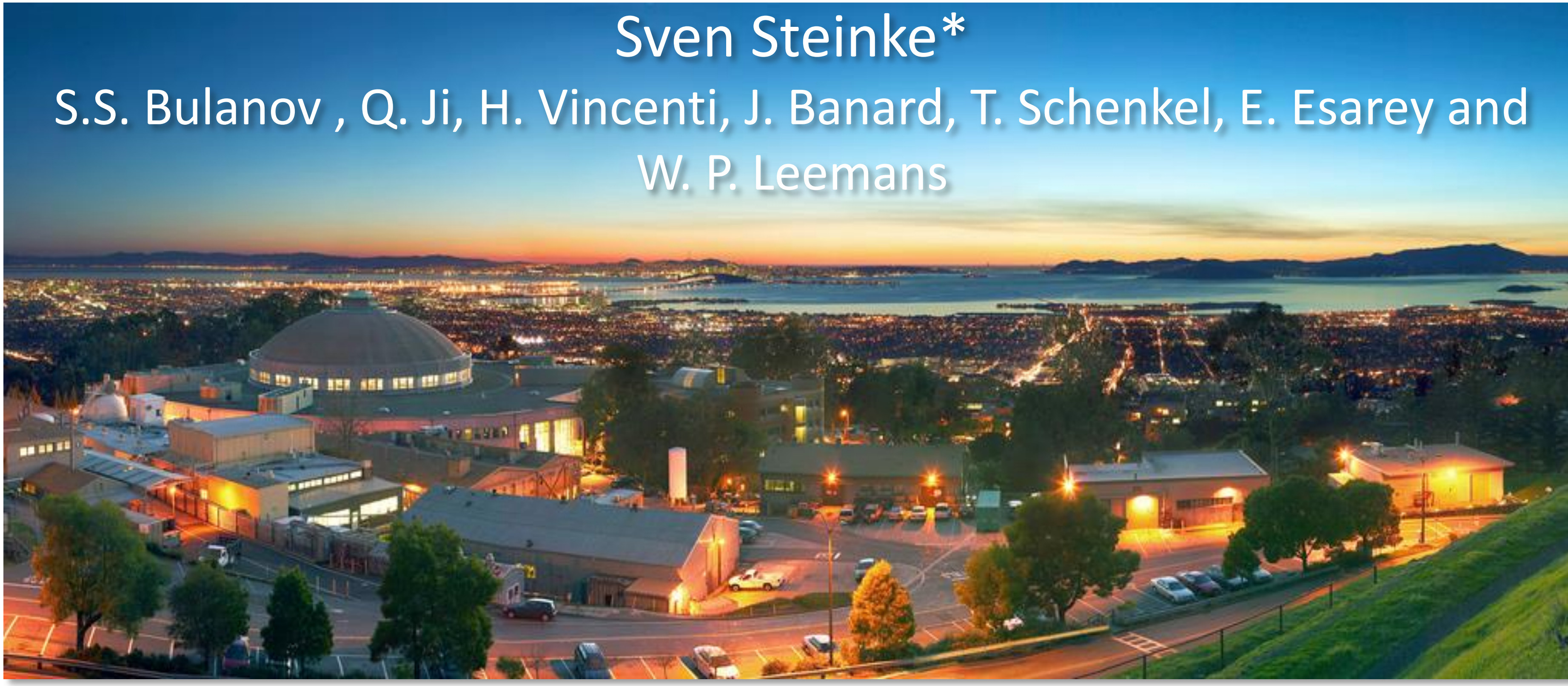
High Intensity Laser Interaction Studies at BELLA

Sven Steinke*

S.S. Bulanov , Q. Ji, H. Vincenti, J. Banard, T. Schenkel, E. Esarey and W. P. Leemans



*ssteinke@lbl.gov

BELLA Center, LBNL

Work supported by Office of Science, Office of FES, US DOE

Contract DE-AC-0205CH11231

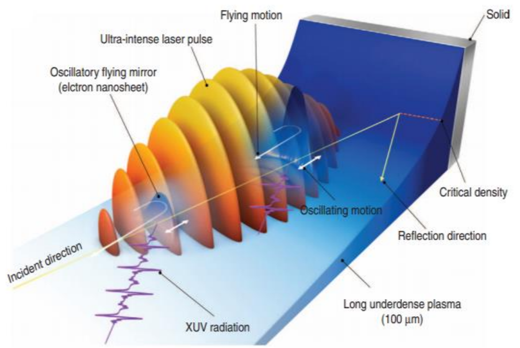
BERKELEY LAB

U.S. DEPARTMENT OF ENERGY | Office of Science

Fusion Energy Science

Multi-Petawatt laser as an engine for breakthrough discovery science

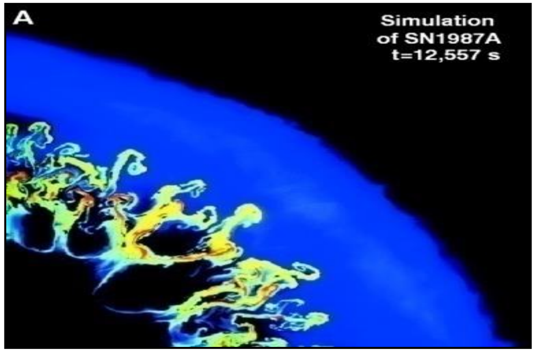
Fundamental Physics of Relativistic Plasmas



Jong Kim et al. Nat. Comm. (2012)

- Laser Ion Acceleration
- High Harmonics from relativistic oscillating mirrors
- Flying mirror experiments

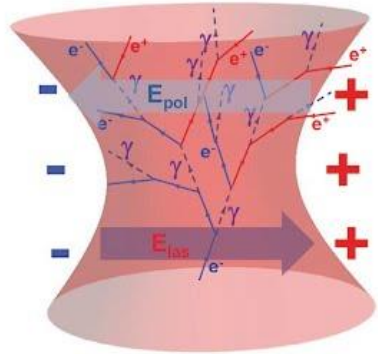
Relativistic Laboratory Astrophysics



Remington et al. Science (1999)

- Plasma instabilities (Rayleigh-Taylor, Weibel)
- Bow waves
- Magnetized jets
- Anti-matter plasma
- Collisionless shocks

High Intensity Particle Physics

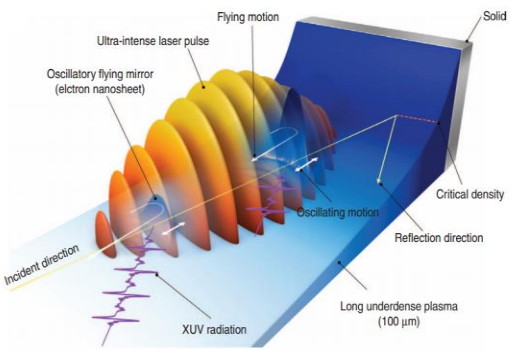


LBNL workshop "Nonlinear QED with ultra-intense PW-class laser pulses" (2012)

- Nonlinear Quantum Electrodymanic nQED: Multiphoton Compton and Breit-Wheeler processes
- EM cascades/ electron-positron pair production

Petawatt lasers as an engine for breakthrough discovery science

Fundamental Physics of Relativistic Plasmas



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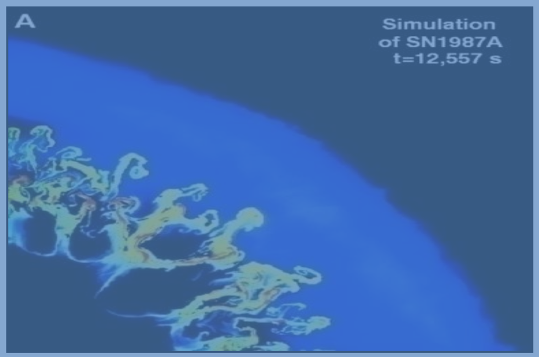

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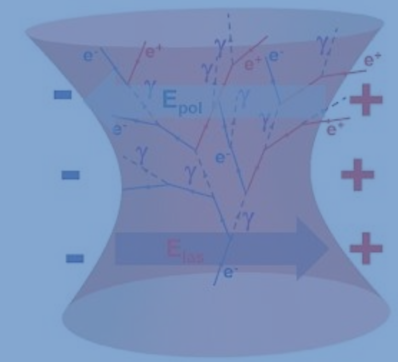

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- EM cascades/ electron-positron pair production

Ion acceleration using sheath fields limited energies and beam quality

R. Snavely et al. Phys Rev. Lett. 2000

VOLUME 85, NUMBER 14 PHYSICAL REVIEW LETTERS 2 OCTOBER 2000

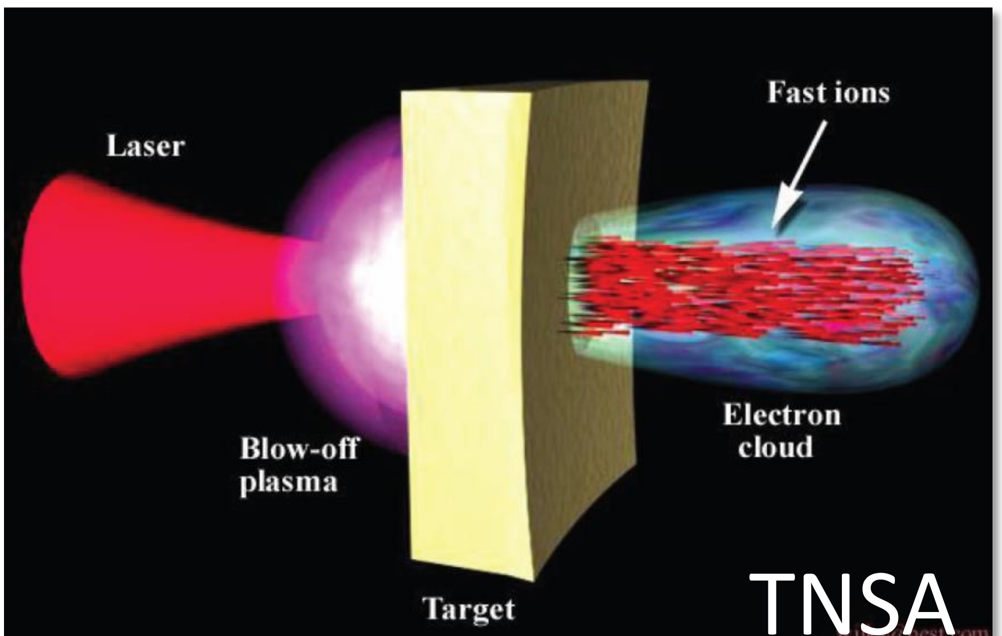
Intense High-Energy Proton Beams from Petawatt-Laser Irradiation of Solids

