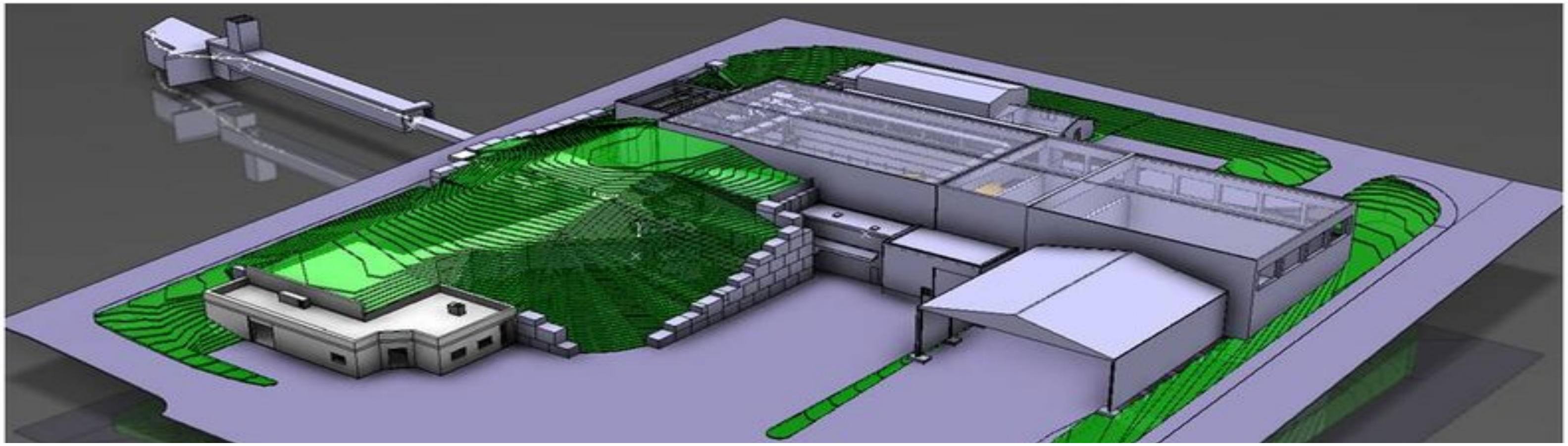
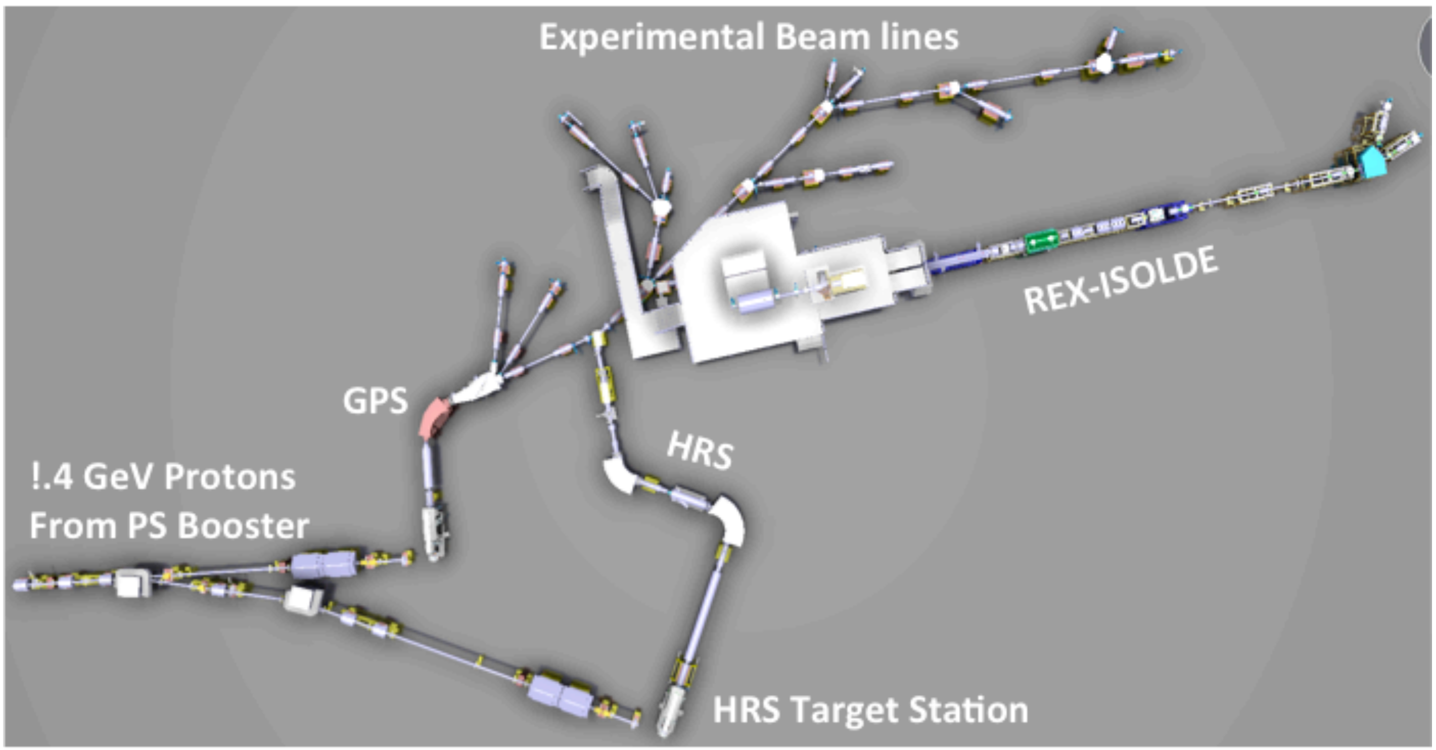
CERN/ISOLDE: TNA6



Yorick Blumenfeld / Maria J. G. Borge , CERN, PH-Dept

ISOLDE Facility

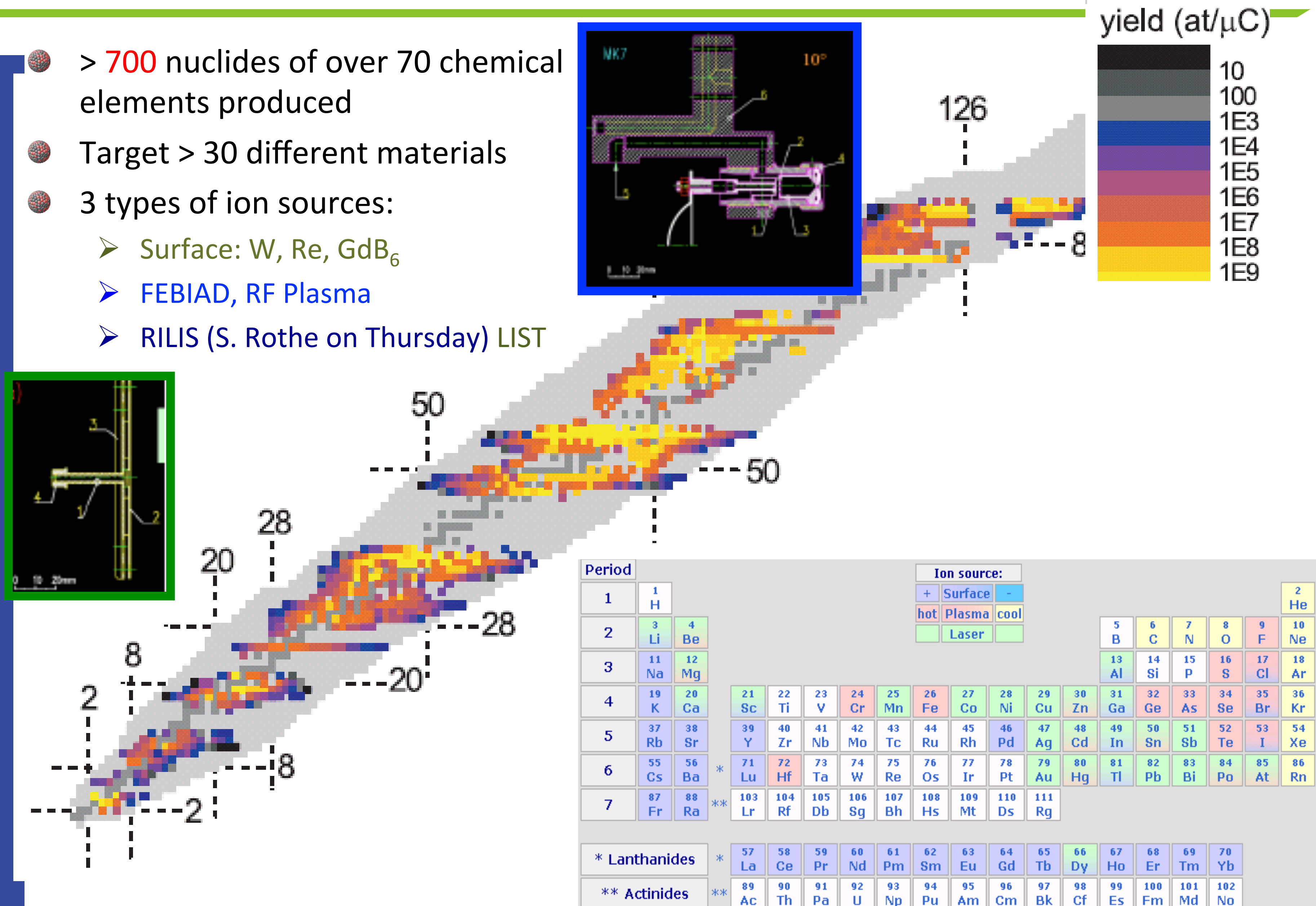
- ISOLDE is the CERN radioactive beam facility
- Nuclei produced via reactions of high intensity high energy proton beam with thick and heavy targets
- Provides low energy or post-accelerated exotic beams



PSB upgrade (2018)
intensity (2uA -> 6uA)
energy (1.4 -> 2GeV)

Produced Nuclei

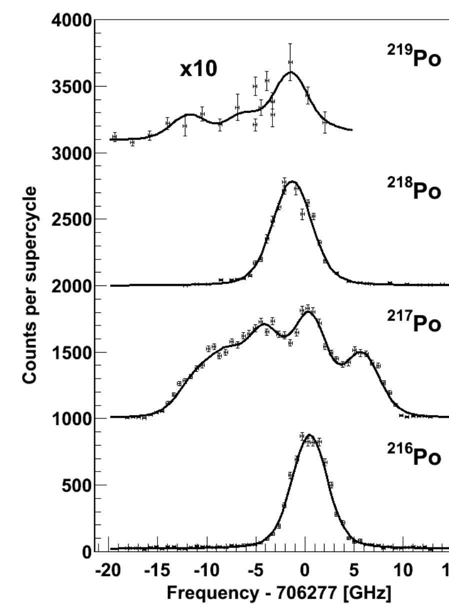
- > 700 nuclides of over 70 chemical elements produced
- Target > 30 different materials
- 3 types of ion sources:
  - Surface: W, Re, GdB_6
  - FEBIAD, RF Plasma
  - RILIS (S. Rothe on Thursday) LIST

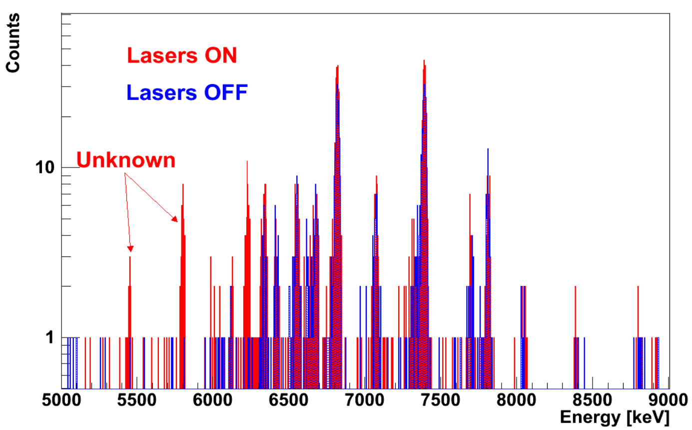


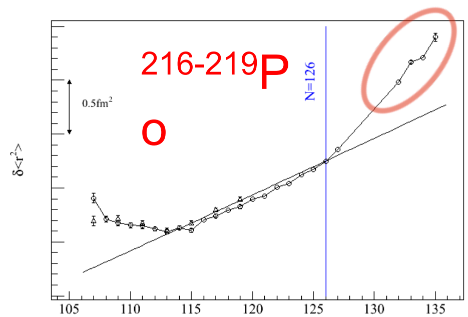
Going beyond the limits with the LIST

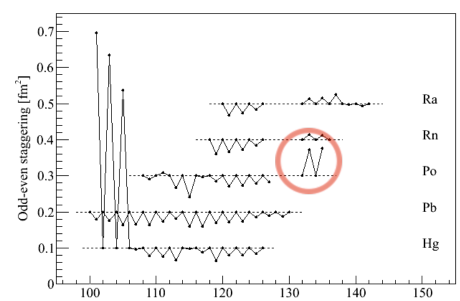
- Neutron-rich beams at ISOLDE are limited by the high isobaric contamination from Fr and Ra.
- The Laser Ion Source Trap can suppress those beams by up to a factor 2000.
- The first decay spectroscopy of ^{219}Po has been performed as well as hfs studies on $^{216\text{-}219}$Po thanks to the suppression of $^{213,218\text{-}220}$Fr

IS456 - Po in-source laser spectroscopy - 2012 LIST campaign









D.Fink, Ph.D thesis U. of Mainz

TNA Selection (TNA6)

- Two types of funding:
  - Travel and subsistence for visiting scientists

  - Partial reimbursement of access costs
    - ✓ 50% technician 2 years (extension of Julien Thiboud contract)
      - Help users in installing experiments, alignment, vacuum
      - Coordinate the orders of cryogenic supply
      - 10% of his time in target building.

    - ✓ Applied fellow for 2 years: Jan Kurcewicz (Dec 1st, 2011)
      - Develop a versatile DAQ for ISOLDE

TNA Selection (TNA6)

- Travel and subsistence for visiting scientists: Selection Committee
  - Maria J G Borge (CERN, Isolde Physics Group Leader)
  - Yorick Blumenfeld (IPN-Orsay, Chair of ISOLDE collaboration committee)
  - Peter Butler (Liverpool, INTC Chair)
  - Magdalena Kowalska (CERN, ISOLDE Physics coordinator)
  - Karl Johnston (Saarbrucken/CERN, ISOLDE Solid State Coordinator)
  - Karsten Riisager (Aarhus)
- Administration: Jennifer Weterings (paid By the Collaboration)
- Two calls per year to scheduled experiments (April-August and September to December)
- All experiments are in principle eligible since Int. Organizations are not required to follow the "Foreign Spokesperson" rule
- Priority is given to young scientists (from master students to post-docs) and new users. Less than 1/3 of the days attributed to permanent scientists.
- ALL Money DISTRIBUTED BETWEEN Sept 2010 – Dec 2012

STATISTICS Until April 1, 2011

Number of beam hours-Full Contract	5200
provided as of 31/03/11	994
Number of users- full contract	400
Supported as of 31/03/11	55
Number of days support- full contract	2800
Supported as of 31/03/11	380
Number of projects – full contract	60
Supported as of 31/03/11	12
T&S – full contract (EUR)	252000
Distributed as of 31/03/11	43700
Number of Experiments / researchers	12 / 55
Rate of days per experiment	4.6 researcher / exp
Access costs – full contract (EUR)	291408
	65644 (994h x 56,04)

