What would it take to demonstrate a coherent X-ray source at ATF?

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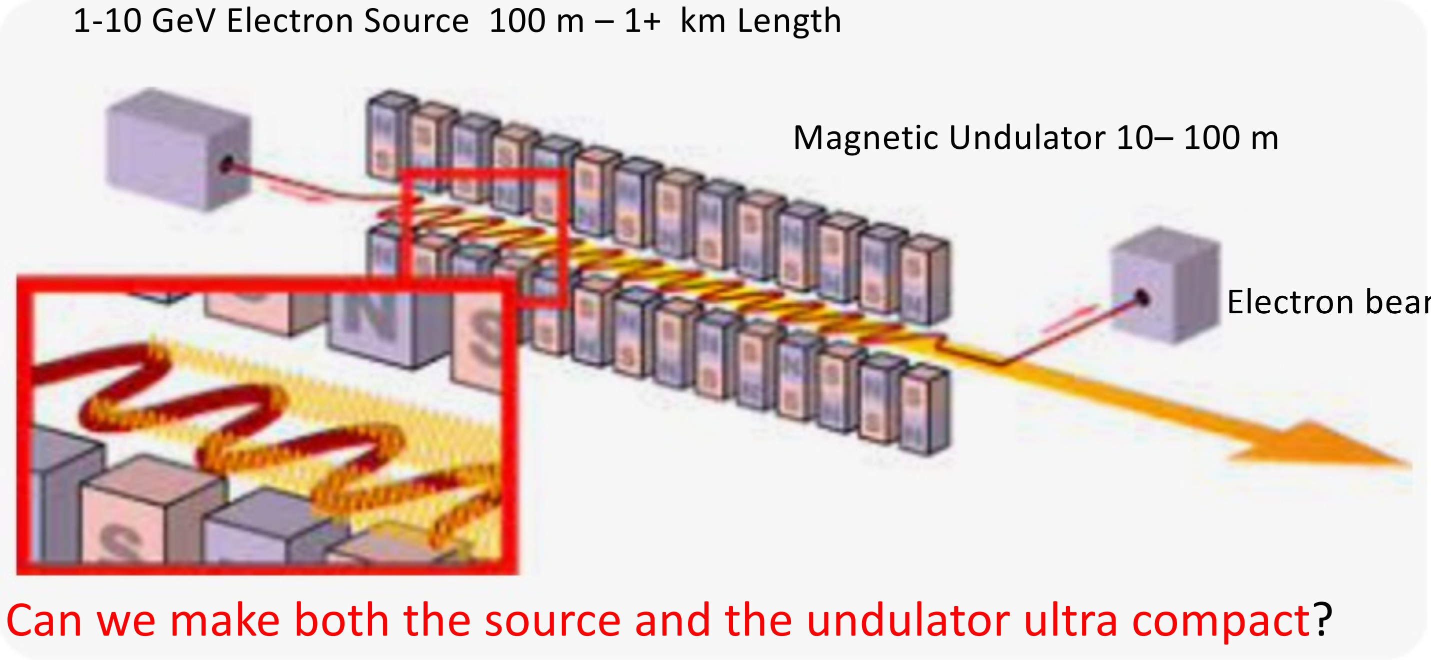
Can we make a coherent X-ray source @ ATF?

High risk, high Pay off idea that requires decade long effort

- Current X-FELs are km scale machines costing $1B+

Wiggles a resonant high brightness electron beam where it is bunched via the FEL instability emitting coherent radiation in forward direction.



1-10 GeV Electron Source 100 m – 1+ km Length

Magnetic Undulator 10– 100 m

Electron beam Dump

End Stations/
Scientific Instruments
Several km long

Can we make both the source and the undulator ultra compact?

Plasma Accelerators can miniaturize the electron source but is the brightness sufficient and what about the undulator?

