Novel laser-driven nuclear reaction scheme for the synthesis of extremely neutron-rich isotopes

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Exploit the unique properties of dense laser-driven ion beams
for nuclear astrophysics

Outline:

- motivation: astrophysical nucleosynthesis of heavy elements
  - → r process
  - → waiting point N=126
- laser ion acceleration: TNSA vs. RPA
- ultra-dense laser-accelerated (heavy) ion beams
  - → novel nuclear reaction mechanism: ‚fission-fusion'
- experimental realization:
  - → proposed realization stages at ELI-NP
  - → sites for exploratory studies: CALA/Garching, CETAL/Magurele

Motivation: Astrophysics

"The 11 Greatest Unanswered Questions of Physics":

(US National Research Council's Board on Physics and Astronomy)

1. What is Dark matter ?
2. What is Dark Energy ?
3. How were the Heavy Elements from Iron to Uranium made ?
4. What is the mass of the neutrino ?
5. Where do the ultrahigh-energy particles come from ?
6. Is a new theory of light and matter needed to explain what happens at very high energies and temperatures ?
7. Are there new states of matter at ultrahigh temperatures and densities ?
8. Are protons unstable ?
9. What is gravity ?
10. Are there additional dimensions ?
11. How did the Universe begin ?

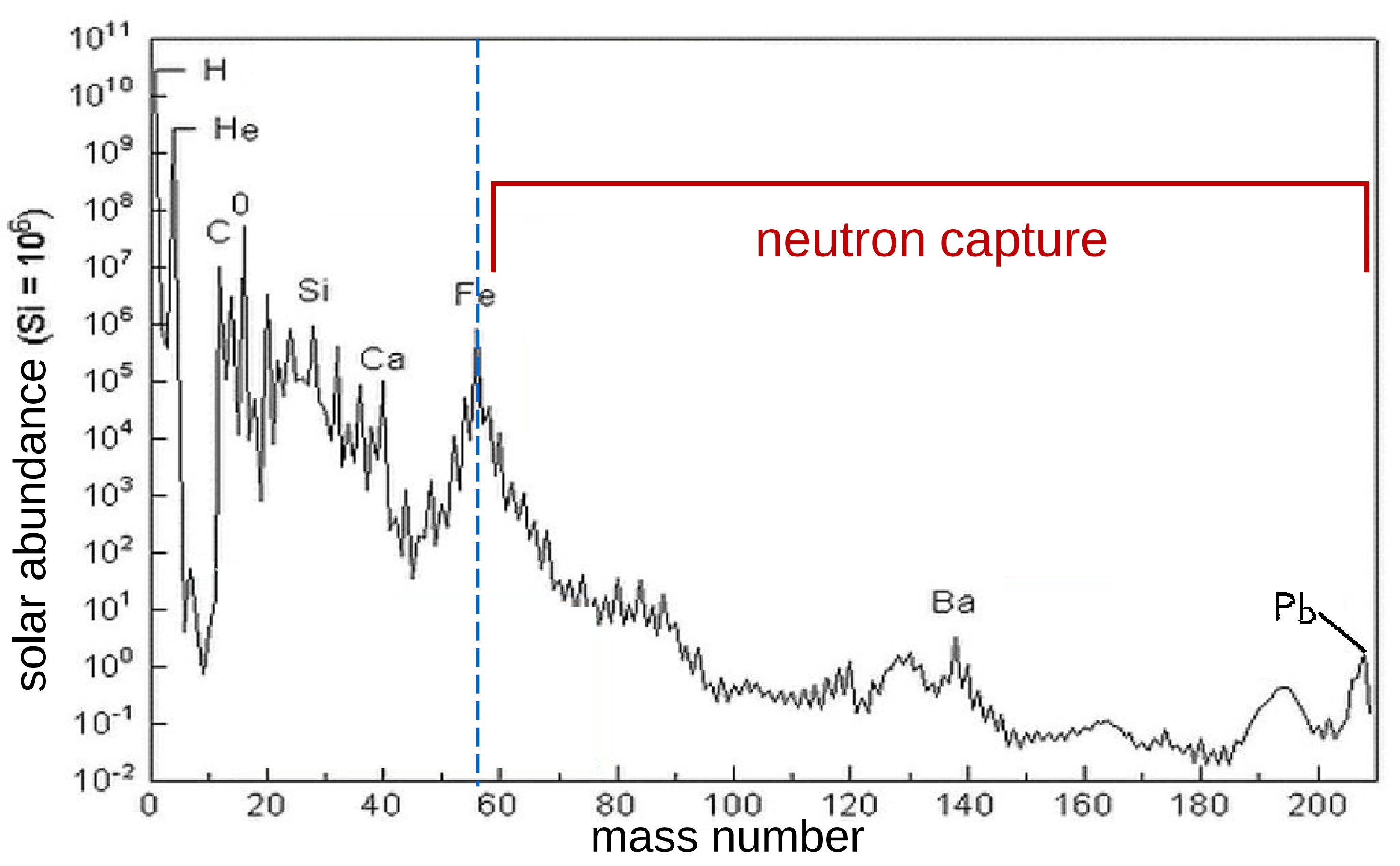
Solar Elemental Abundances

$Z \leq 26$ (Fe): thermonuclear fusion in stars

$Z > 26$: neutron capture

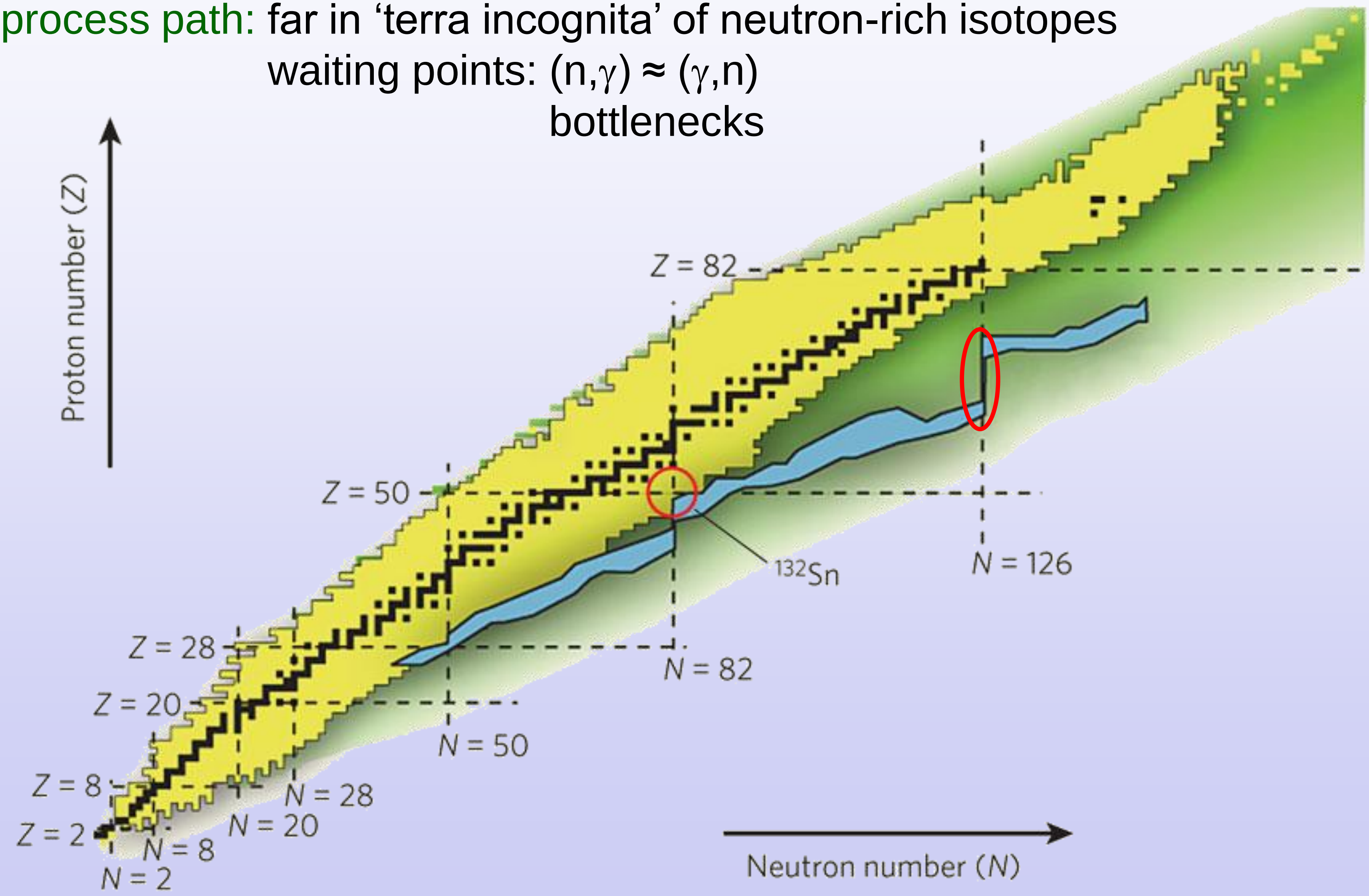
slow: s process

fast: r process (n capture much faster than β decay)



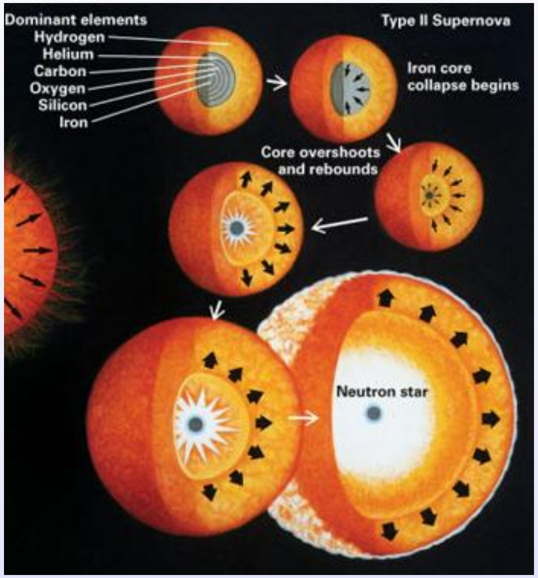
r process nucleosynthesis

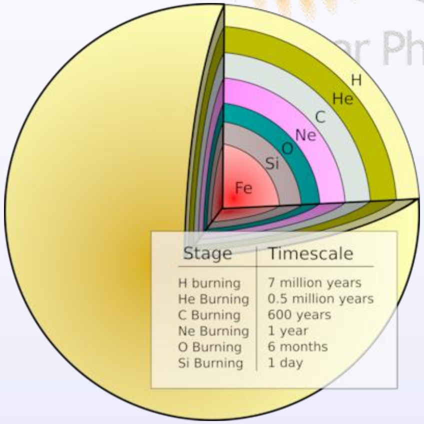
r process path: far in ‘terra incognita’ of neutron-rich isotopes
waiting points: (n,γ) ≈ (γ,n)
bottlenecks



Astrophysical r-Process Scenarios

- physical conditions:
  - temperature ~1•10^9 K
  - neutron density > 1•10^{24} cm^{-3}
  - neutron-to-seed ratio must be high (~ 100): scenario ??





