Applications of Undulator Radiation at ASTA: High-power Beam Diagnostics and an XUV FEL Oscillator

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OUTLINE

I. Introduction

II. Required Beam Parameters

III. Personnel Involved

IV. Experimental Techniques and Expected Outcomes:

  A. Diagnostics with undulator radiation (UR)

   - Characterization of electron beam properties from UR is nonintercepting so applies to high power beam.

  B. Free-electron laser oscillator (FELO) application

   -VUV and soft x-ray (XUV) FEL application:

   simulation examples: GINGER and MEDUSA:OPC

V. Summary

Some Undulator Basics

- **Free-electron lasers are based on the modulation of intrinsic electron beam longitudinal structure at the resonant wavelength as e-beam co-propagates with optical fields in undulator. UR has same resonance.**

$$\lambda_n = \lambda_u (1 + K^2/2)/2n\gamma^2,$$

Where λ is the resonant wavelength (for microbunching)
λ_u is the undulator period
K is the undulator field parameter
n is the harmonic number
γ is the Lorentz factor

e-beam Features from UR features

- Time-resolved Diagnostics planned at ms-, μs-, ns-, and ps-regimes for electron-beam parameters.

Parameter	UR Feature
position	Transverse UR image position,CCD
beam size	Transverse UR image size, ICCD
emittance	Gain in UR, harmonic ratios
bunch length	UR bunch length, streak cam.
bunch phase	UR phase position, streak cam.
energy	UR Central wavelength, spectr.
energy spread	Bandwidth obs. 1/nN, spectr.

- Beam based feedback monitor
- Dual-sweep streak camera, gated ICCD, CCD, spectr.

U5.0 Option

- Undulator U5.0 transfer from LBNL negotiated. Device retired from ALS storage ring in January 2013.
- Period=5.0 cm, K tunable, Length=4.5 m, Wt= 47,000 lbs.

U5.0 Parameter Table

- **Table 1. Engineering design specifications for U5.0 with Nd-Fe-B magnetic blocks and vanadium permendur poles.**

Parameter	Value	Units
Period, λ_u	5.0	cm
Number of periods, N	89	
Length, L	4.55	m
Max. field @1.4cm	0.89	T
Magnetic Gap range	1.4-2.16,4.7	cm
Harmonics	3, 5	-
K value range	0.45-3.9	-

Required Beam Parameters

- **Table 1: Summary of beam parameters requested for the initial high-energy experiments.**

Parameter	Value/Range	Units
Beam Energy	200-300	MeV
Bunch Charge	250/100-3000	pC
Bunch repetition rate	3, (6)	MHz
Number of bunch/macropulse	100-3000	
Transverse emittance/spot size	2 / 150	mm mrad/μm
Bunch length	1 to 0.3	ps
Fractional momentum spread	2x10-4	

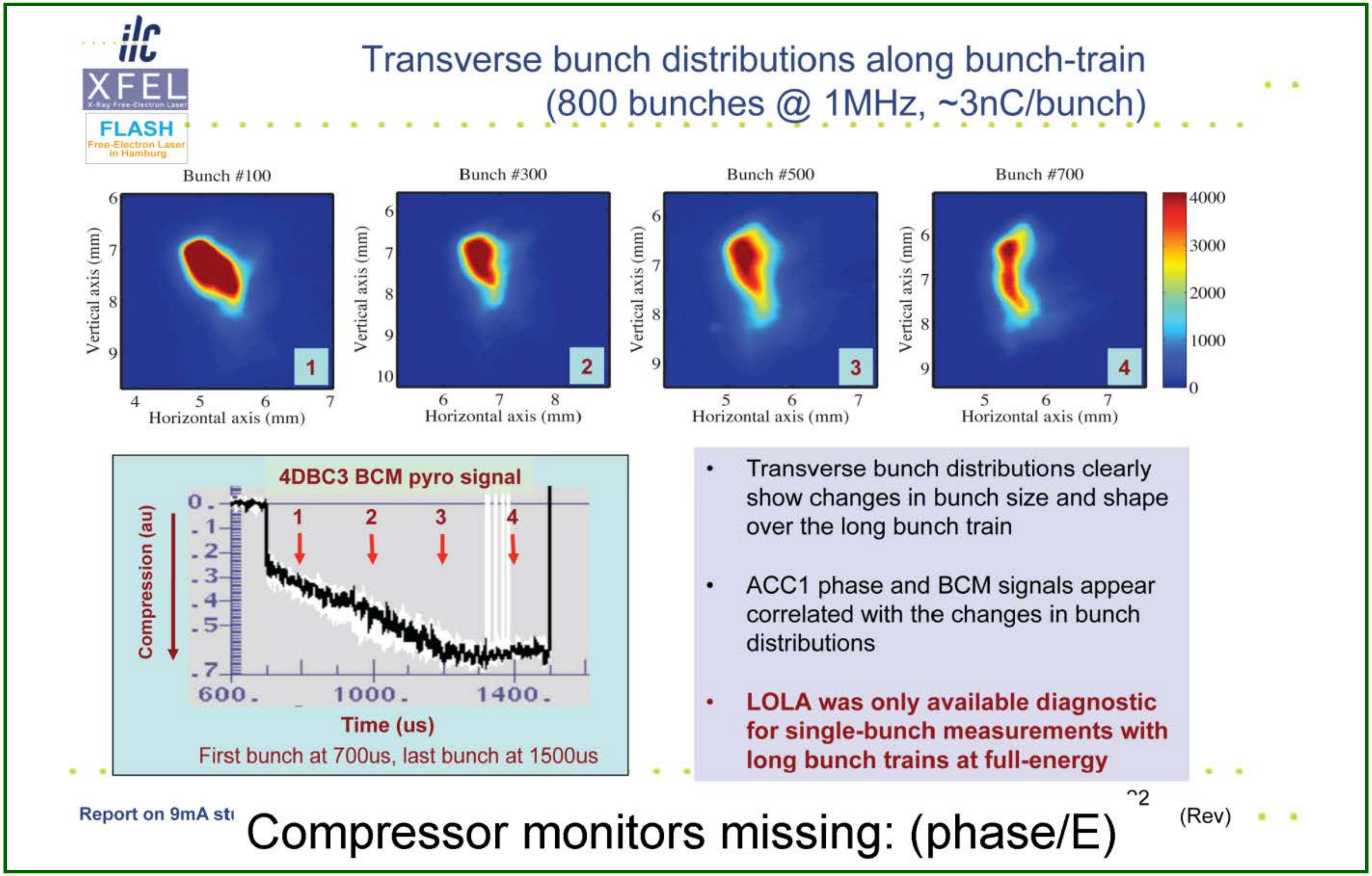
Personnel Involved

- **Table 2: Personnel on team.**

Collaborator	Planning	Experiment	Diagnostics	Analysis	Simulation
A. Lumpkin	yes	Experiment	yes	yes	
M. Reinsch	yes			yes	yes
H. Freund	yes			yes	yes
TBD	yes	VUV optics	yes	yes	

