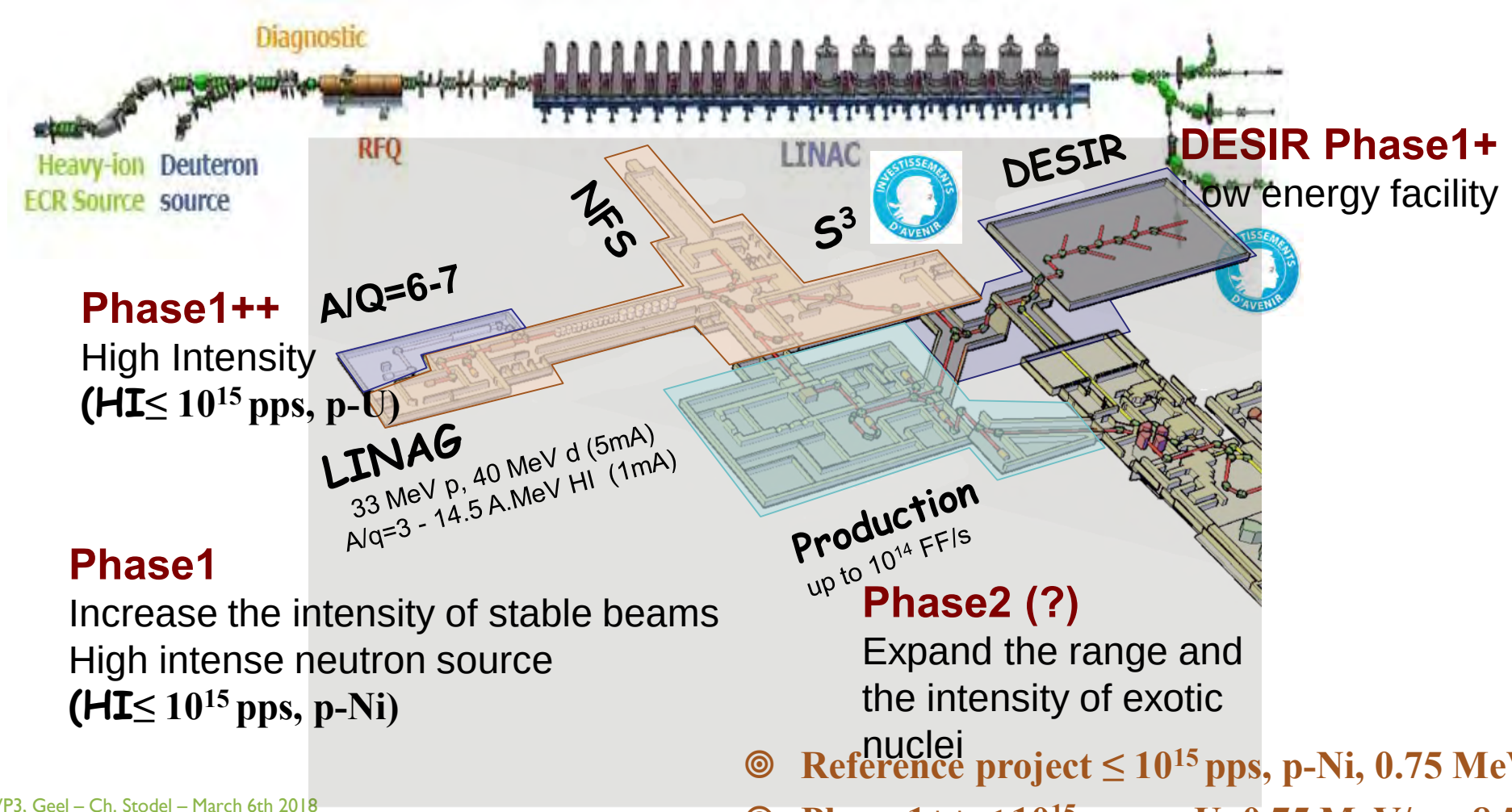
TARGET DEVELOPMENT FOR S³

CH. STODEL, GANIL & CO

Context
I - Target's Stations
II - Targets' Monitoring
III - Targets' Fabrication
Conclusions

SPIRAL2 FACILITY



DESIR Phase1+
Low energy facility

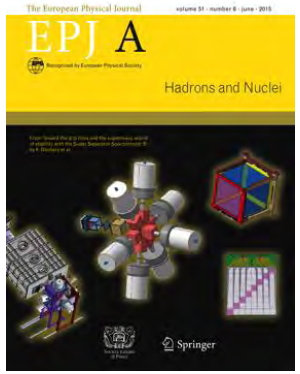
Phase1++
High Intensity
(HI≤ 10^{15} pps, p-U)

Phase1
Increase the intensity of stable beams
High intense neutron source
(HI≤ 10^{15} pps, p-Ni)

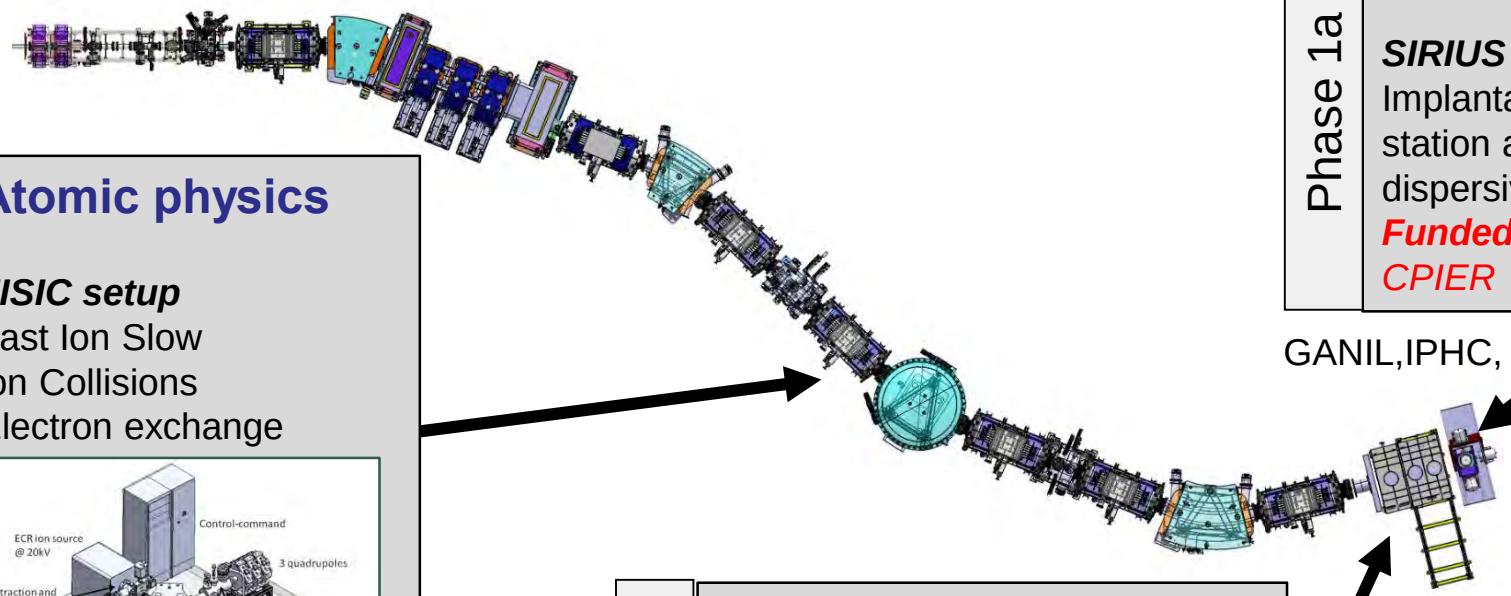
Phase2 (?)
Expand the range and the intensity of exotic nuclei

- **Reference project ≤ 10^{15} pps, p-Ni, 0.75 MeV/n – 14.5 MeV/n**
- **Phase 1++ ≤ 10^{15} pps, p-U, 0.75 MeV/n – 8.5 MeV/n**

S^3 : SUPER SEPARATOR SPECTROMETER
for the study of rare events for atomic and nuclear physics



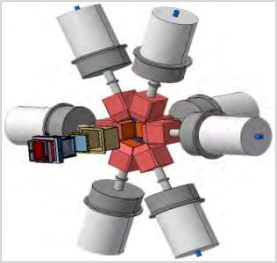
Eur. Phys. J. A (2015) 51: 66



Phase 1a

Delayed spectroscopy

SIRIUS setup
Implantation-decay station at the mass dispersive plan
Funded by new CPIER

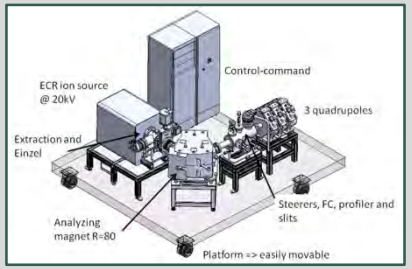


GANIL,IPHC, CSNSM, CEA/Irfu/SPhN

Phase 2

Atomic physics

FISIC setup
Fast Ion Slow
Ion Collisions
Electron exchange



Partially Funded
INSP-CIMAP-JENA/GSI
+ new CPIER

Phase 1b

Ground state properties
(mass, size, moments, spins)

