Perspective on research on laser driven proton-boron fusion and applications

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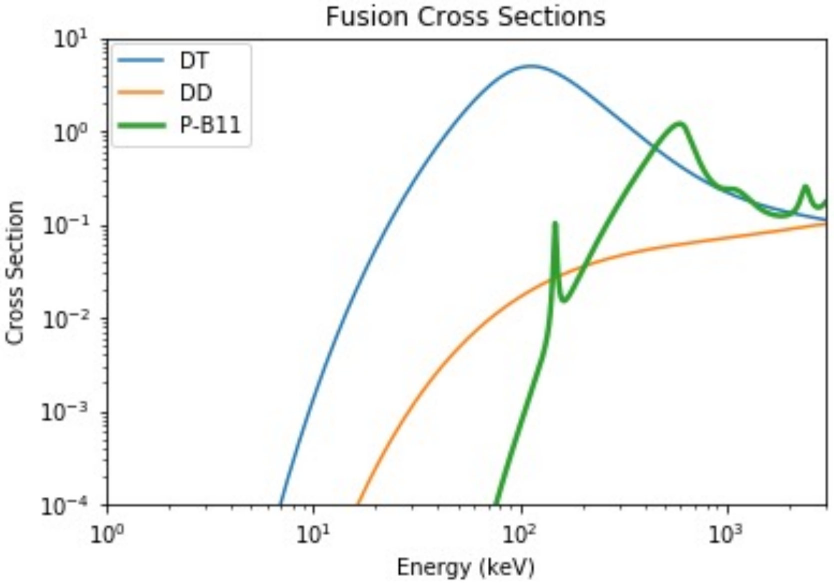
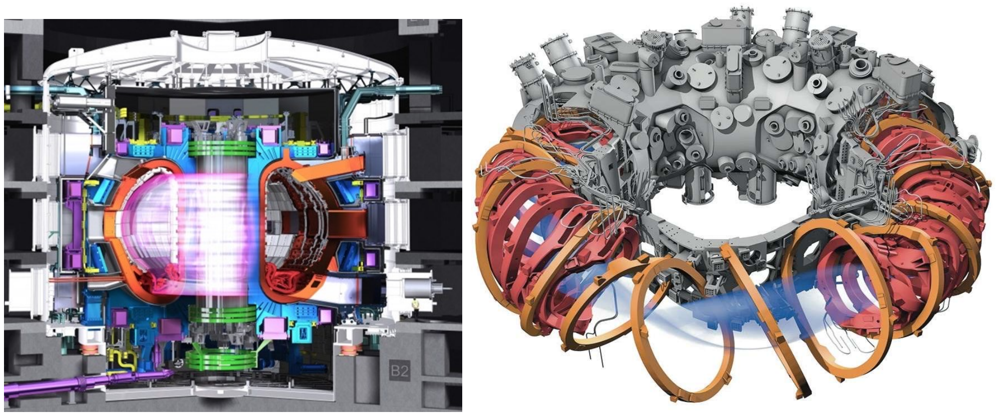
Fusion

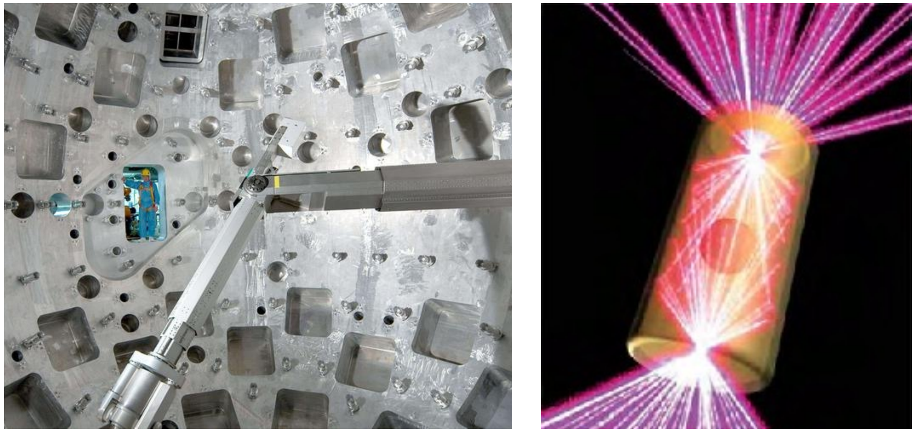
Current upproaches to thermonuclear controlled fusion

$$\boxed{{}_{1}^{2}D + {}_{1}^{3}T \rightarrow \alpha + {}_{0}^{1}n + 17.6\ \text{MeV}}$$


Fusion Cross Sections



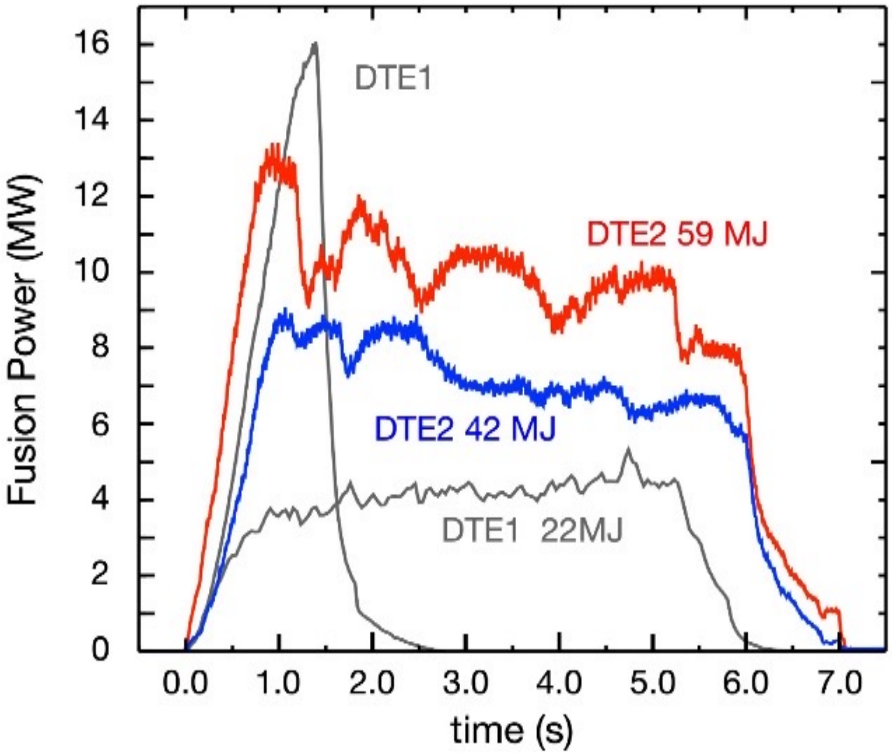
Magnetic Confinement Fusion

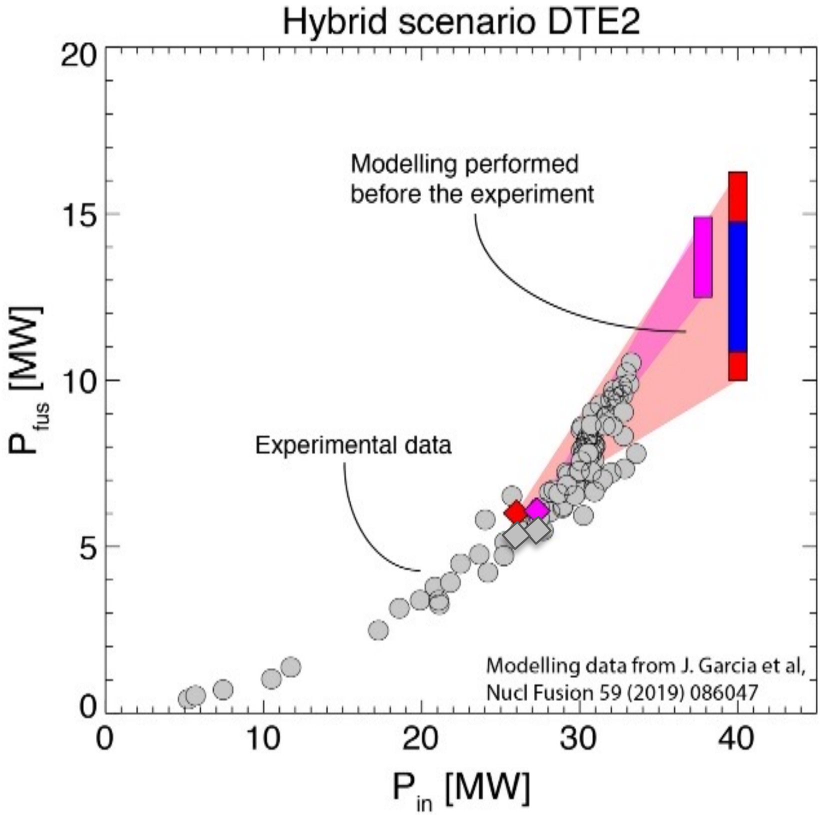


Inertial Confinement Fusion

Latest achievments MCF

High fusion power produced and sustained for 5 seconds



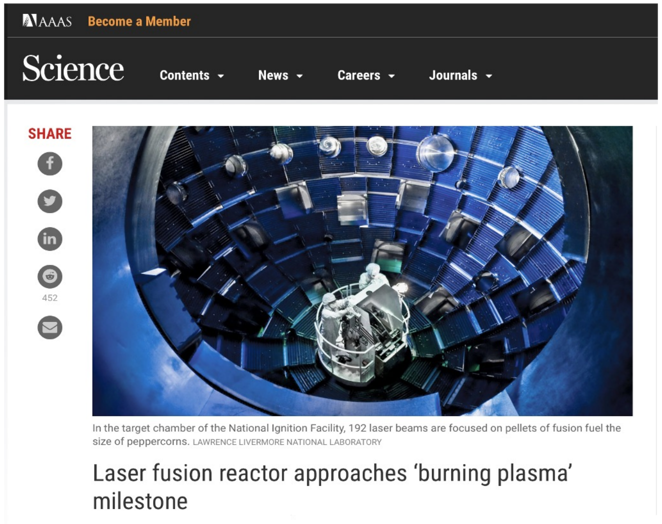


First high confinement plasmas using D-T with berillium-tungsten wall

CONFIRMING MODELING PREDICTIONS

Courtesy Tony Donné

Latest achievments ICF



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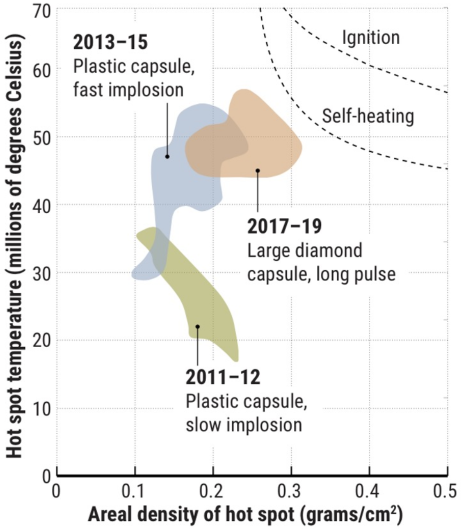
In the target chamber of the National Ignition Facility, 192 laser beams are focused on pellets of fusion fuel the size of peppercorns. LAWRENCE LIVERMORE NATIONAL LABORATORY

Laser fusion reactor approaches 'burning plasma' milestone

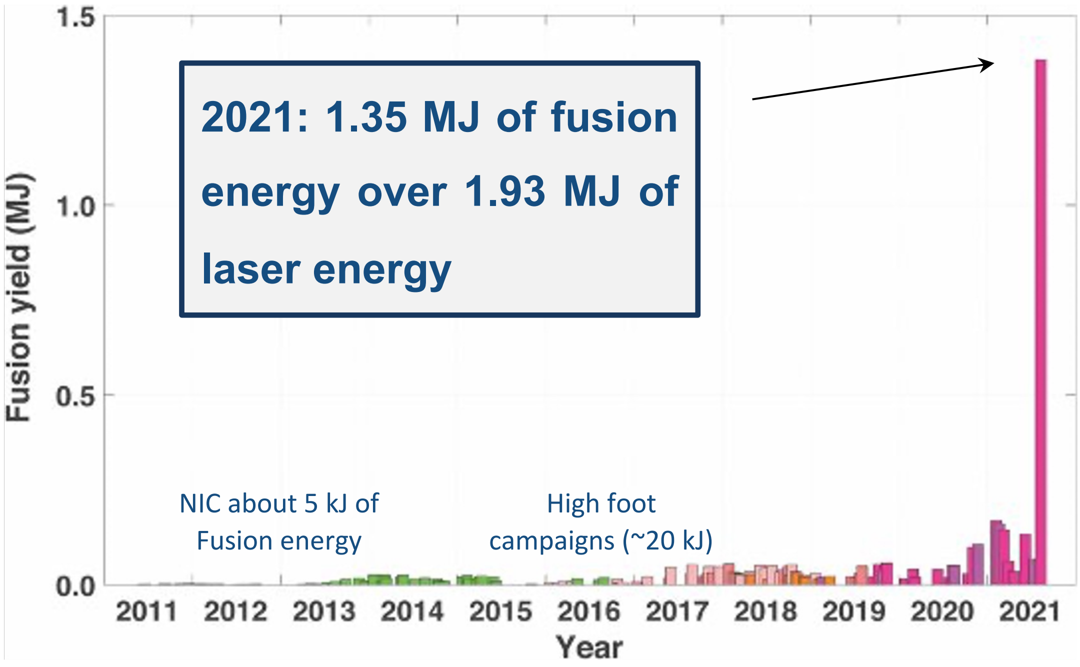
By Daniel Clery | Nov. 23, 2020, 10:45 AM



