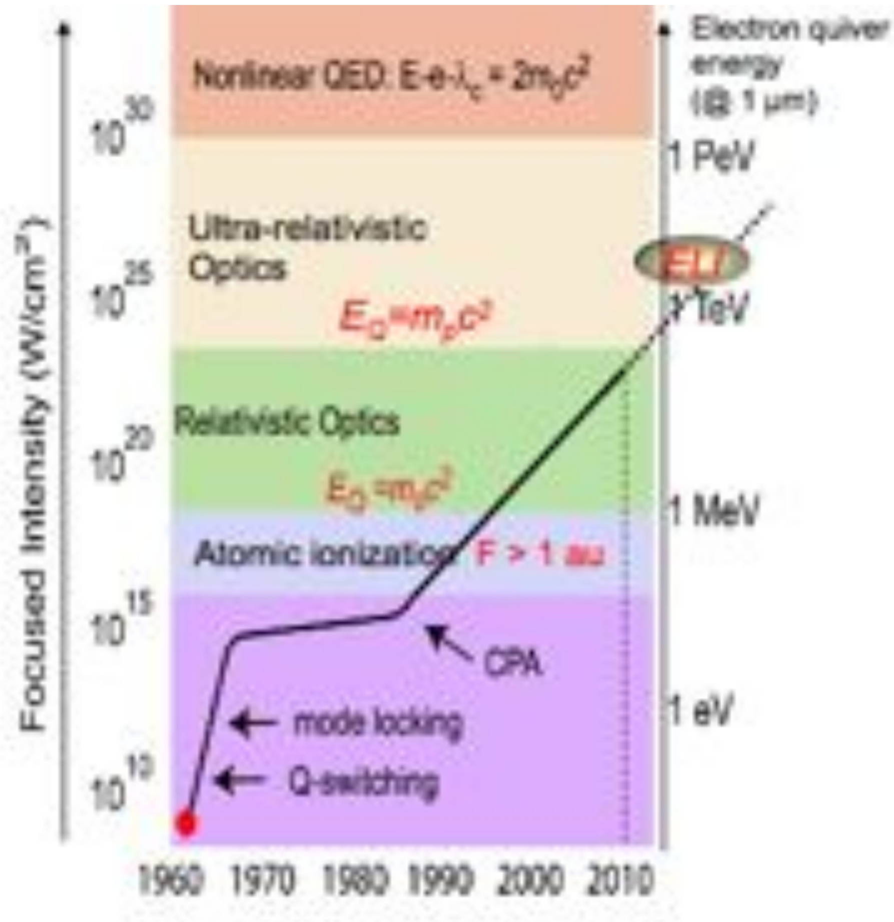
Laser Nuclear Experiments and Facilities in Europe

Markus Roth

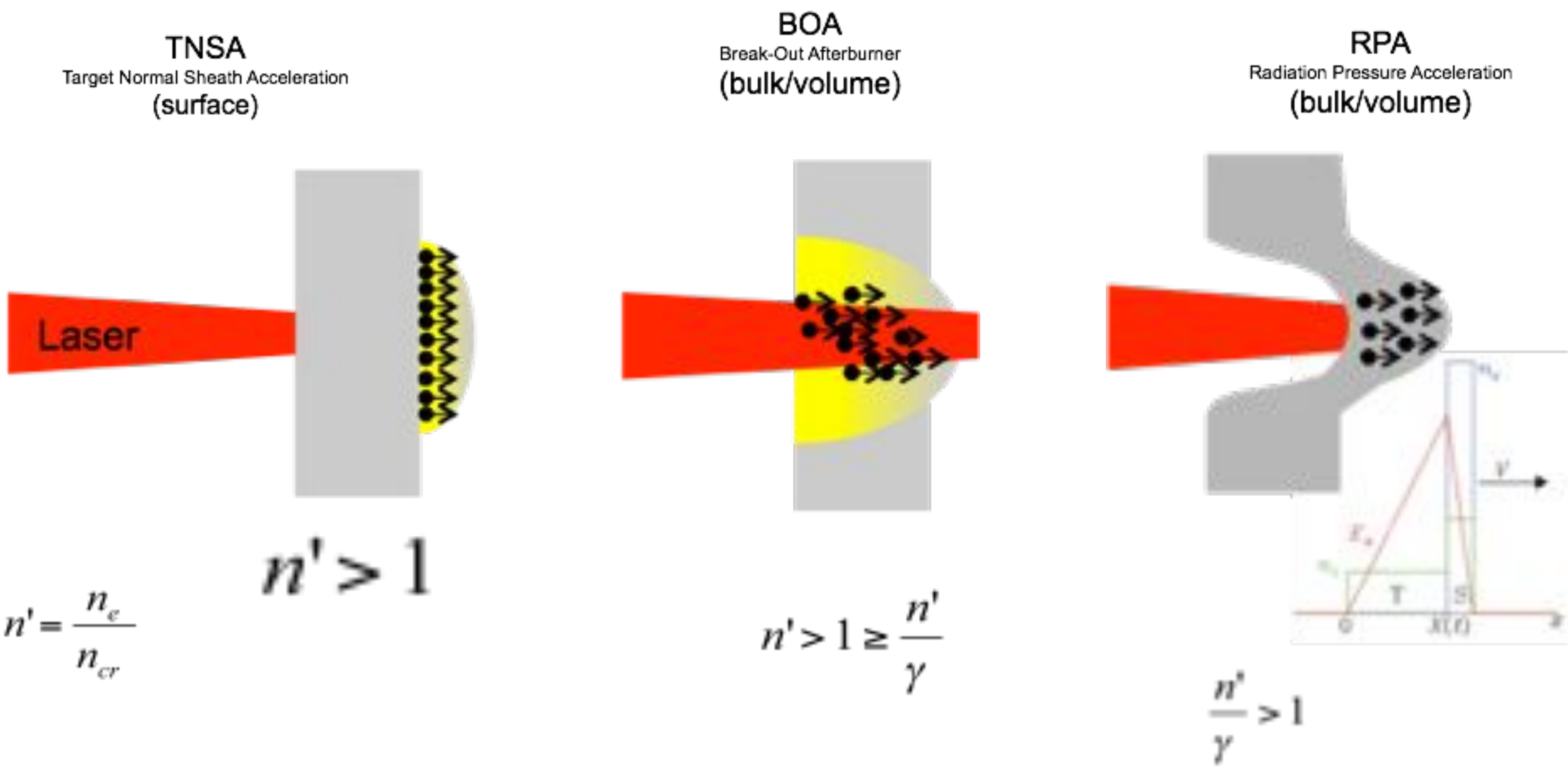
Extreme Light Infrastructure Nuclear Physics (ELI-NP)
Project co-financed by the European Regional Development Fund

Future of short pulse laser development



Overview: Different acceleration mechanisms

from Daniel Jung (LANL, now QUB)



$$n' = \frac{n_e}{n_{cr}}$$

$$n' > 1$$

$$n' > 1 \geq \frac{n'}{\gamma}$$

$$\frac{n'}{\gamma} > 1$$

Present Nuclear Physics Experiments

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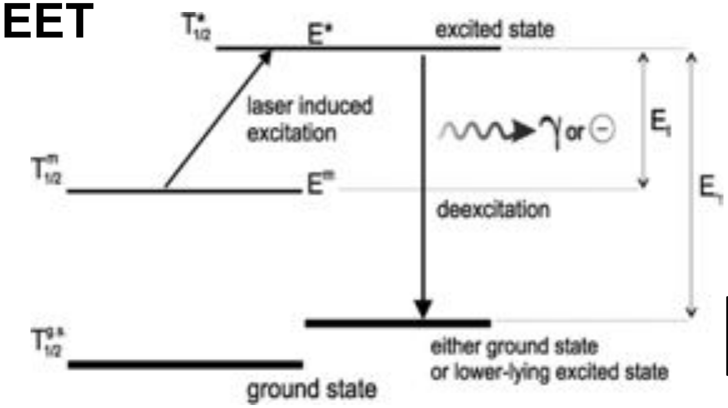
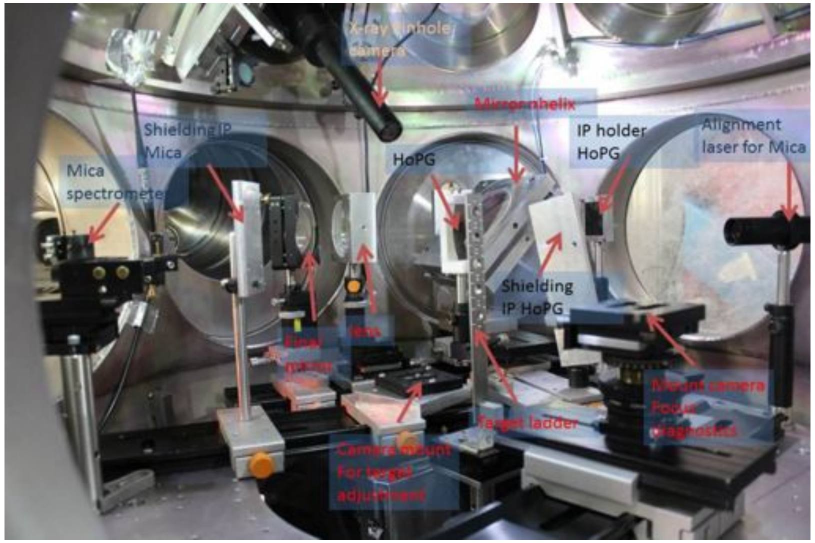
- mostly unexplored nuclear excitation processes like NEET (nuclear excitation by electron transitions) can be studied with lasers
  - nuclei with the right isomeric states can be prepared by the accelerator
  - the laser provides the plasma conditions to initiate the transition

- Example of NEET in Rubidium
  - first dimensioning experiments have been done with PHELIX showing that > 1kJoule long pulse are necessary to reach the right conditions for NEET





See Petit's talk tomorrow

Excitation of the 84mRb isomeric state in a plasma: predictions by G. Gosselin, P. Morel and V. Meot

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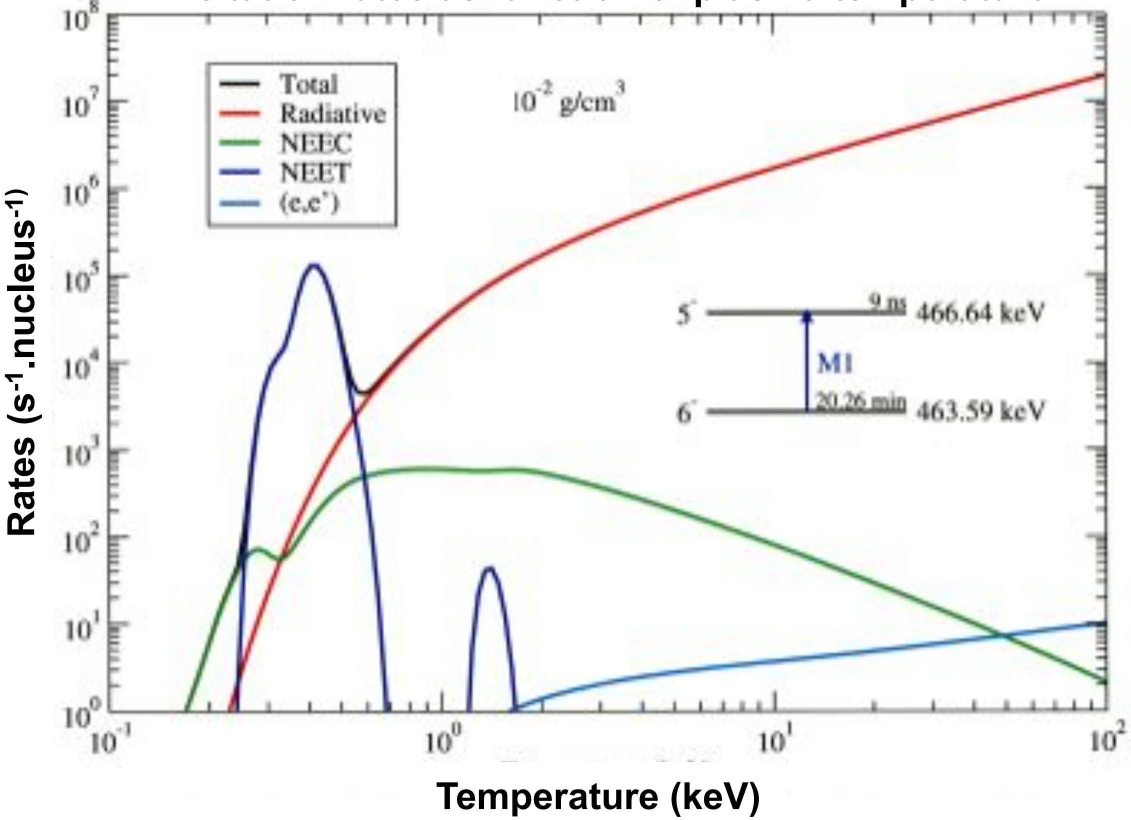
Excitation rates as function of plasma temperature



NEET is the dominant excitation process for plasma temperature of 300 – 400 eV
(Average charge state of 32)

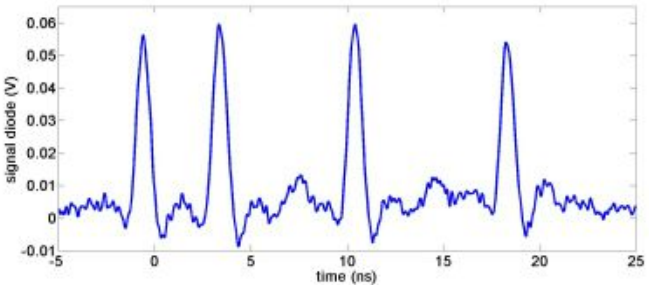
Photoexcitation is dominant for higher temperature

(e,e') weak!

