Enhanced self-seeded FEL with OAM

Chenzhi Xu,Jiawei Yan

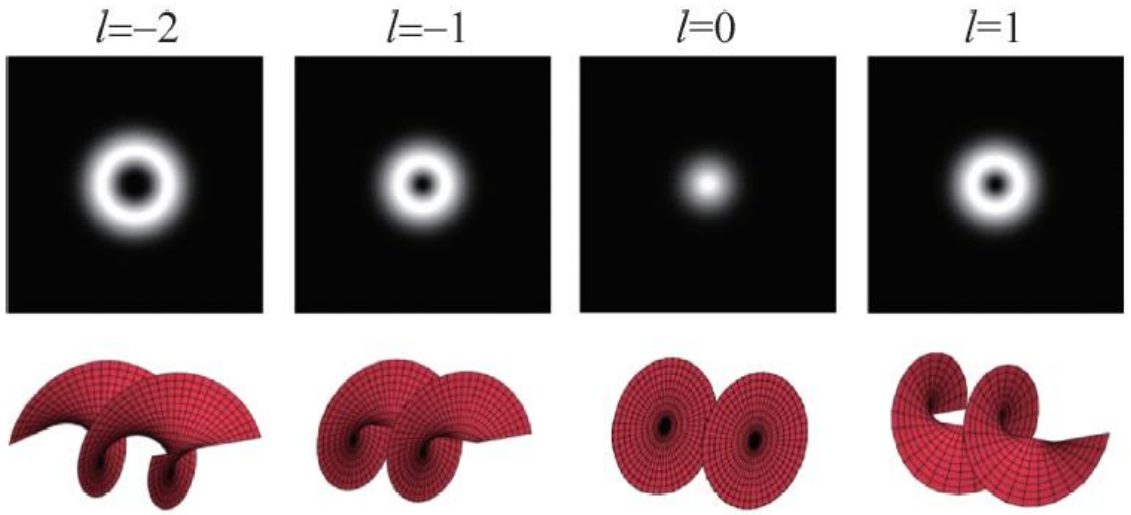
FEL Physics Group

06/09/2023

Outline

- **Motivations**
- Methods for generating OAM light based on FEL physics
- Enhanced Self-seeded FEL with OAM
- Summary and Outlook

Orbital angular momentum light



Intensity profile and phase front for different l.

$$\Phi(\mathrm{r},\varphi) = \mathrm{A}(\mathrm{r},\varphi)\exp(il\varphi)$$

φ: azimuthal phase

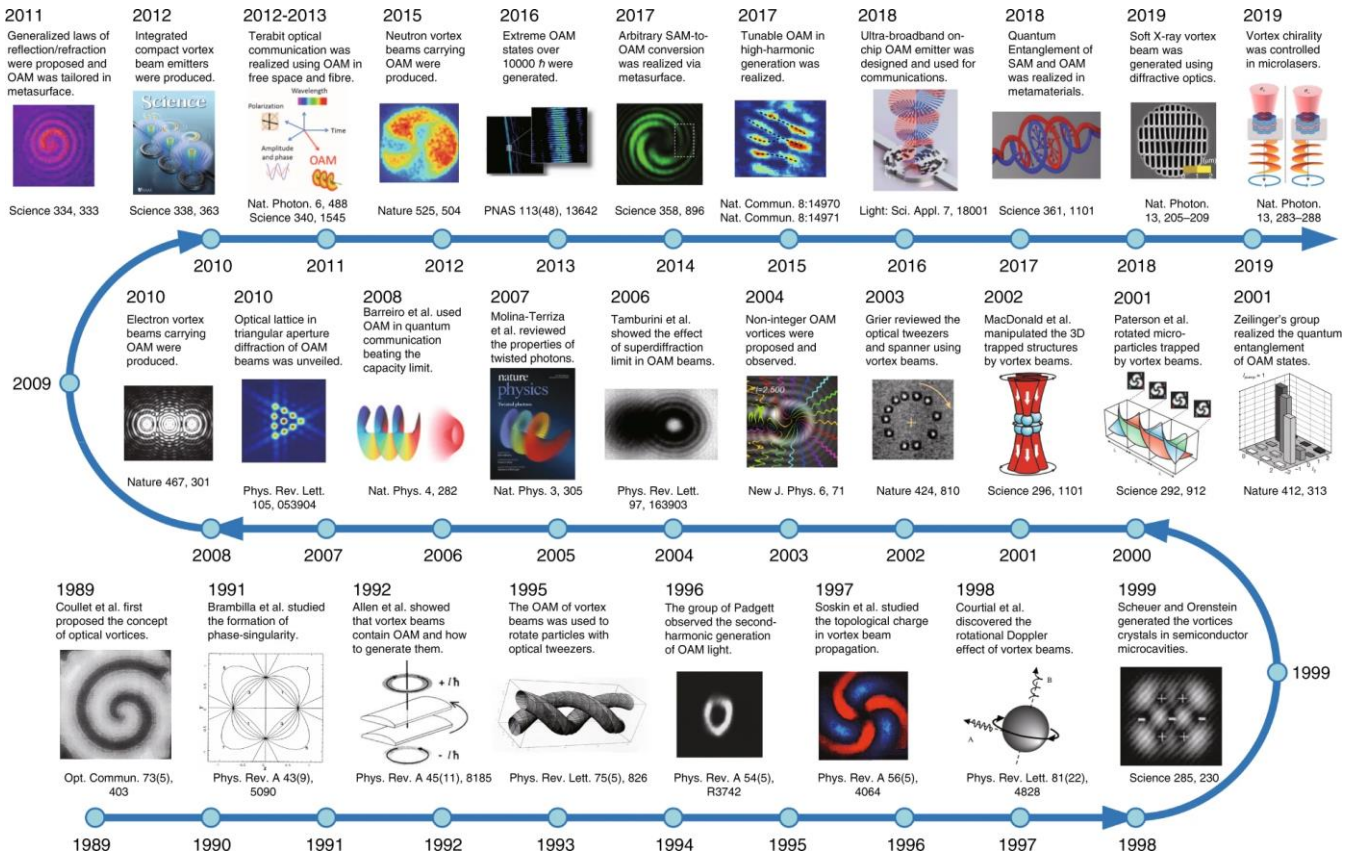
l: integer value, positive or negative (topological charge)

Orbital angular momentum, $\pm l\hbar$ per photon

Allen, Les, et al. Physical review A 45.11 (1992): 8185.

Application of OAM light

Roadmap of the 30-year development of optical vortices



- Optical tweezers — orientational manipulation of particles or particle aggregates
- Optical communications — high-bandwidth information encoding
- Quantum cryptography/computation — higher-dimensional quantum information encoding
- Sensitive optical detection
- Basic science research (e.g., OAM-based spectroscopic and scattering experiments)

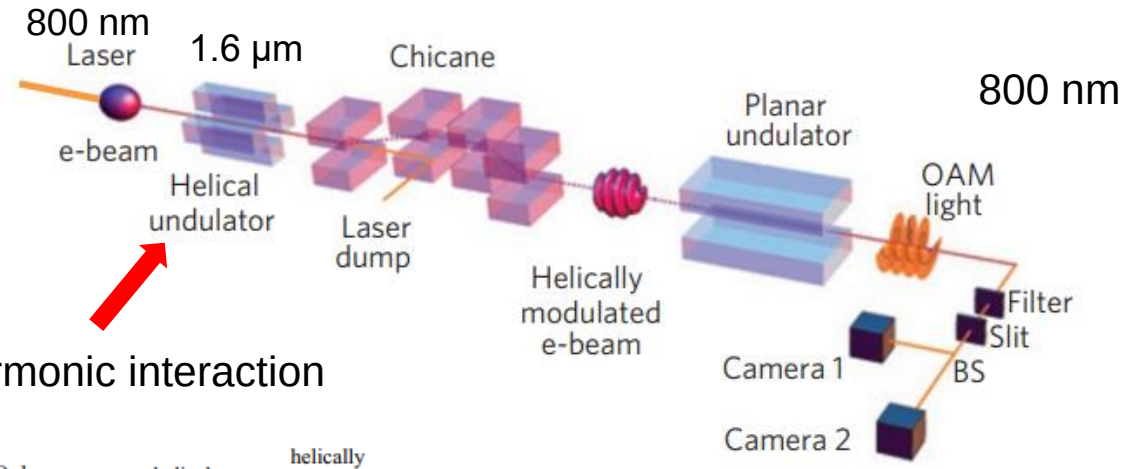
Shen, Y. et al. Light Sci Appl 8, 90 (2019)

Outline

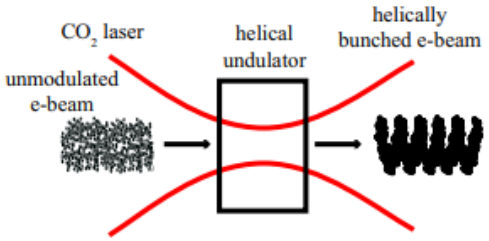
- Motivations
- **Methods for generating OAM light based on FEL physics**
- Enhanced Self-seeded FEL with OAM
- Summary and Outlook

Methods for generating OAM light based on FEL physics

- **Generation of helically modulated e-beam**

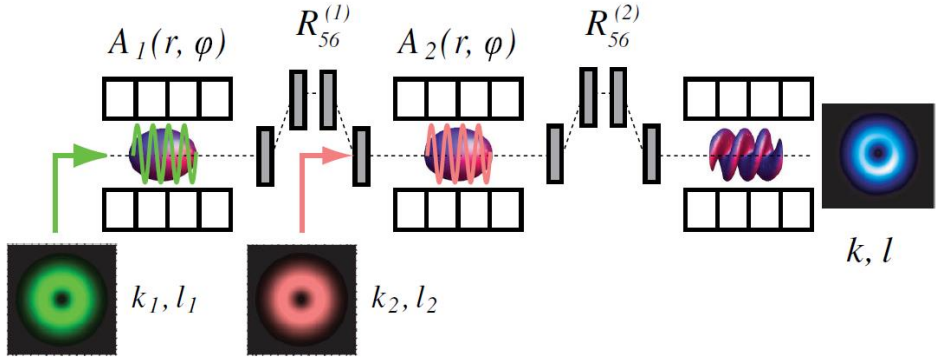


Harmonic interaction



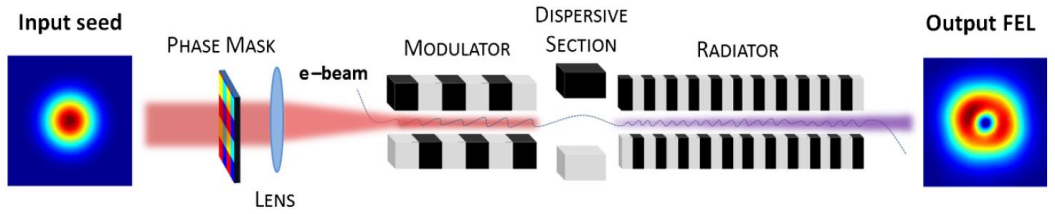
Harmonic interaction in a helical undulator

1. E. Hemsing, et al. PRL 106, 164803 (2011)
2. E. Hemsing et al. Nat. Phys. 9, 549 (2013)



EEHG based scheme

E. Hemsing and A. Marinelli, PRL 109, 224801 (2012)

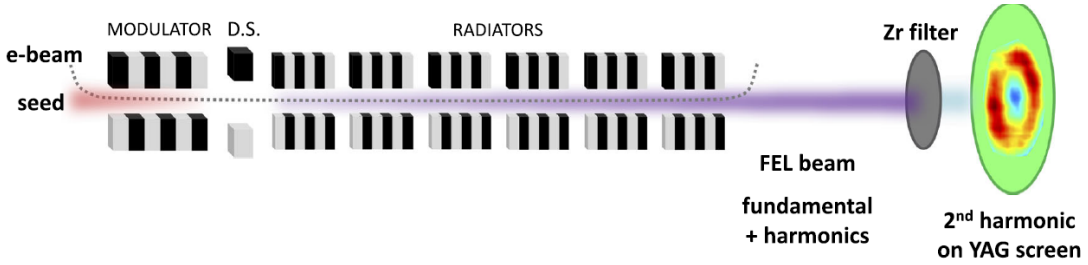


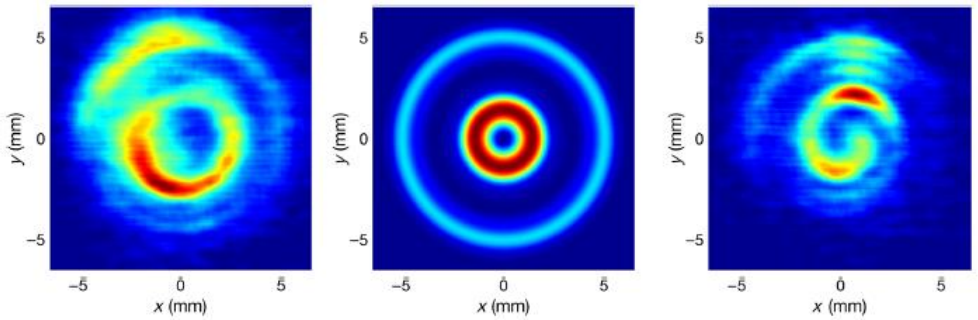
HGHG scheme: seed laser with staircaselike phase pattern

Primož Rebernik Ribič et al, PRL 112, 203602 (2014)

Methods for generating OAM light based on FEL physics

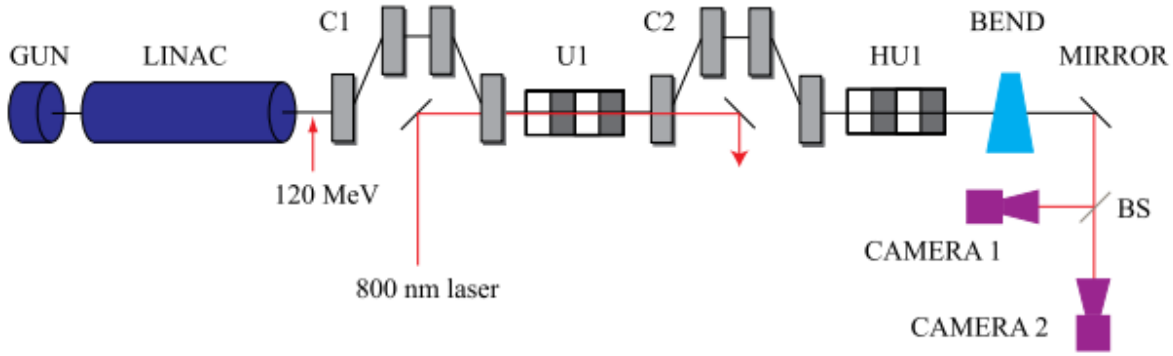
- **Harmonic lasing in helical undulator**

