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A Compact Coherent System Architecture and FEL Effects Occurring in the Deeply Saturated Regime

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School/Workshop on "Trends in Free Electron Laser physics"

"Ettore Majorana Foundation and Centre for Scientific Culture" Erice , May 17 - 23, 2016

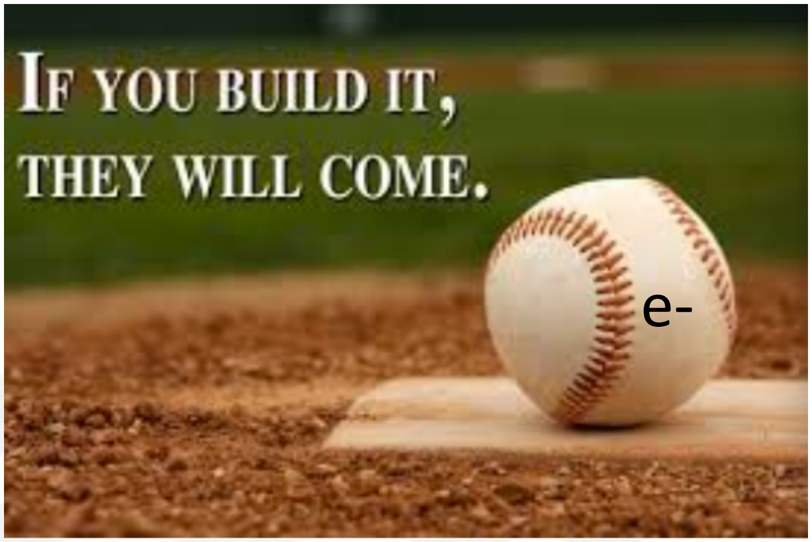
- Thanks to Massimo, Bill, and Rodolfo for organizing!
- It is great to be back in Erice with our colleagues.

Part 1
A Compact Coherent System Architecture

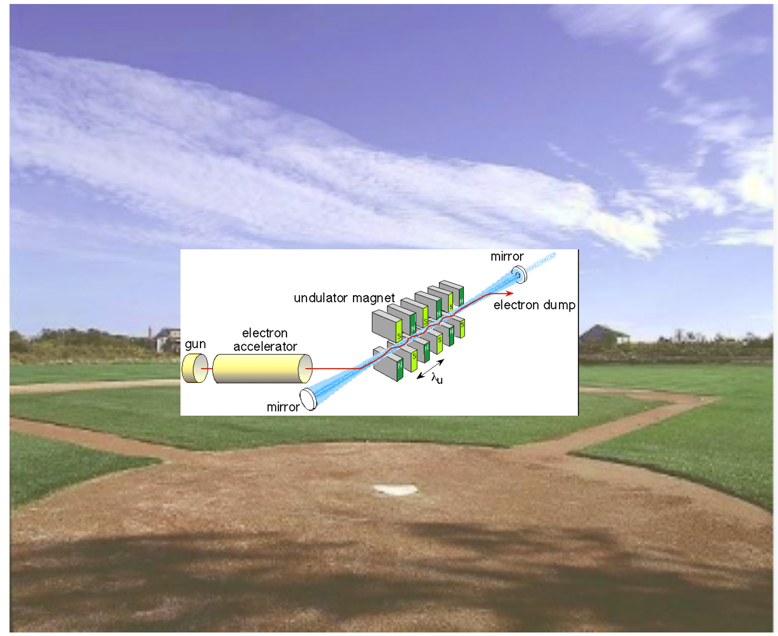
Ultimate wish list for Coherent Light Sources (maybe an FEL)

- Compact
- Tunable
- High-peak power
- High-average power
- Co-location with other wavelengths (or neutrons, etc…)
- "Inexpensive"
- Etc…

To take from a great quote from baseball



Or for compact devices, maybe if we build it, they want it shipped to them!



We have learned from the users that they want ever increasing powers – I don’t think we can build the next machines fast enough!

And the more compact we make them, the more they will want!

And the machines of all levels of average powers are useful as analytical tools.

Application examples and present status for a few wavelength regimes.

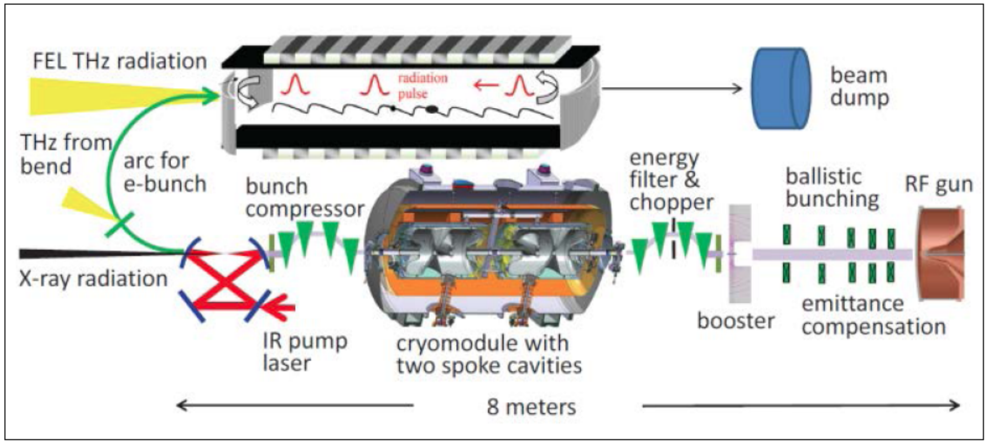
- Today – only time to look at a few examples of sources and their applications with higher-average power systems.
- Some also point to the need of being compact (even "portable").

Let's look at a few examples of the user desires

- THz
- THz plus X-rays
- VUV
- X-rays

THz – one example

- Design study for a Swedish THz FEL at the Stockholm-Uppsala FEL consortium
- THz as a probe for materials – through intermolecular vibrations, intra-molecular vibrations, molecular rotations…
- Proven facilities such as in Neijmegen (FELIX - IR, FLARE - THz), Berlin, Dresden (FELBE)
- Want an accelerator-based source instead of a laser-based source because of high-repetition rate, high-average power, possibility to synchronize with another source (i.e. with an X-ray source), easy to adjust wavelength, potentially narrow band pulses, adjustable polarization.



THz output	
Frequency	0.3 THz – 6 THz
Pulse energy	1- 20 μJ
Pulse length	>1 ps (sub ps)
Bandwidth	few %, 10^{-4}
Rep. Rate	176 MHz (1 kHz)

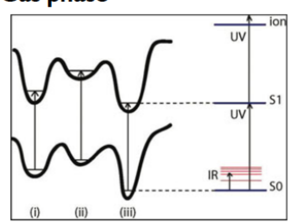
Superconducting accelerators => long macro pulses,
10 ms (176 MHz) compared with 15 μs at Nijmegen (3 GHz) and Berlin (1 GHz) =>

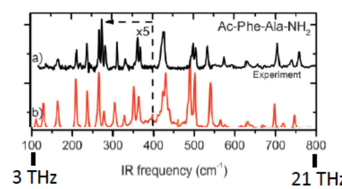
~100 x more average power
Important for spectroscopy in gas phase and when narrow bandwidth

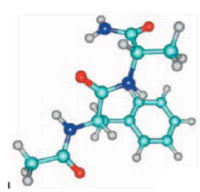
Molecular structure - Gas phase

THz-UV ion dip spectroscopy

Comparison of THz spectra with theory => Structure







Extracted small peptide structure

S. Jaeqx *et al.* Angew. Chem. Int. Ed. **53**, 3663 (2014)

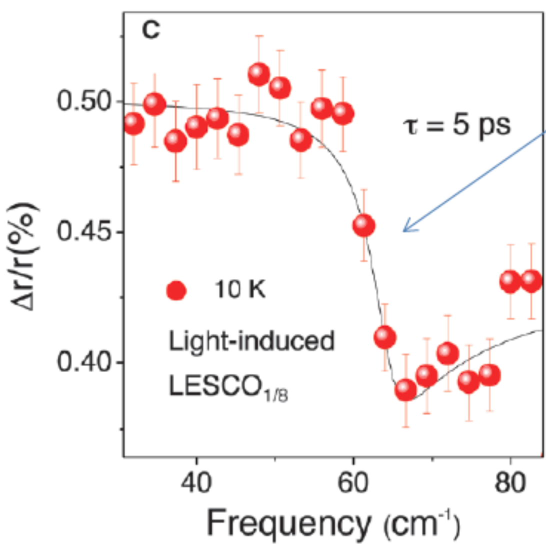
Slides courtesy of Mats Larsson, Stockholm University

THz solid state studies ⟹

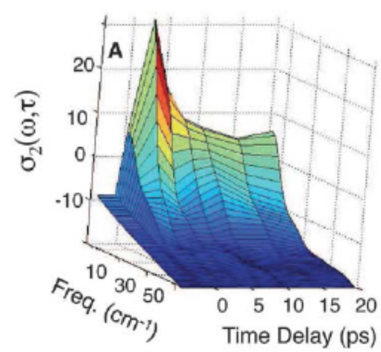
often analyze conductivity ($\sigma(\omega)$) extracted from reflectivity (r)

$r = |(1-N_{compl})/(1+N_{compl})|^2 \rightarrow \varepsilon_{compl} = N_{compl}^{\ 2} \rightarrow \sigma_{compl} = \sigma_1 + i\sigma_2 = \varepsilon_{compl} \cdot \omega/(4\pi i)$

Photo induced superconductivity



Josephson plasma edge - drop in r at 60 cm^{-1}
feature of superconductive state



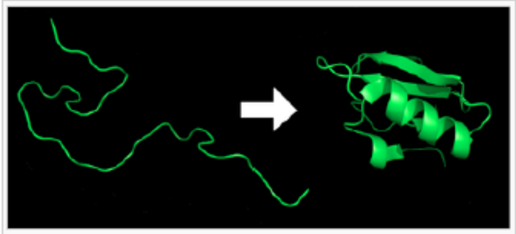
D. Fausti *et al.* *Science* **331**, 189 (2011)

Slides courtesy of Mats Larsson,
Stockholm University

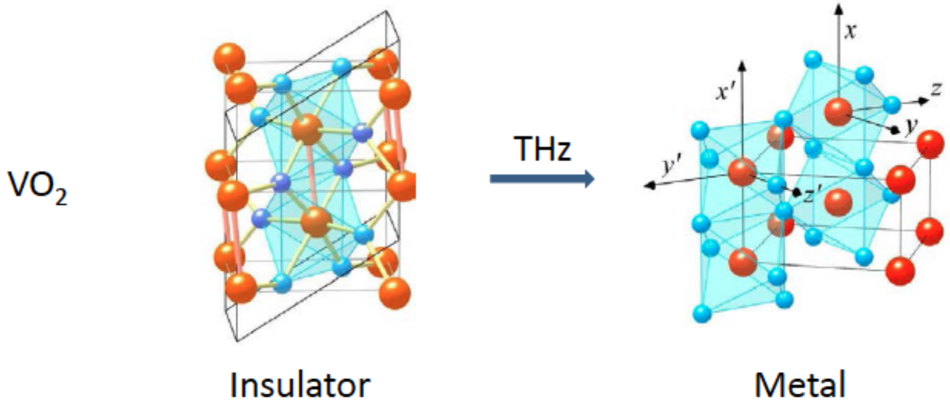
THz plus X-rays – examples

THz pump – X-ray probe

THz-induced motion of proteins probed with X-ray crystallography

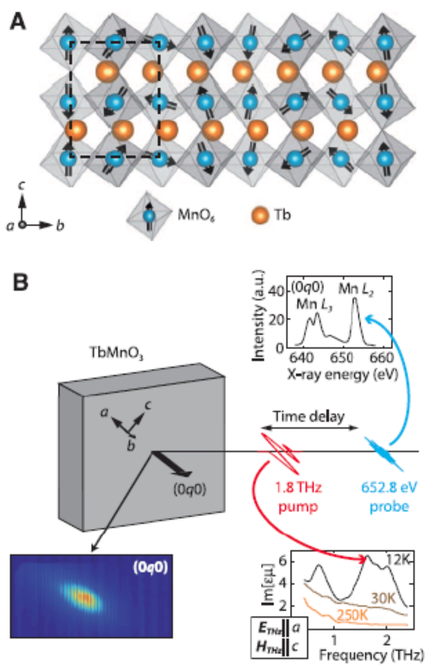


THz-induced phase transitions probed with X-ray diffraction



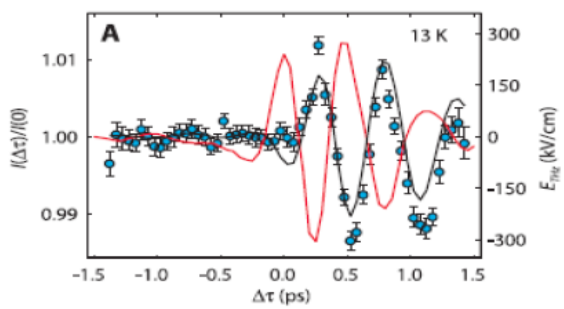
M. Hoffman

THz pump – X-ray probe



Initiate spin dynamics with E-field of THz pulse in multiferroic magnetic material

Probing with soft X-ray diffraction



T. Kubacka et al. Science **343**, 1333 (2014)

Slides courtesy of Mats Larsson, Stockholm University

VUV

How do we go from a large laboratory-based science tool and adapt these for industry and other non “big government laboratory” applications - > i.e. reliability, cheap, turn-key

Transforming FELs for Industry

- Facilities designed for scientific research applications will not be appropriate for EUVL HVM
  - Wavelength tunable → 13.5/6.8 nm
  - Ultrahigh intensity → High Average Power
  - Single end station → Multiple Scanners
  - Real estate unrestricted → Limited
  - Reliability needs to be 100%
- Linear, single-pass FELs are commonplace
- Currently developing (4th Generation):
  - Multi-pass Linac
  - Energy Recovery Linac
  - Regenerative Amplifier FEL
  - FEL Oscillator

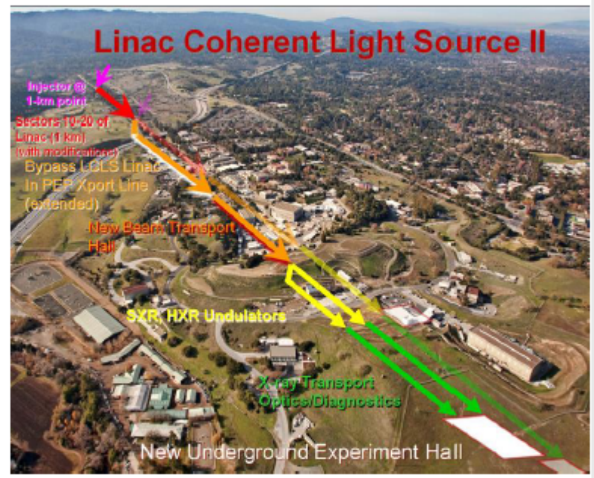


Photo Credit: SLAC LCLS

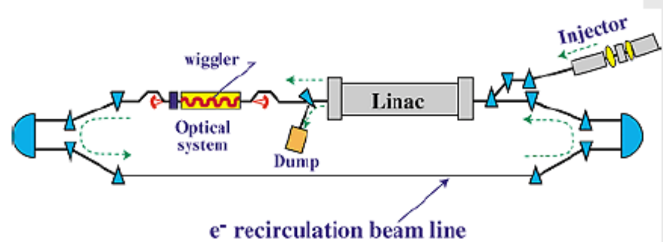


Diagram Credit: Jefferson Lab

Average powers for such an industrial example - the VUV system for chip manufacturing