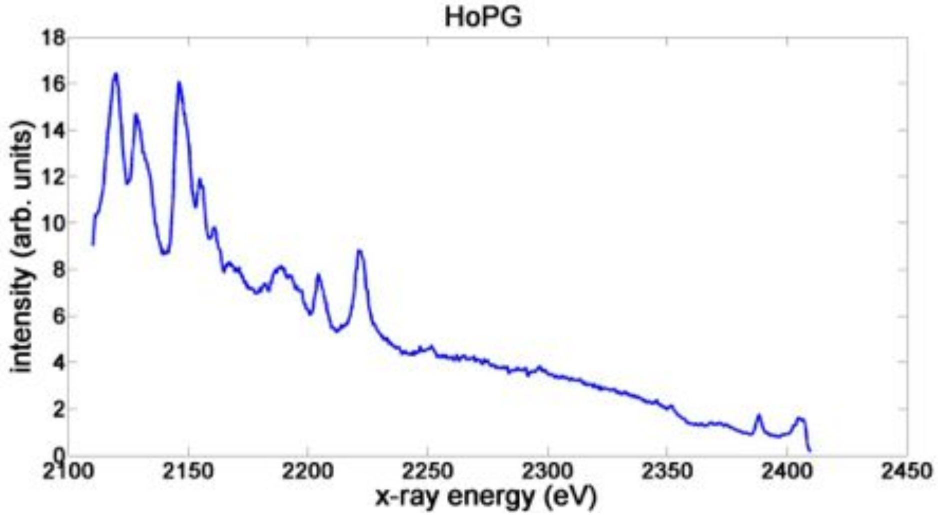
Nanosecond plasma are far from equilibrium – non LTE calculation are necessary

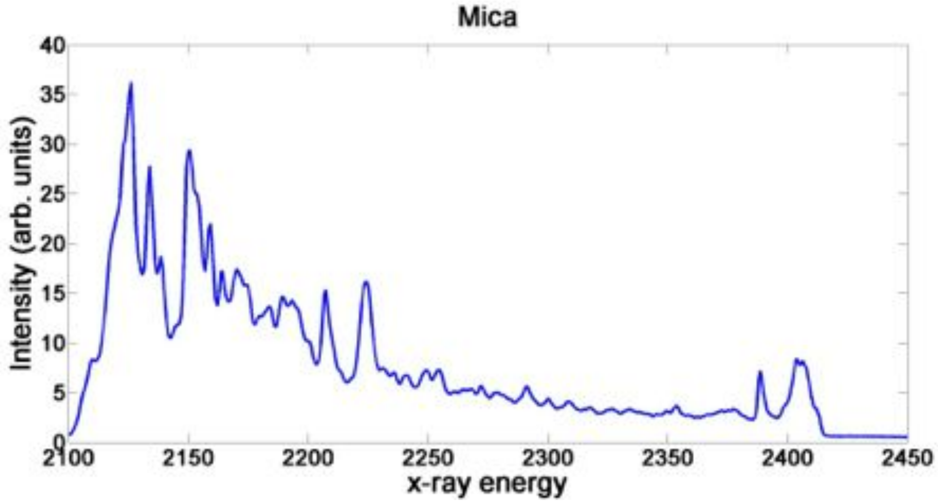
Preliminary results and next steps

- **During the campaign different laser intensities and pulse shapes have been tested (up to 450 J at 2ω)**



- **Multiple spectrometer configurations have been used to record different energy ranges**
- **The detailed spectra are consistent and currently under analysis**





Nuclear activation with Laser-accelerated particles

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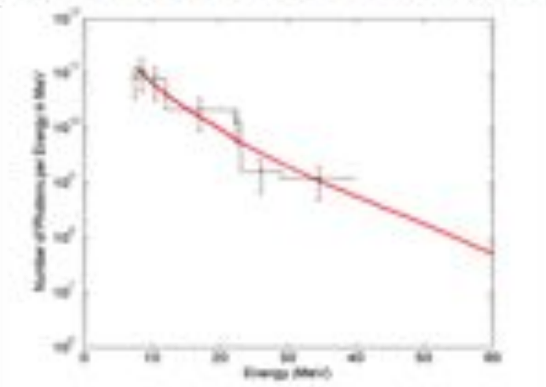
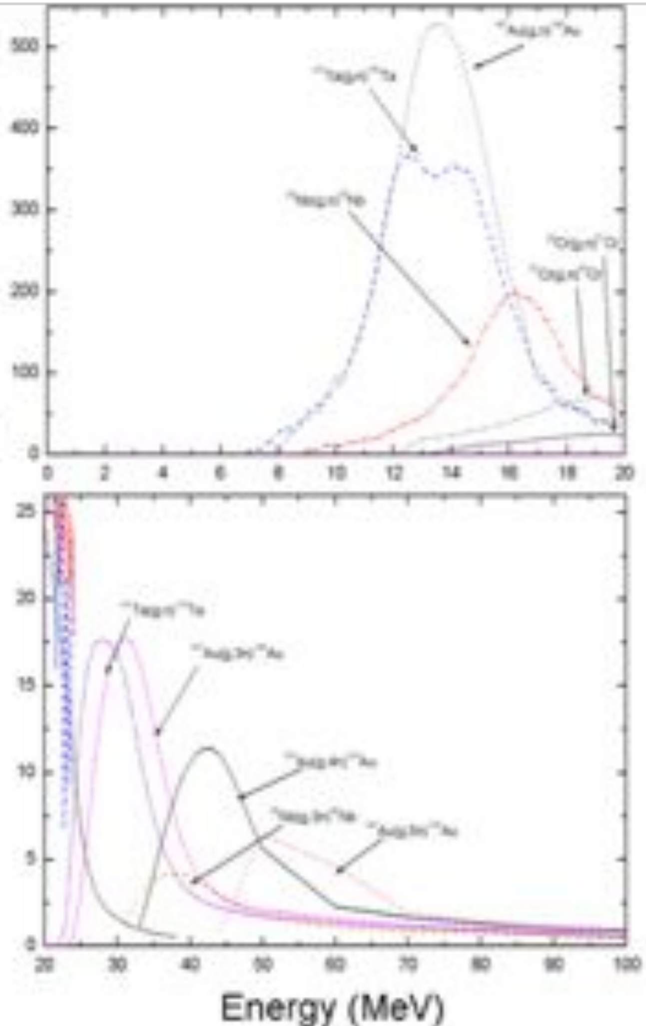
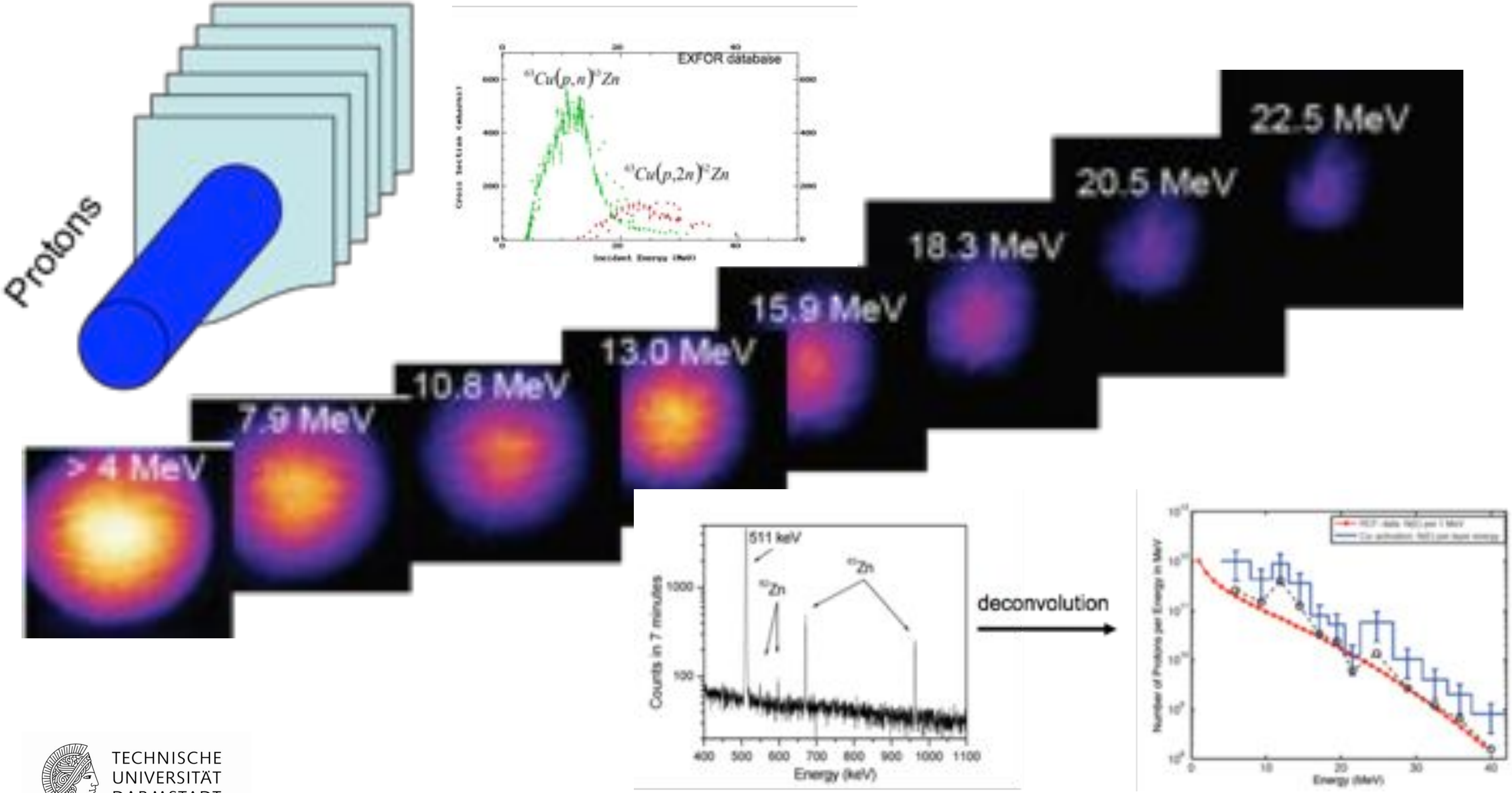
- Compound target as a pseudo alloy:
  composition of several stable elements with different photon-neutron disintegration thresholds
- Large energy range accessible:
  - 7 - 20 MeV via (γ,n)-reaction
  - 7 - 50 MeV via (γ,xn)-reaction
- All components close to laser-plasma interaction zone
- High mass density (13 g/cm³)
- Suitable half-lives for all isotopes





Nuclear activation with Laser-accelerated particles

NAIS: Nuclear Activation Imaging Spectroscopy



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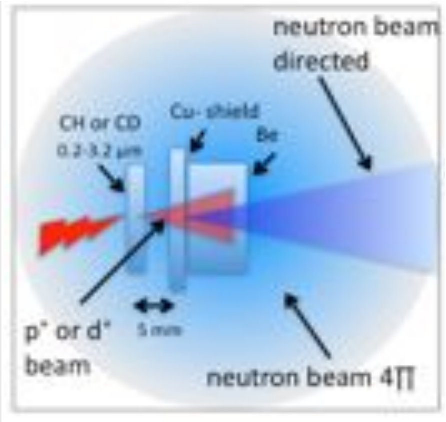
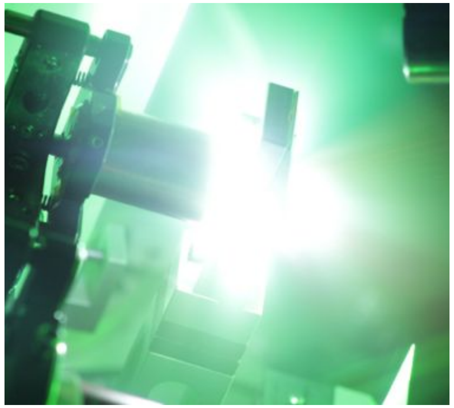
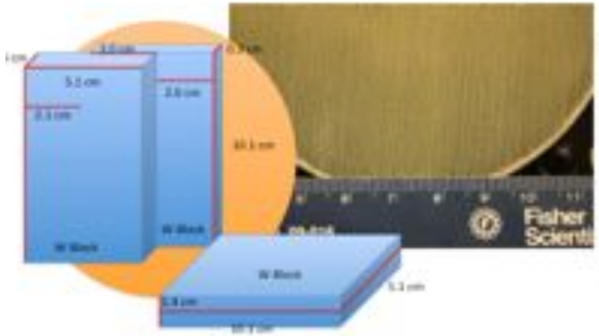
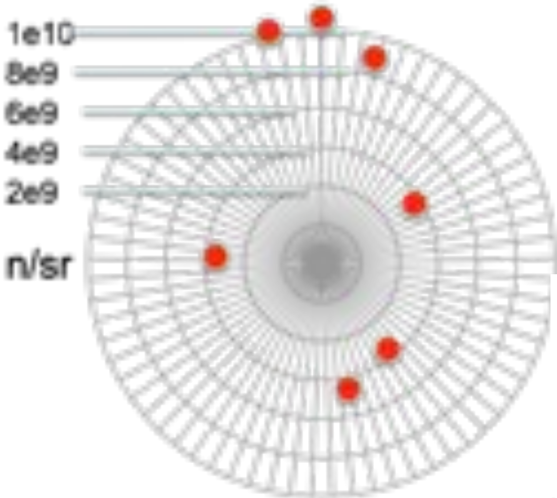
Neutrons

