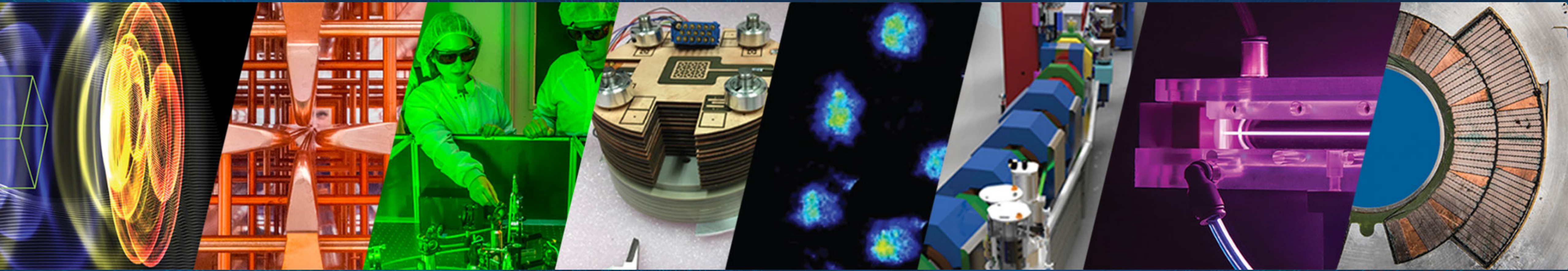
Advanced Ion Acceleration Mechanisms

S. S. Bulanov

BELLA Center, ATAP Division, Lawrence Berkeley National Laboratory, USA



11/8/2022

20th Advanced Accelerator Concepts Workshop (AAC'22)

BERKELEY LAB

ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION ATAP

U.S. DEPARTMENT OF ENERGY | Office of Science

We acknowledge support from the US DOE Office of Science Offices of HEP and FES, and LaserNetUS under Contract No. DE-AC02-05CH11231

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eli beamlines

ELI Beamlines

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Creation of Harmonious Diversity
QST

National Institutes for Quantum and Radiological Science and Technology,

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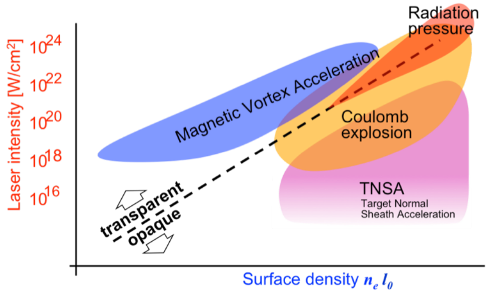
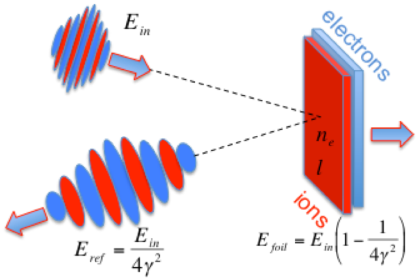
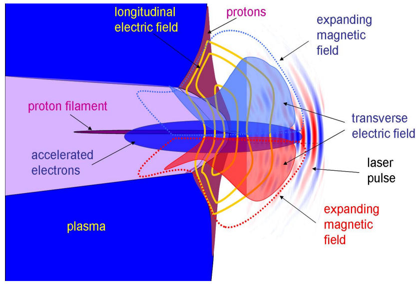
Outline

- Introduction
  - Ion acceleration mechanisms
  - Possible applications
- Radiation Pressure Acceleration
  - Basic theory
  - Limiting factors
  - Optimization
  - Hybrid mechanisms
- Magnetic Vortex Acceleration
  - Basic theory
  - Structured targets
- Conclusions







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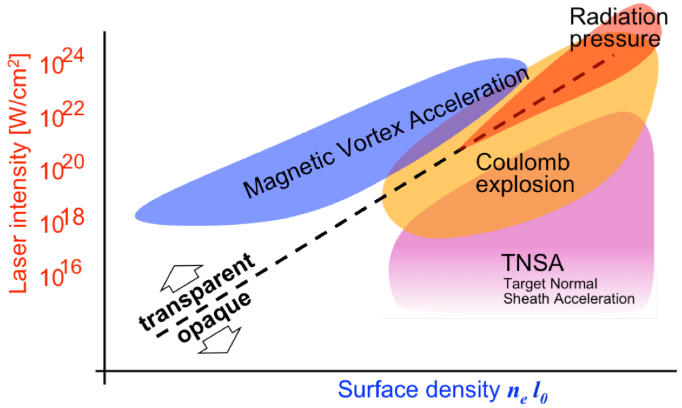
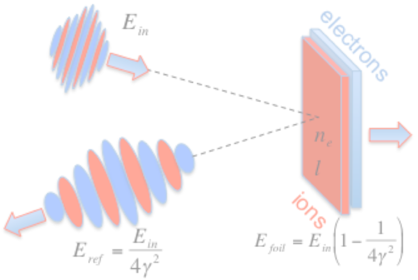
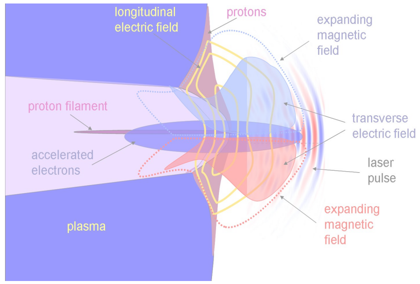






PW-class laser facilities should be able to demonstrate ion acceleration to energies exceeding 100 MeV/u in near term

https://www.eli-beams.eu/about/

L3 HAPLS: 1 PW
L4 ATON: 10 PW

ZEUS
Zettawatt-Equivalent Ultrashort Pulse Laser System

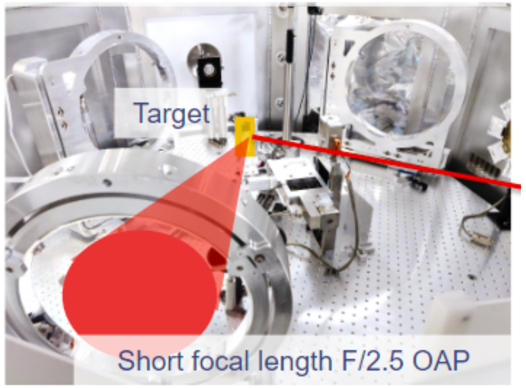
NSF
User Lab

https://zeus.engin.umich.edu/

ZEUS: 3 PW

BELLA Center

New iP2 target chamber



https://bella.lbl.gov/

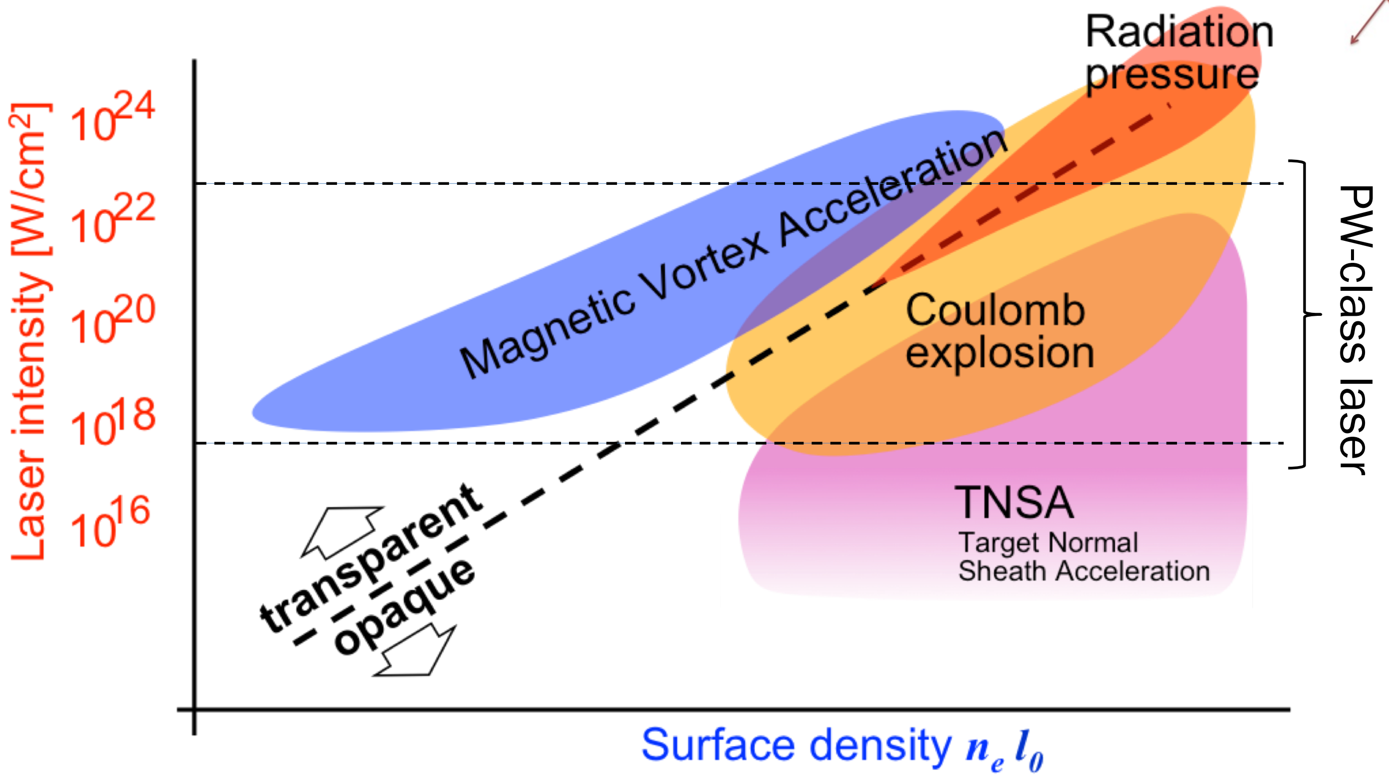
BELLA PW: 1.3 PW

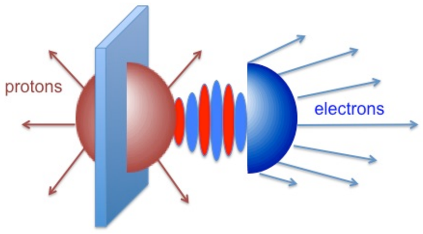
Multi-PW (>2PW) laser facilities: Station of Extreme Light, EP-OPAL, SULF, Apollon (F1), PEARL-X, L4, HPLS, J-EPOCH, SG-II 5 PW, CAEP-PW, CoReLS, ZEUS, ATLAS-3000, Qiangguang…

PW (1-2 PW) laser facilities: BELLA, LFEX, J-KAREN-P, PETAL, Xtreme Light III, Z-Petawatt, Vulcan Petawatt, Orion, Apollon (F2), PEnELOPE, VEGA-3, CETAL, L2, L3 (HAPLS)…

For a detailed list of laser facilities see A. Gonoskov, et al., Rev. Mod. Phys. 94, 045001 (2022)

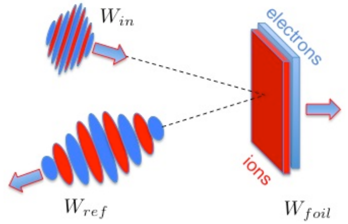
The Ion Acceleration Mechanism is Determined by Laser Intensity and Target Surface Density

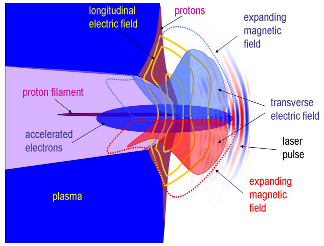




RPA & CE
Laser: High Intensity
Target: Thin solid density foils
Ion Energy: hundreds of MeV

Ion Energy ~ Laser Power



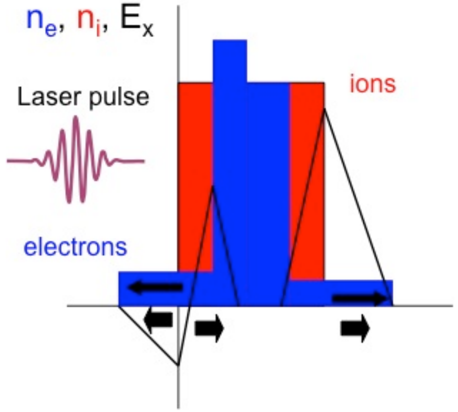


MVA
Laser: High Intensity
Target: Near Critical Density slab
Ion Energy: hundreds of MeV to GeV

