The Green Option for IFE with Laser-Plasma Instability Control Using ML Optimized STUD Pulses
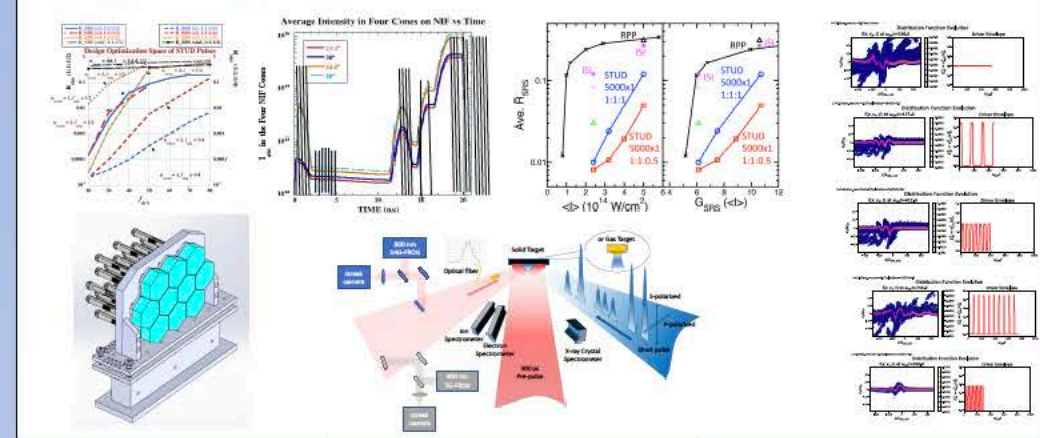
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Highlights

Proposition

1 Slide Summary of the STUD Pulse Program for IFE

- What are STUD pulses? Spike Trains of Uneven Duration and Delay
- What is the STUD pulse program? Ferrari, Mercedes, Prius versions
- The experimental evidence for gross LPI anomalies up and down the line
- How did things get so bad on NIF? > 30% energy into LPI ~ 60 kJ.
- Compare USB (Plane Wave) to RPP/SSD to STUD pulses.
- Key ideas: Plasmas tend to self-organize if you imbue them with coherent energy over long periods of time: Simple growth becomes catastrophic growth
- Try to fool the plasma into not forming memories of continuous pumping. Kill memory accumulation, heal previous growth spurts, spread a little growth everywhere – so *not* in static or very slowly varying hot spots. Scramble the beam spatial profile and turn the laser beam on and off: **The Ferrari STUD pulse program**
- Intersperse crossing beams by synchrony and choose which interact and scramble each other's temporal coherence due to strong coupling SBS: **The Mercedes program**
- In the foot of the pulse, intersperse spikes in time between crossing beams and avoid multi-beam driven instabilities: **The Prius program**
- Show feasibility of all three on high rep rated multi-beam system STUD Pulses @ 2ω.

ARPA-E Program on LPI Control Using STUD Pulses

- Demonstrate laboratory STUD pulse (10 spike array) performance on ALEPH at CSU using RA with 800nm and SRS with 400nm lasers
- Develop computational and theoretical models at the ODE, PDE and IDE levels for these processes controlled by STUD pulses.
- Synthesize these models into surrogate models using ML and DNN.
- Extract STUD pulse design tools based on individual models and the integration of diverse models.
- Are there universal rules? Are they interpretable? Can we design large-scale IFE experiments on JUPITER or T-STAR to test these findings?
- Can we work towards a comprehensive design tool set that solves the inverse problem for LPI for a given IFE target design?
- Give me plasma conditions as a function of space and time and target composition —> spit out a space - time sculpted STUD pulse sequence that can control LPI in that target.
- Or suggest changes to the target more favorable from an LPI point of view. Iterate.

