Ultra-High Intensity Laser Research at BELLA

S. Steinke*, J. H. Bin, A. M. Snijders, J. H. Mao, Q. Ji, K. Nakamura, A. Gonsalves, L. Geulig, S. S. Bulanov, W. P. Leemans, C. G. R. Geddes, C. Schroeder, T. Schenkel, E. A. Blakely, E. E. Esarey

Lawrence Berkeley National Laboratory

4th European Advanced Accelerator Concepts

Sep. 18, 2019

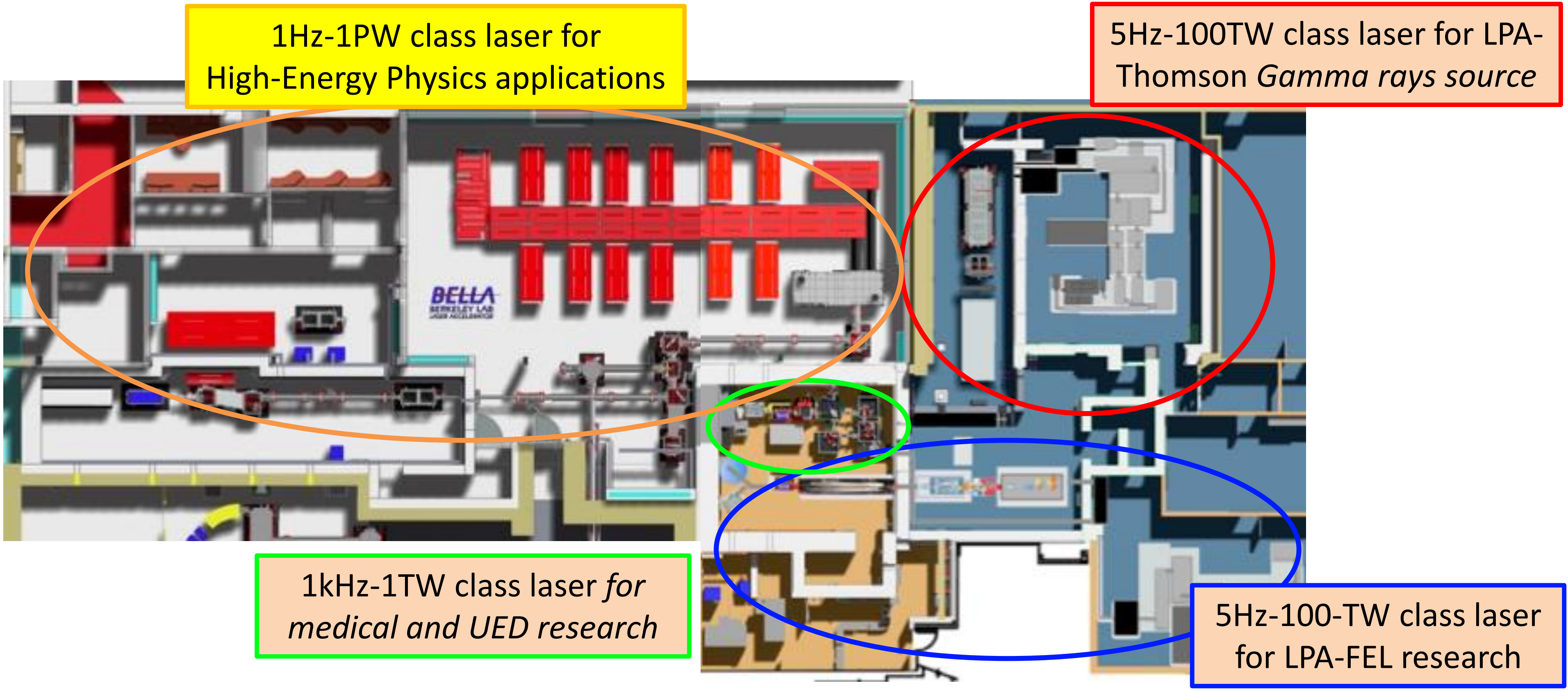
Supported by U.S. DOE under contract
No. DE –AC002-05CH11231

*ssteinke@lbl.gov

Outline

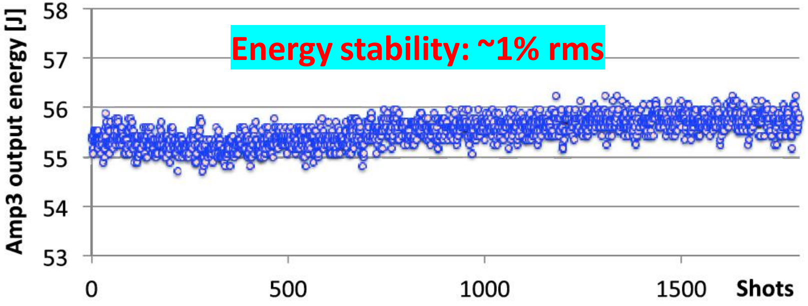
- BELLA facility introduction
- Overview of LaserNetUS campaigns at BELLA PW
- Qubit synthesis under extreme conditions
- Platform for investigating radiobiological effects of laser-accelerated ions
- Upcoming BELLA PW upgrades

LBNL BELLA (BErkeley Lab Laser Accelerator) Center houses four main laser systems

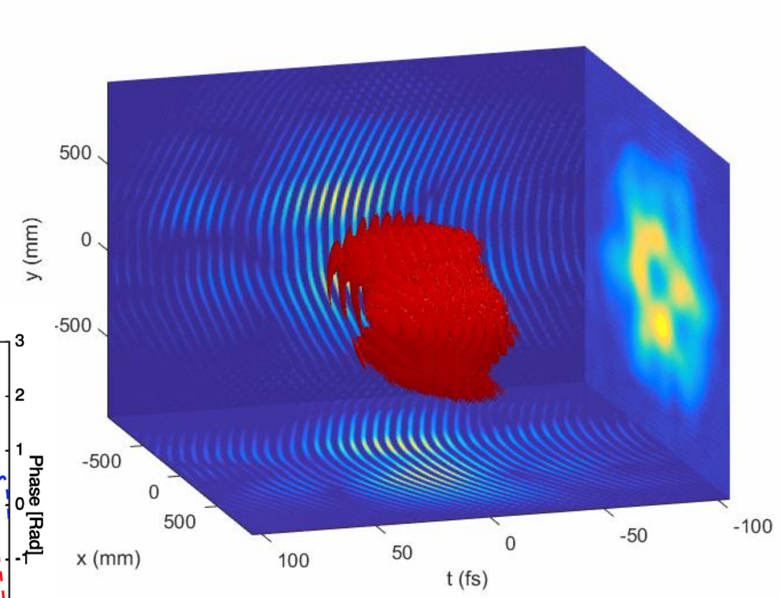


BELLA PW system[1]: High-quality, stable, well-characterized 1 Hz Petawatt laser

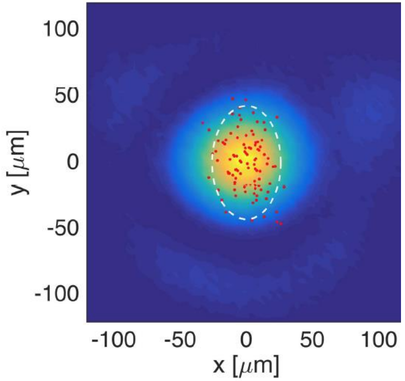
Energy stability: ~1% rms



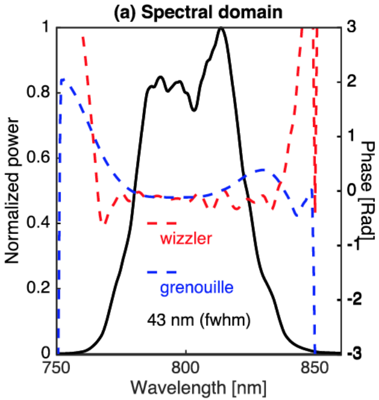
3D STC characterization[2]

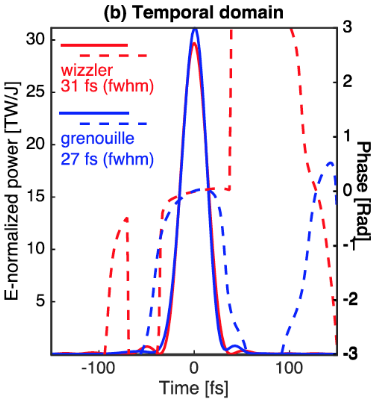


Spatial profile, pointing stability: ~1 urad rms



Temporal profile





[1] K. Nakamura et al., IEEE QE 53 (2017) 1200121.
[2] A. Jeandet et al., Journal of Physics: Photonics 1 (2019) 035001.

