The SPES Projects @LNL:

Status of the Project, Technical Challenges, Instrumentation and Scientific Program

Fabiana GRAMEGNA
LNL Research Division Coordinator
SPES -WP B1- *Scientific Support* - Coordinator

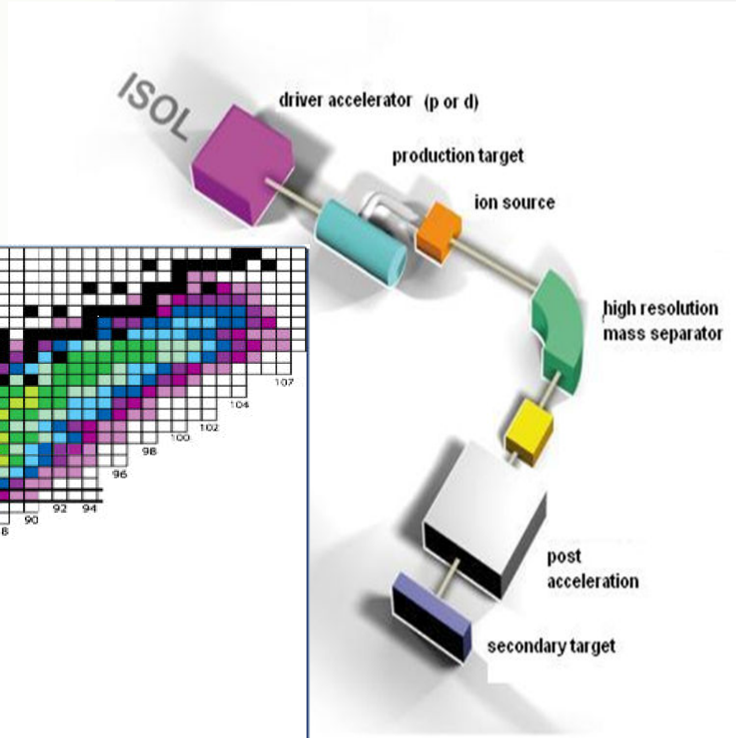
Aperitivo Scientifico:
BOLOGNA - January 29th 2016

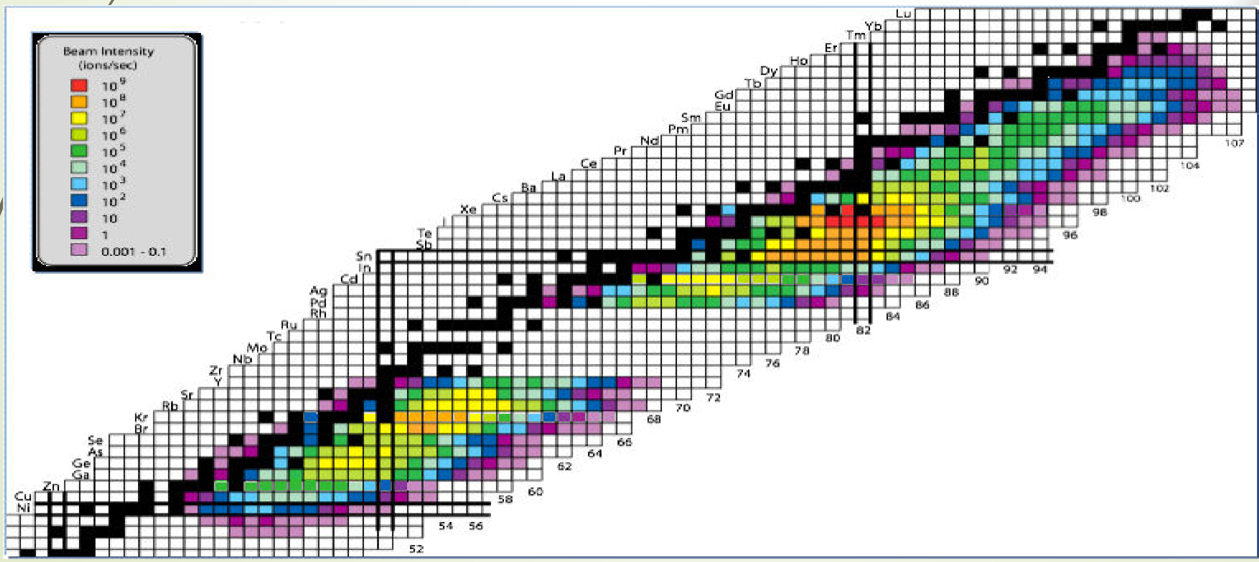
SPES: Selective Production of Exotic Species

- SPES Framework
- SPES *Aims & programs*
- SPES *Phases*
- SPES Status: *Details & Improvements*
- SPES *Physics Program*
- SPES *Instrumentation*
- SPES *& Bologna*

'Commercial' Cyclotron → Proton Driver:

70MeV 0.75 mA 2 exit ports



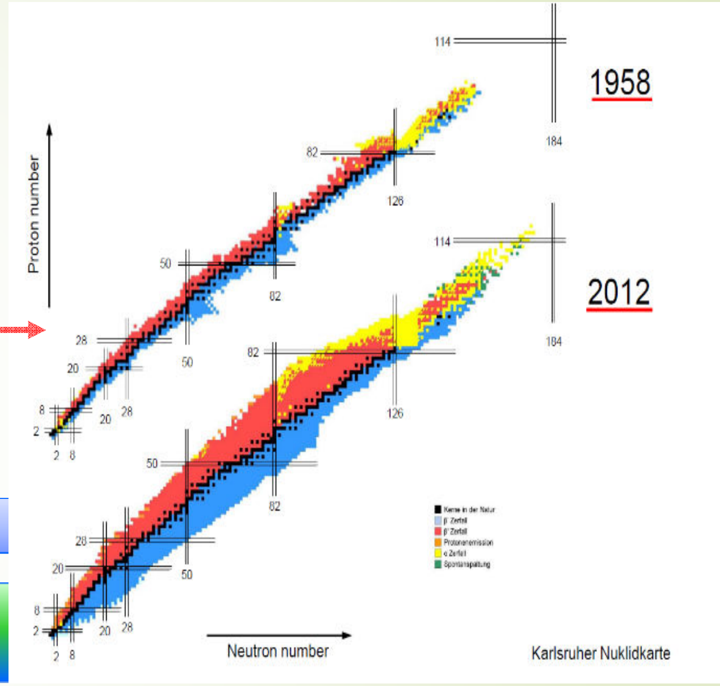


LNL: an international resource for NUCLEAR PHYSICS

The mainframe is at **European level**:

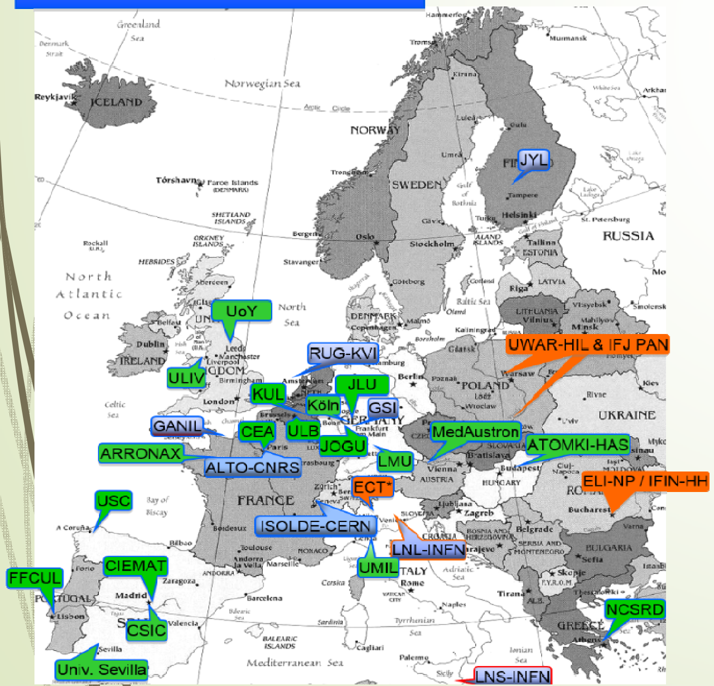
Are we competitive?

Is NP needed?
Did we progress?



FP8 ENSAR2

Partners



7 ⇒ 10 TNA Facilities

30 ⇒ 30 beneficiaries
15 countries

Community: 2700-3000 scientists and highly qualified engineers

Close collaboration with infrastructures outside Europe:
Canada: TRIUMF
China: IMP Lanzhou
Japan: RIKEN & RCNP
Russia: Dubna/JINR
South Africa: iThemba
United States: NSCL & ANL

ENSAR2 – UE FP8

SPES → National & International collaborations are needed

NATIONAL SPES collaborations

Accelerator Technologies & Mechanics
INFN Section and Univ. of Milano, **Bologna**, LNS, LNL, Pavia, Trento and Palermo

Physics Programs & Detectors
INFN Sections of Bari, **Bologna**, Catania, Firenze, Milano, LNL, LNS, Padova, Perugia, Trento, Napoli

INTERNATIONAL collaborations

on
Nuclear Physics & Astrophysics,
Modern Detectors &
Accelerator Technologies

International Laboratories

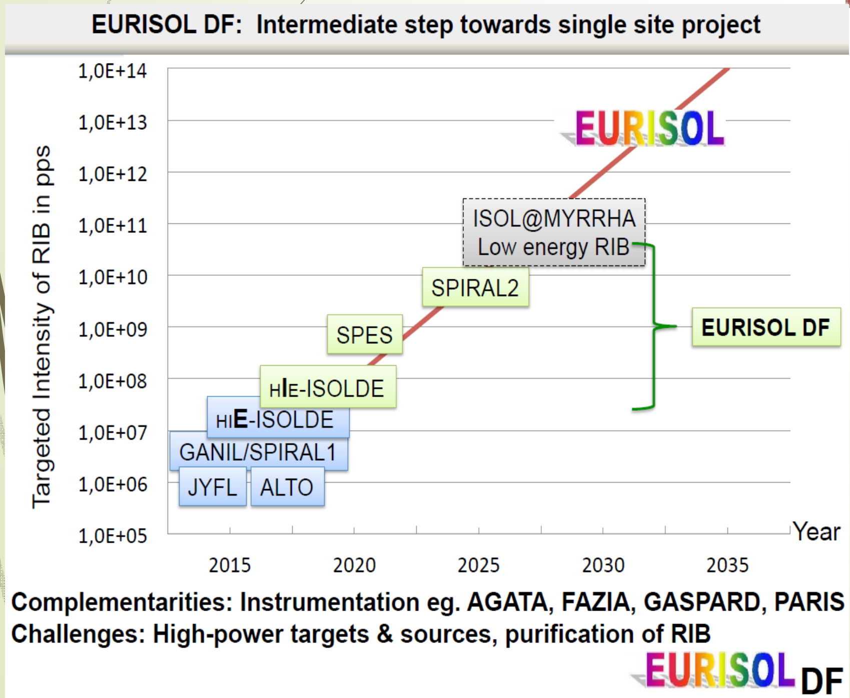
LIA CollAGAIN (ALTO-GANIL-INFN)
LIA POLITA (INFN – COPIN)
LIA COPIGAL (COPIN – GANIL-ALTO)

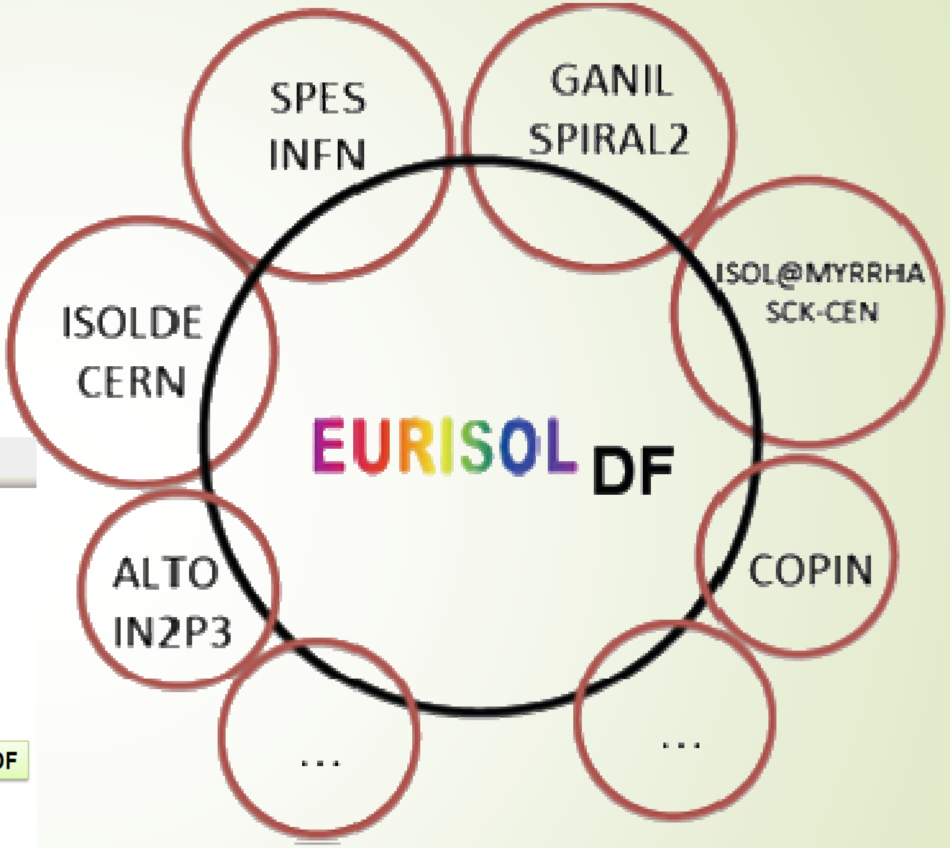
- ISOLDE CERN & SPES
- MoU INFN & iTHEMBA & HRIBF ORNL
- Ongoing collaborations with RIKEN, MSU-FRIBS, RISP-KOREA, BARC, NEW DEHLI, DUBNA, ...
- International collaboration on Innovative Itinerant Detectors AGATA, FAZIA, PARIS, NEDA, GASPARD, ACTAR/GDS
- MoU in preparation with ELI-np

EURISOL Distributed Facility

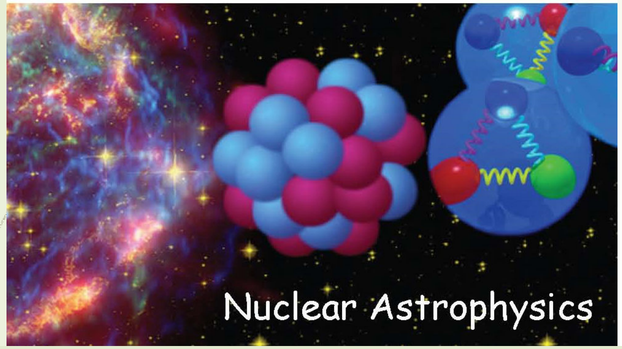
5

- A distribute laboratory for radioactive beams:
- More exotic beams available
- Coordination of competences to face EURISOL technologic challenges
- Joint effort to manage the activity at European level

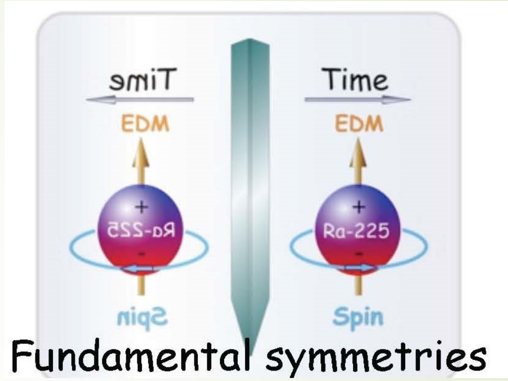




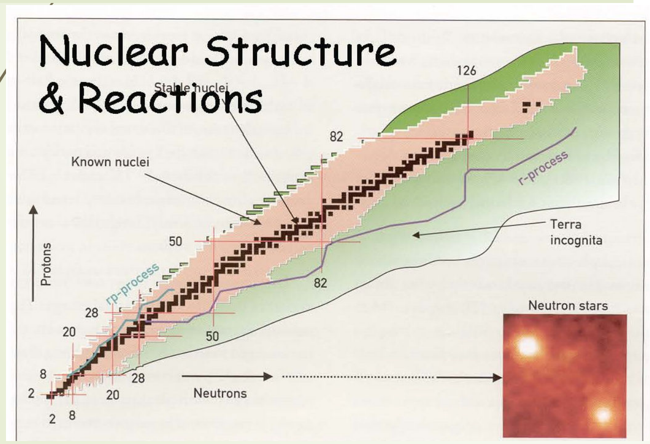
Which Science drives Physics with exotic beams



Powering stellar explosions, neutron star crust etc.



Use rare isotopes as Laboratories where symmetry violations are amplified



Limit of existance: what make nuclei stable? New Shapes, New Collective behaviors

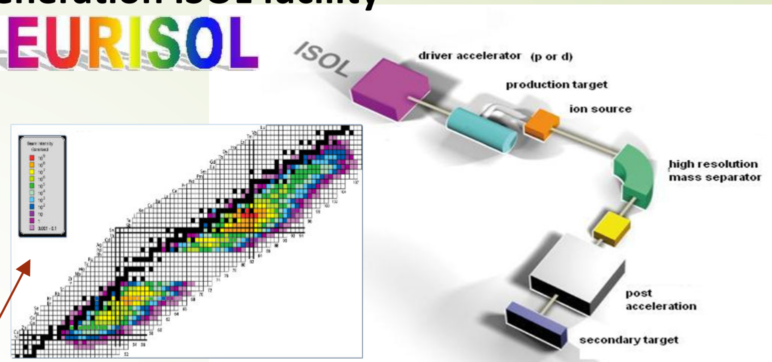
Material Science, Nuclear Medicine, Nuclear Energy

SPES exotic beams for science

SPES Strategy: 4 stages

INFN Istituto Nazionale di Fisica Nucleare

Second generation ISOL facility
Toward EURISOL

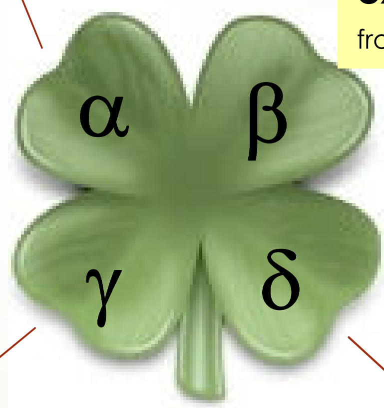


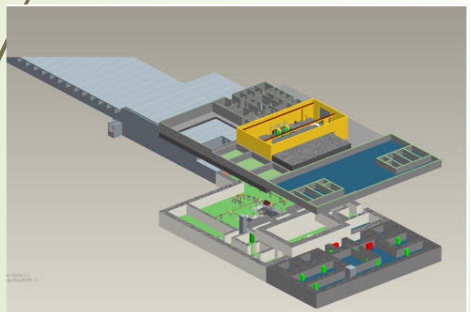
Installed
Under SAT

Funded

Production & re-acceleration of **exotic beams**, especially **neutron–rich** from **p-induced Fission** on **UCx (10^{13} f/s)**

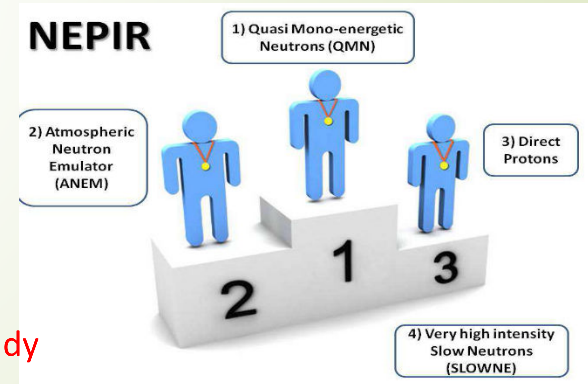
New SPES Building
BEST Cyclotron installation & commissioning:
- 70 MeV proton beam
- 750 μA





Partially funded
6.8 M€

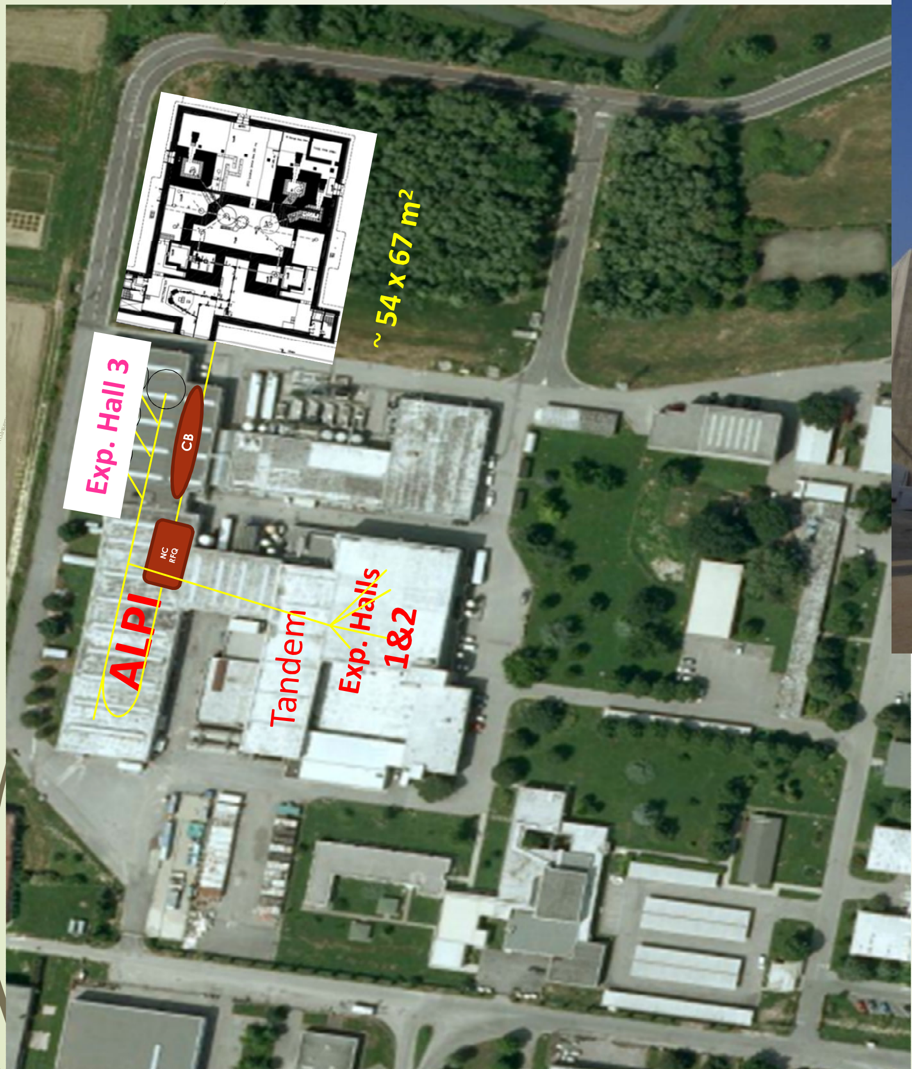
Design study



Research and Production of **Radio-Isotopes for Nuclear Medicine**

Accelerator based neutron source (**Proton and Neutron Facility for Applied Physics**)

SPES layout:



New infrastructure for:

- cyclotron
- RIB (Radioactive Ion Beam)
- application facility

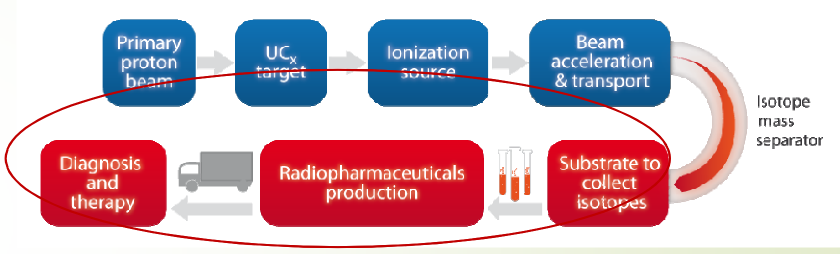
Production of radionuclides for medicine using the SPES cyclotron (production&research)

ISOLPHARMA*

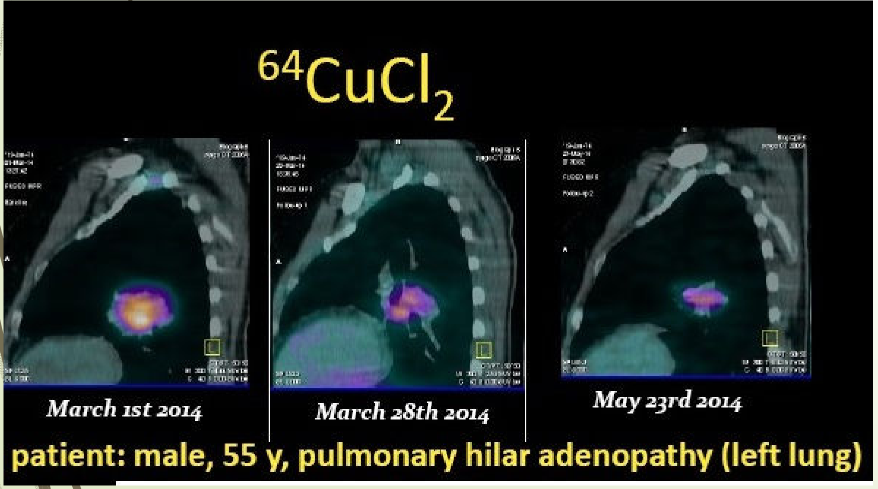
* INFN Patent pending

Use of ISOL technique for Direct isotope on-line separation : very high specific activity

(4-5 order of magnitude than standard)



Radiopharmaceutical	Targeted organs	Half-life	Specific Activity (GBq/mg)	
			SPES production	Neutron capture reaction
$^{89}Sr-SrCl_2$	Bone	50.5 d	≥ 597	≥ 0,004
$^{90}Y-YCl_3$	Liver and endocrine system	64.1 h	≥ 9480	≥ 0,8
$^{125}I-NaI$	Prostat, brain, lung, pancreas, liver	59.4 d	≥ 552	≥ 6
$^{131}I-NaI$	Thyroid	8.02 d	≥ 3911	≥ 0,7
$^{75}Se-H_2SeO_3$	Liver	119.6 d	≥ 323	≥ 3,7



LARAMED

Funded with 6.8 Meuro

Joint Research lab of INFN, CNR, Universities and external companies:

- Cross Section measurements through target activation
- High power targets tests
- Radio-isotope/radio-pharmaceutical Production test facility (^{99m}Tc, ^{64}Cu, ^{67}Cu, ^{82}Sr, ...)

