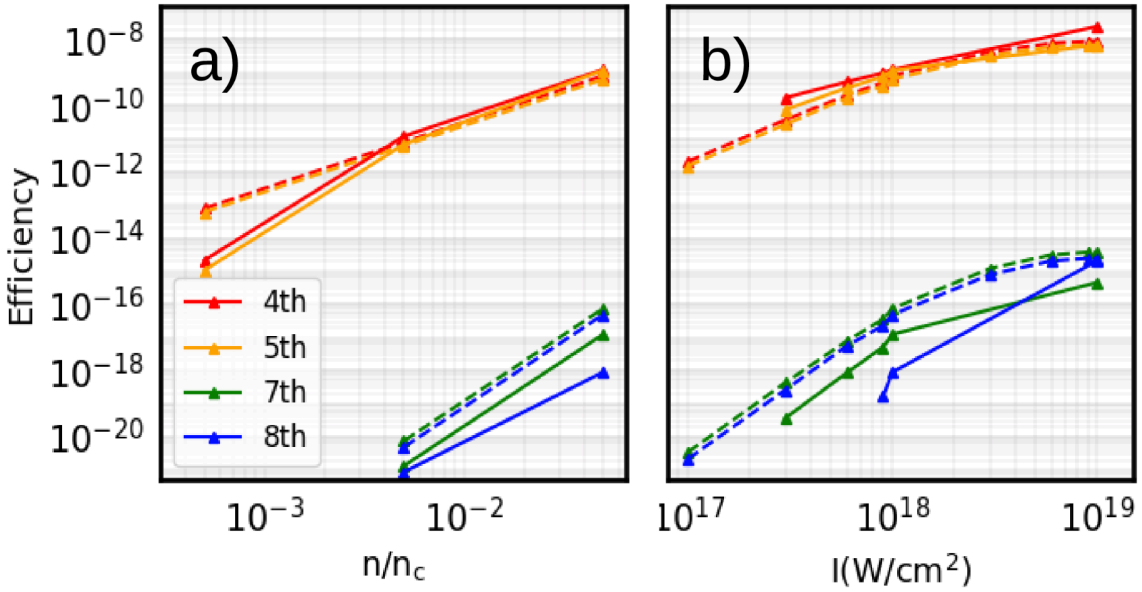
# EFFICIENCY SCALING

Comparison between numerical and analytical fluid model




$$\frac{P_m}{P_0} \propto \left(\frac{n_e}{n_0}\right)^{2m}$$

- femtosecond laser
- total power of 1 TW
- plasma density of $n_e = 0.05 n_c$

number of photons decreases from ~ $10^9$ for the 4-th and 5-th harmonics to ~ $10^4$ for 7-th and 8-th

High repetition rate is useful

✓ Or solid targets: providing higher number of electrons for increasing the efficiency

