VUV — Soft X-ray FELs

John Corlett

Center for Beam Physics
Accelerator & Fusion Research Division
Lawrence Berkeley National Laboratory

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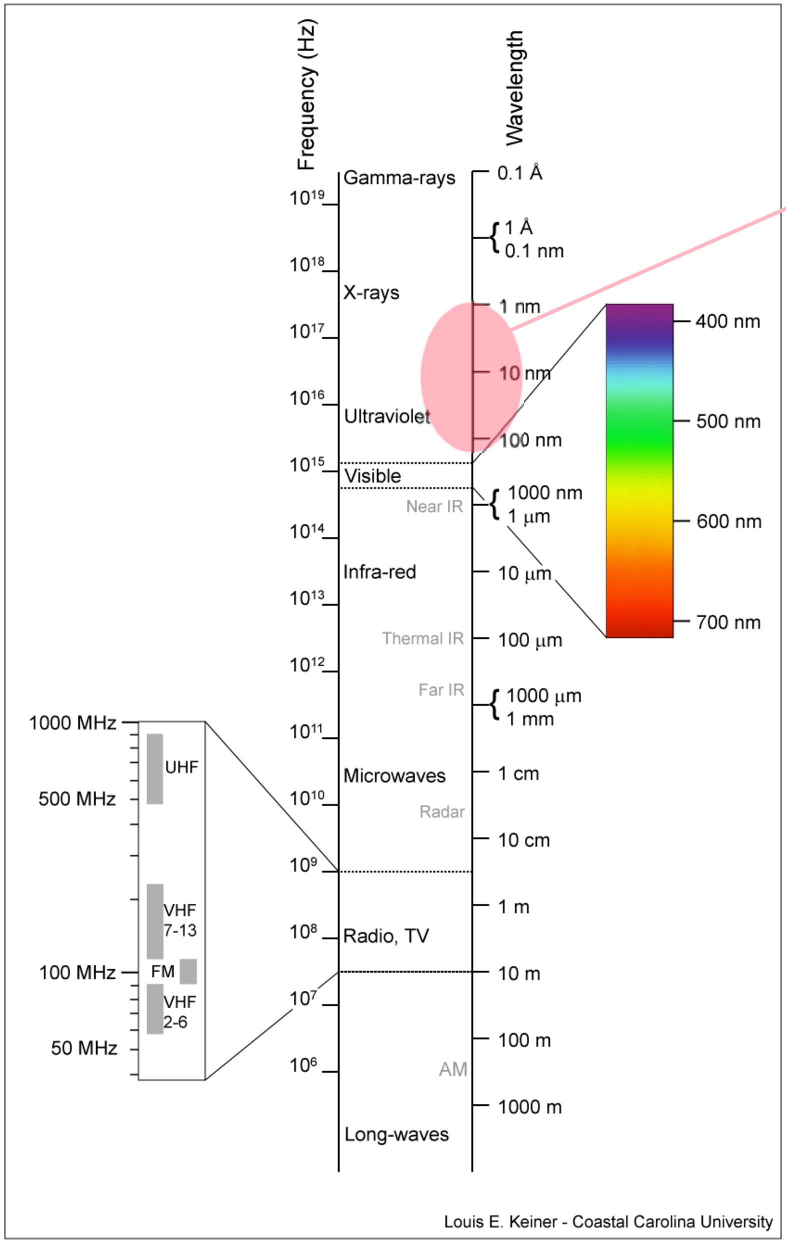
Lecture outline

- FEL physics drivers
  - Practical technological limits to performance
- Options for FEL configurations
  - Oscillator
  - SASE
  - Seeded
    - HGHG
    - Optical manipulations
    - Harmonic cascades
    - SASE self-seeding
- Options for facility configurations
  - Storage ring
  - Single-pass linac
    - Normal conducting
    - Superconducting
  - Energy recovery linac (ERL)
- Some concepts for the future

Machine parameters for VUV – soft x-ray FELs

(1) ELECTRON BEAM ENERGY



λ ~ 190 nm - 1 nm

$$\lambda_{x-ray} = \frac{\lambda_{undulator}}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

$$K = \frac{eB_0\lambda_{undulator}}{2\pi mc}$$

To efficiently radiate at nanometer wavelength, with state-of-the-art undulators

$\lambda_{undulator}$ ~ 1 cm

K ~ 1

$\Rightarrow \gamma \sim 3\times10^3$

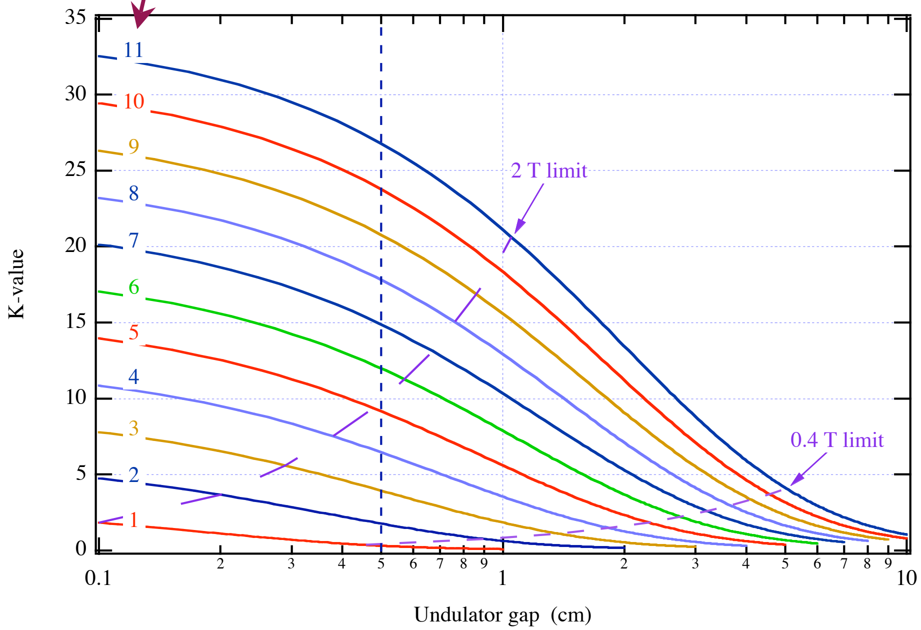
E_{beam} ~ 1 GeV

Limits to undulator performance

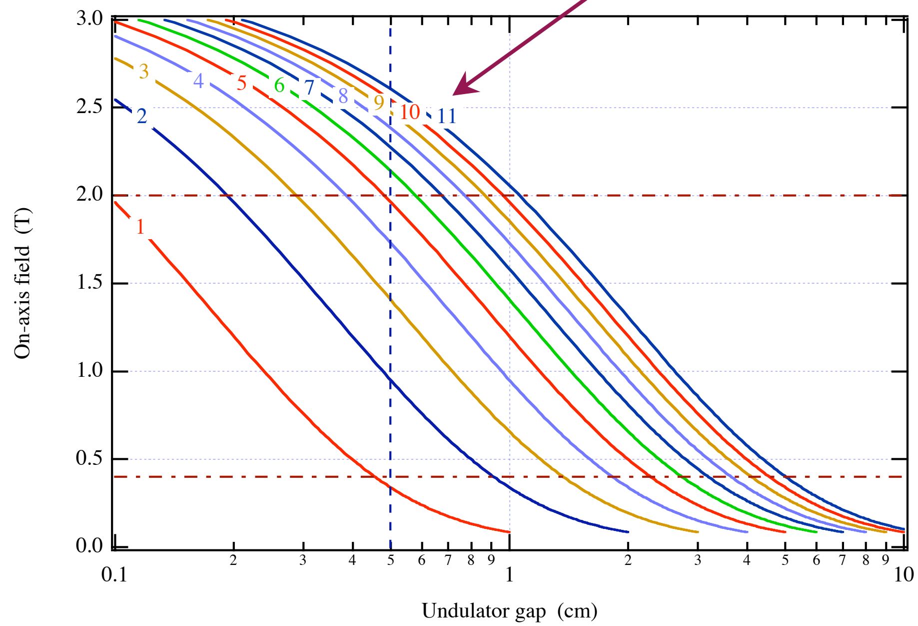
For a planar hybrid undulator with rare-earth cobalt magnetic material and vanadium permendur poles separated by gap g

$$B_o\left[T\right] = 3.33\exp\left[-\frac{g}{\lambda_{undulator}}\left(5.47 - 1.8\,\frac{g}{\lambda_{undulator}}\right)\right]$$

$\lambda_{\text{undulator}}$



$\lambda_{\text{undulator}}$

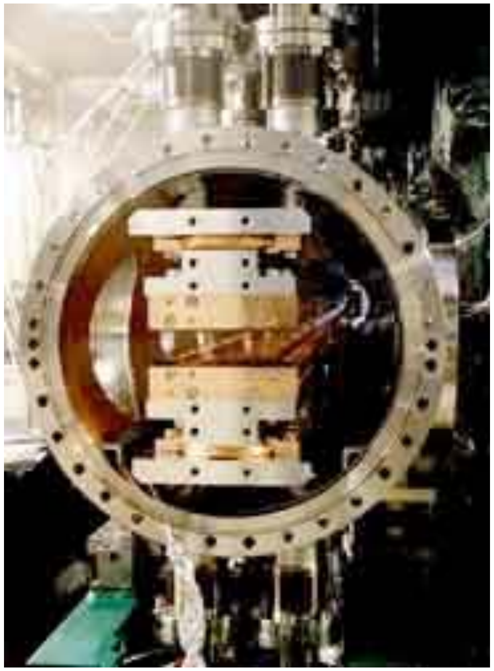


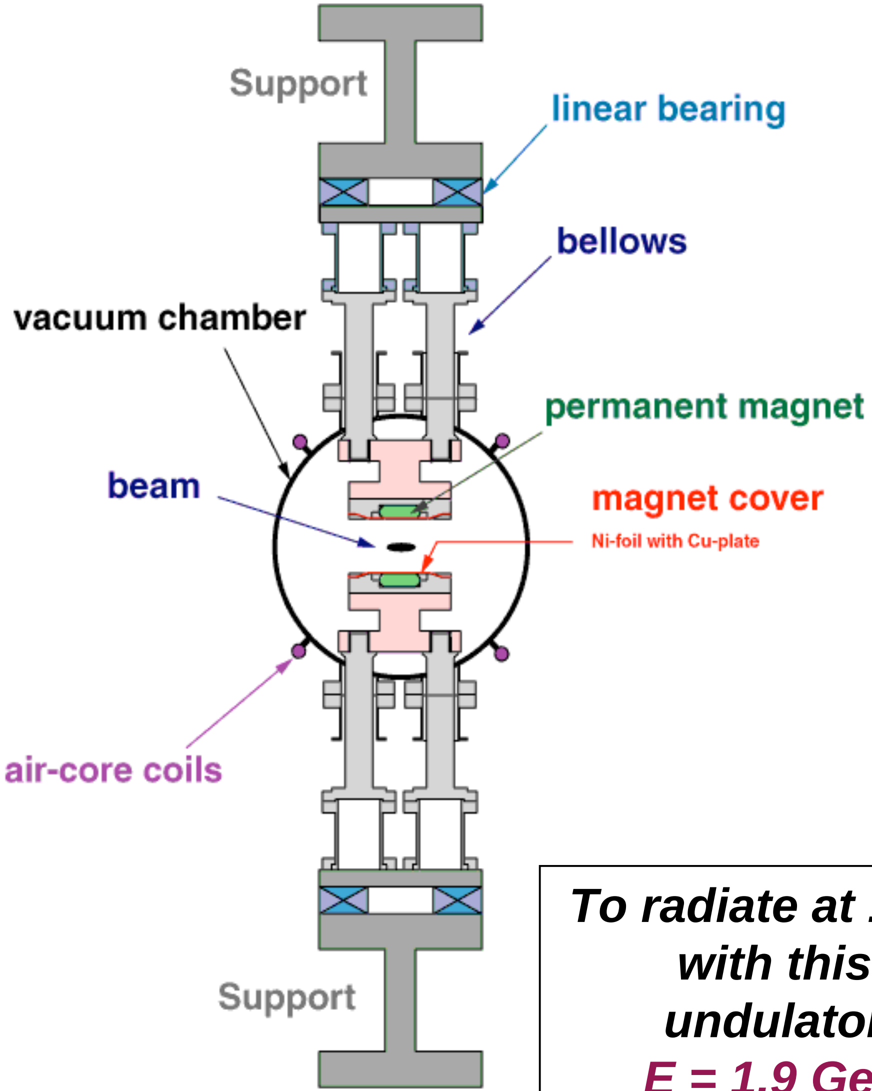
K. Halbach, "Permanent Magnet Undulators", J. Physique, C1, Suppl.2, 44 (February 1983)

SCSS* lased at 49 nm with 250 MeV beam

IN-VACUUM, SHORT-PERIOD UNDULATOR

- **Short-period - 1.5 cm**
- **Narrow-gap - 3.5 mm**
- **K=1.3**
- **Undulator length 4.5 m**





***SPring-8 Compact SASE Source**

To radiate at 1 nm with this undulator
E = 1.9 GeV

http://epaper.kek.jp/f06/PAPERS/MOAAU04.PDF

Machine parameters for VUV – soft x-ray FELs

(2) MATCHING THE PHOTON BEAM AND ELECTRON BEAM PHASE SPACES

$$\left(\frac{\varepsilon_n}{\gamma}\right) \leq \frac{\lambda_{x-ray}}{4\pi}$$

$\Rightarrow$ **Electron beam geometric emittance for nanometer x-rays**

$\varepsilon_n/\gamma \sim 10^{-10}$ m-rad

State of the art $\varepsilon_n \sim 10^{-6}$ m-rad (for ~nC bunches)

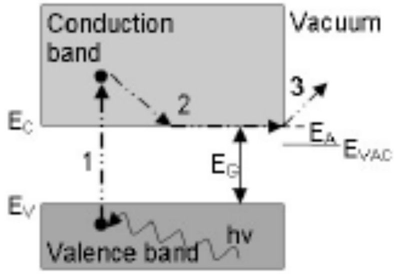
$\Rightarrow \quad \gamma \sim 10^4$

$E_{beam} \sim$ GeV

This is a somewhat soft condition

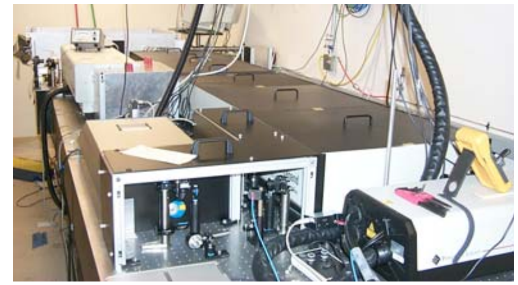
Injector defines the minimum beam emittance

INTEGRATED SYSTEMS: CATHODE, LASER, ACCELERATING SECTIONS



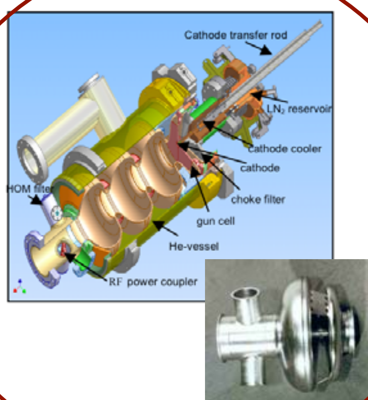
Low emittance, high quantum efficiency cathodes

Integrated systems

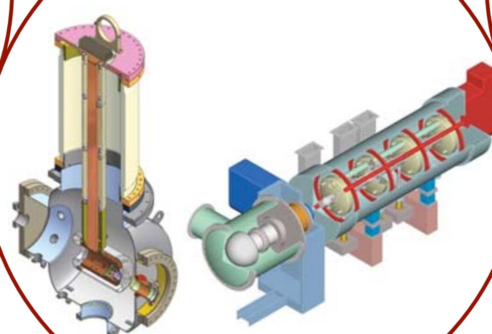


Photocathode laser systems including pulse shaping

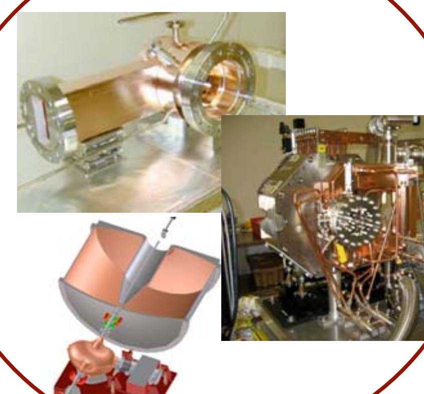
Acceleration technologies



Superconducting RF



DC gun



Normal conducting RF

Worldwide R&D efforts are exploring a range of technologies

Machine parameters for VUV – soft x-ray FELs

(3) ELECTRON BEAM LONGITUDINAL PHASE SPACE

$$\frac{\sigma_E}{E} < \rho$$

$$P_{saturated} \approx \rho I_{beam} \frac{E_{beam}}{e}$$

For $\rho \sim 10^{-3}$

$\Rightarrow$ Energy spread for GeV beam

$\sigma_E < \sim 100$ keV

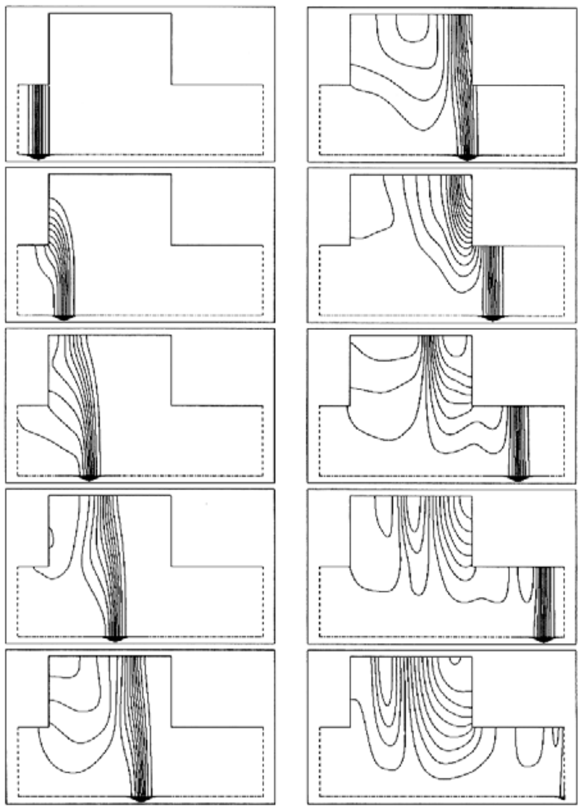
Electron beam peak current $I_{peak} \sim 1$ kA

Saturated peak power ~ GW

Geometric wakefields in accelerating structures

A HEAD-TAIL DISTURBANCE WITH STRONG DEPENDENCE ON IRIS APERTURE

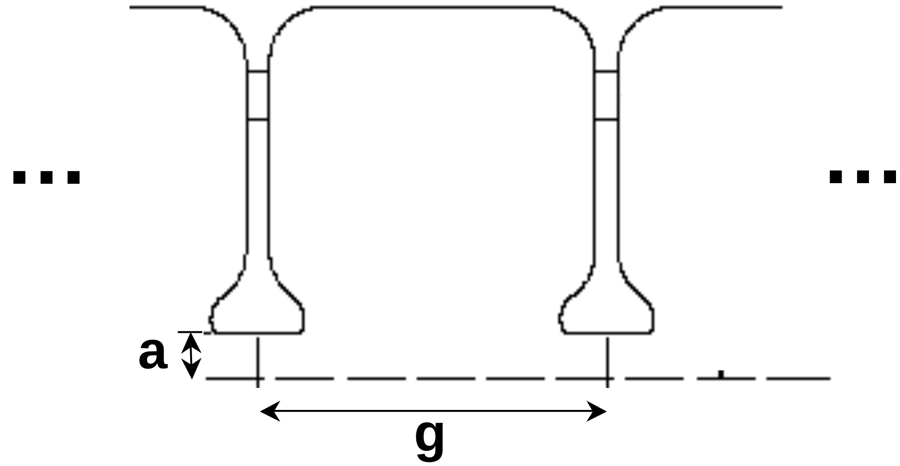
Single cavity



$$w_{\parallel}^{0}(s) = \frac{Z_0 c}{\sqrt{2}\pi^2 a}\sqrt{\frac{g}{s}}$$

$$w_{\perp}^{1}(s) = \frac{2}{a^2}\frac{\sqrt{2}Z_0 c}{\pi^2 a}\sqrt{gs}$$

Periodic structure



$$w_{\parallel}^{0}(s) = A\frac{Z_0 c}{\pi a^2} e^{-\sqrt{\frac{s}{s_1}}}$$

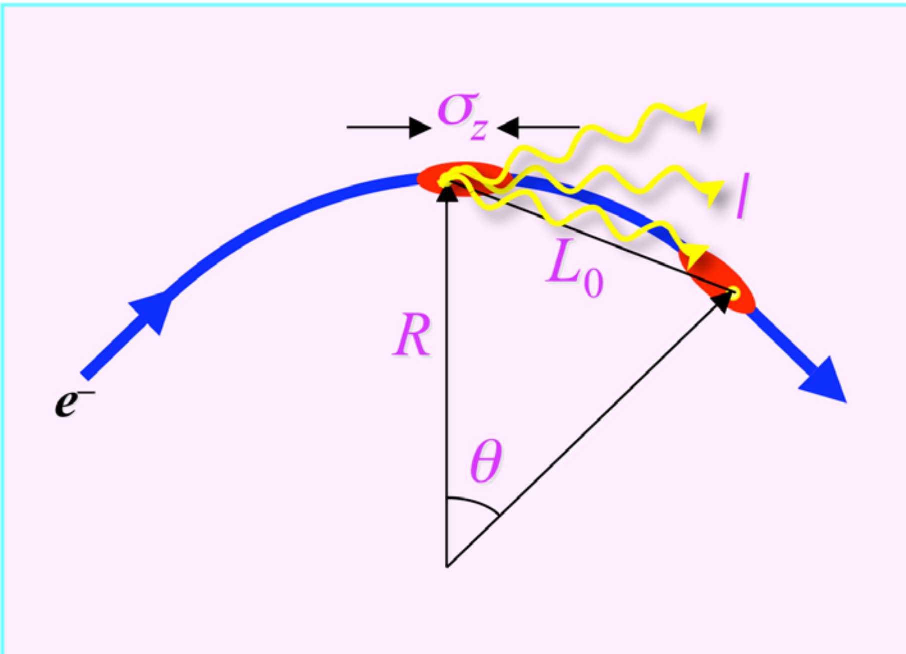
$$w_{\perp}^{1}(s) = \frac{2}{a^2} A \frac{Z_0 c}{\pi a^2} 2 s_1 \left[1 - \left(1 + \sqrt{\frac{s}{s_1}}\right) e^{-\sqrt{\frac{s}{s_1}}}\right]$$

K. Bane, M. Sands, *Wakefields of very short bunches in an accelerating cavity,* SLAC-PUB-4441, 1987
K. Bane, *Short-range dipole wakefields in accelerating structure for the NLC,* SLAC-PUB-9663, LCC-0116, 2003

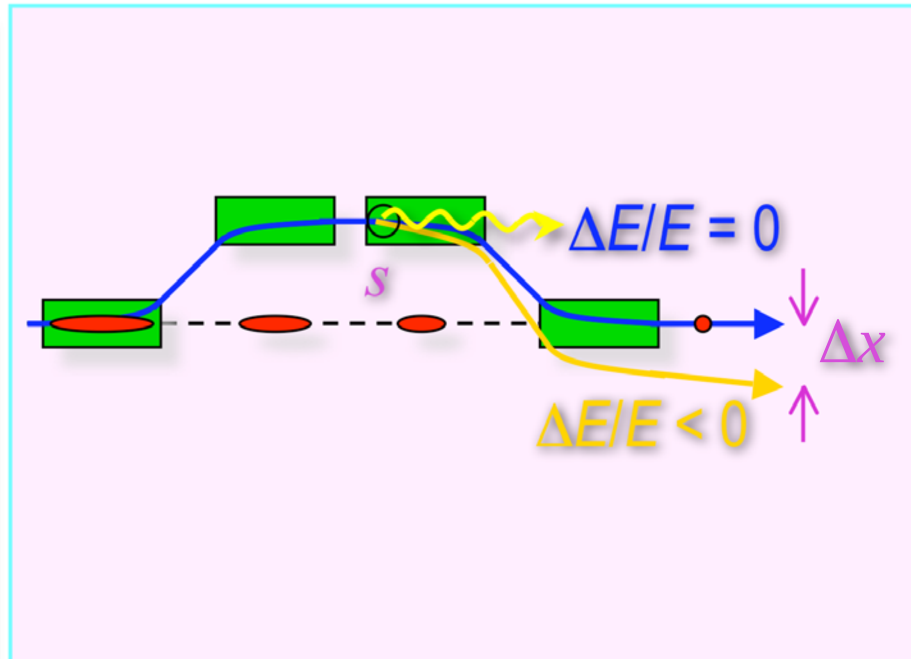
Coherent synchrotron radiation (CSR)

COHERENT EMISSION AT WAVELENGTHS COMPARABLE TO BUNCH LENGTH

Coherent radiation for $\lambda > \sigma_z$



Bend-plane emittance growth



$$W_s \propto \int \frac{1}{\left(s - s'\right)^{1/3}} \frac{\partial \lambda\left(s'\right)}{\partial s'} ds'$$

Courtesy P. Emma, SLAC

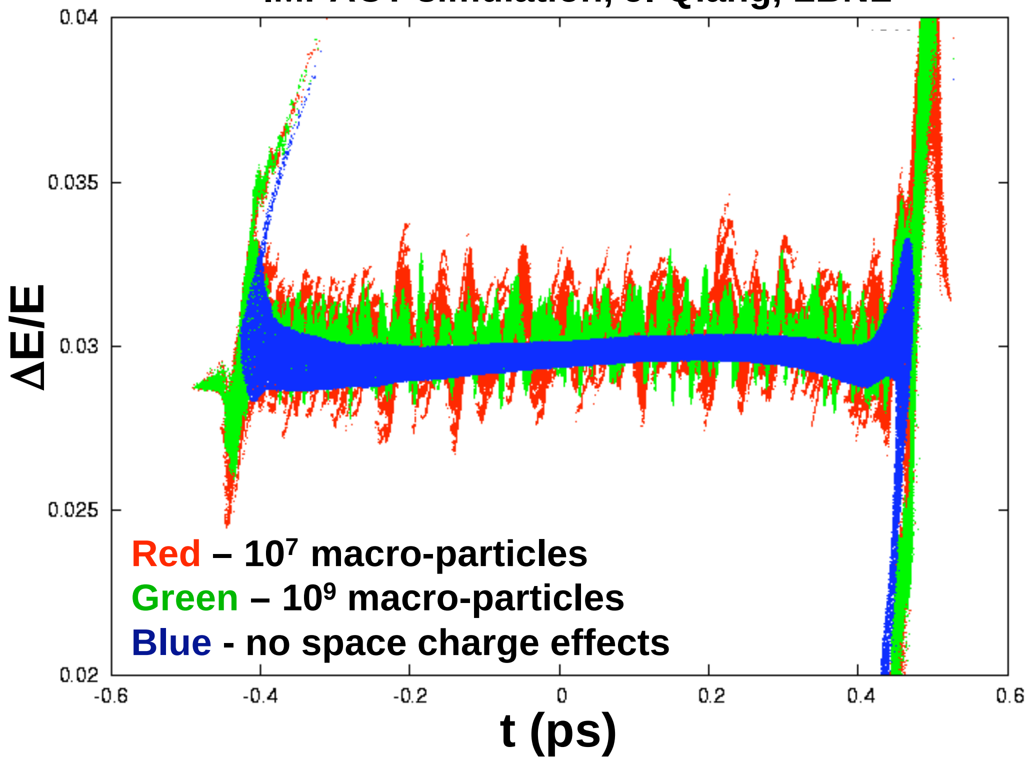
Microbunching instability

MICRON-SCALE MODULATIONS IN BEAM ENERGY

Microbunching instability arises from shot noise in the electron beam, grows under the influence of CSR and space charge, and introduces a modulation in the bunch energy spread

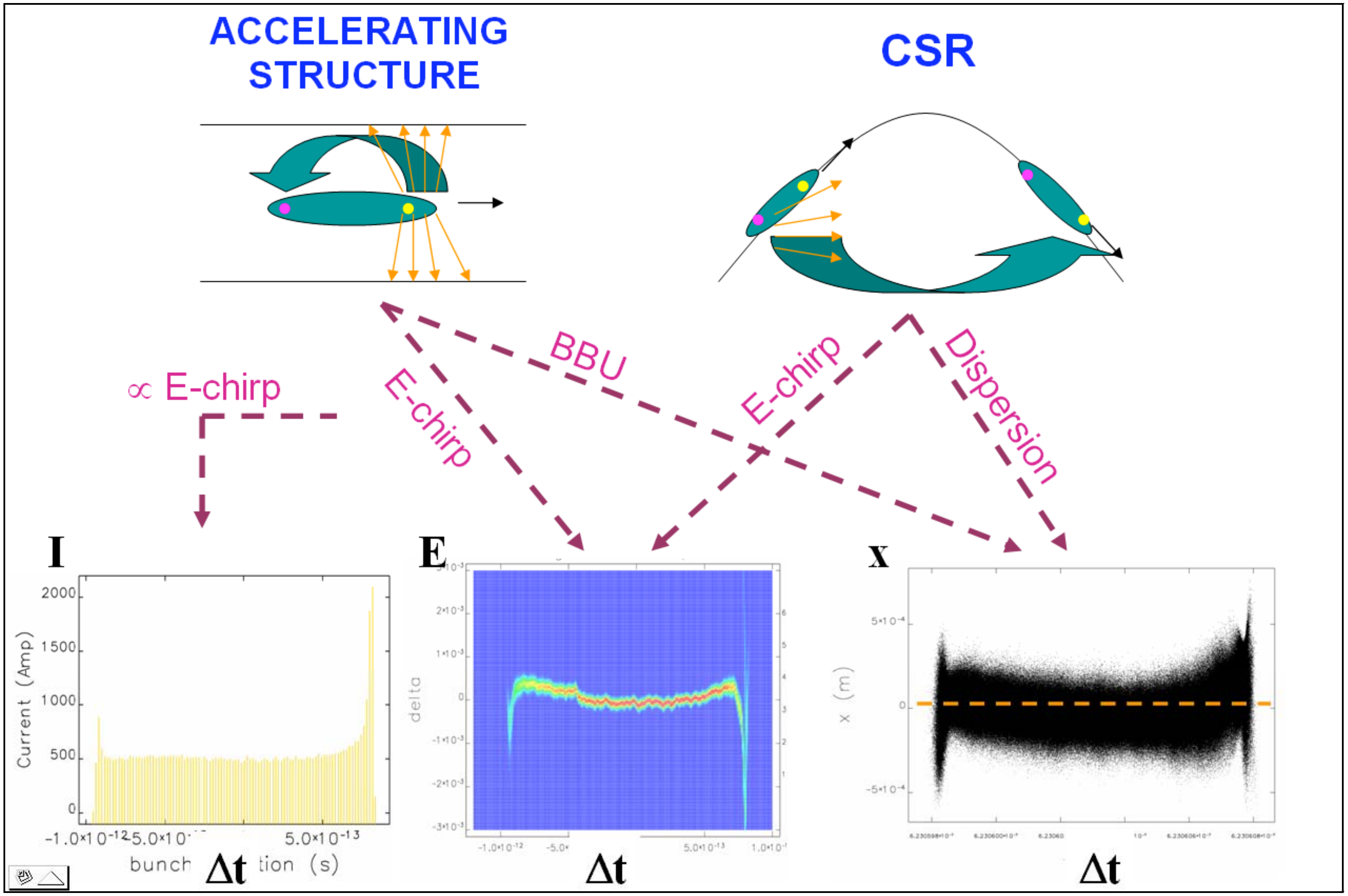
- **Control with "laser heater" which introduces an incoherent energy spread in the low energy beam**
  - ***Landau damping***

IMPACT simulation, J. Qiang, LBNL



Wakefields influence beam phase space

ACCELERATOR DESIGN OPTIMIZATION REQUIRED



Courtesy Simone Di Mitri, Sincrotrone Trieste

Machine parameters for VUV – soft x-ray FELs

(4) GAIN LENGTH

$$l_{gain} \approx \frac{\lambda_{undulator}}{4\pi\rho}$$

For nanometer x-rays, with centimeter period undulator, and $\rho = 10^{-3}$

$l_{gain} \sim 1$ m

For saturated SASE FEL operation, undulator length ~ 20 gain lengths

$l_{undulator} \sim 10$ m

Machine parameters for VUV – soft x-ray FELs

(5) SLIPPAGE

$$N_u \lambda_{x-ray} \ll \sigma_l$$

For saturated SASE output, $N_u \sim 10^3$

For x-ray pulses at 1 nm

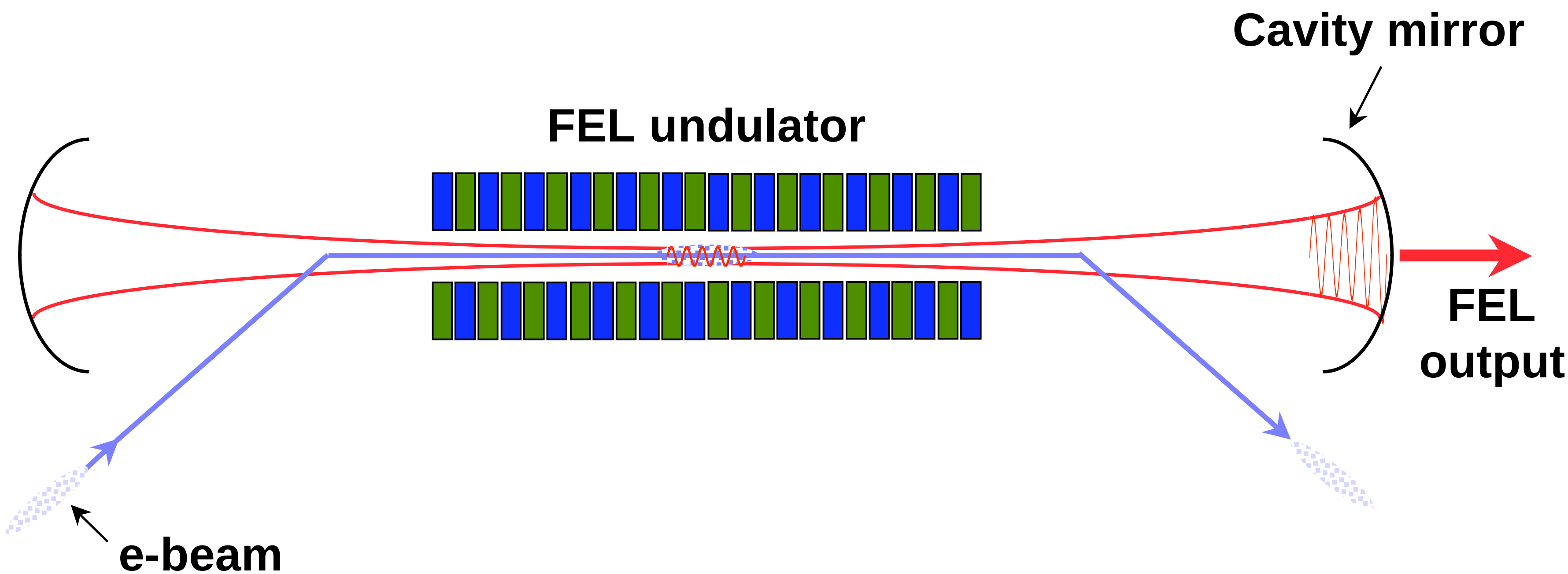
$\Rightarrow N_u \lambda_{x\text{-}ray} \sim$ μm (~ *femtosecond timescale*)