Production laboratory in Joint Venture with external companies:

Selected isotopes of medical interest

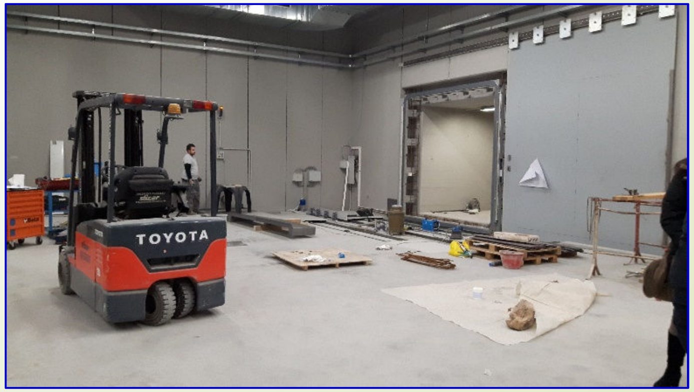
Sr-82/Rb-82 generator

T1/2: **25.6 d** EC 100% **/ 1.3 min**

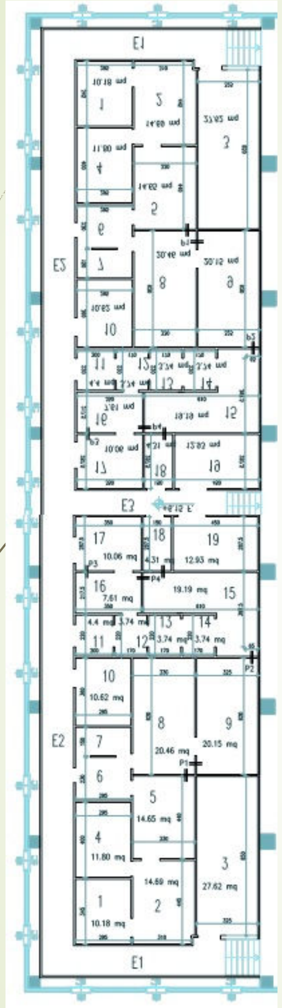
photons 511keV, 776keV

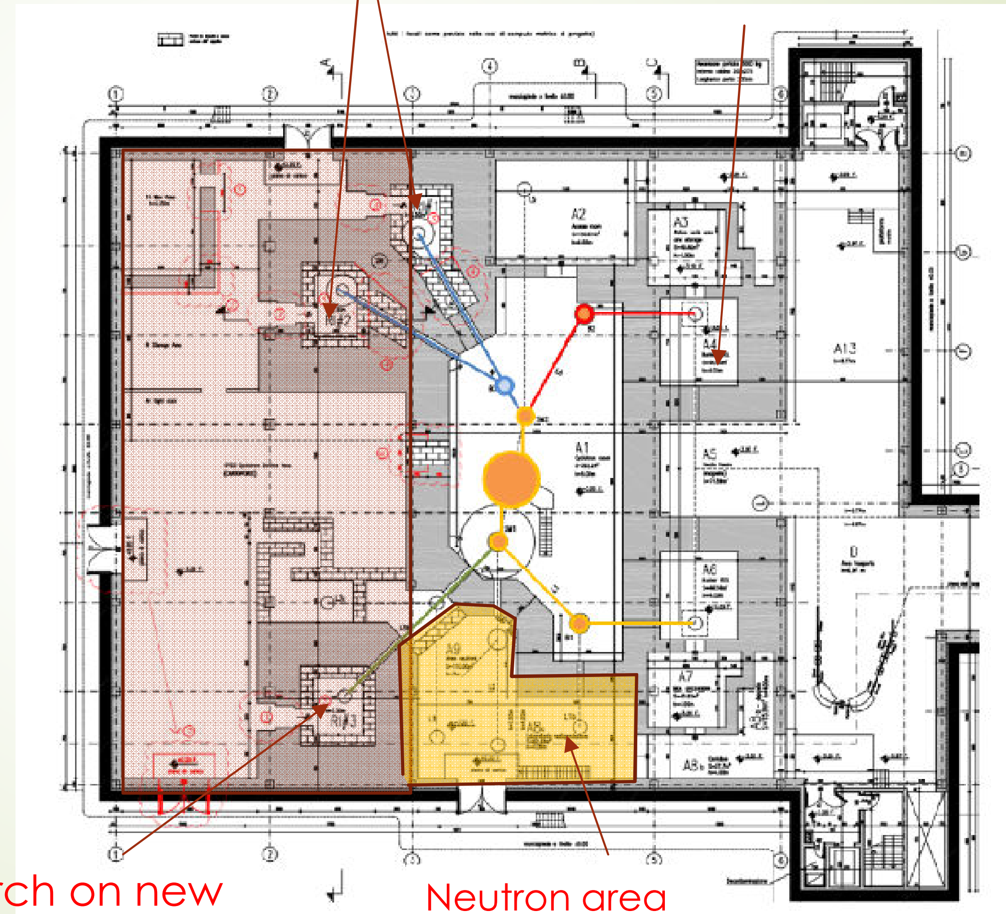
STATUS:

- Building and infrastructures under development
- Design of radiochemistry labs
- Design of beam line and target management
- Contract with company for radioisotopes production to be finalized



SPES LAYOUT: Applications areas





Production of Radioisotopes

LARAMED Temp

Radiochemical Laboratories (second floor)

Research on new radioisotopes

Neutron area

NEPIR: a project for neutron production @ SPES

Design study

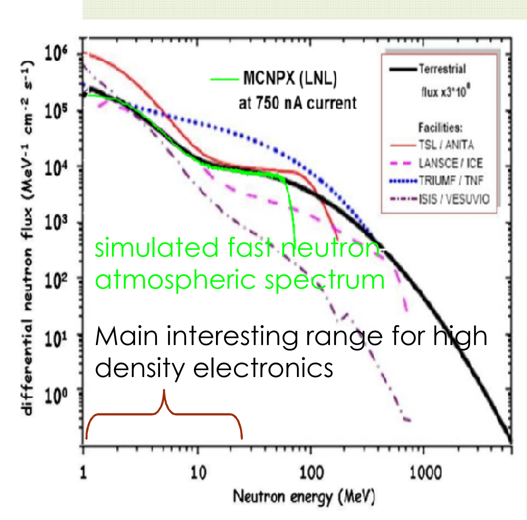
Integral neutron production at SPES Cyclotron

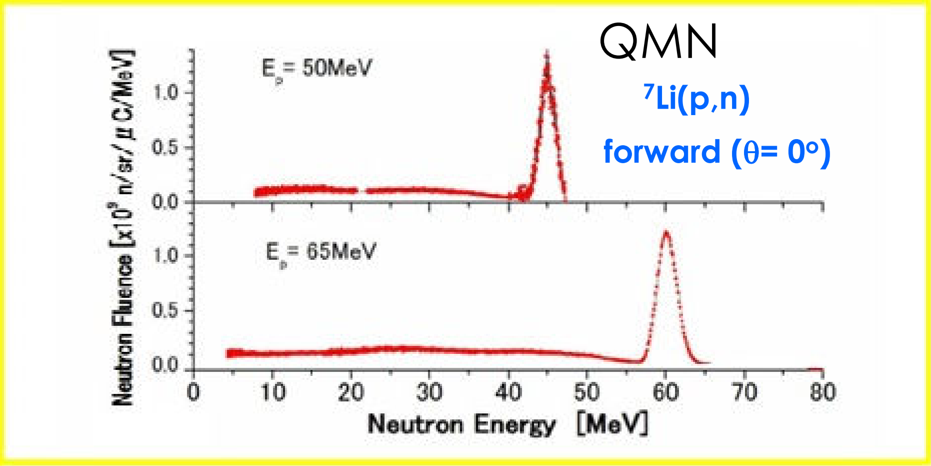
Proton beam= 70 MeV, 500 μA Target = W 5mm

Energy region (MeV)	Sn (n/s) ~ $6\cdot10^{14}$ s^{-1}	Φ_n @ 2.5 m ($n\ cm^{-2}\ s^{-1}$)	Φ_n @ 1 cm ($n\ cm^{-2}\ s^{-1}$)
1 < E < 10	~ $5\cdot10^{14}$ s^{-1}	5×10^8	3×10^{13}
10 < E < 50	~ $1\cdot10^{14}$ s^{-1}	1×10^8	$6x10^{12}$

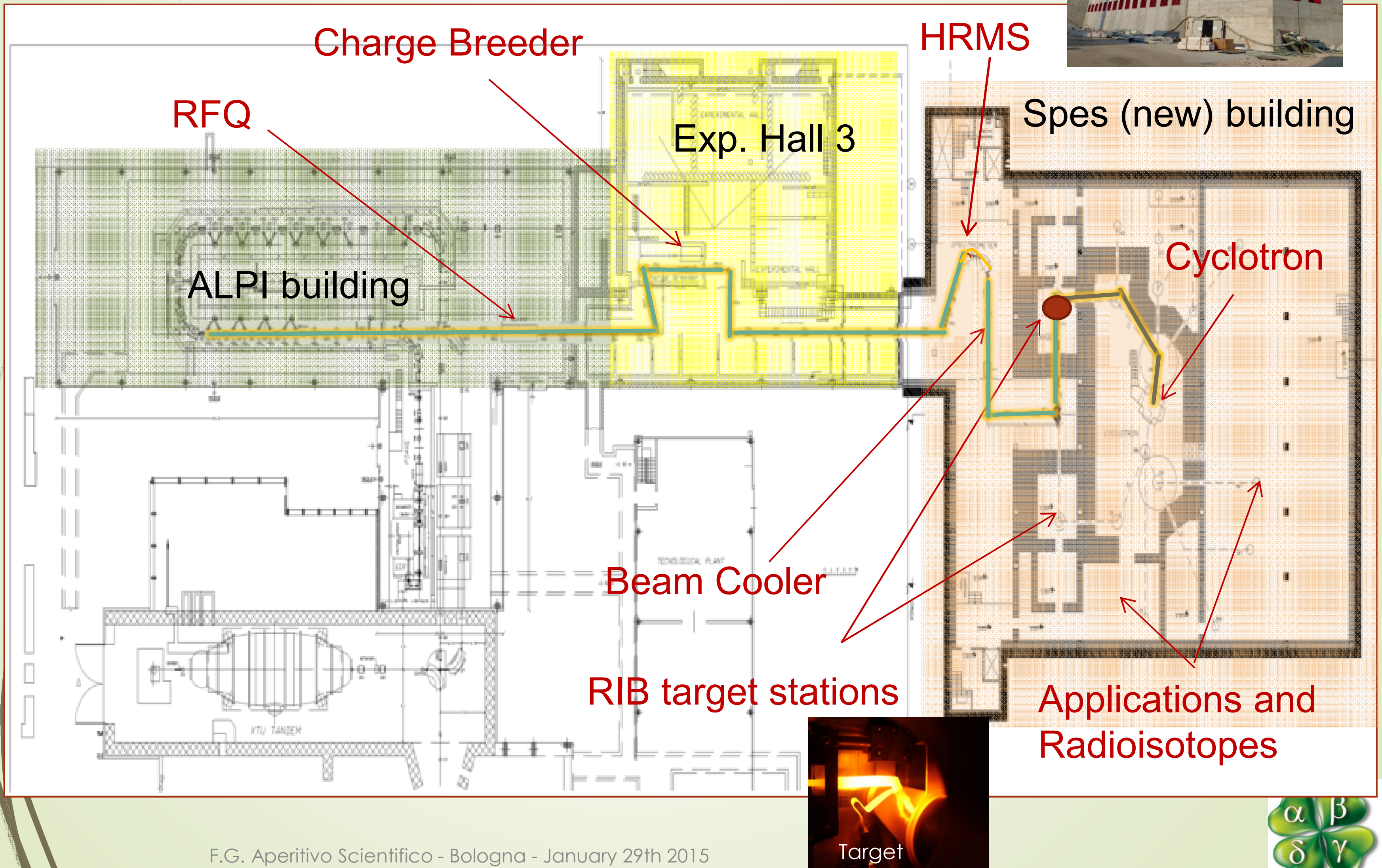
Continuum and Quasi Mono Energetic fast neutron spectra

- Cross section data for basic science and astrophisics
- Oncology studies
- Calibration of radiation instrumentation
- Radiation protection studies (shielding-benchmarks)
- Radiation hardness studies (Single Event Effect)





SPES layout: following the beam transport line

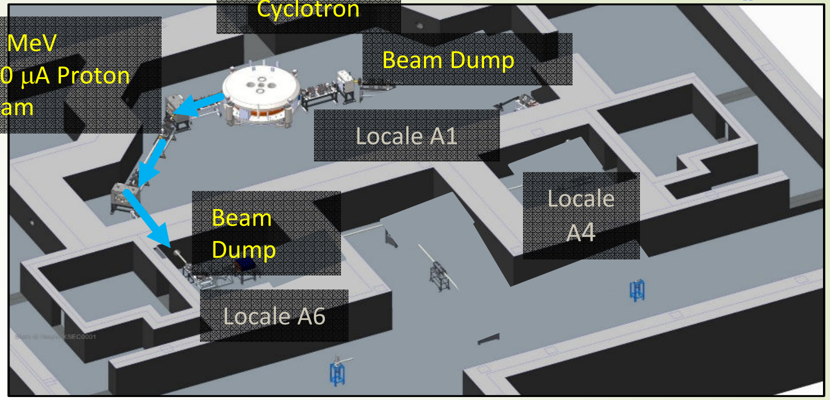


Phase α: cyclotron installation and SAT

Main Parameters

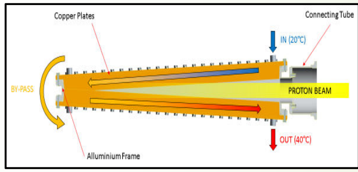
Accelerator Type	Cyclotron AVF 4 sectors
Particle	**Protons (H^- accelerated)**
Energy	**Variable within 30-70 MeV**
Max Current Accelerated	**750 μA** (52 kW max beam power)
Available Beams	**2 beams at the same energy** (upgrade to different energies)
Max Magnetic Field	1.6 Tesla
RF frequency	56 MHz, 4^{th} harmonic mode
Ion Source	Multicusp H^- I=15 mA, Axial Injection
Dimensions	Φ=4.5 m, h=1.5 m
Weight	150 tons

Phase α: cyclotron installation and SAT



Activity time schedule for the Commissioning and the **Site Acceptance Tests**

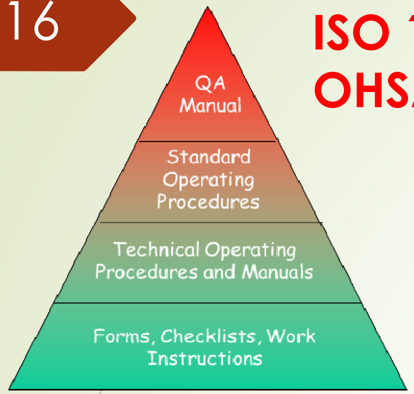
- **Safety System Commissioning** — **done**
- **Source Commissioning** — **done**
- **RF Commissioning** — **done**
- **Beam Commissioning** — **done**
  - **Injection** — **done**
  - **Acceleration without extraction** — **done**
  - **Completion Security SAT System** — **Feb 2016**
  - **Completion High Power Beam Dump** — **Feb 2016**
  - **Extraction and Beam Line 1 tuning** — **2016 1st semester**
  - **Extraction and Beam Line 2 tuning** — **2016 1st semester**
  - **Dual beam extraction** — **2016 1st semester**
  - **Operation and Commissioning LNL-BEST** — **2016 1st semester**



This schedule needs to be fine-tuned with the INFN activities.

- **INFN Training and "customization"** — **April-September**
- **Machine running** — **→ ∞**

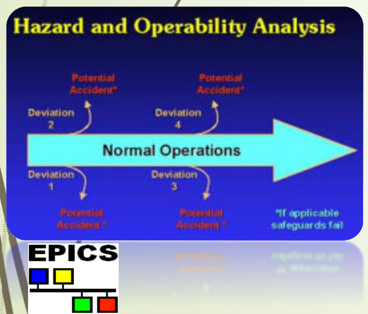
ISO 12100:2010/14121:2007 for all **Quality aspects**
OHSAS 18001:2007 for **Safety issues**

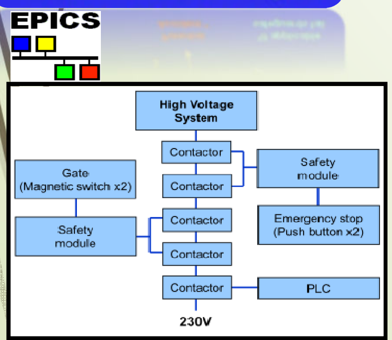


Severity level (S)	Occurrence Probability (P)												
	3	4	5	6	7	8	9	10	11	12	13	14	15
1	3	4	5	6	7	8	9	10	11	12	13	14	15
2	6	8	10	12	14	16	18	20	22	24	26	28	30
3	9	12	15	18	21	24	27	30	33	36	39	42	45
4	12	16	20	24	28	32	36	40	44	48	52	56	60

RISK analisys

- **FMEA** - **Failure Mode and Effects Analyses**
- **FMECA** - **Failure Mode Effects and Criticality Analyses**
- **HAZOP** - **HAZard and Operability study**





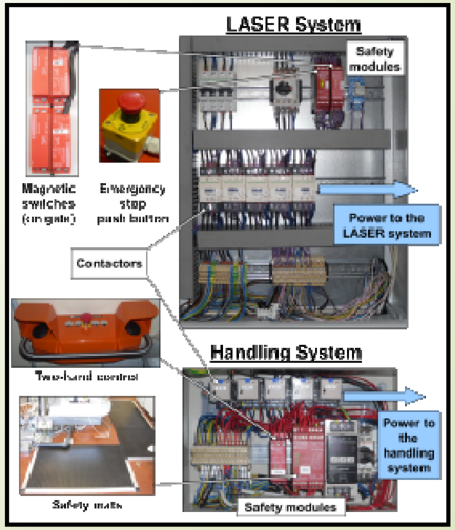
Dedicated control system
based on risk analysis

QSMS defined

On the way the **risk analysis** (collaboration with nuclear eng. Palermo)

Performed **Safety Systems** (software and hardware) for **ISOL lab**.

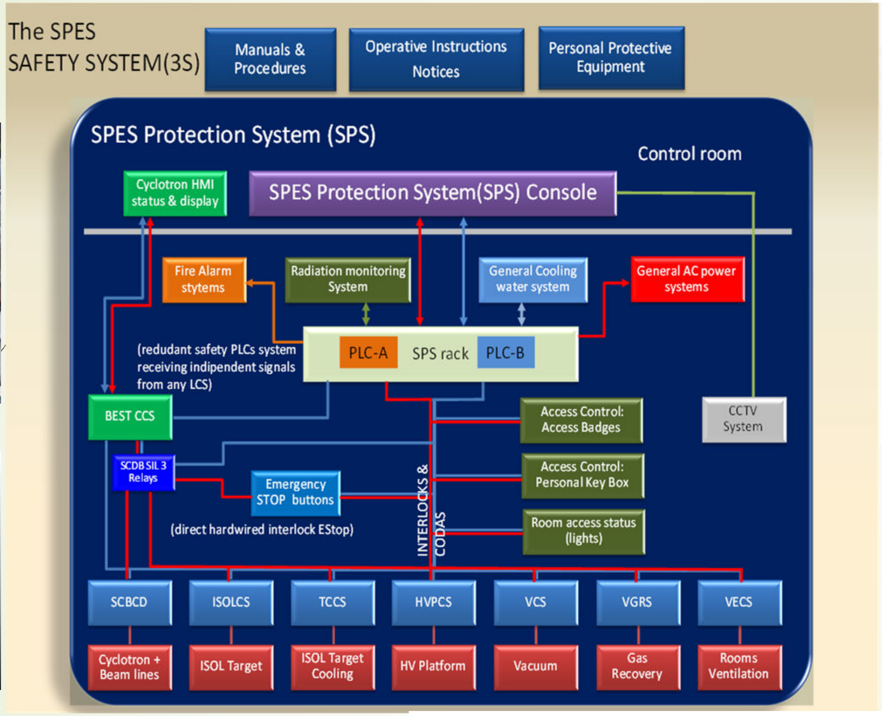
Contacts with italian companies for full design (SOGIN, NUCLECO, ENEL, ..)

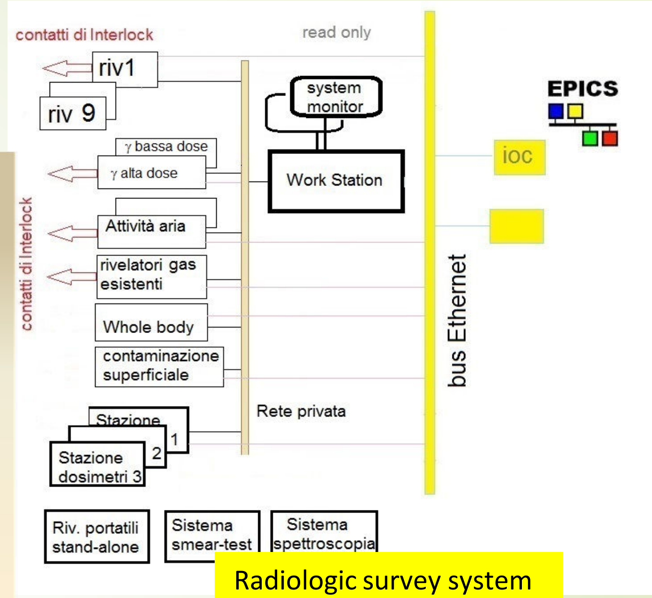


A SIL3 safety system is under development (tender launched)

Cyclotron and beam lines

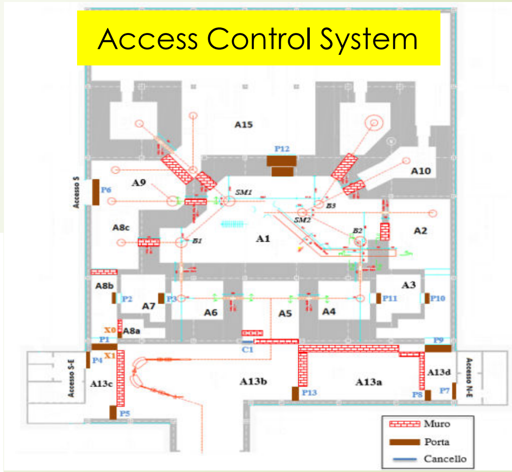
ISOL target

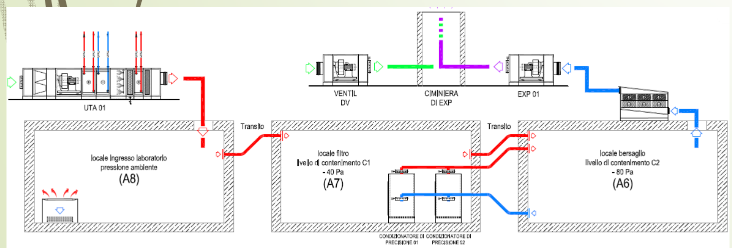




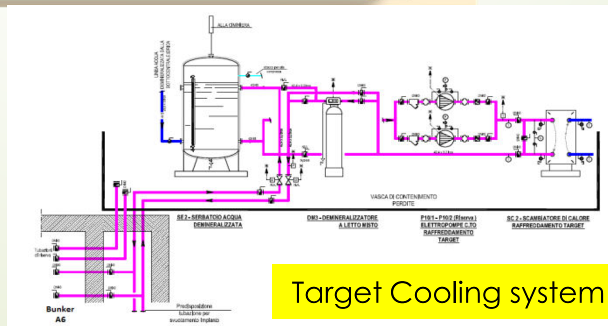
Radiologic survey system

Access Control System



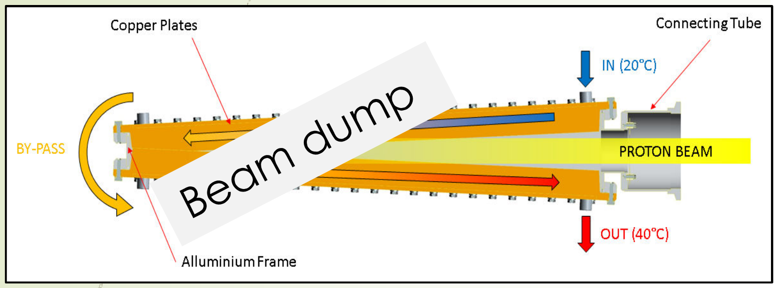


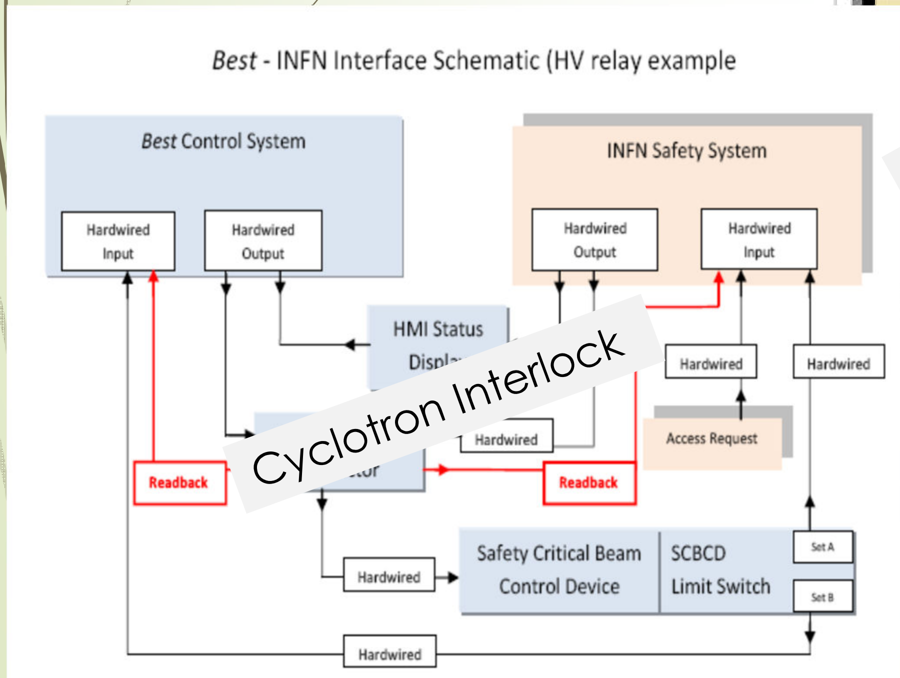
ventilation

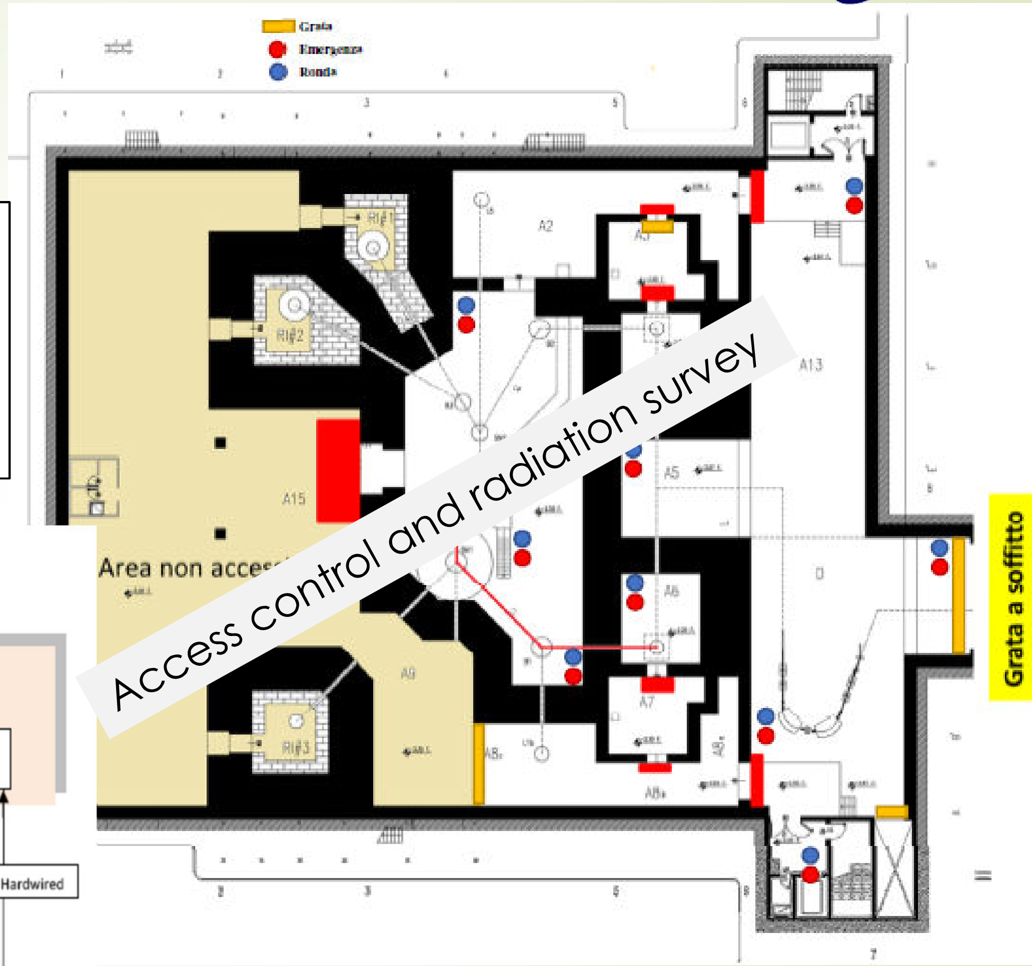


Target Cooling system

Cooling system

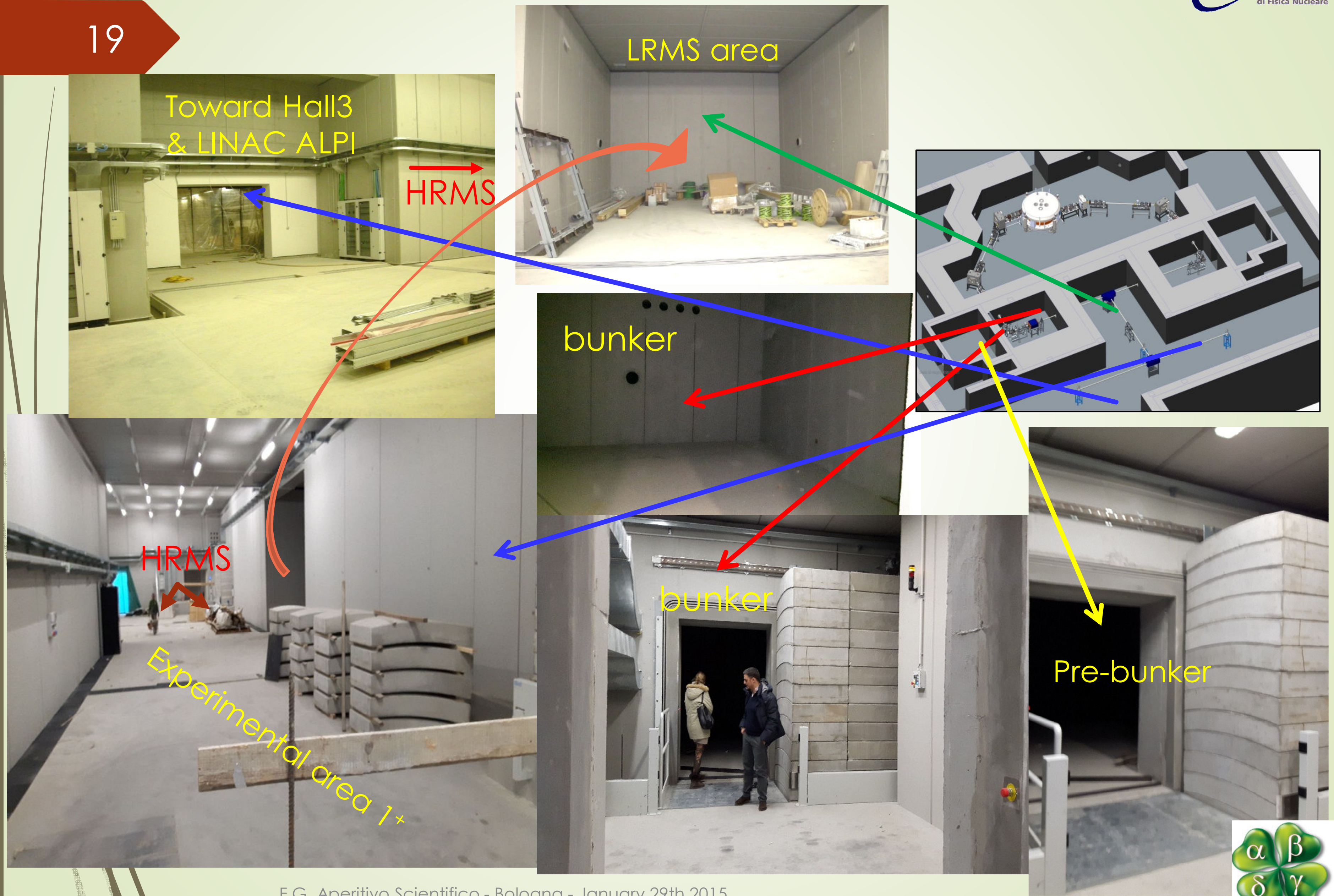




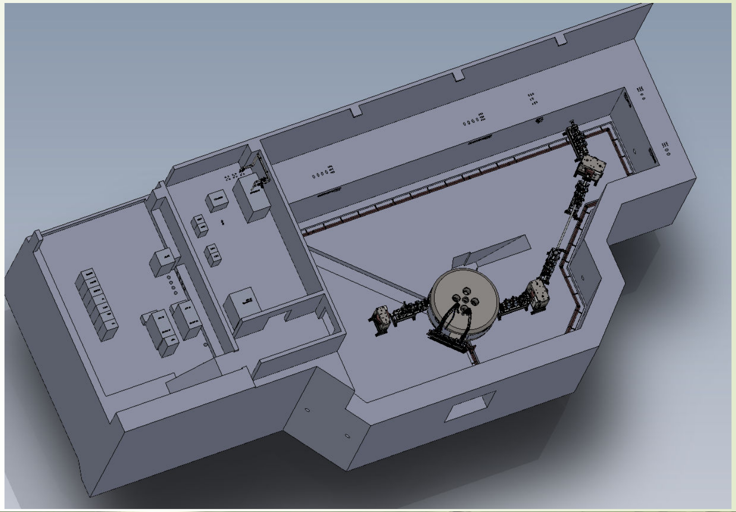


A simplified system is under completion for cyclotron site acceptance tests

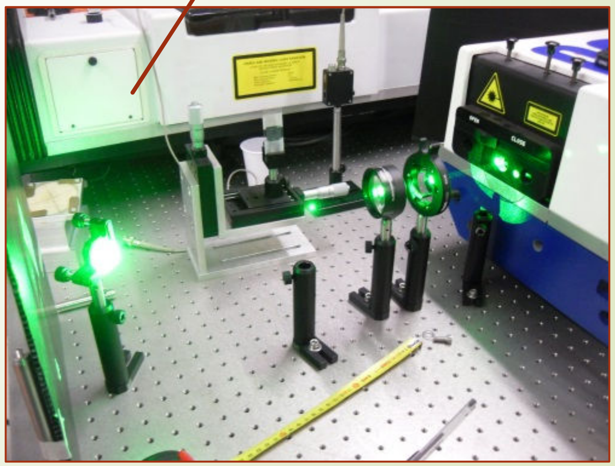
Phase α: The building & the specific areas

