Thermal lensing in Ti:Sa amplifiers – a browser-based GUI and future directions

D.L. Bruhwiler,[#,@] J. van Tilborg,[§] K. Wolfinger,[#] B. Nash,[*] D.T. Abell,[%] P. Moeller,[#] R. Nagler,[#]
N. Goldring,[*] M. Henderson,[#] Q. Chen,[§] C. Tóth[&] and C.G.R. Geddes[§]

[@] *bruhwiler@radiasoft.net*

[#] *RadiaSoft LLC* [§] *Berkeley Lab* [%] *U. of Maryland* [*] *consultant* [&] *retired*

Advanced Accelerator Concepts (AAC) Workshop
Chicagoland 22 July 2024

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of High Energy Physics, under Award Numbers DE-SC0020931 and DE-AC02-05CH11231.

Outline

- Motivation & Scope
- Overview of modeling tools for simulation of high-power amplifiers
- Simulating Ti:Sa amplifiers – wavefront propagation & amplification
- Sirepo-Silas – a browser-based GUI
- Simulating Ti:Sa amplifiers – thermal effects at high repetition rate
- Future directions
- Conclusions

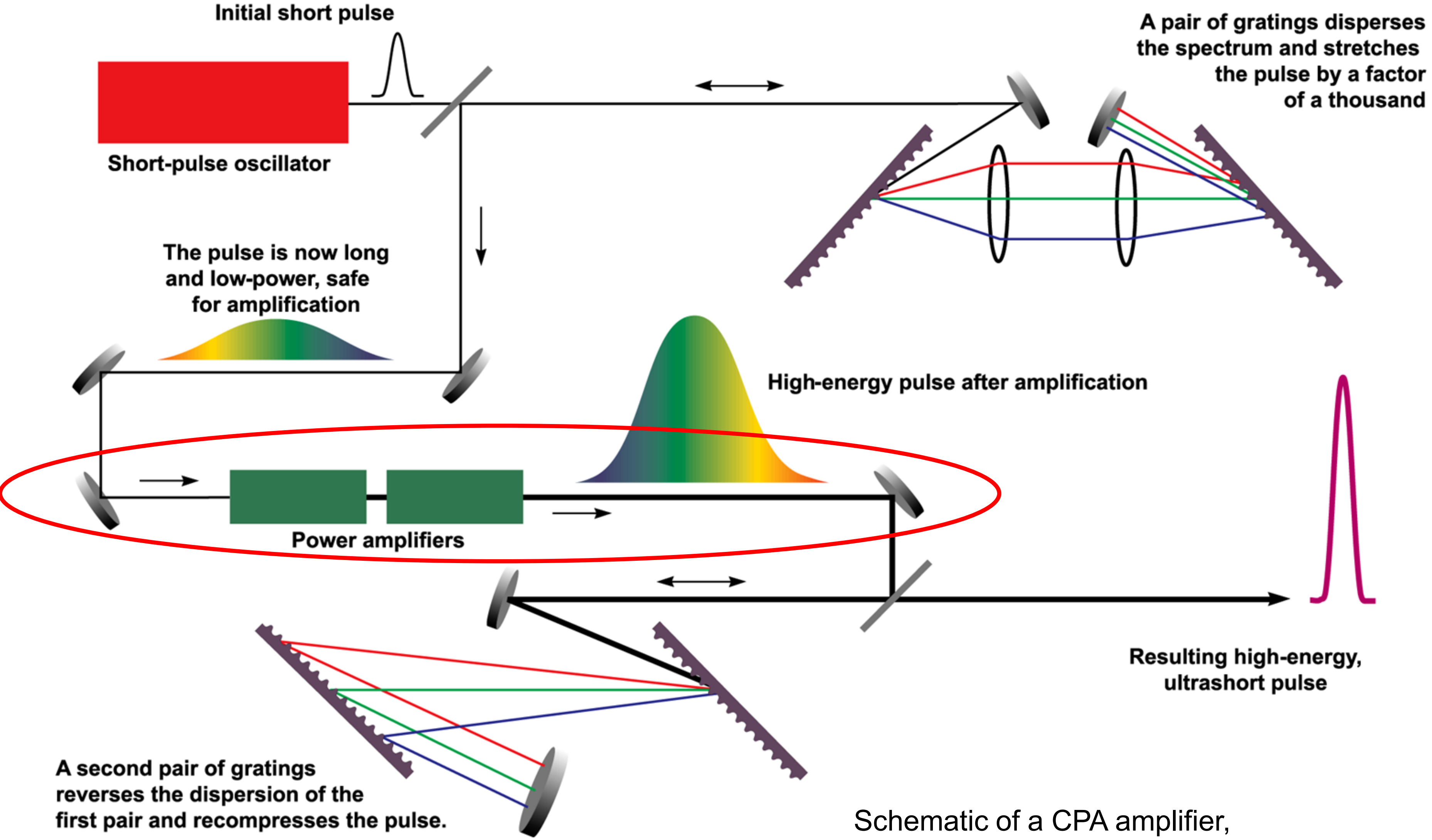
Motivation

- The laser pulse properties required for a future laser-driven collider are routinely demonstrated with Hz class Ti:Sa lasers
    - 1e4 increase in repetition rate is necessary to meet collider luminosity specs
    - ultrashort Ti:sapphire CPA systems are being pushed to higher rep rates
        - some PW-scale systems are moving from 1 Hz towards ~10 Hz
        - 100 Hz and 1 kHz sub-100 TW systems are being deployed
    - new types of crystal amplifiers are being studied
- A series of reports during the late 2010s called out for community software
    - Required capabilities include: "Fully integrated amplifier models including temperature-dependent physical properties and laser properties..."
- DOE, NSF & ELI are funding user facilities based on high-power lasers
    - users/applications require a detailed understanding of the delivered laser pulses
    - facility commissioning & operations require improved understanding

L. Kiani *et al.*, "High average power ultrafast laser technologies for driving future advanced accelerators" *JINST* **18**, T08006 (2023).

Workshop on Laser Technology for k-BELLA and Beyond. 2017. eprint: https://www2.lbl.gov/LBL-Programs/atap/Report_Workshop_k-BELLA_laser_tech_final.pdf.

Scope – simulating crystal CPA amplifiers



Schematic of a CPA amplifier,
courtesy of Berkeley Lab's BELLA Center

Challenges of increasing f_{rep} beyond 1 Hz

- $\tau_{therm} \sim 0.15$ s (*for the particular crystal we studied*)
  - $f_{rep}\, \tau_{therm} \sim 1$ → $f_{rep} \sim 7$ Hz
- $f_{rep} \ll 7$ Hz → thermal effects are perturbative
  - thermal effects can be ignored (?) at 1 Hz, assuming sufficient cooling
- $f_{rep} \sim 7$ Hz → thermal effects are non-perturbative & probably time-dependent
  - suggests 2 Hz to 30 Hz is a difficult operational regime (*for this crystal*)
  - mitigation: i) geometry, ii) type of crystal, iii) more effective cooling, iv) …
- $f_{rep} \gg 7$ Hz → thermal effects are strong but possibly time independent
  - 100 Hz and higher repetition rates are more readily managed, at lower laser power
  - consistent with commercial availability of TW-scale commercial amplifiers
  - consistent with recent deployment of 10 TW-scale systems at 100 Hz
  - the equilibrium temperature profile will depend on geometry & cooling

Existing codes: VBL & COMBINE

- most capable and well-tested codes are VBL and COMBINE (LLNL)
  - amplification, chi(2) and chi(3) effects – also, longitudinal dispersion.
  - thermo-mechanics in COMBINE – capture birefringence and thermal lensing
  - also captures 3D intensity-dependent effects like the Kerr effect
  - both: high-energy ns-scale systems & CPA fs-scale ultra-fast amplifiers
  - validation with ARC (Advanced Radiographic Capability) laser were published
    - ARC is a ps, kJ, PW-class laser
- algorithmic approach: solve 3D coupled partial differential equations

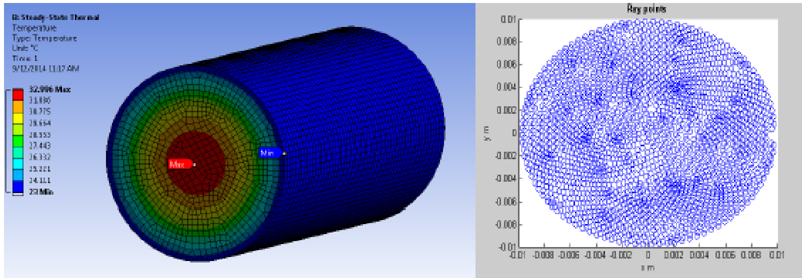


Figure 7. Rod with uniform heat deposition (left) and ray exit points (right).