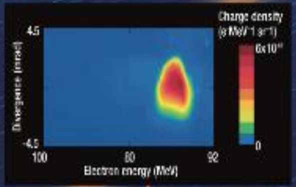
BELLA Center: HEP timeline of LPA Achievements in view of PR department

CONTINUOUS PROGRESS

Since its beginnings in the mid 1990s, BELLA has been in the forefront of LPA performance, and recently continued its string of energy records by producing 8-GeV electron beams.

In a separate achievement, BELLA has demonstrated "staging," the use of one LPA as the input to another, which will become key to achieving the highest energies.

2004: 10TW

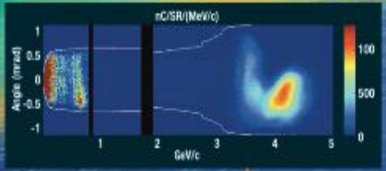


86 MeV

2006: 40TW

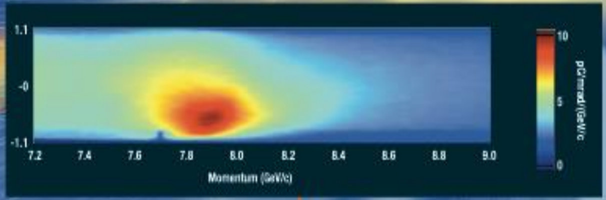
1 GeV

2014: 300TW

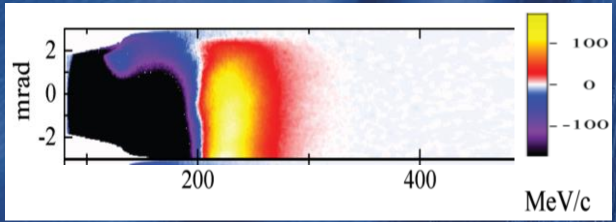


4.2 GeV

2019: 1000TW **& laser heater**



8 GeV



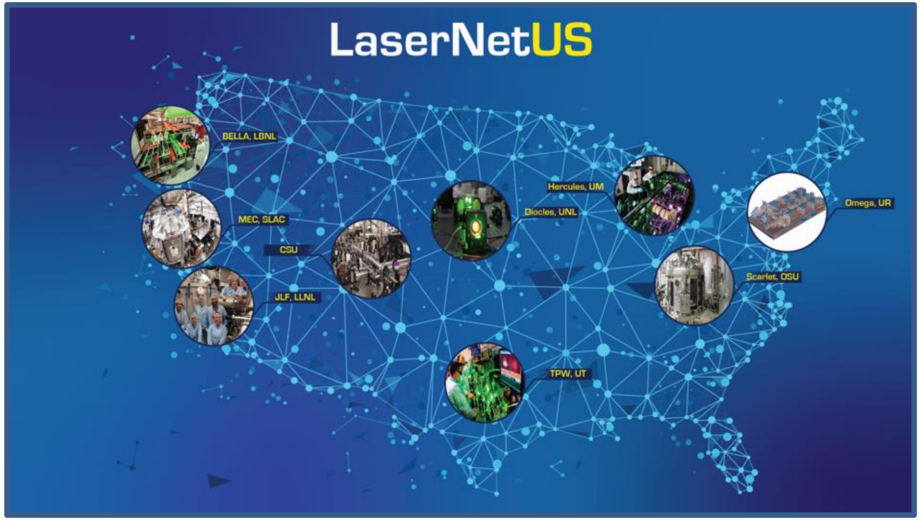
2016: 40TW staging demo

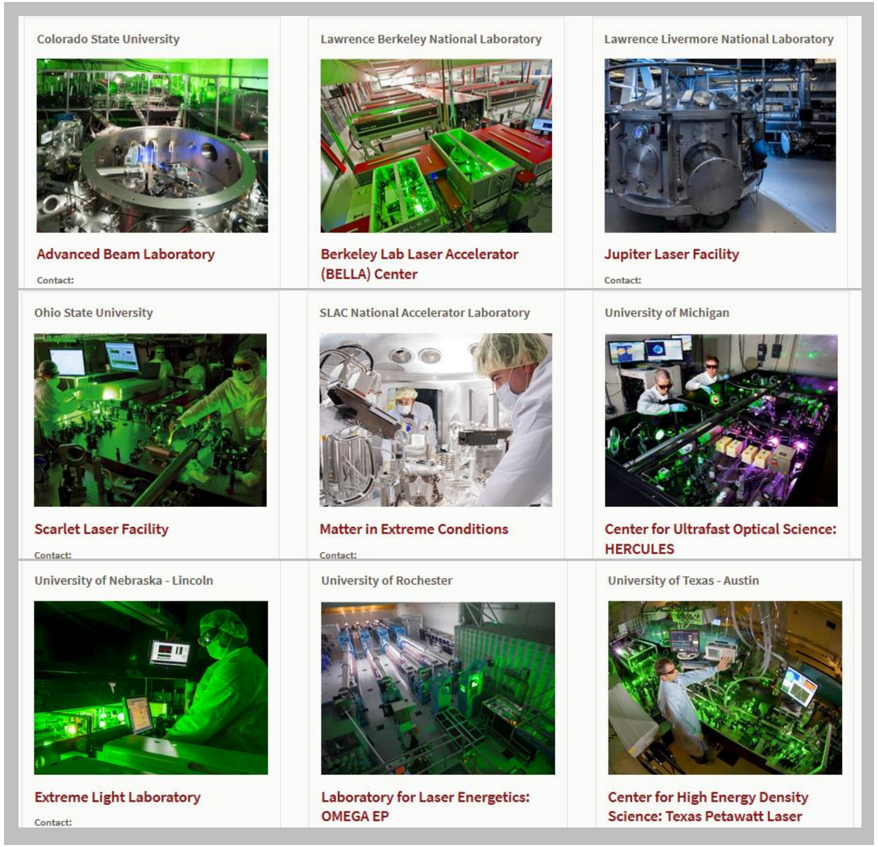
Enabling technologies for ever-higher performance

Shown below: The present 1 PW peak power in ultrashort (30-40 fs) pulses.

BELLA center is part of LaserNetUS (sponsored by DOE FES) and provides user access to PW and HTW facilities

Goal: *Bring together the high-intensity laser science community and enable a broad range of frontier scientific research.*



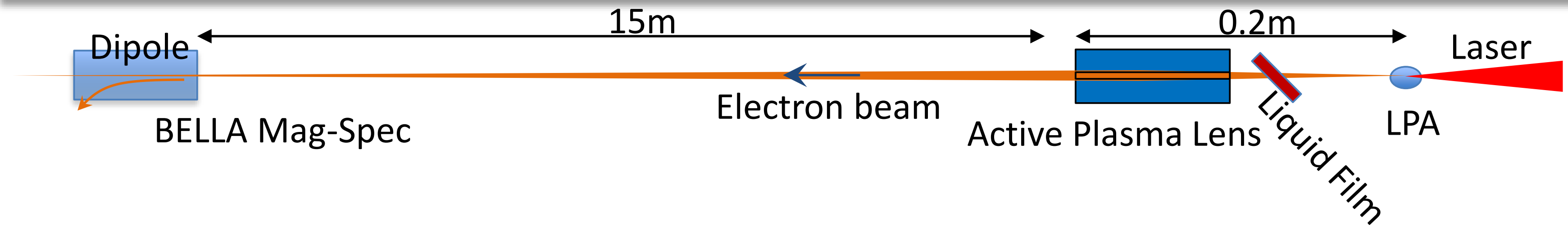


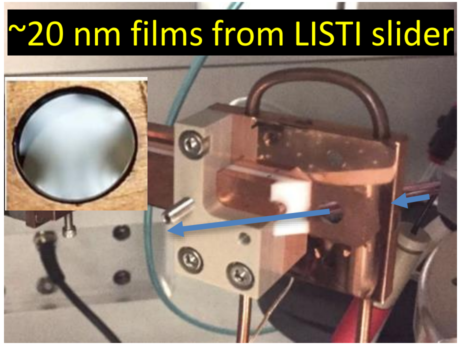
Experimental campaigns in 2019:

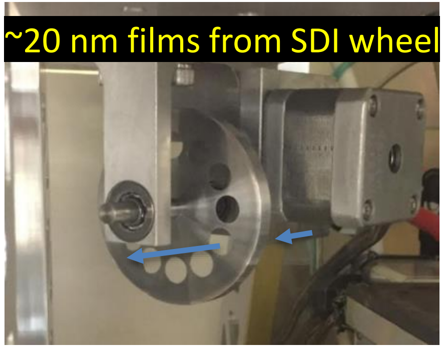
- 3 weeks at BELLA PW
- 4 weeks at HTT

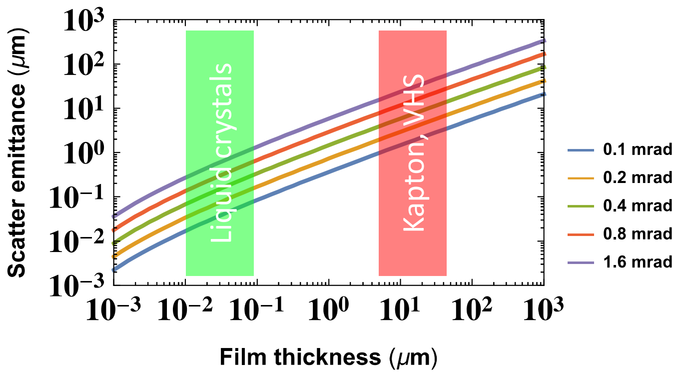
Contact: ssteinke@lbl.gov, www.LaserNetUS.org

Ultra-thin, replenishable liquid crystal based plasma mirror to reduce emittance degradation – collaboration with OSU





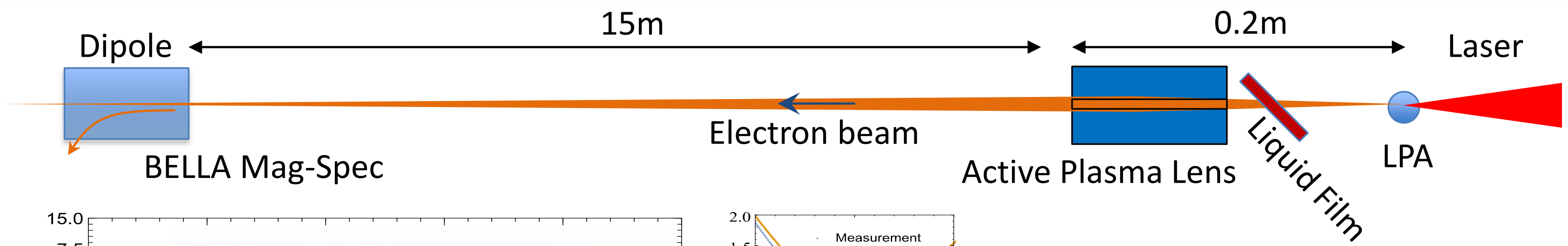


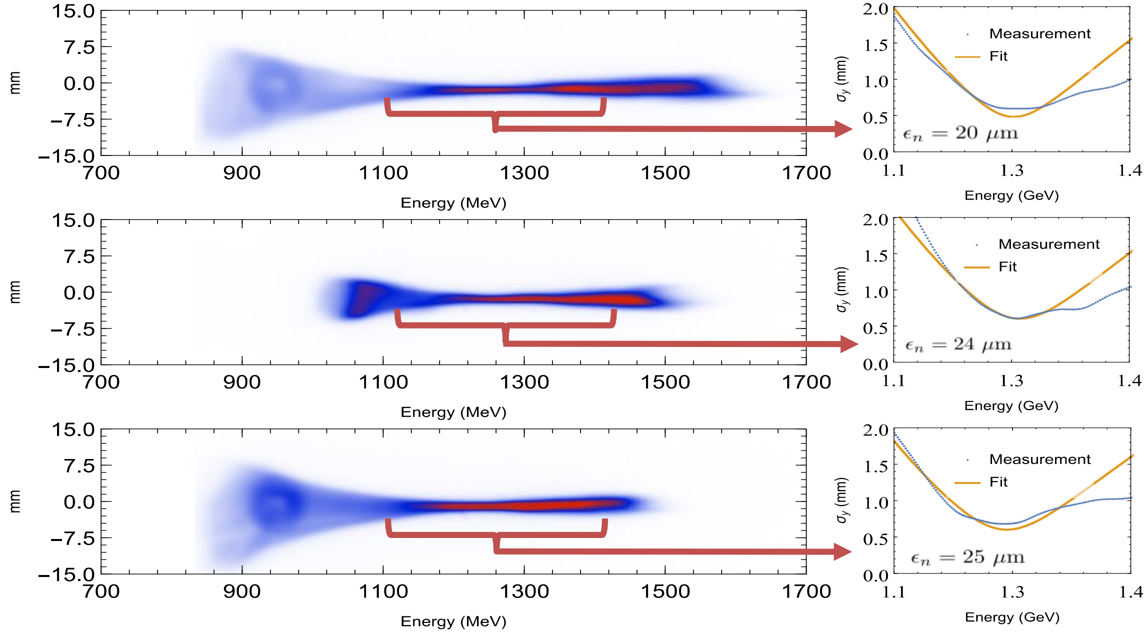


Reid et el., J. Appl. Phys. 70, 7185 (1991).

- Plasma mirror separates electron beam from driver laser, protects APL from drive laser
- Can operate at 1Hz for ~20 hours
- nm scale thickness effectively eliminate emittance growth due to Coulomb scattering

E-beam transport & diagnostics projects at BELLA PW: integration of active plasma lens and replenishable foil

