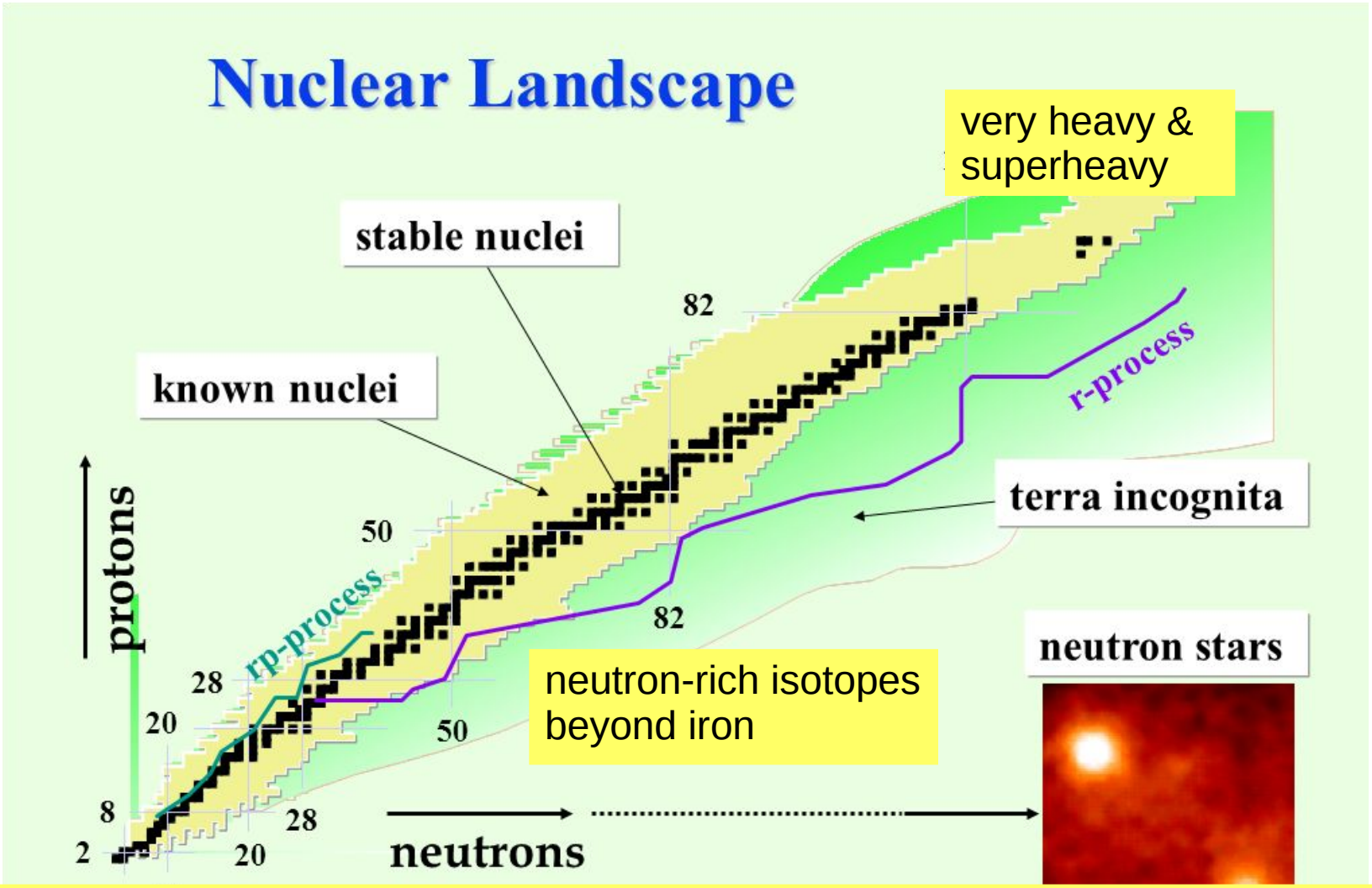
Charting Terra Incognita of Exotic Nuclei

S Franchoo

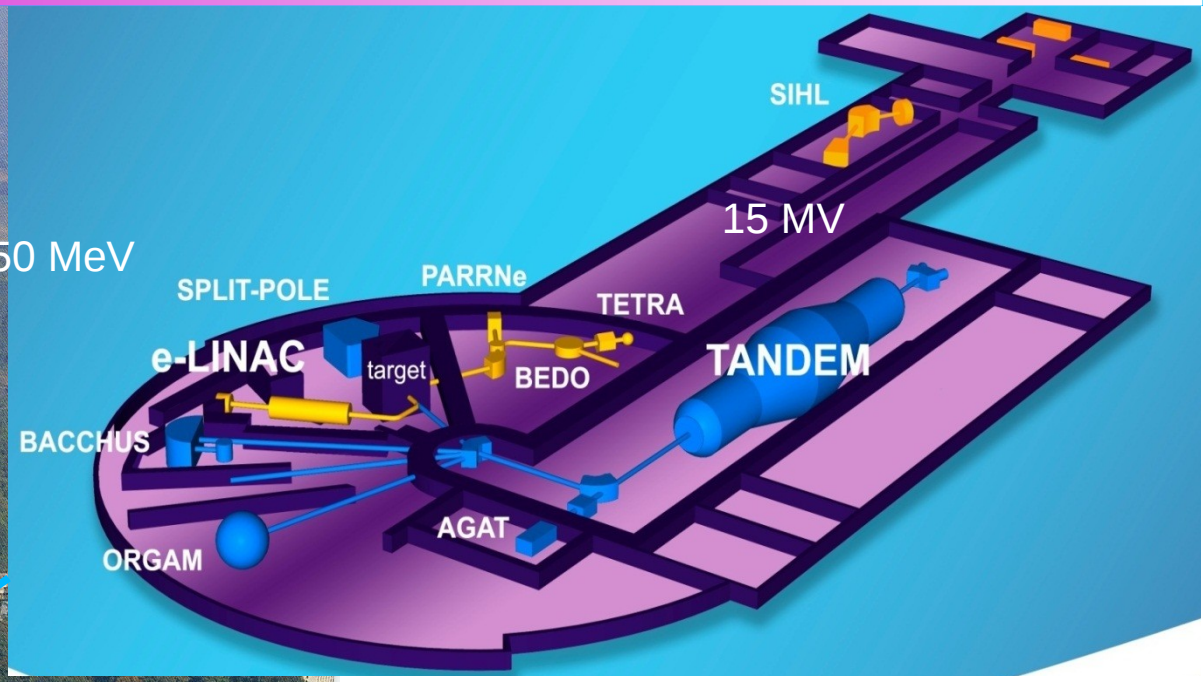
A Drouart, C Gaulard, A Lopez-Martens, E Minaya Ramirez, S Roccia, B Sulignano, D Yordanov et al.

IPN Orsay
CSNSM Orsay
Irfu/SPhN Saclay



Beta decay cannot rule out the existence of isomers or alternative spin assignments, leaving doubt on the level scheme that is obtained. Only the measurement of masses, spins and moments can solve this (m, J^{π}, δr^2, μ, Q)

Terra Incognita



Alto transnational-access user facility

250 users (30 countries) /y

Stable beams 4000 h /y

25% light ion beams

75% heavy ion beams

Radioactive beams 400 h /y

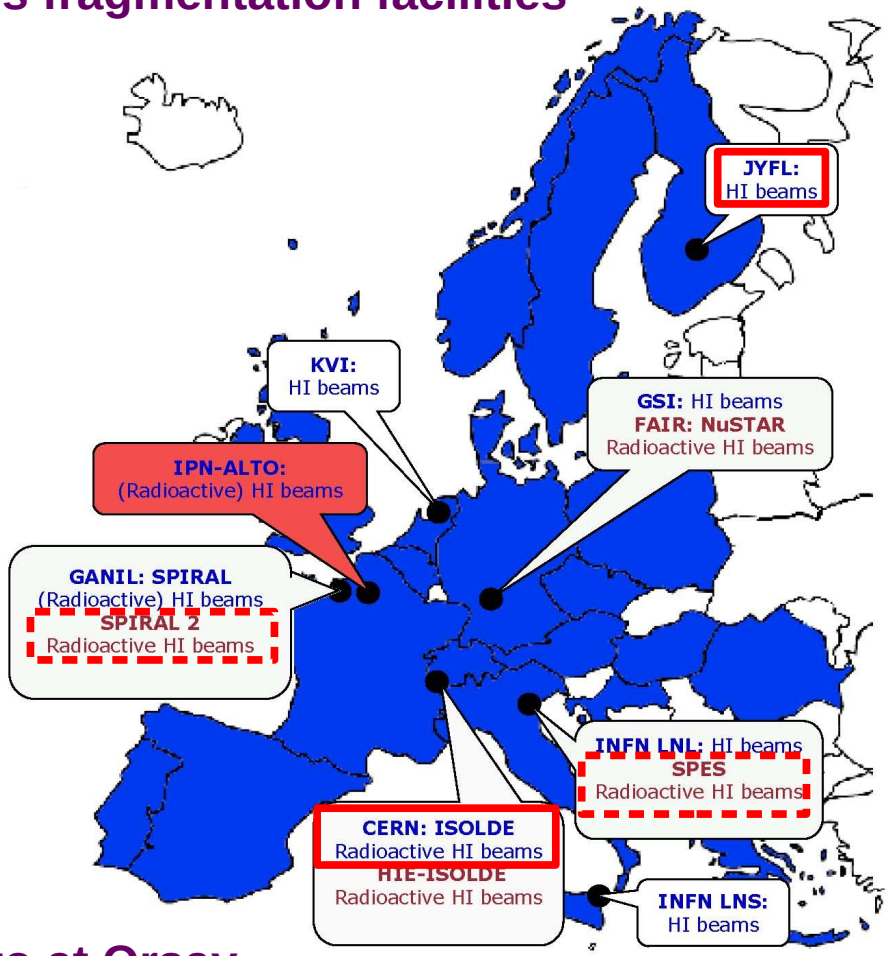
ALTO
Accélérateur Linéaire et Tandem à Orsay