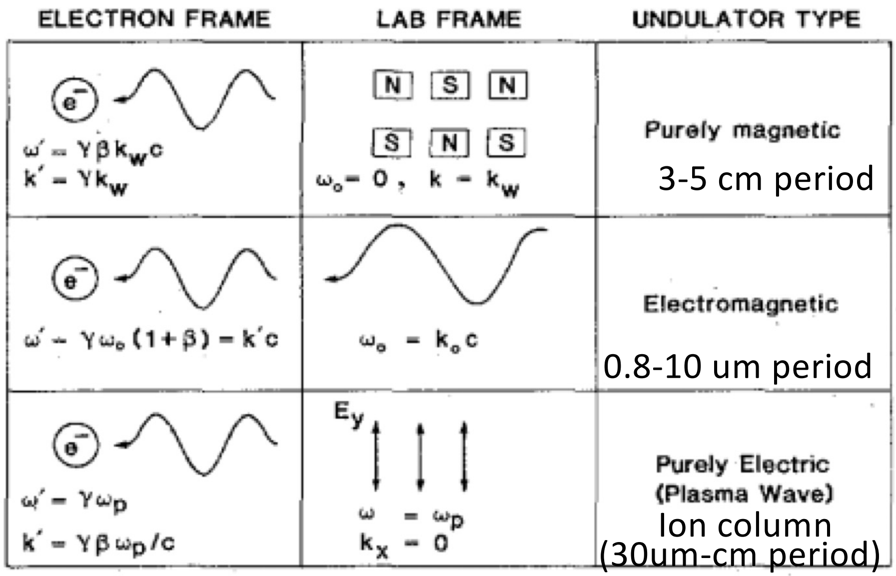
Magnetic, e.m. and electrostatic undulators all look like an electromagnetic wave in the frame of the electron.

$$\begin{pmatrix} k'c \\ i\omega' \end{pmatrix} = \begin{bmatrix} \gamma & i\beta\gamma \\ -i\beta\gamma & \gamma \end{bmatrix} \begin{pmatrix} k_0 \\ i\omega_0 \end{pmatrix} \text{ electromagnetic}$$

$$\begin{pmatrix} k_w \\ 0 \end{pmatrix} \text{ purely magnetic}$$

$$\begin{pmatrix} 0 \\ i\omega_p \end{pmatrix} \text{ purely electric (plasma).} \qquad (1)$$

For $\beta \simeq 1$, the transformed quantities satisfy $\omega' = k'c$ for all the cases, except that their wavelengths are different: $\lambda' = \lambda_{w/\gamma}$ (magnetic), $\lambda_{0/2\gamma}$ (electromagnetic), and $2\pi c/\omega_p \gamma$ (purely electric or plasma). Each electromagnetic wave has a wiggler strength $a_w = eE'/m\omega'c = eA/mc^2$ equal to its corresponding value, $eB\lambda_w/2\pi mc^2$



ELECTRON FRAME	LAB FRAME	UNDULATOR TYPE
e⁻ $\omega' = \gamma\beta k_w c$ $k' = \gamma k_w$	N S N S N S $\omega_o = 0$, $k = k_w$	Purely magnetic 3-5 cm period
e⁻ $\omega' = \gamma\omega_o(1+\beta) = k'c$	$\omega_o = k_o c$	Electromagnetic 0.8-10 um period
e⁻ $\omega' = \gamma\omega_p$ $k' = \gamma\beta\omega_p/c$	E_y $\omega = \omega_p$ $k_x = 0$	Purely Electric (Plasma Wave) Ion column (30um-cm period)

Equivalence among magnetic, electromagnetic, and purely electric (plasma) wigglers.

Ref: C. Joshi et al. IEEE J. Quant. Elect. 23, no. 9 (1987): 1571-1577.

Prebunching of the relativistic electron beam at λ_r before propagation through a wiggler can reduce FEL gain length

The key to getting an exponential gain in FEL is bunching the electrons on a scale of the desired radiation wavelength.