GRAPHIC: PRAV PATEL/LLNL, ADAPTED BY N. DESAI/*SCIENCE*

2020:
More than 150 kJ of fusion energy

Most recent results on NIF (2020-2021)



2021: 1.35 MJ of fusion energy over 1.93 MJ of laser energy

NIC about 5 kJ of Fusion energy

High foot campaigns (~20 kJ)

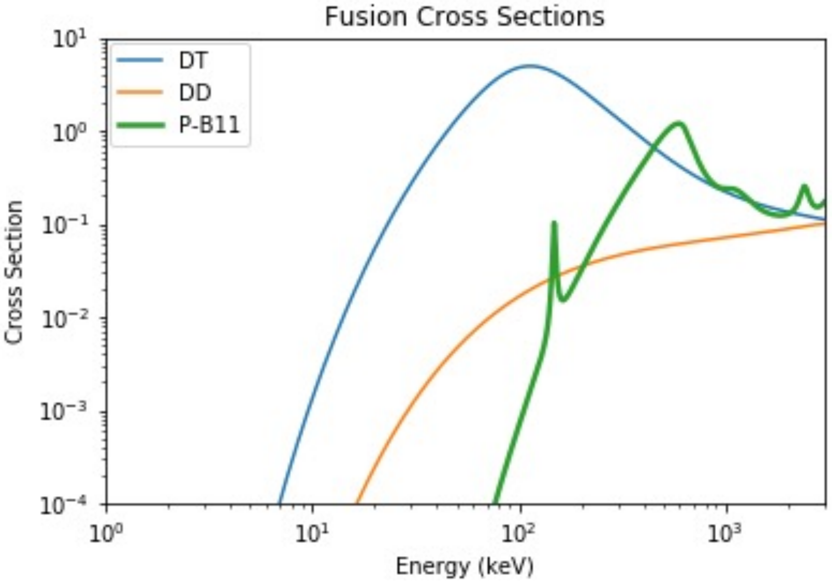
- ✓ Improved radiation uniformity
- ✓ Improved target quality

Reduced impact of Rayleigh Taylor instability

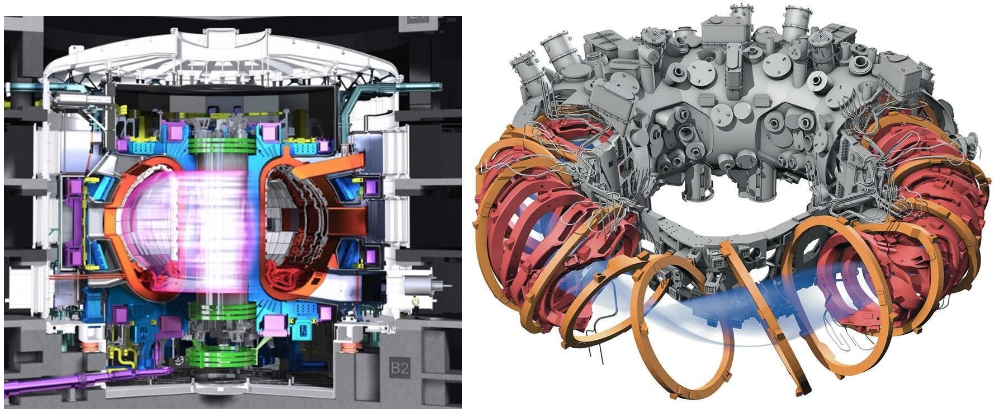
Fusion

CHALLENGES

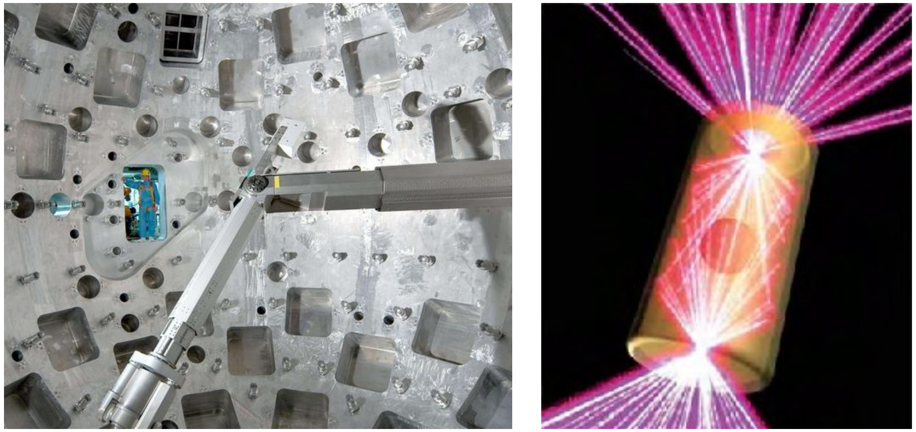
- ✓ Fuel cycle (tritium breeding)
- ✓ Material activation due to neutrons
- ✓ Economy of cost



$$ {}_1^2D + {}_1^3T \rightarrow \alpha + {}_0^1n + 17.6\ \text{MeV} $$



Magnetic Confinement Fusion

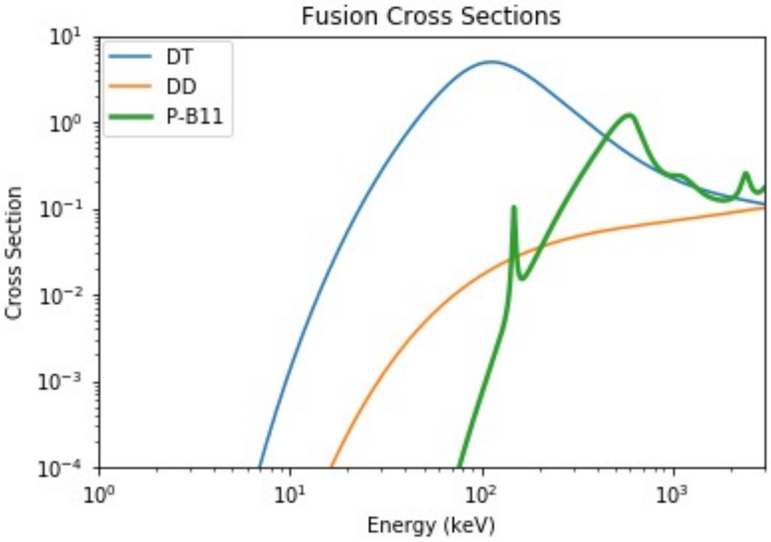


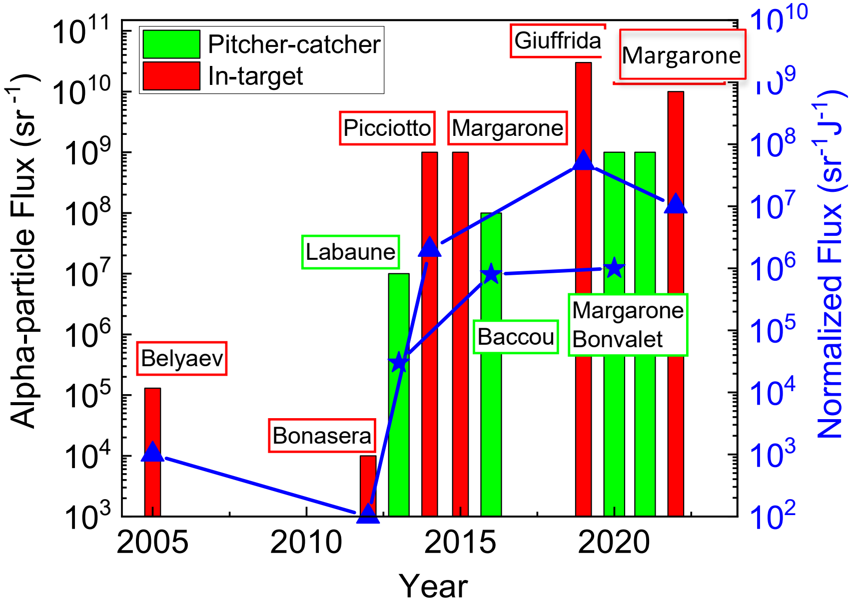
Inertial Confinement Fusion

Hydrogen-Boron Fusion

$$p + {}^{11}B \rightarrow \alpha + {}^{8}Be \rightarrow \alpha + (\alpha + \alpha) + 8.7\ \text{MeV}$$

- ✓ Aneutronic Energy Production (ecologic)
- ✓ Relies on stable fuel elements only
- ✓ Does not need cryogenic technology



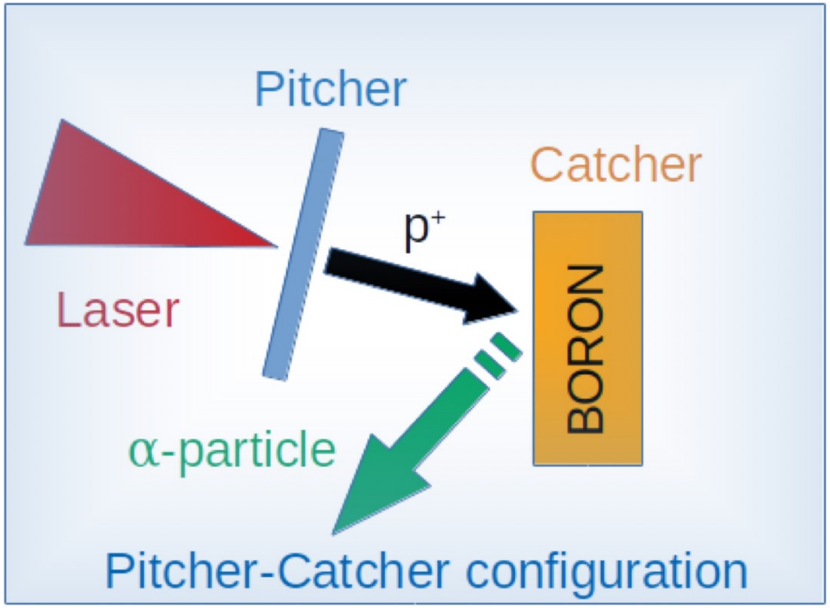


V.S.Belyaev, et al. Phys. Rev. E 72, 026406 (2005)
A.Bonasera, et al. in "Fission and Properties of Neutron-Rich Nuclei" (Sanibel Island, USA: World Scientific) 503–507 (2008) doi:10.1142/9789812833433_0061
C.Labaune, et al. Nat. Commun. 4, 2506 (2013)
A.Picciotto, et al. Physical Review X 4, 031030 (2014)
L.Giuffrida, et al. Phys. Rev. E 101, 013204 (2020)
D.Margarone, et al. Frontiers In Physics, 8, 343 (2020)
D. Margarone et al., Applied Sciences 12, 1444 (2022)

