11.00am

Controlling Plasma Instabilities: A Multidisciplinary Approach

Bedros Afeyan
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Abstract

Plasmas, which make up the fourth state of matter, are notoriously unstable and prone to losing their confinement. How can this be reversed? One method is to use advanced laser technology and stop and start the process in adaptive bursts until the desired ends are met. This is a sophisticated new methodology requiring a multidisciplinary approach to the science and engineering challenges. The theoretical underpinnings and experimental requirements and challenges will be described after an introduction to the canonical approaches to fusion power generation which have many technical challenges still facing them more than 60 years after research began in earnest. The aim is to show how theory, computation, and cutting edge technology from photonics and telecom can be brought to bear on the problem of high average power laser-matter coupling control, which might serve as a paradigm for other energy source research in need of ultrafast, high tech control tools and mechanisms. A key insight of this new technique is the need to combine stochastic and deterministic elements in the space-time construction of the laser pulses for optimal and adaptive control of instabilities.

Biography

Dr. Bedros Afeyan is a plasma physicist by training who started out in Electrical Engineering at Concordia University in Montreal as an undergraduate, worked at Chalk River Nuclear Labs in Ontario for two summers and received his Masters and PhD degrees from the Mechanical and Aerospace Engineering Department of the University of Rochester, in Rochester, NY, working on the nonlinear optics of plasmas. He has worked as a research associate at the University of Maryland, at Lawrence Livermore National Laboratory and at UC Davis, Livermore. His work has been mainly focused on laser-plasma interactions, inertial confinement fusion, magnetic fusion studies of turbulence, Z pinches, nonlinear optics in plasmas and semiconductors, wavelet and multiresolution analysis techniques applied to signal and image processing in high energy density plasma phenomena. He founded and runs a small research company in Pleasanton, CA, Polymath Research Inc. where they work on federal government, national lab and industry funded research. They specialize in nonlinear kinetic plasma physics, modern harmonic analysis applications, Vlasov simulations and wave-wave interaction problems. Polymath Research Inc. has also had long standing collaborations conducting experiments in laser matter interactions at Trident, in LANL and on the Omega laser at LLE.

Optimal Control of Laser Plasma Instabilities: A Multidisciplinary Approach

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USC Smart Energy Summit
ACB 238
January 27, 2011

Work Supported by a DOE NNSA SSAA Grant

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$\omega_{pe}^2 = \frac{4\pi n_e e^2}{m_e}$ $\frac{e^2}{\hbar c} \approx \frac{1}{137}$

Hohlraums Contain Plasmas with Different Conditions at Different Positions at Different Times, Made of H_2, He, Be, CH, B, U or Au

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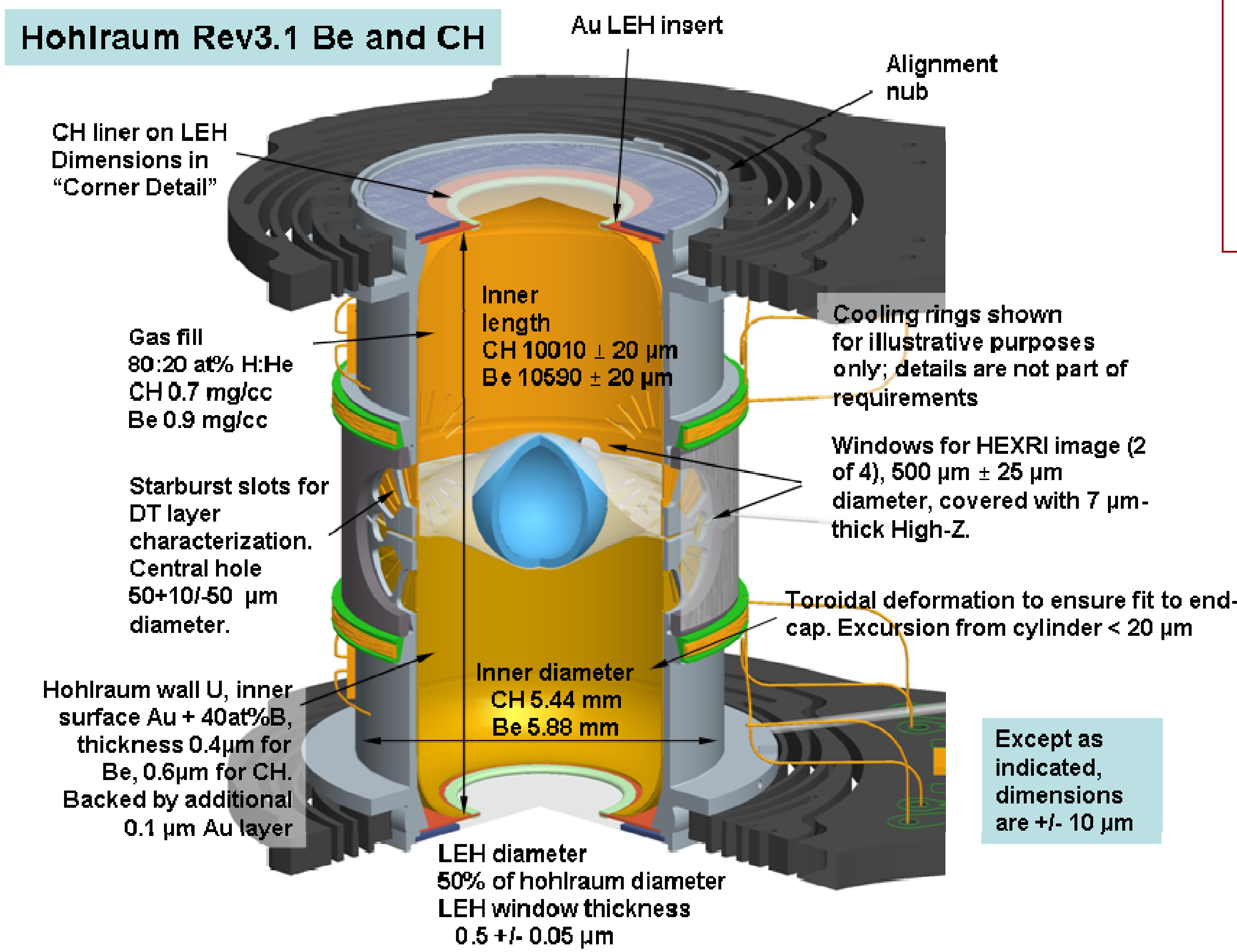

A NIF Hohlraum is a Laser-Plasma Instability (LPI) Candy Store

Non of the plasma conditions or interaction modalities that are dominant on the NIF were ever accessed on Nova or Omega.

Its all different and yet It remains weakly characterized, weakly diagnosed, studied only in passing.