$\Rightarrow$ Can limit minimum duration of "short" pulses at longer wavelengths

***But* there are techniques to overcome this to a significant extent with seeded FELs**

FEL configurations

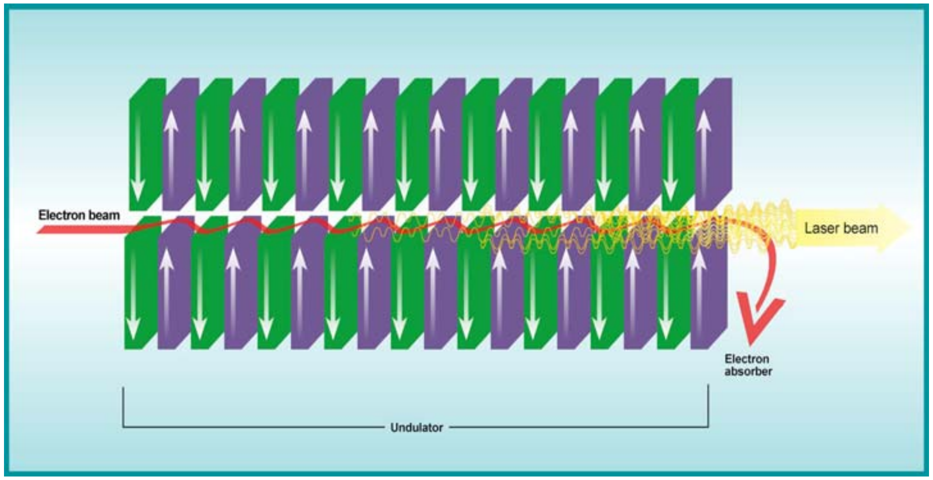
(1) OSCILLATOR

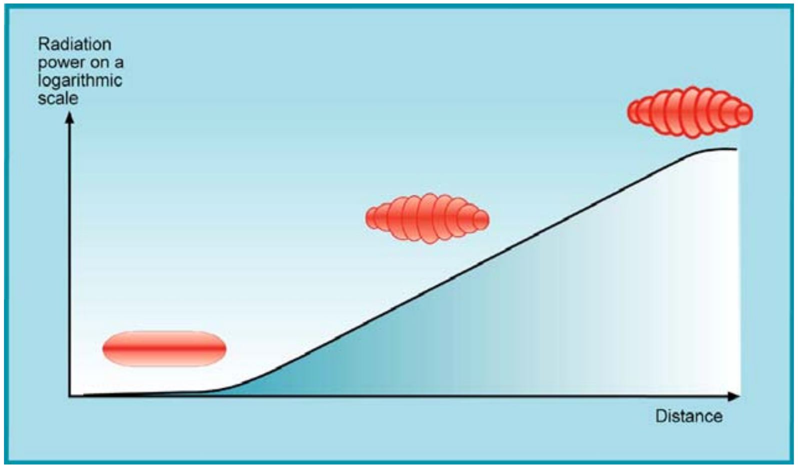


- FEL radiation builds up in optical cavity
- Bunch passage coincides with radiation pulse
- Currently limited in wavelength >~175 nm by availability of mirrors
  - Some advanced oscillator schemes proposed
    - Avoid mirrors
    - Shorter wavelengths with narrow-band reflectors

FEL configurations

(2) SINGLE-PASS SASE FEL

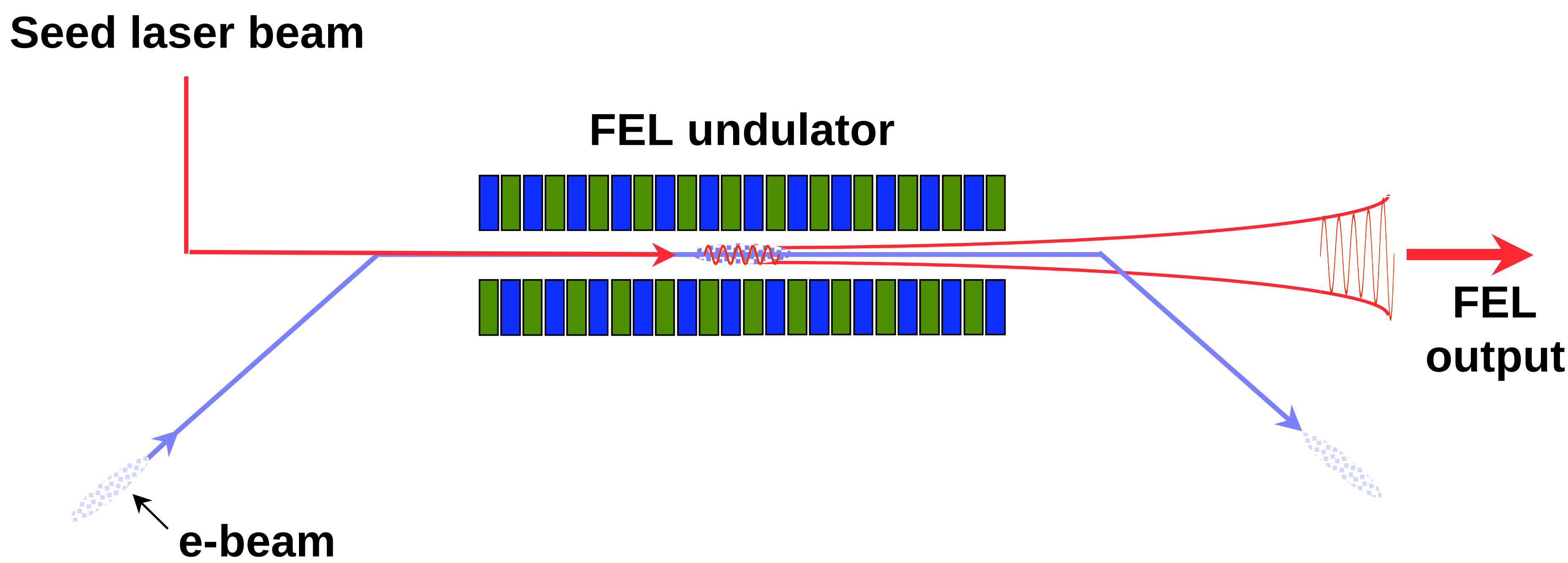




- **FEL process builds up in a single-pass of an undulator, from noise within the FEL gain bandwidth**
- **Avoids use of mirrors**
- **Allows shorter wavelengths**

FEL configurations

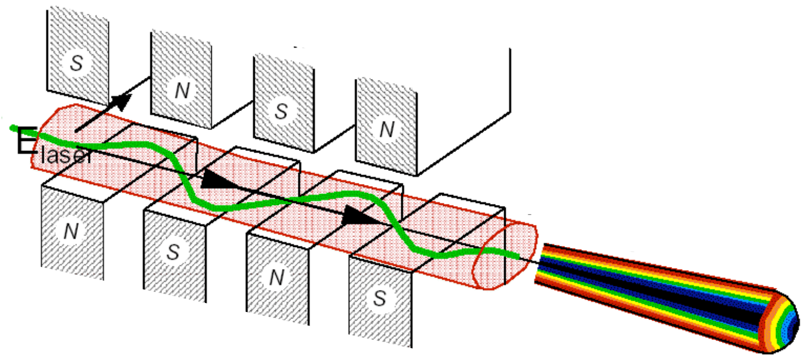
(3) SEEDED FEL

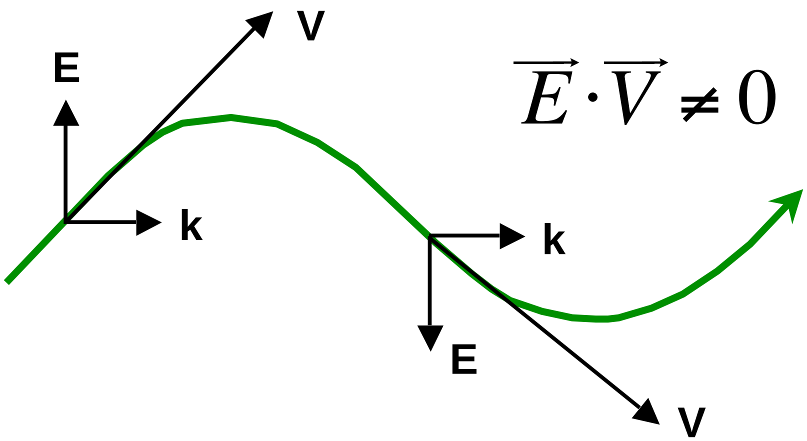


- Laser and undulator tuned to the same wavelength
- The laser introduces bunching into the electron beam
  - Seeds the FEL process
  - FEL output does not grow from noise
- Can also seed oscillators

Optical manipulations

LASER PULSE USED TO MANIPULATE ELECTRON BEAM ENERGY





$$\vec{E} \cdot \vec{V} \neq 0$$

Wiggler period

Undulator parameter

$$\lambda_w = 2\gamma^2 \lambda_L / (1 + \frac{K^2}{2})$$

Laser wavelength

- **Electron beam couples to E-field of laser when co-propagating in an undulator**
- **Over one undulator period, the electron is delayed with respect to the light by one optical wavelength**

Optical manipulations

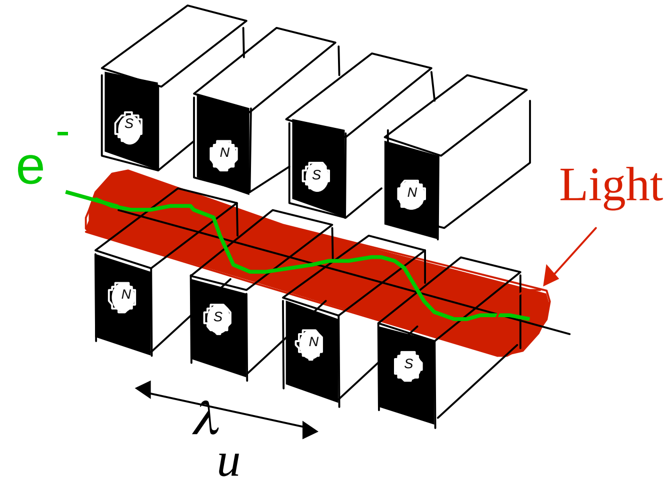
ESTIMATE OF THE ENERGY MODULATION INTRODUCED BY A LASER BEAM

Field energy in the far field including laser and undulator light

Laser field

Undulator spontaneous emission

$$A \,\square\, \iint \left| E_L(\omega,r) + E_R(\omega,r) \right|^2 dS d\omega$$



$$A = A_L + A_R + 2\sqrt{A_L A_R \frac{\Delta\omega_L}{\Delta\omega_R}} \cos(\varphi)$$

$$\Delta\omega_R \geq \Delta\omega_L$$

Electron phase relative to laser wave

$$\Delta E(\varphi) = 2\sqrt{A_L A_R \frac{\Delta\omega_L}{\Delta\omega_R}} \cos(\varphi)$$

$$\Delta\omega_L \cong \frac{1}{N_L} \qquad \Delta\omega_R \cong \frac{1}{N_U}$$

 # optical periods

 # undulator periods

Optical manipulations

NUMERIC EXAMPLE

$$\Delta E(\varphi) = 2\sqrt{A_L A_R \frac{\Delta\omega_L}{\Delta\omega_R}}\cos(\varphi)$$

$$A_R \approx \pi\alpha\hbar\omega_R$$

$$\omega_R = \omega_L$$

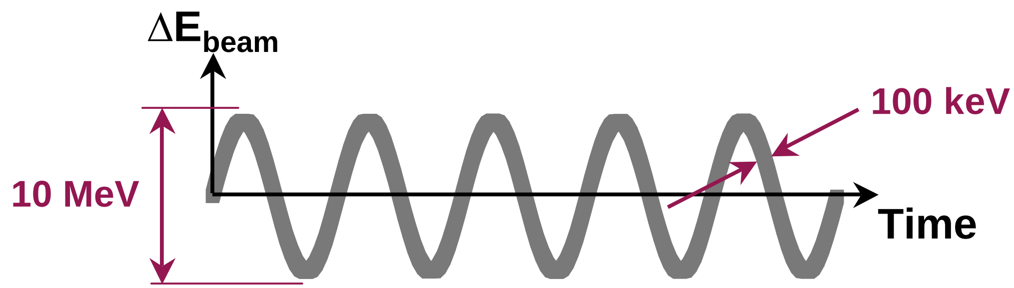
$$\Delta\omega_R = \Delta\omega_L$$

$$\left.\begin{aligned}\hbar\omega_L &= 4.5eV \\ A_L &= 10\mu J\end{aligned}\right\}$$

3rd harmonic Ti:sapphire
100 MW, 100 fs pulse

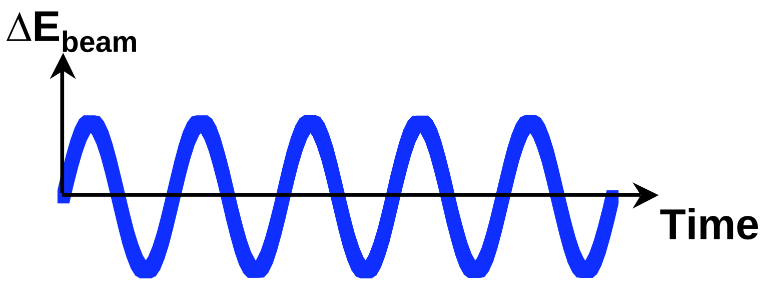
$$|\Delta E| = 5MeV$$

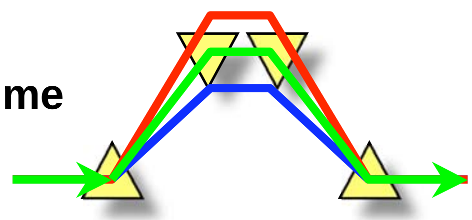
Compare with ~0.1 MeV uncorrelated energy spread



Bunching of the electron beam

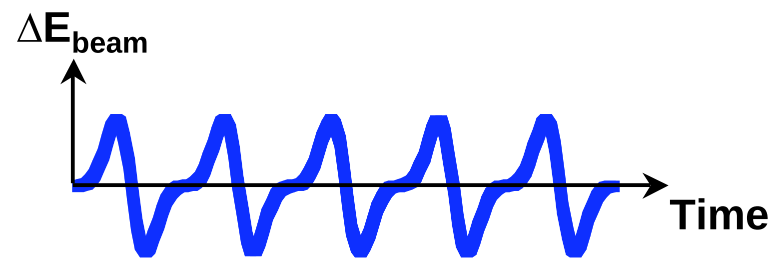
ENERGY MODULATION FOLLOWED BY DISPERIVE SECTION



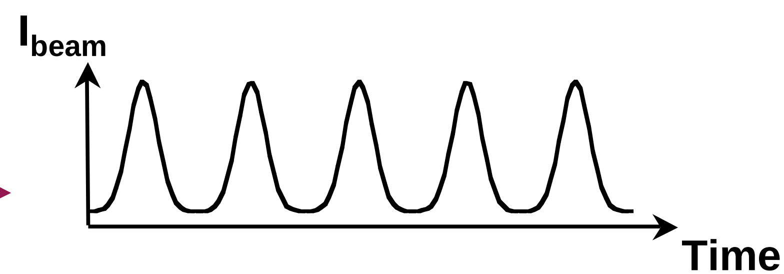


Energy-dependent path length

$$\Delta z = R_{56} \frac{\Delta E}{E}$$

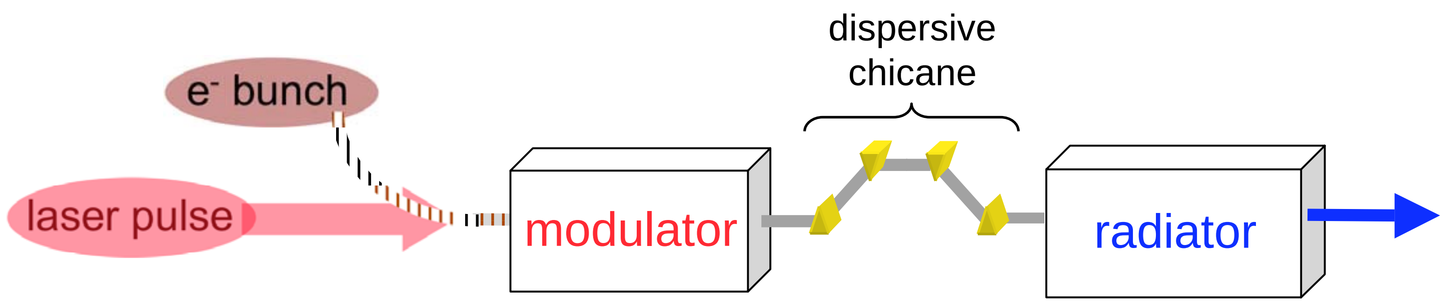


Induced current modulation in the electron beam



High-gain harmonic generation (HGHG)

DEMONSTRATED AT BROOKHAVEN SDL

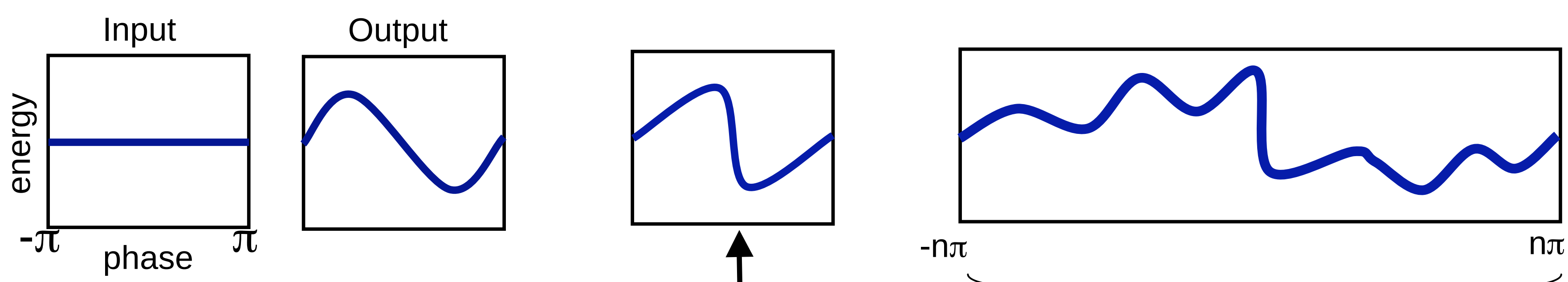


$$\lambda_{laser} = \lambda_{x-ray}^{modulator} = \frac{\lambda_{undulator}^{modulator}}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

$$\lambda_{x-ray}^{radiator} = \frac{\lambda_{x-ray}^{modulator}}{n} = \frac{\lambda_{undulator}^{radiator}}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

n ~ a few-several

e$^-$ beam phase space:



Laser modulates e-beam energy

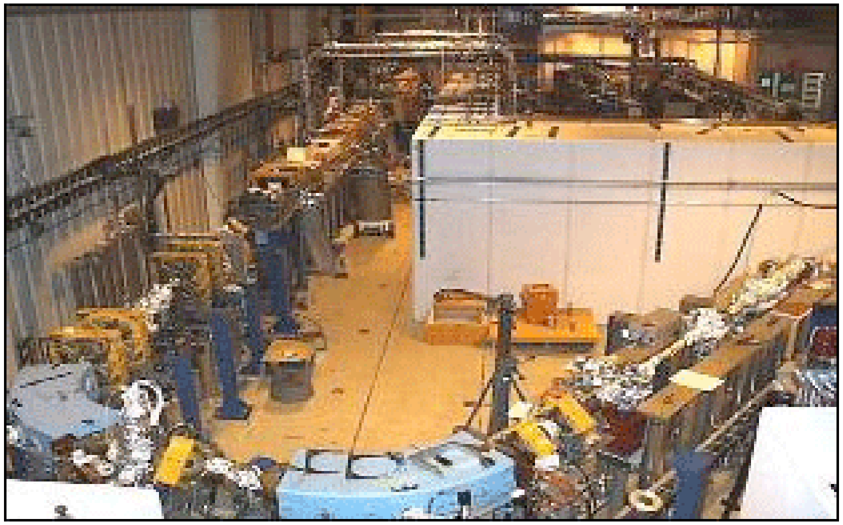
Bunched beam radiates strongly at harmonic in a downstream undulator resonant at λ_{laser}/n

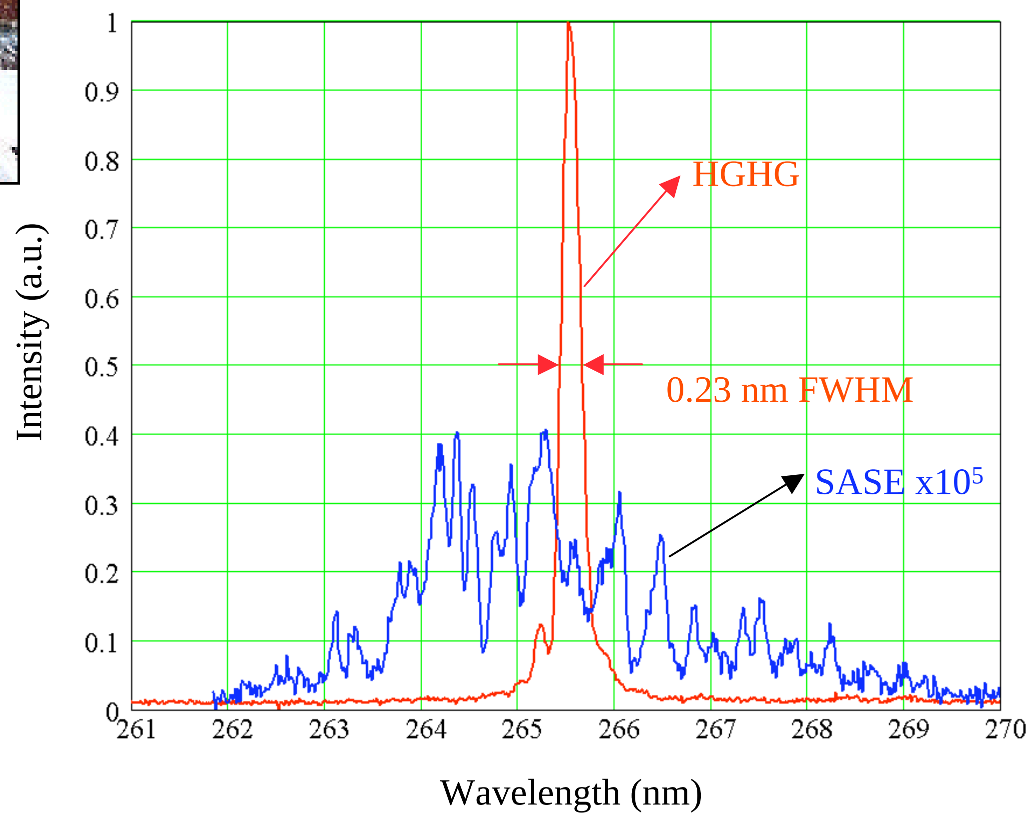
Dispersive section introduces bunching

L.-H. Yu et al, Science 289 932-934 (2000)

High-gain harmonic generation (HGHG)

800-266 nm DEMONSTRATED AT BROOKHAVEN SDL



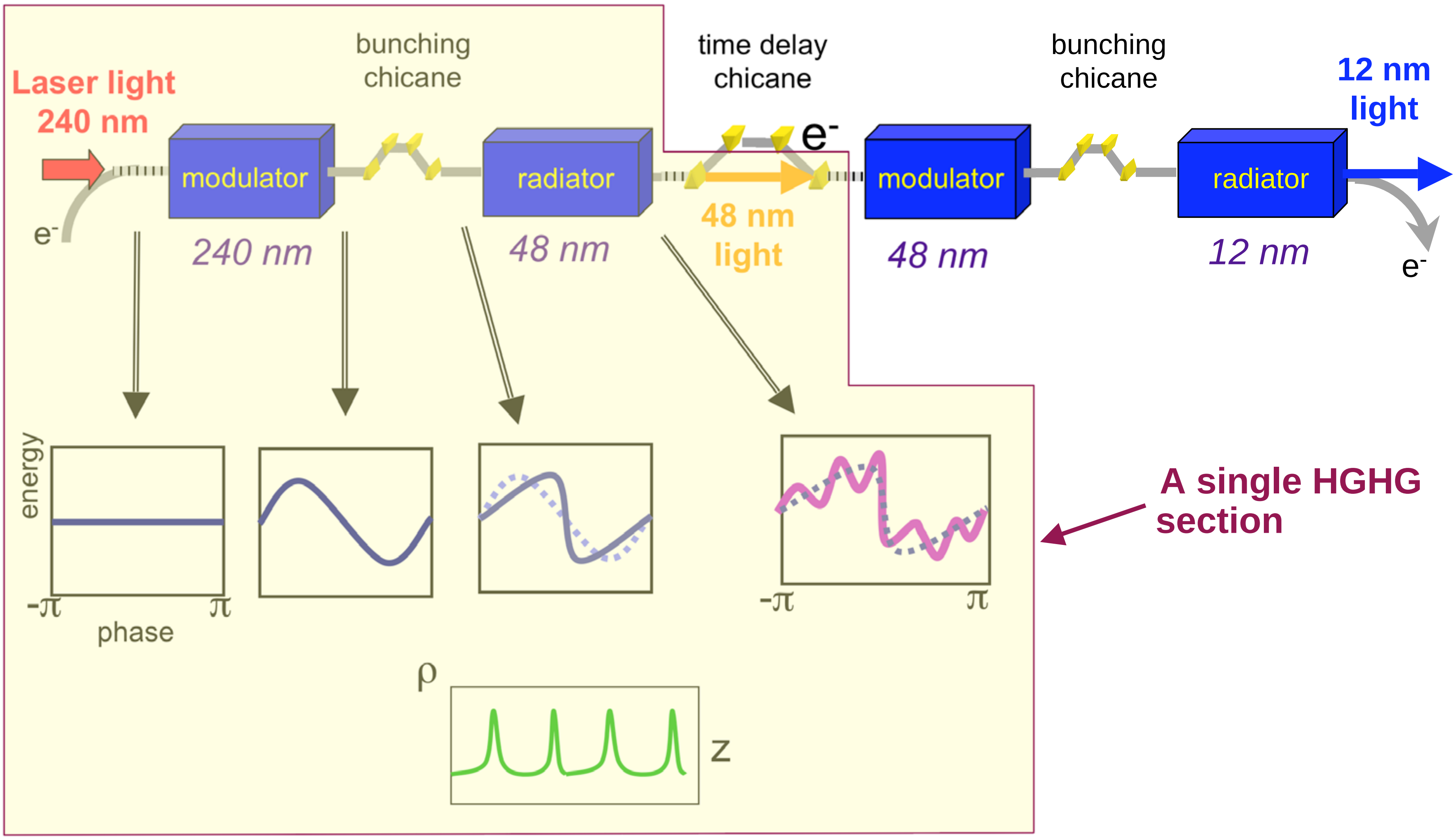


- **Spectrum of HGHG and unsaturated SASE at 266 nm under the same electron beam condition**
  - **Note SASE at saturation would still be order of magnitude lower intensity**

L.-H. Yu et al, Phys. Rev. Let. Vol 91, No. 7, (2003)

FEL configurations

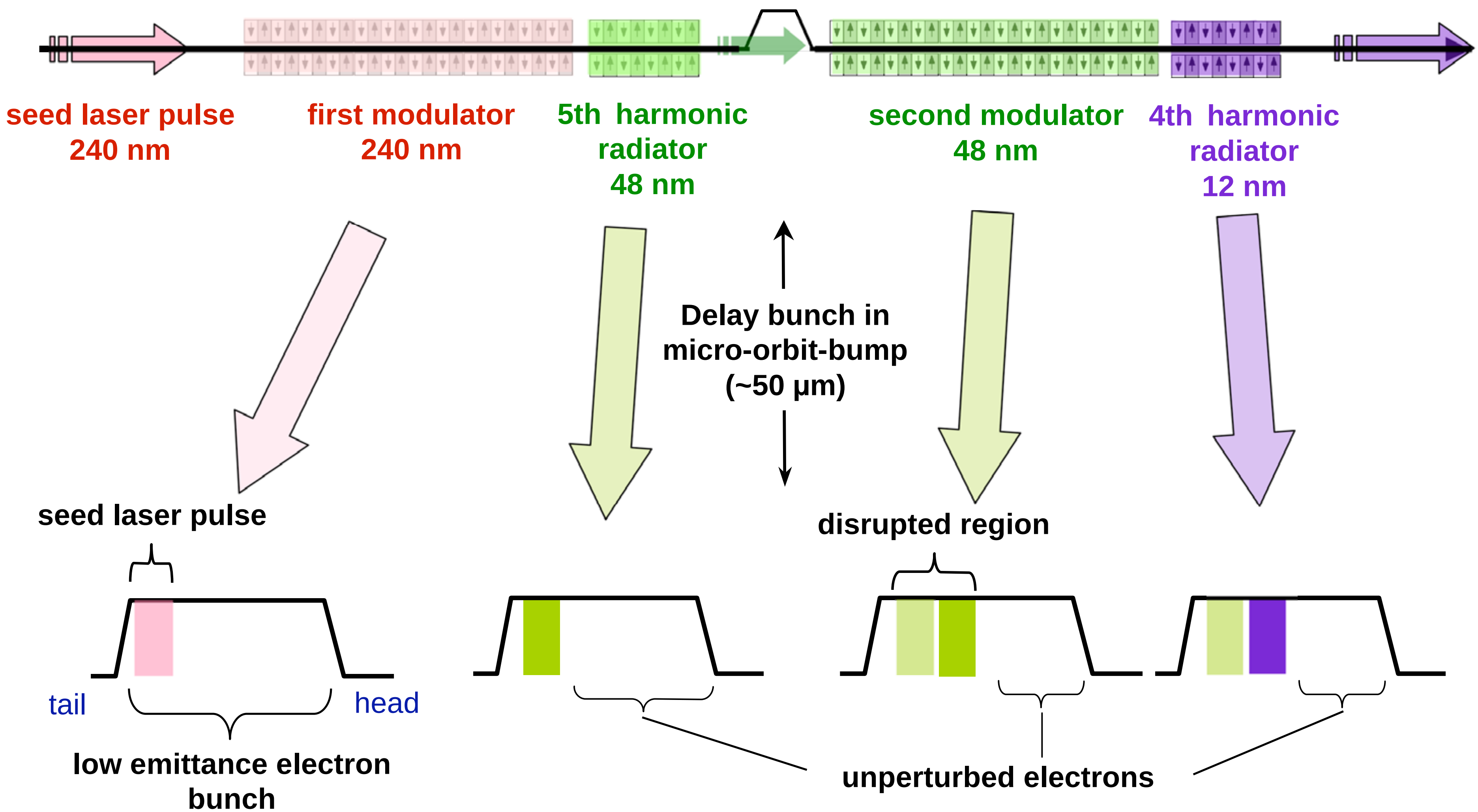
(4) HARMONIC CASCADE REACHES SHORTER WAVELENGTHS



Csonka 1980; Kincaid 1980; Bonifacio 1990; L.-H. Yu 1990

FEL configurations

“FRESH BUNCH” HARMONIC CASCADE CONFIGURATION



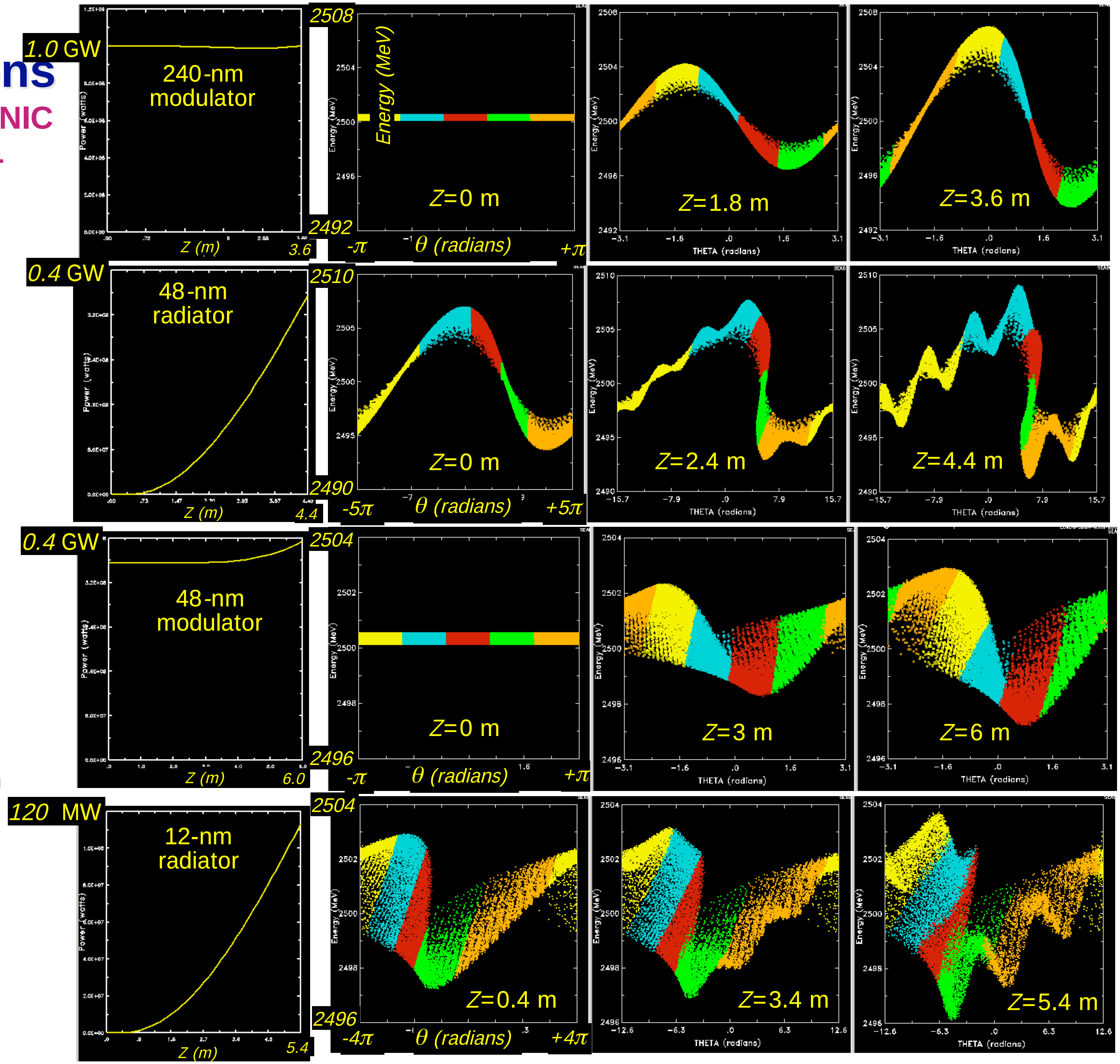
Csonka 1980; Kincaid 1980; Bonifacio 1990; L.-H. Yu 1990

FEL configurations

SEEDED HARMONIC CASCADE FEL SIMULATIONS

At each modulator, radiation interacts with "virgin" e^-

- **At each harmonic upshift $\lambda \Rightarrow \lambda/n$ (modulator to radiator), macro-particle phase multiplied by *n***
- **Bunching effects of dispersive section visible in change from *Z*=6 m in 48-nm modulator to *Z*=0.4m scatter plot in 12-nm radiator**



Optical manipulations

ANOTHER EXAMPLE

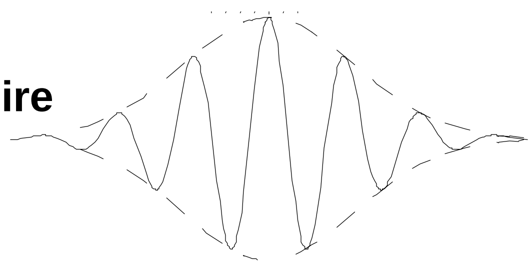
$$\Delta E(\varphi) = 2\sqrt{A_L A_R \frac{\Delta\omega_L}{\Delta\omega_R}}\cos(\varphi)$$

