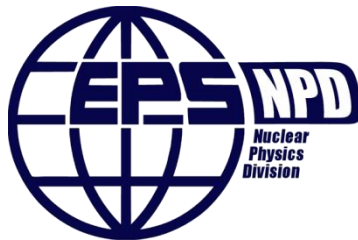


# Experimental nuclear physics activities a short review

Riccardo Raabe

KU Leuven, Instituut voor Kern- en Stralingsfysica



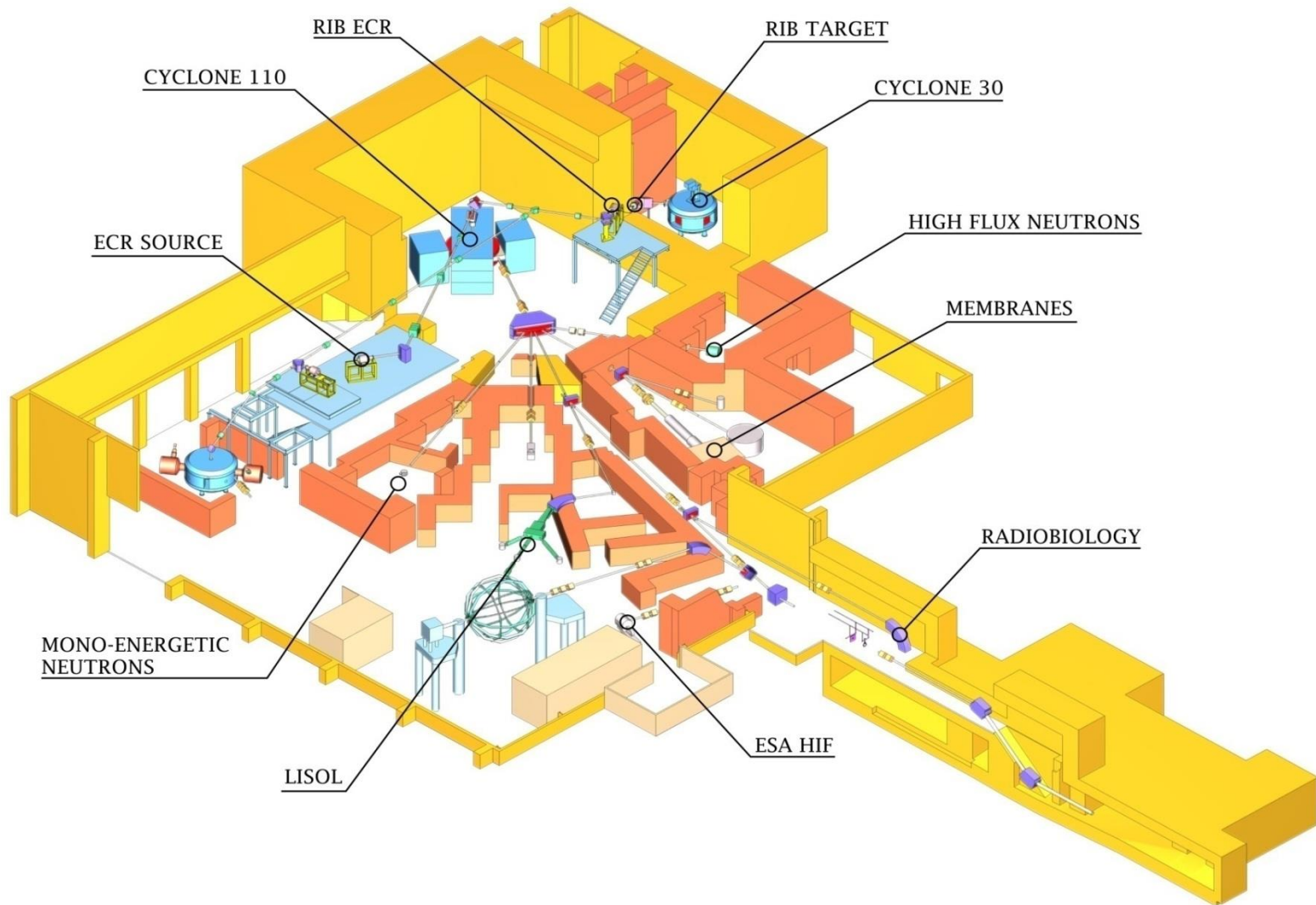
**70<sup>th</sup> Board Meeting**  
**EPS nuclear Physics Division**  
**Leuven, Belgium, October 15, 2015**

# Cyclotron Research Centre at Louvain-la-Neuve

- In operation since beginning of the '70s
- Main machine:  
K=110 cyclotron “Cyclone”
- Programme:
  - nuclear physics research
  - applications
  - neutron therapy
- Second cyclotron (1987):  
 $H^-$  30 MeV, 500  $\mu A$
- **Post-accelerated RI beams (1989-2008)**

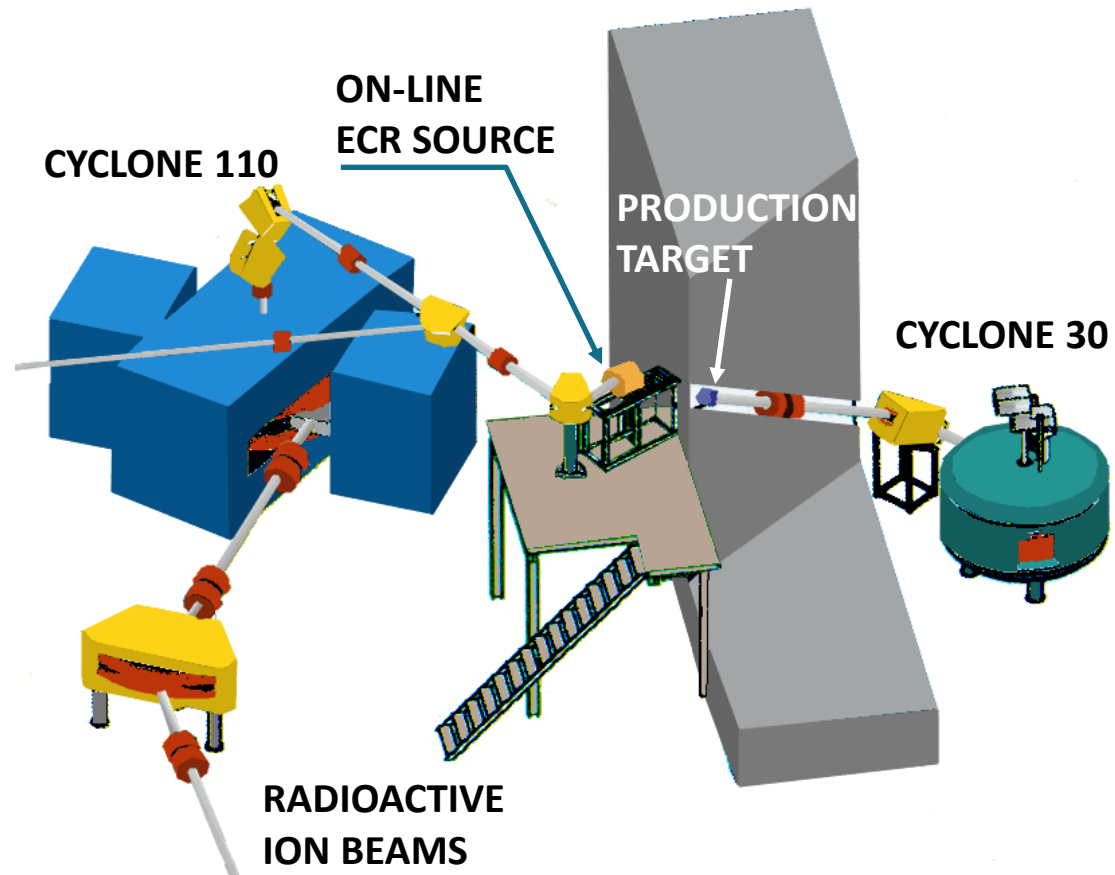


# Cyclotron Research Centre at Louvain-la-Neuve



# Cyclotron Research Centre at Louvain-la-Neuve

- **ISOL method:**  
thick-target (LiF, C),  
transport,  
ionisation (ECR),  
post-acceleration
- **First beam**  
21 June 1989  
 $^{13}\text{N}$  ( $T_{1/2} = 10$  min)  
 $10^6$  pps



