INFN
LEGNARO
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

Legnaro National Laboratories: from Basic Research to Applications of Nuclear Technologies

Diego Bettoni

INFN, LNL, Italy

NuSpIn

Mission:

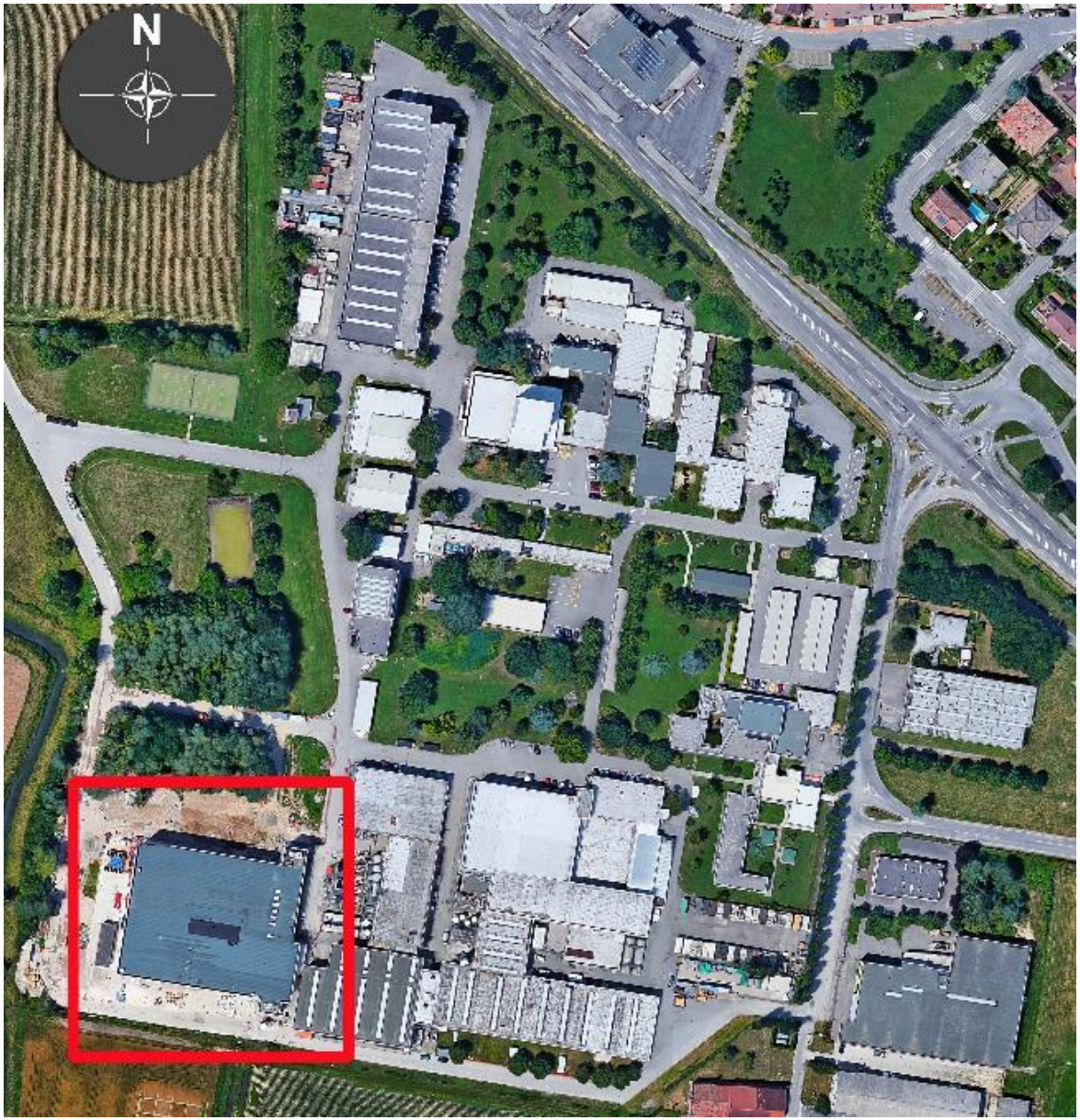
- Nuclear physics and nuclear astrophysics:
  - nuclear spectroscopy
  - reaction dynamics
- Advanced technologies for applications to nuclear physics and other fields
- Technology transfer

Strengths:

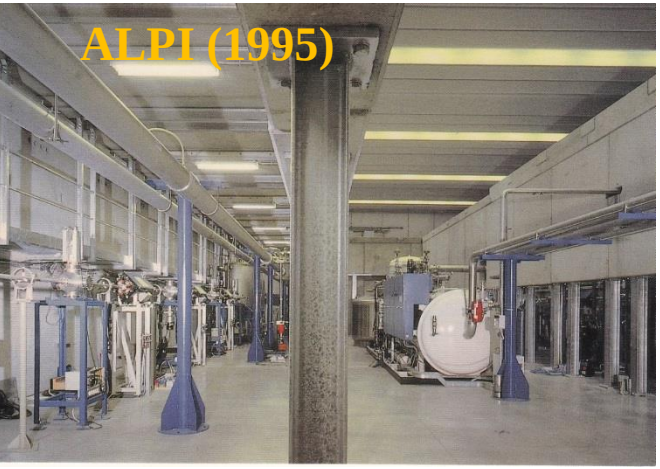
- Development of accelerators (e.g. RFQ)
- Radiation detectors
- Surface technology

Personnel:

- 138 staff
- 700 users (50 % from Italy)



LNL - Accelerators



LNL – Experimental Apparatuses

Summary of activities

Special projects

SPES cyclotron to study nuclear physics
LARAMED Develop/study radioisotopes of biomedical interest
IFMIF RadioFrequency Quadrupole accelerator
ESS Drift Tube LINAC
MUNES neutron source
ITALRAD nuclear physics applied to environment

Physics projects

GAMMA SPECTROSCOPY
APPLIED NUCLEAR PHYSICS
RADIOBIOLOGY and DOSIMETRY
ASTROPHYSICS searches: QUAX

Technological activities

Surface material treatment
Computing infrastructure (Tier2)
Dissemination

The SPES Project

SPES

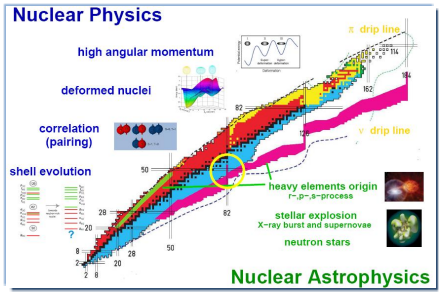
The main project for the future of LNL is SPES: Selective Production of Exotic Species, in which the dual role of the laboratory as a center for fundamental and applied science is very clear.

SPES is a second generation ISOL facility with two main goals:

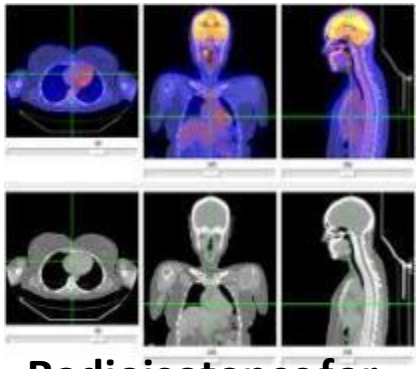
- Production and re-acceleration of exotic beams. Study of nuclei produced in advanced stages of stellar evolution.
- production of radioisotopes for nuclear medicine

SPES Selective Production of Exotic Species

Cyclotron



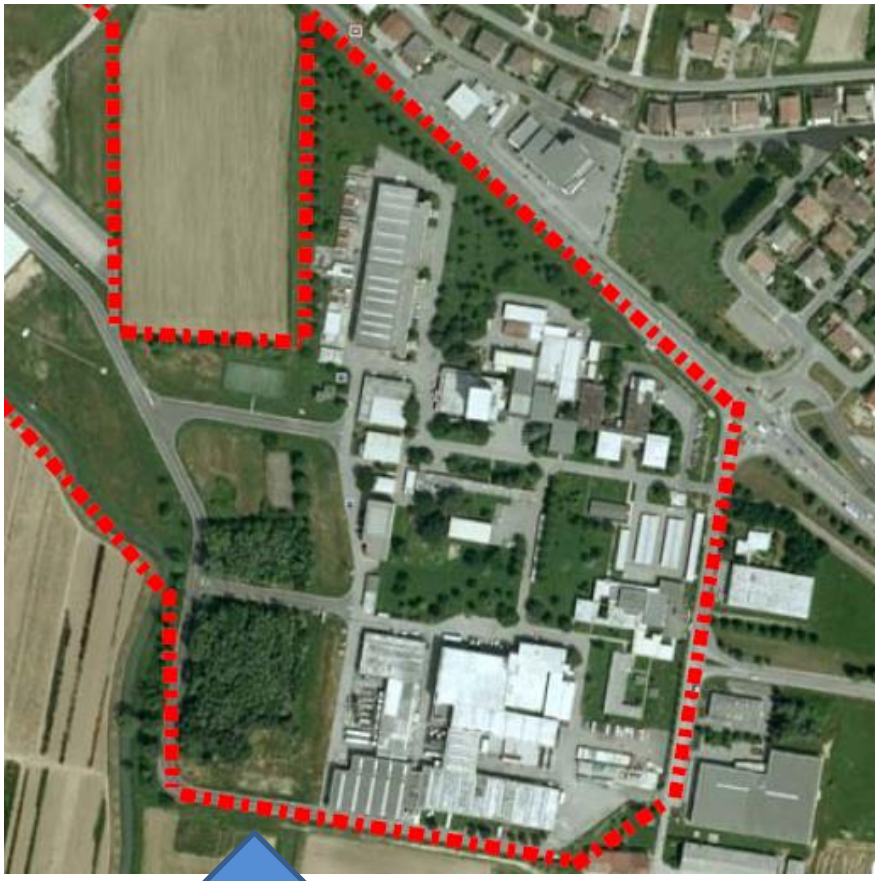
Production & re-acceleration
of **exotic beams**. **Neutron–rich ions**
from p-induced Fission on **UCx (10^{13} f/s)**