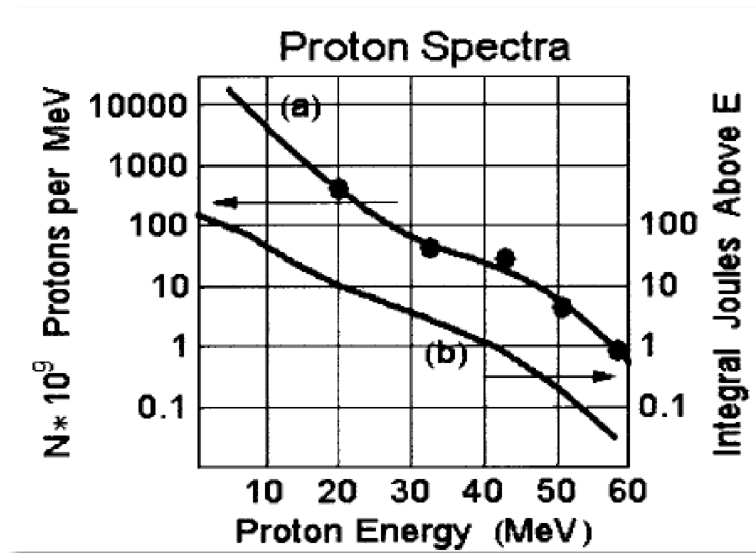
R. A. Snavely,[1,2] M. H. Key,[1] S. P. Hatchett,[1] T. E. Cowan,[1] M. Roth,[3,*] T. W. Phillips,[1] M. A. Stoyer,[1] E. A. Henry,[1] T. C. Sangster,[1] M. S. Singh,[1] S. C. Wilks,[1] A. MacKinnon,[1] A. Offenberger,[4,*] D. M. Pennington,[1] K. Yasuike,[5,*] A. B. Langdon,[1] B. F. Lasinski,[1] J. Johnson,[6] M. D. Perry,[1] and E. M. Campbell[1]
[1]*Lawrence Livermore National Laboratory, University of California, P.O. Box 808, Livermore, California 94550*

< 1 shot per hour

∼60 MeV proton generation

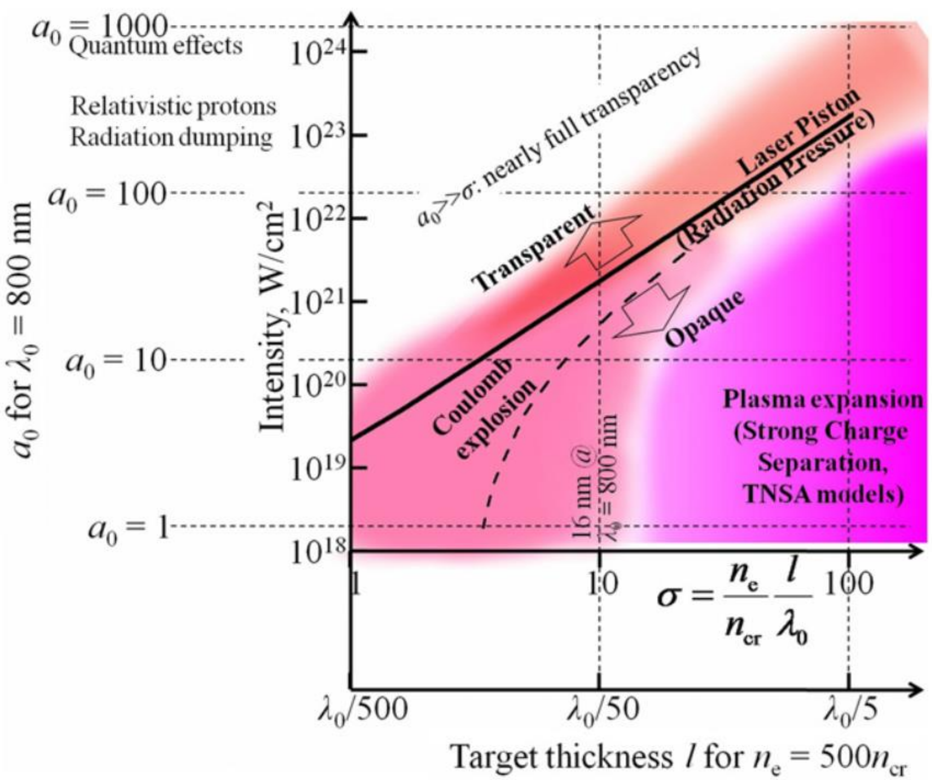
$$T_{e,h} = m_e c^2 \sqrt{1+a_0^2} - 1$$





Multi-PW laser allow exploration of new, efficient regimes of ion acceleration

Optimizing Ion acceleration requires sophisticated laser and target parameters



Daido et al. RPP 75, 056401 (2012)

New acceleration regimes

Opaque targets:

- Plasma expansion (TNSA)
- Radiation Pressure Acceleration (RPA)
- Coulomb explosion (CE)

Transparent targets:

- Magnetic Vortex
- Collision less shocks

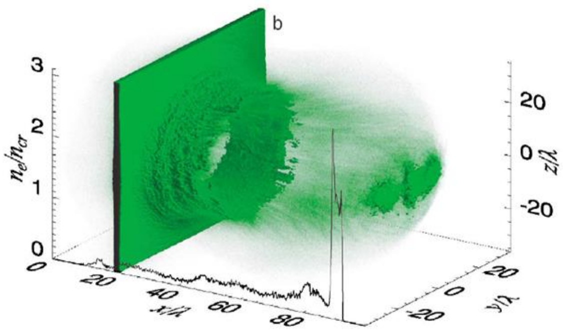
Drive laser needs

- Multi-PW power
- ultra-high intensity contrast
- pulse length <100fs
- excellent focusability
- repetition rate / stability

What laser is needed to get to 250 MeV/u (fs vs. ps) and when will we be able to reach it?

Transformative opportunity

Radiation Pressure Acceleration (RPA)

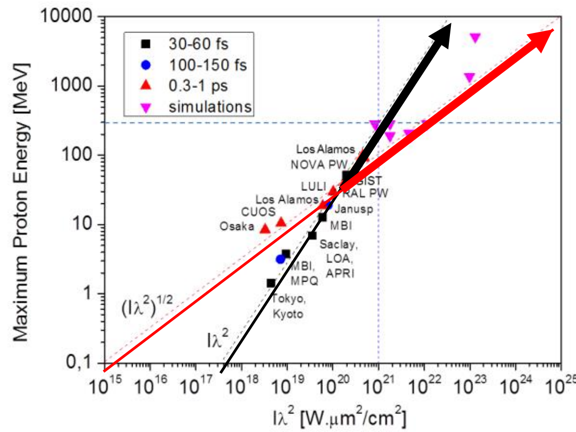


Esirkepov et al. PRL 92, 175003 (2012)

Unique parameter of PW lasers

- More favorable scaling prop to laser intensity
- High efficiency (~10%)
- Ion energies of >200 MeV/u suitable for bio/ medical applications

Determine future path of laser driven ion acc.

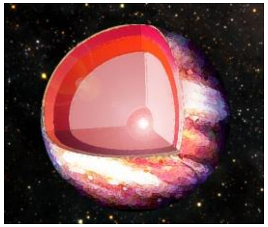


First time measurement of scaling laws with statistical significance

- Will $\sim I\lambda^2$ hold for short laser pulses? (200 vs 80 MeV)
- Clean laser pulse interaction reduces computation time

Potential societal benefit

Advanced understanding of different states of matter- ion heating of matter (WDM)

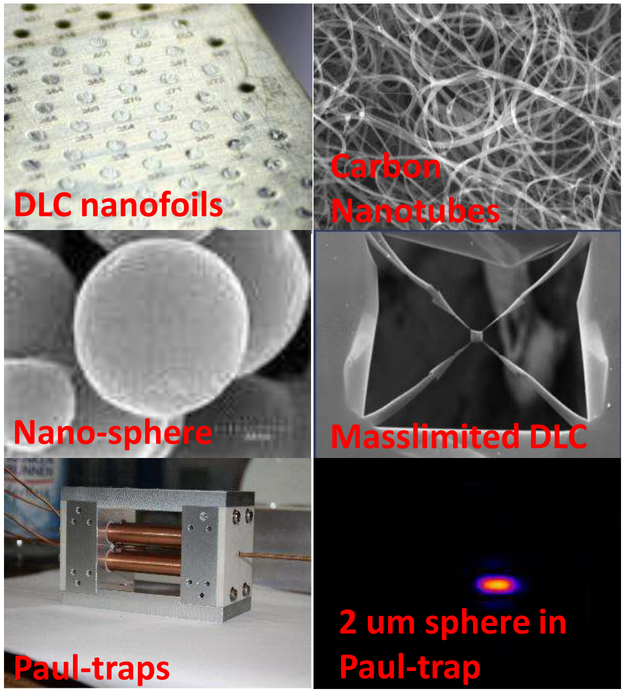


Bio/Medical application- cancer treatment

Radiation damage studies; radiography and fast ignition studies; future accelerators; neutron beams

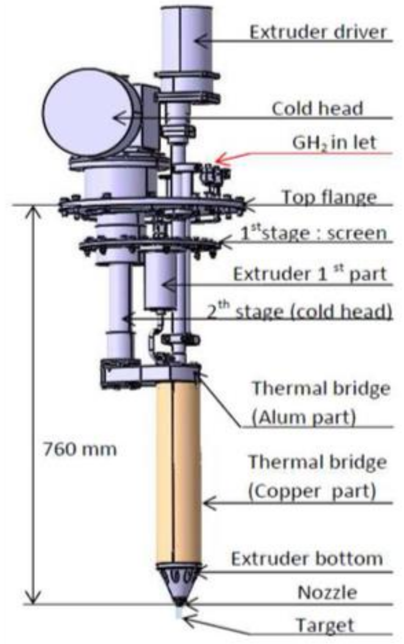
Advanced targetry is crucial for tuning of laser-matter interactions – access to cutting edge nano-fabrication is required

