Apollon First Users' Meeting
Under the auspices of Institut
Lasers & Plasmas

Laser Driven Ion Acceleration and Applications

D.Doria

Centre for Plasma Physics,
School of Mathematics and Physics

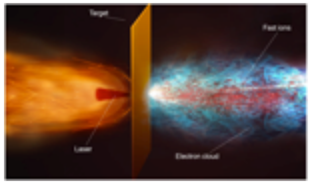
The Queen's University of Belfast

Apollon User Meeting, Paris, 11-12 Feb 2016

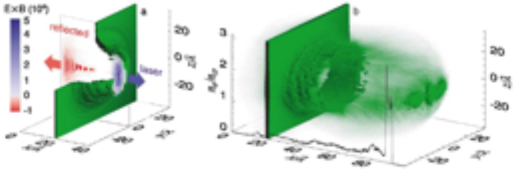
Queen's University Belfast

A-SAIL
ADVANCED STRATEGIES FOR
ACCELERATING IONS WITH LASERS

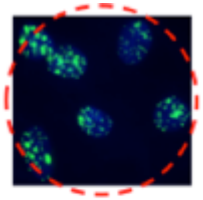
Objectives



TNSA optimization:
scaling, advanced targetry solutions



Acceleration from ultrathin foils
(Radiation pressure effects)
VULCAN (~ ps pulses)
GEMINI (~ 40 fs pulses)
APOLLON(~ 15 fs pulses)



Applications: Radiobiology

The A-SAIL project

A-SAIL
ADVANCED STRATEGIES FOR
ACCELERATING IONS WITH LASERS

Queen's University Belfast
University of Strathclyde
Imperial College London
CLF RAL - STFC

EPSRC
Pioneering research and skills

PROGRAMME GRANT (2013-2019)

A-SAIL's aim

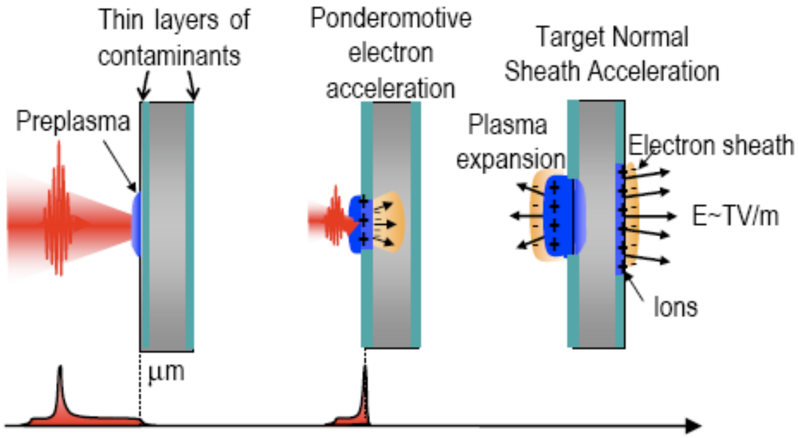
All-optical delivery of dense, high-repetition ion beams at energies above the threshold for deep-seated tumour treatment

4 interlinked research projects aimed to

- Develop laser-driven ion acceleration to the required level of performance
- Assess prospects for medical use

eli beamlines project partner

Established mechanism: Target Normal Sheath Acceleration



S.P.Hatchett *et al*, Phys Plasmas, **7**, 2076 (2000)

P.Mora et al, PRL, **90**, 185002 (2003)

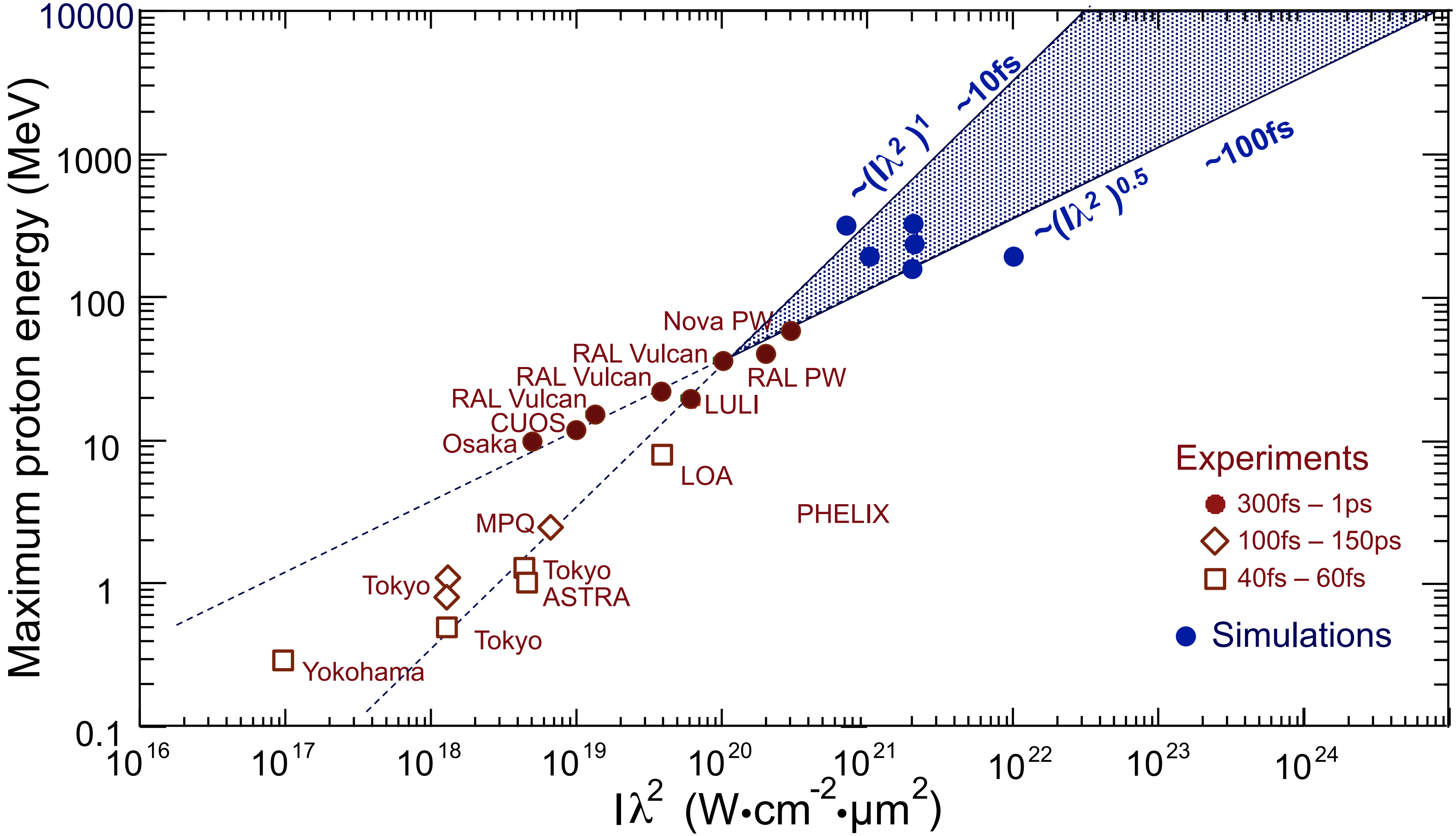
•Relies on production of high energy (MeV) electrons

•Acceleration under effect of the electron pressure and decoupled from laser interaction

- Well tested and robust mechanism
- Effective at realistic intensities
- Broad spectrum, diverging beams
- Conversion efficiency ~ few %
- Energy Scaling a_0 , a_0^2

Maximum TNSA energies: state of the art

A.Macchi, M. Borghesi, M. Passoni, Rev. Mod. Physics, **85**, 751 (2013)

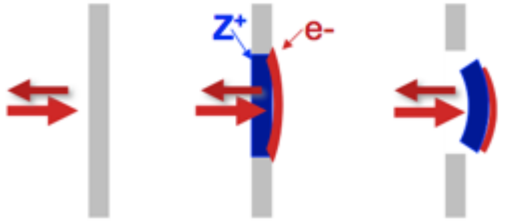


Maximum published energies: ~70 MeV

Acceleration more effective with higher energy, longer pulses, at equal intensities < 10^{20} W/cm^2

Effective on protons, less so on higher-Z species

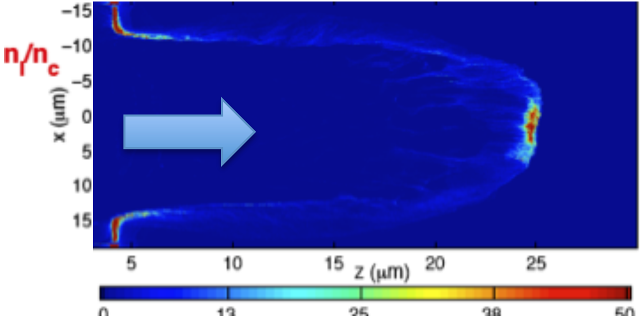
Radiation Pressure Acceleration: Ultra-thin foils

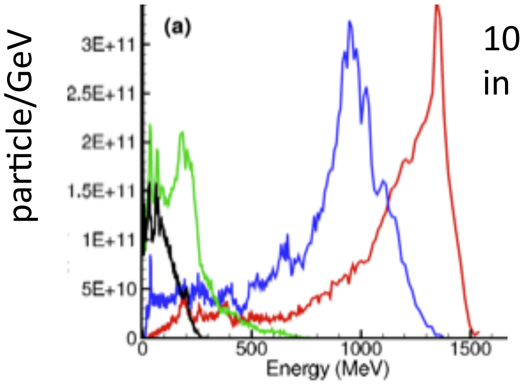


P_L~ 100s Gbar
I ~ 10^{20} Wcm^{-2}

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

2DPIC simulations at 10^{22} W/cm^2





10^{10} particles in peak

Instabilities at lower drive intensities can be mitigated by use of multispecies targets

B. Qiao et al, Phys Rev. Lett., **105**, 1555002 (2010)
B.Qiao, et al, Phys. Plasmas, **18**, 043102 (2011)

- Ultra thin foils
- Narrow-band spectrum (whole-foil acceleration)
- Faster scaling with intensity:

Momentum balance gives

$$E_{ions} \sim \left(I\tau/\eta\right)^2 \sim \left(a_0^2\tau/\eta\right)^2 \text{ , } \eta$$ Areal density

T.Esirkepov, et al. PRL., **92**, 175003 (2004)
APL Robinson et al, NJP, **10**, 013021 (2009)

Target must stay opaque

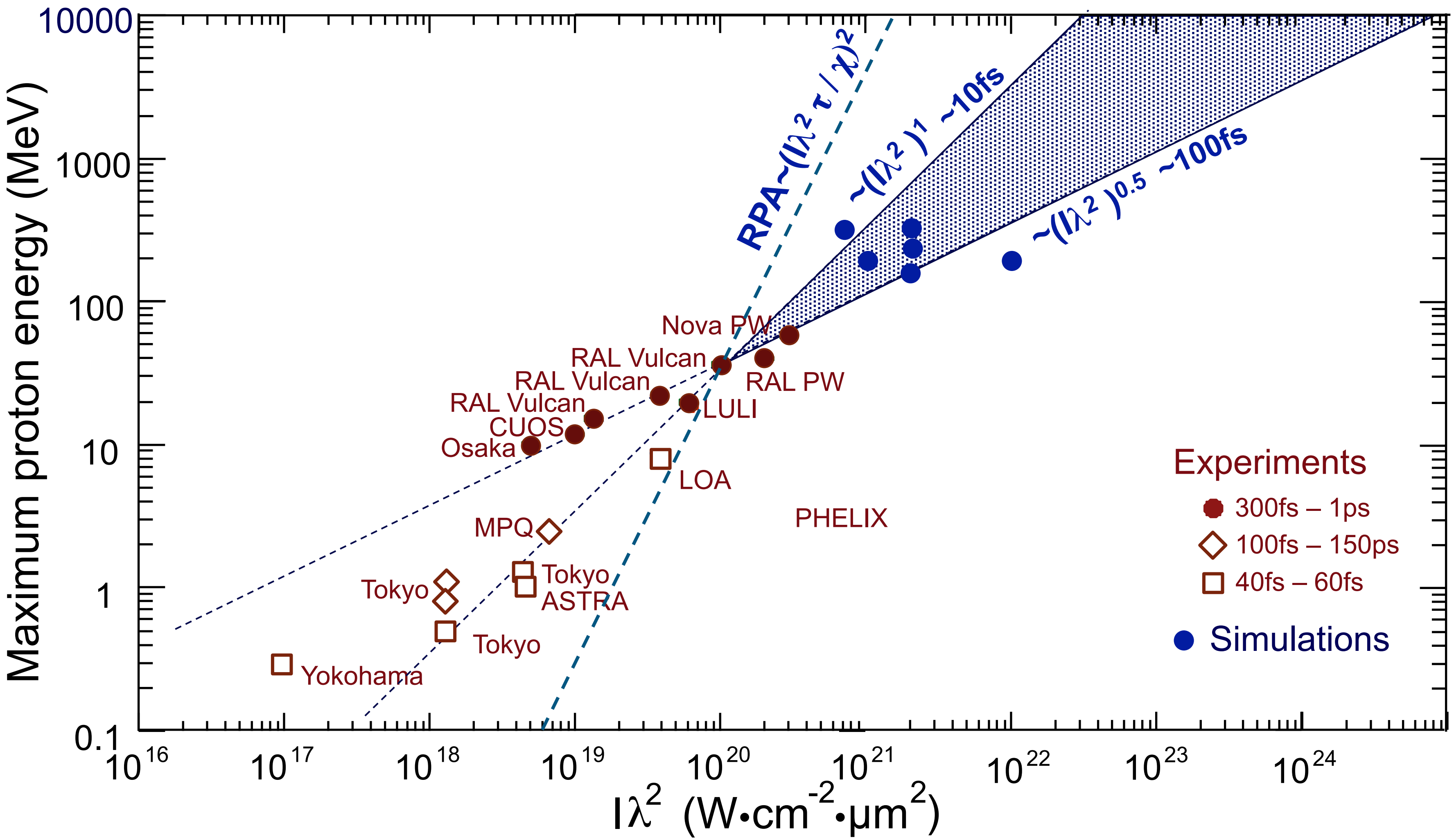
Electron heating

Target disassembly

Transverse instabilities

Maximum TNSA energies: state of the art

A.Macchi, M. Borghesi, M. Passoni, Rev. Mod. Physics, **85**, 751 (2013)



Radiation Pressure Acceleration: Ultra-thin foils

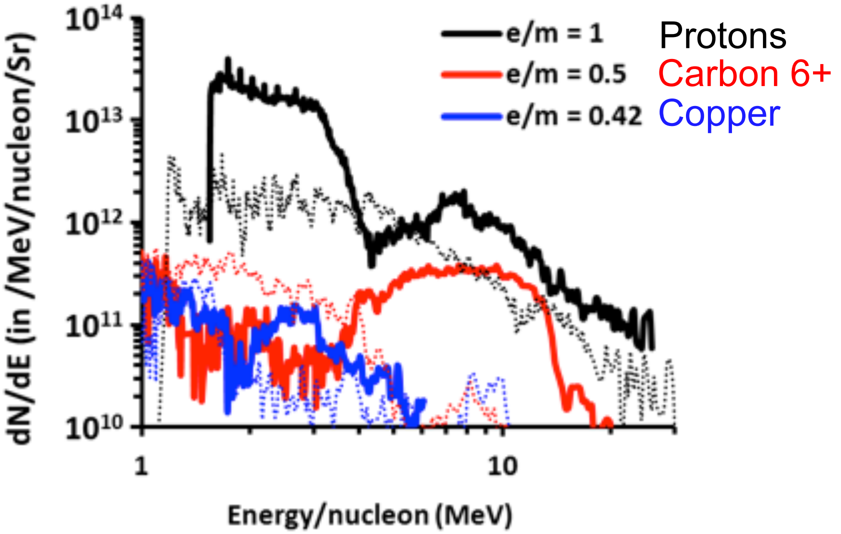
RPA features emerging on VULCAN Petawatt

Experiments using thin metallic targets

100nm Cu

$I = 3 \times 10^{20}$ W/cm^2

Pulse duration: ~ 700 fs



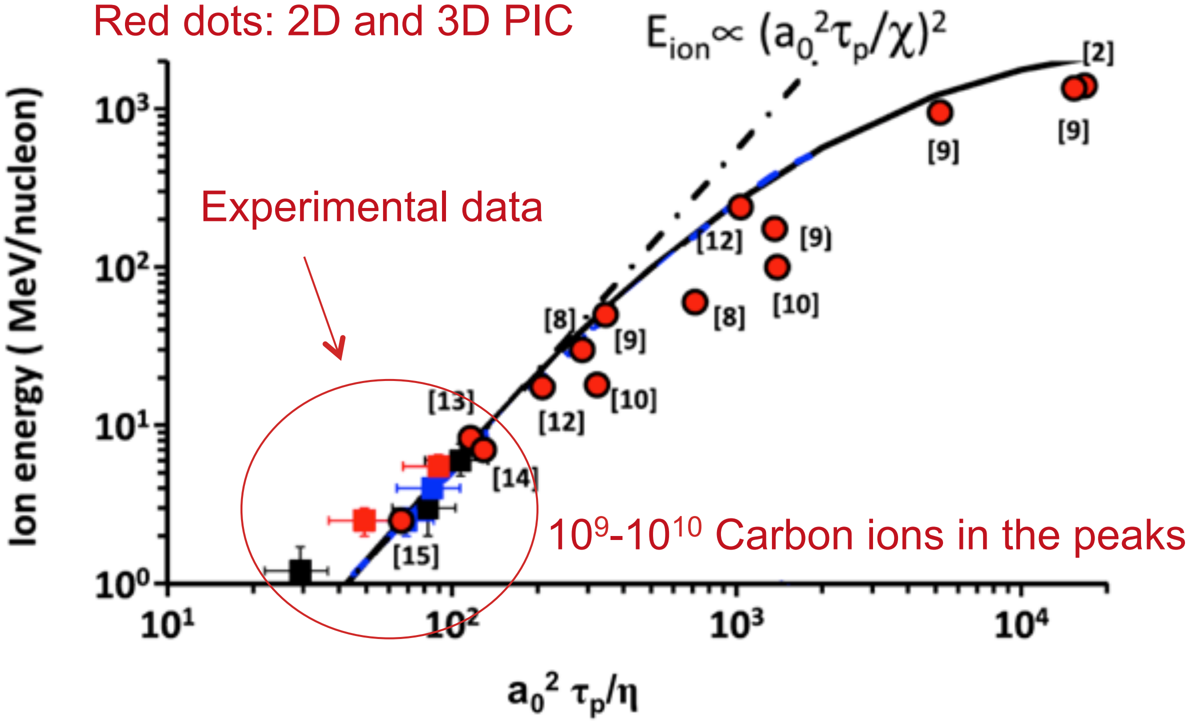
Protons

Carbon 6+

Copper

$$E_{ions} \sim \left(I\tau/\eta\right)^2 \sim \left(a_0^2\tau/\eta\right)^2$$

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



Red dots: 2D and 3D PIC

Experimental data

10^9-10^{10} Carbon ions in the peaks

Targets thicker than 0.5 μm show standard continuous, exponential spectra

Peaks observed regardless of laser polarization –

Hybrid scheme where TNSA and RPA cohesist

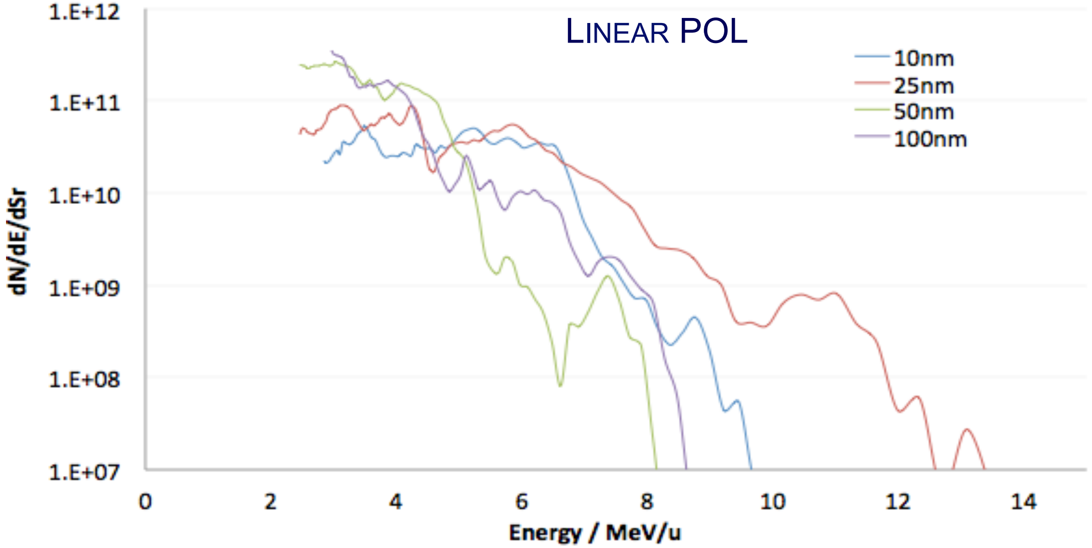
Theory descrived in B. Qiao et al, PRL, 108, 115002 (2012)

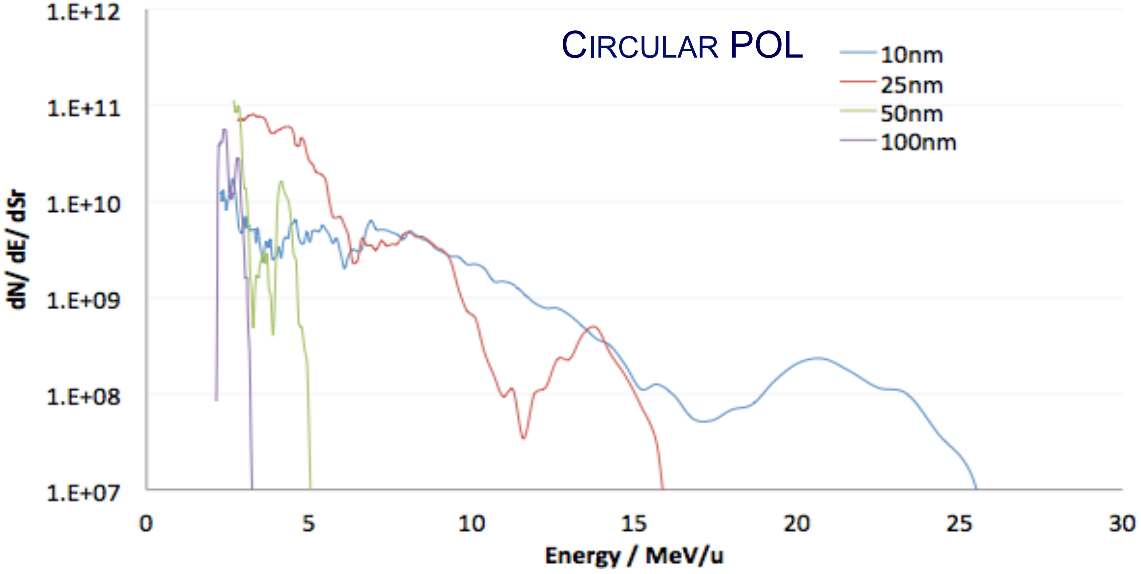
Difficulties in extending scaling due to transparency and instability issues

GEMINI Experimental Ion Spectra

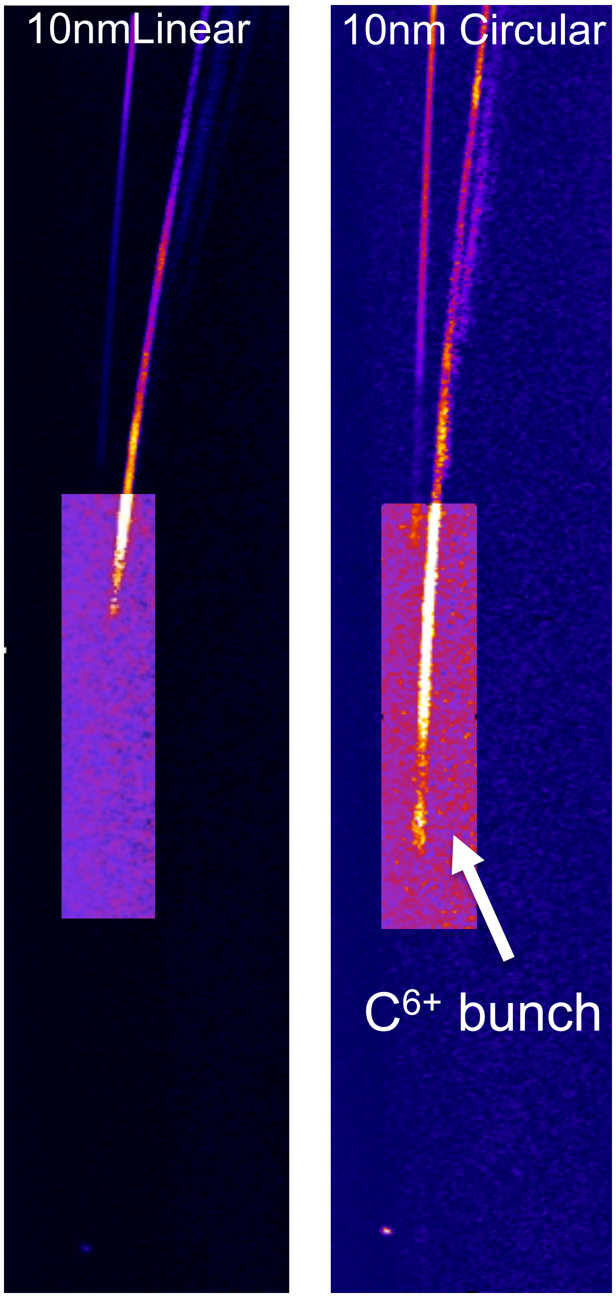
I ~ 3 x 10^{20} W/cm^2
Pulse duration ~ 45 fs

Carbon Spectra

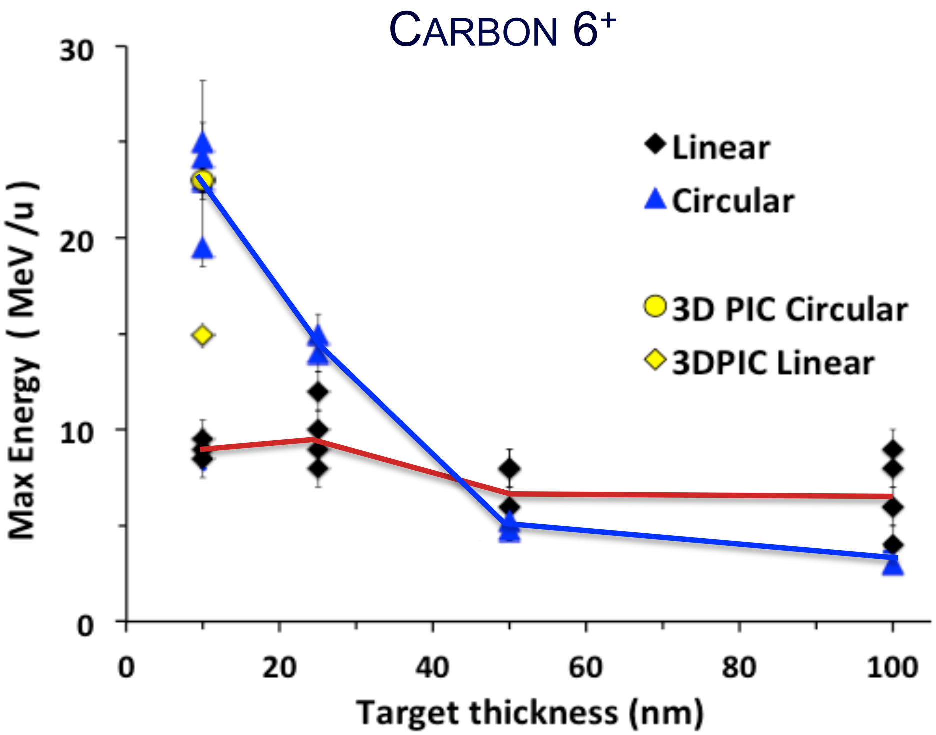


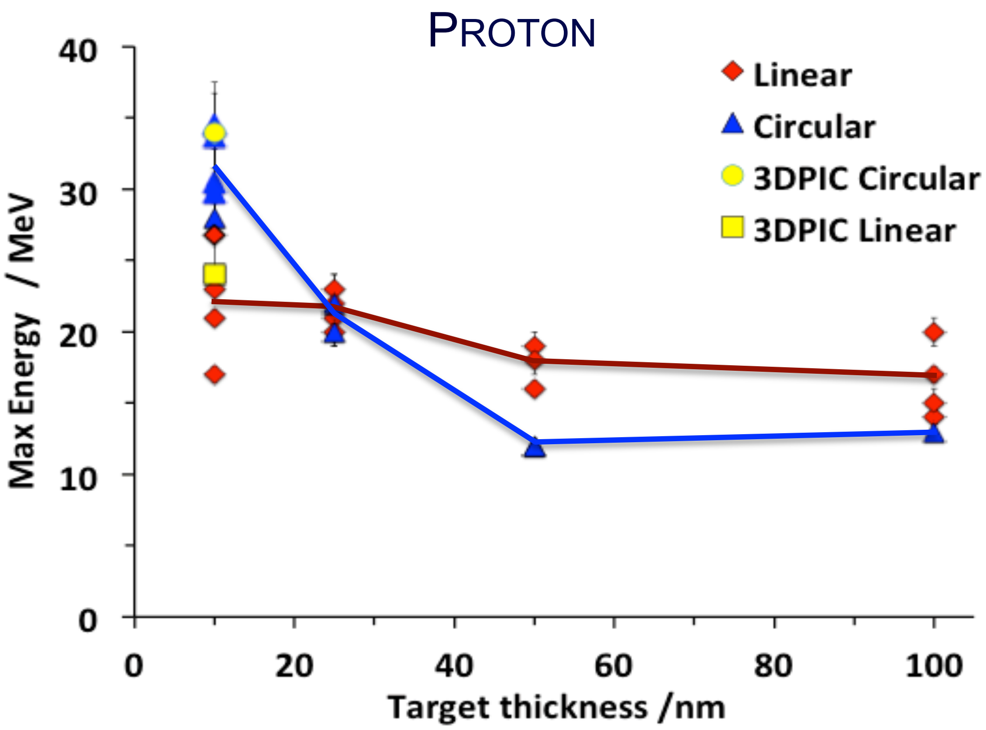


THOMSON PARABOLA



GEMINI Experimental Ion Spectra


Carbon 6^+


Proton

- Very significant energies for CP and 10 nm targets: ~35 MeV for protons, ~300 MeV per Carbon

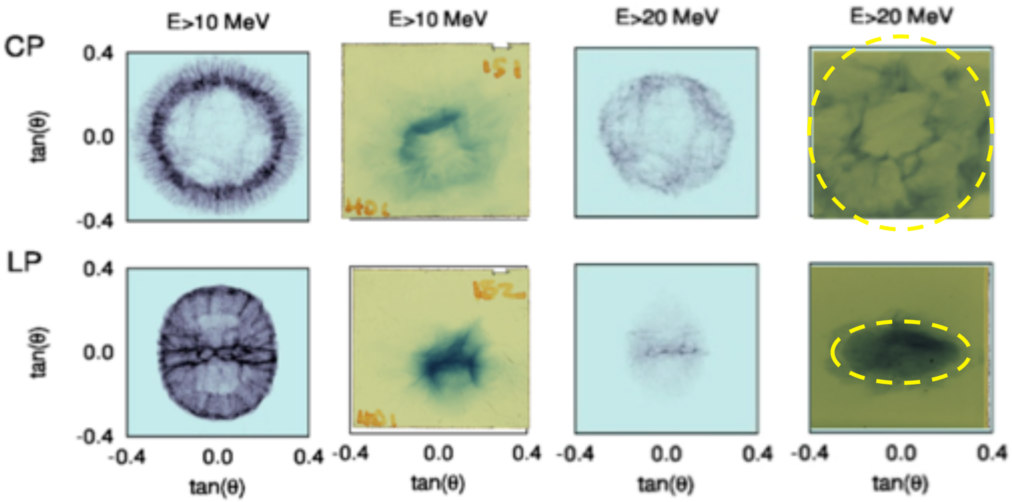
- Energies for circular polarization higher for the thinnest targets: RPA LS dominates?

- 3D PIC simulations reproduce the difference between CP and LP data

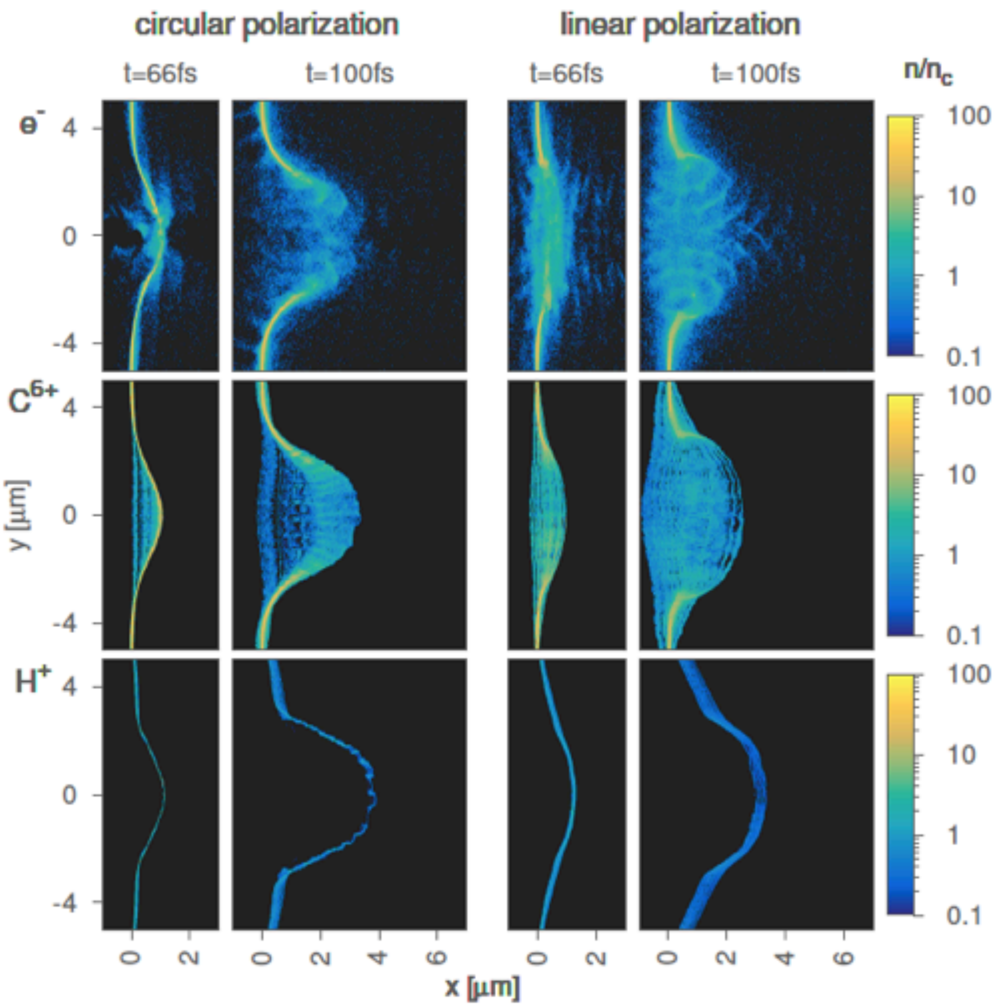
Experiment and Simulation of Beam profile

Proton profile using Radiochromic Film

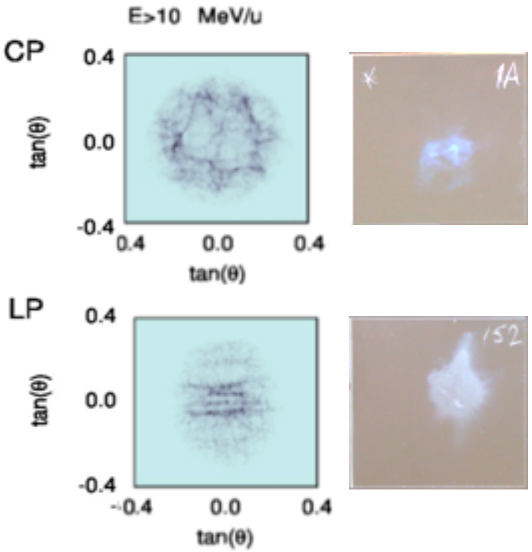
HDV2 LAYER 1 (10MeV) EBT2 LAYER 4 (20MeV)



3D PIC Simulation (PICCANTE)



Carbon ion profile using CR39



Experiment and Simulation of Beam profile

Proton profile using Radiochromic Film

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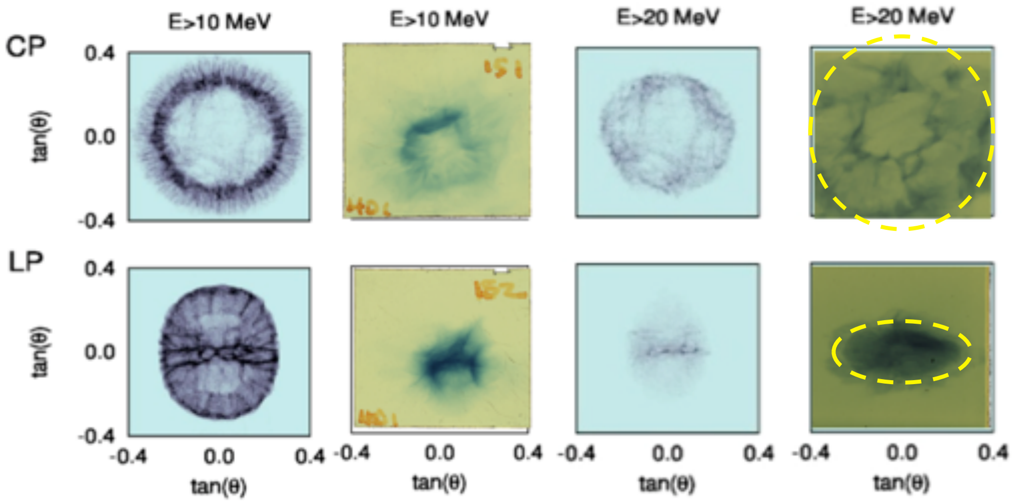
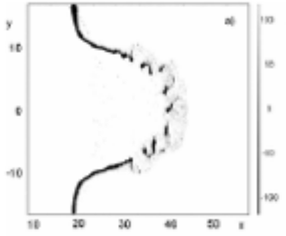
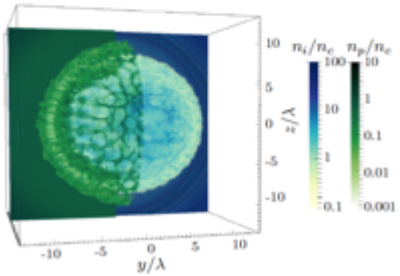


STRUCTURED, LARGER DIVERGENCE BEAM – UNSTABILIZED RADIATION PRESSURE DRIVE ?

RALEYGH-TAYLOR INSTABILITY



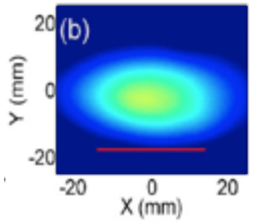


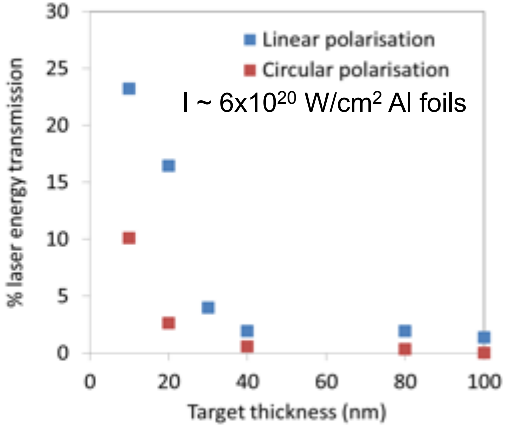
F.Pegoraro and S.V. Bulanov, PRL, **99**, 065002 (2007)

A.Sgattoni et al., PRE **91**, 013106 (2015)

3D PIC Simulation (PICCANTE)

ELONGATION IN POLARIZATION DIRECTION – SIGNATURE OF TRANSPARENCY ?

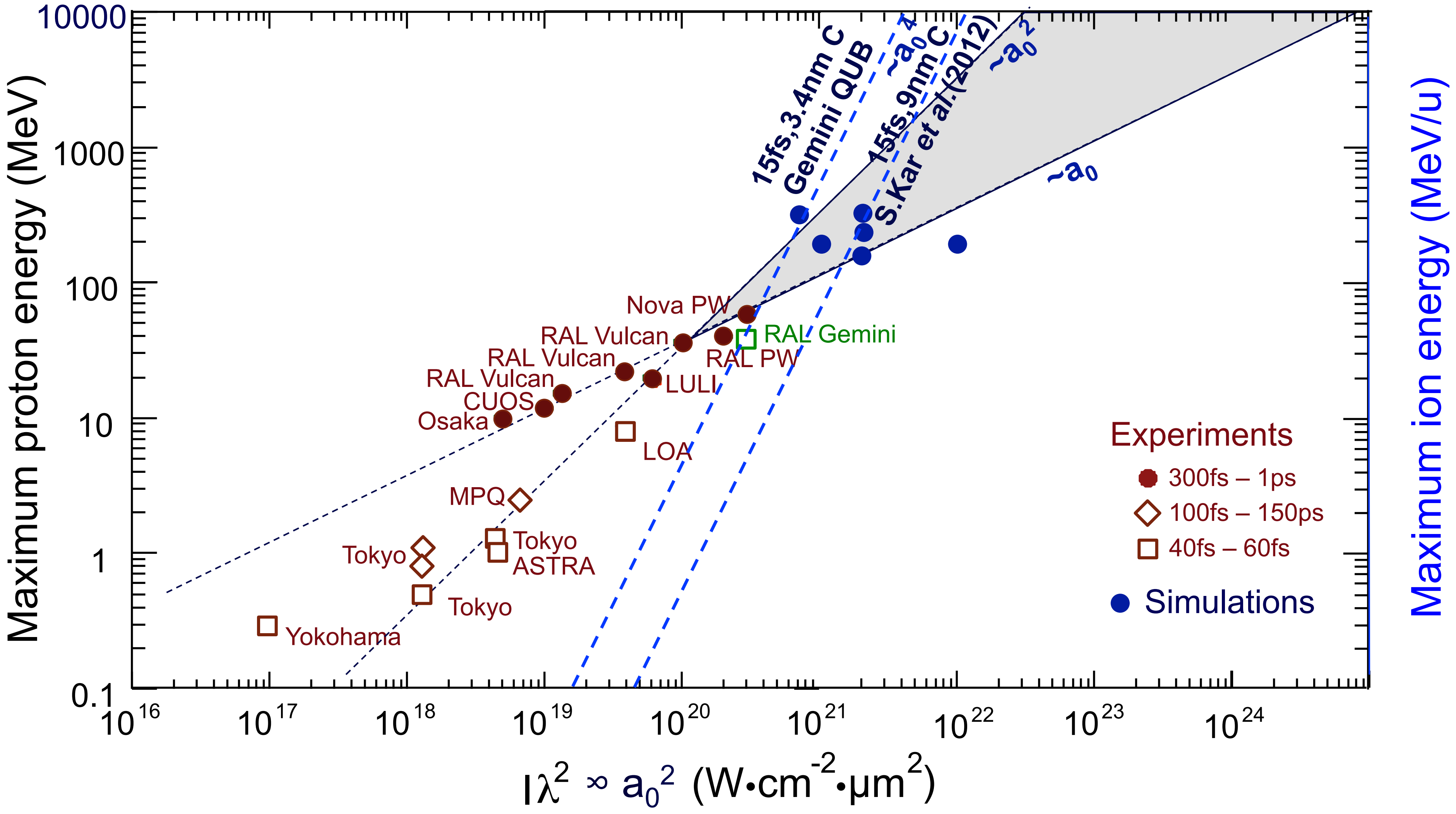




R. Gray et al, NJP, **16**, 093027 (2014)

Maximum TNSA energies: state of the art

A.Macchi, M. Borghesi, M. Passoni, Rev. Mod. Physics, **85**, 751 (2013)



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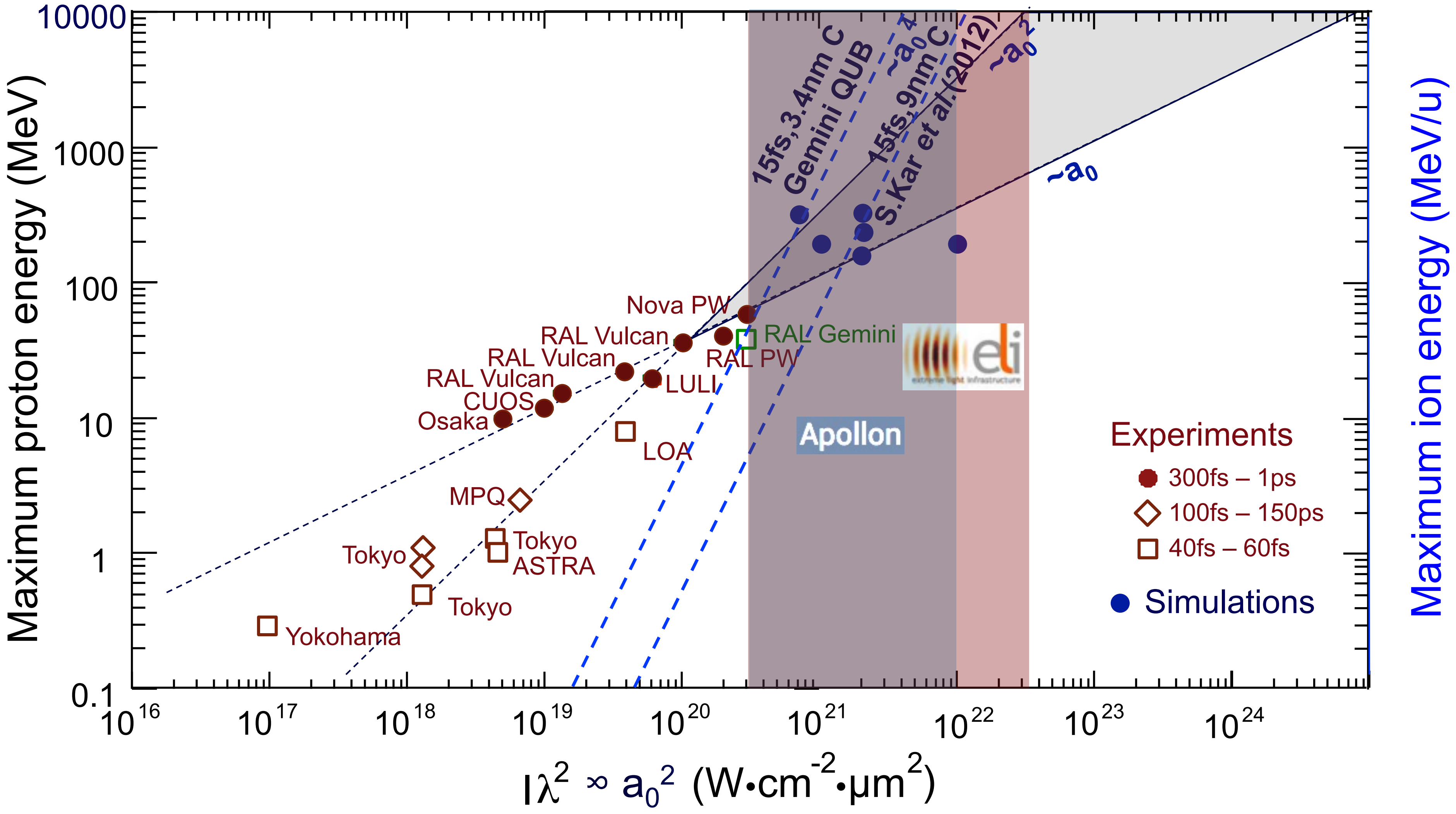
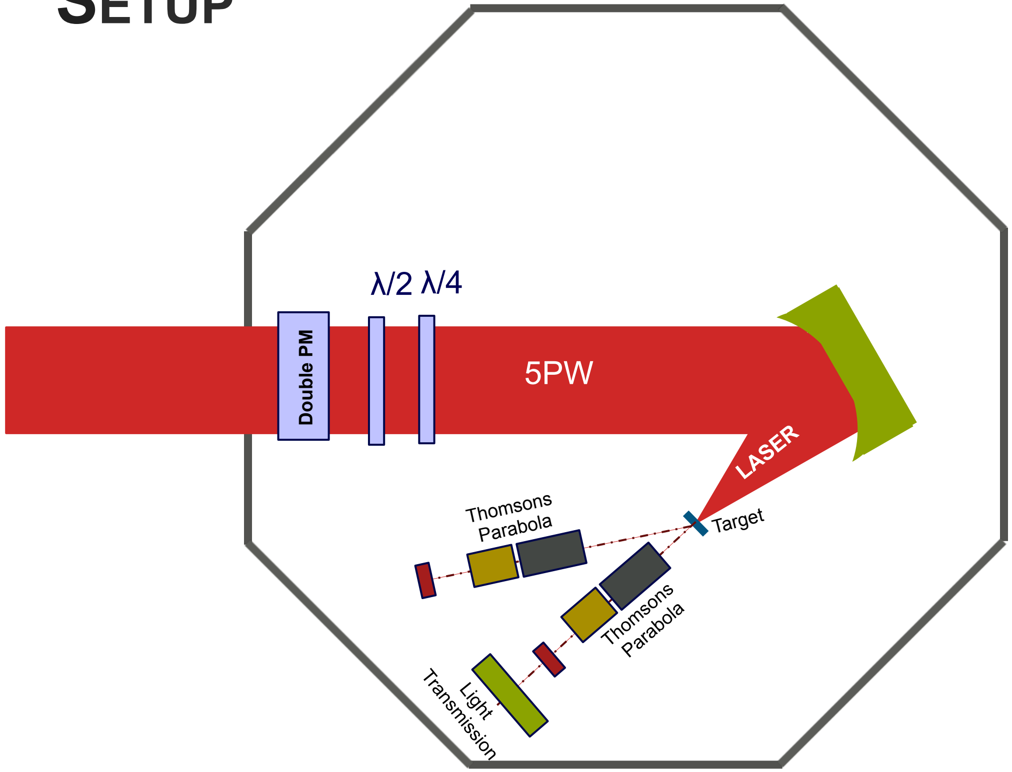
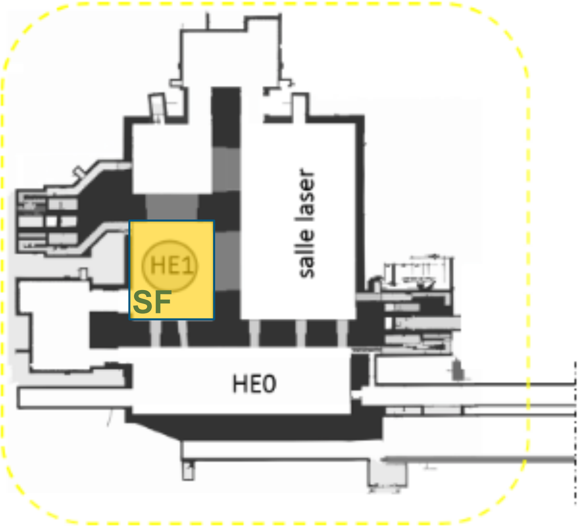


Laser Driven-Ion Acceleration

SETUP



APOLLON LASER (SF)

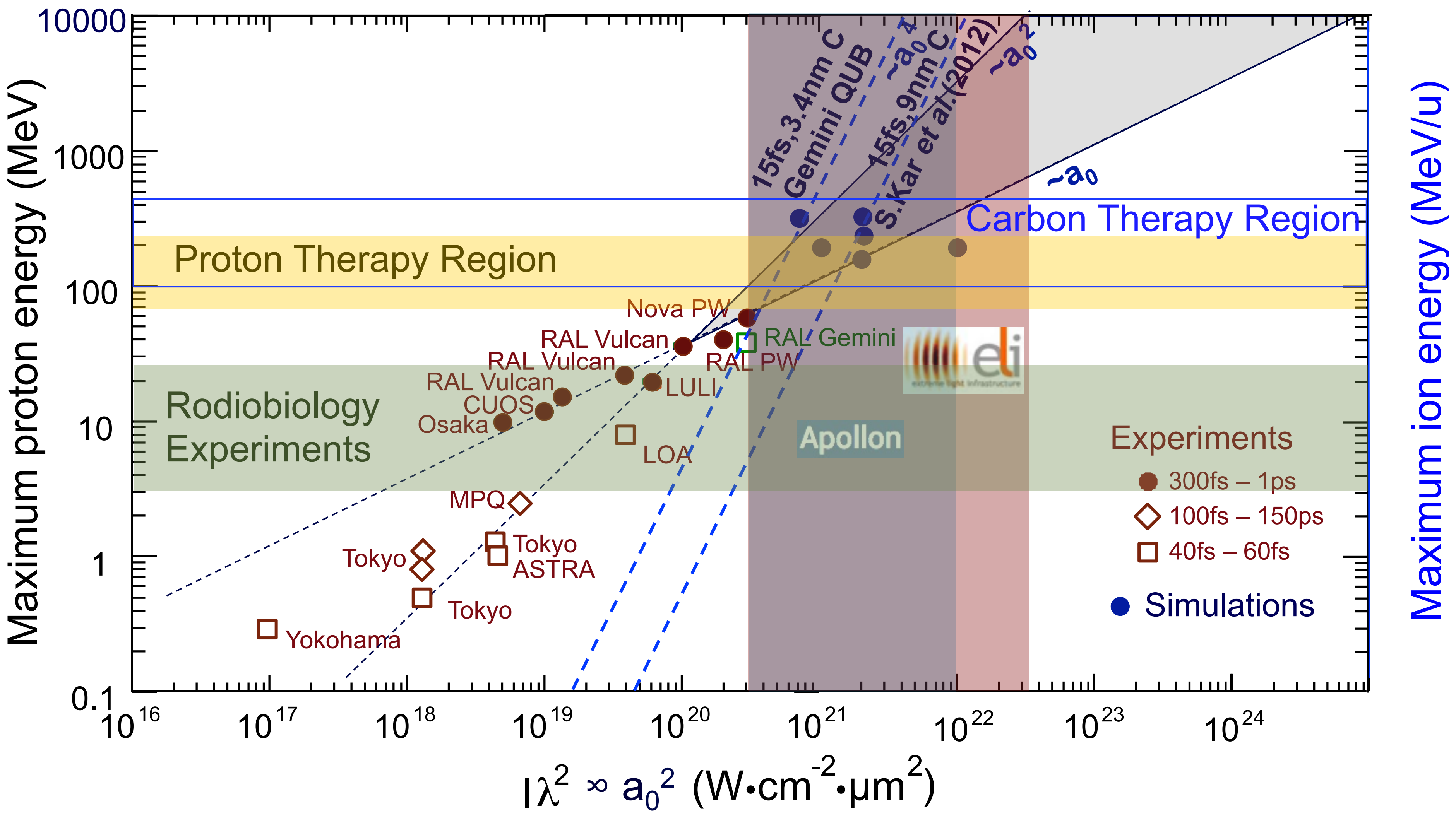


LASER PARAMETERS

Intensity	up to 10^{22} W/cm^2 (~5 PW)
Pulse length	~ 15fs
Wavelength	1053nm
Repetition rate	One shot every min

Radiobiology with Laser Driven-Ion

A.Macchi, M. Borghesi, M. Passoni, Rev. Mod. Physics, **85**, 751 (2013)



WHY Hadrontheray

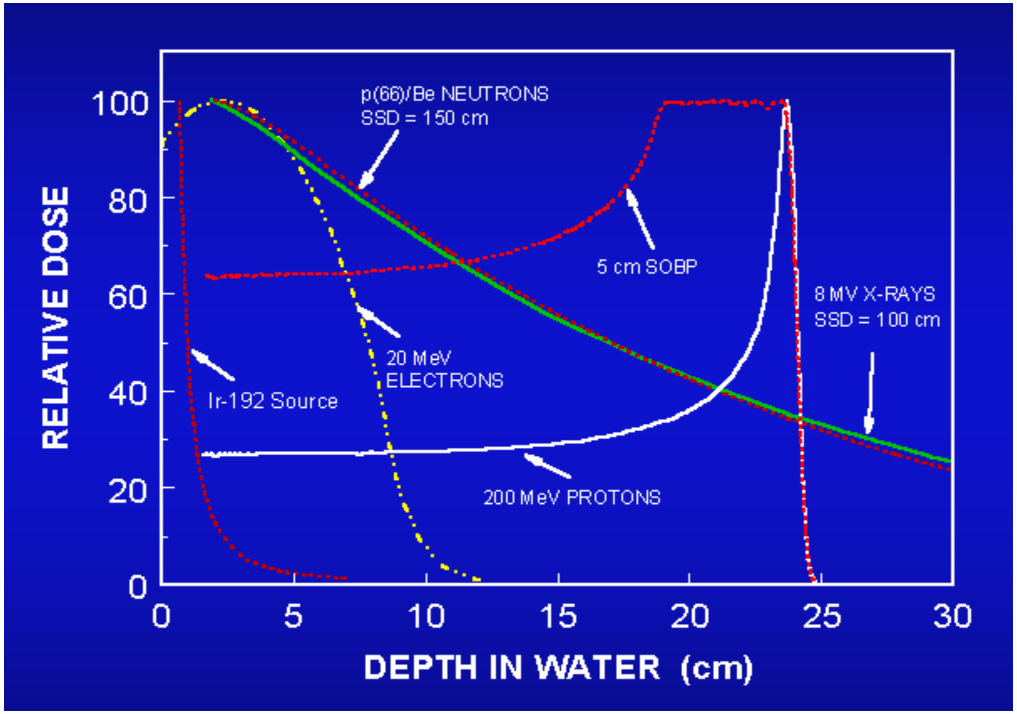
Hadrontherapy is a form of external radiation therapy using protons and ion beams

Improved physical properties:

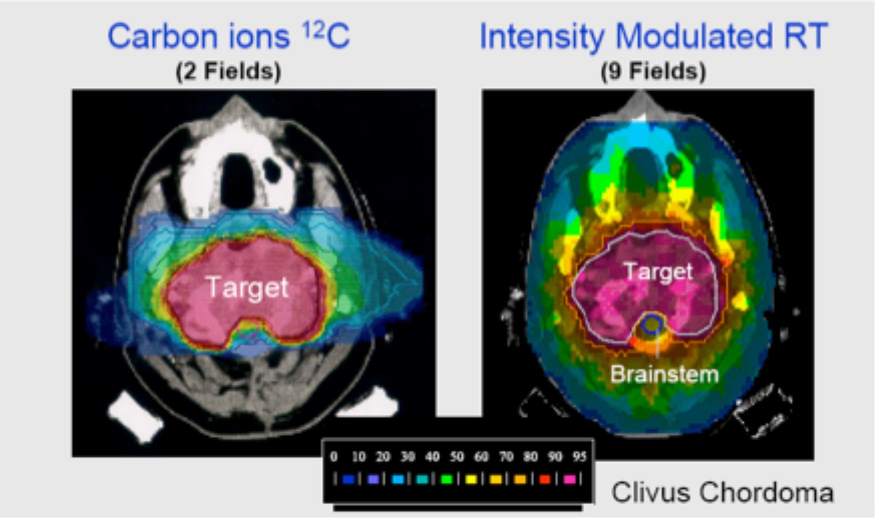
- Ions deposit the energy at the end of their path
- Ions travel straight
- Their energy can be controlled

Main advantages

- Selective dose distribution
- Radiobiological advantage (especially for ions)



Dose burden on the healthy tissues outside of the target volume reduced by a factor 2 to 5



Energies required:
60-250 MeV (protons)
100-450MeV/u (**C-ion**)

Typical dose fraction: 2-5 Gy
1 Gy ~ 10^{10} p+, ~10^{9} C in 5x5x5 cm^3
(delivered in few minutes)

Radiobiology with Laser Driven-Ion

Do ultra-high dose rates deposited in pulsed form cause any biological difference from conventional proton radiotherapy treatment?

- **Kreipl** ***et al*** states that a lack of interaction between direct and indirect DNA lesions may alter biological effect

- **Wilson** ***et al*** suggested that free radical formation may be reduced by ultra-high dose deposition owing to overlap of ion tracks in space and time

- **Fourkal** ***et al*** predicted an increase in LET of the ion bunch when the distance between protons in the bunch becomes less than its velocity divided by the characteristic frequency of the collective excitations supported by the medium

- **Bin** ***et al*** and **Zeil** ***et al*** showed that by combining advanced acceleration and beam transport, nanosecond quasi-monoenergetic proton bunches could be generated with a table-top laser system

Radiobiology with Laser Driven-Ion

What do we want to investigate?

Spatial-Temporal overlapping:

Dose is fixed around few Gy ⇒ High flux, high particle energy (Low LET), Short exposure time

Induced Hypoxia :

Dose is fixed around few Gy ⇒ High flux, Short exposure time

Induced Hypoxia

Spatial-Temporal overlapping ⇐ High dose rate

⇕

High flux
Short exposure time ⇒ NO Monochromatic beam

Radiobiology with Laser Driven-Ion

Early work

Conventional Accelerators

E_p>60MeV, dose 1Gy ~ Dose rate ~ 0.1Gy/s (Cyclo/Synchrotron)

S D Kraft, *et al.*, New Journal of Physics (2010)

E_p~7MeV, dose 0.137Gy/pulse ~ Dose rate ~ 10^8Gy/s (150 TW laser system, Draco)
I ~ 5×10^{20} W/cm^2

Yogo, A. *et al.*, Applied Physics Letters (2011)

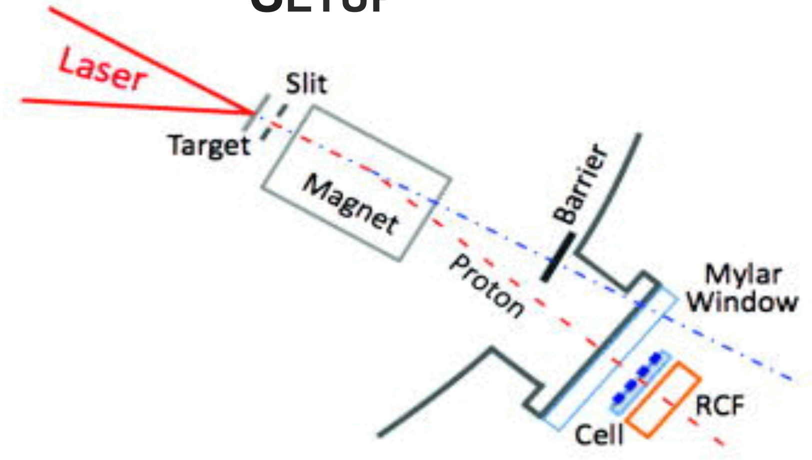
E_p~2.25MeV, 0.2Gy/pulse ~ Dose rate ~ 10^7G/s (25 TW laser system, J-KAREN)
I ~ 5×10^{19} W/cm^2

Doria, D. *et al.*, AIP Advances (2012)

E_p~4MeV, 1Gy/pulse ~ Dose rate ~ 10^9G/s (35 TW laser system, TARANIS)
I ~ 1×10^{19} W/cm^2

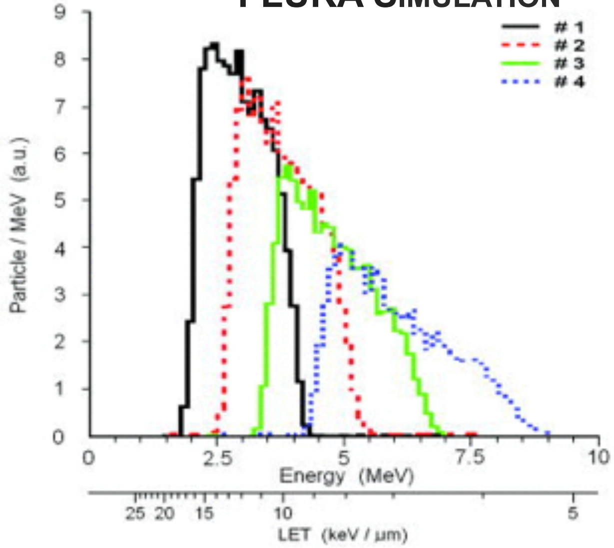
Radiobiology with Laser Driven-Ion

SETUP



ENERGY DISTRIBUTION

FLUKA SIMULATION



TARANIS LASER

LASER PARAMETERS

Energy	~25 J (~35 TW)
Pulse length	< 800fs
Wavelength	1053nm
Repetition rate	One shot every 12 minutes

Proton beam characteristics @ cell plane

Dispersion: in 20mm from 3MeV to 10MeV

Energy Res.: ~ 0.27MeV/mm energy overlapping (500um slit)

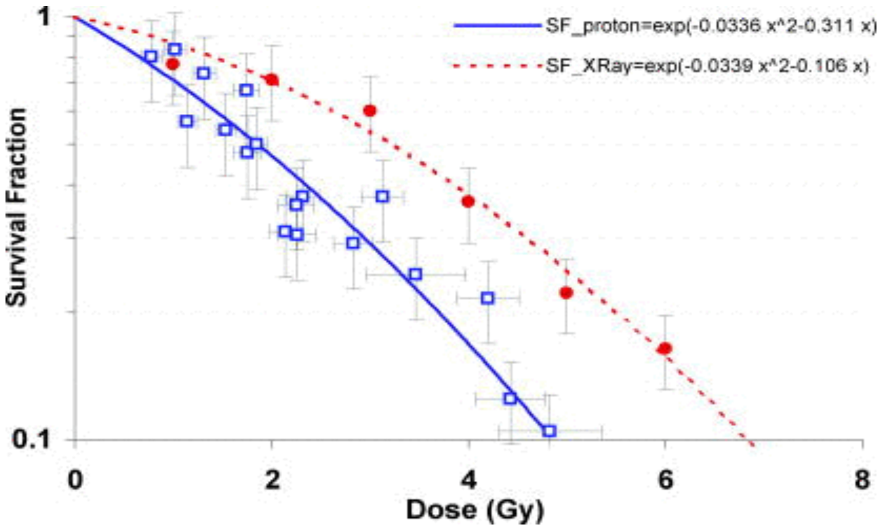
Pulse duration: ~ 1ns (TOF + 500um slit)

Delivered dose @ 5MeV: ~ few Gy/shot

Dose rate: ~ 10^9 Gy/s

Radiobiology with Laser Driven-Ion

SURVIVAL FRACTION FOR V79 CELLS



COMPARISON WITH DATA FROM CONVENTIONAL ACCELERATION:

TARANIS LASER

🟦 5 MeV

□ 3.7 MeV

D. Doria *et al*, AIP Advances, **2**, 011209 (2012)

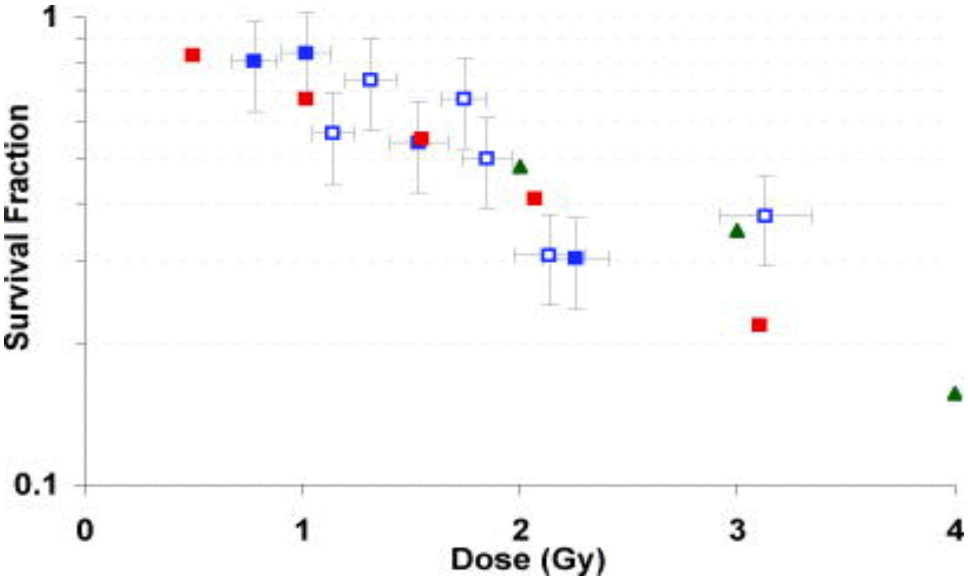
ACCELERATOR

🟥 3.7 MeV

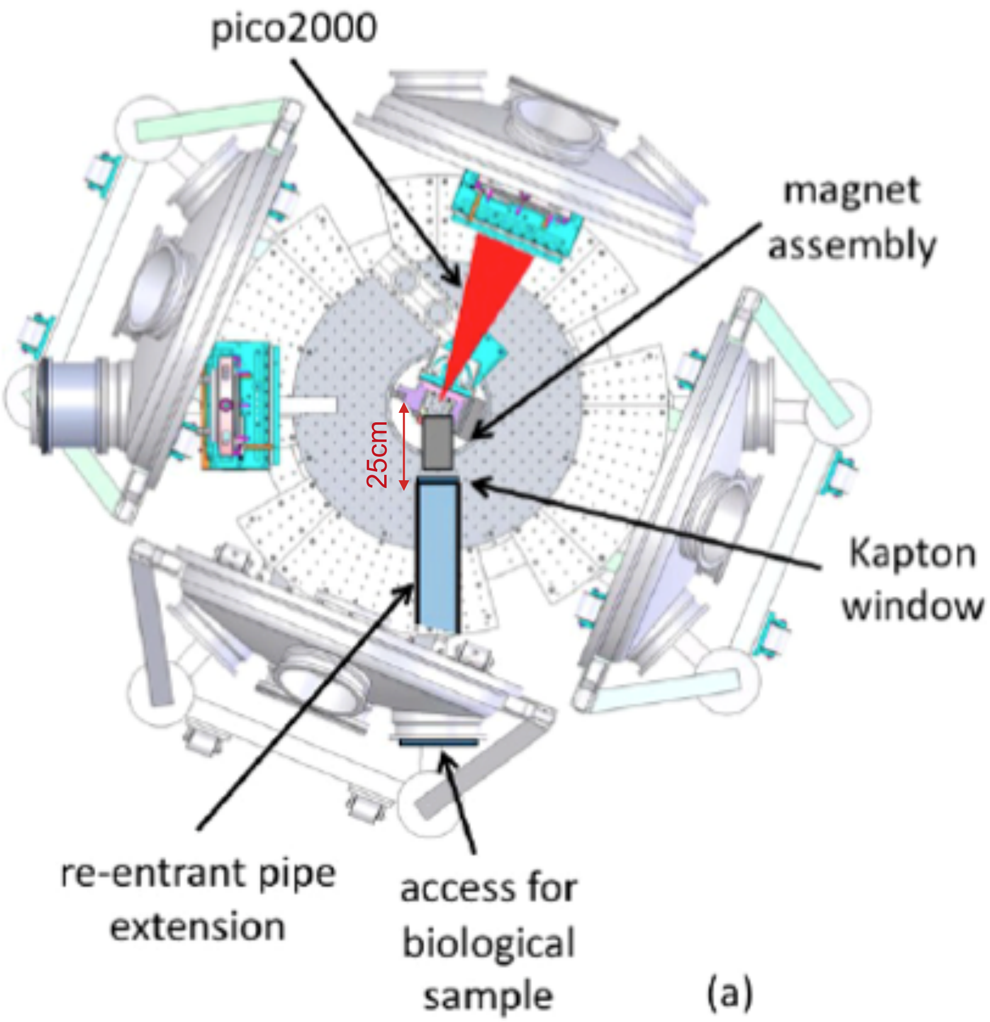
M. Folkard, K. M. Prise, B. Vojvonic, H. C. Newman, M. J Roper, and B. D. Michael, *Int. J. Radiat. Biol* **69**, 729–738 (1996)

▲ 3.2 MeV

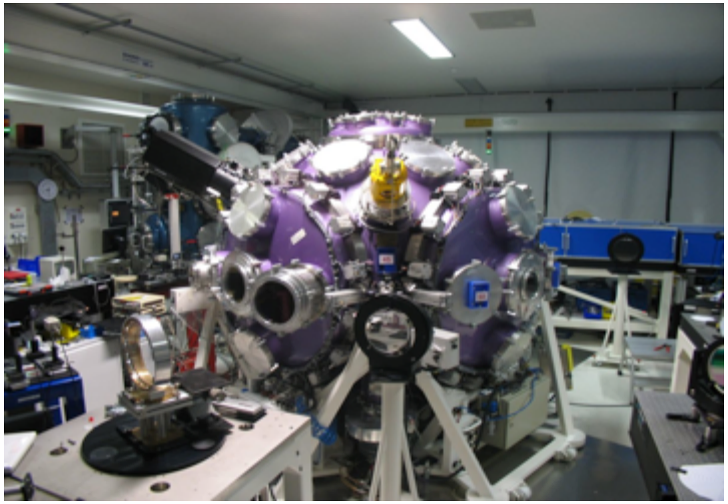
M. Belli, F. Cera, R. Cherubini, F. Ianzini, G. Moschini, O. Sapora, G. Simone, M. A. Tabocchini, and P. Tiveron, *Int. J. Radiat. Biol* **63**, 331–337 (1993)



Radiobiology with Laser Driven-Ion



LULI2000 LASER



LASER PARAMETERS: SOUTH BEAM

Energy	~100 J (~100 TW)
Pulse length	< 1ps
Wavelength	1053nm
Repetition rate	One shot every hour

Proton beam characteristics @ cell plane

Dispersion: in 20mm from 7MeV to 15MeV

Energy Res.: ~ 0.4MeV/mm energy overlapping (400um slit)

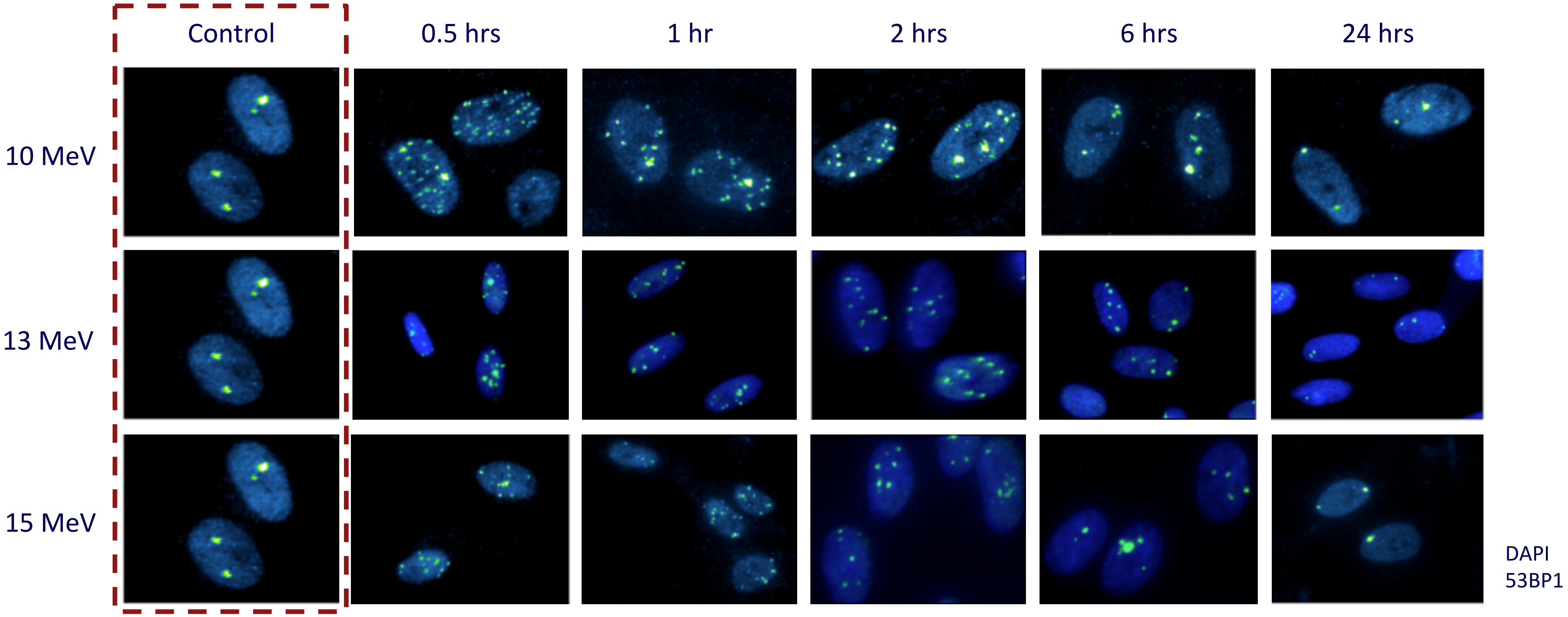
Pulse duration: ~ 0.5ns (TOF + 400um slit)

Delivered dose @ 10MeV: ~ few Gy/shot

Dose rate: ~ $4x10^9$ Gy/s

Radiobiology with Laser Driven-Ion

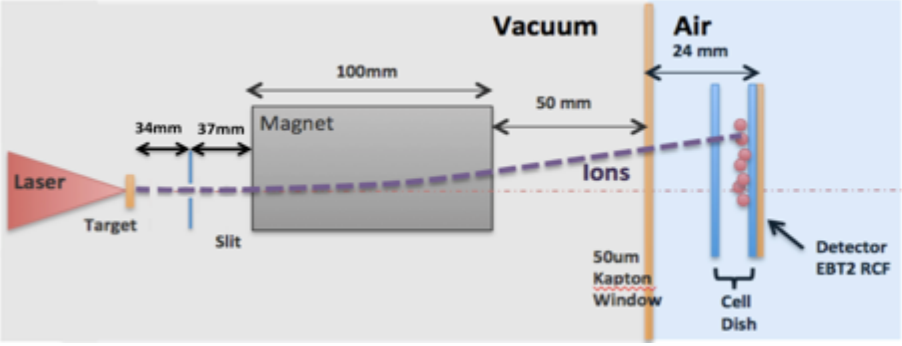
γ-H2AX foci WITH AG0 CELLS



Example images of the 53BP1 foci taken at the positions irradiated by 10MeV, ~13MeV and 15MeV protons, at the 5 different time points of 0.5, 1, 2, 6 and 24hrs post irradiation and the control.

Radiobiology with Laser Driven-Ion

SETUP



GEMINI LASER

LASER PARAMETERS

Energy	~20J (~500 TW)
Pulse length	< 45ps
Wavelength	800nm
Repetition rate	One shot every 30 sec

Proton beam characteristics @ cell plane

Dispersion: in 7mm from 10MeV to 15MeV

Energy Res.: ~ 0.5 MeV/mm energy overlapping (500um slit)

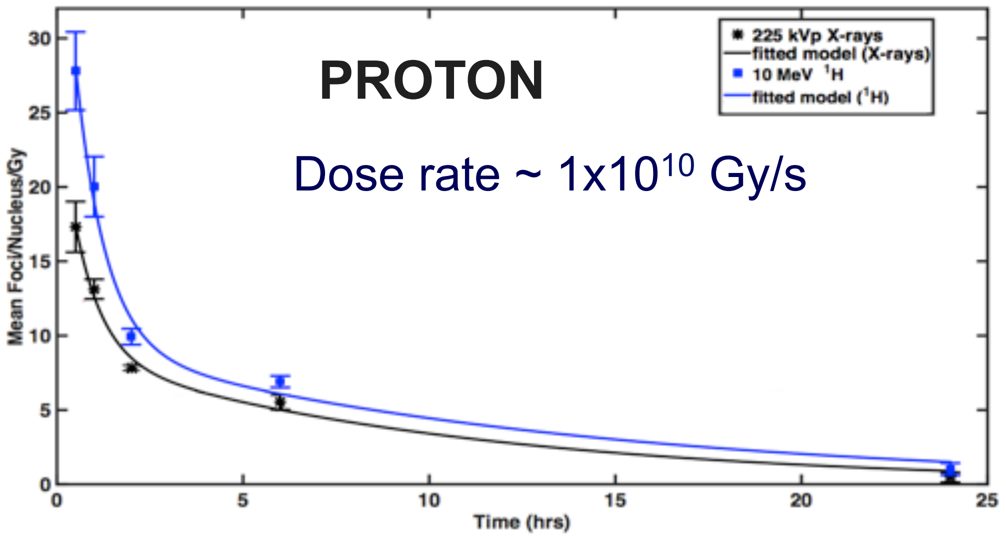
Pulse duration: ~ 0.4ns (TOF + 400um slit)

Delivered dose @ 7MeV: ~ few Gy/shot

Dose rate: ~ 1x10^{10} Gy/s

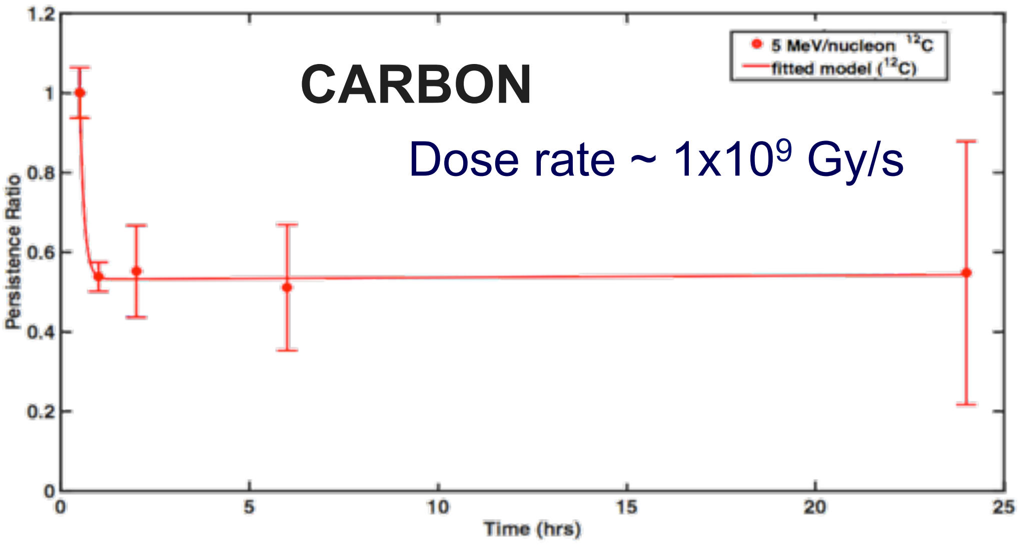
Radiobiology with Laser Driven-Ion

Investigation of DNA DSB of AG0 cells by means of the γH2AX assay



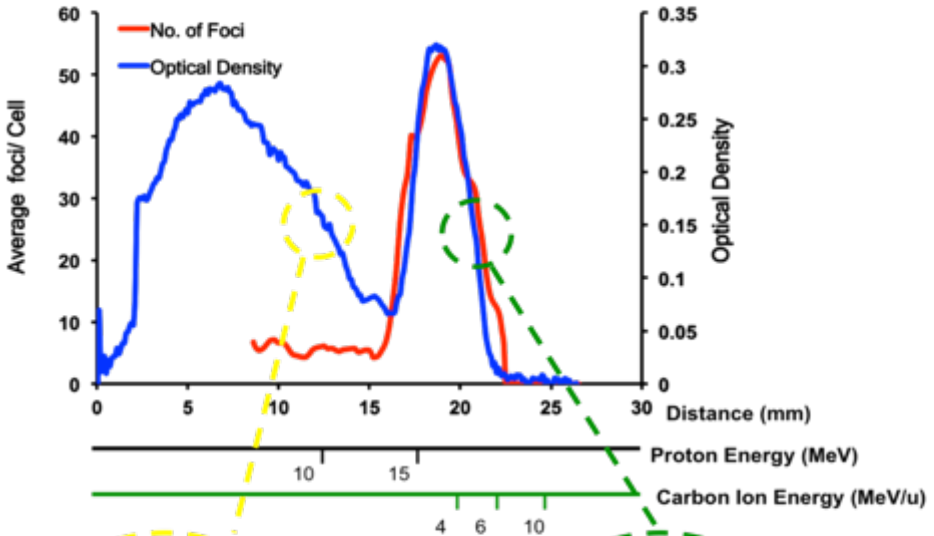
PROTON

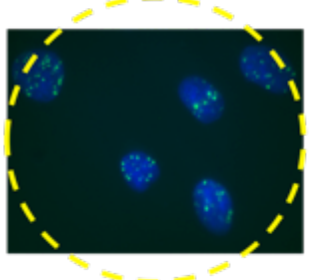
Dose rate ~ 1x10^{10} Gy/s



CARBON

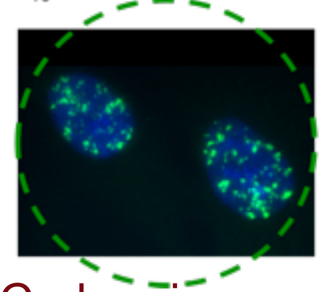
Dose rate ~ 1x10^{9} Gy/s





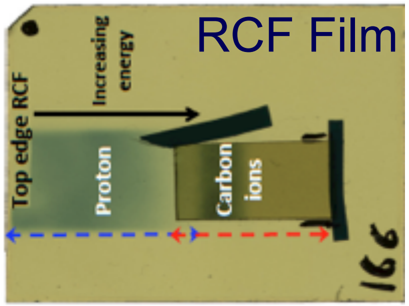
Protons

10 MeV (LET~ 5 KeV/µm)



Carbon ions

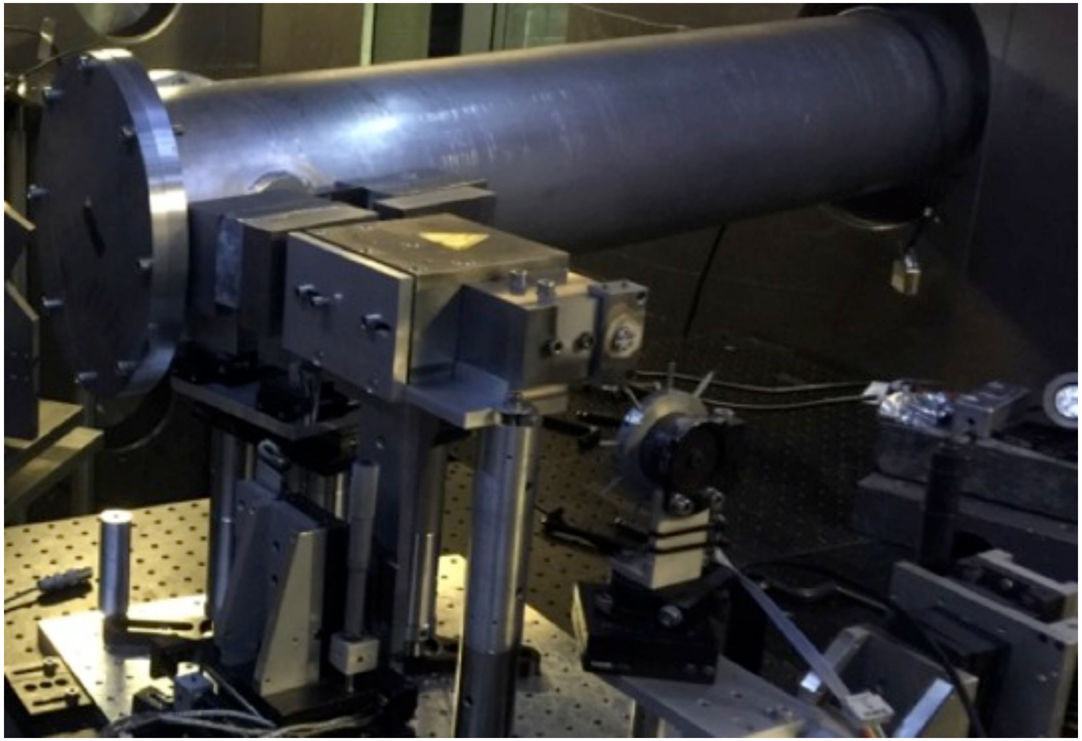
5 Mev/u (LET~ 300 KeV/µm)



RCF Film

Radiobiology with Laser Driven-Ion

SETUP



VULCAN LASER (TAP)

LASER PARAMETERS

Energy	~600J (~1 PW)
Pulse length	~ 600ps
Wavelength	1053nm
Repetition rate	One shot every 30 min

Irradiation of AG01522 cells with laser accelerated protons and carbon ions in;

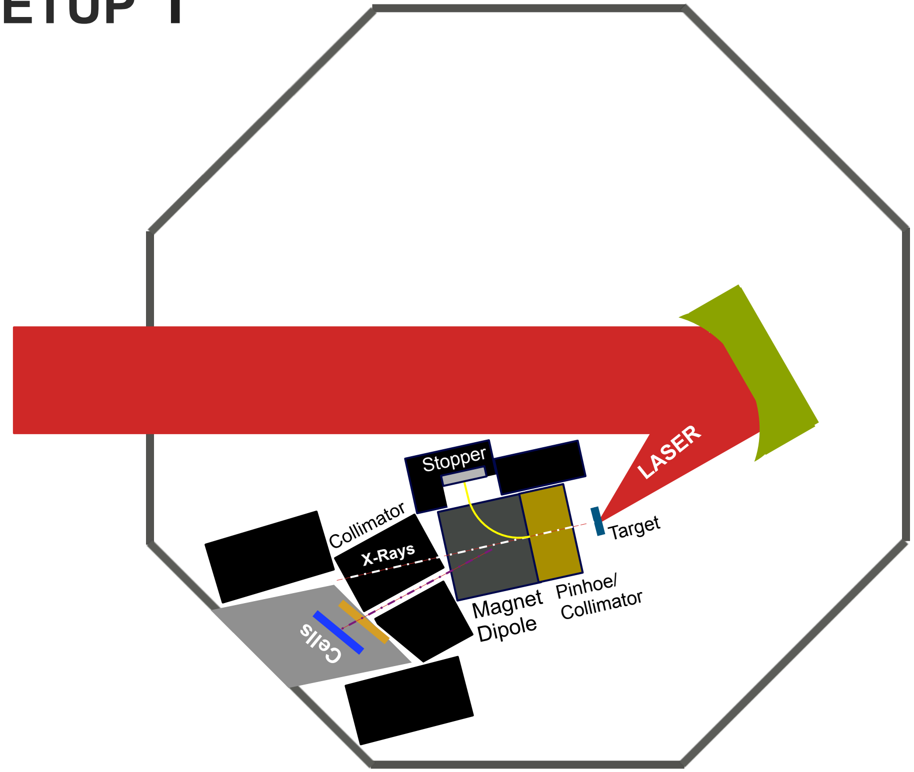
Dose rate: > 1x10^9 Gy/s

- Oxic conditions (21% O_2)
- Physical anoxia/hypoxia (0-0.1% O_2)
- Free radical quenching (0.5% DMSO)
- Chemical hypoxia ($CoCl_2$)

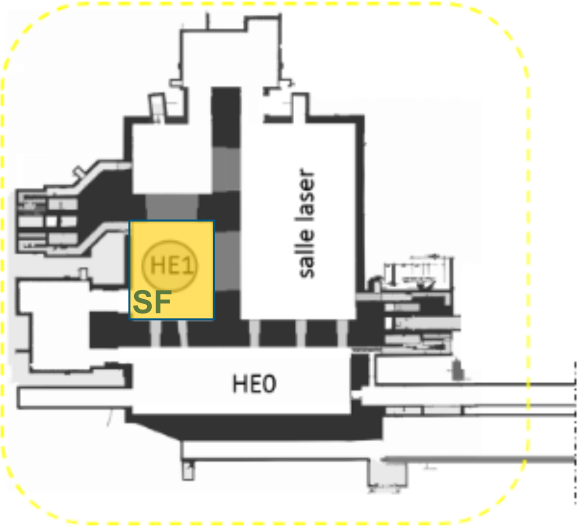
Hypoxic samples kept in reduced oxygen environment post irradiation (5% O_2).

Radiobiology with Laser Driven-Ion

SETUP 1



APOLLON LASER (SF)

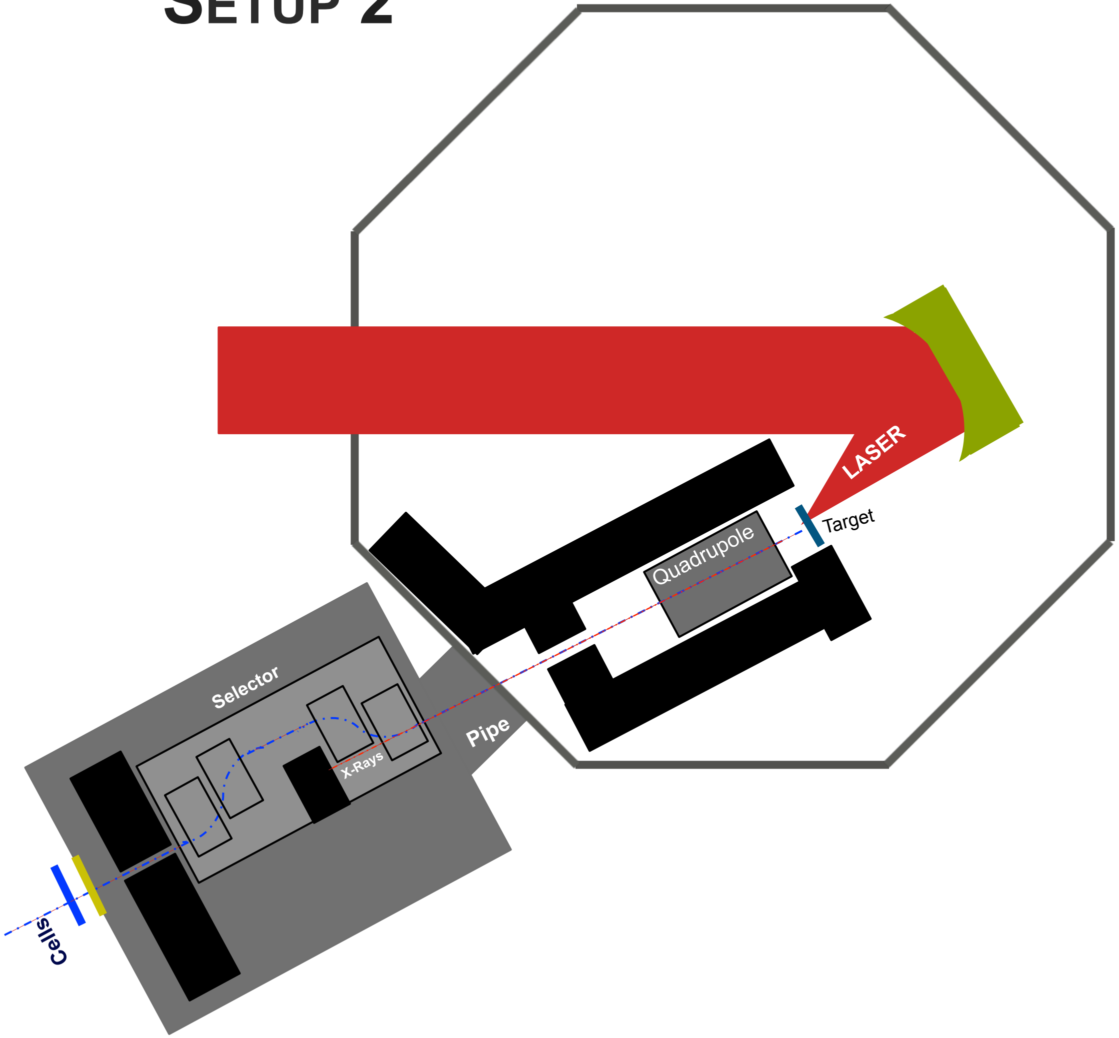


LASER PARAMETERS

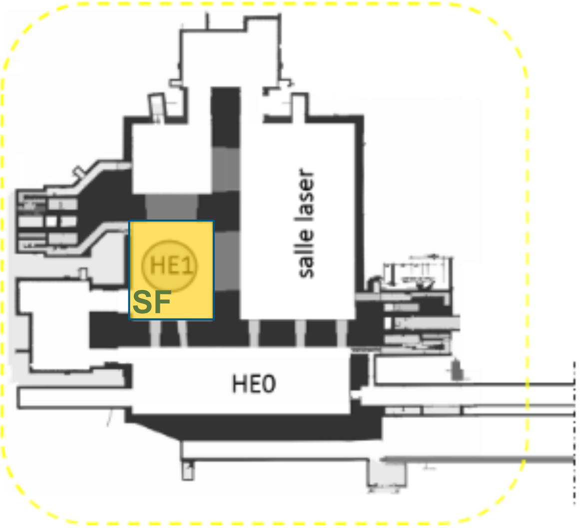
Intensity	up to 10^{22} W/cm^2 (~5 PW)
Pulse length	~ 15fs
Wavelength	1053nm
Repetition rate	One shot every min

Radiobiology with Laser Driven-Ion

SETUP 2



APOLLON LASER (SF)



LASER PARAMETERS

Intensity	up to 10^{22} W/cm^2 (~5 PW)
Pulse length	~ 15fs
Wavelength	1053nm
Repetition rate	One shot every min

Conclusion

We might be able to investigate:

- TNSA Mechanism
- RPA Mechanism:
    - Instabilities
    - Relativistic Transparency
    - Ion energy optimization
- Radiobiology:
- Ultra high dose rate (up to sub 10^{12} Gy/s)
- High dose rate induced Hypoxia
- Spatial-Temporal overlapping
- First study in VIVO

Thank you