Stage	Timescale
H burning	7 million years
He Burning	0.5 million years
C Burning	600 years
Ne Burning	1 year
O Burning	6 months
Si Burning	1 day

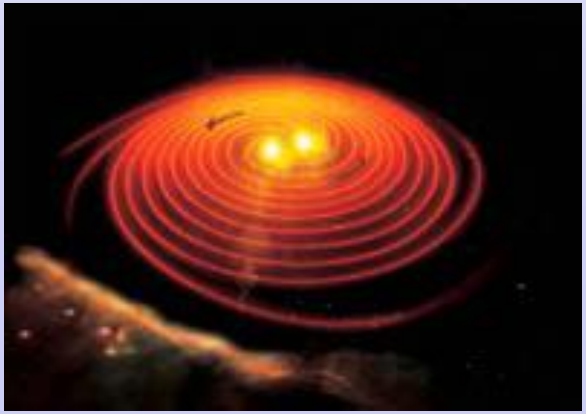
(i) (core collapse) supernovae

- m > 9 m_{solar}, implosion of Fe core (> 1.4 m_{solar})
- reverse β decay: $p + e^- \rightarrow n + \nu_e$ (n-star formation)
- halt by neutron degeneracy pressure
  → infall reverted to outward shock wave
- nucleosynthesis occurs in ν-driven winds
- but: ν wind depletes neutron flux

remnant of SN 1987A

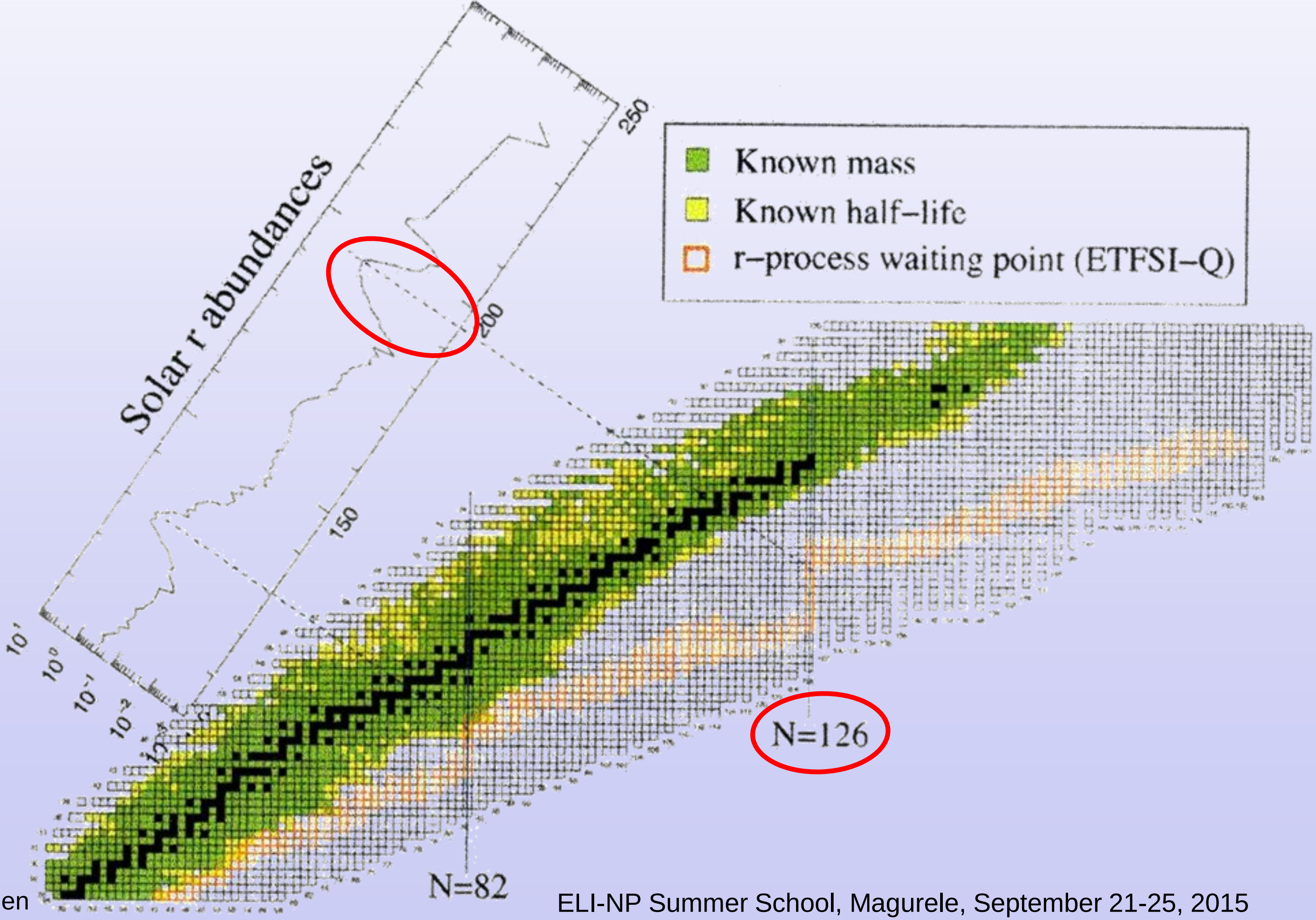
(ii) neutron star mergers (10^{-5}/yr/galaxy)

- decompression of ejected neutron star material

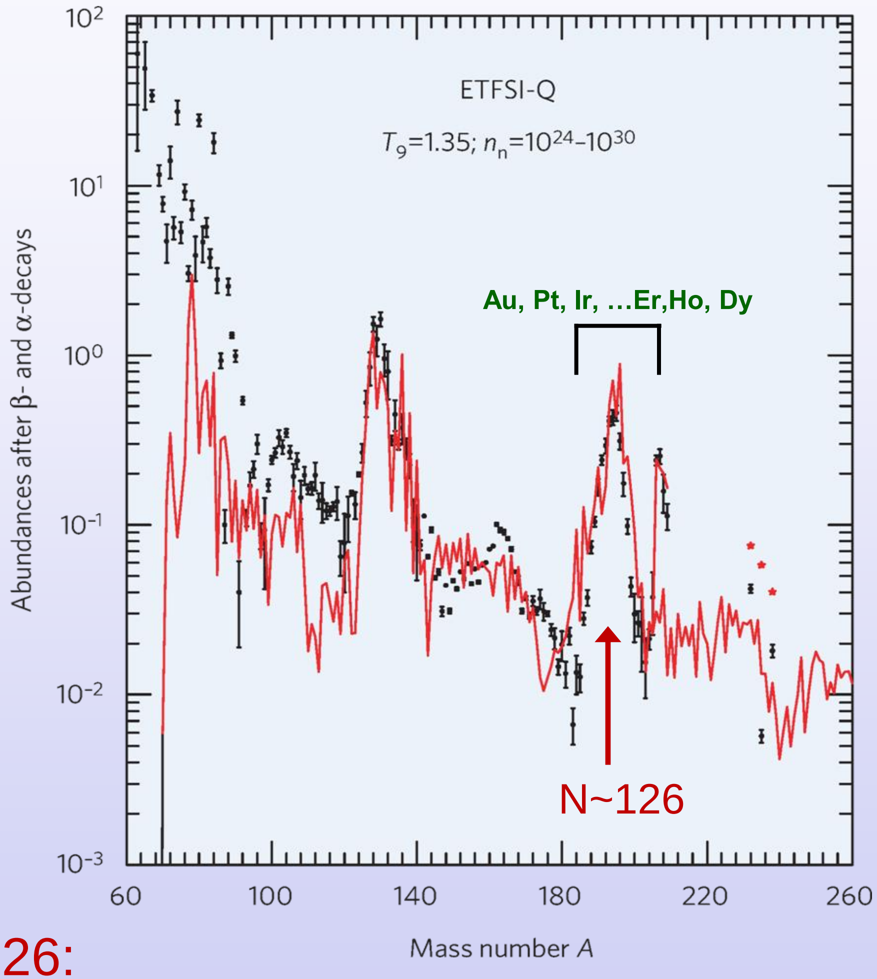


Nucleosynthesis of Heavy Elements

- modelling the r process path (far in ‘terra incognita’):
- masses and lifetimes needed for ~ 1000 neutron-rich isotopes
- measured masses, lifetimes required for model testing



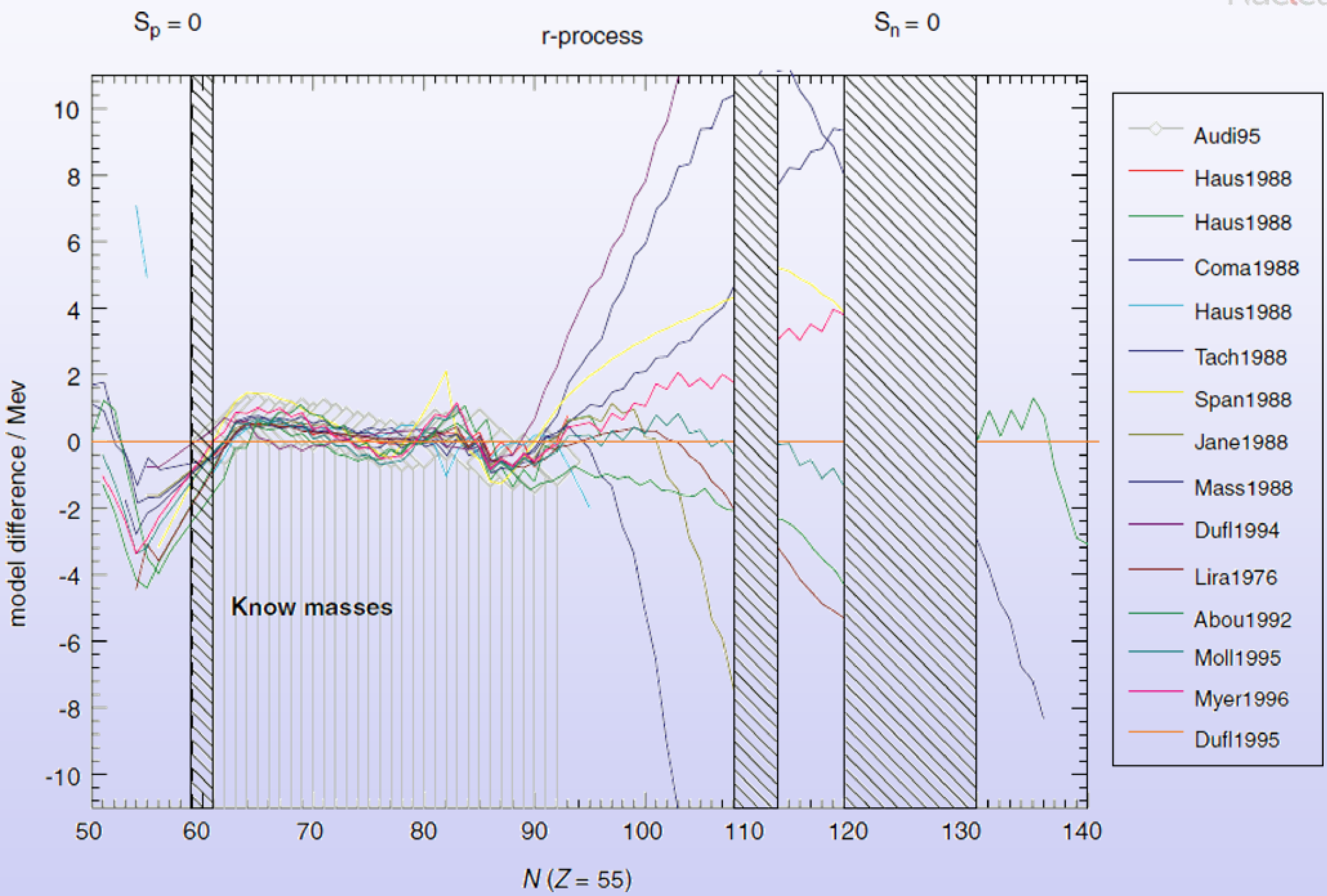
r process: waiting point N=126



waiting point N=126:

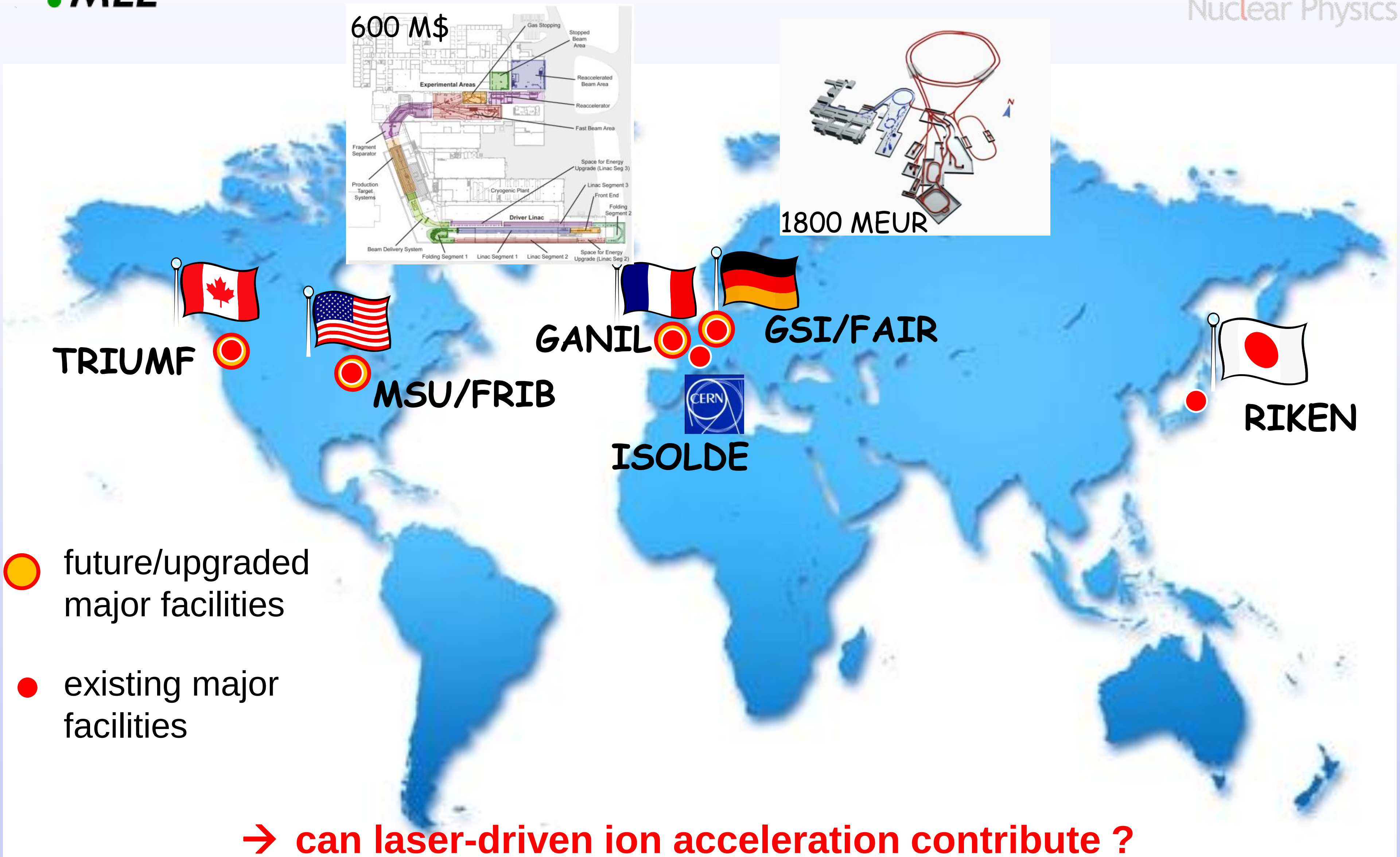
- bottleneck for nucleosynthesis of actinides
- last region of r process ‘close’ to stability
- ~ 15 neutrons away from last known isotope

