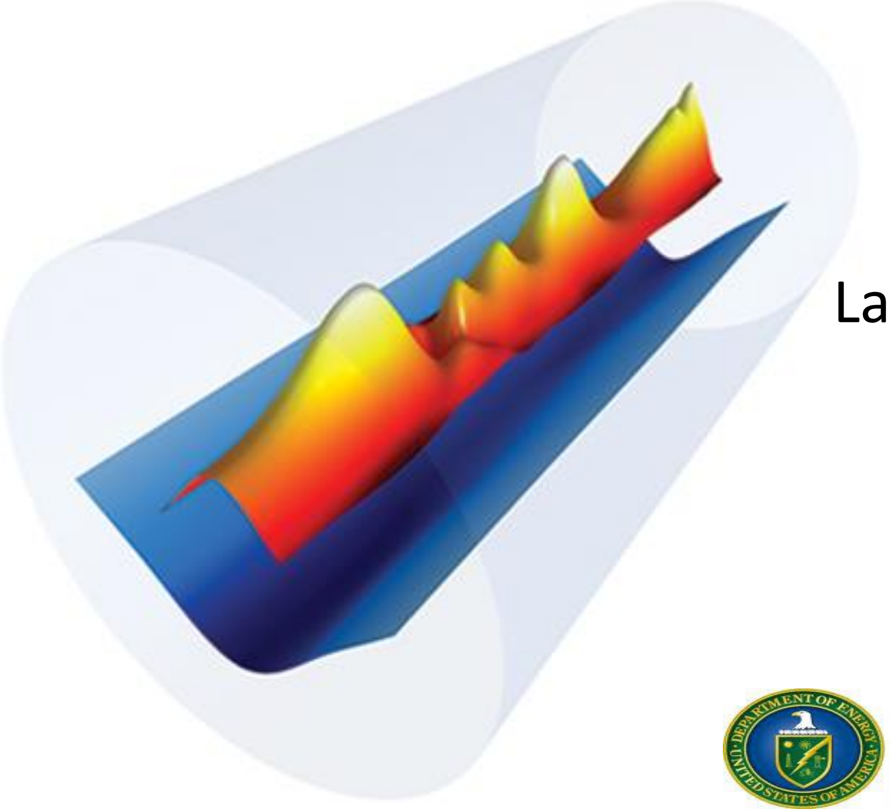
Progress on Laser-Driven Plasma Accelerators for High-Energy Physics and Medical Applications

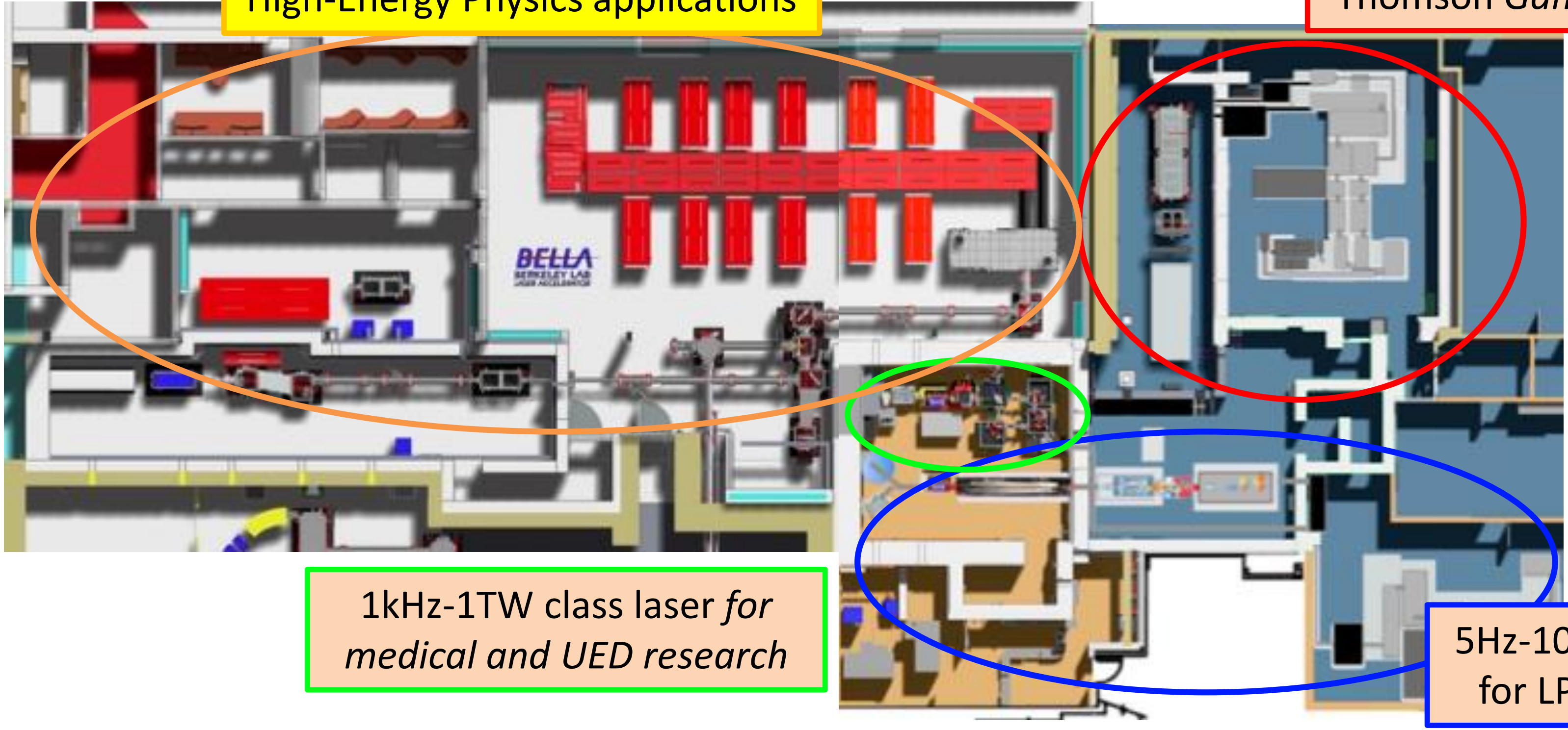


Sven Steinke

Lawrence Berkeley National Laboratory

Joint DESY and University of Hamburg
Accelerator Physics Seminar
Aug. 15 2019

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



1Hz-1PW class laser for High-Energy Physics applications

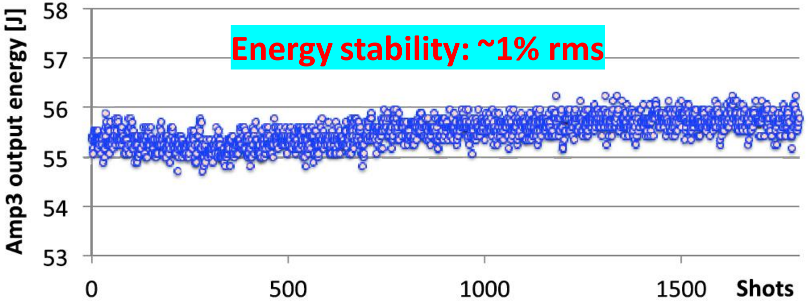
5Hz-100TW class laser for LPA-Thomson *Gamma rays source*

1kHz-1TW class laser *for medical and UED research*

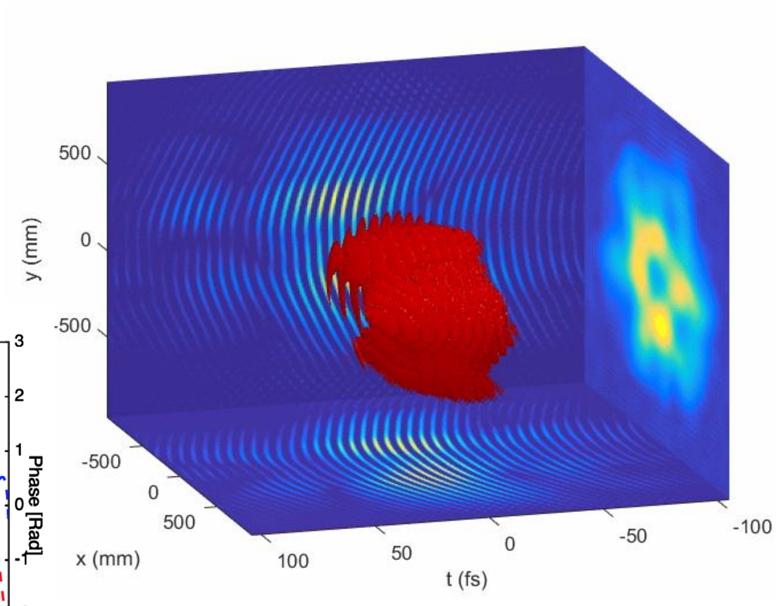
5Hz-100-TW class laser for LPA-FEL research

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

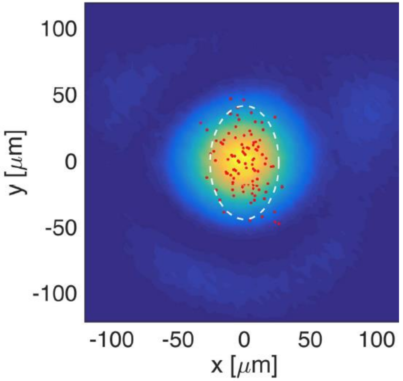
Energy stability: ~1% rms



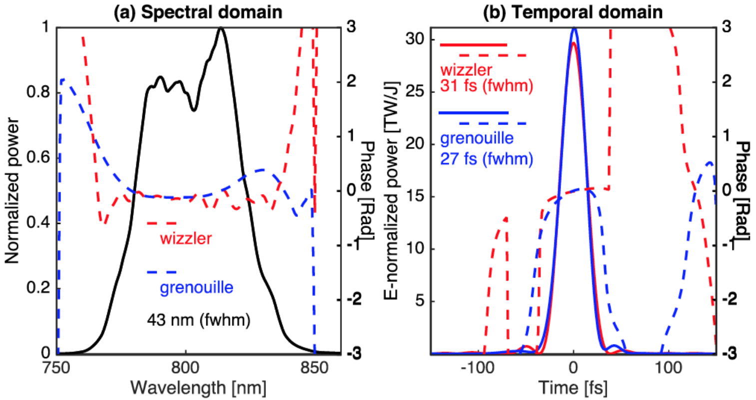
3D STC characterization[2]



