fel 06
BERLIN

Output Bandwidth Effects in Seeded FELs

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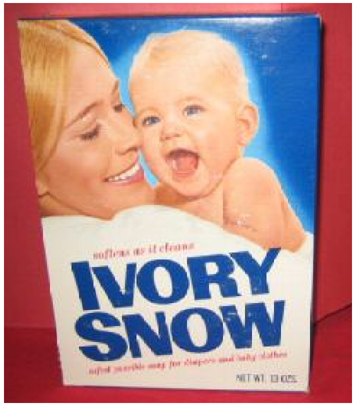
The Seductive Call of Seeded FELs…



Marilyn Chambers
~1970
"99.44% pure"

When we were younger and far more innocent, we listened and responded to the sweet promises associated with seeded FELs, *e.g.*,

- **"Instant" and enduring in *z* transverse and longitudinal coherence**
  - **bandwidth could be set by input pulse duration *e.g.*, $\omega/\Delta\omega$ > 10^5 at 10 nm, 10^6 at 1 nm (compare to SASE where $\omega/\Delta\omega \leq$ 1000-2000)**
  - **Strong, "pure" seed => nearly as pure output**

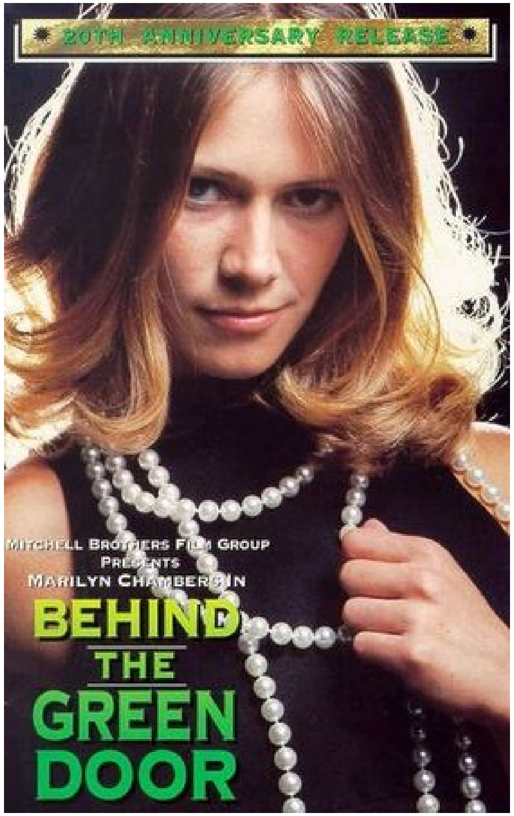
- **Output wavelength set by input seed wavelength**
  - **No λ_{out} jitter from e-beam γ_{in} jitter**
  - **Soft limit on $\gamma(t)$ variation: $\Delta\gamma$ < MAX (½ N_w, $\rho/2$)**

Seductive promises…

But we are older and, perhaps, somewhat wiser now:

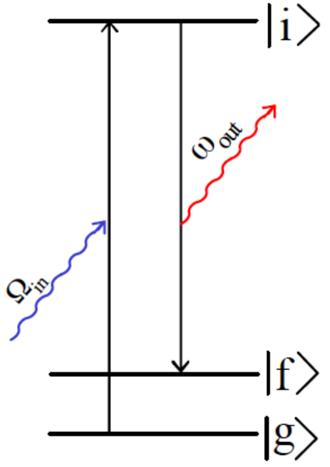
- **The less-than-perfect reality:**
  - **— there are many effects that can seriously increase the bandwidth of a seeded pulse**
  - **— Harmonic cascade FEL's may be particularly sensitive**

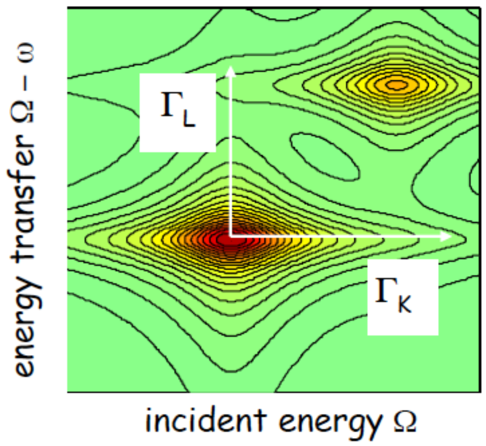
- **This talk is a "behinds the scenes" look at the tawdry reality of how imperfect e-beams can convert "pure", transform-limited input seed pulses into output with depressingly large bandwidths (relative to ultimate limit)**

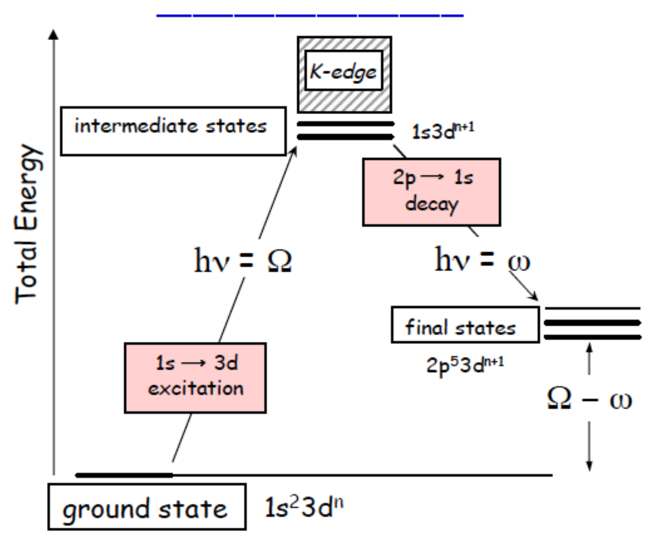


Marilyn Chambers
~1972
not so pure!

RIXS experiments: one reason to seek extremely small output bandwidth





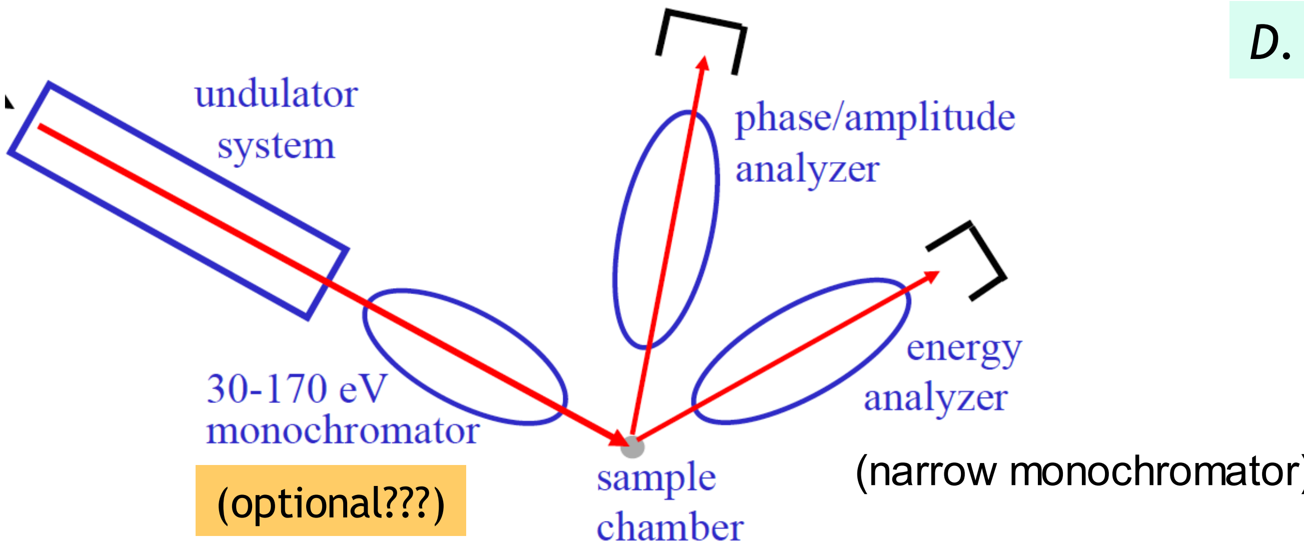


- Resonant Inelastic X-ray Scattering
- inelastic scattering probe of electronic structure
  "multidimensional spectroscopy" ; interest in *meV resolution* at 0.1-1 keV
- At resonance, $\sigma_{elastic} / \sigma_{inelastic}$ can exceed 10^5
- Post-sample, narrow jaw monochromator defines scattered photon energy (ω)
- If (Ω–ω) small, to prevent contamination by elastic-scattered input photons with energy ω, need either similar pre-sample monochromator OR
  a very, very pure, narrow band source (even better than 99.44% pure!)
- Narrow bandwidth insufficient --- also need to limit any medium-band "pedastal" to obtain 10^5 ratio or better

