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

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Fermilab

APT Seminar

June 25, 2013

OUTLINE

I. Introduction

II. Advanced Superconducting Test Accelerator (ASTA)

III. Diagnostics with undulator radiation (UR)

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

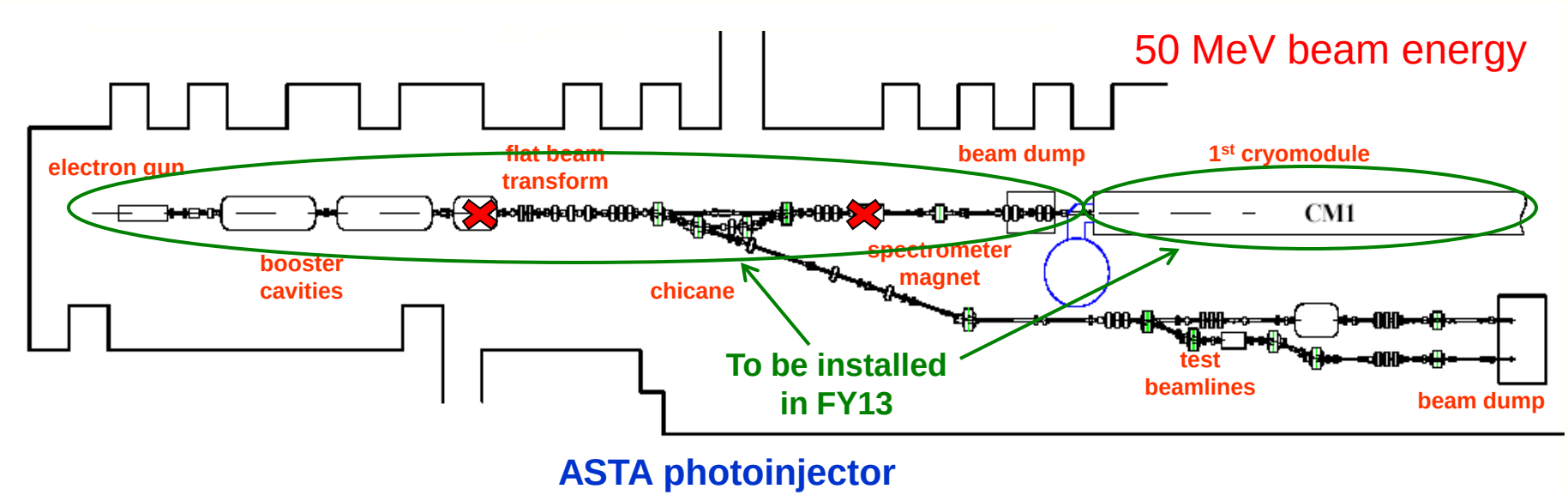
IV. Free-electron laser (FEL) basics

V. VUV and soft x-ray (XUV) FEL application: simulation examples

VI. Summary

FY13 -- 50 MeV Injector + 1 Cryomodule

- **Goal: installation complete and beam commissioning started by end of FY13**
  - RF gun + RF system and photocathode laser system
  - 2 SCRF booster cavities ("CC1" and "CC2") + RF systems
  - 50 MeV beamline elements and instrumentation to the low energy dump
  - Low energy beam dump
  - SCRF cryomodule ("CM2")
- **Installation of 1st AARD experiment (high brightness X-ray channeling source)**

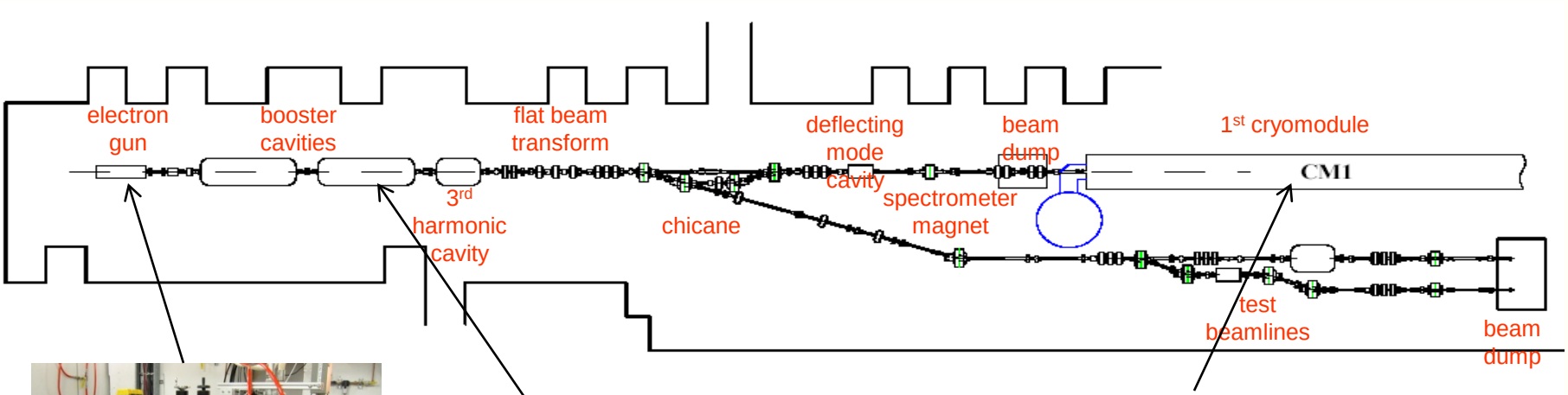


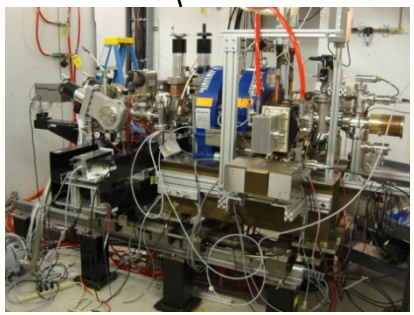
FAAC review 2013

50-MeV Injector for ASTA/FNAL

- **Injector being installed with First beam expected in 2013.**

40-MeV Injector





PC rf gun installed

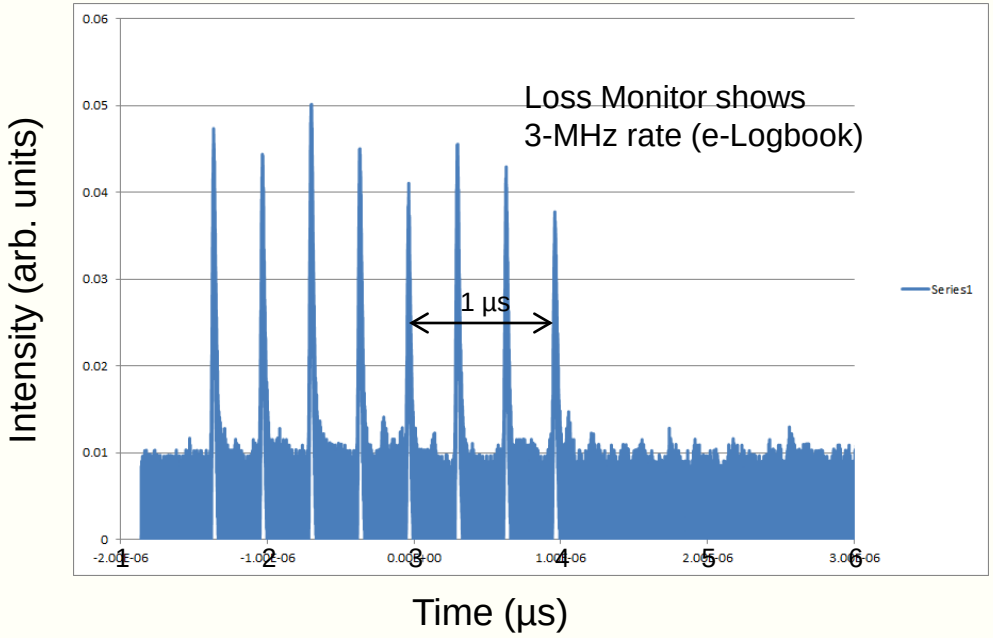
Booster cavity 2 (from DESY and Saclay) installed in ASTA

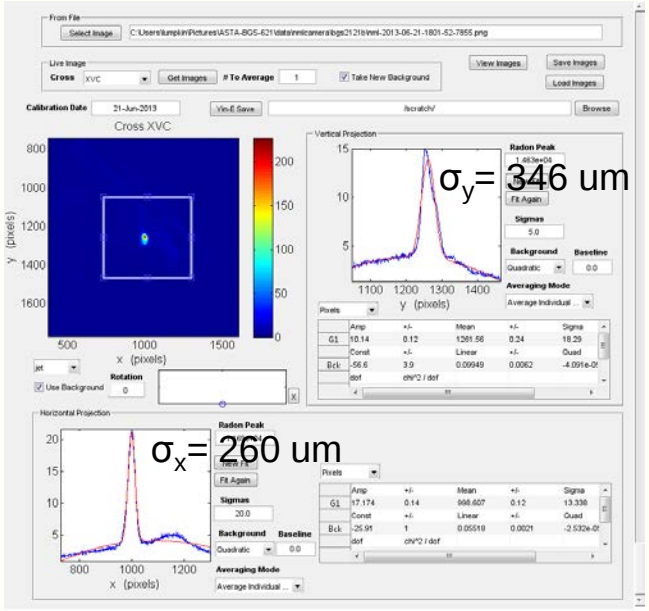
First cryomodule (from FNAL) installed at ASTA.

Courtesy of *M. Church*

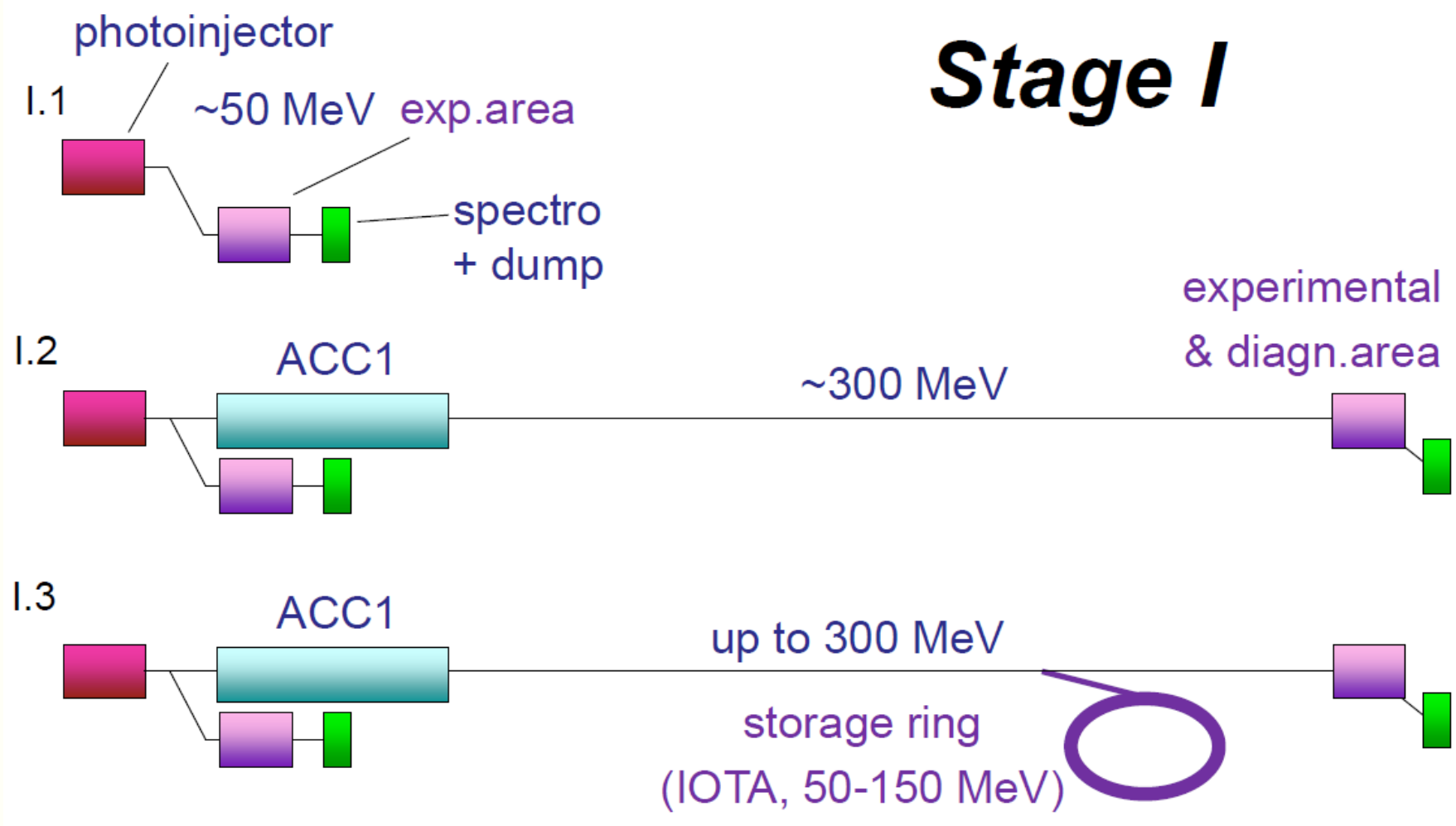
First ASTA photoelectrons: 6-20-13

- **First photoelectrons from Mo cathode on 6-20-13. Subsequent studies on following day to improve beam spot for single micropulse shown at right.**