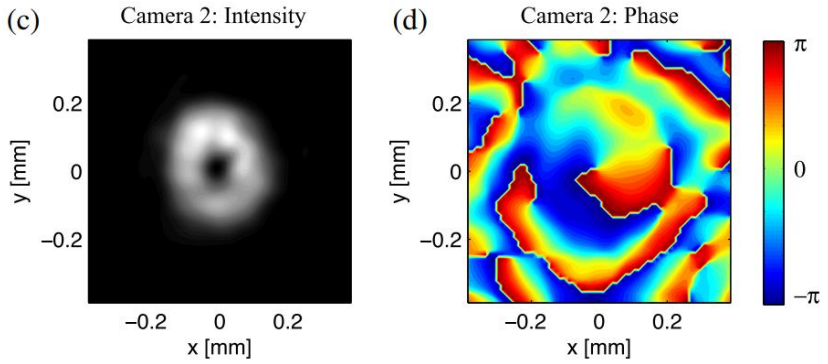




optical vortex generated at 15.6 nm

P.R. Ribic et al. PRX 7, 031036 (2017)





E. Hemsing, et al. PRL 113, 134803, (2014)

Methods for generating OAM light based on FEL physics

- **Self-seeded FEL with OAM**

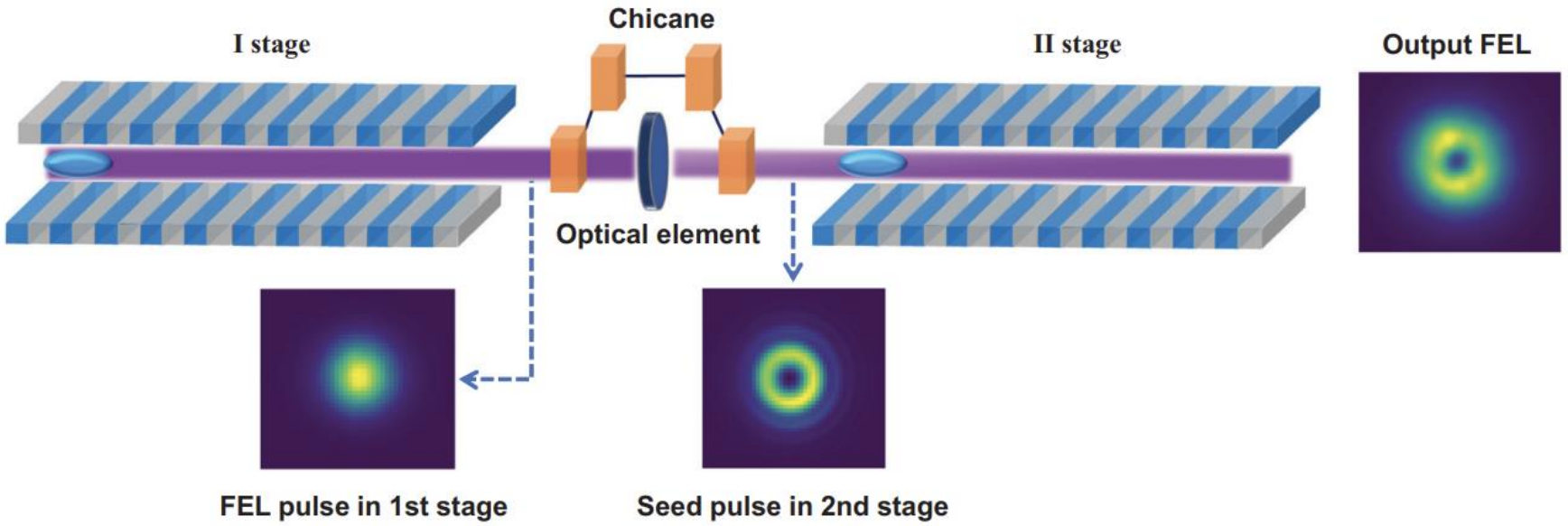


Fig. 1 Schematic layout of the self-seeded FEL with OAM.

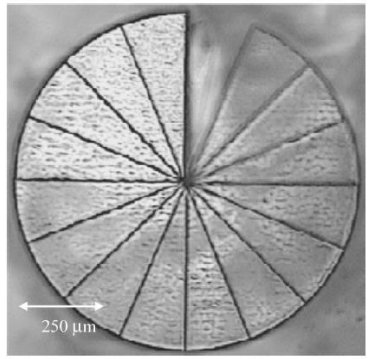
Jiawei Yan and Gianluca Geloni. Adv. Photon. Nexus 2(3), 036001 (2023)

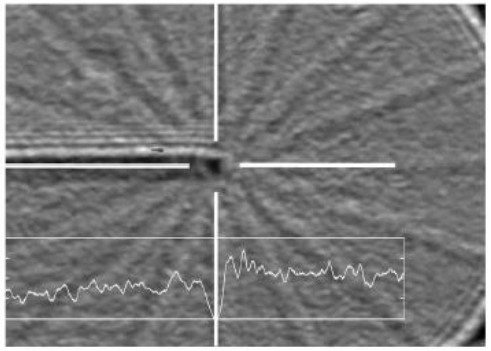
Methods for generating OAM light based on FEL physics

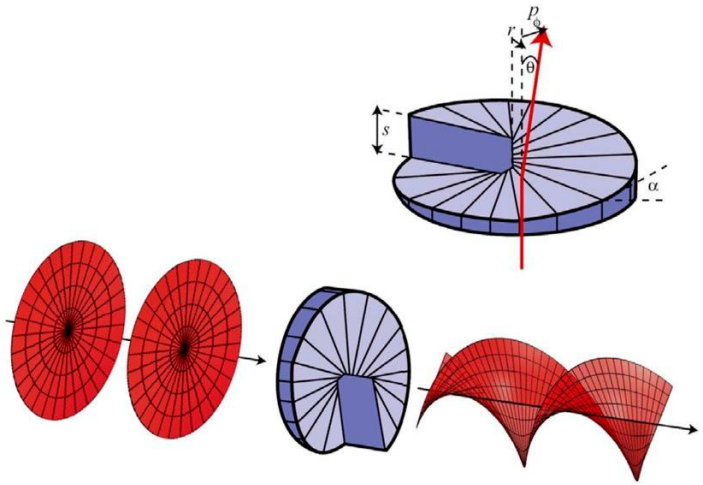
- **Self-seeded FEL with OAM: Optical elements**

$$u(r,z) \longrightarrow u(r,z)\exp(il\varphi)$$

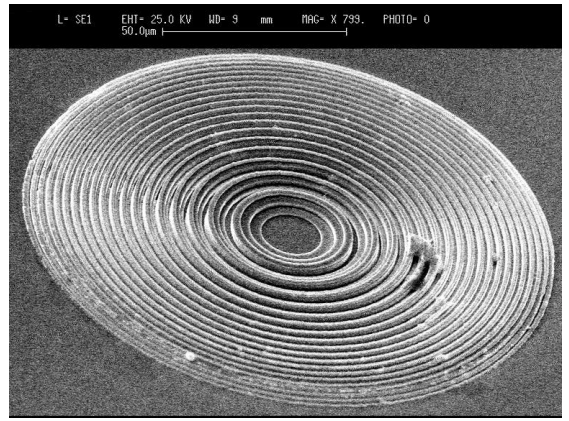
Spiral phase plate

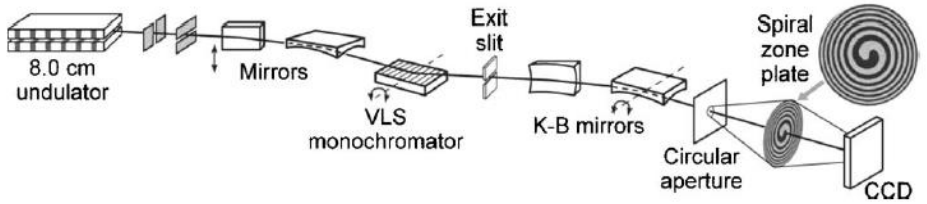






Spiral zone plate





Methods for generating OAM light based on

- **Self-seeded FEL with OAM**

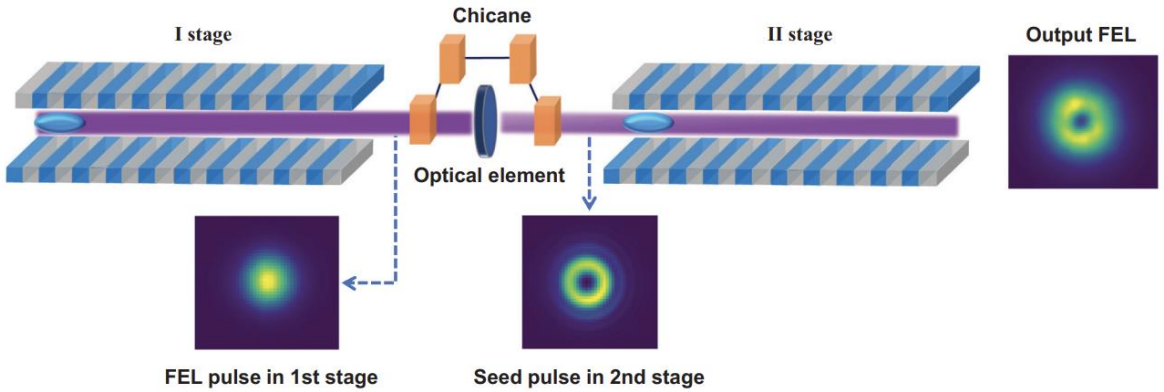
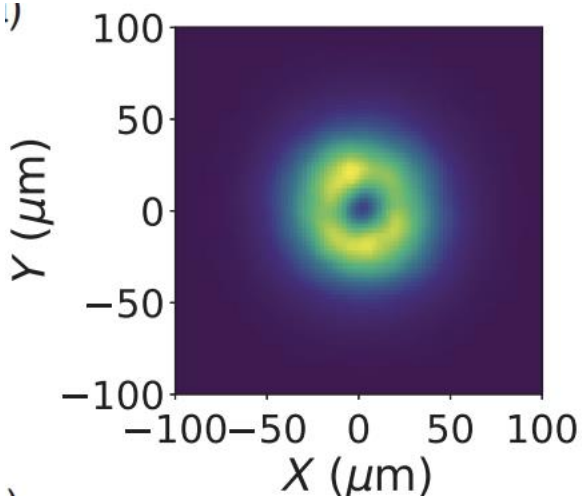
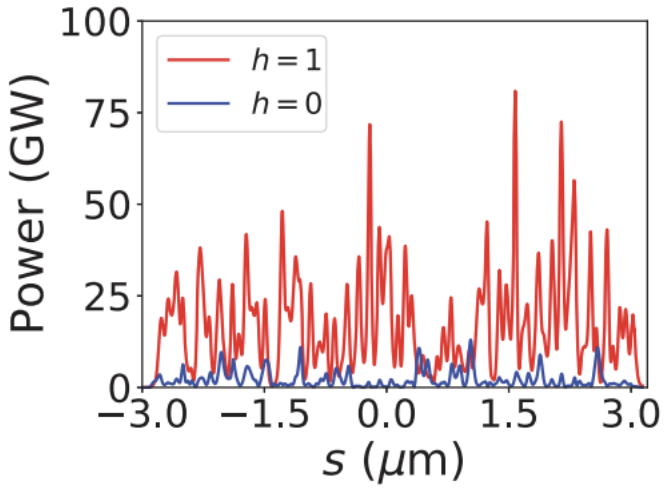


Fig. 1 Schematic layout of the self-seeded FEL with OAM.





Jiawei Yan and Gianluca Geloni. Adv. Photon. Nexus 2(3), 036001 (2023)

Outline

- Motivations
- Methods for generating OAM light based on FEL physics
- **Enhanced Self-seeded FEL with OAM**
- Summary and Outlook

Enhanced Self-seeded FEL with OAM: limits and dream OAM-FEL light

SSOAM limits

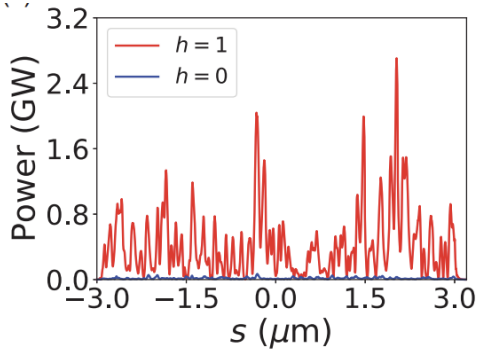
Low purity and Low peak power

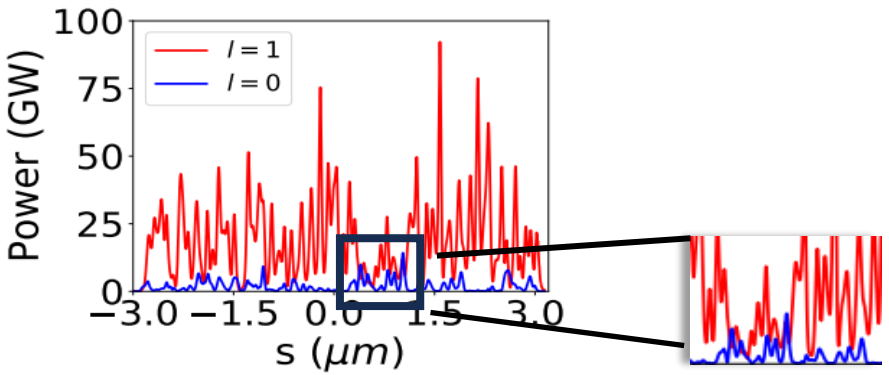
0.96 uJ → **107 uJ**

~ 91% of $l = 1$ → **~ 87% of $l = 1$**

Challenge

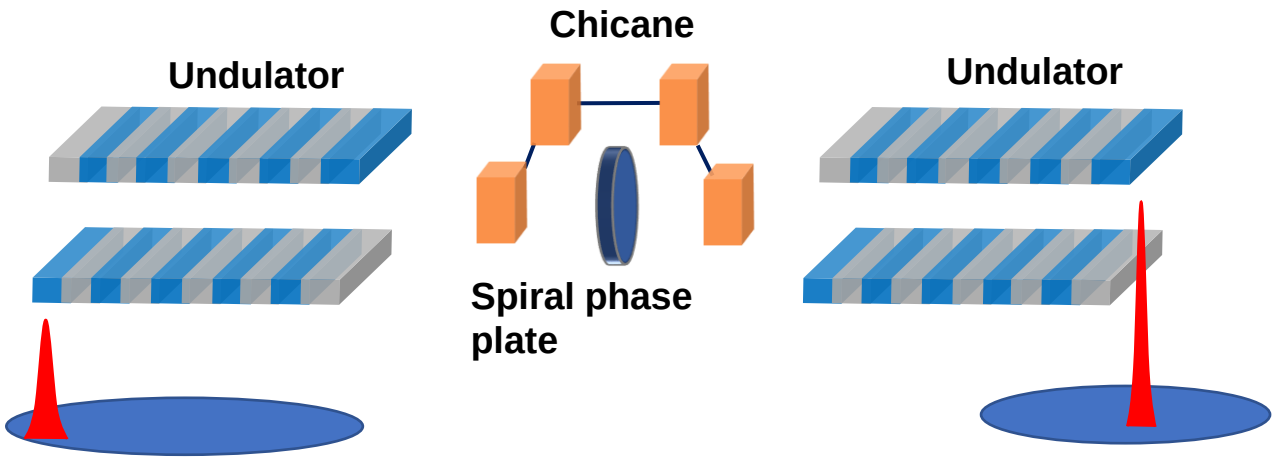
- **High OAM purity**
- **High peak power**
- **Attosecond pulse duration**





