Update on GANIL facilities Exploring the EOS at low densities.

A. Chbihi
(GANIL)

- Status of GANIL
- Cyclotrons: SPIRAL1
- LINAC: SPIRAL2
- Instrumentation and the physics at GANIL:
  - VAMOS-AGATA, LISE, ACTAR: Nuclear structure
- FAZIA-INDRA: nuclear reactions, fusion, fission, multifragmention, EOS

Highlights from GANIL



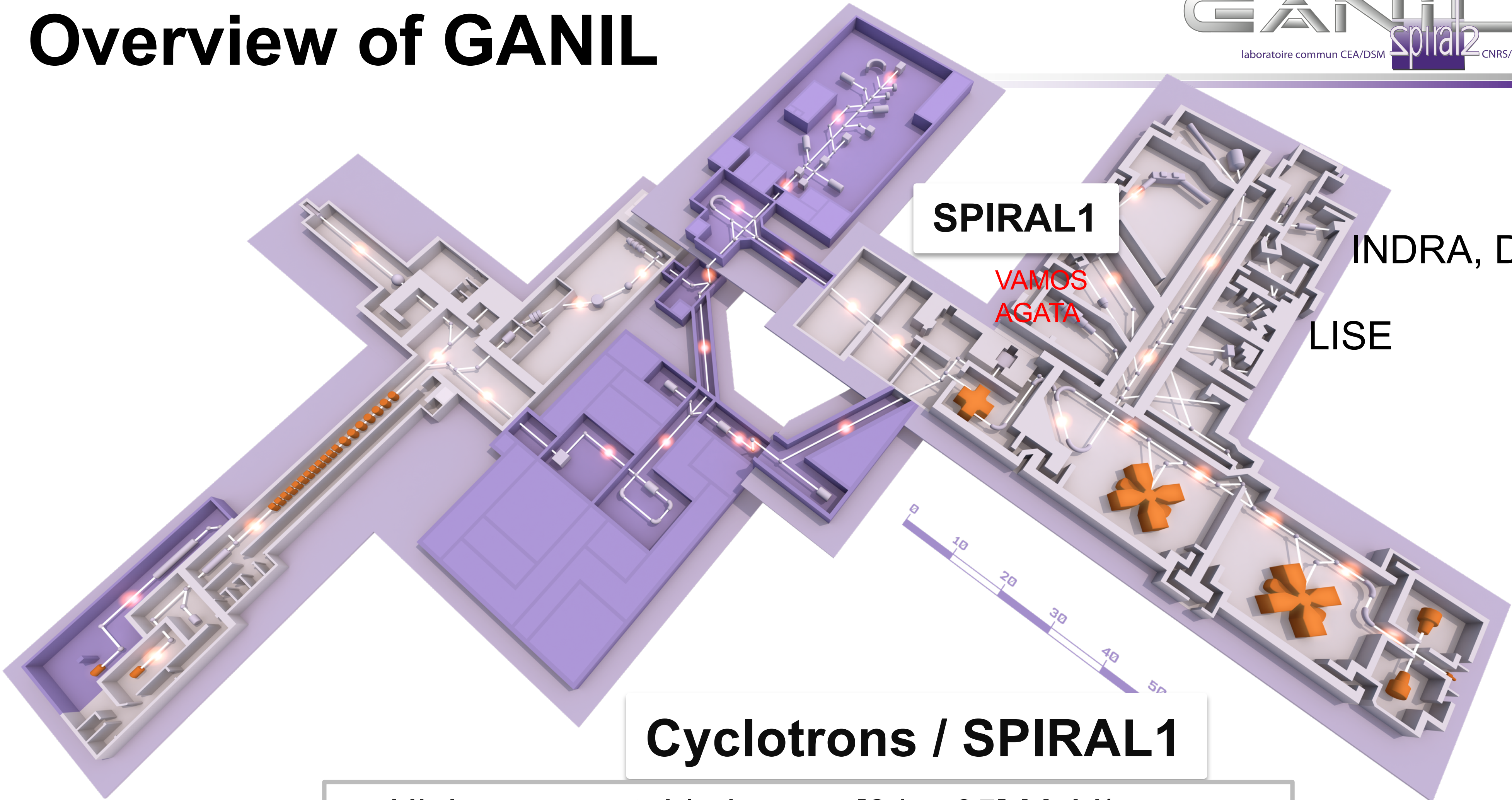
- Commissioning of SPIRAL2 – LINAC
- Commissioning of NFS : first experiment with NFS

- New beams from the SPIRAL1 upgrade

- Experimental campaigns with AGATA coupled to NEDA DIAMANT and to MUGAST+VAMOS

- New detectors: NEDA, ACTAR TPC, FAZIA, MUGAST

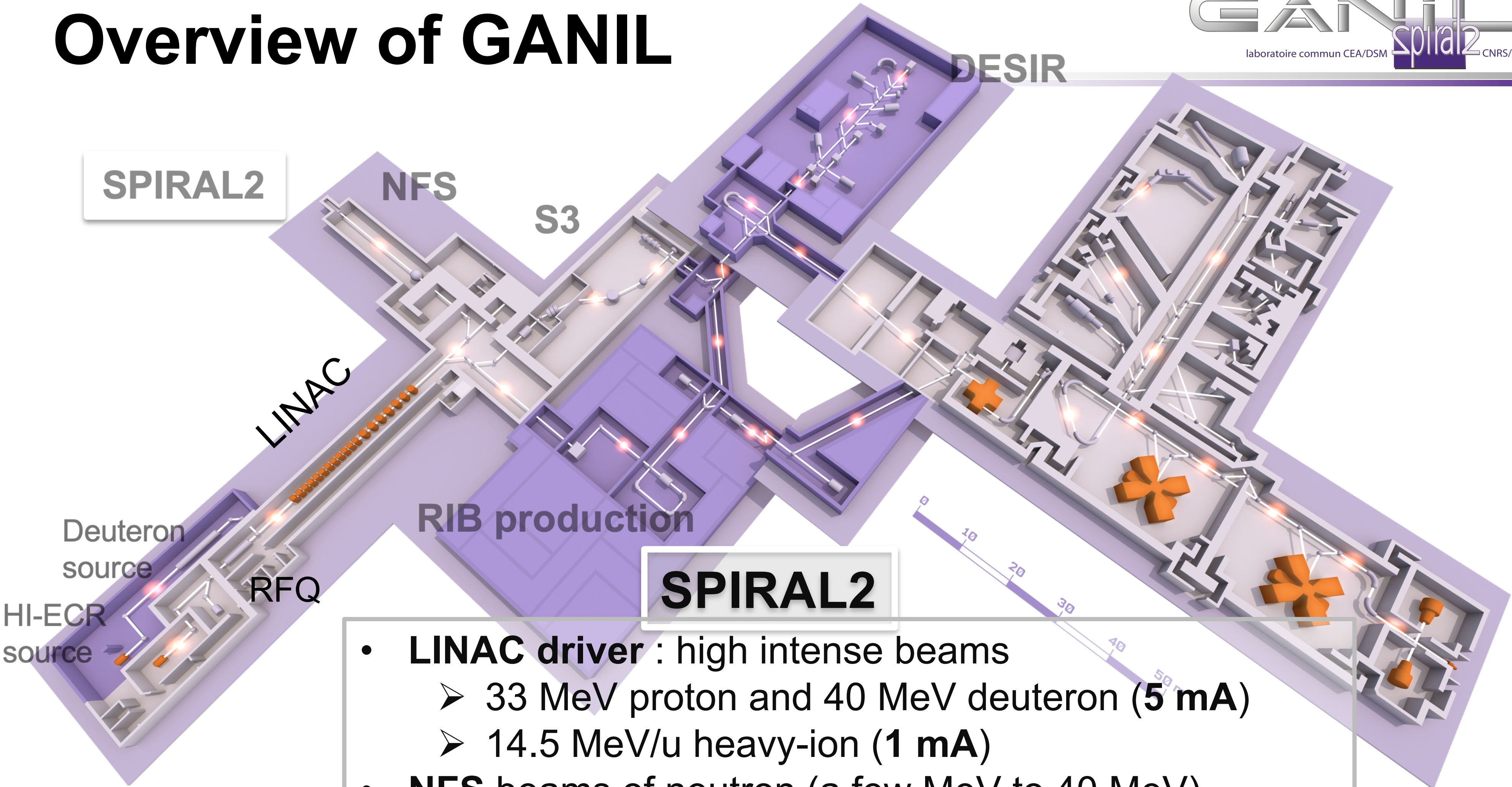
Overview of GANIL



Cyclotrons / SPIRAL1

- High energy stable beams [24 – 95] MeV/u
- RIB produced by fragmentation (LISE, T ***> 10 µs>***)
- RIB with **SPIRAL1** (ISOL , T>10ms): accelerated with CIME up to 20 MeV/u