** Figures borrowed from talks by U. Bergmann and K. Gaffney at SSRL Spear-3 Workshop, October 2003*

Trieste RIXS Instrument Concept

D. Moncton, MIT



System Performance requirements & wishes:

- *Continuous tunability over full energy range*
- *meV-resolution in energy analyzer*
- *Upstream monochromator not needed! iff FERMI source sufficiently pure & narrow band*
  - *1 meV = 1.2 x 10^5 resolution at 10 nm*
- *Upstream monochromator efficiency likely < 20% (details depend upon needed optics)*

Different Bandwidth Considerations

- **To maximize post-monochromator flux on sample :**
  - **Maximize $dP(\omega)/d\omega$ at central λ**
  - **Broadband pedestal and RMS $\Delta\omega$ secondary considerations (*but* important if large shot-to-shot jitter in central λ)**

- **To maximize flux for a relatively broad excitation (but still narrow compared to FEL gain bandwidth):**
  - **Minimize FWHM or RMS $\Delta\omega$**

- **To maximize flux from stimulated narrow line emission AND minimize emission from unwanted excitations at near-by wavelengths (*e.g.*, RIXS):**
  - **Maximize $dP(\omega)/d\omega$ + both minimize RMS $\Delta\omega$ and any underlying pedestal**
  - **“spectral resolution” can be key (*e.g.*, “2D” spectroscopy)**

Sources for "Pedestal" Contamination

- **Spontaneous emission ($\Delta\omega/\omega \sim 1/N_w$):**
  - **— $\sim 2\alpha$ photons/e^- in same transverse mode as FEL**

    FERMI FEL-1 example (800 A, λ=40 nm): P ~ 400 W expected coherent FEL output $\rho I_b E_b \sim$ 2 GW ⇨ little problem
  - **— Most additional emission lies to red *and* at wide angles, generally not relevant for most experiments**

- **Contamination by SASE emission:**
  - **— SASE $\Delta\omega/\omega \sim \rho$**
  - **— similar output angle as amplified seed**
  - **— worse case --- radiator many gain lengths long:**

$$P_{SASE} \ / \ P_{SEEDED} \sim (b_{NOISE} / \ b_{COHERENT})^2$$

$b_{COHERENT} \sim (0.5\text{-}5) \times 10^{-2}$

$b_{NOISE} \sim (2\pi \lambda_f I_b / \rho e)^{-1/2} \sim 2 \times 10^{-5}$ **for FERMI FEL-1**

  - **— Potentially above 10^{-5} for $\lambda_f < 10$ nm, $b_{COHERENT} < 0.01$**

Analytic Considerations on Bandwidth…

- **For a Gaussian output pulse with RMS duration τ_p in power and no amplitude or phase noise**
  $\Delta\omega_{RMS}\,\tau_p = ½$; equivalently, hbar $\Delta\omega_{RMS}\,\tau_p$(ps) = 0.33 meV

- **Both amplitude and phase variations widen $\Delta\omega_{RMS}$:**
  - **Simple amplitude variation $P(t) \propto (1 + \varepsilon \sin \delta\omega\, t)$**
    $P(\omega_0 \pm \delta\omega) \sim (\varepsilon^2 / 8)\, P(\omega_0)$; { simple displacement in ω }
    1% amplitude variation increase background ~ few $\times 10^{-5}$
  - **Simple phase variation $\Delta\phi = \varepsilon \sin \delta\omega\, t$**

$$P(\omega) \propto \sum_{n=0}^{\infty} \exp\left(-(\omega - \omega_0 \pm n\,\delta\omega)^2 / 2\Delta\omega^2\right) \times J_n^2(\varepsilon)$$

(multiple sidebands)

For ε small, first sideband fractional power ~ $\varepsilon^2 / 4$
Significant broadening when $0.25\,\varepsilon^2\,\delta\omega \sim \Delta\omega_{RMS}$

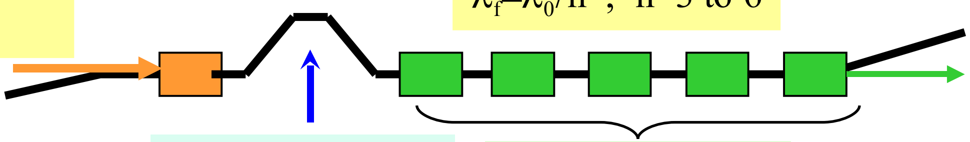
For ε= 0.1 rad and $\delta\omega\,\tau_p$ = 32π, we have equality

FERMI FEL-1 Example

Nominal design:
1.2 GeV, 800 A, 1.5 mm-mrad
Correlated $\Delta\gamma/\gamma \le 0.4\%$ (± 5 in γ)
λ_f=40 to 100 nm; 2 GW

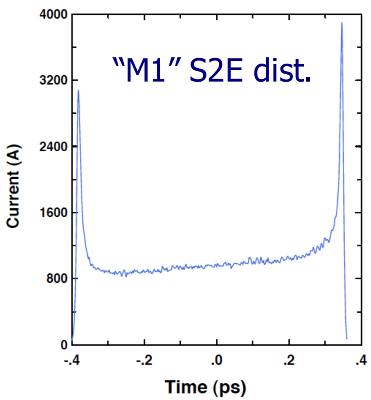
λ_i = 240 to 300 nm
100 MW

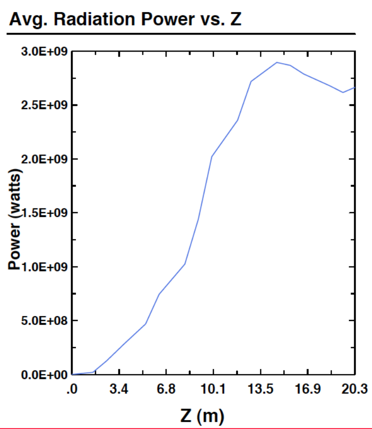
$\lambda_f = \lambda_0/n$, n=3 to 6

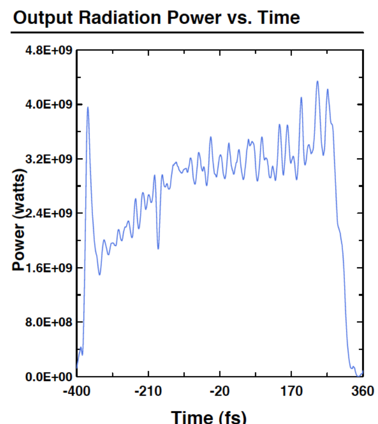


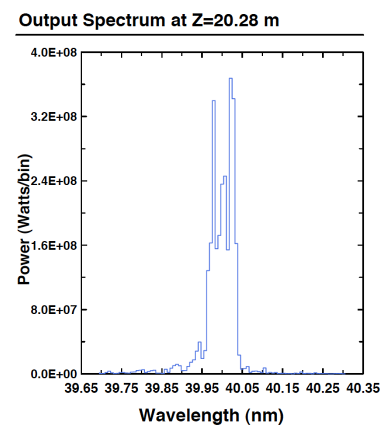
Dispersion Section
$R_{56} \sim 20 - 36\ \mu m$