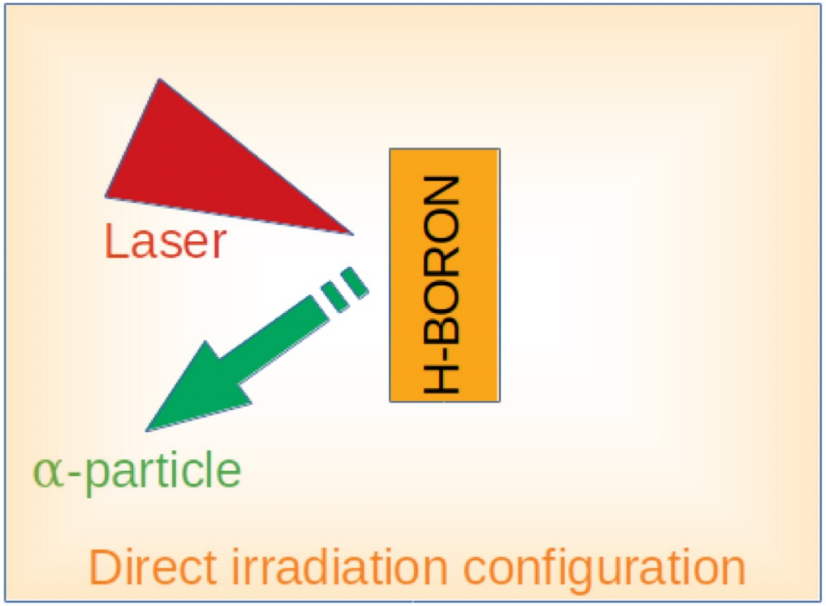
See presentation by Dieter Hoffmann

Approaches used in experiments

Two types of experimental configuration have been used



Pitcher-Catcher configuration



Direct irradiation configuration

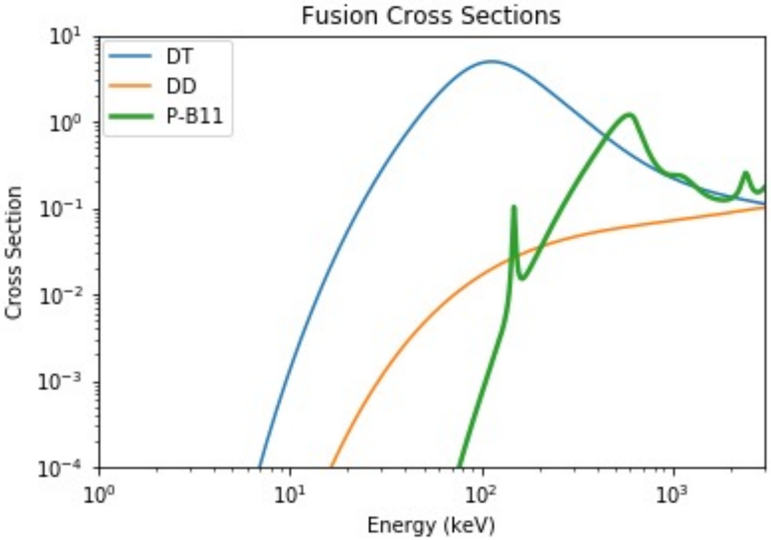
In addition, Labaune et al. used a ns laser to irradiate the catcher before the arrival of protons

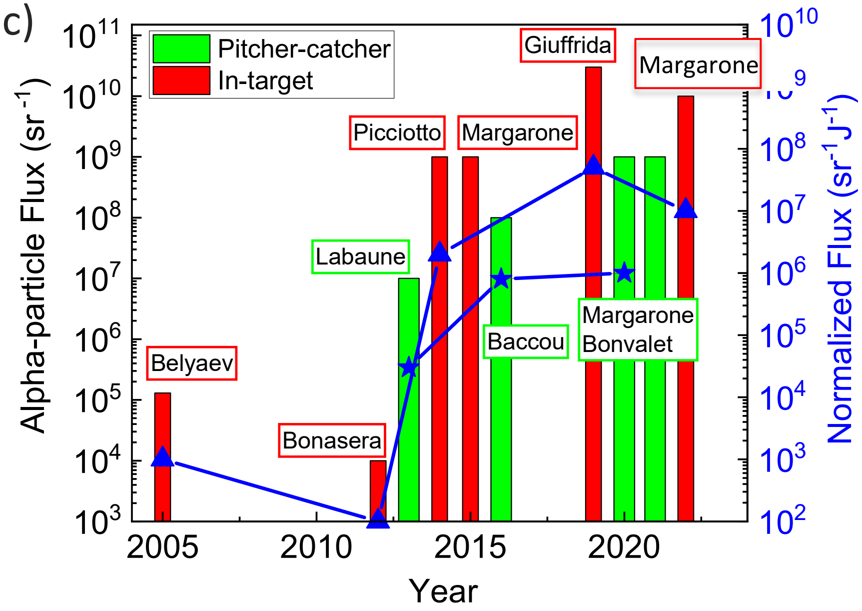
C.Labaune, et al. Nat. Commun. 4, 2506 (2013)

Hydrogen-Boron Fusion

$$p + {}^{11}B \rightarrow \alpha + {}^{8}Be \rightarrow \alpha + (\alpha + \alpha\ ) + 8.7\ \mathrm{MeV}$$

- ✓ Aneutronic Energy Production (futuristic, ecologic)
- ✓ Relies on stable fuel elements only





- ✓ Laser-driven High brightness α-particle sources: short duration / small source size
- ✓ Production of Short half-life radioisotopes for imaging or therapy

PROBONO

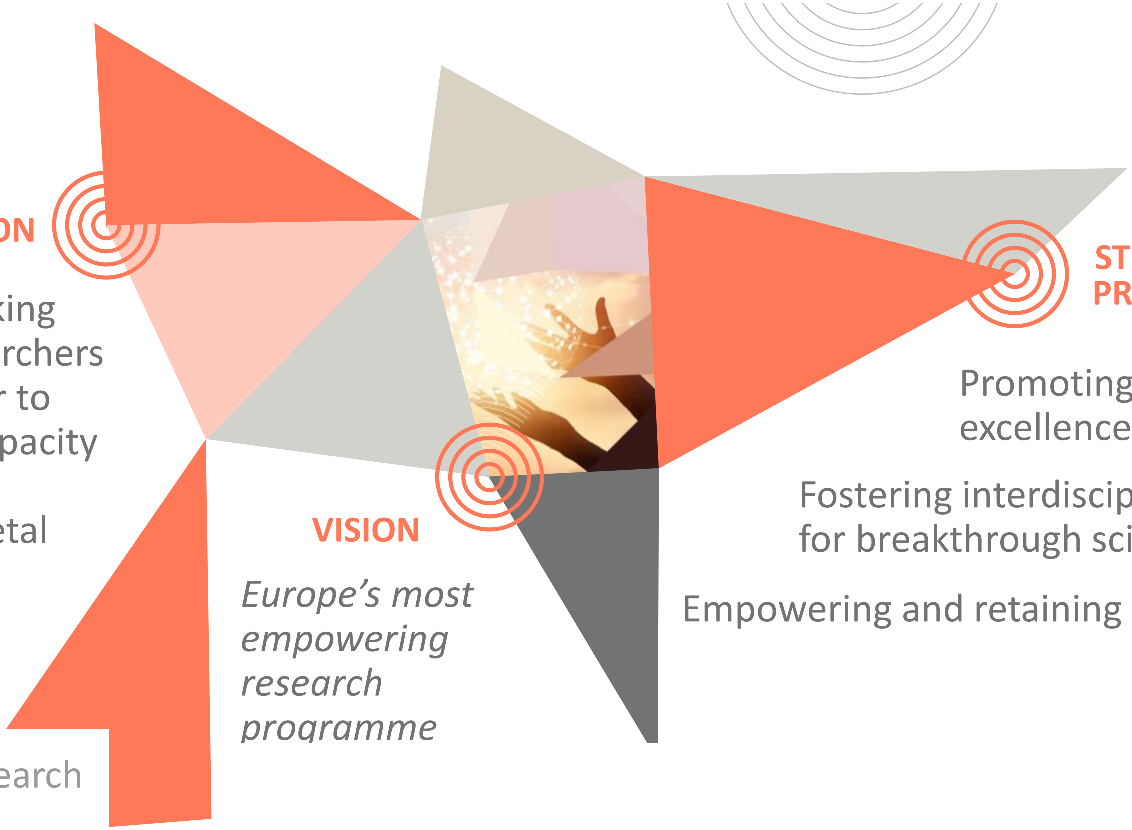
Cost Action CA21128 "**PROton BOron Nuclear fusion: from energy production to medical applicatiOns"** PROBONO – *approved and starting November 2022*

- ✓ Motivation
- ✓ Mission
- ✓ Large international collaboration
- ✓ Benefits

Motivation

& Mission

COST: Mission and Strategic Priorities



MISSION

COST provides networking opportunities for researchers and innovators in order to strengthen Europe's capacity to address scientific, technological and societal challenges

VISION

Europe's most empowering research programme

STRATEGIC PRIORITIES

Promoting and spreading excellence

Fostering interdisciplinary research for breakthrough science

Empowering and retaining young researchers

COST is not funding research itself,
but pooling resources
and research results
by networking

PROBONO: Physics Goals

PHYSICS

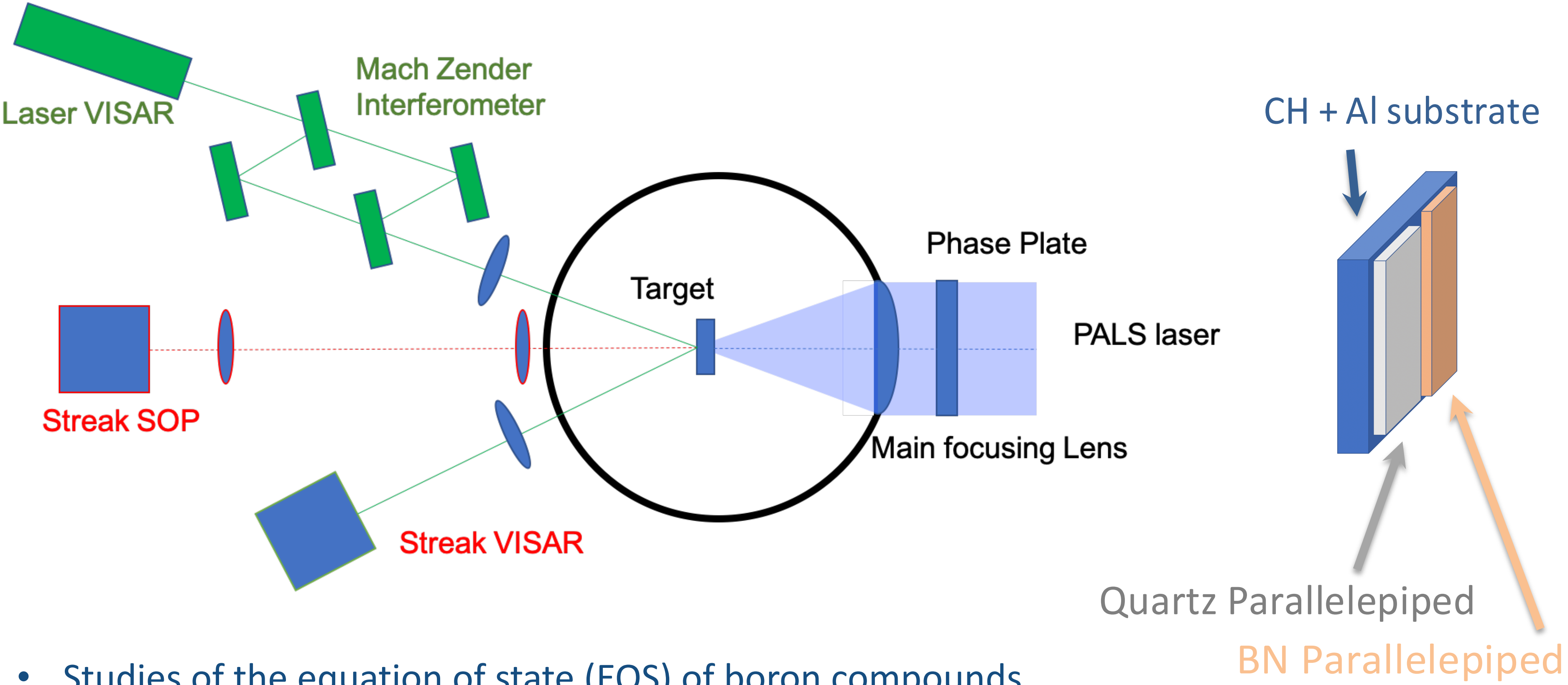
- ✓ Increase of α-particle yield/shot
- ✓ Study possibility of triggering "avalanche" in proton-boron fusion reactions *H.Hora, et al. Matter and Radiation at Extremes 2, 177 (2017)*
- ✓ Consider pB implosion (hybrid approach) (see presentation by Tom Mehlhorn)

  New task - radiation losses very high in hydrogen boron plasma – opacity and EOS measurement needed