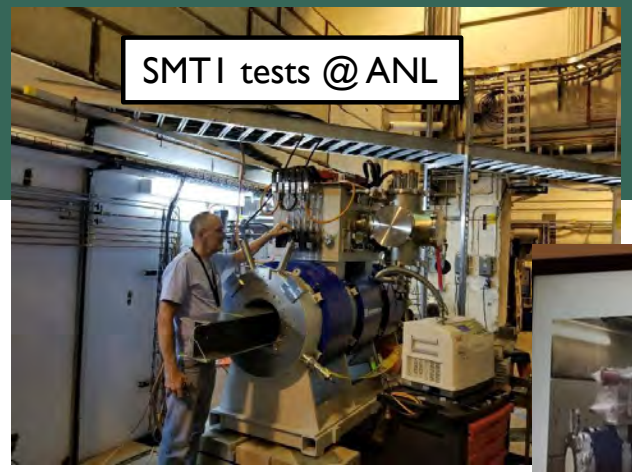
REGLIS³ setup
Low Energy
Branch
Funded

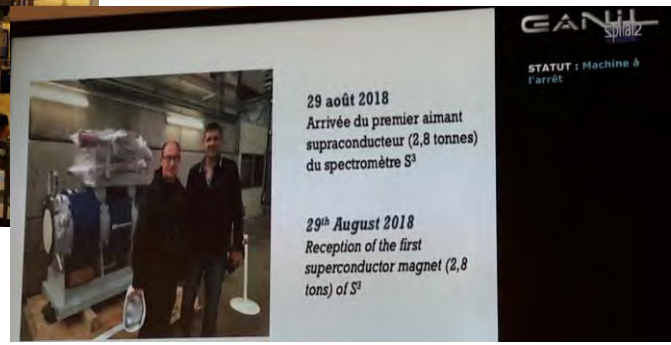
DESIR

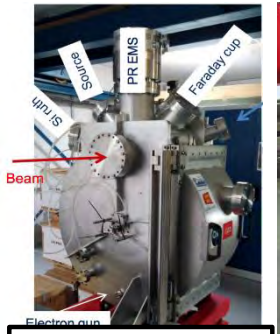
Full assembly & tests planned in 2020


S3-LEB @ LPC


Mdipole @ S3


SMT1 tests @ ANL

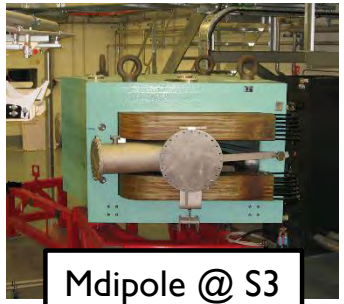




Target System @ GANIL

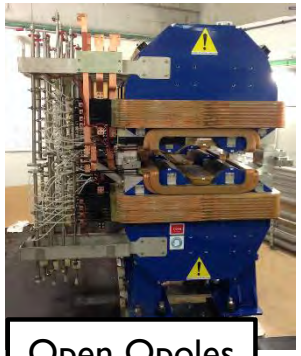

Beam dump @ Irfu


PSS @ AML


Mdipole @ S3

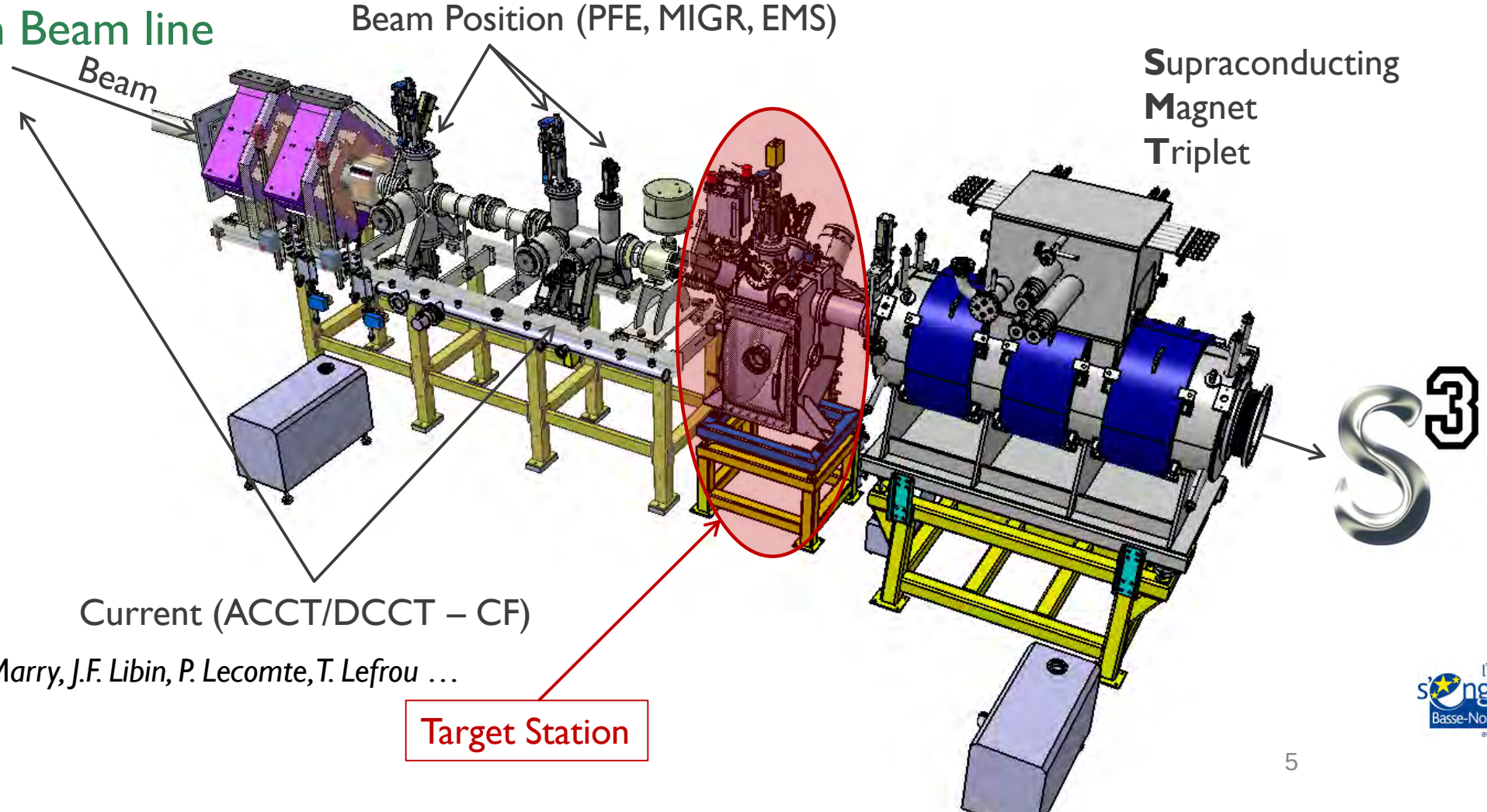

Installation @ S3


Cold Box @ S3


Open Qpoles @ S3


Edipole @ IPNO

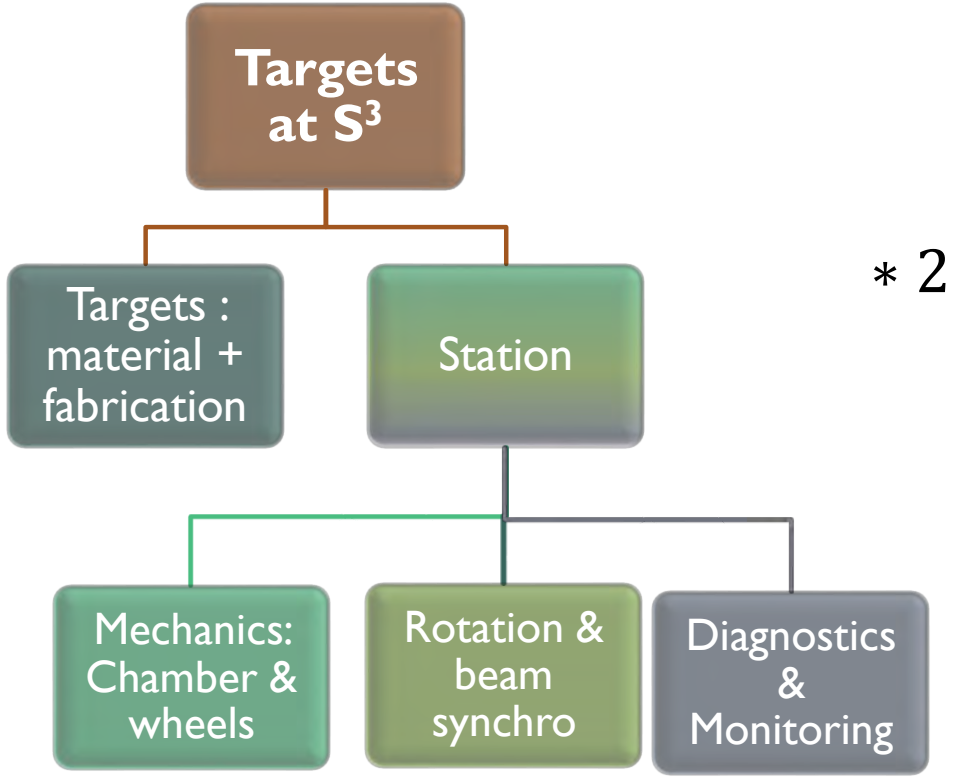
S^3 : SUPER SEPARATOR SPECTROMETER – PART I == TARGETS



F. Lutton, P.Gangnant, C. Marry, J.F. Libin, P. Lecomte, T. Lefrou …

WORKPACKAGE « TARGETS @ S3 »

- **Aim:** Development & exploitation of targets for S^3, including the station, while ensuring their integrity



$* 2$

- Targets @ S3 for 1st day …. Experiments
  - Low Energy Branch

    ^{50}Cr (1 mg/cm² = 110 W), ^{58}Ni, ^{nat}Zn, ^{96}Mo, ^{175}Lu, ^{178,180}Hf,

    $^{206-208}$Pb, ^{209}Bi, ^{208}Pb (250µg/cm² = 6 W),

    ^{238}U (250 µg/cm² = 3,4 W)

  - SIRIUS

    ^{58}Ni, ^{164}Yb/^{170}Er, ^{96}Ru, ^{92}Mo, ^{206}Pb, ^{209}Bi, ^{204}Pb (PbS) (300-500 µg/cm²= 30 W), ^{207}Pb (PbS) (400 µg/cm² = 54 W), ^{208}Pb (PbS) (375 µg/cm²= 6,4 W), ^{209}Bi (Bi203) (440 µg/cm²= 8 W),