Adequate Control of Laser-Plasma Instabilities is Required to Achieve Indirect-Drive Ignition or Direct Drive Ignition

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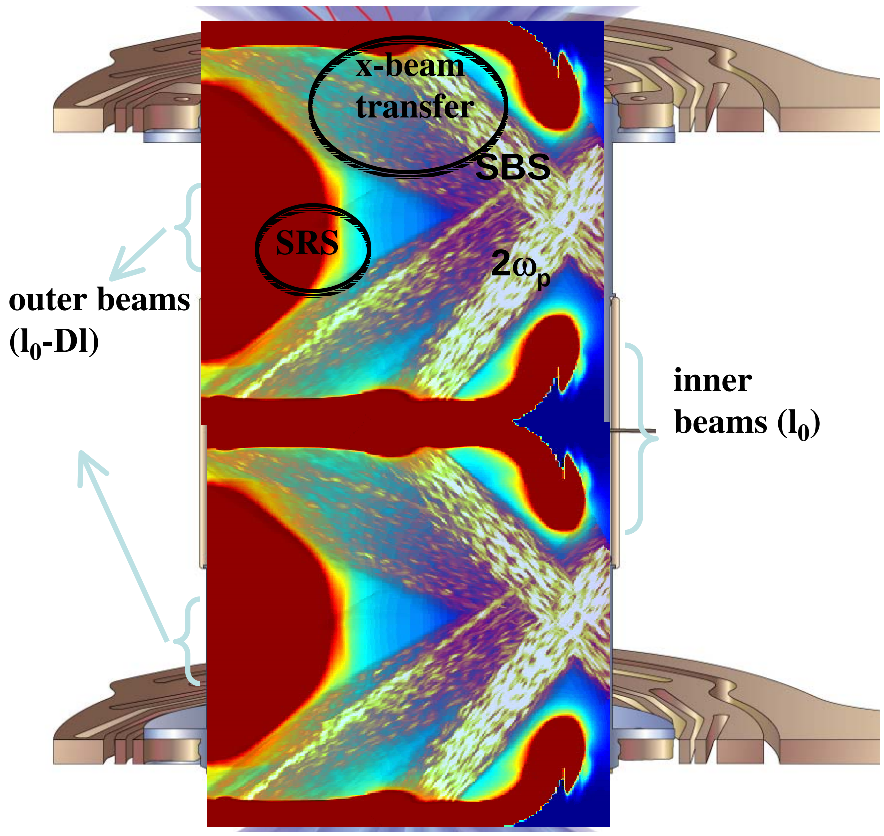

- Energy coupling should be > 90% to achieve high enough T_{rad}

- Implosion symmetry requires controlled power balance between "inner" and "outer" beams (Soft X-ray flux on equator vs. poles) in space *and* time must be maintained.

- low capsule preheat (T_{hot}, f_{hot})

- these requirements translate to control of SBS, SRS, $2\omega_p$, filamentation, cross-beam energy transfer, hot electron and hard X ray generation, etc.

SRS Spectra from the Inner Cone Beams on the NIF Show Alarming Levels With Unpredicted Features

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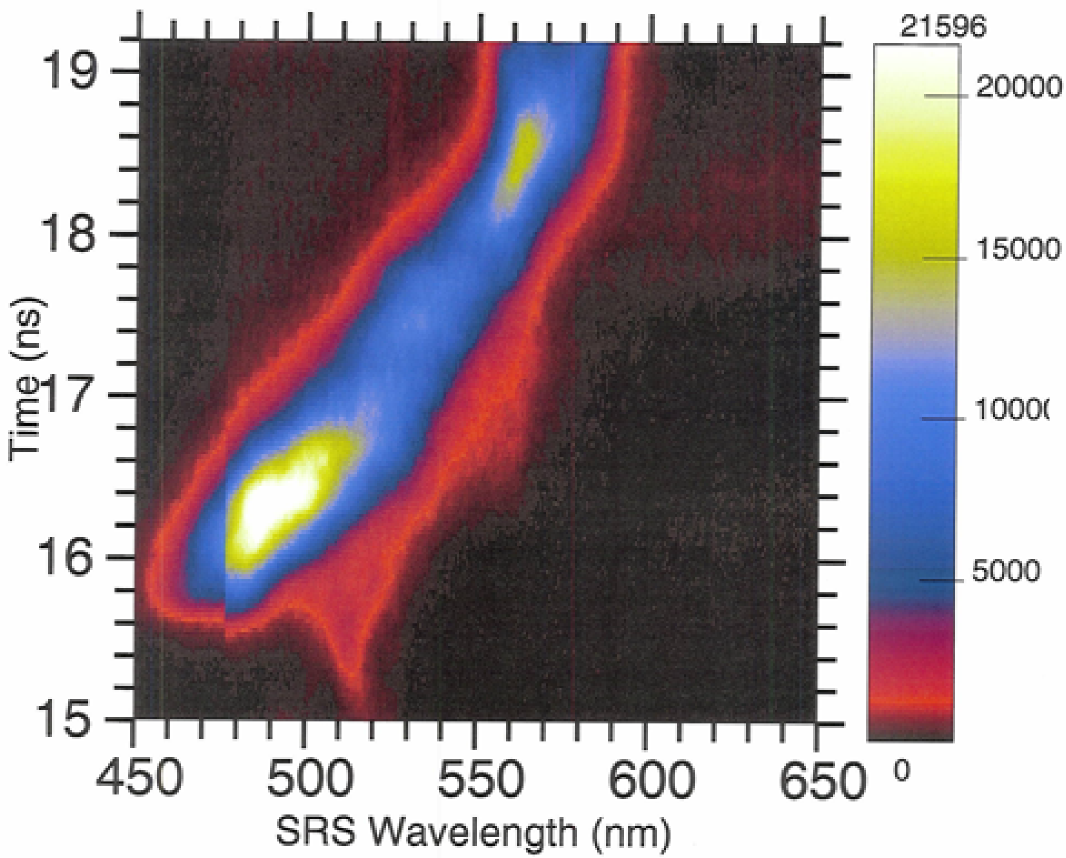
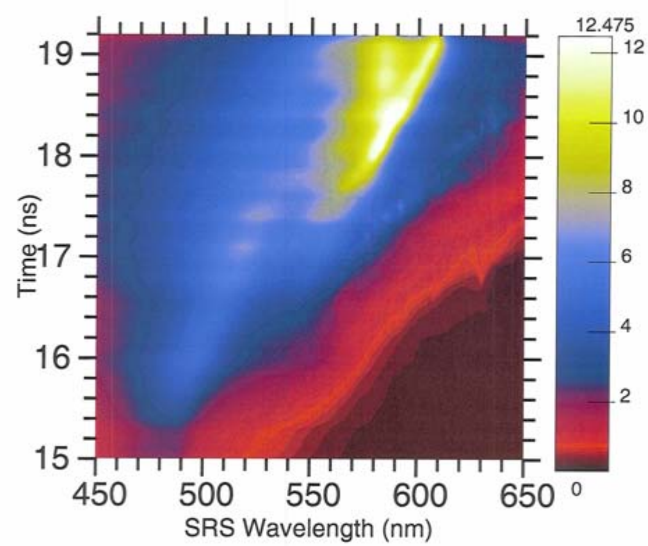
The SRS reflectivity at these high intensities is alarmingly high: > 40%

N091204 “1MJ shot”



Measured streaked spectrometer data

Single beam SRS Gain spectrum from LIP



Insights or Driving Principles that Lead to STUD Pulses

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- Do not leave the laser on and then try to turn LPI off!
  Turn the laser off as often as possible, rapidly, and begrudgingly turn it back on (while keeping the overall energy in the beam constant).

