Laser ion acceleration with PW laser pulses

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Lawrence Berkeley National Laboratory

FES - Online Town Hall Meeting

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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

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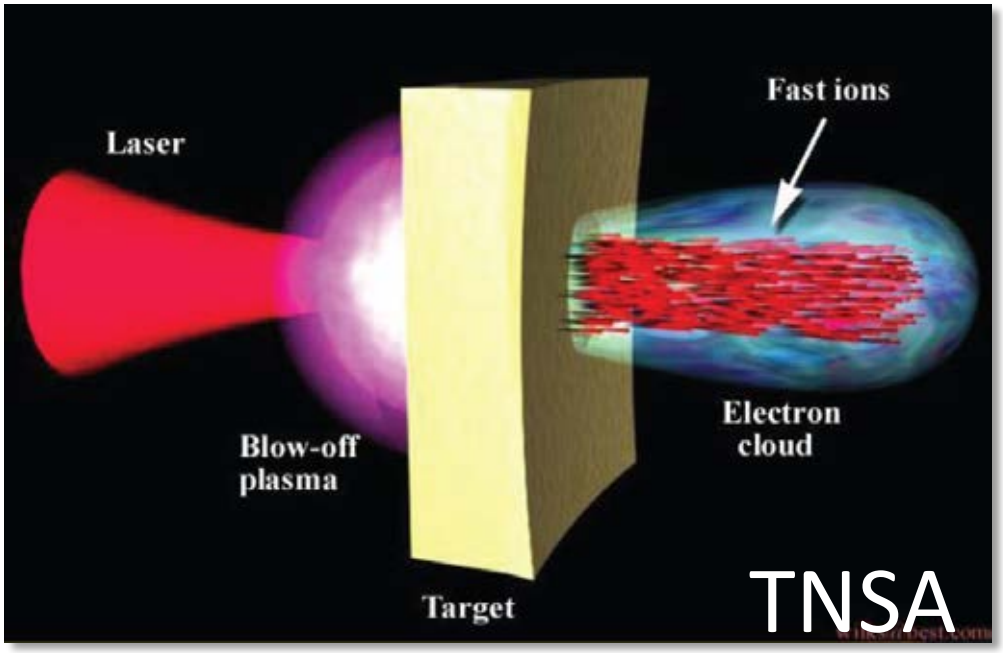
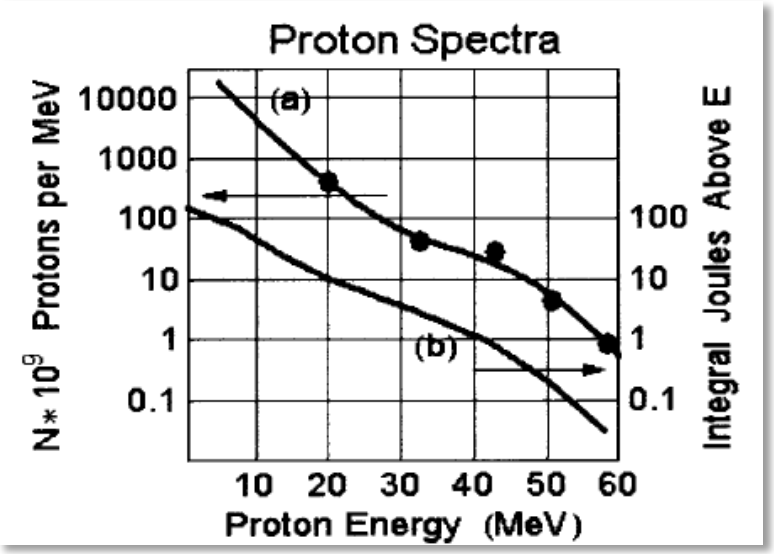
< 1 shot per hour