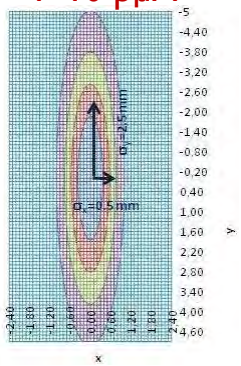
    ^{232}Th (400 µm = 150 W), ^{238}U,

    ^{248}Cm (200-300 µg/cm² (+Ti 1,5 µm) = 45-63 W), ^{243}Am (350 µg/cm² (+Ti 1,5 µm)= 150 W)

STABLE TARGET STATION

- **Aim:** Development & exploitation of targets for S^3, including the station, while ensuring their integrity

σ_t = 0.5 mm
σ_r = 2.5 mm
I=10 pμA



Targets Fabrication

Thickness ±5%

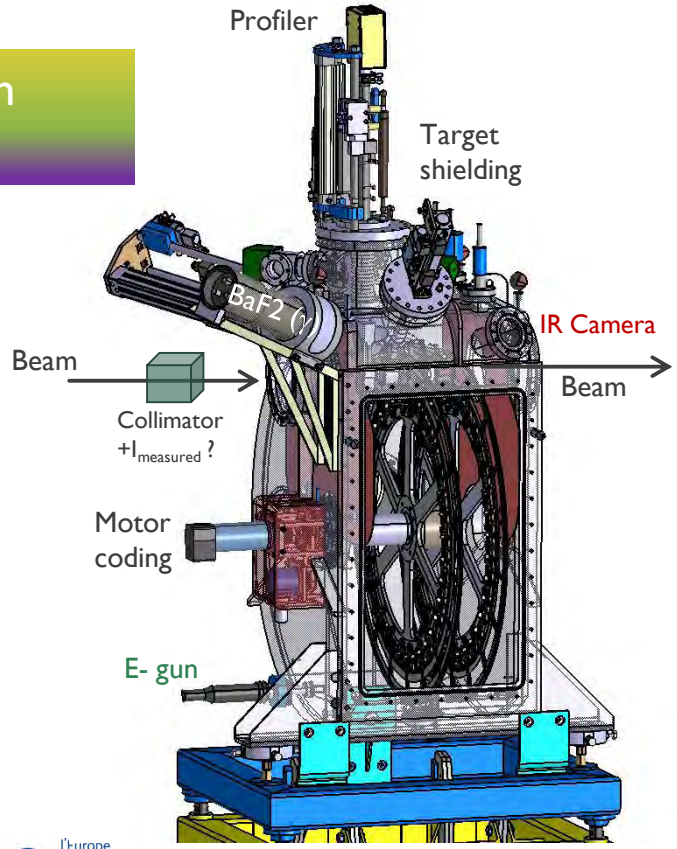
- ✓ SHE: 300-500 μg/cm²
  N=Z : mg/cm²
  Stripper: 30-100 μg/cm²
- ✓ 109*20 mm²

Stable Target Station & diagnostics

Thermal calculation

Φ= 670 mm
ω = 3000 rpm

- ✓ Vacuum : 10^{-7} / $5*10^{-8}$ mbar
- ✓ Distance : 900 mm max
- ✓ Height under beam : 1500 mm± 15
- ✓ Removable sectors
- ✓ Movable and adjustable station

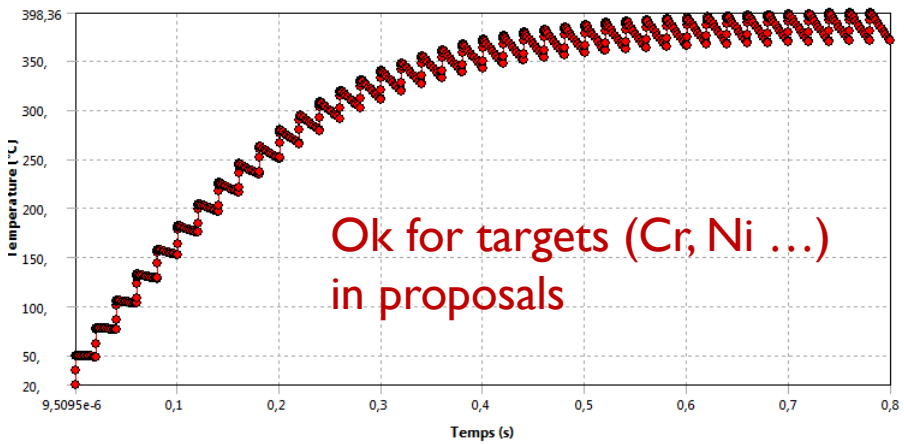


Design Chambre à Cibles Stables / P.Gangnant

DESIGN CASES (STABLE): σ_t = 0.5 mm / σ_r = 2.5 mm - I=10 pμA
Φ = 670 mm - ω = 3000 rpm

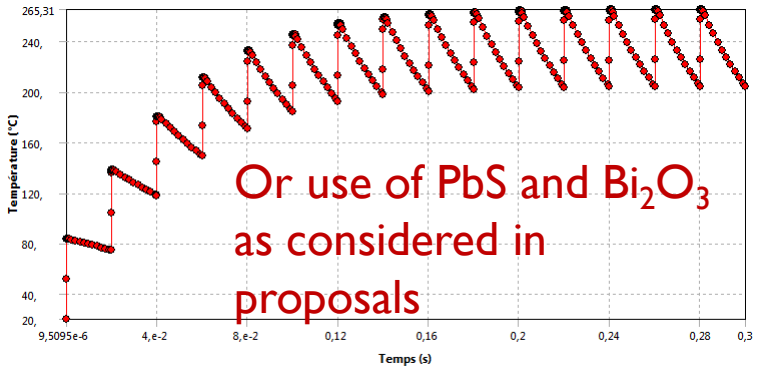
Case 1: T_{fus} high – dP > 100 watts (N=Z)

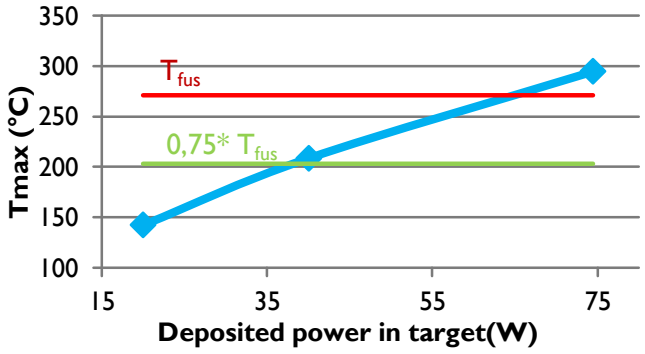
			MeV	P(W)
Beam	^{48}Ca	5MeV/A	240	2400.00
Targets	Ti	2 μm	12.238	122.38
	U	0,15μm	2.1272	21.27
	C	0,05μm	0.2	2.00
Deposited power				145.65



Case 2: T_{fus} (Bi) – dP < 100 watts (SHE)

			MeV	P(W)
Beam	^{70}Zn	5MeV/A	350	3500.00
Targets	C	0.133 μm	1.03	10.3
	Bi	0,46μm	6.06	60.6
	C	0,044μm	0.35	3.5
Deposited power				74.4



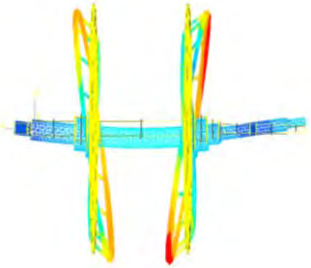


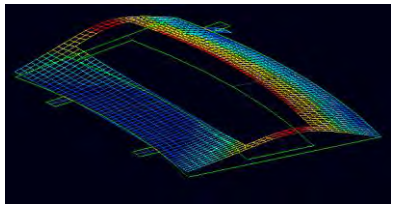
*M. Michel, «Tenue thermique cibles stables S3,» S3-NT-8514-I035728V2.0, 2014.

MECHANICS (STABLE): CHAMBER & WHEELS

- Achievements 2014-16:
  - Conception/Fabrication
  - Vacuum definition & material
  - Vibratory Analysis (SAMCEF): frames, axis, wheels*
  - Wheel balancing: class G2.5 == 0,06 mm/s @1500 rpm

    1 resonance @ 2300±100 rpm (no ground bolting)
- On going - To be done:
  - In Lab: Assembling of equipment, vacuum tests, vibratory tests…
  - Implantation & tests @ S^3 (after the 1st SMT)



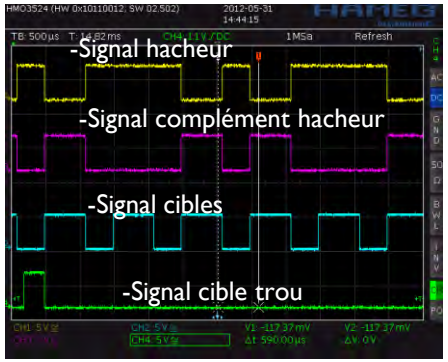


V. Jean, «Caractérisation de cibles tournantes utilisées dans des expériences de physique nucléaire sous vide poussé,» Caen, 2010 (ENSMA Poitiers).

ROTATION & BEAM SYNCHRONIZATION (STABLE)

- Achievements :
  - Acquisition of motor's material including controller modules (compact RIO from NI)
  - Programming:
    - C&C: velocity, choice of target's irradiation modes (beam on/off) *
    - Monitoring*
    - Output anlogic signals

*G. Clusier, «Conception sous LABVIEW d'une supervision pour station-cibles,» Caen, 2012.