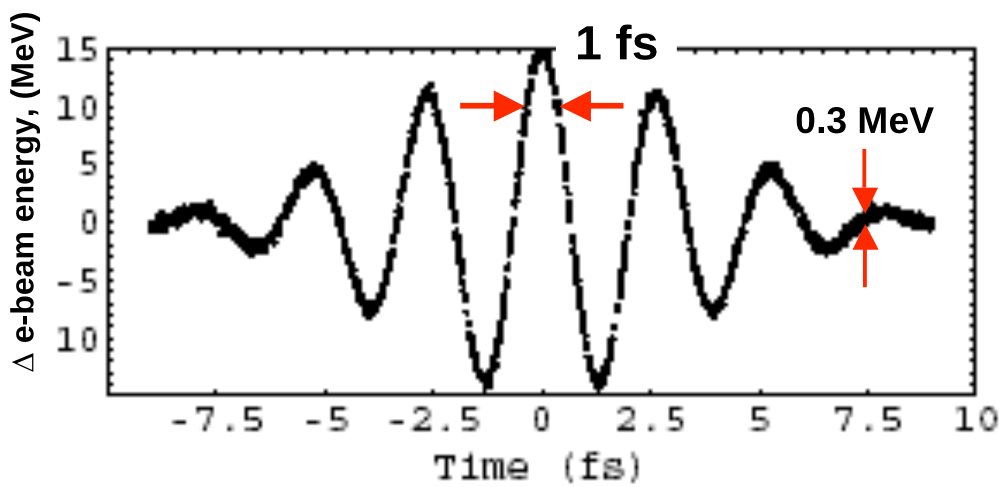
$$A_R \approx \pi\alpha\hbar\omega_R$$

$$\omega_R = \omega_L$$

$$\Delta\omega_R = \Delta\omega_L$$

Few-cycle Ti:sapphire seed laser





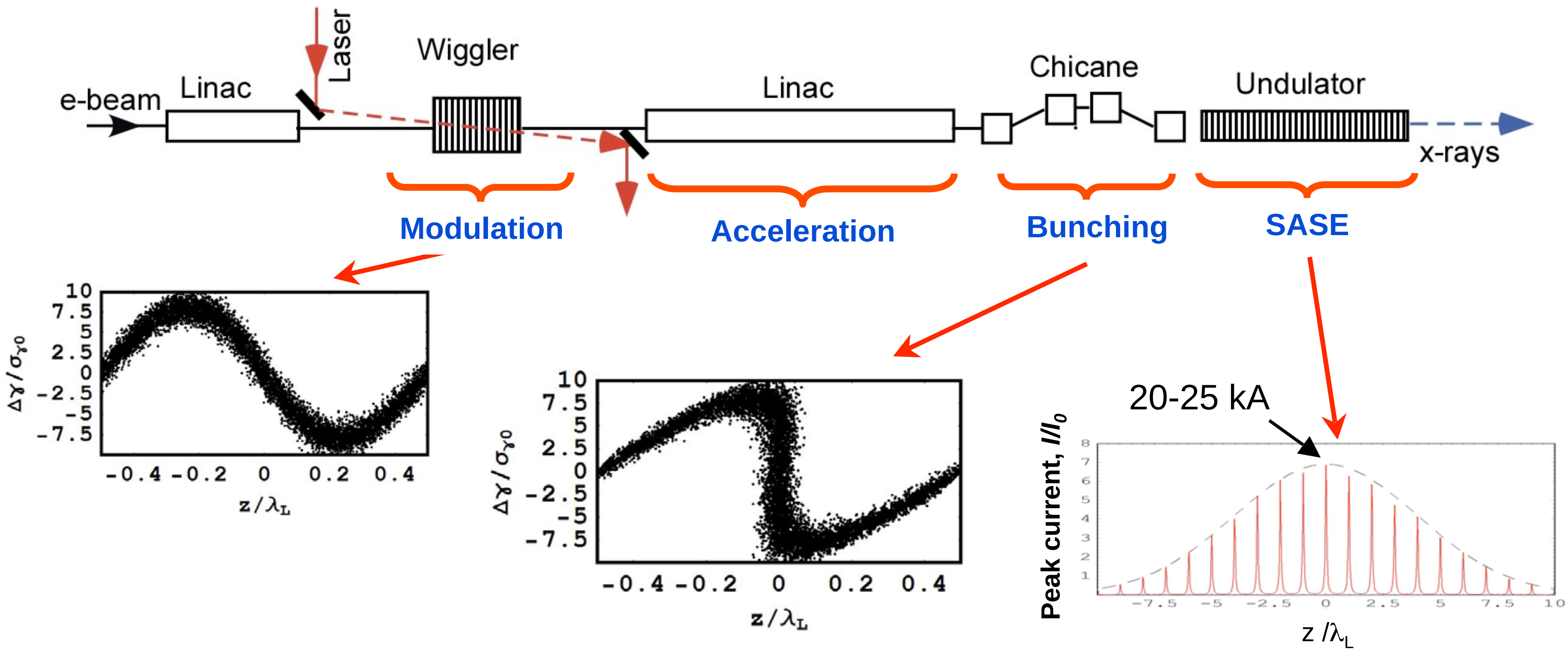
$$\hbar\omega_L = 1.5eV$$

$$A_L = 100\mu J$$

$$|\Delta E| = 10MeV$$

Enhanced-SASE (ESASE)

(5) OPTICAL MANIPULATIONS IMPART SOME CONTROL OF SASE

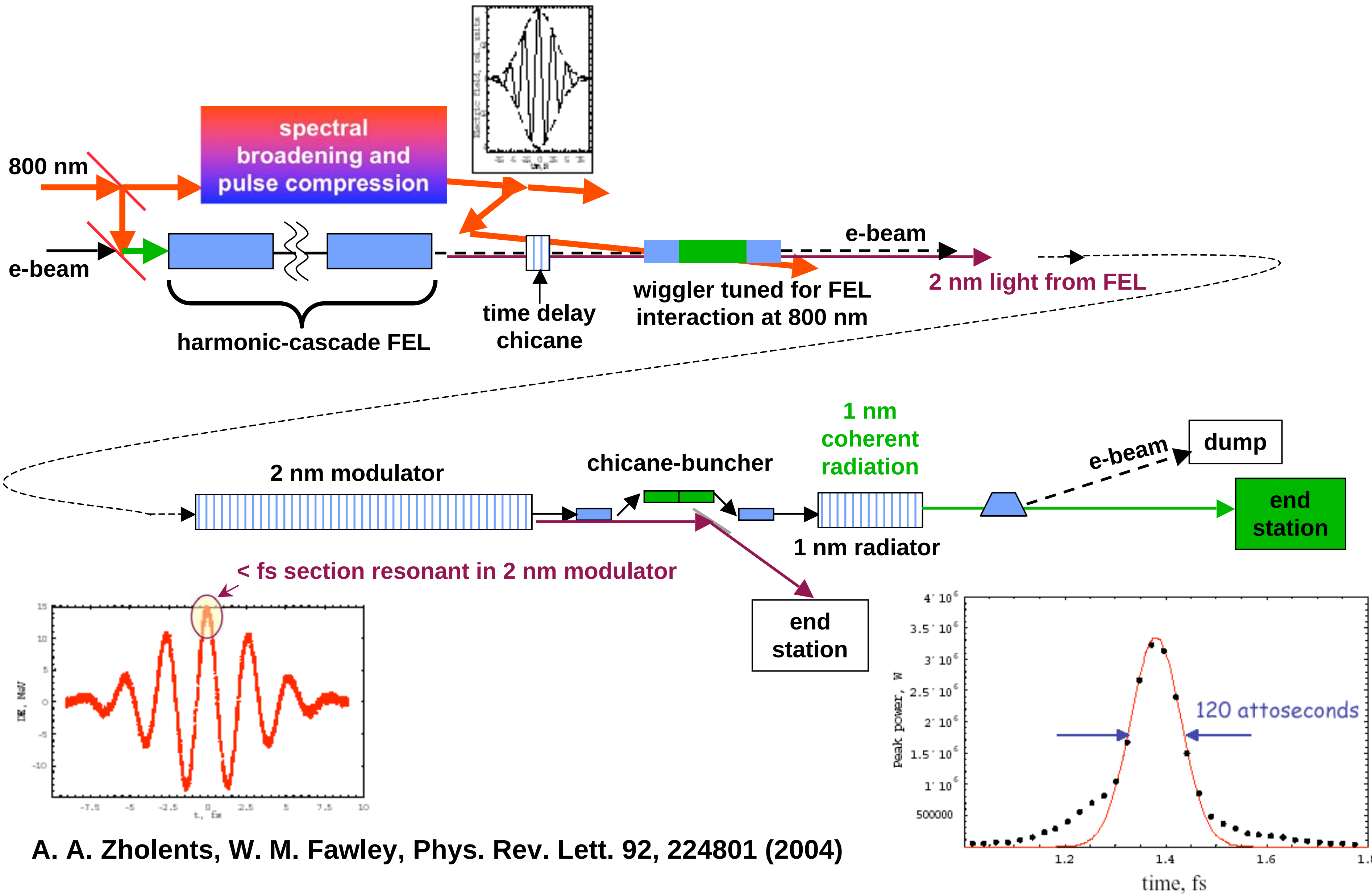


- Precise synchronization of the x-ray output with the modulating laser
- Variable output pulse train duration by adjusting the modulating laser pulse
- Increased peak output power
- Shorter x-ray undulator length to achieve saturation

A. A. Zholents, Phys. Rev. ST Accel. Beams 8, 040701 (2005)

FEL configurations

(6) ATTOSECOND PULSES FROM A SEEDED HARMONIC CASCADE

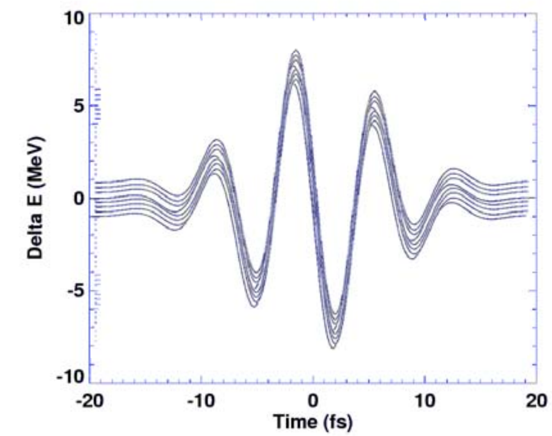


A. A. Zholents, W. M. Fawley, Phys. Rev. Lett. 92, 224801 (2004)

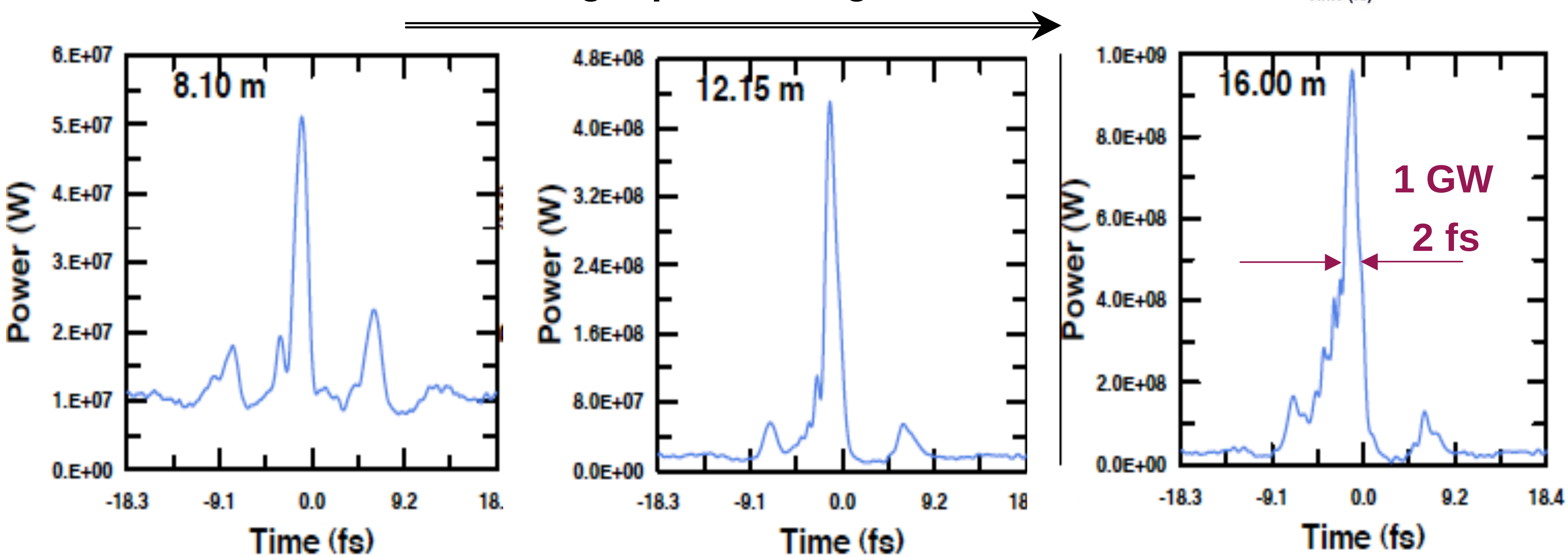
FEL configurations

(7) ULTRAFAST SASE PULSES AT LONGER WAVELENGTH

- **Again, a few-cycle optical pulse modulates electron beam**
  - **This time there is no compression following the modulation**
  - **Take advantage of the energy chirp in the bunch**
  - **Tapered FEL keeps the small section of appropriately chirped beam in resonance**



Evolution of a 26 nm wavelength pulse along undulator



E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, PRSTAB 9, 050702 (2006)

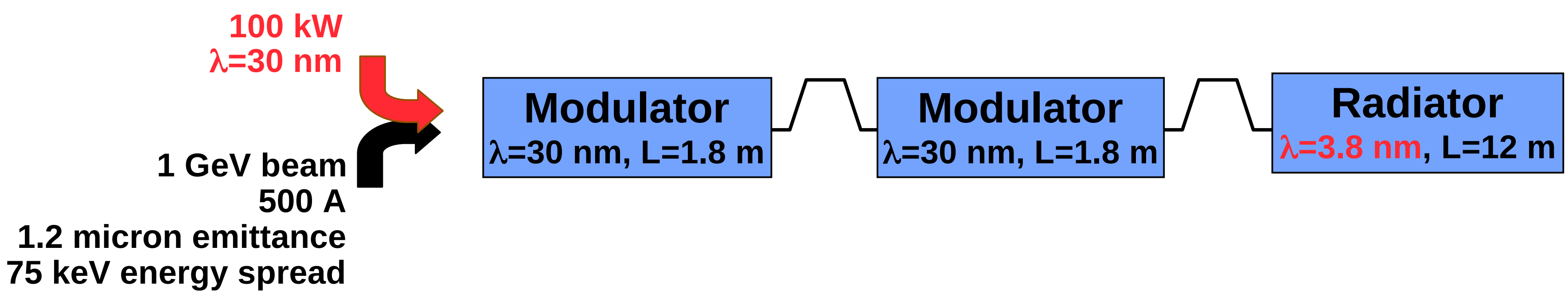
FEL configurations

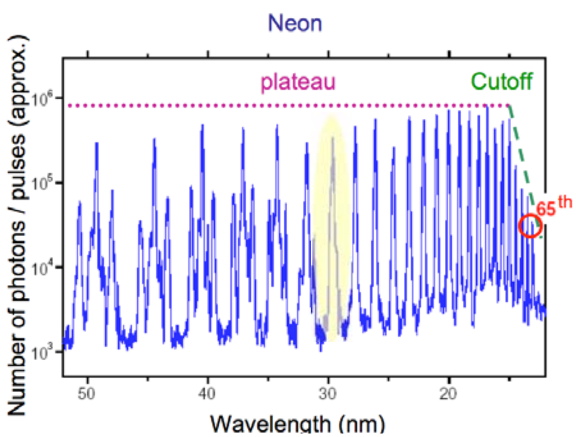
HHG LASER SEED

Example with seed at 30 nm, radiating in the water window

First stage amplifies low-power seed with “optical klystron”

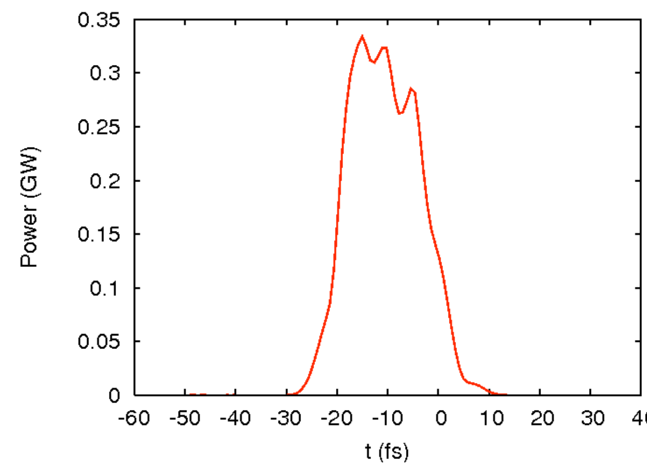
- **More initial bunching than could be practically achieved with a single modulator**
- **Output at 3.8 nm (8th harmonic)**





Lambert et al., FEL04

300 MW output at 3.8 nm (8th harmonic) from a 25 fs FWHM seed



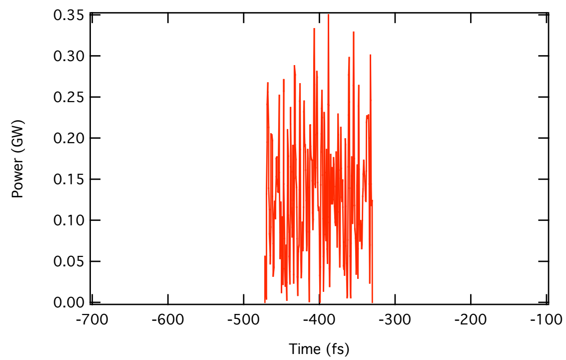
M. Gullans, J.S. Wurtele, G. Penn, A.A. Zholents, Optics Communications 274 (2007) 167-175

SASE & seeded FEL properties

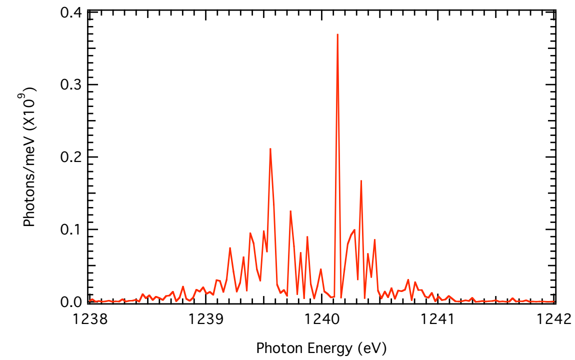
Pulse profile

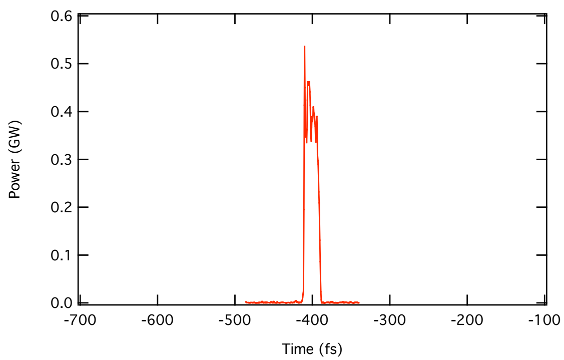
Fourier Transform

Spectrum

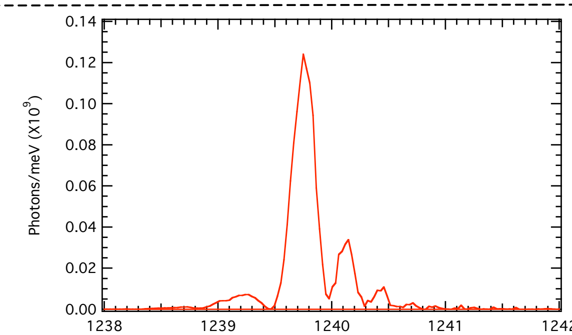


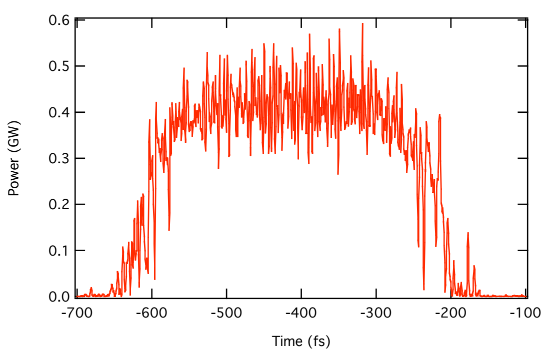
SASE





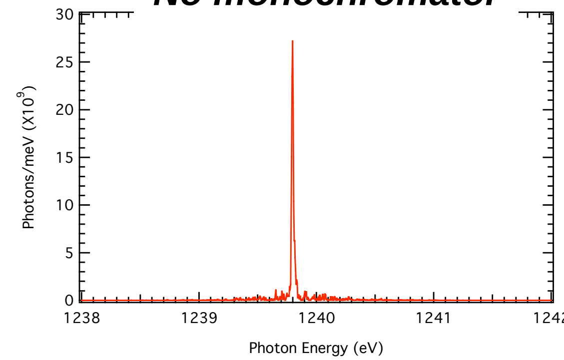
25 fs seed





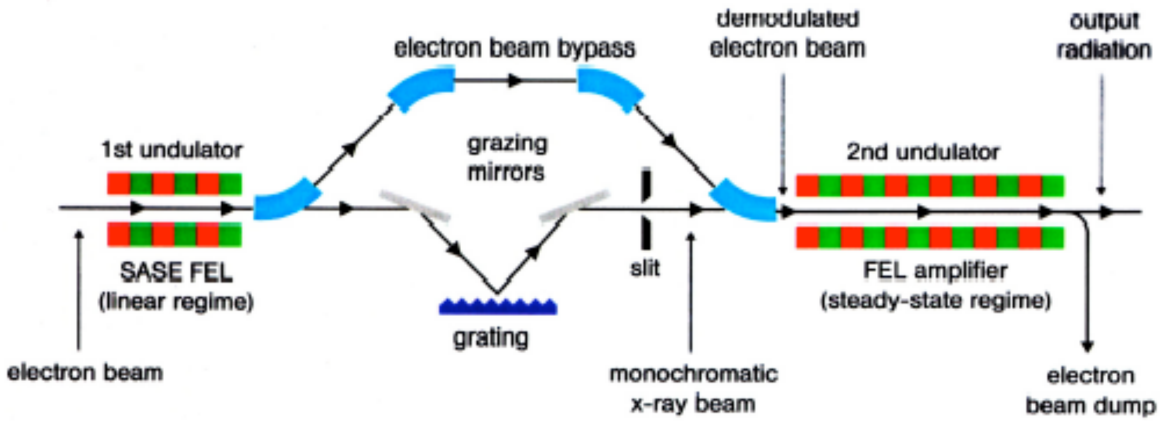
500 fs seed

No monochromator

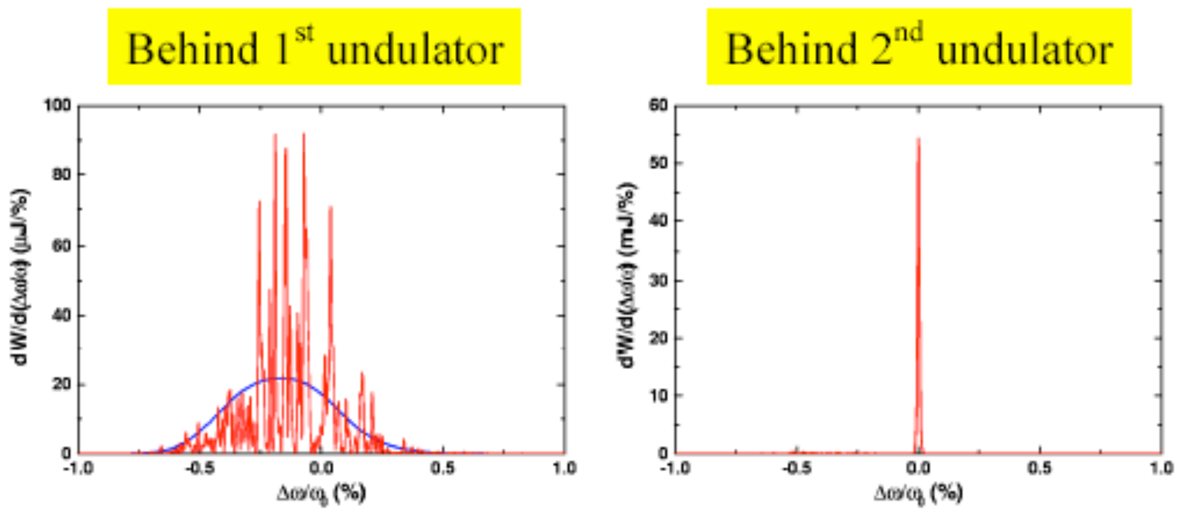


Electron beam is 1.5 GeV, energy spread 100 keV, 250 A current, 0.25 micron emittance; laser seed is 100 kW at 32 nm; undulator period 1 cm

Self-seeded SASE FEL



Spectral power distribution



Optical manipulations of the beam

ALLOW PRECISE CONTROL OF THE FEL OUTPUT

- ***Control of pulse duration***
- ***Control of pulse energy***
- ***Temporal coherence***
- ***Generation of shorter wavelengths in harmonic cascades***
- ***Precise synchronization***
- ***Shorter undulators to reach saturation***

Storage ring : Linac : Recirculating Linac

OPTIONS FOR ULTRAFAST VUV—SOFT X-RAY FEL FACILITIES

- **Storage rings**
  - Electron bunches ~100 ps duration (~10—100 A peak current), highly stable
  - Low-gain seeded FEL
    - Moderate peak brightness, short pulses
  - Repetition rate up to kHz

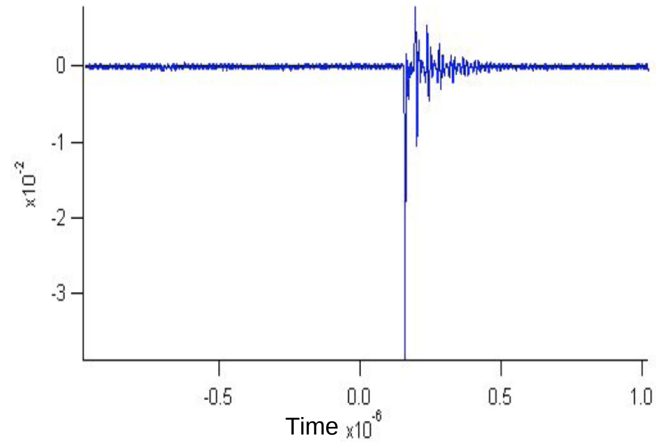
- **Single-pass linacs**
  - Electron bunches ~100—1000 fs (~100—1000 A peak current)
  - SASE or seeded FEL
    - High peak brightness, short pulses
  - Repetition rate
    - MHz-GHz CW for superconducting RF
    - ~100 Hz pulses for normal conducting RF

- **Recirculating linacs (including energy recovery linacs)**
  - Electron bunches ~100—1000 fs (~100—1000 A peak current)
  - Seeded FEL
    - High peak brightness, short pulses
  - Repetition rate up to GHz

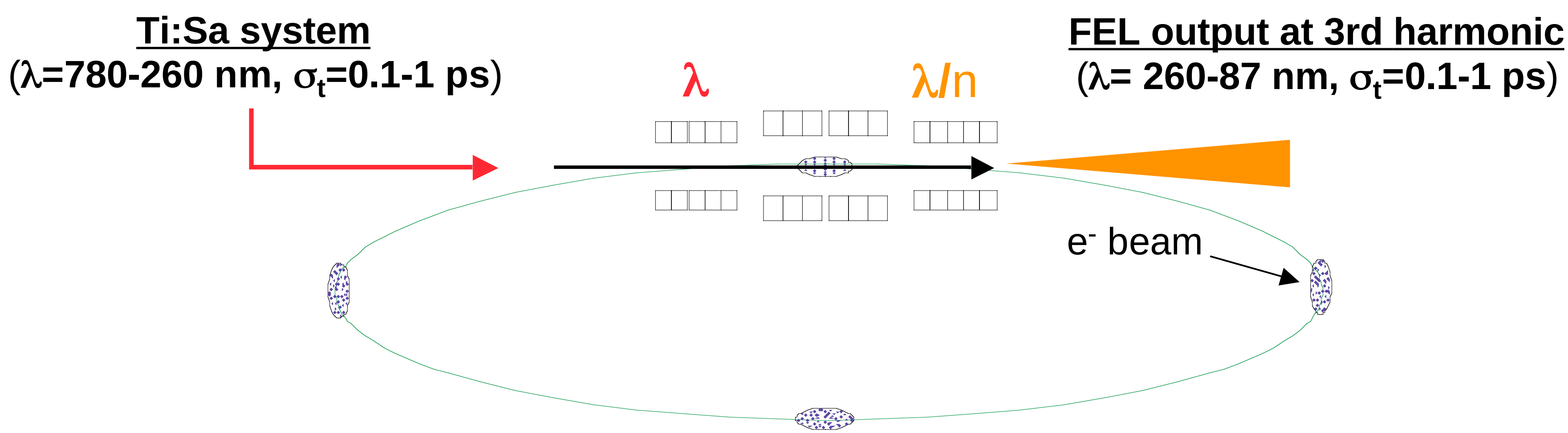
ELETTRA: storage ring, seeded FEL

SEEDED COHERENT HARMONIC (CHG) GENERATION IN A STORAGE RING FEL

- **780 nm -> 260 nm demonstrated at ELETTRA**
- **CHG 10^4 greater than spontaneous emission**
  - **1 kHz seed laser**
  - **1 GW seed power (2.5 mJ)**
  - **100 fs duration**
  - **2 mA bunch current**



- ***Proposal to seed at 260 nm***
  ⇒Coherent harmonic generation at 87 nm



G. DeNinno, Sincrotrone Trieste

Accelerating structures

SUPERCONDUCTING OR NORMAL CONDUCTING

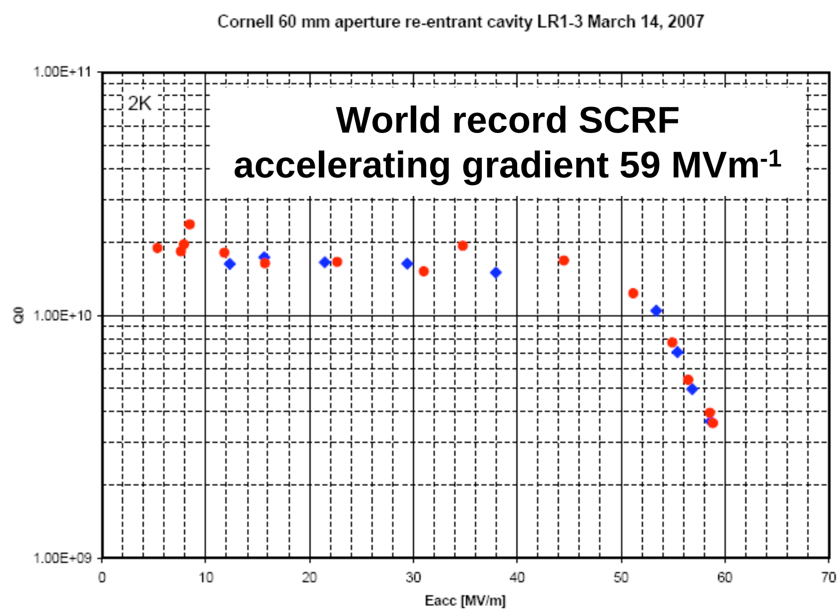
Normal conducting

- High accelerating gradient achievable at high frequency
  - >50 MVm^{-1} at 11 GHz
- High power dissipation in structure walls
  - Operate in pulsed mode for highest gradient
    - E.g. 120 Hz SLAC linac
    - ~ 20 MVm^{-1}

Superconducting

- Low frequency
  - Larger aperture
    - Reduced geometric wakefields
- Capability to operate with long pulses, or CW, with high gradient
  - High beam power
- Options for beam recirculation and energy recovery
- ~20 MVm^{-1} goal for CW operations

$$R_{BCS} \propto \frac{1}{T} f^2 e^{-\frac{a}{T}}$$

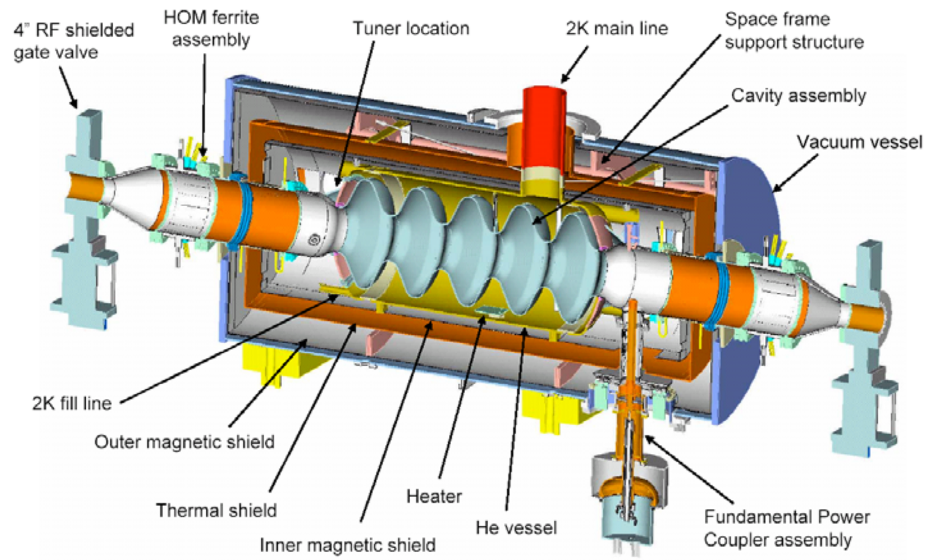


Accelerating structures

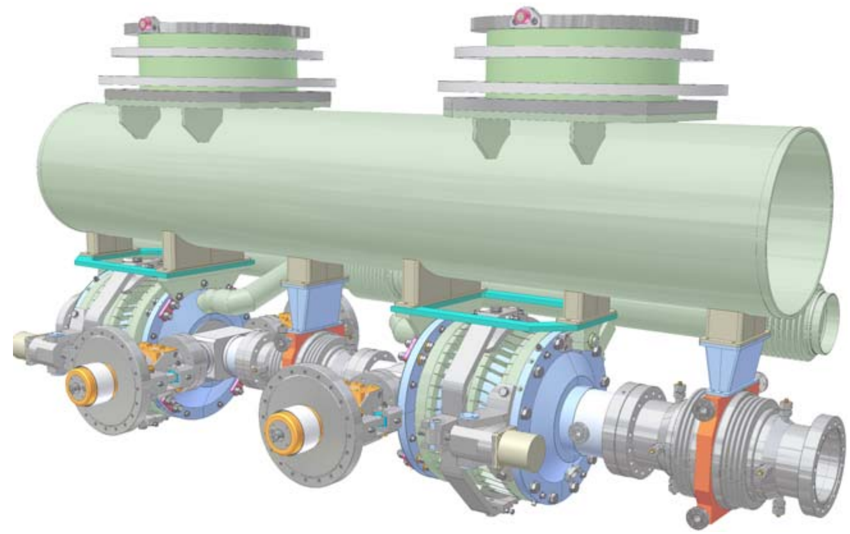
SUPERCONDUCTING RF TECHNOLOGY UNDER DEVELOPMENT

CW operation

- **High accelerating gradient**
  - **Goal ~20 MVm^{-1}**
- **High repetition rate**
- **High beam power**
- **Flexible bunch patterns**
- **Highly stable cavity fields**
  - **RF feedback and controls**
    - **Electron beam energy and timing stability**

