R&D di acceleratori per applicazioni energetiche ai LNS

Giuseppe Torrisi, INFN-LNS

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Sud

Workshop Transizione Energetica (INFN-E e INFN-A)
21–22 Feb 2024
INFN Laboratori Nazionali del Sud

MAIN TOPICS COLLECTED [and reference experiments]

1. **New Acceleration schemes @LNS**

2. **Magnetic plasma-Ion Sources for ADS and plasma-traps for fusion**

3. **Laser-cluster scenario and Polarized nuclear fusion fuel**

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1. New Acceleration schemes @LNS

- **Laser-driven plasma-based acceleration** (e-, Ions) **and nuclear reactions** *(*activation, transmutation, fission and fusion processes) based on laser-matter interaction → *[I-LUCE (INFN—Laser-Induced particle acceleration) facility 100-TW-class laser (fs, 1–10 Hz, I ≥ 10^{19} W/cm^2)*]:
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  2) Ion acceleration by **Target Normal Sheath Acceleration (TNSA)** at above 1–10 MeV/nucleon, sufficient to penetrate into the nucleus of many light atoms enabling studies on:

  - *Proton–boron fusion reaction in plasma:* for future advanced fusion ignition schemes and for laser-driven α particles sources;
  - *Stopping power in warm dense matter:* important issue/property in *Inertial Confinement Fusion (ICF*) implosion study and design *[FUSION_GrV, SAMOTHRACE WP1]*.
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- **Micro-glass capillaries for μ-Beam irradiation** and analysis of *fusion plasma-facing materials and components [SAMOTHRACE WP2]*

2. Magnetic plasma-Ion Sources and plasma-traps

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3. Laser-cluster scenario and Polarized nuclear fusion fuel:

- **The Coulomb Explosion Paradigma** for the enhancement in the yield of reaction products *[ASFIN]*
- Innovative sources and systems, theory and experiments for fusion from polarized nuclei *[VALAR]*

SAMOTHRACE: the ECOSYSTEM

SiciliAn Micro and nanO TecHnology Research and innovAtion Center

Samothrace Ecosystem: The Structure

HUB
UNICT (proposer) UNIME CREA UNIPA UNIKORE PSTS
INFN EMBLEMA CNR DTMNS EHT EDG
IOR TOPNETWORK Stlab Quantumleap UPCM.Italy

SPOKE1
ITM3
UNICT (proposer)
CREA UNIKORE

SPOKE2
ADSes
UNIMe
FBK

SPOKE3
S2-COMMs
UNIPA
UNIKORE

SPOKE4 -
MiSteRi
CNR
Stlab LPE
INGV

SPOKE5
MADE4IS
INFN
UNICT UNIPA

SPOKE6 –
MICTEx
STM

SPOKE7 – I3
MI ENG
PEV Bcame RainShow
TopNet EHT Xenia

SPOKE8 -MedTex
UPCM
IOR ETH ENG
EDG AMED BCame

SPOKE9 - R21
QuantumLeap
UNIKORE UNICT
UNIPA UNIME

28 partners

4 Universities
6 Research institutes
4 Large companies
11 PMEs
3 Innovation expert partners

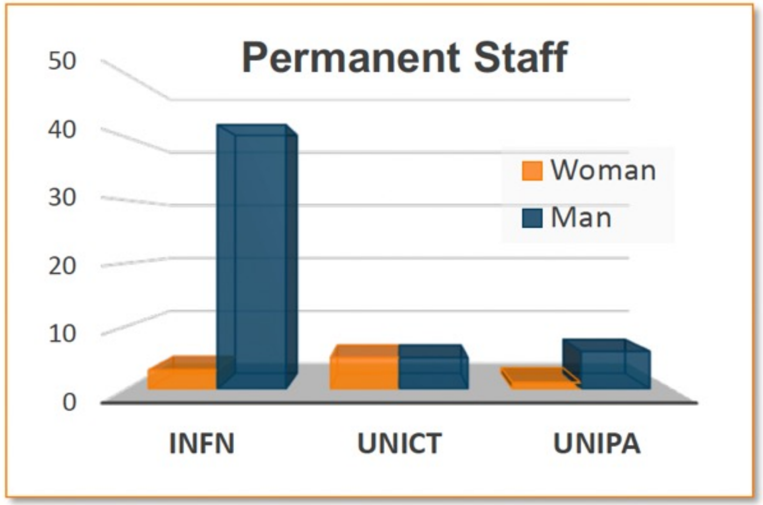
Samothrace Ecosystem at a glance

- 18 Founders → Fondazione Samothrace
- 9 Spokes leaders + 16 affiliates (25 Partners)
- MUR Approved total costs → 138.035.683 €
- PNRR-MUR Contribution → 119.000.000 €
- Start date 10/2022
- Expiration date 30/9/2025 (3 years)
- Total exposed Researchers ytd 980 (28 legal entities)

SPOKE 5 - MADE4IS

S. Tudisco, INFN

Affiliated Partner



Open Positions

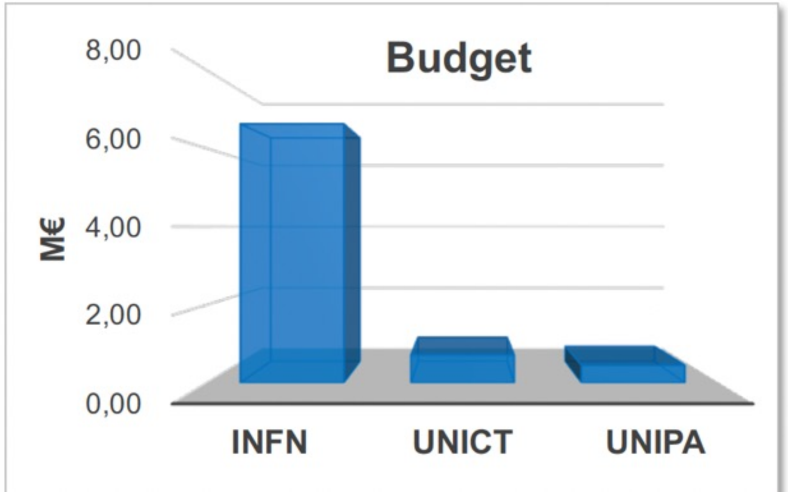
Contracts
INFN - n°5 technologists
UniCT-DFA – n°2 RTDa
UniPa-DiFC – n°1 RTDa

Students
UniCT-DFA – n°2 PhD
UniPa-DiFC – n°2 PhD

SPOKEs Transversal Actions

INFN

UniCT IMM-CNR STM LPE



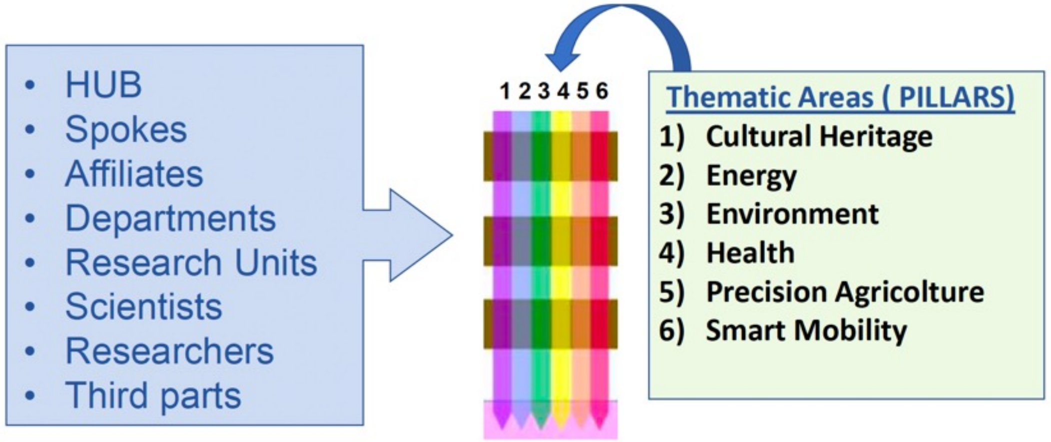
PILLAR ENERGY

INFN-LNS/Energy

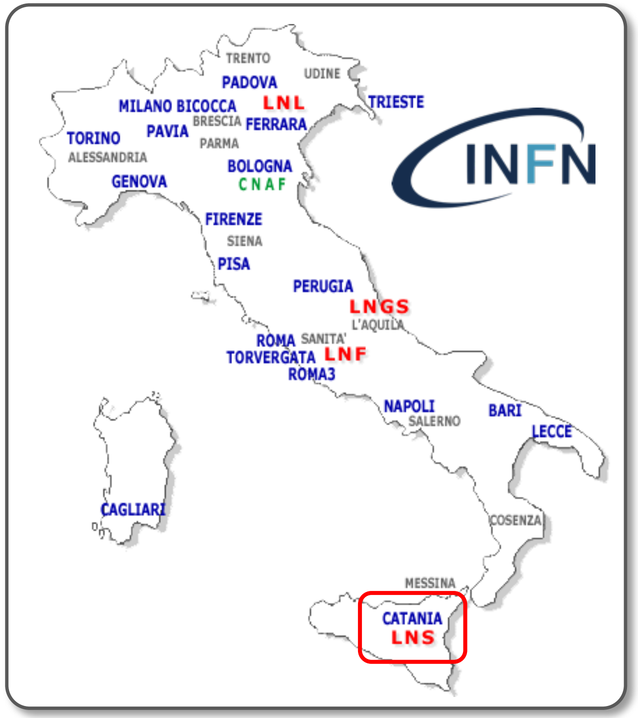
TOPIC-AREA: ***Devices for production/conversion of energy from renewables source***
Devices and diagnostics sensors for fusion energy

Pillar	Coordinators	Affiliation
Health	Sabrina Conoci, Cesare Scardulla,	UNIME UPMC
Smart Agriculture	Sebania Libertino Simona Consoli	CNR UNICT
Smart Mobility	Gaetano Palumbo Filippo di Giovanni (Antonio Imbruglia)	UNICT STMicroelectronics
Energy	David Mascali Alessandra Alberti	INFN CNR
Environment	Francesca D'Anna Giuliana Impellizzeri	UNIPA CNR
Cultural Heritage	Anna Gueli Delia Chillura Martino	UNICT UNIPA
Route2Innovation	Francesca Tosato Filippo D'Arpa Sebastiano Distefano (Francesco Cappello)	Quantum Leap DTMNS PSTS PSTS

Samothrace Ecosystem:
➡ reconcile Hierarchical Structure with Thematic areas



Spoke 5 organization



Partners

- UniPA
- UniCT

Work package

- WP1. **Micro accelerators** for Health and **Energy**
- WP2. **Micro e Nano beams** for Health and **Energy**
- WP3. **Photodetectors and digital ACQ** for Environment, Agritech, Health
- WP4. **Detectors** for particle therapy, Health
- WP5. **Diagnostics and technologies** for Fusion Power, **Energy**

Transversal collaborations

SPOKE5 → **IMM-CNR**, **STM**, **LPE**

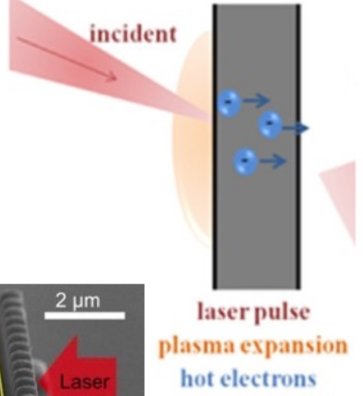
SiciliAn Micro and nanO TecHnology Research and innovAtion Center

Work Packages

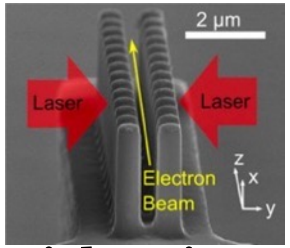
Micro Accelerators

Laser Plasma Acceleration

LP



DL

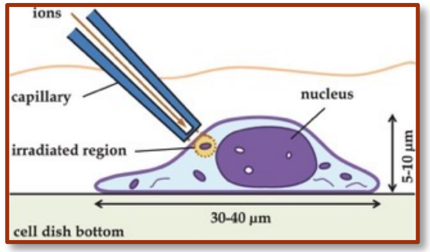


Dielectric Laser Acceleration

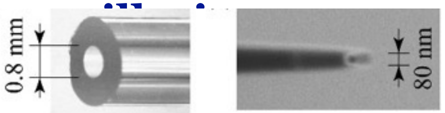
WP1

G.A.P. Cirrone - INFN

Micro/Nano Beam Lines



Micro-Nano

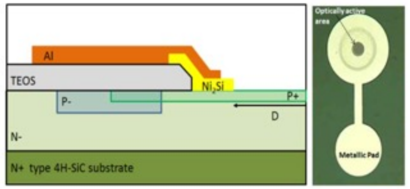


Micro and nanobeams, protons/light ions in the keV/MeV range

WP2

G. Cosentino - INFN

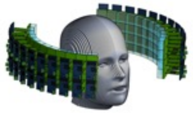
Photodetectors

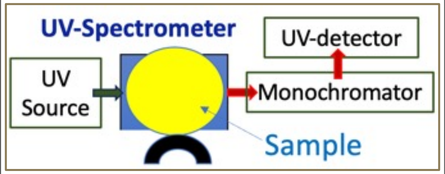


SiC-APD UV sensors

SiPM => SiCPM

ToF-PET





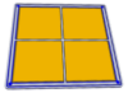
WP3

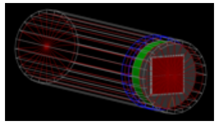
A. Tricomi - INFN
S. Albergo - UNICT
G. Marsella - UNIPA

Particle Detectors

- ✓**Dosimeters**
- ✓**Micro-dosimeters**
- ✓...
- ✓beam-monitors
- ✓Imaging devices

SiC devices



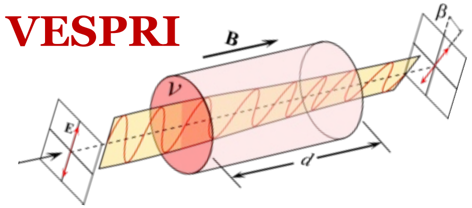


WP4

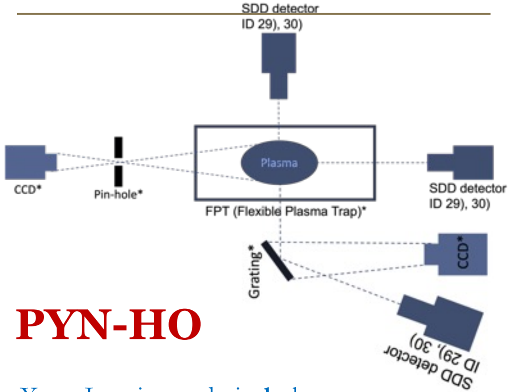
G. Cardella - INFN
E. Geraci - UNICT
M. Marrale - UNIPA

Diagnostics for Fusion

VESPRI



mm-wave polarimeter



PYN-HO

X-ray Imaging and pin-hole Spectrometer

WP5

D. Mascali - INFN

INFN
UniPA
UniCT

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- **Innovative sources and systems, theory and experiments for fusion from polarized nuclei**

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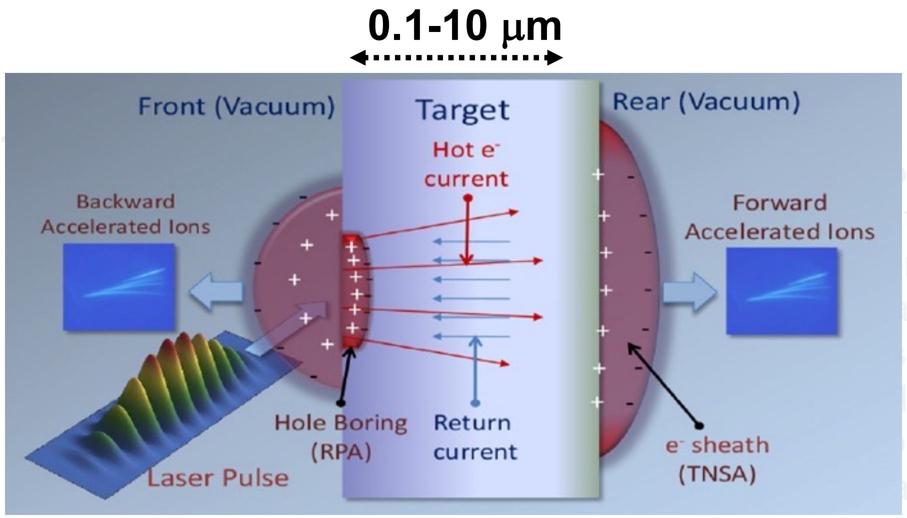
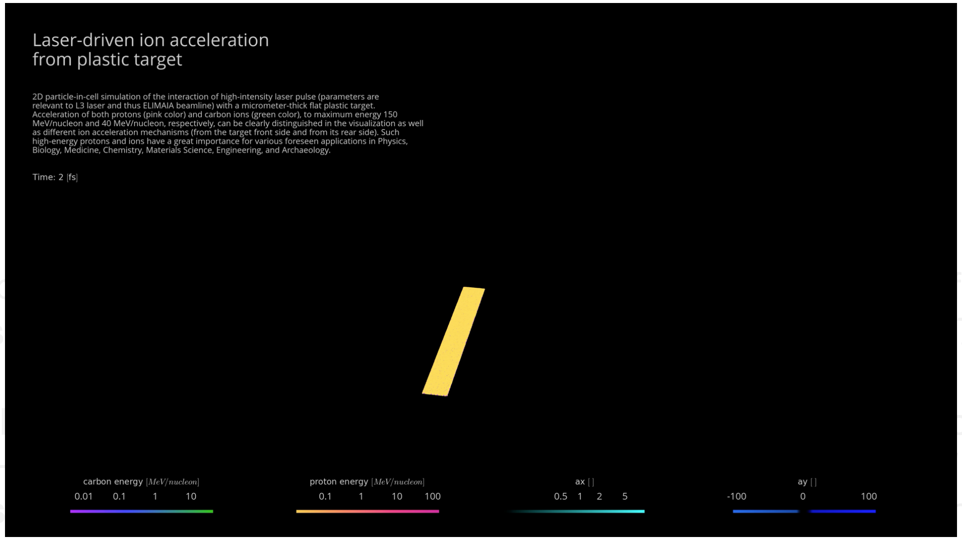
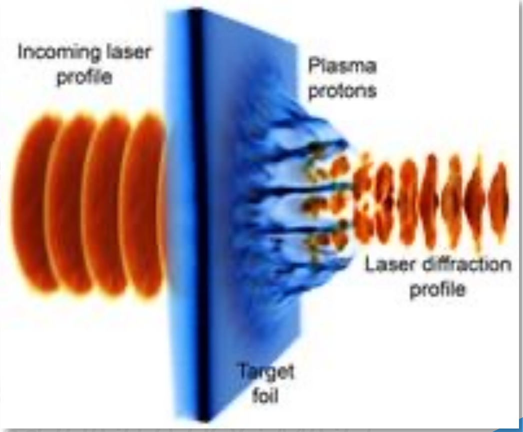
Laser-driven ion acceleration



The **energy gain** for ions in a laser-plasma accelerator is of **several tens of MeV/μm** (just few tens of MeV/m in conventional accelerators due to breakdown effects)





Protons and ions (up to 100 MeV), electrons (up to 8 GeV), gammas, neutrons

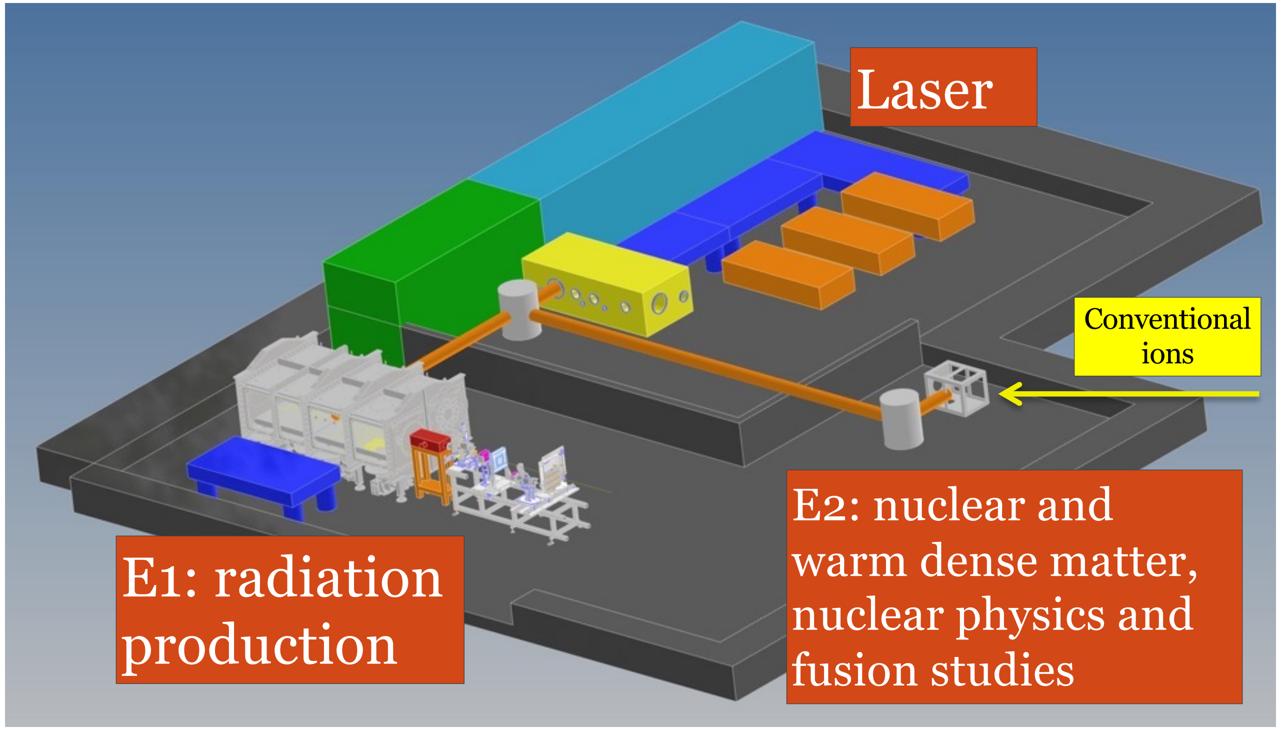
I-LUCE - INFN - Laser indUCEd radiation production

An high-power (up to 0.5 PW), ultra-short (down to 23 fs) Ti:Sa laser will provide two laser outputs

- 45TW/23fs/10Hz
- 0.5PW/23fs/3Hz

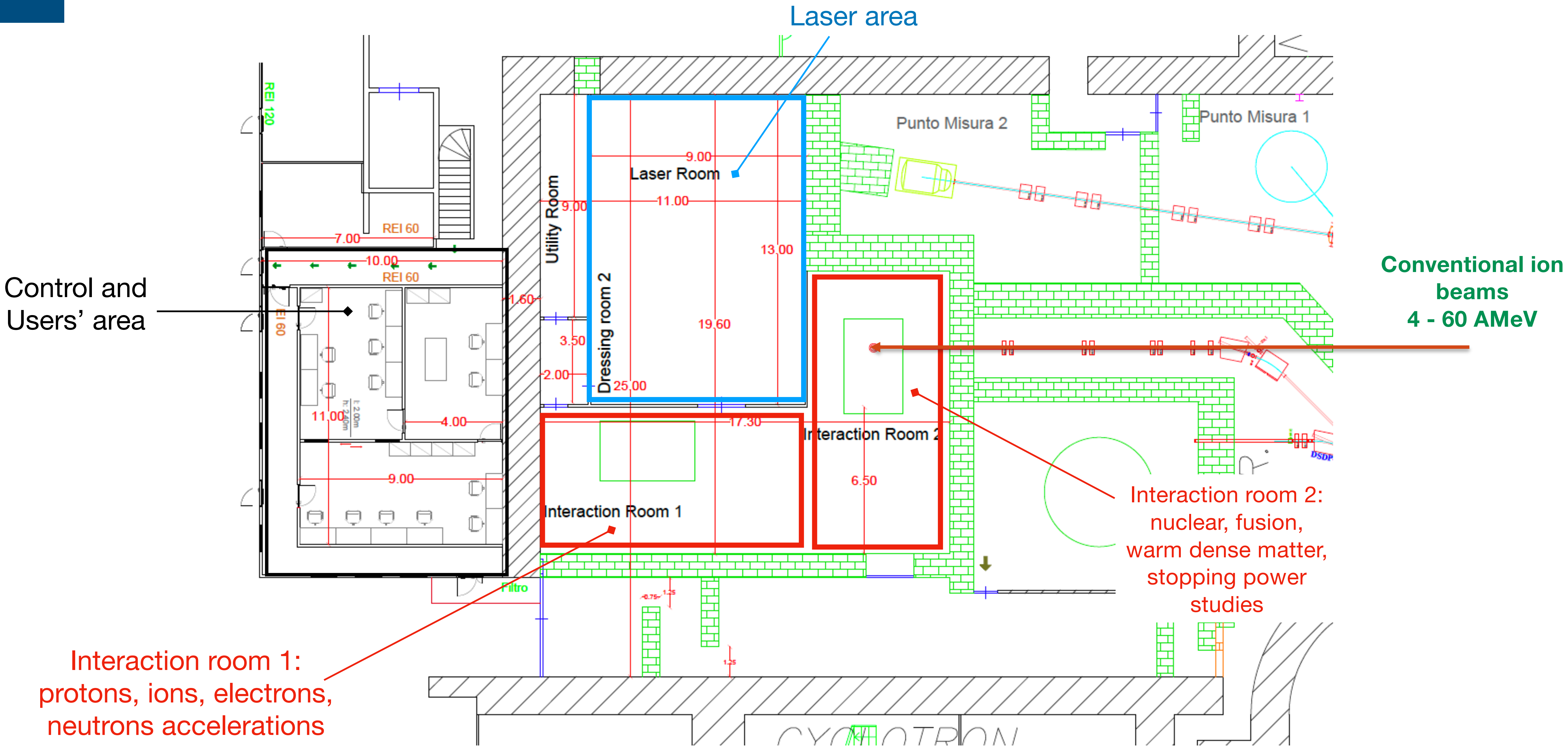
Pulse duration can be scaled down to 500fs (with compressor) and ns scale level with a consequently variation on laser intensity