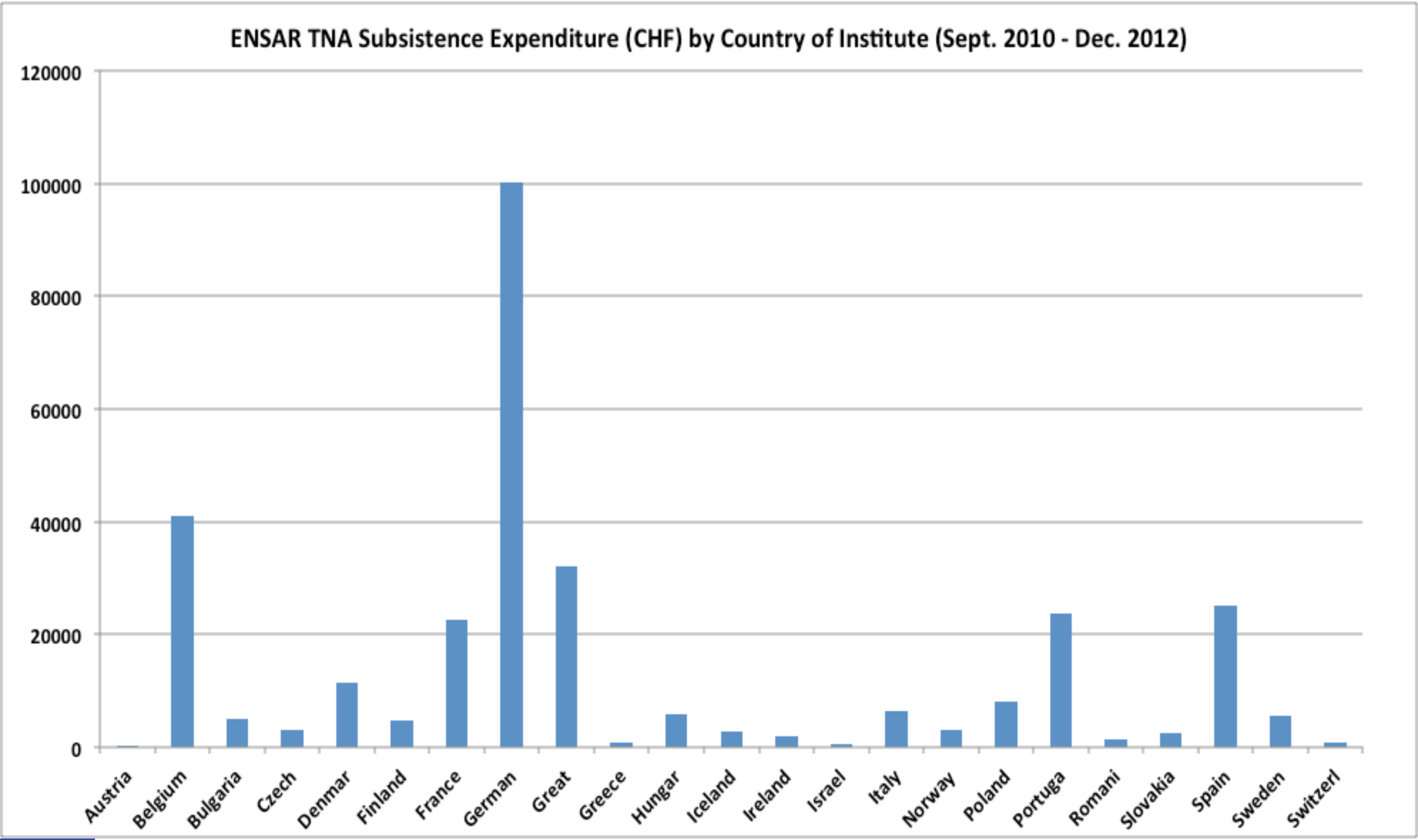
STATISTICS Until April, 2013

Number of beam hours-Full Contract	**5200**
provided as of 31/12/12	6946,4
Number of users- full contract	400
Supported as of 31/12/12	352 (User counted 1 per IS-exp)
Number of days support- full contract	2800
Supported as of 31/12/12	2244
Number of projects – full contract	60
Supported as of 31/12/12	75 (different experiments)
T&S – full contract (EUR)	252000
Distributed as of 31/12/12	256947 (309672CHF)
Number Experiments / researchers	75 / 352
Rate of days per experiment	4.69 researcher / exp
Access costs – full contract (EUR)	291408
Access costs up to 31/12/12	389276 (= 6946,4 x 56,04)

TransNational Access Sep 2010 - Dec 2012

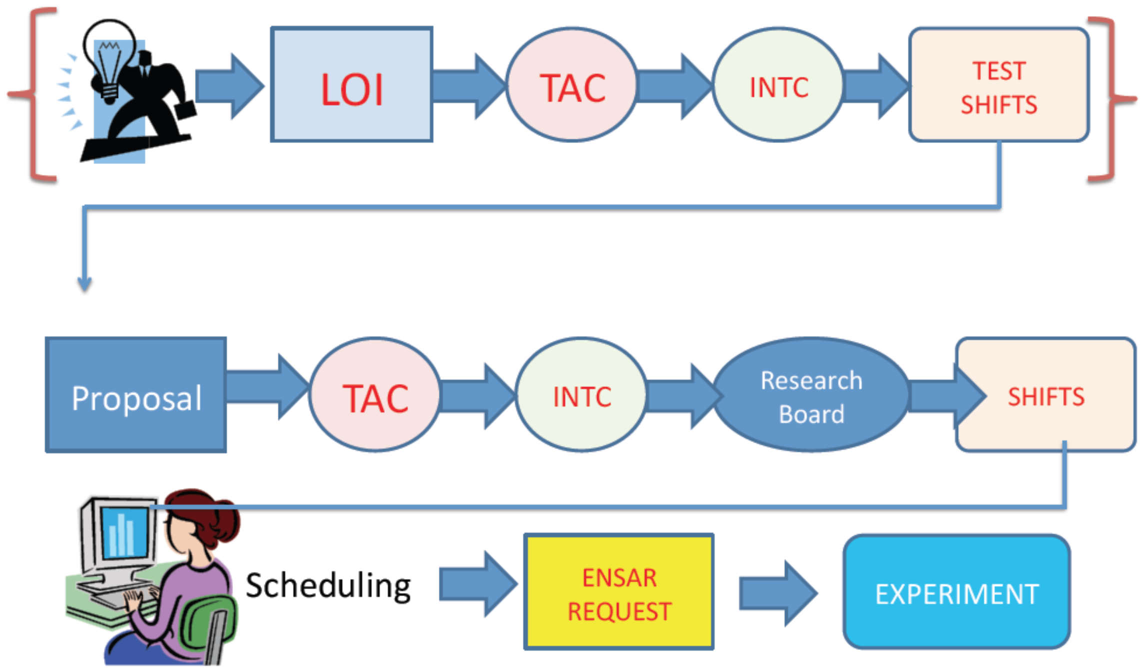
Year	Money Expended	N. Exp covered	Exp Number (number of people)	Num people covered	Rate people /exp
2010	52440 (43700)	12	IS430(6); IS447(4); IS449(6); IS453(3); IS463(2); IS481(2); IS487(3); IS488(3); IS491(15); IS498(2); IS499(6); IS501(3)	55	4,61
2011	118266 (96939)	44	IS413(4); IS433(4); IS441(2); IS445(2); IS448(3); IS451(7); IS453(8); IS457(4); IS463(3); IS466(5); IS471(2); IS473(3); IS475(4); IS476(3); IS477(6); IS478(3); IS481(3); IS482(3); IS483(6); IS484(3); IS485(4); IS487(3); IS489(3); IS492(4); IS494(5); IS496(5); IS497(4); IS498(3); IS500(1); IS501(4); IS504(7); IS506(2); IS507(3); IS510(4); IS511(4); IS515 (7); IS517(3); IS518(3); LoI21(3); LoI31(2); LoI32(7); LoI86(3); LoI87(4); LoI88(1)	178	4,04
2012	140174 (116308)	47	IS433(2); IS437(2); IS453(1); IS456(5); IS471(4); IS4373(8); IS475(3); IS476(2); IS478(5); IS479(5); IS481(2); IS482(1); IS484(1); IS487(2); IS488(1); IS489(1); IS495(5); IS496(3); IS497(5); IS498(3); IS501(1); IS505(5); IS506(3); IS508(5); IS509(2); IS510(2); IS512(4); IS515(1); IS518(2); IS520(7); IS524 (6); IS528(1); IS529(3); IS530(6); IS532 (5);IS534(6); IS535(5); IS336(6); IS537(8); IS539(5); IS540(1); IS541(7); IS543(4); IS545(2); LoI83(2); LoI132(2); LoI144(1)	163	3,46

Summary of Expenditure per country



Procedure & Meetings of the INTC

- ISOLDE and Neutron time of Flight Experiments Committee
  - 11 External members including the Chairman
  - 2 referees per proposal
  - Max 6 pages to describe the proposal
  - The INTC recommends
  - The CERN Scientific Board approves beam.



- Meetings 2010-2013
  - 4-5 February 2010
  - 23-24 June 2010
  - 4-5 November 2010
  - 2-3 February 2011
  - 6-7 July 2011
  - 3-4 November 2011
  - 1-2 February 2012
  - 31 Oct – 1 November 2012 (Only HIE-ISOLDE)
  - 26-27 June 2013

INTC Members (2013)

External members **2011-2012**

Chairman: Peter Butler

Scientific Secretary: Magdalena Kowalska

N Alahari, J Billowes, PAButler, U Habermeier, P-H Heenen, R Julin, N Orr, D Ridikas, Z Salman, C Scheidenberger, J Vaagen

Members exchange in half every 2 years, total period 4 years:

2013

Chairman: Klaus Blaum

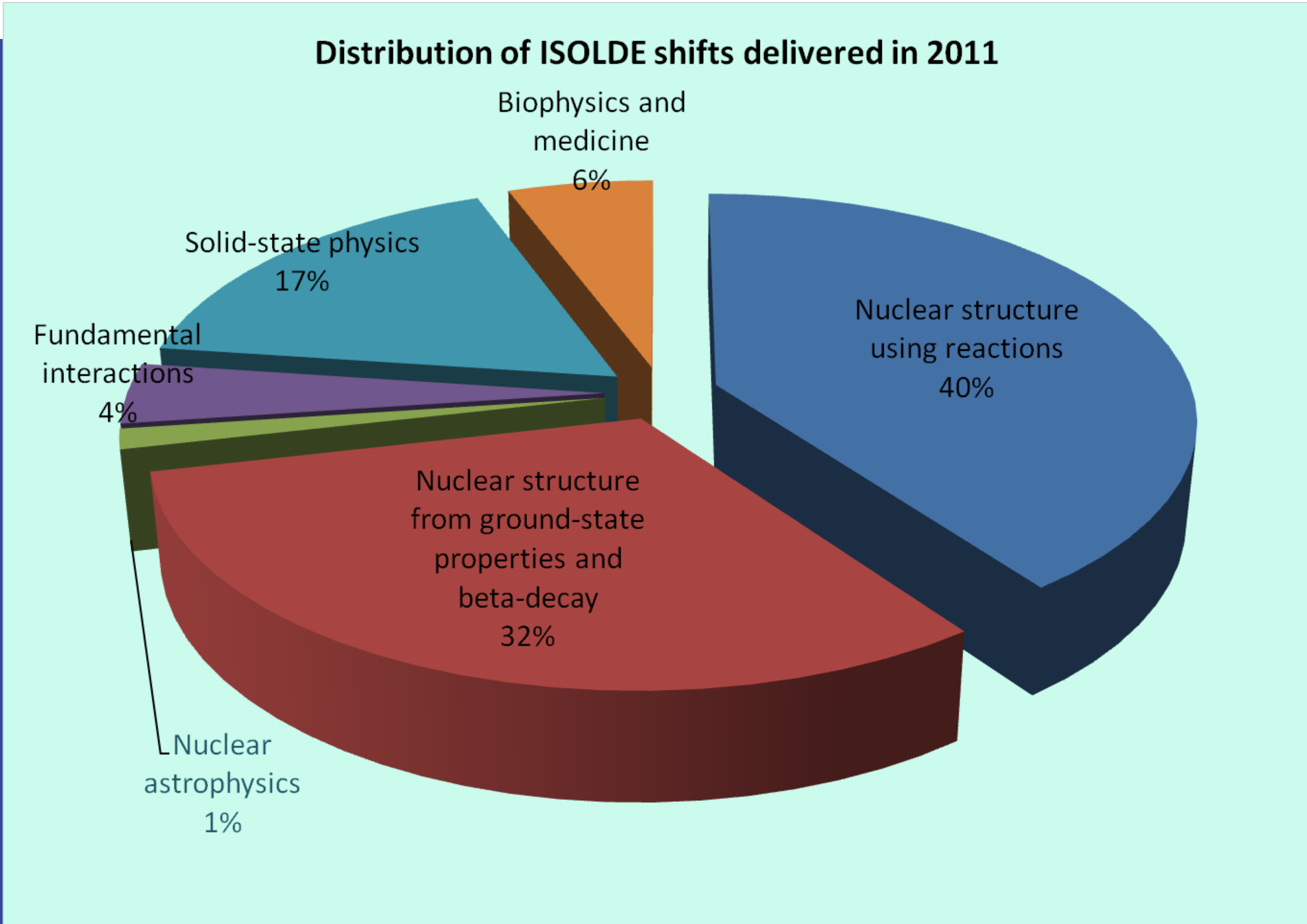
Scientific Secretary: Magdalena Kowalska

ALAHARI, Navin	GANIL, Caen. France
BLANK, Bertram	CEN Bordeaux-Gradignan, France
BAUM, Klaus	Max-Planck-Institut f. Kernphysik, Heidelberg, Germany
BLOCK, Michael	GSI Helmholtzzentrum f. Schwerionenforschung GmbH, Germany
CATFORD, Wilton	University of Surrey, U.K.
DE ANGELIS, Giacomo	INFN Lab. Naz. di Legnaro, Italy
DOBACZEWSKI, Jacek	University of Jyväskylä, Finland & University of Warsaw, Poland
KOWALSKA, Magdalena (**Scientific Secretary**)	CERN, PH-SME (ISOLDE Physics Coordinator)
MCGLYNN, Enda	University of Dublin, Ireland
RIDIKAS, Danas	CEA Saclay, IRFU/SPhN, France; presently on leave to the IAEA
SALMAN, Zaher	PSI, Zürich, Switzerland
VAAGEN, Jan	Universitetet i Bergen, Norway

PUBLICATIONS

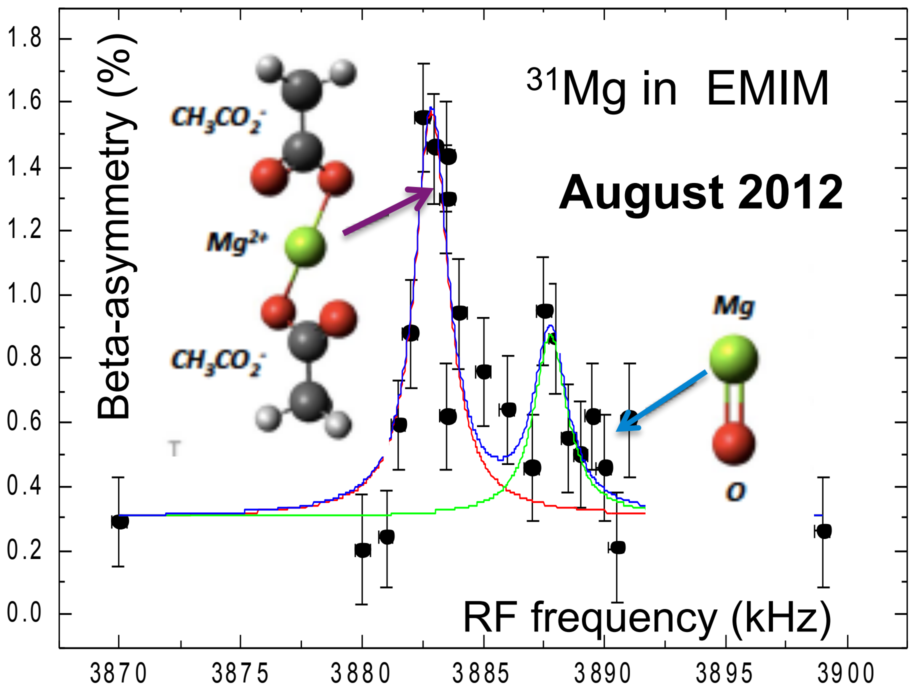
YEAR	N. PUBLICATIONS	PH. D thesis
2010	67	V. Bilstein T.E. Cocoolios R. Domínguez Reyes D. Fink S. Naimi D. Neidherr K. Wimmer
2011	49	M. Albers J. Lommen O. Müller M. Thürauf M. Zboril
2012	62	Ch. Borgmann E. Estevez J.G. Johansen T. E. Mølholt A.B. Perez Cerdán M. Seidlitz M. Stachura
2013	17……	P. Kessler B. Siebeck

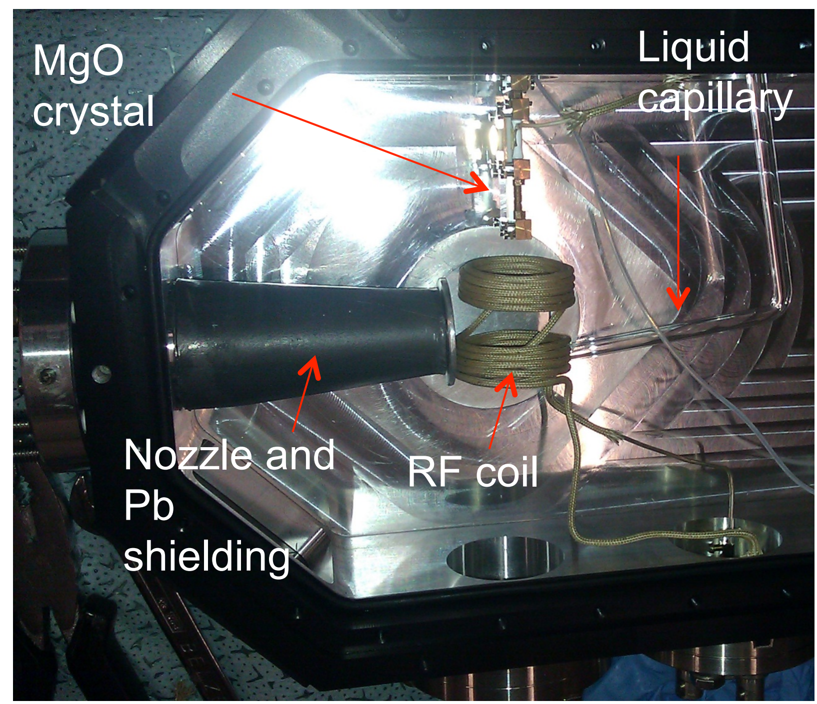
Experimental hall



First beta-NMR in a liquid sample: proof of principle experiment

- Motivation: study of metal-ion interaction with biomolecules
- Probe nucleus: $^{31}Mg^{+}$ -> spin 1/2, half-life 230 ms, ca. $5*10^5$ ions/s
- Sample: ionic liquid (EMIM)
- Spin polarization via optical pumping with lasers
- Beta-decay asymmetry observed up to 0.1 mbar pressure above liquid

