Three-Plus Decades of Tapered Undulator FEL Physics

William M. Fawley

2015 Int. FEL Conference

Daejon KOREA

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Outline

A caveat – this is a very personally-biased talk!

- Why amplifier tapering is important
- Brief review of basic 1982 KMR theory and suggestions
- 1980's Livermore ELF & PALADIN experiments
- 1990's "dark ages"
- 2000's: rebirth of high gain, amplifier taper physics
  - tapering for SASE devices?
  - experimental tapering returns: both SASE and seeded
  - renewed interest in theoretical optimization for TW-FELs
- A quick look at an inviting future...

Why Taper?

- Energy extraction efficiency --- defeat the smallness of ρ
  - Std. result at saturation: $P_{RAD} \approx 1.6 \rho P_{BEAM}$
  - XUV & X-ray region: $\rho \lesssim 10^{-3}$
- For 2X or greater power increase, 50% undulator extension is *cheap!!!* (relative to *total* facility cost)
- In the post-saturation regime:
  - Bandwidth control for SASE FELs
  - Sideband growth reduction for seeded FELs
- Some other good reasons (but not covered here):
  - Production of very intense, ultrashort pulses
  - Reverse taper to change power/bunching ratio upstream of circularly-polarized "afterburner"
  - IFEL acceleration

KMR Trapped Particle & Tapering Theory

(where FEL's began --- for me at least)

1436 IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. QE-17, NO. 8, AUGUST 1981

Free-Electron Lasers with Variable Parameter Wigglers

NORMAN M. KROLL, PHILIP L. MORTON, AND MARSHALL N. ROSENBLUTH

(Invited Paper)

KMR Theory --- Decelerating Buckets…

- Hamiltonian analysis stimulated by analogy of FEL ponderomotive wells to RF acceleration buckets in linacs (P. Morton)
- Electrons could be both trapped and then stably decelerated via reducing *K*
  (ignoring effects of diffraction, betatron motion, spontaneous emission, *etc.*)

Standard FEL longitudinal equations:

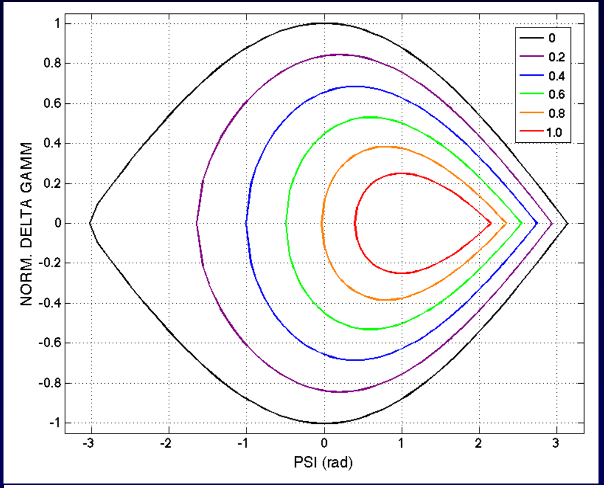
$$\frac{d\psi}{dz} = k_w - \frac{k_s}{2\gamma^2}(1 + a_w^2 + \gamma^2\beta_1^2 - 2a_w a_s \cos\psi) + \frac{d\varphi}{dz}$$

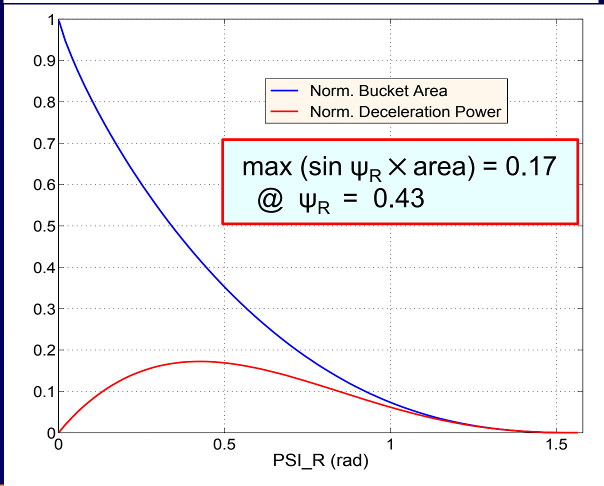
$$\frac{d\gamma}{dz} = -\frac{a_w e_s}{\gamma}\sin\psi \, .$$

To keep a resonant "design" electron at constant ψ_R , balance gamma loss by reduction in a_w ($\equiv K_{RMS}$); eikonal phase derivative can be important

KMR often remembered for a constant ψ_R (z) approach
Resultant bucket area is a strong function of ψ_R

It is convenient for discussion and probably desirable as a design characteristic to choose γ_r so that ψ_r is constant. Then





KMR Theory - Variable Ψ_R ?

☛ KMR were no dummies – they knew ψ_R could be varied:

mum one. Again, in anticipation of the amplifier case, we note that an increase of a_s with z can eliminate the detrapping associated with an increase in ψ_r so that an increase of ψ_r with z should have some advantages for an amplifier.

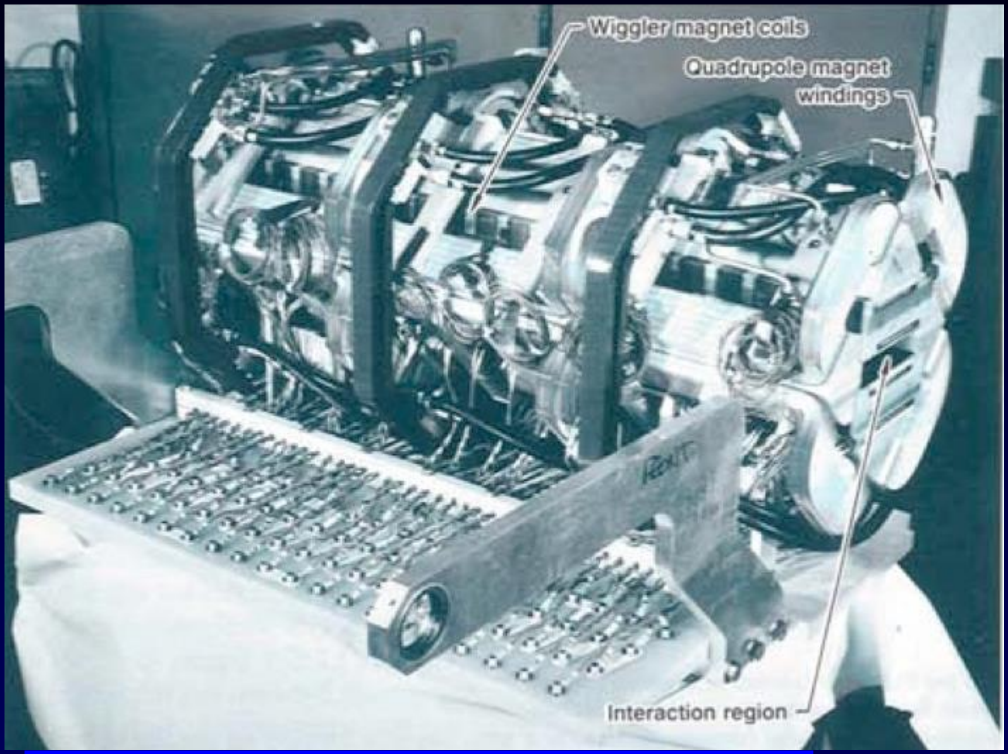
- "Fine-tuning" Ψ_R and K in saturation region can improve trapping --- this is now well-appreciated by many

- FRED/GINGER "self-design" algorithm (mid-1980's):
  $\Psi_R = \Psi_R^0 + g\,(z - z_0)$ for $z_0 \leq z \leq z_M$,
  then constant with z ; z_0 typically $z_{sat} - 2L_G$

1984-6 ELF Expts. @ Livermore

- Joint LBNL – LLNL experiment to study physics of
  high gain, high energy extraction FELs
- Initial expt. @ 35 GHz (8 mm) in over-moded waveguide
  - seeded with low power (~50 kW) magnetron
  - later expts. at 140 & 250 GHz for fusion plasma heating
- Findings included:
  - importance of good matching to undulator transport
  - high gain and saturation for untapered undulator
  - confirmation of "launching losses" (factor of 1/9 in power coupling)
  - SASE studies: expt. stimulated K-J Kim classic SASE paper
  - very high energy extraction efficiency (>35%) for tapered undulator

ELF: Undulator & Untapered 35 GHz Results



1-m section of ELF Undulator
Designed by K. Halbach LBNL
fully electromagnetic
every 2 periods individually controllable

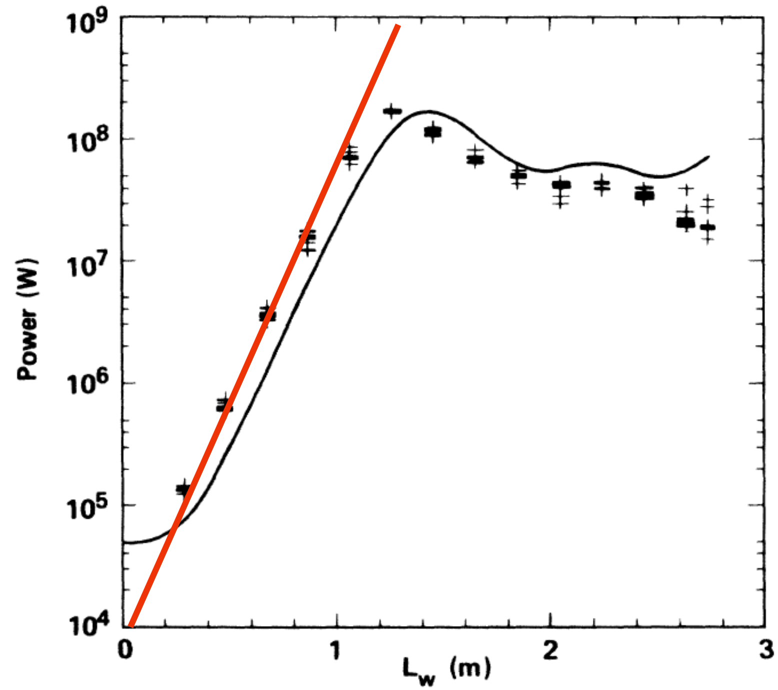


FIG. 1. Amplified signal output as a function of wiggler length for uniform (flat) wiggler. Crosses indicate experimental values and the solid line is the result of numerical evaluation.