ASTA Buildout and Operation Occurs in Stages: Stage I



ASTA Proposal 2013

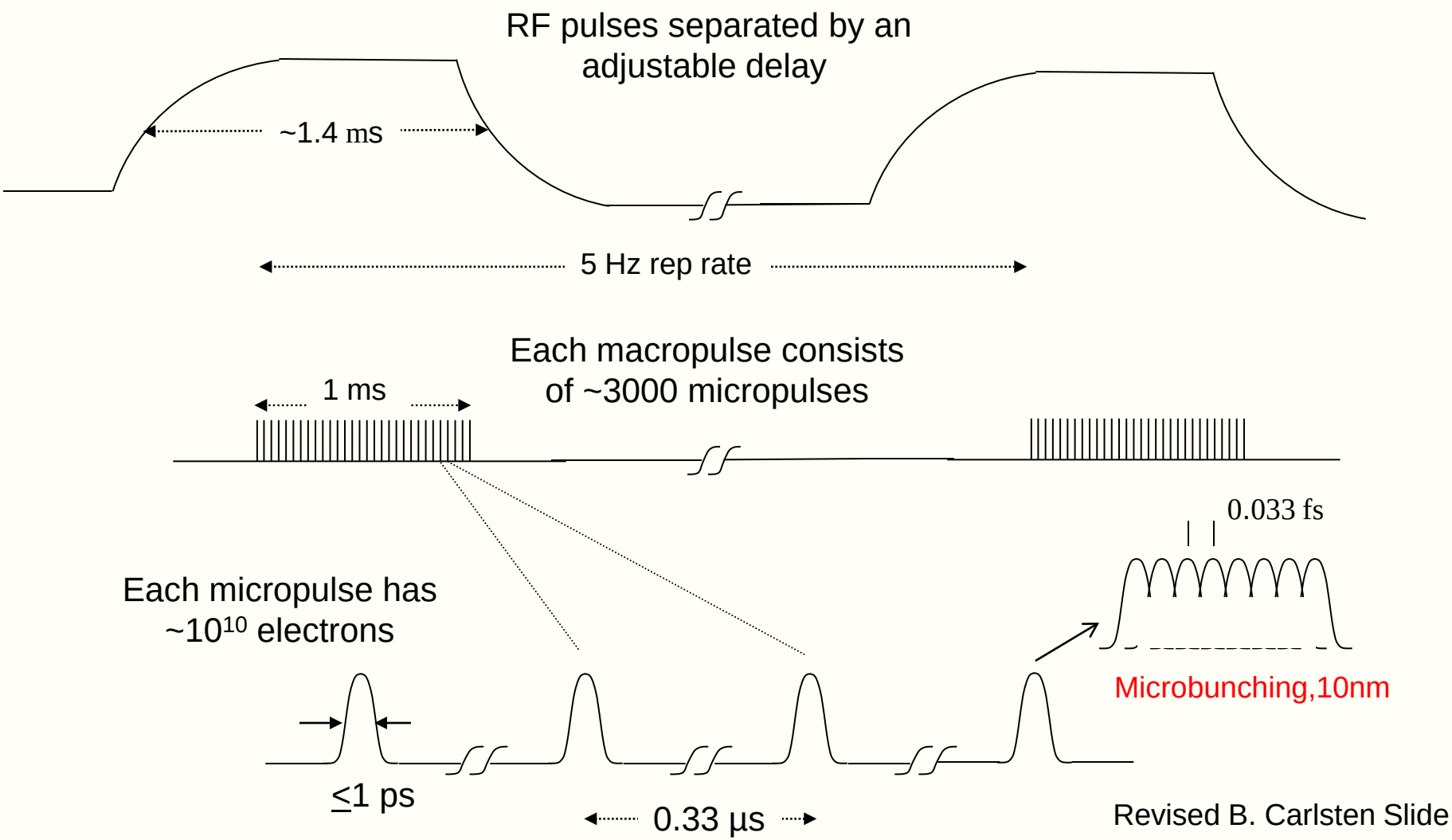
Experimental Areas 1 & 2

Parameter	Value	Range	Unit	Comments
Energy Exp A 1	50	5-50	MeV	maximum determined by booster cavity gradients
Energy Exp A 2	820	50-820	MeV	1500 MeV with 6 cryomodules
μpulse charge	3.2	0.02-20	nC	maximum determined by cathode QE and laser power
μpulse spacing	333	10-∞	ns	laser power
μpulse train *T*	1	1 macrop	ms	maximum limited by modulator and klystron power
Train rep rate	5	0.1-5	Hz	minimum may be determined by egun *T*-regulation and stability considerations
Emittance rms norm	5	<1 … >100	π μm	maximum limited by aperture and beam losses
Bunch length rms	1	0.01-10	ps	min obtained with Ti:Sa laser; maximum obtained with laser pulse stacking
Peak current	3	>9	kA	3 kA with low energy bunch compressor; 9 kA possible with 3.9 GHz linearizing cavity

* 3.2nC × 3000 bunches × 5 Hz × 0.82 GeV = 40 kW

V. Shiltsev, GARD13

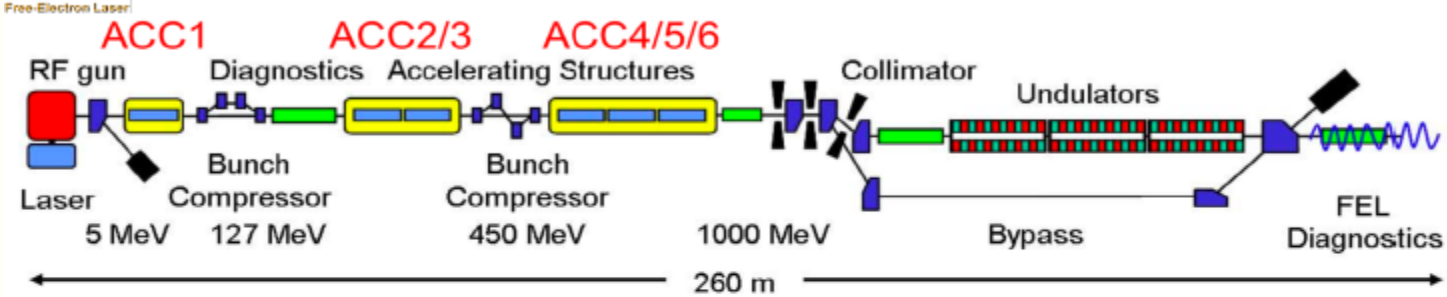
ASTA Temporal Pulse Format



Revised B. Carlsten Slide

FLASH 9-mA Studies

TTF/FLASH 9mA Experiment



Comparison of machine parameters

		XFEL	ILC	FLASH design	9mA studies
Bunch charge	nC	1	3.2	1	3
Bunch rate	MHz	5	2.7	9	3
# bunches		3250	2625	7200	2400
Pulse length	µs	650	970	800	800
Current	mA	5	9	9	9

Nominal experiment setup

- 3nC/bunch
- Bunch rates: 40kHz – 3MHz
- Laser #1: 40kHz – 1MHz; Laser #2: 3MHz
- RF systems operating nominally on crest
- BC magnets on, but no compression
- Beam through Bypass line to dump
- RF gun: 1.5 cell warm PC gun
- ACC1: 8 SC cavities
- ACC23: 2x 8 SC cavities
- ACC456: 3x 8 SC cavities
- LLRF: digital I/Q control of VS
- Piezo tuners: ACC3, ACC5, ACC6

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teport on 9mA studies (FLASH Seminar, 24 Nov 09)

FLASH Macropulse Data

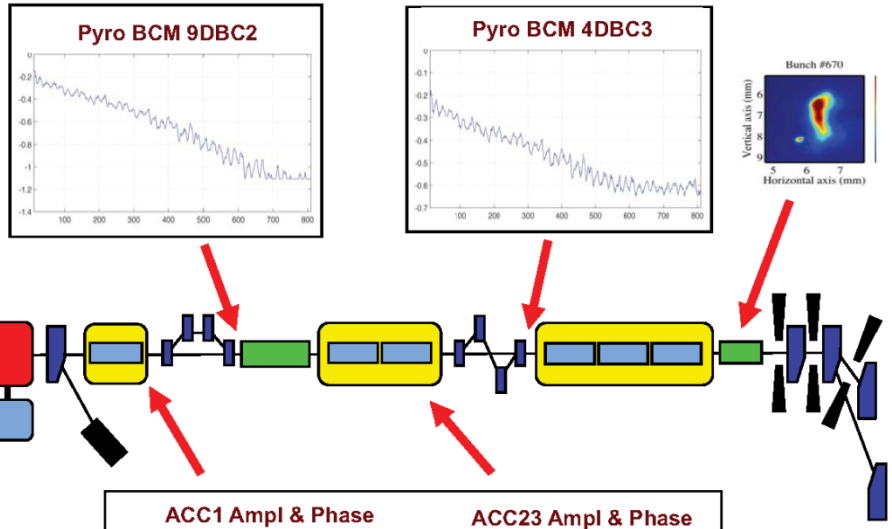
Injector setup – compression

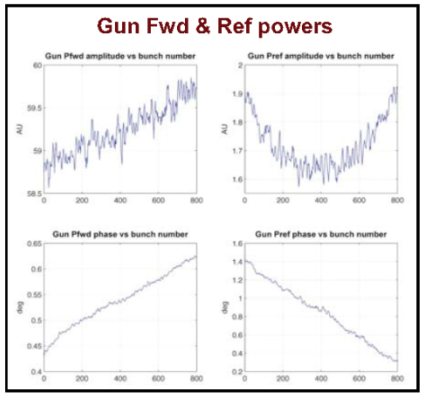
FLASH. Free-Electron Laser in Hamburg

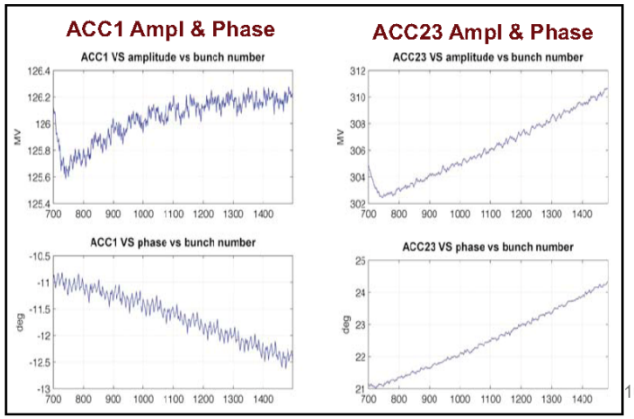
Bunch compression monitor (BCM)

Pyros BCMs show the bunch compression increases over the train

Gun, ACC1, and ACC23 phase setpoints include slopes to compensate for phase slopes in the gun and laser (delicate balance)