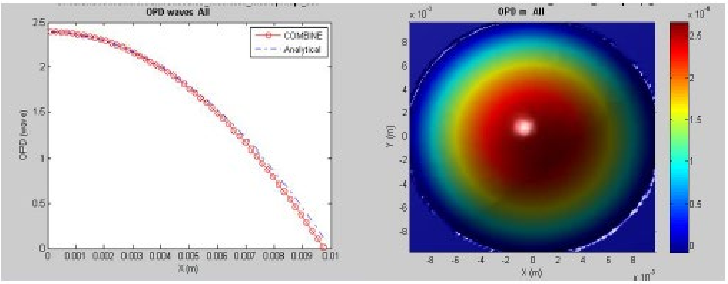


Figure 8. Comparison with analytical optical path difference expression along diagonal (left) and map (right).

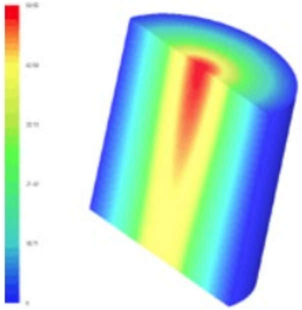
R.A. Sacks, K.P. McCandless, E. Feigenbaum *et al*., "The virtual beamline (VBL) laser simulation code," High Power Lasers for Fusion Research III, *Proc. of SPIE* **9345**, 93450M (2015).

M. Rehak and J.M. Di Nicola, "COMBINE*: an Integrated Opto-Mechanical Tool for Laser Performance Modeling," High Power Lasers for Fusion Research III, *Proc. of SPIE* **9345**, 93450K (2015).

Commercially available codes

- 4 relevant commercial products:
  - LASCAD, VirtualLab Fusion, PlanOpSim and Ansys Zemax OpticStudio
  - there may be others
- capabilities overlap to a certain extent with other codes
- closed pricing model, with modules to be bought separately
- underlying algorithms are proprietary, for the most part

Graphical user interface of **LASCAD**



Temperature distribution in an end pumped rod

Laser Cavity Analysis & Design (LASCAD), https://www.las-cad.com

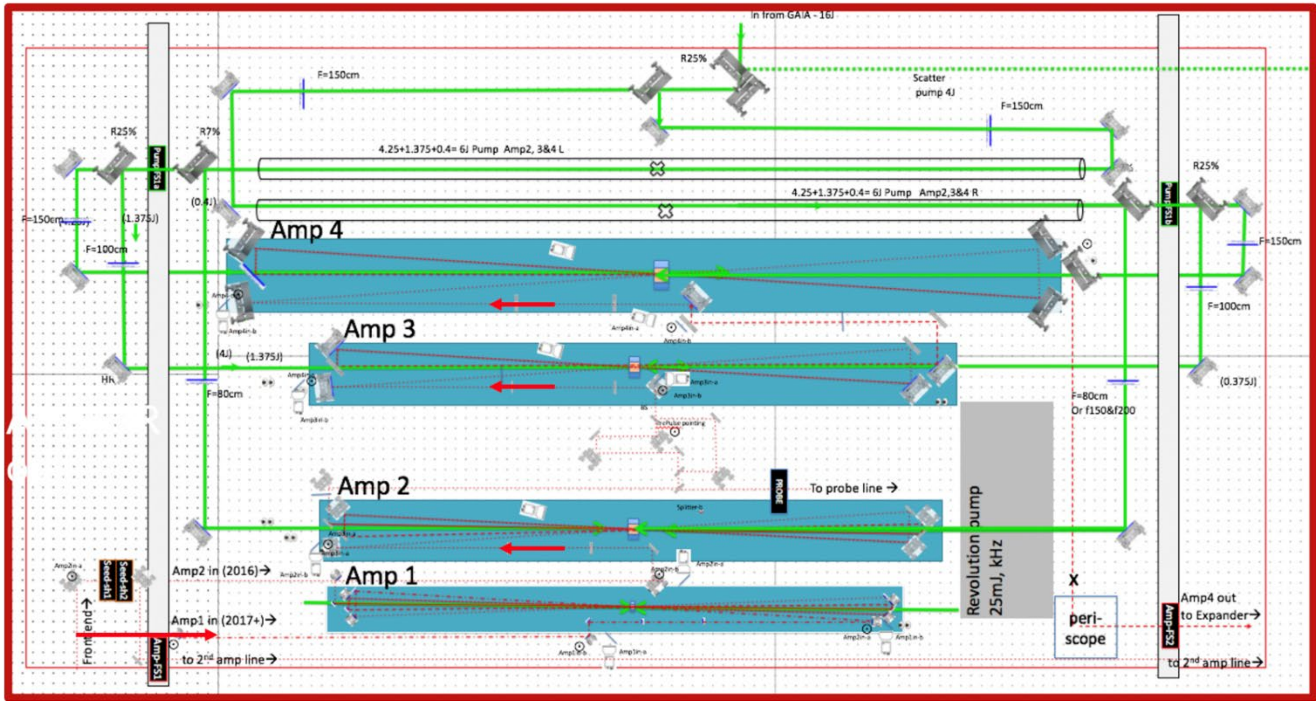
VirtualLab Fusion, https://www.lighttrans.com/products-services/virtuallab-fusion/virtuallab-fusion-packages.html

PlanOpSim – Enlightened Planar Optics, https://planopsim.com

Ansys Zemax OpticStudio website, https://www.ansys.com/products/optics/ansys-zemax-opticstudio

Benchmarking exercise: 100 TW Ti:Sa amplifier

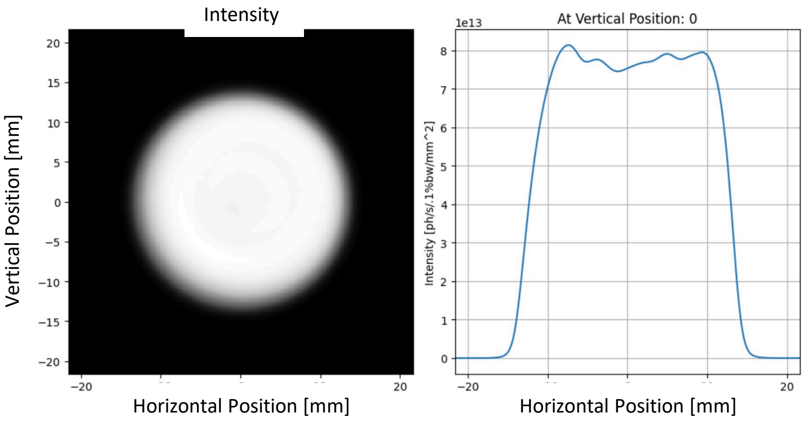
- ▶ amplifier components
  - Crystal
  - Lens
  - Mirror
  - Telescope
  - Beam splitter
- ▶ Simulation challenges
  - 3D gain calculation
  - Fourier optics



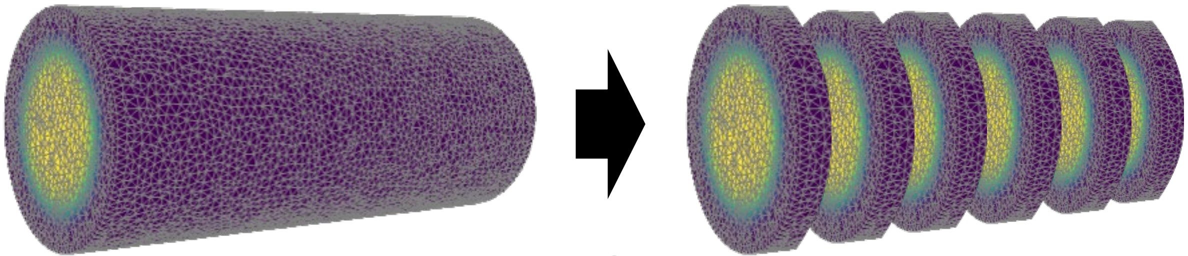
Schematic 100TW laser amplifier layout,
courtesy of Berkeley Lab's BELLA Center