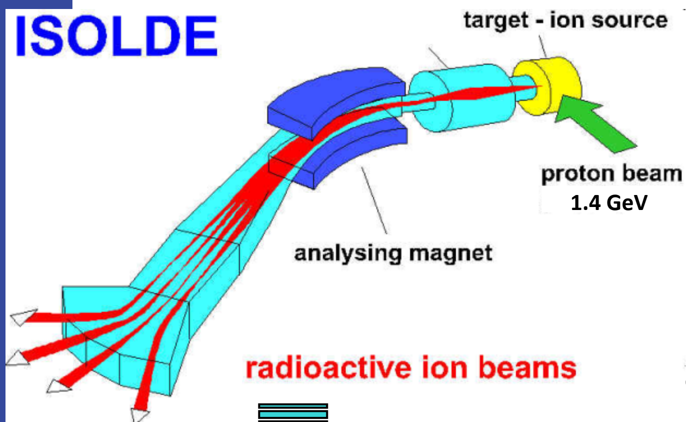




M. Stachura, A. Gottberg, M. Kowalska, L. Hemmingsen (Copenhagen, CERN, Madrid) and COLLAPS collaboration

New medical isotopes

i. Collection at ISOLDE

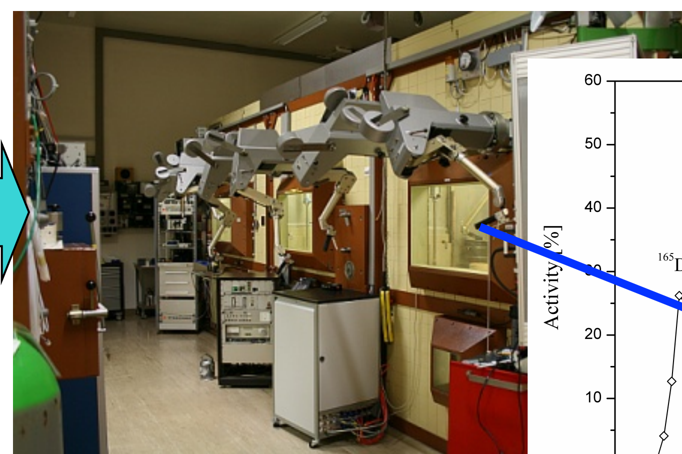


iv. Injection into mouse

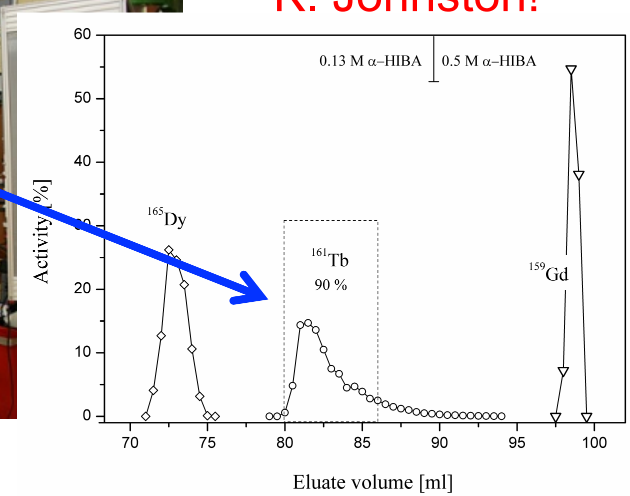
v. PET/SPECT imaging and tumor treatment

ii. Shipping to PSI

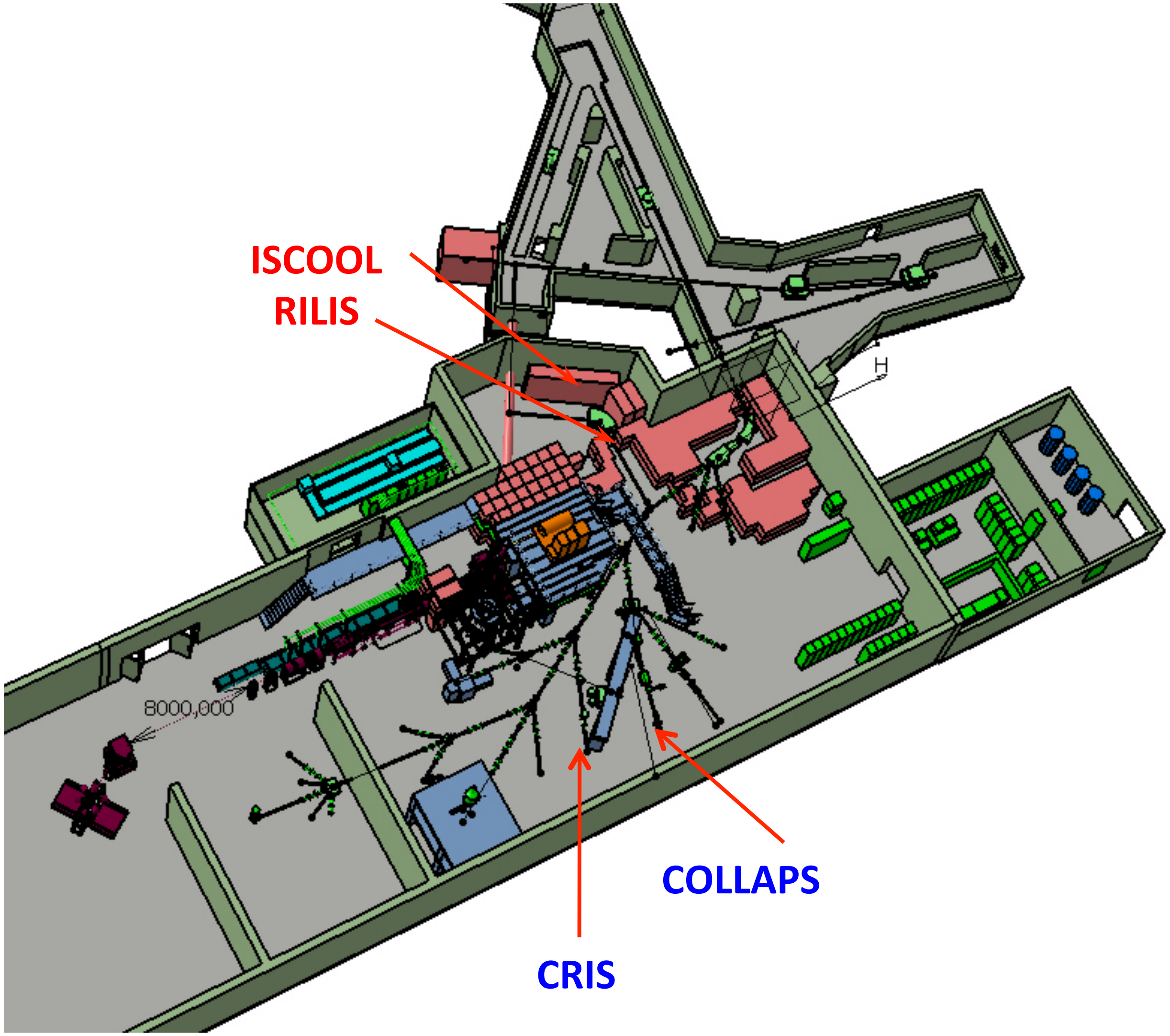
iii. Radiochemical purification and labeling



Presented By K. Johnston!