- **1W – 10 W**
  - Metrology, Microscopy, Imaging
  - Fixed to variable wavelength
- **10kW – 30 kW**
  - **Power exposure tools**
  - **Fixed wavelength**

X-rays

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An example need for a “compact” coherent, high power source source

Recovering lost ancient literature:
X-ray phase contrast tomography reveals the secrets of Herculaneum papyri

Vito Mocella[1],
Emmanuel Brun[2], Claudio Ferrero[2], Daniel Delattre[3]

[1]CNR-IMM-Istituto per la Microelettronica e Microsistemi- Unità di Napoli, Italy
[2]ESRF- The European Synchrotron Grenoble Cedex – France
[3]CNRS-IRHT-Institut de Recherche et d'Histoire des Textes -Paris – France

Slides courtesy of
Vito Mocella,
CNR Napoli

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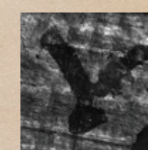
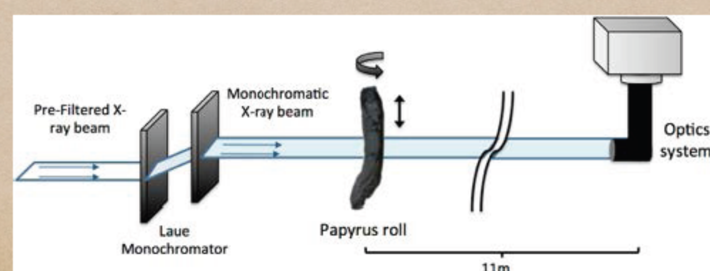
Our approach

- We radically changed the paradigm of the technique:
  - The morphological information as the internal deformation or the length of the papyrus, the arrangement and the characteristics of the fibers which make up the structure of the support is only the starting point
  - Our attempt is to retrieve a special kind of information, the text, identified with the weak relief of ink deposited on the papyrus surface.

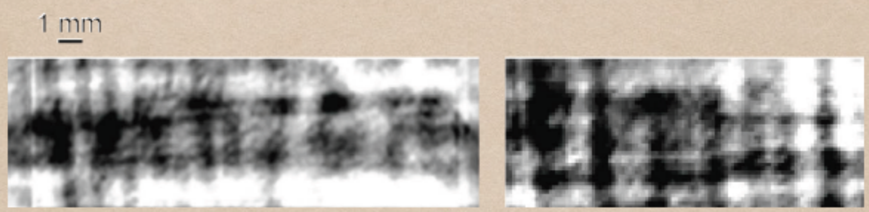


- Letters can be read using Propagation Based – edge detection
- Even if Papyrus and Ink absorb quite uniformly a significantly enhancing the



Words from fragment

Edge detection is enough to distinguish letters



ΠΙΠΤΟΙΕ ΕΙΠΟΙ

"would fall" "would say"

Letters sequences

inside the scroll

The script here is noticeably different from that of fragment from PHerc.Paris. 1

1 mm

ΑΡΝ

can be a single word like
αρν-εισθαι ... 'to deny'

ΗΕΥ

feminine definite
article "The"

"Eu.."
first syllable of a nominal
cf. for example, in English
euphonia, euphonic,..

ΚΙ

for example, a word of the
verb family κινεῖν 'to move'

Future Prospects (1)

Improve the experimental technique

new experiments are scheduled very soon

Improve data analysis:

algorithms available for segmentation fail when applied to a so complex surface
many collaborations are starting right now

New compact coherent sources

Future Prospects (2)

A promise that many text from the library of the 'Villa dei Papiri',

the contents of which have so far remained unknown,
may in future be deciphered without damaging the papyrus in any way.

New prospects not only for the many papyri still unopened,

but also for others that have not yet been discovered, perhaps including a second library of Latin papyri at a lower, as yet unexcavated level of the Villa

The ultimate wish ->
A compact, portable, very coherent (maybe not an FEL) light source to enable ON-SITE analysis at archeological sites.

Look for Vito's invited talk at NA-PAC in Chicago

- **OK, a couple of things:**
  - ***Not every future compact light source will be the same.***
    - Massimo mentioned last evening that we maybe did not completely succeed in architecting the ultimate compact light source.
    - But actually, I think we did - there are just many architectures and we now succeeded by knowing all of the pieces.
  - How to make these devices more compact for a few of these users?

- **A Compact Coherent System Architecture**
  - Use newly developed and ever emerging high peak power lasers to drive coherent light sources with laser plasma accelerated beams and wave undulators.

- But we rely on lasers for the machine and the radiation producing section – What is the state of the art and what direction are these lasers headed?

- See, for example, the recent call for FY2016 Research Opportunities in Accelerator Stewardship as a demonstration of the constant movement of lasers moving forward
- The Department of Energy is trying to guide laser developments specifically for particle accelerators and applications through investments

(See more information on the DOE HEP Accelerator Stewardship Web-site including the recent 2013 workshop on lasers for accelerators.)

(b) Ultrafast Laser Technology Program
Technical Contact: Eric Colby, 301-903-5475, Eric.Colby@science.doe.gov

Lasers are used or proposed for use in many areas of accelerator applications: as drivers for novel accelerator concepts for future colliders; in the generation, manipulation, and x-ray seeding of electron beams; in the generation of electromagnetic radiation ranging from THz to gamma rays; and in the generation of neutron, proton, and light ion beams. In many cases, ultrafast lasers with pulse lengths well below a picosecond are required, with excellent stability, reliability, and beam quality. With applications demanding ever-higher fluxes of particles and radiation, the driving laser technology must also increase in repetition rate—and hence average power—to meet the demand.

These applications have some general technological requirements in common:

- Ultrafast pulses (<1 ps)
- High average powers (>1 kW up to 100 kW or more)
- Diffraction limited beams
- Good (ps) to excellent (fs) pulse timing
- Robust and reliable operation

Many important applications also require, or can benefit from:

- High pulse energy (>0.01 J up to 1 kJ)
- High pre-pulse power contrast (better than10^{-9})
- High wall plug efficiency (>20% with a goal of 30% or higher)
- Longer laser wavelengths (>1.5 μm out to 10 μm)

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The primary goals of the Ultrafast Laser Technology Program are to develop the enabling technologies that will ultimately lead to construction of demonstration prototypes for one or more of the principal types of ultrafast lasers needed for accelerator applications, and to enhance industry's capability to produce the necessary technologies. Ultrafast lasers for accelerator applications fall into four basic laser types, summarized in Table 1 below.

Table 1. Target performance parameters for the four principal types of ultrafast lasers

	Type I	Type II	Type III	Type IV
Wavelength (μm)	1.5-2.0	0.8-2.0	2.0-5.0	2.0-10.0
Pulse Energy	3 μJ	3 J	0.03–1 J	300 J
Pulse Length (fs)	300	30–100	50	100–500
Repetition Rate	1–1000 MHz	1 kHz	100 kHz	100 Hz
Average Power (kW)	Up to 3	3	3 and up	30
Energy Stability	<1%	<0.1%	<1%	<1%
Beam Quality	M^2<1.1	Strehl>0.95	M^2<1.1	M^2<1.1
Wall-plug Efficiency	>30%	>20%	>20%	>20%
Pre-Pulse Contrast	N/A	>10^{-9}	N/A	>10^{-9}
CEP-capable	Required	N/A	Required	N/A
Optical Phase Noise	<5^o	N/A	<5^o	N/A
Wavelength Tunability Range	0.1%	0.1%	10%	0.1%

Looking to Type II to help build our tool set for future FELs that could be compact.

- Type I laser systems, used both to directly power laser-driven accelerators-on-a-chip, and as subassemblies of coherently combined fiber arrays used to generate higher pulse energies.
- Type II laser systems, used to excite plasma waves for particle trapping and high gradient acceleration, and for the generation of x-rays through Compton backscattering.
- Type III laser systems, used for generating high repetition rate radiation pulses through nonlinear processes, particularly high-harmonic generation (HHG).
- Type IV laser systems, used for plasma-based sources of protons, light ions, and neutrons.

- US National Academies of Sciences, Engineering, and Medicine Committee on “Opportunities in the Science, Application, and Technology of Intense Ultrafast Lasers”
- Speak to Stephen Milton here if you have questions or input or thoughts as he is the accelerator representative on this board for our community for this important report.

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❖ One architecture relying on high-intensity lasers

- G. Dattoli, E. Di Palma, V. Petrillo, J.V. Rau, E. Sabia, I. Spassovsky, S.G. Biedron, J. Einstein, S.V. Milton, “Pathway to a Compact SASE FEL Device,” Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 798, 21 October 2015, Pages 144–151.
- Milton, J. Einstein, and S. Biedron, 2016, "1D FEL Simulations Utilizing Laser Undulators," In: High-Brightness Sources and Light-Driven Interactions, Proceedings of the Compact (EUV & X-ray) Light Sources Conference, OSA technical Digest (online) (Optical Society of America, 2016), paper ET3A.3. (2 pages)

Opportunity

- **Utilize intense lasers**
  - Laser/Plasma acceleration
    - Has achieved nearly 5-GeV energies
    - Resulting beam has potential as a driver for an FEL, *albeit not so "compact" as one needs the drive laser and shielding*
  - Use the intense beam as a laser-based undulator
    - This has its own complication (discussed in a few minutes)
  - Combine
    - A *relatively* compact FEL

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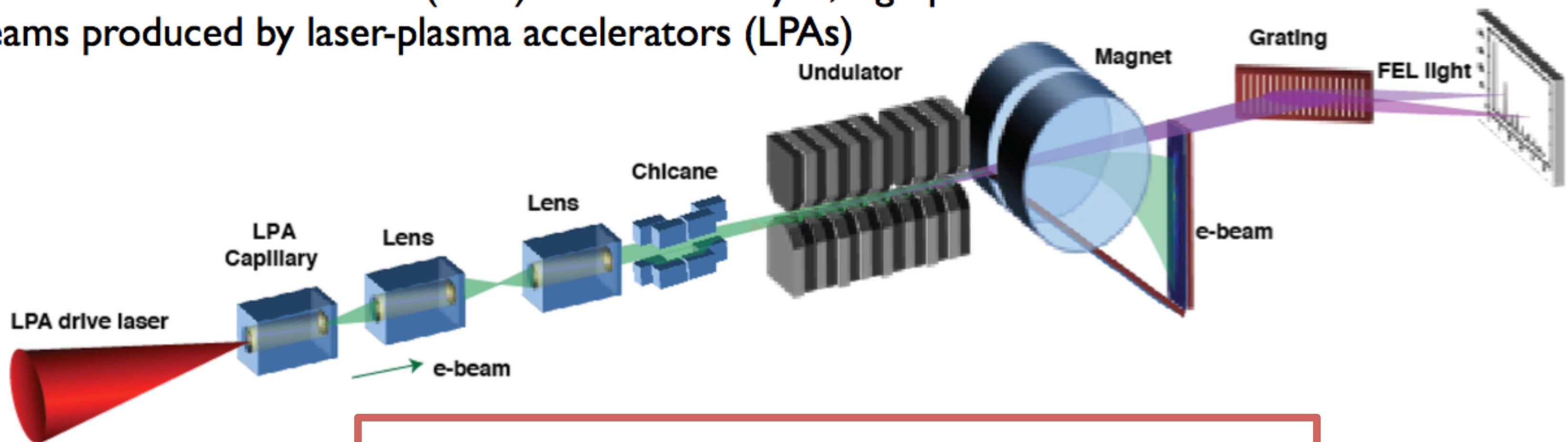
LPA-driven FEL: Free-electron lasers (FELs) from driven by fs, high-peak current, e-beams produced by laser-plasma accelerators (LPAs)

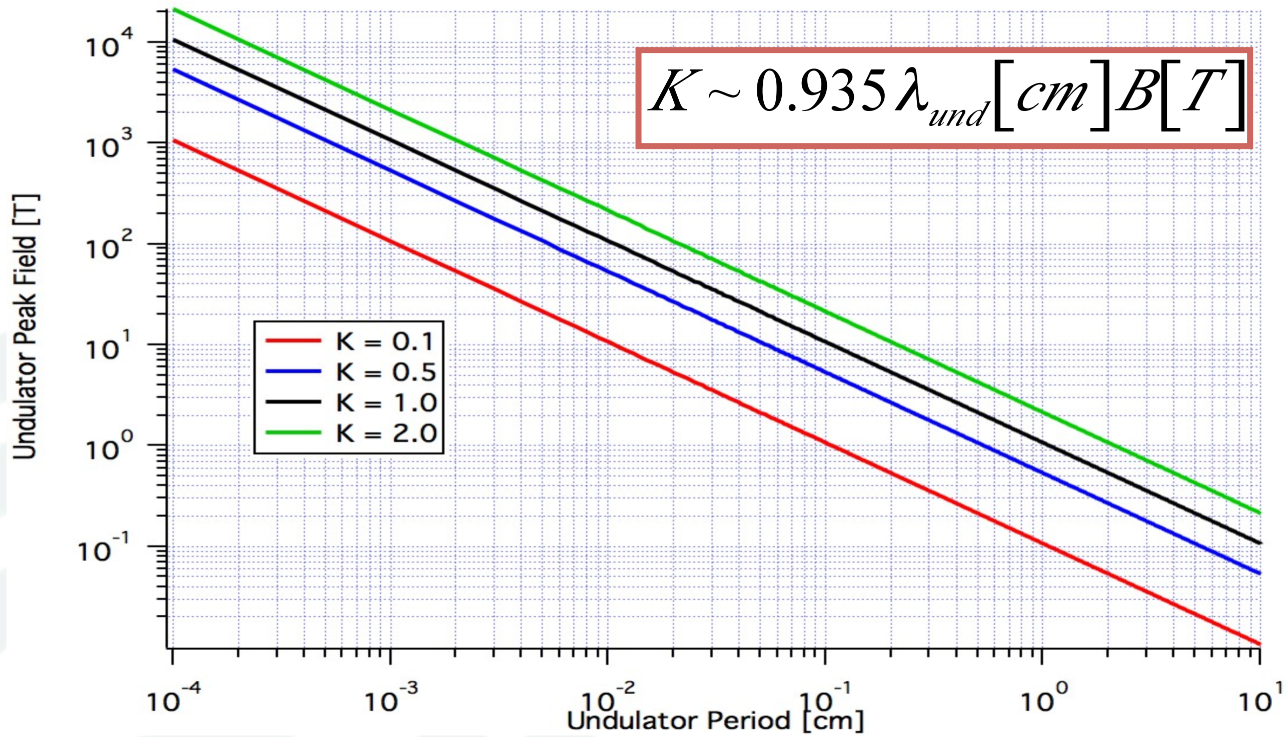


From Schroeder et al. 2013 FEL Conf.