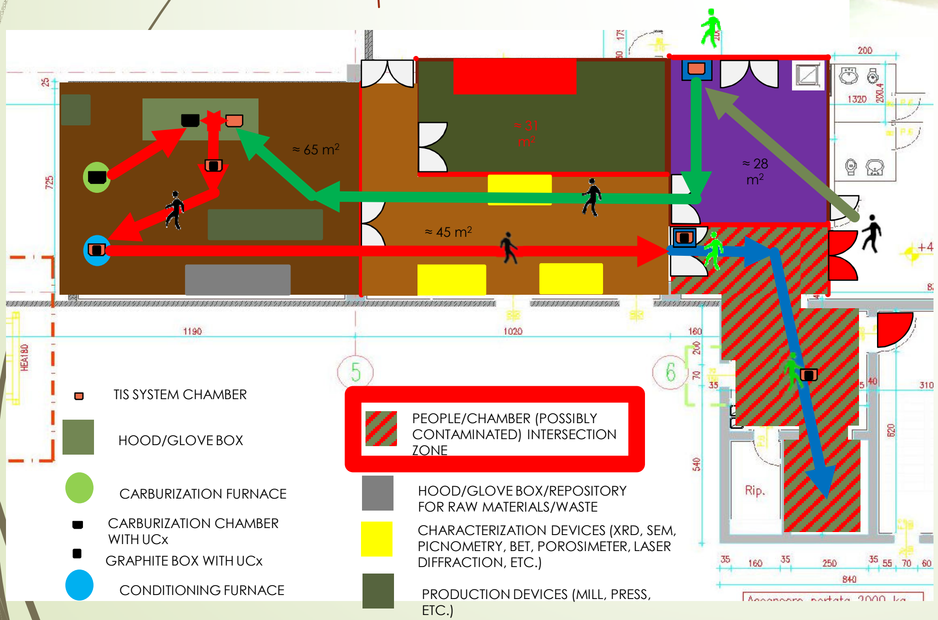


Phase α: The building & the specific areas



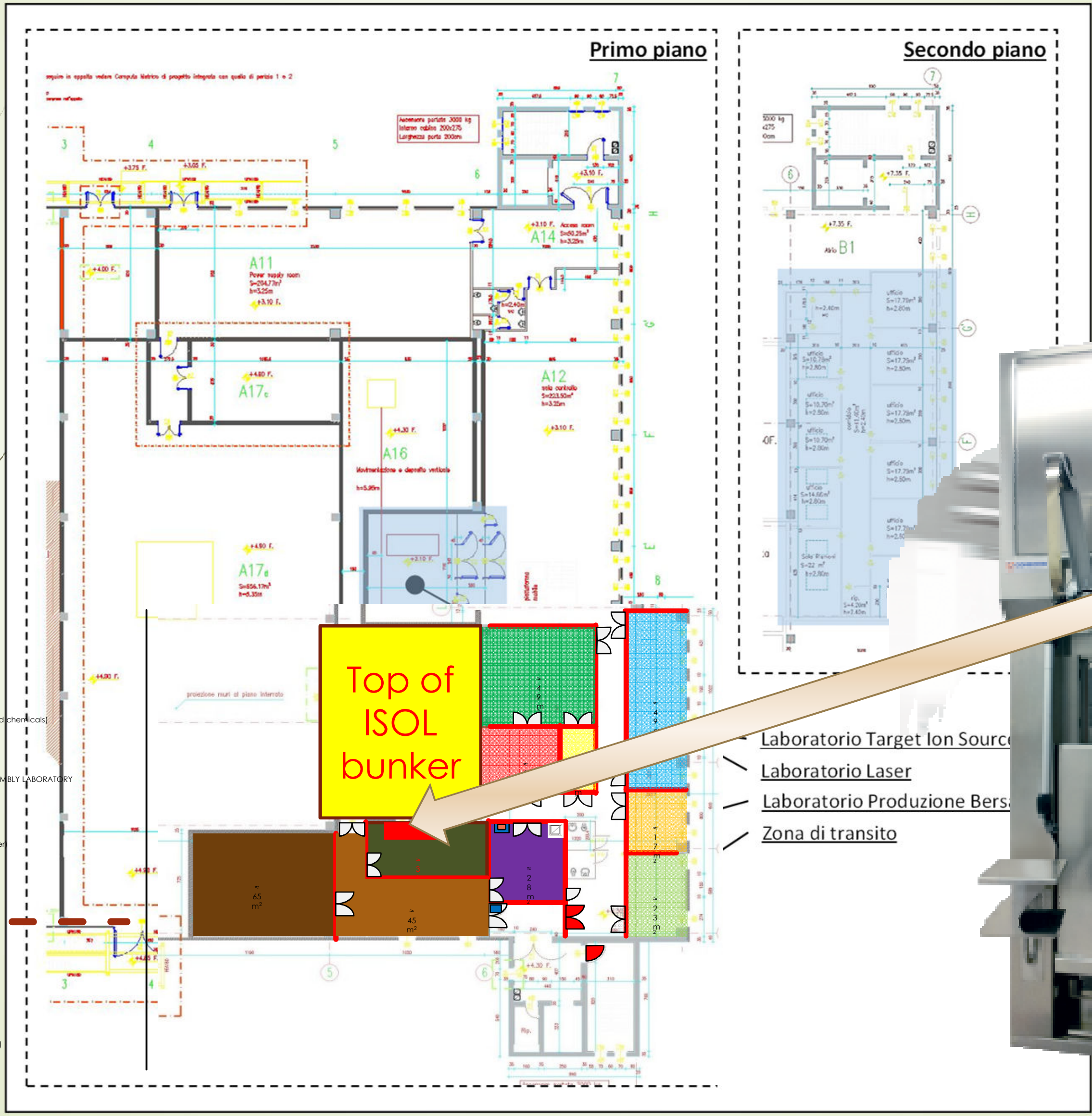
Phase α: The building & the specific areas





Phase α: The building & the specific areas

HOT CELL for target inspection & components maintainance Radioactive materials enter from back



- WALL
- DOOR
- CLEAN CHEMISTRY LABORATORY
- STORAGE (semi finished products and chemicals)
- OFF-LINE IONIZATION LABORATORY
- MECHANICAL WORKSHOP AND ASSEMBLY LABORATORY
- HIGH TEMPERATURE LABORATORY
- STORAGE (TIS system and TIS chamber
- TIS SYSTEM CHAMBER
- TRANSFER DEVICES
- CHANGING ROOM
- HOT CELL LAB
- HOT CELL (2 accesses)
- UCx LAB (characterization/transport)
- UCx LAB (production/storage)

PLANTS: air and water

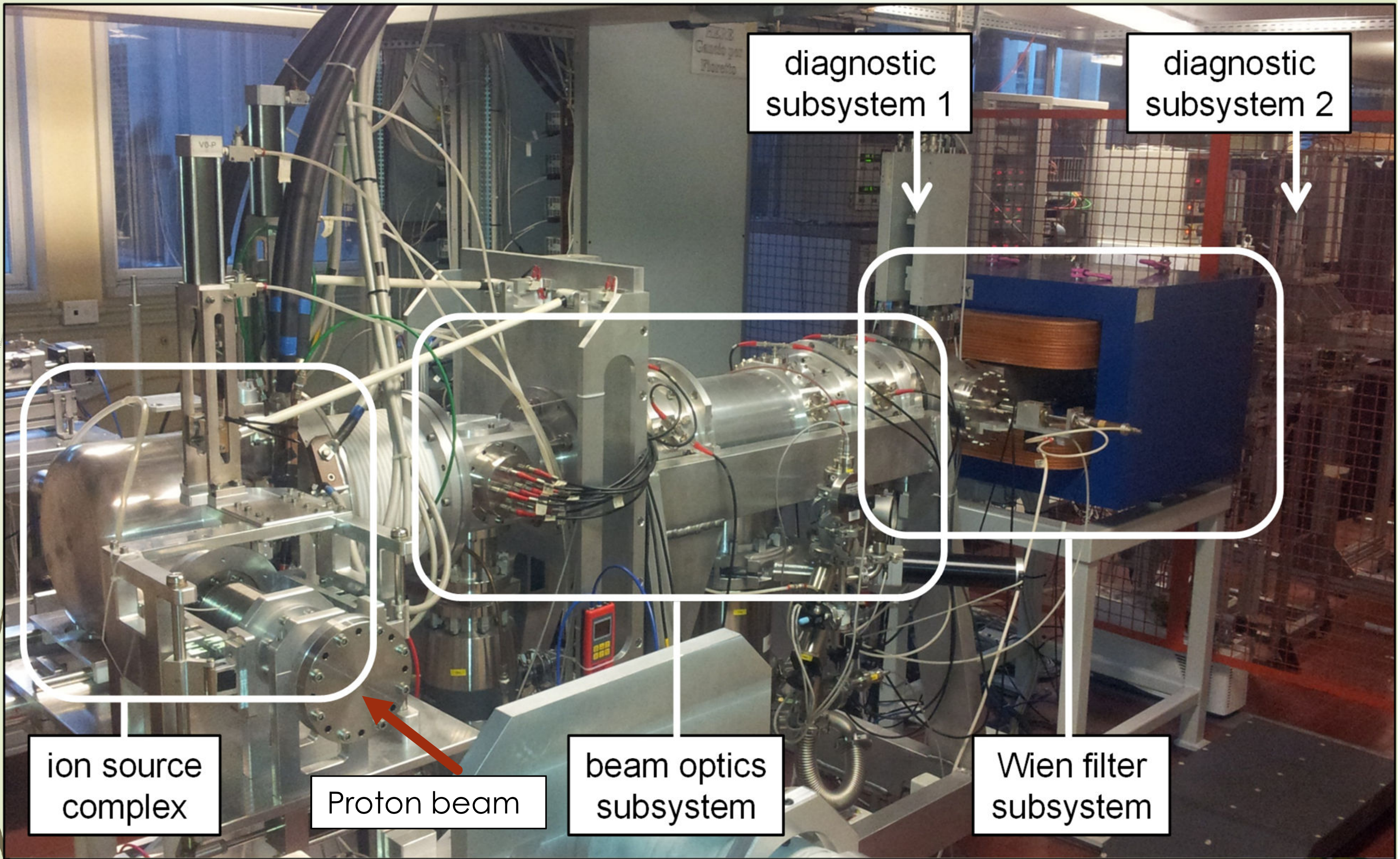
UTA air treatment cyclotron vault

Modules for Water Cooling

Cyclotron cooling

Phase β: the Target Ion Source System

The *Rad-Hard* version of SPES Front End —HOT→ Inside the bunker



Phase β: the Target Ion Source System

A. Andrighetto et al.

SPES Target :

Optimized for 8 kW power dissipation

(E= 40 MeV, I= 200 μA)

7 UCx coaxial disks:

thickness: 1.3 mm

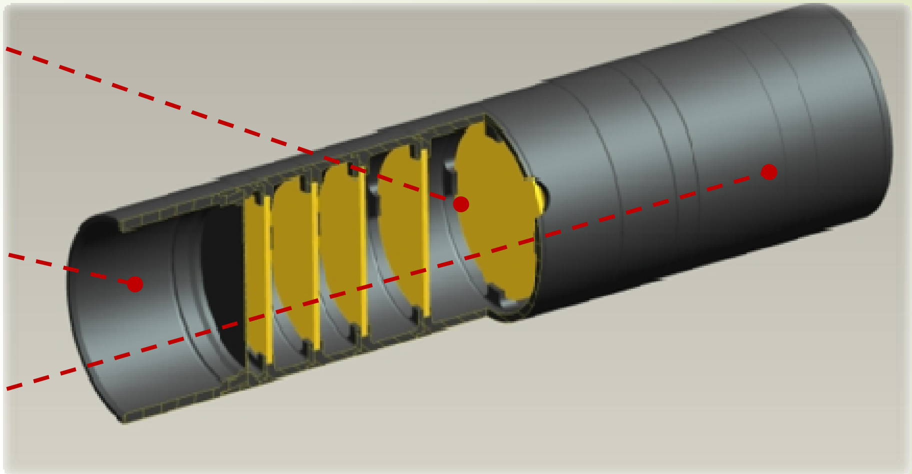
diameter: 40 mm

Graphite box:

external diameter: 49 mm

average length: 200 mm

3 graphite dump disks



SPES Heater, Ionizer & Chamber

Tantalum tube:

external diameter: 50 mm

thickness: 0.35 mm

length: 200 mm

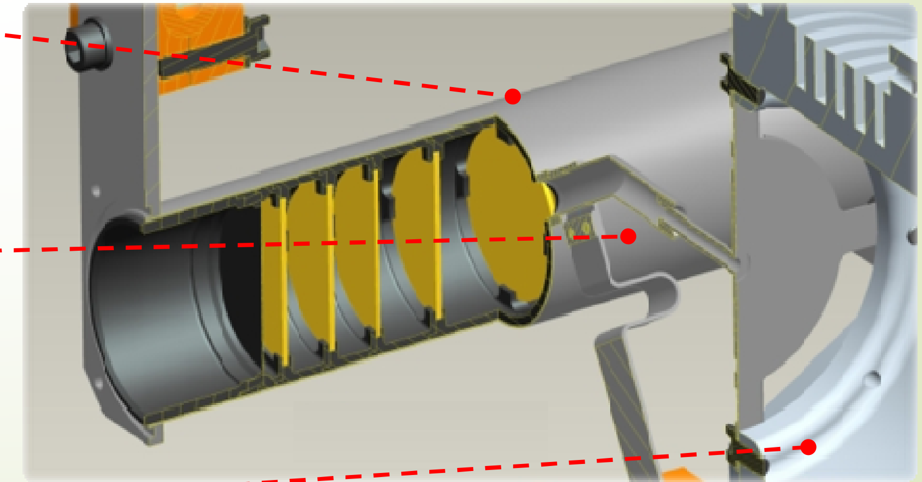
Ionizer & transfer tube:

thickness: 1 mm

height: 34 mm

Inner diameter: 3 mm

Aluminum target unit



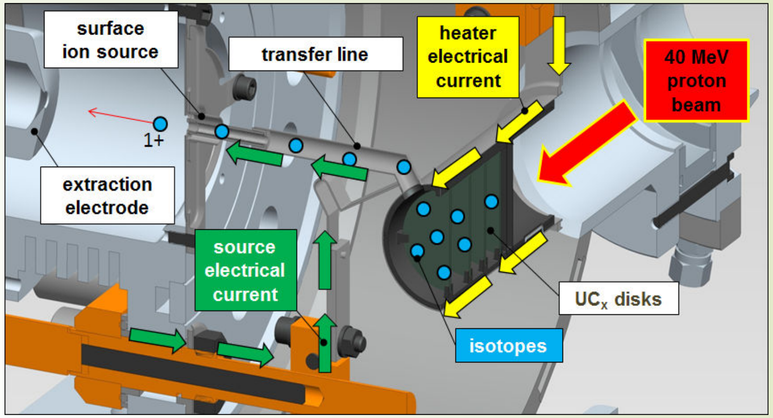
Phase β: the Target Ion Source System

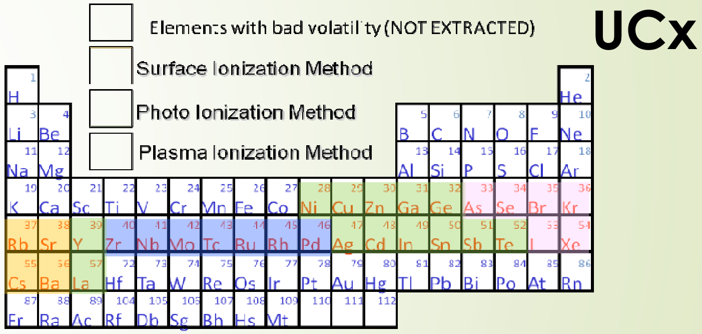
Production Target

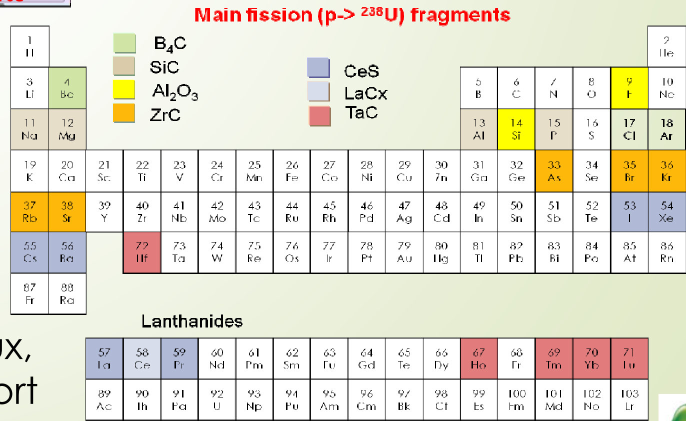
- Characterized by:
- Material of the target (production yield)
- Release time (≈1s for Fast Targets)
- Element Vapour pressure

Ion source target

- Characterized by:
- Ionization efficiency
- Emittance
- The SELECTIVITY of the source depends on the ionization efficiency of each element.







Yield of a nuclear species

$$Y = \sigma \cdot \Phi_p \cdot N \cdot \varepsilon_d \cdot \varepsilon_e \cdot \varepsilon_i \cdot \varepsilon_t$$

It depends on → half-life, cross-section, proton flux, diffusion and effusion time, ionization and transport efficiencies

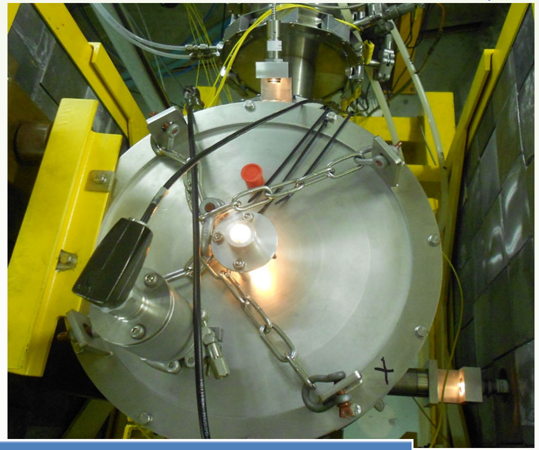
SPES: Target Power test @ iThemba LABS

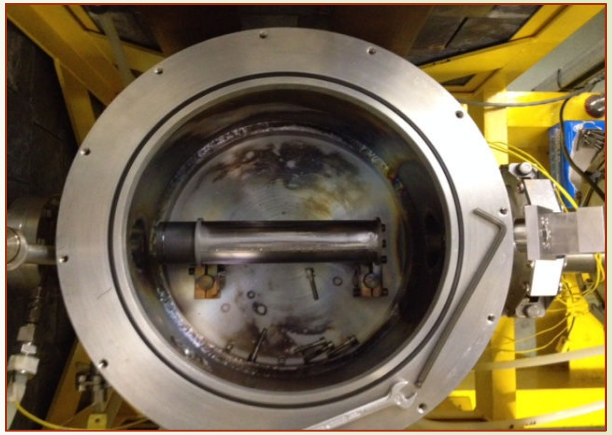
SPES target **in-beam power test** (SiC target) May 2014

Heater power compensated by proton beam.

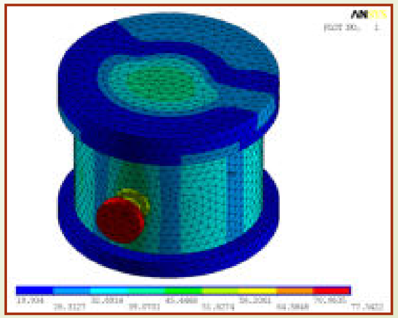
- Up to **4 kW proton** beam in target.
- ***Stable temperatures***
- ***Stable vacuum*** (3 10^{-5} mbar)

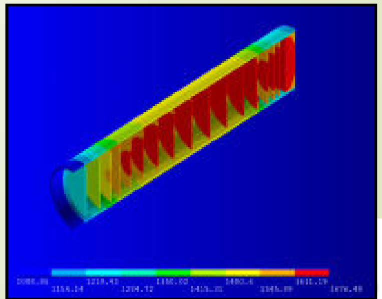
Proton beam 66MeV 60 μA





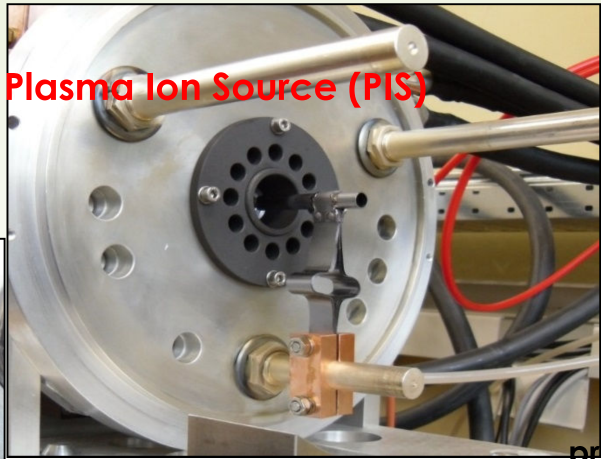
Measure [°C]	Estimated by FEM model [°C]
1° disk: 1365 ± 30°C	1390
Box: 1230 ± 25°C	1267
Dump on chamber: 728°C ± 10°C	750

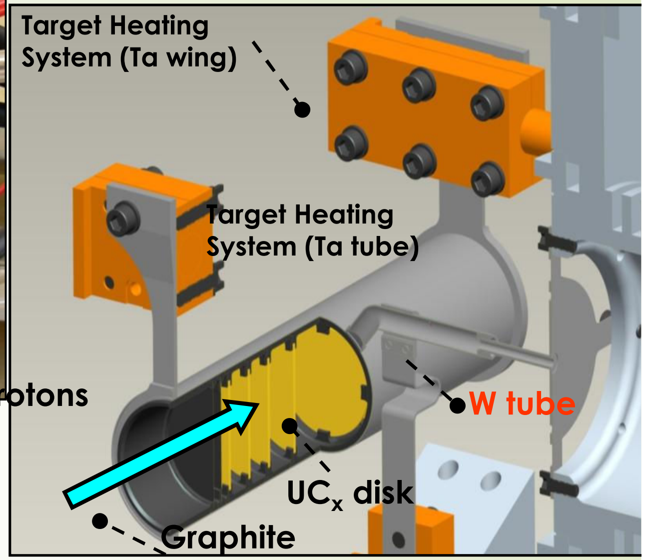




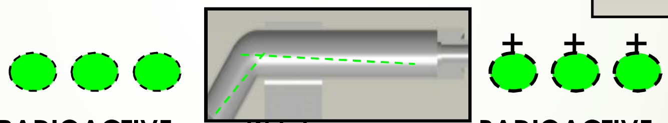
Phase β: the Target Ion Source System

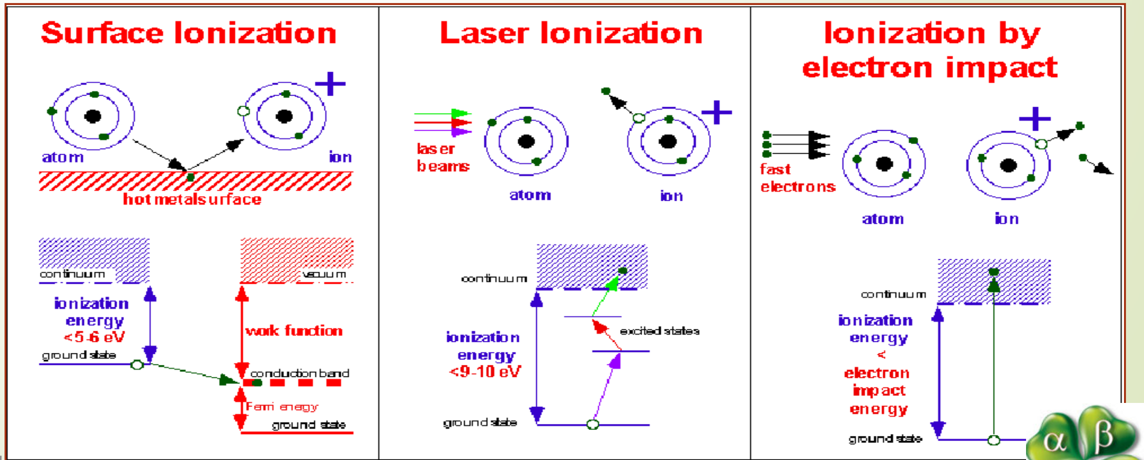
A. Andrighetto et al.