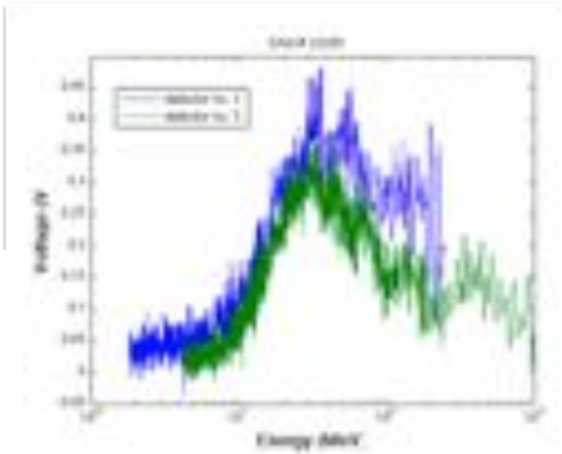




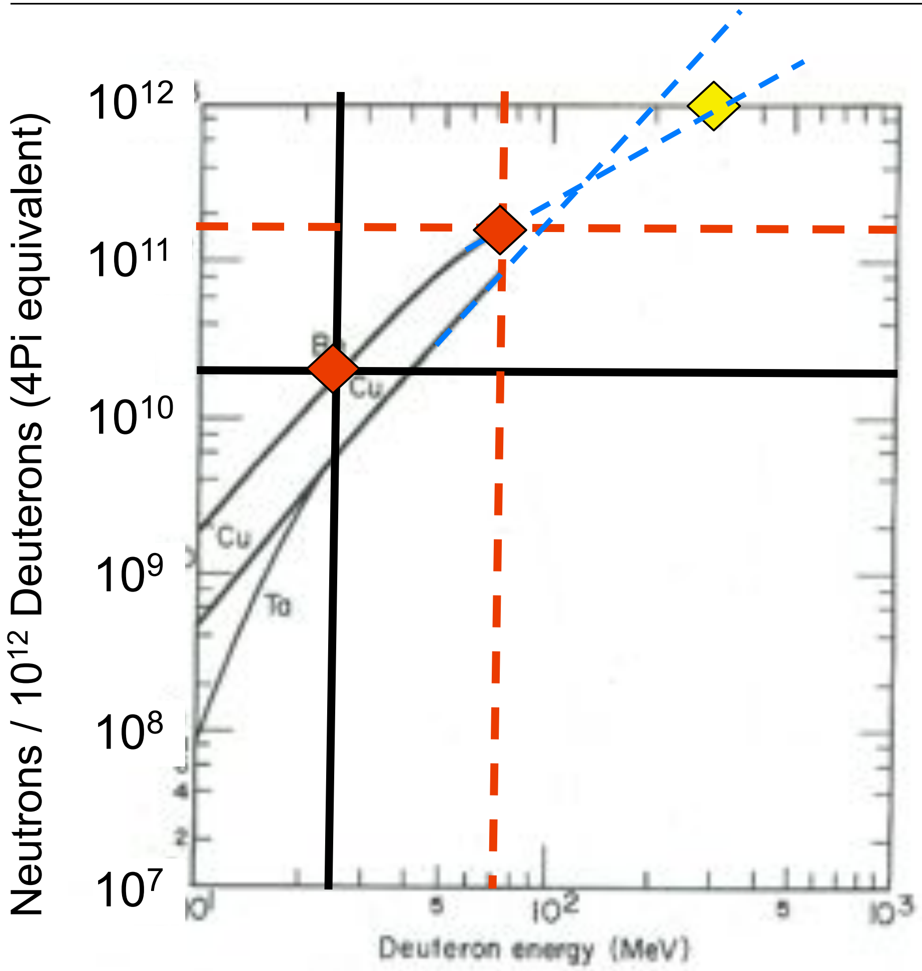




Neutrons:
$>10^{10}$/sr
>200 MeV
Peak @ 70 MeV



Future Nuclear Experiments



present: 10^{12} deuterons @ 20 MeV
yield is consistend with data from 1975

Second campaign: Higher energies and higher D_2 resulted in more than 10^{11} neutrons @ 70 MeV and up to energies of 200 MeV

Using BOA and cryo Targets VPIC indicate 200 MeV/u ...

@500 MeV we start to get into the real spallation regime

@ 10 kJ HESP laser, would yield close to 14^{14} n in a shot and maybe 10^{15} in real spallation mode in < 1 ns

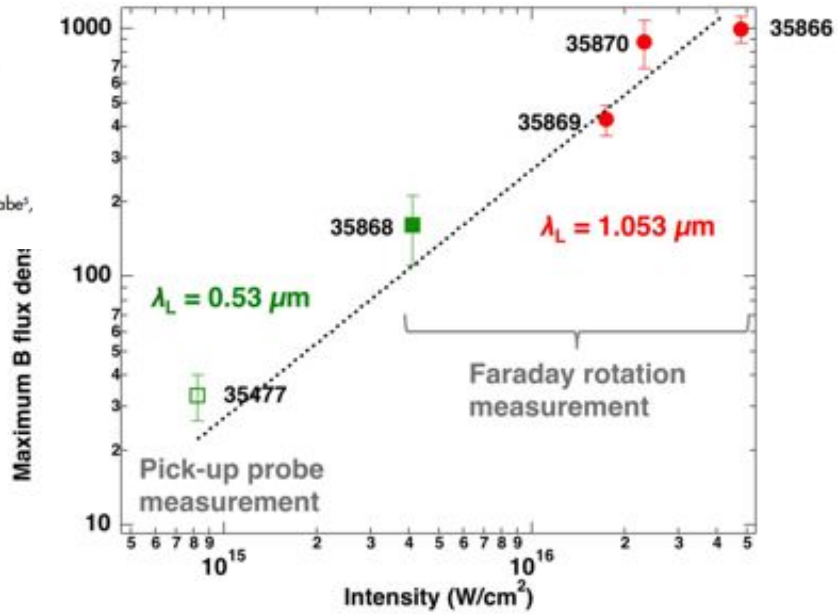
10^{21} n/cm^2/s and 2x10^4 n/µm^2 to alter material

B-fields I


TUD Target

Kilotesla Magnetic Field due to a Capacitor-Coil Target Driven by High Power Laser

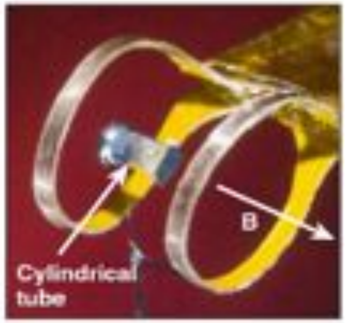
Shinsuke Fujioka[1], Zhe Zhang[1], Kazuhiro Ishihara[1], Keisuke Shigemori[1], Youichiro Hironaka[1], Tomoyuki Johzaki[2], Atsushi Sunahara[3], Naoji Yamamoto[4], Hideki Nakashima[4], Tsuguhiro Watanabe[5], Hiroyuki Shiraga[1], Hiroaki Nishimura[1] & Hiroshi Azechi[1]



For new experiments contact Joao Jorge Santos @ CELIA

Omega coils (300 ns rise) can reach 10-20T

Coil geometry
Radius = 2 mm
Separation = 5.25 mm



A symmetric Helmholtz coil pair was driven to 40 T (pickup coil measurement) using a 300 J, 1-2 ns Vulcan laser pulse; below is closest experience to provide the simulation B_{20} for NIF:

Collisionless shock and supernova remnant simulations on VULCAN*

N. C. Woolsey, Y. Abou Ali, R. G. Evans, R. A. D. Grundy, and S. J. Pestehe

P. G. Carolan, N. J. Conway, R. O. Dendy, P. Helander, and K. G. McClements

J. G. Kirk

P. A. Norreys, M. M. Notley, and S. J. Rose

Drawing from John Moody

Arrow shows current direction

B-fields II

There will be two orientations or energy levels with energies $+\mu B$ and $-\mu B$

and

The difference between these energy levels is $= 2\mu B$

and is shown to be equal to $= g_N \mu_N B$ (I = 1/2)

$$\mu_N = (e / 2 m_p)(h / 2\pi)$$

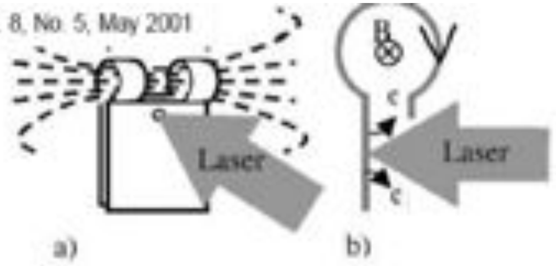
$$= 5.051 \times 10^{-27} \, JT^{-1} \qquad \mu = g_N \sqrt{I(I+1)} \, \mu_N$$

Energy splitting of a proton in a 1 kT field:

4.7×10^{-22} J = 2.3 meV

A lot larger than the width of the resonance

Phys. Plasmas, Vol. 8, No. 5, May 2001

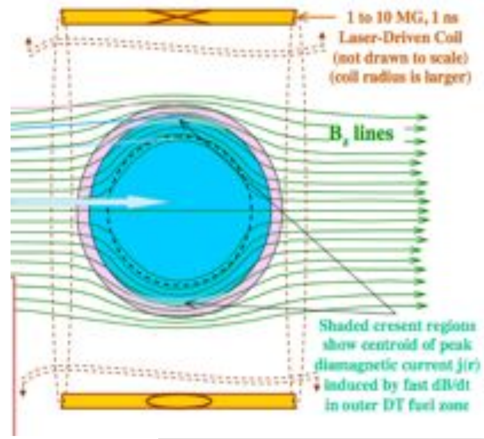


Self magnetic insulation and short pulse may explain the voltage holding

FIG. 3. Millimeter-scale Helmholtz coils (a) are used to create strong magnetic fields. A 1 μm wavelength laser at 10^{18} W/m² irradiates the back plate of the Helmholtz coil target to drive a hot electron source. The hot electrons generate a potential difference between the front and back plates and a return current in the Helmholtz coils results in the magnetic field. (b) shows a side view of the Helmholtz coil and the laser passing through a hole in the front plate.

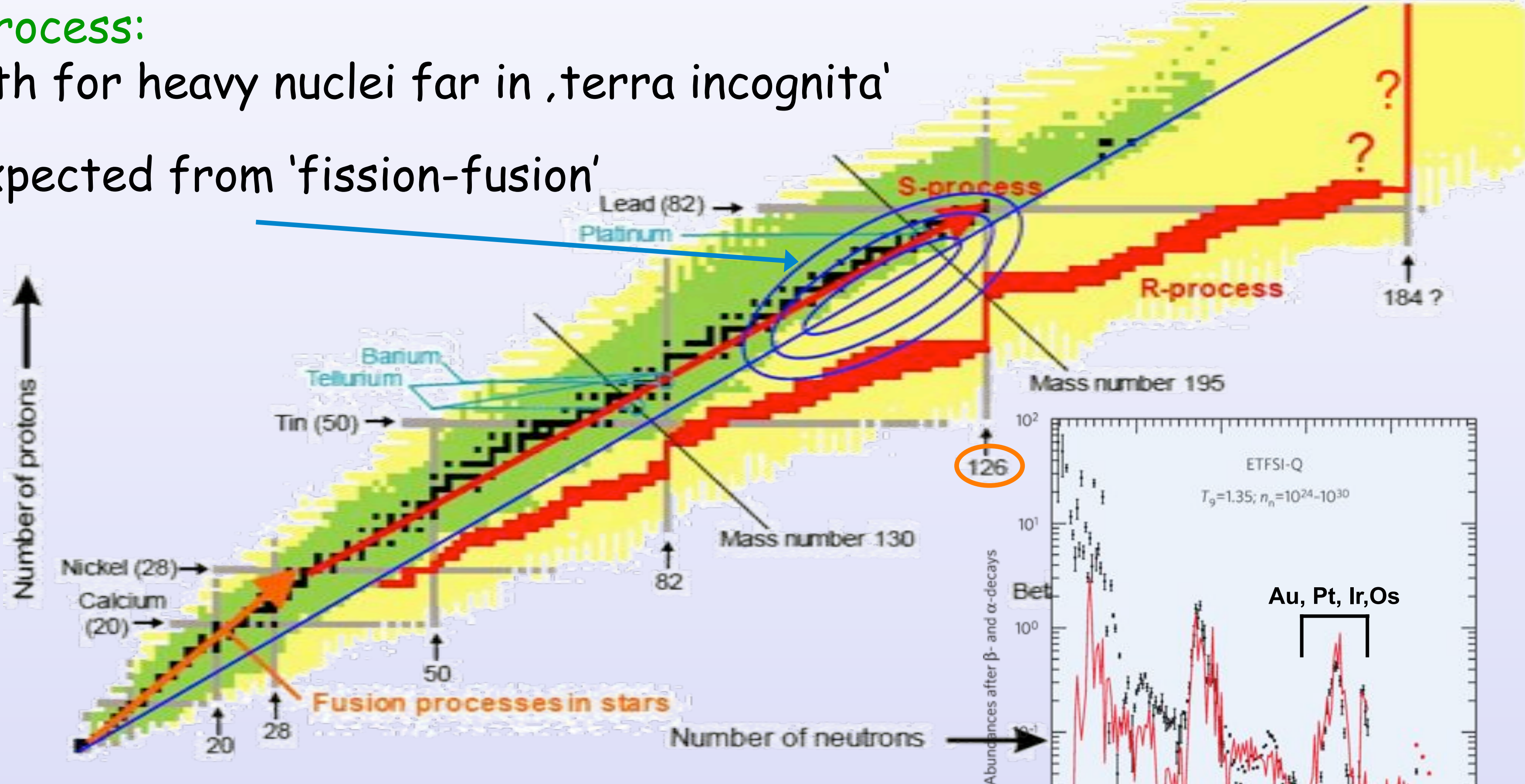
Laser driven ion beam

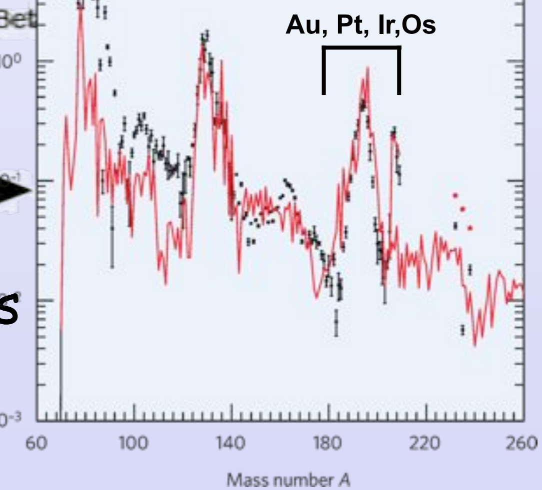
guided by B-field



r process: waiting point N=126

- r process:
  - path for heavy nuclei far in ‚terra incognita‘
  - expected from ‘fission-fusion’





- waiting point N=126: bottleneck for nucleosynthesis of actinides
- last region of r process ‘close’ to stability

Exp. Scheme for "Fission-Fusion"