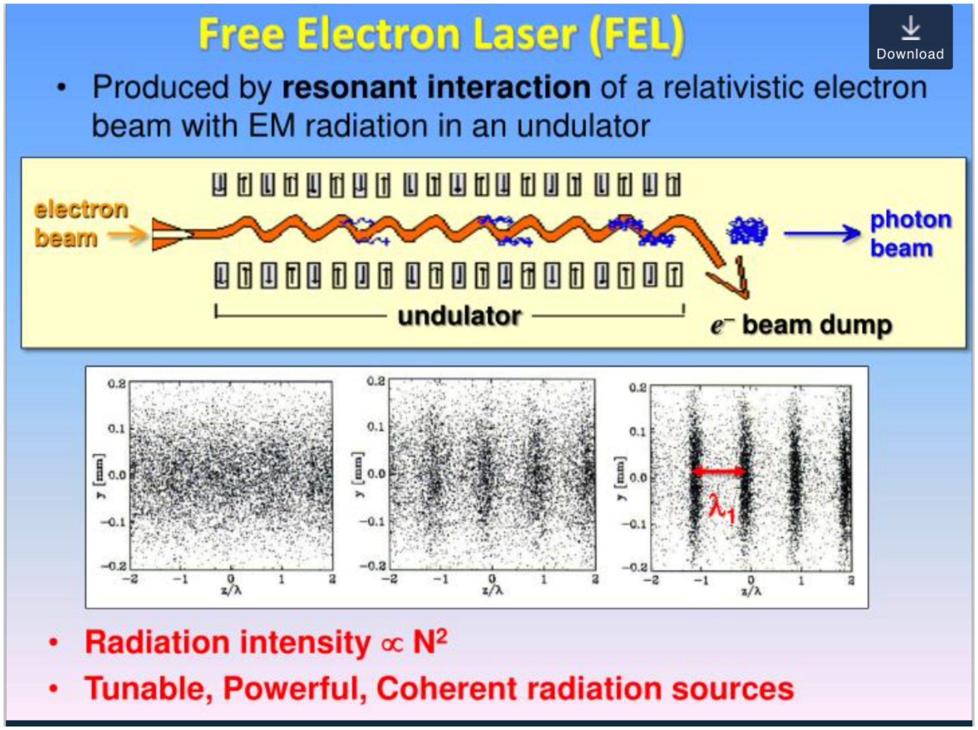
Initially electrons are uniformly distributed over many radiation wavelengths. In an em undulator, collisions between electrons and photons generate ICS radiation that is not phase coherent- total radiation is proportional to N (this is akin to spontaneous emission in QE)

The trick is to bunch the electrons , but this requires electrons to have a very small transverse emittance.

Now electrons in a single bunch can emit as a single macro-particle;

Radiated power scaling as N^2. And many such bunches act as a phased array. The radiation is “superradient” also called SASE

$$b = \left|\sum_{j=1}^{N_b} exp(ikz_j)\right| \Big/ N_b$$



Free Electron Laser (FEL)

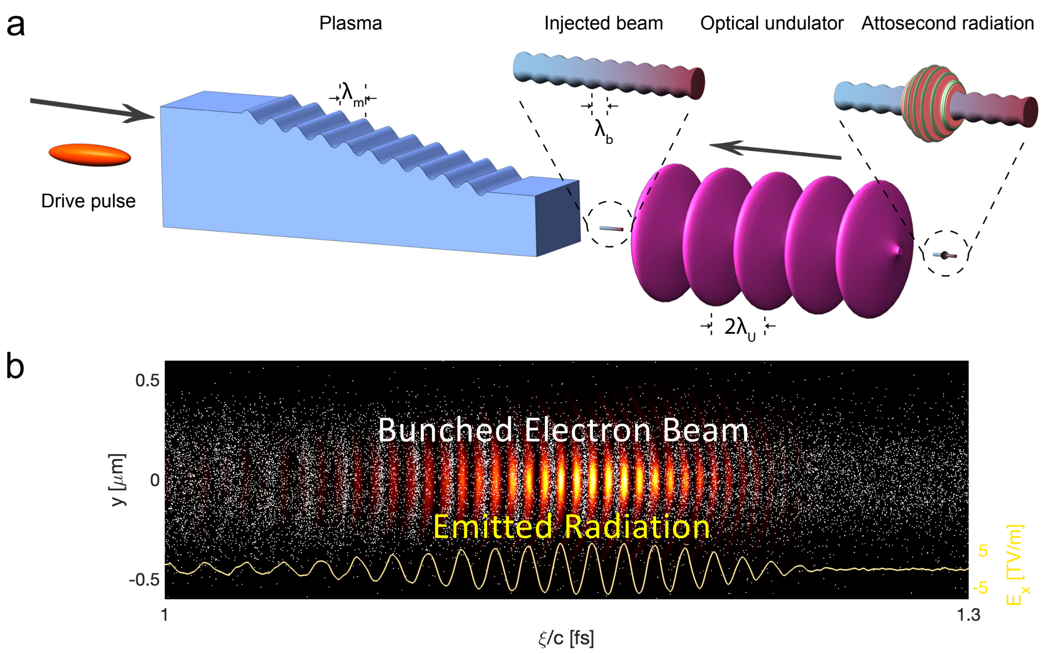
- Produced by **resonant interaction** of a relativistic electron beam with EM radiation in an undulator