At FNAL, A. Lumpkin is a photon science experimentalist with extensive experience with undulator radiation, M. Reinsch at LBNL is a FELO simulations expert with the GINGER code, and H. Freund at LANL is a FELO simulations expert with his MEDUSA:OPC code.

FLASH 3-mA Data



Transverse bunch distributions along bunch-train (800 bunches @ 1MHz, ~3nC/bunch)

First bunch at 700us, last bunch at 1500us

- Transverse bunch distributions clearly show changes in bunch size and shape over the long bunch train
- ACC1 phase and BCM signals appear correlated with the changes in bunch distributions
- **LOLA was only available diagnostic for single-bunch measurements with long bunch trains at full-energy**

Report on 9mA st

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(Rev)

Compressor monitors missing: (phase/E)

Example UR Results

- **Duke Storage Ring FELO circa 1998, 107 m ring circumference, E=500 MeV, Und. period=10 cm, L=3.4 m.**

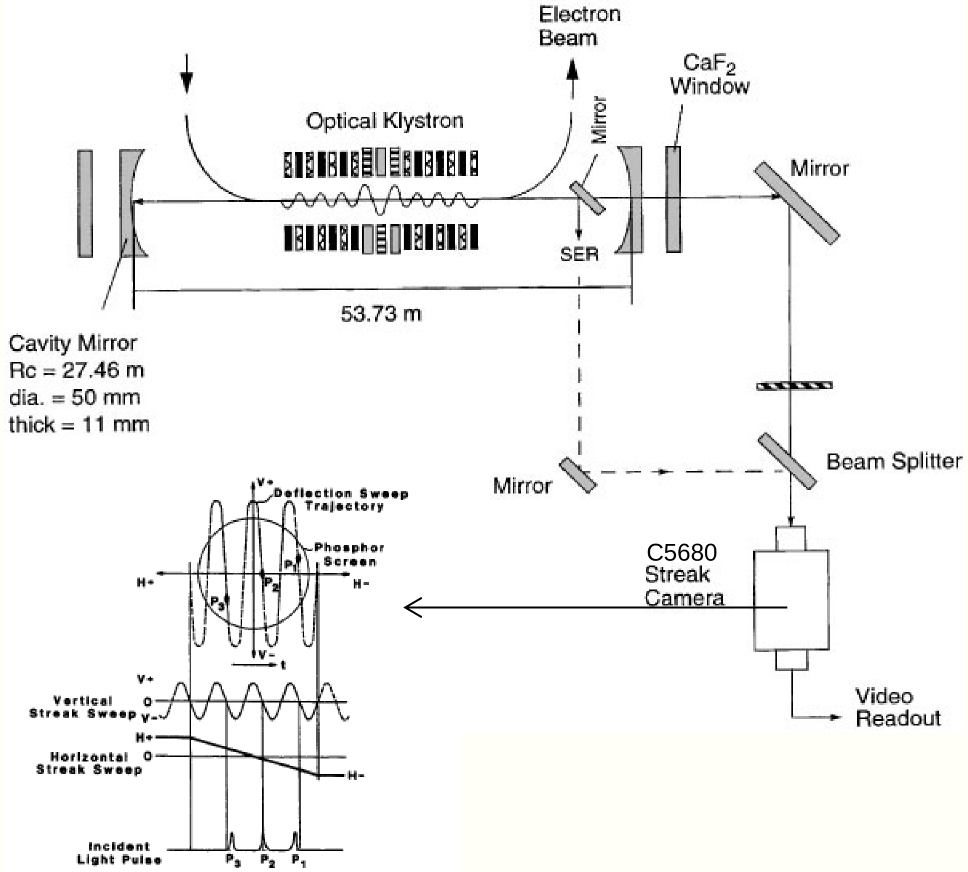
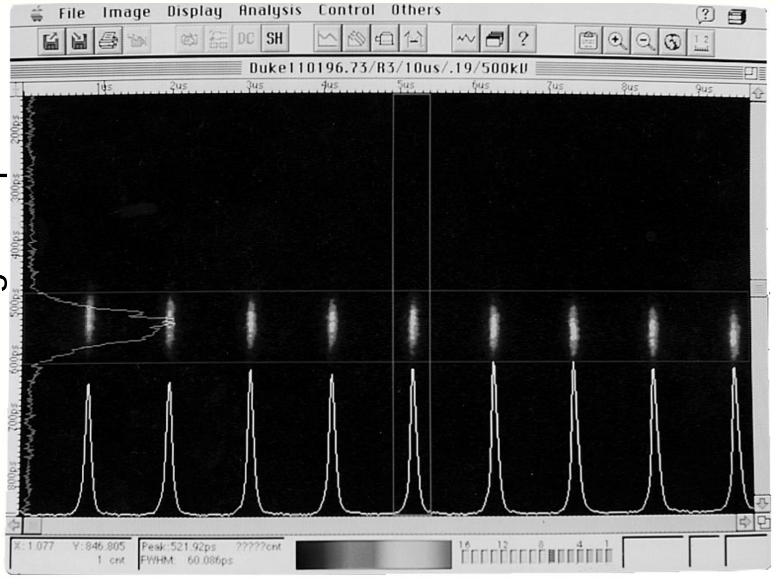


Fig. 1. Schematic of dual-sweep streak technique.