Spatial profile,
pointing stability: ~1 urad rms

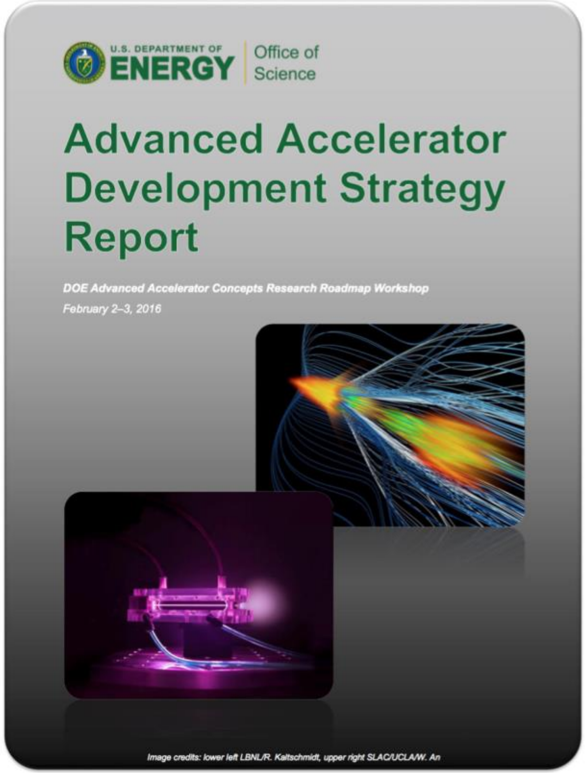


Temporal profile



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

Strategy report for advanced accelerators from DOE covers laser and beam driven plasma + dielectric wakefield



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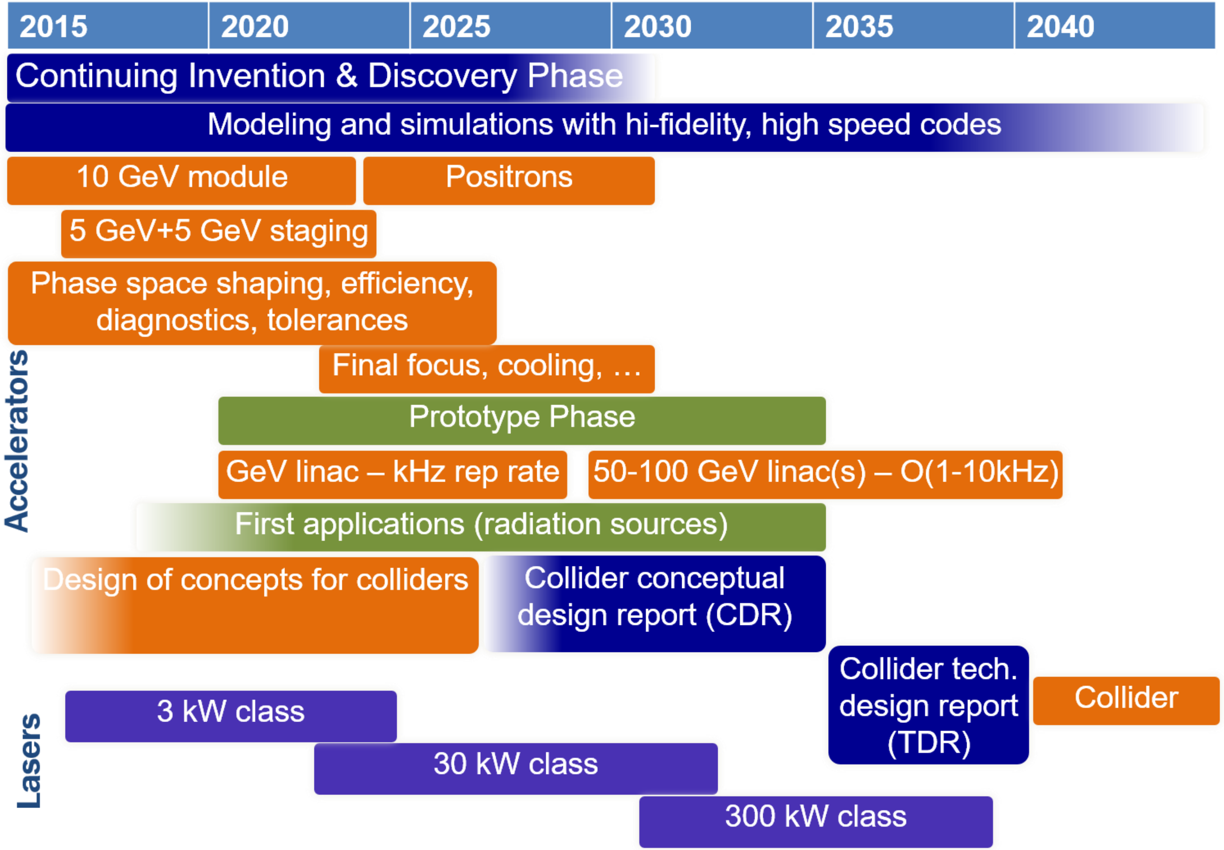
Advanced Accelerator Development Strategy Report

DOE Advanced Accelerator Concepts Research Roadmap Workshop

February 2–3, 2016

Image credits: lower left LBNL/R. Kaltschmidt, upper right SLAC/UCLA/W. An



2015 | 2020 | 2025 | 2030 | 2035 | 2040

Continuing Invention & Discovery Phase

Modeling and simulations with hi-fidelity, high speed codes

Accelerators

10 GeV module

Positrons

5 GeV+5 GeV staging

Phase space shaping, efficiency, diagnostics, tolerances

Final focus, cooling, …

Prototype Phase

GeV linac – kHz rep rate

50-100 GeV linac(s) – O(1-10kHz)

First applications (radiation sources)

Design of concepts for colliders

Collider conceptual design report (CDR)

Collider tech. design report (TDR)

Collider

Lasers

3 kW class

30 kW class

300 kW class

LPAs are operational at plasma density: $10^{16} - 10^{18}$ cm^{-3}

- Laser-plasma interaction length:

$$L_{\text{deplete}} \propto n^{-3/2}$$

- Accelerating gradient: (require > GV/m)

$$E_z \sim \left(m_e c \omega_p / e\right) \propto \sqrt{n}$$

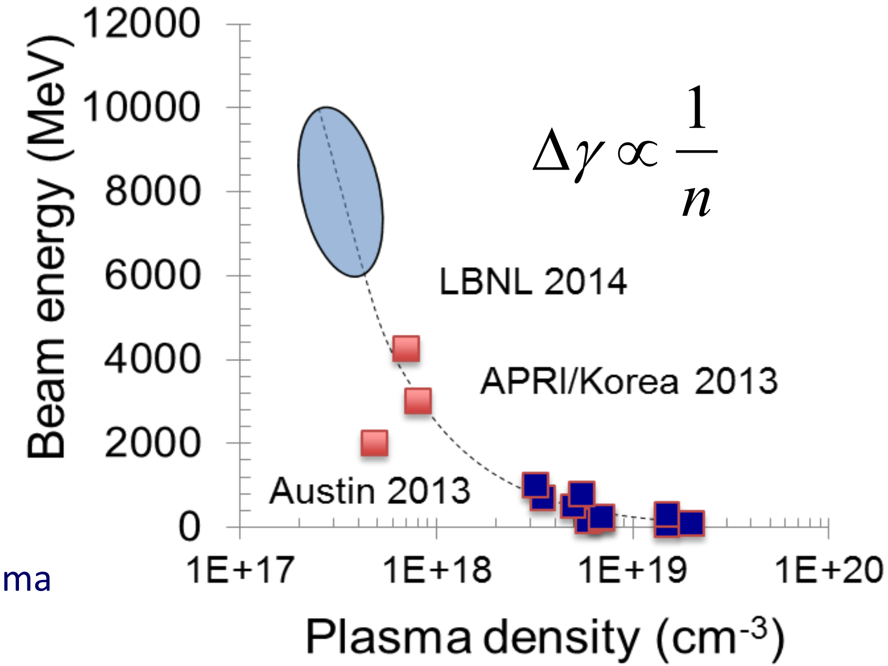
- Energy gain (per LPA stage):

$$E_z \cdot L_{\text{int}} \propto 1/n$$

- For high-energy applications, laser depletion (and reasonable gradient) necessitates staging laser-plasma accelerators

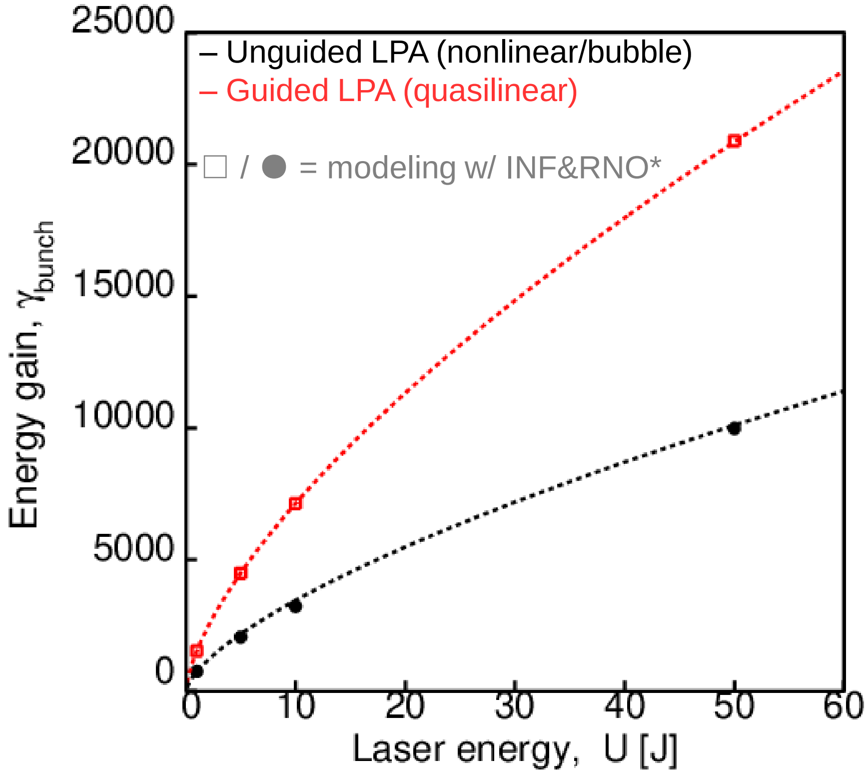
- Bunch charge: $N_e \propto 1/\sqrt{n}$

Next step 6-10GeV with 2-4x10^{17}cm^{-3}



Schroeder et al., W. P. Phys. Rev, ST, 13, 101301 (2010).