- **Radiation intensity ∝ N^2**
- **Tunable, Powerful, Coherent radiation sources**

Fig. by Zirong Huang (SLAC)

Main Goal: Generation of a coherent KeV X-ray beam Using a PWFA and an Optical Undulator

Compression factor =1/4.5g where g= $(i/n_p)(dn_p/dk_p 1/z)$



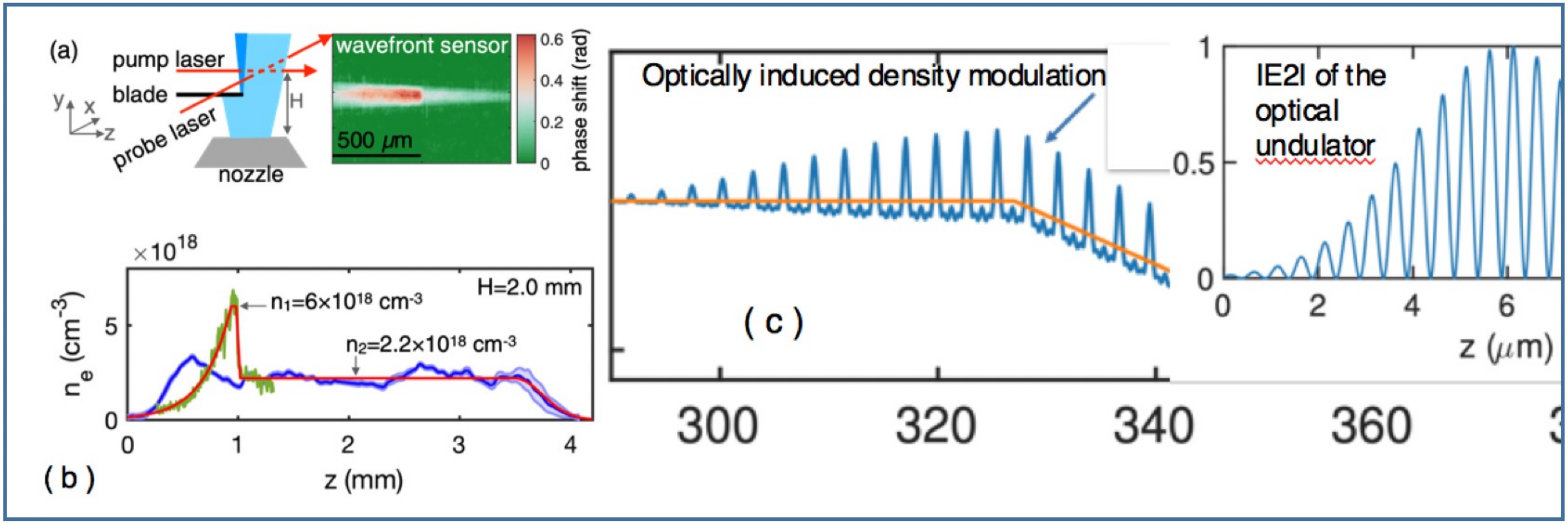
Nature communications 13, no. 1 (2022): 3364.
X.Xu et al, PRAB 27, no. 1 (2024): 011301.)

Can we generate
a coherent beam of soft x-rays with
brightness orders of magnitude greater
compared to Inverse Compton scattering by
Employing the FEL instability
In a 1000 sq ft lab-scale facility ?