Chen Z 2018 Phys. Rev. E 97 043202



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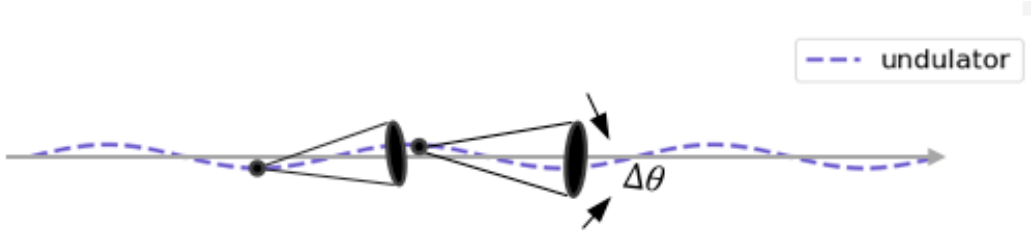
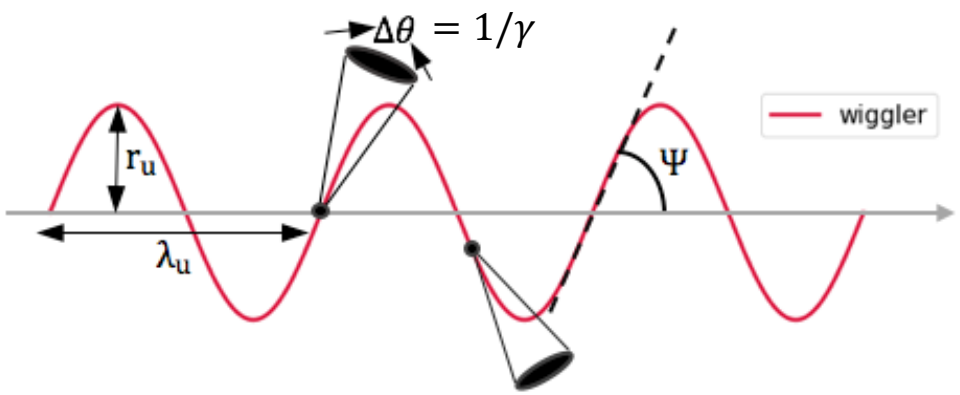
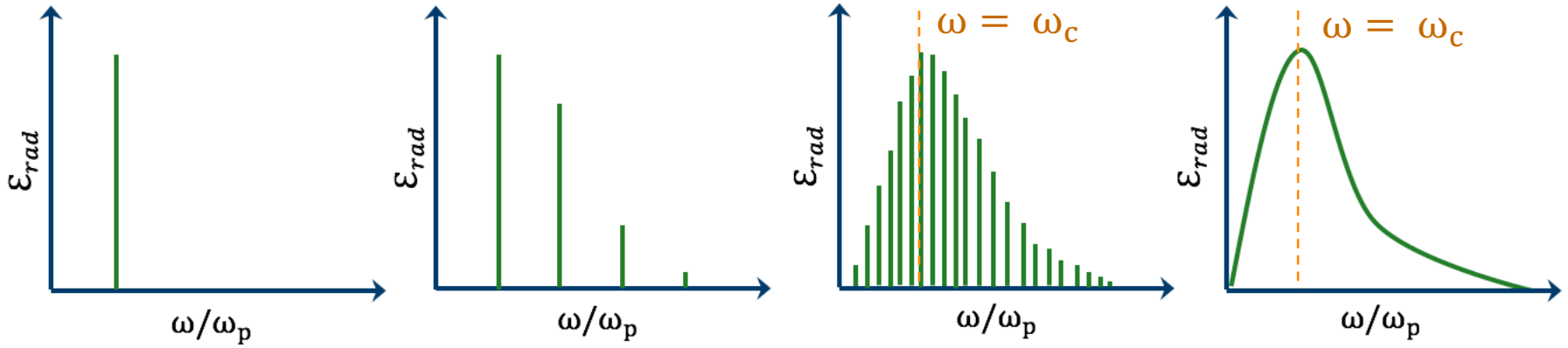
# BASICS OF LASER-DRIVEN BETATRON RADIATION



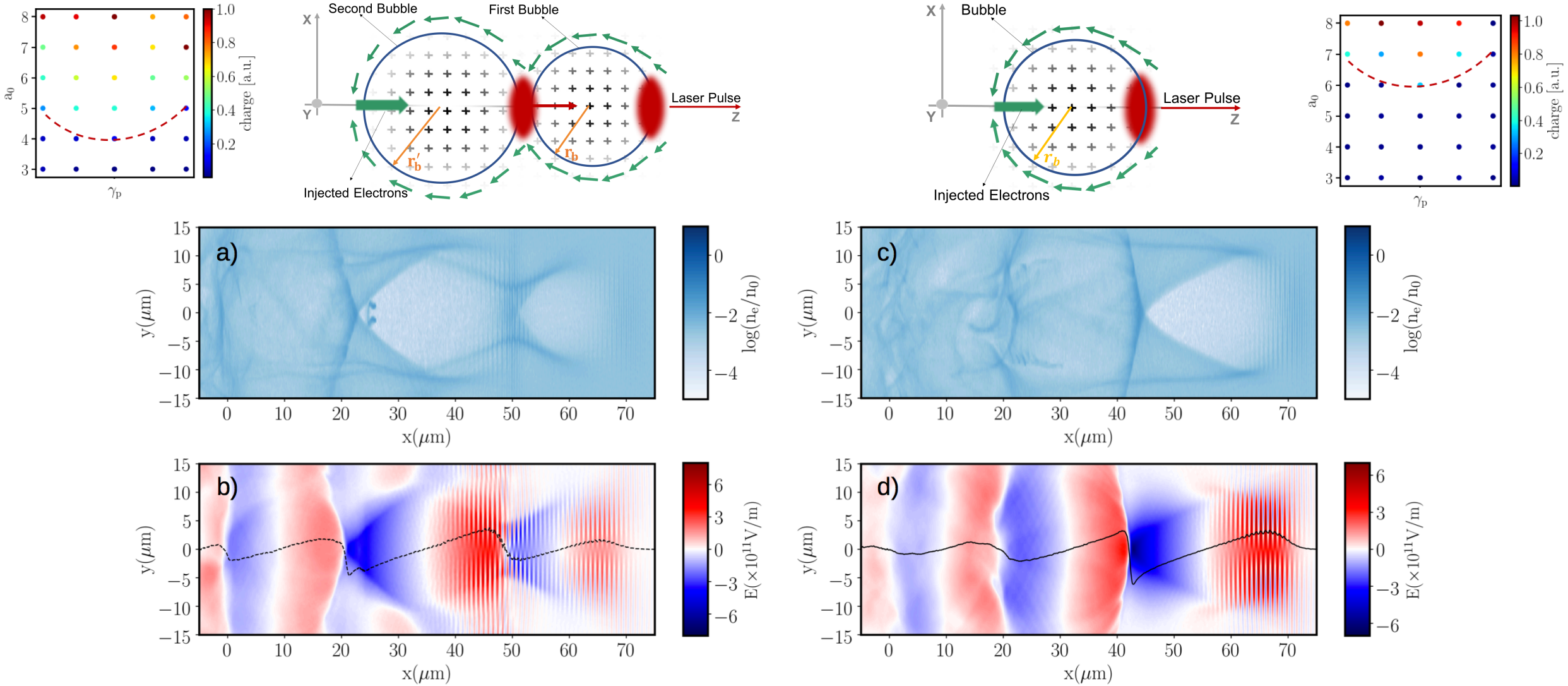




$$K = \gamma k_u r_u$$




$K \ll 1$ $K \sim 1$ $K > 1$ $K \gg 1$

# TANDEM PULSE LASER WAKEFIELD ACCELERATION




✓ Lower injection threshold for the double-pulse scheme



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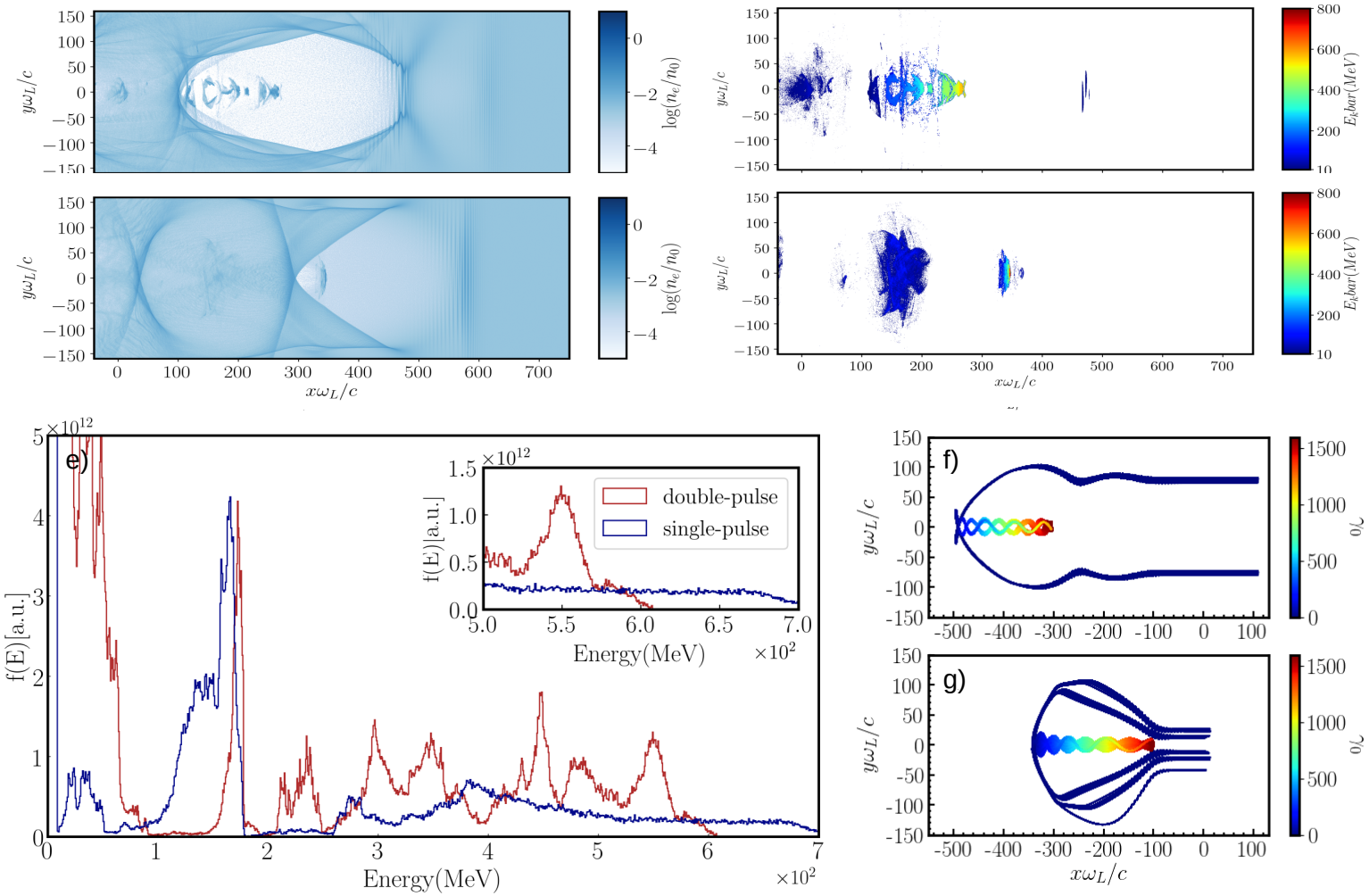
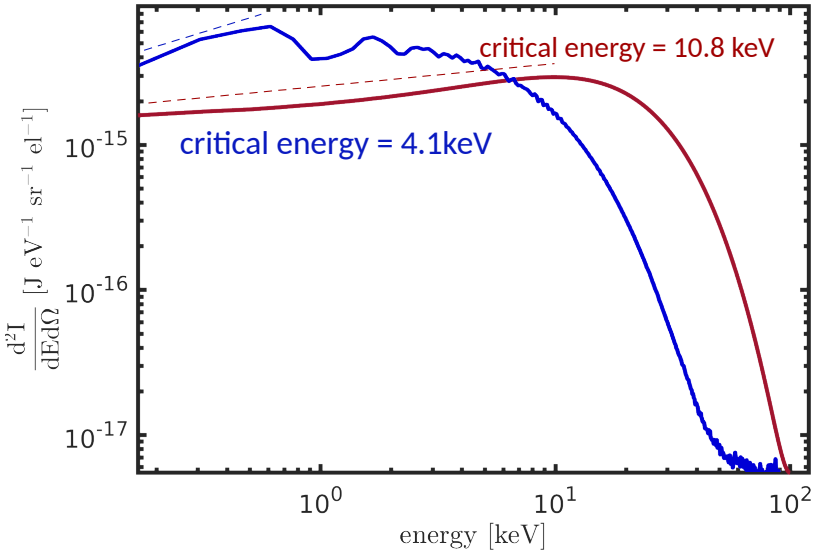
# TANDEM PULSE LASER WAKEFIELD ACCELERATION

## PIC Simulation + Post-processing




- Post-processing
- Calculating the far field based on the electron trajectory (Liénard–Wiechert potentials)

Horný, Vojtěch, et al. "Temporal profile of betatron radiation from laser-driven electron accelerators." *Physics of Plasmas*24.6 (2017): 063107.