- To be done:
  - In lab : Longevity test (endurance) @3000 rpm
  - @S³: Coupling and tests with ECSF LINAG

ACTINIDE TARGET STATION

- Considerations: ^{232}Th, ^{238}U, ^{243}Am, ^{248}Cm, $^{239/242/244}Pu$

0,3 - 0,5 mg/cm² ≈ 25 mg ≈ 10^2 –10^8 Bq

Material Supply

ORNL / Dubna

Target fabrication

Thickness ±5%

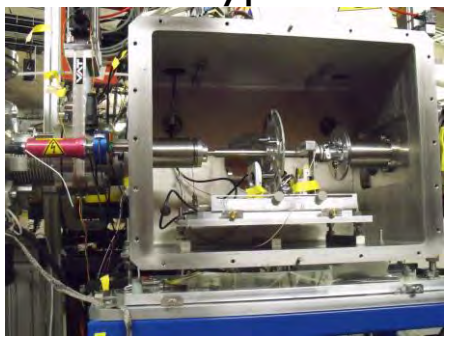
✓ SHE: 300-500 µg/cm²
✓ Method: + backing : Ti <2 µm
✓35*15 mm²

Actinide target station + diagnostics

Thermal Calculation

Φ= 150 mm
ω = 5000 rpm

Prototype



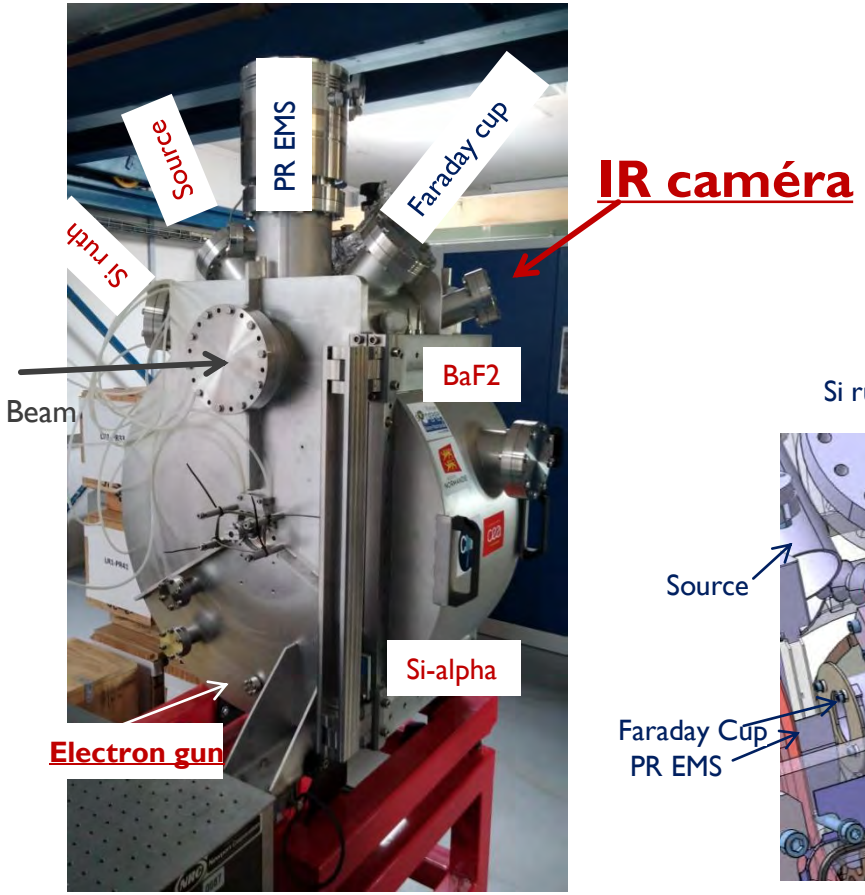
J. Radioanal. Nucl. Chem. 2015, Volume 305, Issue 3, pp 761-767

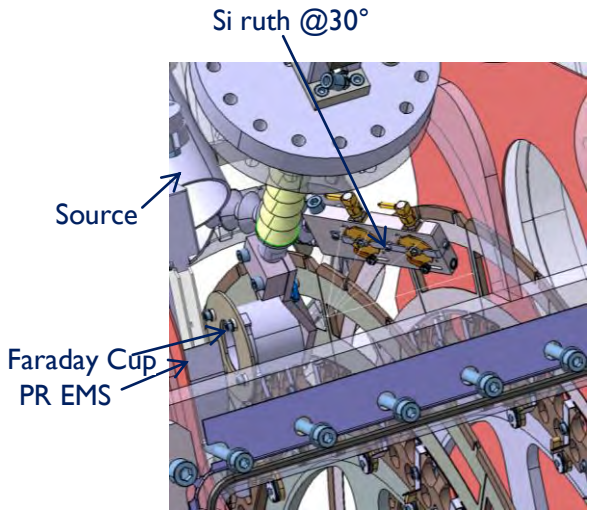
- ❑ 2016 – 2017 – 2018 : **ANR** TACTIC – PRCI TATTOO (slides below)
- ❑ « Consortium » between experts

- ❑ **Article 26:** authorisation for the use of actinide at S^3

- ❑ 2019 ….: **Actinide Station** : design, fabrication

DIAGNOSTIC & MONITORING





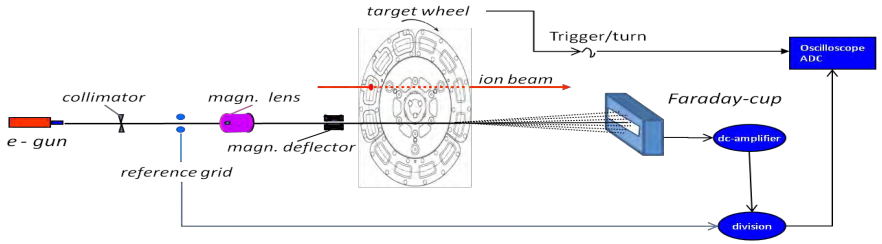
- For 1st experiments :
  - Beam properties with profilers, Faraday Cup, collimator
  - Target thickness/structure: alpha energy loss, Scattered beam, electron transmission
  - Beam synchronization: γ detection
- On going - To be done:
  - Integration of equipment
  - Insertion commands
  - Signal processing & Data Acquisition (NUMEXO2*)
  - Tests
  - IR camera measurements (beam profile, Ttargets)

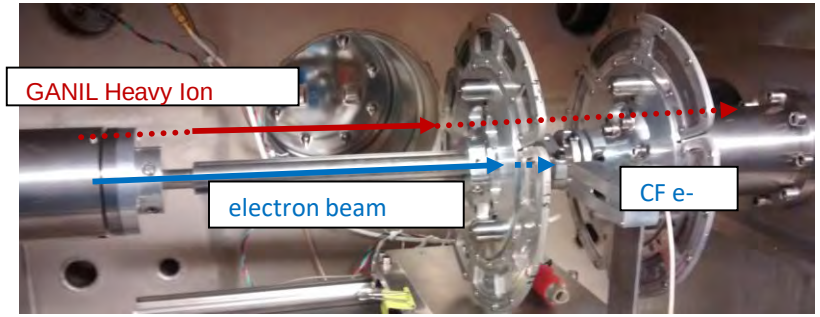
*C. Houarner, « Specifications liées au FPGA V6 (Protocoles, IPs...) pour CIBLE-S3 - Ver 13,» http://wiki.ganil.fr/gap/wiki/cible, Caen, 2017.

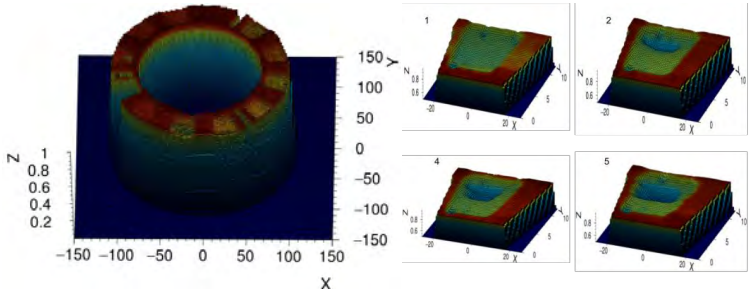
DIAGNOSTIC & MONITORING – *ELECTRON GUN*

Electron Gun - R. Mann (patent DE 10242962 A1-GSI) [9, 10]

Principle : measuring attenuation of electron current using angular scattering and absorption *resolution (≤ 0.4mm , 15µs)*







- Achievements :
  - Tests with intense heavy ion beams *
  - Operation principal demonstrated *
  - Electronic working functions **

- On going - To be done:
  - Upgrade of the existing e-gun for targets' R&D
  - Reception of a « commercial » e-gun for reliable operation

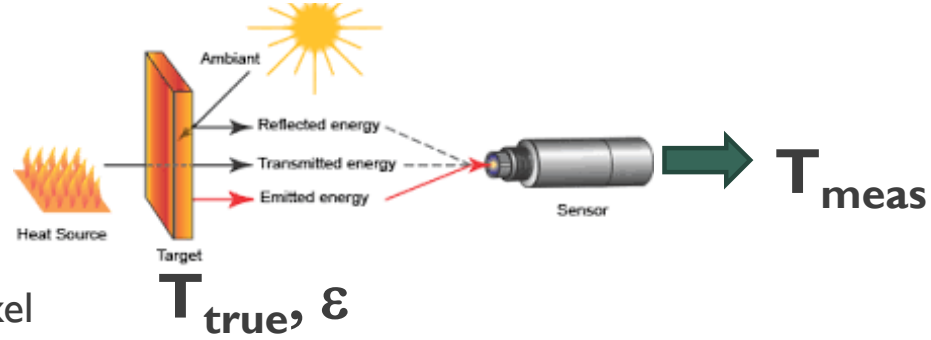
*C. Stodel et al, «High Intensity targets stations for S3,» J. of Radioanal. and Nuc. chem., vol. 305, n°3, pp. 761-767, 2015.