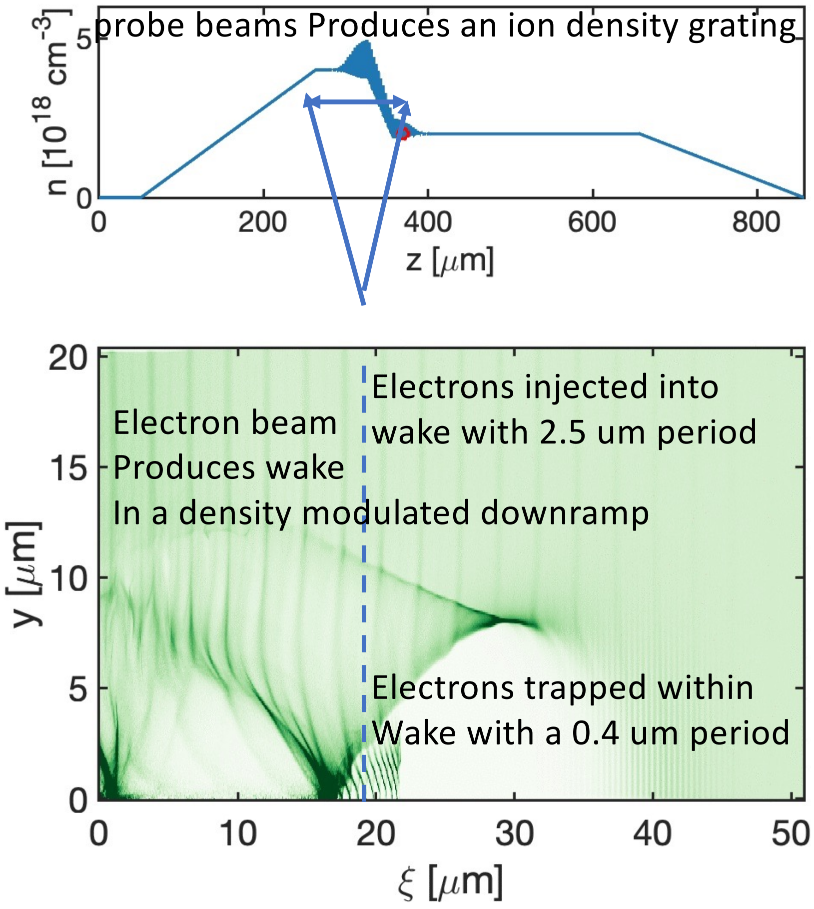
OUR PROPOSAL
PWFA for energy, charge,
emittance.
Develop an optical undulator to reduce
the resonant energy from GeV to MeV
and prebunch the electrons on soft X-ray
wavelength scale.

ATF can demonstrate microbunching of self-injected electrons on various spatial scales- 400 nm to < 10nm

Diagnostic: VUV grazing incident spectrometer



3D PIC simulation of 1:1 mapping of the injected electron train into a compressed bunch train (experiment already carried out at UCLA



Ionization by Interference of two degenerate probe beams Produces an ion density grating

Electron beam Produces wake In a density modulated downramp

Electrons injected into wake with 2.5 um period

Electrons trapped within Wake with a 0.4 um period

Laser spot size is 6 um or Z_r= 100 um

Plasma density 1.5 e19 cm-3

Compression factor 2.5/0.4= 6

For reaching XUV-X-ray regime we will Need a compression factor of 50-100

We have shown the generations of ionization Gratings and diagnosed them by TS.

The Goal has to be achieved in several steps
(EXPECTED SCIENTIFIC OUTCOMES)

- 1) Microbunch a density downramp at 200 nm spatial scale and diagnose it using collective Thomson scattering. (Year 1 and 2)

- 2) Create a nonlinear fully blown-out wake (PWFA) across this modulated downramp and demonstrate mapping and bunching factor of the trapped electrons by measuring CTR harmonics using a VUV spectrograph. Deduce the beam emittance from these measurements

  (Year 3 and 4)

- 3) Collide a tightly focused single 2 ps CO2 laser pulse with an a0~3 at 10^0 with the electrons at the bottom of the downramp with precision delay line. Make careful measurements of the photon spectrum and compare it with the CTR spectrum (year 4 and 5)

Requires facility upgrades at several levels

1) Linac upgrade : high charge short pulse capability for producing wake
1.5-2 nC in a single, 100 MeV , <100 fs compressed pulse

2) Ti- Sapphire upgrade Can start with 800 nm (20 mJ in a single 100 fs
pulse but will need 20 mJ in 100 fs in the 4th harmonic
to reach 500 Ev-1 KeV photon energy.

3)CO_2 laser upgrade Need a_0 of >3 in a single <2 ps pulse

4) Need VUV spectrograph to cover 300-30 nm region
Eventually need a soft x-ray CCD camera for single photon detection

Quad Chart

Scientific/Technical Outcomes

1) Microbunch a density downramp at 200 nm spatial scale and diagnose it using collective Thomson scattering.