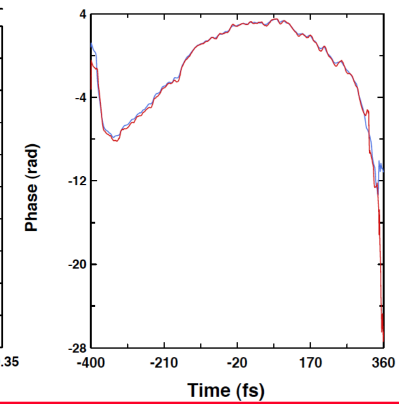
6-segment radiator
Apple configuration

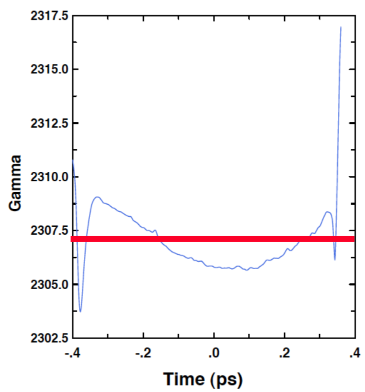


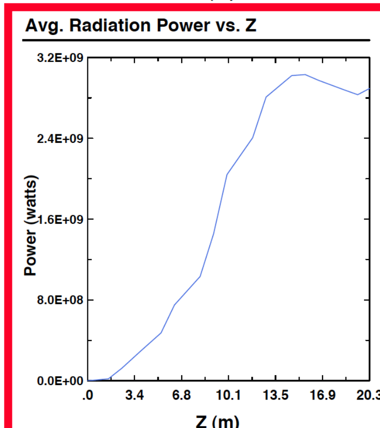


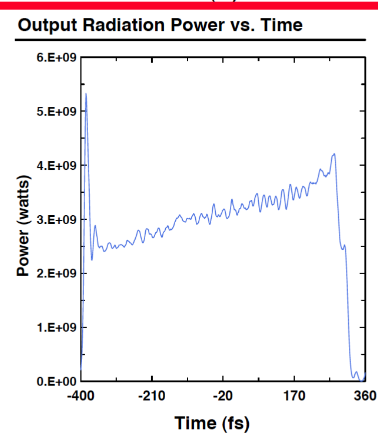


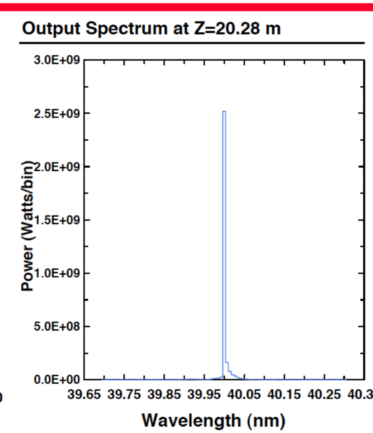


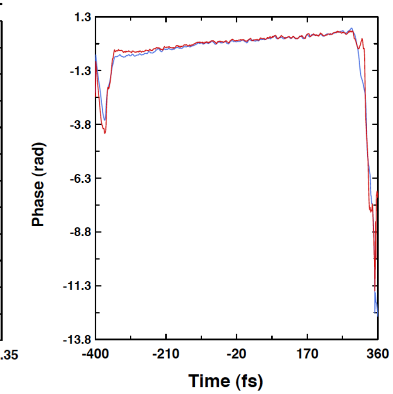




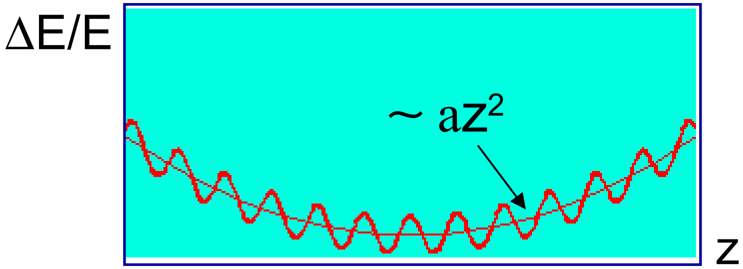






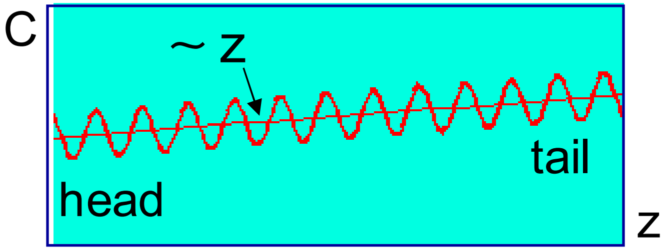


E-beam Energy Chirp + Dispersive Section => Frequency Offset/Chirp in Output Signal*



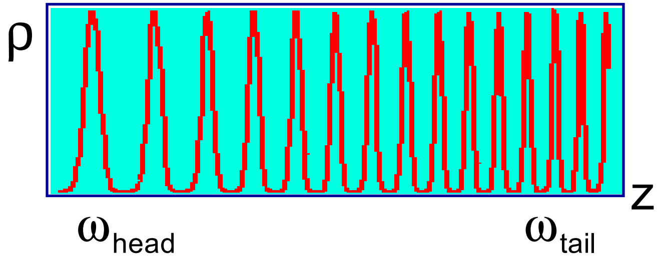
“Slow” quadratic energy chirp ($\tau \sim \tau_p$) +

“fast” ($c\tau \sim \lambda_{IN}$) superimposed energy modulation at modulator exit



Compression factor:

$$C = \frac{1}{1 + hR_{56}}; \quad h = \frac{d(\Delta E / E)}{dz}$$



More compression at beam tail than head produces electron microbunching modulation with $\omega_{head} < \omega_{tail}$

*) S. G. Biedron, S.V. Milton, and H.P. Freund, NIM A **475** (2001) 401; T.Shaftan *et al.*, Phys. Rev. E, **71**, (2005) 046501.

Estimate for Quadratic Beam Energy Chirp-Induced Bandwidth

- **In low gain limit, eikonal phase variation due to γ'' can dominate P(ω)**

Writing $\phi(t) = \frac{1}{4}\frac{(t - t_M)^2}{\tau_p^2}\zeta$ with $\zeta \equiv \frac{4\pi R_{56}}{\lambda_{IN}}\frac{\gamma''}{\gamma_0}\tau_p^2 = \frac{8\pi R_{56}}{\lambda_{IN}}\frac{\Delta\gamma_{\max}^{quad}}{\gamma_0}$,

for a Gaussian amplitude output pulse with max ($\Delta\gamma/\gamma$) < max gain bandwidth

$$\Delta\omega\tau_p \Rightarrow \frac{1}{2}\left(1+\zeta^2\right)^{1/2}$$

Previous "M1" FEL-1 example has ζ~13; good agreement of measured $\omega/\Delta\omega$ (= 1300) as compared to transform limit of ~ 23000

Limiting bandwidth increase to 50% (*i.e.*, $\zeta \leq 1$) requires

$\frac{\Delta\gamma_{\max}^{quad}}{\gamma_0} \leq \frac{\lambda_{IN}}{8\pi R_{56}} \approx 7\times10^{-5}$ for R_{56} = 24 μm and λ_{IN}=40 nm

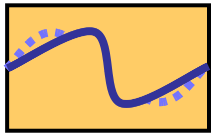
Note that for ζ>>1, $\Delta\omega \propto \gamma''\tau_p \Rightarrow$ worse bandwidth for long pulses!!!