Enhanced Self-seeded FEL with OAM

- The scheme of ESSOAM



Enhanced Self-seeded FEL with OAM

- Enhanced Self-amplified spontaneous emission (ESASE)

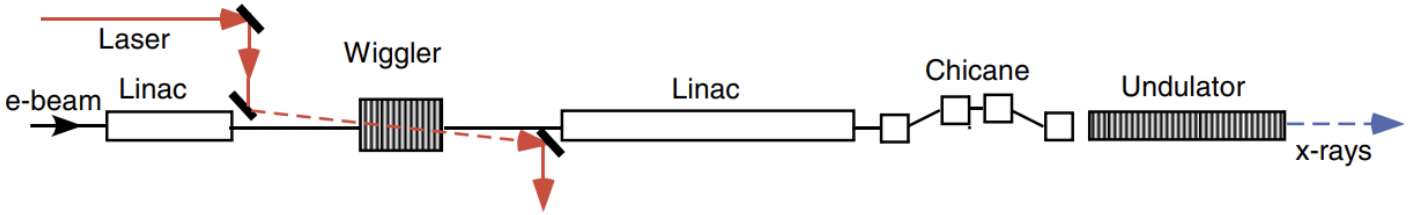


FIG. 1. (Color) A schematic of ESASE x-ray FEL.

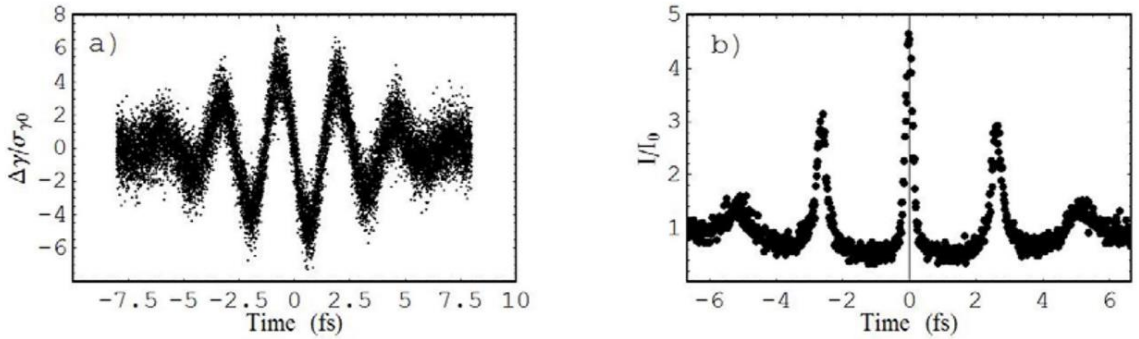
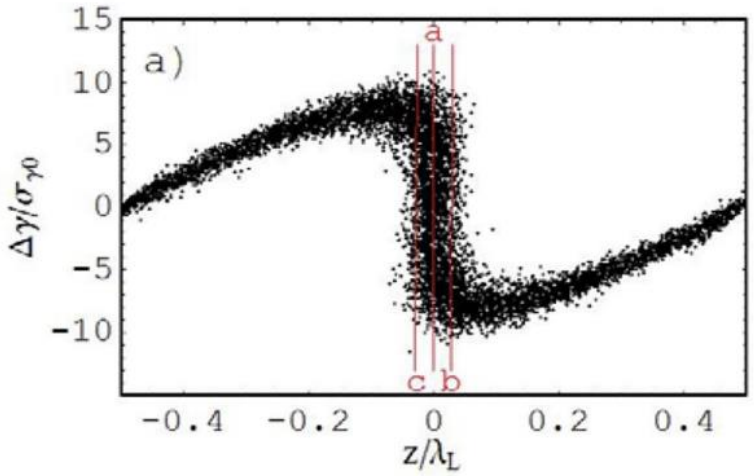


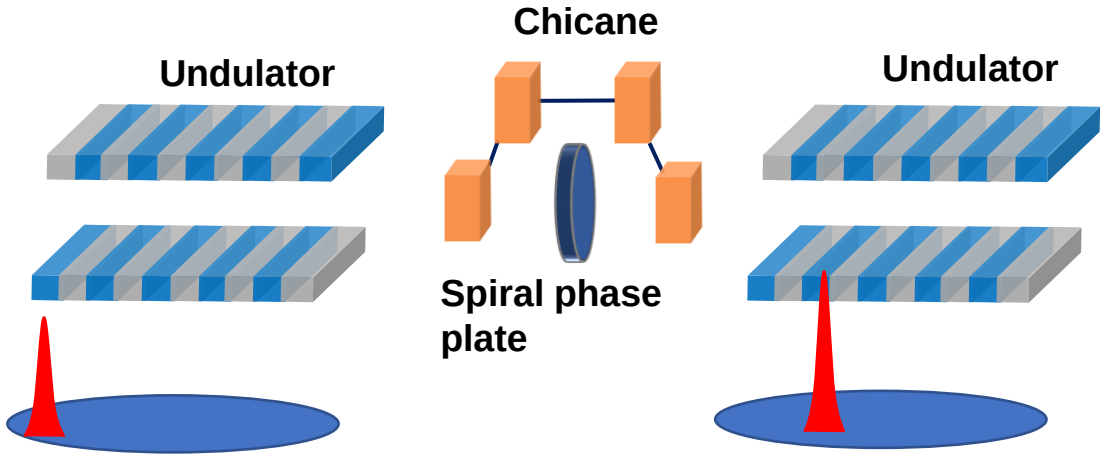
FIG. 5. Energy and peak current modulations produced in interaction with a few-cycle laser pulse. Only a part of the electron bunch affected by the interaction is shown.

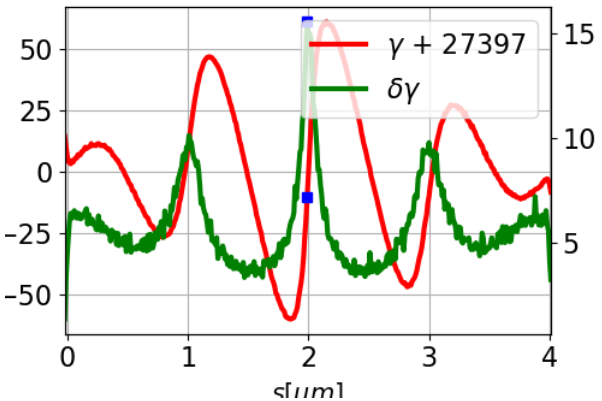


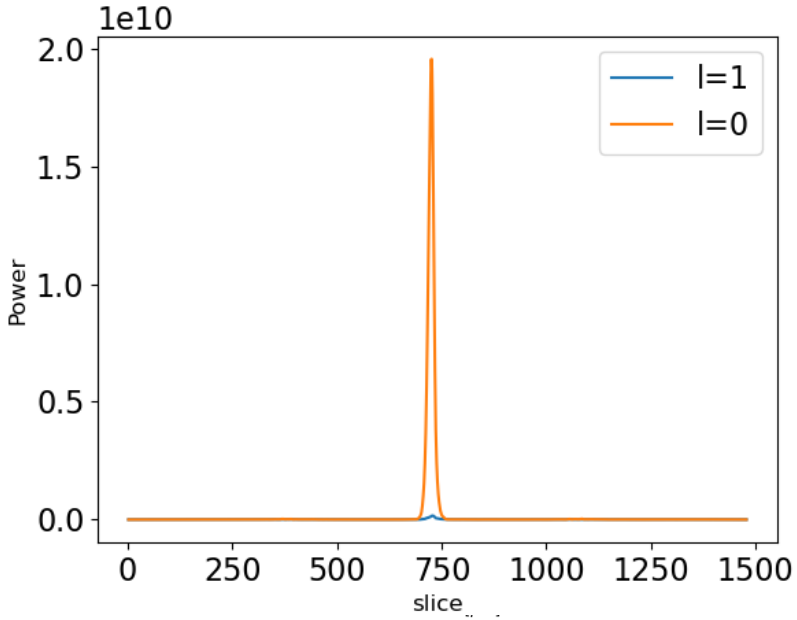
Zholents A A. Physical Review Special Topics-Accelerators and Beams, 2005, 8(4): 040701.

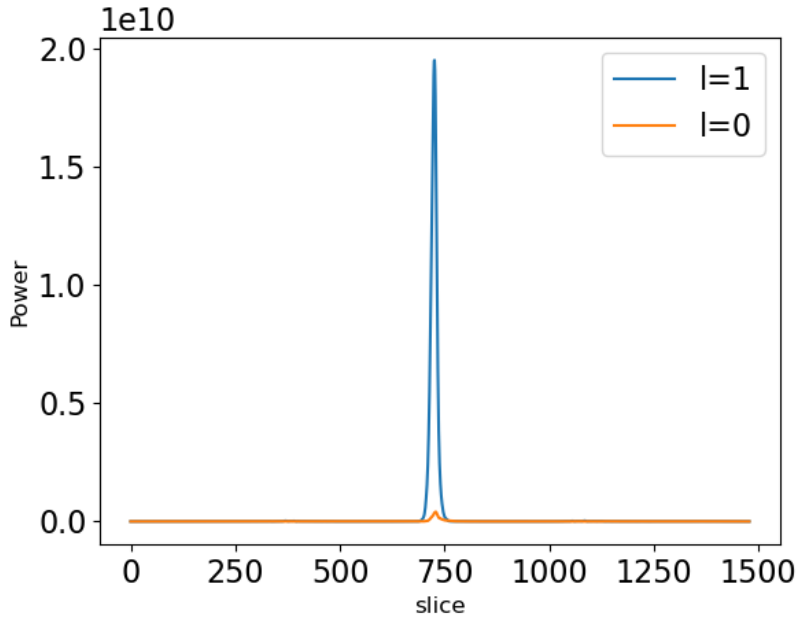
Enhanced Self-seeded FEL with OAM

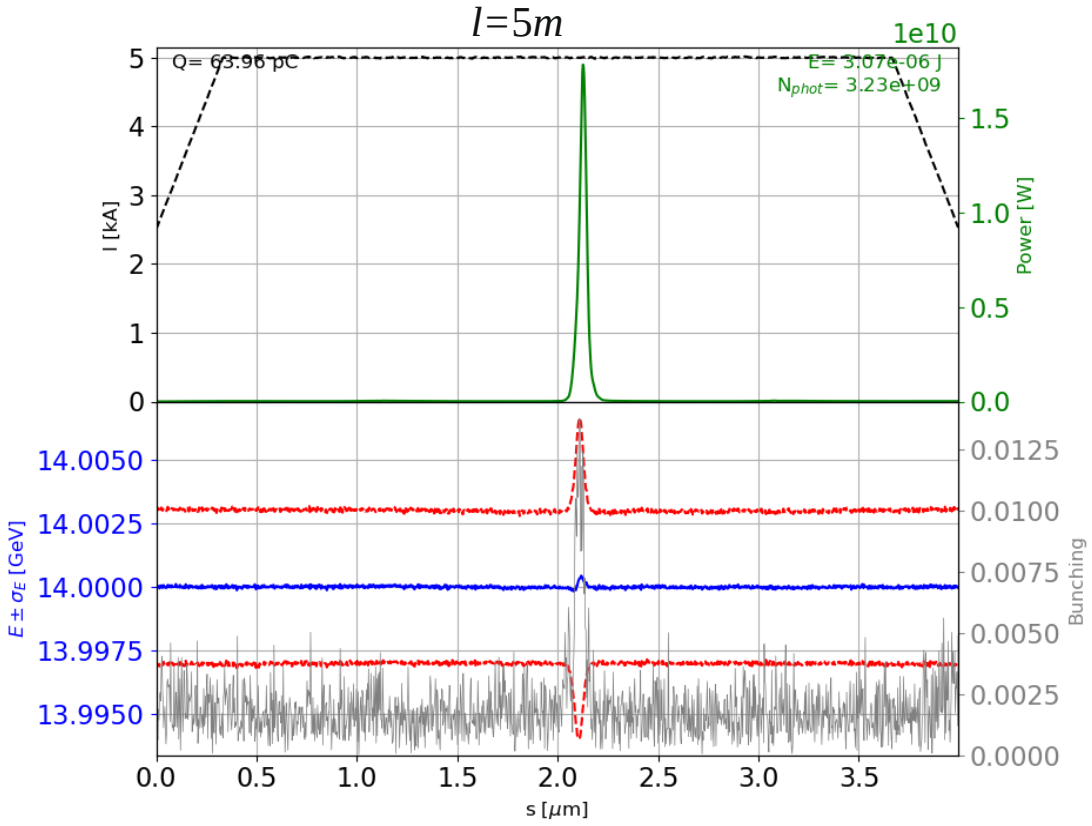
- First stage amplification and mode conversion