~60 MeV proton generation

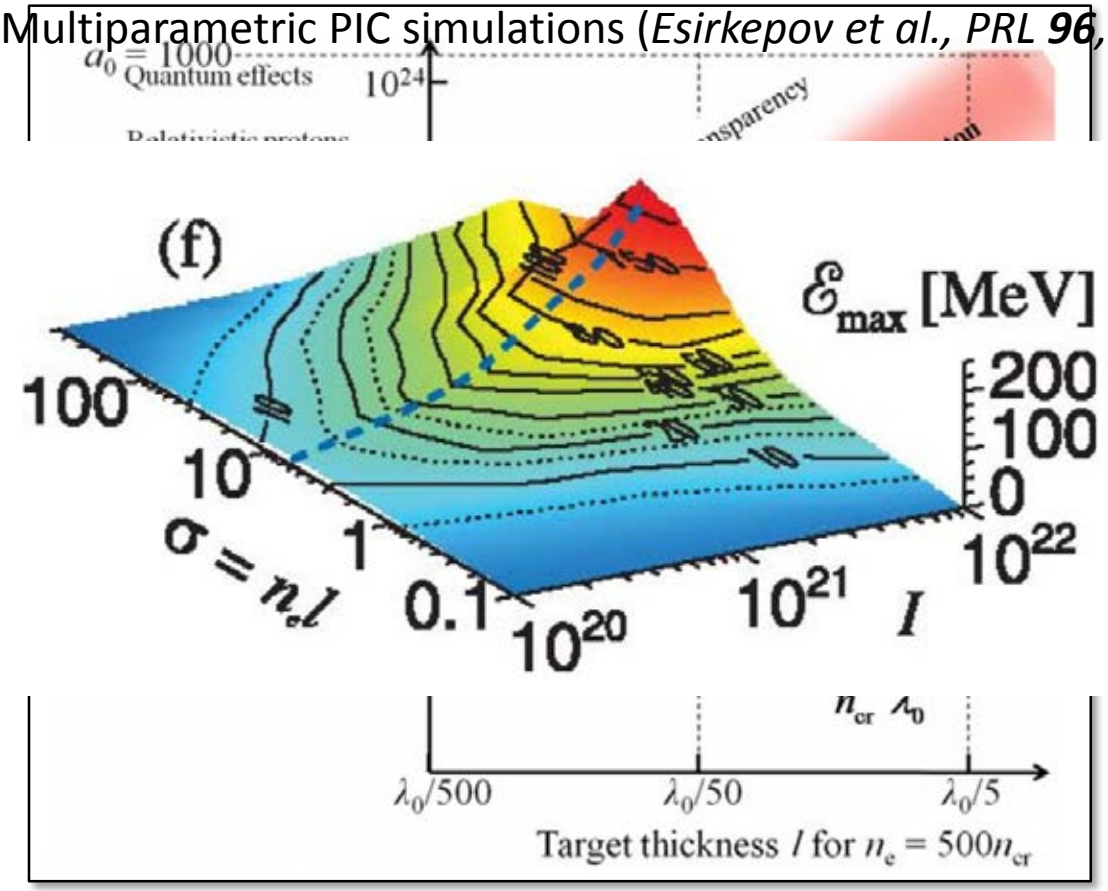


$$T_{e,h} = m_e c^2 \sqrt{1 + a_0^2} - 1$$



State-of-the-art PW laser allow exploration of new ion acceleration regimes

Multiparametric PIC simulations (*Esirkepov et al., PRL **96**, 105001 (2006)*):



Daido et al. RPP 75, 056401 (2012)

Opaque targets:

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

Transparent targets:

- Magnetic Vortex
- Collision less shocks

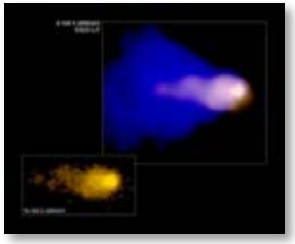
Drive laser needs:

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

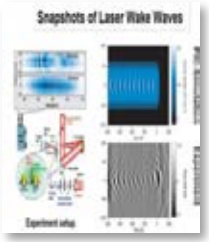
Laser-matter interaction experiments with state-of-the-art PW lasers provide access to exciting opportunities in relativistic astrophysics

Wake

The Mouse Pulsar



Electron Wake



Mattis et al, (2006)

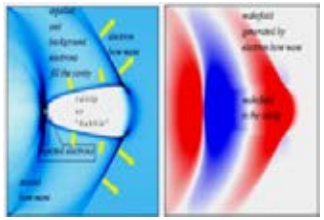
Ion Wake experiment

Borghesi, et al. (2005)

Bow Wave

Chandra image of M87

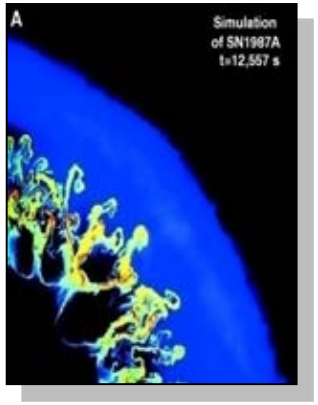
Electron Bow Wave

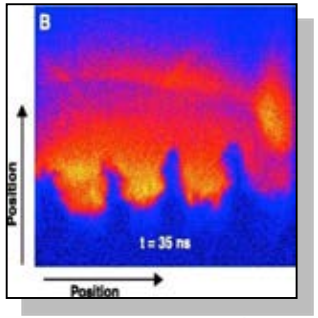


Esirkepov et al (2008)

Instabilities

Simulation of SN1987A

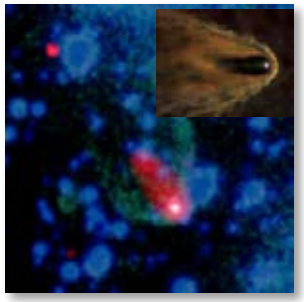


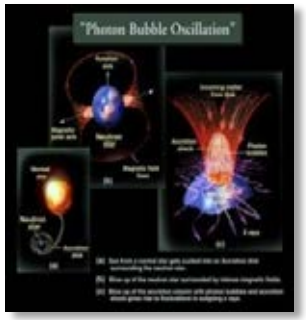


B. A. Remington et al., Science 284, 1488 (1999)

Photon Bubbles

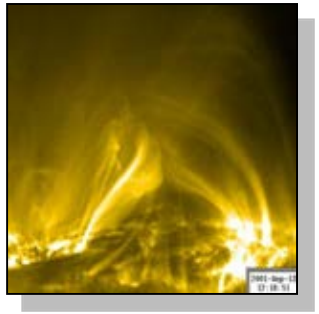
"Black Widow" pulsar

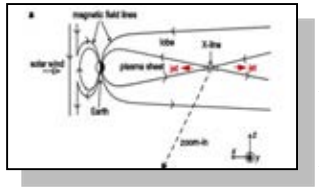




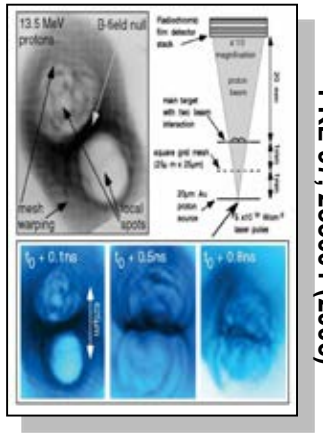
Magnetic Reconnection

Solar flare/ 12.09.2001(12:18:51)