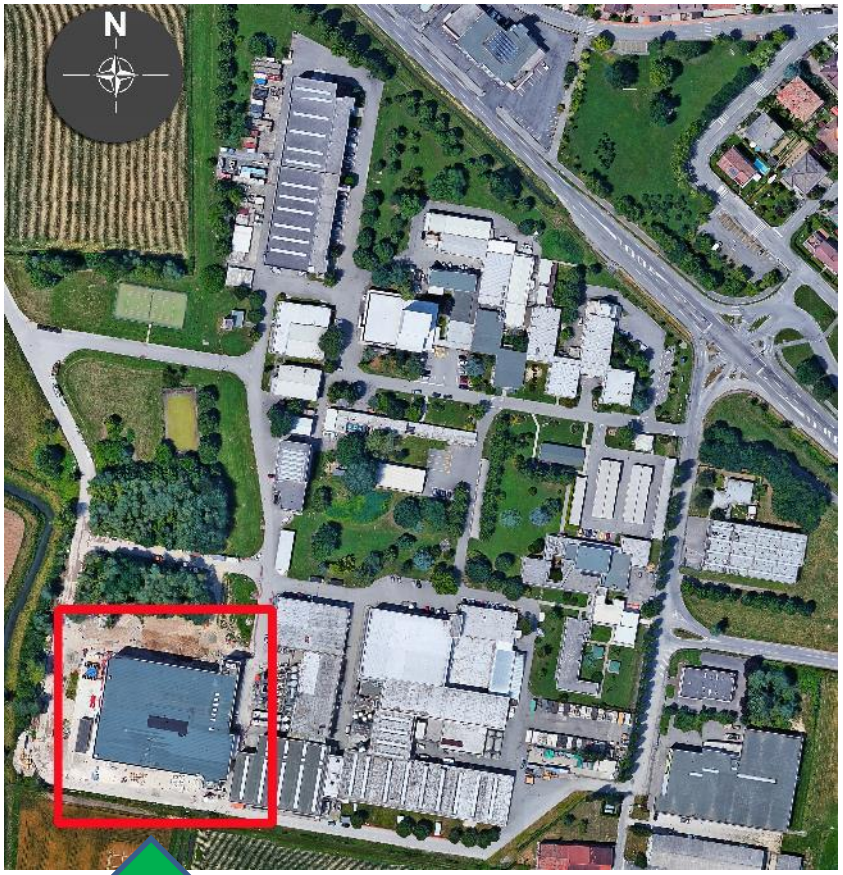


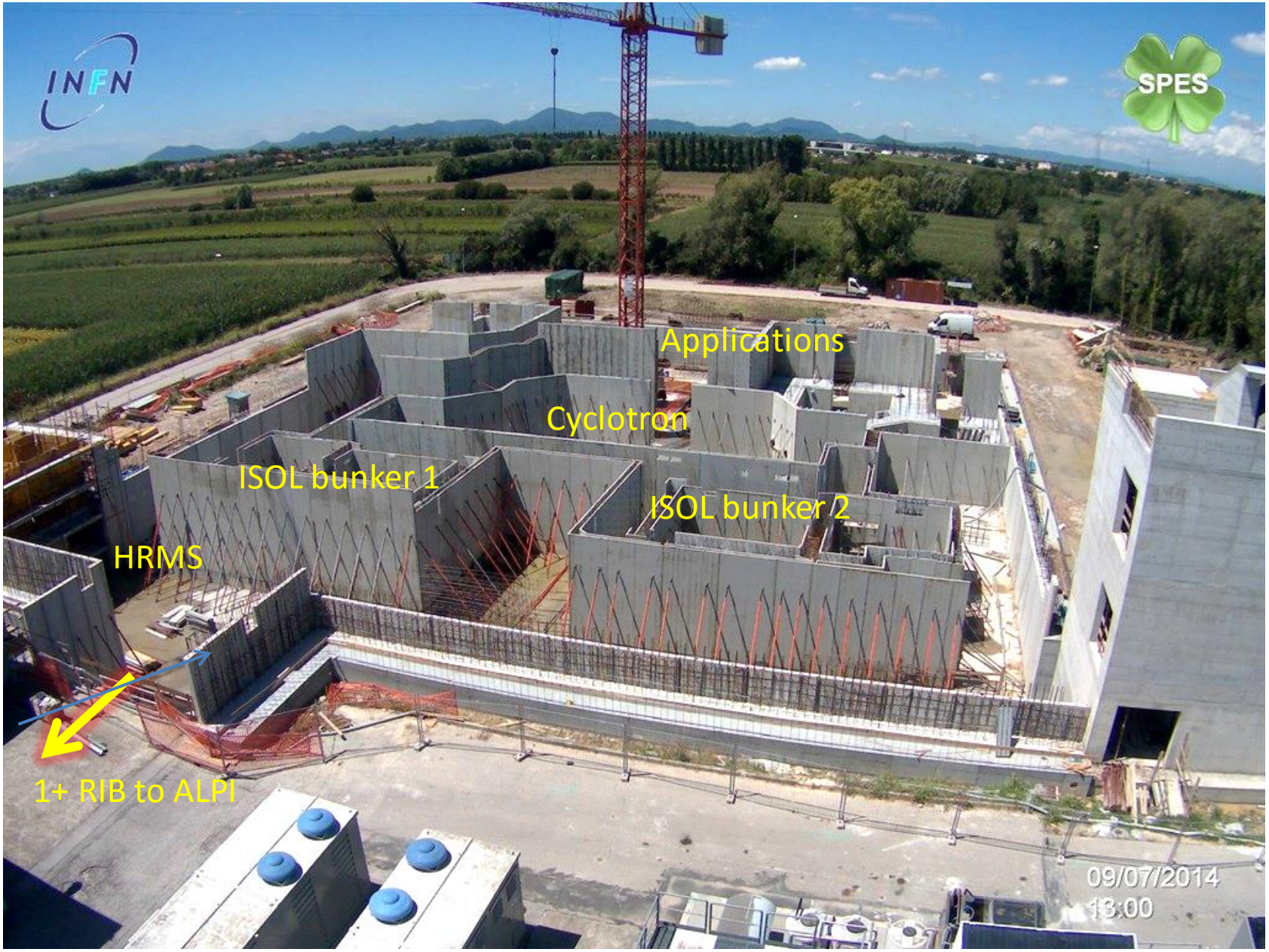
Radioisotopes for Nuclear Medicine

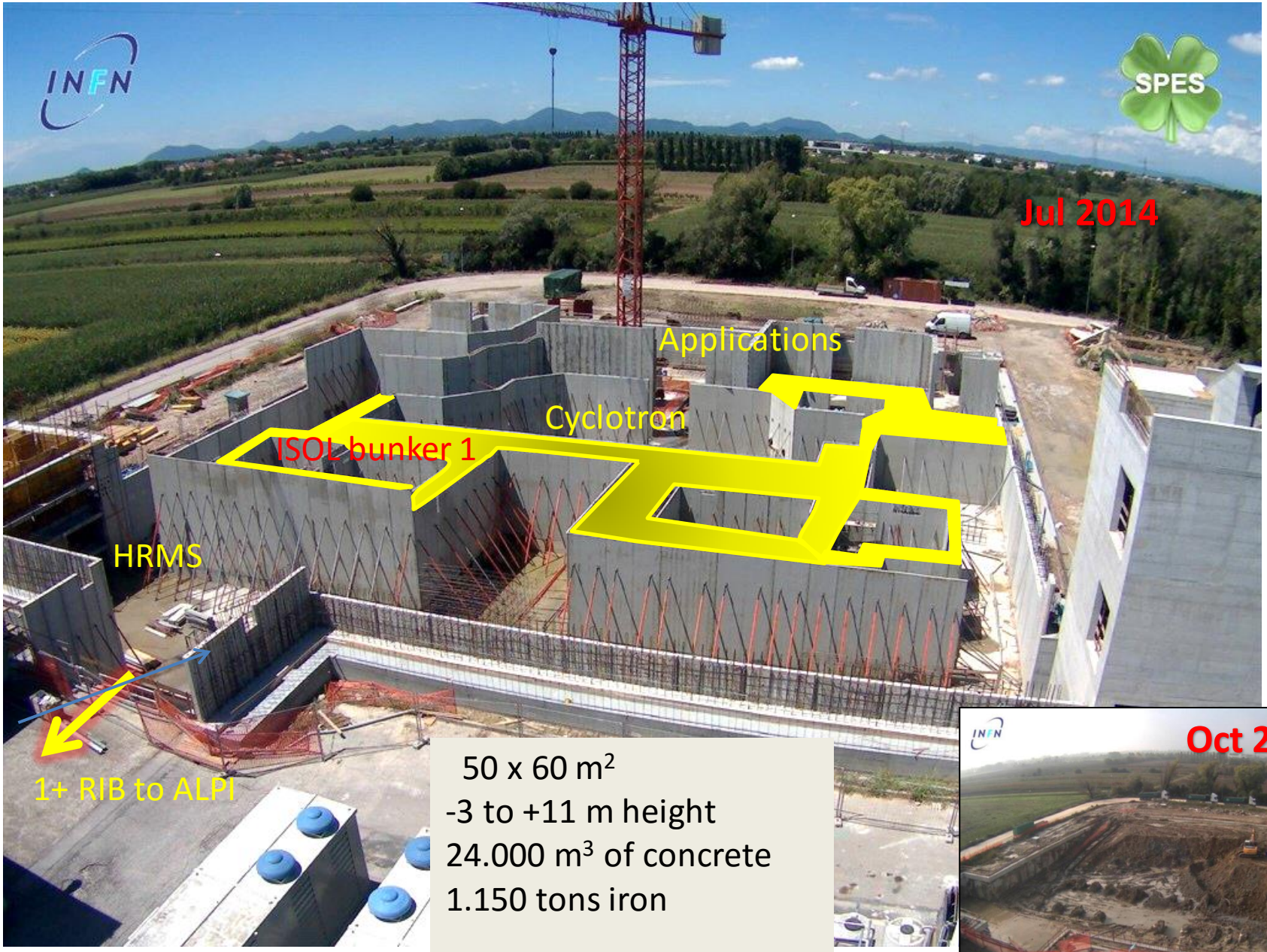
Accelerator based neutron sources

SPES-α



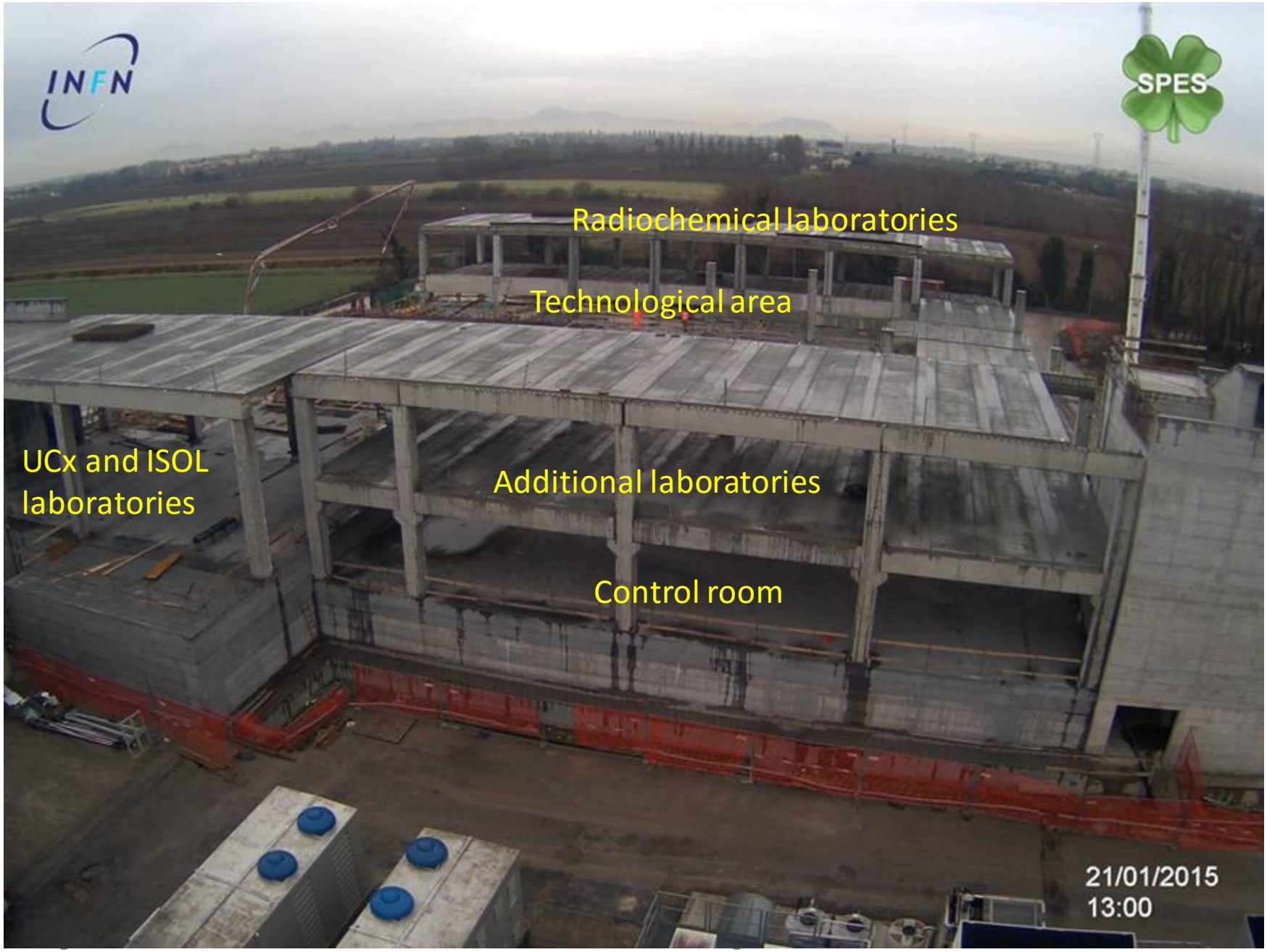



INFN
SPES
Applications
Cyclotron
ISOL bunker 1
ISOL bunker 2
HRMS
1+ RIB to ALPI
09/07/2014
13:00



50 x 60 m^2
-3 to +11 m height
24.000 m^3 of concrete
1.150 tons iron

3-4 m shielding wall thick


INFN
SPES
Radiochemical laboratories
Technological area
UCx and ISOL laboratories
Additional laboratories
Control room
21/01/2015
13:00

The Spes Building 2016

the Cyclotron

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** (upgradable to different energies)

Endurance test ongoing (5 days at 200μA, 40 MeV)
expected: SAT completed in June
Training completed in July

Use of cyclotron for tuning and INFN practice up to temporary authorization expiry (end 2017)

SPES-β

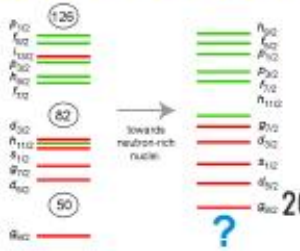
Nuclear Physics

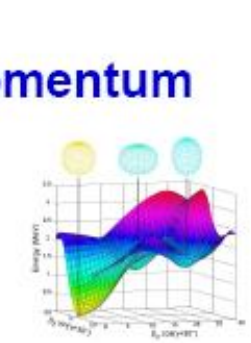
high angular momentum

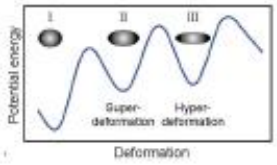
deformed nuclei

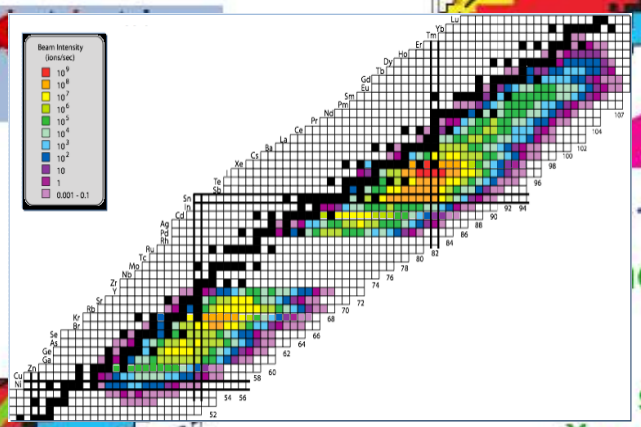
correlation (pairing)

shell evolution









π drip line

ν drip line

82

126

114

162

184

28

20

8

2

50

heavy elements origin
r−,p−,s−process

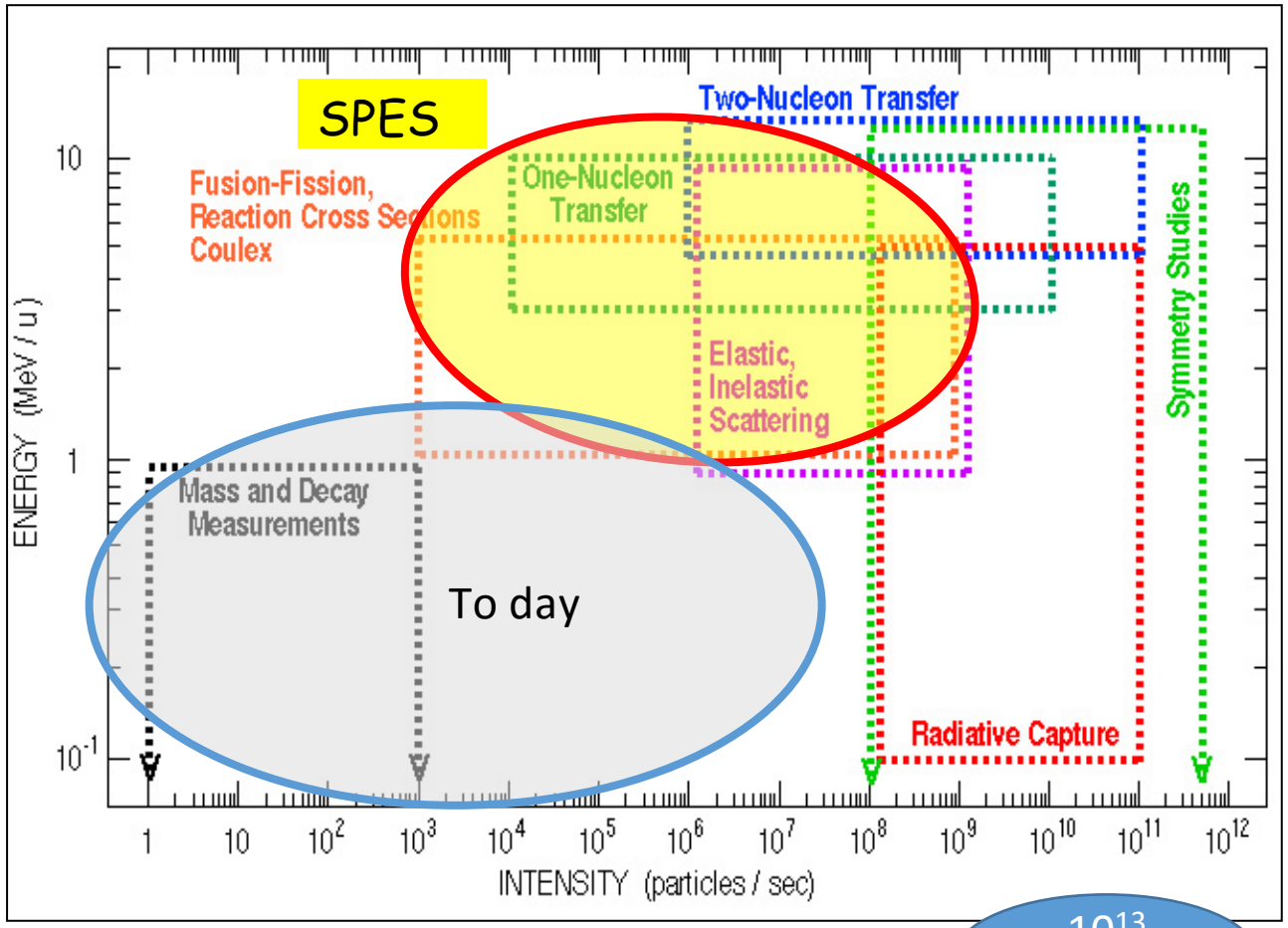
stellar explosion
X−ray burst and supernovae

neutron stars

Nuclear Astrophysics

Physics Domain with RIB

Nuclear Physics and Astrophysics



EURISOL

Second generation

today

today

Second generation

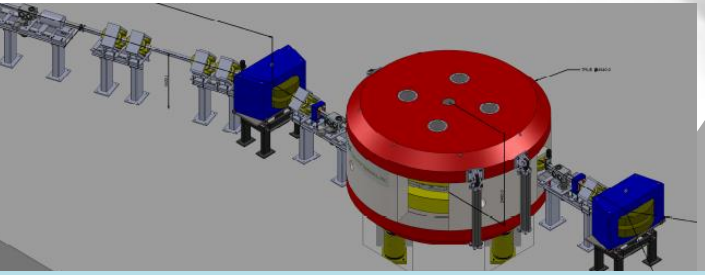
EURISOL

10^{13} fiss/s

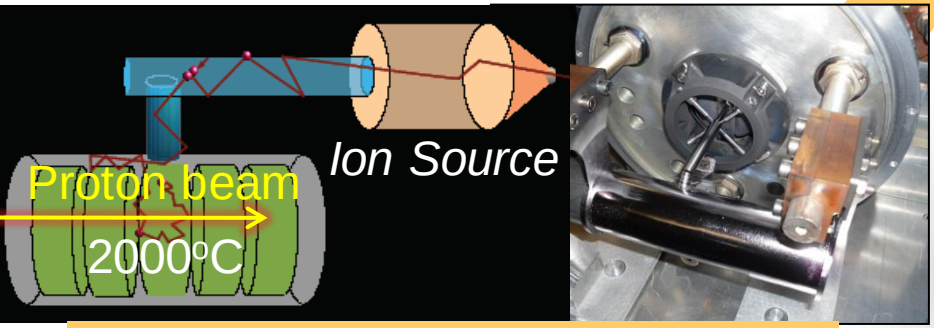
Main Components of the ISOL Facility

Components		SPES choice
Proton driver	Primary beam for reaction into the ISOL target	**Cyclotron** 70MeV 750 microA
ISOL system	Target ion-source assembly producing exotic beams (reaction products)	New concept **Direct target** with UCx 10^{13} fission/s (10kW primary beam)
Beam transport and selection	Mass selection to clean the exotic beam from unwanted isotopes	**Mass Separators**: Wien filter 1/150 Low resolution Mass Separator 1/300 Beam cooleer & HRMS 1/20.000 MRMS 1/1.000 (after Charge Breeder)
Charge Breeder	Increase ion charge fron 1+ to n+	**ECR type CB**
Pre-accelerator	Adapting the beam energy to re-accelerator acceptance	**RFQ** normal conductive
Re-accelerator	Accelerate the exotic beam	**ALPI linac**

SPES ISOL Layout

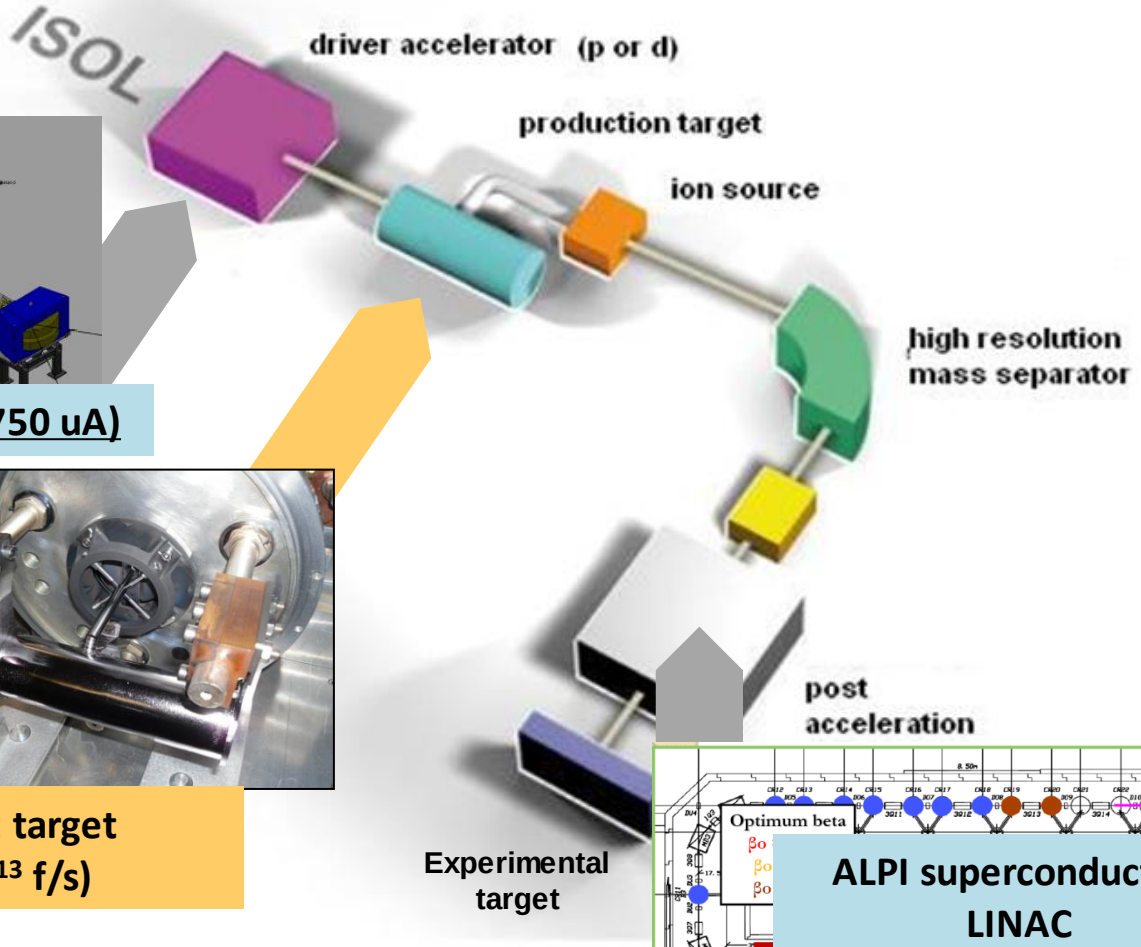


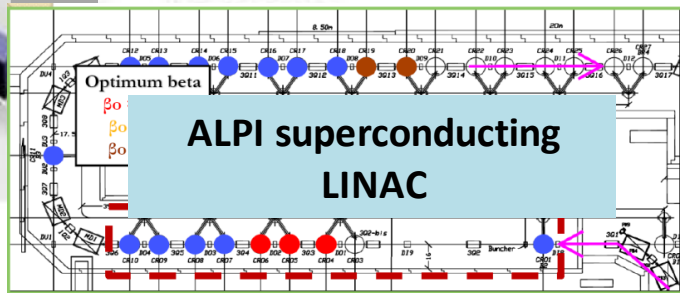
Cyclotron p-driver (30-70 MeV, 750 uA)