Orzechowski et al., PRL 57, 2172 (1986)

- ➡ FRED code quickly developed in parallel to ELF studies, included waveguide geometry, multiple transverse modes, full 3D particle motion & KMR "self-design" tapering algorithm

ELF: 35 GHz Tapered Wiggler Results

Orzechowski et al., PRL 57, 2172 (1986)

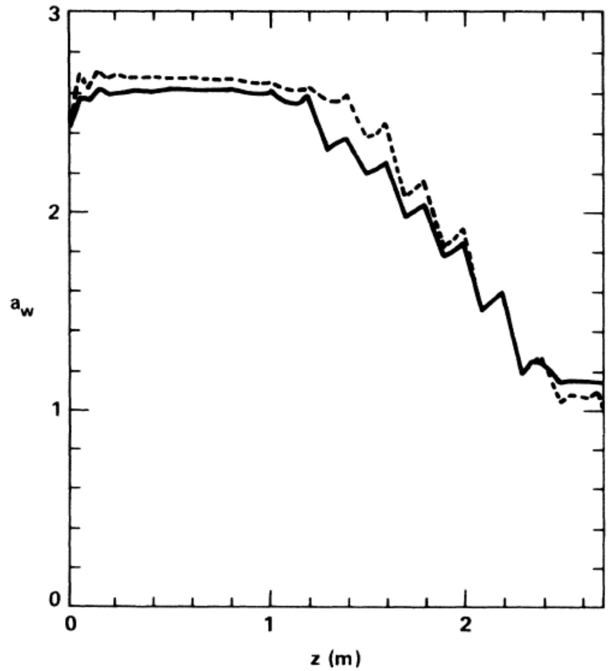


FIG. 2. Optimum wiggler field profile for tapered wiggler. The dashed line corresponds to empirical evaluation and the solid line is the numerical prediction.

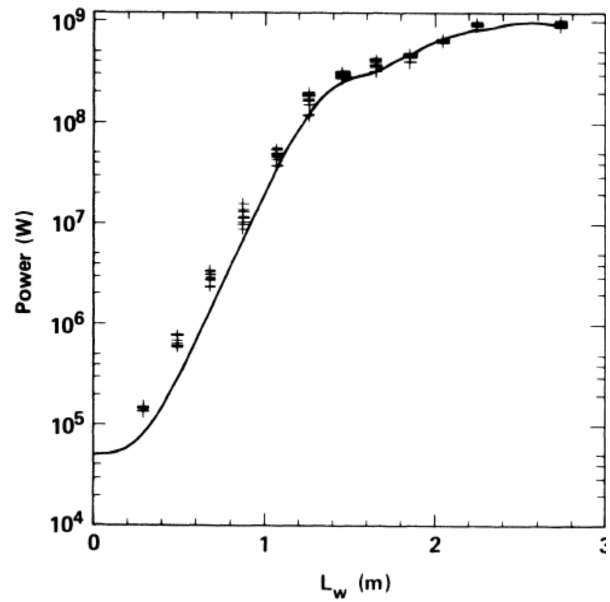
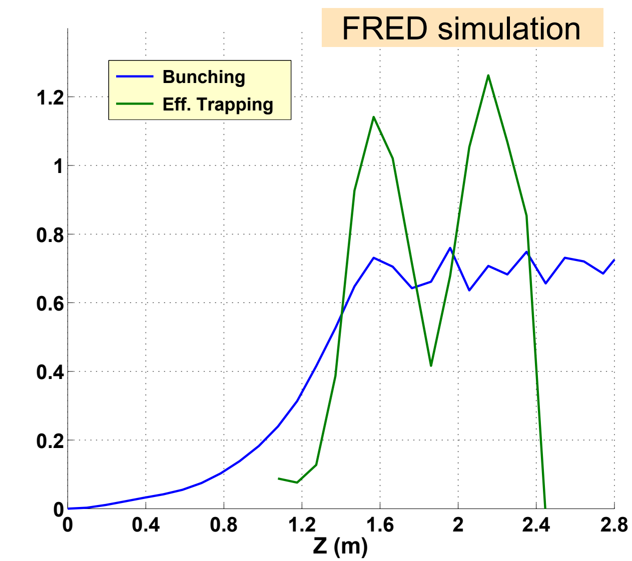
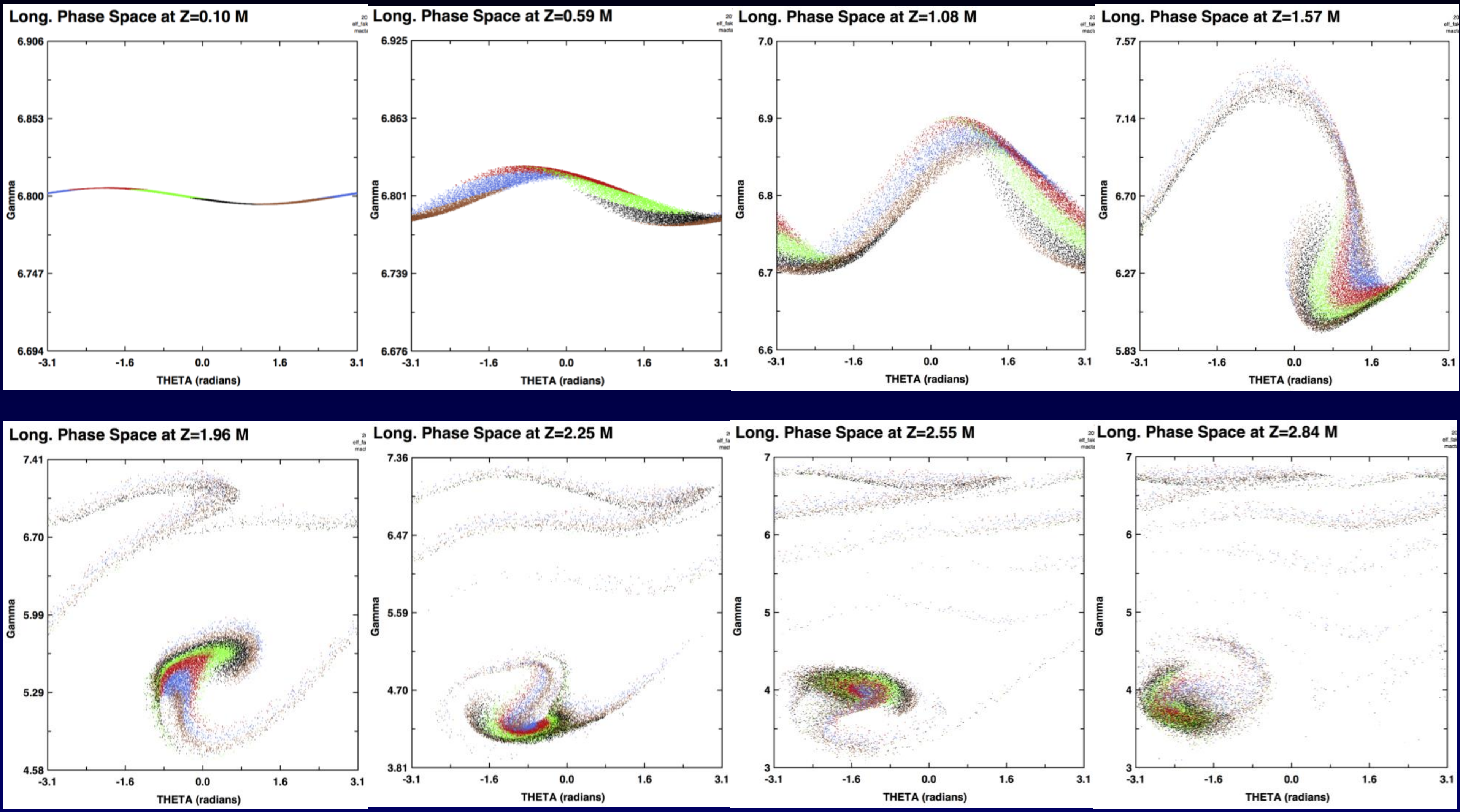


FIG. 3. Amplified signal output as a function of wiggler length for tapered wiggler field. Crosses indicate experimental values and the solid line is the results of the numerical evaluation.