The big question --- how does one limit γ'' ?

Why Not Use a (Very) Small R56?

Following Yu (PRA 44,5178 (1991), $b_h \approx 2\exp\left[-\frac{1}{2}n^2\sigma_\gamma^2\left[\frac{d\theta}{d\gamma}\right]^2\right]\times J_h\left(n\Delta\gamma\frac{d\theta}{d\gamma}\right);\quad \frac{d\theta}{d\gamma}=\frac{2\pi R_{56}}{\lambda_{IN}\gamma_0}$

For strong harmonic content, $\Delta\gamma\frac{d\theta}{d\gamma}\approx 1$; $\pi/2$ gives “upright” phase space:



For *classic* HGHG beginning at 240 nm, $\Delta\gamma\approx\sigma_\gamma,\ R_{56}\approx\frac{\lambda_{IN}}{4}\left(\frac{\gamma_0}{\sigma_\gamma}\right)\approx 400\,\mu m\quad for\ \frac{\sigma_\gamma}{\gamma_0}=10^{-4}$

For low gain HG (LUX/FERMI) with CSE in 1st radiator, $\Delta\gamma\geq\frac{\pi}{2}h_{max}\sigma_\gamma$

$$R_{56}\leq\frac{\lambda_{IN}}{2\pi}\left(\frac{\gamma_o}{\sigma_\gamma}\right)\frac{1}{h_{max}}\leq 65\,\mu m\quad for\ h_{max}=6\ and\ \frac{\sigma_\gamma}{\gamma_0}=10^{-4}$$

In “classic” HGHG, reducing R_{56} makes post-dispersion section microbunching drop rapidly ($J_n(x) \sim x^n$ for $x \leq n$)

=> degraded S/N ratio vis-à-vis shot noise (see Z. Huang, Poster)

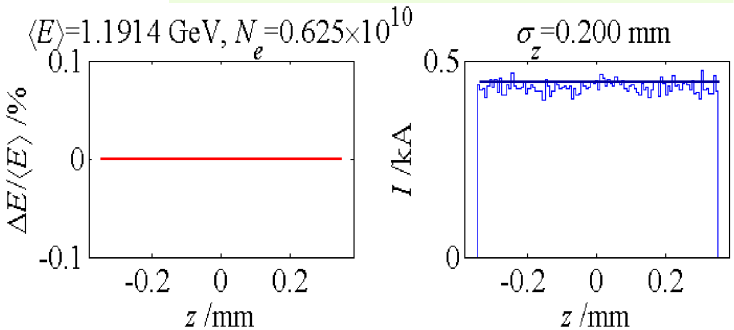
⇒ more exp. gain (and thus radiator length) needed to reach saturation

⇒ more output sensitivity to variation in e-beam (*e.g.*, I_B, γ, σ_γ, ε)

IMHO, multi-stage, high gain cascades with $\Delta\gamma\leq\sigma_\gamma$ have little hope of achieving narrow bandwidths unless γ'' term nearly eliminated

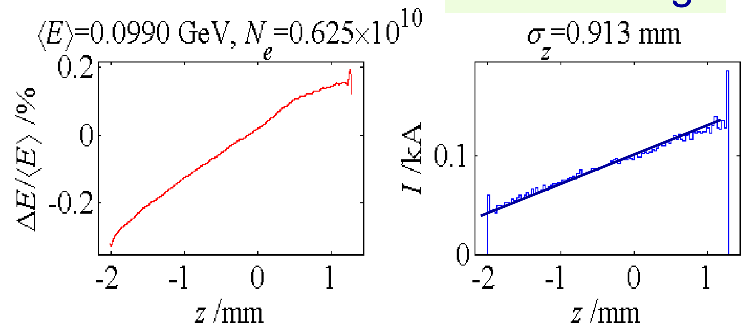
Reverse “LiTracking” with wake fields*

Begin tracking at accel. exit



Wanted final conditions

End tracking



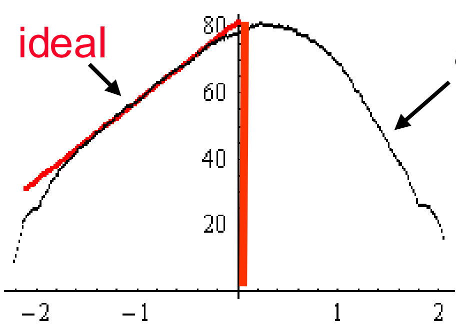
ramped current!

Required conditions at start of accelerator

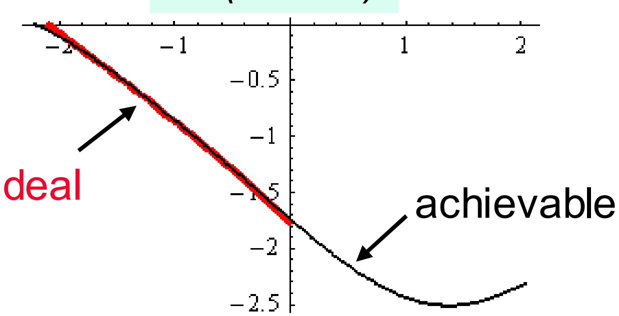
LiTrack calculation: no LSC or CSR effects

Wake potential: $W(s) = -\int_s^\infty w(s-s')\lambda_z(s')\,ds'$ where $w(s) = A\dfrac{Z_0 c}{\pi a^2} L \exp\left(-\sqrt{s/s_0}\right)$

Current from injector (A)



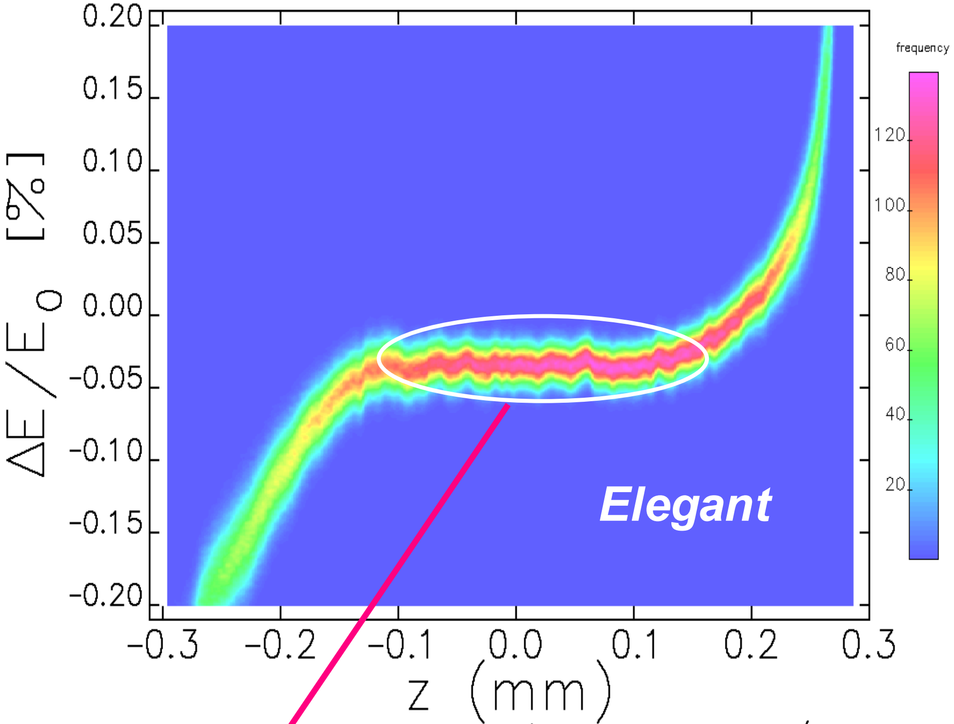
W (MV/nC)