- Do not assume you have any way of knowing the evolving, silent, (kinetic) plasma conditions *as modified* by the presence of many high intensity lasers. Try and control LPI assuming *nothing* up front about the plasma conditions.

- Once an instability is tamed and in the small signal gain regime, then and only then, try and extract what the plasma conditions were. Maybe then you'll find that you can (novel diagnostics relying on pump-probe measurements).

- Don't forget that there will always be crossing, overlapping and interacting beams in all laser fusion or ICF schemes. Make sure you can control the overlapped beam triggered instabilities by controlling their (x-t) interactions.

Where Did the Three Main Ideas Embedded in STUD Pulses Come From?

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- Throughout 2008 and early 2009, fever pitch assertions were made that LPI on the NIF will be **tamed**, is **under control**, is **predictable**, is **essentially linear in character**, **benign**, **weak** and **nonthreatening**. The panel of experts at the Jason Review of the NIC in January 2009 strongly disagreed with this view.
- It suggested the question: ***What would the conditions have to be in order to guarantee that LPI is strictly in the linear regime or any other desired regime in a controlled way?*** Gedanken experiment in April of 2009 with Maxwell's demons led to the conclusion: ***turn lasers on and off on the "instability growth inside a hot spot" time scale***.
- Around the same time, Mike Campbell and Bill Krupke were excited about the "**Million (or a Billion) Fiber-Laser March on Fusion**" idea of Mourou et al., and wanted to know what would LPI be like then? An analysis indicated that the hot spot structures in very many overlapped beam conditions would be randomly varying all the time. The idea of ***scrambling the hot spots so that by switching the lasers on and off their cumulative local effect would be minimized*** was born. **Spike trains of uneven duration and delay, STUD pulses** was the sum of these two ideas.
- A week went by before the realization that ***overlapping beams would be controllable by interlacing their individual STUD pulses***. This was a nice bonus!

A New Approach to LPI Control

- Instead of just phase control (in space-time) through masks and electro-optic modulators, or the all purpose PS solution, it is better to pursue the intentional variation of the amplitude and duration of short bursts of laser light ==> **STUD pulses**: Spike Train of Uneven Duration or Delay.

- Use **variable width spikes** to last 4-8 growth times of the most unstable mode to be avoided, and then shut off the pump long enough to disallow self-organization of plasma into coherent large amplitude waves which can then do real damage. Then, repeat, adapting to changing plasma conditions.

- Divide and conquer the laser's propensity to whip up the plasma into a coherent pump driven LPI haven. **Start and stop and scramble the locations of the interaction processes to avoid cumulative damage**. Three main reasons you win with STUD pulses: Don't allow growth in entire hot spot, avoid hitting the same driven wave by the same or similar hot spot over and over again, damp the wave between recurrence of hot spots to the same locations where previous waves were driven.

Three Physical Mechanisms Are Primarily Responsible for the potential for Unprecedented Control of Laser-Plasma Instability with STUD Pulses

- By **turning the pump on and off** on a time scale short compared to the hot spot traversal time, get lower gains per hot spot. (STUD and Pseudo-STUD, SDL and WDL). Never reach steady state in hot spots.

- By turning the **laser off roughly half the time**, you allow time in between spikes for the driven EPWs or IAWs to damp. No damping effect exists in the Rosenbluth Gain model of parametric amplification in an inhomogeneous linear profile plasma for a continuous pulse. (STUD and Pseudo-STUD, SDL mostly)

- By **scrambling the hot spots around in space between spikes**, break the repeated growth of locally driven EPWs and IAWs when the pump is on at the same place all the time. Recurrence time being long wins. (STUD, SDL mostly. In WDL eliminate absolute instabilities)

What Do STUD Pulses Look Like?

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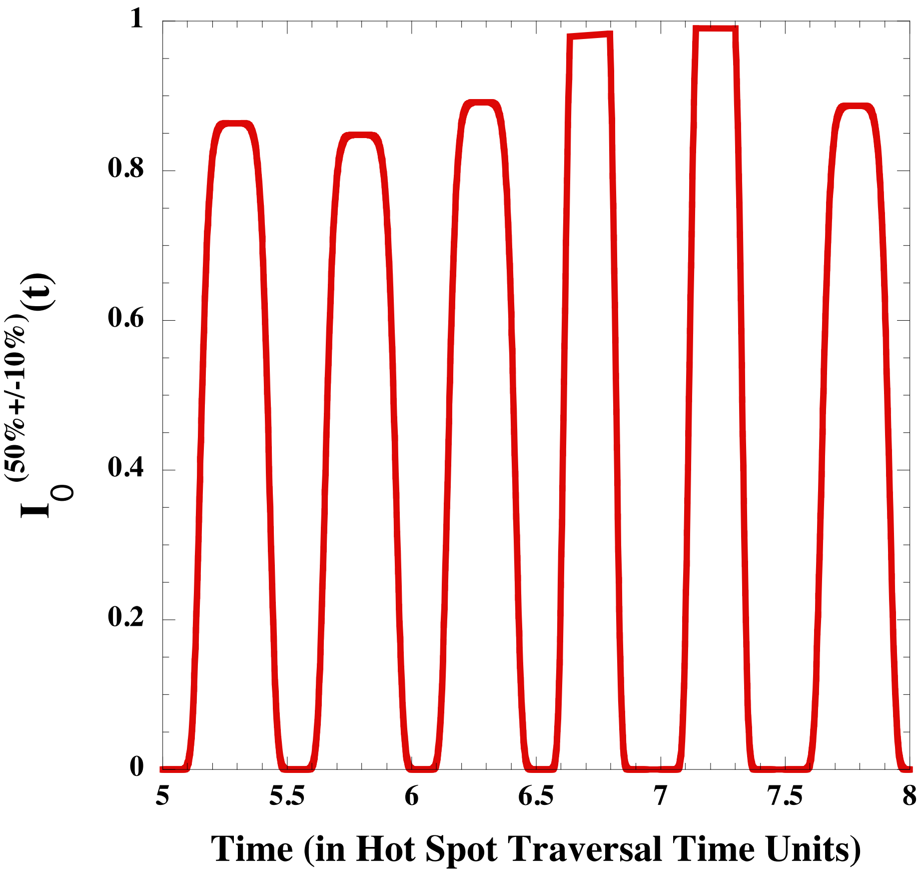
$$I_0(t) = \sum_{n=1}^{N_{SPIKES}} I_0^{(n)} \exp - \left[\frac{\left(t - t_c^n\right)}{\left(t_W^n/2\right)} \right]^{2\sigma_n}$$