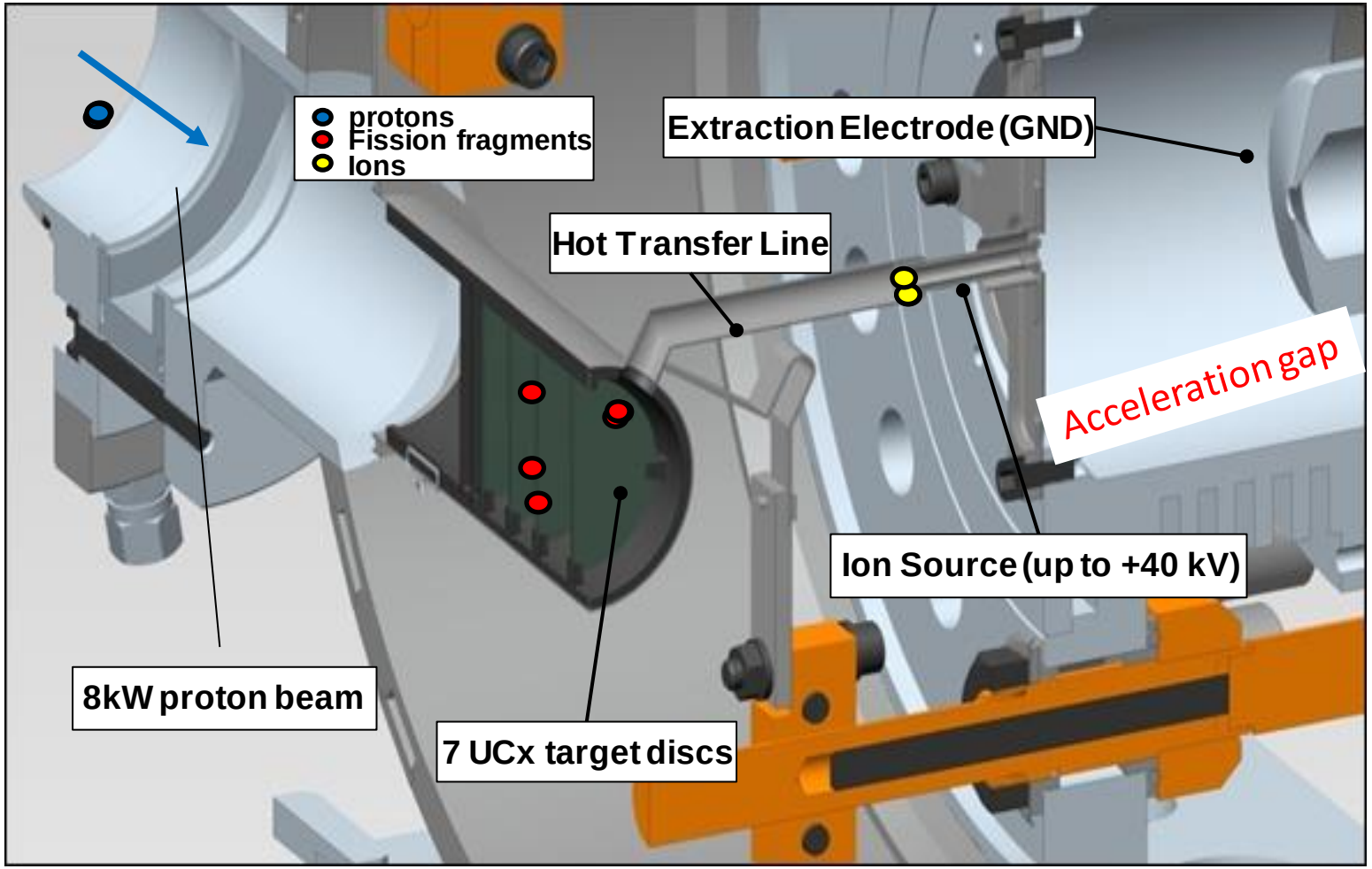
NEW CONCEPT: direct target multi-foil UCx (for 10^{13} f/s)

Beam commissioning expected in 2019





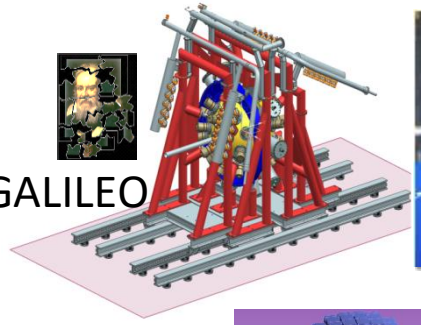
Target-Ion-Source Complex

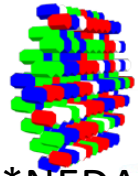


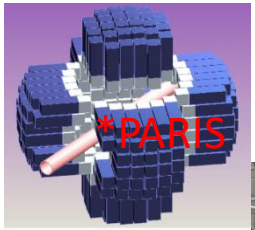
47 Letters of Intents were presented, from international collaborations

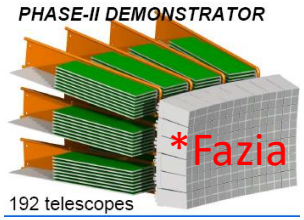
SPES LOIs Topics

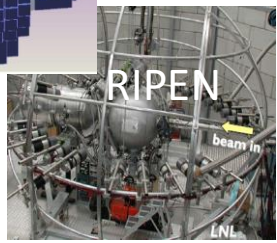
- GS properties
- moments
- Coulex
- DirReac with ActiveTarget
- DirReac with Si
- Mn transfer



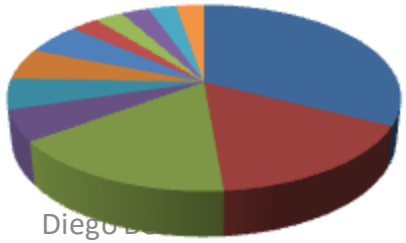




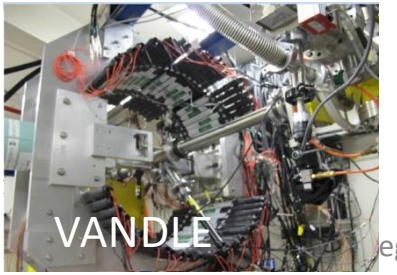


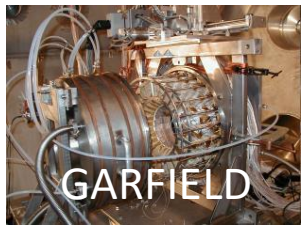


SPES LOIs Spokespersons

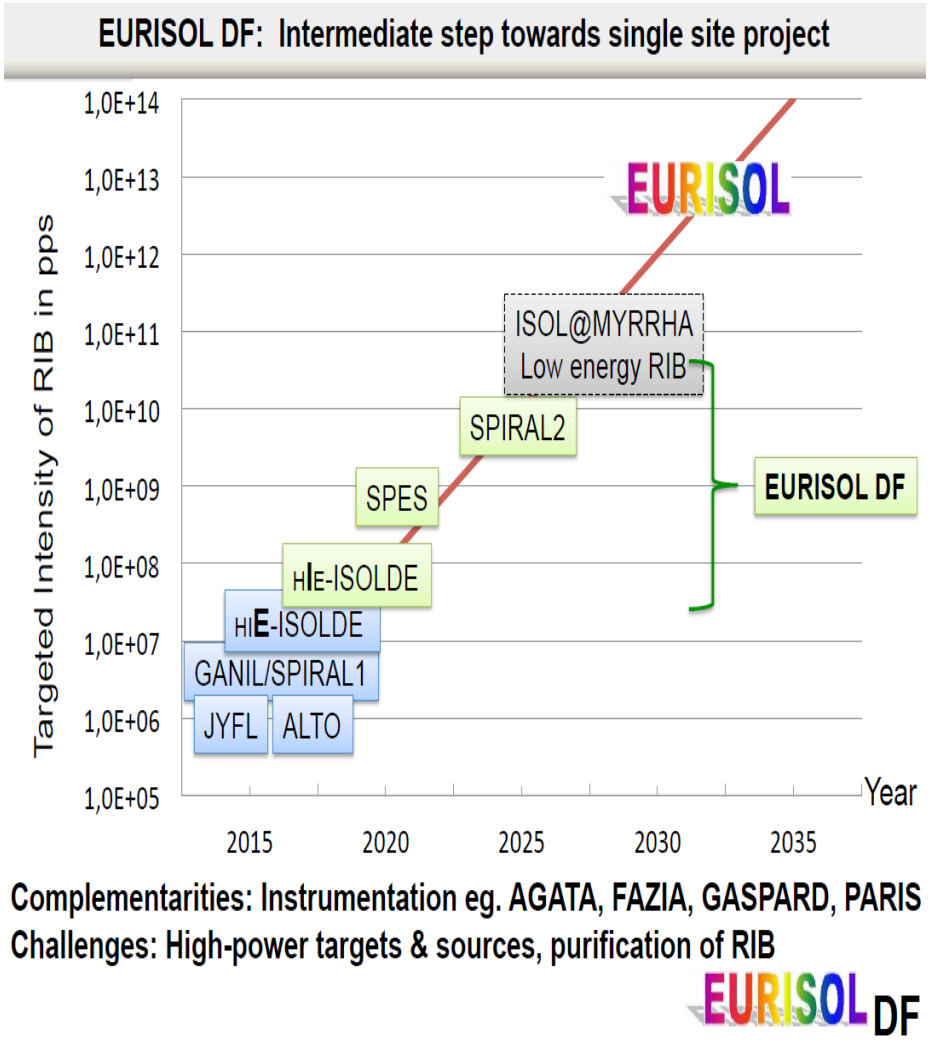


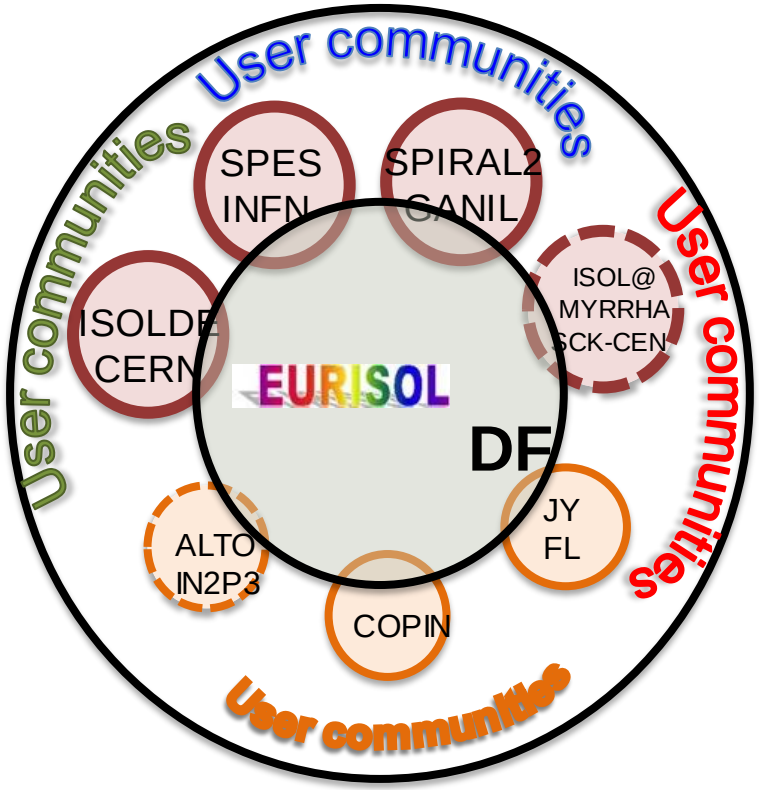
- Italy
- France
- Poland
- Russia
- USA
- Belgium
- Croatia
- Norway
- Bulgaria
- Spain
- Russia
- China





EURISOL Distributed Facility

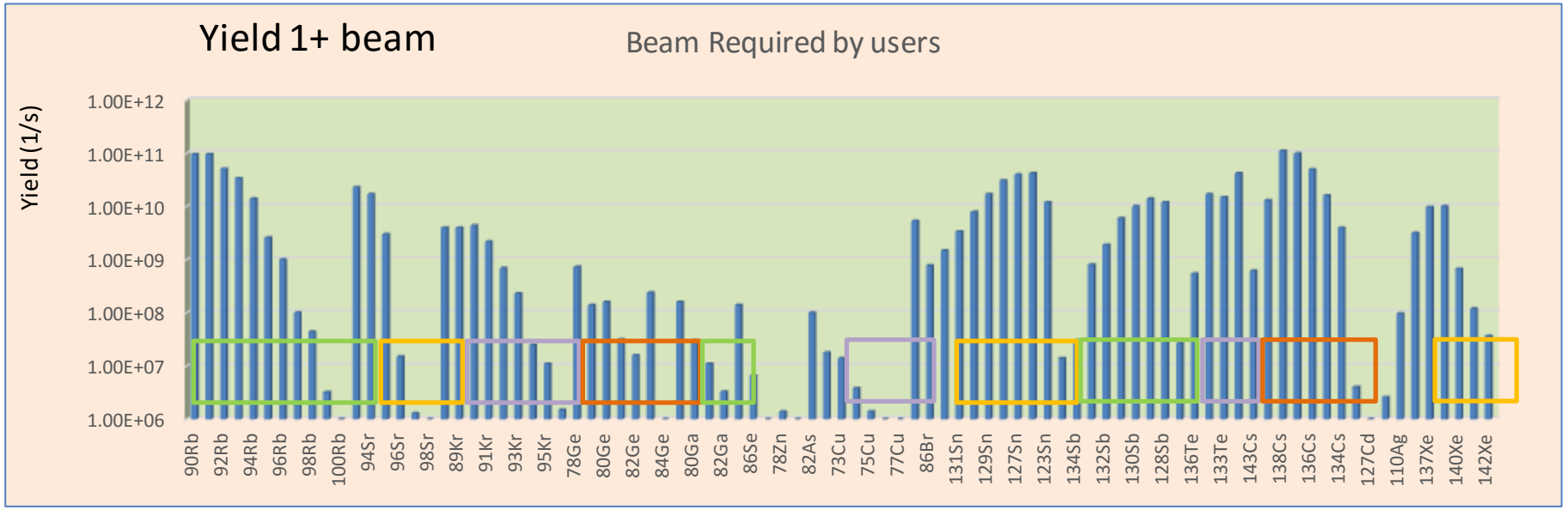




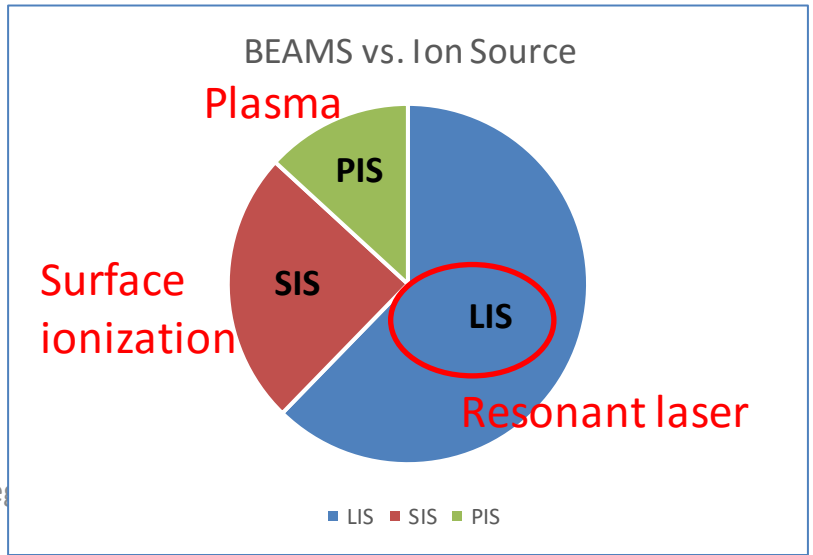
- A **distribute laboratory** for radioactive beams:
- **More exotic beams** available
- **Coordination of competences** to face EURISOL technologic challenges
- **Joint effort** to manage the activity at European level

LOI n-rich Ribs…

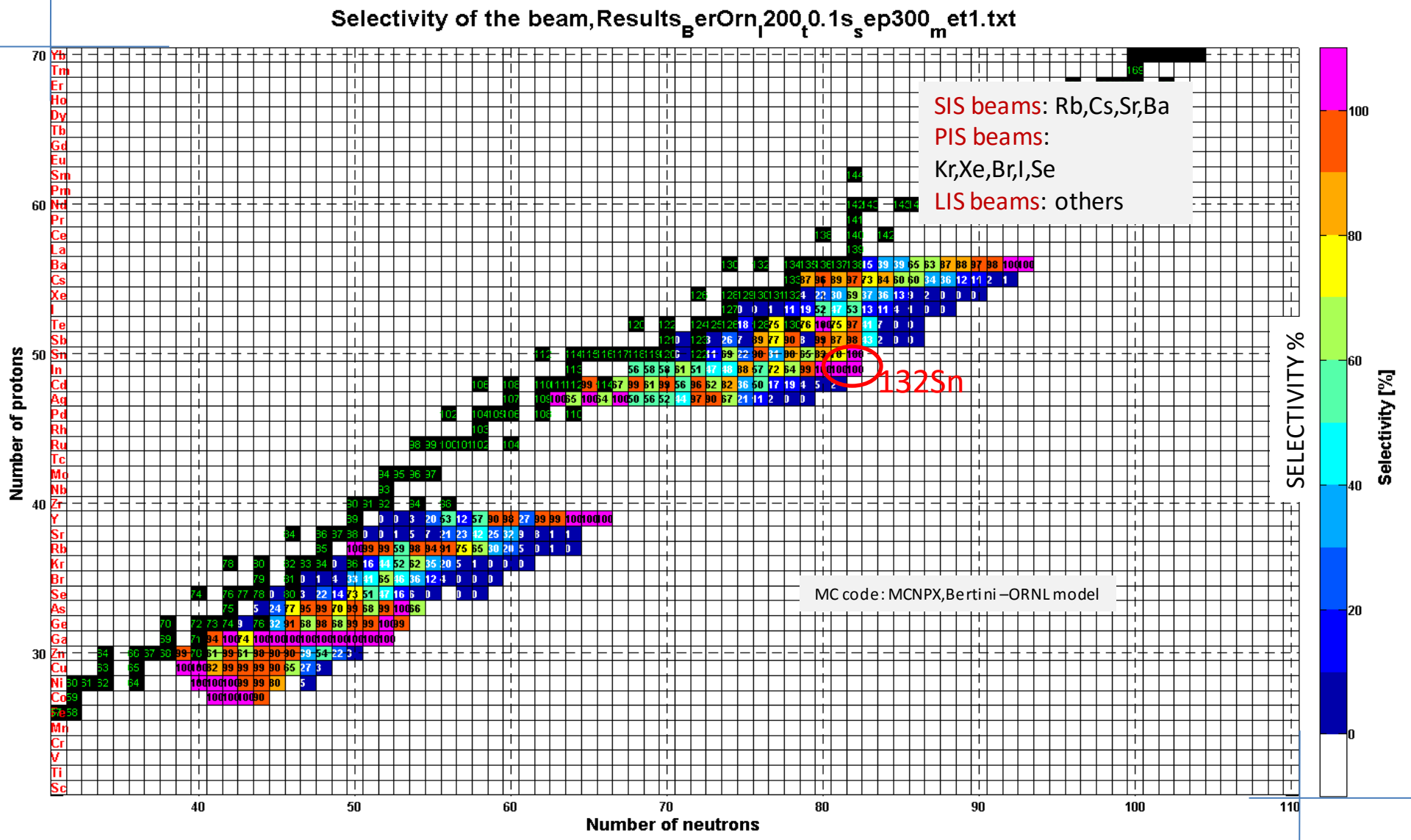
Path toward beam selectivity: **Reaction** → ion-source → mass separation



