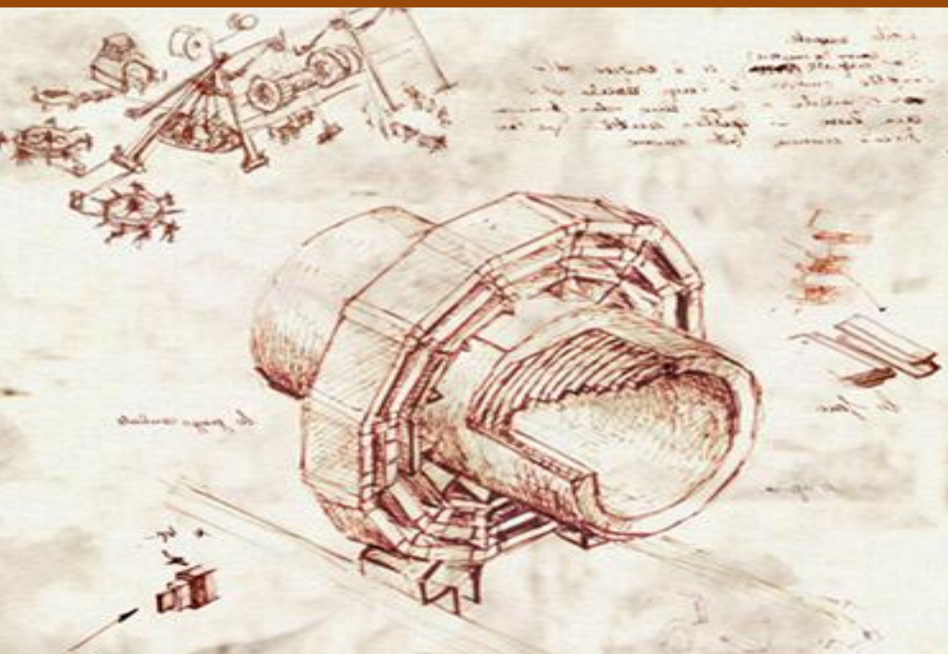
John Adams Institute for Accelerator Science

Unifying physics of accelerators, lasers and plasma



LHC sketches by Sergio Cittolin (CERN) – used with permission

Prof. Andrei A. Seryi
John Adams Institute

Lecture 9: Proton plasma acceleration

USPAS 2016

June 2016

Imperial College London
Royal Holloway University of London
University of Oxford

USPAS16 Course Lectures Timeline

- **Monday**
  - Lecture 1: Basics of accelerators and the art of inventiveness
  - Lecture 2: Transverse dynamics
  - Lecture 3: Synchrotron radiation
- **Tuesday**
  - Lecture 4: Synergies between accelerators, lasers and plasma
  - Lecture 5: Conventional acceleration
  - Lecture 6: Plasma acceleration
- **Wednesday**
  - Lecture 7: Light sources
  - Lecture 8: Free Electron Lasers
  - Lecture 9: Proton plasma acceleration
- **Thursday**
  - Lecture 10: Advanced beam manipulation I
  - Lecture 11: Advanced beam manipulation II
  - Lecture 12: Inventions and innovation in science & future directions

Proton and ion plasma acceleration

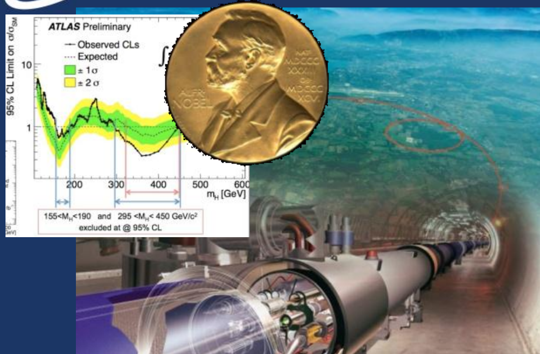
- **Motivation**
- **DNA and radiation effects**
- **Conventional approaches**

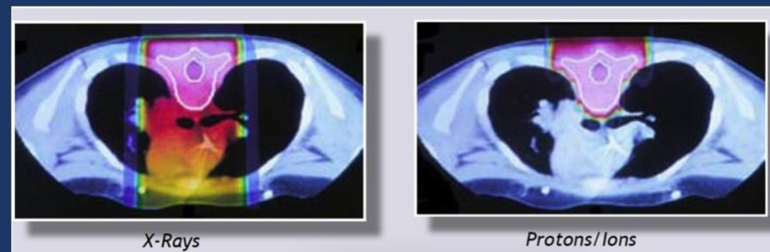
- **Basics of ion acceleration with high intensity lasers**
  - **Sheath acceleration**
  - **Radiation pressure acceleration**

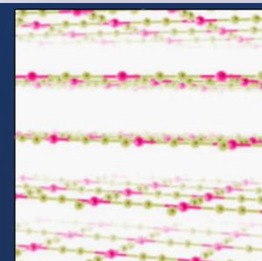
- **Beam driven acceleration**
  - **Electron beam driven**
  - **Proton beam driven**

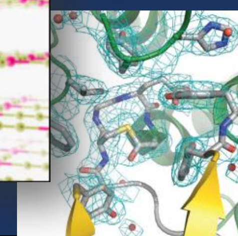
John Adams Institute for Accelerator Science

Accelerators for science and society









Accelerators: high energy physics, nuclear physics, healthcare, security, energy, life science, novel materials, industry…

Tens of millions of patients receive accelerator-based diagnoses and treatment each year in hospitals and clinics around the world

All products that are processed, treated, or inspected by particle beams have a collective annual value of more than $500B

The fraction of the Nobel prizes in Physics directly connected to accelerators is about 30%

Particle accelerators for medical use

Most of them are used to treat cancer with X-ray beams (radiotherapy)

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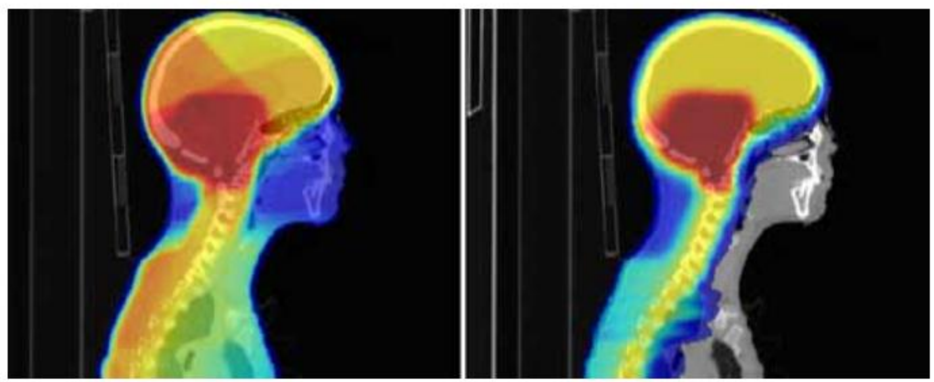
2014

£110 million for research into personalised cancer treatments

23 October 2014

A new university and business partnership is receiving £35 million of public investment in research to drive innovation and growth.



The funding will support the establishment of the Precision Cancer Medicine Institute (PCMI) at the University of Oxford, in collaboration with Oxford University Hospitals Trust. The PCMI will research a wide range of cancer therapies, including the use of genomics and molecular diagnostics, advanced cancer imaging, trials of new drugs, minimally invasive surgery and proton beam therapy. The project will receive £35 million of funding from the UK Research Partnership Investment Fund (UKRPIF), and has attracted an additional £75 million in private investment.

Note significant difference of distribution of dose for X-rays and protons

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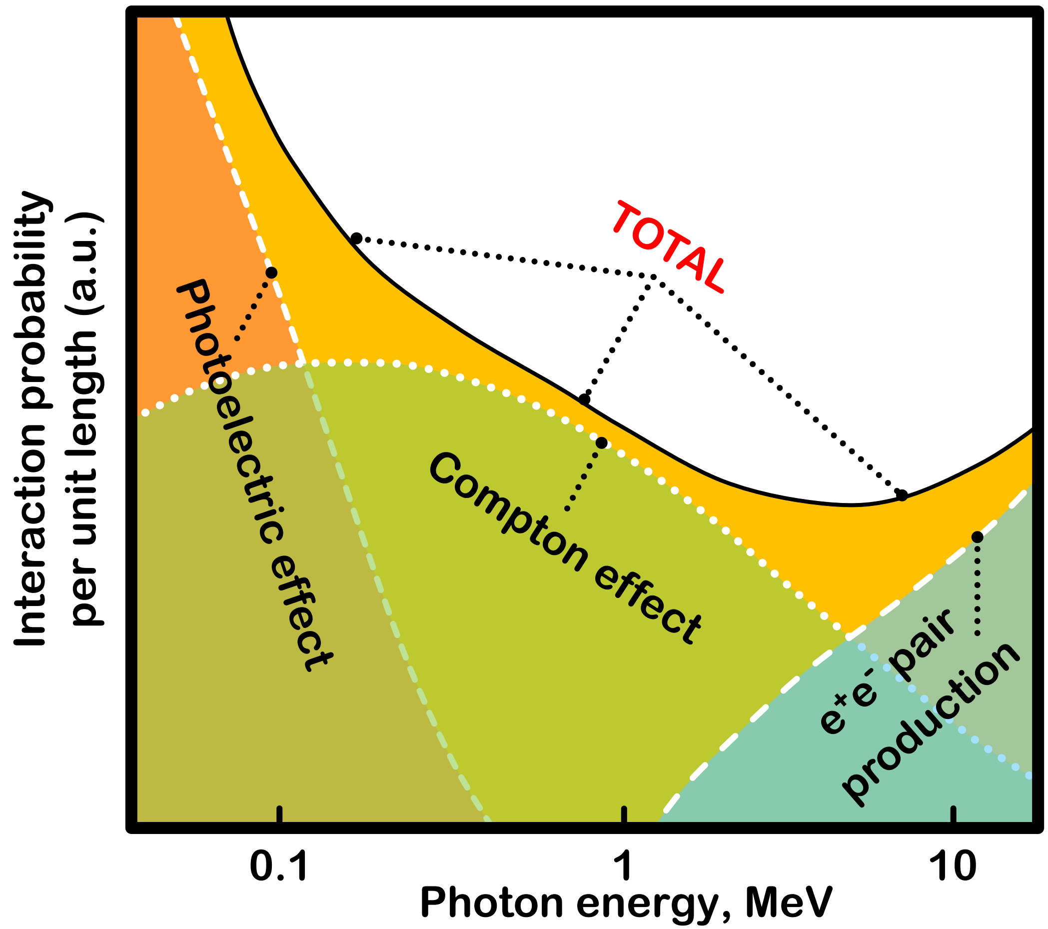
Photon-matter interaction



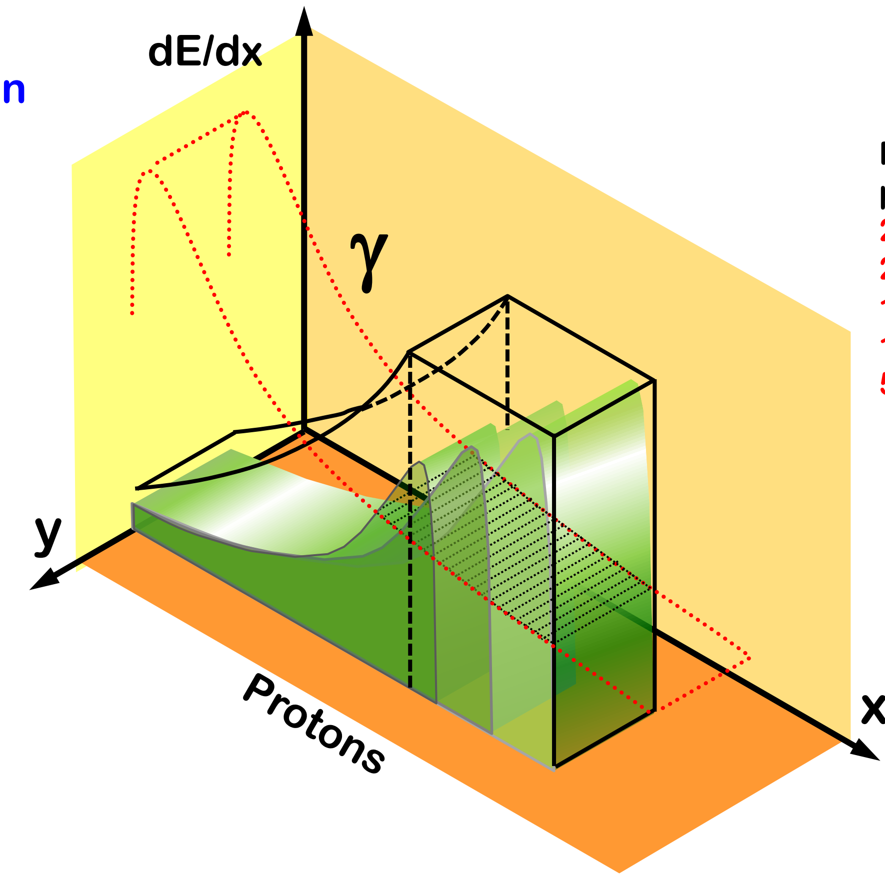
Photons penetrating through a medium will lose their energy due to several factors

Bragg peak

In contrast to photons, charged particles lose their energy in matter primarily through a Coulomb interaction with the outer-shell electrons of the absorber's atoms

Excitation and ionization of atoms result in a gradual slowdown of the particle. A slower moving particle will interact with an atom for longer time, resulting in a larger energy transfer

Therefore, the charged particles will have an increased energy loss per unit length at the end of their passage through the medium



Penetration range for protons in water:
250 MeV — 38 cm
200 MeV — 26 cm
150 MeV — 15.6 cm
100 MeV — 7.6 cm
50 MeV — 2.2 cm

Bragg peak — the peak in energy loss that occurs just before the charged particles come to a complete stop (William Bragg, 1903)

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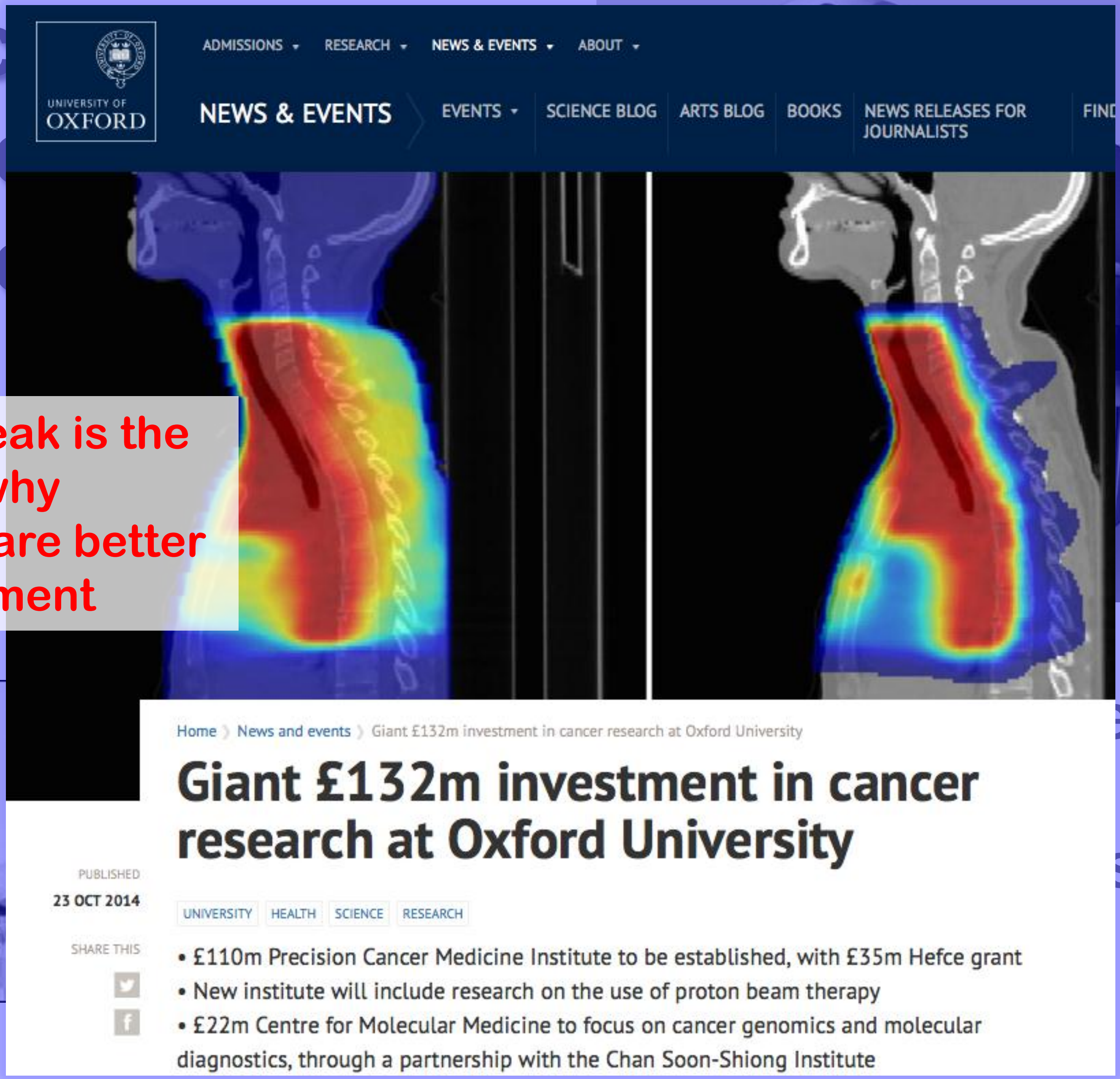

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Giant £132m investment in cancer research at Oxford University

PUBLISHED
23 OCT 2014

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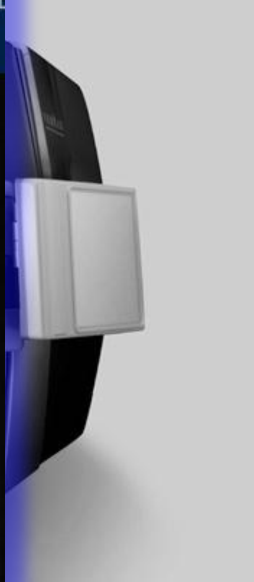
UNIVERSITY HEALTH SCIENCE RESEARCH

- £110m Precision Cancer Medicine Institute to be established, with £35m Hefce grant
- New institute will include research on the use of proton beam therapy
- £22m Centre for Molecular Medicine to focus on cancer genomics and molecular diagnostics, through a partnership with the Chan Soon-Shiong Institute

Bragg peak is the reason why protons are better for treatment



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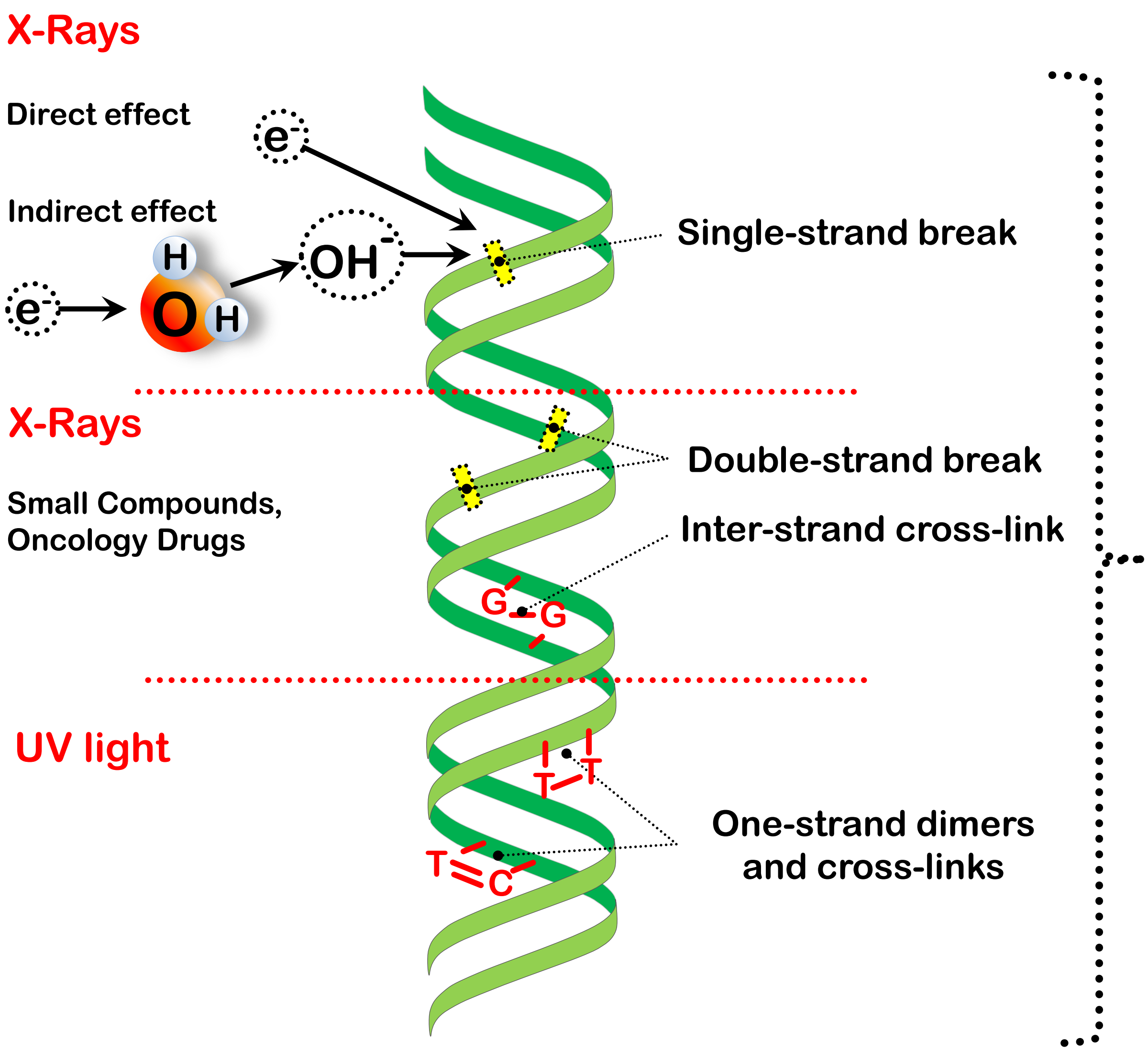
DNA response to radiation