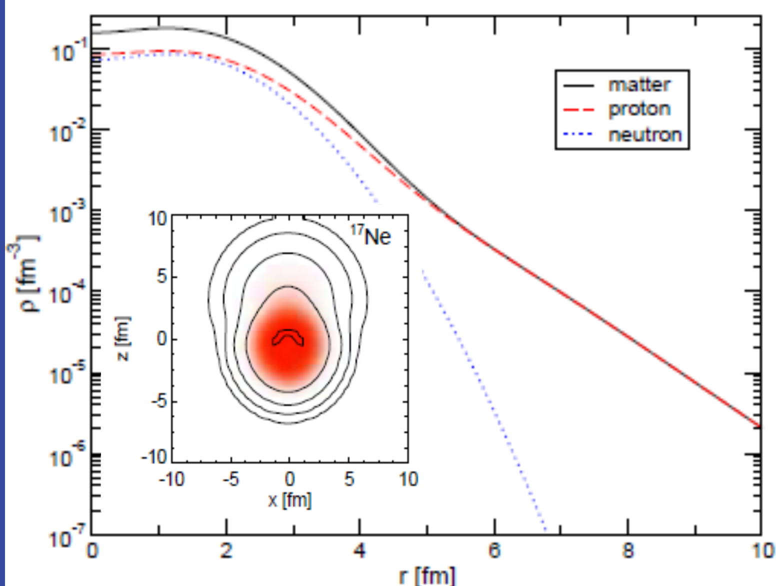
Laser spectroscopy

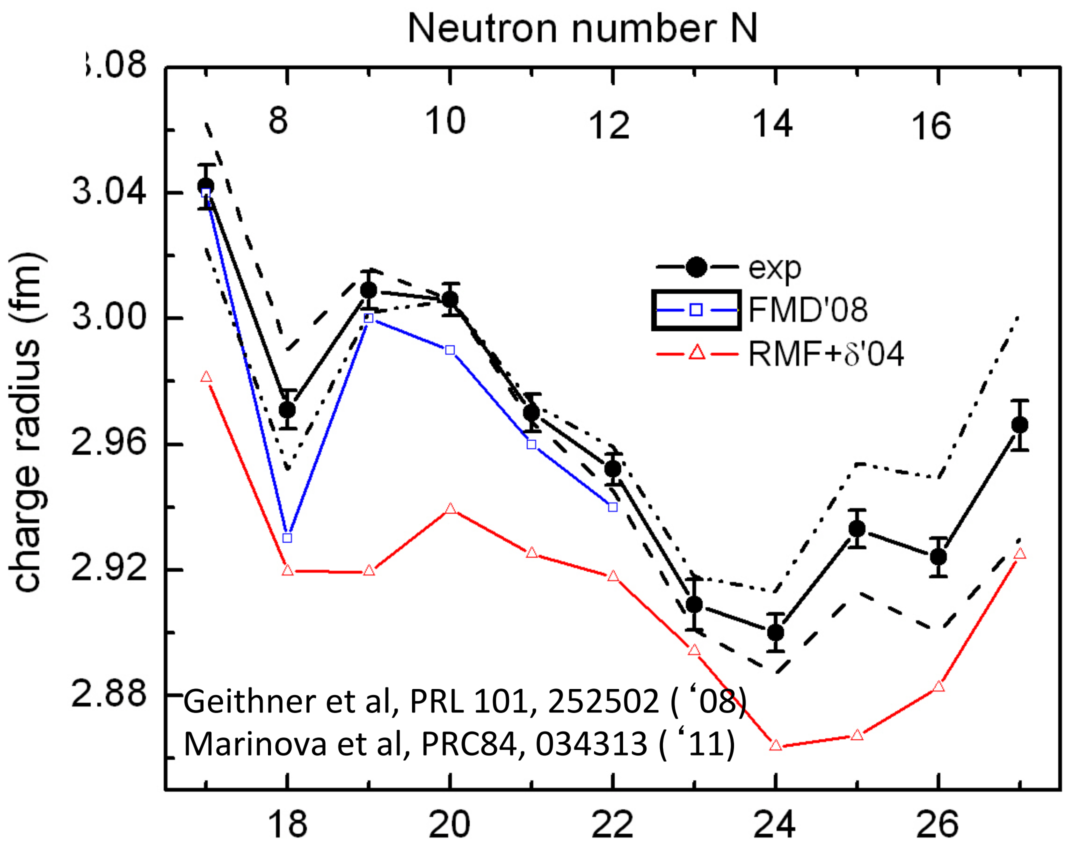


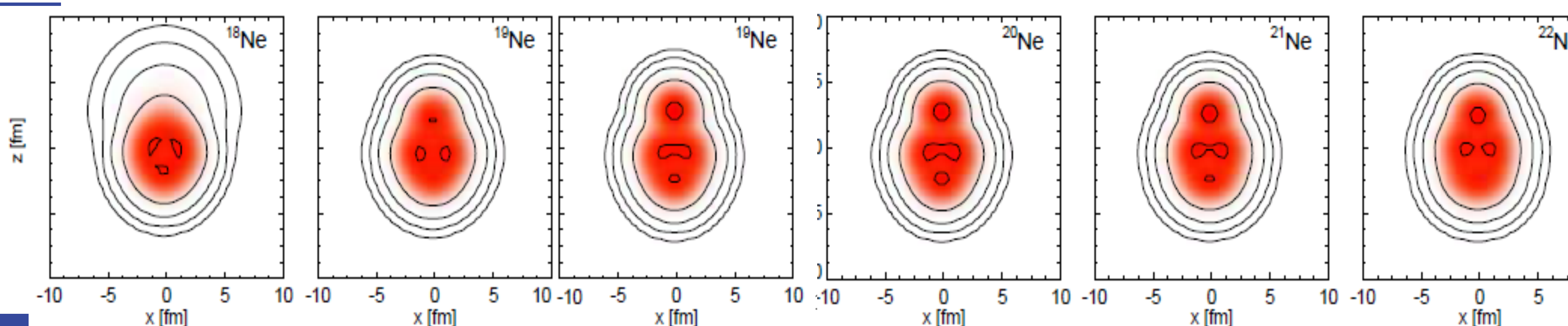
COLLAPS – Ne charge radii

Laser spectroscopy & Massses

Intrinsic density distributions of dominant proton FMD configurations

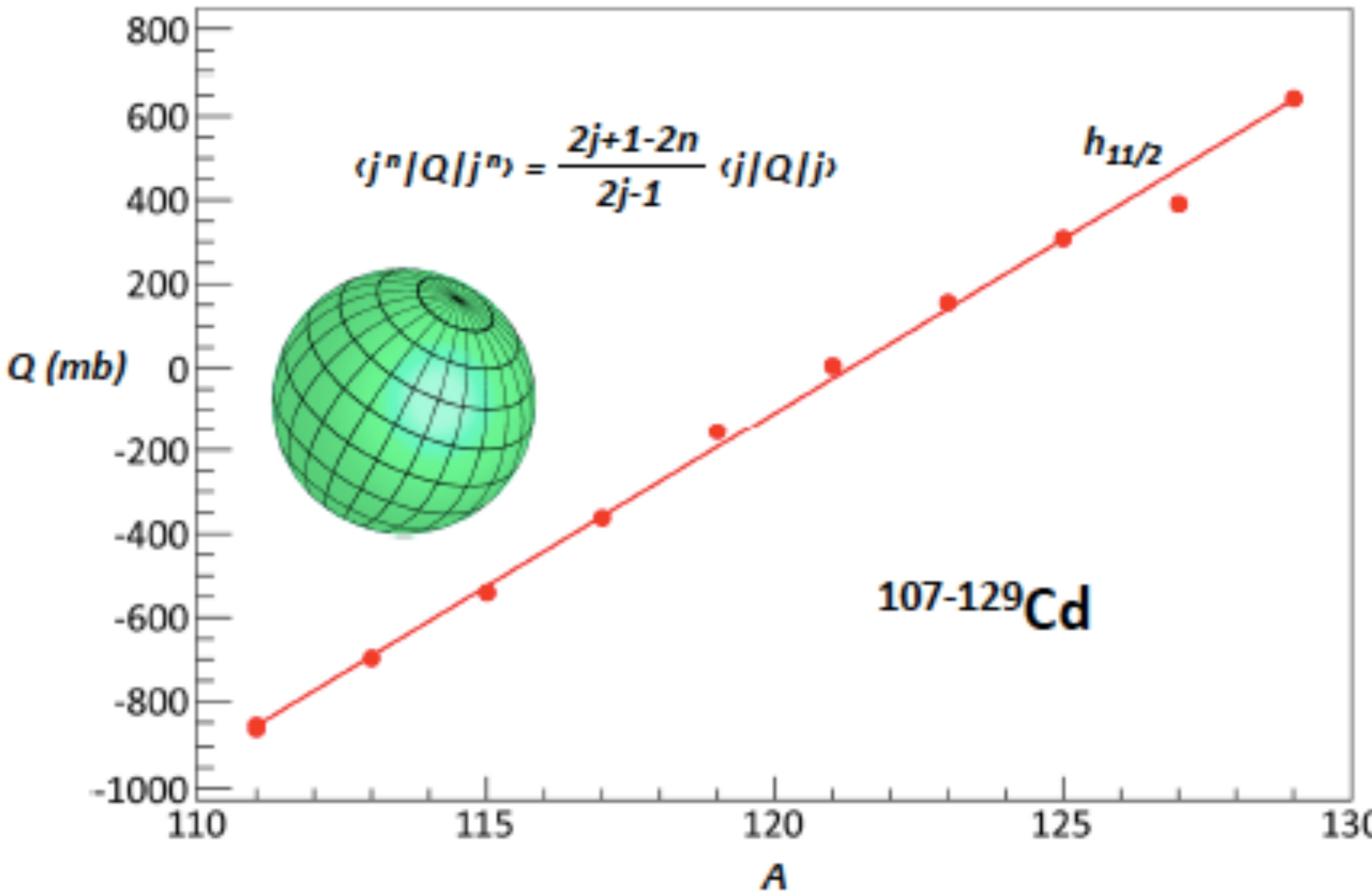






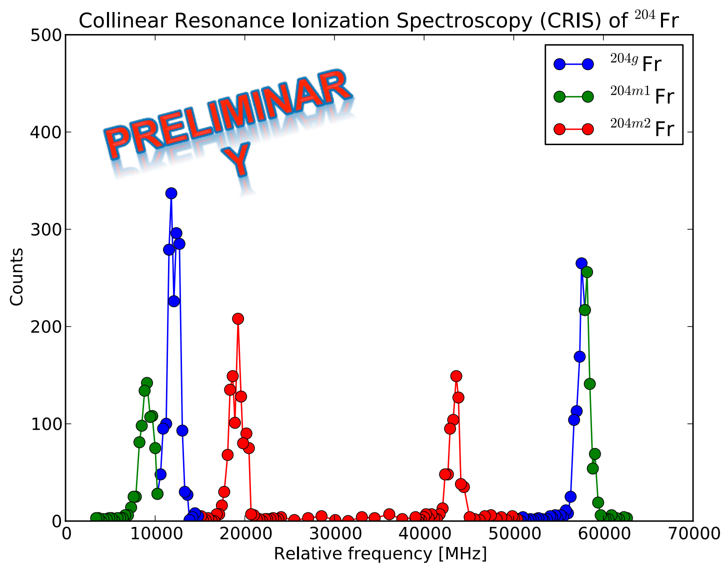
Beautiful regularity of $h_{11/2}$

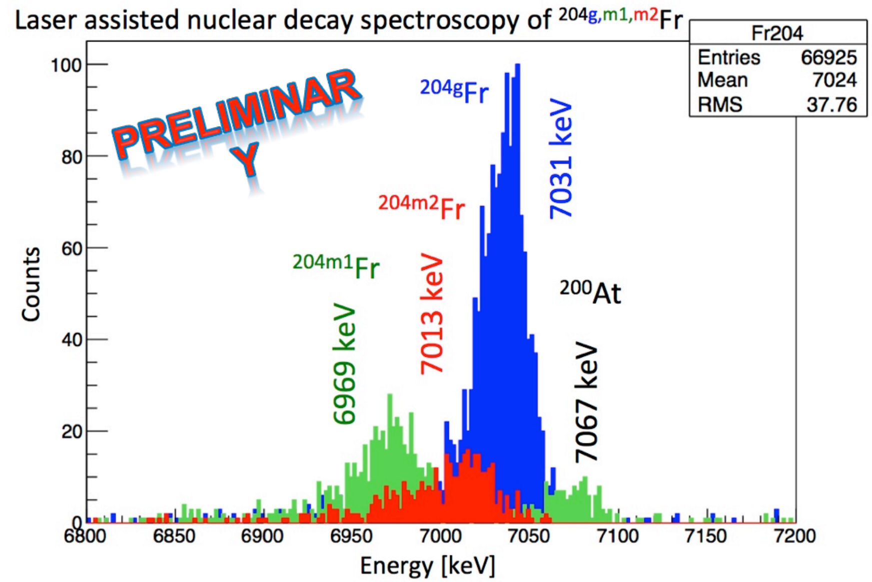
The nucleus in the shell - model picture



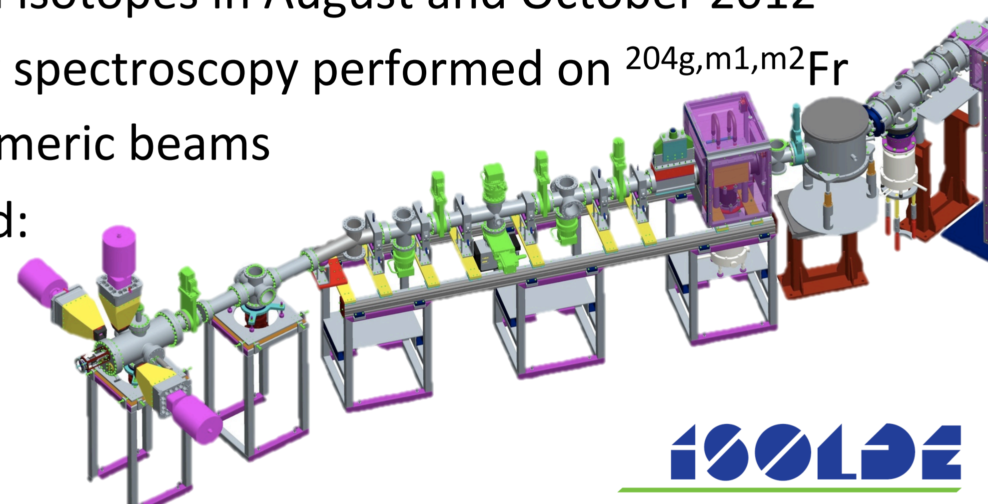
D. T. Yordanov, Phys. Rev. Lett., 110, 192501 (2013)

Collinear Resonant Ionization Spectroscopy



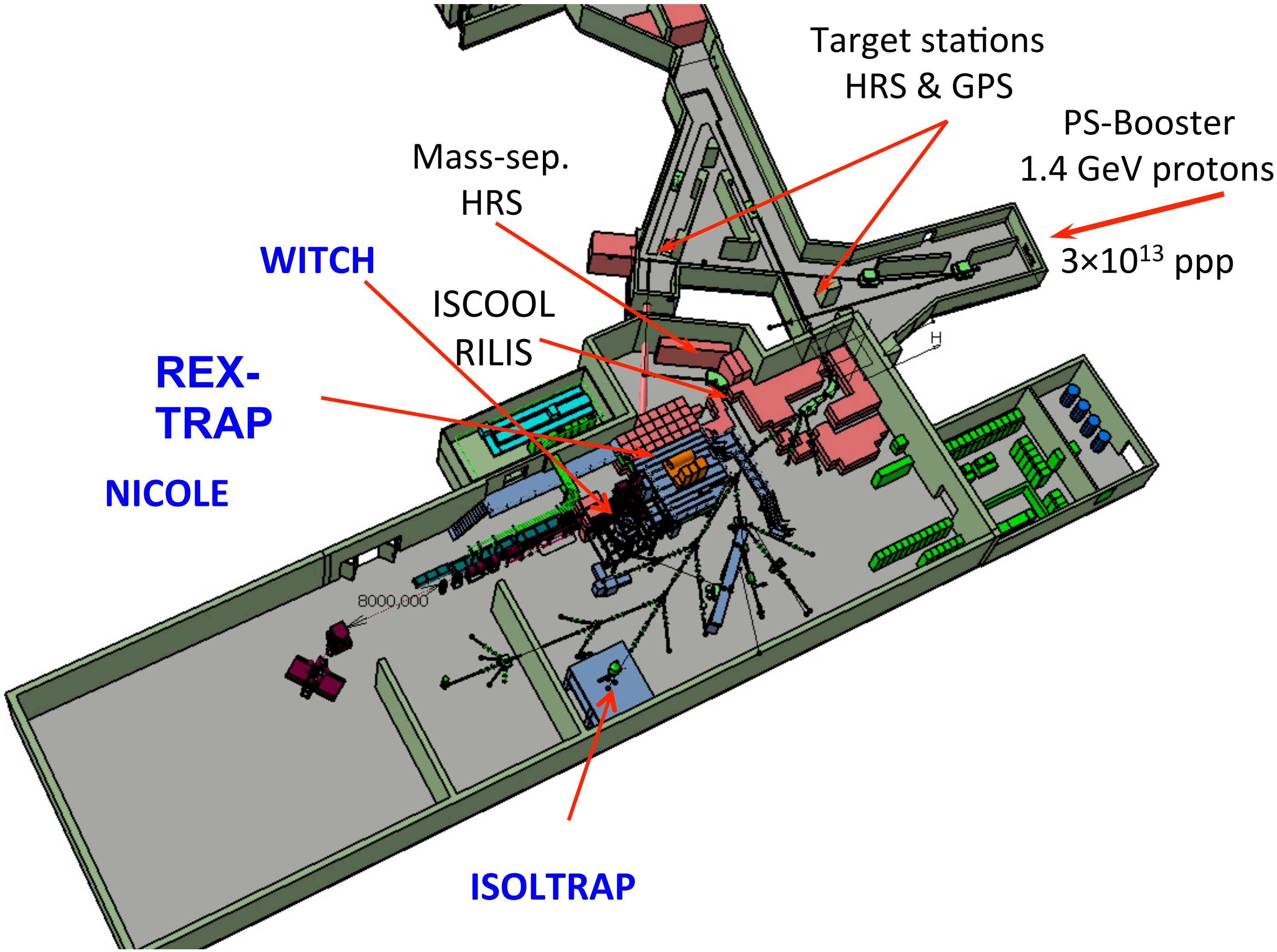


- CRIS performed on francium isotopes in August and October 2012
- Laser assisted nuclear decay spectroscopy performed on $^{204g,m1,m2}Fr$
- Successful production of isomeric beams
- Francium isotopes measured:
- $^{202,203,204,205,207,211}Fr$
- $^{218,219,220,221,229,231}Fr$



ISOLDE

Trap Experiments



ISOLTRAP: High-precision mass of ^{82}Zn

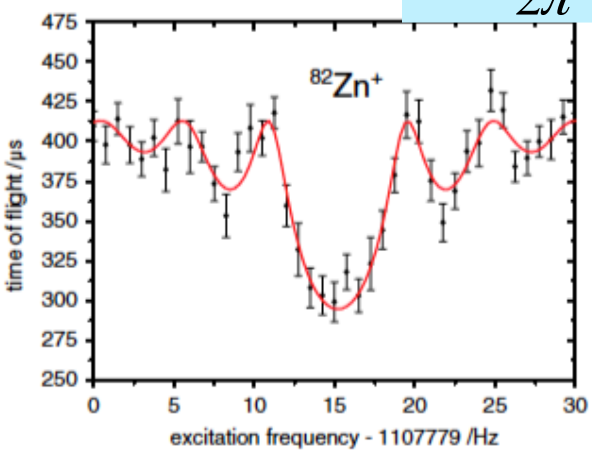
Combined ISOLDE technical know-how:
neutron-converter, quartz transfer line, laser ionisation

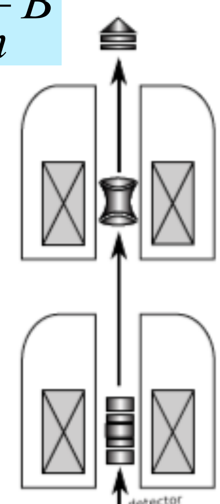
Nuclear structure:
N=50 shell closure

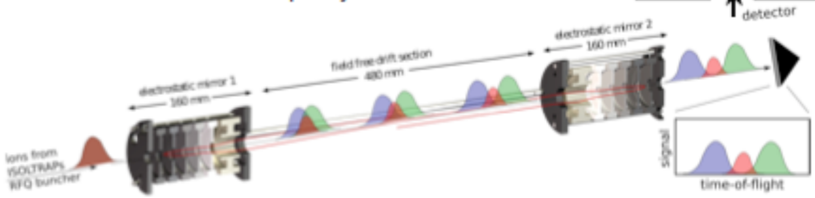
Astrophysics:
r-process path

Astrophysics:
neutron star structure

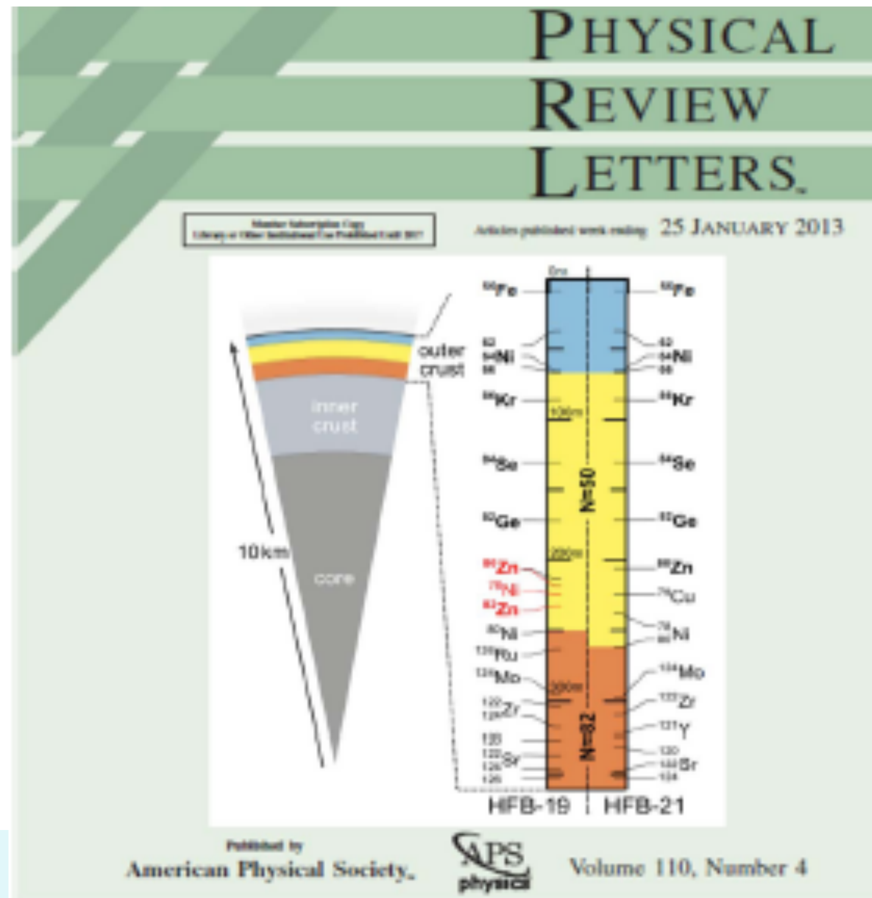
$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$





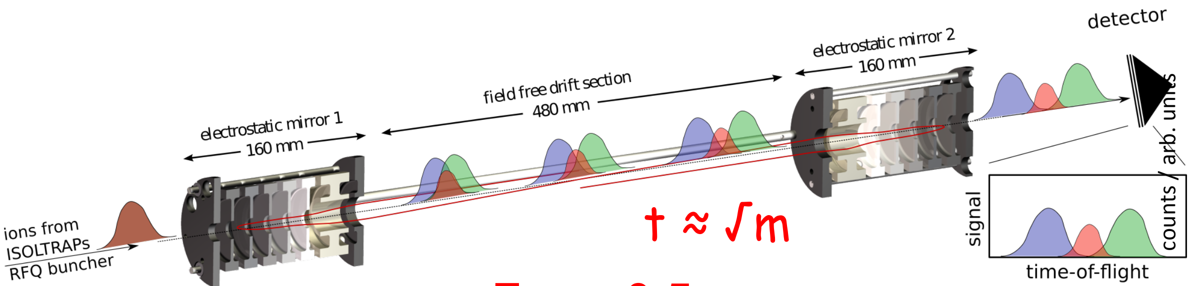


CERN Courier, 53, n 3, 2013



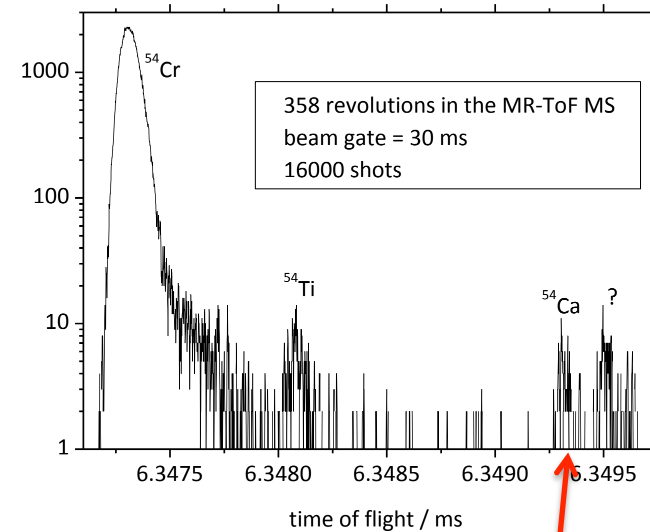
Masses of $^{52\text{-}54}$Ca isotopes: around and beyond the magic number N=32

- Masses of ^{51,52}Ca measured with conventional TOF resonances in ISOLTRAP's precision trap.
- Direct mass-measurement using the MR-TOF on $^{52\text{-}54}$Ca

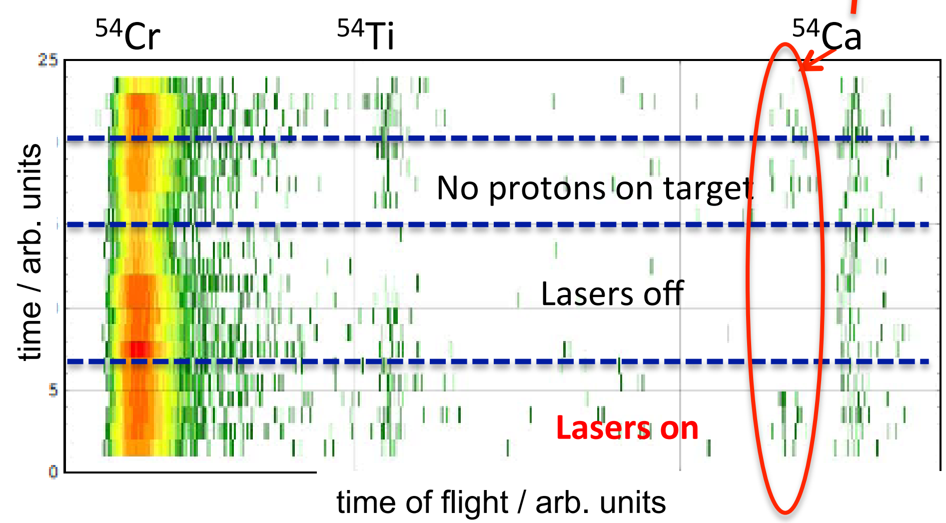


$t \approx \sqrt{m}$

From 0.5m – 27km !