# Cyclotron Research Centre at Louvain-la-Neuve

- **Nuclear astrophysics**

$^7\text{Be}$ ,  $^{13}\text{N}$ ,  $^{18}\text{F}$ ,  $^{18,19}\text{Ne}$

- **$^6\text{He}$  beam**

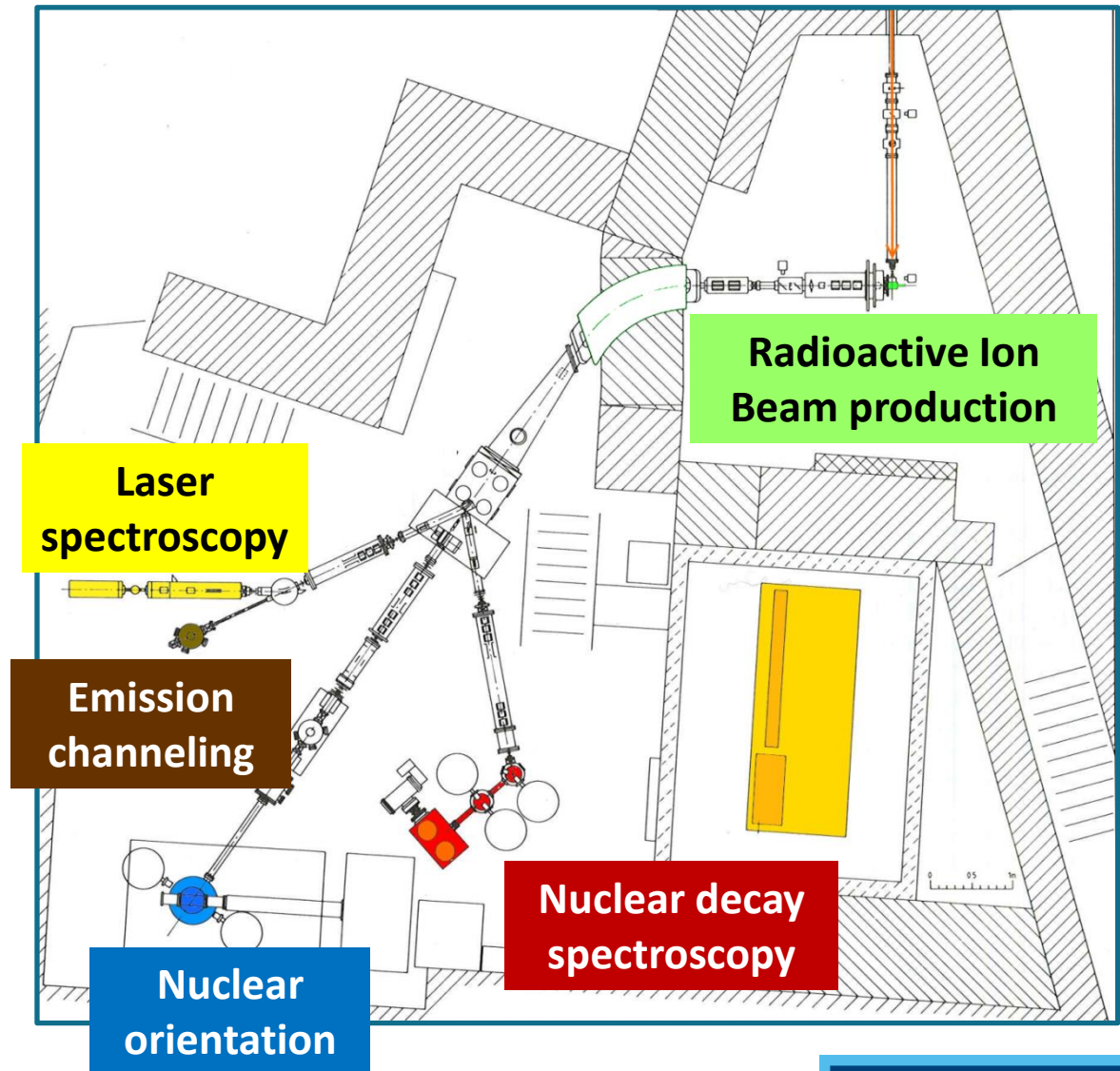
Studies on halo structure  
and reaction dynamics

<i>Element</i>	<i>Half live, <math>T_{1/2}</math></i>	<i>charge state</i>	<i>beam intensity [pps on target]</i>	<i>energy range [MeV]</i>
$^6\text{Helium}$	0.8 s	1+	$9 \cdot 10^6$	5.3 - 18
		2+	$3 \cdot 10^5$	30 - 73
$^7\text{Beryllium}$	53 days	1+	$2 \cdot 10^7$	5.3 - 12.9
		2+	$4 \cdot 10^6$	25 - 62
$^{10}\text{Carbon}$	19.3 s	1+	$2 \cdot 10^5$	5.6 - 11
		2+	$1 \cdot 10^4$	24 - 44
$^{11}\text{Carbon}$	20 min	1+	$1 \cdot 10^7$	6.2 - 10
$^{13}\text{Nitrogen}$	10 min	1+	$4 \cdot 10^8$	7.3 - 8.5
		2+	$3 \cdot 10^8$	11 - 34
		3+	$1 \cdot 10^8$	45 - 70
$^{15}\text{Oxygen}$	2 min	2+	$6 \cdot 10^7$	10 - 29
$^{18}\text{Fluorine}$	110 min	2+	$5 \cdot 10^6$	11 - 24
$^{18}\text{Neon}$	1.7 s	2+	$6 \cdot 10^6$	11 - 24
		3+	$4 \cdot 10^6$	24 - 33, 45 - 55
$^{19}\text{Neon}$	17 s	2+	$2 \cdot 10^9$	11 - 23
		3+	$1.5 \cdot 10^9$	23 - 35, 45 - 50
		4+	$8 \cdot 10^8$	60 - 93
		6+	$3 \cdot 10^7$	171
$^{35}\text{Argon}$	1.8 s	3+	$2 \cdot 10^6$	20 - 28
		5+	$1 \cdot 10^5$	50 - 79

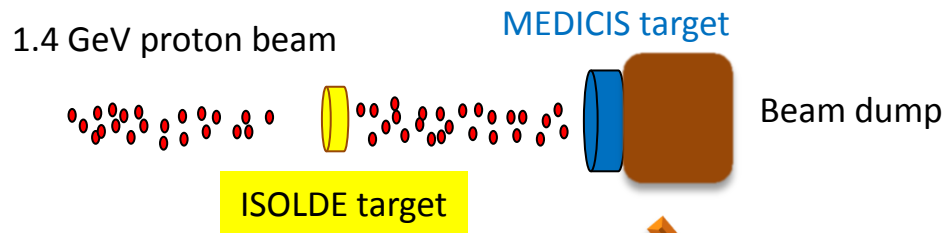
# Cyclotron Research Centre at Louvain-la-Neuve

## LISOL facility (1974-2014)

- Present-day research directions initiated here:
  - decay spectroscopy
  - ground-state properties (laser spectroscopy, nuclear orientation)
  - fundamental interactions (nuclear orientation)
  - solid-state physics
- **RIB production in-gas recoil laser ion source**



# LISOL separator



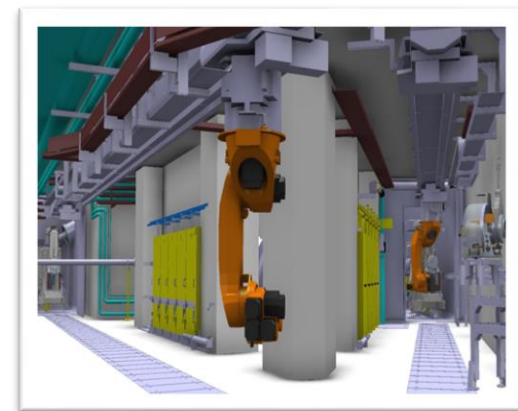
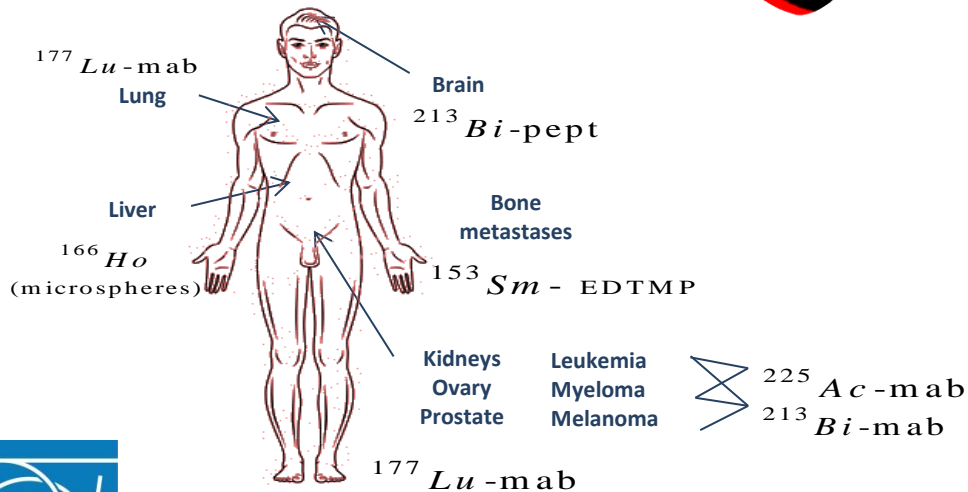
Mass separator  
**LISOL magnet**