Low-energy isol vs fragmentation facilities

Triumf (Cnd)

NSCL (MI)

Oak Ridge (TN)



Riken (Jp)

Uniqueness of Alto at Orsay

low-energy neutron-rich nuclear physics with reduced isobaric contamination

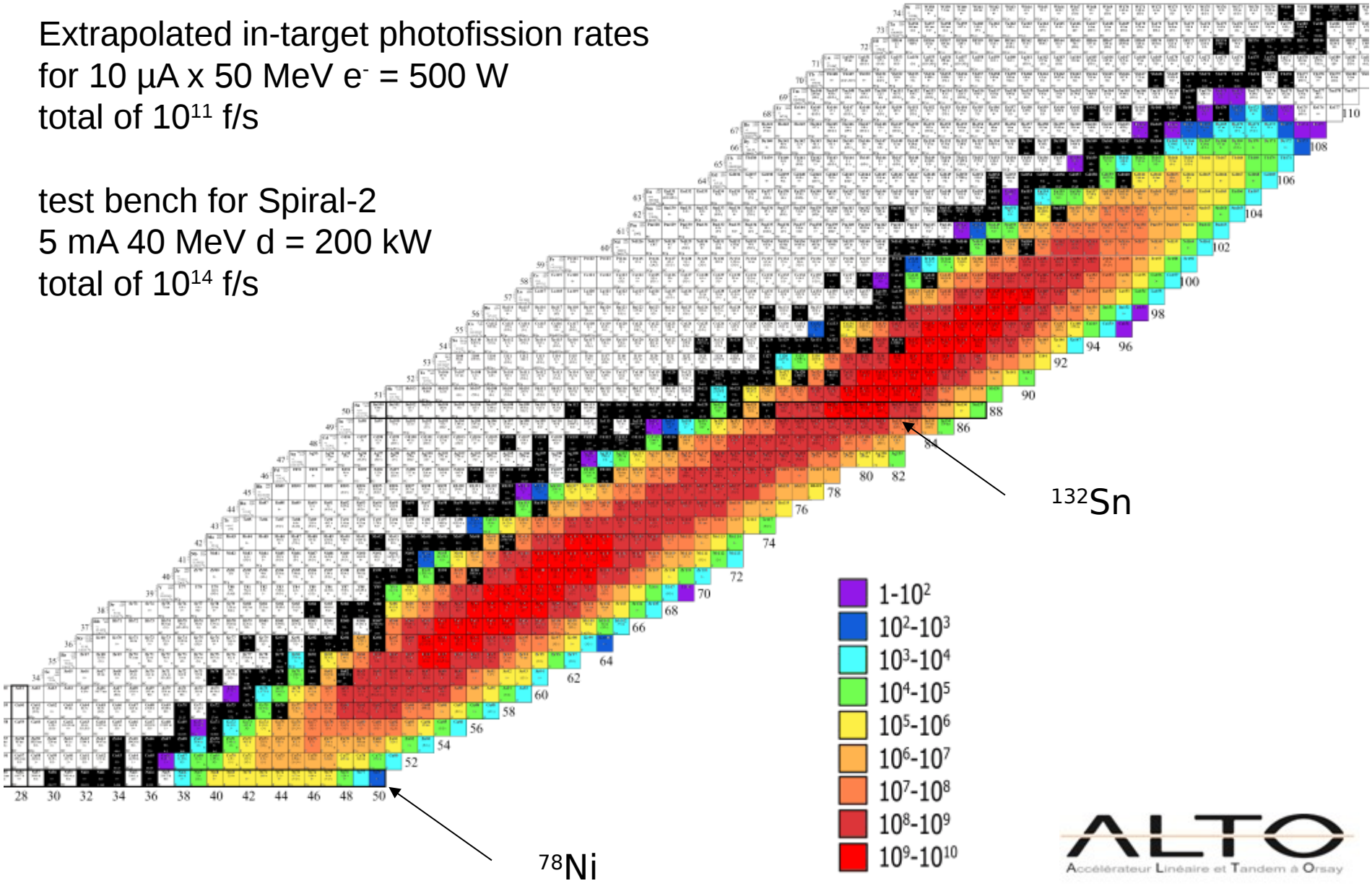
- photofission (cold process, little excitation energy)
- mass separation (A selection) & laser ionisation (Z selection)

ALTO
Accélérateur Linéaire et Tandem à Orsay

Terra Incognita

Extrapolated in-target photofission rates
for 10 µA x 50 MeV e^- = 500 W
total of 10^{11} f/s

test bench for Spiral-2
5 mA 40 MeV d = 200 kW
total of 10^{14} f/s



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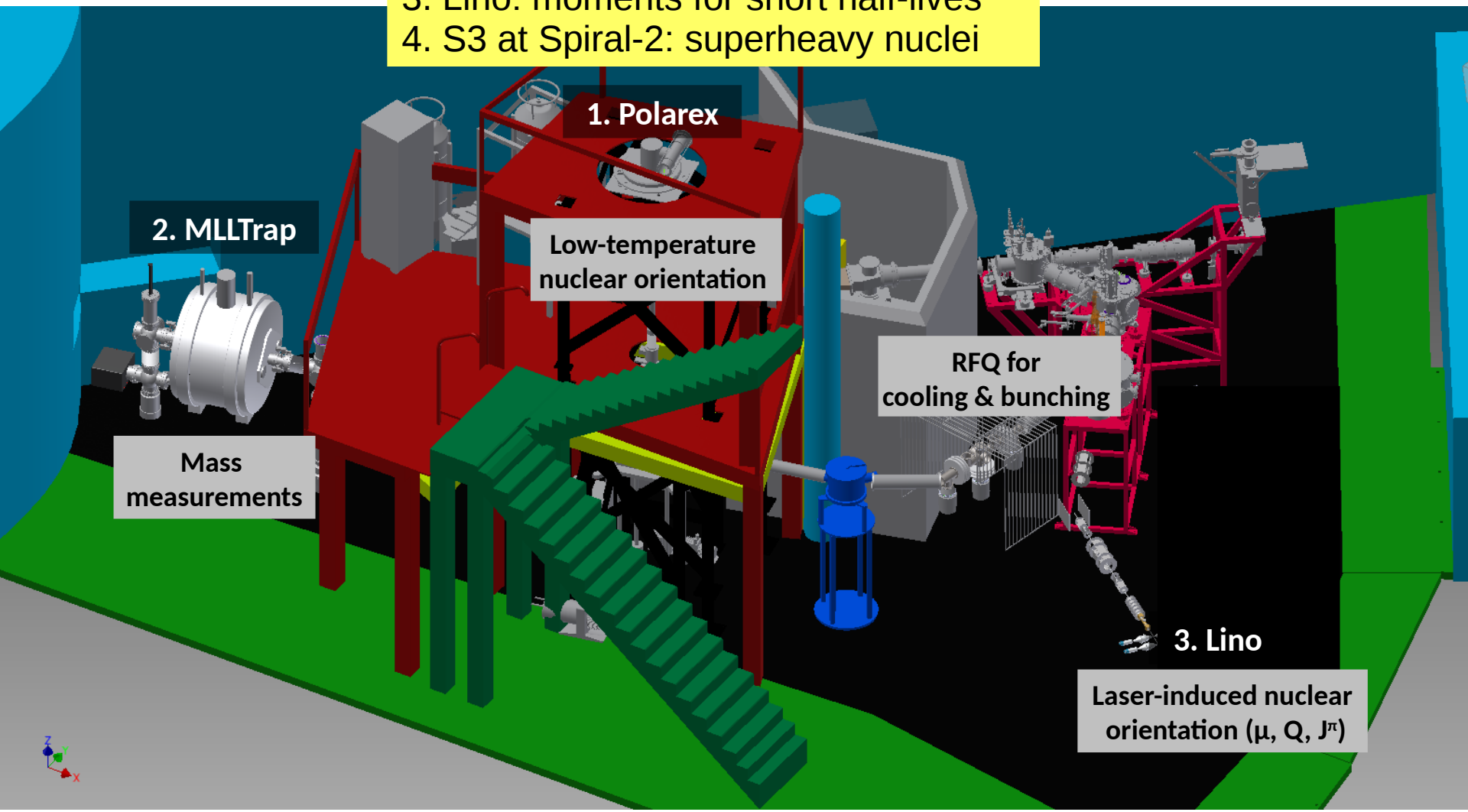
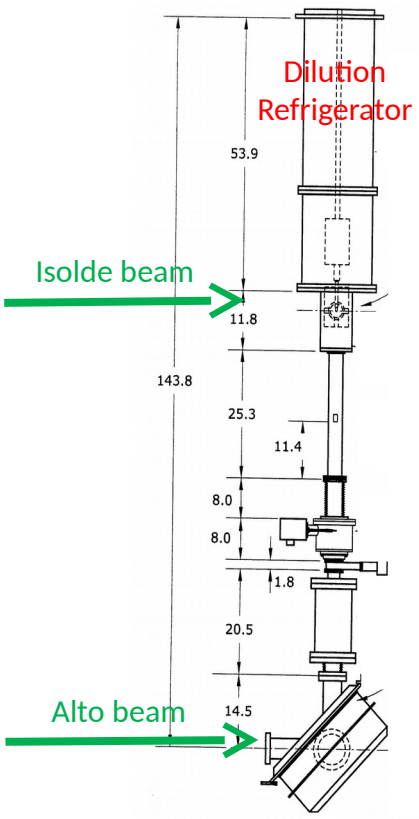
Terra Incognita