Nano-scale reduced mass targets

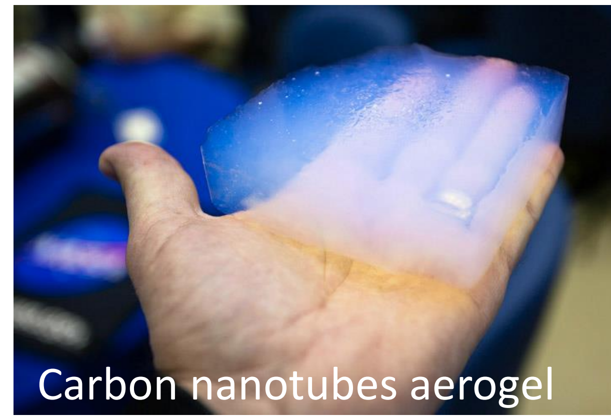


Carbon disc with 1um diameter, 5nm thickness (mc^2=1J)

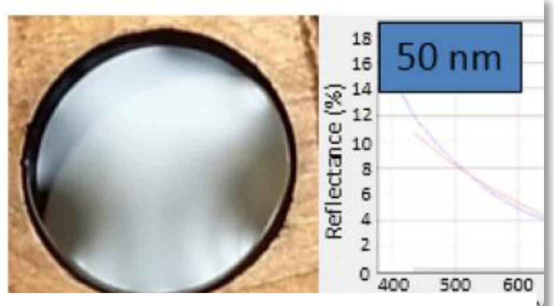
LMU Munich, MBI Berlin



Solid hydrogen extruder, 10-50 micron thick, 10 mm wide solid hydrogen tape (CEA, France)

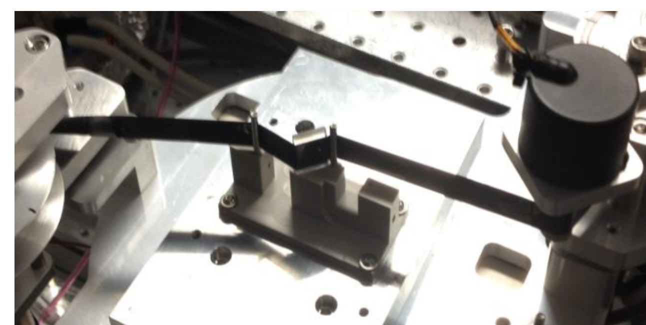


Univ. of Pennsylvania

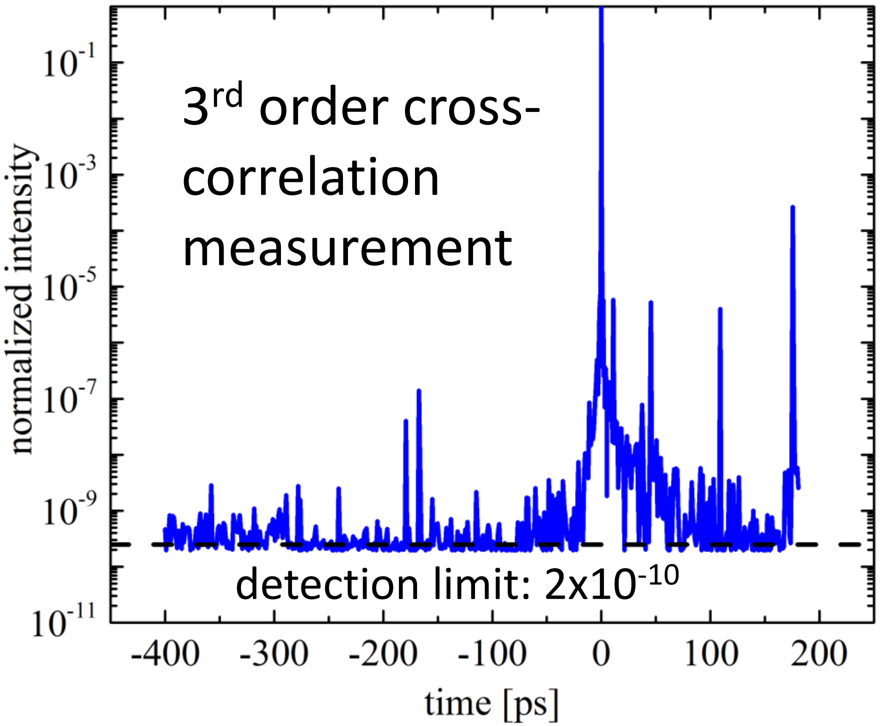


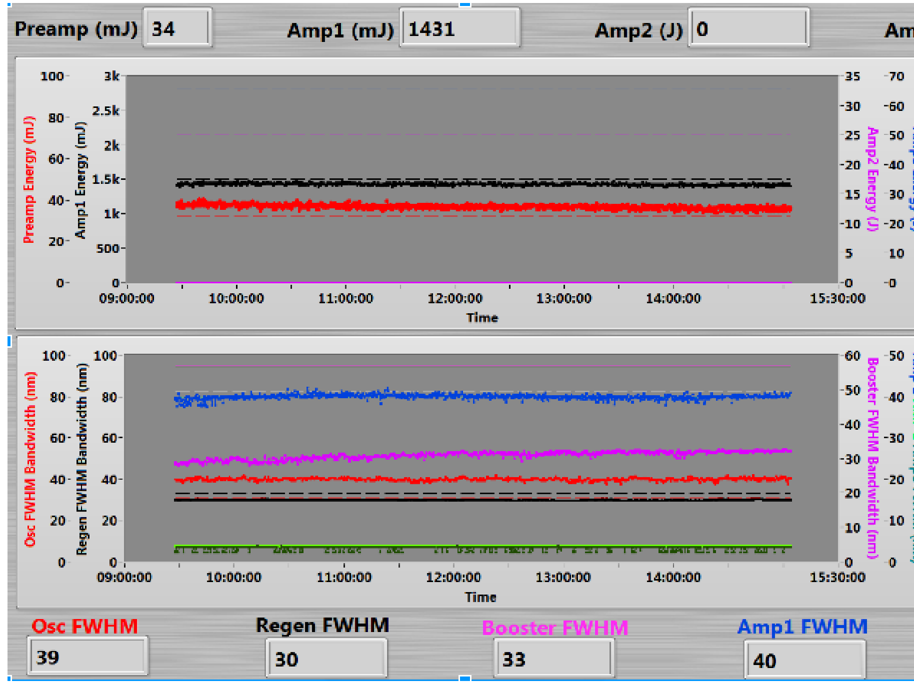
Liquid Xtals(Ohio state Univ.)

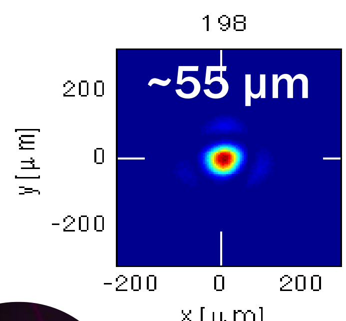
High precision tape drive (BELLA Center)

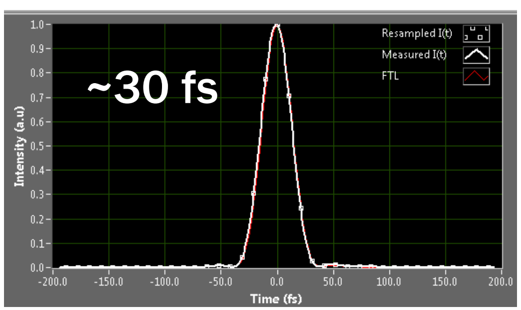


BELLA laser: (still) highest rep rate PW-laser for high intensity LPA experiments towards 10 GeV

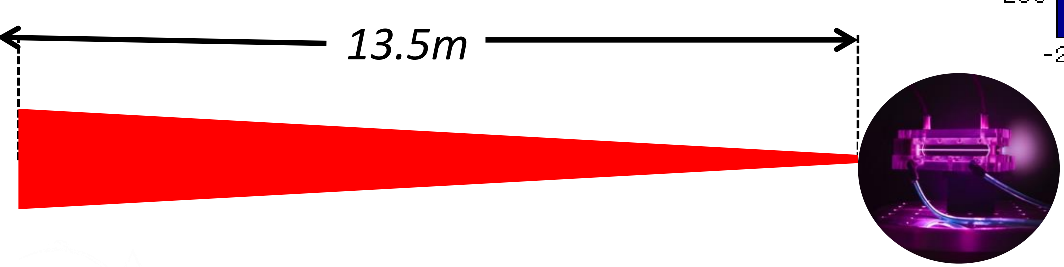








Petawatt laser operating at up to 42 J in ~30 fs at 1 Hz

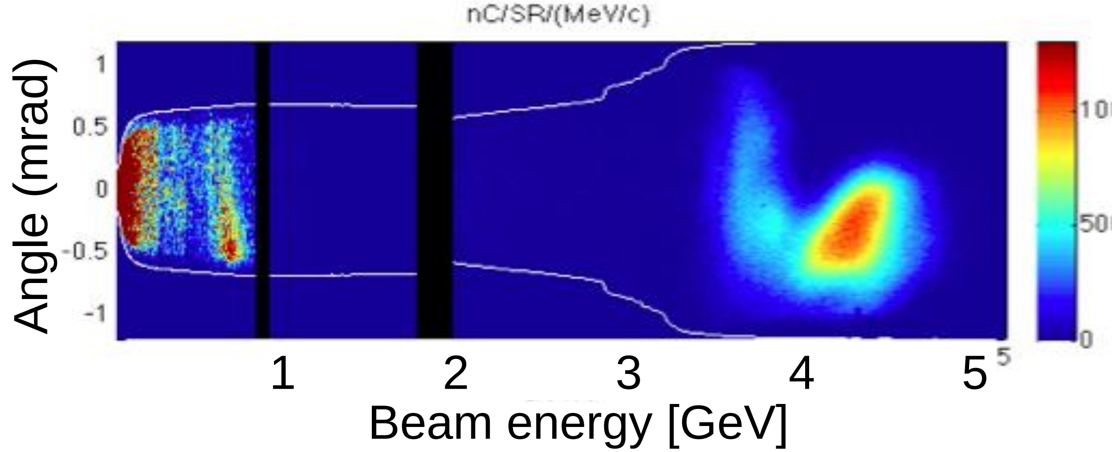


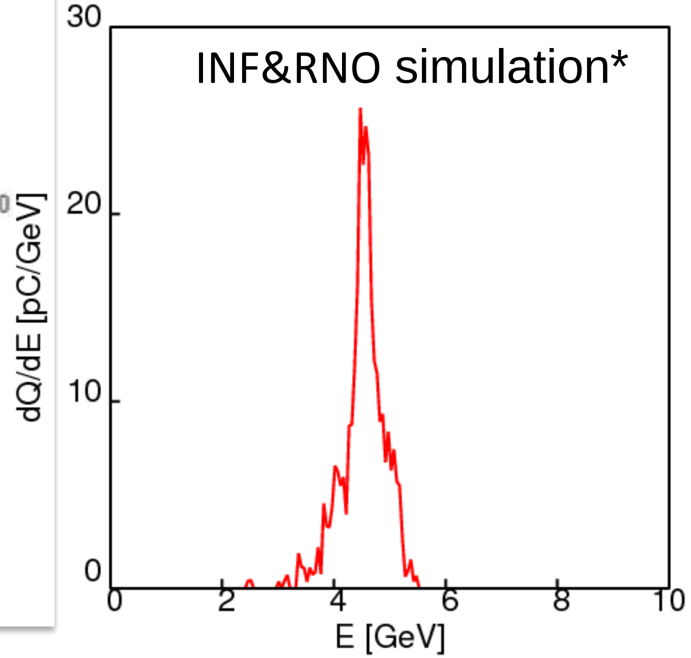
Intensity ~1.5x10^{19} Wcm^{-2}
Acc. fields ~10-50GV/m