Ion Energy ~ Laser Power$^{2/3}$

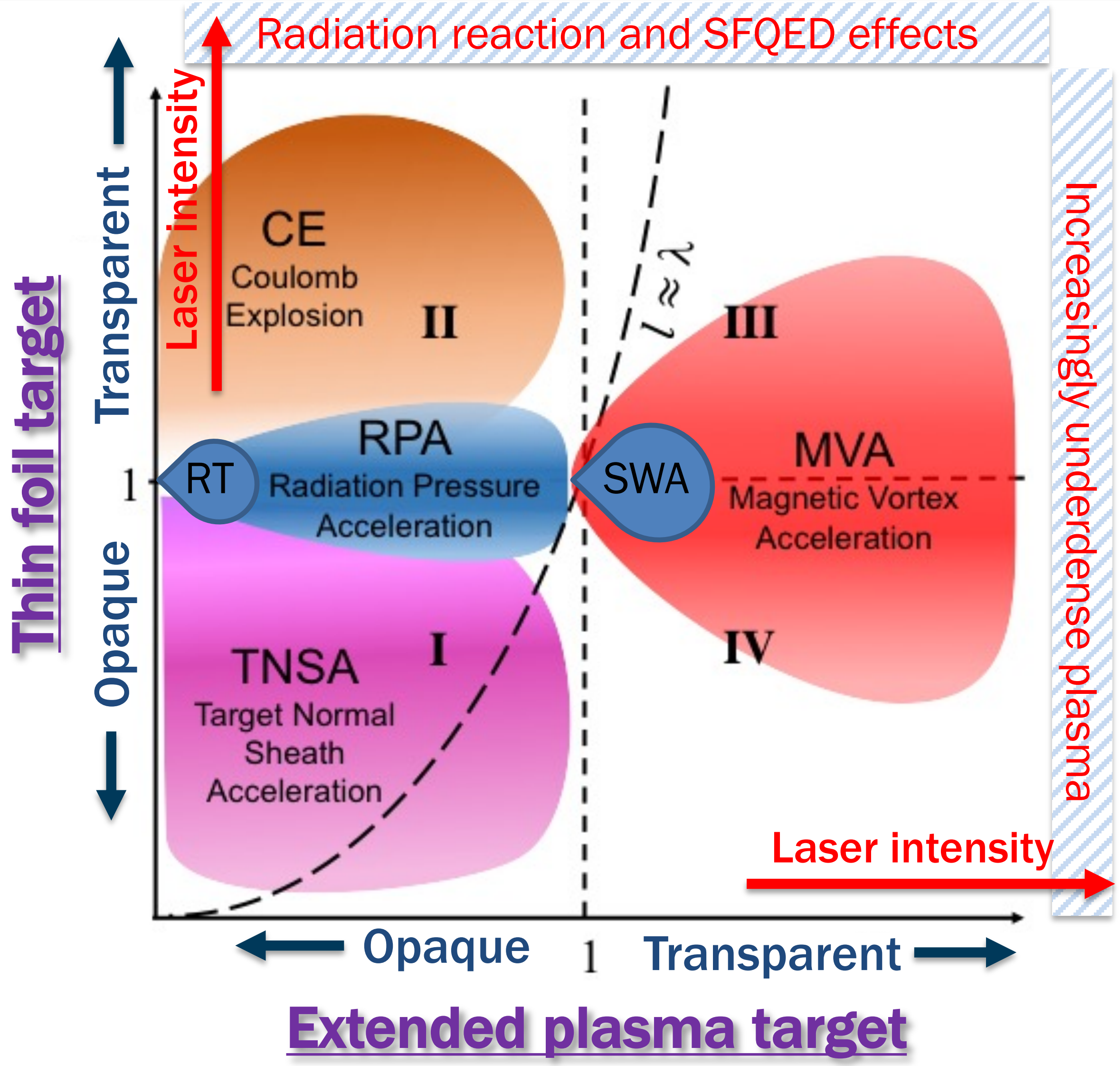
TNSA
Laser: Low Intensity
Target: Thick solid density foils
Ion Energy: ~100 MeV

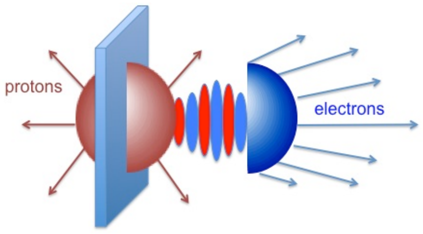
Ion Energy ~ Laser Power$^{1/2}$



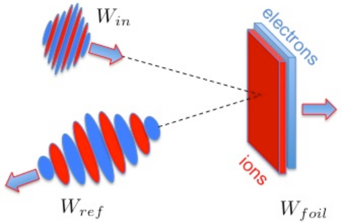
Applications: Radiography, Deflectometry, Cancer Therapy, Injection into conventional accelerators, Fast Ignition, Isochoric heating of matter, Nuclear Physics…

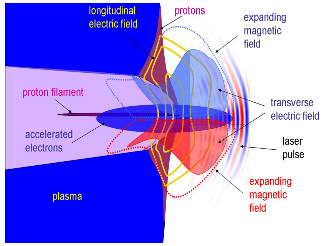
The transparency of the target is one of the most important parameters characterizing laser ion acceleration





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





MVA
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Ion Energy: hundreds of MeV to GeV
Ion Energy ~ Laser Power$^{2/3}$

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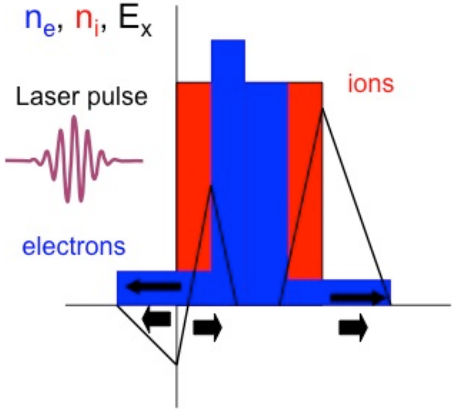
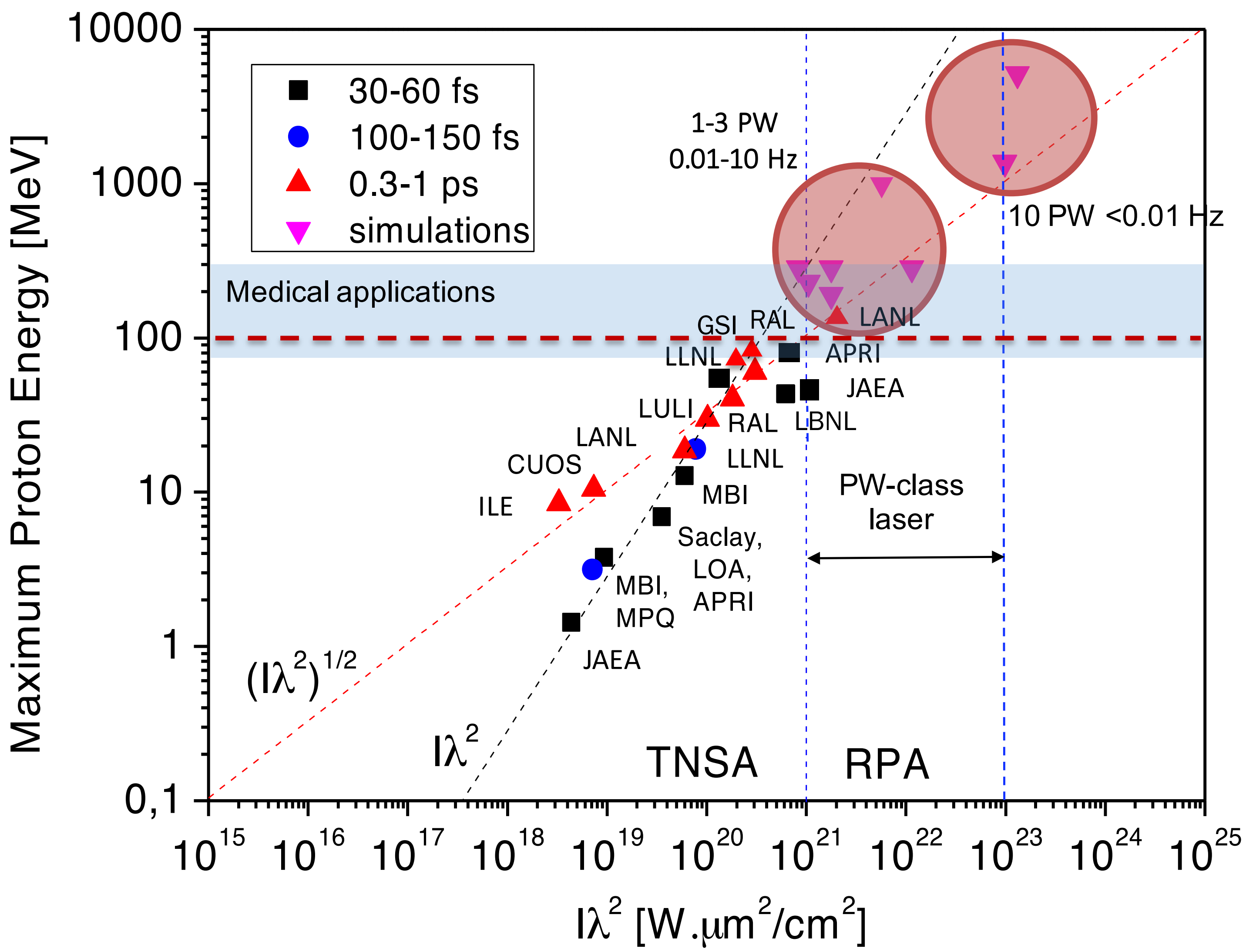


S. S. Bulanov, et al., Physics of Plasmas 23 , 056703 (2016)

Advanced Acceleration Mechanisms are needed to generate ion beams with energies needed for applications



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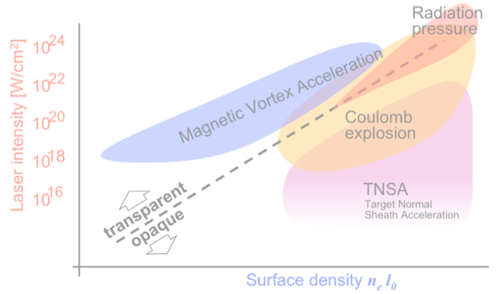
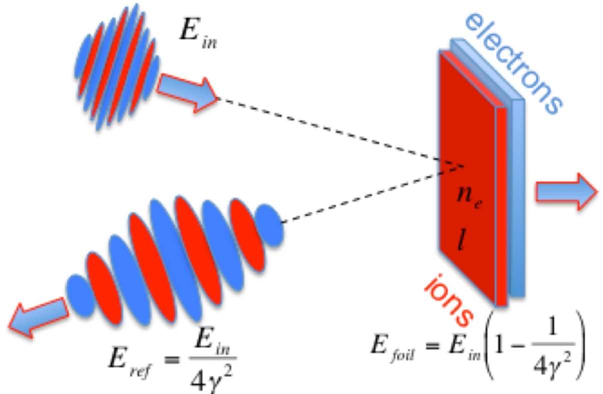
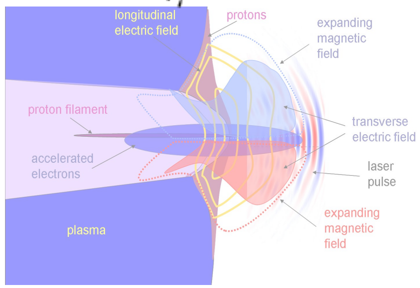






Radiation Pressure Acceleration has a long history

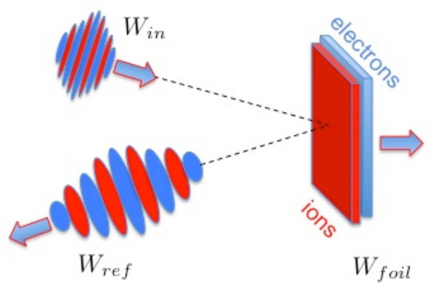
The idea goes back to

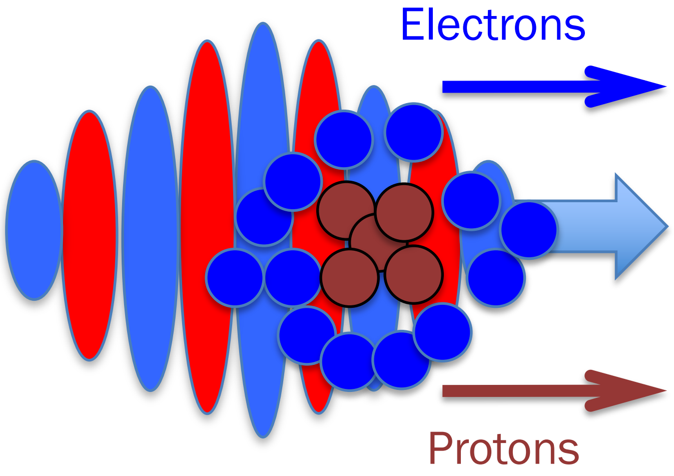
P. N. Lebedev, Ann. Phys. (Leipzig) 6, 433 (1901);

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

A. S. Eddington, Mon. Not. R. Astron. Soc. 85, 408 (1925).

In the mid 1950's ion acceleration by strong electromagnetic wave was suggested by V. I. Veksler, Sov. J. Atomic Energy 2, 525 (1957).