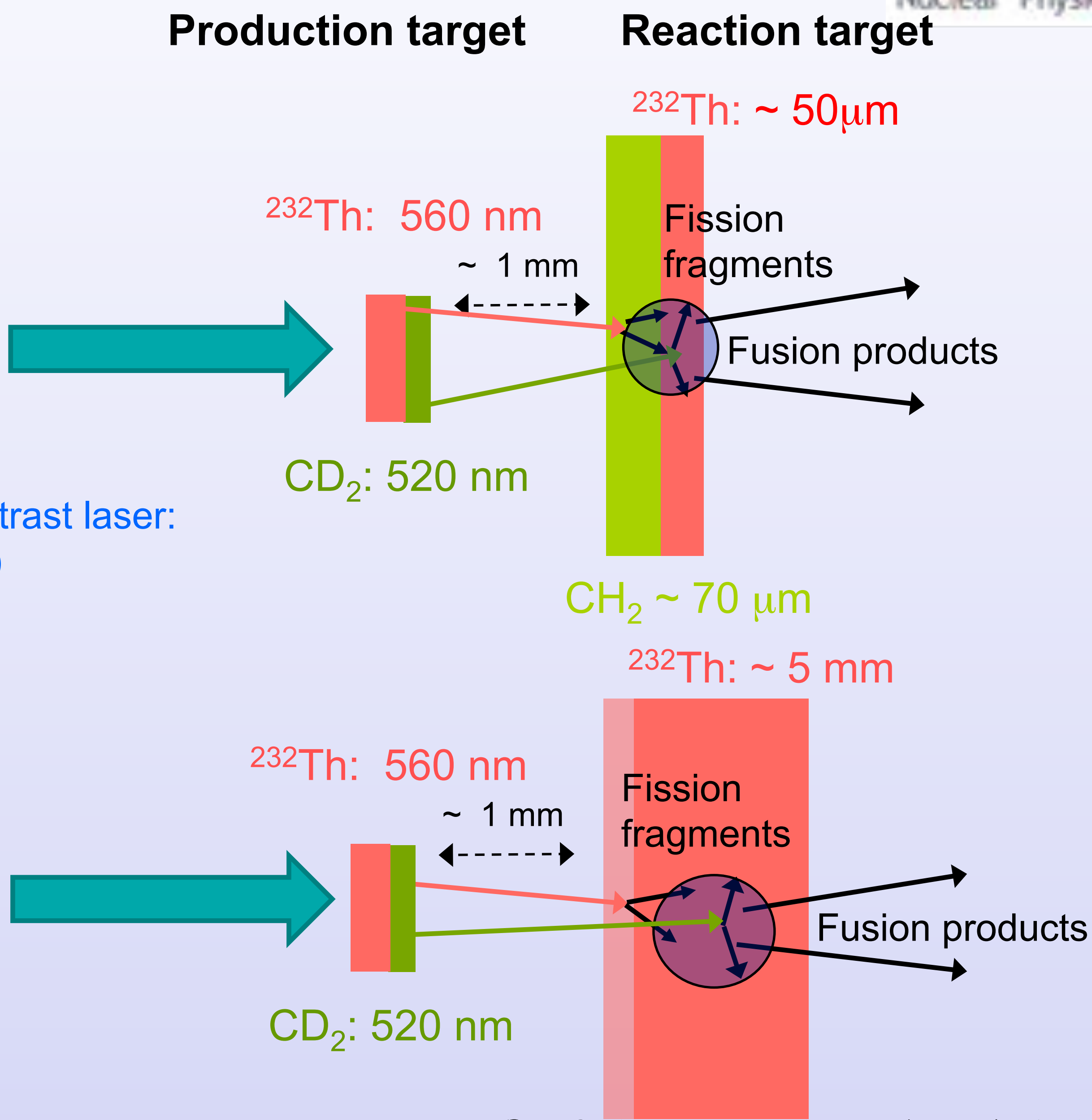
conventional stopping:

high-power, high-contrast laser:
300 J, 30 fs (10 PW)

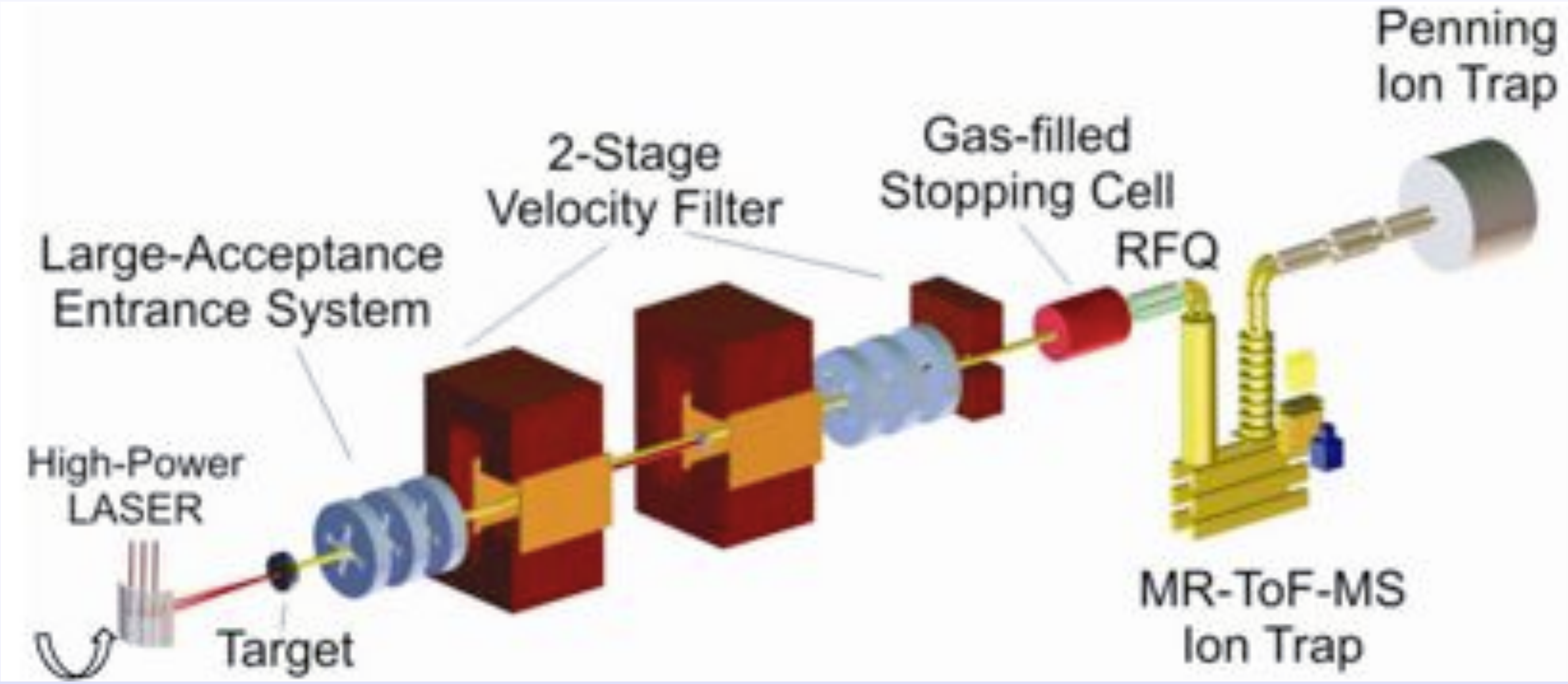
1.0×10^{23} W/cm^2

focal diam. ~ 3 μm

collective stopping:



In-flight Separator for Fission-Fusion Experiment



H. Geissel (GSI/U Giessen)

- infrastructure requirements: tbd
  - magnet power supplies
  - HV power supplies
  - cooling water
  - shielding requirements
  - .....

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	$2.8 \cdot 10^{11}$	$1.8 \cdot 10^{11}$
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 targeted

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

Perspectives BOA and RPA

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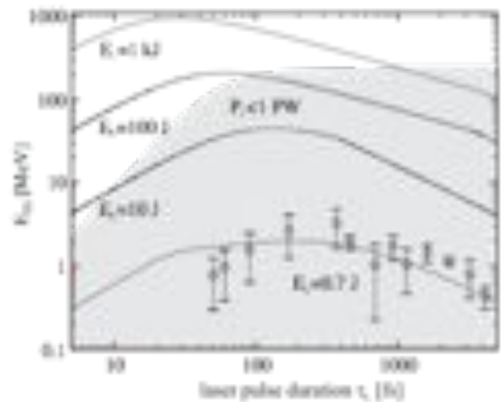
- BOA and RPA require H-concentrations much higher than possible with conventional H-rich solids.
  - With similar proportions, ions tend to accelerate together → ion energy ∝ ion mass[1]
  - Consistent with Trident results with C foils[2]
  - Opposite to TNSA (protons outrun everything)

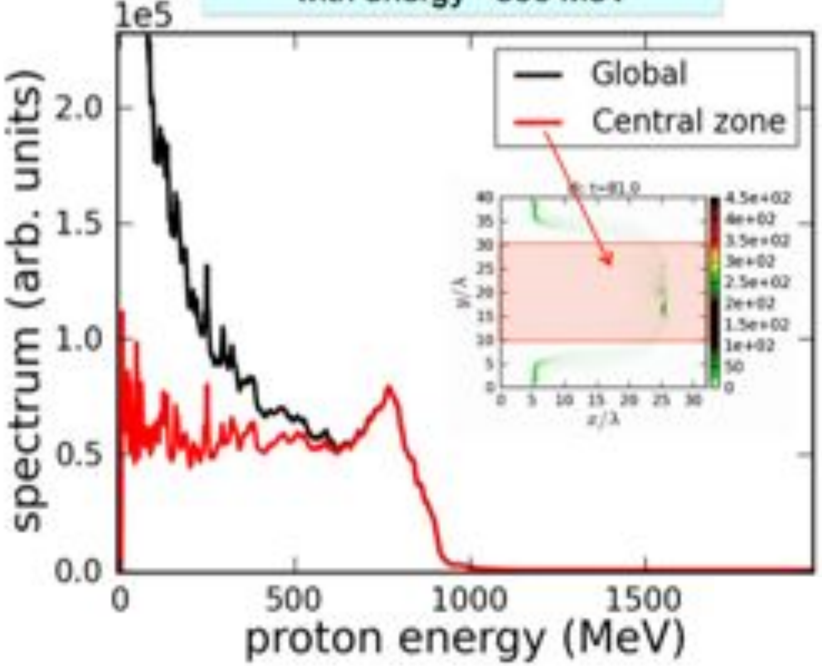
for a 10 kJ 100 PW laser one can expect 3x10^13 protons >500MeV

2.2kJ, 60 PW laser @38 fs



J. Schreiber PRL **97**, 045005 (2006)

19% of laser energy goes into 6×10^{12} forward directed protons with energy >500 MeV

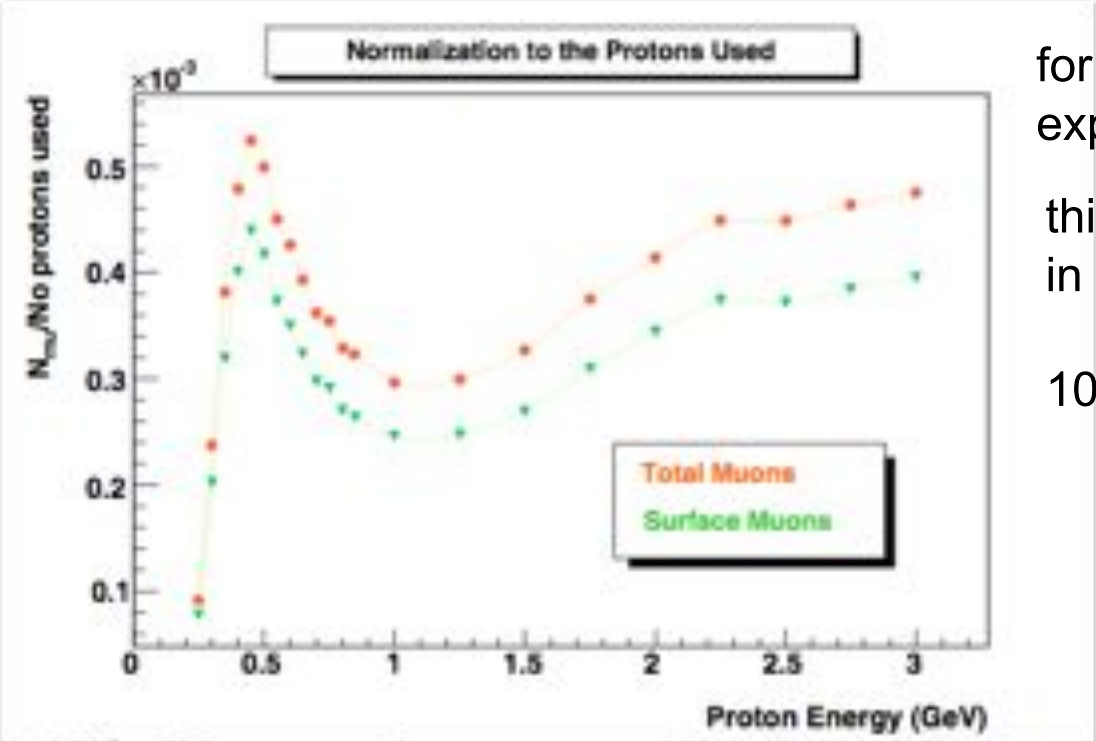


- Simulation parameters from Qiao et al. (PRL 2009):
  - Peak intensity: 1.89×10^{22} W/cm^2
  - Circular polarized, super-Gaussian in space, Gaussian in time, 38 fs width
  - 1 micron thick Proton target ($n_e = 30\ n_{cr}$)

Pulsed muon facility

kJ multi-PW laser can accelerate protons to > 500 MeV (even up to multi GeV)
the pulses are ultra intense and ultra short

Pulsed proton beams are transformed into pulsed pion beams and muon beams



5×10^{-4} of them can be converted into muons!

for a 10 kJ 100 PW laser one can expect 3x10^13 protons >500MeV

this would convert to 1.3e11 muons in < 100 ps

100 A of muon beam pulse

Adriana Bungau
STFC/RAL, Chilton, Didcot, Oxon, UK
Proceedings of IPAC'10, Kyoto, Japan

Applications

- **muons for dynamic B-field measurements**
- **muon- catalized fusion**

Addressing two interesting questions:

Number of reaction during lifetime (2.2 μs)
Can be increased by comressing the fuel to e.g.
5 times liquid density (from 340 to 1200 reactions)

alpha particle sticking
dependend on density and temperature of the fuel

ideal for a combined experiment with a compression driver
(e.g. NIF)


RIKEN RESEARCH

Research Highlights | Highlight of the Month | Frontlines | RIKEN People | News Features | News Roundup | Archive

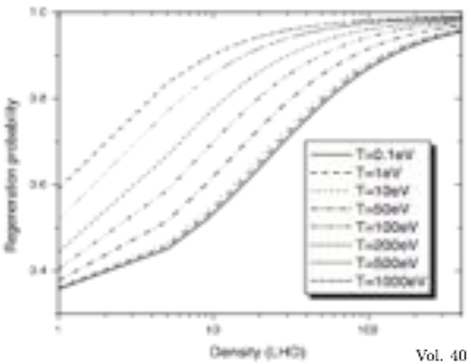
Frontlines

Muon catalyzed fusion for energy production

25 September 2009

Muon research at the RIKEN–RAL Muon Facility could lead to commercially viable fusion technology for clean energy generation