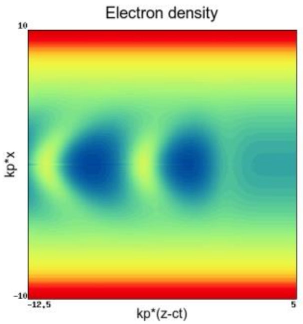
Guided LPA: For given laser energy, the energy gain is larger than in unguided LPAs due to lower density and longer length[4]



$$n_0[\mathrm{cm}^{-3}] \simeq 7.6 \times 10^{16} a_0^{4/3} (k_p w_0)^{4/3} (k_p L)^{2/3} (U[\mathrm{J}])^{-2/3}$$

a_0=1.6, $k_p w_0$= 4, $k_p L$=1.8

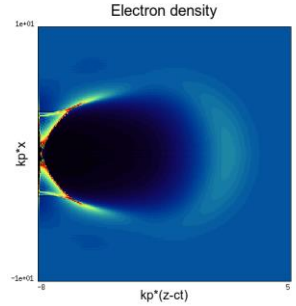
e.g., n_0=2.6x10^{17} cm^{-3} for U=10 J, a_0=1.5



a_0=4.5, $k_p w_0 = 2\sqrt{a_0}$, L_{fwhm}=(2/3)w_0

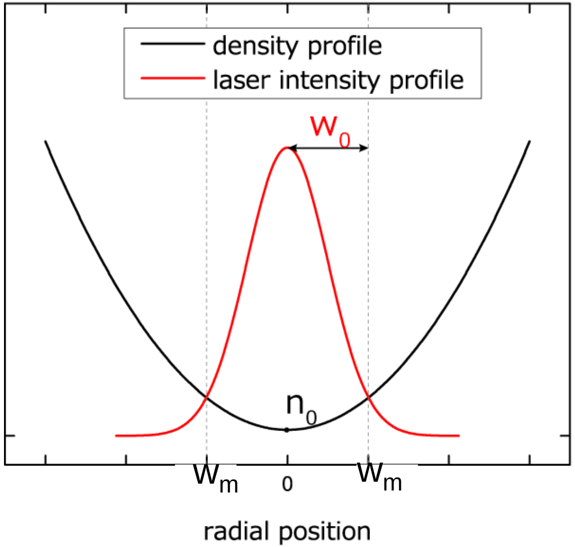
$$n_0[\mathrm{cm}^{-3}] \simeq 2.1 \times 10^{17} a_0^{7/3} (U[\mathrm{J}])^{-2/3}$$

e.g., n_0=1.5x10^{18} cm^{-3} for U=10 J, a_0=4.5



[4] W. Lu et al., PRSTAB 10 (2007) 061301, C. Benedetti et al., PPCF 60 (2017) 014002.

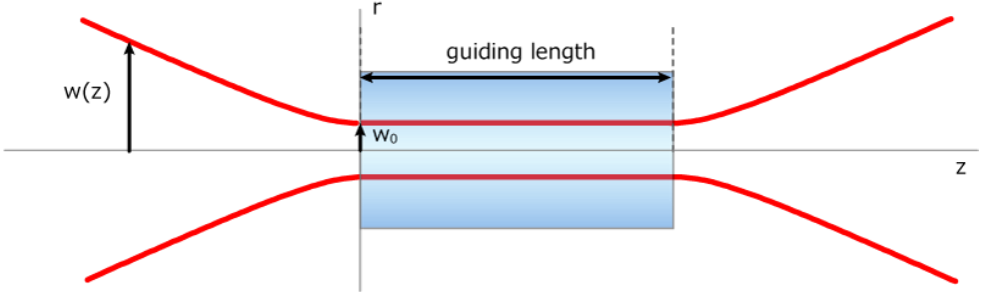
Pre-formed waveguide can mitigate diffraction to increase acceleration length and beam energy



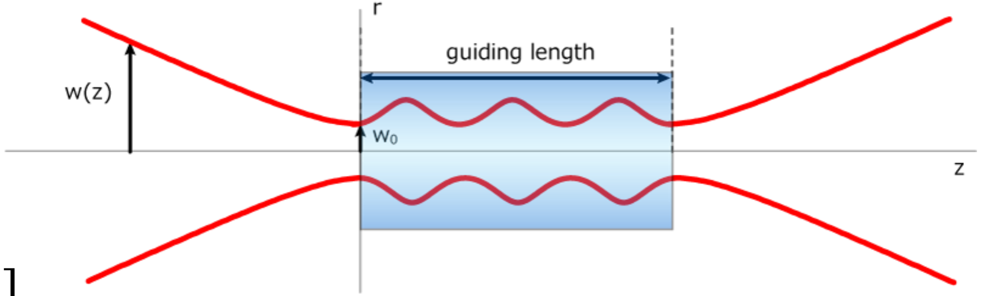
$$n(r) = n_0 + \frac{r^2}{\pi r_e {w_m}^4}$$

$$w^2(z) = \frac{w_0^2}{2}\left[1 + \frac{w_m^4}{w_0^4} + \left(1 - \frac{w_m^4}{w_0^4}\right)\cos\left(2\frac{\lambda}{\pi w_m^2}z\right)\right]$$

Matched guiding ($w_m = w_0$)



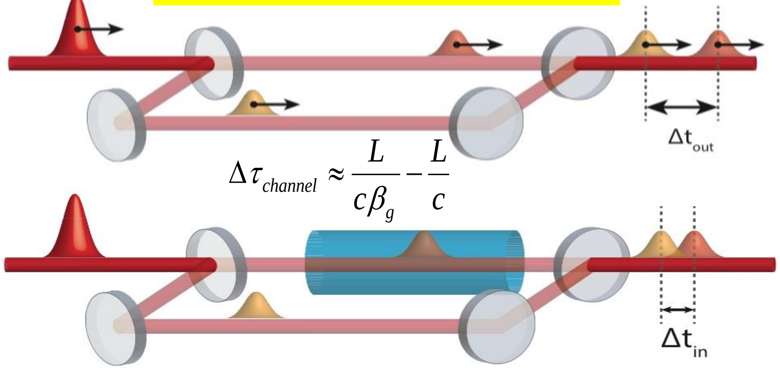
Mismatched guiding ($w_m > w_0$)



Laser pulse intensity high over long distance ($w_m \sim w_0$ desired)

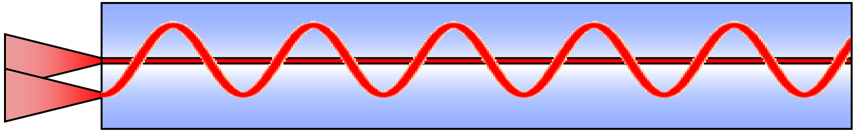
Plasma channels measured using group velocity and centroid oscillation techniques

n_0 from group velocity[7]



$$\Delta\tau_{channel} \approx \frac{L}{c\beta_g} - \frac{L}{c}$$

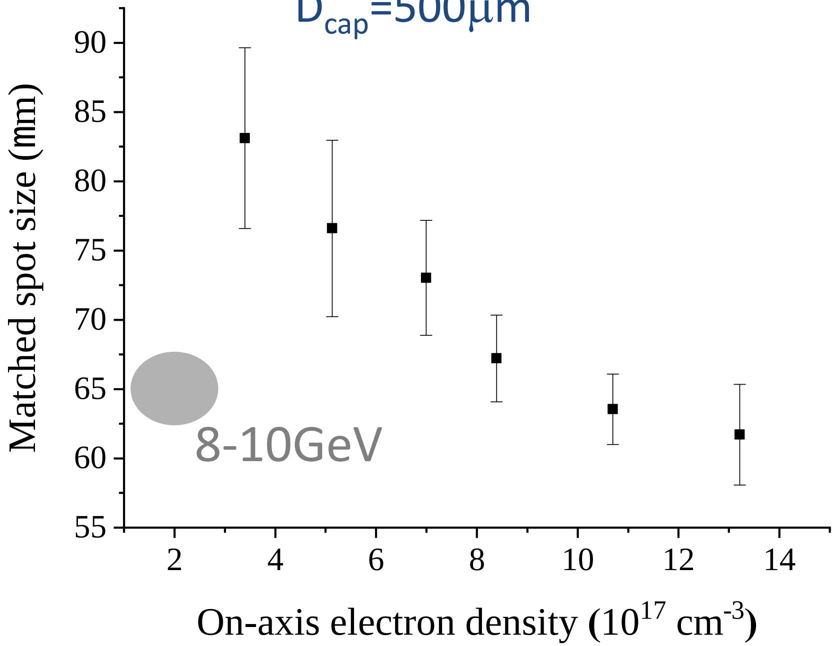
W_m from Centroid/spot size oscillation[8]



$2\pi Z_m$

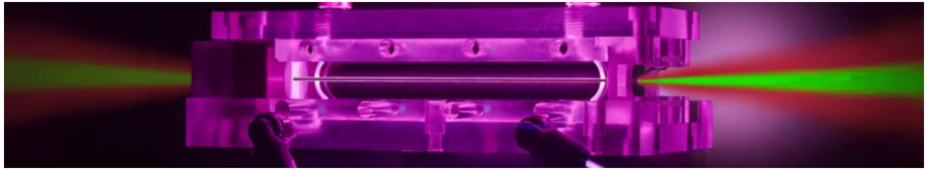
$$w_m = \sqrt{\frac{\lambda Z_M}{\pi}}$$

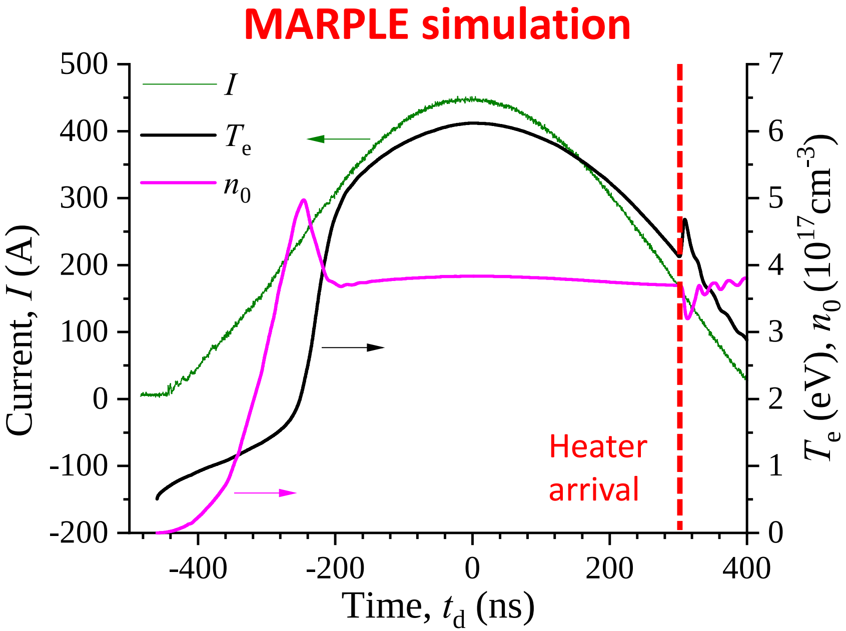
D_{cap}=500μm



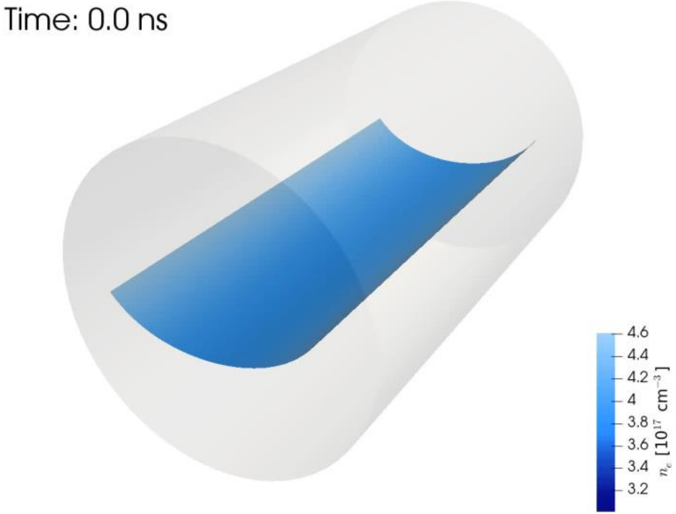
[7] J. Daniels et al., Phys. Plasmas 22, 073112 (2015); J. Van Tilborg et al., Phys. Rev. E 89, 063103 (2014). [8] A. J. Gonsalves et al., Phys Plasmas 17 (2010).