The STUD Pulse Program for IFE: Future Perspective

Challenge/Opportunity	Approaches
LPI control and at-will exploitation are beyond reach of traditional attempts, which assert throwing enough bandwidth at the problem will make all LPI go away. False. There is not enough bandwidth to stop hot spots from lighting up and bringing the rest of the plasma to self-organize, if lasers kept on all the time. **Must fight to erase plasma memory buildup. STUD pulse program could eliminate LPI initiated in multiple laser hot spot self-organization.**	Key technology: **Ferrari, Mercedes, Prius** **Deterministically modulate in time, scramble hot spot patterns in space.** Interlace crossing beams, change speckle patterns of crossing beams in the strong coupling limit of SBS especially near Mach -1. Key variables: T_{pulse} fixed vs I_{max} fixed L_{sing}: Ratio of Spike duration to speckle length f_N: Duty cycle of 'on' time in one 'on' + 'off' pair n_{scram}: Number of spikes btw speckles are scrambled

Timeliness

Why now?
All-Optical means of generating sub-ps arbitrary waveform generation already exist: STACCATTO and STILETTO & SLICER, for instance (LLNL). High Rep-Rated lasers coming on board where STUD pulses and ML can go hand in hand.
Goals (e.g. 5 years):
Install on ALEPH (800 nm & 400 nm), and JUPITER + Texas PW Next in the Green. Use Machine Learning to optimize STUD pulses.
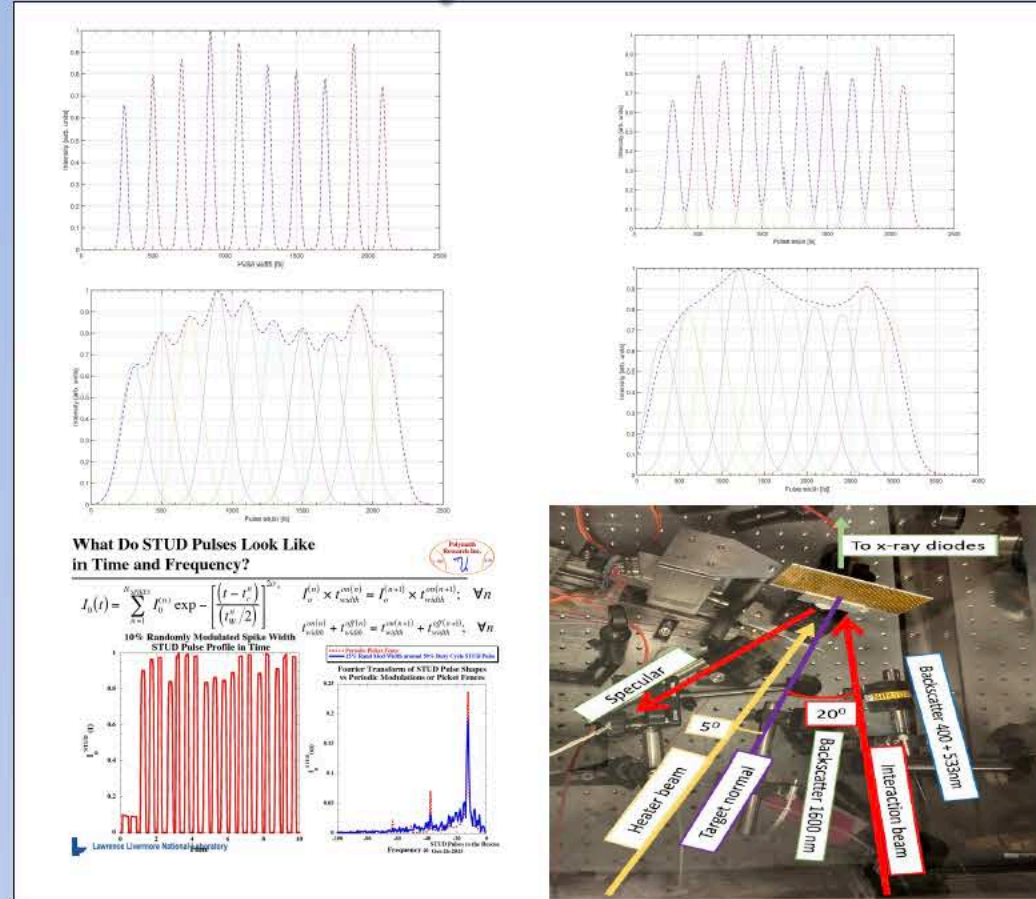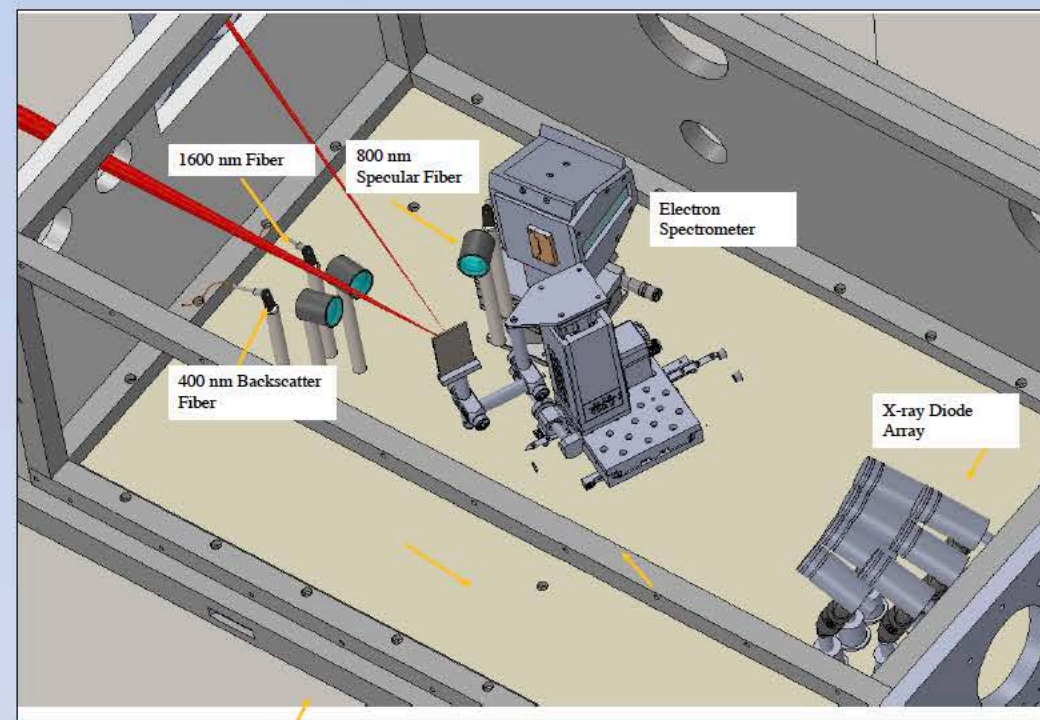
Impact