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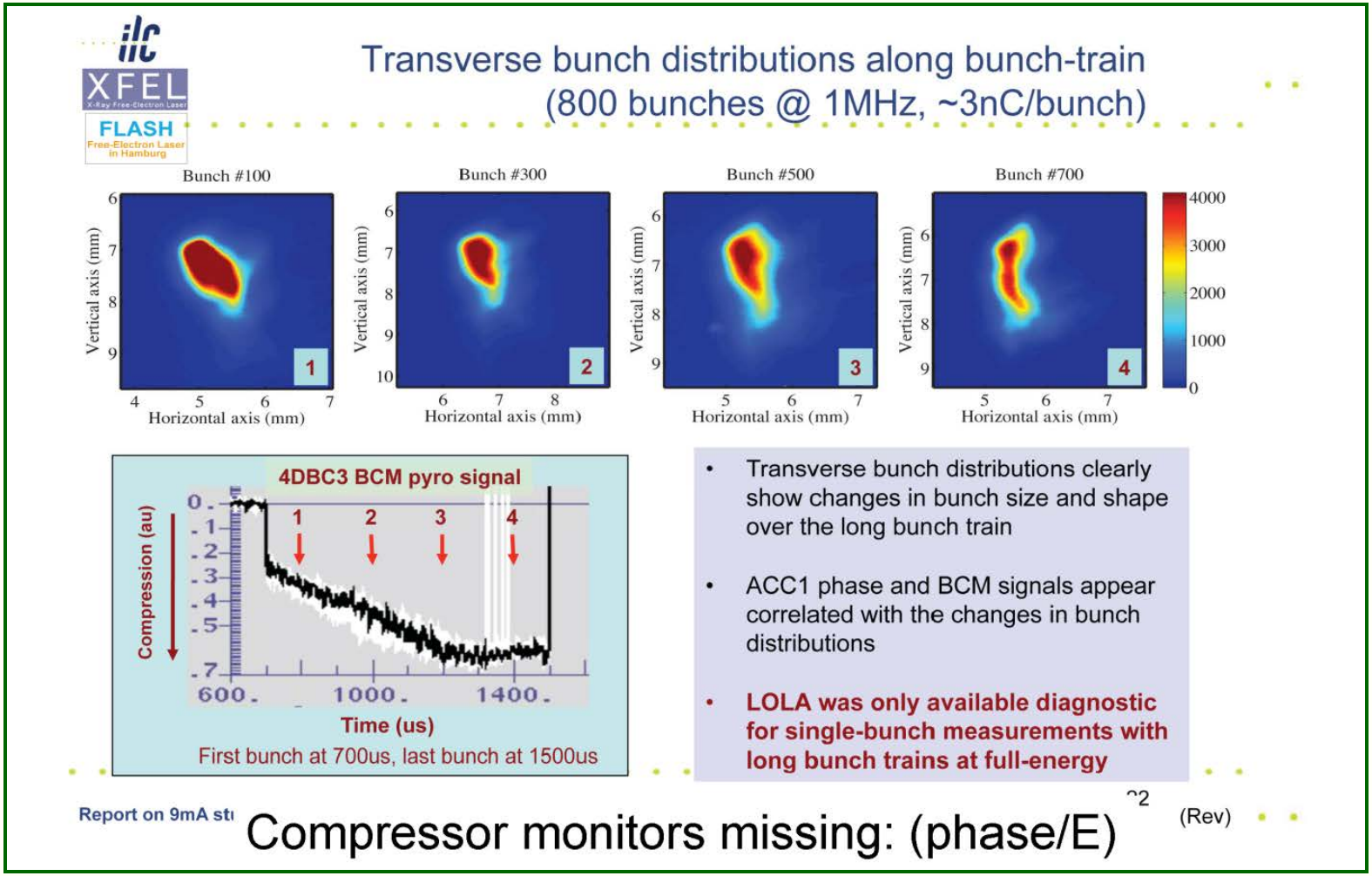
FLASH 3-mA Data



Radiation Producing Devices

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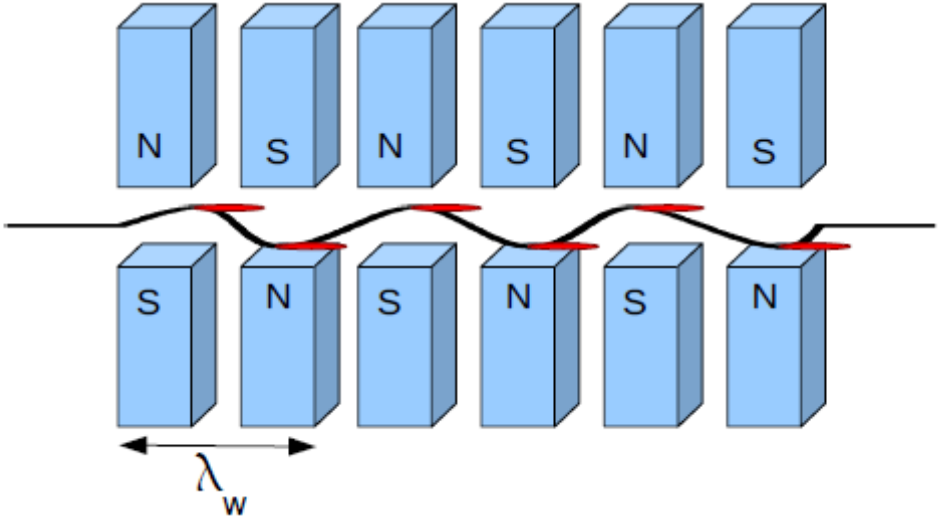
Radiation Producing Devices: Wigglers

- A wiggler is a series of N_w strong bends of alternating sign
- The beam "wiggles" in a sinusoidal trajectory



- Trajectory angle and amplitude characterized by K parameter

$$K = \frac{\theta_{\max}}{1/\gamma} \qquad x_{\max} = \frac{K\lambda_w}{2\pi\gamma}$$

See, e.g., K. J. Kim, AIP Conf. Proc. 184 (1989)

M.Borland Talk, FNAL 12/2011

Radiation from Undulators

- If K≤3 radiation from successive periods interferes constructively
- Average forward electron velocity is

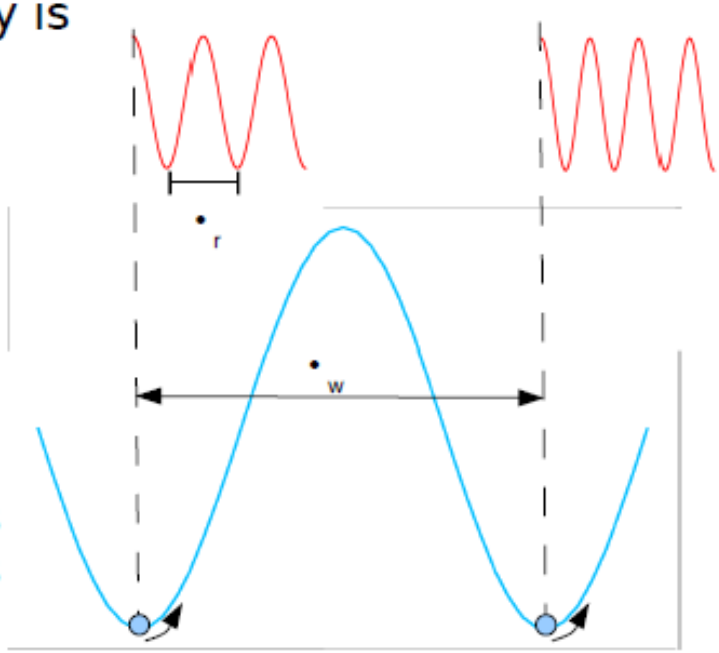
$$\bar{v}_z = c\left(1 - \frac{1+\frac{1}{2}K^2}{2\gamma^2}\right)$$

- Radiation has v=c, so after each period it slips ahead by

$$\Delta l = \frac{\lambda_w\left(1+\frac{1}{2}K^2\right)}{2\gamma^2}$$

- Coherent addition between poles for certain radiation wavelengths

$$\lambda_r n = \Delta l, \qquad n = 1, 2, 3, \ldots$$



- Undulator radiation peaked at *odd* harmonics

$$\lambda_{r,n} = \frac{\lambda_w\left(1+\frac{1}{2}K^2\right)}{2n\gamma^2} \qquad \Delta\theta \sim \frac{1}{\gamma\sqrt{N}} \quad \text{for} \quad \frac{\Delta\lambda}{\lambda} \sim \frac{1}{N}$$

Tutorial on Accelerator-Based Light Sources, M. Borland, March 29, 2011

Diagram after B. McNeil, "How an FEL works", FEL2010

e-beam Features from UR features

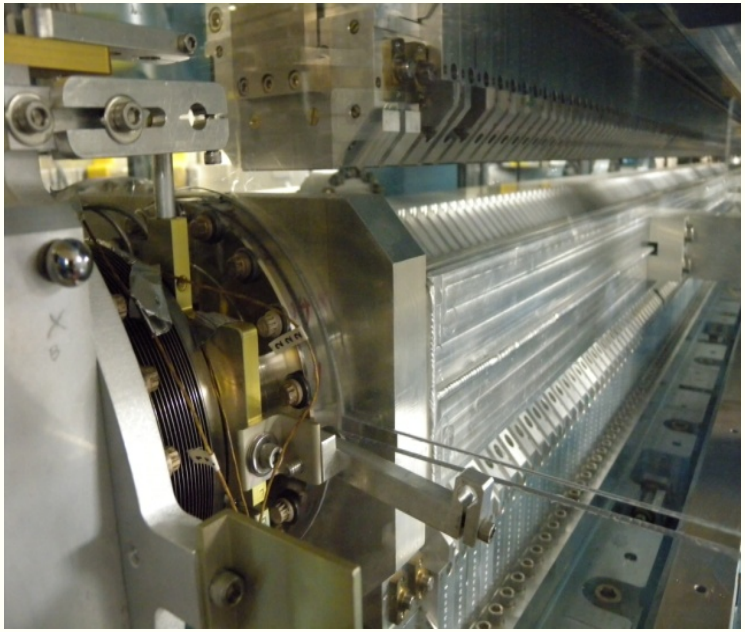
- Time-resolved Diagnostics planned at ms-, μs-, ns-, and ps-regimes for electron-beam parameters.

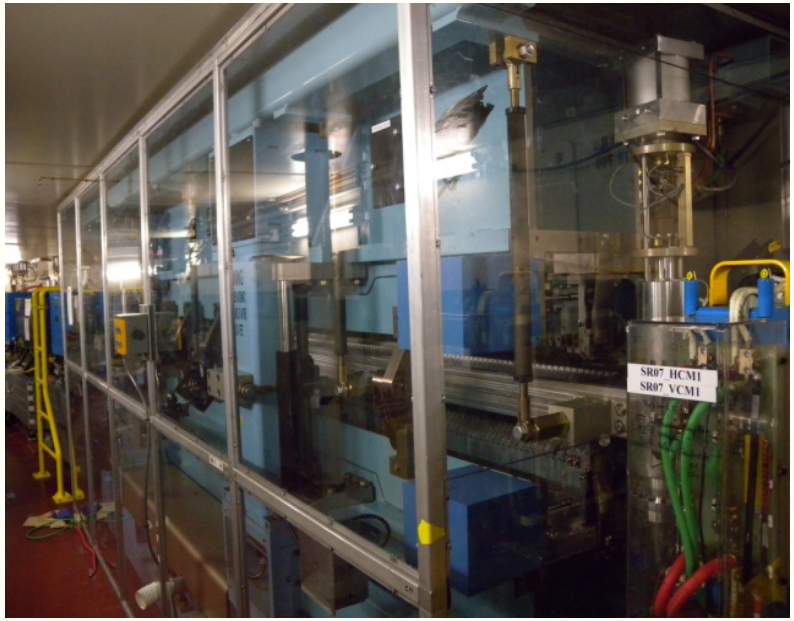
• position	Transverse UR image position
• size monitor	Transverse UR image size
• emittance	Gain in UR, harmonic ratios
• bunch length	UR bunch length, streak cam.
• bunch phase	UR phase position, streak cam.
• energy	UR Central wavelength, spectr.
• energy spread	Bandwidth obs. 1/nN, spectr.