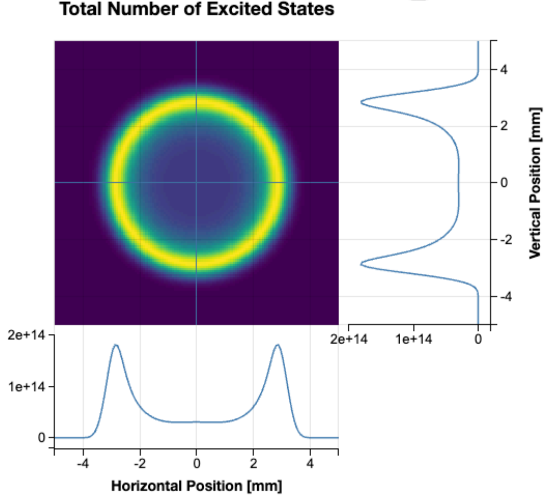
3D to 2D via operator splitting

- Laser
  - SRW compatible
  - 2D arrays: fields and photon count
  - Dual direction propagation



- Crystal
  - FEniCS thermal transport
  - 2D excited state density
  - 1kHz and 1Hz rep rates





- Gain
  - 1D Frantz-Nodvik for each cell of 2D mesh
  - Applied to each laser-crystal slice interaction
  - Updates local excited state density

Leveraging the SRW[1] code

- SRW's wavefront propagation algorithm (in this case) is in essence a linear canonical transforms (LCT)[2]
  - we decompose each ABCD matrix according to Pei & Huang[3]
  - this decomposition yields 3 simpler matrices
    - **SRW takes these and applies Fourier optics to the 2D wavefront**

- We are developing a Python library for LCTs[4]
  - will enable propagation via more general ABCD matrices

[1] O. Chubar, SRW: Synchrotron Radiation Workshop, https://github.com/ochubar/srw

O. Chubar and R. Celestre, "Memory and CPU efficient computation of the Fresnel free-space propagator in Fourier optics simulations," *Optics Express*, **V.27** (2019); doi:10.1364/OE.27.028750

[2] J. Healy *et al.*, *Linear Canonical Transforms: Theory and Applications*, **V.198** (2016); doi:10.1007/978-1-4939-3028-9

[3] S.-C. Pei & S.-G. Huang, "Two-dimensional nonseparable discrete linear canonical transform based on CM-CC-CM-CC decomposition," J. Opt. Soc. Am. A, **V.33** (2016); doi:10.1364/JOSAA.33.000214

[4] B. Nash *et al.*, "Linear Canonical Transform Library for Fast Coherent X-Ray Wavefront Propagation," Intern. Part. Accel. Conf. (2022); doi:10.18429/JACoW-IPAC2022-THPOPT068

Successful validation with experiment: 100 TW amplifier

► System configuration

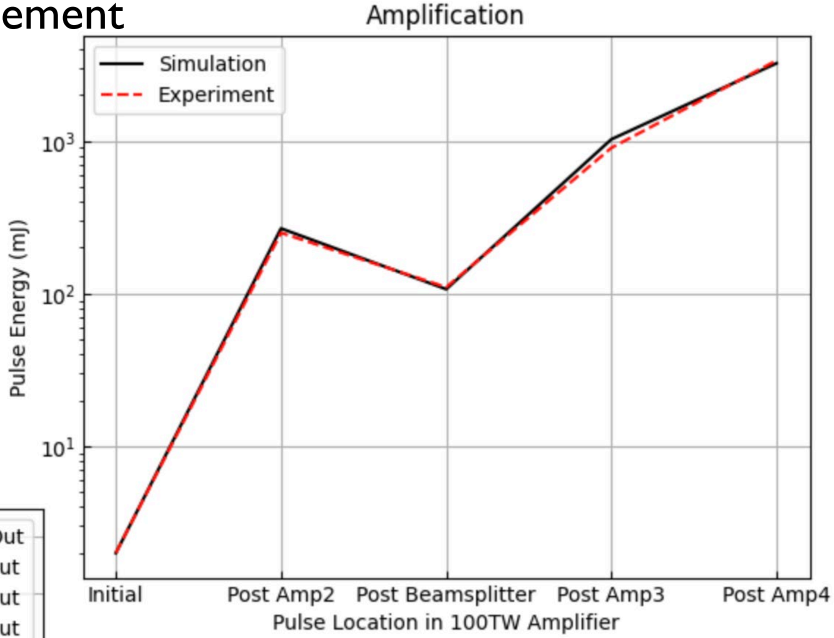
- 3 crystals w/ 10 passes
- 1 beam splitter
- supergaussian pumps

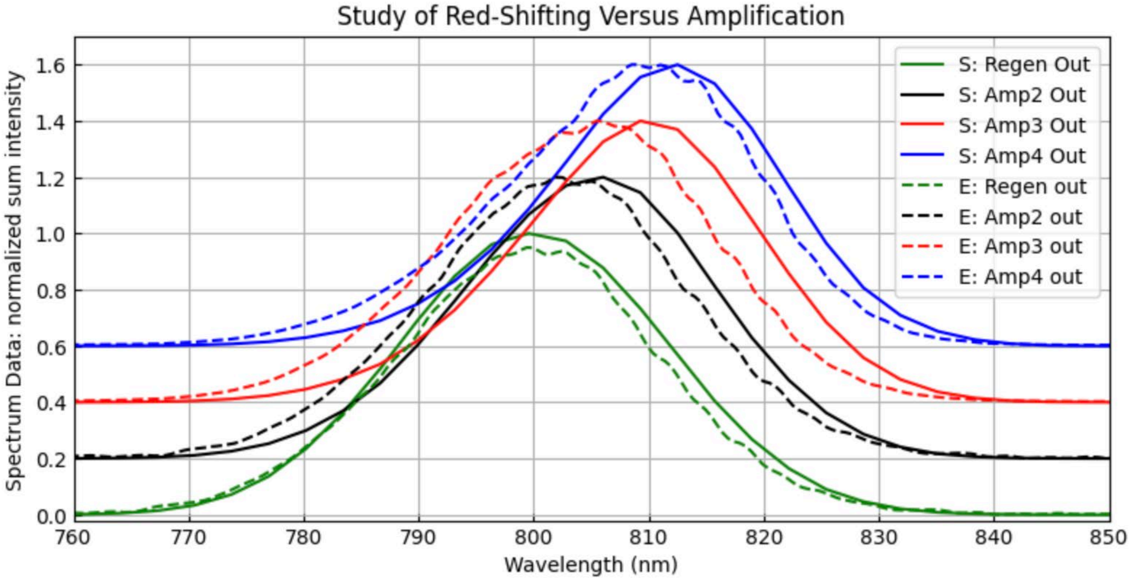
► Amplification

- 10 mJ to more than 3 J
- quantitative agreement achieved!