4.25 GeV beams have been obtained from 9 cm plasma channel powered by 310 TW laser pulses (15 J)

*C. Benedetti et al., proceedings of AAC2010, proceedings of ICAP2012

Electron beam spectrum



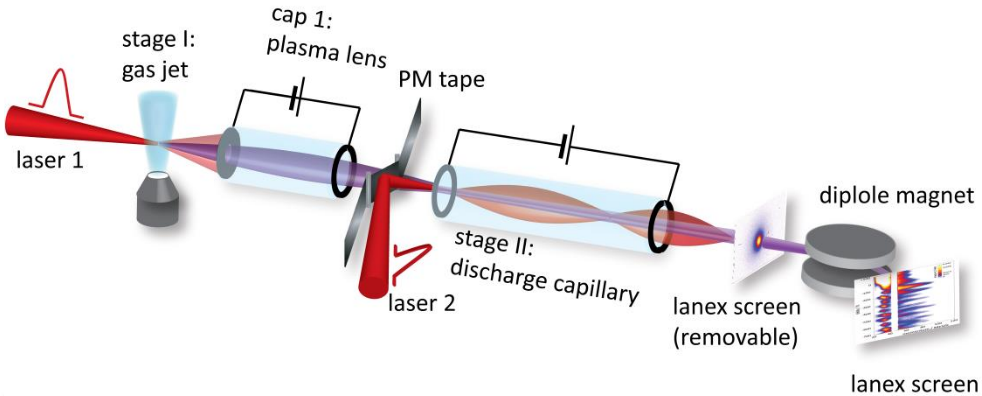


	Exp.	Sim.
Energy	4.25 GeV	4.5 GeV
ΔE/E	5%	3.2%
Charge	~20 pC	23 pC
Divergence	0.3 mrad	0.6 mrad

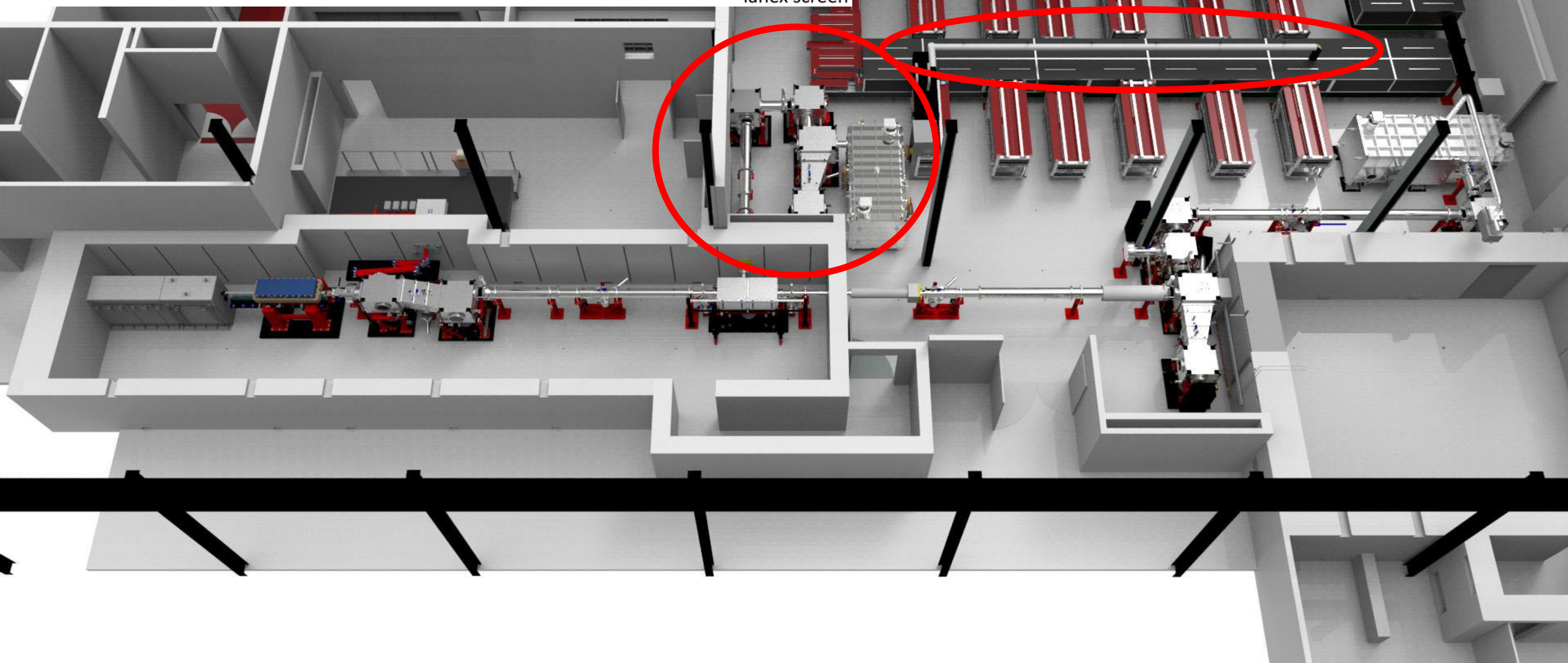
- **Laser** (E=15 J):
  - Measured) longitudinal profile (T_0= 40 fs)
  - Measured far field mode (w_0=53 µm)
- **Plasma:** parabolic plasma channel (length 9 cm, n_0~6-7x10^{17} cm^{-3})

W.P. Leemans et al.,PRL 2014

BELLA-PW Laser facility



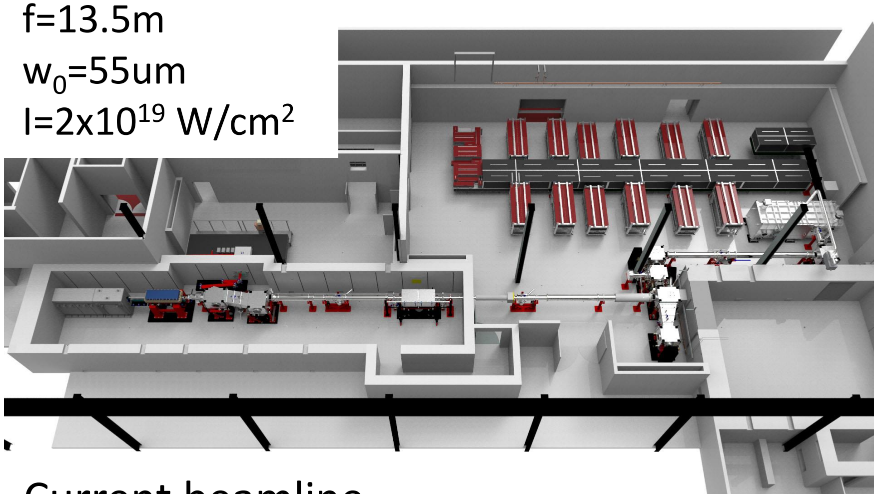
Proposed setup



3 Phases of BELLA-i for ultra-high intensity HED "science with error bars"

Phase I: Long focal length (FY 17)

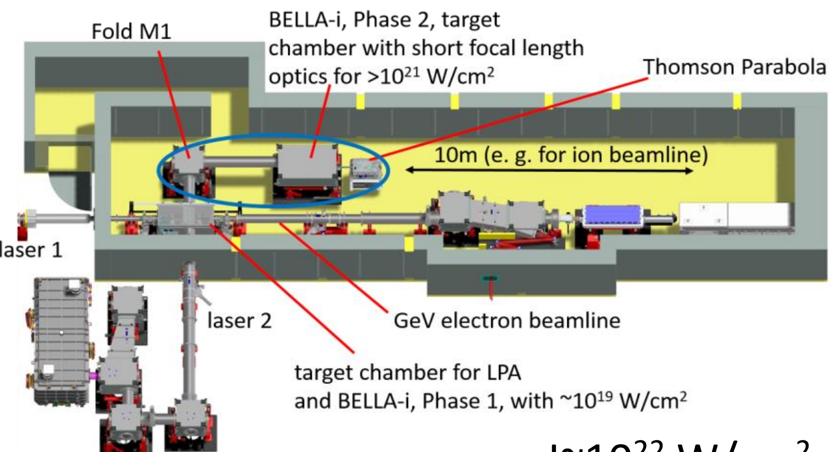
1 Hz
f=13.5m
w_0=55um
I=$2x10^{19}$ W/cm^2



Current beamline

- Electron acceleration towards 10 GeV
- Long focal length ion acceleration:
  - Large focal spot leads to narrow divergence and enables efficient transport
  - Isochoric heating
  - TNSA scaling from 30-600fs at 1 Hz

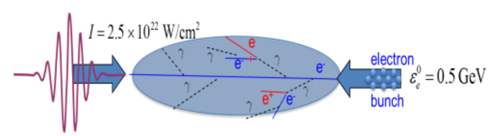
Phase II: new short focal length beamline (FY 18)

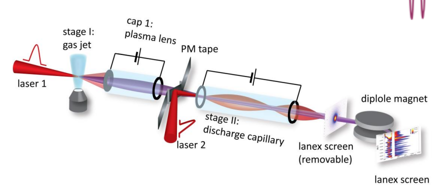


2 beam setup in TC1:

I~10^{22} W/cm^2

Compton & Breit-Wheeler



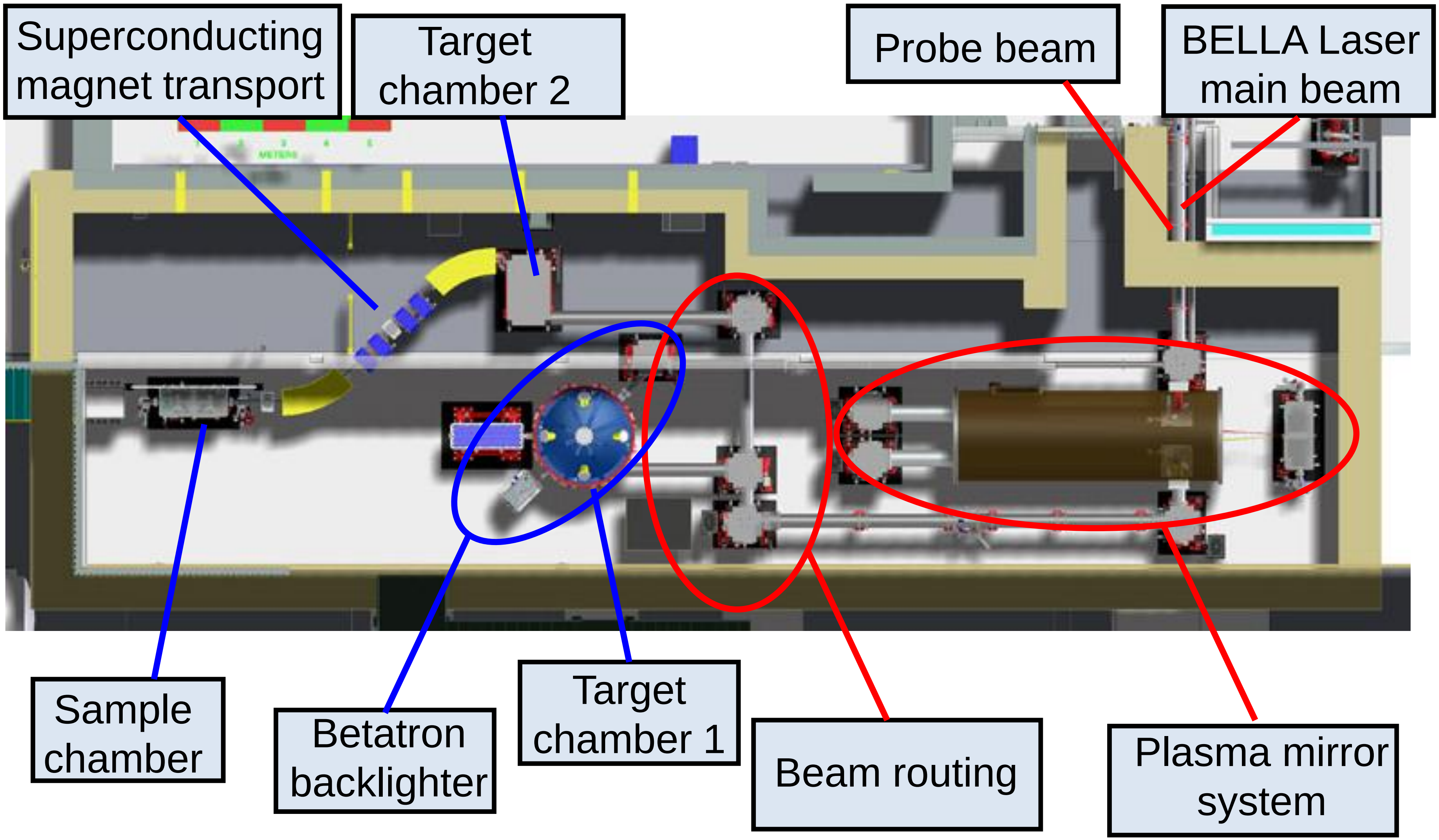


Staging of LPAs

1 beam setup in TC2:

- PM to increase contrast to ~10^{-12}
- Advanced mechanisms of ion acceleration & ion transport
- Betatron backlighter for WDM studies

Phase III: We are proposing to expand the facility by adding short focal length capability – ultra-high intensity

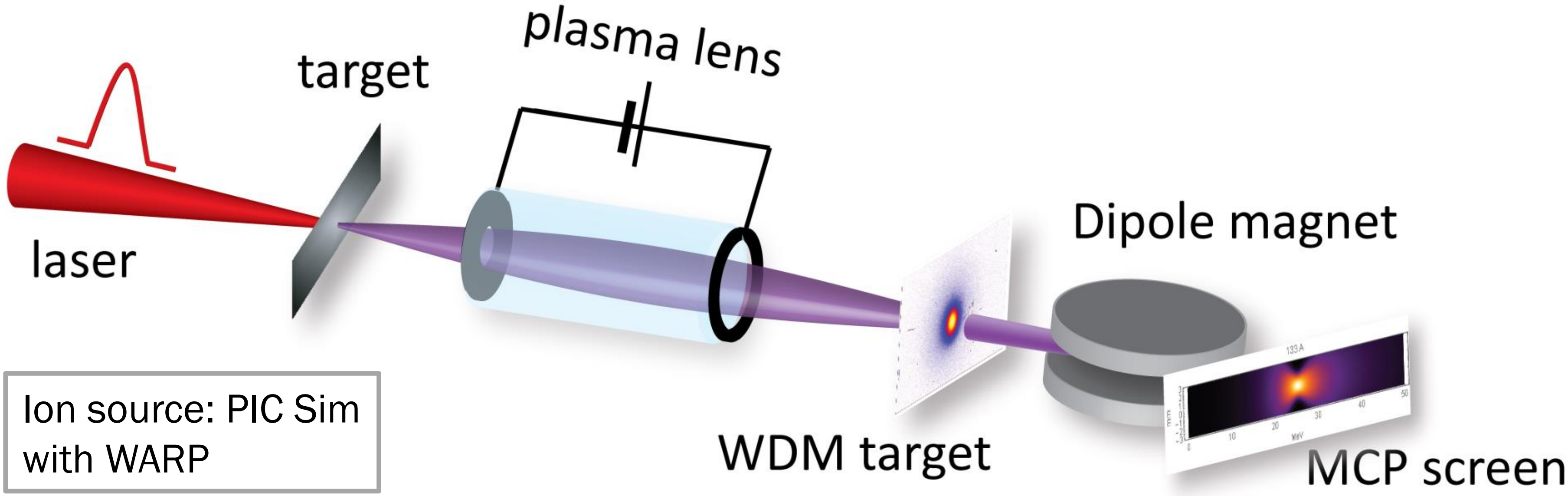


BELLA-i - a facility for high energy density physics and discovery plasma science at Berkeley Lab

BELLA-i	phase 1	phase 2	phase 3
peak intensity (W/cm^2)	2 x 10^{19}	10^{22}	10^{22}
pulse length	30 fs	30 fs	30 fs
peak pulse energy	40 J	40 J	40 J
laser spot size	55 µm	5 µm	5 µm
peak repetition rate	1 Hz*	1 Hz*	1 Hz
contrast (ns)	10^{-10}	10^{-12}	10^{-14}
diagnostics (details to be determined)	• optical spectrometers • ion and electron spectrometers • …	• optical pump- probe • betatron x-rays • MeV protons • …	• same as 2 • beamline for experiments with laser accelerated ions • …
1st access (estimates)	2016-2018	2018-2019	2019-2020

1. experiments with the existing, long focal length BELLA beamline in the existing cave
2. experiments in the existing BELLA cave with a new dual-beam line
   - * shielding in the BELLA cave limits the repetition rate for experiments with generation of intense pulses of >20 MeV protons
3. experiments in a new cave with improved shielding and with a beam line for laser accelerated ions
   - * improved shielding in a three-times larger experimental area for continuous operation at 1 Hz

Outline

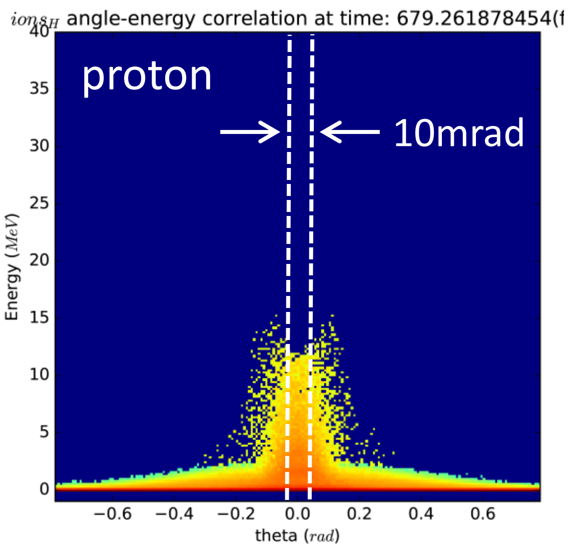


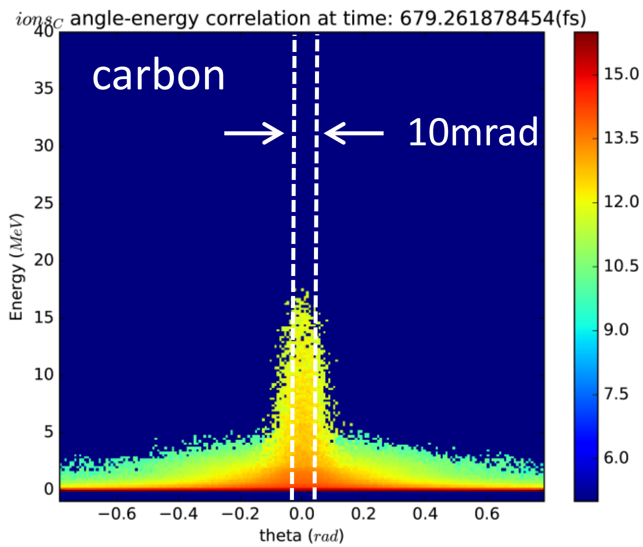
Ion source: PIC Sim with WARP

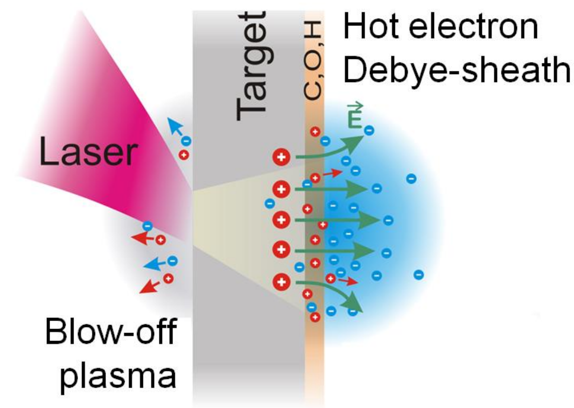
Transport:TWISS Parameter

Isochoric heating: Hydra

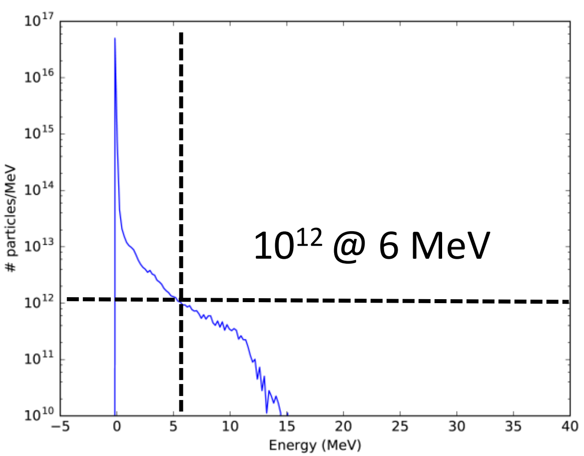
Large Laser Spot leads to collimated beam and increased number of ions