$$I_o^{(n)} \times t_{width}^{on(n)} = I_o^{(n+1)} \times t_{width}^{on(n+1)}; \quad \forall n$$

$$t_{width}^{on(n)} + t_{width}^{off(n)} = t_{width}^{on(n+1)} + t_{width}^{off(n+1)}; \quad \forall n$$

STUD Pulse Shape 10% Random Modulation of a 50% Duty Cycle



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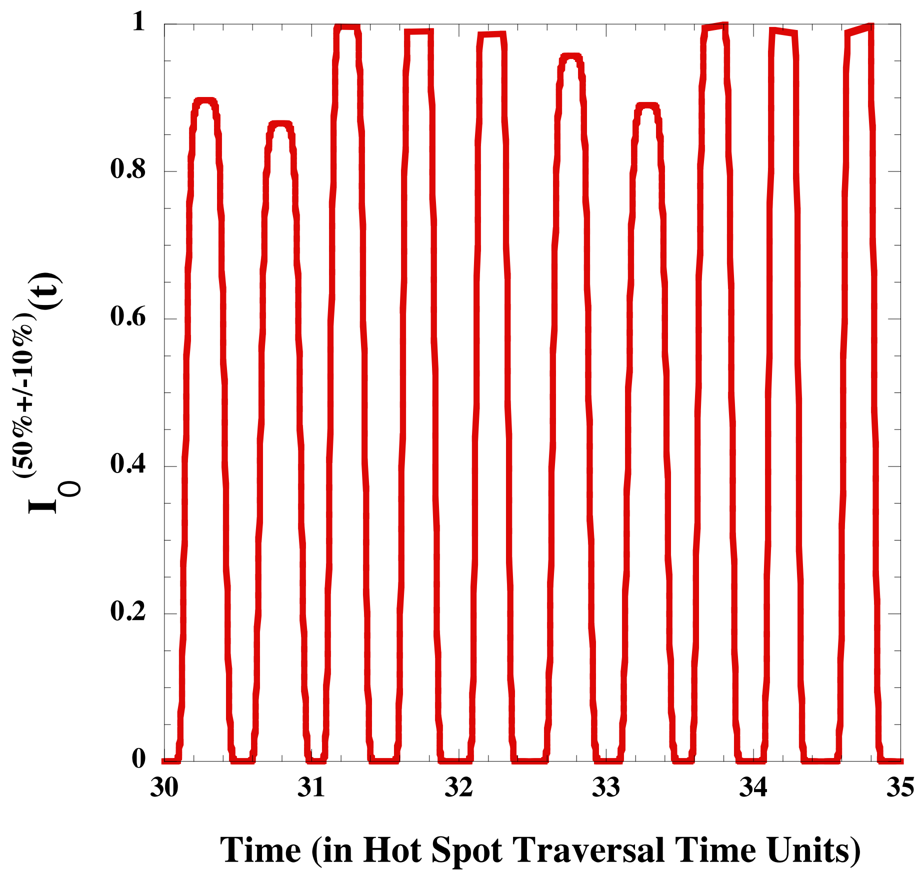

What Do STUD Pulses Typically Look Like?

$$I_0(t) = \sum_{n=1}^{N_{SPIKES}} I_0^{(n)} \exp - \left[\frac{\left(t - t_c^n \right)}{\left(t_W^n / 2 \right)} \right]^{2\sigma_n}$$