- ✓ Exploring laser-driven high-brightness α-particle sources
- ✓ Which will allow:
  - Study the α-particle (ion) stopping power in plasmas *W. Cayzac, et al. NATURE COMMUNICATIONS, 8:15693 (2017)*
  - Study self-heating regime induced by the α-particles generated in fusion *M. Temporal, et al., European Physical Joirnal D, **71**, 132 (2017)*
  - Develop our understanding on low-rate nuclear reactions in plasmas for astrophysical research *M. Gatu Johnson, et al., Physics of Plasmas 24, 041407 (2017)*
  - Develop a compact alternative to standard α-particle sources used to produce radioisotopes

PROBONO: Physics Goals

PALS laser facility at Prague, Czech Republic in 2022



- Studies of the equation of state (EOS) of boron compounds
- SOP and VISAR system
- Accessible pressure range 10-35 Mbar

PROBONO: Simulations

Laser-plasma interaction and Ion acceleration

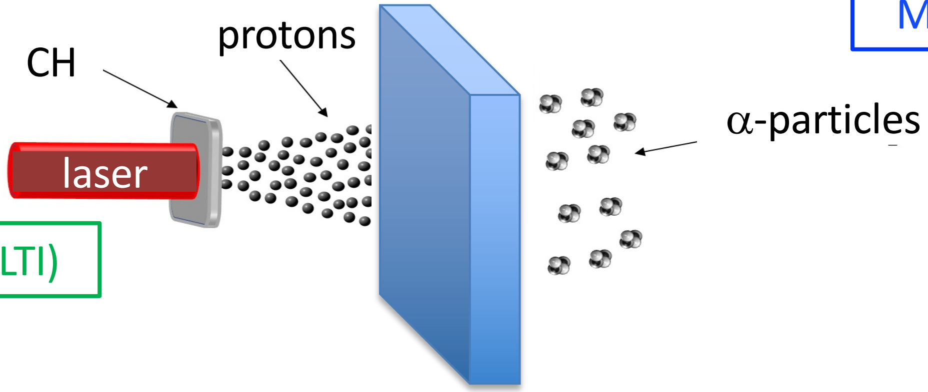
PIC Code (SMILEI)

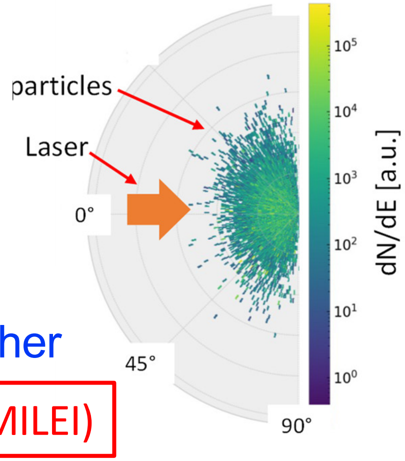
Nuclear reactions and transport

Monte Carlo Code (FLUKA)

ASE - preplasma

Hydro Code (CHIC, MULTI)

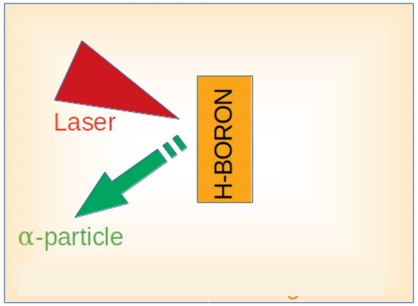




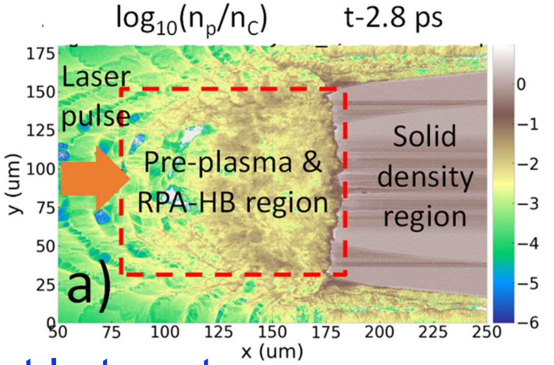
Chain of numerical codes used to simulate the experiment Pitcher-Catcher

ASE - preplasma

Hydro Code (CHIC, MULTI)



PIC Code (SMILEI)



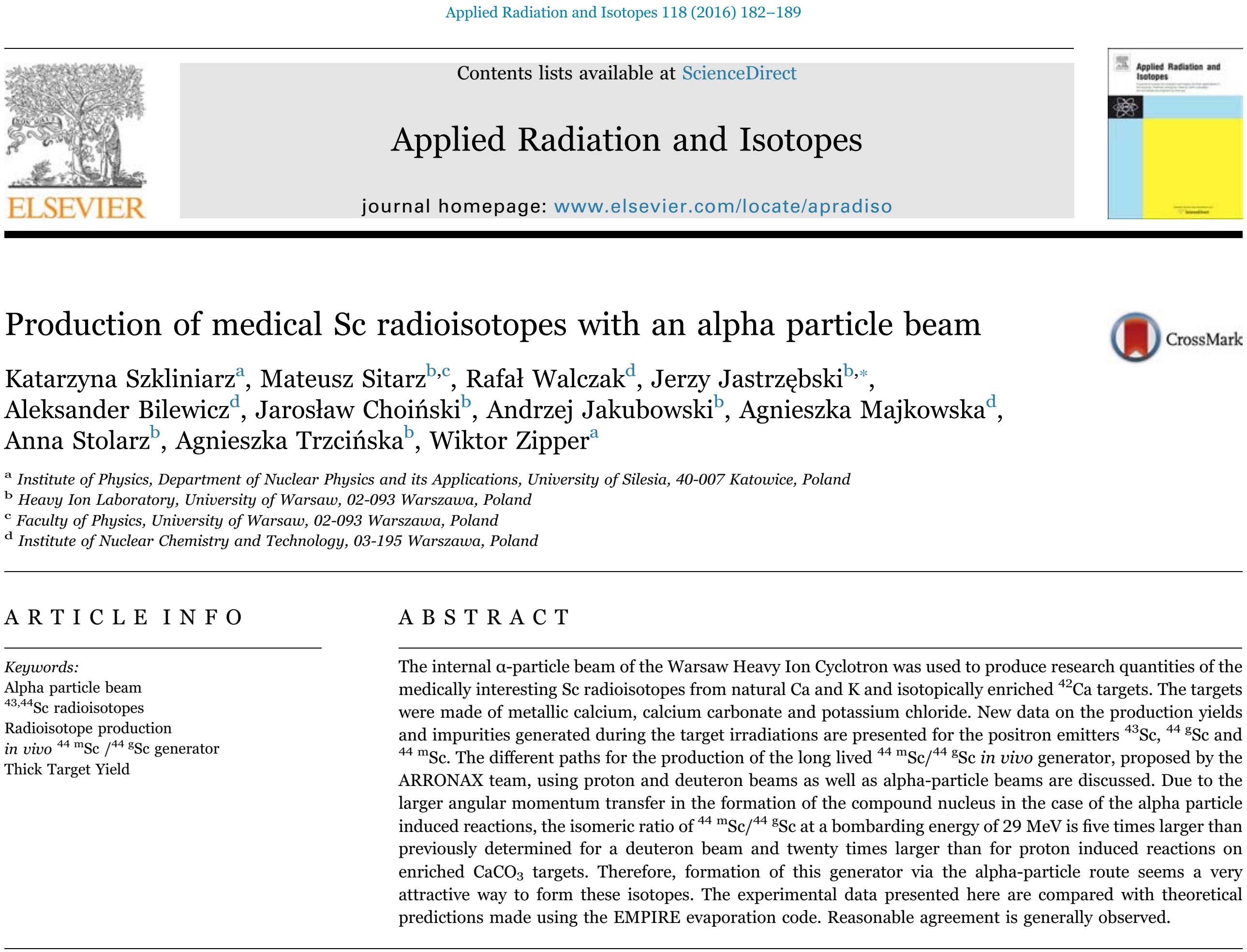
Chain of numerical codes used to simulate the experiment In-target

See presentation by Philippe Nicolaï

Courtesy Ph. Nicolaï

PROBONO: Medical application

- ✓ Perform the first experiments related to the production of radioisotopes, their separation, …



Applied Radiation and Isotopes 118 (2016) 182–189

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journal homepage: www.elsevier.com/locate/apradiso

ELSEVIER

Production of medical Sc radioisotopes with an alpha particle beam

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[d] *Institute of Nuclear Chemistry and Technology, 03-195 Warszawa, Poland*

ARTICLE INFO

Keywords:
Alpha particle beam
^{43,44}Sc radioisotopes
Radioisotope production
in vivo $^{44\,m}$Sc /$^{44\,g}$Sc generator
Thick Target Yield

ABSTRACT

The internal α-particle beam of the Warsaw Heavy Ion Cyclotron was used to produce research quantities of the medically interesting Sc radioisotopes from natural Ca and K and isotopically enriched ^{42}Ca targets. The targets were made of metallic calcium, calcium carbonate and potassium chloride. New data on the production yields and impurities generated during the target irradiations are presented for the positron emitters ^{43}Sc, $^{44\,g}$Sc and $^{44\,m}$Sc. The different paths for the production of the long lived $^{44\,m}$Sc/$^{44\,g}$Sc *in vivo* generator, proposed by the ARRONAX team, using proton and deuteron beams as well as alpha-particle beams are discussed. Due to the larger angular momentum transfer in the formation of the compound nucleus in the case of the alpha particle induced reactions, the isomeric ratio of $^{44\,m}$Sc/$^{44\,g}$Sc at a bombarding energy of 29 MeV is five times larger than previously determined for a deuteron beam and twenty times larger than for proton induced reactions on enriched $CaCO_3$ targets. Therefore, formation of this generator via the alpha-particle route seems a very attractive way to form these isotopes. The experimental data presented here are compared with theoretical predictions made using the EMPIRE evaporation code. Reasonable agreement is generally observed.

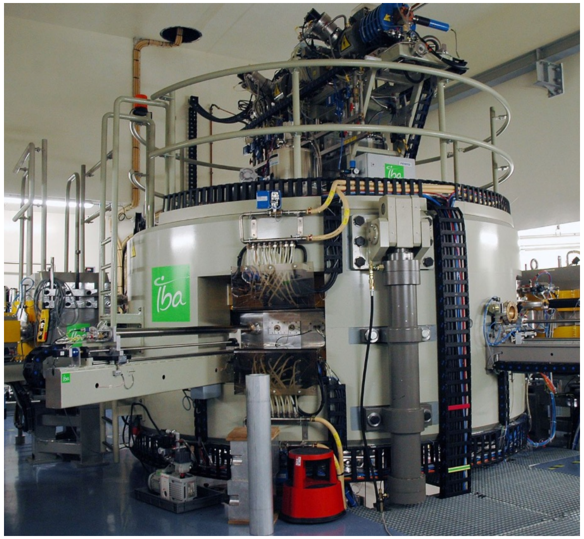
See presentation by Juan Esposito

PROBONO: Medical application

Recently radioisotopes produced by

Large Heavy Ion Cyclotron systems

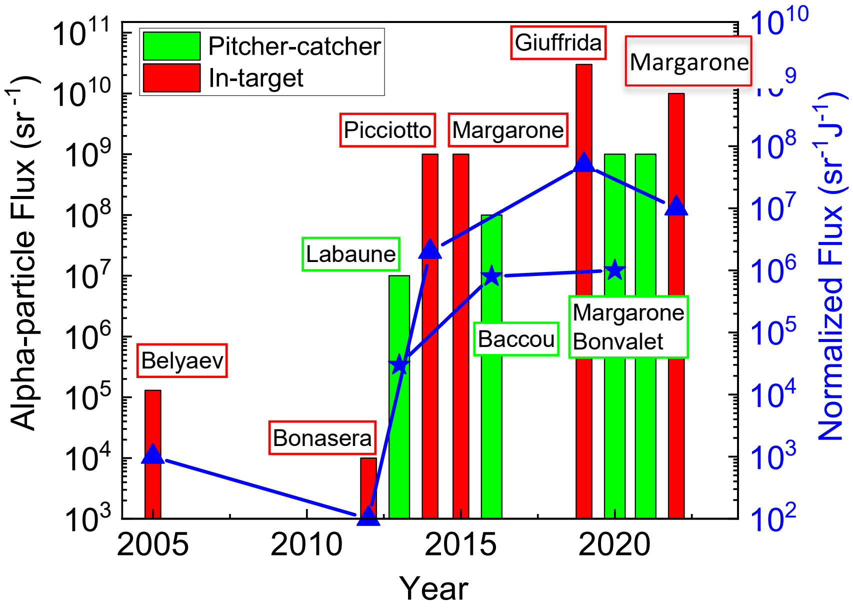
(ARRONAX or U-120M).