“Heater” laser to increase channel strength & guide laser pulses at lower density



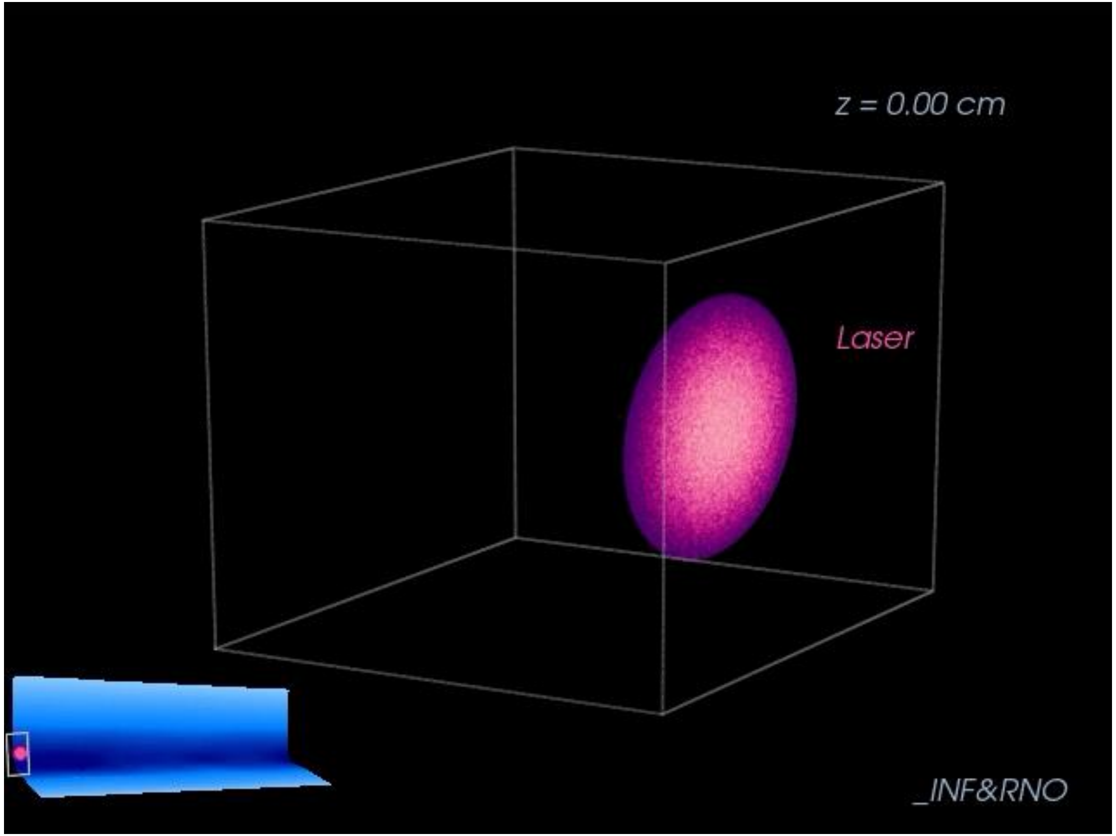

MARPLE simulation

- Nanosecond pulse locally heats plasma through Inverse Bremsstrahlung (IB)[9]
  - •absorption of photons by free electrons
- Electron density distribution is changed
  - •n_0 reduces
  - •w_m reduces locally (faster rise of density from axis)



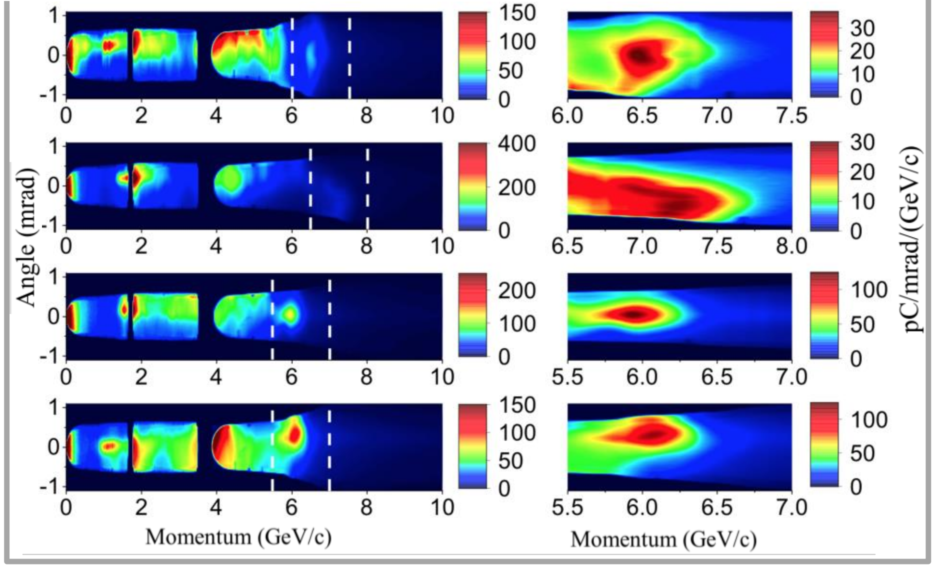
[9] C. Durfee *et al.*, *PRL 71* (1993) 2409; P. Volfbeyn *et al.*, *POP 6* (1999) 2269; N. Bobrova *et al.*, *POP* 20 (2013) 020703;

Simulation shows non-linear bubble regime with multiple electron bunches



Electron beams with energy up to 7.8GeV observed

Experiment 3.4x10^{17}cm^{-3}



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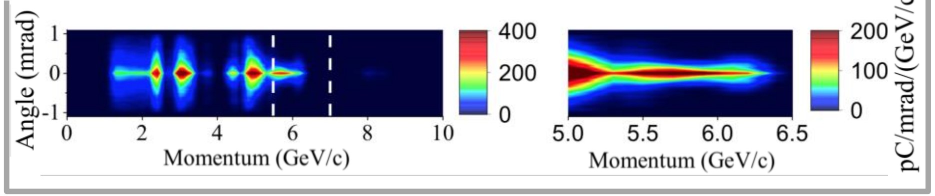
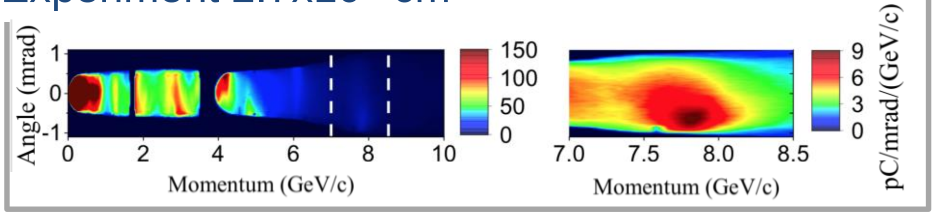
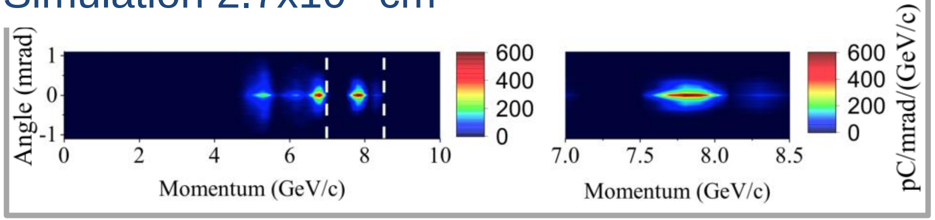


Experiment 2.7x10^{17}cm^{-3}



Simulation 2.7x10^{17}cm^{-3}

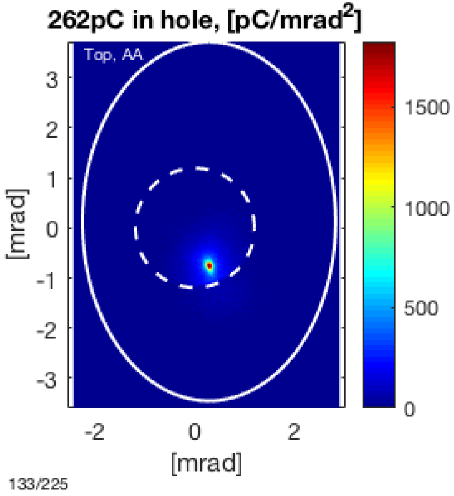


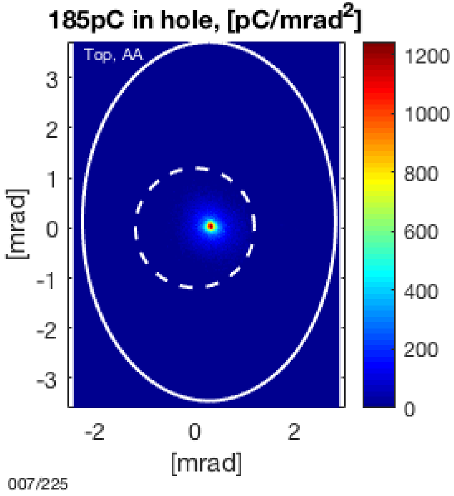
- Non-localized injection produces large energy spread
- Up to 60 pC (of >200 pC) in 6 GeV peaks
- Highest energy bunches dE/E~10%
- 0.5-1 joule energy in e beam

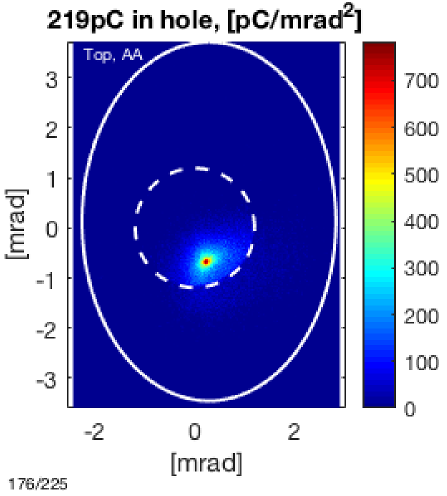
Gonsalves et al., PRL 122 (2019) 084801.