Consequences

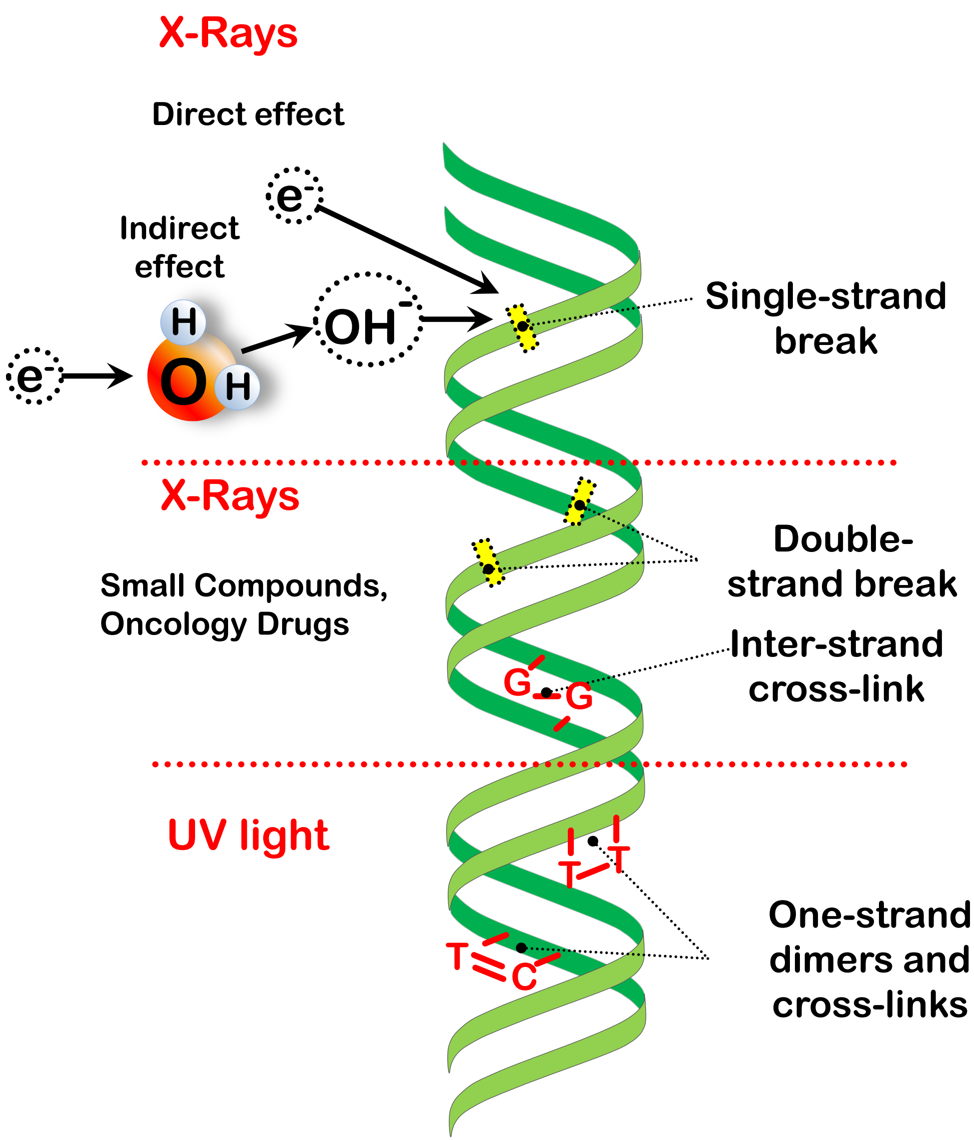
Temporary cell cycle arrest (M, G1, S or G2 phases)

Inhibition of transcription, replication, chromosome segregation ➔ Cell death

Mutations, chromosome aberrations ➔ Cancer

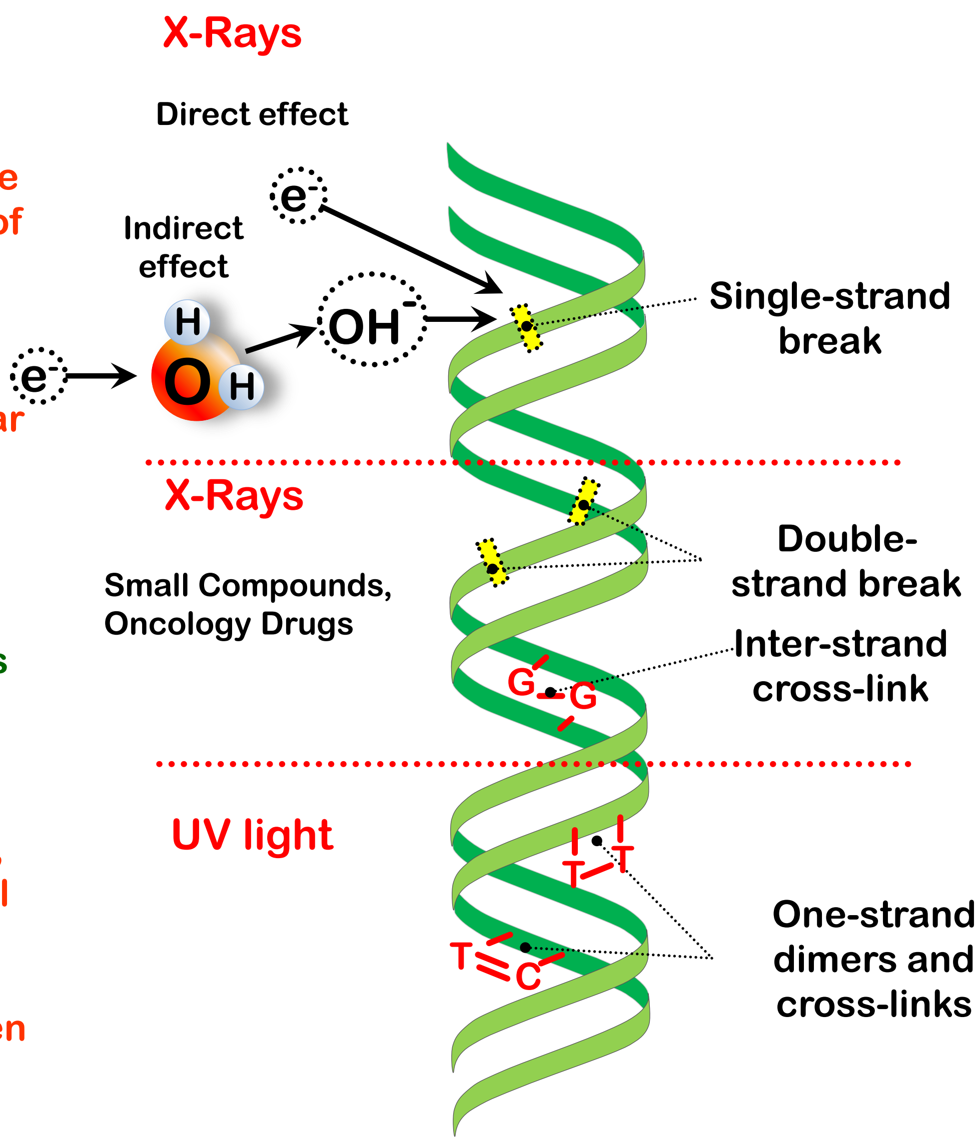
DNA response to radiation

- **Ionizing radiation effect on DNA**
  - can be various from "zero" to negative or positive depending on the intended purpose, the initial state of the irradiated object, the radiation dose and the concomitant agents
  - In some cases penetrating radiation simply does not cause DNA damage passing through the cell without any side effects
  - Direct radiation effect takes place when x-rays create ions (e-) physically breaking the nucleotide pairs of the DNA
  - Nevertheless, in majority of cases the low charged x-rays particles act indirectly by inducing water radiolysis and production of OH- hydroxide highly active free radicals forming hydrogen peroxide and causing single-strand breaks



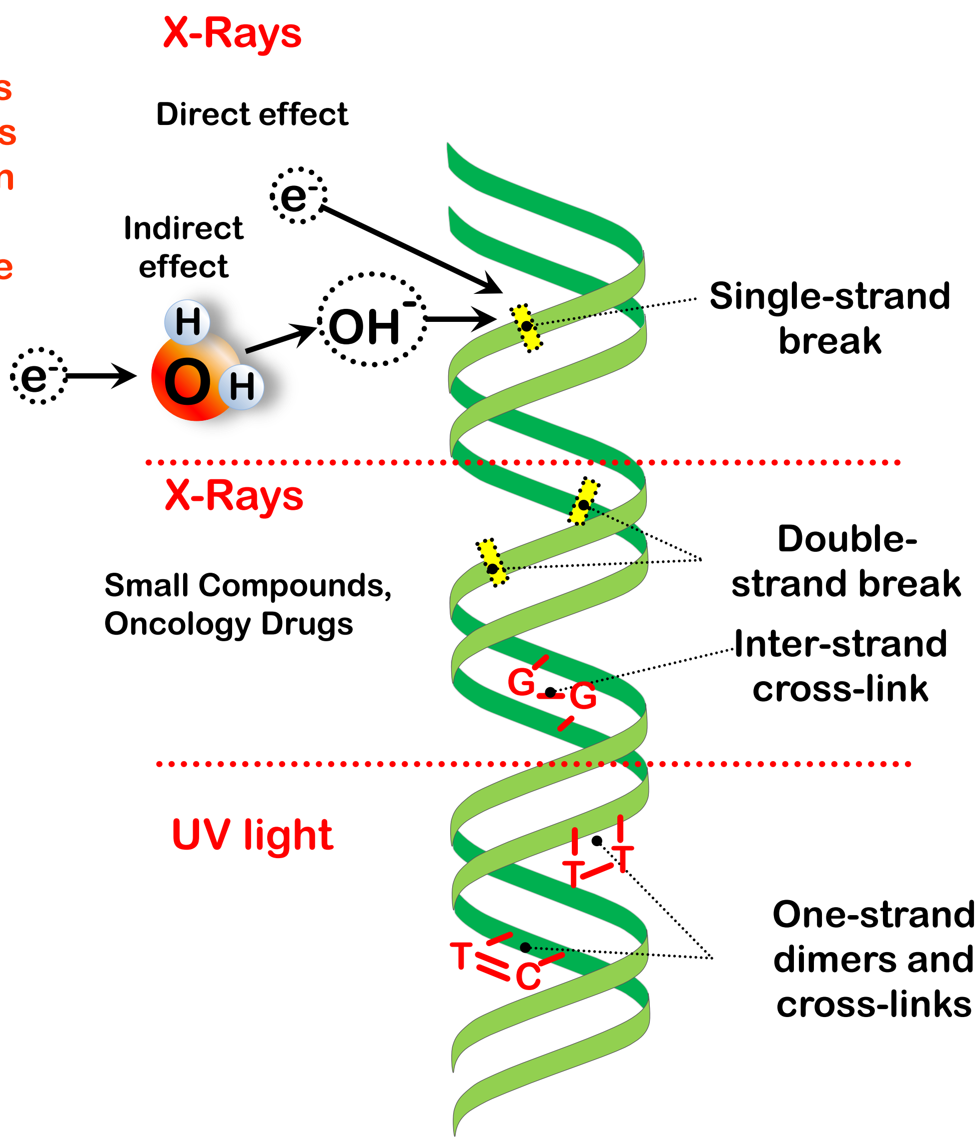
DNA response to radiation

- **Cell repair mechanism important**
  - Several minor defects such as one strand dimer formations (UV light effect) or single-strand breaks could be corrected by internal cell mechanism of the base excision repair involving endonucleases and DNA polymerase
  - Nevertheless some errors could appear also on this step (for example wrong nucleotide(s) insertion could cause future coding mismatch)
  - Difficult to repair double-strand breaks are the most detrimental damages produced in DNA by ionizing radiation
  - Loss of whole parts of chromosomes containing tumour suppressors genes, an amplification of oncogenic-potential regions could lead to tumour cells creation and their proliferation, i.e. carcinogenesis. In the lucky case, when apoptosis scenario is not damaged, these defective cells should undergo "the cell suicide"



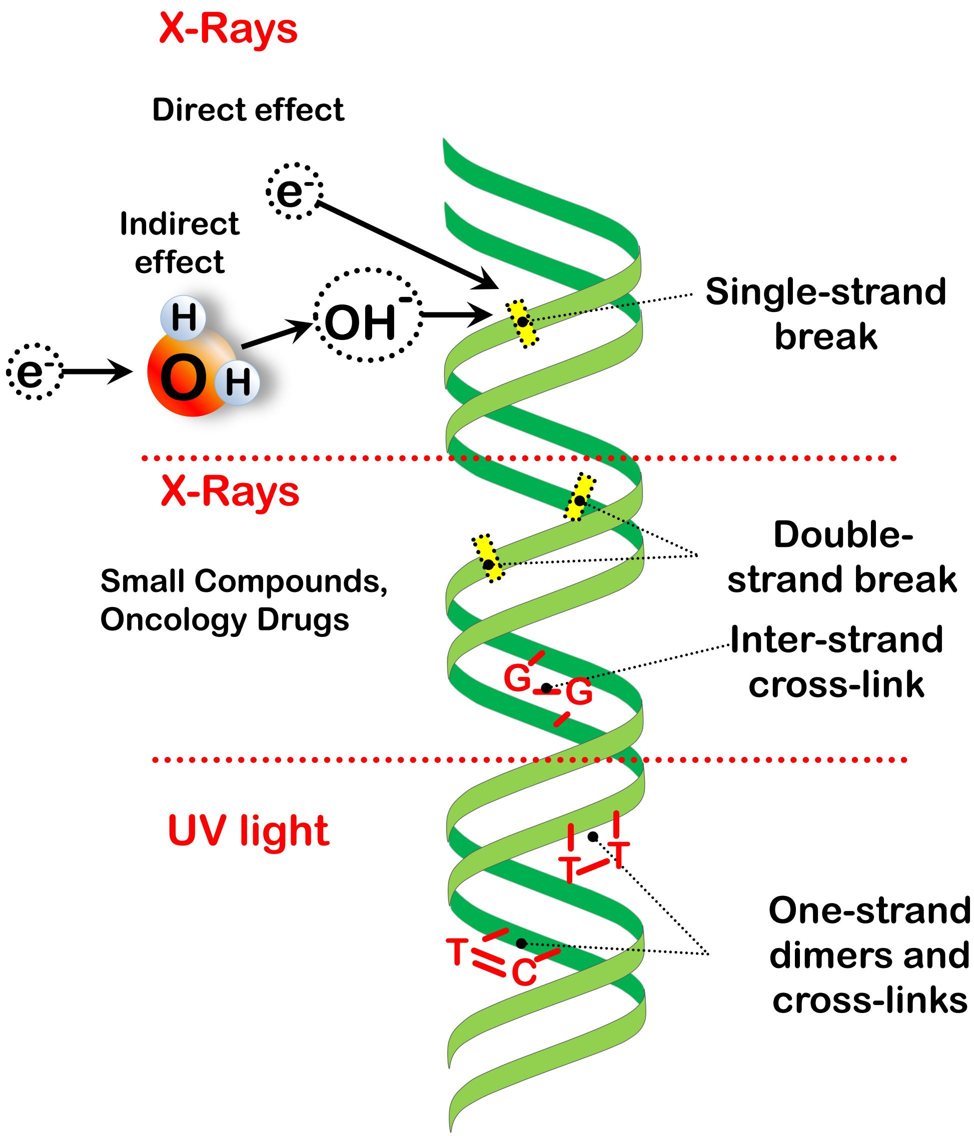
DNA response to radiation

- **Consequences of DNA damage**
  - Temporarily arrests on different stages of cell cycle (Mitosis, both check-points or DNA replication) as well as inhibition of transcription and variety of cell division abnormalities also could cause defective cells death
  - Mutations, chromosome mis-pairings defects in some cases could be eliminated by the same mechanism



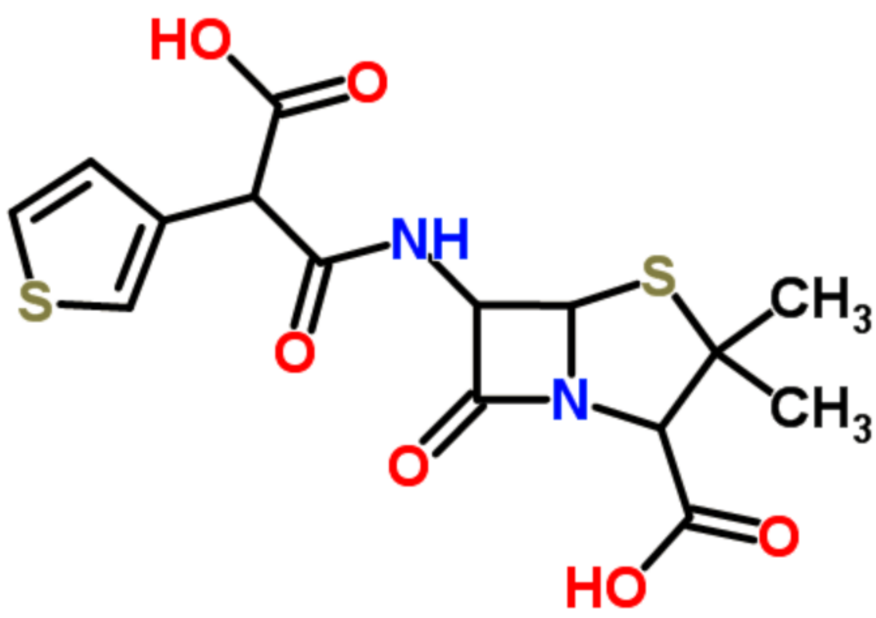
DNA response to radiation

- **Positive effects of DNA damage**
  - What could kill any normal cell also could be destructive for a malignant one
  - To enhance the destructive effect of x-rays irradiation some concomitant agents such as small compounds, approved cancer drugs could be involved
  - Apoptosis scenario, launched by strong synergetic effect, leads to cell death



Small Compound

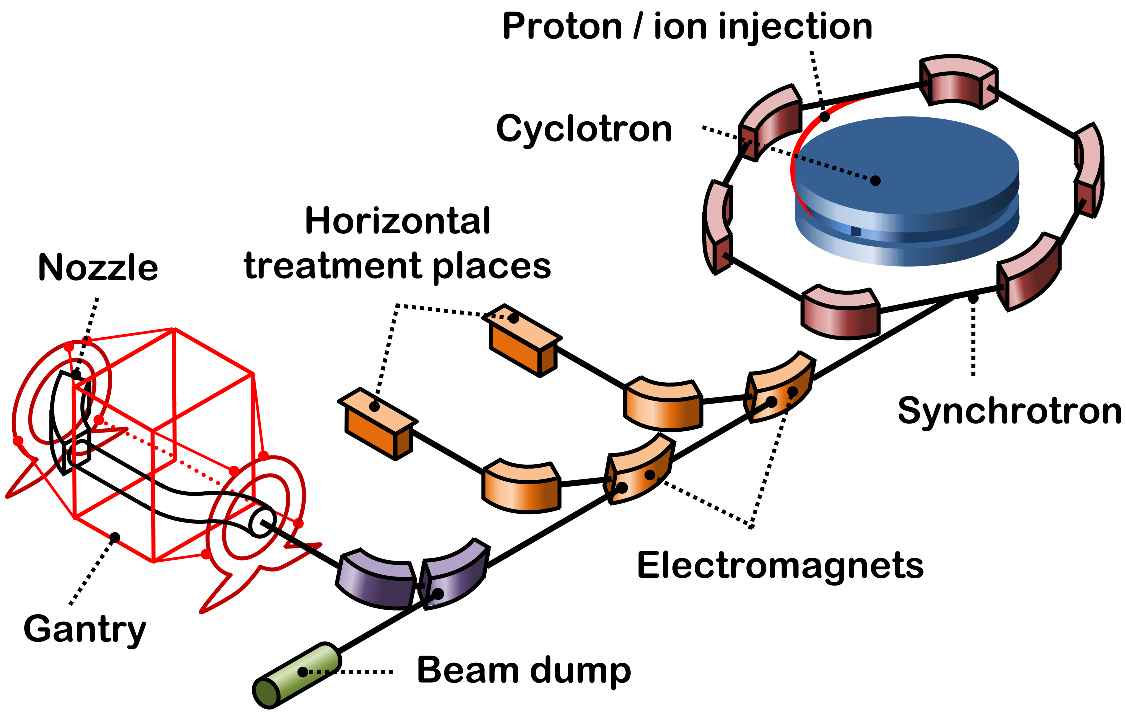
- **Small compounds**
  - In molecular biology Small Compound is a low molecular weight organic compound that may help regulate biological processes
  - The upper limit for small compounds molecular weight is approximately 900 daltons, which allows them to rapidly diffuse across cell membranes so that they can reach intracellular sites of action
    - Dalton (Da) defined as one twelfth of the mass of an unbound neutral atom of C12 in its nuclear and electronic ground state
  - Most drugs are small molecules



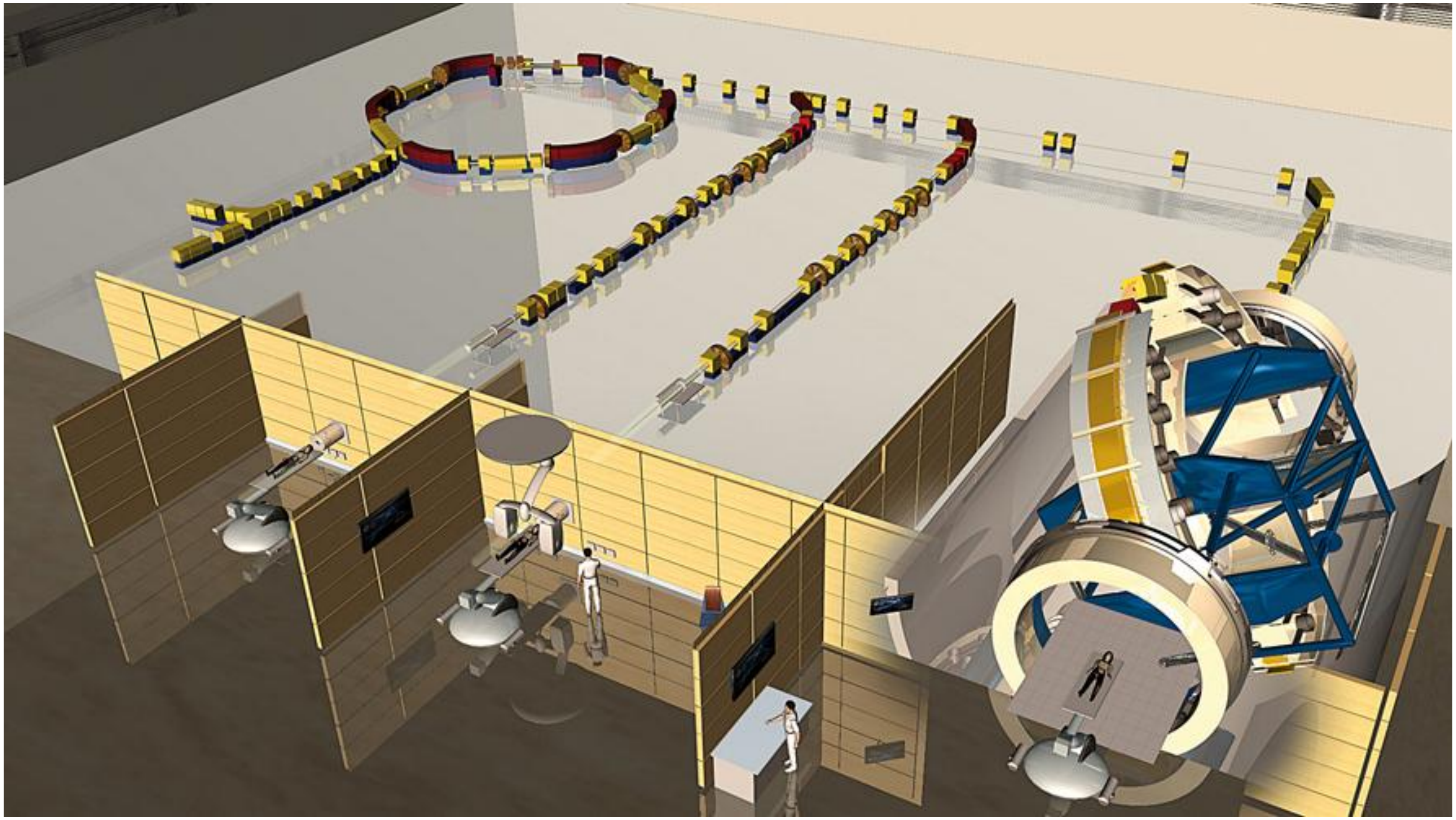
Example: $C_{15}H_{16}N_2O_6S_2$ Mass 384 Da

http://www.chemspider.com/Chemical-Structure.5272.html?rid=1c16cad5-d333-4e10-b26d-4f64f4e8e962&page_num=0