J. Kallunkathariyil et al, «S^3 Target Monitoring with an Electron gun,» AIP Conf. Proc. 1962, 030019-1-9 (2018); doi 10.1063/1.5035536

**A. Lebehot, T. Lefrou, Y. Georget et C. Stodel, «Caractérisation d'une chaîne de mesure autour d'un canon à électrons,» Caen, 2016

DIAGNOSTIC & MONITORING – *IR CAMERA*

R&D thermal camera



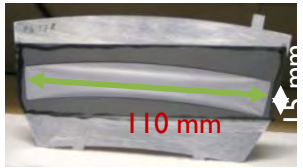
- Achievements:
  - <u>FLIR SC7000</u>:
    - 1.5 à 5 µm;
    - 5-1500°C;
    - 320*256: 380 Hz or 80*64: 3500Hz = Resolution of 0.3mm per pixel
  - Preliminary measurements of emissivity, window transmission & reflectivity with external heating, temperature with various set-up *
- To be done:
  - Can we control target temperature under irradiation ?: Temperature = fct (emissivity)
  - Can we measure beam spot dimensions?
  - How to deport it ? Resolution (spatial and temperature) after deport ?
  - Analysis of images for decision

**C. Leveille, C. Stodel et T. Lefrou, «Mise en œuvre d'une caméra thermique pour cibles tournantes S3,» Caen, 2016.*
+ E. Duguet,, O. Bajeat, Ch. Stodel « Thermal measurements of heated materials with pyrometers and IR camera », April-June 2018

TARGETS: MATERIAL & FABRICATION

- ✓ Next « Chanda » with WP targets nuclear data + …..
- ✓ INTDS Community
- ✓ ORNL / Dubna

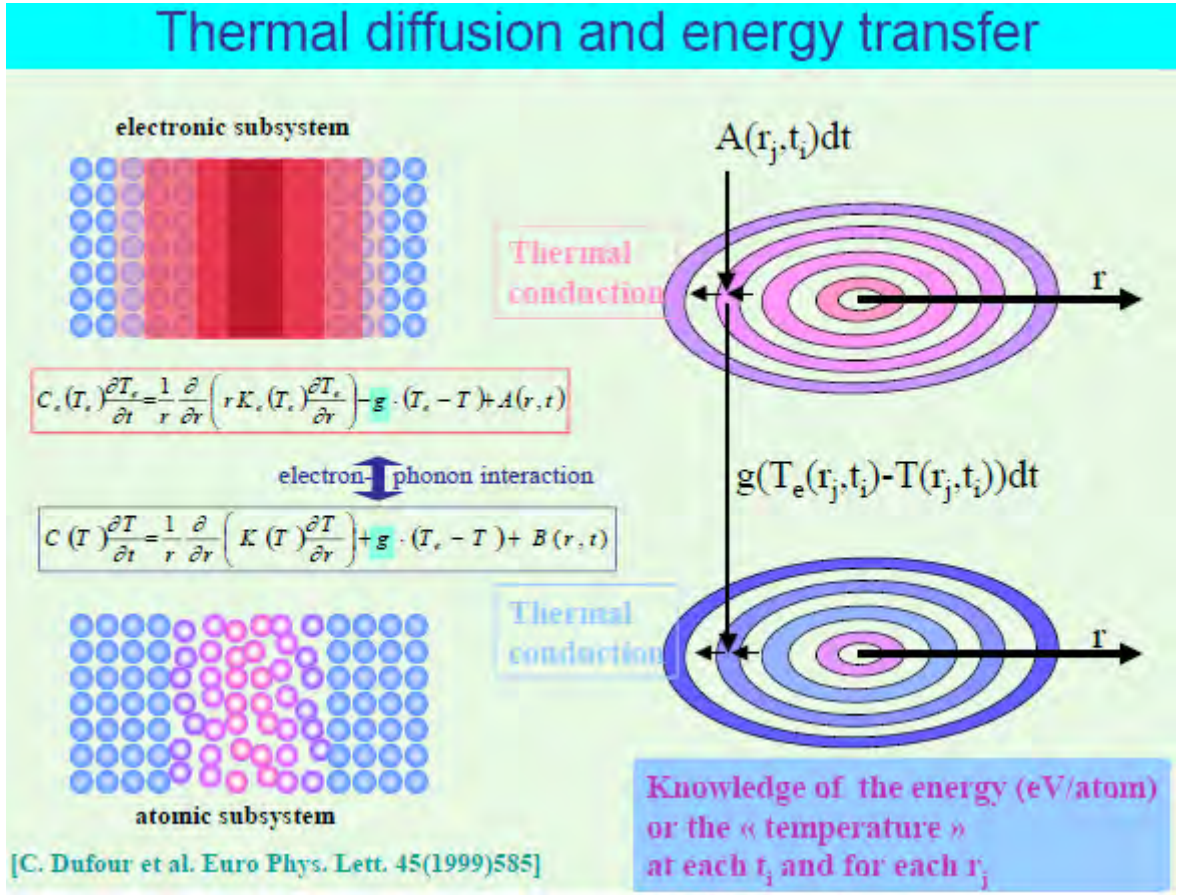
TARGETS: MATERIAL & FABRICATION

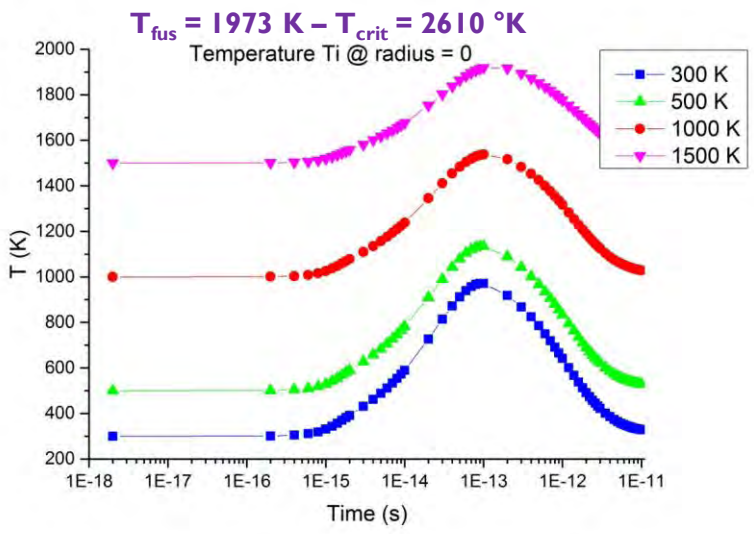


- GANIL target lab + network (INTDS) for Stable targets
- On going - To be done:
  - Fabrication & characterization for experiments
  - R&D for actinides (deposition process & backings) (cf TATTOO project)
  - Damage simulations:"fast super-heating" * (next slide) and sputtering yields (need of experimental data)

**Ch. Stodel « Thermal Spike model applied to thin targets irradiated with heavy ions at low energy » INTDS 2018*

THERMAL SPIKE MODEL: ^{48}Ca (5MeV/u) + Ti (2µm)





What about actinide oxydes ?

+ Sputtering yield

ACTINIDE TARGETS: MATERIAL & FABRICATION → TATTOO

THIN ACTINIDE TARGET COOPERATION
HERSTELLUNG VON DÜNNEN AKTINIDENTARGETS
COOPÉRATION SUR LES CIBLES MINCES D'ACTINIDE

- DFG / ANR
- Klaus Eberhardt, Radiochemist, JGU Mainz
- Christelle Stodel, Physicienne, GANIL
- Bettina Lommel, Head of the department Target lab., GSI, Darmstadt
- Claire Le Naour, Radiochimiste, IPN Orsay
- Nicolas Clavier, Radiochimiste, ICSM, Marcoule

TACTIC - TATTOO

- ✓ 2016 : ANR TACTIC
  IPNO – GANIL
  SHE
- ✓ 2017 (ANR) & 2018 (DFG): PRCI TATTOO :
  IPNO- JGU-GSI – ICSM – GANIL
  Fission, nuclear clock, SHE (HI + neutron reactions)

The Committee acknowledges the high scientific level of the proposal, the solidity of the consortium and the large interest in transuranic targets. The panel of experts has recommended the funding of the project, if possible, but, in view of the large number of good submitted projects and the limited amount of resources, the Committee is not able to recommend the funding of the present project.

Points forts

The project is of high level in fundamental research. It will be beneficial for GANIL. The contributions of the two countries are well balanced.