- Beam based feedback monitor

U5.0 Option

- Undulator U5.0 transfer from LBNL under negotiation. 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	-

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
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	

Streak Camera Basics

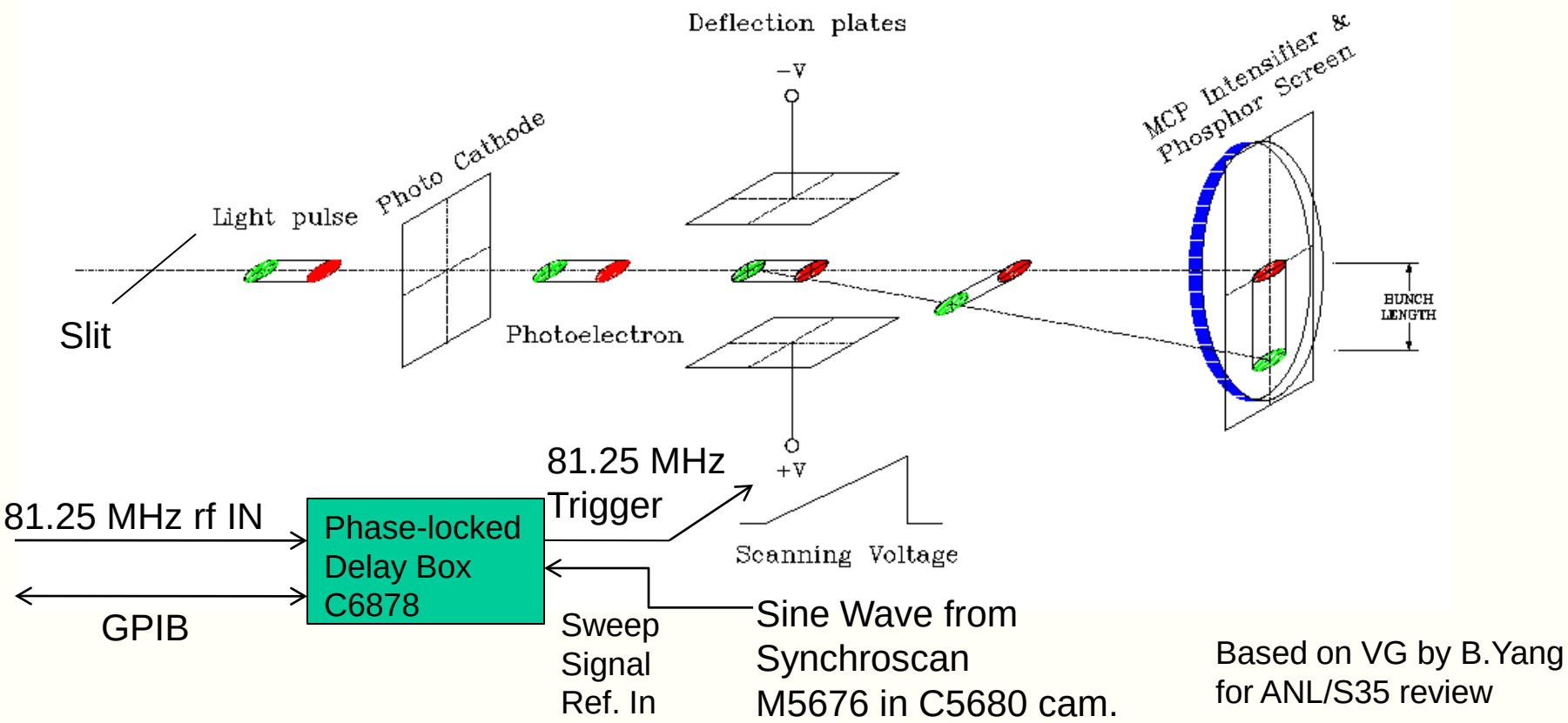
Input optics relay photons passing through a slit onto a photocathode.

(1) The streak tube deflection plates displace the photoelectrons dependent on the photons' arrival time.

(2) A streak tube MCP amplifies the electron number, and a potential difference between the MCP and phosphor results in the conversion of the electron distribution to a visible light streak image. This image is recorded by a readout video camera.

Streak Camera Principles

- **Addition of synchroscan plugin module and the C6878 phase-locked delay box enabled new series of experiments at A0 (ASTA in planning)**



Based on VG by B.Yang for ANL/S35 review

Example UR Results-1

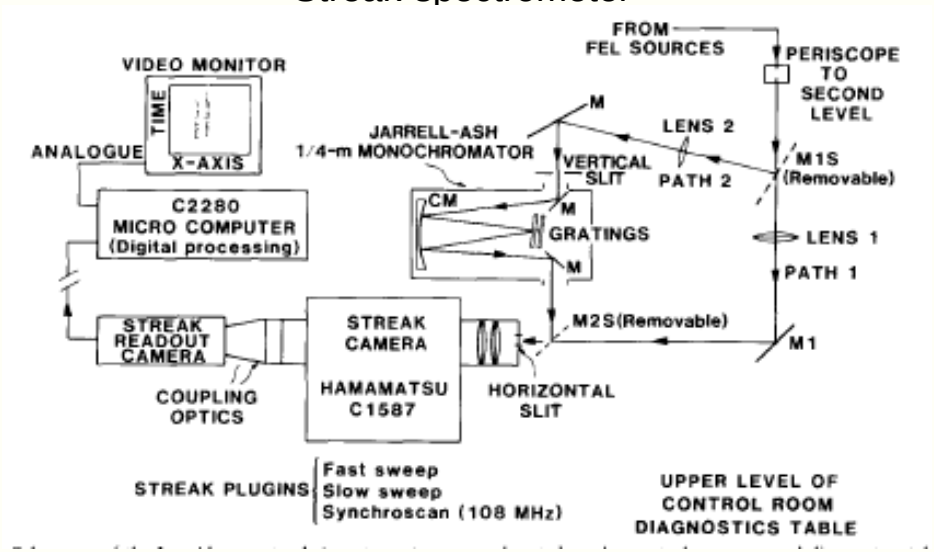
- **Boeing/LANL Visible FELO project at 630 nm.**

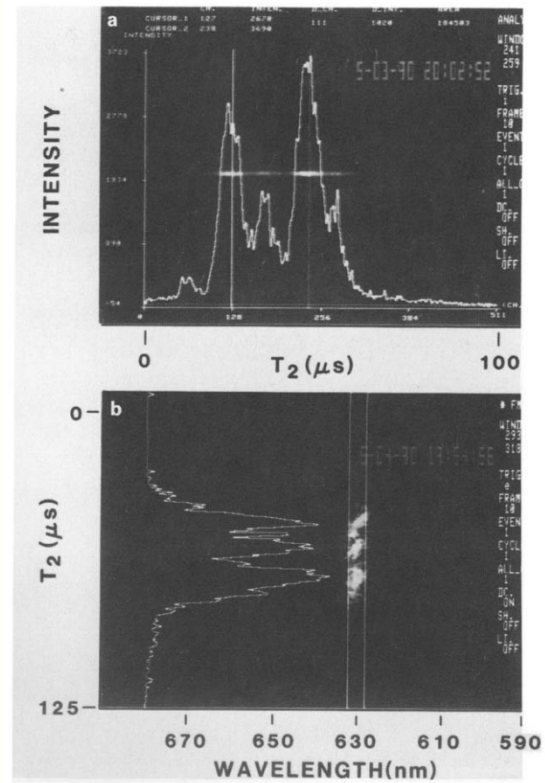
Nominal burst-mode FEL parameters

Electron beam :
Energy 110 MeV
Peak current 100-300 A
Micropulse (FWHM) 8-10 ps
Energy spread (FWHM) 0.5-1%
Micropulse repetition rate 4 MHz
Macropulse width 60-100 us

Undulator:
period=2.2 cm
Length =5 m

Streak-spectrometer





A.H.Lumpkin et al., NIMA 285, 17 (1989)

Example UR Results-2

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

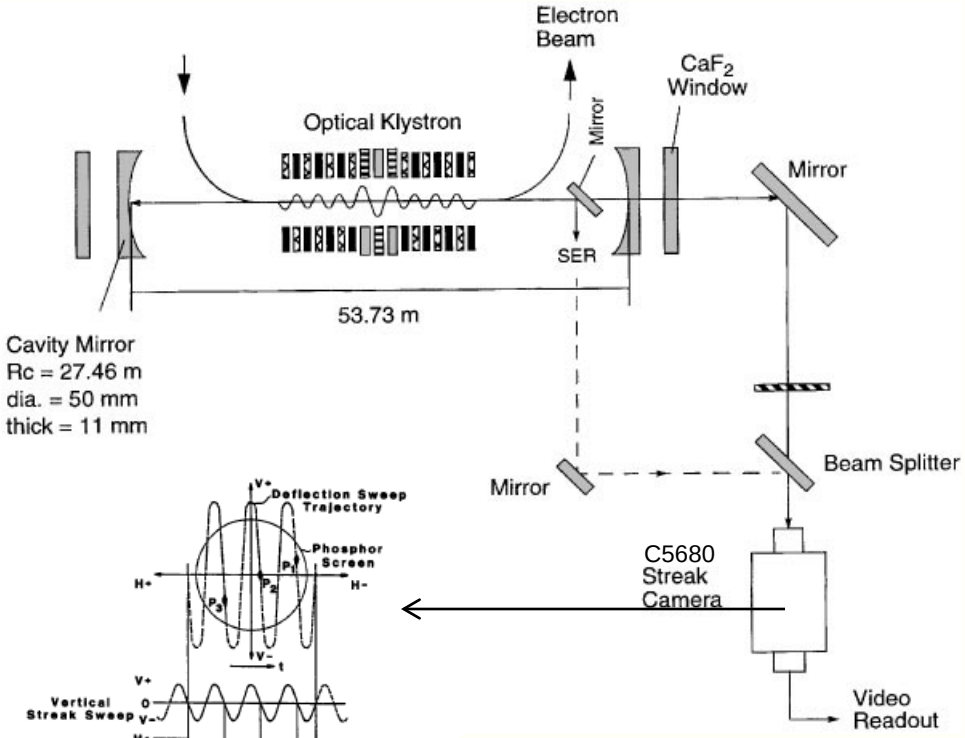
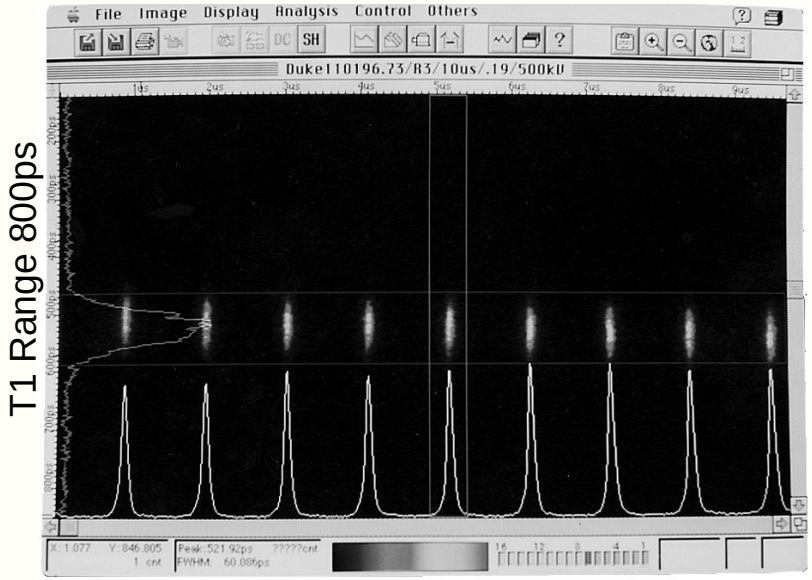


Fig. 1. Schematic of dual-sweep streak technique.



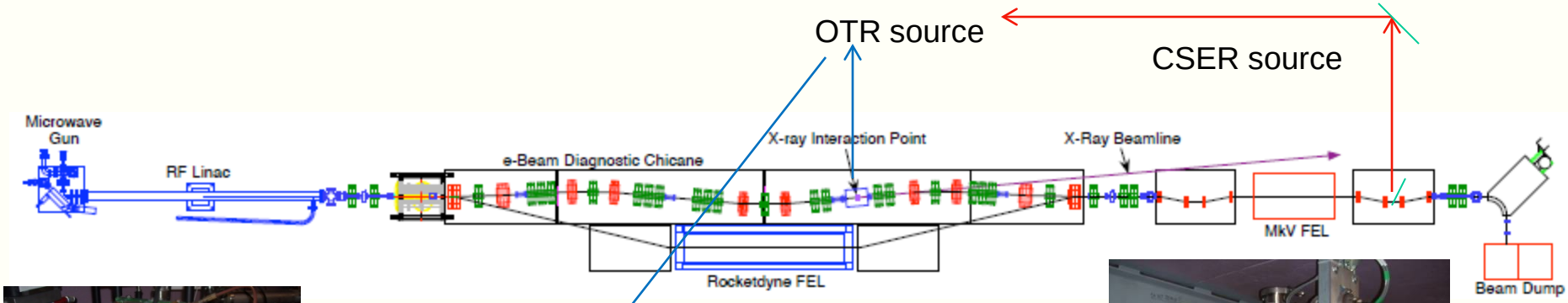
T2 Range 10µs

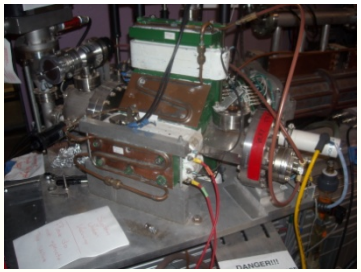
Rev freq=2.78 MHz, λ=450 nm, SER
Bunch length=60ps FWHM

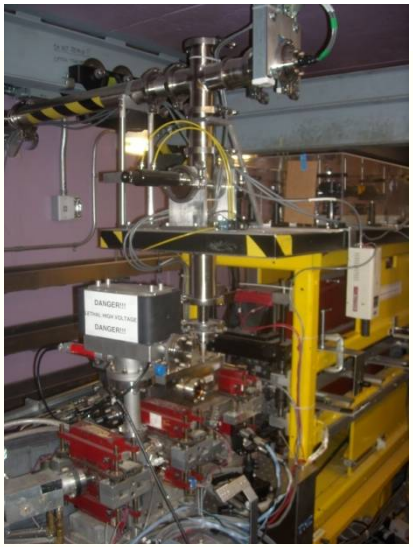
A.H.Lumpkin et al., NIMA 407, 338 (1998)

Example UR Results-3

Univ. of Hawaii S-band microwave gun and S-band electron linac drive Mark V FEL (mid-IR 4.5 µm). Look at UR but, 7th harmonic coherent spontaneous emission radiation(CSER) at 652 nm (tests in May 2013).