Teiichiro Matsuzaki
Director
RIKEN Facility Office at Rutherford Appleton Laboratory (RAL)
RIKEN Nishina Center for Accelerator-Based Science

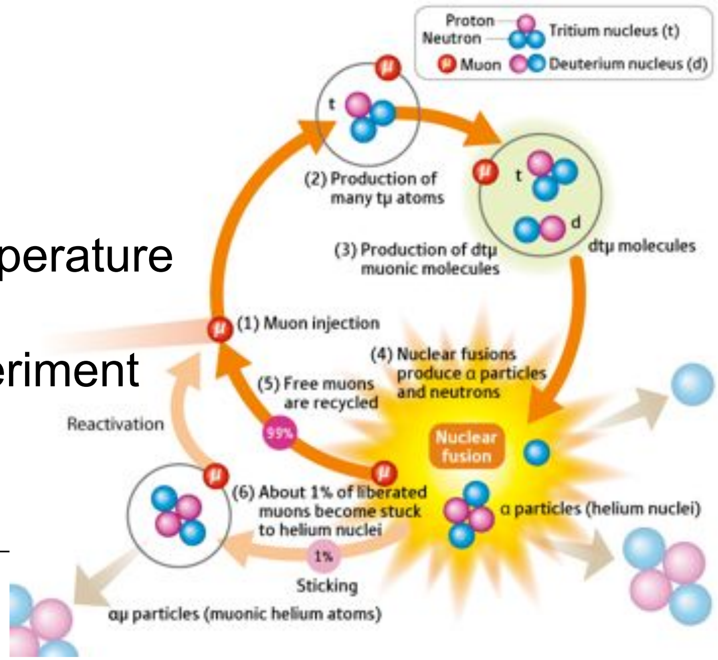


compression and temperature
hard to maintain cw
but not in pulsed experiment

STUDY OF MUON CATALYZED FUSION IN DEUTERIUM–TRITIUM FUEL UNDER COMPRESSIVE CONDITIONS

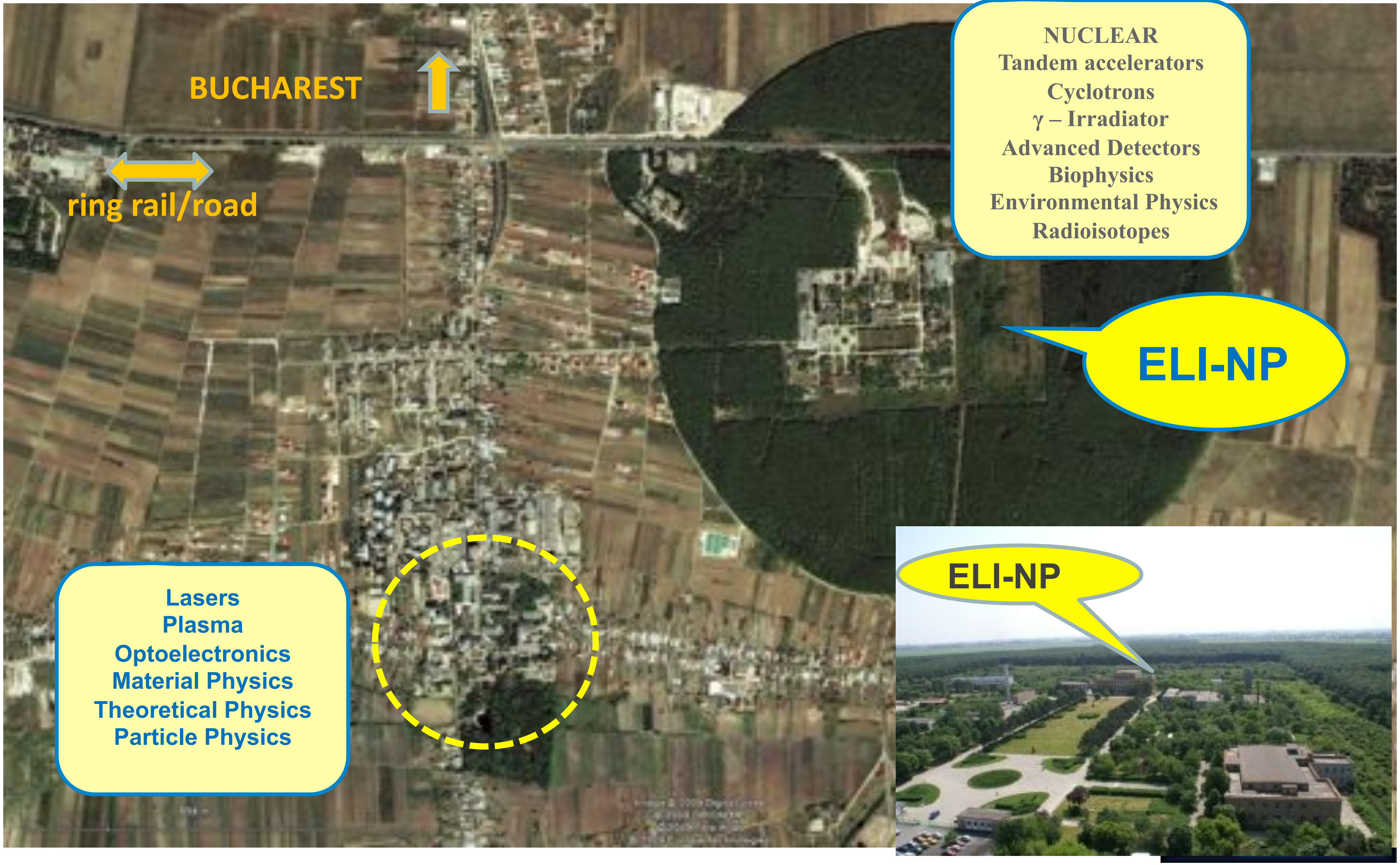
M.R. Pahlavani[a,†], S.M. Motevalli[a,b‡]

Vol. 40 (2009) *ACTA PHYSICA POLONICA B*



Picture 3.4.2014

Bucharest-Magurele National Physics Institutes



ELI-NP

Extreme Light Infrastructure - Nuclear Physics facility (ELI-NP) will consist of two components:

- A very high intensity laser, where the beams from two 10 PW lasers are coherently added to the high intensity of 10^{23}-10^{24}W/cm^2 or electrical fields of 10^{15}V/m.
- Will start with a combination of a 10 PW with a 1 PW laser system
- A very intense ($10^{13}\gamma$/s), brilliant γ beam, 0.1 % bandwidth, with E_γ > 19 MeV, which is obtained by incoherent Compton back scattering of a laser light off a very brilliant, intense, classical electron beam (E_e > 700 MeV) produced by a warm linac.
- Infrastructure will cover: frontier fundamental physics, new nuclear physics and astrophysics, applications in nuclear materials, radioactive waste management, material science and life sciences.

ELI-NP will allow either combined experiments between the high-power laser and the γ beam or stand-alone experiments.

ELI-NP Infrastructure

Large equipment:

High power laser system, 2 x 10PW maximum power

Thales Optronique SA and SC Thales System Romania (~65 M€)

Gamma radiation beam, high intensity, tunable energy up to 20MeV, relative bandwidth 10^{-3}, produced by Compton scattering of a laser beam on a 700 MeV electron beam produced by a warm LINAC

European Consortium EuroGammaS led by INFN Rome (~65 M€):

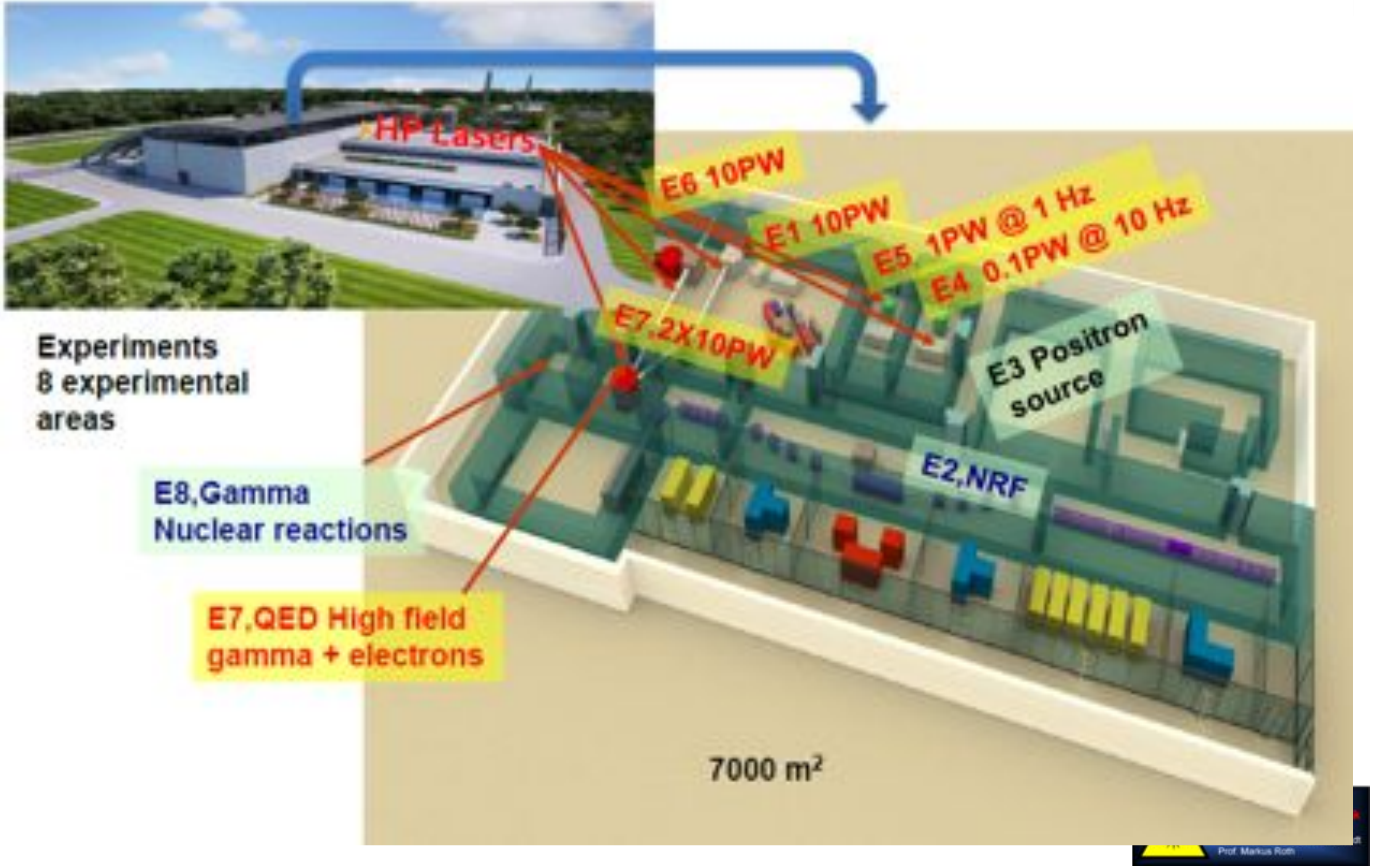
INFN (Italy), University "La Sapienza" Rome (Italy), CNRS (France), ALSYOM (France), ACP Systems S.A.S.U. (France), COMEB Srl (Italy), ScandiNova Systems (Sweden)

Buildings – 33000sqm total – *STRABAG (~65M€)*

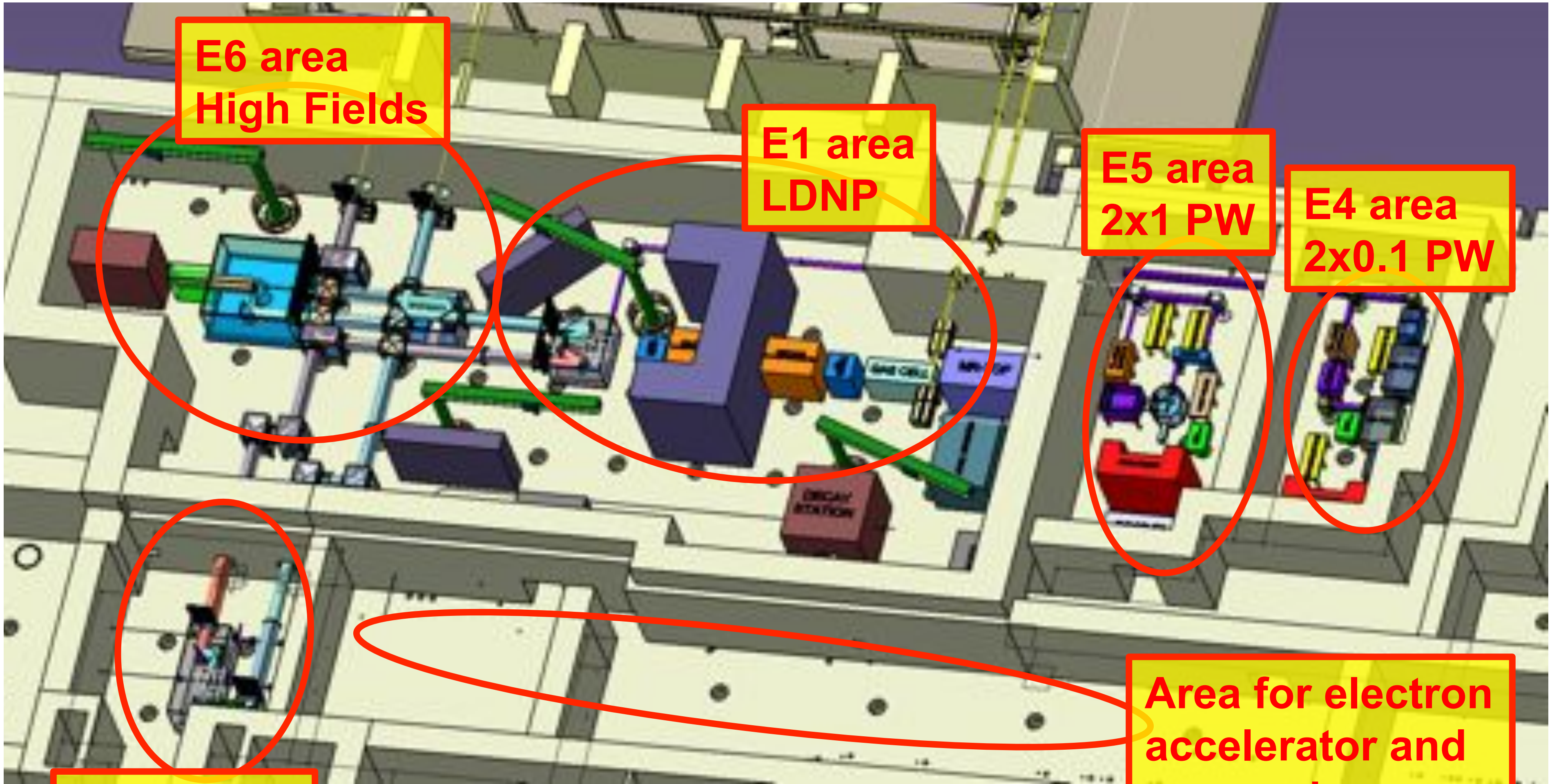
Experiments:

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

ELI-NP Experiment Building

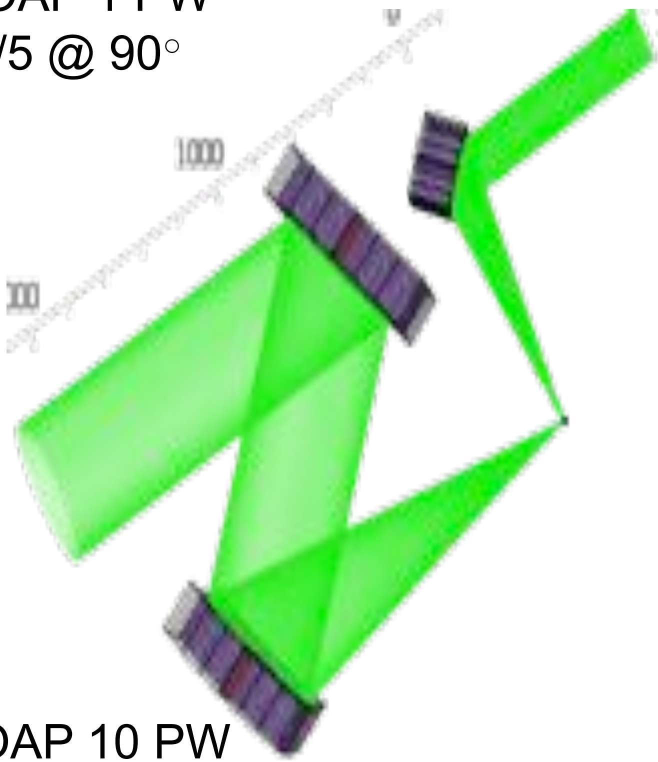


Draft 3D view of experimental areas for laser driven experiments

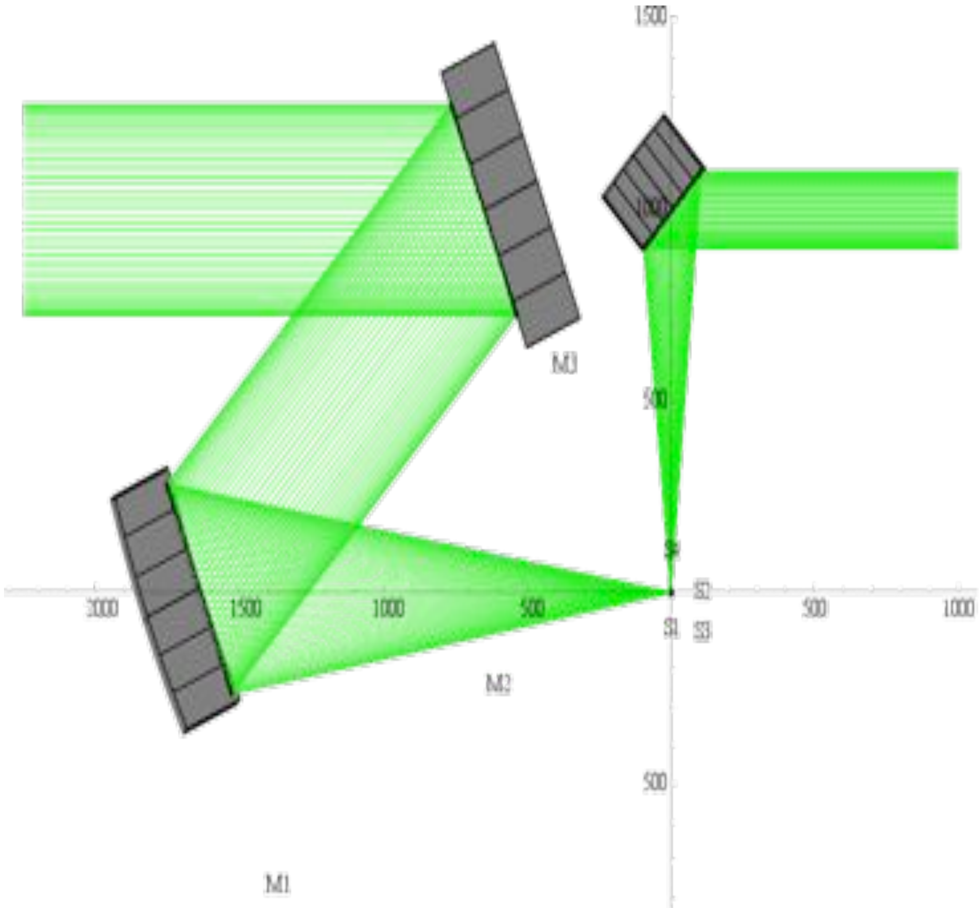


10PW + 1PW configuration

OAP 1 PW
f/5 @ 90°



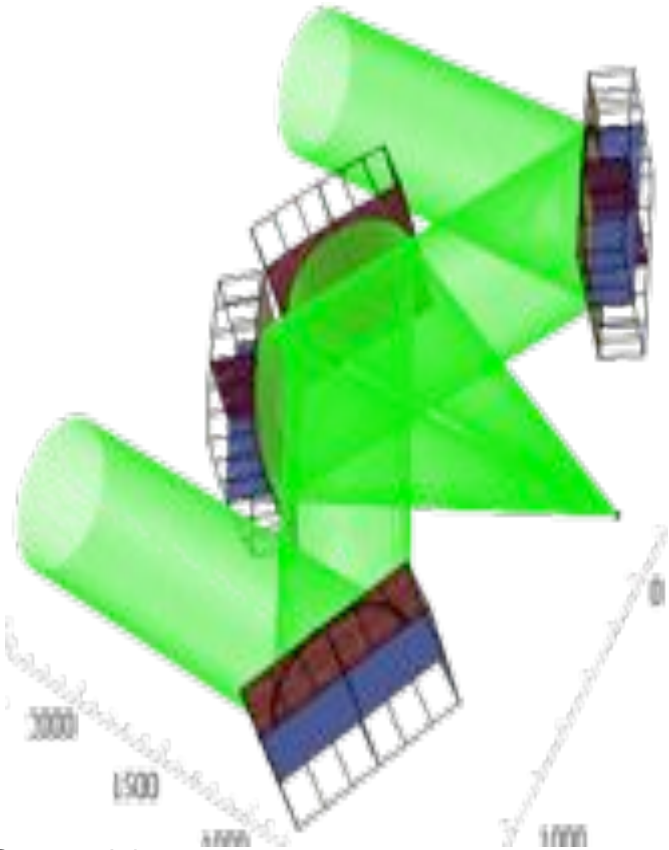
OAP 10 PW
f/3 @ 45°

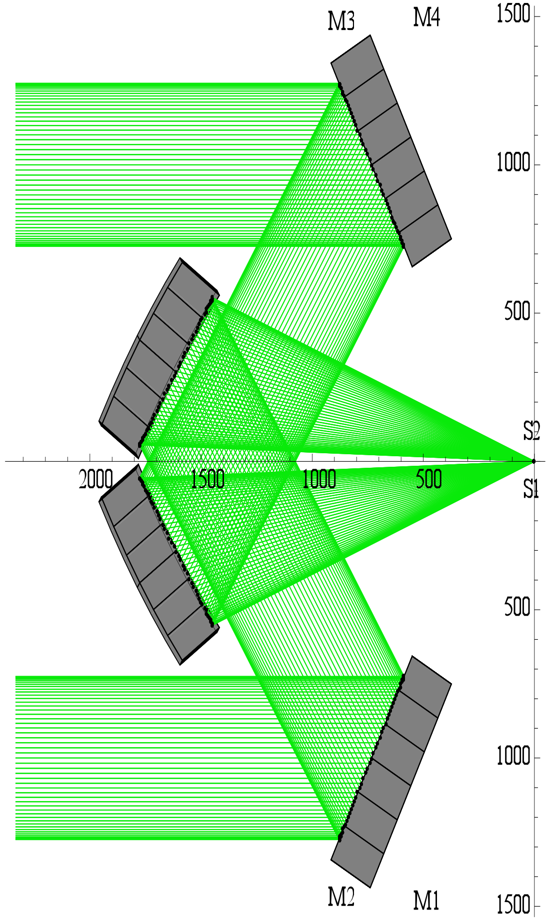


+ gas/ablation plasma target
+ secondary target foils or other (millimetric) devices

F. Negoita, negoita@tandem.nipne.ro

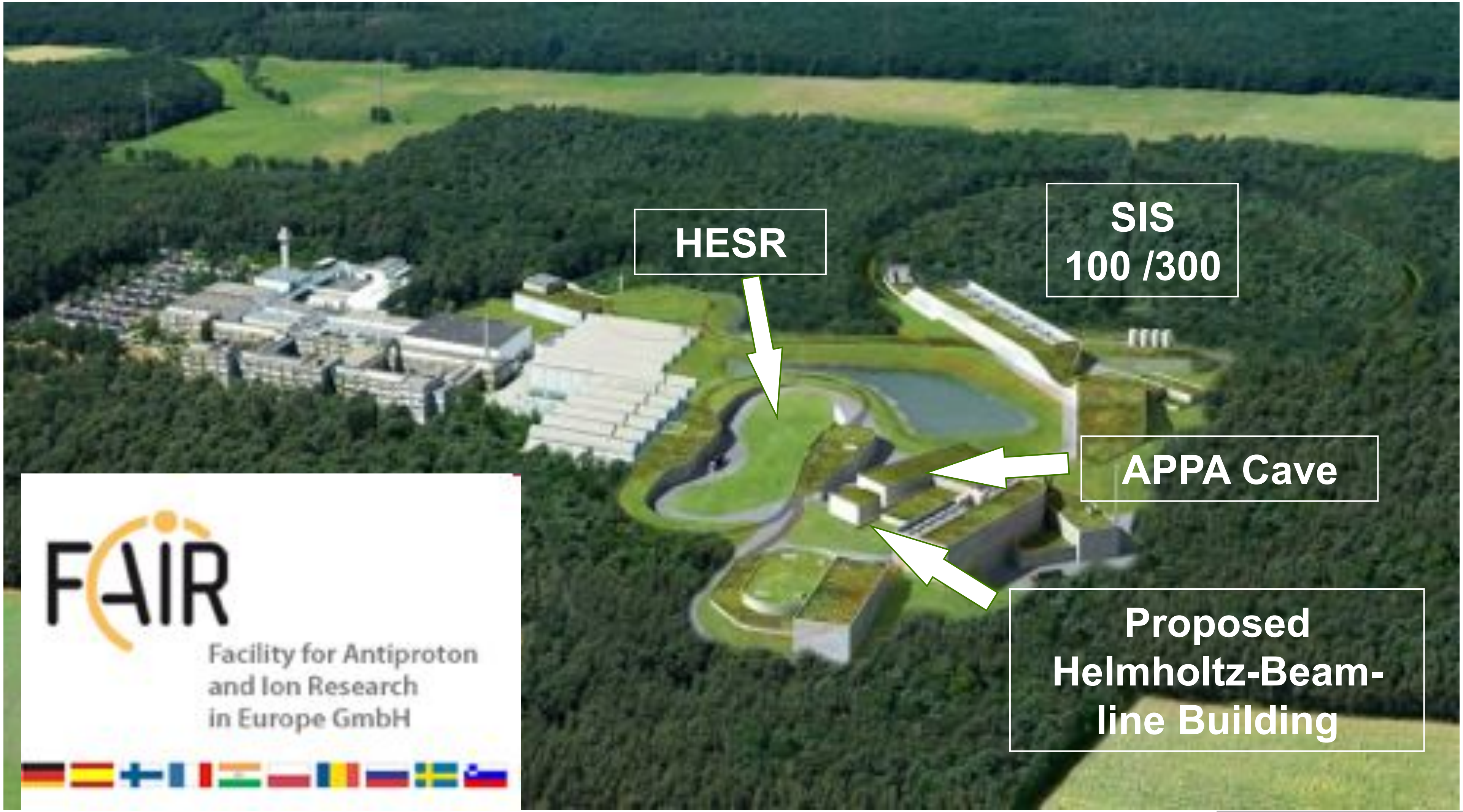
2x10PW configuration (upgrade)





OAP 10 PW
f/3 @ 45°

FAIR – A key laboratory for HEDP and ultra-high field physics !