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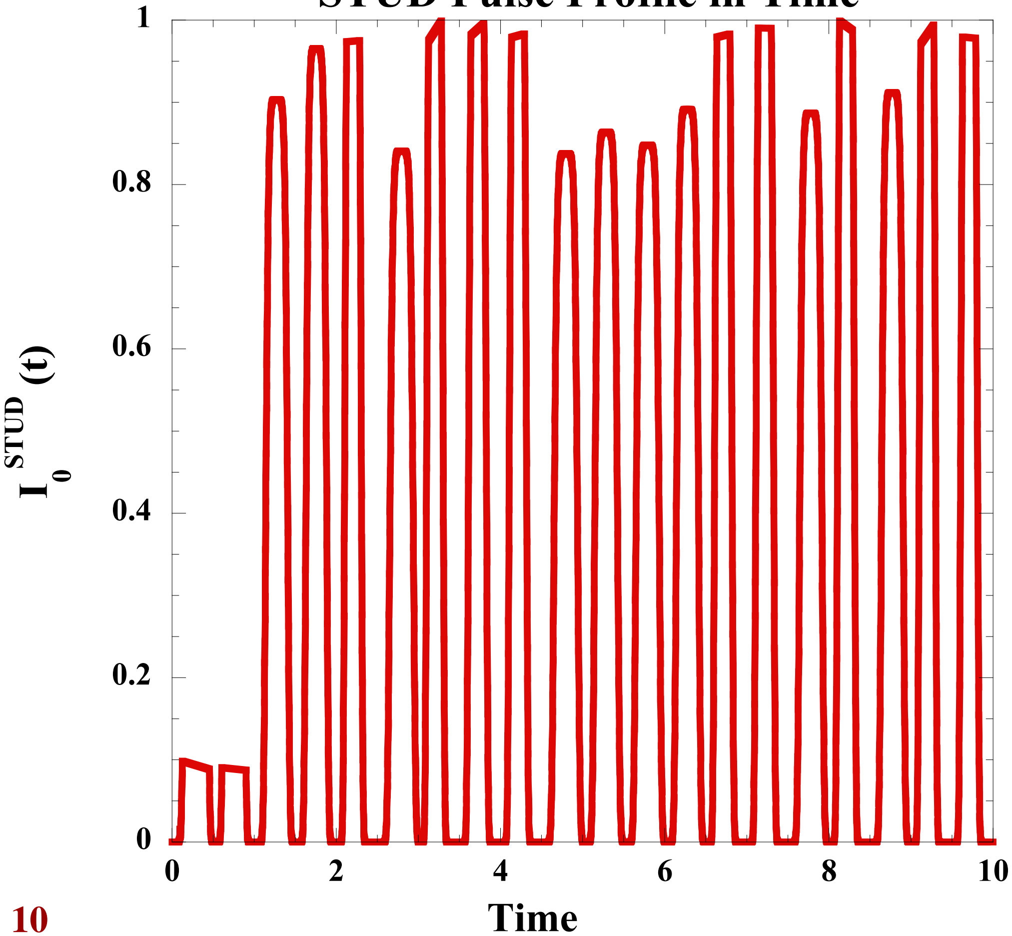
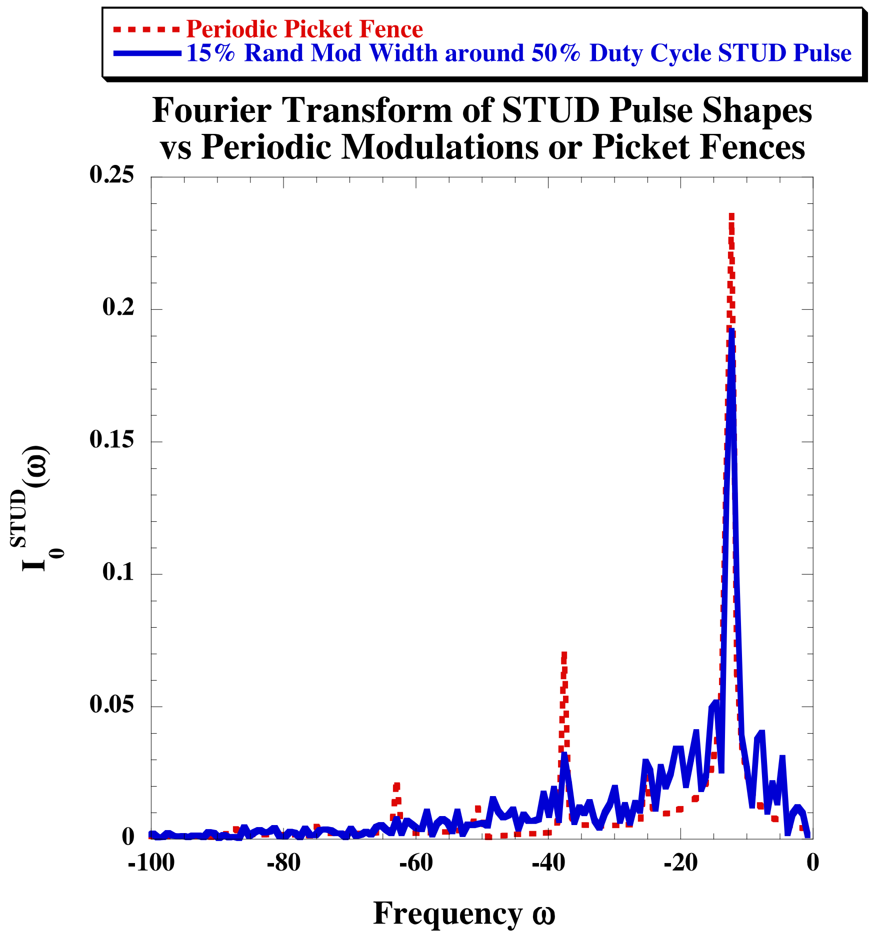
10% Randomly Modulated Spike Width STUD Pulse Profile in Time