Duke110196.73/R3/10us/.19/500kV

X: 1.077 Y: 846.805
1 cnt

Peak: 521.92ps ?????cnt
FWHM: 60.086ps

T1 Range 800ps

T2 Range 10µs

Rev freq=2.78 MHz, λ=450 nm, SER
Bunch length=60ps FWHM

A.H.Lumpkin et al., NIMA 407, 338 (1998)

Diagnostic Options with U5.0

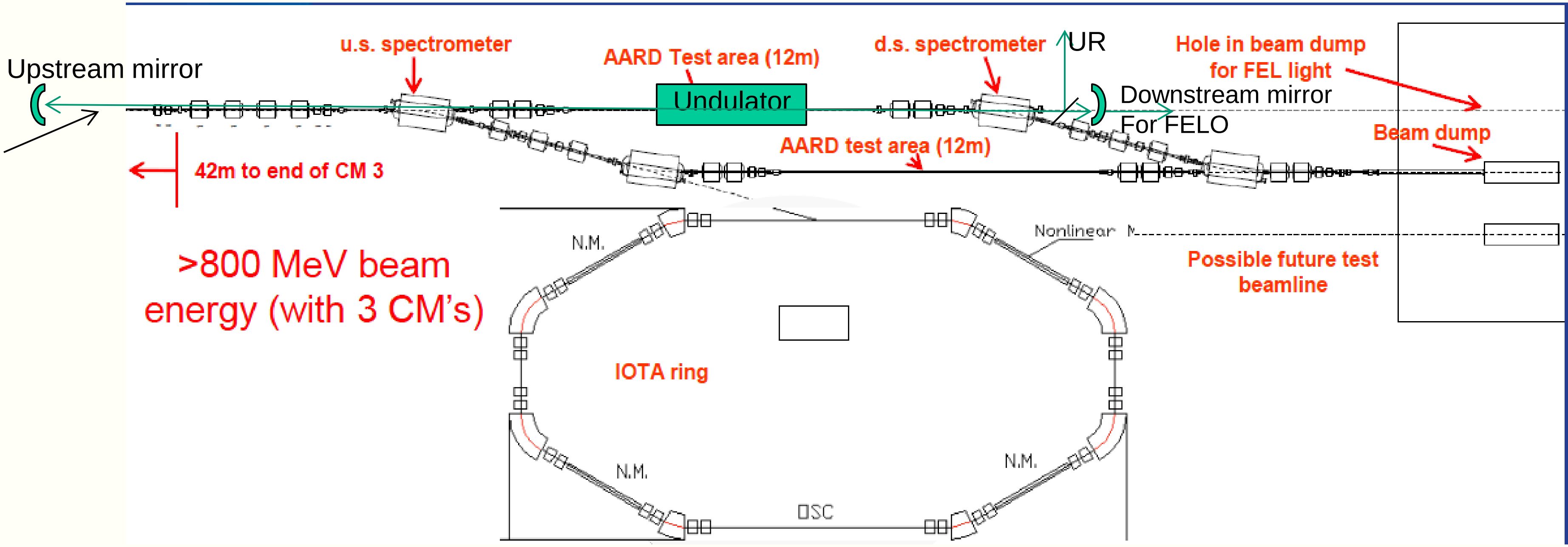
- **Table 2: Electron beam energy and UR wavelengths**

Phase #	Beam Energy (MeV)	UR Fundamental (nm)	Period (cm), *K*	UR Harmonics (nm) 3, 5
1	125	680	5.0, 1.2	226
1	150	472	5.0, 1.2	157
	200	265	5.0, 1.2	88
1	250	170	5.0, 1.2	57
1	250	262	5.0, 1.8	87
1	300	382	5.0, 3.0	127
2	500	42	5.0, 1.2	14, 8.3
3	800	16	5.0, 1.2	5.3
3	800	13.7	5.0, 0.9	---
4	900	3	1.1, 0.9	

FELO in High-energy Beamline

- UR diagnostic and Concentric cavity configuration option.

XUV FEL Oscillator



Upstream mirror

u.s. spectrometer

AARD Test area (12m)

Undulator

d.s. spectrometer

UR

Hole in beam dump for FEL light

Downstream mirror For FELO

AARD test area (12m)