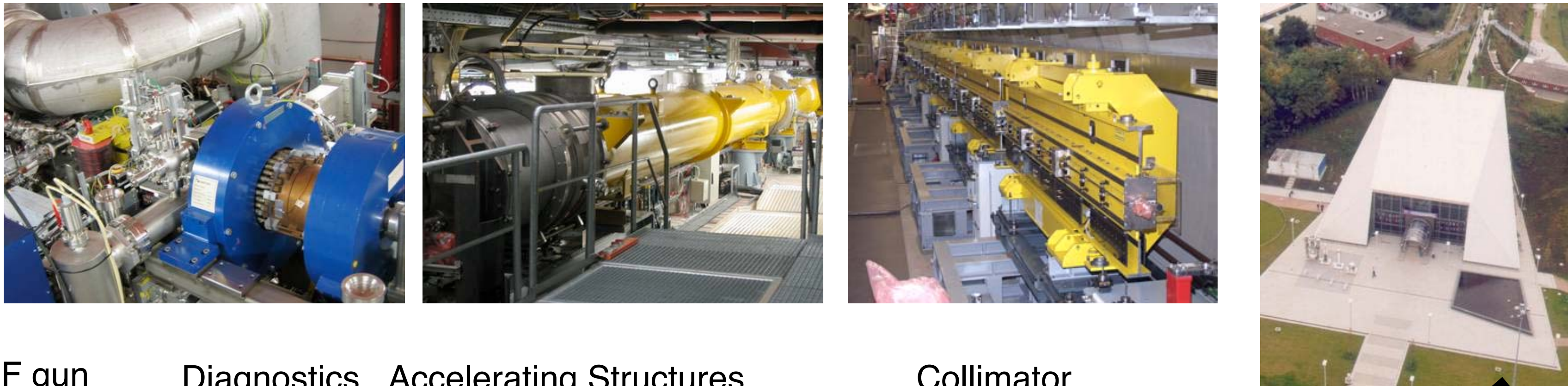


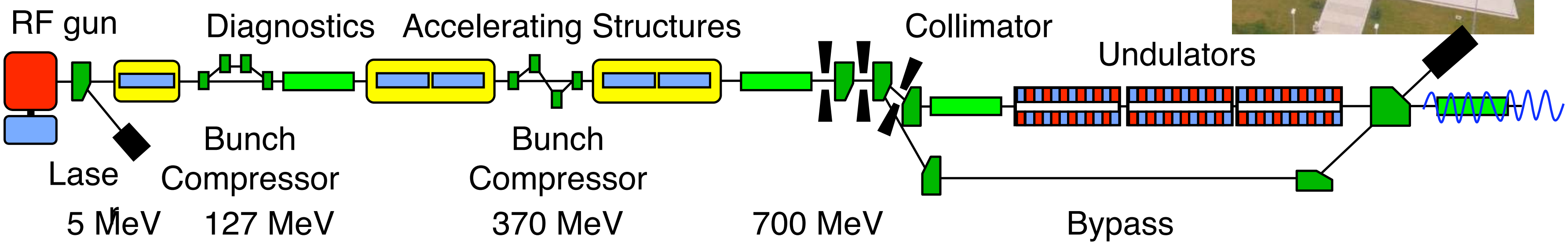
BNL 703 MHz cryomodule

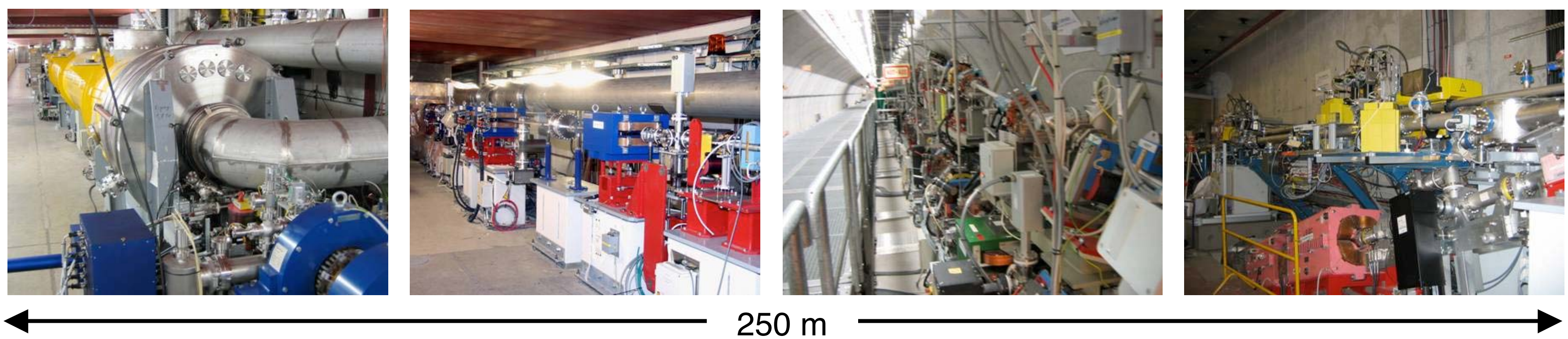


Cornell 1.3 GHz SCRF cryomodule components

FLASH: single-pass pulsed SCRF linac, SASE FEL







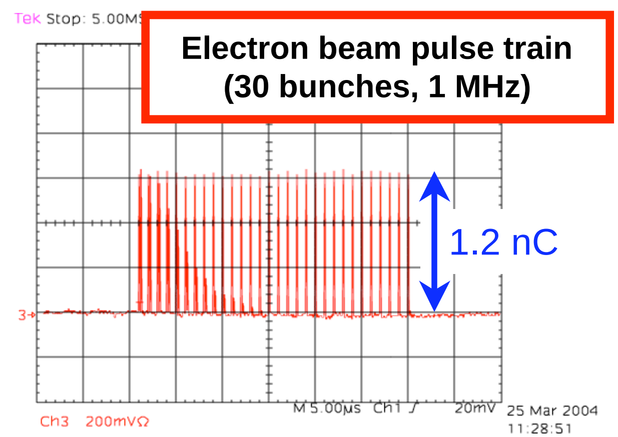
- **Bunch charge < 1 nC**
- **Emittance 2 – 4 mm-mrad**
- **Peak current 2.5 kA**
- **Energy spread 10^{-3}**

Courtesy Siegfried Schreiber, DESY

FLASH performance

- **Pulse trains of up to 800 μs duration**
- **Up to 10 Hz repetition rate (currently 5 Hz)**
- **Change bunch pattern on user request, by control of photocathode laser**
  - **Number of bunches**
  - **Different bunch frequencies: kHz,up to MHz**

- **Fixed gap undulators**
  - **B=0.48 T, K=1.23, λ_u=2.73 cm, gap=12 mm**
  - **Tuning by electron beam energy variation**
  - **374 – 720 MeV**
- **Wavelength range (fundamental): 13-47 nm**
- **Pulse energy average: 100 μJ**
- **Pulse energy peak: 200 μJ**
- **Peak power: ~ 5 GW**
- **Average power: > 100 mW**
- **Pulse duration (FWHM): 10-50 fs**
- **Spectral width (FWHM): 0.5-1 %**
- **Peak brilliance: 10^{29} – 10^{30} ph (s 0.1%BW mm mrad)$^{-1}$**



Upgrade to 1 GeV, to lase at 6.5 nm, in progress

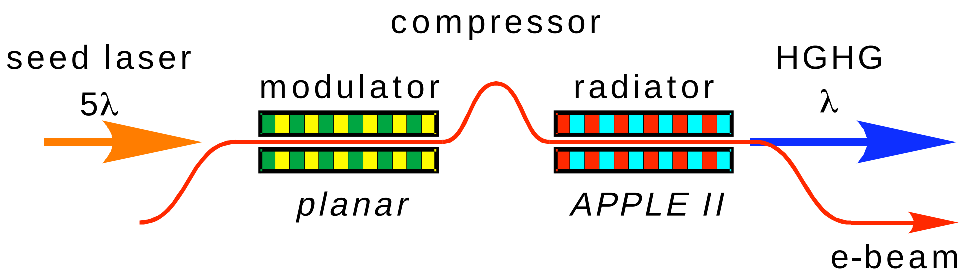
Courtesy Siegfried Schreiber, DESY


FERMI
@elettra
Linac Extension
Undulator Hall
Experimental Hall
Worlds first harmonic cascade seeded FEL facility
Under construction, first light late 2009

FERMI@elettra: pulsed normal conducting linac, seeded FEL

FEL-1: short (40-300 fs) photon pulses at 100-20 nm, peak power ~1 to >5 GW

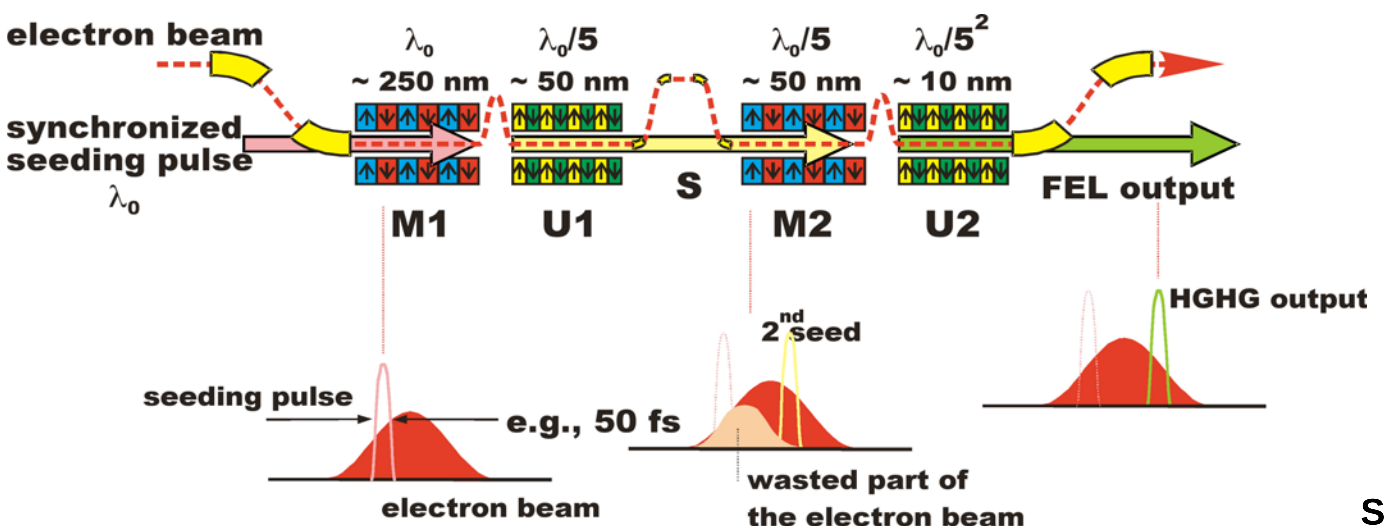
1-Stage HGHG



- **variable polarization output**
- **50 Hz rep rate**
- **1 micro-pulse per macro pulse**

FEL-2: narrow-band (< 5 meV) photon pulses at 40-10 nm, peak power ~ 0.5 to a few GW

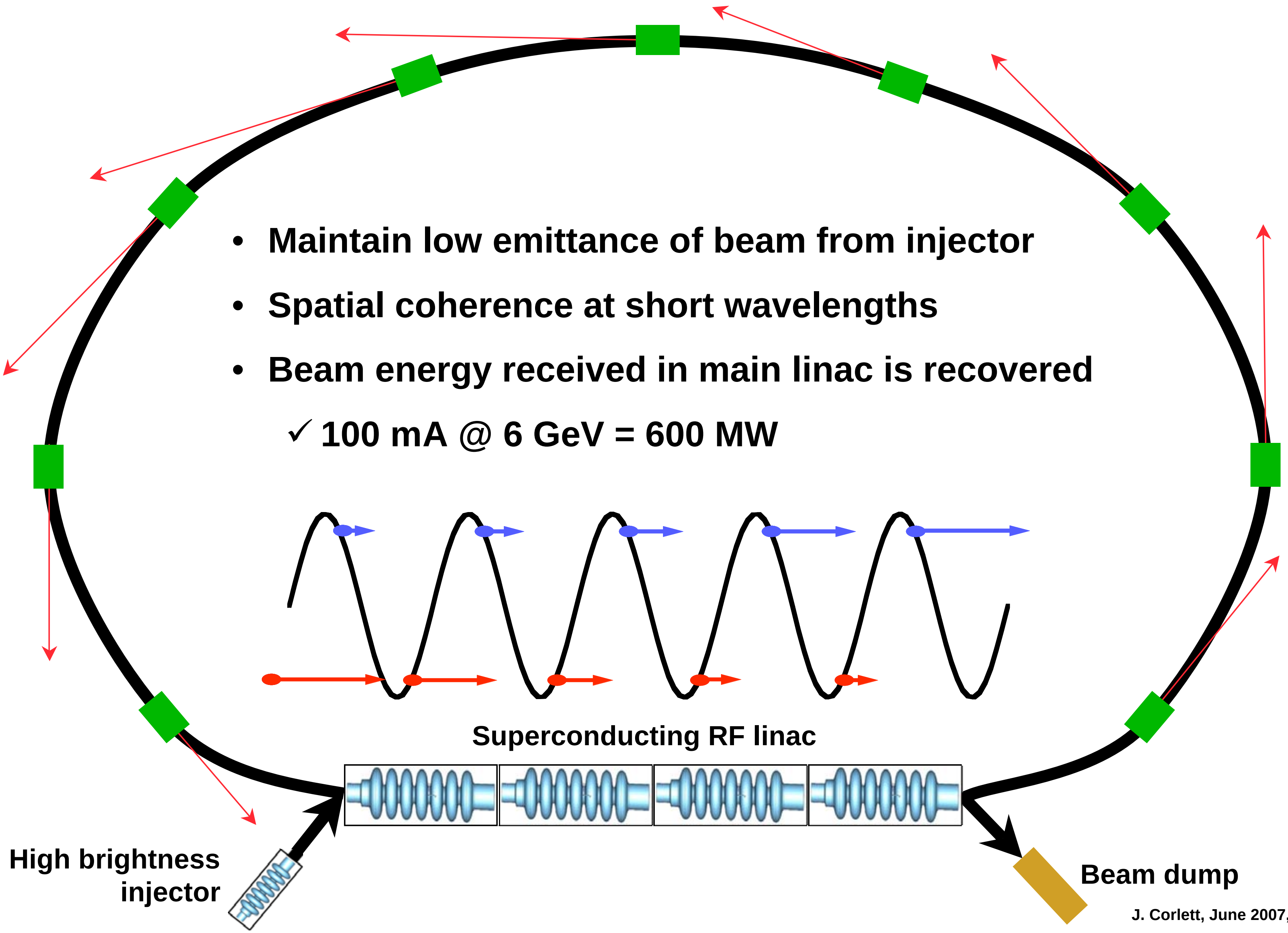
2-Stage cascade HGHG



S. Milton, Sincrotrone Trieste

Energy recovery linac (ERL)

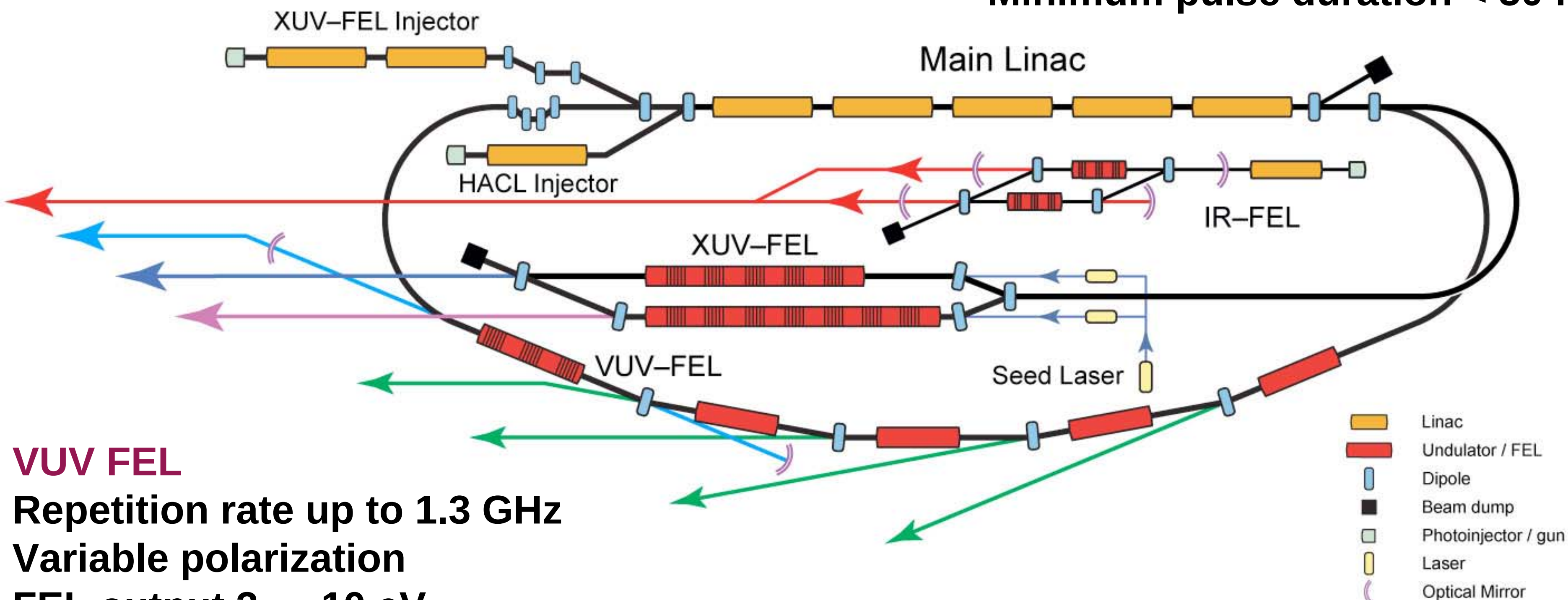
- Maintain low emittance of beam from injector
- Spatial coherence at short wavelengths
- Beam energy received in main linac is recovered
  - ✓ 100 mA @ 6 GeV = 600 MW



4GLS

PROPOSAL FOR ERL-BASED FACILITY

XUV FEL
HHG seeded
Repetition rate ~1 kHz
Variable polarization
FEL output up to 8 — 100 eV
Up to 400 μJ per pulse
Minimum pulse duration < 50 fs

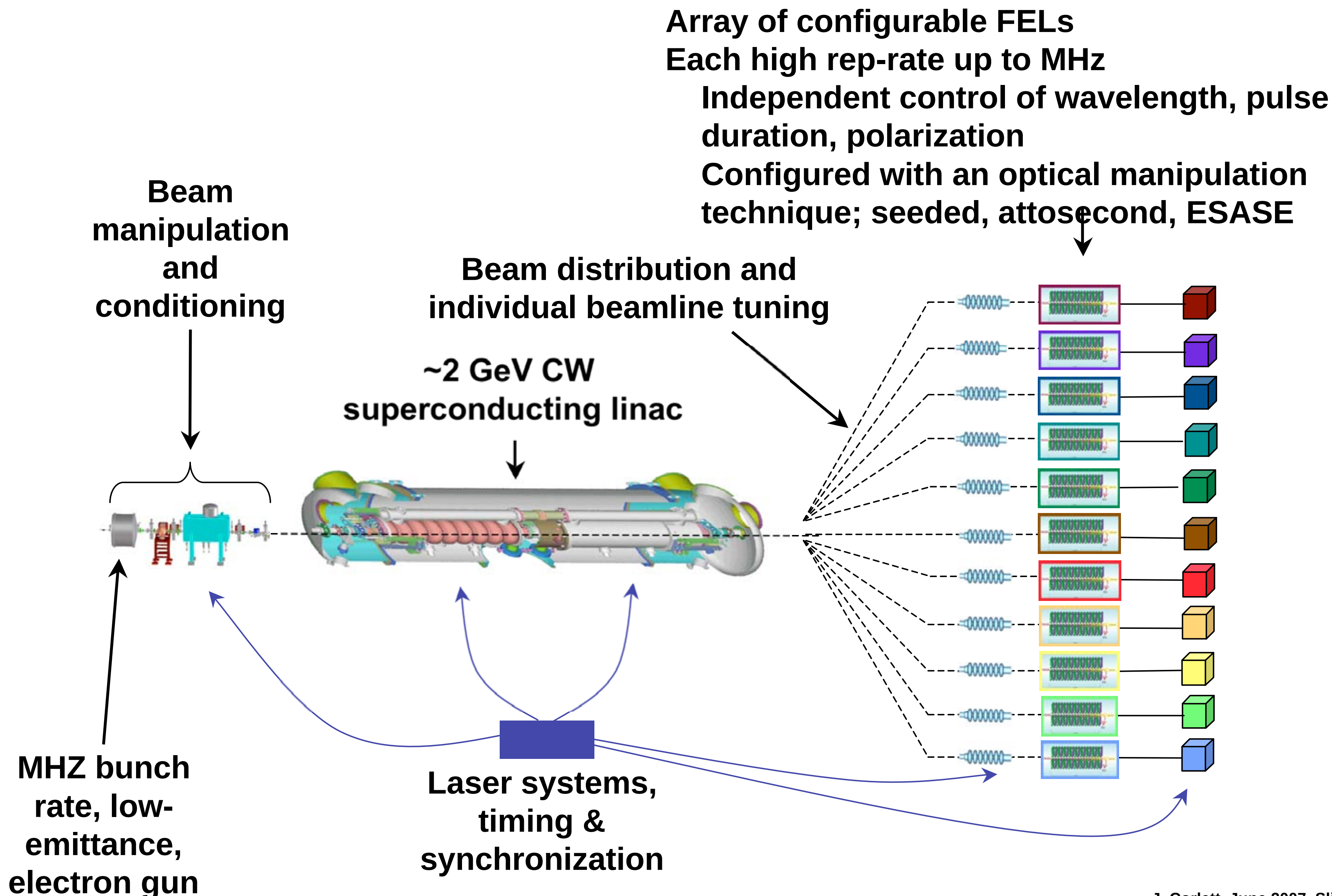


VUV FEL
Repetition rate up to 1.3 GHz
Variable polarization
FEL output 3 — 10 eV
Up to 70 μJ per pulse
Minimum pulse duration < 170 fs

J. Clarke, CCLRC Daresbury

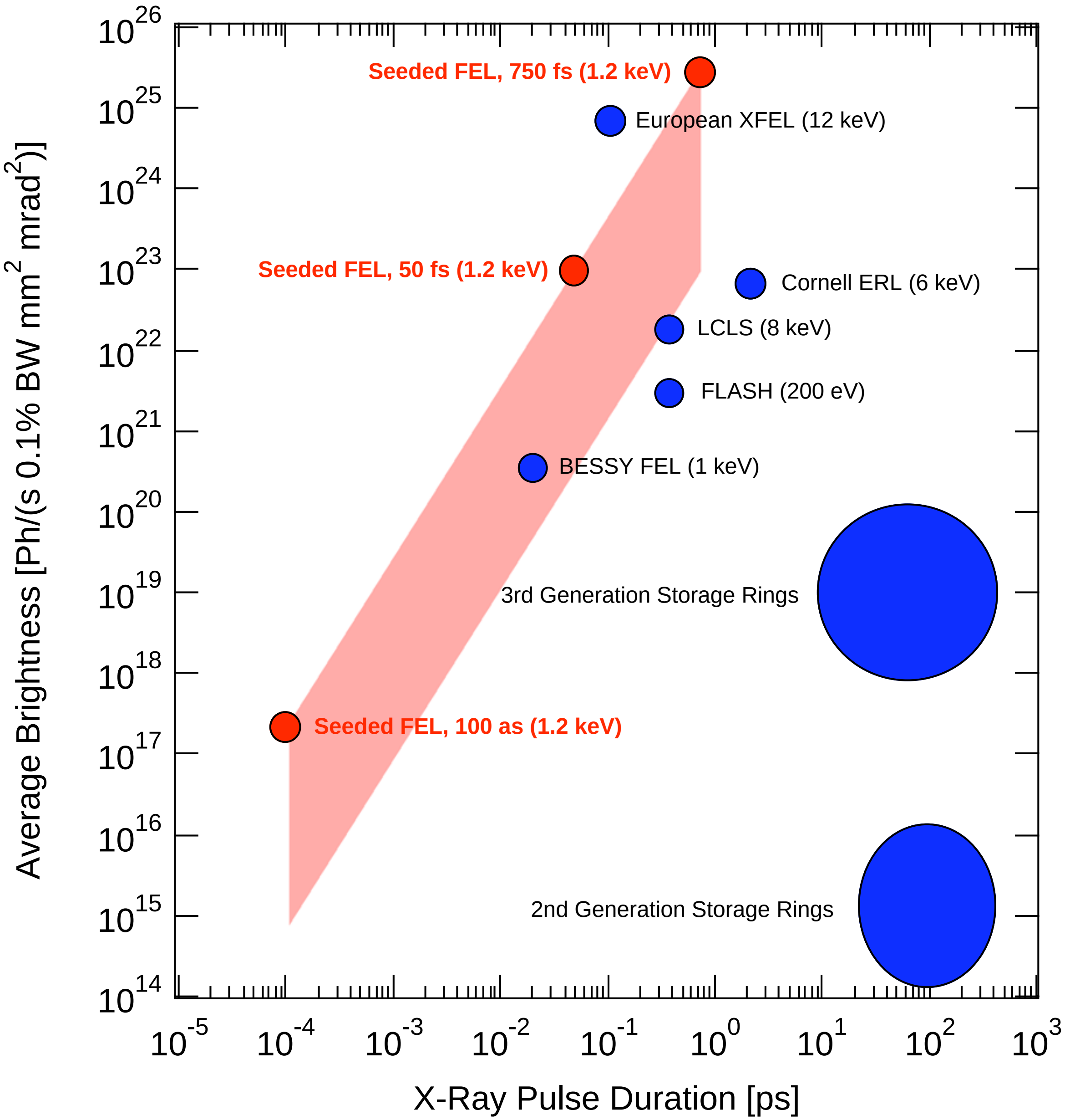
Concept for a future FEL facility at LBNL

A HIGH REP-RATE, SEEDED, VUV — SOFT X-RAY FEL ARRAY



High rep-rate seeded FEL performance

TIME-DOMAIN EXPERIMENTATION IN THE VUV-SXR REGIME
PARAMETER SPACE COMPLEMENTS OTHER FACILITIES



Accelerator R&D required for future FELs

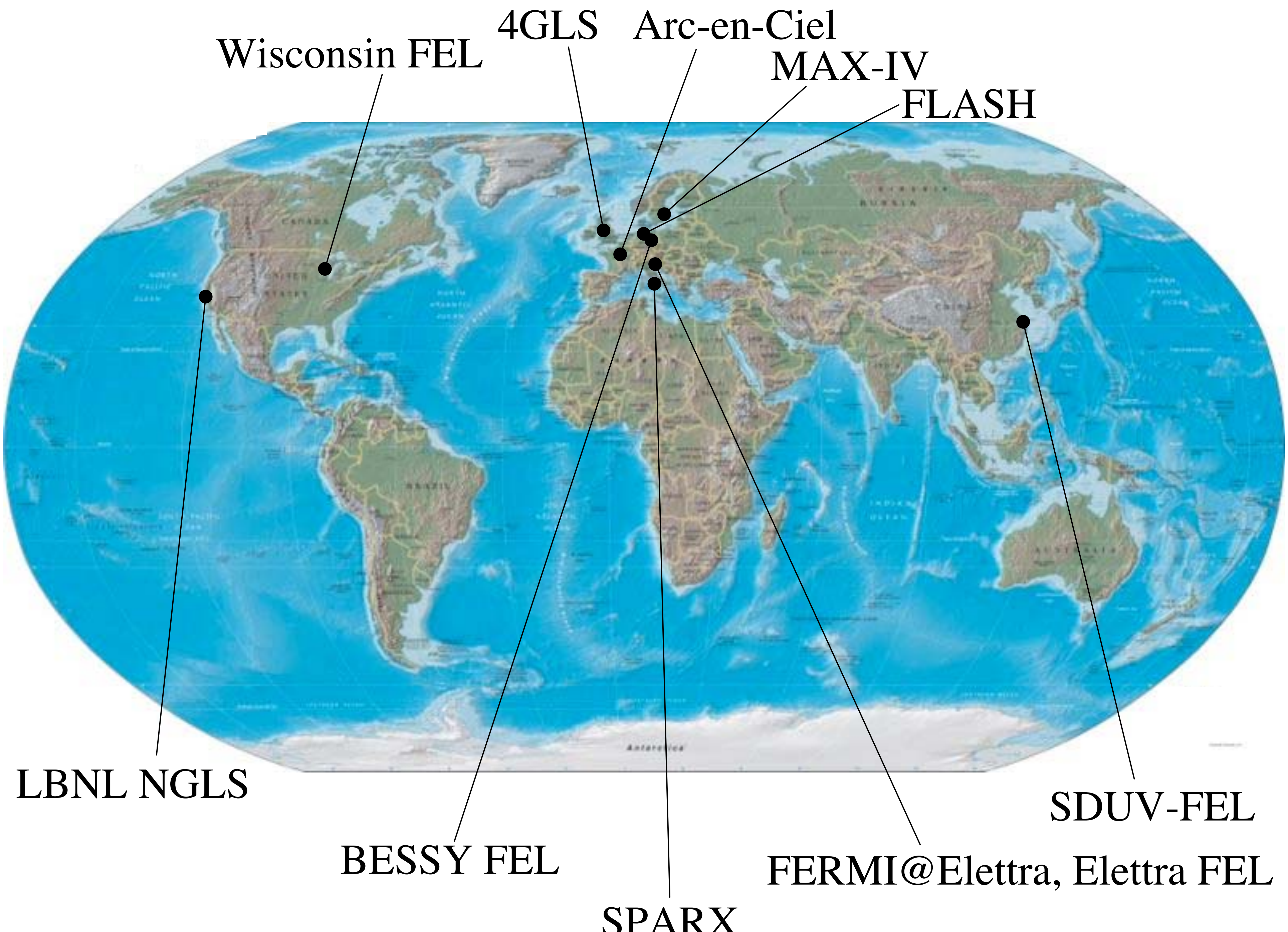
- Injector
  - Cathode (low emittance, high QE, power handling)
  - Photocathode laser (pulse shaping, power)
  - Accelerating structures (high gradient, low loss)
- Accelerator
  - CW superconducting RF
    - High gradient
    - High Q
    - High reliability
- FEL
  - Seed laser (pulse shaping, tunability, power)
  - Short-period undulators
- Accelerator physics
  - Emittance control and manipulations
  - Low emittance beam transport
  - Bunch compression strategies
  - Micobunching suppression
- Other technologies
  - High-resolution diagnostics
  - Timing and synchronization systems

APPENDIX 1

VUV – SOFT X-RAY FACILITIES UNDER CONSTRUCTION, PROPOSALS, AND CONCEPTS

VUV – soft x-ray FEL projects

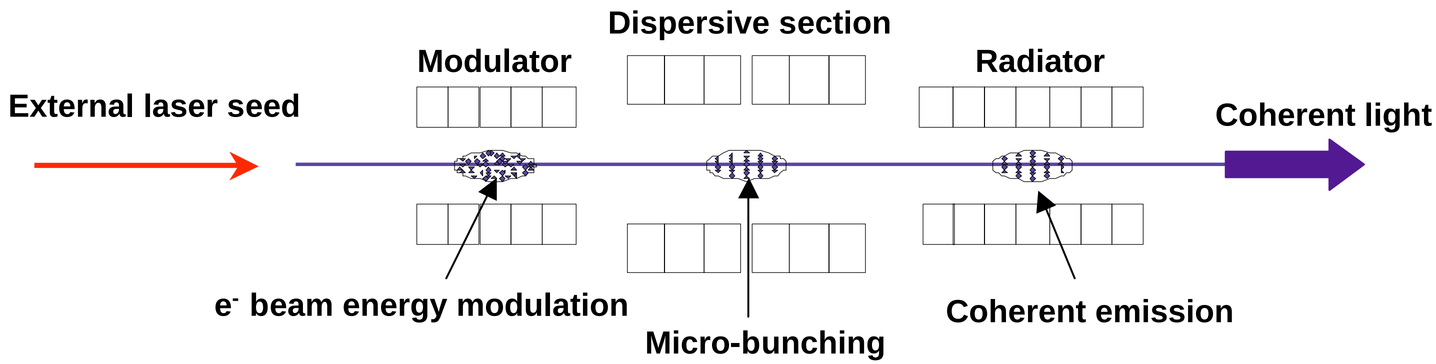
Accelerator	Project	Institution	Type of facility	Shortest photon wavelength in the fundamental (nm)	Project status
Storage ring	Elettra storage ring FEL	Sincrotrone Trieste, Trieste, Italy	Storage ring FEL	80	Operational
Energy recovery linac	4GLS	CCLRC, Daresbury, U.K.	CW superconducting linac ERL, spontaneous undulator radiation and seeded FEL component	0.15	Proposal
	Arc-en-Ciel	SOLEIL, CEA Saclay; Ecole Polytechnique; CNRS Orsay; France	CW superconducting linac ERL, spontaneous undulator radiation and SASE and HGHG FELs	<1	Concept under development
Single-pass linac	MAX-IV	MAX-Lab, Lund University, Swededn	Pulsed normal conducting linac, HGHG optical klystron cascade FEL	1	Proposal
	LBNL NGLS	LBNL, Berkeley, CA, USA	CW superconducting linac, HGHG FEL	1	Concept under development
	Wisconsin FEL	U. of Wisconsin Synchrotron Radiation Center, and MIT, USA	CW superconducting linac, HGHG FEL	1	Concept under development
	BESSY FEL	BESSY, Berlin, Germany	CW superconducting linac, HGHG FEL	1.2	Proposal
	SPARX	INFN, ENEA, Frascati, Italy	Pulsed normal conducting linac, SASE FEL	1.5	Concept under development
	FLASH	DESY, Hamburg, Germany	Pulsed superconducting linac, SASE FEL	6.4	Operational
	FERMI@Elettra	Sincrotrone Trieste, Trieste, Italy	Pulsed normal conducting linac, HGHG FEL	10	Funded for construction
	SDUV-FEL	Shanghai Institute of Applied Physics, Shanghai, China	Pulsed normal conducting linac, HGHG FEL	88	Funded for construction



Wisconsin FEL
4GLS
Arc-en-Ciel
MAX-IV
FLASH
LBNL NGLS
BESSY FEL
SPARX
FERMI@Elettra, Elettra FEL
SDUV-FEL