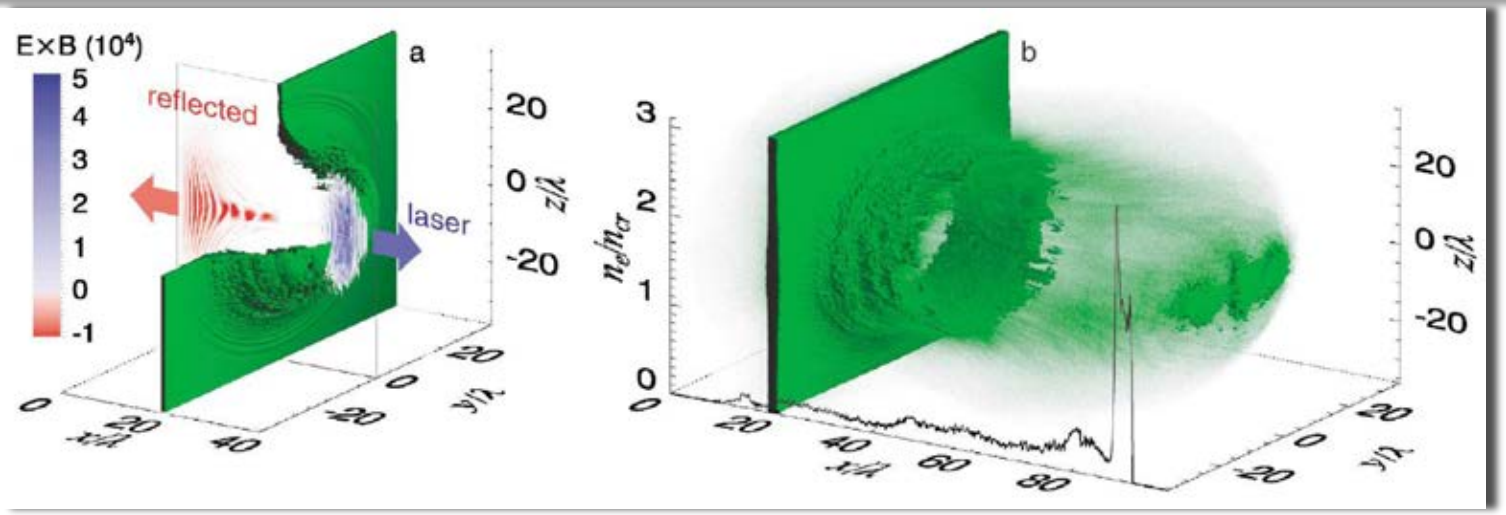
M. Oieroset, et al., Nature (2001)



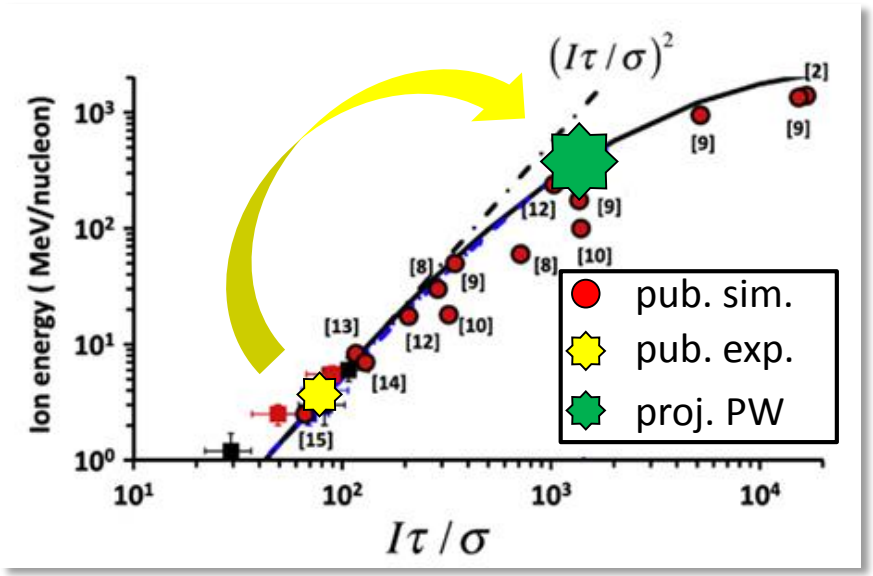
Nilson et al, PRL 97, 255001 (2006)

- Phenomena in relativistic astrophysics such as magnetic reconnection and collisionless shock waves are very closely related to the physics of laser-ion acceleration
- Recent review: S. V. Bulanov, Plasma Phys. Rep. 2015

Dominant Radiation Pressure Acceleration (RPA) becomes accessible for the first time



Esirkepov et al. PRL 2004



Steinke et al. PRSTAB 2013, Borghesi et al. PROC EAAC 2013

Initial (balance) condition:

$$P_{rad} = 2I/c \equiv P_{es} = (en_0 D)^2/2$$

areal density

Requires target design with flexibility and ultra-high laser contrast since D=30 nm (for diamond target)

But acceleration of any target ions possible (D,Fe,Ti,Au,…)

Relativistic transparency close to RPA Conditions can yield 100s of MeV electron sheets with solid density – "flying mirrors"

Un-Balance Condition (Diamond):

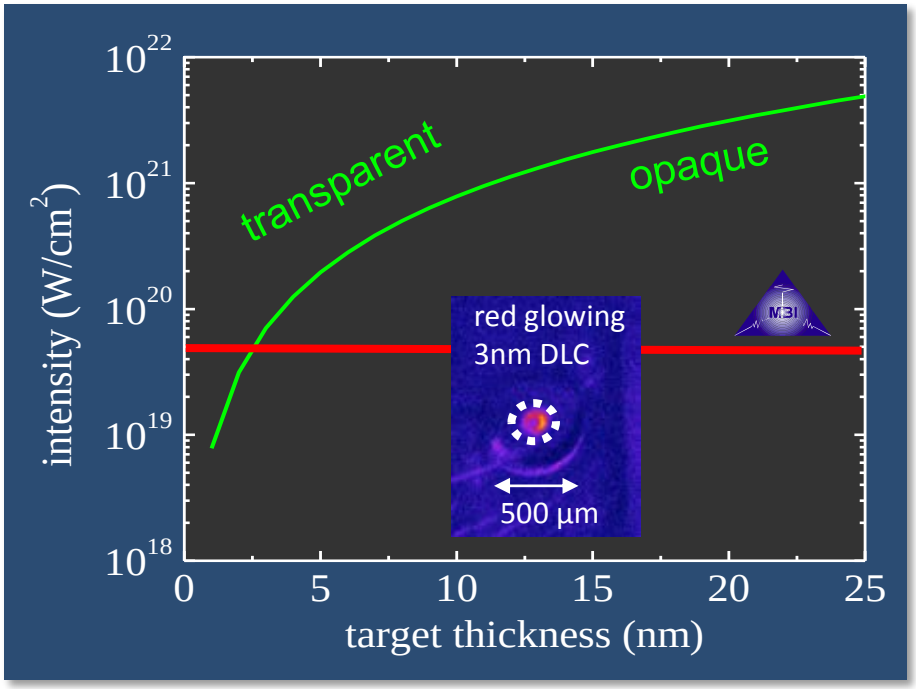
$$P_{rad} = 2I/c > P_{es} = (en_0 D)^2/2$$