Nuclear Mass Model Predictions



→ **exp. data needed for extremely neutron-rich isotopes !**

Radioactive Beam Facilities



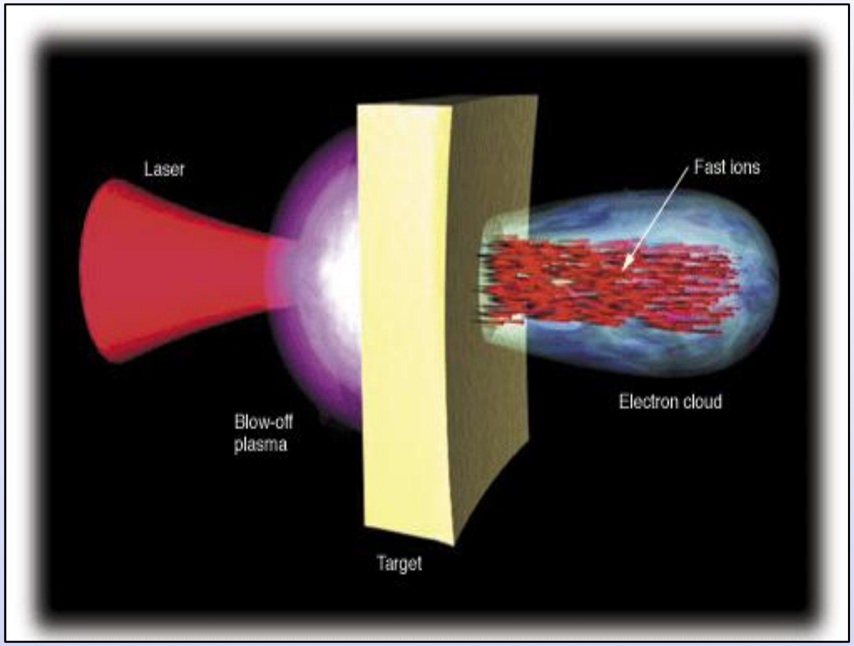
- ◉ future/upgraded major facilities
- ● existing major facilities

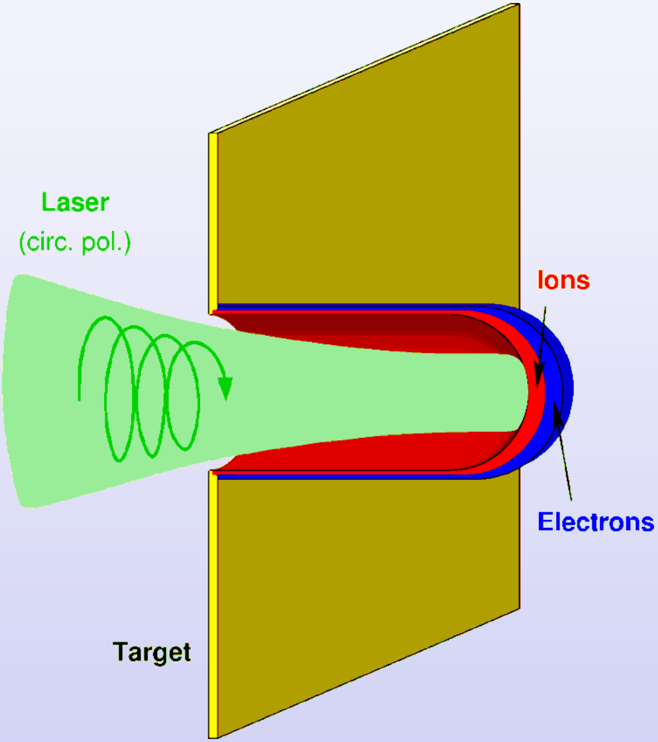
→ can laser-driven ion acceleration contribute ?

Laser-Ion Acceleration

Target Normal Sheath Acceleration (TNSA)

Radiation Pressure Acceleration (RPA)





thick targets (~μm)

$$E_{\text{ion}} \propto \sqrt{I_{Laser}}$$

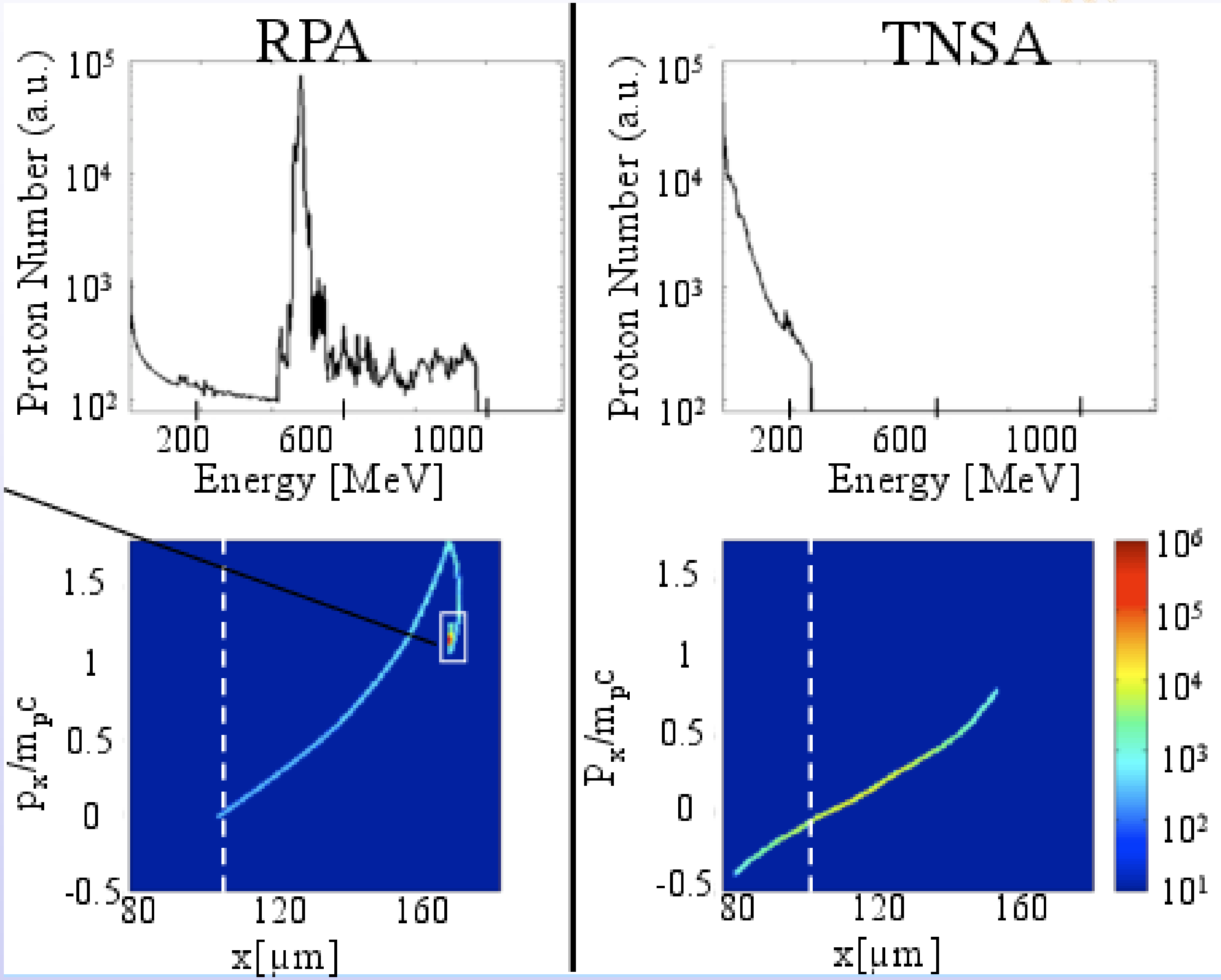
thin targets (~ nm)

$$E_{\text{ion}} \propto I_{\text{Laser}}$$

L. Robson et al., Nature Physics 3, 58 (2007)

A. Henig et al., PRL 103 (2009) 245003

Comparison: TNSA vs RPA @ 10^{21} W/cm^2



almost all protons in small phase-space volume

note: beam is
quasi-neutral

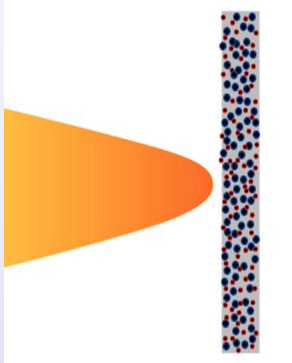
- RPA dominates for high intensities over TNSA (I ≥ 10^{22} -10^{23} W/cm^2)
- excellent longitudinal emittance possible: $\Delta E \Delta t \sim$ 10 MeV * 5 fs ~ $5 \cdot 10^{-8}$ eV s
- extremely short pulse duration: foil thickness/c : 30 nm ≈ 100 attoseconds

courtesy: M. Zepf

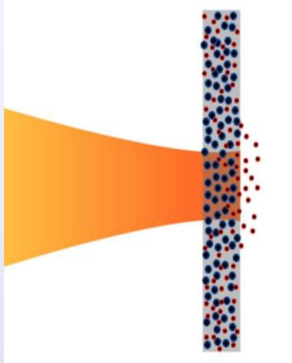
RPA: Hole-Boring vs. Light Sail Regime

- light sail regime:

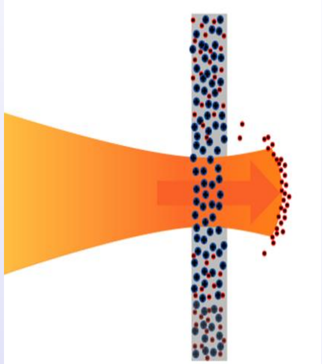
  - the target is sufficiently thin for the laser pulse to punch through the target and accelerate a slab of plasma as a single object



