Ultra-intense laser-plasma interactions with the BELLA-i PW user facility

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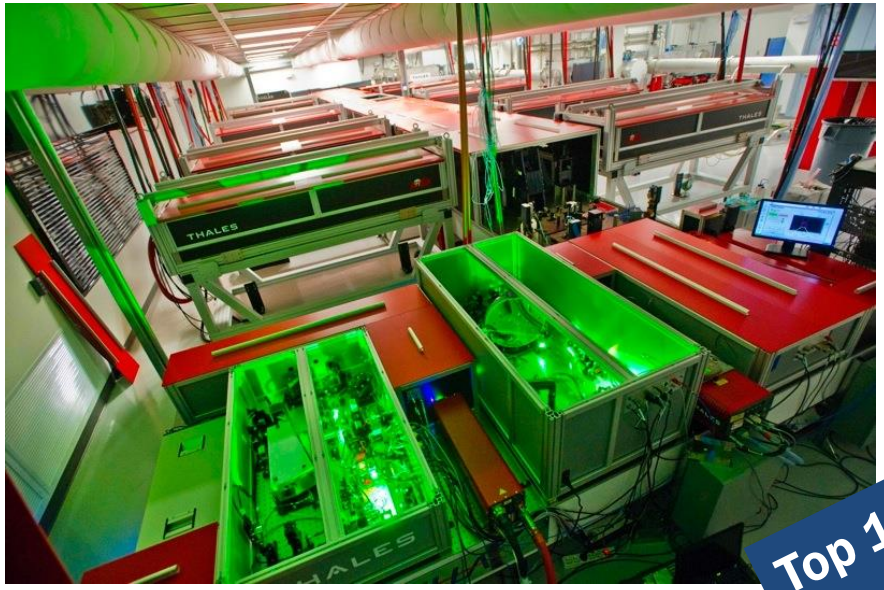
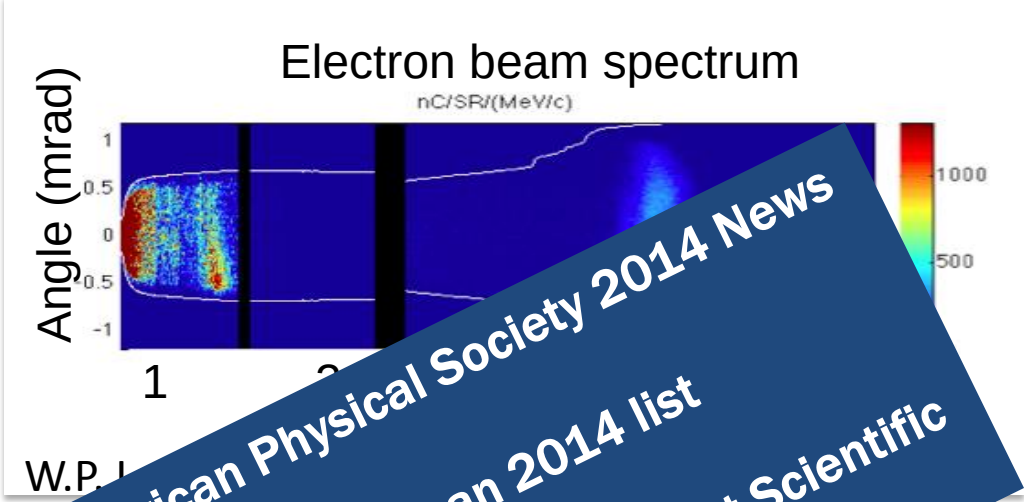
Frontiers of Plasma Science Town Hall, Bethesda MD

June 30 – July 1, 2015

BELLA: the highest rep rate PW-laser in the world for laser plasma acceleration experiments

- Unique tool for development of 10 GeV laser plasma accelerator and other collider relevant concepts





Top 10 American Physical Society 2014 News

Top 20 Scientific American 2014 list

NERSC 2015 Award for High Impact Scientific Achievement

sciencewr.com

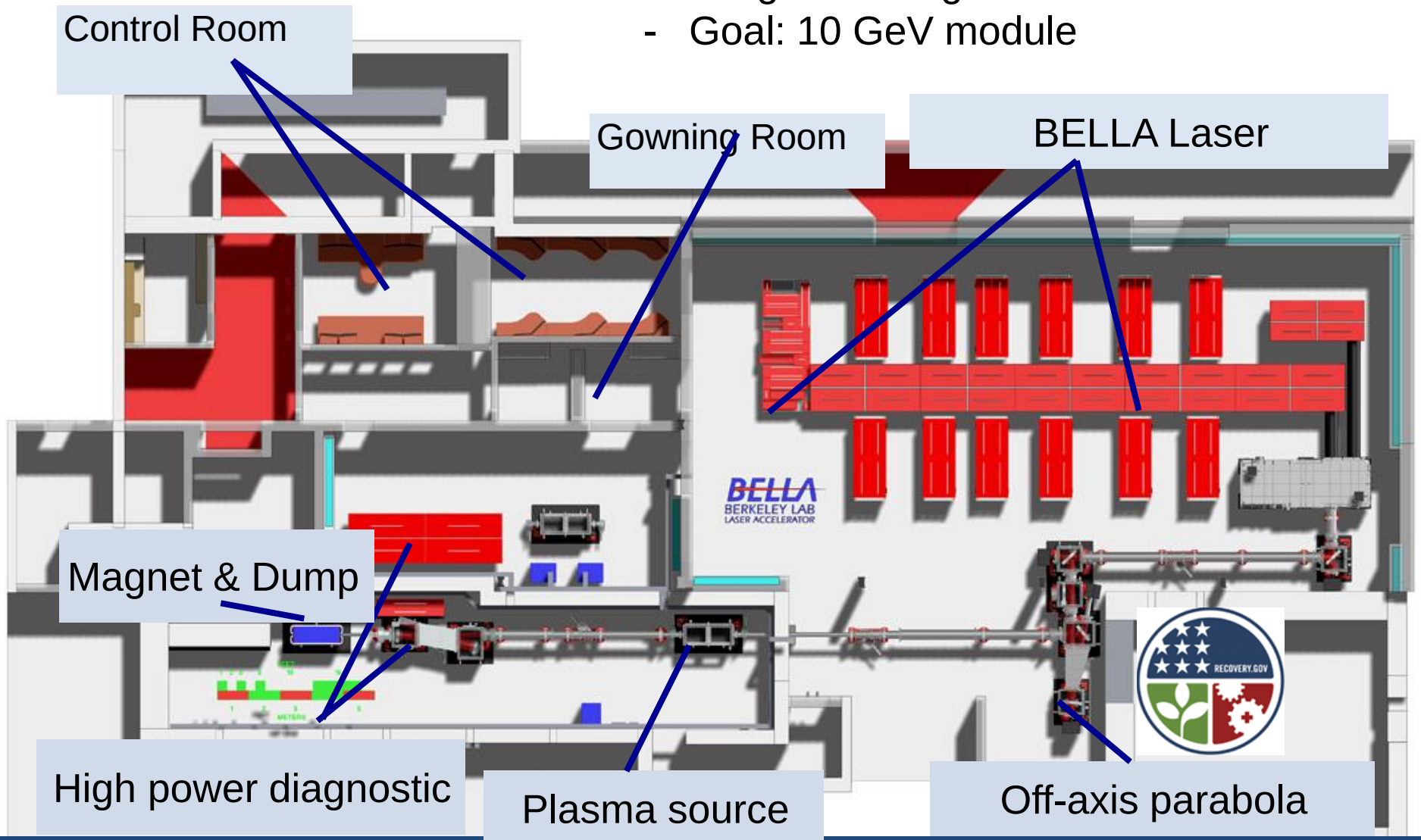
MEDICINE TECH PHYSICS HUMAN VIDEO

eak World Record for
t Particle Accelerator with
werful Laser

- First commercial Petawatt laser operating at > 42 J in ~30 fs at 1 Hz

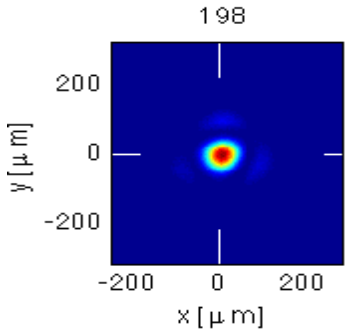
Present BELLA PW laser and long focal length beamline

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

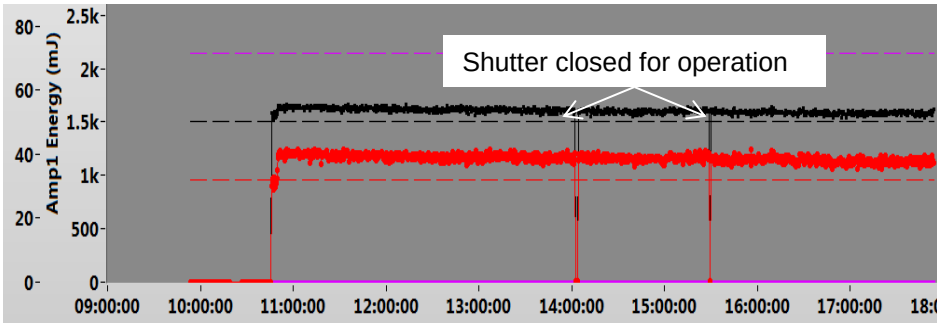


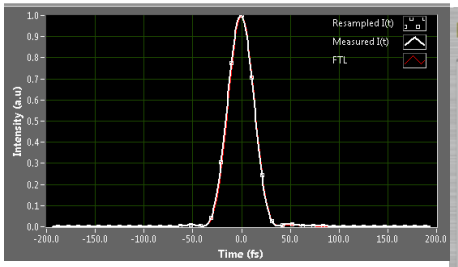
Laser quality and experienced operations team are key to succesfull experimental campaigns

- Experienced team
  - High mode quality
  - Pointing stability
  - Know-how in handling high peak power
- Important improvements:
  - Pulse shaper
  - Ultra-stable oscillator and regenerative amplifier pump