- taper determined empirically by optimizing power every 2 λ_u
  - min. allowable *K* reached at 2.2 m ➡ no additional power gain in z
  - taper increases power 5.5X (7.5 dB); 50% deceleration, 70% bunching fraction
- empirical optimization very close to KMR-style self-design taper
- FRED code: very good agreement in taper & power

Calculated Phase Space in ELF Taper



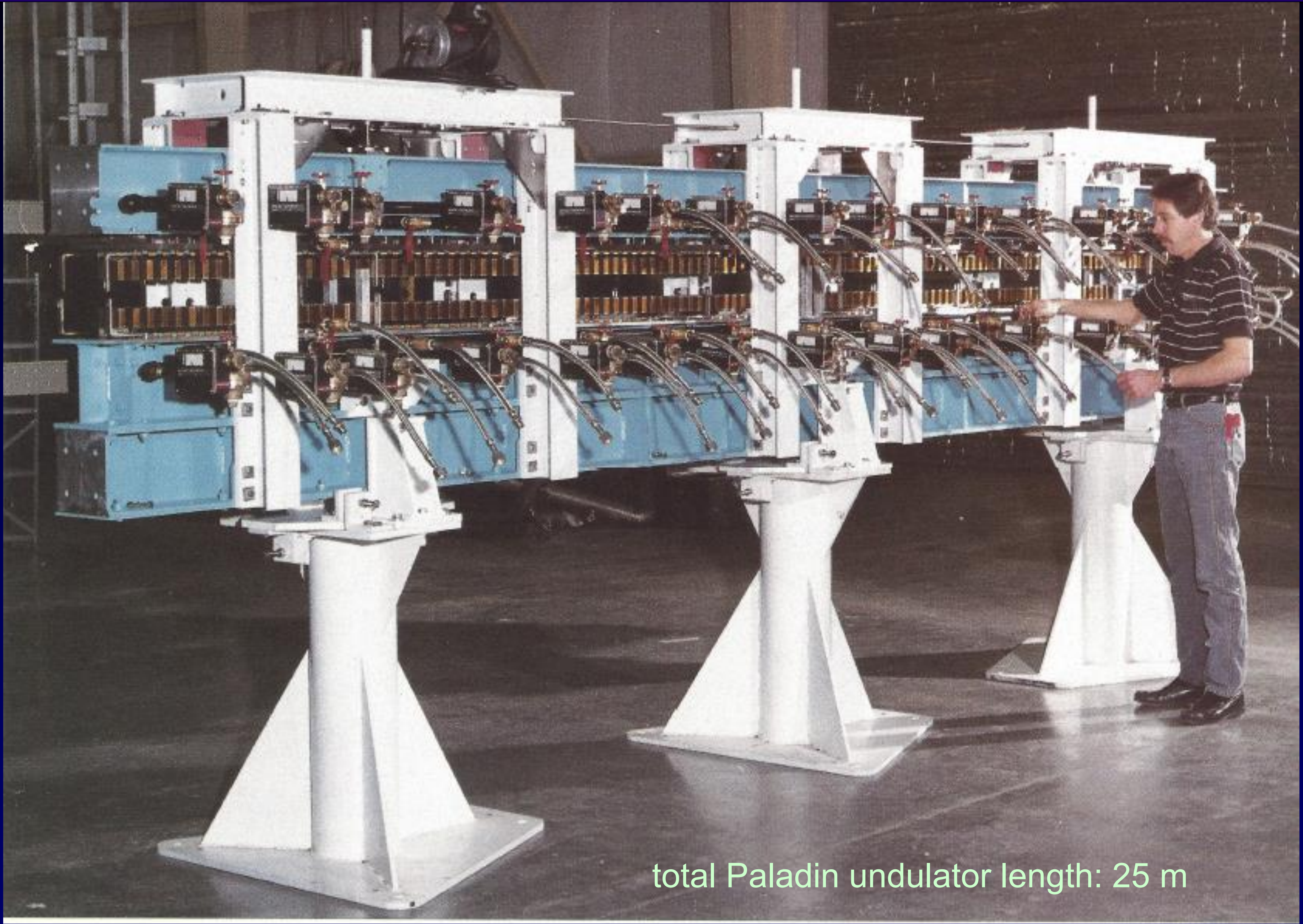
GINGER time-steady simulation (“FRED-mode”) using expt.-determined taper

1988-90: LLNL 10.6µm Paladin Expt.

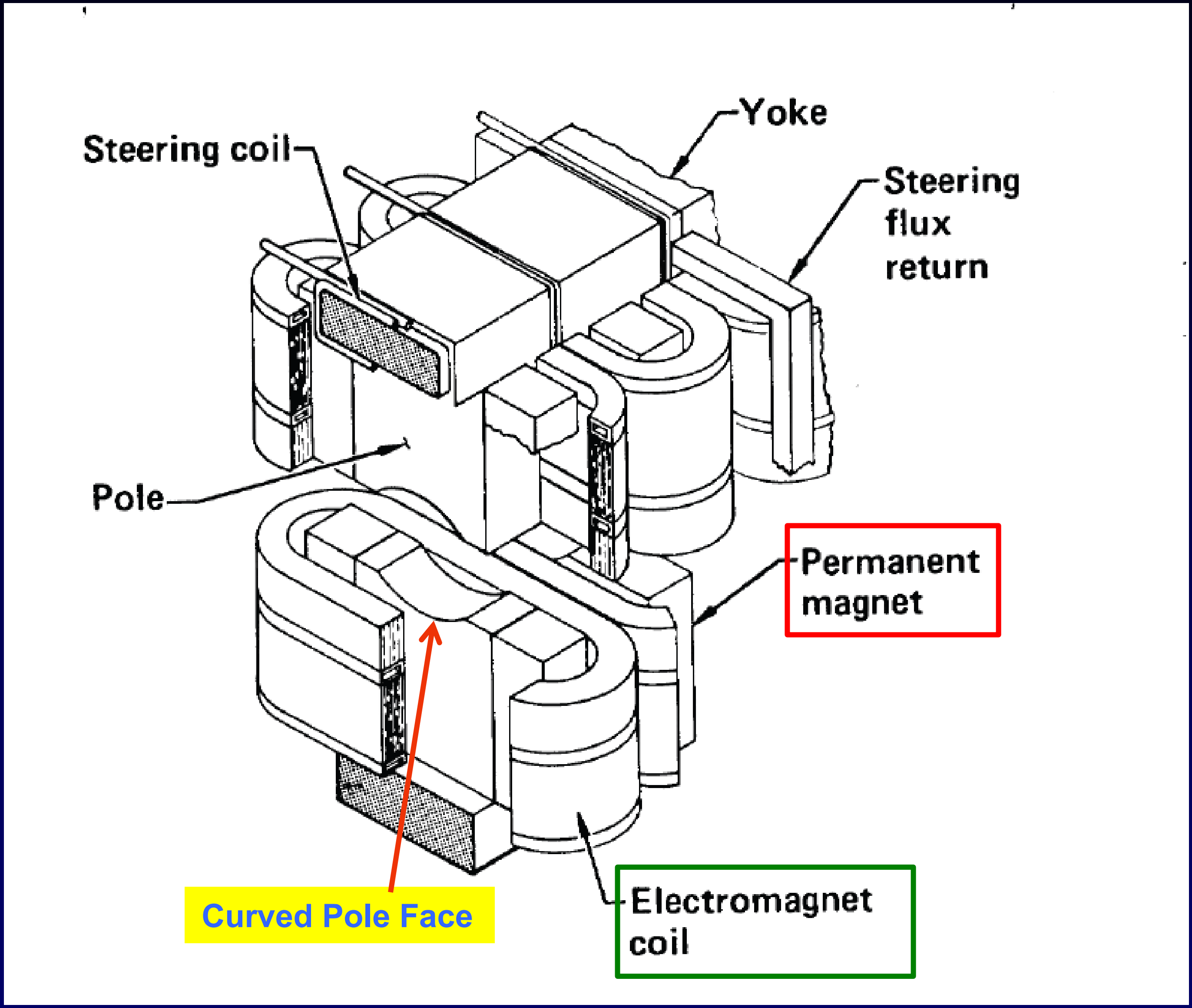
- Based on 45-MeV Advanced Test Accelerator
  - designed for 10-kA charged particle beam propagation experiments, not for 1-2 kA high brightness applications

- Paladin Goals:
  - no waveguide ➡ gain&refractive guiding effects critical ✔
  - technological proof for undulator lengths >= 25 m ✔
  - "curved" pole tip focusing worked ✔
  - demonstrate tapering scaled as expected to "optical" regime ✗
  - demonstrate (to "Star Wars" program managers) that high-efficiency, high charge/pulse induction linacs had sufficient brightness to drive single-pass, optical FELs ✗