1. Polarex: electromagnetic moments
2. MLLTrap: mass measurements
   & in-trap spectroscopy
3. Lino: moments for short half-lives
4. S3 at Spiral-2: superheavy nuclei





Low-Temperature Nuclear Orientation

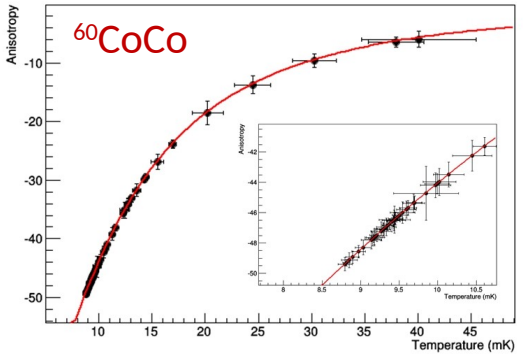
low temperature external magnetic field (15 mK, 1.5 T)
implantation in ferromagnetic host (10-100 T internal field)

Uniqueness

- coupling to nuclides from Alto
- unlike Isolde, beam line connected from below
  more detectors around the sample
  accurate spatial anisotropy of emitted radiation

Off-line at CSNSM

- renovation of cryostat
- reached 8.8±0.1 mK



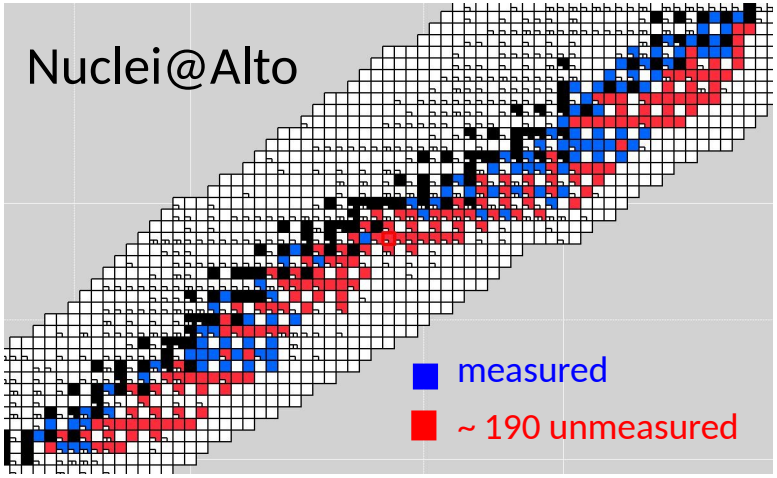
Fusion-evaporation ^{2}H + ^{56}Fe at Alto tandem

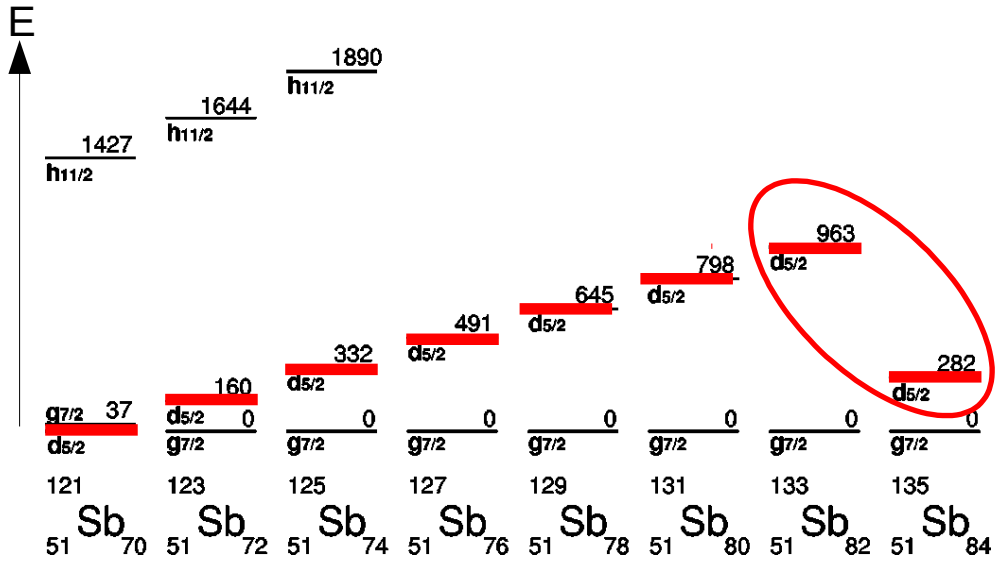
- ^{56,58}Co: magnetic moment
- $^{56\text{-}58}$Co: M1+E2 multipolarity mixing

A Etilé, to be published

Magnetic properties close to ^{132}Sn

- shell-model unable to reproduce antimony
- signature for diffuse nuclear surface?
- predict same effect for ^{136,137}I
- obtain single-particle orbitals from characteristic magnetic moments of Sb, I





J. Shergur et al., PRC 65, 034313 (2002)

Versatility of Polarex

- measure magnetic moment of ^{137}I
- followed by γ-decay in ^{137}Xe
  > parity admixtures
- and β-delayed neutron emission
  > neutron barrier penetration

1. Polarex

Polarex at CSNSM

Polarex platform at Alto

1.1 move Polarex to Alto	H. Silvin	Polarex installed	31.12.16
1.2 vacuum and cryogenics tests	S. Roccia		
1.3 off-line physics runs	C. Gaulard		
1.4 beam-line design	A. Hüe	all drawings	31.12.17
1.5 beam-line construction	C. Planat	beam line	30.6.18
1.6 on-line experiments	C. Gaulard		