This goes ½ way. The beam is derived from an intense laser, but it relies on a more or less a **conventional undulator**.

Note, however, that the beams derived from such a source are quite special and **very high peak current** and **low emittance**.

Conventional Undulators



$$K \sim 0.935\,\lambda_{und}[cm]\,B[T]$$

Field versus undulator period -> if you want short period you need EXTREMELY high fields to get a reasonable K-value …..

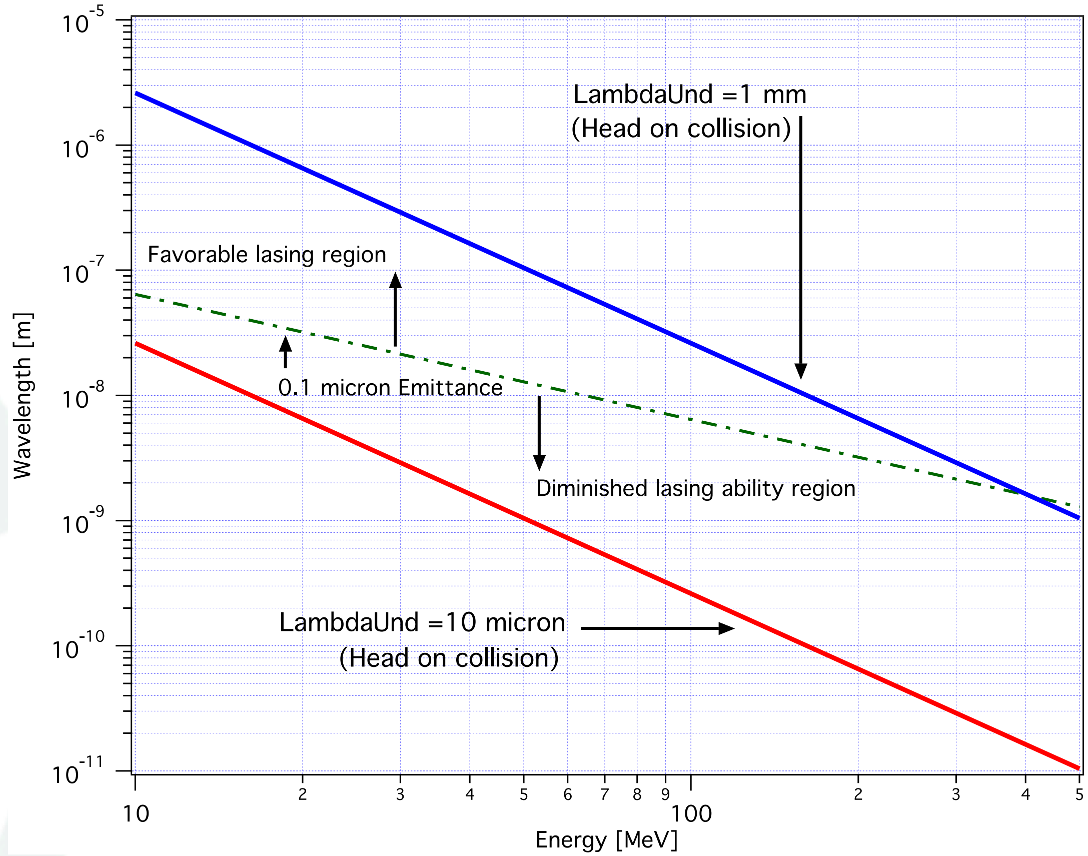
Problems of a Laser Directly as an Undulator

❖Problem 1 - The period is too short

The emittance scales as 1/gamma but the wavelength scales as one over gamma squared….so we can't just think "short wavelength laser equals short wavelength FEL output."

Diffraction limit – the beam will not be fully participating in the FEL process.

What can we do? Effectively lengthen the laser undulator wavelength



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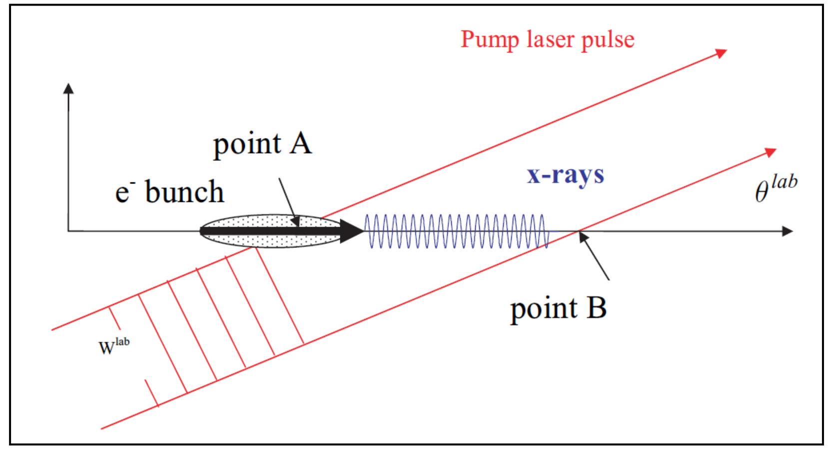
Problems (cont.)

- This can be corrected by crossing at an angle

Lawler, et al., J. Phys. D: Appl. Phys. **46** (2013) 325501

$$\lambda_{rad} = \frac{\lambda_{pump}(1-\beta)}{1-\beta\cos(\theta)}(1+K^2/2)$$



Depending on the choice of θ^{lab} one can vary the angle dependent term between

$$\lambda_{\mathrm{pump}} \quad \text{and} \quad \sim\lambda_{\mathrm{pump}}/(4\gamma^2)$$

and basically has the appearance of a variable undulator period depending on the crossing angle.

Problems (cont.)

- **Problem 2 - The intense laser pulse is too short**
  - 10 to 20 cycles
    - Need very high intensity (short pulse) to achieve a meaningful K value
  - ***Still***, not enough periods to reach saturation
  - Even worse with the crossing angle
    - Only a few of these periods would interact with the beam

Lawler et al. solution

- **"Shear" the laser pulse with gratings**
  - This has the effect of making the few-period long optical pulse look to the electron beam like it is composed of many periods.

J. Phys. D: Appl. Phys. **46** (2013) 325501

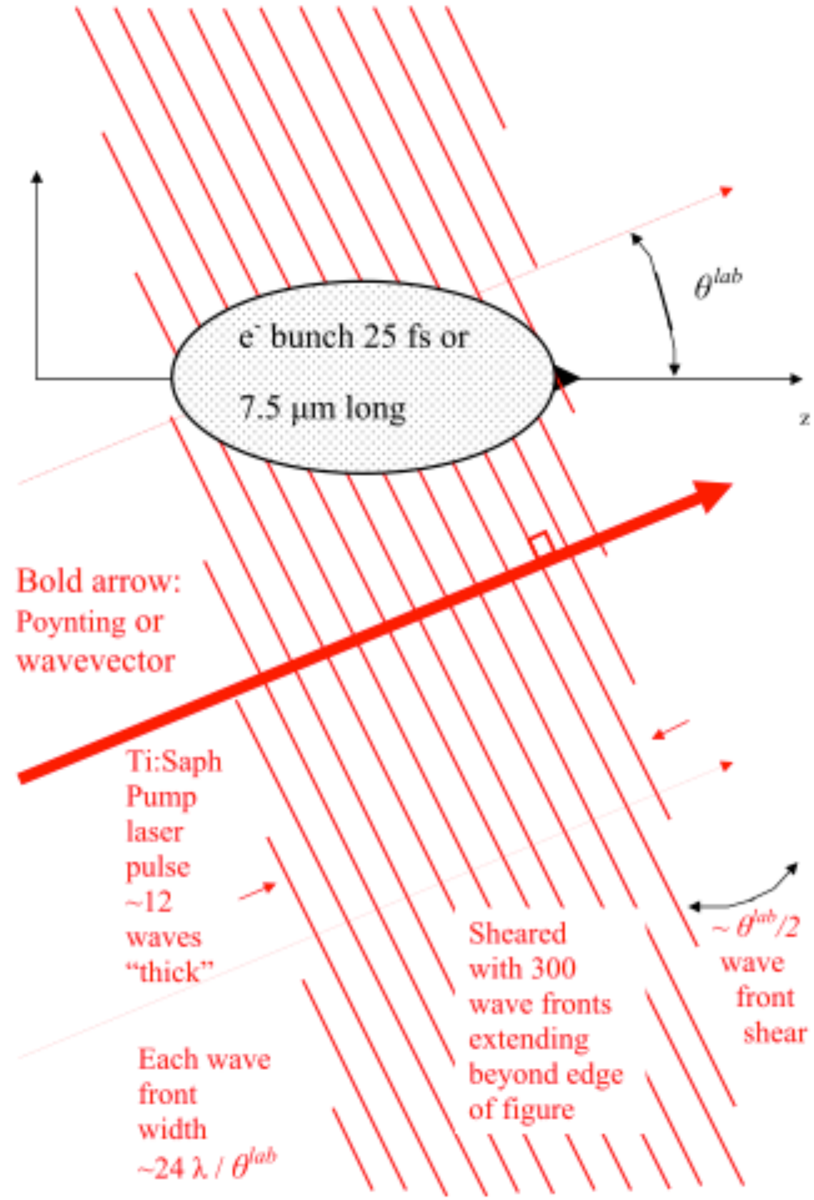


Figure 2. Schematic of a short (12 wave) electron bunch interacting with a sheared (300 wave) pump laser pulse ($\lambda = \lambda_{pump}$) viewed from the lab frame.

The "Beam's" View

Lab Frame

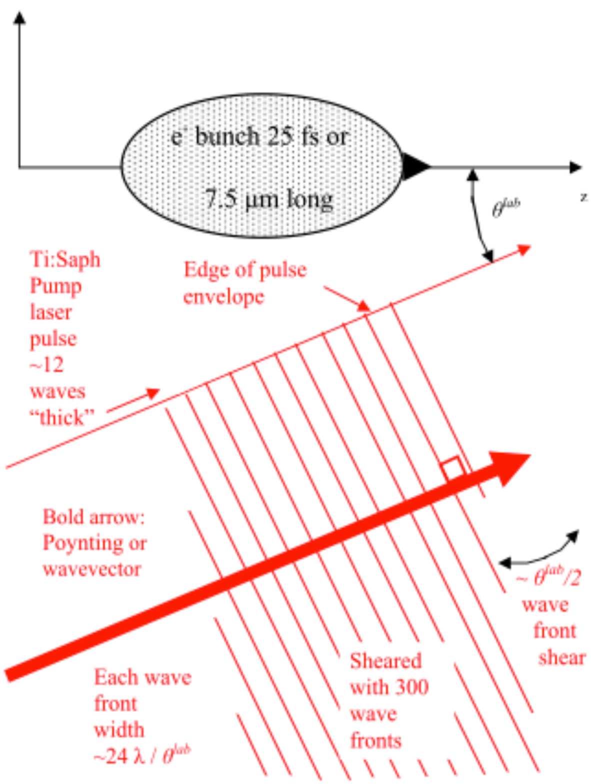


Figure 3. Schematic viewed from the lab frame similar to figure 2 except at an earlier time just before the sheared pump laser pulse reaches the electron bunch.

Electron Rest Frame

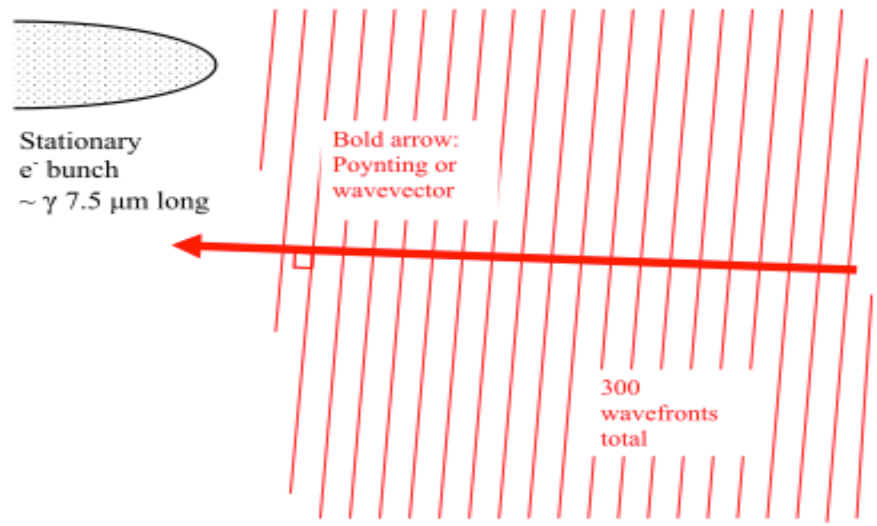
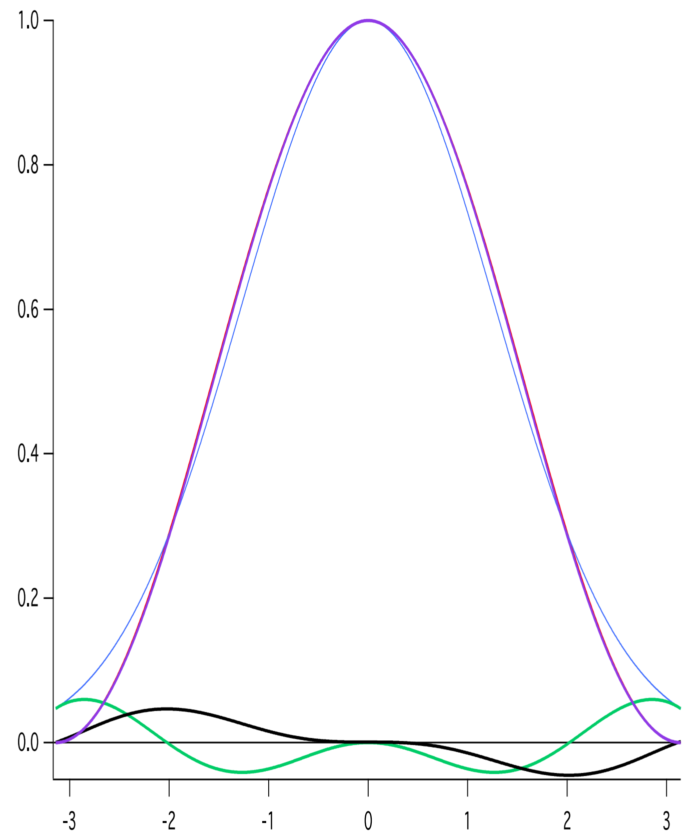


Figure 4. Schematic similar to figure 3 except viewed from the electron rest frame.

