Plasma acceleration and high energy density science

Cameron Geddes

LLNL HEDS Seminar Series

18 February, 2021

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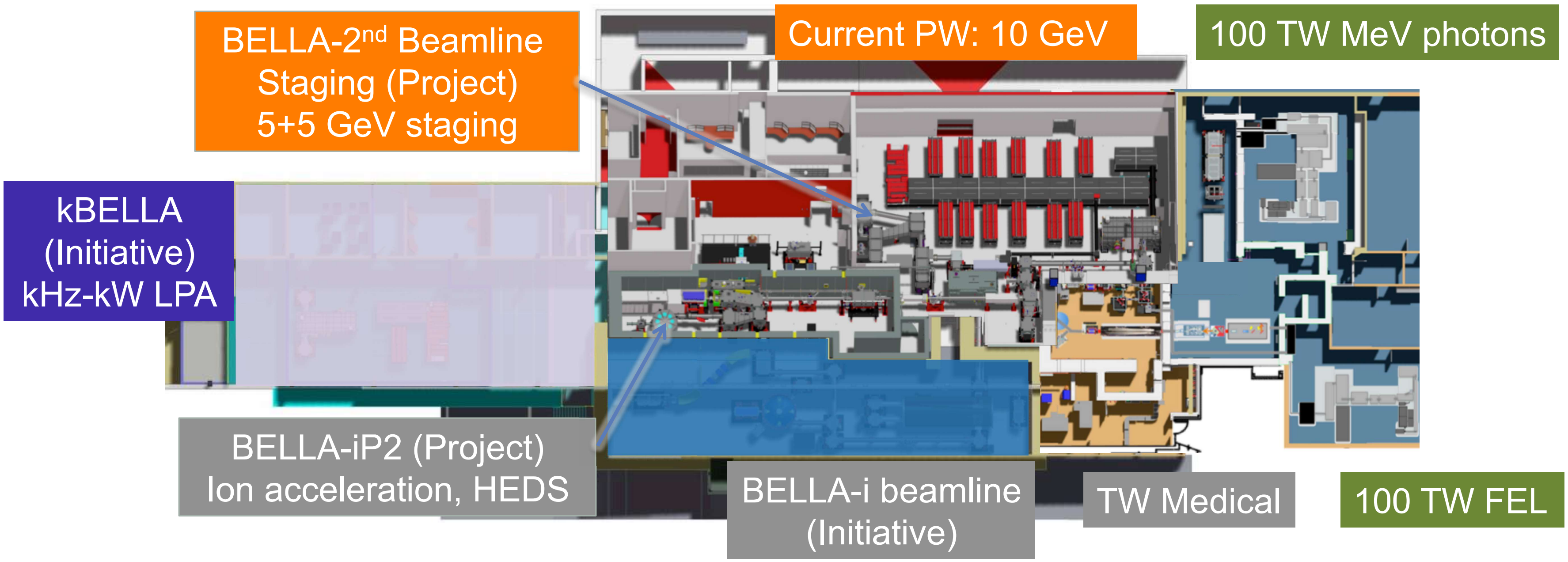
Close Collaborations with other ATAP Programs & LBNL Divisions

BELLA Experimental Facilities: World-Leading Capabilities Driving Plasma Acceleration and HEDS

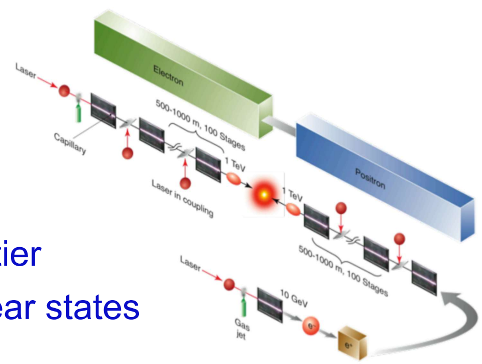
Exisiting and planned laser facilities in Building 71 at LBNL



Unique resource of and for the DOE and beyond
State of the art: 1 Hz at PW, 5 Hz at 100 TW

Ultraintense Lasers Enable Science and Applications: From the Frontiers of Fundamental Physics to Industry, Security and Medicine

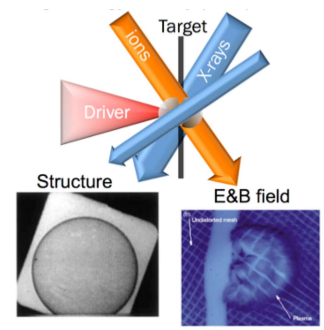
HEP Future Particle Colliders
NP Nuclear Science



Extend energy frontier

Access exotic nuclear states

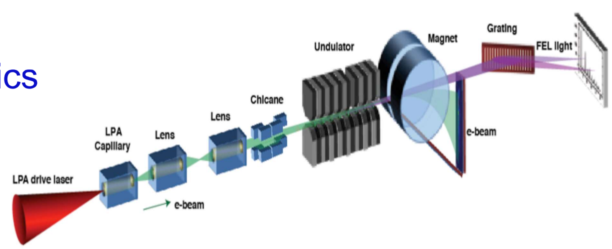
FES High Energy Density Science
NIH/NCI Oncology



Precision probes/pumps

New therapy sources

BES and Industry Coherent X-rays

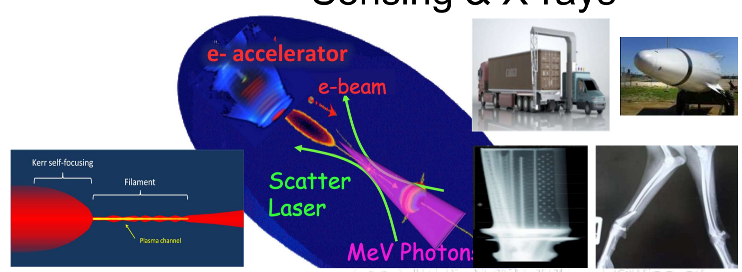


Compact FELs

Molecular dynamics

Microelectronics

DoD, NNSA, Industry and Medical
Sensing & X-rays



Precision

Mono-Energy

High res.

Remote sensing

Outline

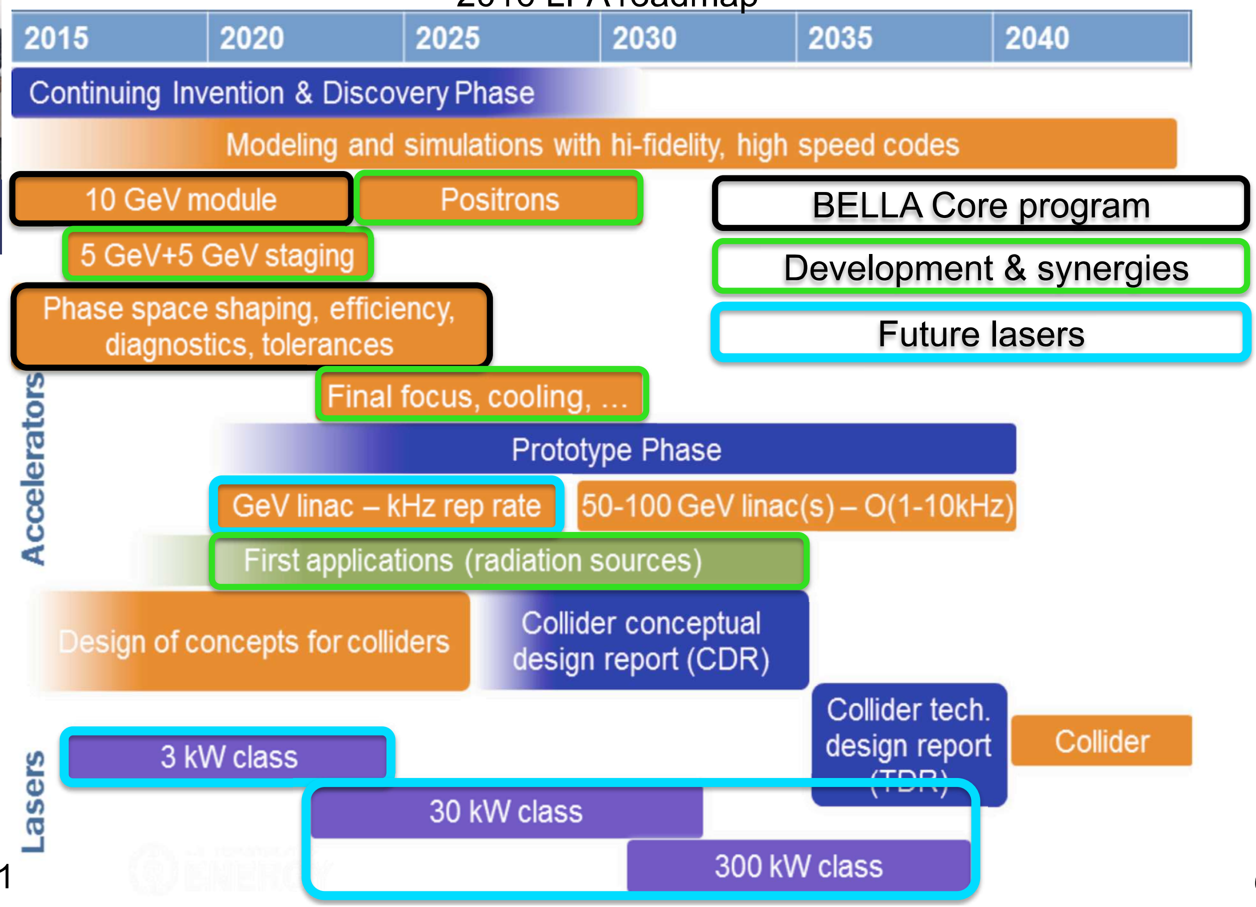
- Plasma accelerators
- Advanced sources & high energy density science
- kHz precision frontier

BELLA Center is Focused on Executing the U.S. Advanced Accelerator Development Strategy

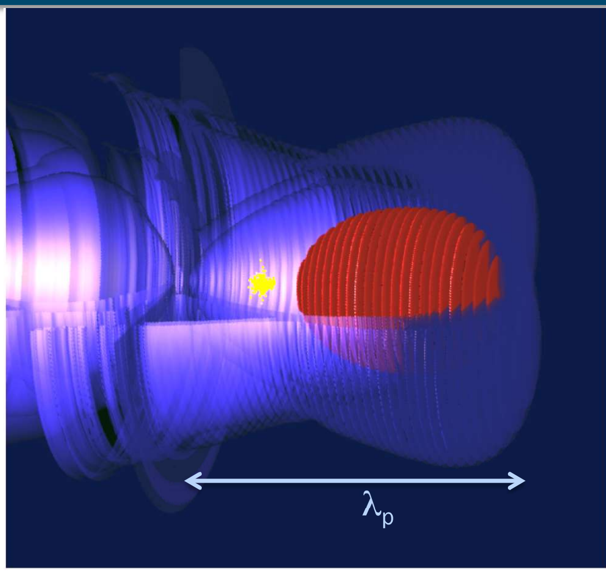
Plasma based Accelerator Concepts for Colliders Workshop, January 6-8, 2016