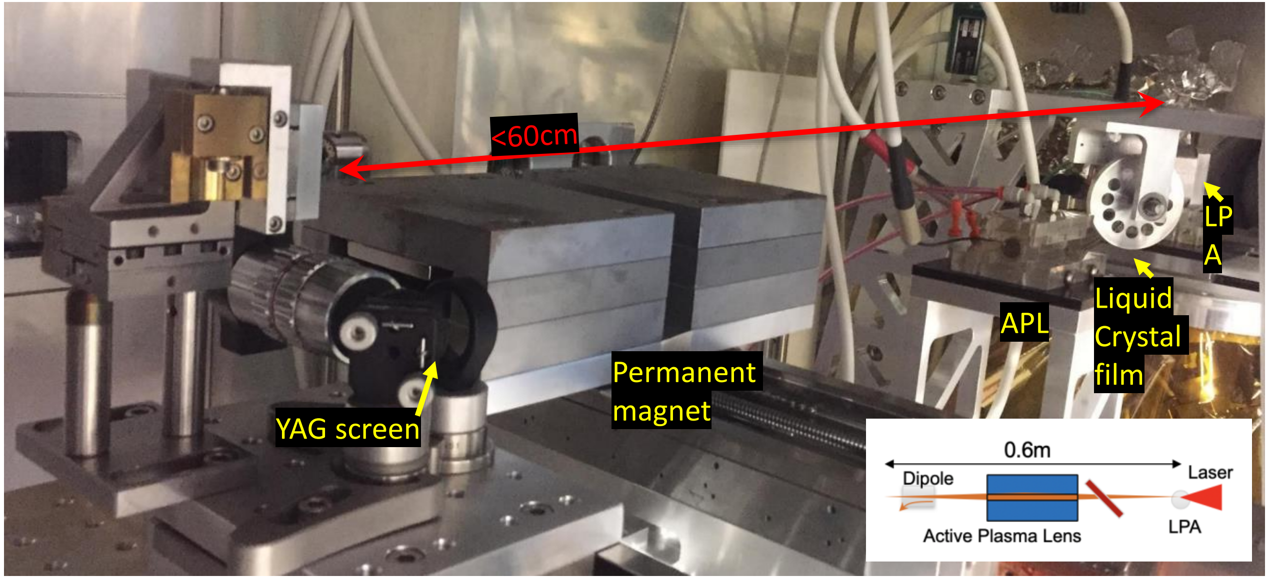




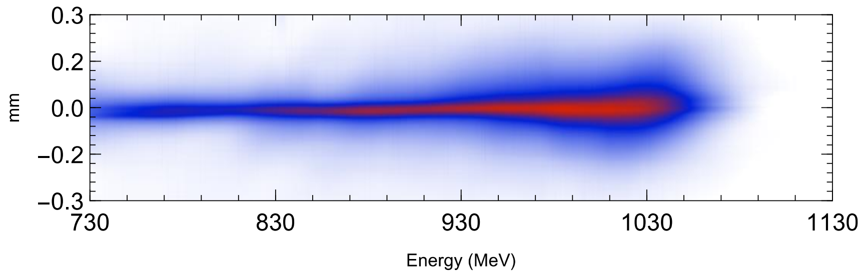
- BELLA PW laser used to generate 1-1.5 GeV electron beams
- APL focused beams to magnetic spectrometer: Single-shot energy-sliced emittance measured.
- Emittance diagnostic no longer affected by degradation in APL protector (plasma mirror)

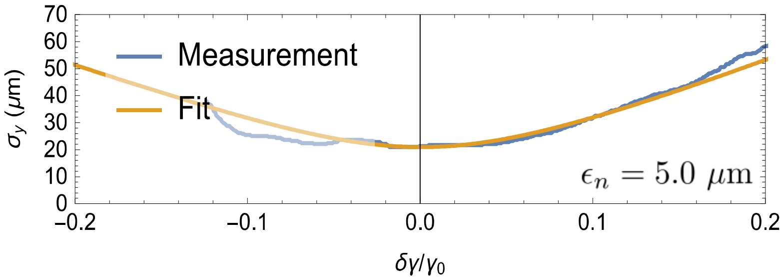
Technique from Weingartner *et al.* PRAB 2012

Compact multi-GeV high-resolution spectrometer

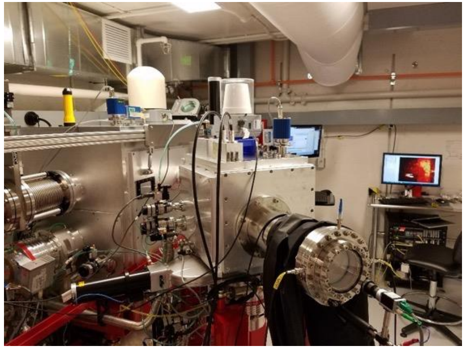


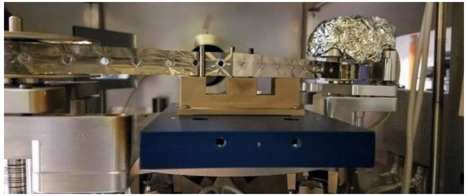
- Two 10 cm long, 0.9T dipoles in dogleg configuration provide dispersion
- <1% energy resolution for electrons up to 2 GeV when using APL
- Entire setup including target < 1m in length
- Scalable to 10 GeV



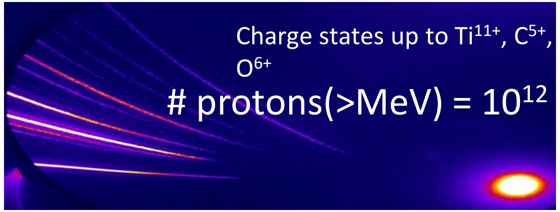


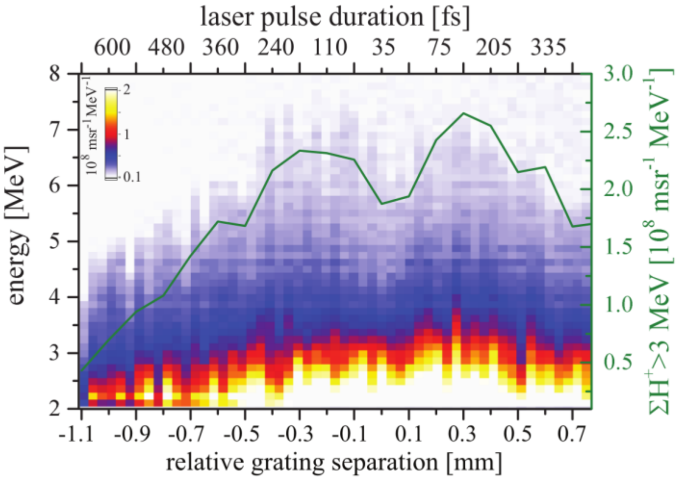
Petawatt experiments with statistical relevance –
Laser sweeping under optimum condition leads flat-top acceleration field



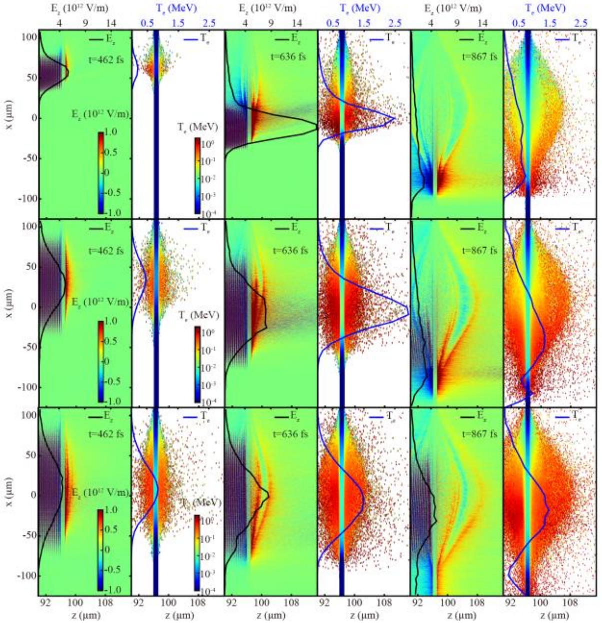


Setup: Tape-drive target and MCP-based Thomson Parabola Spectrometer adapted for rep-rated experiments.





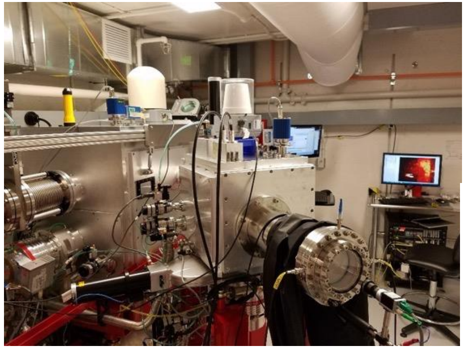
Experiment: Laser pulse duration scan with 70 consecutive shots obtained at 0.5 Hz rate

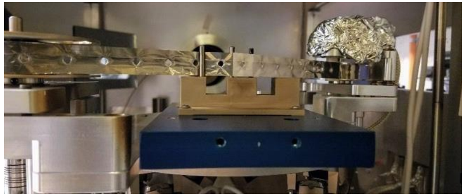


WARP simulations: Higher electron temperature and increased number of hot electrons for the optimum pulse duration ($2w_0/c$ ~ 140fs) due to sweeping effect.