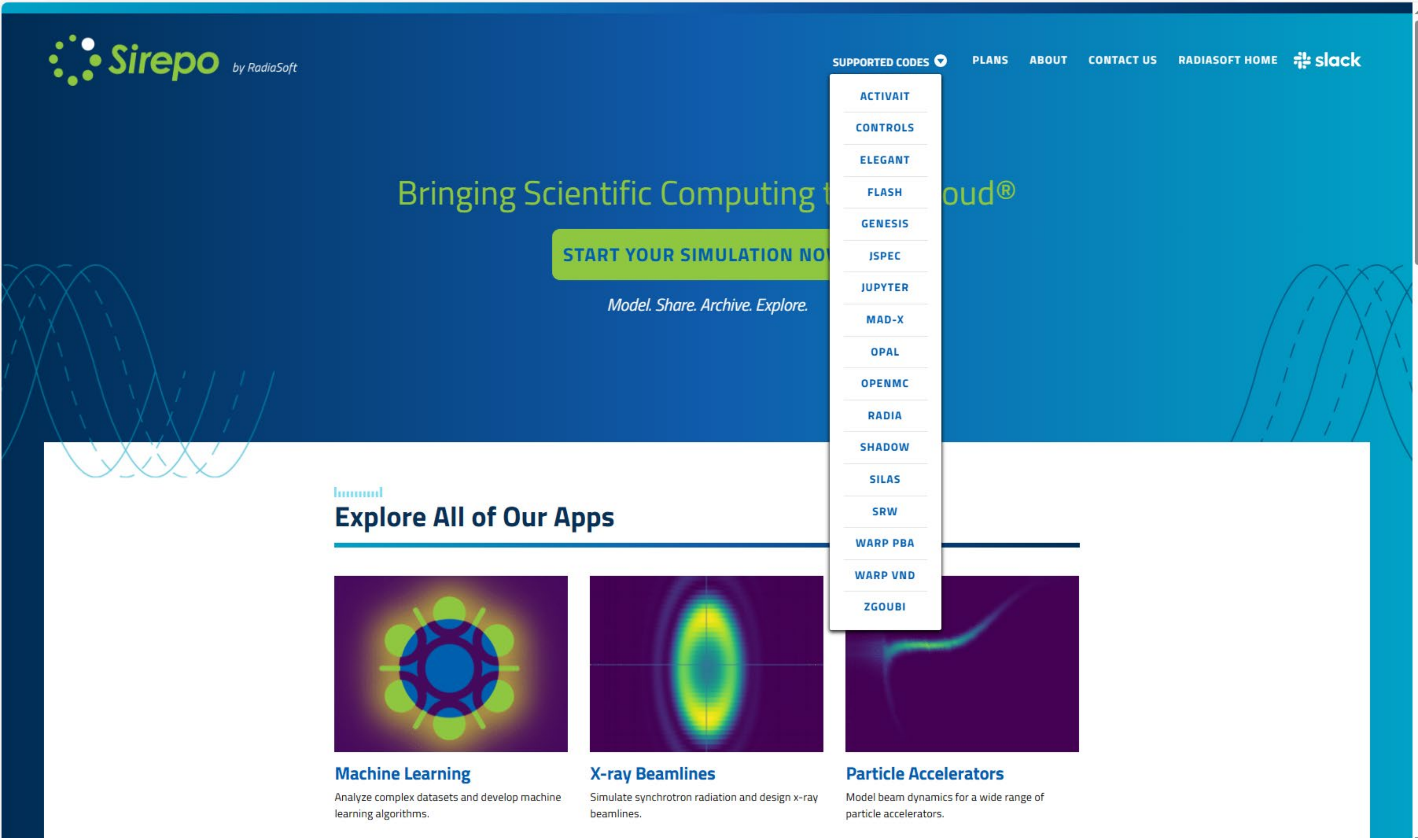
► Red-shifting

- 800 nm to 810 nm
- similar bandwidth
- qualitative agreement





https://sirepo.com is a community gateway for science



Bringing Scientific Computing t oud®

Model. Share. Archive. Explore.

Explore All of Our Apps

Machine Learning

Analyze complex datasets and develop machine learning algorithms.

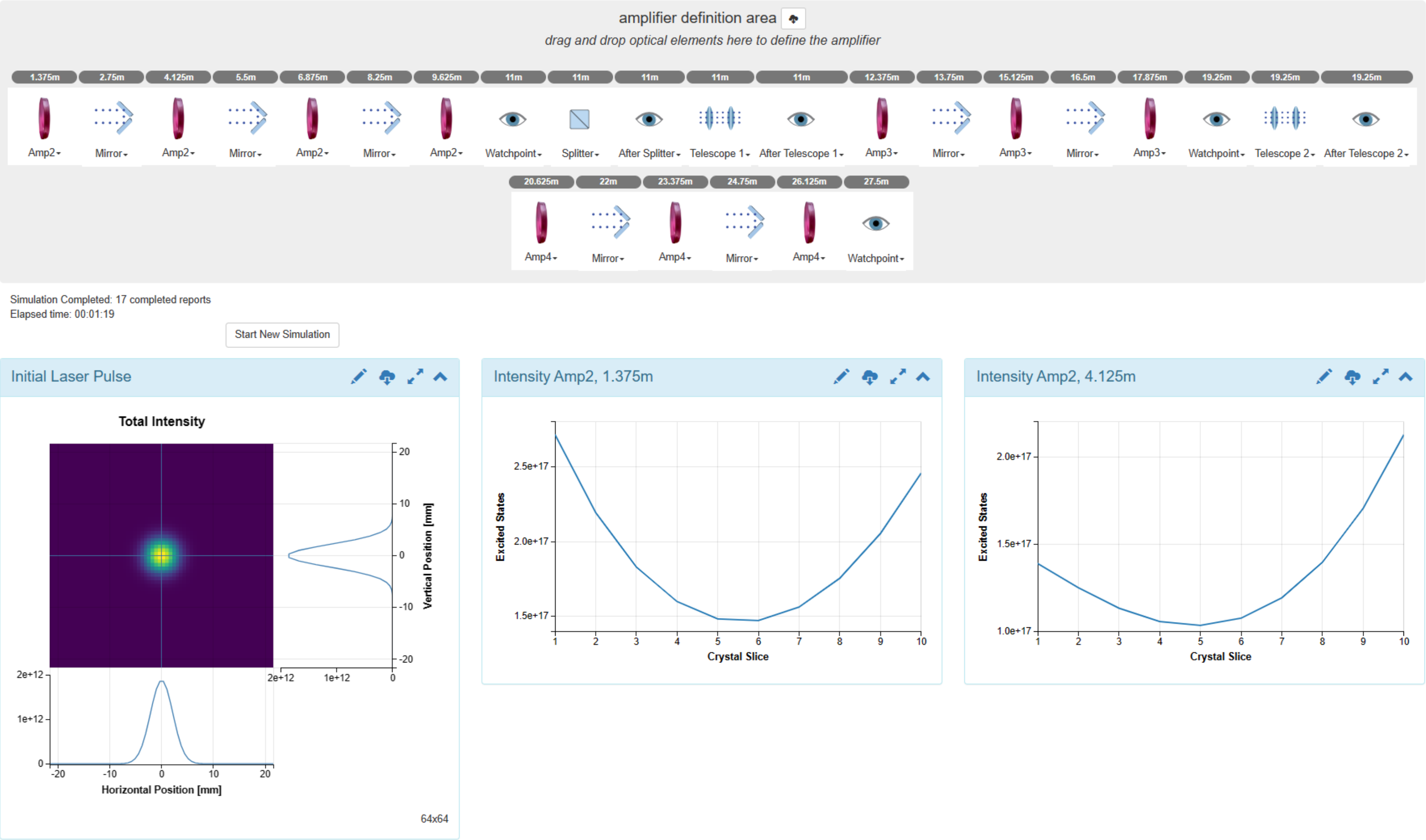
X-ray Beamlines

Simulate synchrotron radiation and design x-ray beamlines.

Particle Accelerators

Model beam dynamics for a wide range of particle accelerators.