ELETTRA storage ring FEL

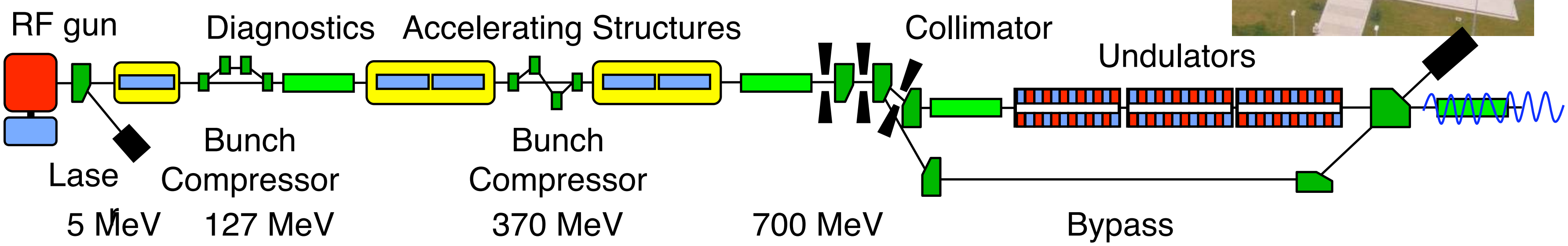
SEEDED OPTICAL KLYSTRON IN A STORAGE RING



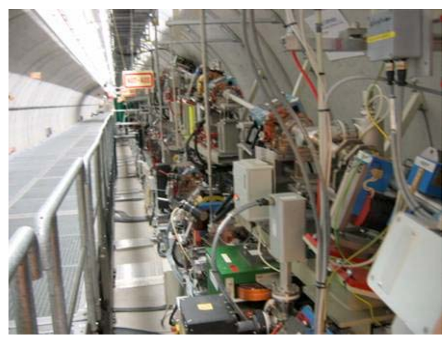
G. DeNinno, Sincrotrone Trieste

FLASH overview





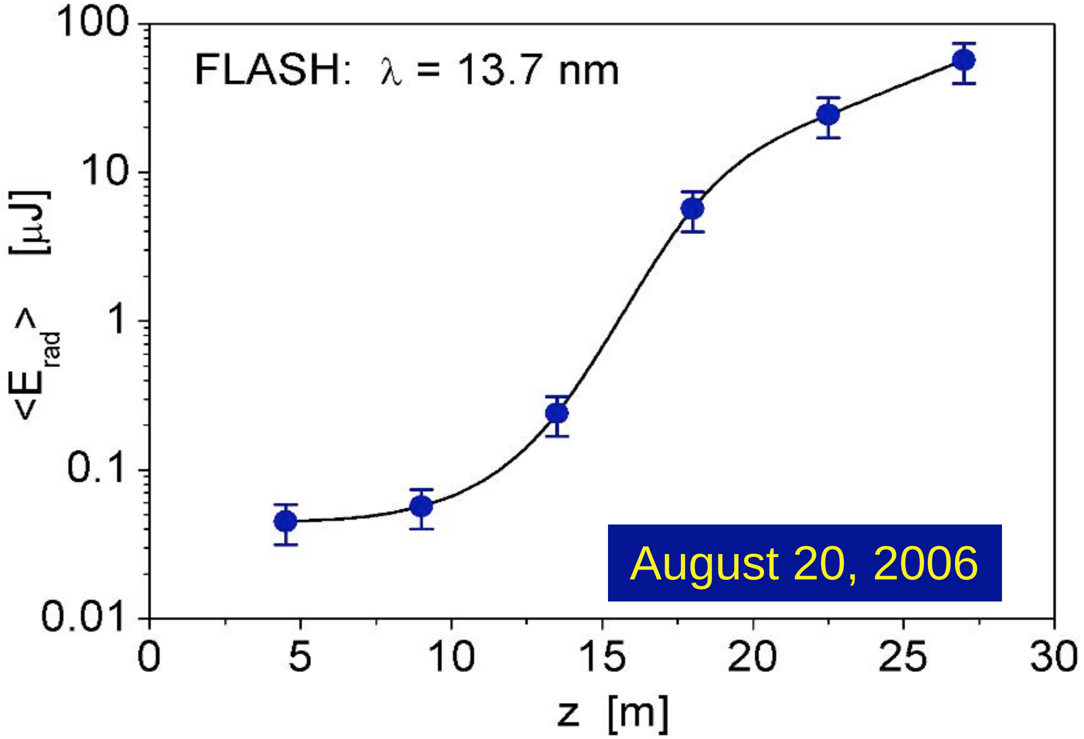



250 m

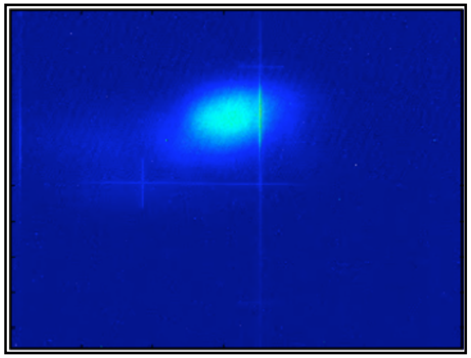
- **Bunch charge < 1 nC**
- **Emittance 2 – 4 mm-mrad**
- **Peak current 2.5 kA**
- **Energy spread 10^{-3}**

Courtesy Siegfried Schreiber, DESY

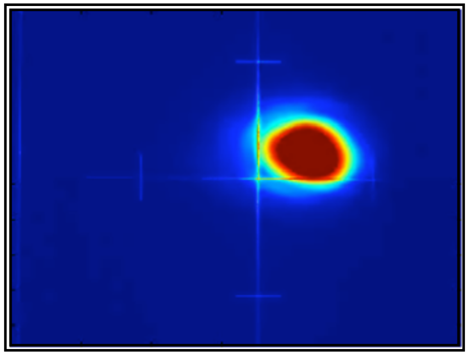
FLASH is the shortest wavelength FEL
Lasing at 13.7 nm



<E> = 5 μJ



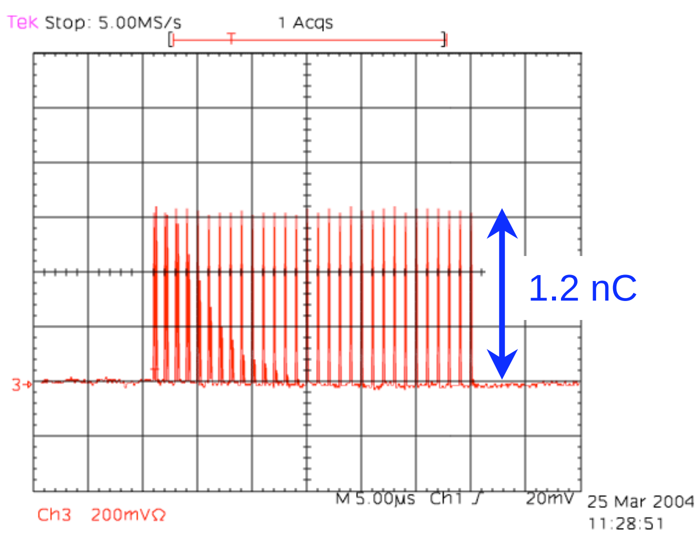
<E> = 70 μJ



Courtesy Siegfried Schreiber, DESY

FLASH time structure

- TESLA type superconducting linac
- Pulse trains of up to 800 μs duration
- Up to 10 Hz repetition rate (currently 5 Hz)
- Change bunch pattern on user request, by control of photocathode laser
  - Number of bunches
  - Different bunch frequencies: 1 MHz, 250 kHz, 100 kHz, up to MHz



Electron beam pulse train (30 bunches, 1 MHz)

Courtesy Siegfried Schreiber, DESY

SASE performance

- **Averaged at 13.7 nm exceeds 70 μJ**
- **Peak radiation energy ~170 μJ**
- **Pulse duration estimate around 10 fs**
- **Peak power exceeds 5 GW**
- **Fixed gap undulators**
  - **B=0.48 T, K=1.23, λ_u=2.73 cm, gap=12 mm**
  - **Tuning by electron beam energy variation 374 – 720 MeV**

- **Wavelength range (fundamental):** 13-47 nm
- **Pulse energy average:** 100 μJ
- **Pulse energy peak:** 200 μJ
- **Peak power:** ~ 5 GW
- **Average power:** > 100 mW
- **Pulse duration (FWHM):** 10-50 fs
- **Spectral width (FWHM):** 0.5-1 %
- **Peak brilliance:** 10^{29} – 10^{30} ph (s 0.1%BW mm mrad)$^{-1}$

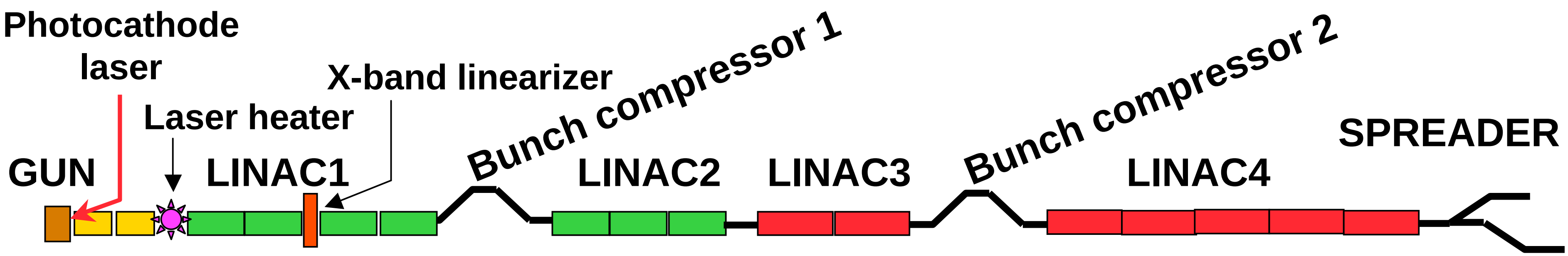
Upgrade to 1 GeV, to lase at 6.5 nm, in progress

Courtesy Siegfried Schreiber, DESY


FERMI
@elettra
Linac Extension
Undulator Hall
Experimental Hall
FERMI@Elettra at Sincrotrone Trieste, Italy
Worlds first harmonic cascade seeded FEL facility

FERMI accelerator configuration

SINGLE-PASS NORMAL CONDUCTING LINAC



$E_0 \approx 100$ MeV
$I \approx 60$ A (10ps)

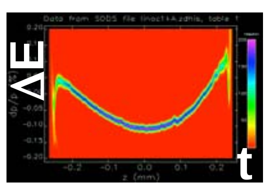
$E_1 \approx 220$ MeV
$R_{56} \approx -0.03$ m
Compression factor = 3.5

$E_2 \approx 600$ MeV
$R_{56} \approx -0.02$ m
Compression factor = 3.0

$E_3 \approx 1200$ MeV
$I \approx 800$A (700fs)
$I \approx 500$A (1.4ps)

FEL hall (not shown)

	"Medium" bunch	"Long" bunch
Bunch length	700 fs (flat part)	1.4 ps (flat part)
Peak current	800 A	500 A
Emittance(slice)	1.5 micron	1.5 micron
Energy spread(slice)	<150 keV	<150 keV
Flatness, $\|d^2E/dt^2\|$	<0.8 MeV/ps^2	<0.2 MeV/ps^2

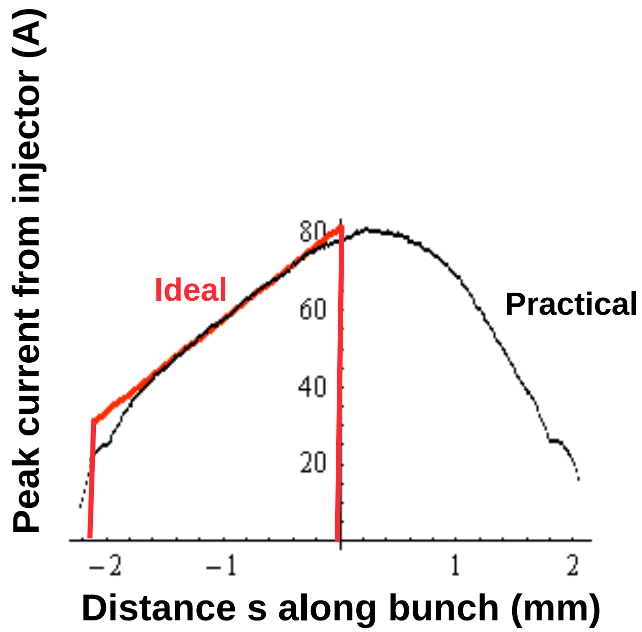


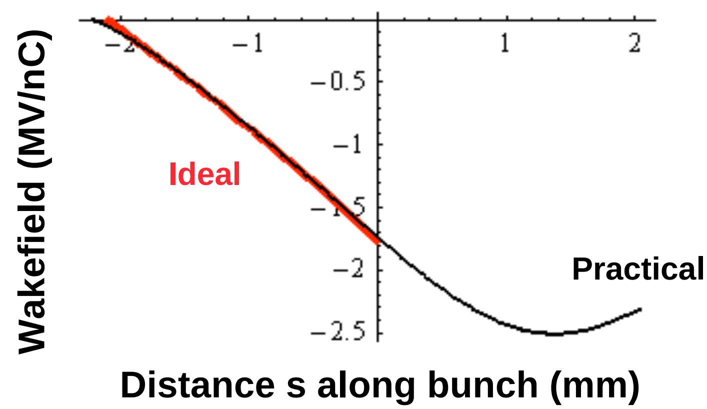
Correct for geometric wakefields

SHAPE THE BUNCH CURRENT DISTIBUTION

$$W(s) = -\int_s^\infty w(s - s')\lambda_z(s')\,ds'$$

$$w(s) = A\frac{Z_0 c}{\pi a^2} L \exp\left(-\sqrt{s/s_1}\right)$$

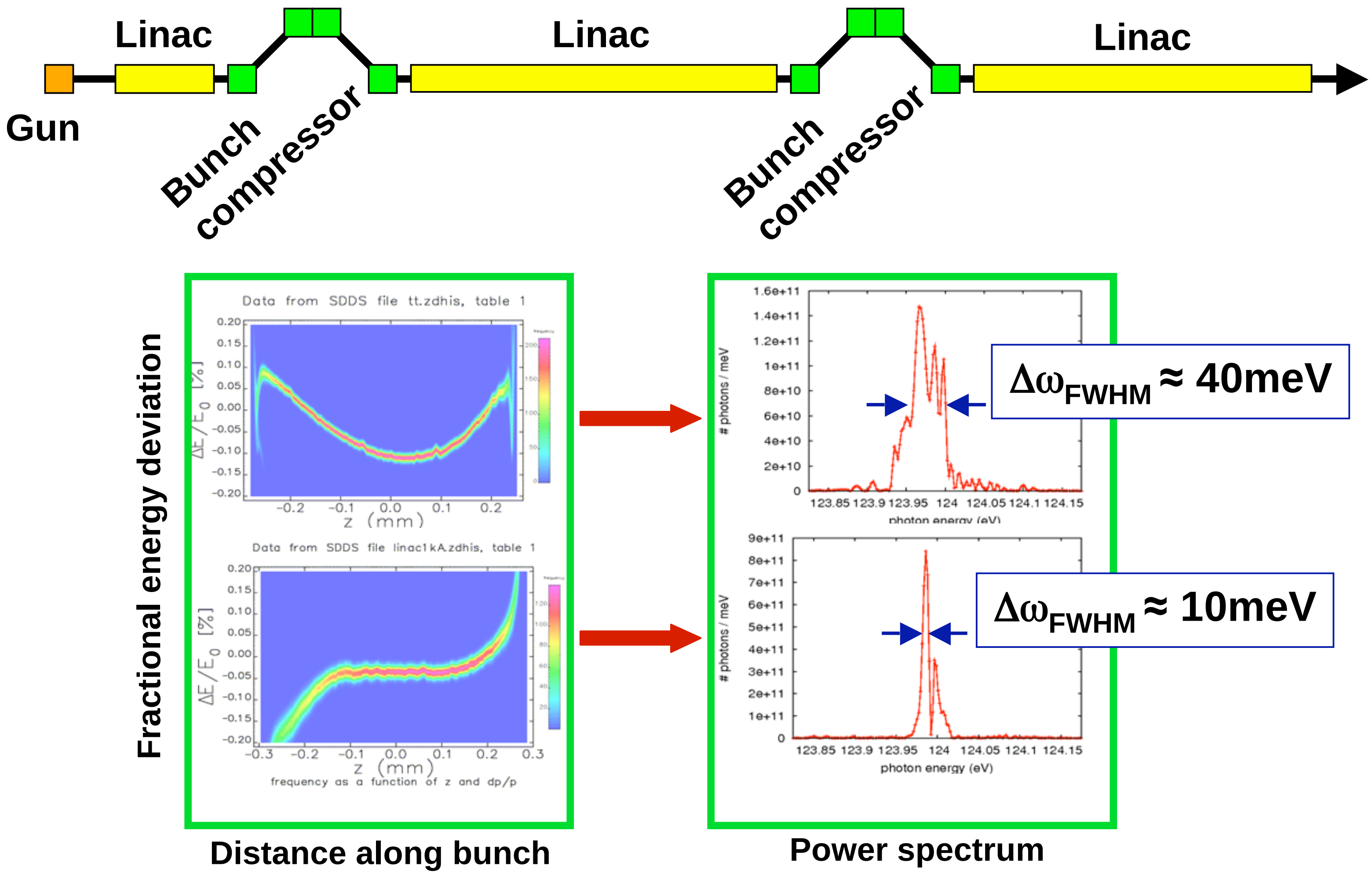




M. Cornacchia, S. Di Mitri, G. Penco, A. Zholents, Phys. Rev. S.T. – Acc. and Beam, 9, 120701 (2006)

Acceleration, compression, transport

OPTIMAL DEISGN OF THE ACCELERATOR IMPROVES FEL PERFORMANCE

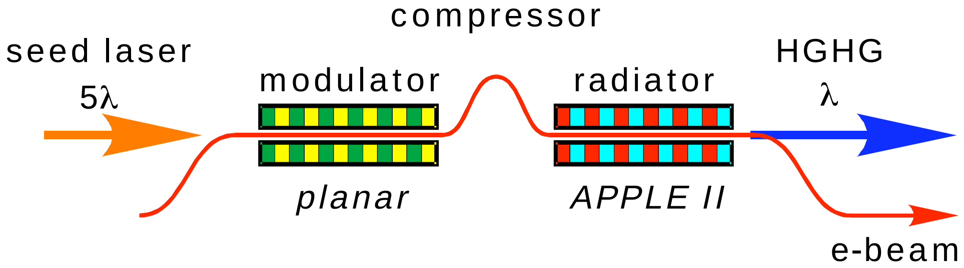


M. Cornacchia, S. Di Mitri, G. Penco, A. Zholents, Phys. Rev. S.T. – Acc. and Beam, 9, 120701 (2006)

FERMI FEL configurations

FEL-1: short (40-300 fs) photon pulses at 100-20 nm, peak power ~1 to >5 GW

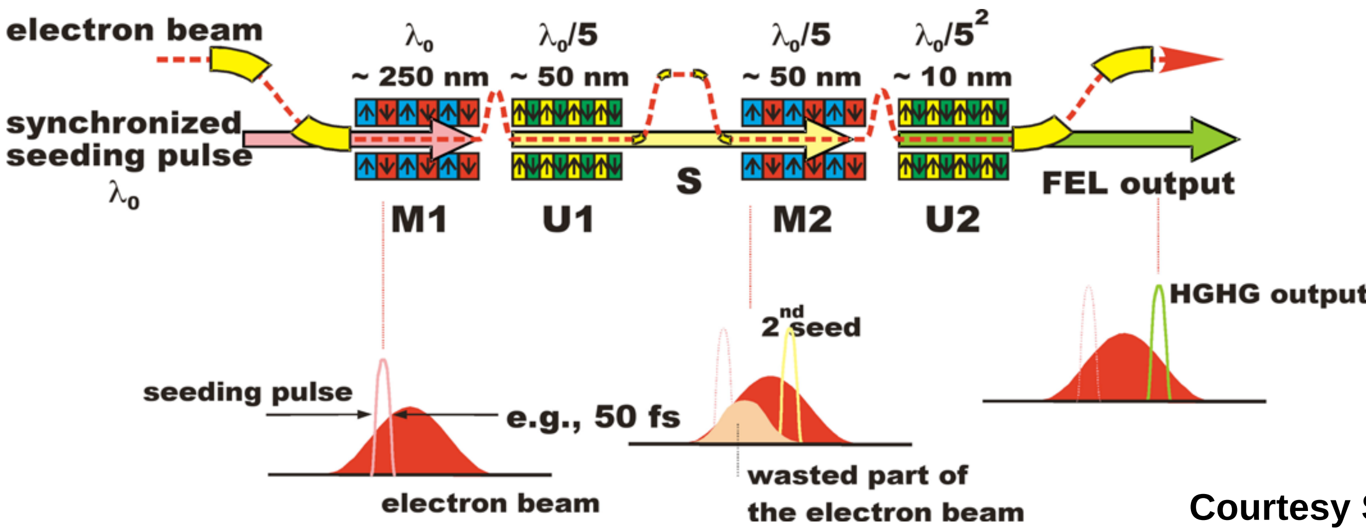
1-Stage HGHG



- **variable polarization output**
- **50 Hz rep rate**
- **1 micro-pulse per macro-pulse**

FEL-2: narrow-band (< 5 meV) photon pulses at 40-10 nm, peak power ~ 0.5 to a few GW

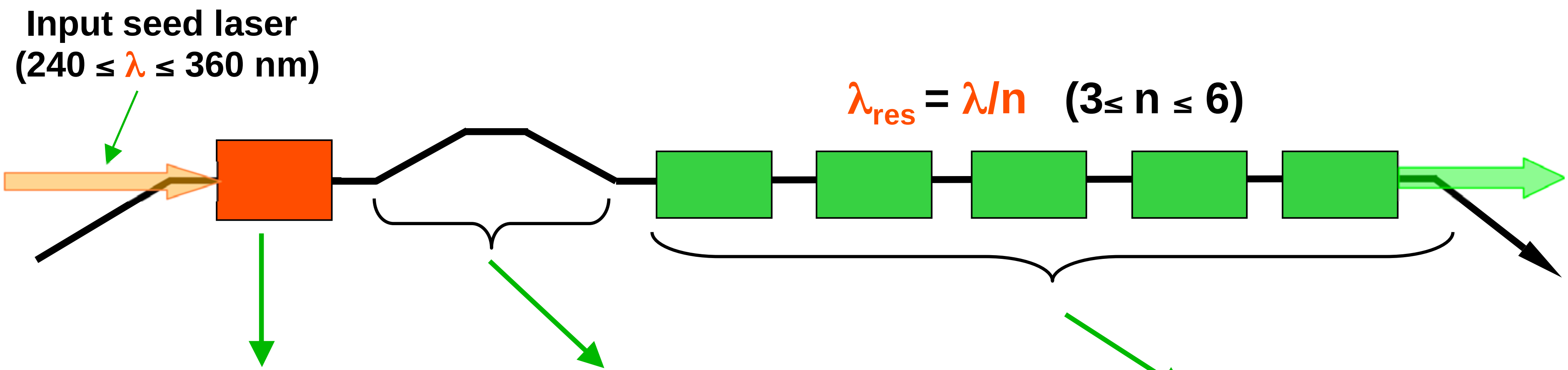
2-Stage cascade HGHG



Courtesy S. Milton, Sincrotrone Trieste

FEL-1 configuration

100 - 40 nm



Modulator

Parameter	*Value*
Type	Planar
Structure	One segment
Period	16 cm
K	3.9 - 4.9
Length	3.04 m

Dispersive section

Parameter	*Value*
R_{56}	~ 32 mm
Length	~ 1 m

Radiator

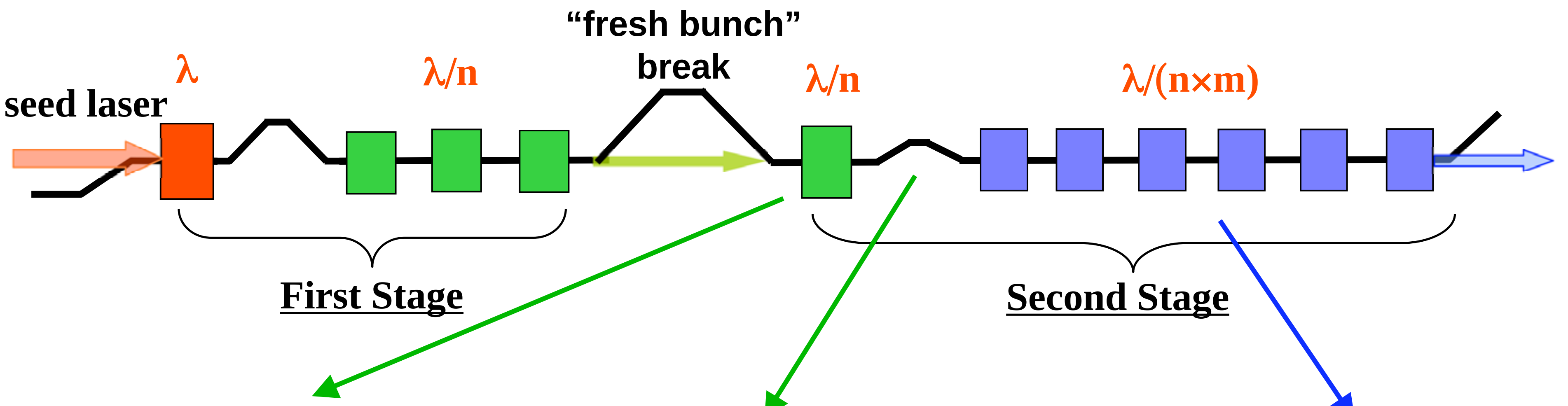
Radiator	*Value*
Type	Apple
Structure	~ 5 Segments
Period	6.5 cm
K	2.4 - 4
Segment length	2.34 m
Break length	1.06 m
Total length	15.94 m

Total length of FEL-1 ~ 20 m

G. De Ninno, Sincrotrone Trieste

FEL-2 configuration

40 - 10 nm FRESH BUNCH CONFIGURATION



2nd Stage Modulator

Parameter	*Value*
Type	Planar
Structure	One segment
Period	6.5 cm
K	2.4 - 4
Length	2.08 m

Dispersive section

Parameter	*Value*
R_{56}	~ 6.4 mm (at 10 nm)
Length	~ 1 m

Radiator

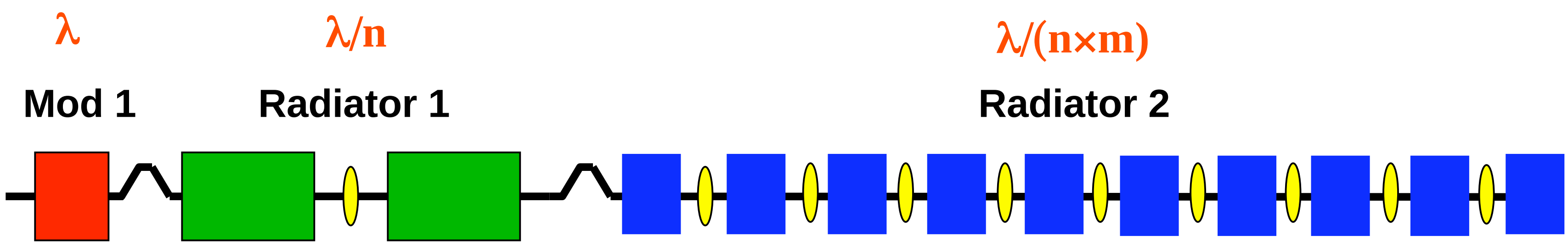
Parameter	*Value*
Type	Apple
Structure	Segmented
Period	5 cm
Segment length	2.4 m
K	1.1 - 2.8
Break length	1.06 m
Total length	19.7 m

Total length FEL-2 (fresh bunch) ~ 37.5 m

G. De Ninno, Sincrotrone Trieste

FEL-2 configuration

40 - 10 nm WHOLE BUNCH CONFIGURATION



- **Second stage is radiator only; delay section and second modulator eliminated**
- **Allows "full" bunch to emit in second stage,** *but: requires smaller initial* σ_γ

Total length FEL-2 (whole bunch) ~ 50 m

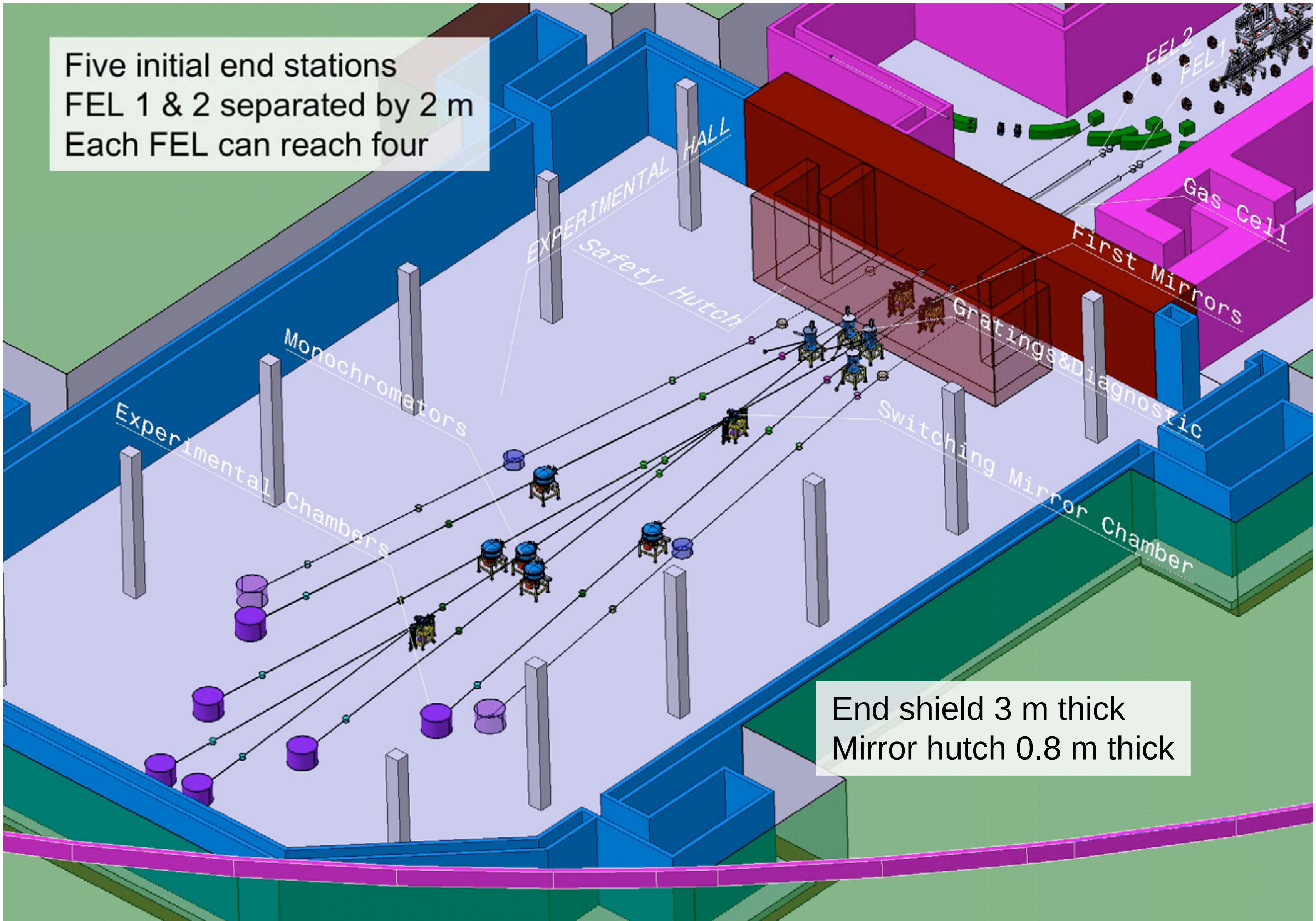
FERMI FELs

FEL PARAMETERS

Parameter	FEL-1	FEL-2
Wavelength range [nm]	100 to 20	40 to 10
Output pulse length (rms) [fs]	< 100	> 200
Bandwidth (rms) [meV]	17 (at 40 nm)	5 (at 10 nm)
Polarization	Variable	Variable
Repetition rate [Hz]	50	50
Peak power [GW]	1 to >5	0.5 to 1
Harmonic peak power (% of fundamental)	~2	~0.2 (at 10 nm)
Photons per pulse	10^{14} (at 40 nm)	10^{12} (at 10 nm)
Pulse-to-pulse stability	≤ 30 %	~50 %
Pointing stability [μrad]	< 20	< 20
Virtual waist size [μm]	250 (at 40 nm)	120
Divergence (rms, intensity) [μrad]	50 (at 40 nm)	15 (at 10 nm)

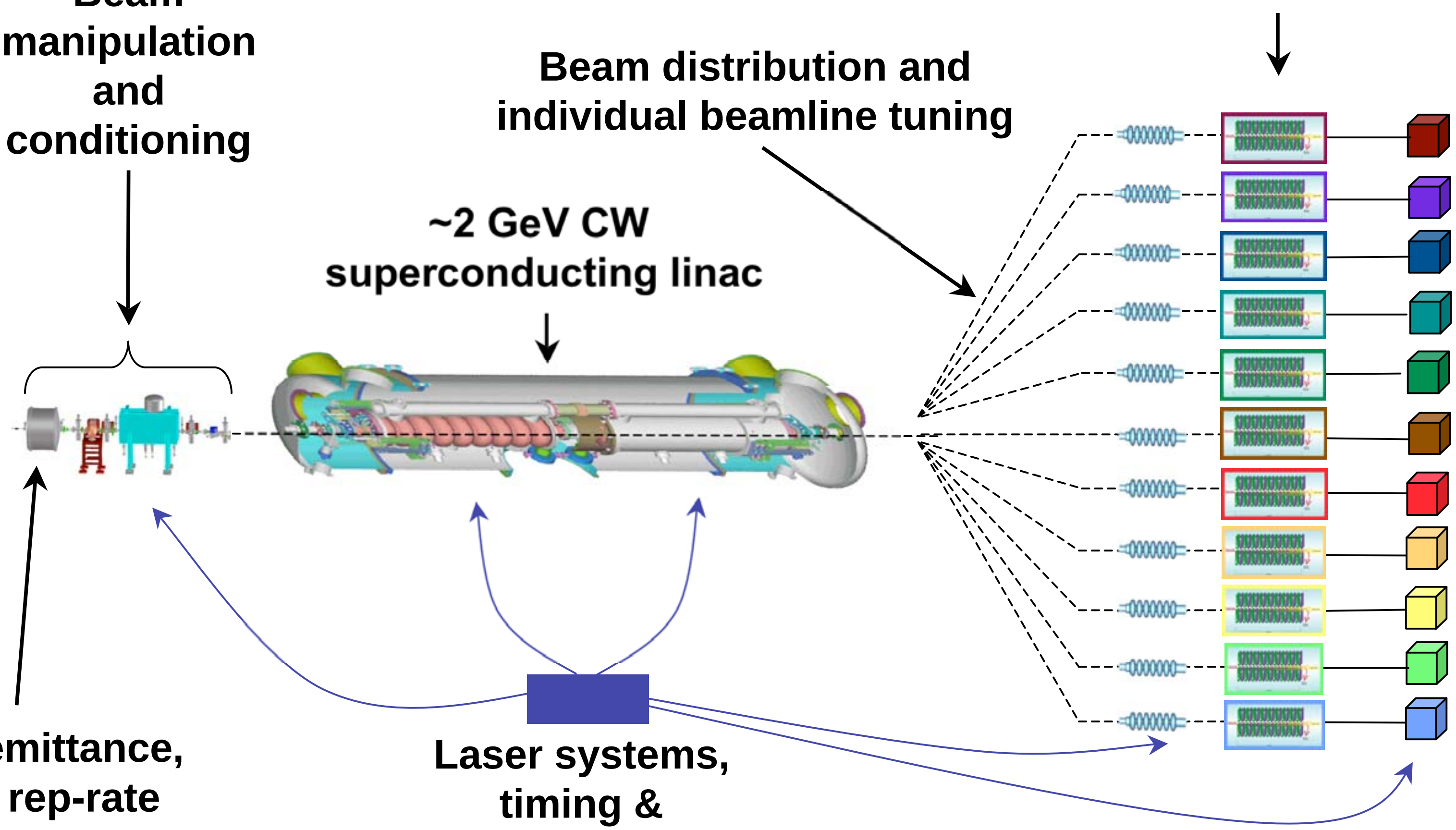
FERMI experimental hall

PHOTONS FROM EITHER FEL SWITCHABLE TO ENDSTATIONS



Vision for a future light source facility at LBNL

A HIGH REP-RATE, SEEDED, VUV — SOFT X-RAY FEL ARRAY



LBNL seeded FEL performance goals

DRIVEN BY USER NEEDS

	Ultrafast	High resolution	Attosecond
Wavelength range (nm)	200 - 1	200 - 1	200 - 1
Repetition rate[1] (kHz)	100	100	100
Peak power (GW)	1	1	0.1 - 0.3
Intensity stability[2]	5%	5%	5%
Timing stability[3,4] (fs)	10	10	tbd
Pulse length[5] (fs)	1 - 100	500 - 1000	~0.1
Bandwidth	2-3 x transform limit	2-3 x transform limit	transform limit
Harmonics[6]	≤few %	≤few %	≤few %
Source position stability	<10% source size	<10% source size	<10% source size
Pointing stability (μrad)	<10	<10	<10
Spot size (μm)	~50	~50	~50
Divergence (μrad)	~5	~5	~5
Polarization	Variable, lin/circ	Variable, lin/circ	Variable, lin/circ
Wavelength stability[7]	tbd	tbd	tbd
Background signal[8]	tbd	tbd	tbd

NOTES:

1) 10 kHz initially, need additional gun developments for higher rate, but linac & other infrastructure will accommodate this

2) Most experiments will incorporate a pulse energy measurement, stability then not critical; spectroscopies & non-linear expts more demanding

3) Synchronization available from seeded systems

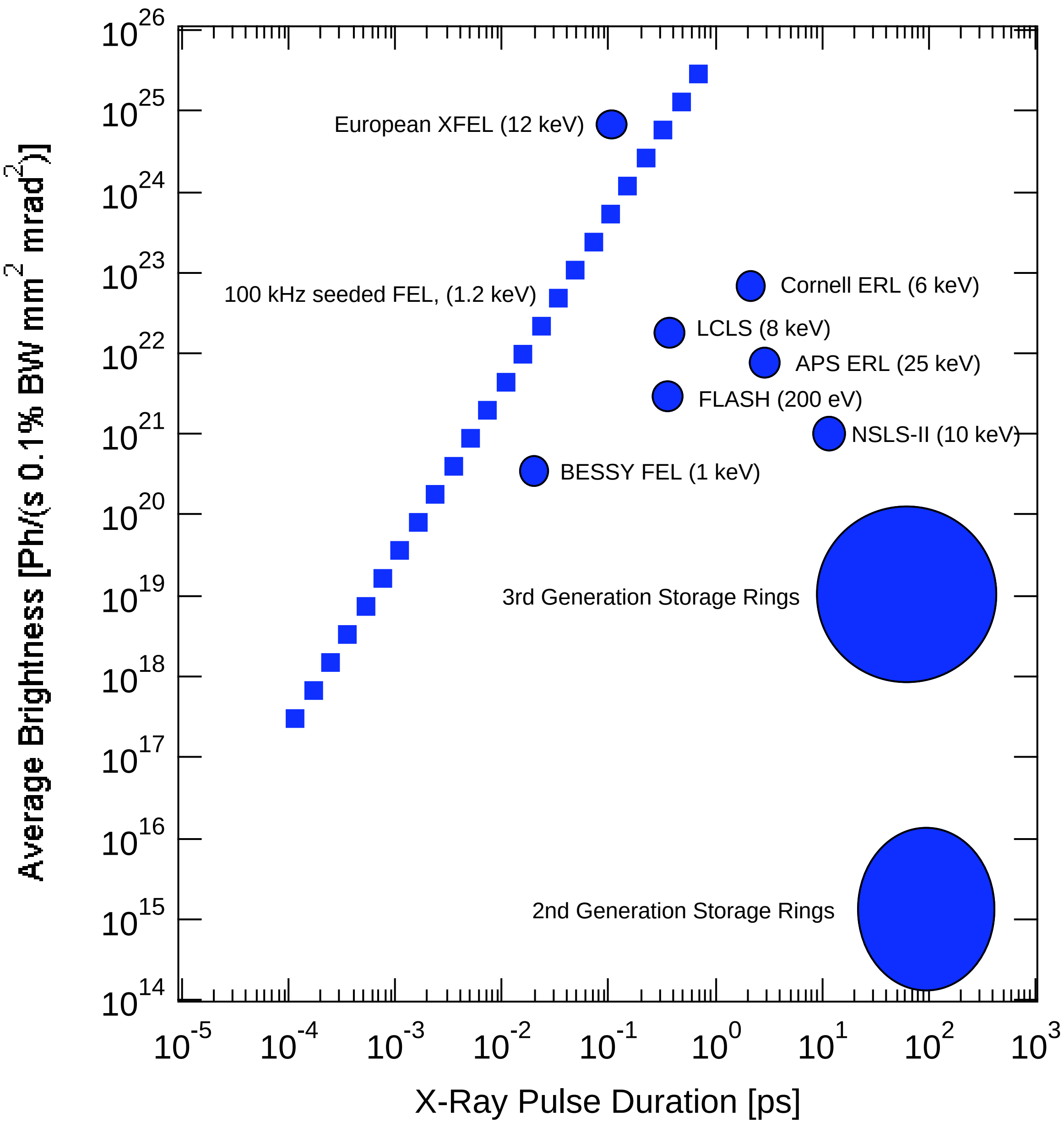
4) Timing stability for the attosecond mode will need to be developed

5) Capabilities for <20 fs pulse durations to be explored (in R&D plan)

6) Up to third harmonic, may be useful to achieve wavlengths shorter than nm

7) Currently under study for the FERMI project

8) Dependent on FEL configuration and mode of operation



Average brightness versus pulse duration for storage ring, ERL, and FEL sources. Values are shown for optimized brightness at the photon energies indicated, based on available data. For the European XFEL and FLASH this reflects the use of bunch trains. For a 100-kHz seeded-FEL facility utilizing optical manipulations to control pulse duration, a dashed line indicates performance range.