The radiation pressure of a super-intense electromagnetic pulse on a thin plasma slab was studied in

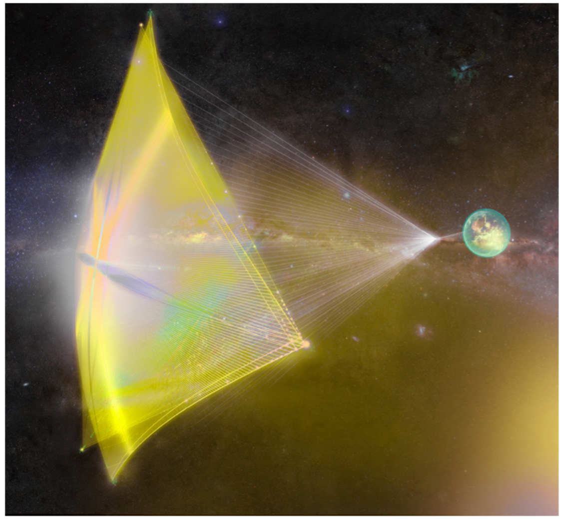
T. Zh. Esirkepov, M. Borghesi, S. V. Bulanov, G. Mourou, T. Tajima, Phys. Rev. Lett. 92, 175003 (2004).

There is an analogy between the RPA mechanism and the "Light Sail" scheme for the spacecraft propulsion. This scheme, which uses the photon momentum transfer to the light-sail, was proposed by

F. A. Zander, Technika i Zhizn, No. 13, 15 (1924).

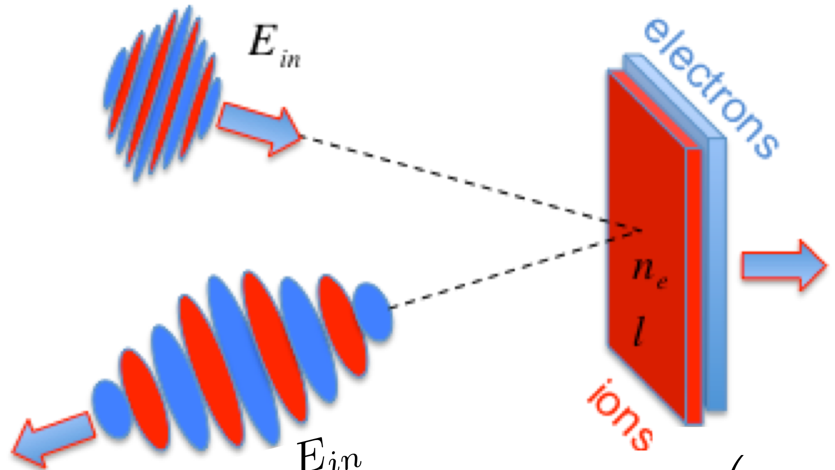
The use of lasers for propelling the sailcraft over interstellar distances has been considered in

R. L. Forward, Missiles and Rockets, 10, 26 (1962);
G. Marx, Nature, 211, 22 (1966);
J. L. Redding, Nature, 213, 588 (1967);
J. F. L. Simmons and C. R. McInnes, American Journal of Physics 61, 205 (1993)

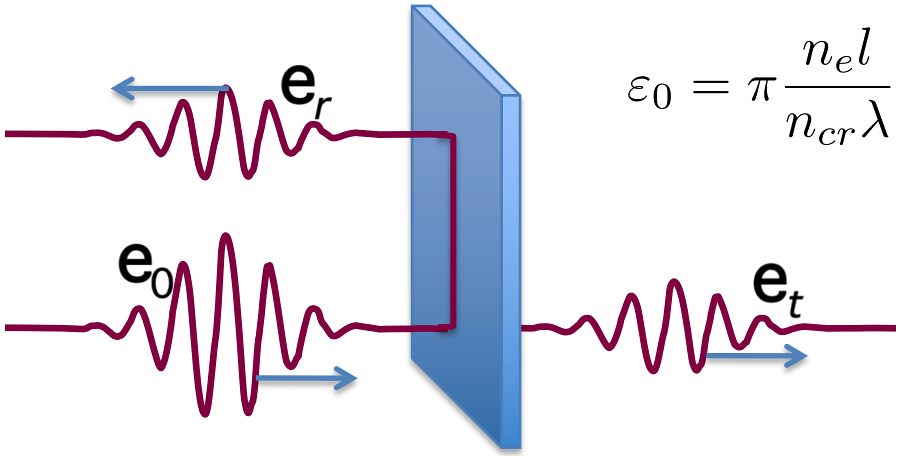


Breakthrough Starshot is a $100 million research and engineering program aiming to demonstrate proof of concept for a new technology, enabling ultra-light unmanned space flight at 20% of the speed of light; and to lay the foundations for a flyby mission to Alpha Centauri within a generation.

The calculation of the reflection coefficient plays a central role in the analytical model of radiation pressure acceleration



$$E_{ref} = \frac{E_{in}}{4\gamma^2} \qquad E_{foil} = E_{in}\left(1 - \frac{1}{4\gamma^2}\right)$$



$$\varepsilon_0 = \pi \frac{n_e l}{n_{cr}\lambda}$$

$$\frac{dp}{dt} = \frac{K\left|E_L[t - x(t)]^2\right|}{4\pi n_e l}\,\frac{\gamma - p}{\gamma + p}$$

Reflection coefficient

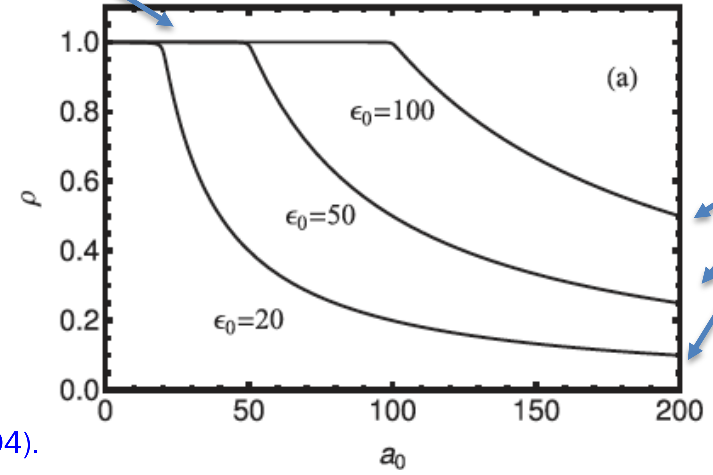
$$K = 2|\rho|^2 + |\alpha|^2$$

Absorption coefficient

Opaque foil:

$$\frac{\varepsilon_0}{\sqrt{1+\varepsilon_0^2}}, \quad a_0 \ll \varepsilon_0$$

The dependence of the reflection coefficient on a_0

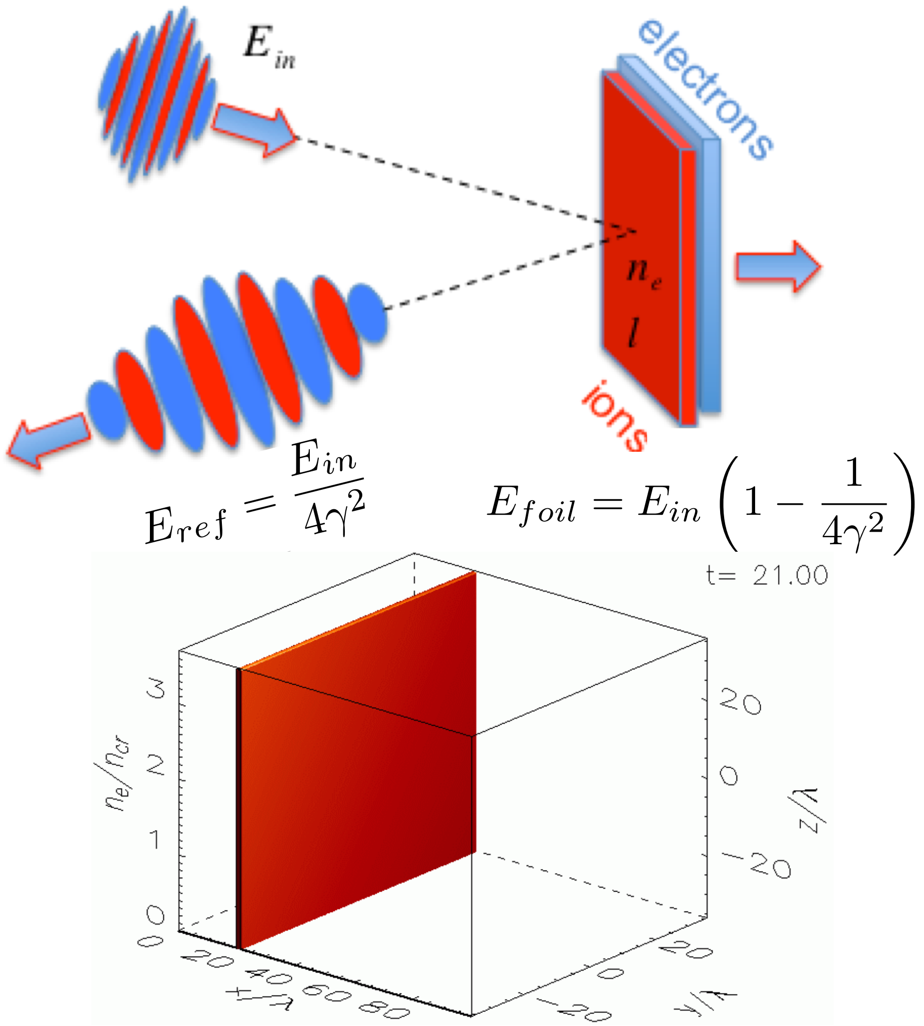


Transparent foil:

$$\varepsilon_0/a_0, \quad \varepsilon_0 \ll a_0$$

T. Zh. Esirkepov, M. Borghesi, S. V. Bulanov, G. Mourou, T. Tajima, Phys. Rev. Lett. 92, 175003 (2004).

Radiation pressure acceleration mechanism shows most favorable scaling with laser energy



- non-relativistic case: ion energy ~ [laser energy]^2

$$\mathcal{E}_a = 8 \times (10^{11}/N_{tot})^2 (m_p/m_a)(\mathcal{E}_{las}/1\ \mathrm{J})^2\ \mathrm{MeV}$$

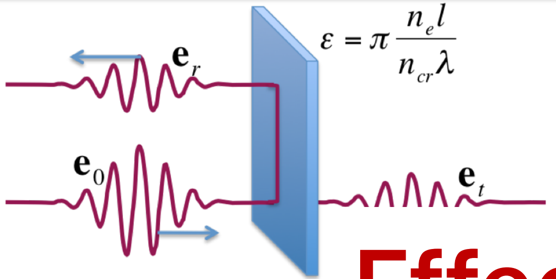
- ultra-relativistic case: ion energy ~ [laser energy]

$$\mathcal{E}_a = 6.25 \times (10^{11}/N_{tot})(\mathcal{E}_{las}/100\ \mathrm{J})\ \mathrm{GeV}$$

O. Klimo, et. al., Phys. Rev. STAB 11, 031301 (2008)
S. V. Bulanov, et. al., Comp. Rendus Physique 10, 216 (2009)

There are several factors that limit the effectiveness of the radiation pressure acceleration.