- Longer wavelength option for IFE made possible.
- Much higher frequency conversion efficiency in crystals with STUD pulses.
- Control and exploitation of LPI for the greater good.
- Femtosecond Plasma Phase Space Photonics **FP³**.
- Sculpt structures in plasma phase space.
- Enable flexible and disposable X ray optics in HED plasmas.
- Solve CBET problems elegantly.

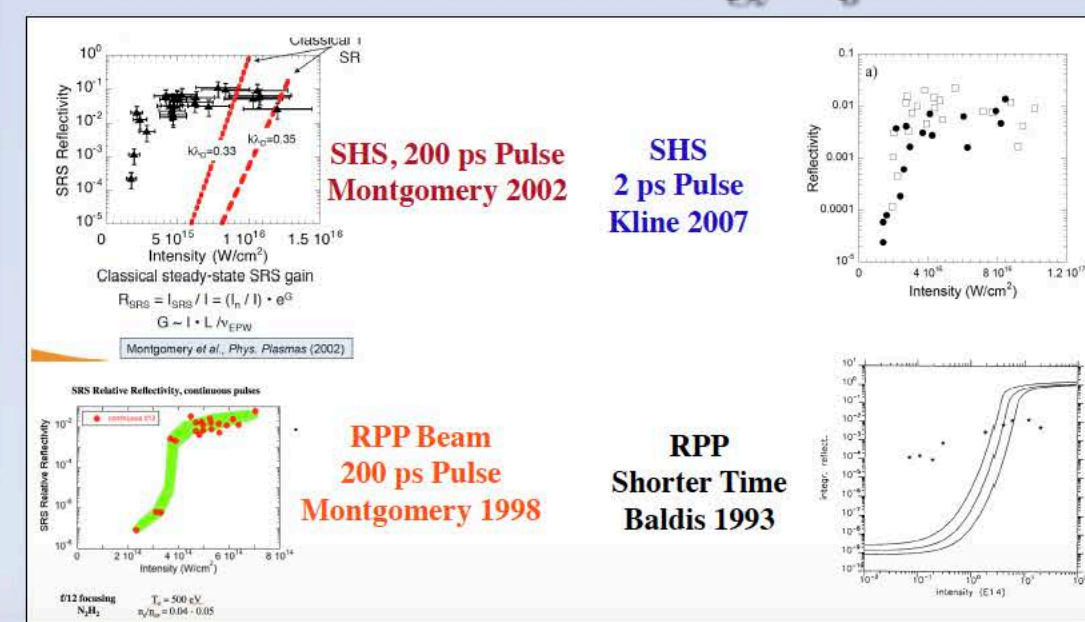## Spike Trains of Uneven Duration and Delay: STUD Pulses

What Do STUD Pulses Look Like in Time and Frequency?

$$I_L(t) = \sum_i f_i^{on} \exp\left[-\frac{(t-t_i^c)^2}{(t_d^i/2)^2}\right]\cdot f_i^{on} \times f_i^{rand,i} \times f_i^{rand,i}$$

RA STUD Pulse Experimental Configuration at ALEPH

1600 nm Fiber
800 nm Specular Fiber
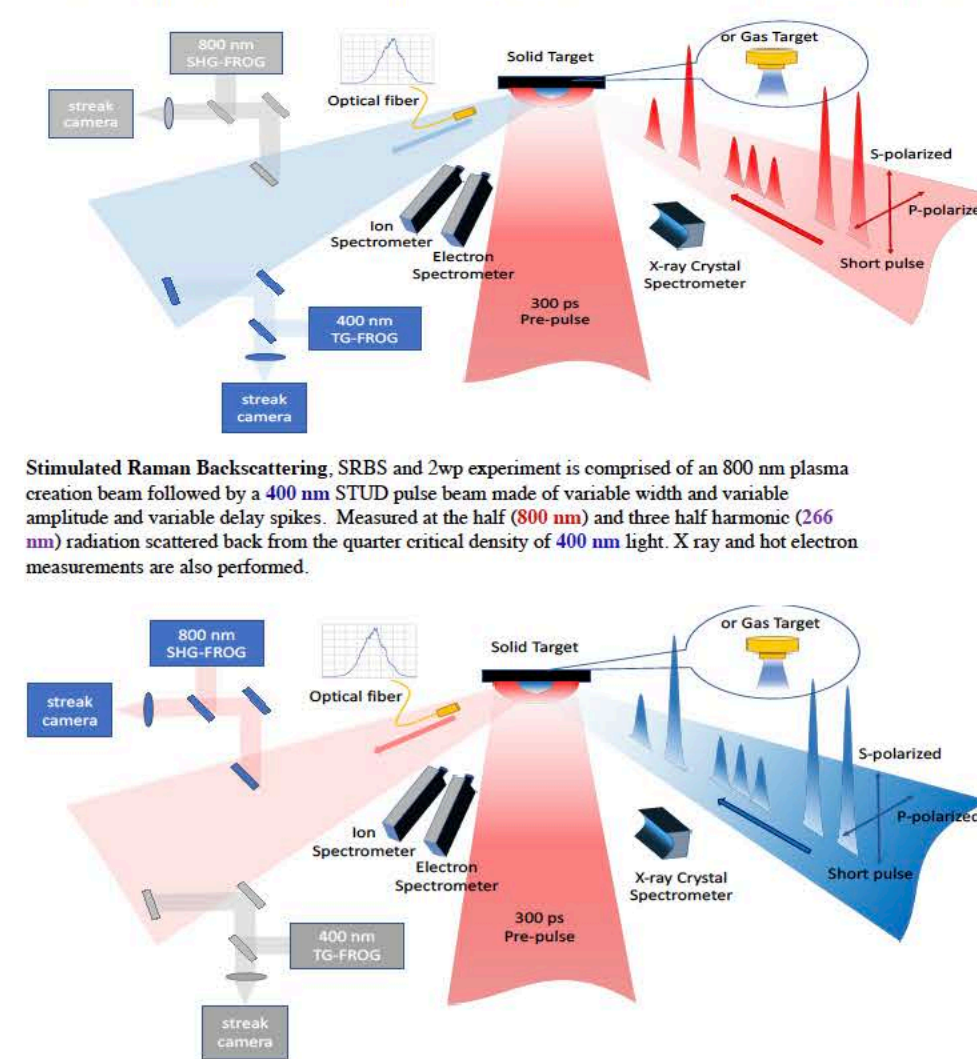Electron Spectrometer
400 nm Backscatter Fiber
X-ray Diode Array