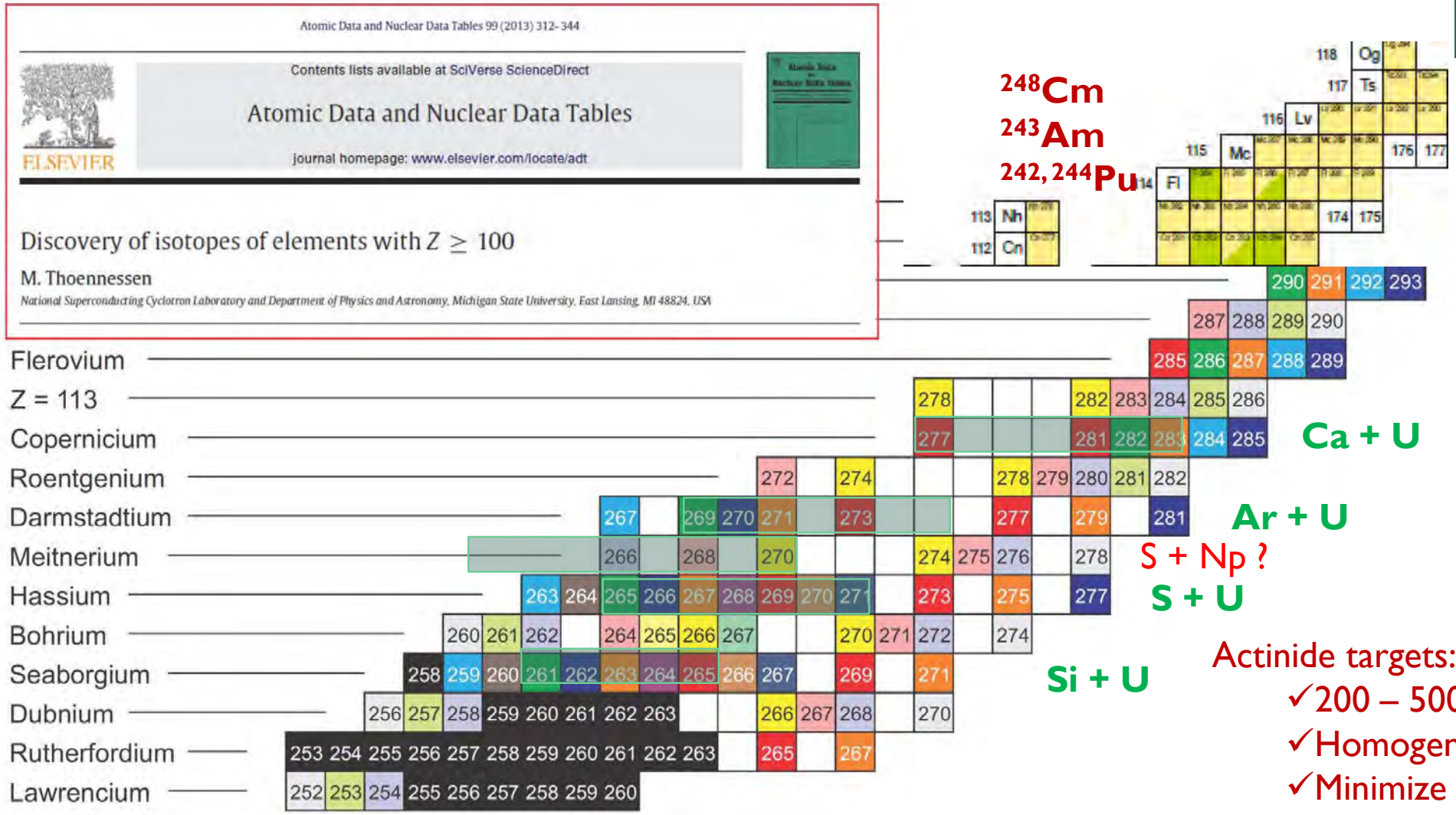
Points faibles

The costs are high.

Synthèse

The Committee considers that TATTOO is a very good project. Nevertheless, costs on GANIL instruments and equipment, ICSM instruments and equipment and IPNO instruments and equipment must be reduced by € 25,000, € 10,000 and € 20,000, respectively, and € 5,000 in IPNO meeting costs. (Total € 60,000)
This summary reflects the collective analysis of the committee taking into account all reports and discussions during the scientific evaluation meeting

APPLICATION I –SCIENTIFIC PROGRAM OF SHN



Actinide targets:

- ✓200 – 500 µg/cm²
- ✓Homogeneous
- ✓Minimize Eloss in backing

APPLICATION 2 -

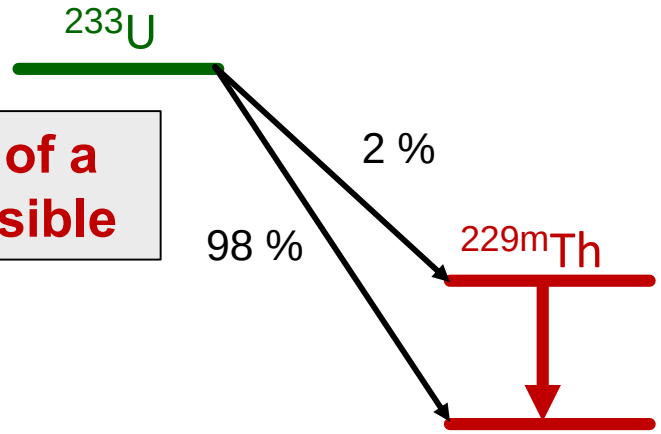
ARTICLE Nature Vol. 533, pp. 47-51, 2016
doi:10.1038/nature17669

Direct detection of the ^{229}Th nuclear clock transition

Lars von der Wense[1], Benedict Seiferle[1], Mustapha Laatiaoui[2,3], Jürgen B. Neumayr[1], Hans-Jörg Maier[1], Hans-Friedrich Wirth[1], Christoph Mokry[3,4], Jörg Runke[2,4], Klaus Eberhardt[3,4], Christoph E. Düllmann[2,3,4], Norbert G. Trautmann[4] & Peter G. Thirolf[1]

Today's most precise time and frequency measurements are performed with optical atomic clocks. However, it has been proposed that they could potentially be outperformed by a nuclear clock, which employs a nuclear transition instead of an atomic shell transition. There is only one known nuclear state that could serve as a nuclear clock using currently available technology, namely, the isomeric first excited state of ^{229}Th (denoted ^{229m}Th). Here we report the direct detection of this nuclear state, which is further confirmation of the existence of the isomer and lays the foundation for precise studies of its decay parameters. On the basis of this direct detection, the isomeric energy is constrained to between 6.3 and 18.3 electronvolts, and the half-life is found to be longer than 60 seconds for $^{229m}Th^{2+}$. More precise determinations appear to be within reach, and would pave the way to the development of a nuclear frequency standard.

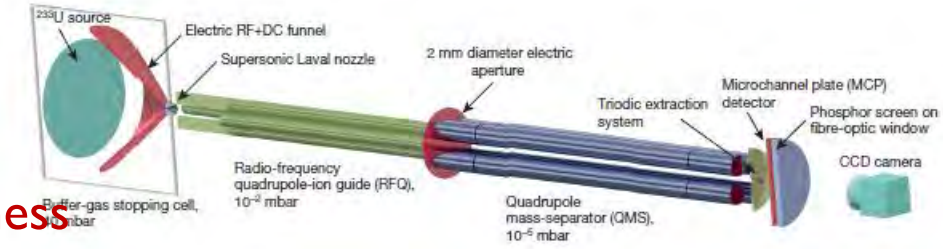
Laser excitation of a nuclear level possible

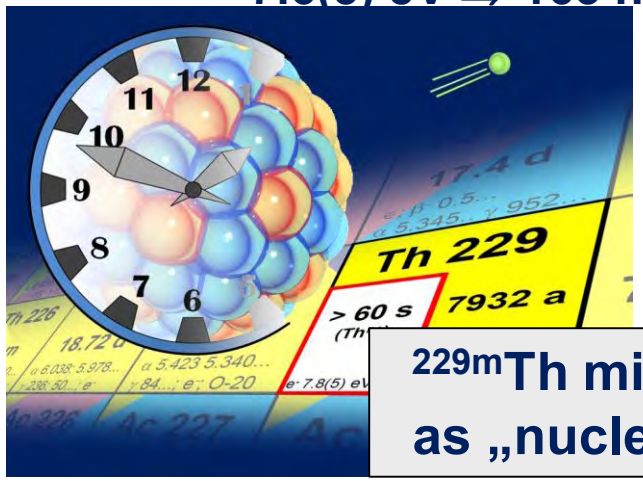


7.6(5) eV ⇒ 163 nm (deep UV)

^{233}U-source:

- ✓Thin (11µg/cm²)
- ✓Homogeneous
- ✓Low surface roughness





Courtesy of K. Eberhardt

^{229m}Th might serve as „nuclear clock"

APPLICATION 3 – NEUTRON INDUCED FISSION

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First results from the new double velocity–double energy spectrometer VERDI

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ABSTRACT

The VERDI spectrometer (VElocity foR Direct mass Identification) is a two arm time-of-flight spectrometer built at the European Commission Joint Research Centre IRMM. It determines fragment masses

FALSTAFF_LoI 2016
Fission fragment distributions and neutron multiplicities
D. Doré, E. Berthoumieux, S. Panebianco
F. Farget, J. Pancin

Actinide sample:

- ✓Thin (150-200 µg/cm²)
- ✓Homogeneous
- ✓On ultra-thin backing: Ni (250 nm) or PL (220 nm)

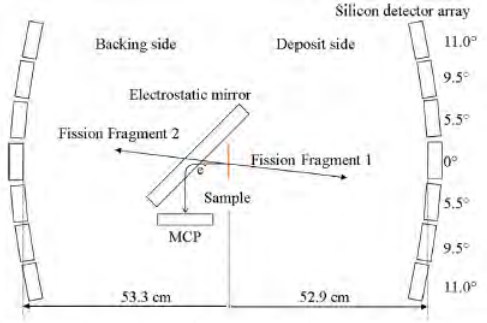

Fig. 1. VERDI diagram showing the central Fission Electron Time-of-flight Start (FIETS) detector and the two energy detector spheres at the end of each time-of-flight section (not to scale). Fragments can be detected by one of the silicon detector pairs, while the electrons, emitted by the target, are deflected by the electrostatic mirror into the direction of the micro-channel plate (MCP) detector.

APPLICATION 3 – NEUTRON INDUCED FISSION

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Scientific Workshop on Nuclear Fission dynamics and the Emission of Prompt Neutrons and Gamma Rays, THEORY-3

Neutron-induced fission measurements at the time-of-flight facility *n*ELBE

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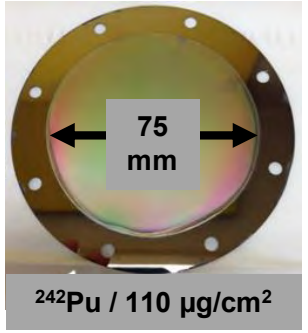
Abstract

Neutron-induced fission of ^{242}Pu is studied at the photoneutron source *n*ELBE. The relative fast neutron fission cross section was determined using actinide fission chambers in a time-of-flight experiment. A good agreement of present nuclear data with evaluations has been achieved in the range of 100 keV to 10 MeV.