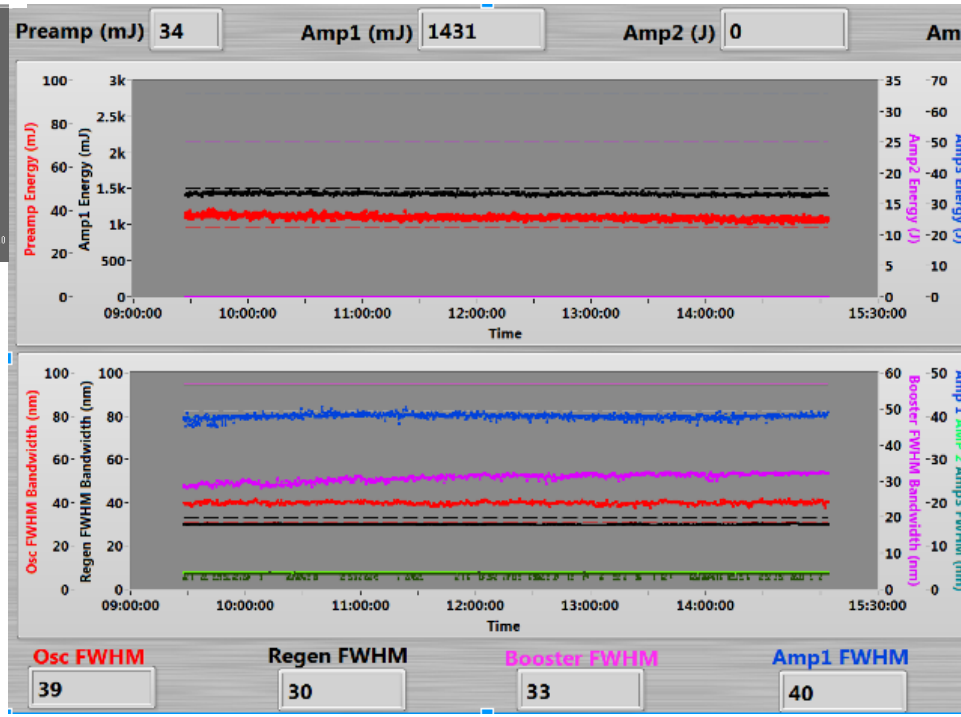


Frontend laser energy stability: Stable >7 hours



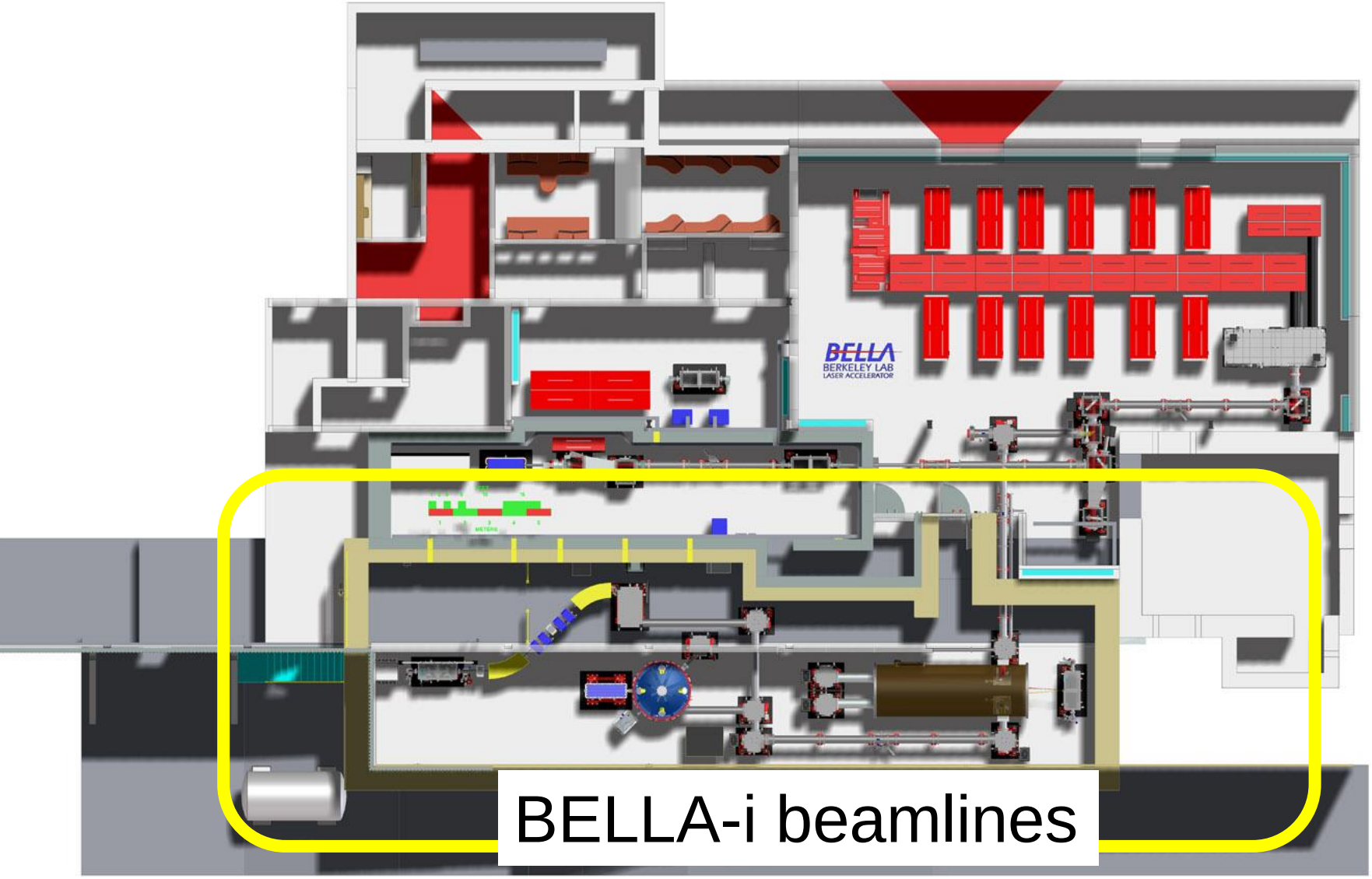


30 TW/J w/ Dazzler



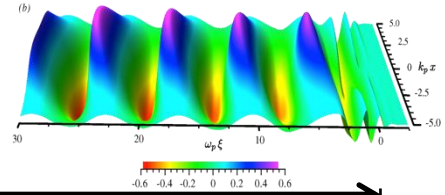
- Development of 10 GeV module
- Collider relevant concepts
- Accelerator stewardship

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

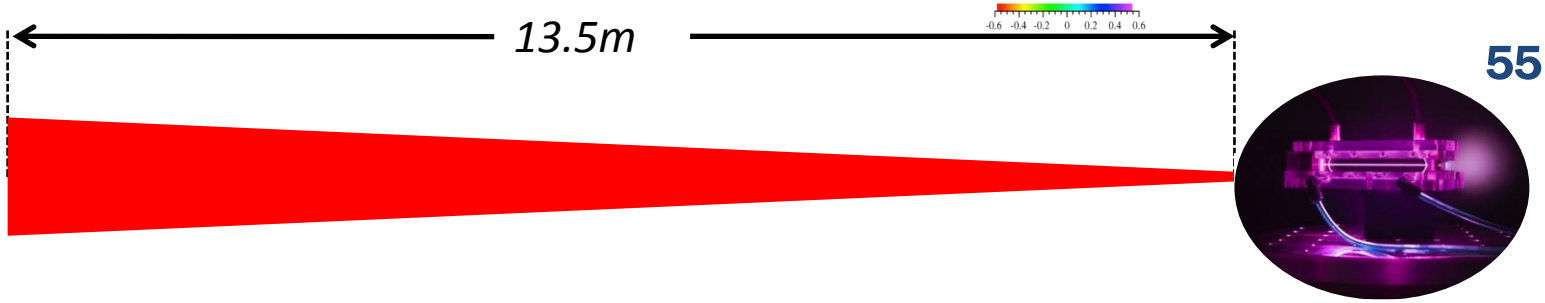


For electron acceleration, BELLA is focused with long focal length. For ions (etc.) it requires short focal length and plasma mirrors

Electron acceleration



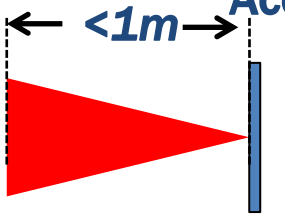
Intensity ~1.5×10^{19} Wcm^{-2}
Acc. fields ~10-50GV/m



55 micron spot

Ion acceleration

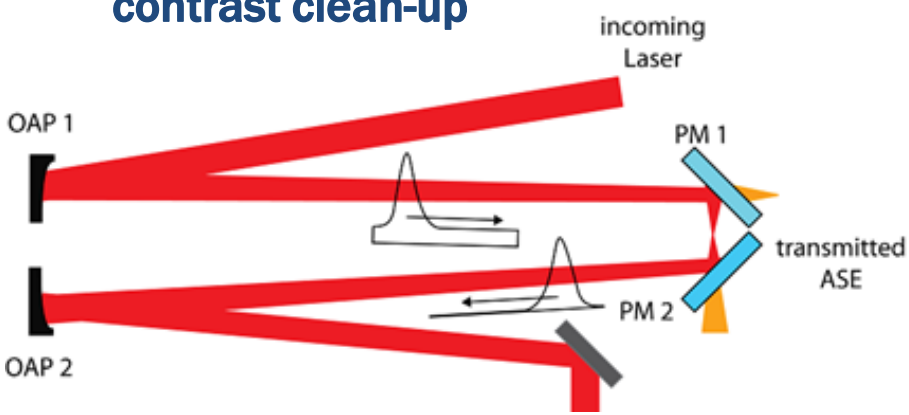
Intensity ~$3\text{-}5\times10^{21}$ Wcm^{-2}
Acc. fields ~TV/m



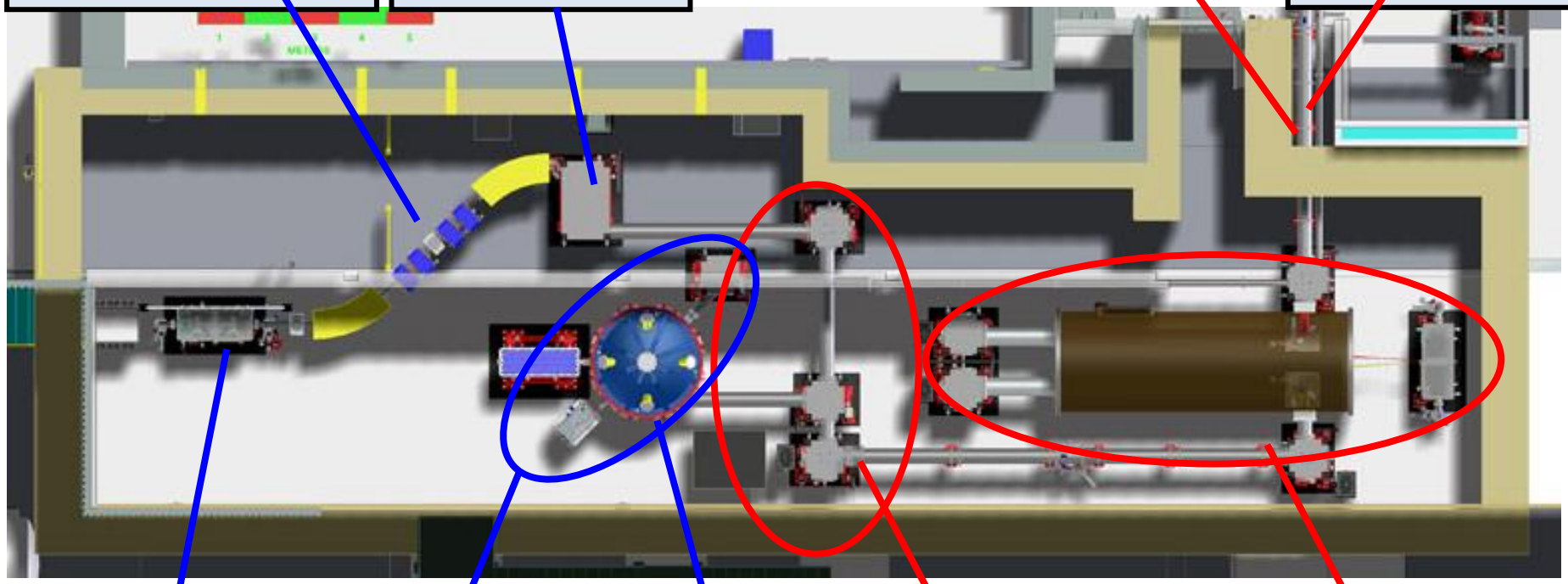
4-5 micron spot

+

Plasma mirror technology for contrast clean-up



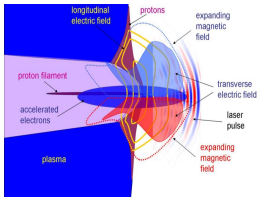
BELLA-i beamlines: expand the facility by adding short focal length capability – ultra-high intensity



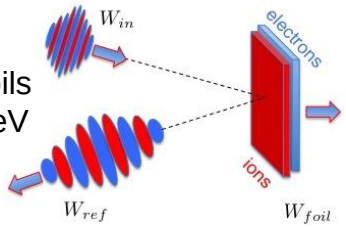
Ion Acceleration

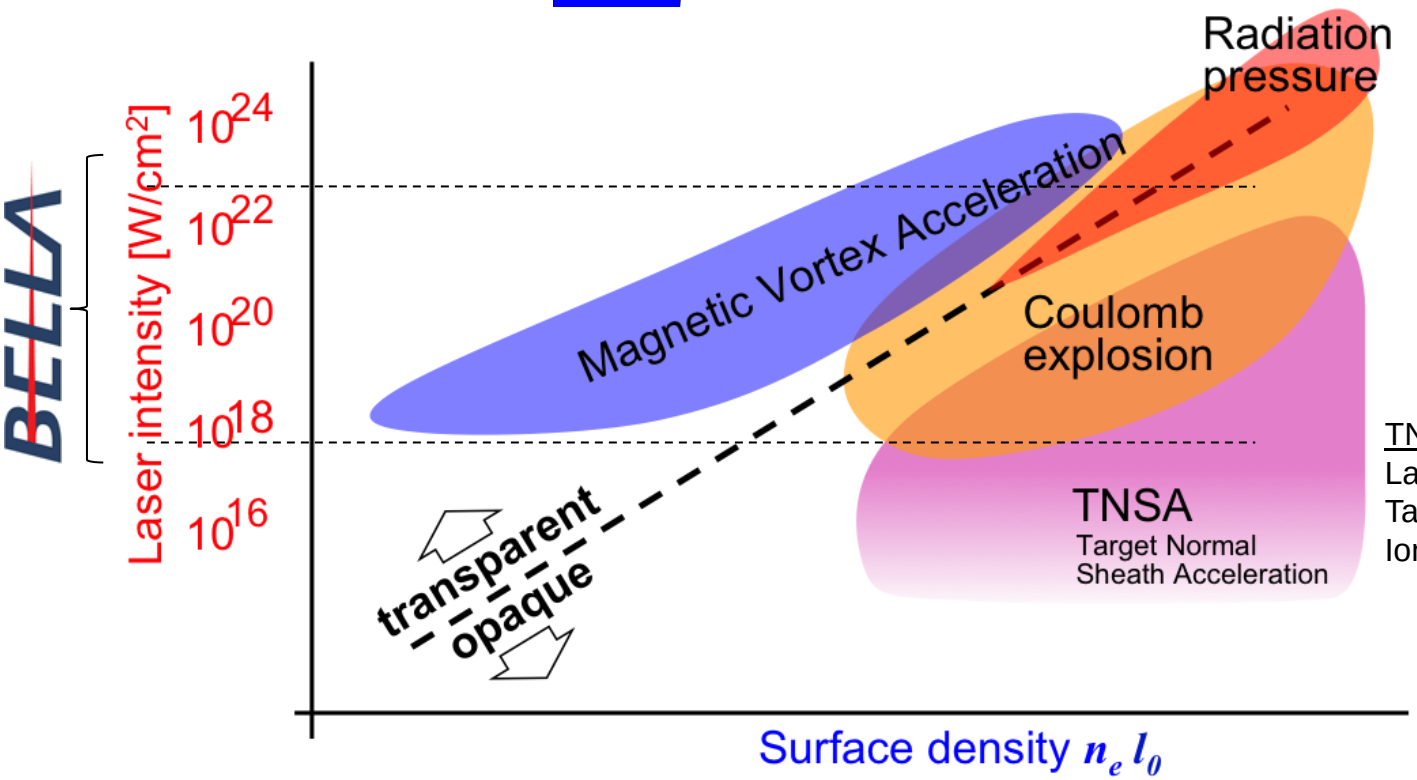
High intensity BELLA-i allows study of different ion acceleration mechanisms

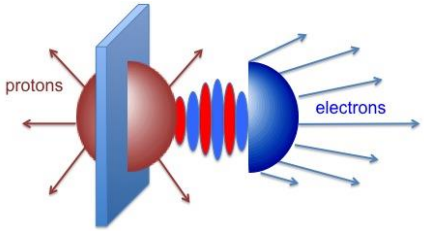
MVA
Laser: High Intensity
Target: Near Critical Density slab
Ion Energy: hundreds of MeV to GeV



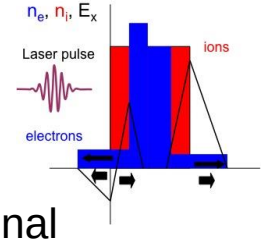
RPA & CE
Laser: High Intensity
Target: Thin solid density foils
Ion Energy: hundreds of MeV