Lasers will be directed towards two different experimental areas E1 and E2

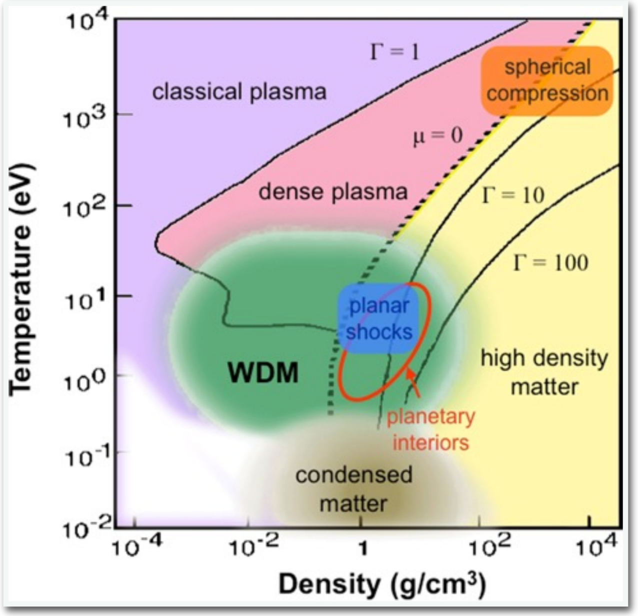


Laser/plasma and ions: world almost unique environment

I-LUCE layout



An irradiation point for fusion studies

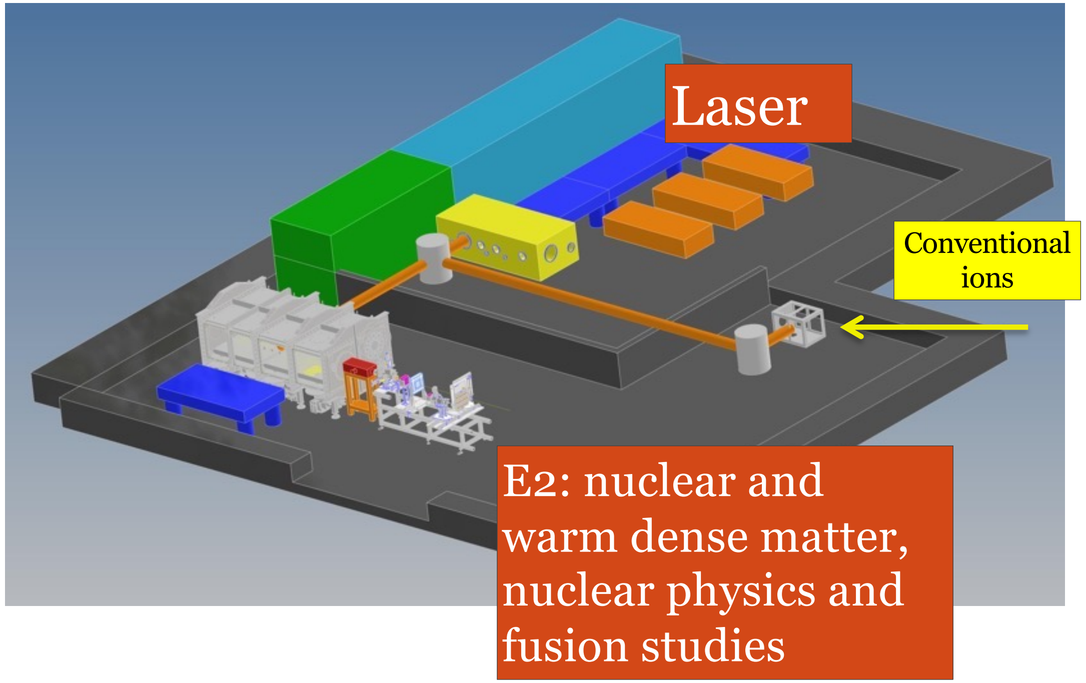


$$n \approx \frac{I}{e^2 T}$$

$$T \approx \left(\frac{I}{1.37 \times 10^{16}\ \mathrm{W/cm^2}} \right)^{1/2}$$

An high power laser: 8J/23fs/1Hz
A plasma generated by the laser:
Temperature: 2 eV - 200 eV
Density: 10^{25} m^{-3}
Ion beams in a wide Z range and energy up to 70 AMeV provided by the TANDEM and Cyclotron accelerators

E2 will allow for studies in the inertial confinement regime



Laser/plasma and ions: world almost unique environment

High-power modality: 500TW/3Hz

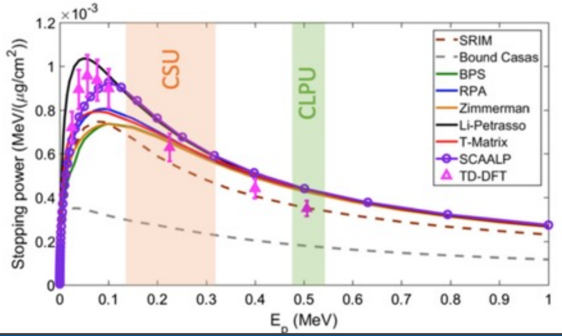
Laser main parameters

Laser Power	500 TW
Energy per pulse	>10 J
Pulse duration	≤ 25 fs
Focusing surface	36 μm^2 or better
Max power density (at the target)	$1.33 \cdot 10^{21}$
$I^* \lambda^2$	$8.5 \cdot 10^{20}$
Contrast ratio @100 ps (ASE)	$> 10^{10}$
Repetition rate	3 Hz

Main radiations

Protons Ions	Max energy	70 MeV
	Particle per pulse (at 30 MeV)	10^{11} MeV^{-1} Sr^{-1}
	Energy spread	100%
	Beam divergency (max)	±20°
Eletrons	Max energy	3 GeV
	Particles per pulse	10^9
	Beam divergency (max)	± 20 mad
Neutrons	Particles per pulse	10^{10}
	Energy spread	100
	Beam divergency	Isotropic
Gamma X-beams	Synchrotron radiation of the electrons inside the plasma or breemsstrahlung	
	Energy	up to 80 MeV Directionality in the beam

Nuclear physics mid-term plan



Stopping power in plasma

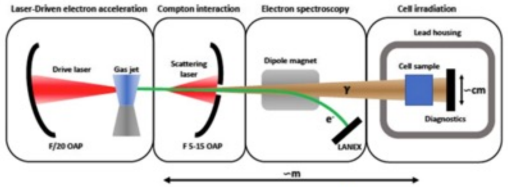
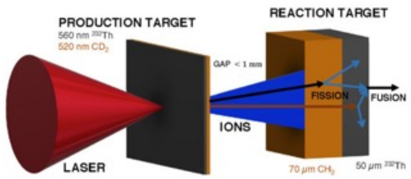
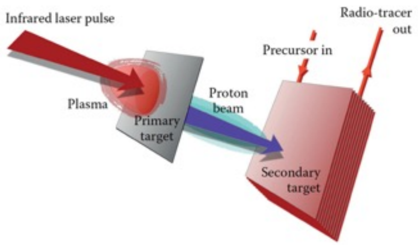


Fig. 48 Setup for the high-brilliance γ production via inverse Compton-scattering (from Sarri et al. [371])

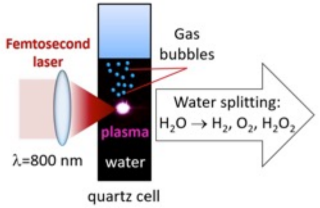
Positrons generation



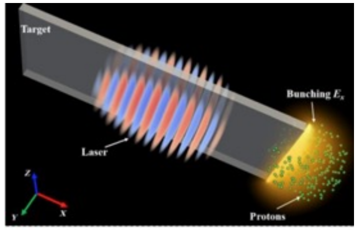
Nuclear reaction schemes



Radioisotopes



Hydrogen generation



Protons and electrons generation

Chapter 6.2 Laser applications

Eur. Phys. J. Plus (2023) 138:1038
https://doi.org/10.1140/epjp/s13360-023-04358-7

THE EUROPEAN PHYSICAL JOURNAL PLUS

Regular Article

Check for updates

Nuclear physics midterm plan at LNS

C. Agodi[1], F. Cappuzzello[1,2], G. Cardella[3], G. A. P. Cirrone[1], E. De Filippo[3], A. Di Pietro[1], A. Gargano[4], M. La Cognata[1,a], D. Mascali[1], G. Milluzzo[1], R. Nania[5], G. Petringa[1], A. Pidatella[1], S. Pirrone[3], R. G. Pizzone[1], G. G. Rapisarda[1,2,b], M. L. Sergi[1,2], S. Tudisco[1], J. J. Valiente-Dobón[7], E. Vardaci[4,8], H. Abramczyk[9], L. Acosta[10], P. Adsley[11], S. Amaducci[1], T. Banerjee[4], D. Batani[12], J. Bellone[1,2], C. Bertulani[11,13], S. Biri[14], A. Bogachev[15], A. Bonanno[1,16], A. Bonasera[1,11], C. Borcea[17], M. Borghesi[18], S. Bortolussi[19,20], D. Boscolo[14], G. A. Brischetto[1,2], S. Burrello[1,21,22], M. Busso[23,24], S. Calabrese[1], S. Calinescu[17], D. Calvo[25], V. Capirossi[25,26], D. Carbone[1], A. Cardinali[27], G. Casini[28], R. Catalano[1], M. Cavallaro[1], S. Ceccuzzi[29], L. Celona[1], S. Cherubini[1,2], A. Chieffi[24,30], I. Ciraldo[1,2], G. Ciullo[31,32], M. Colonna[1], L. Cosentino[1], G. Cuttone[1], G. D'Agata[1,2], G. De Gregorio[4,33], S. Degl'Innocenti[34], F. Delaunay[1,2,35], L. Di Donato[1,36], A. Di Nitto[4,8], T. Dickel[37,38], D. Doria[17,39], J. E. Ducret[40], M. Durante[14], J. Esposito[7], F. Farrokhi[1], J. P. Fernandez Garcia[21], P. Figuera[1], M. Fisichella[1], Z. Fulop[14], A. Galatá[6], D. Galaviz Redondo[41], D. Gambacurta[1], S. Gammino[1], E. Geraci[2,3], L. Gizzi[42], B. Gnoffo[2,3], F. Groppi[26,27], G. L. Guardo[1], M. Guarrera[1], S. Hayakawa[43], F. Horst[14], S. Q. Hou[44], A. Jarota[8], J. José[45], S. Kar[18,46], A. Karpov[15], H. Kierzkowska-Pawlak[9], G. G. Kiss[14], G. Knyazheva[15], H. Koivisto[47], B. Koop[72], E. Kozulin[14], D. Kumar[37,38], A. Kurmanova[1], G. La Rana[4,8], L. Labate[42], L. Lamia[1,2], E. G. Lanza[3], J. A. Lay[48,49], D. Lattuada[1,6], H. Lenske[50], M. Limongi[24,30,51], M. Lipoglavsek[52], I. Lombardo[2,3], A. Mairani[72], S. Manetti[26,27], M. Marafini[71], L. Marcucci[34], D. Margarone[53], N. S. Martorana[1,3], L. Maunoury[40], G. S. Mauro[1], M. Mazzaglia[1], S. Mein[72], A. Mengoni[5,54], M. Milin[55], B. Mishra[1], L. Mou[7], J. Mrazek[56], P. Nadtochy[57], E. Naselli[1], P. Nicolai[12], K. Novikov[15], A. A. Oliva[1], A. Pagano[3], E. V. Pagano[1], S. Palmerini[23,24], M. Papa[3], K. Parodi[73], V. Patera[58], J. Pellumaj[7,31], C. Petrone[24], S. Piantelli[28], D. Pierroutsakou[4], F. Pinna[25], G. Politi[2,3], I. Postuma[19,20], P. Prajapati[1,59], P. G. Prada Moroni[35], G. Pupillo[7], D. Raffestin[12], R. Racz[14], C.-A. Reidel[14], D. Rifuggiato[1], F. Risitano[3,60], F. Rizzo[2,3], X. Roca Maza[61,62], S. Romano[1,2], L. Roso[63], F. Rotaru[17], A. D. Russo[1], P. Russotto[1], V. Saiko[15], D. Santonocito[1], E. Santopinto[64], G. Sarri[46], D. Sartirana[25], C. Schuy[14], O. Sgouros[1], S. Simonucci[65], G. Sorbello[1,36], V. Soukeras[1], R. Spartá[1], A. Spatafora[1,2], M. Stanoiu[17], S. Taioli[66,67,68], T. Tessonnier[72], P. Thirolf[73], E. Tognelli[34], D. Torresi[1], G. Torrisi[1], L. Trache[17], G. Traini[70], M. Trimarchi[3,60], S. Tsikata[69], A. Tumino[1,6], J. Tyczkowski[9], H. Yamaguchi[43], V. Vercesi[19,20], I. Vidana[3], L. Volpe[63], U. Weber[14]

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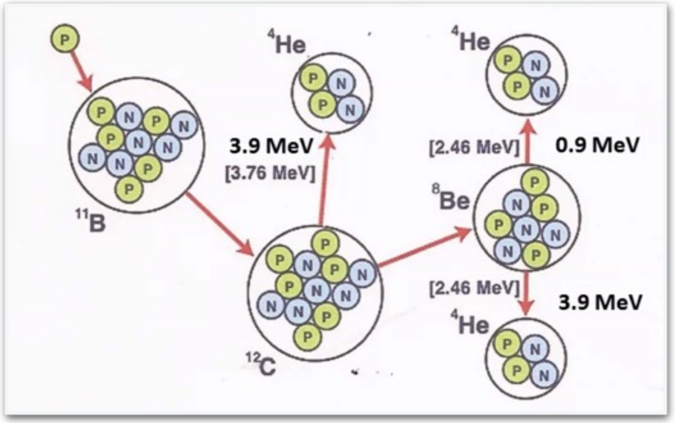
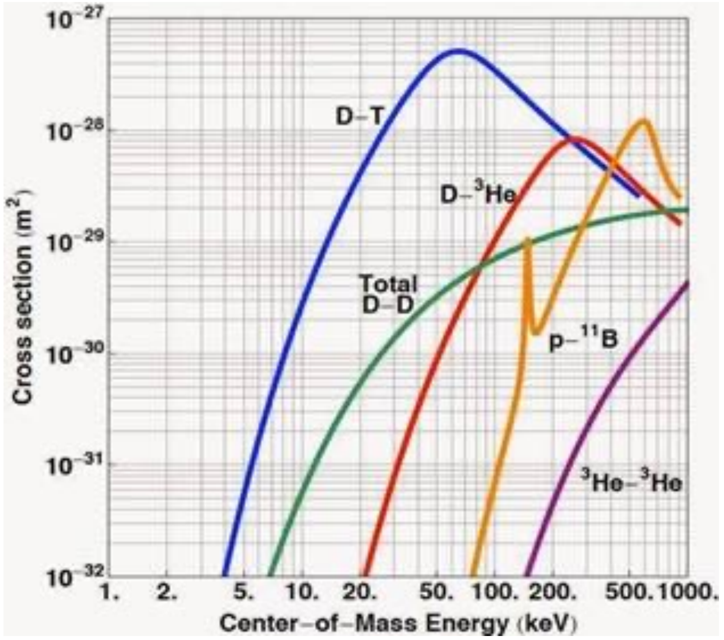
Why the p-^{11}B fusion reaction?

$p(11B, \alpha)8Be$

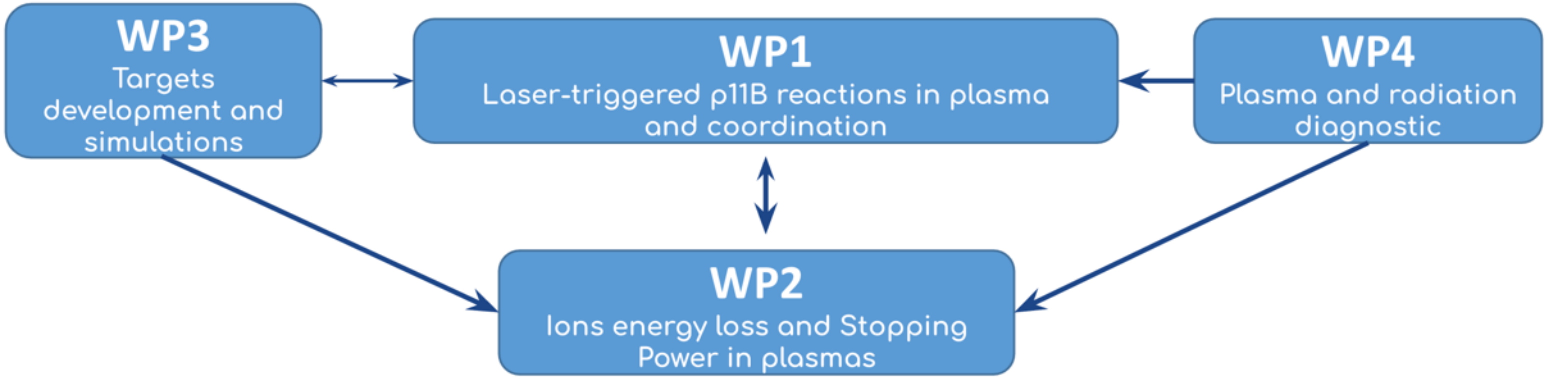




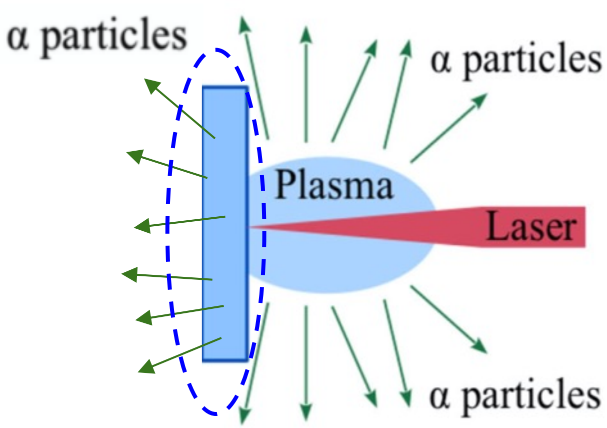
- **Neutronless fusion reactions**
- Two resonance at **148 keV** and **580 keV** in the system center of mass
- It is considered as a **potential candidate** in inertial fusion scheme
- Reagents **more abundant in nature** with respect to other fusion reactions of interest, and easier to handle (with respect to tritium, for example)
- Interest for the realisation of intense α **sources** for applications

M.Oliphant, L.Rutherford, Proc. R. Soc. London A 141 259 (1933)

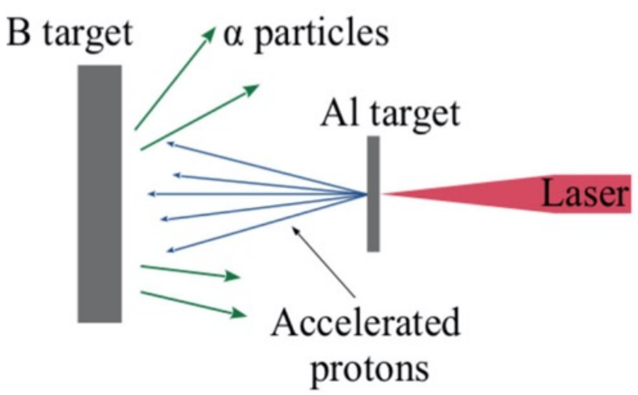
FUSION: an INFN project to study the p-11B fusion reaction



In-target scheme



Pitcher-catcher scheme



- New targets, diagnostics and irradiation schemes for p11B fusion reaction in plasma and in catcher configuration
- Protons and alphas stopping powers measurements in plasma
- PIC and hydrodinamic simulation to predict the emission

Stopping power of ions in plasma is a process of fundamental importance in many applications:

- Inertial Confinement Fusion
- Astrophysics and Nuclear Astrophysics
- High-energy Density Physics
- Plasma strippers
- Solid State Physics

❑ High-energy

$v_p \gg v_{th}$

- The stopping power (energy deposited per unit length) of the ions in the plasma can be described by perturbative approaches based on a first Born approximation
- Most stopping experiments can be interpreted within the SSM frame

❑ Low-energy

$v_p \approx v_{th}$

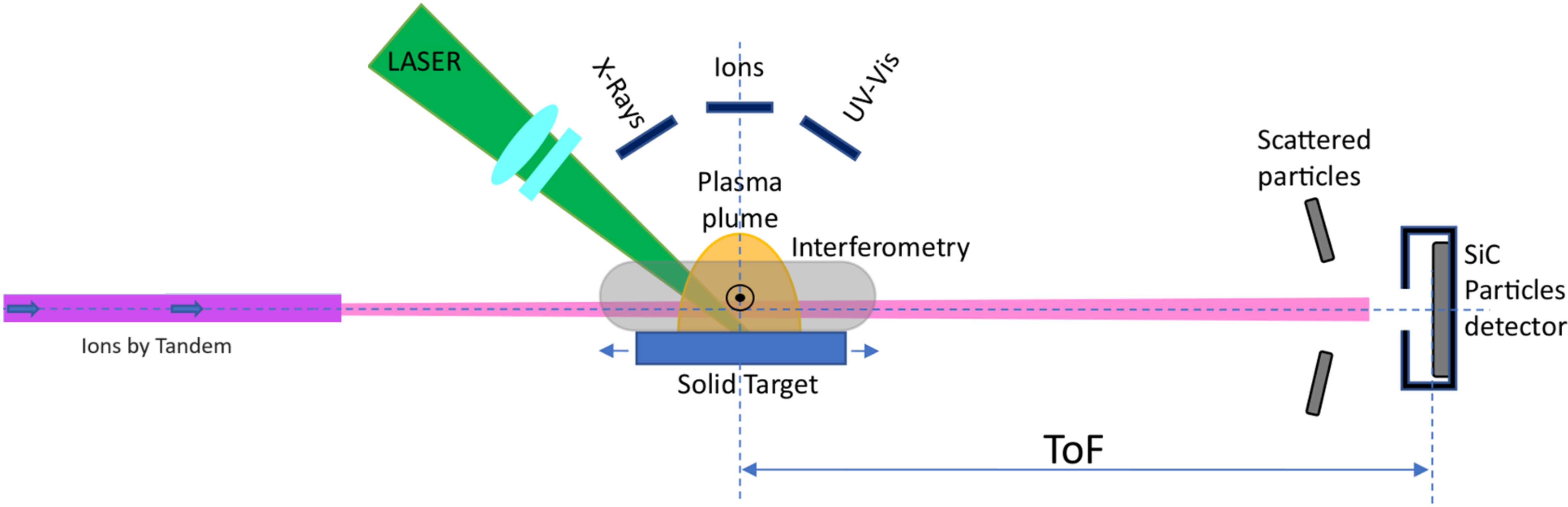
- The ion-plasma interaction involves both strong collisions and collective plasma excitations, and the coupling between the projectile and the plasma is maximal
- Large discrepancies appear between the various theories, reaching up to 30-50 % between perturbative predictions and data from nonperturbative approaches

Characterization of ions stopping power in plasma at I-LUCE facility

Collaboration: C. Altana, G. Castro, S. Cavallaro, C. Ciampi, G.A.P. Cirrone, R. De Angelis, S. De Luca, G. Lanzalone, L. Malferrari, F. Odorici, L. Palladino, G. Pasquali, A. Russo, A. Trifirò and S. Tudisco

Partecipating INFN sections:Catania, LNS, LNGS, Bologna, Firenze

Proposed Setup at I-LUCE facility



LNS has the only possibility, together with GSI, to deliver a beam with low energy by Tandem accelerator that cross a plasma plume generated under vacuum by a laser beam interacting with a solid target.