Facility for Antiproton & Ion

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Nuclear Structure & Astrophysics
(Rare-isotope beams)

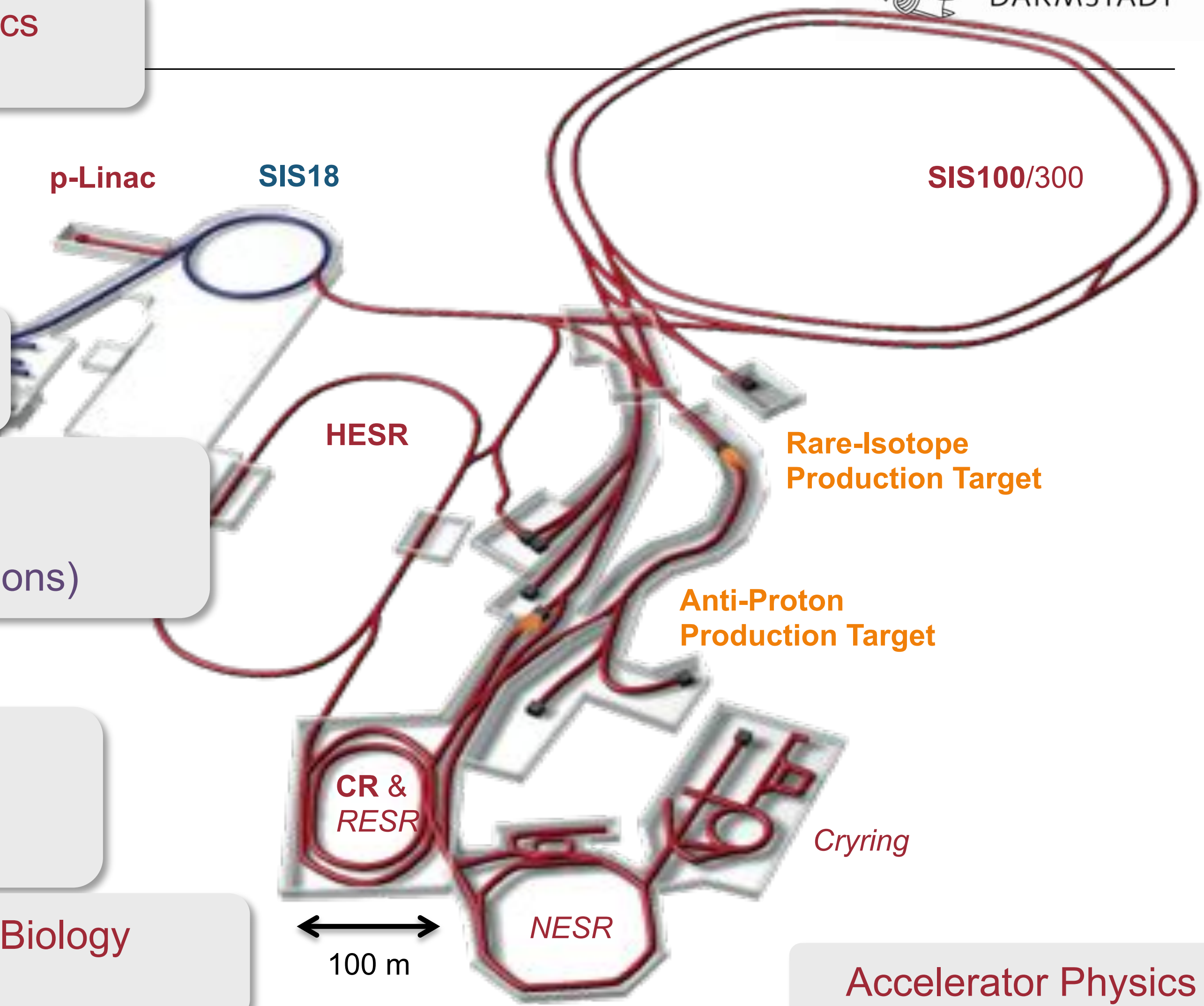
Hadron Physics
(Stored and cooled
14 GeV/c anti-protons)

QCD-Phase Diagram
(HI beams 2 to 45 GeV/u)

Fundamental Symmetries
& Ultra-High EM Fields
(Antiprotons & highly stripped ions)

Dense Bulk Plasmas
(Ion-beam bunch compression
& petawatt-laser)

Materials Science & Radiation Biology
(Ion & antiproton beams)



Accelerator Physics

Acc Performance for FAIR Experiments

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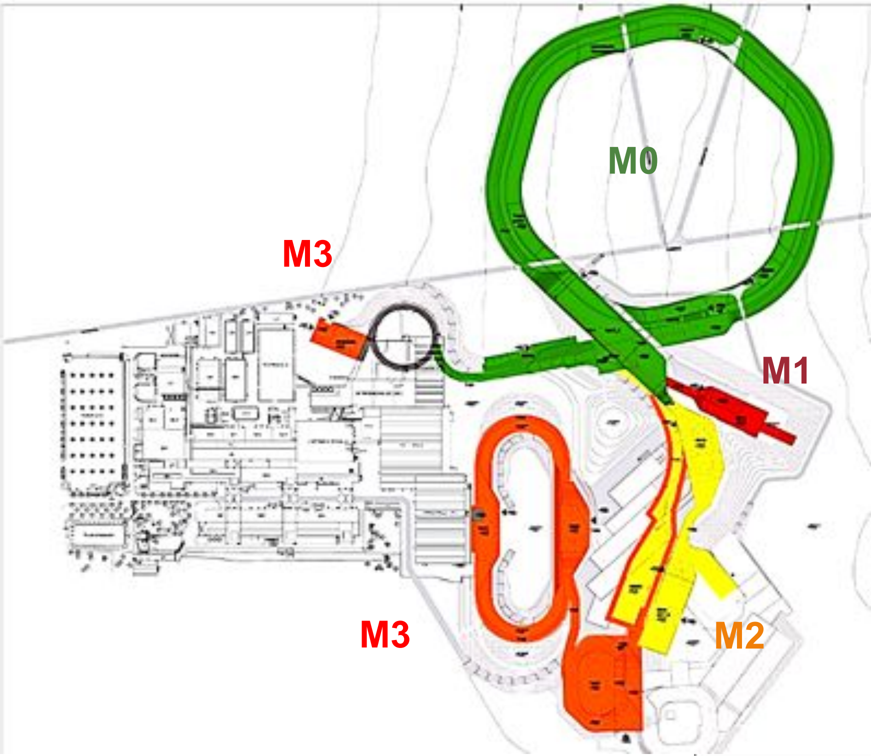
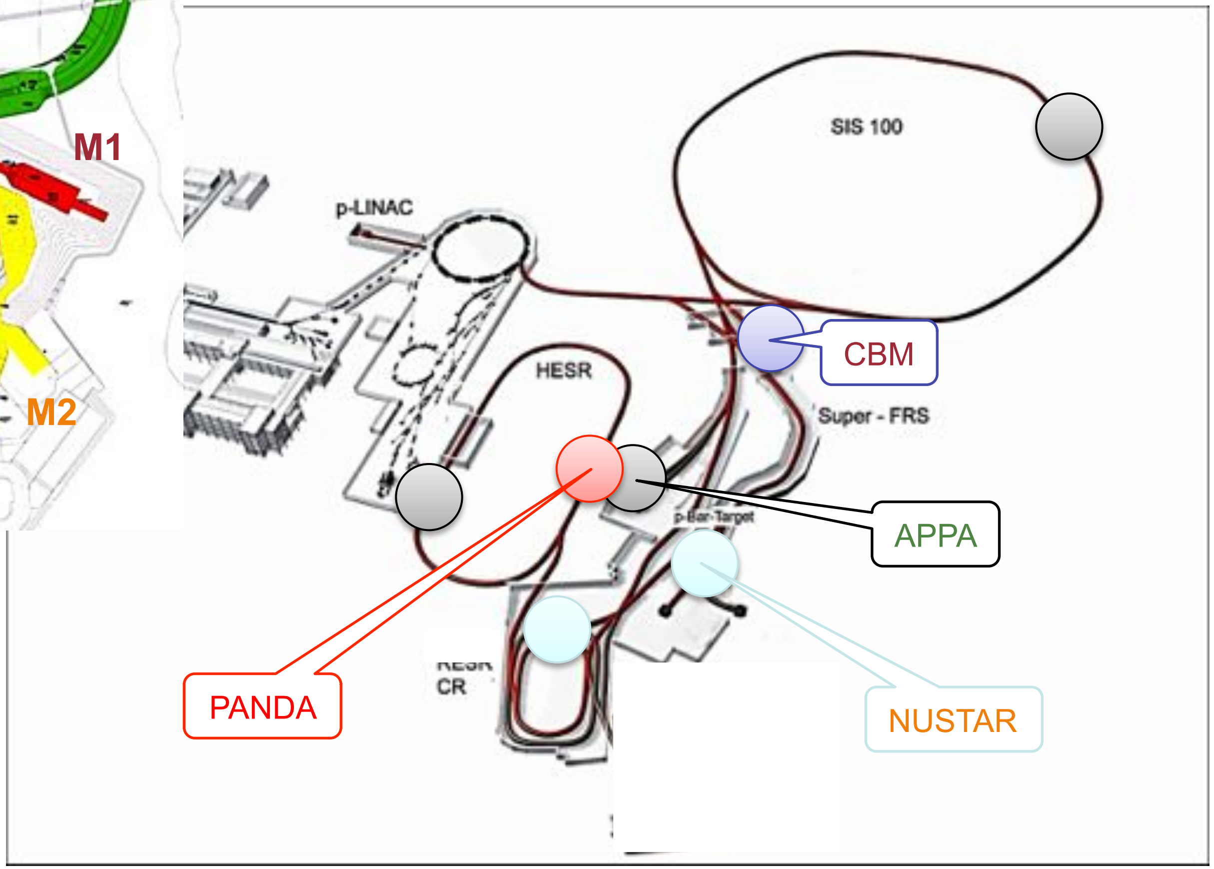
- Beam Intensities:
  - intensities of primary beams: x 100 – x 1000
  - intensities of secondary beams: x 10.000
- Beam Energies:
  - energies: x 30
- Unprecedented Variety of Ions:
  - antiprotons
  - protons to Uranium, radioactive beams
- Beam Quality:
  - cooled antiprotons
  - intense cooled RIBs
- Pulse Structure:
  - extremely short pulses (70 ns) to slow extraction (quasi CW)
- Parallel Operation:
  - (Finally) operation of up to four experiments simultaneously

FAIR Modularised Start Version



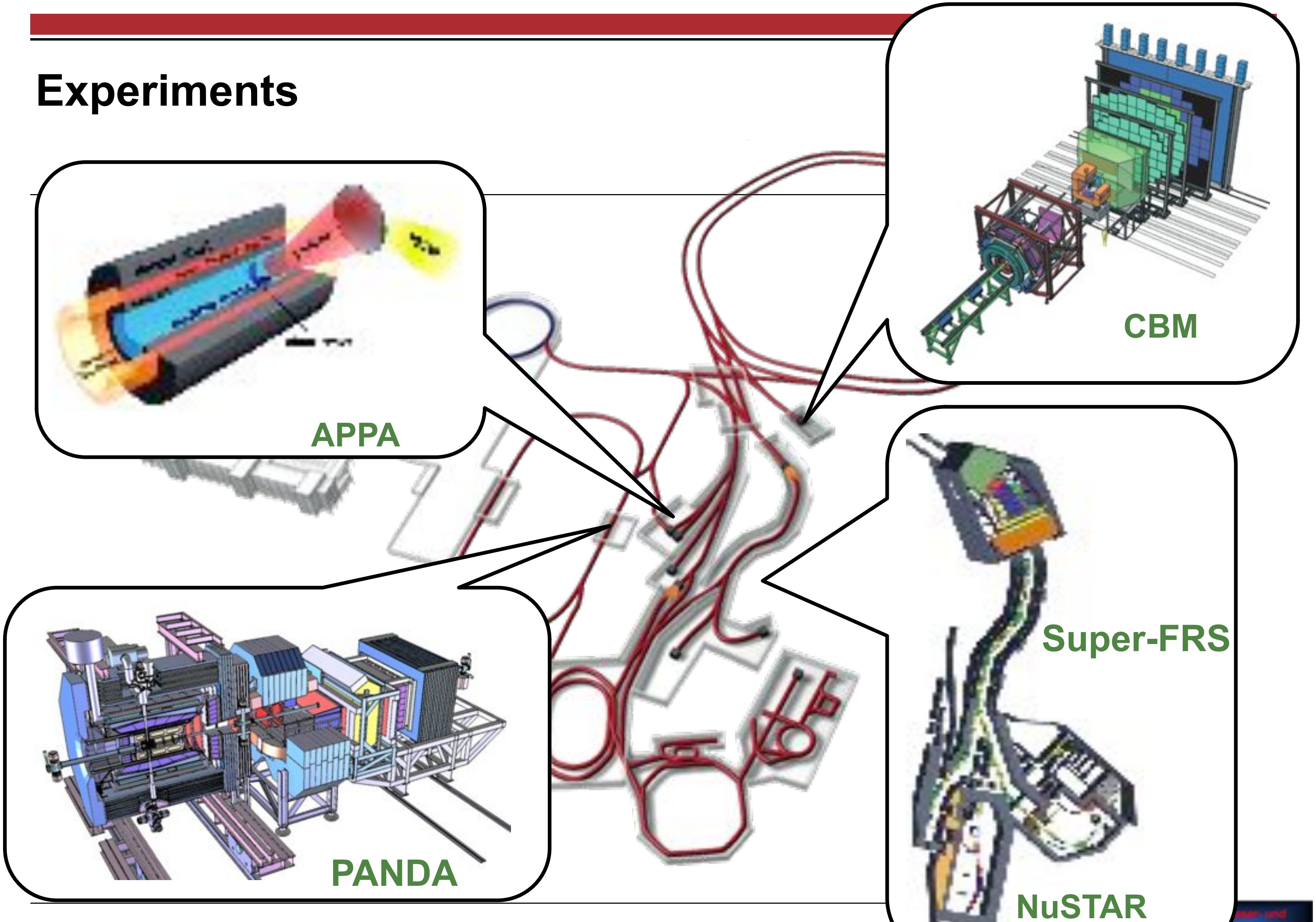
Science with the MSV



Experiments

M0: SIS100
M1: CBM,APPA
M2: NUSTAR
M3: PANDA

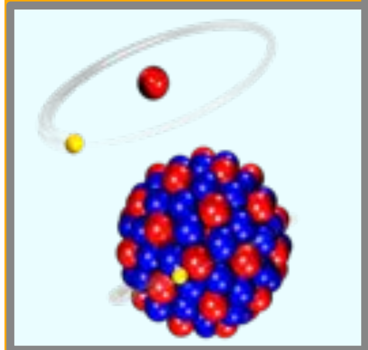
Experiments

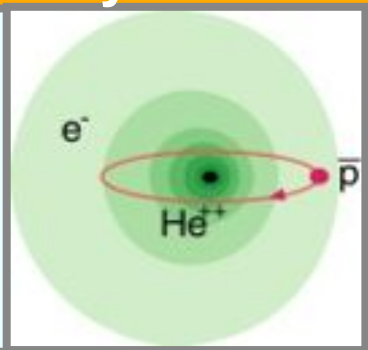


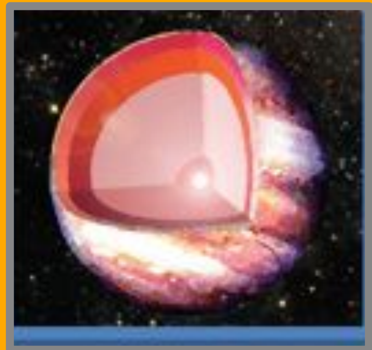
Atomic Physics, Plasma Physics, and Applied Sciences APPA@FAIR