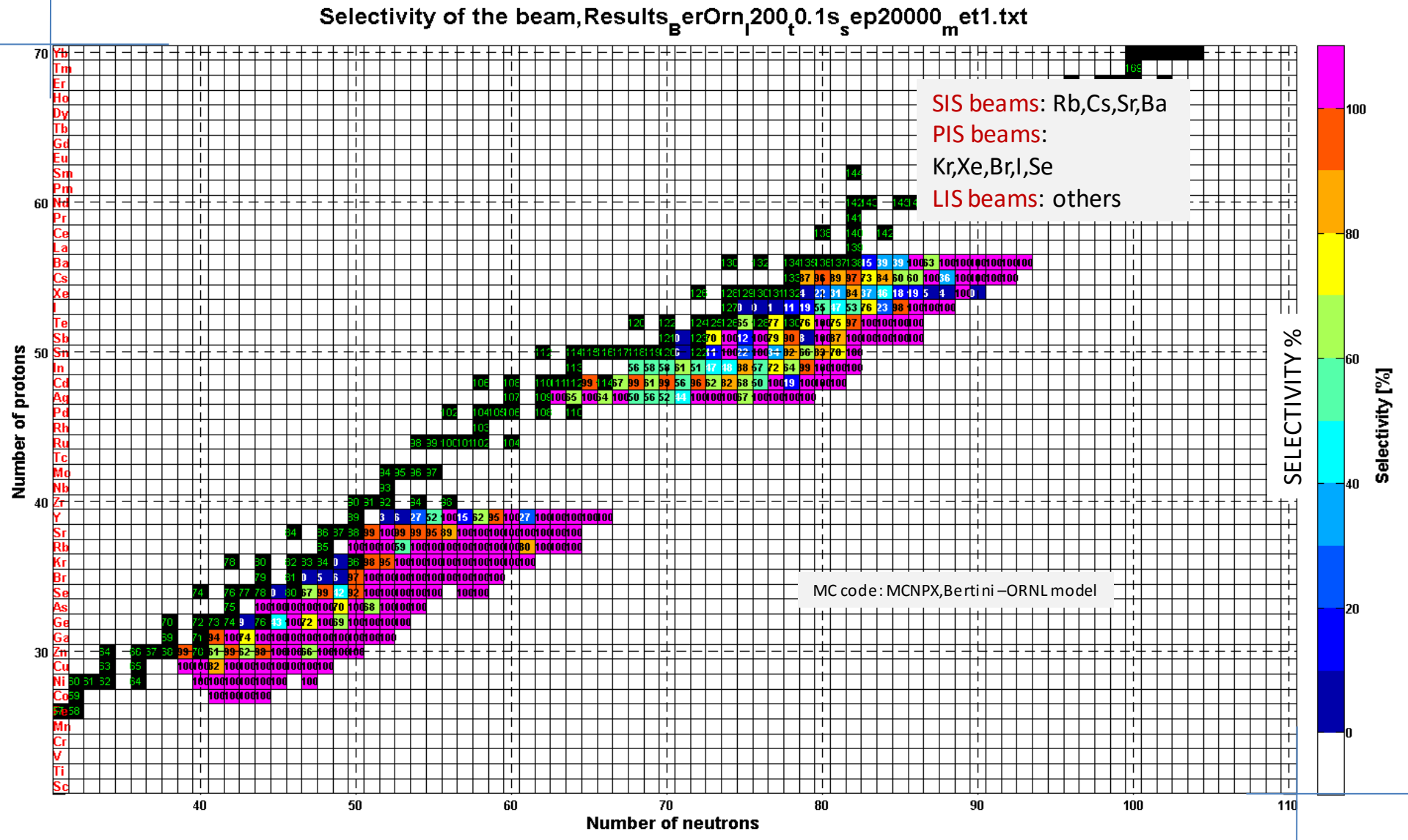
		19 Elements	
Total beams	89		LOI %
Beams with 200_LRMS	47		53%
Benefit with 5.000_HRMS	3	→ 50 beams	56%
Benefit with 10.000_HRMS	17	→ 67 beams	75%
Benefit with 15.000_HRMS	25	→ 82 beams	92%
Benefit with 20.000_HRMS	7	→ 89 beams	100%



Beam Selectivity with LRMS (1/200)



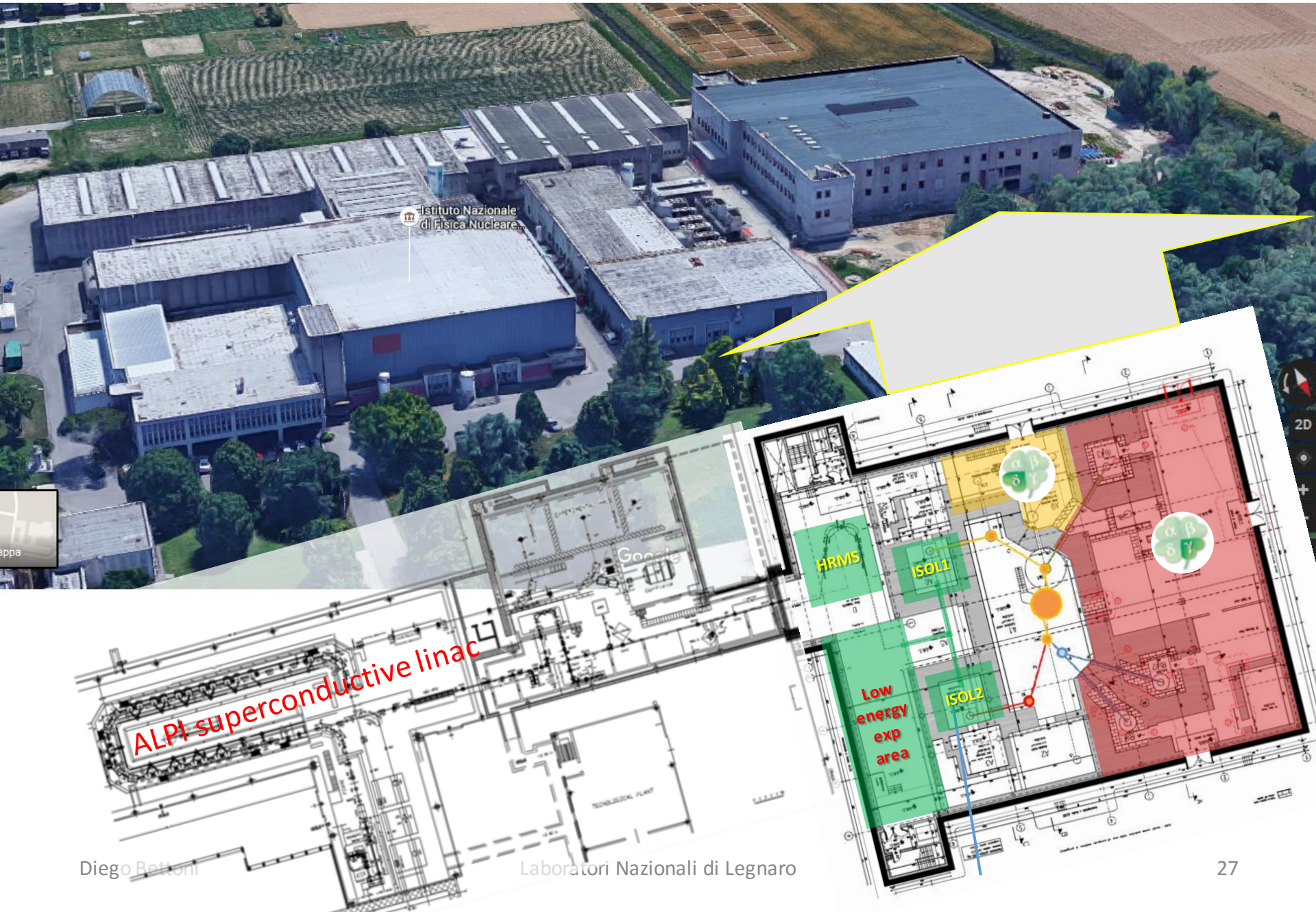
Beam Selectivity with HRMS (1/20.000)



First Beams at SPES

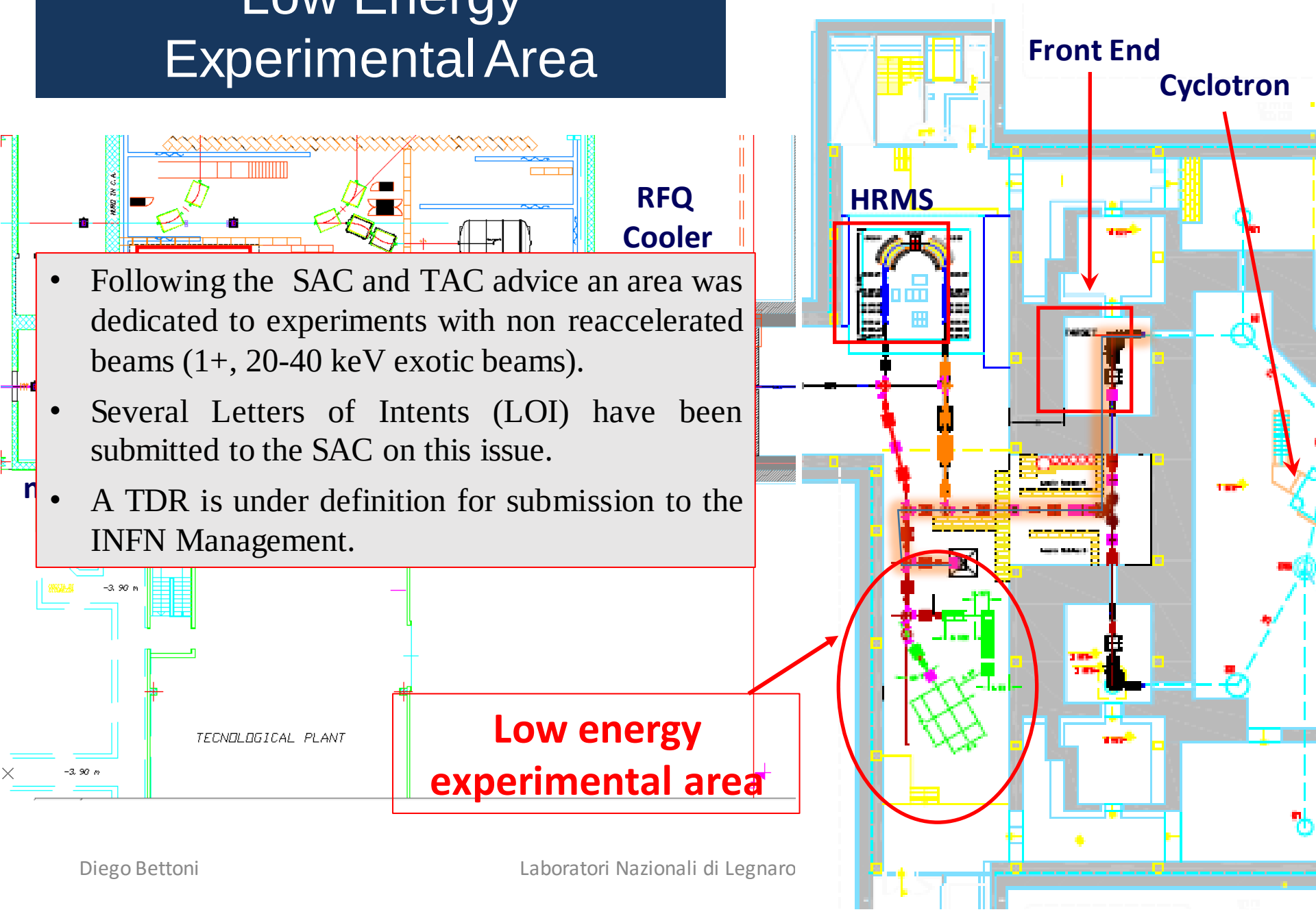
	beam	selection LRMS	target	source	note
RIB commissioning at SPES	26Al		SiC		LOI for reacceleration
	26Si		SiC		LOI for reacceleration
Beams at high selection	83Ge	100	UCx	LIS	LOI for 1+
	84Ge	100		LIS	LOI for 1+
	80Ga	100		LIS	LOI for 1+
	83Ga	100		LIS	LOI for 1+
	110Ag	100		LIS	LOI for 1+
	132Sb	100		LIS	LOI for reacceleration
High request (10 LOI)	132Sn	100		LIS	LOI for reacceleration
Medium request (5 LOI)	132Te	100		LIS	LOI for reacceleration
Medium request (5 LOI)	130Sn	83		LIS	LOI for reacceleration
Medium request (5 LOI)	134Te	97		LIS	LOI for reacceleration
Medium request (4 LOI) easy beam	94Rb	75		SIS	LOI for reacceleration
Easy beam	91Rb	100		SIS	NO LOI
	92Rb	100		SIS	NO LOI
	138Cs	76		SIS	LOI for reacceleration

SPES infrastructure - layout



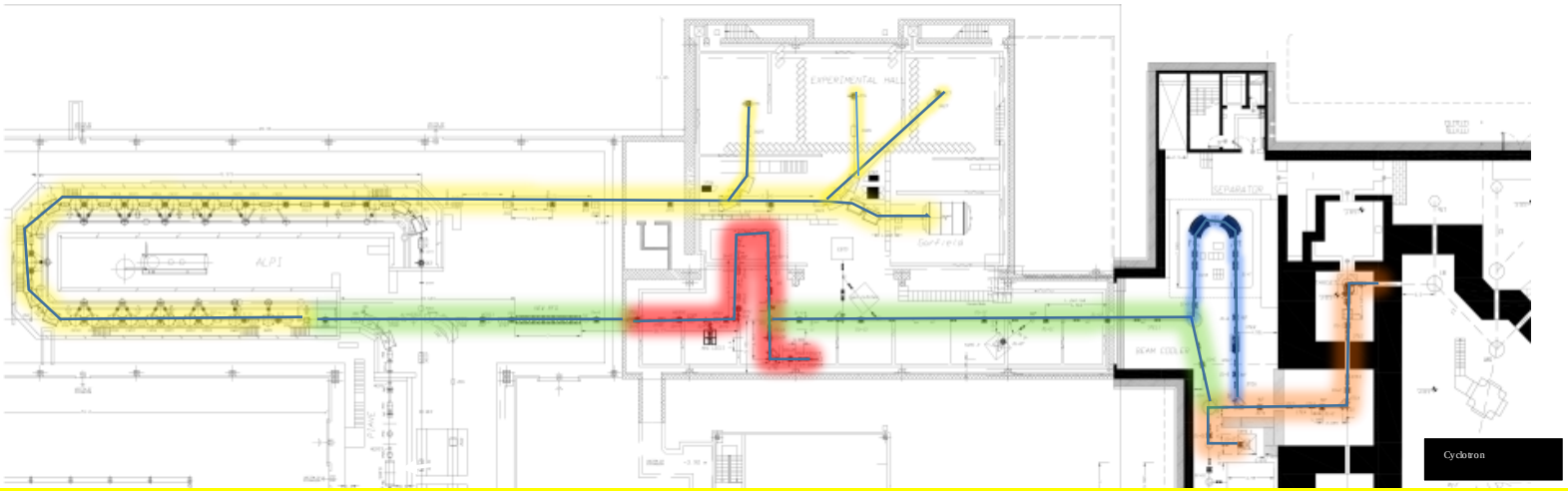
SPES Layout: ISOL Facility

Low Energy Experimental Area



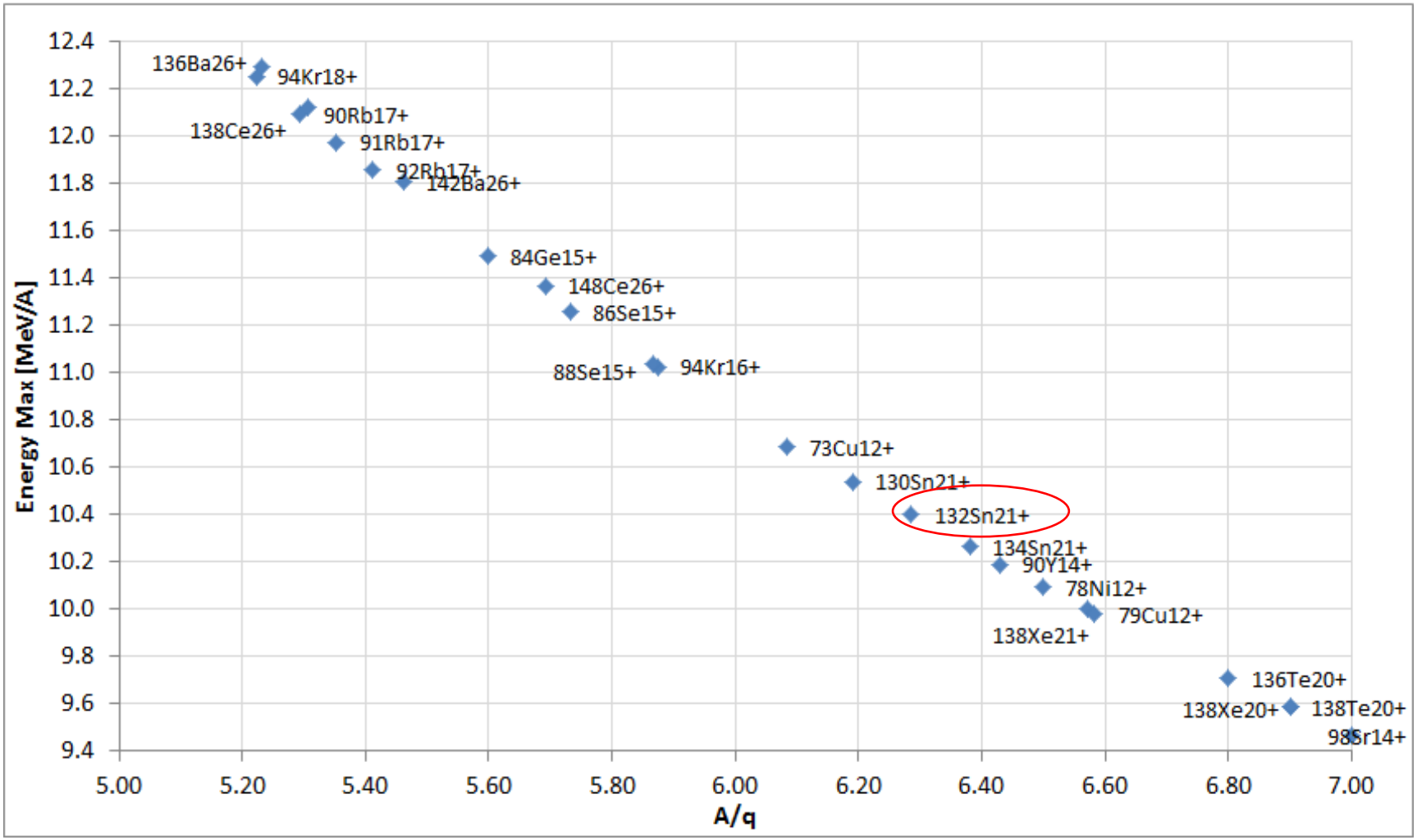
- Following the SAC and TAC advice an area was dedicated to experiments with non reaccelerated beams (1+, 20-40 keV exotic beams).
- Several Letters of Intents (LOI) have been submitted to the SAC on this issue.
- A TDR is under definition for submission to the INFN Management.