More is Different in space & time: Plasmas Self-Organization the Presence of Continuous Coherent Energy Injection

SHS, 200 ps Pulse Montgomery 2002
SHS 2 ps Pulse Kline 2007
RPP Beam 200 ps Pulse Montgomery 1998
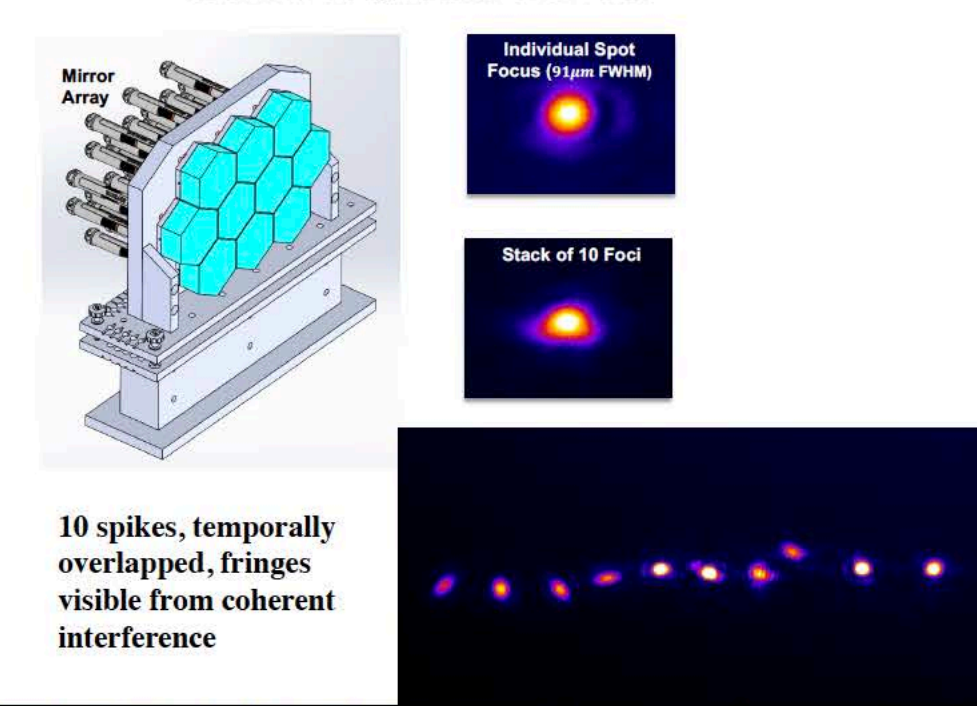RPP Shorter Time Baldis 1993