Activities at INFN-LNS

- **INFN FUSION project financed by the INFN Committee V**

- **Cost Action**

  PROBONO: PROtonBOron Nuclear fusion: from energy production to medical applicatiOns

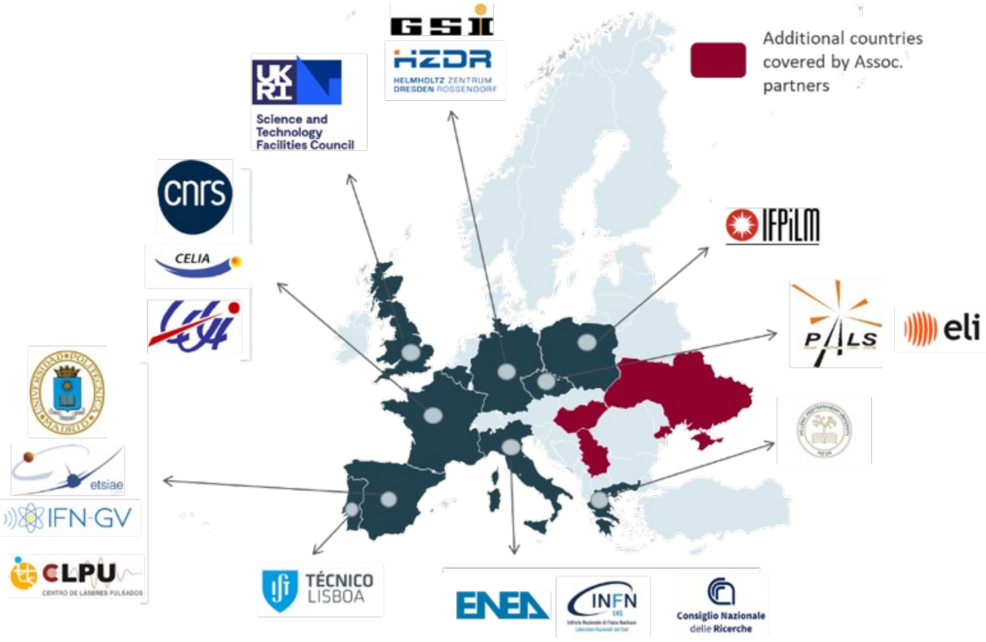
Energy applications
Medical applications
Table-top sources
Radioisotopes

Patents:
EP 2 833 365 A1 - reaction scheme
EP3266470A1 - medical applications

- **HiPER+ initiative for Inertial Confinements Fusion (ICT) studies**

  18 Institutes

  INFN- LNS associated partner



Involvement in WP3 (Task 32.2)
Modelling of protons and alpha stopping power in plasma will be performed with the Geant4 Monte Carlo code with a module dedicated to the simulation of the interaction of 3.5 MeV alphas in plasma
Involvement in WP7
To make the I-LUCE facility available for future studies in the laser-plasma environnement

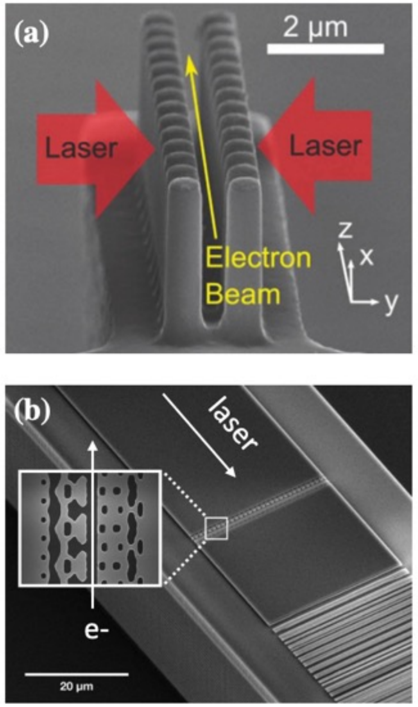
MAIN TOPICS COLLECTED [and reference experiments]

1. New Acceleration schemes @LNS

- **Laser-driven plasma-based acceleration** *(e-, Ions)* **and nuclear reactions** (activation, transmutation, fission and fusion processes) based on laser-matter interaction → *[I-LUCE (INFN—Laser-Induced particle acceleration) facility 100-TW-class laser (fs, 1–10 Hz, I ≥ 10^{19} W/cm2)]*:
  1) Electron acceleration by **Laser Wake Field Acceleration (LWFA)**
  2) Ion acceleration by **Target Normal Sheath Acceleration (TNSA)** at above 1–10 MeV/nucleon, sufficient to penetrate into the nucleus of many light atoms enabling studies on:
  - *Proton–boron fusion reaction in plasma:* for future advanced fusion ignition schemes and for laser-driven α particles sources;
  - *Stopping power in warm dense matter:* important issue/property in Inertial Confinement Fusion (ICF) implosion study and design *[FUSION_GrV, SAMOTHRACE WP1]*.

- **Dielectric Laser Accelerator (DLA) on chip** based on microstructures, lasers @high-rep. rates, commercial dielectrics @higher breakdown threshold, higher gradients (1-10 GV/m). DLAs reduce size/cost for demo on *Colliding Beam Fusion reactor (CBFR) [MICRON_GrV, SAMOTHRACE WP1]*

- **Micro-glass capillaries for µ-Beam irradiation** and ... *-facing materials and components [SAMOTHRACE WP2]*



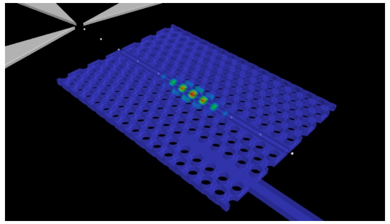
2. Magnetic plasma-ion sources and plasma-traps :

- **R&D High intensity ECR/MDIS ion source** for ADS ...
- **R&D on Diagnostics:** soft-X and hard X spectrosco... ...tudy of magnetized plasmas for fusion in compact traps and reactors (TOKAMAK). Reflectometers/interferometers ... y *[PANDORA_Gr3 experiment, DTT, SAMOTHRACE WP5]*
- Stopping power investigation in plasma for magnetic ...) plasma
- **Wave propagation/absorption in fusion plasmas:** ... ment of antennas and systems for the excitation and control of thermonuclear fusion plasmas thriugh Ion Cyclotron ... n Cyclotron Heating (ECH) *[DTT]*
- **New generation plasma chambers and resonators** ... Design, numerical investigation and experimental tests of advanced plasma chambers ensuring better radiation ... ty, control and confinement *[IRIS and IRIS2.0 POC MISE]*

3. Polarized nuclear fusion fuel:

- **Innovative sources and systems, theory and expe... polarized nuclei**

MICRON_Gr5 Experiment:
Optical Integrated DIELECTRIC LASER ACCELERATOR (DLA) useful as compact/cheap demo for CBFR



high-Q photonic-crystal cavity.
(Courtesy of C2N)

cost-effective and **portable dielectric** particle accelerator in a **table-top** configuration

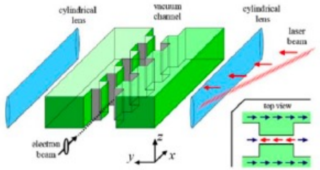
- based on low-cost, **mass production micro-optical chips** driven by **solid state laser**
- **10X higher accelerating gradient** with respect to metallic conventional RF LINAC

Many DLA structures

1-D grating Structure

Silica, λ=800 nm, Ez=700 MV/m

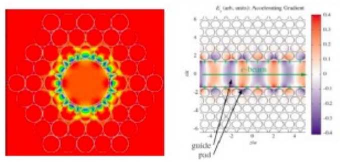
T. Plettner, *et al*, *PRST-AB*, **9**, 111301 *(2006)*.



2-D Fiber Structures

Silica, λ=1053 nm, Ez =400 MV/m

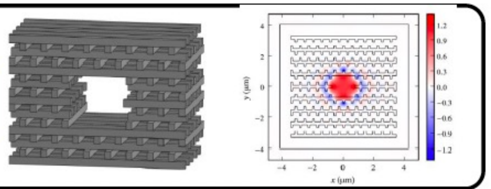
B. Cowan, *PRST-AB*, **6**, 101301 (2003).
X. Lin, *PRST-AB*, **4**, 051301 (2001).



3-D Woodpile Structures

Silicon, λ=1550 nm, Ez=301 MV/m

Z Wu, *et al*, *PRST-AB*, **17**, 081301 (2014).
B. Cowan, *et al*, *PRST-AB*, **11**, 011301 (2008).



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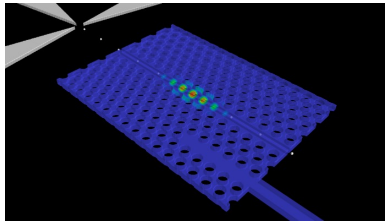

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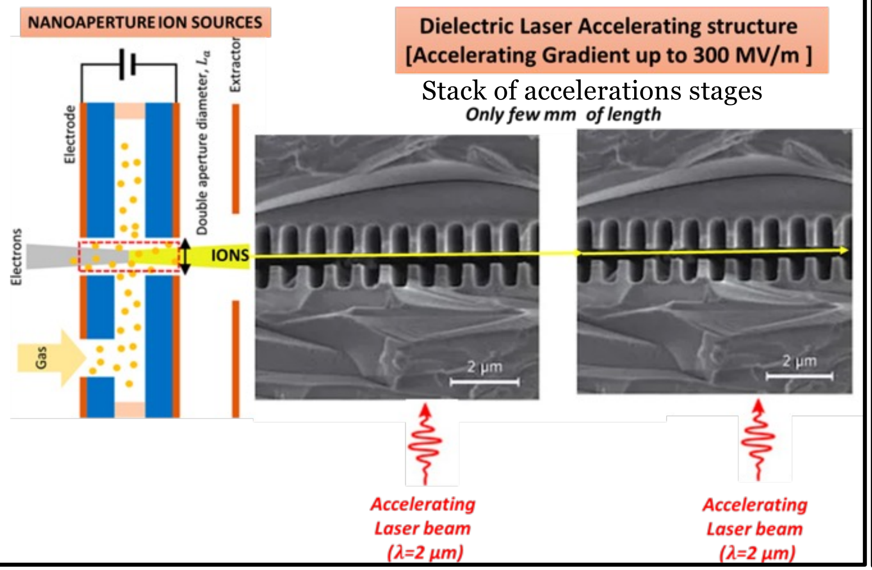
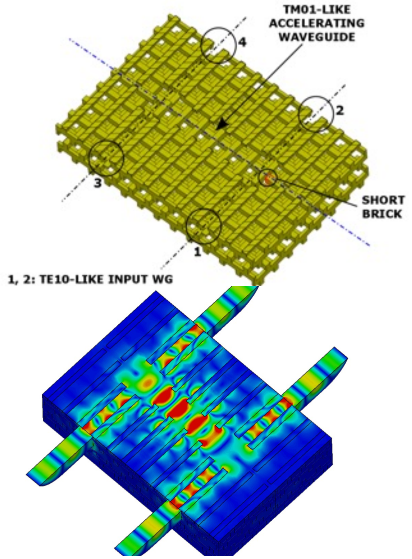
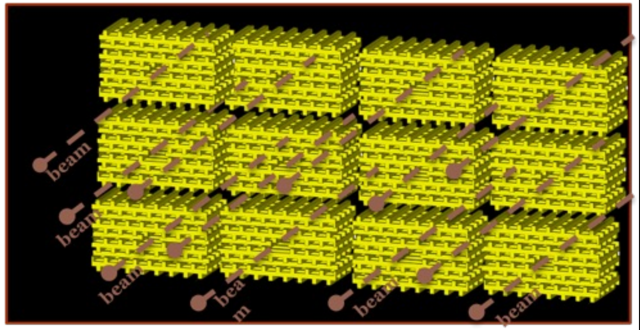


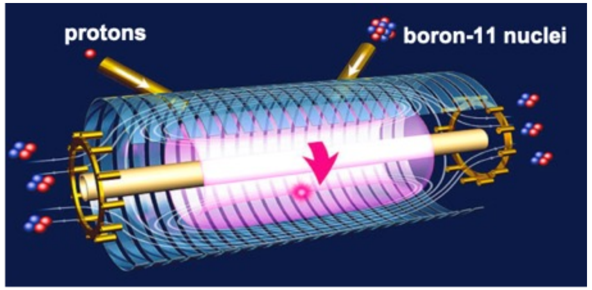




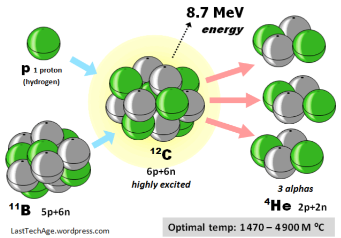
2D Arrays of DLAs can be assembled

Structure dimensions:
5.2 µm x 7.8 µm x 34.2 µm

Potential applications for Aneutronic fusion reaction p-11B in **Colliding Beam Fusion Reactor (CBFR)**
[BNL-48642 "Nuclear Fusion of Protons with Ions of Boron", Alessandro G. Ruggiero Brookhaven National Laboratory]



*Two beams of ions are fired into this reactor, one **of protons (red, upper left)** and **one of boron-11 nuclei (red/blue, upper right)**. Neutrons are blue here. The magnetic compression of the gas allows these to fuse into **helium-4 nuclei** (left and right), with the production of energy. This reaction is advantageous **as it does not produce neutrons**.*



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- **Micro-glass capillaries for μ-Beam irradiation** and analysis of *fusion plasma-facing materials and components [SAMOTHRACE WP2]*

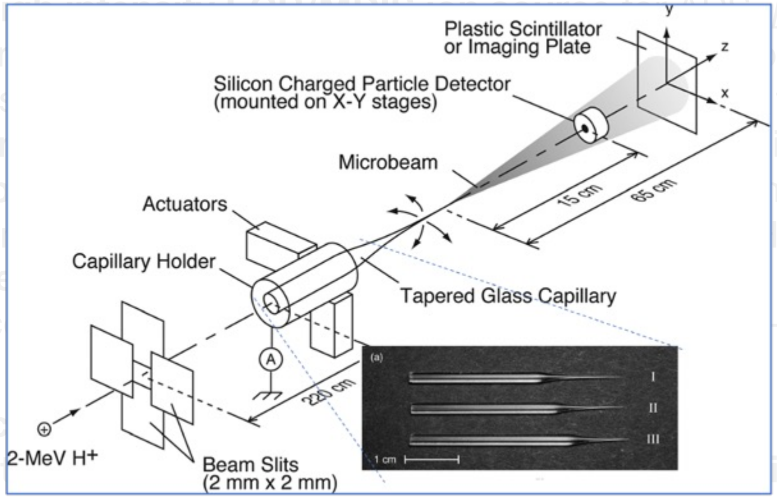
2. Magnetic pl...

- **R&D H...** ... *[TRASCO, PS-ESS]*
- **R&D o...** ...y / tomography for ... ompact traps and reactors ... to control plasma ... *THRACE WP5]*
- **Stoppi...** ...ic confinement fusi...
- **Wave p...** ...heoretical study; de... ...ation and control of thermo... ...eating (ICH) and E...
- **New ge...** **...for compact reac...** ...ental tests of advanc... ...-plasma coupling, stability, control and confinement *[IRIS and IRIS2.0 POC MISE]*

3. Polarized nuc...

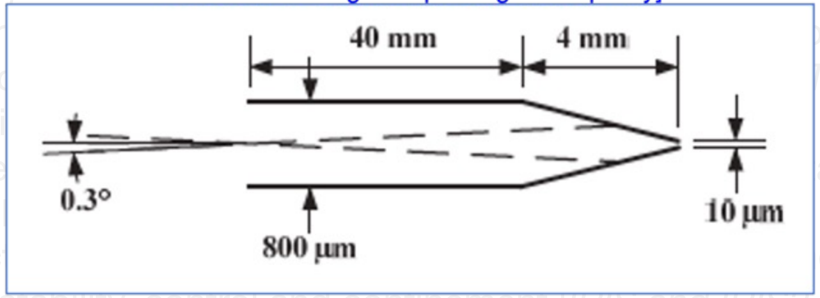
- **Innova... ...iments for fusion from polarized nuclei**

[Journal of Applied Physics 110, 044913 (2011); doi: 10.1063/1.3624617]



Schematic representation of the experimental setup (not to scale). Three types of tapered glass capillaries used in this study

[G.U.L. Nagy, I. Rajta, and K. Tokési , Guiding of 1 MeV proton microbeam through a tapered glass capillary]



focused H+ beam of 1 MeV energy through a tapered-shape insulator capillary made of borosilicate glass. intensity measured by a beam chopper and a Faraday-cup,

micro-nano Ion Beams
beam analysis techniques the field of materials relevant to fusion

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LABORATORI NAZIONALI DEL SUD

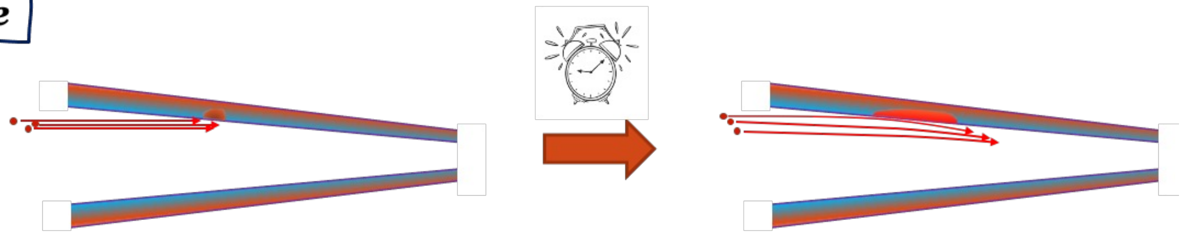
From standard accelerated beams to microbeams

Needs space and strong magnets. Strong impact on the Laboratory infrastructure

Highly focused ion beams

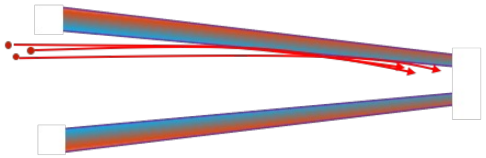
Mechanism of ion transmission through a capillary

keV range



The transmission of keV ions through a capillary is achieved by the repulsion from the potential energy induced from charge patches on the inner walls. Known as self-organized charge-up process.

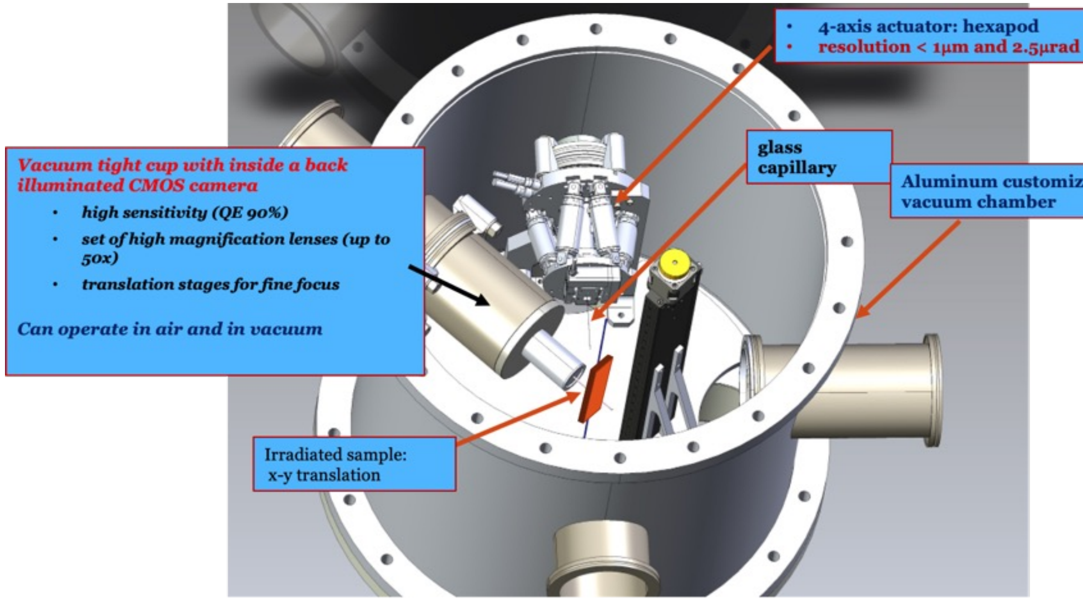
MeV range



The transmission of MeV ions is due by scattered ions on the inner walls.

Microcapillary for collimation and beam guiding

Partially dedicated beamline -> Removable system. Low impact on the Laboratory



The microbeam line based on glass microcapillaries

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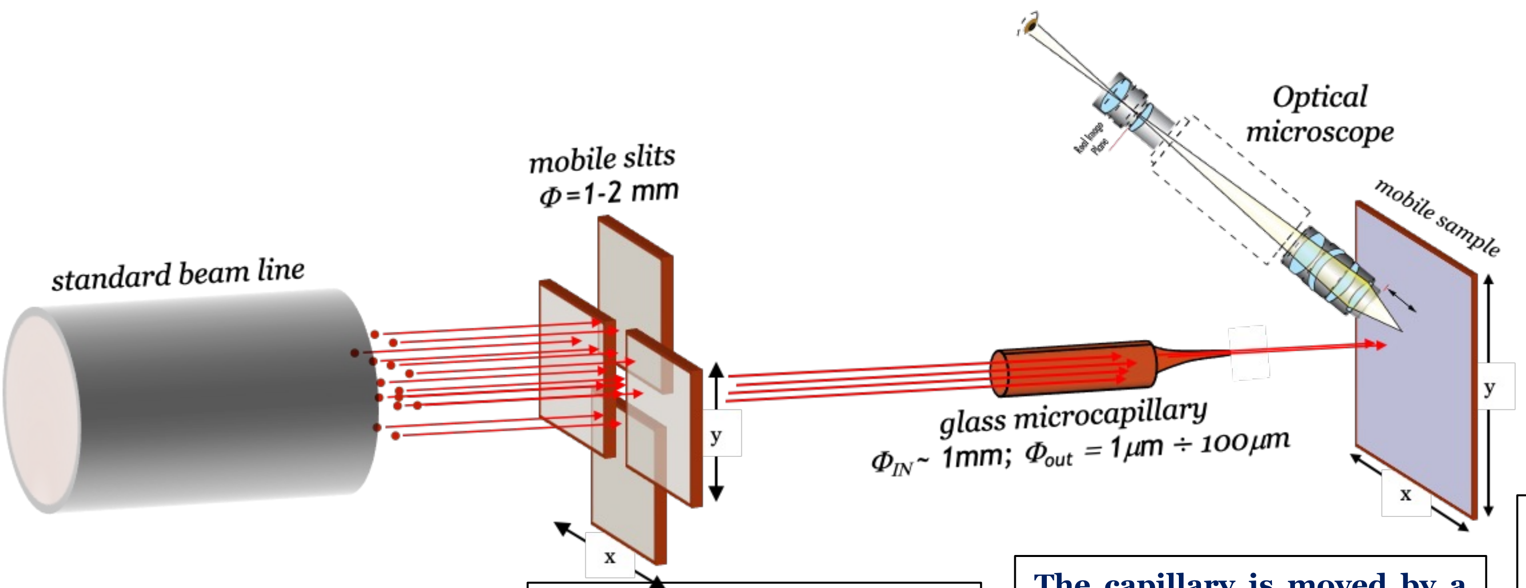
MOTIVATION: Plasma-wall interactions (PWI) in controlled fusion devices with magnetic confinement need for detailed material analyses and for experimental simulation of radiation- induced damage



Proton and Ion beams from Ion Source or Particle Accelerator

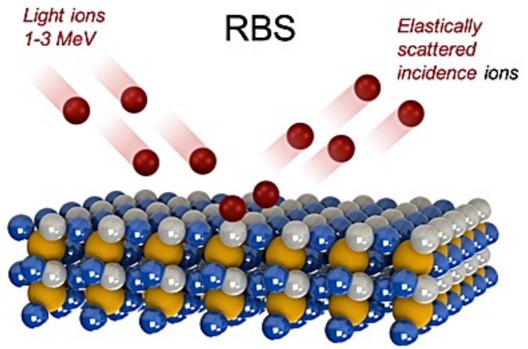
The beam must be appropriately shaped before injection through the capillary

The capillary is moved by a 6-axis actuator with micrometric resolution, for alignment with the beam axis.