Overview of GANIL

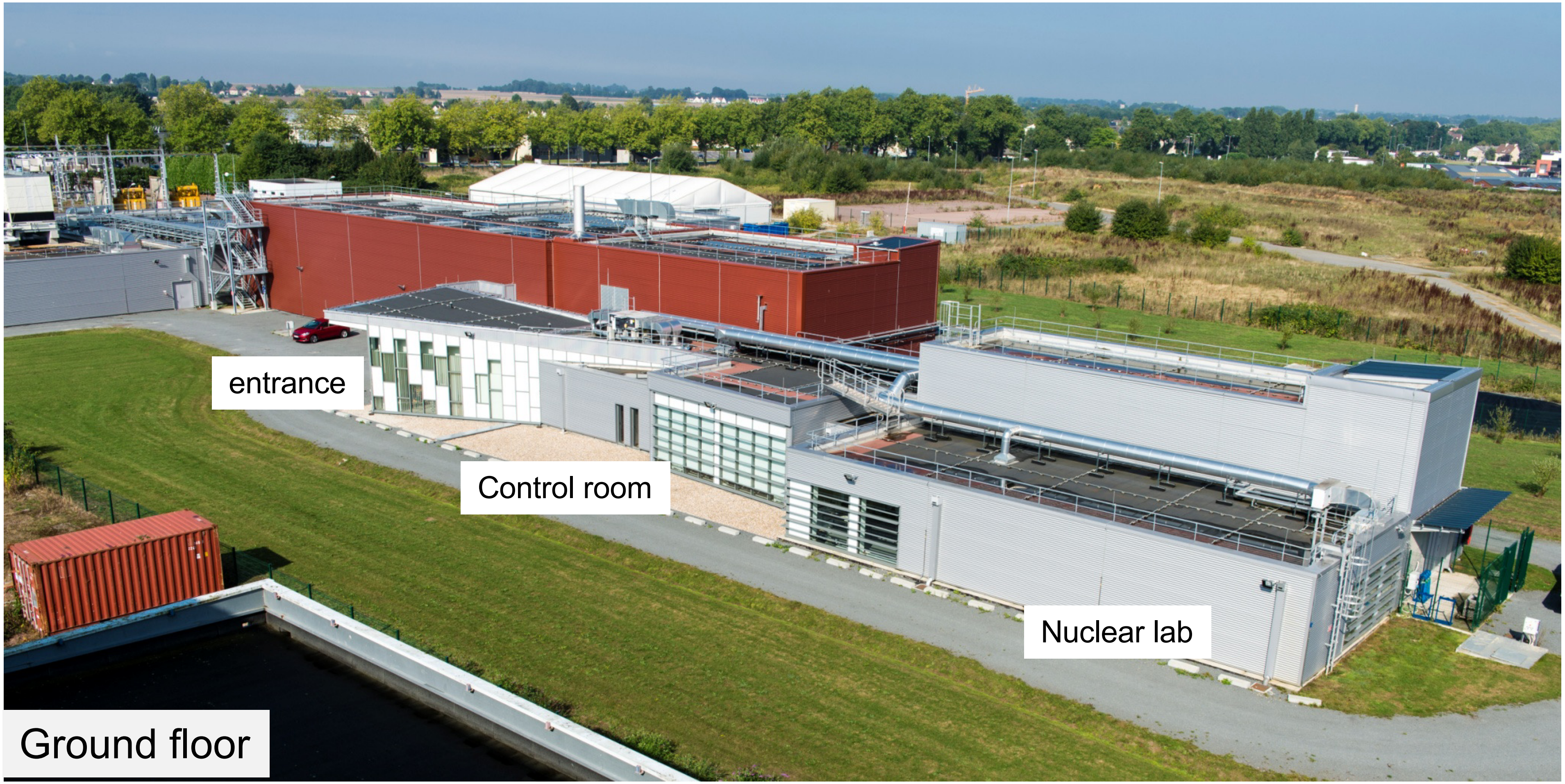


- **LINAC driver** : high intense beams
  - ➢ 33 MeV proton and 40 MeV deuteron (**5 mA**)
  - ➢ 14.5 MeV/u heavy-ion (**1 mA**)
- **NFS** beams of neutron (a few MeV to 40 MeV)

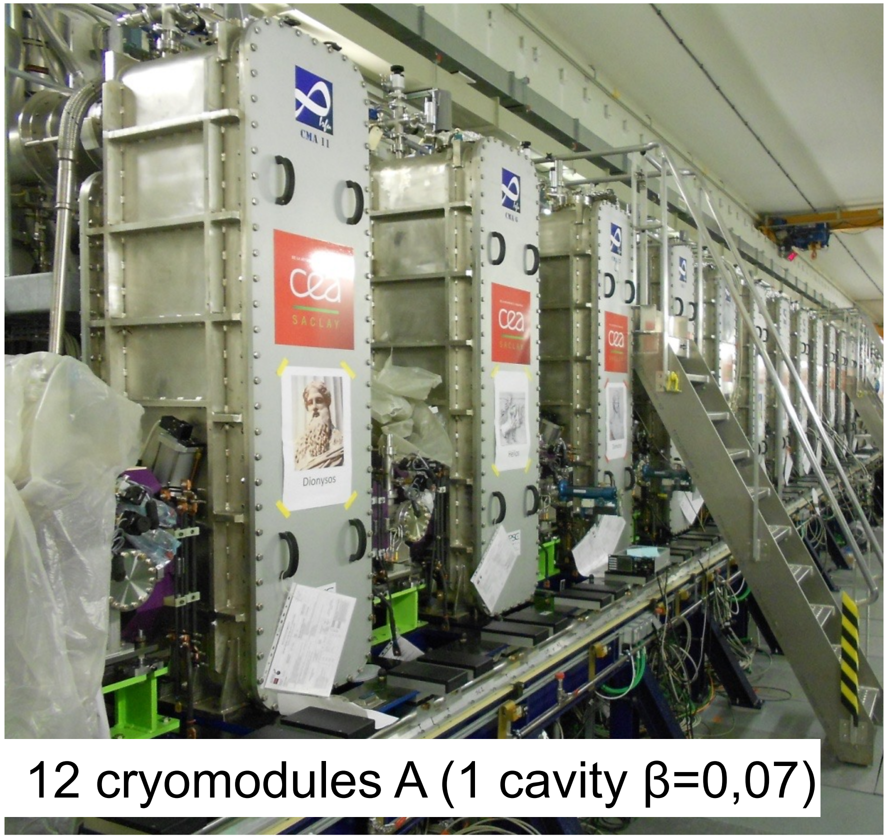
- **S3** super separator spectrometer (fusion ev. reactions, spectroscopy for SHE, N=Z). Commissioning

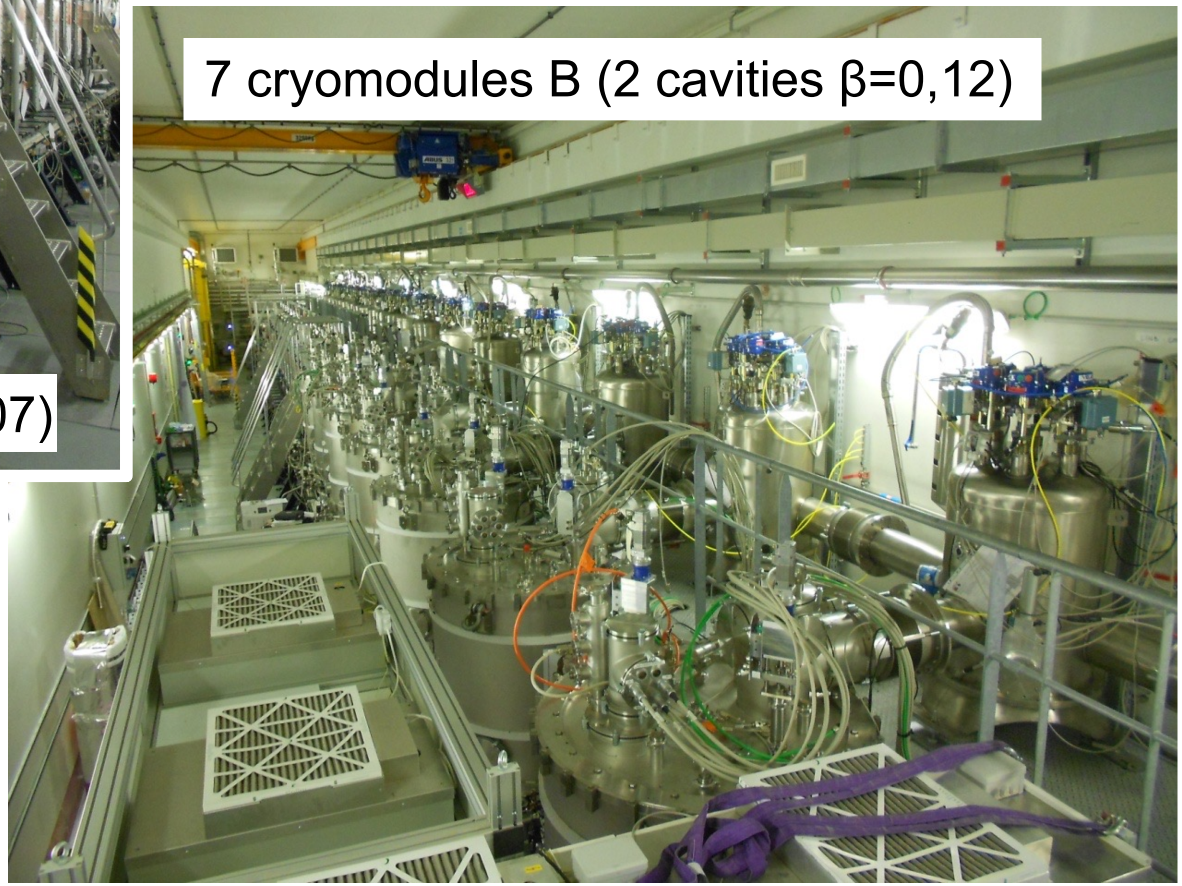
- DESIR: study of exotic ions at low E, from S3 / SP1
- Production of fission fragments induced by n + U reactions (stand by)