Conventional proton therapy facilities

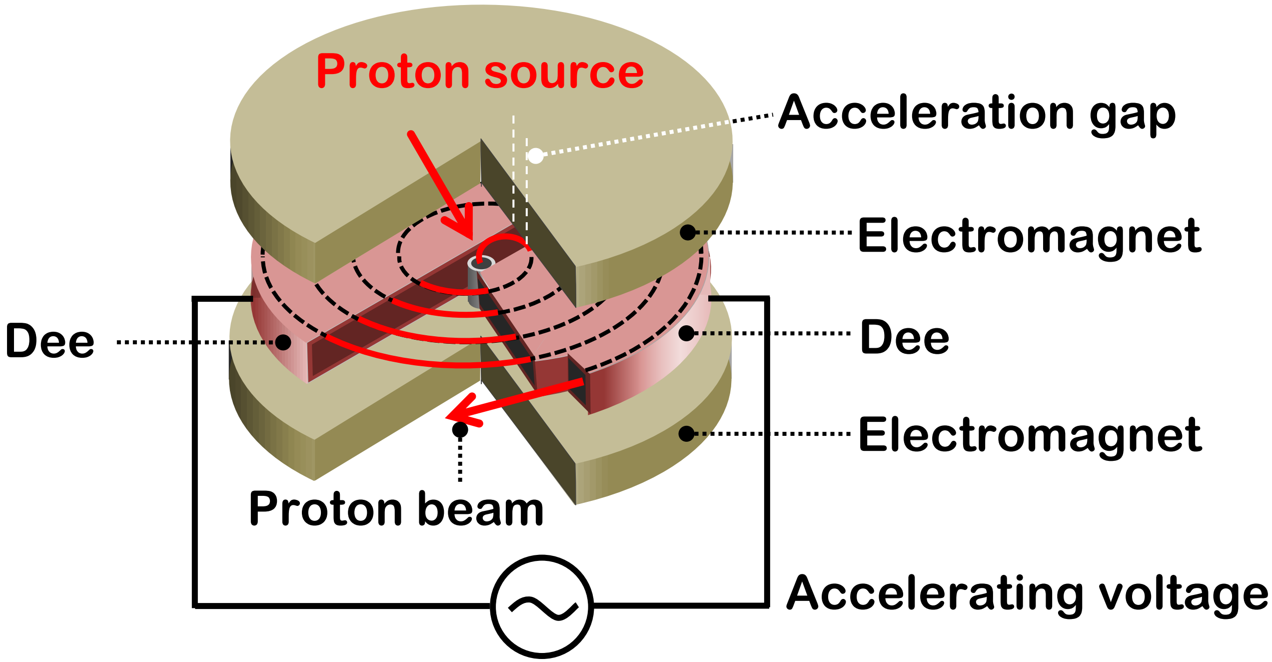


Heidelberg Ion-Beam Therapy Center



Heidelberg Ion-Beam Therapy Center

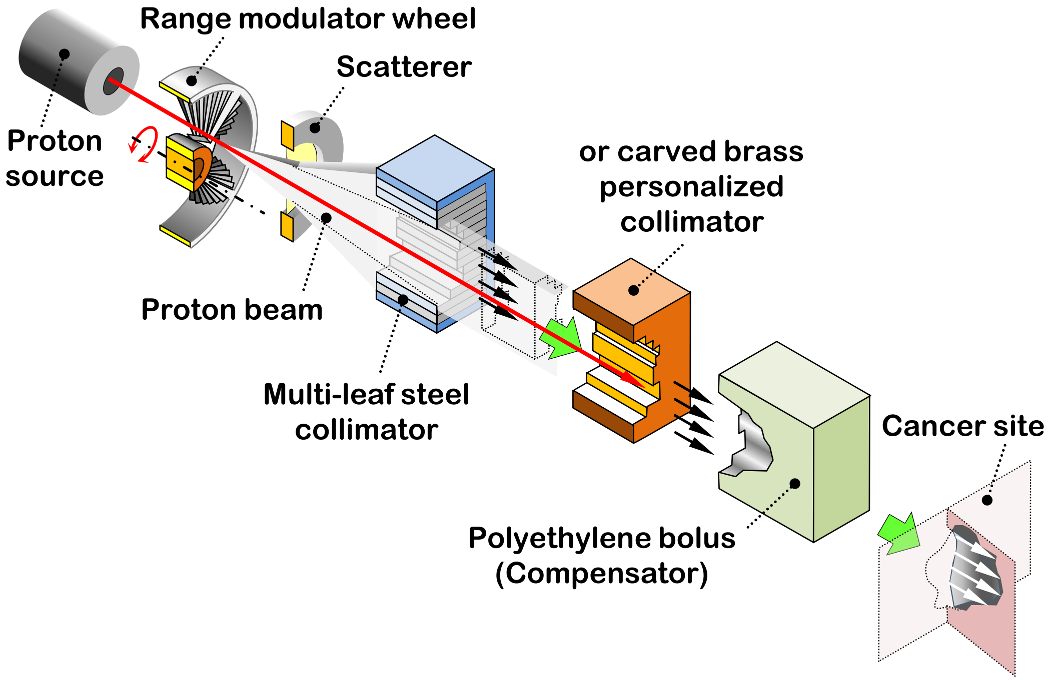
Cyclotron – often used as a source of protons



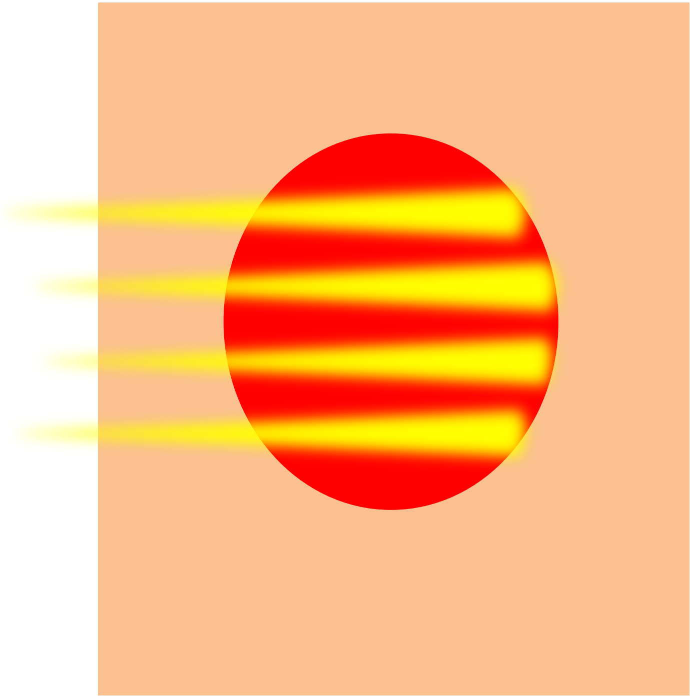
For non-relativistic proton beam $v/R=\omega_0$ is constant
This resonant condition break when proton become relativistic

Cannot easily change energy of accelerated beam –
therefore need to use additional masks to degrade the energy of protons

Elements of proton therapy beamline

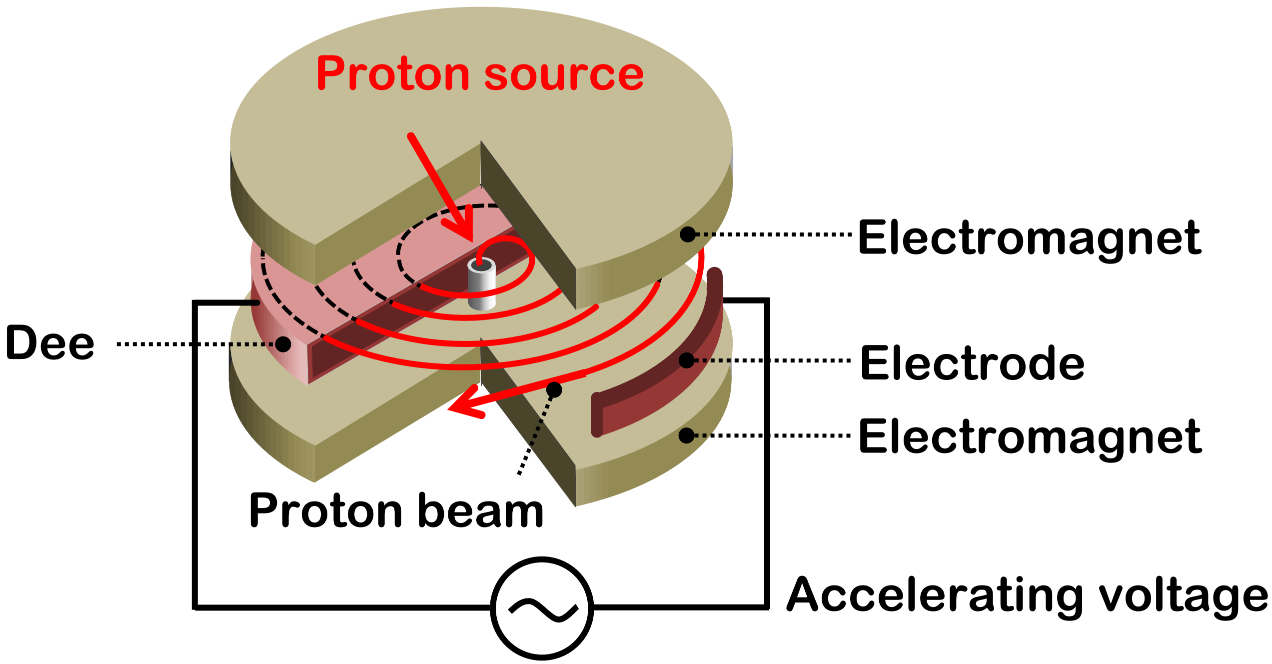


Pencil beam scanning



Synchrotrons, which can produce smaller beams, and can easily change energy of the beam, can do *"pencil beam scanning"*

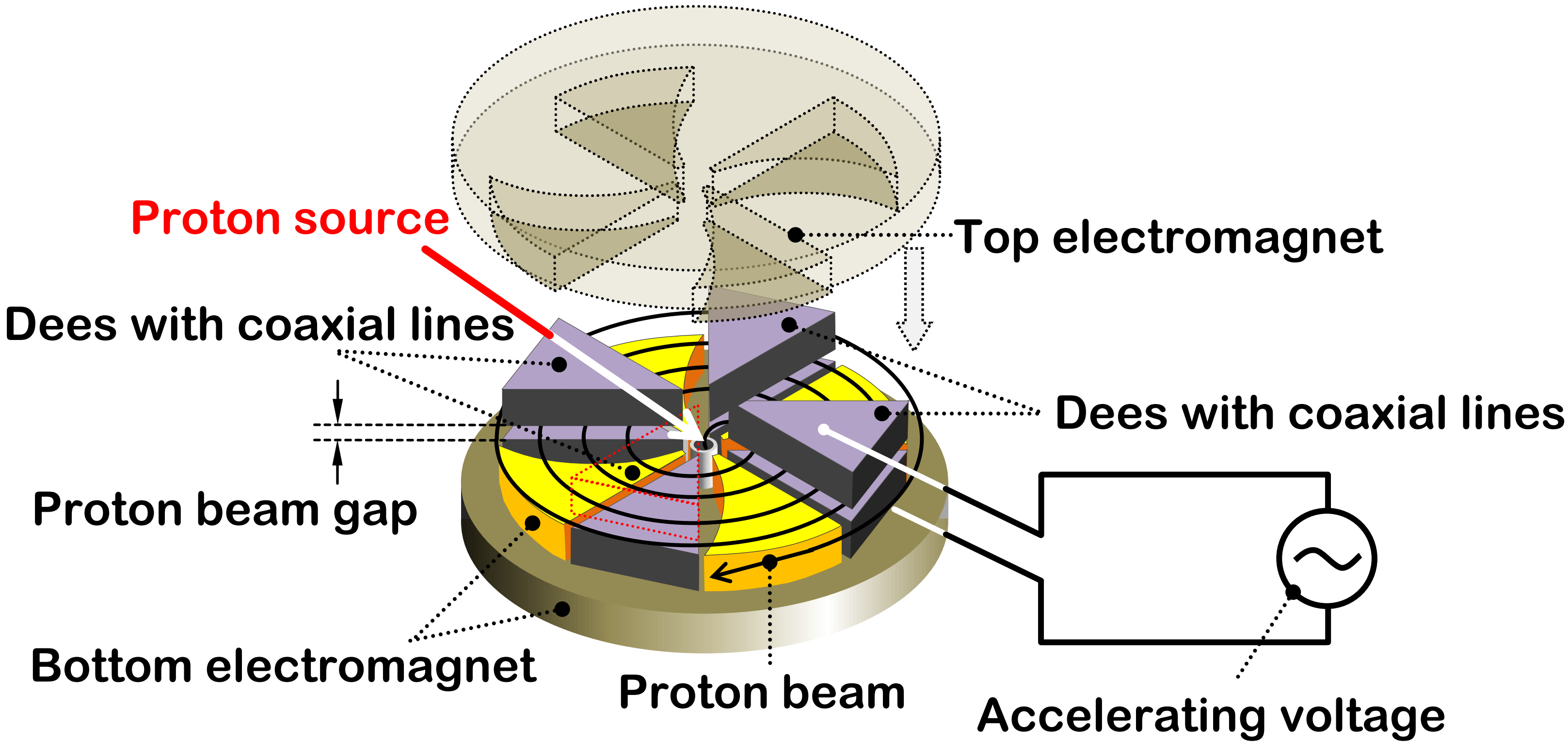
Synchrocyclotron



In contrast to a standard cyclotron, a synchrocyclotron can have variable energies of the accelerated beam and it can also achieve higher energies — several hundreds of MeV

Relativistic effects are compensated by continuously decreasing the frequency of the accelerating voltage during acceleration => these are pulsed machines

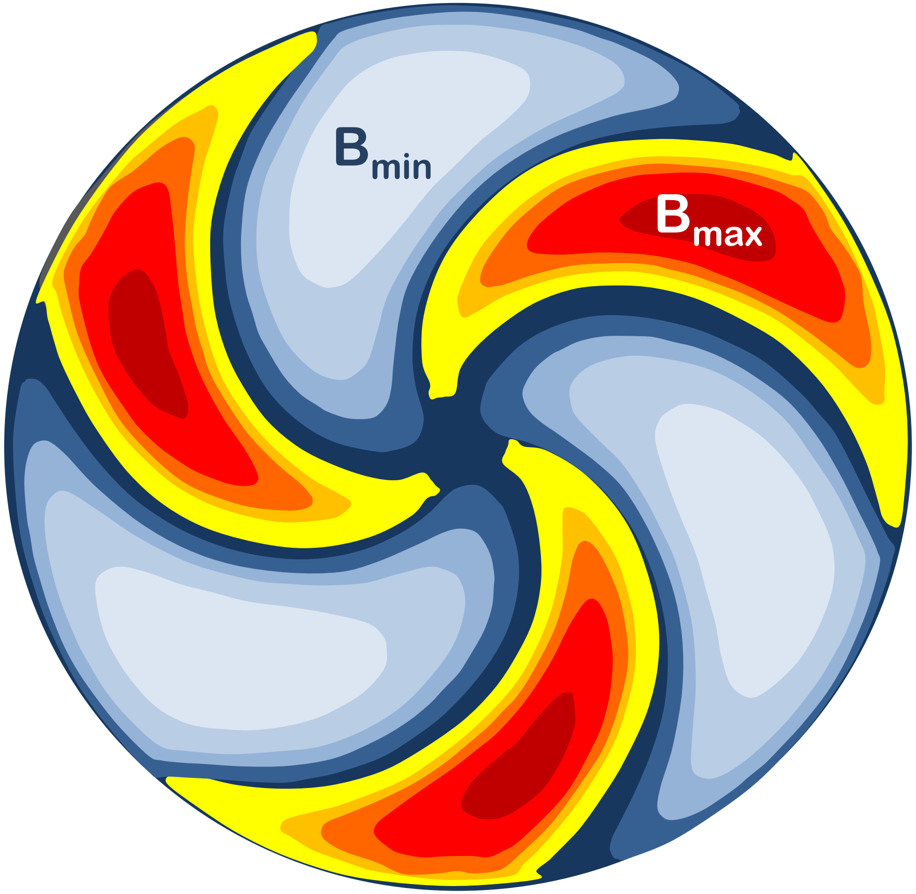
Isochronous cyclotron



In isochronous cyclotron relativistic effects are compensated by increasing magnetic field with radius

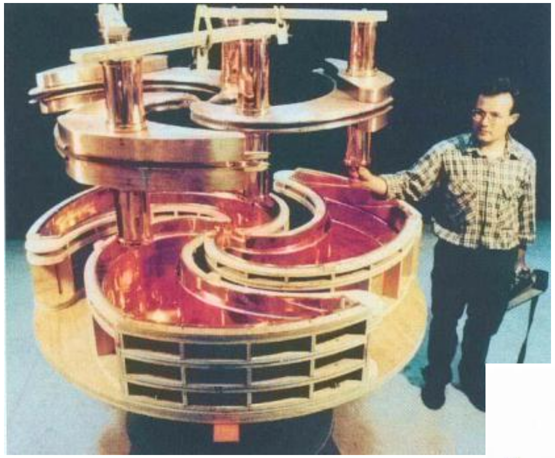
Accelerating frequency is constant => suitable for CW and thus a popular choice for proton therapy

Isochronous cyclotron

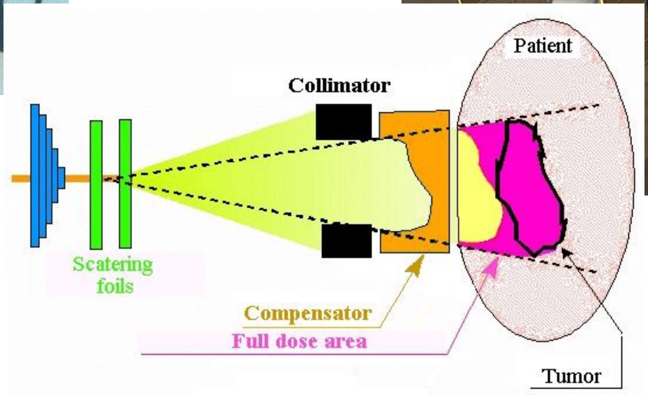


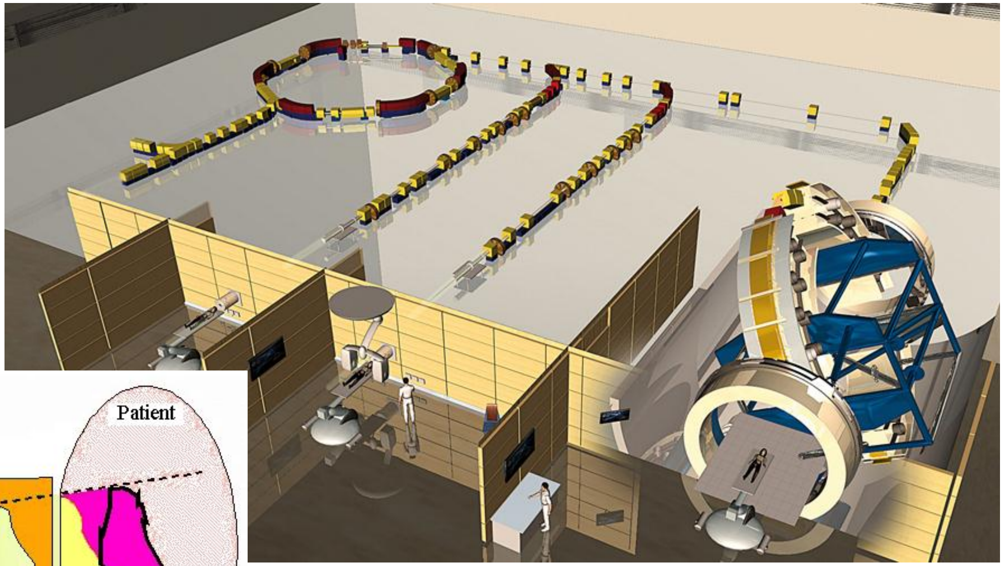
Example of field profile in isochronous cyclotron

Laser acceleration of protons or ions - motivation



RF cavity of the TERA compact proton therapy superconducting cyclotron





Heidelberg Ion-Beam Therapy Center

- Proton therapy systems require 250 MeV protons
- Such systems, especially the beam delivery gantries, are large and expensive
- Desire to create compact laser –plasma acceleration proton therapy systems is one of main motivations of plasma acceleration of protons

Laser driven ion acceleration mechanisms

- **Thermally driven schemes**
  - **TNSA, BOA, CESA**
- **Coherent schemes**
  - **LS-RPA, HB-RPA, relativistic transparency**

- **Mechanisms and understanding**
  - **Mechanisms compete, often more than one acting**
  - **Very complicated phenomena - mechanisms represent improvement of our understanding**

- Reviews:
- A.Macchi, M. Borghesi, M. Passoni, Ion acceleration by superintense laserplasma interaction, Rev. Mod. Physics, 85, 751 (2013)
- H. Daido, M. Nishiuchi, and A. S. Pirozhkov, Review of laser-driven ion sources and their applications, Rep. Prog. Phys. 75, 056401 (2012)
- M.Borghesi, J.Fuchs, S.V. Bulanov, A.J.Mackinnon, P.Patel. M.Roth, Fast ion generation by high-intensity laser irradiation of solid targets and applications, Fusion Science and Technology, 49, 412 (2006)