Beam dump

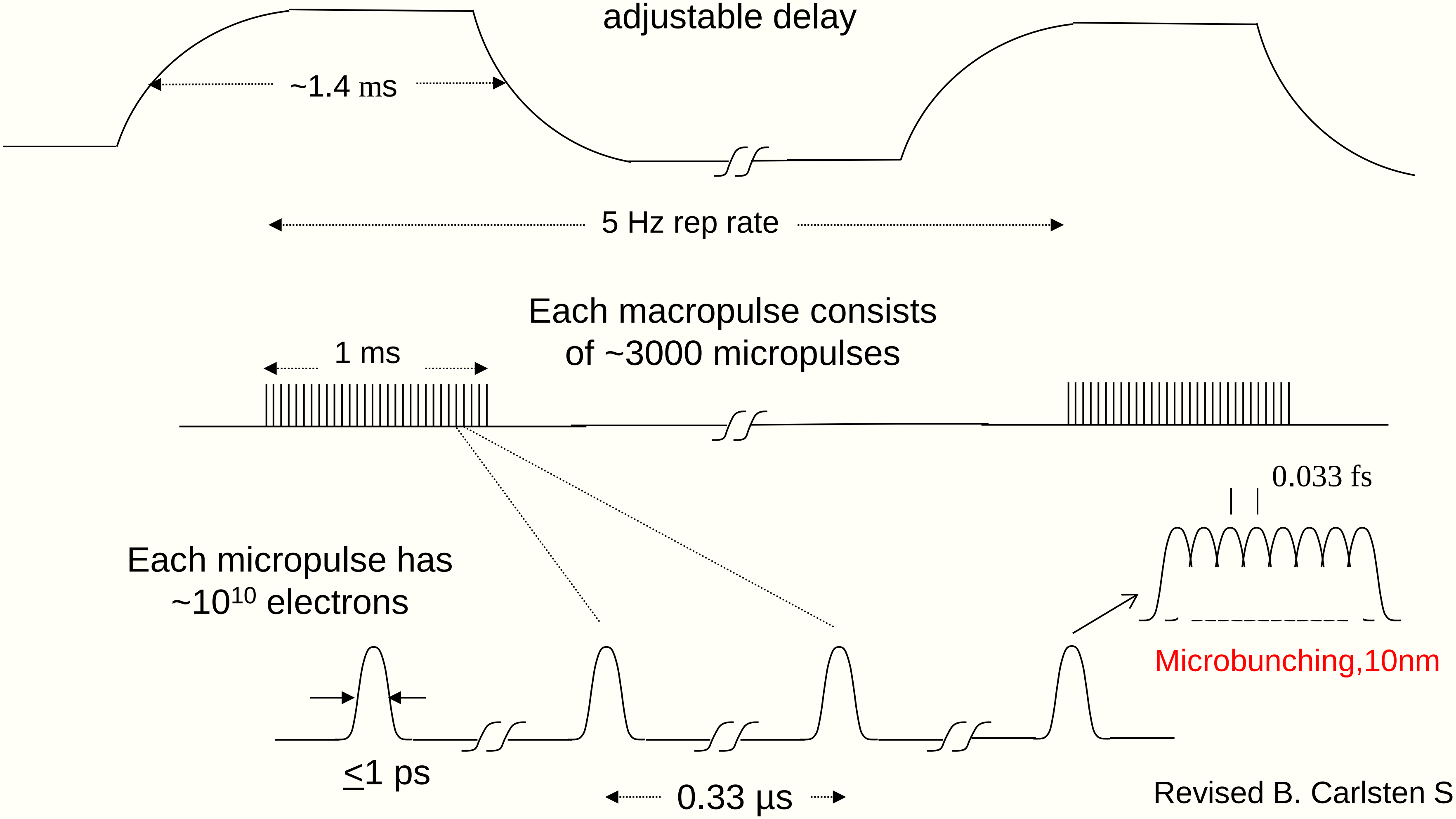
42m to end of CM 3

>800 MeV beam energy (with 3 CM's)

IOTA ring

Possible future test beamline

ASTA Temporal Pulse Format



RF pulses separated by an adjustable delay

Each macropulse consists of ~3000 micropulses

Each micropulse has ~10^{10} electrons

Revised B. Carlsten Slide

XUV FELO Application at ASTA

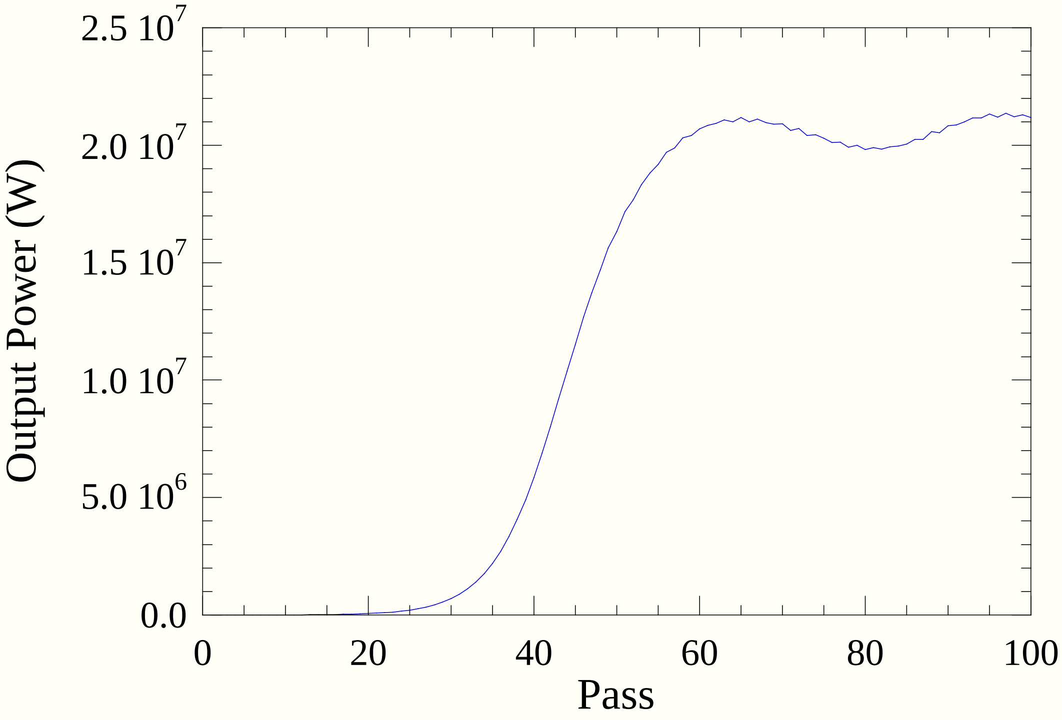
- The ASTA beam provides unique capabilities that all enable XUV FELO experiments.

Feature	Resultant
Low emittance photoinjector	Needed gain per pass
3 MHz micropulse rep. rate.	Cav. Rnd Trip of 100m
3000 micropulses in 1 ms.	Passes for saturation
SCRF energy stability	Stable wavelength
GeV scale energy	XUV wavelengths
High power at 5 Hz	High power FELO