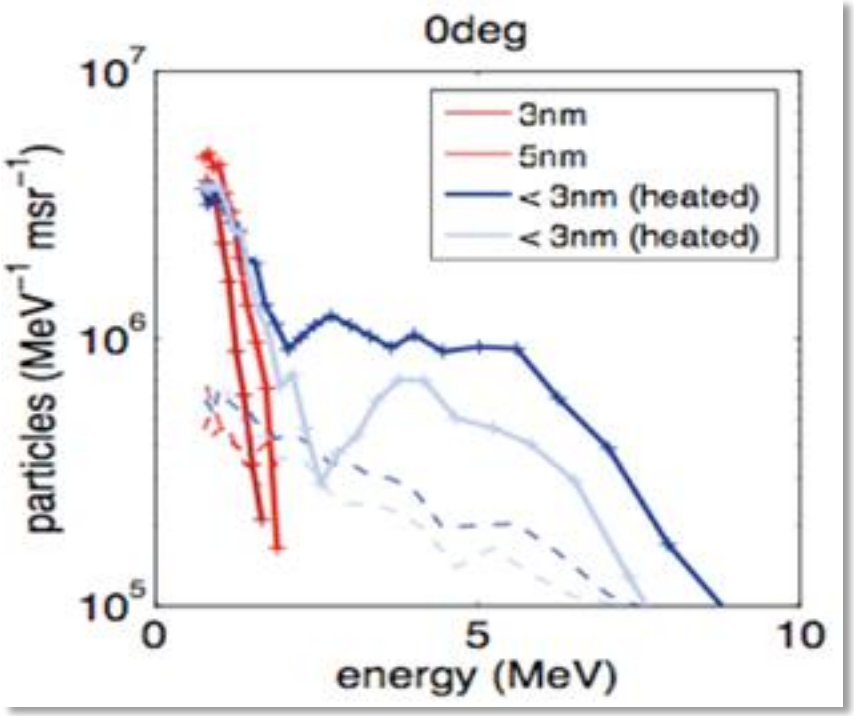
$$\Rightarrow D < 25\ nm$$

Implies 300 MeV electron bunches of solid density at relaxed target conditions (thickness of ~25 nm)

→ Flying mirror (see talk by S. S. Bulanov)

→ Coulomb explosion of bulk ions (*Braenzel el .al., PRL 2015*)



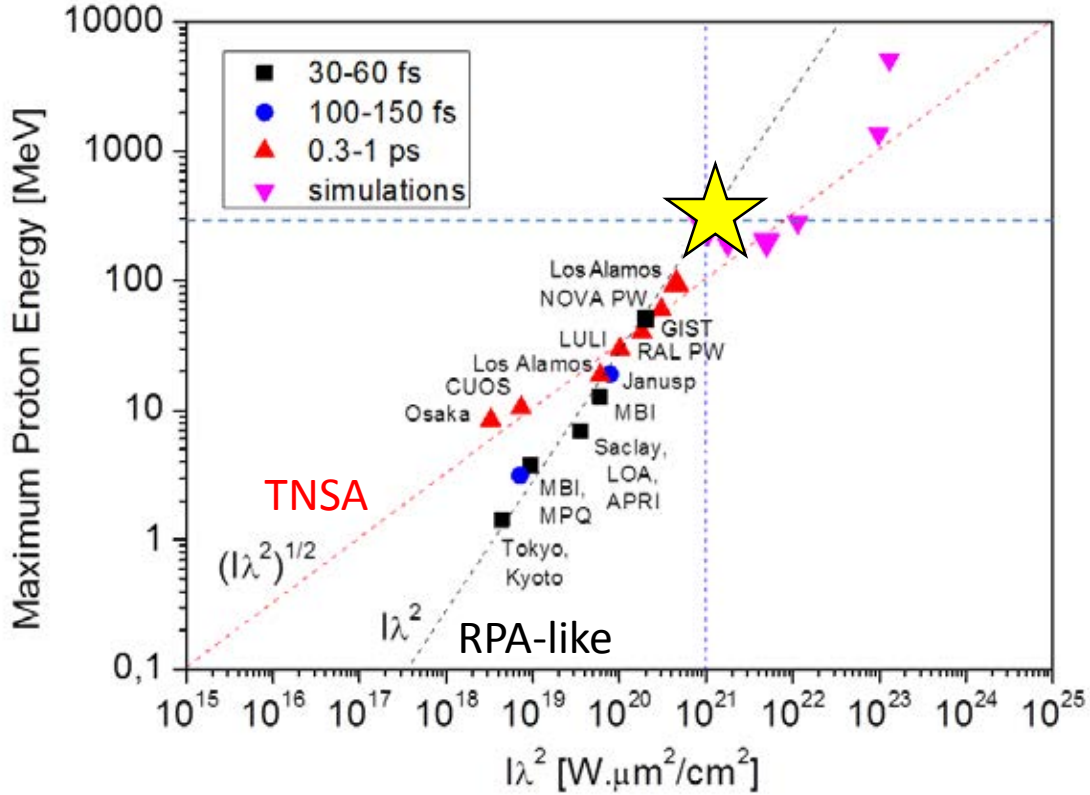


Data for a laser intensity of 10^{19} Wcm^{-2}

Steinke et al.