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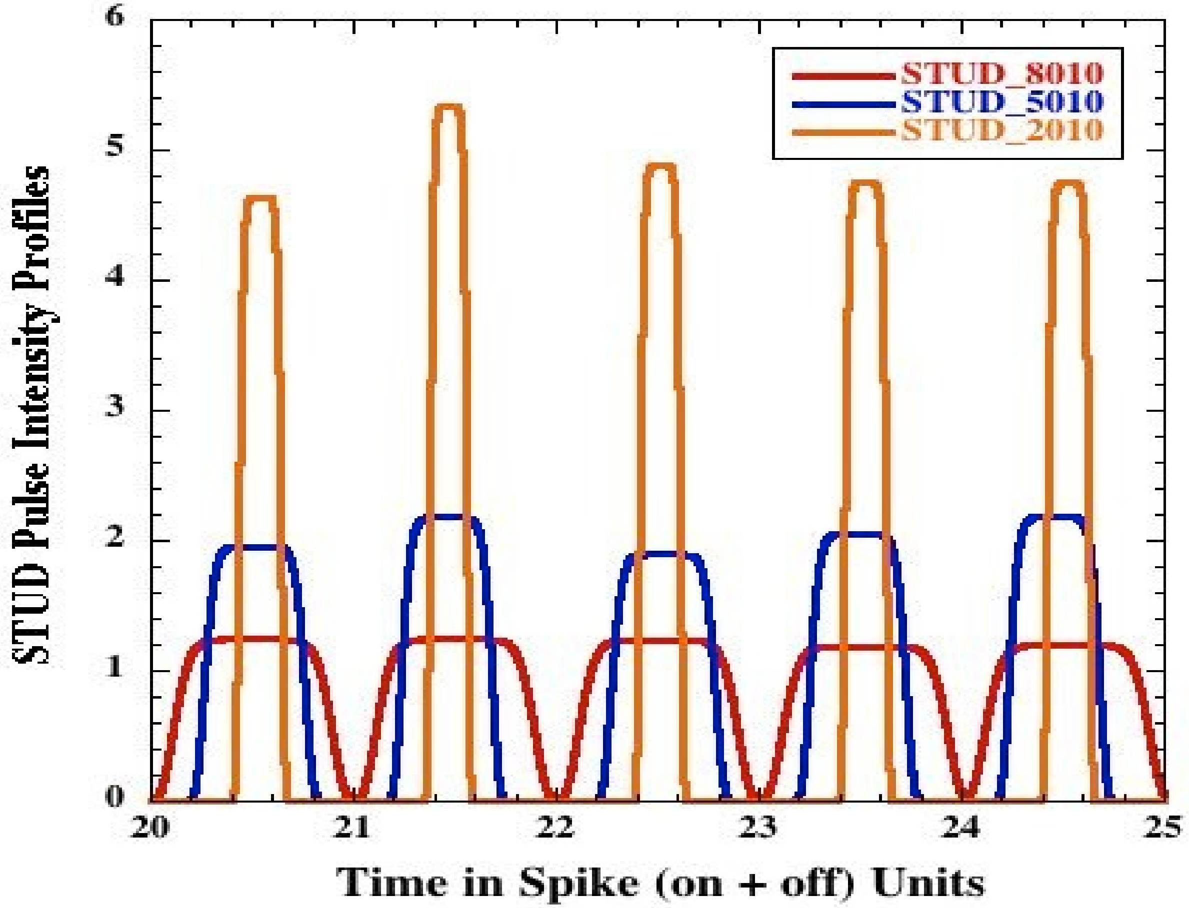
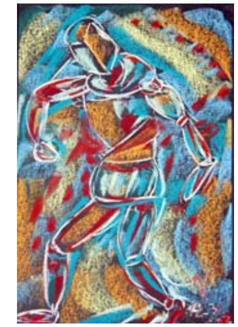
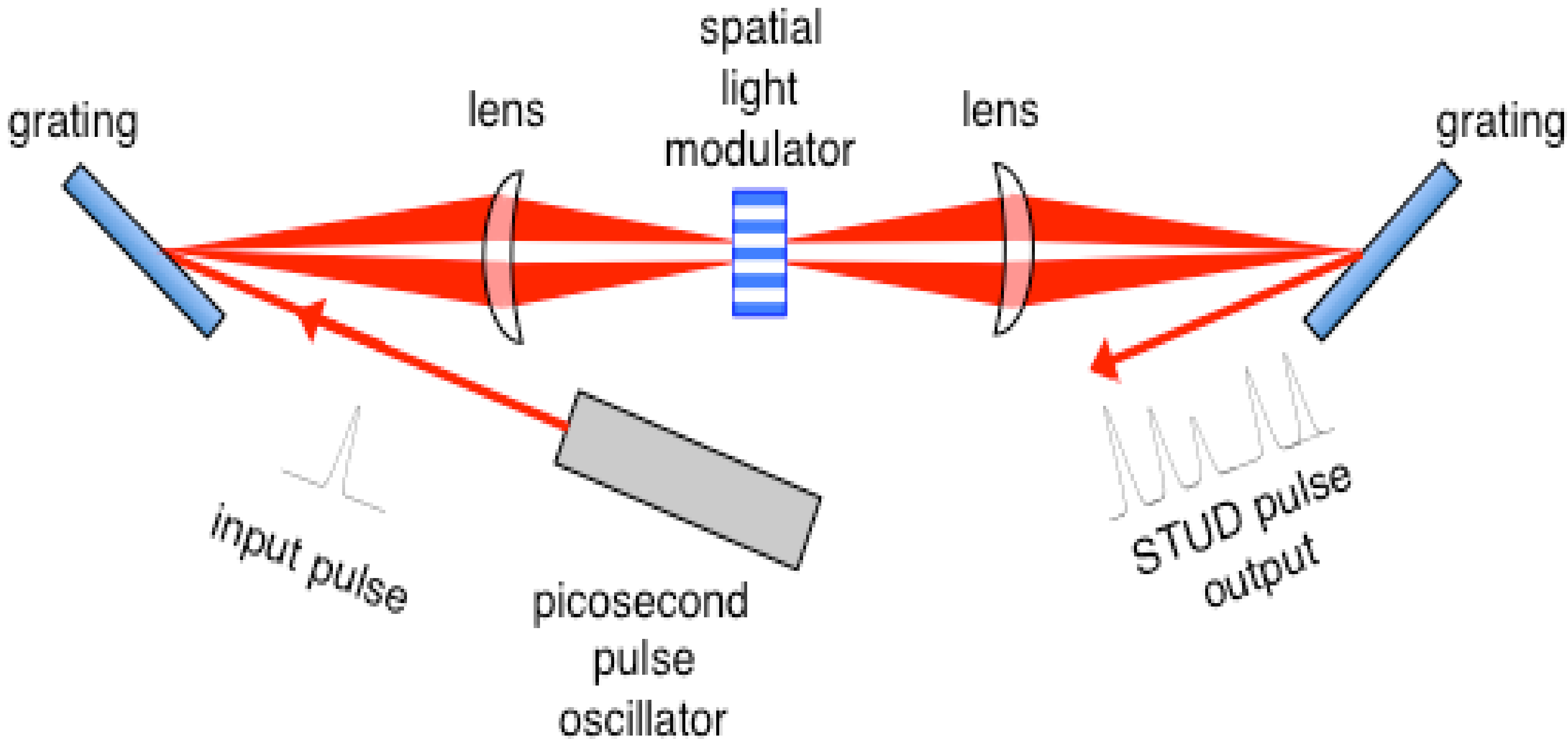
STUD Pulses with 3 Different Duty Cycles: 20%, 50%, 80%
With ~ 10% Pulse Width and Compensated Height Random Jitter