10 µA of α-particles ≈ 10^{14} α/s

(for instance, ARRONAX produces 2×375 µA protons but only 70 µA of α-particles)

α-yield achieved in laser experiments



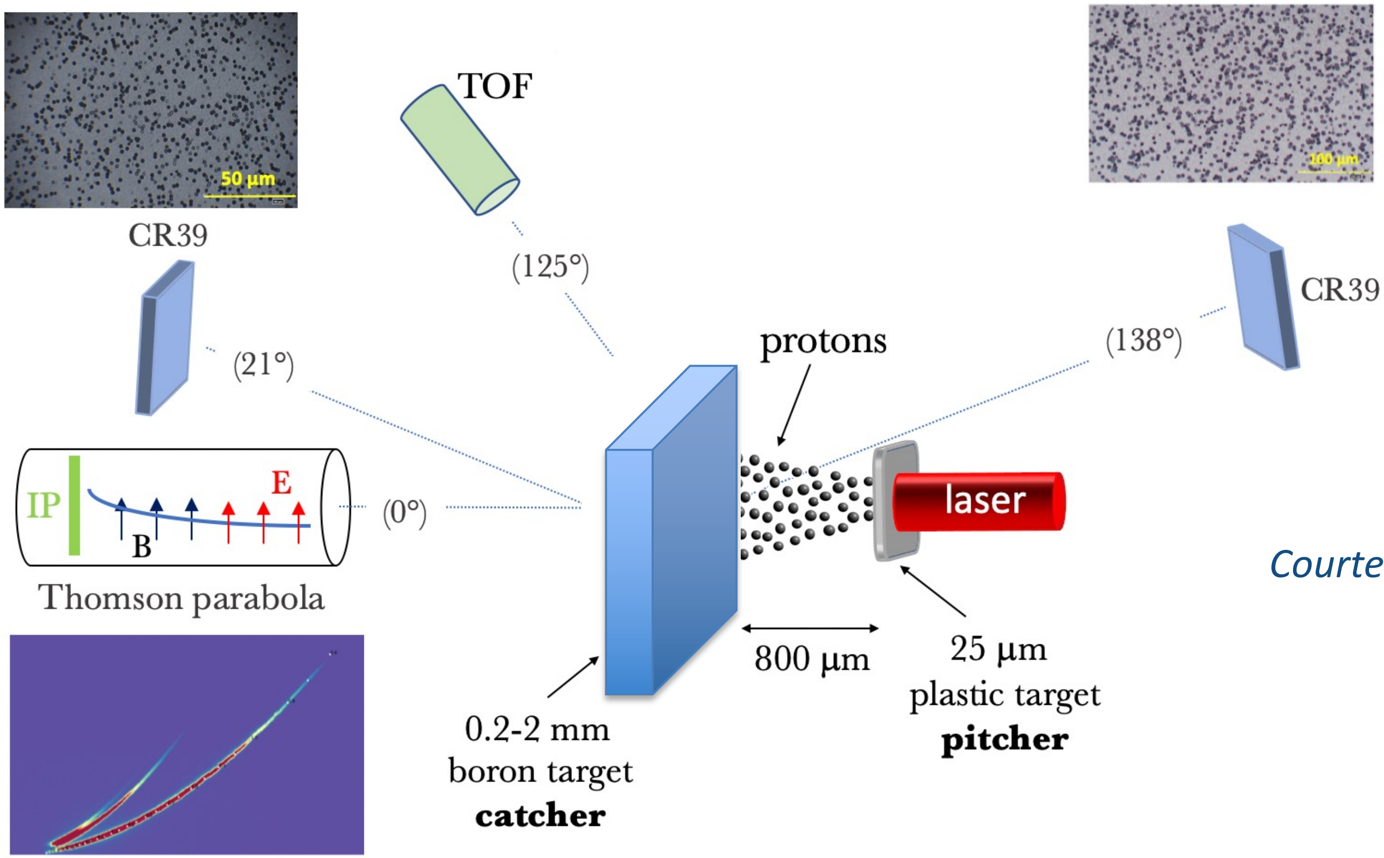
Laser experiments show a maximum of 10^{11} α/sr/shot.

In order to be competitive, we need:

i) use a new generation of 100 Hz laser systems

ii) increase the α-yield of at least 1 order of magnitude

PROBONO: Diagnostics



Courtesy Ph. Nicolai

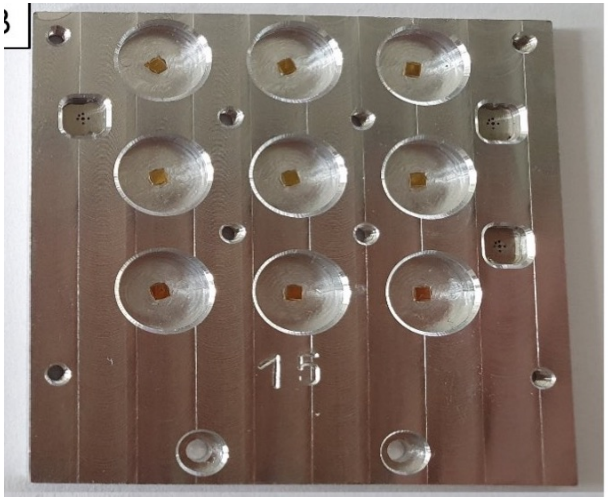
- ✓ Develop new diagnostics for better characterization of α-particle generation
- ✓ Develop high repetition rate (HRR) diagnostics
- ✓ Use new approaches to the analysis of data (i.e. machine learning…)

See presentation by Fabrizio Consoli, Noaz Nissim

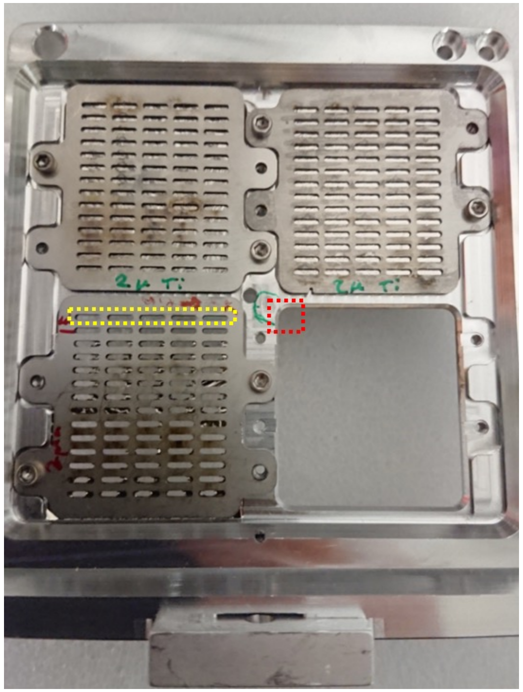
PROBONO: Targetry

TARGETRY

- ✓ Develop new targets increasing α-particle production
- ✓ Develop new holders containing many targets assuring precise positioning easy to align (HRR)
- ✓ Avoiding/shielding target debris after each shot



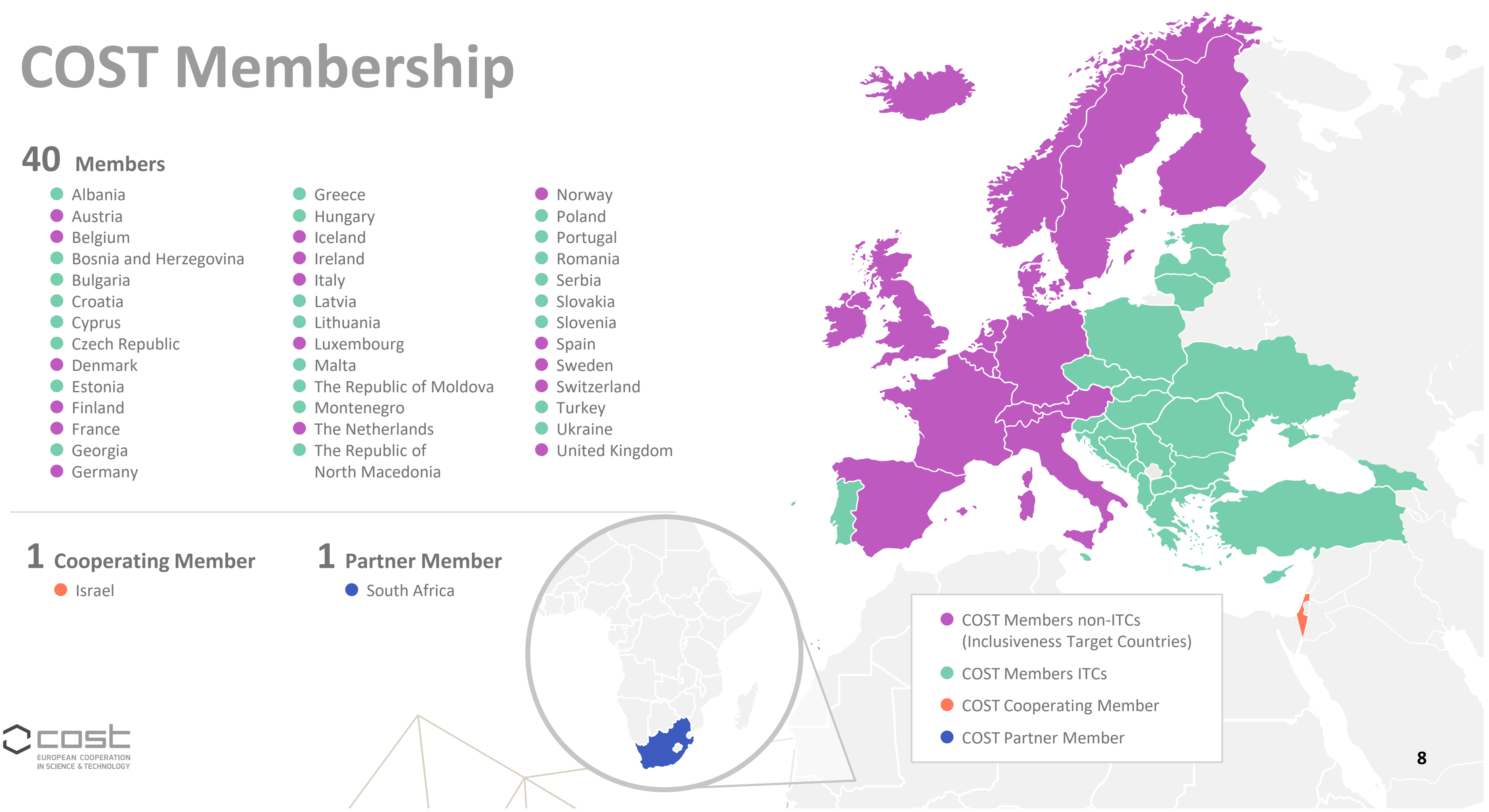
Examples of multiple target holders used at
PALS
CLPU