MEDUSA:OPC Simulations at 120 nm

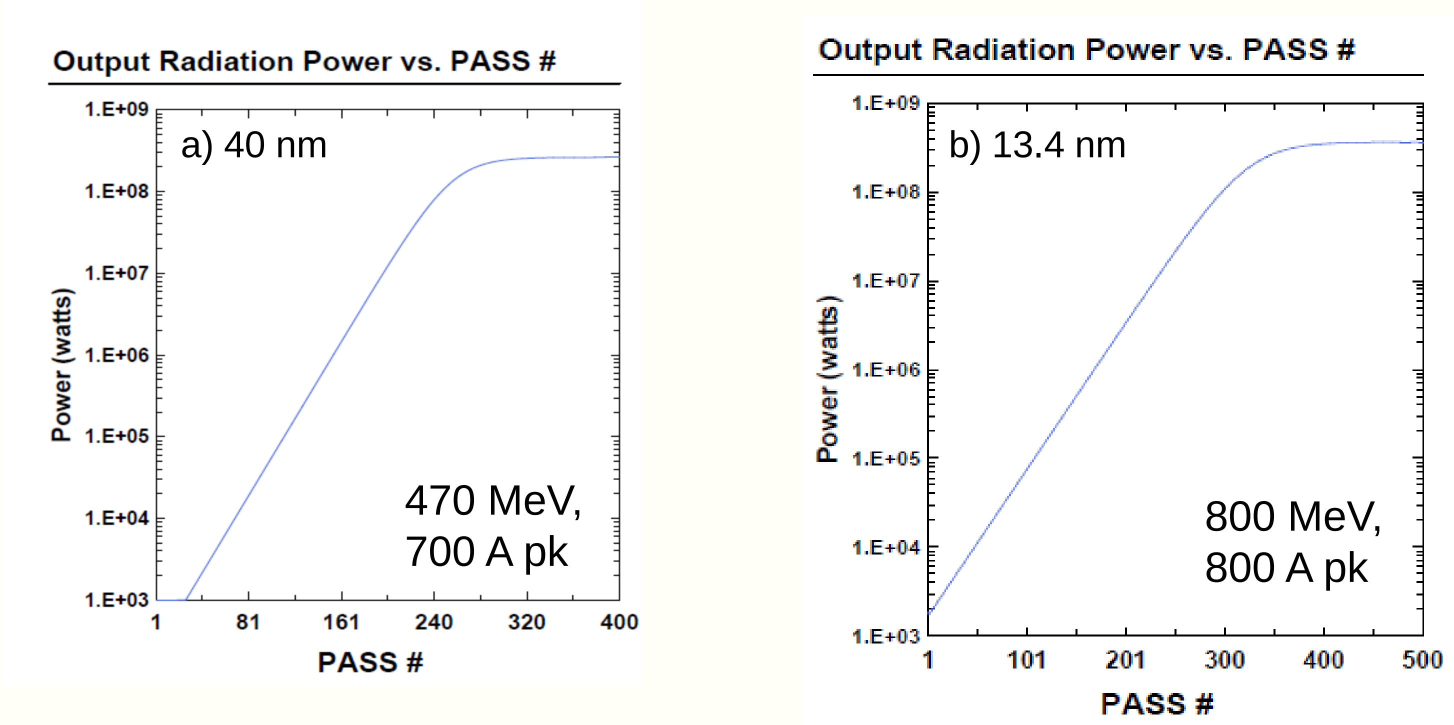
- **Beam energy 301 MeV, I_{pk}=100 A, 1-mm radius hole**

Electron Beam	
Energy	301.25 MeV
Current	100 A
Normalized Emittance	2 mm-mrad
Energy Spread	0.05%
x_{rms}	122 microns
α_x	1.0
y_{rms}	120 microns
α_y	1.0
Wiggler	
Period	5.0 cm
Amplitude	2.4614 kG
K_{rms}	0.813
Length	88 periods
Resonator	Concentric
Wavelength	120 nm
Cavity Length	50 m
Radii of Curvature	25.32 m
Mirror Reflectivity	80%
Hole Radius	1.0 mm
Total Loss	52%



GINGER Results at 40 and 13.4 nm

- **Simulations run with GINGER code with oscillator module at LBNL by M . Reinsch. Concentric cavity.**



Initial GINGER simulations for output power saturation at the fundamental wavelength of a) 40.0 nm and b) 13.4-nm for a concentric cavity with multilayer mirror reflectances of 50 % and 68%, respectively.

FELO Options with U5.0

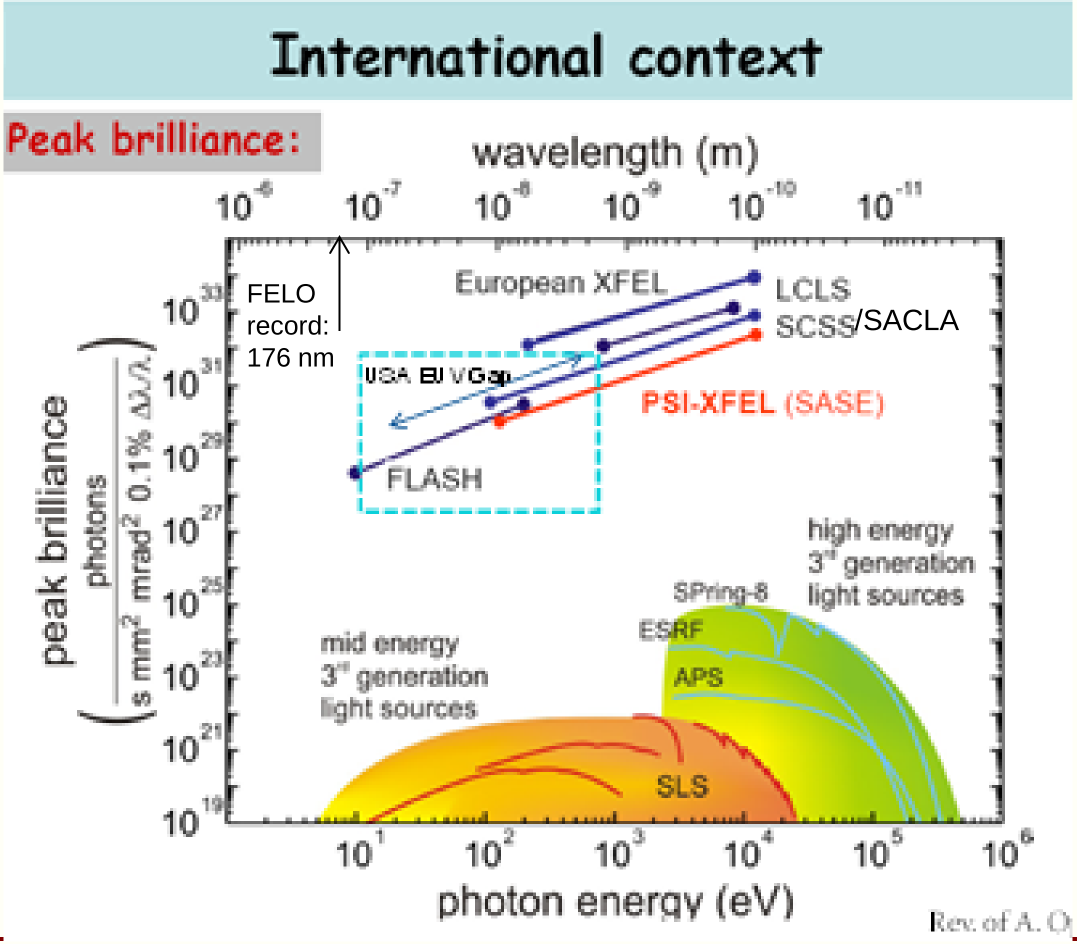
- Table 3: Phase, beam energy, and FEL wavelengths.