Chemical separation



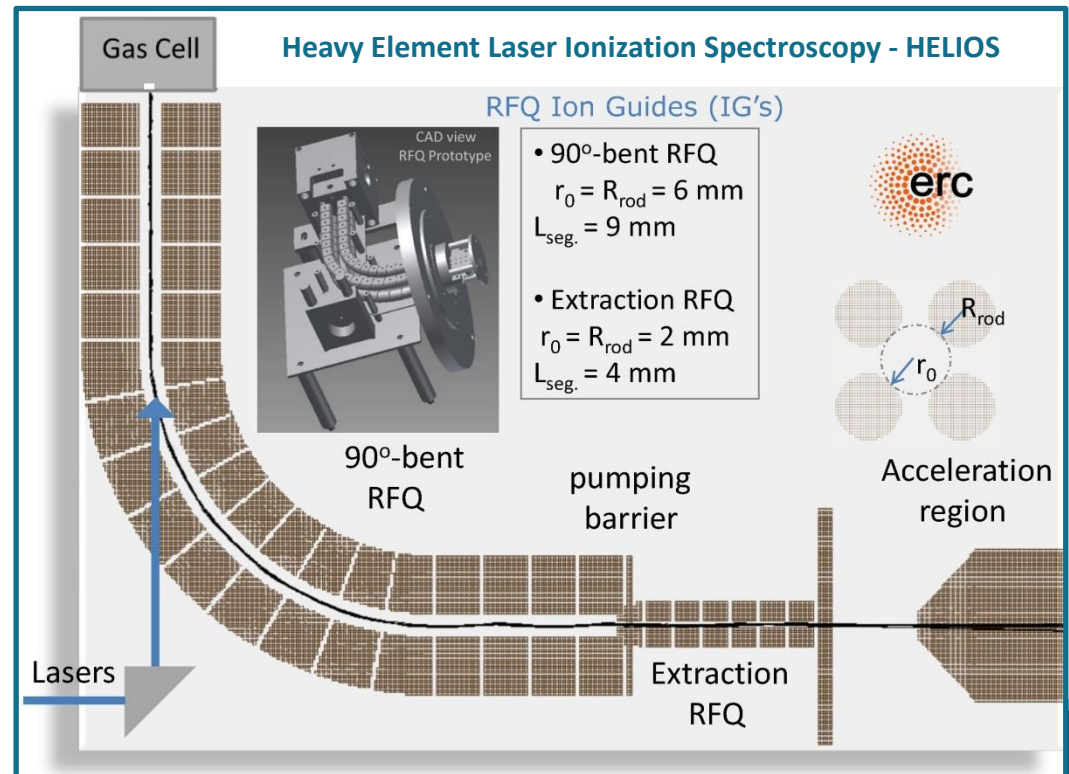
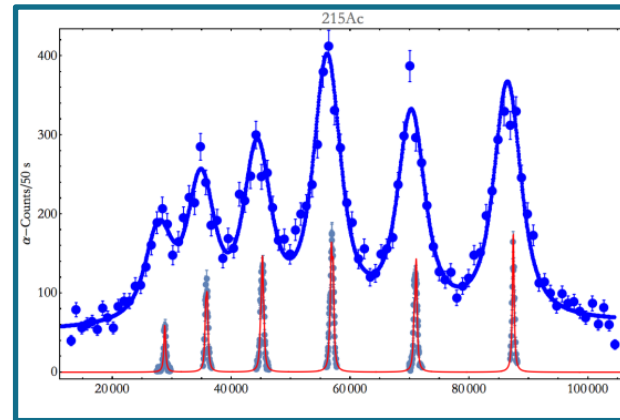
Shipment to hospital



**KU LEUVEN**

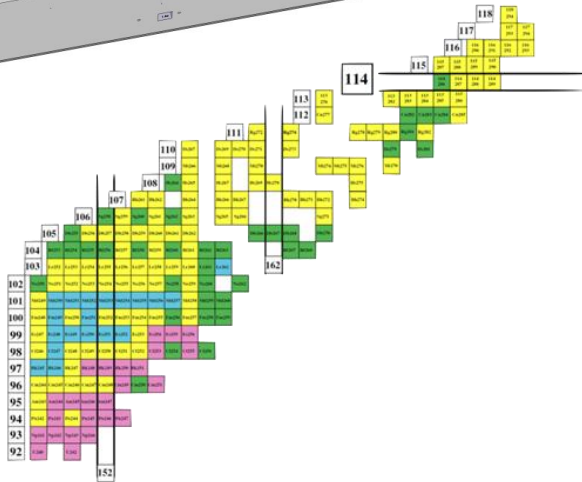
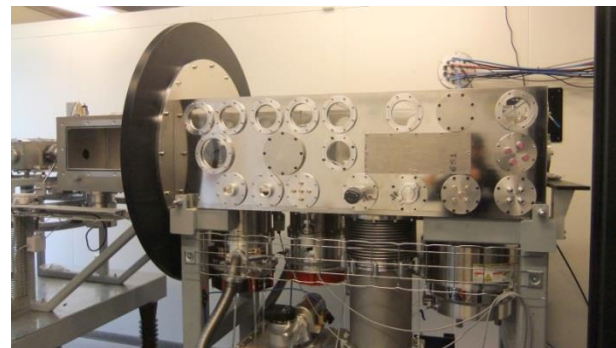
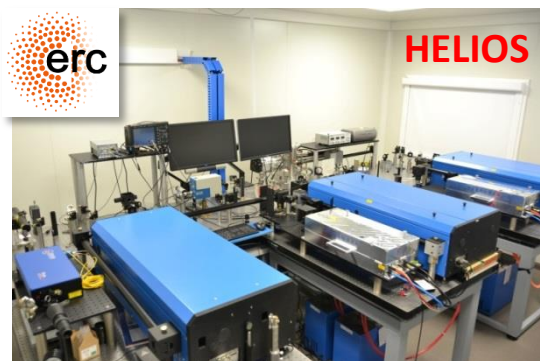
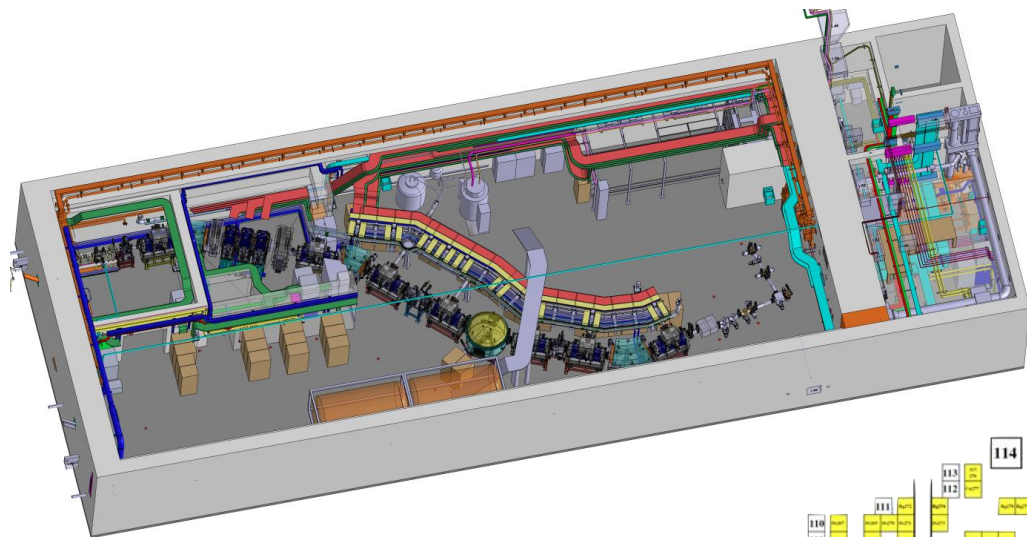
# From in-source to in-jet laser spectroscopy: HELIOS

- **In-source laser spectroscopy**  
fast, efficient  
but low resolution
- **In-jet**  
Strong reduction of broadening effects  
→ improved resolution
- Proof-of-principle:  
 $^{215}\text{Ac}$  at LISOL
- **HELIOS** (ERC PVD)  
Dedicated laser facility at the IKS  
Towards the heaviest elements