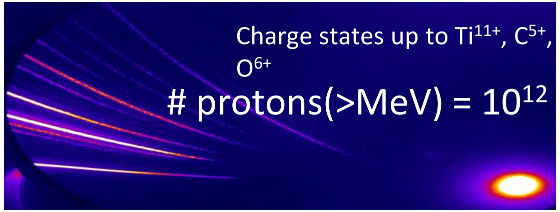
S. Steinke et al., under review

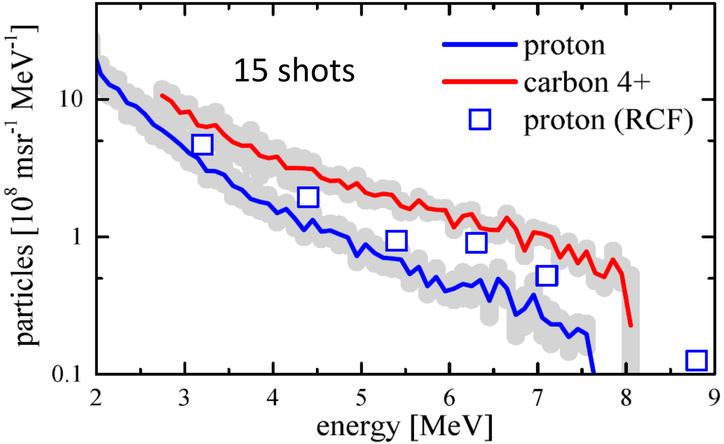
Petawatt experiments with statistical relevance – Laser sweeping under optimum condition leads flat-top acceleration field



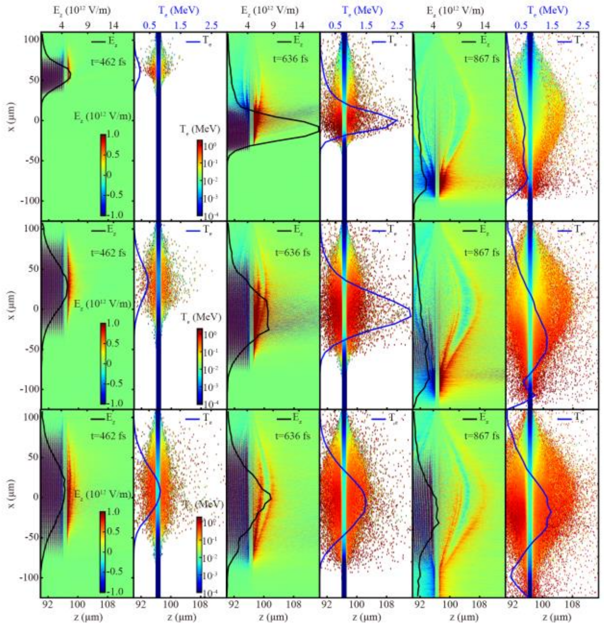


Setup: Tape-drive target and MCP-based Thomson Parabola Spectrometer adapted for rep-rated experiments.





Experiment: Laser pulse duration scan with 70 consecutive shots obtained at 0.5 Hz rate

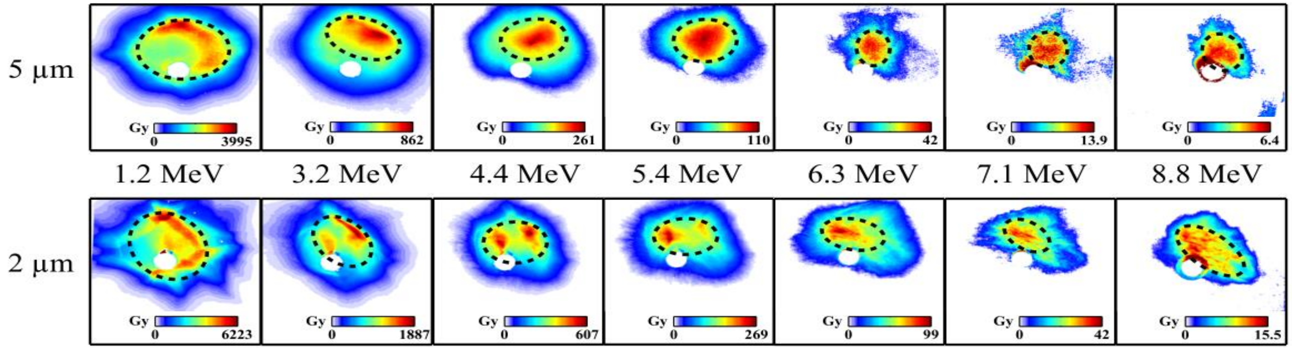


WARP simulations: Higher electron temperature and increased number of hot electrons for the optimum pulse duration ($2w_0/c$ ~ 140fs) due to sweeping effect.

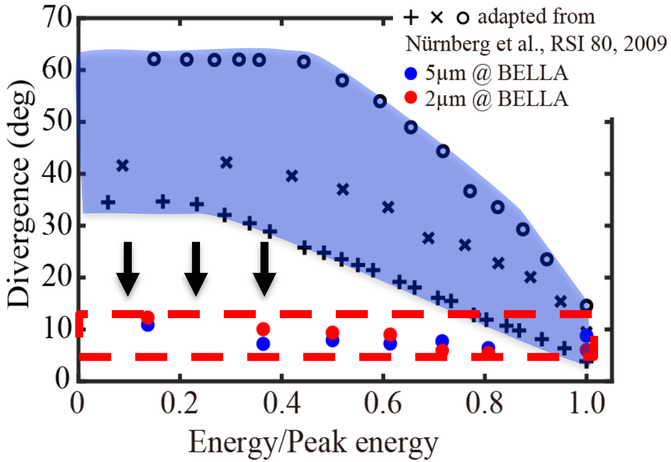
S. Steinke et al., under review

Larger laser spot size results in achromatic divergence and unprecedented charge density proton beams

Ti:



Processed RCF data: in-house charge response calibration at NDCX-ii [*J.H. Bin et al., RSI 90, 053301 (2019)*]



- 10^{12} protons > 1 MeV
- Strongly reduced divergence (5 times)

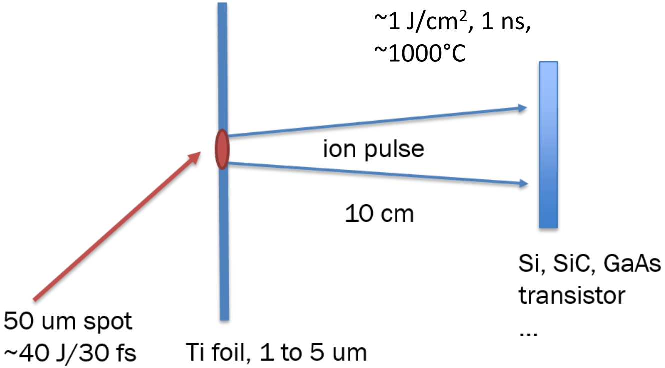
Charge density exceeds values from large single shot laser systems*

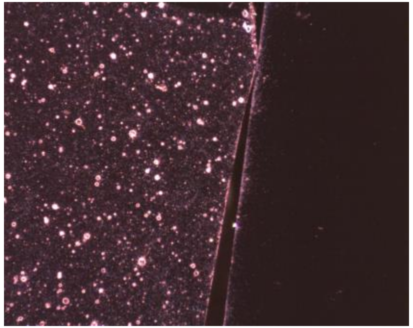
Ideally suited for subsequent beam transport

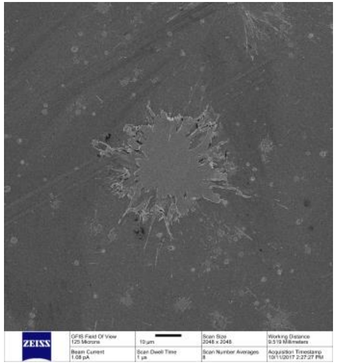
S. Steinke et al., under review

* *J. Schreiber et al., RSI* ***87****, 071101 (2016).*

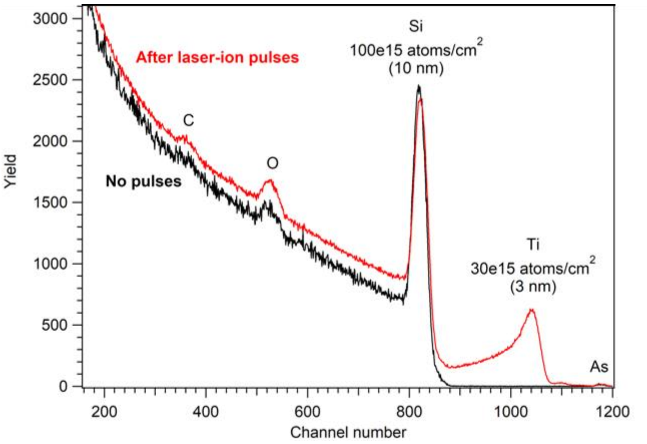
Pulsed implantation of SiC with ion pulses from BELLA – towards formation of vacancy centers