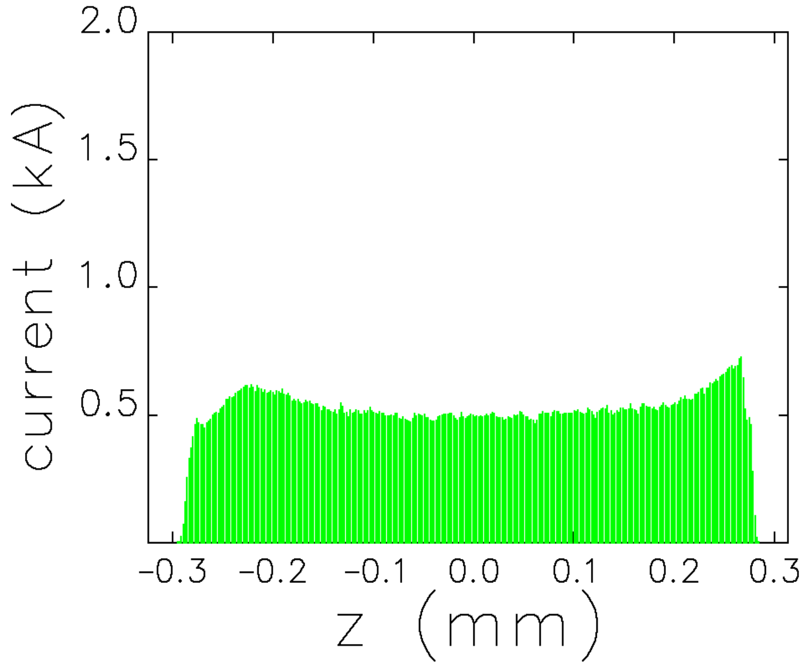


*Courtesy
M. Cornacchia
G. Penco
S. Di Mitri

How well can we do (in theory at least…)?

Example of "flat-flat" distribution ("L4") taken from Technical Optimization Study for FERMI@ELETTRA FELs ;
(CSR but no LSC effects included)

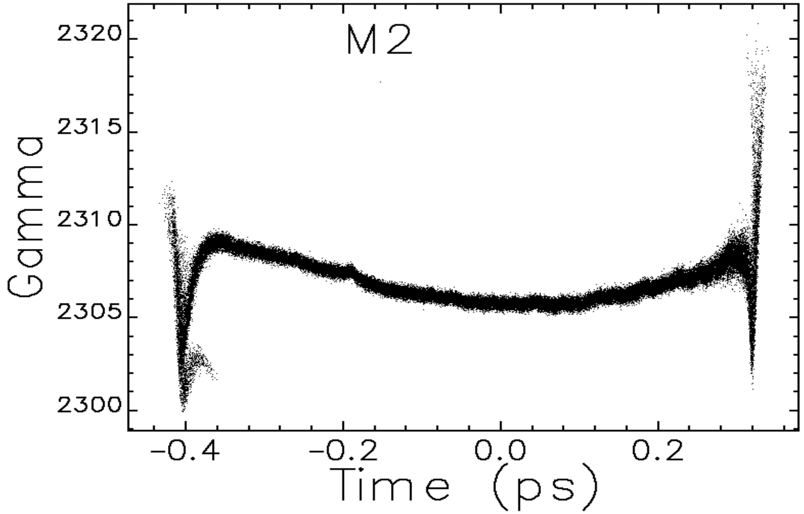


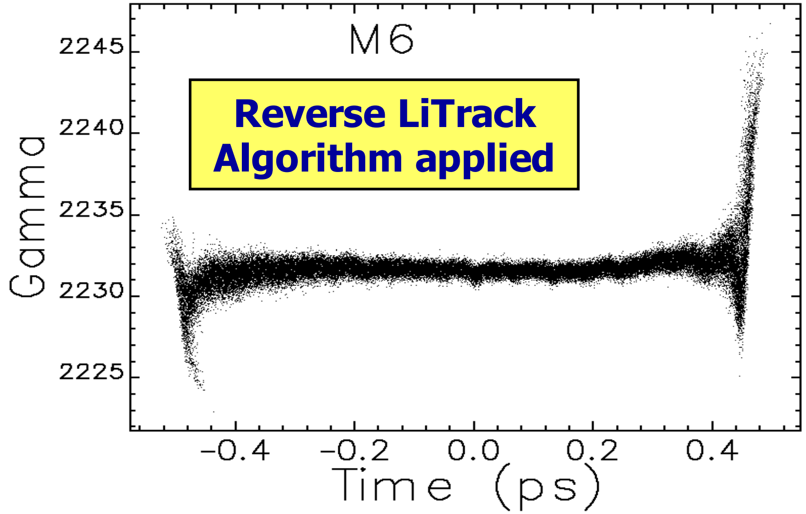


99.4% pure ???

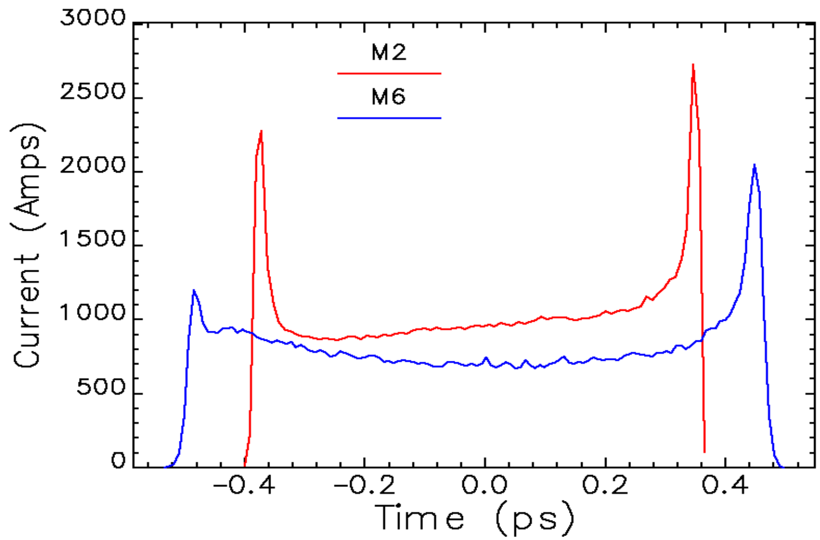
Courtesy G. Penco, S. Lidia, M. Cornacchia, S. DiMitrii