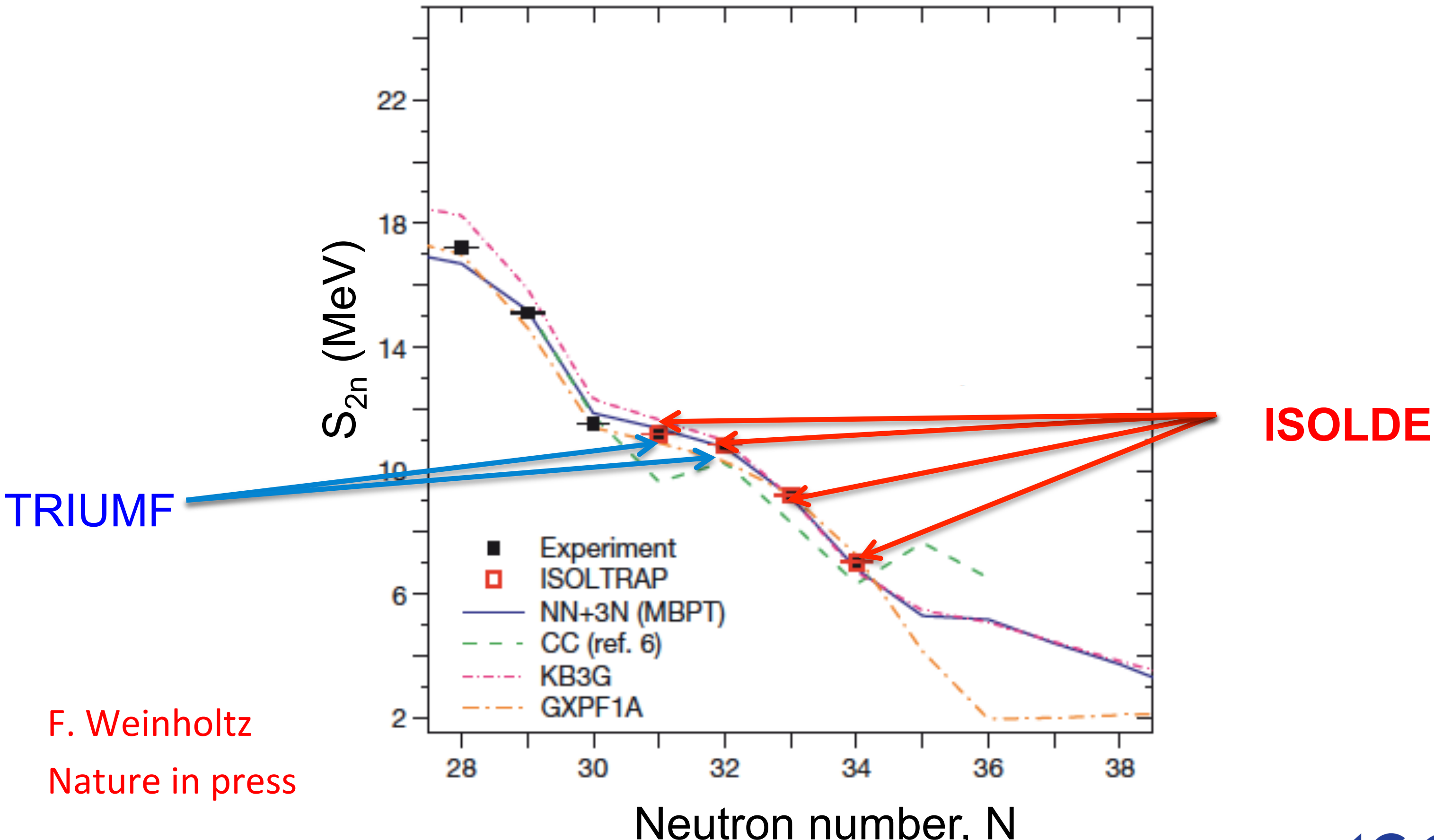
- MR-TOF MS offers a way to separate background for direct single-ion detection using MCP (time scale: tens of ms)
- direct time-of-flight mass measurements become possible, ex. ^{54}Ca (ISOLDE yield 10/s)



R. N. Wolf *et al.*, Nucl. Instr. and Meth. A 686, 82-90 (2012))
S. Kreim *et al.*, INTC-P-317, IS 532 (2011)

Proof of the magic character of N=32

- Prominent shell closure at N=32.
- Correct prediction from 3N-forces from Chiral effective Field theory



F. Weinholtz

Nature in press

Why to study the N=Z ^{72}Kr Nucleus?

Nuclear structure:

- Shape coexistence in the mass region was first proposed for ^{72}Se [Ham74].
- ^{72}Kr ground state is predicted to be oblate deformed [Dic72] and [Naz85].
- First excited 0^+ state in ^{72}Kr found to be a shape isomer [Bou03].
- Possibility of study np-pairing effects as ^{72}Kr belongs to N=Z line.

[Ham74] J.H. Hamilton et al., Phys. Rev. Lett. 32, 239 (1974)
[Dic72] F. Dickmann et al., Phys.Lett. 38B, 207 (1972)
[Naz85] W. Nazarewicz et al., Nucl. Phys. A435, 397 (1985)
[Bou03] E. Bouchez et al., Phys. Rev. Lett. 90, 082502 (2003)

Nuclear astrophysics:

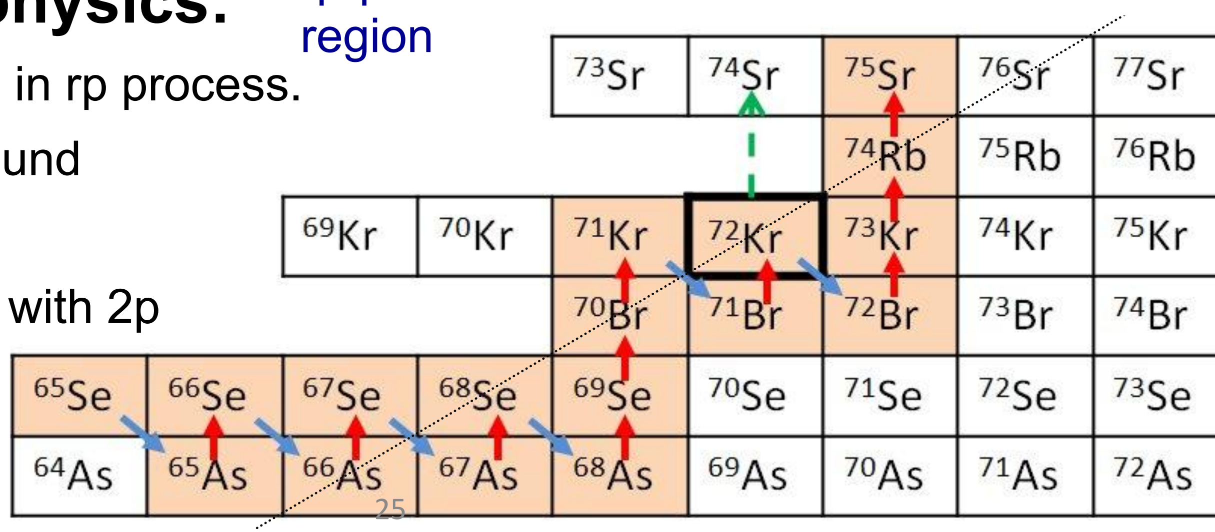
- ^{72}Kr “waiting point" in rp process.

  ^{73}Rb is unbound

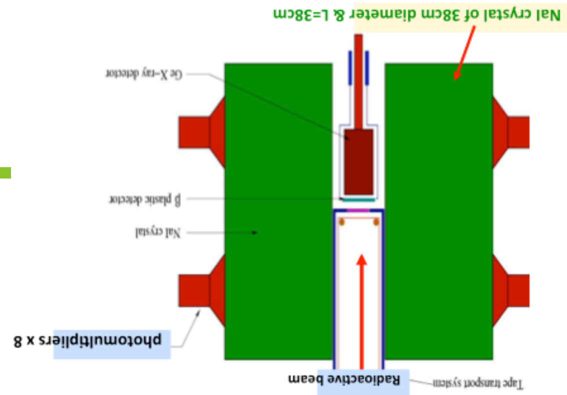
  ↓

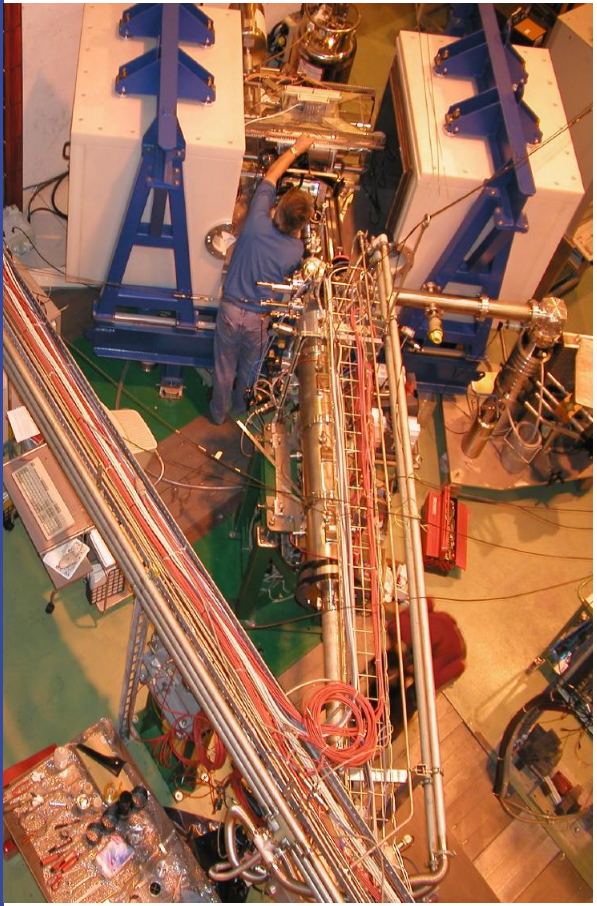
- β decay competes with 2p capture.

rp-process in N=Z nuclei & A=70-80 region



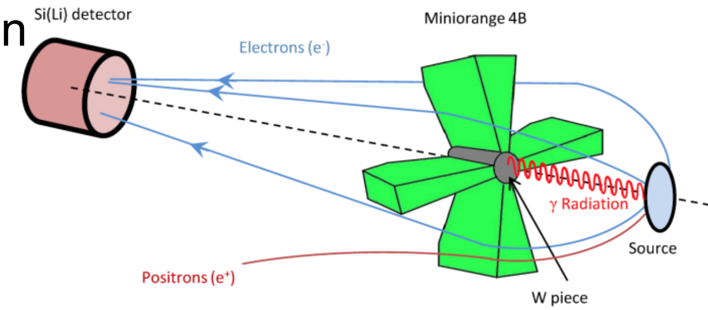
TAGS @ISOLDE: The case of ^{72}Kr



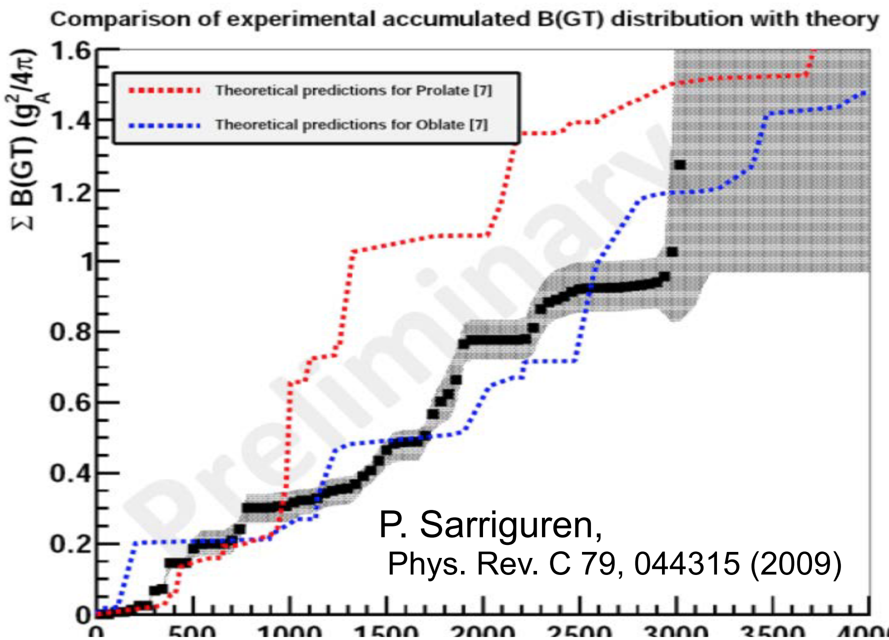


Briz, ISOLDE Workshop 2012

- Conversion electron studies to determine the multiplicities of the low gamma transitions



- B(GT) obtained by measuring the intensity of the full gamma de-excitation cascade from each fed level to the ground state.



P. Sarriguren, Phys. Rev. C 79, 044315 (2009)

The B(GT) distribution favours oblate deformation!