So -> the electron beam sees more "undulator" periods because the twelve laser periods have been sheared and sliced to appear as if there were 300 wavefronts (300 "undulator" periods).

The Third and Last Problem

- **Varying Undulator Strength**
  - Sure, one might be able to flatten and shape the temporal distribution, but it adds further complexity to an already complex system (more drama).
- **This is what we set out to study**
  - How well would the FEL process work with something that looked like a laser undulator?

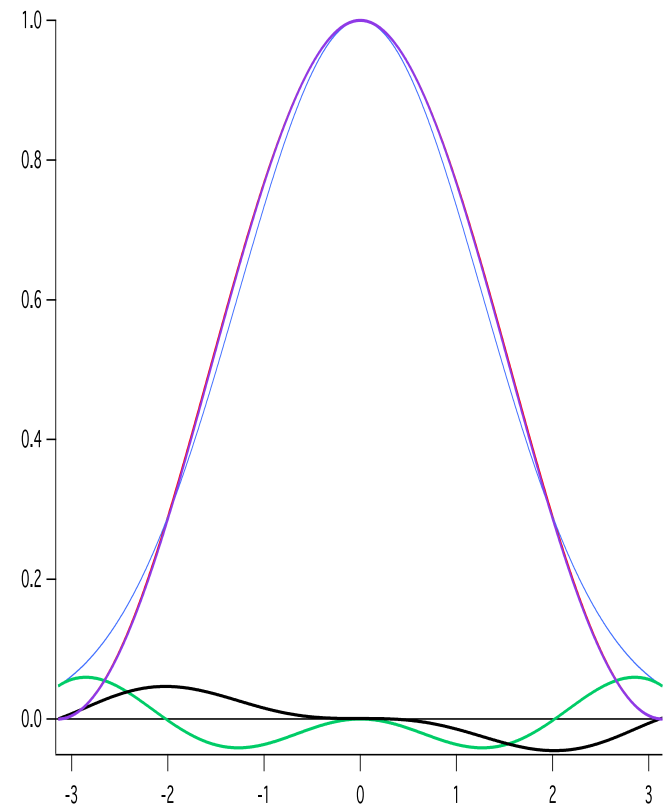


ONEDFEL

- **Written by H. Freund**
  - Based on MEDUSA/MINERVA
- **As the name says it is a 1D FEL code**
  - That's only partly true as there are some higher dimension-like features and also the ability to include 3D-like corrections to the calculations.
- **SVEA (Slowly varying envelope approximation) Used**
- **Non-wiggler averaged motion used for the particles**
  - This is important in very high gain systems
    - Where the gain length is on the order of the length of a period

ONEDFEL

- **Requires an input wavelength**
  - This is somewhat artificial (not starting up from noise – it is seeded at a very low level)
- **Simple to implement a variety of undulator profiles**
  - We will use a $\sin^2$-like profile
    - Similar to a Gaussian without the problems of the ends
  - The resonant wavelength the varies along the length of the undulator due to the varying *K* value (**since the laser intensity varies in time**)



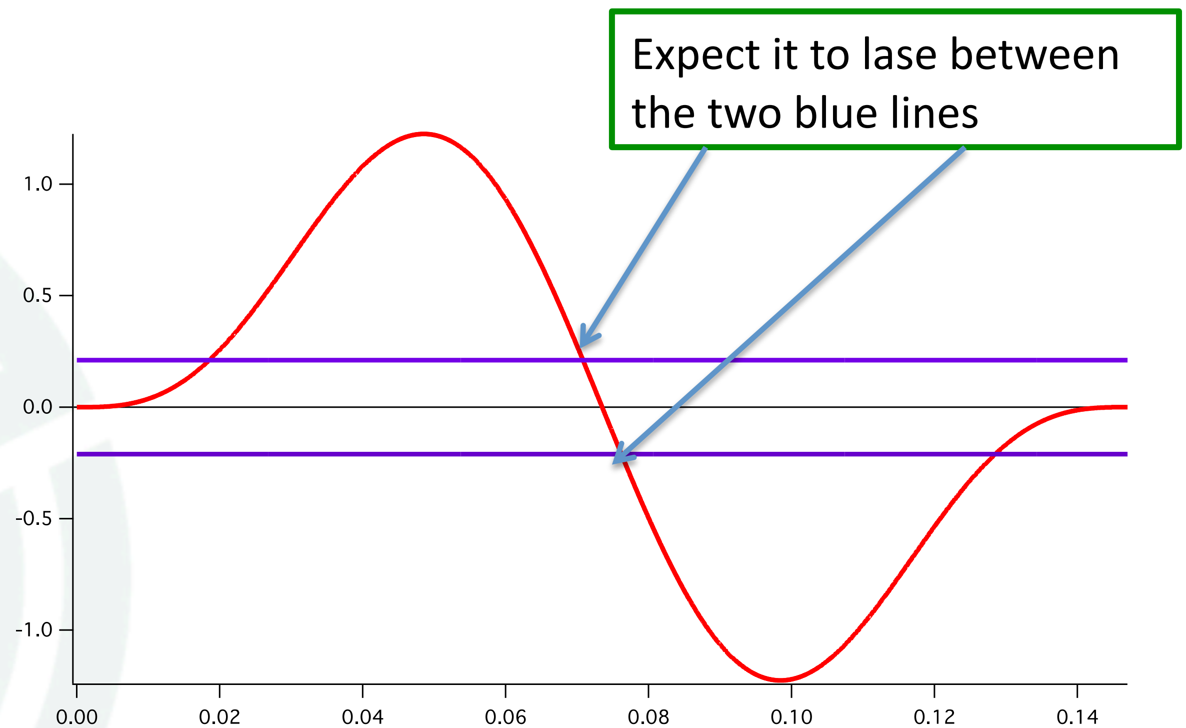
$$K(s) = K_{\max} \sin^2 \frac{\pi s}{L_{und}} \qquad 0 < s < L_{und}$$

Blue Gaussian and Red (chopped ends) is $\sin^2$

Possible Expectation

- **Should only be a small region where one gets significant gain**
  - The rate of change of the resonant condition should be less than the growth rate. In other words – we do not want the K value to change too fast. We don't want the resonant condition to change too much!

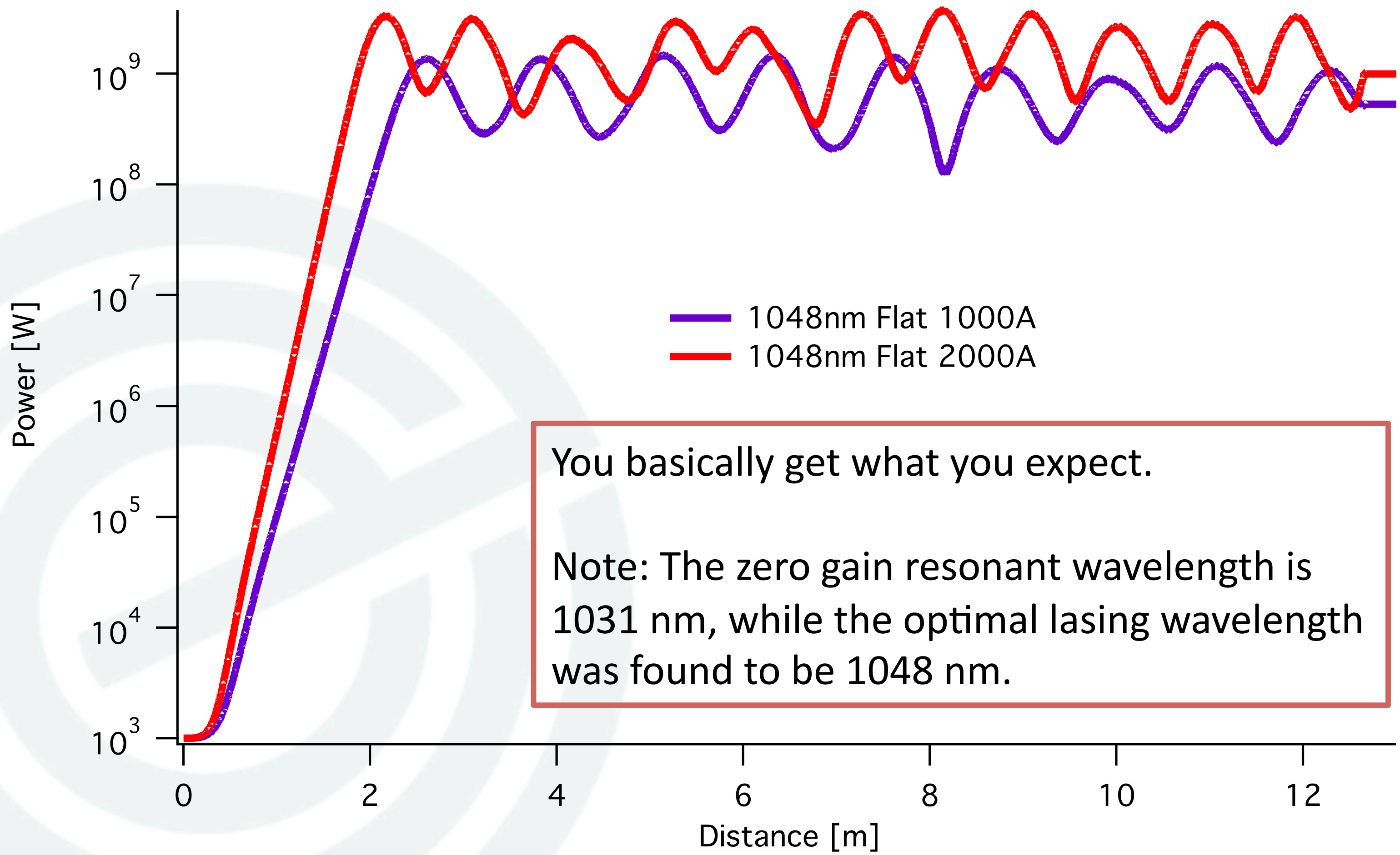
$$\frac{\rho}{2.3L_{gain}} > \frac{K\,{}^{dK}\!/_{ds}}{2\left(1+{}^{K^2}\!/_{2}\right)}$$



Basic simulation input

- **Start with a simple case**
  - Semi ordinary conditions
  - Undulator
    - K = 2.1
    - λ = 2.54 cm
    - 500 periods
  - Beam
    - Normalized emittance = 10 mm-mrad
    - Fractional energy spread = 0.15%
    - Current = 1000 A -> 2000 A
    - Energy = 100 MeV

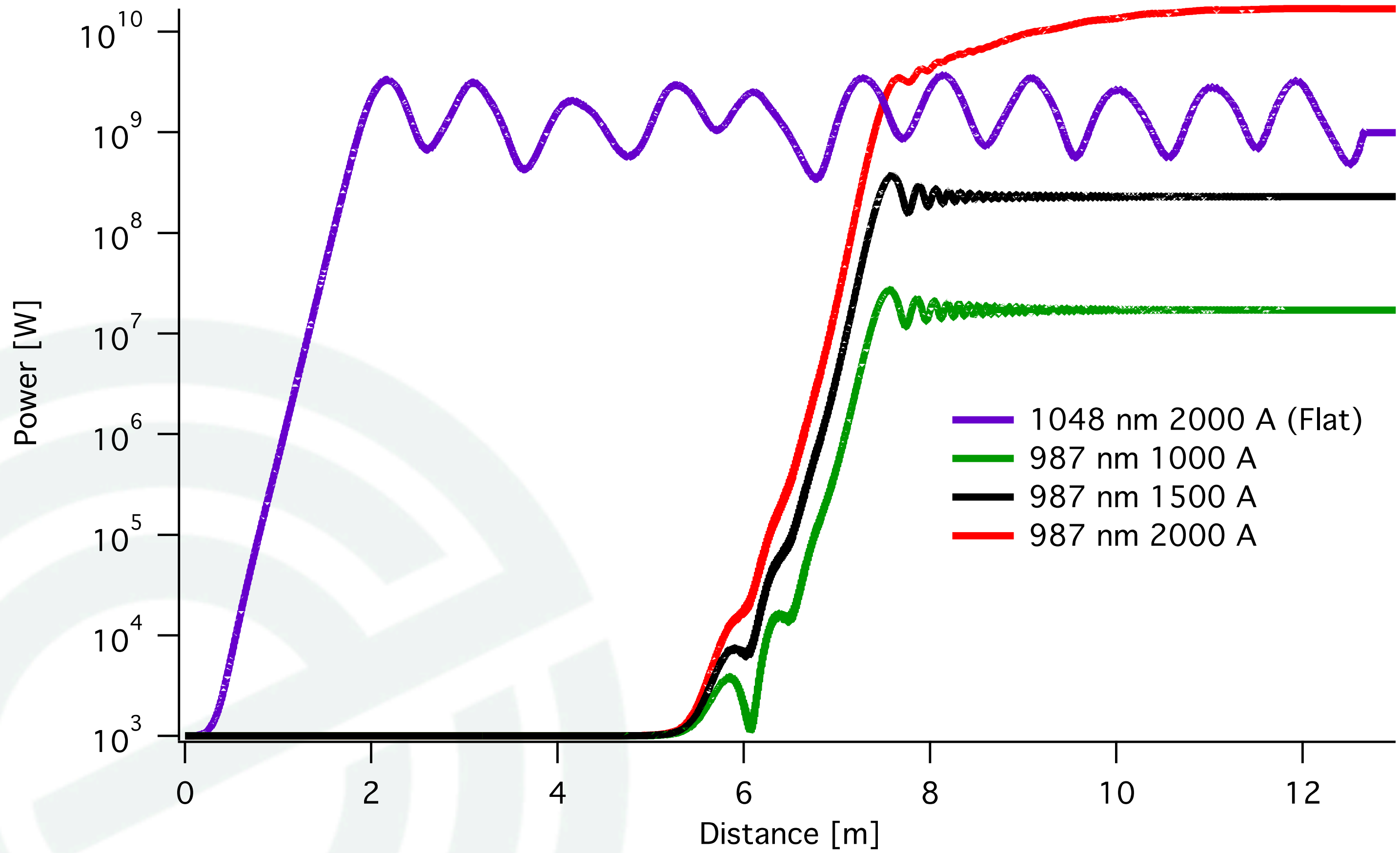
"Flat" Undulator Case Results



You basically get what you expect.