Updates in progress – Snowmass 2021

2016 LPA roadmap



Precision Engineering of Relativistic Plasmas Enables High Performance

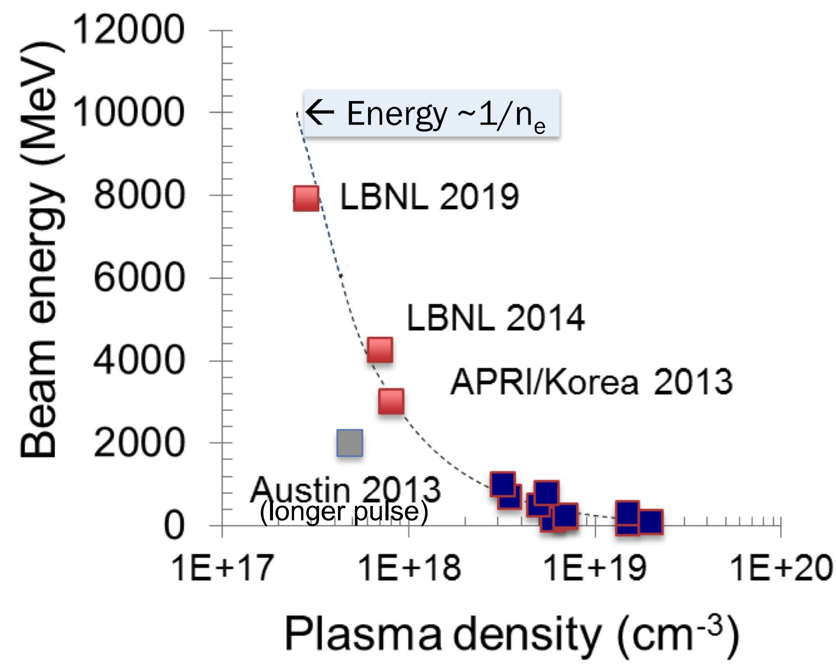


Resonant Excitation Results in Predicatable Structure

- Accurate scaling laws for charge, energy, laser requirements…

Example scalings	Typical at $n_e \sim 10^{17}/cm^3$
$\lambda_p = 2\pi c/\omega_p \sim n_e^{-1/2}$	100 μm
Gradient ~ $n_e^{1/2}$	10 GV/m
Energy ~$1/n_e$	10 GeV/stage in 10's of cm

Scalings strongly validated: close integration of theory, experiment, and simulation



Allows design of accelerator systems

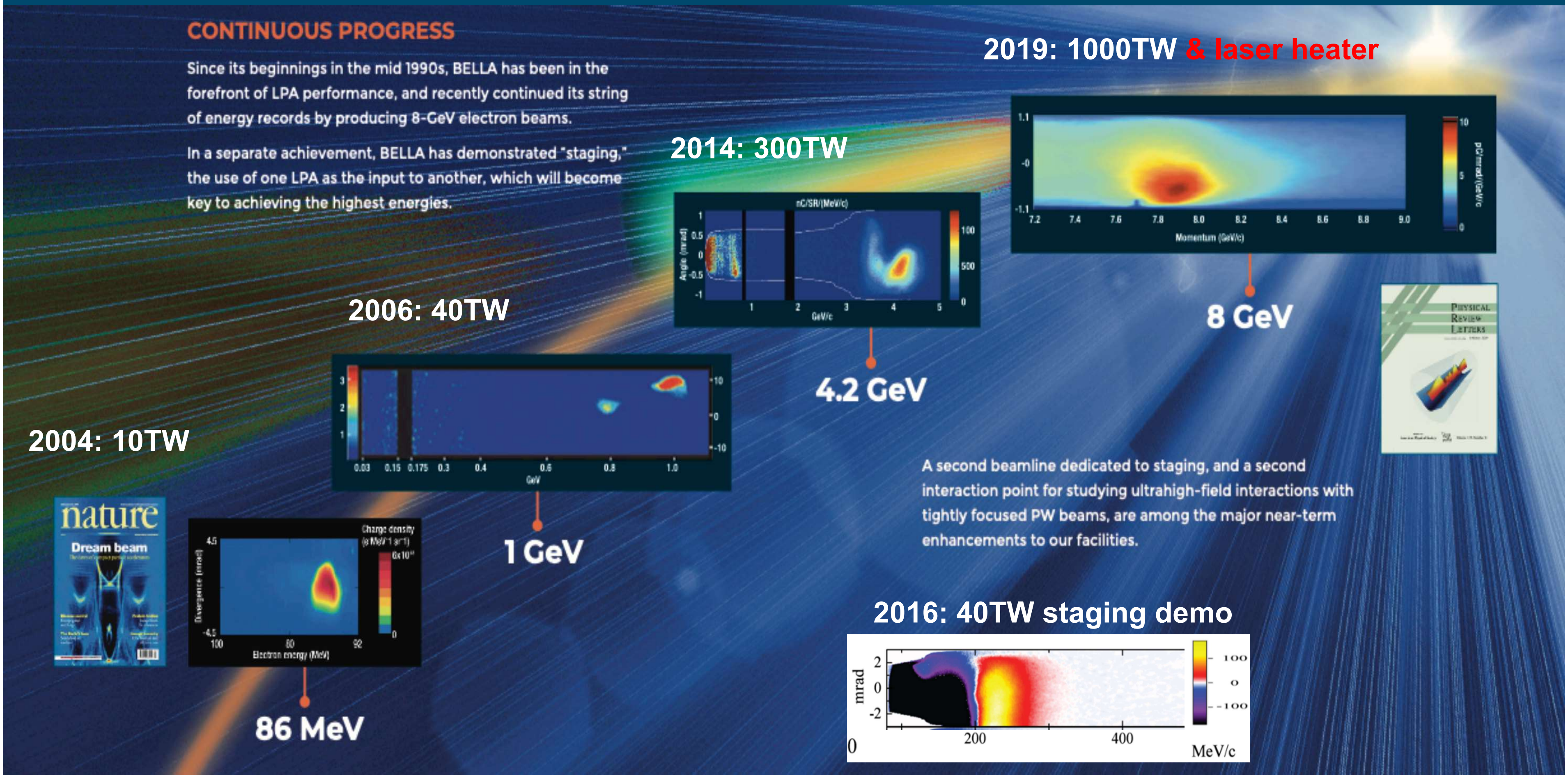
BELLA Center: Timeline of LPA Records

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.

A second beamline dedicated to staging, and a second interaction point for studying ultrahigh-field interactions with tightly focused PW beams, are among the major near-term enhancements to our facilities.

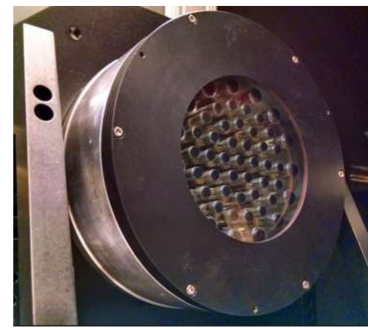


The BELLA PW enables precision 1 Hz experiments

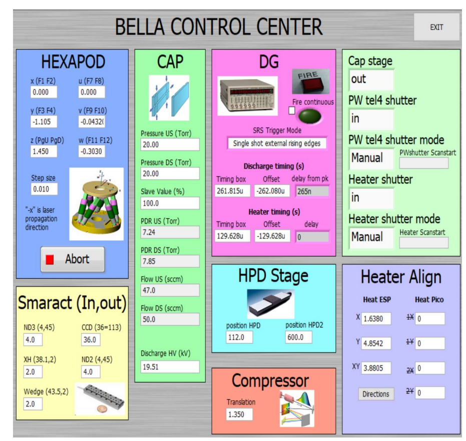
BELLA PW laser performance

- >40 J on target with a 1% level fluctuation
- <1.3 µrad pointing fluctuation
- Focus to 53 um,
  - 75% energy in main structure,
  - <6% peak fluence fluctuation.
- Compressed to 33 fs,
  - >90% energy in main pulse
  - <5% peak power fluctuation.
- Peak intensity 1.7 x 10^{19} [W/cm^2]
  - <8% fluctuation.
- Contrast
  - 1 ns >10^9
  - 5 ps >10^6

High quality laser including XPW, Deformable Mirror

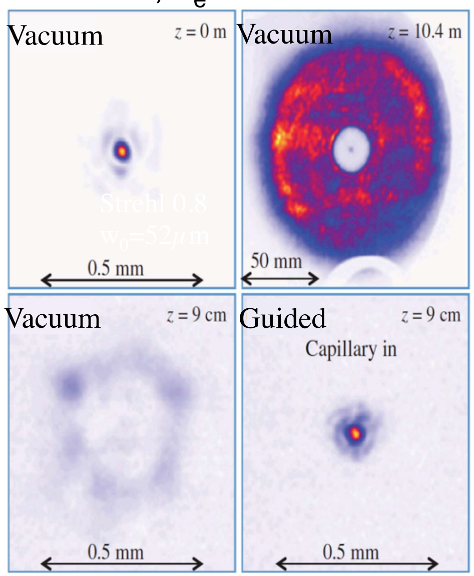


State of art Controls

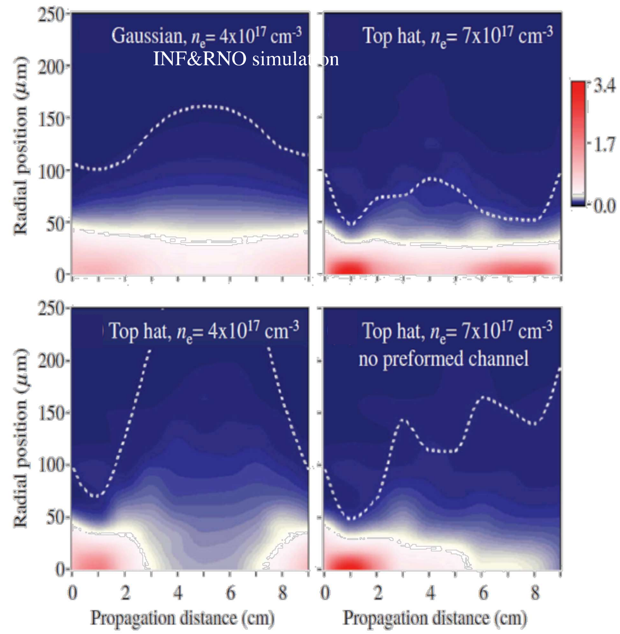


Guiding of laser over many focal depths requires compensation for non-ideal laser mode