Phase #	Beam Energy (MeV)	FEL Fundamental (nm)	Period (cm), *K*	FEL Harmonics (nm) 3, 5
1	125	680	5.0, 1.2	226
1	150	472	5.0, 1.2	157
	200	265	5.0, 1.2	88
1	250	170	5.0, 1.2	57
1	250	262	5.0, 1.8	87
1	300	120	5.0, 0.8	40
2	500	42	5.0, 1.2	14, 8.3
3	800	16	5.0, 1.2	5.3
3	800	13.4	5.0, 0.9	4.4
4	900	3	*1.1, 0.9	(1)

*SC undulator prototype in ILC program in UK, PAC07

International FEL Context

- **Summary of emerging and proposed FELs. Only SASE FELs for VUV, soft x-ray, and hard x-ray regimes so far.**



SUMMARY

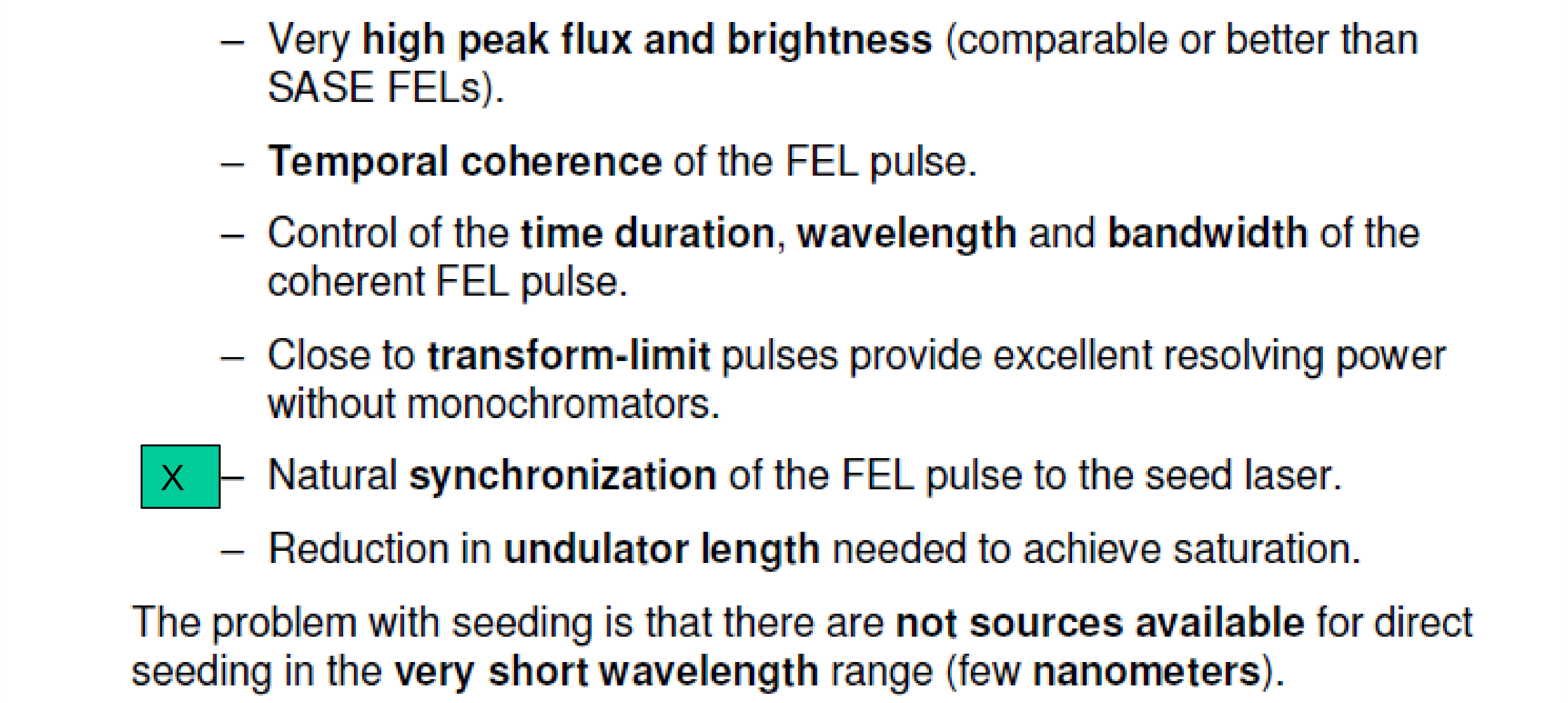
- Nonintercepting electron beam diagnostic techniques based on time-resolved imaging of UR are proposed.
  - UR emissions at resonance on fundamental and harmonic wavelengths expected.
  - Studies of CUR strength due to beam microbunching would complement the evaluations of 6-D beam quality. Gives electron beam micropulse properties.
  - Support initial CM2 beam studies with visible-UV UR.
- Diagnostics should be extended to VUV and soft x-ray regime where possible at ASTA.
- Significant opportunity for first XUV FELO demonstration at ASTA (set new world record for shortest λ with oscillator. Coherence, sub-ps, transform limited bandwidth, tunable 200-120 nm initially)
- With 6-MHz e-beam, could do built-in Compton backscattering source within FELO as done at Duke FELO source. (gamma energies of MeV)

U5.0 Transport from California

- **Available unique power source at Fermilab for cross country overland hauling.**

Benefits of an FELO

- **Photon noise seeds the start-up of the FEL pulse within the electron pulse and the multiple passes result in growth of microbunching at resonant λ and harmonics.**



- Very **high peak flux and brightness** (comparable or better than SASE FELs).
- **Temporal coherence** of the FEL pulse.
- Control of the **time duration**, **wavelength** and **bandwidth** of the coherent FEL pulse.
- Close to **transform-limit** pulses provide excellent resolving power without monochromators.
- X – Natural **synchronization** of the FEL pulse to the seed laser.
- Reduction in **undulator length** needed to achieve saturation.