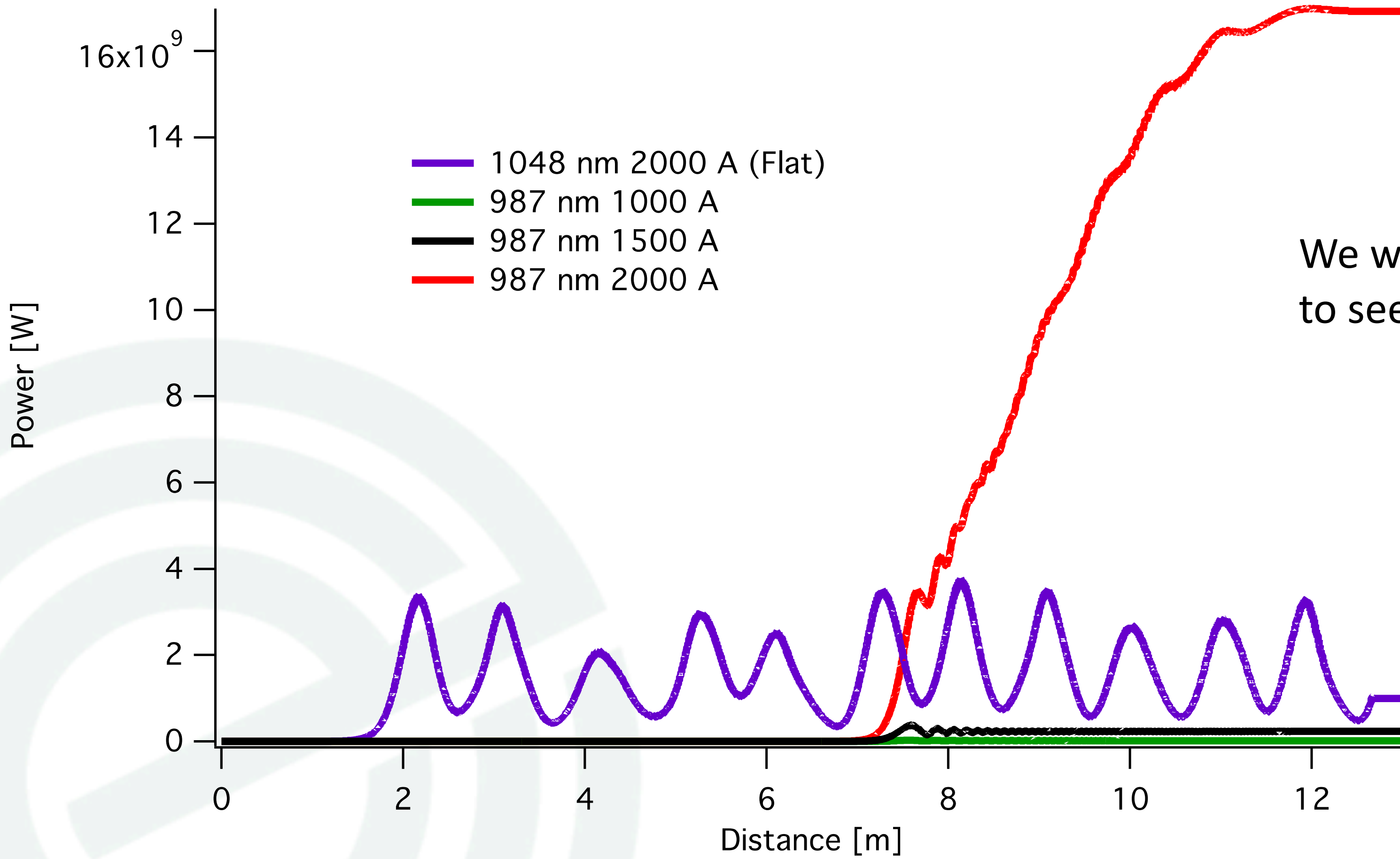
Note: The zero gain resonant wavelength is 1031 nm, while the optimal lasing wavelength was found to be 1048 nm.

Sin^2-like Undulator Case



Now one sees a very interesting feature. If the gain is high enough for the system to reach saturation within the previously described window then tapering effects come into play and one can get very high powers.

Sin²-like Undulator Case (Linear)



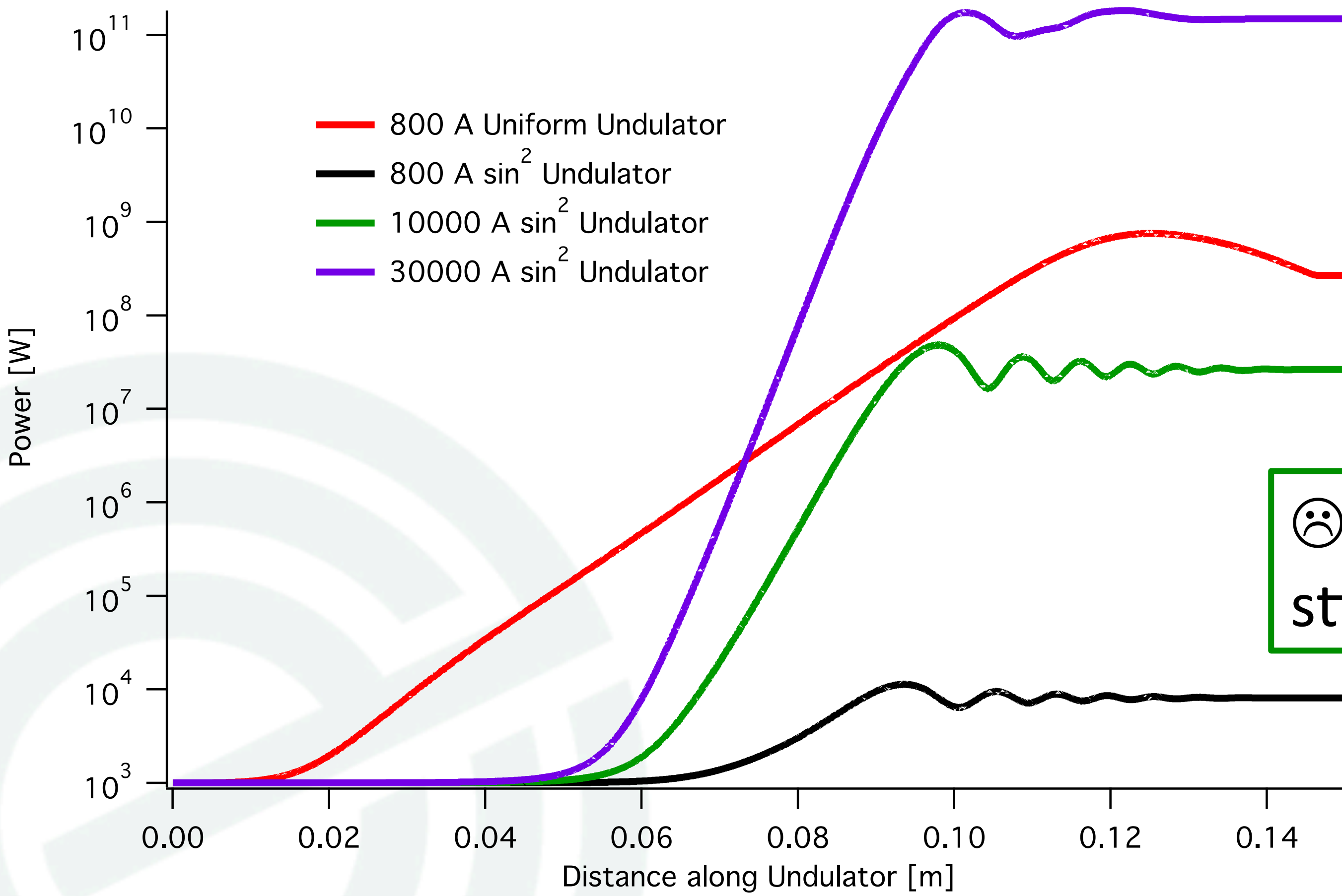
We were excited to see this!

The tapering gain is much more apparent on a linear scale. Also note the optimal wavelength is **blue shifted** compared to the zero gain resonant wavelength. **This is due to the K value being lower at the onset of gain.**

More Extreme Simulation Case

- **Lawler et al. paper like case**
  - Something more akin to a laser undulator system
  - Undulator
    - K = 0.435
    - λ = 0.049 cm
    - 300 periods
  - Beam
    - Normalized emittance = 0.06 mm-mrad
    - Fractional energy spread = 0.1%
    - Current = 800 A -> 10000 A (We did range between 0.8-10kA)
    - Beam Energy 168.8 MeV

More Extreme Case Results



☹ - we are still exploring

Optimal wavelength for $\sin^2$ case tuned to 2.46 nm. Could not achieve high enough gain to see significant tapering effect.

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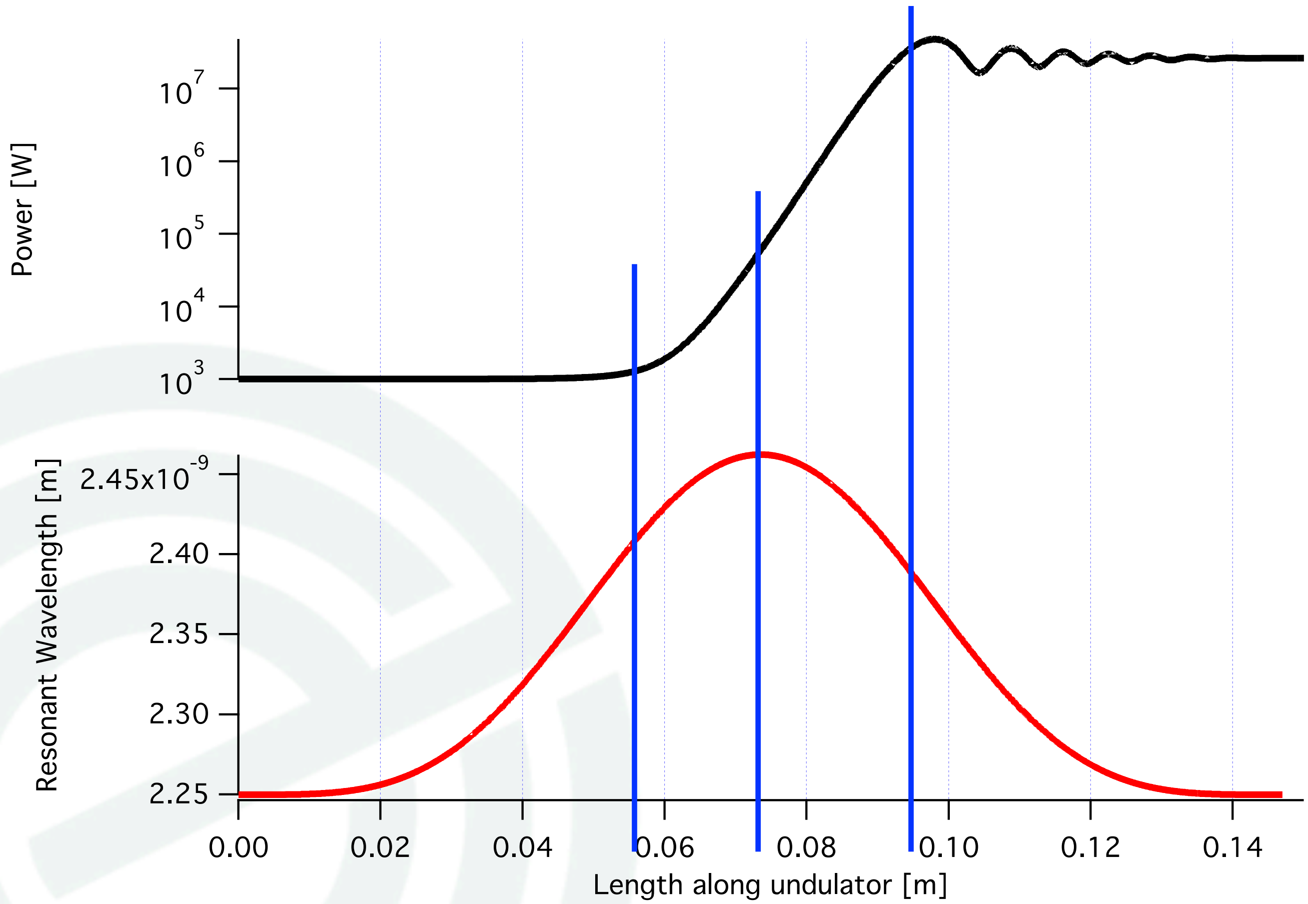
Some Tapering Gain Still Seen



Trying to overlay the laser intensity over the growth – a little taper ☺

Caveats

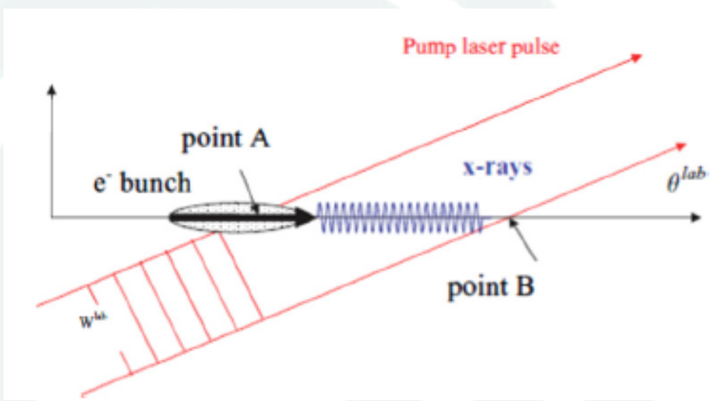
- **The fixed wavelength in ONEDFEL**
  - This is not necessarily real and could be creating artifacts.
    - A significant modification to ONEDFEL would be required to fix this.
- **3D effects**
  - These were explored, but only briefly, using the MEDUSA FEL code
    - Has an impact on the tapering effect
    - Parameter space is very large to explore

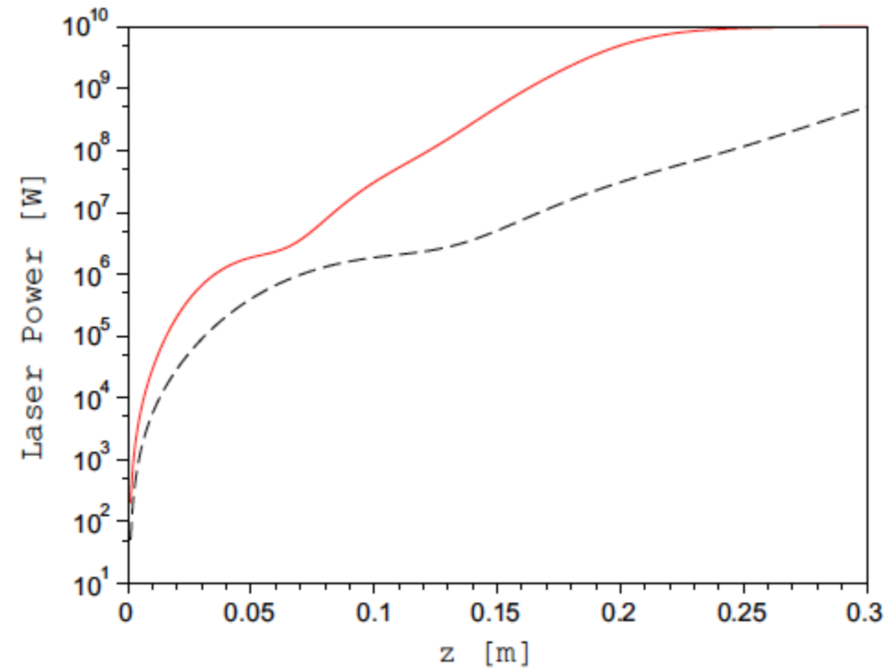
Results from PROMETEO

Wave Undulator and LPA

Sheared beam operating parameters.