High-precision mass measurements

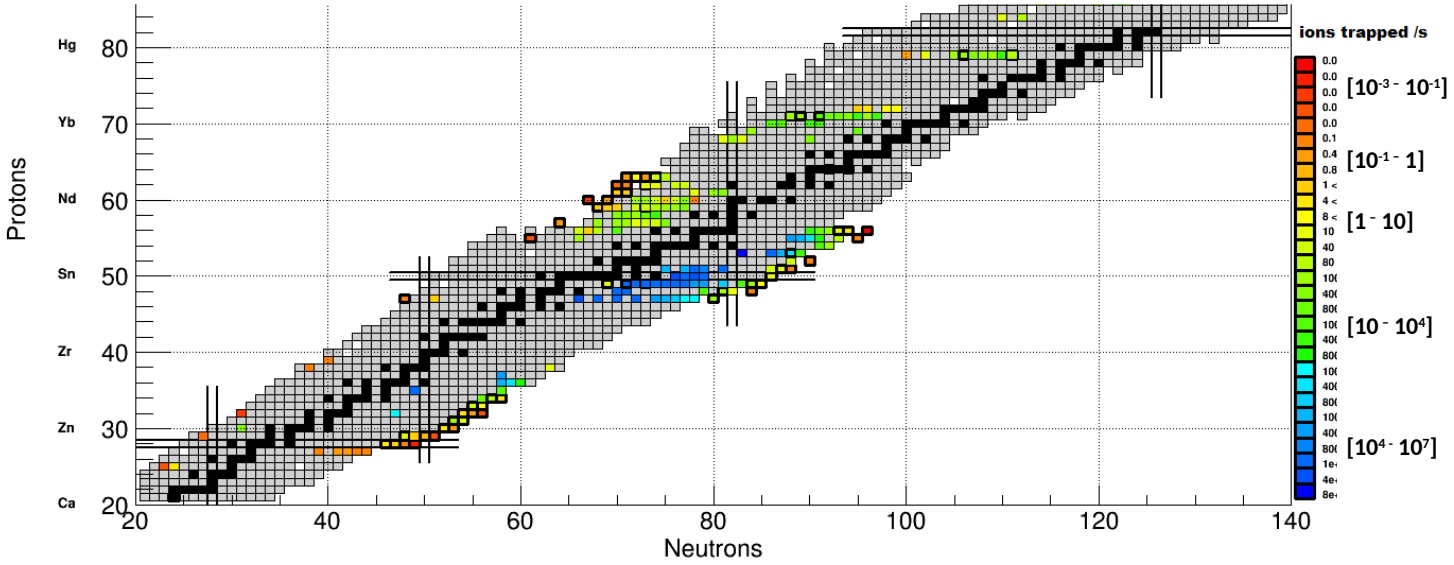
$M(N,Z) = Z\,M_p + N\,M_n - B(N,Z)$

- δm > 10 keV
- $T_{1/2}$ > 80 ms
- 100 trapped ions in 10 h
- photofission & fusion-evaporation

Phase imaging

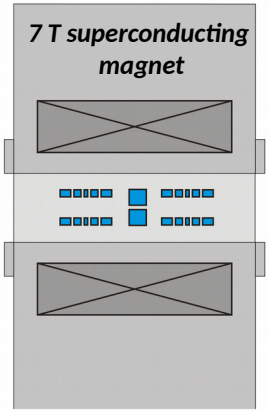
Tof

Field	δm/m
Chemistry: identification of molecules	10^{-5} - 10^{-6}
Nuclear physics: shells & pairing	10^{-6}
Astrophysics : r(p)-process, waiting points	10^{-7}
Nuclear fine structure: deformation, halos	10^{-7} - 10^{-8}
Nuclear models and formulas: IMME	10^{-7} - 10^{-8}
Weak interaction studies: CVC & CKM	10^{-8}
Atomic physics: binding energies, QED	10^{-9} - 10^{-11}
Metrology: fundamental constants, CPT	≤10^{-10}

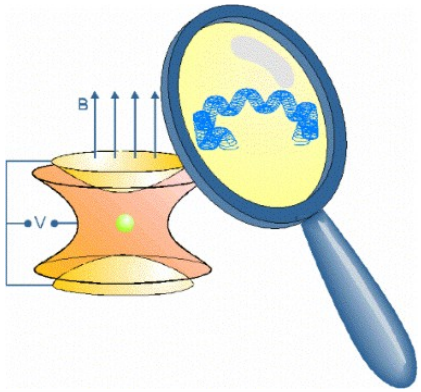


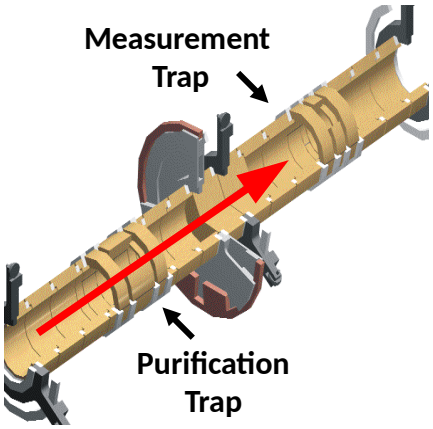
High-precision mass measurements

Cooled & bunched beam



Selected ions

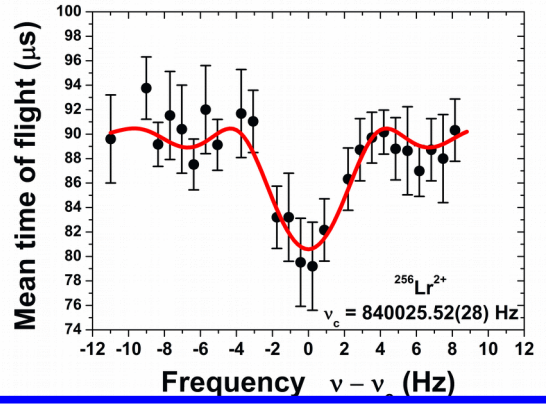




$$\nu = \frac{qB}{2\pi m}$$

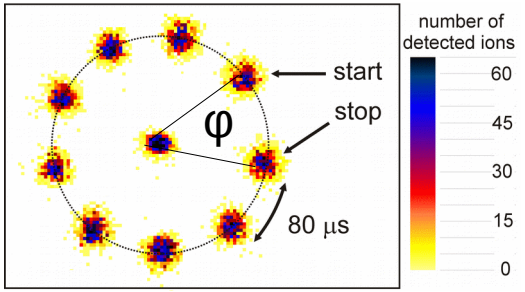
Time-of-flight ion-cyclotron-resonance

E Minaya Ramirez et al, Science 337 (2012)



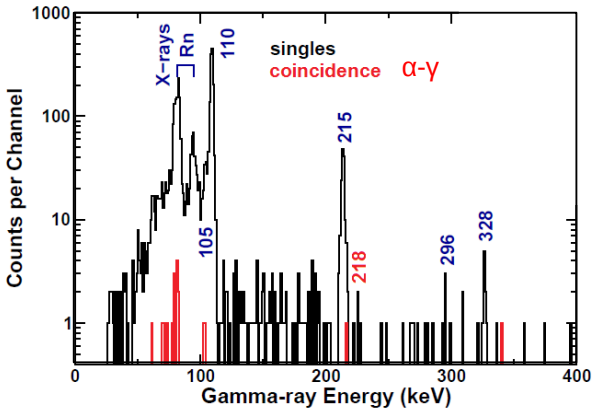
Phase-imaging ion-cyclotron-resonance

Eliseev et al, PRL 110 (2013)



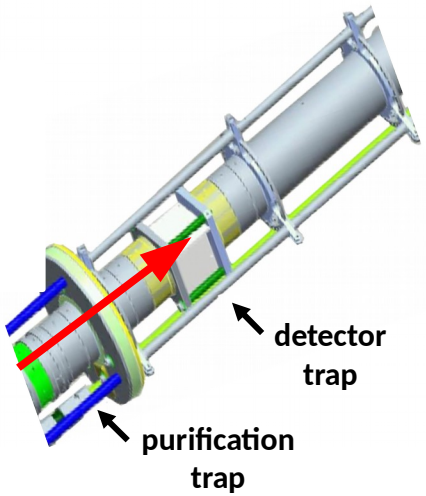
Trap-assisted spectroscopy

detector after purification in trap

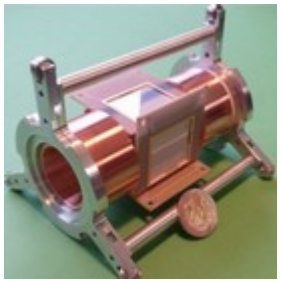


P Kuusiniemi et al, EPJA 30, 551 (2006)

In-trap decay spectroscopy

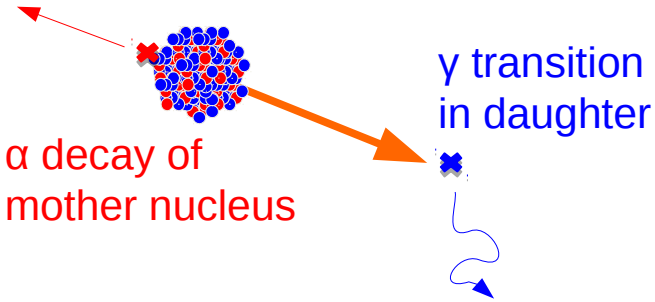


detector
inside trap



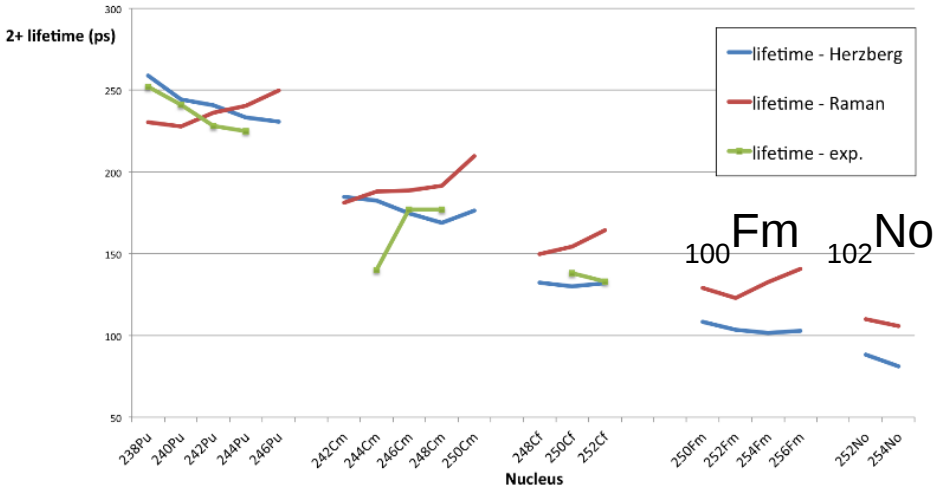
C Weber et al, Int. J. of Mass Spectrometry 349 (2013)