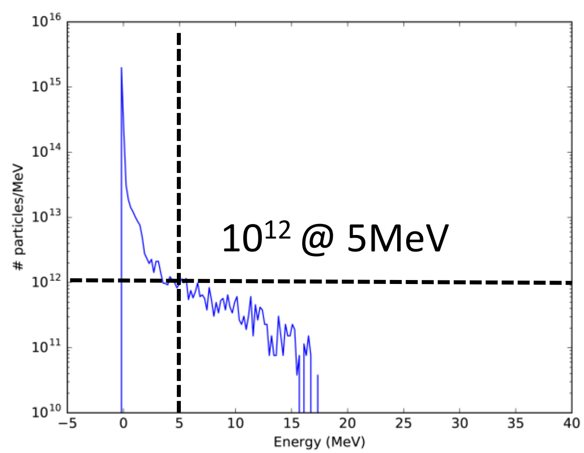






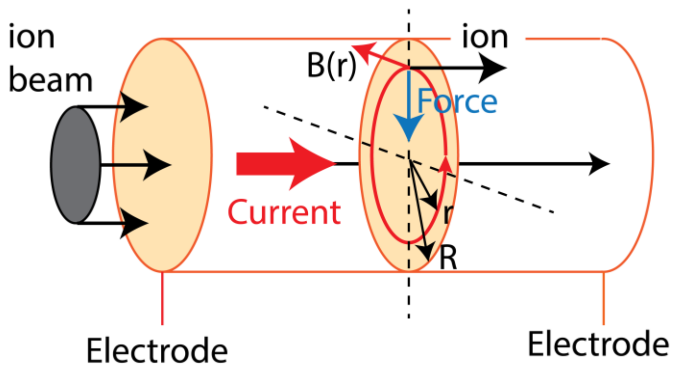
Proton and Carbon spectra within 10mrad:





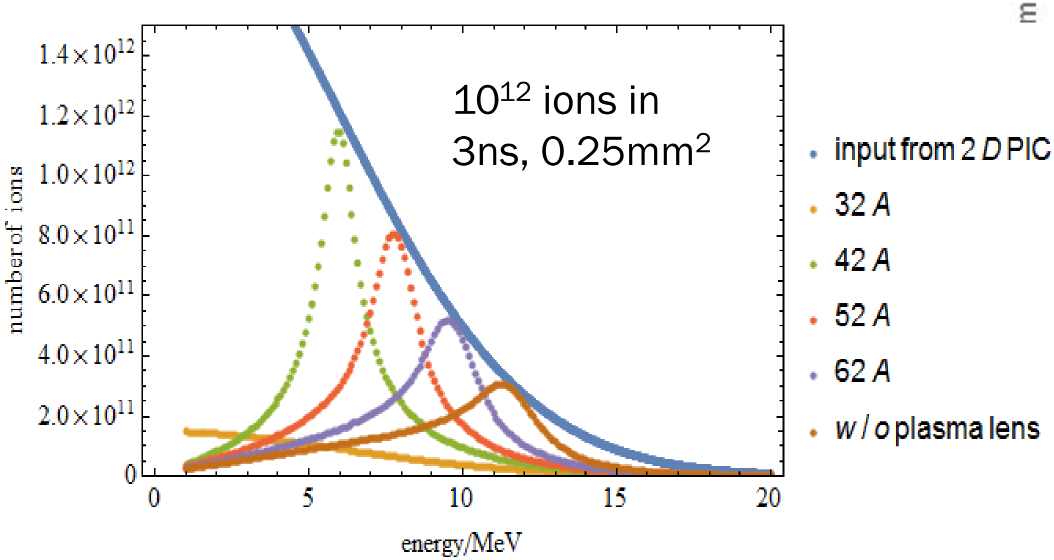
Transport of 10^{12} ions at 5-10 MeV to EMP-free environment possible with plasma lens

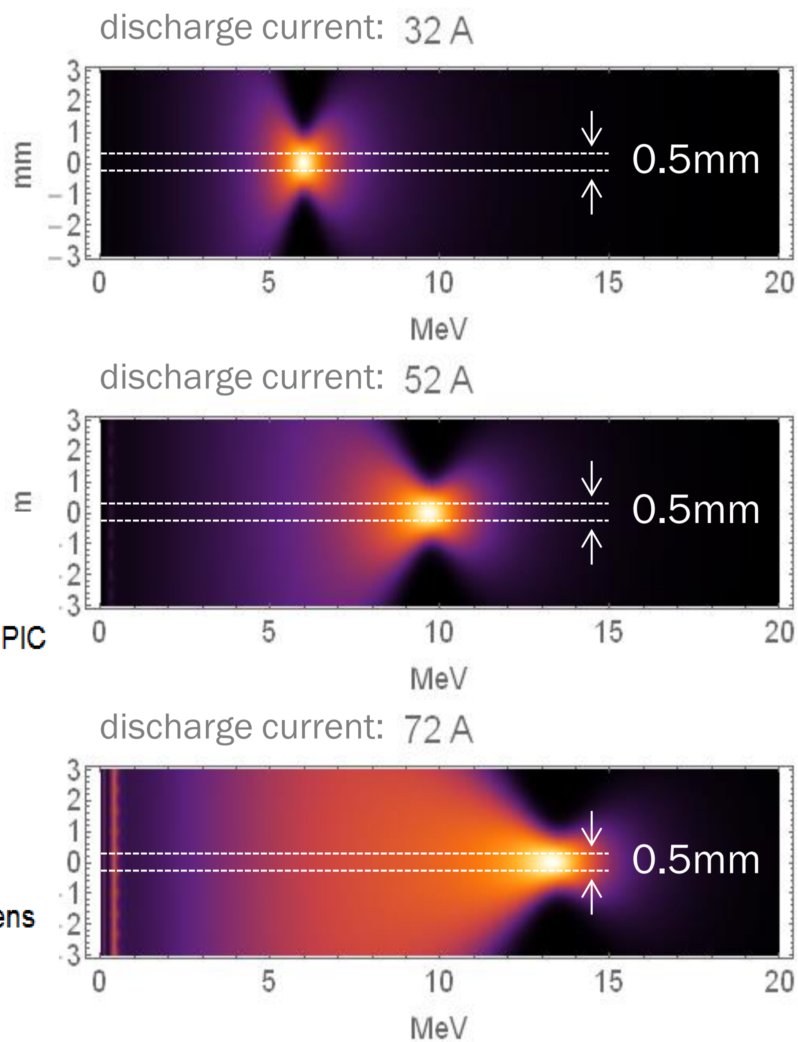
Active plasma lens to focus an ion beam to a 500µm spot 1m downstream of plasma lens:



Panofski et al. RSI 1950

Charge distribution at WDM target:

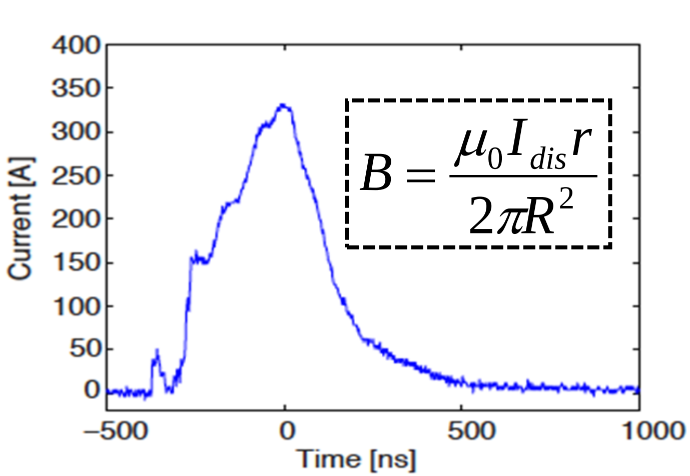


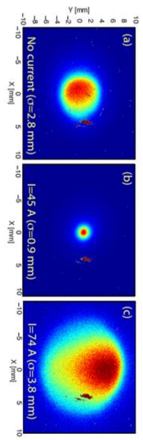


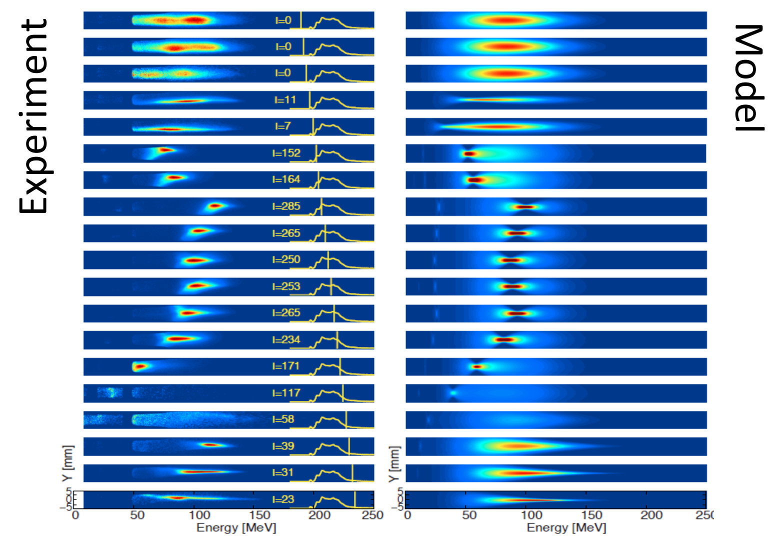
Developed Active Plasma Lens for efficient e-beam coupling to the 2^{nd} stage and emittance measurement