$\lambda_L \equiv$ laser wavelength	$\simeq 750$ nm
$I_L \equiv$ laser intensity	$\simeq 10^{22}$ W/m^2
$n_{lab} \equiv$ lab-frame e-beam density	$\simeq 4.3 \cdot 10^{24}$ m^{-3}
$K = 0.435$	
$\varepsilon \equiv$ normalized emittance	$= 1$ mm $\cdot$ mrad
$\lambda_u \equiv$ equivalent undulator period	$\simeq 13$ μm



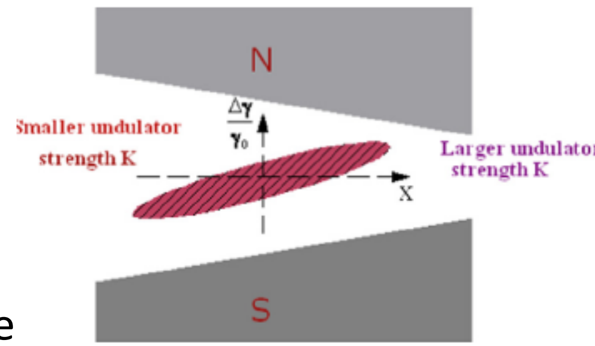


Power versus longitudinal coordinate (m) for a LPA-Wave Undulator FEL. Without (continuous line) and with (dotted line) inhomogeneous broadening effects and current density dilution due to beam transverse section increase.

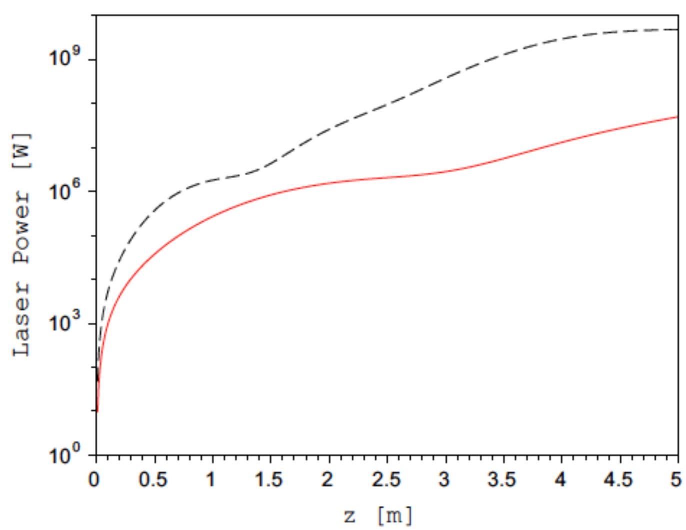
See references in NIM Paper

LPA e-beam and Transverse Gradient Undulators

For larger energy spread and lower beam current different solutions should be devised to mitigate such a detrimental. Transverse gradient undulators (TGU) can both counteract the effect due to energy distribution and provide a more efficient operation. In TGU devices a transverse tapering of the magnetic field is induced providing an energy dispersion in the tapering direction.



. Transverse gradient undulator and energy position correlation.



Plasma beam and FEL parameters.

Undulator parameter	$K=2$
Undulator period	$\lambda_u = 1$ cm
Beam energy	$E = 1$ GeV
Resonant wavelength	$\lambda \approx 1$ nm
Peak current	$I \approx 10$ kA
Energy spread	$\sigma_e \approx 10^{-2}$
Normalized emittances	$\gamma\epsilon_{xy} \approx 1\,\mu$mrad
Horizontal and vertical size	$\sigma_{x,y} \approx 11.3\,\mu$m
FEL parameter	$\rho \approx 6 \cdot 10^{-3}$

Where the transverse tapering parameters have been chosen to halve the effect of the inhomogeneous broadening.

Recent Z. Huang's concept; T. Smith et al (1979) TGU, and others

Summary of the Coherent Compact Device

- ONEDFEL was used to explore FEL operation with an undulator field having a $\sin^2$ field profile similar to what one might expect from a laser undulator
- Gain must be very high for this to work
- At high enough gain one can reach saturation and then see additional gain from the natural tapering of the undulator field
- PROMETEO used to examine Wave Undulator configurations and the transverse gradients undulator based FELs were simulated.

What we skipped but what ELSE is needed Technical challenges

- Very high repetition rates (and high average powers) require new SRF accelerator architectures
- Better controls
- How we actually design the experiment for shearing with gratings. Need some pretty robust and high quality optics and controls.
- Etc….

Based on discussions at last night's amazing dinner – I wanted to mention a couple of machine-side activities in the field

What is in a new SRF architecture?

1) A new niobium surface processing technique "N doping" has been developed and demonstrated at Fermilab which dramatically reduces the cryogenic refrigeration

2) Recent results from Cornell University [4] have shown that 1.3-GHz, single cell niobium cavities coated with Nb3Sn can be operated with gradients of 10 Megavolts/m with a quality factor (Q0) of 2 x 1010 at a temperature of 4.2K..

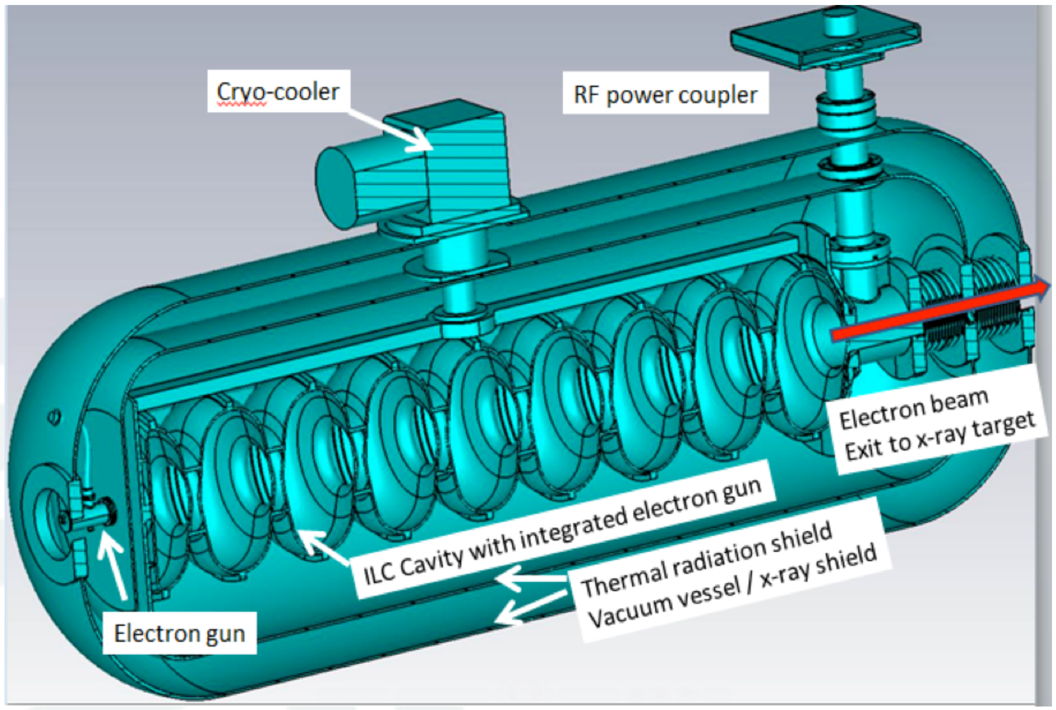
3) With reduced dynamic heating due to the advancements highlighted in 1) and 2), one can then envision conduction.

4) Recent Fermilab proprietary technology utilizing a single, injection-locked, 1 kW, magnetron has demonstrated excellent phase and amplitude control at 2.45 GHz on a single-cell SRF cavity.

5) An SRF gun cavity with an integrated thermionic cartridge or Field-Emission (FE) electron cathode provides the opportunity to integrate the gun cavity into the accelerating cavity creating a very short and compact accelerator design.

6) A robust and very low heat leak fundamental RF power coupler capable of handling many 10's of kW of RF power. A new proprietary FNAL design based on previous work [8] incorporates an RF shield to decrease the magnetic field at the outer wall of the coupler eliminating the need for copper plating and shunting dynamic losses out to an intermediate temperature (e.g. 60 K) vs into the SRF cavity at 4.5 K.

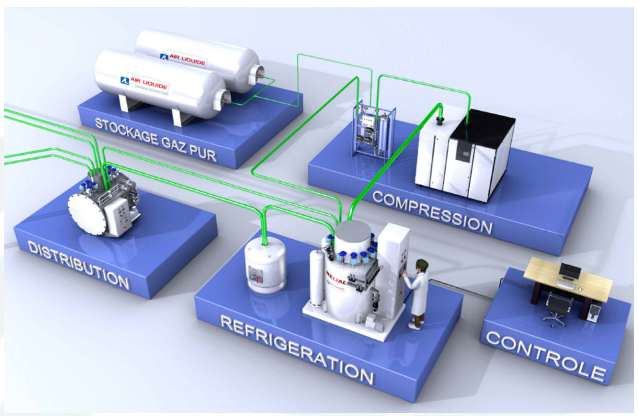
New architectures for SRF accelerators



SRF 2015 Talk – "SRF, COMPACT ACCELERATORS FOR INDUSTRY & SOCIETY"
(R. Kephart, B. Chase, I. Gonin, A. Grassellino, S. Kazakov, T. Khabiboulline, S. Nagaitsev, R. Pasquinelli, S. Posen, O. Pronitchev, A. Romanenko, V. Yakovlev - Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA, S. Biedron, S. Milton, N. Sipahi - Colorado State University, Fort Collins, Colorado 80523, USA, S. Chattopadhyay and P. Piot
Northern Illinois University, DeKalb Illinois 60115, USA)

New architectures for SRF accelerators

❖ **Get rid of the huge infrastructures by using cryo-cooling**



4K GM-JT CRYOCOOLER SERIES

Performance Specifications

Model Number	CG304SC	CG308SC	CG310SC
3rd Stage Capacity* Watts @ 4.3 K (50/60 Hz)	1.0/1.2	3.0/3.5	4.2/5.0
Electrical Supply 50/60 Hz	3 phase, 200 V		
Power Consumption 50/60 Hz	4.5/5.4	5.1/6.4	5.1/6.4
Cooling Water L/min. (gal./min.)	5.5-6.5 (1.5-1.7)	8.0-10.0 (2.1-2.6)	8.0-10.0 (2.1-2.6)
Refrigeration Unit Weight kg (lbs.)	18.0 (39.7)	35.0 (77.2)	50.0 (110.2)
Compressor Weight kg (lbs.)	205 (452)	220 (485)	220 (485)
Maintenance Hours	10,000		

Standard Scope of Supply

- V304SC, V308SC or V316SC Cold Head
- U304CWA or U308CWA Compressor
- Helium Vapor Gauge (with CG308SC and CG310SC models)
- Hydrogen Vapor Gauge
- 6 m (20 ft.) Helium Gas Lines
- 6 m (20 ft.) Valve Motor Cable
- Tool Kit

Advanced 4K cryo-coolers like this commercial example from Sumitomo can provide up to 5 Watts of refrigeration at 4.2 K in very compact, simple, reliable package. Note that for this unit the entire system weight is under 600 lbs for a 5 W.

Source: http://www.shicryogenics.com//wp-content/ uploads/2012/11/Cryocooler-Product-Catalogue.pdf

Advanced Controls

Artificial Intelligence-Based Control

- **Why we need it**
  - High-frequency jitter
  - Non-linear systems
  - Many parameters to vary
  - Time-varying dynamics
  - Etc…

A.L. Edelen, S.G. Biedron, S.V. Milton, D. Bowring, B.E. Chase, J.P. Edelen, J. Steimel, "Neural Network Model of the PXIE RFQ Cooling System and Resonant Frequency Response," IPAC 2016; A.L. Edelen, S.G. Biedron, S.V. Milton, B.E. Chase, D.R. Edstrom, P. Stabile, "Neural Network-based Model Predictive Control for Particle Accelerators," accepted to the April 2016 IEEE Transactions on Nuclear Science; E. Meier, S.G. Biedron, G. LeBlanc, M.J. Morgan, "Development of a Novel Optimization Tool for Electron Linacs Inspired by Artificial Intelligence Techniques in Video Games," Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 632 (2011) 1-6.

Trip to the Artificial Intelligence Zoo
Let's Apply AI techniques to Controls Engineering

Biological Sciences and Psychology are our inspiration!

- Machine Learning
- Learning Theory
- Computational Statistics
- Artificial Intelligence
- Mathematical Optimization
- Model-free Methods
- Model-based Methods
- Ensemble Methods
- Intelligent Control
- Nonlinear Control
- Adaptive Control
- Optimal Control
- Robust Control
- Stochastic Control
- System Identification
- Support Vector Machines
- Neural Networks
- Decision Trees
- Fuzzy Logic

Part 2

Deep Saturated Free Electron Laser Oscillators and Frozen Spikes

P. L. Ottaviani, S. Pagnutti, G. Dattoli, E. Sabia, V. Petrillo, P.J.M. van der Slot, S. Biedron and S. Milton, “Deep Saturated Free Electron Laser Oscillators and Frozen Spikes,” under review.

Deep Saturated Free Electron Laser Oscillators and Frozen Spikes

- FEL oscillators operating in the deep saturated regime have formation of sub-peaks of the optical pulse.
- These are very stable and have a duration corresponding to the coherence length.
- We have some ideas on the physical mechanisms underlying their growth.
- We have also looked at the intra-cavity nonlinear harmonic generation in this regime.
- We have some thoughts on the possibility of exploiting these spikes.

- We have examined cases with different gain coefficients and bunch lengths.
- The number of spikes formed in deep saturation does not depend on the number of undulator periods.
- The number of spikes seems to be associated with the coherence length of the process itself.