5-m Paladin Undulator Section



Paladin Hybrid Undulator Cross-Section



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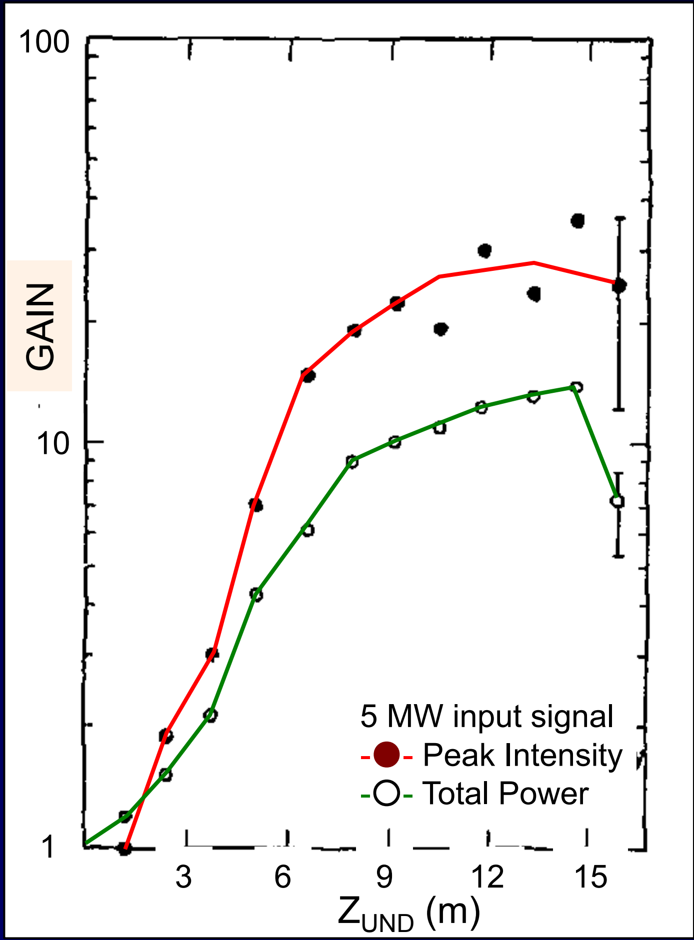
- Original hope: 2+ kA & 30 dB gain relative to 5 MW seed
- Results were: 0.5 kA & 14 dB gain, saturation @12-15 m



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The Problem:

Brightness!

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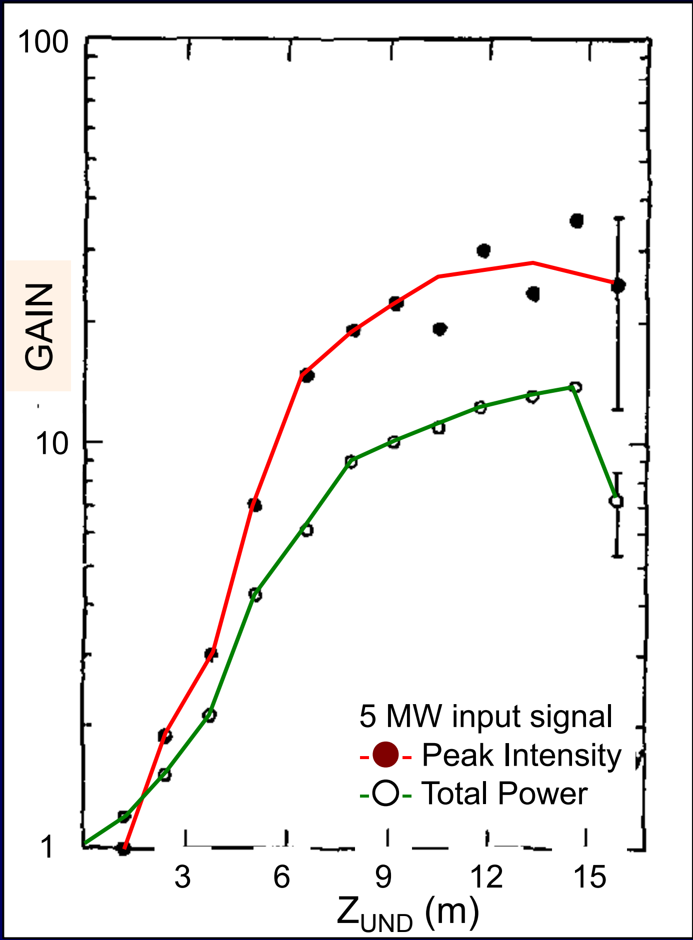

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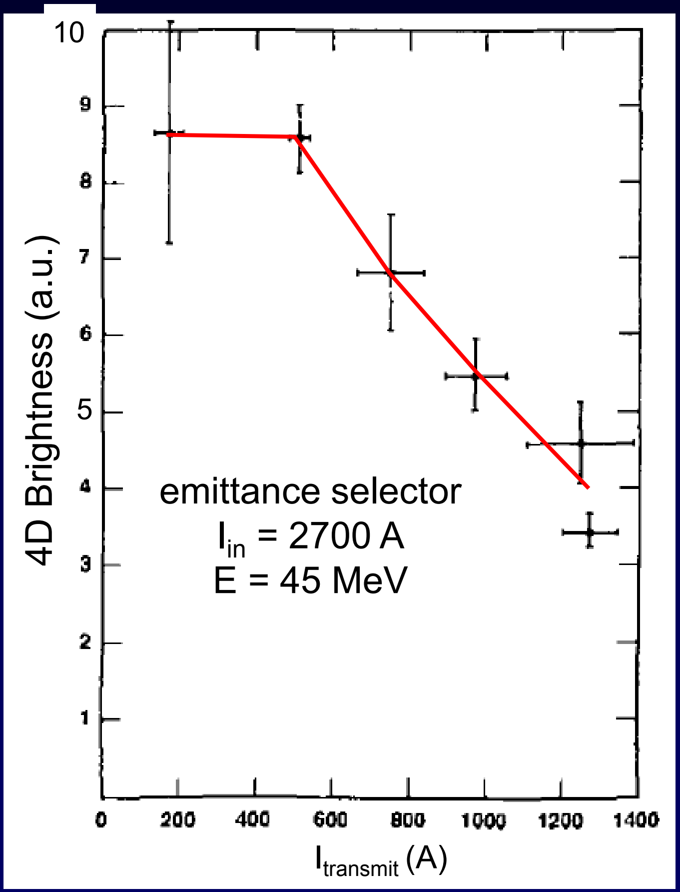
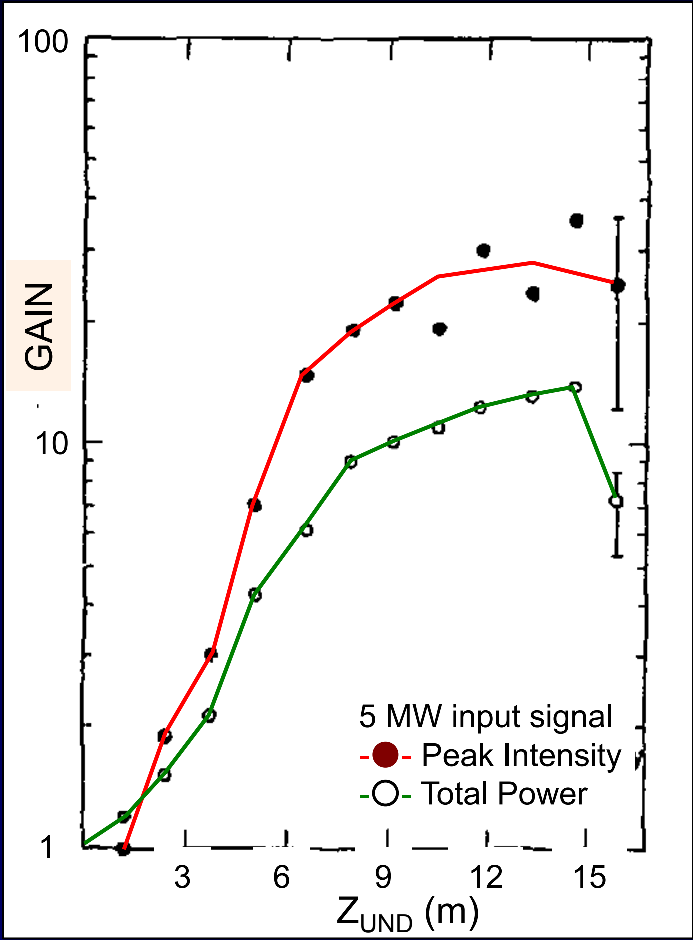
ATA cathode used a velvet felt emitter (needed for high currents) ➡ poor brightness above 1 kA. Also degradation from corkscrew & BBU instabilities





Figures from Orzechowski *et al.*, LINAC 88, UCRL-99391

"Dark Ages" 1990's Decade

- After collapse of "Star Wars" FEL interest, U.S. amplifier program endured a virtual exile into the low-funding wilderness ...
- But there were seeds of a renaissance:

  ➢ strong interest in a scientific, non-military x-ray FEL

  ☞ semi-bootlegged, multi-US DOE-lab & UCLA + DESY-centered European design efforts