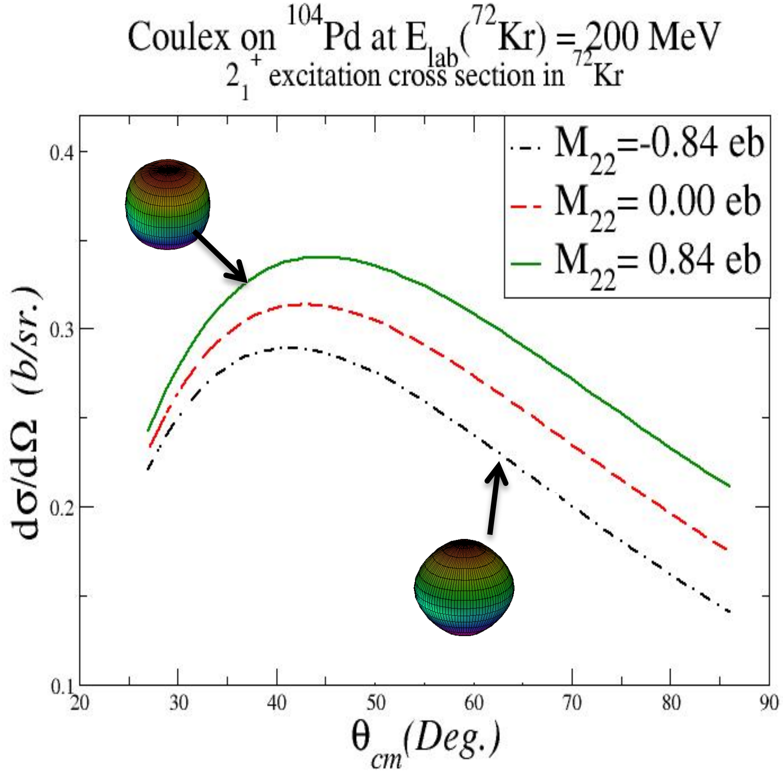
Coulomb excitation of ^{72}Kr

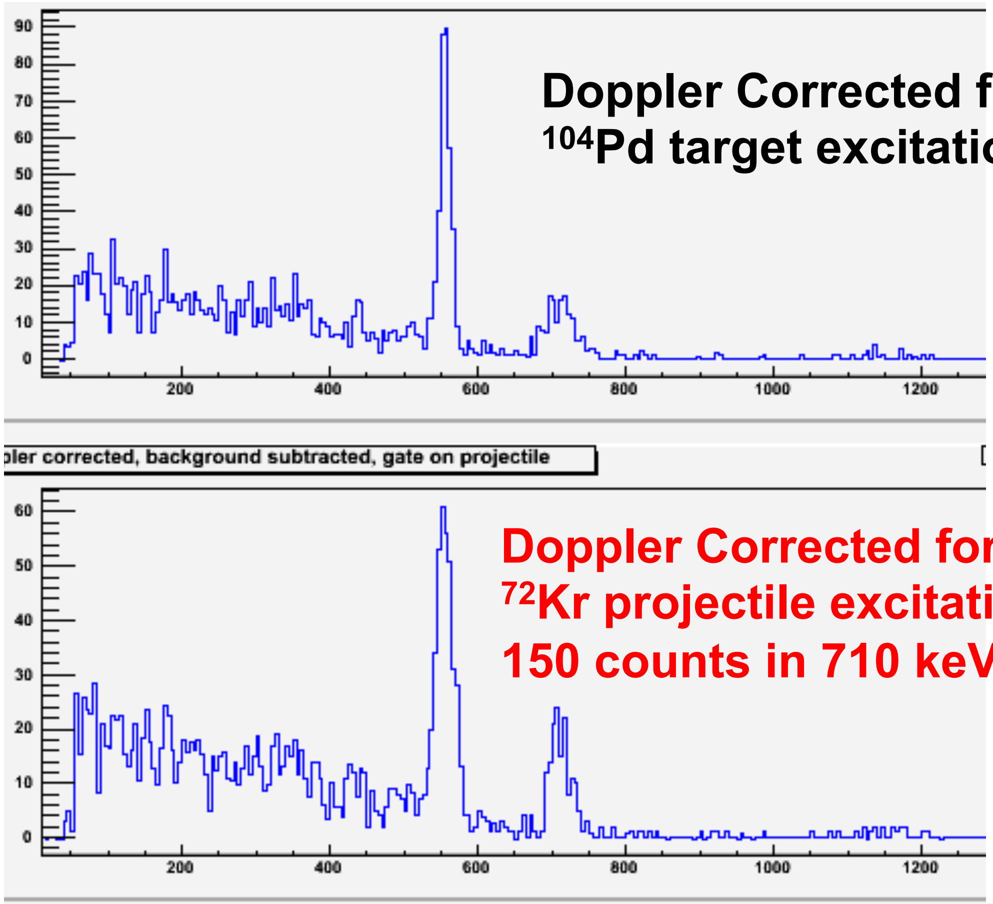
Use of submicron $Y_2 0_3$ material for target => Yield increase x 10

Coulex Spectra - number of counts in 710 keV depends on the shape of ^{72}Kr

Oblate ^{72}Kr expected

The technique

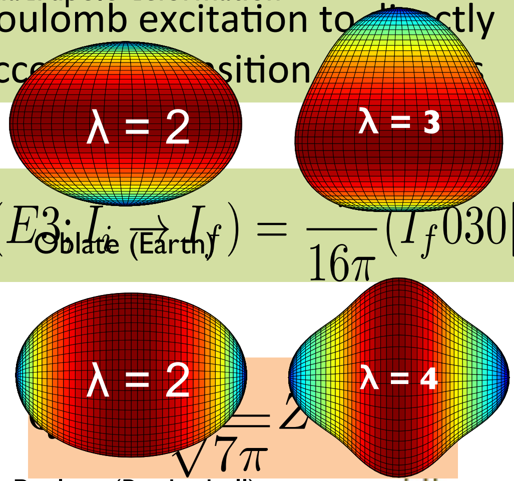




Searching for pear-shaped nuclei at ISOLDE

Quadrupole deformation

Coulomb excitation to ...ctly acc... ...sition ...

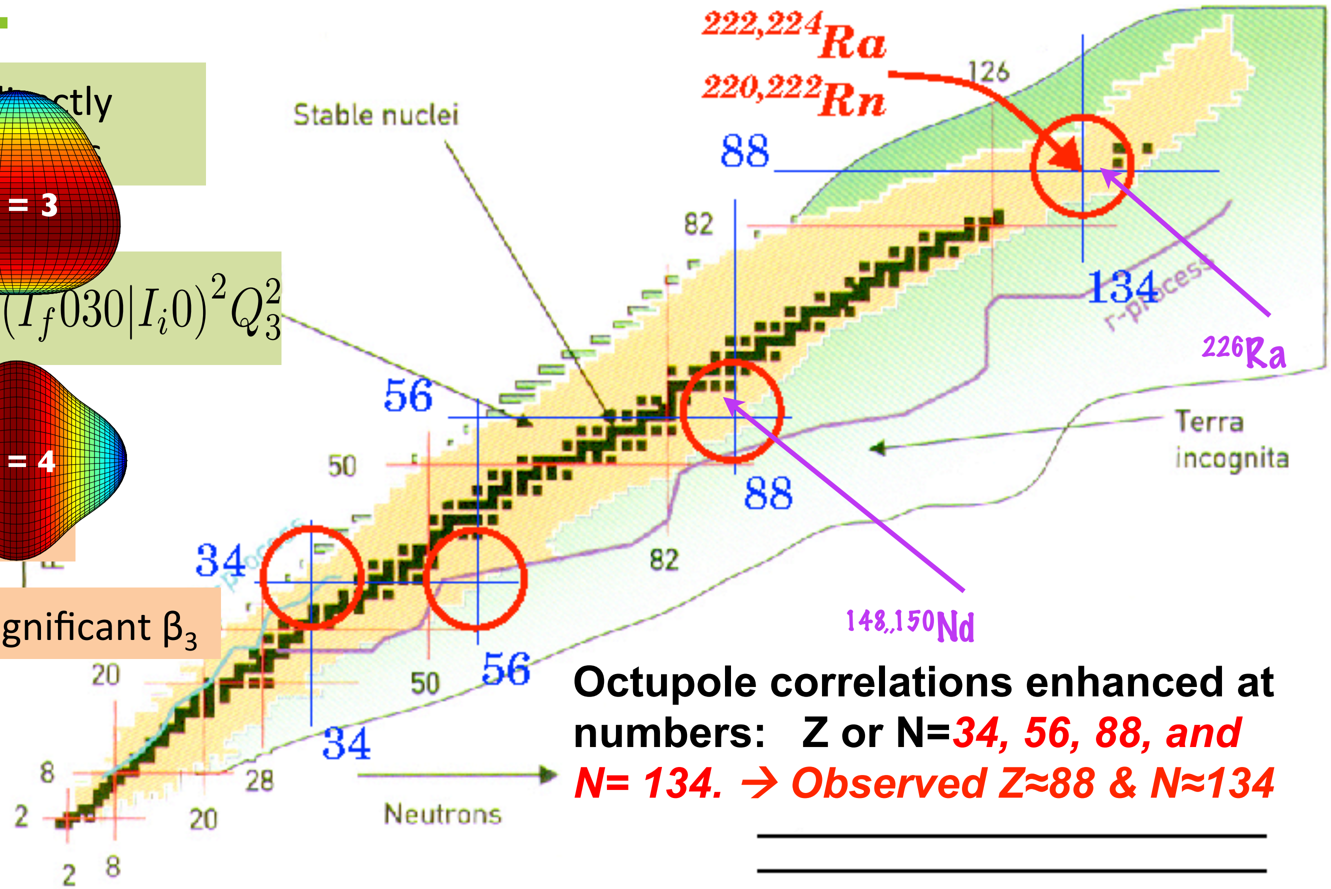


$$B(E3; I_i \to I_f) = \frac{\quad}{16\pi}(I_f 030|I_i 0)^2 Q_3^2$$

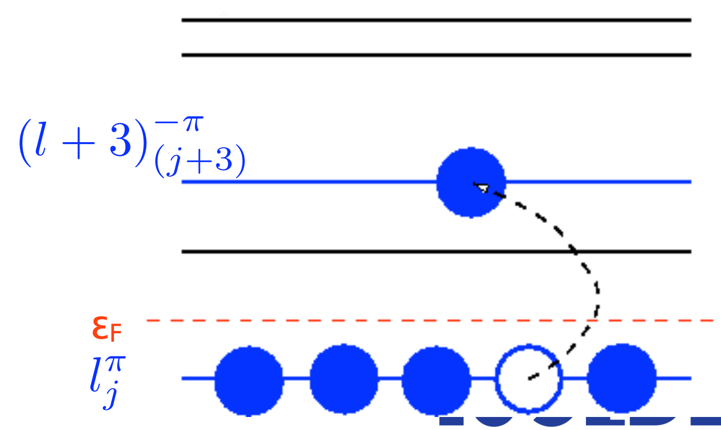
Oblate (Earth)

Prolate (Rugby ball)

B(E3) ≳ 30 s.p.u. gives significant β_3



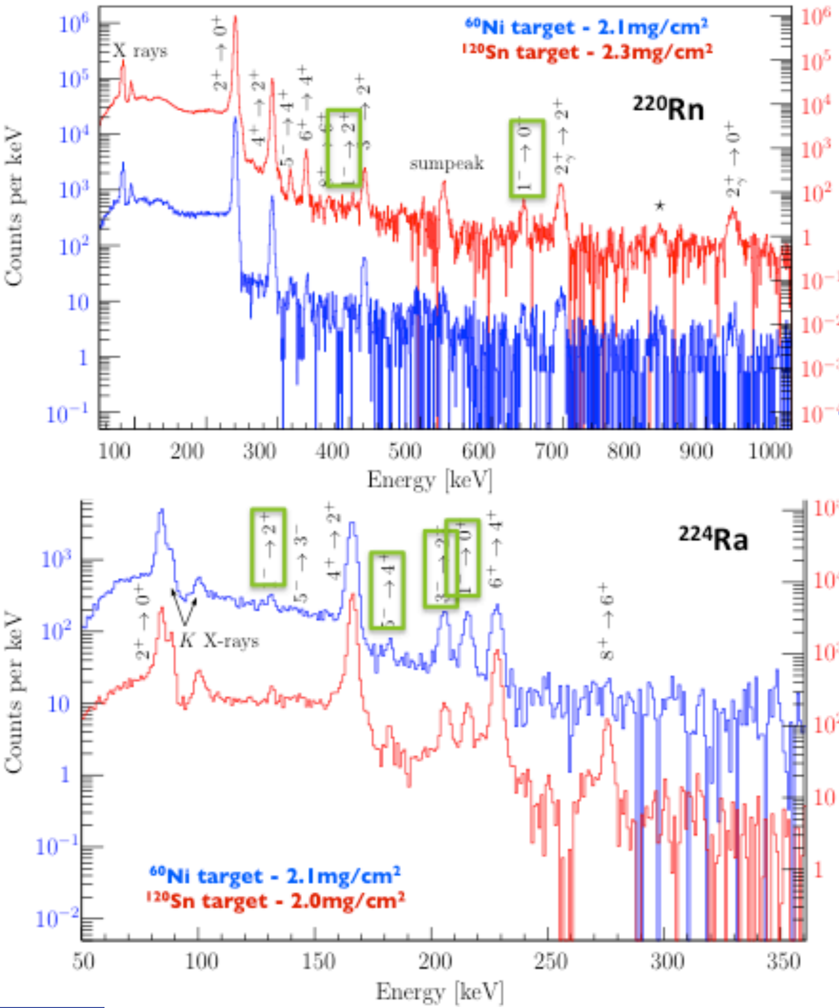
Octupole correlations enhanced at numbers: Z or N=*34, 56, 88, and N= 134. → Observed Z≈88 & N≈134*

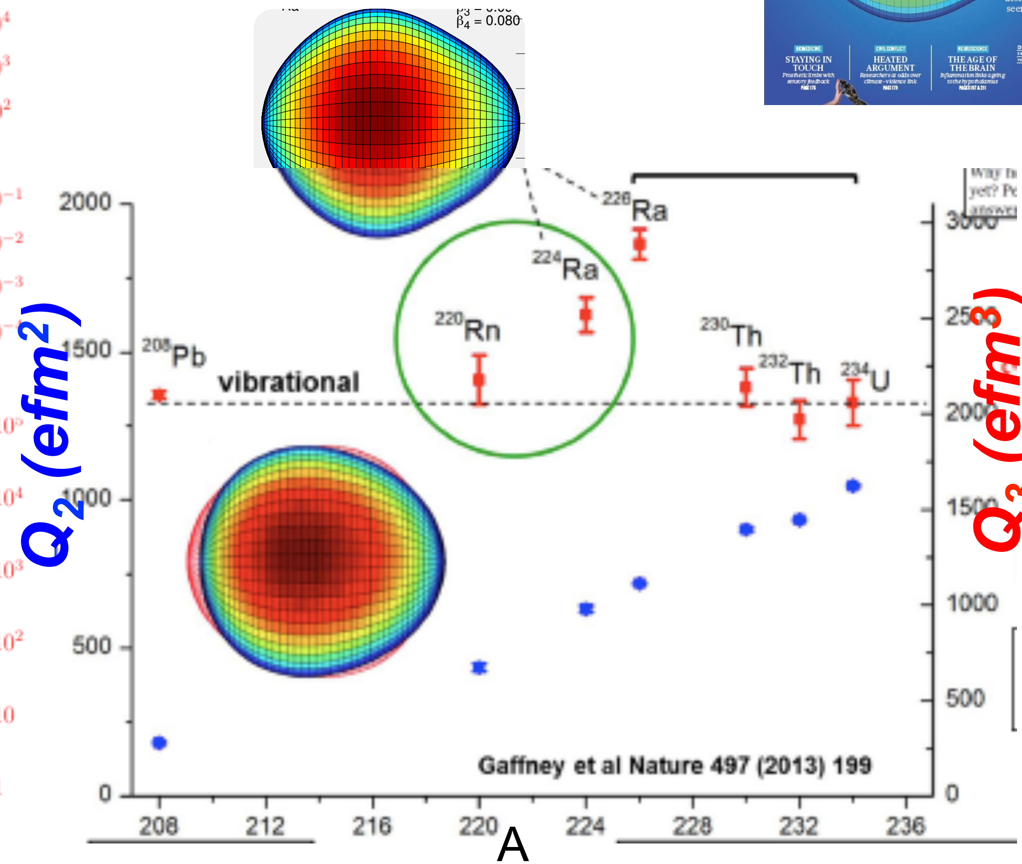


Microscopically driven...