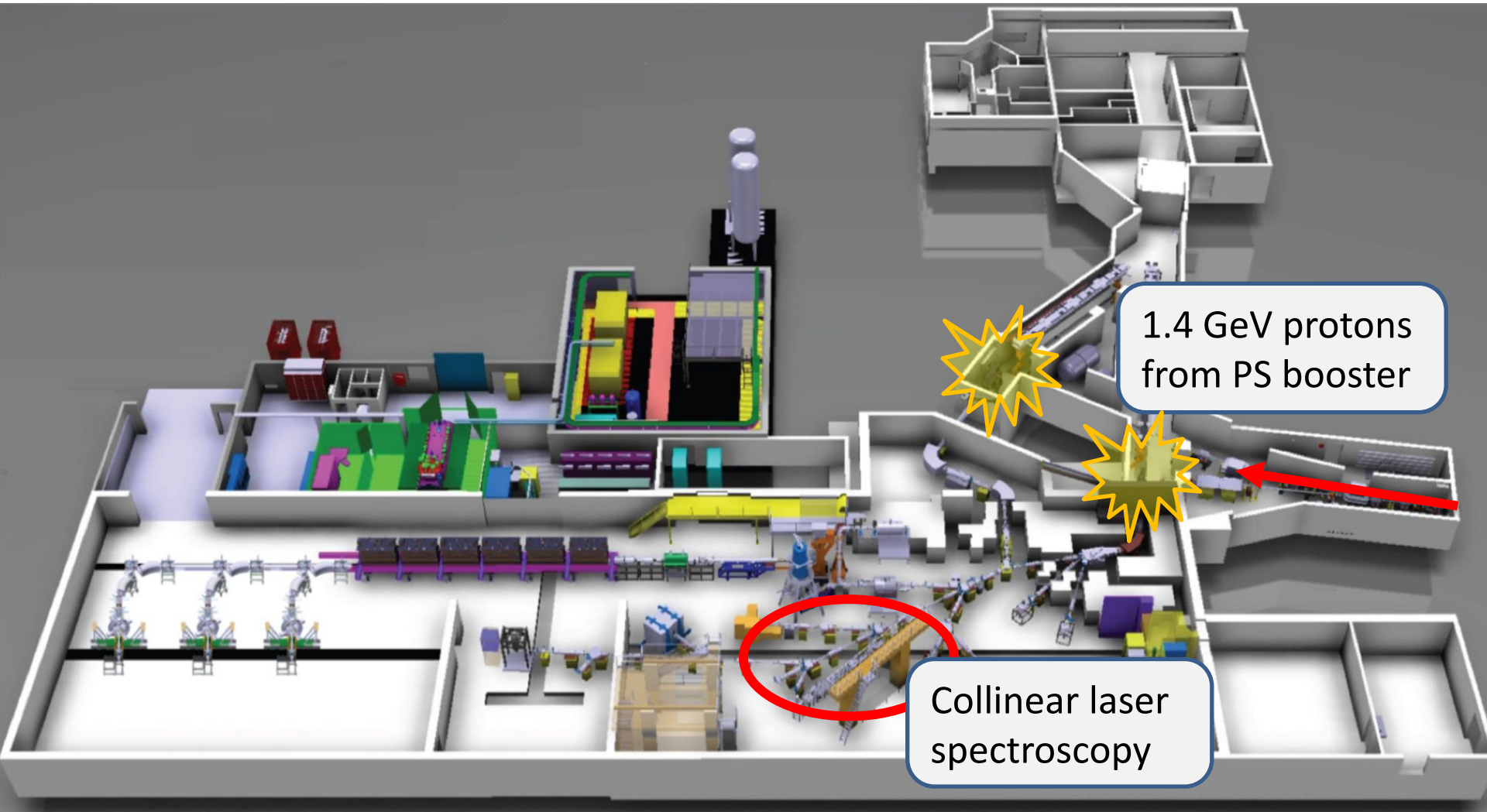
## S3 Low-Energy Branch at GANIL

- Production at the Super Separator Spectrometer S3 (GANIL)
- Laser resonance ionization spectroscopy in the heavy element region
- Mass measurements, isomeric beams, decay studies...



# Collinear laser spectroscopy at ISOLDE

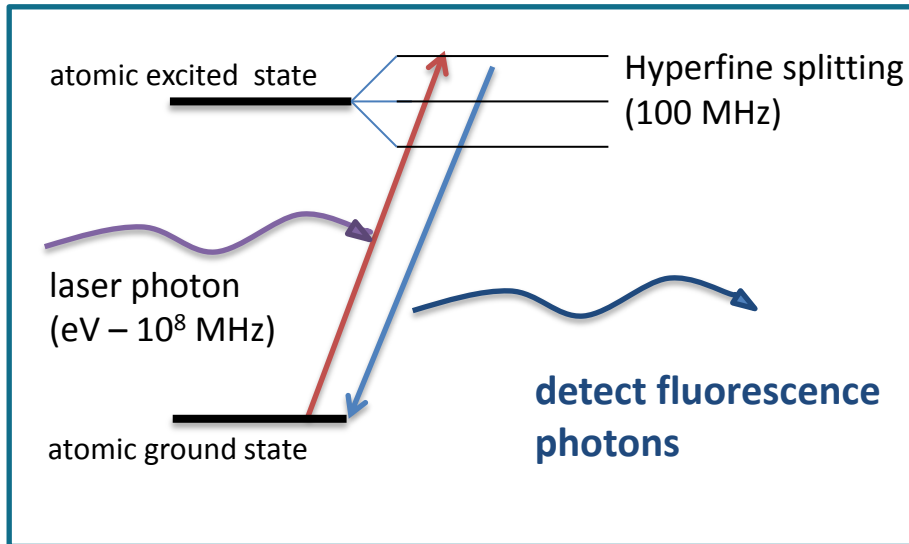
G. Neyens



KU LEUVEN

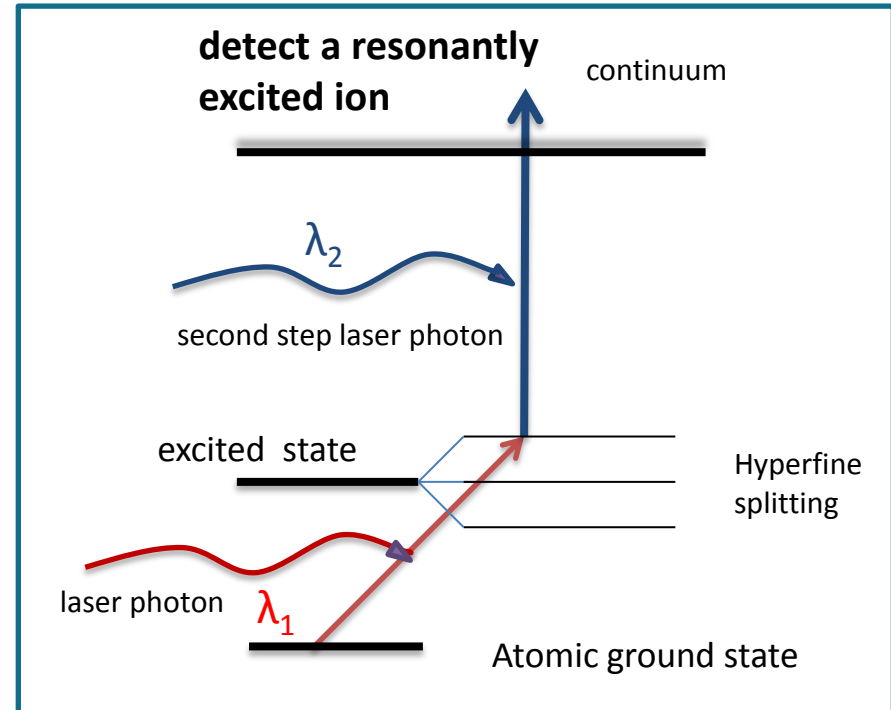
## Two beam lines at ISOLDE

### COLLAPS



- low background (few /s) with bunched beams
- moderate efficiency (0.01%)
- high resolution (~ 40-60 MHz)
- **need about 5.000 ions/s** from ISOLDE
- atoms or ions