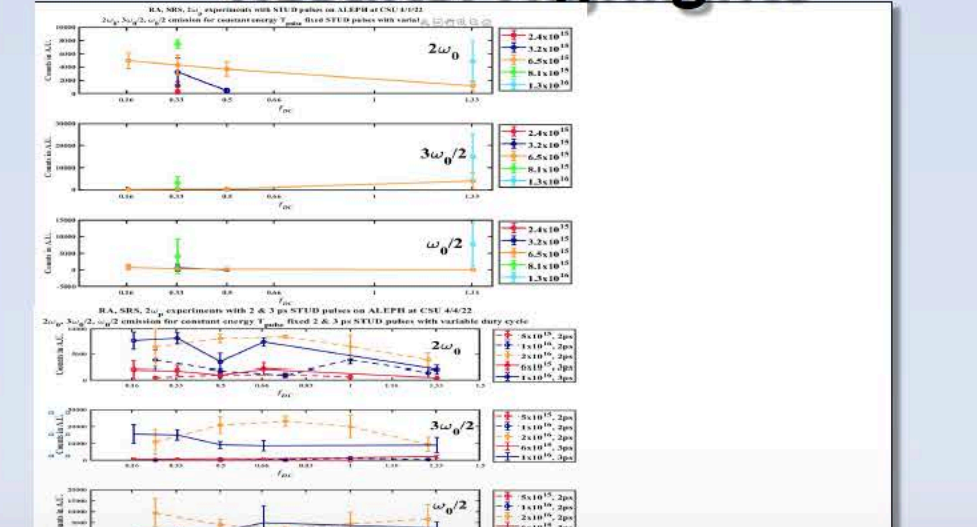## CSU FP³ STUD Pulse Exprt's Controlling RA & SRS/2ω_p