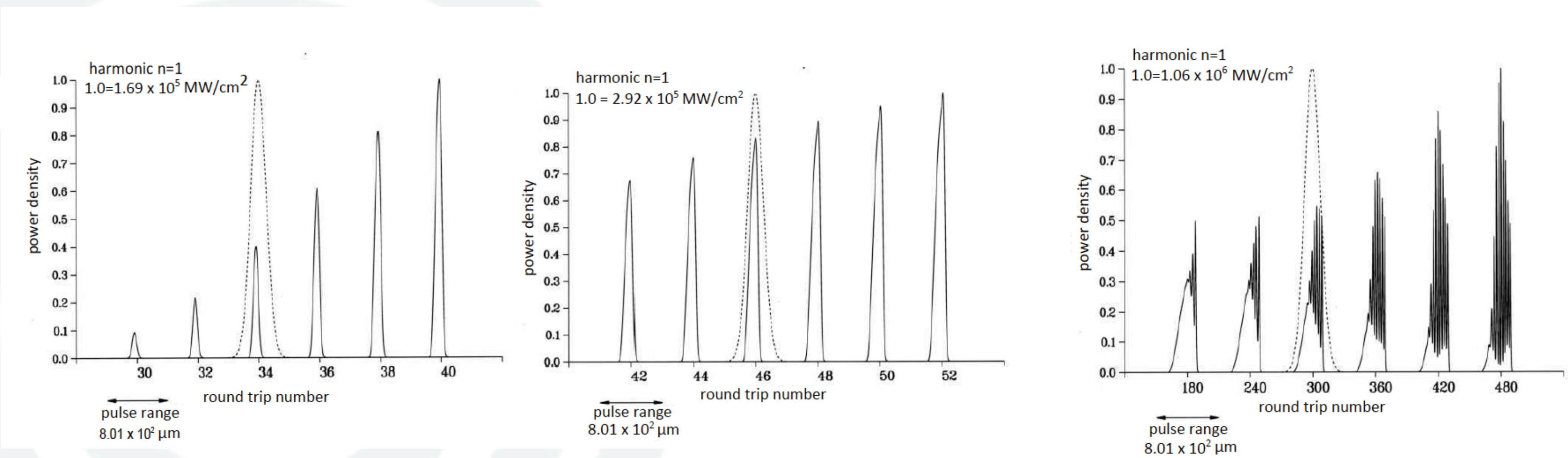
- We considered an FEL oscillator operating in the visible at a nominal wavelength of **500 nm**, driven by an electron pulse having a kinetic energy of **155.3 MeV**, a current density of **2.86 x 10^8A/m^2** and the longitudinal extentz = 100m. This corresponds to a **333 fs** pulse with a peak current of **90 A** and an **rms radius of 65m**. The undulator has **77 periods** with a period length of **2.8 cm**. The **rms energy spread is 0.01%**. The resonator has a **resonant length of 3.6897533 m** and the total roundtrip **loss is 6%**.
- These parameters result in a small signal gain of 1, a total slippage length of 38.5m and a coherence length of 9.78m.

$$\Delta = N\lambda_s \equiv \textit{Slippage Length}$$

$$\theta = \frac{4\,\delta L}{g_0 \Delta}$$

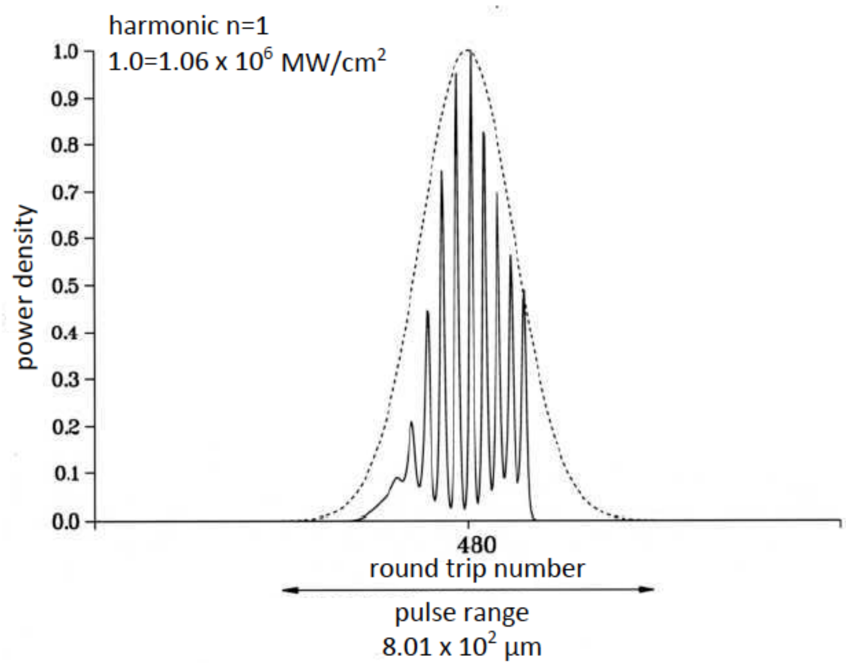
$$\sigma_z \equiv \textit{Bunch Length}$$

- A series of snap-shots from PROMETEO showing the growth of an optical pulse at differentround trips as the optical cavity is set at zero detuning.
- The relevant dynamics is, at the beginning, fairly transparent; the optical pulse grows in the form of a homogeneous and almost Gaussian distribution, which over the round trips, tend to spread over all the electron bunch length.
- BUT -> One of the consequences of the lethargy mechanism is an asymmetry, getting more pronounced with increasing saturation and characterized by a sharp front edge.



E = 155:3Mev; J = 2.68 x 10^8 A/m^2 ; ρ = 2.33 x 10^{-3}; σ_ε = 10 x $^{-4}$; σ_z = 100 m; g_0 = 1; η = 0:06; number of periods N = 77; λ_s = 500.33 nm; Δ = 38.5m; l_c = 9.78 m

With increasing intracavity intensity, approaching the equilibrium intensity, the optical longitudinal shape acquires a modulation, starting from the front part and covering progressively the entire electron bunch



Each spike 10's of fs at 500 nm

- After many round trips, optical spikes develop each of which extracts the maximum possible energy out of one segment of the electron beam equal to one slippage distance in length, the distance by which the optical pulse overtakes the electrons over the length of the undulator.
- Further increase of the field intensity determines the emerging of further peaks.

Relationship of the spikes

$$n_S \approx \frac{\sigma_z}{\sigma_S}, \quad \sigma_S \approx l_c = \frac{\lambda_s}{4\pi\rho\sqrt{3}}$$

For a number of spikes n_S, the bunch length σ_z, the length of the spike σ_S, the coherence length l_c, ρ is the Pierce parameter, and the radiation wavelength is λ_s

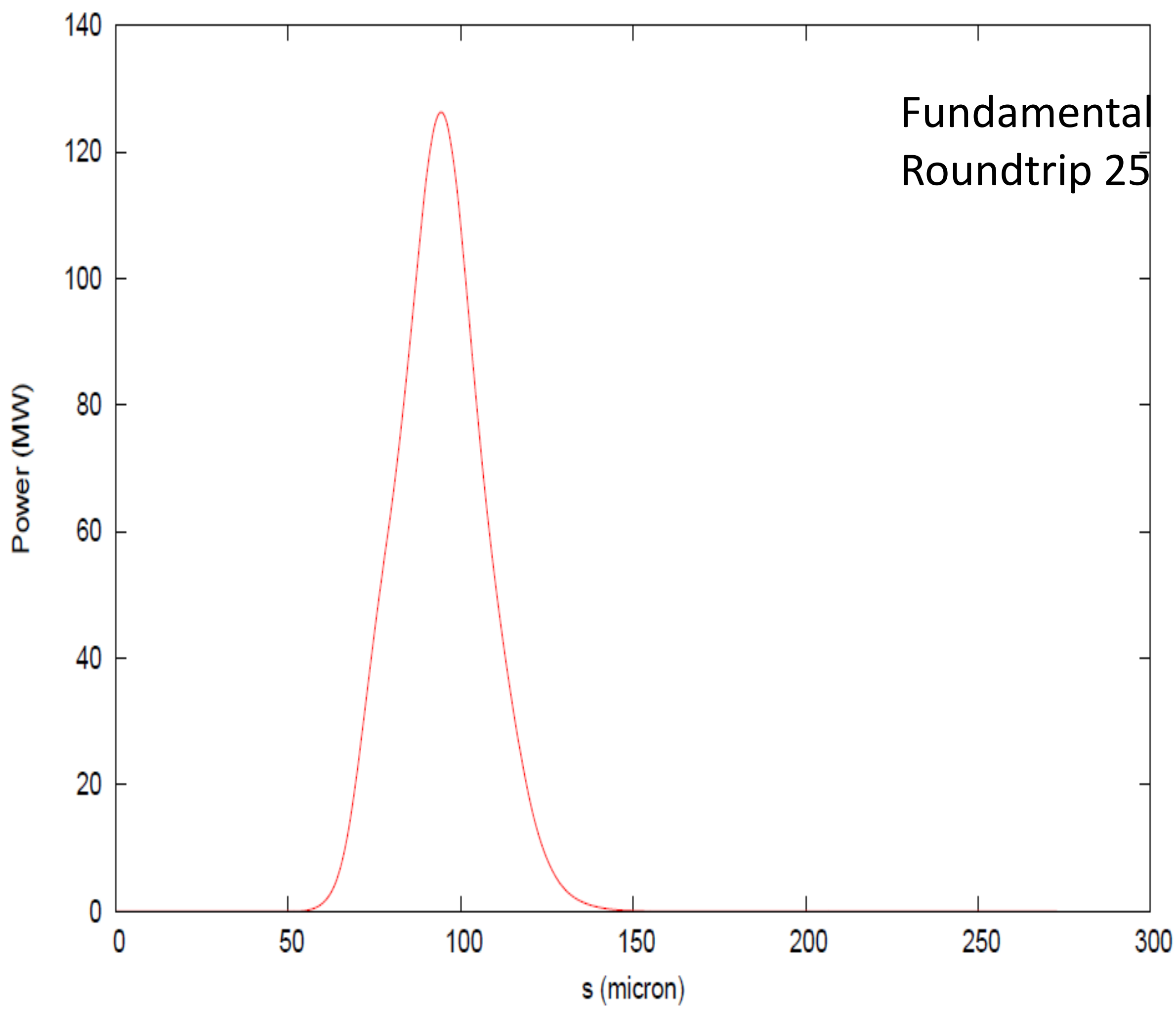
Spike formation

- **In the spike formation phenomenology, we have deliberately used the language and a notation more appropriate to SASE than to oscillator FEL devices as:**
  - The peaks we are describing resemble the spikes of the high gain regime
  - they become locked in phase by the operating conditions in the optical cavity.

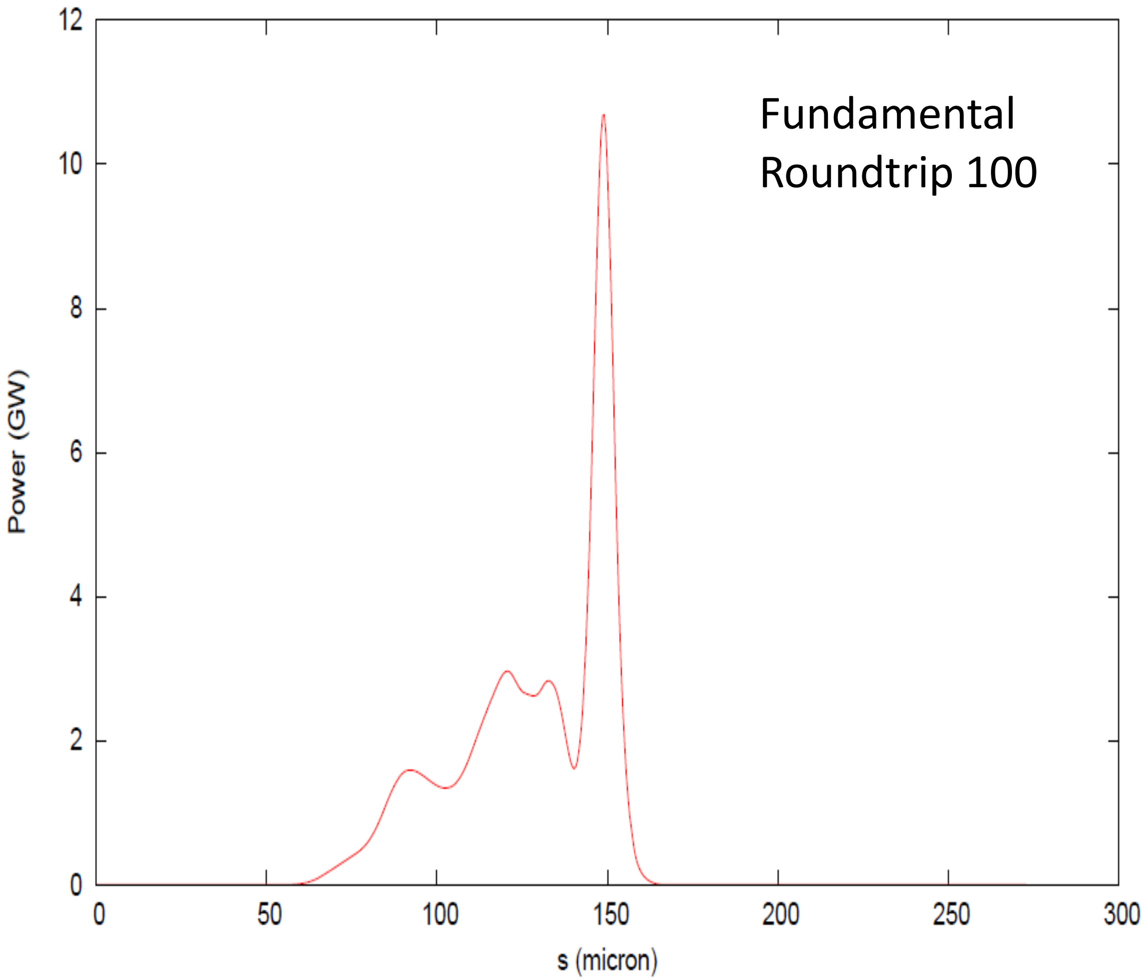
R. Hajima, N. Nishimori, R. Nagai and E. J. Minehara., Nucl. Instr. Meth. A 483, 113-118 (2002).