SPIRAL-2 phase 1 building



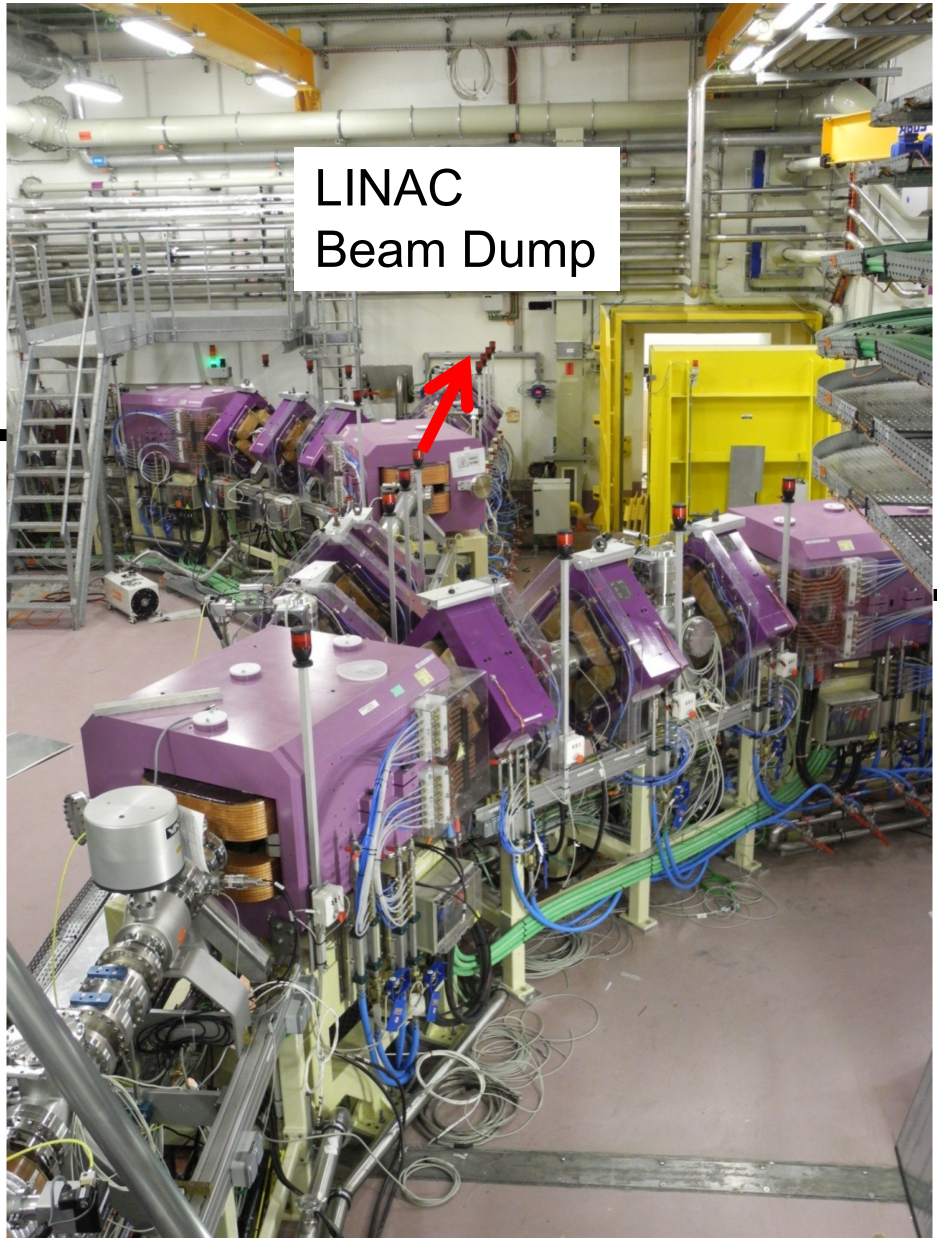
Cryomoduls


12 cryomodules A (1 cavity β=0,07)


7 cryomodules B (2 cavities β=0,12)