Laser-plasma THERMAL ion acceleration schemes

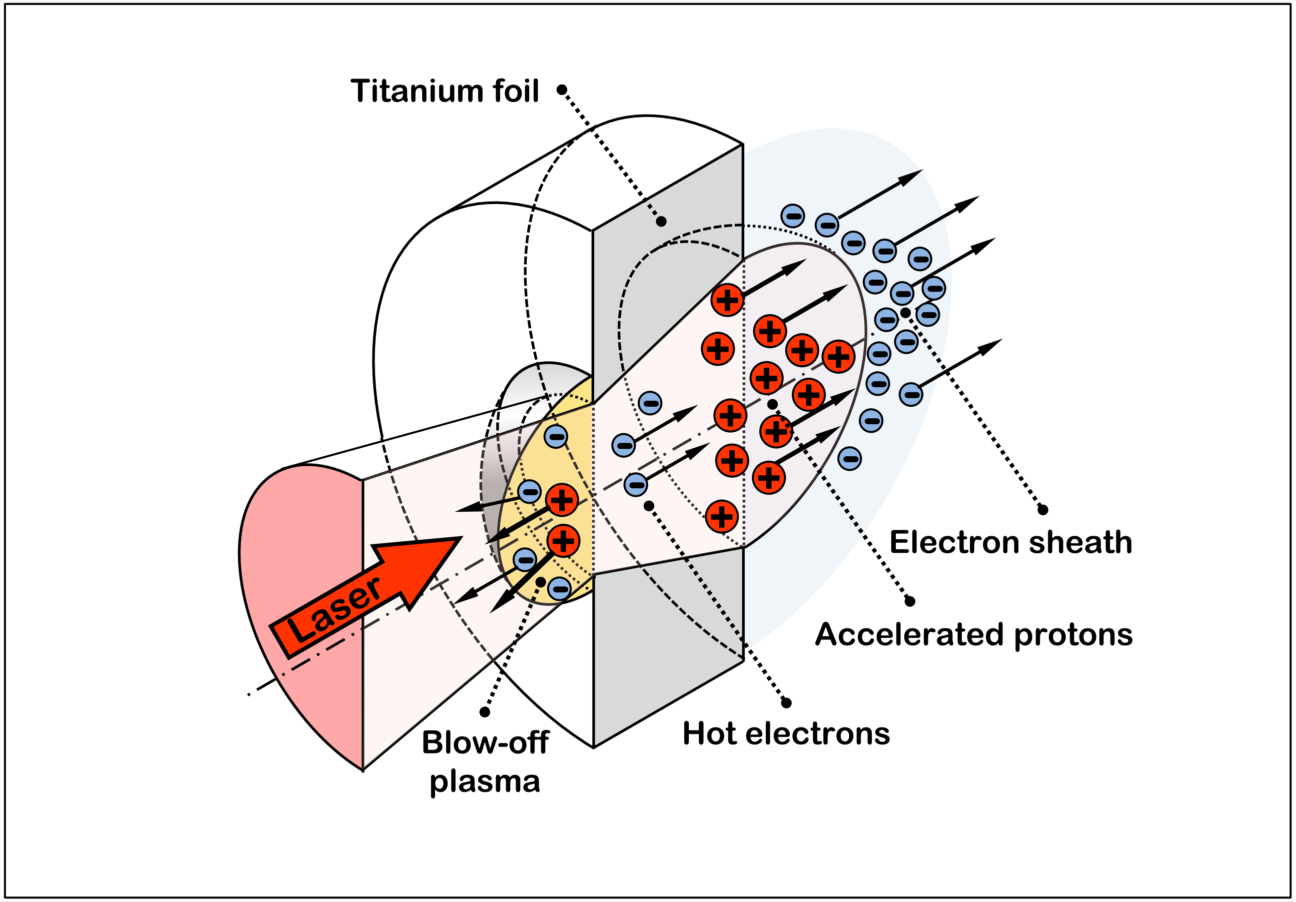
Thermally-driven Acceleration structures

- Target Normal Sheath Acceleration (TNSA)
  → Laser interacting with a metal foil - stopped at the front surface
  → ponderomotively drives front surface e^-
  → transported to rear surface - sheath of hot e^-
  → e^- thermal pressure drives sheath expansion
  → lighter ions are dragged along at high velocity expansion

- Break-Out Afterburner (BOA)
  → Laser penetrates the metal foil (e^- heating & relativistic effects)
  → direct laser heating – of sheath e^-
  → higher speed of sheath expansion

- Collision-less Electrostatic Shock Acceleration (CESA)
  → heating of electrons by the laser (commonly in gas)
  → electron-ion double layer may be created under right conditions
  → double layer propagates freely driven by the thermal pressure
  → plasma ions are reflected off the double layer potential

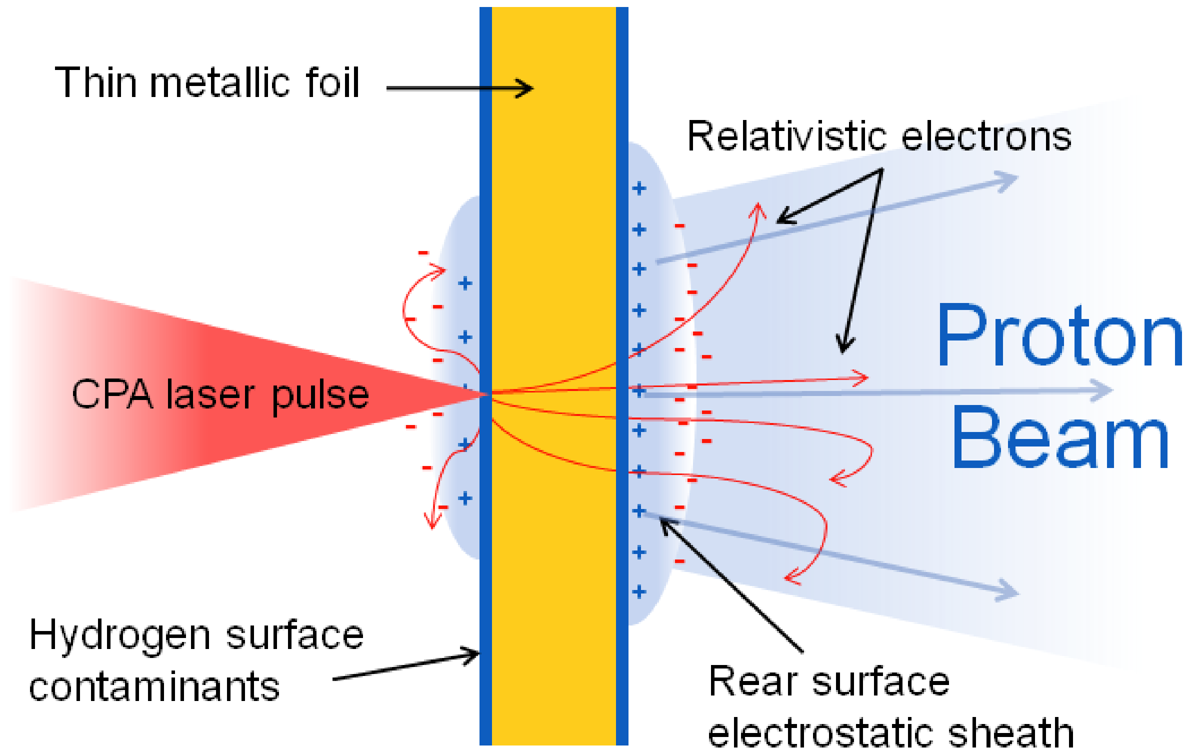
Sheath laser acceleration of protons



Laser pulse is focused on a thin metal foil that creates plasma

The plasma electrons quickly become relativistically hot and leave the foil, creating a sheath of charge, which then pulls out the ions and protons from the plasma

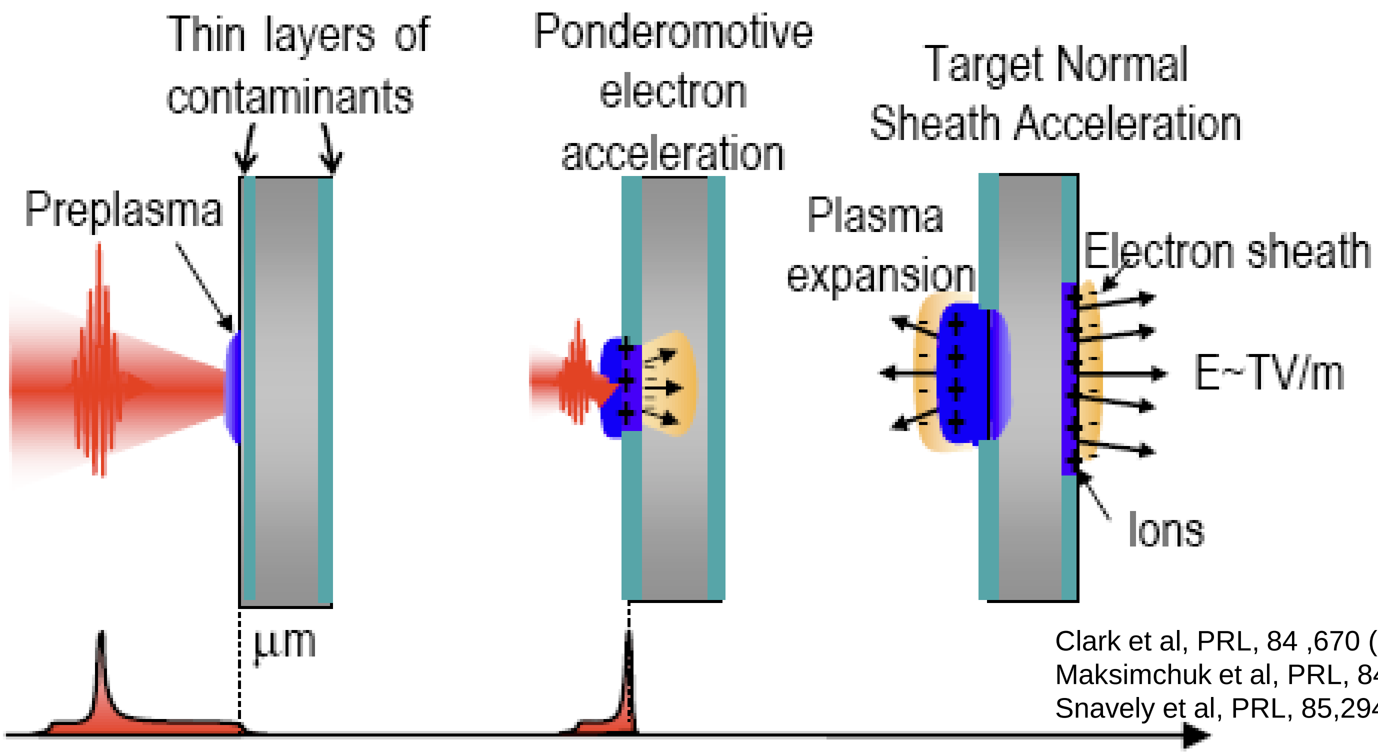
TNSA – importance of surface quality



Hydrogen surface contaminants on the foil surface are most readily accelerated in the sheath field set up at the plasma vacuum boundaries

K. Markey, CLF

TNSA – and laser pulse profile



Clark et al, PRL, 84 ,670 (2000)
Maksimchuk et al, PRL, 84, 4108 (2000)
Snavely et al, PRL, 85,2945 (2000)

Note that pre-plasma forms much in advance of main laser pulse arriving

Target Normal Sheath Acceleration (TNSA)

Freely expanding thermal plasma (isothermal)

$$n(x,t) = n_0 \exp\left(-\frac{x}{c_s t}\right)$$

Sound speed in plasma (ion vibration phase velocity)

$$c_s = \sqrt{\frac{T_e}{M}}$$

Freely expanding thermal electrons (non-isothermal)

$$\tau = \omega_{pi} t / \sqrt{2e}$$

$$v_{\text{front}} \simeq 2 c_s \ln(\tau + \sqrt{\tau^2 + 1})$$

DOI: 10.1103/PhysRevLett.90.185002

Ion energy accelerated by expanding thermal electrons sheath

$$E_m^{\text{PEM}} = 2 q_i k_B T_e [\ln(\tau + \sqrt{\tau^2 + 1})]^2$$

DOI: 10.1103/PhysRevLett.97.045005

First experiments

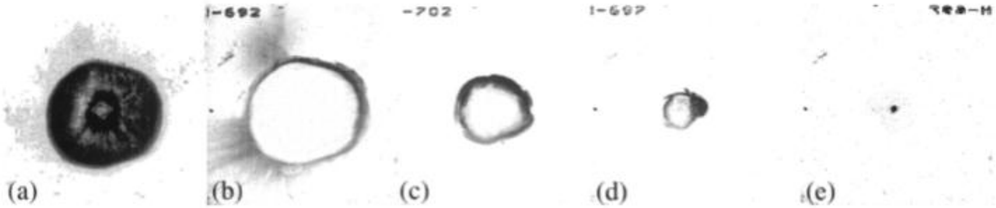


FIG. 1. Ring structure observed on RCF/CR39 "sandwich" track detectors: (a) radiochromic film (front surface); (b) tracks on CR39 from 3 MeV protons; (c) 8.9 MeV, (d) 11.6 MeV, (e) 17.6 MeV protons (track detectors were 5 cm × 5 cm × 0.75 mm thick).

Clark, E.L. et al., 2000. Measurements of energetic proton transport through magnetized plasma from intense laser interactions with solids. Physical Review Letters, 84, p.670.

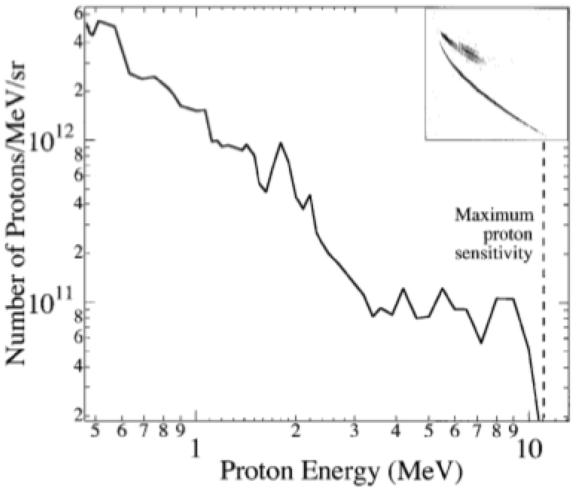


FIG. 3. Proton spectrum indicating multiple peaks and a flattening of the spectrum at ~4 MeV. Data from the Thomson parabola is inset.

Clark, E.L. et al., 2000. Energetic heavy-Ion and proton generation from ultraintense laser-plasma interactions with solids. Physical Review Letters, 85(8), p.1654.

Snavely, R.A. et al., 2000. Intense high-energy proton beams from Petawatt-laser irradiation of solids. Physical Review Letters, 85(14), p.2945.

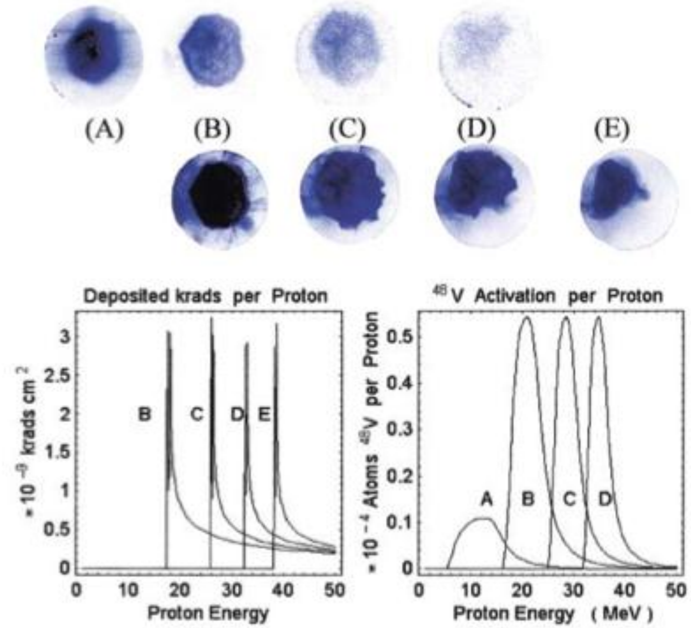
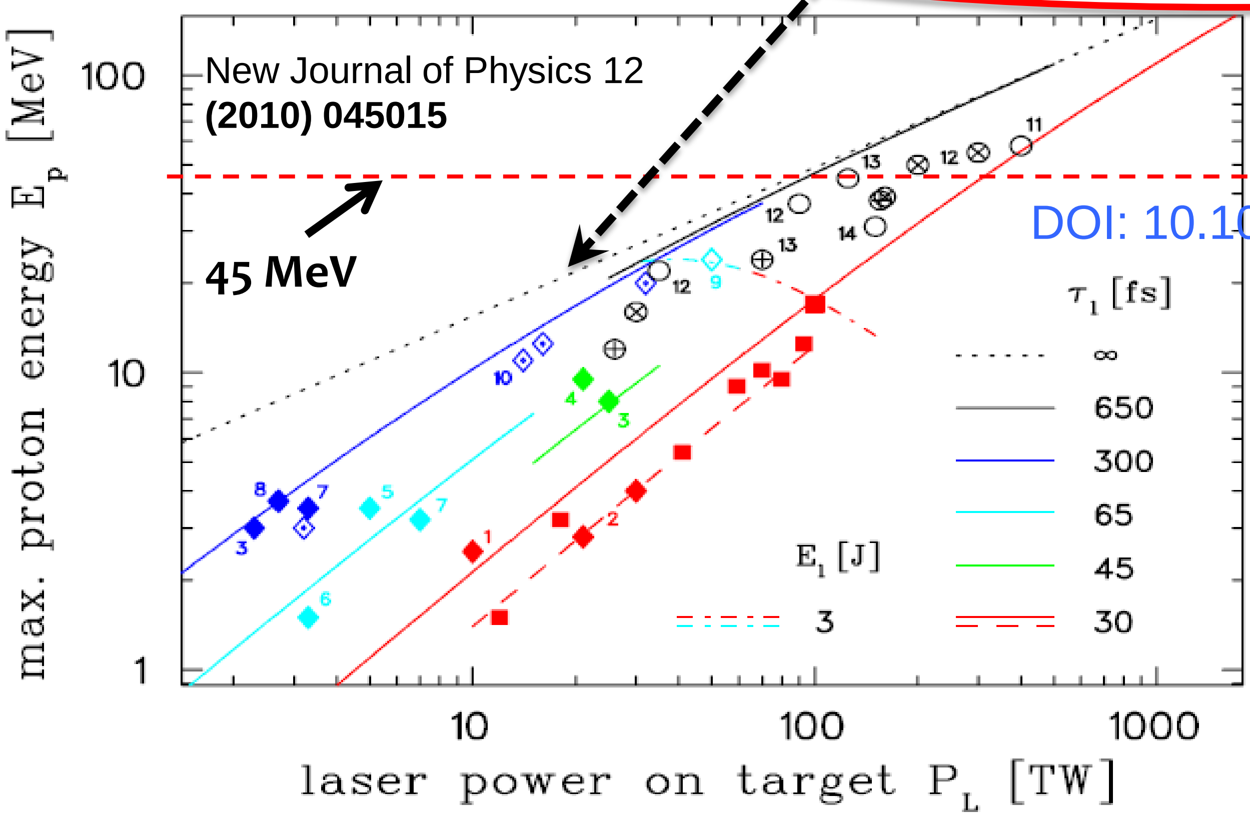


FIG. 2 (color). Data for a normal incidence 445 J shot on 100 μm CH from the Ti nuclear activation and RC film detector described later in the text: Ti foil autoradiographs (top row) and RC film images (middle row). The plots show Monte Carlo modeling of (below left) the RC film detector response in krads cm^2 per proton normally incident in the film layers; the nuclear activation response (below right) of the Ti layers to protons through the successive filter layers of the detector.

Target Normal Sheath Acceleration (TNSA)

Schreiber, J., et. al., Analytical model for ion acceleration by high-intensity laser pulses, Phys. Rev. Lett. 97, 045005 (2006). doi:10.1103/PhysRevLett.97.045005

$$E_m^{PEM} = 2q_i k_B T_e[\ln(\tau + \sqrt{\tau^2 + 1})]^2$$



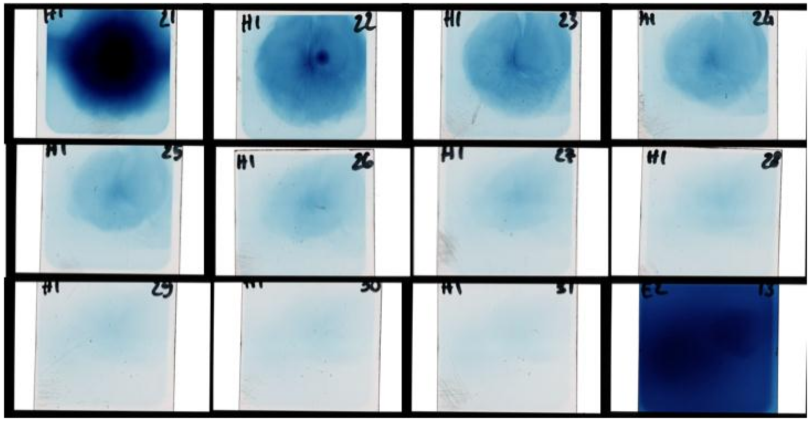
DOI: 10.1088/1367-2630/12/4/045015

Zeil, K., et. al. The scaling of proton energies in ultrashort pulse laser plasma acceleration, New Journal of Physics **12**, 16 (2010). doi:10.1088/1367-2630/12/4/045015

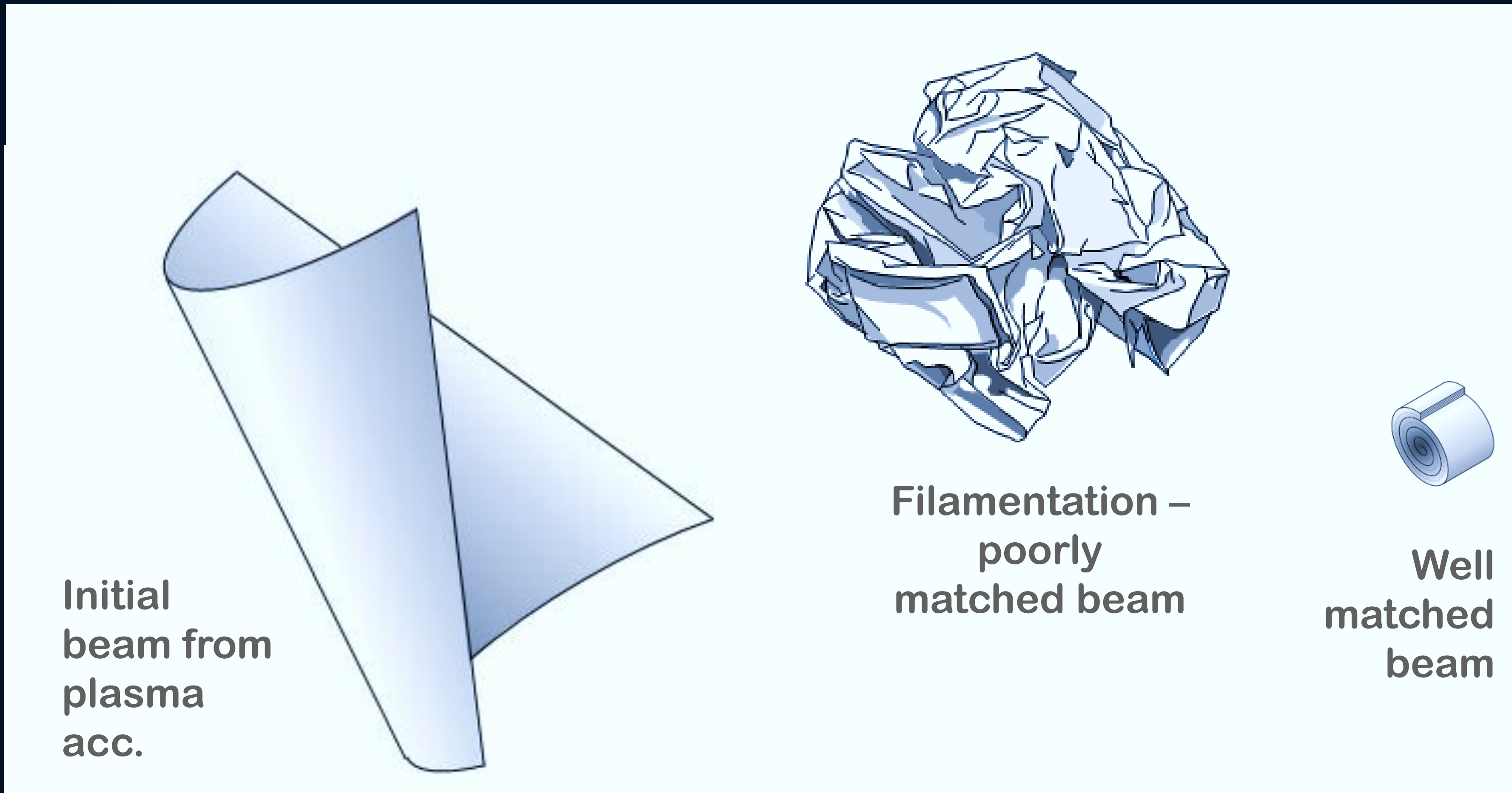
Beam property from TNSA

- **Beam emittance:**
  - **Very large divergence ~ 10deg**
  - **Small emitting size formally show low emittance**
    - **emittance < 0.01 π mm-mrad (0.004 mm-mrad - Cowan, PRL 2004)**
  - **However, this low emittance may quickly filament and increase if not captured appropriately**
- **High brightness: 10^{11} –10^{13} protons/ions per shot (> 3 MeV)**
- **High current: kA range**
- **Very compact: E~1-10 TV/m (acceleration lengths: ~ μm)**
- **But wide spectrum and not many p at high E edge**