Actinide sample:

- ✓500 - 1000 µg/cm²
- ✓Active diameter 40-80 mm
- ✓Homogeneous
- ✓Surface roughness as low as possible
- ✓On ultra-thin backing (low surf roughness)

Backing: Si-wafer, sputtered with thin Ti-layer.
In total: 37 mg ^{242}Pu for 8 targets



Courtesy of K. Eberhardt

Two fission chambers (^{235}U and ^{242}Pu, details in [Kögler et al., 2013a,b]) have been developed at the Helmholtz-Zentrum Dresden-Rossendorf (HZDR). The included fission samples were produced at the Institute for Nuclear Chemistry of the University of Mainz by molecular plating [Vascon et al., 2015]. The homogeneity of these very thin actinide targets (^{235}U: $n_A \approx 450\ \mu g/cm^2$, ^{242}Pu: $n_A \approx 150\ \mu g/cm^2$) was improved by using titanium coated silicon wafer as backing material (cf. Fig. 1).

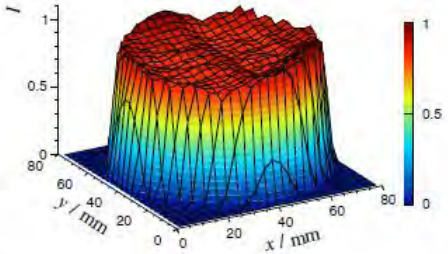


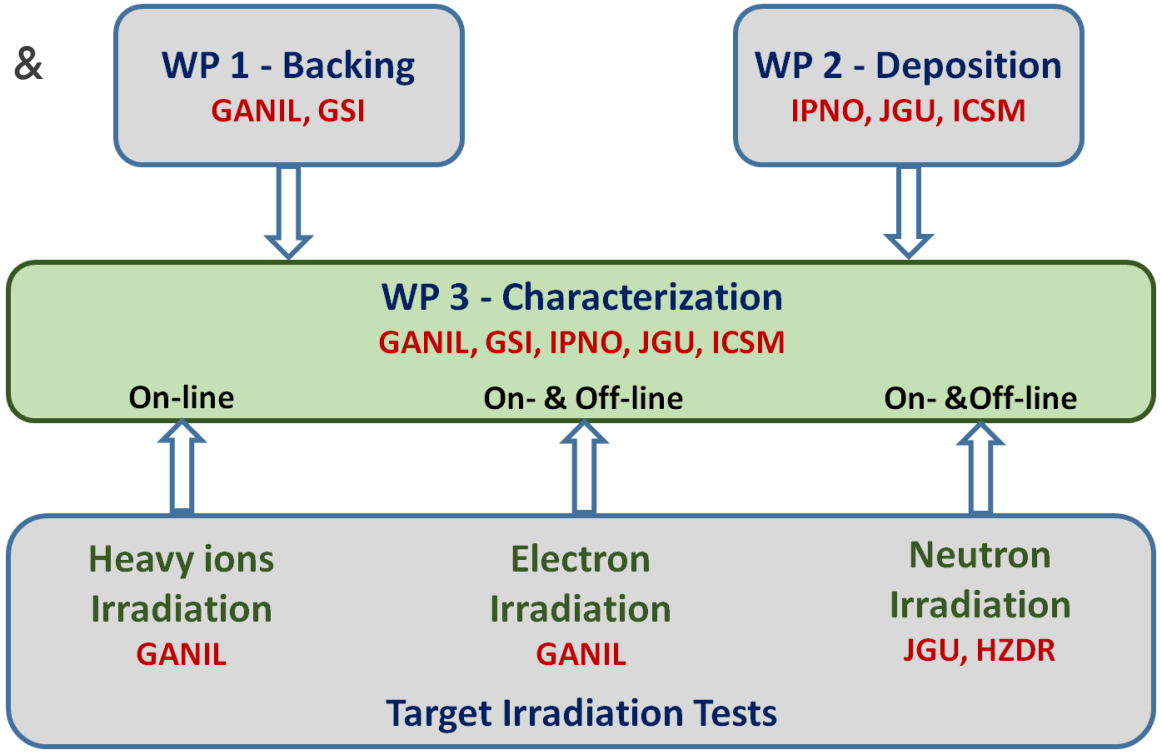
Fig. 1. Radiographic image of a ^{242}Pu target included in the fission chamber. The image (refer to [Vascon et al., 2015]) reflects the activity distribution of the sample, which is related to its homogeneity. A homogeneous target is important for the precise examination of neutron-induced fission cross sections, if an inhomogeneous neutron beam smaller than the target area is used.

Layer homogeneity by Radiographic Imaging

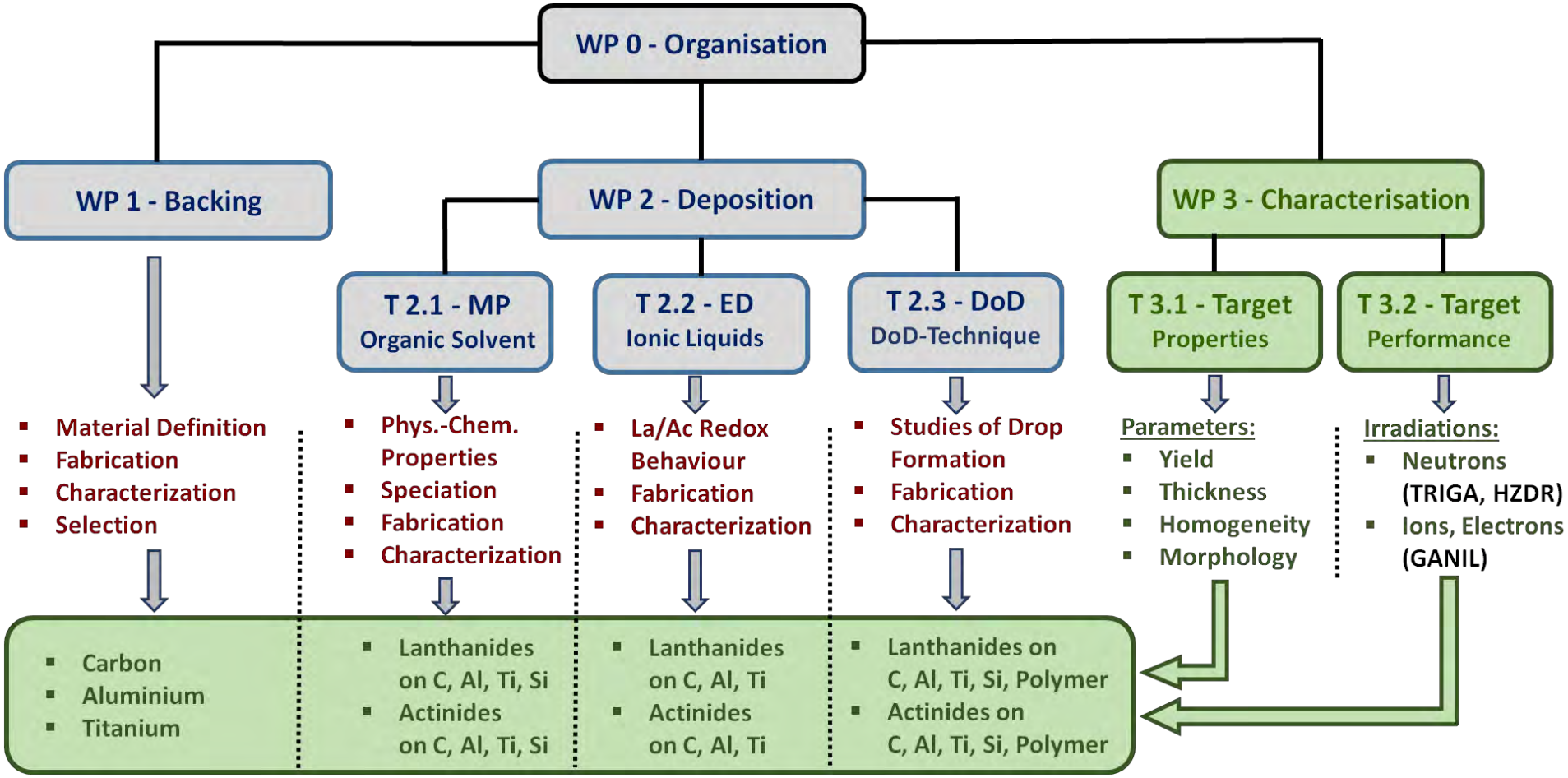
TATTOO OBJECTIVES

✓ Supply thin actinide targets which have specific characteristics depending on the application (thickness, choice of backing, roughness, homogeneity ….) for French and German physicists (heavy-ion- and neutron-induced reactions, σ & structure of HN & SHN at S3, fission studies = σ & process at NFS…)

- Development of novel fabrication methods for actinide targets on various substrates
- Characterization and performances under irradiation of backings and deposits



WORK PROGRAM



TATTOO:WP1 BACKINGS (GSI & GANIL)

Carbon : 5 – 2000 µg/cm²
Titanium: ≈ 1.5 / 2 µm
Aluminium: oxide layer

TATTOO

Study of structure /surface according to interlayer material, processes, conditions etc..(high-resolution 3D microscope)
Ti < 1.5 µm pin-hole free
Large surface homogeneous

12 Ton manual Press
5mm Pellet

Rolling Mill

TATTOO:WP2 DEPOSITION

T2.1 Organic Solvent – IPNO/ICSM/JGU

systematic studies → better understanding of deposition mechanism and deposition kinetics.
42 cm² ^{242}Pu targets on Ti-coated Si wafers
$^{233, 234,235,238}$U, ^{237}Np and ^{232}Th deposited on 2 µm thin Al foils [34, 12-13, 41-43]

T2.2 ED Ionic Liquid – IPNO/ICSM

high chemical, thermal, electrochemical and radiolytic stability, low or negligible vapour pressure, non-flammability and high conductivity → **deposition in metallic form**
Studies on the ED of actinides in IL are limited and mainly focused on uranium [57-60]. Depositions at constant potential, on Au, Pt, C or stainless steel electrodes and in TFSI based IL