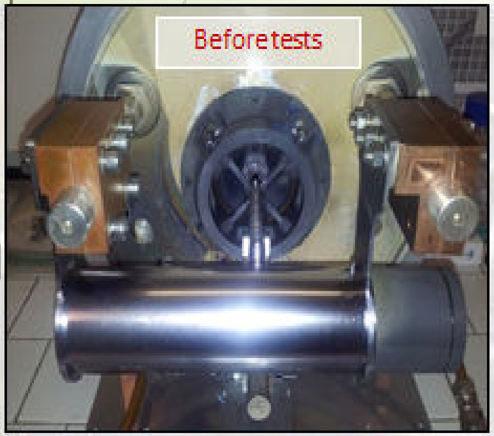
ION SOURCE DEVICE

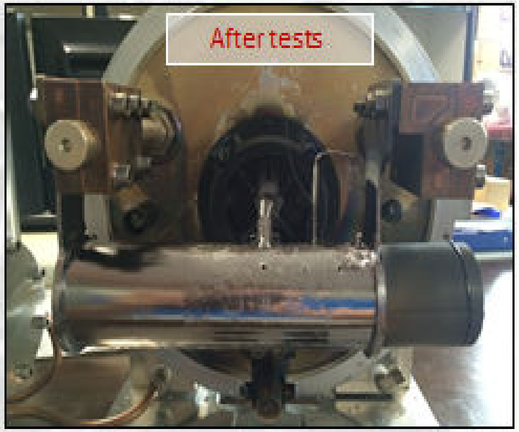




TIS - Endurance Tests

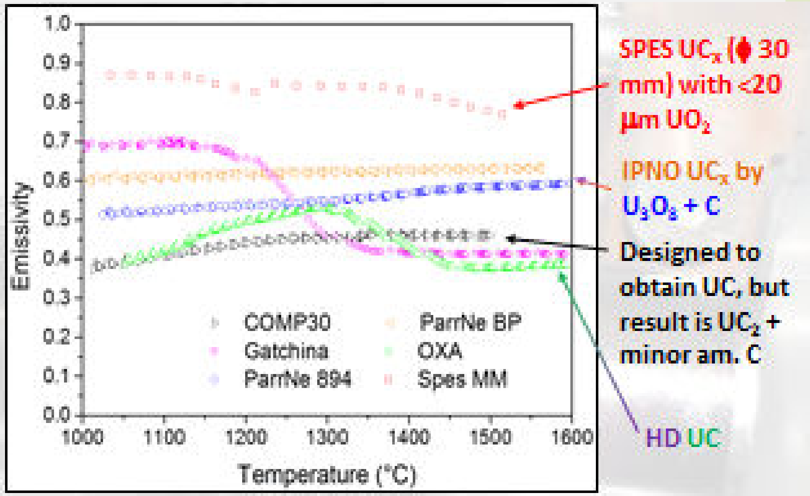
High temperature tests with Joule heating thermal load (1300 A target heater, 350 A line) Heating power ~ 12KW > primary proton beam thermal load ~ 10KW.





~ 415 testing hours at high T
→ 220 hours at max power(12KW)
79 heating cycles supported →
9 with current ramps of 1s from 0 A to 1300 A
→ TIS STILL OPERATIVE!

Emissivity measurements on different UCx targets types

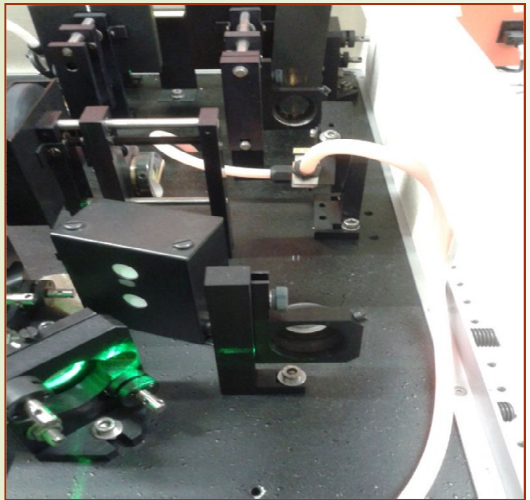


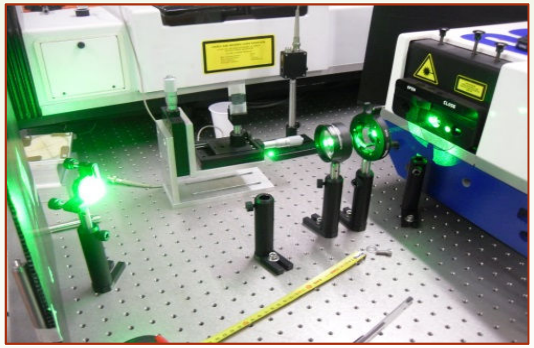
Direct Emissivity measurements on heated UCx disks using a dual frequency pyrometer

TESTS performed on Uranium Carbide samples from different compositions and synthesis produced by several laboratories (Partners in ACTILAB)

Phase β: the Target Ion Source System

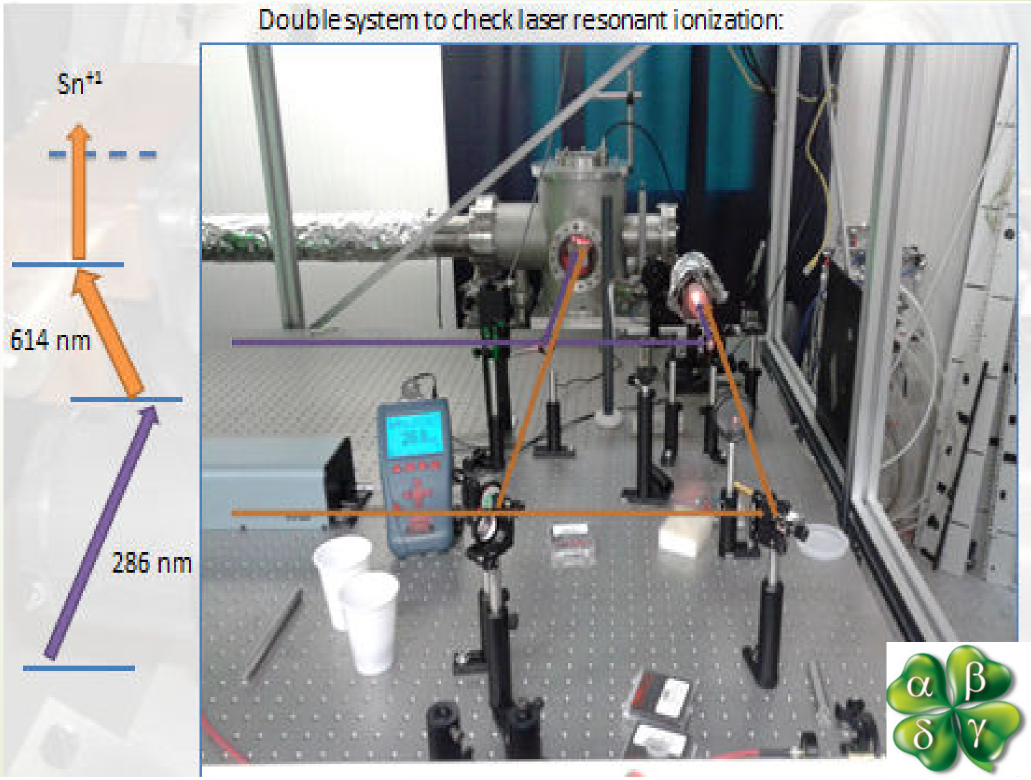
A new SPES laser laboratory was built @LNL in 2013



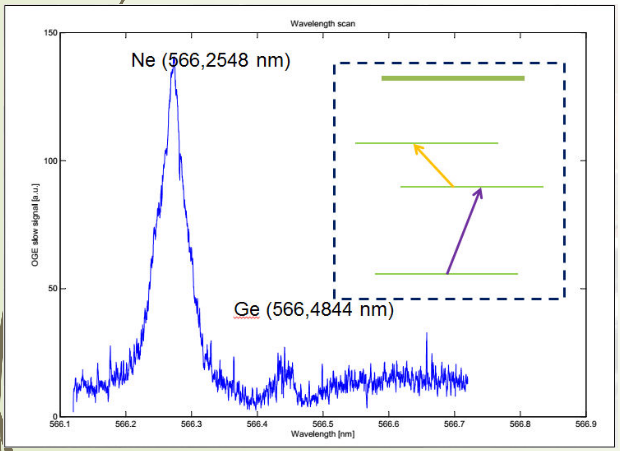


A tunable dye laser system ready for atomic spectroscopy study

HCL +ToF on Tin Laser Ionization



Germanium spectroscopy study



First step + Second step

Phase β: ISOL safety → system handling and storage

Horizontal handling system

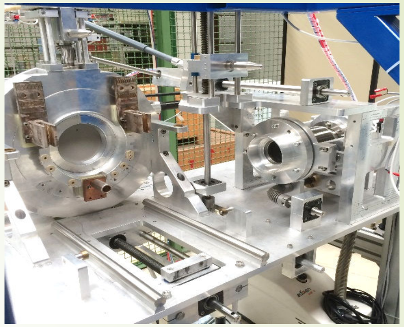
- A two cartesian axis system mounted onto an AGV unit allows the handling and transfer of the TIS.

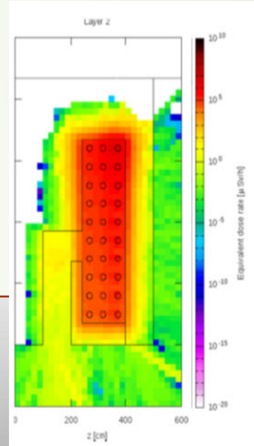
Test bench handling

- A test-bench Front End coupling table allows to verify the TIS connection /disconnection from proton and RIB beam lines.
- A tool to disconnect the puller was developed too.

Puller removing system

- Once per year it is expected to change the puller, an highly activated component.
- The handling system is equipped with a tool able to extract the puller and to store it in a shielded box.





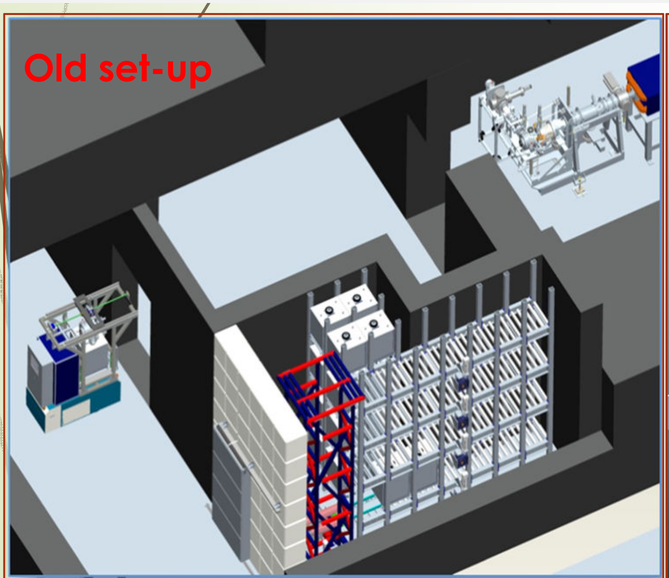
Radiation dose always below **20 μSv/h** in the corridor.

An **optimized thickness of Lead vs. concrete** of walls is ongoing to study.

Results have **to be validated** by RP service.

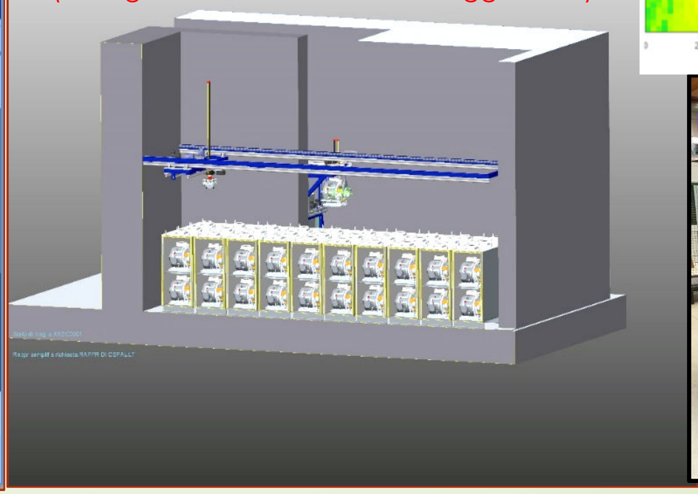
Storage of several **700 kg of lead box** containing the target chamber

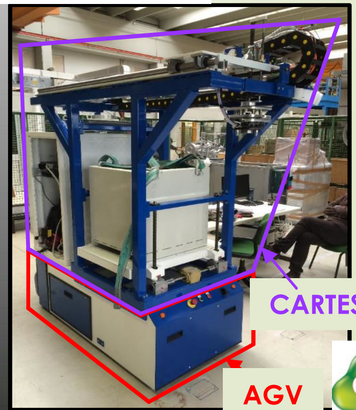
Storage of the target chamber (**40 kg**) inside many lead boxes



New set-up

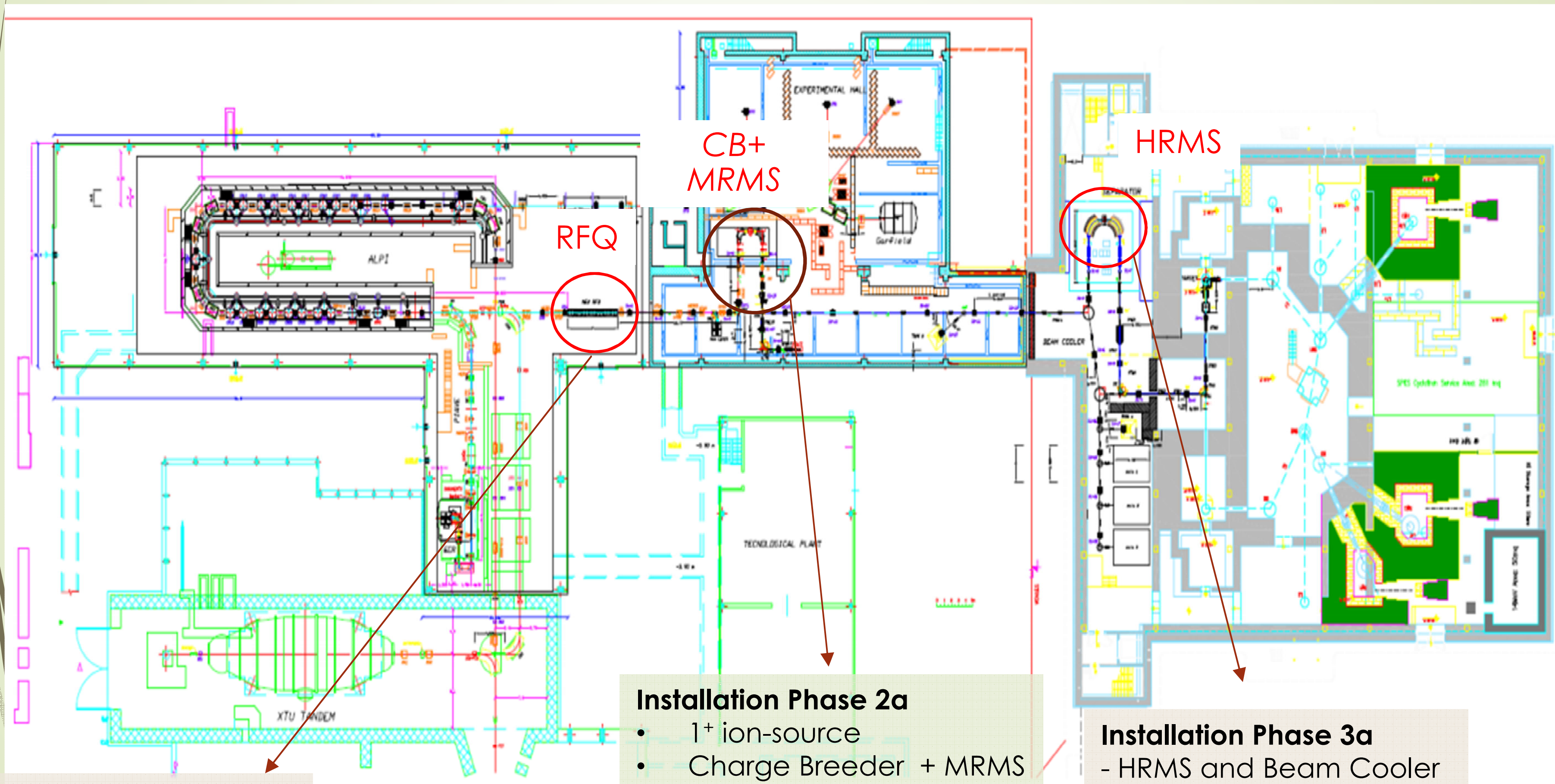
(taking into account the SAC suggestions)





32

Phase β: HRMS , CB+ MRMS & beam line to ALPI - RFQ



Installation Phase 2a

- 1^+ ion-source
- Charge Breeder + MRMS
- N^+ beam line up to RFQ entrance

Installation Phase 3a

- HRMS and Beam Cooler
- 1^+ beam lines to Charge Breeder

Installation Phase 3b

- RFQ
- RIB line to ALPI
- ALPI up-grade

Phase β: Experimental area for non-re-accelerated beams

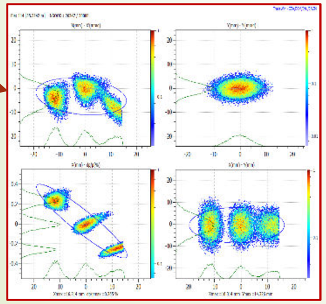
According to the **Scientific Advisory Committee** advise, an **area** for **non re-accelerated RIBs experiments** was defined. Preliminary design was performed to evaluate general layout and cost.

Working group:

F.Gramegna, (coordination)
M.Cinausero (physics)
A.Mendez (ORNL, electrostatic design)
A.Monetti (engineering and beam transport)
L.Bellan (beam transport)

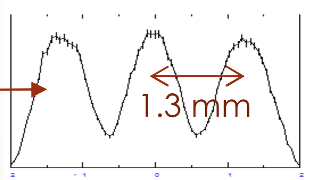
1

$$\frac{\Delta M}{M} = \frac{1}{200}$$

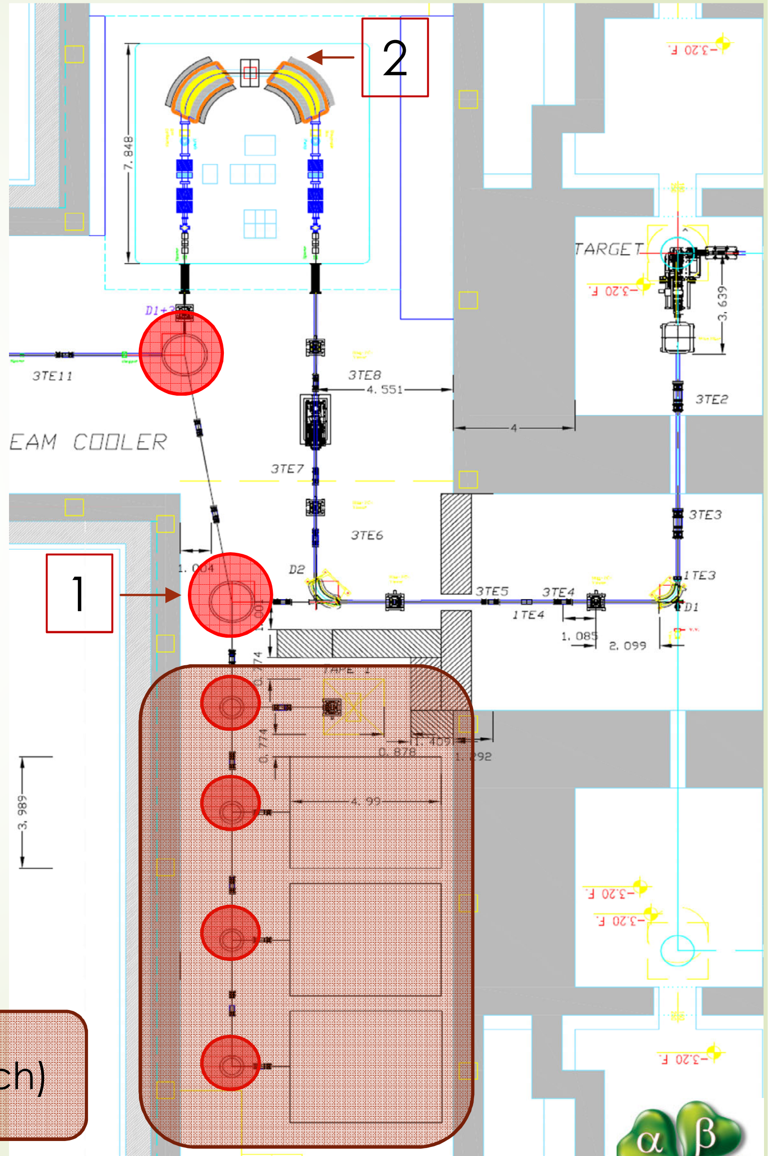


2

$\Delta M = 2.5\ 10^{-5}$

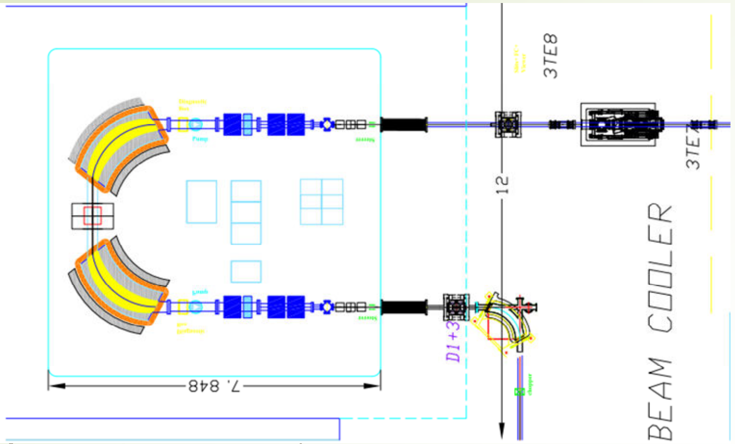


$$\frac{\Delta M}{M} = \frac{1}{20000}$$

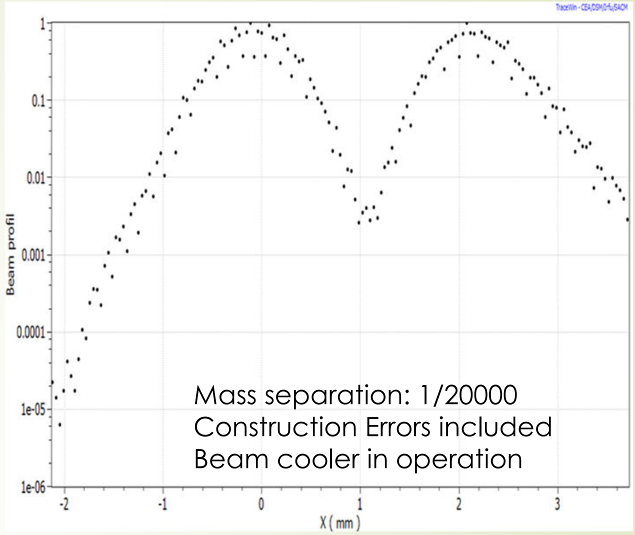


- Three experimental areas available (20m² each)

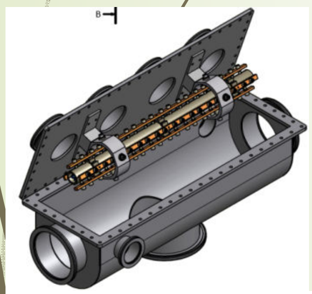
Phase β: HRMS and beam line to ALPI

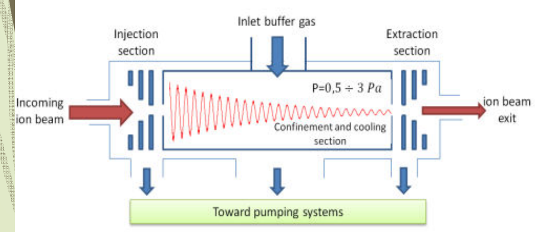


Type	Max range
Misalignment (x,y) *(no effect on R)*	0.5 mm
Tilt (xy,yz,xz)	0.1°
Field error	0.05%
All errors	0.25 mm, 0.05°, 0.025%

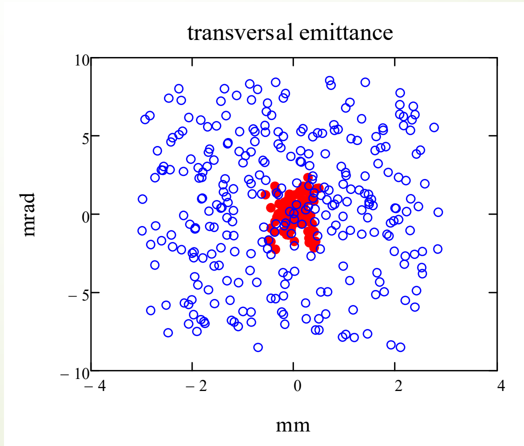


Beam Cooler to match the HRMS input requirements





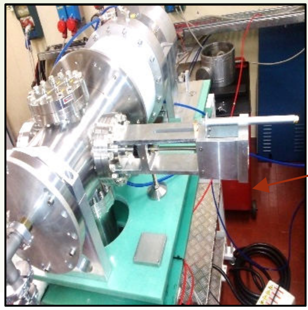
COOLBEAM experiment financed by INFN-CSN5, 2012→2015 -Collaboration: LNL-LNS-Mi

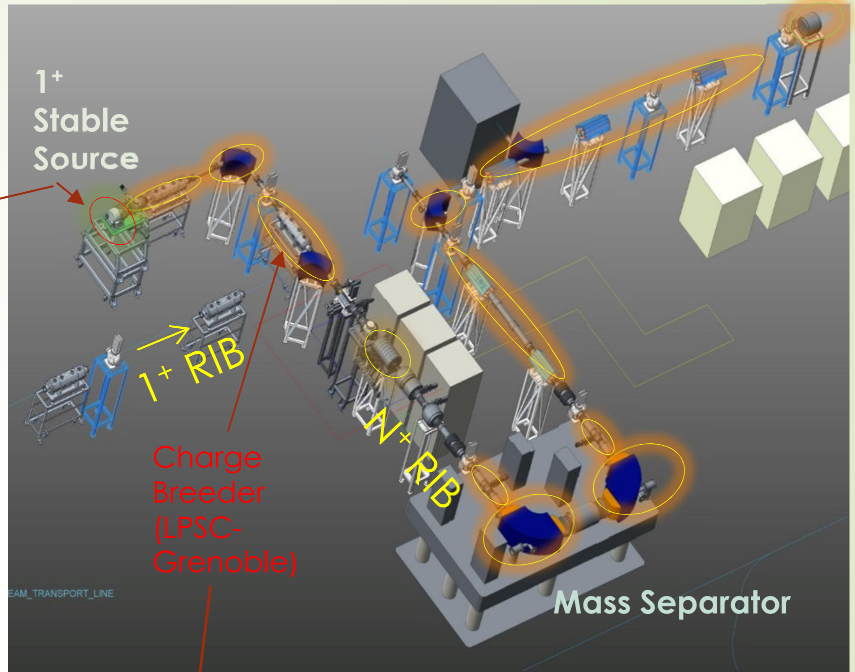


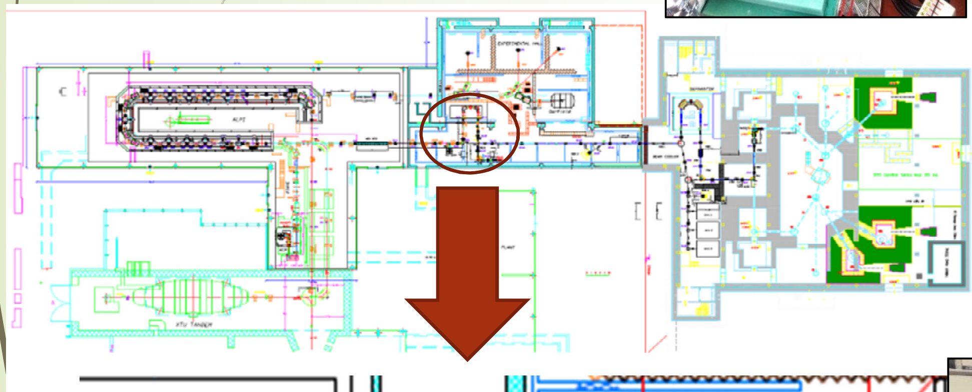
Input T emittance
Output T emittance

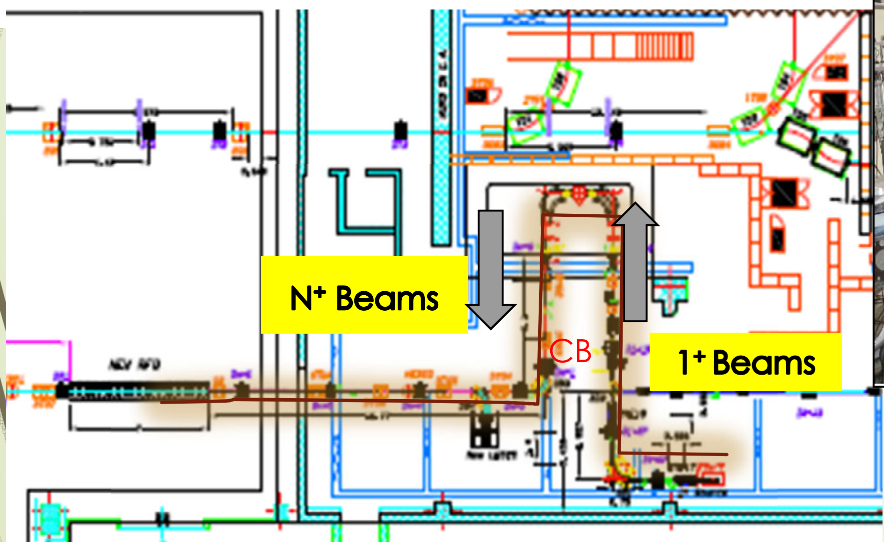
Phase β: Transport line to the RFQ → Charge Breeder & MRMS

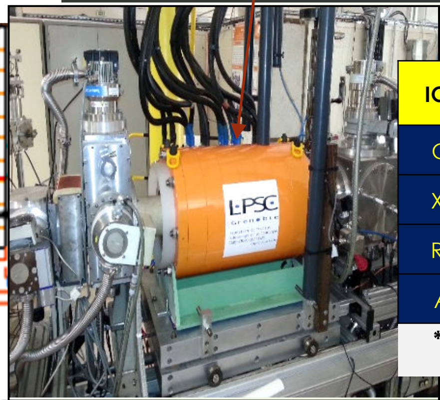
- 1^+ ion-source
- Charge Breeder
- Medium Resolution Mass Separator
- N^+ beam line up to RFQ entrance







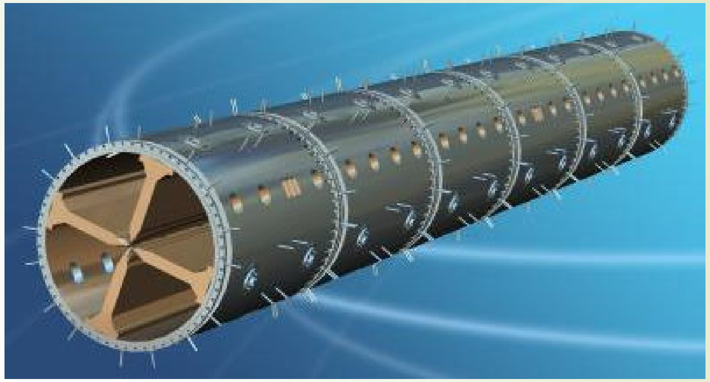




		EFFICIENCY* [%]		
ION	Q	SPES req	Best LPSC	SPES-CB
Cs	26	≥ 5	8,6	11,7
Xe	20	≥ 10	10,9	11,2
Rb	19	≥ 5	6,5	7,8
Ar	8	≥ 10	16,2	15,2

**results obtained for the same 1^+ injected current*

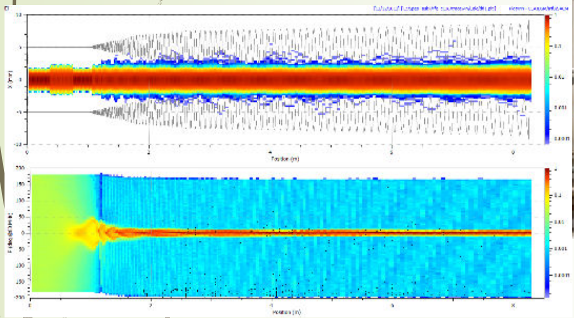
Design almost completed .
Additional study to finalize RF and Tank.
Construction started (electrodes).