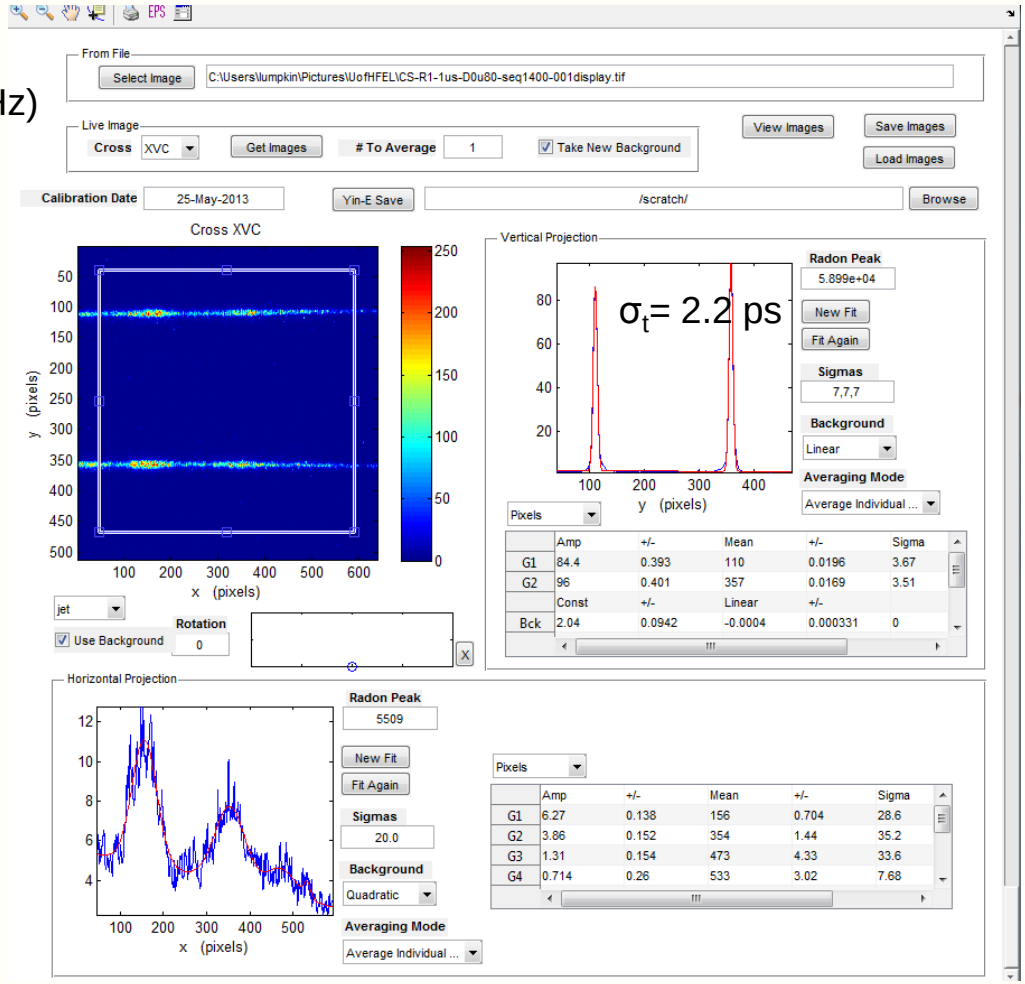




CSER Streak Camera Results:R1-1μs

Alpha=12.50 A, slew= -3.9,3.2 pix

Synchroscan (119.0 MHz)
R1 cal.=0.62 ps/pixel



Microbunching Mechanisms

- Microbunching of an electron beam, or a z-dependent density modulation with a period λ, can be generated by several mechanisms:
  - The Long.Space Charge-induced microbunching (LSCIM) starts from noise fluctuations in the charge distribution which causes an energy modulation that converts to density modulation following Chicane compression. This is a broadband case.

    (Not good for FEL as described in May 2011 APC seminar)
  - The laser-induced microbunching (LIM) occurs at the laser resonant wavelength (and harmonics) as the e-beam co-propagates through the undulator with the laser beam followed by Chicane compression. This is narrow-band, also like FELO.
  - In self-amplified spontaneous emission (SASE) induced microbunching (SIM) the electron beam is also bunched at resonant wavelength and harmonics. This is narrow band.
- A microbunched beam radiates coherently. (COTR,CUR,FEL)

Some FEL 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.**

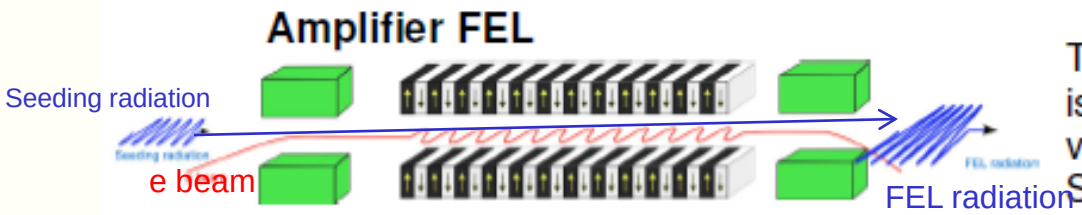
$$\lambda_n = \lambda_u (1 + K^2/2)/2n\gamma^2,$$

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

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.



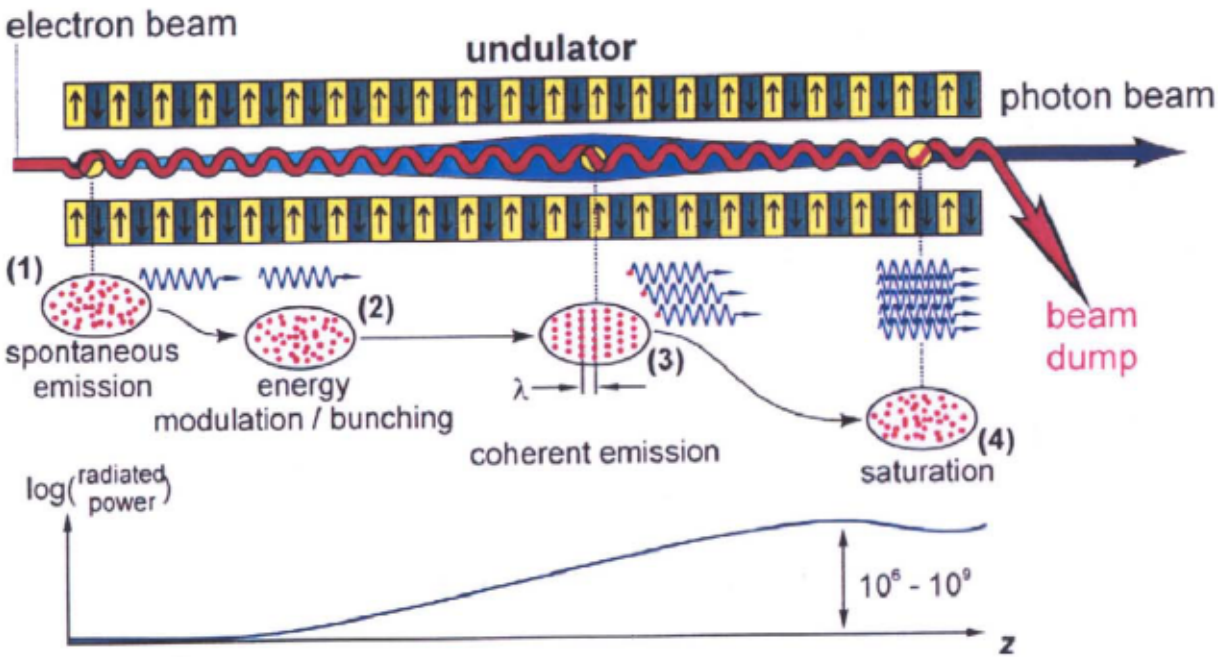
The tunability toward short wavelengths is limited by the lack of availability of very short wavelength seed lasers.
Spectral quality limited by the quality of the electron beam.

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

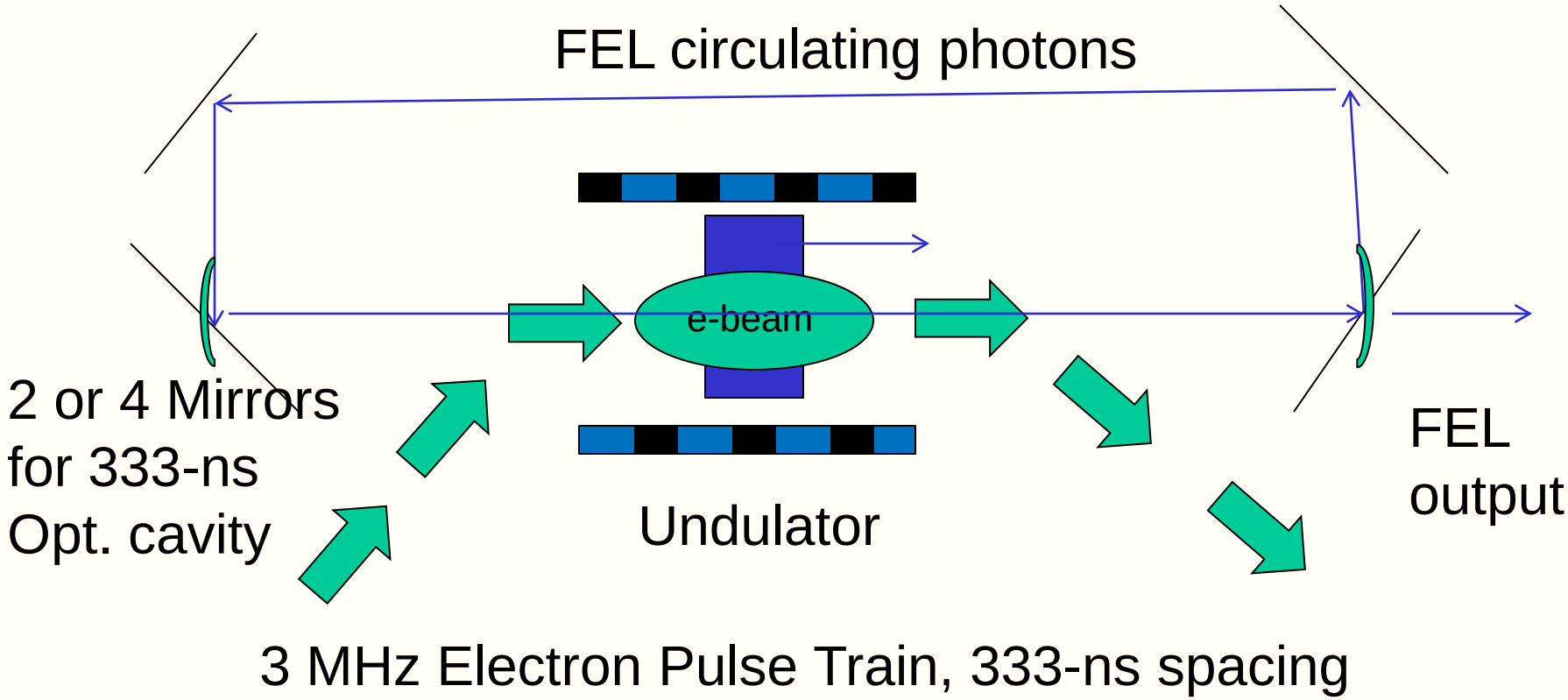
XUV FELO Application at ASTA

- **The ASTA beam provides six unique capabilities that enable XUV FELO experiments**

• 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 wavelength
• High power:1 ms at up to 5 Hz	High power FELO