Application of Reverse Tracking to "Medium" Pulse Distributions for FERMI FEL-1

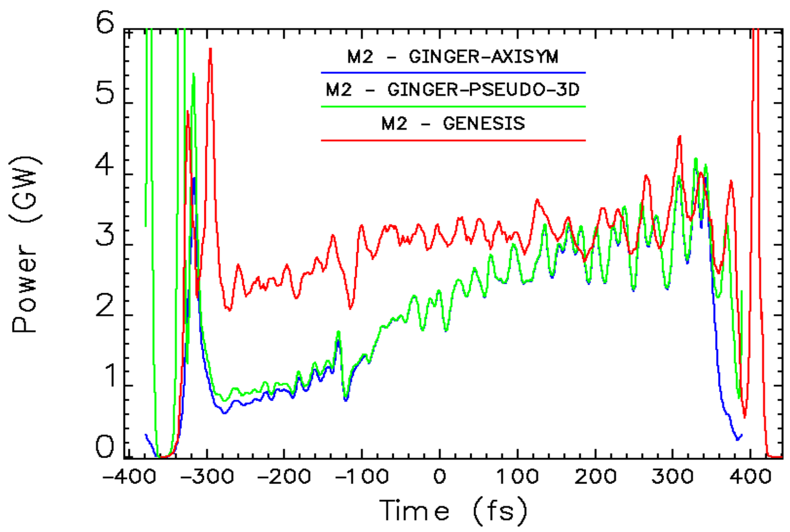


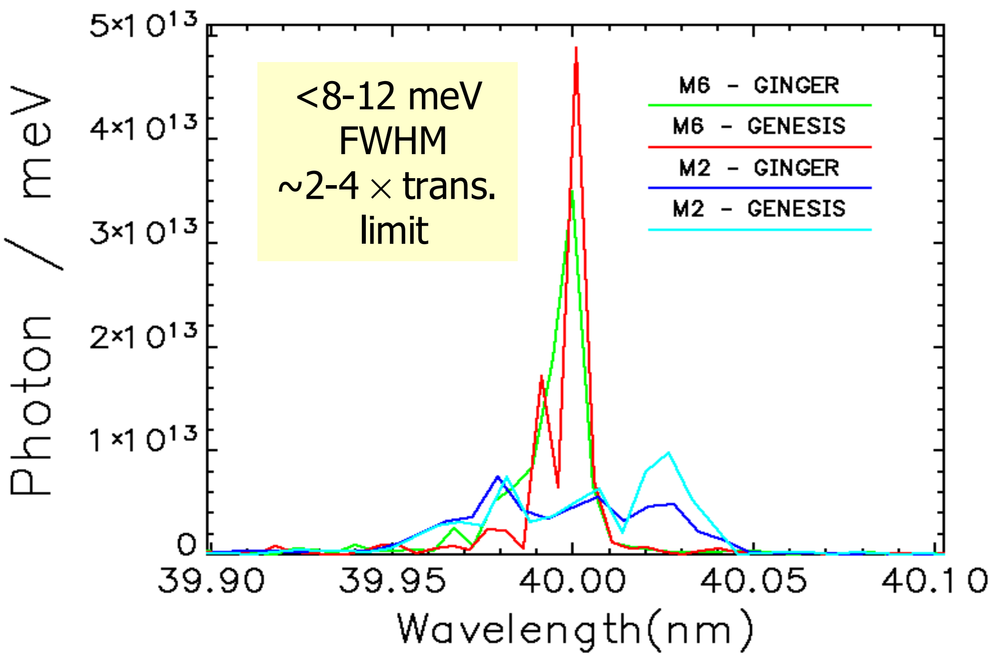


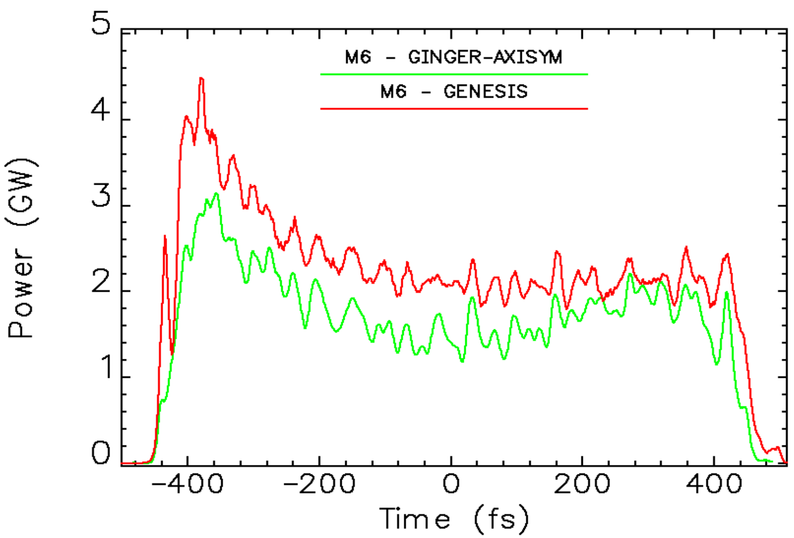
- "Start-to-End" simulation (GPT/ASTRA to ELEGANT)
- FERMI "medium" pulse for FEL-1 (time-domain experiments usually)
- Main goal for M2 was flat current over 800 fs
- Main goal for M6 was flat energy
- Low concern about current spikes



Improved $\gamma(t)$ ⇨ Strong Bandwidth Decrease

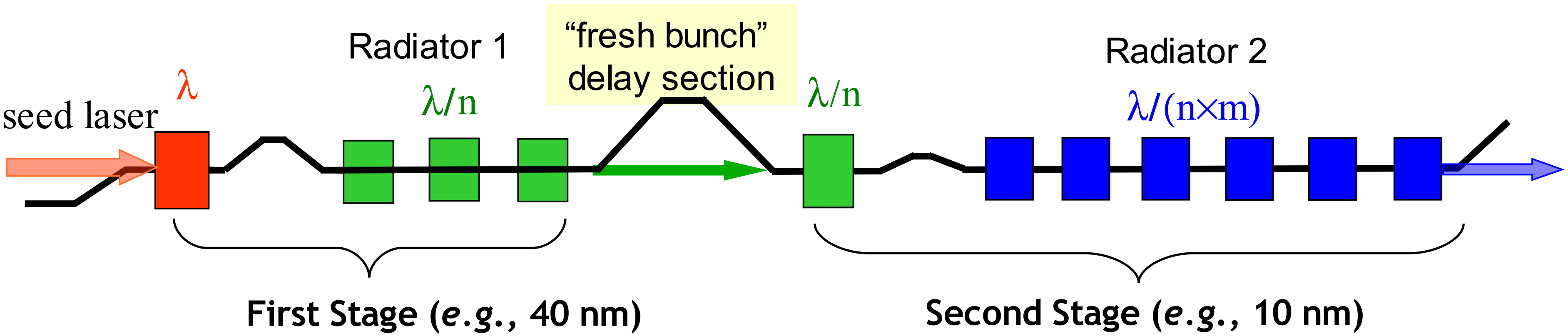




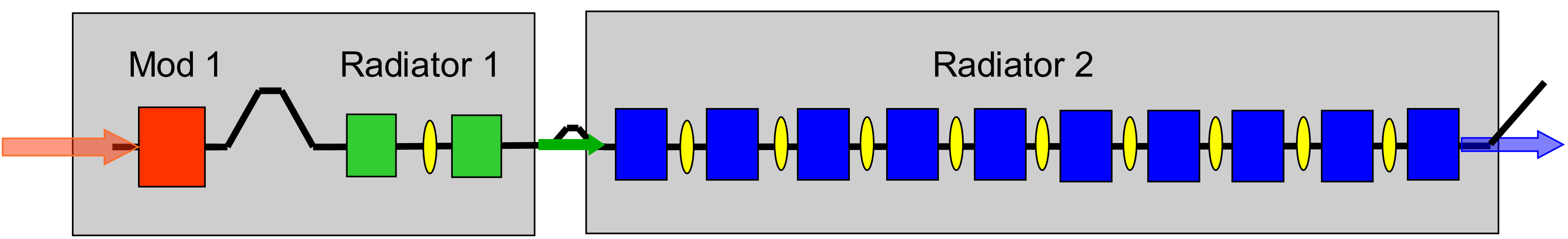


- FEL-1 40-nm output power for S2E “M2” and “M6” distributions
- electron pulse fully covered by constant input power laser seed
- “PSEUDO-3D” ⇨ FEL radiation field forced *artificially* to same instantaneous transverse centroid position as the e-beam
- ~5-meV resolution in simulations