[**Review** "Accelerator techniques and nuclear data needs for ion beam analysis of wall materials in controlled fusion Devices" M. Rubel et al., EPJ Techniques and Instrumentation 10, 3 (2023)]

Ion Beam Analysis

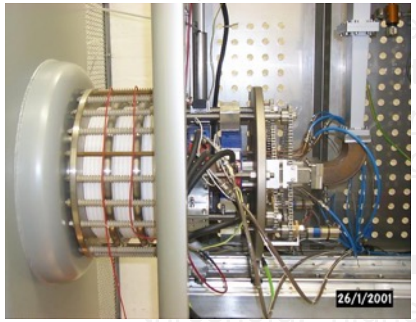
KeV and MeV ions can interact with a micrometer region of the sample. Real-time imaging

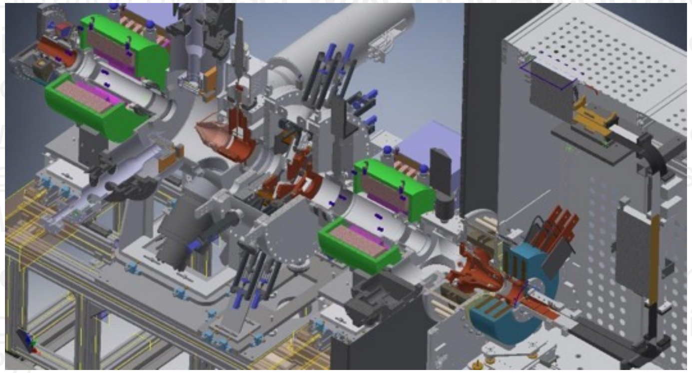


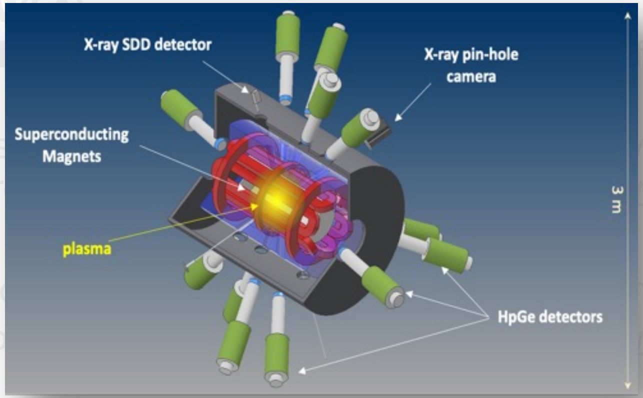
Detailed mapping of species with a resolution of 1-30 μm can be carried out **with μ-RBS, μ-NRA, μ-EPS and μ-PIXE**, i.e. using micro-beams formed in a quadrupole-equipped beamline or **MICRO-CAPILLARIES**

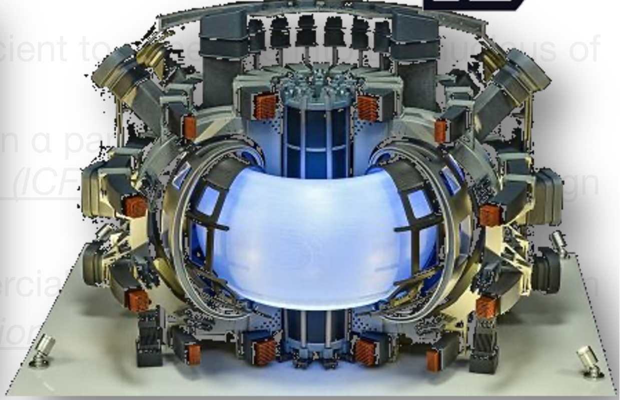
1. New Acceleration schemes @LNS

Magnetic traps for hot plasmas excited by e.m. waves









- **Micro-glass capillaries for μ-Beam irradiation** and analysis of <u>fusion plasma-facing materials and components</u> [SAMOTHRACE WP2]

2. Magnetic plasma-ion sources and plasma-traps :

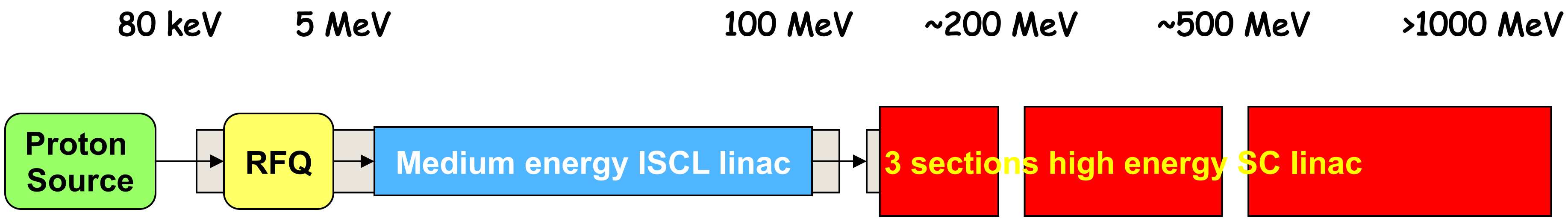
- **R&D High intensity ECR/MDIS proton source** for ADS *[TRASCO, PS-ESS]* driving a subcritical reactor to transmute nuclear waste
- **R&D on Diagnostics:** soft-X and hard X spectroscopy / tomography for the study of magnetized plasmas for fusion in compact traps and reactors (TOKAMAK). Reflectometers/interferometers to control plasma density [*PANDORA_Gr3 experiment, DTT, SAMOTHRACE WP5*]
- **Wave propagation/absorption in fusion plasmas:** theoretical study; development of antennas and systems for the excitation and control of thermonuclear fusion plasmas thriugh Ion Cyclotron Heating (ICH) and Electron Cyclotron Heating (ECH) *[DTT]*
- **Stopping power investigation** for <u>*magnetic confinement fusion (MCF)*</u> plasma
- **New generation plasma chambers and resonators for compact reactors:** Design, numerical investigation and experimental tests of advanced plasma chambers ensuring better radiation-plasma coupling, stability, control and confinement [*IRIS_Gr5 and IRIS2.0 POC MISE*]

3. Laser-cluster scenario and Polarized nuclear fusion fuel:

- **The Coulomb Explosion Paradigma** for the enhancement in the yield of reaction products *[ASFIN]*
- Innovative sources and systems, theory and experiments for fusion from polarized nuclei *[VALAR]*

INFN

The TRASCO LINAC (1GeV, 30 mA, CW)

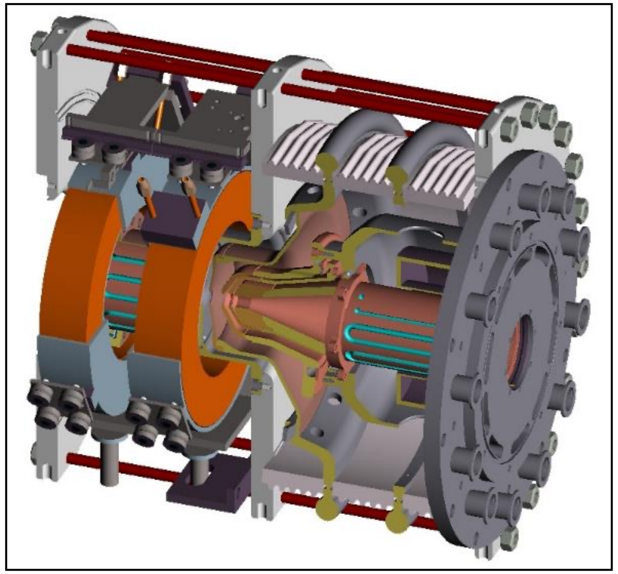


Source	RFQ	ISCL	High Energy SC Linac
Microwave RF Source High current (35 mA) 80 keV	High transmission 95% 30 mA, 5 MeV (352 MHz)	5 - 100 MeV SC linac Baseline design: Reentrant cavities (352 MHz) Alternative design: $\lambda/2$, $\lambda/4$ $8\beta\lambda$ FODO focussing with sc magnets	3 section linac: – 100 - 190 MeV, β=0.47 – 190 - 450 MeV, β=0.65 – 450 – 1000/(1600) MeV, β=0.85 Five(six) cell elliptical cavities Quadrupole doublet focussing: multi-cavity cryostats between doublets – (352.2 MHz CERN/LEP) – 704.4 MHz

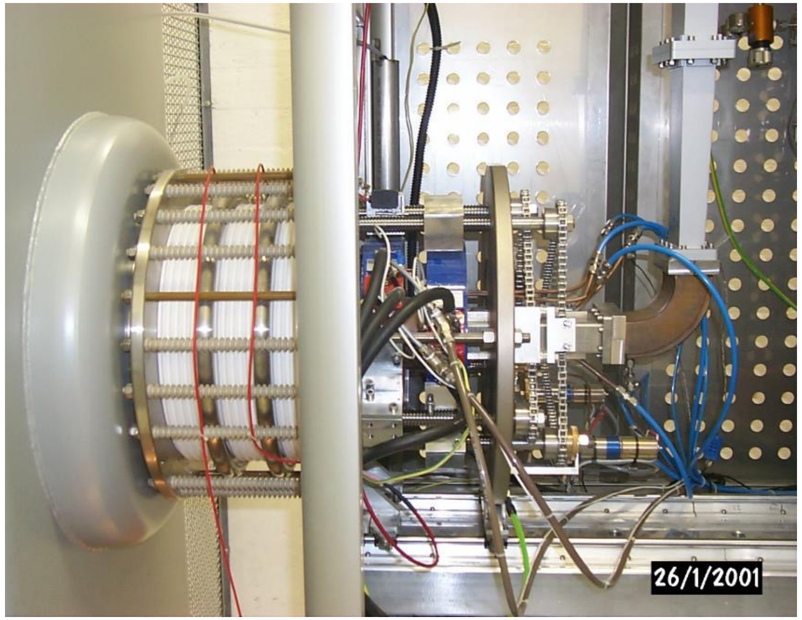
The TRASCO–AC Group,
Status of the high current proton accelerator for the TRASCO program. Report No. INFN/TC-00/23

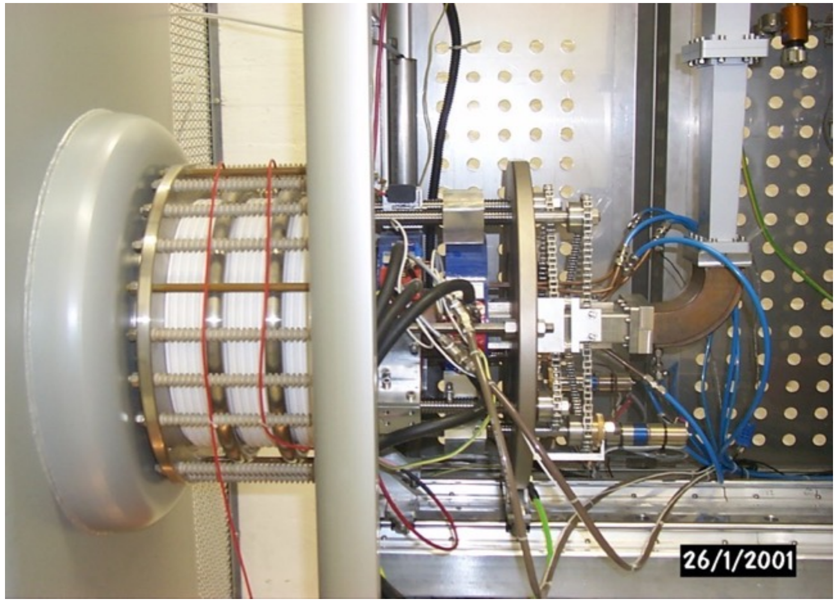
TRIPS (TRasco Intense Proton Source)

INFN
Istituto Nazionale
di Fisica Nucleare
LABORATORI NAZIONALI DEL SUD



Proton beam current:
35 mA dc
Beam Energy:
80 keV
Beam emittance:
$\varepsilon_{RMS} \leq 0.2\ \pi$ ***mm mrad***
Reliability:
close to 100%



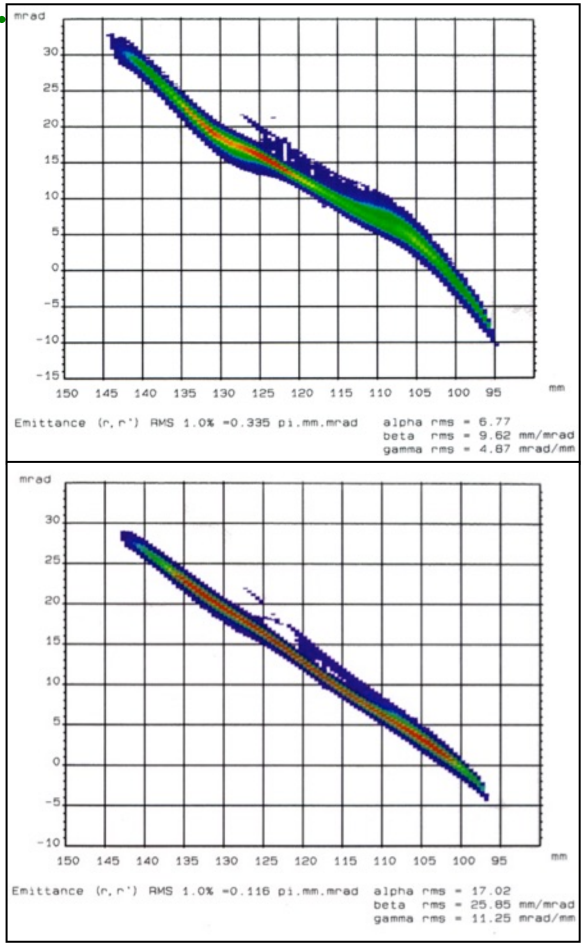


Jan. 2001: completed

R. Gobin, R. Ferdinand, L.Celona, G. Ciavola, S. Gammino, Rev.Sci.Instr. 70(6),(1999), 2652

P—Y. Beaubais, R. Gobin, R. Ferdinand, L.Celona, G. Ciavola, S. Gammino, J. Sherman Rev.Sci.Instr. 71,(2000), 1413

L.Celona, G. Ciavola, S. Gammino, F. Chines, R. Gobin, R. Ferdinand, Rev.Sci.Instr. 75(5),(2004), 1423



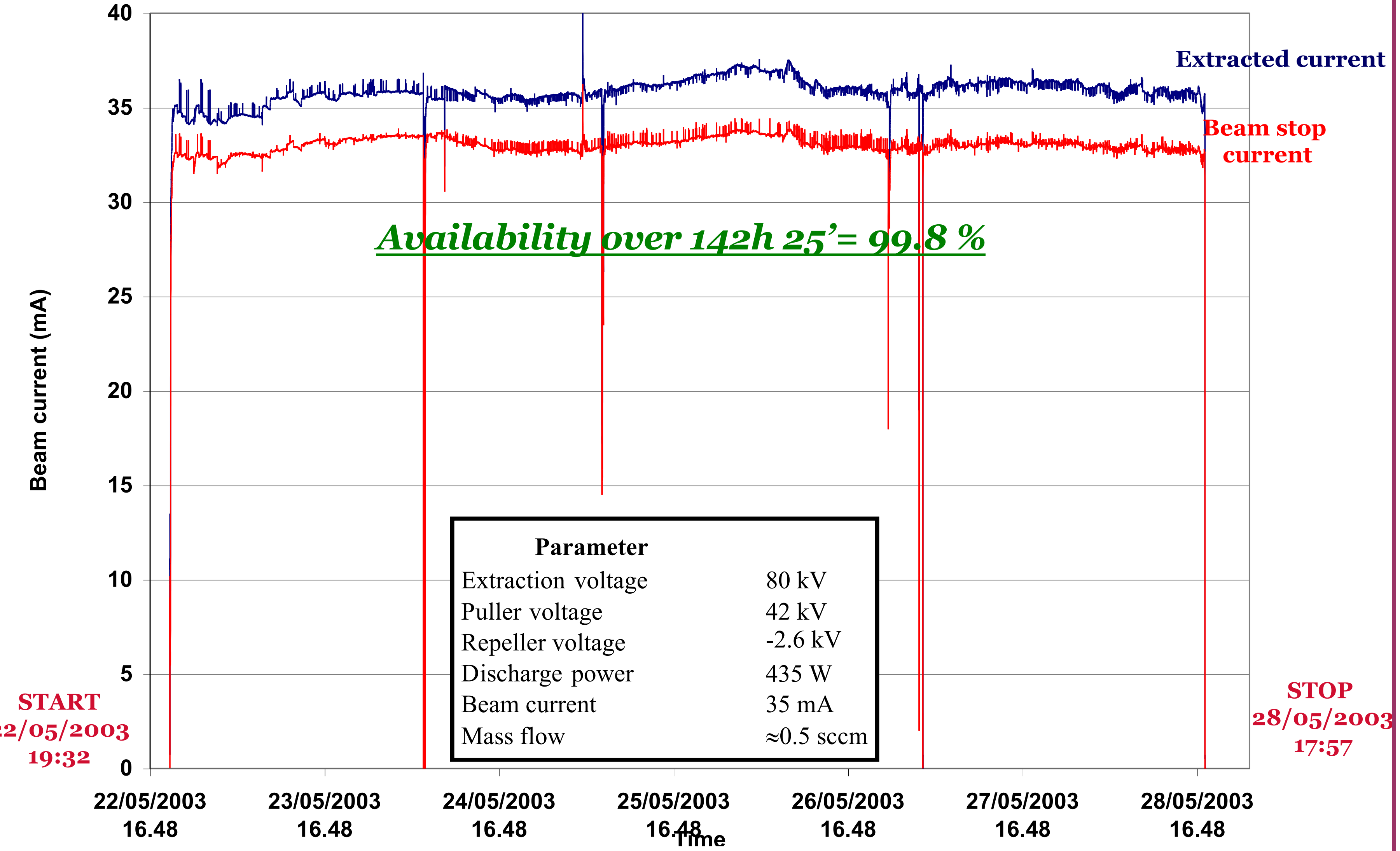
LNS contribution to TRASCO:

First test of a proton source with the long term reliability needed for ADS

	Requirement	Status
Beam energy	80 keV	80 keV
Proton current	35 mA	55 mA
Proton fraction	>70%	80% at 800 W RF power
RF power, Frequency	2 kW (max) @2.45 GHz	Up to 1 kW @ 2.45 GHz
Axial magnetic field	875-1000 G	875-1000 G
Duty factor	100% (dc)	100% (dc)
Extraction aperture	8 mm	6 mm
Reliability	≈100%	99.8% @ 35mA (over 142 h)
Beam emittance at RFQ entrance	≤0.2 πmmmrad	0.07÷0.20 πmmmrad

Space charge compensation and emittance decrease

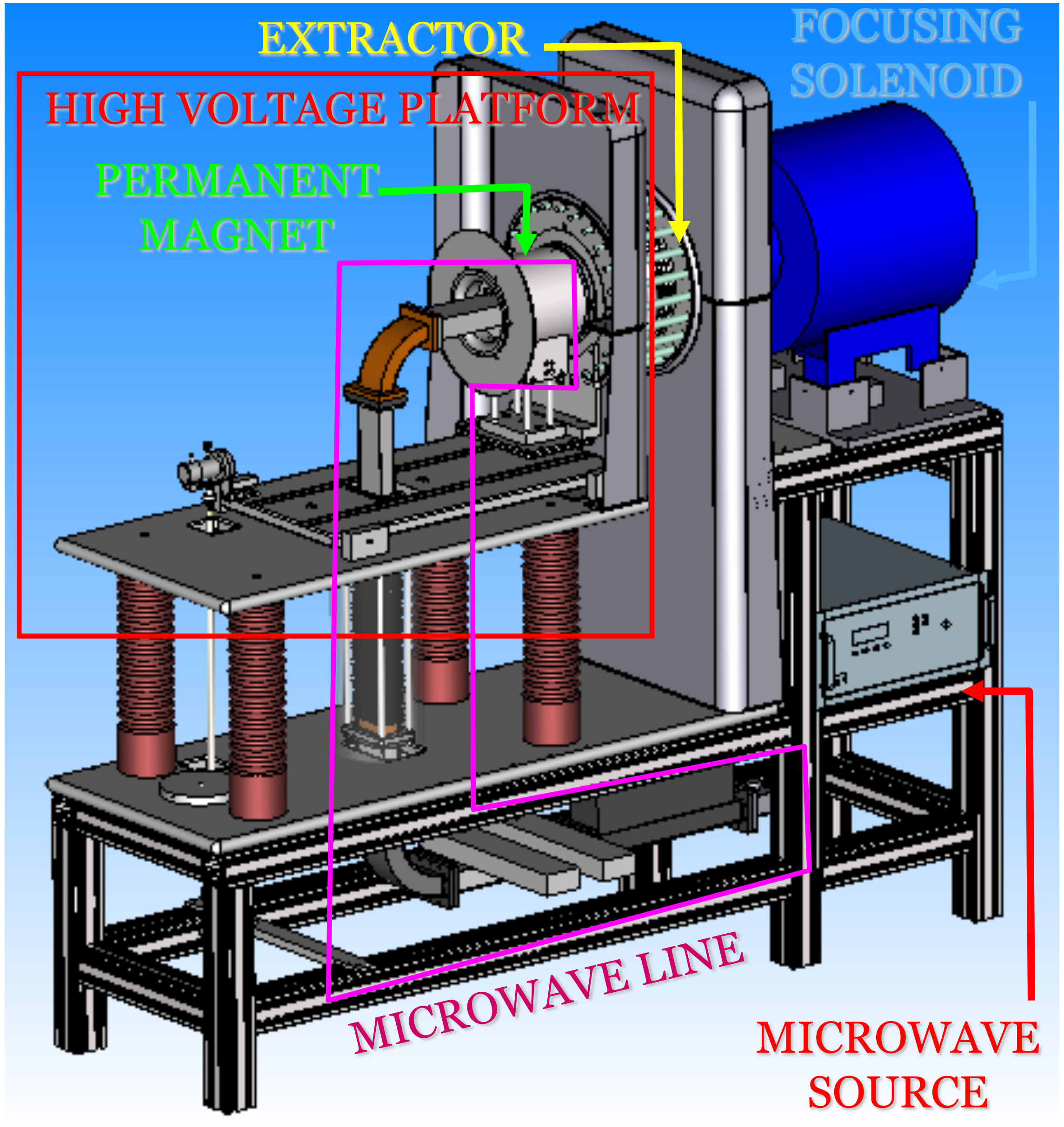
TRIPS reliability test: 35mA @ 80kV



Parameter	
Extraction voltage	80 kV
Puller voltage	42 kV
Repeller voltage	-2.6 kV
Discharge power	435 W
Beam current	35 mA
Mass flow	≈0.5 sccm

L.Celona, G. Ciavola, S. Gammino, F. Chines, R. Gobin, R. Ferdinand, Rev.Sci.Instr. 75(5),(2004), 1423

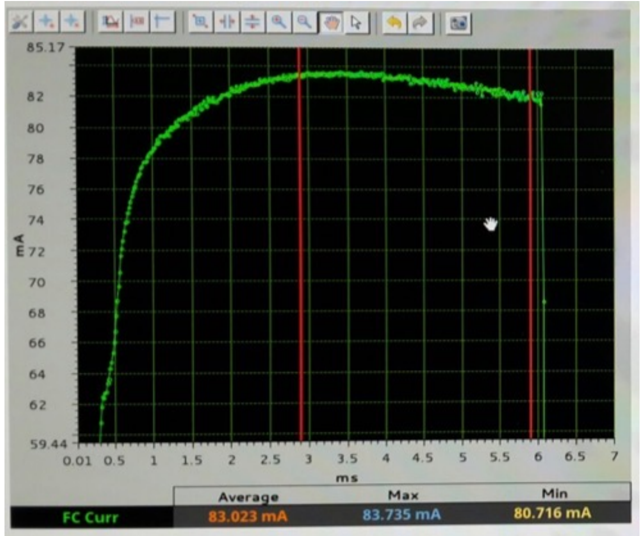
VIS ion source description



PS-ESS: two decades of R&D towards high reliability, easy operation, reproducibility