- Andrea Pisent (WP coordinator, LNL)

Synergies with Torino & Padova INFN sections for the mechanics development (P. Mereu and A. Pepato respectively), common aspects with ESS DTL and IFMIF RFQ design

Physics design



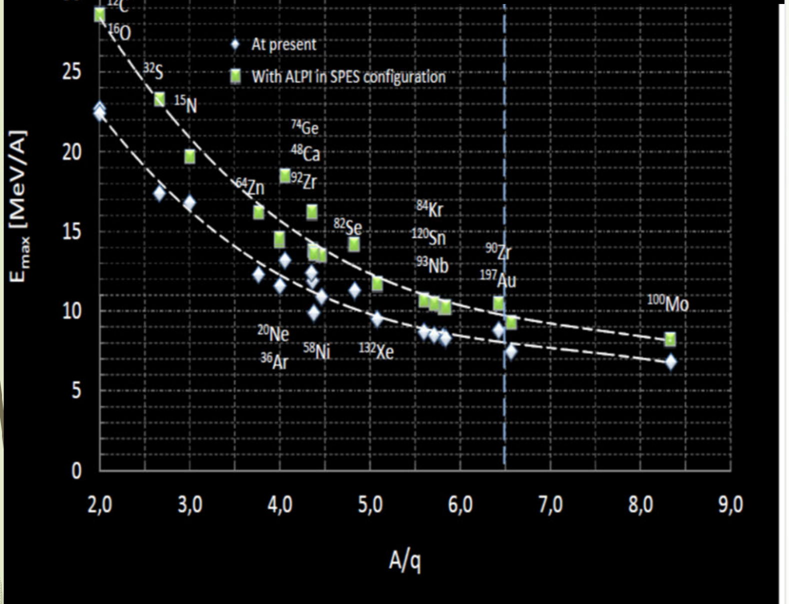
High power RF Coupler
200kW 100% duty cycle

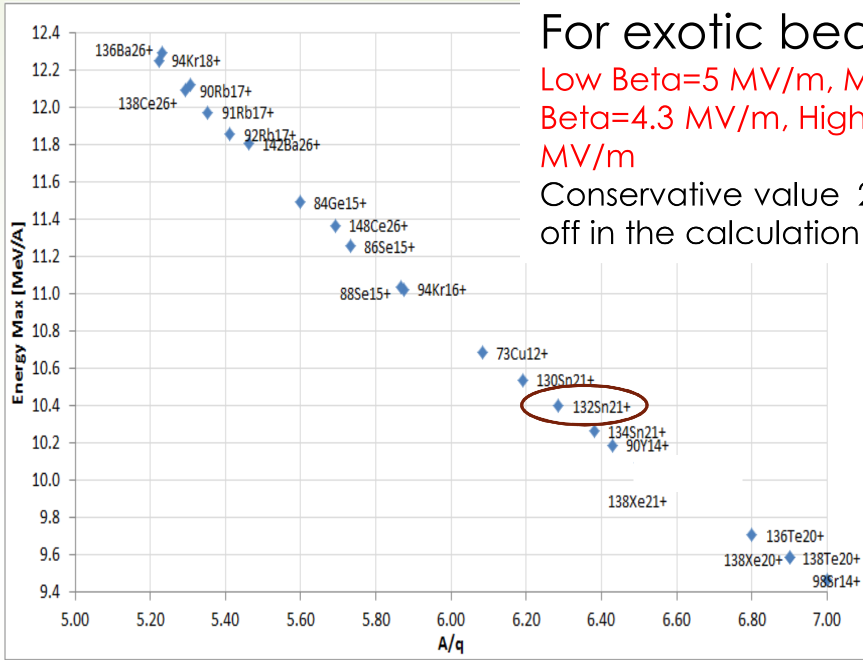
Parameter (units)	Design Value
Operational mode	CW
Frequency (MHz)	**80.00**
Injection Energy (keV/u)	5.7 (β=0.0035)
Output Energy (keV/u)	727 (β=0.0395)
Accelerated beam current (μA)	100
Charge states of accelerated ions (Q/A)	7 – 3
Inter-vane voltage V (kV, A/q=7)	63.8 – 85.84
Vane length L (m)	6.95
Average radius R_0 (mm)	5.33 – 6.788
Synchronous phase (deg.)	-90 – -20
Focusing strength B	4.7 – 4
Peak field (Kilpatrick units)	1.74
Transmission (%)	95
Output Long. RMS emittance (mmmrad)/ (keVns/u)/(keVdeg/u)	0.055 / 0.15 / 4.35

- **Schedule : Dec 2015 to Sept 2019**
  - Electrodes call for tender : dec 2015
  - Electrode production : sept 2016
  - Completion of 24 electrodes : sept 2018
  - Tank call for tender : march 2016
  - Tanks Completion : dec 2018
  - Assembly and low power testing : june 2019
  - High power tests : sept 2019

Phase β: Re-accelerated beams with ALPI

For stable beams

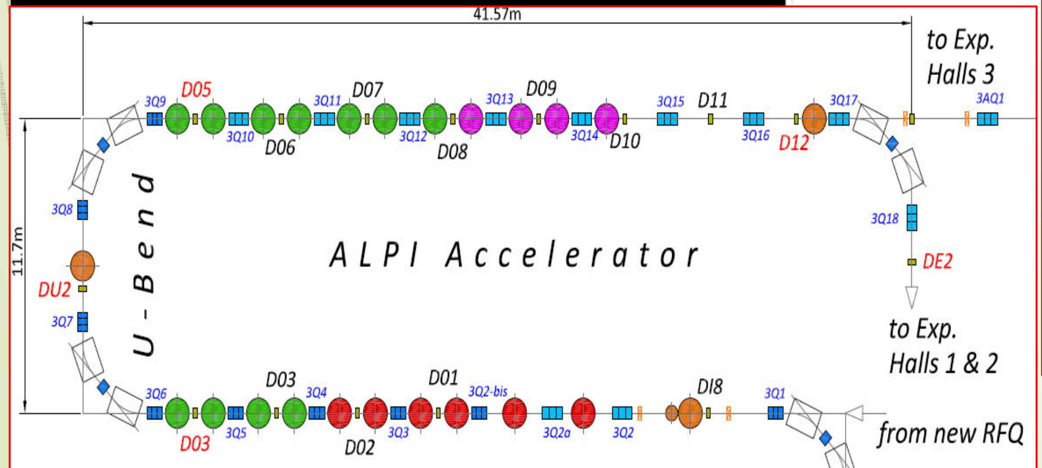




For exotic beams

Low Beta=5 MV/m, Medium Beta=4.3 MV/m, High Beta=5.5 MV/m

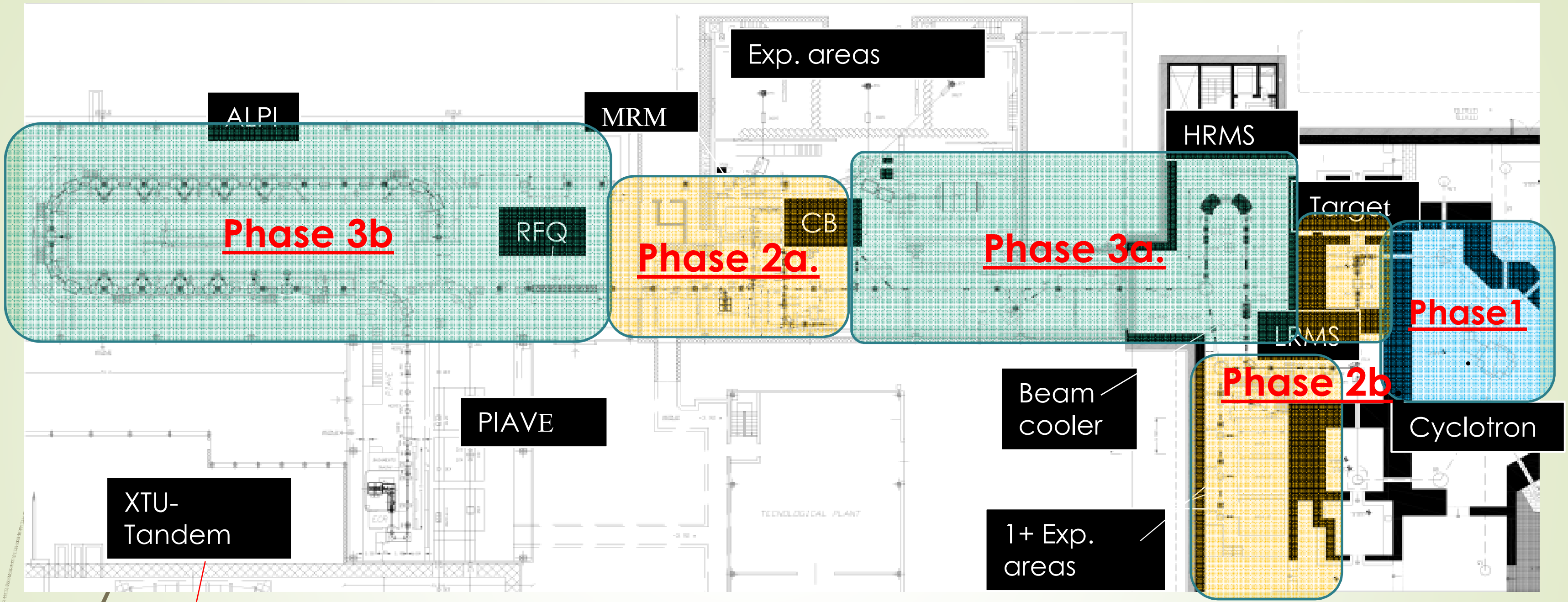
Conservative value 2 cavities off in the calculation



Re-shaping and improvement of low beta cavities.

Added high beta cryostats to improve the final energy.

SPES layout: following the installation phases



- Phase 1. 2016- First Operation with the cyclotron
- Phase 2a. 2017- RNB ALPI Injector (1^+ source + Charge Breeder + MRMS)
- Phase 2b. 2018- SPES target, LRMS, experimental 1+ Beam Lines
- Phase 3a. 2019- HRMS and beam line to the CB
- Phase 3b. 2019- RFQ and ALPI

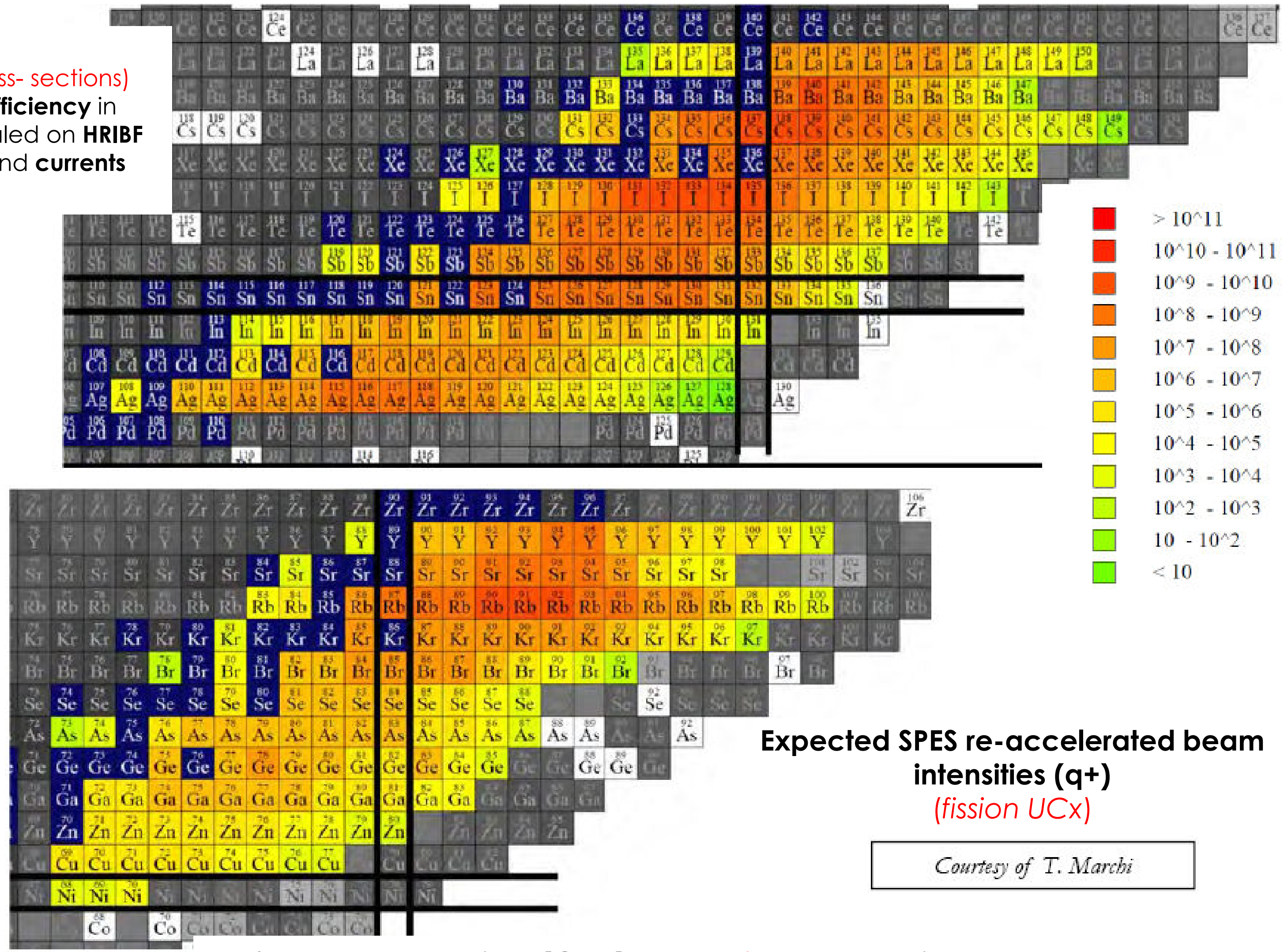
SPES Expected beams

https://web.infn.it/spes/index.php/news/spes-beam-tables

SPES exotic beams for science

INFN Istituto Nazionale di Fisica Nucleare

- **MCNPX Calculation**
- **BERTINI – ORNL** (FF cross- sections)
- **Release** & **ionization efficiency** in agreement and re-scaled on **HRIBF experimental values** and **currents** (**200μA/5μA**)



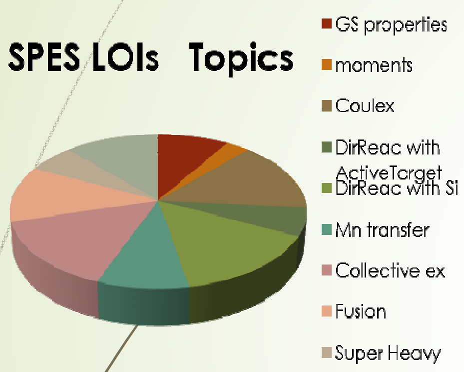
Expected SPES re-accelerated beam intensities (q+)
(fission UCx)

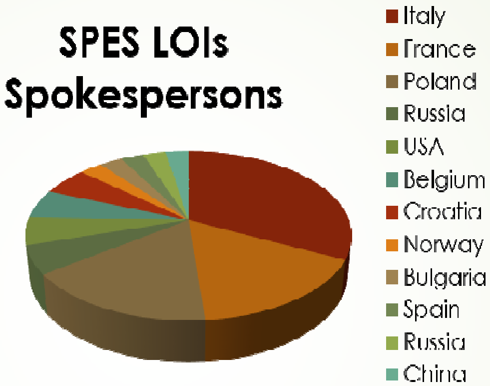
Courtesy of T. Marchi

before acceleration (@1+) 10-40 times more intense

Physics @SPES

Presented 37 Letters of Intents

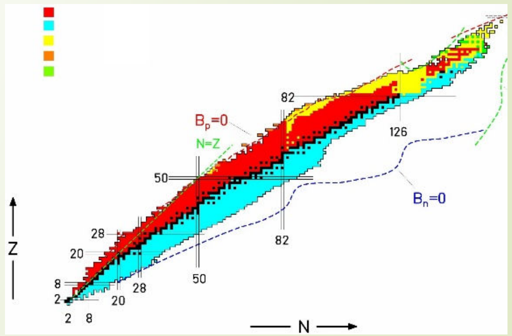




The **SAC was impressed** with the **number of LOI's** and the **broad scientific spectrum** proposed to be studied with the SPES Radioactive Ion Beams (RIB). The SAC **appreciates the progress of the SPES project**

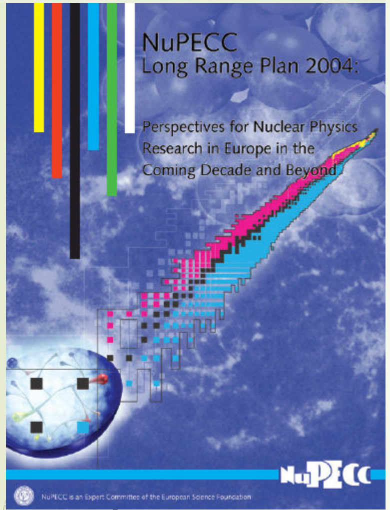
One Day Workshops

Napoli (2012): Transfer Reactions
Firenze (2012): Coulomb Excitation
Catania (2013): Isospin in Reaction Mechanisms with RIBs
Milano (2013): Collective Excitations of Exotic Nuclei (DDR, Pygmy Resonances)
Legnaro (2014): Fusion-evaporation Reactions with RIBs
Milano (2015): Physics at SPES with non re-accelerated beams
Caserta (2015): Nuclear Astrophysics at SPES

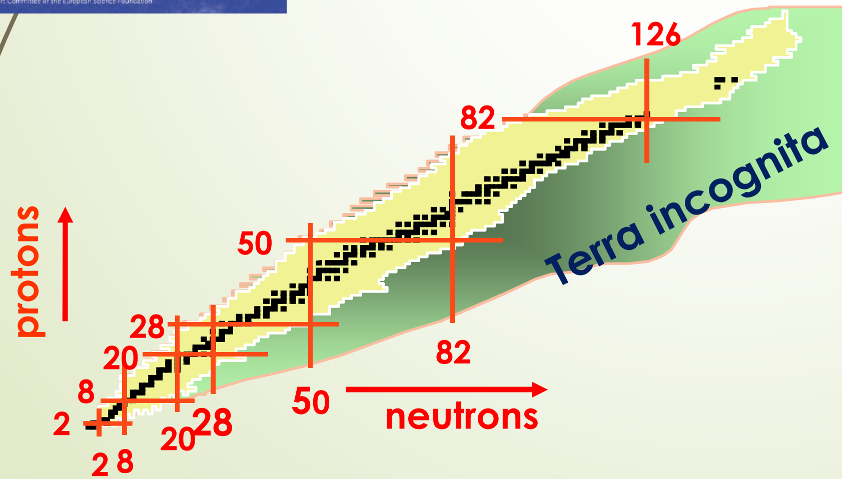


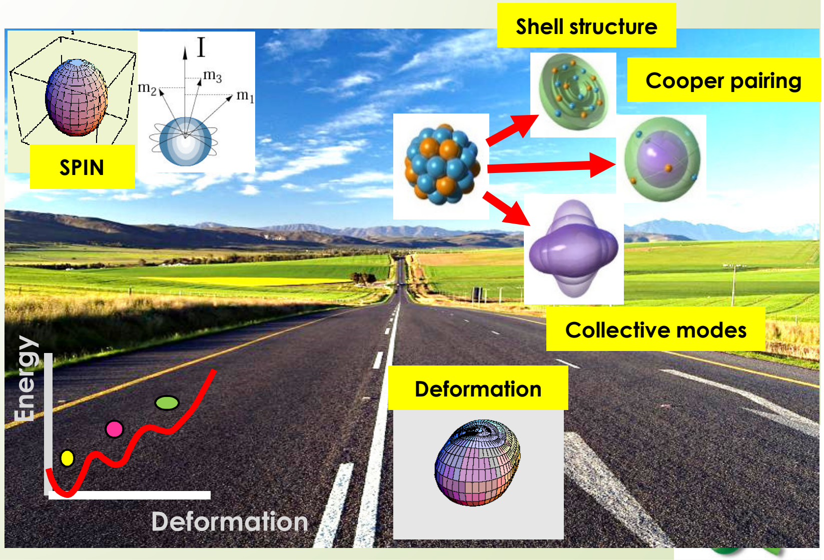
SPES α+β: Nuclear Physics KEY Questions

Nuclear Structure & Reaction Dynamics: Long Standing Questions



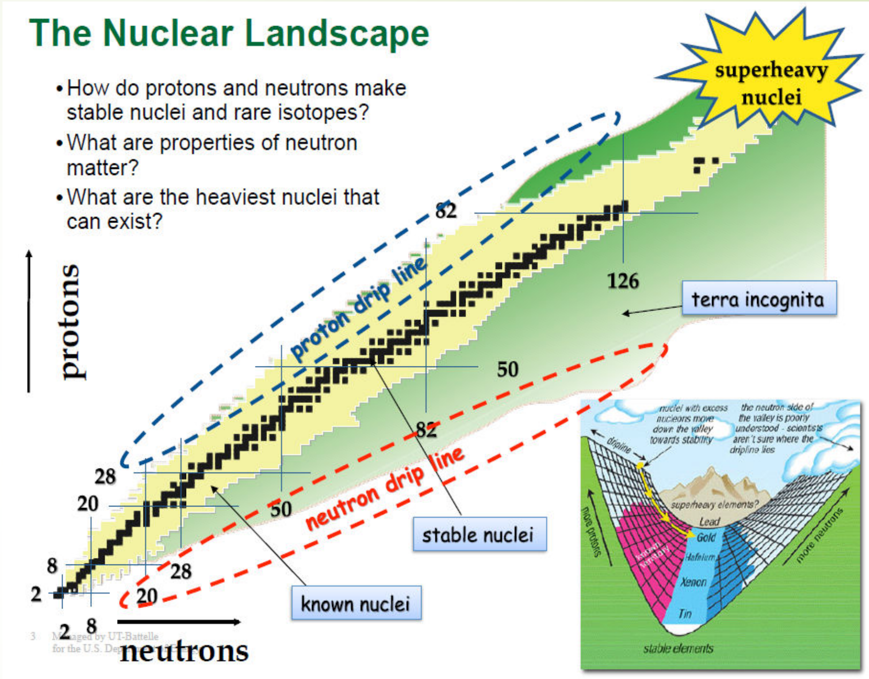
- **Which are the limits for existence of nuclei?**
  - Where are the proton and neutron **drip lines** situated?
  - **Where** does the nuclear chart **end**?
- **How does the nuclear force depend on varying proton-to-neutron ratios?**
  - What is the **isospin dependence** of the **spin-orbit force**?
  - Which is the **shell evolution** moving **far from stability** (magic numbers, proton-neutron interaction, shell gap creation and disappearence)?
- **How to explain collective phenomena from individual motion?**
  - What are the **phases** (**NEOS**), relevant degrees of freedom, and symmetries of the nuclear many-body system?
- **How are complex nuclei built from their basic constituents?**
  - What is the **effective nucleon-nucleon interaction**?
  - How does QCD constrain its parameters?
- **Which are the nuclei relevant for astrophysical processes and what are their properties?**
  - What is the **origin** of the **heavy elements**?





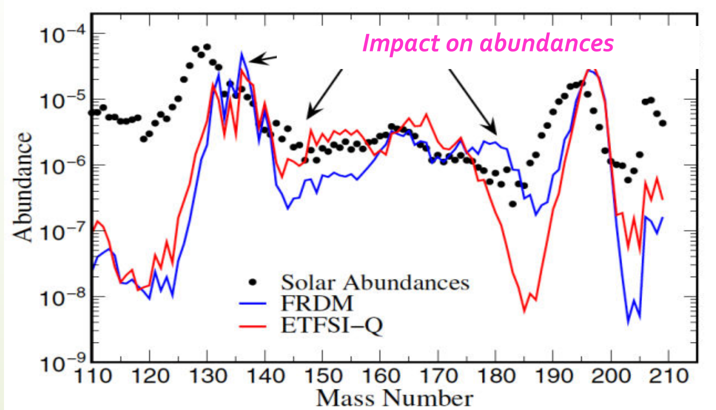
Moving away from the stability valley → Exotic Nuclei & Limit of Nuclear Existence

- Limit of Nuclear Existence ?
- Robustness of Magic Numbers ?
- Validity of Quantum Numbers
- Change in Structure due to n-excess ?
- β-decay and r-process path location ?