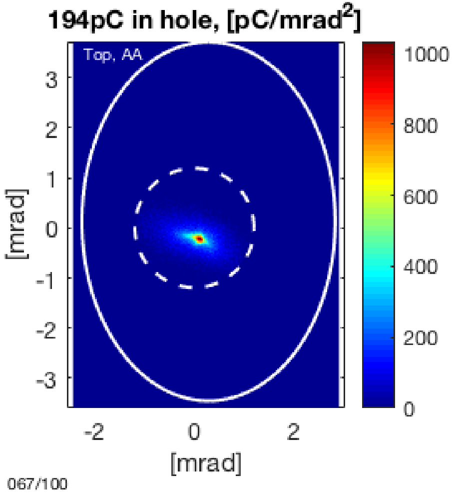
Lanex screen before magnet shows beam divergence down to 150 urad FWHM

Shots shown are based on whether beams are well centered along beamline. Most shots do not pass through the diagnostic acceptance (white dashed circle).

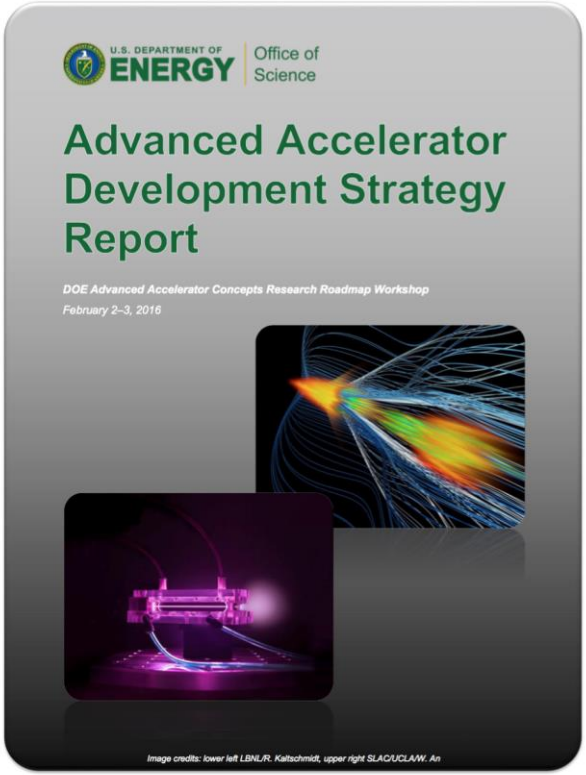








Strategy report for advanced accelerators from DOE covers laser and beam driven plasma + dielectric wakefield



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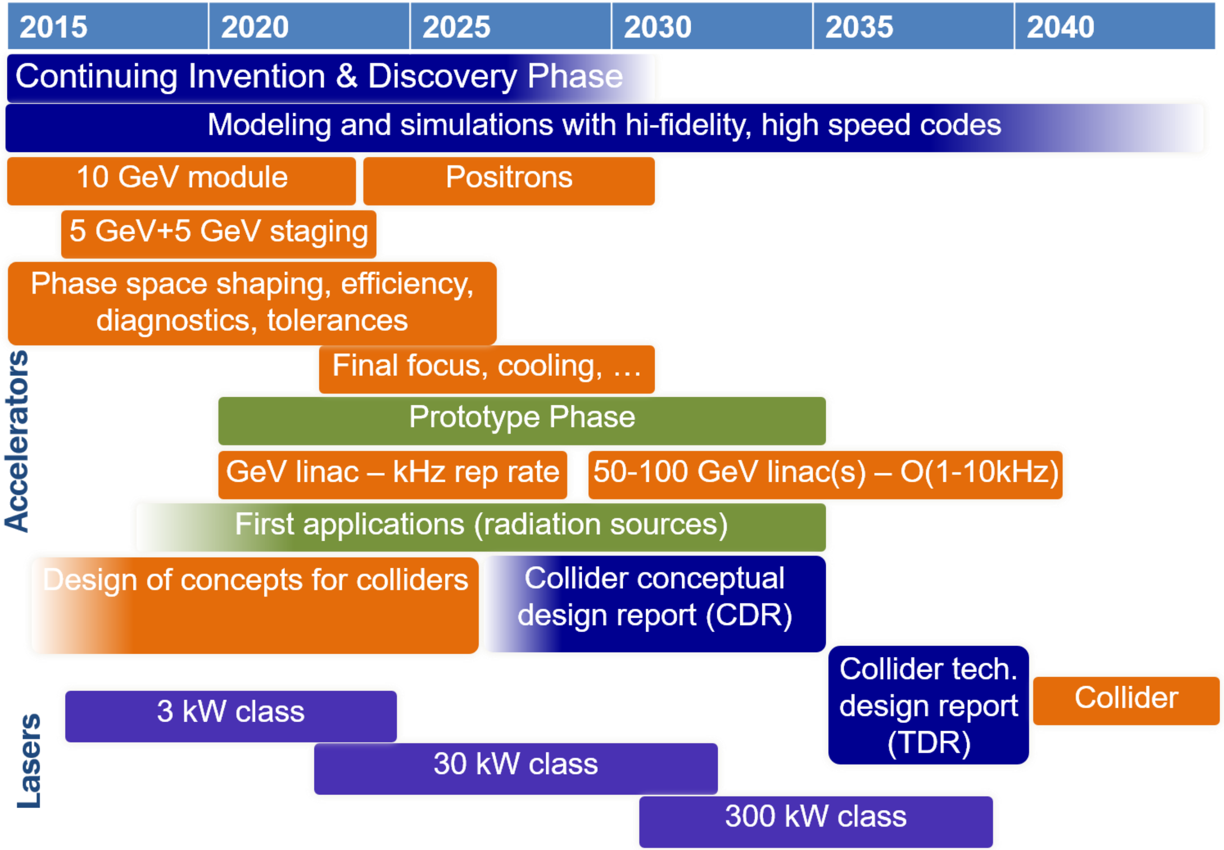

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Collider

Lasers

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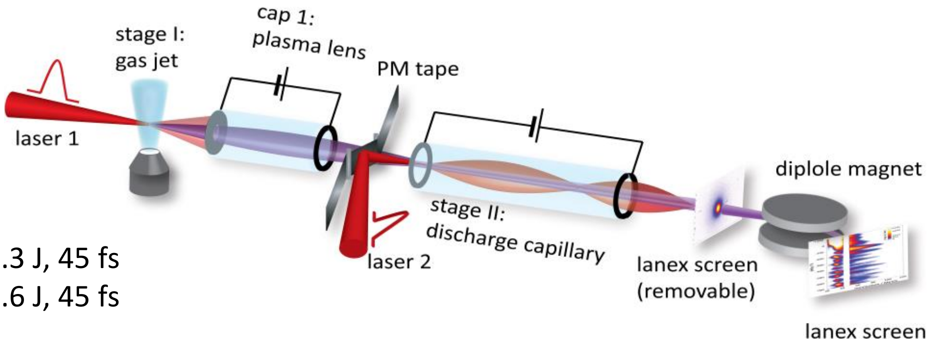
30 kW class

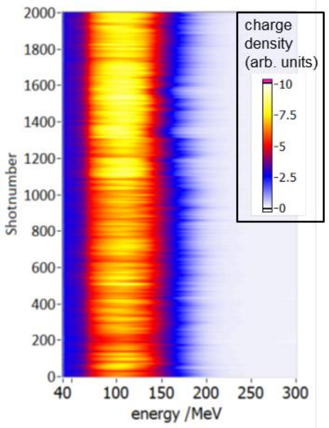
300 kW class

Multistage coupling of two independent LPAs successfully demonstrated with 40 TW laser (TREX)



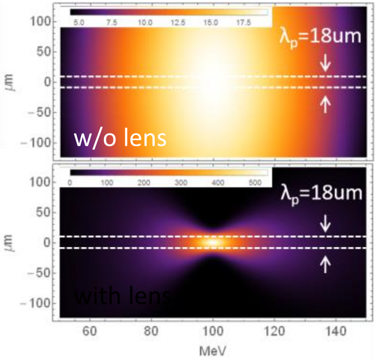
TREX:
laser 1: 1.3 J, 45 fs
laser 2: 0.6 J, 45 fs

Stable Injector



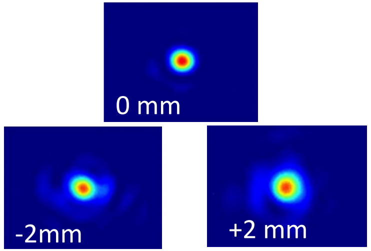
Plasma Lens Transport

Beam at stage 2 entrance:

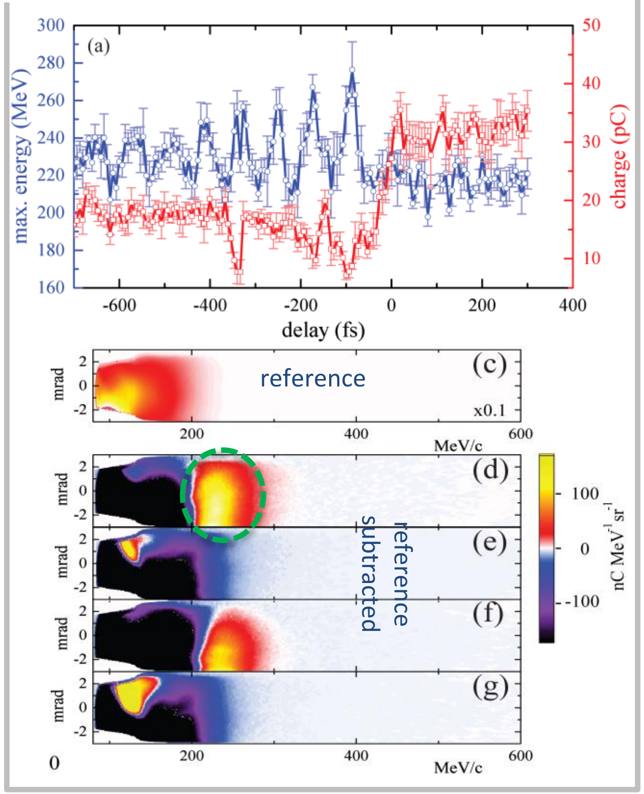


Plasma Mirror Tape

- Reflectivity <80%
- Strehl ratio >0.8
- Small pointing fluctuation
- Hours of runtime



Staging Result



*S. Steinke PoP 23, 056705 (2016); B. H. Shaw, PoP 23, 063117 (2016); J. van Tilborg, PRL **115**, 184802 (2015); S. Steinke, Nature **530**, 190 (2016)*

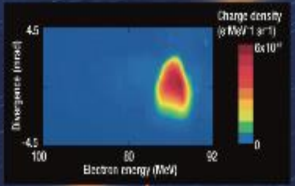
BELLA Center: Timeline of LPA Achievements in view of PR department

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

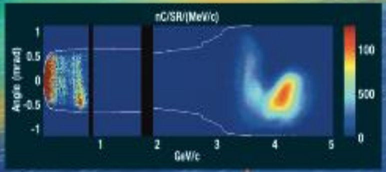


86 MeV

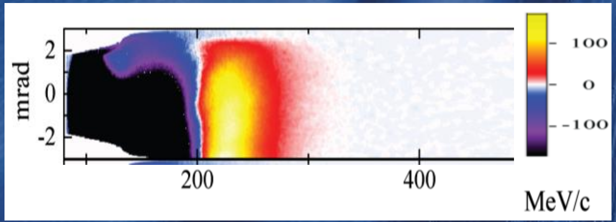
2006: 40TW

1 GeV

2014: 300TW

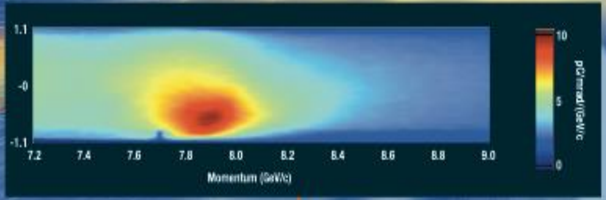


4.2 GeV



2016: 40TW staging demo

2019: 1000TW & laser heater



8 GeV

Enabling technologies for ever-higher performance

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

The rise of ion beam therapy started at Berkeley Lab

1946 E. Lawrence & R. Wilson (later founded Fermi Lab) recognized potential of Hadron therapy during calculation of radiation shielding.