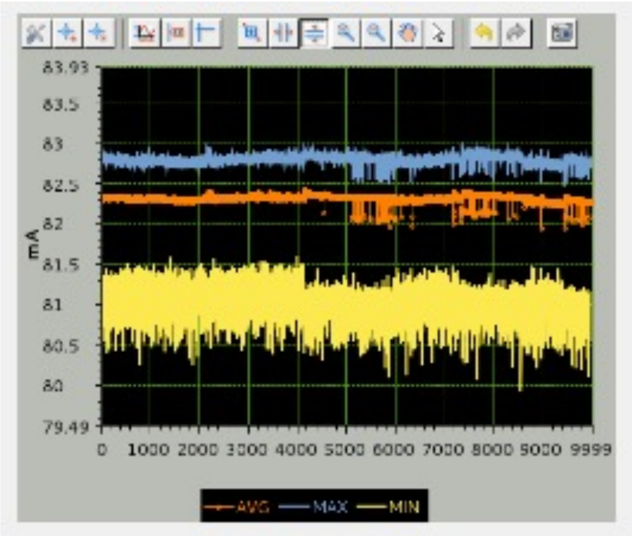
2018, Feb. 1st - Source fully assembled in Lund by INFN-LNS team (4 weeks for the disassembly in Catania, less than 3 weeks for assembly phase in Lund)

Beam characterization

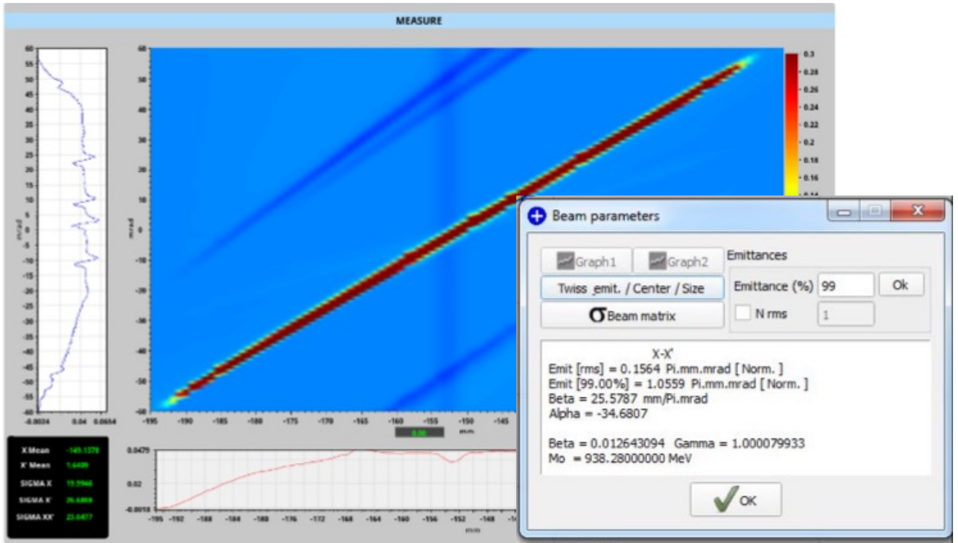


Pulse stability: ±1%
(better than ±2%)

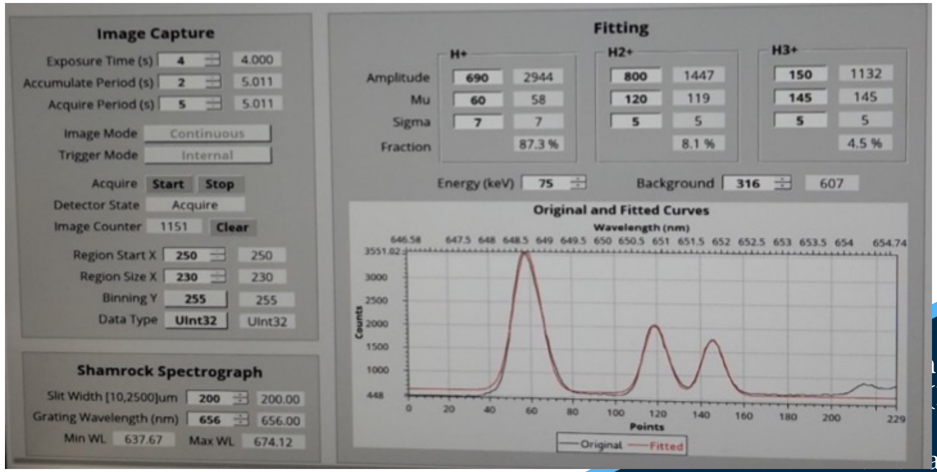
Pulse repeatability:
±1.8% **(< ±3.5%)**



Emittance: 1.06 π.mm.mrad **(< 1.8)**
Max divergence: 55 mrad **(< 80)**



Proton Fraction: 83% **(> 75%)**

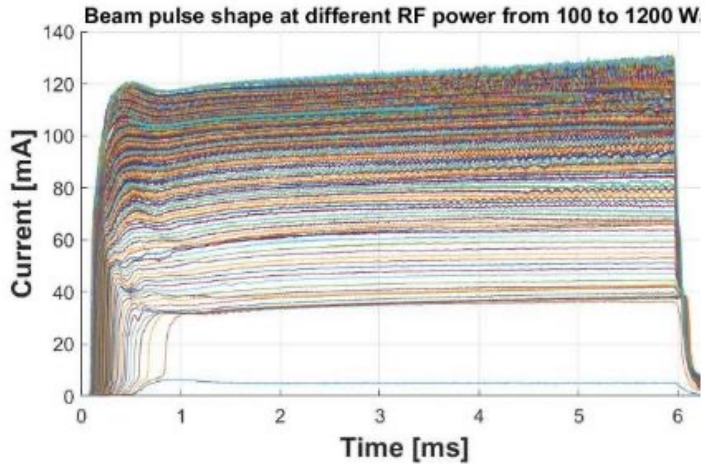


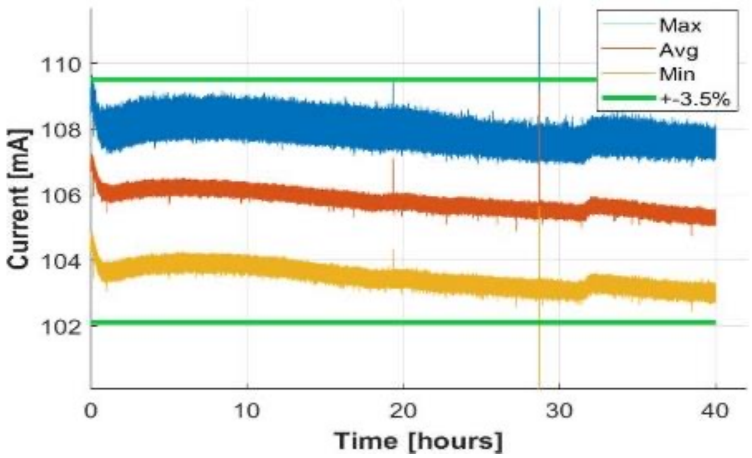
Source nominal configuration

109 A coil1; 67 A coil2; 228 A coil3; 3.75 SCCM H_2

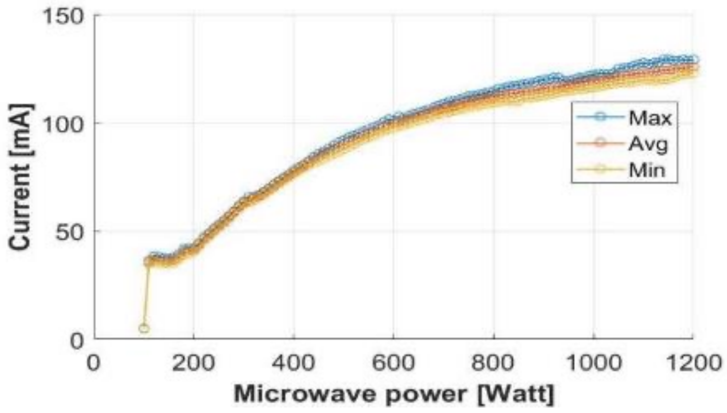
Intra-pulse stability < ±2% SATISFIED

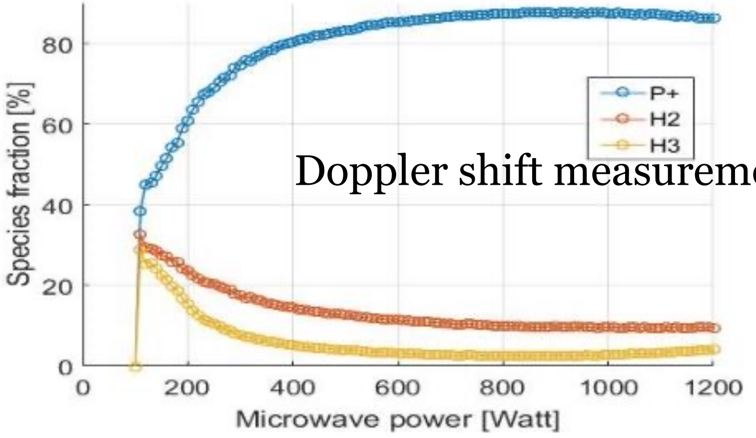
Pulse to pulse stability < ± 3.5% SATISFIED





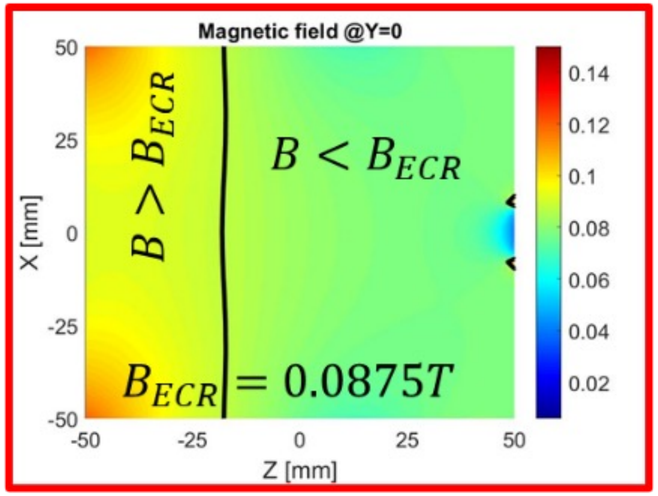
Proton current range 67-74 mA SATISFIED





Doppler shift measurement

High Stability Microwave Discharge Ion Sources: a new frontier just disclosed

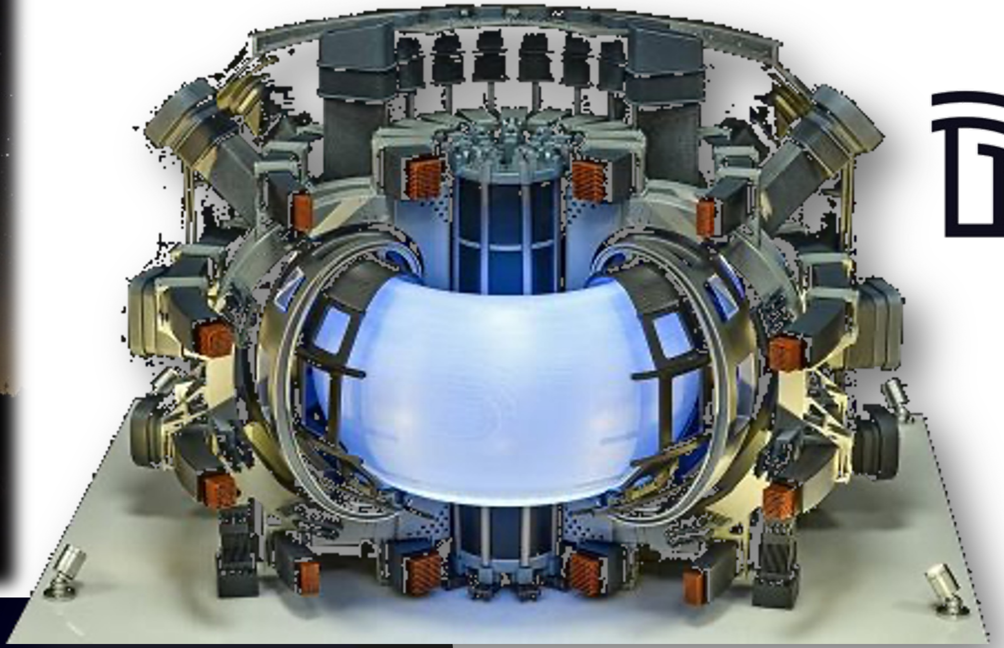


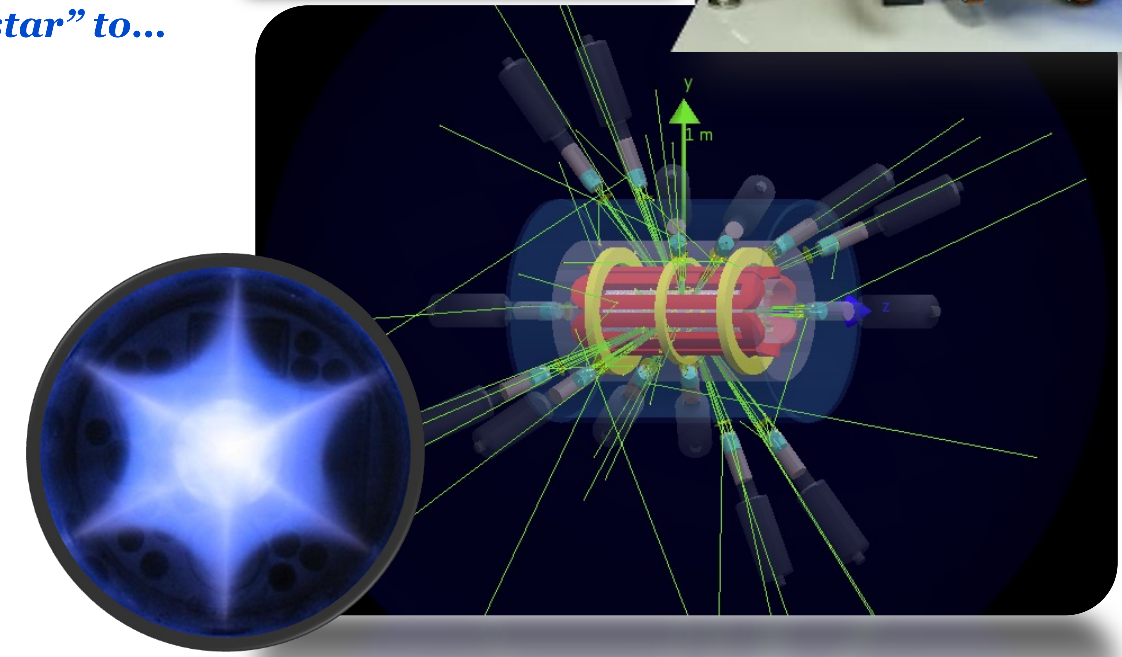
All super stable configurations present a particular magnetic field shape. Deep analysis of the involved physics is under way.

L. Neri, L.Celona, Rev.Sci.Instr. 70(6),(1999), 2652

Efforts at LNS since 10-15 years to make an innovation of research goals, methods, instruments → **use of plasmas for fundamental science and applications**

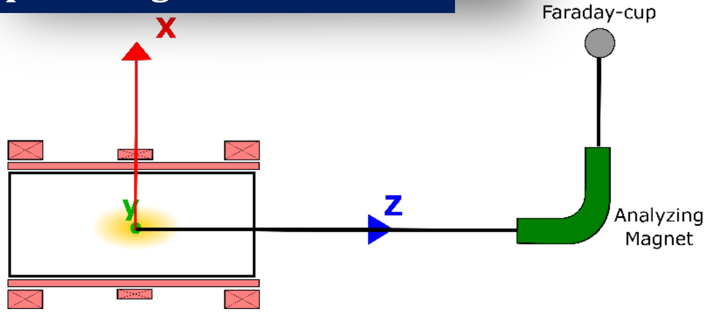
From a laboratory ECR "Plasma star" to…



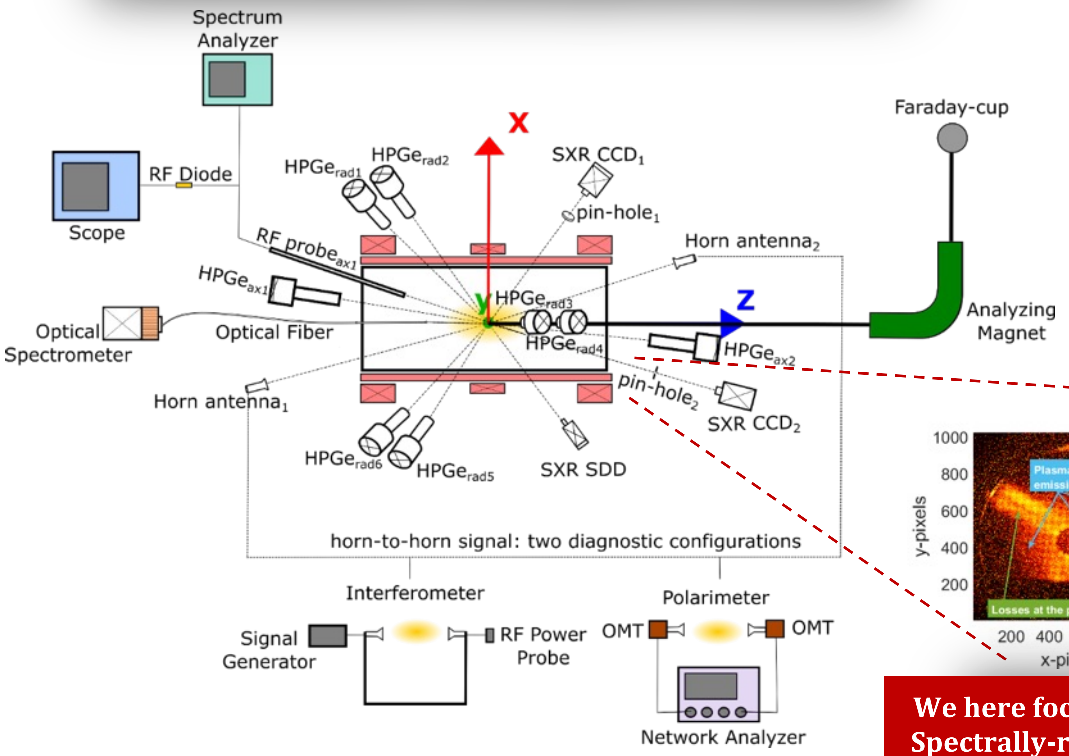


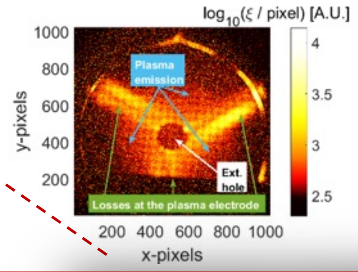
Divertor Tokamak Test: LNS is partner of the Consortium

Typical diagnostic in ECRIS



PANDORA plasma multidiagnostics systems





We here focus on High Resolution Spectrally-resolved X-ray Imaging

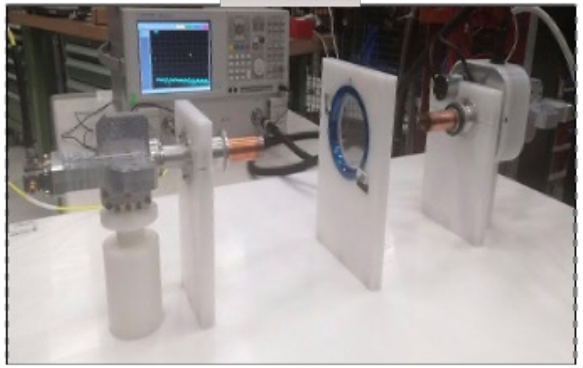
In the frame of the **PANDORA** project an **innovative multi-diagnostic approach** to correlate plasma parameters to nuclear activity has been proposed. This is based on several detectors and non-invasive techniques (*Optical Emission Spectroscopy, RF systems, InterferoPolarimetry, time- and space-resolved X-ray spectroscopy*), allowing **detailed investigations of magnetoplasma properties**.

Diagnostic tool	Sensitive Range	Measurement	Resolution - Measure Error
SDD	1 ÷ 30 keV	Volumetric soft X-ray Spectroscopy: warm electrons temperature and density	Resolution ~ 120 eV ε_{ne} ~ 7%, ε_{Te} ~ 5%
HPGe detector	30 ÷ 2000 keV	Volumetric hard X-ray Spectroscopy: hot electrons temperature and density	FWHM @ 1332.5 keV < 2.4 keV ε_{ne} ~ 7%, ε_{Te} ~ 5%
Visible Light Camera	1 ÷ 12 eV	Optical Emission Spectroscopy: cold electrons temperature and density	Δλ = 0.035 nm R = 13900
X-ray pin-hole camera	2 ÷ 15 keV	2D Space-resolved spectroscopy: soft X-ray Imaging and plasma structure	Energy Resolution ~ 0.3 keV Spatial Resolution ~ 0.5 mm
W-band super-heterodyne polarimeter	W-band 90 ÷ 100 GHz	Plasma-induced Faraday rotation: line-integrated electron density	ε_{ne} ~ 25%
Microwave Imaging Profilometry (MIP)	60 ÷ 100 GHz	Electron density profile	ε_{ne} ~ 1% ÷ 13%
Multi-pins RF probe	10 ÷ 26.5 GHz	Local EM field intensity	ε ~ 0.073 ÷ 0.138 dB
Multi-pins RF probe + Spectrum Analyzer (SA)	10 ÷ 26.5 GHz (*probe range*)	Frequency-domain RF wave	SA Resolution bandwidth: RBW = 3 MHz
Multi-pins RF probe + Scope + HPGe detector	10 ÷ 26.5 GHz (*probe range*)	Time-resolved radiofrequency burst and X-ray time-resolved Spectroscopy	80 Gs/s (*scope*) time scales below ns
Thomson Scattering	0.5 ÷ 500 eV	EEDF, absolute electron density global electron drift velocity	Condition-dependent (a function of spectral width, dependent on temperature, and area, dependent on density)

Plasma system scenarios

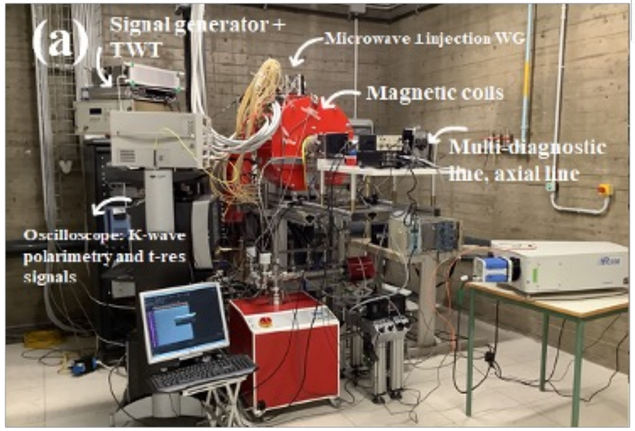
The system was designed to be tested on the **PANDORA plasma trap (C)** which represents an "*intermediate*" case between the ultra-compact plasma ion sources (**FPT (B)** and **Test-bench (A)**) and the large-size thermonuclear **Fusion devices (D)**.