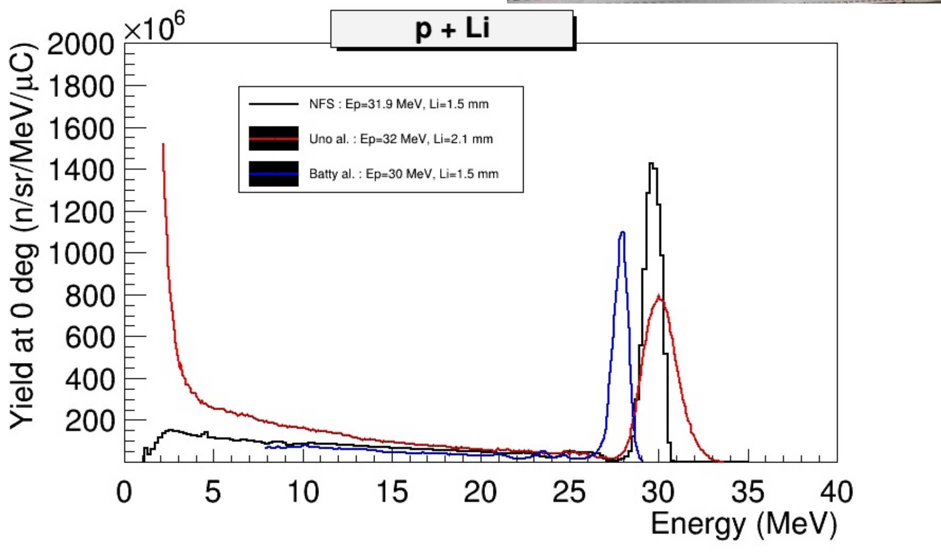
High Energy Beam Line

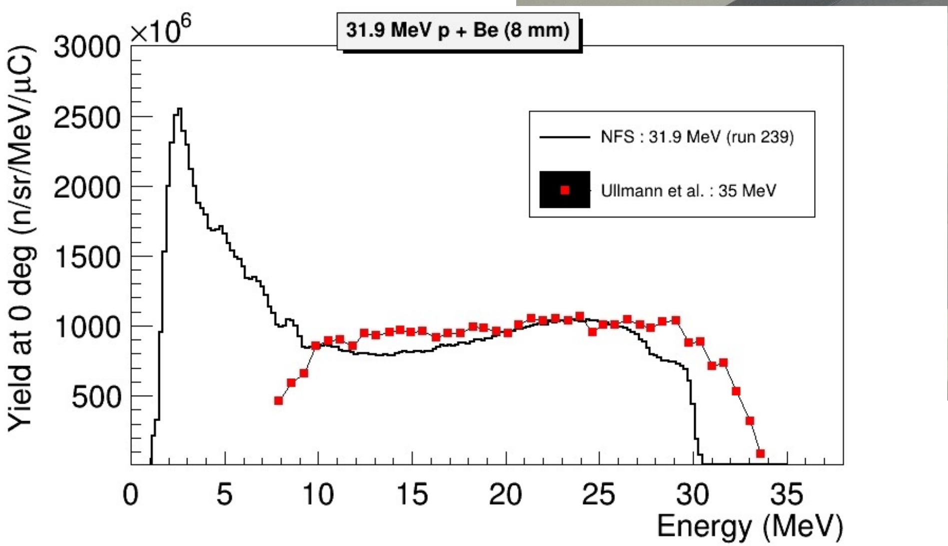
NFS

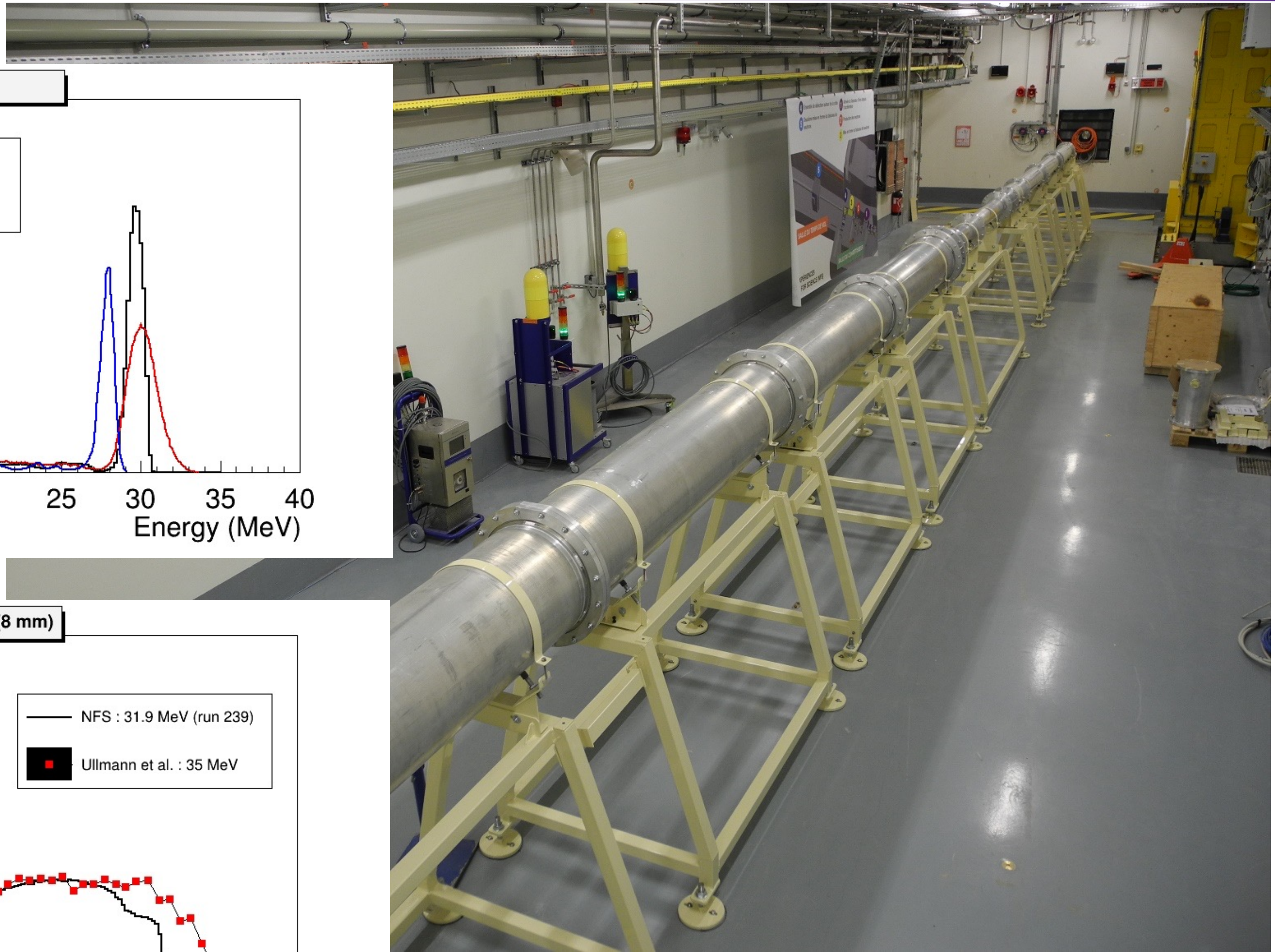


To S3 and
Production Building

neutron beams

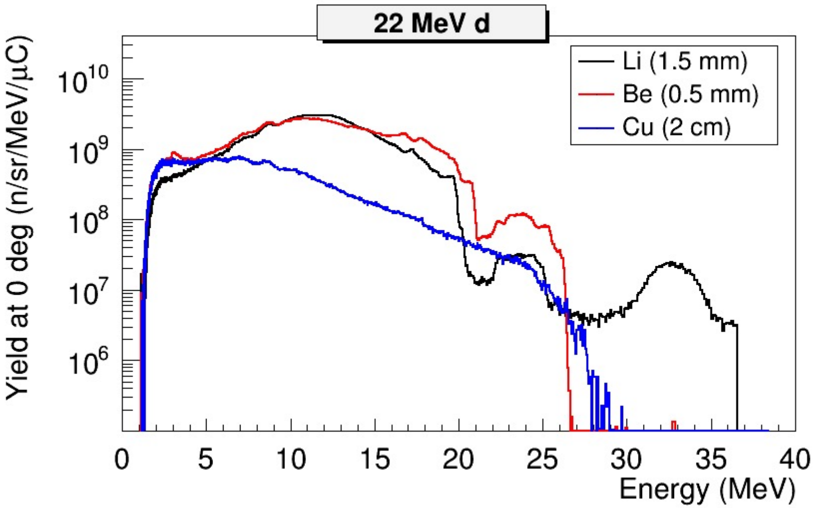




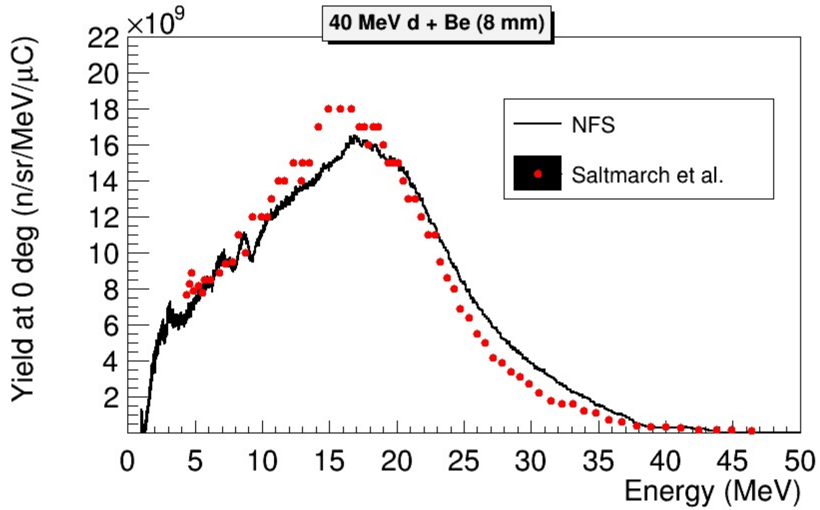


next step neutron beam produced by d

n-beam produced by d



courtesy of X. Ledoux



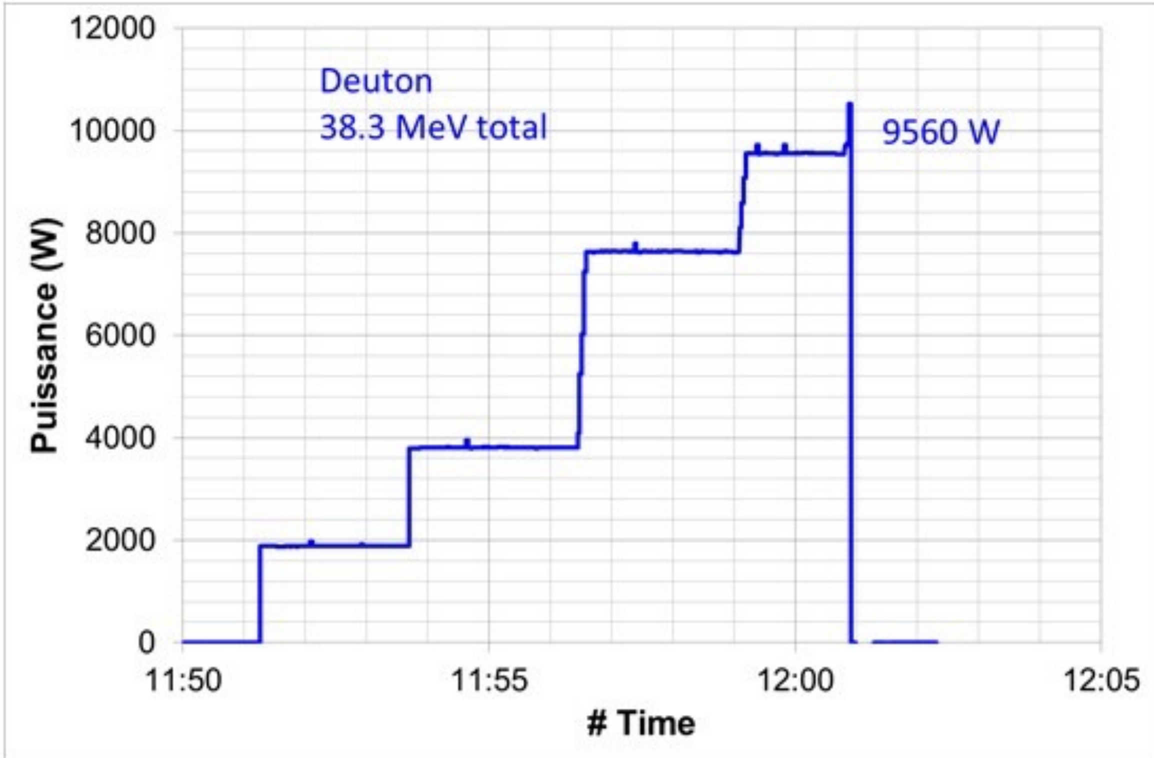
40 MeV d beam at 50 µA →

E MeV	Flux at 5 m
0-40	8.10^7 n/cm²/s
5	2.10^6 n/cm²/MeV/s
14	5.10^6 n/cm²/MeV/s
30	6.10^5 n/cm²/MeV/s

NEWS

18/11/21

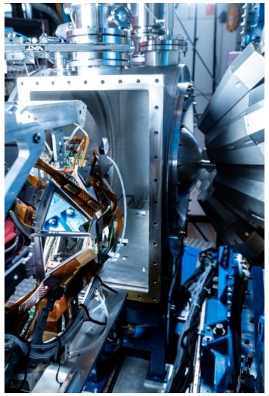
SPIRAL2 LINAC 10 kW



Le 16 Novembre 2021, un faisceau de deuterium de 5000µA crête a été accéléré à 19.15 MeV/A sur le beam dump SAFARI. L'absence de pertes détectées a permis d'augmenter la puissance à ~10kW de faisceau.

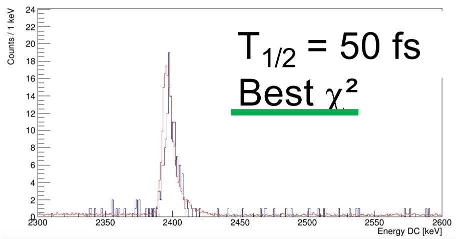
On 16 November 2021, a 5000µA peak deuterium beam was accelerated to 19.15 MeV/A on the SAFARI beam dump. The absence of detected losses allowed the power to be increased to 10kW of beam.

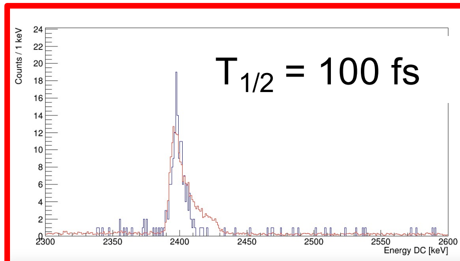
MUGAST campaign 2020



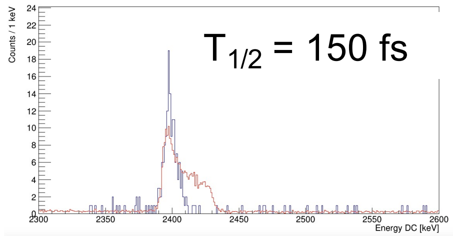
NUCLEAR STRUCTURE.
3-body contribution in ^{20}O structure
$^{19}O(d,p)^{20}O$ DSAM Target
Constraining the 3-body term in Oxygen from the fs lifetime measurement in the 2^+_2 and 3^+_1 states

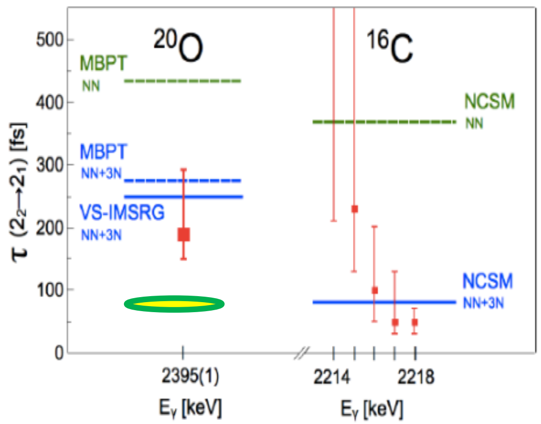
Analysis I. Zanon (PhD-INFN)
P.I. E. Clément (GANIL), A. Goasduff (INFN-LNL)





M. Ciemala et al , (PRC. C101, 021303(R) (2020))



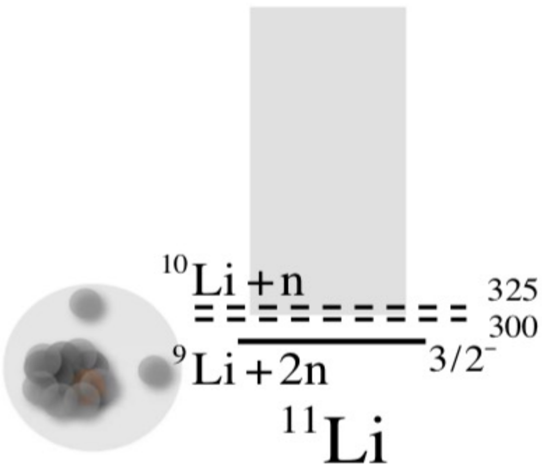


Preliminary : Shorter than previous measurement ; shorter than ab-initio discussion …