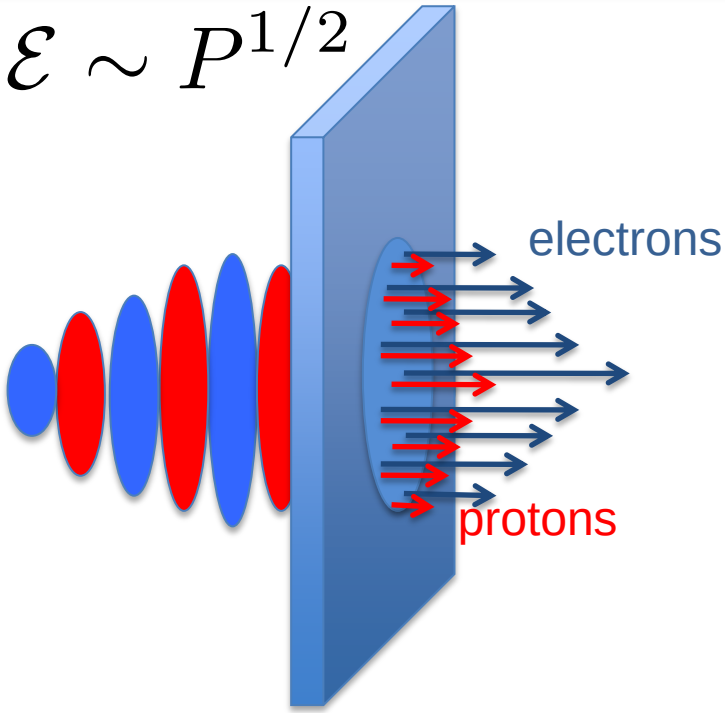
TNSA
Laser: Low Intensity
Target: Thick solid density foils
Ion Energy: ~100 MeV



Applications: Radiography, Deflectometry, Cancer Therapy, Injection into conventional accelerators, Fast Ignition, Isochoric heating of matter, Positron Emission Tomography, Nuclear Physics…

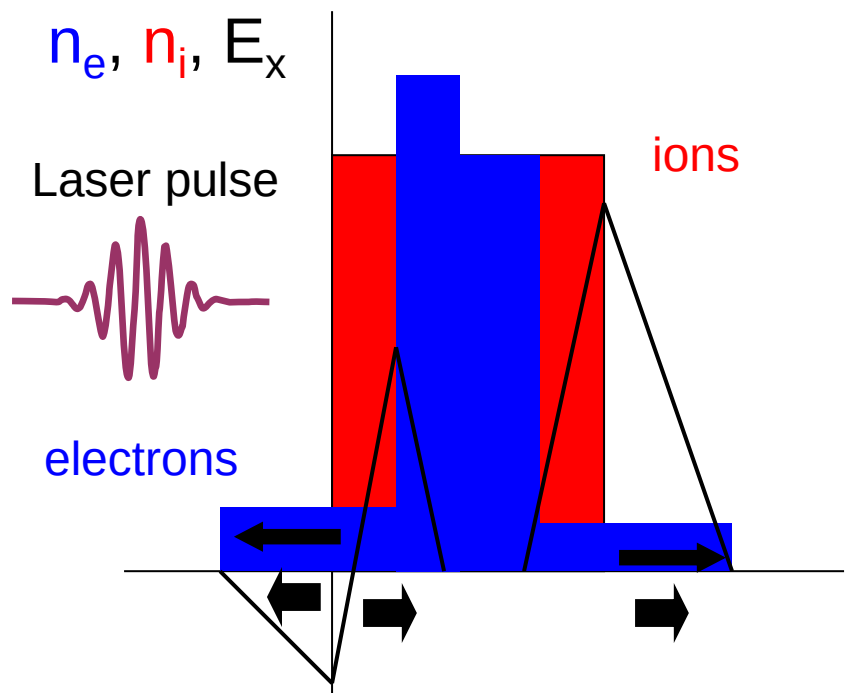
Target Normal Sheath Acceleration: optimal for low intensity and thick targets

$$\mathcal{E} \sim P^{1/2}$$



Normal Sheath Acceleration

- **Poor contrast requires thick target**
- **Prepulse creates preplasma on surface**
- **Pulse drives some e^- through target**
- **Charge separation at rear accelerates protons**



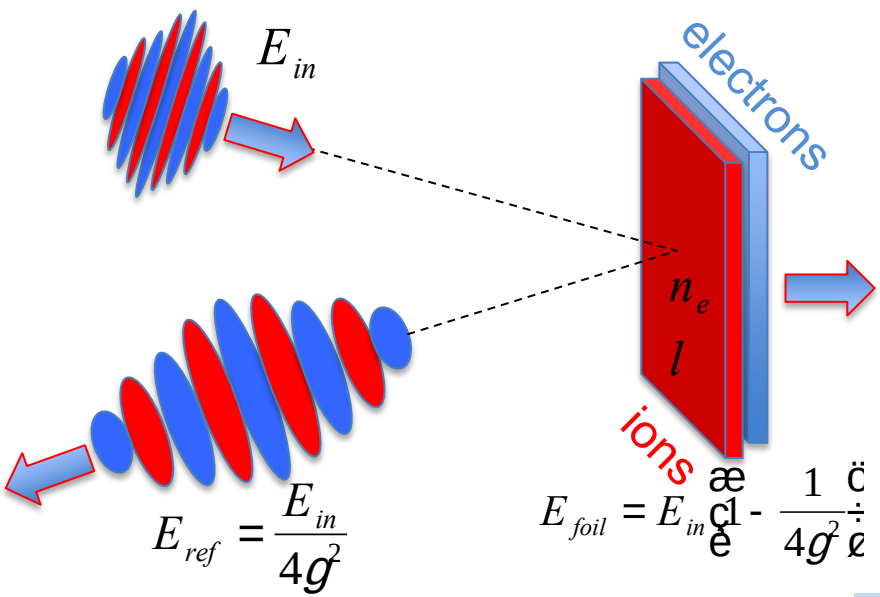
The TNSA ion energy scales as

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

where $$a_0 = \frac{eE}{m_e \omega c} = \sqrt{\frac{I\lambda^2}{1.37 \times 10^{18}\ \mathrm{W/cm^2}}}$$

S. C. Wilks *et al.*, Phys. Plasmas **8**, 542 (2001).

Radiation Pressure Acceleration requires high intensity and high contrast laser pulses



In the nonrelativistic regime:

$$E \sim w^2$$

Normalized laser fluence

The ion momentum scales as

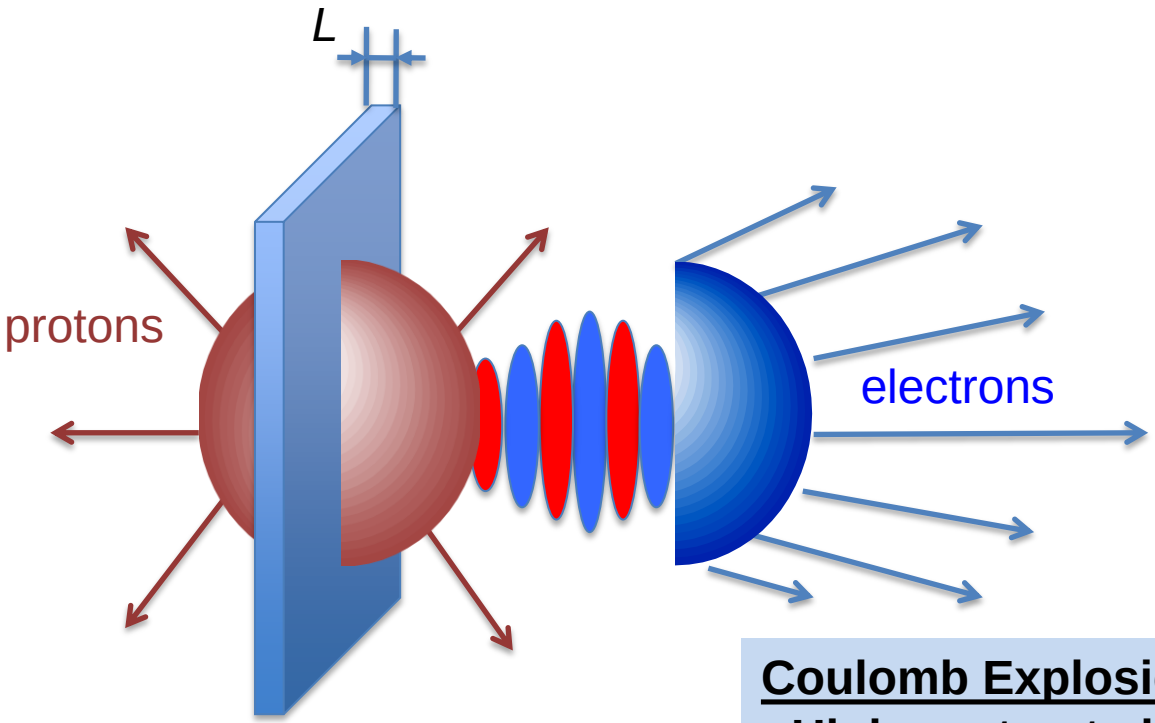
$$\frac{p_\alpha}{m_p c} = \frac{2w(w+1)}{2w+1}$$

Radiation Pressure Acceleration Regime

- **High contrast allows the interaction of non-expanded target with the main laser pulse**
- **Pulse is reflected by the target**
- **The target is accelerated by the radiation pressure**

T. Esirkepov, *et al.*, Phys. Rev. Lett. **92,** 175003 (2004)

Coulomb Explosion: High Intensity Laser Pulse is Able to Evacuate All the Electrons from the Target



$$\mathcal{E} \sim P^{1/2}$$

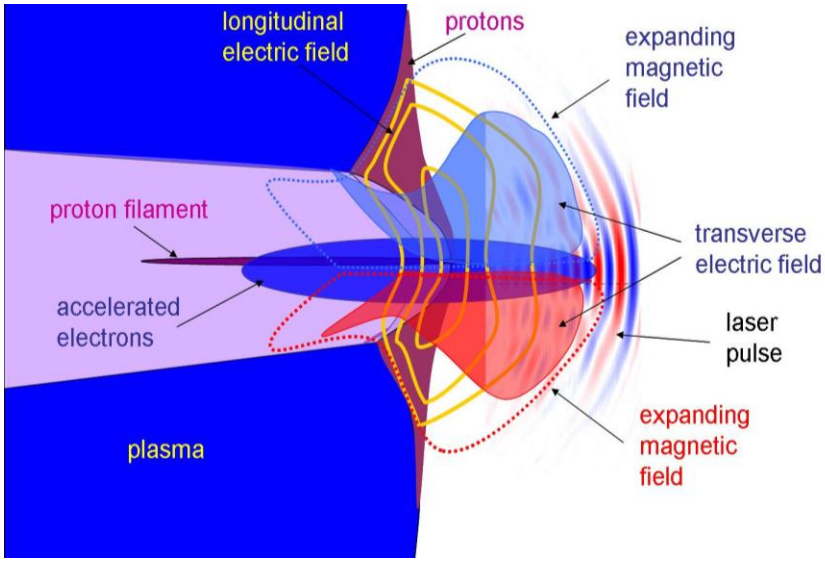
$$a = p\frac{n_e}{n_{cr}}\frac{l}{l}$$

S. V. Bulanov, *et al.*, Phys. Lett. A **299**, 240 (2002).

Coulomb Explosion Regime

- **High contrast allows sub-micron target which become transparent to laser**
- **Pulse propagates through target**
- **Removes most electrons from target**
- **Much larger charge separation at rear**
- **Best designs use high-Z/low-Z layers**

Magnetic Vortex Acceleration generates ion beams from near critical density plasma slab



Magnetic Vortex Acceleration Regime

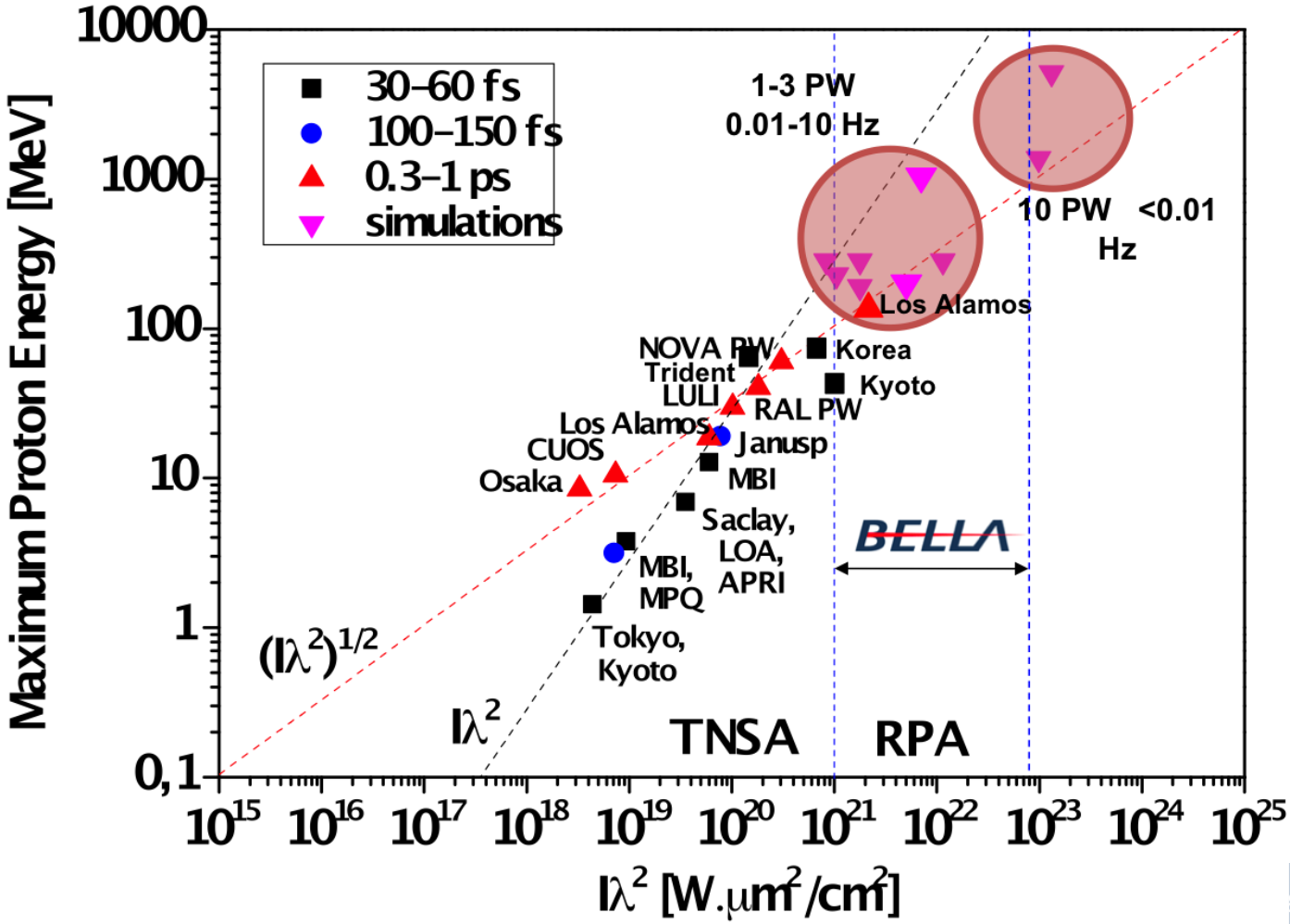
- **Target – plasma slab of near critical density with thickness much larger then the laser pulse length**
- **The pulse propagation inside the target generates a channel in electron and ion densities as well as strong moving electric and magnetic fields**
- **Upon exiting the plasma the magnetic field generates a quasi-static electric field that accelerates and collimates ions from a thin filament formed in the propagation channel**