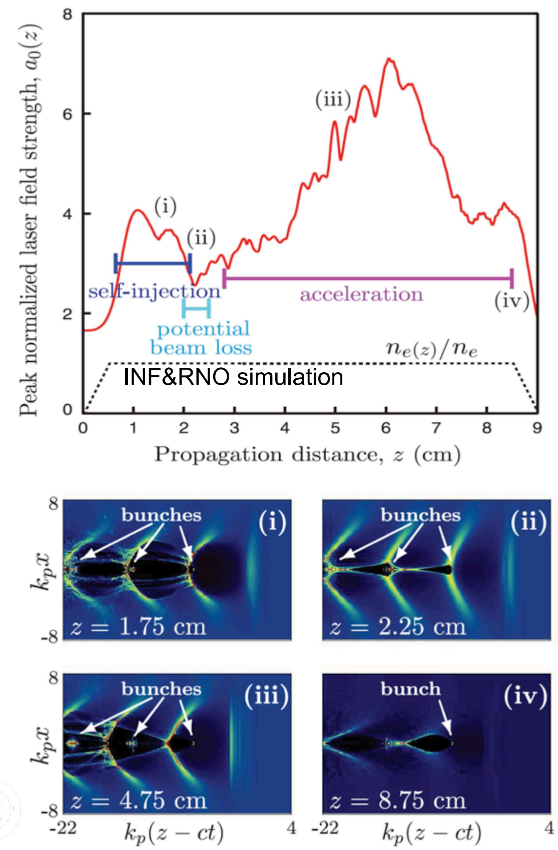
Laser close to a flat-top near field
16J, n_e = 7.5x10[17]



Density for guiding increased



Affects guiding and acceleration

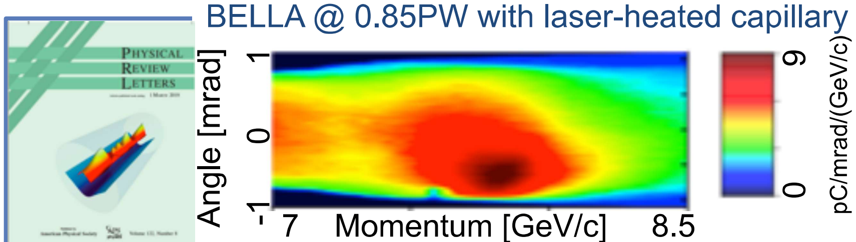


Continuous Progress
Towards 10 GeV Collider-Class Per-Shot Stage

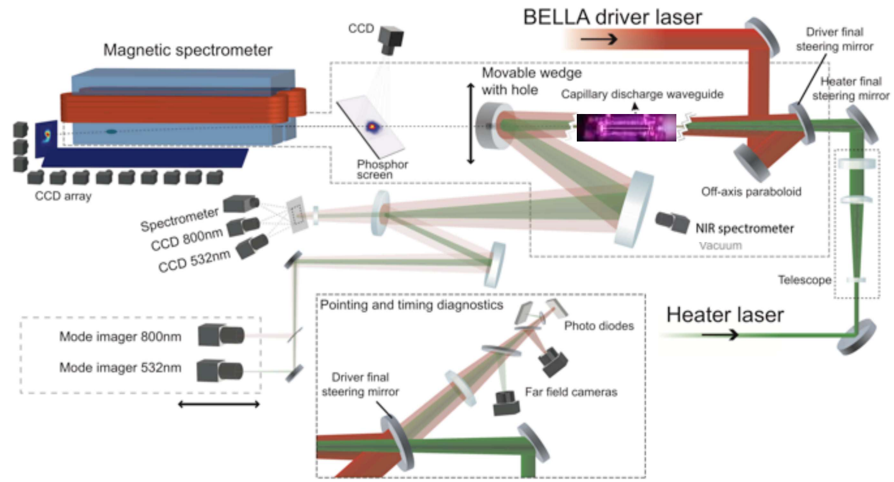
Efficient systems via control and development

- 2014: 4GeV. Using capillary waveguide
- 2017: 6GeV. Required a new beamline for hybrid waveguide (laser-heated capillary)
- 2018: 8GeV. Required optimization of the waveguide regime through theory & simulation

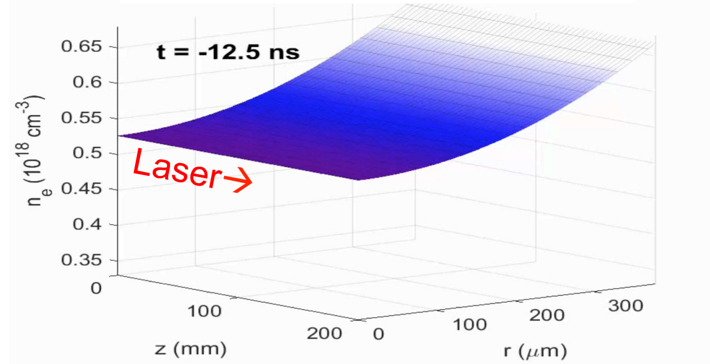
BELLA @ 0.85PW with laser-heated capillary



Gonsalves et al., PRL (2019)



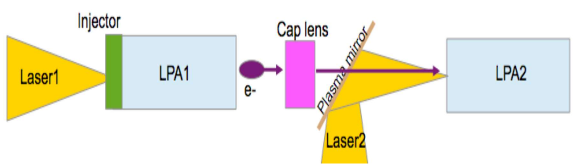
Laser heater deepens channel



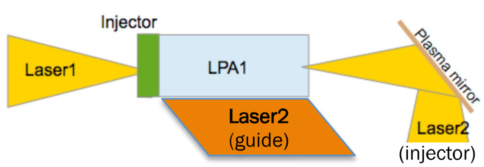
- Towards efficient 10 GeV stages: shaped guides, controlled injection, structure and loading control…

2nd Beamline Will Provide a Platform to Enable Key Elements of Advanced Accelerator R&D Roadmap

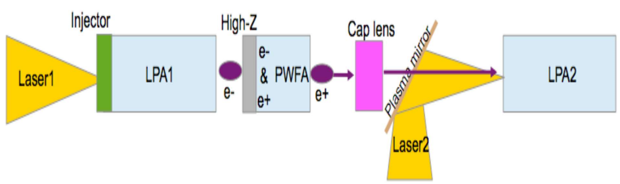
Staging

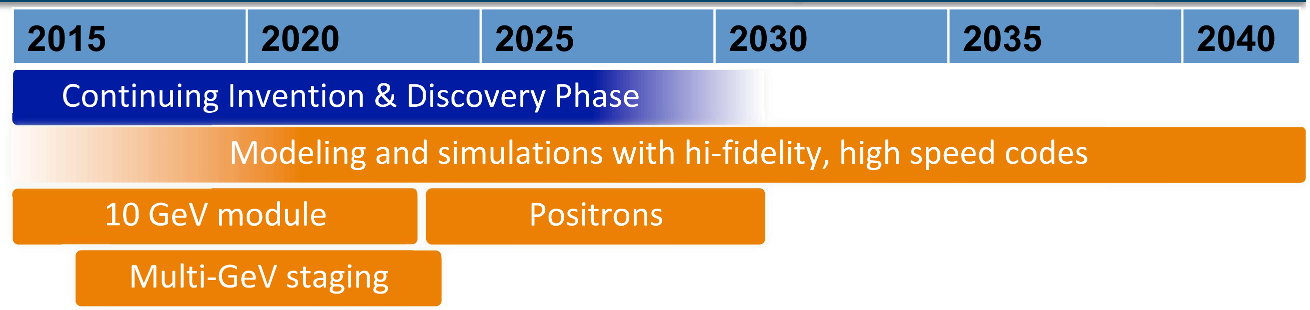


Injection & guiding



Positron generation & acceleration





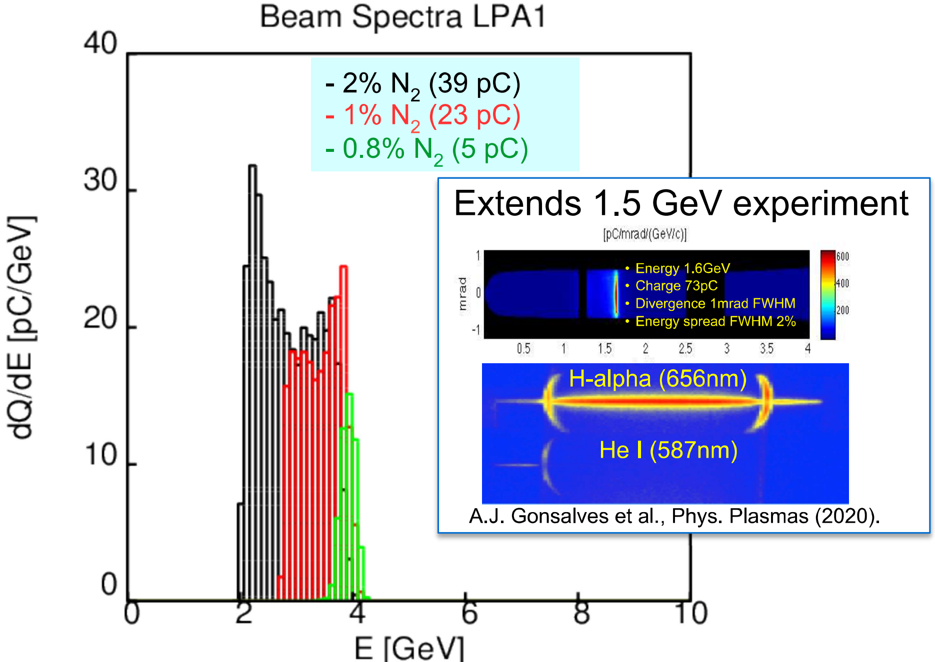
Design complete, installation in progress

Goal: multi-GeV staging. Future: multi-beam HEDS

Flexible Focusing and Controlled Injection
Key to Multi-GeV staging

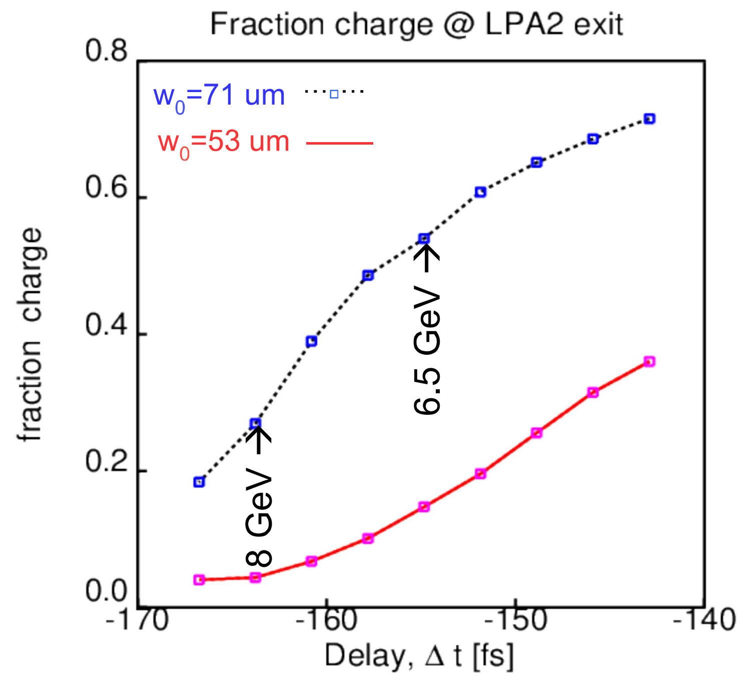
Ionization injection at start of first stage