(A)



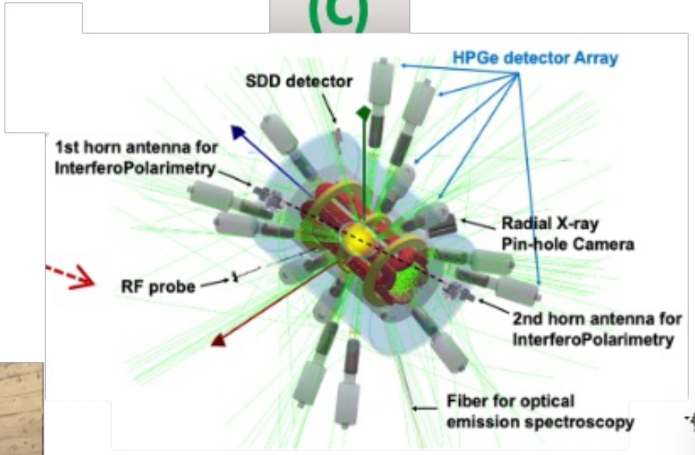
Test-Bench (without plasma)

(B)



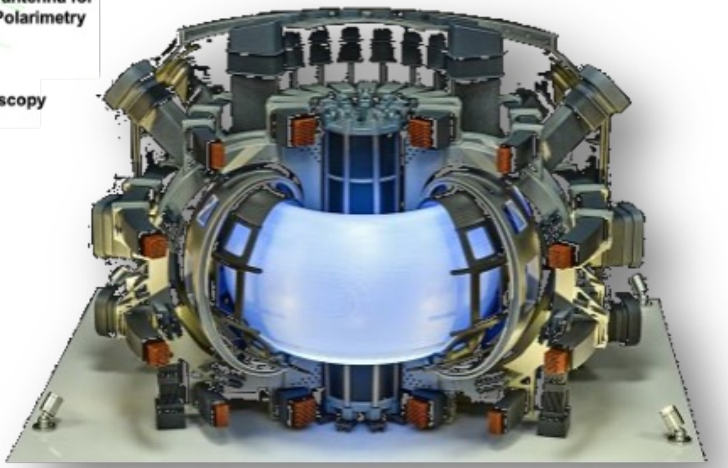
Flexible Plasma Trap

(C)



PANDORA Trap

(D)



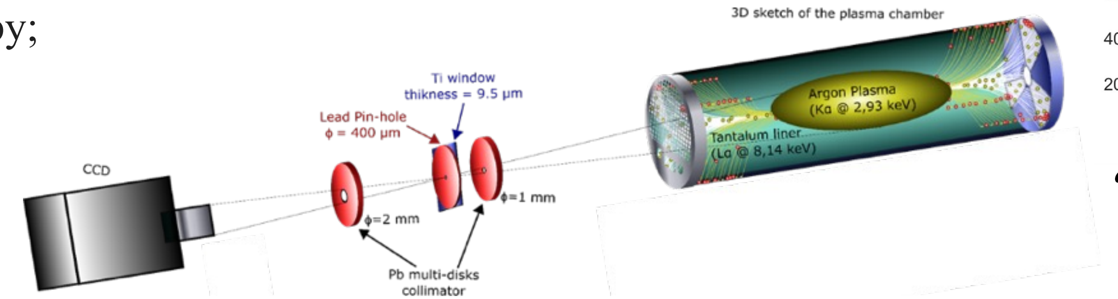
Fusion Device

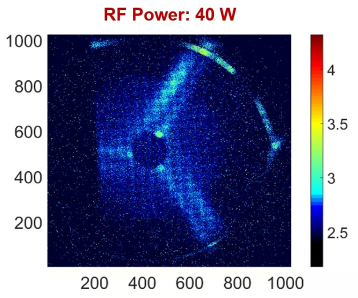
WP5 Detectors and Technologies for Fusion Power

INFN-LNS/Energy

Development of X-ray detectors:

- New SiC/GaN sensors for X-ray detection;
- High resolution X-ray CCD pin-hole system for plasma imaging and spatially-resolved spectroscopy;

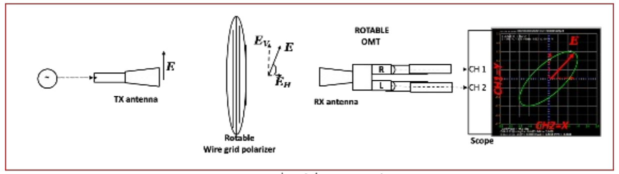




"Live" X-ray imaging of plasma emission

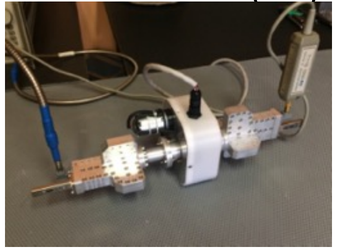
Sub-THz interferopolarimetry:

- new polarimetric system for the line-integrated electron density measurement, based on the detection of Lissajous figure by means of a Super-heterodine scheme;

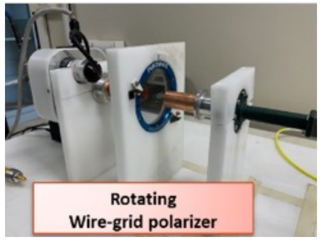


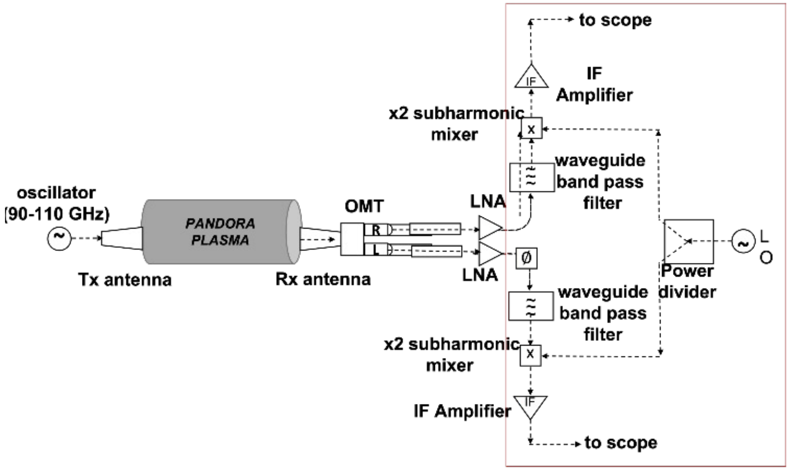
experimental arrangement

OrthoMode Trasducer (OMT)

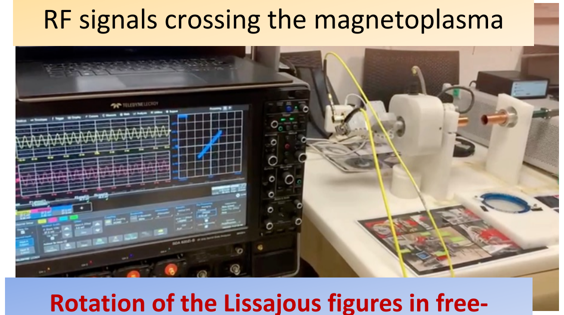


Wire-grid polarizer SETUP

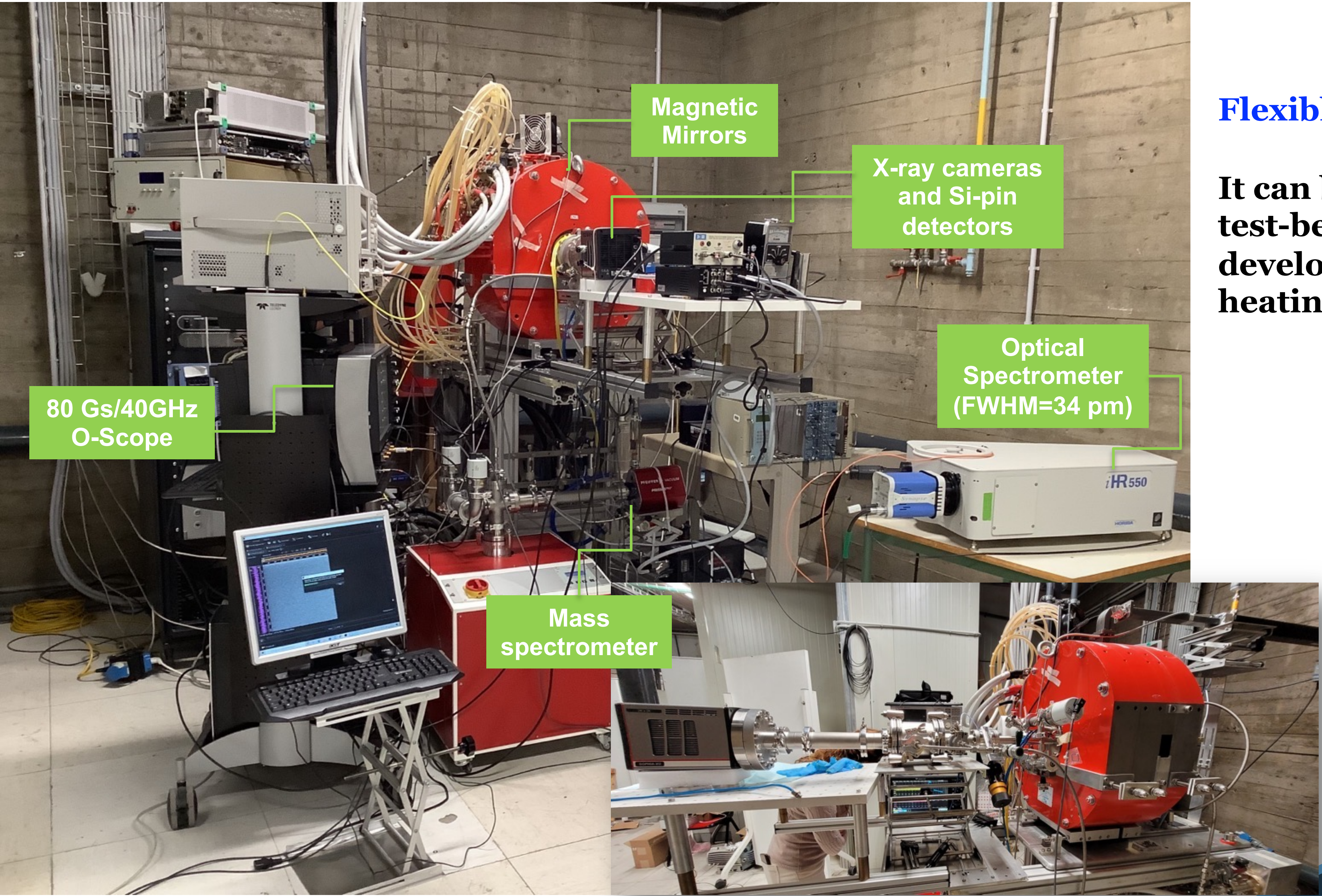




Detection the Lissajous figure from a **two channels scope** of a direct probing RF signals crossing the magnetoplasma



Rotation of the Lissajous figures in free-space (rotating the RX antenna) and with polarizer (for different polarizer angles)



Flexible Plasma Trap @ LNS

It can be considered as a test-bench for the development of diagnostics, heating systems, etc.

MAIN TOPICS COLLECTED [and reference experiments]

1. **New Acceleration schemes @LNS**
   - **Laser-driven plasma-based acceleration** *(e-, Ions)* **and nuclear reactions** (activation, transmutation, fission and fusion processes) based on laser-matter interaction → *[I-LUCE (INFN—Laser-Induced particle acceleration) facility 100-TW-class laser (fs, 1–10 Hz, I ≥ 10^{19} W/cm2)]*:
     1) Electron acceleration by **Laser Wake Field Acceleration (LWFA)**
     2) Ion acceleration by **Target Normal Sheath Acceleration (TNSA)** at above 1–10 MeV/nucleon, sufficient to penetrate into the nucleus of many light atoms enabling studies on:

     - *Proton–boron fusion reaction in plasma:* for future advanced fusion ignition schemes and for laser-driven α particles sources;
     - *Stopping power in warm dense matter:* important issue/property in Inertial Confinement Fusion (ICF) implosion study and design *[FUSION_GrV, SAMOTHRACE WP1].*
   - **Dielectric Laser Accelerator (DLA) on chip** based on microstructures, lasers @high-rep. rates, commercial dielectrics @higher breakdown threshold, higher gradients (1-10 GV/m). DLAs reduce size/cost for demo on *Colliding Beam Fusion reactor (CBFR) [MICRON_GrV, SAMOTHRACE WP1]*
   - **Micro-glass capillaries for μ-Beam irradiation** and analysis of *fusion plasma-facing materials and components [SAMOTHRACE WP2]*

2. **Magnetic plasma-ion sources and plasma-traps :**
   - **R&D High intensity ECR/MDIS ion source** for ADS *[TRASCO, PS-ESS]*
   - **R&D on Diagnostics:** soft-X and hard X spectroscopy / tomography for the study of magnetized plasmas for fusion in compact traps and reactors (TOKAMAK). Reflectometers/interferometers to control plasma density [*PANDORA_Gr3 experiment, DTT, SAMOTHRACE WP5*]
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3. **Polarized nuclear fusion fuel:**
   - **Innovative sources and systems, theory and experiments for fusion from polarized nuclei**

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3. **Polarized nuclear fusion fuel:**
   - **Innovative sources and systems, theory and experiments for fusion from polarized nuclei**

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Sud

In-plasma research

- ***β-dacays*** *in plasmas*
- ***Plasma heating*** *by EBWs*
- ***multiple frequency heating*** *effects*
- ***Cyclotron maser*** *instability*

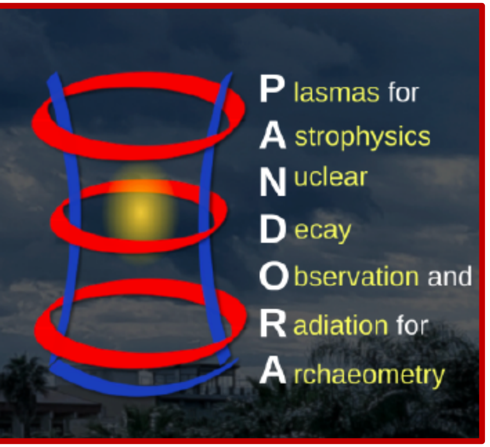
Plasma modelling @ INFN-LNS

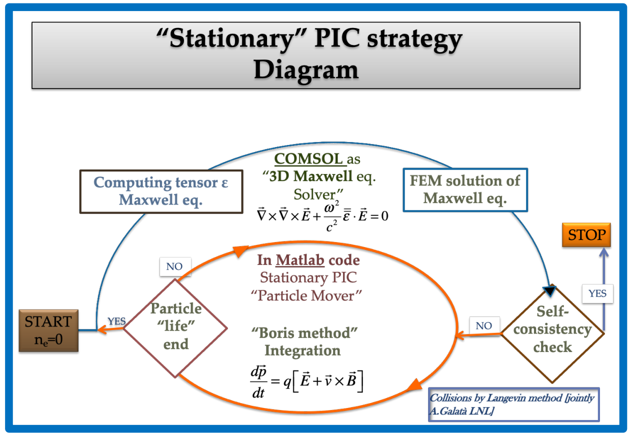
- *Supporting* ***design of new ion sources***
- ***Modelling wave-plasma interaction*** *in the ECR domain*
- ***Design of ICH antennas*** *for ECR devices*
- *Supporting* ***development of diagnostics*** *(interferopolarimetry+X-ray)*

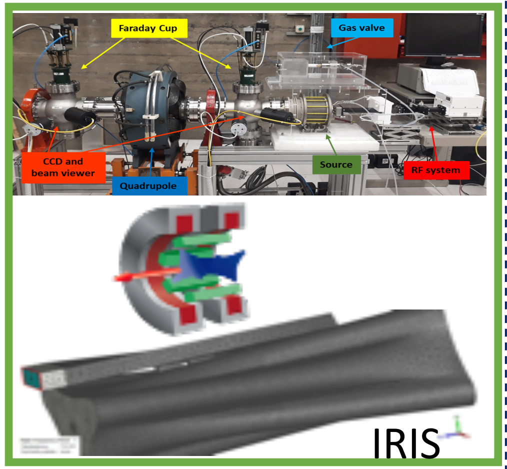
Ion Sources

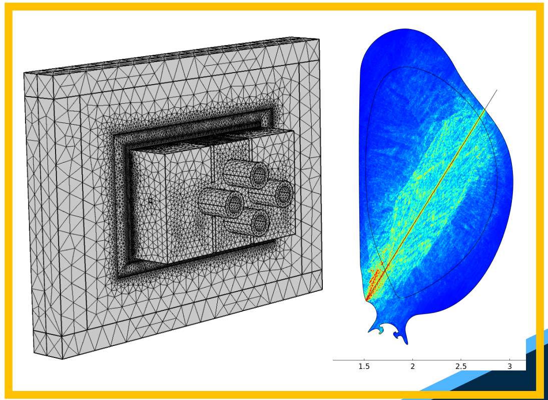
DTT

- ***Contribution to ICH-task*** *by supporting antenna design and plasma simulations (use of full-wave code)*
- *Preliminary use* ***of wave-optics tools*** *to support interferopolarimetry*
- ***Profilometry*** *by inverse scattering approach*









Theoretical study of electromagnetic propagation and related absorption mechanisms in magnetized plasmas for laboratory (fusion) and compact traps in several frequency range (AW, IC, LH, EC)

- Solution of the electromagnetic dispersion relation in the complex domain of the wave-vector* (at fixed frequency), resulting from the **Maxwell-Vlasov equation system for magnetized plasmas**
  - Wave propagation
  - Wave spatial damping

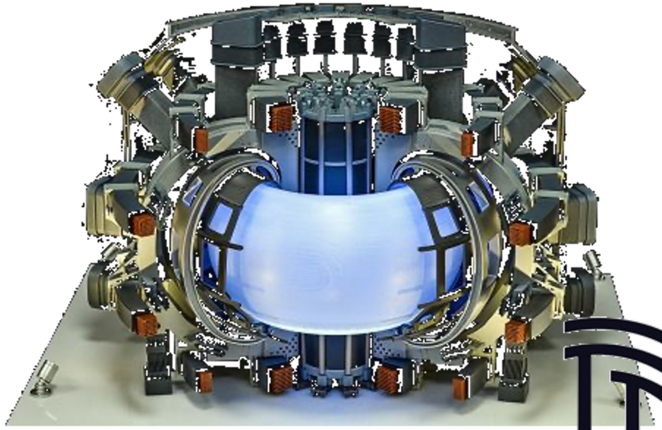
- Solution of the **electromagnetic Integro-Differential Maxwell-Vlasov equation system for magnetized plasmas in Cartesian and Toroidal geometry** with BC established by external antennas at fixed frequency°
  - Distribution of the electromagnetic field inside the plasma
  - RF Power Deposition Profiles inside the plasma

- **Solution of the 2D (in velocity space) Fokker-Planck equation** with a quasi-linear diffusion term due to the RF wave*°
  - Determination of the ion/electron distribution function under the action of electromagnetic field
  - Characterization of a fast ion/electron tail of the distribution function and consequences on wave destabilization

*A. Cardinali, DisEMag, FokPlanck numerical codes

° M. Brambilla, FELICE, TORIC, SSFPQL numerical codes

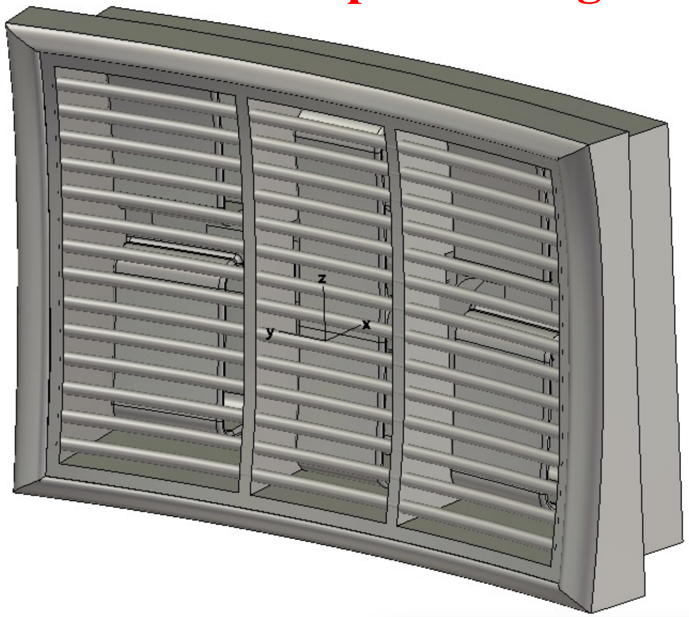
INFN-DTT at LNS

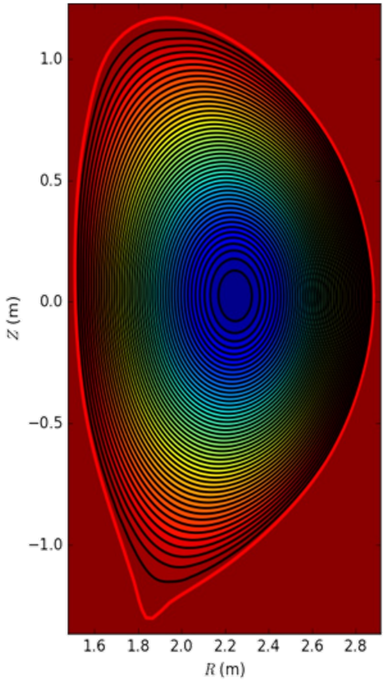


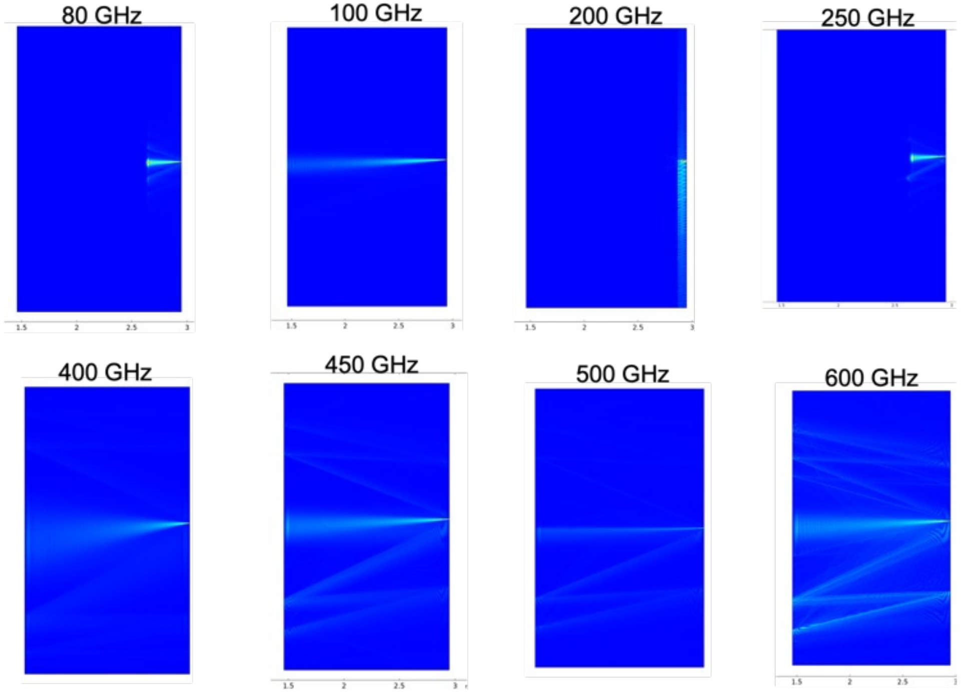
As a spin-off of R&D on plasma heating and diagnostics, <u>now coordinating LNS contribution</u> to Ion Heating, interferopolarimetry and X-ray measurements

Sub-task:

ICH Antenna Conceptual Design

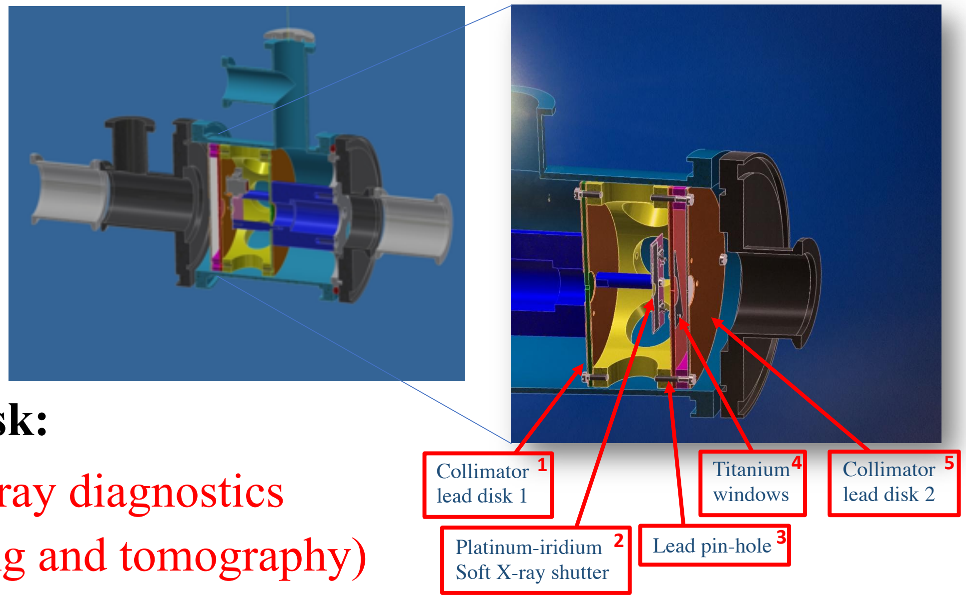






Sub-task:

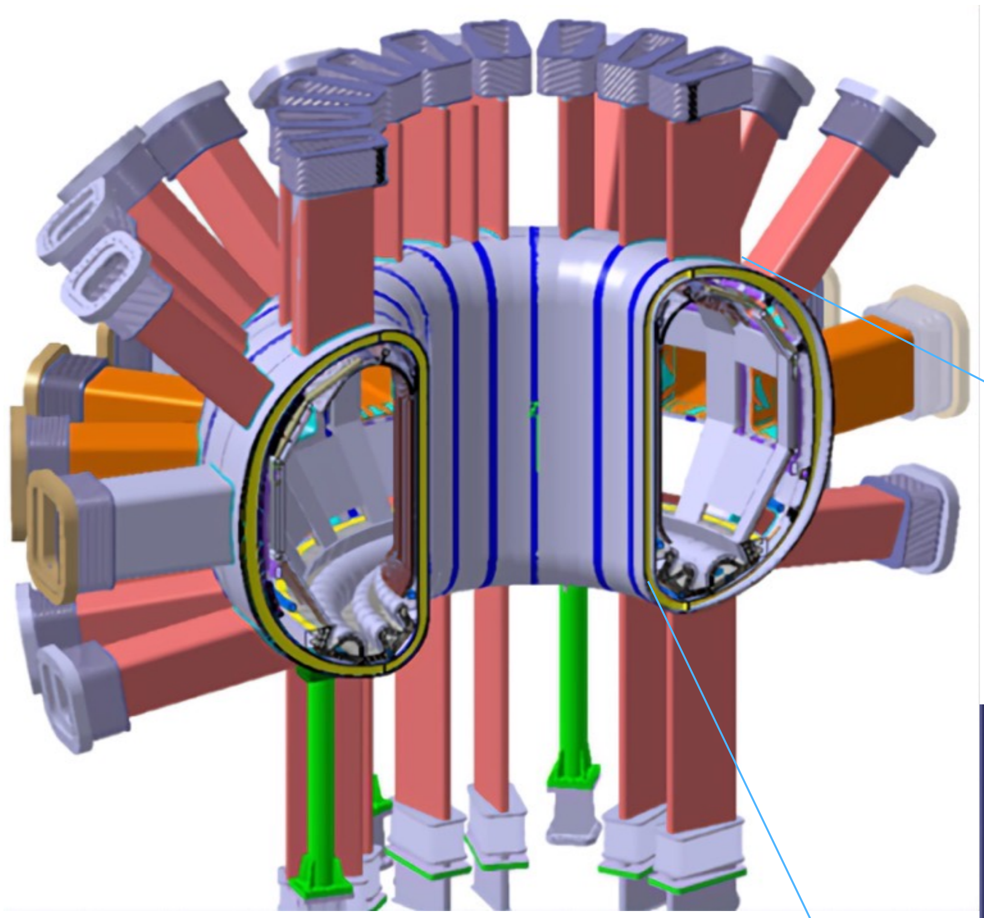
Interferopolarimetry

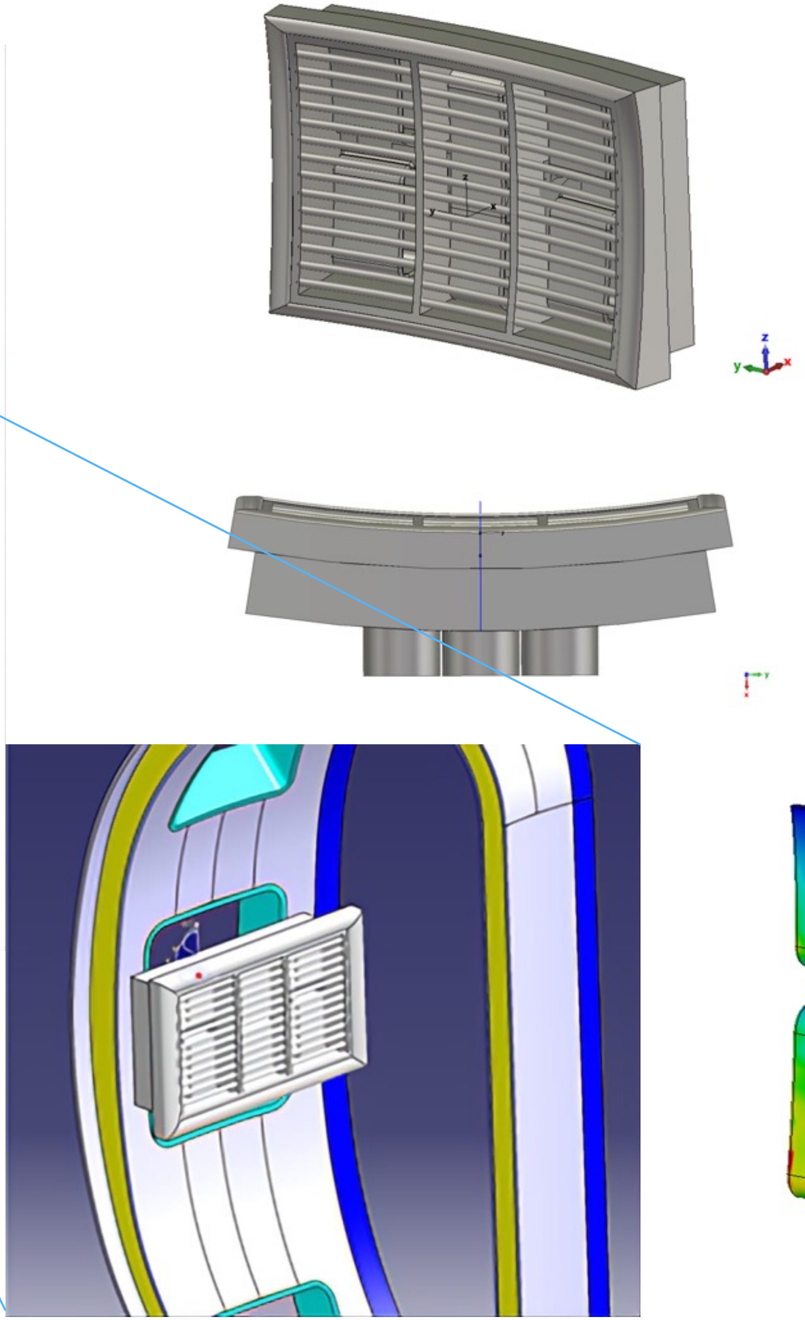


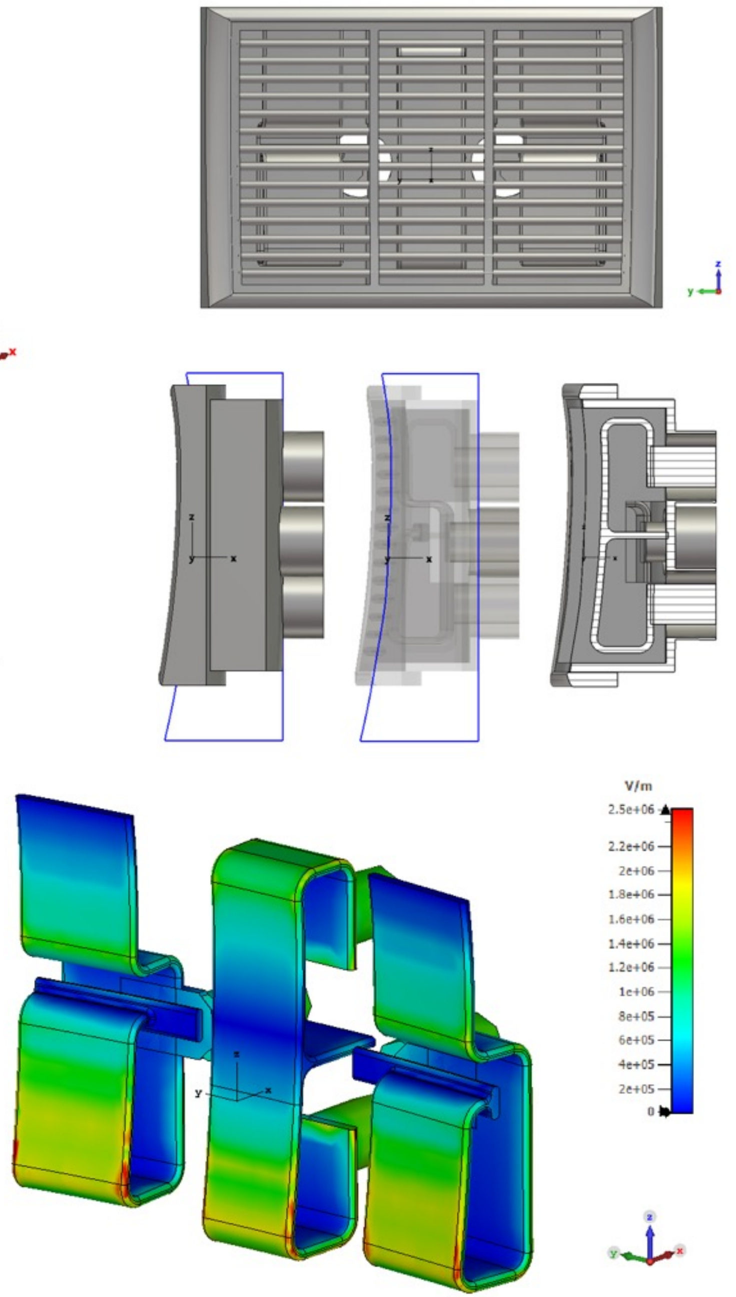
Sub-task:

Soft X-ray diagnostics (imaging and tomography)

ICH Antenna DESIGN

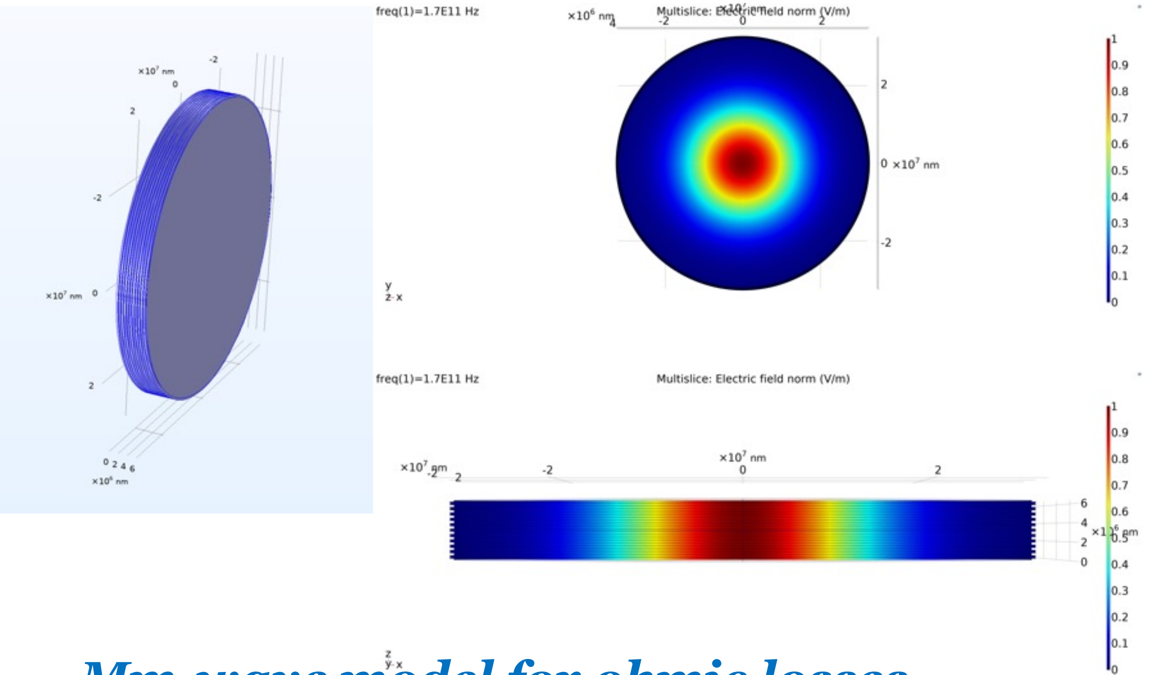




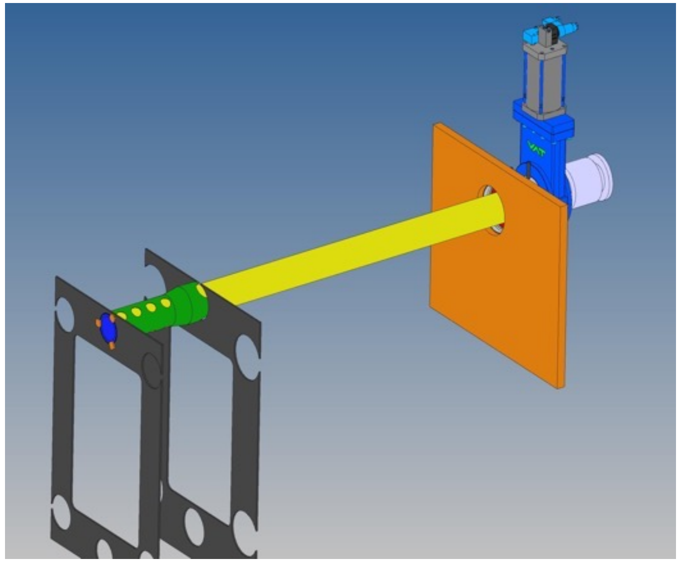


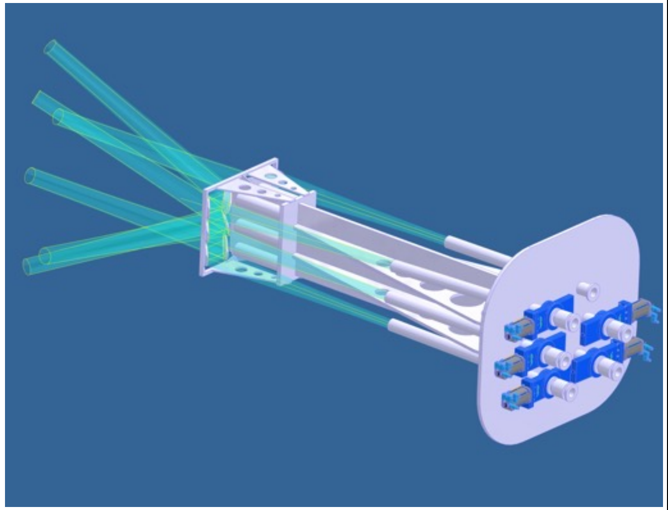
Divertor Tokamak Test Design of the **ICH Antenna**

ECH Waveguides Design



Mm-wave model for ohmic losses





Overall view from the mounting flange connection side with the centering system

Cooling and mounting/interfaces

MAIN TOPICS COLLECTED [and reference experiments]

1. New Acceleration schemes @LNS
   - **Laser-driven plasma-based acceleration** *(e-, Ions)* **and nuclear reactions** (activation, transmutation, fission and fusion processes) based on laser-matter interaction → *[I-LUCE (INFN—Laser-Induced particle acceleration) facility 100-TW-class laser (fs, 1–10 Hz, I ≥ 10^{19} W/cm2)]*:
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     - *Stopping power in warm dense matter:* important issue/property in Inertial Confinement Fusion (ICF) implosion study and design *[FUSION_GrV, SAMOTHRACE WP1].*
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3. **Polarized nuclear fusion fuel:**
   - **Innovative sources and systems, theory and experiments for fusion from polarized nuclei**

IRIS 2.0

Innovative Resonator Ion Source

INFN Partners

LNS, LNL (D. Mascali, G. S. Mauro, G. Torrisi, O. Leonardi, A. Galatà, C. S. Gallo, E. Naselli, A. Pidatella, F. Russo(1) and G. Sorbello(1,3)

EU Partners

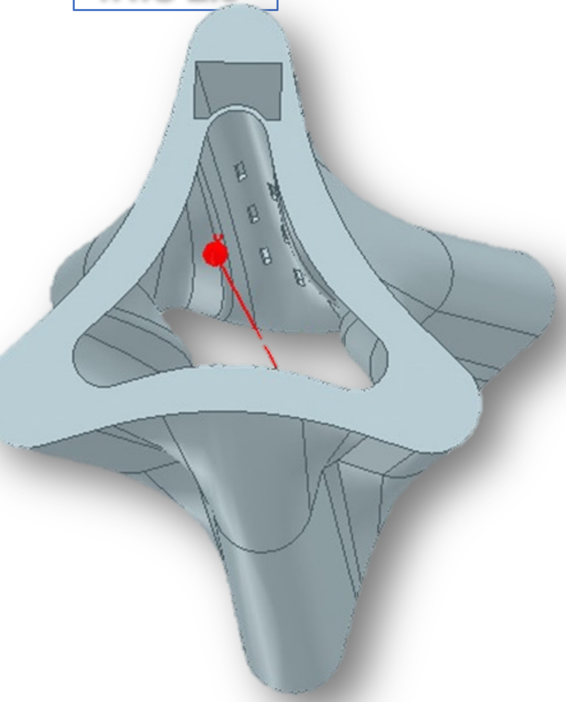
ATOMKI-Debrecen (Hungary, R. Racz, S. Biri)

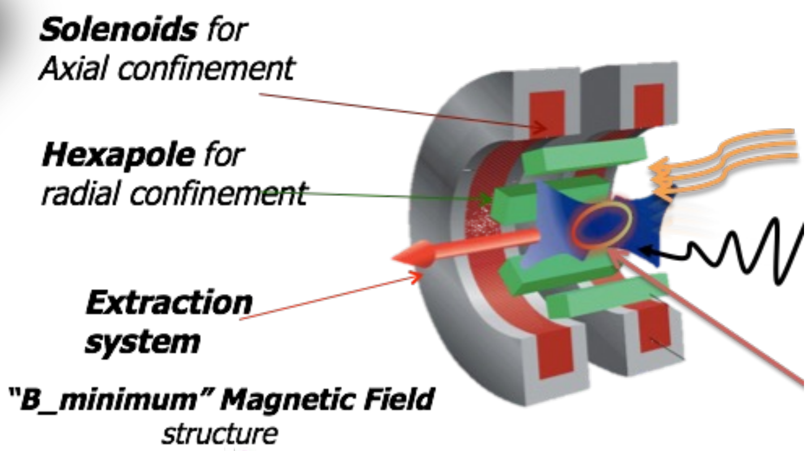
Jyvaskyla University (Finland, H Koivisto, R Kronholm)

Industrial Partners

UMAS Technology

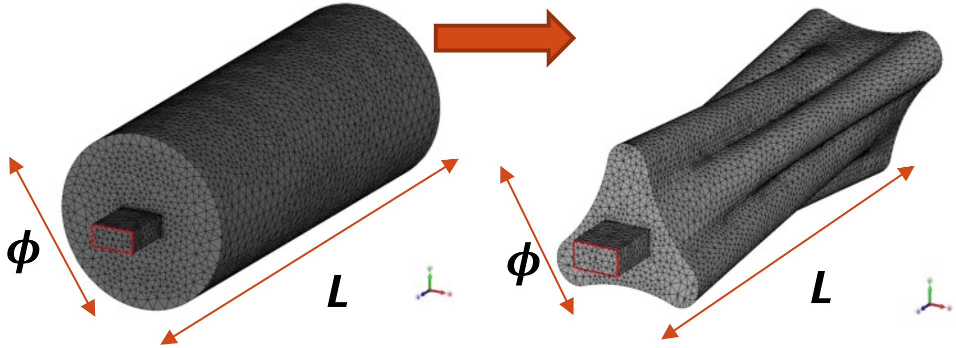
DB-Science

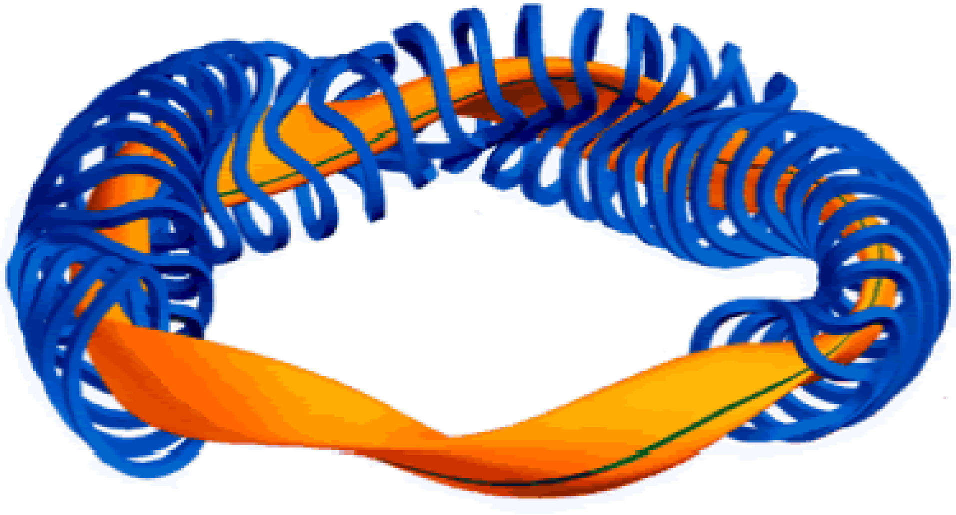




Inspired by Thermonuclear Reactors called "Stellarators"

Breaking cylindrical symmetry

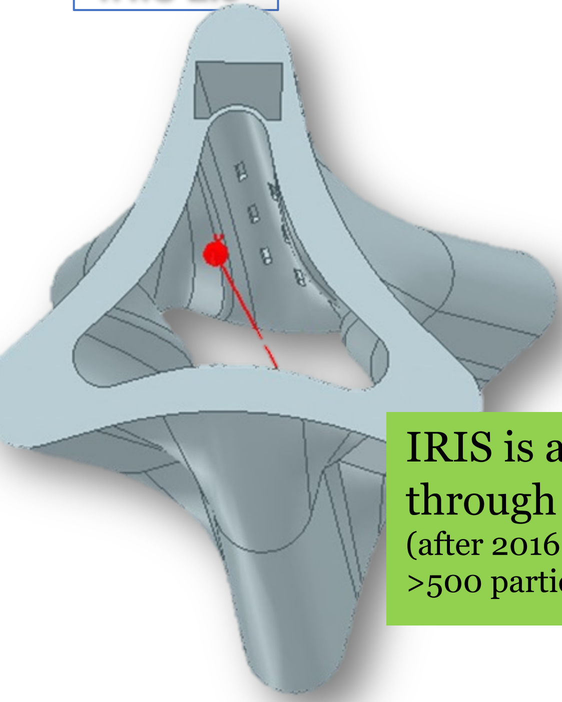




W7-SX Stellarator @ MPI-IPP

IRIS 2.0

Innovative Resonator Ion Source



INFN Partners

LNS, LNL

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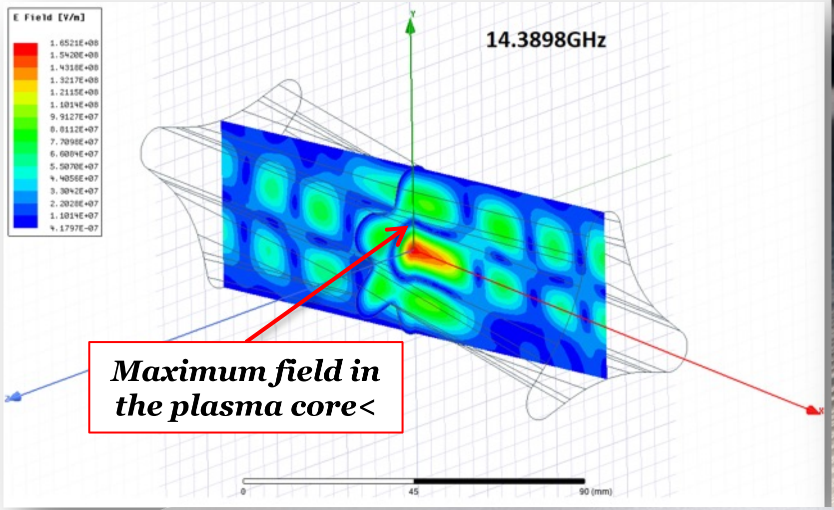
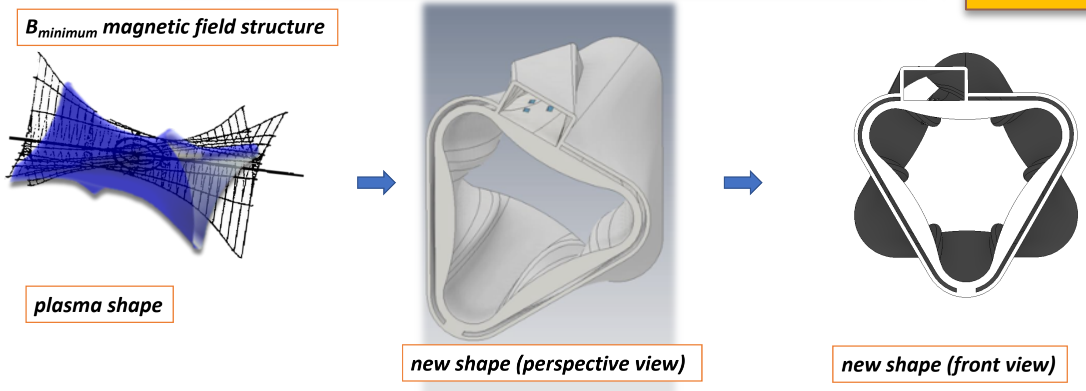
IRIS is a project supported by INFN through the competitive Grant n.73 (after 2016 selection – 7th in the final ranking over >500 participants)