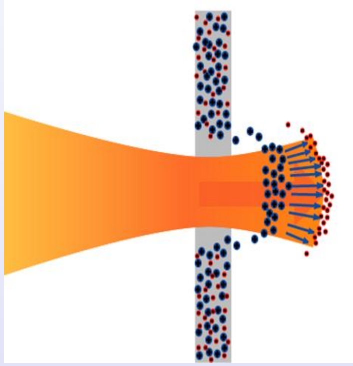
ultra thin foil (d~5-10 nm)



electrons leave the foil

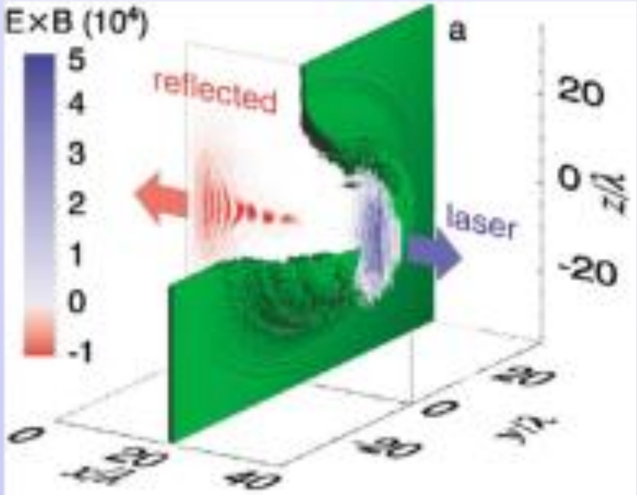


light sail



electrons pull ions

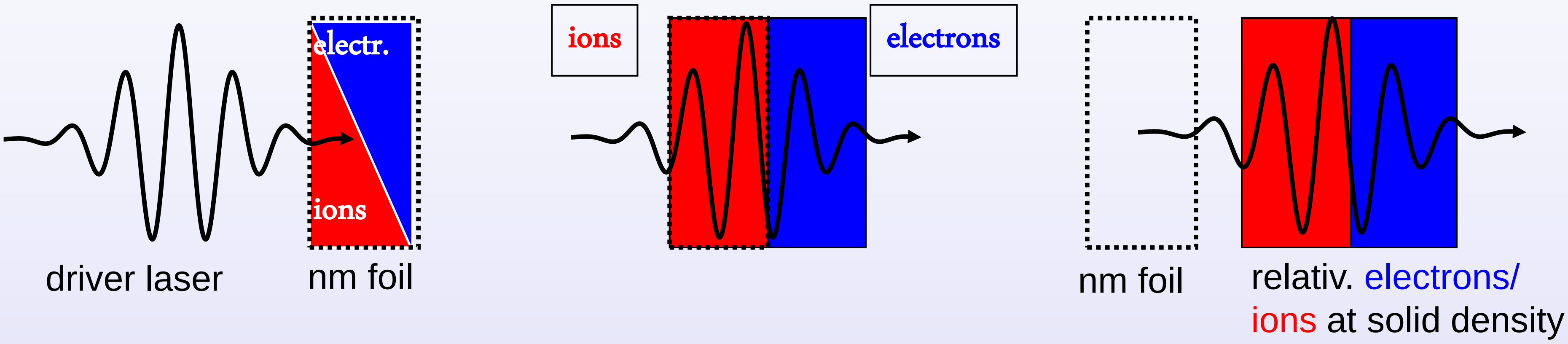
circularly polarized laser pulse: focused on an ultra-thin foil
→ fully ionizing the foil



- hole boring regime:

- laser pulse interacts with semi-infinite target (overdense plasma: opaque)
→driving material ahead of it as a piston
no interaction with the target rear surface

Radiation Pressure (Ion) Acceleration



- ‘cold’ compression of electron sheet, followed by electron breakout

- dipole field between electrons and ions

- ions + electrons accelerated as neutral bunch (avoid Coulomb explosion)

- solid-state density: 10^{22} - 10^{23} e/cm^3

  ‘classical’ bunches: 10^{8} e/cm^3

→ ~ 10^{14} x density of conventionally accelerated ion beams

Estimate of Laser Parameters

- (Simplistic) 1D RPA model for relativistic hole-boring regime:

Robinson et al., Plasm. Phys. Contr. Fusion 51 (2009) 024004

'pistoning parameter' Ξ : $$\Xi = I_L / (m_i n_i c^3)$$

I_L: laser intensity
n_i: ion density

achievable ion energy: $$E_i = E_u \cdot A = 2 m_i c^2 \Xi / (1 + 2\sqrt{\Xi})$$

E_u: ion energy/nucleon

conversion efficiency: $$\chi = 2\sqrt{\Xi} / (1 + 2\sqrt{\Xi})$$

accelerated ions: $$N_i E_i = \chi W_L$$

W_L: laser pulse energy

- acceleration of ^{232}Th ions to ~7 MeV/u with λ_L=0.8 mm:

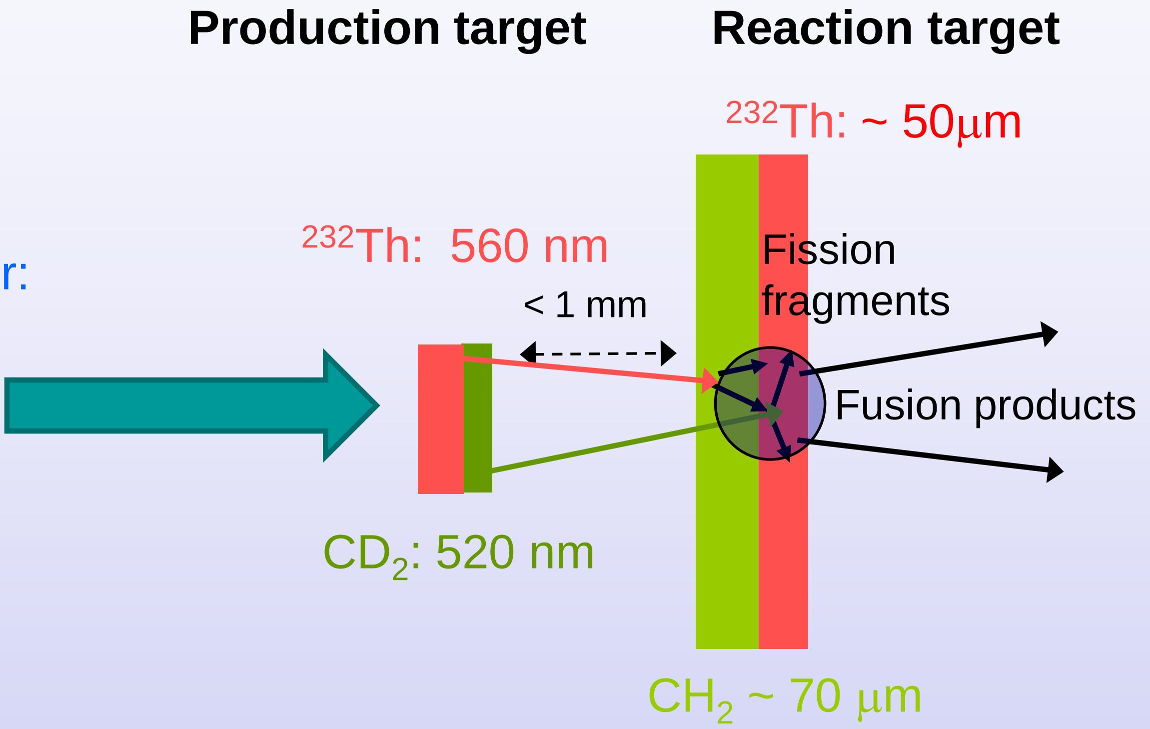
laser intensity $I_L = 1.2 \cdot 10^{23}$ W/cm^2 (a_L = 167, circular polarized)
→ $\Xi = 3.8 \cdot 10^{-3}$, χ = 11%
focal spotsize A_F: $W_L = I_L \cdot A_F \cdot t_L$ W_L: laser pulse energy, t_L: laser pulse duration
assume W_L = 300 J, t_L = 32 fs:
→ A_F = 7.1 μm^2 (3 μm diameter)

Exp. Scheme for "Fission-Fusion"

^{232}Th: $t_{1/2}$: $1.4 \cdot 10^{10}$ a

high-power, high-contrast laser:

- 300 J, ~30 fs (10 PW)
- $\sim \cdot 10^{23}$ W/cm^2
- focal diam. ~ 3 µm



Production target

Reaction target

^{232}Th: ~ 50µm

^{232}Th: 560 nm

< 1 mm

Fission fragments

Fusion products

CD_2: 520 nm

CH_2 ~ 70 µm

CD_2: - light ions induce Th target fission

CH_2: - induce fission of Th beam

- decelerate (beam-like) fission fragments for optimum fusion

D. Habs, PT et al., Appl. Phys. B 103, 471 (2011)

Fission Stage of Reaction Scheme

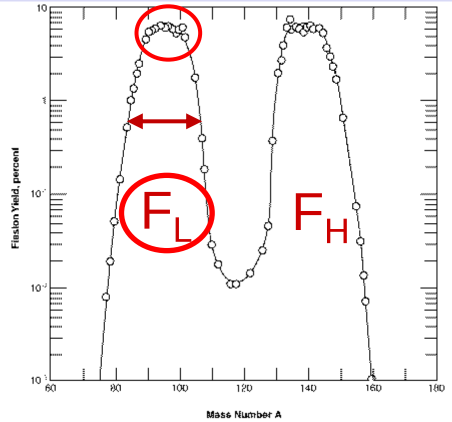
beam (~ 7 MeV/u): d, C, ^{232}Th
target: p, C, ^{232}Th

^{232}Th + p, C → $F_L + F_H$: beam-like fission fragments
d, C + ^{232}Th → $F_L + F_H$: target-like fission fragments

- (geometric) fission cross section estimate:

Th + Th: $R = R_1 + R_2 + D \approx 15$ fm: $\sigma_{fis} \sim 700\ \mathrm{fm}^2 \approx 7 \cdot 10^{-28}\ \mathrm{m}^2$
Th + C: $R \sim 10.5$ fm : $\sigma_{fis} \sim 350\ \mathrm{fm}^2 \approx 3.5 \cdot 10^{-28}\ \mathrm{m}^2$
d + Th: $R \sim 8.5$ fm : $\sigma_{fis} \sim 230\ \mathrm{fm}^2 \approx 2.3 \cdot 10^{-28}\ \mathrm{m}^2$

- fission mass distribution:



^{232}Th:
$\langle A_L \rangle \sim 91$, $\Delta A_L \sim 14$ amu (FWHM)
$\Delta A_L \sim 22$ amu (at 10% of max. yield)
$\langle Z_L \rangle \sim 37.5$ (Rb,Sr)

deep-inelastic neutron transfer towards fissioning Th (N=146)

Fusion Stage of Reaction Scheme

conventional radioactive ion beam facilities:

→ intense, low-density ion beam + stable target

here: light fission fragments of beam + light fission fragments of target

- $F_L + F_L$ → $\langle {}^{A}Z \rangle \approx {}^{182}75$: nuclei close to N=126 waiting point
- $F_L + F_H$ → ^{232}Th : original nuclei
- $F_H + F_H$ → unstable : (search for superheavy species ??)

- fusion-evaporation calculations (PACE4 code):

(Z=35,A=102) + (Z=35, A=102): E_{lab}= 270 MeV (E* = 65 MeV)

^{190}Yb (Z=70,N=126): 2.1 mb
^{189}Yb (N=125): 15.8 mb
^{188}Yb (N=124): 61.7 mb
^{187}Yb (N=123): 55.6 mb

Collective Stopping Power Reduction (?)

- Bethe-Bloch for individual ion:

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

binary collisions
k_D = Debye wave number

long-range collective interaction
ω_p = plasma frequency

- reduction of atomic stopping power for ultra-dense ion bunches:

- plasma wavelength (~ 5 nm) « bunch length (~560 nm):

  → collective effects cancel: only binary collisions contribute

- dense ion bunch: considered as ~1700 atomic layers with ~3Å distances

- „snowplough effect“: first layers of ion bunch remove electrons of target foil

- predominant part of bunch: screened from electrons (n_e reduced)

→ reduction of dE/dx : avoids ion deceleration below V_C:

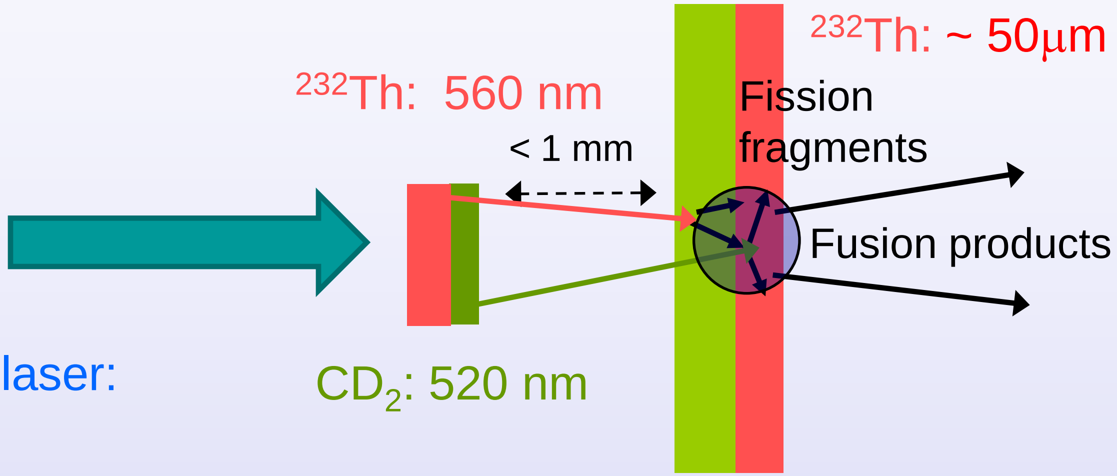
→ would allow for thick reaction targets for fusion reactions