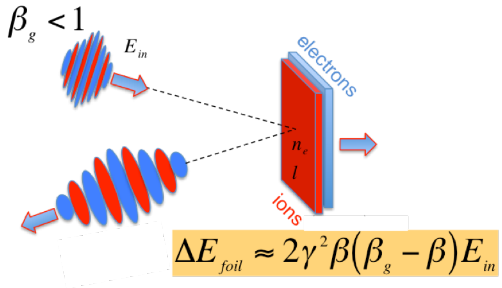
-Transparency



S. S. Bulanov, et al.,
Physics of Plasmas 19 , 093112 (2012)

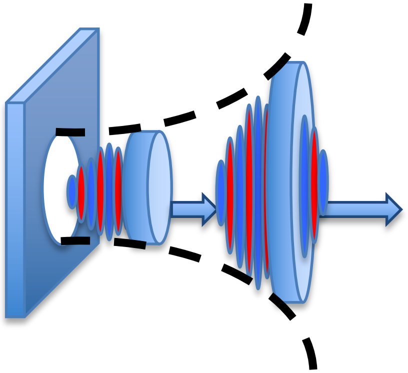
Effects of laser contrast?
(not covered in this talk)

-Group velocity



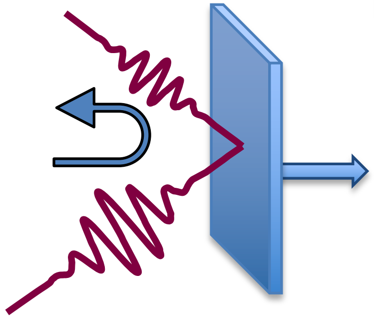
S. S. Bulanov, et al.,
PRL **114**, 105003 (2015)

-Transverse expansion/deformation



Instabilities?
(not covered in this talk)

-Off-normal incidence



S. S. Bulanov, et al.,
Physics of Plasmas 23 , 056703 (2016)

Transverse expansion of the target dominates the limiting of maximum ion energy due to the increasing target transparency

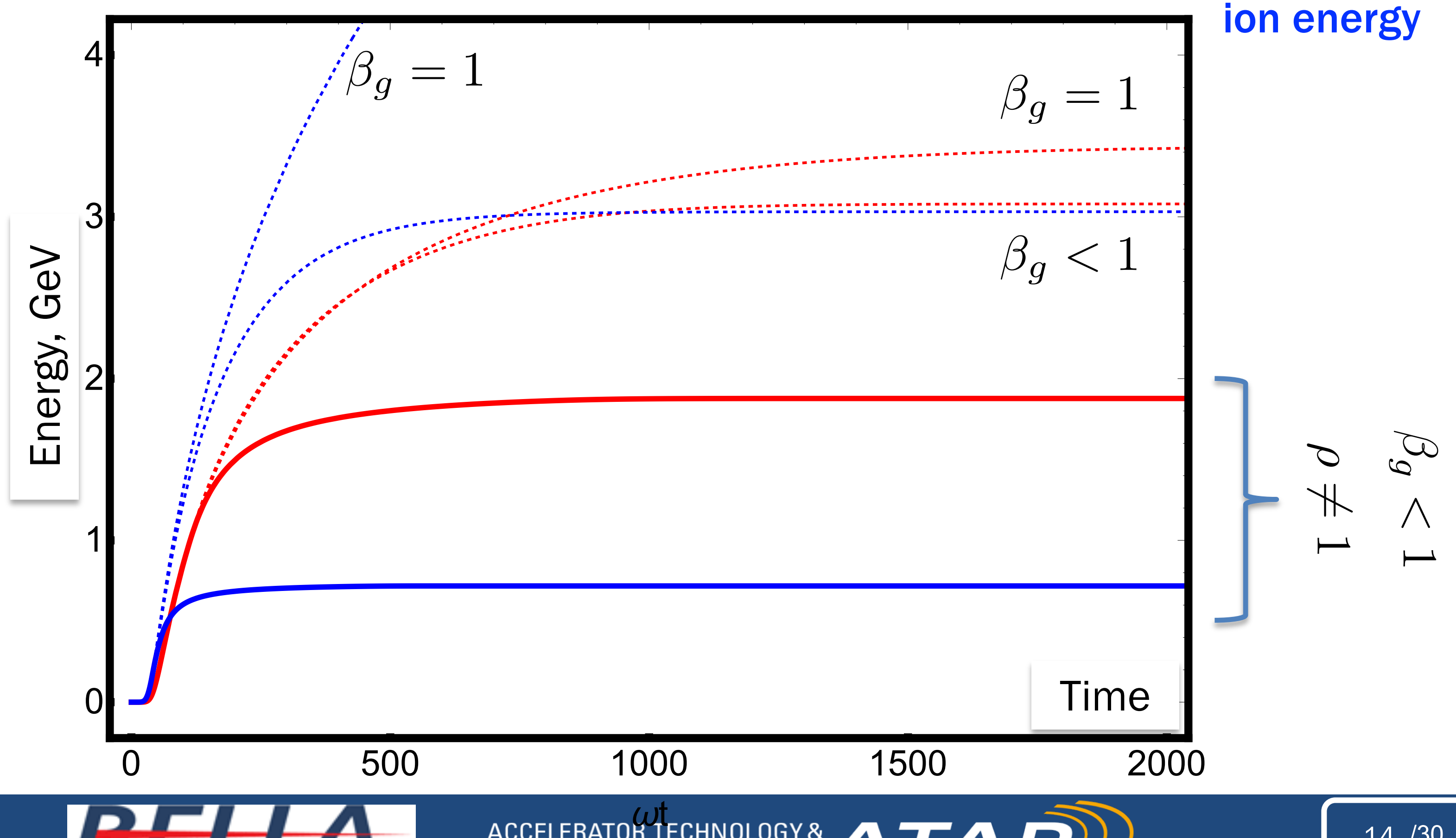
Limiting effect of laser group velocity

$$\frac{d\beta}{\omega t} = \kappa\beta_g(1-\beta^2)^{1/2}(\beta_g-\beta)(1-\beta\beta_g)$$

Transverse expansion/deformation

laser: 1.8 PW, 30 fs,
f/D=1 f/D=2
Foil: 0.25 λ, 400 n_{cr}

The evolution of the maximum ion energy

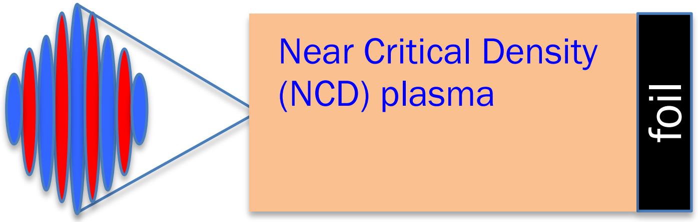


S. S. Bulanov, et al., PRL **114**, 105003 (2015)

Optimization of the radiation pressure acceleration

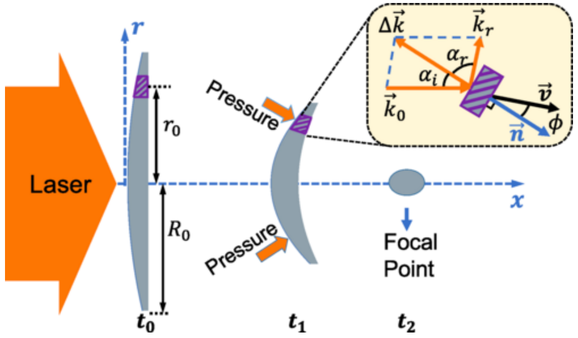
Composite targets

S. S. Bulanov, et al., PRL (2015)



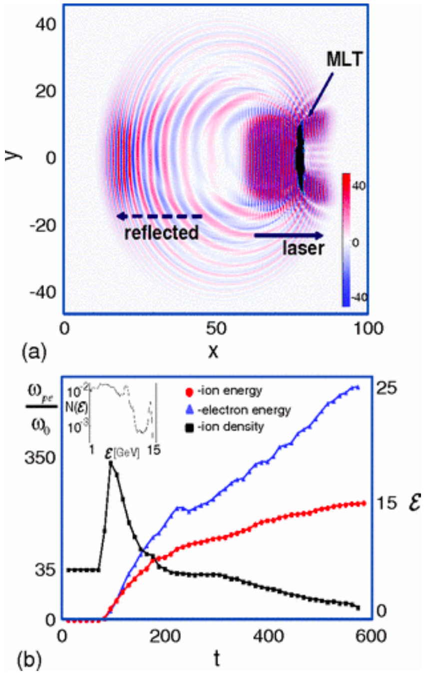
J. H. Bin, et al., PRL (2015)

Shaped targets



T. Wang, et al., PRL (2021)

Mass limited, phase locked target



S. V. Bulanov, et al., PRL (2021)

Laser pulse shaping

- Intensity profile
- Frequency chirp

S. S. Bulanov, et al., PoP (2012)
F. Mackenroth & S. S. Bulanov, PoP (2019)

Hybrid schemes

- RPA+TNSA

A. Higginson, et al., Nat. Comm. (2018)

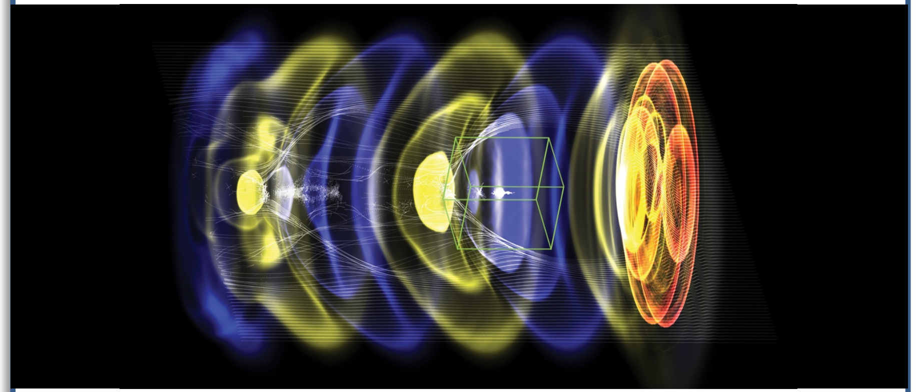
- RPA+CE

S. S. Bulanov, et al., Med. Phys. (2008)

Most simulation setups of laser ion acceleration lead to the demonstration of hybrid mechanisms: WARPX simulation of laser thin foil interaction

WarpX: open-source particle-in-cell code with advanced algorithms at Exascale

PI: Jean-Luc Vay (LBNL)
DoE Exascale Computing Project



- Advanced algorithms for plasma acceleration
- Performance-portability
- Built on AMReX (LBNL, ECP co-design center)
- Users/contributors welcome!
  - >30 contributors from LBNL, LLNL, CEA, DESY, SLAC
- 2021: 10 multi-GeV stages
- Goal 2023: TeV multi-stage collider

https://ecp-warpx.github.io
Vay, J-L., *et al., Nucl. Instrum. Meth. A* 909 (2018)