How Do We Generate STUD Pulses? 4*f* or 6*f* System of USP Laser

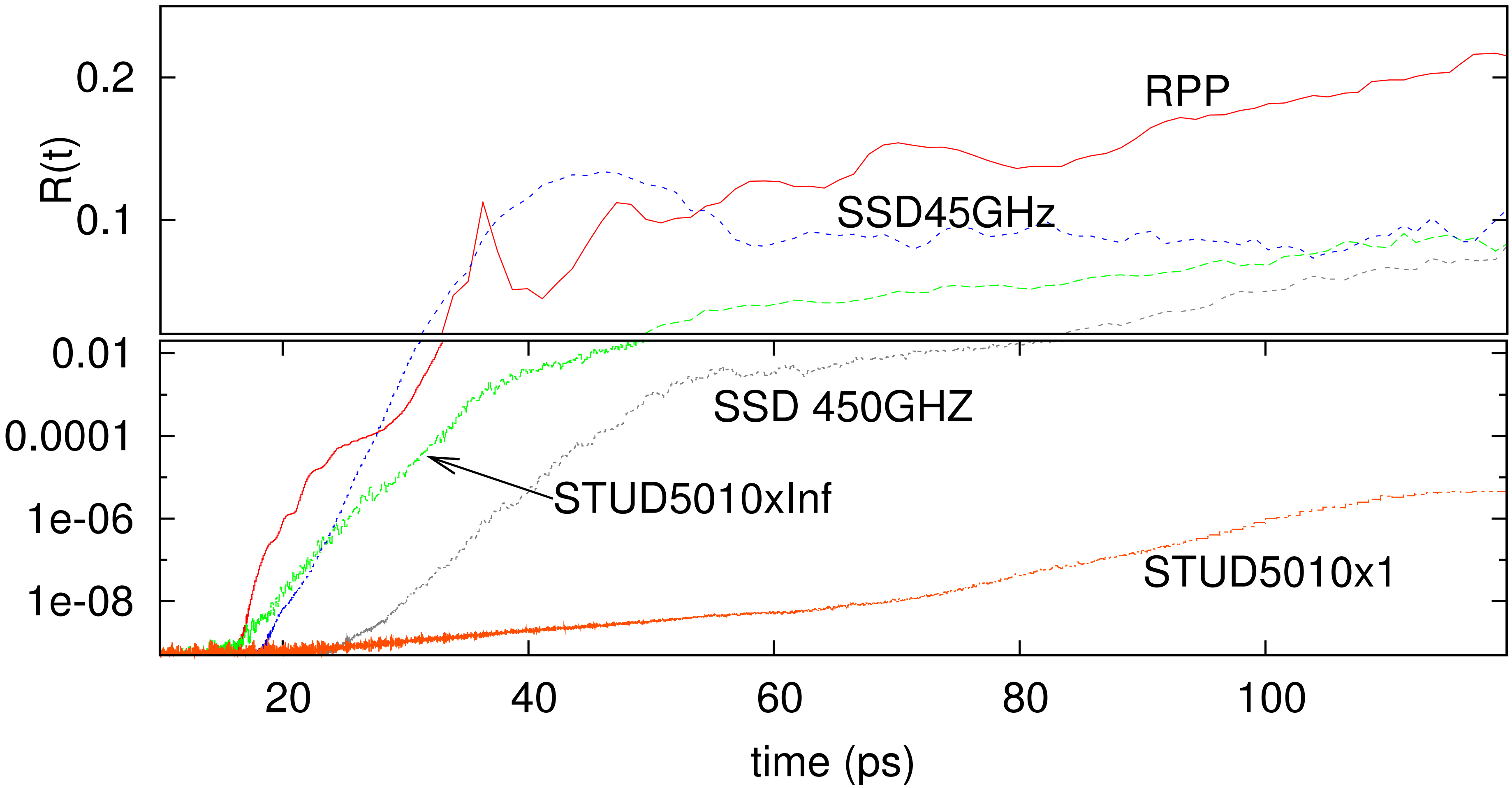


STUD Pulse Generator

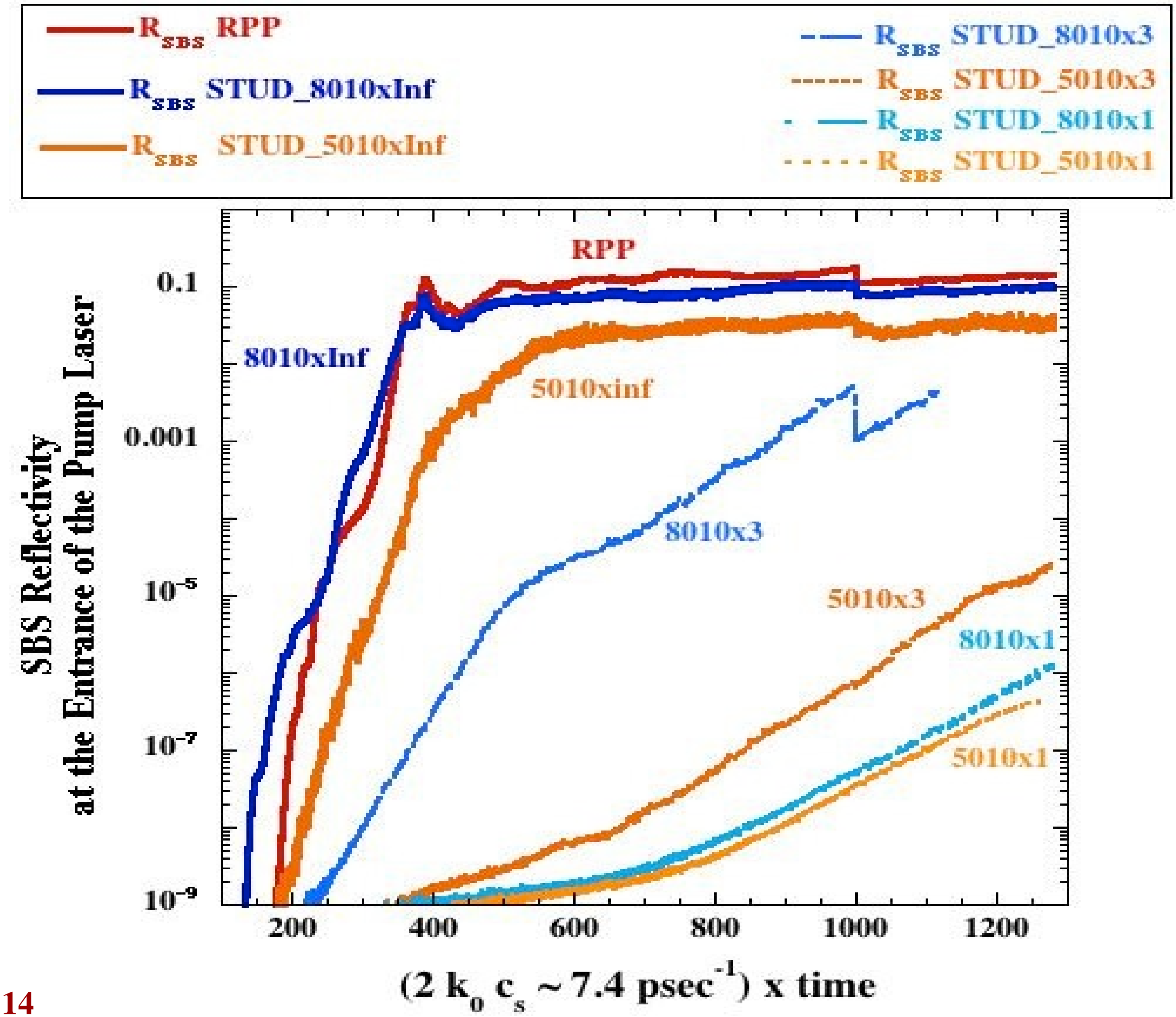


Wiener, *Ultrafast Optics*, 2009

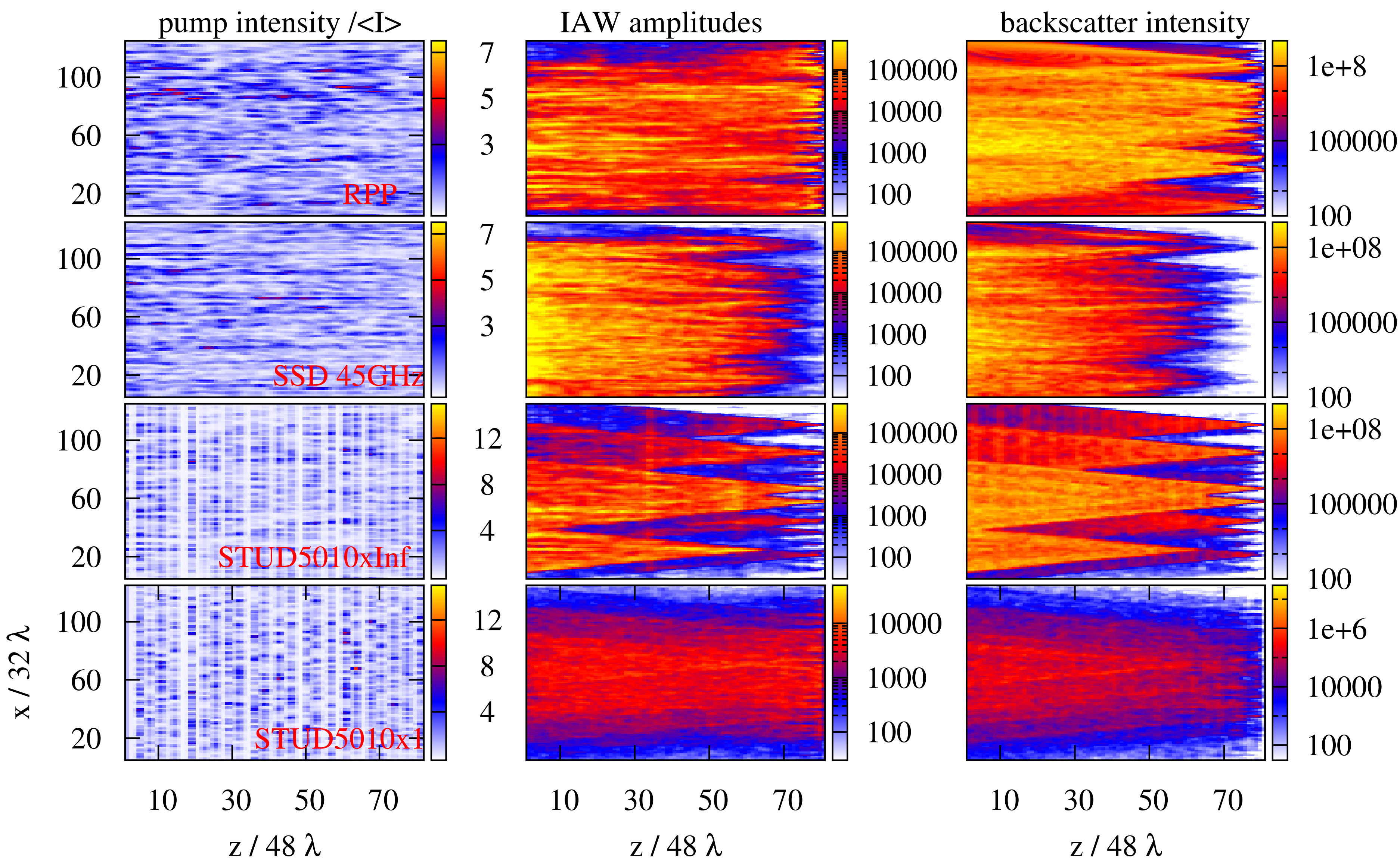
Advantages of STUD 5010x1 Pulses Over RPP and SSD



Advantages of STUD 5010x1 Pulses Over 8010 and RPP Choices



Snapshot in Time of the Performance of RPP, SSD45, STUD 5010×∞ & STUD 5010×1



3 Major Experimental Tools Are Needed in Order to Explore the Effectiveness of and to Optimize STUD Pulses in the Green

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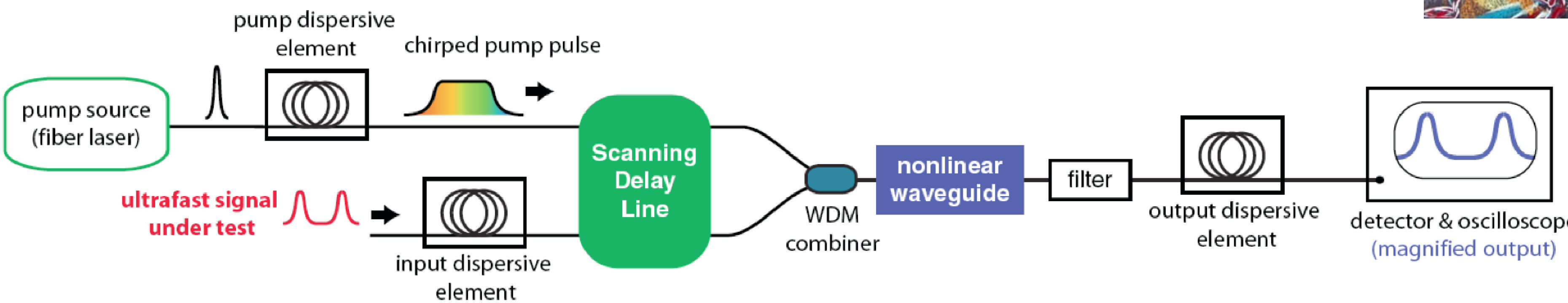
- Need **ps time scale Thomson Scattering** capability

- Need **ps time scale backscatter streaked spectrometry**

- **TIME LENSES will allow STUD pulse design at longer time scales to be compressed down to psecs AND the dilation of Raman and Brillouin scattered signals up from psecs so that an electronic scope can be used to measure that time history.**

- **Need a *tunable* short pulse OPO** for pump-probe experiments where small signal gain can be measured once STUD pulses control the instability and direct measurements of the slope of the plasma distribution function become possible.

How Do Time Lenses Work?