The maximum ion energy scales as $E_i = m_e c^2 2\pi^2 Z_i \frac{n_e}{n_{cr}} \left(\frac{R_{ch}}{\lambda}\right)^4 \propto P^{2/3}$

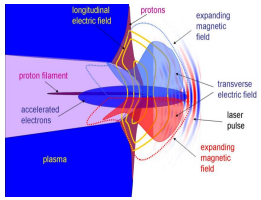
S. S. Bulanov, et al., Phys. Plasmas **17**, 043105 (2010)

High intensity BELLA allows study of different of ion acceleration mechanisms: up to 1 GeV

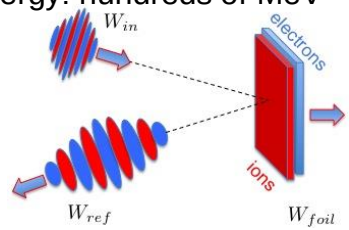
High power: 30 J, 30 fs
High contrast: 10^{10} -10^{12}
Tight focusing: f/D=1-4
High Intensity: I=10^{21}-10^{22} W/cm^2



MVA
Laser: High Intensity
Target: Near Critical Density slab
Ion Energy: hundreds of MeV to GeV



RPA & CE
Laser: High Intensity
Target: Thin solid density foils
Ion Energy: hundreds of MeV



TNSA
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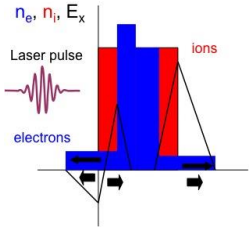
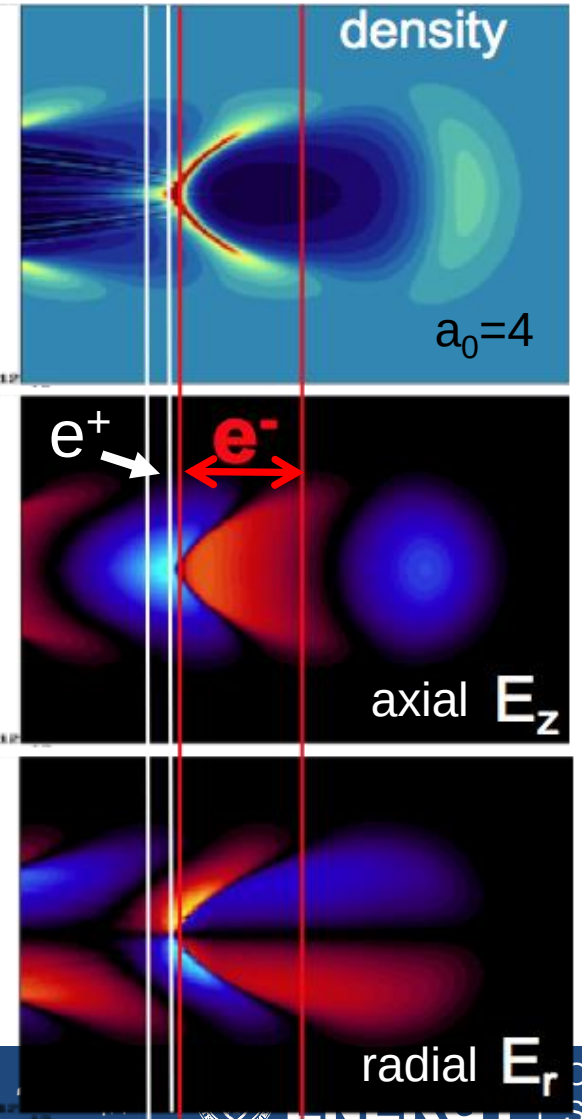


Electron Acceleration:
Highly Nonlinear Wakefields

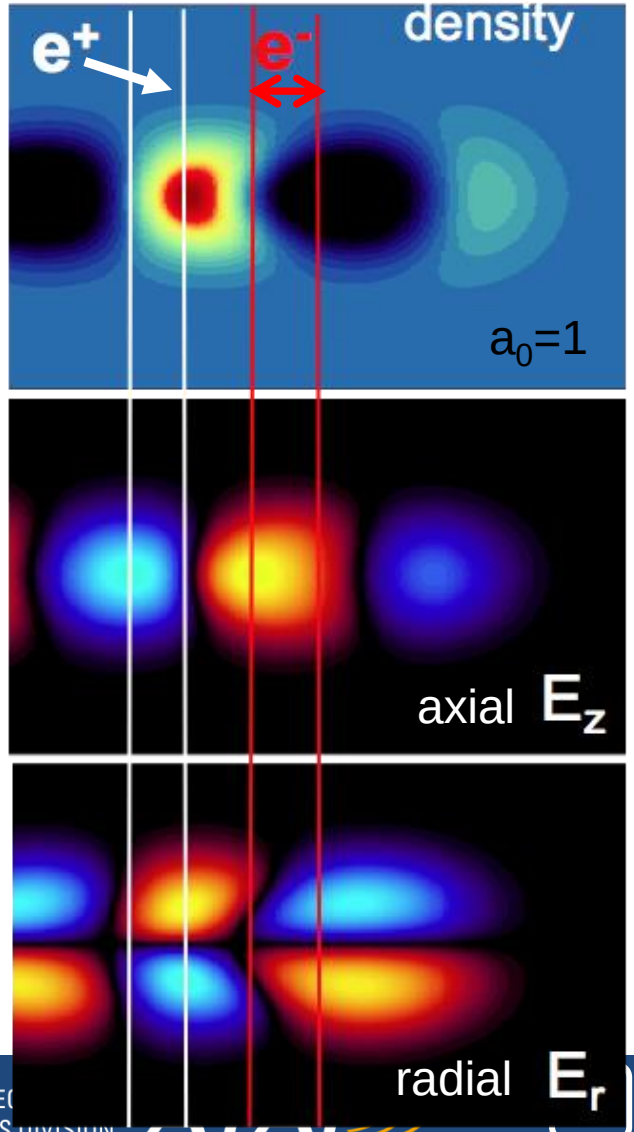
Electron acceleration: BELLA-i allows access to highly nonlinear wake regimes

Bubble/blow-out



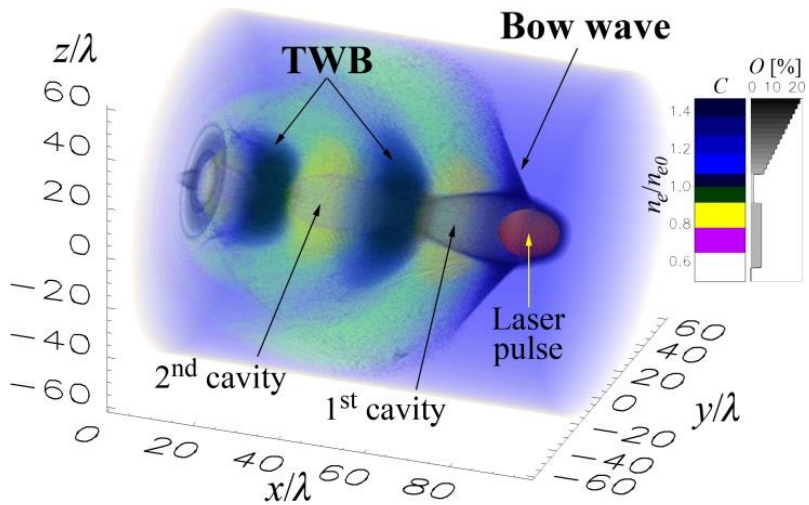
- Blowout regime
  - a_0 >> 1
  - very asymmetric
    - focuses e-
    - defocuses e+
  - self-trapping
  - self-guiding
  - highest fields
- Quasi-linear
  - a_0 ~ 1
  - symmetric e+/e-
  - dark current free
  - channel required
  - tailor focusing forces via laser profile