Foil: 50 nm

Laser: a_0=42, w_0=2.1 λ

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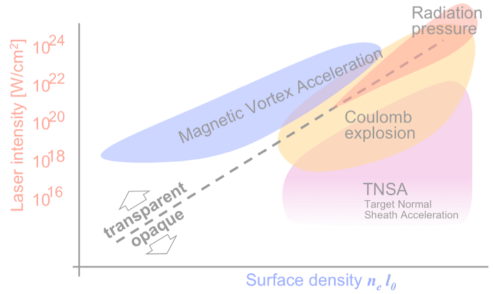
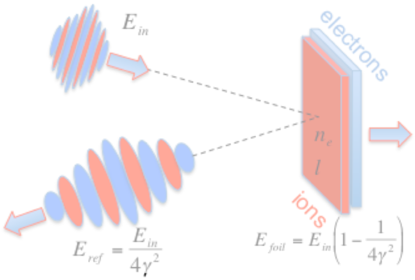
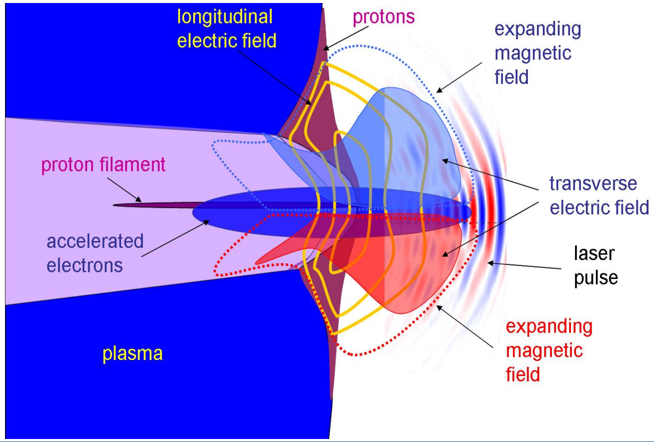
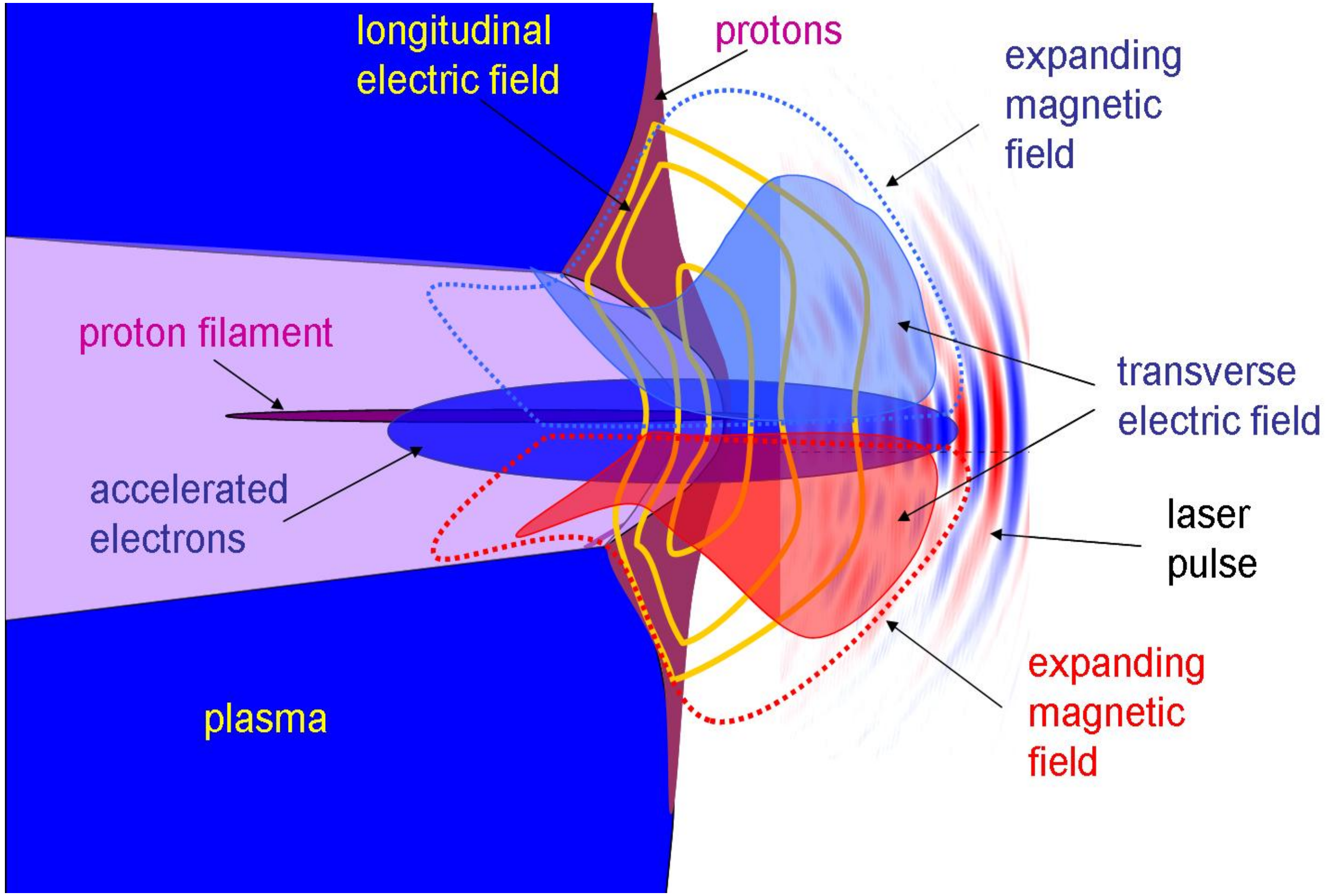






Magnetic Vortex Acceleration (MVA) in Near Critical Density plasma



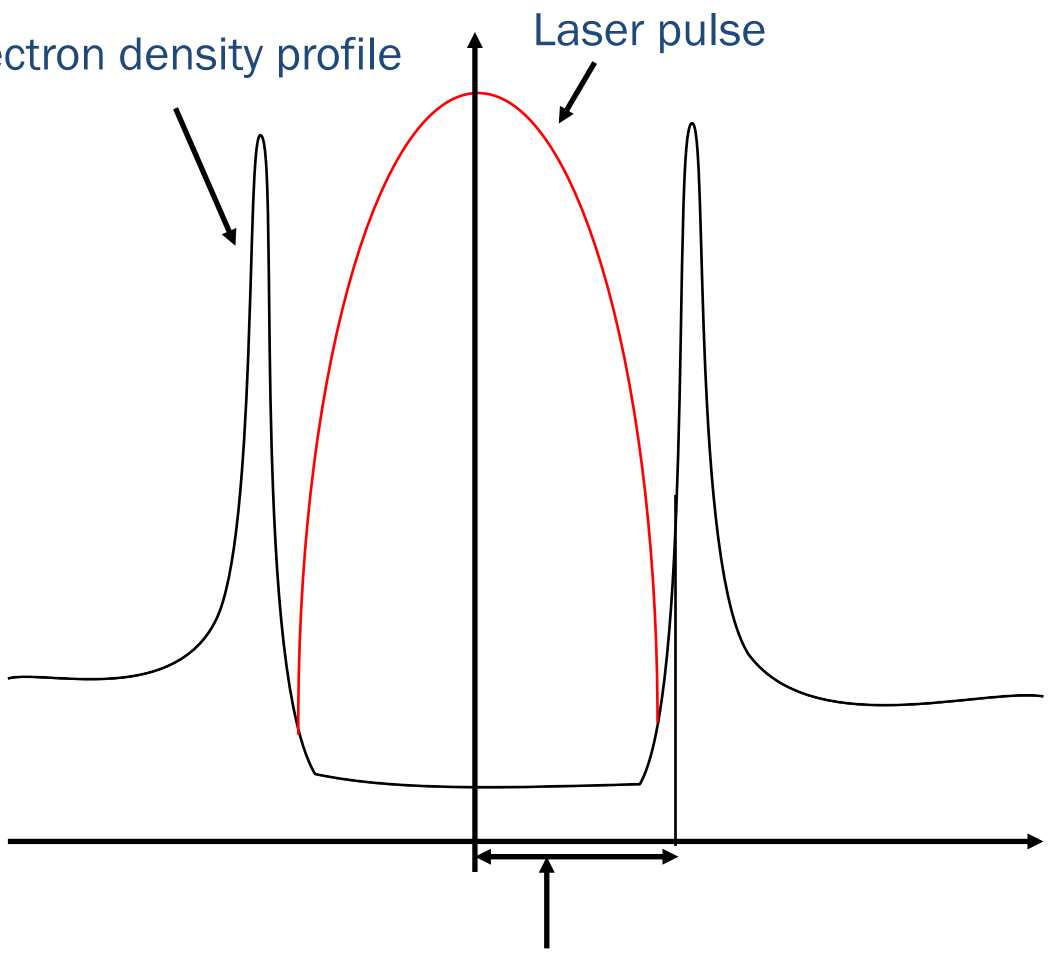
T. Zh. Esirkepov, *et al.*, JETP Lett. 70, 82 (1999).
A. V. Kuznetsov, *et al.*, Plasma Phys. Rep (2001)
L. Willingale, et al., Phys. Rev. Lett (2006)
T. Zh. Esirkepov and S. V. Bulanov, Phys. Rev. Lett. (2006)
A. Yogo, *et al.,* Phys. Rev. E (2008)
Y. Fukuda, *et al*., Phys. Rev. Lett. (2009)
T. Nakamura, *et al*., Phys. Rev. Lett. (2010)
S. S. Bulanov, et al., Phys. Plasmas (2010)
S. S. Bulanov, et al., PRAB (2015)
M. Helle, et al., PRL (2016)
A. Sharma, Sci. Reports (2018)
J. Park, et al., PoP (2019)
S. Hakimi, et al., PoP (2022)
…

Near Critical density Targets:

- **Less requirements for laser contrast than in RPA**
- **Potential high repetition rate operation**

Laser pulse propagates in self-generated channel, channel radius and laser field amplitude are determined by plasma density and laser power

Laser pulse in a waveguide



The MVA relies on the laser ability to reach the back side of the target

Target transparency is determined by laser depletion in near critical density plasma