2) Create a nonlinear fully blown-out wake across this modulated downramp and demonstrate mapping and bunching factor of the trapped electrons by measuring CTR harmonics using a VUV spectrograph. Deduce the beam emittance from these measurements

3) Collide a tightly focused single 2 ps CO2 laser pulse with an a0~3 at 10^0 with the electrons at the bottom of the downramp with precision delay line. Make careful measurements of the photon spectrum

ATF Facilities Upgrade Roadmap

1) Linac upgrade ; high charge short pulse capability for producing wake
1-2 nC in a single <100 fs compressed pulse. Focus e
Beam to less than 30 um spot size.
2) Ti- SAPH upgrade Can start with 800 nm (20 mJ in a single 100 fs
pulse but will need 20 mJ in 50 fs in a 3rd harmonic
3)CO_2 laser upgrade Need a_0 of >3 in a single <2 ps pulse
4) Need VUV spectrograph to cover 300-50 nm region
5) Ability to time synchronize the linac with lasers to within 1ps and spatial overlap of 5 microns

Lasers/e-beam Parameters Required

Need a 20 mJ , < 100fs Ti-saph ionization laser
Need two 5 mJ lasers to create an interference pattern
Need a 1mJ laser with variable delay to do TS

Need 5 TW CO2 laser to collide with the electrons as they exit the wake

Beyond the Current Roadmap

Will need an energy upgrade of the Ti-saphhire laser to 1 J level.
Need frequency upconversion to forth harmonic
Need ability to propagate this compressed pulse to the chamber
Need an x-ray CCD with extended soft x-ray capability

Upgraded Electron Beam

Parameter	Units	Typical Values	Comments
Beam Energy	MeV	100 MeV	
Bunch Charge	nC	1-2.0 nC	
Compression	fs	Down to 100 fs (up to 15 kA peak current)	
Transverse size at IP (s)	microns	30 (dependent on IP position)	
Normalized Emittance	microns	30	
Rep. Rate (Hz)	Hz	1	
Trains mode	---	Single bunch	

Available CO_2 Laser Requirements

Configuration	Parameter	Units	Typical Values	Comments
CO_2 Regenerative Amplifier Beam	Wavelength	mm	9.2	*Wavelength determined by mixed isotope gain media*
	Peak Power	GW	~3	
	Pulse Mode	---	Single	
	Pulse Length	ps	2	
	Pulse Energy	mJ	6	
	M^2	---	~1.5	
	Repetition Rate	Hz	1.5	*3 Hz also available if needed*
	Polarization	---	Linear	*Circular polarization available at slightly reduced power*
CO_2 CPA Beam	Wavelength	mm	9.2	*Wavelength determined by mixed isotope gain media*
Note that delivery of full power pulses to the Experimental Hall is presently limited to Beamline #1 only.	Peak Power	TW	5	*~5 TW operation will become available shortly into this year's experimental run period. A 3-year development effort to achieve >10 TW and deliver to users is in progress.*
	Pulse Mode	---	Single	
	Pulse Length	ps	2	
	Pulse Energy	J	~5	*Maximum pulse energies of >10 J will become available within the next year*
	M^2	---	~2	
	Repetition Rate	Hz	0.05	
	Polarization		Linear	*Adjustable linear polarization along with circular polarization can be provided upon request*

Other Experimental Lasers

Ti:Sapphire Laser System	**Units**	**Stage I Values**	**Stage II Values**	**Comments**
Central Wavelength	nm	800	800	*Stage I parameters are presently available and setup to deliver Stage II parameters has been completed*
FWHM Bandwidth	nm	20	13	
Compressed FWHM Pulse Width	fs	<50	<75	*Transport of compressed pulses will initially include a very limited number of experimental interaction points. Please consult with the ATF Team if you need this capability.*
Chirped FWHM Pulse Width	ps	≥50	≥50	
Chirped Energy	mJ	10	200	
Compressed Energy	mJ	7	~20	*20 mJ is presently operational with work underway this year to achieve our 100 mJ goal.*
Energy to Experiments	mJ	>4.9	>80	
Power to Experiments	GW	>98	>1067	

Nd:YAG Laser System	**Units**	**Typical Values**	**Comments**
Wavelength	nm	1064	*Single pulse*
Energy	mJ	5	
Pulse Width	ps	14	
Wavelength	nm	532	*Frequency doubled*
Energy	mJ	0.5	
Pulse Width	ps	10	