Ion beam from TARANIS facility, QUB
E ~10 J on target in 10 μm spot
Intensity: ~10^{19} W/cm2, duration : 500 fs
Target: Al foil 10um thickness



Challenge of low-size, large divergence beams



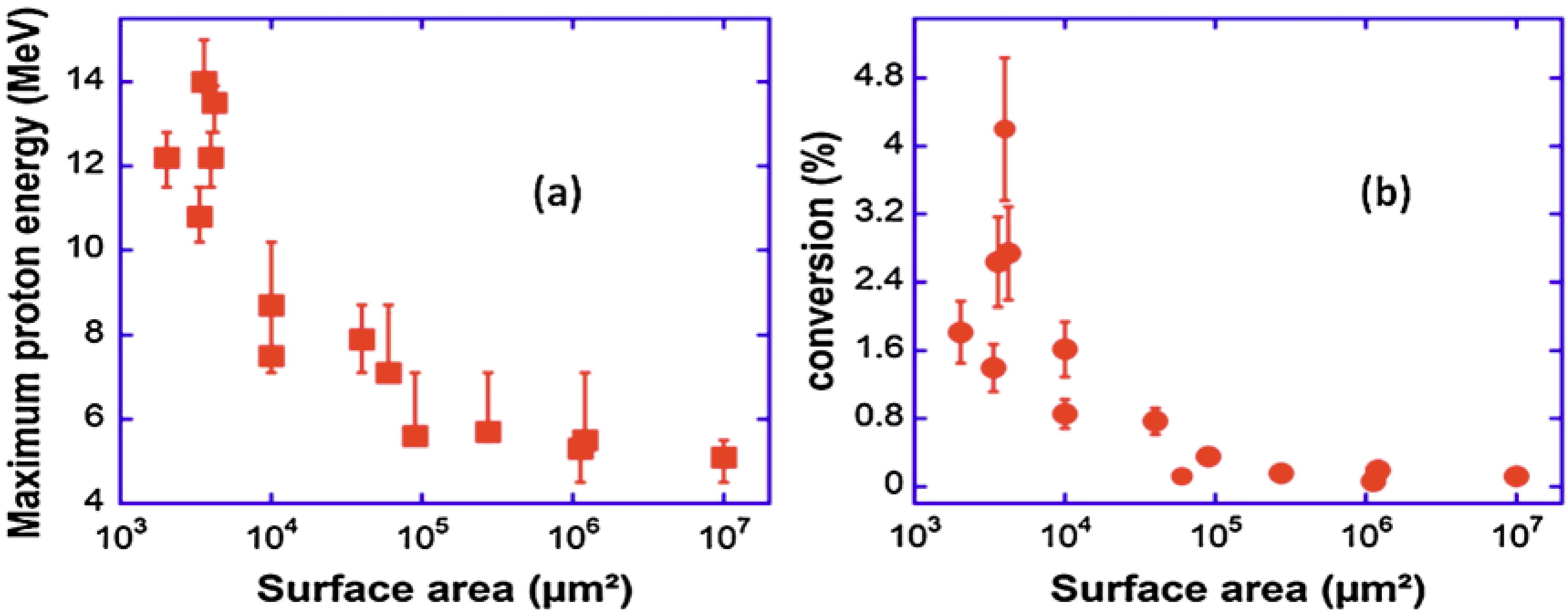
Can we apply our inventiveness to figure out how to capture, match and use the plasma-accelerated beam?

TNSA- further optimization

- **Brute force:**
  - **Increase intensity**
- **More optimal:**
  - **Enhance E coupling to electrons**
  - **Increase electron density**

- **Possible approaches:**
  - **Reduction of foil thickness**
  - **Reduced mass targets**
  - **Enhanced coupling by target structuring**
  - **Enhanced electron acceleration**
    - **matching of plasma profile**
    - **grazing incidence on conical targets**

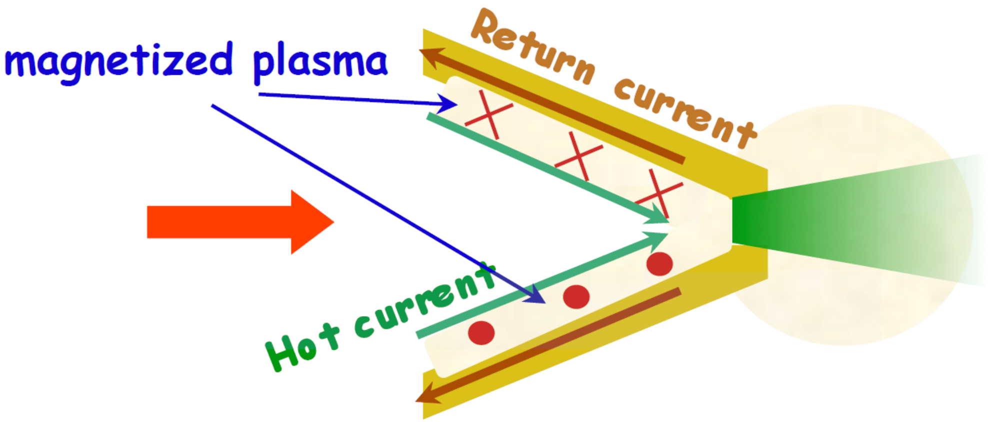
TNSA- reduced mass target

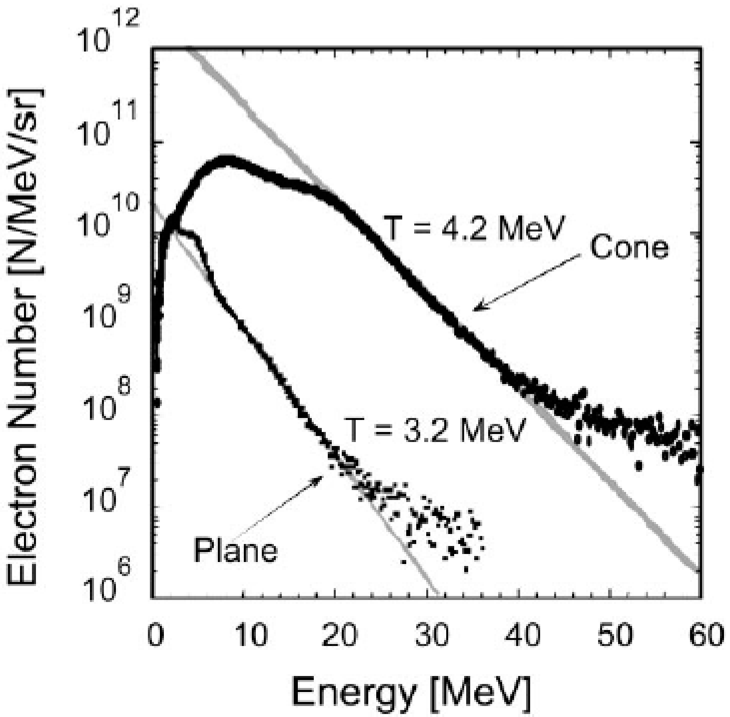


- **Reduced mass target resulted in increase of proton energy and increased efficiency**
  - **LULI, 100 TW, I~ 10^{19} W/cm^2**
  - **Targets used were as small as 20 μm x 20 μm**

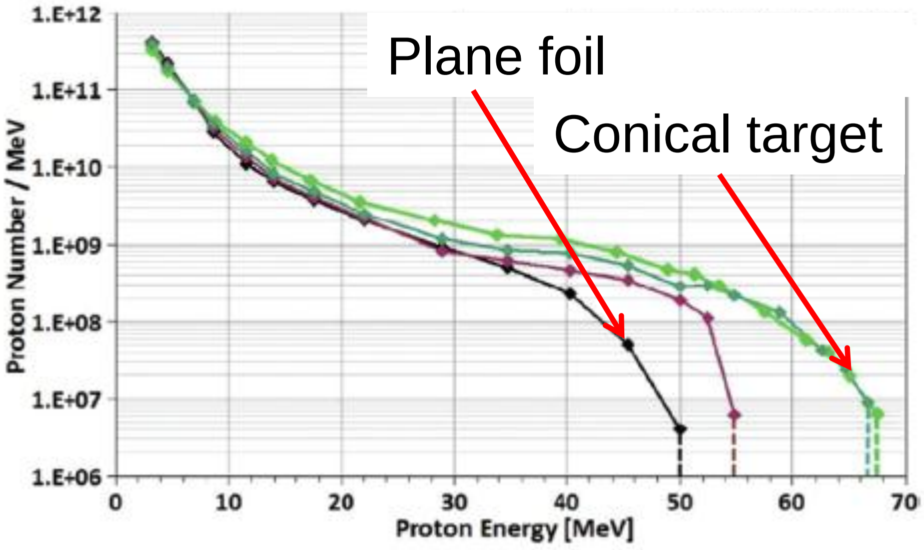
S. Buffechoux et al, Phys Rev Lett.,105, 015005 (2010)
O. Tresca et al PPCF, 53, 105008 (2011)

TNSA- conical target



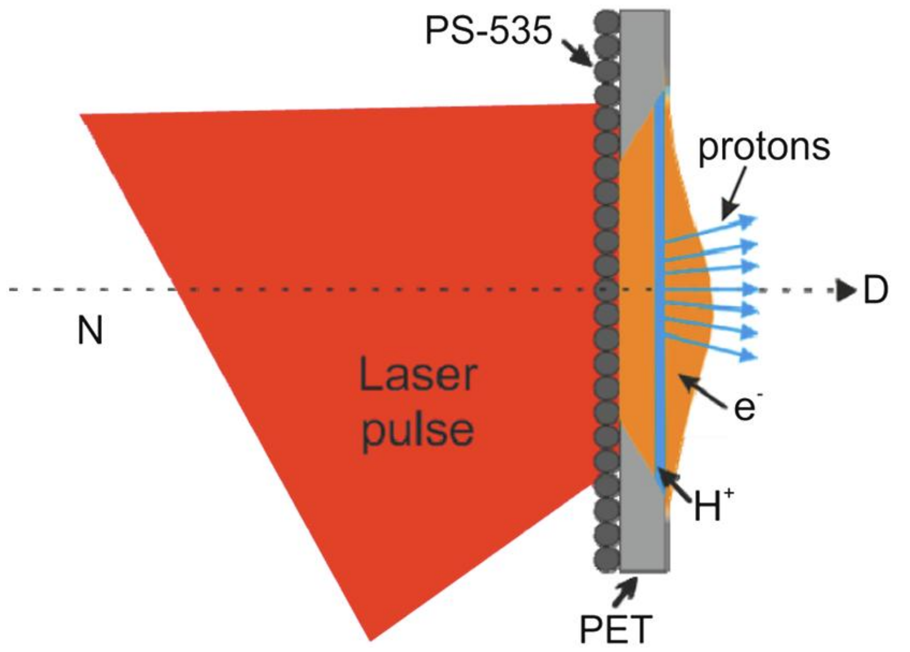


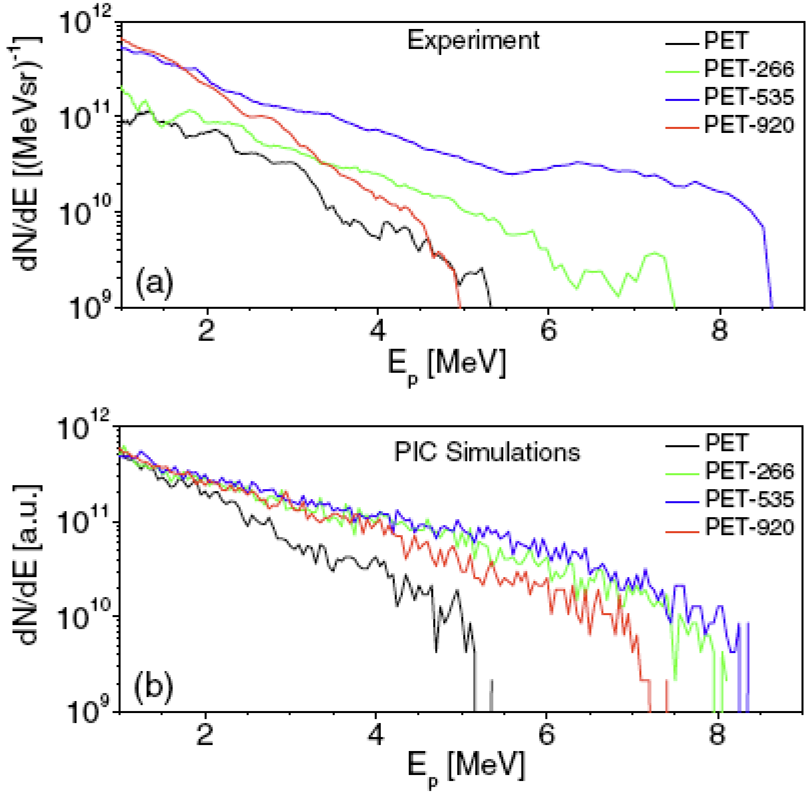
- **Enhanced acceleration**
  - **More efficient coupling into hot electrons due to interaction with walls (direct electron acceleration)**
  - **Trident laser, 80 J, 700 fs**



S. Gaillard et al, Phys. Plasmas, 18, 056710 (2011)
T.Kluge et al, NJP, 14, 23038 (2012)

TNSA- structured targets





- **Improved acceleration**
  - **Best results with spheres of ø 535 nm (optimum absorption)**
  - **I ~ 5 10^{19} W/cm^2, 30 fs, 2 µm f.s.; High Contrast: 5 10^{11} @ -10ps**

D. Margarone et al, PRL,109, 234801 (2012)

Laser-plasma THERMAL ion acceleration schemes

Thermally-driven Acceleration structures

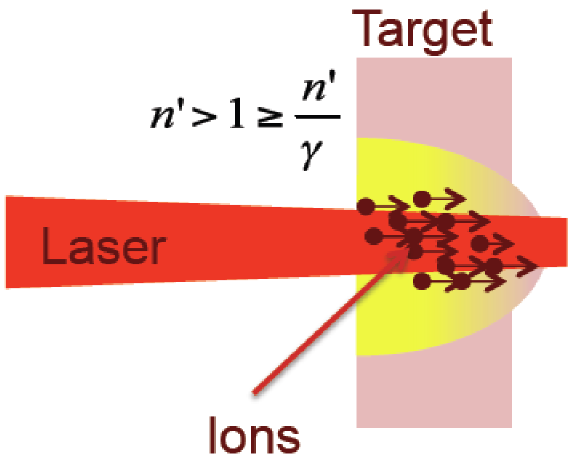
- Target Normal Sheath Acceleration (TNSA)
  → Laser interacting with a metal foil - stopped at the front surface
  → ponderomotively drives front surface e^-
  → transported to rear surface - sheath of hot e^-
  → e^- thermal pressure drives sheath expansion
  → lighter ions are dragged along at high velocity expansion

- Break-Out Afterburner (BOA)
  → Laser penetrates the metal foil (e^- heating & relativistic effects)
  → direct laser heating – of sheath e^-
  → higher speed of sheath expansion

- Collision-less Electrostatic Shock Acceleration (CESA)
  → heating of electrons by the laser (commonly in gas)
  → electron-ion double layer may be created under right conditions
  → double layer propagates freely driven by the thermal pressure
  → plasma ions are reflected off the double layer potential

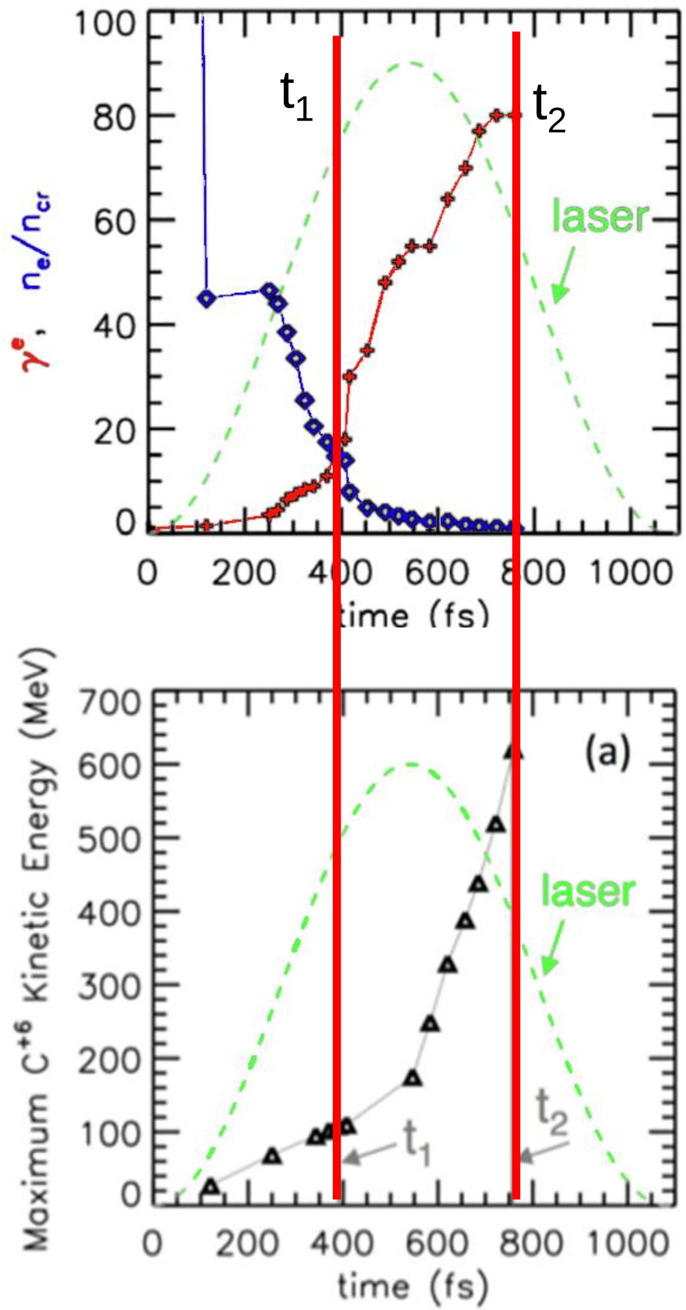
Break-Out Afterburner – relativistic transparency

In BOA, an initially solid-density target become **relativistically transparent**, resulting in enhanced ion acceleration



t_1: relativistic transparent $n' > 1 \geq n'/\gamma$

t_2: classically underdense $n' < 1$

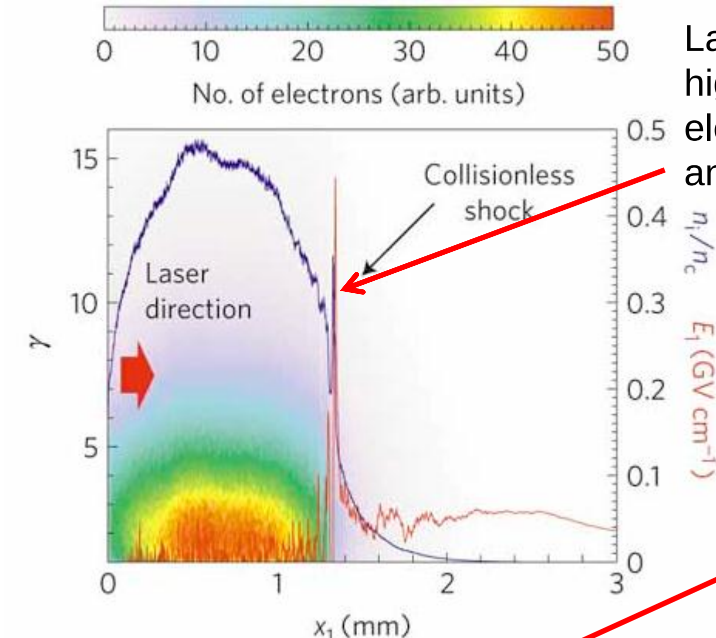


Yin, et al., Laser and Particle Beams 24 (2006), 1–8 Albright, et al., Phys. Plasmas 14, 094502 (2007)

Yin, et al., Phys. Plasmas 14, 056706, (2007) Yin, et al., Phys. Rev. Lett. 107, 045003 (2011)

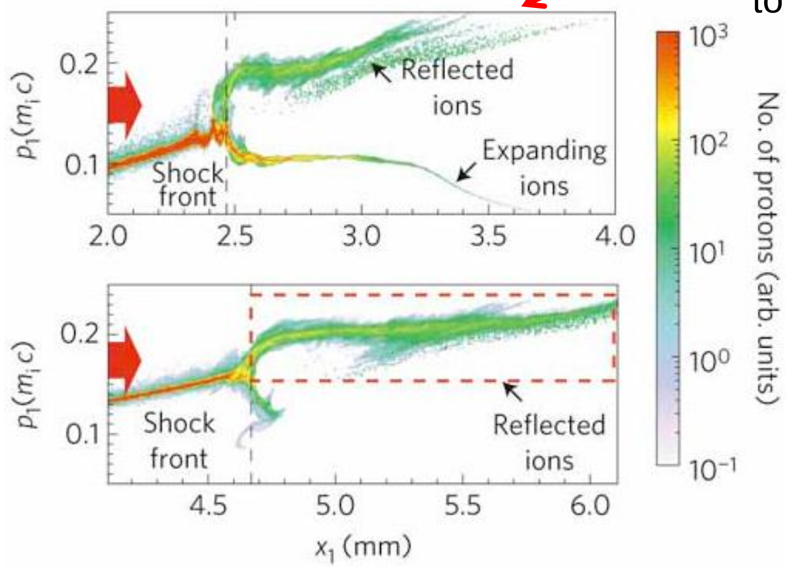
Yin, et al., Phys. Plasmas 18, 063103 (2011)

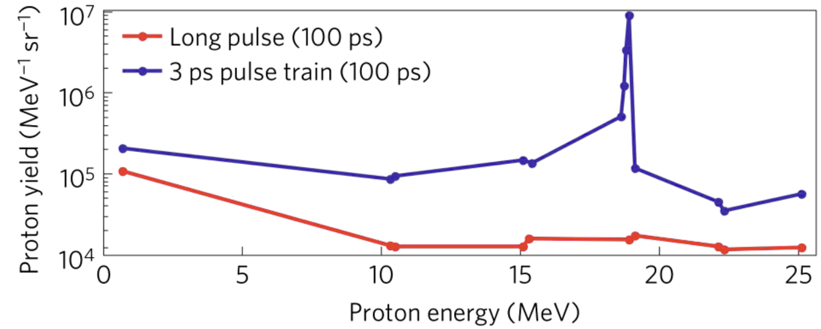
Shock acceleration

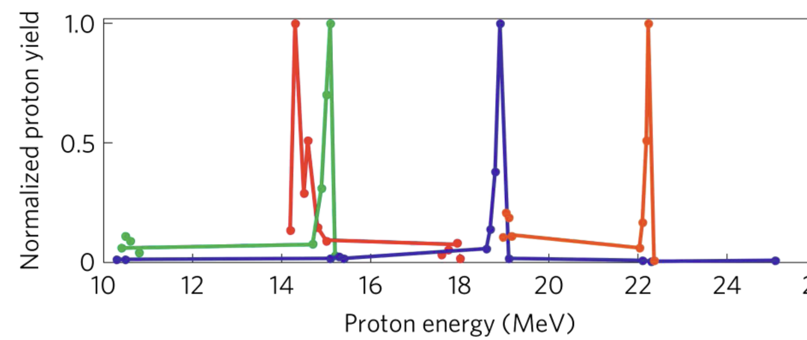


Laser piston launches high Mach number electrostatic shock into an overdense plasma