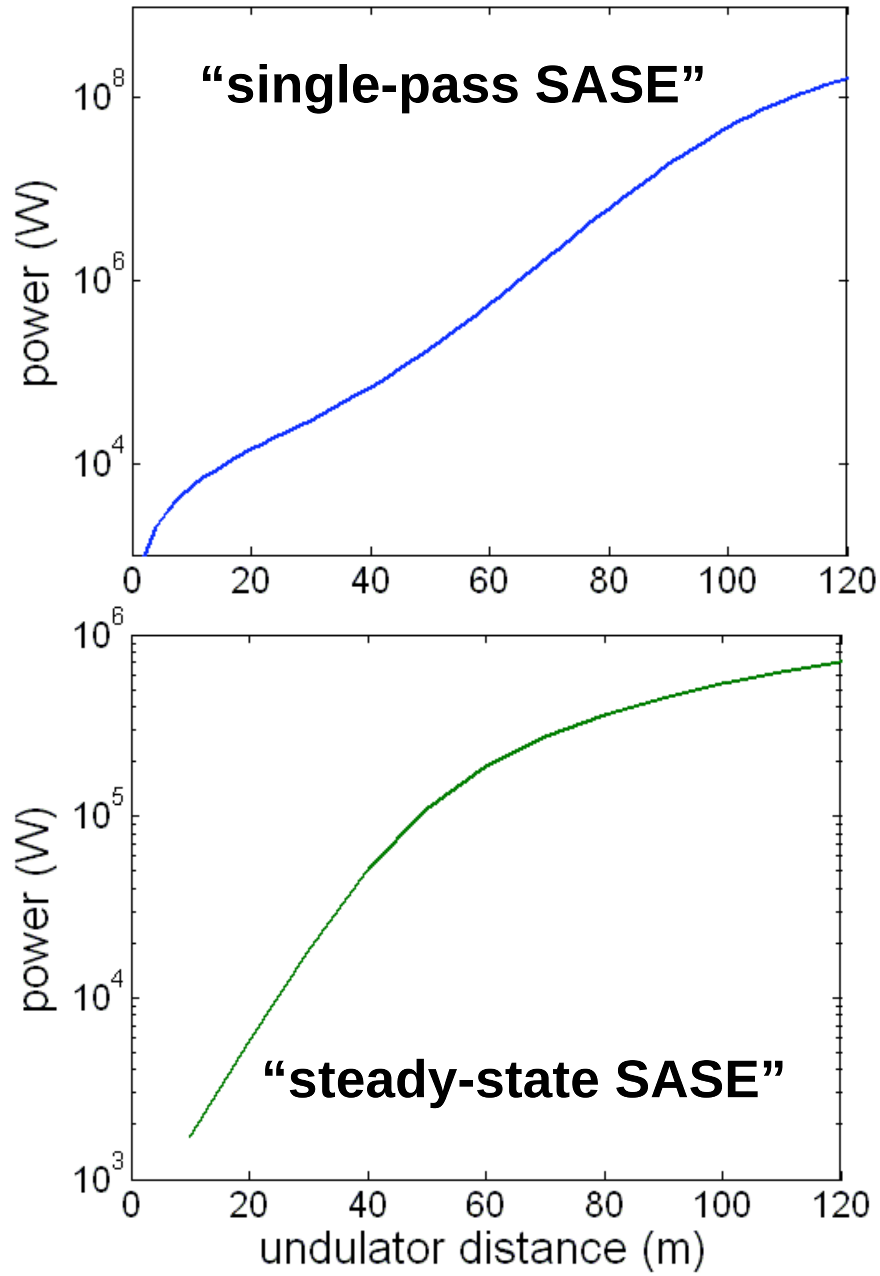
FEL options on PEP

CONCEPT FOR STORAGE-RING BASED FEL - SASE MODE (IN BYPASS)

- **Low-emittance lattice with wiggler (including intrabeam scattering)**

Electron energy	4.5 GeV
Norm. emittance in x/y	0.6 μm
Peak current	300 A
Bunch length	10 ps
Energy spread	0.114%
Undulator period	5 cm
Undulator parameter	7.75
Peak magnetic field	1.65 T
FEL wavelength	10 nm

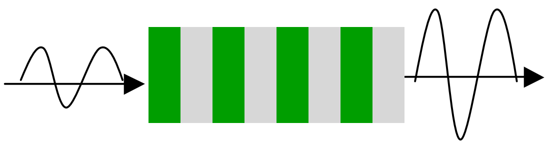
- **Steady-state mode increases energy spread but can operate at ring frequency**

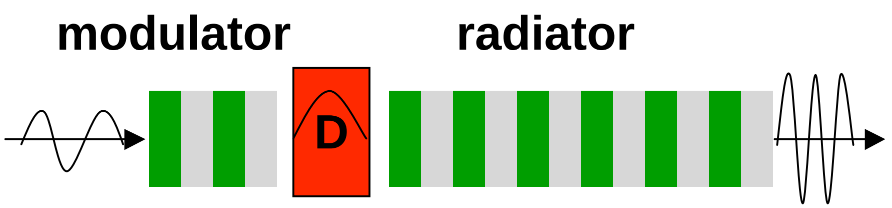


FEL options on PEP

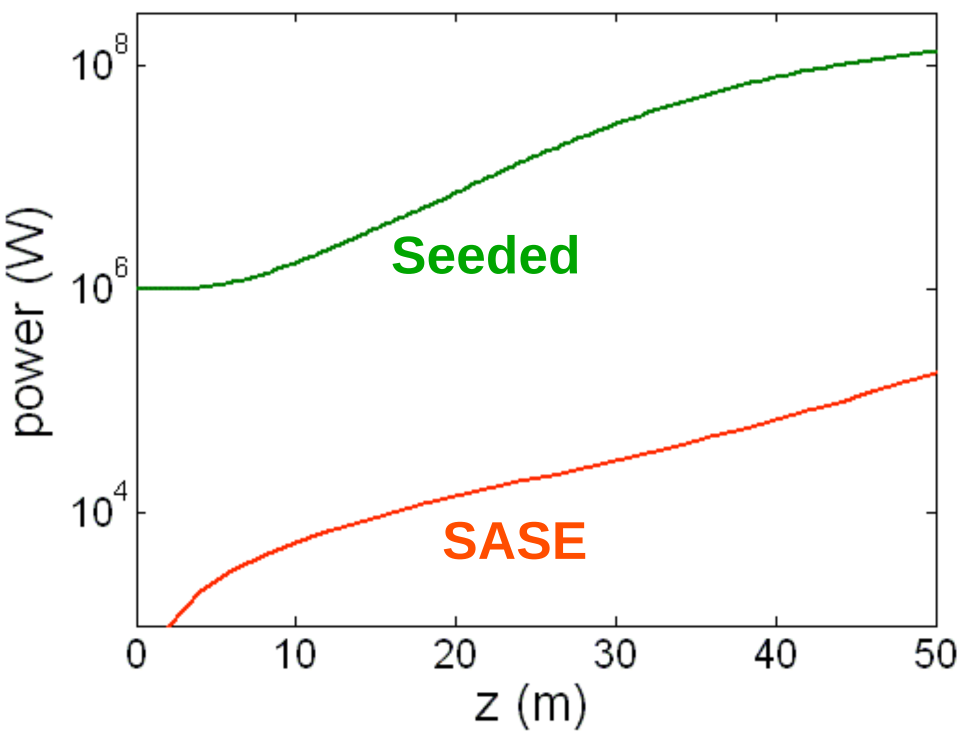
CONCEPT FOR STORAGE-RING BASED FEL - SEEDED MODE

- Laser seeded storage ring FEL recently demonstrated at Elettra
- Explore HHG laser (~10 fs, 10 nm, 1 MW) to seed a small portion of PEP bunch:

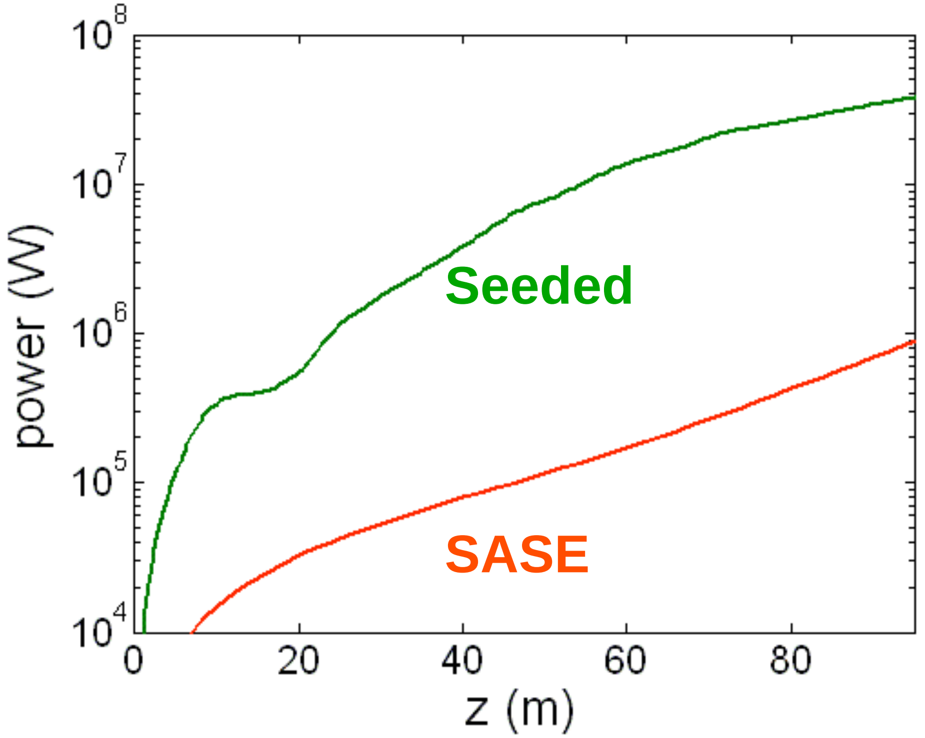




amplifier mode at 10 nm

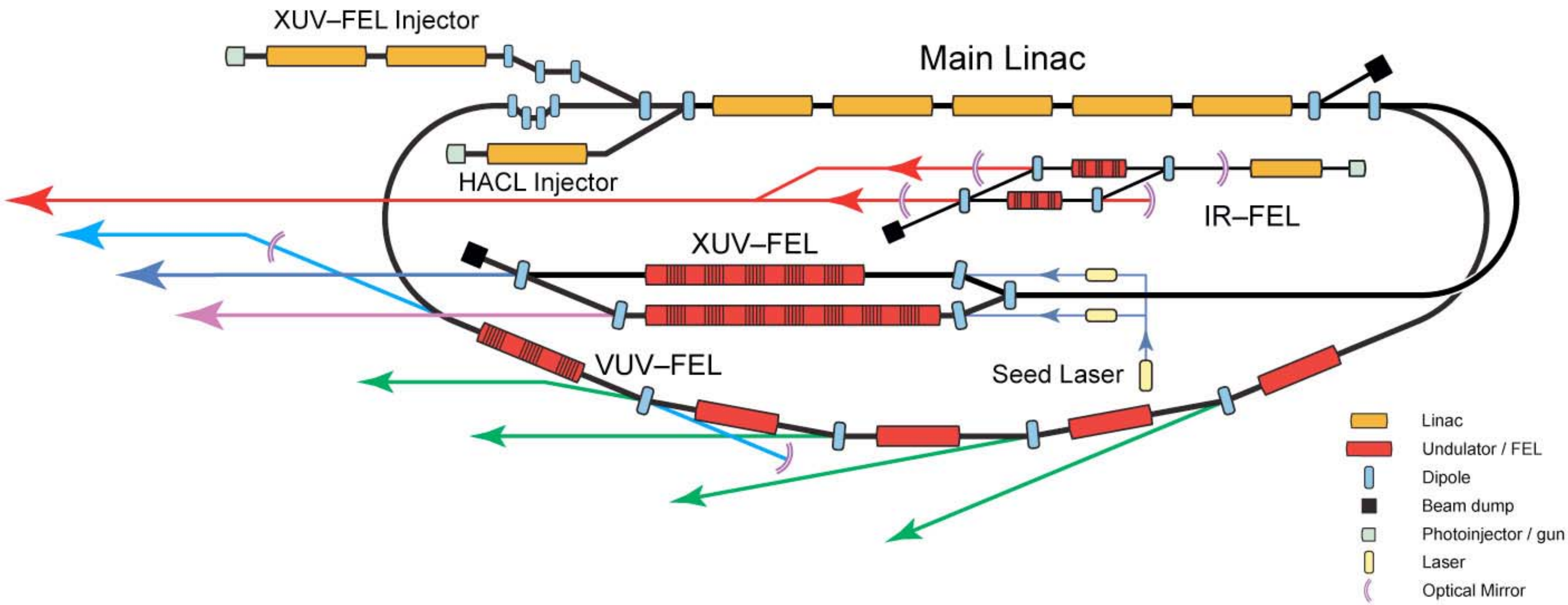


HGHG mode at 10/3=3.3 nm



4GLS

PROPOSAL FOR ERL-BASED FACILITY



J. Clarke, CCLRC Daresbury

4GLS

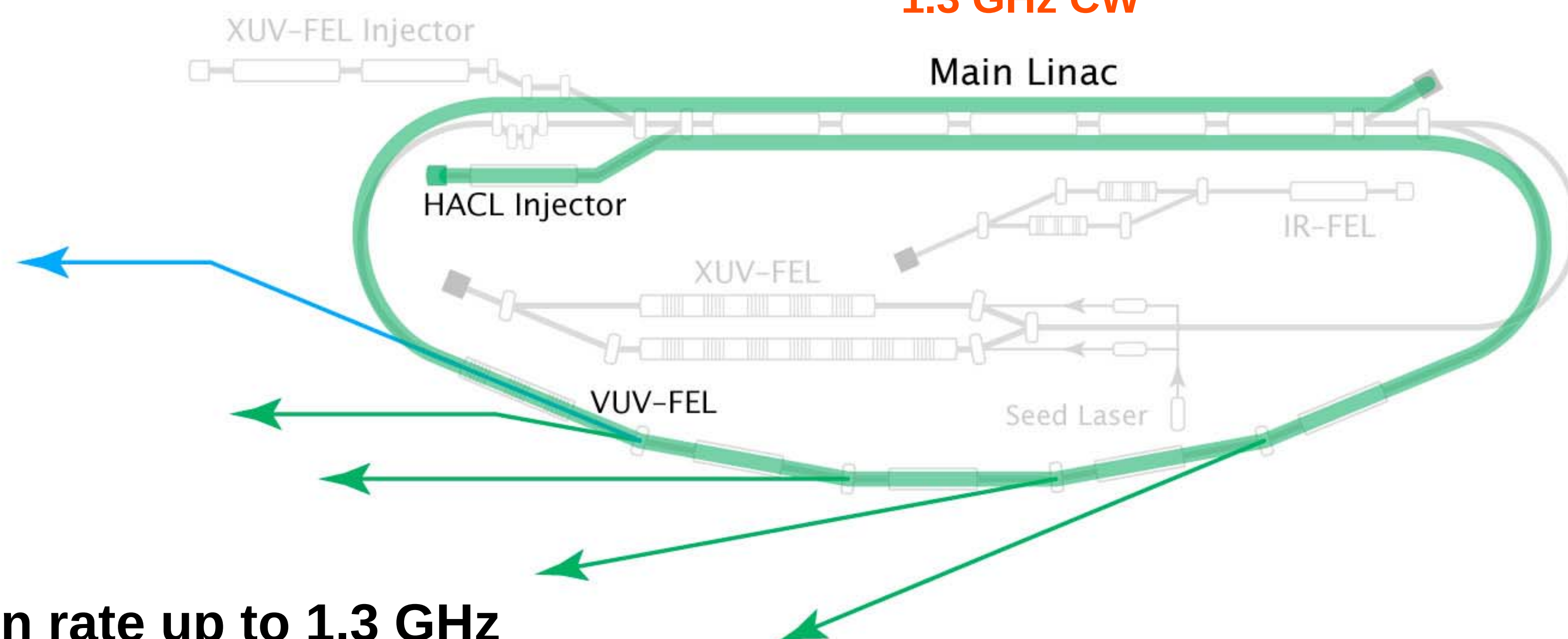
HIGH AVERAGE CURRENT LOOP

Undulator sources and VUV-FEL

Progressive bunch compression, ~1 ps to 100 fs

100mA, 550 MeV, 2 mm mrad, 77 pC

1.3 GHz CW



VUV FEL
Repetition rate up to 1.3 GHz
Variable polarization
FEL output 3 — 10 eV
Up to 70 μJ per pulse
Minimum pulse duration < 170 fs

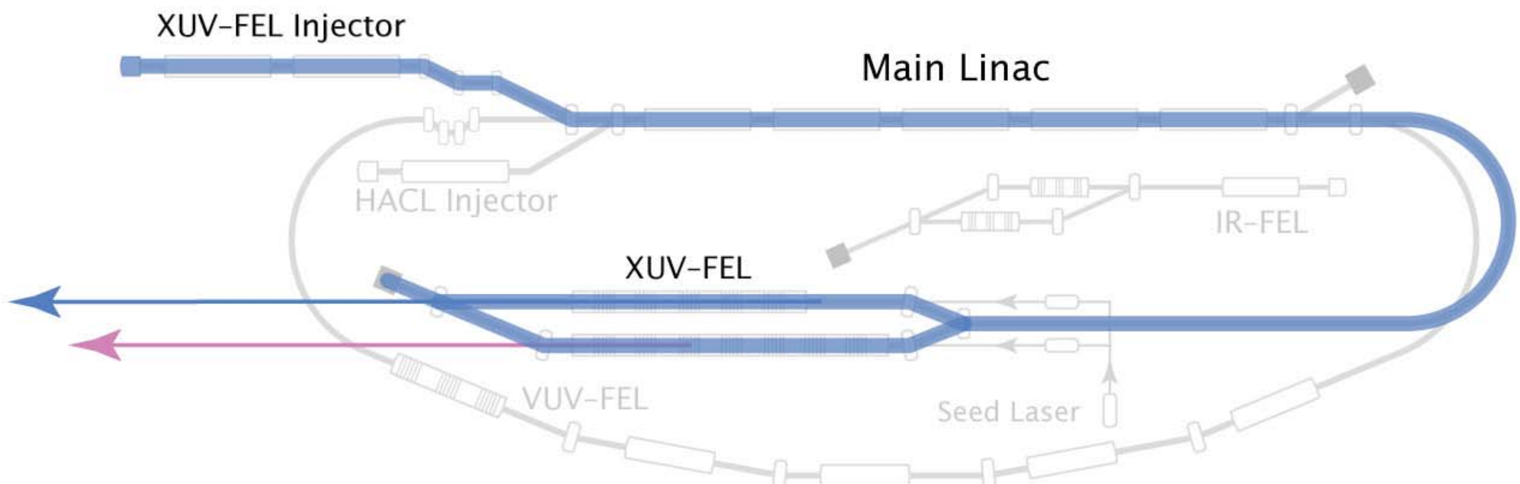
J. Clarke, CCLRC Daresbury

4GLS

PROPOSAL FOR ERL-BASED FACILITY - XUV FEL BRANCH

1 nC, 750 MeV, 2 mm mrad, 1.5 kA

1 kHz CW

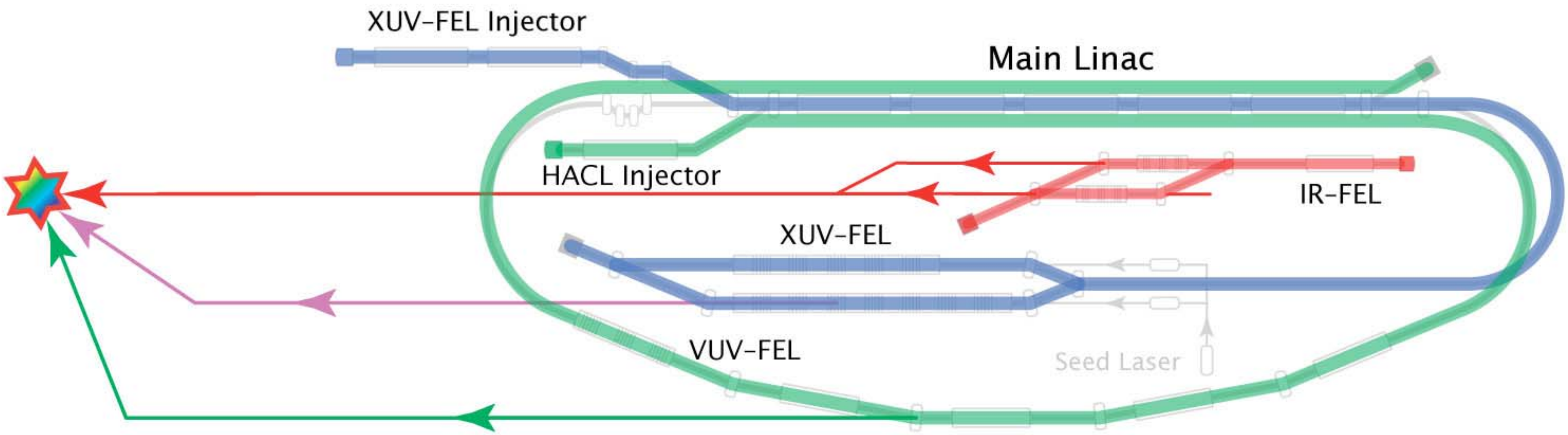


HHG seeded
Repetition rate ~1 kHz
Variable polarization
FEL output up to 8 — 100 eV
Up to 400 μJ per pulse
Minimum pulse duration < 50 fs

J. Clarke, CCLRC Daresbury

4GLS

PROPOSAL FOR ERL-BASED FACILITY - SIMULTANEOUS OPERATION



Short pulses and combined sources are key to 4GLS

J. Clarke, CCLRC Daresbury

Three phases project

- ARC-EN-CIEL phase 1 :

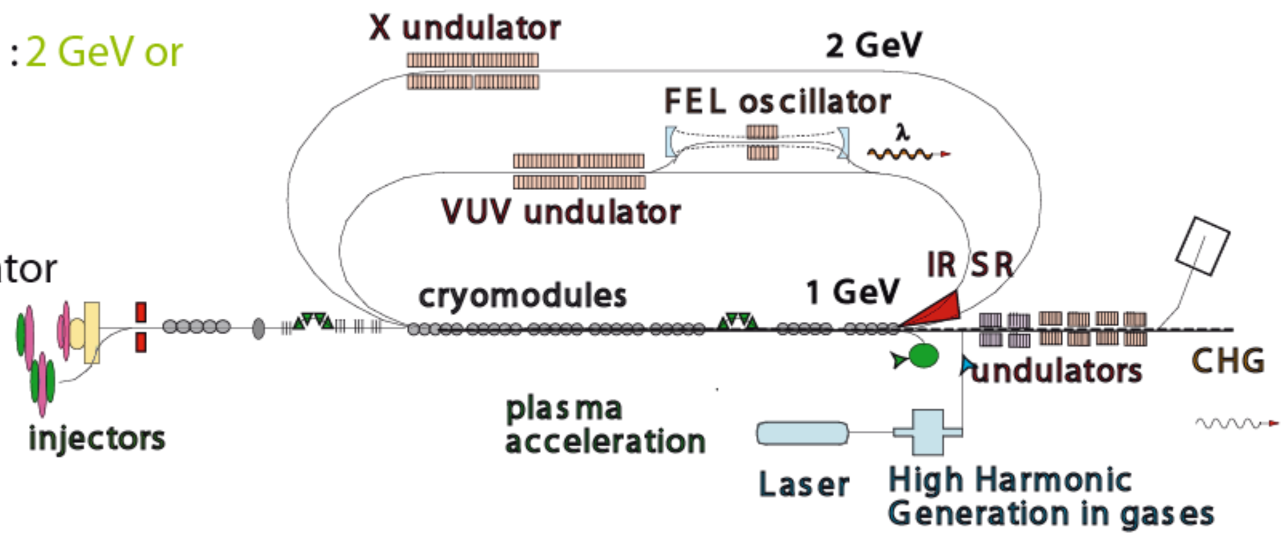
  Linear accelerator : 220 MeV (or 330 MeV), low energy spread, low emittance
  femtosecond HGHG sources : 100-10 nm, high brilliance and coherence

- ARC-EN-CIEL phase 2 :

  Linear accelerator : 1 GeV
  HGHG sources : down to 1 nm

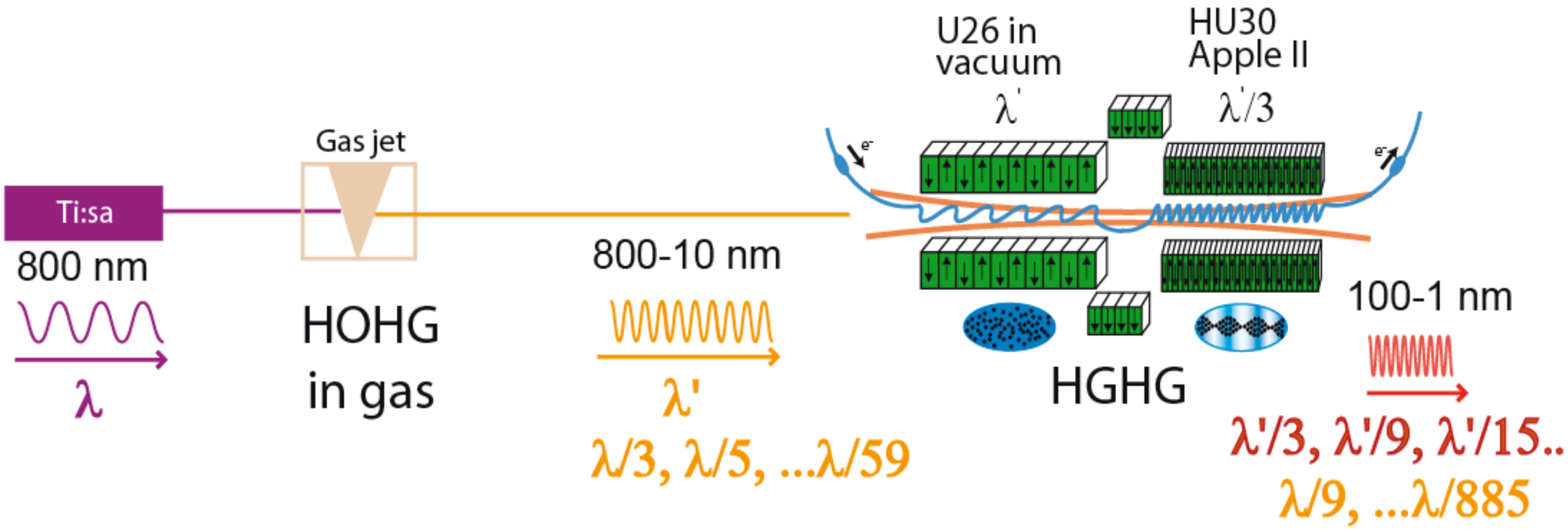
- ARC-EN-CIEL phase 3 :

  Additionnal loops : 2 GeV or increased current
  HGHG sources
  UV FEL oscillator
  VUV and X undulator



Christelle Bruni & Marie-Emmanuelle, SOLEIL

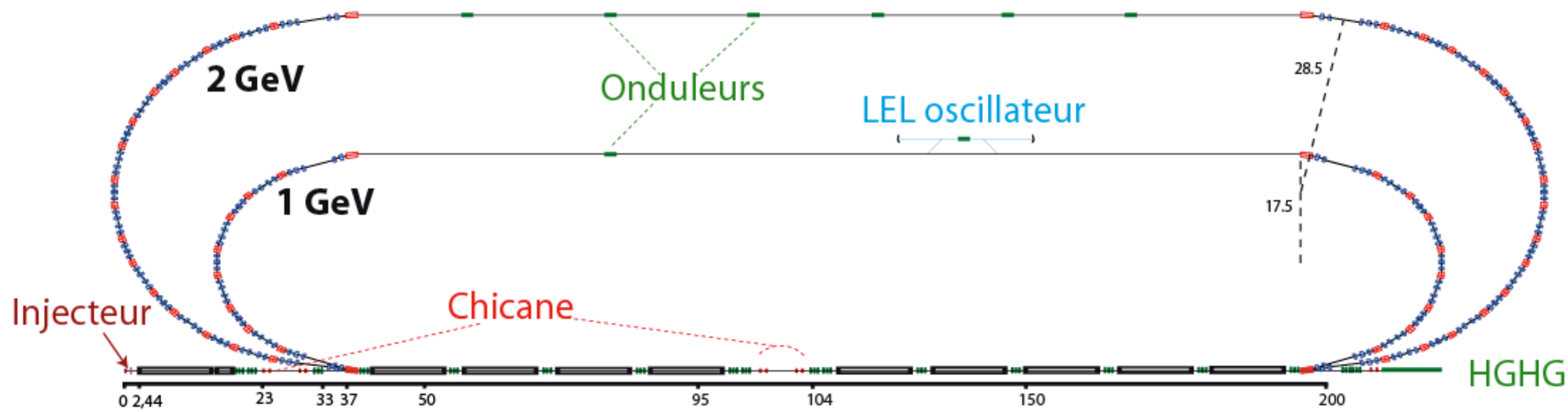
High Gain Harmonic Generation



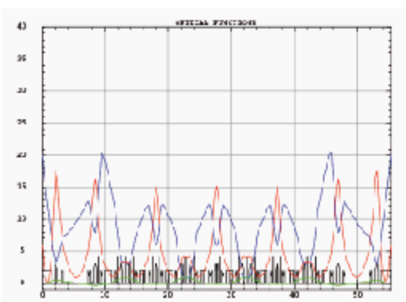
External seed : High Order Harmonic Generation (**HOHG**):

- **Experiment demonstration at SPA** (SCSS prototype accelerator) :
  G. Lambert et al. (French/Japonesse collaboration)
- **FEL seeded at 160 nm (H5 in gas) @150 MeV** :
  Coherent radiation observed at 160 (H1 und.), 52 (H3 und.) and 32 nm (H5 und.)

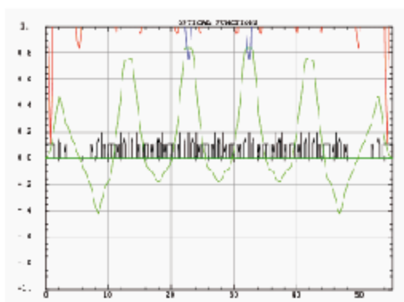
ERL configuration



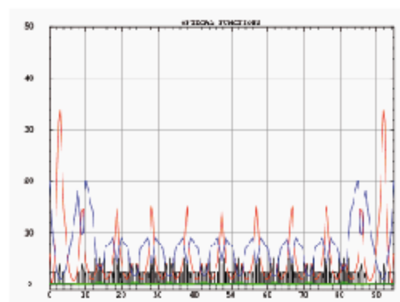
Recirculation ARC : optical function (A. Loulergue et al.)



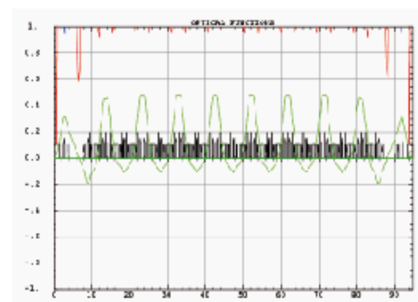
1 GeV, beta function



1 GeV, dispersion



2 GeV, beta function

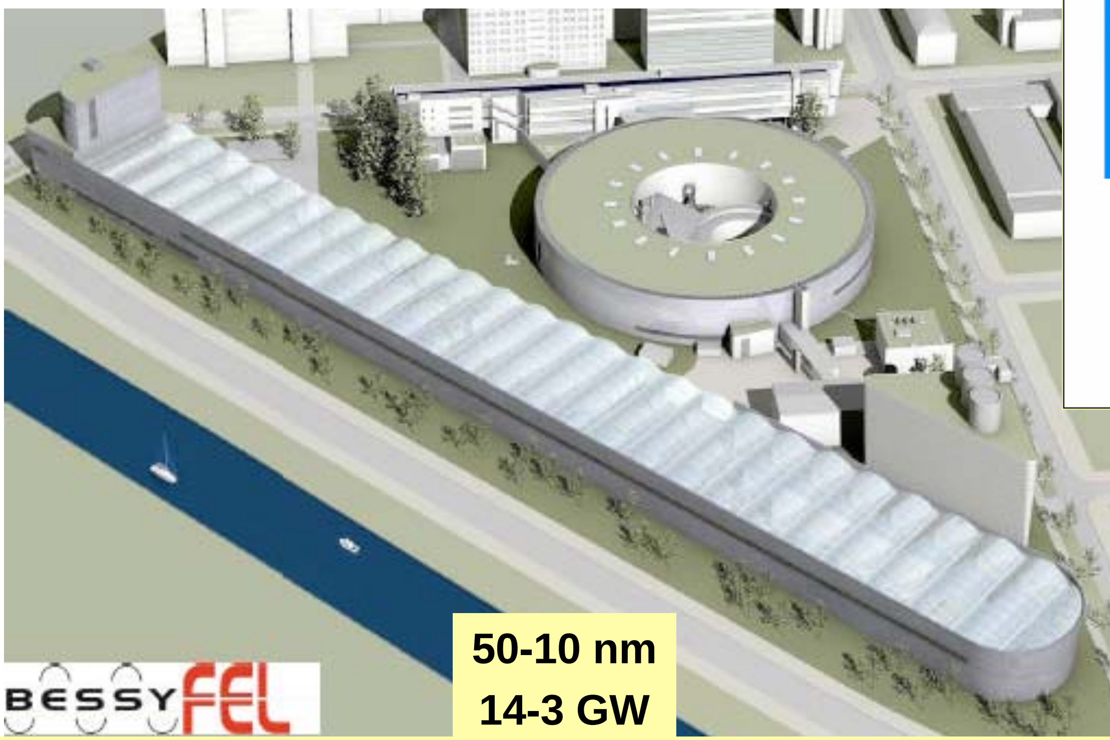


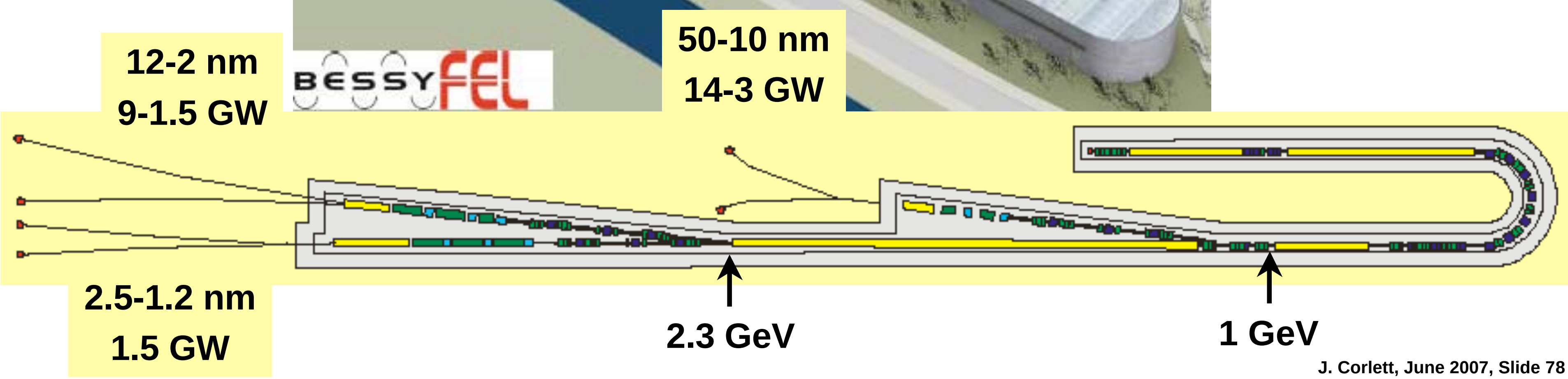
2 GeV, dispersion

BESSY FEL

PROPOSAL FOR LINAC-BASED FEL FACILITY

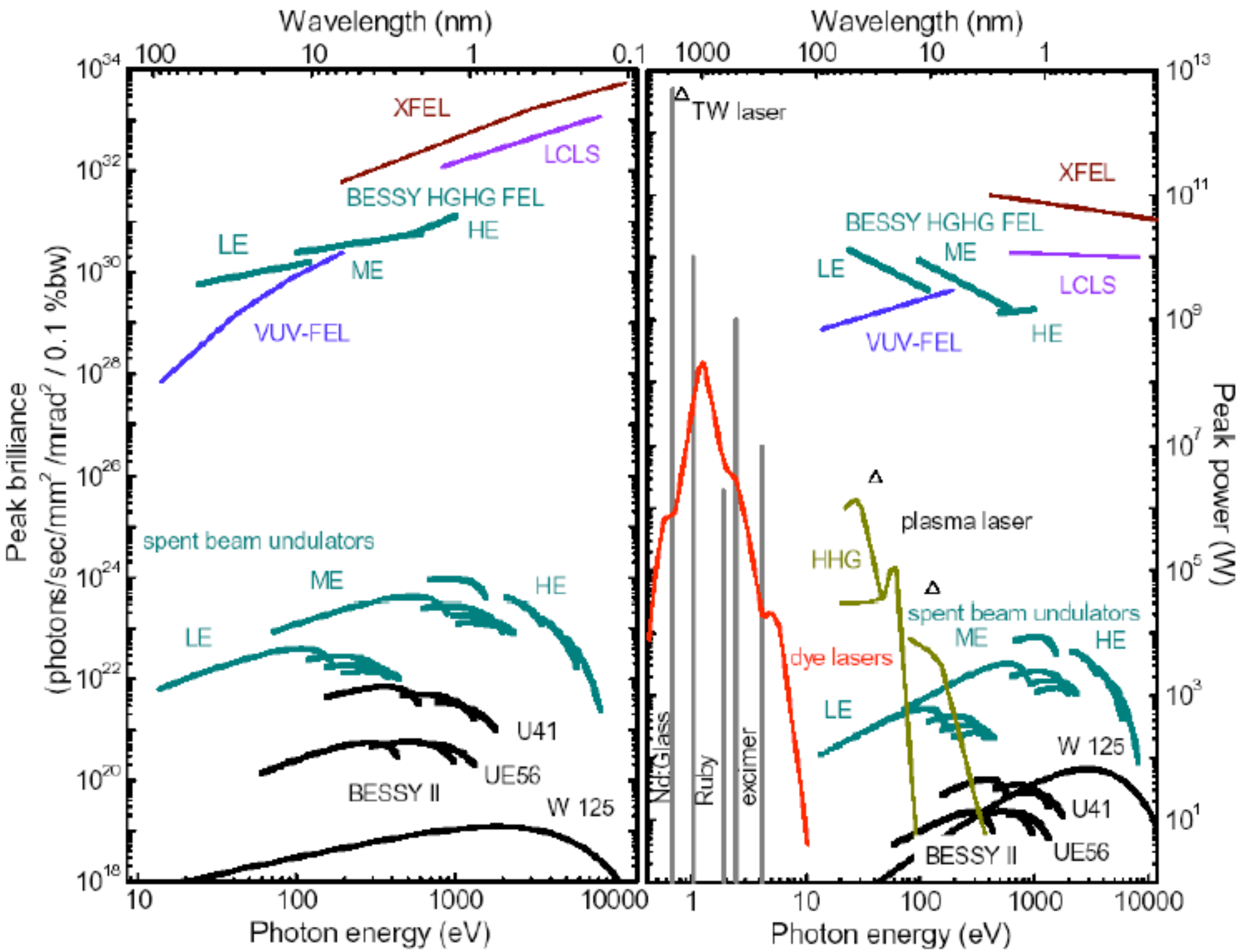
- **VUV-soft x-ray facility using harmonic cascade FEL's**
- **TESLA scrf technology developed for CW operations**





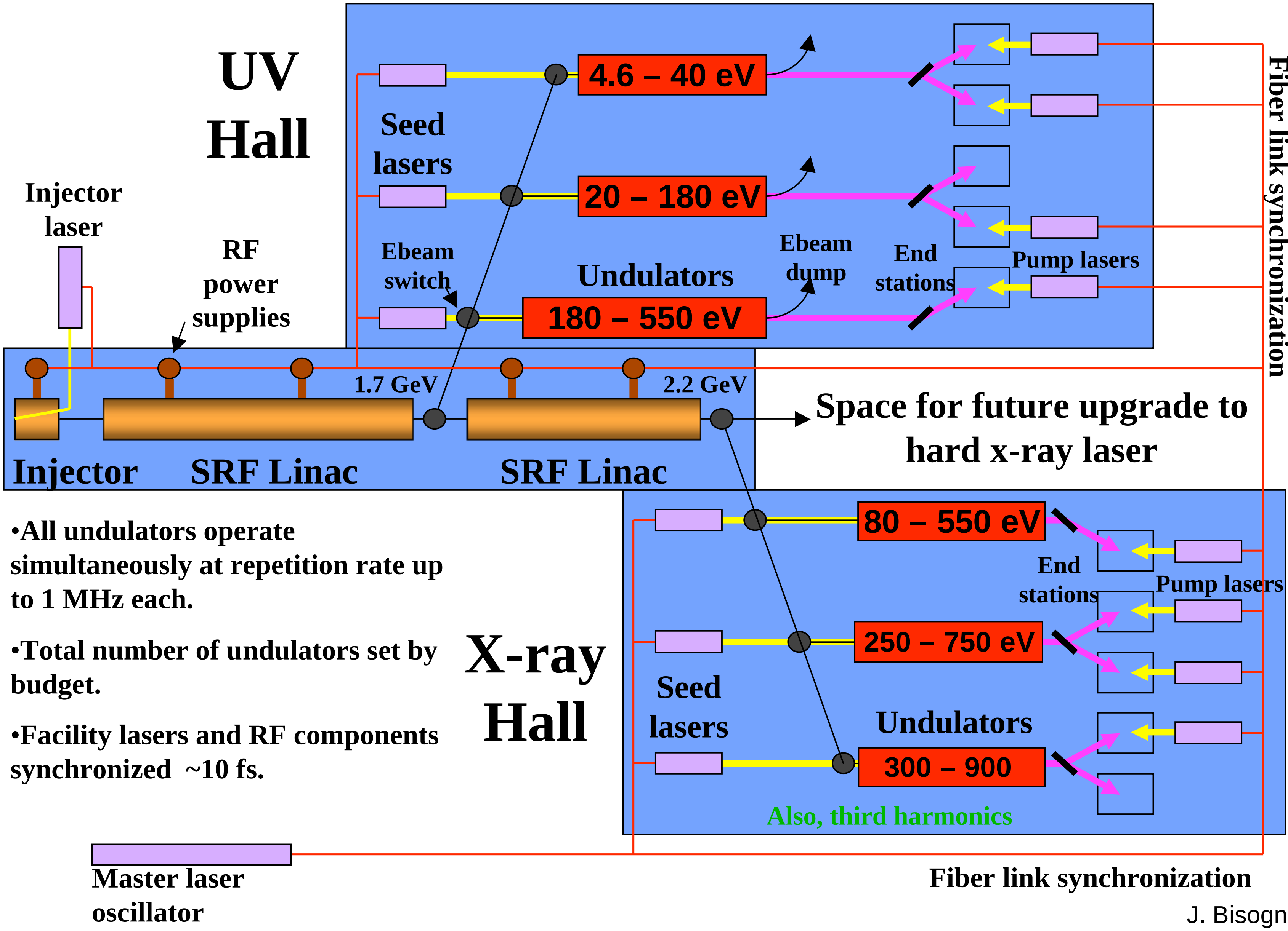
BESSY FEL

PROPOSAL FOR LINAC-BASED FEL FACILITY



Wisconsin FEL

CONCEPT FOR LINAC-BASED SEEDED FEL FACILITY



•All undulators operate simultaneously at repetition rate up to 1 MHz each.

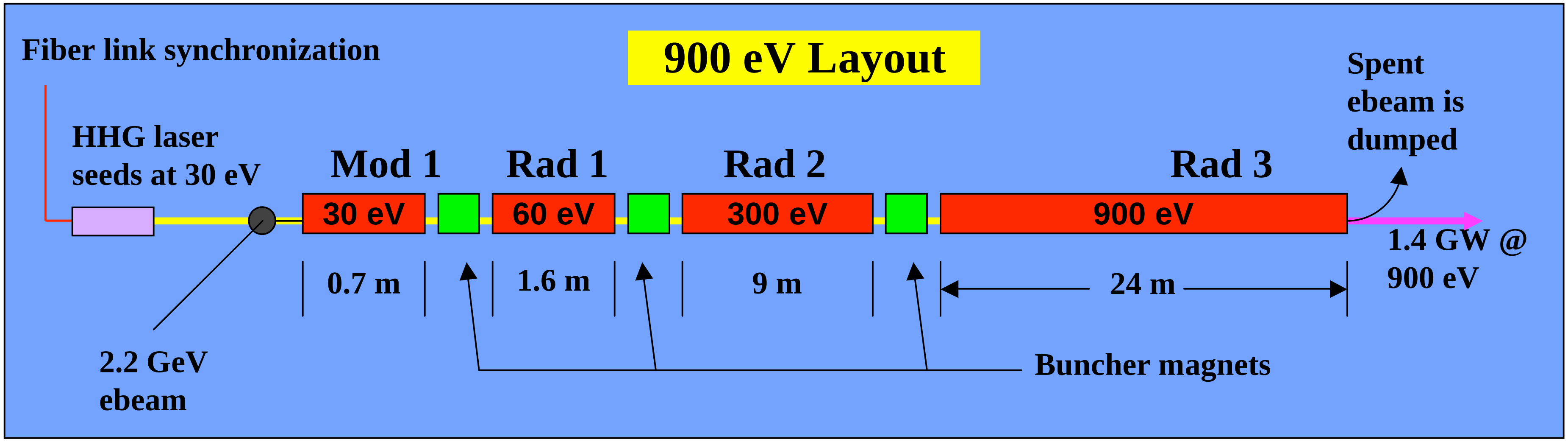
•Total number of undulators set by budget.

•Facility lasers and RF components synchronized ~10 fs.

J. Bisognano, SRC

Wisconsin FEL

UW 300 – 900 BEAMLINE

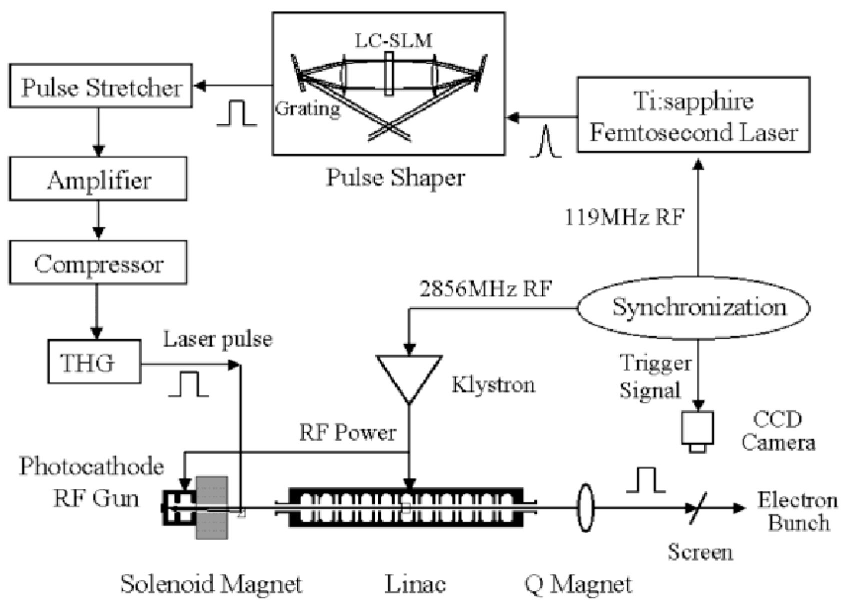


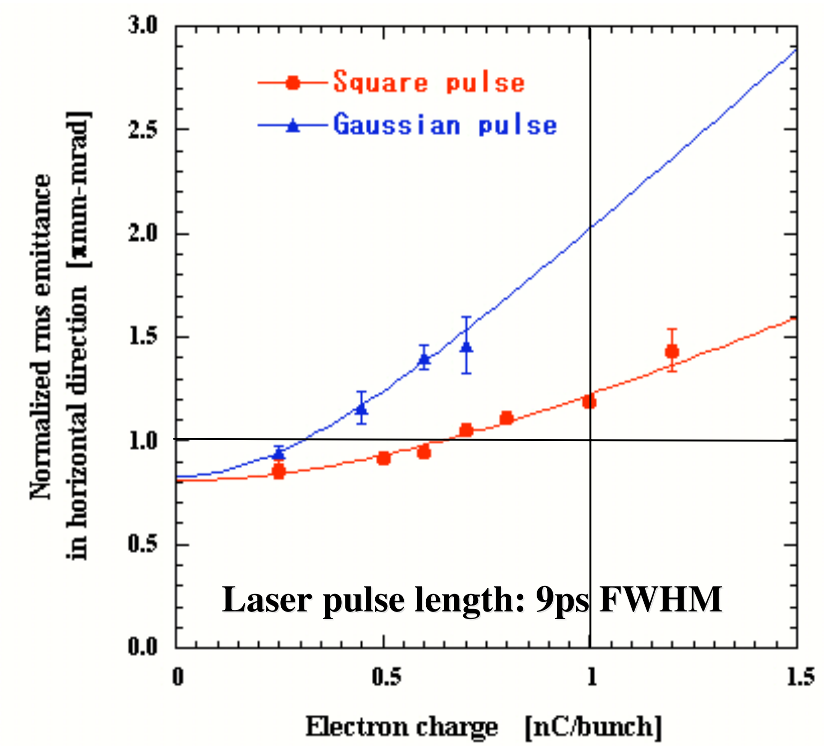
APPENDIX 2

TECHNOLOGIES FOR FUTURE FELS

1.2 mm-mrad demonstrated with 1 nC charge

LASER PUSE SHAPING CRITICAL IN PRODUCING HIGH QUALITY BEAMS

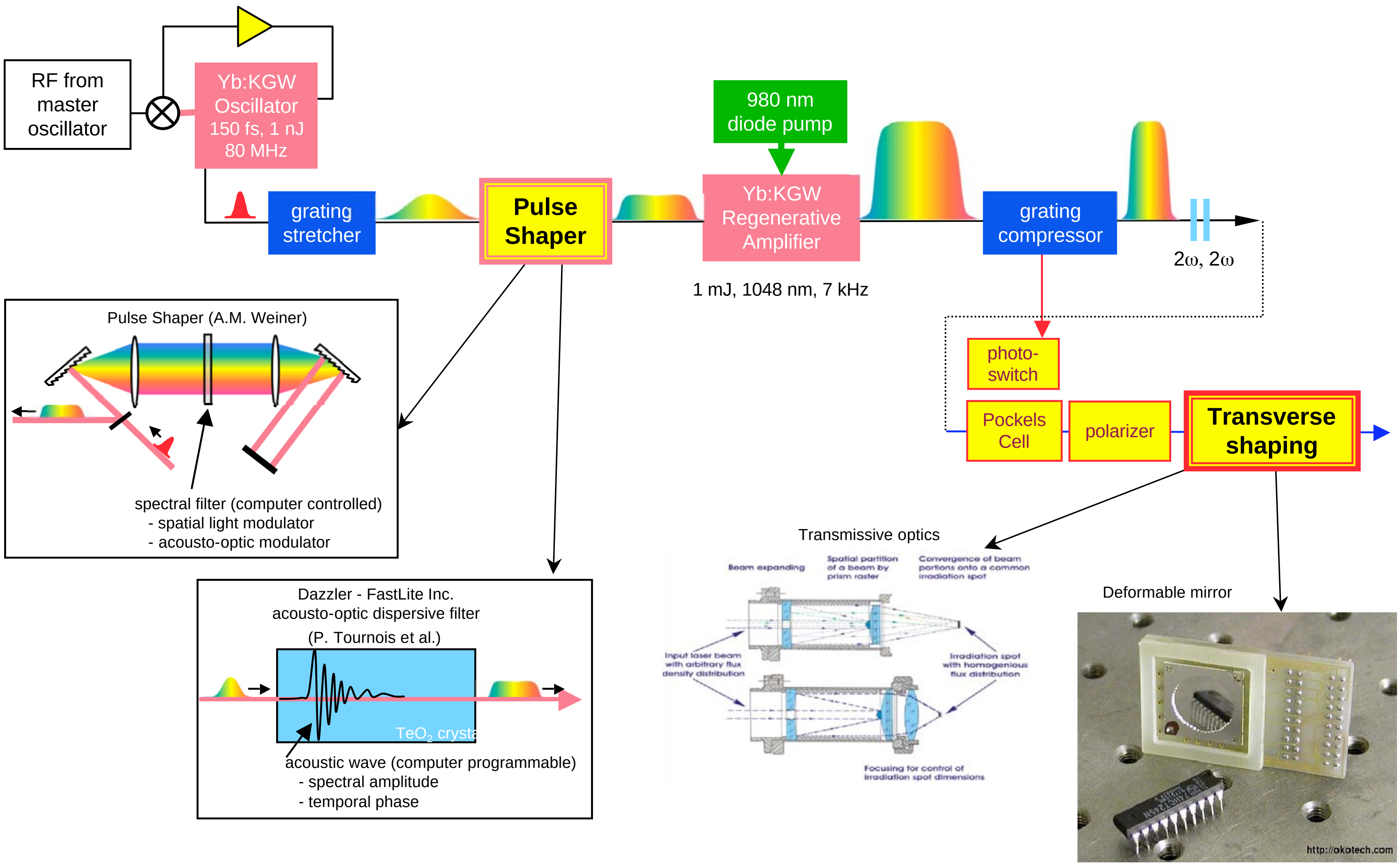




http://accelconf.web.cern.ch/AccelConf/e02/PAPERS/TUPRI075.pdf

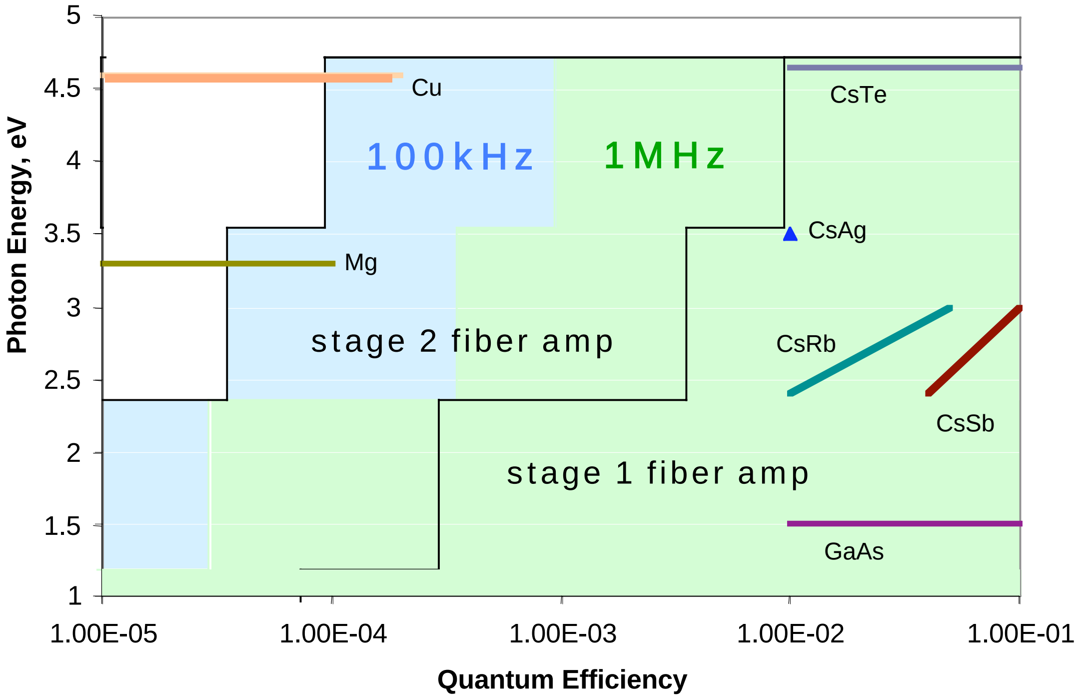
Laser pulse shaping is critical

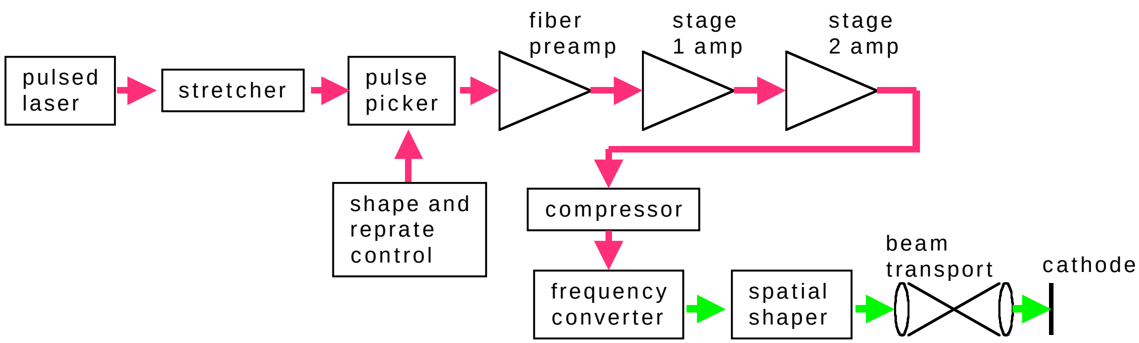
TEMPORAL AND SPATIAL SHAPING TO CONTROL PHOTOEMISSION



Photocathode laser systems design

HIGH POWER FIBER LASER

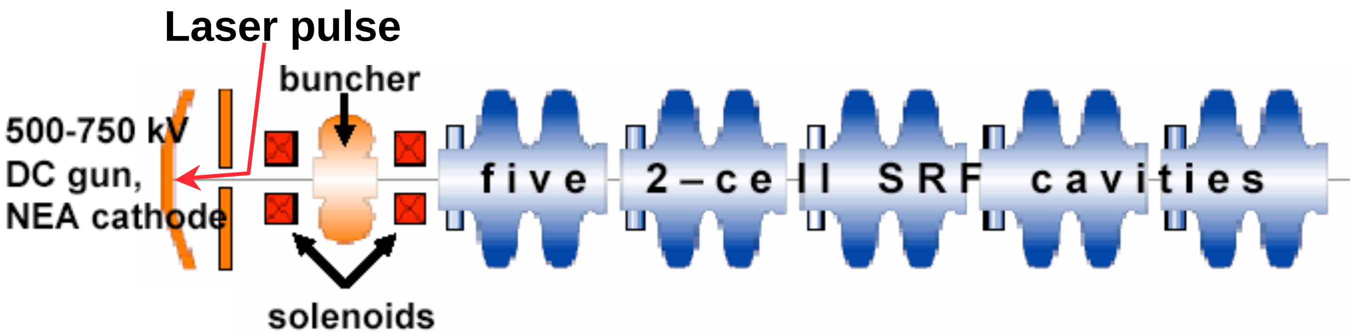




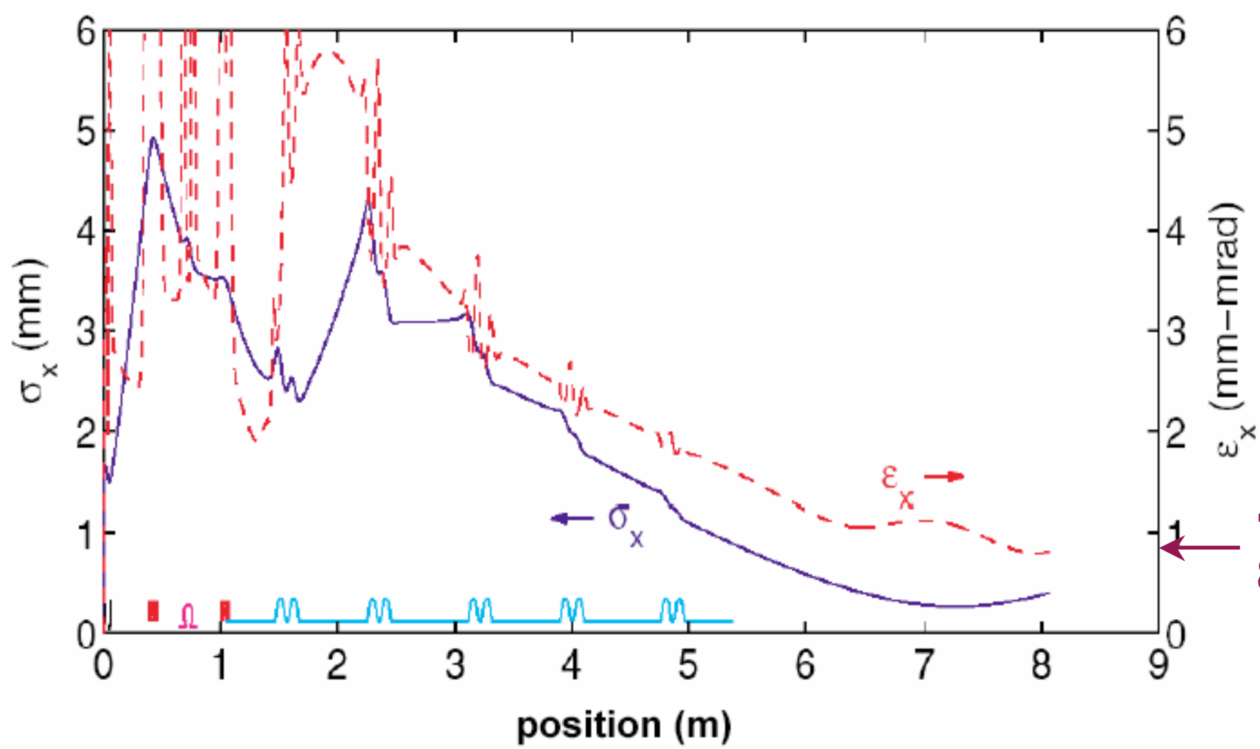
- **200 W fiber lasers available**
  - **1064 nm**
  - **Stage 1 amplifier**
    - **20 μJ at 1 MHz**
- **Harmonic conversion for some cathode materials**
- **Stage 1 is sufficient for cathodes with QE>10^{-3}**
  - **nC bunches from metals requires ~2 mJ in IR**
  - **Stage 2 amplifier**
    - **Large mode area amp**
    - **200 μJ at 1 MHz**
      - **nC bunches at ~100 kHz achievable**

DC gun and SCRF injector

MULTIVARIATE OPTIMIZATION PREDICTS EXCELLENT PERFORMANCE



http://prst-ab.aps.org/pdf/PRSTAB/v8/i3/e034202



< 1 mm-mrad
800 pC

Optical manipulations

NUMERIC EXAMPLE

$$\Delta E(\varphi) = 2\sqrt{A_L A_R \frac{\Delta\omega_L}{\Delta\omega_R}}\cos(\varphi)$$

$$A_R \approx \pi\alpha\hbar\omega_R$$

$$\omega_R = \omega_L$$

$$\Delta\omega_R = \Delta\omega_L$$

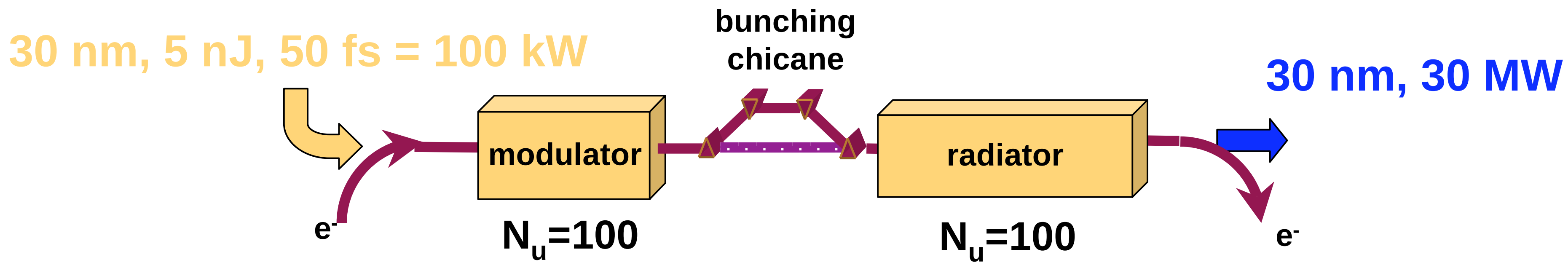
$$\left.\begin{aligned} \hbar\omega_L &= 45eV \\ A_L &= 5nJ \end{aligned}\right\}$$

HHG seed, 30th harmonic of Ti:sapphire

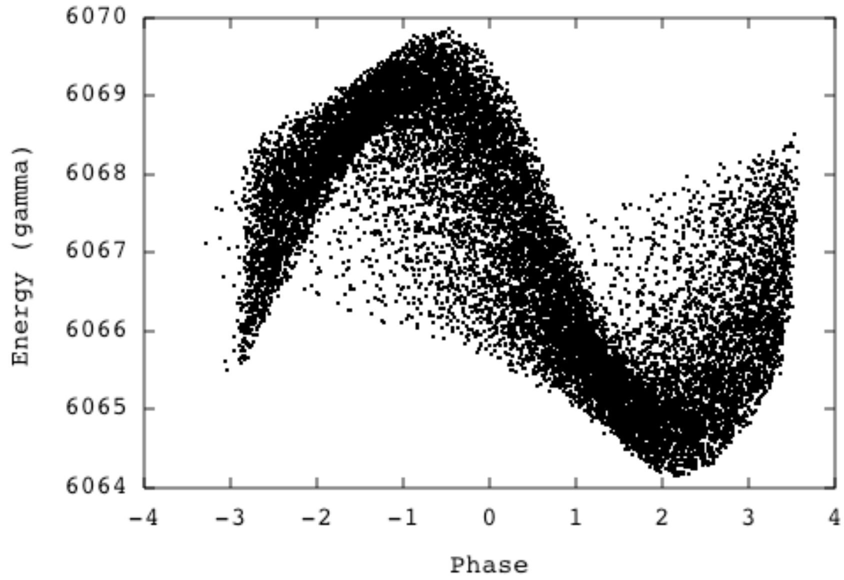
$$|\Delta E| = 360keV$$

Compare with ~100 keV incoherent energy spread in the beam

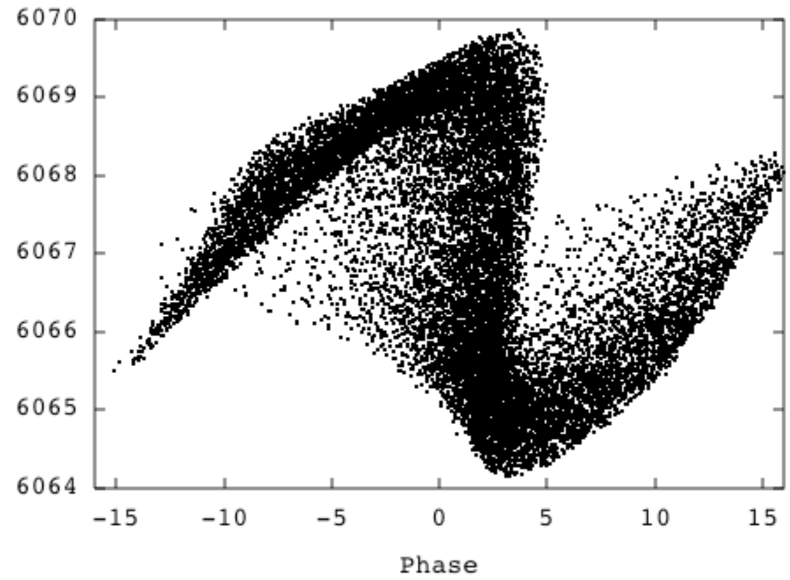
Optical klystron



Section of e-beam: modulation



Section of e-beam: bunching

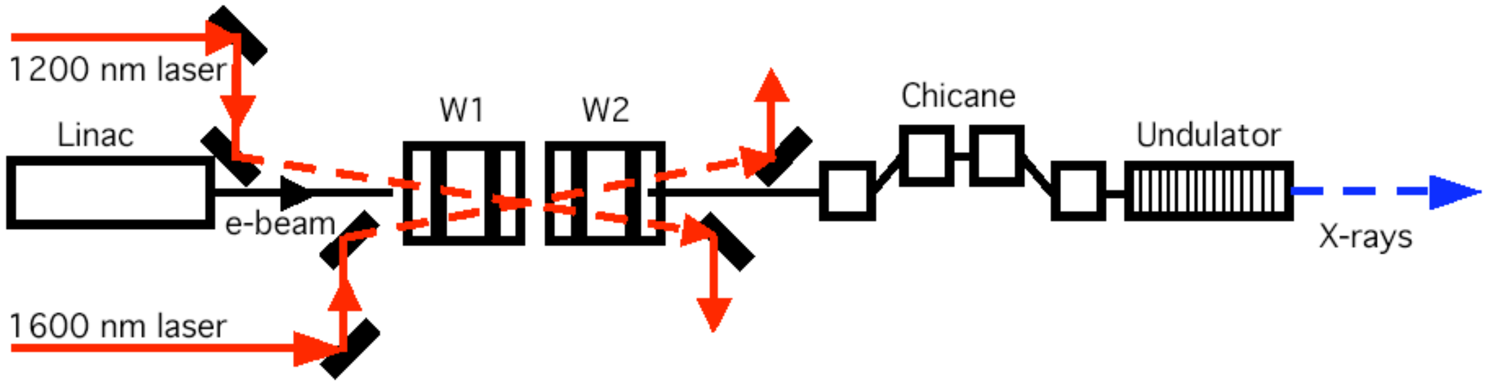


Skrinsky, Vinokurov,1977

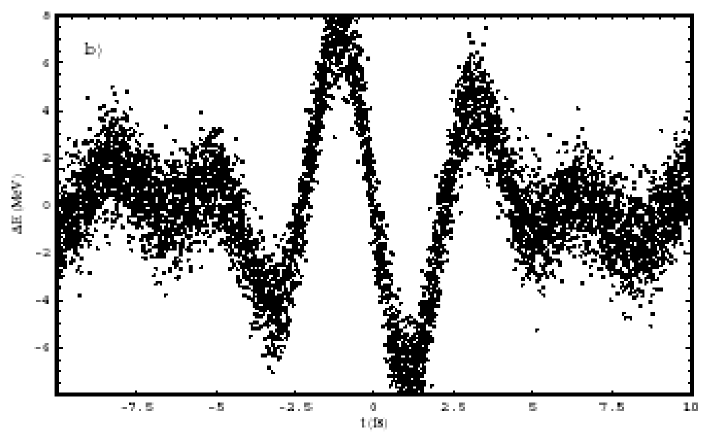
FEL configurations

(n) ATTOSECOND SASE PULSES

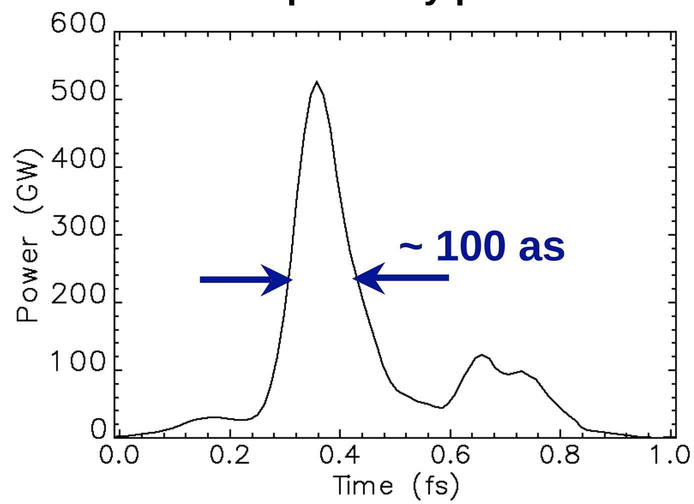
- **Attosecond x-ray pulse using energy modulation with two lasers**



Energy modulation with two lasers



Output x-ray pulse

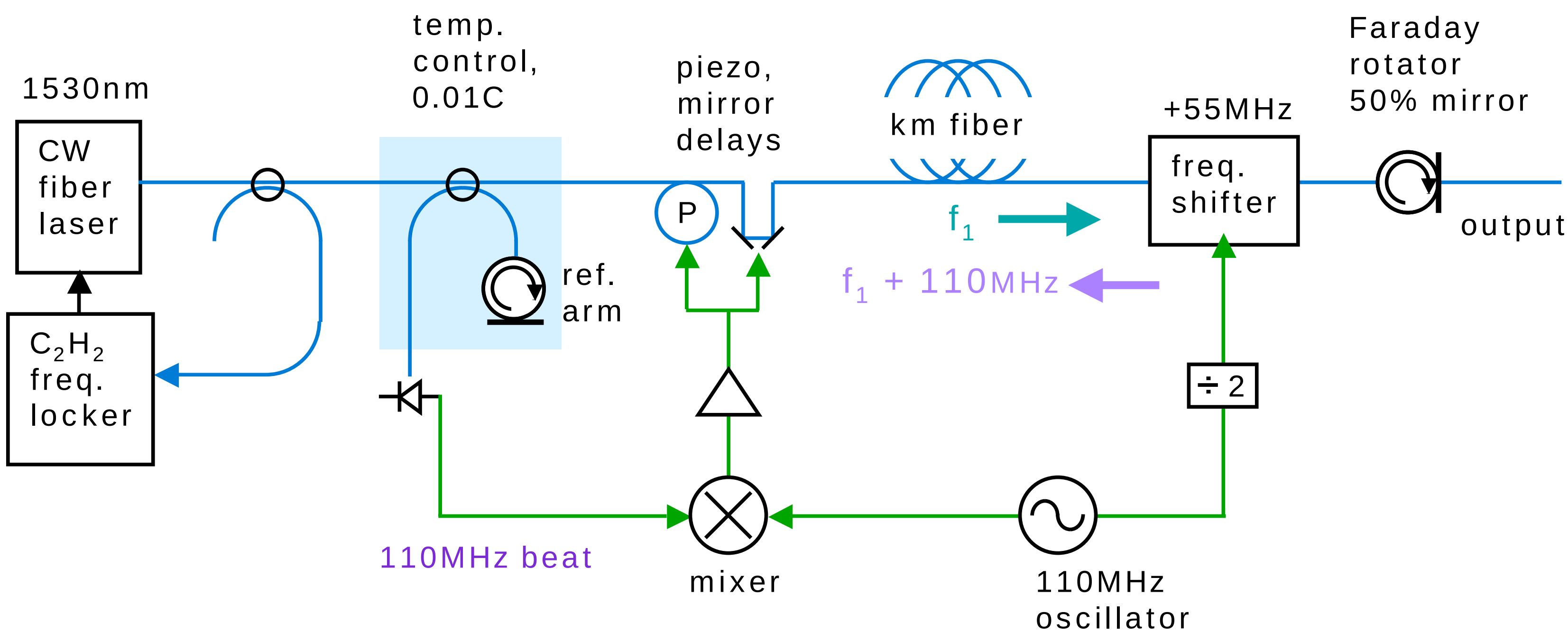


A.Zholents, W.M. Fawley, Phys. Rev. Lett. 92, 224801 (2004)
A.Zholents, G. Penn, Phys. Rev. ST Accel. Beams 8, 050704 (2005)

Interferometric phase delay controller

STABILIZED TIMING SYSTEM

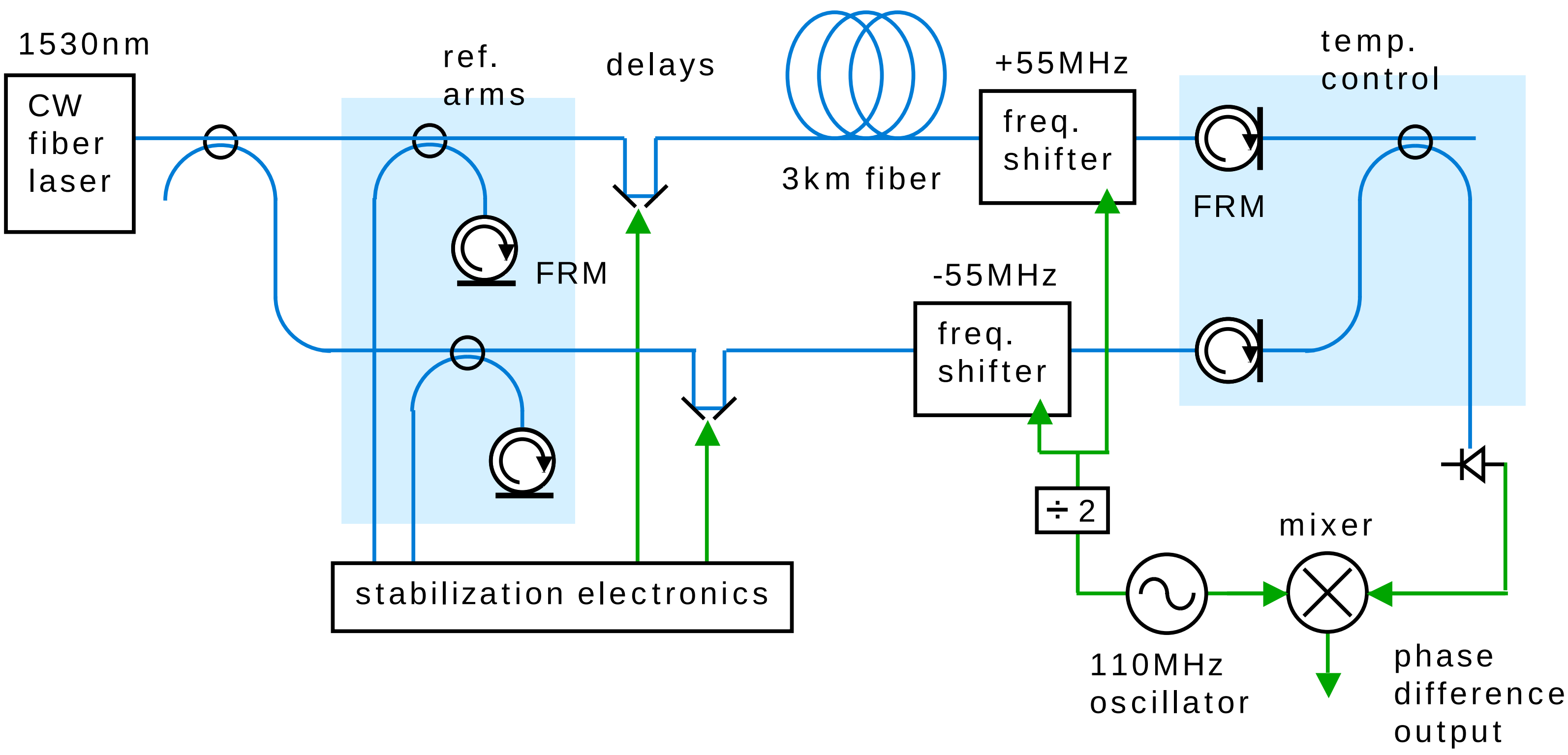
- **Measure delay with frequency shifting interferometer**
  - **Developed for radiotelescope arrays (ALMA)**
  - **RF phase = optical phase**
- **Laser frequency stability = allowable error / total delay**
  - **Required stability is 10^{-9} for 10fs, 2km**



R. Wilcox

Comparing two phase stabilized fibers

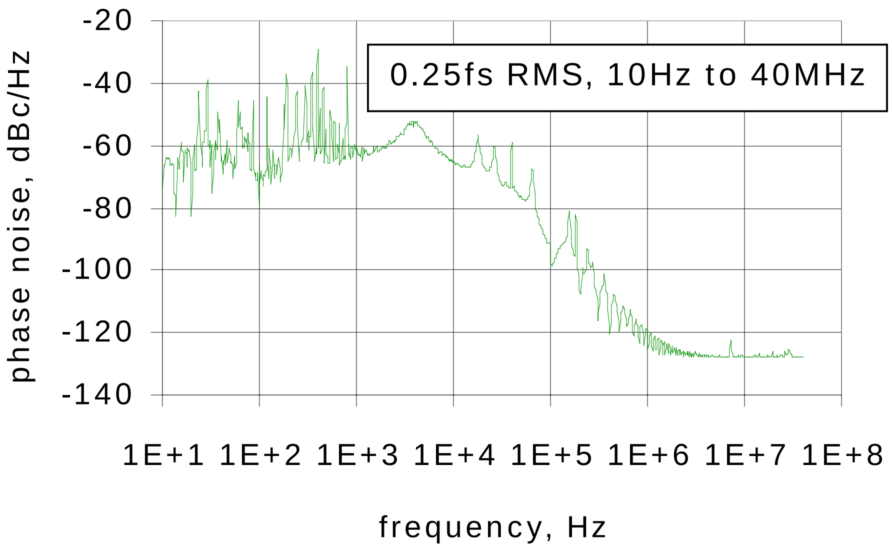
- Unequal arm Mach-Zehnder interferometer, 3km vs. ~4m
- 2km are LAN fiber, 1km is on spool
- Two arms independently controlled, relative phase measured



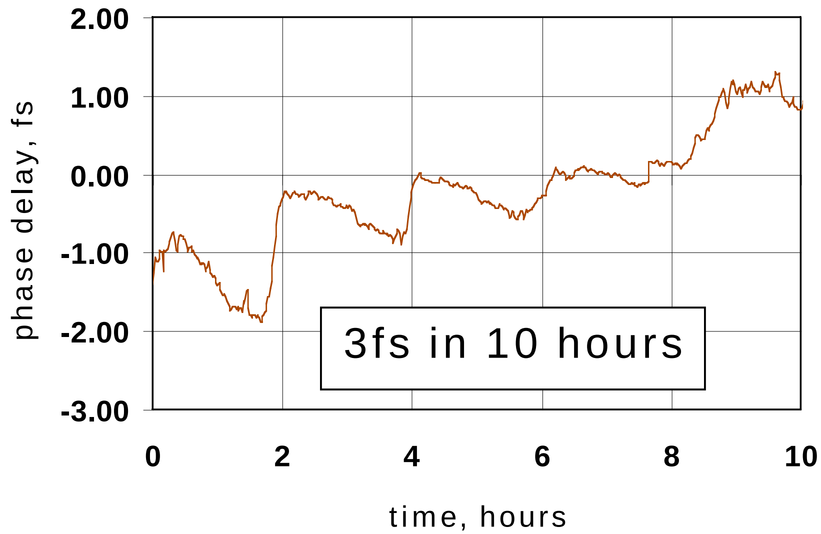
R. Wilcox

Results of two-arm experiment

Jitter versus frequency:



Phase delay in fs versus time:



- **Drift from room and outside temperature**
- **Total correction is ~100ps per day**

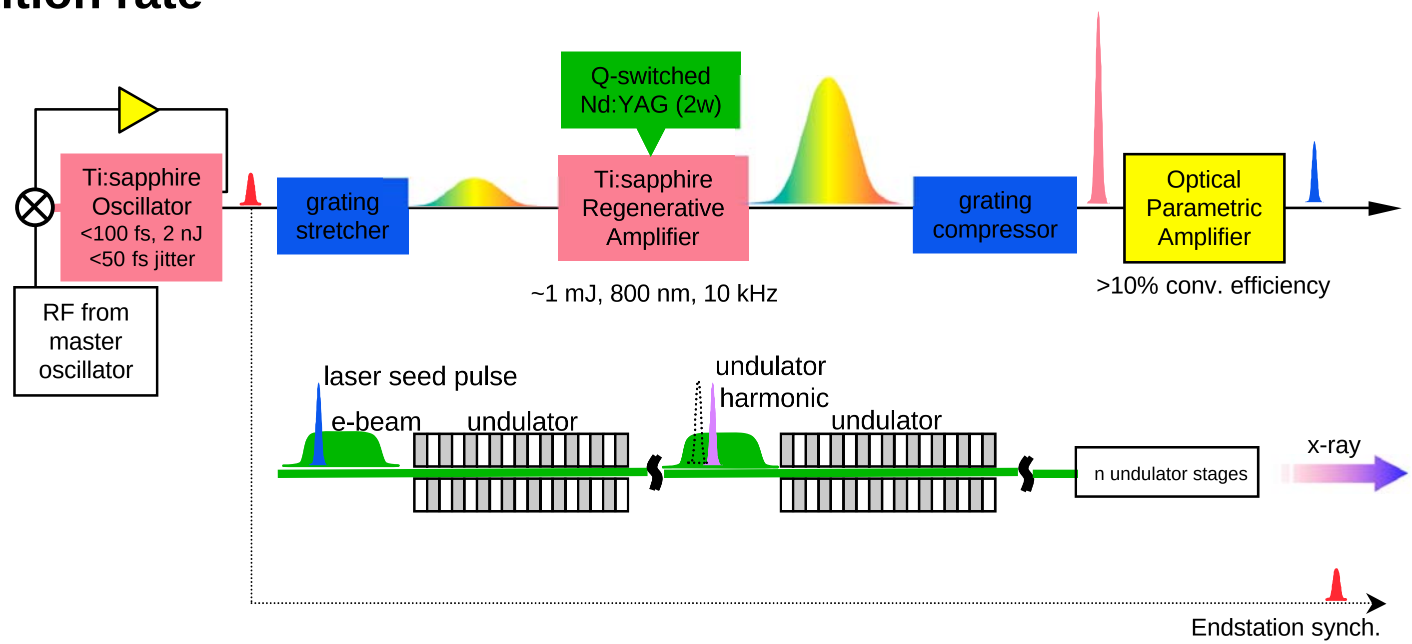
We can deliver stable relative phase over two fibers
LBNL will deliver timing & synchronization systems to LCLS

R. Wilcox

FEL seed laser

OPTICAL PARAMETRIC AMPLIFIER PROVIDES FEL SEED

- **Wavelength tunable**
  - **190-250 nm**
- **Pulse duration variable**
  - **10-200 fs**
- **Pulse energy**
  - **10-25 μJ**
- **Pulse repetition rate**
  - **10+ kHz**



- **Endstation lasers seeded or synchronized to Ti:sapphire oscillator**

Noise evolution in seeded FEL

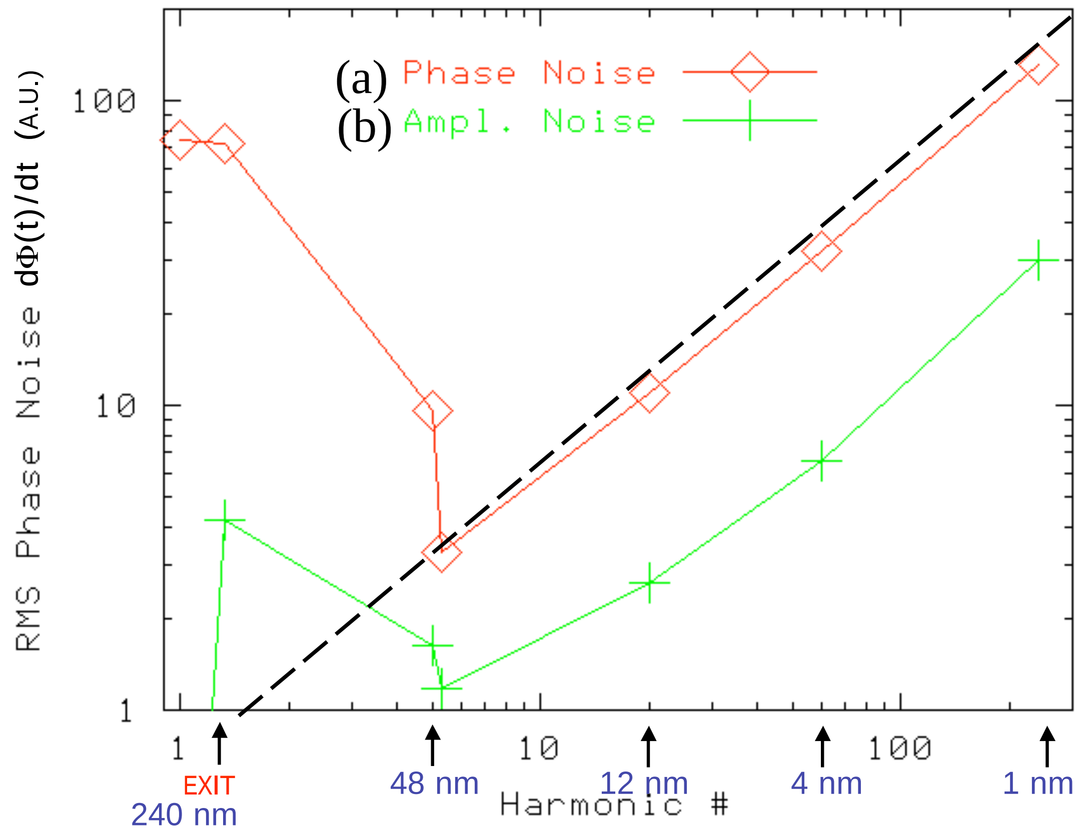
SIMULATIONS FOR A 4-STAGE CASCADE 240 nm $\Longrightarrow$ 1 nm

- **Input laser seed initialized with broadband**
  - **(a) phase noise**
  - **(b) amplitude noise**

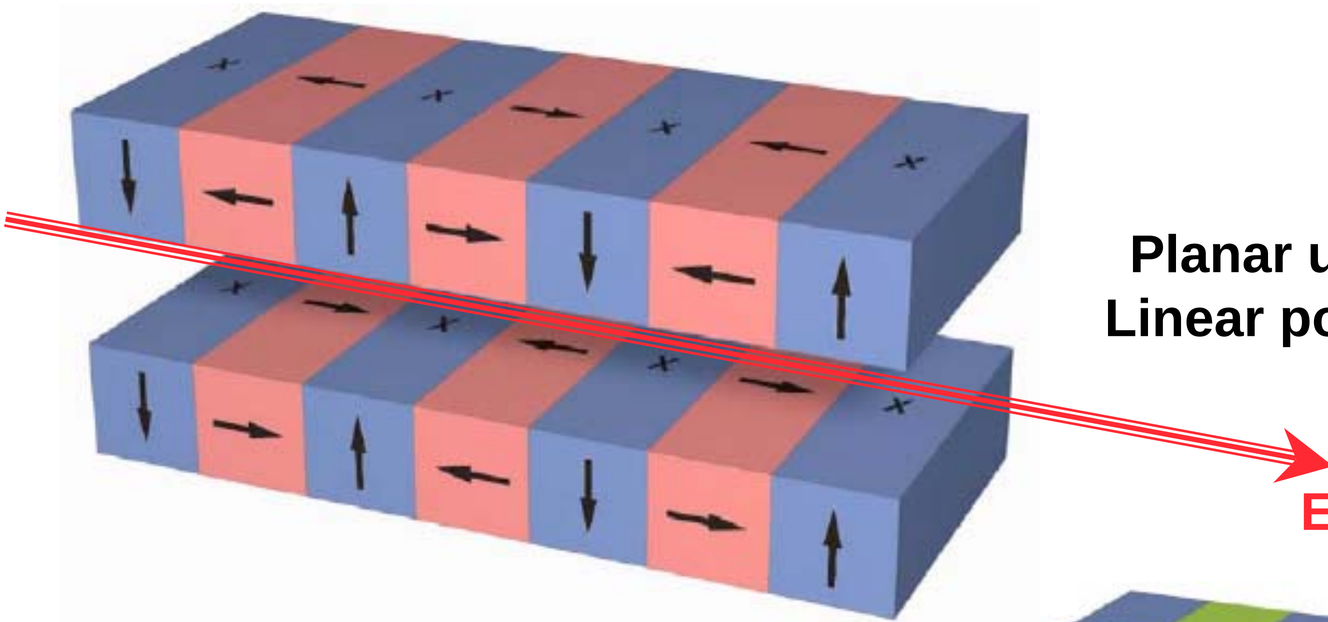
- **Fields resolved in simulation on 240 nm/c temporal resolution or better**
  - **Noise reaches minimum at 48-nm stage (slippage averaging)**
  - **In later stages noise increases due to harmonic multiplication of low frequency components**

RMS phase noise dF(t)/dt after removal of average component

$$\left(\frac{P_{\text{signal}}}{P_{\text{noise}}}\right)_{\text{out}} \approx N^2 \left(\frac{P_{\text{signal}}}{P_{\text{noise}}}\right)_{\text{in}}$$



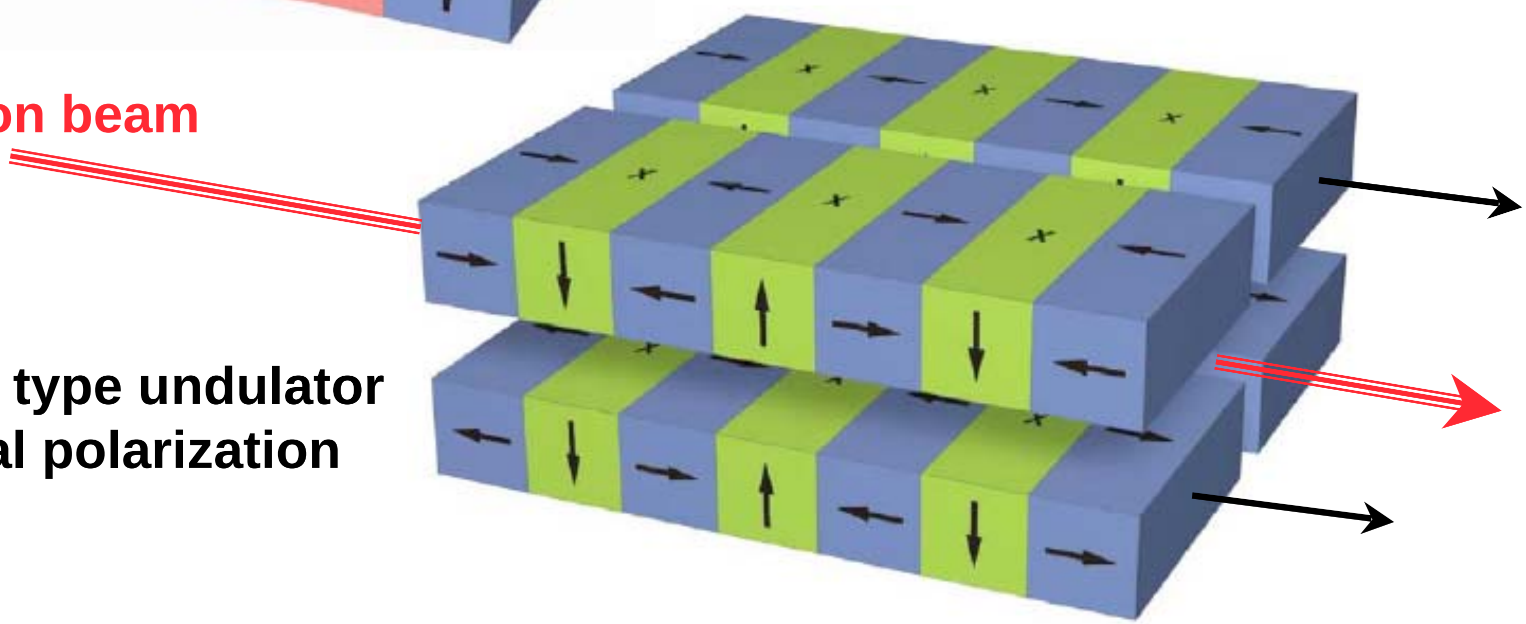
Final radiator controls polarization of photon beam



Planar undulator
Linear polarization

Electron beam

Electron beam

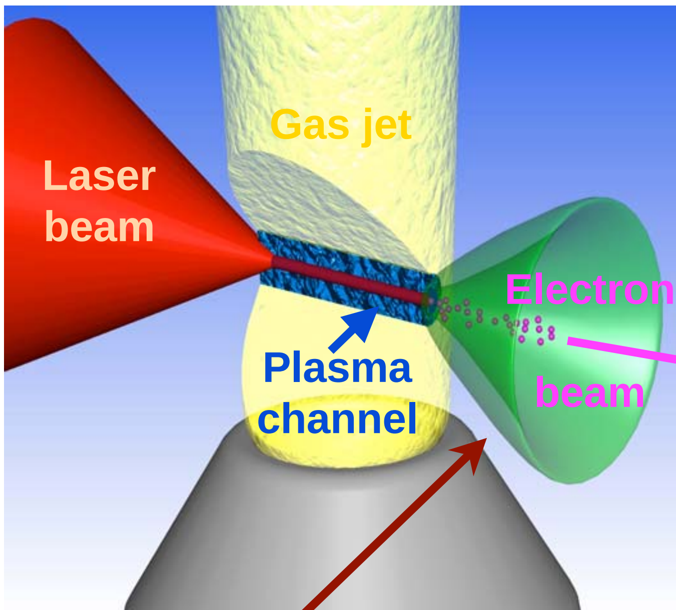


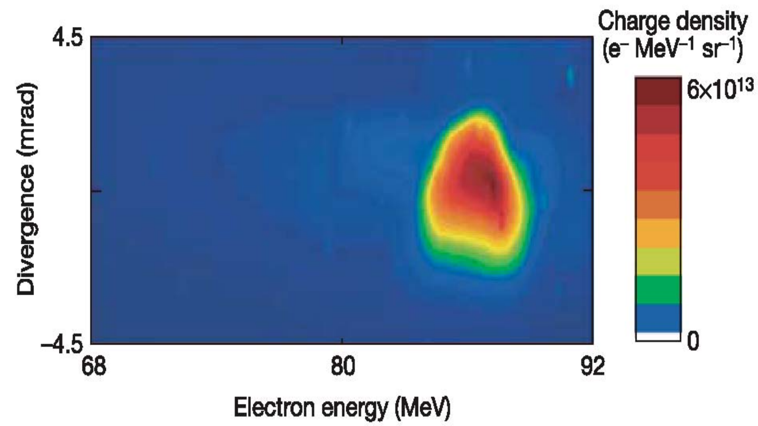
"APPLE" type undulator
Elliptical polarization

Laser wakefield accelerator

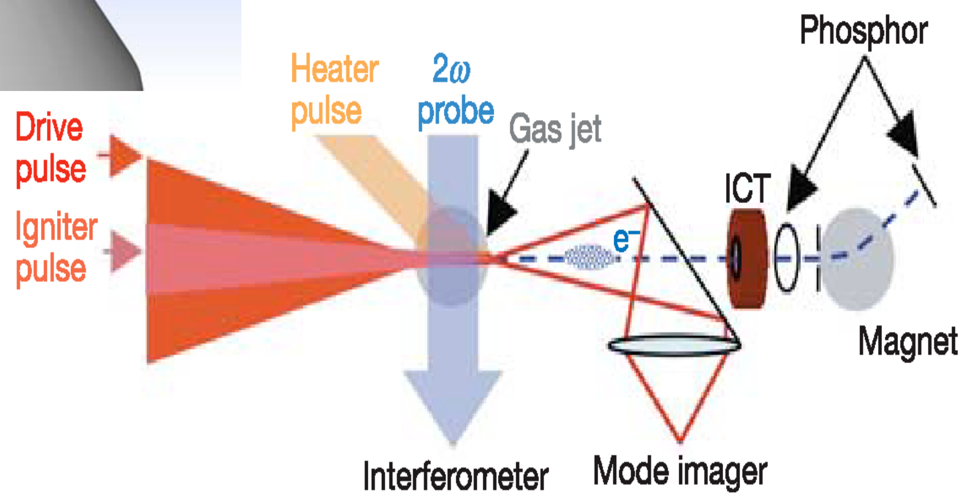
✓ **Step 1: Electron gun: 100 MeV in < 2mm**

~ 1% energy spread
~ 1 mm-mrad emittance





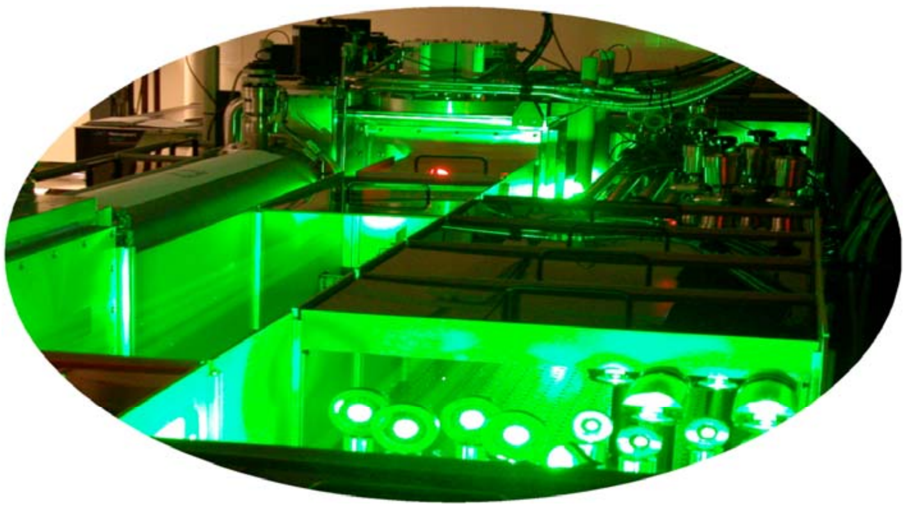
+ CSR from emerging beam

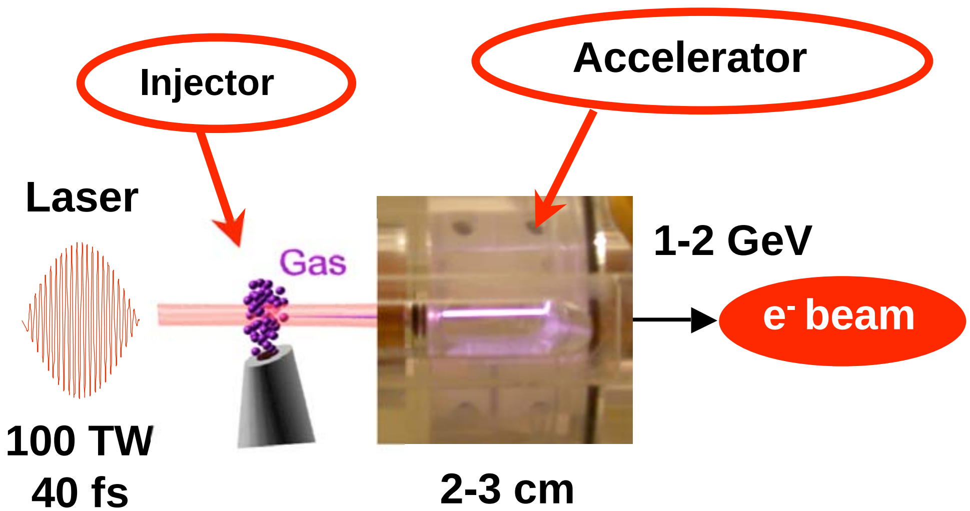


C. G. R. Geddes, et al, Nature, 431, p538, 2004

Laser wakefield accelerator

✓ Step 2: Accelerator: 1 GeV in < 5 cm





1 GeV achieved

Potential to use the electron beam in an FEL