Controllable 4 GeV beam



Particle loss due to wake evolution, bunch size

Adjust with focal match: $w_0 \sim 70$ micron



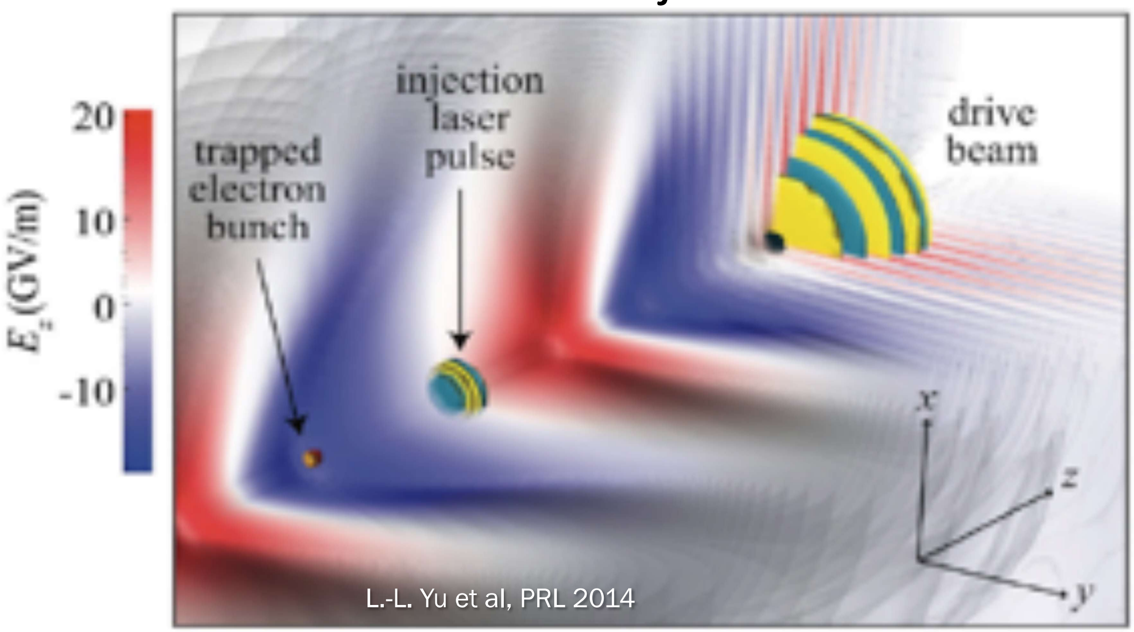
Basis of near term multi-GeV staging experiment

Longer term: low emittance injector and matched guide for near 100% efficiency and 10 GeV

*Gonsalves et al, POP (2020)

Ionization injection and other multi-beam experiments require precision control

nm ε injectors



Long wavelength drive laser/beam excites wake without injecting particles

High a_0, low E

Short wavelength injection laser injects particles without exciting wake

Low a_0, high E

Injection of sub-micron bunch with low transverse momentum enables nm-class emittance

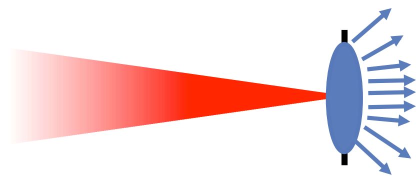
Requires precision alignment ≤ μm

Priority for active alignment, pilot beams and repetition rate to execute

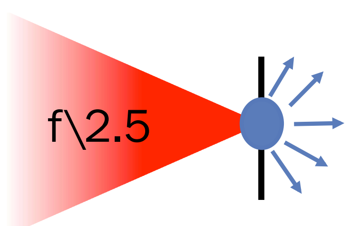
Outline

- Plasma accelerators
- Advanced sources & high energy density science
- kHz precision frontier

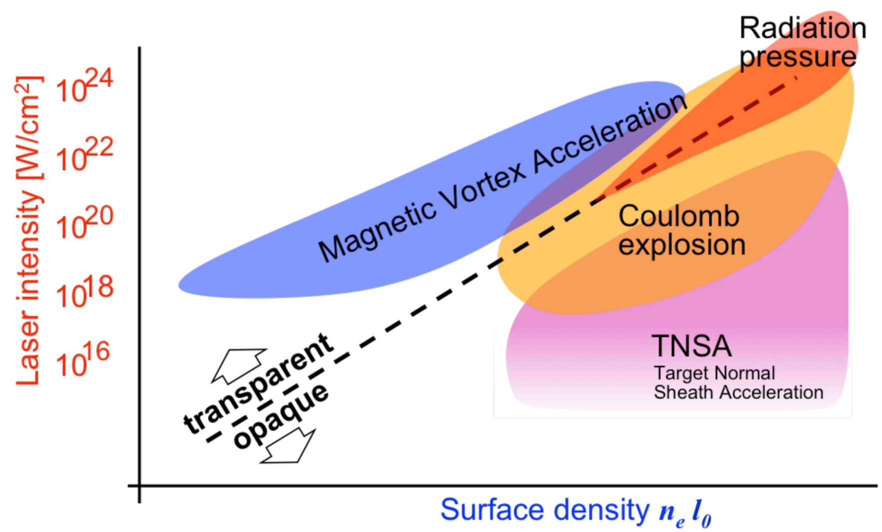
Ion acceleration



in operation, 2x10^{19} W/cm^2, large laser spot, 50 μm, low divergence ion pulses with ~10^{12} protons



Late 2021, >10^{21} W/cm^2, small laser spot, ~10 μm, (ultra)-relativistic plasma science at 1 Hz, advanced ion acceleration mechanisms, ions to >100 MeV, ...

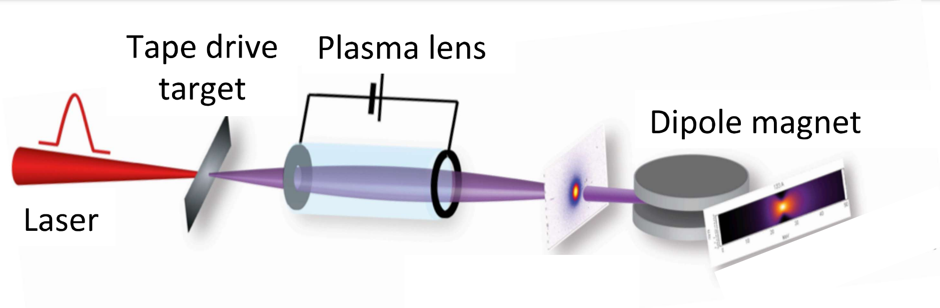


LLNL collaborations/users including Tammy Ma, Scott Wilks, Derek Mariscal, Graeme Scott, Elizabeth Grace, Kelly Swanson, Raspberry Simpson (MIT)

BELLA PW Ion Acceleration and Transport Enabling Applications

Rep-rated experiments

- Tape-drive target and MCP-based Thomson Parabola Spectrometer
- Plasma lens focusing
- Thousands of shots
- Stable source enables applications



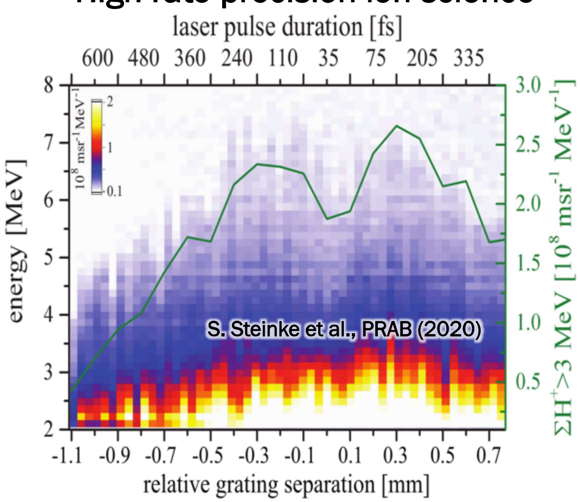
In-air setup:

1. scintillator

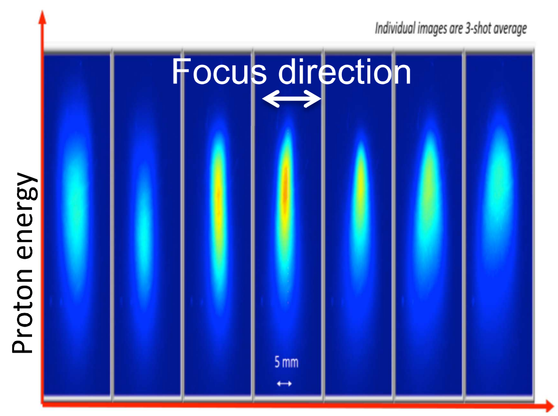
2. RCFs

3. radiation biology cell samples

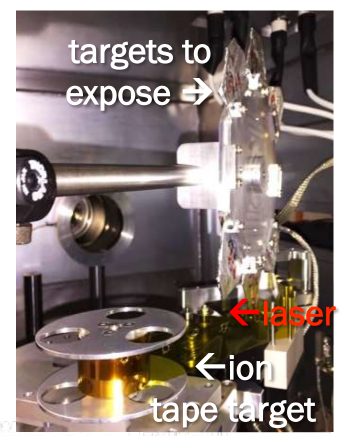
High rate precision ion science



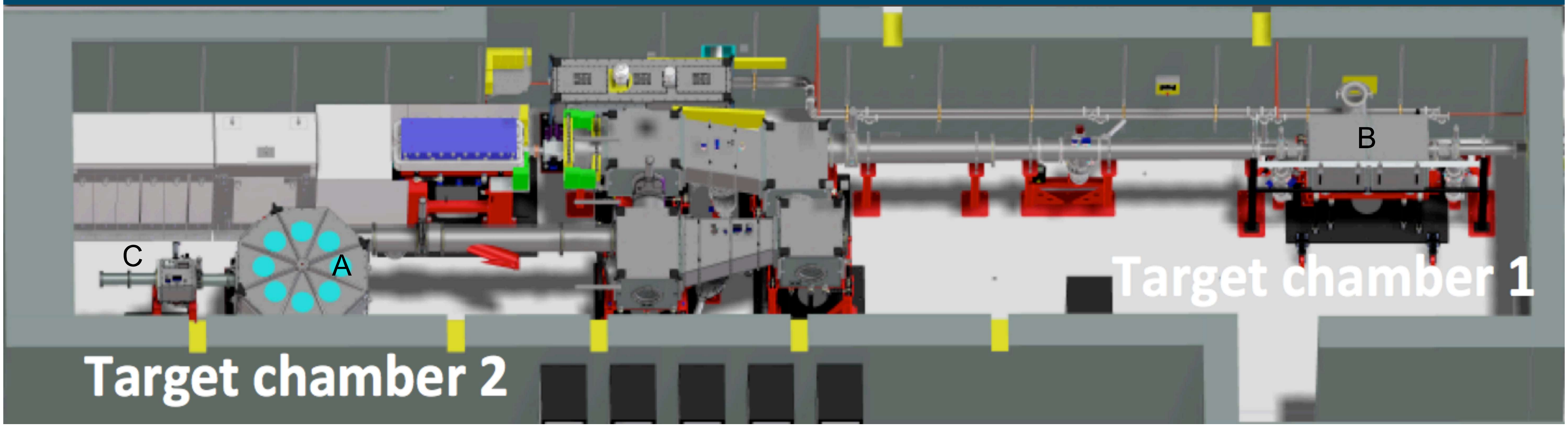
Plasma lens: controlled focus



Materials



High intensity laser beamline: new opportunities in discovery plasma science



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) $<10^{-14}$

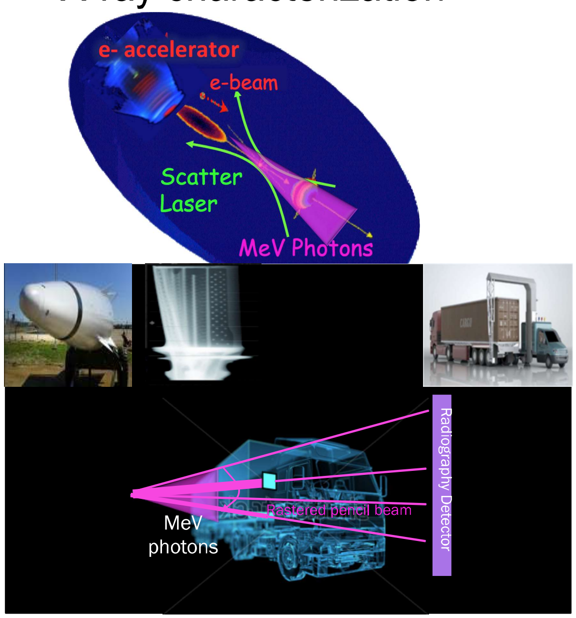
C. Expansion space for diagnostic, probe laser, ion beamlines, betatron backlighter for WDM studies

Opportunities in

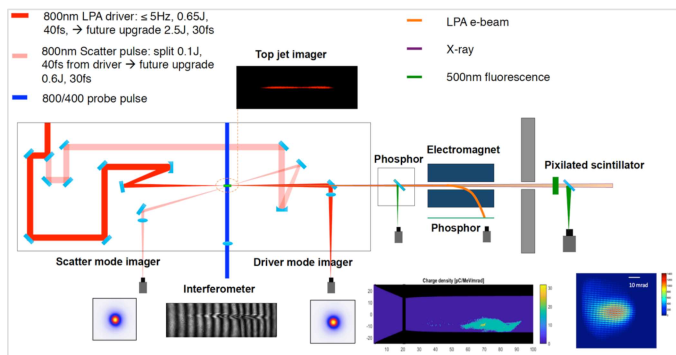
- **Fundamental Physics of Relativistic Plasmas**
  advanced ion acceleration, relativistic oscillating mirror, flying mirror
- **Relativistic Laboratory Astrophysics**
  plasma instabilities, bow waves, magnetized jets, antimatter plasma, collisionless shocks

Dual 100 TW laser systems drive photon sources and HEDS experiments

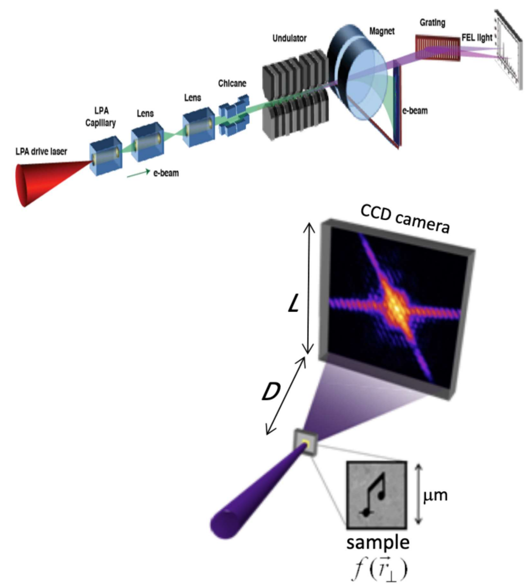
Precision MeV mono-energetic X-ray characterization



Flexible multi-beam HEDS



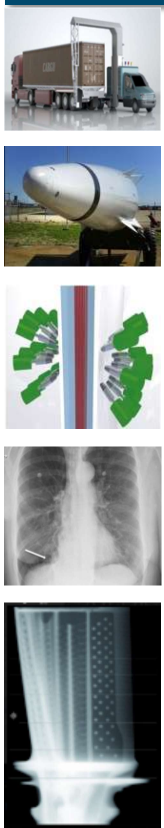
Compact Free Electron Lasers



- 1 to 5 Hz, 2.4 J primary + 0.6 J 2nd beam, ≥40 fs, 800 nm
- Available now for high energy density science, …

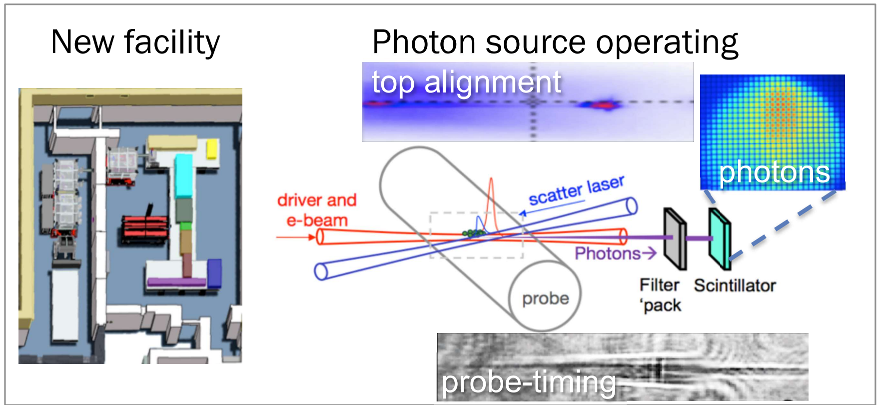
LLNL simulations with Dave Grote, Alex Friedman

MeV Compton (Thomson) MeV Photon Source Operational: Revolutionary X-ray Applications, Prototypes Collider Components at GeV Scale



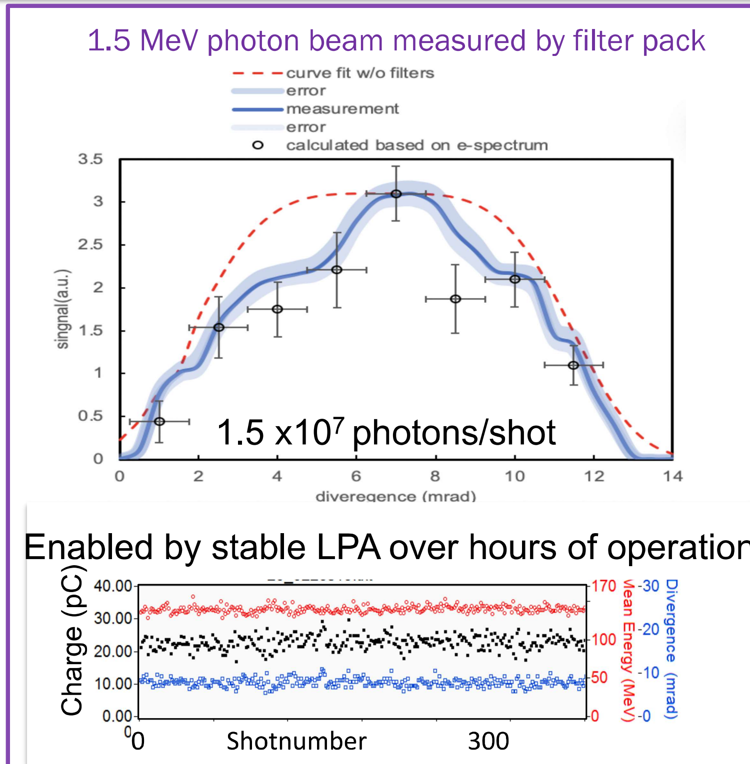
Mono-energetic MeV photons by collision w/laser:

- Enable: precision measurements below µm & ps



Reduce X-Ray & CT Dose 10x-100x and improve material separation 10x[1]

- Application and user (LaserNetUS) experiments
- Next: 9 MeV photons, guiding, electron deceleration, energy spread at 10% level with path to below 1%



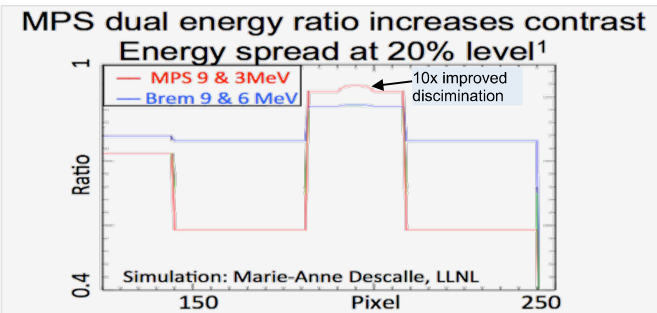
1: Report: "Impact of Monoenergetic Photon Sources on Nonproliferation Applications ," 2018
C. Geddes, et al., (2017)

Ostermayr et al., DPP 2020 BO04.00002 : The BELLA Center Hundred Terawatt laser system…
Tsai et al, DPP 2020 - BO04.00003 : MeV photon generation based on Thomson scattering…

Strong mono-energetic photon source impact on nonproliferation
Potential (unfunded) for HEDS, stockpile, defense/industry, medicine

<u>Energy selection: enhances signal</u>

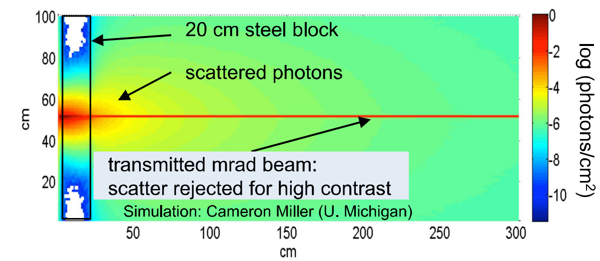
- **Radiography:** maximize transmission and Z-contrast, reduce dose



1: Final report of project "Impact of Monoenergetic Photon Sources on Nonproliferation Applications ," C. Geddes, B. Ludewigt, J. Valentine, B. Quiter, M.-A. Descalle, G. Warren, M. Kinlaw, S. Thompson, D. Chichester, C. Miller, S. Pozzi (2017)

<u>fs emission: time resolution</u>

<u>mrad divergence: mitigates scattter</u>



<u>≤ micron emission spot: resolution</u>

Simulation: Glen Warren (PNNL)