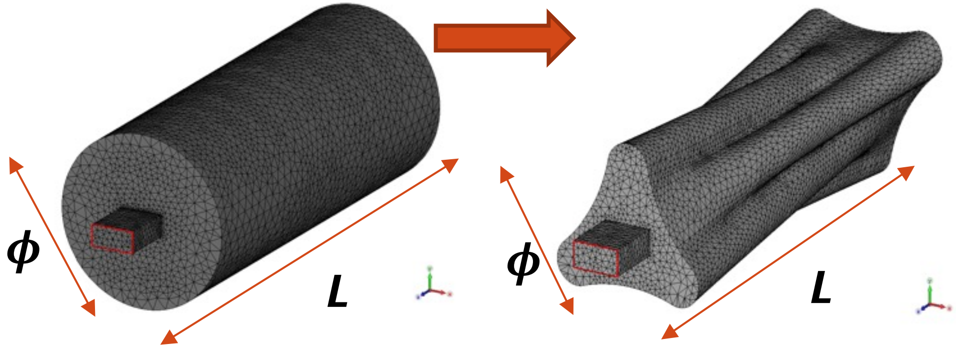
IRIS: italian patent pending n. 102020000001756

International patent pending N. PCT/IB2021/050696 // (E0130645) BRE-sz

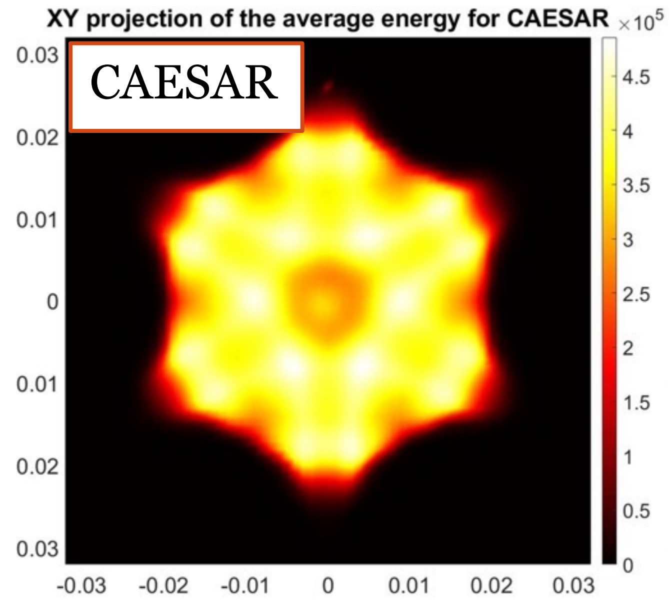
Innovative Resonator Ion Source (IRIS)

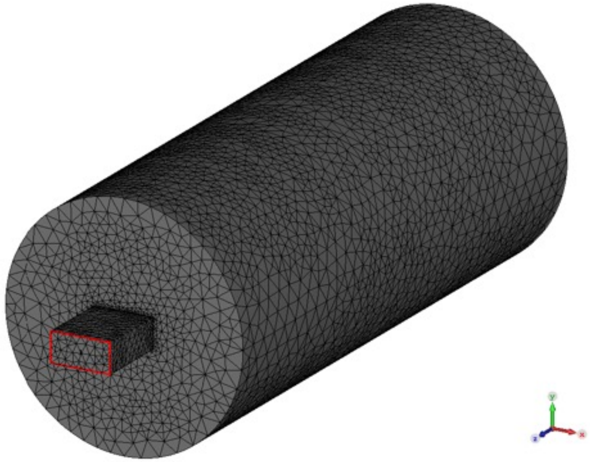


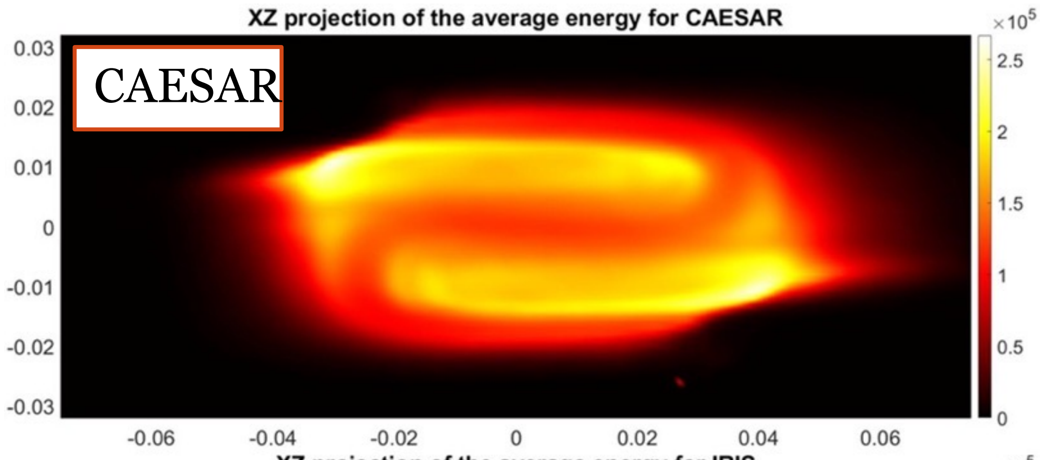
Breaking cylindrical symmetry

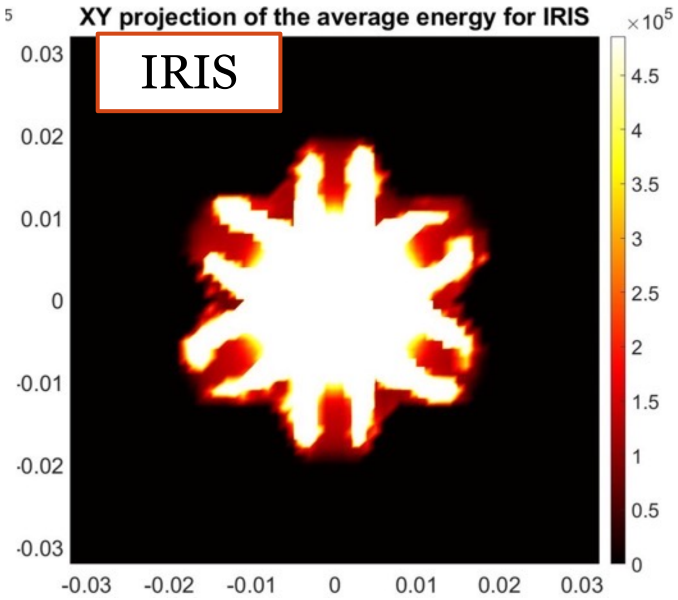


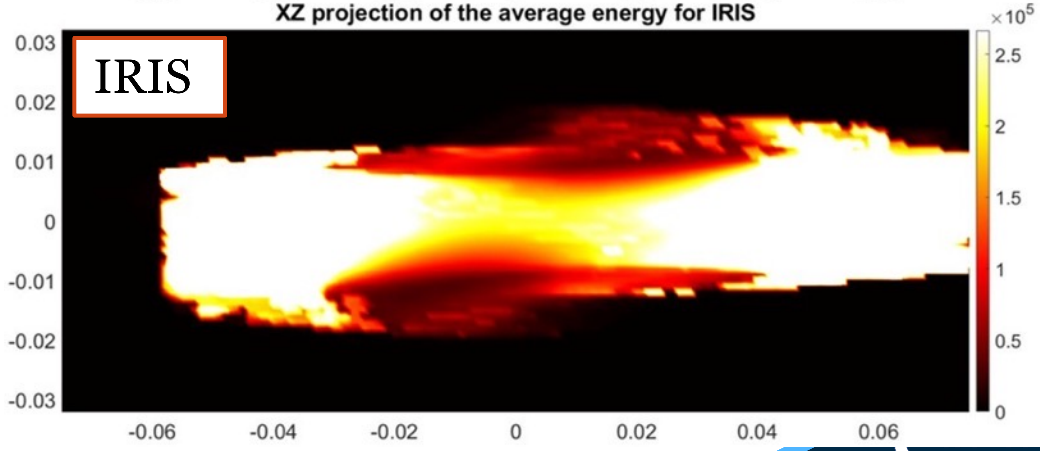
Stationary PIC simulations: Energy





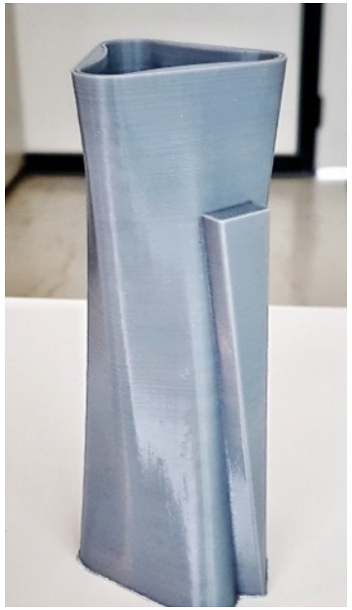


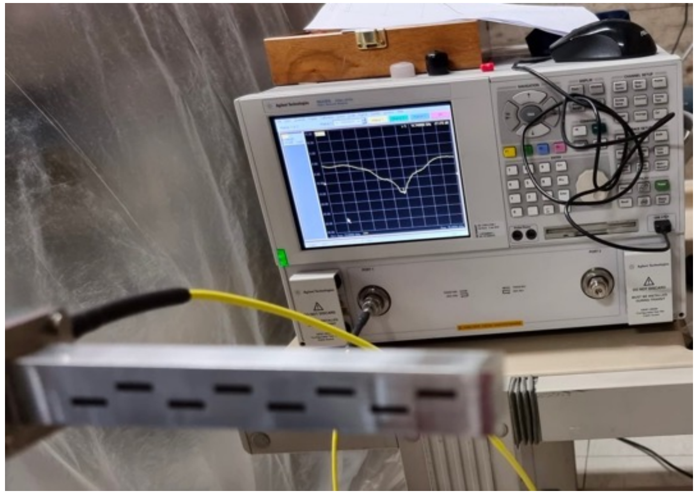


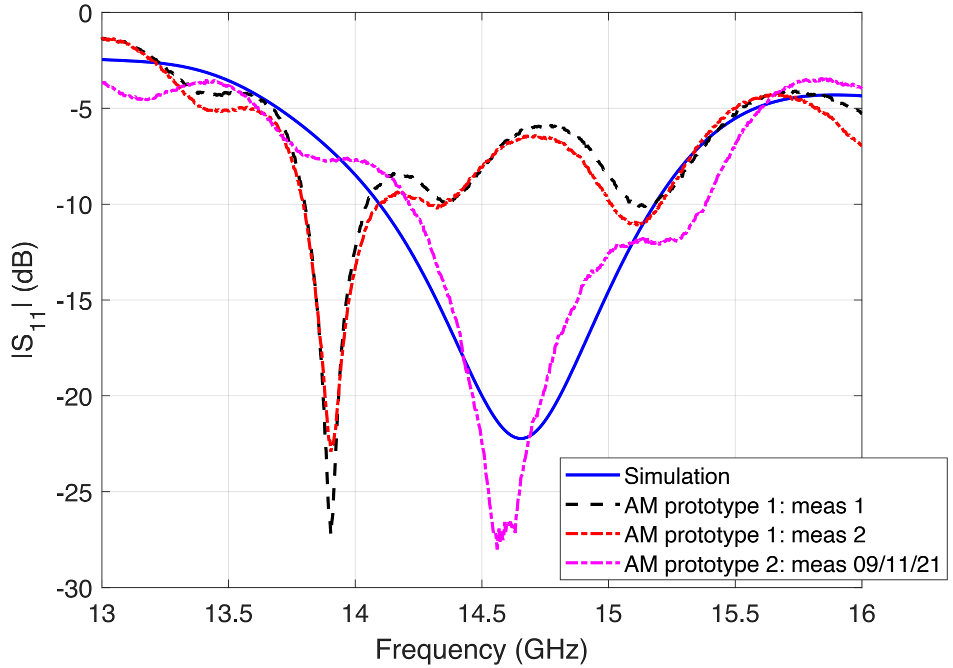


Additive manufacturing (AM)

3D printing IRSI towards 1:1 prototype







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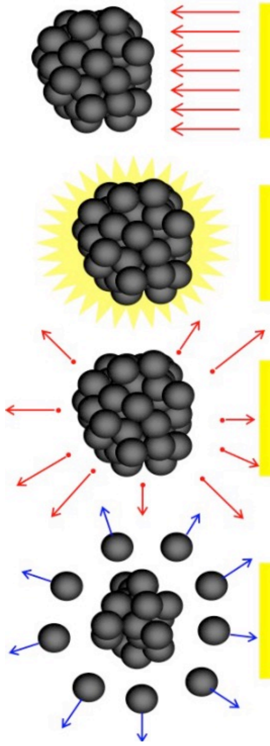
3. **Laser-cluster scenario and Polarized nuclear fusion fuel:**
   - **The Coulomb Explosion Paradigma** for the enhancement in the yield of reaction products
   - Innovative sources and systems, theory and experiments for fusion from **polarized nuclei**

Laser-cluster scenario

THE COULOMB EXPLOSION PARADIGMA
The interaction of ultra-short laser pulses with an expanding gas mixture at controlled temperature and pressure inside a vacuum chamber causes the formation of plasmas with multi-keV temperature.



Step 1
Clusters are irradiated by high intensity laser pulse (~10^{16}~10^{18} W/cm^2).

Step 2
Laser pulse energy is first absorbed by electrons via heating mechanisms such as rapid collisional heating.

Step 3
Electrons escape from the cluster and leave positive charge build-up on the cluster.

Step 4
The cluster “explodes” and deuterons acquire multi-keV kinetic energy.

It is proven that if the temperature of the cluster is close to the critical one (for the compound), the laser absorption is enhanced causing an **enhancement in the yield of reaction products**

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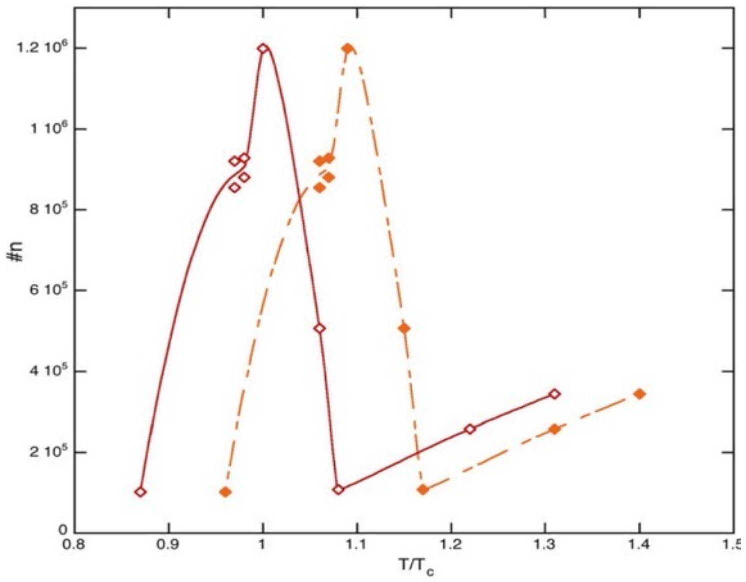
Neutron enhancement from laser interaction with a critical fluid

H.J. Quevedo [a], G. Zhang [b,1], A. Bonasera [b,c,*], M. Donovan [a], G. Dyer [a], E. Gaul [a], G.L. Guardo [c], M. Gulino [c,d], M. La Cognata [c], D. Lattuada [c], S. Palmerini [e,f], R.G. Pizzone [c], S. Romano [c], H. Smith [a], O. Trippella [e,f], A. Anzalone [c], C. Spitaleri [c], T. Ditmire [a]



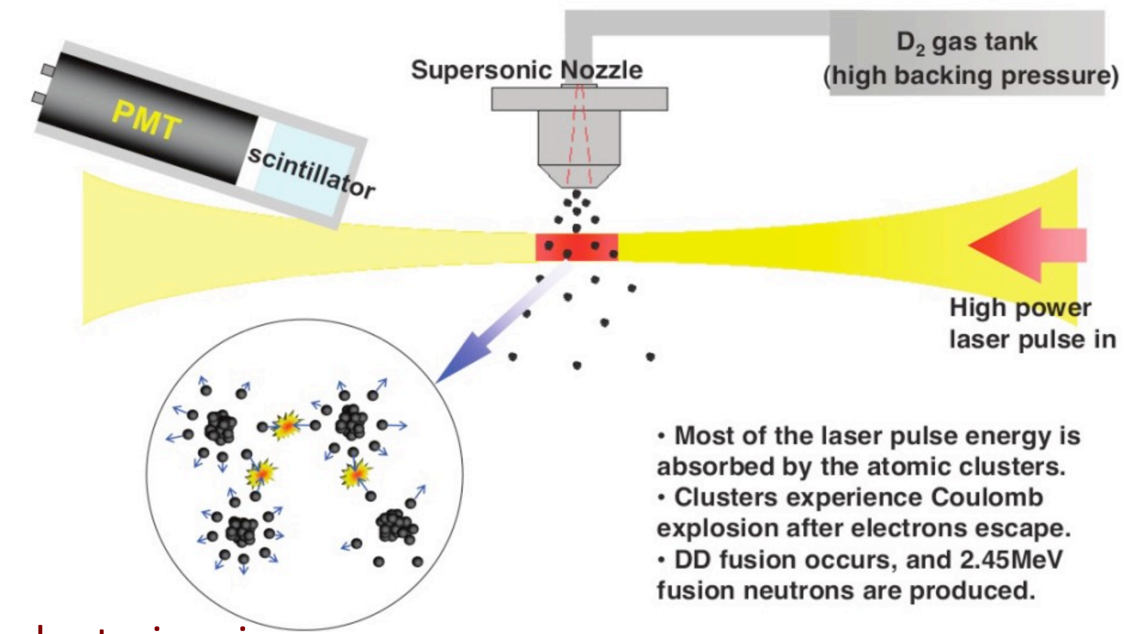
Deuterium-deuterium fusion

$$d + d \rightarrow {}^{3}\mathrm{He}(0.82MeV) + n(2.45MeV)$$

$$d + d \rightarrow p(3.02MeV) + t(1.01MeV)$$

$$d + {}^{3}\mathrm{He} \rightarrow p(14.7MeV) + {}^{4}\mathrm{He}(3.6MeV)$$

Nuclear fusion from laser-cluster interaction



- Most of the laser pulse energy is absorbed by the atomic clusters.
- Clusters experience Coulomb explosion after electrons escape.
- DD fusion occurs, and 2.45MeV fusion neutrons are produced.

PHYSICAL REVIEW C
covering nuclear physics

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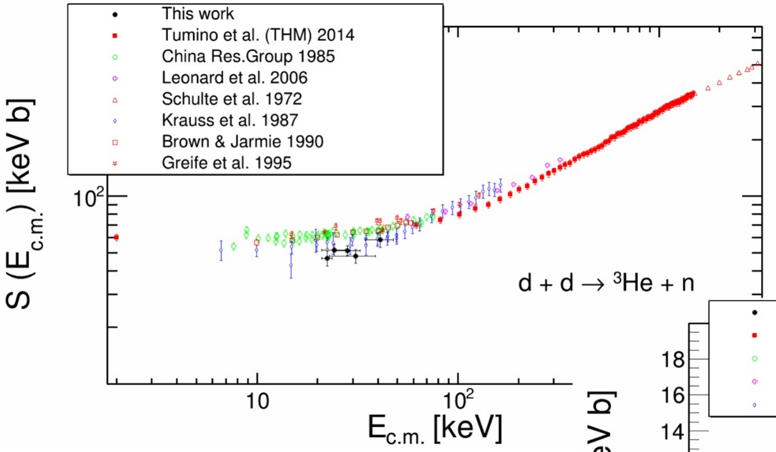
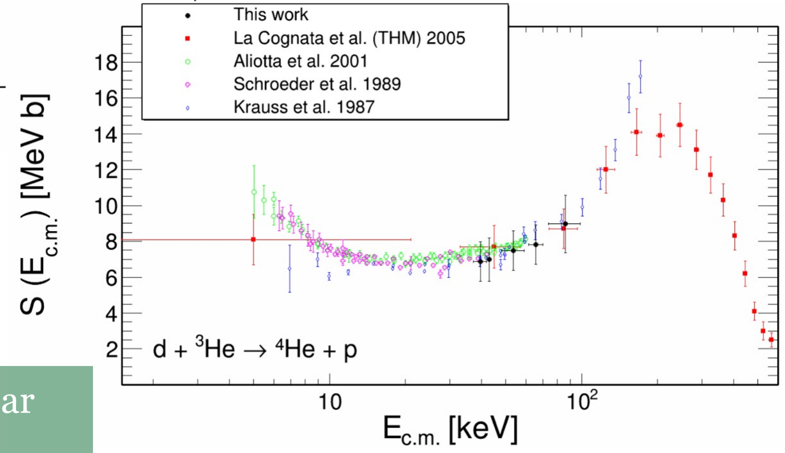
Model-independent determination of the astrophysical *S* factor in laser-induced fusion plasmas

D. Lattuada, M. Barbarino, A. Bonasera, W. Bang, H. J. Quevedo, M. Warren, F. Consoli, R. De Angelis, P. Andreoli, S. Kimura, G. Dyer, A. C. Bernstein, K. Hagel, M. Barbui, K. Schmidt, E. Gaul, M. E. Donovan, J. B. Natowitz, and T. Ditmire

Phys. Rev. C **93**, 045808 – Published 19 April 2016

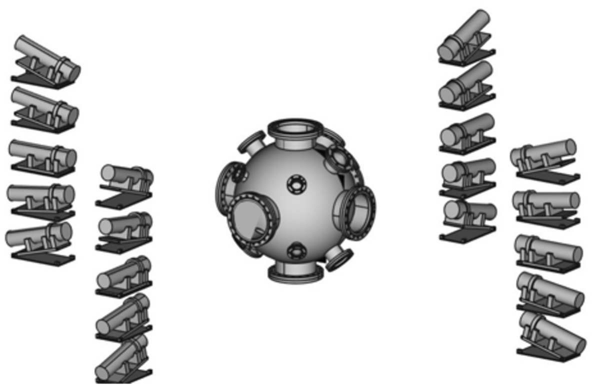




deuterium ions
Kinetic Energy < 10^2 keV
Density ~ 10^{18} atoms/cm^3
10^5-10^7neutrons per shot

This method will open the way for a new approach to study nuclear reaction of interest for energy production such as d+d or p+11B
In addition, the same reactions can be explored by means of the Trojan Horse Method

Versatile Array for Laser-induced Astrophysics Research



Science-driven, portable, cost-efficient

- cryo-cooled supersonic nozzle
- compact interaction chamber
- neutron ToF detectors (plastic/liquid scintillators)
- charged particle ToF detectors (SiC/CVD diamond detectors + FCs)
- 2 TPS
- (CR39 for checks/normalization)

The AsFiN laser collaboration:
A. Bonasera, G.L. Guardo, M. La Cognata, L. Lamia, D. Lattuada, A.A. Oliva, R.G. Pizzone, G.G. Rapisarda, S. Romano, D. Santonocito, A. Tumino

Moreover, in the framework of the POL-fusion experiment (under the coordination of **Prof. G. Ciullo**), it is possible to investigate the enhancement in the d+d reaction cross section with polarized beam.

R&D di acceleratori per applicazioni energetiche ai LNS

Giuseppe Torrisi, INFN-LNS

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Sud

THANK YOU