In-trap life-time measurements of heavy nuclei



distance travelled depends on life-time
of initial state: ~50 µm for 100 ps
use magnification by field of trap
to reconstruct position of α and γ decay

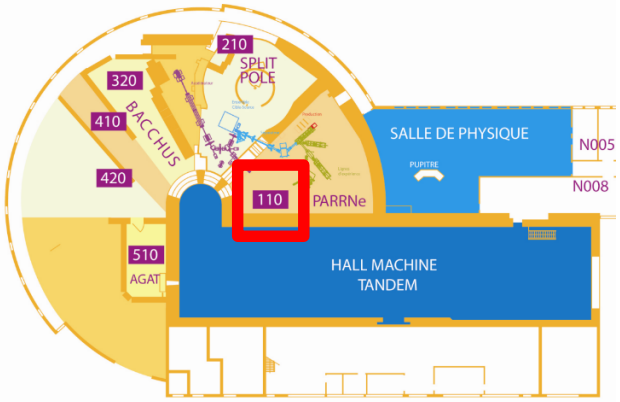
towards superheavy α emitters at S3



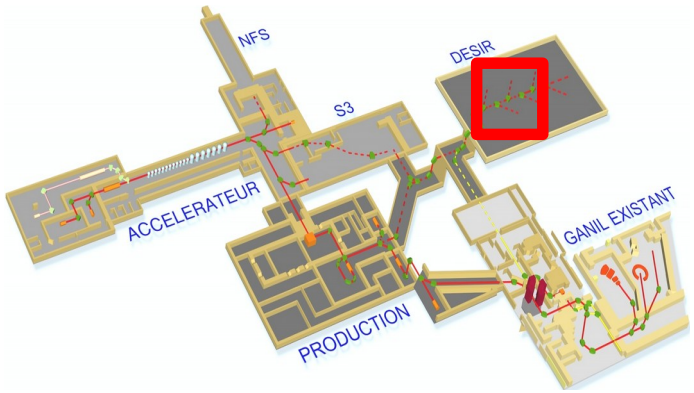
2. MLLTrap

Munich

Alto



Spiral-2

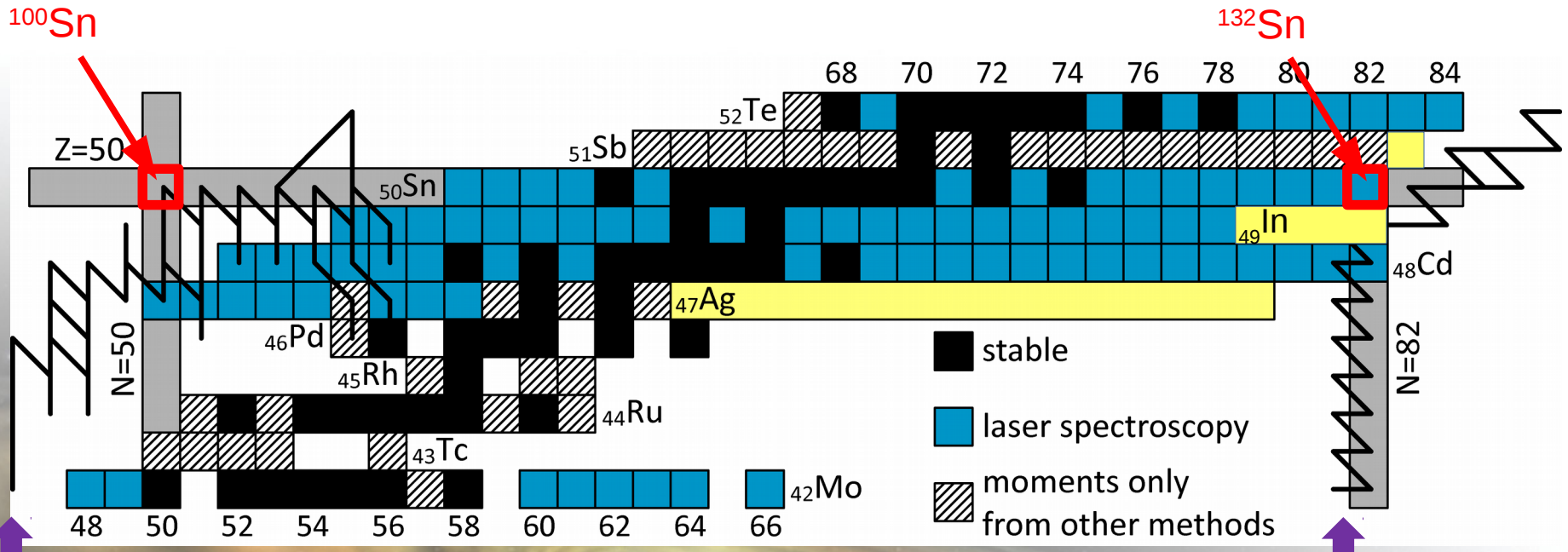


2.1 move MLLTrap to Alto	A. Semsoun	MLLTrap installed	30.6.16
2.2 RFQ design	L. Perrot	all drawings	30.6.17
2.3 RFQ construction	C. Planat	RFQ	31.12.17
2.4 electrode tests for RFQ and MLLTrap	T. Corbin	control & command	30.6.18
2.5 off-line test of RFQ and MLLTrap	E. Minaya		
2.6 on-line test of RFQ and MLLTrap	E. Minaya		
2.7 on-line experiments	E. Minaya		

3.1 simulation of detector geometry	N. N. (postdoc)	simulation package	30.6.17
3.2 design and construction of detectors	A. Lopez-Martens	detectors	31.3.18
3.3 detector tests at CSNSM	K. Hauschild		
3.4 off-line tests at Alto	A. Lopez-Martens		

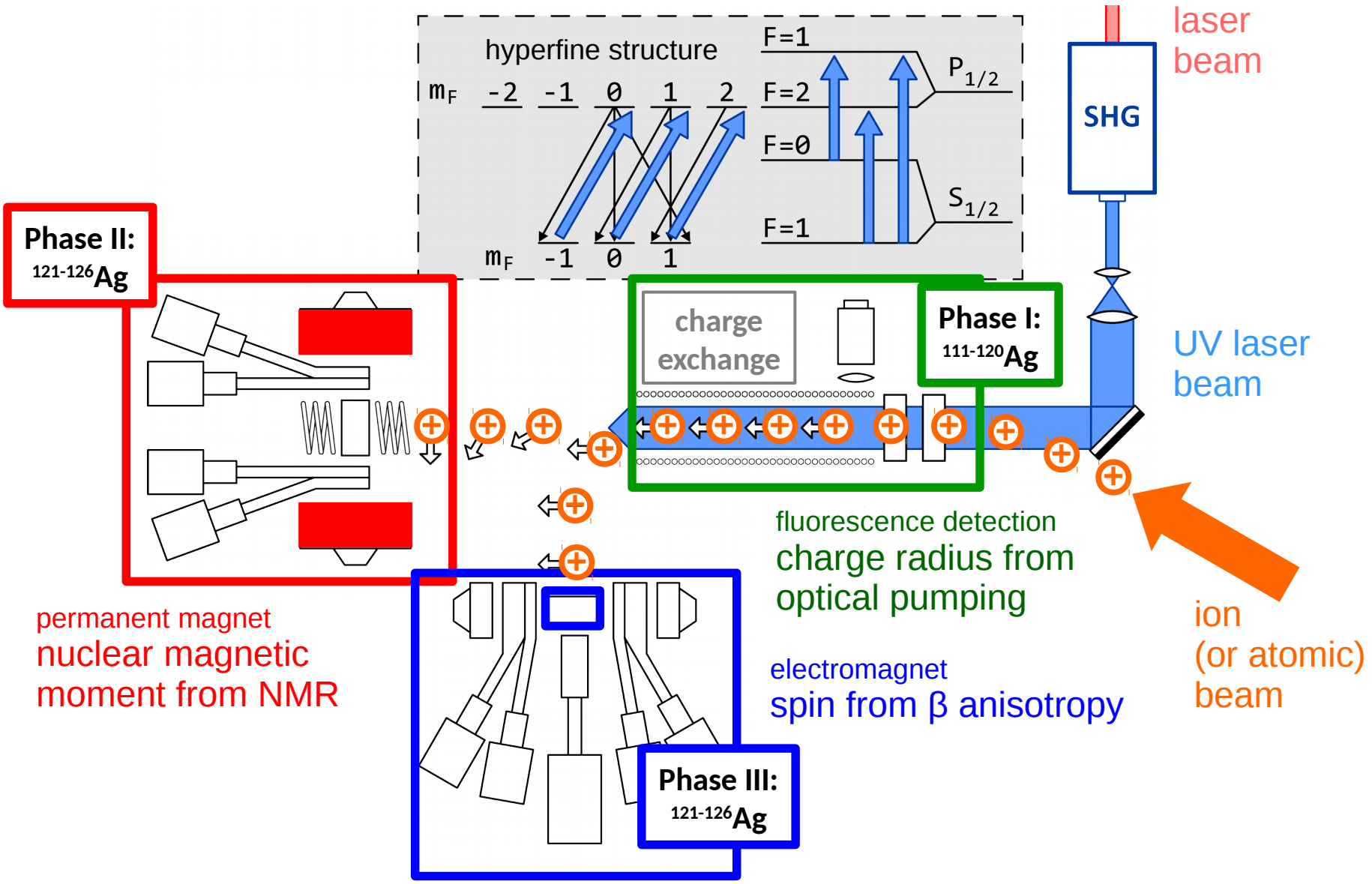
Laser Induced Nuclear Orientation at Alto