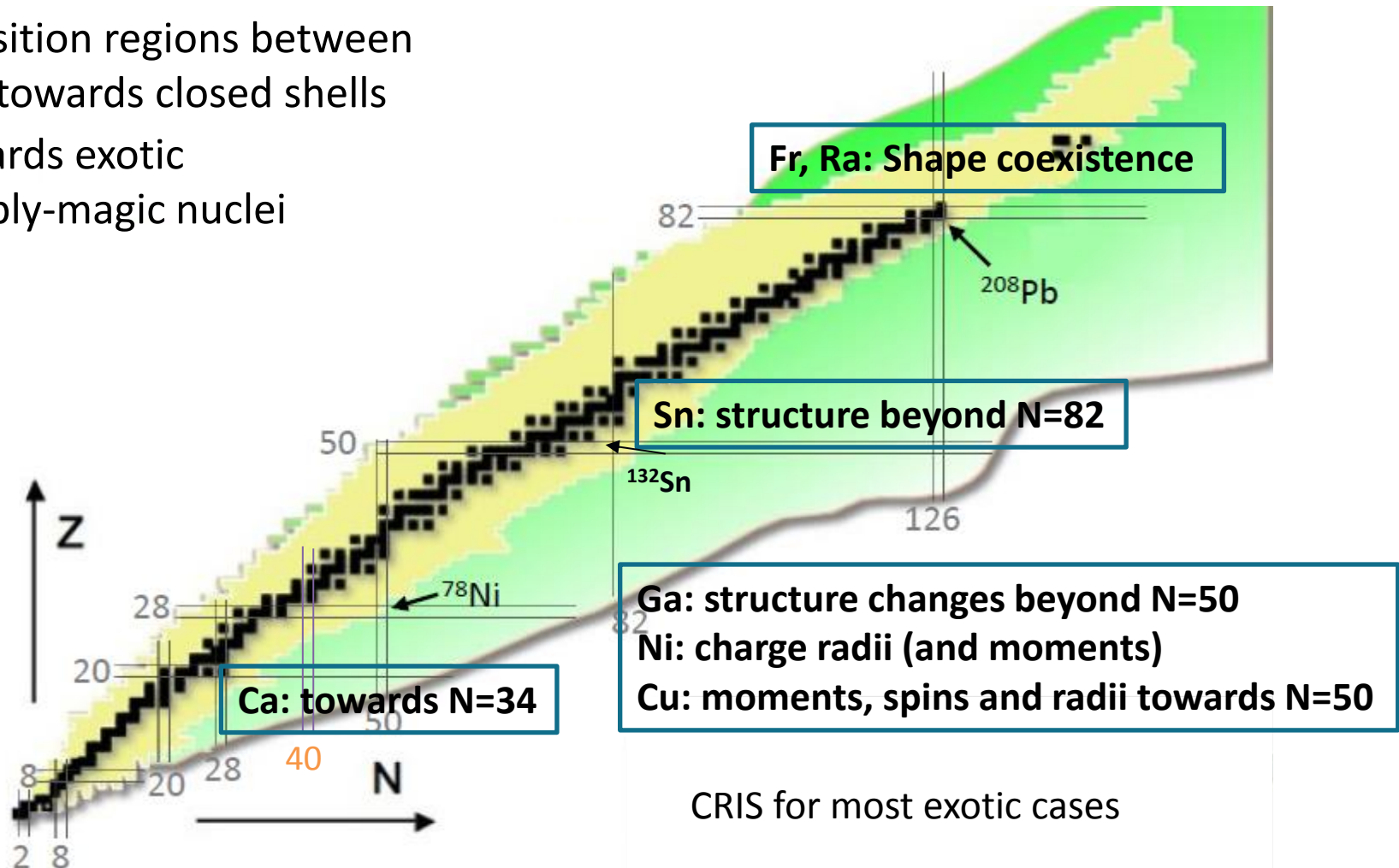
### CRIS



- ultra-low background ( 1 event /10 min)
- high efficiency (~1%)
- high resolution (~ 20-50 MHz)
- **need about 100 ions/s** from ISOLDE
- atoms (and ions)

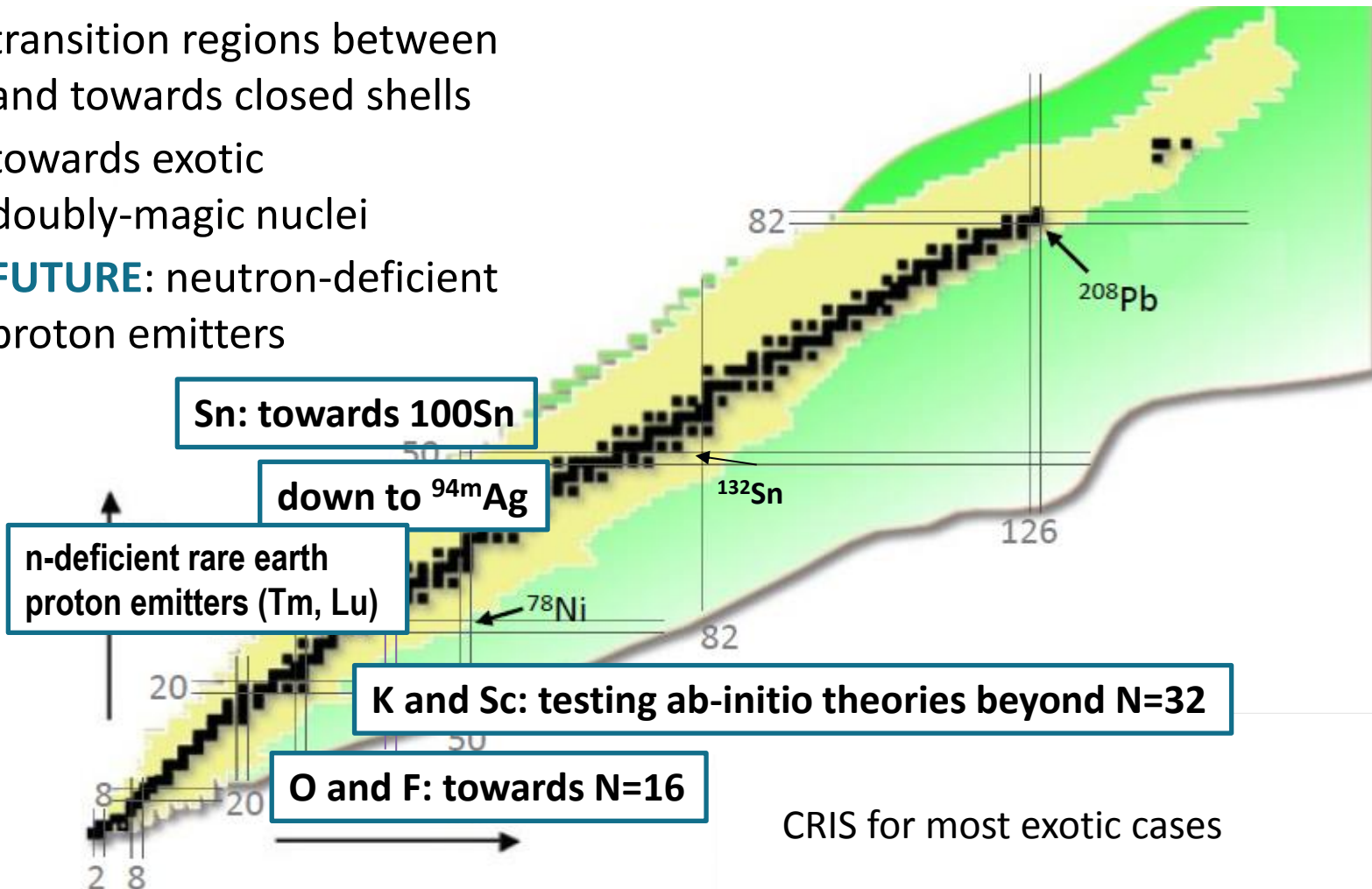
## Current focus

- transition regions between and towards closed shells
- towards exotic doubly-magic nuclei