EXTRA SLIDES

3D simulations using a full PIC code

Xinlu Xu et al PHYSICAL REVIEW ACCELERATORS AND BEAMS 27, 011301 (2024)

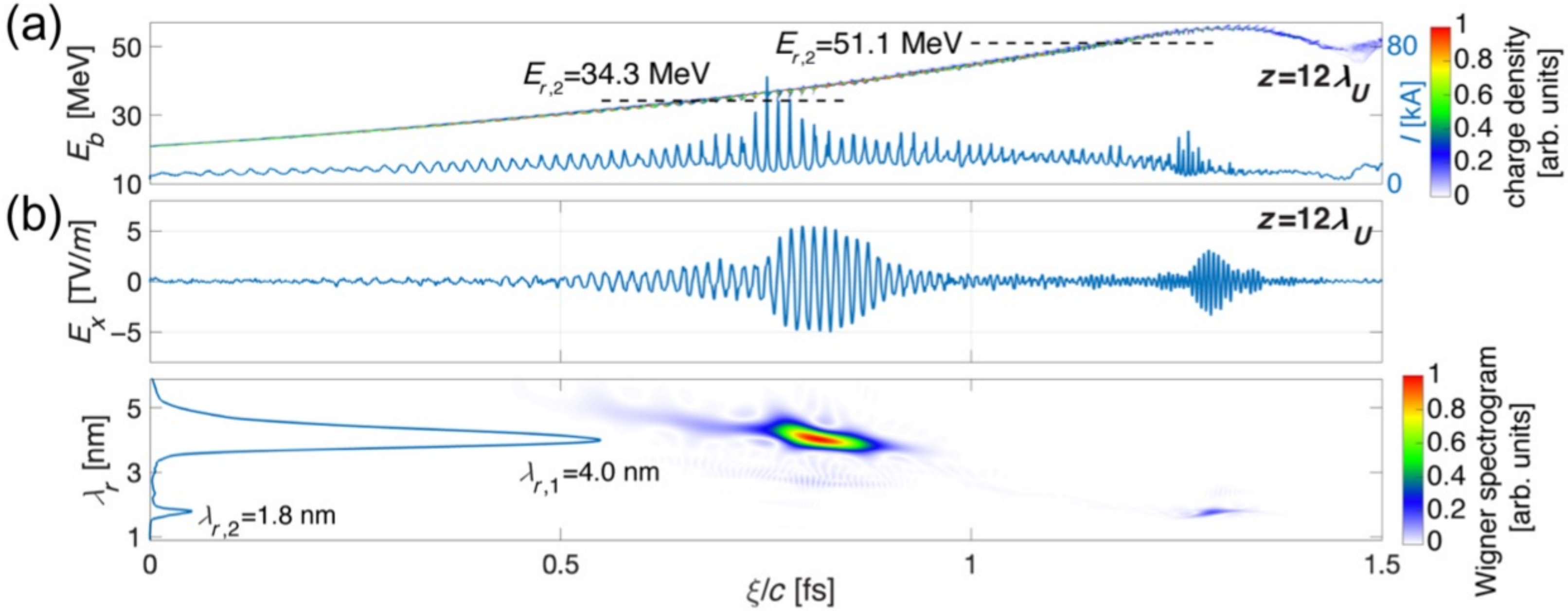


FIG. 4. Generation of two attosecond pulses with different wavelengths. (a) Longitudinal phase space at $z = 12\lambda_U$ and the