→ theoretical calculations & experimental data needed

Exp. Scheme for "Fission-Fusion"

Production target **Reaction target**

conventional stopping:



^{232}Th: 560 nm

< 1 mm

CD$_2$: 520 nm

^{232}Th: ~ 50µm

Fission fragments

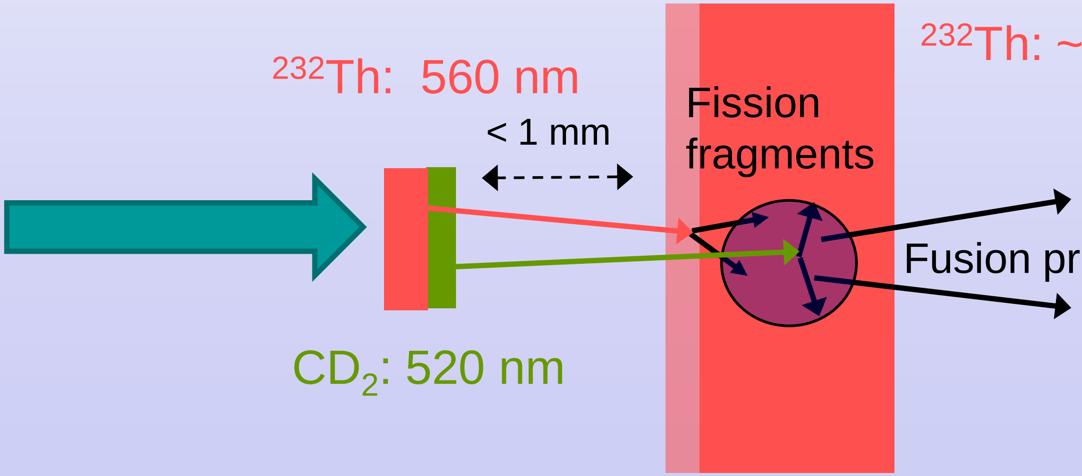
Fusion products

CH$_2$ ~ 70 µm

high-power, high-contrast laser:

- 300 J, ~30 fs (10 PW)
- ~10^{23} W/cm^2
- focal diam. ~ 3 µm

collective stopping:



^{232}Th: 560 nm

< 1 mm

CD$_2$: 520 nm

^{232}Th: ~ 5 mm

Fission fragments

Fusion products

→ full conversion of reaction target into fragments (?)

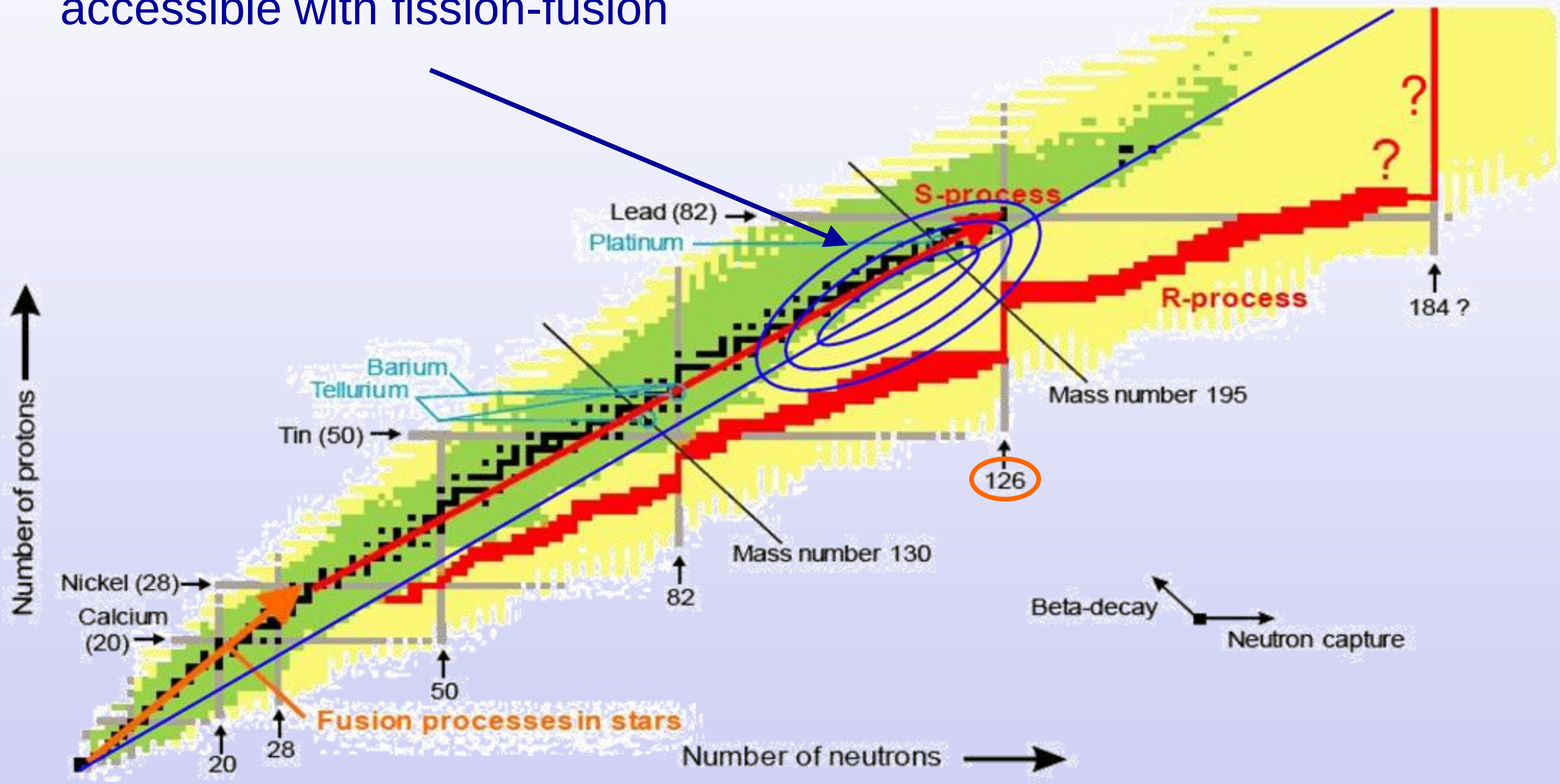
Fission-Fusion Yield / Laser Pulse

laser acceleration (300 J, ε~10%):	normal stopping	reduced stopping
^{232}Th :	$1.2 \cdot 10^{11}$	$1.2 \cdot 10^{11}$
C :	$1.4 \cdot 10^{11}$	$1.4 \cdot 10^{11}$
protons :	$2.8 \cdot 10^{11}$	$2.8 \cdot 10^{11}$
beam-like light fragments	$3.7 \cdot 10^{8}$	$1.2 \cdot 10^{11}$
target-like light fragments	$3.2 \cdot 10^{6}$	$1.2 \cdot 10^{11}$
fusion probability F_L(beam) + F_L (target)	$1.8 \cdot 10^{-4}$	$1.8 \cdot 10^{-4}$
neutron-rich fusion products (A≈ 180-190)	1.5	$4 \cdot 10^{4}$

- laser development in progress:
  diode-pumped high-power lasers: increase of repetition rate expected

r process: waiting point N=126

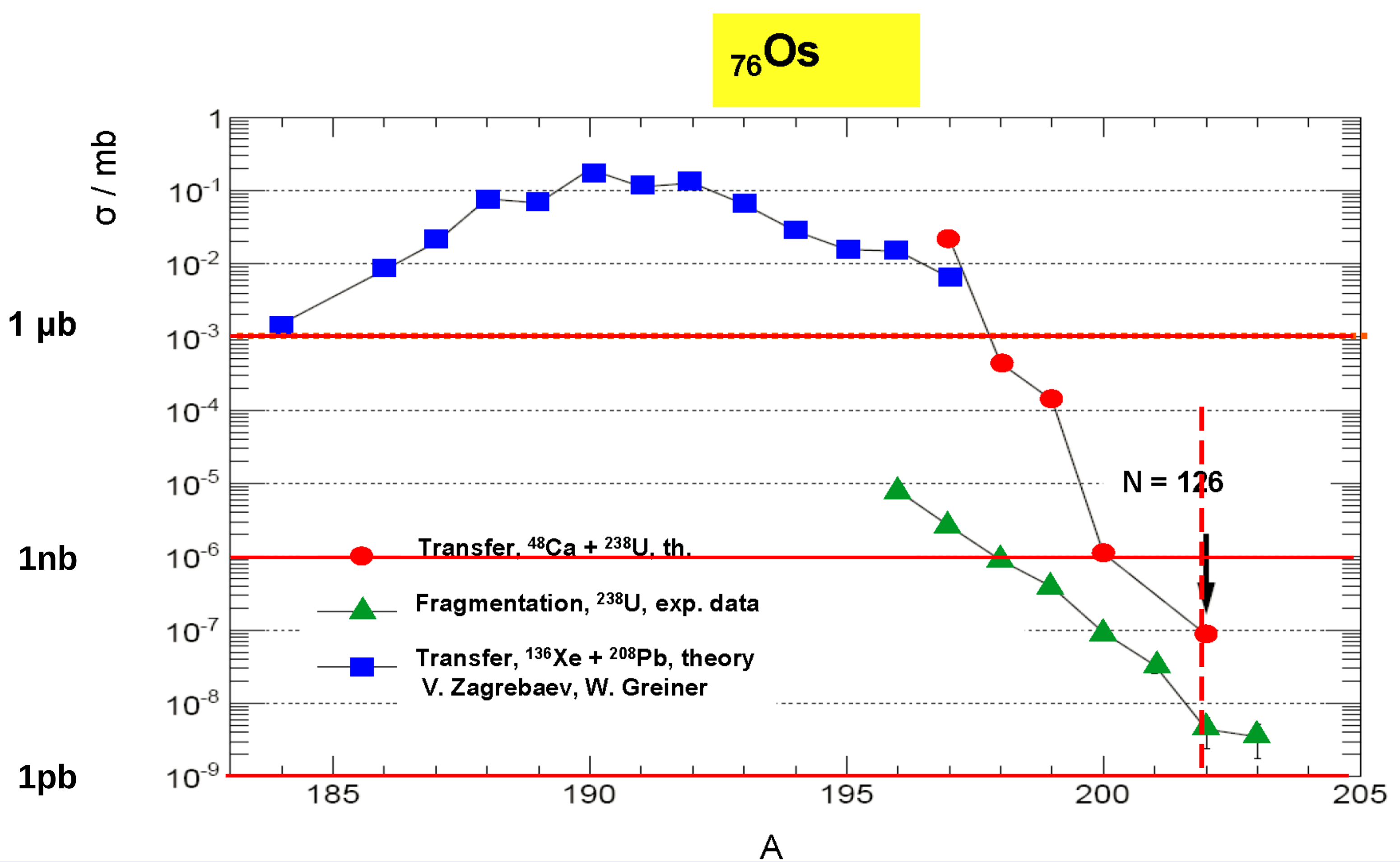
accessible with fission-fusion



Towards N=126 Waiting Point

- “conventional” fusion reaction:

  cross sections: transfer (theor.) vs. fragmentation (GSI experiment)

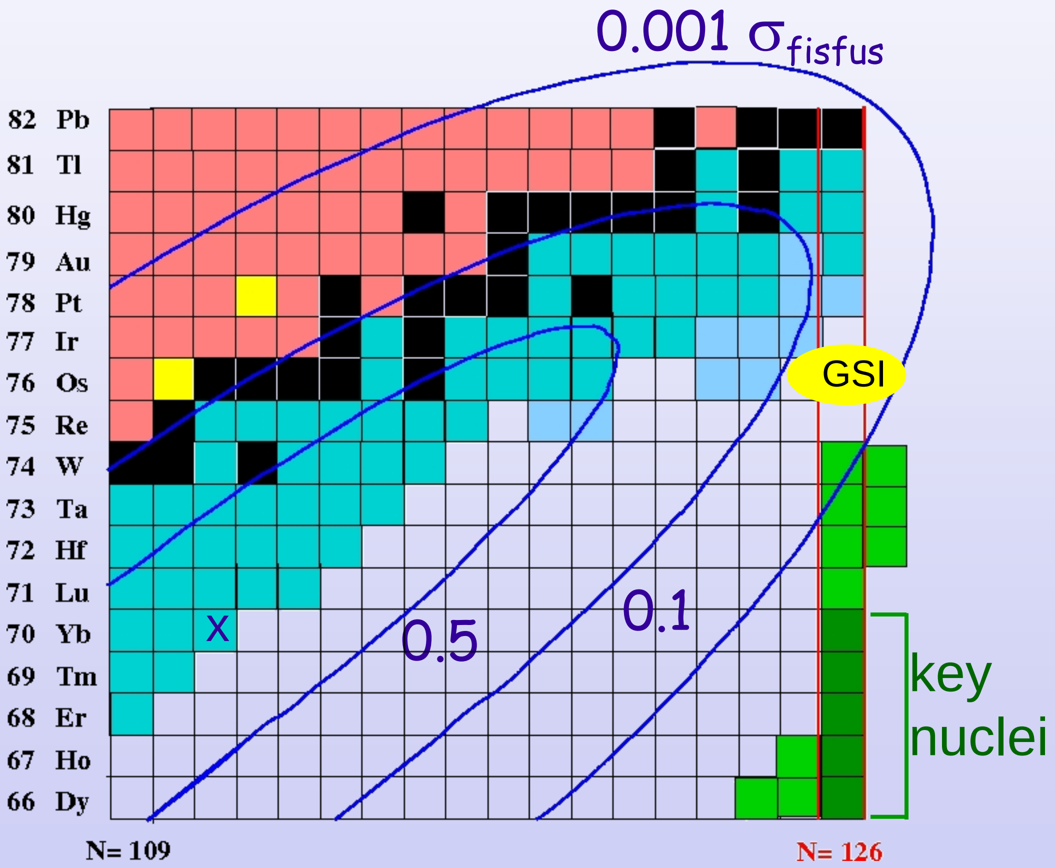


S. Heinz et al. (GSI)

Towards N=126 Waiting Point

- r process path:

  - known isotopes ~15 neutrons away from r process path (Z≈ 70)



- measure:
  - masses, lifetimes, structure
  - β-delayed n emission prob. $P_{\nu,n}$
  - lifetime measurements: already with few pps

- visions:
  - test predictions: r process branch to long-lived (~ 10^9 a) superheavies (Z≥110) → search in nature ?
  - improve formation predictions for U, Th
  - recycling of fission fragments in (many) r process loops ?