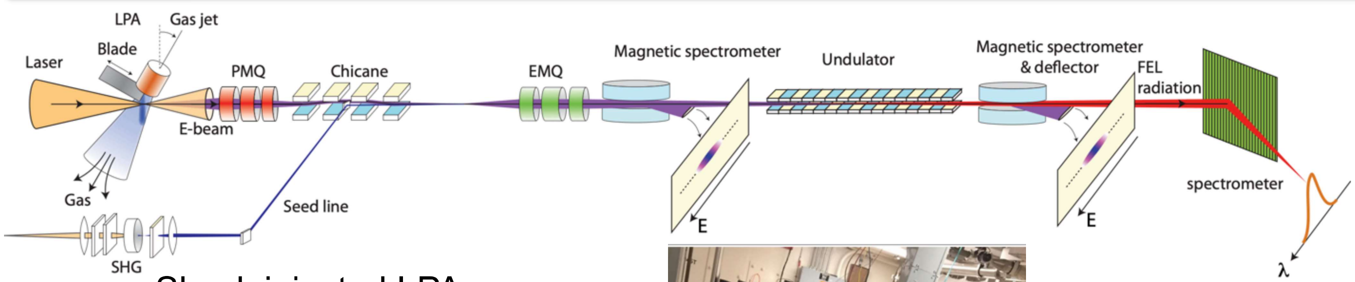
<u>Enables precision measurements for nonproliferation, nuclear physics, medicine and industry</u>

Cargo, single sided detection, treaty verification and safeguards cases detailed

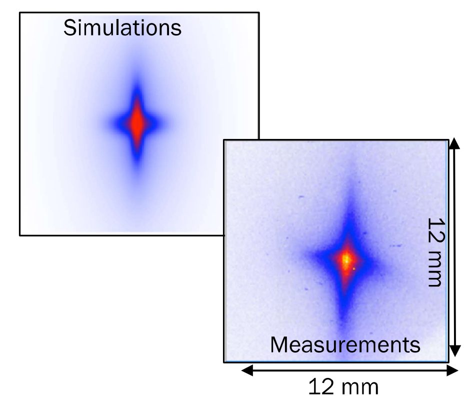
Dose reduced 10x-100x with energy control + narrow divergence
Material discrimination improved 10x
Spatial and temporal resolution improved more than 100x (fs, micron)

LLNL collaboration with Harry Martz, Steven Glenn, Joseph Bendahan

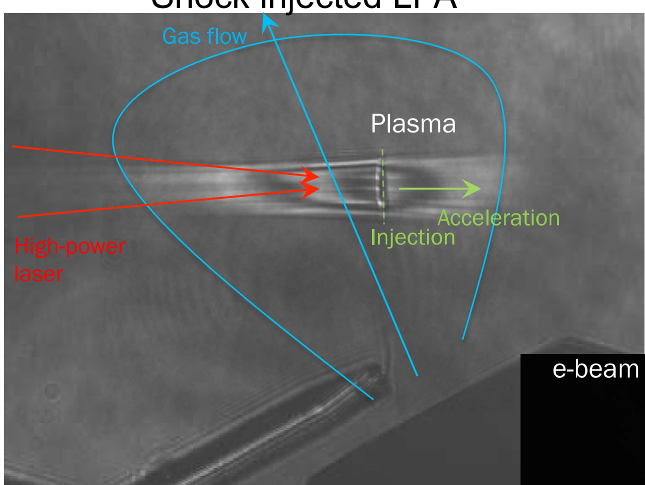
LPA-FEL project: control phase-space to enable a LPA-based Free Electron Laser (a compact coherent X-ray source)

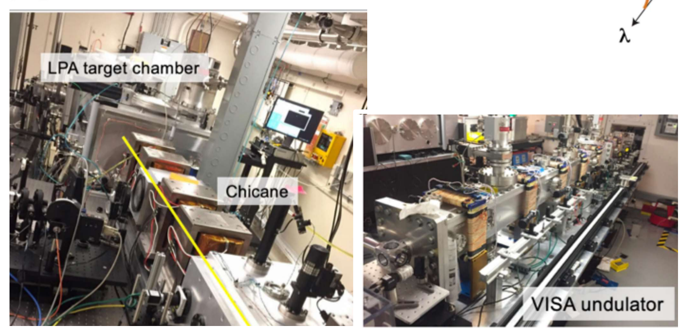


Transport studies in progress



Shock injected LPA





Approaching required charge density on single 100 MeV shots

APS DPP 2020, talk by S. Barber (*meetings.aps.org/Meeting/DPP20/Session/BO04.1*)

LPA de-compression
- dE/E few-% to <<1%

Strong-focusing undulator
- Preserve charge density

Phase1: 100 MeV→ 3eV FEL

Phase2: 300 MeV→ 27eV FEL
- Strong overlap with HEP
- Novel phase-space diagnostics

Future: compact keV LPA FEL

DOE BES ECRP and Moore foundation

LaserNetUS user access to PW and 100 TW systems

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

- HEDS, light source, HEP oriented users
- Collaborative projects welcome
- Enables new science & facility capabilities

Recent proposal areas include:

- ion acceleration (upcoming LLNL run)
- plasma mirrors
- betatron sources, hydro and imaging
- NDE, material processing…

Synergistic BELLA R&D

- FLASH Radiation Biology with laser-plasma ion beams
- Quantum Information Science / Qbit & material synthesis
- COVID droplet microenvironments

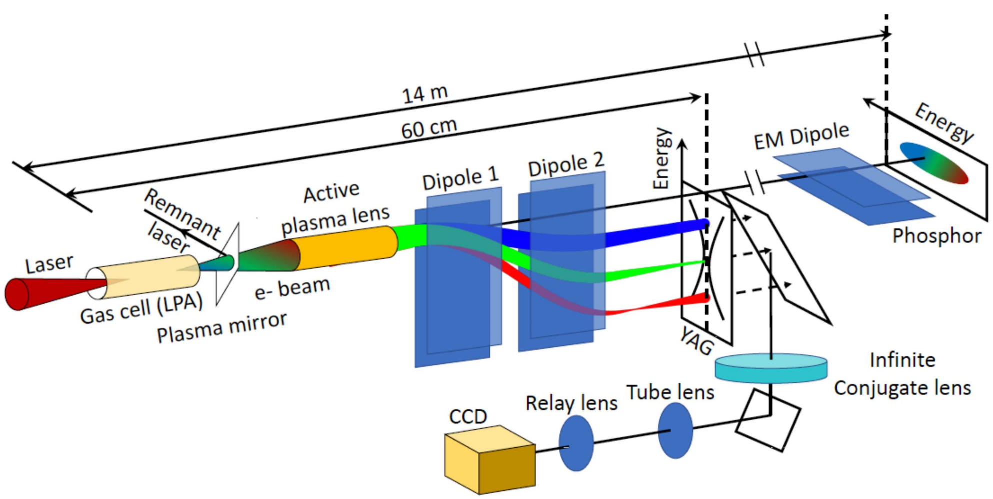
Compact diagnostic enables single shot emittance measurements

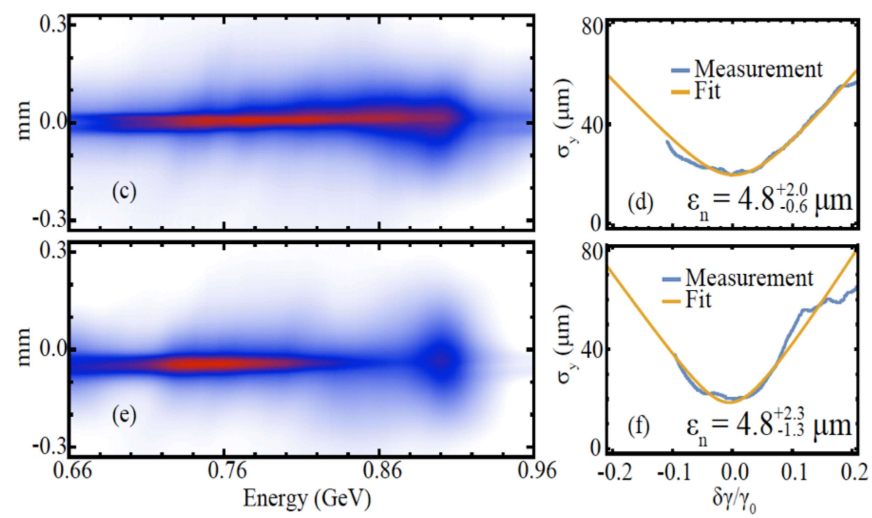
Tight focusing (6cm APL) coupled to dipoles for high-resolution energy and emittance characterization

- 4-5 μm emittance from ionization injection, 0.25 PW in 1.3 e18 of 99% He / 1%N2
- Compact spectrometer (<60cm), range to above 10 GeV

Liquid crystal plasma mirror protects plasma lens (OSU collaboration)

- Sub-micron emittance degradation



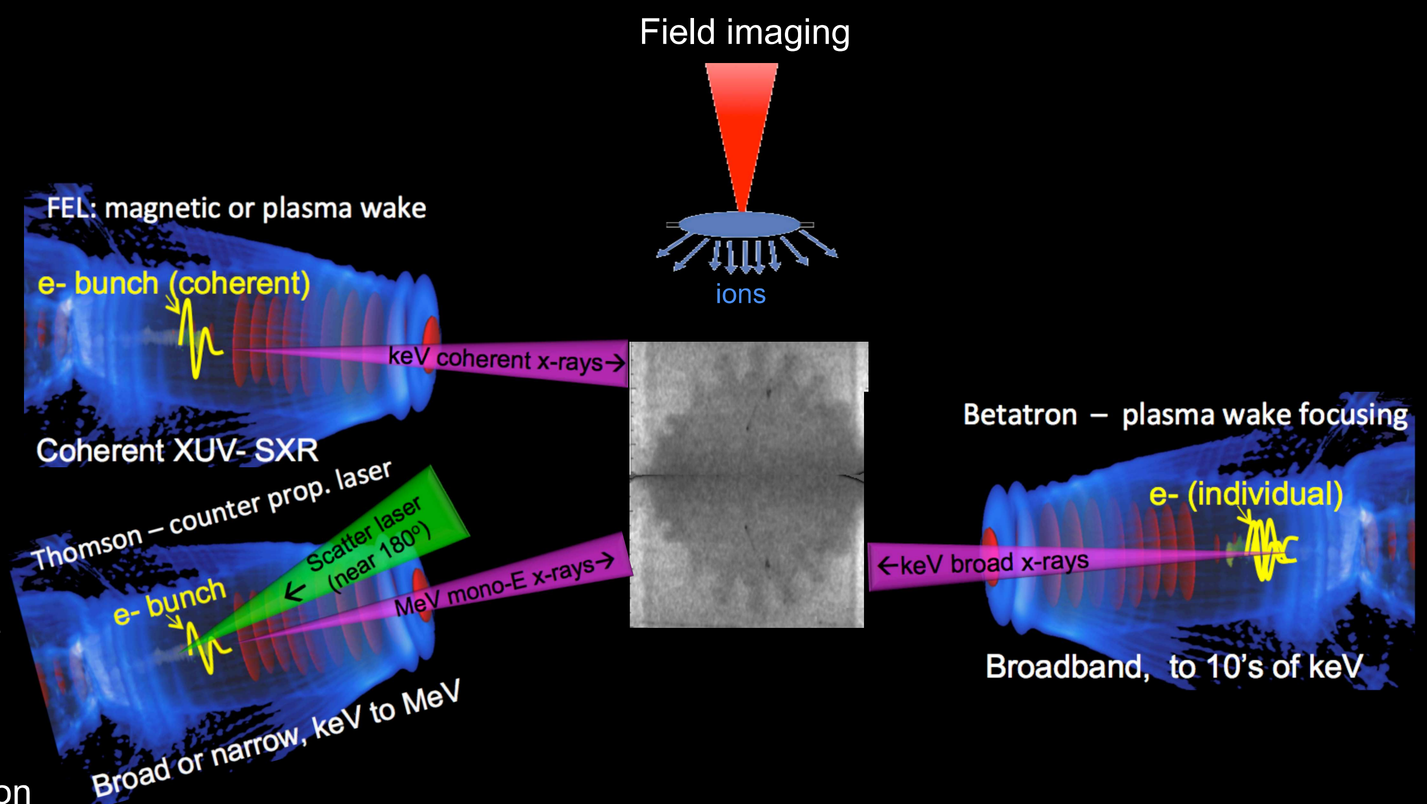


Barber et al. APL 116, 234108 (2020)