$$L_{target} < L_{ch} \sim n_e^{-2/3} P^{1/3}$$

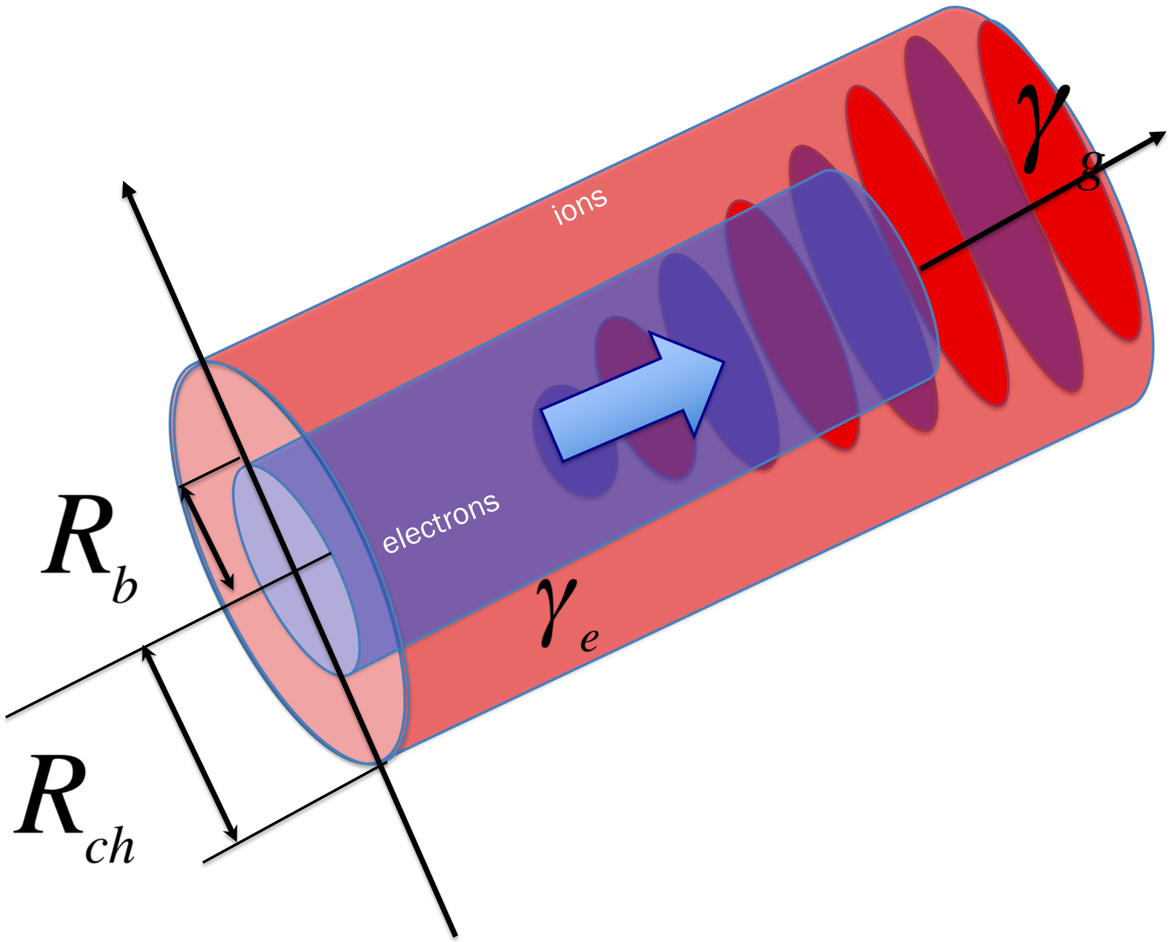
Radius of the self-generated channel

$$R_{ch} \sim n_e^{-1/3} P^{1/6}$$

Amplitude of the laser field in the channel

$$a_{ch} \sim n_e^{1/3} P^{1/3}$$

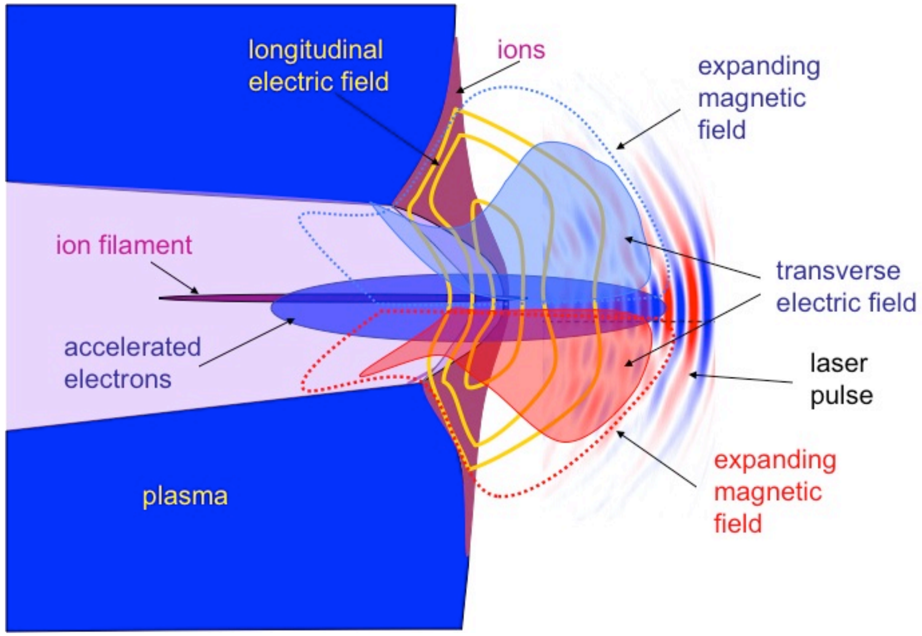
The electron current in the channel is pinched. This leads to the magnetic field intensification.



The magnetic field generated by the pinched electron current in the laser generated channel is determined by the laser power

$$\frac{eB_{max}}{m\omega c} \sim \left(\frac{P}{P_c}\right)^{1/2}$$

The electric field generated at the back of the target accelerates and collimates ions



- non-relativistic case: ion energy ~ [laser power]$^{4/3}$

$$\mathcal{E} \sim P^{4/3}$$

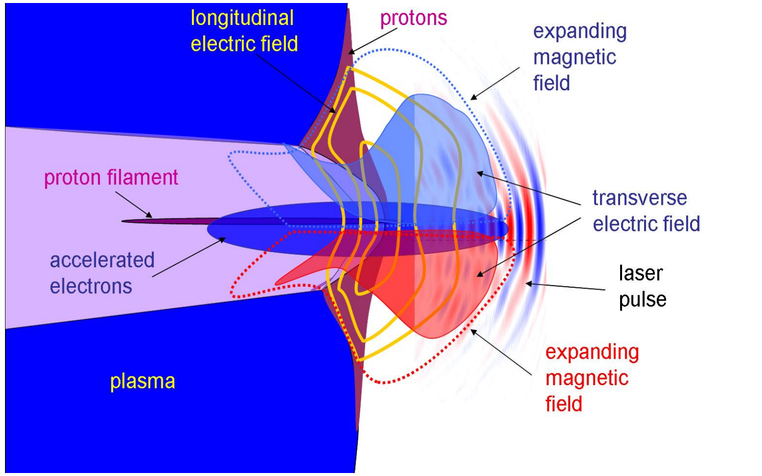
- ultra-relativistic case: ion energy ~ [laser power]$^{2/3}$

$$\mathcal{E} \sim P^{2/3}$$

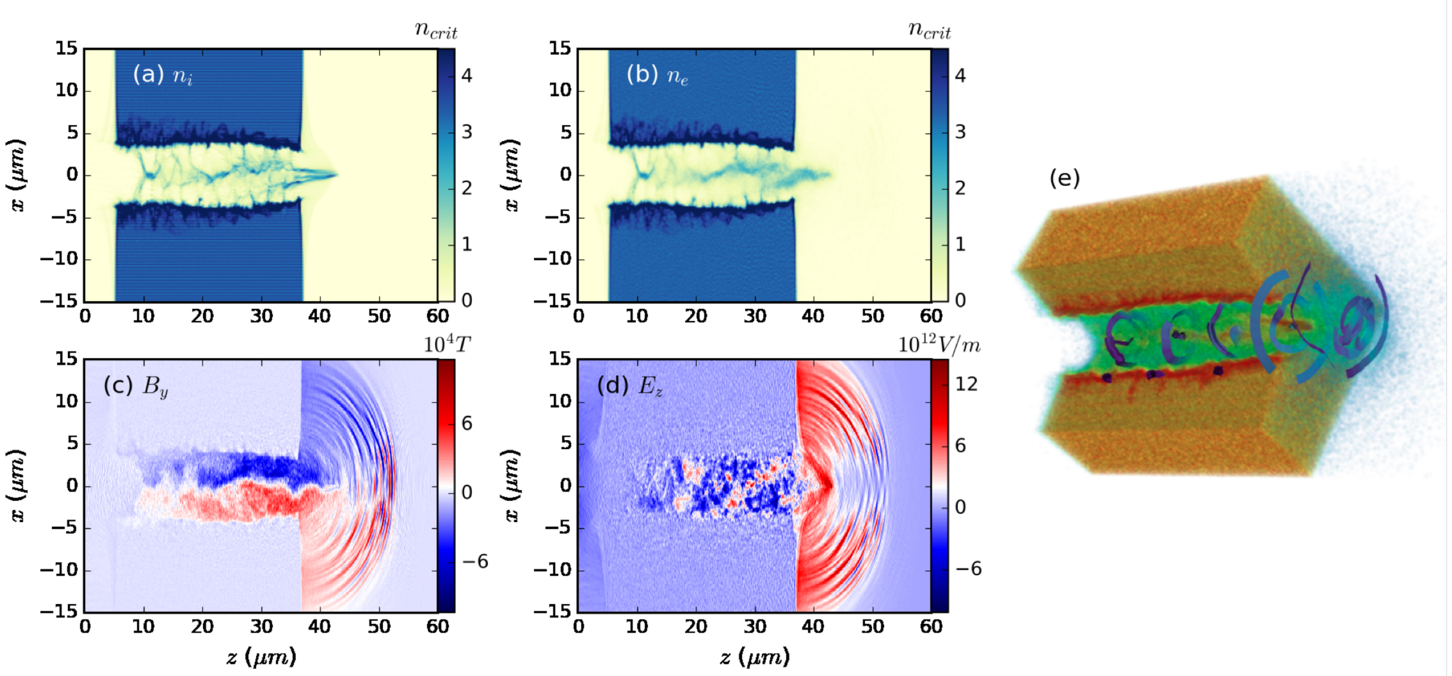
3D PIC simulations illustrate the key features of the theoretical model: channel creation, pinching of the electron current, and strong magnetic field generation

MVA model parameter:

- Target: e- + p plasma with density ~3.3n_{crit}
- Target length: L = 40λ



Laser:
λ=0.8μm, P=1 PW, I=3x10^{22} W/cm^2
a_0=118, w_0=1.86λ



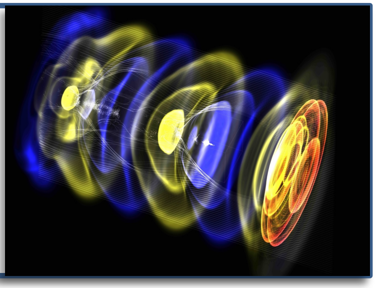
J. Park, et al., PoP (2019)

WarpX – open-source particle-in-cell code with advanced algorithms at Exascale

PI: Jean-Luc Vay (LBNL)
>30 contributors internationally

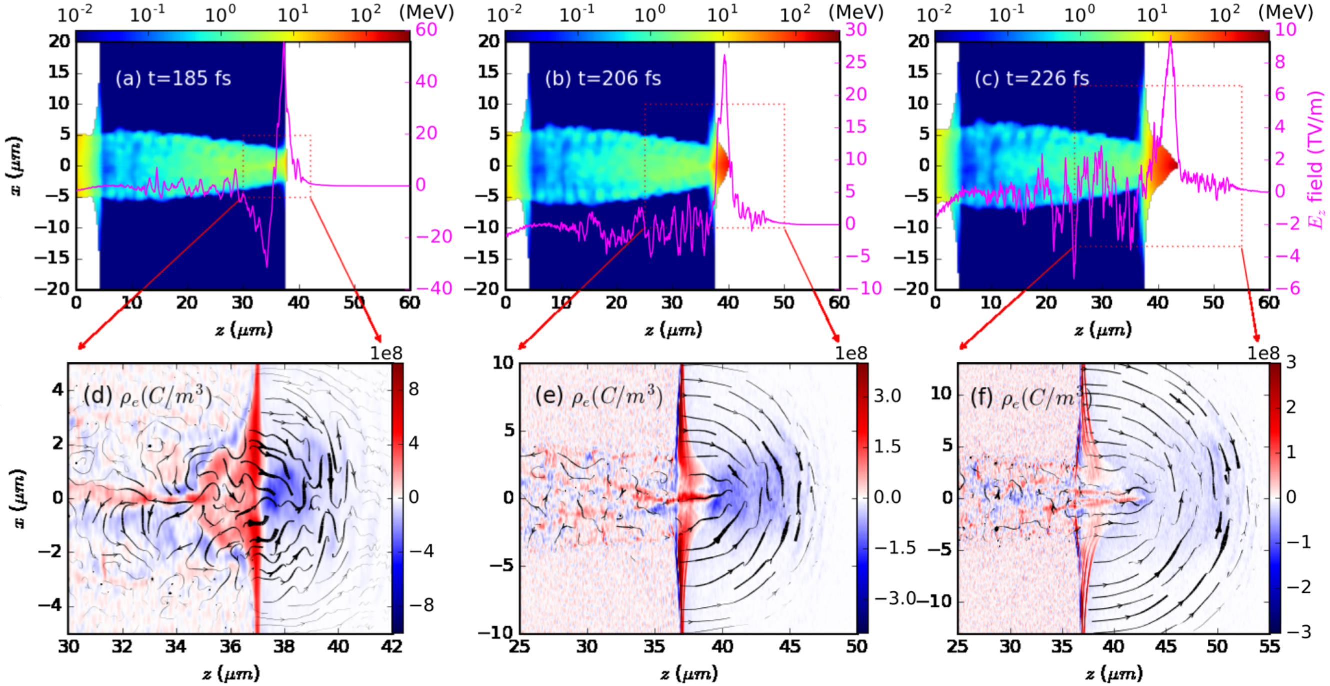
https://ecp-warpx.github.io
Vay, J-L., *et al., Nucl. Instrum. Meth. A* 909 (2018)