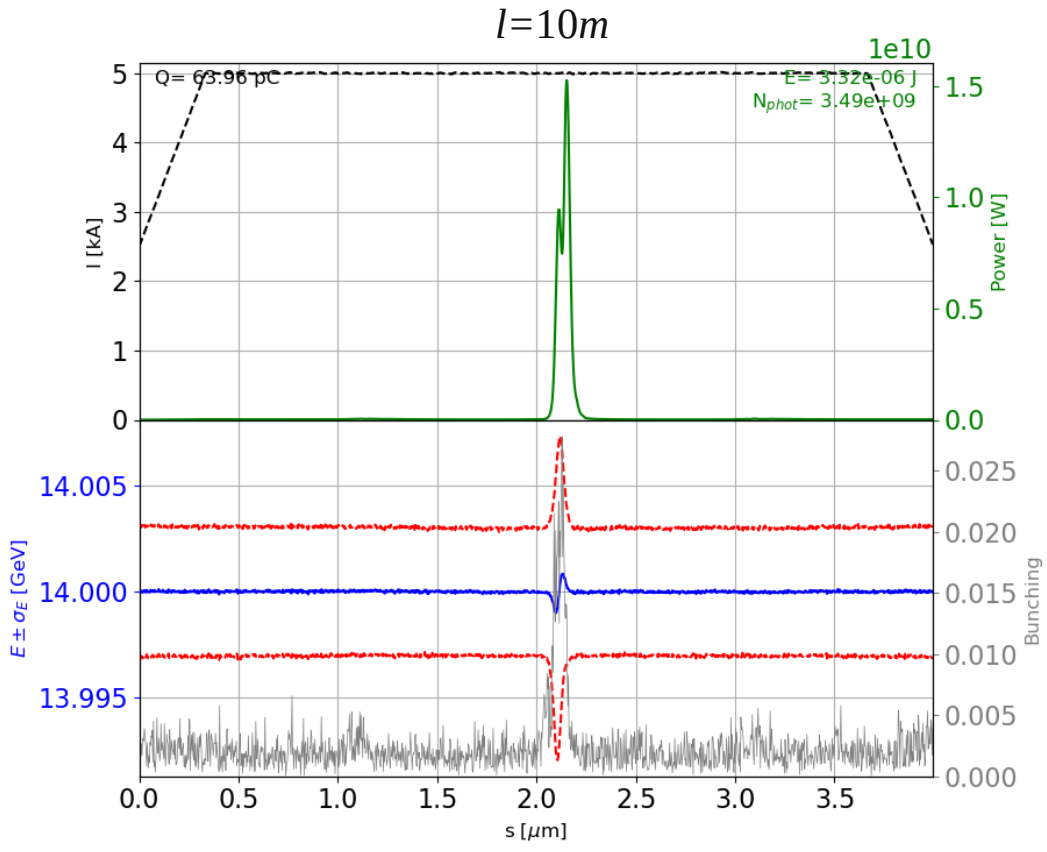


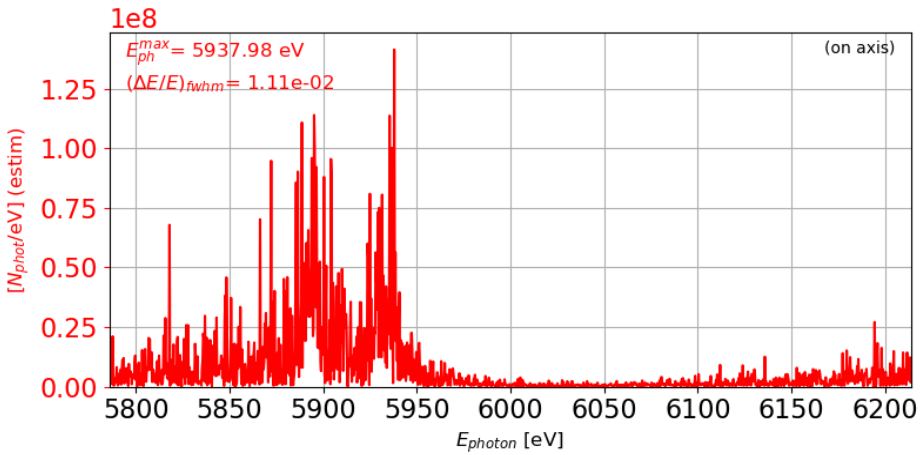


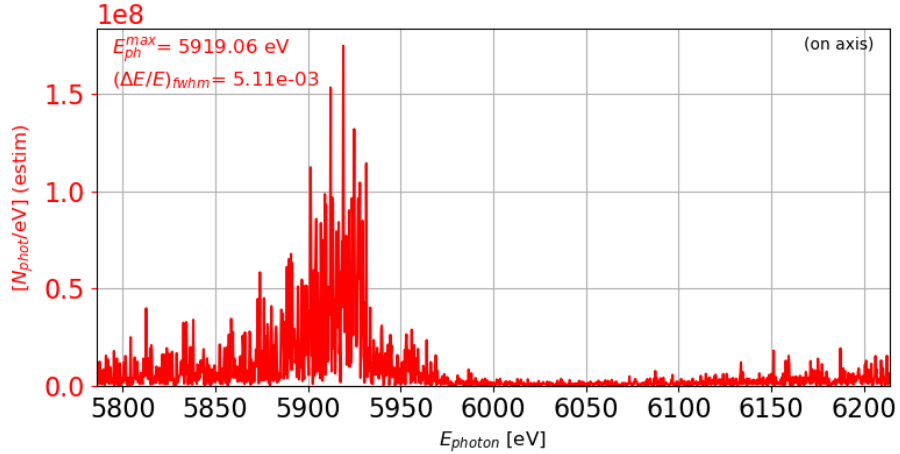


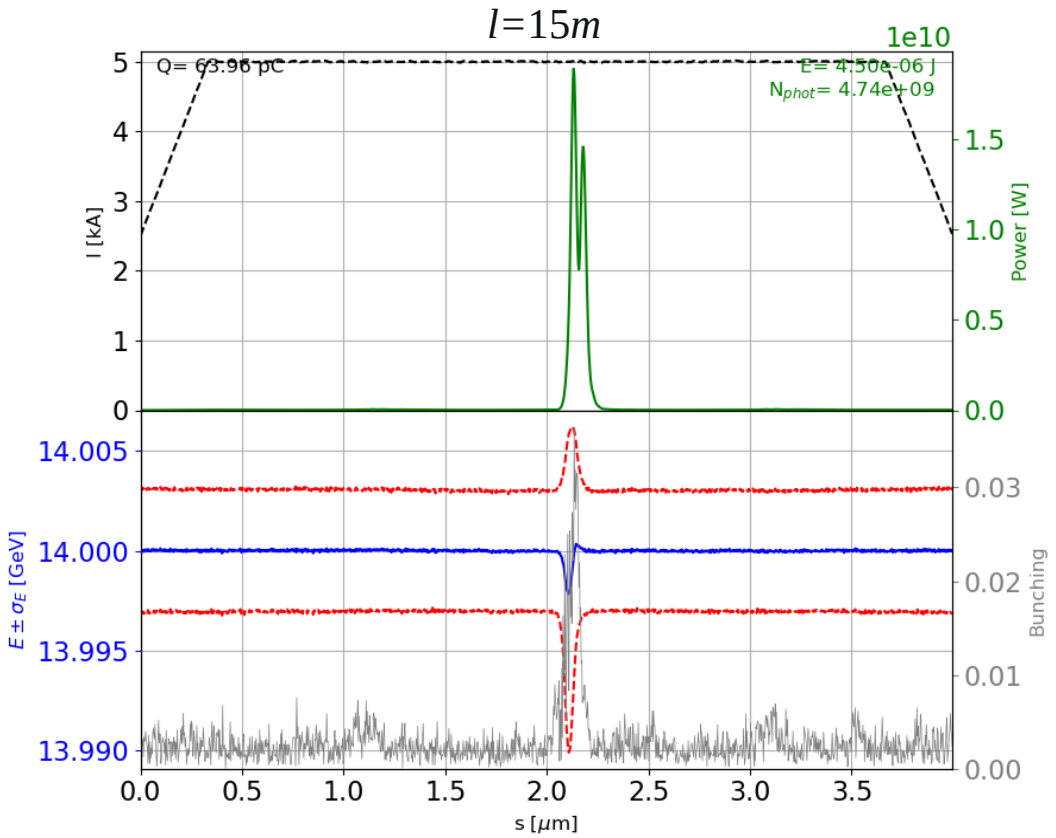


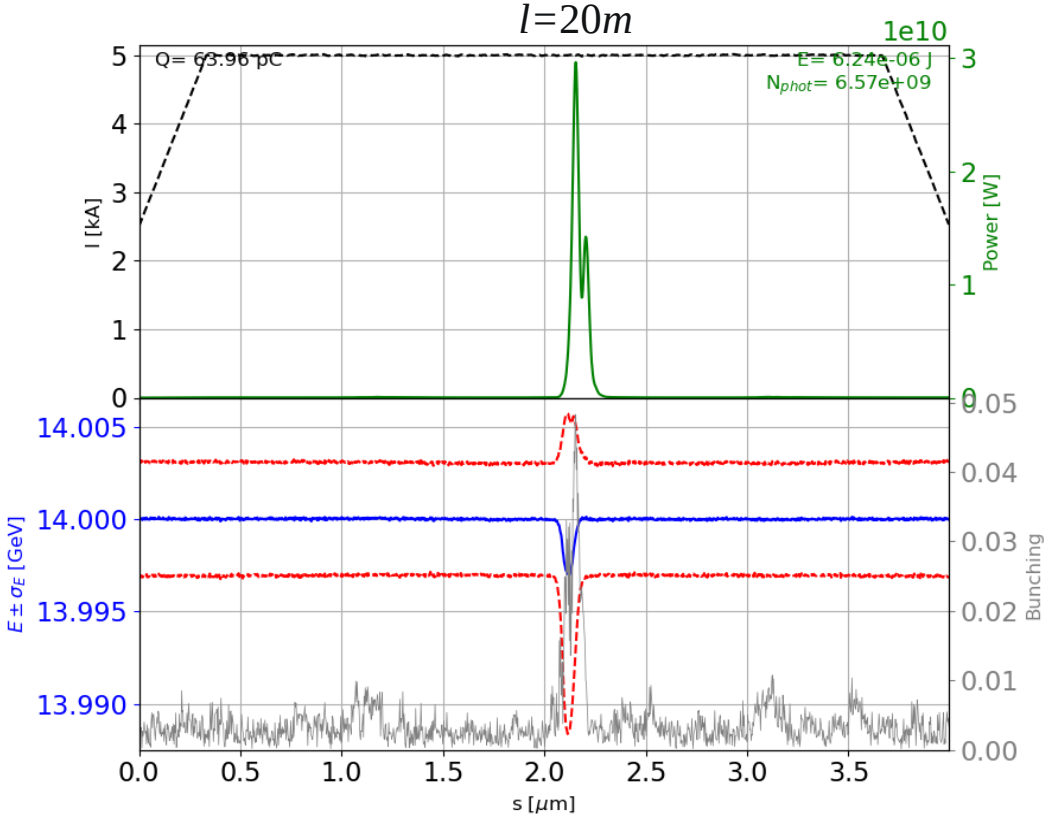

l=5m
1e10
Q= 63.96 pC
E= 3.07e-06 J
N_phot= 3.23e+09
I [kA]
Power [W]
E ± σ_E [GeV]
Bunching
s [μm]

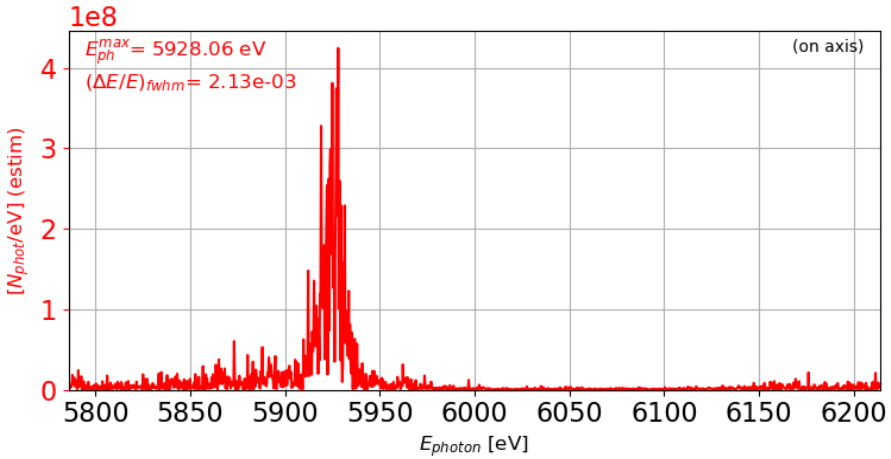

l=10m
1e10
Q= 63.96 pC
E= 3.32e-06 J
N_phot= 3.49e+09
I [kA]
Power [W]
E ± σ_E [GeV]
Bunching
s [μm]

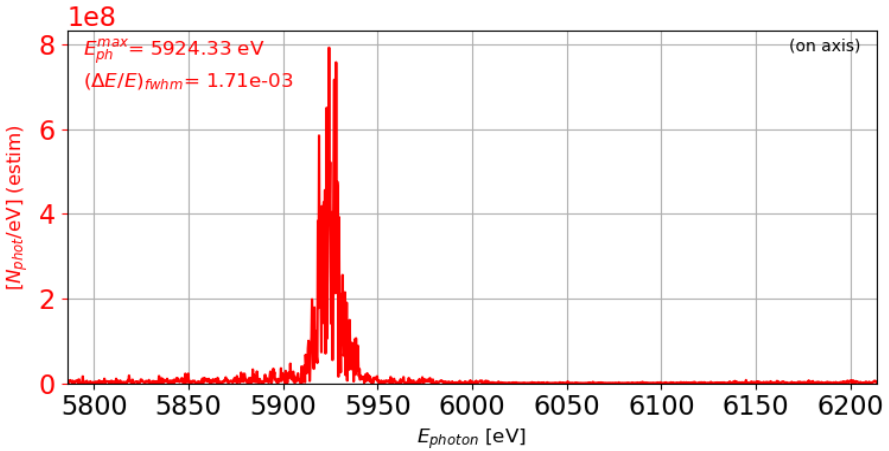

1e8
E_ph^max= 5937.98 eV
(ΔE/E)_fwhm= 1.11e-02
(on axis)
[N_phot/eV] (estim)
E_photon [eV]