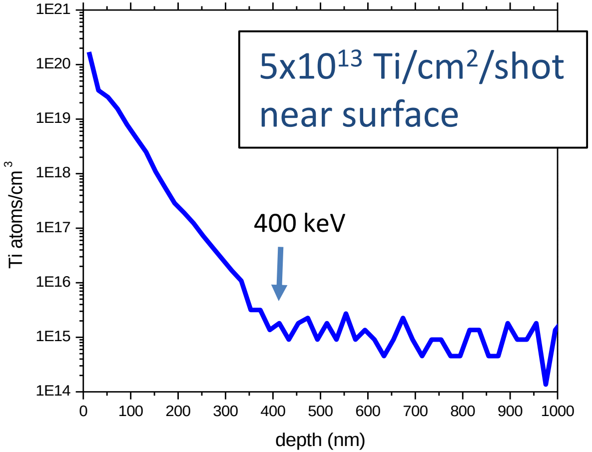




Channeling - RBS, Ryan Thorpe, Rutgers



SIMS: Secondary Ion Mass Spectrometry



Ultra-high instantaneous dose-rate FLASH increases differential response between normal and tumor tissue

To create a platform for investigating radiobiological effects of laser-accelerated ion beams for the treatment of cancer. Long term impact is to establish Advanced Particle Therapy Research Facility (a technology test-bed facility) at LBNL.

WORKSHOP ON UNDERSTANDING HIGH-DOSE, ULTRA-DOSE-RATE AND SPATIAL FRACTION-ATED RADIOSURGERY

Co-Sponsored by National Cancer Institute and the Radiosurgery Society®

Tuesday, August 21, 2018

RESEARCH ARTICLE *Science Translational Medicine 6:245ra93 (2014)*

RADIATION TOXICITY

Ultrahigh dose-rate FLASH irradiation increases the differential response ... and tumor tissue in mic...

Vincent Favaudon,[1,2*] Laura Caplier,[3†] Vir... Mano Sayarath,[1,2†] Charles Fouillade,[1,2] M...

CANCER RESEARCH UK

Experimental 'pulse radiotherapy' kills canc... healthy tissue

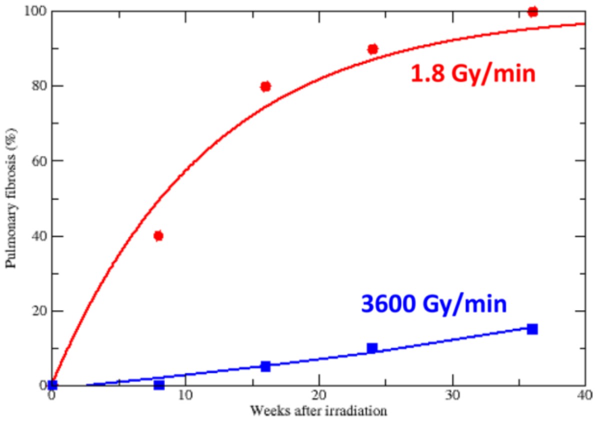
In collaboration with:

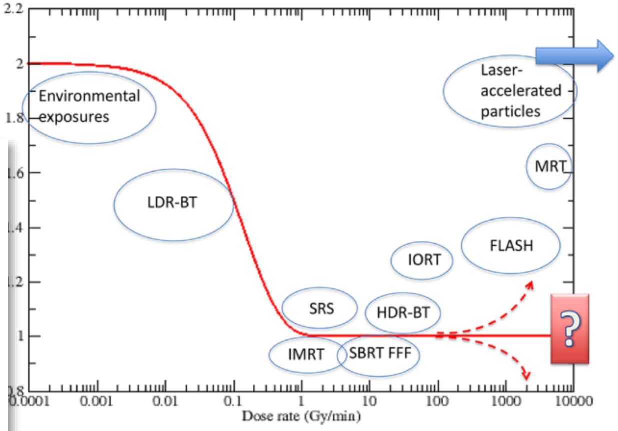
LBNL - BSE

A. Snijders, J. H. Mao, E. Blakely

UCSF

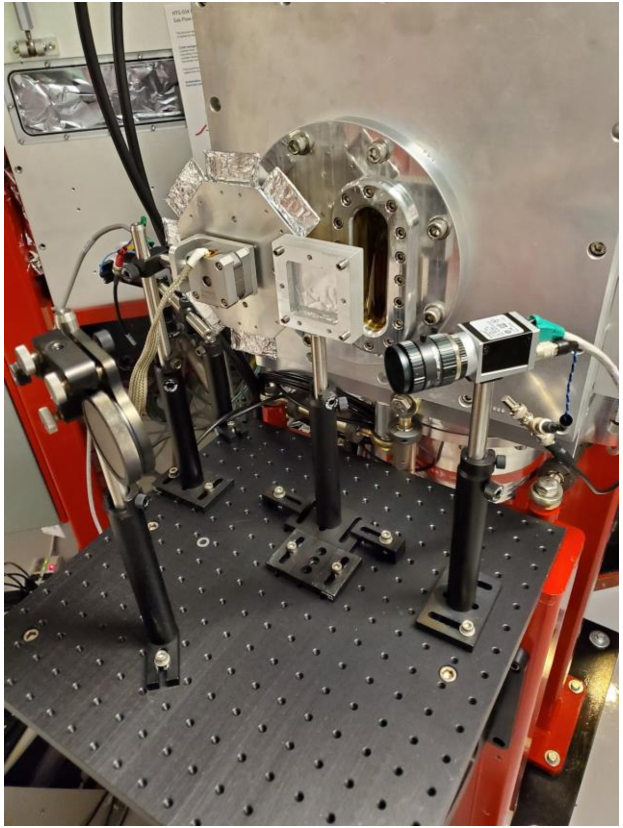
M. Roach III, B. Faddegon

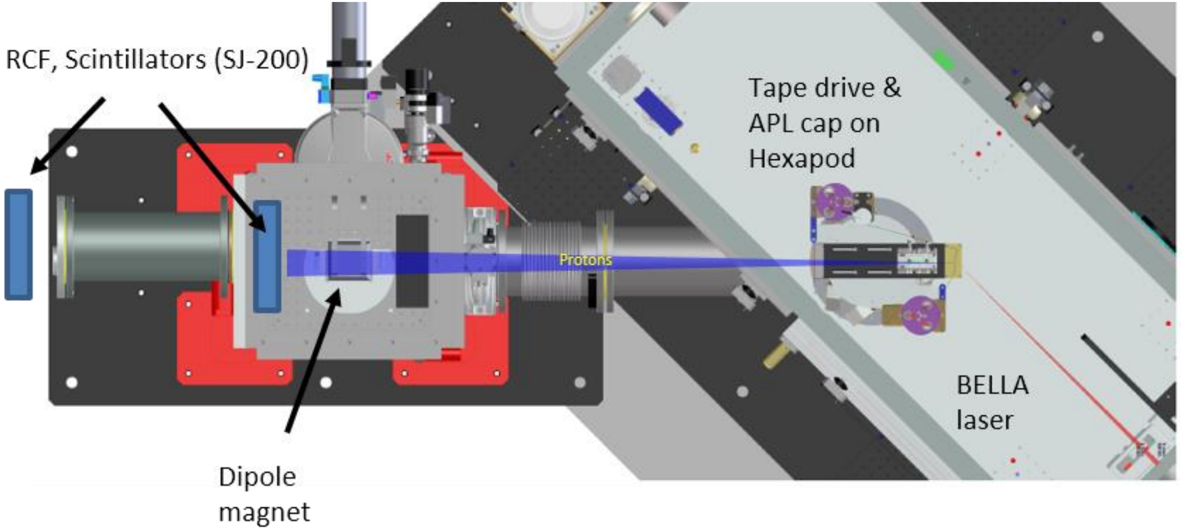




Durante et al., Br J Radiol 2018; **91**: 20170628.