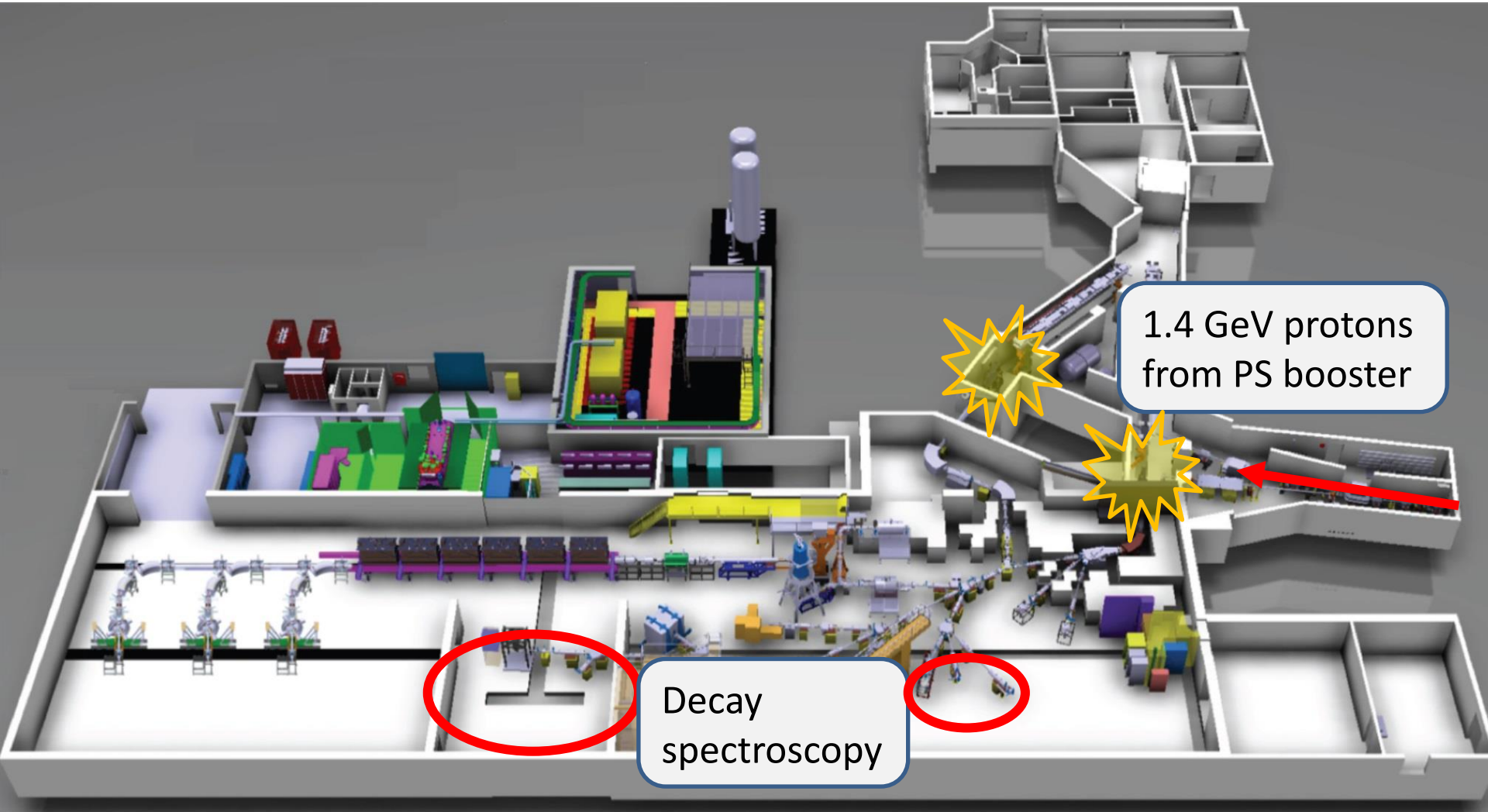
## Current focus

- transition regions between and towards closed shells
- towards exotic doubly-magic nuclei
- **FUTURE**: neutron-deficient proton emitters



# Decay spectroscopy: ISOLDE Decay Station IDS

P. Van Duppen, M. Huyse

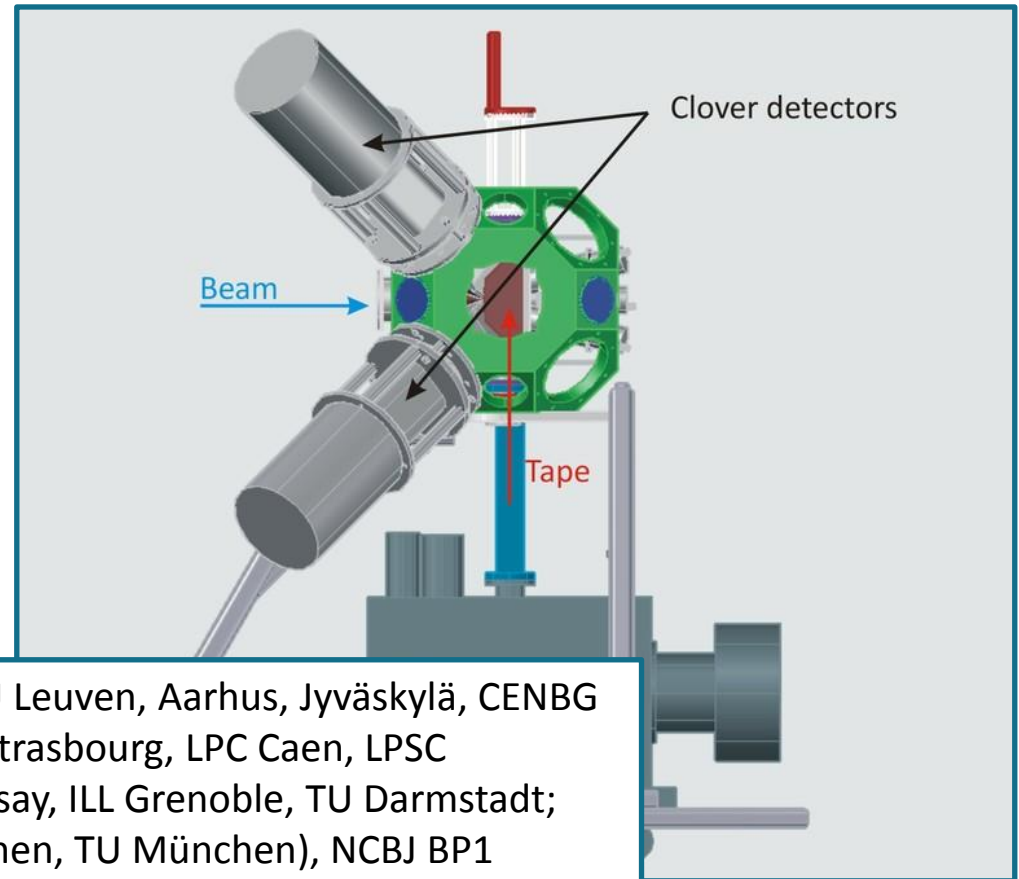


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# Decay spectroscopy: ISOLDE Decay Station IDS

P. Van Duppen, M. Huyse

- Permanent, flexible setup exploiting the ISOLDE RIBs
- Tape station
- Ge clovers + Ge Miniball + ancillary: LaBr<sub>3</sub>, neutron detectors, silicon detectors
- B- $\gamma$ ,  $\alpha$ - $\gamma$ , fast timing, electron spectroscopy...
- Focus from our groups:  
n-rich Ni  
n-poor Pb



Collaboration: KU Leuven, Aarhus, Jyväskylä, CENBG Bordeaux, IPHC Strasbourg, LPC Caen, LPSC Grenoble, IPN Orsay, ILL Grenoble, TU Darmstadt; Köln, LMU München, TU München), NCBJ BP1 Poland, IFIN-HH Bucharest, CIEMAT Madrid, IEM-CSIC Madrid, IFIC-CSIC Valencia, UCM Madrid, Lund, ISOLDE, STFC Daresbury, Liverpool, Manchester, Surrey, York)

**KU LEUVEN**

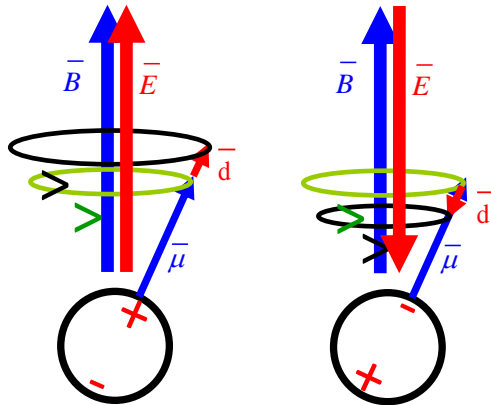
# Fundamental properties of the weak interaction

N. Severijns

## 1. Measurement of the electric dipole moment $d_n$ of the neutron



compare neutron precession frequencies in parallel and antiparallel B- and E-fields



$$\hbar \nu_{\uparrow\uparrow} = 2(\mu B + d_n E)$$

$$\hbar \nu_{\uparrow\downarrow} = 2(\mu B - d_n E)$$

$$\hbar \Delta \nu = 4 d_n E$$

non-zero if  $d_n \neq 0$

### Motivation:

Search for new source of CP violation that could hint to origin of baryon-asymmetry

### Leuven involvement/responsibilities:

- data taking
- Analysis
- (part of) systematic effects
- precision magnetometry (Cs- & K-based)

Precise control of value and stability of magnetic field B is crucial for sensitivity

→ magnetic field compensation & precision magnetometry

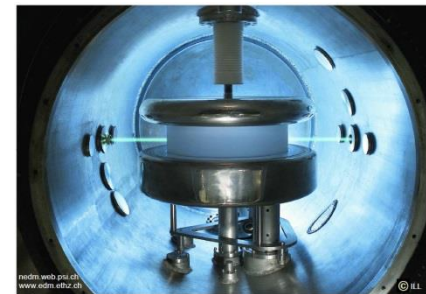
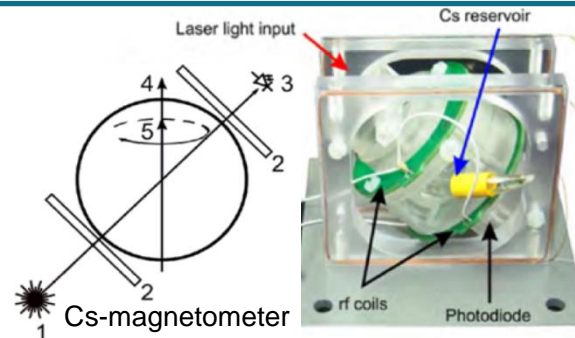
### Status:

- current phase:
  - data taking ongoing;
  - reach existing limit by end of 2015;
  - reach  $\sim 1 \times 10^{-26} \text{ e.cm}$  level by end of 2017
- next phase (2018-2023):
  - improve sensitivity to  $10^{-27} \text{ e.cm}$  level