Schematic diagram showing the concept of temporal magnification, or “Time-Lens”, using **nonlinear optical mixing in a waveguide**. The scanning delay line allows a delay between the measurement window and the input pulse. The measurement window is as large as 200-ps, with <1-ps resolution on a single shot. The nonlinear wave guide mixes the linearly chirped pulse with the input pulse, encoding the time-dependence of the input pulse on the chirped pulse. The input pulse is filtered out, and the **encoded chirped pulse stretches out in time via linear dispersion in a long fiber**. The stretched pulse is then measured using a conventional oscilloscope. Temporal magnification up to M=500 have been reported.

“**High-speed optical sampling using a silicon-chip temporal magnifier**,” R. Salem, M.A. Foster, A.C. Turner-Foster, D.F. Geraghty, M. Lipson, A.L. Gaeta, *Optics Express* **17,** 4324 (2009)

Summary: Use STUD Pulses

- **STUD pulses** allow optimal LPI control and design flexibility.

- Exponential growth and uncontrolled behavior is mitigated by modulating the incident laser in time with new **design principles** stated and illustrated.

- The relative durations of **growth**, **damping** and **hot spot recurrence** time determine the likelihood of success. In terms of length scales, $L_{INT} \approx L_{HS} \approx 2 \times L_{SPIKE}$ leads to excellent results with STUD 5010x1 pulses.

- The march back to **GREEN ICF & IFE** can be discussed in earnest.

- Keeping NLO processes linear (tamed) and then letting them run wild (at the end of the pulse for **Shock Ignition**) by using staggered and then overlapped STUD pulses makes the success of SI more likely.