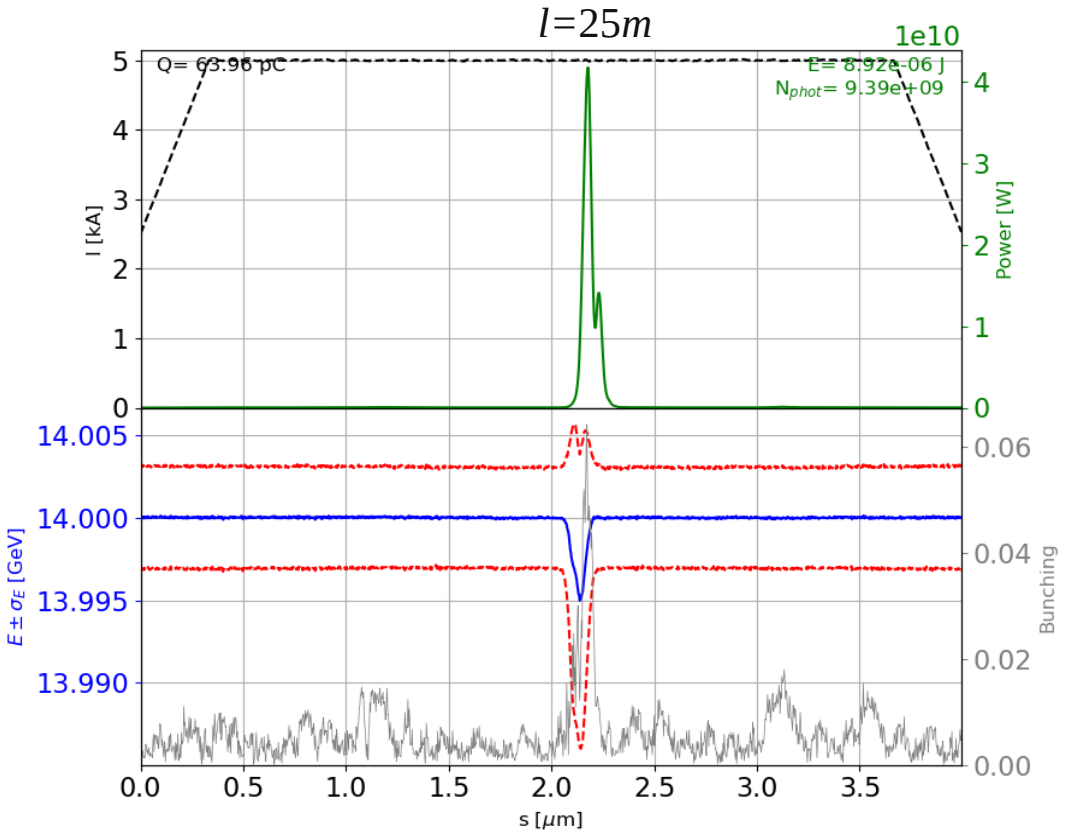

1e8
E_ph^max= 5919.06 eV
(ΔE/E)_fwhm= 5.11e-03
(on axis)
[N_phot/eV] (estim)
E_photon [eV]

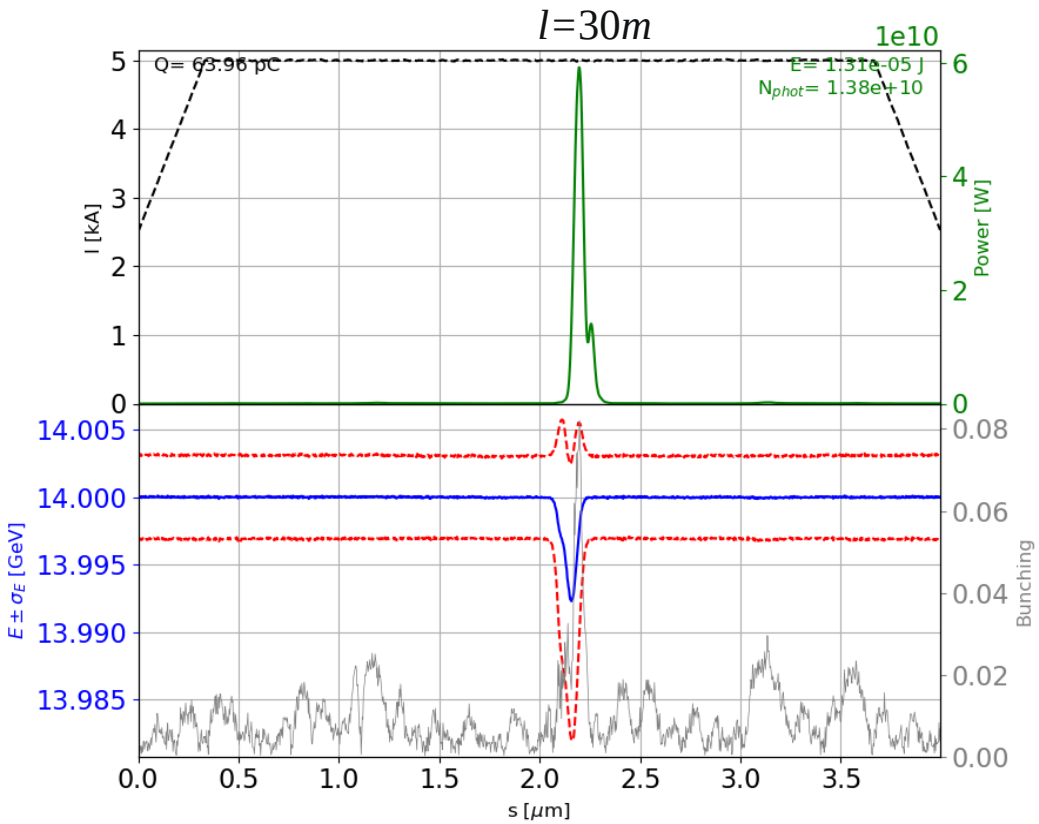

l=15m
1e10
Q= 63.96 pC
E= 4.50e-06 J
N_{phot}= 4.74e+09
I [kA]
Power [W]
$E \pm \sigma_E$ [GeV]
Bunching
s [μm]

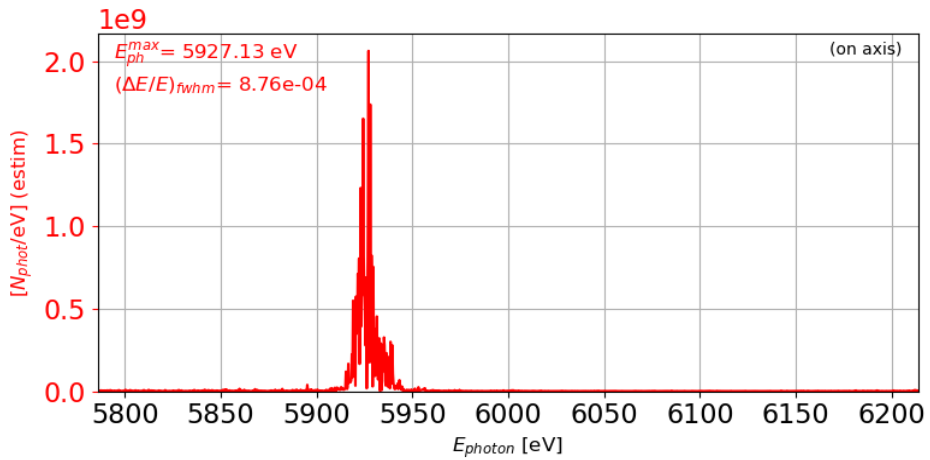

l=20m
1e10
Q= 63.96 pC
E= 6.24e-06 J
N_{phot}= 6.57e+09
I [kA]
Power [W]
$E \pm \sigma_E$ [GeV]
Bunching
s [μm]

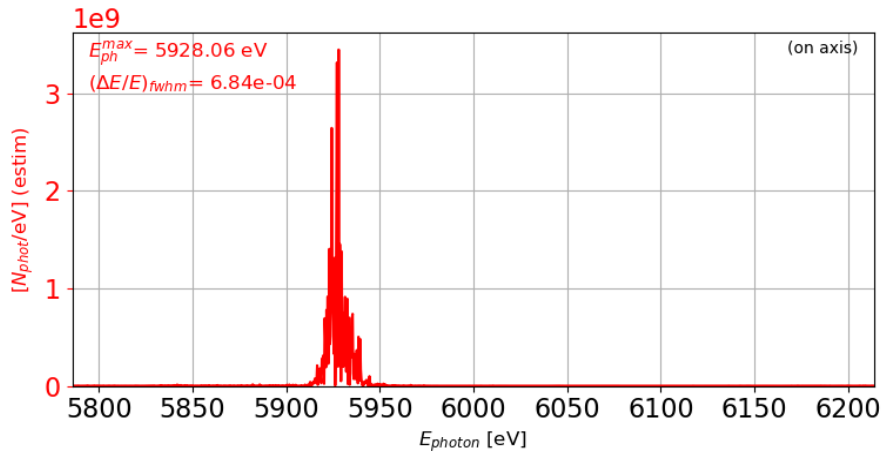

1e8
E_{ph}^{max}= 5928.06 eV
$(\Delta E/E)_{fwhm}$= 2.13e-03
(on axis)
$[N_{phot}/eV]$ (estim)
E_{photon} [eV]


1e8
E_{ph}^{max}= 5924.33 eV
$(\Delta E/E)_{fwhm}$= 1.71e-03
(on axis)
$[N_{phot}/eV]$ (estim)
E_{photon} [eV]

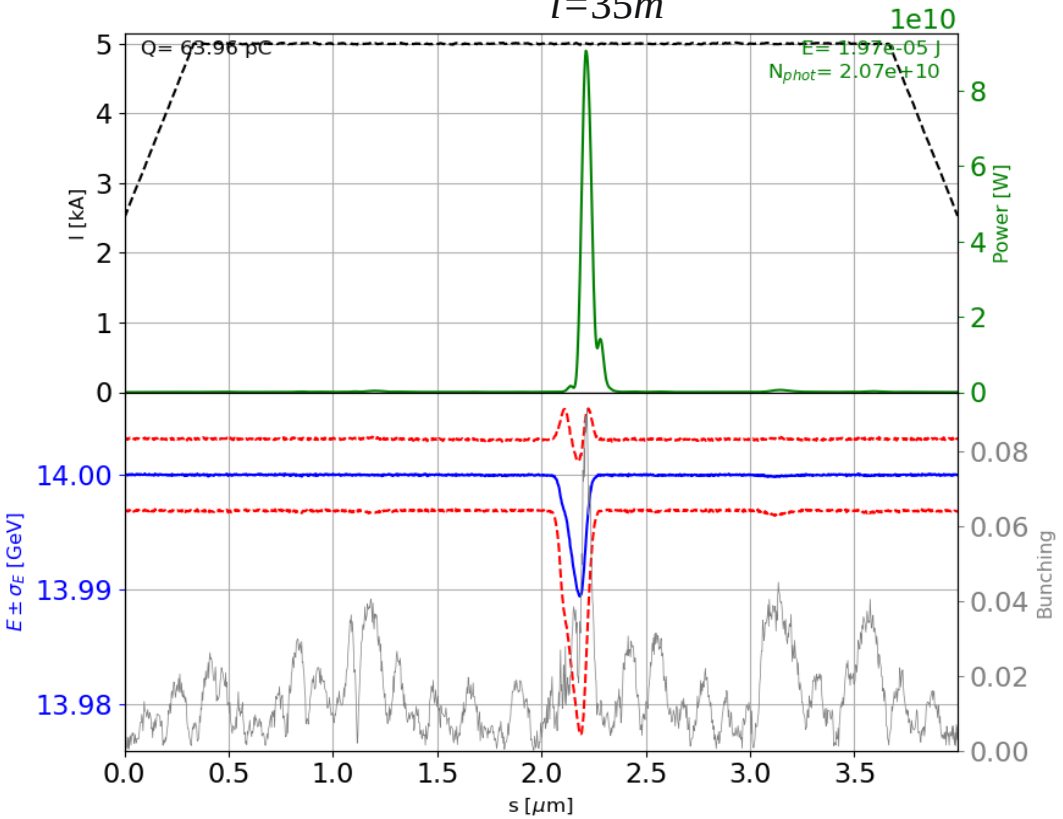

l=25m
1e10
Q= 63.96 pC
E= 8.92e-06 J
N_phot= 9.39e+09
I [kA]
Power [W]
E ± σ_E [GeV]
Bunching
s [μm]

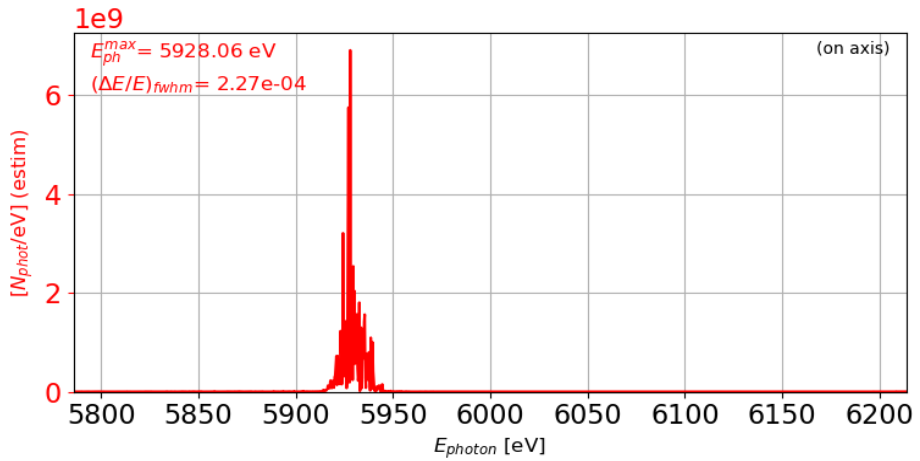

l=30m
1e10
Q= 63.96 pC
E= 1.31e-05 J
N_phot= 1.38e+10
I [kA]
Power [W]
E ± σ_E [GeV]
Bunching
s [μm]


1e9
E_ph^max= 5927.13 eV
(ΔE/E)_fwhm= 8.76e-04
(on axis)
[N_phot/eV] (estim)
E_photon [eV]