# TANDEM PULSE LASER WAKEFIELD ACCELERATION

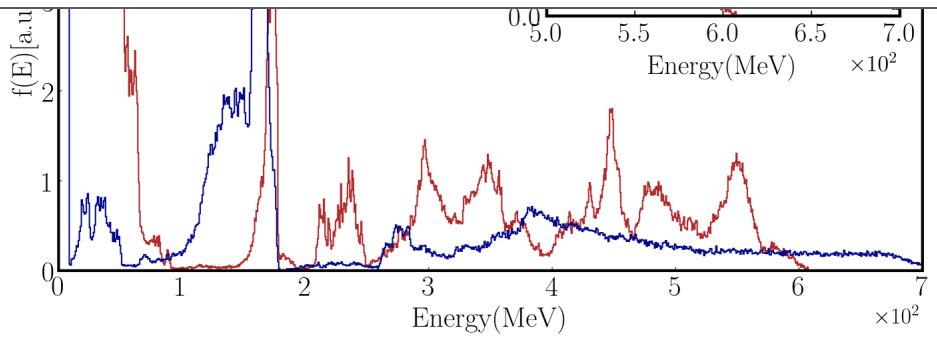
## PIC Simulation + Post-processing

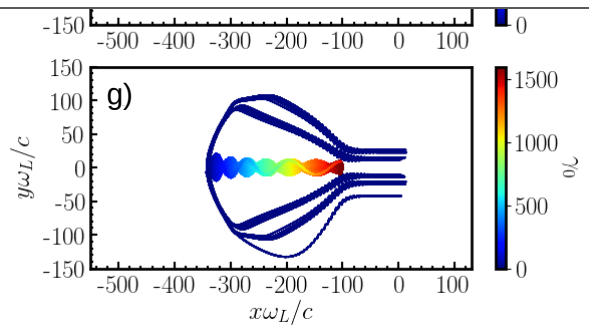


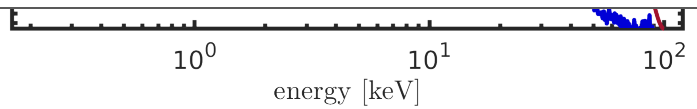
**Electron self-injection threshold for the tandem-pulse laser wakefield accelerator**

Physics of Plasmas **27**, 023106 (2020); https://doi.org/10.1063/1.5117503

Zahra M. Chitgar[1,2,a)], Paul Gibbon[1,3], Jürgen Böker[4], Andreas Lehrach[2,4], *and* Markus Büscher[5,6]



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# TOWARD A NEAR-FIELD RADIATION MODEL

Run PIC to extract electron trajectory

↓

Calculate current density J

↓

DS Field solver: calculating the radiation (Down to 0.001nm resolution)

↓

near-field spatio-temporal information such as phase coherence and polarization

**DS Scheme advantage:**

- ✓ Dispersion-free
- ✓ Faster than standard Yee Scheme in PIC

- ✓ **The 2D model is developed and parallelized and is being benchmarked**



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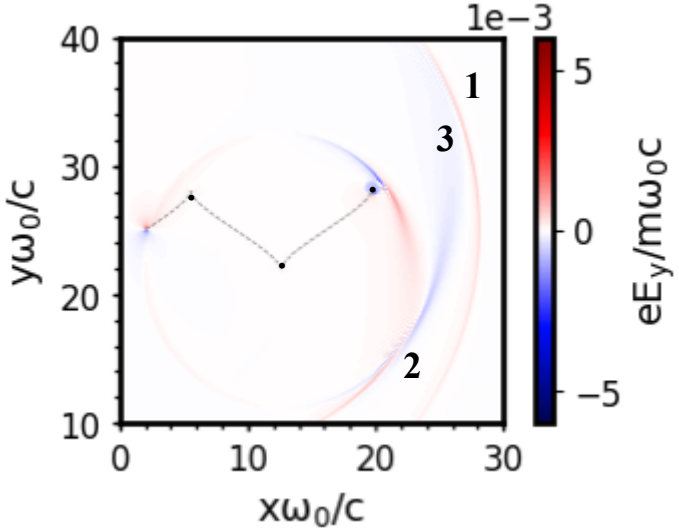
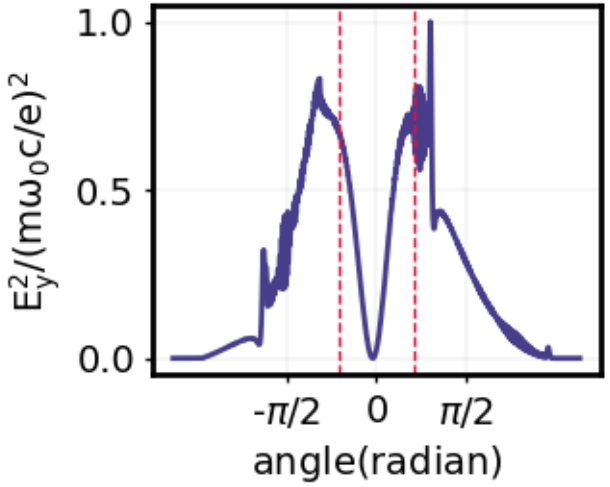
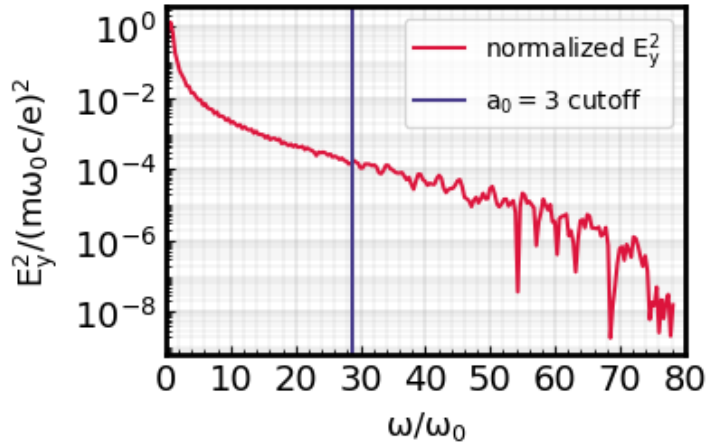
# 2D NUMERICAL FLUID MODEL BENCHMARK