The Open Questions:

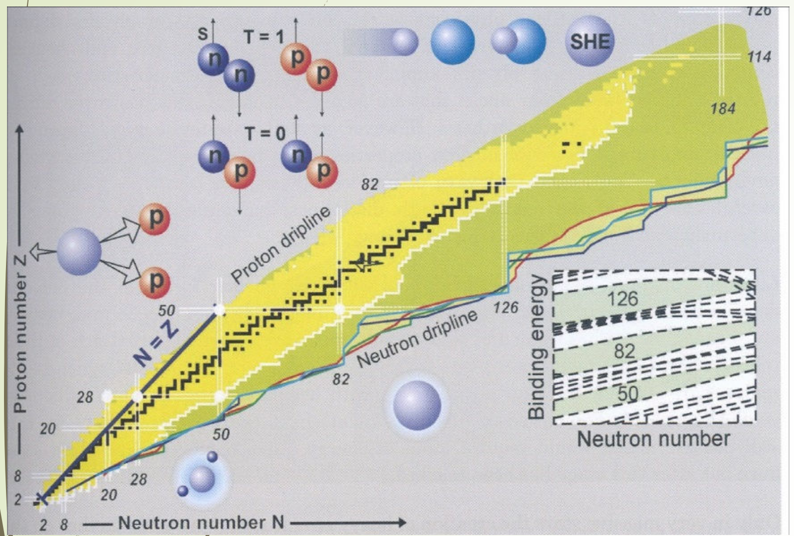
1. Shell Evolution & interactions
2. Symmetries (isospin mixing T=0, T≠0 in N=Z nuclei)
3. Order & Chaos Transition
4. Collective States: Part-Vib-Coupling, Pygmy & Giant Resonances
5. β–decay & r-process
6. Isospin effects on structure & reaction dynamics

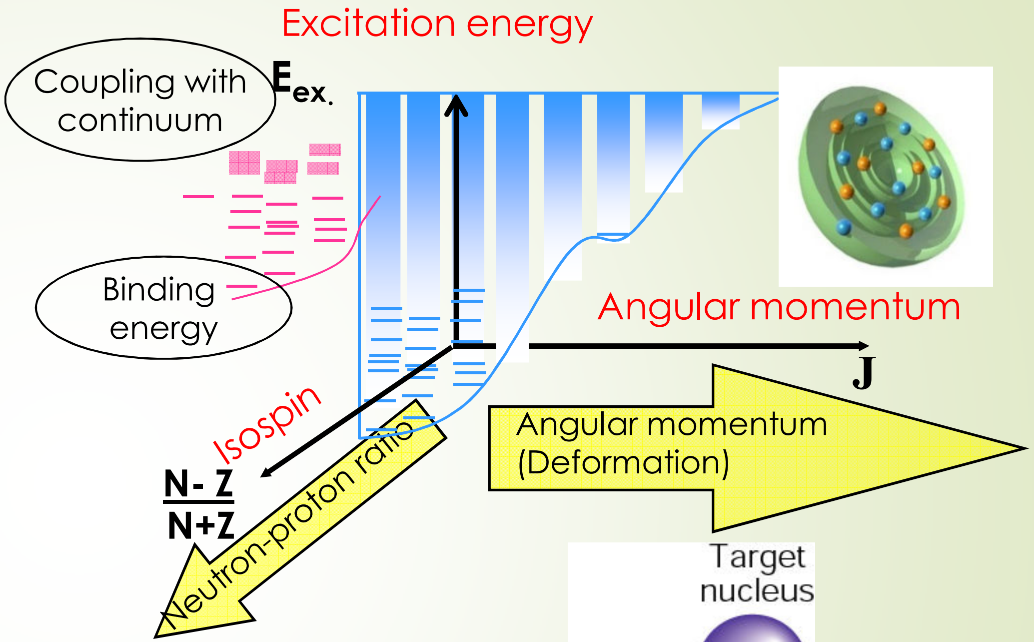


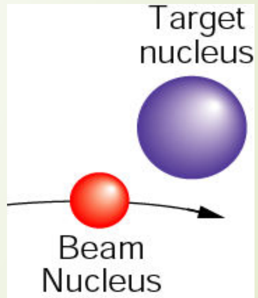
The Experimental tecniques:

- Coulomb Excitation
- Transfer Reactions
- Decay Spectroscopy
- Reaction Studies

The Why and How of Radioactive Beam Research







Extrapolating to the region far from stability is quite dangerous, some of the '**basic truths**' of nuclear physics have to be revisited:

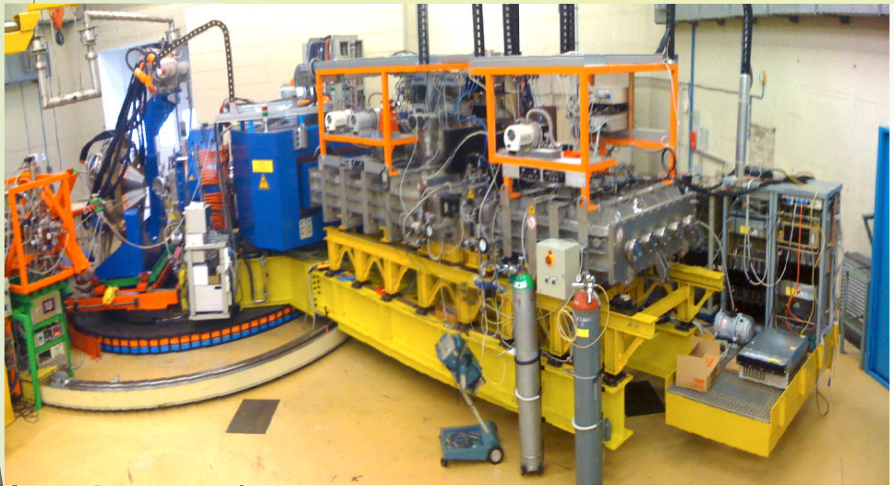
- the **nuclear radii** of some nuclei do not all scale with a $A^{1/3}$ dependence.
- the well-known **magic numbers** for Z and N seem to be dependent on N and Z, respectively.
- **nucleon correlations and clustering** seem to play a very important role in nuclear binding.
- The dependence of the nuclear interaction on the **isospin** degree of freedom, (linked to **proton-to-neutron** ratio) is believed to shed a new and elucidating light on a number of aspects of the **nuclear interaction** and **dynamics**

Nuclei Under Extreme Conditions

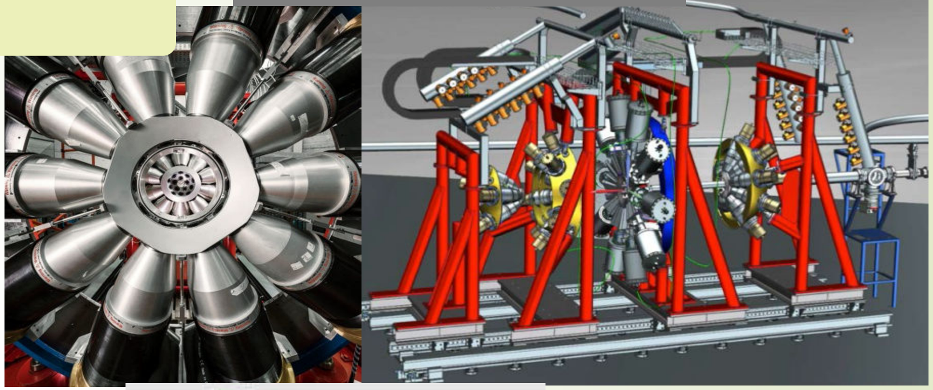
- Isospin: N/Z ratios much larger (or smaller) than the stability line
- Spin: highly rotating nuclei
- Temperature: "hot" nuclei

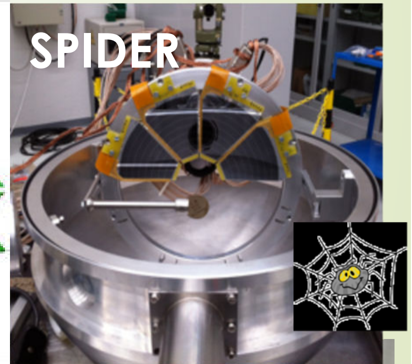
Instrumentation @SPES

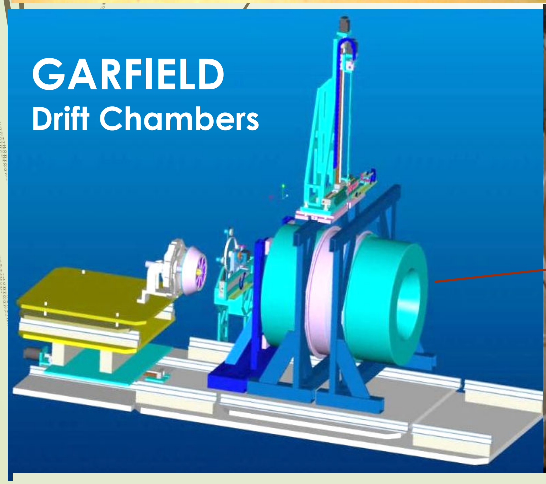
PRISMA large acceptance **magnetic spectrometer**
$\Omega \approx 80$ msr; $B\rho_{max} = 1.2$ Tm $\Delta A/A \sim 1/200$
Energy acceptance ~ ±20%

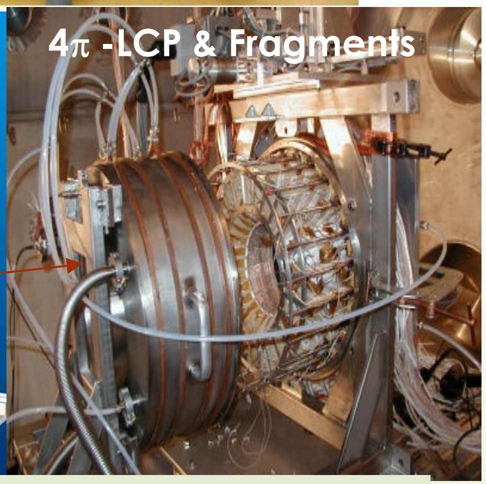


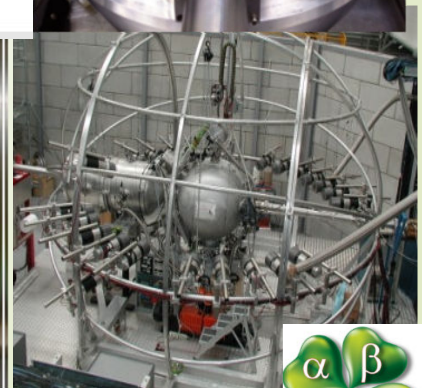
GALILEO γ-array







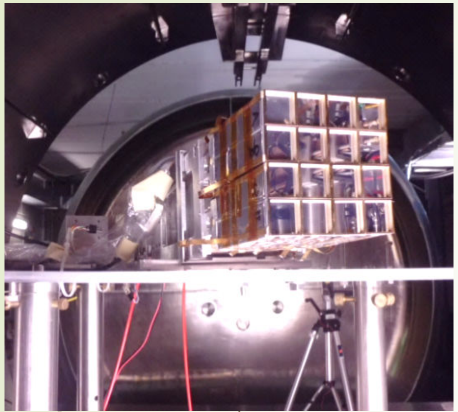


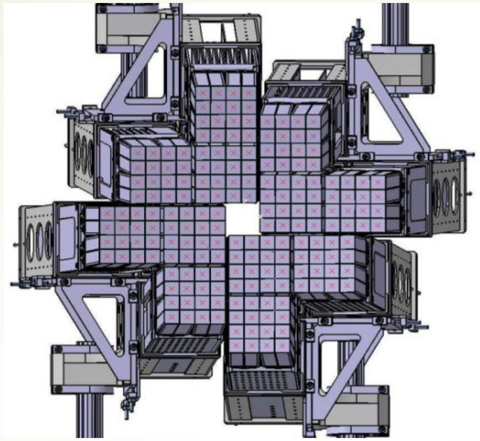


NUCLEX: Bologna, LNL, Fi, Pd, Na collaboration

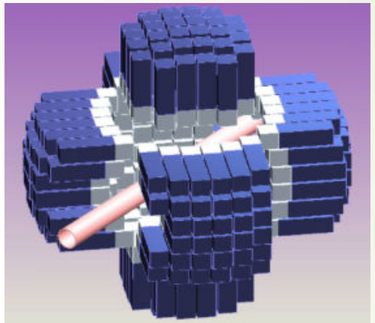
International Collaborations: itinerant detectors

FAZIA: **LCP & fragments detection**

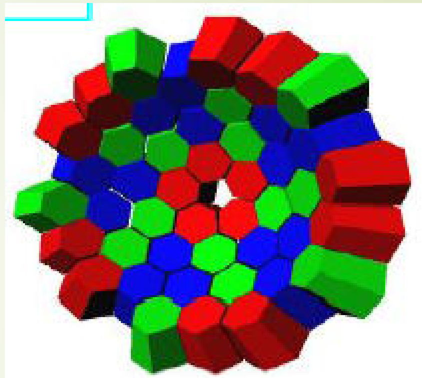


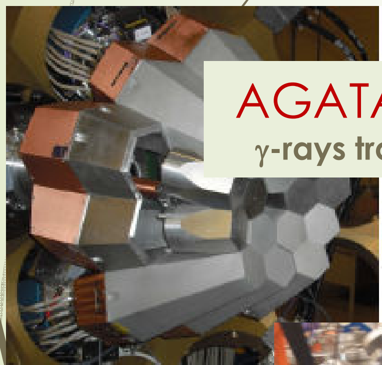


PARIS (High Energy γ-ray Detector Array)

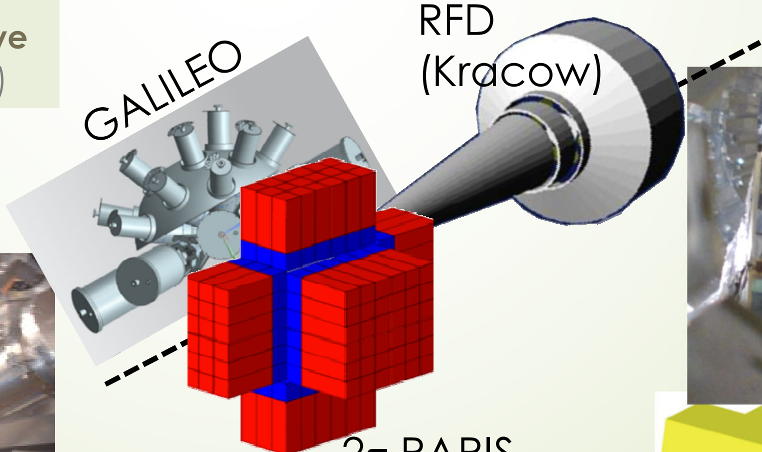


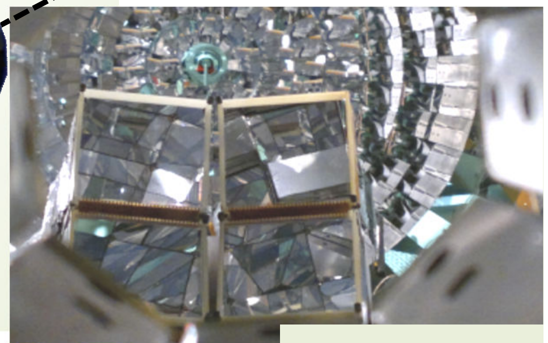
NEDA (NEutron Detector Array)





AGATA : innovative γ-rays tracking array)

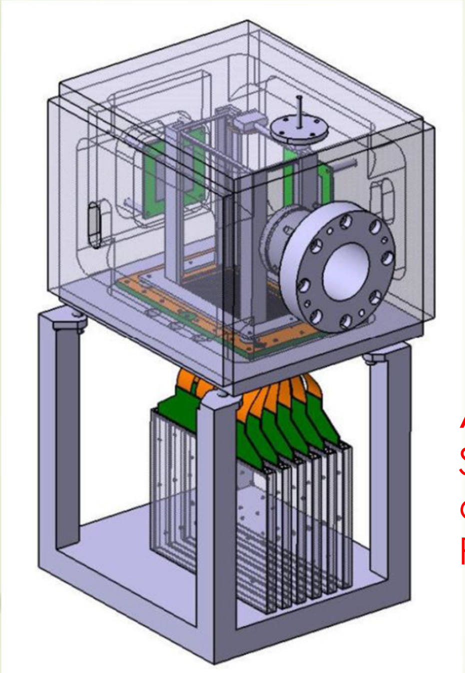


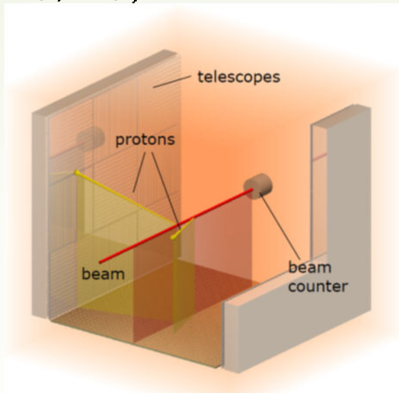


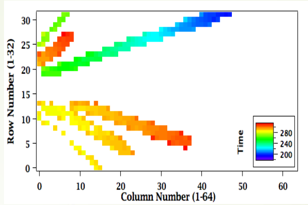
FARCOS

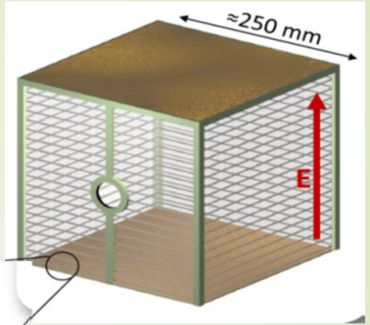
Instrumentation@SPES

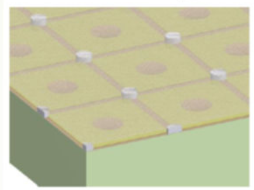
ATS @ SPES within the NUCL-EX collaboration
(LNL, Bologna, Fi, Pd, Na)

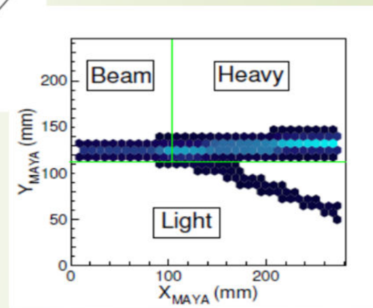








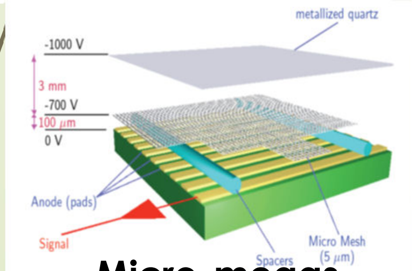




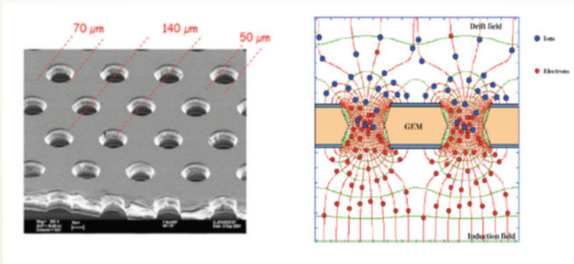
ACTAR : **Active Target Detector**

Starting activity with ACTAR collaboration: ENSAR2 GDS network and PRIN national project (submitted)

The **ACTAR TPC** collaboration is actually composed by:
Centre d'Etudes Nucleaires de Bordeaux Gradignan (CENBG), France
Grand Accelerateur National d'Ions Lourds (GANIL), France
Institut de Physique Nucleaire d'Orsay (IPNO), France
Institut de Recherche sur les lois Fondamentales de l'Univers (IRFU), France
University of Leuven (KUL), Belgium
Universidade de Santiago de Compostela (USC), Santiago, Spain



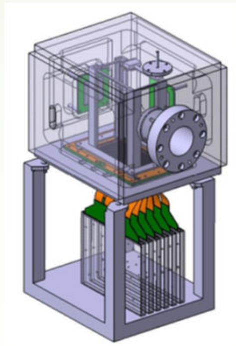
Micro-megas technology for the amplification region : low cost 5€/cm



Gas Electron Multipliers: GEM

GDS – Network within ENSAR2 – INFN WP leader

A very advantageous collaboration is ongoing with BOLOGNA



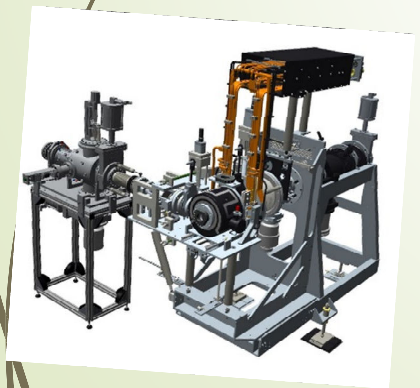
Technical collaboration on SPES accelerator construction

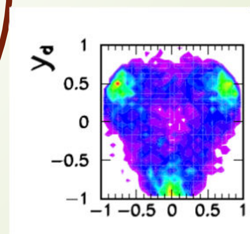
- Mechanical Workshop
- Technical Office

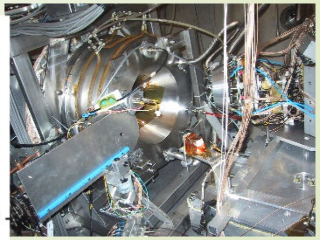
Technical collaboration on SPES detector study and construction

- Mechanical Workshop
- Technical Office
- Electronic Workshop

Scientific Collaboration On Nuclear Physics within the 3° National Comittee:
NUCL-EX collaboration @ GARFIELD
ACTIVE TARGET for SPES



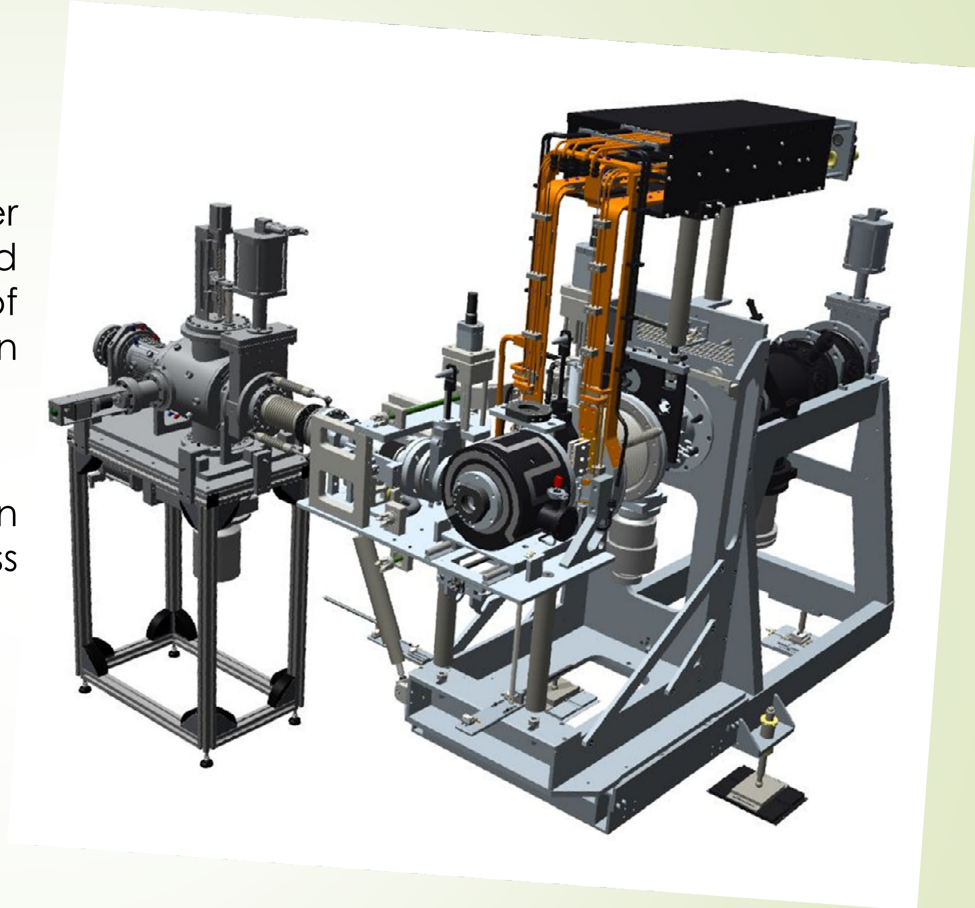




Front End SPES on-line upgrade

System for quick removal of the power connections , signals , high voltage and cooling (water) of the removable part of the Front End for SPES (TIS & proton injection line)

INFN Bologna Technical Office:
monitoring of the mechanical construction & interface with LNL for the process planning



INFN Bologna Mechanical Workshop:
construction of mechanical components for the *quick removal system* of the movable SPES Front End

Courtesy of M. Rossignoli

INFN-Bologna: technical collaboration on SPES

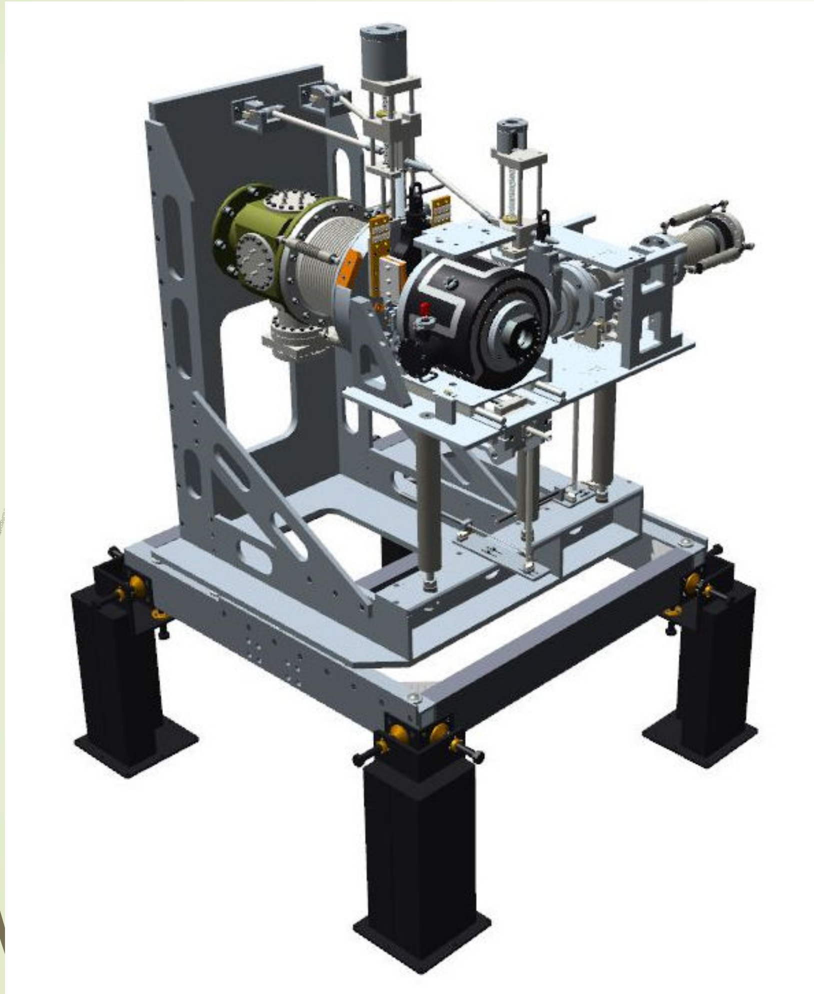
Subject: **1⁺ Source**

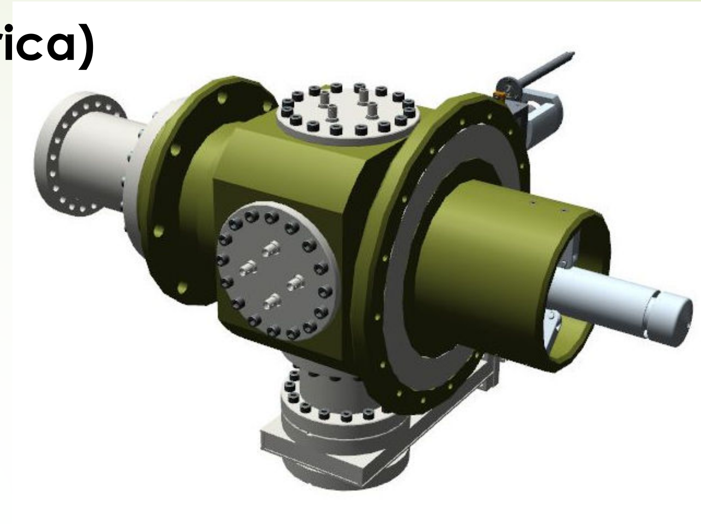
1⁺ Ion Source – for the Charge Breeder of the SPES project;

INFN Bologna Technical Office:
Modular chassis design for the block Source 1⁺: 3D CAD and constructive 2D drawings;
Construction phases coordination

INFN Bologna Mechanical Workshop:
Construction of the modular frame and of the main parts of the source (dishes cooled, ditching table and support-feets

Front End iThemba (South Africa)





Front End designed and under construction within the collaboration with iThemba laboratories in South Africa

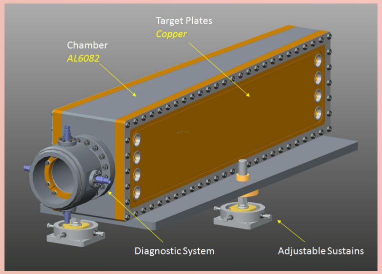
INFN Bologna Technical Office:
3D CAD design of the entire apparatus and drawing of all constructive tables. Redesign of the extractor block (in green).