Silas – drag & drop UI to define amplifier layout

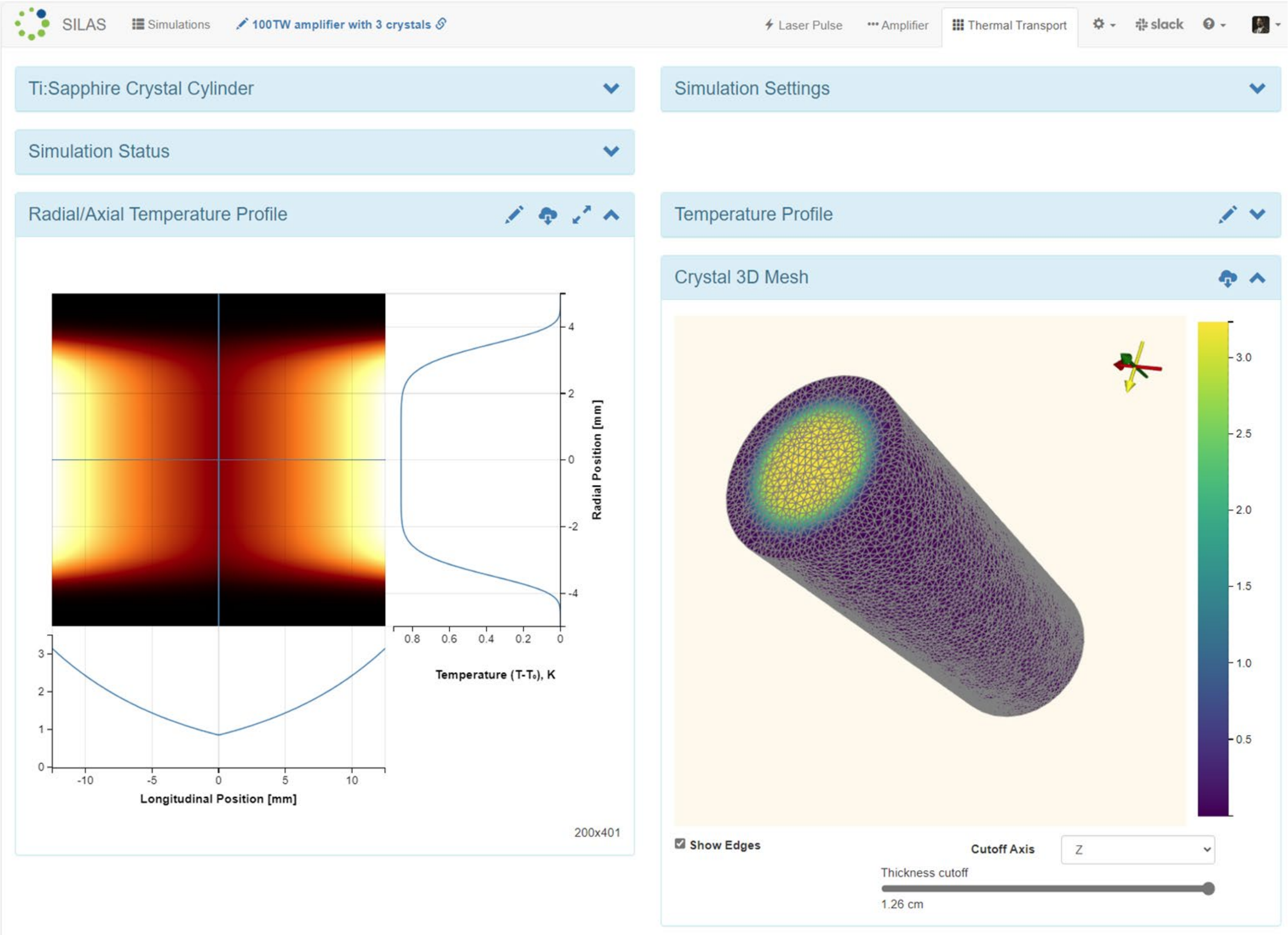


amplifier definition area

drag and drop optical elements here to define the amplifier

Simulation Completed: 17 completed reports
Elapsed time: 00:01:19

Silas – invokes FEniCS for thermal calculations



☑ Show Edges

Cutoff Axis: Z

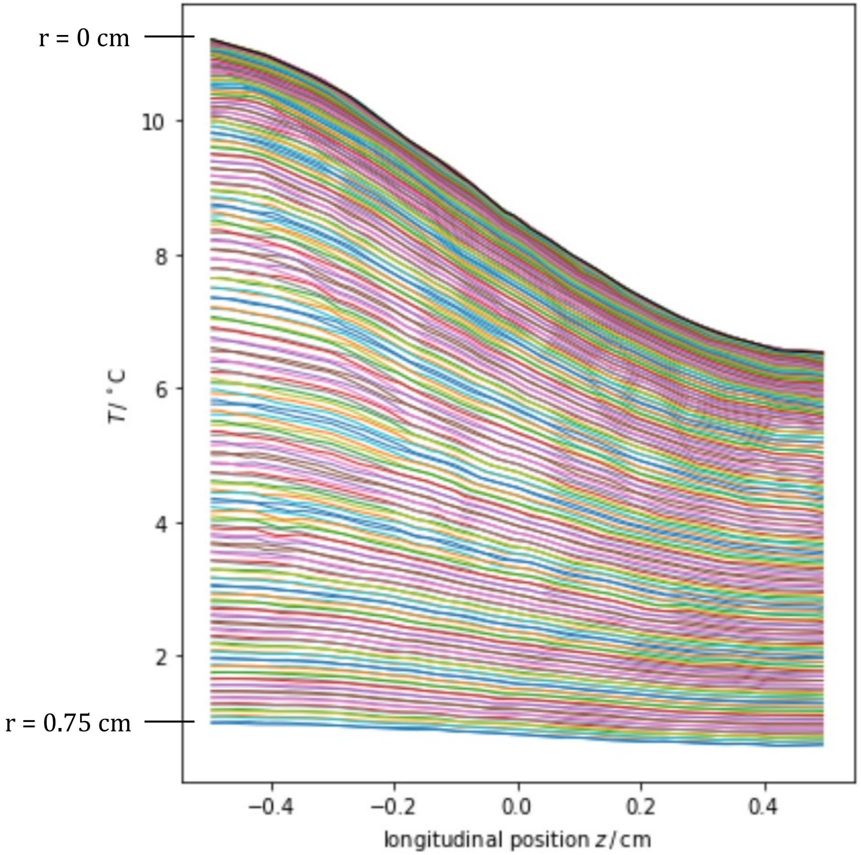
Thickness cutoff: 1.26 cm

Thermal lensing is inferred from temp profiles

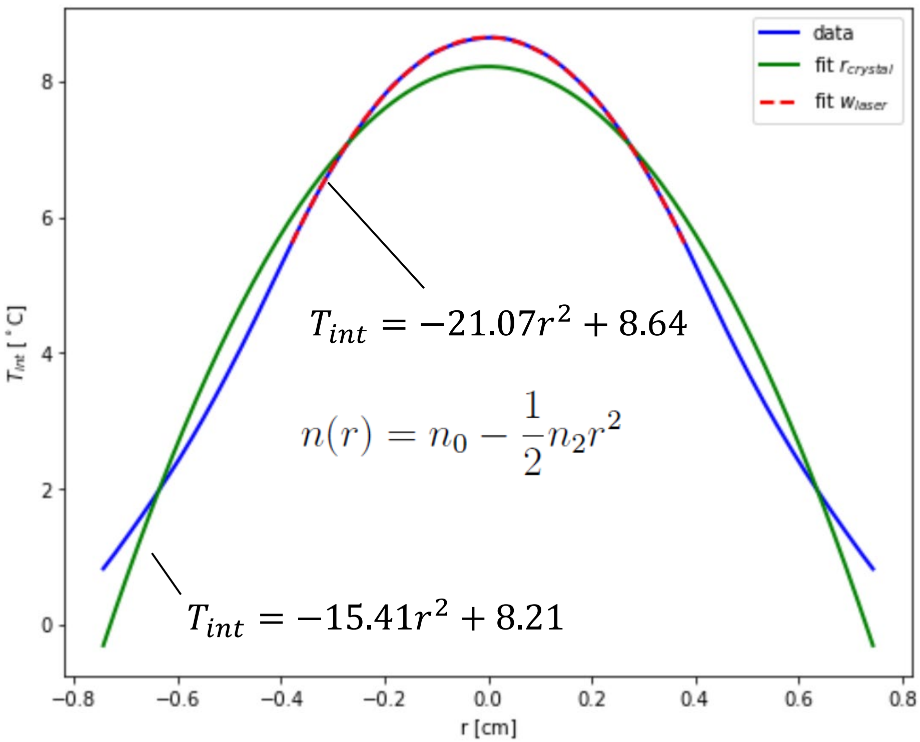
simulation parameters

- crystal length, L = 1.0 cm; radius, R = 0.75 cm
- pump laser, w = R/2; absorption length, α = 1.2 cm^{-1}
- energy deposited: 35 mJ/pulse * 1kHz rep rate = 35 W

Equilibrium longitudinal temperature profiles for r between [-0.75 cm, 0.75 cm] with dr = $r_{max}/100$