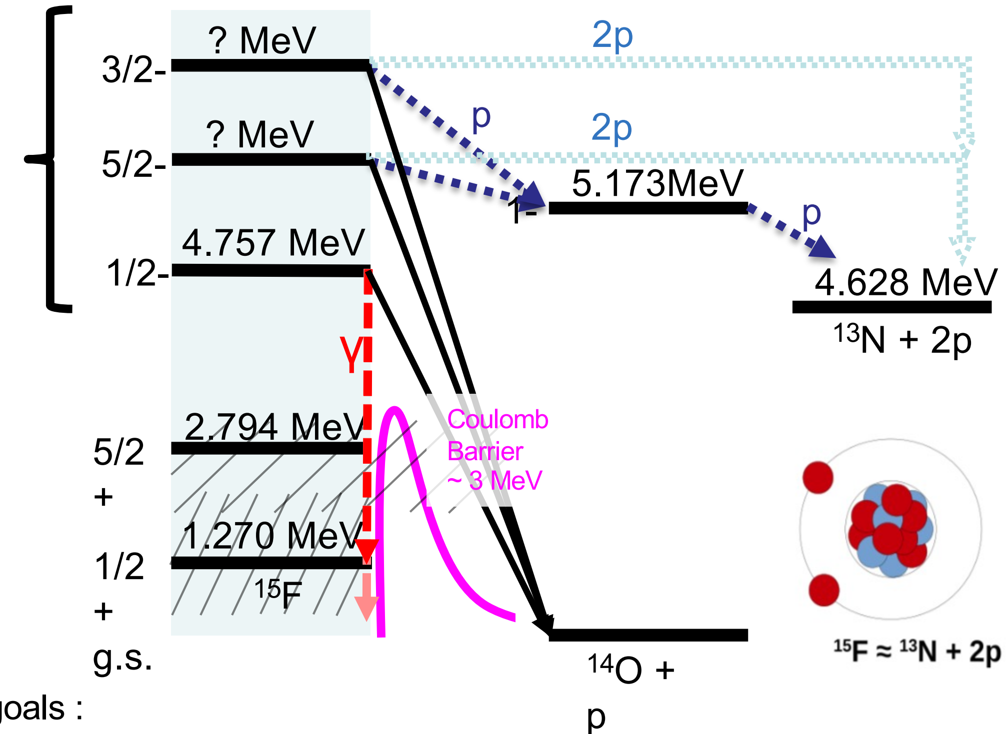
On the Origin of Nuclear Clustering

Jacek Okołowicz,[1,*] Marek Płoszajczak[2,**] and Witold Nazarewicz[3,4,5,***]

Jacek Okołowicz et al. *Progress of Theoretical Physics Supplement*, Vol. 196, Oct. 2012



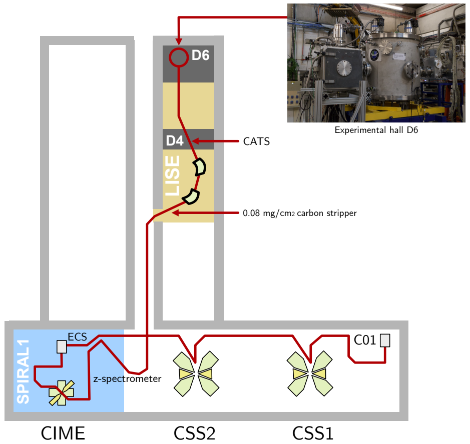
In ^{15}F, is the structure influenced by the coupling to the nearby 2p-decay channel ?



Three goals :

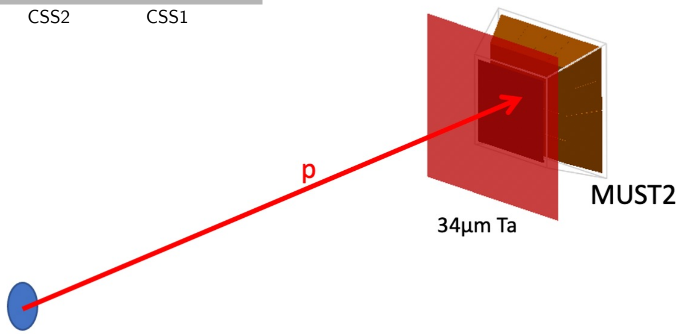
- Measurement of the excited negative parity states of ^{15}F: ^{1}H(^{14}O,p) ^{14}O
- Measurement of the two-proton decay branching ratio and decay mechanism : ^{1}H(^{14}O,2p) ^{13}N or ^{1}H(^{14}O,p) ^{14}O*(p) ^{13}N
- Observation of the γ branching ratio: ^{1}H(^{14}O) ^{15}F$^{(*)}$(γ) ^{15}F(p) ^{14}O

Experimental setup

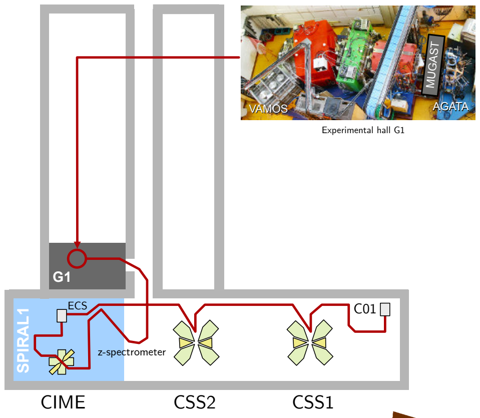


First experiment (May 2018):

- At LISE
- Spiral1 7.46 MeV/u $^{14}O^{8+}$ RIB

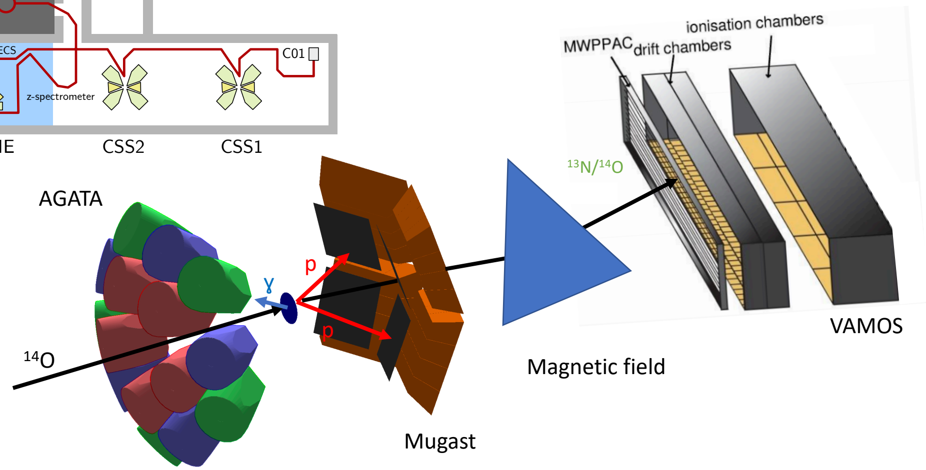


Measurement of the resonant elastic scattering excitation function



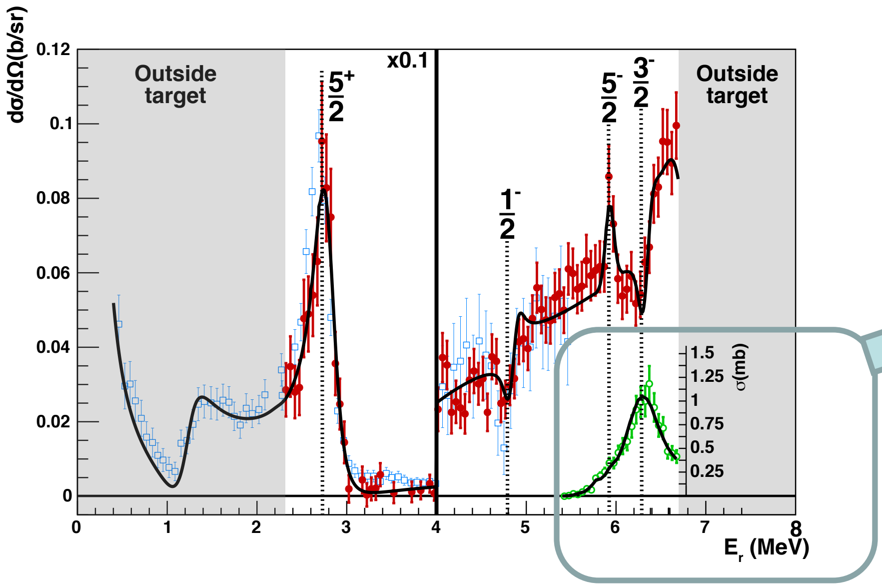
Second experiment (April 2019):

- With MUGAST VAMOS and AGATA
- Spiral1 7.42 MeV/u $^{14}O^{8+}$ RIB



2 proton correlations measurement
γ-emission measurement

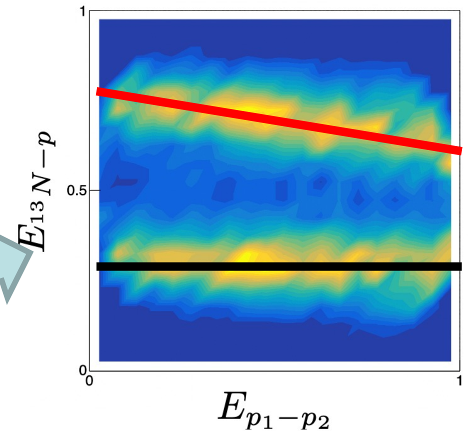
Results: ${}^{1}H({}^{14}O,p){}^{14}O$



J^π	E_r(MeV)	${}^{15}F \rightarrow {}^{14}O_{g.s.} + p$ Γ (keV)	C^2S	${}^{15}F \rightarrow {}^{14}O_{1^-} + p$ Γ (eV)	C^2S
$5/2^+$	2.81(12)	251(26)	1.0(1)	-	-
$1/2^-$	4.88(21)	30(15)	$6(3)\times10^{-3}$	-	-
$5/2^-$	5.93(10)	3(2)	$3(2)\times10^{-3}$	40(20)	$4(3)\times10^{-2}$
$3/2^-$	6.33(13)	28(13)	$1.1(3)\times10^{-3}$	330(80)	$9(3)\times10^{-4}$