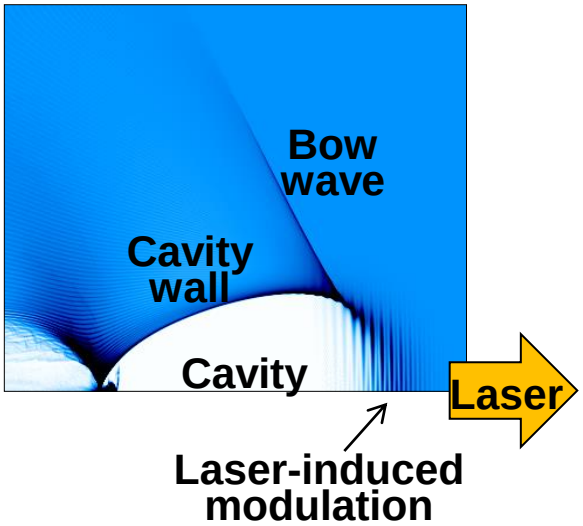
Quasi-linear

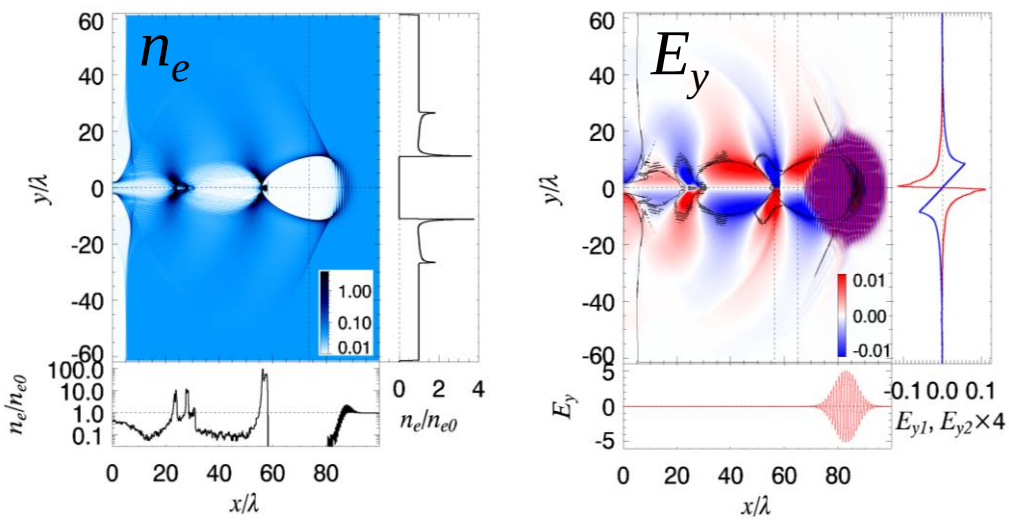


High Intensity Laser Generates Nonlinear Bubble Wakes in Underdense Plasmas

3D PIC simulation







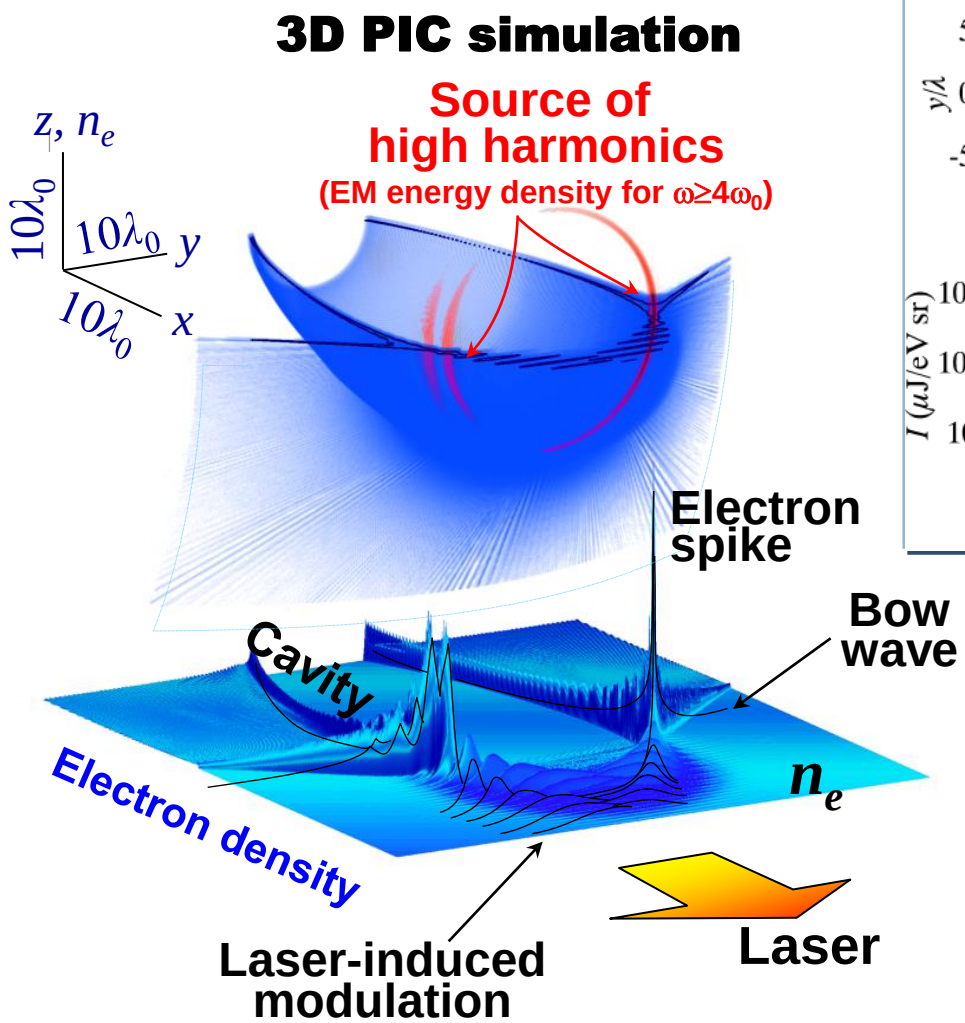
Laser pulse a_0=6.62

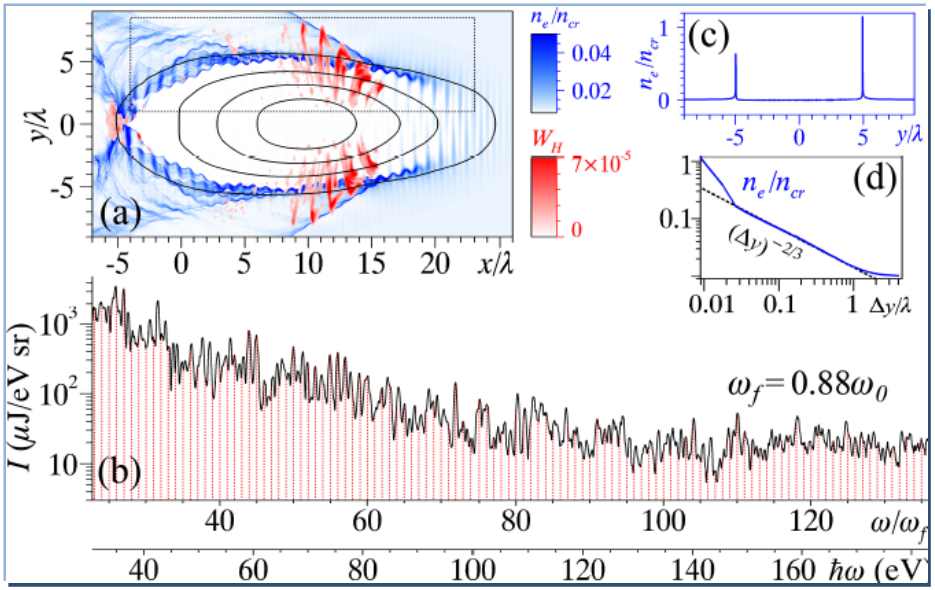
10x10x10μm^3
Linearly polarized (y-axis)

Plasma n_e= 1.14×10^{18} cm^{-3}

T. Zh. Esirkepov, et al., PRL 101, 265001 (2008).

High Harmonics Generation by Electron Density Cusps Oscillating in Laser Field





(a) The electron density (blue), laser envelope (curves for a = 1,4,7,10), and electromagnetic energy density, W_H, for frequencies from 60 to 100 ω_0 (red).

(b) The upper spike emission spectrum for the dashed rectangle in (a).

(c) The electron density profile 10 laser cycles earlier than (a) and the right spike structure (d).

A.S. Pirozhkov et al., *Phys. Rev. Lett.* 108, 135004 (2012)

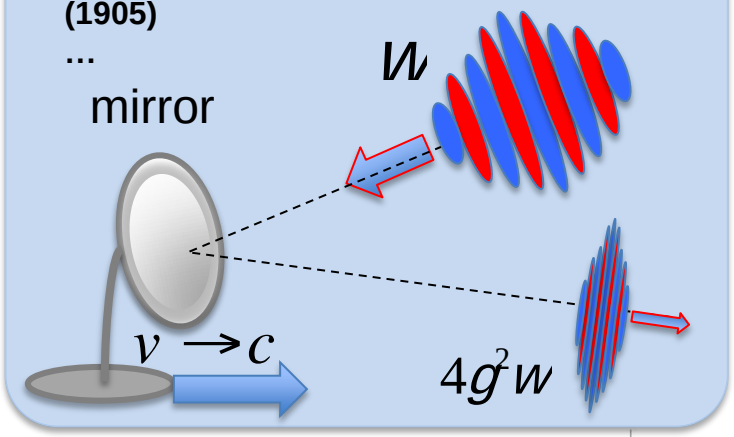
Flying Mirrors

Electromagnetic Pulse Intensification and Shortening by Flying Mirror formed in laser-plasma interaction

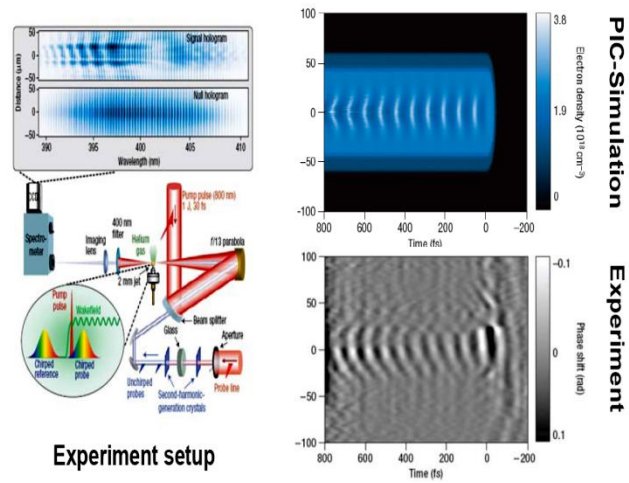
Double Doppler Effect

A. Einstein, Ann. Phys. (Leipzig) 17, 891 (1905)

…



Snapshots of Laser Wake Waves

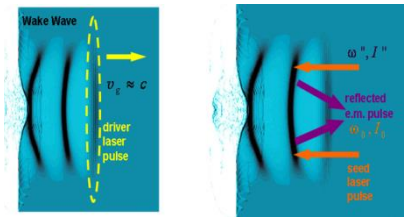


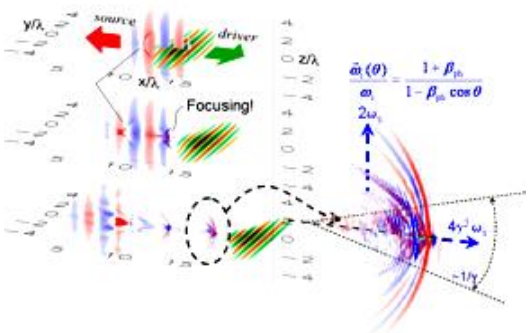
N. H. Matlis et al, Nature Phys. (2006)

Paraboloidal relativistic mirrors are formed by the wake wave left behind the laser driver pulse

S.V.Bulanov, T. Esirkepov, T. Tajima, Phys.Rev.Lett. 91, 085001 (2003)

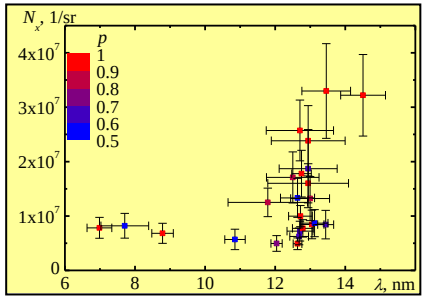
Theory

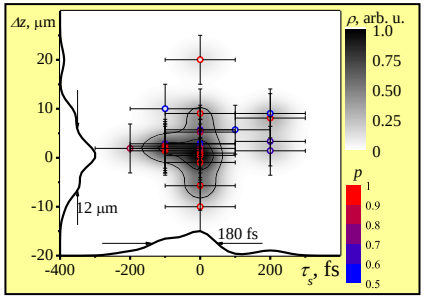




$$\frac{I''_{\max}}{I_0} \approx \kappa\, \gamma_{ph}^6 \left(\frac{D}{\lambda}\right)^2$$

Experiment





λ_x **= 14.3 nm**

$\Delta\lambda_x$ **= 0.3 nm,** $\Delta\lambda_x/\lambda_x$ **= 0.02**

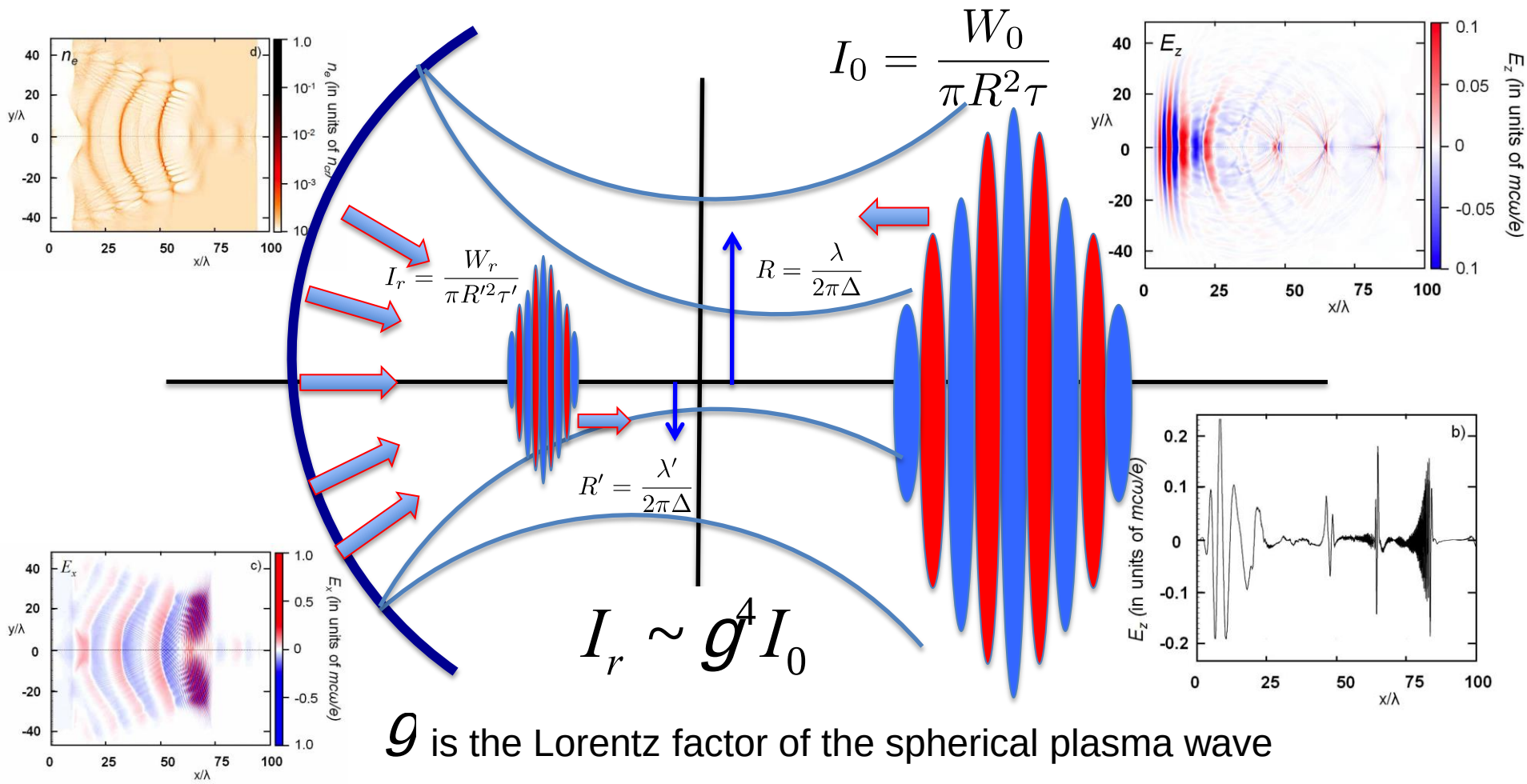
Reflected pulse duration:

τ_x **~ 1.4 fs**

(femtosecond pulse)

M. Kando, et al.,
Phys. Rev. Lett. 99, 135001 (2007)
A. S. Pirozhkov, et al.,
Phys. Plasmas 14, 080904 (2007)
M. Kando, et al.,
Phys. Rev. Lett., 103, 235003 (2009)

Spherical Plasma Wave Acting as a Spherical Flying Mirror Focuses the Intensified Pulse



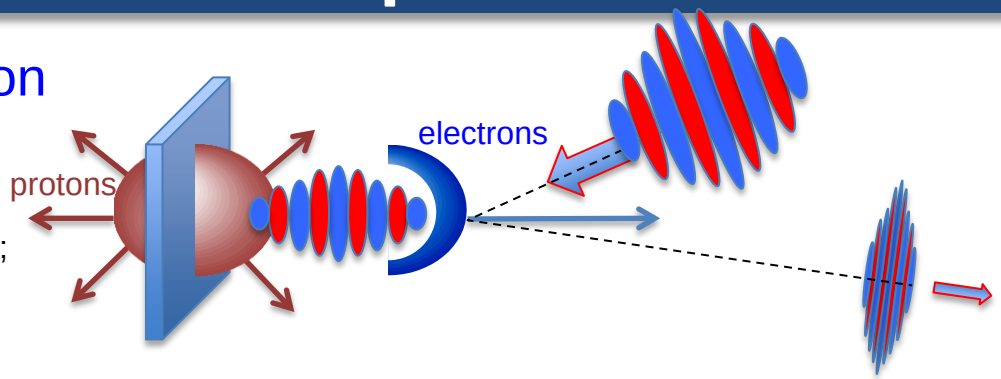
g is the Lorentz factor of the spherical plasma wave