See presentation by Edmond Turcu, and by Andrey Shukurov

Large collaboration

Large collaboration



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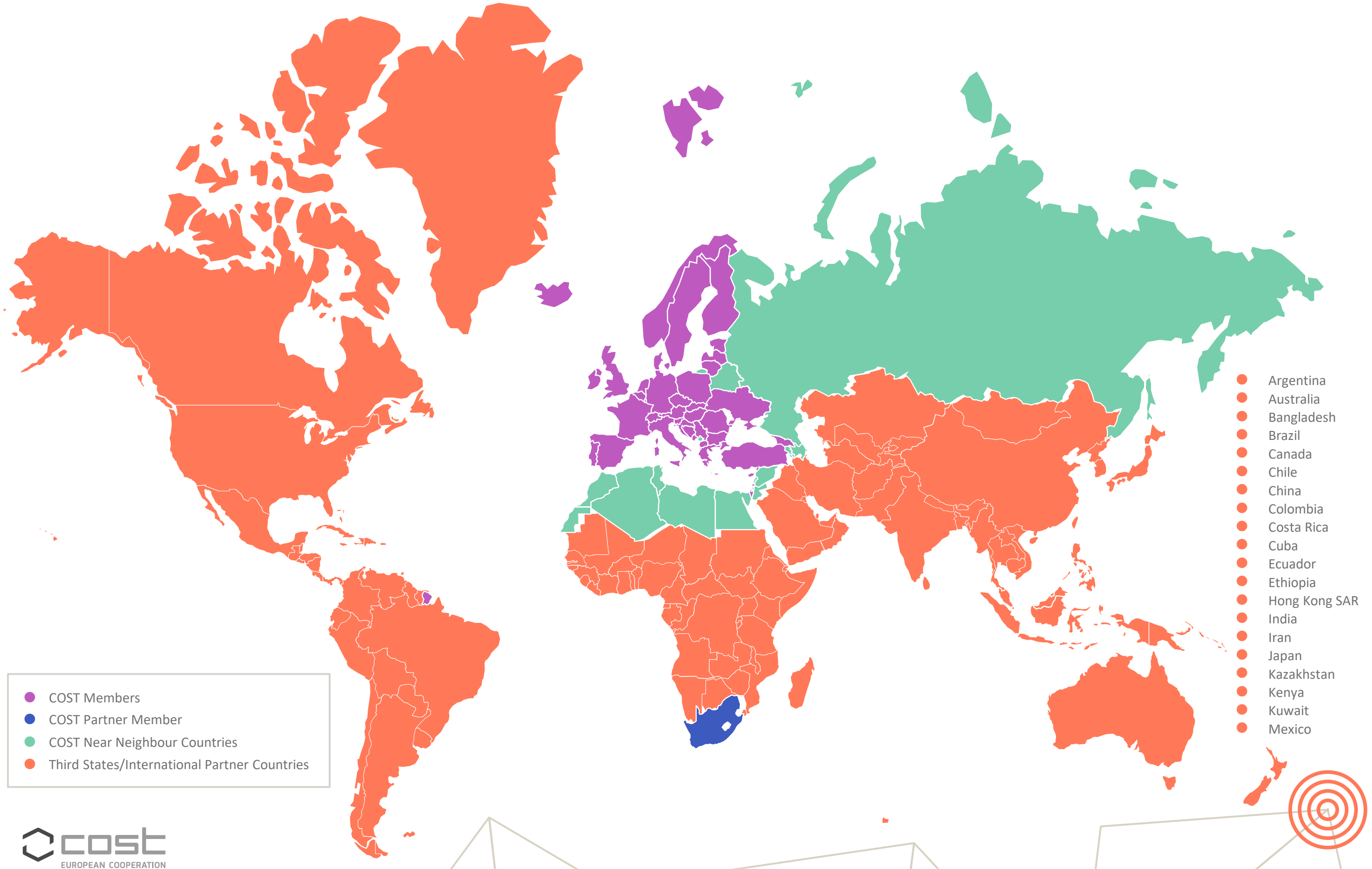
Large collaboration



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●	Kosovo*	36
●	Lebanon	12
●	Morocco	36
●	Palestine**	7
●	Russian Federation	***
●	Syrian Arab Republic	1
●	Tunisia	55

●	Argentina	14	●	Malaysia	2
●	Australia	69	●	Nepal	1
●	Bangladesh	1	●	New Zealand	13
●	Brazil	40	●	Nigeria	3
●	Canada	63	●	Pakistan	2
●	Chile	12	●	Peru	2
●	China	30	●	Republic of Rwanda	1
●	Colombia	11	●	Saudi Arabia	2
●	Costa Rica	5	●	Senegal	1
●	Cuba	1	●	Singapore	10
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●	Iran	8	●	United States	211
●	Japan	47	●	Uruguay	2
●	Kazakhstan	2	●	Uzbekistan	1
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Large collaboration

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"PROton BOron Nuclear fusion: from energy production to medical applicatiOns"

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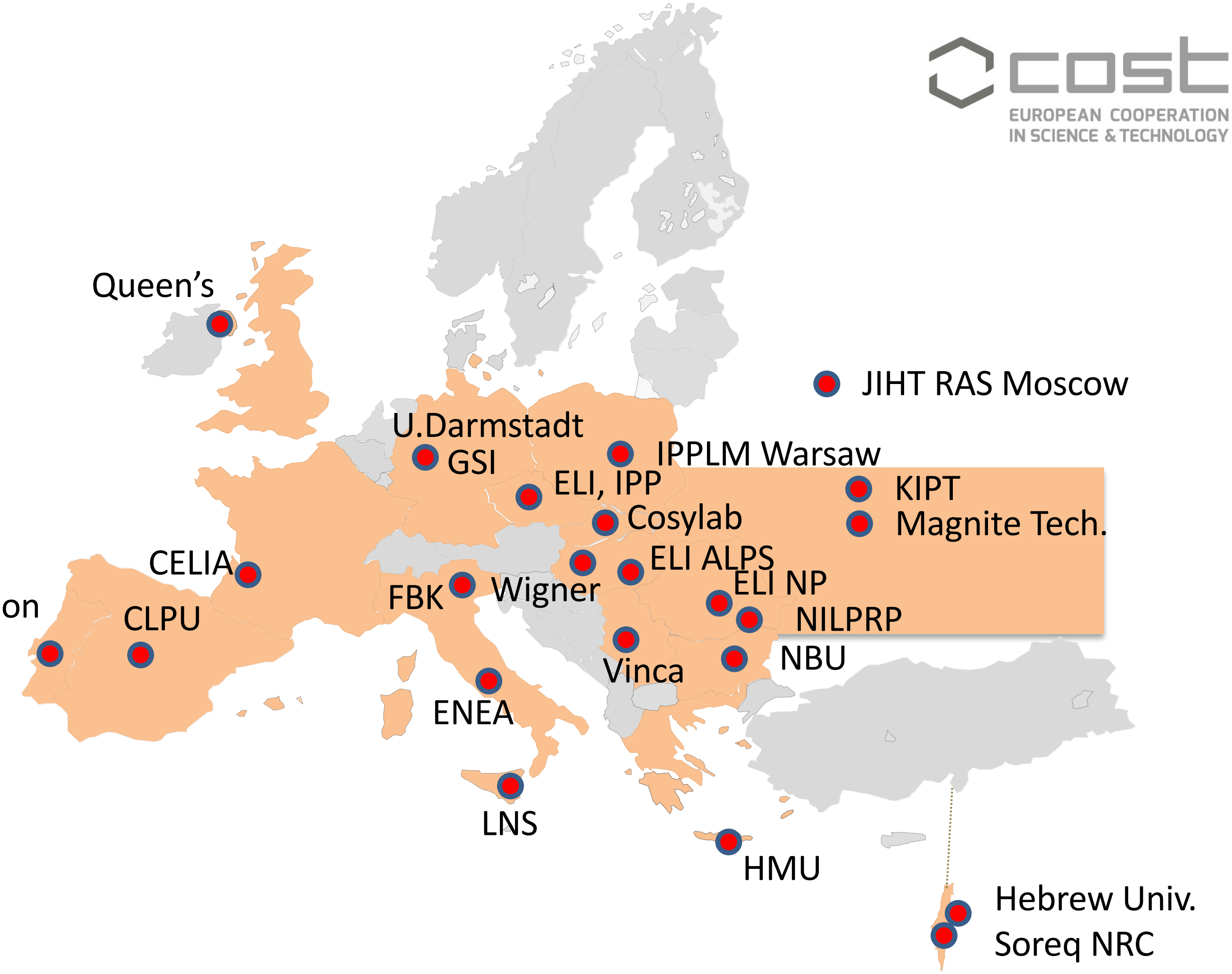
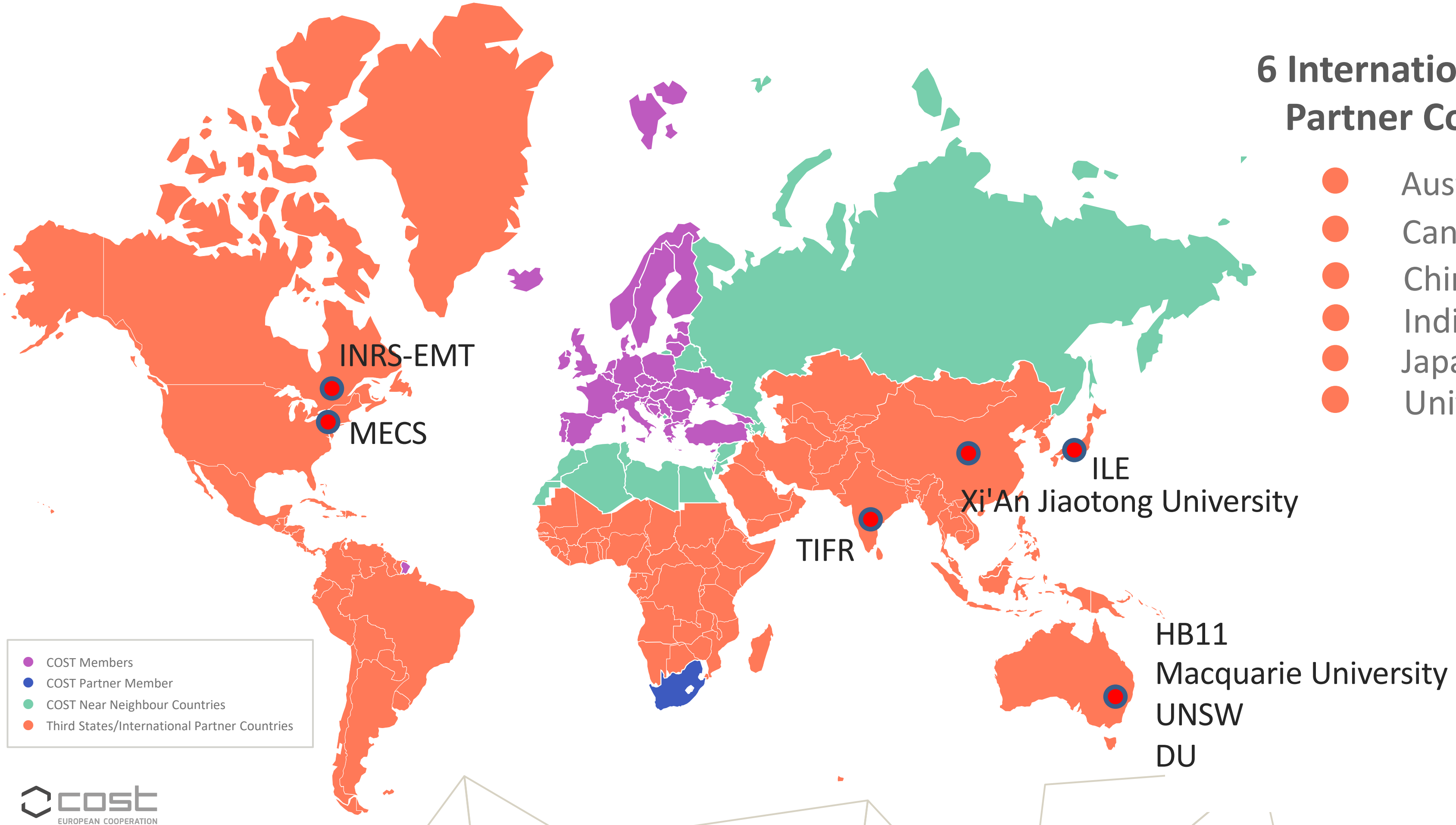