Meter-scale focusing for emittance measurement

Discharge pulse enables gradients of **>3000 T/m:**

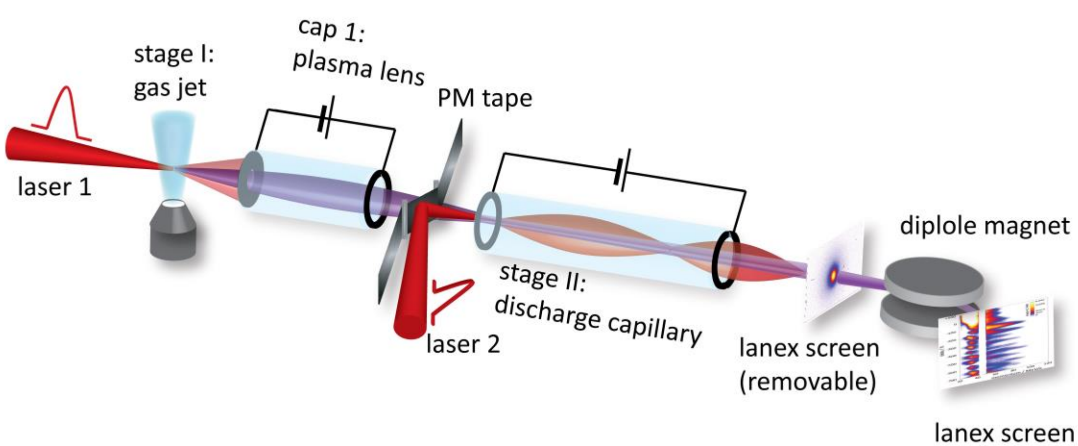


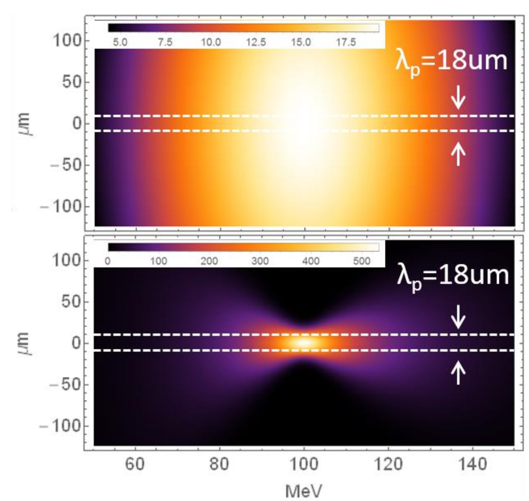




van Tilborg et al., PRL 184802 (2015)

Millimeter-scale focusing for staging experiment





Steinke et al., Nature 530, 190 (2016)

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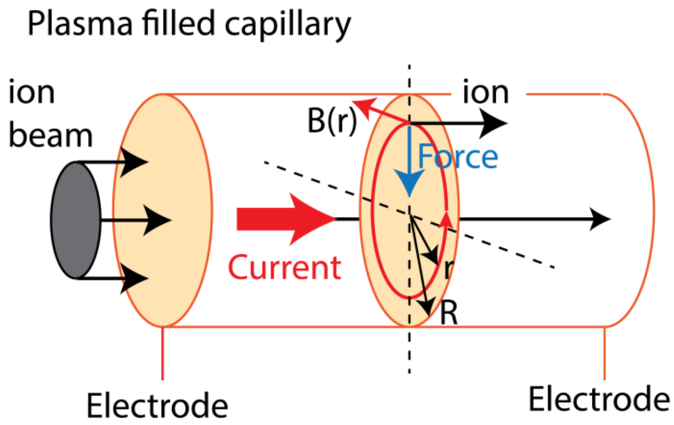
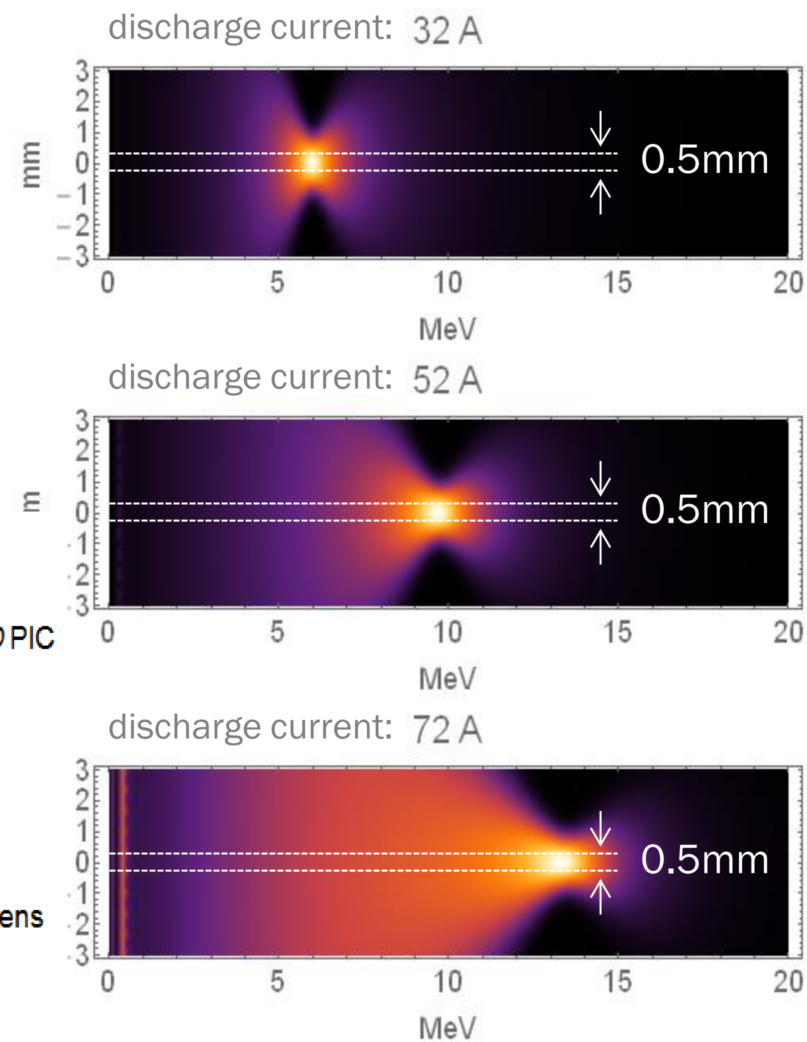
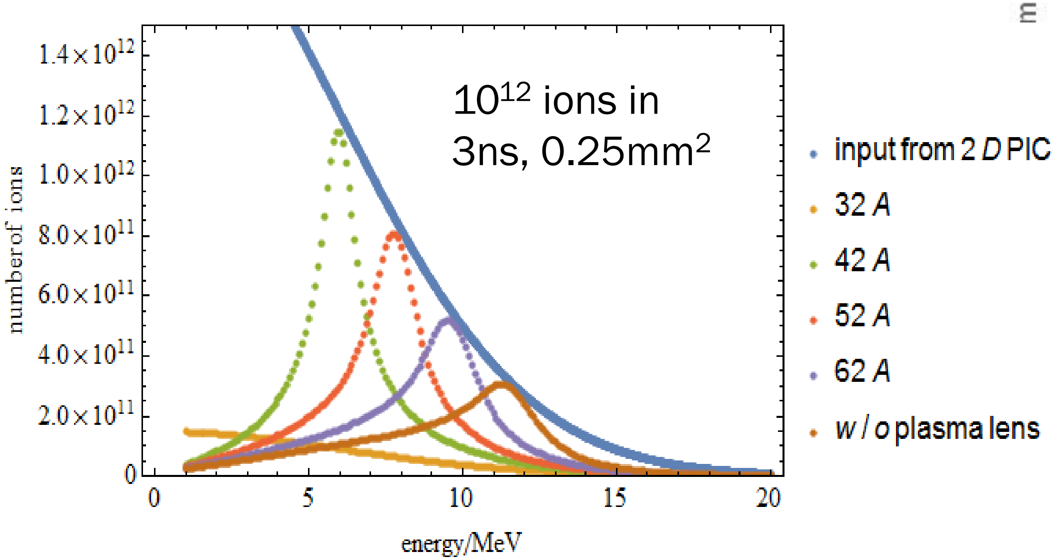