VUV FEL Oscillator Configuration

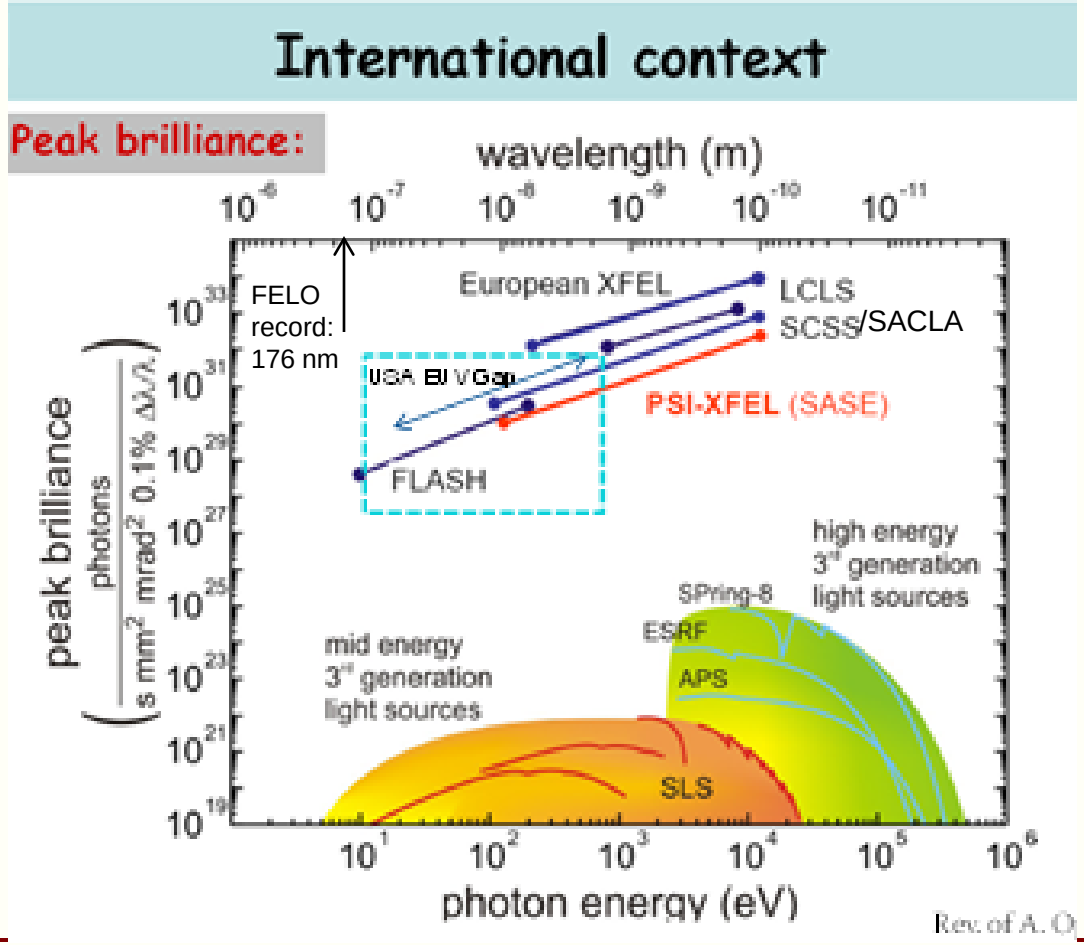
- **The bright beams, pulse structure, and new multilayer mirrors will make FEL oscillator feasible at ASTA.**



source need.

International FEL Context

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

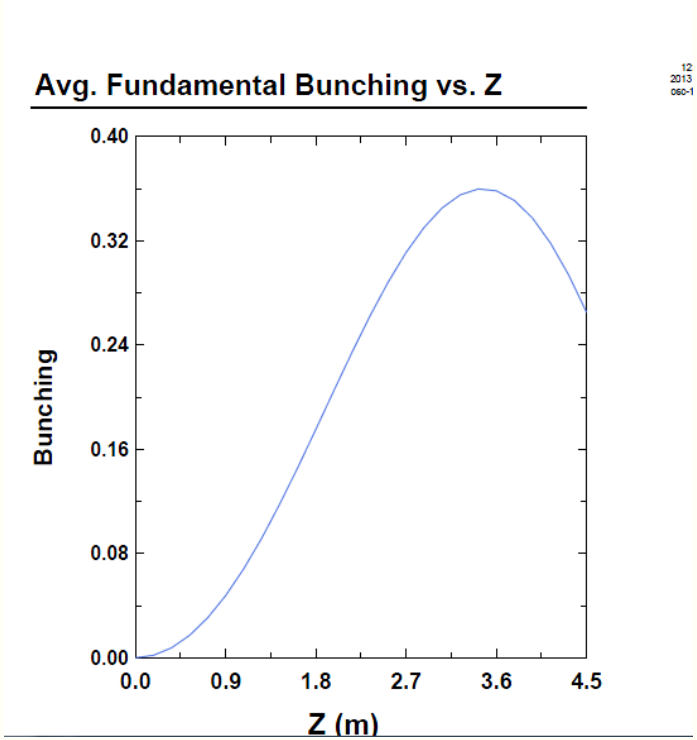


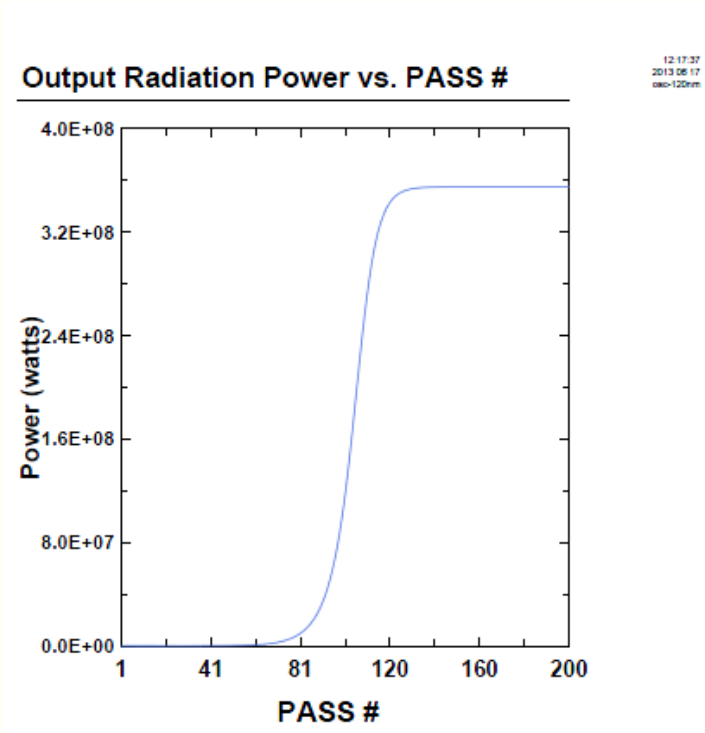
GINGER and MEDUSA Codes

- GINGER code developed for SASE FELs by W. Fawley while at LBNL. This was a single pass application.
- Oscillator module added subsequently and used by J. Wurtele's section at LBNL. (Ryan Lindberg now at ANL).
- M. Reinsch has provided simulations using nominal ASTA electron beam parameters, the U5.0 parameters and mirror reflectivity values into XUV down to 13.4 nm.
- MEDUSA was developed by H. Freund for SASE FELs, but it is now merged with an optical propagation code (OPC) developed in Europe by P.J. van der Slot.
- Freund has provided simulation results using similar sets of input parameters at 120, 100, and 13.4 nm.
- Note: shortest wavelength record for FELO is ~176 nm.

GINGER Simulations at 120 nm

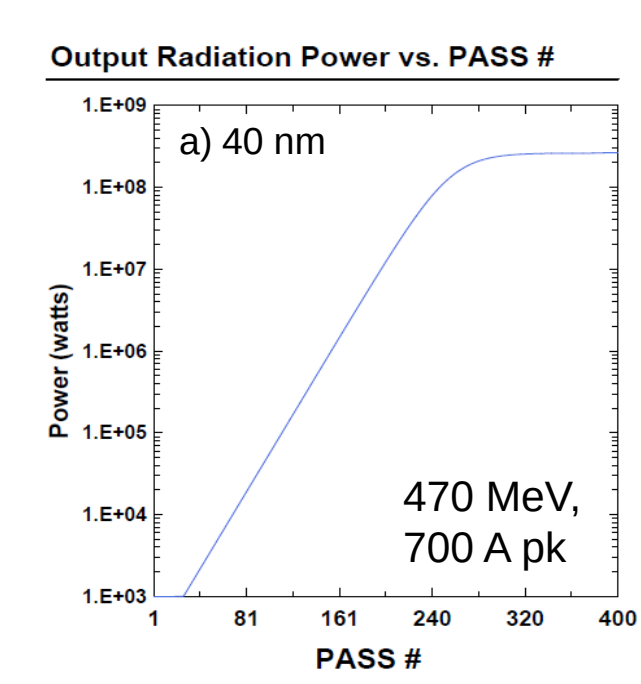
- **Beam energy 300 MeV, I_{pk}=100 A, 100-μm radius hole**

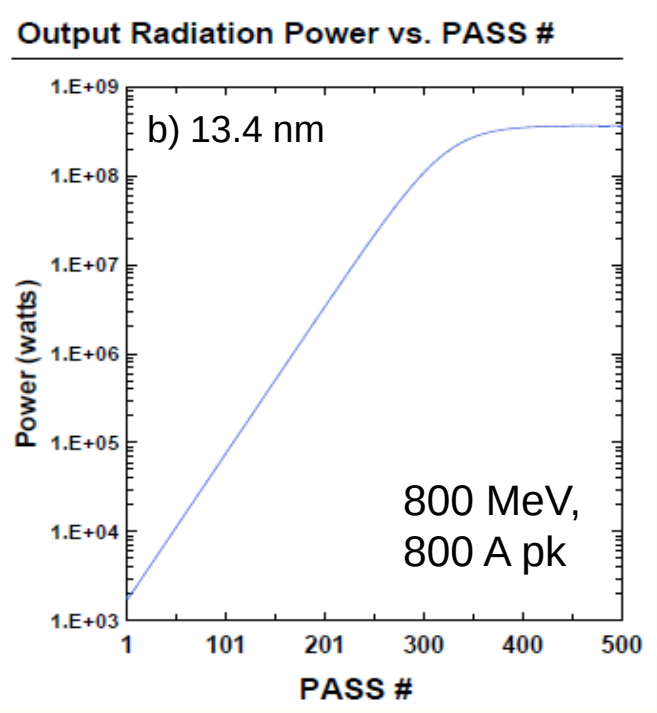




GINGER Results at 40 and 13.4 nm

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



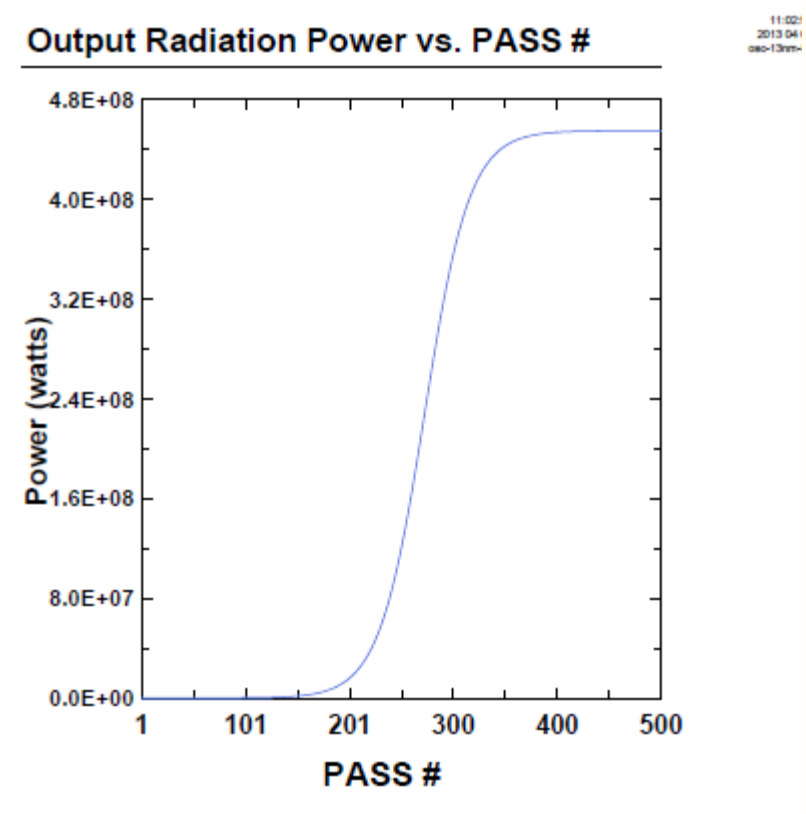


Initial GINGER simulations for output power saturation at the fundamental wavelength of a) 40.0 nm and b) 13.4-nm for a concentric cavity with multilayer mirror reflectances of 50 % and 68%, respectively.