HEDS probes: compact MeV penetrating sources + coherent keV sources + charged particles

Coherent precision

Penetrate dense cores, μm resolution

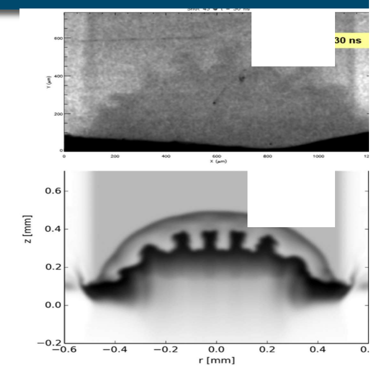


keV μm resolution

Advanced imaging to enable precision HEDS, collaboration opportunity

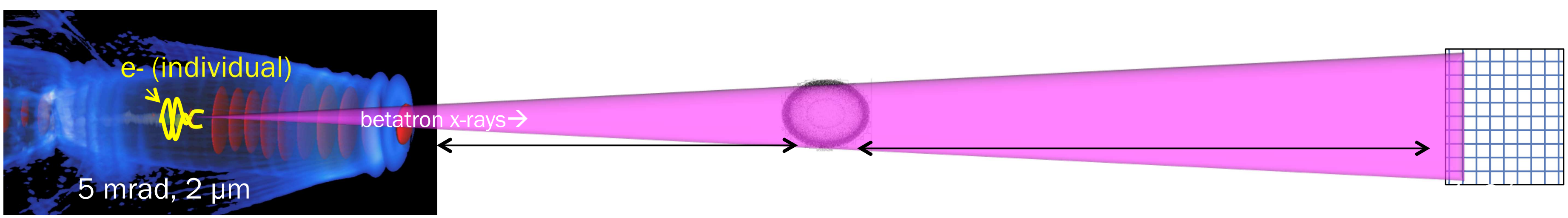
Related: F. Albert et al LLNL

HEDS diagnostic opportunities / needs



- Narrow angle of emission implies longer stand off
- Need to know:
  - What is the desired probe energy, bandwidth
  - Photon # coupled to detector aperture at this energy

    Poisson Dynamic range? Target absorption dynamic range? Other?
  - Where is coherence needed? longitudinal, transverse?
  - When do we care about/need to block laser/electron effect on target?
- Diagnostic constraint: Narrow divergence 1-100 mrad (dep. on source & energy) implies longer source-to-target distance; therefore also longer target to detector



Outline

- Plasma accelerators
- Advanced sources & high energy density science
- kHz precision frontier

Science Need: kHz Key to Efficient, High Quality Accelerators & Ultrafast Science

Laser plasma accelerator potential shown

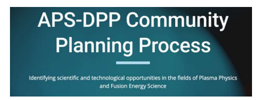
- Order of magnitude performance increase needed for HEP and applications
- Theory & simulation show attainable

Realizing potential requires precision

Broad ultrafast science potential

- HEDS precision time resolved tomography over thousands of shots
- Attoscience, Molecular Dynamics, Sensing, Nuclear Science, Radiation biology
- Sources for Bioimaging, COVID, Microelectronics, HEP detectors,
- Applications limited by rate & performance

Realizing potential requires rate



Increasing laser energy only does not enable applications – not efficient

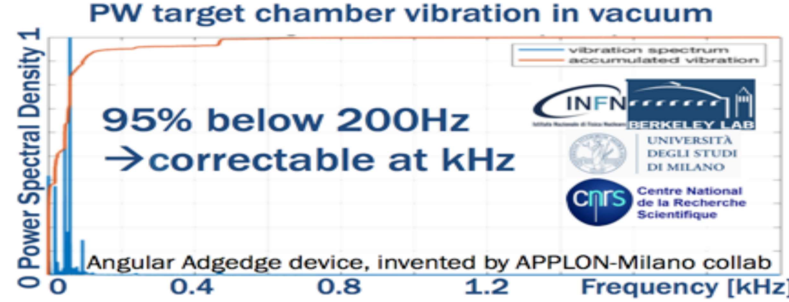
Precision laser shaping and control required for quality and efficiency

- Laser pointing: from μrad to < 0.1 μrad
- Focal spot/wave front: now at fluctuation limit
- Near field: currently not well controlled
- Pulse shape, carrier envelope phase…

Ground & air motion fall off at O[100Hz]

Correction at kHz >10 fold - key to LPA performance

PW target chamber vibration in vacuum



BELLA mJ kHz: 10x reduced pointing fluctuation
Other groups: CEP, spectral phase…

Laser Control and Stabilization for Precision LPA on Existing Lasers

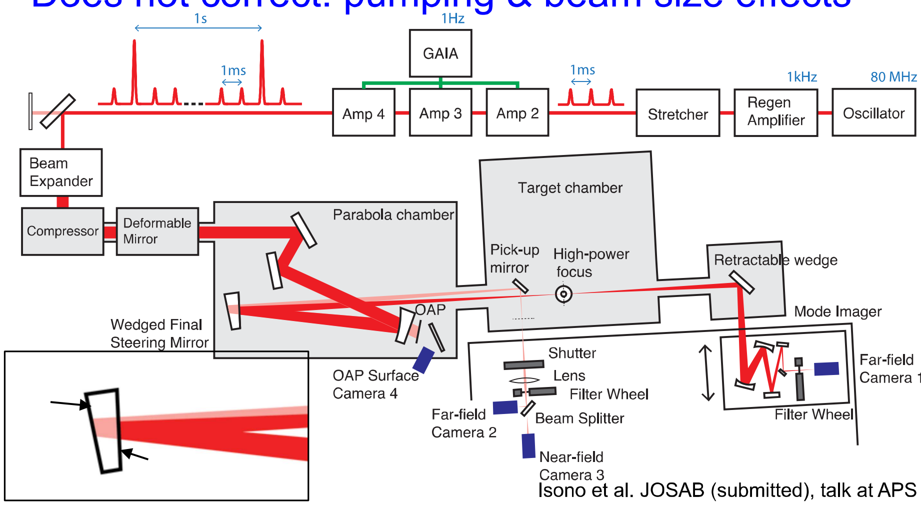
kHz-mJ regen pilot beam to characterize 100TW system

- Wedged steering mirror: 'copy' of pulse
- Position and angle on target in both planes

Pilot well correlated to amplified pulse

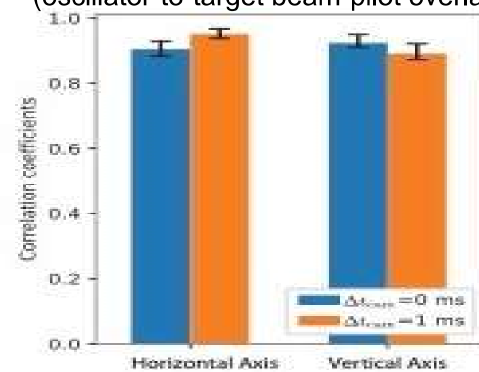
- Diagnostics: non-perturbative at high-power
- Correction to be enabled at kHz – potential 10x improved pointing
- Path to correction of other parameters

Does not correct: pumping & beam size effects

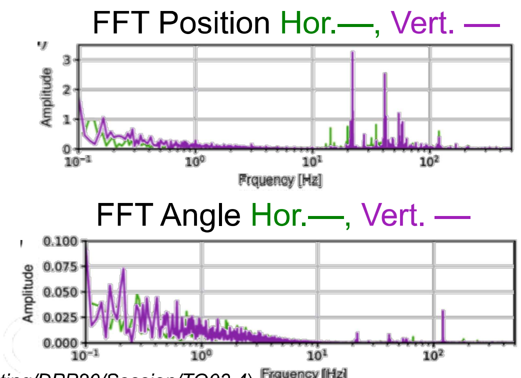


Pilot well correlated to amplified beam

(oscillator-to-target beam-pilot overlap)



Fluctuation primarily < 100 Hz

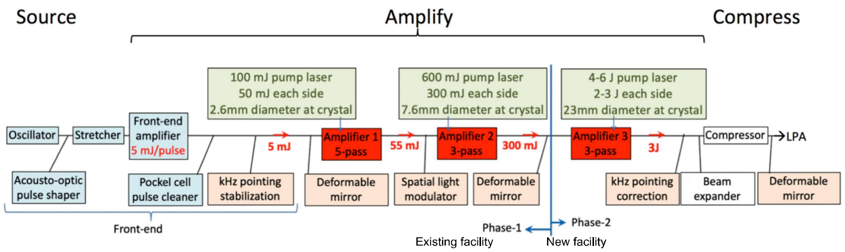


Isono et al. JOSAB (submitted), talk at APS DPP 2020 (*hmeetings.aps.org/Meeting/DPP20/Session/TO03.4*)

Ti:sapphire kHz Design Ready to Build

Ti:sapphire – extend existing systems

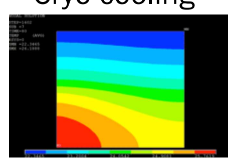
Near term 3J / GeV LPA available



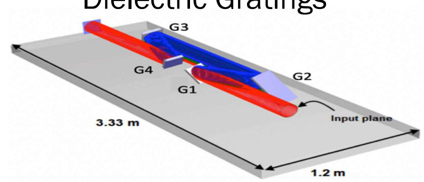
Laser energy pump
Diode pump lasers (Commercial)

Also: Colorado State, TRUMPF, MIT-LL

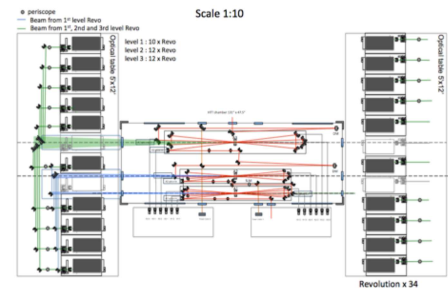
Heat extraction
Cryo cooling



Compression
Dielectric Gratings



Design detailed: Layout and > 200 line BOM



Based on established 100 TW system

Direct path to GeV kHz system for LPA studies.