Large collaboration



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Large collaboration

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1 Cooperating member

Israel

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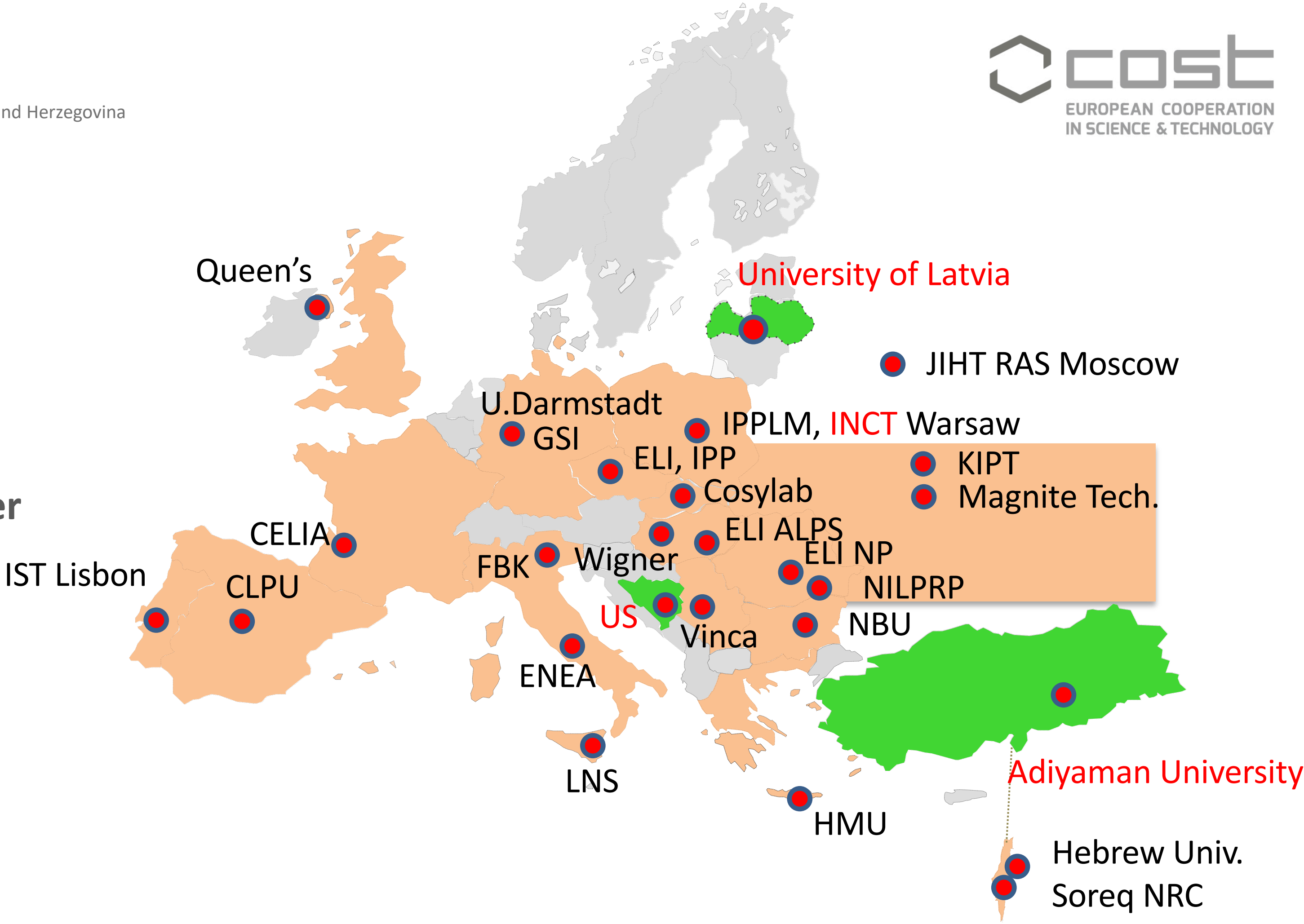
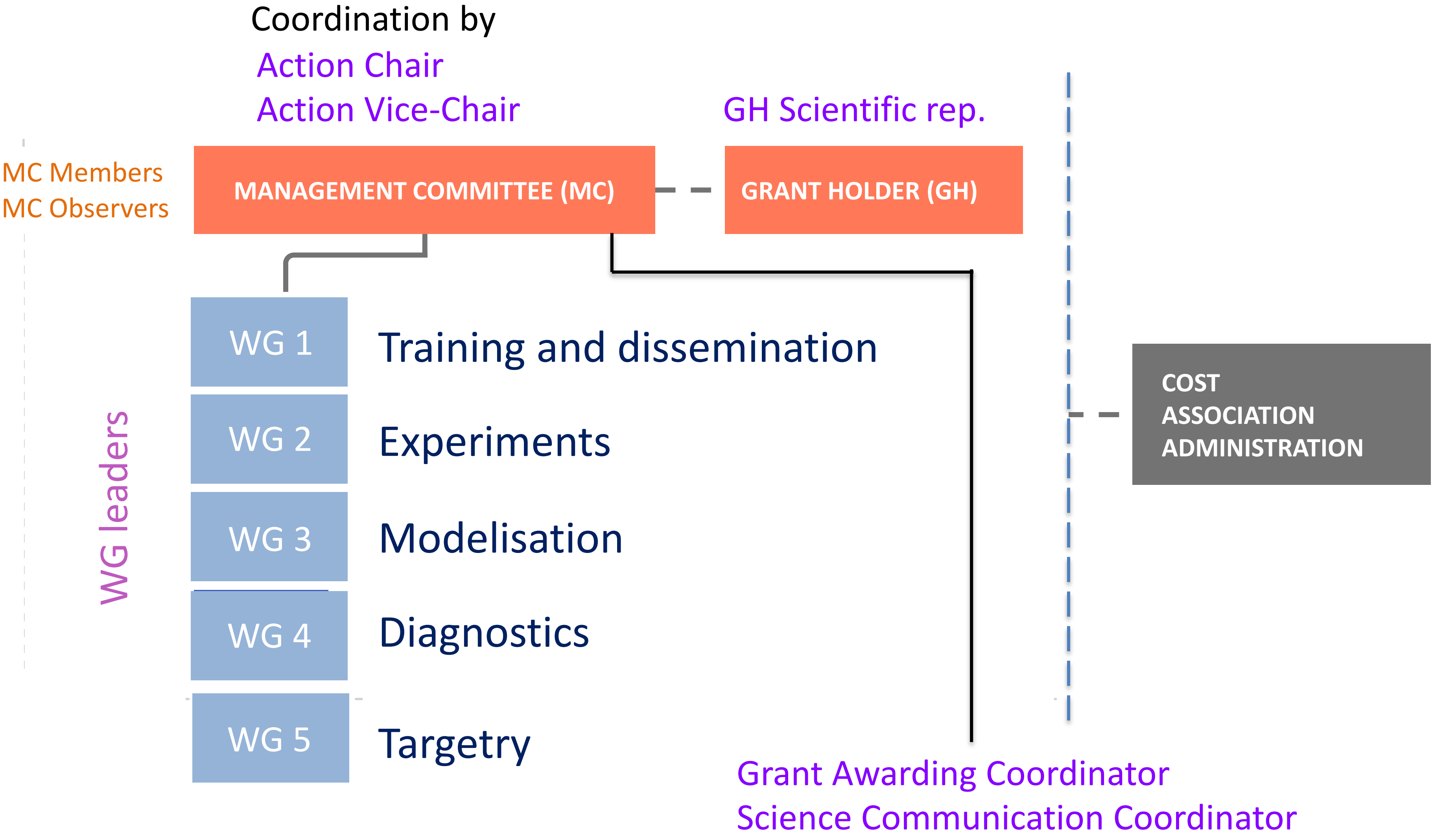


Structure

Structure



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WG 3	Modelisation
WG 4	Diagnostics
WG 5	Targetry

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Structure

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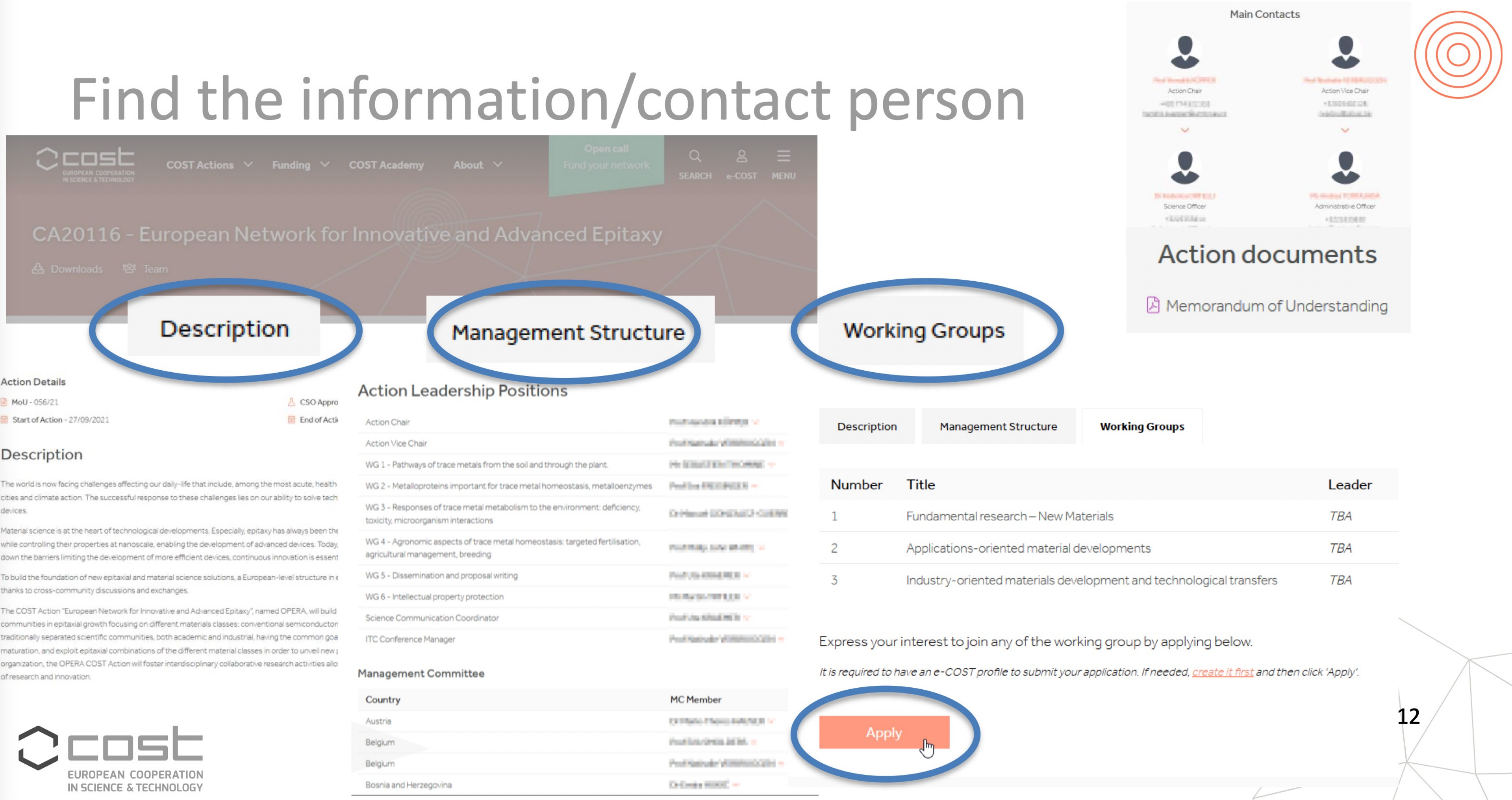


CA20116 - European Network for Innovative and Advanced Epitaxy

Action Details

MoU - 056/21

Start of Action - 27/09/2021

CSO Appro

End of Acti

Description

The world is now facing challenges affecting our daily-life that include, among the most acute, health
cities and climate action. The successful response to these challenges lies on our ability to solve tech
devices.

Material science is at the heart of technological developments. Especially, epitaxy has always been the
while controlling their properties at nanoscale, enabling the development of advanced devices. Today,
down the barriers limiting the development of more efficient devices, continuous innovation is essent

To build the foundation of new epitaxial and material science solutions, a European-level structure in e
thanks to cross-community discussions and exchanges.

The COST Action "European Network for Innovative and Advanced Epitaxy", named OPERA, will build
communities in epitaxial growth focusing on different materials classes: conventional semiconductor
traditionally separated scientific communities, both academic and industrial, having the common goa
maturation, and exploit epitaxial combinations of the different material classes in order to unveil new p
organization, the OPERA COST Action will foster interdisciplinary collaborative research activities allo
of research and innovation.