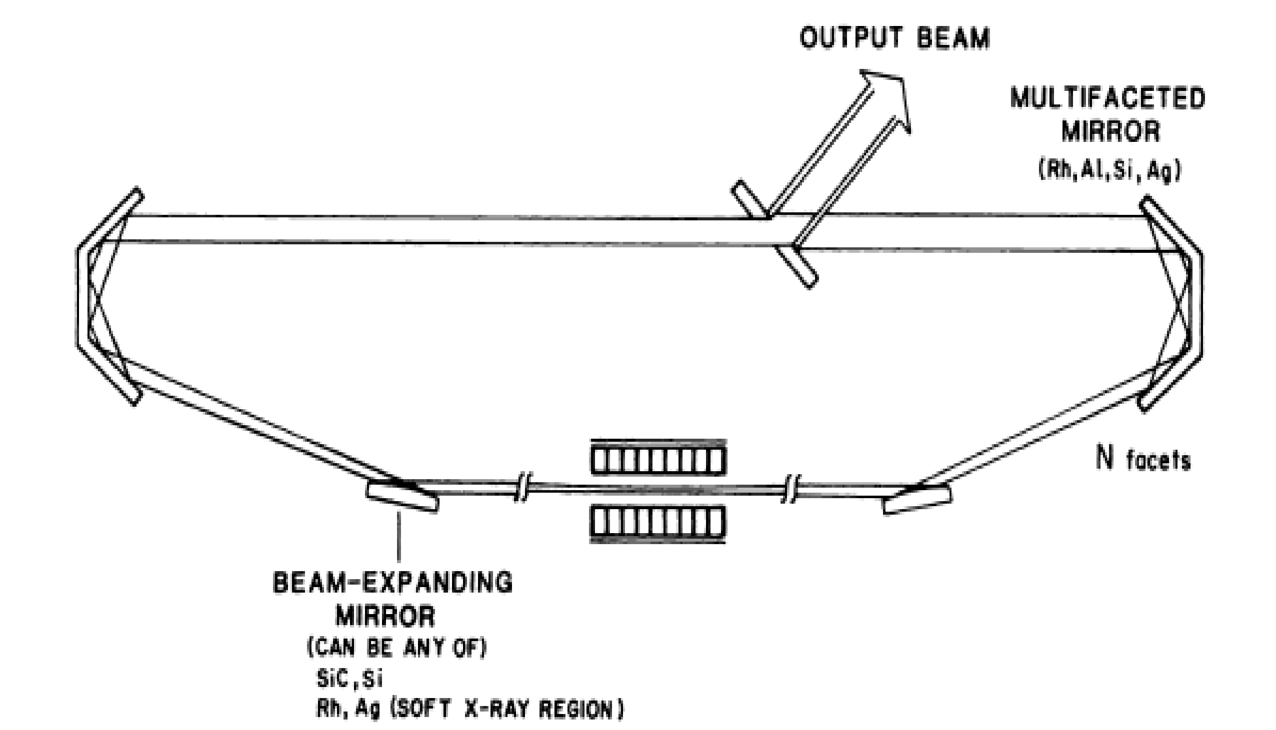
The problem with seeding is that there are **not sources available** for direct seeding in the **very short wavelength** range (few **nanometers**).

Need to explore processes at the XUV frontier.

Revised E. Allaria Slide

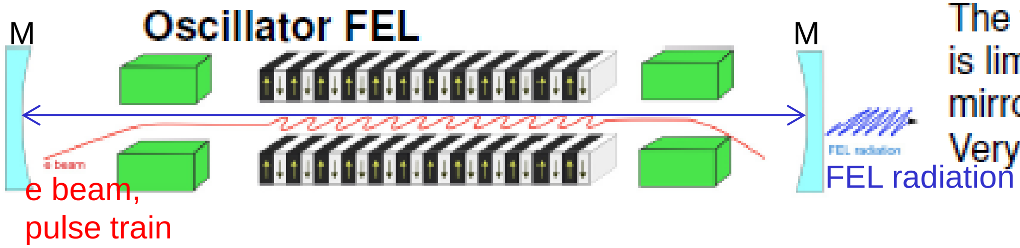
Ring Optical Resonator Option

- A schematic of the ring optical resonator for an XUV FEL oscillator using multifaceted mirrors and on-axis beam-expanding mirrors (B. Newnam et al., SPIE vol.1552 (1991)). This would provide broadband subregions in λ.

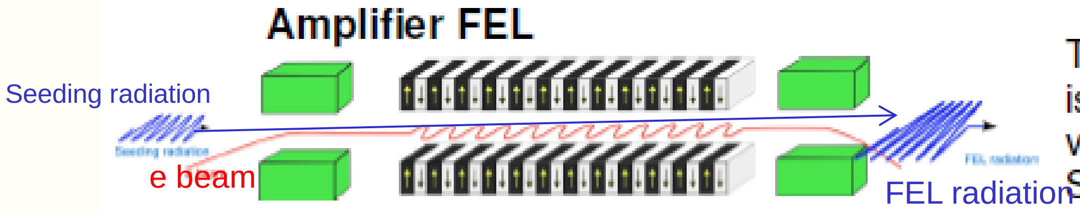


FEL Configuration Types

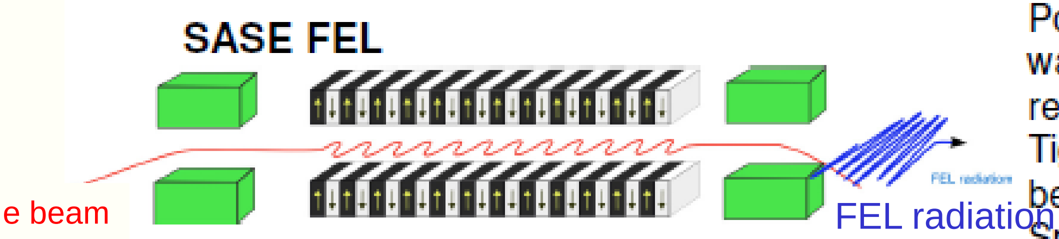
- **Fundamental physical properties impact options.**



The tunability toward short wavelengths is limited by the availability of high quality mirrors.
Very good spectral quality.



The tunability toward short wavelengths is limited by the lack of availability of very short wavelength seed lasers.
Spectral quality limited by the quality of the electron beam.