GINGER results at 13.4 nm

- **Use hole output coupling of 100 μm radius in downstream multilayer mirror.**

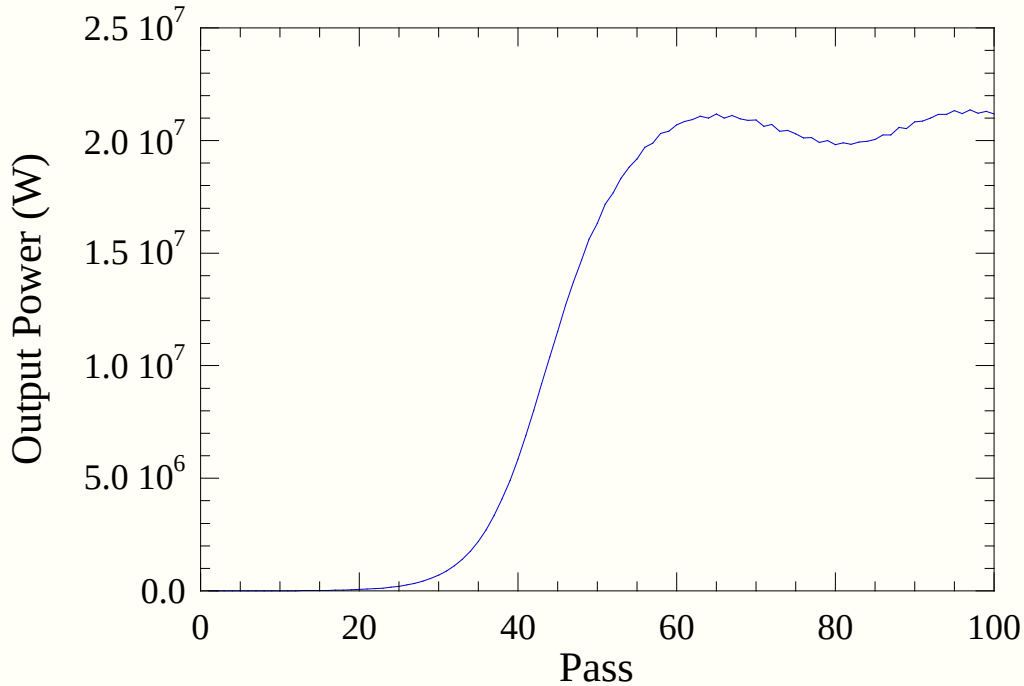
E=800 MeV,
I_{pk}=900 A,
$\varepsilon_{x,y}$=2 mm mrad



MEDUSA:OPC Simulations at 120 nm

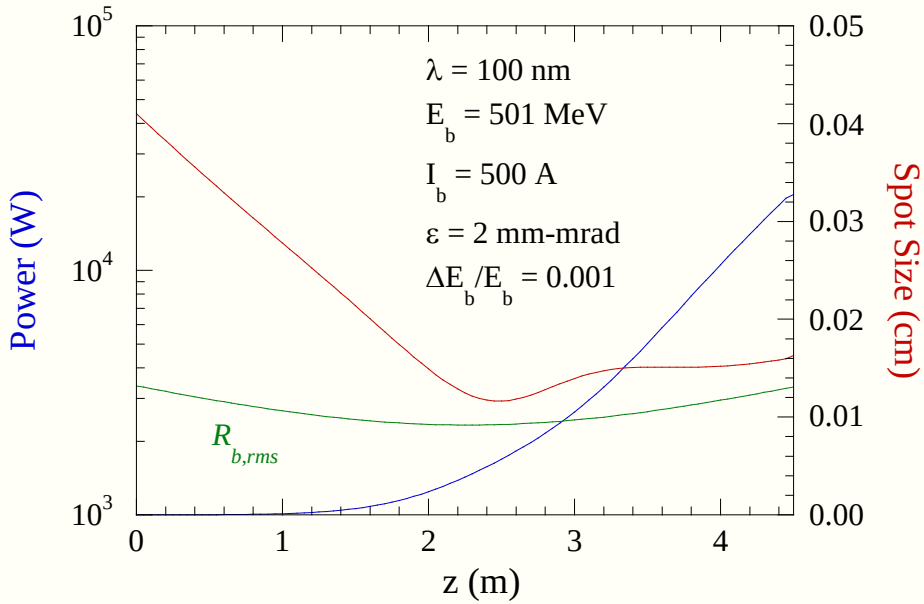
- **Beam energy 301 MeV, I_{pk}=100 A, 1-mm radius hole**

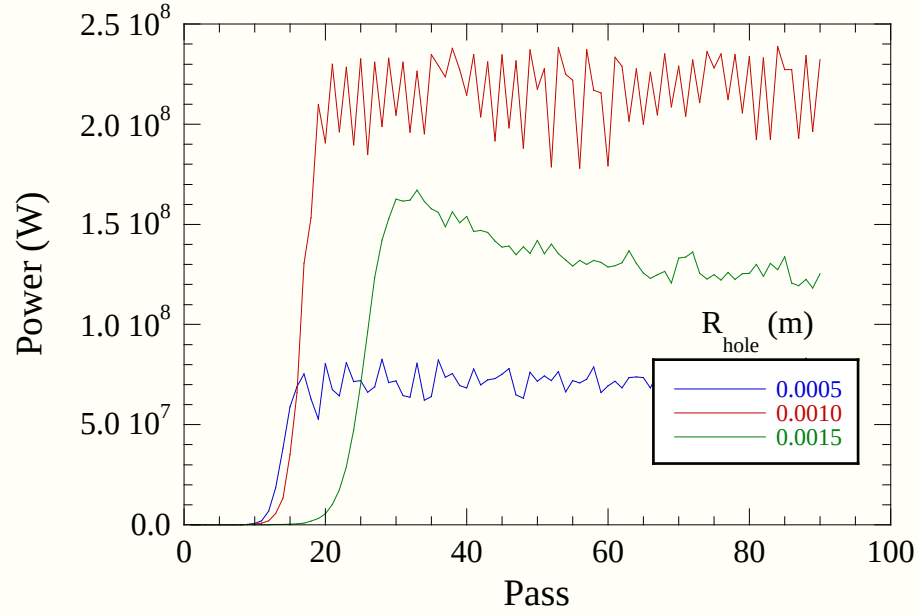
Electron Beam	
Energy	301.25 MeV
Current	100 A
Normalized Emittance	2 mm-mrad
Energy Spread	0.05%
x_{rms}	122 microns
α_x	1.0
y_{rms}	120 microns
α_y	1.0
Wiggler	
Period	5.0 cm
Amplitude	2.4614 kG
K_{rms}	0.813
Length	88 periods
Resonator	Concentric
Wavelength	120 nm
Cavity Length	50 m
Radii of Curvature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



Medusa:OPC results at 100 nm

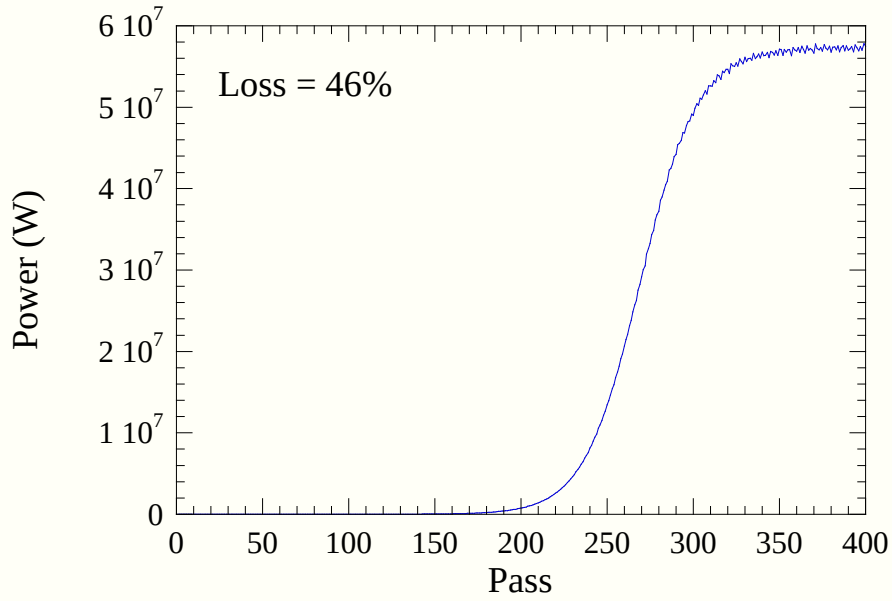
- **Hole outcoupling radius evaluations by H. Freund.**

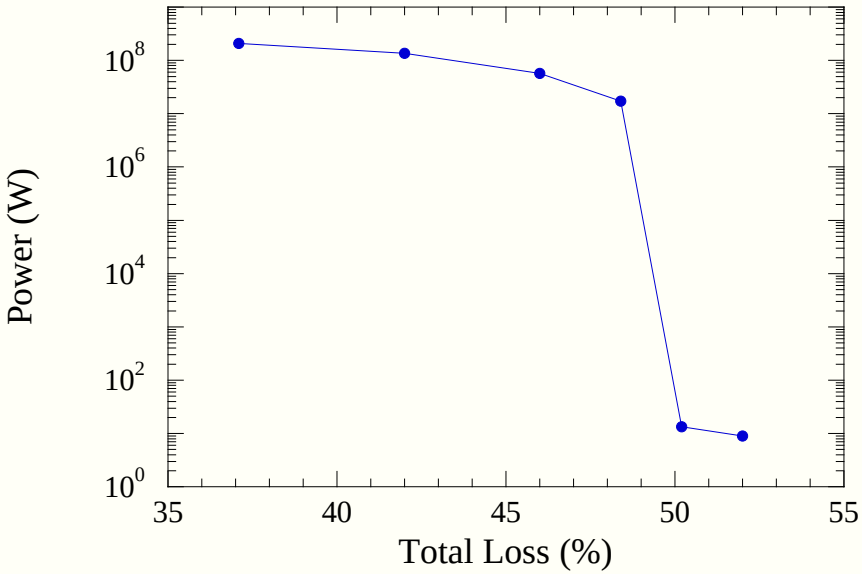




Medusa:OPC results at 13.4 nm

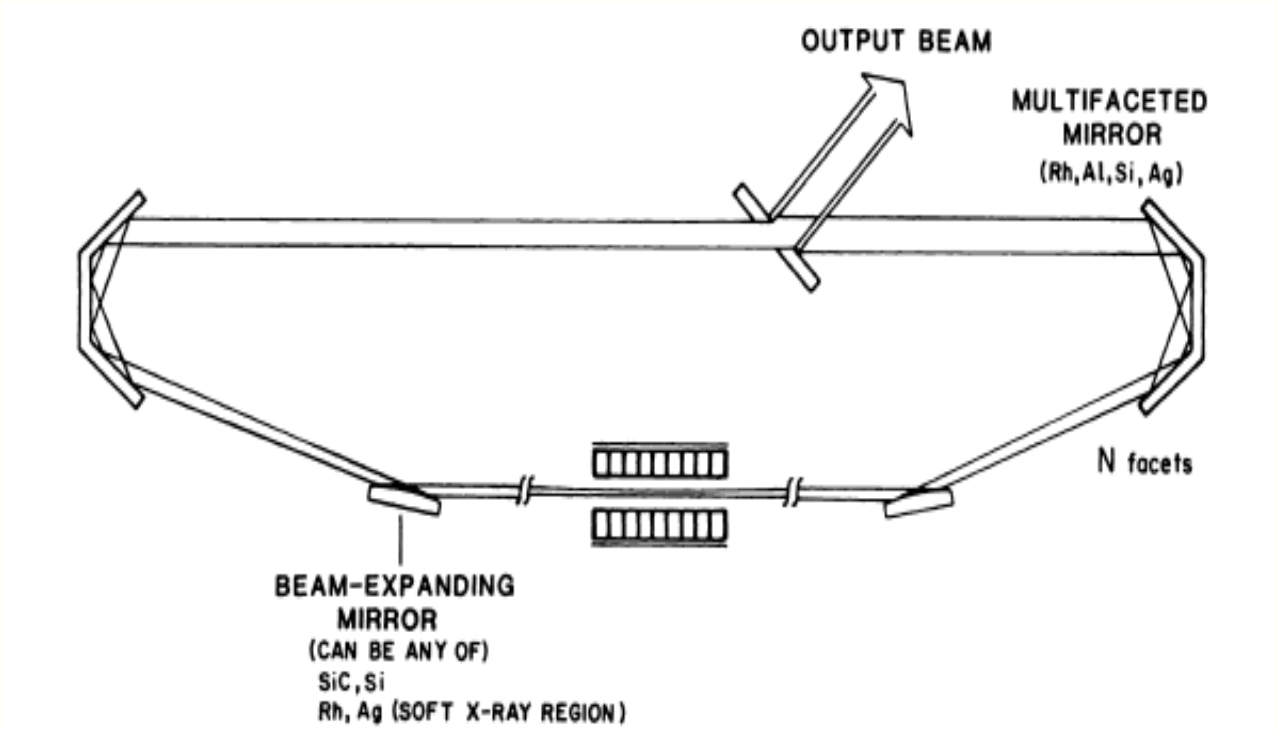
- **Transmissive coupling evaluated by H. Freund (LANL).**