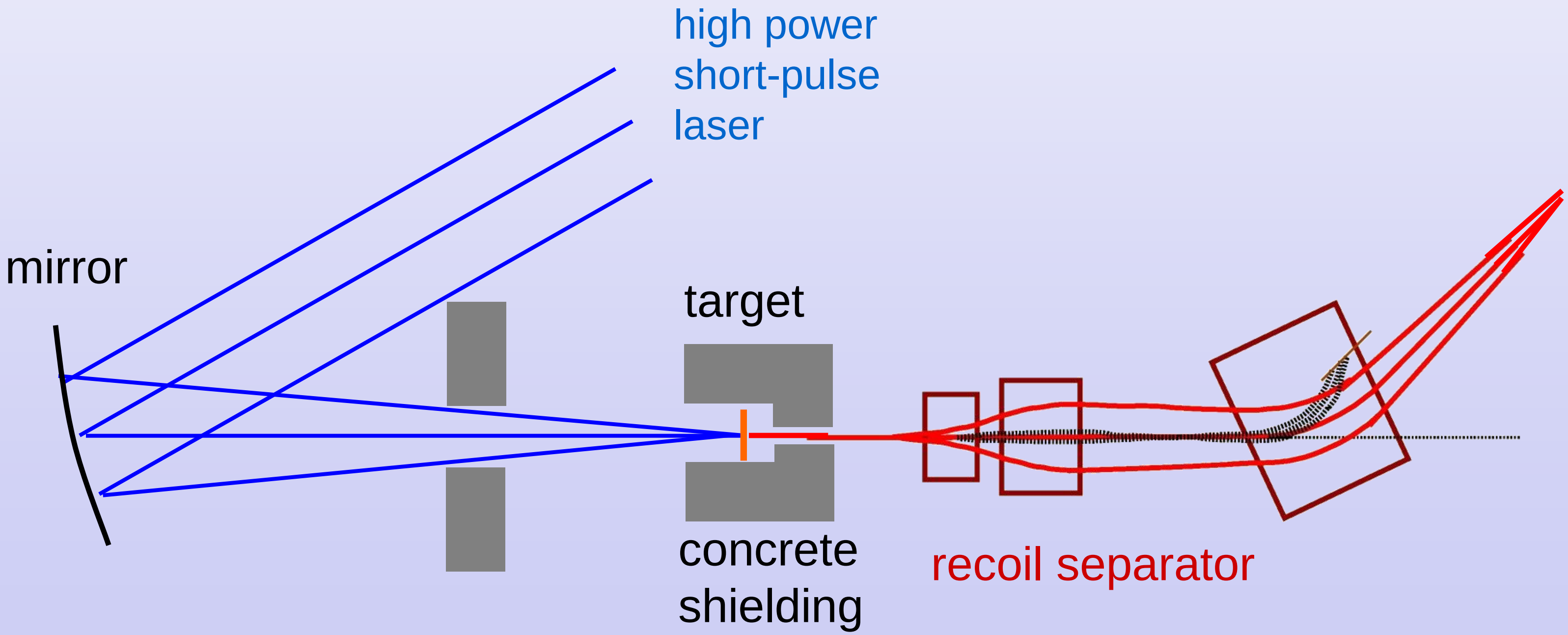
Staged Experimental Approach

- Develop RPA-based laser ion acceleration of heavy elements:
  - laser-ion acceleration of heavy species: energies, charge states …
  - optimized target development (multi-layer, repetition rate capability)
  - control of ion energy
- Theoretical consolidation required:
  - 2D/3D simulations for RPA of heavy species
  - robust reaction yield estimates
- Proof-of-Principle experiments:
  - test concept of collective effects on ion beam stopping range
  - perform proof-of-principle experiment for ‘fission-fusion’ mechanism
  - optimize reaction yields: fission stage, fusion stage
- Physics program:
  - identification of reaction products: decay spectroscopy
  - separation of species of interest: recoil separator
  - measurement of fusion product properties: masses, lifetimes, …

Diagnostics of reaction products

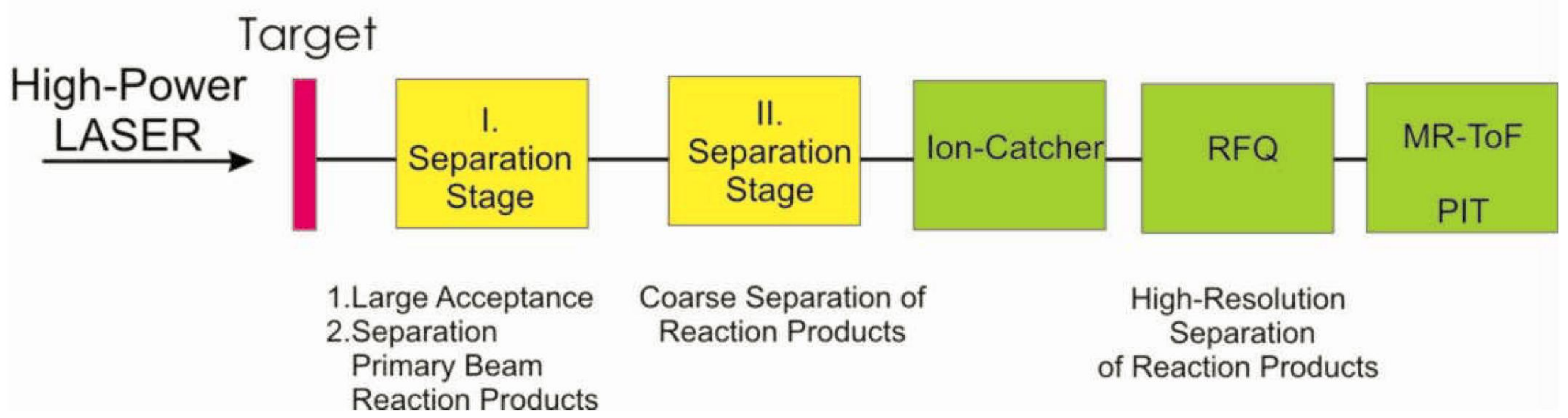
1. separation of reaction products:

→ needs to accept wide range of masses, momenta, charge states
→ in-flight separation: first stage to measure phase space of reaction products
→ enables further experimental stages: isotopic separation, access to rare decay modes, experiments with exotic species…



Separation scenario for exotic nuclei at ELI-NP

- multiple-stage separation for laser-induced exotic nuclei:



Target

High-Power LASER

I. Separation Stage

II. Separation Stage

Ion-Catcher

RFQ

MR-ToF

PIT

1. Large Acceptance
2. Separation
   Primary Beam
   Reaction Products

Coarse Separation of Reaction Products

High-Resolution Separation of Reaction Products

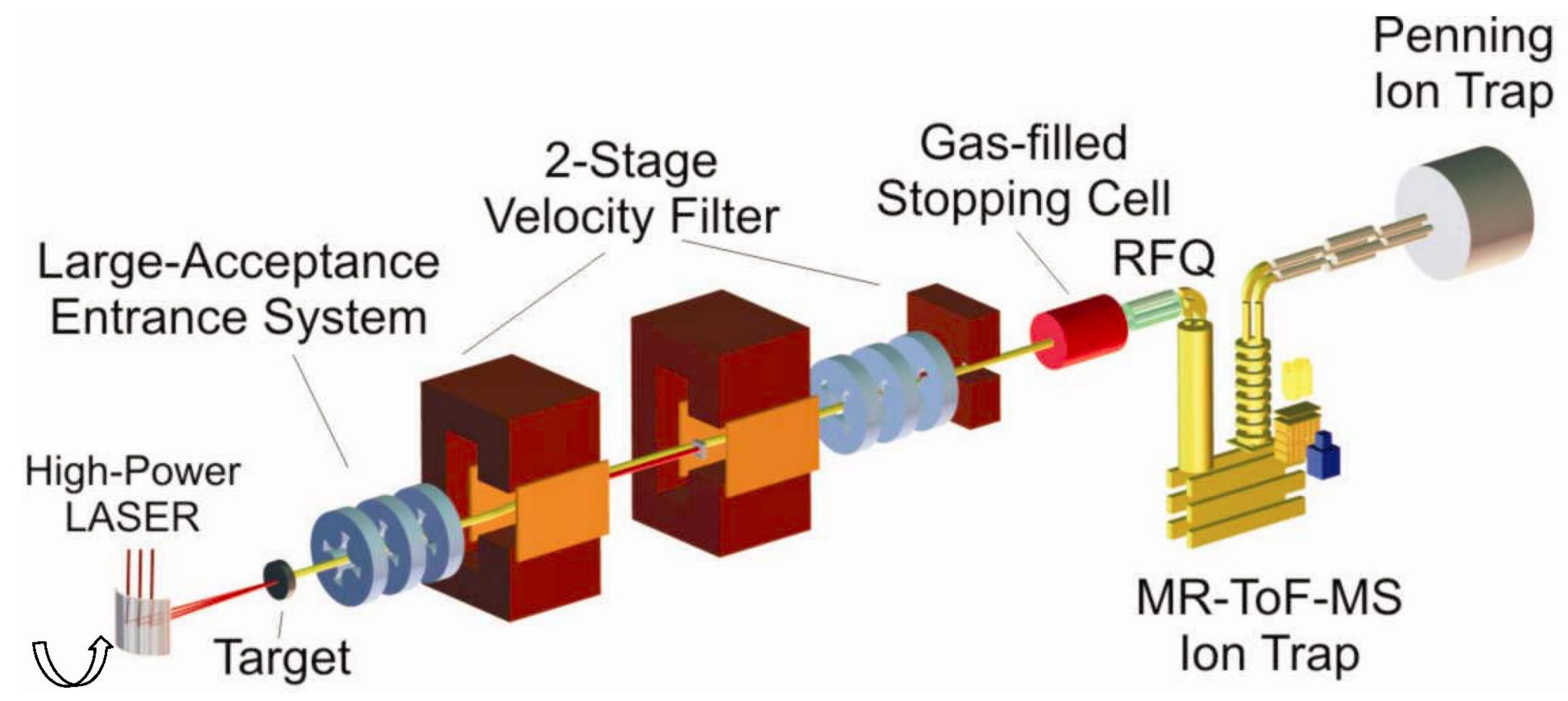
courtesy: H. Geissel (GSI/U Giessen)

- Separation criteria:
  (between fusion evaporation residues and large-emittance projectiles):

  - magnetic rigidity separation
  - velocity separation

In-flight Separator for ELI-NP

concept proposed by H. Geissel (GSI/U Giessen)