Intruder orbitals of opposite parity and **ΔJ, ΔL = 3** close to the Fermi level

Pear Shaped Nuclei





^{224}Ra Stable octupole deformed

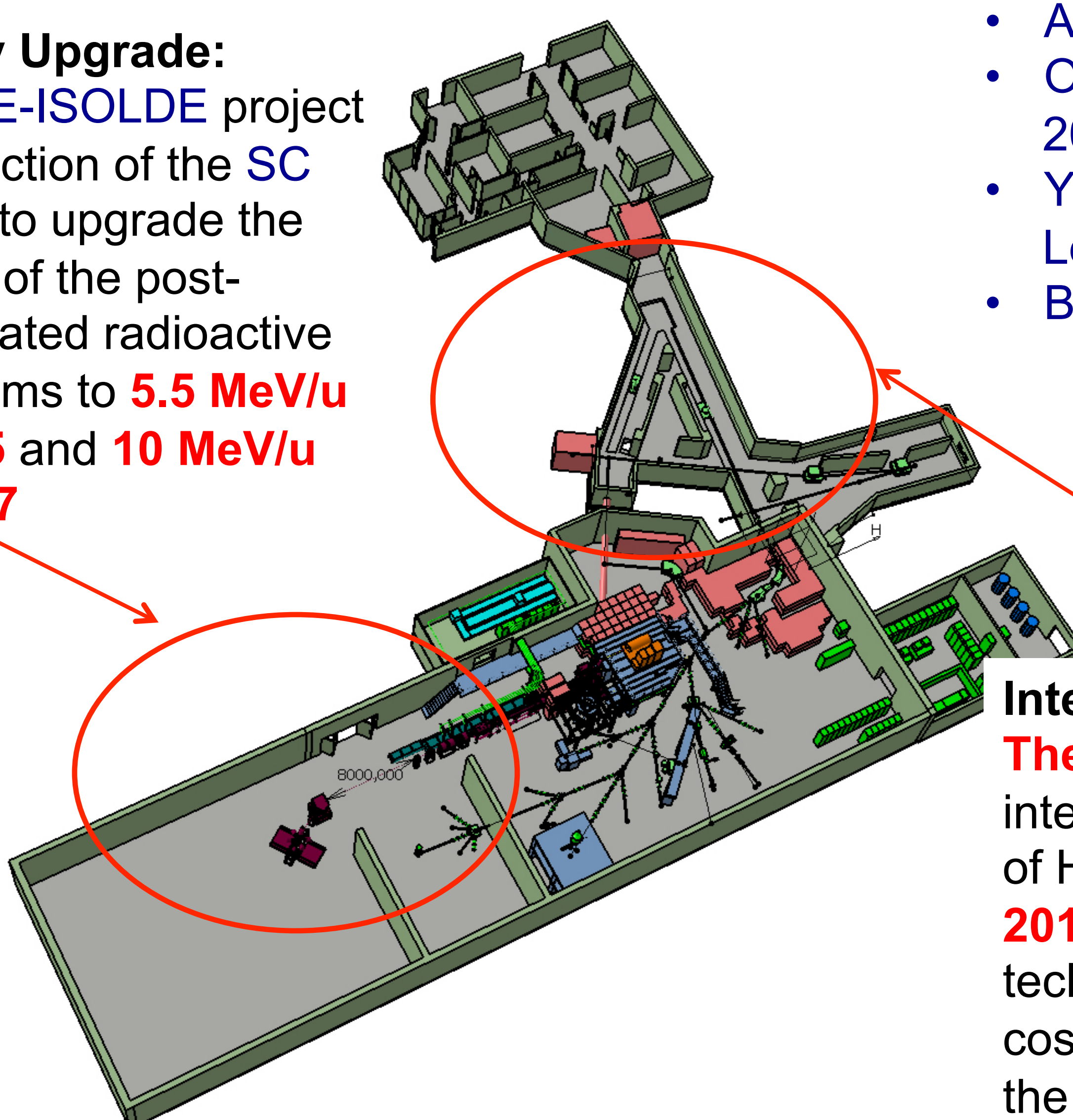
^{220}Rn Vibrational

Nature 497 (2013)199

Near Future: HIE-ISOLDE project

Energy Upgrade:
The HIE-ISOLDE project construction of the SC LINAC to upgrade the energy of the post-accelerated radioactive ion beams to **5.5 MeV/u in 2015** and **10 MeV/u by 2017**

- Approved Dec 2009
- Offically started Jan 2010
- Yacine Kadi project Leader
- Budget 40 M$



Intensity Upgrade:
The design study for the intensity upgrade, also part of HIE-ISOLDE, **started in 2011**, and addresses the technical feasibility and cost estimate for operating the facility at **10 kW** once LINAC4 and PS Booster

Physics @ HIE-ISOLDE

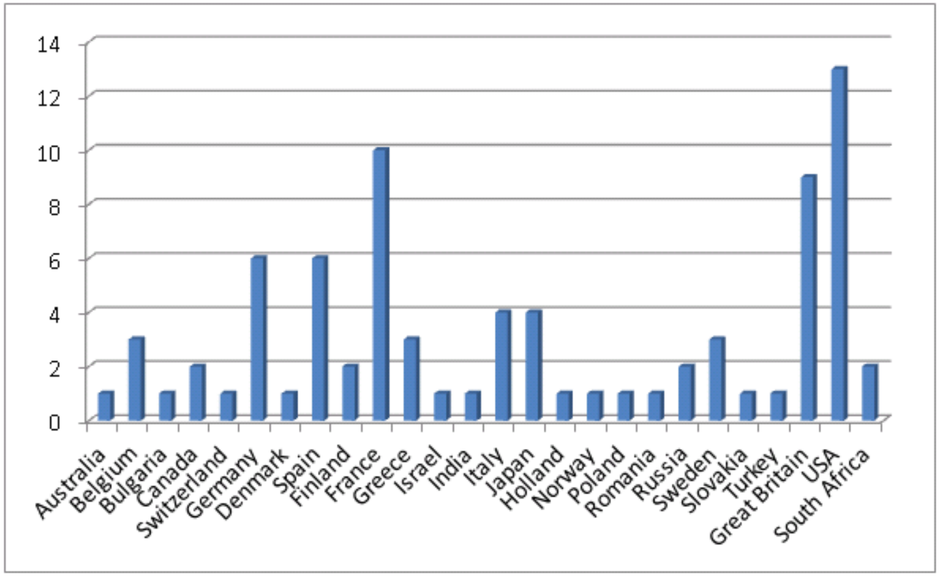
- May 2010: 34 LoI submitted
- 1 Nov 2012: INTC endorsed the increase of 2 GeV-proton energy for ISOLDE
- 31 Oct 2012: 30 proposals for HIE-ISOLDE defended
  - 800 shifts requested
  - More than 400 shifts approved.

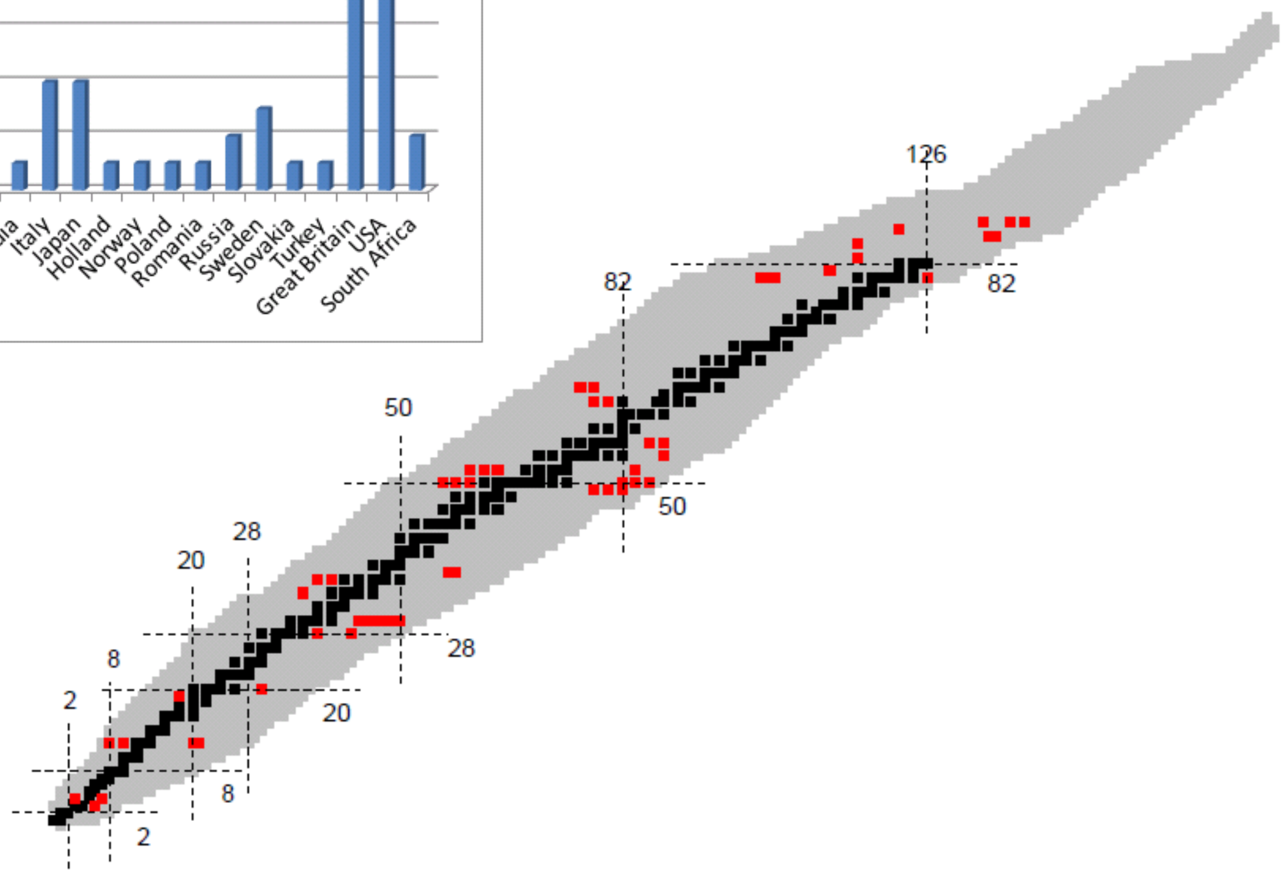
Instrumentation

- Miniball + T-ReX (upgrade planned) : COULEX + Transfer (18)
- Multipurpose reaction chamber (5)
- Helicoidal orbital spectrometer : transfer reactions (5)
- MAYA / ACTAR: resonant scattering + transfer. (2)
- For 2016: TSR storage ring, well received, Integration study till Q3-2013

Nuclei from all submitted HIE-ISOLDE proposals

number of institutes (82) per country involved in HIE-ISOLDE
Proposals submitted in October 2012





Summary and outlook

- The future of ISOLDE is bright. It will restart **in June 2014** with the low energy program. Very busy period from January 2014

- With more than 40 year of operation ISOLDE remains as pioneering ISOL-installation both at the level of designing new devices and production of frontier Physics.

- Average 50 experiments per year and 450 users, 90 active exp.

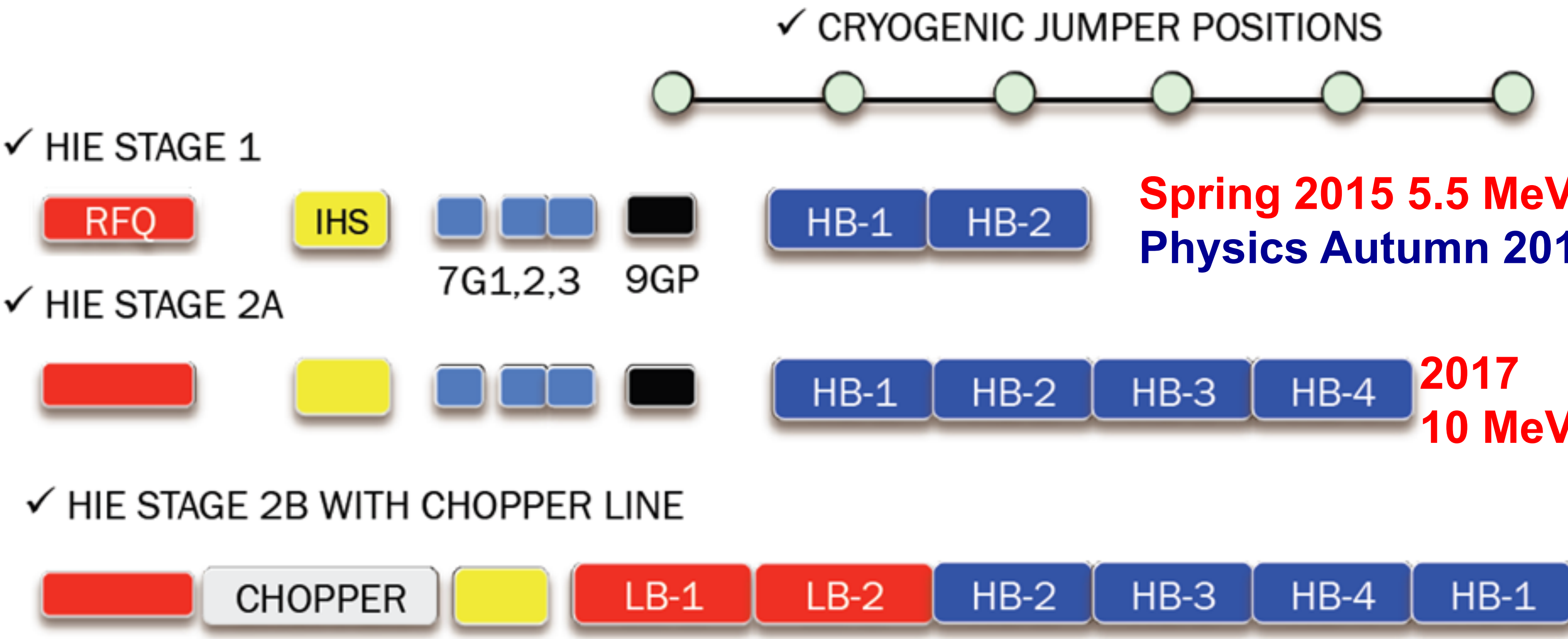
- NO ENSAR TNA Money use in 2015

- Post accelerated beams up to 5.5 MeV/u for the wide range of nuclei produced at ISOLDE will be available from **Autumn 2015.**

- HIE-ISOLDE will be the only next-generation radioactive beam facility (as identified by the NuPECC LRP) available in Europe in 2015, and the most advanced ISOL facility world-wide.

Thanks for your attention !

SC-LINAC Installed in 3-phases



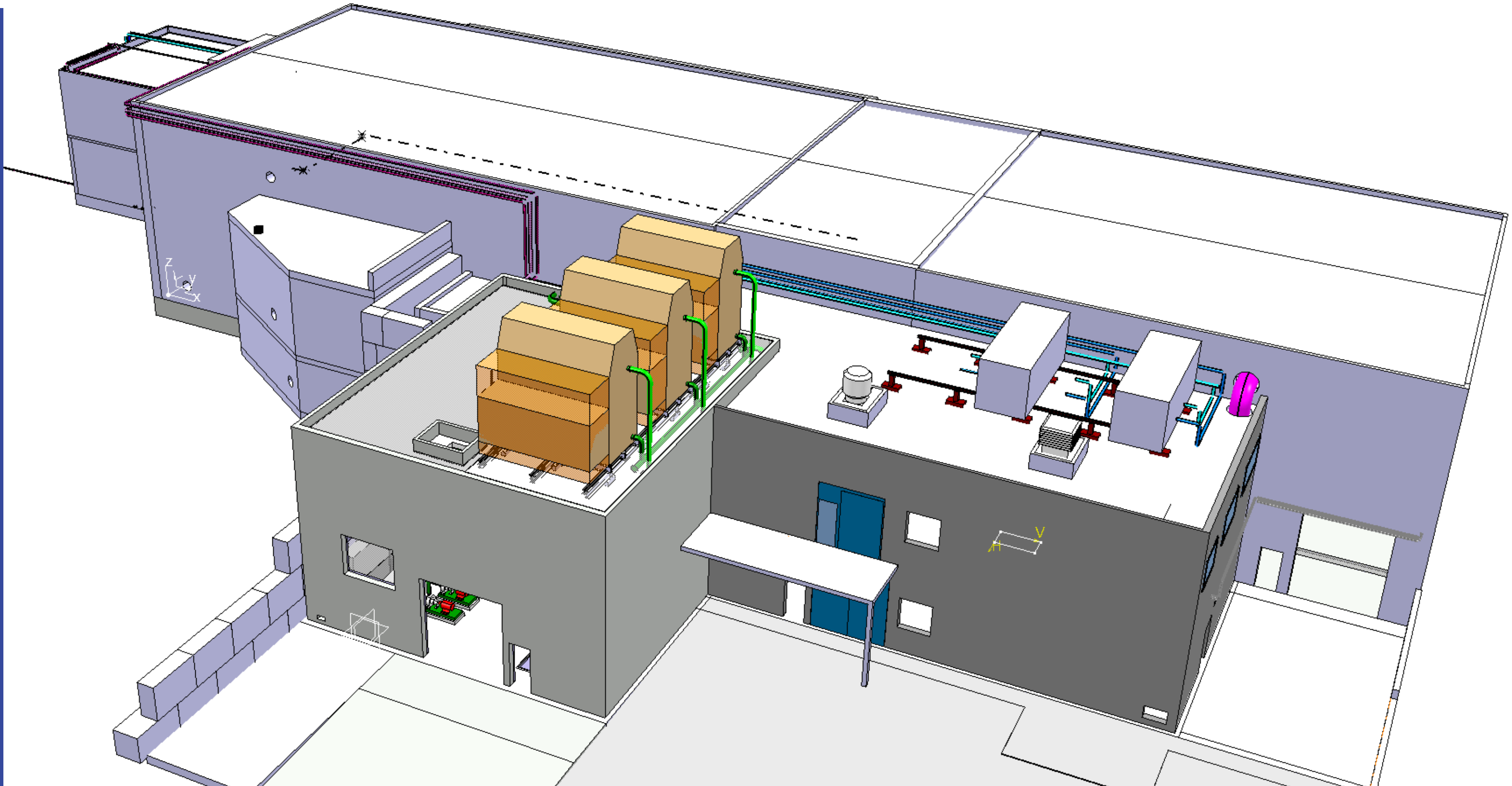
Spring 2015 5.5 MeV/A
Physics Autumn 2015

2017
10 MeV/A

2018 (LS2)