“Fresh-” and “Whole-Bunch” Approaches to FERMI FEL-2

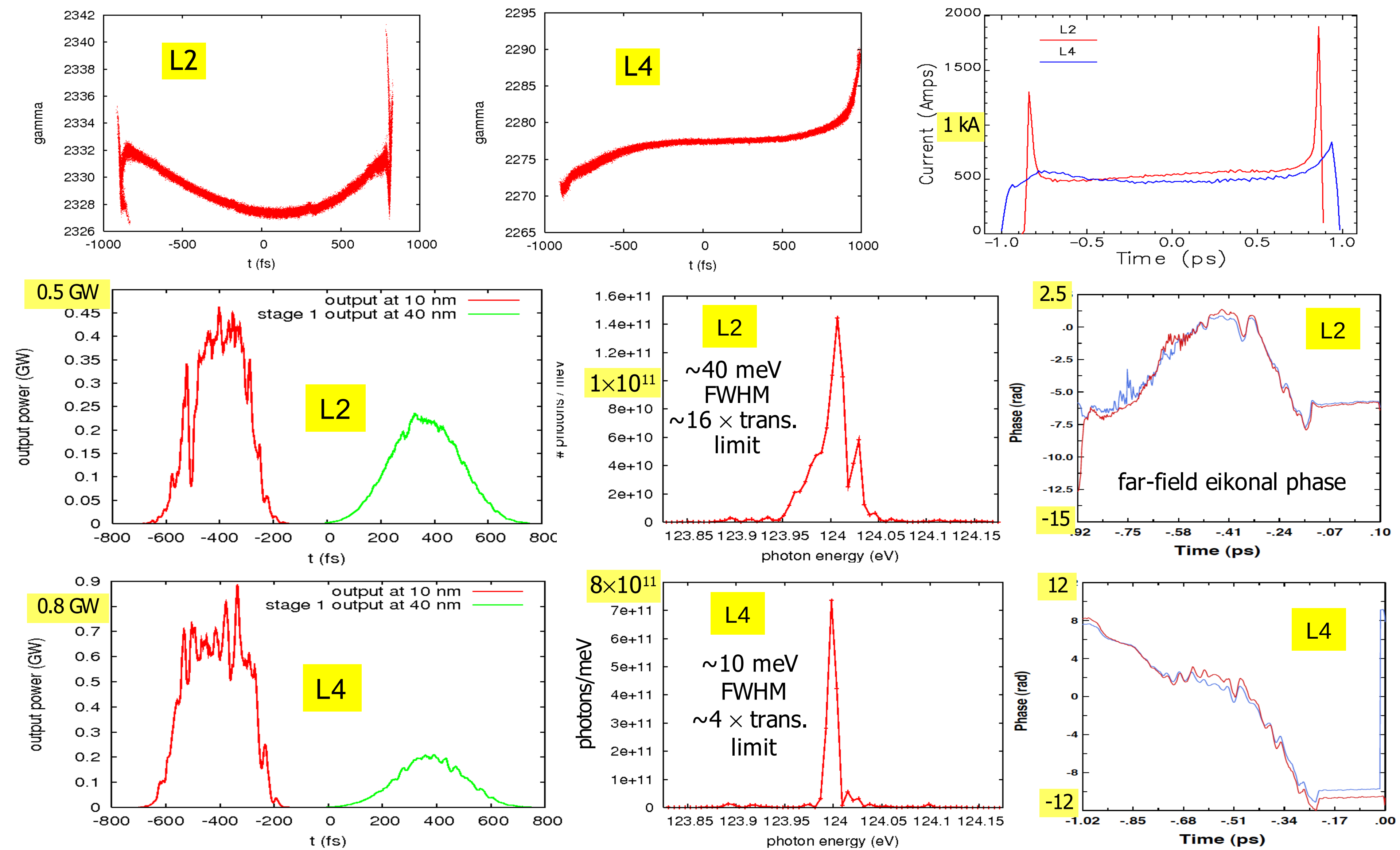


Total length FEL-2 (*fresh bunch*) ~ 37.5 m

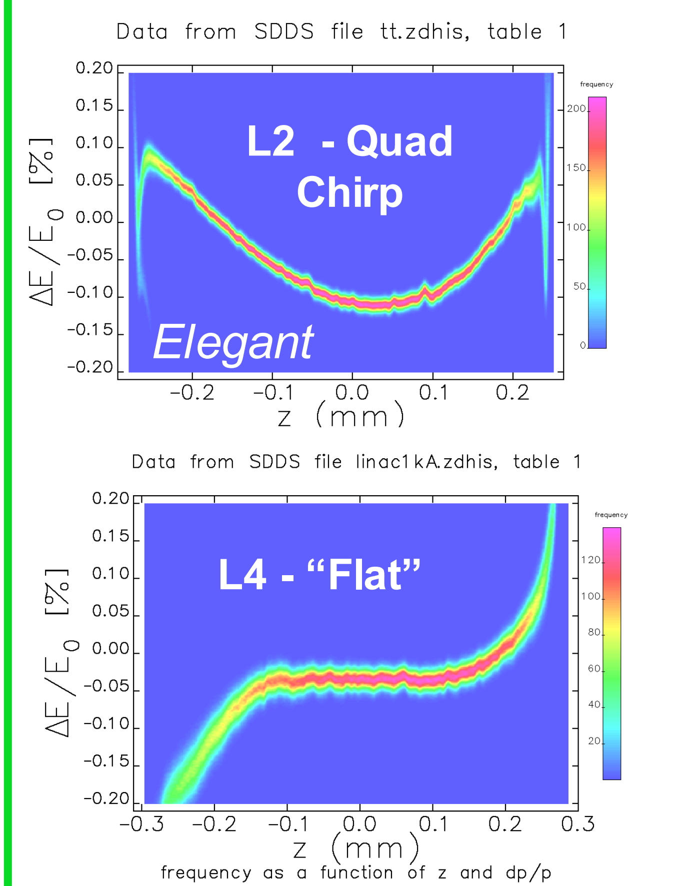


Total length FEL-2 (*whole bunch*) ~ 50 m

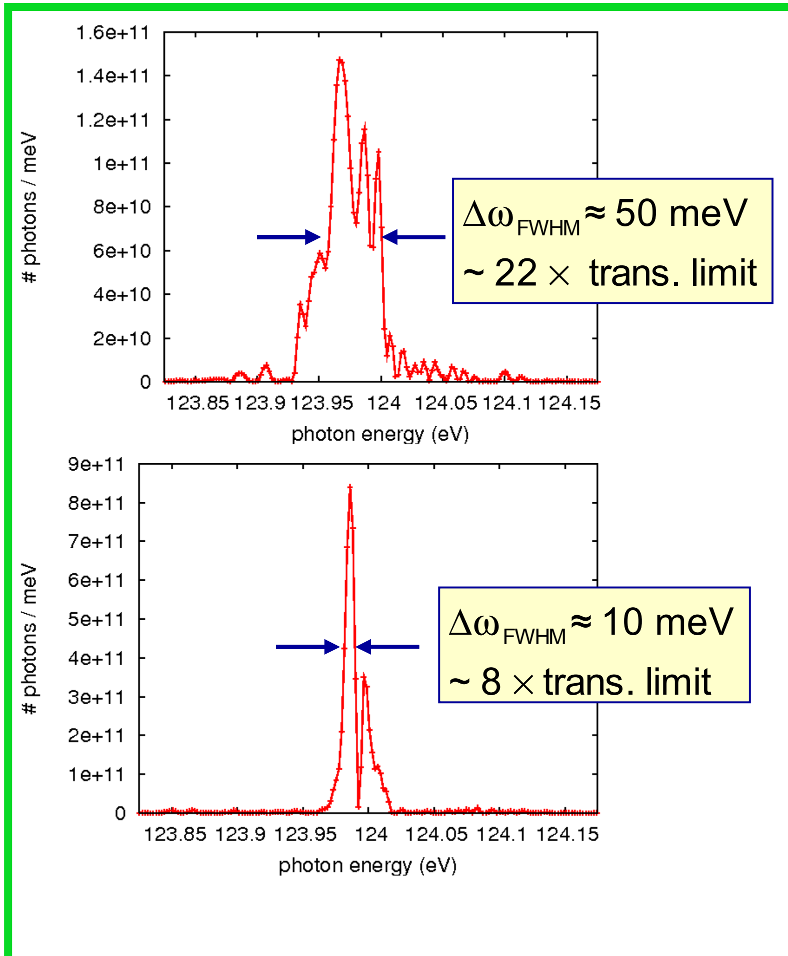
“Fresh Bunch” FEL-2 10-nm Results



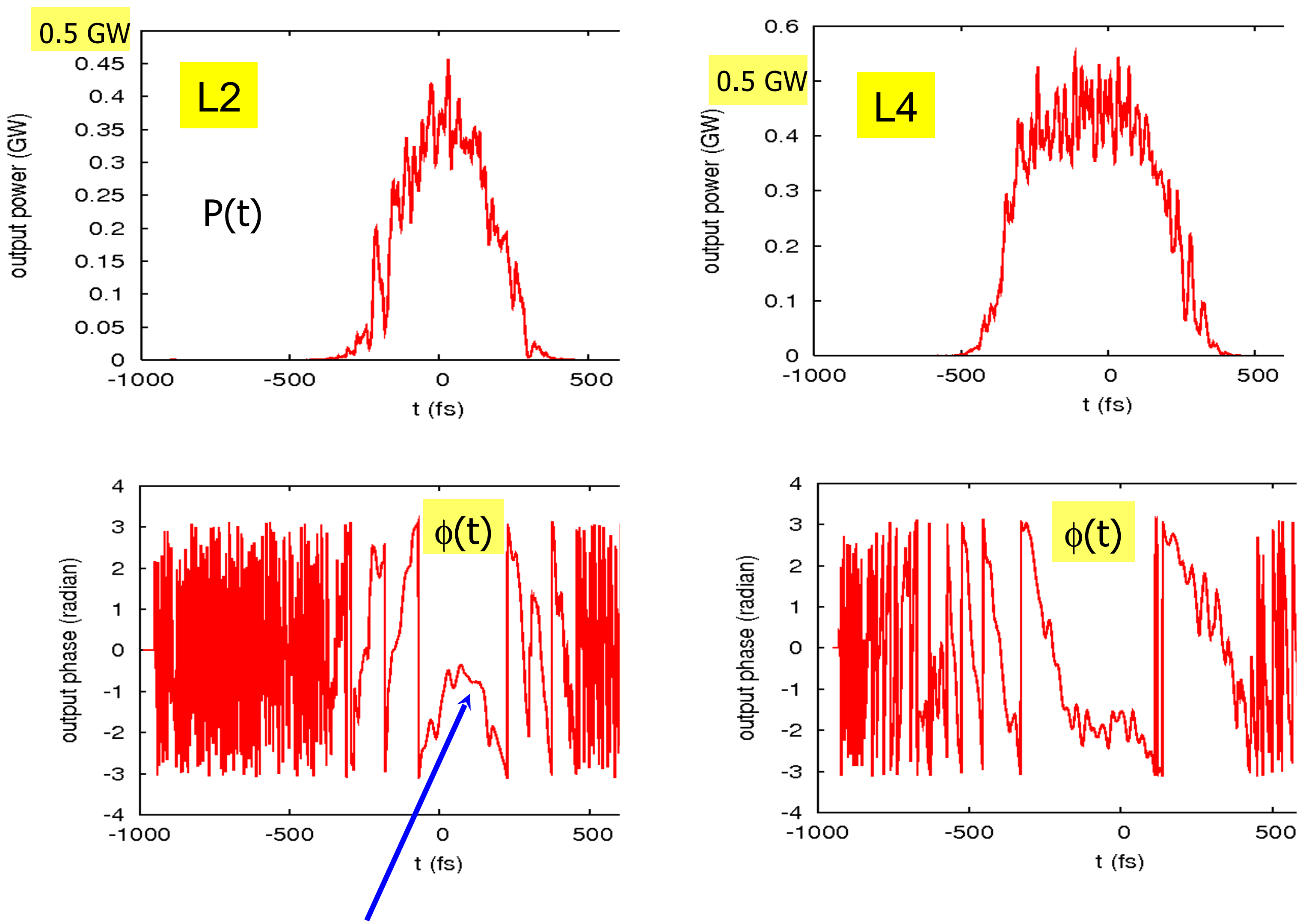
"Whole Bunch" Approach FEL-2 Output at 10-nm



Longitudinal phase space

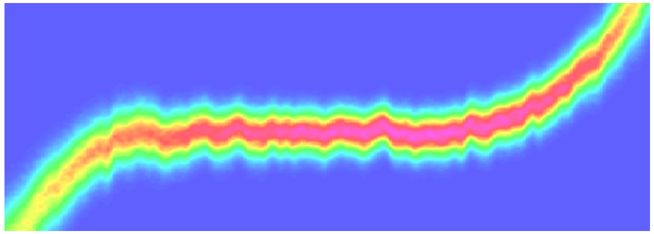


Whole Bunch Output Power and Phase



Strong quadratic dependence

CSR/LSR-induced "fast" γ variations



- **Variations which are "fast" compared τ_p but slow compared to τ_{slip} will increase $\Delta\omega$ via R_{56} phase effect**
- **Final amplitude very difficult to compute numerically**
  - **massive macroparticle numbers (*e.g.,* > 10^8) needed for correct initial noise level**
  - **Large effort at LBNL to apply "new" tools to problem (IMPACT code; Vlasov code)**
- **Unlike slow quadratic chirp, no real hope of correcting via input seed $\omega(t)$ manipulation**
  - **These fast $\gamma \Rightarrow \omega$ variations increase output photon phase space (slow chirp nearly fully coherent --- Murphy et al. preprint)**
- **"Laser heater" may be essential for control of CSR/LSC**

Summary

- **Output of a nearly "pure", transform-limited pulse not likely from seeded FEL employing harmonic upshift**
  - —**SASE contamination might be problematic in some cases**