Laser spectroscopy of silver and indium near ^{132}Sn (Z=50, N=82)

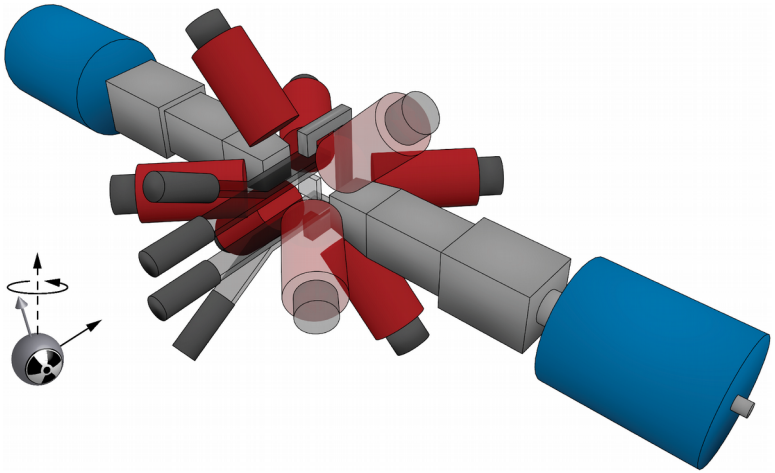


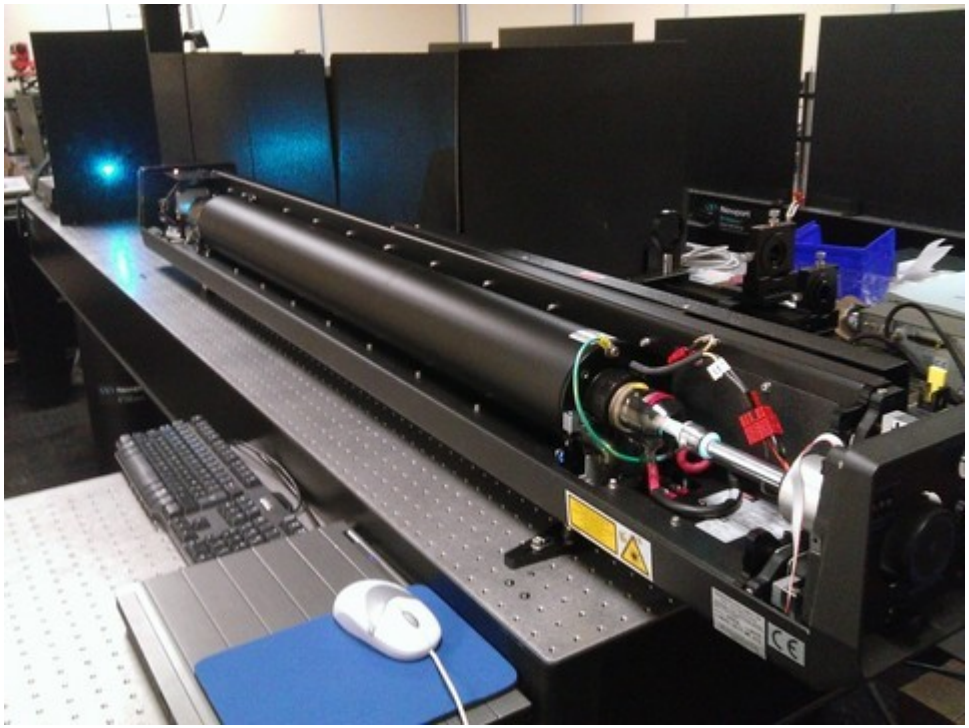
rp process

r process


hyperfine structure
m_F -2 -1 0 1 2
m_F -1 0 1
F=1
F=2
F=0
F=1
$P_{1/2}$
$S_{1/2}$
SHG
laser beam
Phase II:
121-126Ag
charge exchange
Phase I:
111-120Ag
UV laser beam
fluorescence detection
charge radius from optical pumping
ion (or atomic) beam
permanent magnet
nuclear magnetic moment from NMR
electromagnet
spin from β anisotropy
Phase III:
121-126Ag

3. Lino





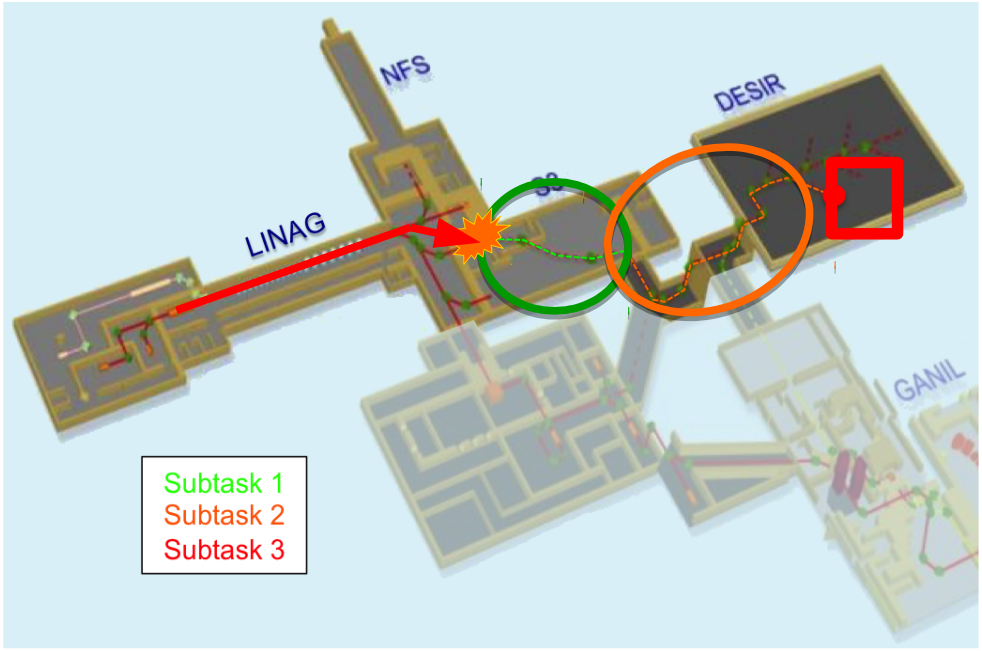
presently acquired:

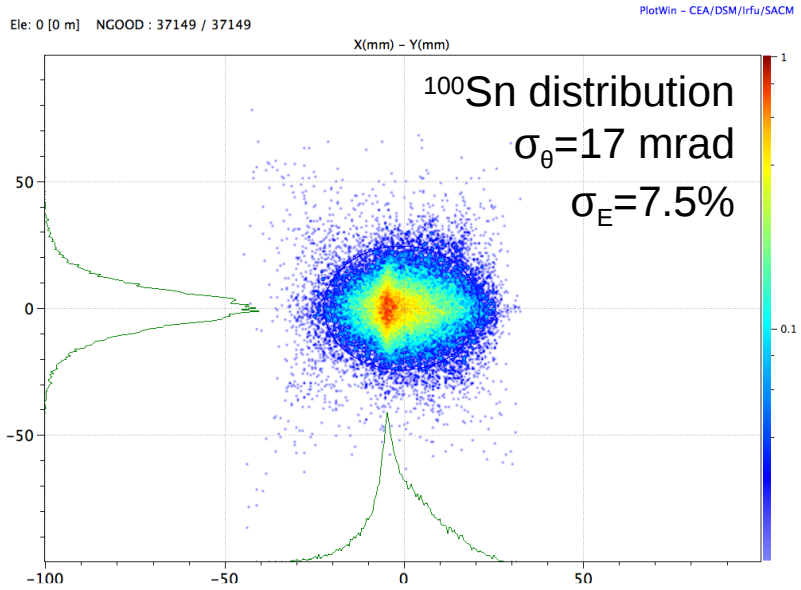
- Ar^+ pump laser
- tunable dye laser
- second harmonic generator