Installation phases



- ✓ installation of Charge Breeder and related mass separator: ready in 2018
- ✓ installation of ISOL and 1+ beam line up to the tape station: ready in 2019
- ✓ Radioactive Low energy beams: ready in 2020
- ✓ Installation of RFQ and 1+ beam line up to Charge Breeder: ready in 2020
- ✓ Reaccelerated beams: ready in 2021

Expected SPES reaccelerated beams



Energy from SPES Post-Accelerator as function of A/q

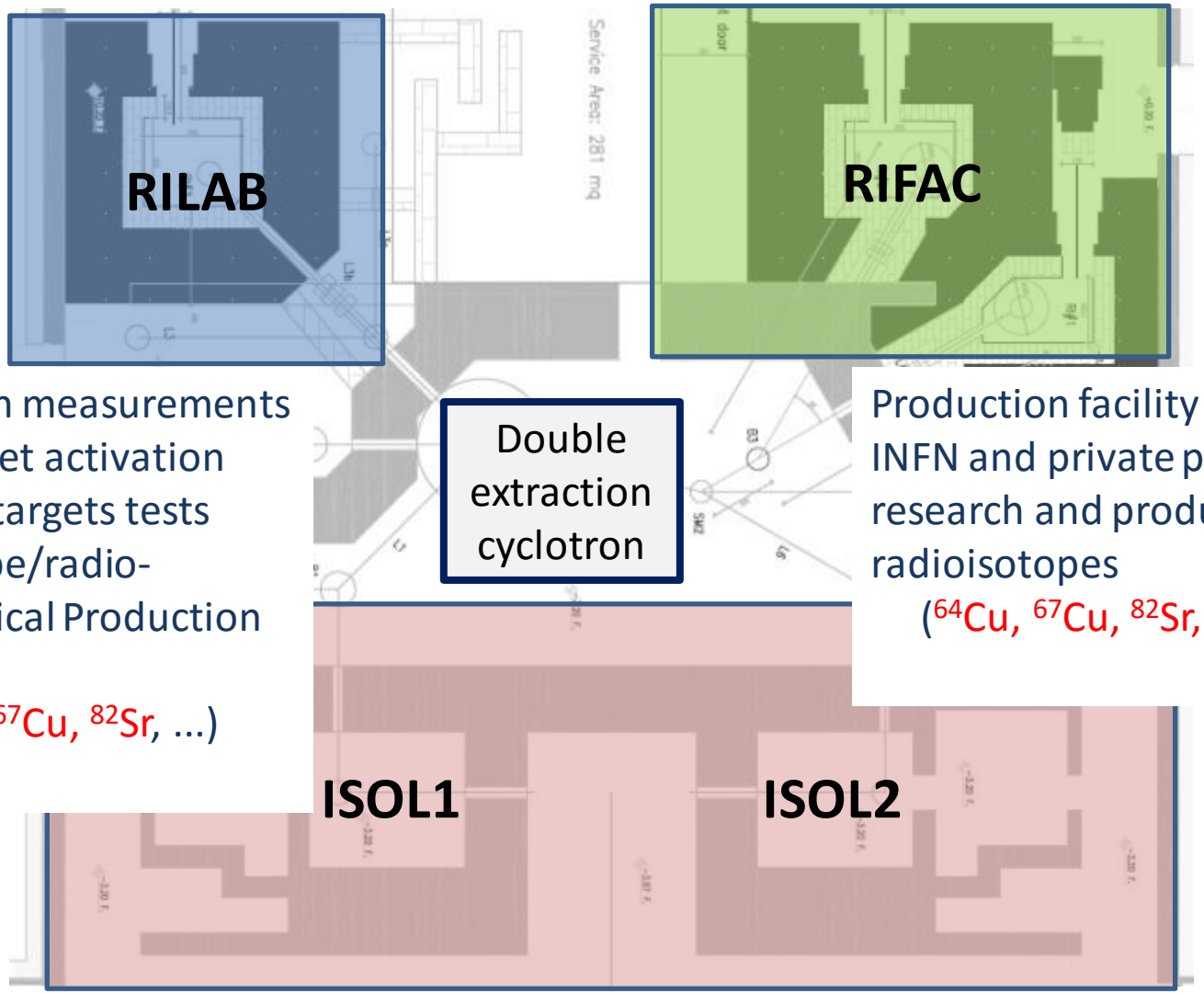
ISOL facility installation phases: main milestones

2017				2018				2019				2020				2021			
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
	FASE 2A: INSTALLATION						FASE 2A: HW COMM	FASE 2A: BEAM COMM	Charge breeder and MRMS Operation and test										
								FASE 3A: INSTALLATION				FASE 3A: HW COMM		FASE 3A: BEAM COMM					
			FASE 2B: INSTALLATION					FASE 2B: HW COMM	FASE 2B: BEAM COMM	FASE 2B: RIB COMM									
								FASE 3B: INSTALLATION		FASE 3B: HW COMM		FASE 3B: BEAM COMM				FASE 3B: RIB COMM			

SPES-γ Radioisotopes for Nuclear Medicine

Research

Production

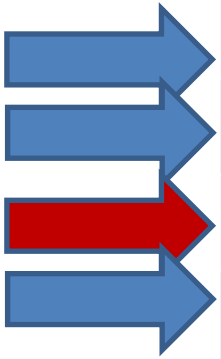


- Cross Section measurements through target activation
- High power targets tests
- Radio-isotope/radio-pharmaceutical Production test facility
  (^{99m}Tc, ^{64}Cu, ^{67}Cu, ^{82}Sr, ...)

Double extraction cyclotron

Production facility operated by INFN and private partner for research and production of radioisotopes
(^{64}Cu, ^{67}Cu, ^{82}Sr, ^{68}Ge, ...)

LARAMED
LAboratory for RAdioisotopes for MEDicine



Radioisotope	Half-life
Fe-52	8.3 h
Cu-64	12.7 h
Cu-67	2.58 d
Sr-82	25.4 d
Ge-68	270.8 d
I-124	4.18 d
Ac-225	10 d

LARAMED Research Projects

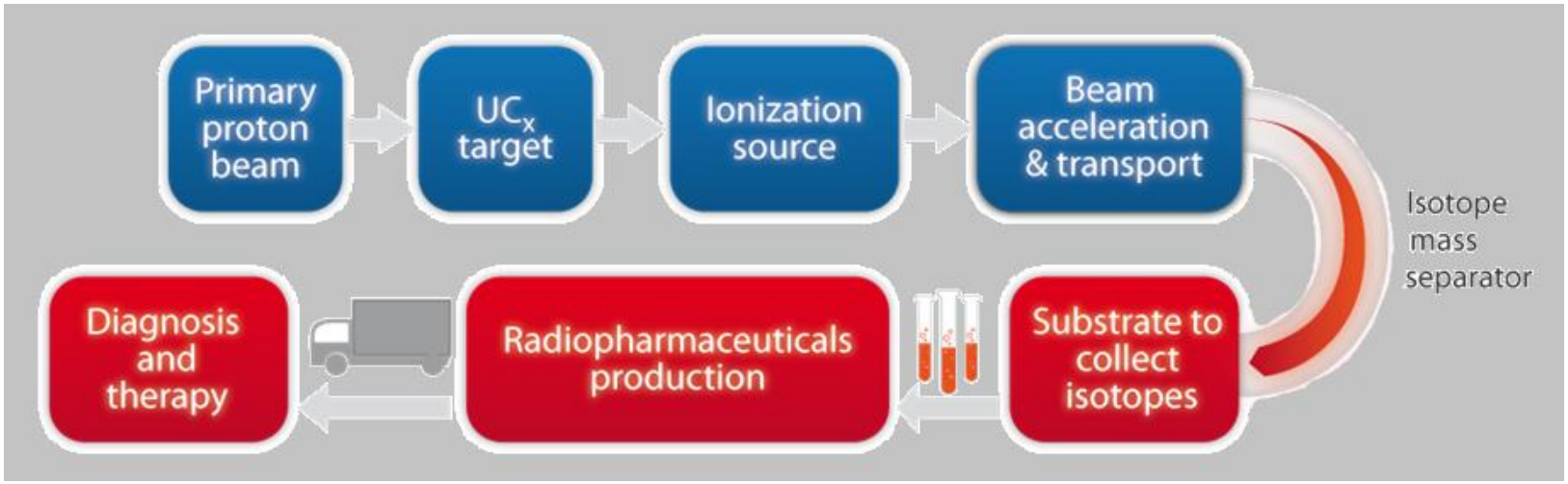
Activity	Project name
Accelerator-Tc99m alternative (direct) production route through hospital cyclotrons	APOTEMA/TECHN-OSP (2012-2017)
Alternative Cu-64/Cu-67 production for theranostic application	COME (2016)
Alternative Sc-47 production for theranostic application	PASTA (2017-2018)
Participation to the IAEA ' Coordinated Research Project ' (CRP) on Cu-67, Re-186 and Sc-47 alternative production	CRP (2016-2019)
Participation to IAEA ' Coordinated Research Project ' (CRP) on Mo-99/Tc-99m alternative production	CRP (2011-2015)

ISOLPHARM

Use of ISOL technique for Direct isotope on-line separation : very high specific activity (10^{4-5} than standard)

ISOLPHARM

High specific activity radio**PHARM**aceuticals production with **ISOL** technique



⟶ HUGE SPECIFIC ACTIVITY

ISOL** technique leads to the production of **radioactive ion beams

(Isolpharm is a international INFN patent)

Specific activity: ISOL *vs* others

The **specific activity** is a measure of the **activity per mass** and is usually expressed in units of GBq/mg or Ci/mg.

Essential for the radioisotope conjugation to *in-vivo* carriers for targeted drug delivery

Radiopharmaceutical	Targeted organs	Half-life	Specific Activity (GBq/mg)	
			ISOLPHARM technique 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	Prostate, 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

Radiopharmaceutical	Targeted organs	Half-life	Specific Activity (GBq/mg)	
			ISOLPHARM technique production	^{235}U fission
^{133}Xe	Lung and liver	5.25 d	**≥ 6920**	≥ 3

After 2 days of irradiation: 4.1E+15 atoms of ^{89}Sr = 18 mCi (patient dose: 4 mCi every 6 months).

SPES-δ Multidisciplinary Neutron Source

- Accelerator based neutron sources have many applications: Nuclear astrophysics, Characterization of nuclear waste, BNCT...
- The cyclotron can also be used as a neutron source
- The high-intensity TRASCO RFQ LINAC (30 mA) and energy up to 5 MeV in the development phase at LNL, originally considered as SPES injector, can also be used as an intense neutron source.

Conclusions

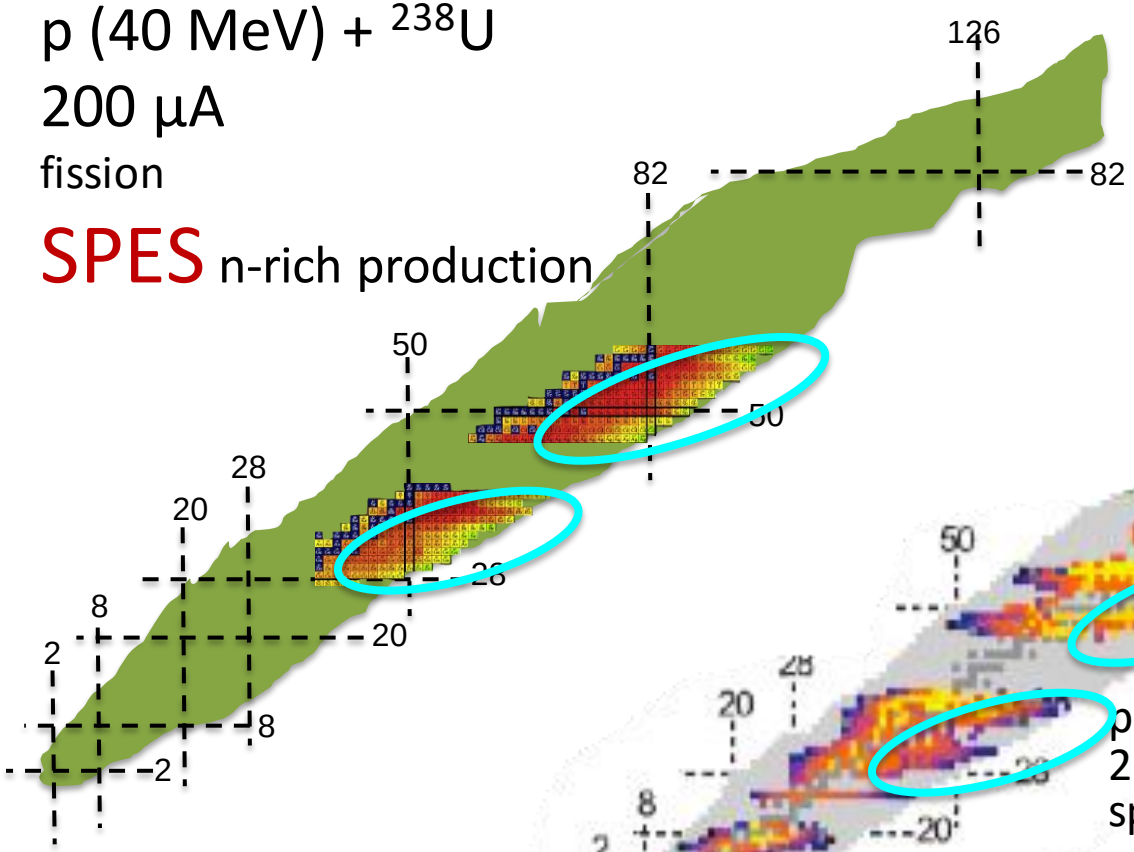
- SPES is in the construction phase
- Infrastructure and cyclotron are completed
- In the next two years the ISOL system and the Charge Breeder will be installed
- In 2019 radioactive ion beams with no reacceleration will be available
- Reacceleration will be completed in 2021 using ALPI to reach 10-11 MeV/N

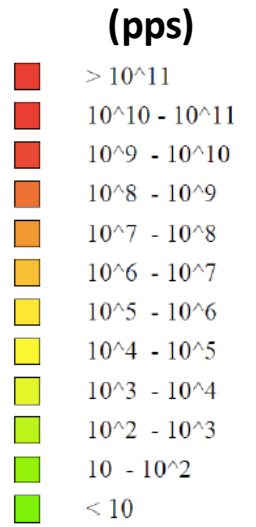
Backup

Comparison SPES vs. ISOLDE

p (40 MeV) + ^{238}U
200 µA
fission

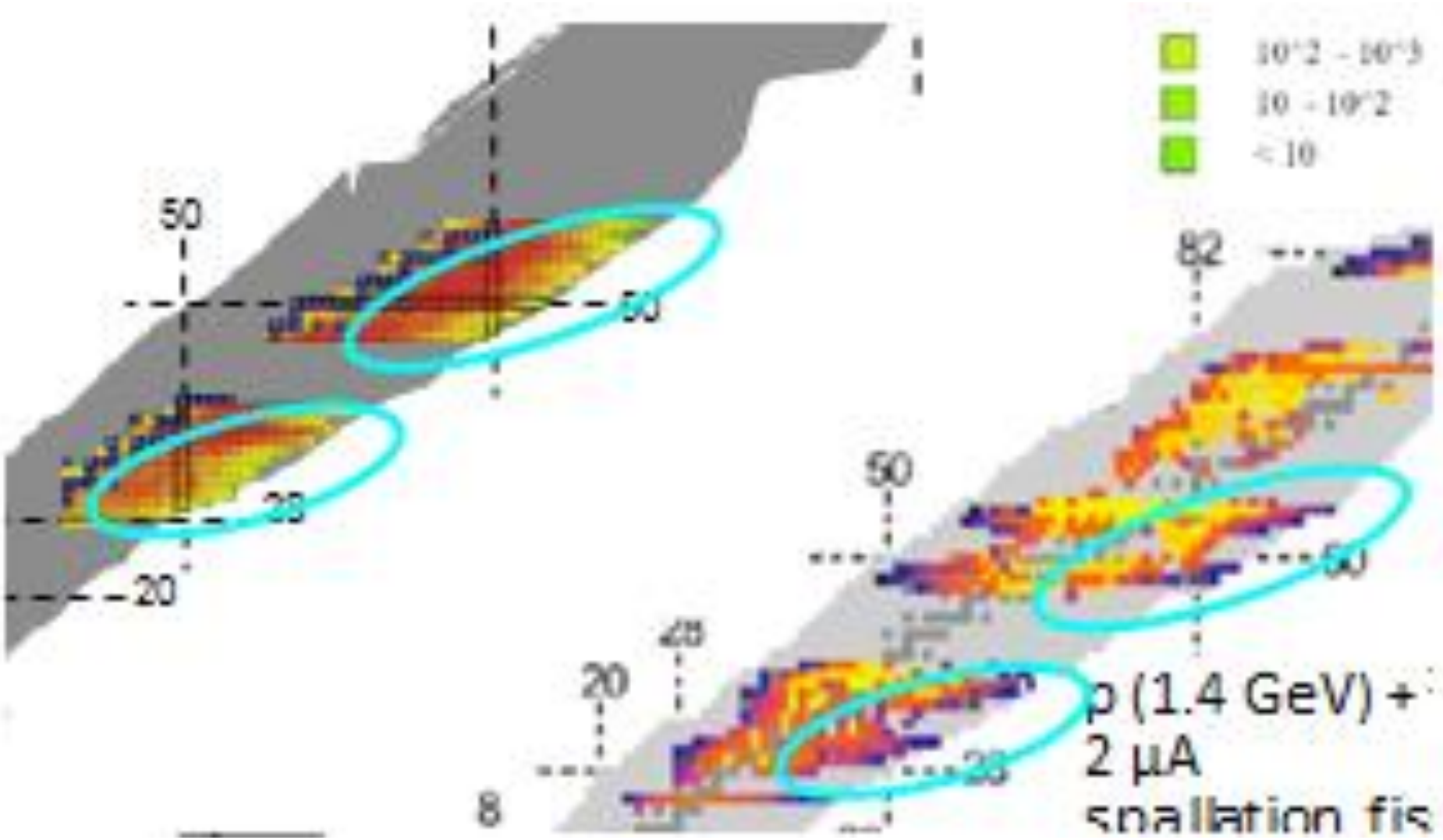
SPES n-rich production



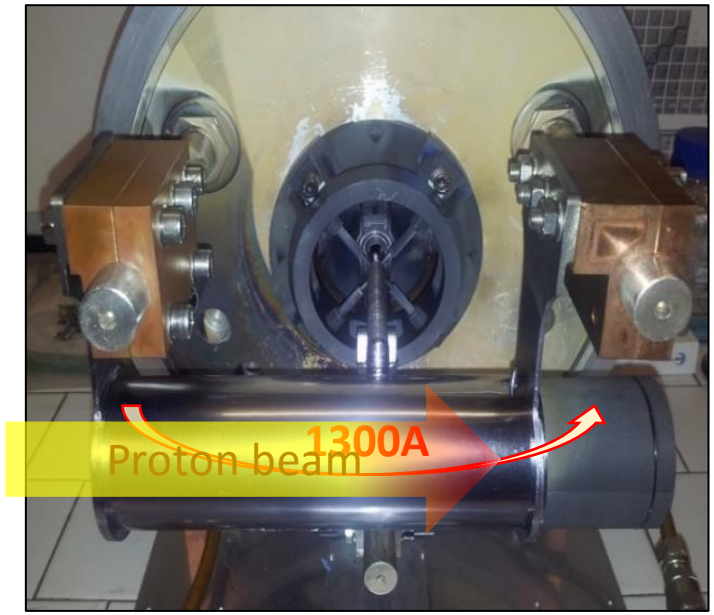


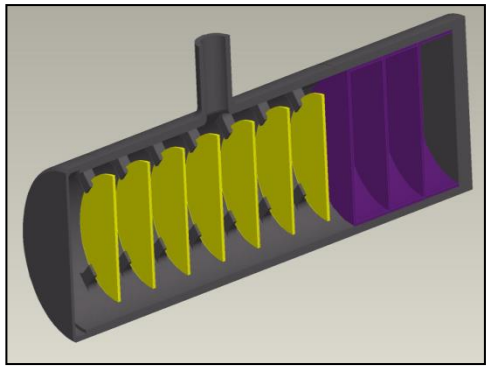
p (1.4 GeV) + ^{238}U and others target
2 µA
spallation, fission, fragmentation

