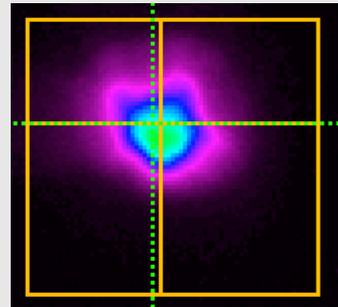
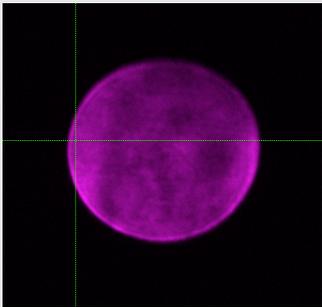


Update on FERMI @Elettra and the Issue of Circularly-Polarized On-Axis Harmonics

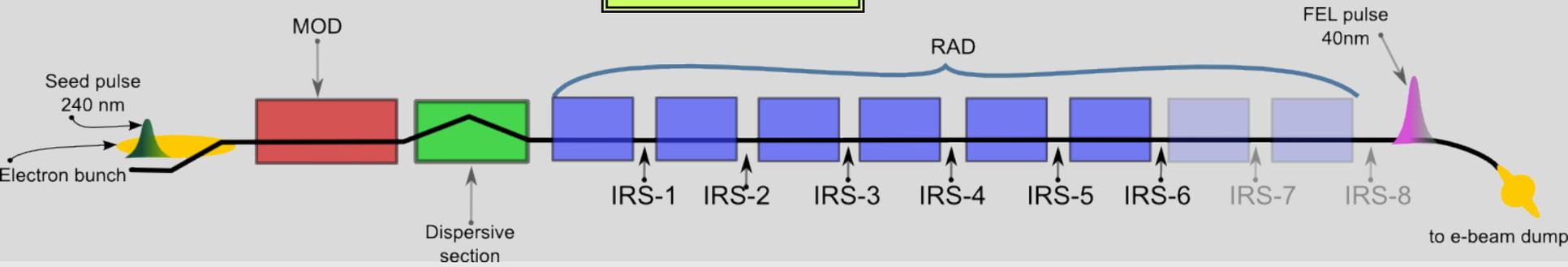
W. Fawley for the FERMI Team

Slides courtesy of S. Milton & Collaborators

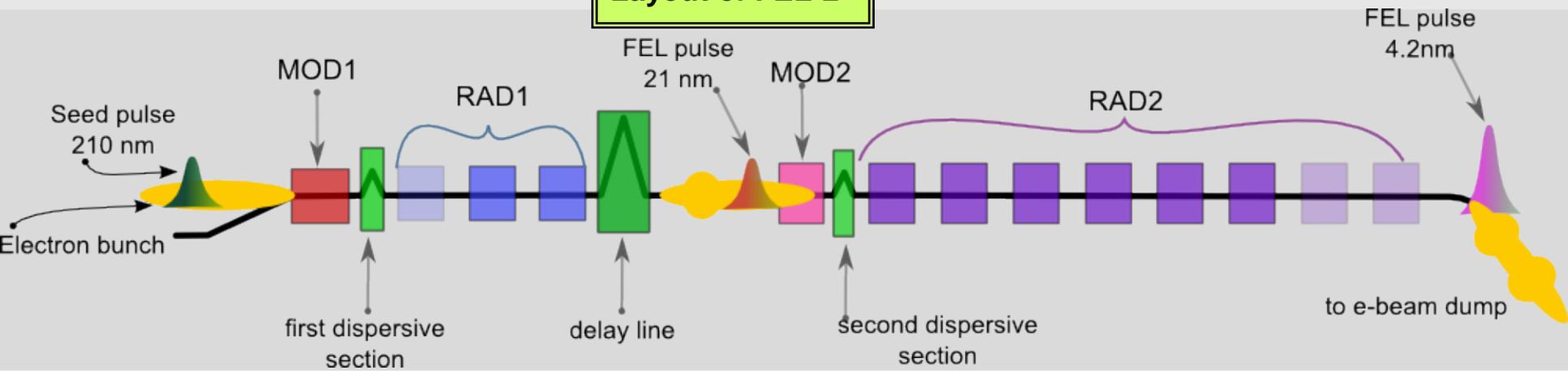


- **FERMI@Elettra** is a single-pass FEL user-facility, with output wavelengths of 100 to 20 nm (FEL-1) and 20 to 4 nm (FEL-2) ; total project cost ~ **130 M-Euros**
- **Major characteristics:**
 - 1.5 GeV, 50 Hz, 800 A, ~400 fs, 1.5 mm-mrad e-beam
 - Seeded harmonic cascade (“HGHG”-like); 2 stages for FEL-2
 - High peak power (~GW), ultrashort (100 fs to 10 fs) output pulses
 - Synchronization to external laser sources
 - APPLE II-type undulators for both variable wavelength and polarization
 - Advanced feedback and feed-forward systems to improve output stability
 - Use of 3rd harmonic extends λ range down to L-edges of magnetic materials
- **Commissioning** began in fall 2009...
 - Gun to laser heater Sept.- Nov. 2009 [**done**]
 - Laser heater and accel. to BC1 (diags) Feb.-Mar. 2010 [**now!**]
 - BC1 and remaining linac summer 2010
 - Undulator installation early fall 2010 → **first light late 2010**
- FEL-1 begins user operations in early 2011, **FEL-2 in late 2011**

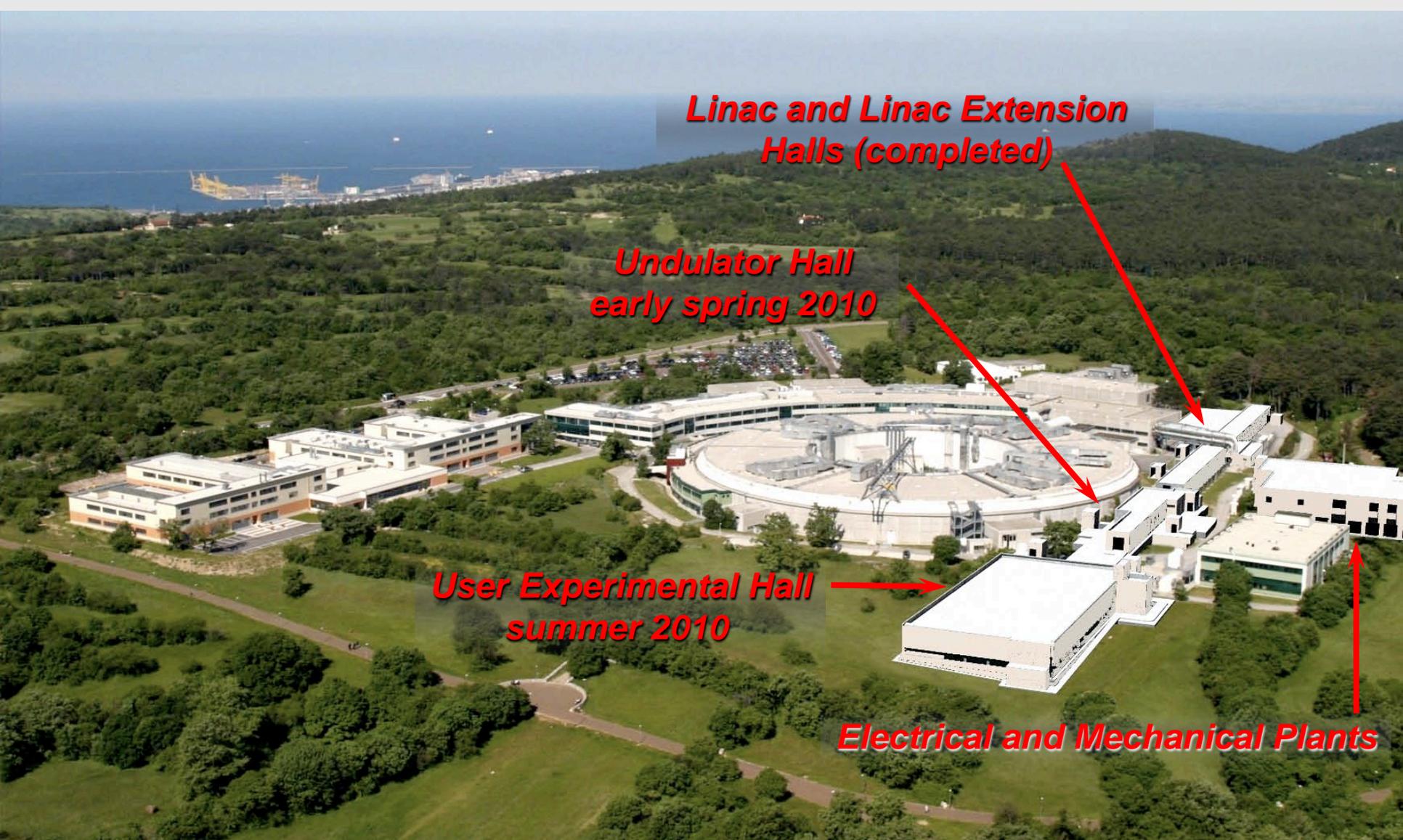
Layout of FEL-1



Layout of FEL-2



Space exists for additional radiator undulators if needed or wanted. Possible upgrades later will consider use of EEHG, HHG schemes.



Linac and Linac Extension Halls (completed)

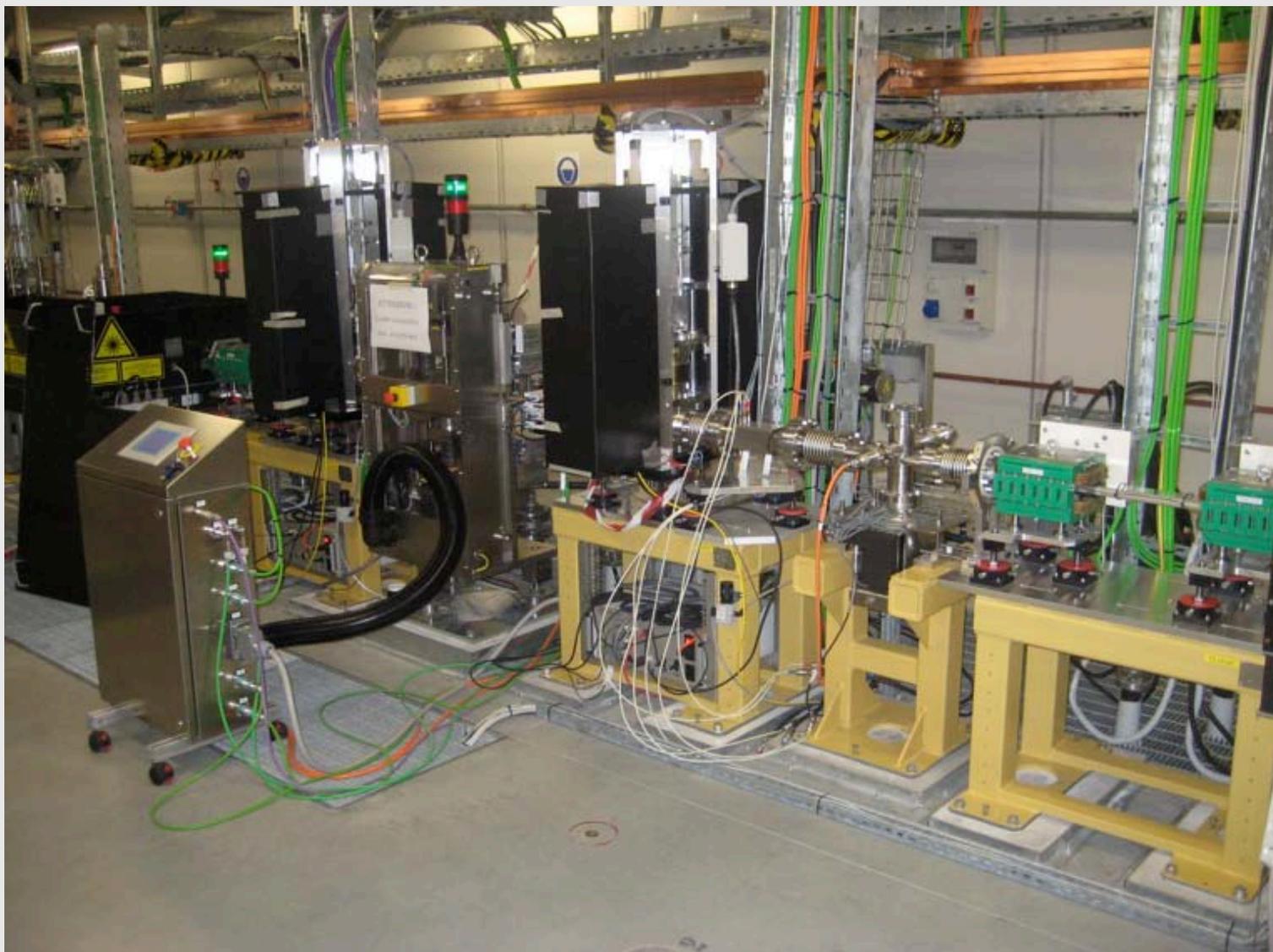
Undulator Hall early spring 2010

User Experimental Hall summer 2010

Electrical and Mechanical Plants



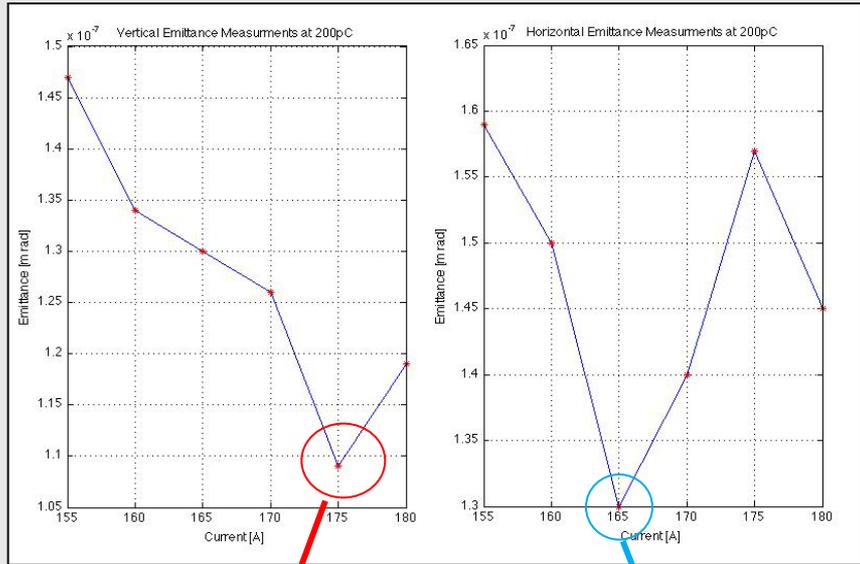




Emittance measurements @ 5MeV, 74 MeV

Nov. '09 slit method measurements of the X- and Y-emittance varying the gun solenoid strength (@200pC charge)

Quad Scan - 10Feb10
vertical beam size; 74 MeV



Y-plane: Min. value of 1.08 μrad at 175 Amps

X-plane: Min. value of 1.30 μrad at 165 Amps

lh/power_supply/psq_lh.04

Imin: -5 Imax: 1

Steps: 10

CCD

lh/diagnostics/msrccd_lh.01

Image: 3

ROI Defined gaussian fit

Background Subtraction

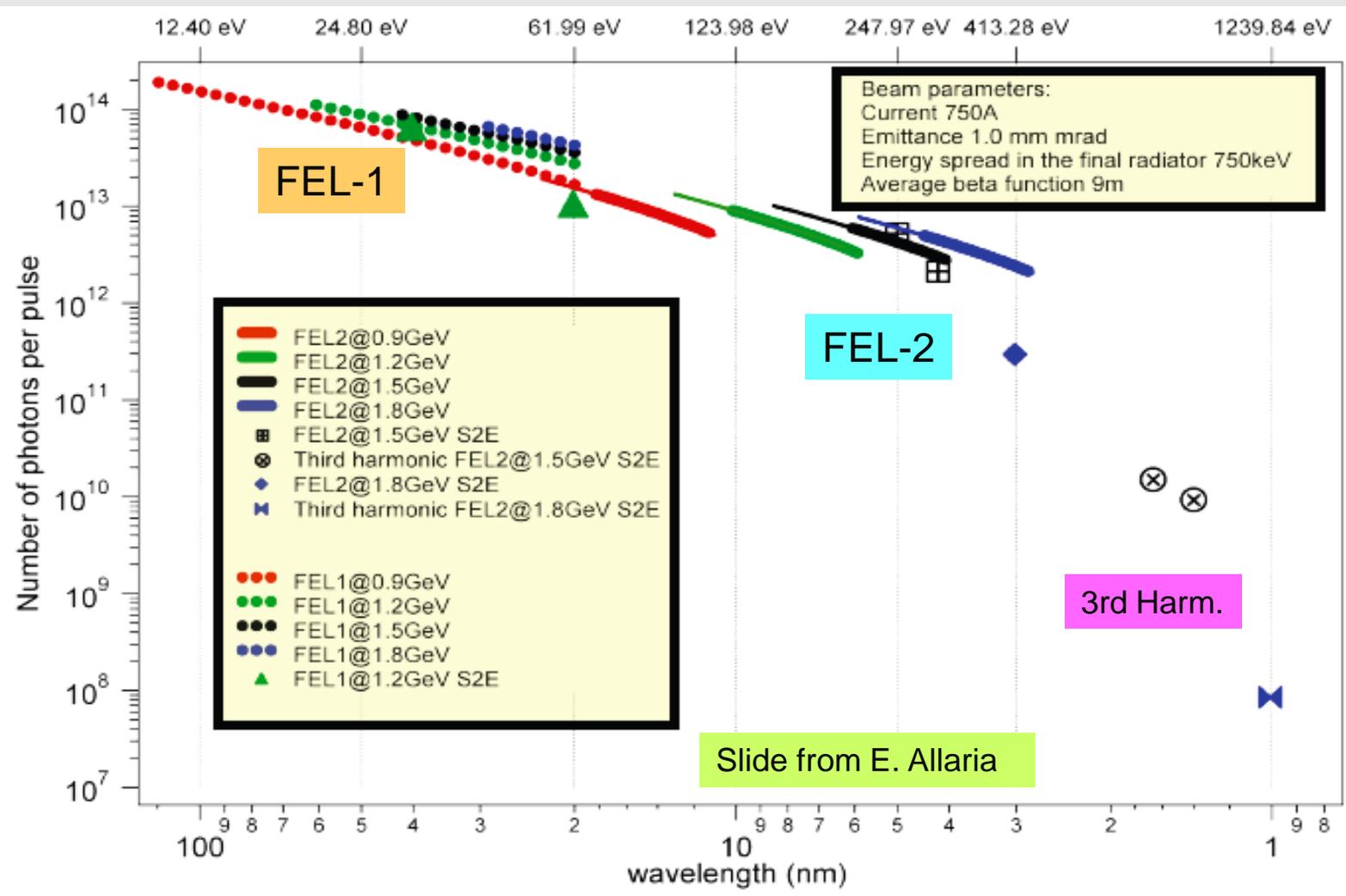
Beam Energy (MeV): 73.4

START MEASURE

Twiss par. in Ver. Plane
 $\epsilon_{\text{geom}} = 9.58 [\text{nm rad}]$
 $\beta = 1.68 \text{ m}$
 $\alpha = 2.78$
 $\gamma = 5.18$

norm. emittance: 1.38 mm mrad

Slide courtesy of M.Petronio, A.Lutman



Lines predicted using M.Xie formulae for expected FERMI parameters assuming 40fs pulse length
 Points Ginger and Genesis simulations for S2E files

- E-beam energies of 1.5 GeV needed for reasonable gain at 4 nm
 - final radiator λ_w reduced to 35 mm to help gain
- Incoherent energy spread is a “known unknown” (or “unknown known” ???)
 - BC1 results in summer ‘10 should help settle an important beer bet
- FEL-2 will be first operational 2-stage harmonic upshift FEL
 - can we go from ~200 nm to ~4 nm in 2 stages?
 - final radiator deep in exp. gain regime
 - output bandwidth sensitivity to quadratic chirp, e-beam imperfections
 - $\langle E \rangle$, timing jitter are important issues determining jitter in P_{out}
- Diagnostics below 20 nm get tougher and tougher....
- Will pump probe synchronization work smoothly?
- 3rd harmonic emission critical for magnetic materials studies in 1-2 nm region

- Linearly-polarized undulators with $K \geq 1$ have odd harmonic, on-axis emission due to electron “figure-8” motion in x-z plane
- “Pure” helical undulators do not generate harmonic emission ($h > 1$) on axis
 - Freund *et al.* (*PRL* **94**, 074802) claimed coherent emission on-axis; **disproved** by Geloni *et al.* (*NIM A*, 581, 856), Allaria *et al.* (*PRL* **100**, 174801)
 - Off-axis emission exists for all $h > 1$; well-known effect in light sources
 - But there is destructive interference of emission from non-zero sized **coherent** sources when viewed by off-axis observer:

$$I \propto \exp\left[-\frac{1}{2}h^2k^2\sigma_r^2 \sin^2 \theta\right]$$

- For large Fresnel numbers, this interference damps overall off-axis harmonic emission by > 2 orders of magnitude for $h \geq 2$
 - Resultant emission is within a narrow angle centered about $\bar{\theta} = \left(\frac{\lambda_w}{2Z_R}\right)^{1/2} \frac{1}{\gamma_z}$ and a FWHM width $\approx \bar{\theta}$ (see Geloni *et al.*)
 - Depending upon transverse coherent bunching parameters, this angle can be a factor of h smaller than the far-field opening angle for the FEL radiation at the fundamental wavelength

“Worse-Case” Estimate of Circularly-Polarized Harmonic Emission

- Off-axis emission from a **purely helical undulator** (destructive interference effects)
- Adapting Geloni *et al.*'s analysis for 2nd harmonic to high gain amplifier at saturation

$$\frac{P_{h=2}}{P_{fund}} \approx \left(\frac{f_b^{(h=2)}}{f_b^{(h=1)}} \right)^2 \left(\frac{\pi}{2} \right) \frac{1}{k_w Z_R^{(h=1)}} \approx O(10^{-5} - 10^{-4})$$

Rough analytic estimates suggest for $h=3$, another factor $\sim (4 k_w Z_R)^{-1}$ appears (in addition to using microbunching fraction for $h=3$)

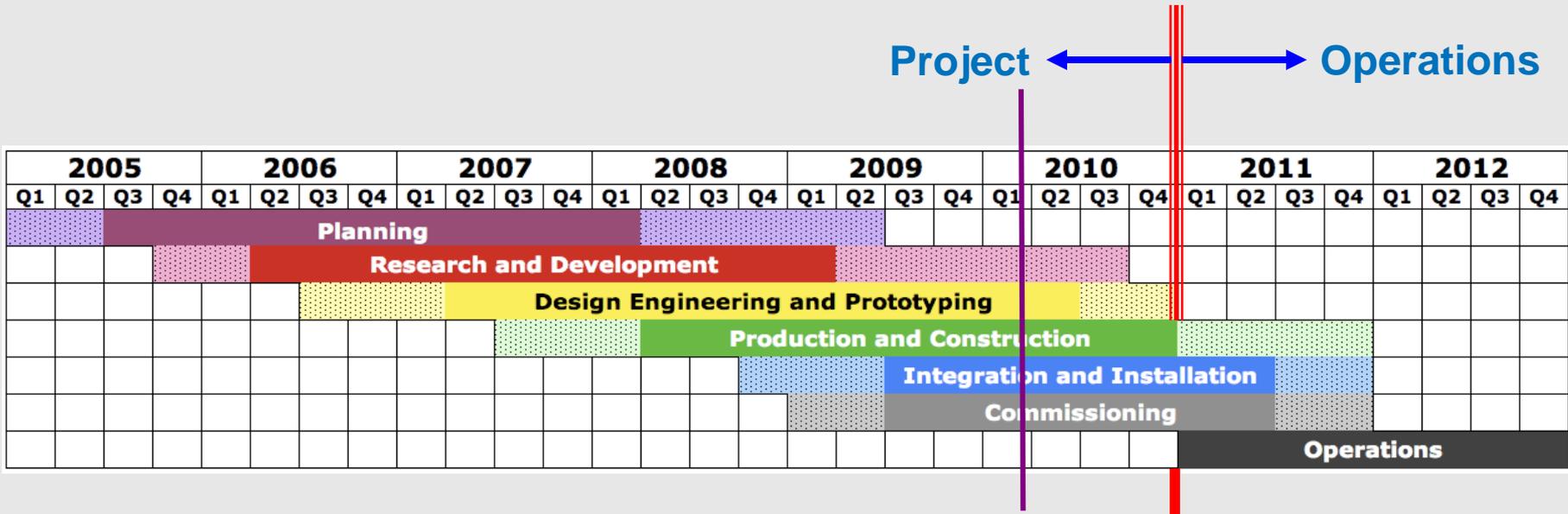
Fundamental Wavelength / Energy	# photons/pulse fundamental	Harmonic Wavelength / Energy	# photons / pulse harmonic
3 nm 413 eV	4.2E+11	1.5 nm (h=2) 826 eV	1.7E+06
		1 nm (h=3) 1240 eV	250
5 nm 248 eV	3.2E+12	2.5 nm (h=2) 496 eV	1.2E+08
		1.33 nm (h=3) 744 eV	2E+04

- Two schemes can be easily implemented into 2nd radiator of FEL-2 using existing APPLE-II design:
 - BESSY (APPLE topology) has found that combining predominantly circular polarization together with a small linear component produces on-axis radiation output that is up to 90% circularly polarized
 - Sequential cross-polarized undulators have been suggested by K.-J. Kim and others to produce a net on-axis harmonic component (e.g., for fixed gap, linearly polarized undulators as in the LCLS)

- There are other schemes to produce significant $h=3$ emission (for FERMI, in an “afterburner” configuration, using the final one or two undulator sections)
 - biharmonic configuration where a moderate amount of 3rd harmonic B_{\perp} is added mechanically (e.g., pole-shaping) to the nominal fundamental B_{\perp}
 - Modification of the “Figure-8” undulator scheme of Tanaka and Kitamura (NIM A, 365, 368 [1995]) by combining an interior, short period ($\lambda_w = \lambda_w^0 / 3$) circularly-polarized undulator emitting on-axis at its fundamental together with a separate “exterior”, longer period ($\lambda_w = \lambda_w^0$) linearly-polarized undulator which produces most of the necessary overall K for FEL resonance

Our friends are pulling for us!

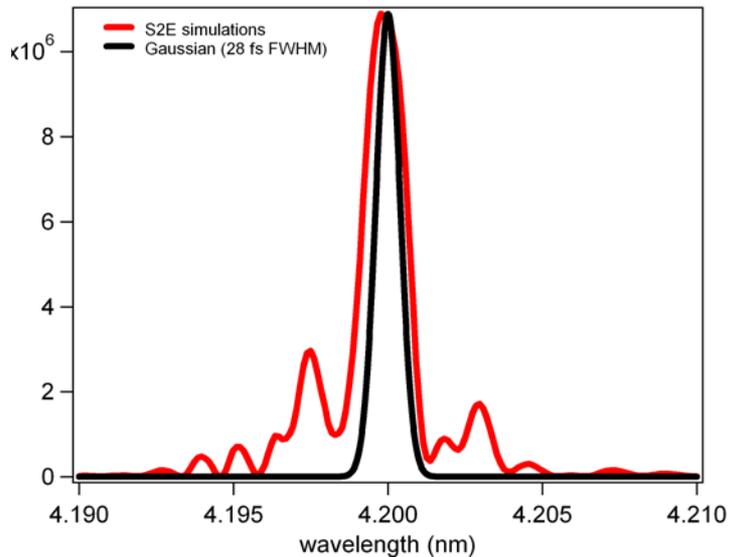
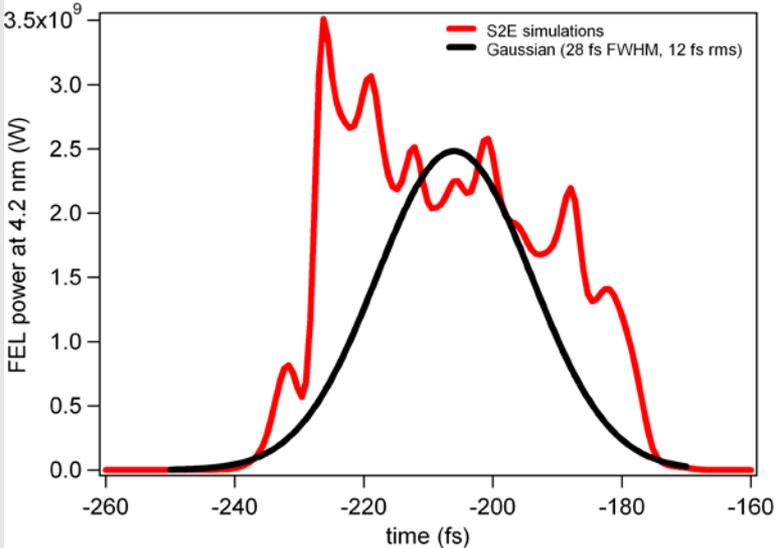
QuickTime™ and a
decompressor
are needed to see this picture.



- “Shaded” areas merely underline the fact that there are many areas involved, some of which are phased to start earlier or later than other areas

- Time dependent simulations using the elegant2genesis file created from the elegant file.
- Easier simulation procedure, slightly reduction of high frequency noise.
- The present layout is used with 6 undulators in the final radiator.

- The 4.2nm case has been producing starting with 120MW of seed laser at 201.6 nm (70 fs FWHM long).
- About 120MW are produced at 16.8nm from RAD1 (~40 fs FWHM long).
- At final output, more than 2GW are produced at 4.2nm from RAD2 (~50 fs FWHM long).



■ The FEL-2 bandwidth is a factor ~4 larger with respect to the one of a Gaussian pulse with the same FWHM. However the main spectral peak is comparable with the spectrum from a Gaussian with a FWHM of 28 fs.

Slide From Allaria et al. MAC Dec. 09