1954 First human cancer treatment at 184-inch cyclotron.

1955 First treatment with helium ions (C. Tobias).

1967 LBL's Heavy Ion Linear Accelerator (HILAC) was built. C. Tobias et al., started investigating heavy ion cancer therapy.

1970s heavy ions from HILAC were piped to Bevatron (Bevalac). Long-term clinical trials establish biomedical properties of heavy ions, resulting in first evidence for safe and effective treatment of cancer.

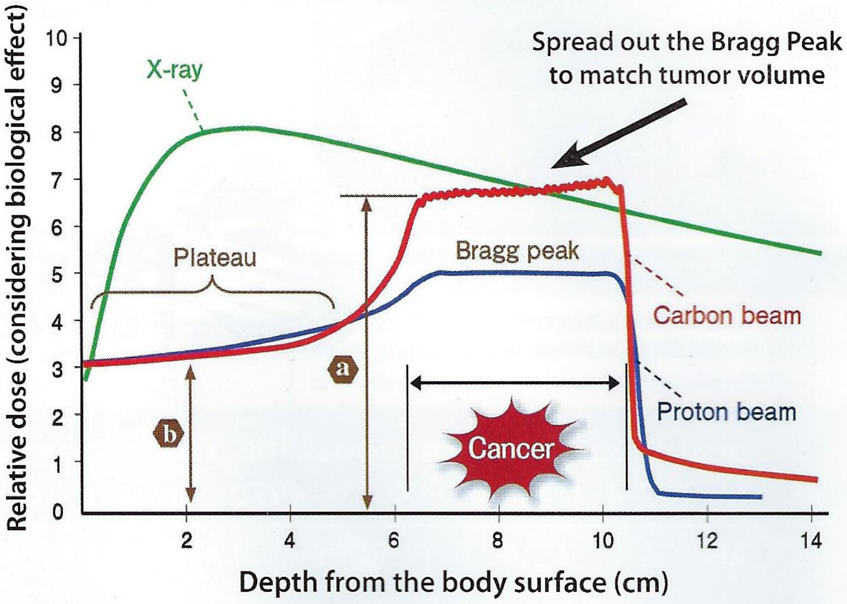
<1993 ~3000 patients were treated at 184-inch Cyclotron and Bevalac.

Cancer patients were treated at the Bevalac with the help of a plastic head positioner and beam compensator.

https://newscenter.lbl.gov/2010/10/18/ion-beam-therapy/

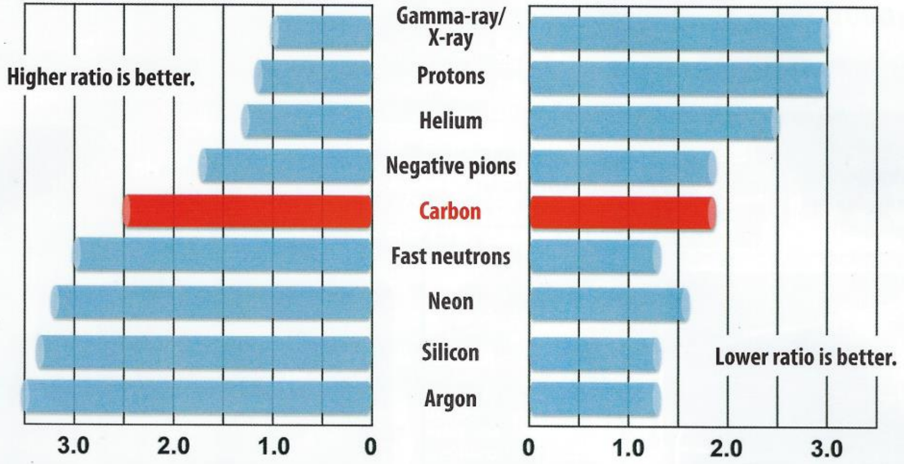
Carbon ion radiotherapy offers superior dose conformity in the treatment of deep-seated malignant tumors compared with conventional X-ray therapy

Peak-to-Plateau ratio of the RBE (a/b) is larger in carbon ion beams than for proton beams.



Graph courtesy of Hirohiko Tsujii et al., Radiological Sciences, 50(7), 4, 2007

RBE: Relative Biological Effectiveness
OER: Oxygen Enhancement Ratio



RBE represents the biological effectiveness of radiation in the living body. The larger the RBE, the greater the therapeutic effect on the cancer lesion.

OER represents the degree of sensitivity of hypoxic cancer cells to radiation. The smaller the OER, the more effective the therapy for intractable cancer cells with low oxygen concentration.

Best Medical International, 2018

Prostate cancer irradiation represents improvements of radiotherapy technology

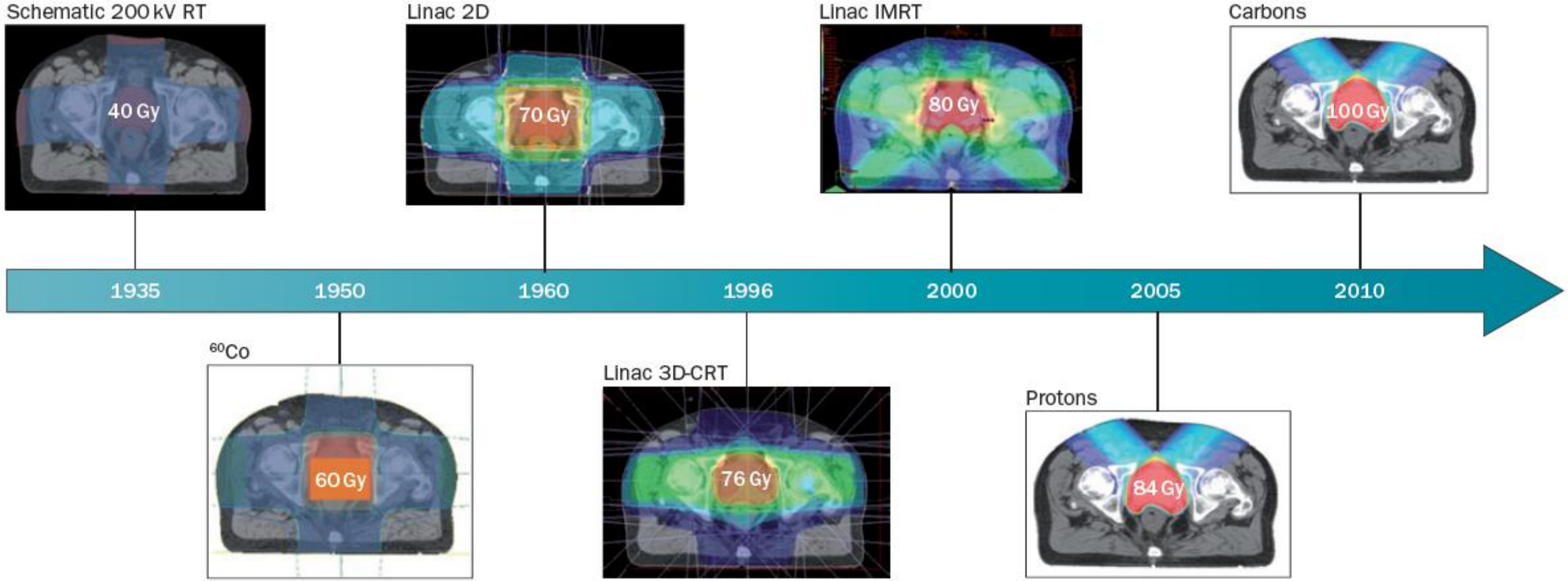


Figure 1 | Prostate cancer radiotherapy 1935–2010. Prostate cancer irradiation is a good example of the improvement of radiotherapy technology over the past decades. By increasing the beam energy and the precision of the targeting, it was possible to escalate the dose to the prostate without exceeding the tolerance dose of healthy tissues; allowing the move from palliative irradiation to curative treatment. Abbreviations: 3D-CRT, 3D conformal radiotherapy; IMRT, intensity modulated radiotherapy; RT, radiotherapy.

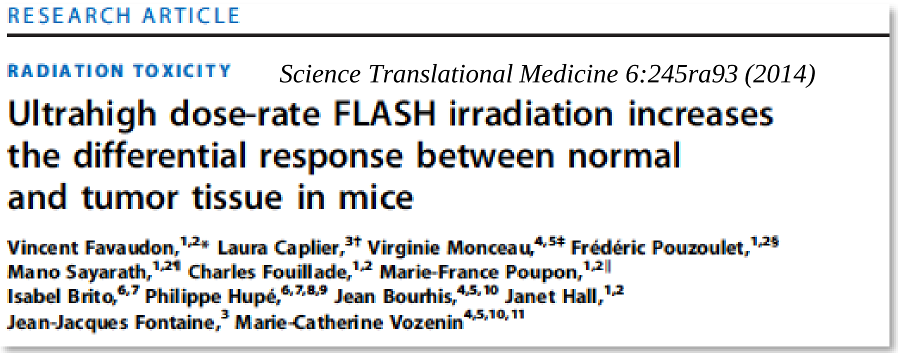
Thariat et al., Nature Reviews Clinical Oncology 10:52-60, 2013

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

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



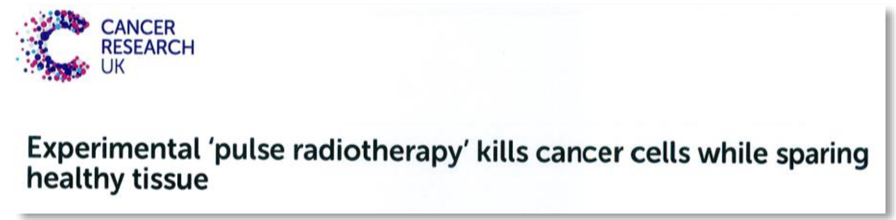
RESEARCH ARTICLE

RADIATION TOXICITY

Science Translational Medicine 6:245ra93 (2014)