ISOLDE total production


10^2 - 10^3
10 - 10^2
< 10
50
50
28
20
82
50
50
20
28
8
p (1.4 GeV) +
2 μA

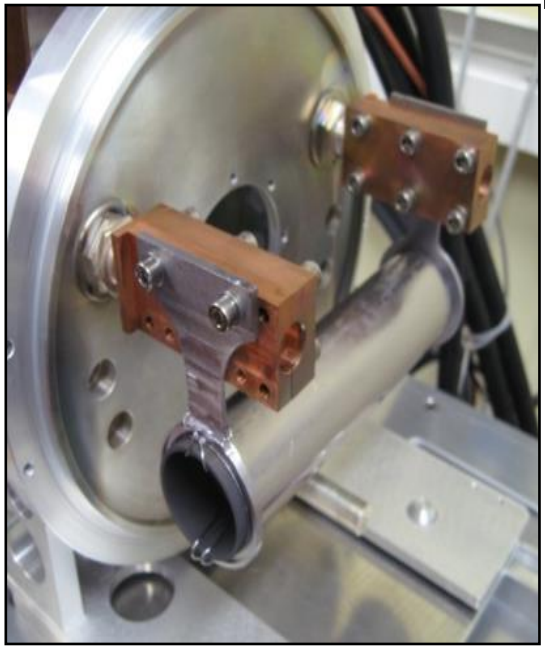
SPES Target ion-source system

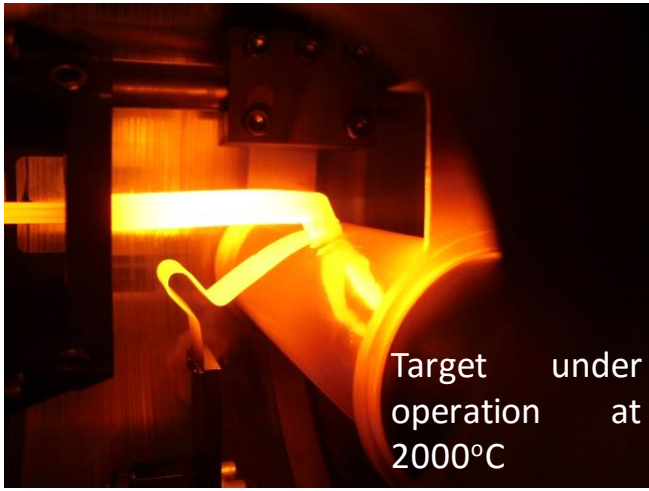




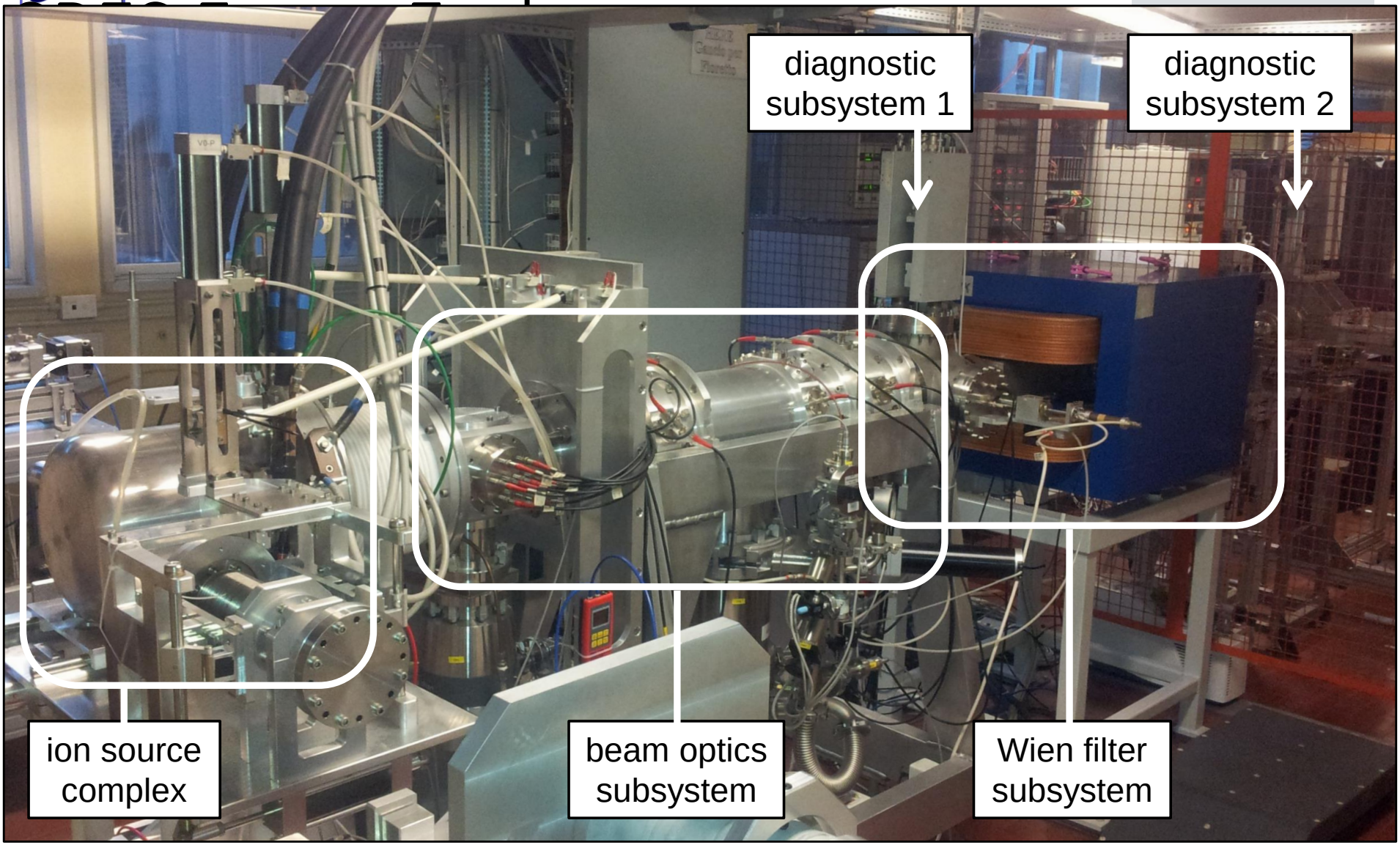
Target container: operating temperature 2000-2300 °C

Heathing: balance between proton beam and Ohmic current





SPES ISOL system

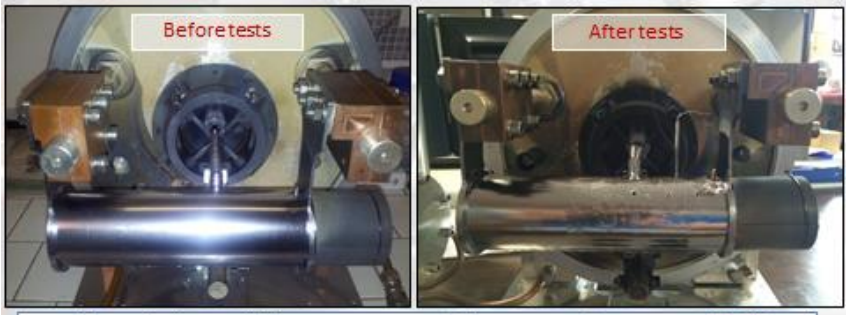


System under operation for source commissioning.
Updated version (radiation hardness improved) under construction.

ISOL system developments

TIS unit endurance test:

Tests at high temperature with Joule heating thermal load (1300A target heater, 350A line):
heating power ≈ 12 kW > primary proton beam thermal load (≈10 kW)



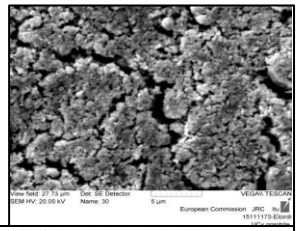
- ≈ 415 testing hours at high temperature -> ≈ 220 hours at maximum power (12kW)
- 79 heating cycles sustained -> 9 with current ramps of 1 s from 0 A to 1300A (!)
  to 350A (!)

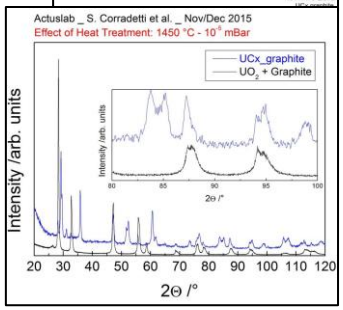
TIS UNIT STILL OPERATIVE !!

SPES TACS October 2015 WG-01

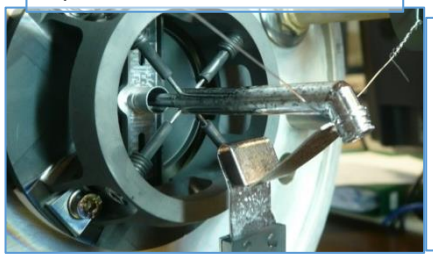
Synthesis of a novel type of UC_x using graphene

Experiment at JRC-ActUsLab-Karlsruhe: n. AUL-176





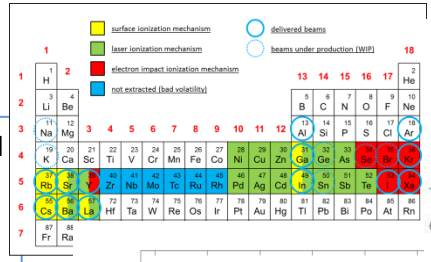
Surface ionization source:
≈ 60 heating-cooling cycles
≈ 380 h (16 days) of
operation at 2000-2200°C



Plasma source: optimized to avoid hot-spot and to maximize current
New alignment system
≈ 40 heating-cooling cycles
≈ 160 working hours @ 2000°C

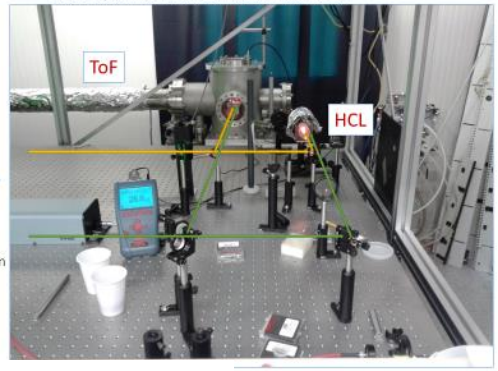
M.Manzolaro, A.Monetti, M.Lollo, M.Rossignoli

Laser Source

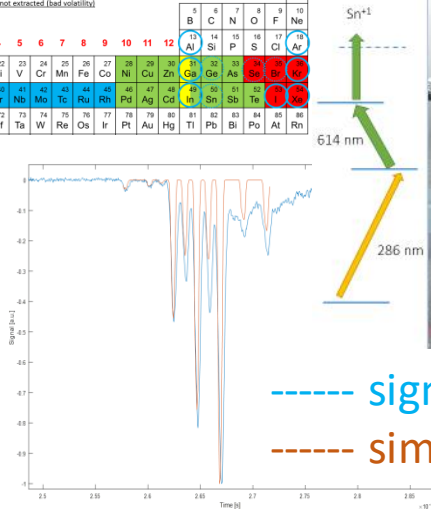


HCL + ToF on Tin laser ionization

Double system to check laser resonant ionization:



WG-03

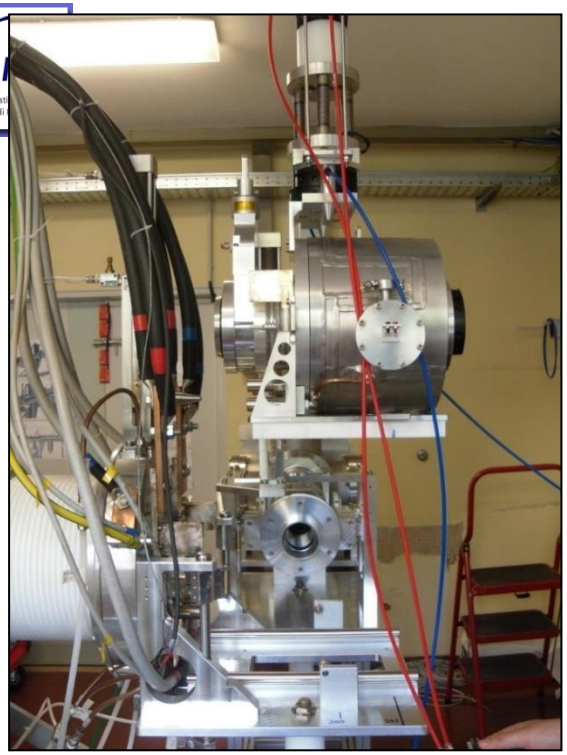


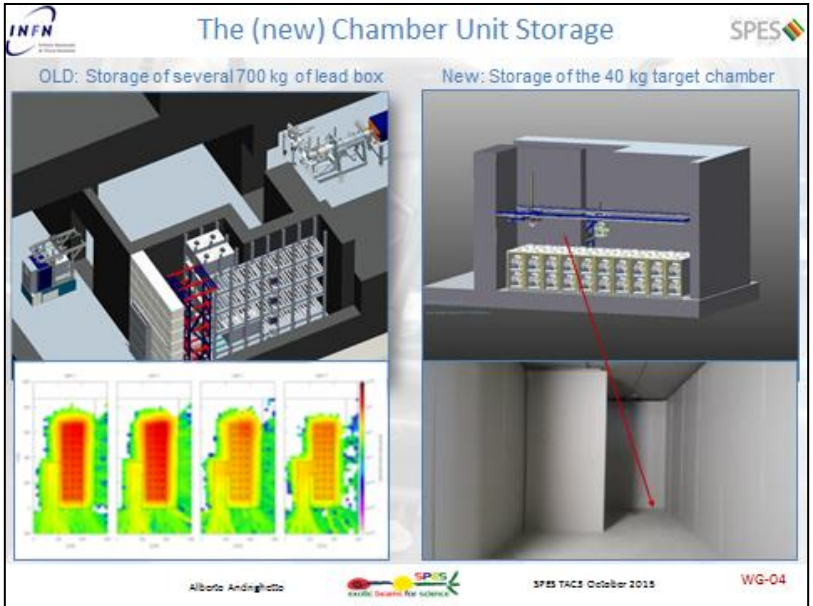
------ signal
------ simulation

Daniele Scarpa

AGV **test** at LNL

- Movement test in automatic mode
- Experimental tests with 3 transponder





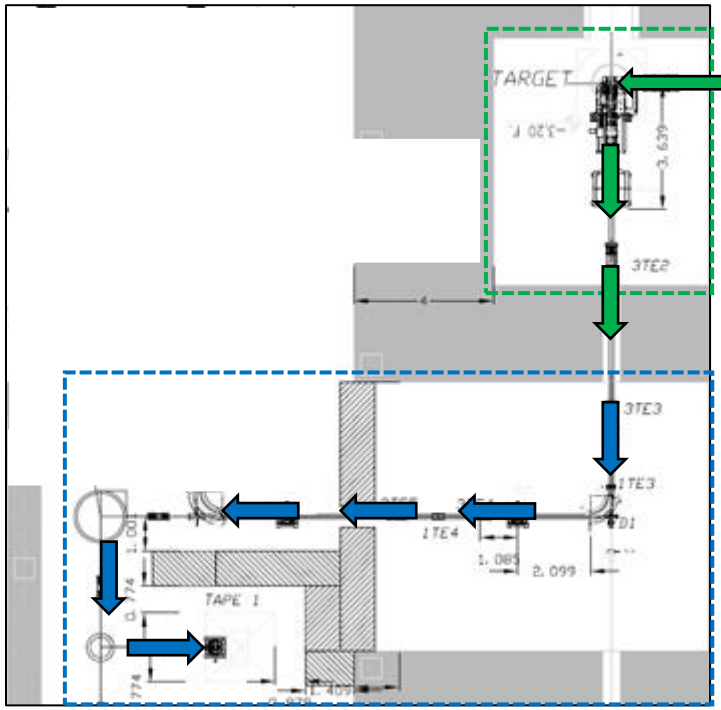
$^{82}Sr/^{82}Rb$

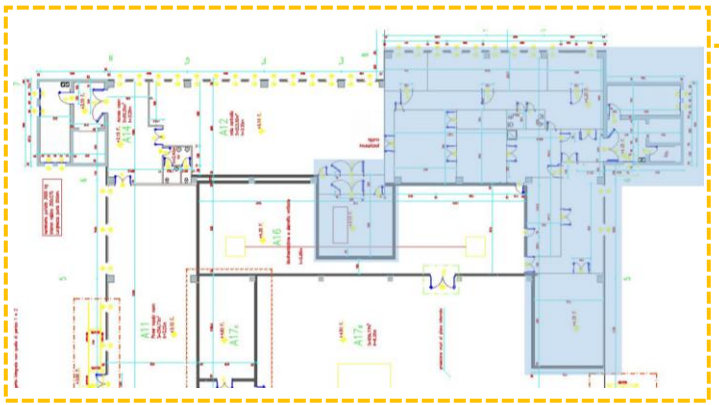
- The ion Rb^+ is a biologic analog of K^+, fundamental in the heart cell operation.
- Once administered by intravenous injection, Rb+ is assembled in the myocardium and, when sustituted with a γ emitter radioisotope, **it can be used as tracer to study the cardiac operation.**

Isotope	Sr-82 → Rb-82	
$\tau_{1/2}$	25d	1.27m
EC	100% in Rb82	-
$\beta+$	-	100%
$\beta-$	-	-

- This radioisotope is actually produced in low energy cyclotrons, that do not allow high yields due to low energy and intensities .