Short pulse laser are favorable to achieve maximum ion energies

Experimental data of the last 15 years:



Possible applications (incomplete):

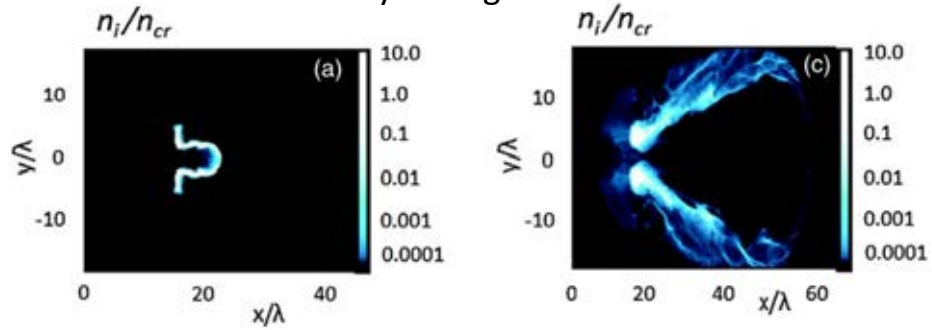
- Towards IFE and FI
- Driver for WDM
- (bio-) medical applications (e.g. 250MeV protons for Hadron therapy)
- Space Effects and Radiation Effect testing in a compact setup

e.g. 1PW focused abberation free with f/# 3

Accessing RPA involves addressing complex laser-plasma physics

Transverse expansion - finite spot size effects (***Exp.:*** *Dollar et al., PRL 108, 175005 (2012)*):

Evolution of the ion density during the interaction with the laser pulse:

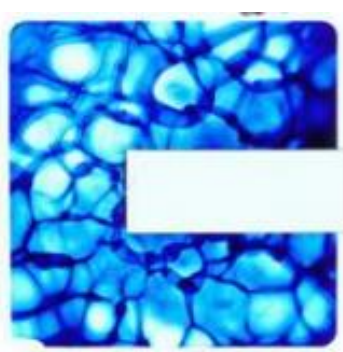


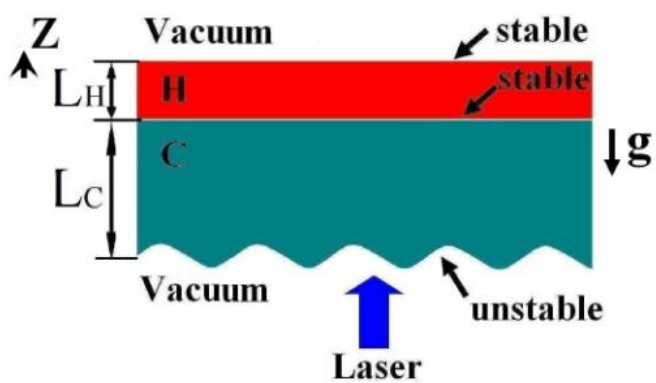
Bulanov et al., PRL 114, 10503 (2015)

Need to sacrifice focal power to avoid early termination of acc.

PW lasers to relax focal power while maintaining ultra-high intensity

Radiation Pressure driven Rayleigh-Taylor-like plasma instabilities:





Yu et al., PRL 065002 (2010)

Palmer PRL 108, 225002 (2012)

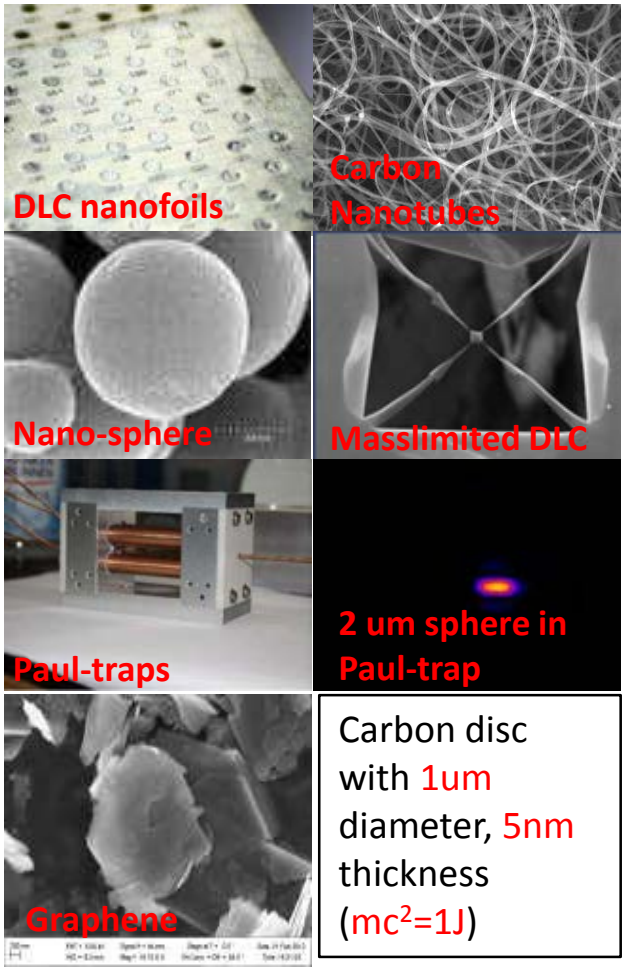
Multi-layer targets buffer instabilities effectively

(***Exp.:*** *Steinke et al., PRSTAB 16, 011303 (2013)*)