  - —**Combination of quadratic energy chirp (from wakes) + dispersion section (needed for strong microbunching at harmonics) ⇒ linear frequency chirp across pulse**
    - **Limits on γ'' can be quite small**
    - **Some hope of correction reverse chirp on input seed laser**
  - —**Fast timescale $\gamma(t)$ variations (CSR/LSC) + dispersion section also increase output bandwidth + dilute output phase space**
    - **Laser heater may be needed for control (but too large a needed σ_γ may prevent efficient harmonic cascade)**
  - —**Spontaneous emission relatively weak; subharmonic emission mainly off-axis ⇒ probably no serious contamination issue**
  - —**3^{rd} harmonic contamination from final radiator may require filtering; likely amplitudes 0.1 – 1.5%**

Thanks…

We happily acknowledge many useful discussions with S. Lidia, W. Graves (MIT), M. Cornacchia (SLAC/Trieste), P. Emma (SLAC), G. DeNinno, E. Allaria, S. DiMitri, P. Craievich, & G. Penco (Trieste)

As a postscript, we note (courtesy of Wikipedia) **:**

On July 28, 1999, Marilyn Chambers made her triumphant return to the O'Farrell Theater in San Francisco. (Then) Mayor Willie Brown proclaimed it "Marilyn Chambers Day" and presented her with a key to the city.

In the 2004 election, Marilyn Chambers ran for Vice President (of the US) on the *Personal Choice Party* ticket, a quasi-libertarian party. She lost… (but supposedly received > 60 votes).

She also was the first woman in the US adult film industry to actually make any **real money** and achieve some sort of a power status.