ISOL system up to tape station





1) RIB bunker operation

2) LASER installation

3) 1+ beam line operation

4) SPES ISOL laboratories operation

Building and infrastructures (P. Favaron)

within the end of 2019

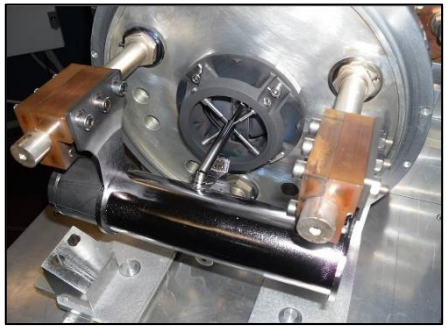
first low intensity and low energy RIB @ SPES (^{26}Al)

(40 MeV 20 µA proton beam > SiC target)

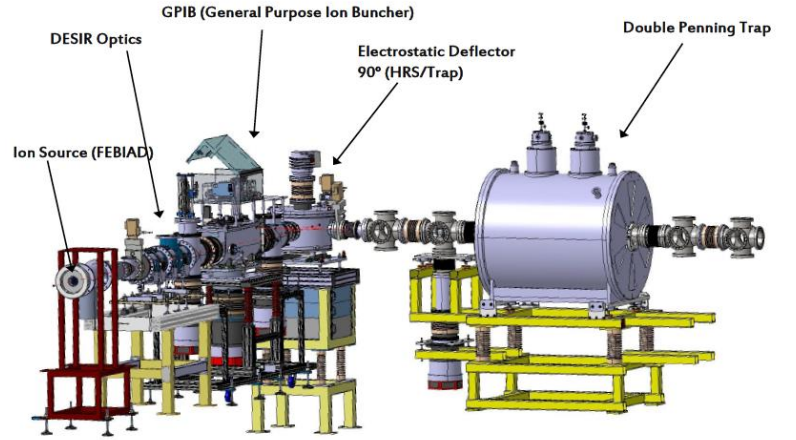
Mattia Manzolaro & Alberto Andrighetto

ISOL production and SPES Low Energy experimental area

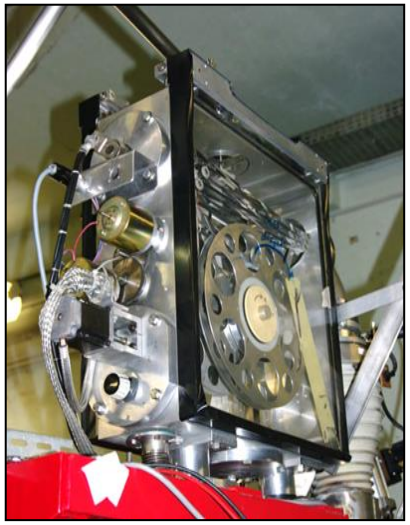
Front end and Target – Ion Source unit

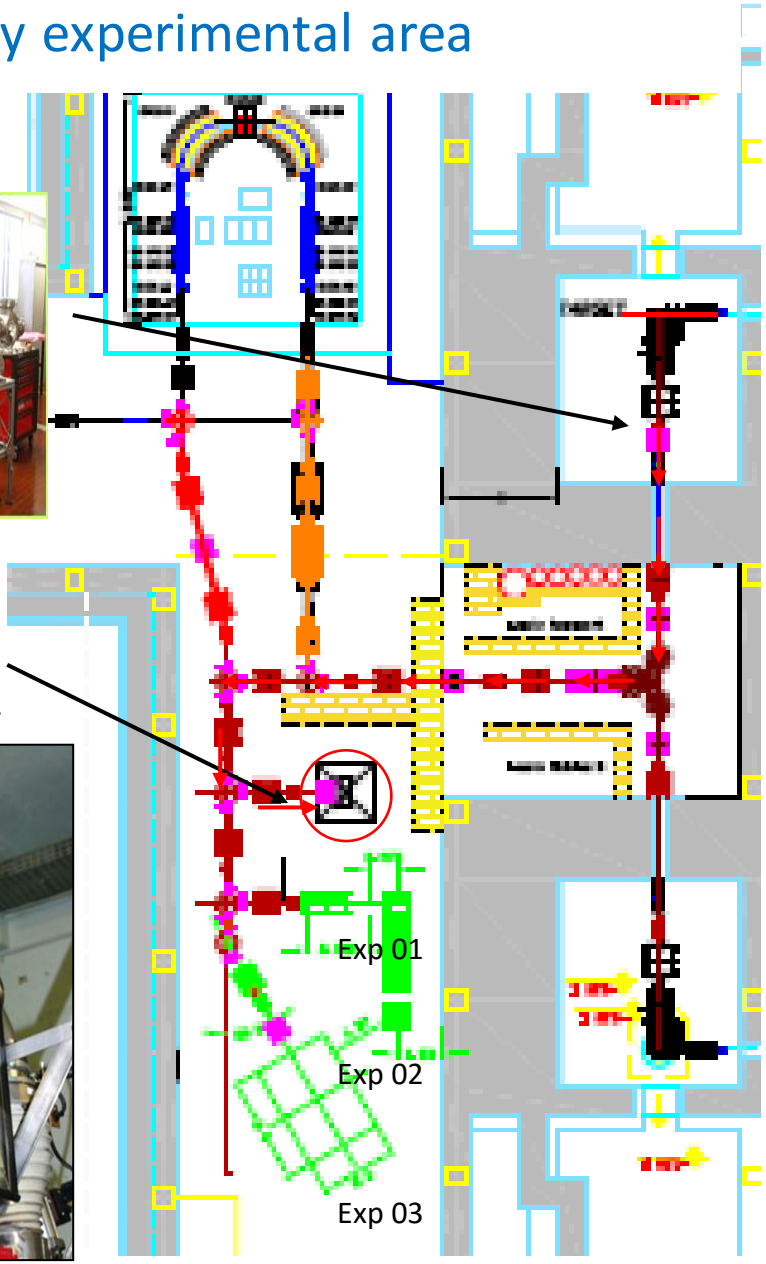


PIPERADE @ CENBG Bordeaux



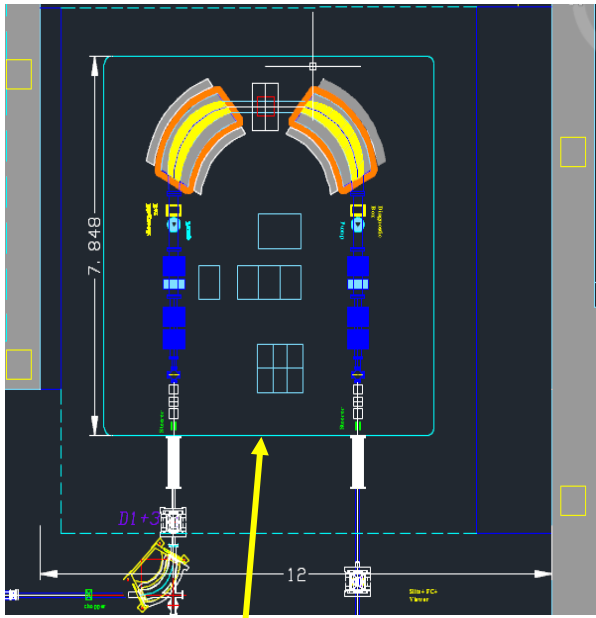
tape station with:
- gamma detectors,
- beta detectors
- neutron detectors



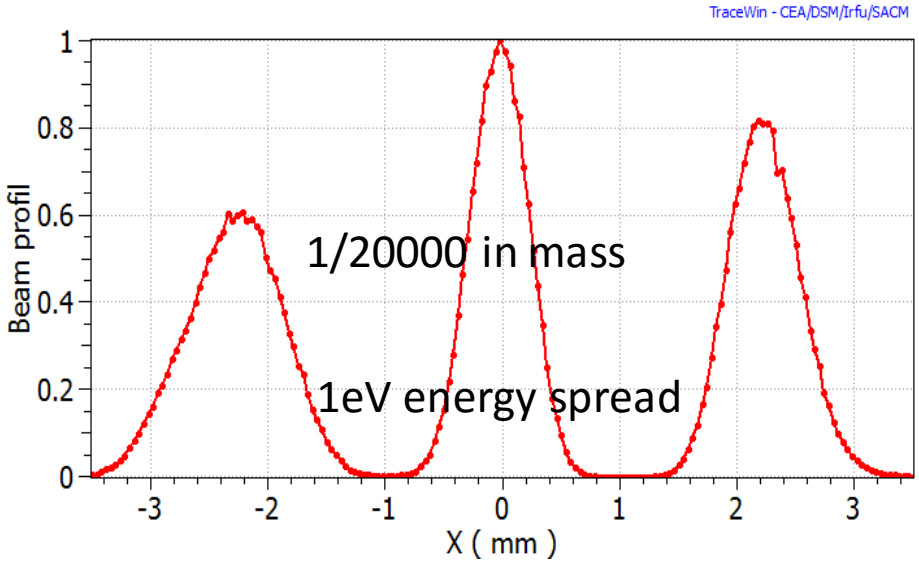


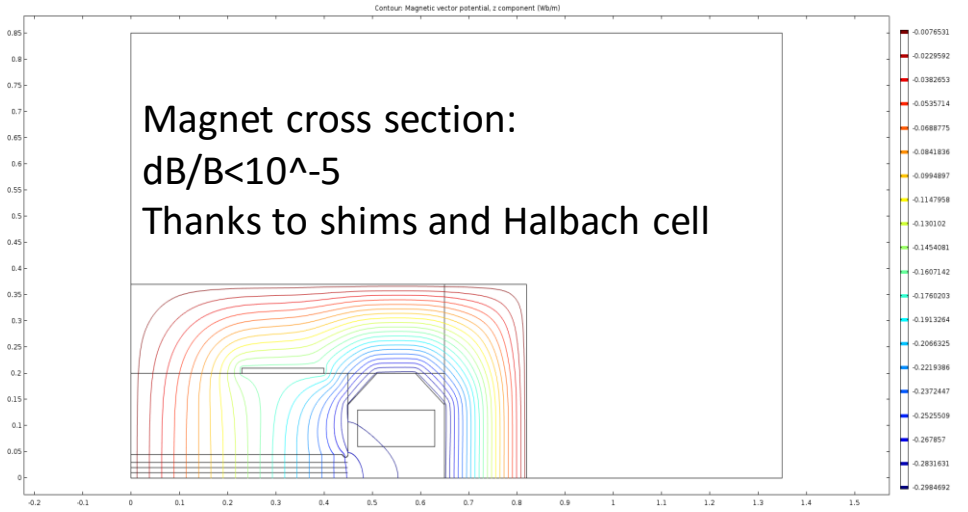
HRMS

- Physical design ready, integration with beam cooler and beam lines under way
- Preliminary dipole design and feasibility check with potential manufacturer done
- Evolution:
  - Critical Design Review in April 2018
  - Authorization to tender October 2018
  - Commissioning 2021



220 kV platform

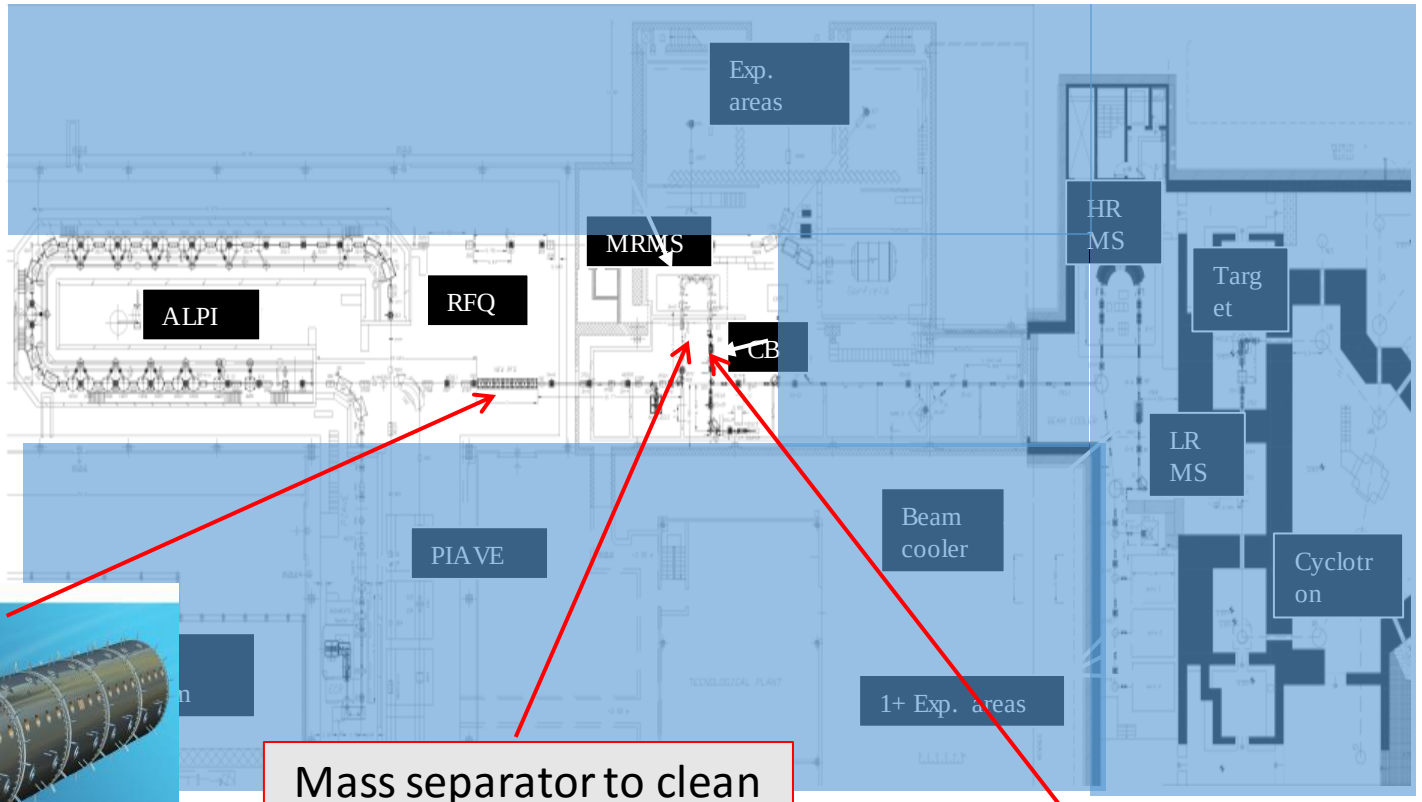


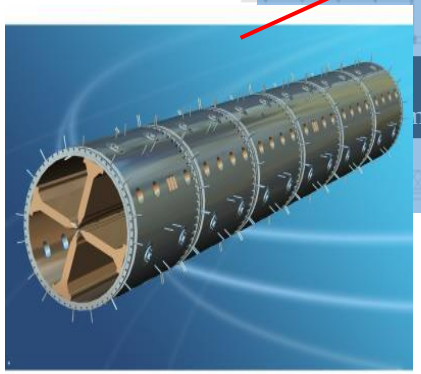


ΔE= ± 1 eV
Emittance $_{rms,n}$ = 0.68 π mm mrad

Collaboration with LPC_Caen for Beam Cooler development (SCIRaC - SPIRAL2)

n+ Beam transport and reacceleration

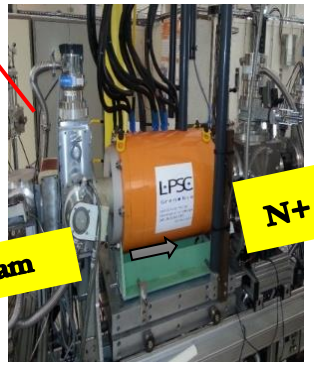




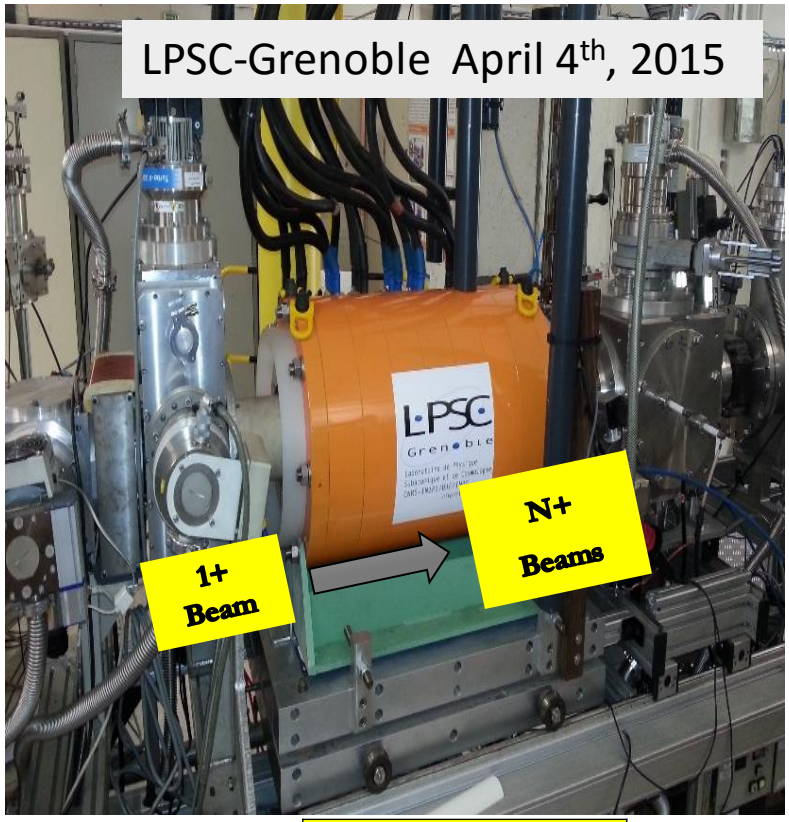
Mass separator to clean the beam from CB contaminants

Pre-accelerator
RFQ (700 keV/n)

ECR_Charge Breeder
from 1+ to n+



Phase 2: Validation of the SPES-Charge Breeder



ION	Q	EFFICIENCY* [%] 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

A.Galatà

Development at LPSC (Grenoble). Upgraded PHOENIX booster as Part of a MoU in the frame of the European Associated Laboratories (LEA-Colliga)

- 2015 Commissioning at LPSC
- 2015 Delivery to LNL
- 2016-17 Installation and test

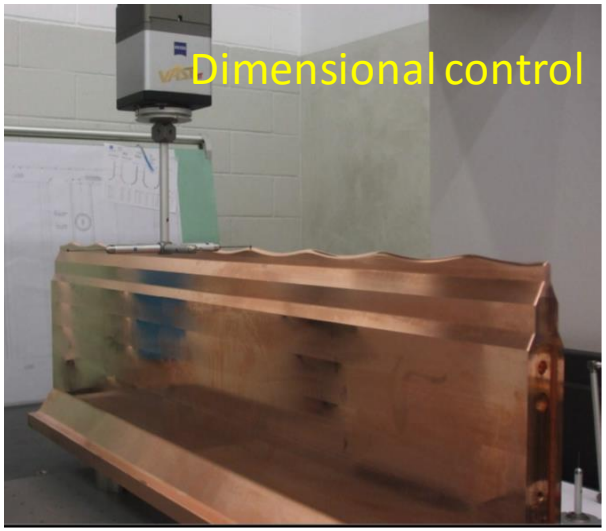
M.Manzolaro

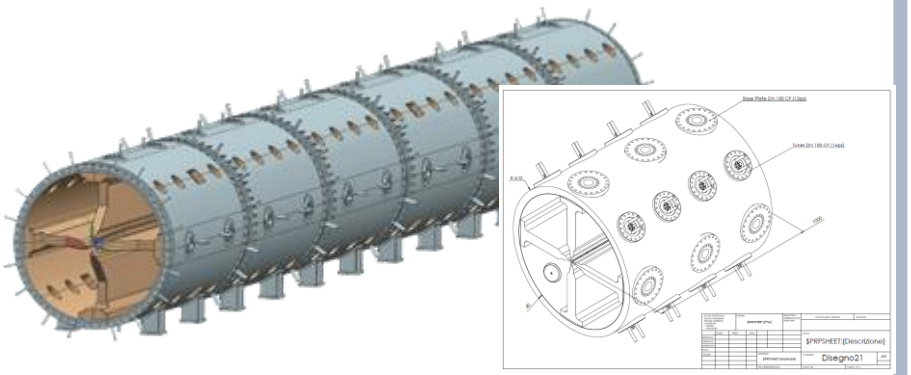
Assembly of 1+Source Front-End

SPES production, similar to ISOL source

Exotic Beam RFQ Injector for ALPI

- Construction of vanes: tender completed in July 2016. Prototype in construction
  - 1st set of 4 electrodes (module 5) was successfuly delivered in April 2017
  - 2st set of 4 electrodes (module 4) was brazed in May 2017
- June 2017: Tender for tank construction