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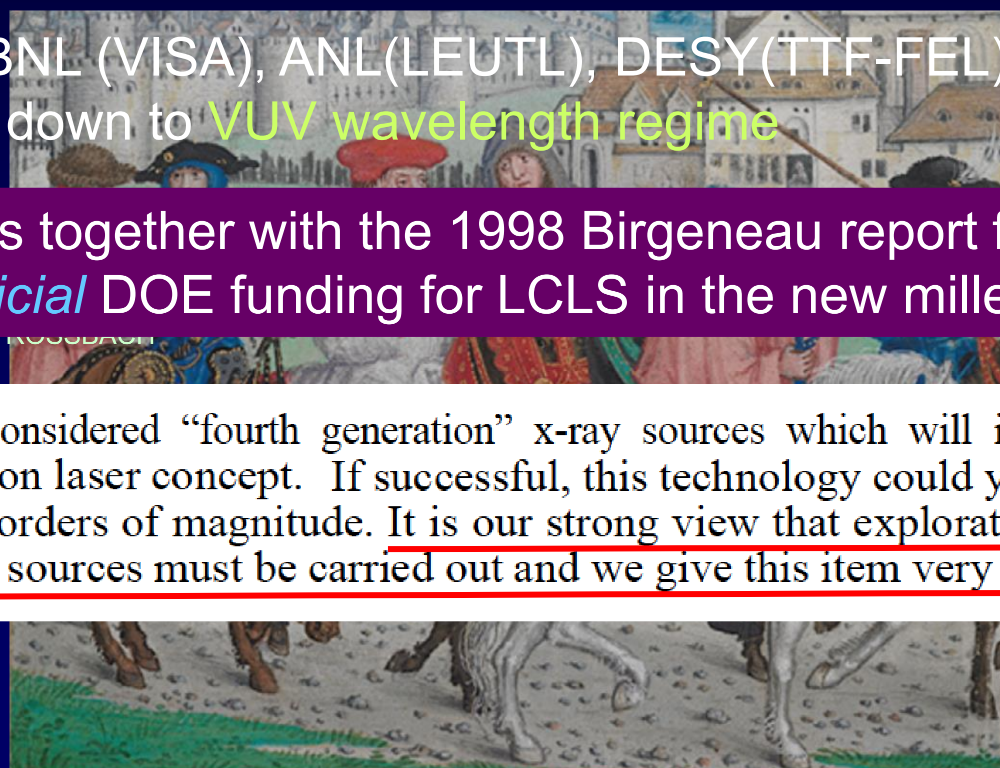


- Experiments at BNL (VISA), ANL(LEUTL), DESY(TTF-FEL) confirmed scaling of SASE down to VUV wavelength regime

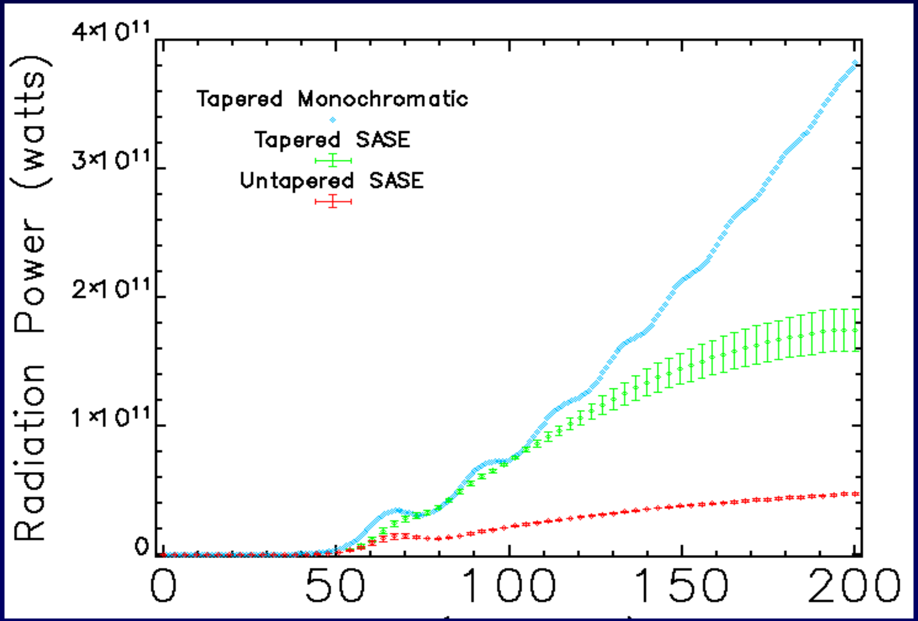
These results together with the 1998 Birgeneau report finally stimulated *official* DOE funding for LCLS in the new millennium

We have also considered "fourth generation" x-ray sources which will in all likelihood be based on the free electron laser concept. If successful, this technology could yield improvements in brightness by many orders of magnitude. It is our strong view that exploratory research on fourth generation x-ray sources must be carried out and we give this item very high priority.

Back to the Future: Tapering SASE Amplifiers

- With LCLS go-ahead, amplifier tapering physics again became relevant
- Question arose during mid-LCLS design: can a taper strongly increase SASE FEL output beyond saturation?
- Study by WMF, ZH, Kim, Vinokurov (FEL01, NIM A 483, 537–541 [2002]) showed 4X power increase over untapered case & reasonable trapping fraction (~30% decreasing slowly over last 100 m)

>> necessary to reduce asymptotic tapering rate (ψ_R) to 0.2 from ~ 0.4 optimum found for time-steady case



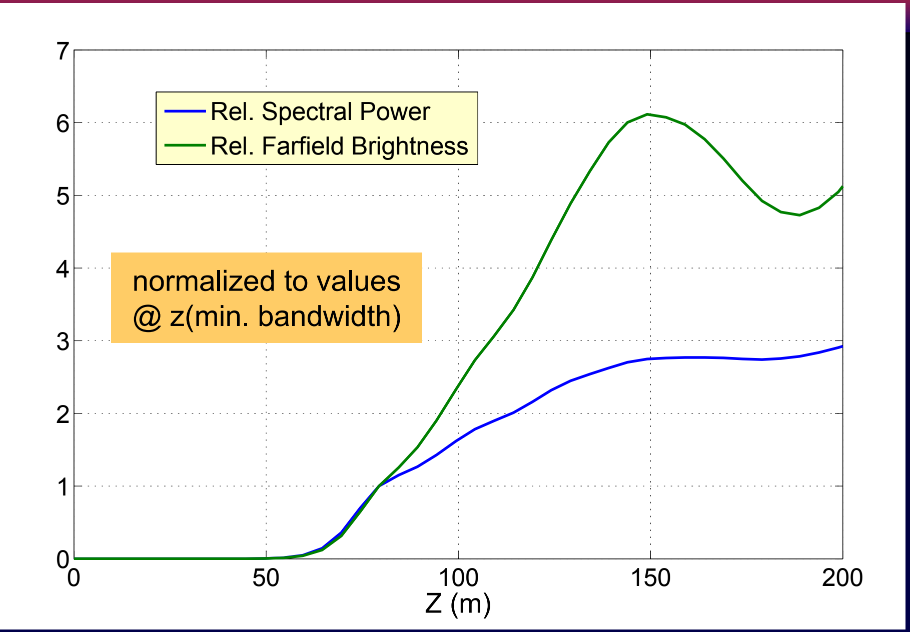
Spectral Brightness, Transverse Mode Evolution

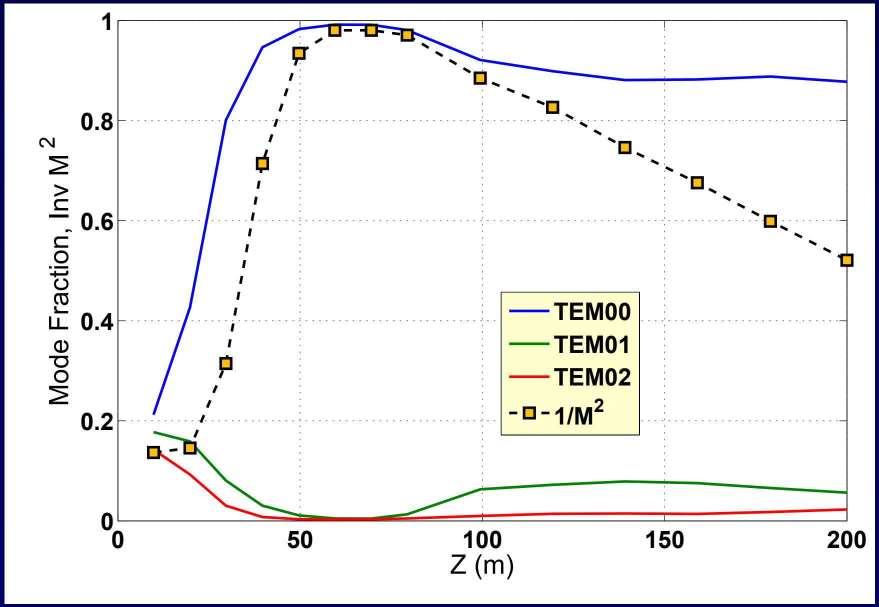
- Importantly, in addition to the power increase, there is improved spectral brightness