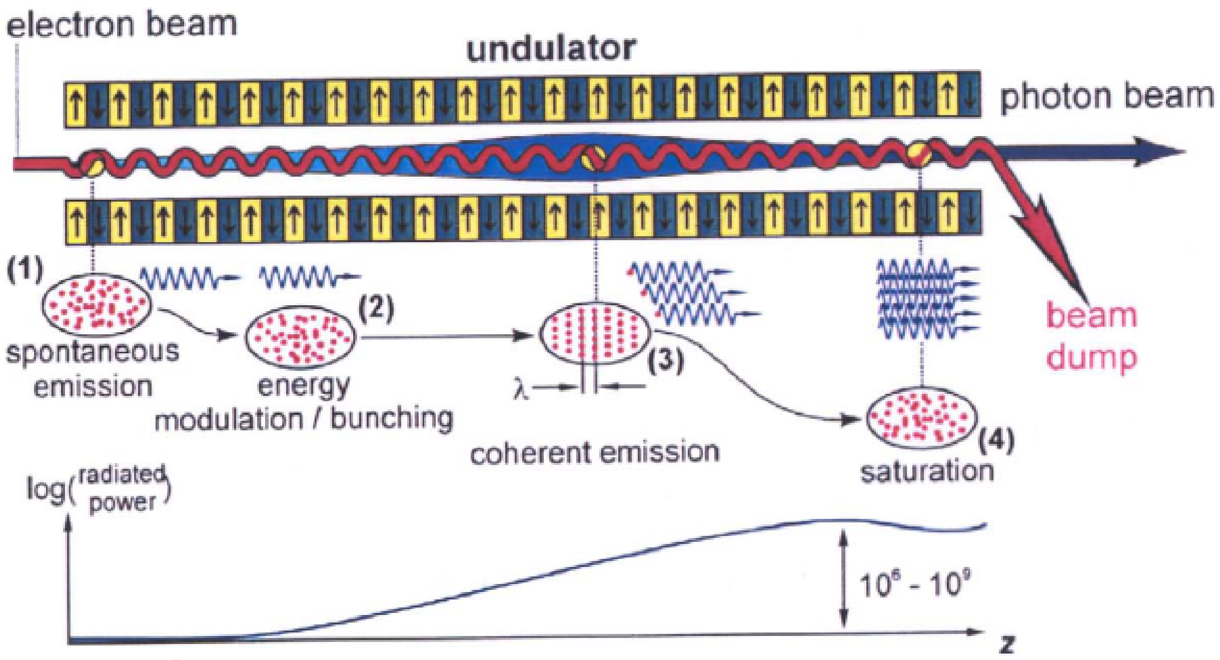


Potentially completely tunable, FEL wavelengths only depend on the resonance condition.
Tighter requirements for the electron beam parameters.
Spectral properties affected by the limited coherence.

E.Allaria, Seeded FEL WS

SASE FEL Basics

- **Since SASE FEL starts from noise, intensity and spectral content fluctuate.**



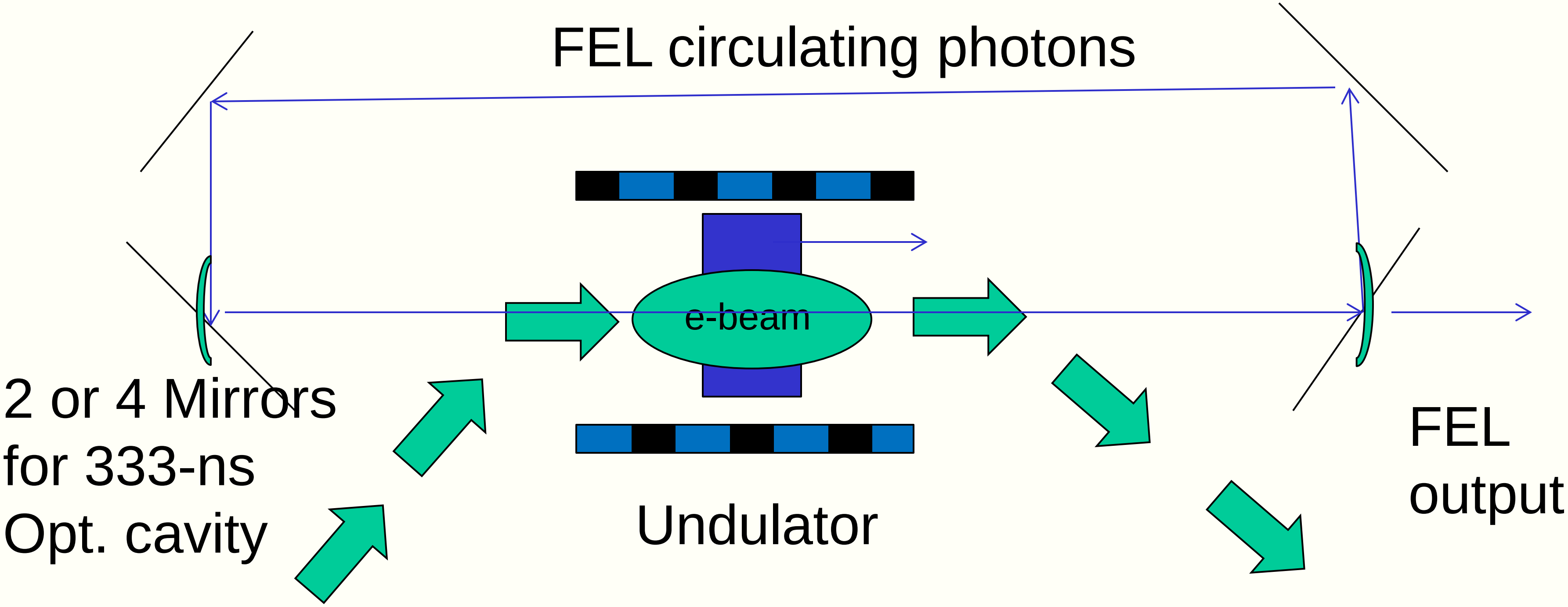
SASE Radiation has full Transverse Coherence

See Bonifacio, R., C. Pelligrini, and L. Narducci, Opt. Commun. 50, 373 (1984)

D. Moncton Talk, Oct.2007

VUV FEL Oscillator Configuration

- **The bright beams, pulse structure, and new multilayer mirrors will make FEL oscillator feasible at ASTA.**



FEL circulating photons

e-beam

2 or 4 Mirrors
for 333-ns
Opt. cavity

Undulator

FEL
output

3 MHz Electron Pulse Train, 333-ns spacing