LBNL: S. S. Bulanov, et al., Physics of Plasmas 19, 020702 (2012)
S. V. Bulanov, et al., Physics of Plasmas 19, 113102 (2012); *ibid*, Physics of Plasmas 19, 113103 (2012)

Flying Mirrors are Generated using the Laser Driven Ion Acceleration Setup

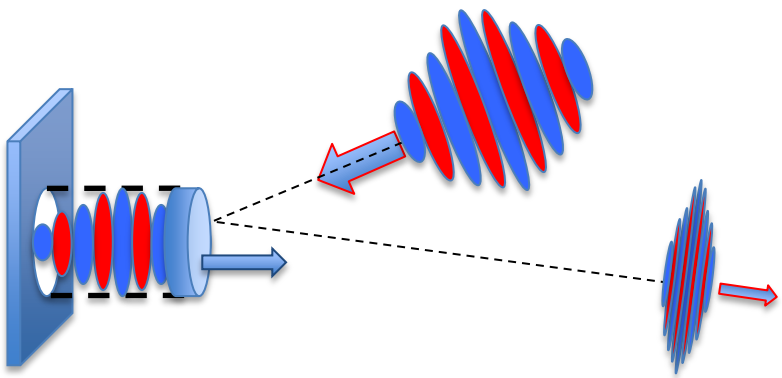
Flying Mirror from Coulomb Explosion

V.V. Kulagin, et al., Phys. Rev. Lett. **99,** 124801 (2007);
D. Habs, et al., Appl. Phys. B **93**, 349 (2008);
J. Meyer-ter-Vehn, H.-C. Wu, Eur. Phys. J. D **55,** 433 (2009);
H.-C. Wu, et al., Phys. Rev. Lett. 104, 234801 (2010).



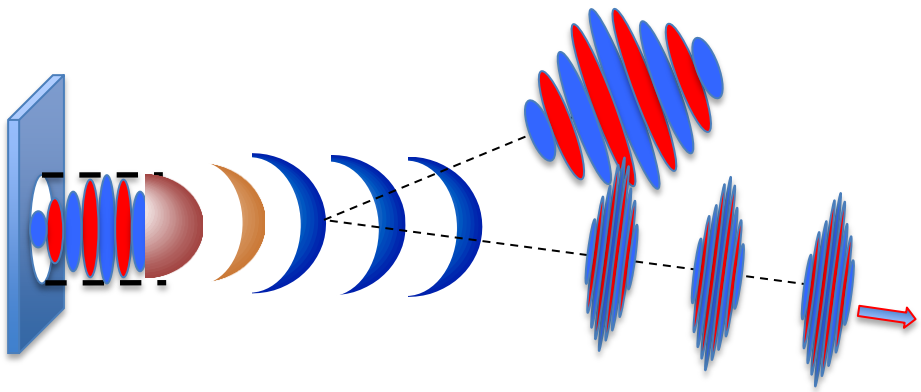
Flying Mirror from Radiation Pressure Acceleration

T.Zh. Esirkepov, et al., Phys. Rev. Lett. 103 (2009) 025002.



Flying Mirror from multiple electron layers (Directed Coulomb Explosion)

S. S. Bulanov, et al., Phys. Lett. A **374**, 476 (2010).



High Intensity Particle Physics
Nonlinear QED

High Intensity Particle Photon Interactions

- Nonperturbative Quantum Field Theory

- Matter in extreme conditions

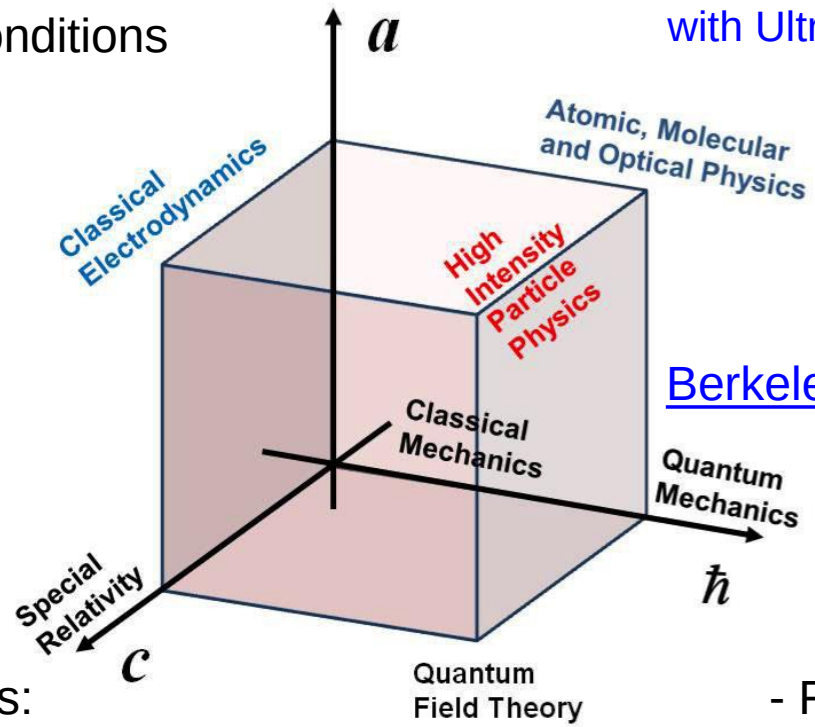
- Electromagnetic Cascades

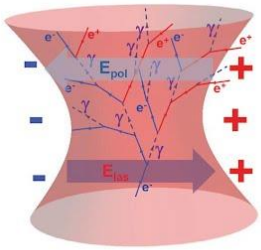
- Electromagnetic Avalanches

- Ultimate Laser Intensity Limit

- Next generation lasers:
  - day-to-day operation
  - new laser-matter interaction applications

Workshop on
"Nonlinear QED Phenomena
with Ultra-Intense PW-class Lasers"
LBNL, May 2012





Berkeley Cube

- Future γγ colliders

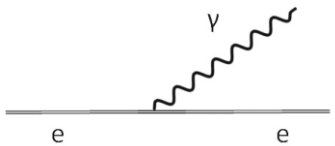
- Future lepton colliders

- Various astrophysical phenomena

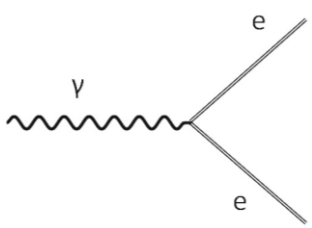
Electromagnetic cascades: high event rates for PW lasers colliding with e-beams

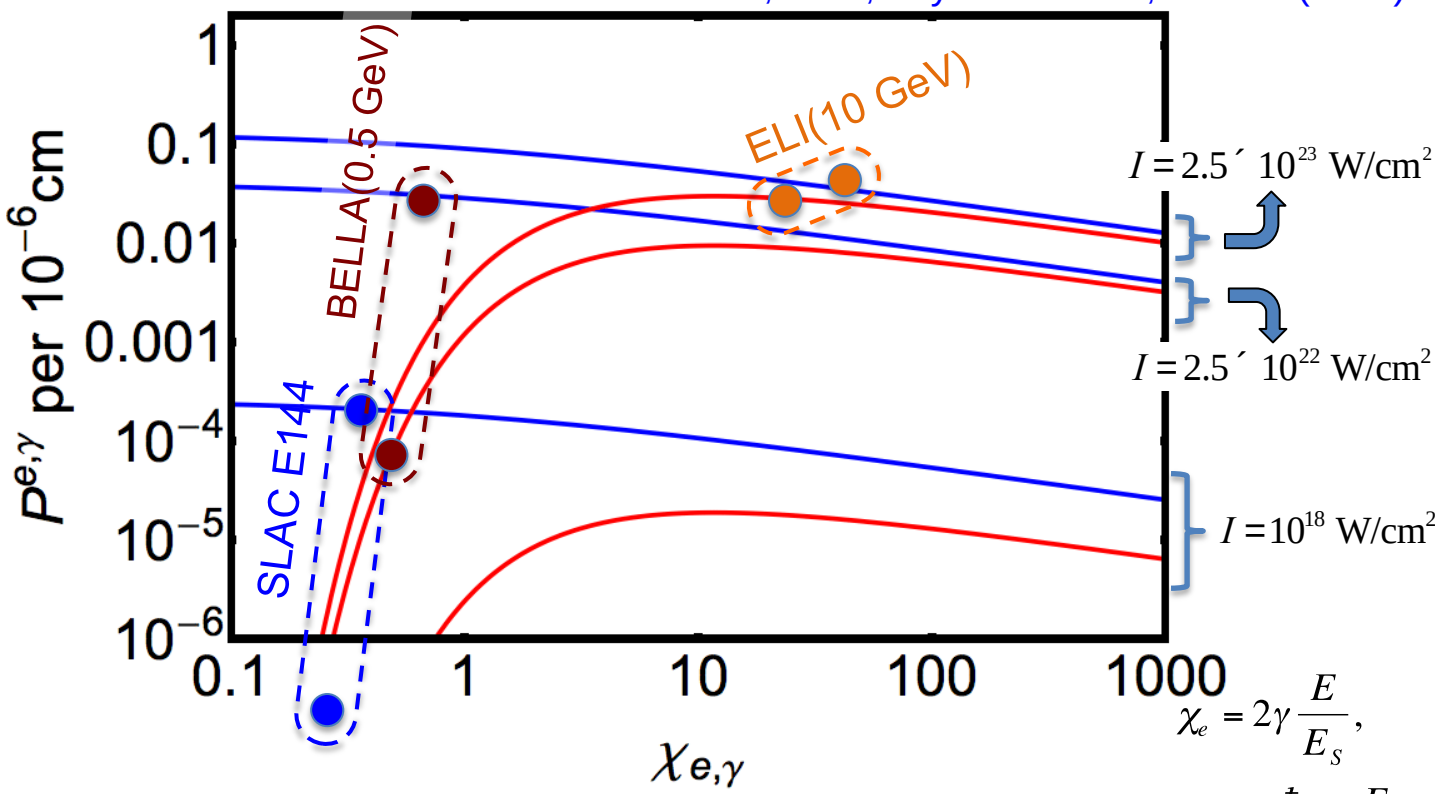
LBNL: S. S. Bulanov, et al., Phys. Rev. A 87, 062110 (2013)

Multiphoton Compton effect



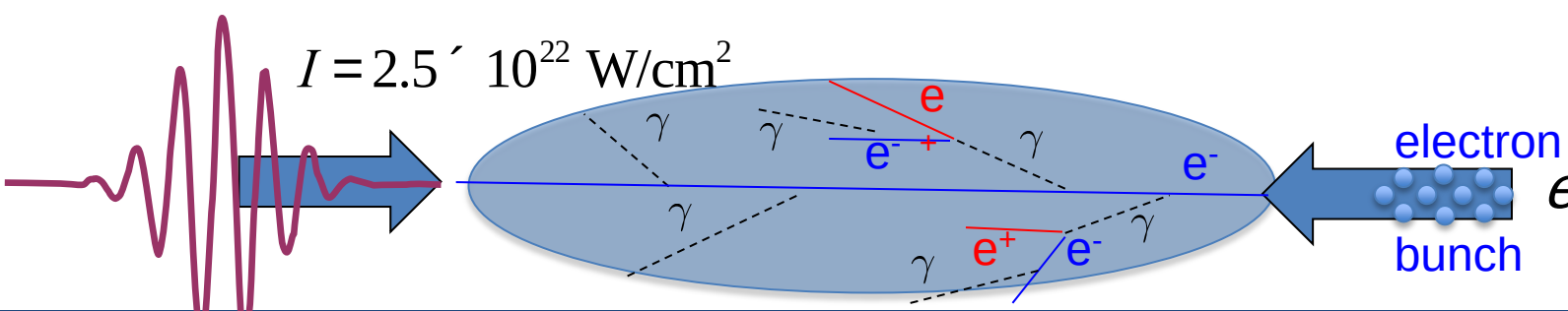
Multiphoton Breit-Wheeler effect





$$\chi_e = 2\gamma \frac{E}{E_S},$$

$$\chi_\gamma = 2\frac{\hbar\omega}{mc^2}\frac{E}{E_S},$$



$$e_e^0 = 0.5\,\text{GeV}$$

BELLA-i facility provides high intensity laser beamlines enabling a wide range of frontier plasma science

- **Build a short focal length beamline on BELLA with plasma mirror and diagnostics to enable high intensity laser-matter experiments**
  - Complements present long focal length beamline for electron acceleration experiments
  - Plasma mirror technology is routinely used on staging experiment and will enable access to unprecedented clean interaction physics
- **Enables laser-driven frontier plasma science**
  - Ion acceleration in various regimes
    - RPA: compete acceleration of very thin foils (>100 MeV)
    - MVA: acceleration in near-critical plasmas (approach 1 GeV)
  - Ion beams for warm dense matter, medical applications, etc.
  - Nonlinear plasma wakes, bow waves, high harmonics, flying mirrors
  - Nonlinear QED, lab astrophysics, etc…
- **User facility open to frontier plasma science community**
  - LBNL Workshop on science with BELLA-i (late fall)
- **BELLA-i will help maintain and enhance US leadership in the world of ultrafast ultra-intense laser-driven science and applications**
  - Vigorous competition overseas (e.g., 3 ELI facilities in Europe)