(present limit (90% CL):

$$d_n < 3.0 \times 10^{-26} \text{ e.cm}$$

S. Afach et al., Phys. Rev. C (2015) accepted)



KU LEUVEN

# Fundamental properties of the weak interaction

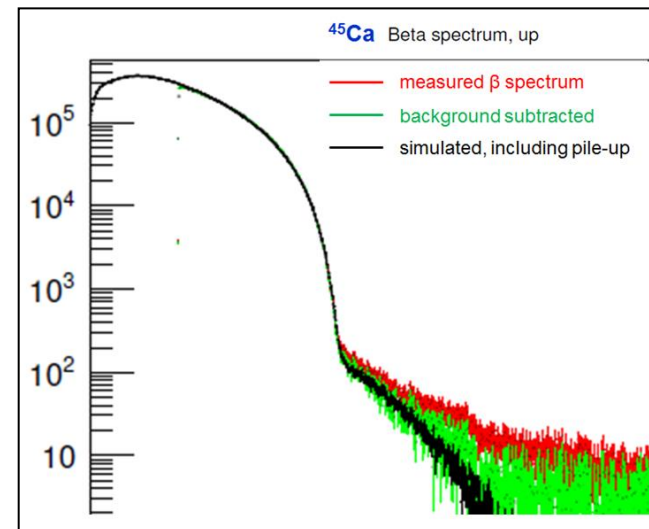
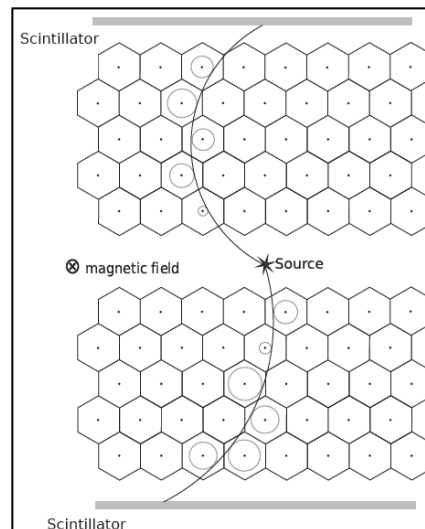
N. Severijns

## 2. Precision $\beta$ -spectrum shape measurements

Leuven, Krakow, MSU-NSCL, LPC Caen...

$$d\Gamma \propto G_F^2 F(Z, E) f(p, E, \Omega) \left[ 1 + k \frac{1}{E_\beta} b_{\text{Fierz}} + k' E_\beta b_{\text{WM}} \right]$$

- **$b_{\text{Fierz}}$ : scalar / tensor type weak currents**  
zero in Standard Model; competitive with LHC for left-handed neutrinos
- **$b_{\text{WM}}$ : weak magnetism**  
Standard Model term; strong interaction effect  
0.1 to 1% change; needs to be known better



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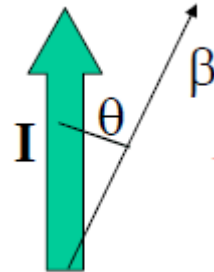
# Fundamental properties of the weak interaction

N. Severijns

## 3. $\beta$ -asymmetry of $^{35}\text{Ar}$ to determine $V_{ud}$ (unitarity)

Leuven, Liège, ISOLDE, Prague, LPC Caen, Michigan...

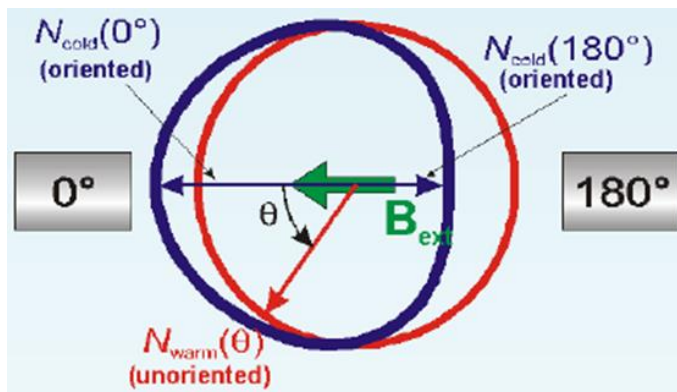
- $V_{ud}$  quark mixing matrix element  $\rightarrow$  CKM unitarity test
- Sensitive to physics beyond Standard Model: scalar currents, heavy Z bosons, etc.
- Competitive with LHC for left-handed neutrinos



e.g. Hardy & Towner, Rep. Prog. Phys. 73 (2010) 046301  
Phys. Rev. C 102 (2009) 142302

Mirror beta transitions offer potential to provide additional data, apart from superallowed Fermi  $\beta$  transitions

O. Naviliat-Cuncic & N. Severijns, Phys. Rev. Lett. 102 (2009) 142302



polarization by:

- collinear optical pumping at ISOLDE (1ste phase)
- in a Magneto Optical Trap (coll. Ulg; later phase)

$A(^{35}\text{Ar})$  is best candidate:

$$\Delta A/A = 0.5\% \rightarrow \Delta V_{ud} = 0.0004$$

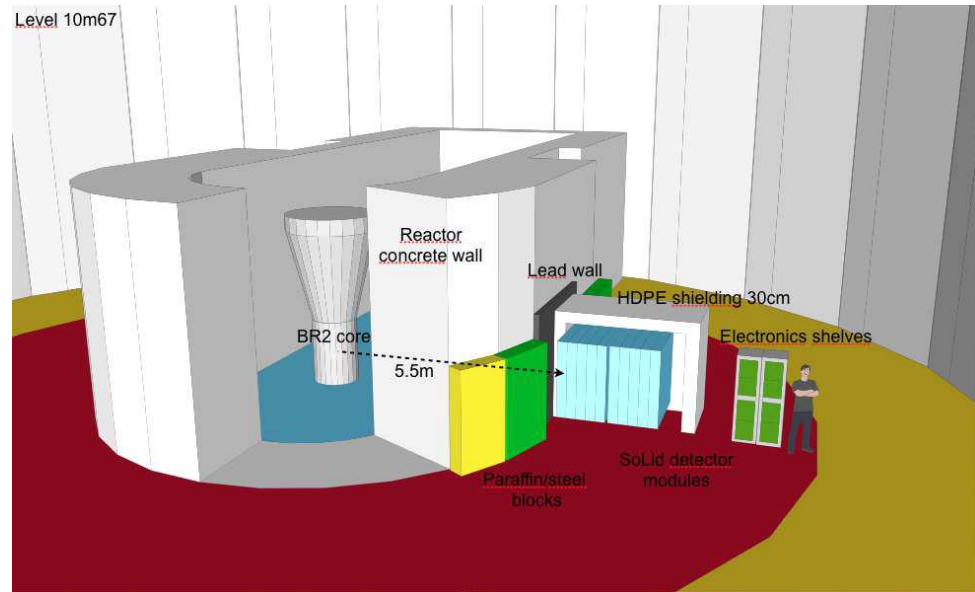
(Note:  $\Delta V_{ud} (0+ \rightarrow 0+) = 0.00022$ )

N. Severijns & O. Naviliat-Cuncic, Phys. Scr. T152 (2013) 014018

KU LEUVEN

# SoLid project at SCK•CEN

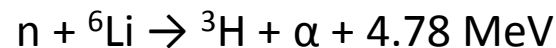
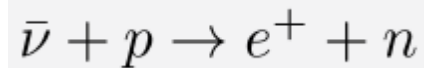
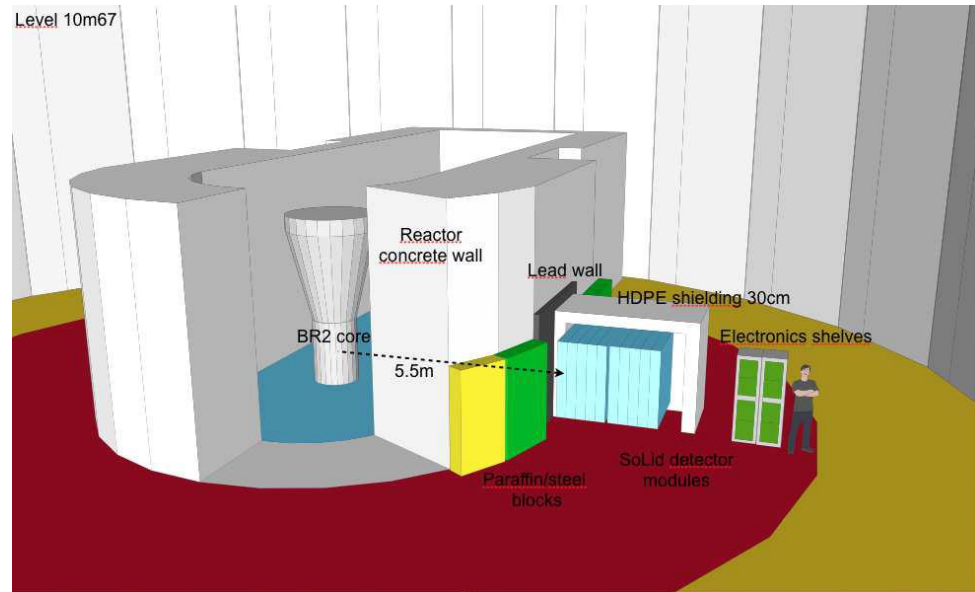
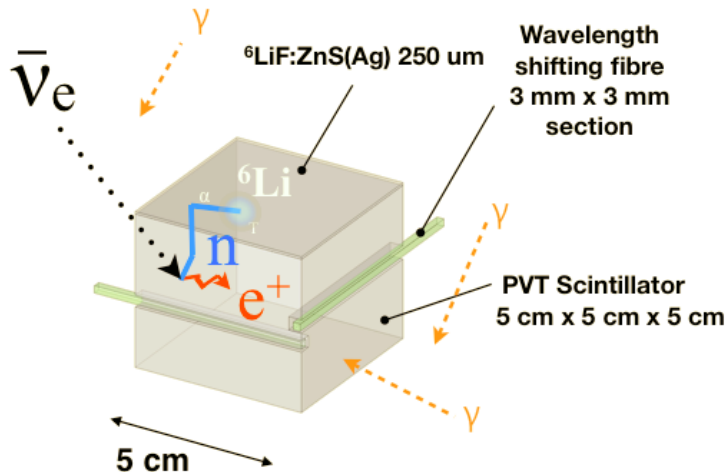
- Deficit of anti- neutrinos in several experiments at nuclear reactors (after recent analysis)  
→ existence of fourth 'sterile' neutrino??
- SoLid: Short baseline Oscillation search with Lithium-6 Detector
  - BR2: very compact core
  - Detector planes close to reactor
  - Low background conditions
  - Unique detector technology: excellent background discrimination