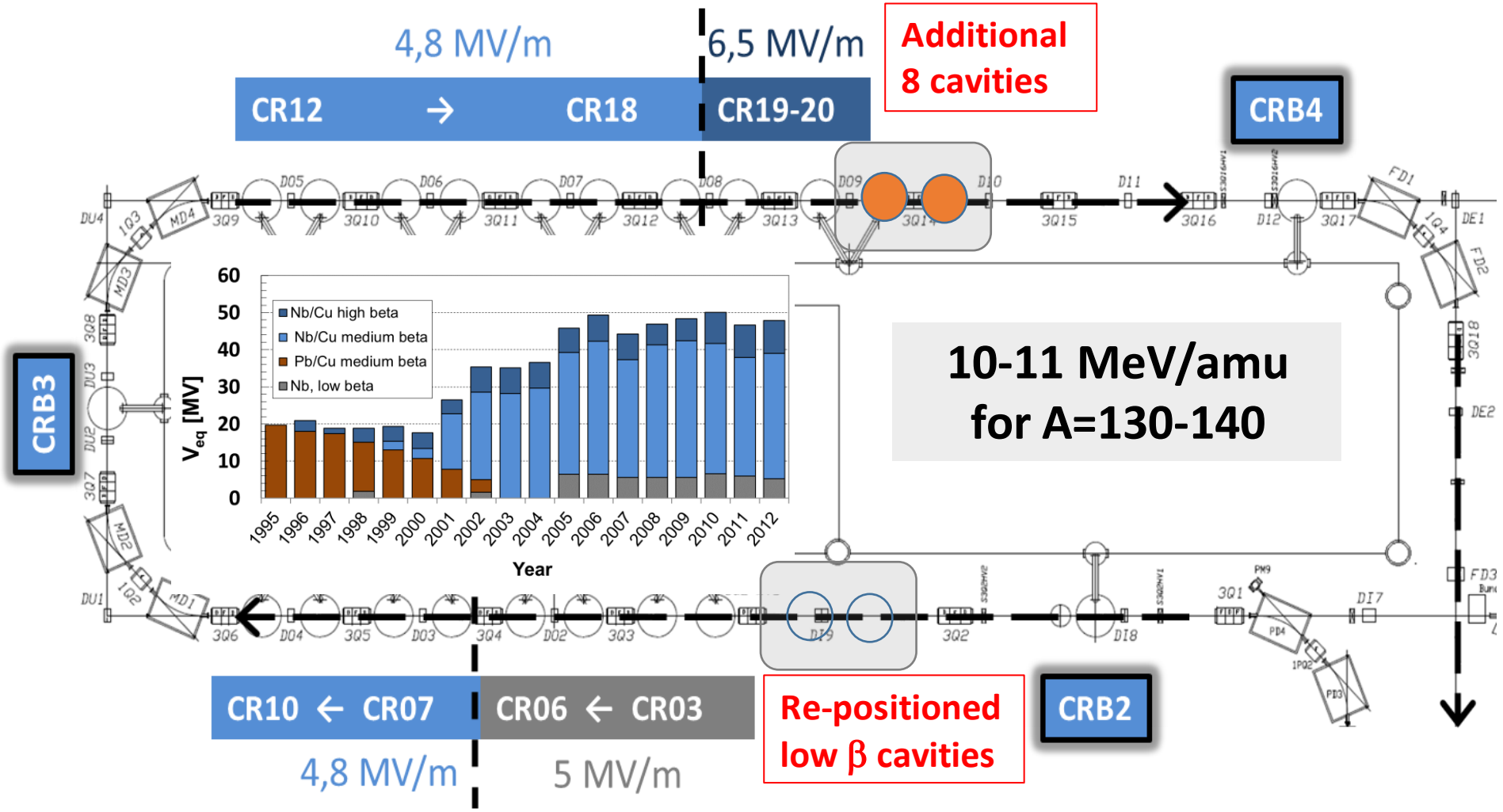
- Energy 5.7 –> 727.3 keV/A [β=0.0395] (A/q=7)
- Beam transmission >93% for A/q=3÷7
- RF power (four vanes) 100 kW (f=80 MHz) for up to 1 mA beam (…future high current stable beams)
- Mechanical design and realization, similar to the Spiral2 one, takes advantage of IFMIF technological experience

IFMIF synergy

200 kW **RF amplifier** (175 MHz→ 80 MHz tuning required);

200 kW **Power Coupler**

Matching into ALPI SC linac



$^{68}Ge/^{68}Ga$

Isotope	Ge-68 → Ga-68	
$\tau_{1/2}$	271d	68m
EC	-	-
$\beta+$	-	100%
$\beta-$	100% in Ga-68	-

- Together with F-18 e C-11, recently, the request of the β^+ emitter radionuclide ^{68}Ga has grown exponentially.
- This interest is based on the fact that Ga-68 proved to be very useful being stably labeled to small peptidic biomolecules , used in the diagnosys of many pathologies of peptide receptor tissues.
- The production, by means of medium-high energy cyclotrons, will provide an effective solution to the problem of availability of the generator nuclide ^{68}Ge, whose production, with the methods used nowadays, is insufficient.

^{64}Cu and ^{67}Cu

- In the last few years a new radiopharmaceutical has been developed, labelled with Cu-64 e Cu-67, that selectively concentrates in hypoxic cells
- The new molecule ([64/67Cu]ATSM) has proved to be particularly useful in **diagnosys and therapy** of prostatic neoplasies, where the tracer [^{18}F]FDG cannot be used.
- A cyclotron of medium-high energy is an effective tool to increase the production yields of Cu-64/67 and, consequently, enhance the availability of [*Cu]ATSM

Isotope	Cu-64	Cu-67
$\tau_{1/2}$	12.7h	2.5d
EC	41%	-
β+	19%	-
β-	39%	100%

[$^{64/67}$Cu]ATSM

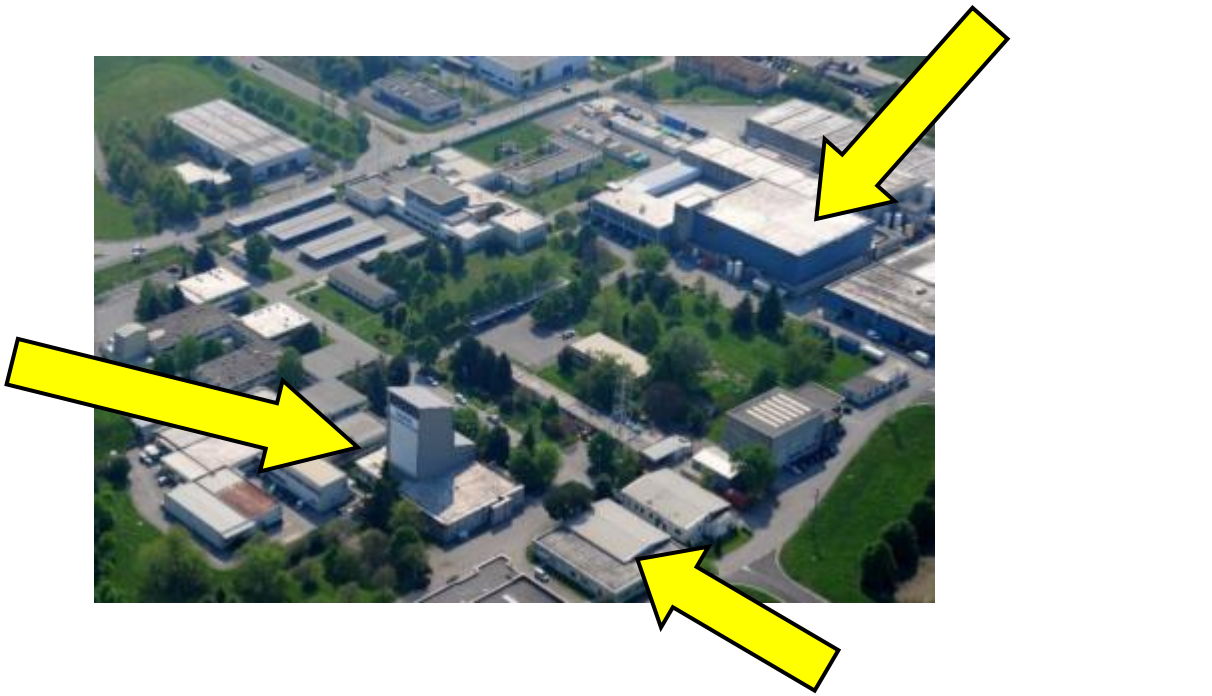
Mo-99/Tc-99m

Isotopo	Mo-99 →	Tc-99m
$\tau_{1/2}$	66h	6h
γ	-	100%
$\beta+$	-	-
$\beta-$	100% in Tc-99 e Tc - 99m	-

- Il Tecnezio 99 metastabile e' usato in 20 milioni di procedure diagnostiche nel mondo ogni anno. Circa l'85% delle procedure di imaging in medicina nucleare utilizzano questo isotopo.
- Prodotto per tutto il mondo in alcuni speciali **reattori nucleari**, ne e' adesso difficile l'approvvigionamento, per la chiusura di alcuni centri di produzione.
- In tutto il mondo si stanno studiano strategie alternative per la produzione di **Tc-99m,** mediante **acceleratori**

Accelerators used for interdisciplinary studies at LNL

- **CN** Van de Graaff



■ TANDEM- XTU - ALPI

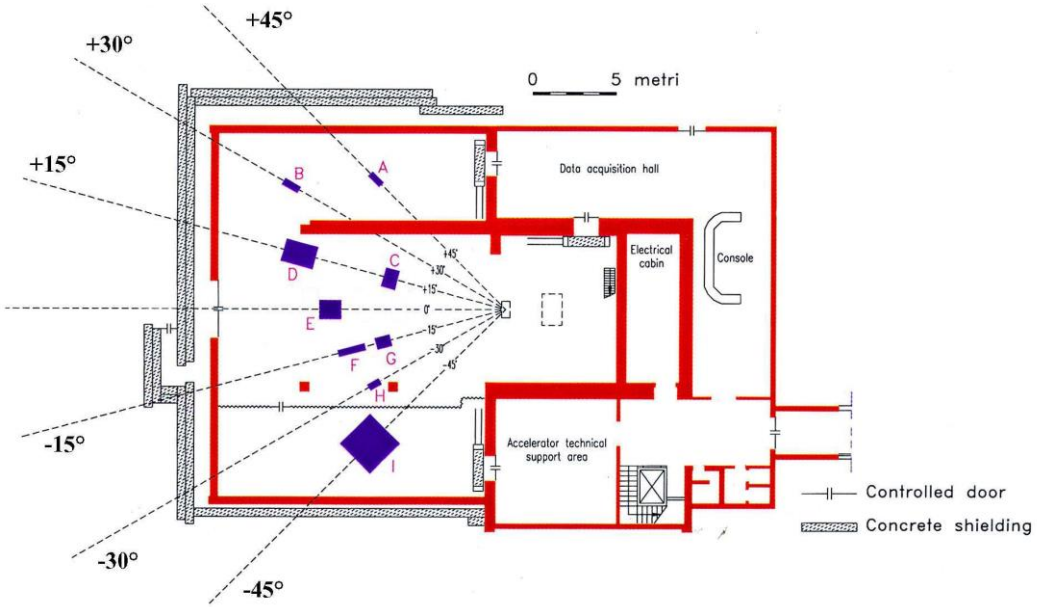
■ AN2000 Van de Graaff

FACILITIES SUPPORTED by ENSAR (UE Fp7)

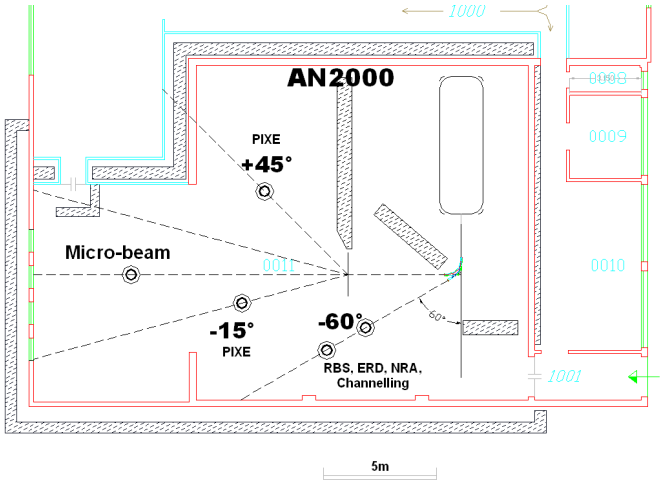
CN (oper. since 1961)

7 beam lines (1-6MV pulsed/cont, $^{1}H,^{2}H,^{3}He,^{4}He,^{14}N$)

- Radio-Biology (broad beam in air, single ion microbeam in air – resolution: **5μm**)
- Neutron dosimetry (monoenergetic $^{7}Li(p,n)$)
- Neutron Spectrometry (Be(p,n))
- Radiation Damage
- Ion Beam Analysis (NRA, EBS, IBIL, PIXE)
- Nuclear cross section measurements / nuclear astrophysics



AN2000 (oper. 1971)



5 beam-lines (0.25-2.2MV $^{1}H,^{3}He,^{4}He$)

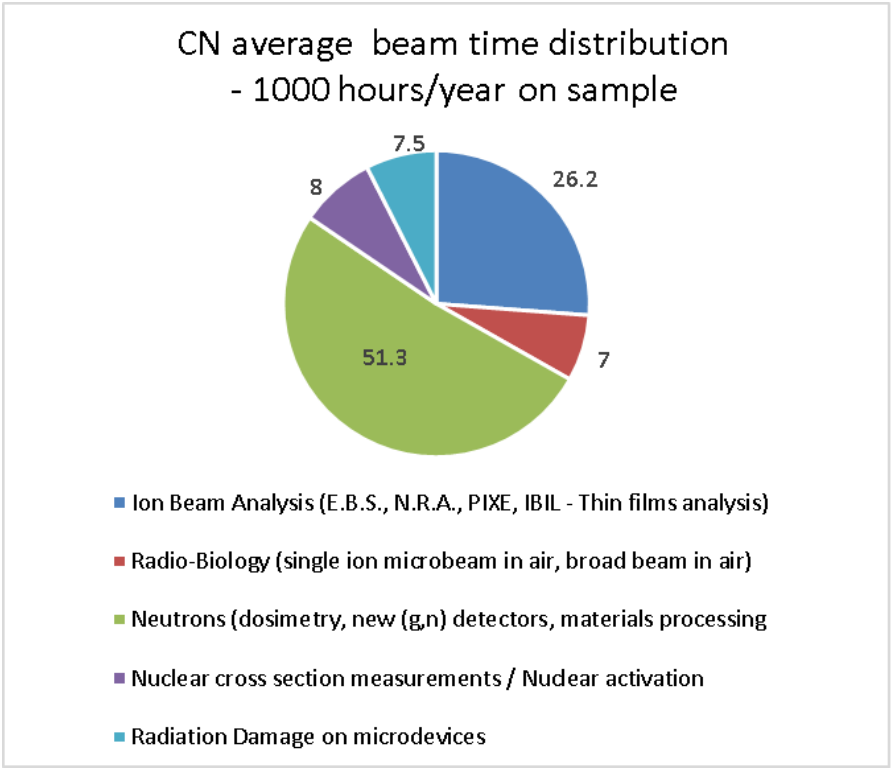
- Micro-beam (resolution: **1 μm**)
  - MicroPIXE, microIBICC, microIBIL
  - Ion Beam Writing
  - Rarefied beam / single event)
- Ion Beam Analysis
  - NRA, RBS, ERD, IBIL
  - Ion Channelling
- PIXE
  - Archaeology
  - Environmental

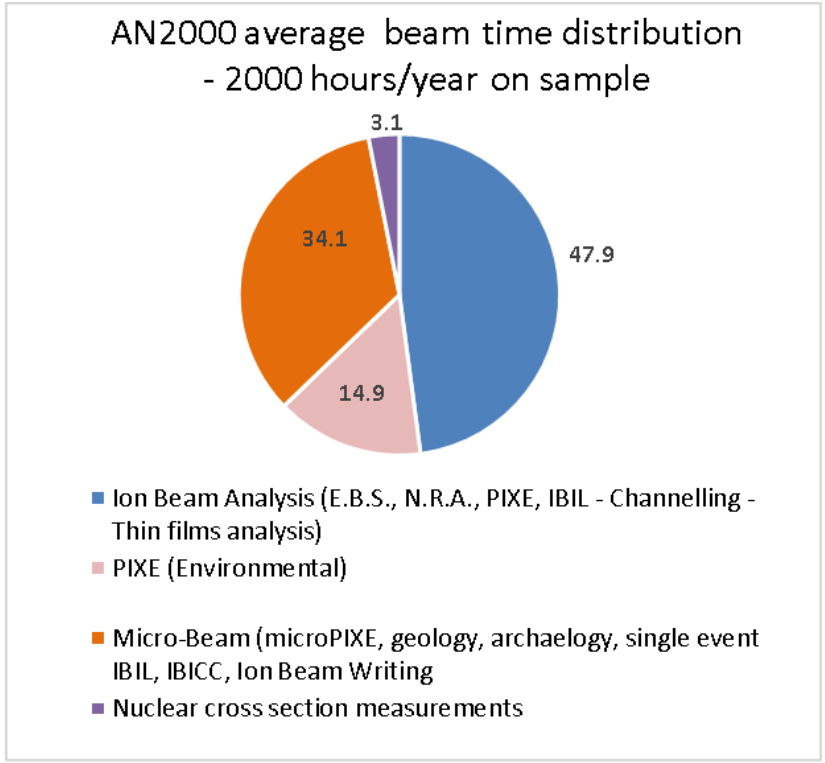
Research groups and institutions involved in the interdisciplinary activities at the AN2000 and CN accelerators

CN	
Average Nr. EXPERIMENTS / YEAR	27
External Institutions	
Univ. Firenze, Modena e Reggio, Pisa, Padova, Roma3, Trento, Torino; CNR-Pd, CNR-Trieste, INAF-IASF Bologna, Politecnico Milano e Torino	

AN2000	
Average Nr. EXPERIMENTS/YEAR	26
External Institutions	
Univ. Bologna, Firenze, Modena e Reggio, Padova, Trento, Torino, Venezia, Verona; CNR-ICIS-Pd, CNR-ISAC-Bo, CIEMAT, CNAM (Spain), Nat. Inst Nucl. Phys. Bucharest (Romania), IUAC (India)	

ISI PUBLICATIONS ~ about 120/year





Source: INFN-LNL 2014