Integrated radial temperature profile

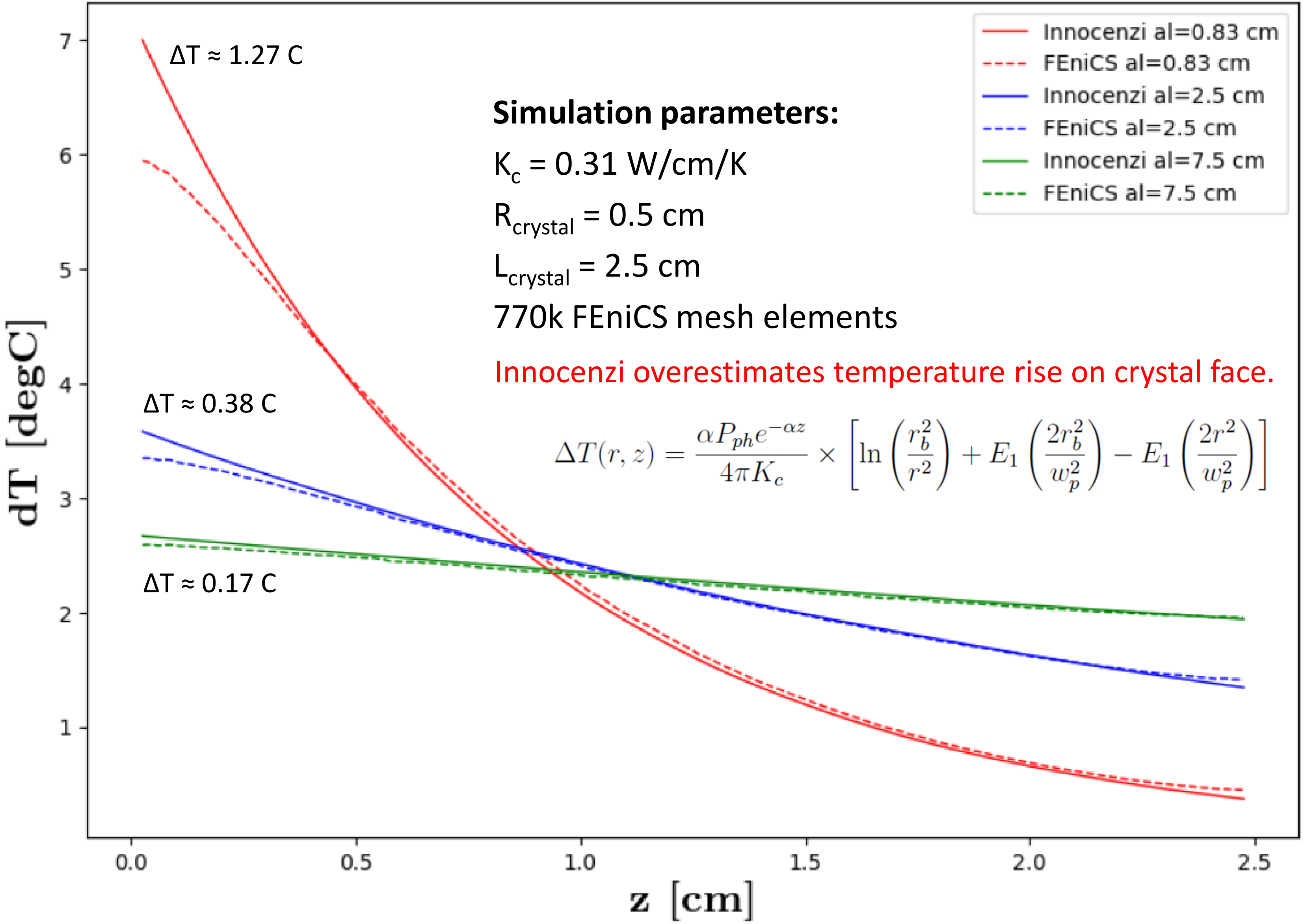


$$T_{int} = -21.07r^2 + 8.64$$

$$n(r) = n_0 - \frac{1}{2}n_2 r^2$$

$$T_{int} = -15.41r^2 + 8.21$$

Simulations are needed for strong absorption



ΔT ≈ 1.27 C

ΔT ≈ 0.38 C

ΔT ≈ 0.17 C

Simulation parameters:

K_c = 0.31 W/cm/K

$R_{crystal}$ = 0.5 cm

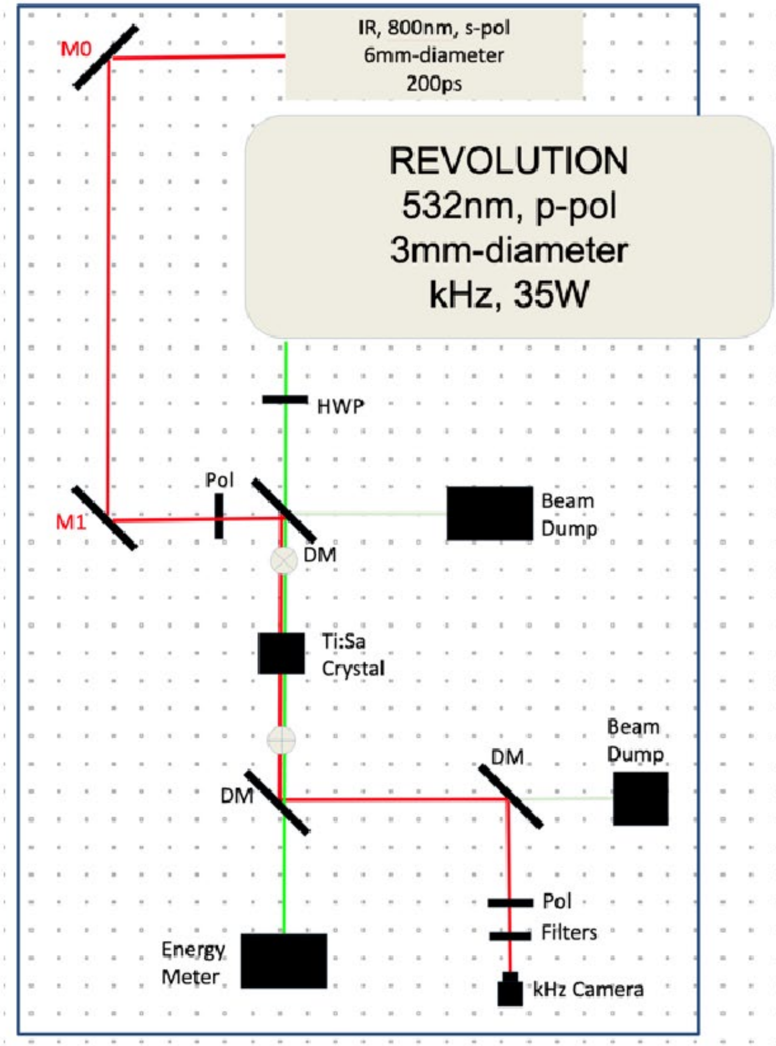
$L_{crystal}$ = 2.5 cm

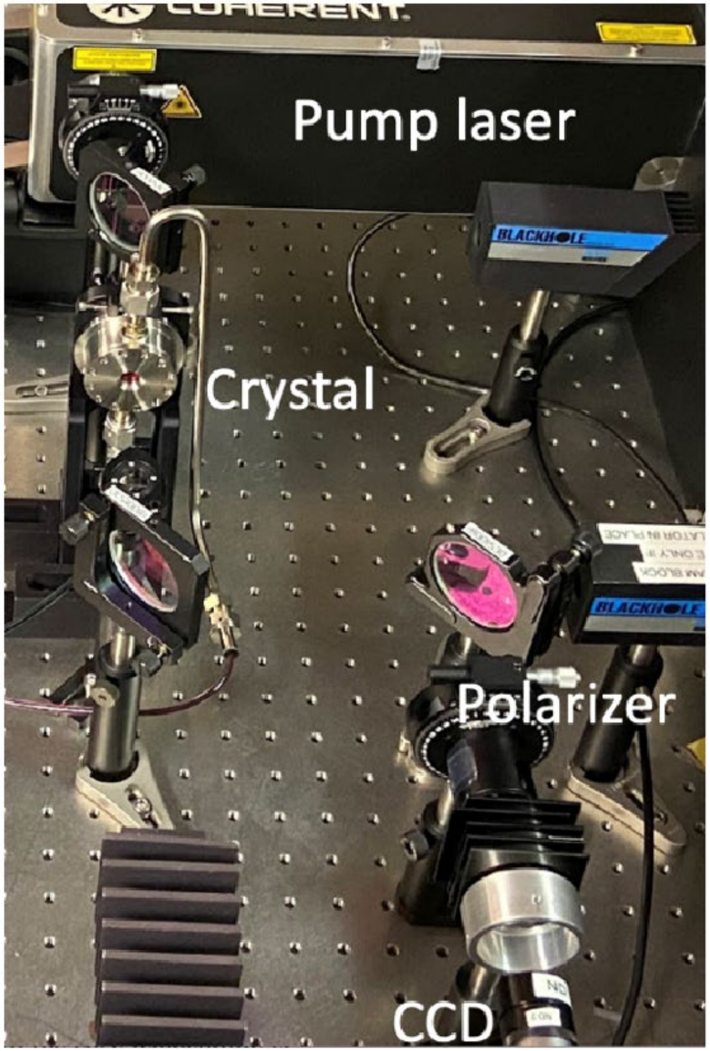
770k FEniCS mesh elements

Innocenzi overestimates temperature rise on crystal face.

$$\Delta T(r,z) = \frac{\alpha P_{ph} e^{-\alpha z}}{4\pi K_c} \times \left[\ln\left(\frac{r_b^2}{r^2}\right) + E_1\left(\frac{2r_b^2}{w_p^2}\right) - E_1\left(\frac{2r^2}{w_p^2}\right) \right]$$