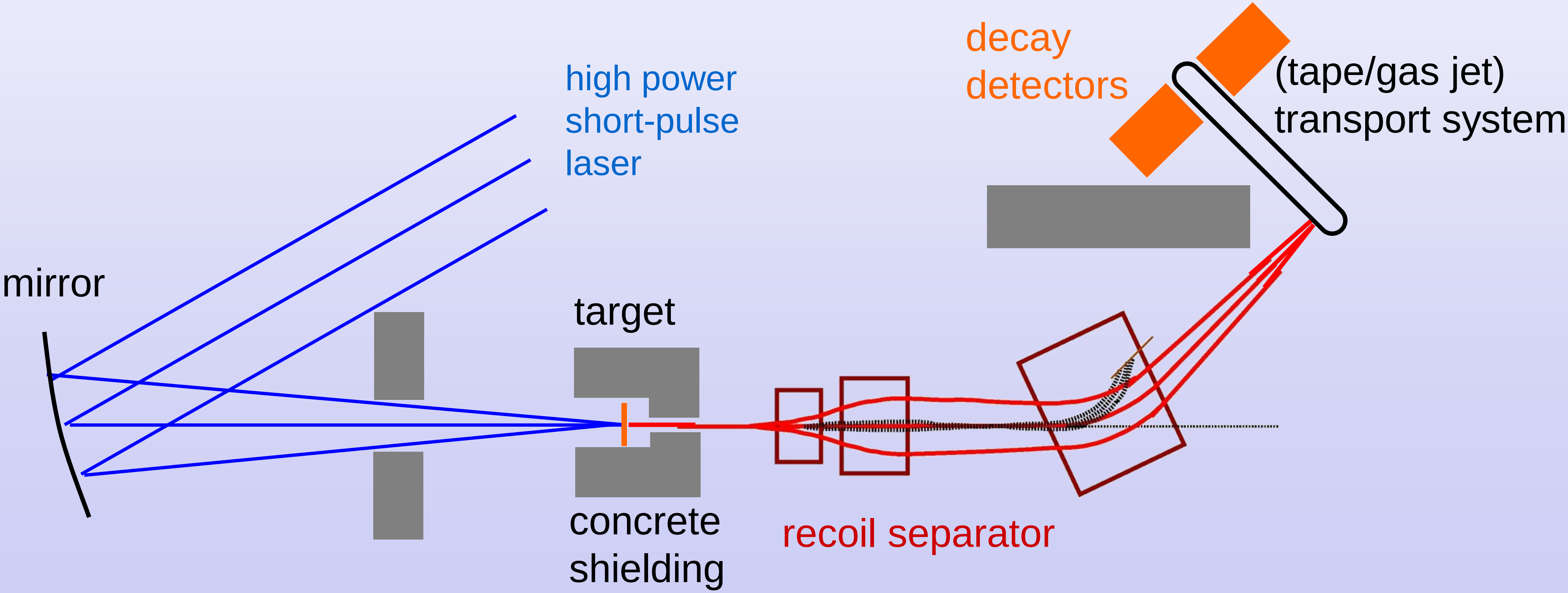


Experimental layout

1. separation of reaction products

2. characterization of reaction products

   - decay spectroscopy (α, β, γ)



high power short-pulse laser

decay detectors

(tape/gas jet) transport system

mirror

target

concrete shielding

recoil separator

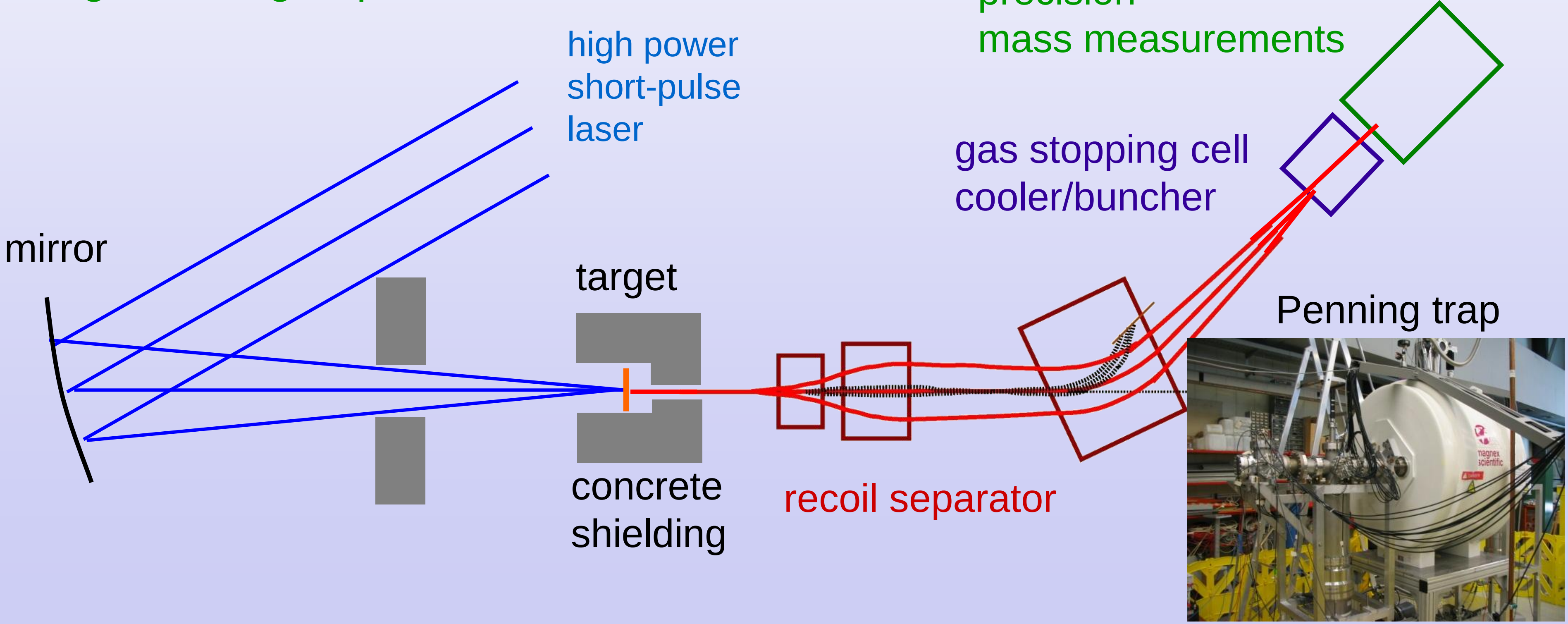
Experimental layout

1. separation of reaction products

2. characterization of reaction products
   - decay spectroscopy

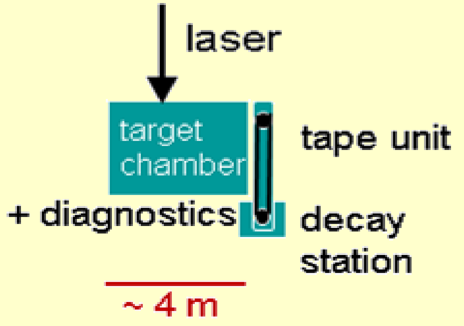
3. precision mass measurements:
   e.g. Penning trap or MR-TOF


MR-TOF

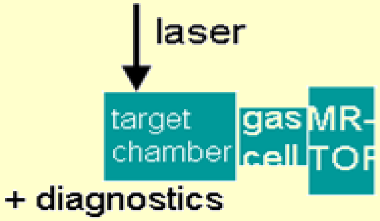


Experimental Stages

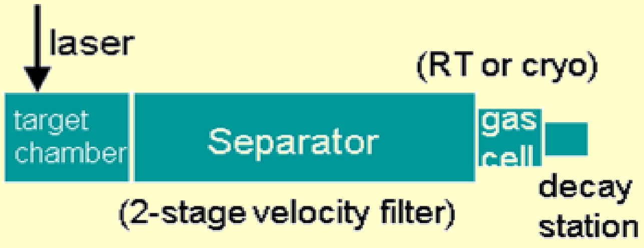
identify reaction products: decay spectroscopy



(coarse) separation of reaction products: time-of-flight mass spectrometry (MR-TOF)



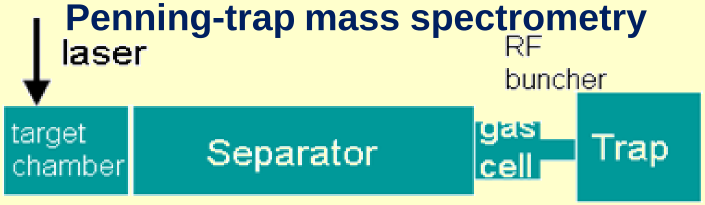
high-resolution separation of reaction products thermalization (gas cell) decay spectroscopy



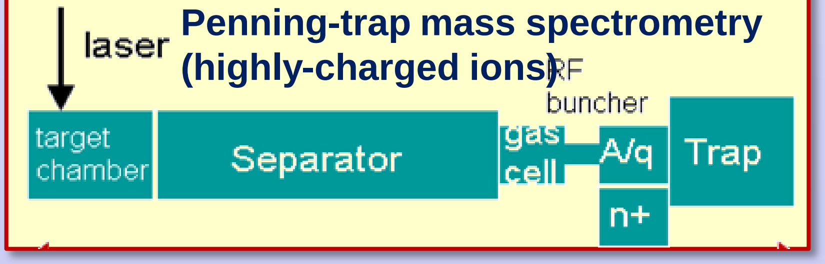
laser-driven generation of extremely n-rich isotopes

high-resolution separation thermalization (gas cell) ToF mass spectrometry (MR-TOF)

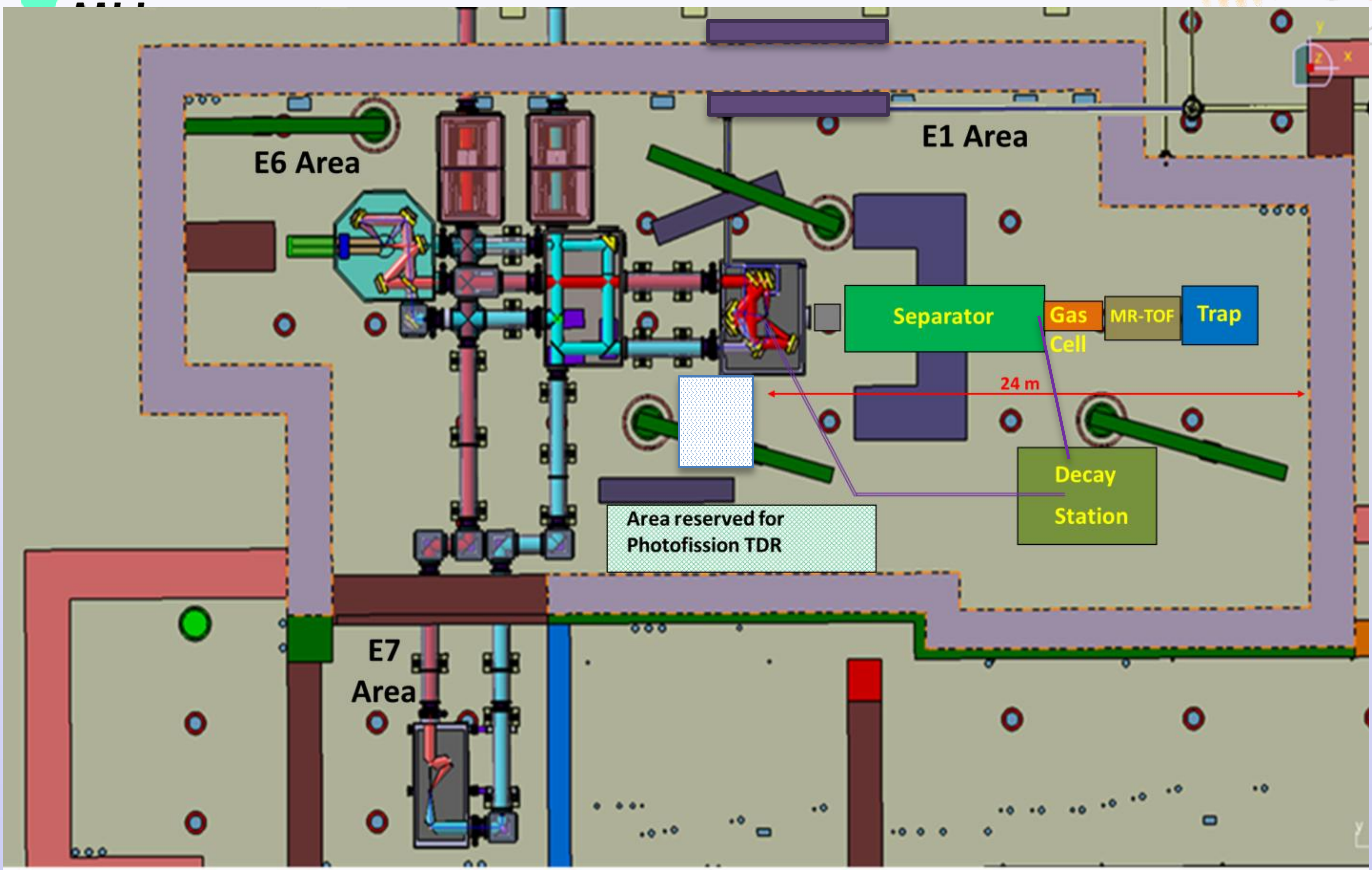
high-resolution separation thermalization (gas cell) Penning-trap mass spectrometry



high-resolution separation thermalization (gas cell) Penning-trap mass spectrometry (highly-charged ions)