RA-centric experiment is comprised of an 800 nm plasma creation 310 ps pulse followed by an obliquely incident STUD pulse sequence of 10 spikes whose width is varied between 50 fs and 3 ps. The delays between the spikes are variable and programmable. Each macropulse is comprised of up to 5 Joules. The spot size is 140μm. This high intensity beam produces resonance absorption and produces 400 nm light. The delay between the plasma creation and the RA driving beams helps select density scalelengths and temperatures that are best suited to study resonant absorption physics and its control. Our optimum choice was 200 ps after heater peak.
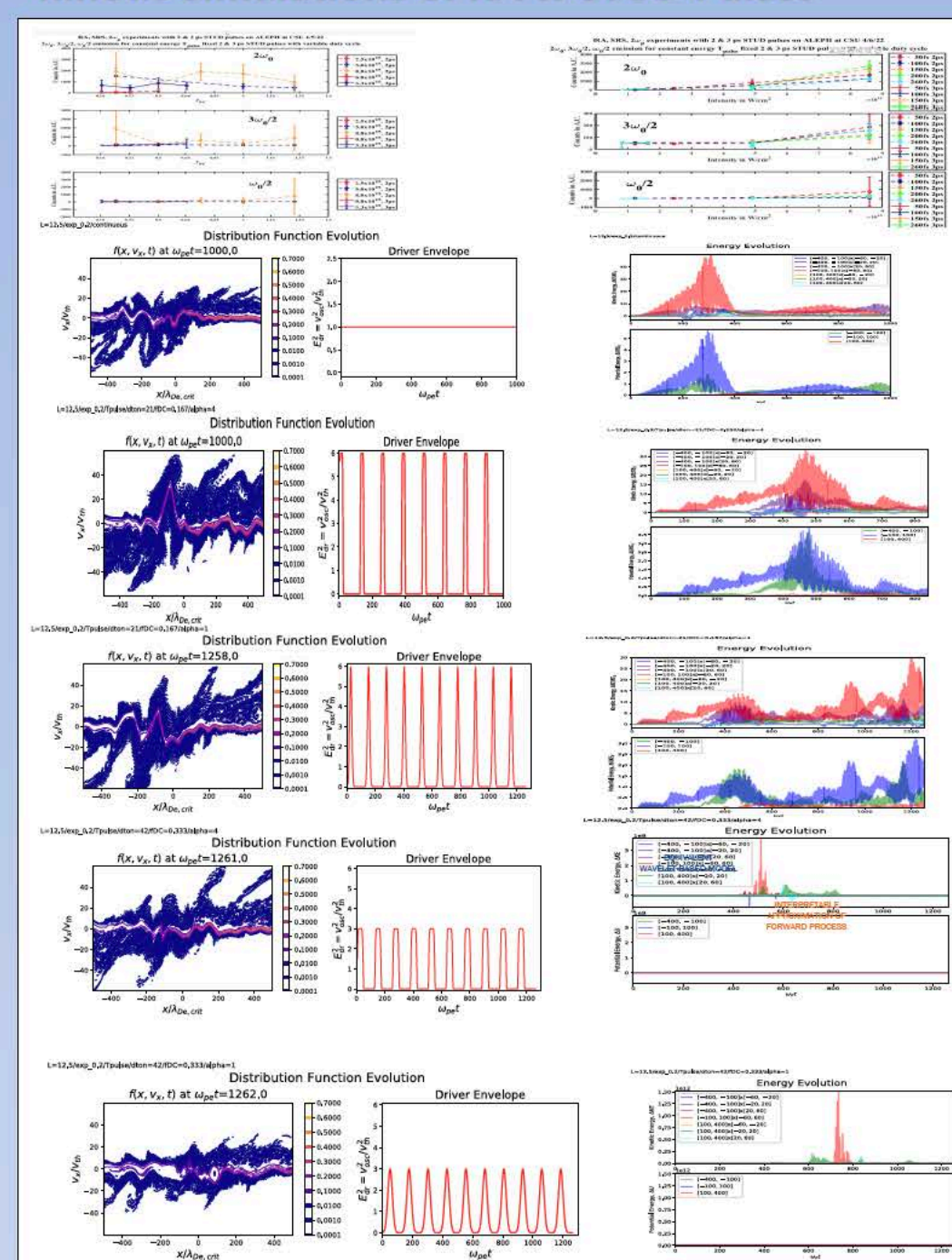

Stimulated Raman Backscattering, SRBS and 2wp experiment is comprised of an 800 nm plasma creation beam followed by a 400 nm STUD pulse beam made of variable width and variable amplitude and variable delay spikes. Measured at the half (800 nm) and three half harmonic (266 nm) radiation scattered back from the quarter critical density of 400 nm light. X ray and hot electron measurements are also performed.

Scheme for the ogeneration f STUD Pulses

Individual Spot Focus (91μm FWHM)
Stack of 10 Foci

10 spikes, temporally overlapped, fringes visible from coherent interference

RA STUD Pulse Experimental Results: Highlights

Kinetic Simulations of RA w STUD Pulses

Crucial Machine Learning Component of The STUD Pulse Program

Dynamical Representation Learning | Multi-fidelity Surrogate & UQ | Multi-fidelity Optimization | Explainability

Machine Learning Thrust

Encoding Pulse Shapes   Encoding Energy Spectra

Wasserstein Autoencoders
Self-Attention based Transformers
Neural ODE (NODE)
Fourier Neural Operators
GP-NODE

Forward Process
Inverse Process

Fourier Feature Networks: new family of NN surrogates

Accurate Uncertainty Estimation with DNNs

Sample Results