ECP EXASCALE COMPUTING PROJECT
U.S. DEPARTMENT OF ENERGY | Office of Science



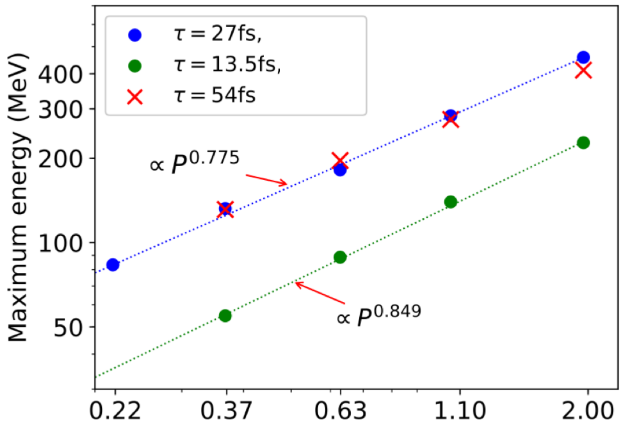
The magnetic field strength and maximum proton energy scalings with laser power from 3D PIC simulations agree well with theoretical predictions

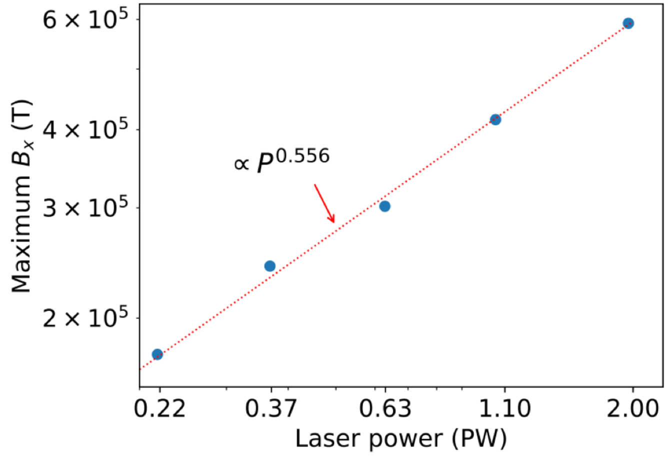
Proton energy distribution at t=185, 206, 226 fs



Charge density and electric field at t=185, 206, 226 fs

Maximum proton energy



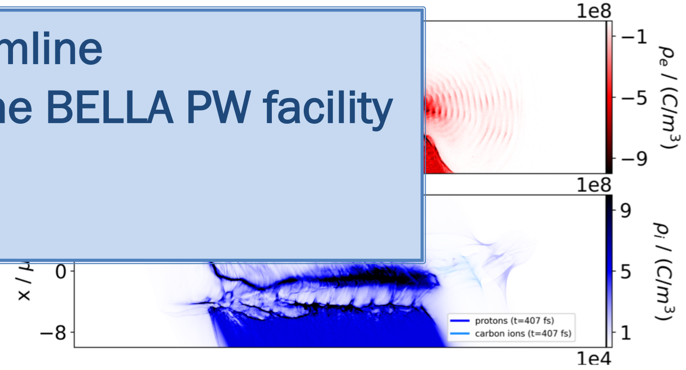


Maximum magnetic field strength

WG6: New capabilities of the iP2 beamline for laser-solid interaction studies at the BELLA PW facility

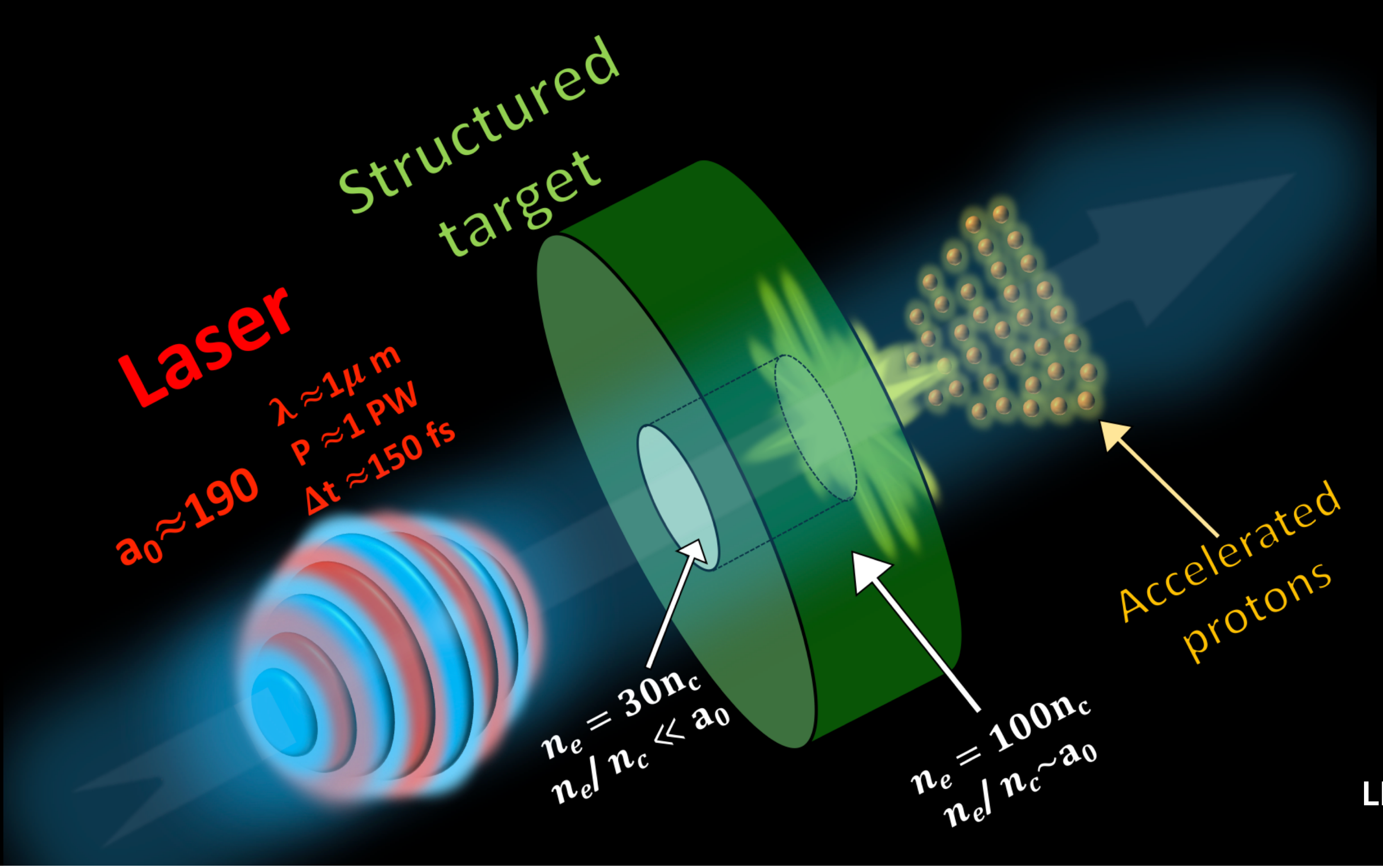
9 Nov 2022, 13:50

S. Hakimi



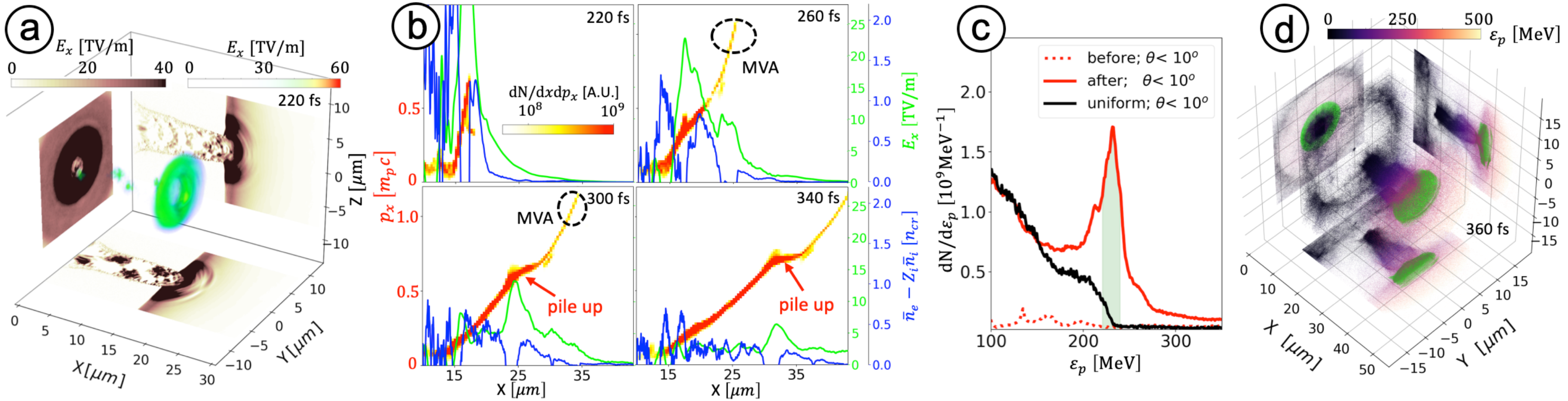
Off-normal incidence

Laser ion acceleration from structured targets leads to the production of quai-monoenergetic high charge ion beams



LBL/UCSD/HZDR collaboration

Energy-chirp compensation of laser-driven ion beams enabled by structured targets



2-PW, 120-fs laser can produce a quasi-monoenergetic peak centered at 230 MeV.
The number of protons in a 40 MeV energy interval is about 5 × 10^{10} particles (7.8 nC).

Z. Gong, et al., Phys. Rev. Res., in press

EPOCH

- Introduction
  - Ion acceleration mechanisms
  - Possible applications

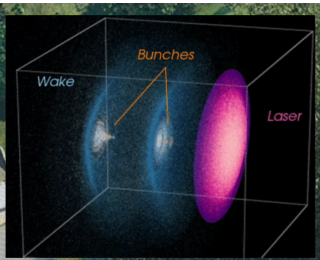
- Radiation Pressure Acce
  - Basic thee
  - Limi
  - ns

- rtex Acceleration
  - Basic theory
  - Structured targets

- Conclusions

Experimental studies of MVA mechanism at PW-class laser facilities

BELLA Center houses multiple laser facilities addressing laser, accelerator, and light source R&D and applications, including laser ion acceleration.