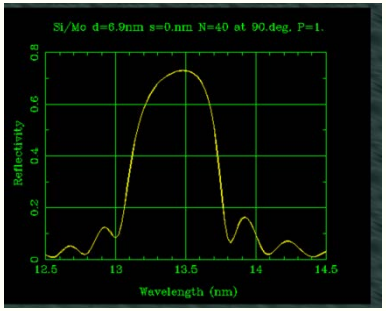
Ring Optical Resonator Option

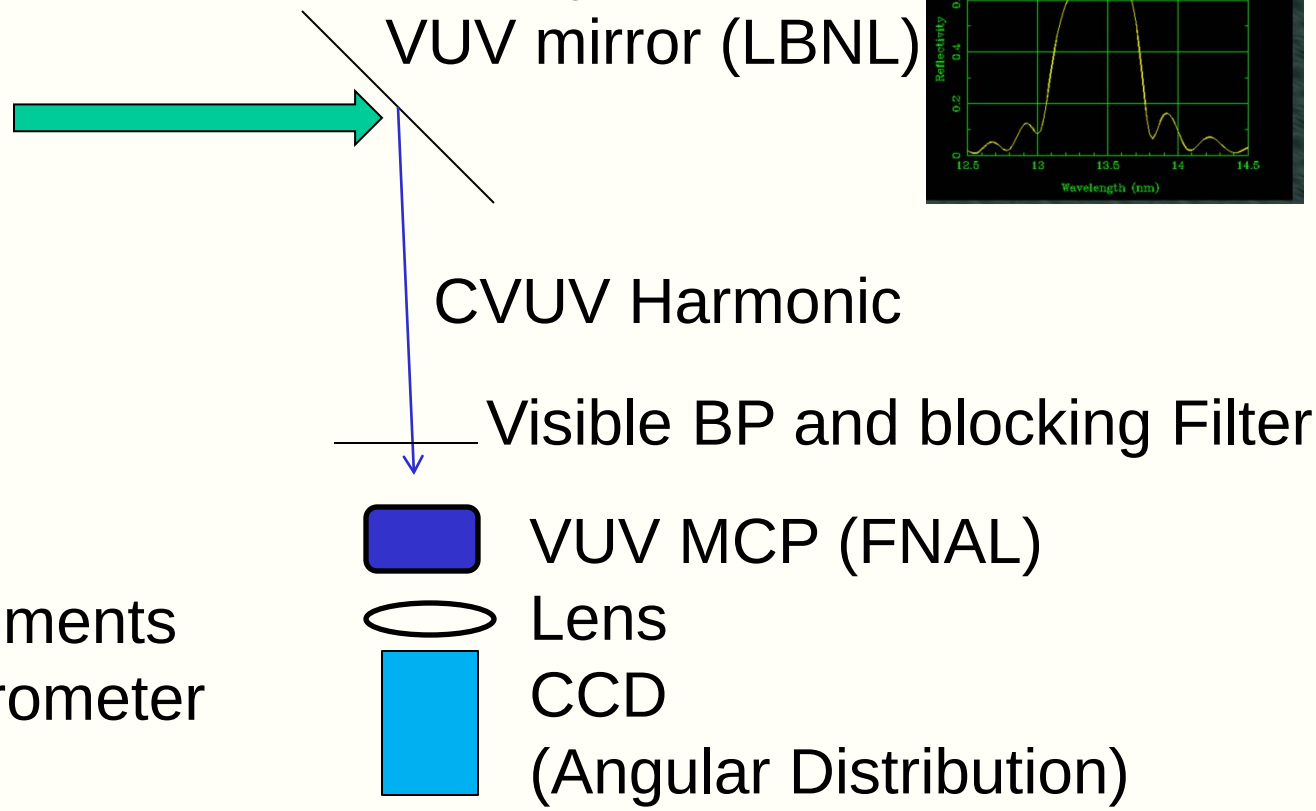
- A schematic of the ring optical resonator for an XUV FEL oscillator using multifaceted mirrors and on-axis beam-expanding mirrors (B. Newnam et al., SPIE vol.1552 (1991)). This would provide broadband subregions in λ.



Schematic of VUV test station

- **Narrowband reflectivity VUV mirror selects harmonic.**





Extend measurements
With VUV spectrometer
if possible.

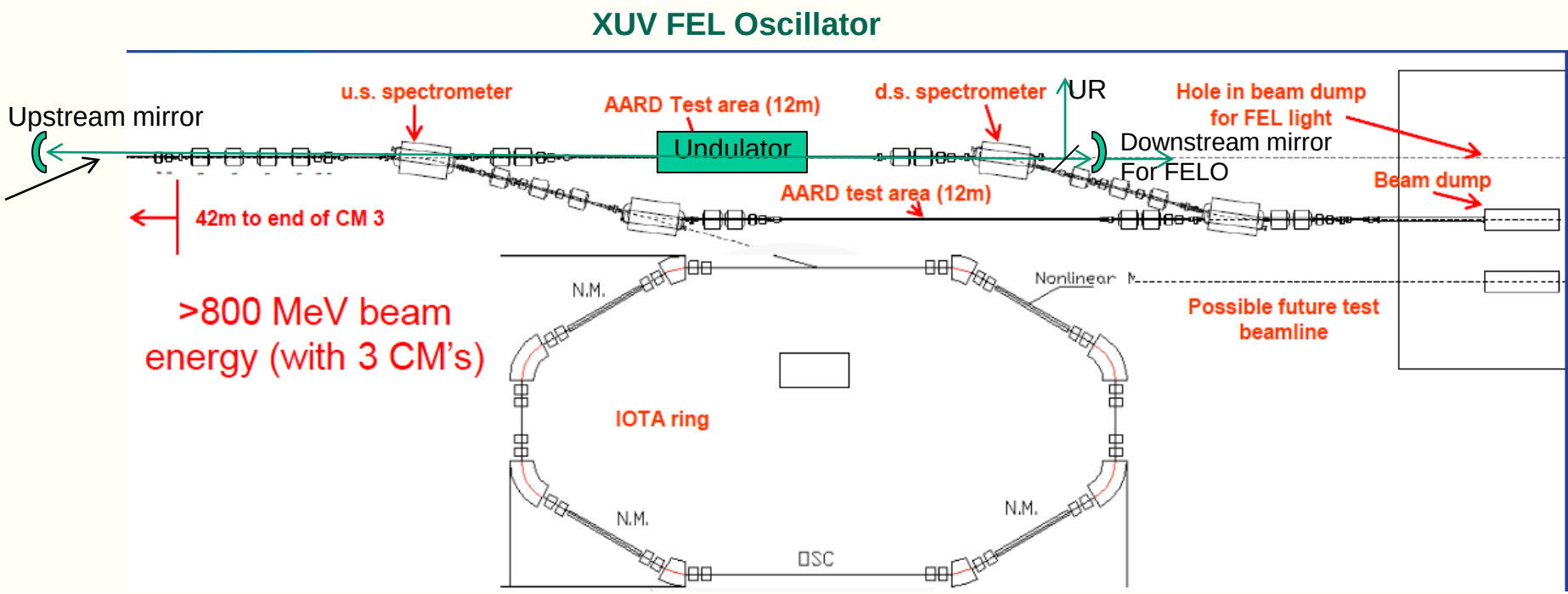
FELO Options with U5.0

- **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	13.7	5.0, 0.9	---
4	900	3	1.1, 0.9	

FELO in High-energy Beamline

- **Concentric cavity configuration option.**



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

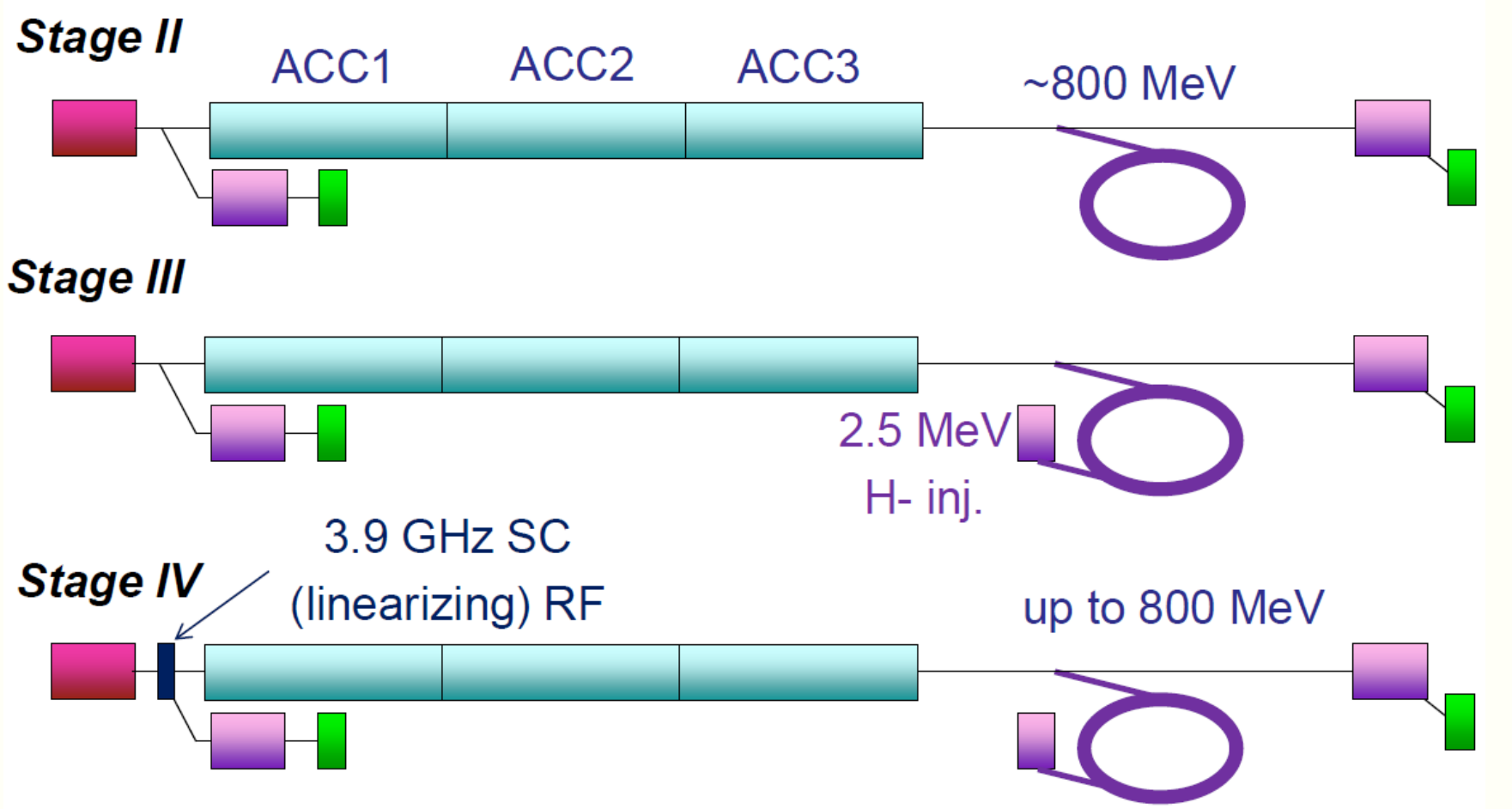
SUMMARY

- 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.
  - Could support initial CM2 beam studies with visible-UV UR.
- Diagnostics should be extended to VUV and soft x-ray regime where possible at ASTA into harmonic frontier. (several technology challenges: mirrors, optics, detectors, filters, etc.)
- Significant opportunity for first XUV FELO demonstration at ASTA (Can share e-beam with IOTA at 125-150 MeV)
- First photoelectrons from PC rf gun obtained 6-20-13 at ASTA.
- Installation of 50-MeV beamline expected in FY13, then first beam.

U5.0 Transport from California

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

ASTA Buildout and Operation Occurs in Stages: Stages II, III, IV



ASTA Proposal 2013