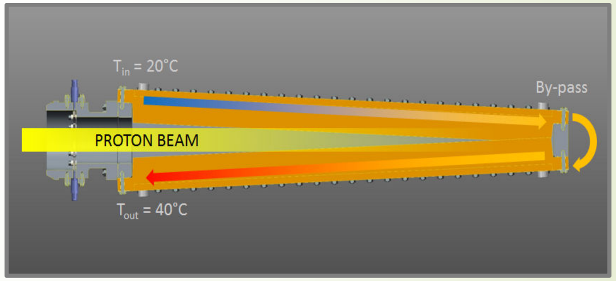
INFN Bologna Mechanical Workshop:
Construction of the extractor block and of various components

Other activities in collaboration with LNL

INFN Bologna Technical Office:

- Support for the 3D CAD design and construction tables of various subsystems of the SPES project
- Support for the integration of CAD drawings and of all the information and linked files in the management system and in the Windchill archive server
- Strong relation between LNL-Bo for the planning and management of mechanical achievements at the INFN Bologna workshop



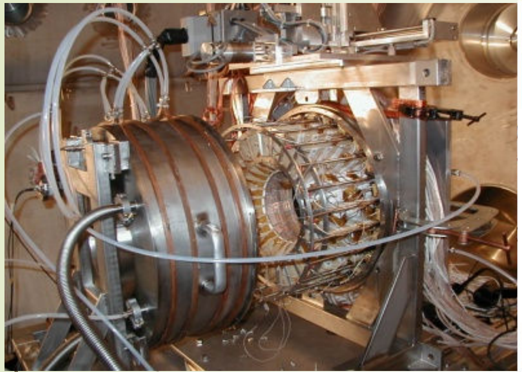


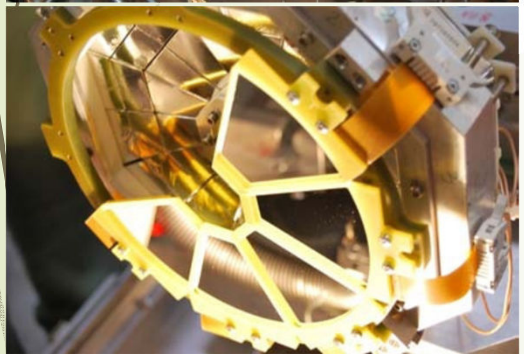
INFN Bologna Mechanical Workshop:

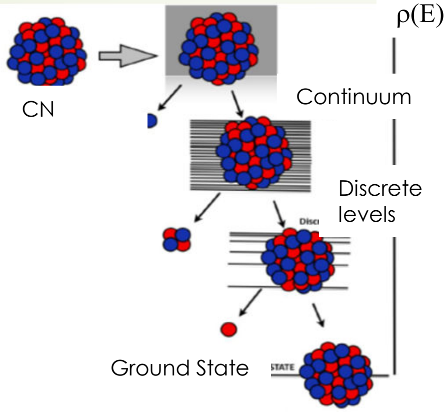
- Construction of various components for the realization of the high power Beam Dump of the SPES project
- Construction of several mechanical components for activities linked to the SPES project

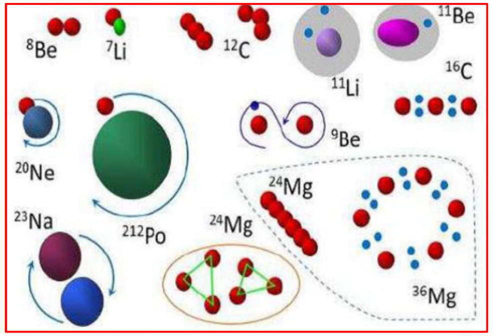
Physics: NUCLEX @SPES (Bologna-LNL-Fi-Pd-Na)

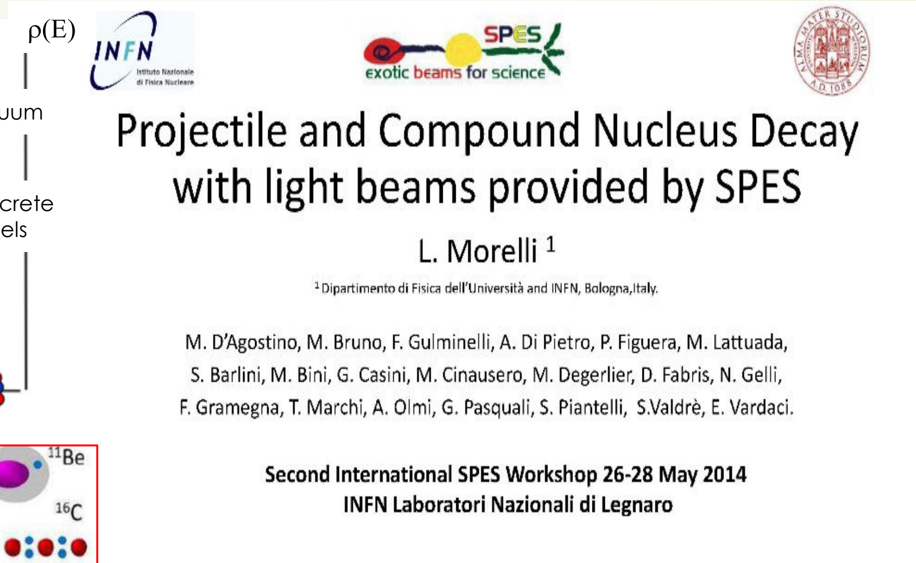
SPES LoI (L. Morelli, et al.)











Projectile and Compound Nucleus Decay with light beams provided by SPES

L. Morelli [1]

[1] Dipartimento di Fisica dell'Università and INFN, Bologna, Italy.

M. D'Agostino, M. Bruno, F. Gulminelli, A. Di Pietro, P. Figuera, M. Lattuada, S. Barlini, M. Bini, G. Casini, M. Cinausero, M. Degerlier, D. Fabris, N. Gelli, F. Gramegna, T. Marchi, A. Olmi, G. Pasquali, S. Piantelli, S.Valdrè, E. Vardaci.

Second International SPES Workshop 26-28 May 2014
INFN Laboratori Nazionali di Legnaro

- The statistical theory of CN decay
- Above the threshold for particle decay, level densities are accessible only through evaporation reactions → decreasing of NLD as a function of increasing N-Z
- Hot light nuclei in this mass region and excitation energy (~3 A.MeV) are produced in multi-fragmentation in a wide range of N/Z

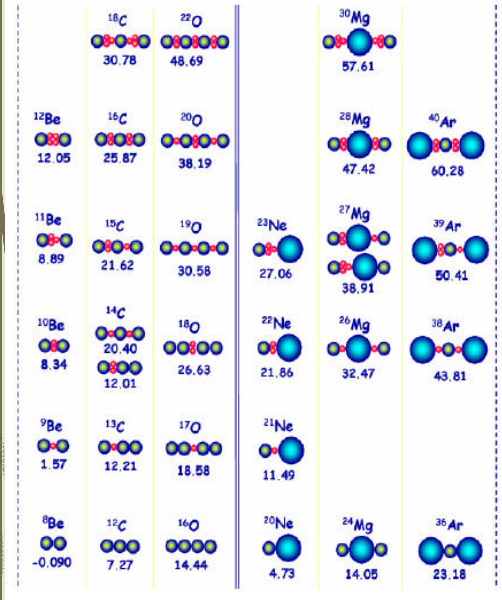
- Compound Nucleus formation & Decay
- Level Density for A~20, e*~3A.MeV

REACTION	ACN	ZCN	E*CN
$^{17}F + {}^{7}Li$	24	12	2-3 A MeV
$^{25}Al + {}^{7}Li$	32	16	2-3 A MeV
$^{25}Al + {}^{11}B$	36	18	2-3 A MeV
$^{10}Be + {}^{4}He$	14	6	

Physics: NUCLEX @SPES (LNL-Bologna-Fi-Pd-Na)

SPES LoI (T. Marchi -Pre-equilibrium emission: a tool to study dynamic effects and clustering structure in exotic nuclei)

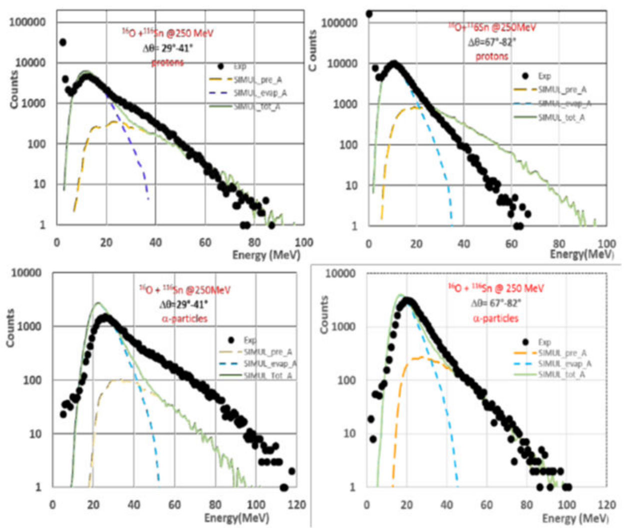
Extension of the Clustering concept:

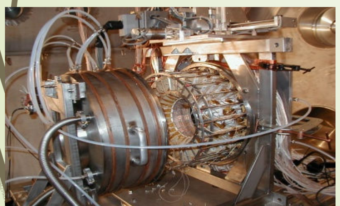


In light nuclei at the drip line clustering might be the prefered decay mode.

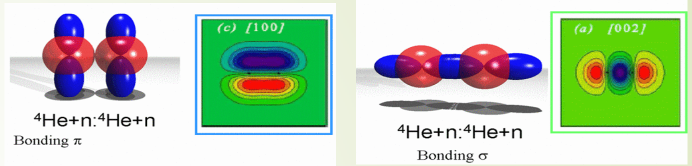
Nuclear states built on clusters bound by valence neutrons in their molecular configurations might appear

$^{16}O+^{124}Sn$ 16 AMeV





What about heavy nuclei?



1. Pre-equilibrium processes
2. Coalescence vs Preformation

Cluster emission, transfer and capture in nuclear reactions

P.E. Hodgson[a], E. Běták[b,1]

Physics Reports 374 (2003) 1–89

Presently these structures are mainly described by theory, but must be experimentally verified at the new radioactive beam facilities

Exotic Projectile	Stable Target	Compound	Beam Energy Range
^{130}Sn	^{28}Si	^{158}Gd	6 - 11 AMeV
^{132}Sn	^{28}Si	^{160}Gd	6 - 11 AMeV
^{130}Sn	^{30}Si	^{160}Gd	6 - 11 AMeV
^{132}Sn	^{30}Si	^{162}Gd	6 - 11 AMeV
^{130}Sn	^{27}Al	^{157}Eu	6 - 11 AMeV
^{132}Sn	^{27}Al	^{159}Eu	6 - 11 AMeV

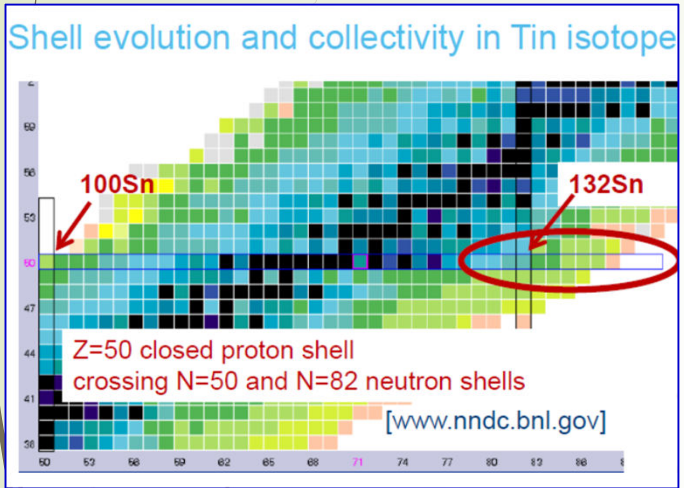
Physics: NUCLEX @SPES (LNL-Bologna-Fi-Pd-Na)

SPES LoI

1) R. Raabe - Shell structure in the vicinity of ^{132}Sn with an active target.
2) A. Di Pietro - Study of cluster states using the Resonance Scattering Method.

ATS@SPES

$f_{7/2}$ vs $p_{3/2}$ neutron orbitals in Sn like in Ca?



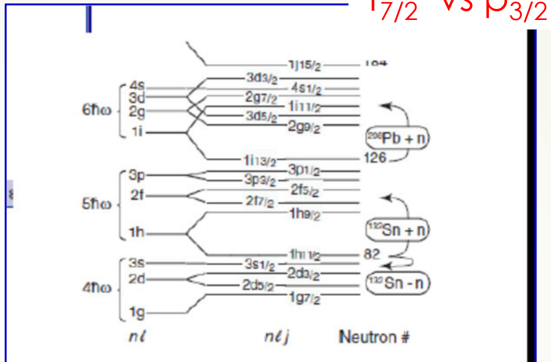
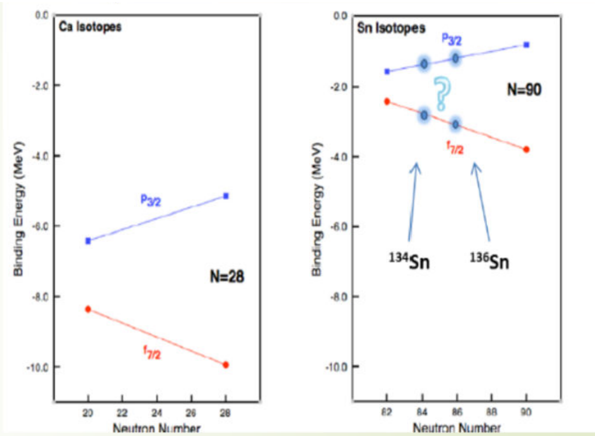


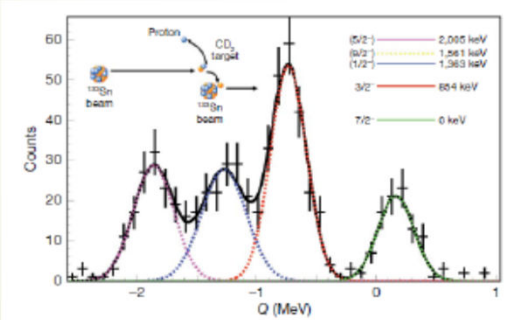
FIG. 1. Single-neutron states expected to be populated in the present one-neutron transfer study of ^{131,133}Sn and ^{209}Pb.

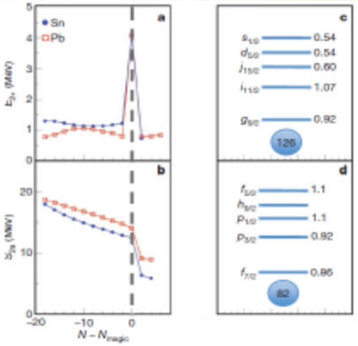


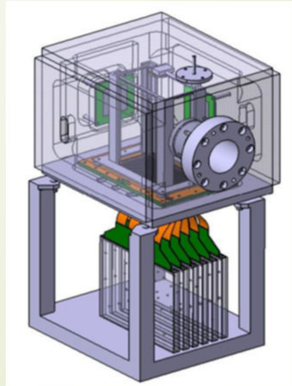
MagicTin

T. Marchi - Marie Curie Program

PRIN 2015 (Milano, LNL-Bologna-Padova, Firenze







[K.L. Jones et al, Nature 465 (2010) 454]

Evidences of ^{132}Sn double magicity
Resolution ~ 300 keV

Bologna Workshop; Technical Office & Electronic Workshop involved

55

Conclusions

- The SPES project is financed by INFN up to the completion
- The Cyclotron is completely installed & under test
- The Site Acceptance Tests are undergoing

} α

- ISOL:
  - The ISOL system will be installed in 2016
  - First radioactive beam in 2018 (no reacceleration)
  - Re-accelerated beams 2019

} β

- Applications:
  - A program for study and production of radioisotopes for medical use is started
  - First beams available for medicine and neutrons in 2016

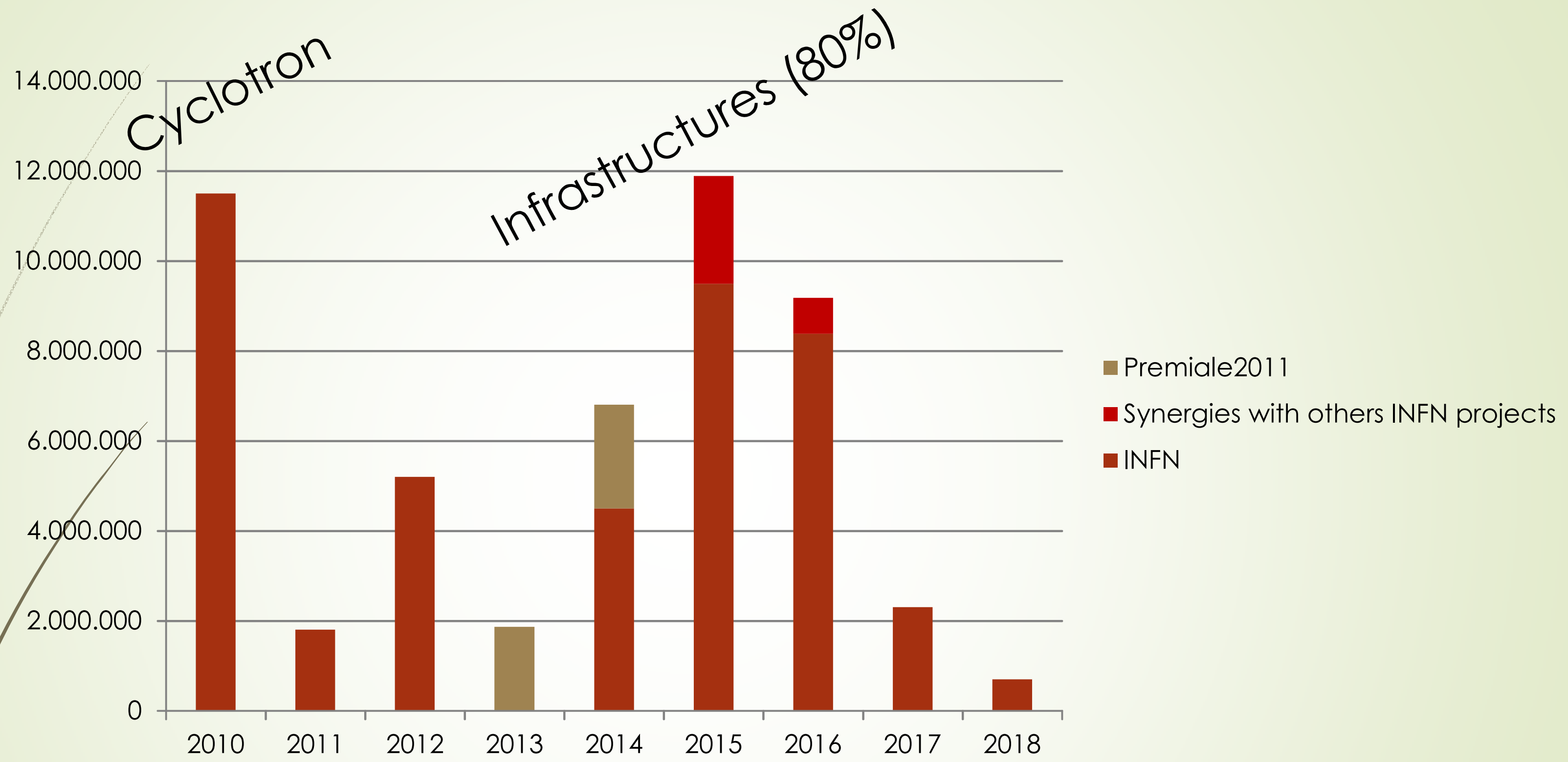
} δ

  - A neutron facility for fast neutrons is under design → γ

THANK YOU

BACKUP SLIDES

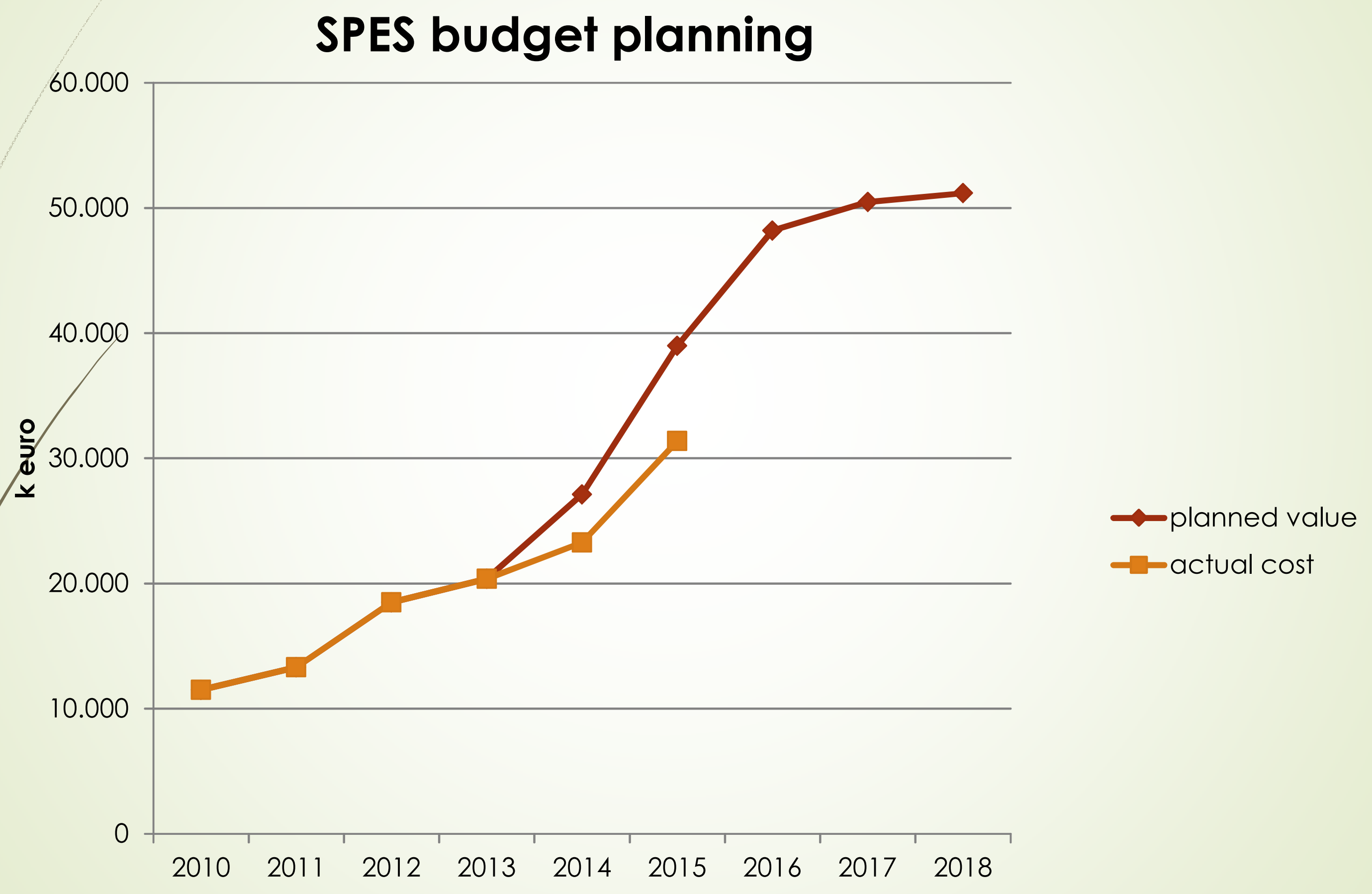
SPES - Economic plane



Approved project funding for completion: Nov 2014

Total SPES construction 2010-2018 (51.200 kEuro)	2010	2011	2012	2013	2014	2015	2016	2017	2018	Grand Total
Estimate (2013)	11,500	1,800	5,200	1,900	6,700	12,900	8,200	2,300	700	51,200
Invested (June 2015)	11,500	1,800	5,200	1,900	2,900	8.100				

SPES Budget Planning



SPES Construction phase: MAIN TENDERS

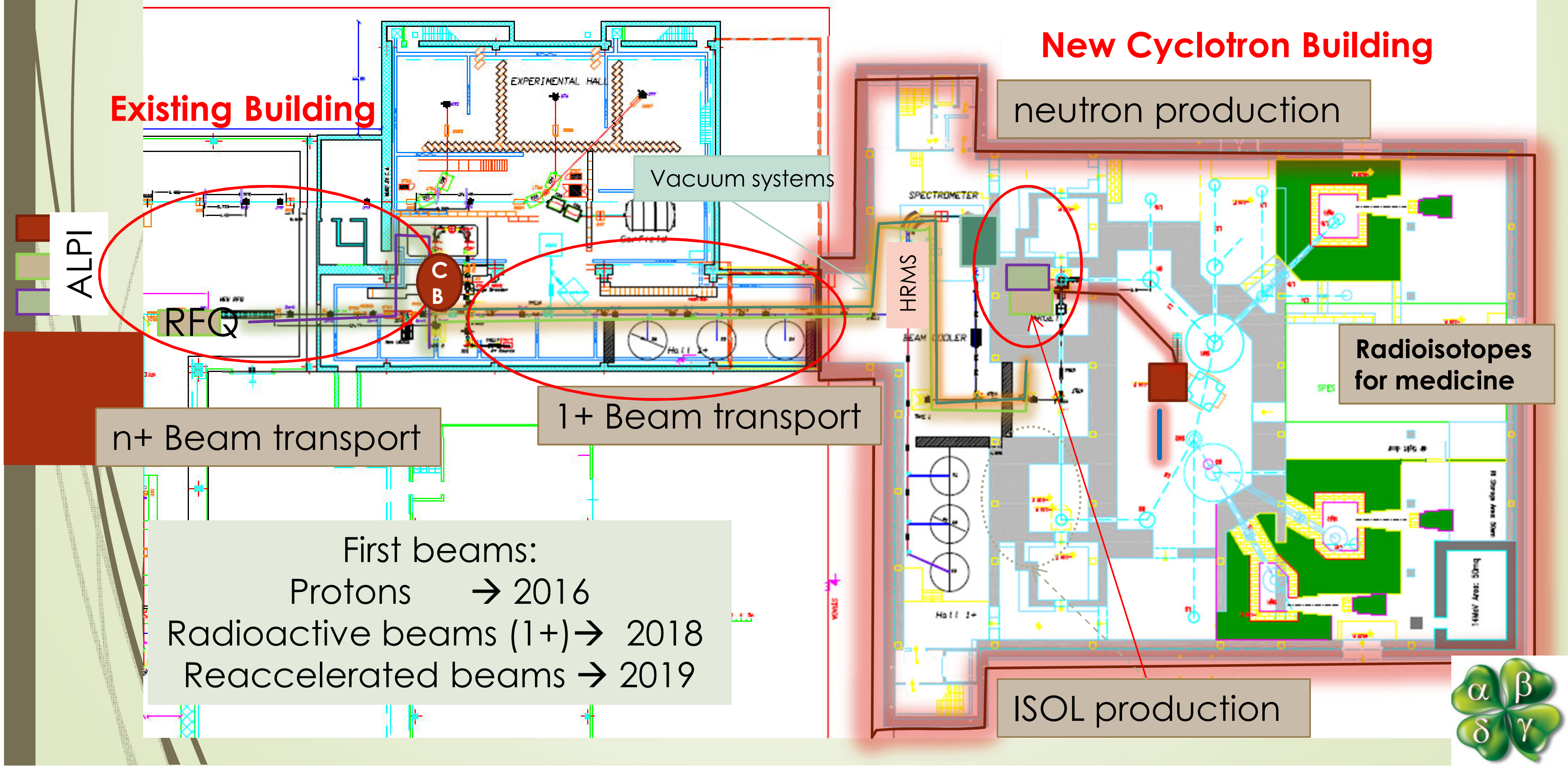
2010-2012
ISOL target
Cyclotron and Building

2013-2014
Laser source
Vacuum systems
Charge Breeder &
n+ beam transport

2015
Safety
RFQ
Plant upgrade

2016
1^+ beam line
UCx Lab , Vacuum systems, RFQ and installation

2017
High Resolution
Mass Separator

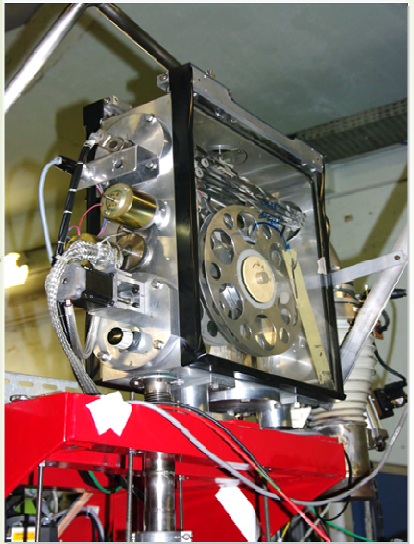


First beams:
Protons → 2016
Radioactive beams (1+) → 2018
Reaccelerated beams → 2019

Phase β: Diagnostics & Tagging for RIBs

Study group (mainly researchers in NP) to define instrumentation to be implemented for SPES (report at the beginning of 2016)

E.Fioretto (coordinator)
D.Fabris, G.Montagnoli, D.Mengoni, G.Collazuol, M.Poggi, R.Cherubini & collaboration with LNS

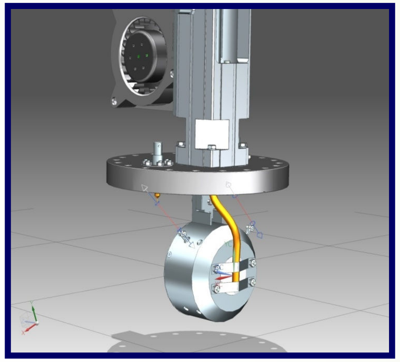


Tape station based on BEDO system, Orsay design

Working group:
F. Gramegna
T. Marchi
J. Bermudez

collaborators
D. Conventi
M. Rossignoli
M. Bellato (Pd)
G. Collazuol (Pd)
G. Tortona (Na)

Low intensity beam monitors



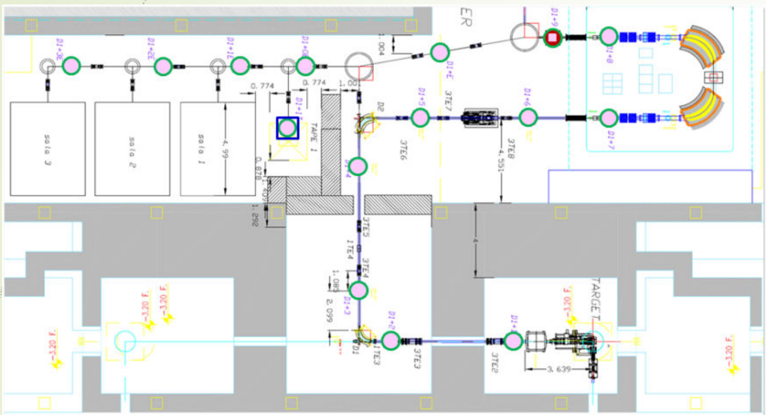
SPES → 30 new diagnostics with
- Beam profile monitors for pilot beams
- Beam profile monitors for low intensity beams
- Faraday cups
- 3 Beam Emittance Meters

- **2 Tape stations** for beam characterization
- **Diagnostic plate for commissioning**

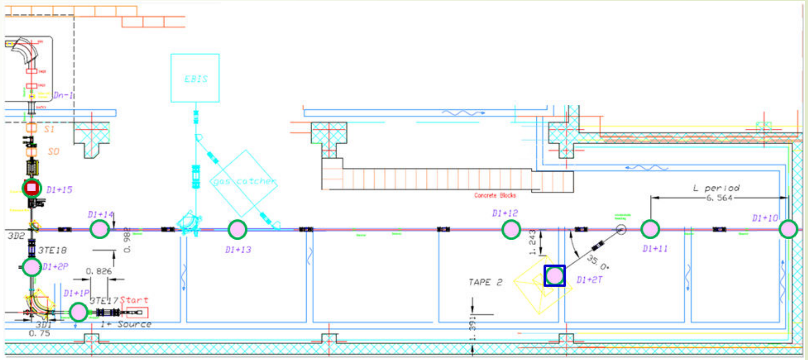
ALPI
- **Upgrade of the diagnostics boxes** with Beam Profile Monitors for low intensity beams
- **Installation of beam profile monitors for RIBs** on the different beam lines **in the experimental areas**.