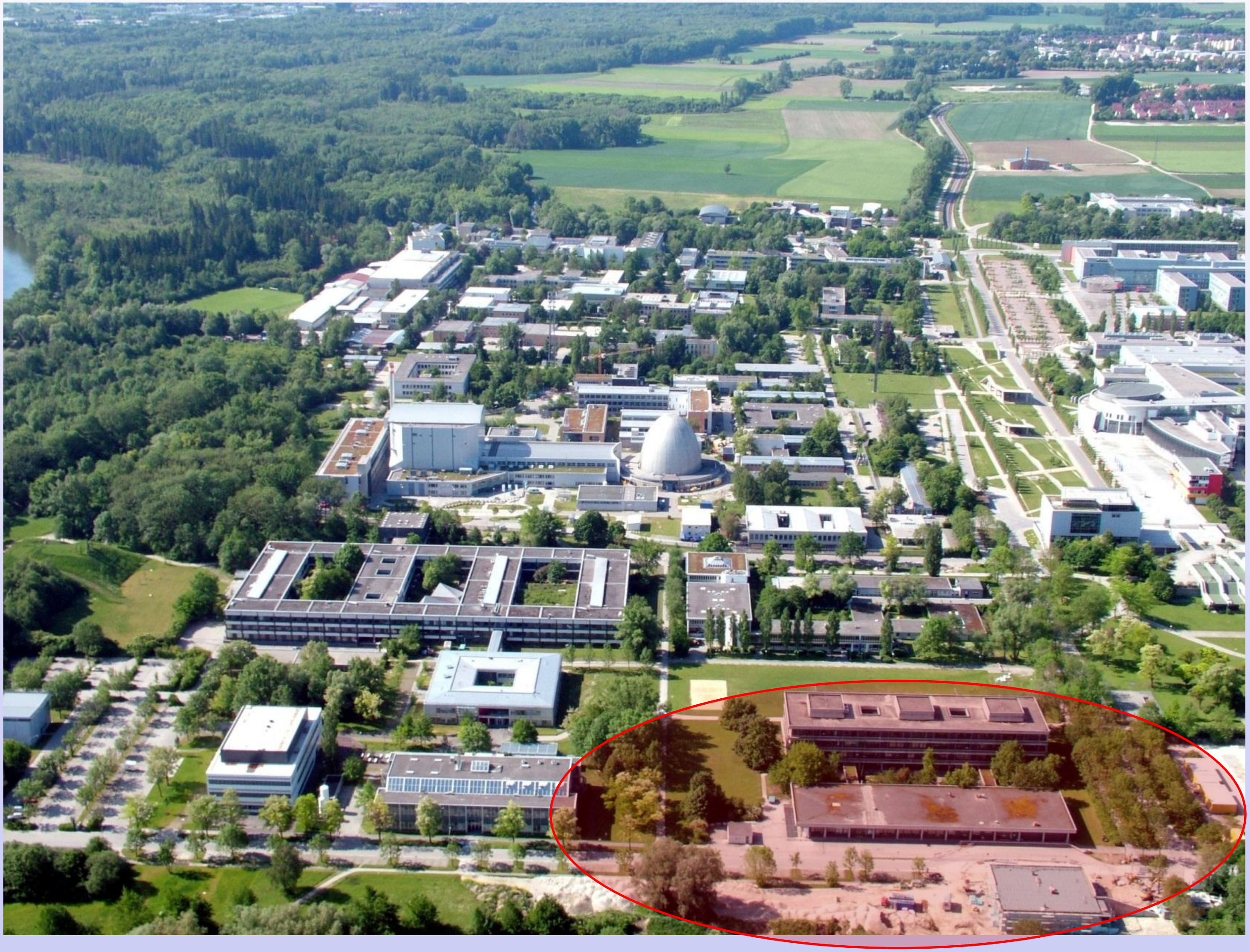
ELI-NP: E1 experimental area layout



also: 1 PW laser beam (1 Hz) for preparatory studies

Exploratory Studies: CALA (Garching)

(Center for Advanced Laser Applications)



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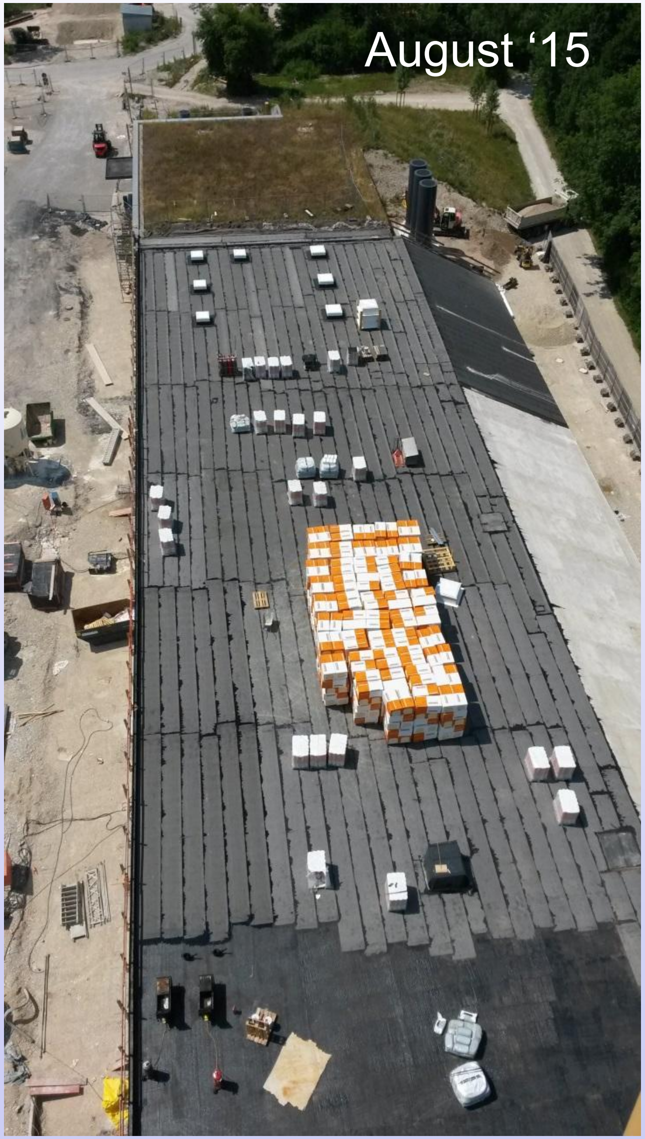
January ‘15



August ‘15

CALA Lasers and Beamlines

- ATLAS-3000: 60 J, 20 fs, 3 PW, 1 Hz (Ti:Sa)
- PFS-PRO: 0.5 J, 5 fs, 0.1 PW, 5 kHz (OPCPA)

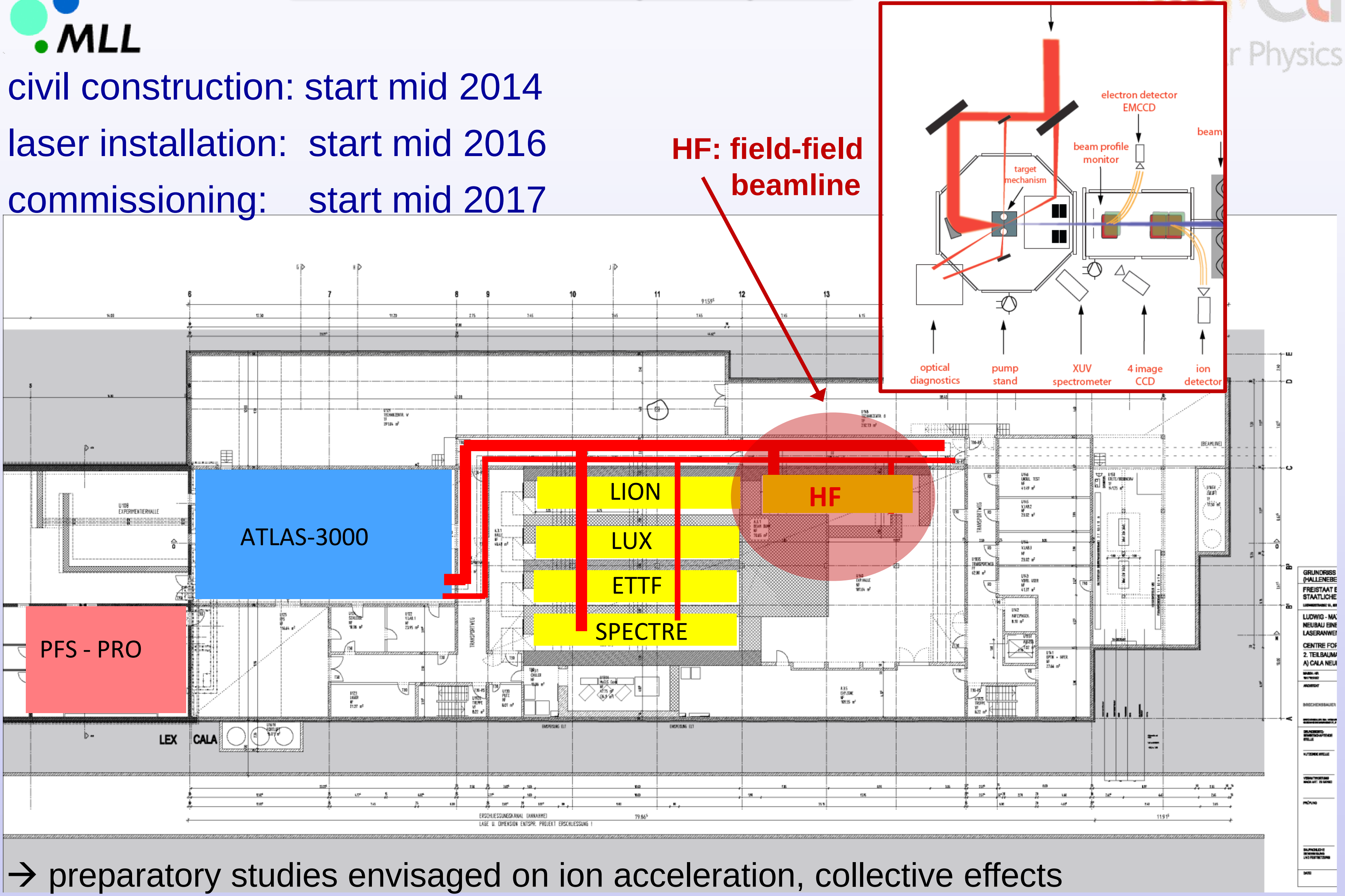
Beamlines	Purpose	Secondary sources	
ETTF	electron acceleration	E_e = 2-5 GeV, 1nC, 1 Hz	E_γ: 0.1 – 10 MeV 10^9 γ/s
LUX	Undulator radiation (perspective: X-FEL)	E_e = 2-5 GeV, 1nC, 1 Hz	E_γ: 1-20 keV
SPECTRE	Thomson scattering	E_e = 100 MeV, 0.05 nC	E_γ: 50-70 keV, 10^{10} γ/s @ 5 kHz
LION	ion acceleration	p: ≤ 200 MeV C: ≤ 400 MeV/u	
HF (High-Field)	(heavy) ion acceleration	Pb, Th: < 10 MeV/u	~$2 \cdot 10^{10}$/s

CALA: Facility Layout

civil construction: start mid 2014

laser installation: start mid 2016

commissioning: start mid 2017



HF: field-field beamline

→ preparatory studies envisaged on ion acceleration, collective effects

Radioactive Beam Facilities

ELI-NP has the potential to appear on the map of radioactive ion beam facilities

- ○ future/upgraded major RIB facilities
- ● existing major RIB facilities

Conclusions

Exploiting laser-generated ion beams for nuclear astrophysics:

- laser ion acceleration (RPA):

  - generation of ultra-dense ion bunches

    → novel ‚fission-fusion' reaction mechanism
    → fusion between 2 neutron-rich fission fragments

  - reduction of electronic stopping ?
  - may lead much closer towards N=126 r-process waiting point
  - R&D program needed for stepwise approach:

    laser-ion acceleration
    (collective ?) stopping behaviour
    target development
    theory support needed: simulation: 3D RPA, rate assessment

- realization of these schemes:

  → preparatory studies: CALA (Garching), CETAL (Magurele)

  → unique contribution to astrophysics possible by laser-driven ion acceleration at ELI-NP

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Thank you for your attention !