3D Time dependent simulations (Genesis 1.3)

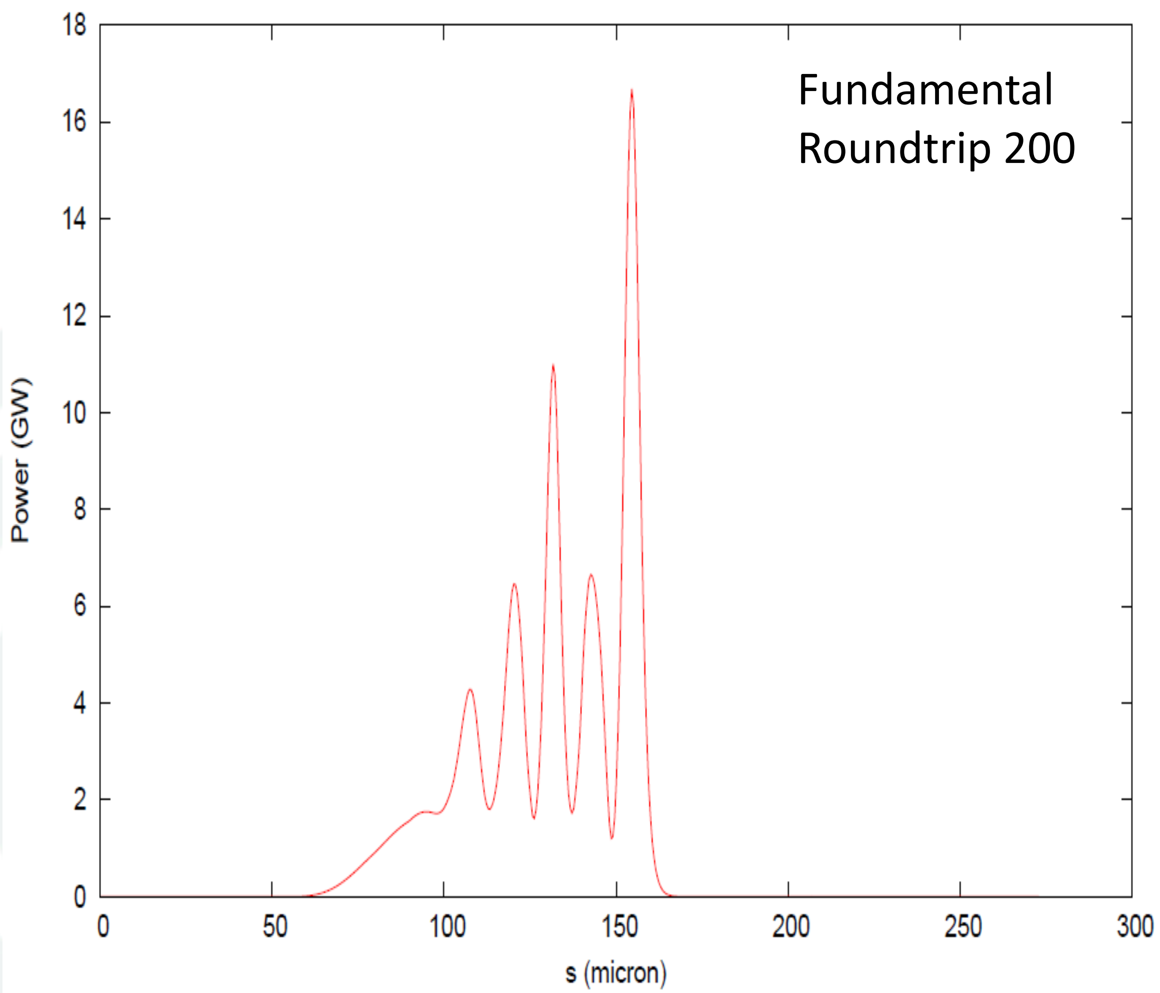
Beam energy	157.6	MeV
Peak current	133	A
Pulse duration	150	fs
$\delta\gamma/\gamma$	0.01	%
L_{cav}	3.690	m
δL_{cav}	0	μm
λ	495	nm
N_u	50	
λ_u	2.8	cm
K_{rms}	1.506	



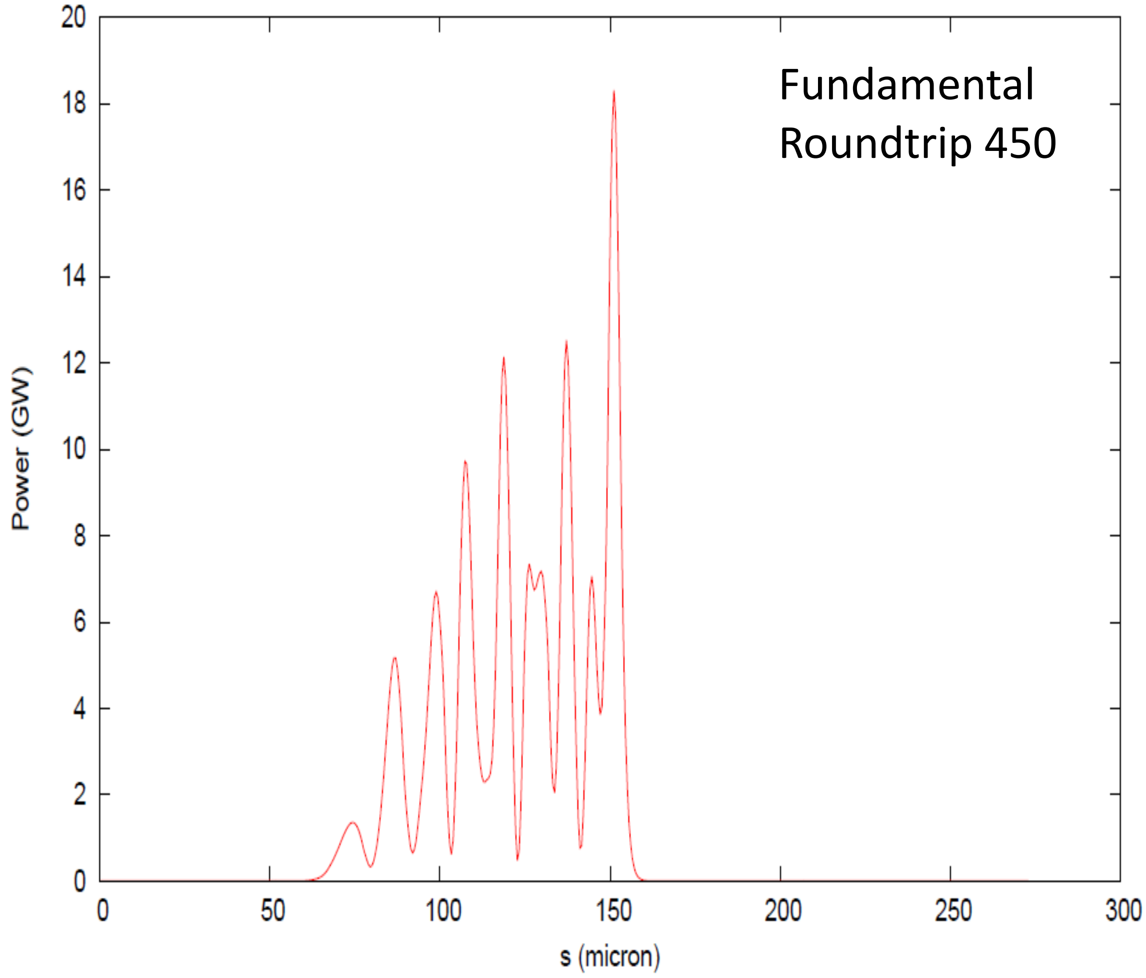
Evolution temporal pulse shape



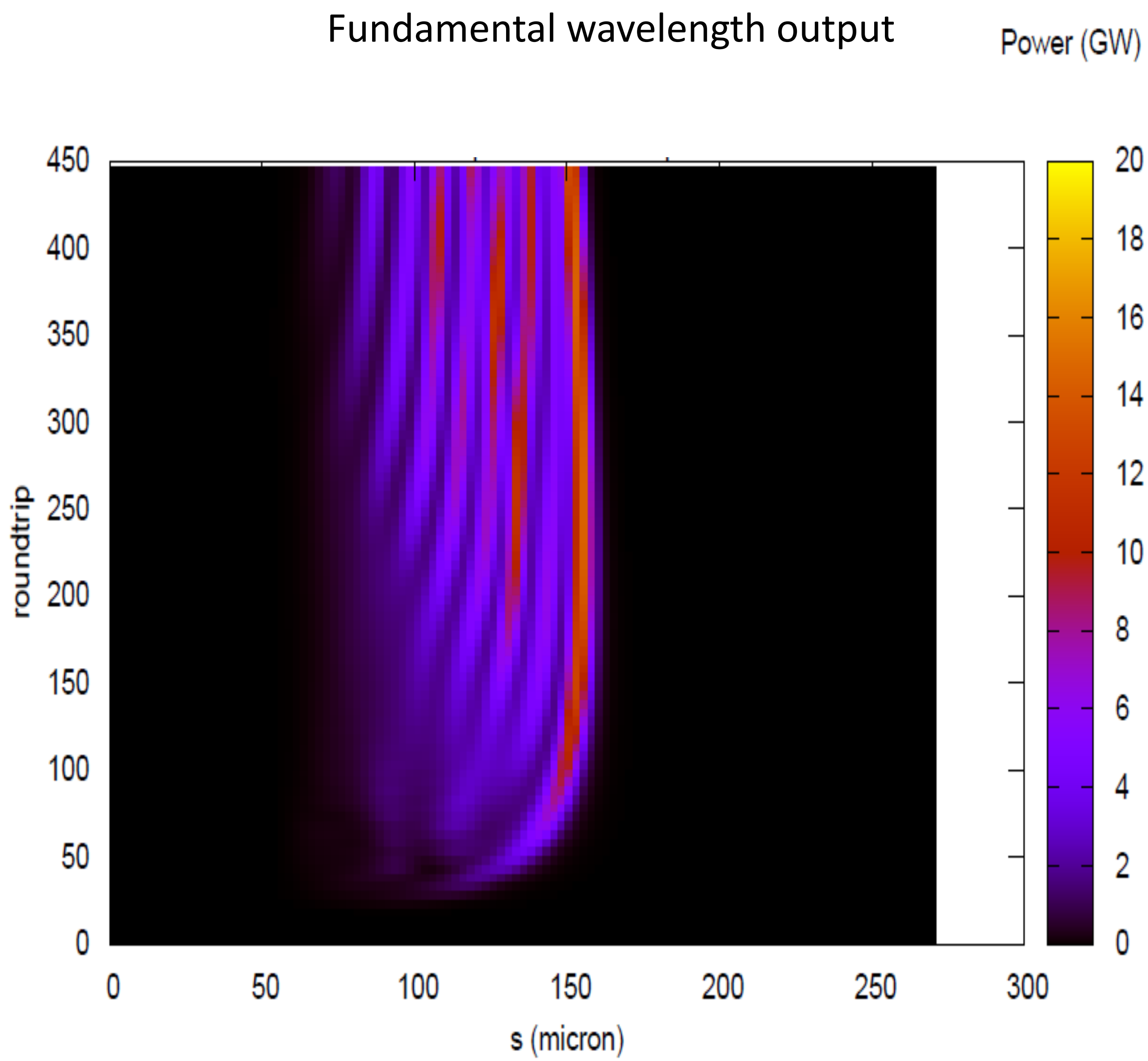
Evolution temporal pulse shape



Evolution temporal pulse shape

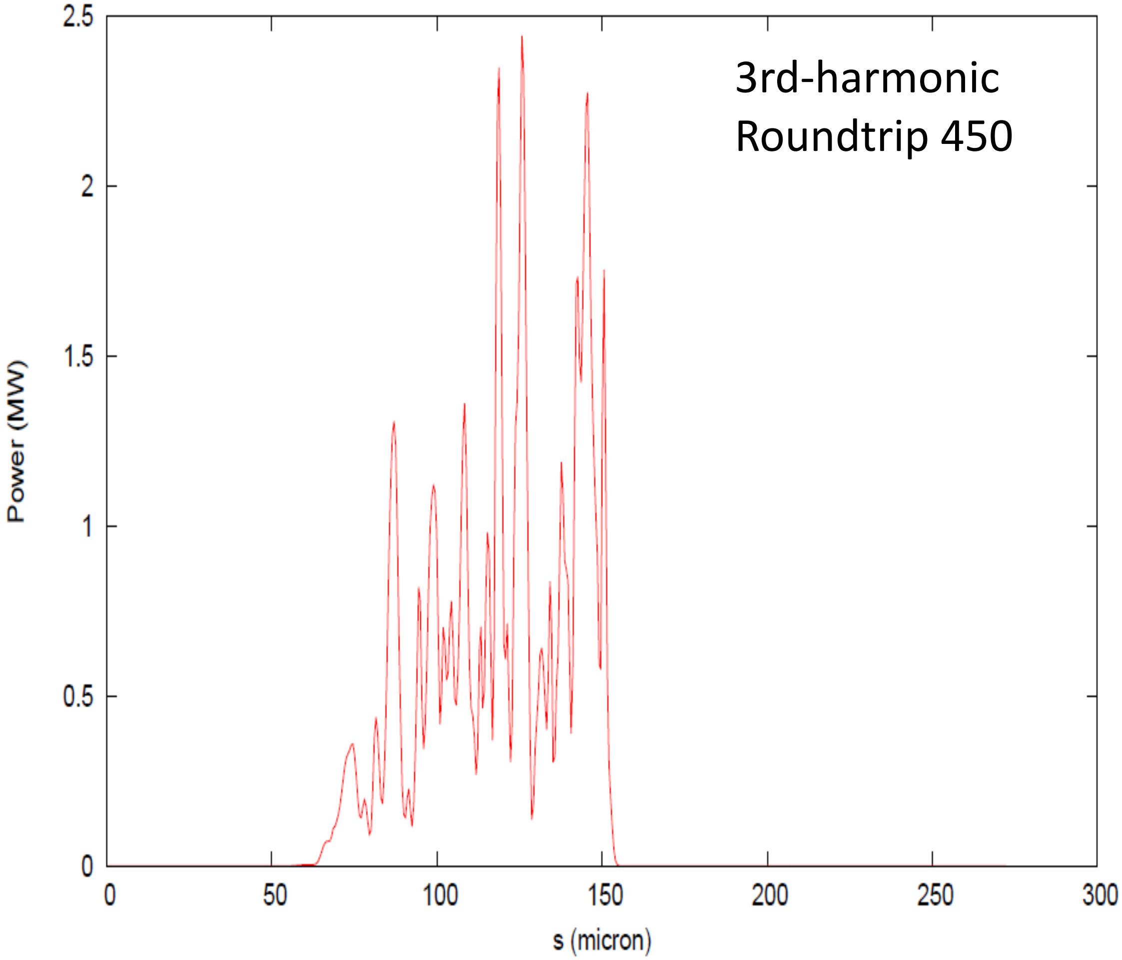


Evolution temporal pulse shape



Electrical & Computer ENGINEERING

Evolution temporal pulse shape



Summary

- In the deeply saturated regime, we see the emergence of a comb structure inside the optical pulse itself, consisting of a series of sub-pulses with a length comparable to the coherence length. It is well known that this is due to the side-band instability and has been experimentally observed in FEL oscillators operating in mid IR and FIR.
  B. A. Richman, J. M. J. Madey and E. Szamers, Phys. Rev. Lett. 16, 1682 (1989); G. M. H. Knippels et al. Phys. Rev. Lett. 75, 1755 (1995); D. A. Jaroszinsky et al. Phys. Rev. Lett. 78, 1699 (1997); F. Ciocci, R. Bartolini, A. Doria, G. P. Gallerano, E: Giovenale, M. F. Kimmitt, G. Messina and A. Renieri, Phys. Rev. Lett. 7, 928, (1993).
- We presented a physical mechanism underlying the emergence of these spikes, in particular we discuss the interplay with mode locking induced by the cavity and a possible link with the spikes emerging in the high-gain SASE regime.
- We discussed the importance of such a mechanism on the intracavity non-linear harmonic generation.
- We used the code PROMETEO to analyze the evolution of the FEL oscillator dynamics from small signal to deep saturated regime and compared results from the 3D GENESIS.
- Also have needs here for technological advances in terms of the lasers, optics, high rep rate linacs, controls, etc.…

Classes and USPAS Colorado State

- 13-24 June 2016
- A variety of one and two-week courses
- Not too late to sign up!

- http://uspas.fnal.gov/programs/2016/colorado/index.shtml

- Also many online classes for those desiring a Master's or PhD degree in electrical engineering in accelerators

Compact

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