LBNL - LLE –LLNL
MIT-LL and Colorado State discussions

Other technologies needed for high efficiency > few % and repetition rates beyond kHz class

U.S. DEPARTMENT OF ENERGY | Office of Science

Towards Application Luminosity Needs: Developing High Repetition Rate Lasers (Joint with BACI)

Fiber lasers enable: beyond kHz with high efficiency

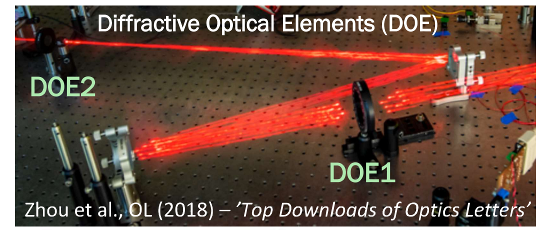
- Critical for collider roadmap
- Combine ~100 fibers ✕ Stack 100 pulses temporally for Joule energy

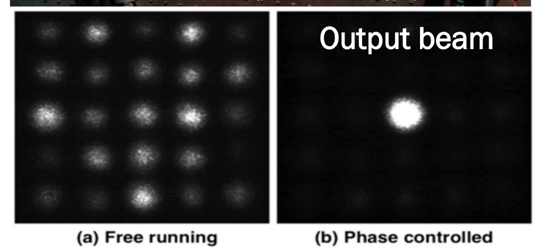
LBNL – U. M. – LLNL projects developing architecture

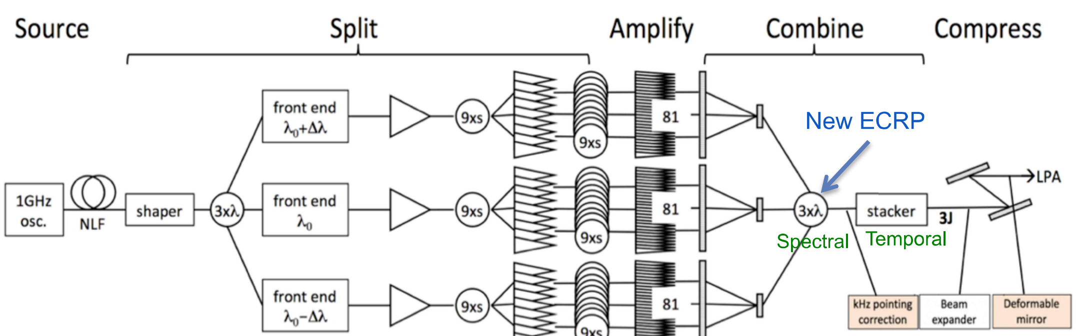
- Stewardship: Scalable diffractive combining – Combined 81 low energy beams
  Coherent pulse stacking – Stacked 81 high energy pulses
- ECRP (Qiang Du): Controls for efficient combining & stacking
- New ECRP (Tong Zhou): Spectral combining for 30fs pulses & LPA demo

Near term path to hundreds of mJ, 10's of fs systems

- Future 10 Joule class, 10's of kHz collider drivers

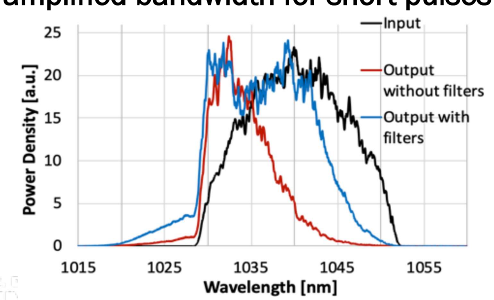






Coherent combined fiber laser architecture

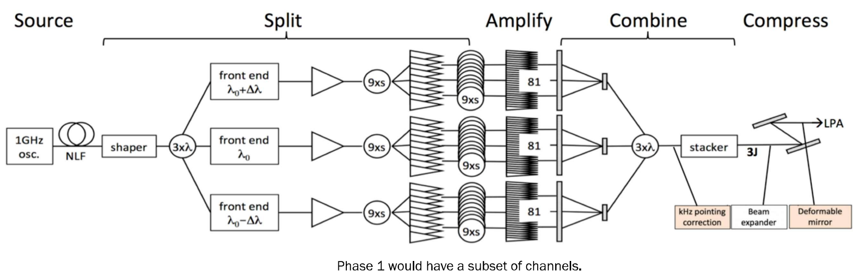
Distributed Spectral Filtering preserves amplified bandwidth for short pulses



Zhou et al., Advanced Solid State Lasers 2020

Laser Technology Path Established for Future High Efficiency

Fiber combination

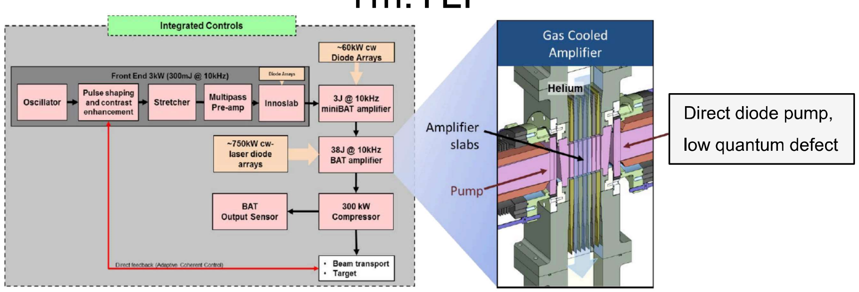


Phase 1 would have a subset of channels.

LBNL-U.M.-LLNL

LLNL lead – Leily Kiani

Tm:YLF



LLNL with LBNL discussion

Courtesy: Tom Spinka, LLNL

R&D under accelerator stewardship program

- Technical roadmaps in progress for both technologies

Path in next 5 years for fiber and Tm:YLF

- 100's of mJ, 100 fs class systems feasible
- Build full Joule-class compressor & support systems to provide for future expansion
- Laser development platform

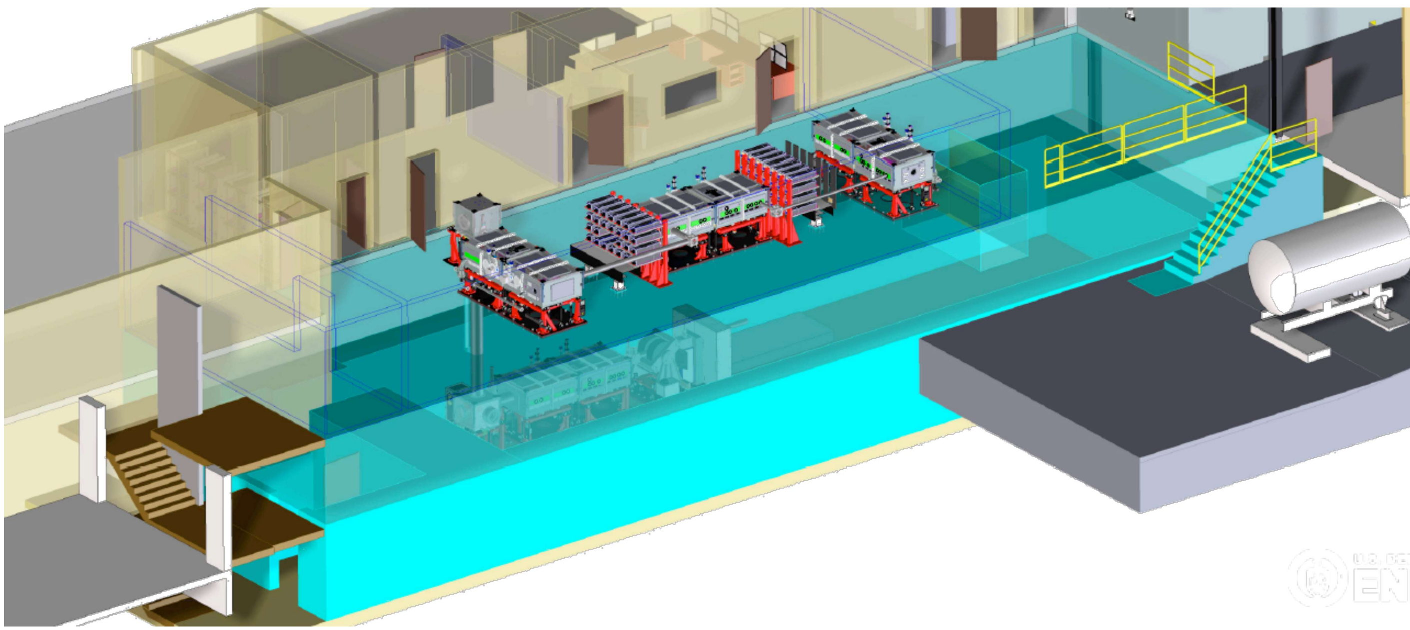
Future path for fiber and Tm:YLF

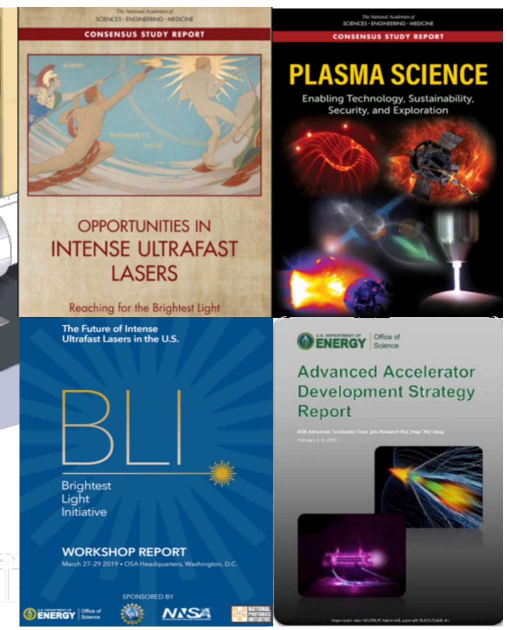
- Highly efficient systems
- 10's of kHz at Joules of energy and 30-60fs

kBELLA Initiative Under Development for kHz, Joule-class LPA

High priority in community and funding agency plans for precision LPA

- Ti:sapphire is ready to execute at GeV class in next few years
- Fiber & Tm:YLF offer path to future high efficiency, with lower energy in near term
- Facility supporting multiple lasers for immediate experiments and long term development
- Key step on collider roadmap and enables photon sources and precision HEDS





Summary

LPA performance advancing strongly

- 8 GeV record using laser-heated capillary

2nd Beamline will enable high quality LPA staging

- Platform for: controlled injection, laser produced guides, and positrons
- Flexible spot size will assist both staging and single stage campaigns

Photon sources, user experiments and ion acceleration reinforce program

- Common techniques with collider at accessible scale
- HEDS pumps and probes

Precision control of laser drivers is key to LPA advancement

- Path to efficient future kHz systems via fiber combination and other approaches
- kHz, Joule class is a key next step for control and applications

LBNL-LLNL collaboration opportunities ranging from simulations to ion acceleration to photon sources