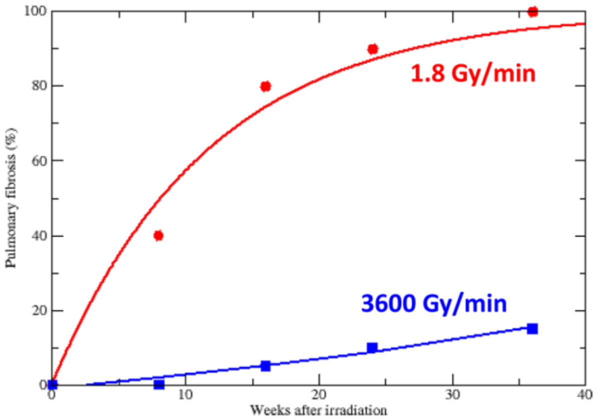
Ultrahigh dose-rate FLASH irradiation increases the differential response between normal and tumor tissue in mice

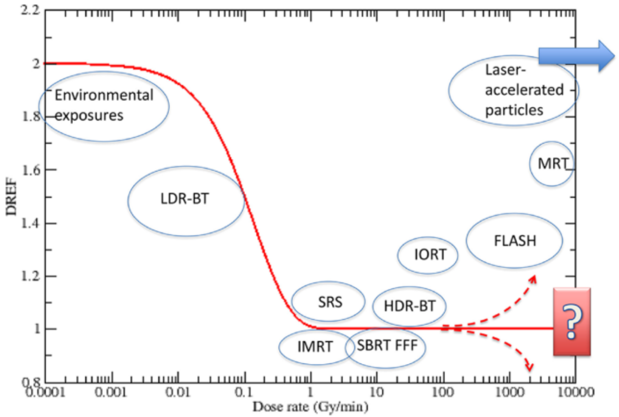
**Vincent Favaudon,[1,2*] Laura Caplier,[3†] Virginie Monceau,[4,5‡] Frédéric Pouzoulet,[1,2§]
Mano Sayarath,[1,2¶] Charles Fouillade,[1,2] Marie-France Poupon,[1,2||]
Isabel Brito,[6,7] Philippe Hupé,[6,7,8,9] Jean Bourhis,[4,5,10] Janet Hall,[1,2]
Jean-Jacques Fontaine,[3] Marie-Catherine Vozenin[4,5,10,11]**



CANCER RESEARCH UK

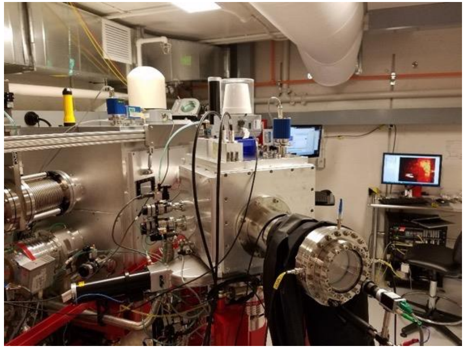
Experimental 'pulse radiotherapy' kills cancer cells while sparing healthy tissue

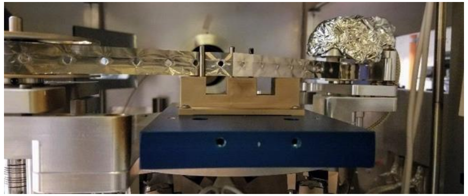




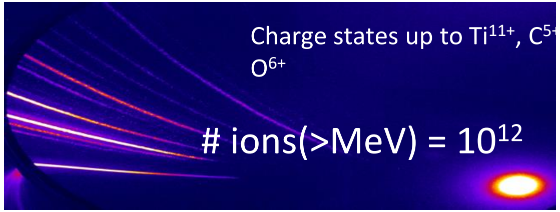
Durante et al., Br J Radiol 2018; **91***: 20170628.*

First Petawatt experiments at high repetition rate and statistical relevance revealed new physics of acceleration mechanism



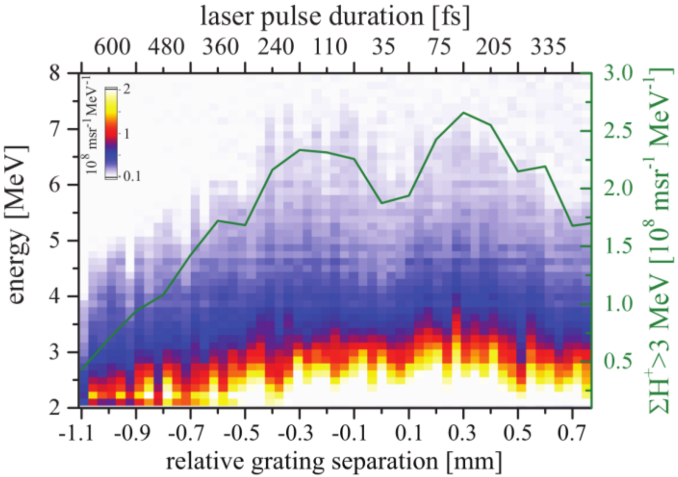


Setup: Tape-drive target and MCP-based Thomson Parabola Spectrometer adapted for rep-rated experiments.

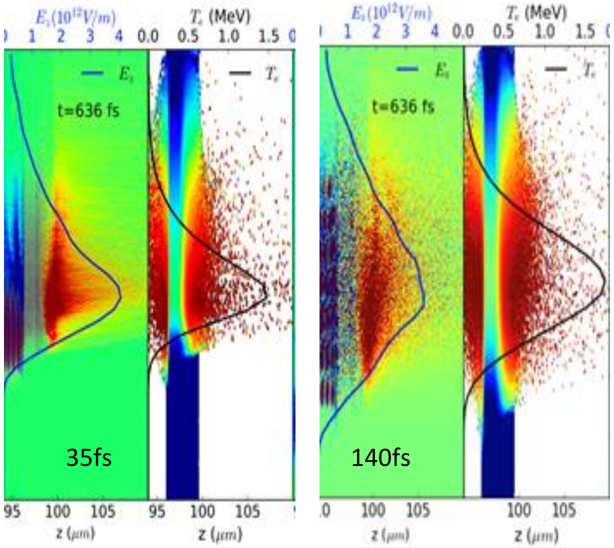


Charge states up to Ti^{11+}, C^{5+} O^{6+}

ions(>MeV) = 10^{12}



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

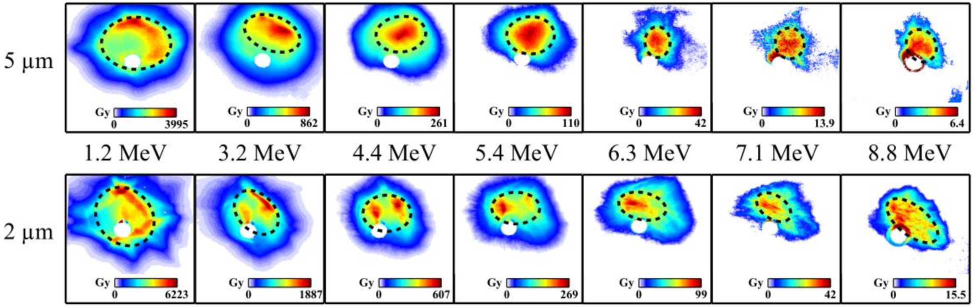


WARP simulations: Higher electron temperature and increased number of hot electrons for the optimum pulse duration ($2w_0/c$ ~ 140fs) due to sweeping effect.

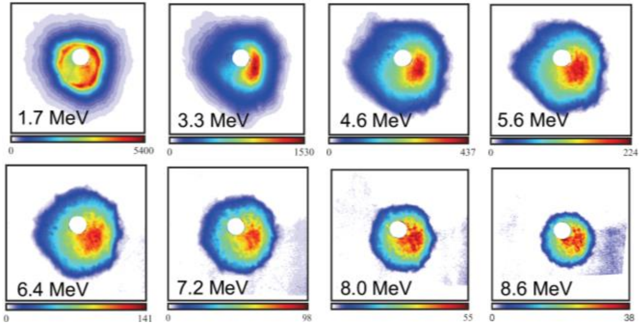
S. Steinke et al., under review

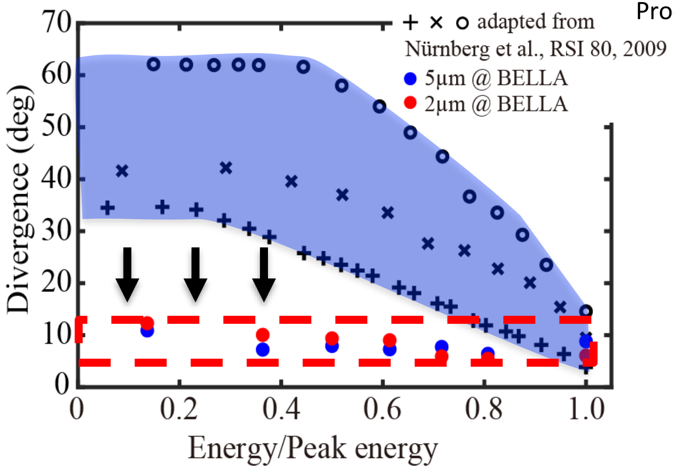
Larger laser spot size results in achromatic divergence and unprecedented charge density proton beams

Ti:



13 micron Kapton:





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)

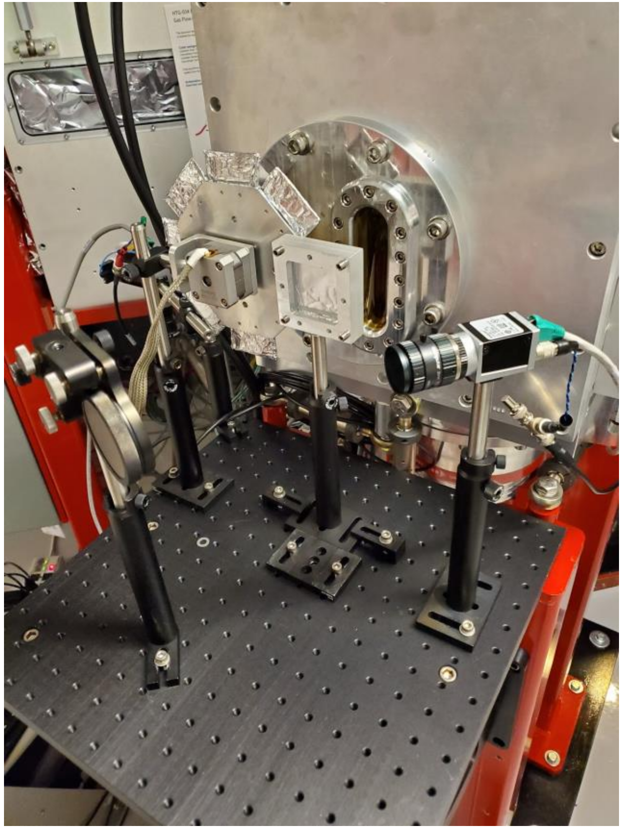
Charge density exceeds values from large single shot laser systems*