4.1 beam-line design	L. Perrot	all drawings	30.6.16
4.2 beam-line construction	C. Planat	beam line	31.12.16
4.3 HV and DAQ tests	T. Corbin	control & command	31.12.16
4.4 off-line commissioning	D. Yordanov		
4.5 on-line experiments	D. Yordanov		

Use the experimental set-ups from Alto with the exotic beams from S3 at Spiral-2

Optical simulations





7 charge states in 50 mm window
with 54% transmission

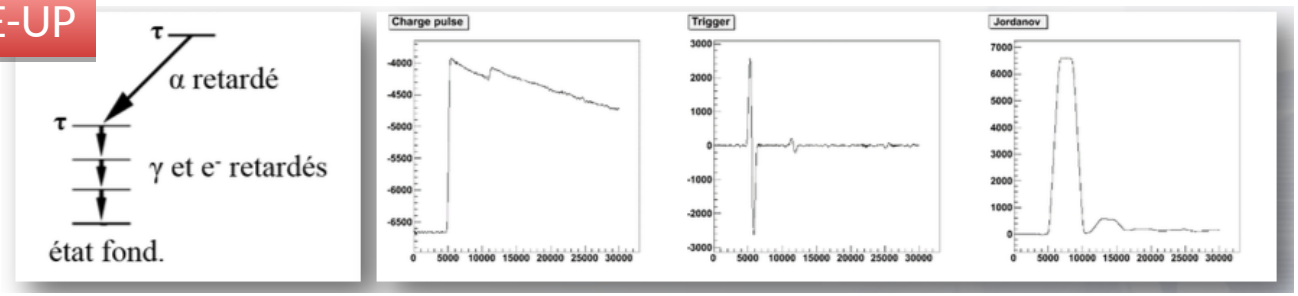
1. S3 beam line from target to final focal point
2. Low-energy line from final focal point to Desir
3. Behaviour of decaying ions inside MLLTrap

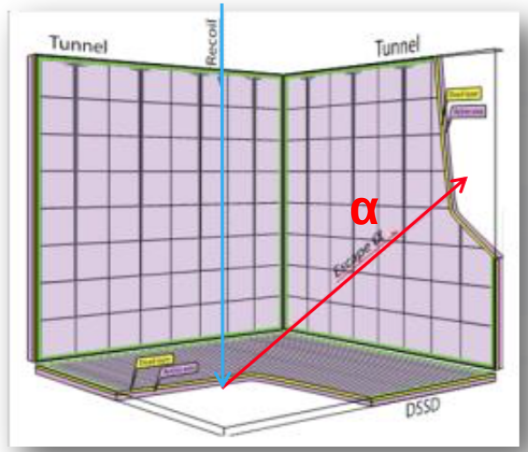
- simulation of experiments with realistic physical input
- include measured 3D field maps
- define tune parameters for converging & mass-resolving mode

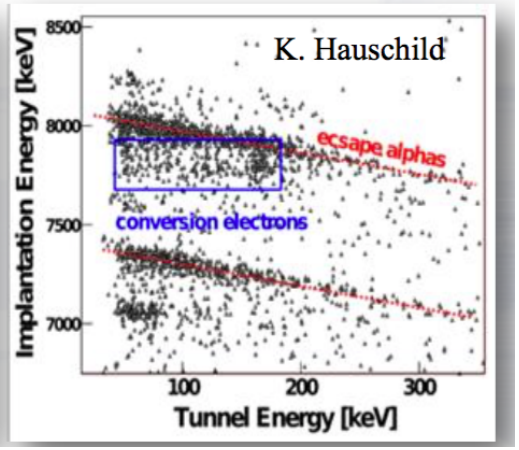
Pulse-shape algorithms

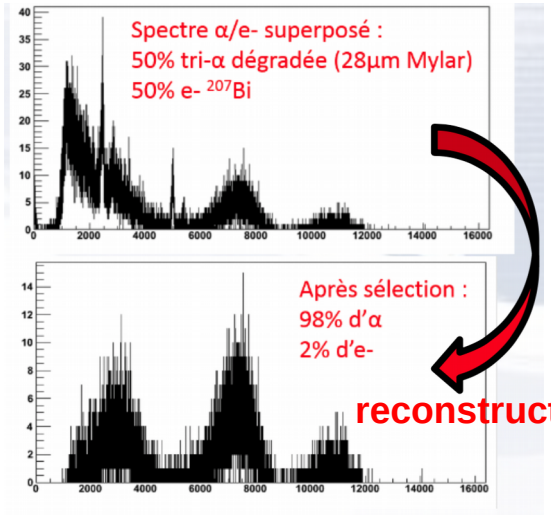
- recursive algorithm to extract relevant parameters sample by sample
- energy and time for energy resolution & pile-up rejection
- rise time for α/e- particle identification
- synergy MLLTrap at Alto & Sirius silicon set-up at S3

PILE-UP









Physics programme for first day experiments

Very heavy, superheavy elements & N=Z line

S3 high beam intensity, mass resolution and transmission, Sirius silicon detector

Doubly magic ^{218}U; spectroscopy of Fm isotopes; bridge the gap between cold and hot fusion; isomers beyond Z=110; ^{112}Ba-^{108}Xe -^{104}Te super-allowed α decay

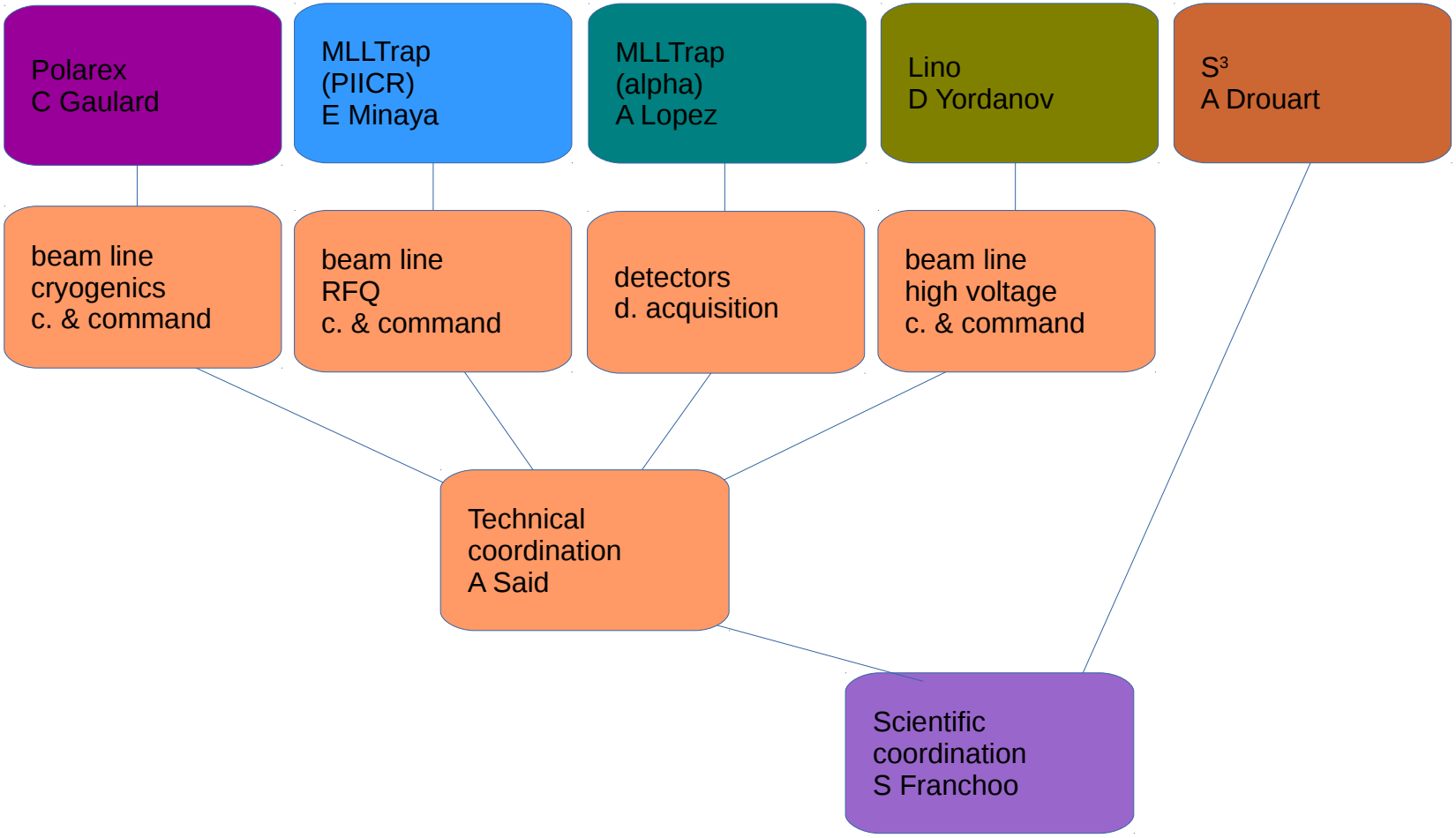
Ground-state properties

Nuclei not available elsewhere, high selectivity, gas catcher with coupling to Desir

^{94}Ag, ^{100}Sn, ^{80}Zr mass and charge radius, decay of ground and isomeric states, laser spectroscopy of transactinides (^{254}No,...)

