Extreme Light Infrastructure - Nuclear Physics
ELI - NP

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Extreme Light Infrastructure (ELI)

Gerard Mourou 1985: Chirped Pulse Amplification (CPA)

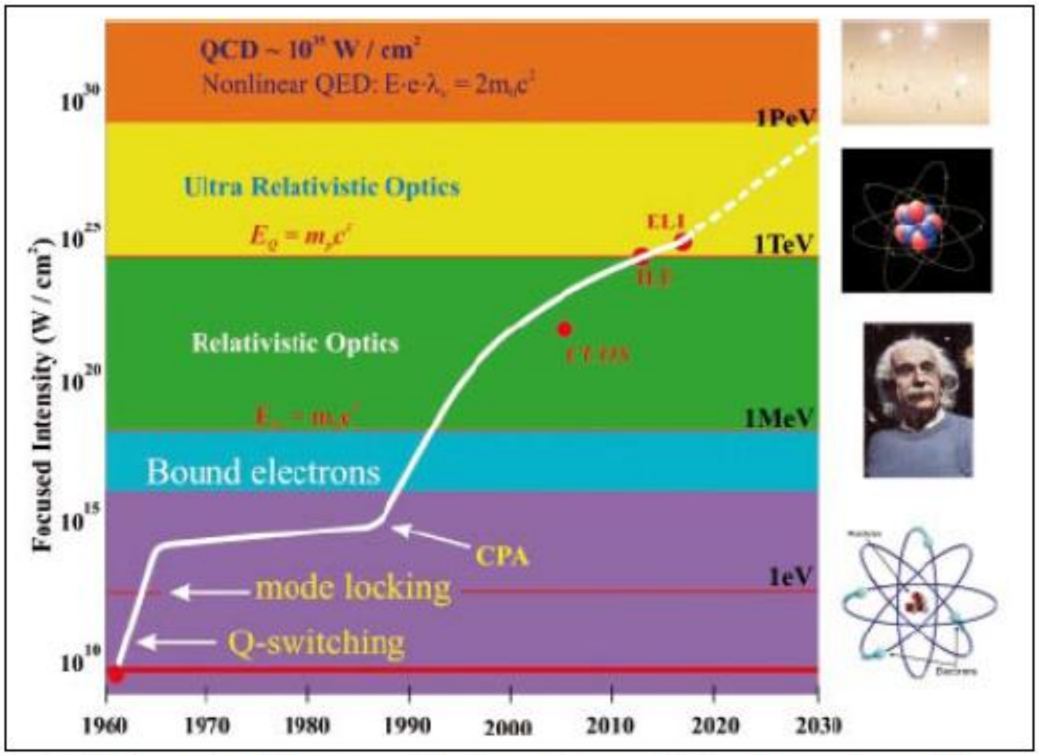


FIG. 1: **Maximum laser intensity as a function of time and fields of research accessible with these intensities.**

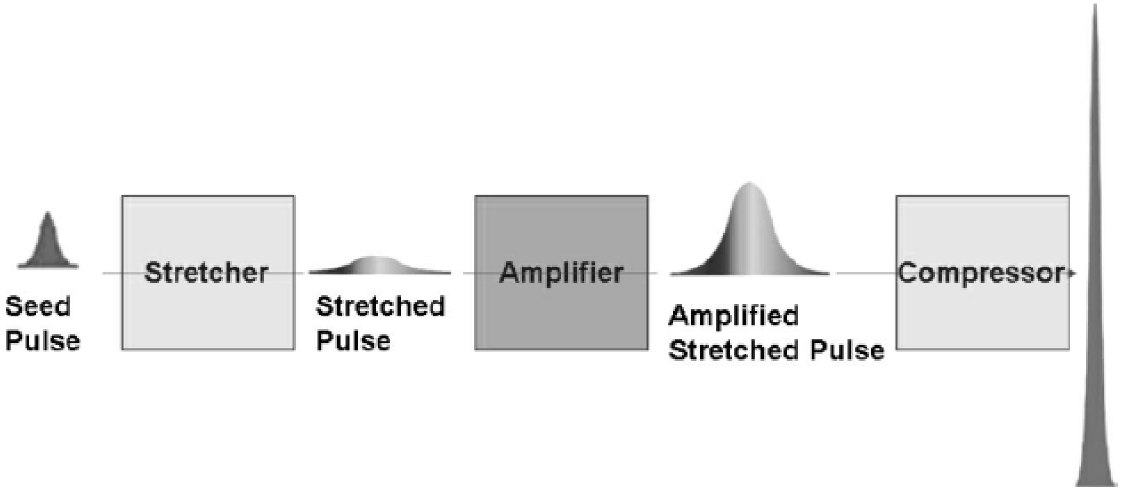
Optik & Photonik December 2010 No. 4

Chirped Pulse Amplification (CPA) Mourou 1985

Idea: to stretch (and chirp) a fs pulse from an oscillator (up to 10,000 times), increase the energy by linear amplification, and thereafter recompress the pulse to the original pulse duration and shape

During amplification, the laser intensity is significantly decreased in order

- to avoid the damage of the optical components of the amplifiers;
- to reduce the temporal and spatial profile distortion by non-linear optical effects during the pulse propagation



Extreme Light Infrastructure

2006 – ELI on ESFRI Roadmap

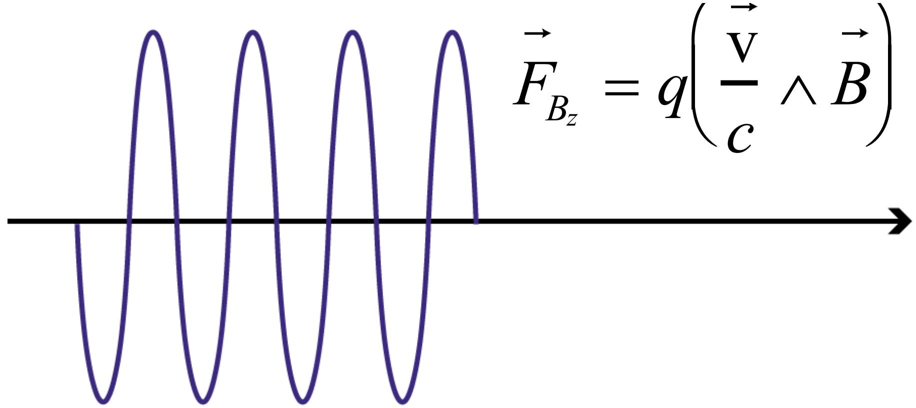
ELI-PP 2007-2010 (FP7)

- ELI-Beamlines (Czech Republic)
- ELI-Attoseconds (Hungary)
- ELI-Nuclear Physics (Romania)

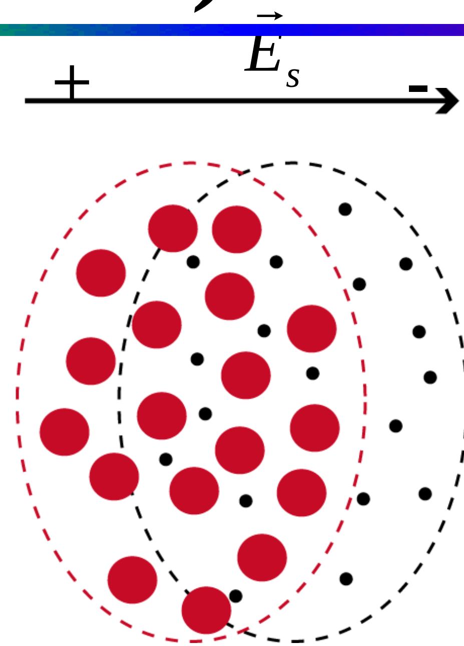
Project Approved by the European Competitiveness Council (December 2009)

ELI-DC (Delivery Consortium): April 2010

Wake-Field acceleration
(Tajima, Dawson 1979)



$$\vec{F}_{B_z} = q\left(\frac{\vec{\mathrm{v}}}{c} \wedge \vec{B}\right)$$



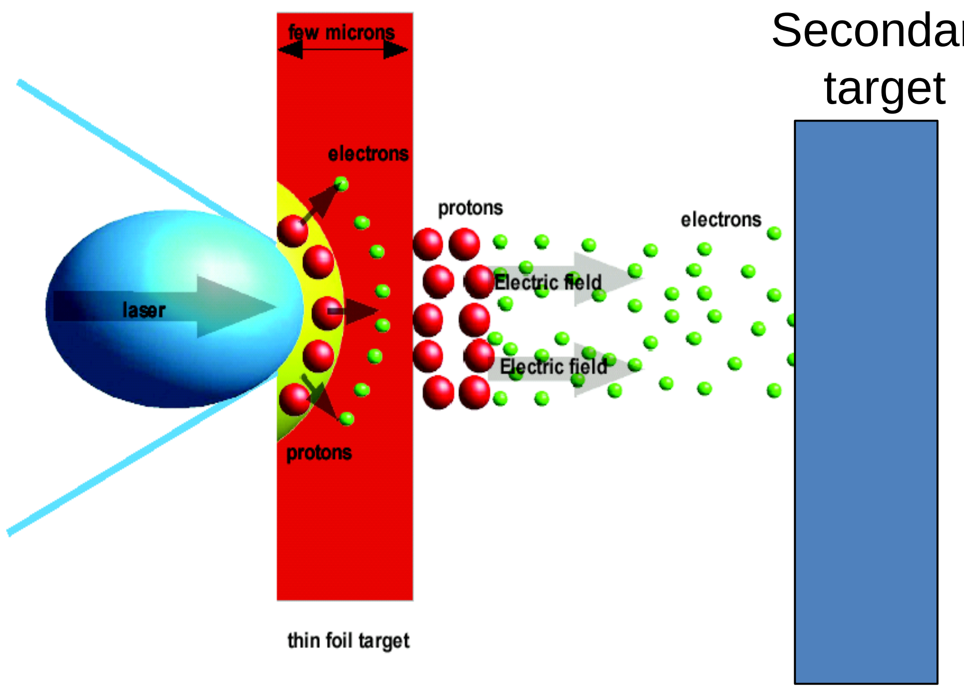
1) $\vec{\mathrm{v}} \wedge \vec{B}$ pushes the electrons.

2) The charge separation generates an electrostatic longitudinal field. (Tajima and Dawson: Wake Fields or Snow Plough)

$$E_s = \frac{c\gamma m_o \omega_p}{e} = \sqrt{4\pi\gamma m_o c^2 n_e}$$

3) The electrostatic field $\qquad E_s \approx E_L$

Target Normal Sheath Acceleration (TNSA)



Secondary radiations
- electrons bremssstrahlung
- gamma rays, neutrons

Primary radiations

Electrons are expelled from the target due to the ponderomotive force

Heavy ions are accelerated in the field created by the electrons

$E \sim I_{laser}^{1/2}$

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

Nuclear Experimental studies

- Charged particles are registered using Thomson spectrometers coupled with CR-39 plastic track detectors or phosphorescent MCP

- Activation of a secondary target – threshold processes

Electrons

Laser intensity **~ 10^{19} W/cm^2**

- Collimated beams were obtained, even of the size of the incident laser beam
- The energies up to hundreds MeV at ~ 1PW lasers (VULCAN, etc.)
- Intensities may go up to 10^{12} particles/laser pulse

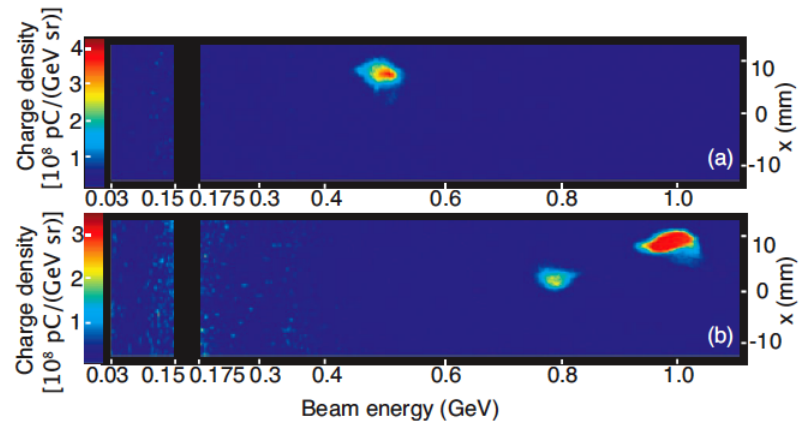


FIG. 43. (Color) Single-shot electron bunch spectra of the capillary-guided LWFA (Leemans, Nagler, *et al.*, 2006; Nakamura *et al.*, 2007). Examples are shown of bunches at (a) $0.50^{+0.02}_{-0.015}$ GeV (5.6% rms energy spread, 2.0 mrad divergence rms, ~50 pC charge) and (b) $1.0^{+0.08}_{-0.05}$ GeV (2.5% rms energy spread, 1.6 mrad divergence rms, ~30 pC). The 0.5 GeV (1.0 GeV) bunch was obtained in a 225 (310) μm capillary with a density of 3.5×10^{18} (4.3×10^{18}) cm^{-3} and input laser power of 12 TW (40 TW). The black stripe denotes the energy range not measured by the spectrometer. In (b) a second bunch at 0.8 GeV is also visible.

Esarey, Schroeder, and Leemans

Rev. Mod. Phys., Vol. 81, No. 3, 2009

Protons, Heavy Ions

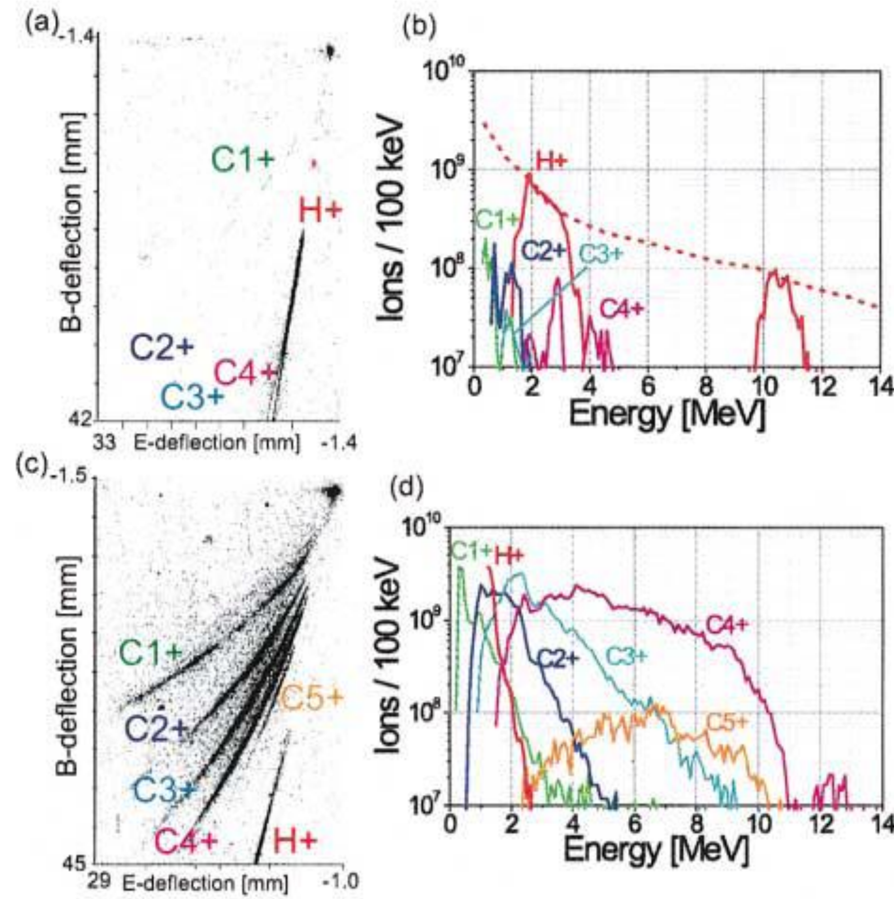
Heavy ion beams at LULI (France)

Laser pulses:
30 J, 300 fs, 1.05 mm => 5×10^{19} W/cm^2.

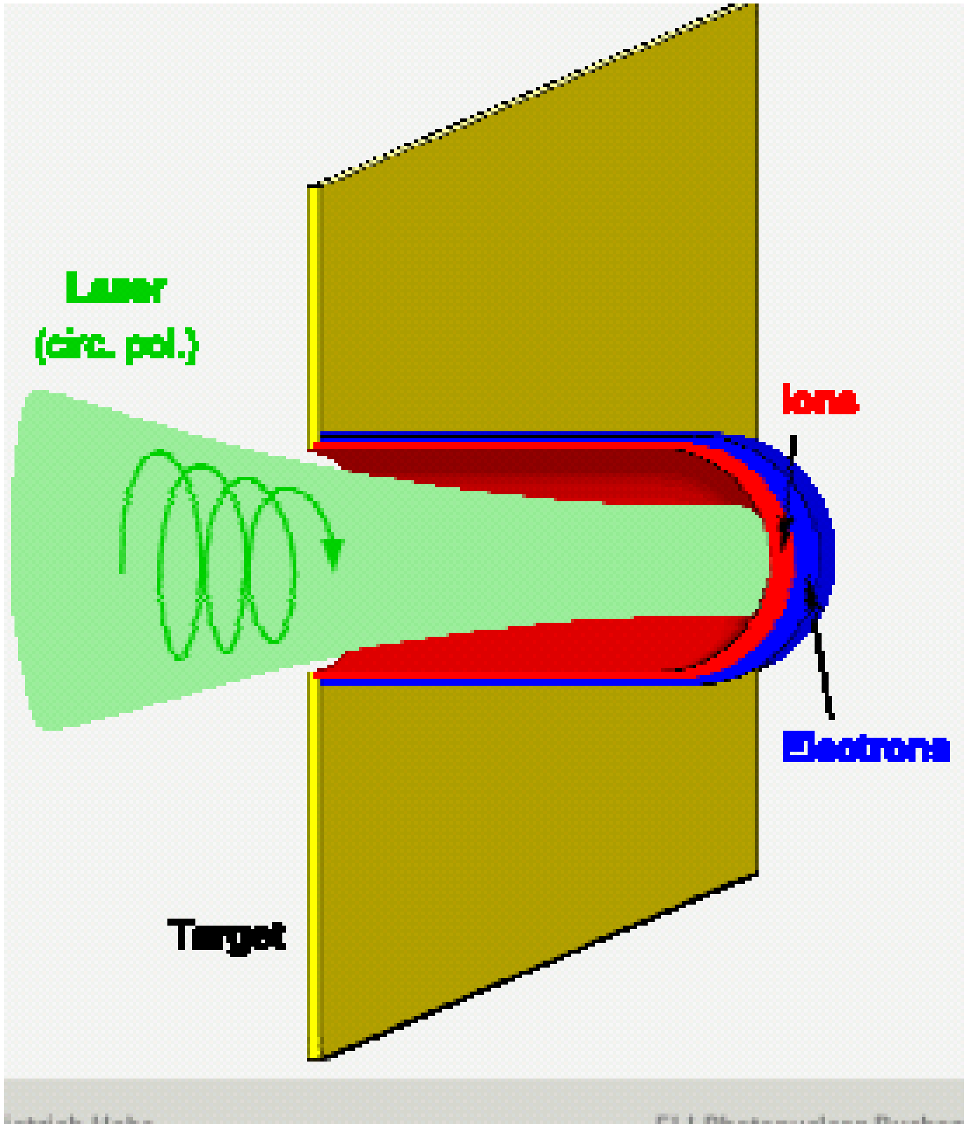
Target: 1 mm C
on rear side of 50 mm W foils

Detection: Thomson parabola spectrometers
+ CR-39 track detectors

- Protons come from surface contamination
- Heating the target the protons are removed and heavy ions are better accelerated



Radiation Pressure Acceleration RPA



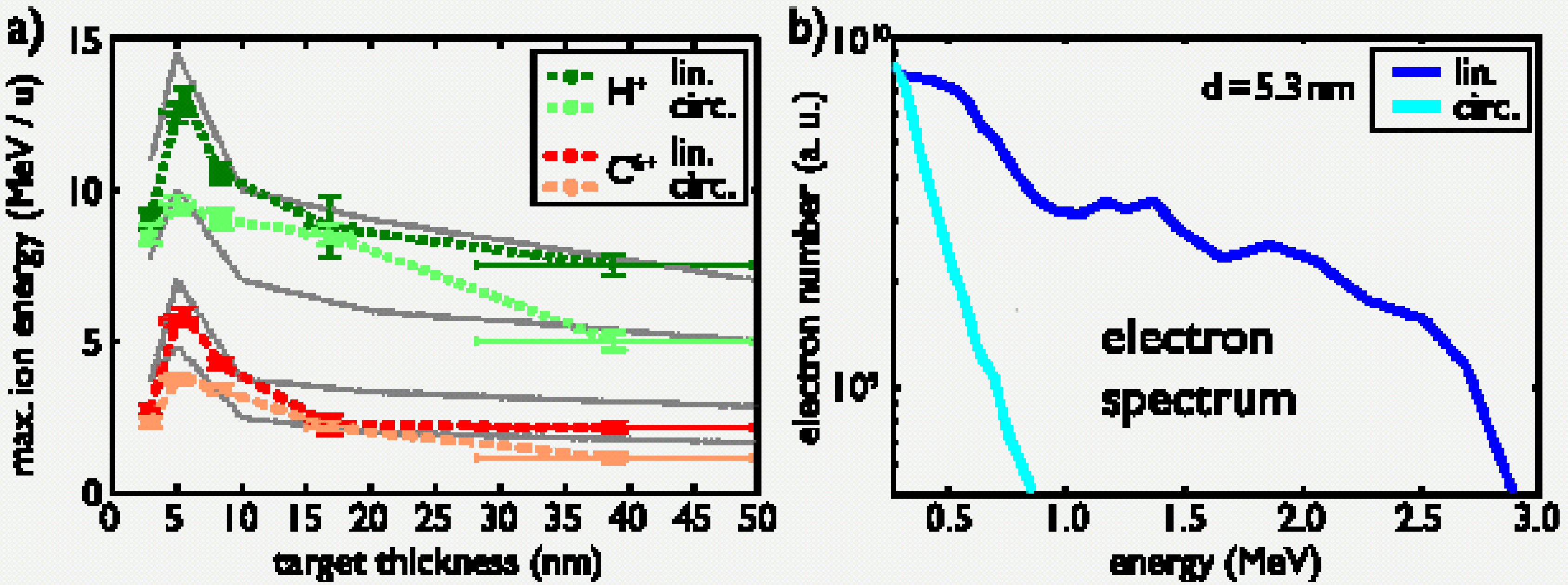
Electrons and ions accelerated
at solid state densities 10^{24}e cm^{-3}
(Classical beam densities 10^{8}e cm^{-3})

E~ I $_{laser}$

RPA DLC foils

Max-Born Institute (MBI), Berlin

Laser Power: 15 TW (700 mJ in 45 fs)
Focused Intensity: $a_L = 5$, **Contrast:** > 10^{11}



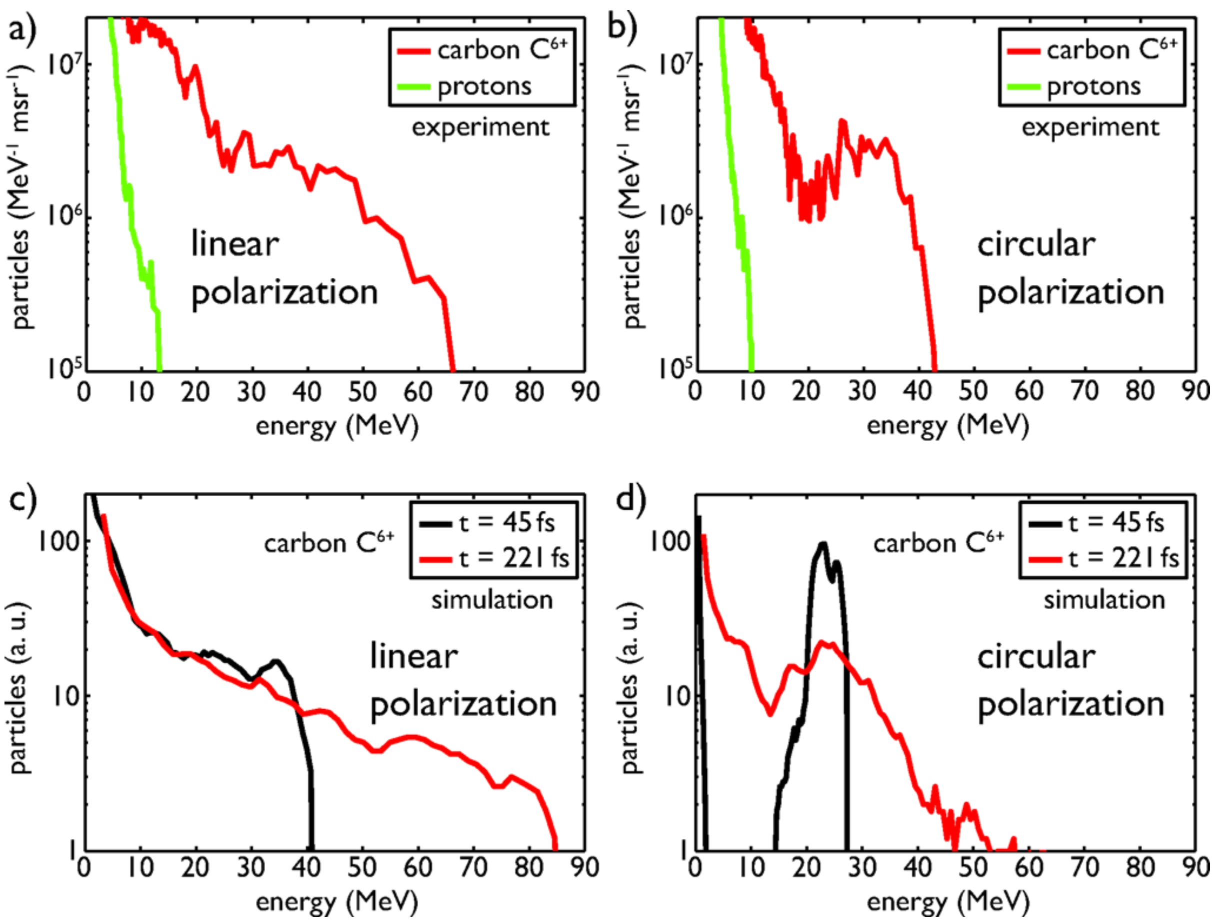
Peak at very low target thickness of 5.6 nm

Cold target for circular polarization

$$a_L \approx \sigma, \qquad \sigma = \left(\frac{n_e}{n_c}\right)\cdot\left(\frac{D}{\lambda}\right), \qquad a_L = \sqrt{I_L \cdot \lambda^2}$$

A. Henig et al., *"Radiation pressure acceleration of ion beams driven by circularly polarized laser pulses"*, Phys. Rev. Lett. **103**, 245009 (2009).

RPA DLC foils



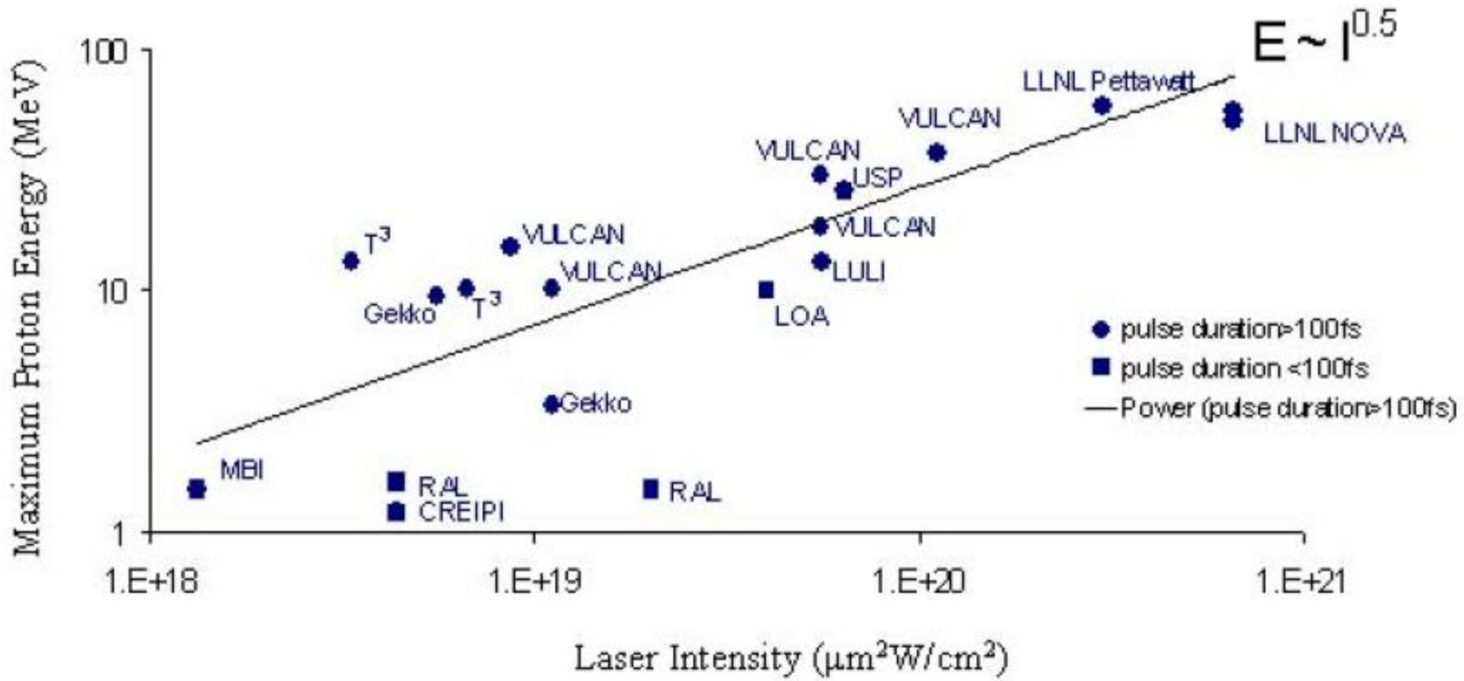
Experiment

Theory

2D PIC simulations

Proton acceleration

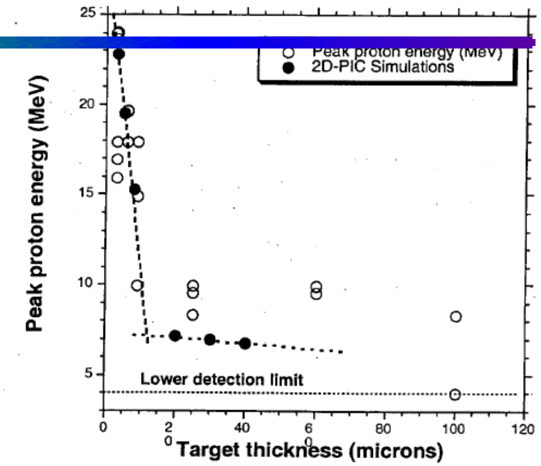
- Maximum energy scales with laser beam intensity approximately as $I^{0.5}$
- TNSA at work at intensities of $10^{19} – 10^{21}$ W/cm^2



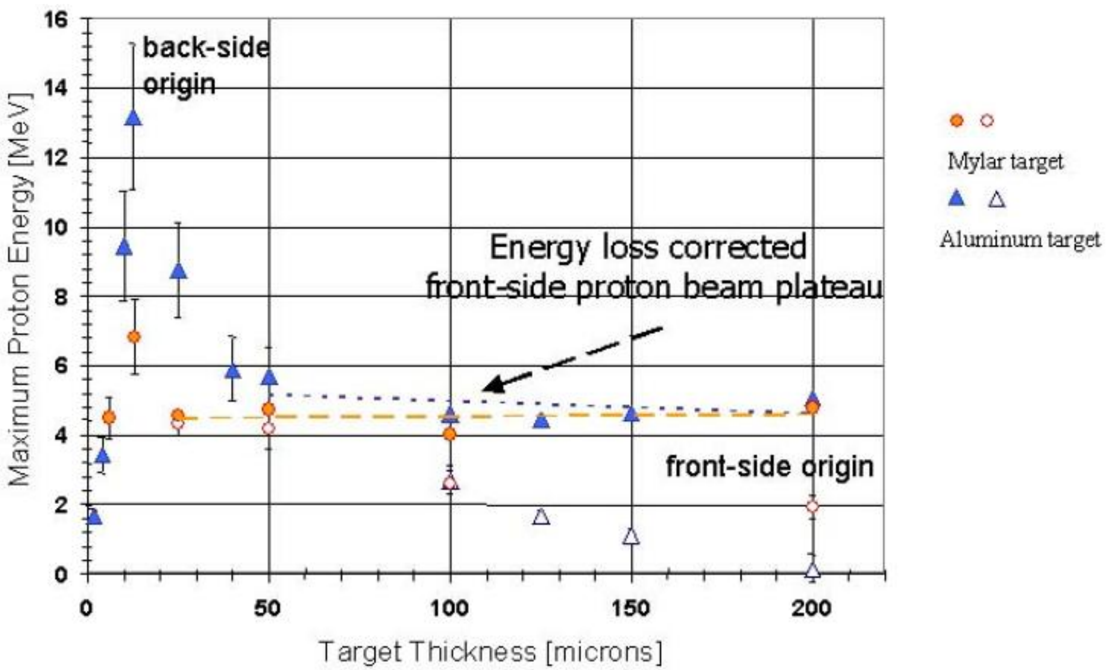
T. Lin et al., 2004, Univ. of Nebraska Digital Commons

Proton acceleration

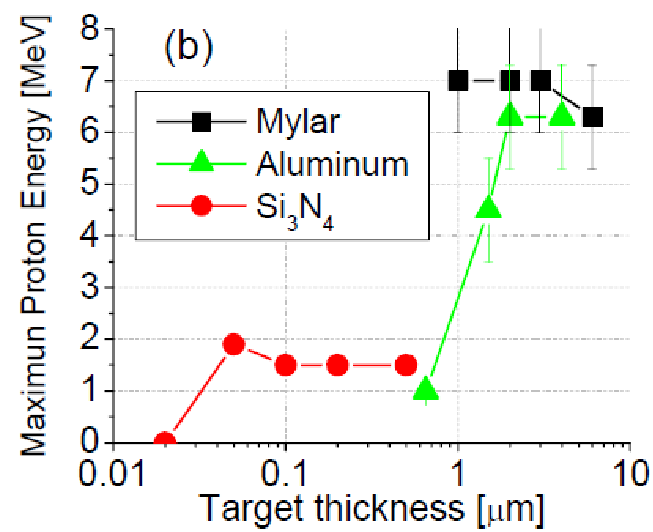
- Plateau of proton energy with increasing foil thickness
- Graphs show results for multi-TW-class lasers



LLNL 100fs, 10^{20}W/cm^2 (2001)



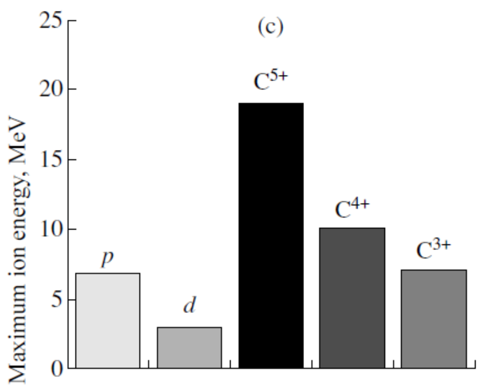
T. Lin et al., 2004, Univ. of Nebraska Digital Commons



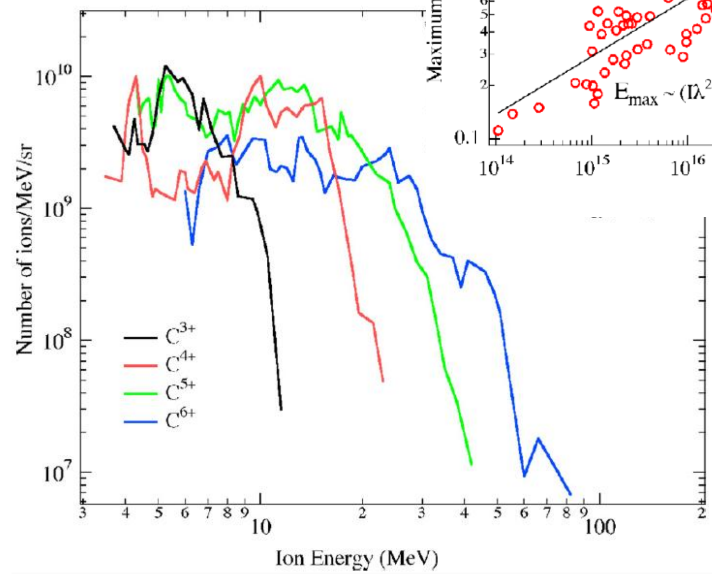
Hercules laser, Michigan, 3x10^{20}W/cm^2, 30fs

Ions acceleration

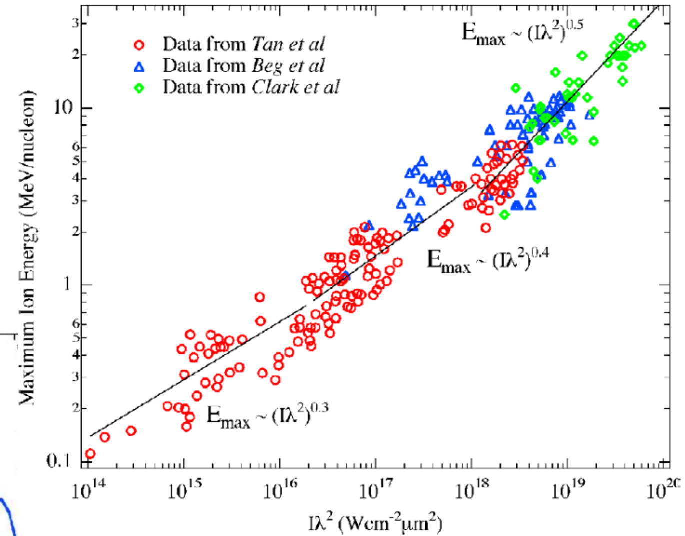
- Dependence of maximum energy function of the ion species
- Graphs show results for multi-TW-class lasers



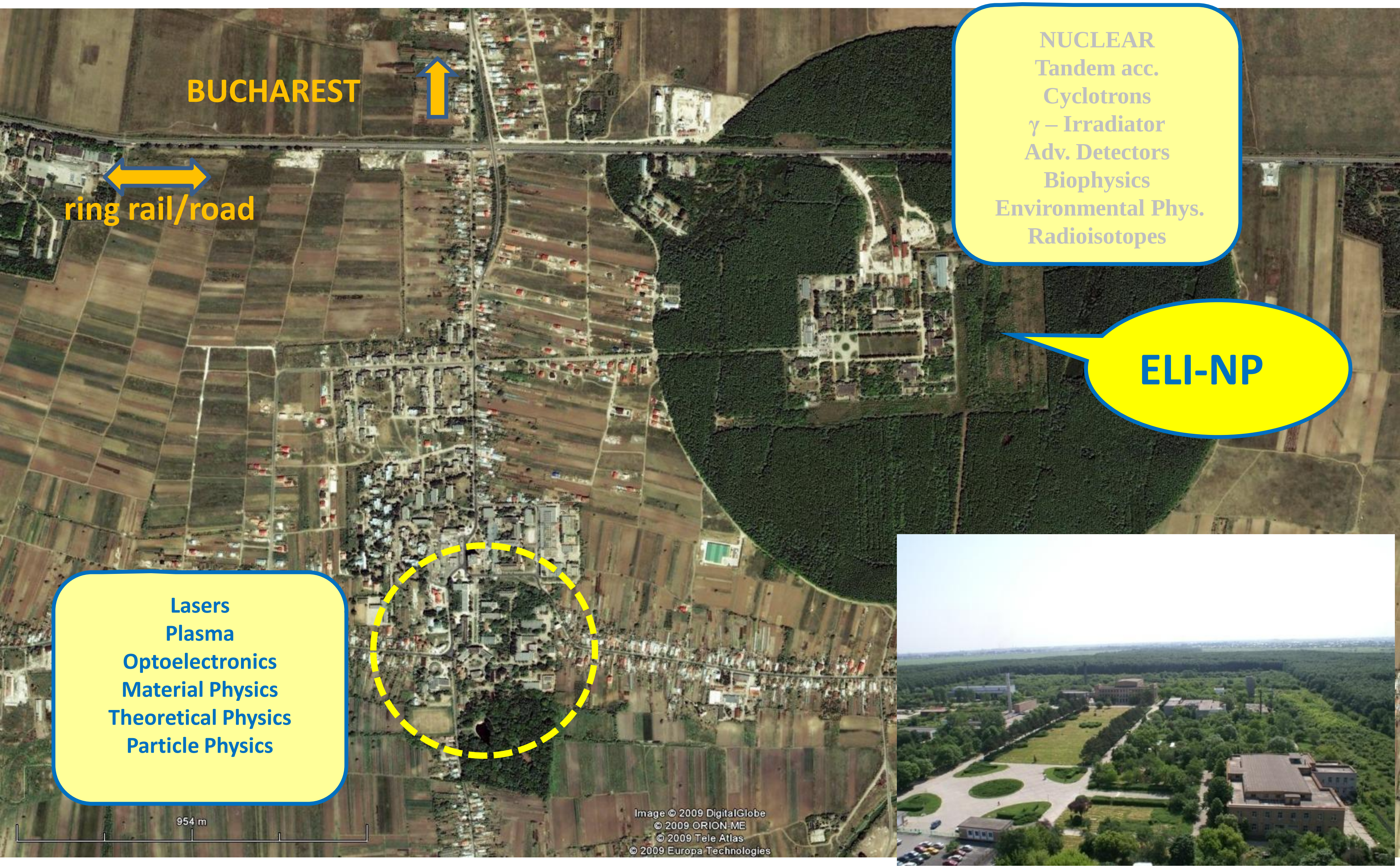
Mylar target irradiated with a 10^{19}W/cm^2 laser pulse



Vulcan 50TW, Appleton Lab,
2x10^{19}W/cm^2, thick lead target



Bucharest-Magurele National Physics Institutes



ELI-Nuclear Physics

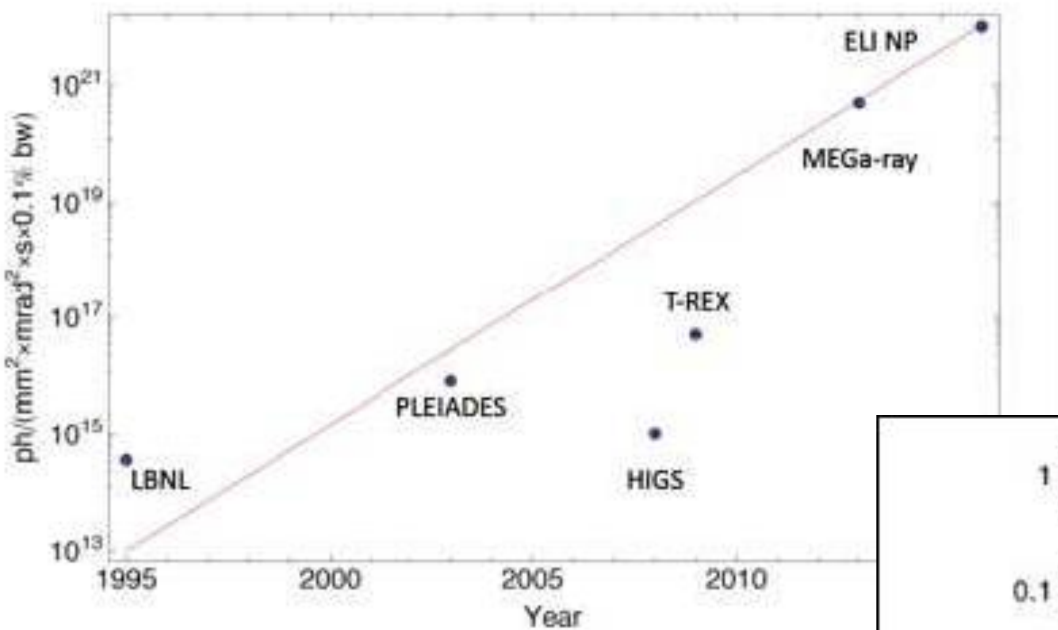
"White Book" (100 scientists, 30 institutions) (***www.eli-np.ro***)

Feasibility Study: 293 Meuro w/o VAT

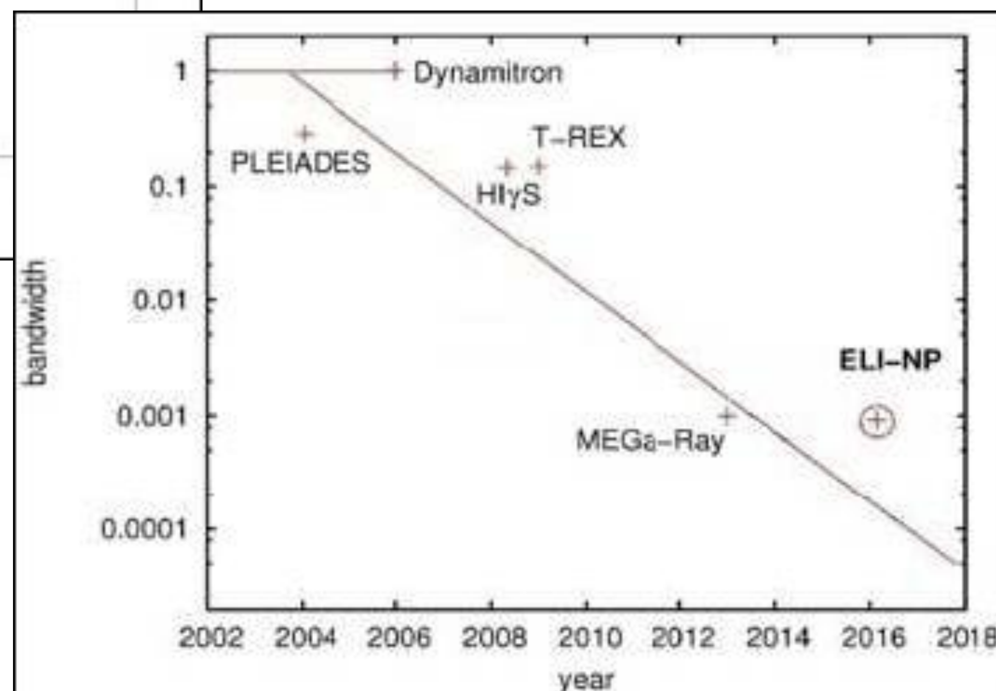
"Extreme Light" :

- *two 10 PW APOLLON-type lasers*
- *brilliant γ beam, up to 20 MeV, BW:10-3*
  produced by Compton scattering on a 700 MeV electron beam

ELI-NP γ beam

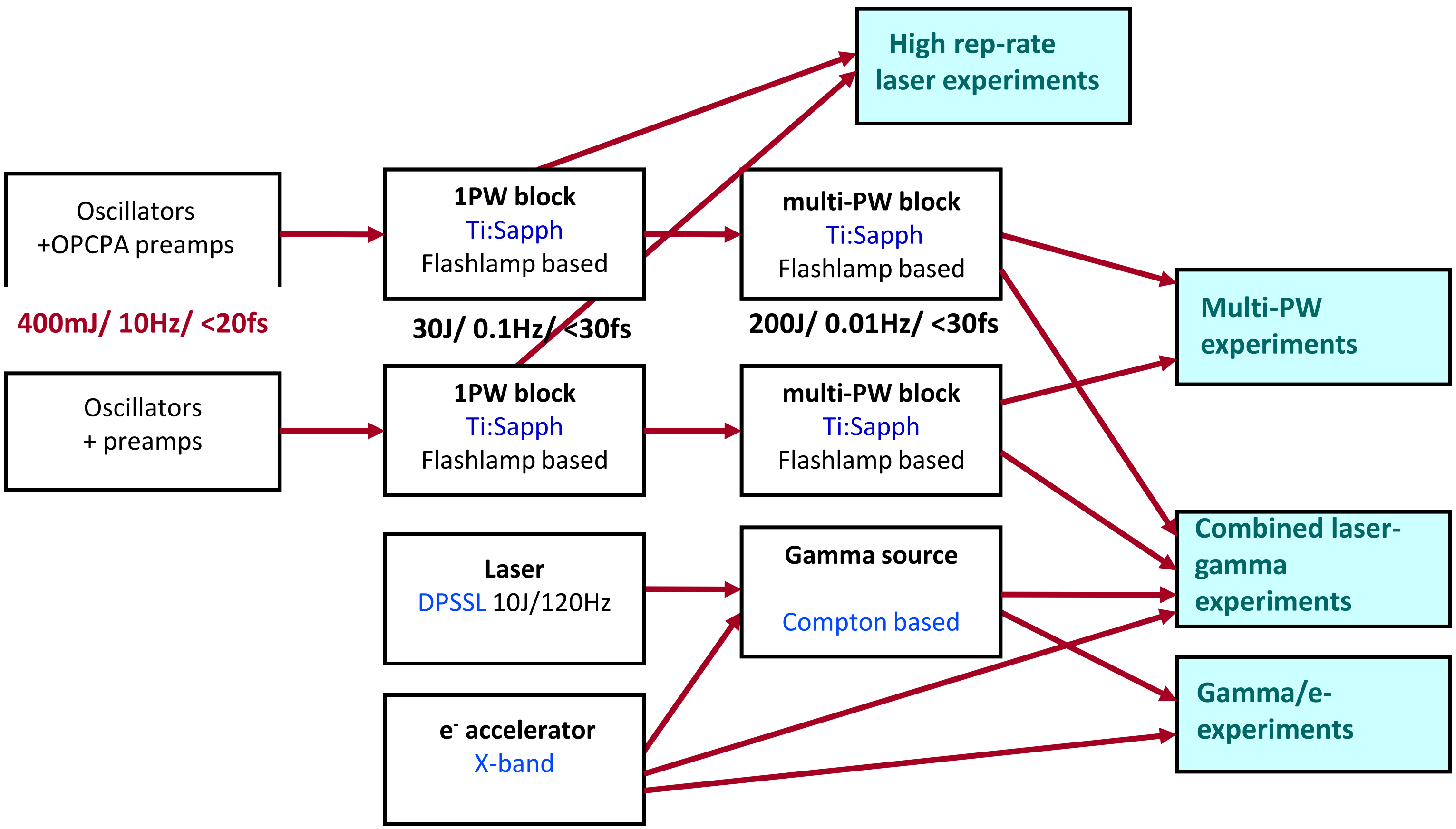


ELI NP
MEGa-ray
T-REX
PLEIADES
HIGS
LBNL
10^21
10^19
10^17
10^15
10^13
ph/(mm^2×mrad^2×s×0.1% bw)
1995
2000
2005
2010
Year



Dynamitron
PLEIADES
T–REX
HIγS
ELI–NP
MEGa–Ray
1
0.1
0.01
0.001
0.0001
bandwidth
2002
2004
2006
2008
2010
2012
2014
2016
2018
year

ELI-NP Facility Concept



ELI-NP

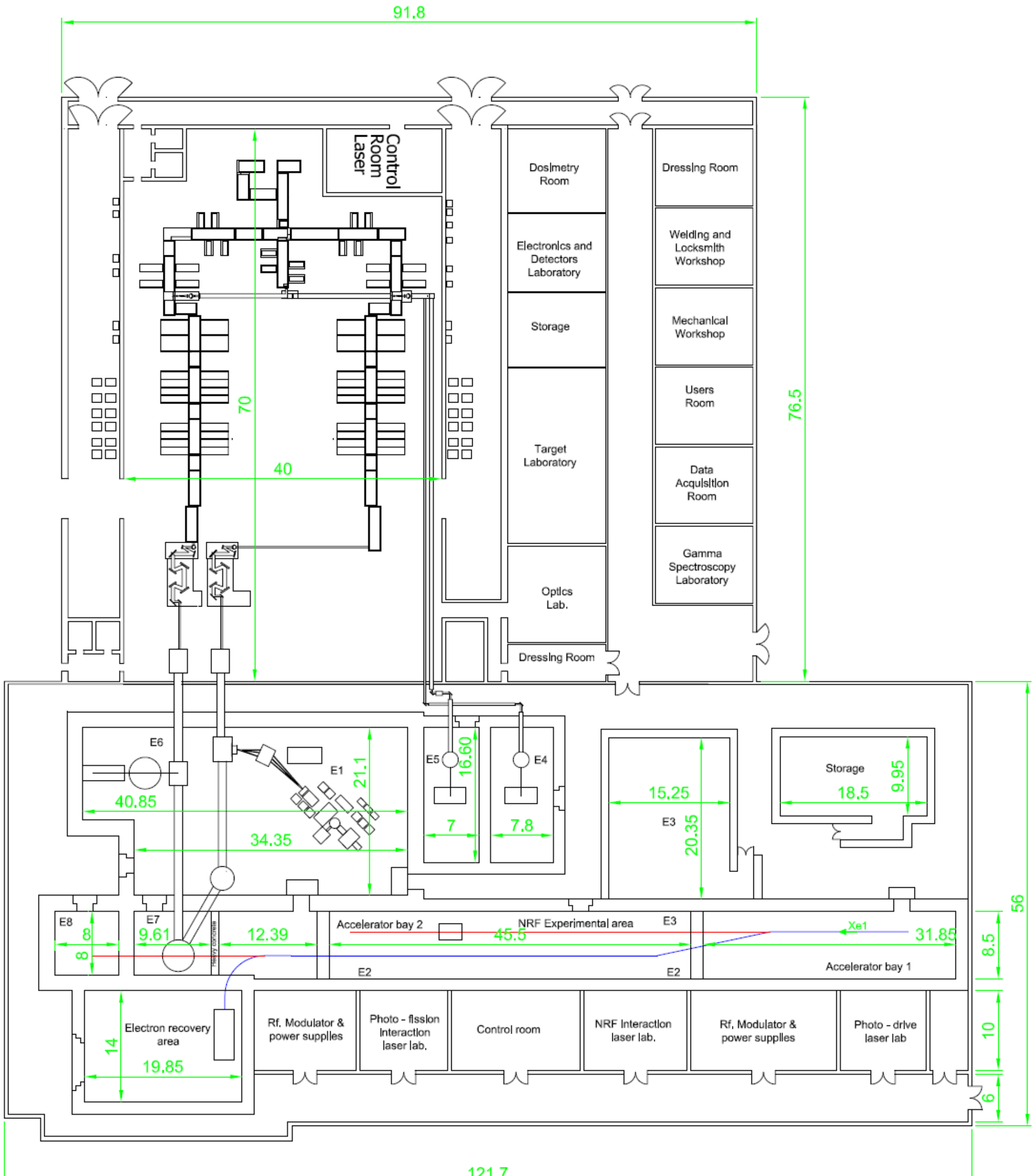
➢ Large equipments:

- Laser system, 2 x 10PW maximum power
- Gamma beam system, tunable energy up to 20MeV, bandwidth 10^{-3}

➢ Buildings – special requirements, 33000sqm total

➢ Experiments:

8 experimental areas, for gamma, laser, and gamma+laser



Control Room Laser
Dosimetry Room
Electronics and Detectors Laboratory
Storage
Target Laboratory
Optics Lab.
Dressing Room
Welding and Locksmith Workshop
Mechanical Workshop
Users Room
Data Acquisition Room
Gamma Spectroscopy Laboratory
91.8
76.5
70
40
E6
E1
E5
E4
E3
40.85
34.35
21.1
16.60
7
7.8
15.25
20.35
Storage
18.5
9.95
E8
E7
8
9.61
12.39
Accelerator bay 2
NRF Experimental area
45.5
Xe1
31.85
E2
Accelerator bay 1
Electron recovery area
14
19.85
Rf. Modulator & power supplies
Photo - fission interaction laser lab.
Control room
NRF Interaction laser lab.
Photo - drive laser lab
56
8.5
10
6
121.7

ELI – Nuclear Physics Research

- *Nuclear Physics experiments to characterize laser – target int.*
- *Photonuclear reactions.*
- *Exotic Nuclear Physics and astrophysics*

  complementary to other NP large facilities (FAIR, SPIRAL2).
- *Applications based on high intensity laser and very brilliant γ beams.*

  Complementary to the other pillars

ELI - Nuclear Physics

*in '**Nuclear Physics Long Range Plan in Europe**'* as a major facility

Experimental issues …

For high-resolution spectroscopy one must use **event-based detection** instead of track detectors

Experimental problems:

- Large radiation flux in a very short amount of time (< 1 ns)
- The low repetition rate for the laser pulse
- Several types of radiations are produced simultaneously (electrons, heavy ions, gamma and X rays)

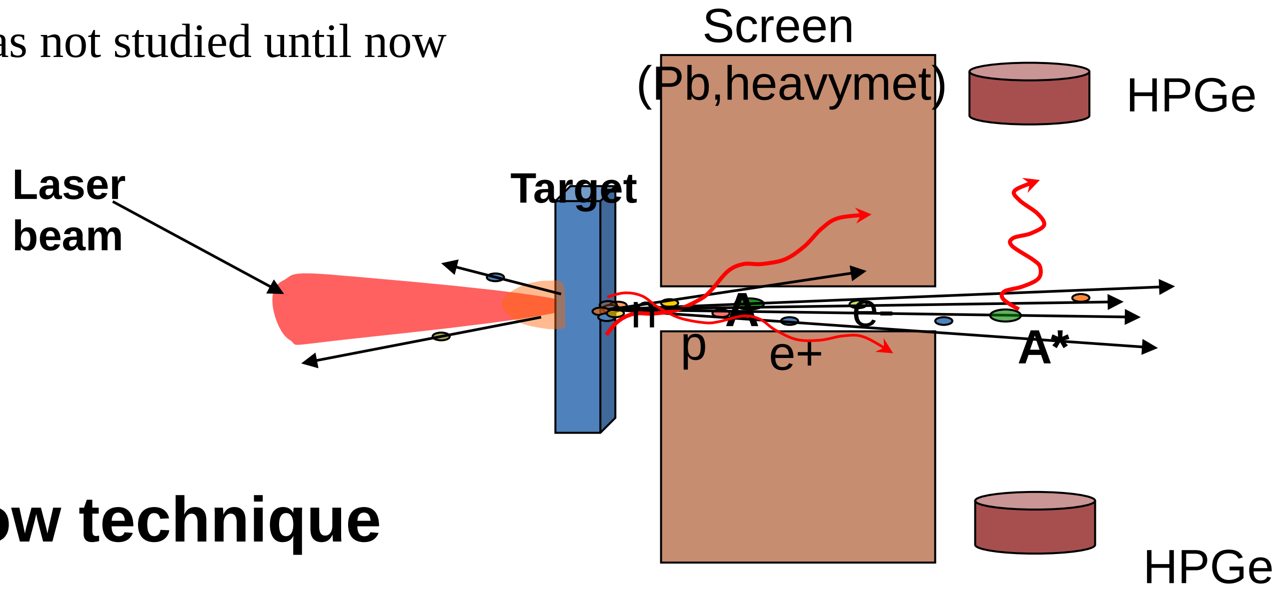
Similar problems exist at other nuclear physics facilities

… and possible solutions

- High granularity detection systems (arrays)
  - More difficult to overload since every individual element cover a small solid angle
  - The statistics accumulates faster because many detectors give signal after one laser shot
- Reduction of dead time
  - Digital electronics
  - “Trigger-less” data acquisition, keeping the detection system continuously active
- Separate different types of radiations before detection
  - Beam transportation

“Prompt” gamma rays

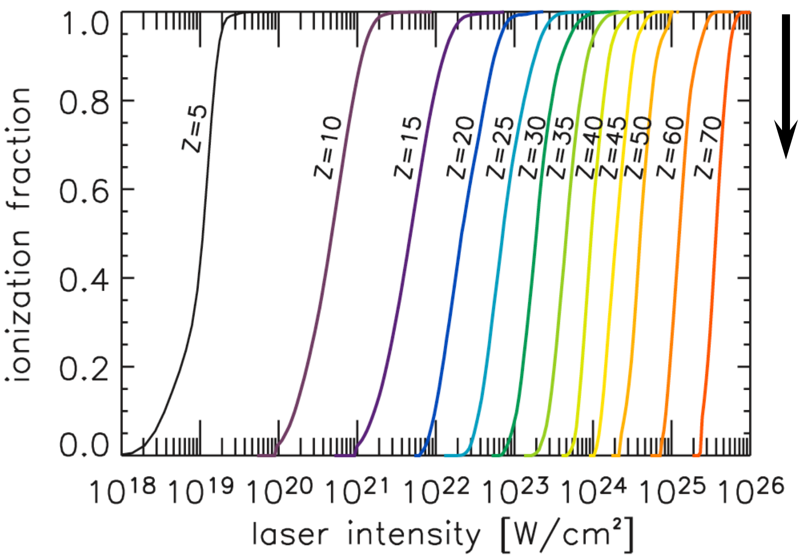
Gamma decay of nuclei from the beam created by laser was not studied until now



Shadow technique

- From the target the nuclei might come out in excited states
- Pointing Ge detectors directly to the target can overload them
- If Ge detectors “look” 1-2 cm after the target, with the proper screening, the gamma decay from excited states with $T_{1/2}$ ~ ns can be observed

Heavy ions from primary target



H. G. Hetzheim and C. H. Keitel
Phys. Rev. Lett. 102, 083003 (2009)

- Many nuclei coming from the target may be completely stripped
- Using one large acceptance magnetic spectrometer one may end up with indeterminations in the trajectory reconstruction, since several ions can enter and arrive in the focal plane in the same time
- Possible solution: several spectrometers, with small entrance solid angle but relatively large momentum acceptance, combined with a pre-selection of the ions to be analyzed using magnetic elements and electric fields.

Photonuclear Physics with MeV-range photon beams

- Pure EM-interaction

  (nuclear-) model independent

  “small“ cross sections, penetrating (thick targets)

- Minimum projectile mass

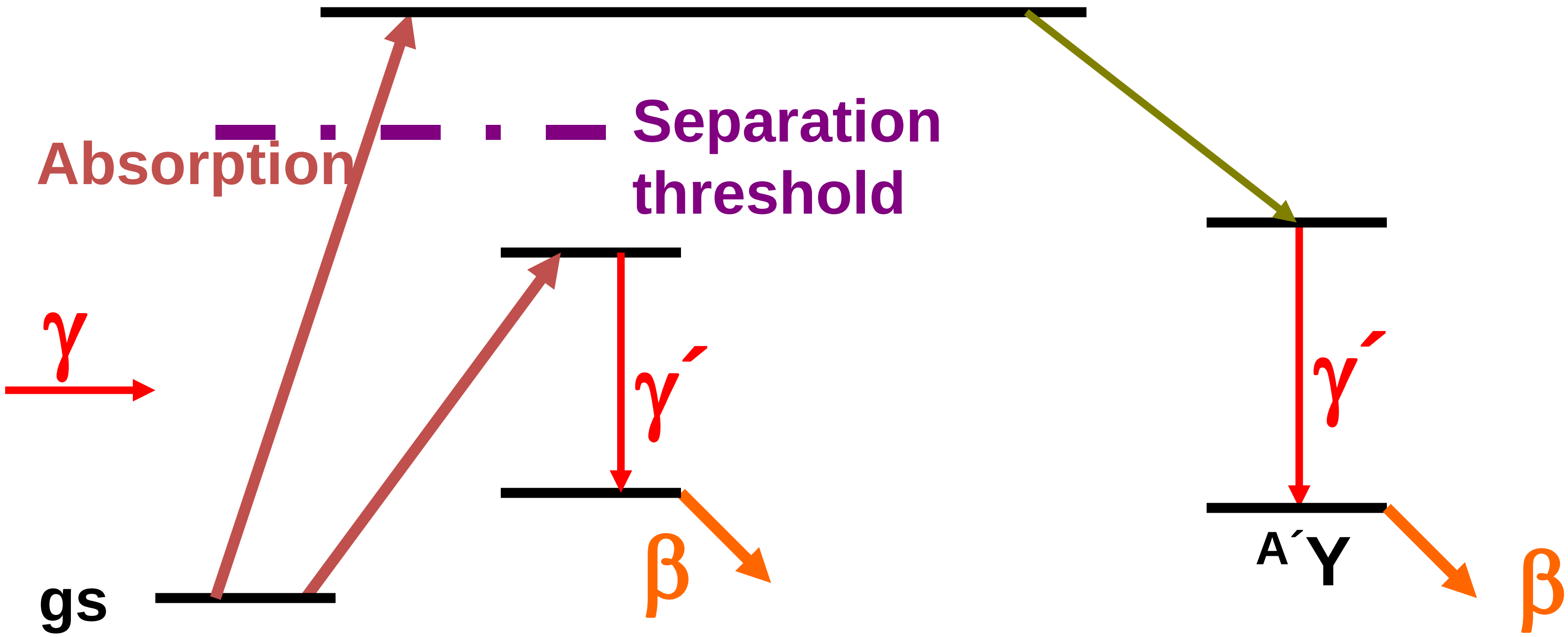
  min. angular mom. transfer,

  spin-selective: dipole-modes

- Polarisation

  “Parity physics“

Photonuclear Reactions

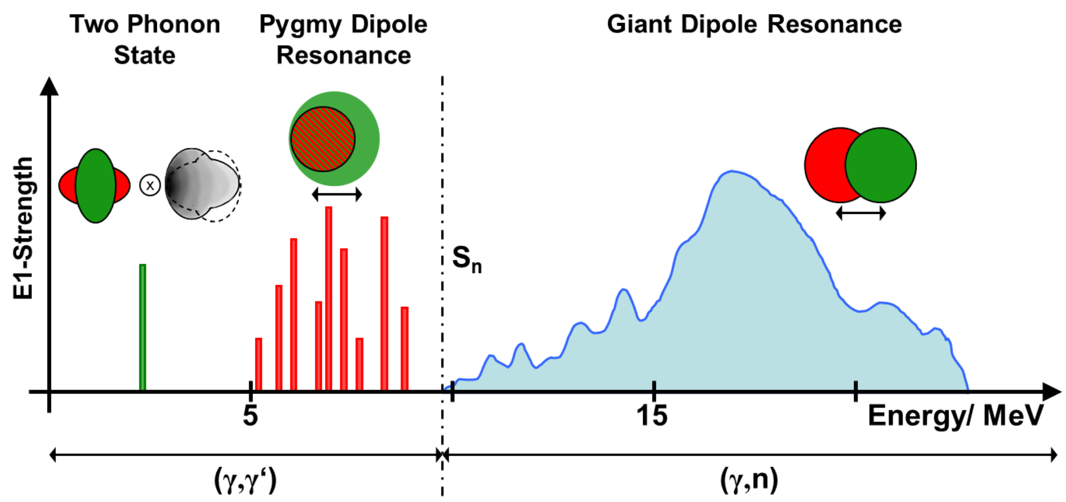


Nuclear Resonance Fluorescence (NRF)

Photoactivation

Photodisintegration (-activation)

Realm of Nuclear Photonics



$$B(\lambda L)\uparrow = \Gamma_0 \cdot \left(8\pi \sum_L \left(\frac{E_j}{\hbar c}\right)^{2L+1} \cdot \frac{(L+1)}{L[(2L+1)!!]^2} \cdot g\right)^{-1}$$

- aim: determination of transition strengths: need absolute values for ground state transition width
- NRF-experiments give product with branching ratio: $A_{j\to 0} \propto I_{j\to 0} \propto \frac{\Gamma_0^2}{\Gamma}$
- assumption:
    - no transition to low-lying states observed
    - but: many small branchings to other states?
- self-absorption: measurement of absolute ground state transition widths

ELI – NP Experiments (1)

Stand-alone High Power Laser Experiments

- *Nuclear Techniques for Characterization of Laser-Induced Radiations*
- *Modelling of High-Intensity Laser Interaction with Matter*
- *Stopping Power of Charge Particles Bunches with Ultra-High Density*
- *Laser Acceleration of very dense Electrons, Protons and Heavy Ions Beams*
- *Laser-Accelerated Th Beam to produce Neutron-Rich Nuclei around the N = 126 Waiting Point of the r-Process via the Fission-Fusion Reaction*
- *A Relativistic Ultra-thin Electron Sheet used as a Relativistic Mirror for the Production of Brilliant, Intense Coherent γ-Rays*
- *Studies of enhanced decay of ^{26}Al in hot plasma environments*

ELI – NP Experiments (2)

Laser + γ /e− Beam

- *Probing the Pair Creation from the Vacuum in the Focus of Strong Electrical Fields with a High Energy γ Beam*
- *The Real Part of the Index of Refraction of the Vacuum in High Fields: Vacuum Birefringence*
- *Cascades of e+e− Pairs and γ -Rays triggered by a Single Slow Electron in Strong Fields*
- *Compton Scattering and Radiation Reaction of a Single Electron at High Intensities*
- *Nuclear Lifetime Measurements by Streaking Conversion Electrons with a Laser Field.*

ELI – NP Experiments (3)

Standalone γ /e experiments for nuclear spectroscopy and astrophysics

- *Measuring Narrow Doorway States, embedded in Regions of High Level Density in the First Nuclear Minimum, which are identified by specific (γ, f), (γ, p), (γ, n) Reactions*
- *Precision Tests of Fluctuating Quantities in Nuclear Physics of Highly Excited Nuclear Levels in Comparison to Random-Matrix-Theory and Quantum Chaos*
- *Dipole polarizability with high intensity, monoenergetic MeV γ-radiation for the evaluation of neutron skin*
- *Nuclear Transitions and Parity-violating Meson-Nucleon Coupling*
- *Study of pygmy and giant dipole resonances*
- *Gamma scattering on nuclei*
- *Fine-structure of Photo-response above the Particle Threshold: the (γ ,α), (γ,p) and (γ ,n)*
- *Nuclear Resonance Fluorescence on Rare Isotopes and Isomers*
- *Multiple Nuclear Excitons*
- *Neutron Capture Cross Section of s-Process Branching Nuclei with Inverse Reactions*
- *Measurements of (γ, p) and (γ, α) Reaction Cross Sections for p-Process Nucleosynthesis*
- *High Resolution Inelastic Electron Scattering (e,e')*

ELI – NP Experiments (4)

Applications

- *Laser produced charge particle beams may become an attractive alternative for large scale conventional facilities*
- *Laser-driven betatron radiation - gamma beams*
- *High Resolution, high Intensity X-Ray Beam*
- *Intense Brilliant Positron-Source:* $10^7 e^+$/[s(mm mrad)^2 0.1%BW]
- *Radioscopy and Tomography*
- *Materials research in high intensity radiation fields*
- *Applications of Nuclear Resonance Fluorescence*

Photonuclear Reactions Applications

- *Management of Sensitive Nuclear Materials and Radioactive waste*
  isotope-specific identification , ex: $^{238}U/^{235}U$, ^{239}Pu,
- *Burn-up of nuclear fuel rods*
  measuring the final ^{235}U, ^{238}U *content may allow to use fuel elements 20% longer*
- *Medical applications– new radioisotopes and radiopharmaceuticals*
  Producing of medical radioisotopes via the (γ, n) reactions
  ex. $^{100}Mo(\gamma, n)\,^{99}Mo$, $^{195}Pt\,(\gamma, \gamma')\,^{195m}Pt$
- *Extremely Brilliant Neutron-Source produced via the (γ ,n) Reaction w/o Moderation*
  10^5n/[s (mm mrad)^2 0.1% BW], E~1eV

ELI-NP Next Steps

- *January 2012: Submission of the Application to DG-Regio*
- *June 2012: Tender Procedures*
- *September 2012- September 2014: Civil Construction*
- *July 2015 : Lasers and Gamma Beam – Phase 1*
- *December 2016 : Lasers and Gamma beam Phase 2*
- *2012-2014: TDR for experiments*
- *2014-2016: experimental set-ups*
- *January 2017: beginning of operation*


Thank You !

ELI-NP γ beam

Table 9: The main specifications of the ELI-NP machine

Quantity	Value	Units
Peak gamma brilliance	$>1.5\times10^{21}$	Photons/sec/mm^2/mrad^2/(0.1% BW)
Effective Beam repetition	12,000	Hz (100 micro-bunches at 120 Hz rep rate)
Gammas per pulse	8×10^{8}	Photons at 100% BW
Spectral beam flux	10^{6}	Photons/sec/eV
Gamma pulse duration	2	Picoseconds
Gamma collimation	0.1	mrad at 0.1% BW
Gamma bandwidth	10^{-3}	$\Delta E/E$
Gamma source size	10	Microns
Electron beam energy	600	MeV
Laser pulse energy	1.5	Joules
Gamma-ray energy	1–13 (with 532 nm laser interaction)	MeV

Stopping power

of ion bunches with solid state density

Bethe-Bloch formula for individual ion:

$$-\frac{dE}{dx} = 4\pi n_e \frac{Z_{\text{eff}}^2 e^4}{m_e v^2}\left(\ln\left(\frac{m_e v^2}{e^2 k_D}\right) + \ln\left(\frac{k_D v}{\omega_p}\right)\right)$$

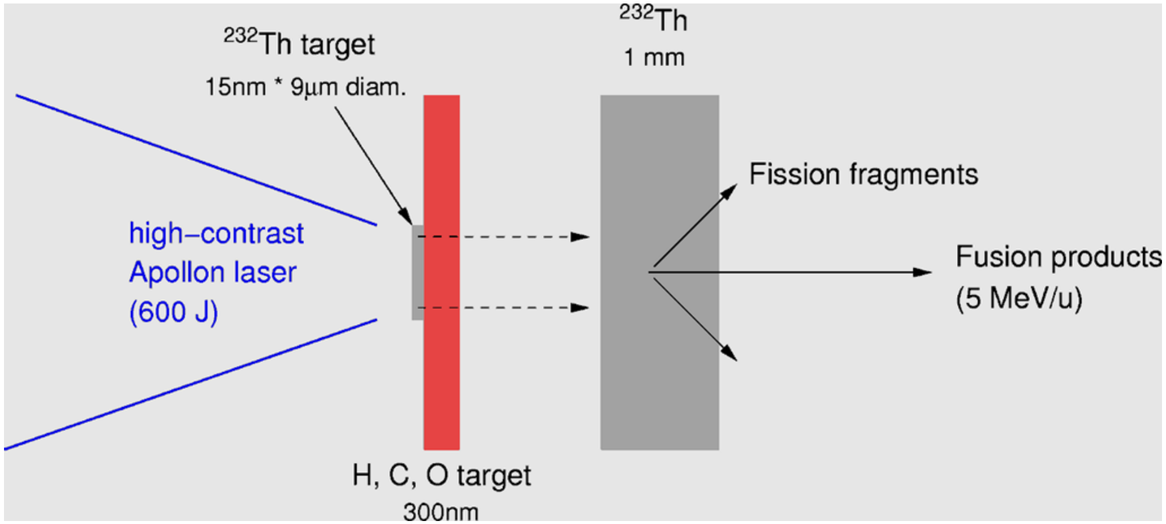
binary collisions
k_D = Debye wave number

long-range
collective interaction
ω_p = plasma frequency

a) enhanced stopping (10^5 ×) in low-density targets
dense bunch interacts with collective wake
→ reduced fraction of nuclear reaction

b) reduced stopping in solid target
first electrons of bunch kick out electrons of foil like a snow plow.
→ enhanced fraction of nuclear reactions.

Fission-fusion reaction



10 MeV/u H, C, O, ^{232}Th, beam + ^{232}Th target

a) **Fission** H, C, O + Th $\longrightarrow$ $F_L + F_H$ fission fragments in target
^{232}Th + ^{232}Th $\longrightarrow$ fission of beam in $F_L + F_H$

Reaction of radioactive short-lived light fission fragments of beam +
Radioactive short-lived light fission fragments of the target

b) **Fusion:** $F_L + F_L$ $\longrightarrow$ $^{A}Z \approx {}^{200}80$ nuclei close to N=126 waiting point
$F_L + F_H$ $\longrightarrow$ ^{232}Th old nuclei
$F_H + F_H$ $\longrightarrow$ unstable

Lifetime measurements in femtosecond range

LMU MLL

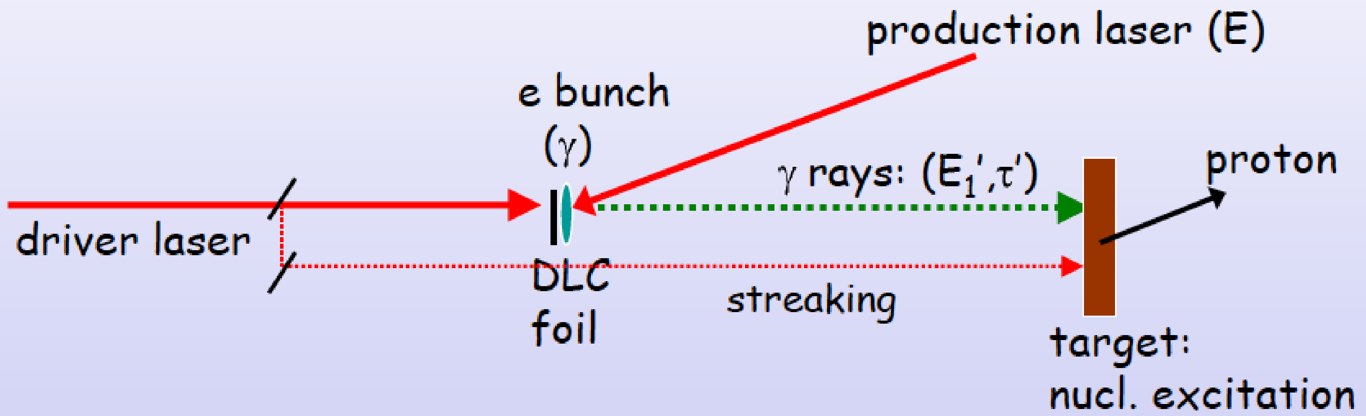
Proton streaking

eli extreme light infrastructure

- (schematical) layout of proton streaking setup

reflection:
energy $E' = E \cdot 4\gamma^2$
pulse $\tau' = \tau / 4\gamma^2$

1. excitation: $\gamma \sim 1600$, $E \sim 1$ eV: $E_1' \sim 10$ MeV, $\tau' \sim 10^{-21}$ s
2. streaking 10^{22} W/cm^2

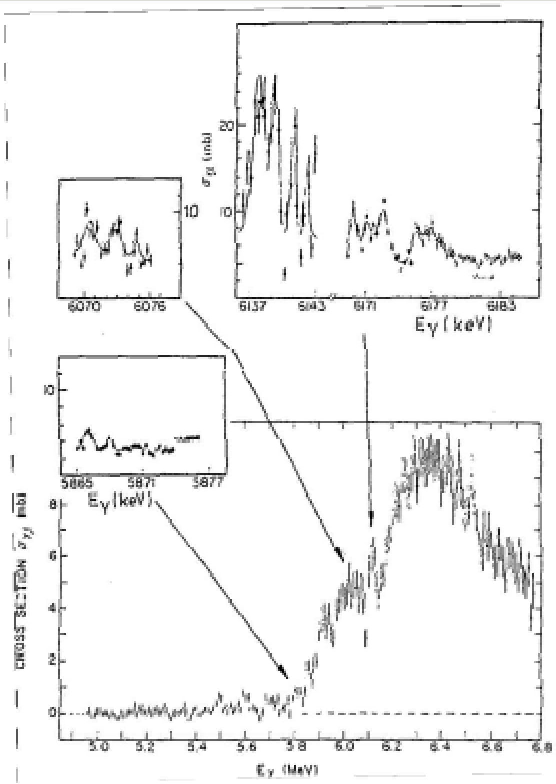


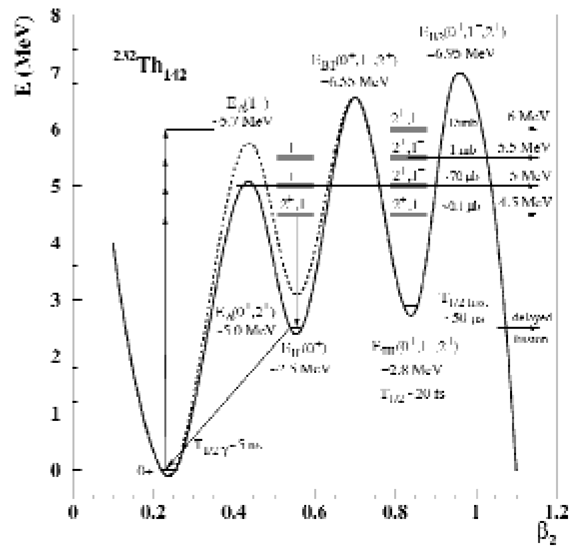
- phase-correlated laser field superimposed to excited/decaying nucleus
- emitted proton: energy modulated by laser field (accelerated or decelerated)

→ tune delay between 2 laser fields: measure 'time of birth' for protons

^{232}Th triple-humped barrier

High-resolution intermediate structure



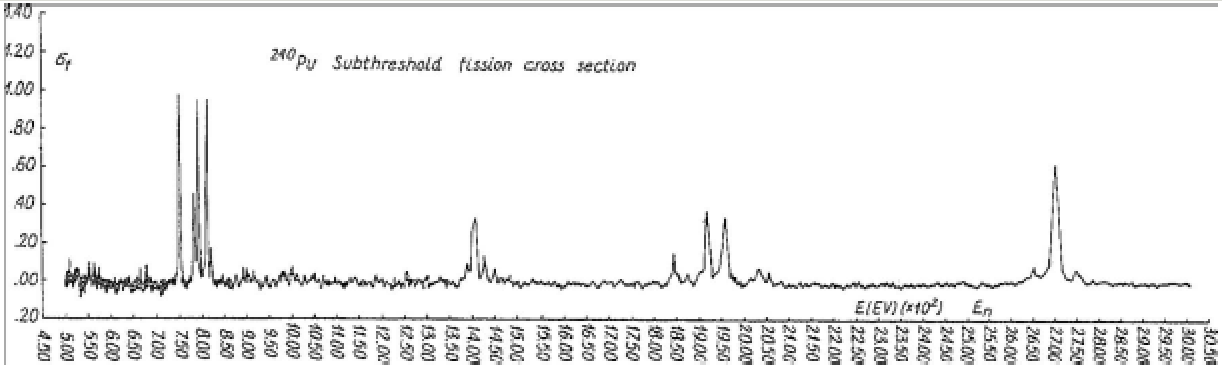


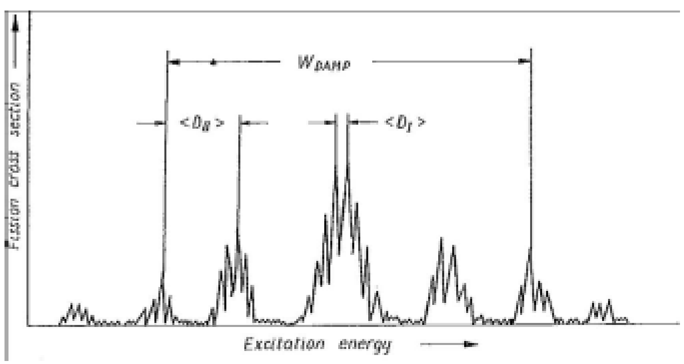
Zhang et al. determined the ground state of the resonance to 2.8 MeV via level density,
it was, however, not the 2nd but the 3rd minimum
(which he assumed to be very shallow).

J.W. Knowles et al., Phys. Lett. B 116, 315 (1982).   Zhang et al., Phys. Rev. Lett. 53, 34 (1984).

Intermediate structure

High-resolution





W_D = 100 keV = damping width

D_{III} = 2 keV ; BW ≈ 3×10^{-4}

D_{II} = 2 keV ; BW ≈ 3×10^{-4}

D_I = 10 eV ; BW ≈ 10^{-6}

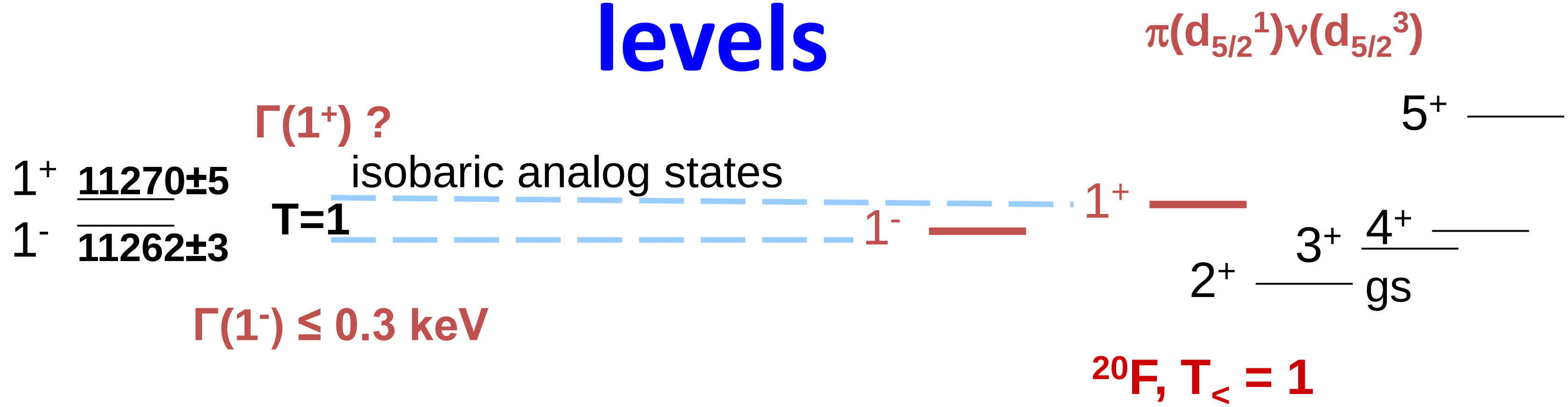
Excitation energy *E* above ground state from level density

Rotational band 3rd min. $E(2^+) - E(1^-)$

Rotational band 2nd min. $E(2^+) - E(0^+)$

$$\frac{\hbar^2}{2\Theta_{III}} = 2.0\,\mathrm{keV}; \quad \frac{\hbar^2}{2\Theta_{II}} = 3.3\,\mathrm{keV}$$

The ^{20}Ne case: parity mixing of yrast levels



ΔE=7.5±5.7 keV

"enhancement factor"

670 ± 7000

Goal: measure parity violation in simple states !

Understand effects of weak interaction microscopically

^{20}Ne

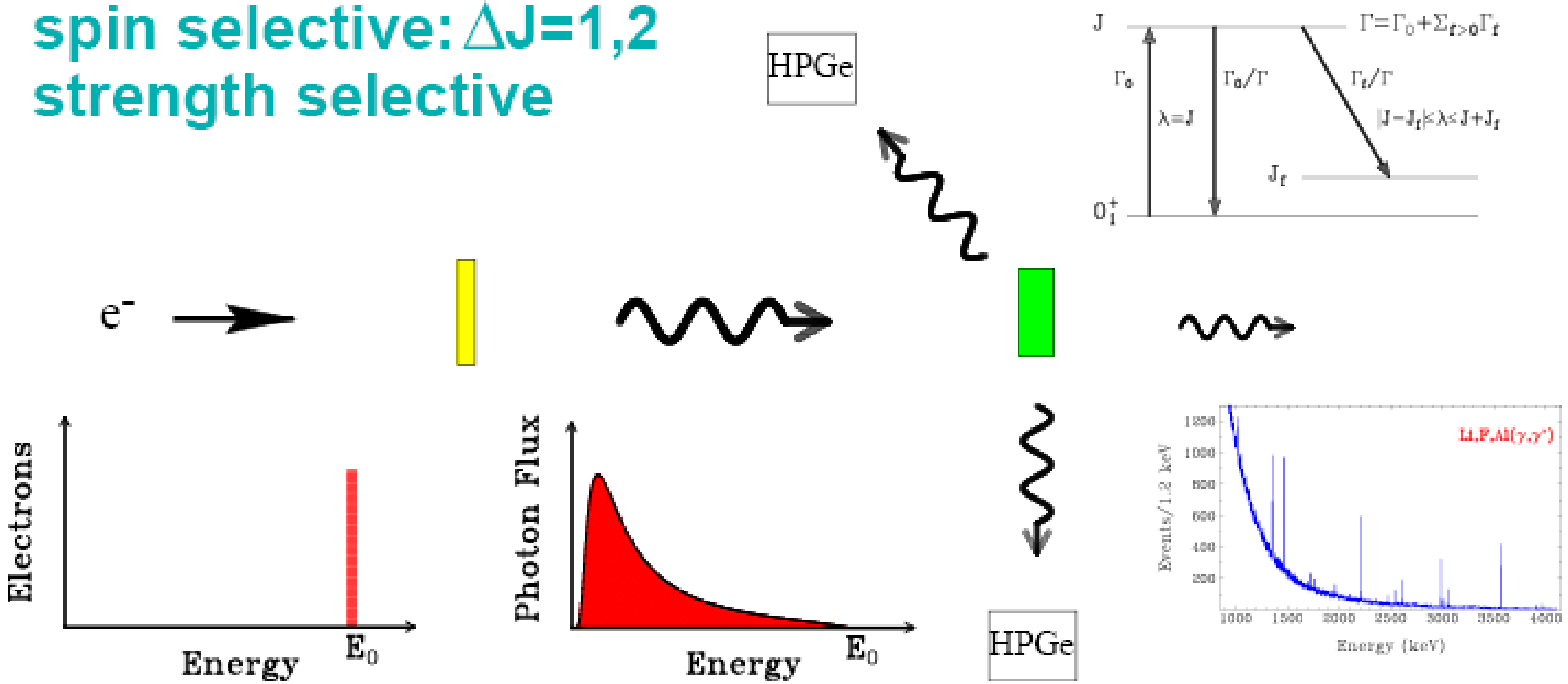
0^+ —— **$T_<=0$**

► **e.g., study the parity doublet in ^{20}Ne !**

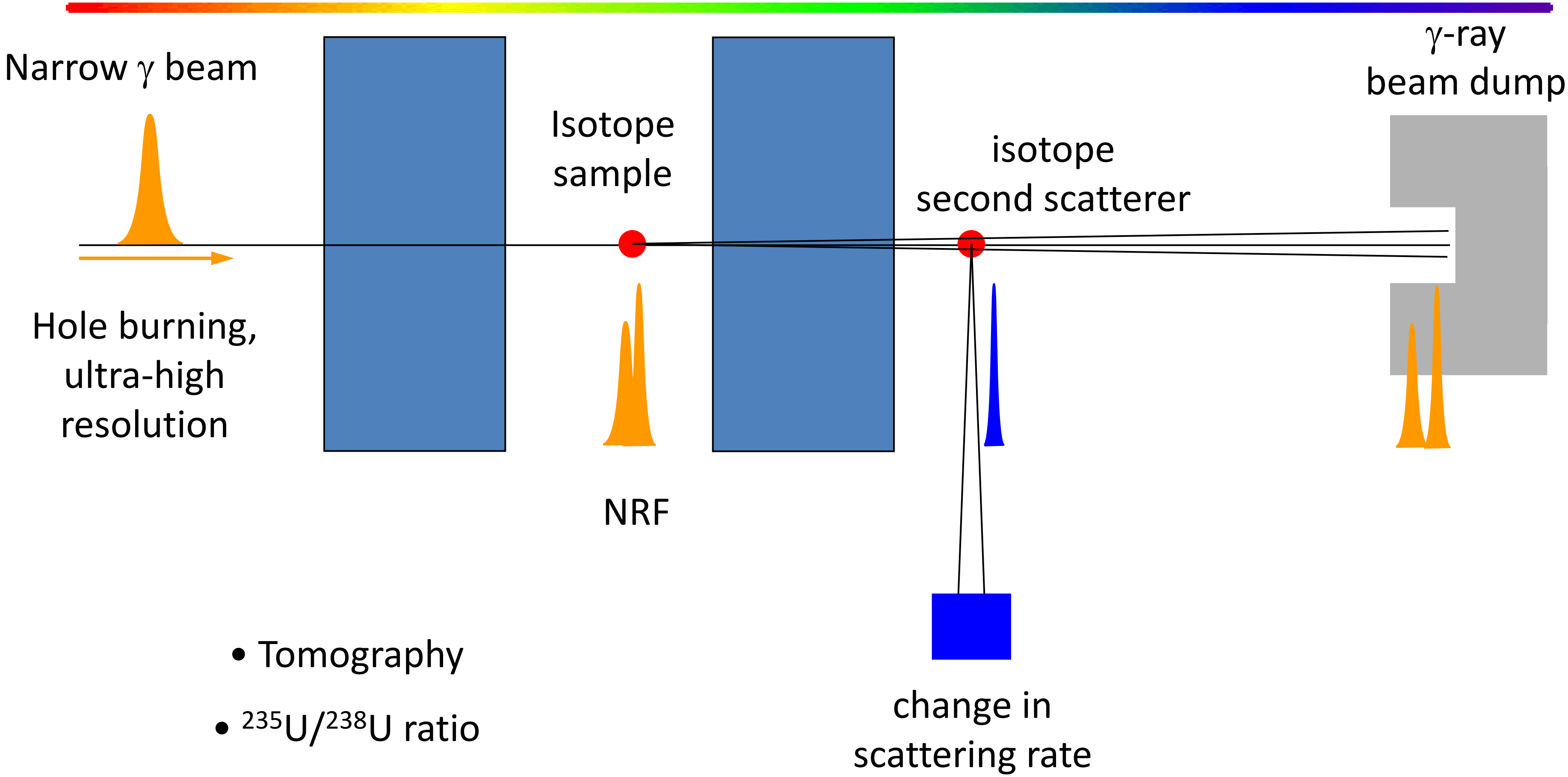
Photon Scattering
(Nuclear Resonance Fluorescence)

Traditionally Bremsstrahlung: Kneissl,Pietralla,Zilges, J.Phys.G 32, R217 (2006).

high energy resolution
spin selective: $\Delta J=1,2$
strength selective



Nuclear Resonance Fluorescence Applications



- Tomography
- $^{235}U/^{238}U$ ratio