- Also reasonable output transverse mode content and M^2

- Later work by Freund and Miner (J. APP. PHYS. **105**, 113106 [2009]) confirmed basic observations

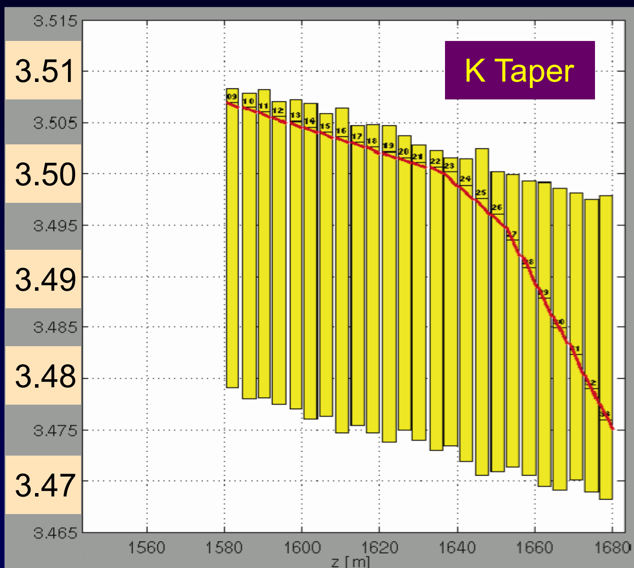
- Also very recent work by Schneidmiller and Yurkov

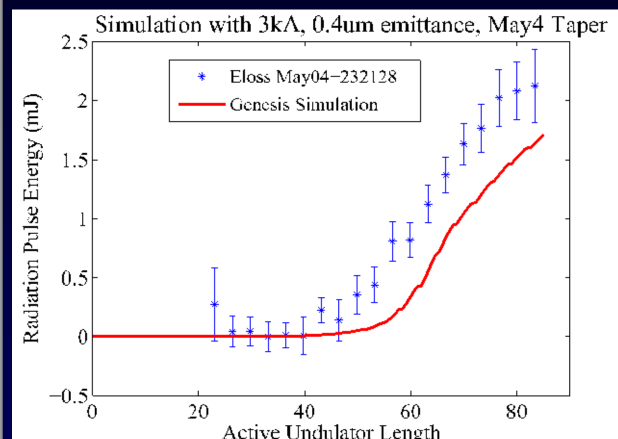


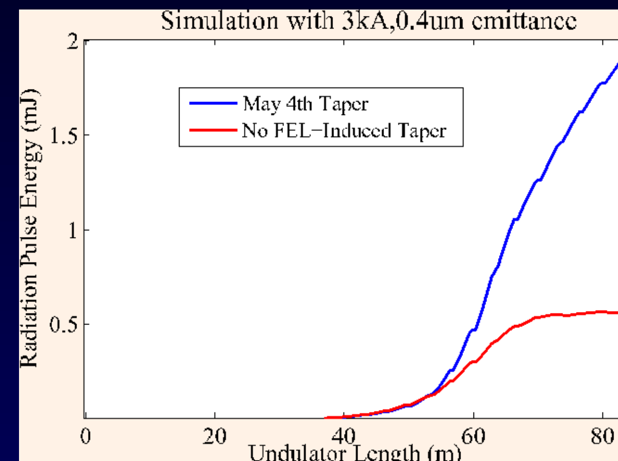


Real-life SASE Tapering: Hard X-ray Results @ LCLS

- After achieving saturation in spring 2009, LCLS team quickly explored tapering to increase SASE power at 8-keV:



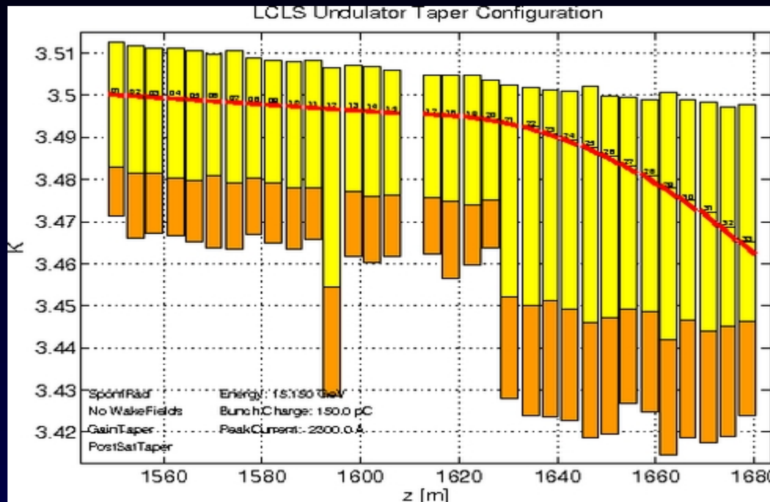


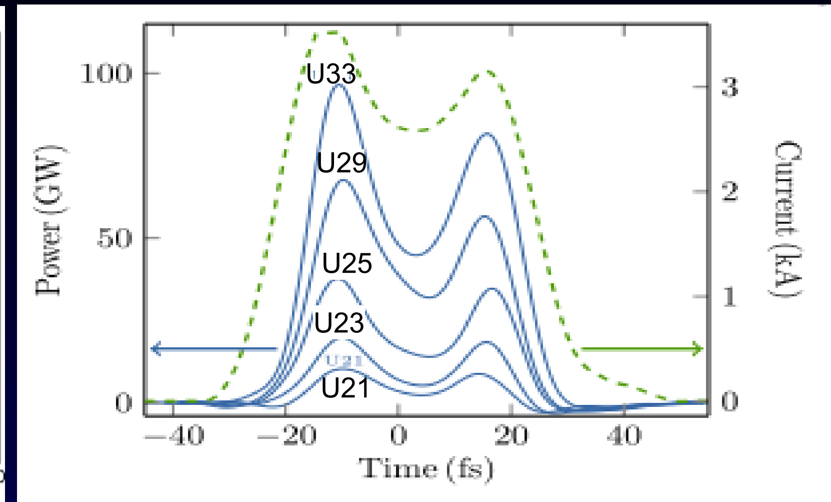


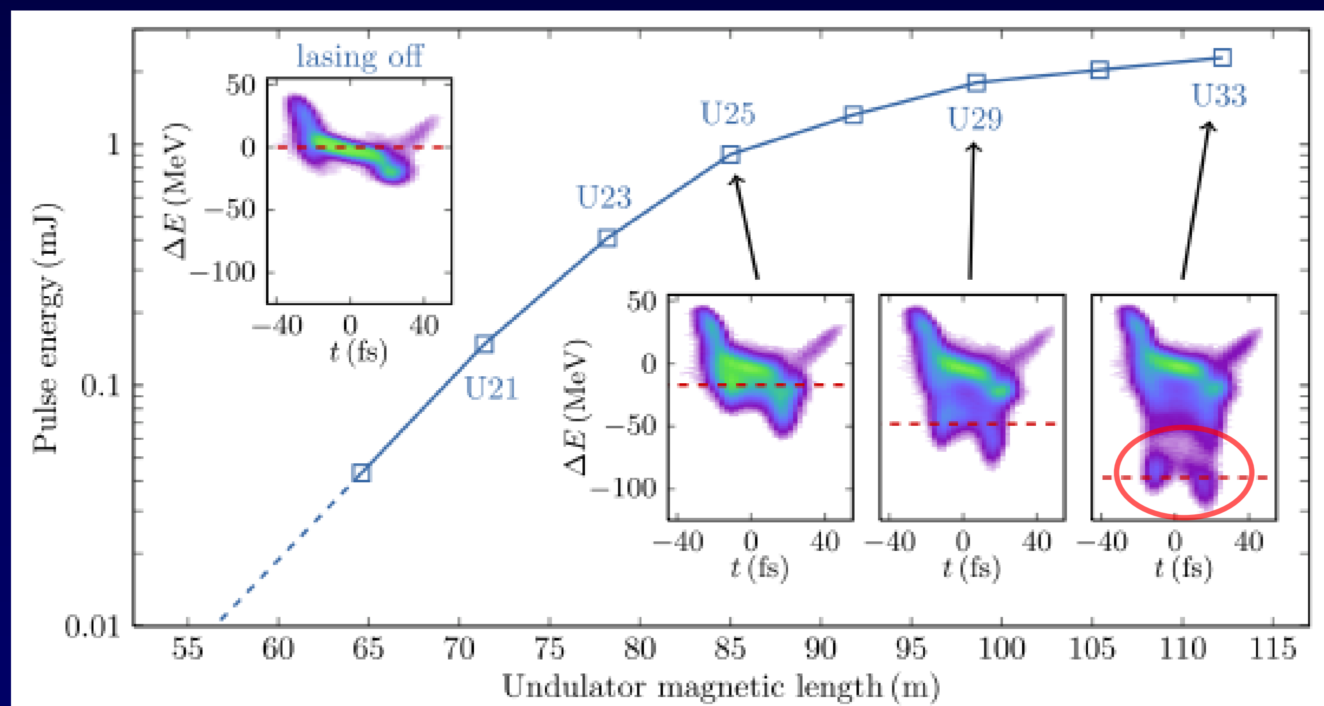
Results from Ratner et al., Paper TUOA03, FEL09:

- Tapering: ~3X output pulse energy gain relative to saturation
- Reasonable agreement with simulation modeling
  - uncertainty if wakefields were increasing current spike & emission)
- New XTCAV: successful deployment in 2013 now gives time-resolved indications of FEL energy extraction, trapping phenomena

LCLS HXR tapering example: 15.2GeV, 150pC, 10.2keV SASE XTCAV results







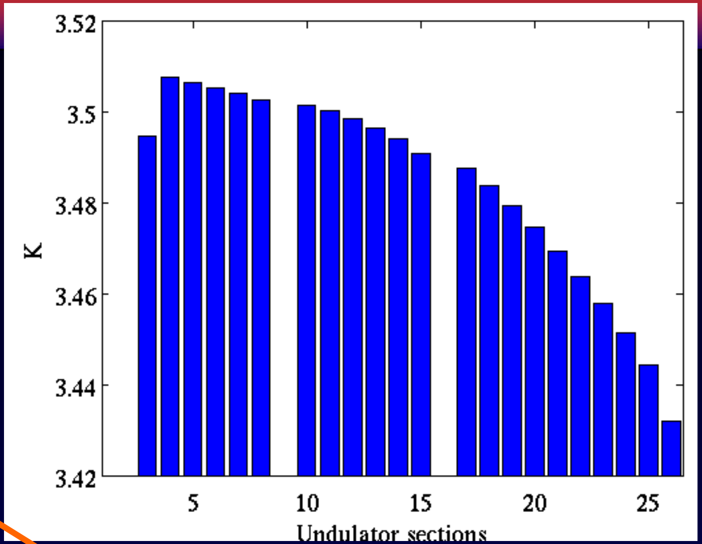
~ quadratic tapering
0.5% deceleration
evidence for trapped particle group at U33

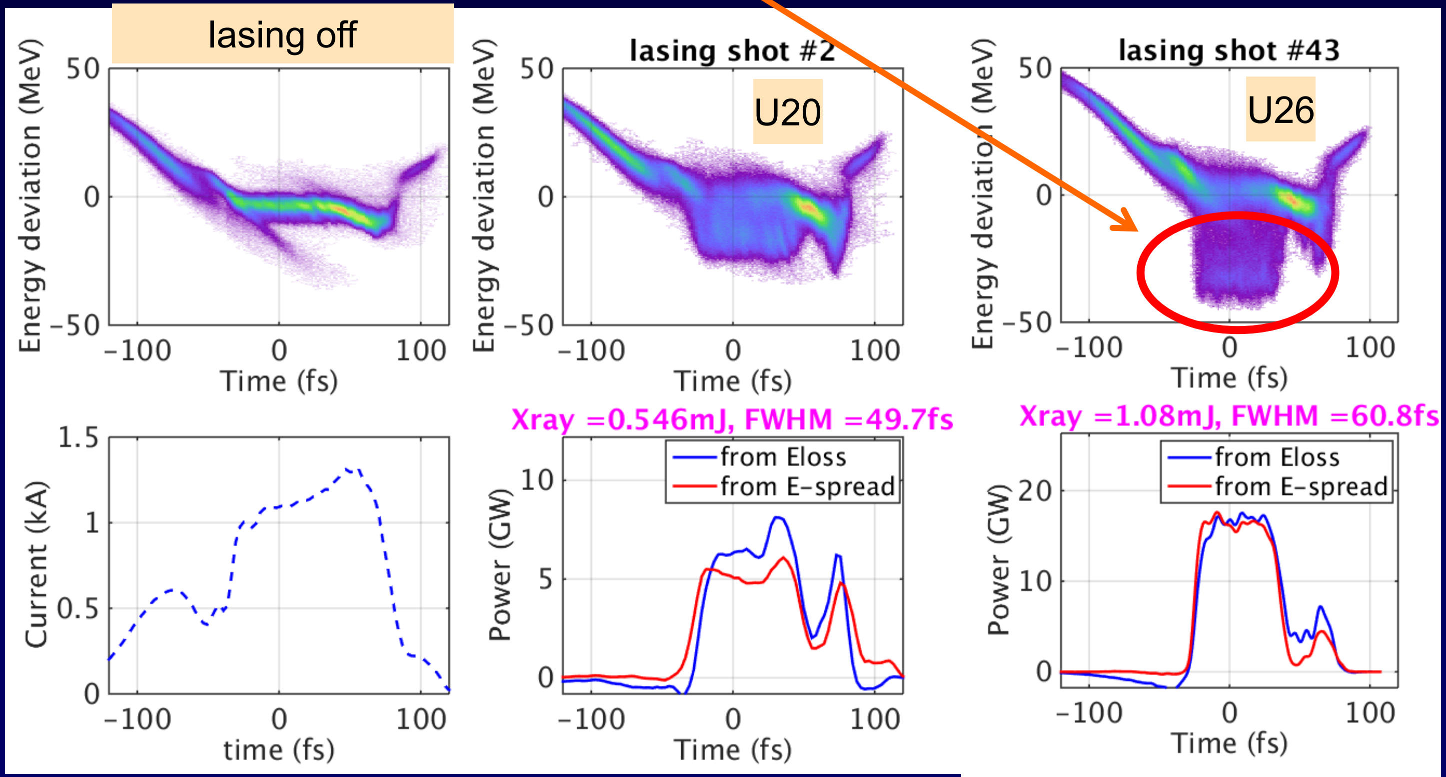
Data analysis and slide courtesy Y. Ding

LCLS 9-MAY-2014: Self-Seeded SXR @530eV - XTCAV

3.44 GeV ; 1200 A
slotted foil
100 pC unspoiled
~ quadratic tapering
> 2% in K^2
⇒ 3X power increase

some evidence for trapped particles





Data analysis and slide courtesy Y. Ding

≳ 2011: Renewed Interest in Strong Tapering

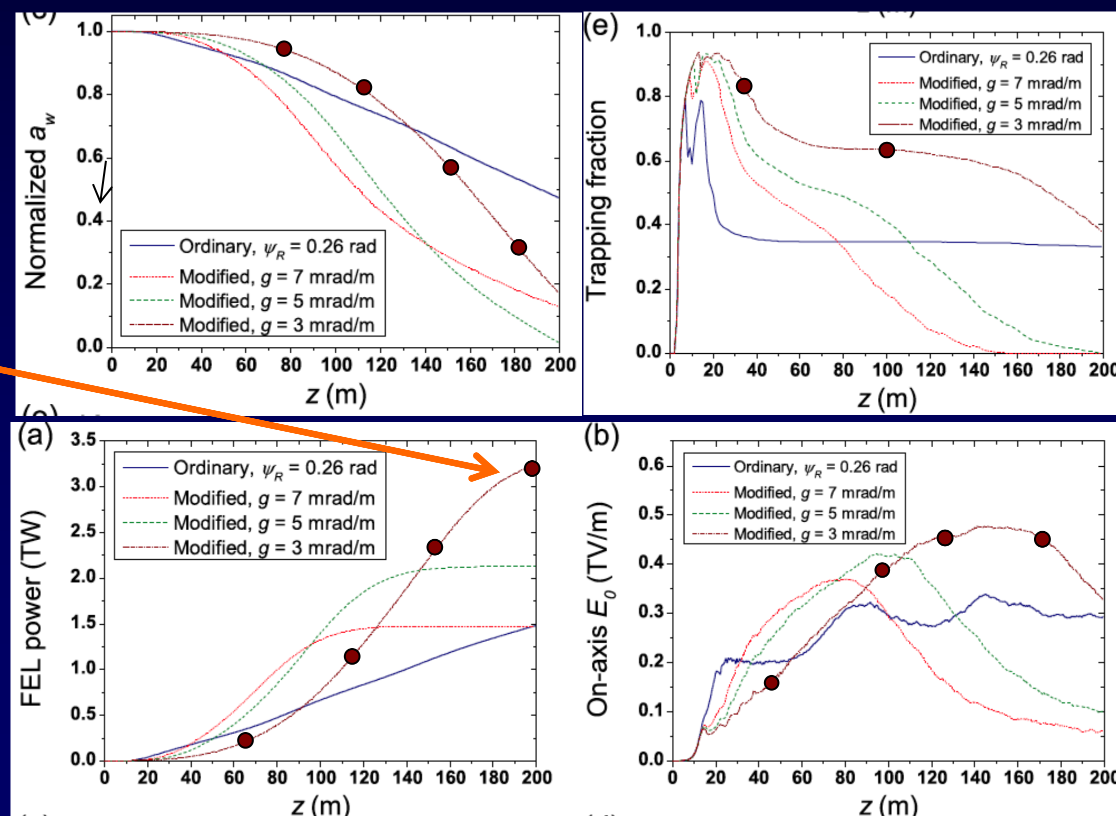
- New desire to reach TW-power level at hard x-rays for biological studies stimulates new work in self-seeded tapering optimization
  - Jiao *et al.* (2011+/SLAC)
  - Mak-Curbis-Werin (2014+/Lund)
  - Schneidmiller&Yurkov (2014+/DESY)
  - “I due Claudi”: C. Emma & C. Pellegrini (2015:UCLA/SLAC)