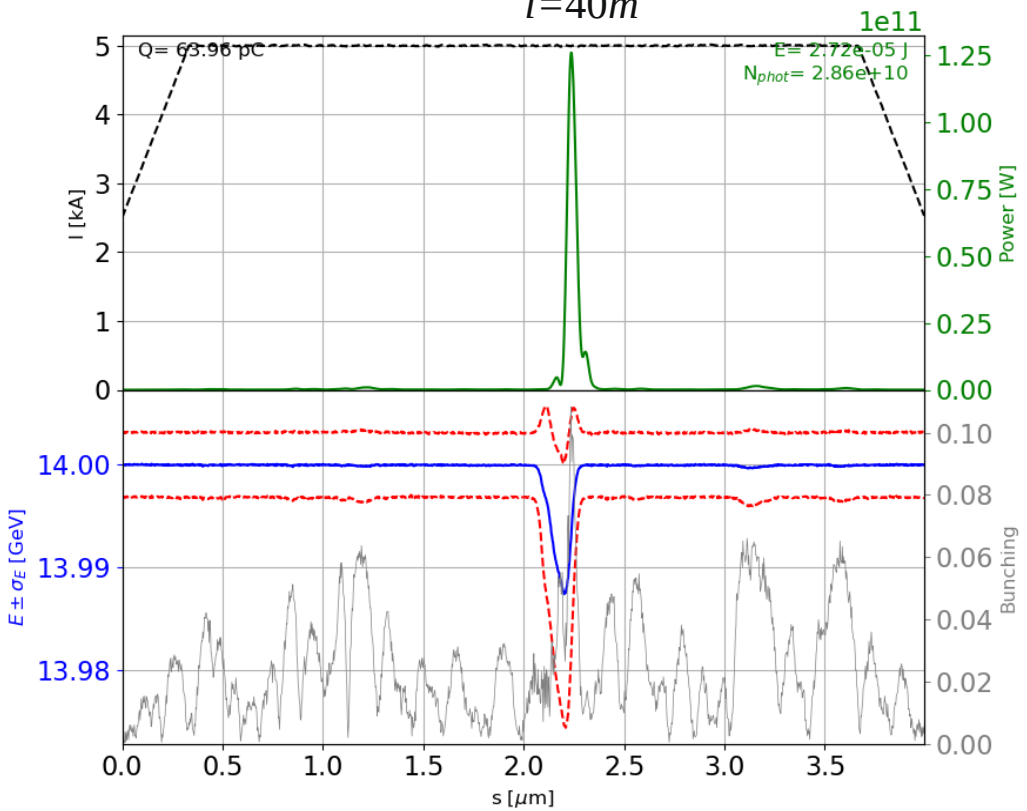

1e9
E_ph^max= 5928.06 eV
(ΔE/E)_fwhm= 6.84e-04
(on axis)
[N_phot/eV] (estim)
E_photon [eV]

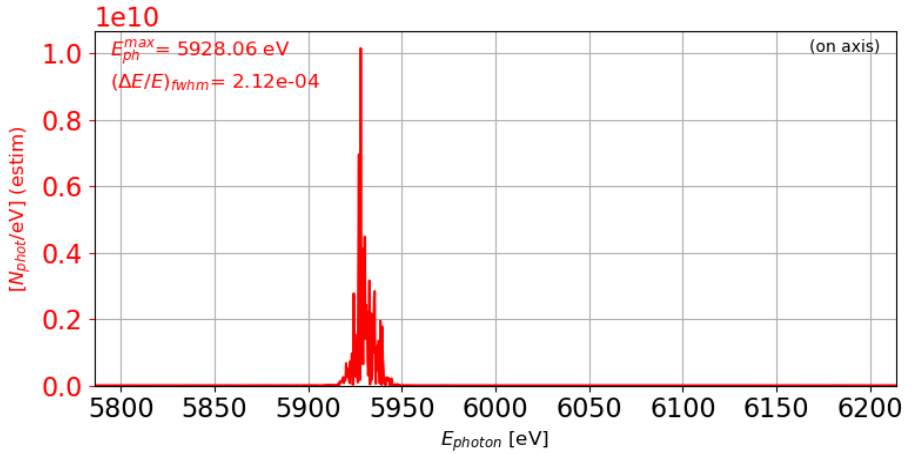
l=35m


1e10
Q= 63.96 pC
E= 1.97e-05 J
N_{phot}= 2.07e+10
I [kA]
Power [W]
$E \pm \sigma_E$ [GeV]
Bunching
s [μm]


1e9
E_{ph}^{max}= 5928.06 eV
$(\Delta E/E)_{fwhm}$= 2.27e-04
(on axis)
$[N_{phot}/eV]$ (estim)
E_{photon} [eV]

l=40m

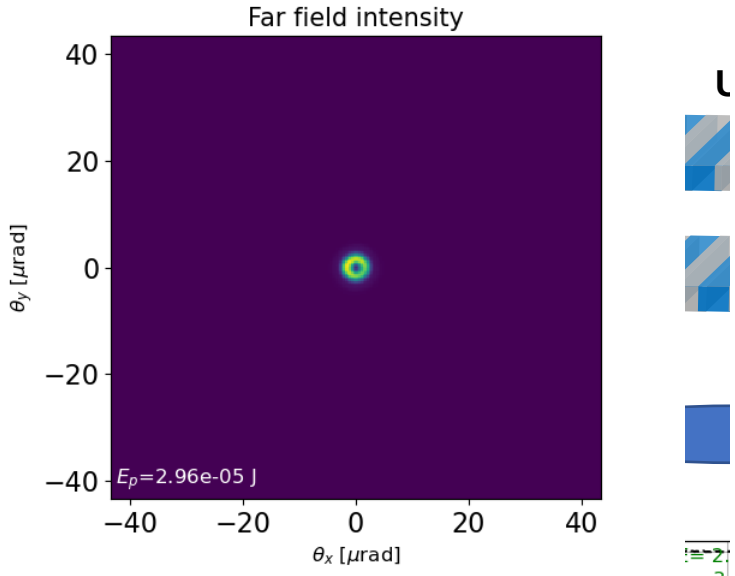

1e11
Q= 63.96 pC
E= 2.72e-05 J
N_{phot}= 2.86e+10
I [kA]
Power [W]
$E \pm \sigma_E$ [GeV]
Bunching
s [μm]

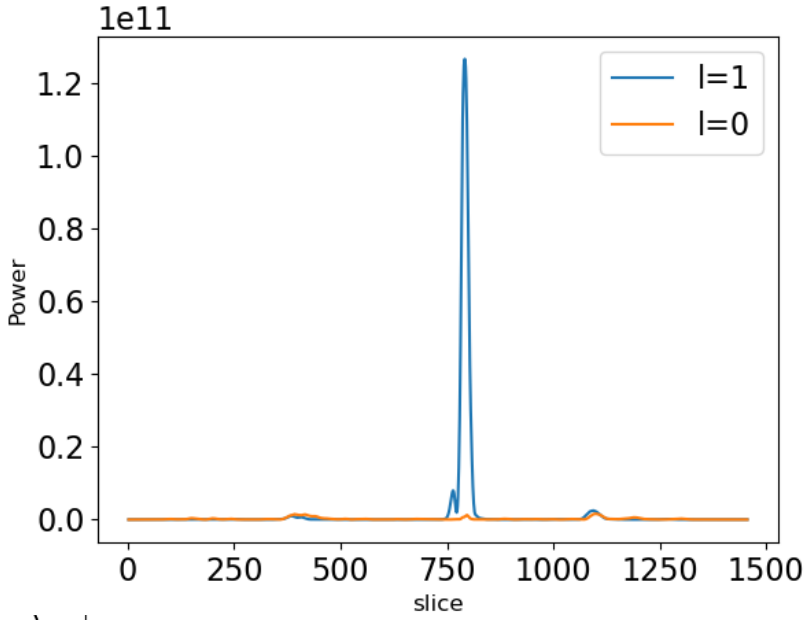

1e10
E_{ph}^{max}= 5928.06 eV
$(\Delta E/E)_{fwhm}$= 2.12e-04
(on axis)
$[N_{phot}/eV]$ (estim)
E_{photon} [eV]