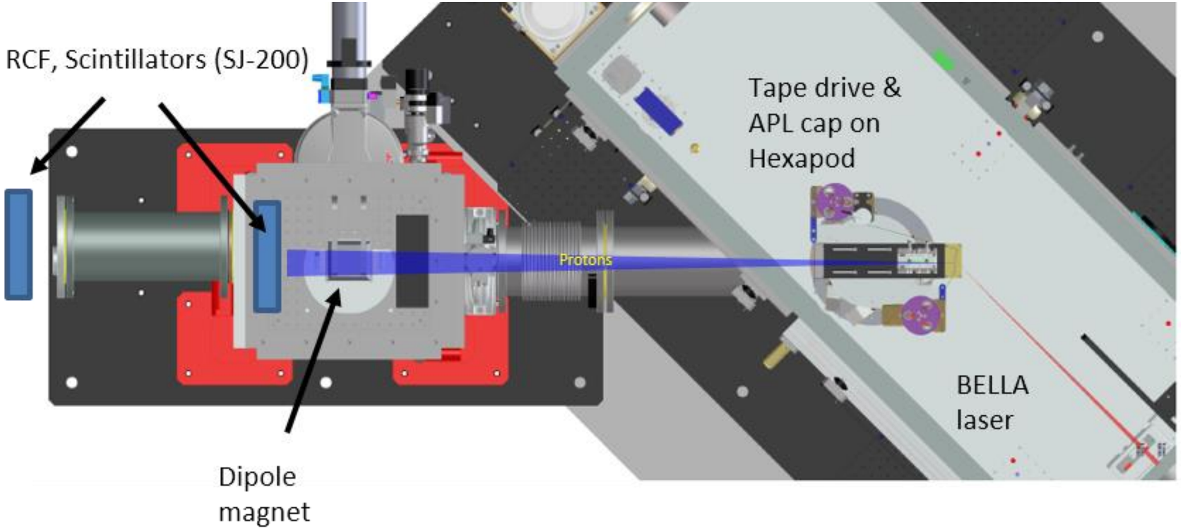
Ideally suited for subsequent beam transport

S. Steinke et al., under review

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

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

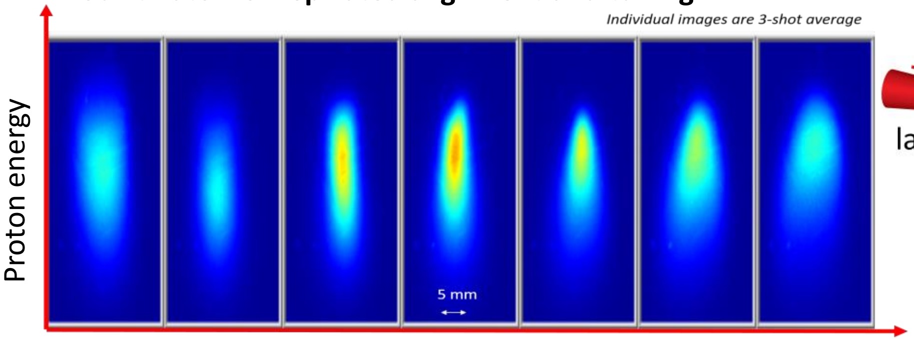




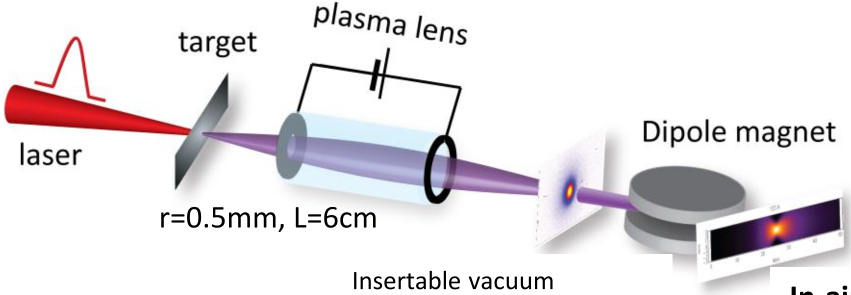
- 1mm x 60mm APL placed 5mm behind source
- APL captures 25mrad
- Proton source imaging at 300-fold magnification at 1.5m with RCF and scintillators

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

1. Scintillator for rep-rated alignment and tuning:



Discharge current, i.e. focus strength



Insertable vacuum scintillator

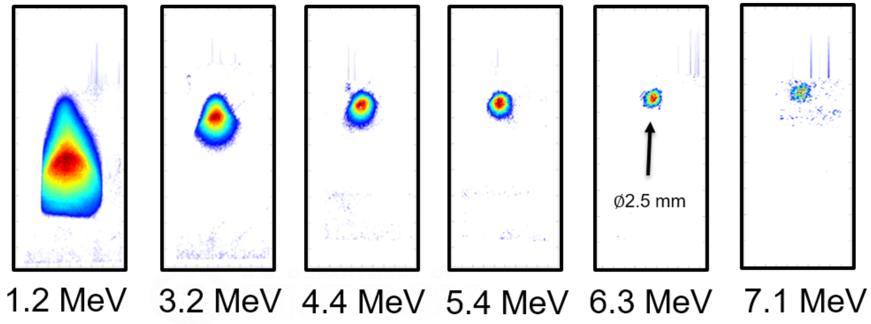
In-air setup:

1. scintillator

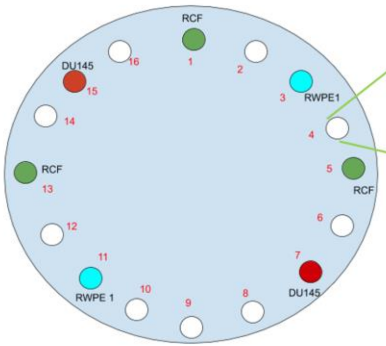
2. RCFs

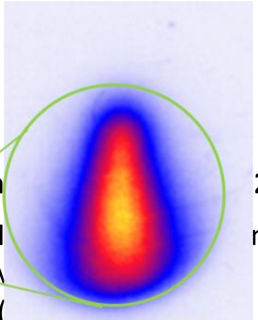
3. cell samples

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



3. Cell-sample wheel to study Radiobiological effects:



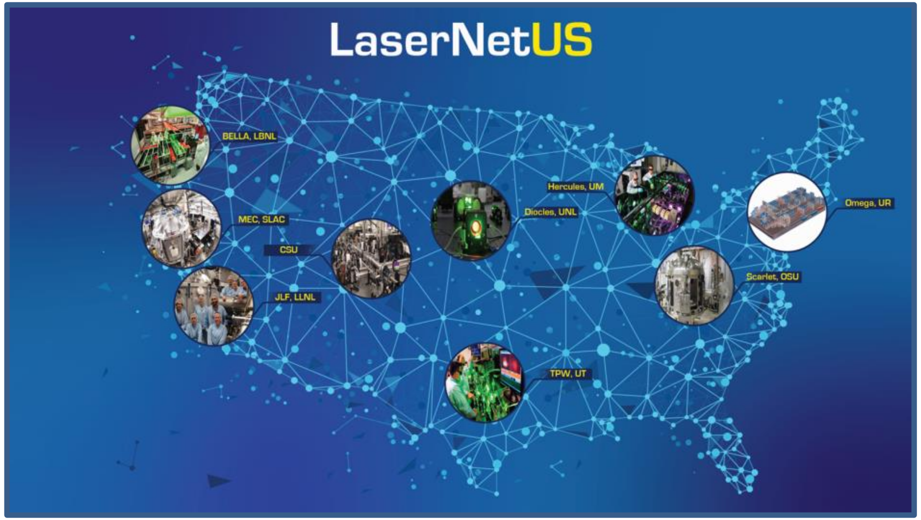


Run 2019):

- I mples with v 10 to 150 Gy (.shot)
- >2000 PW target shots (including plasma lens alignment and online dose monitoring)

BELLA center is part of LaserNetUS and provides user access to PW and HTW facilities

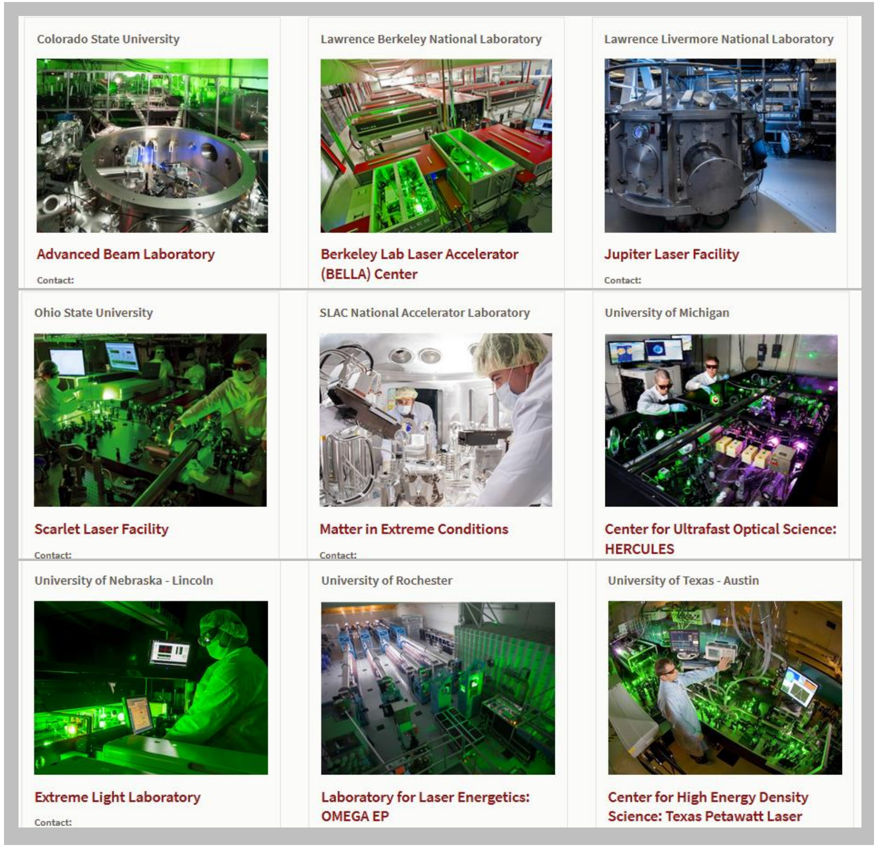
Goal: *Bring together the high-intensity laser science community and enable a broad range of frontier scientific research.*



For the first time in 2019:

- 3 weeks at BELLA PW
- 4 weeks at HTT

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



Colorado State University
Advanced Beam Laboratory
Contact:

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Berkeley Lab Laser Accelerator (BELLA) Center

Lawrence Livermore National Laboratory
Jupiter Laser Facility
Contact:

Ohio State University
Scarlet Laser Facility
Contact:

SLAC National Accelerator Laboratory
Matter in Extreme Conditions
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University of Michigan
Center for Ultrafast Optical Science: HERCULES

University of Nebraska - Lincoln
Extreme Light Laboratory
Contact:

University of Rochester
Laboratory for Laser Energetics: OMEGA EP

University of Texas - Austin
Center for High Energy Density Science: Texas Petawatt Laser

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MHD simulations

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