Fawley 1995, Jiao *et al.* 2012 studies of deep tapering

- Fawley FEL95 paper on diffractive **limits on extraction efficiency:**
  - "optical guiding" limits in diffraction regime throttle max. on-axis E-field, precludes perfect TEM00 output mode
  - *P* eventually increases linearly with *z*, not quadratically
  - asymptotic normalized energy extraction per gain length $\lesssim 2\rho\ (Z_R / L_G)$
- Jiao *et al.* {PRST-AB, 15, 050704 (2012)} semi-empirical extension of classic KMR approach:
  - underlying goal: maximize power for fixed undulator length
  - extended 1D theory to include diffraction, optical guiding, radially-resolved particle trapping; allow z-dependent e-beam radius
  - bottom line: ~20% power increase relative to constant ψ_R optimum (self-seeded, 8-keV LCLS-1 with 4-kA, 0.3 mm-mrad, 200-m L_u)
- Note: sidebands *IGNORED*

Mak-Curbis-Werin approach to variable Ψ_R taper

- Work presented at IPAC14 & FEL14; PRST-AB 18, 040702 (2015)
- Another semi-empirical study maximizing output power for fixed undulator length
- Modified KMR: $\Psi_R = gz$ for all z (*i.e.*, $\Psi_R \equiv 0$ at $z=0$)
  - improves trapping in early saturation region, more deceleration in deep saturation
- Application to MAX IV FEL at 3-keV shows 2X power improvement for 200-m L_u
- Note: sidebands *IGNORED*

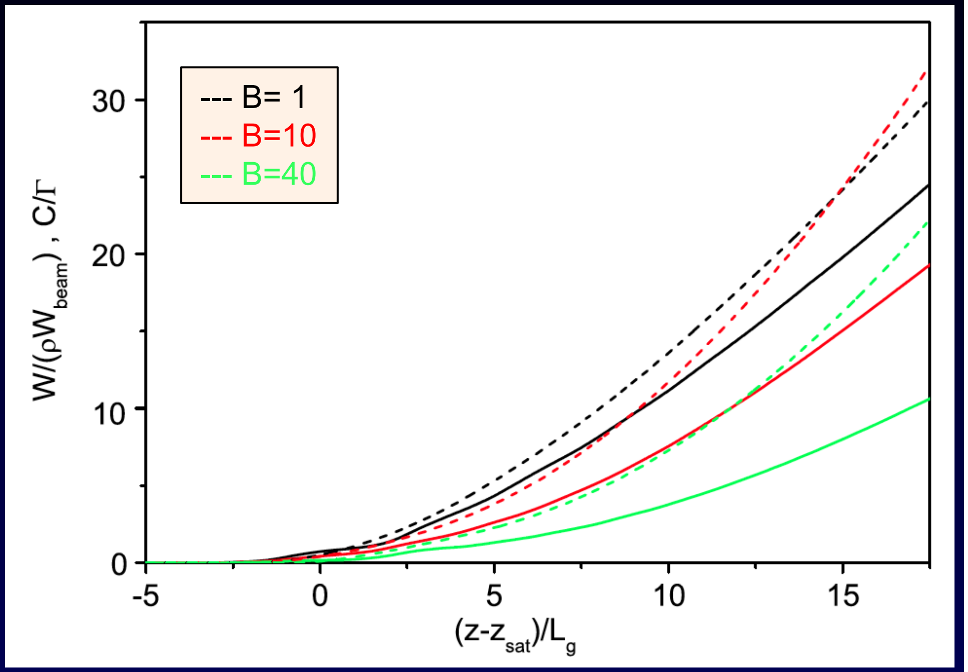


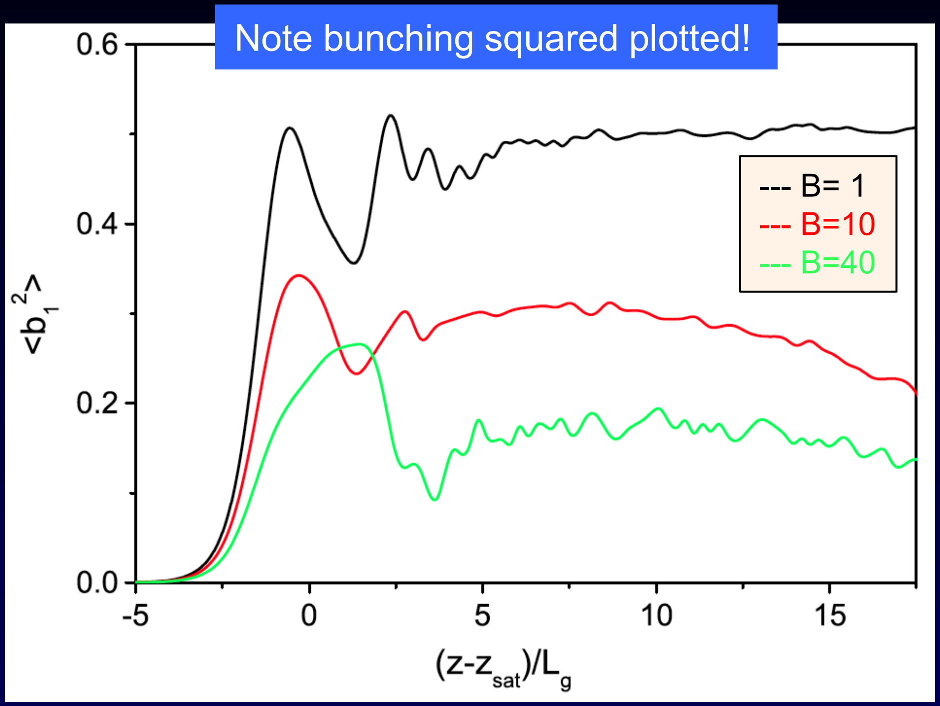
Schneidmiller-Yurkov analysis of optimized taper

- Details presented at FEL14, PRST-AB **18**, 030705 (2015);
  more in talk MOC02 (today 2:00 PM)
- Fundamental work for understanding the FEL physics behind optimizing high gain amplifier tapers (low ε_N and σ_E limit)
  - Critical parameters are normalized diffraction parameter $B \sim Z_R/L_G$ and Fresnel number $N \equiv Z_R / z$
  - Details of the formation of trapping&/bunching modulation in the region $2\ L_G$ before z_{SAT} are relatively insensitive to B ; start taper there
  - Many normalized quantities (power, bunching fraction, optimum deceleration, mode characteristics) follow self-similar solution
- Optimal deceleration shows FEL power initially follows quadratic z^2 dependence followed by eventual asymptotic linear z dependence

- Note: sidebands *IGNORED*

Optimized S&Y Taper Results





FAST simulations with initial $\sigma_E = 0$; L_G is field gain length

Left: Solid line is radiation power "W" normalized to nominal saturation power
Dashed line is deceleration "C" normalized to gain parameter

- Note B=1 (diffraction effects important) case quickly enters linear gain regime, while B=40 (quasi-1D) remains ~quadratic for P vs. z

Right: high diffraction case does better in bunching!

So... what about sidebands?

- Sidebands well-known to KMR, oscillator community in 1980's
- Basic cause is synchrotron motion by trapped particles in ponderomotive well
- Shot noise growth in exp. gain regime *always* provides an initial broadband seed for sidebands
- Some detuning due to power growth
  - but weak since $\Omega_{SYN} \sim P^{1/4}$
- Check out poster WEP076 by Emma&Pellegrini: "Tapering Studies for TeraWatt Level X-Ray FELs with a Superconducting Undulator and Built-in Focusing"
- My personal opinion: this is a problem we want to have!

An exciting future beckons...

- We now have the joy&benefits of multiple operational (or soon-to-be!) single-pass amplifiers that can access the post-saturation regime

☞ this should be a truly golden age for XUV and x-ray FEL's

- For both external- and self-seeding, systematic experimental studies of best optimization for tapering are needed:
  - best *K(z)* for max. power in a given undulator length
  - best *K(z)* for min. spectral bandwidth & sideband control
  - best *K(z)* for minimizing shot-to-shot fluctuations
  - note: FERMI (FEL-1) presently uses *K(z)* to control bandwidth
- Similar efforts are needed for SASE configurations:
  - > initial 100+ kHz LCLS-2 soft x-ray operations will likely begin in SASE mode
- Experimental confirmation of the usefulness of reverse tapers for temporal manipulation of the output pulse (incl. harmonics)

The best is yet to come!

Thank you for your attention

I gratefully acknowledge important assistance for this talk from
Y. Ding (SLAC) & M. Yurkov & E. Schneidmiller (DESY)

Over my scientific career, I also have been *very* lucky to have interacted with multiple dozens of truly superb colleagues in both FEL theory and experiment

In particular I have learned and learned (and forgotten far too much!) from

T. Scharlemann, D. Prosnitz, K-J Kim, A. Sessler, J. Wurtele, M. Xie, A. Zholents, Z. Huang, H.-D. Nuhn, P. Emma, C. Pellegrini, S. Reiche, C. Schroeder, E. Allaria, S. Di Mitri & L. Giannessi