Thermal physics validation: 1 kHz pump laser, single crystal





Experiments conducted at the LBNL BELLA Center

Thermal decay time is measured: 154 ms

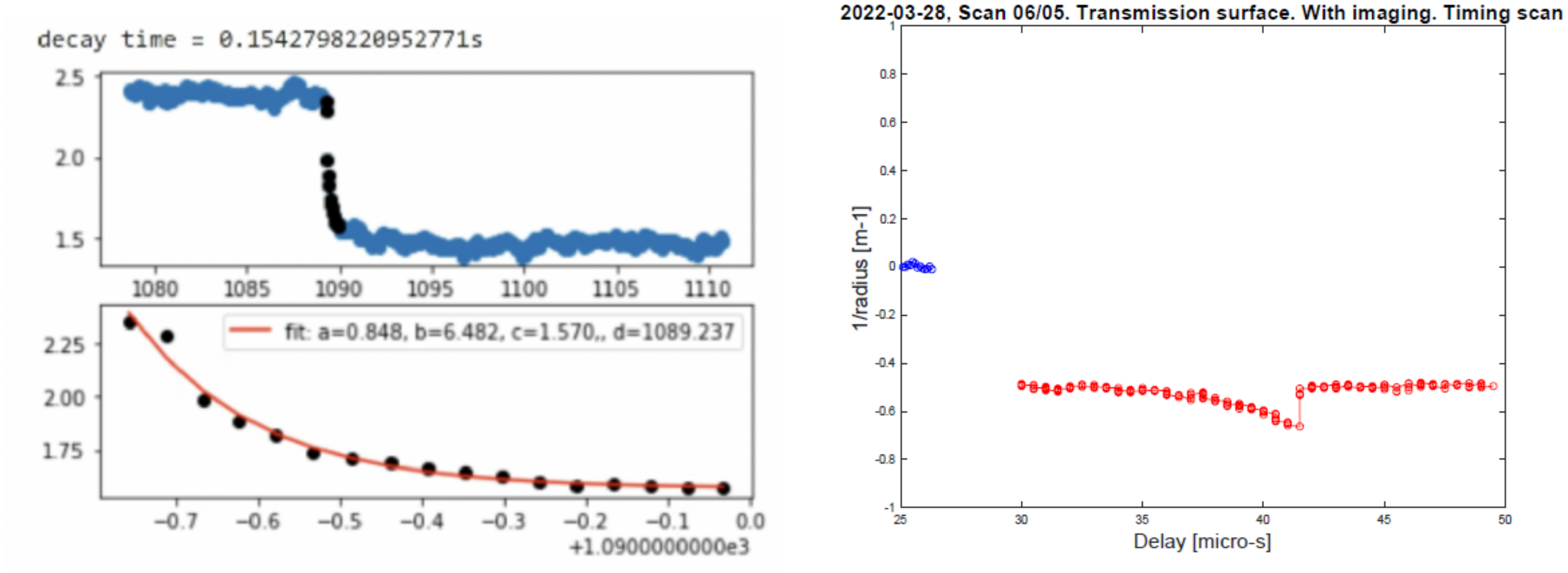


Figure 30: (left) Measurement of the thermal relaxation time once the pump laser is turned off. An exponential fit yields a relaxation time of 154 ms. (right) Compared to the background wavefront curvature (blue points), the red points represent the wavefront (spherical or parabolic) curvature in a kHz-pumped Ti:S crystal. Once can see a permanent wavefront curvature (to a radius of 1/0.5=2 meter), with an additional non-thermal transient increase around at the timing where the pump and seed lasers overlap (at timing box setting 42 µs).

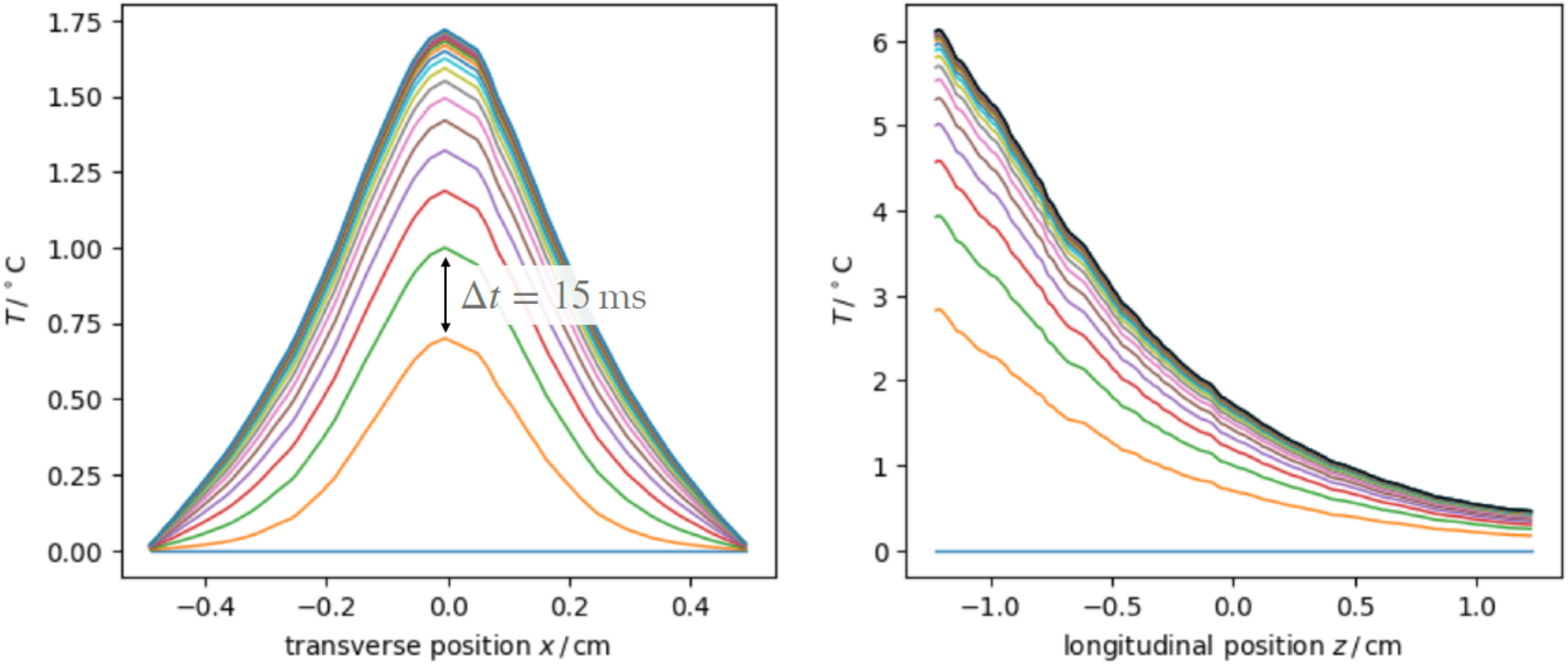
Experiments conducted at Berkeley Lab's BELLA Center

3D FEniCS simulations agree with measured relaxation time

Cylindrical crystal:
radius $a = 1$ cm
length $\ell = 2.5$ cm
$\kappa = 0.31$ W/cm·K
$\rho = 3.98$ gm/cm³
$c_p = 0.267$ J/gm·K
$\alpha = 0.292$ cm²/s

$$\tau_{10} = \frac{a^2}{\nu_{01}^2 \alpha}$$

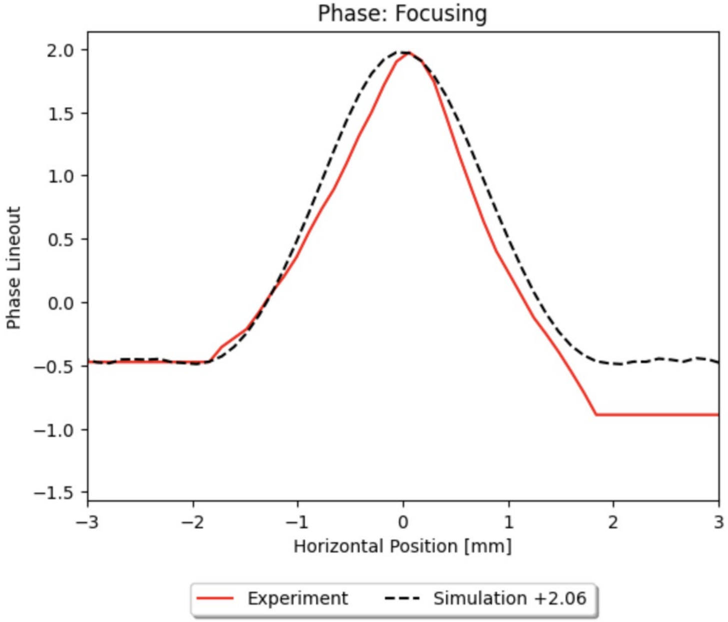
$\tau_{10} \approx 150$ ms $\Rightarrow$
$\alpha \approx 0.288$ cm²/s



For numerical simulations of general PDEs, we use the open-source *FEniCS Computing Platform* (https://fenicsproject.org). It uses UFL, the Unified Form Language (DOI: 10.48550/arXiv.1211.4047), to represent PDEs in variational form. For details of simulation (and theory), see D.T. Abell, *et al.*, in *Proc. IPAC'22*, DOI: 10.18429/JACoW-IPAC2022-THPOTK062.