${}^{1}H({}^{14}O,2p){}^{13}N$

Dalitz plot



Sequential emission of 2 protons

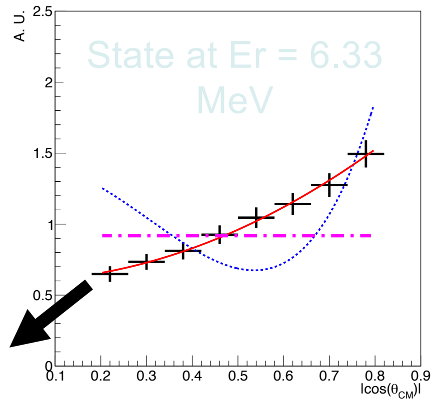
First proton

Second proton

Jπ = 5/2-

Jπ = 1/2+

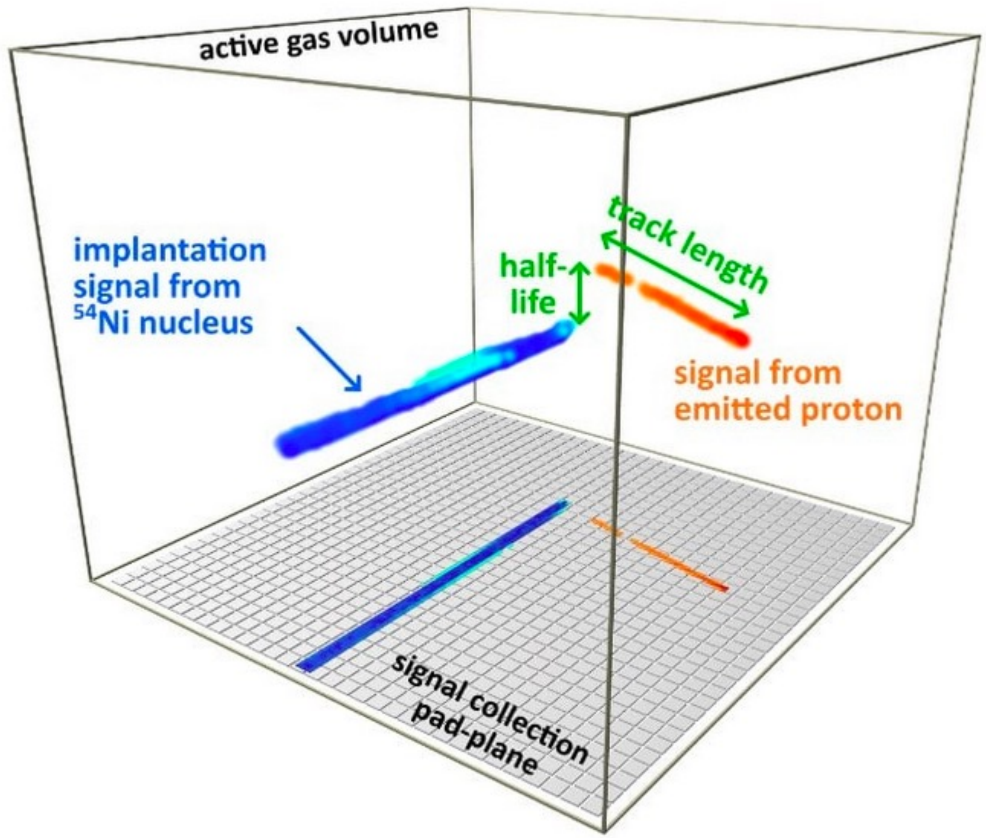
Jπ = 3/2-



polynomials fit of the angular distribution of the first proton

Very narrow resonances confirmed, V. Girard-Alcindor et al to be submitted

ACTAR TPC
4D observation of emitted proton



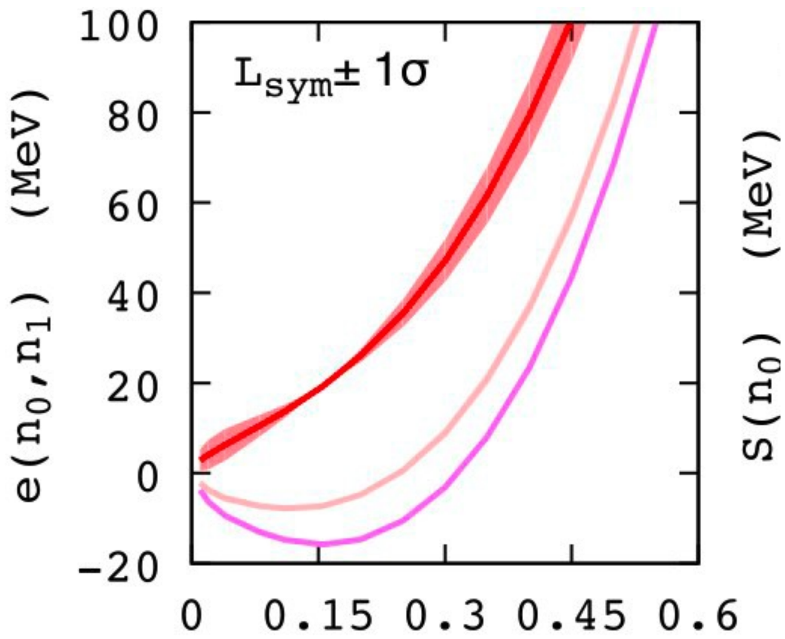
- The direct observation of the ^{54}Ni isomeric state

Exploring the EOS at low densities.

- Goals:
  - constrain the density dependence of the symmetry energy at low densities
  - improve the knowledge of volume and surface contributions to the symmetry energy in nuclei
  - investigate the experimental transport coefficients (experimental input to models)
  - effects of the cluster production on the symmetry energy and related observables

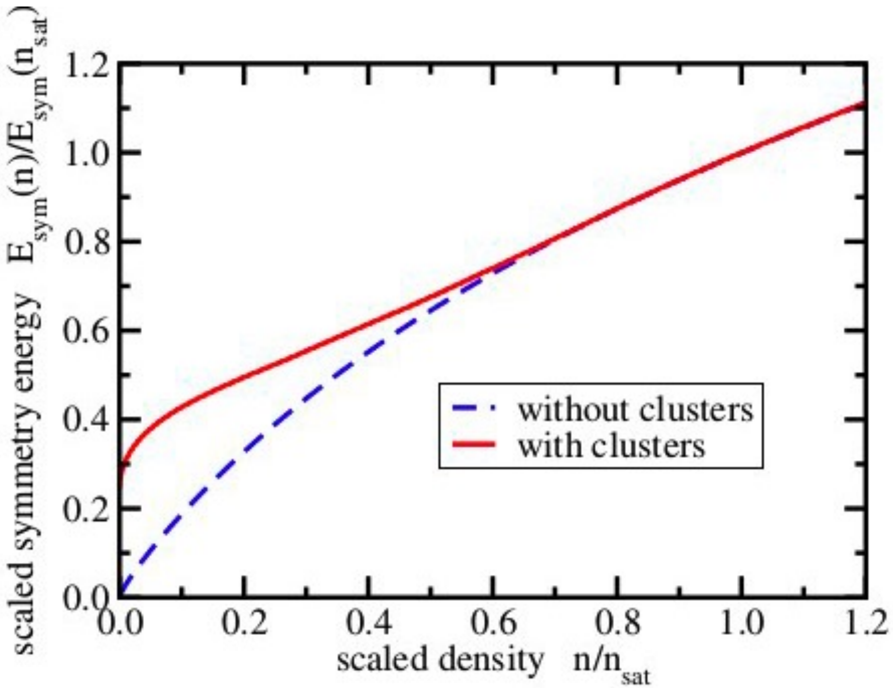
- Tools:
  - measurement of the isotopic distributions of fragments & clusters produced in HI-collisions at Fermi energies
  - determination of symmetry energy coefficients
  - experimental study of isospin diffusion and migration processes and how to disentangle them from secondary decays.
  - characterization of the cluster production