Experiment setup for determining capture efficiency and emittance measurement at PW power

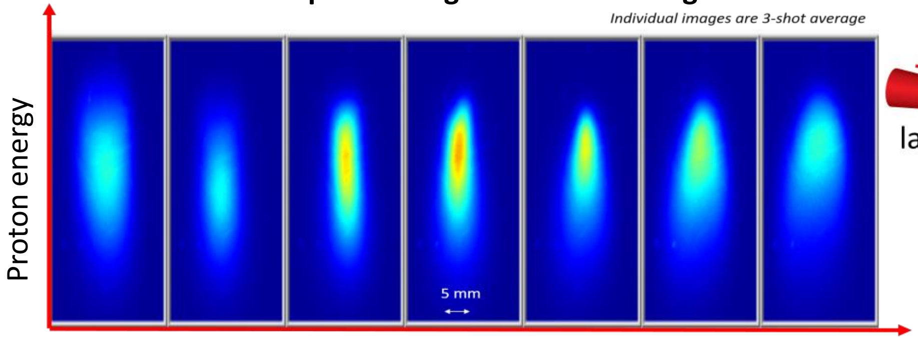




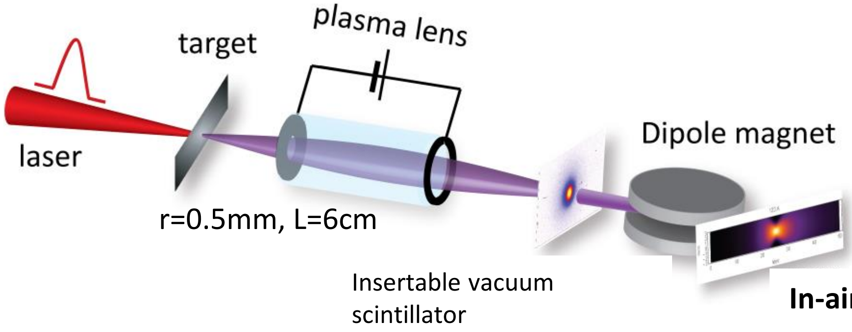
- 1mm x 60mm APL placed 5mm behind source
- APL captures 25mrad
- Proton source imaging at 300-fold magnification at 1.5m with RCF and scintillators

FLASH-Radiobiological studies enabled by BELLA-PW-driven proton beams

1. Scintillator for rep-rated alignment and tuning:



Discharge current, i.e. focus strength



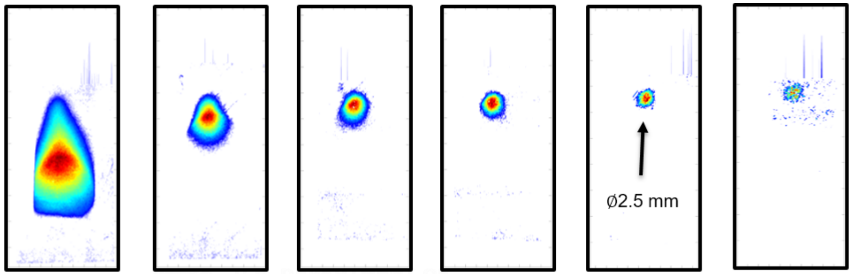
In-air setup:

1. scintillator

2. RCFs

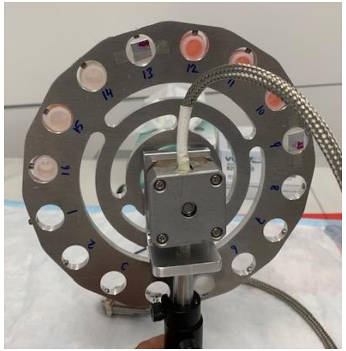
3. cell samples

2. Radiochromic film stacks for precise dose characterization (see J.H. Bin et al., RSI (2019):



1.2 MeV 3.2 MeV 4.4 MeV 5.4 MeV 6.3 MeV 7.1 MeV

3. Cell-sample wheel to study Radiobiological effects:

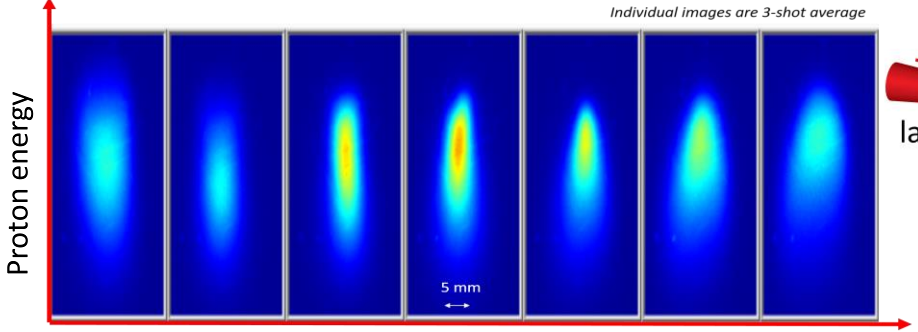


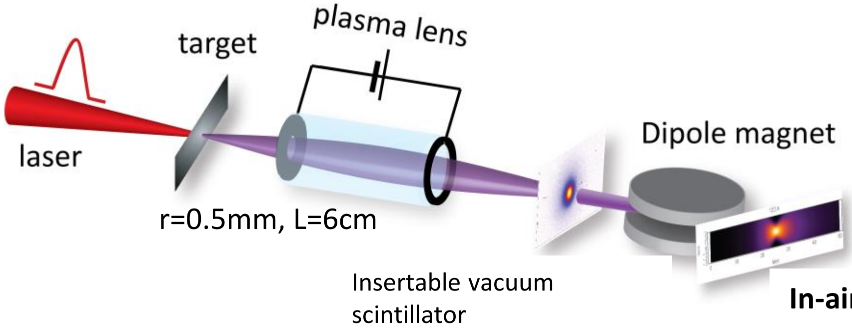
Run summary (June 3, 2019):

- Irradiated 45 cell samples with variable doses at 0.5Gy/shot)
- 1500 PW target shots (including plasma lens alignment and online dose monitoring)

FLASH-Radiobiological studies enabled by BELLA-PW-driven proton beams

1. Scintillator for rep-rated alignment and tuning:



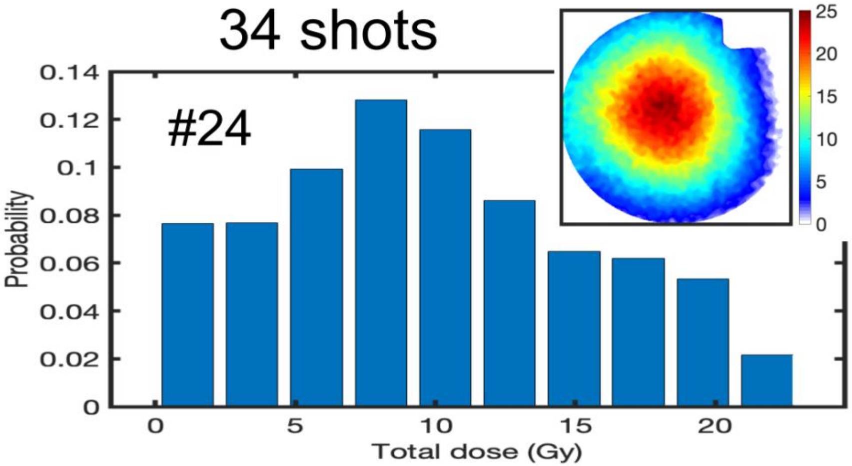


In-air setup:

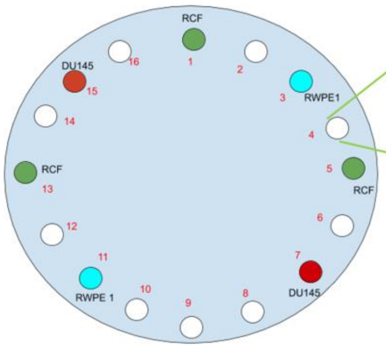
1. scintillator

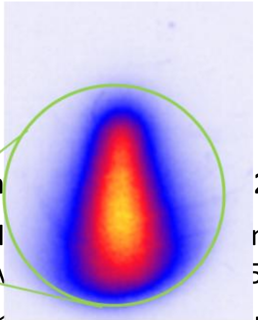
2. RCFs

3. cell samples



3. Cell-sample wheel to study Radiobiological effects:





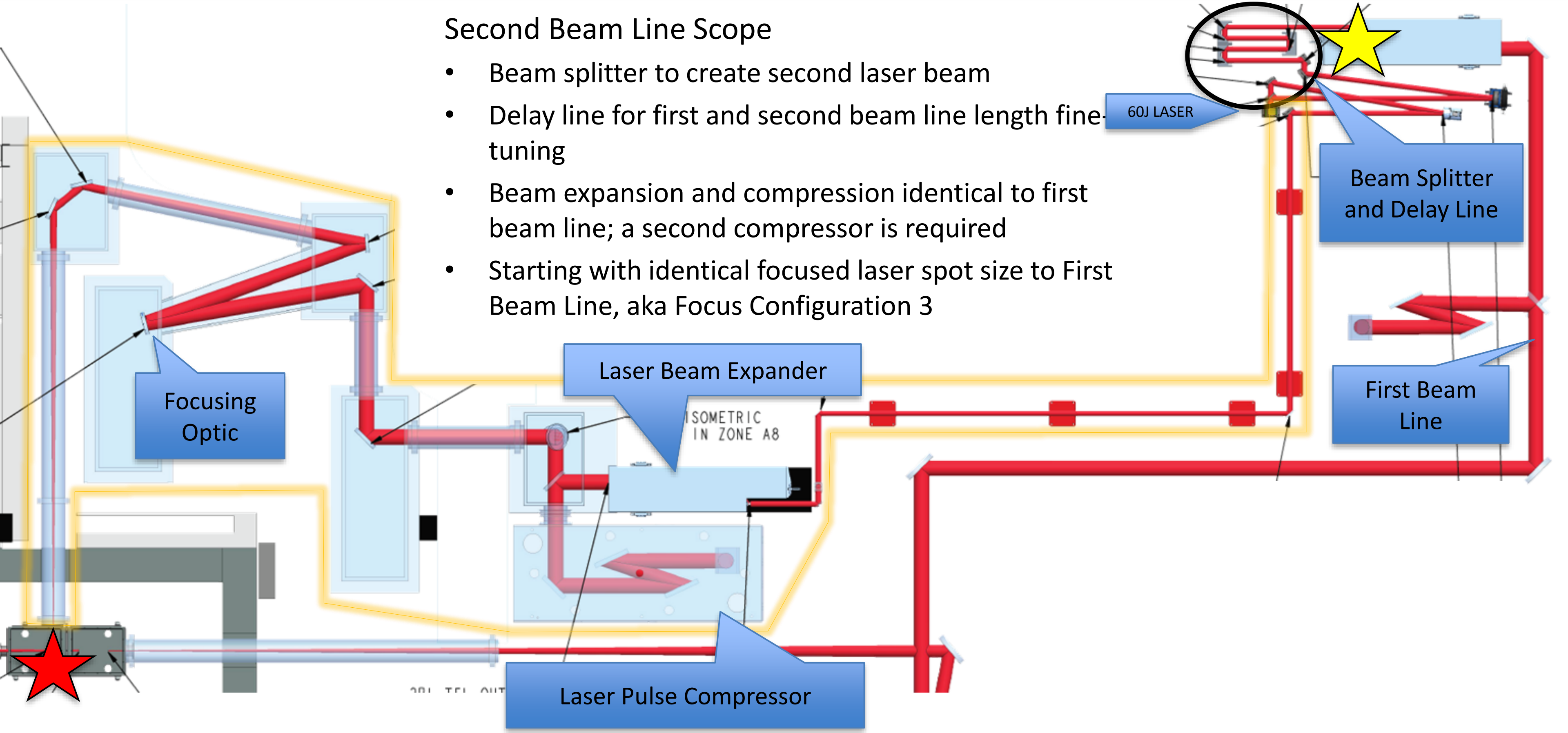
Run ... 2019):

- I ... mples with v ... 5Gy/shot)
- 1500 PW target shots (including plasma lens alignment and online dose monitoring)

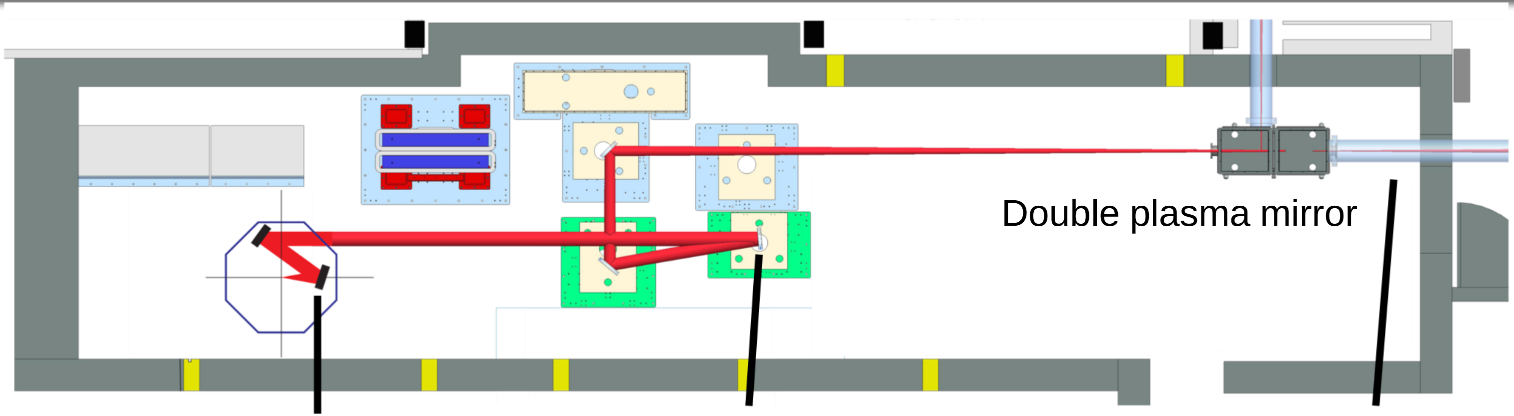
The Second Beam Line uses the same laser and will deliver a second focused laser beam for staging experiments

Second Beam Line Scope

- Beam splitter to create second laser beam
- Delay line for first and second beam line length fine-tuning
- Beam expansion and compression identical to first beam line; a second compressor is required
- Starting with identical focused laser spot size to First Beam Line, aka Focus Configuration 3



New ultra-high intensity laser beamline to provide 50 MeV/u ions for in vivo irradiation of small mammals and exciting opportunities in discovery plasma science



Opportunities in

- **Fundamental Physics of Relativistic Plasmas** advanced ion acceleration, relativistic oscillating mirror, flying mirror
- **Relativistic Laboratory Astrophysics** plasma instabilities, bow waves, magnetized jets, antimatter plasma, collisionless shocks
- **High Intensity Particle Physics** Nonlinear QED, Multiphoton Compton and Breit-Wheeler processes, EM cascades

Features

A. New target chamber for highest laser intensities $>10^{21}$W/cm^2
B. Double plasma mirror for temporal contrast enhancement of laser (ns-ps) $<10^{-14}$
C. Expansion space for diagnostic, probe laser, ion beamlines, betatron backlighter for WDM studies