5.1 optical modes and physics cases	A. Drouart		
5.2 PSA algorithms and tests at Irfu/SPhN	B. Sulignano	PSA software	30.6.17
5.3 user-friendly simulation framework	A. Drouart	simulation package	30.6.17
5.4 off-line tests at S^3	B. Sulignano		
5.5 on-line experiments	A. Drouart		

Terra Incognita



- monthly technical meetings and yearly scientific workshop
- publications will be submitted to peer-reviewed journals

Task	Responsible	Deliverable	Date
1.1 move Polarex to Alto	H. Silvin	Polarex installed	31.12.16
1.2 vacuum and cryogenics tests	S. Roccia		
1.3 off-line physics runs	C. Gaulard		
1.4 beam-line design	A. Hüe	all drawings	31.12.17
1.5 beam-line construction	C. Planat	beam line	30.6.18
1.6 on-line experiments	C. Gaulard		
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3.2 design and construction of detectors	A. Lopez-Martens	detectors	31.3.18
3.3 detector tests at CSNSM	K. Hauschild		
3.4 off-line tests at Alto	A. Lopez-Martens		
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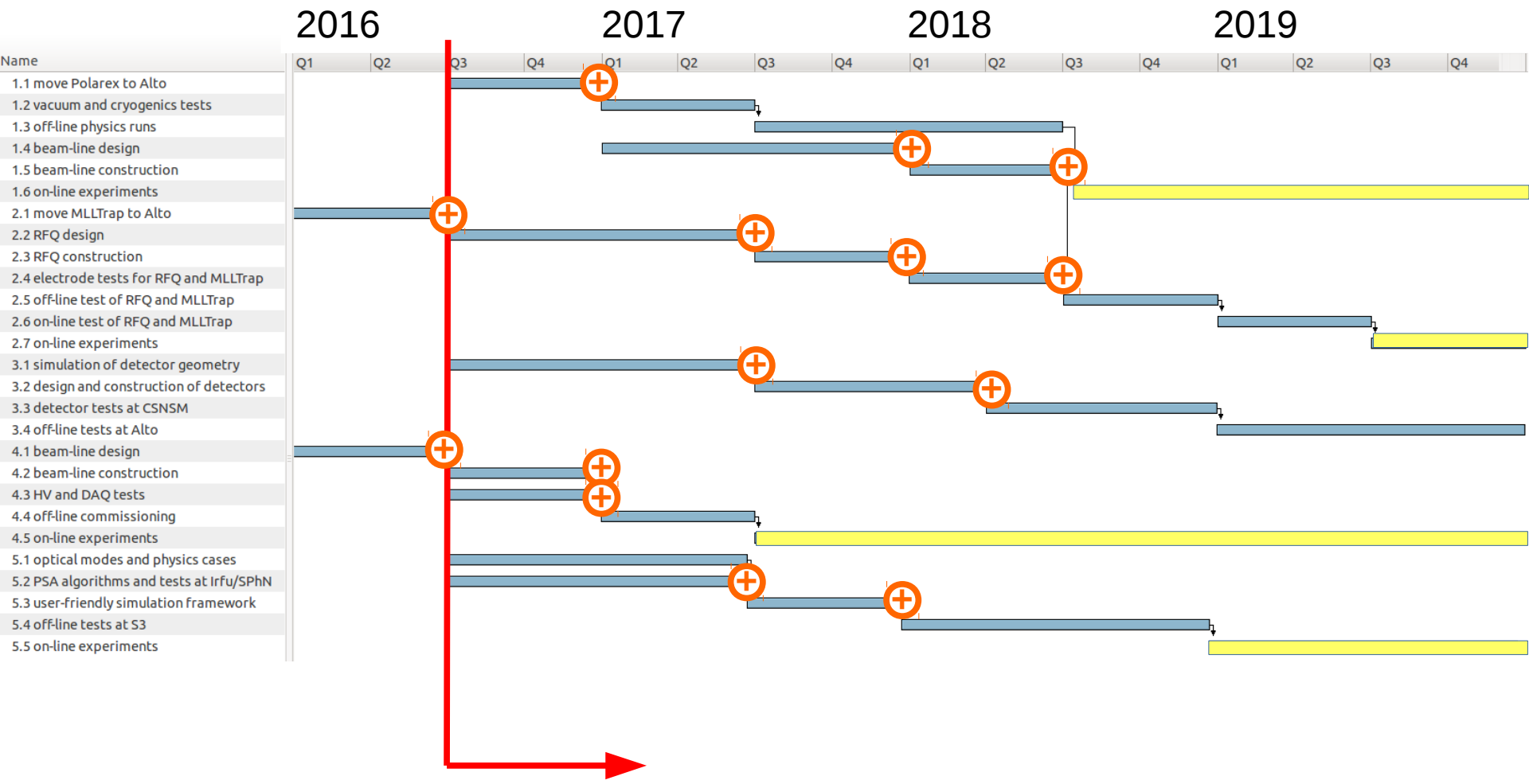
5.1 optical modes and physics cases	A. Drouart		
5.2 PSA algorithms and tests at Irfu/SPhN	B. Sulignano	PSA software	30.6.17
5.3 user-friendly simulation framework	A. Drouart	simulation package	30.6.17
5.4 off-line tests at S^3	B. Sulignano		
5.5 on-line experiments	A. Drouart		

Terra Incognita



Terra Incognita

1	Polarex	beam line	95		CSNSM
2		postdoctoral fellow	75		CSNSM
3	MLLTrap	RFQ	75		IPN
4		PIICR detection	30		IPN
5		in-trap detection	60		CSNSM+Irfu
6		postdoctoral fellow	100		CSNSM
7	Lino	beam line	195		IPN
8	S^3	postdoctoral fellow	150		Irfu
9		PhD position	100	**50**	Irfu
10		workshop & missions	20	**10**	Irfu
			900	**840**	

Additional funding

- 360 kE by IPN: 60 kE moving MLLTrap, 100 kE RFQ, 200 kE Lino lasers
- Sirius detector system: CPIER grant Vallée de Seine 2015-2020

Advantages of our project

- synergy: bringing together IPN, CSNSM, Irfu/SPhN around low-energy nuclear physics, one of the main orientations of the community in France
- local investment: it is based at Orsay
- uniqueness of Alto
  - reduced isobaric contamination from photofission
  - innovative instrumentation with Phase Imaging pushing the limits
  - extension to polarised beams with Lino only at Alto
- fully in line with Irfu/SPhN & IN2P3 scientific strategy for S3 & Desir at Spiral-2
- the collaboration possesses the low-energy nuclear physics know-how since several physicists have been working before at GSI, Jyvaskyla, Isolde

Polarex

Connections adaptation (vacuum, mechanics)	5
Support structure for detectors	20
Automatisation (vacuum, thermometry)	30
Beam profiler	10
Vertical beam-line (HV, pumps, mechanics)	30
	95

RFQ

Power installation	10
Differential pumping system	40
Main chamber	15
Vacuum components	5
HV platform	20
Gas regulation	5
Electrodes and mechanics	25
HV plate electronics	8
RF amplifier	7
RF probes	10
DC modules	15
Fast switches	12
Function generator	3
	175

PIICR detection

MCP with delay-line anode, fast-timing amplifiers, timing discriminators and digitisers RoentDek Handels GmbH	30

In-trap detection + actuator

5cm x 5cm pixelised electron detector	5
Electronics 300 E/ch x 100 ch	30
233U source	5
Actuator Sub-Miniature XYZ Linear Stage	20
	60

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Vacuum pumps, valves, flanges	30
Charge exchange, deflection, quadrupole	40
HV & data acquisition (3 high-precision 10 kV power supplies, voltage amplifier, digital-to-analog converter, scaler, PXI crate)	70
Optical detection (photomultipliers, electronics)	30
High-precision HV with ripple < 10^{-5}	25
	195