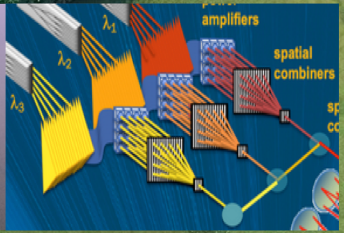


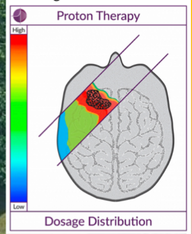
BELLA-PW 1st and 2nd beamlines
40 Joule in ~30fs (1 PW @ 1Hz)
- multi-GigaVolt e- acceleration
- Medium-intensity p+ acceleration

BELLA-HTT
3 Joule in 30fs (100 TW @ 5Hz)
- Mono-chromatic gamma rays
- Pump-probe X-rays
- Medium-intensity p+ acceleration

Future kBELLA: 100TW, operation at 1kHz

BELLA FIBER
100s mJ in <100fs (>1kHz)
- Laser R&D
- Light sources at >1kHz

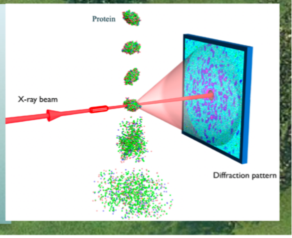




BELLA-IP2 at BELLA-PW
40 Joule in 30fs (1 PW @ 1Hz)
- High-intensity p+ acceleration
- Strong-field physics

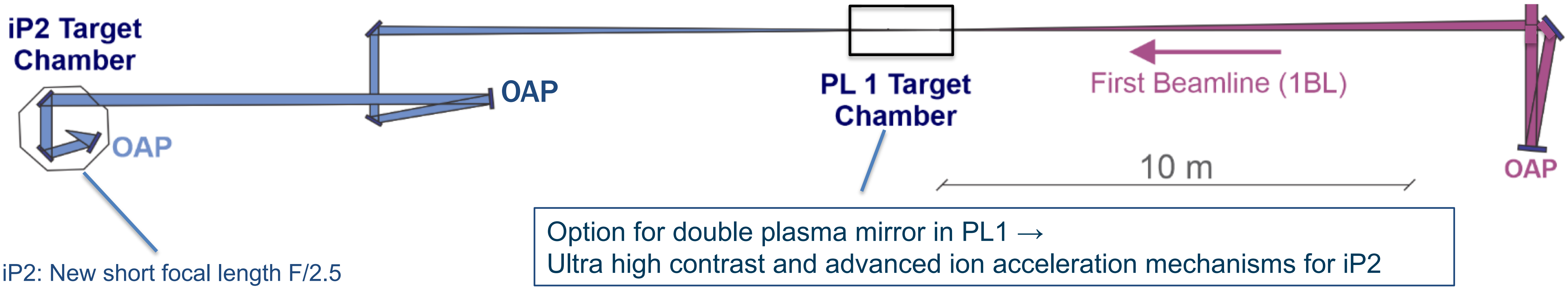
1TW-kHz, 4mJ Joule in 4fs (1 TW @ 1kHz)
- Few-MeV electrons & X-rays
- Emergency response etc

BELLA-HTU, 3 Joule in 30fs (100 TW @ 5Hz)
- Electron transport line
- Undulator X-rays

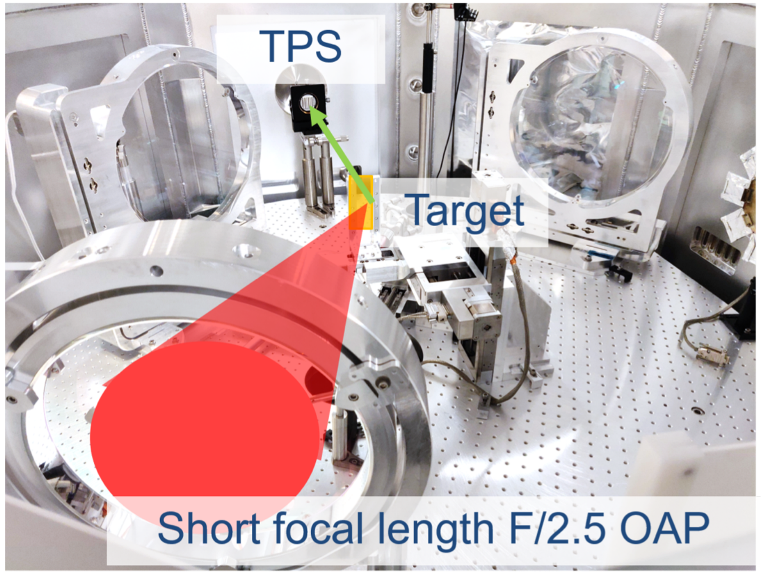


All systems are Ti:sapphire-based except for the fiber system under construction

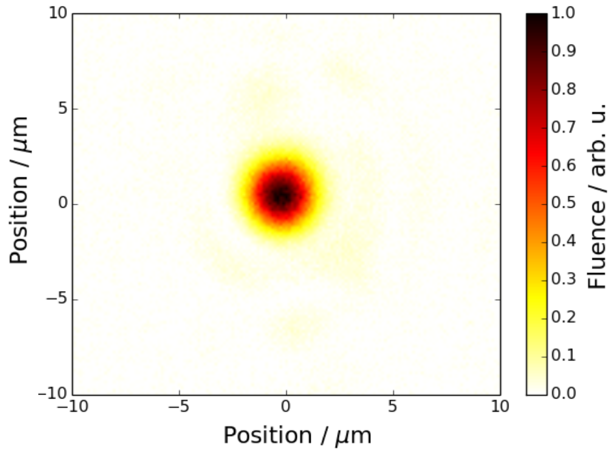
BELLA iP2: Short focal length setup to achieve high intensity on target for ion acceleration and HEDS studies

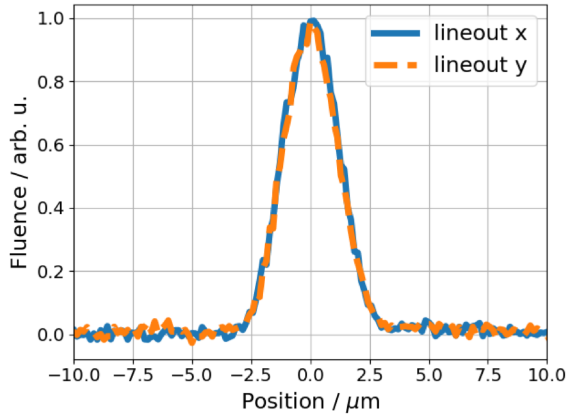


Option for double plasma mirror in PL1 →
Ultra high contrast and advanced ion acceleration mechanisms for iP2



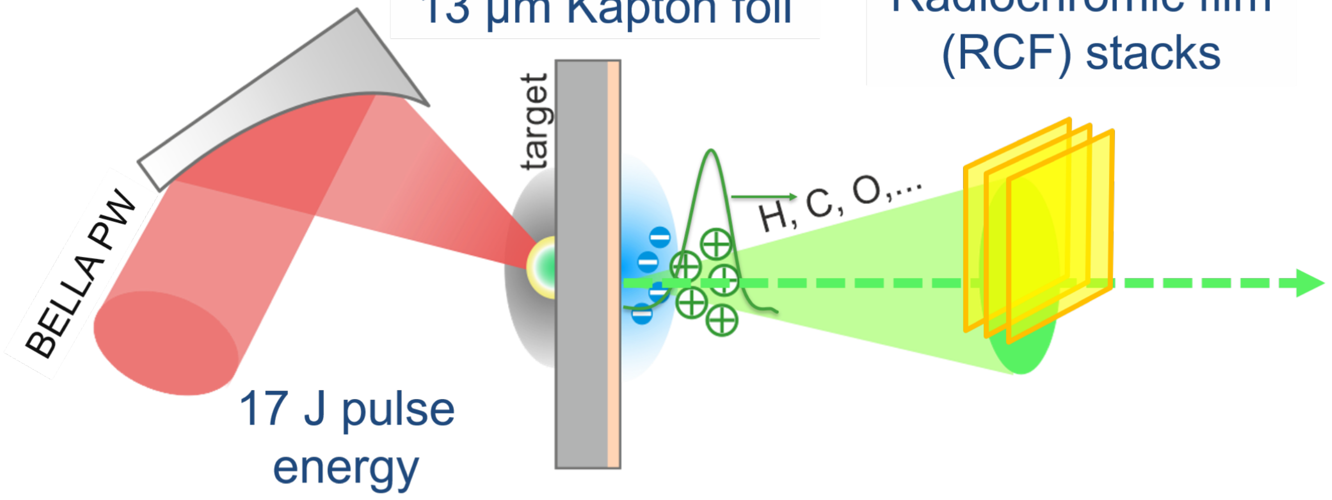
Focal spot measurements indicate >5x10^{21} W/cm^2 for 40 J pulse energy



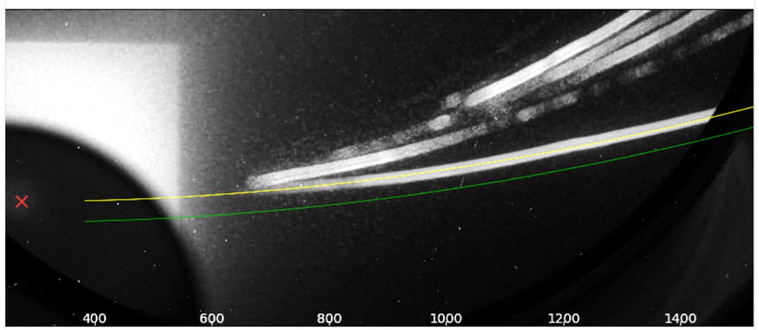


Available for user experiments through LaserNetUS

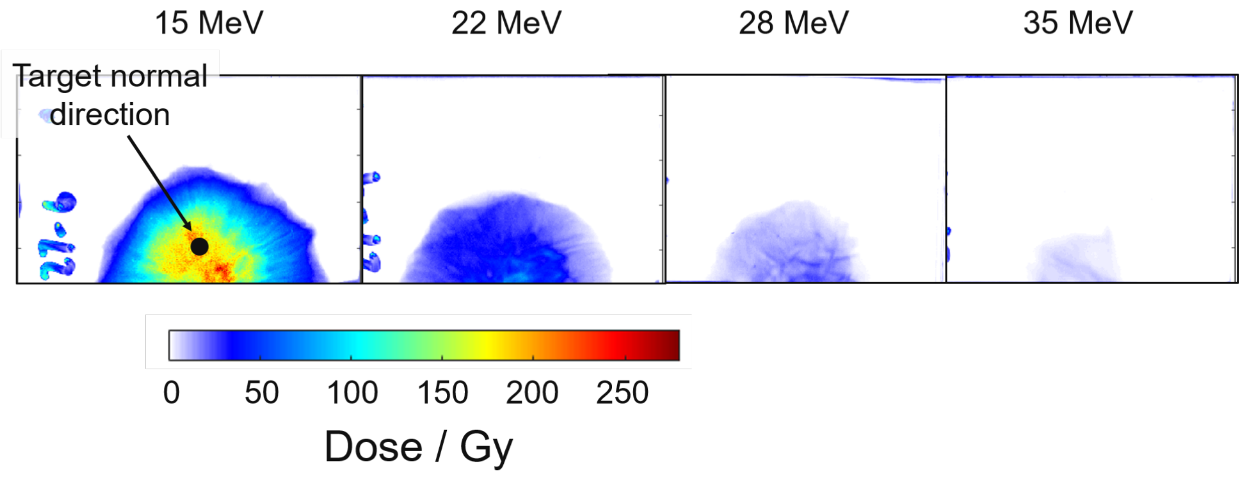
BELLA iP2: Proton energies > 40 MeV demonstrated at 17 J pulse energy on target using TNSA. Stay tuned for MVA results!



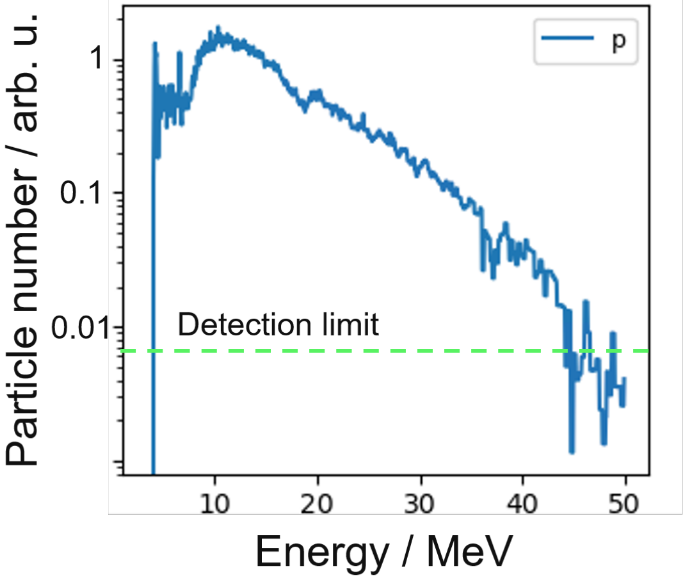
Thomson parabola spectrometer (TPS)



Proton beam profiles (preliminary)



Proton spectrum (preliminary)



Conclusions

1. Advanced Ion Acceleration Mechanisms are needed to accelerate ions to energies exceeding 100 MeV/u

2. Radiation Pressure Acceleration and Magnetic Vortex Acceleration seem to be the most promising options

3. The concept of target transparency plays the central role in analyzing the efficiency of advanced ion acceleration mechanisms

4. Optimization of acceleration mechanisms is needed to overcome different limiting factors and generate ion beams with required for application properties
    - Composite targets for RPA and MVA
    - Laser pulse and target shaping

5. Looking forward to the results of ion acceleration experiments at PW-class laser facilities in the MVA and RPA regimes