# SoLid project at SCK•CEN

- Segmented scintillator detector array  
**novel detector design**

- Solid detectors
- 5x5x5 cm cubes:  
detection of positrons and neutrons
- 24 x 24 x 40 detectors
- Light collection  
by multi-pixel photon counter



# Post-accelerated ion beams: HIE-ISOLDE

RR, P. Van Duppen, M. Huyse

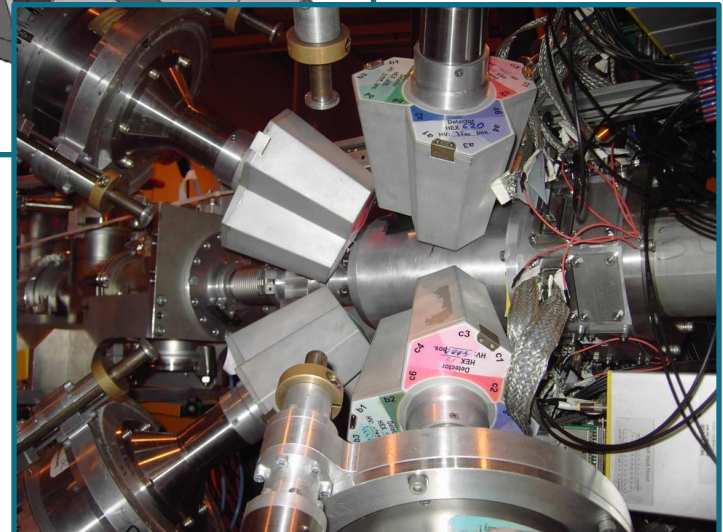
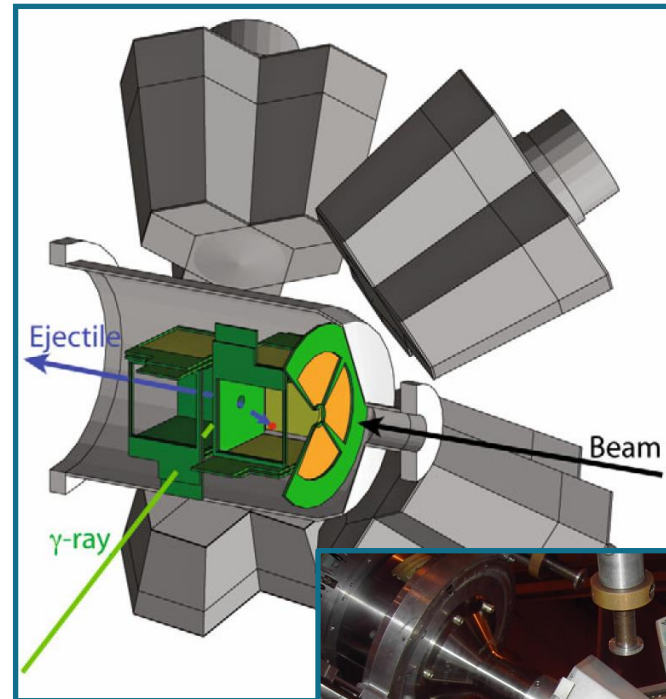
- 4 MeV/nucleon from Oct 2015
- 10 MeV/nucleon from 2017



# Miniball + Si: Coulomb excitation, transfer reactions

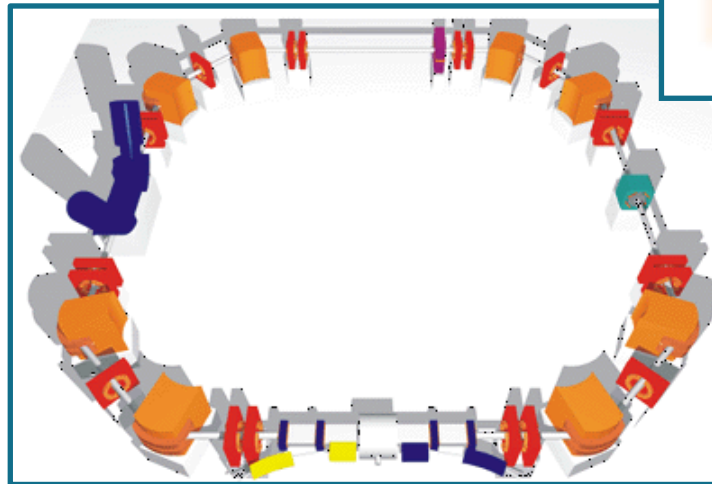
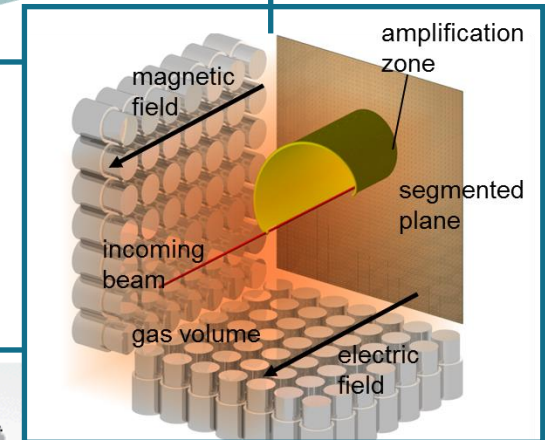
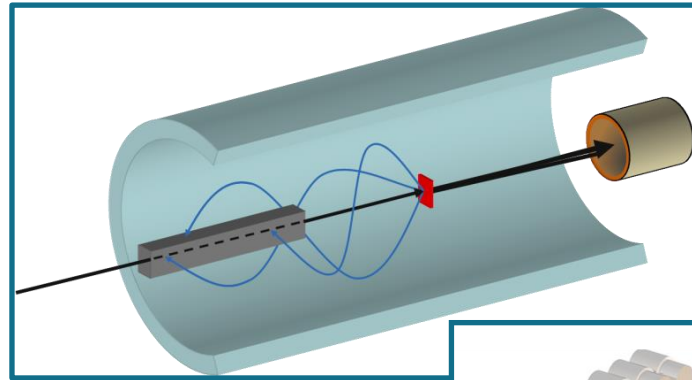
RR, P. Van Duppen, M. Huyse

- $^{80}\text{Zn}$   
J. Van de Walle et al, PRL 99, 142501 (2007)
- $^{68,70}\text{Cu}$   
I. Stefanescu et al., PRL98, 122701 (2007)
- $^{182-188}\text{Hg}$   
N. Bree et al, PRL 112, 162701 (2014)
- $^{66}\text{Ni}(\text{d},\text{p})$   
J. Diriken et al, PLB 736, 533 (2014)  
J. Diriken et al, PRC 91, 054321 (2015)
- $^{66}\text{Ni}(\text{t},\text{p})$   
J. Elsevier et al, to be submitted



# Instrumentation

- IDS
- VITO at ISOLDE (polarised beams)
- DESIR at GANIL
- Miniball+Si upgrade
- Helical Orbit Spectrometer
- Active target:  
**SpecMAT** (ERC RR)
- Storage Ring at ISOLDE



# Summary

- Strong links with theory groups in Belgium and abroad
- Expertise in
  - RIB production and handling
  - decay spectroscopy
  - laser spectroscopy
  - Coulex and direct reactions
- To study
  - nuclear structure far from stability (shell evolution, shape coexistence)
  - properties of weak interaction
- Strongly European-oriented (ISOLDE, GANIL, PSI, SPES, GSI, Jyväskylä...)