Panofski et al. RSI 1950

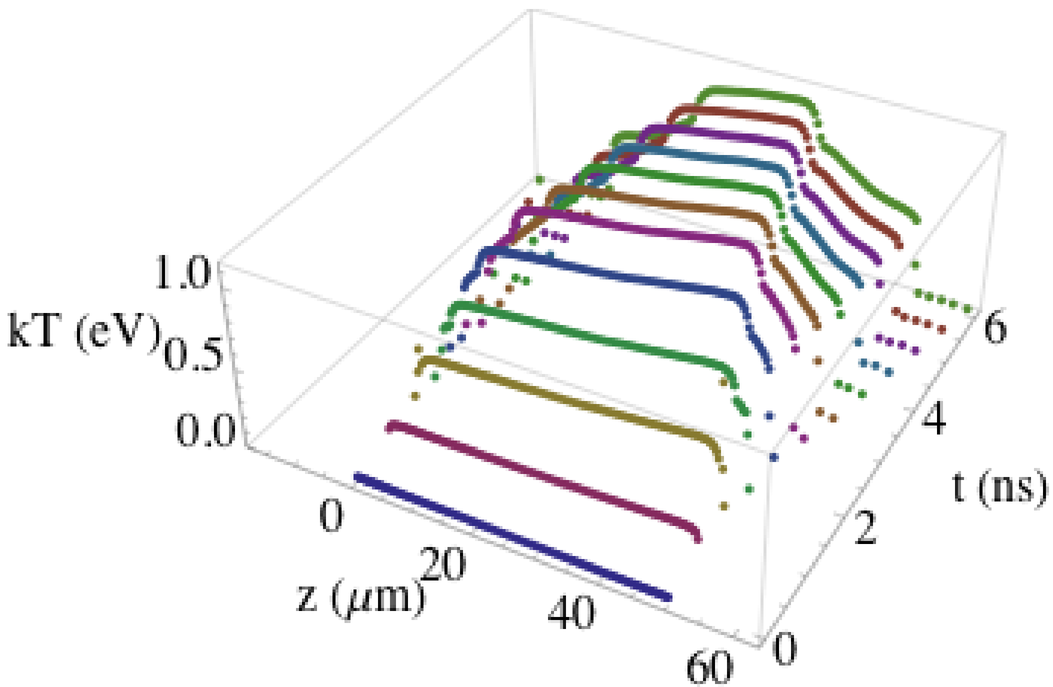


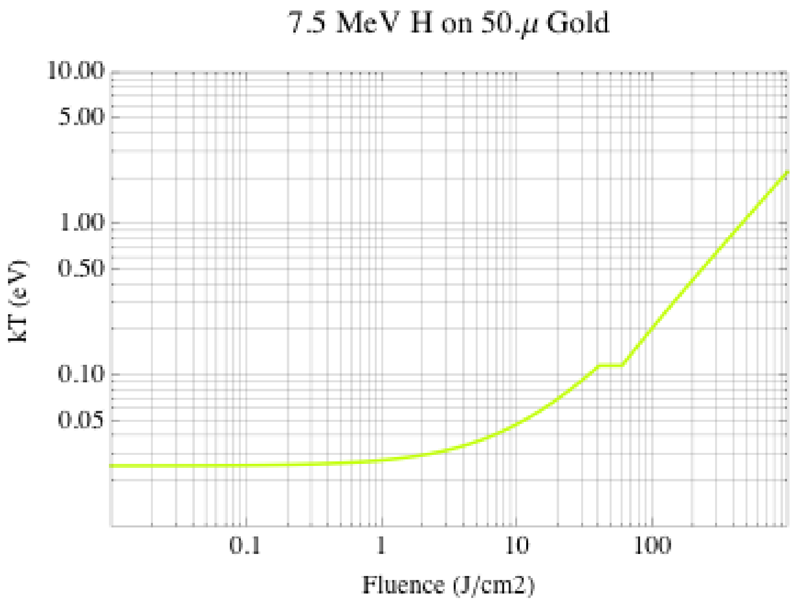
Charge distribution at WDM target:



HYDRA results suggest: WDM possible

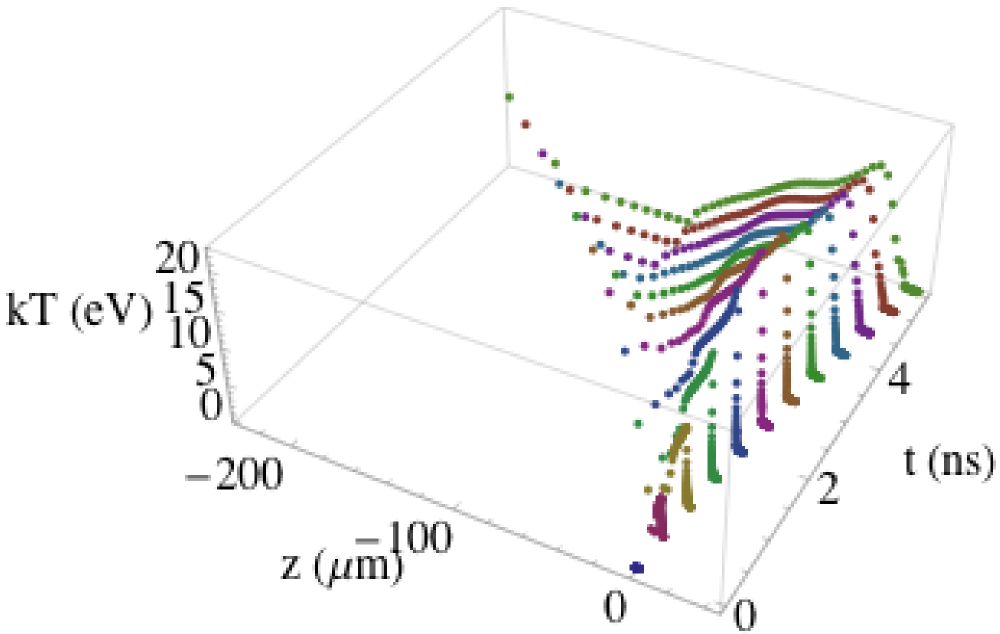
Target: 50 μm Au foil
Beam:
0.25 mm radius (Gaussian); 3 ns full width
10^{12} protons at 7.5 MeV
Central fluence 480 J/cm^2

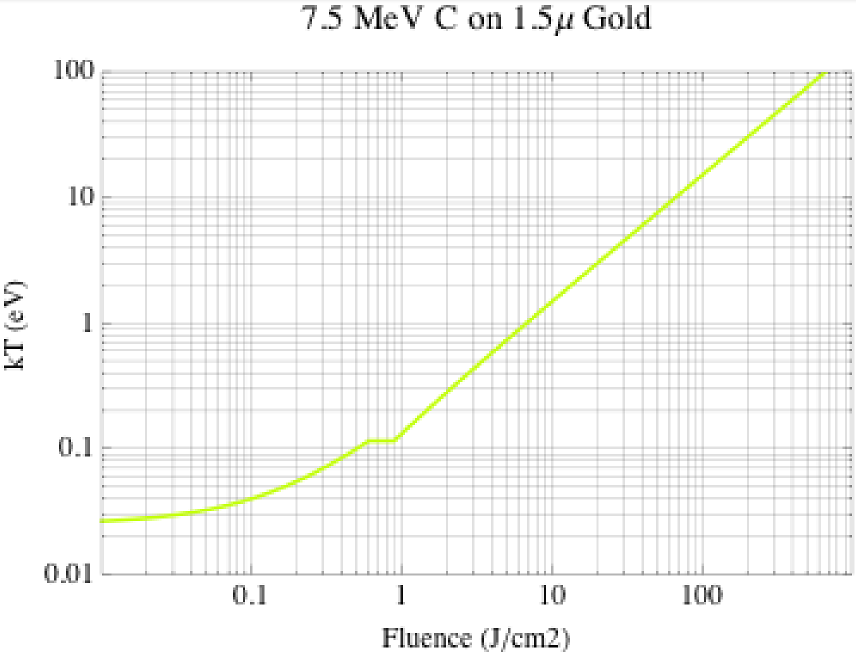




HYDRA results suggest: WDM possible

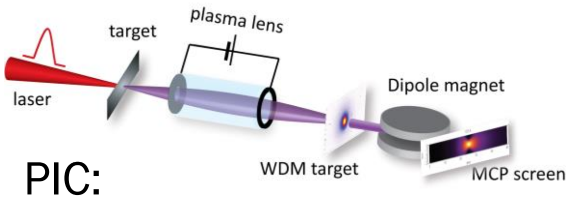
Target: 1.5 μm Au foil
Beam:
0.25 mm radius (Gaussian); 3 ns full width
Central fluence 480 J/cm^2



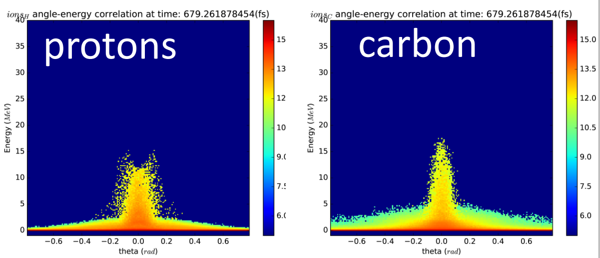


BELLA-I as an engine for breakthrough discovery
“science with error bars”

Phase I: TNSA& WDM

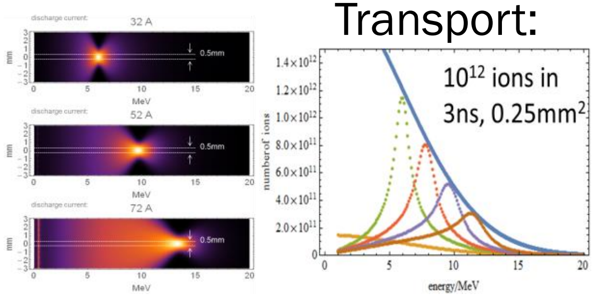


PIC:

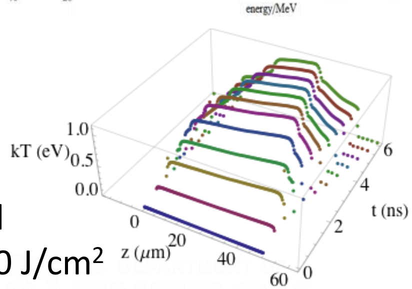


10^{12} H+ @(7+/-2) MeV, 10mrad

Transport:



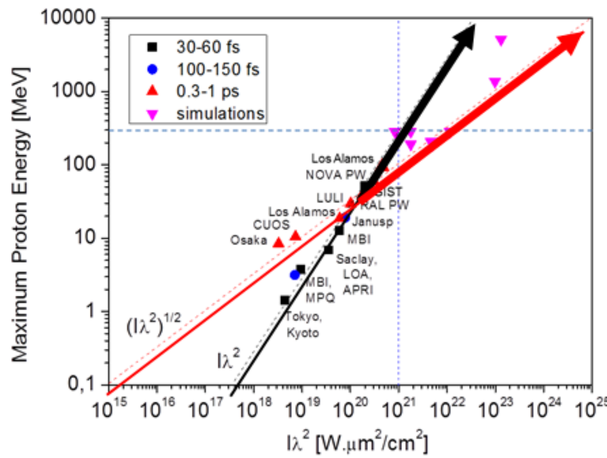
HYDRA:



50 um gold
fluence 480 J/cm^2

Phase I-III:

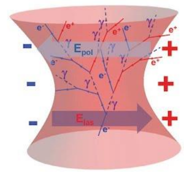
Determine future path of laser driven ion acc.



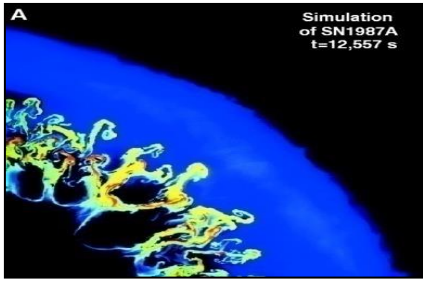
First time measurement of scaling laws with statistical significance

- Will $\sim I\lambda^2$ hold for short laser pulses? (200 vs 80 MeV)
- Clean laser pulse interaction reduces computation time

High Intensity Particle Physics & Rel. Lab Astrophysics



Nonlinear Quantum Electrodymanic nQED:
Multiphoton Compton and Breit-Wheeler processes
EM cascades/ electron-positron pair production



- Plasma instabilities
- Bow waves
- Magnetized jets
- Anti-matter plasma