three first points already presented by Quentin
experiment INDRA-VAMOS



with or without cluster predictions

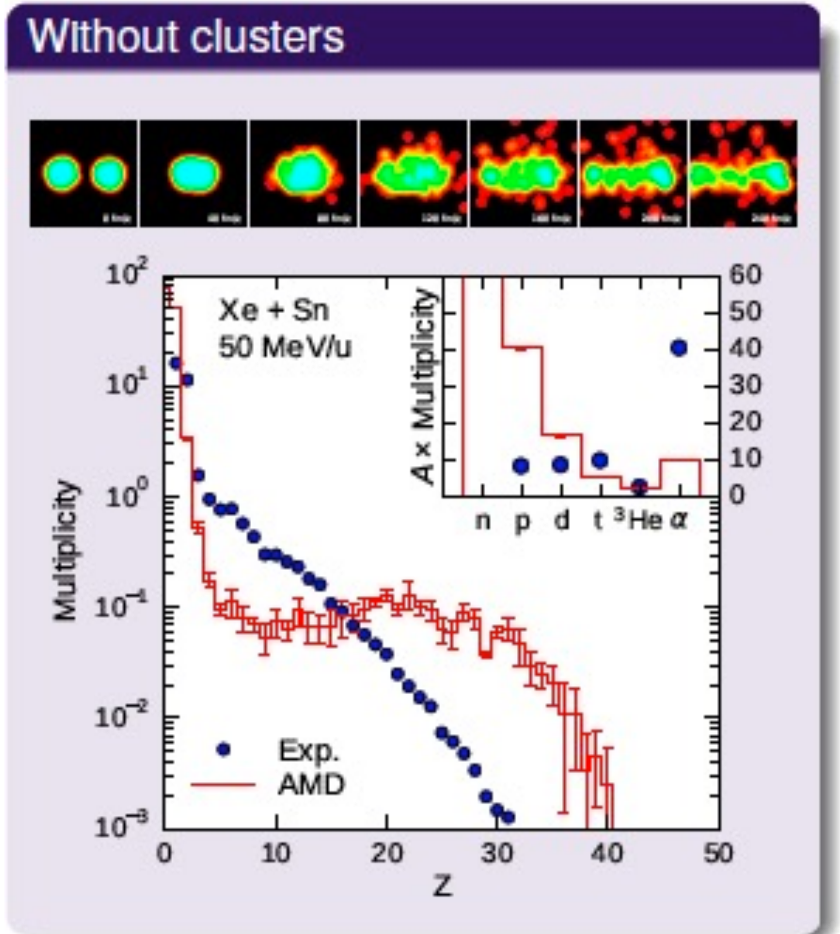
Margueron PRC 97 (2018) 025805

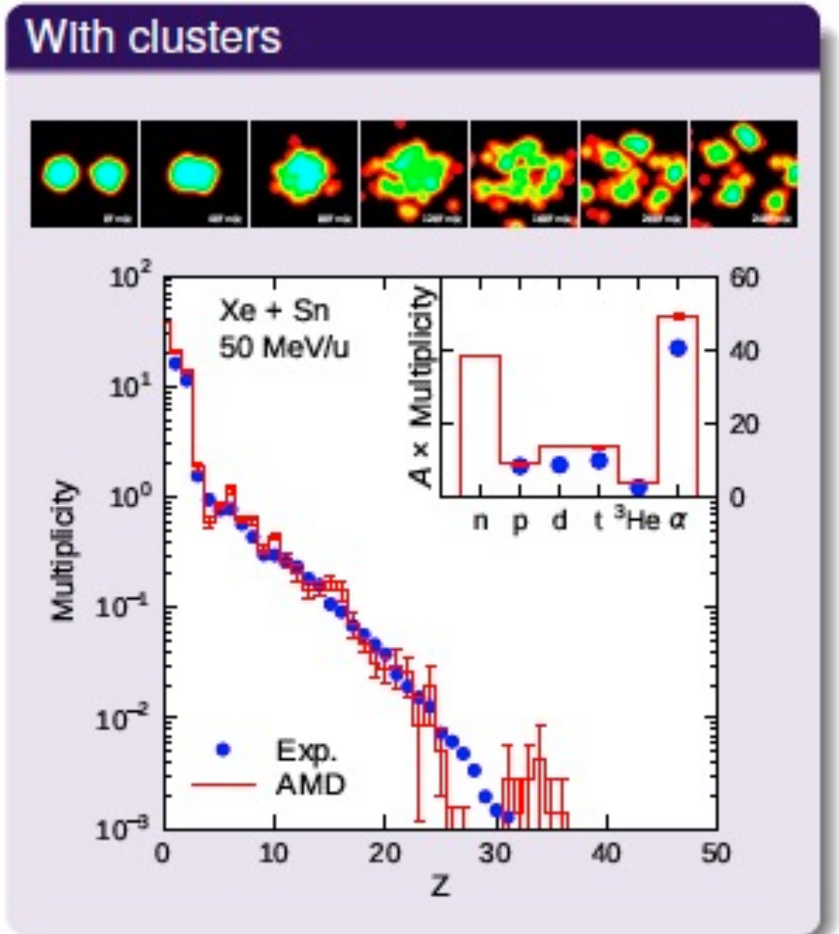


Typel, JoP: C.S. 420 (2013) 012078

effects of the clusters on the collision dynamics

Akira Ono, Journal of Physics: Conference Series 420 (2013) 012103



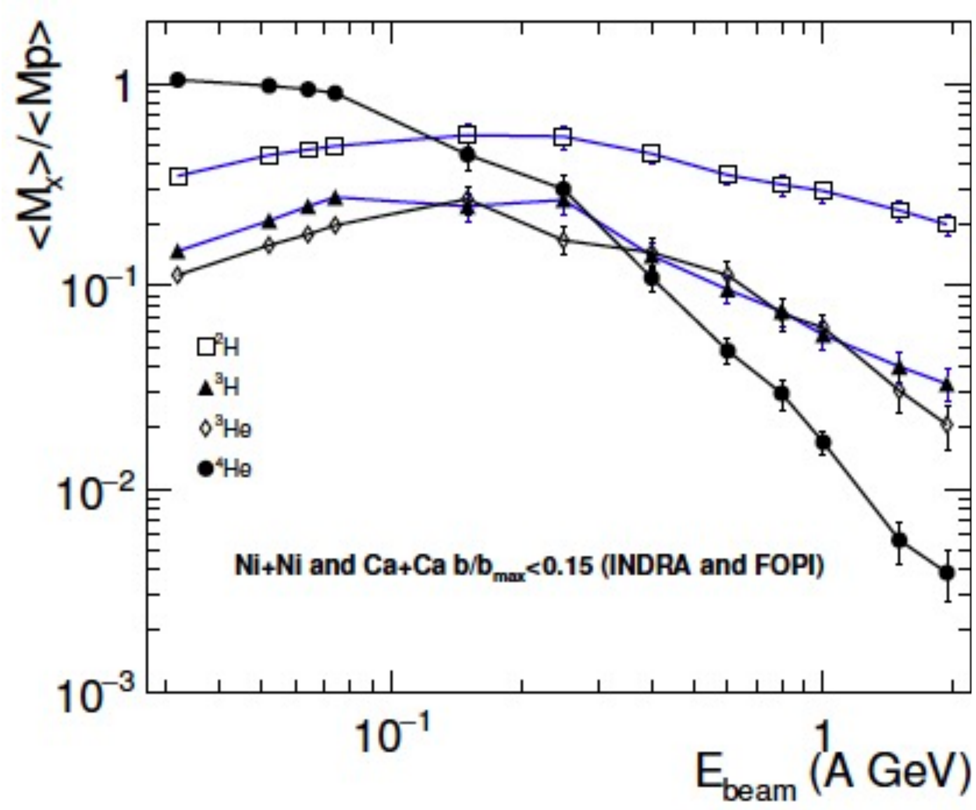


overestimation of free protons (neutrons)
underestimation of alpha's

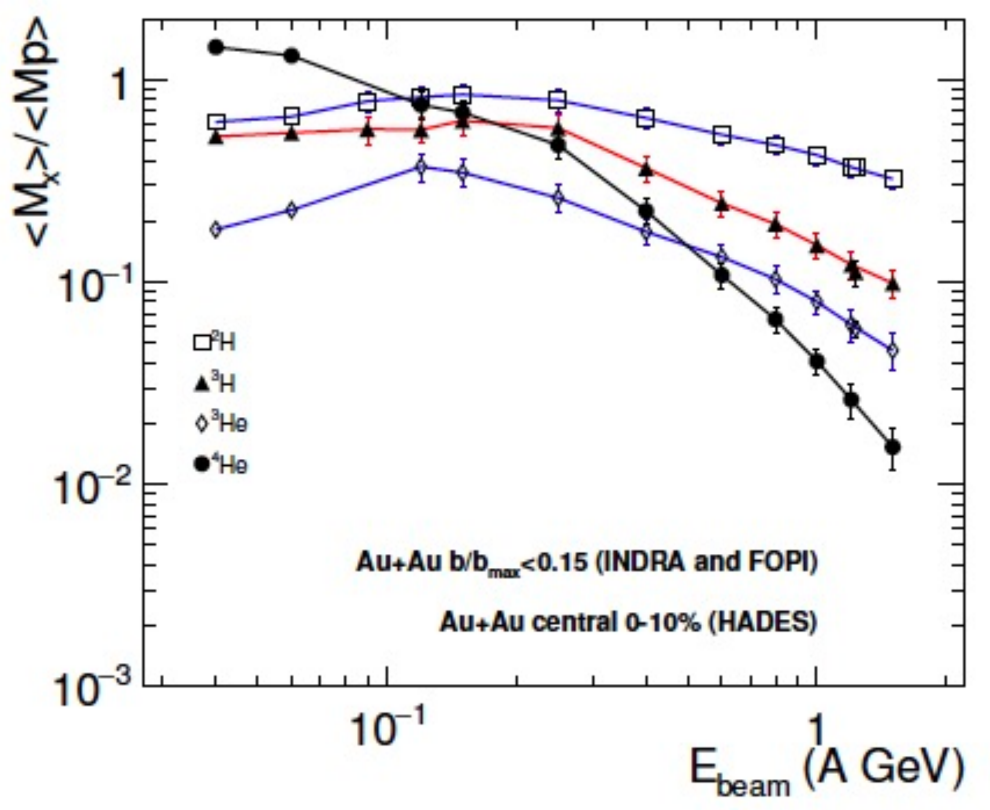
butter reproduction of the whole Z-distribution and LCP

Light cluster production in central symmetric HI reactions from Fermi to GeV energies

Ni+Ni and Ca+Ca
INDRA+FOPI



Au+Au
INDRA+FOPI+HADES



R. Bougault et al., Symmetry 2021, 13, 1406

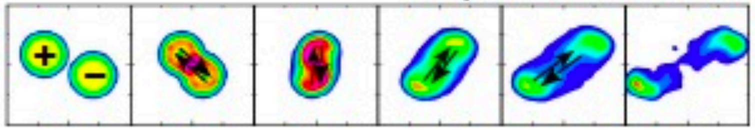
First INDRA-FAZIA campaign

E789 – Isospin transport and symmetry energy

Isospin equilibration

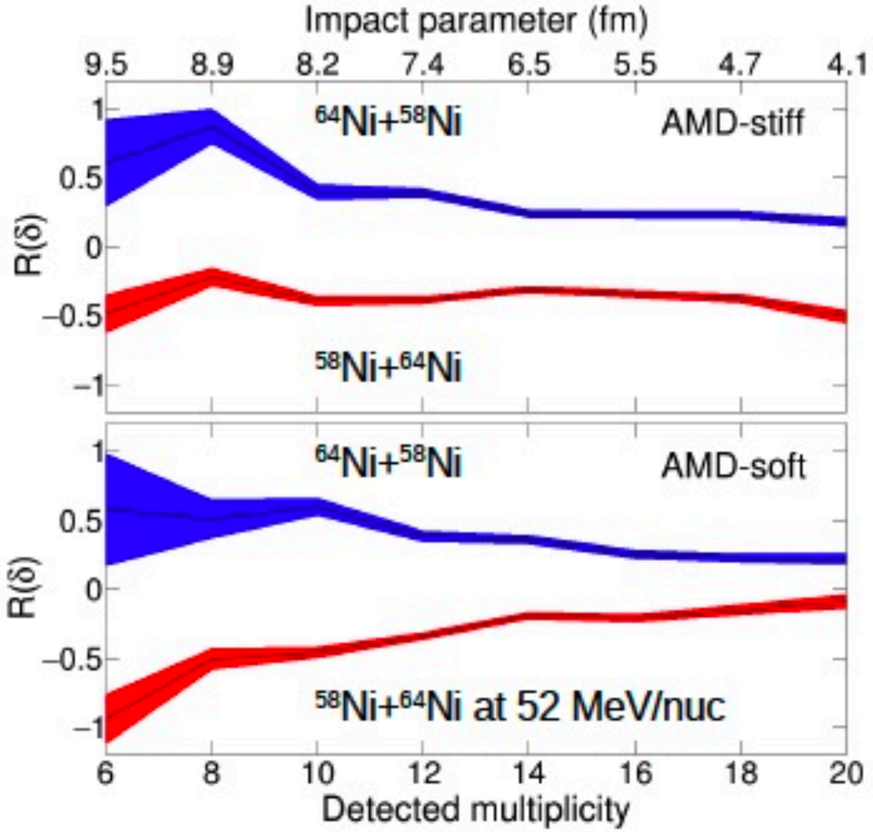
Projectile and target N/Z equilibrate with time
Equilibration rate sensitive to the EoS parameters
Needs to follow N/Z as a function of time

adapted from Xu PRC16



Experimental approach

Interaction time and window size depend on b
Replace time by centrality (multiplicity)
Isospin equilibration ratio built on 4 systems



E789 INDRA-FAZIA experiment

^{58,64}Ni+^{58,64}Ni collisions at 32 and 52 MeV/nuc
Good Z,A resolution of FAZIA → (N-Z)/A ratios
Full angular coverage of INDRA → centrality