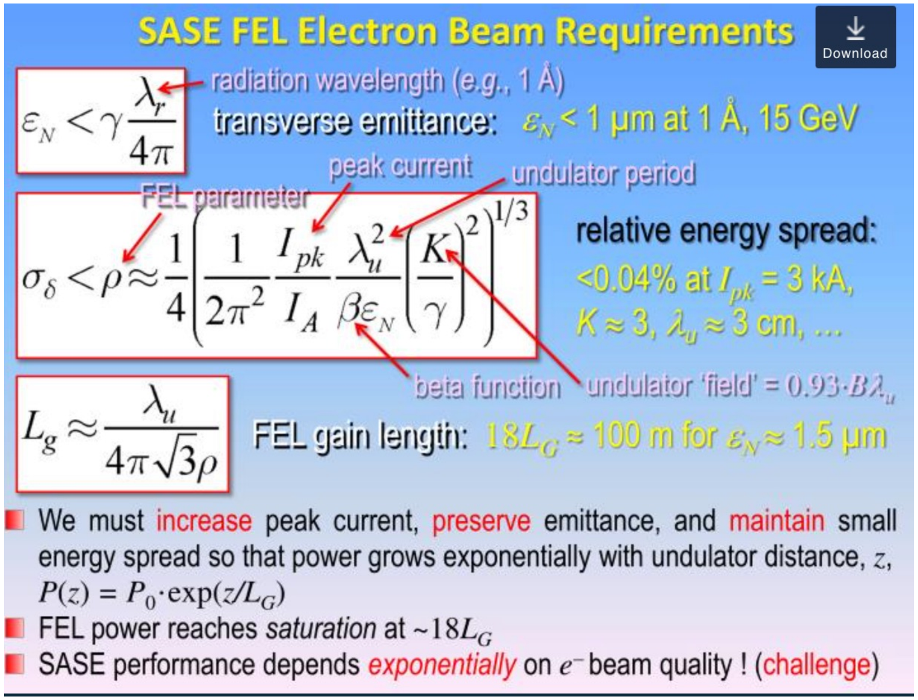
XFELs could be made much more compact if plasma accelerator-based electron source and an electromagnetic undulator could be used.

Remember we do not need to get GW beams.
In a PoP experiment we need to get <2-3 e-foldings of growth (7-20 times)

Unfortunately a short, K=3 laser pulse will blowout the plasma electrons in ω_p^{-1} before it reaches it’s peak amplitude

Alternatively we keep K (t)/ γ_b constant thereby maintaining the resonance. But then we need a chirped beam.

Which beam parameters are important to SASE FEL & Why?



SASE FEL Electron Beam Requirements

$$\boxed{\varepsilon_N < \gamma \frac{\lambda_r}{4\pi}}$$

radiation wavelength (e.g., 1 Å)

transverse emittance: $\varepsilon_N < 1$ μm at 1 Å, 15 GeV

FEL parameter

peak current

undulator period

$$\boxed{\sigma_\delta < \rho \approx \frac{1}{4}\left(\frac{1}{2\pi^2}\frac{I_{pk}}{I_A}\frac{\lambda_u^2}{\beta\varepsilon_N}\left(\frac{K}{\gamma}\right)^2\right)^{1/3}}$$

relative energy spread:
<0.04% at $I_{pk} = 3$ kA,
$K \approx 3$, $\lambda_u \approx 3$ cm, …

beta function

undulator ‘field’ = $0.93 \cdot B\lambda_u$

$$\boxed{L_g \approx \frac{\lambda_u}{4\pi\sqrt{3}\rho}}$$

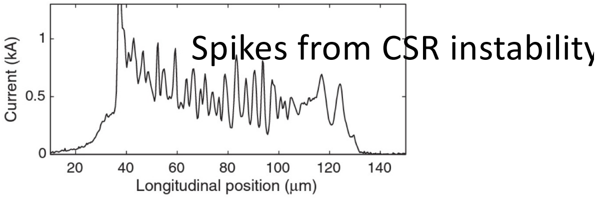
FEL gain length: $18L_G \approx 100$ m for $\varepsilon_N \approx 1.5$ μm

- We must increase peak current, preserve emittance, and maintain small energy spread so that power grows exponentially with undulator distance, z, $P(z) = P_0 \cdot \exp(z/L_G)$
- FEL power reaches *saturation* at $\sim 18L_G$
- SASE performance depends *exponentially* on e^- beam quality ! (challenge)

Fig. by Zirong Huang (SLAC)

How does a FEL work? Plasma Physics perspective

- Free electron laser amplifies current fluctuations inherent in electron beams (often called shot noise) via a single component plasma instability known as the free electron laser instability akin to stimulated Raman Forward scattering instability in static plasmas.



- The initially broadband noise is randomly polarized with no phase coherence or directionality and can be thought of as spontaneous emission.

Spontaneous emission in a certain narrow resonant spectral (ω_r, k_r) window beats with the static magnetic field $(0. k_u)$ to produce a beat wave $(\omega_r+0, k_r +k_u)$.

The phase velocity of this beat pattern $v_{ph}= \omega_r/(k_r + k_u) < c$ and therefore can

trap the resonant electrons and bunches them through velocity bunching which then scatter more photons providing a feedback for the instability.