The propagating electrostatic structure reflects ions in the target to v ~2 v_s







Monochromatic proton peaks observed in experiments using overdense gas jet with $C0_2$ laser @ 10^{16} W/cm^2 (UCLA)

L.Silva et al, PRL 92, 015002 (2004)
D.Haberberger et al, Nature Phys., 8, 95 (2012)

Laser-plasma COHERENT ion acceleration schemes

Coherently-driven Acceleration structures

- Radiation Pressure Acceleration: Light-sail (LS-RPA)
  - → Laser stopped at the front surface of a metal foil
  - → photon momentum reversed @ reflection point
  - → photon momentum flux conversation – radiation pressure
  - → Radiation pressure drives part of the foil forward – light-sail

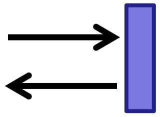
- Radiation Pressure Acceleration: Hole-boring (HB-RPA)
  - → extended plasma instead of a thin foil
  - → only laser irradiated spot / region – driven by radiation pressure
  - → hole is bored in the plasma

- Relativistically Induced Transparency Acceleration
  - → radiation pressure speed dictated by plasma-ion mass
  - → laser drives an electron perturbation – not dragging ions
  - → speed of e^- perturbation : relativistic effects induced
  - → plasma ions are reflected off the e^- perturbation potential

Radiation pressure acceleration

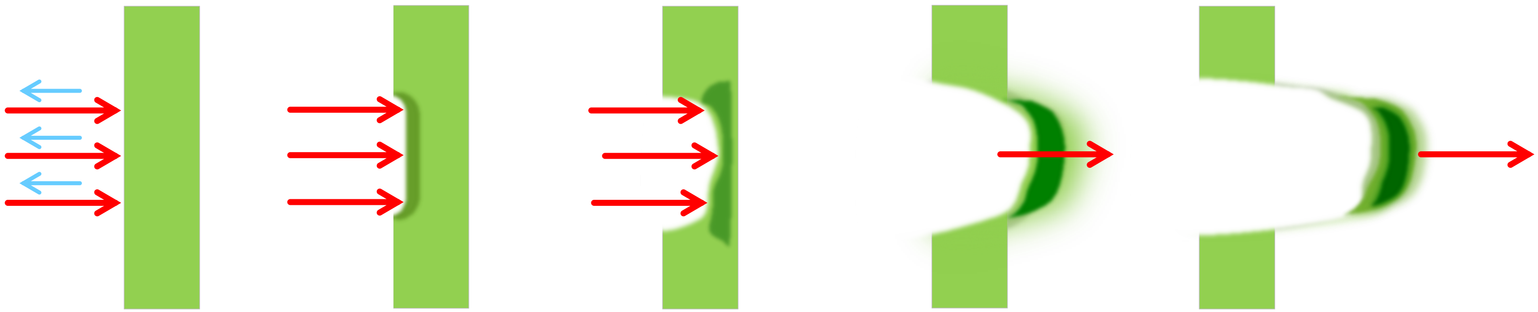
Radiation pressure due to light reflection from a mirror:

$$p_R = \frac{2I_L}{c}$$



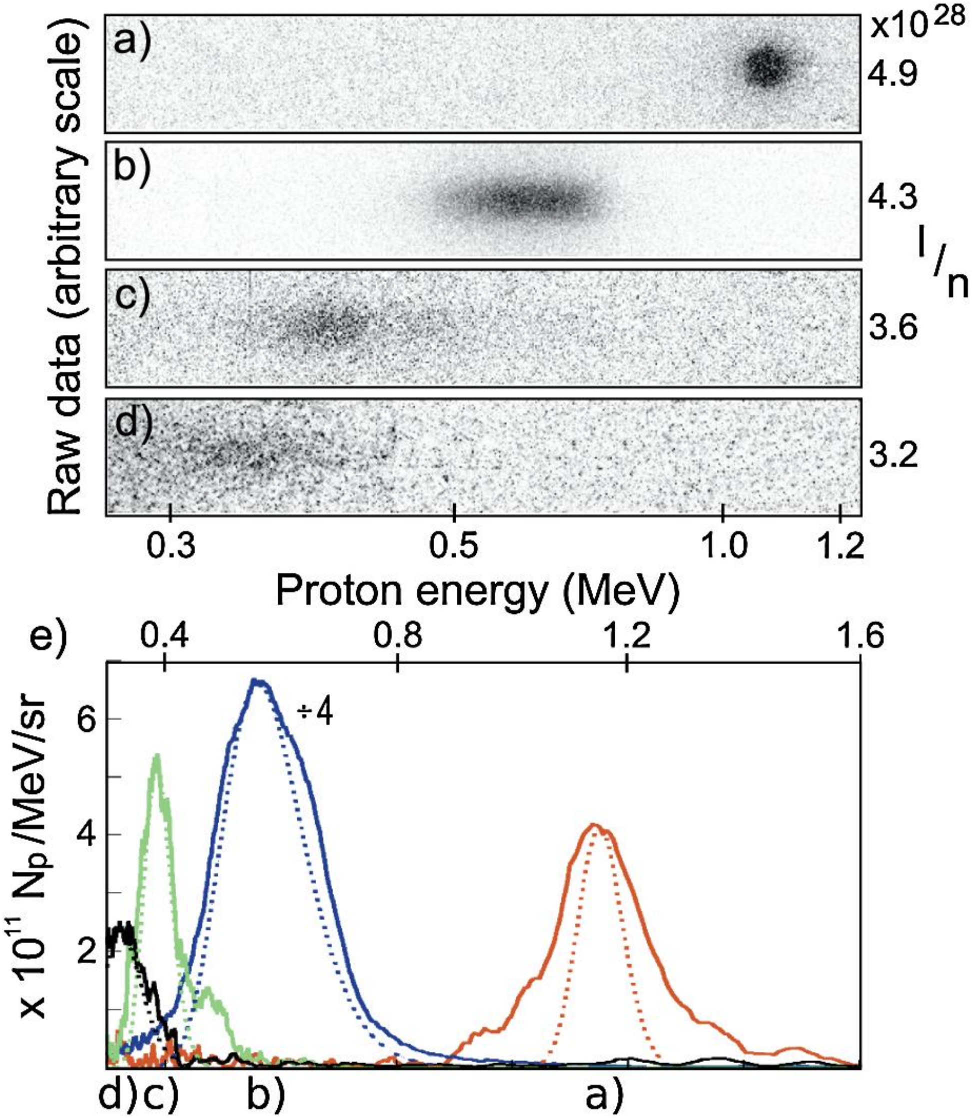
$P_L = 60$ Gbar

$@\,10^{20}\,\mathrm{Wcm^{-2}}$



Hole-boring mechanism of radiation pressure acceleration of protons

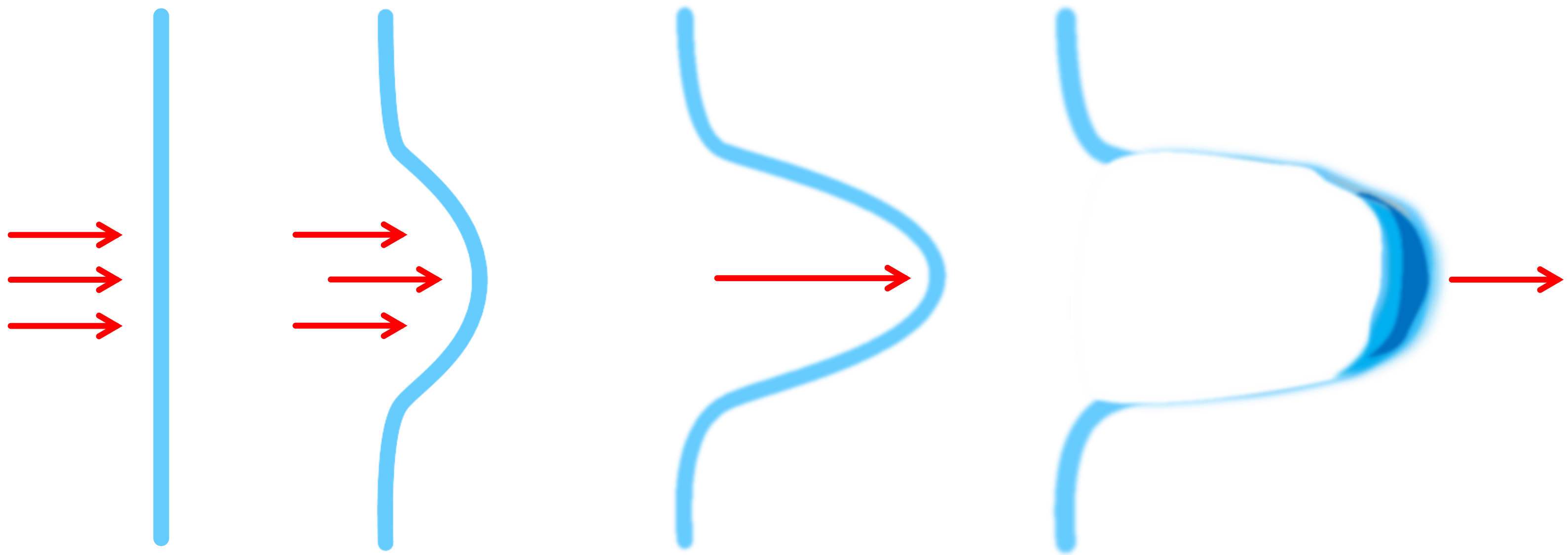
RPA Hole Boring



- **Proton beam**
  - Near monochromatic!
- **Laser:**
  - CO_2 laser, 0.5 TW, 5 ps, I ~ 5 10^{15} W/cm^2
  - Circularly polarized
- **Target:**
  - Hydrogen gas jet , n ~ 10^{19}-10^{20} cm^{-3}
- **Imperial College-BNL**

C.A. Palmer et al, Phys. Rev. Lett, 106, 014801 (2011)

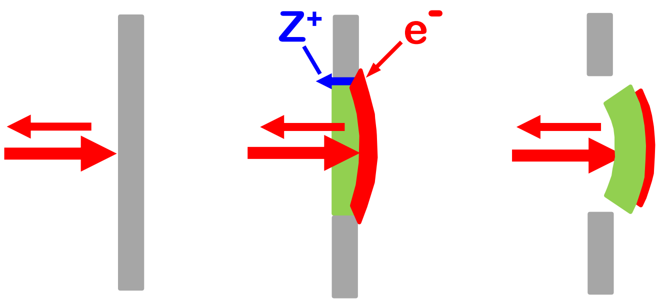
Light sail radiation pressure acceleration



The foil is so thin that it starts to accelerate immediately as a whole

Radiation Pressure on thin foils - Light Sail

- **Principle and features**
  - Cyclical re-acceleration of ions
  - Narrow-band spectrum
    - whole-foil acceleration
  - Fast scaling with intensity



- **Issues at present intensities**
  - Competition with TNSA
  - Electron heating cause foil damage
    - ultrathin foils are needed for moderate a_0

$$F_R = (1+R) A \frac{I_L}{c}$$

$$\Rightarrow v_i = \frac{(1+R)\tau}{m_i n_i d} \frac{I_L}{c} \propto I\tau\eta^{-1}$$

$$\eta = m_i n_i d$$

areal density

- **Improvements**
  - Use of circular polarization:
    - No JxB acceleration
    - No TNSA
    - No target heating
    - Quasi-static pressure drive

$$E_{ions} \sim (I\,\tau / \eta)^2$$

T.Esirkepov, et al. Phys. Rev. Lett., 92, 175003 (2004)
APL Robinson et al, NJP, 10, 013021 (2009)

Light Sail Acceleration – Simple model

Foil driven by light pressure:

$$F_R = (1+R) A \frac{I_L}{c}$$

- Acting on material mass *m,* and $m = m_i n_i A d$, where *d* is the thickness of the target, n_i is the ion density, and m_i is the ion mass.
- Hence,

$$F_R = (1+R) A \frac{I_L}{c} = m \frac{dv}{dt} = m_i n_i A d \frac{v_i}{t}$$

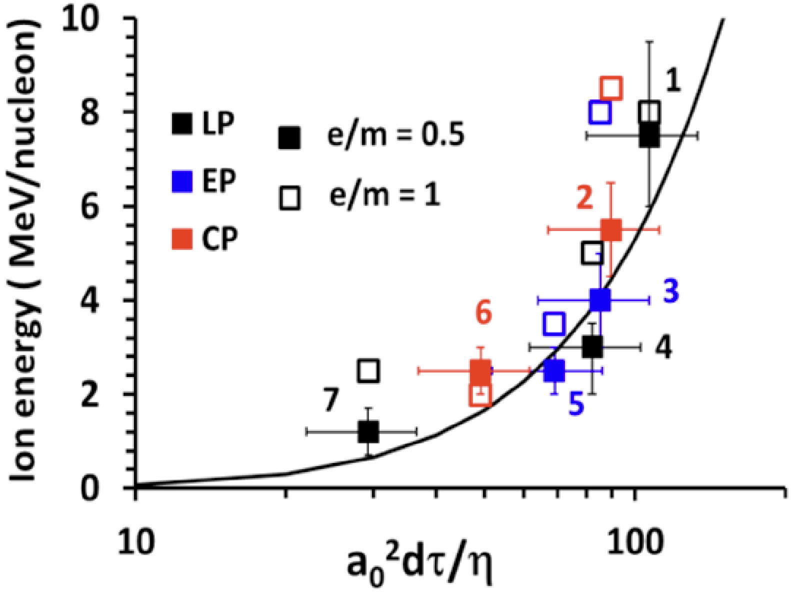
$$\rightarrow v_i = \frac{(1+R)\tau}{\rho d} \frac{I_L}{c}$$

- Energy scaling more favorable in light-sail stage, in non-relativistic case, **velocity gained is proportional to I_L**

RPA Light Sail – scaling

Energy of peak scales as

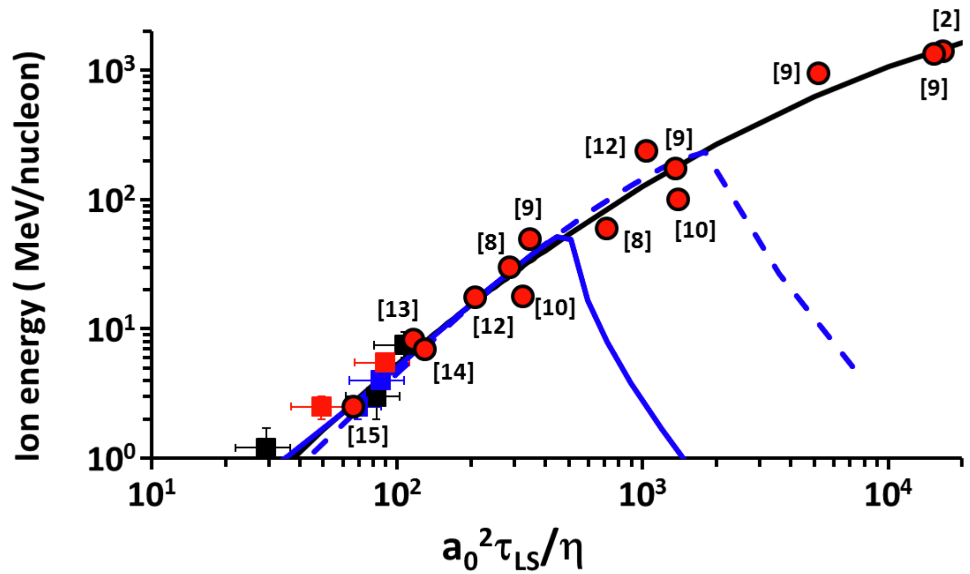
$$\left(I\tau/\eta\right)^2$$



A. Henig, Phys. Rev. Lett. 103, 245003 (2009)
S.Steinke et al, Phys. Rev. ST,16, 011303 (2013)
B. Aurand et al, NJP,15, 033031 (2013)

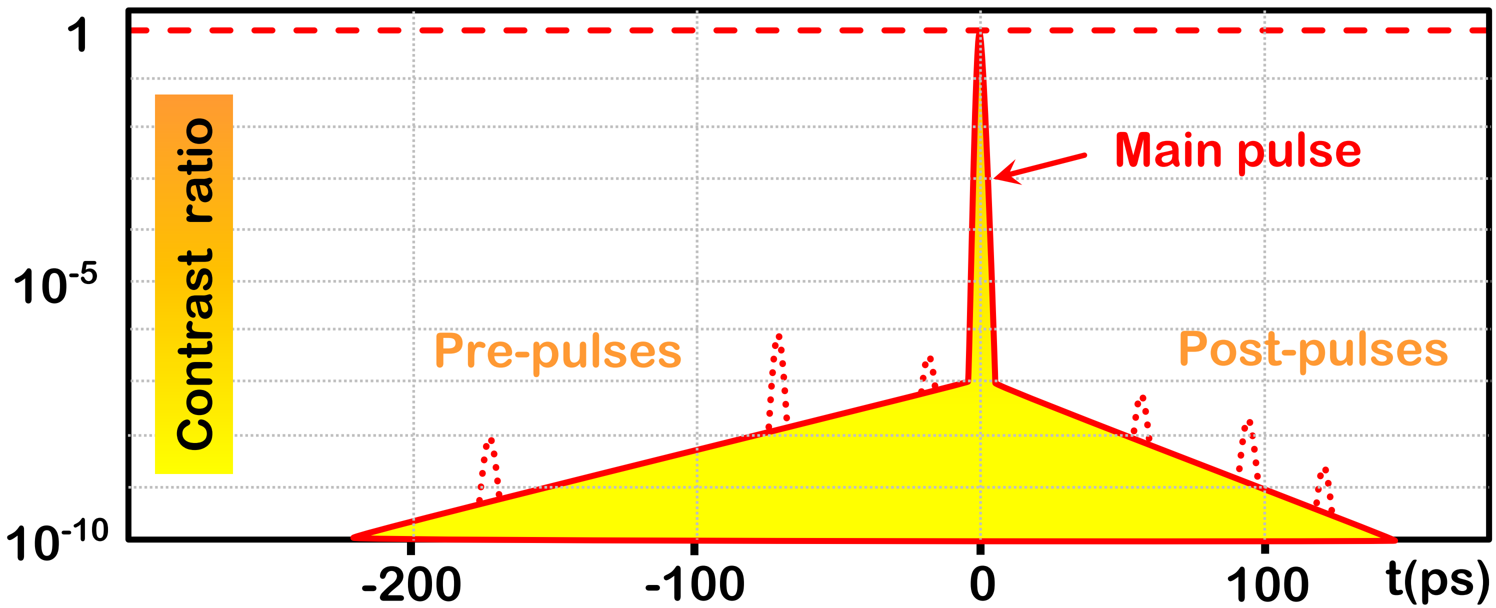
Scaling to 10PW systems

2D and 3D PIC results from multispecies simulations of stable RPA



S. Kar et al, Phys. Rev. Lett, 109, 185006 (2012)

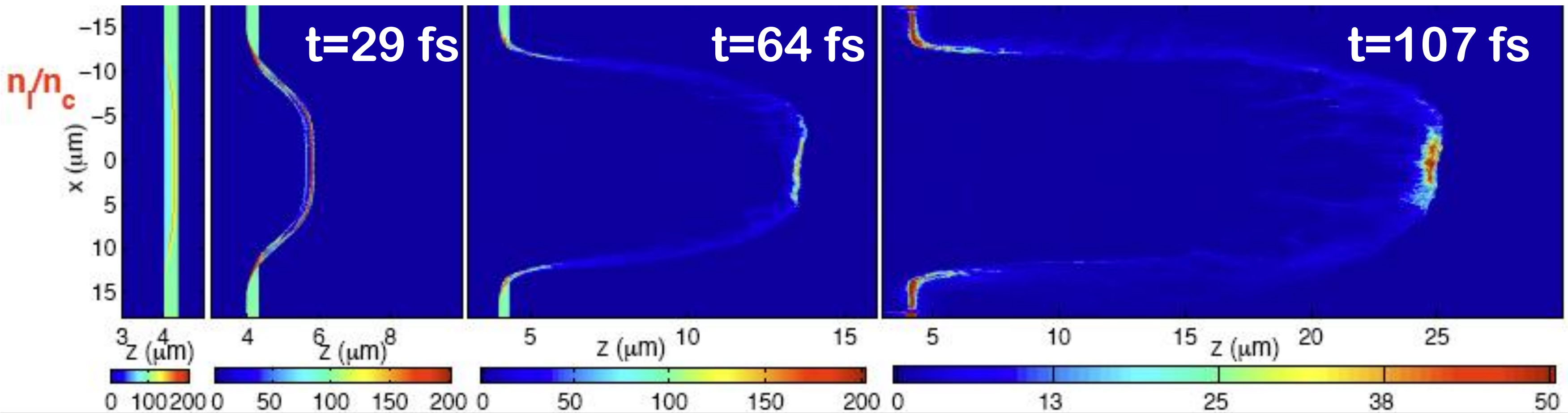
Recall shape of CPA-compressed pulse

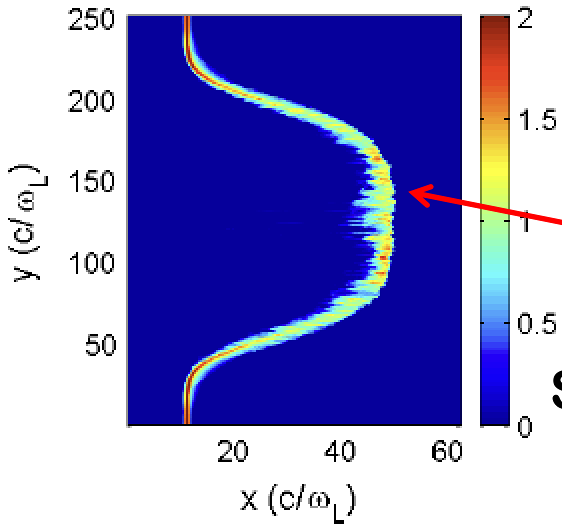


- **High contrast ratio is needed for proton plasma acceleration**
  - As pre-pulse can damage the thin foil before the main pulse arrive
  - In particular for light-sail regime

RPA Light Sail – prediction of GeV beams

Simulations predict GeV beams with 10 PW pulses at 10^{22} W/cm^2





Foil of n_0=100nc and λ_0=0.35 μm
Laser pulse at $I_0=6.3\times10^{22}$ W/cm^2

B. Qiao et al, Phys Rev Lett,102,145002 (2009)

Simulations also predict instability of the process

A.P.L Robinson et al., NJP (2009)

Limits on RPA accln. struc. velocity

RECAP
RPA driven ion velocity
(inversely on ion mass)

$$\text{Rad pressure} \Rightarrow P_L = (1+R)\frac{I_L}{c}$$

$$m_i\ n_i(A_t\ d_t)\ \Delta v_i = (1+R)\frac{I_L}{c}\ A_t\ \Delta\tau_L$$

$$\Delta v_i = \frac{(1+\mathbf{R})/\mathbf{n_i}}{\mathbf{m_i}\ d_t}\ \Delta\tau_\mathbf{L}\ \frac{I_L}{c}$$

3 Major LIMITS

Ion mass : $\Delta v_i \propto \frac{1}{\mathbf{m_i}}$

Target Transparency : $\Delta v_i \propto \mathbf{R/n_i}$

Shorter pulses @ higher I_L : $\Delta v_i \propto \Delta\tau_\mathbf{L}\ \mathbf{I_L}$

Control the Ion acceleration structure velocity

ion inertia dictates the laser-front speed in critical layer interactions

unperturbed density gradient

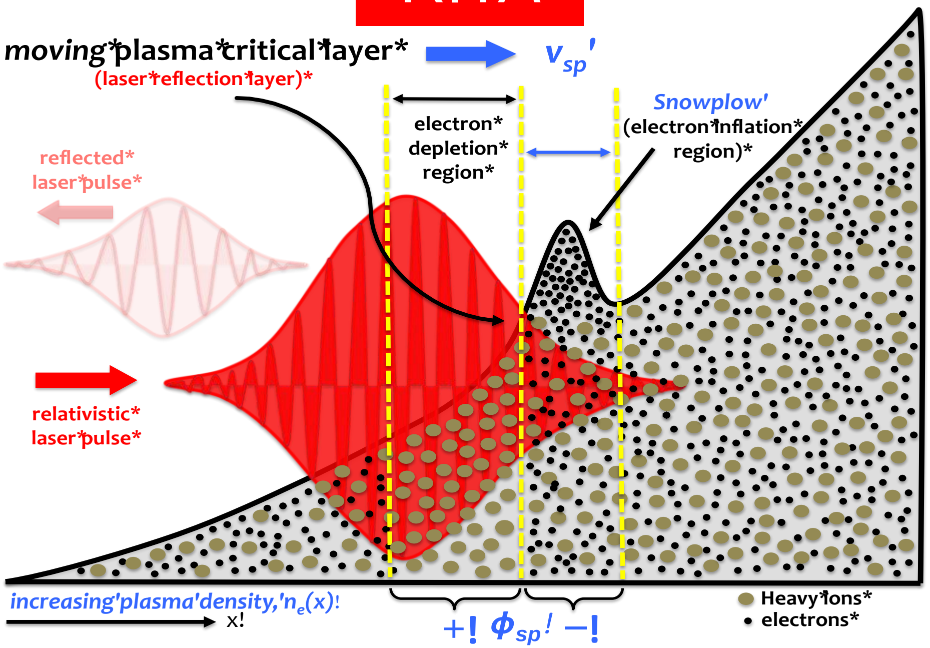
$$\omega_{pe}^2(x) = \frac{4\pi e^2}{m_e}\, n_e(x)$$

laser-driven relativistic e- quiver

$$\omega_{pe}^2(x,t) = \frac{4\pi e^2}{m_e}\,\frac{n_e(x)}{\gamma_\perp(x,t)}$$

$$\frac{\omega_{pe}^2(x)}{\sqrt{1+a^2(x,t)}} = \omega_0^2$$

RITA



laser front propagates purely by electron dynamics

DOI: 10.1103/PhysRevE.88.043105

Control Relativistically Induced Transparency

speed of the *induced transparency front*

Rising intensity and Rising density gradient

Simple 1D model → ignored second-order effects

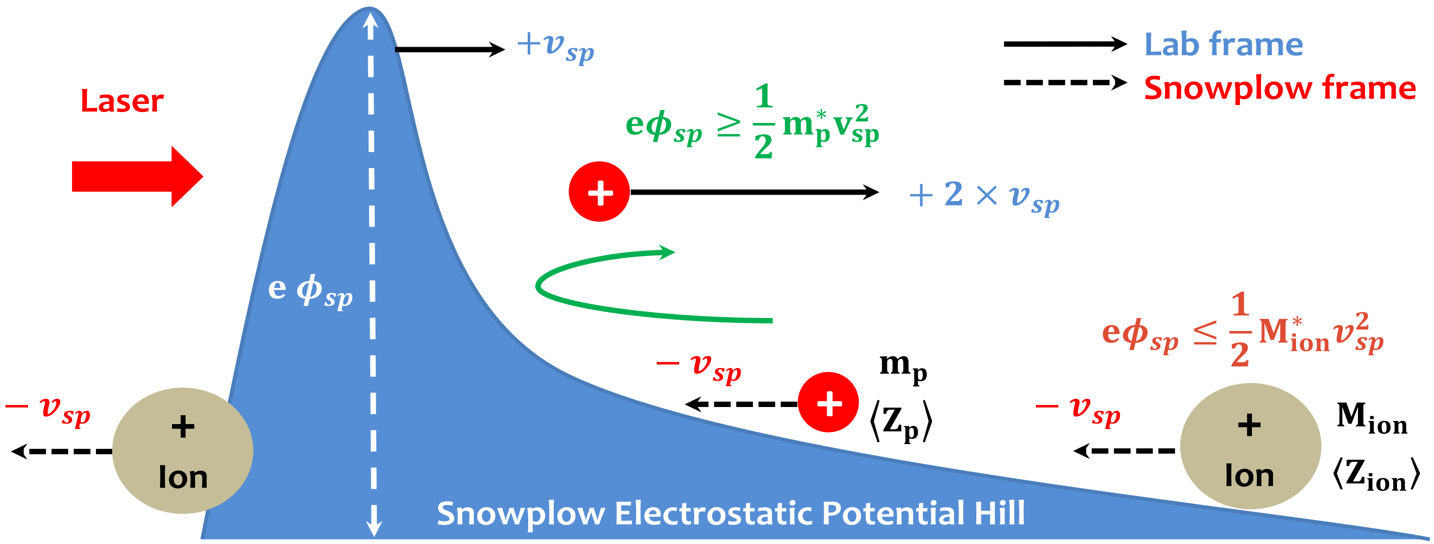
$$\frac{\omega_{pe}^2(x)}{\sqrt{1+a^2(x,t)}} = \omega_0^2$$

$$\frac{\delta x}{\delta t} = \frac{1}{2}\frac{\partial a^2(x,t)}{\partial t}\left(\frac{1+a^2(x,t)}{\omega_{pe}^2(x)}\frac{\partial \omega_{pe}^2(x)}{\partial x} - \frac{1}{2}\frac{\partial a^2(x,t)}{\partial x}\right)^{-1}$$

linear intensity-rise laser
linear density gradient

$$v_{sp}(t) \simeq \frac{\alpha a_0^2}{2\delta}\frac{1}{a(x,t)}c \simeq 0.5\left(\frac{\alpha}{\delta}\right)a_0 c$$

Snowplow Action – trapping & acceleration



Background ions - NOT significantly perturbed

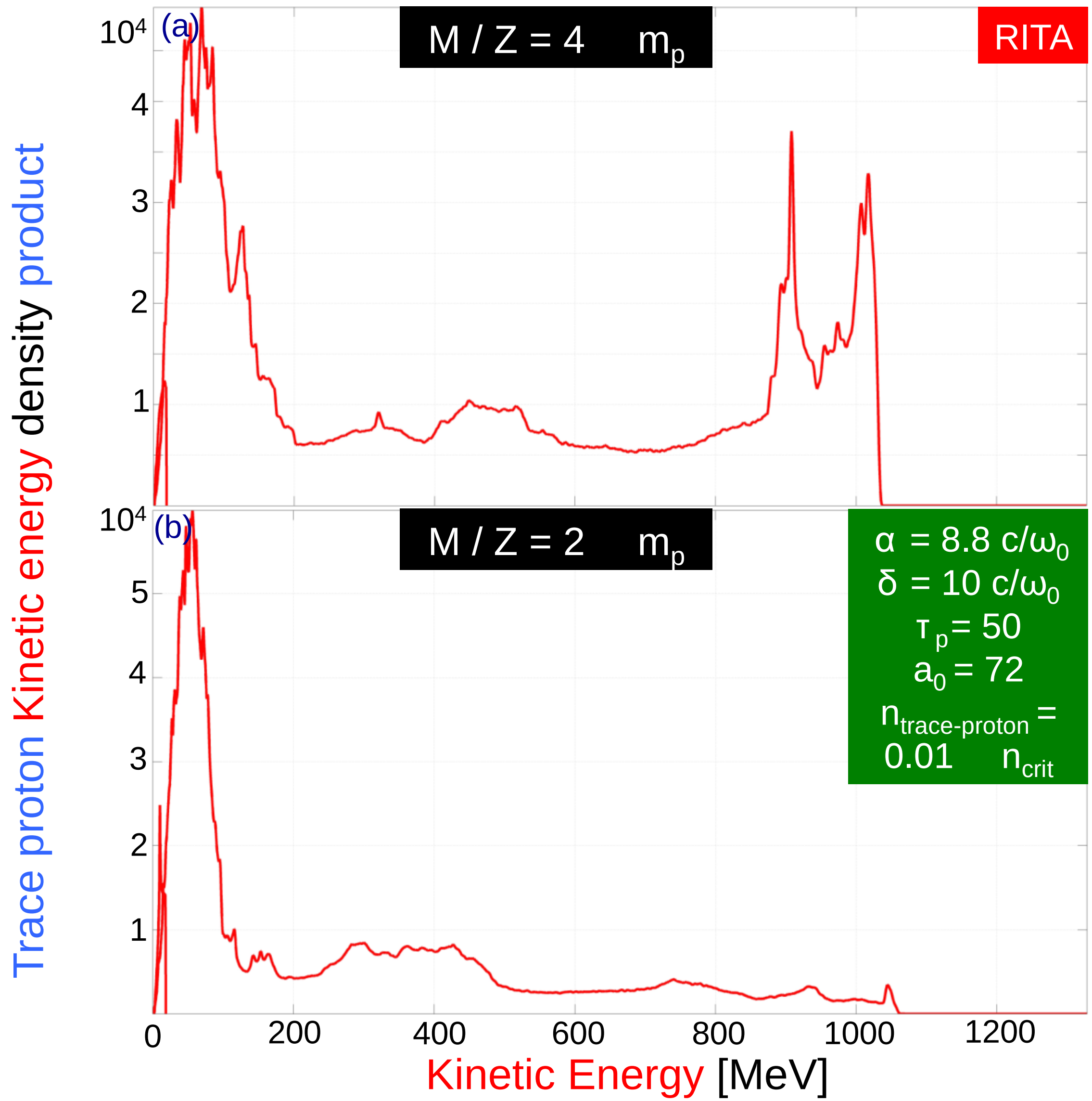
Threshold potential - $e\Phi_{sp} = (\gamma - 1) m_e c^2$

Kinetic energy - $\frac{1}{2} m_p [2 \times v_{sp}]^2$

Threshold intensity - $a_{th} \simeq \frac{1}{2\sqrt{2}} \frac{m_p^*}{m_e} \left(\frac{v_{sp}}{c} \right)^2$

Effect of heavy-ion motion

proton energy spectrum

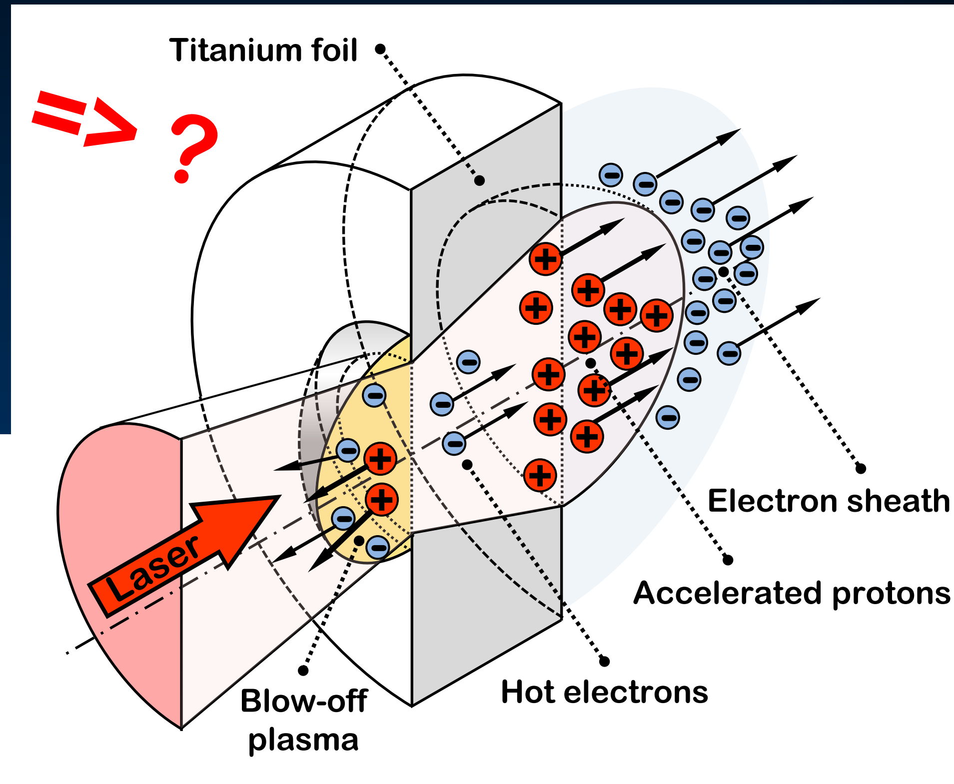


Summary of PIC scaling predictions to 200MeV

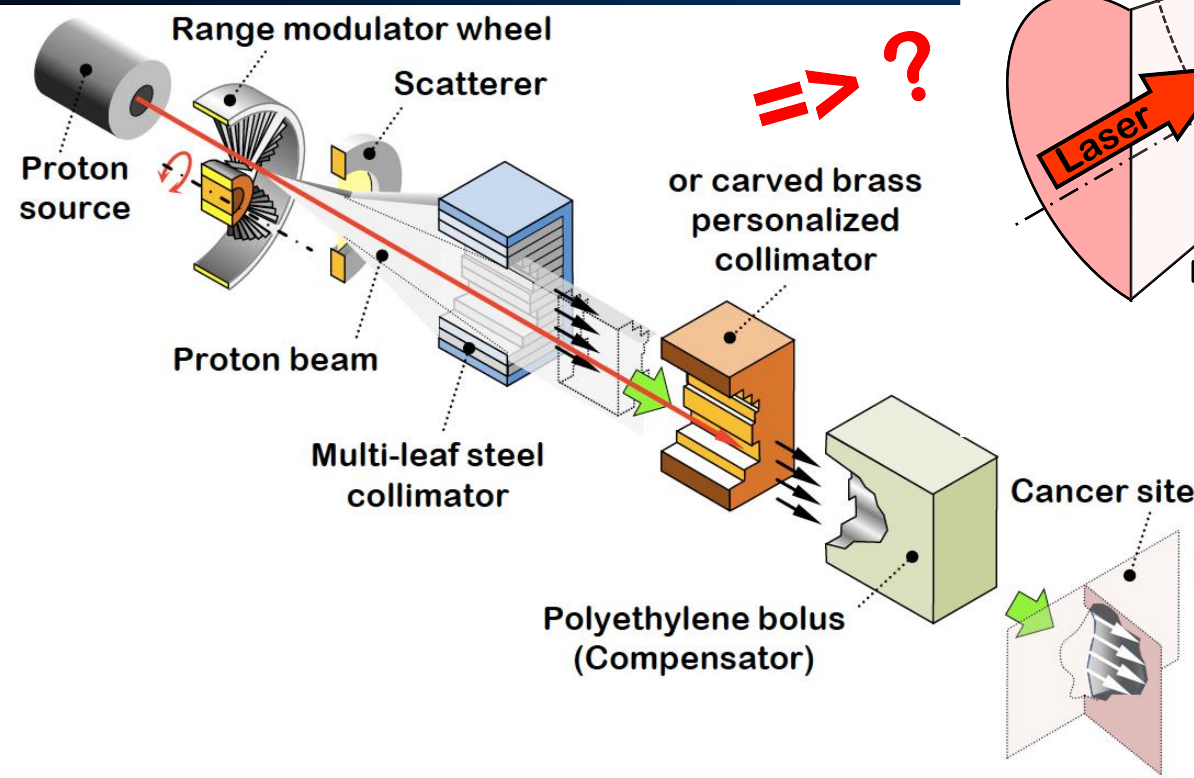
- **TNSA:**
  - 200 MeV @ $I\lambda^2$ ~ mid 10^{21} W/cm^2 for 0.5-1 ps pulses
    ~ 10^{22} for 30 fs pulses
  - Endpoint in the spectrum - not many particles….
- BOA:
  - More efficient heating, 200 MeV may be closer @ $I\lambda^2$ ~ 3 10^{21} W/cm^2 for 0.5 ps pulses (?)
  - Endpoint in the spectrum – few particles….
- **RPA HB:**
  - E_{ion} ~ $I\lambda^2/n$ …. decreasing density helps- operating below γn_c, may make 200 Mev @ few 10^{21} W/cm^2 feasible
  - dense ion bunch, monochromatic
- **RPA LS:**
  - E_{ion} ~ $(I\tau/(nd))^2$, multispecies for better stabilization – 200 MeV possible at few 10^{21}W/cm^2 if drive on suitably thin foil can be stabilized (loose focusing, multi PW beam)
  - Dense bunch, monochromatic

After M.Borghesi, EAAC 2013

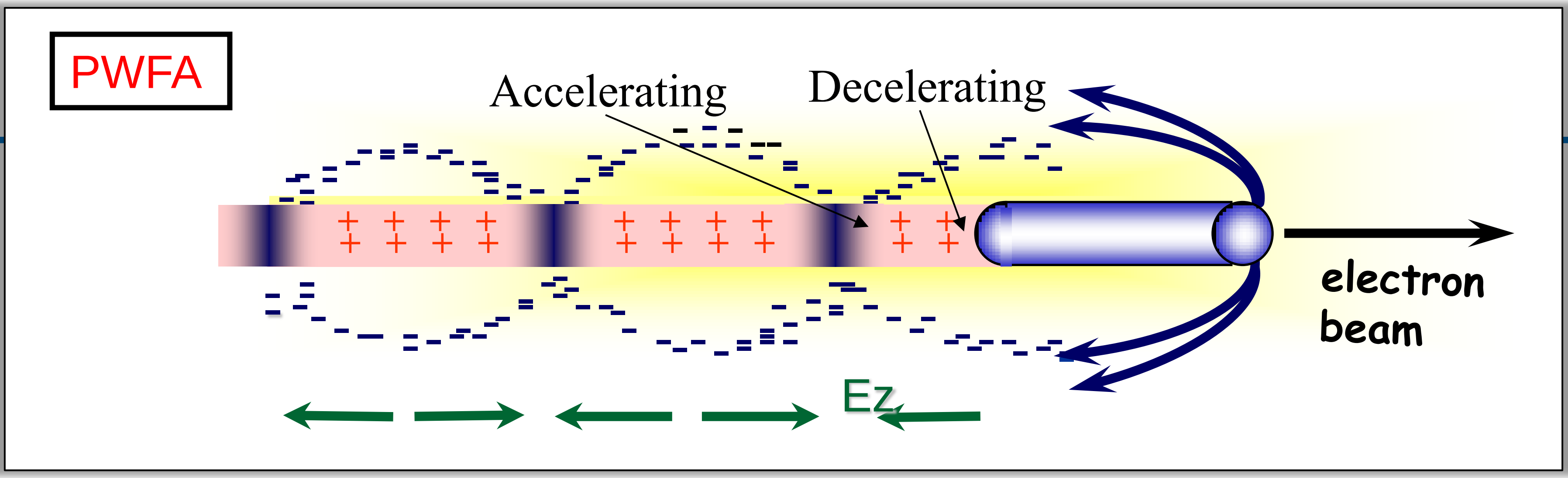
Future p-therapy



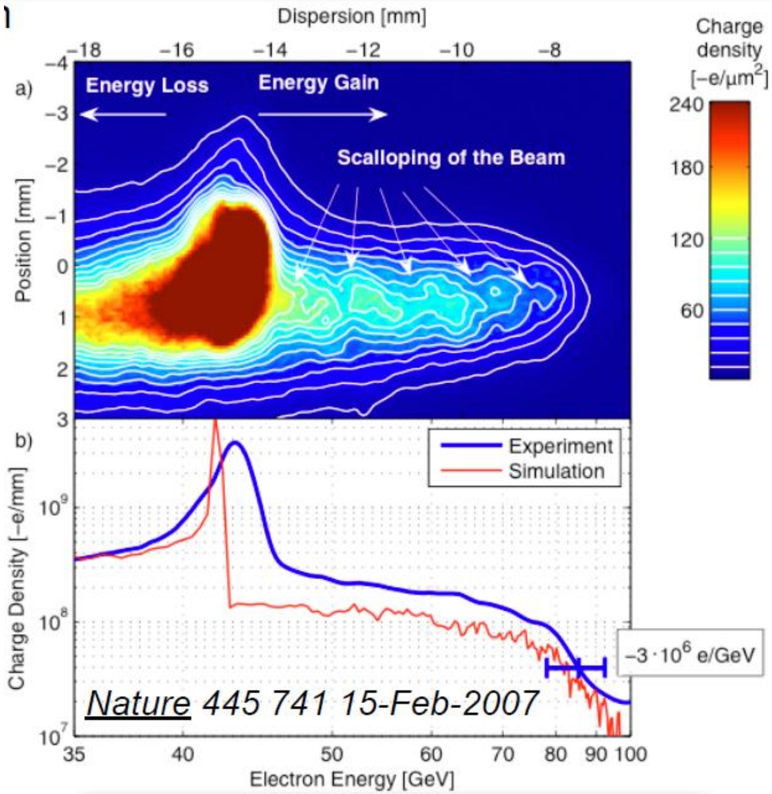
TNSA (RPA, light sail, etc.)