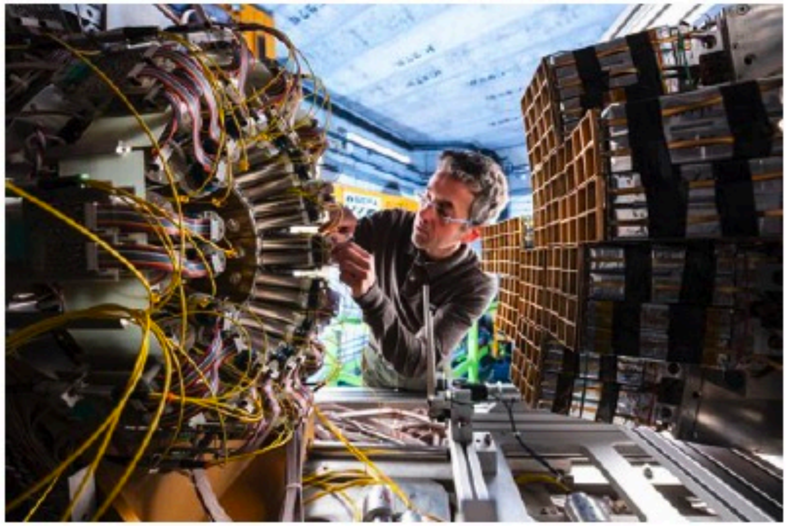
Simulations at 52 MeV/A

AMD-soft and AMD-stiff + GEMINI
Realistic response of INDRA-FAZIA device
Measurable dependency on L_{sym} EoS parameter

INDRA-FAZIA coupling in GANIL

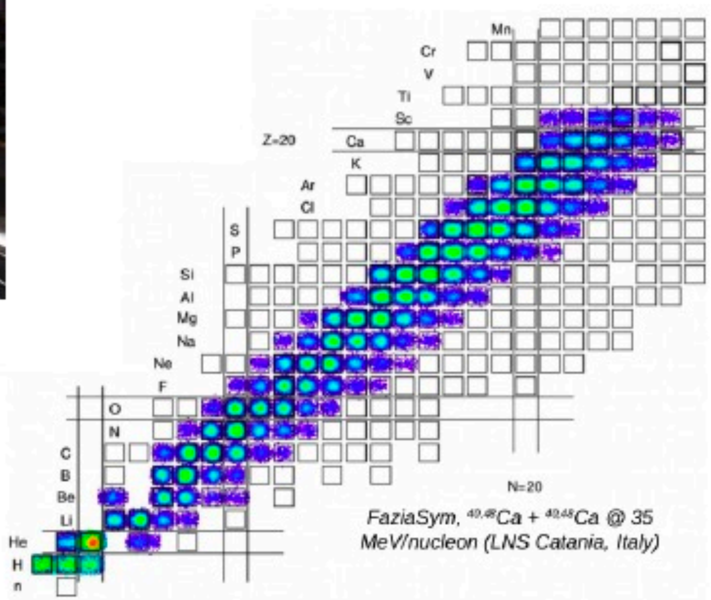
INDRA (1993)
240 modules (θ from 14° to 178°)
Si-CsI or CsI telescopes
Fully analogic electronics

FAZIA (2018)
12 Blocks : 192 modules (θ from 1.5° to 13°)
Si-Si-CsI(Tl) telescopes
Fully digital electronics



FAZIA performances
Z-identification up to Z=54
A-identification up to Z~20-25
Isospin-related observables of interest

INDRA performances
Z-identification up to Z=92
A-identification up to Z=5-8
Centrality (impact parameter) estimator



E789 – Overview of the data

Reactions

$^{58}Ni+^{58}Ni$ at 32 MeV/nuc ~30 10^6 events
$^{58}Ni+^{64}Ni$ at 32 MeV/nuc ~30 10^6 events
$^{64}Ni+^{58}Ni$ at 32 MeV/nuc ~30 10^6 events
$^{64}Ni+^{64}Ni$ at 32 MeV/nuc ~30 10^6 events
$^{58}Ni+^{58}Ni$ at 52 MeV/nuc ~30 10^6 events
$^{58}Ni+^{64}Ni$ at 52 MeV/nuc ~30 10^6 events
$^{64}Ni+^{58}Ni$ at 52 MeV/nuc ~30 10^6 events
$^{64}Ni+^{64}Ni$ at 52 MeV/nuc ~30 10^6 events
Partial identification and calibration available

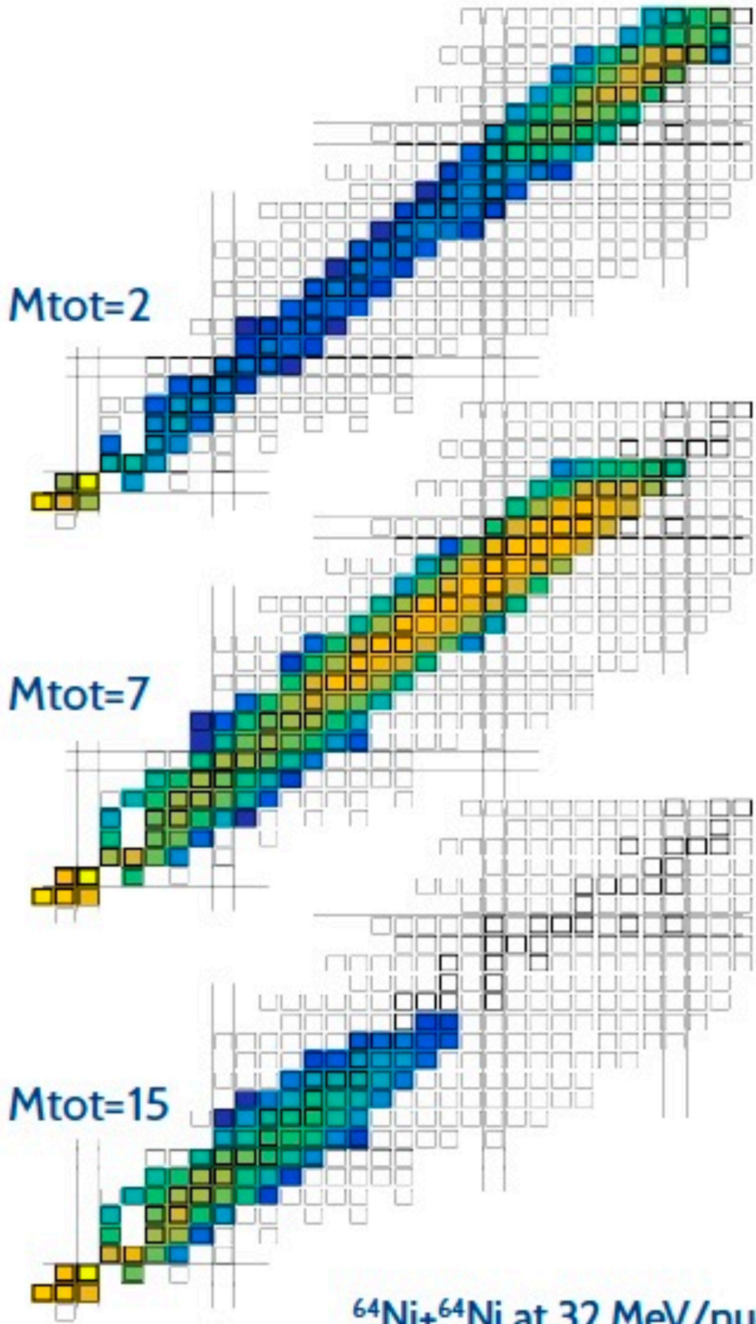
Observables of interest

Z and A of forward-emitted fragments (FAZIA)
Total multiplicity to estimate centrality (INDRA+FAZIA)

Preliminary results

Population of the nuclear chart for different centrality

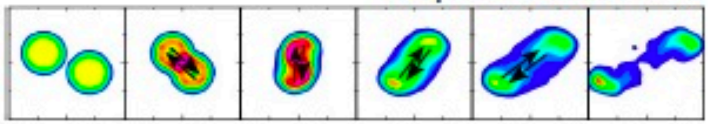
First time we can show the evolution of reaction mechanism in 2D !

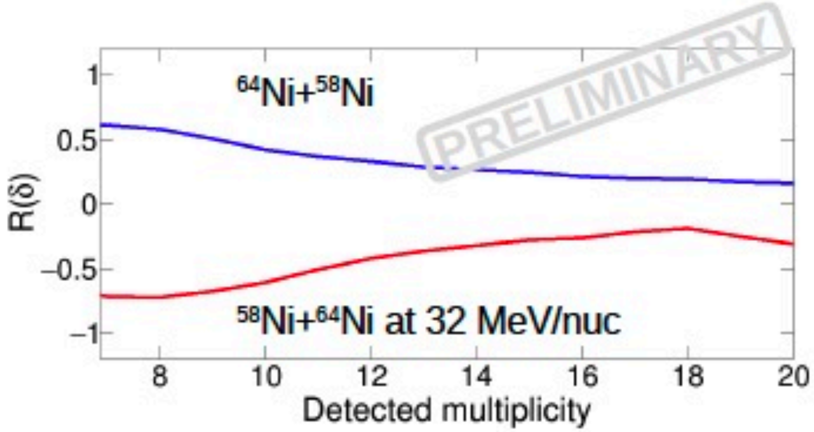


$^{64}Ni+^{64}Ni$ at 32 MeV/nuc

E789 – Preliminary diffusion plot

adapted from Xu PRC16





Equilibration ratio

Quasi-projectile Z and A measured with FAZIA
Mixed systems normalized to the extreme ones

$R(\delta) = (2X_i - X_1 - X_2)/(X_1 - X_2)$, with $X_i = f(Z,N) = \delta$

$R(\delta) = +1\ (-1)$: no isospin equilibration

$R(\delta) = 0$: full isospin equilibration

Preliminary result

Small equilibration at high impact parameter
Partial equilibration at low impact parameter

Next steps

Multiplicity → impact parameter, model-independent method [Frankland, in preparation]
Compare with transport models exploring the proper parameter space (Bayesian analysis)

Expected scientific impact

EoS empirical parameter probability distribution and correlations between parameters
Compare to parameter distributions coming from astrophysic observations
Any tensions between micro- and macro-parameters would sign new physics

new INDRA electronics. 2021
Mesytech

will be used in next spring in the INDRA-FAZIA campaign of measurements

Conclusion

- End of the LINAC commissioning
- the first experiments with neutron beam from NFS already started
- The results of the INDRA-VAMOS will be submitted for publication soon
- Analysis of the INDRA-FAZIA experiments are in the way
- Cluster production as function of wide range of incident energy should give important constraints to the models.
- The next INDRA-FAZIA campaign of measurements (with the new iNDRA-electronics) should give interesting results.