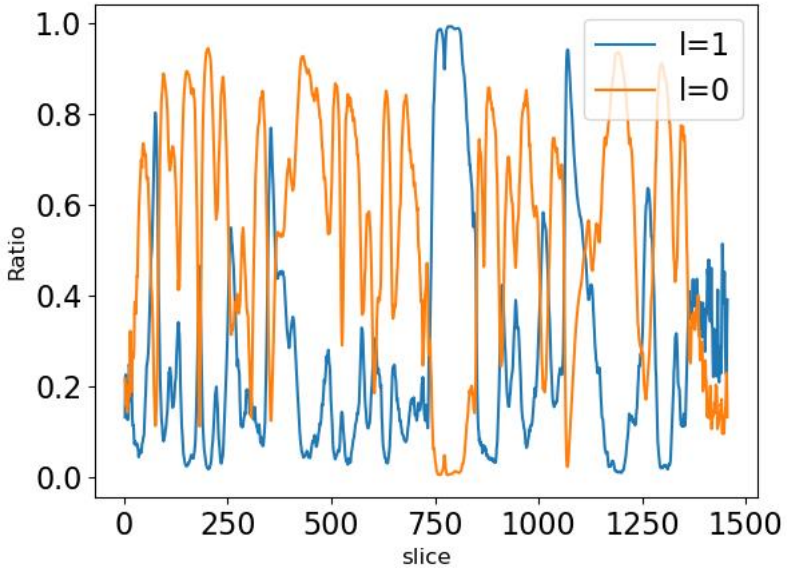
Enhanced Self-seeded FEL with OAM

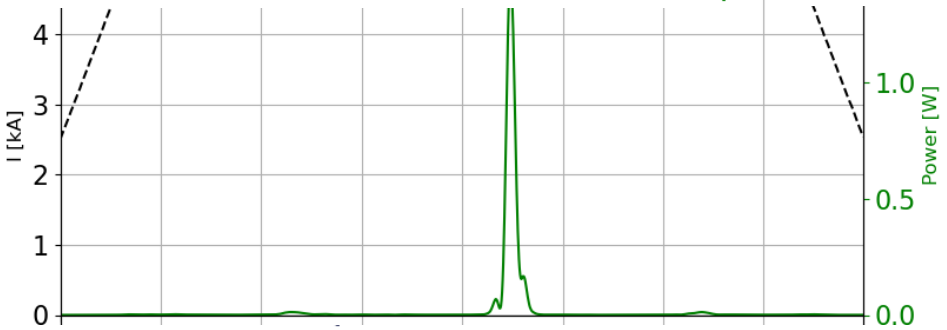
>100 GW, ~ 150 as, 6 keV

- The scheme of ESSOAM



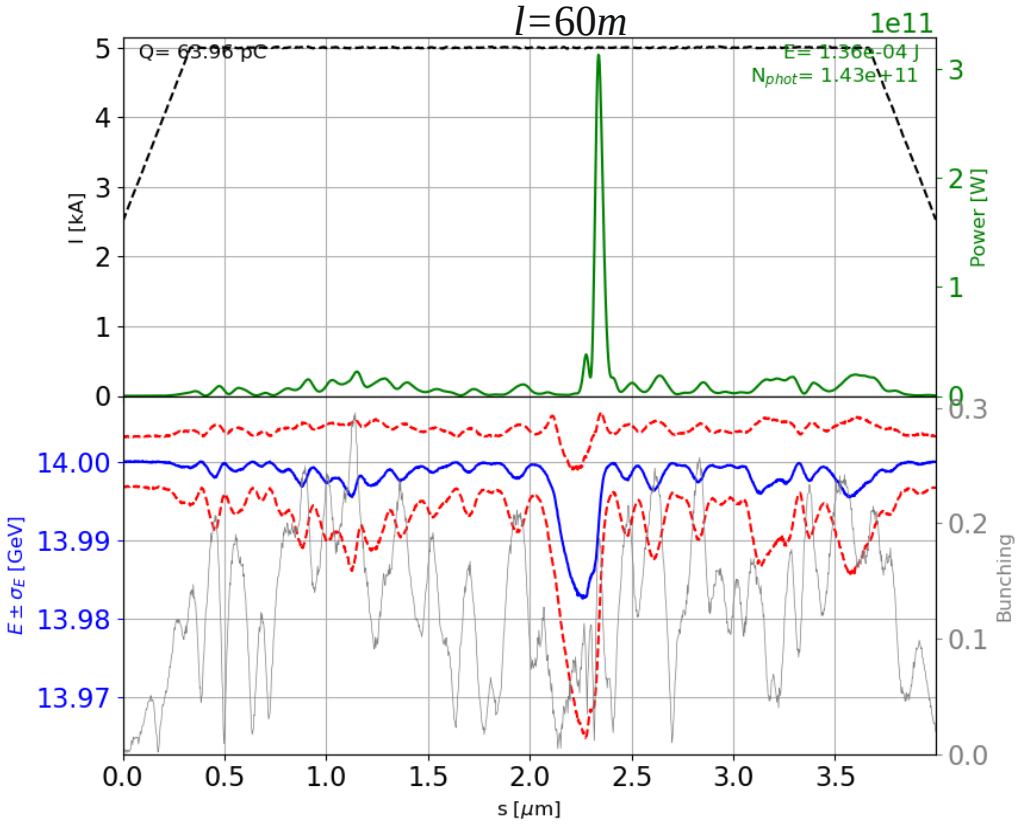


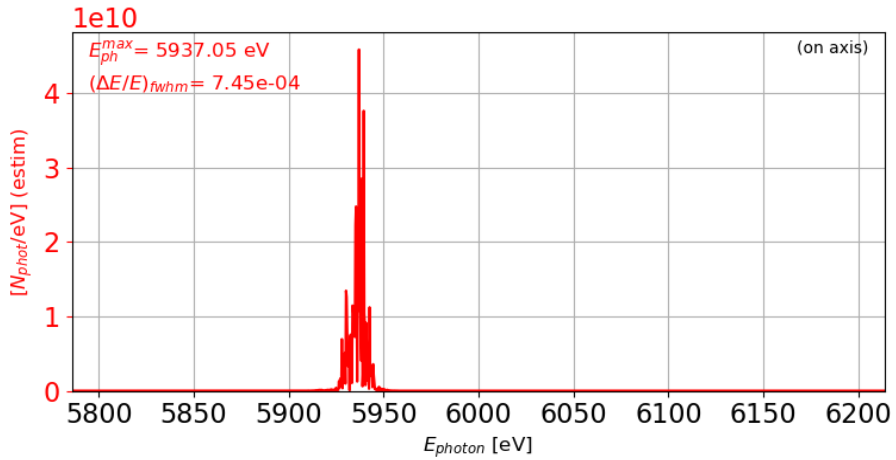


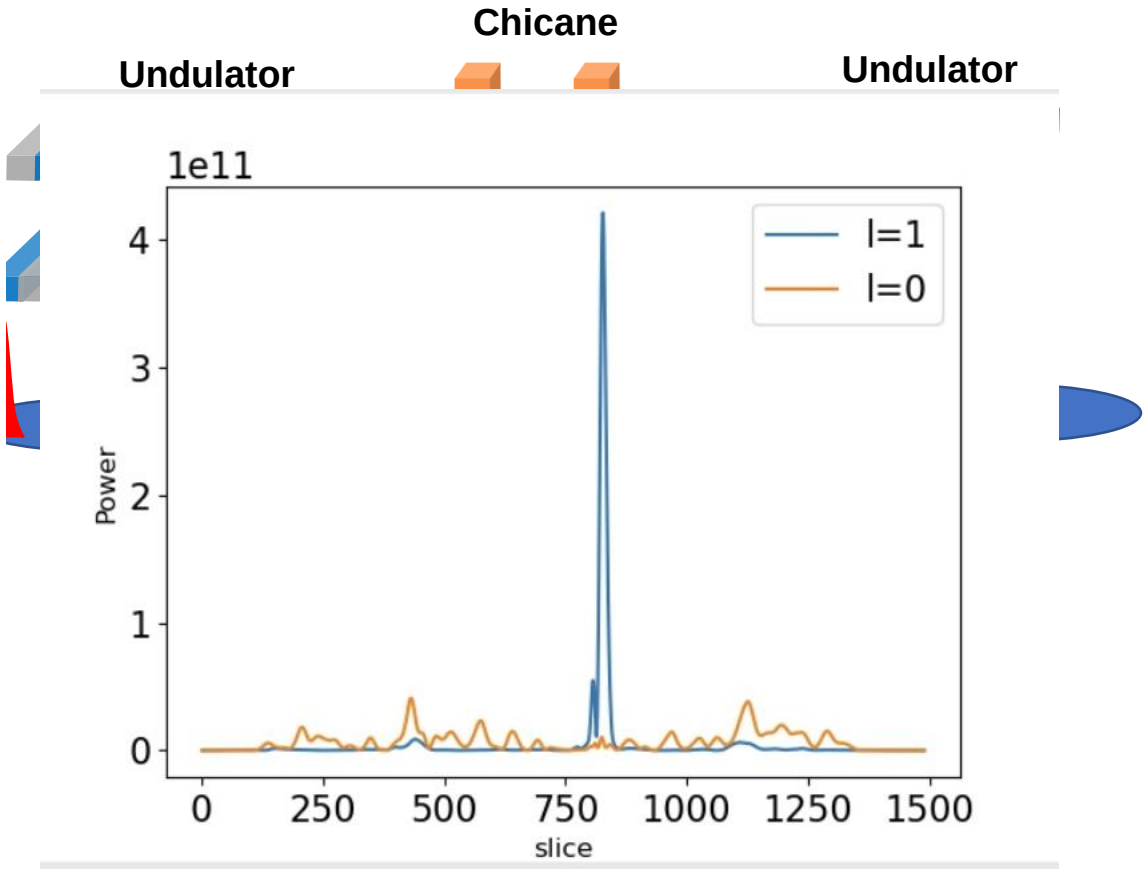


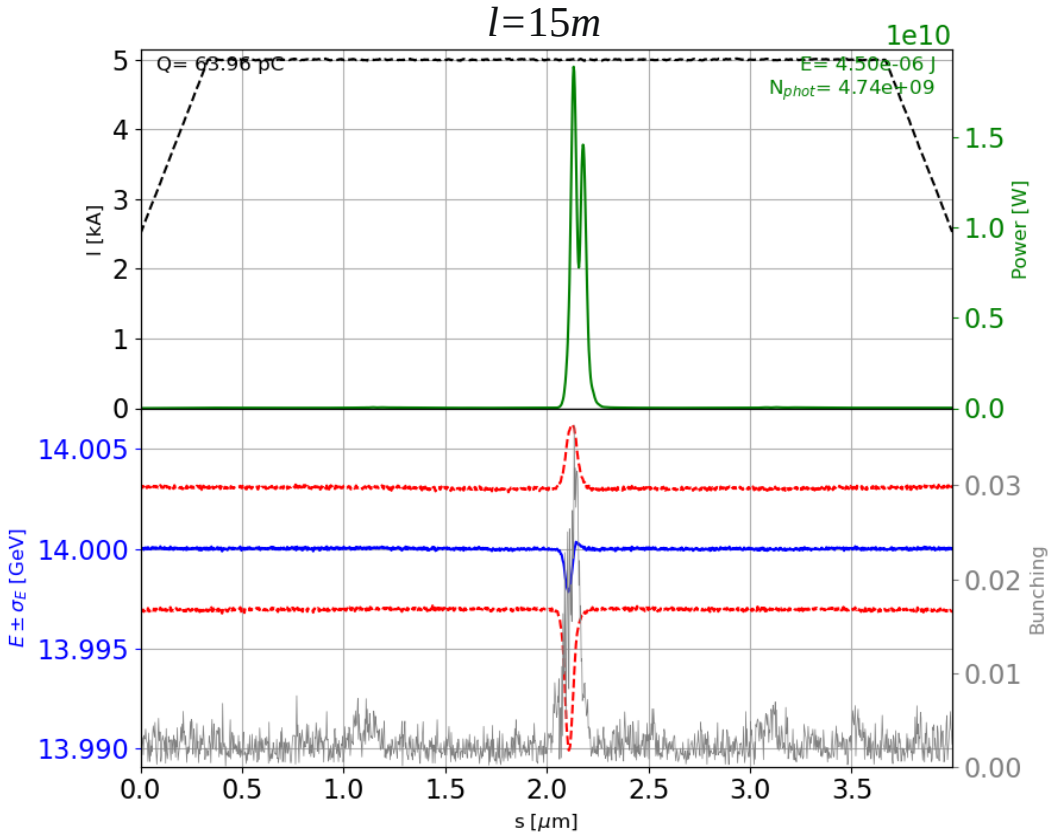
Photon energy	Pulse energy	OAM mode	Pulse duration
6~9 keV	>50 uJ	1, -1, 2, -2	< 200 as

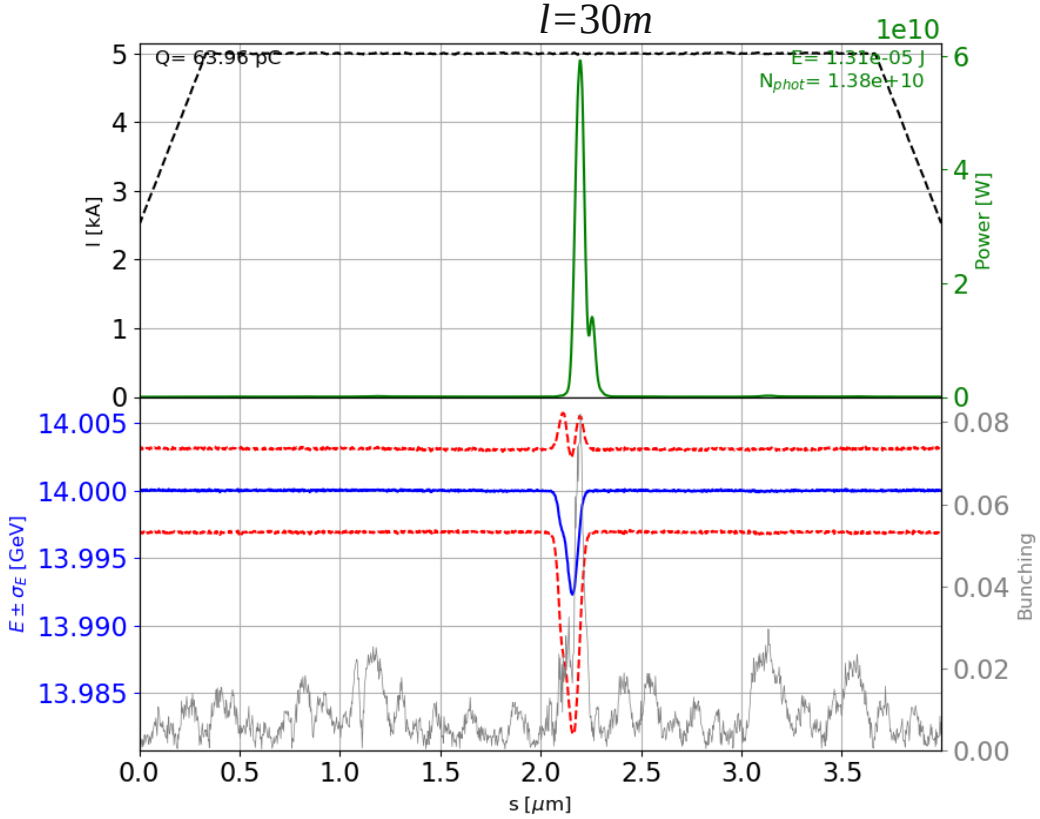
Chenzhi Xu,04/08/2023

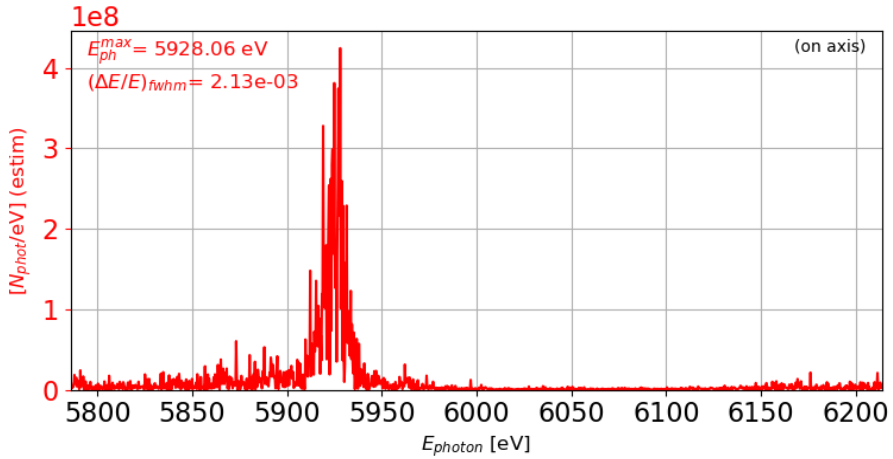


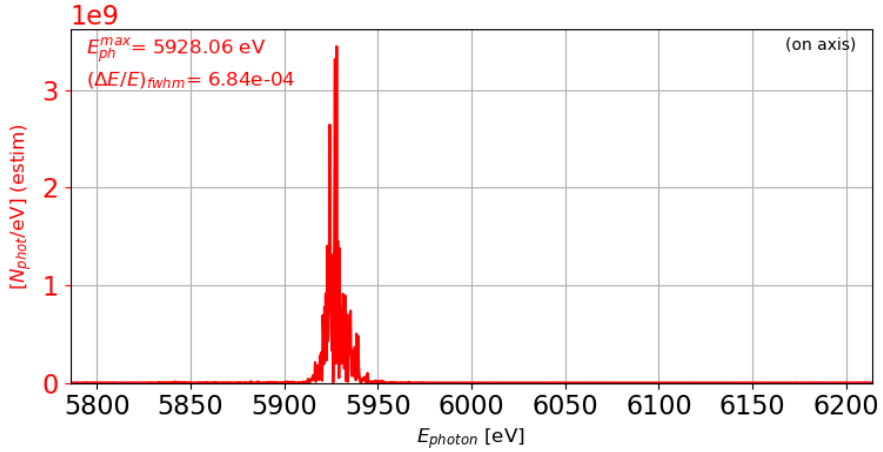




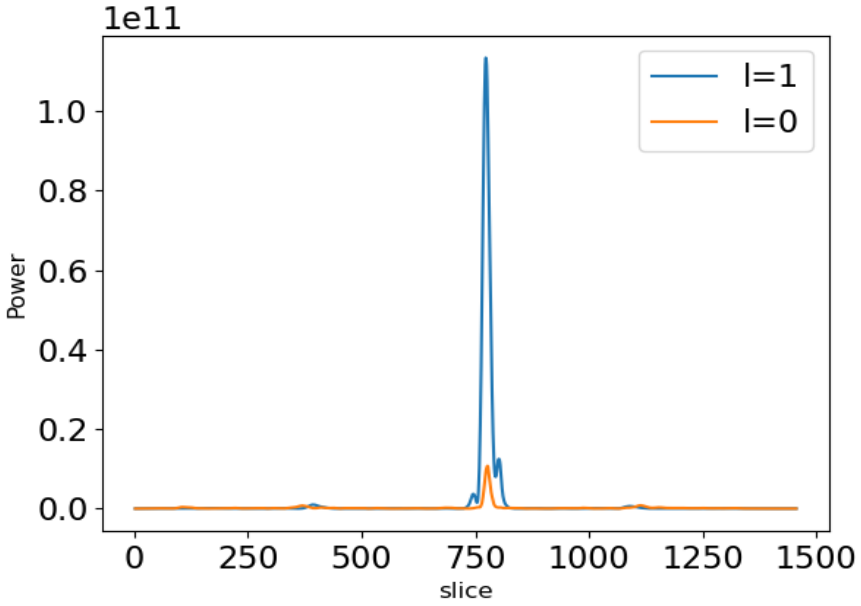

l=15m
1e10
Q= 63.96 pC
E= 4.50e-06 J
N_{phot}= 4.74e+09
I [kA]
Power [W]
$E \pm \sigma_E$ [GeV]
Bunching
s [μm]


l=30m
1e10
Q= 63.96 pC
E= 1.31e-05 J
N_{phot}= 1.38e+10
I [kA]
Power [W]
$E \pm \sigma_E$ [GeV]
Bunching
s [μm]

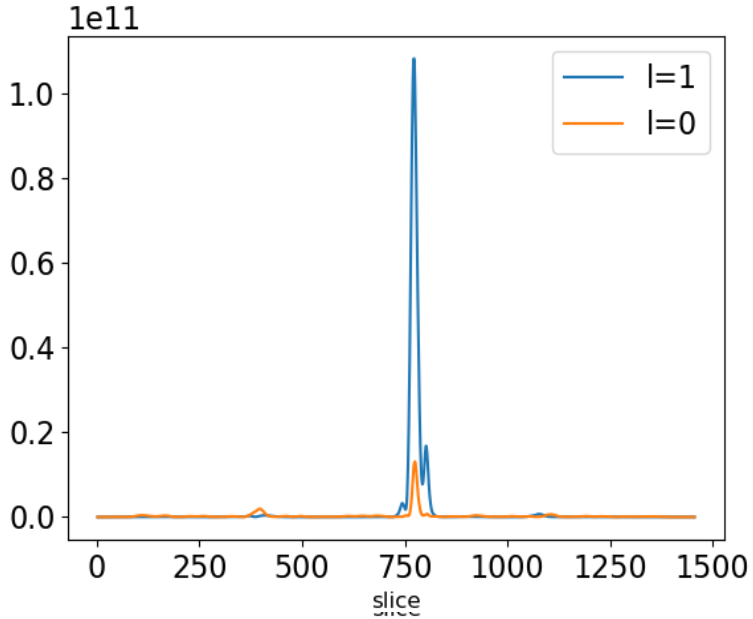

1e8
E_{ph}^{max}= 5928.06 eV
$(\Delta E/E)_{fwhm}$= 2.13e-03
(on axis)
[N_{phot}/eV] (estim)
E_{photon} [eV]


1e9
E_{ph}^{max}= 5928.06 eV
$(\Delta E/E)_{fwhm}$= 6.84e-04
(on axis)
[N_{phot}/eV] (estim)
E_{photon} [eV]