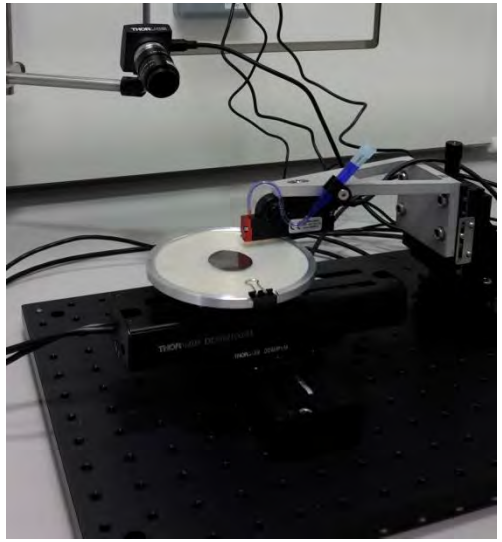
TATTOO

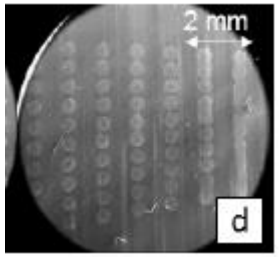
Reference
Determination of physico-chemical properties
Speciation of Eu, Ce, U

Electro-analytical studies, systematics studies….
Redox behavior of Eu, Ce, U

TATTOO:WP2 DEPOSITION:T2.3 DOD TECHNIQUE @ JGU

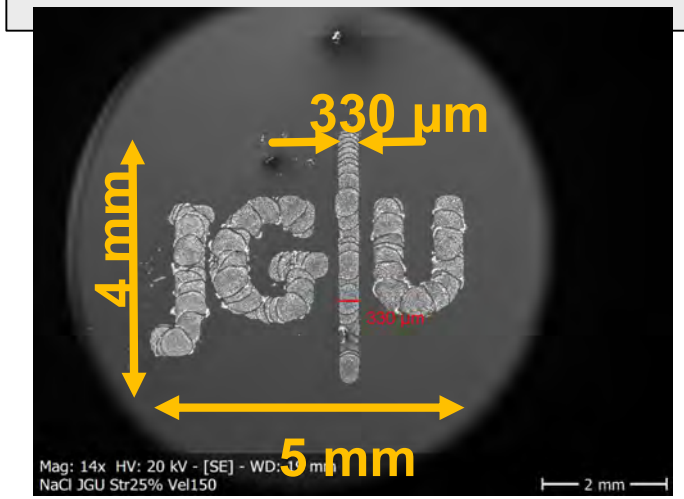
R. Haas et al, *Nuclear Instruments and Methods A*, vol. 874, pp. 43-49, 2017





^{140}La, ^{198g}Au tracers as natural nitrate solution
on graphene 12 µm or Ti 50µm
diam 25 mm

Printing of JGU-Logo with NaCl-solution on Ti-surface



TATTOO

Organic solvents
Other substrate, thickness
Diam = 100 mm

Study of drop formation

Stroke: 16.25 µm

Stroke velocity: 150 µm/ms

Droplet size: 15 ± 5 nL

Courtesy of K. Eberhardt

TATTOO WP3: CHARACTERIZATION – T3.1 PROPERTIES

T3.1 Properties - ALL

Optical microscope
Scanning electron microscope
MEB-FIB
Energy dispersive X-ray analysis,
High precision balances
UV-Vis photometer

Energy loss mapping - Egun

Radiocative tracer (neutron irradiation)
Radiographic imaging

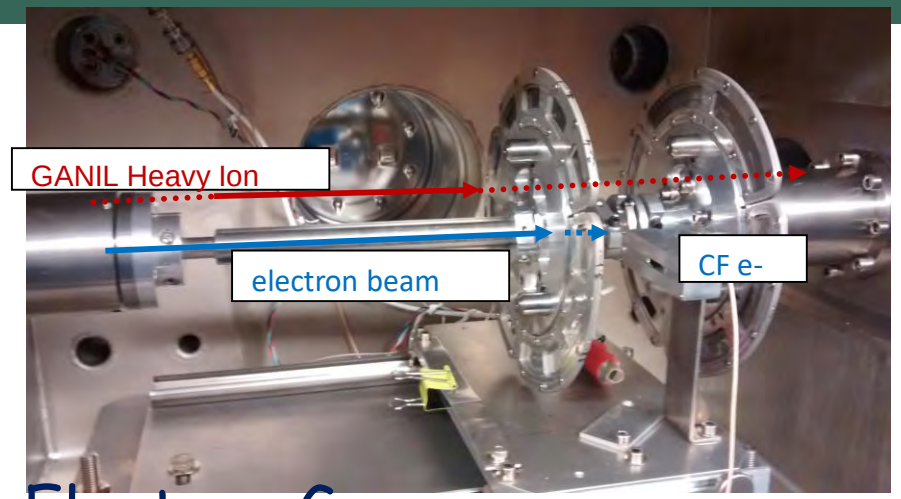
Inductive-coupled plasma atomic emission spectroscopy
g-ray spectrometry
HT-Raman Spectroscopy
High temperature Environmental SEM

TATTOO

Knowledge & experience gained shared among all partners of TATTOO (+CIMAP)

JGU: 3D Optical Profiler in radioactive controlled area
GSI: High-Resolution 3D Microscope

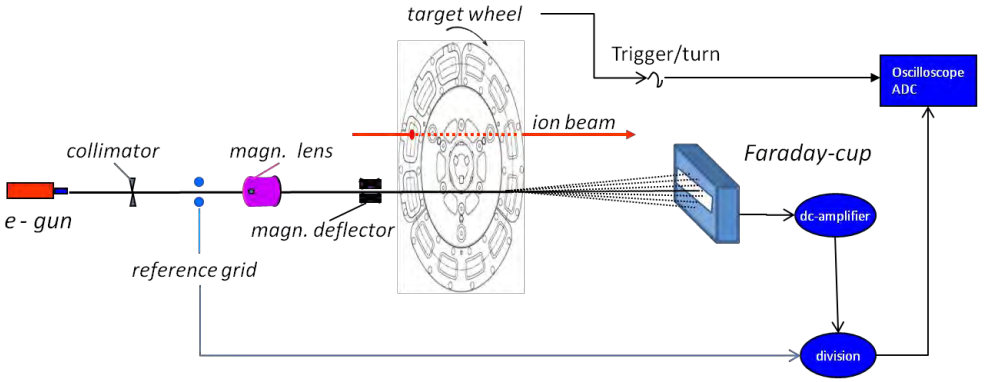
TATTOO WP3: CHARACTERIZATION – T3.2 PERFORMANCES WITH HEAVY IONS

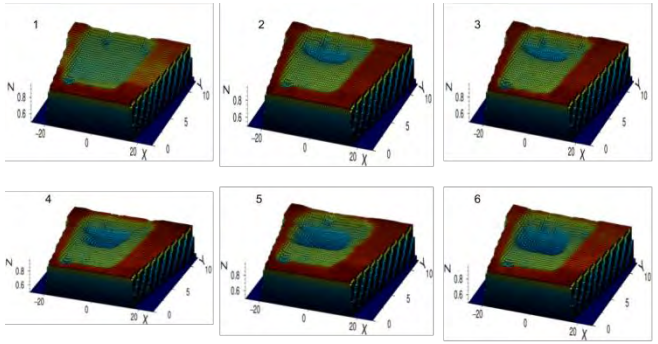


Electron Gun - R. Mann (patent DE 10242962 A1-GSI)

FLIR SC7000: 1.5 à 5 µm / 5-1500°C
320*256:380 Hz // 80*64: 3500Hz
(3000 rpm = 50 Hz; 3500Hz= 70 images)
Resolution of 0.3mm per pixel

Principle : measuring attenuation of electron current using angular scattering and absorption





TATTOO WP3: CHARACTERIZATION – T3.2 PERFORMANCES WITH NEUTRONS

✓ Neutrons of variable energy @nELBE

✓ Thermal Neutrons : Measurements of the layer thickness are possible using radioactive tracers or by Neutron Activation Analysis (NAA)

TRIGA MARK II

Continuous Thermal Power… 100 kW

Neutron Flux…$7 \cdot 10^{11}$- $4 \cdot 10^{12}$ n cm^{-2} s^{-1}

Several irradiation facilities

WORK PROGRAM

WP	Tasks	Partner
0	**Organisation**	GANIL/JGU
	Annual coordination meeting organisation	
	Workshop organisation	
	Web site creation	
1	**Backings**	GANIL, GSI
	Production	
	Characterization	
2	**Deposition**	
2.1	**Molecular Plating (MP)**	IPNO, JGU
	Physico-chemical properties of solvents	IPNO
	Deposition of lanthanides: Speciation and layer properties	IPNO + JGU
	Deposition of actinides: Speciation and layer properties	IPNO + JGU
2.2	**Ionic Liquids (IL)**	IPNO
	Redox-behaviour of lanthanides and actinides in IL	
	Deposition of lanthanides: Speciation and layer properties	
	Deposition of actinides: Speciation and layer properties	
2.3	**DoD-technique**	JGU
	Design and build set-up for large area deposits	
	Deposition of lanthanides: Optimization and layer properties	
	Deposition of actinides: Optimization and layer properties	
3	**Target characterization**	ICSM
3.1	**Properties (pre- and post-irradiation)**	IPNO/JGU/ICSM
3.2	**Performances under irradiation**	GANIL
	Technical development	GANIL
	Irradiation with heavy ions	GANIL
	Irradiation with neutrons	JGU/HZDR

CONCLUSION & PERSPECTIVES

- One Target station ready for first experiments at S^3 (stable and U or Th)
- Monitoring on targets to be optimized with the use of the electron technique, IR camera
- Use of an « Actinide Prototype Target Station » with GANIL beams
- Simulations/data on targets sputtering and lifetime necessary
- Actinide:
  - S^3 Target Station to be designed
  - **R&D on targets technology**