Phase β: Diagnostics & Tagging for RIBs

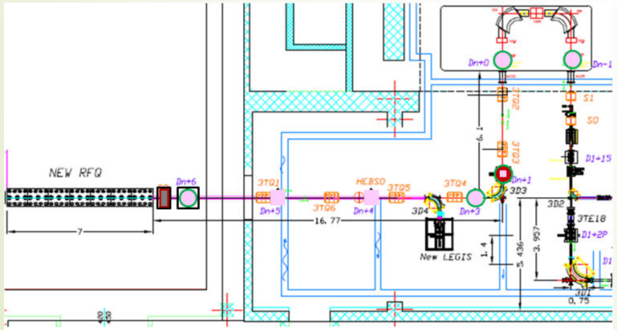
The main problem is the difficulty to develop a device able to cover the full operating range. For this reason a realistic solution is represented by at least two different kinds of devices with an overlapping operative range. To this end **typical instrumentation and techniques used in nuclear physics experiments** can be used for beam diagnostics if they are redesigned looking the peculiarity of this application.



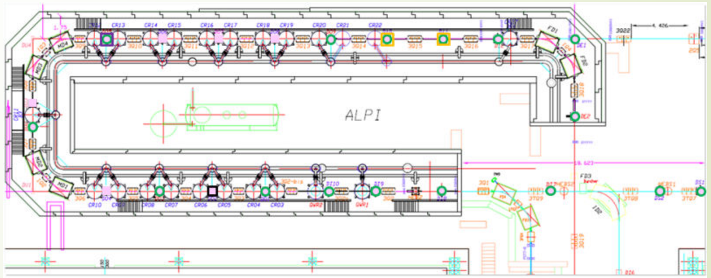
- 15 Beam Profile Monitors (BPM)
- 1 Beam Emittance Meter (BEM)
- 15 Beam Current Monitors
- 1 Tape station



- 9 Beam Profile Monitors (BPM)
- 1 Beam Emittance Meter (BEM)
- 9 Beam Current Monitors
- 1 Tape station

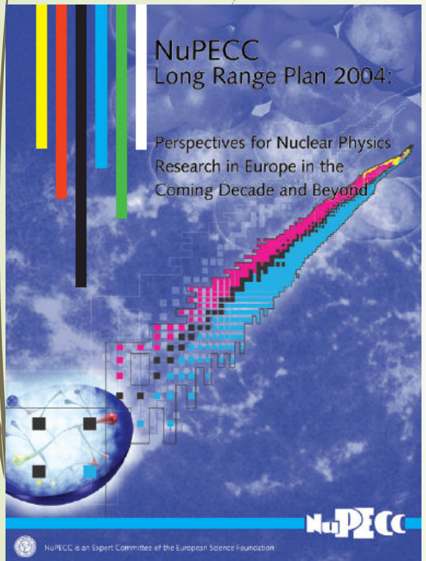


- 7 Beam Profile Monitors (BPM)
- 1 Beam Emittance Meter (BEM)
- 5 Beam Current Monitors
- 1 Diagnostic plate (temporary)
- 2 MCP (Timing)



- 27 Beam Profile Monitors (BPM)
- 21 Beam Current Monitors
- 1 MCP detector (Timing)
- 1 Si detector (Timing)
- 2 Fast FC for E meas. by TOF

Long Standing Questions of Nuclear Structure and Reaction Dynamics

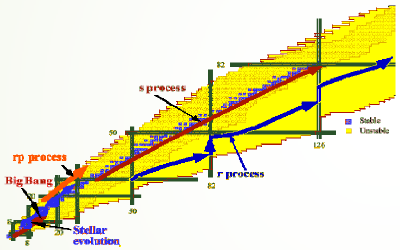


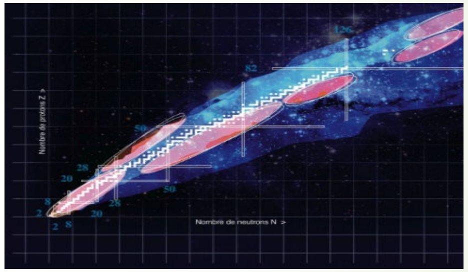
What are the limits of the heaviest elements?

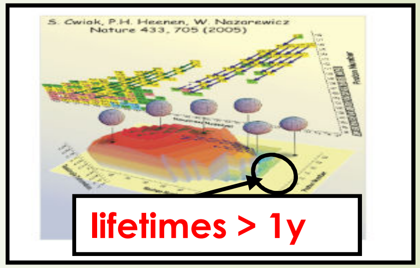
SCIENCE Magazine- Top 125 Questions:
Are there stable high-atomic-number elements?

What are the limits of stability?

How the elements are made in the Universe?







A Challenge for the Italian NP Community

- Development of a comprehensive model of atomic nuclei valid even far from stability
- Understanding the origin of the elements and modelling of the extreme astrophysics environments
- Test of fundamental symmetries
- New applications of isotope science

NUCLEAR PHYSICS: STABLE & EXOTIC BEAMS

LNS & LNL: an italian working consortium for NUCLEAR PHYSICS

- **LNS →**

✓ the Superconducting Cyclotron
(Intermediate energies → Reaction Dynamics)

✓ the TANDEM (Astrophysics)

- **LNL →**

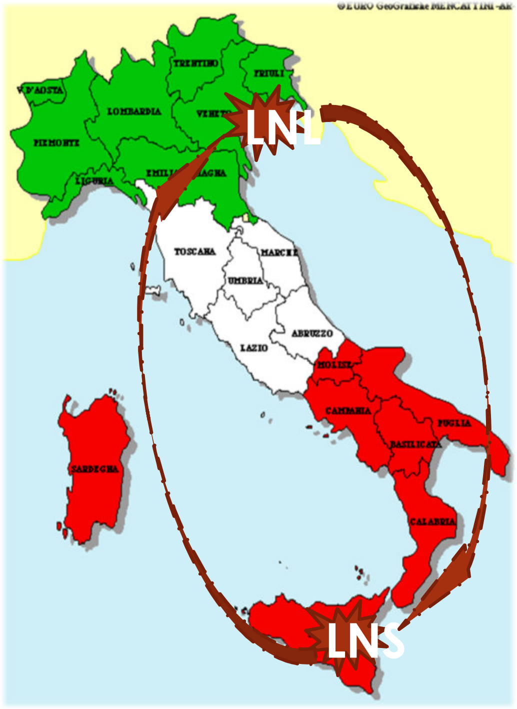
✓ The SC LINAC ALPI & PIAVE
(low & medium energies → Reaction and Structure)

✓ The TANDEM (Nuclear Structure)

LNS & LNL: a working consortium for NUCLEAR PHYSICS

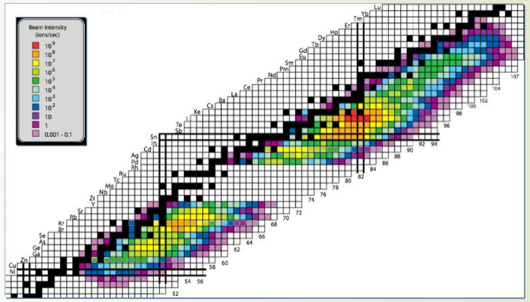
ISOL & FRAGMENTATION
LOW ENERGY & INTERMEDIATE ENERGY

RADIOACTIVE BEAMS:
→ our BET on future



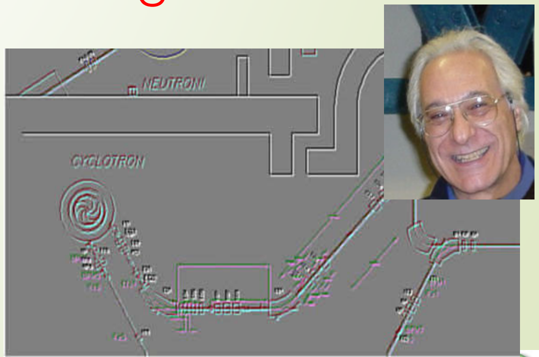
SPES: Selective Production of Exotic Species

- European framework
- Physics with SPES (mainly UCx fission but also SiC, B4C etc.)
- Instrumentation



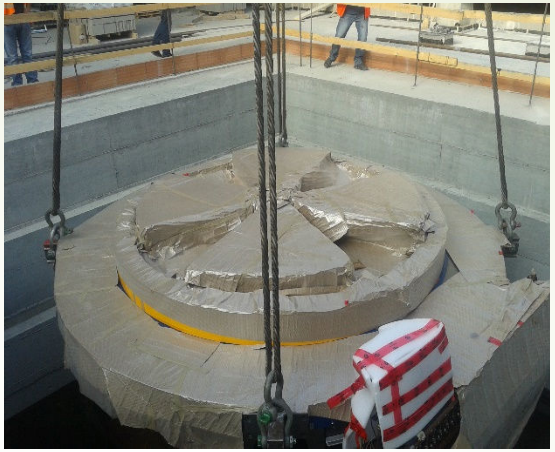
FRIBS: Radioactive Ion Beams at Intermediate Energy produced by the In-Flight method at LNS

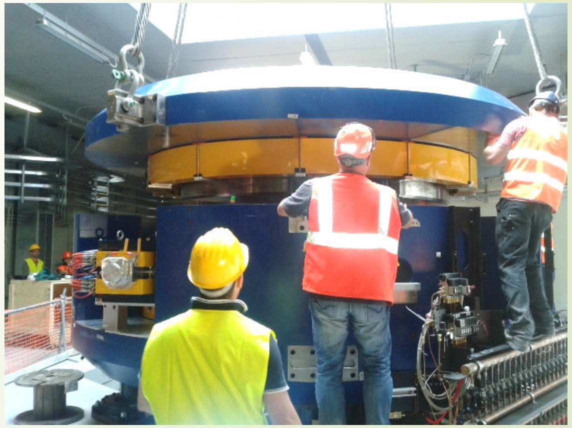
- European framework
- Physics with FRIBS (intermediate energy, light ions)
- Instrumentation



Phase α: cyclotron installation and SAT

May 2015





Scientific program: LoIs → some examples

SPES One-day Workshop
Transfer Reactions with RIBs
Napoli April,20th 2012

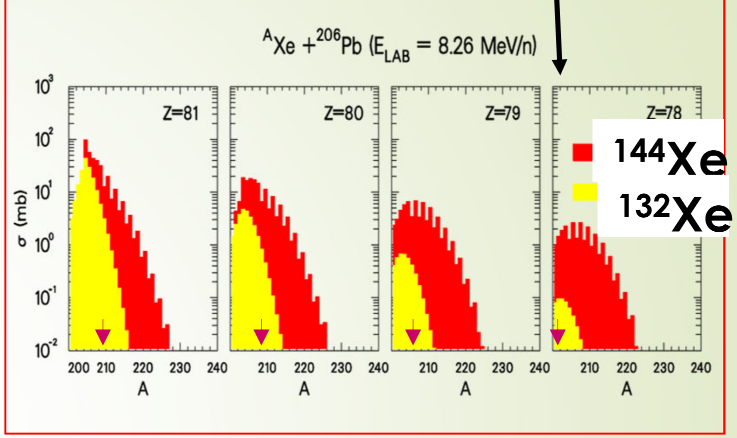
Neutron-rich Radioactive Beams & Transfer Reactions:
a tool to investigate nuclei far from stability

Direct Reactions → traditional tool to get **structure** information from **nuclear dynamics**:

- Coulomb Excitation, inelastic to collective states & single particle transfer Reactions → well described by first-order **one-step** mechanism.

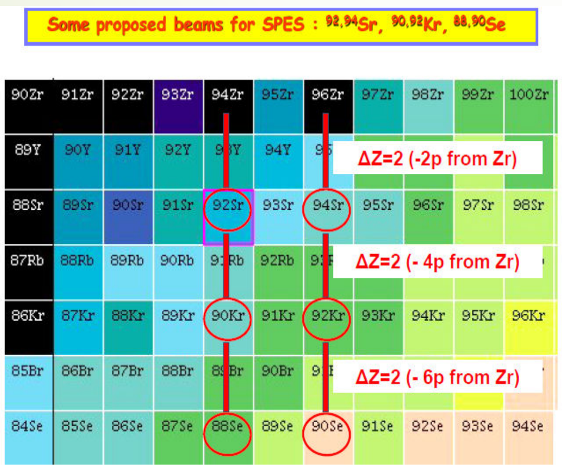
But Two-nucleon & Multi-pair Transfer Reactions → quite complicated processes

- pairing correlations strongly affect (and enhance) Two-particle Transfer Reactions → not obvious the quantitative connection.
- orders of magnitude more complex in the case of multi-particle (or multi-pair) transfers → they cannot be treated as a ***genuine* direct process**.

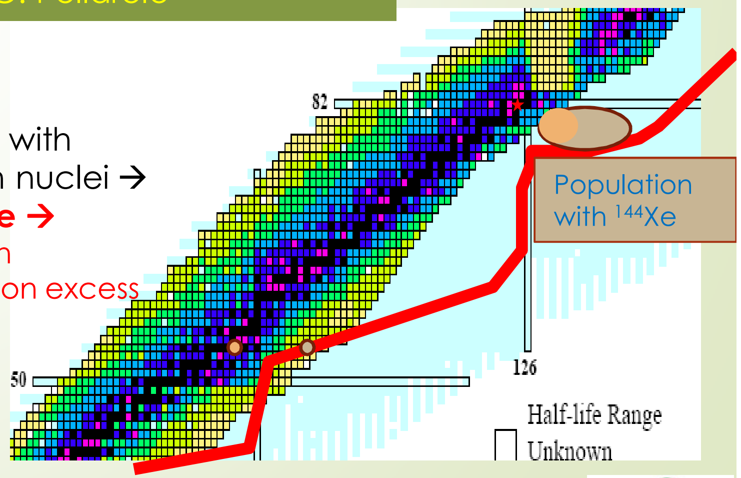


Coupled channel calculations (Grazing).
G. Pollarolo

Target ^{206}Pb



Study of **NN correlations** with neutron-rich nuclei →
pairing force →
modified with neutron/proton excess



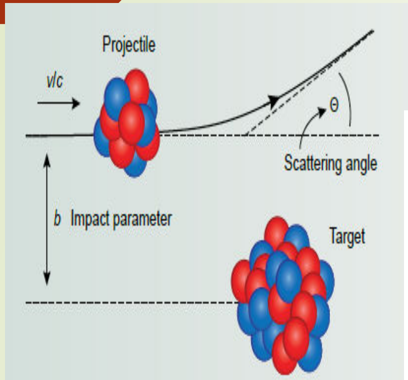
Beams ^{132}Xe ^{144}Xe

Scientific program: LoIs → some examples

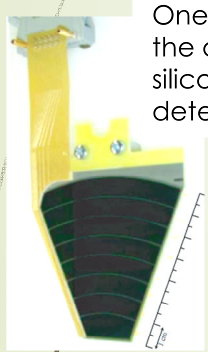
SPES One-day Workshop

Coulomb Excitation with RIBs

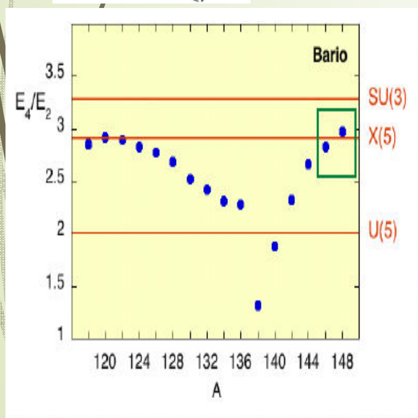
Sesto Fiorentino 27-28 September 2012

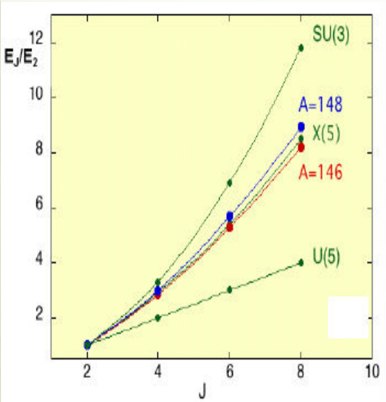


Very precise tool to measure the collectivity of nuclear excitations and in particular nuclear shapes. A projectile nucleus is scattered by a heavy target: Collective States of the exotic nucleus are excited as it passes through the Colulomb field of the target. The de-excitation γ-rays are measured in coincidence with the scattered fragment. The CE cross section can be measured counting the ratio between the observed γ-rays and the number of incoming particles.

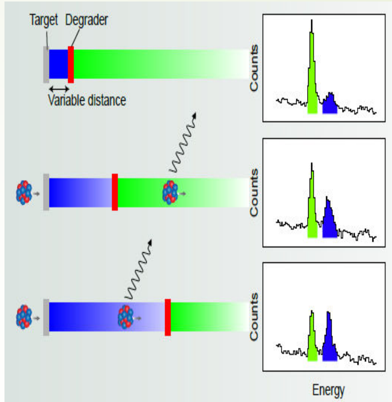


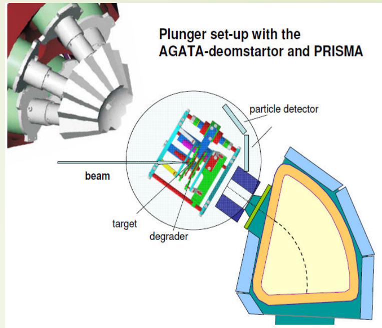
One sector of the annular silicon strip detector

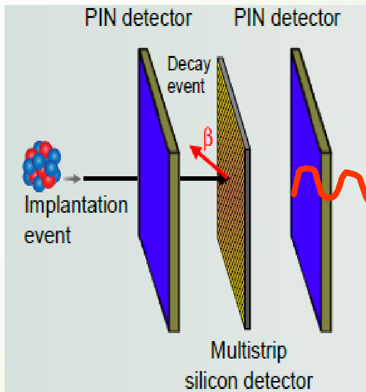


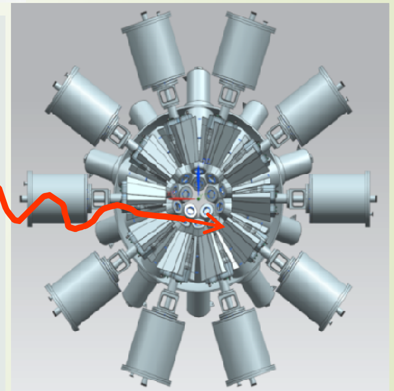


Lifetime measurements : plunger









Coulex of ^{146}Ba:

Shape Phase Transition Phenomena & **Dynamical Symmetries** studied by **Multiple Coulomb Excitation**

Scientific program: LoIs → some examples

LoI Proposed previously at the SPES International meeting:

C. Gross (ORNL-USA): *Nuclear Structure of n-rich nuclei determined through* ***β-decay spectroscopy*** *of Fission Fragments*

T. Kurtukian – Nieto (CENBG & University of Bordeaux, France): *Measurement of the decay* characteristics of nuclei around A=90 relevant to the **r-process** nucleosynthesis

A. Gottardo (IPN Orsay, France): ***Neutron decay*** *spectroscopy @ SPES*

B. Rubio (IFIC , Valencia, Spain): ***β-decay studies*** *using the gamma Total Absorptision Technique*

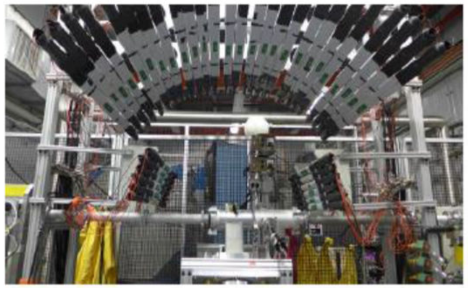
SPES Project — SPES one-day Workshop "Physics at SPES with non re-accelerated beams"

20-21 April 2015 *Milano*
Europe/Rome timezone

* Large positive response: 65 attendees

* Participants from Italy, CERN-Switzerland, Riken-Japan, Oak Ridge-USA, TRIUMF-Canada, Bordeaux-France, Orsay-France, Spain, Greece.

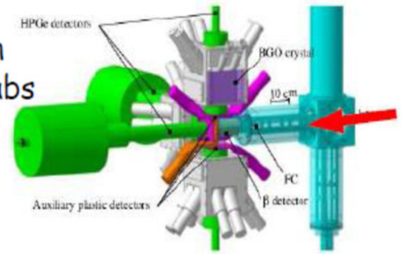
- 18 talks, 5 concerning LOI.

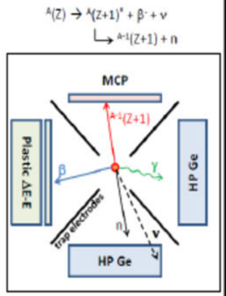


VANDLE = Versatile Array of Neutron Detectors for Low Energy

- Nuclear structure - beta strength above S_n
- Nuclear structure - energy "levels"
- Nuclear structure - Gamow-Teller vs forbidden transitions
- Nuclear astrophysics - r-process
- Nuclear energy - neutron energy spectrum

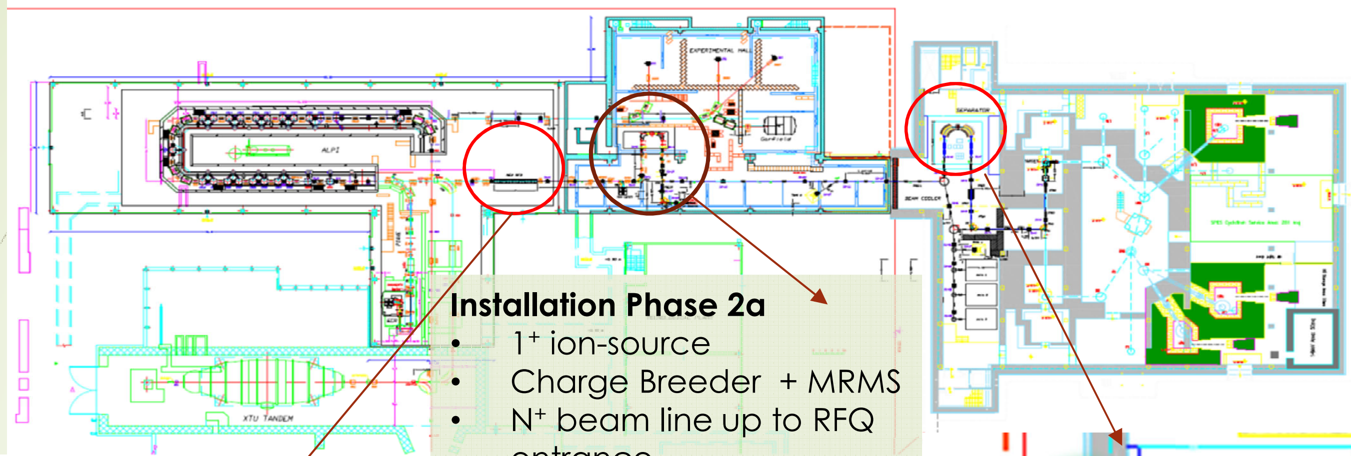
Close collaboration with ALTO and I-Themba Labs to design decay station





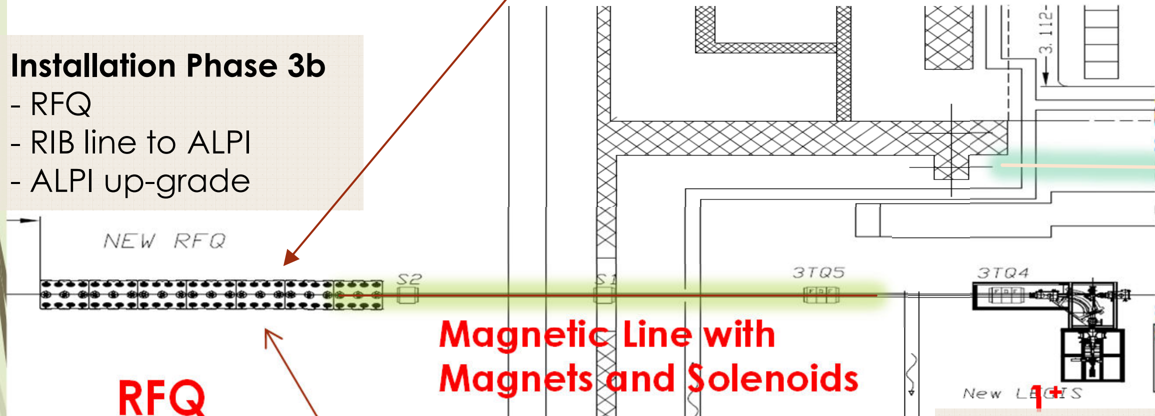
New techniques proposed
Egs. MR-TOF, Pauli Traps

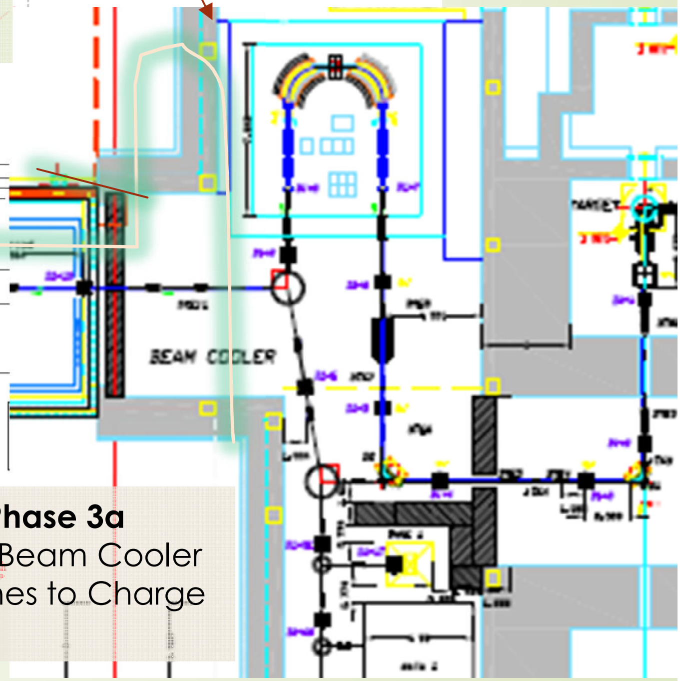
Phase β: HRMS , CB+ MRMS & beam line to ALPI - RFQ



Installation Phase 2a
- 1^+ ion-source
- Charge Breeder + MRMS
- N^+ beam line up to RFQ entrance

Installation Phase 3b
- RFQ
- RIB line to ALPI
- ALPI up-grade





Installation Phase 3a
- HRMS and Beam Cooler
- 1^+ beam lines to Charge Breeder

RFQ