Advanced tagetry to allow acc. for max. duration and composition for apps

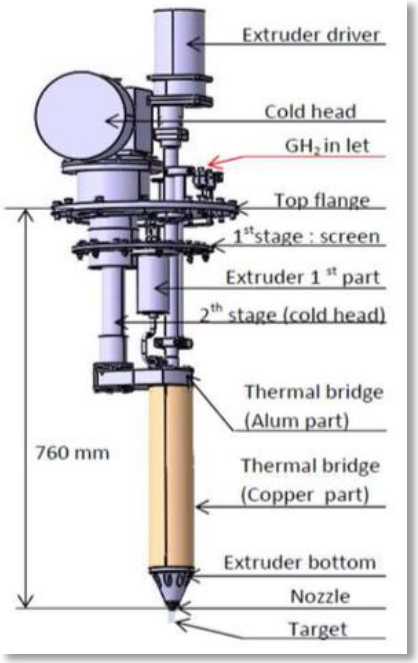
Advanced targetry is crucial for tuning of laser-matter interactions – access to cutting edge nano-fabrication is required

Nano-scale reduced mass targets

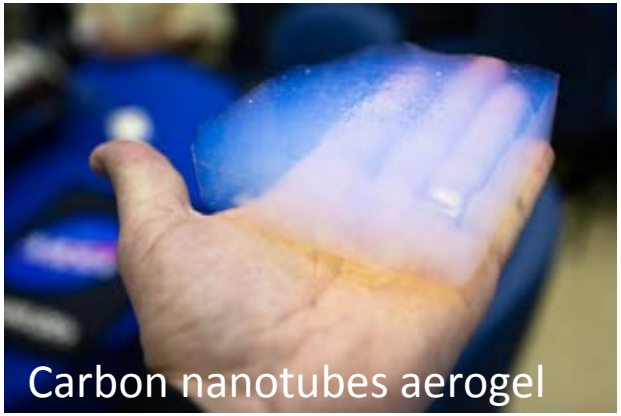


Carbon disc with 1um diameter, 5nm thickness (mc^2=1J)

LMU Munich, MBI Berlin

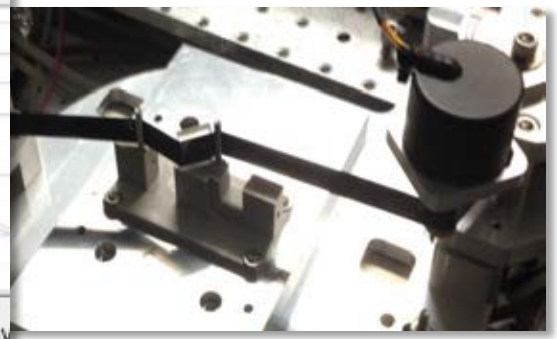


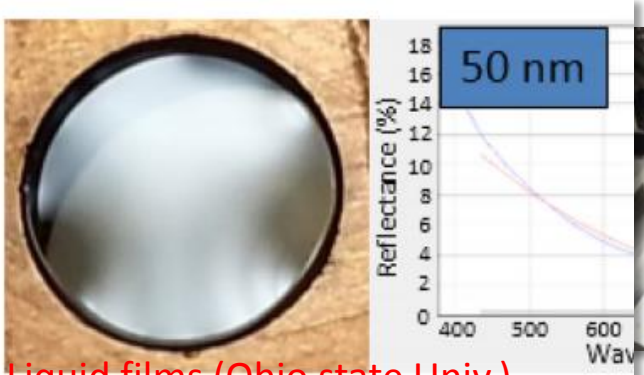
Solid hydrogen extruder, 10-50 micron thick, 10 mm wide solid hydrogen tape (CEA, France)



Univ. of Pennsylvania

High precision tape drive (BELLA Center)