## Thomson scattering

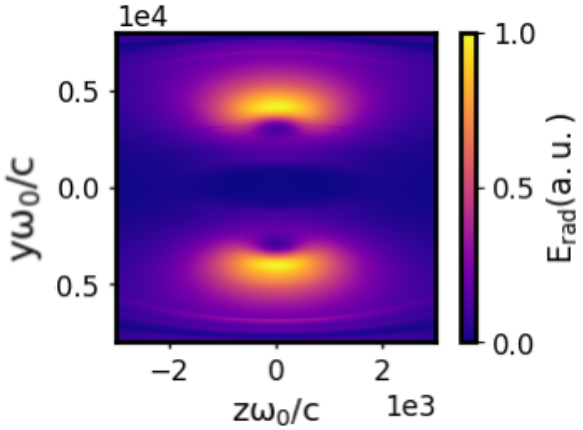


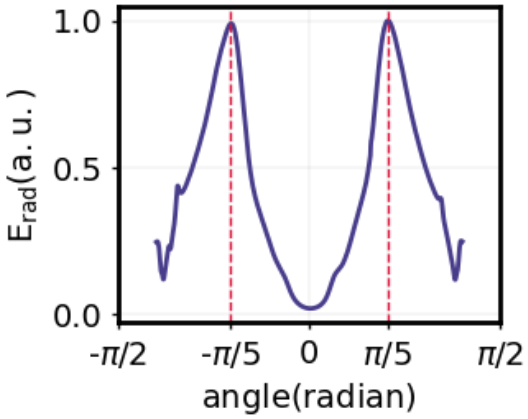



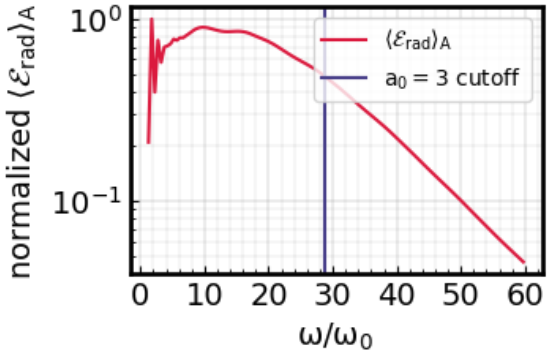




### Comparison with CASPER:

Sinha, Ujjwal, and Naveen Kumar. "Pair-beam propagation in a magnetized plasma for modeling the polarized radiation emission from gamma-ray bursts in laboratory astrophysics experiments." *Physical Review E* 101.6 (2020): 063204.



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# SUMMARY

- CP HHG using bi-color drivers, PIC simulation
- Relevance of developing a Fluid Model
- Fluid Model Benchmark for CP HHG and Thomson Scattering
- Laser-driven Betatron Radiation in a Tandem pulse scheme

❖ **OUTLOOK:** Near-field time- and space-resolved model for keV betatron radiation

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