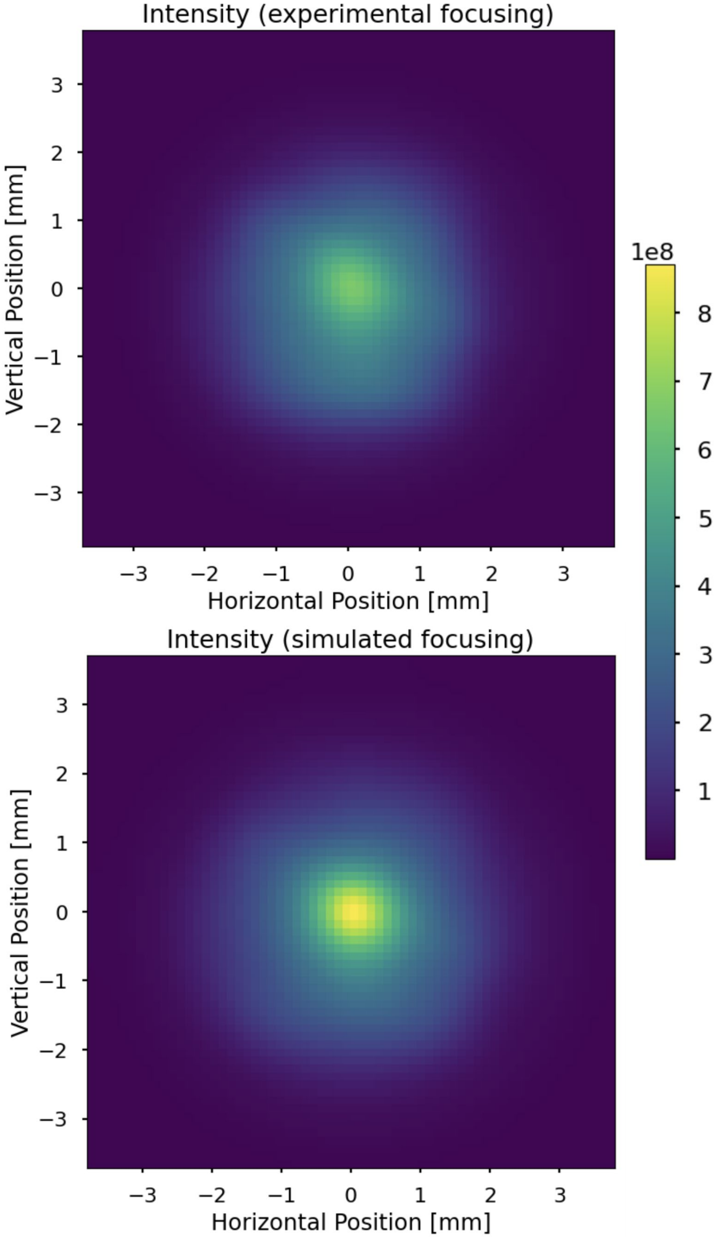
Tabulated values of κ and c_p for Ti:Sa are highly variable.
One can find reasonable values that indicate agreement with FEniCS simulations.
Conclusion: It is important to know the properties of each crystal.

Validation of wavefront simulations w/ thermal lensing



Experiment

Simulation



Peak Intensity differences:

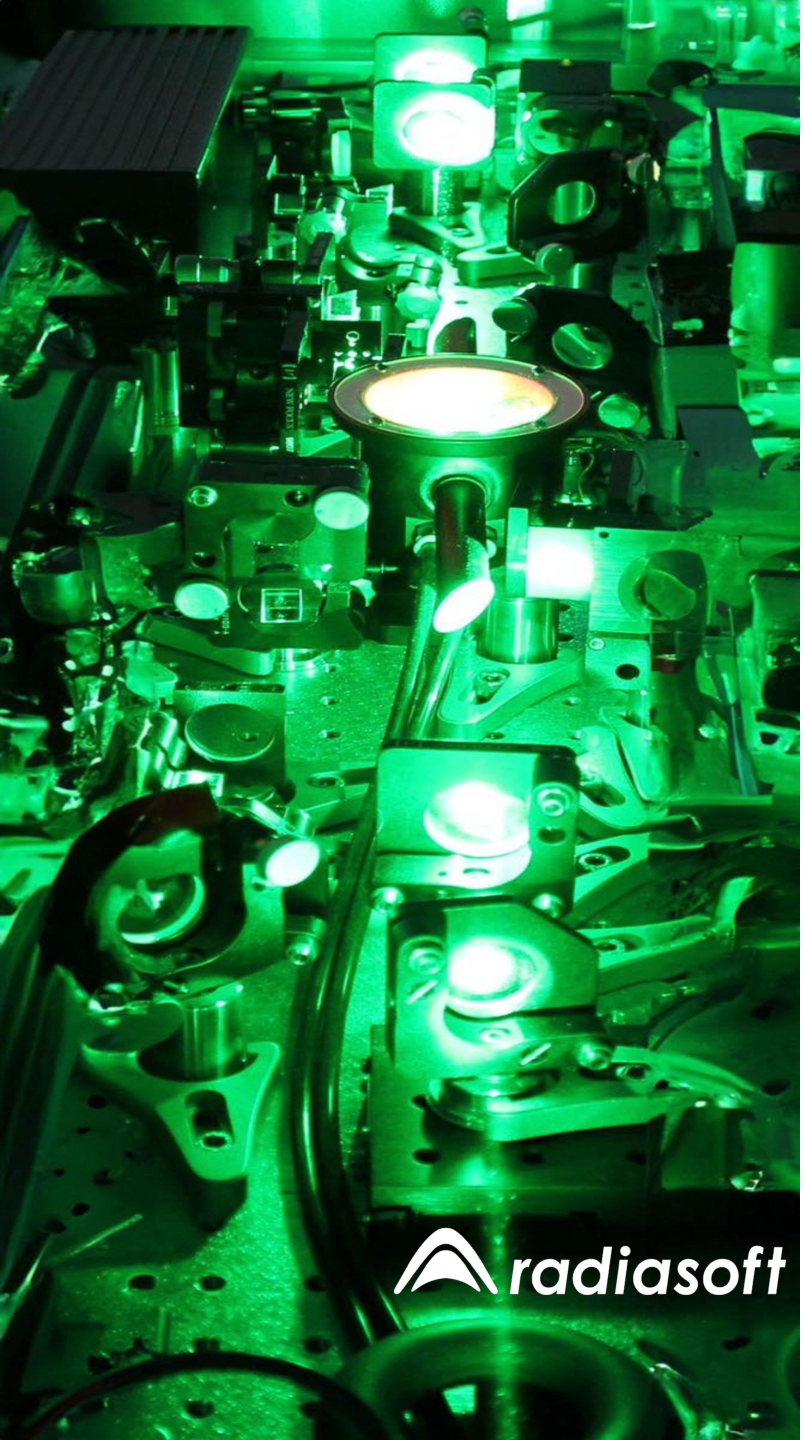
- Gain: 8% (stronger in simulation)
- Focus: 27% (weaker in simulation)

Future Work

- Sirepo-Silas fully supports design, commissioning, & operations of laser facilities, including 3D laser pulse details needed for user experiments
- Physics goals (*info on potential DOE funding is expected July 29*)
    - validate and verify the rslaser physics engine at 100 TW and PW scales
    - misalignment of optical elements, crystals, pump lasers and other key components
    - capture spatio-temporal structure of laser pulses in the near field & at focus
    - propagate hotspots through the amplifier to understand causes / origins
- Operational goals (*funding yet to be identified*)
    - ML-based surrogate models bring rslaser capabilities to FPGA for real-time controls
    - implement support for deformable mirrors
    - develop/deploy digital twin framework to high-power laser facilities

Conclusions

- Community software for Ti:Sa amplifier modeling is available
  - operator splitting (slicing laser pulse & crystals) allows for 2D simulations
    - provides Fourier optics, together with laser amplification and thermal effects
    - 2D & 3D thermal modeling via the FEniCS code; available in Sirepo-Jupyter
  - Sirepo–Silas brings these capabilities to your browser
  - open source Python library – rslaser, https://github.com/radiasoft/rslaser/
    - complex dependencies (SRW, FEniCS), but runs 'out of the box' on Sirepo-Jupyter
- Experiments at Berkeley Lab's BELLA Center provide validation
  - experimental thermal focusing is slightly stronger than in simulations
  - robust capture of amplification from 10 mJ to 3 J in a 100 TW system
- Openly available community software provides important benefits
  - can be further developed to support community-specified requirements
  - can be used to develop ML-based surrogate models for real-time controls



Thanks! Questions?

This material is based upon work supported by the U.S. DOE, Office of Science, Office of High Energy Physics, under Award Numbers DE-SC0020931 and DE-AC02-05CH11231.

The following disclaimer applies to all research funded by the US Department of Energy: