Nuclear Energy and Waste Transmutation With High Power Accelerator and Laser Systems

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Global Facts

World energy consumption

- 10 GTeP
- 2000 W / habitant (Europe 4000W, USA 9000W, Africa 500…)

NUCLEAR ENERGY :GLOBAL FACTS

A rather Young form of energy, of limited importance at the world level (7%),economically viable source of electricity (320GWe.y,16%)

Production concentrated in a few countries (USA+FR+J)= 2/3 of the world

A passionately contested energy for

Its origin related to defense, Its cost structure (high investments ,delayed returns)

Questions insufficiently dealt with in the past :Proliferation

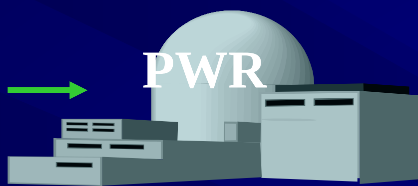
(Pu mostly) , Safety and Nuclear waste management

These questions generate social concerns for the future

Management of current waste
Two types of waste policies

U ore
200t

enriched U
30t



Once-through case (US,Sw)

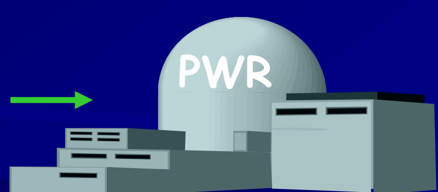
1GWe.yr=1t of
fissioned material

Waste:
- Fission products
- 100% U, Pu
- 100% Np, Am, Cm

Geogical storage of spent fuel
?????

U ore

enriched U



Pu recycling(Fr,J)

U,Pu precious fuel!!!
Waste:
- Fission products
- 0.1% Pu
- 100% Np, Am, Cm

U, Pu (MOX)

Reduction of final waste

Partition
&Transmutation

- Once-through
Pu recycling

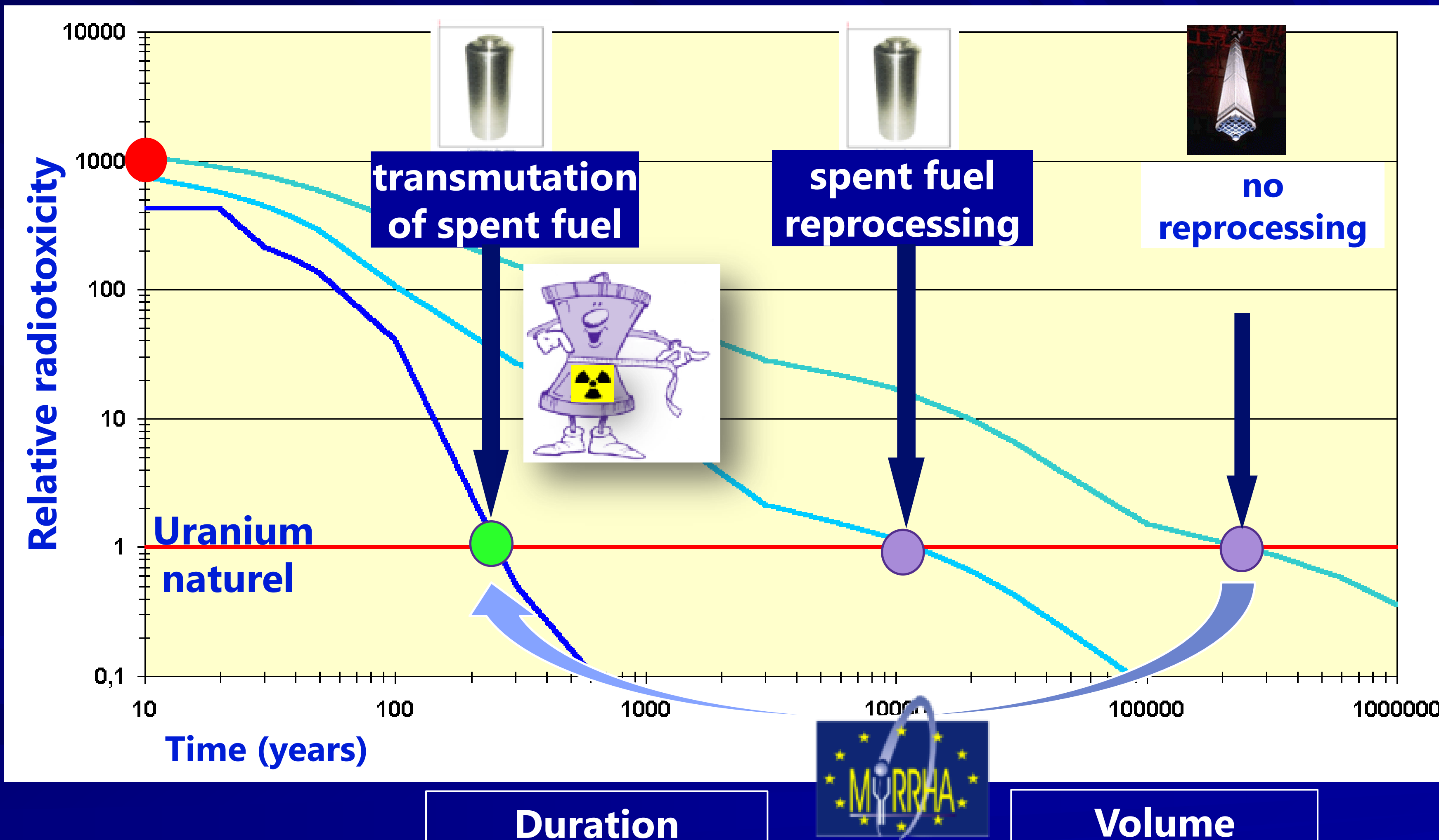
- possibility of
multirecycling

Fuel Cycle for High Level Waste ??

1 ton UO_2 used fuel (50 GWd/t)

	No Recycling Once Through	Todays Recycling PUREX (La Hague)	Tomorrow Recycling
935 kg U 12 kg Pu	**Nearly 1 ton as HLW to Geological Disposal**	U + Pu recycled	U + Pu recycled
1 kg Np 0,8 kg Am 0,6 kg Cm	Presently adopted in US, SE, FIN Decision for industrial Geol. Disp., under construction	**53 kg HLW to Geolo. Disp. In vitrified waste form** Presently adopted in FR, JP, … No formal decision for industrial Geol. Disp. yet	**MA recycled & ~50 kg HLW to Geolo. Disp. In specific packaging** Presently R&D programme (FR, JP, EU, CN, ROK, USA)
~50 kg PF (3,5 kg PFVL)	**Burden of HLW for more than 300,000 y**	**Burden of HLW for more than 10,000 y**	**Burden of HLW for ~300 y**
	Industrial scale	Industrial scale	R&D level

Motivation for transmutation



Duration Reduction 1.000x

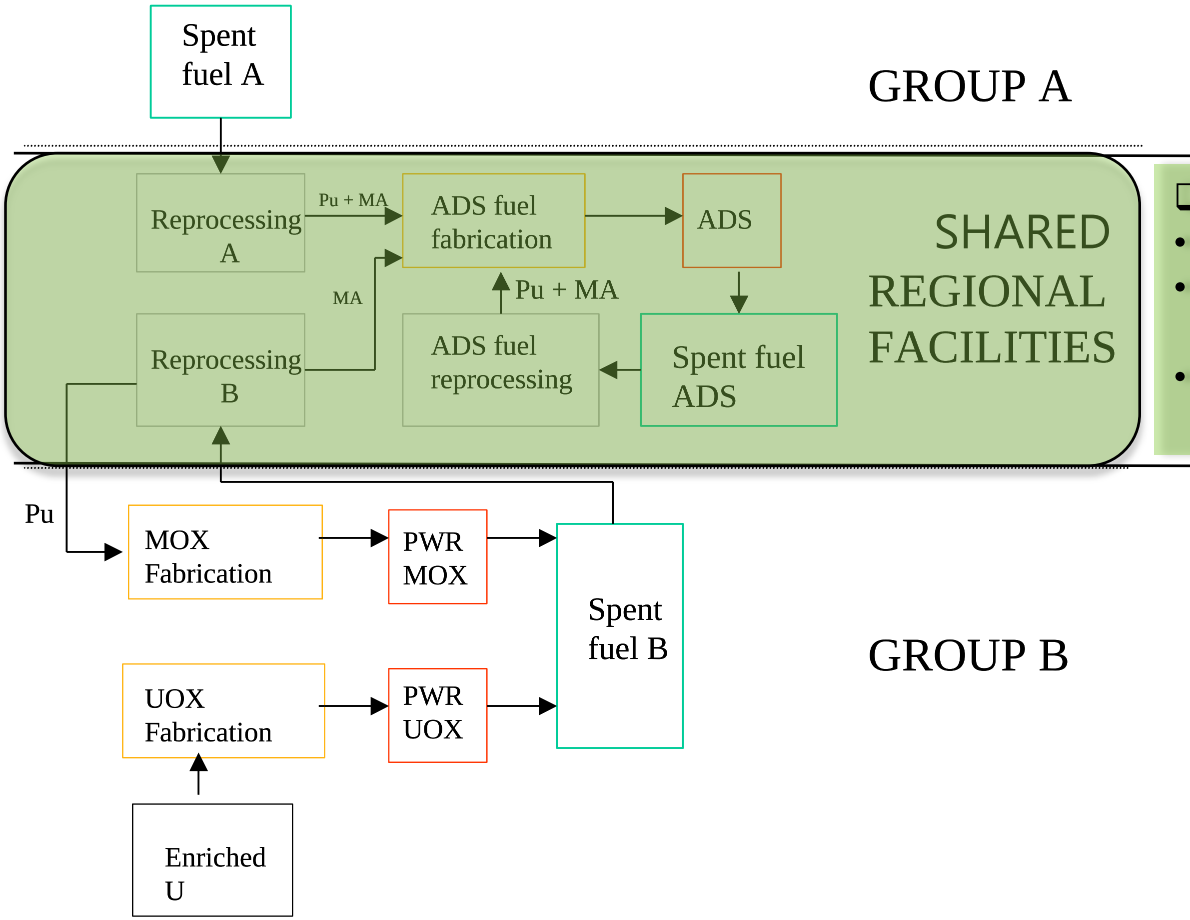
Volume Reduction 100x

European approach to P&T

- P&T useful for countries
  - in phase out
  - with active nuclear programme
- Reduction of volume & heat load of waste
- P&T should be seen at a regional/European level
- Nuclear Energy Scenario studies: 4 country groups
  - A:
  - B:
  - C:
  - D:

In any Nuclear Energy scenario efficient transmutation of MA by fast neutrons can be achieved in a subcritical reactor

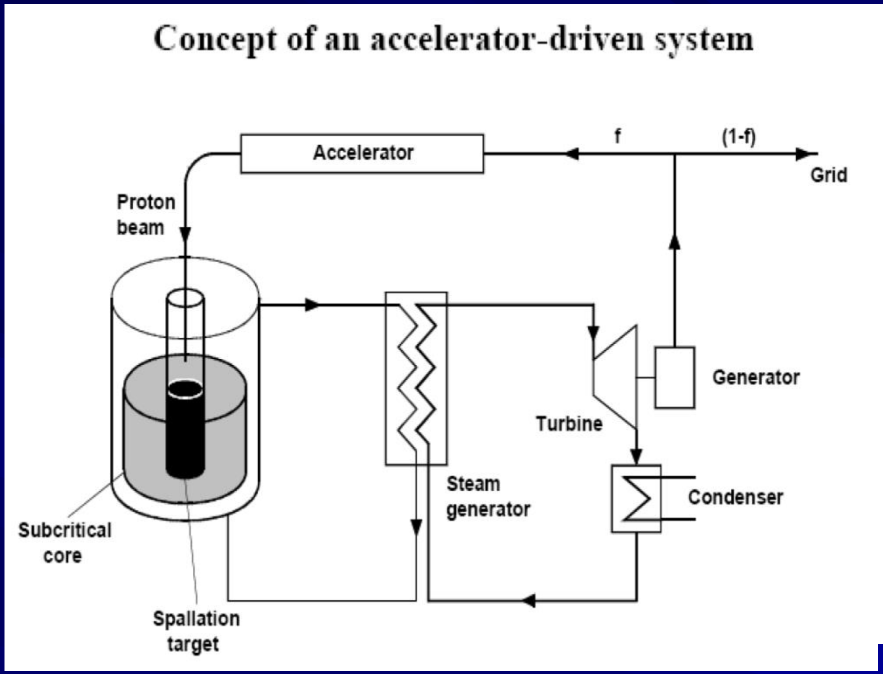
Even with opposite policies towards Nuc.Ener, it is possible to share dedicated facilities for advanced HLW Mgt

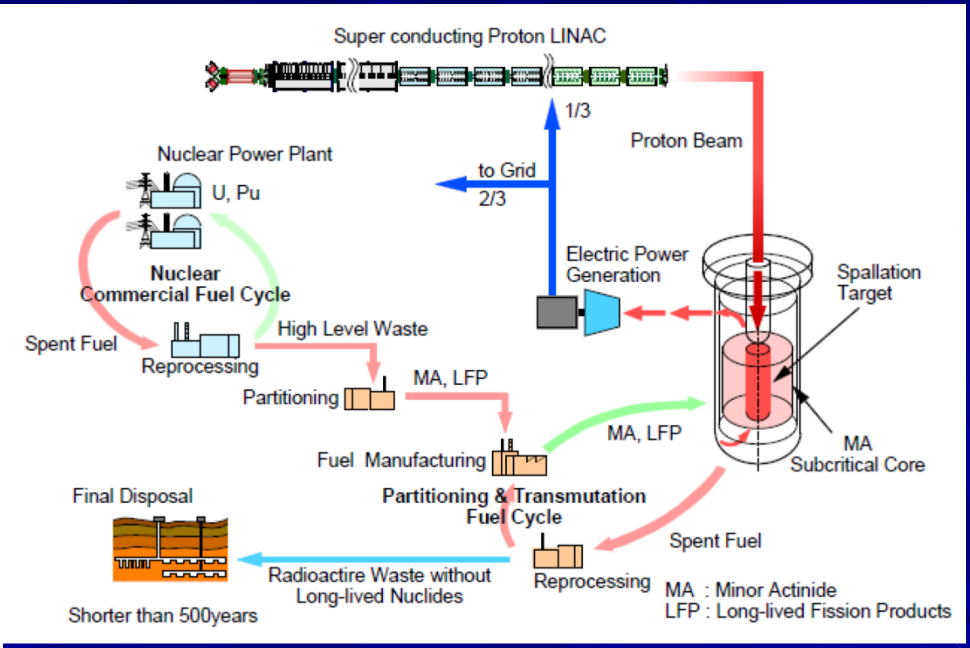


- **Advantages for A**
  - ADS shared with B
  - ADS burn A's Pu& MA
  - Smaller Fu-Cycle units & shared

Scenario 1 objective: elimination of A's spent fuel by 2100
A = Countries Phasing Out, B = Countries Continuing

What is an ADS?

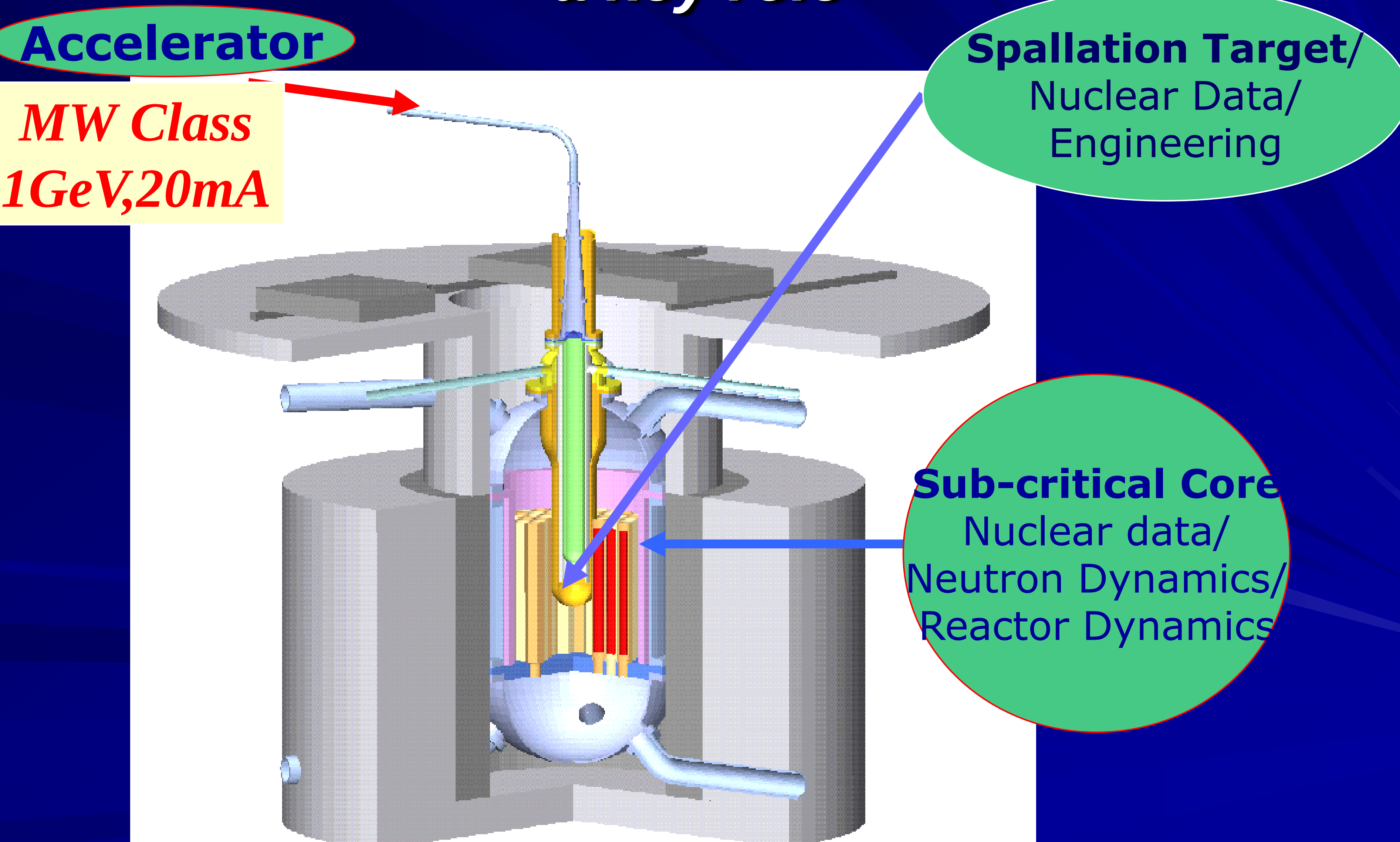




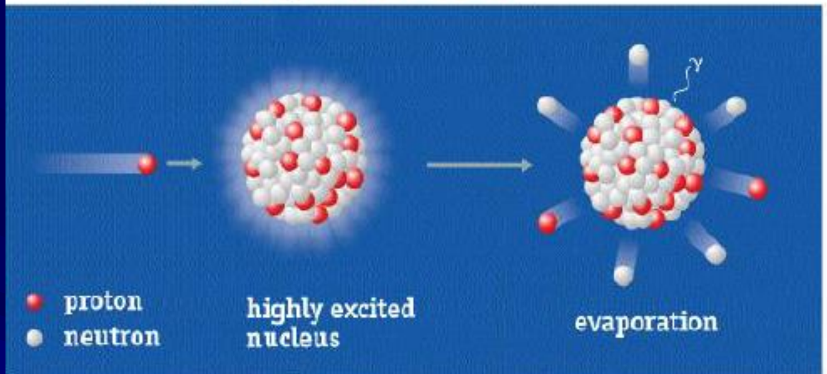
An **Accelerator-Driven-System** is:

- a subcritical neutron multiplication assembly (nuclear reactor, $k_{eff}<1$),
- driven by an external neutron source,
- obtained through the spallation mechanism with high energy (~ 1GeV) protons,
- impinging on massive (high Z) target nuclei (Pb, Pb-Bi, W, Ta, U).

Transmutation with an ADS
How and where Nuclear Physics plays a key role

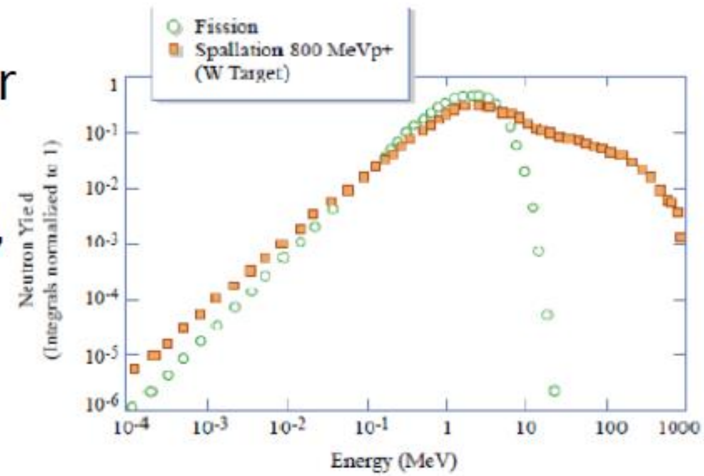


Neutrons are produced through the **spallation process** on heavy nuclei: At 1GeV, each proton produce 32 neutrons by spallation



Spallation: A nuclear process in which a high energy proton excites a neutron rich nucleus which decays sending out neutrons (and other particles).

- The average energy deposited on the target, about 50 MeV/n, is lower than for deuteron induced nuclear processes.
- Neutrons with a broad energy spectrum, peaked on 1 MeV.



Modern and efficient neutron sources to day:
High energy High power MW class Accelerators.
Recent examples SNS (USA) ,ESS (EU) ,JPARC (Jp)
(Multi GeV- 1-5 MW)

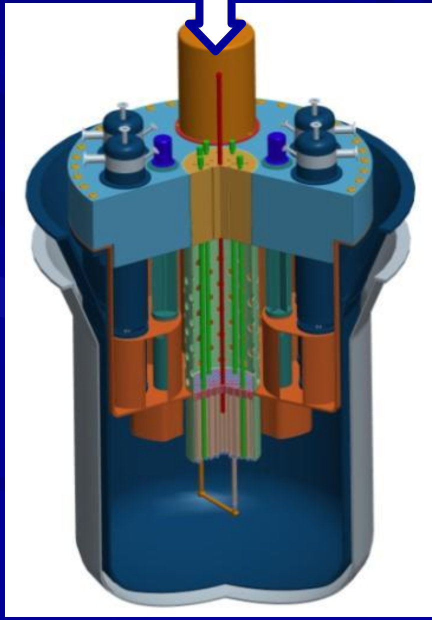
MYRRHA - Accelerator Driven System
ESFRI List EU-Roadmap 2010

Accelerator	
particles	protons
beam energy	600 MeV
beam current	2.4 to 4 mA
mode	CW
MTBF	> 250 h

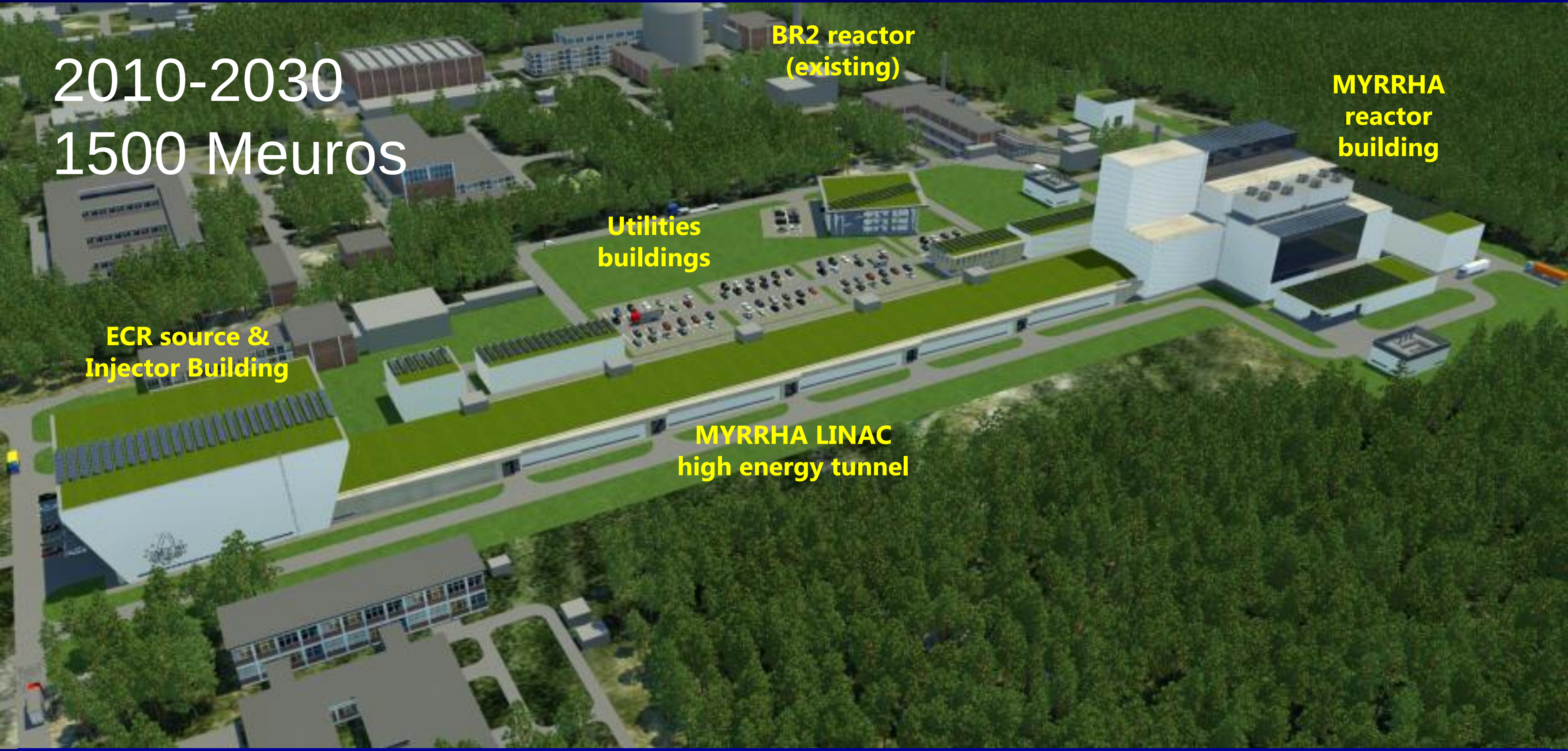
Reactor	
power	~85 MW_{th}
k_{eff}	0.95
spectrum	fast (flexible)
fuel	30 to 35% Pu MOX
coolant	LBE

- Demonstrate the **ADS concept** (coupling accelerator + spallation source + power reactor)
- Demonstrate **Transmutation** (experimental fuel assemblies)
- Fast neutron source:
- **Multipurpose and flexible Irradiaton facility**

Target	
main reaction	spallation
output	$2 \cdot 10^{17}$ n/s
material	LBE (coolant)
power	2.4 MW



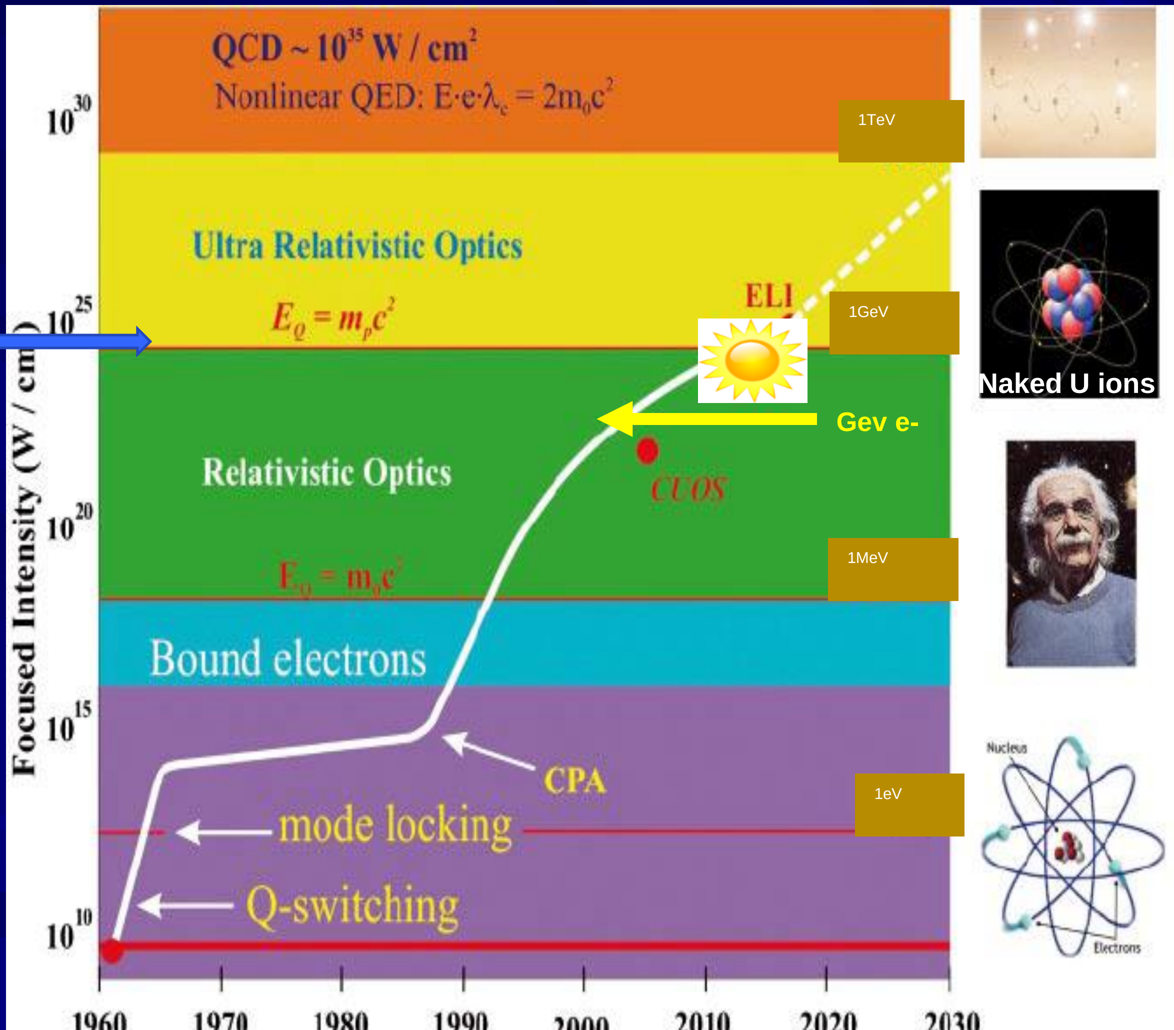
MYRRHA A glance into the future…



But Producing relativistic protons by standard accelerator technology is very demanding in accelerating structures , real estate and money.
O. Napoly CEA Saclay

ELI: Extreme Light Infrastructure
World Roadmap for High Power Lasers

10^{25}W~ 10%Solar Power on 1 cm2



10^9W ~ Power of a nuclear reactor on 1 cm^2

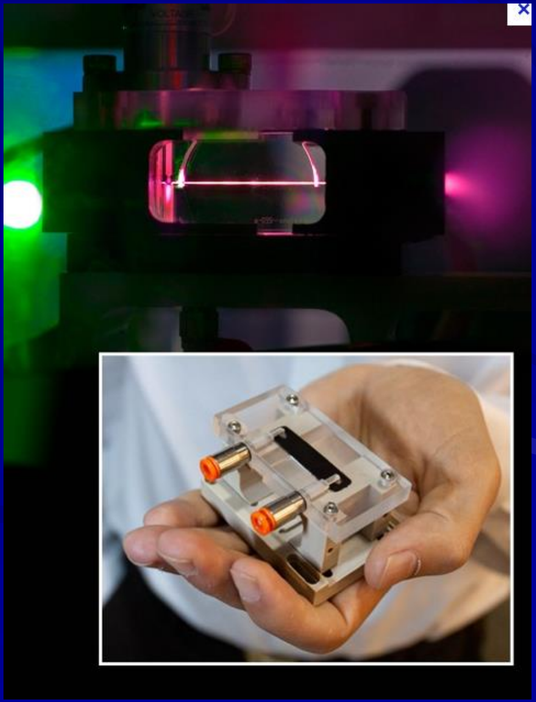
At focal point of the laser(microns) E= $9x10^6$ MV/cm for an intensity of 10^{23}W/cm2

30 GeV e- acceleration within few mm

G. Mourou, T. Tajima, Science 331,41 (2011)

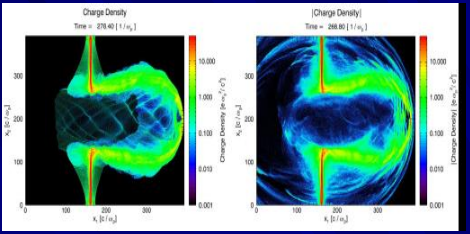
Exciting Perspectives

High Intensity Lasers with High Rep Rate can offer an enormous reduction in size of Accelerators

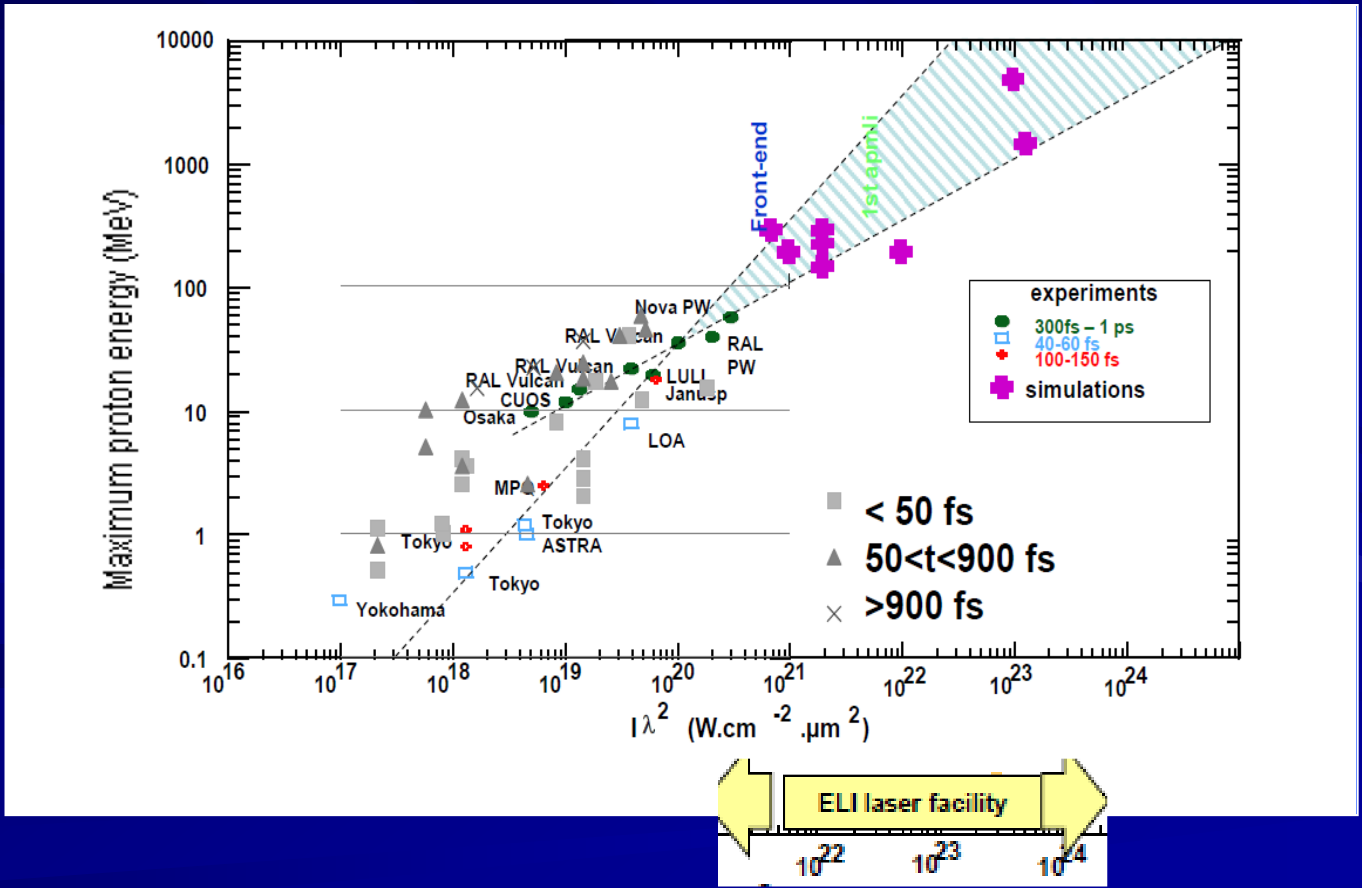


Proton acceleration

- Maximum energy scales with laser beam intensity approximately as $I^{0.5}$

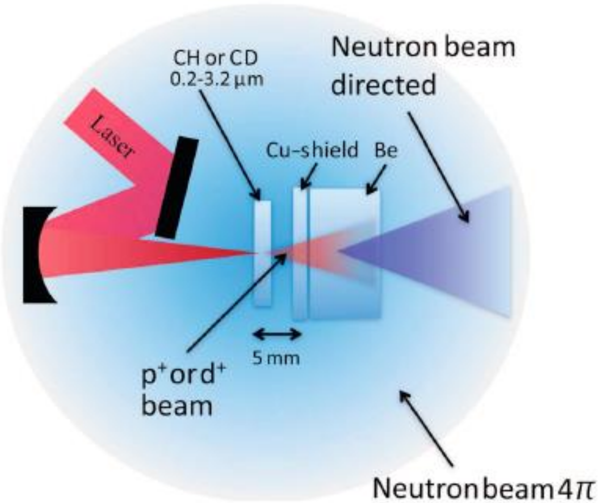


RPA simulations 10^{23} W/cm2 ,15 fs

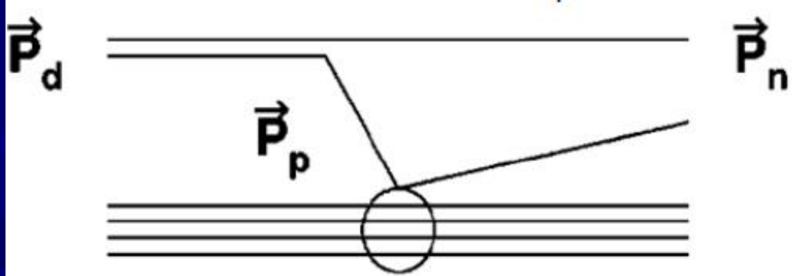


From M.Roth and I.Pomerantz

Laser neutron generation - Ion driven

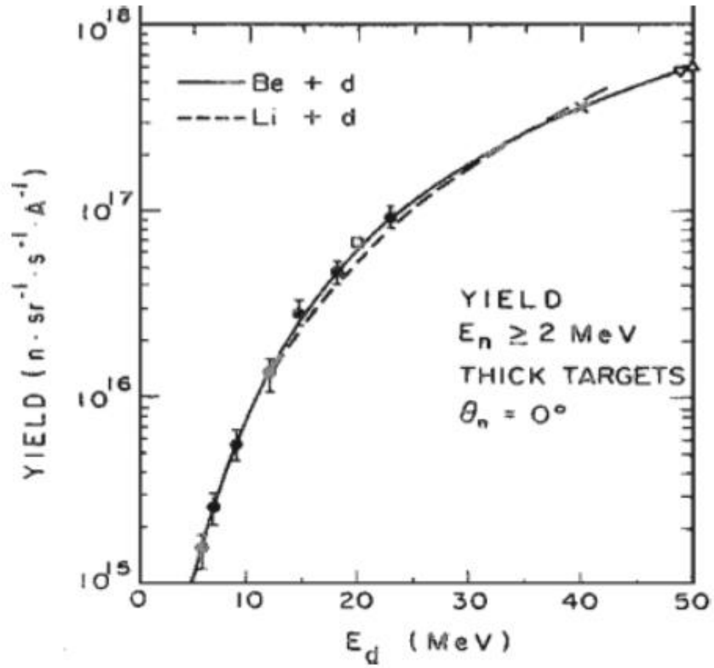


Forward deuteron breakup channel



Roth, M. et al. Phys. Rev. Lett. 110, 044802 (2013)
Jung, D. et al. Phys. Plasmas 20, 056706 (2013)

Takes advantage of the high (p,n) cross sections of low-z materials

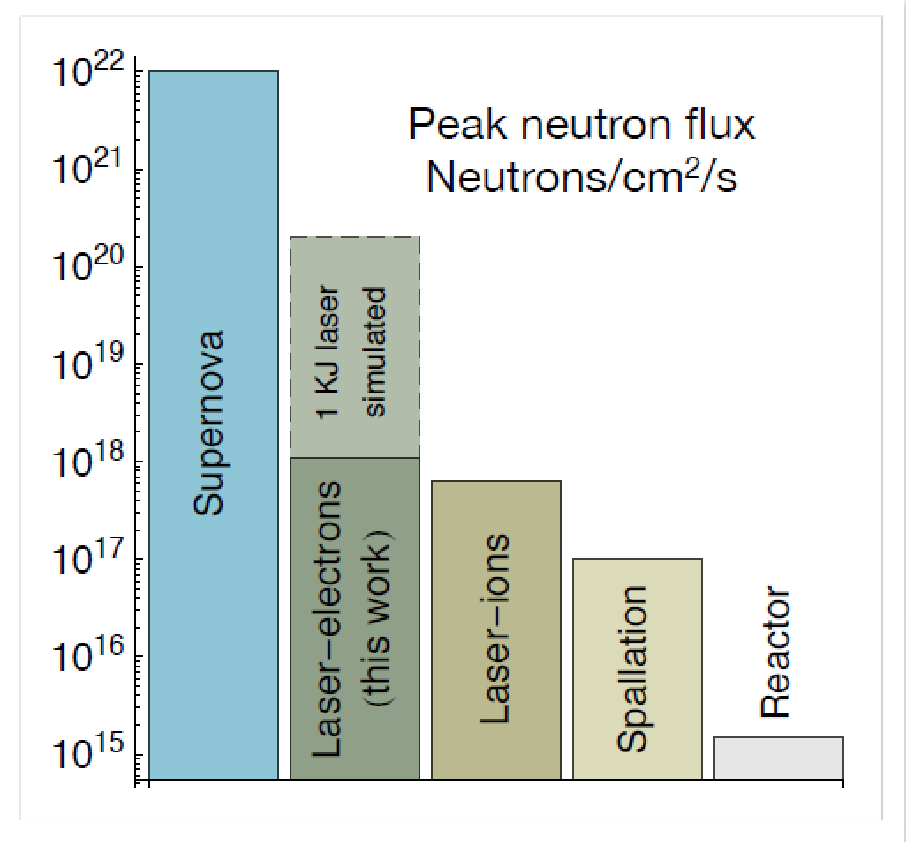


Requirements for being efficient:
Eion >10s of MeV

Requires a high energy, high contrast

Laser driven neutron sources
High peak neutron flux Neutrons/cm^2/s

	Los Alamos NATIONAL LABORATORY EST. 1943
	M. Roth, et al., Phys. Rev. Lett. 110, 044802 (2013).
Energy / peak power	80 J / 200 TW
Drive beam particles	Deuterons (10's of MeV)
Converter material	Beryllium
Neutrons per shot	Up to 10^{11}
Neutron pulse duration	100s of ps
Peak flux	6×10^{17} n/cm^2/s
Neutron directionally	Some beam-like component
Dominant (x,n) mechanism	Deuteron disassociation
Neutron energy spectrum	Up to 10's of MeV

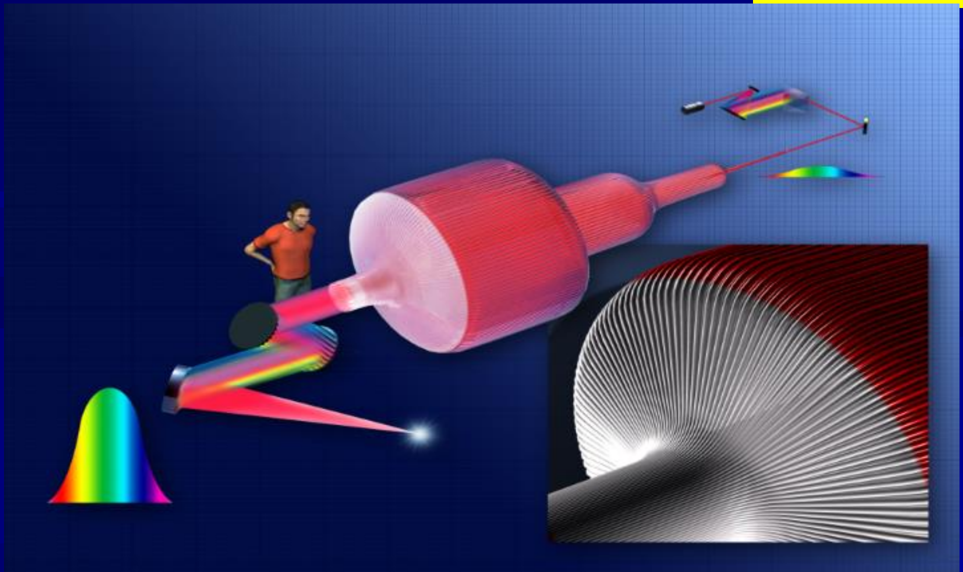


For the future,HPLS have still two handicaps
Efficiency at the grid
Repetition rate at high power

Input 150kW

Output: 40J@1Hz = 40W
efficiency<10^{-3}

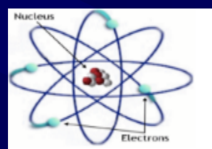
ICAN (European Project)
The Future is Fibre Accelerators (Nature Photonic April 2013)

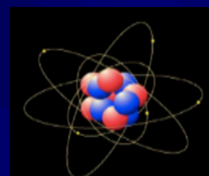


A Fiber Laser based CW Ion driver would be a ‘modest’ but paying first step!!

ELI-NP

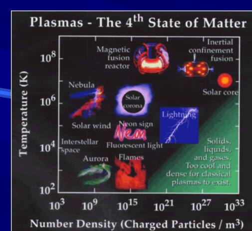
Explore matter and its constituents : from atom to vacuum with new powerful probes at the frontiers of existing technologies
High Power lasers and High energy and brilliant gamma beams



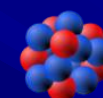


1) Ultra-short High power laser pulse(25fs) 2 X1O PW, 1/mn

HP Laser



Femto -scale



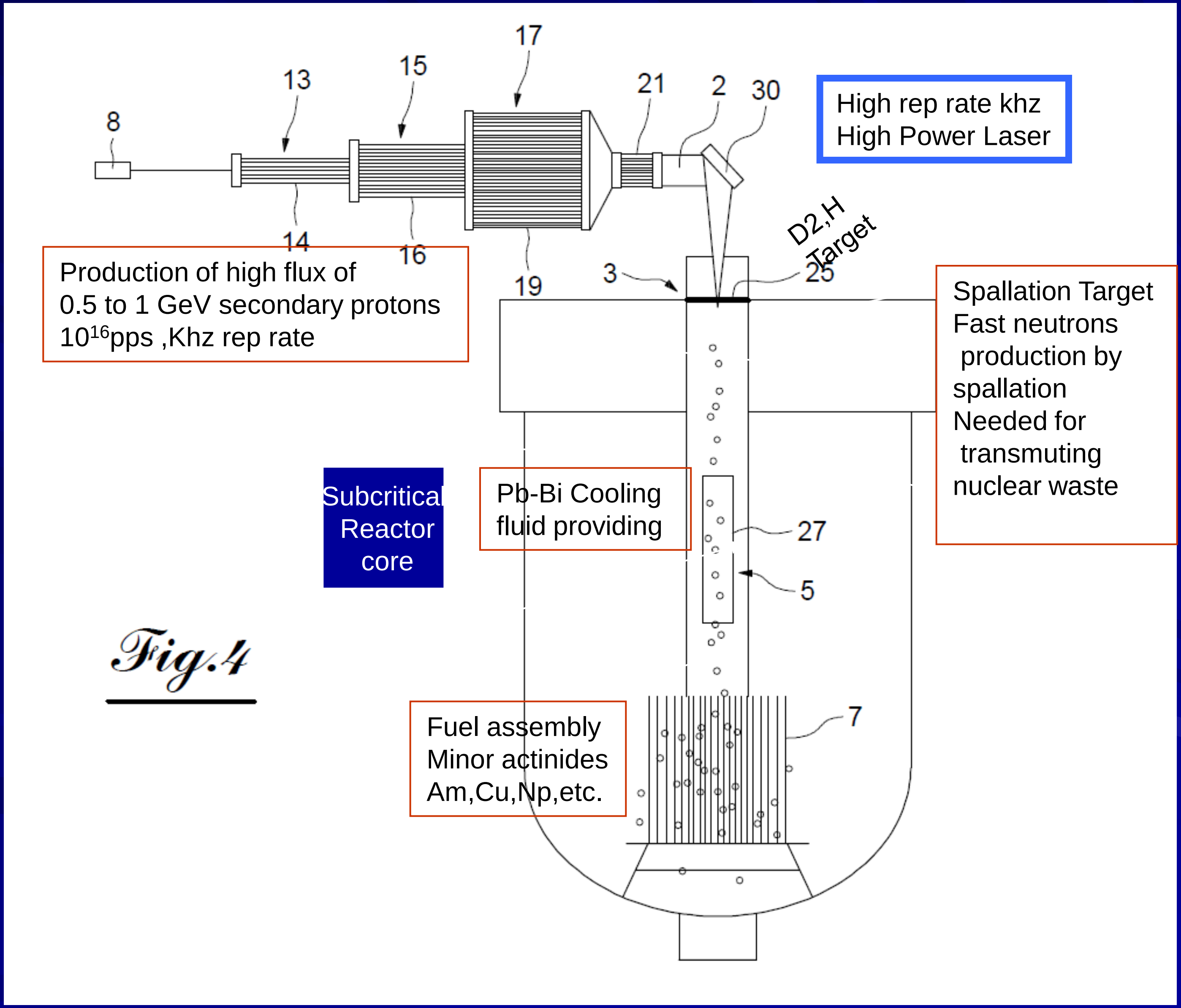
Collisions electron-laser



2) GAMMA beams high flux , monochromatic, ~qqs10^{-3} , E= 0.2-19 MeV

Concept of a Laser Driven Transmutation System - LDS

(S.Gales, G.Mourou, T.Tajima)



Some Conclusions

- ***Nuclear energy does not appear any more to be a solved technical question***
  - ***Overall (societal, economic) boundary conditions have evolved significantly since 1980 and will still do so in future***
  - ***Innovation is and will be required .***
  - **Basic research can contribute via :**
  - **Specific competences (improved data, accelerators, High Power Lasers, simulation,)**
  - **More open approach (less short-term, multidisciplinary.)**

- ***Transmutation of high level waste is a feasible solution to reduce the heat load , the volume and the time storage of remaining waste . In addition on the long term it will make the future of Nuclear energy more acceptable***

Academia via its competence and its independence can provide a unique contribution to the future of nuclear energy.

Thank you for your patience !!