Focus sur les techniques d'accélération laser-plasma

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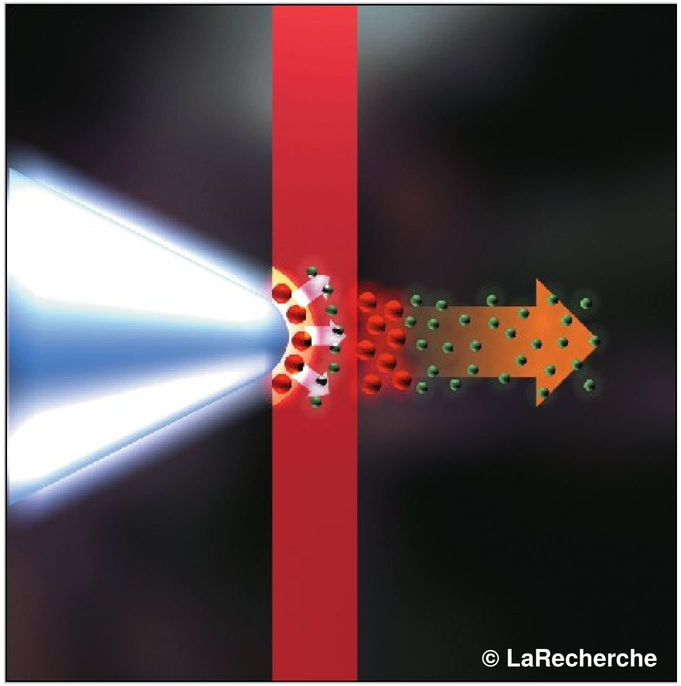
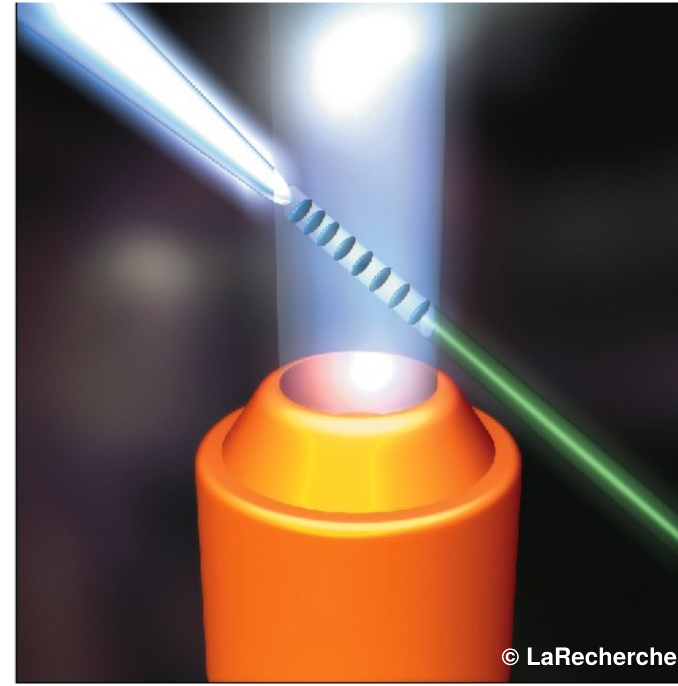
Les accélérateurs laser-plasma





High accelerating gradients (GV/m → TV/m): smaller machines
Industrial advantages: reduced radioprotection burden, ease of beam distribution
Exciting features: rich physics behind, exotic parameters (duration, brillance, …), versatility

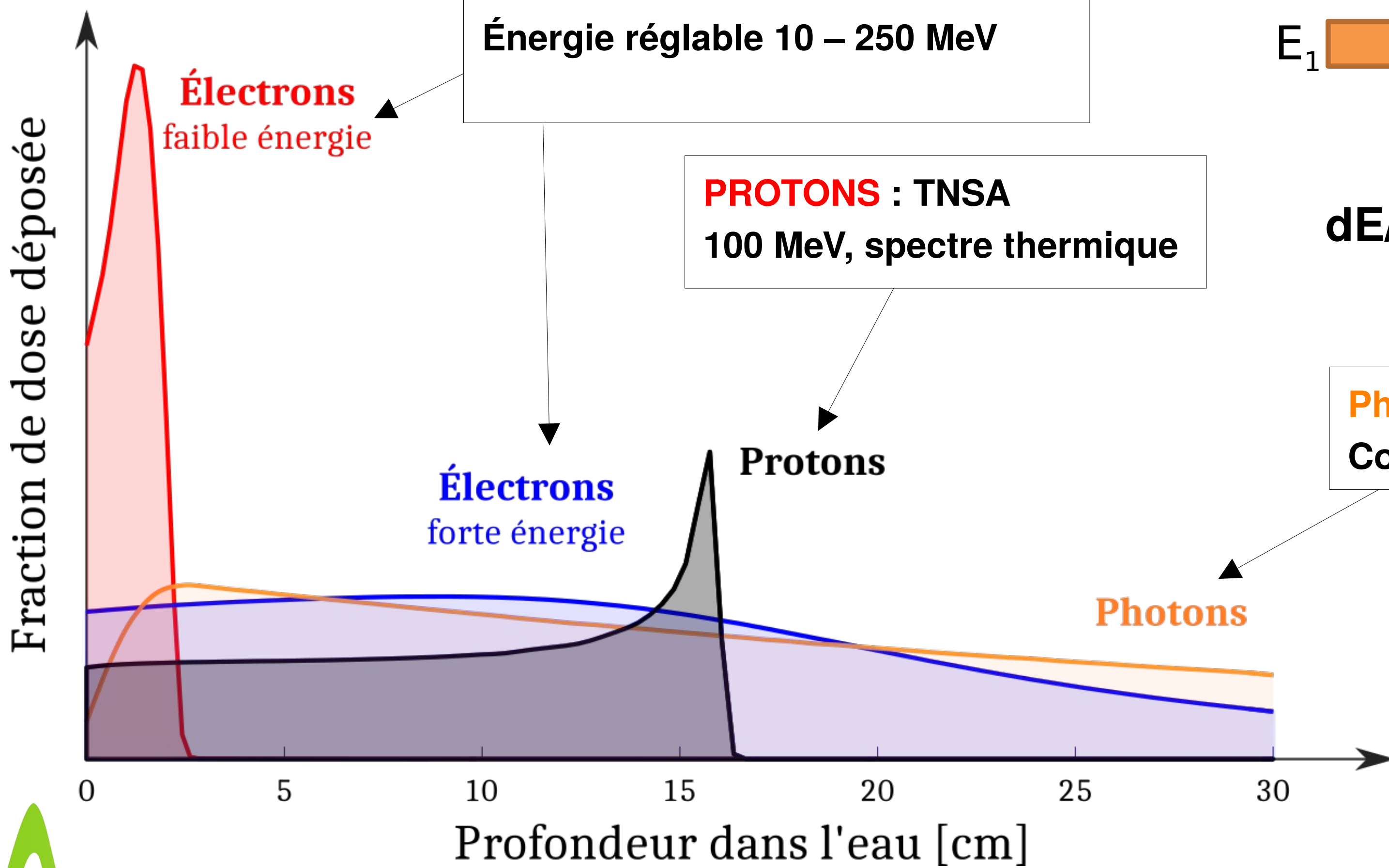
Energies: 100s MeV (protons), >1 GeV (electrons)
Duration: 10fs - ps
Charges: pC – 100s nC

Source versatile et réglable

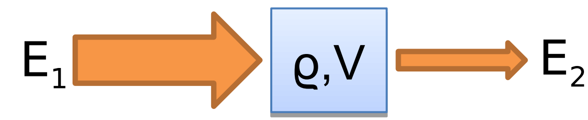
ÉLECTRONS : mécanismes divers
Énergie réglable 10 – 250 MeV

PROTONS : TNSA
100 MeV, spectre thermique

Photons : bétatron, Compton inverse, freinage



Deposited dose



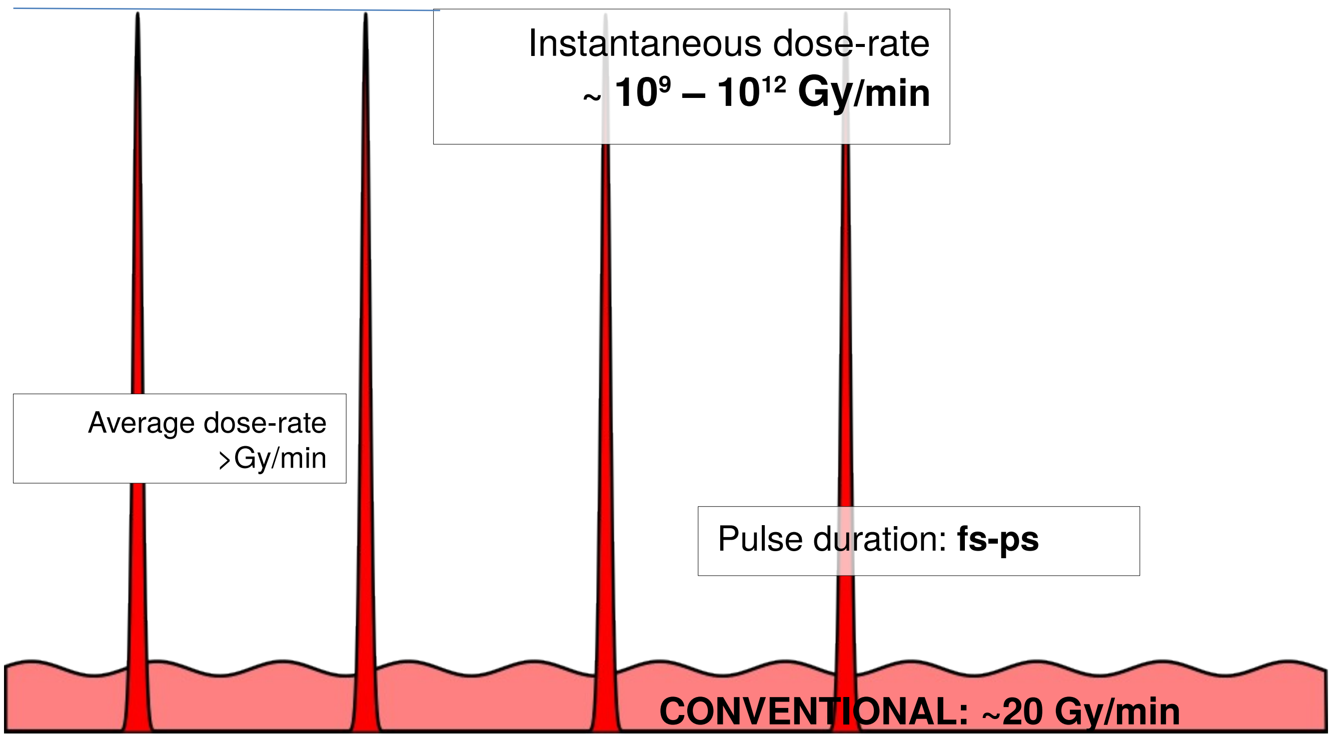
Gy = J/kg

dE/dz = LET [keV/µm]

Echelle temporelle : *fractionnement rapide*(*)

Considering common ~1Watt average power laser:
(at ~20 Gy/min. condition)

LASER-DRIVEN



Repetition: **Hz - kHz (or single)**

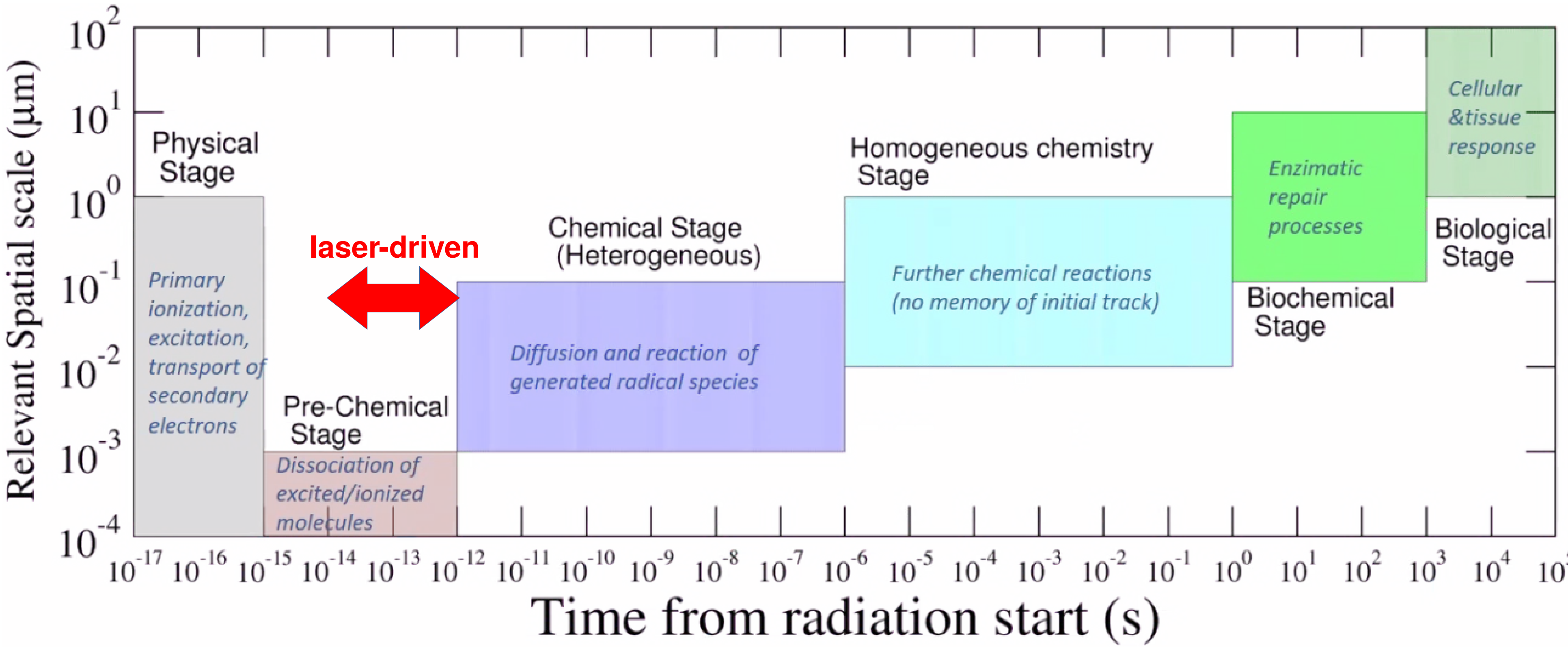
High rep. rate, low dose
kHz, **100s µGy/pulse**.
Continuous-like?

~Hz rep. rate, **~100s mGy/pulse**.
Fast-fractionated (*)

Single pulse (>10Gy) irradiation
FLASH (?)

(*) Bayart et al., Sci Rep. 2019

Dose et temps



(courtesy E. Scifoni, Uni TN)

Échelles spatiale (Salle Jaune, LOA)

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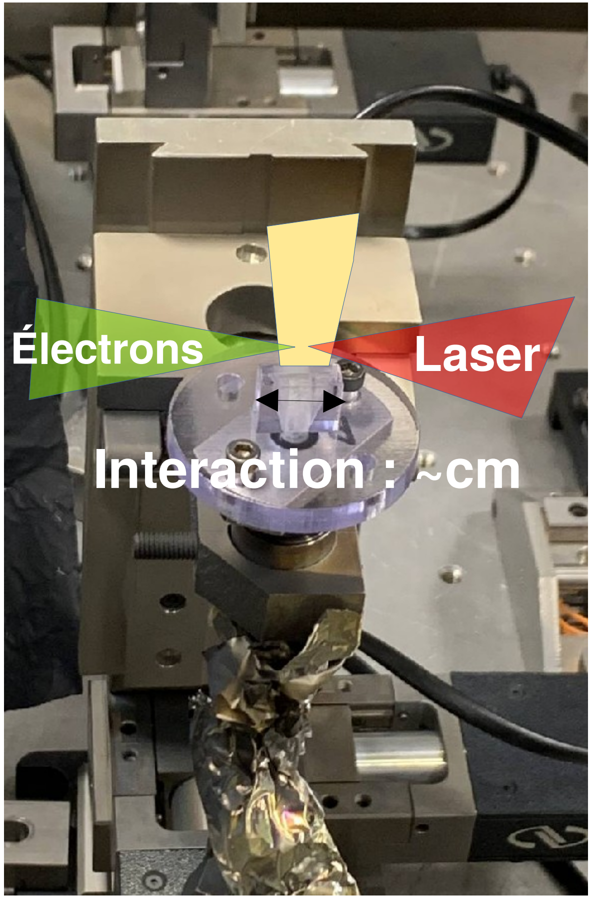

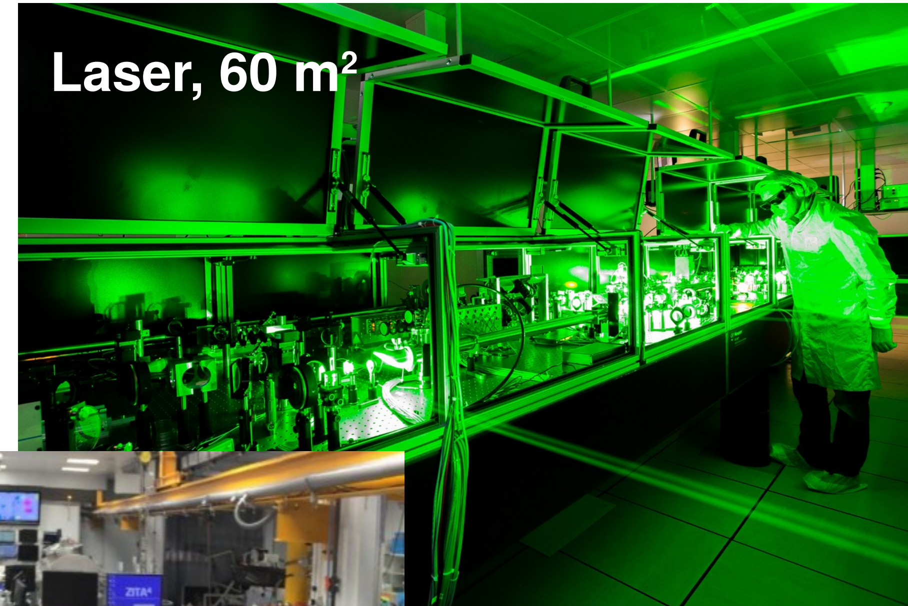

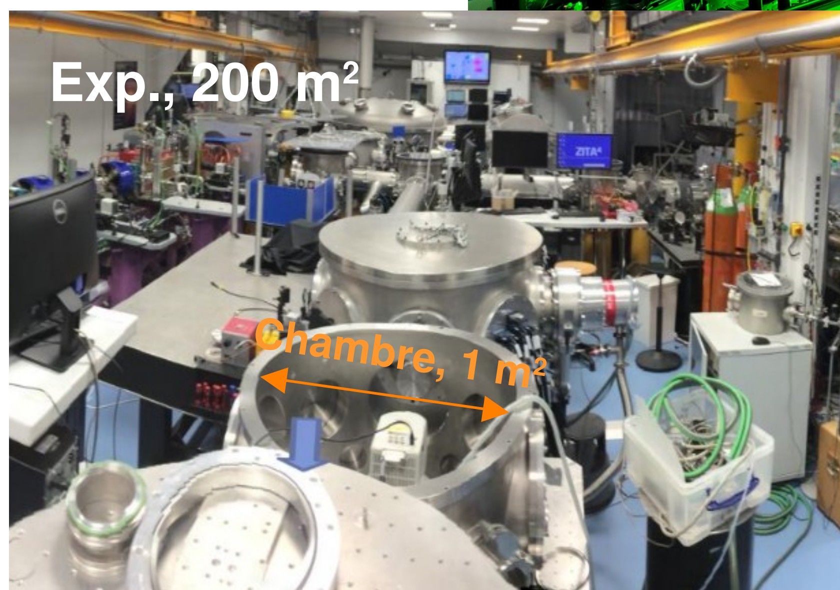

Protons

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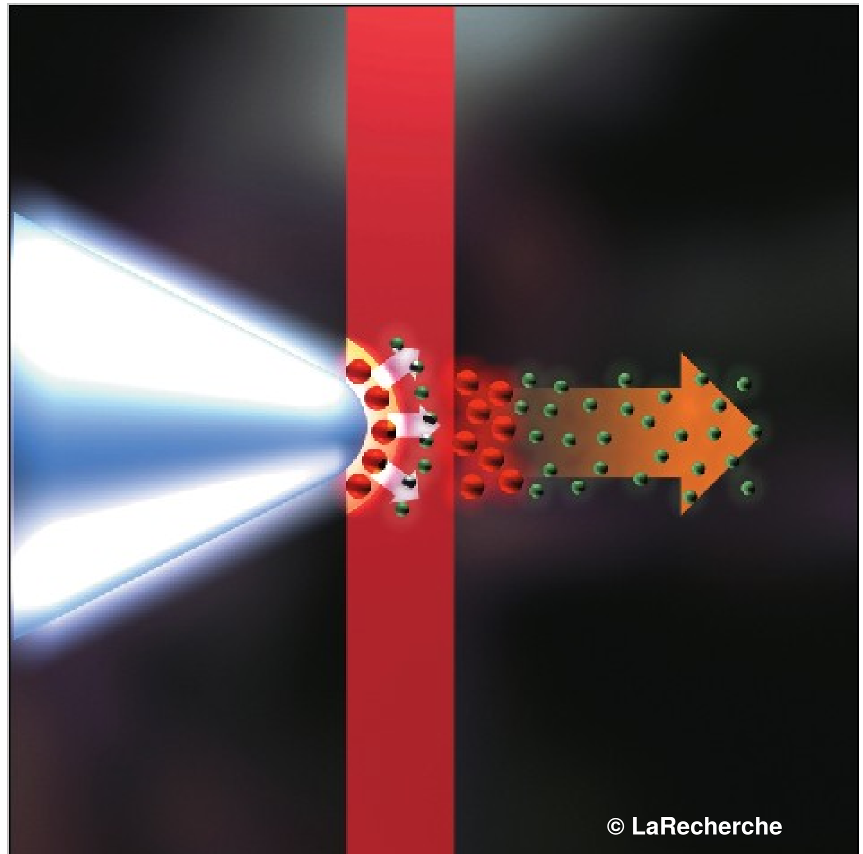
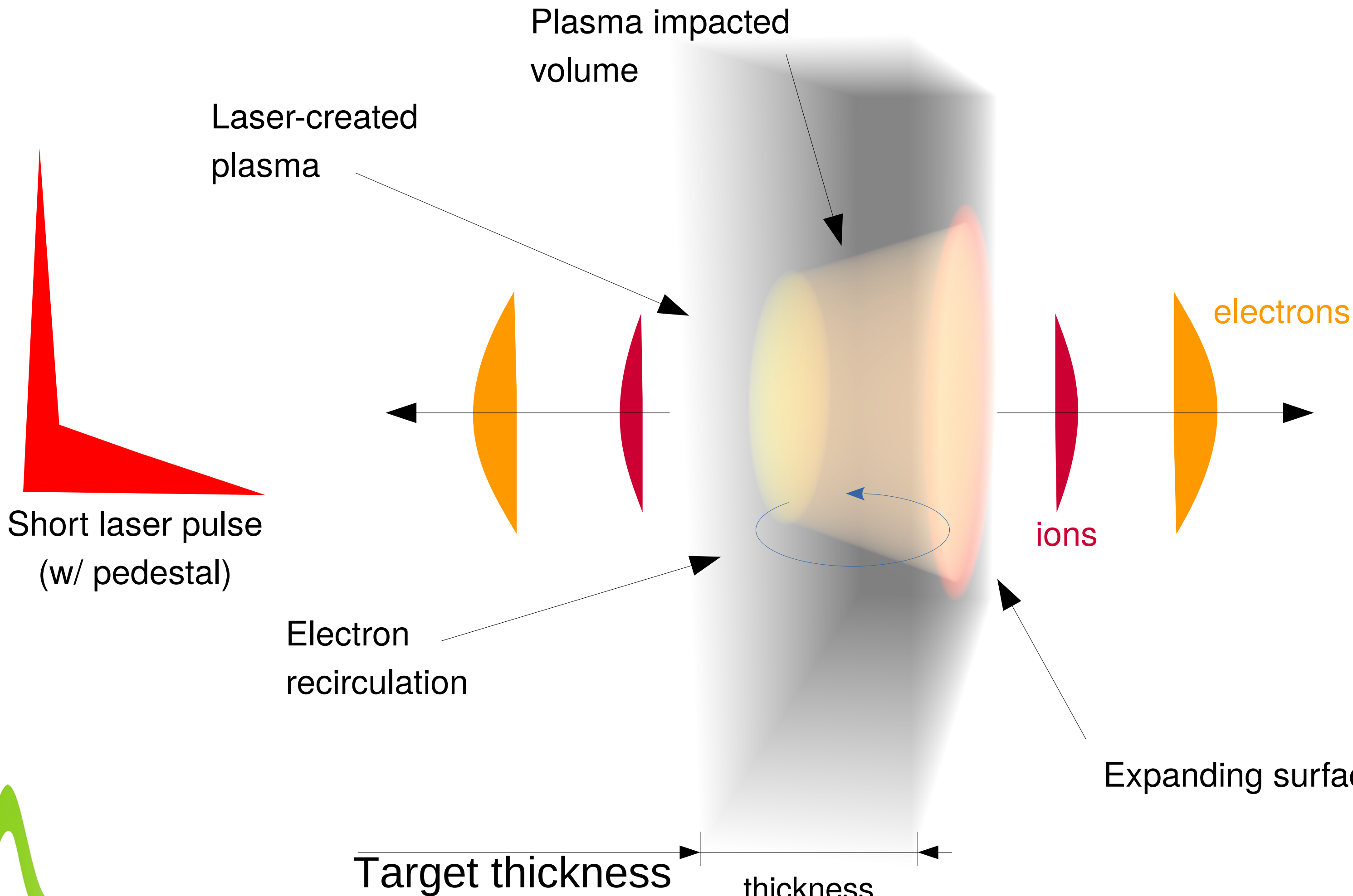
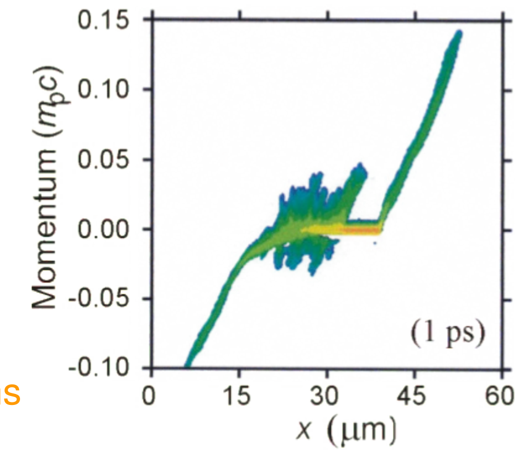


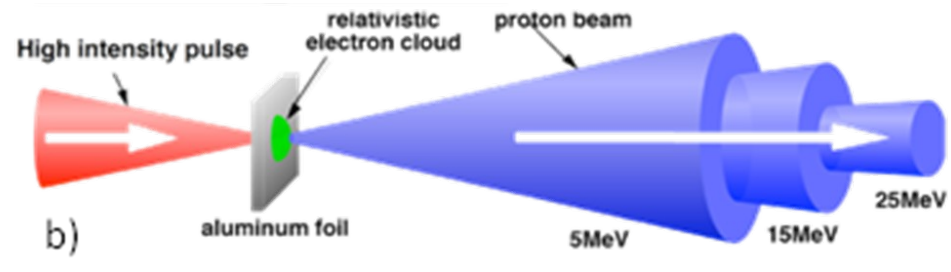
TNSA: Target Normal Sheath Acceleration

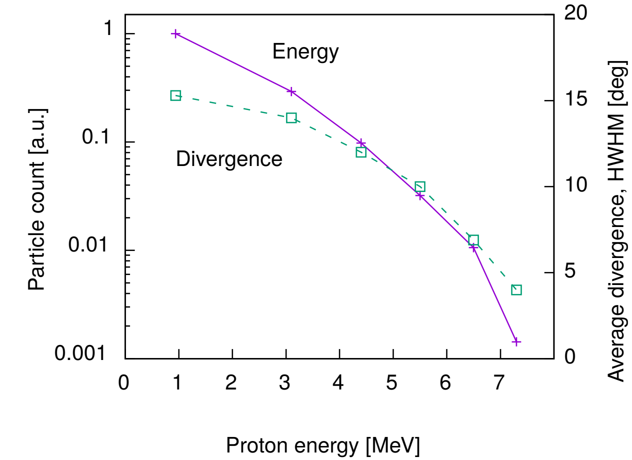


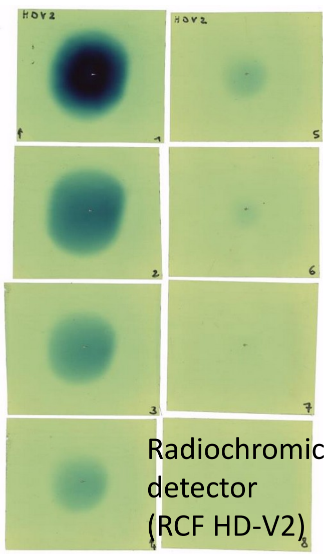


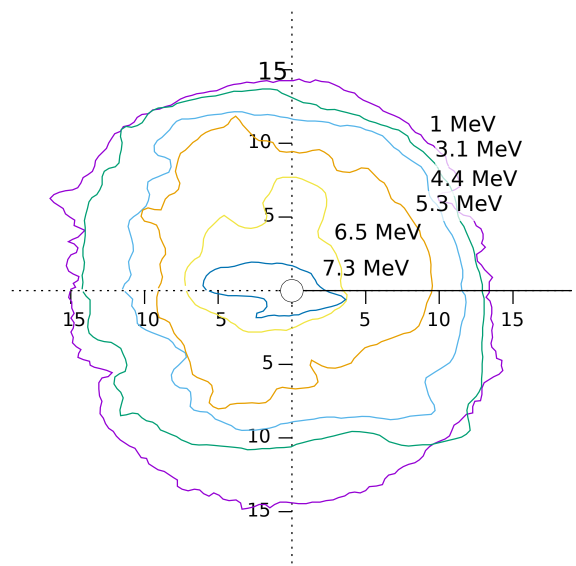
$$E_p \propto I_0^{1/2}$$

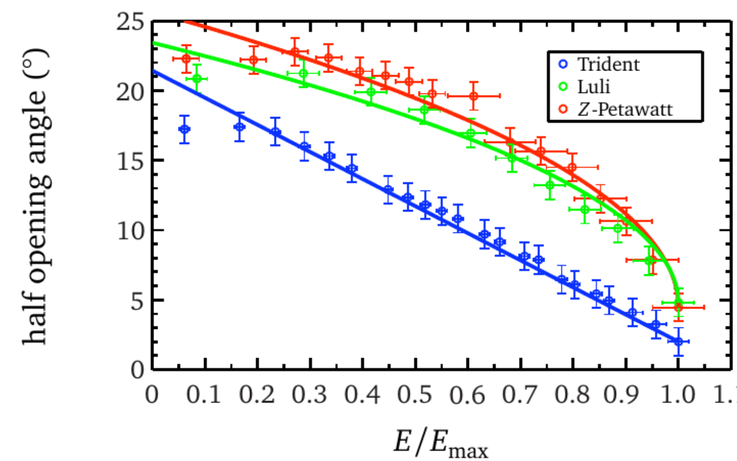
Energy, charge and divergence









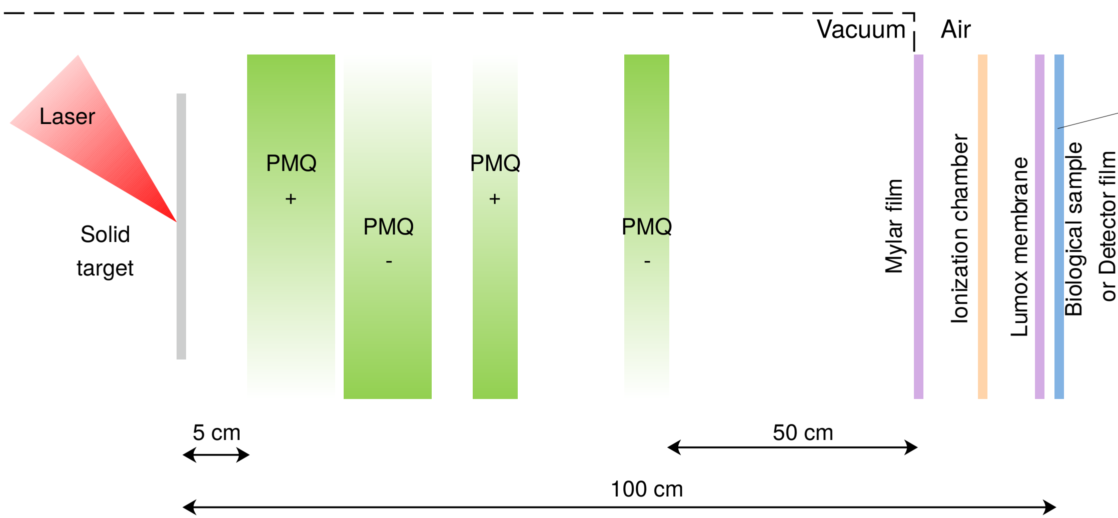


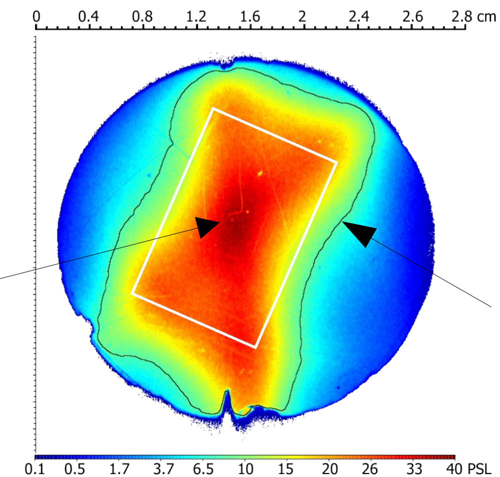
Charge: 1 – 10 nC (depending on laser energy and waist)

Spectrum: thermal (with sharp cutoff)

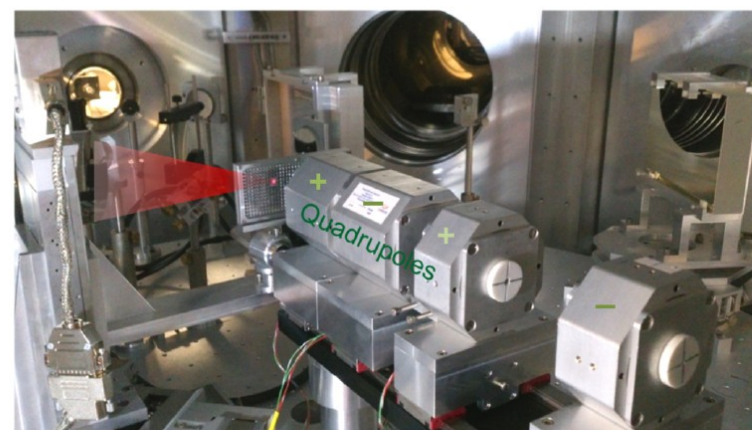
M. Roth, doi:10.5170/CERN-2016-001.231 (2016)

Transport par quadrupoles permanents (LOA, 2017)





10^8 protons/2 cm^2
(~50/100 um^2)
0.7Gy/shot (~ns)



L. Pommarel, Ph.D thesis, EDOM 2017
F. Schillaci, L. Pommarel et al., J. Inst. 2016
L. Pommarel et al, Phys. Rev. Acc. Beam, 2017

Effet de cadence

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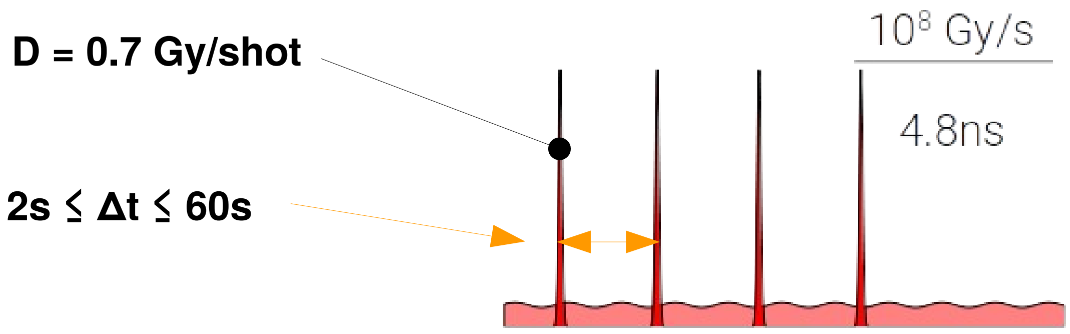
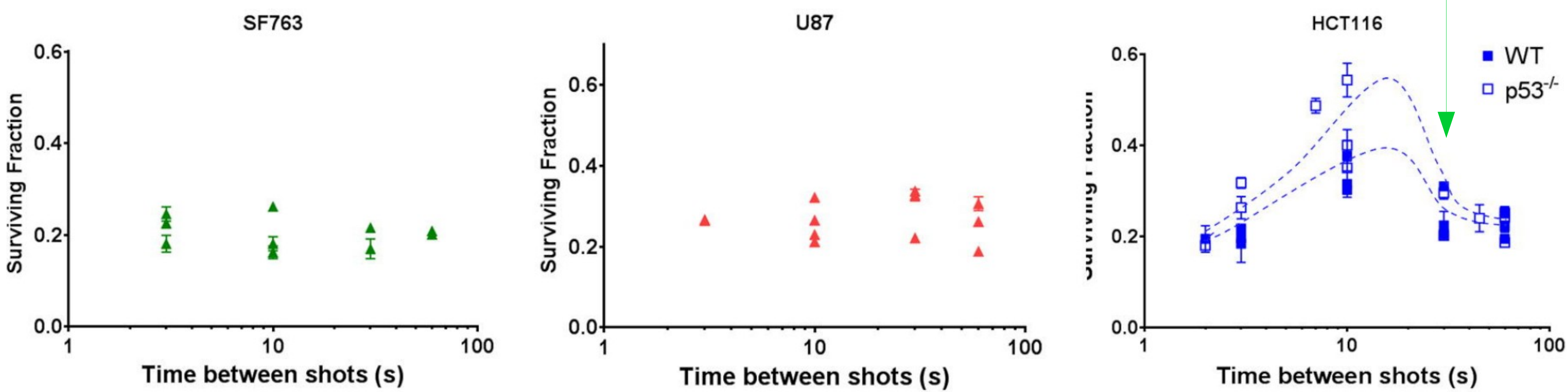


- Toxicity varies with time (at constant dose)
- D_{10}(WT) → D_{10}(p53)

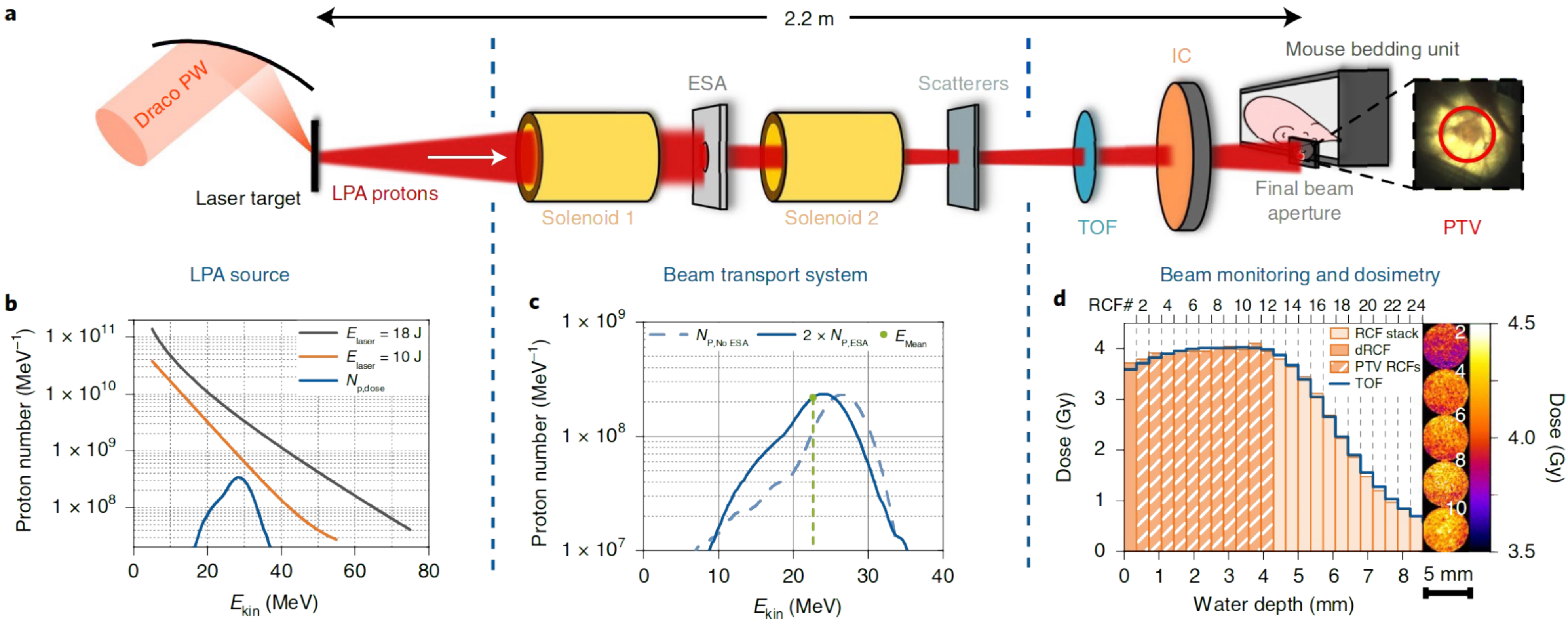
Survival assay

Varying pace at D_{10}(HCT116-WT) ≈ 4.2 Gy (**6 shots**)



Bayart, E. et al. Sci. Rep. 2019

Transport par solénoïde pulsé (HZDR Dresde, 2022)



4 Gy/tir, 5 mm diamètre,
4 mm SOBP

Kroll et al, Nat Phys 2022

Single pulse laser irradiation: FLASH

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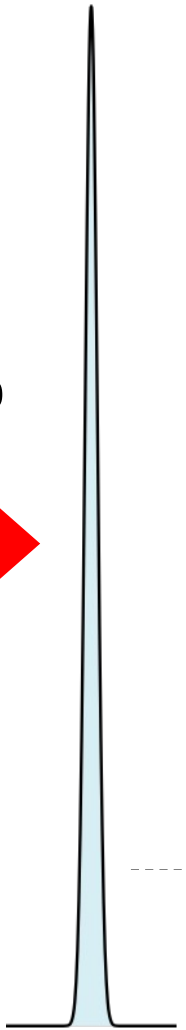
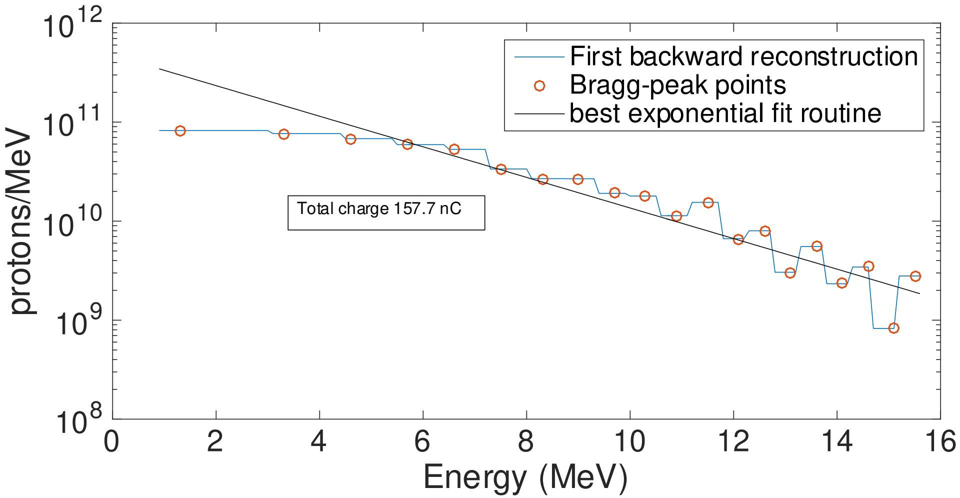
Pico2000 laser



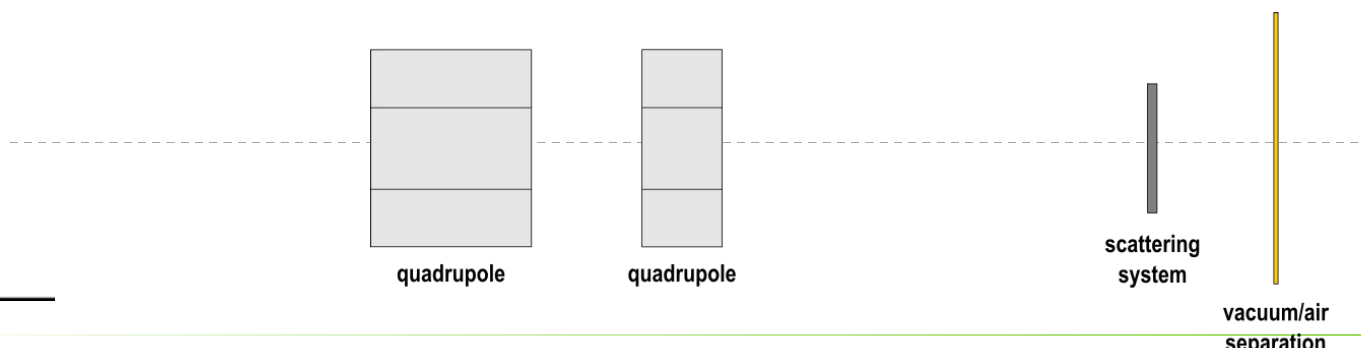


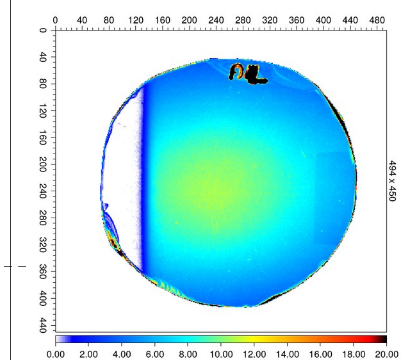
PROTON SOURCE

Duration: ~ps

Charge: > 150 nC/pulse

E_{max}: 20 MeV





>10 Gy, 5 ns, σ>1 cm²

Laser-driven protons, FLASH

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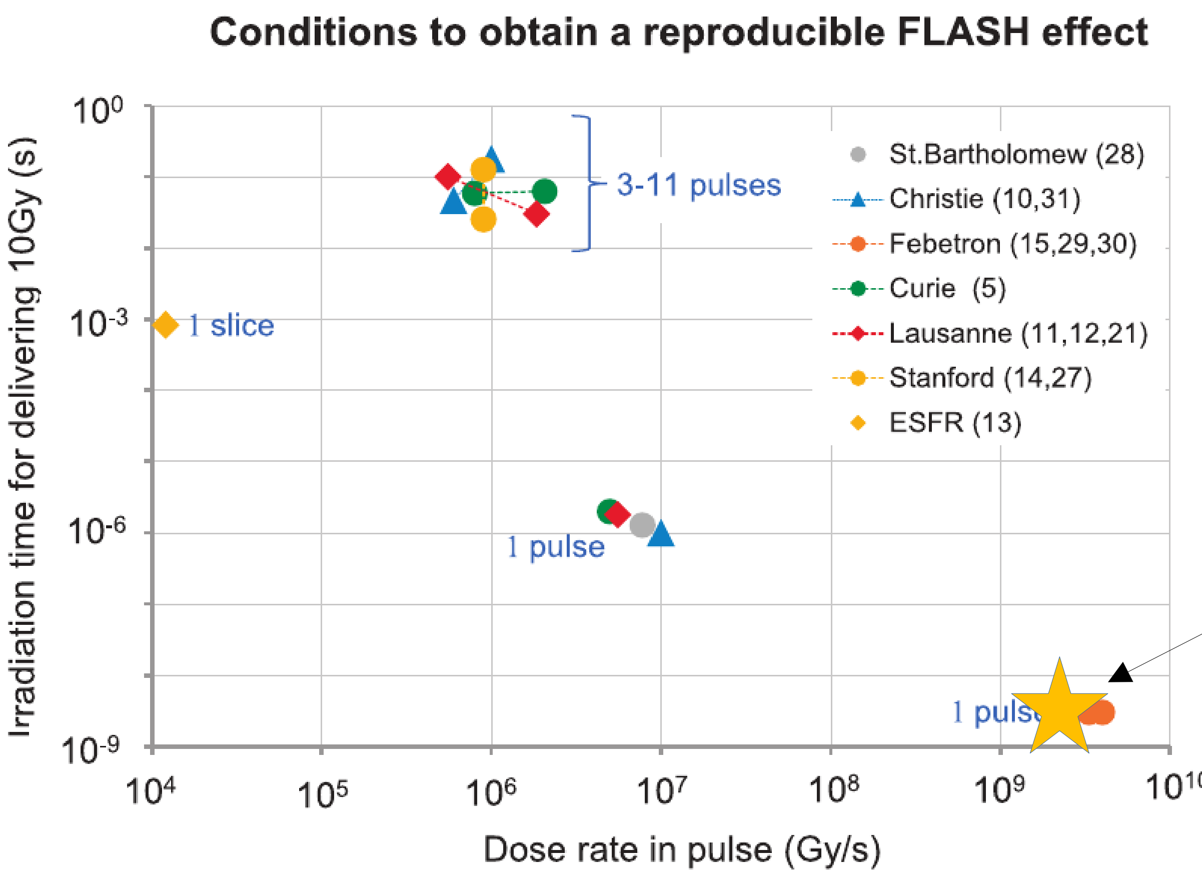

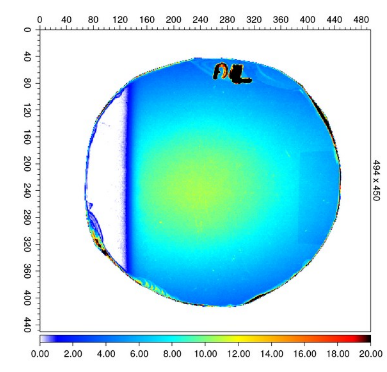

10 Gy, 5 ns, σ>1 cm²

(although ***high-LET*** radiation quality)

J. D. Wilson et al., Frontiers in Oncology, vol. 9, Jan. 2020, doi: 10.3389/fonc.2019.01563.

Conclusions protons

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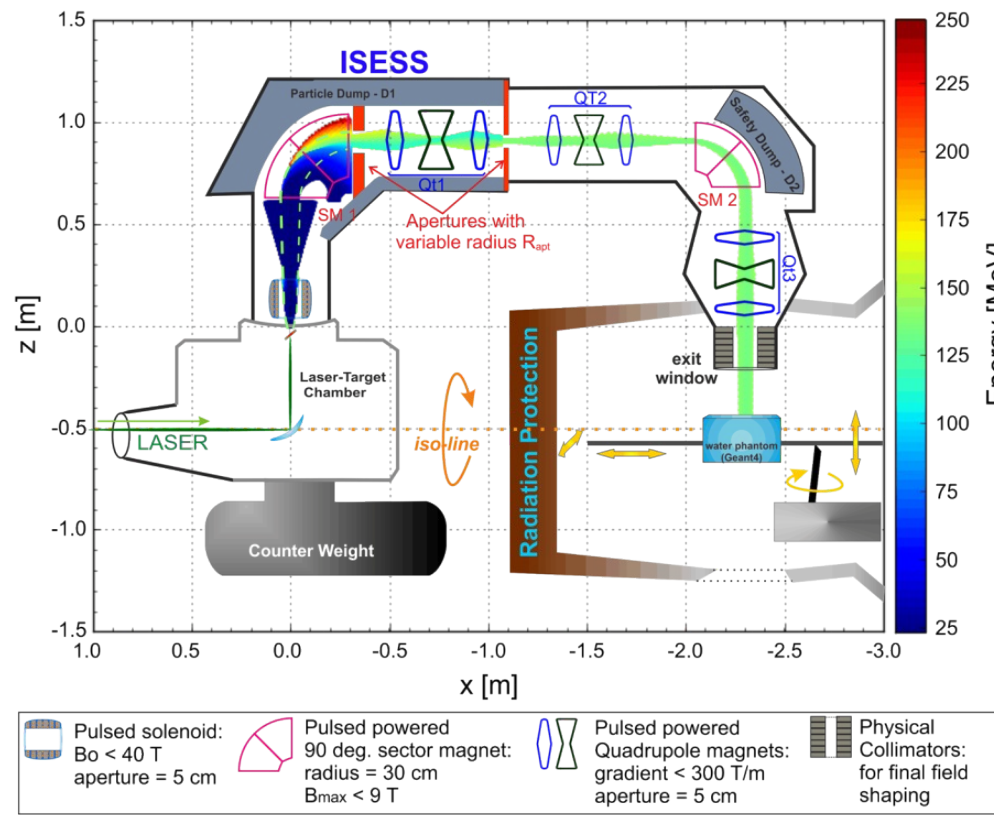
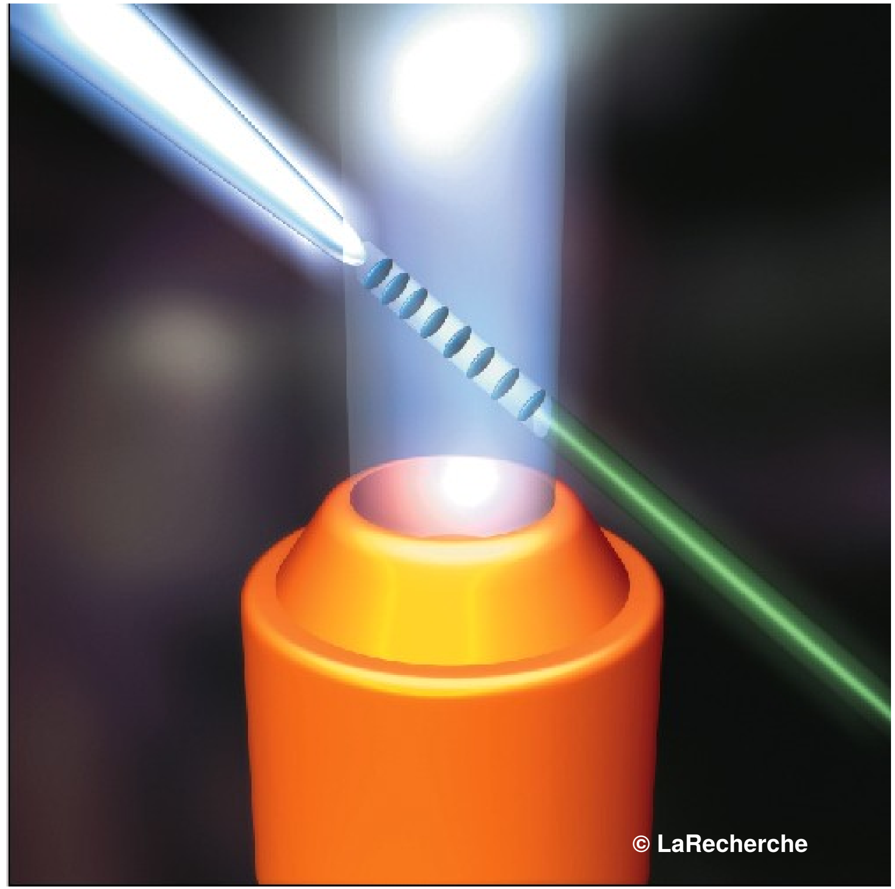
- Accélérateur compacte ↗
- Gradient accélérateur très important (TV/m) ↗
- Énergies thérapeutiques difficiles à obtenir ↘
- Spectre difficile à manier (grosse pertes d'efficacité) ↘

  → plus grand laser !
- Option : « gantry pulsé »

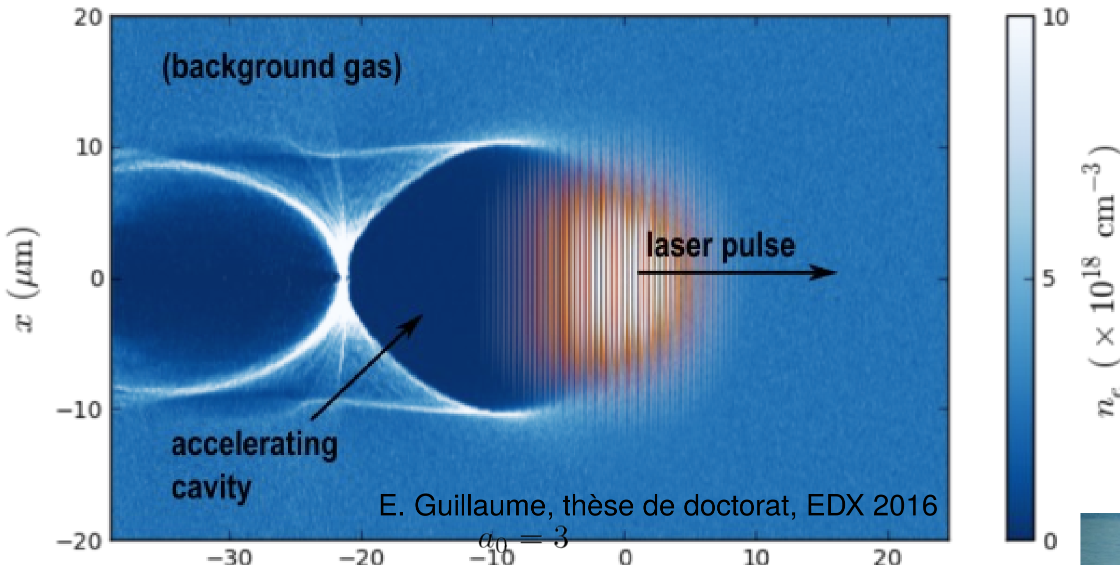


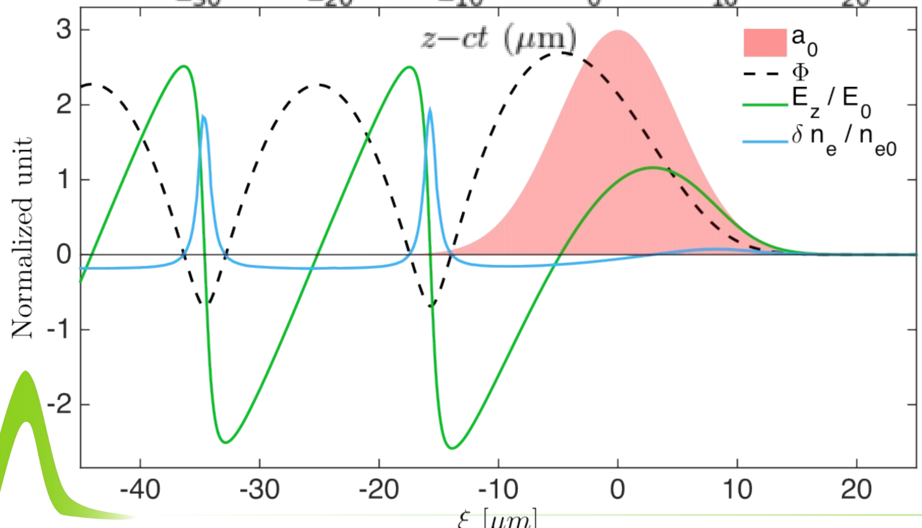
Masood et al, APB 2014

Électrons



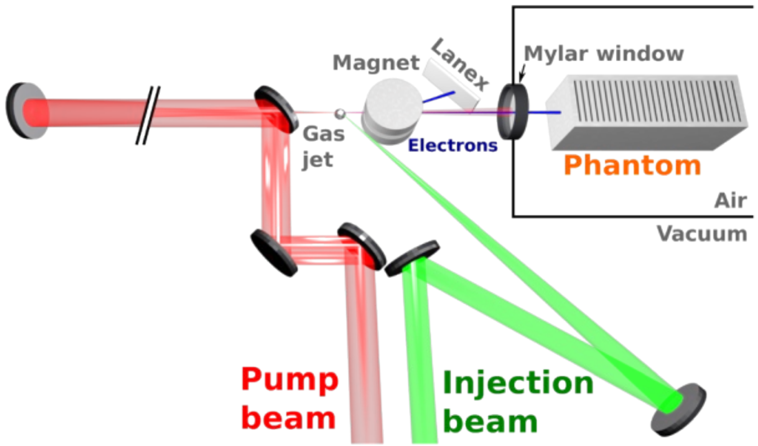
Accélération d'électrons par laser



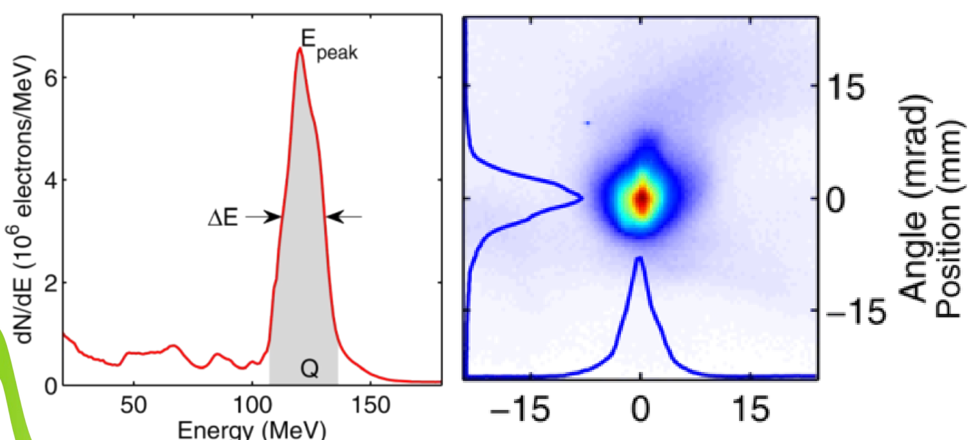


- Formation d'une onde de sillage
- Formation d'une cavité accélératrice
- Piégeage et accélération des électrons
- Énergies et conditions diverses...

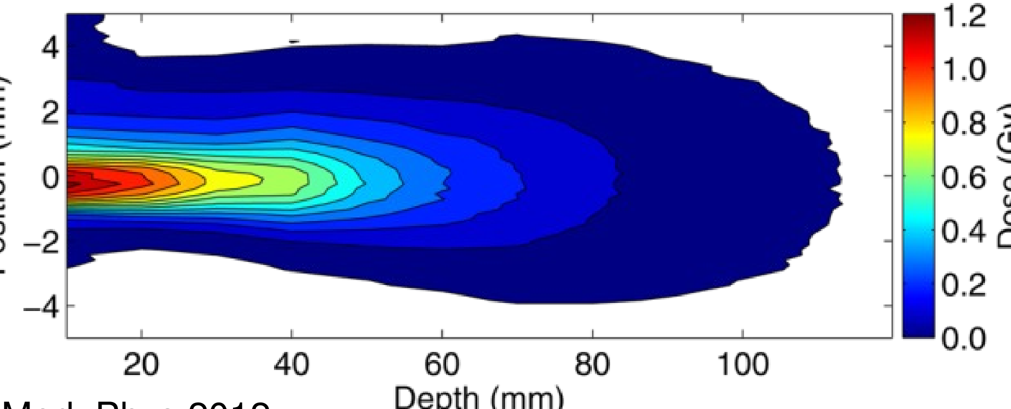
Premières irradiation de fantôme (LOA, 2012)



- Faisceau peu divergent (irradiation directe, PBS)
- Contrôle sur le spectre (changement d'énergie)
- E = 120 MeV (spectre piqué)
- ~100s mGy/tir, mais petite surface

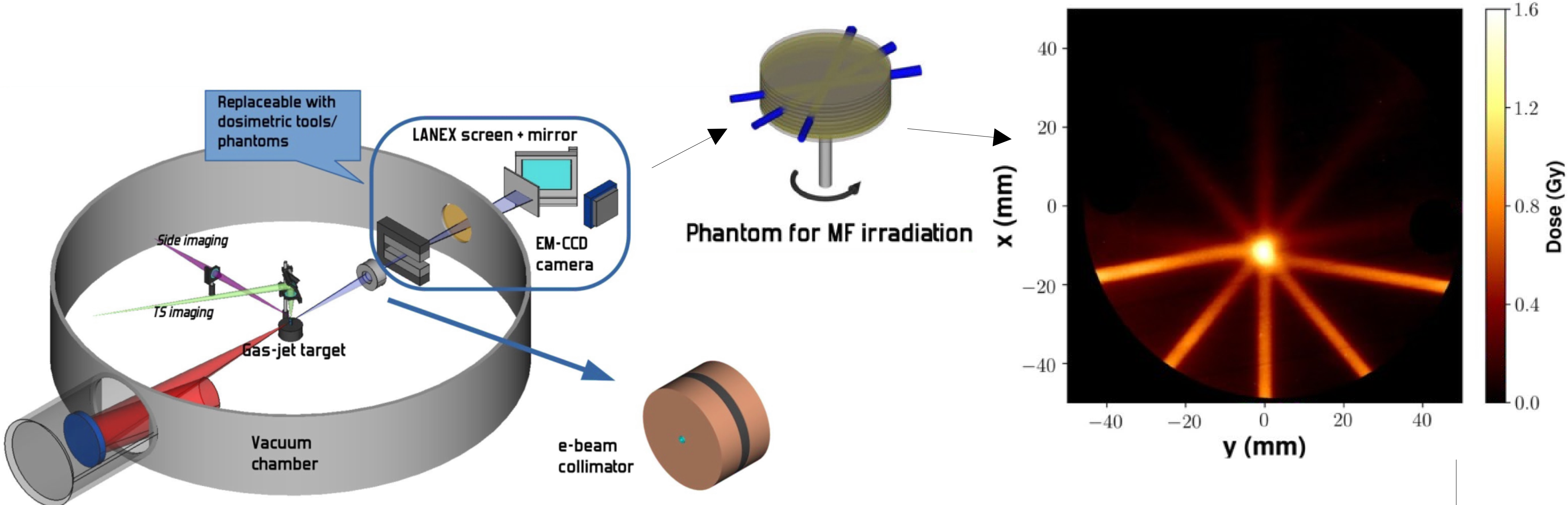


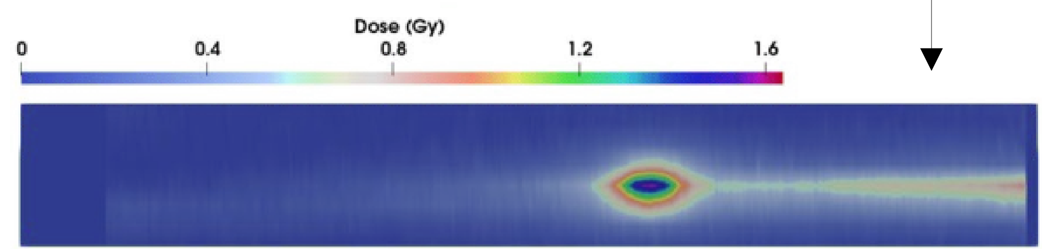
Distribution de dose dans équivalent-eau



Lund et al., Med. Phys 2012

Irradiation multi-axe (Pise, 2020)





- Spectre large : 50 – 250 MeV
- Trou de filtrage
- Irradiation sur plusieurs axes

Labate, L. et al. SciRep 2020

Premières expériences en radiobiologie (LOA, 2022)

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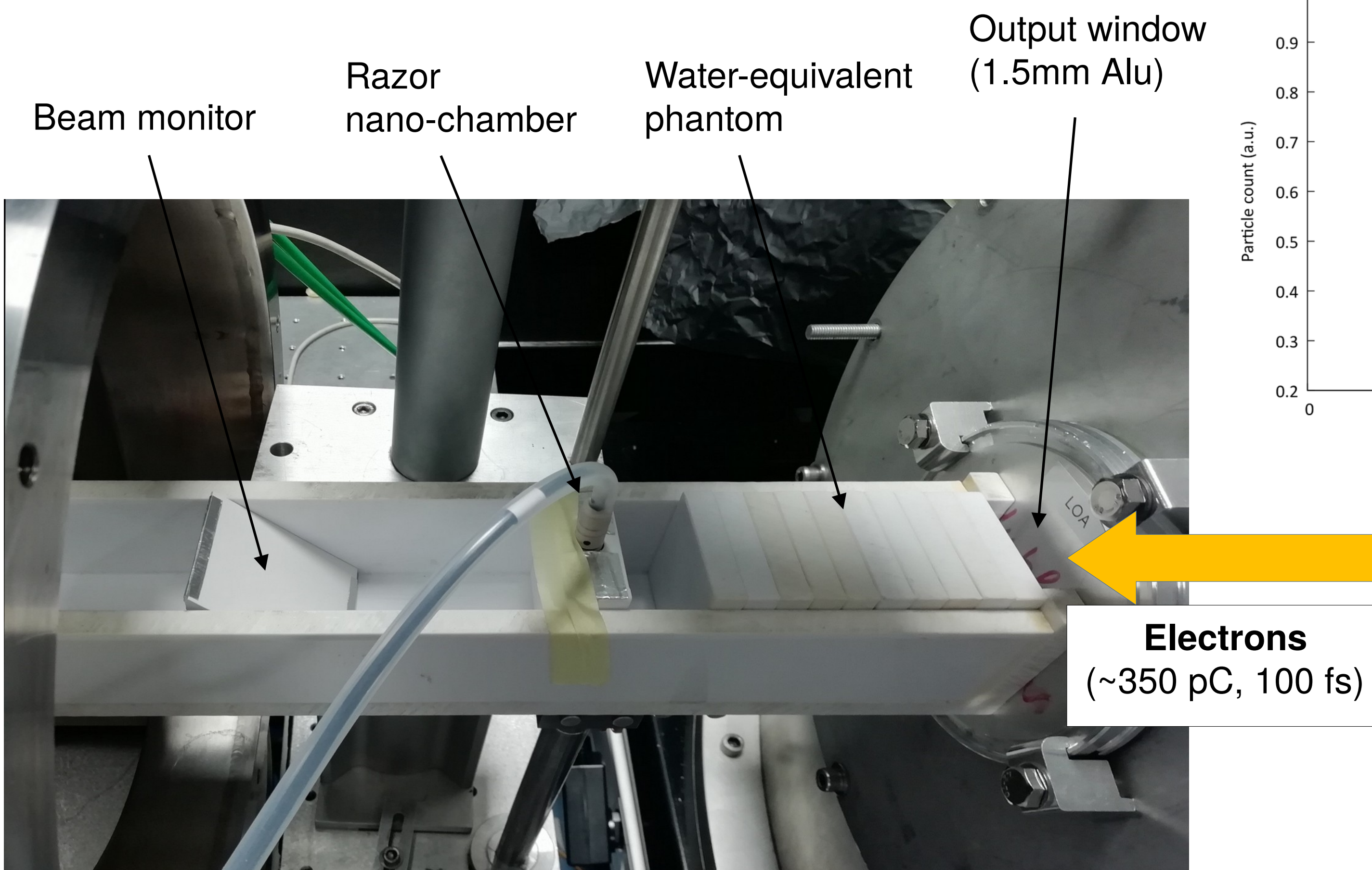

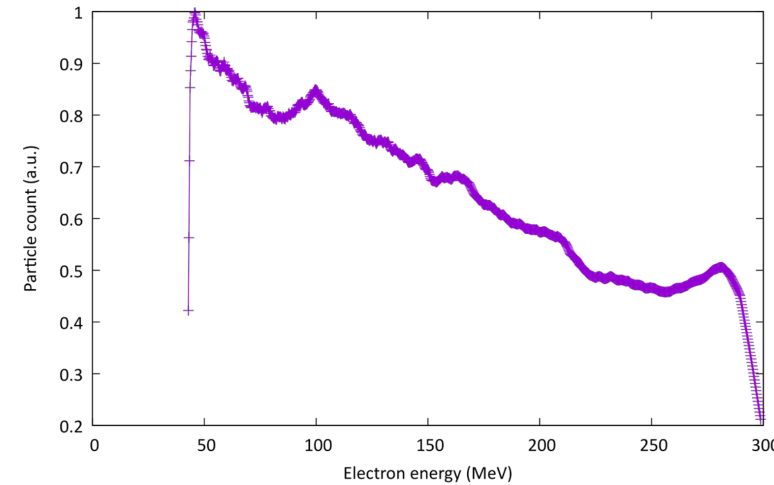

D_{5cm} = 1.1 Gy/shot
$D'_{5cm,inst} > 1\ 10^{13}$ Gy/s
$D'_{5cm,avg}$ = 66 Gy/min

D_{10cm} = 400 mGy/shot (± 3.5% rms)
$D'_{10cm,inst} > 4\ 10^{12}$ Gy/s
$D'_{10cm,avg}$ = 20 Gy/min
Diamètre: 1 cm^2

Conclusions électrons

- Accélérateur compacte ↗
- Gradient accélérateur assez important (GV/m) ↗
- Énergies thérapeutiques déjà disponibles ↗
- Le spectre permet une marge de contrôle (LEE, VHEE, spectre, etc.) ↗
- Nécessité de filtrage du faisceau (mais pbs possible) ↘
- Option : « gantry tout optique » ↗

Perspectives

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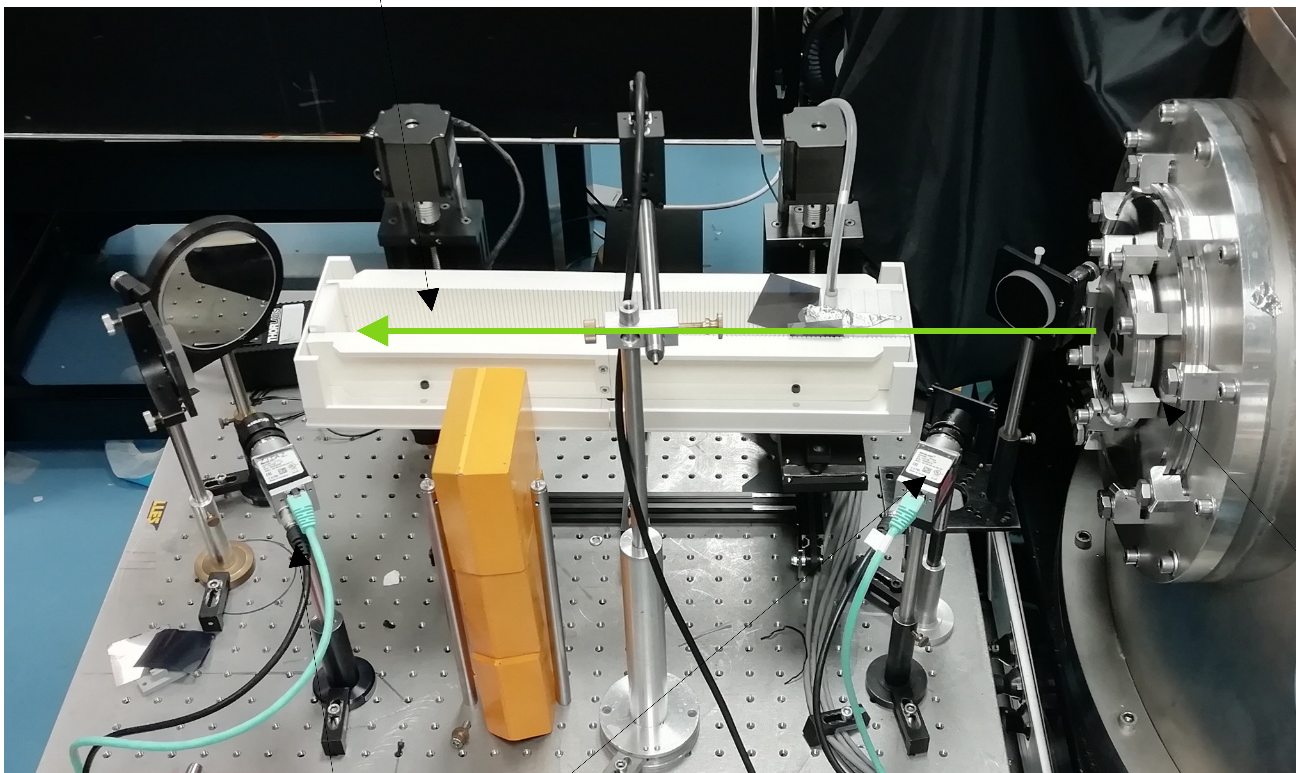
- Radiobiologie : étude de très haut débits de dose en modalité de « fractionnement rapide ».
- FLASH-Laser : une seule impulsion (problématique) ou grande puissance moyenne (possible).
- Applications pré-cliniques :
  - Protons : 4 mm SOBP, 10 Gy/tir (state-of-the-art).
  - Électrons : pas de limitation de pénétration, ~Gy/tir.cm2 (10s Gy/min)
- Perspective clinique ?

Fantôme d'irradiation VHEE (LOA, oct. 2023)

Fantôme motorisé



Accélérateur 20-200 MeV

Fénêtre Alu, 1.5mm

Répérage axe faisceau