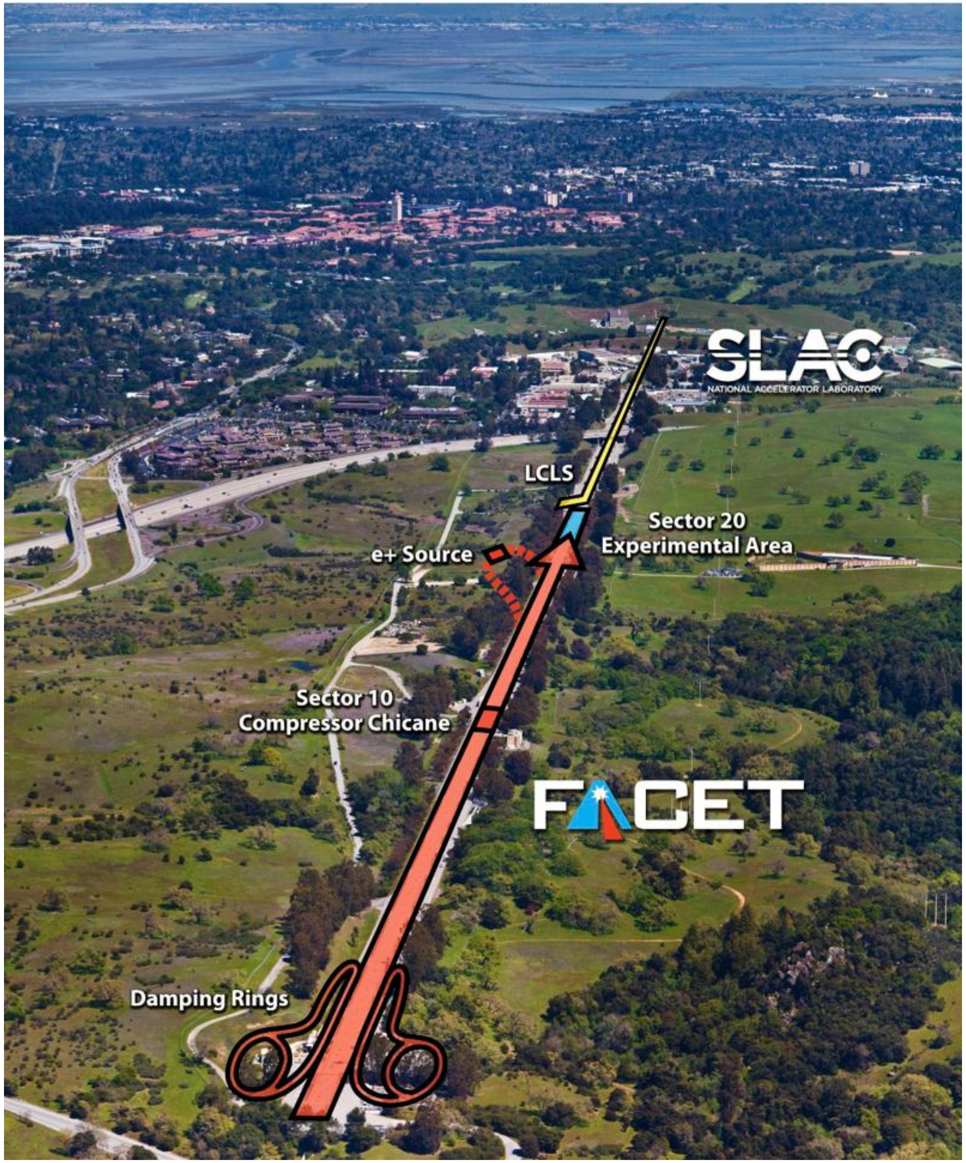
Can TRIZ methodology be applied to help solving the challenges of plasma acceleration driven proton therapy?



- **Beam driven plasma acceleration**
- **Max energy achieved 80 GeV (doubling SLAC linac energy)**
- **Next gen experiments at FACET (SLAC)**



FACET

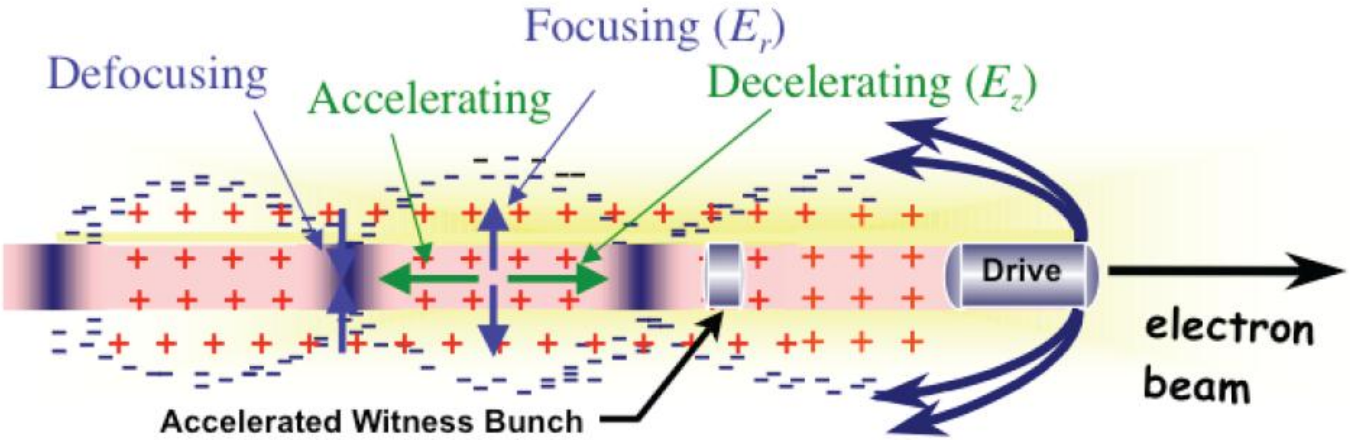


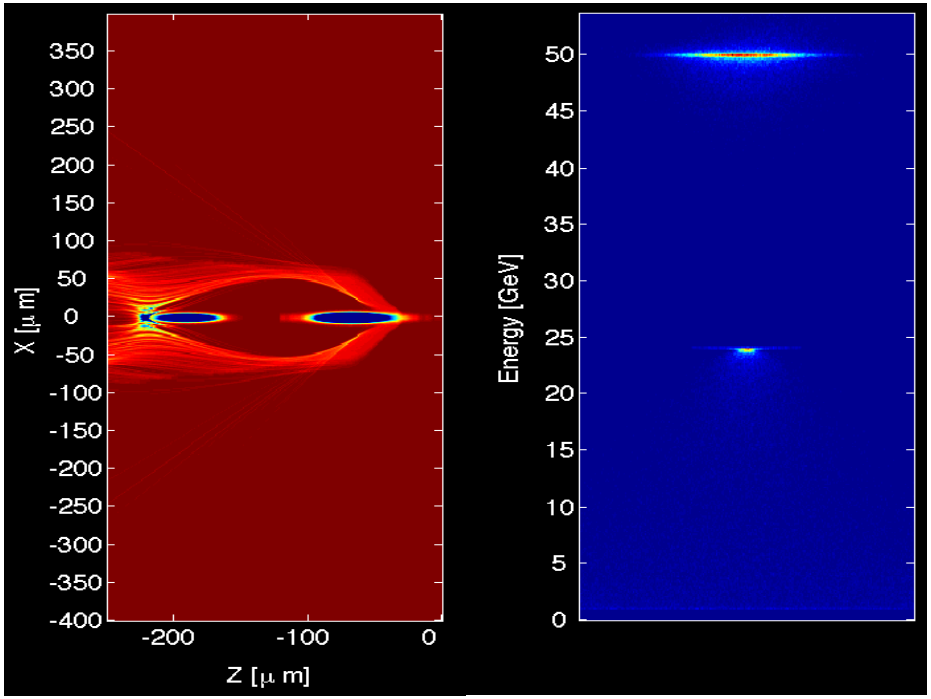
FACET
Facility for Advanced Accelerator Experimental Tests at SLAC
(commissioned in 2011, was running until 2016)

Beam Parameters	
Energy	23 GeV
Charge	3 nC
Sigma z	20 µm
Sigma r	10 µm
Peak Current	22 kAmps
Species	e^- & e^+

FACET-II is planned

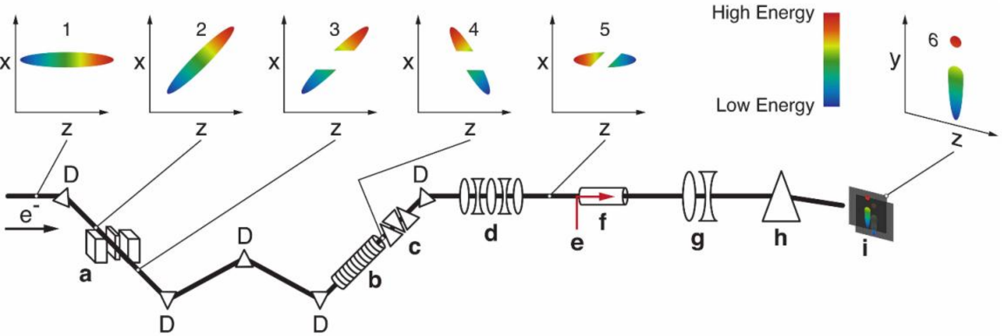
FACET plans



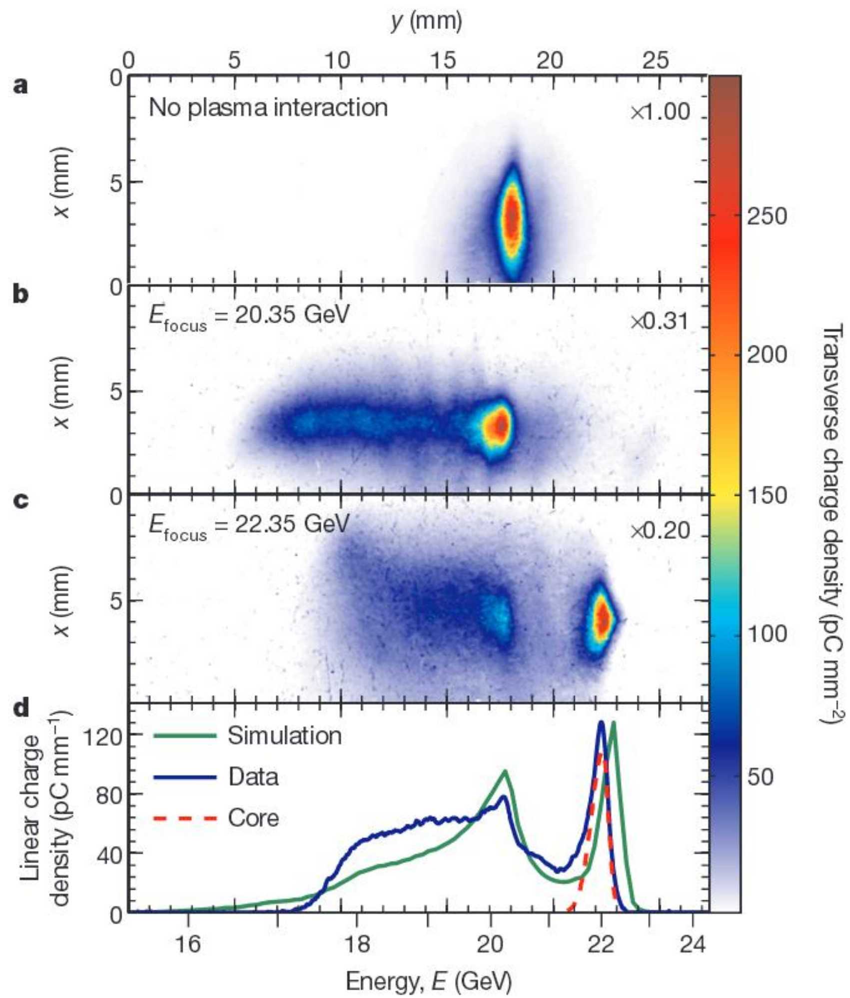


Two electron bunches formed by notch collimator will allow study energy doubling, high efficiency acceleration, emittance preservation (simulations)

FACET results (examples)



Creation of drive-witness beams

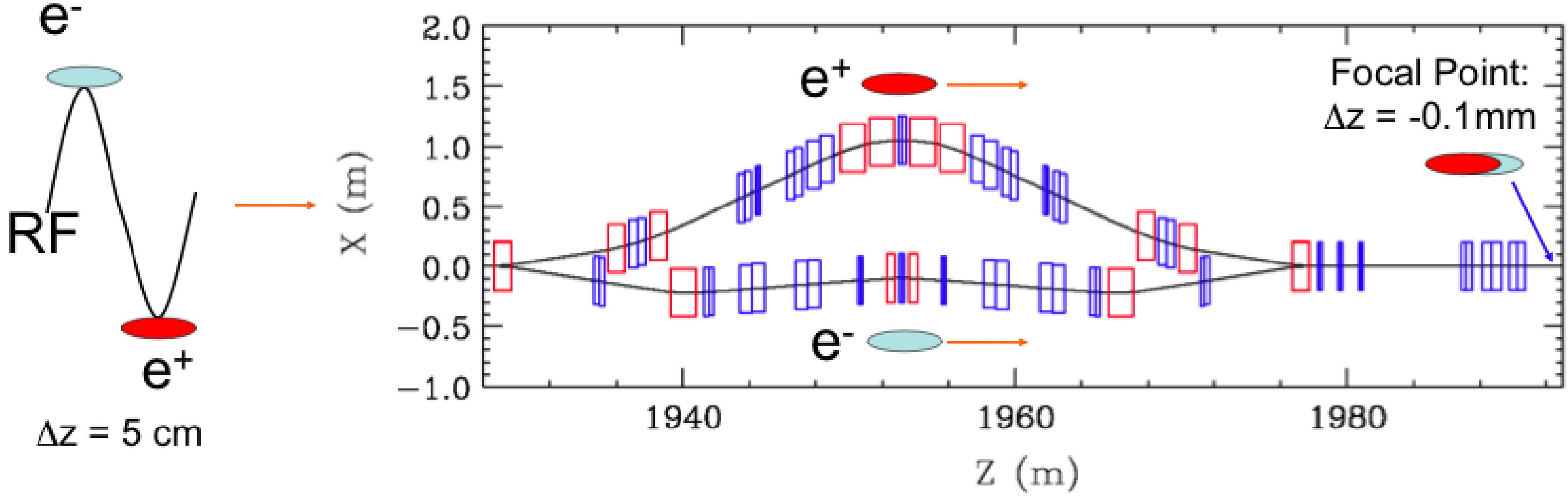


Acceleration demonstration

M. Litos et al., Nature, 6 November 2014 (10.1038/nature13882)

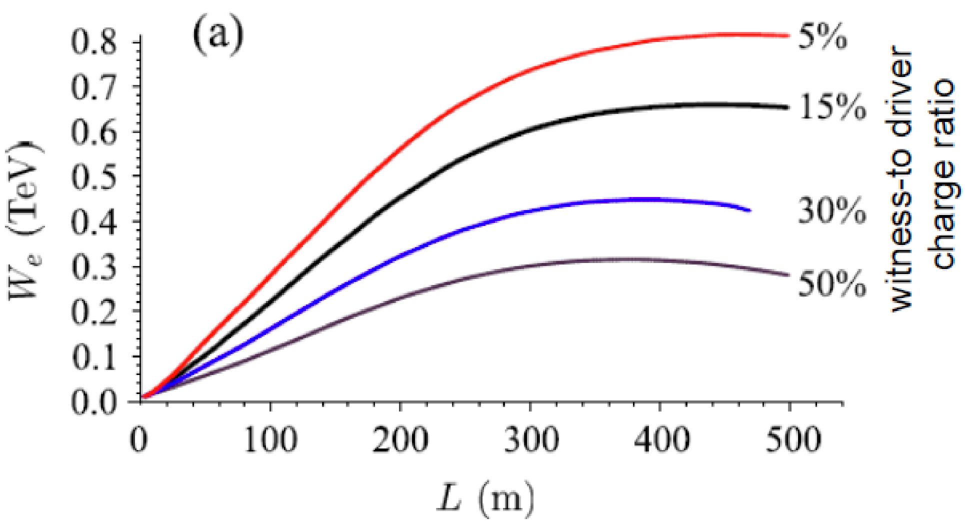
FACET possible future capability

Extract e- & e+ from damping rings on same linac pulse
Accelerate bunches to sector 20 while 5cm apart
Use ‘Sailboat Chicane’ to put them within 100µm at entrance to plasma
Large beam loading of e- wakes with high charge e+ beams



Proton plasma acceleration - motivation

- Max energy of e- in plasma wakefield accelerators is limited
  DWe < Wd
  where D – transformer ratio, We – final energy of electrons, Wd- energy of driver
- To reach TeV e- energies, need either staging or proton beam as driver



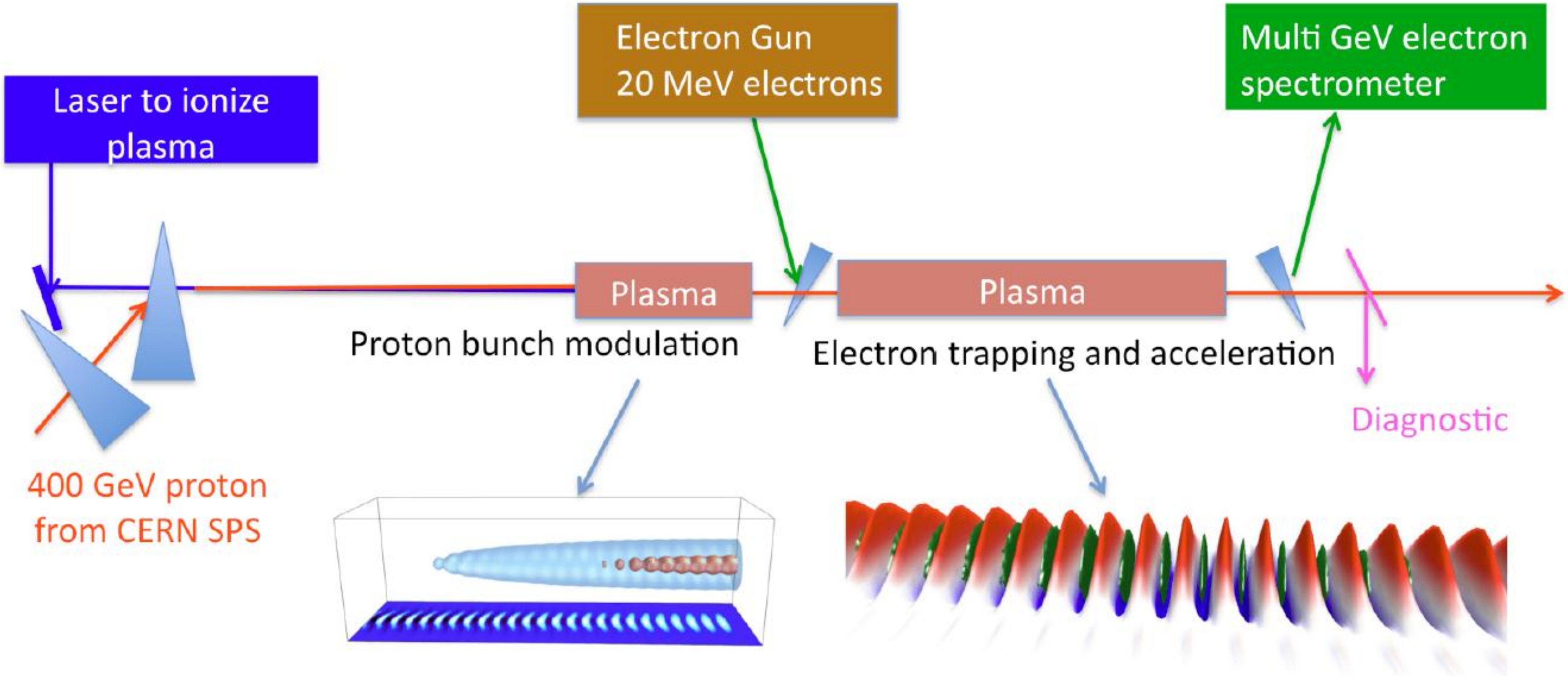
A.Caldwell, K.Lotov, A.Pukhov, F.Simon, Nature Physics 5, 363 (2009)

Background: energy content <40 J (laser), <120 J (electrons) 20 kJ (SPS), >150kJ (LHC)

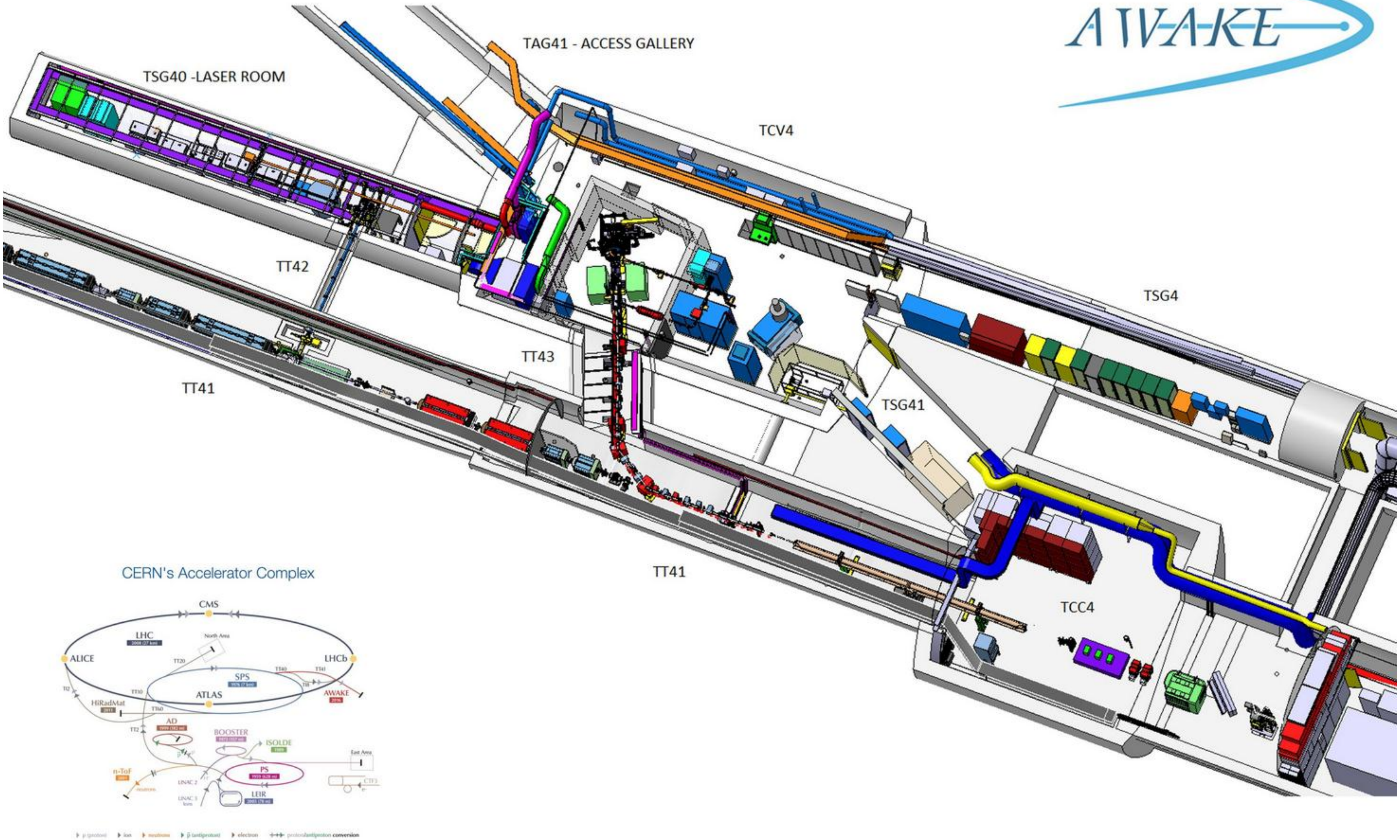
1TeV p-beam can get e- to TeV, but p-beam need to be as short as 0.1mm – hard to test

First experiments will use long p-beam and self-modulation – study of physics of process – AWAKE experiment

AWAKE – proton driven plasma acceleration



AWAKE


TSG40 -LASER ROOM
TAG41 - ACCESS GALLERY
TCV4
TT42
TSG4
TT43
TT41
TSG41
TT41
TCC4
CERN's Accelerator Complex
CMS
LHC
ALICE
LHCb
SPS
ATLAS
AWAKE
HiRadMat
AD
BOOSTER
ISOLDE
PS
n-ToF
LEIR

Summary of the lecture

- **We have discussed**
  - **Basics of radiation effects on DNA**
  - **Conventional tools for particle therapy**
  - **Basics of ion acceleration with high intensity lasers**
    - **Sheath acceleration**
    - **Radiation pressure acceleration**
  - **Beam driven acceleration**
    - **Electron beam driven**
    - **Proton beam driven**