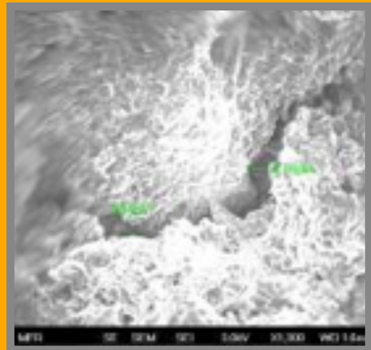
Highest Charge States	*Extreme Static Fields*
Relativistic Energies	*Extreme Dynamical Fields and Ultrashort Pulses*
High Intensities	*Very High Energy Densities and Pressures*
High Charge at Low Velocity	*Large Energy Deposition*
Low-Energy Anti-Protons	*Antimatter Research*

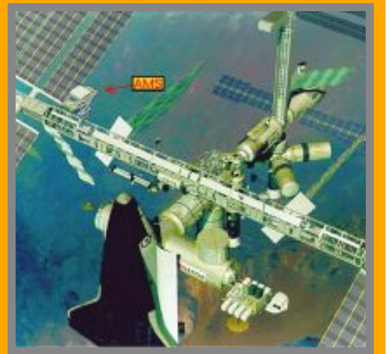
Atomic Physics | **Plasma** | **Materials** | **Bio**







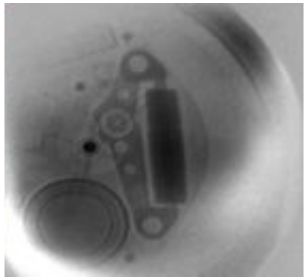




SPARC	FLAIR	HEDgeHOB/WDM	MAT/BIOMAT	BIO/BIOMAT
strong field research ... probing of fundamental laws of physics	**anti-matter** ... matter / anti-matter asymmetry	**planetary interiors** ... states of matter common in astrophysical objects	**extreme conditions** ... radiation hardness and modification of materials	**aerospace engineering** ... radiation shielding of cosmic radiation

First APPA Experiments
(prominent examples)

BIOMAT
- Materials under multiple extreme conditions (pressure, heat, irradiation)
- Radiation shielding of cosmic radiation
- Day-1 experiments
  - Sample irradiation at APPA cave using high pressure cells
  - Irradiation of biological samples at APPA cave



HEDgeHOB/WDM
- Phase transitions shocked/compressed matter
- Opacity measurements of Warm Dense Matter

  Day-1 experiments
  - Proton microscopy of shocked/compressed materials
  - Opacity changes from Cold- to Warm Dense-Matter

SPARC
- Precision test of QED in the strong field domain ($\alpha Z \approx 1$)
- Model independent determination of nuclear parameter

  Day-1 experiments
  - Ion channeling at APPA cave and HESR
  - Precision laser spectroscopy of fine structure levels at HESR

Civil Construction

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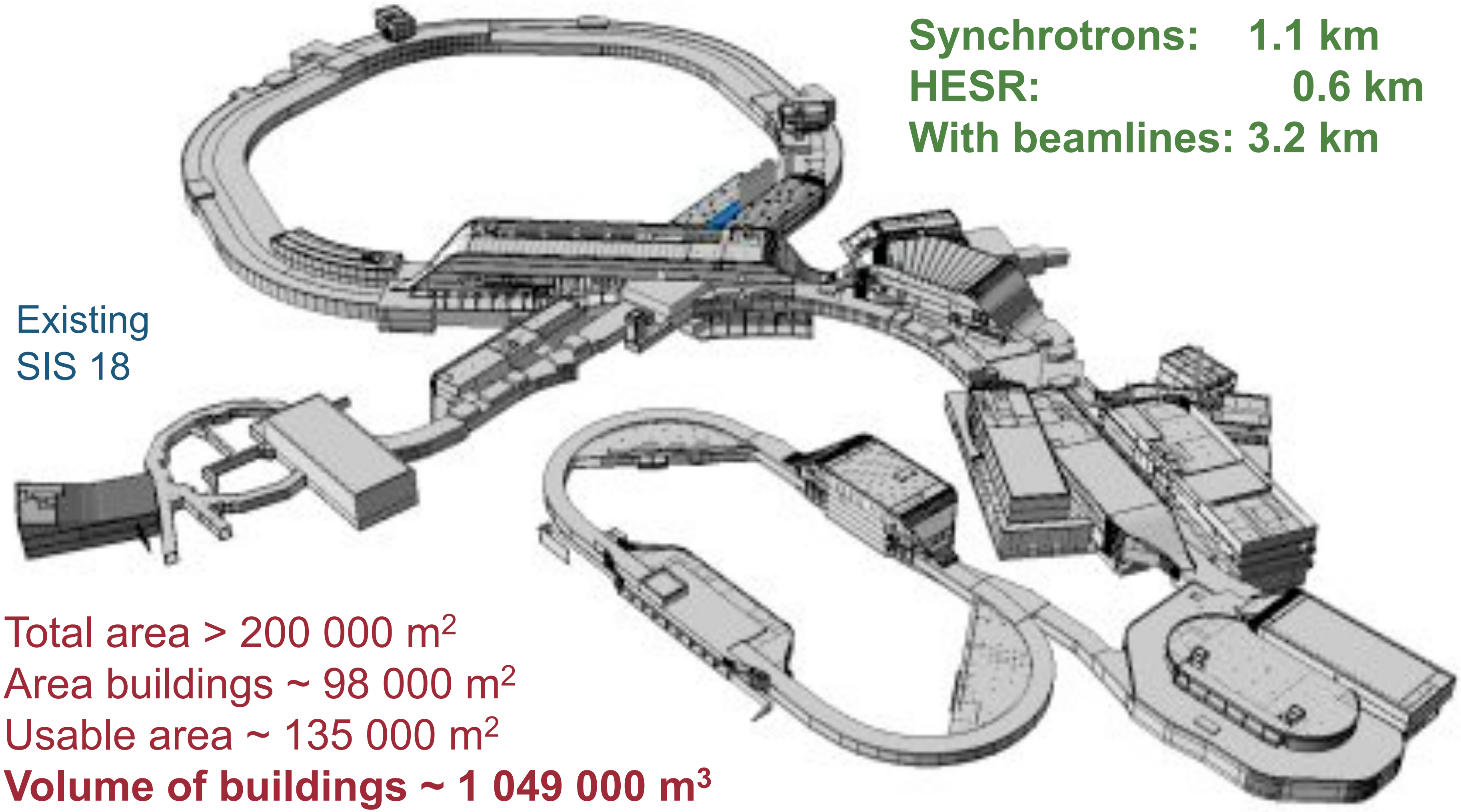
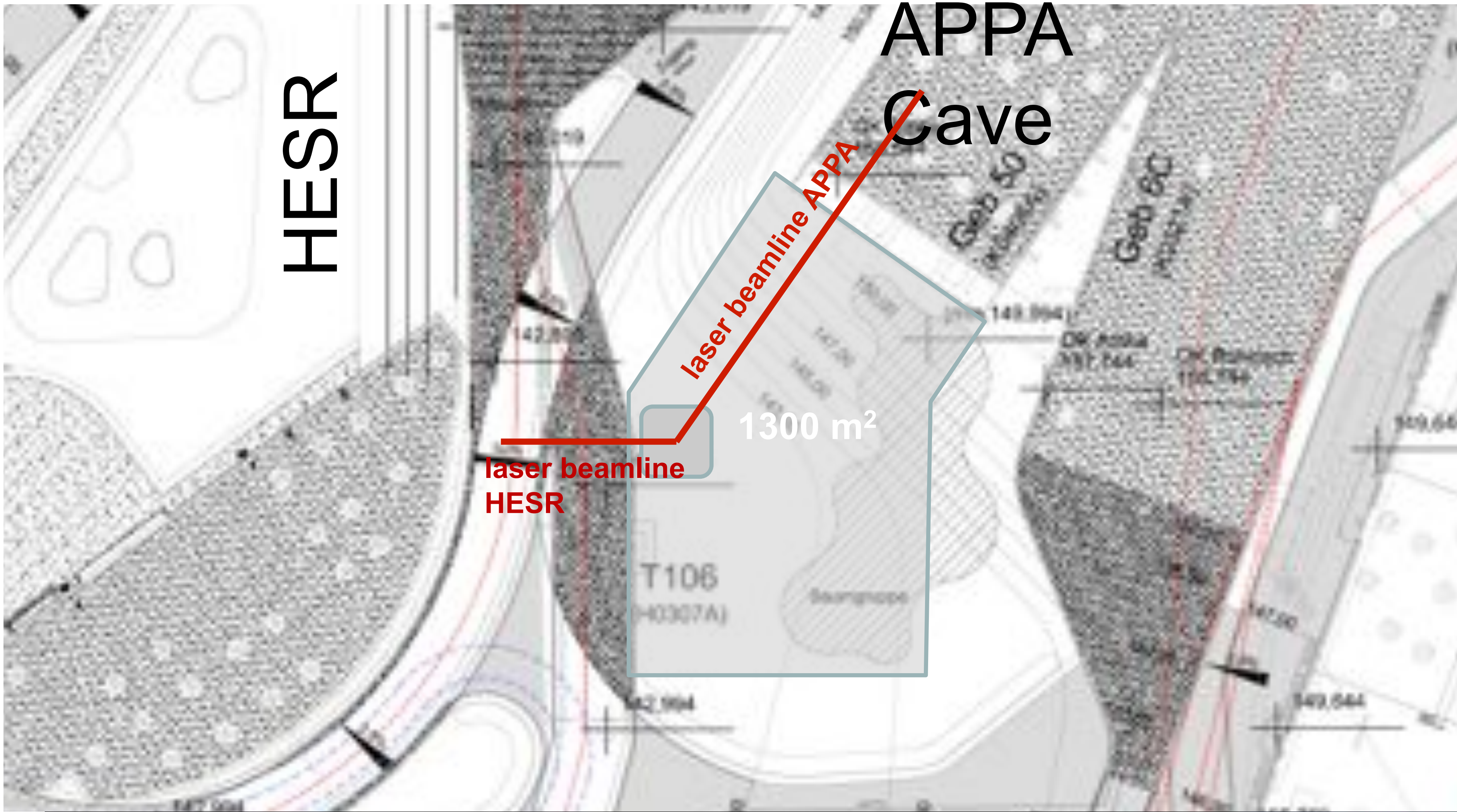
Synchrotrons: 1.1 km
HESR: 0.6 km
With beamlines: 3.2 km



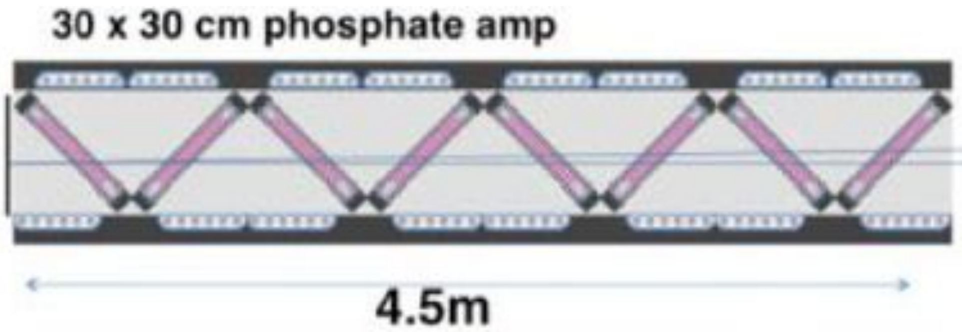
Existing
SIS 18

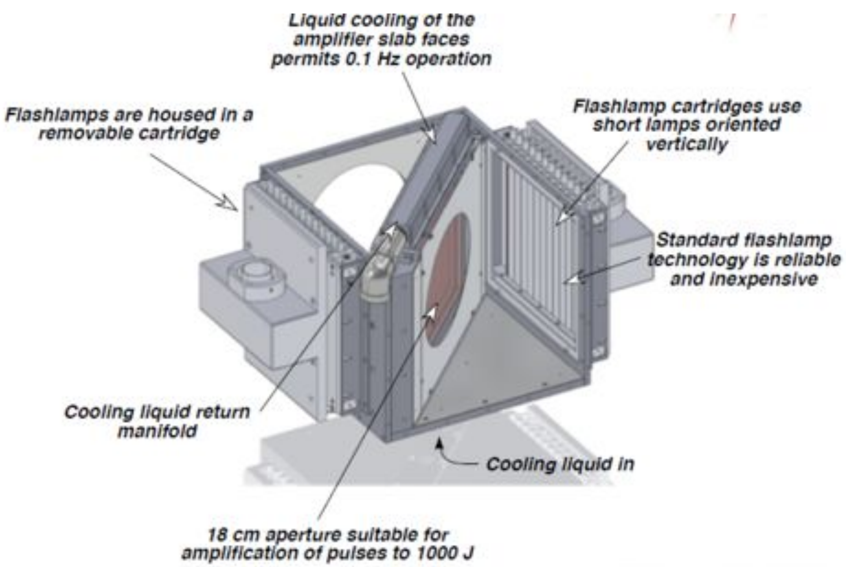
Total area > 200 000 m^2
Area buildings ~ 98 000 m^2
Usable area ~ 135 000 m^2
Volume of buildings ~ 1 049 000 m^3
Substructure:~ 1500 pillars, up to 65 m deep

Site for the implementation of the Helmholtz Beamline at FAIR



PHELIX could develop to a compact 1/10s kJ laser





Specifically designed main amplifier section could be more compact than present PHELIX technology

Even more compact cooled 18 cm aperture amplifier (~1 kJ possible energy) has been demonstrated at 1/10 shot rate

(National Energetics, Texas)

Technical Requirements for a laser facility at FAIR

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Laser parameters	Actual (PHELIX)	proje	TWO BEAMLINES !! →	Preference (me)
Laser energy - short pulse	250 J	400 J	1 kJ	1 kJ
Laser Energy - long pulse (2ω)	200 J	1 kJ	10 kJ	2 kJ
Pulse duration	500 fs	350 fs	150 fs	350 - 150 fs
Temporal contrast	10^{-10}	10^{-12}	10^{-14}	10^{-13}
power	400 TW	1.1 PW	7 PW	3- 7 PW
Repetition rate	1 shot/90 min	1 shot/ 1 -10 min	1 Hz	1 shot / min
Proton energies	20 MeV	50 -100 MeV	200 MeV	400 MeV

LLP Laser- und Plasmaphysik
Institut für Kernphysik
Technische Universität Darmstadt
Prof. Markus Roth

FAIR Construction Site

Bird's View

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FAIR in 2018+