Action Leadership Positions

Action Chair	[redacted]
Action Vice Chair	[redacted]
WG 1 - Pathways of trace metals from the soil and through the plant.	[redacted]
WG 2 - Metalloproteins important for trace metal homeostasis, metalloenzymes	[redacted]
WG 3 - Responses of trace metal metabolism to the environment: deficiency, toxicity, microorganism interactions	[redacted]
WG 4 - Agronomic aspects of trace metal homeostasis: targeted fertilisation, agricultural management, breeding	[redacted]
WG 5 - Dissemination and proposal writing	[redacted]
WG 6 - Intellectual property protection	[redacted]
Science Communication Coordinator	[redacted]
ITC Conference Manager	[redacted]

Management Committee

Country	MC Member
Austria	[redacted]
Belgium	[redacted]
Belgium	[redacted]
Bosnia and Herzegovina	[redacted]

Main Contacts

[redacted]
Action Chair
[redacted]

[redacted]
Action Vice Chair
[redacted]

[redacted]
Science Officer
[redacted]

[redacted]
Administrative Officer
[redacted]

Action documents

Memorandum of Understanding

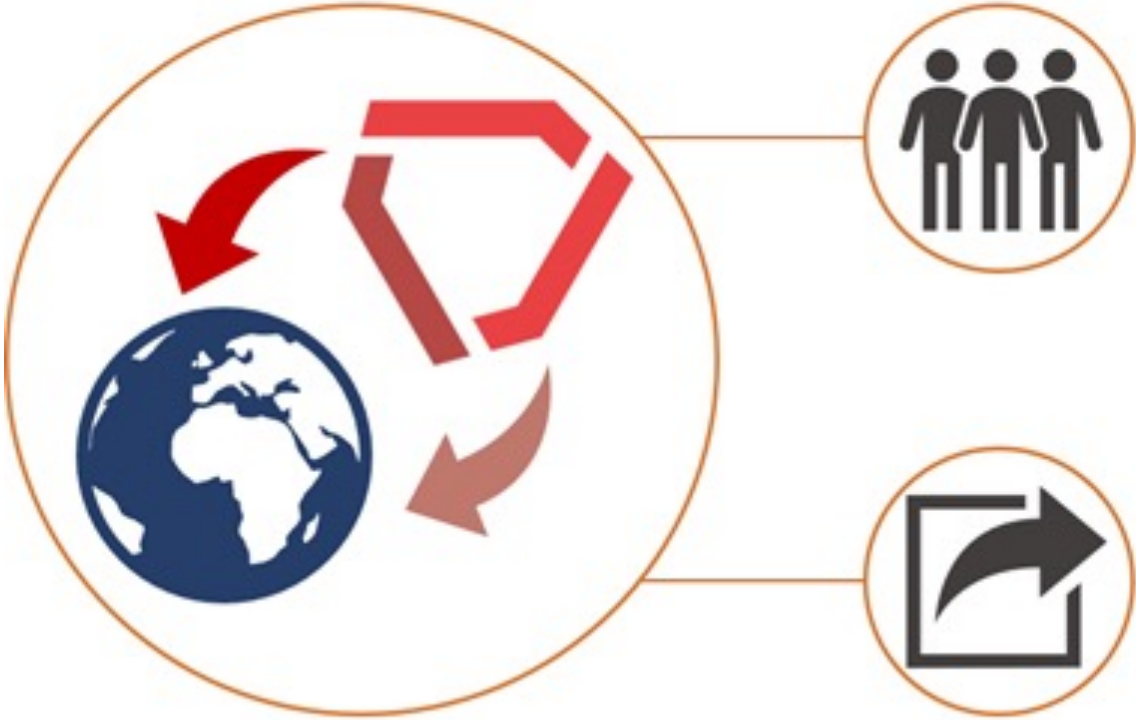
Number	Title	Leader
1	Fundamental research – New Materials	*TBA*
2	Applications-oriented material developments	*TBA*
3	Industry-oriented materials development and technological transfers	*TBA*

Express your interest to join any of the working group by applying below.

It is required to have an e-COST profile to submit your application. If needed, create it first and then click 'Apply'.

https://www.cost.eu/actions/CA21128

Training and Dissemination



TARGET PUBLIC

- ✓ Researchers
- ✓ Industry
- ✓ Citizens
- ✓ Politicians

MEANS and MATERIAL

- ✓ Scientific papers,
- ✓ Workshops,
- ✓ Seminars
- ✓ Informative videos,
- ✓ Press releases,
- ✓ Website,
- ✓ Profiles in social media

PROBONO: Aims

CAPACITY BULDING

- ✓ Exchange of knowledge and building collaborations
- ✓ Facilitating access to large laser facilities
- ✓ Fostering opportunities for training and boosting the careers of young researchers, involving underrepresented groups, gender, and researchers from countries/regions with less capacity or support in the field.

Facilities

Laser Installations

- ✓ Prague Asterix Laser System (PALS) in Czech Republic
- ✓ LFEX laser facility at the University of Osaka in Japan
- ✓ VEGA at CLPU (Centro de Láseres Pulsados) in Spain
- ✓ LOA and CELIA laboratories in France
- ✓ Vulcan facility at Rutherford Appleton Laboratory in the UK
- ✓ TARANIS laser at Queens University Belfast (UK),
- ✓ PHELIX laser at GSI Darmstadt (Germany),
- ✓ ABC laser at ENEA Centro Ricerche Frascati (Italy),
- ✓ Zeus laser facility at HMU/IPPL in Greece
- ✓ Extreme Light Infrastructure (ELI) in Hungary, Romania and the Czech Republic

These systems differ in energies, peak intensity, pulse duration, so that the researchers will be able to access different plasma regimes. Also, they offer various diagnostics, probing capabilities and repetition rate regimes.

Laser Parameters

CENTRO DE LÁSERES PULSADOS

CLPU VEGA II LASER (Ti:Sa) 100 TW

- ✓ E = 3 J
- ✓ 10 Hz
- ✓ τ = 30 fs
- ✓ λ = 810 nm
- ✓ spot ≤ 10 μm
- ✓ I ~ 10^{20} W/cm^2
- ✓ Contrast 3 10^{-10}

CLPU VEGA III LASER (Ti:Sa) 1 PW

Laser Parameters

FZU Institute of Physics of the Czech Academy of Sciences

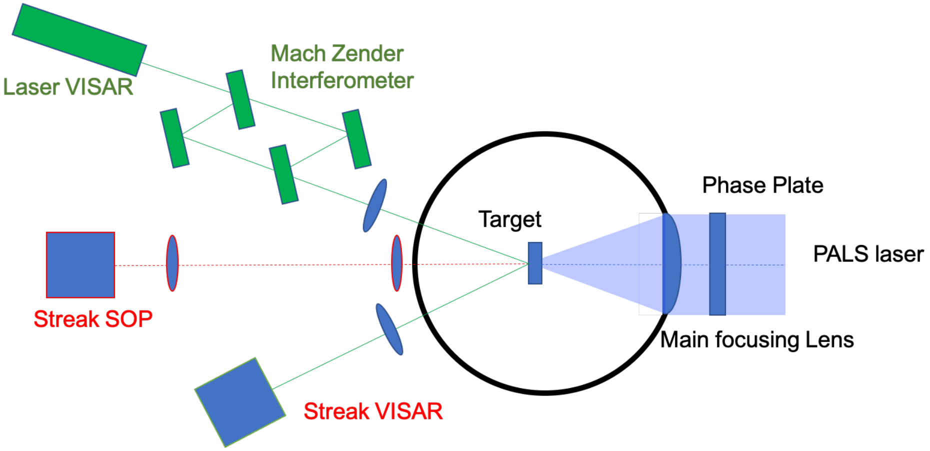
IPP INSTITUTE OF PLASMA PHYSICS OF THE CZECH ACADEMY OF SCIENCES

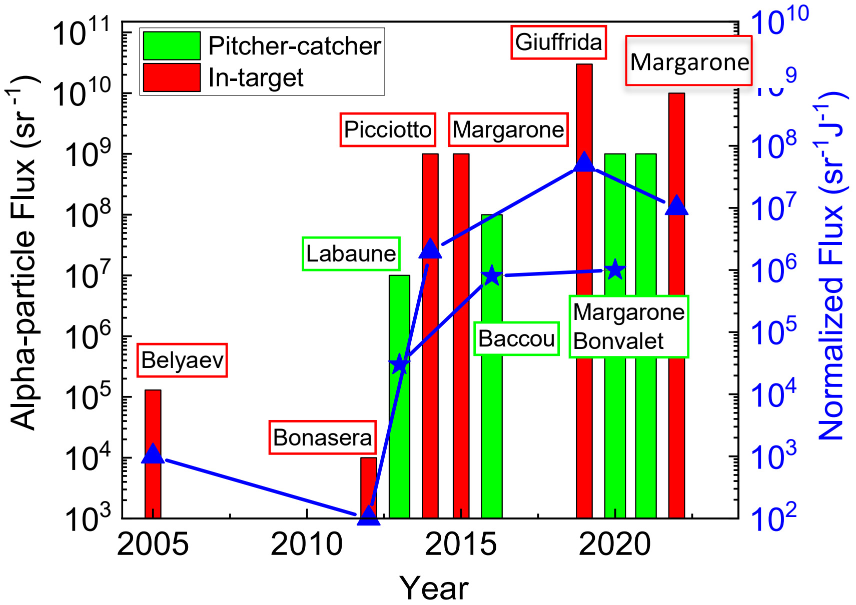
The PALS Iodine Laser

- ✓ $\lambda = 1.3\ \mu m$
- ✓ $\tau = 300$ ps
- ✓ E = 1500 J
- ✓ 3ω $\lambda = 0.44\ \mu m$ $E \leq 500$ J

PROBONO: Physics Goals

PALS laser facility at Prague, Czech Republic in 2022



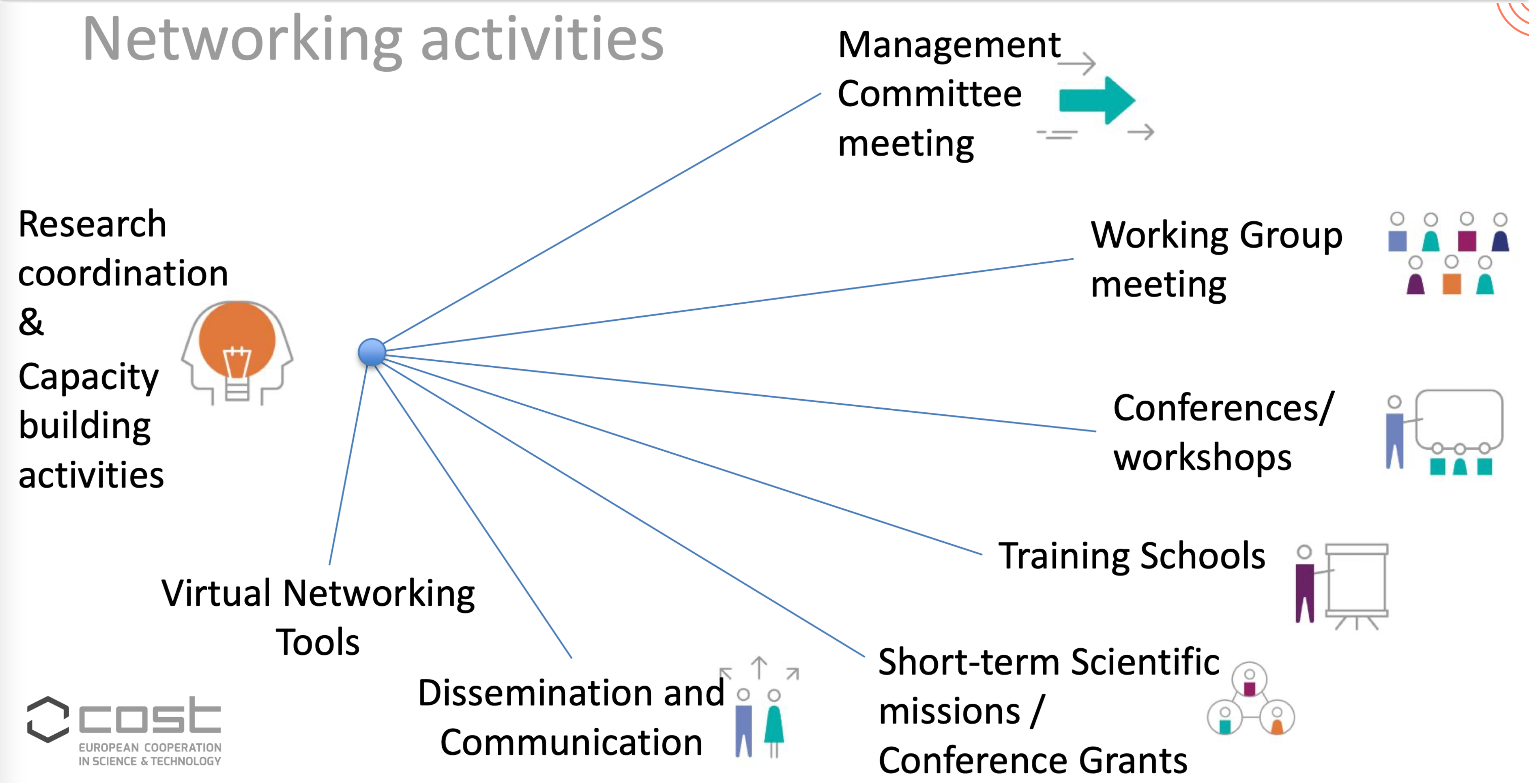


Studies of the Equation Of State (EOS)

Laser experiments show a maximum of 10^{11} α/sr/shot.

Benefits

Benefits



Networking activities

Research coordination & Capacity building activities

Management Committee meeting

Working Group meeting

Conferences/ workshops

Training Schools

Short-term Scientific missions / Conference Grants

Dissemination and Communication

Virtual Networking Tools

COST
EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Conclusions

- ✓ The COST project PROBONO is a first opportunity to structure the reserach on proton boron fusion and its application at he European (and international) level.
- ✓ It is a good framework for collaboration of academic reserach groups with the industries and companies:
  - ✓ Those working on lasers (e.g. Thales), targetry and diagnostics (e.g. SourceLab)
  - ✓ Those addressing research in Fusion (e.g. HB11, …)
- ✓ Participation is open to all interested research groups (application via website)

https://www.cost.eu/actions/CA21128

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Thank you!