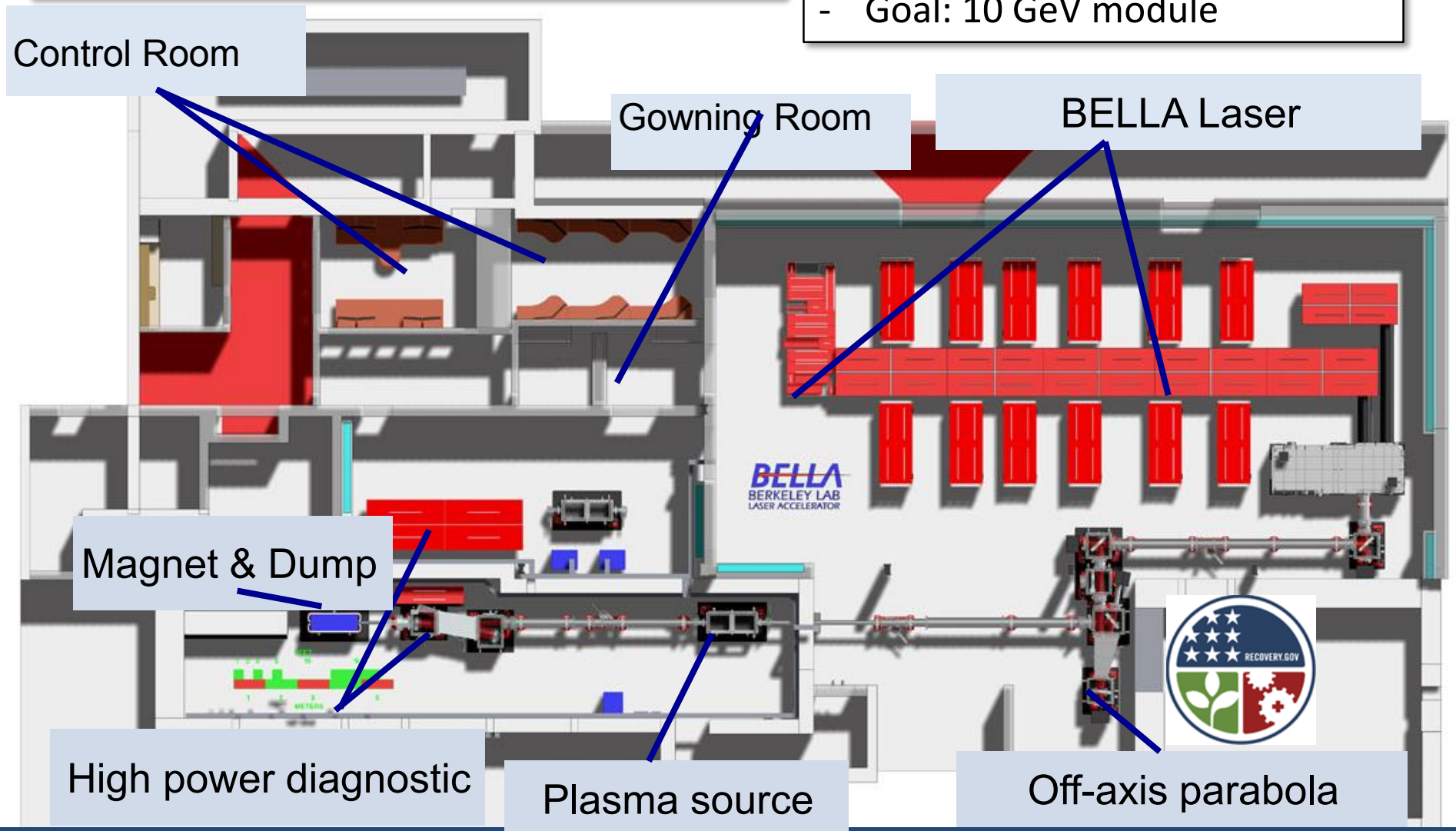


Liquid films (Ohio state Univ.)

Present BELLA PW laser and long focal length beamline

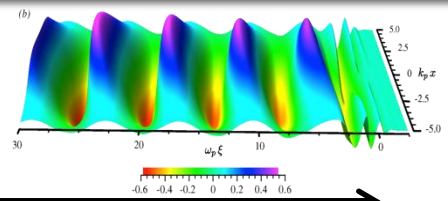
BELLA is routinly running at: 30J, 30fs, 1Hz for hours of run time, 3-5 days per week

BELLA currently has one beamline
- Long focal length
- Goal: 10 GeV module

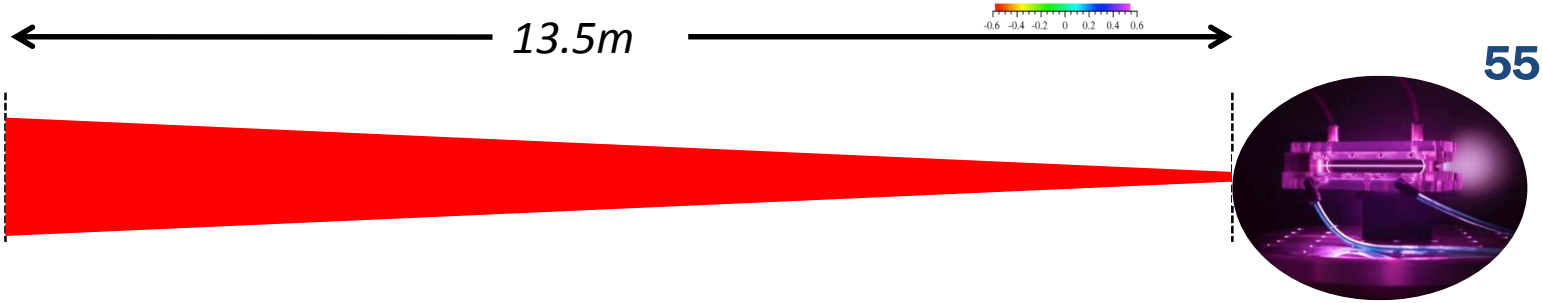


For electron acceleration, BELLA is focused with long focal length. For ions (etc.) it requires short focal length and plasma mirrors

Electron acceleration



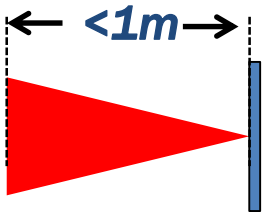
Intensity ~1.5x10^{19} Wcm^{-2}
Acc. fields ~10-50GV/m



55 micron spot

Ion acceleration

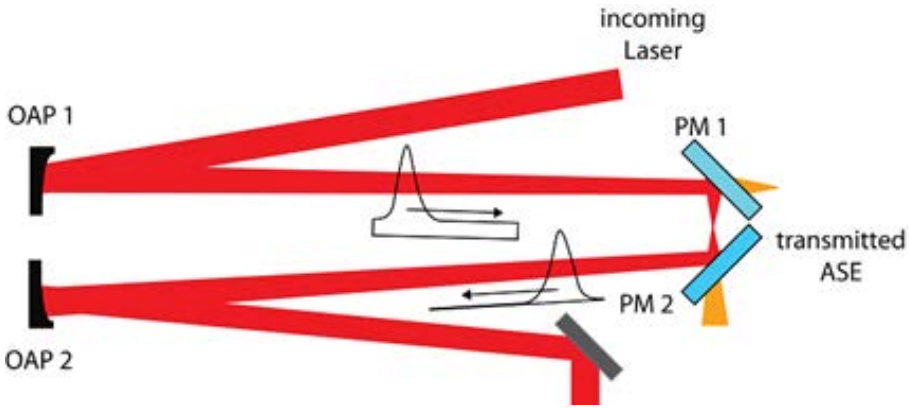
Intensity <10^{22} Wcm^{-2}
Acc. fields ~TV/m