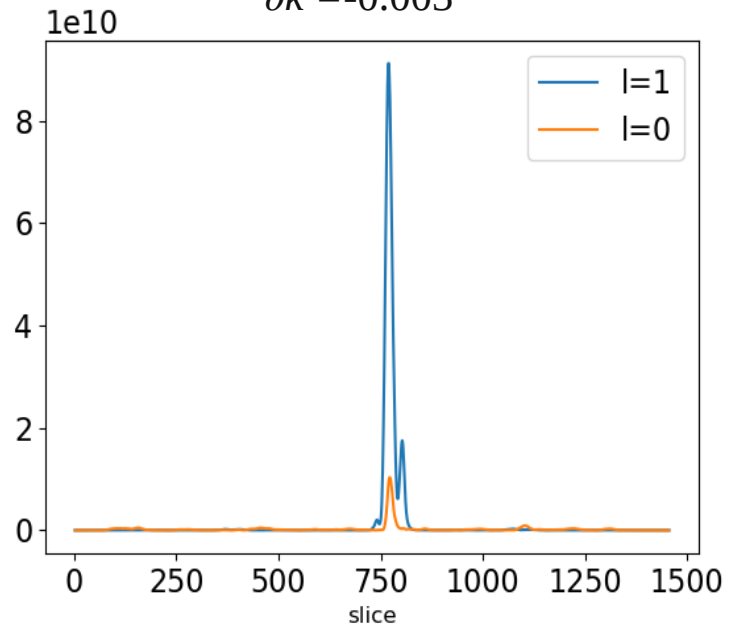
δk=-0.001



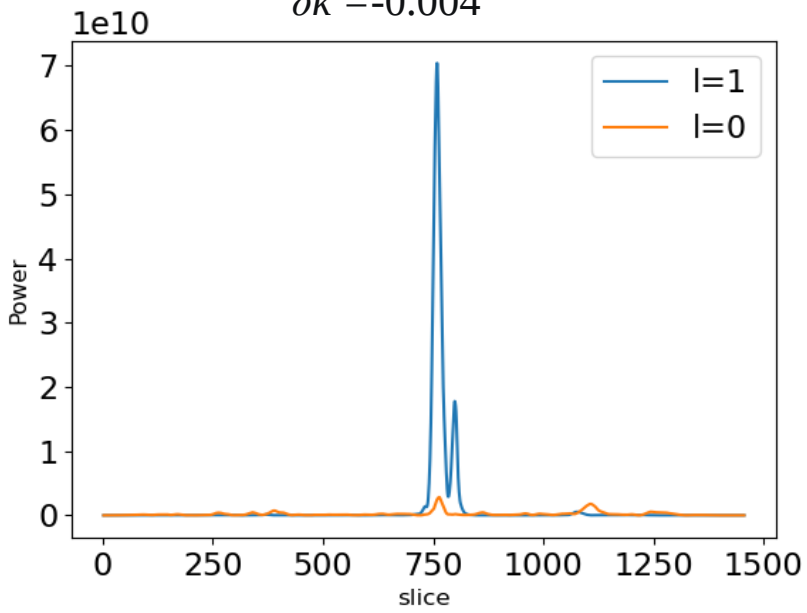
δk =-0.002



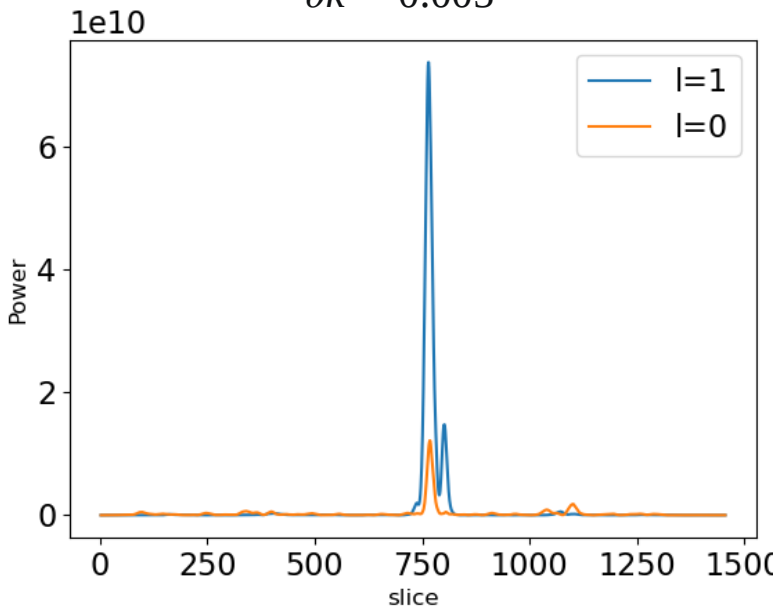
δk =-0.003



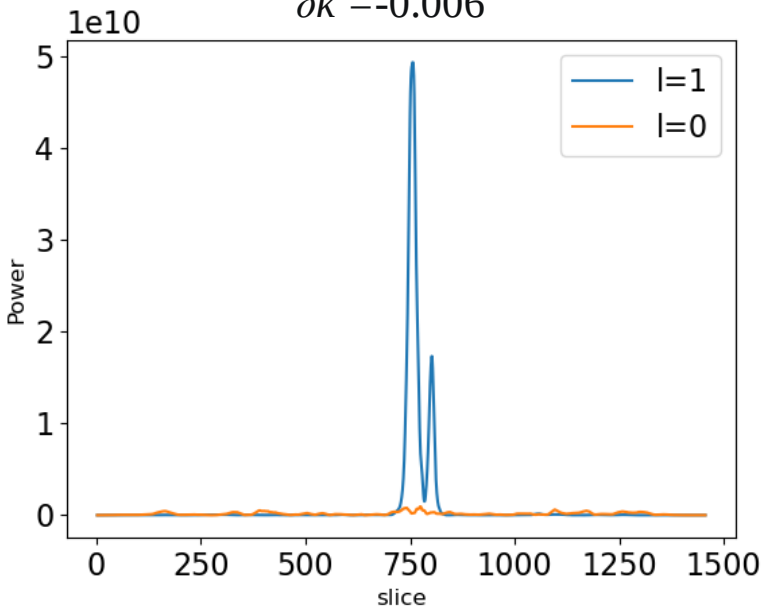
δk =-0.004



δk =-0.005

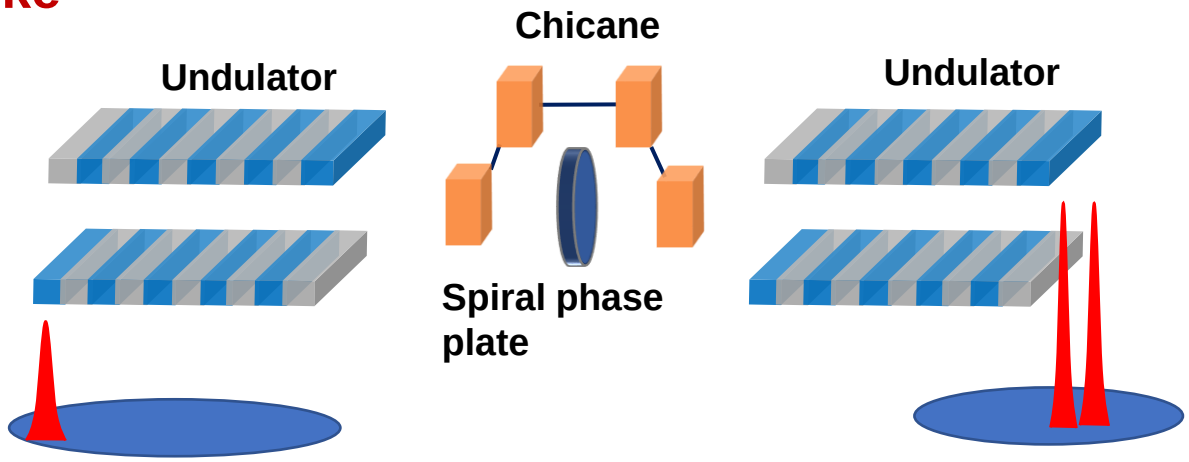


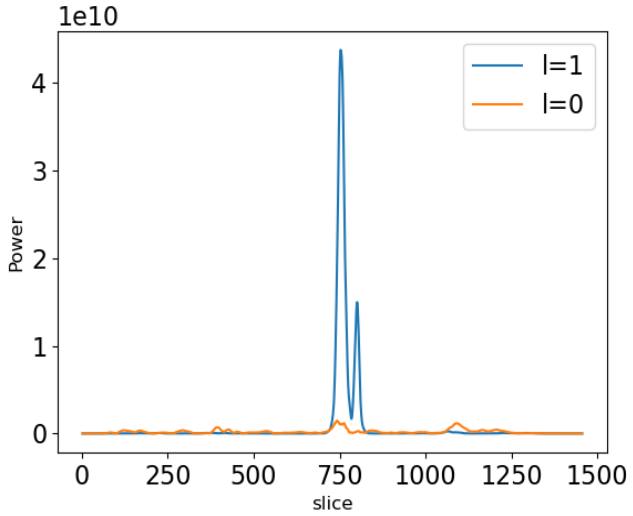
δk =-0.006



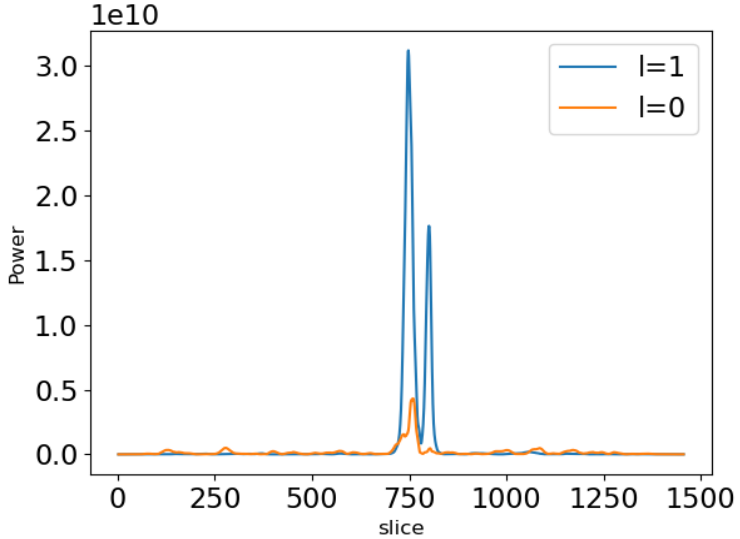
Enhanced Self-seeded FEL with OAM : two spike

- Change detuning

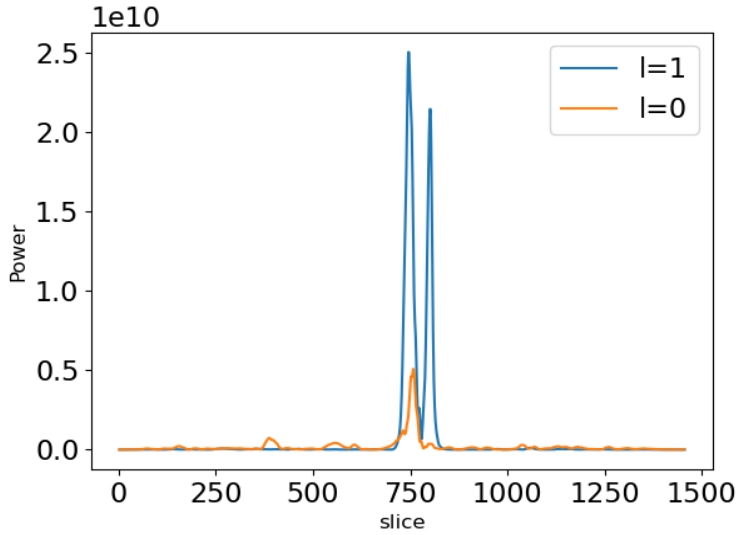




δk =-0.007



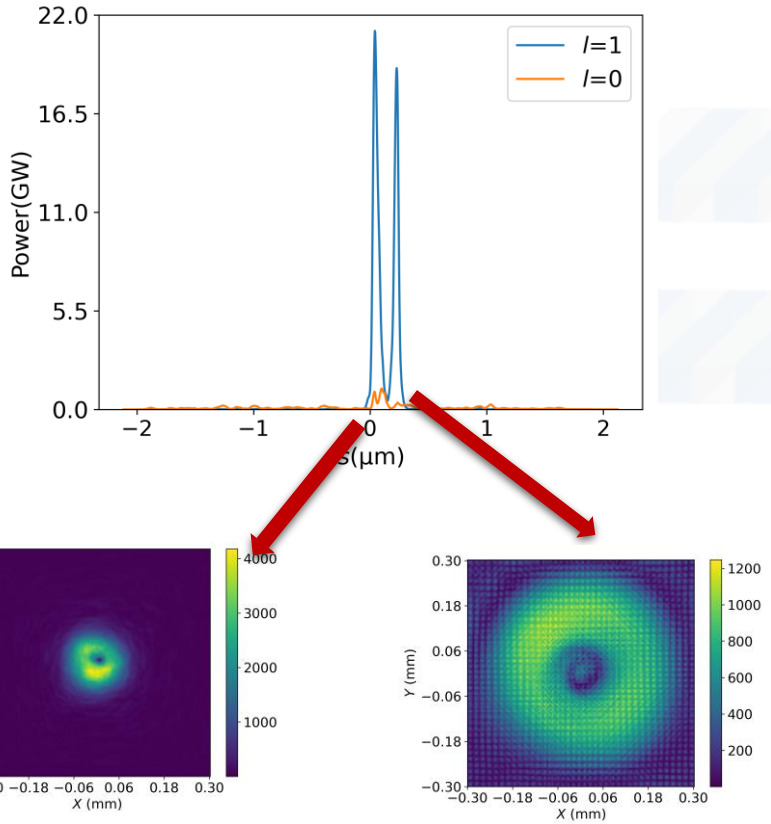
δk =-0.008



δk =-0.009

Enhanced Self-seeded FEL with OAM : two spike

Twin attosecond OAM pulse



~174 as **~135 as**

Outline

- Motivations
- Methods for generating OAM light based on FEL physics
- Enhanced Self-seeded FEL with OAM
- **Summary and Outlook**

Summary

- ✓ **Enhanced Self-seeded FEL with OAM is proposed to generate X-ray OAM pulse with high OAM purity, high peak power and attosecond pulse duration;**
- ✓ **The X-ray OAM pulse with two spikes can be generated in the ESSOAM scheme;**
- ✓ **Optimization & experiment consideration for both schemes are further required.**

Thanks for your attention!
Questions and comments welcome!