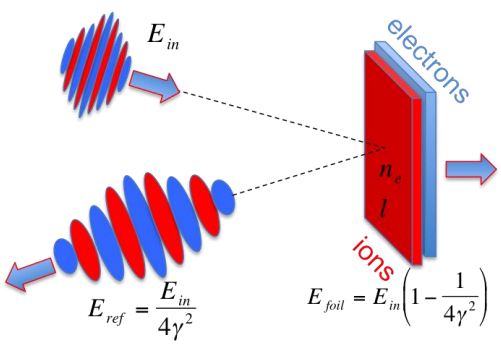
Extras

BELLA-i: Accelerator Science+Applications

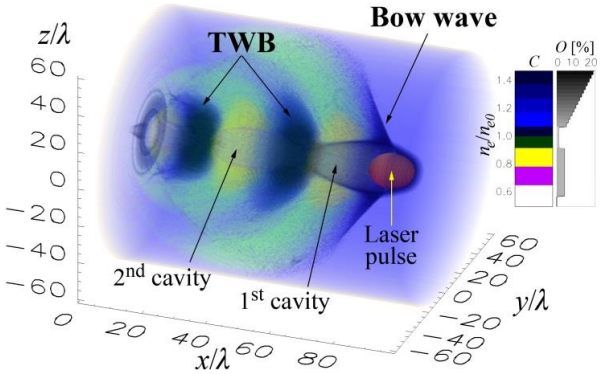
Eric Esarey et al., LBNL

FES-HEP Briefing, DoE, May 21, 2015

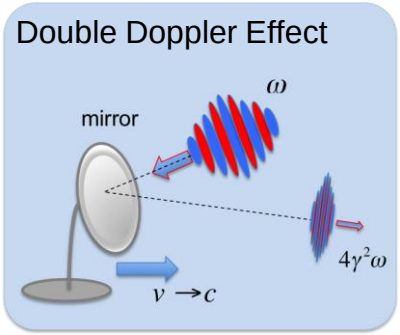
Ion Acceleration



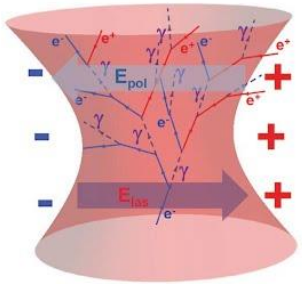
Electron Acceleration



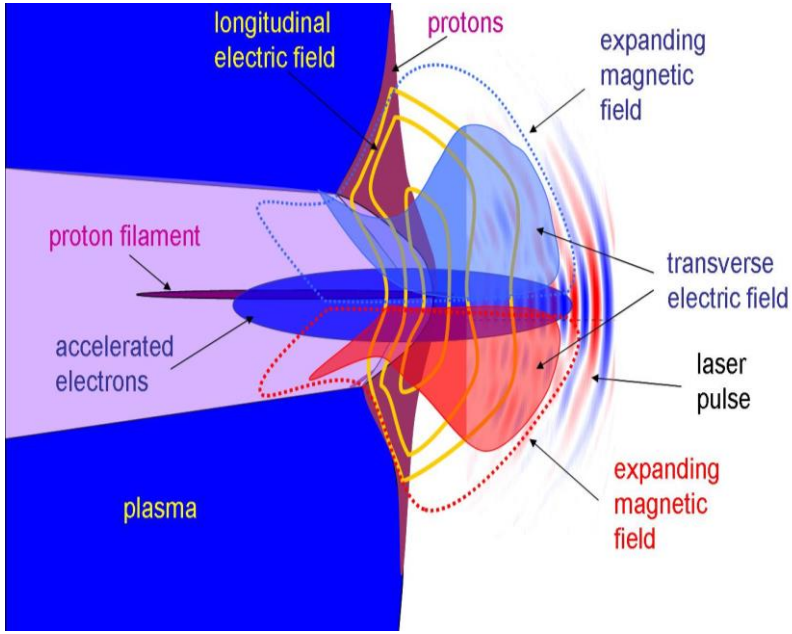
Relativistic Flying Mirrors



High Intensity Particle Physics



Novel mechanisms have been invented that promise to provide better beam quality

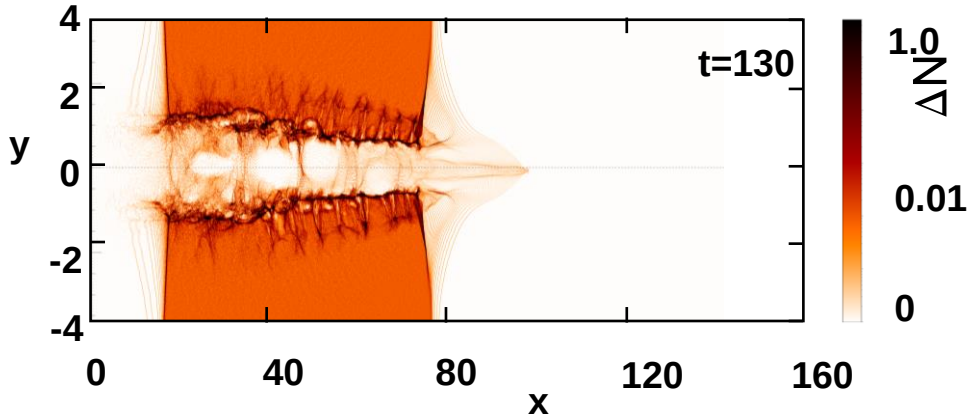


Magnetic vortex acceleration

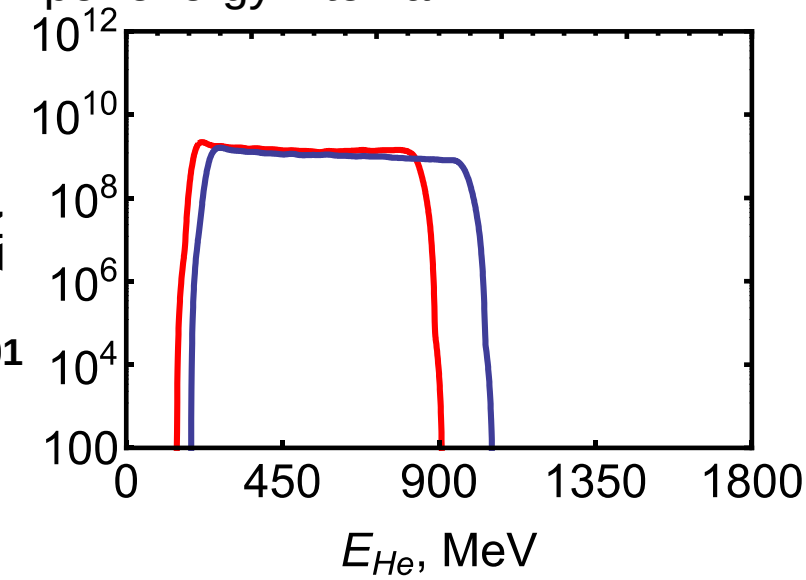
- Requires
  - PW laser
  - High contrast
  - Near critical density targets

100's of MeV to GeV protons

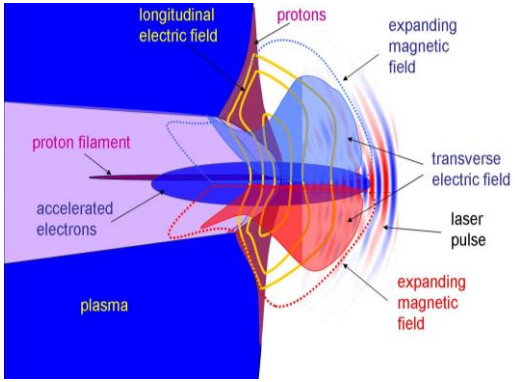
He ion density distribution

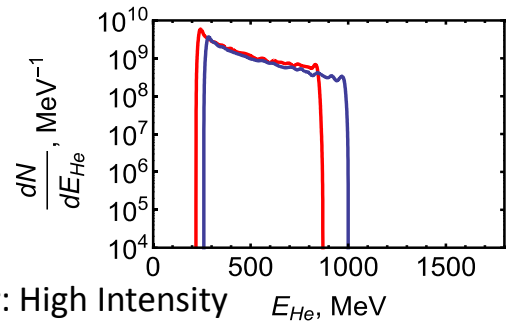


The number of He^3 and He^4 ions per energy interval



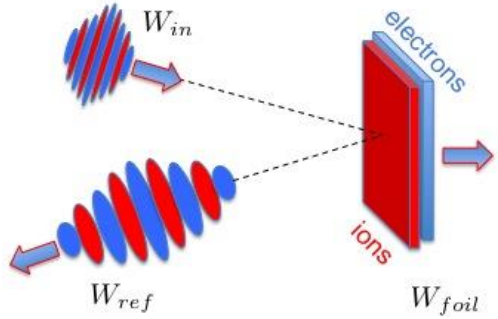
High laser power at BELLA allows for the the study of different mechanisms of ion acceleration

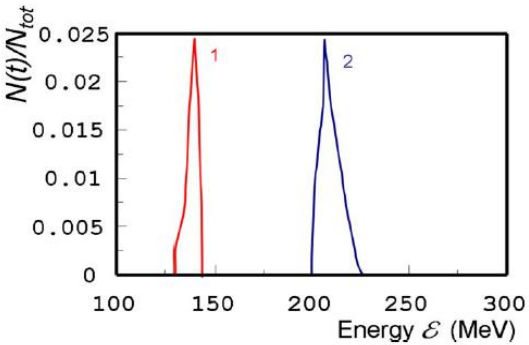


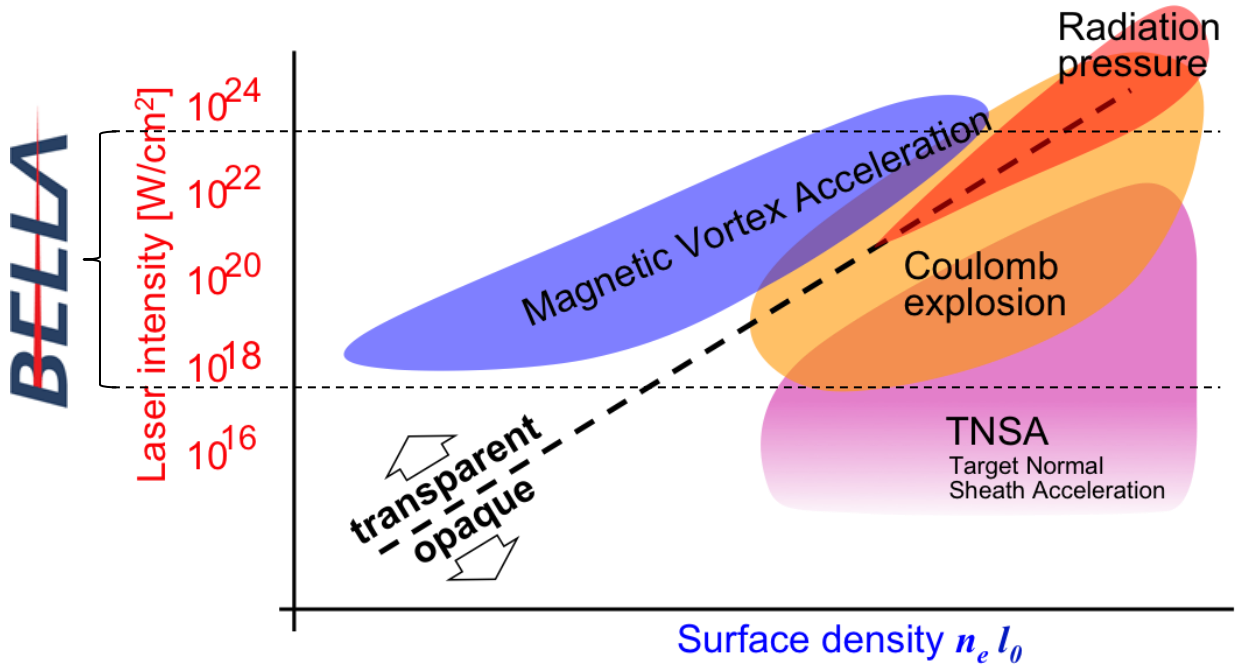


MVA
Laser: High Intensity
Target: Near Critical Density slab
Ion Energy: hundreds of MeV to GeV

RPA
Laser: High Intensity
Target: Thin solid density foils
Ion Energy: hundreds of MeV



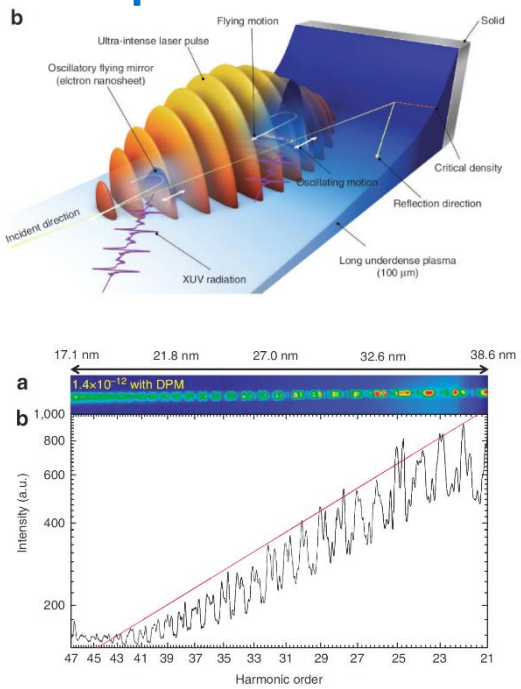




HHG accompanies ion acceleration in the laser irradiation of thin foil targets

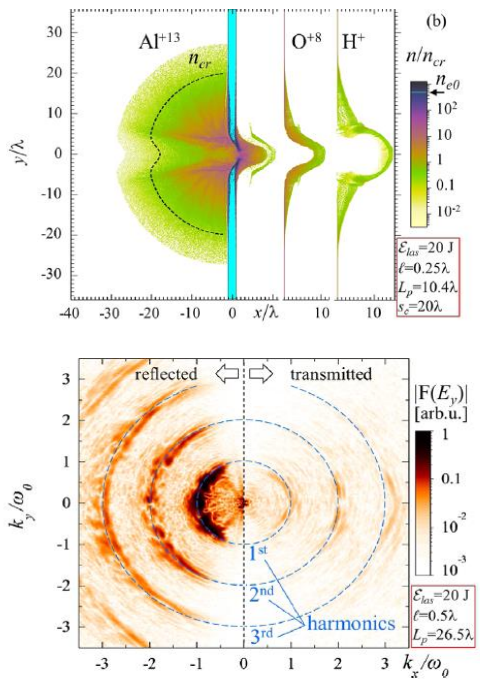
HHG generation in plasma corona

Experiment:



I Jong Kim, et al.,
Nat. Commun. 3, 1231 (2012)

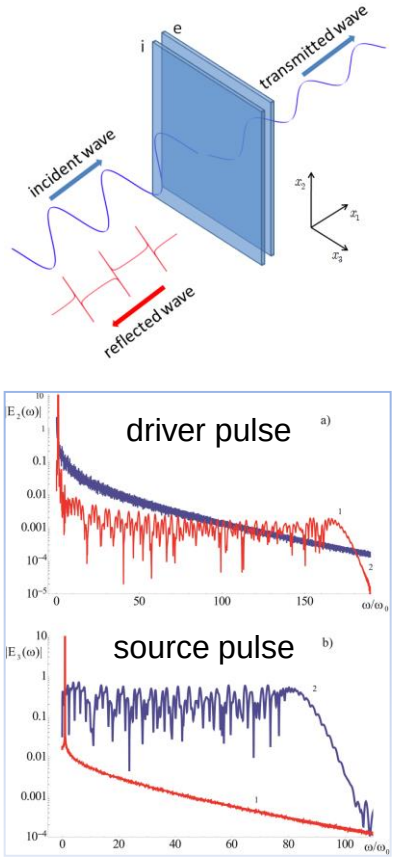
PIC Simulations:



T. Zh.Esirkepov, et al.,
NIMA, 745, 150 (2014)

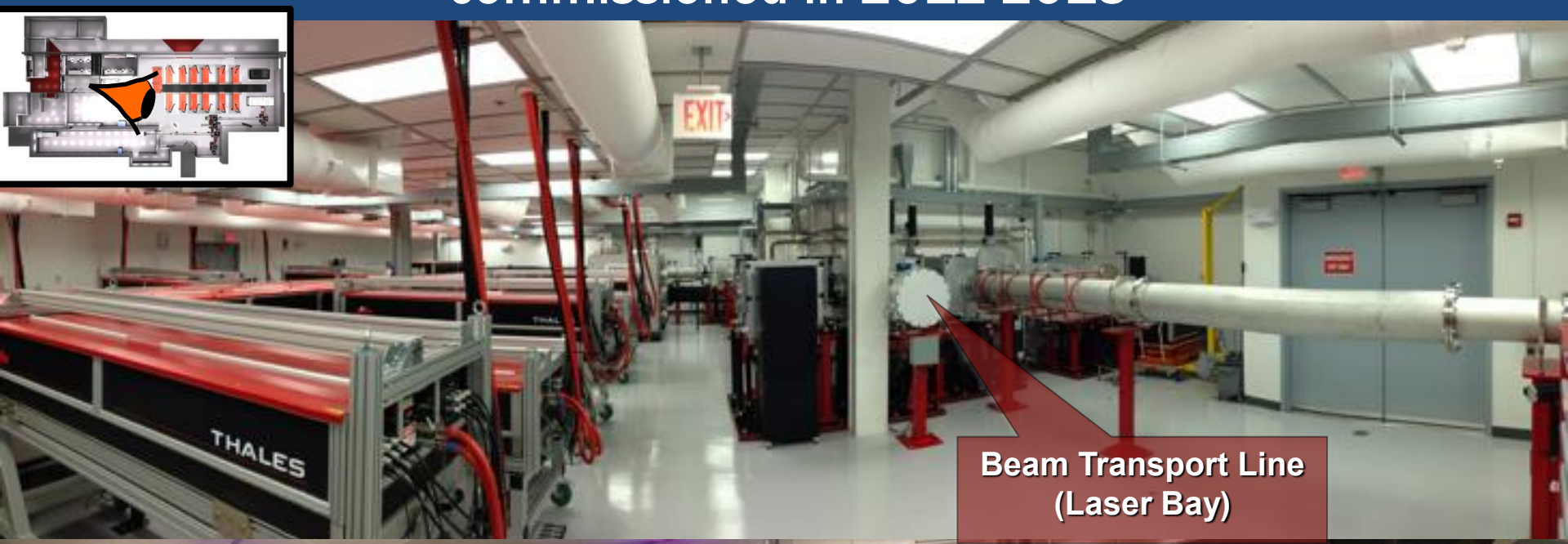
HHG generation during the RPA of a thin foil

Theory:

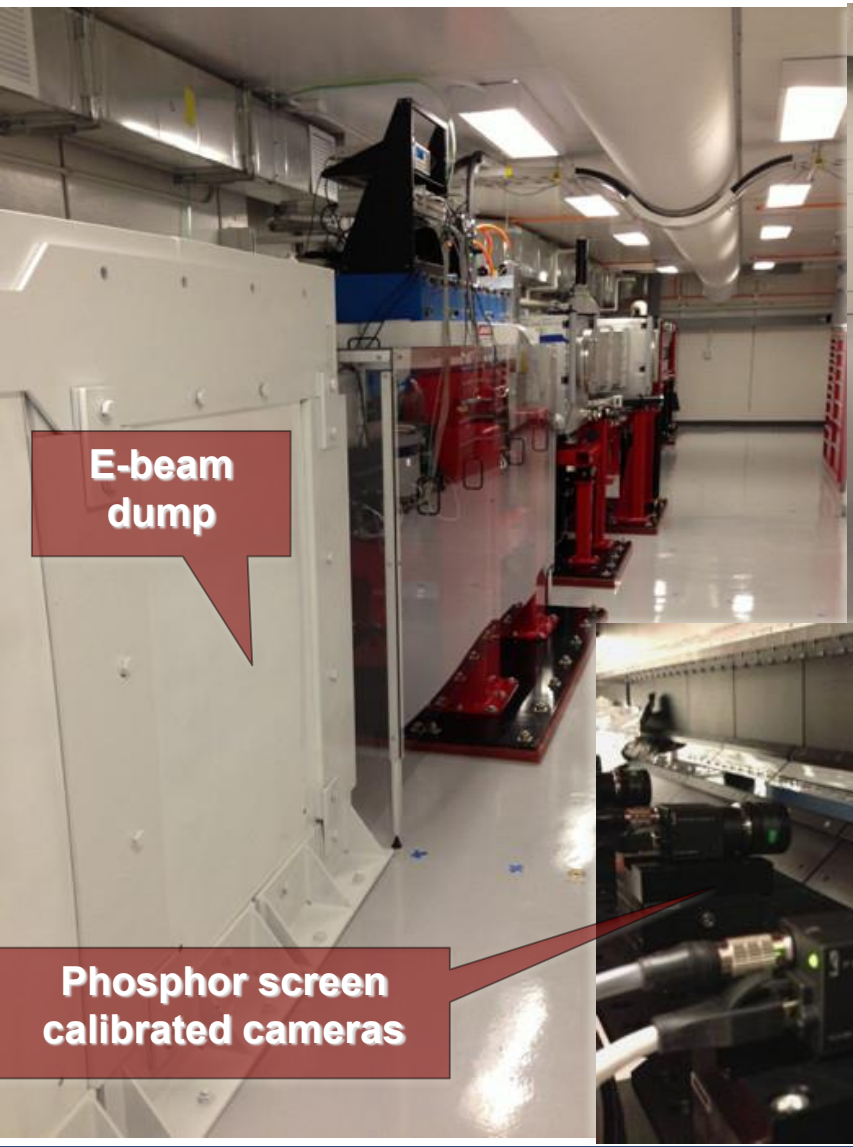


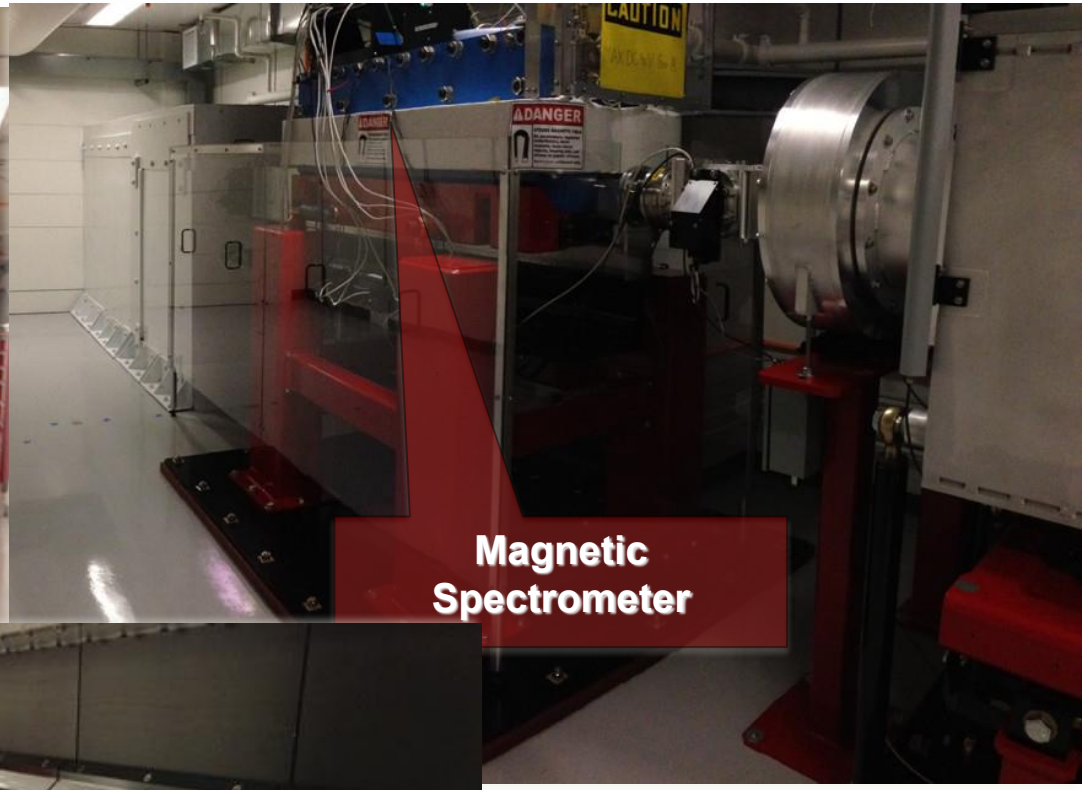
S. V. Bulanov, et. al,
Phys. Plasmas 20, 123114 (2013)

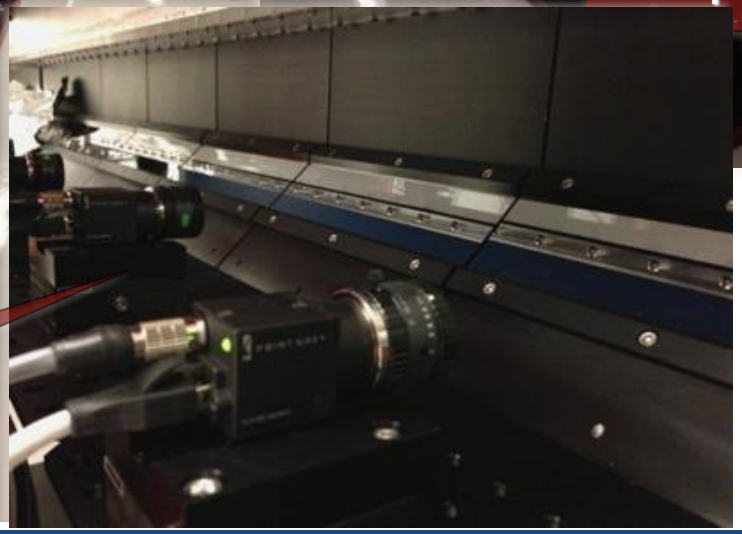
All major mechanical and electrical systems were installed and commissioned in 2012-2013



e-Beam diagnostics include energy, transverse profile and charge transformers



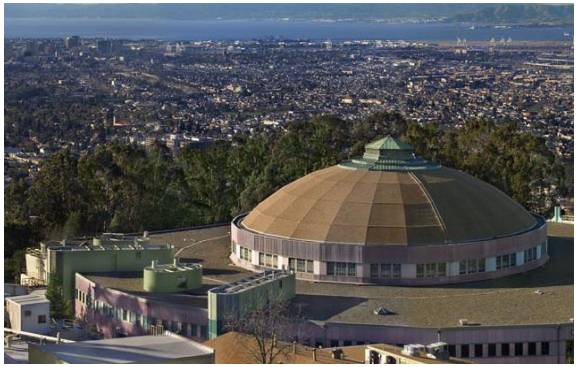




- Single shot
- 30 MeV-11 GeV
- Two ICTs
- Phosphor screen

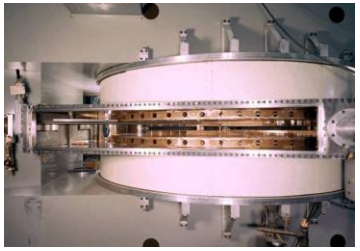
The proposed facility upgrade will be planned *ab initio* as a user facility with community input

- LBNL runs multiple National and Local User Facilities (ALS, 88”, NCEM, Molecular Foundry)
- Experiments at BELLA will be proposal driven with PAC guidance (call once a year)
- During project design we will seek guidance through a Scientific Advisory Committee that will later transition into a Program Advisory Committee



Advanced Light Source (DOE-BES)
3rd Generation Light Source
35 Beamlines, Multidisciplinary program with 2000 users

88 Inch Cyclotron (DOE-NP, NRO, USAF)
Heavy Ion Facility
Nuclear Science
Applied Program



MOLECULAR FOUNDRY

Nanoscience Center – 7 Facilities
Access for proprietary customers