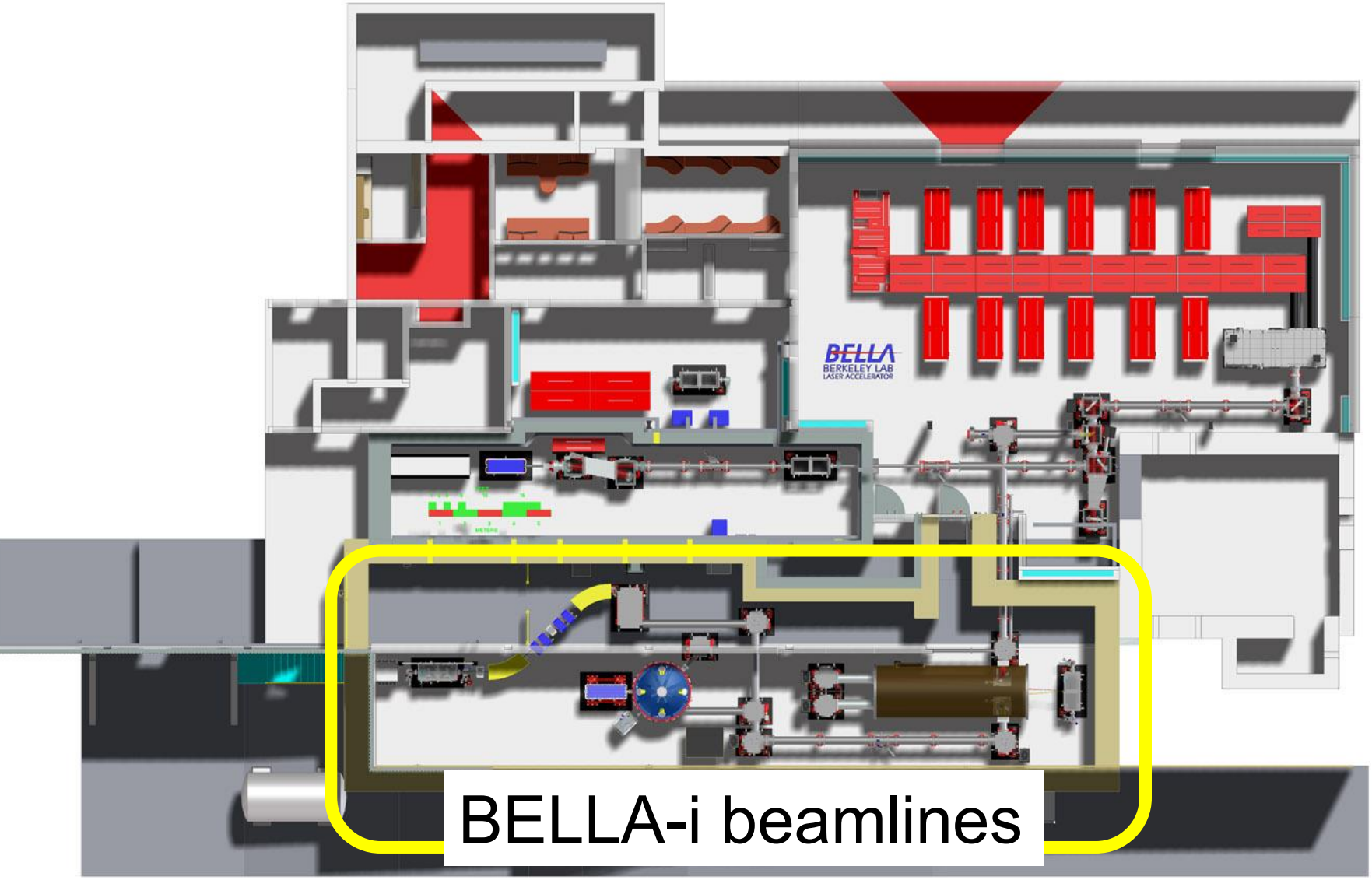
4-5 micron spot

+

Double-Plasma mirror technology for contrast clean-up

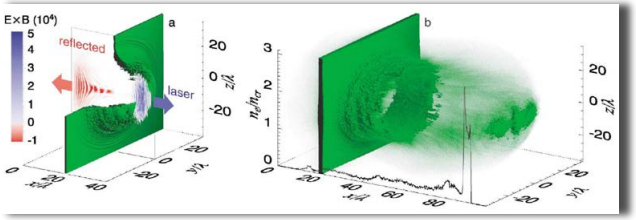


Projected BELLA-i beamlines: expand the facility by adding short focal length capability – ultra-high intensity

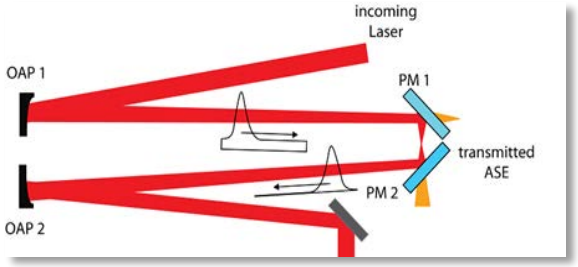


Short pulse, high contrast PW lasers constitute an excellent tool for Frontier Plasma Science with errorbars

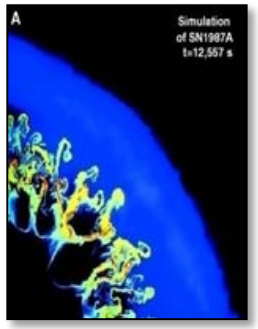
- **Ion energies of >200 MeV in reach** via Radiation Pressure Acceleration (RPA)



- Study the physics of ion acceleration
- requires **PW laser pulses** with pulse duration **<100fs**, aberration free & tight focusing, **ultra-high intensity contrast** and repetition rate



- requires **advanced targetry lab**
- ideal setting to study **relativistic astrophysics** or **high field physics** (talk by S. S. Bulanov) or **Relativistic surface high harmonics** (whitepaper by C. Roedel)



Challenges

Plasma Physics:

- Scaling the physics (and PIC simulations) of ion acceleration to **higher ion beam energies** and achieve **quasi-monoenergetic beams** with **reduced divergence** at **high conversion efficiency.**
- Understand the impact of **transverse expansion** and **plasma instabilities** on acceleration physics/ laser solid interaction

Technical:

• Provide laser PW pulses with duration <100fs and ns-(Prepulse/ ASE) intensity contrast >12-14 orders of magnitude and flat wavefront to allow focusing to ultra-high intensities (10^22 W/cm^2) . Such laser pulses **allow realistic modelling** due to the fs duration and "absence" of ns prepulses

• advanced targetry to optimize ion acceleration, buffer instabilities or self-focus/ guide laser pulses