Period 100ns
Resolution 1-2 ns
Background < 1%

Cooling & Ventilation

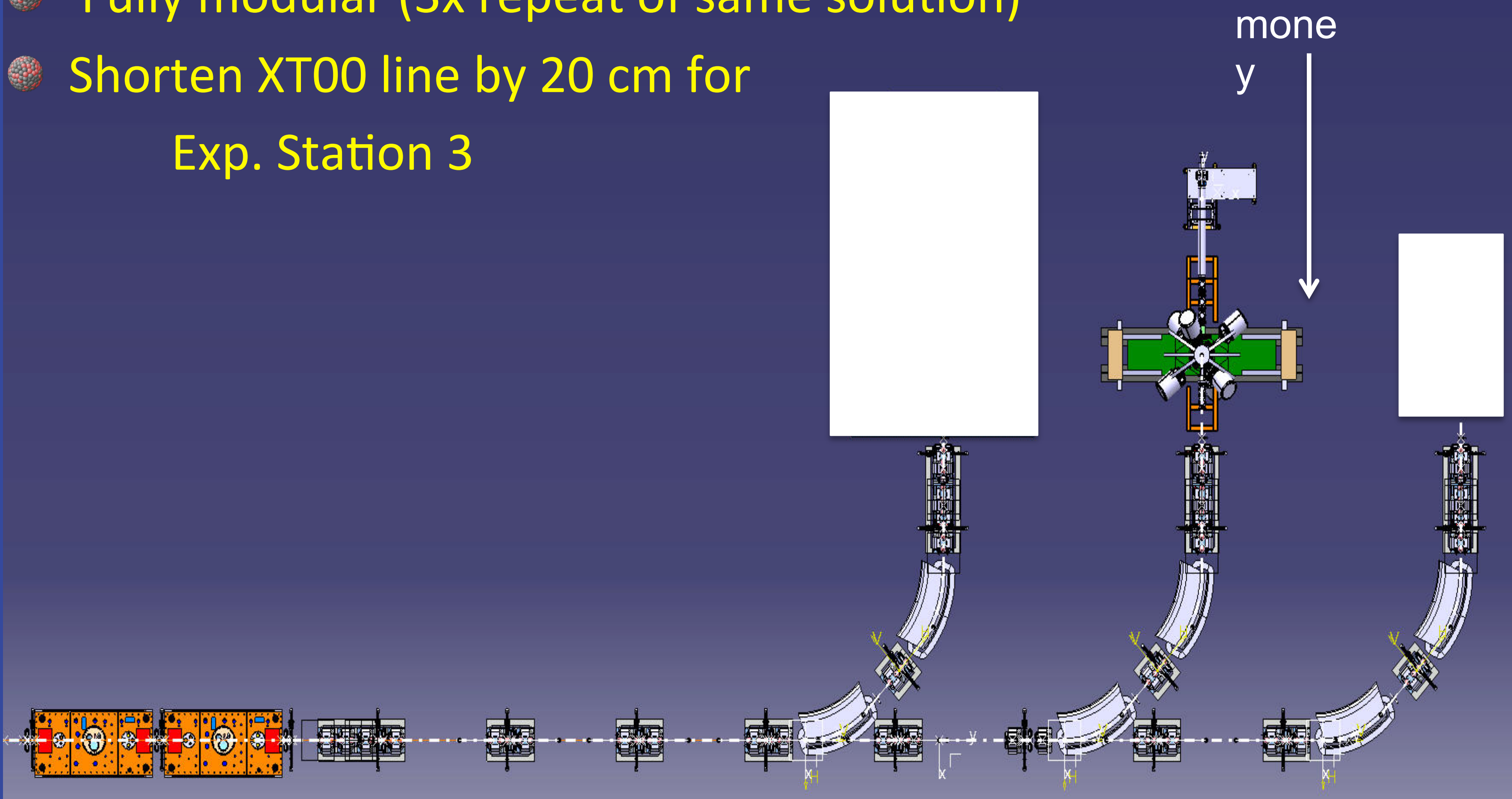


Civil Engineering finished December 2012

Cooling & Ventilation: Oct 2012 – June 2013

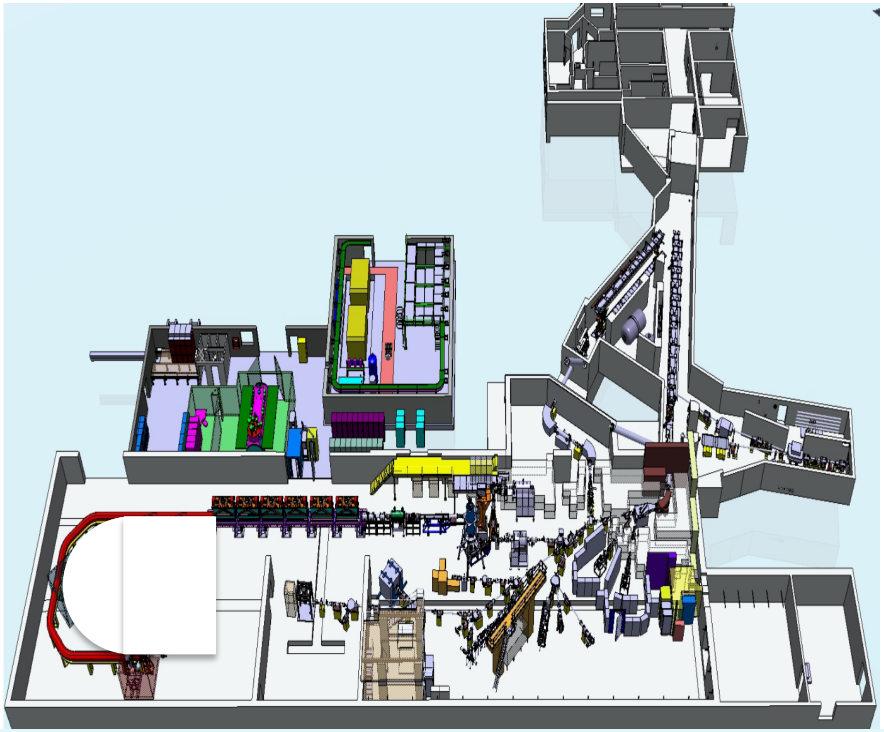
Proposed Three beamlines

- Layout can accommodate 3rd experimental station
- Fully modular (3x repeat of same solution)
- Shorten XT00 line by 20 cm for
  Exp. Station 3



Design Study for Mid-2014

- Intensity Upgrade
  - Thermal Studies
  - Target Material Studies
  - Fluka Simulations
  - Cooling & Ventilation renew
  - Frontend
  - High Voltage
  - Beam Dumps
- Beam Quality
  - Vacuum
  - RFQ Cooler
  - REXEBIS Upgrade
  - Off-line Separator
  - HRS
    - Layout
    - Controls



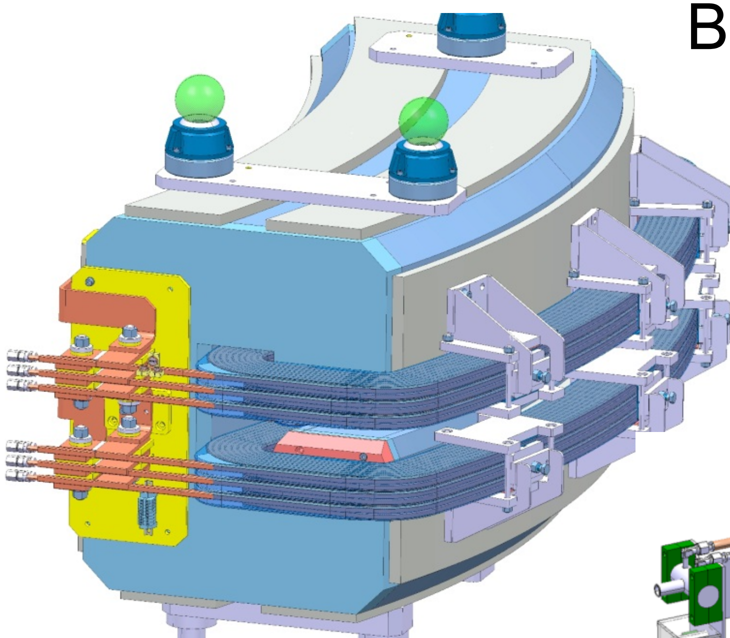
Linac 4 and PSB upgrade ($1x10^{14}$ protons per bunch ($3.3x10^{13}$)

2GeV beam energy (1.4GeV)

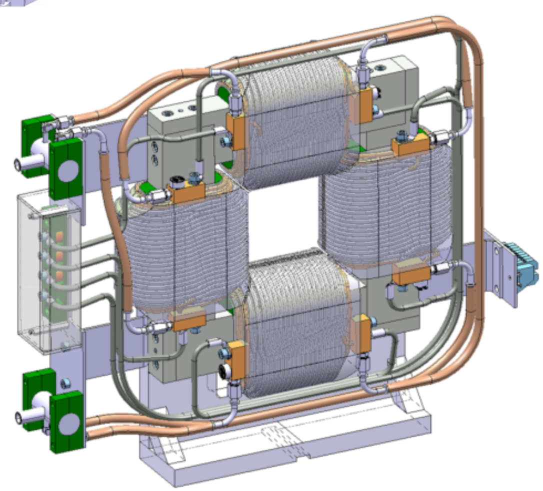
Protons/pulse	Intensity µA	Energy GeV	Cycle s	Power kW*
3.3×10^{13}	2.2	1.4	1.2	3.1
1×10^{14}	6.7	1.4	1.2	9.3
1×10^{14}	6.7	2	1.2	13.3

Beam Line elements

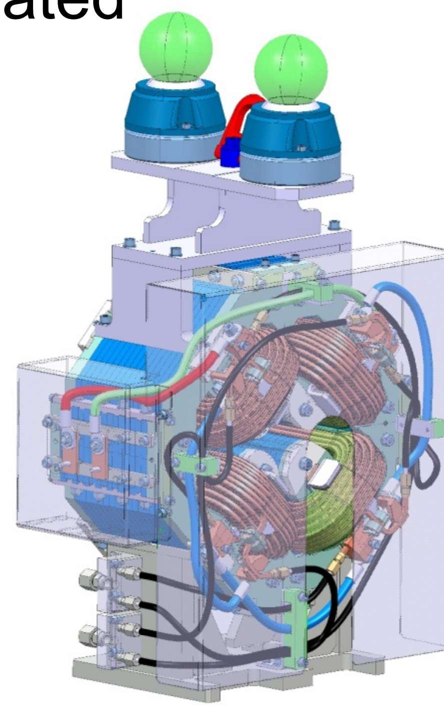
Fully designed!
Beam optics calculated



45 deg Dipole

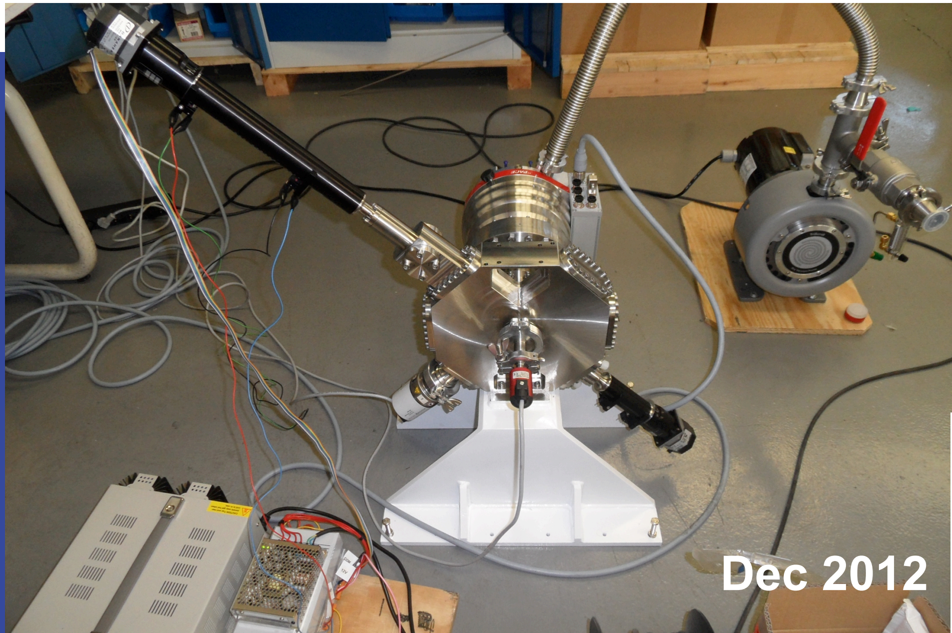


Steerer



Quadrupole

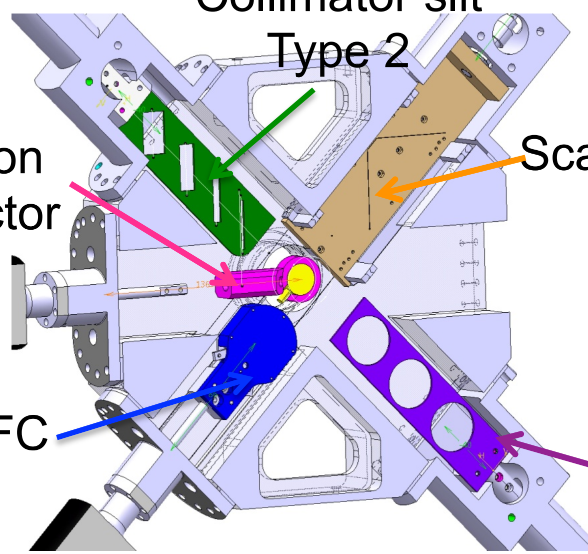
Diagnostic box

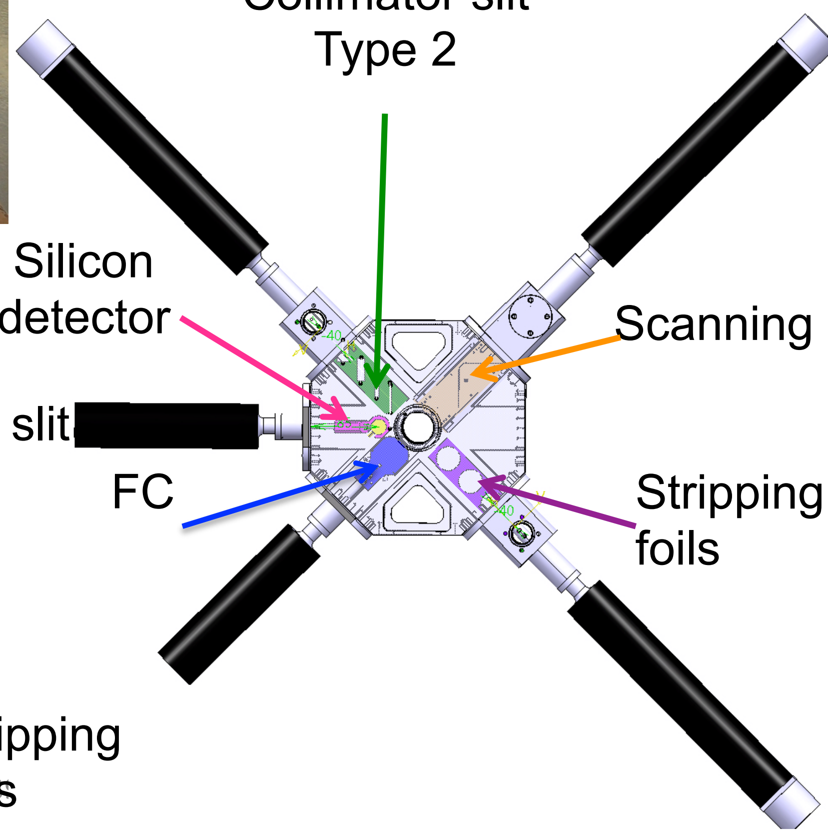


Highly demanding due to the reduce space

Prototypes already tested.

Call for tender launched.

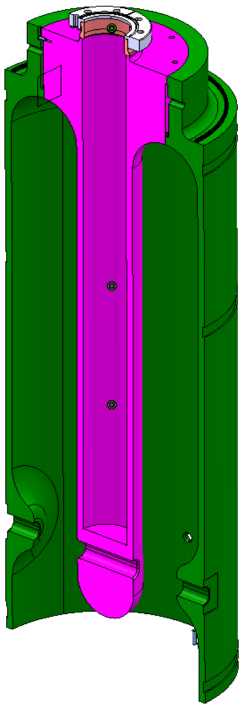


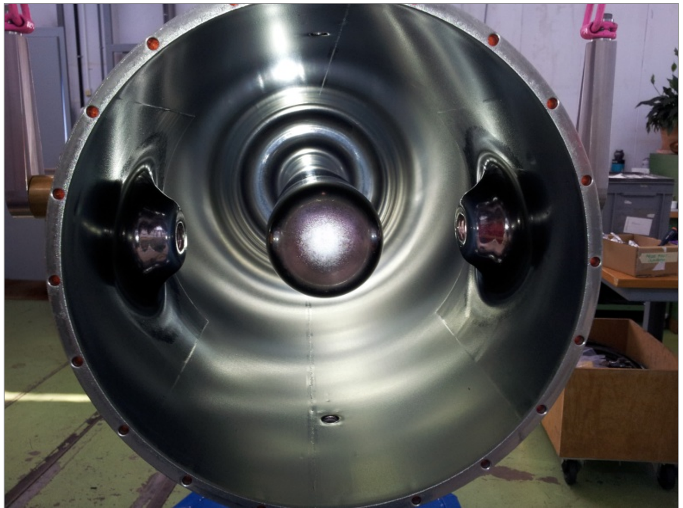


Cavity prototypes designed & built a@ CERN

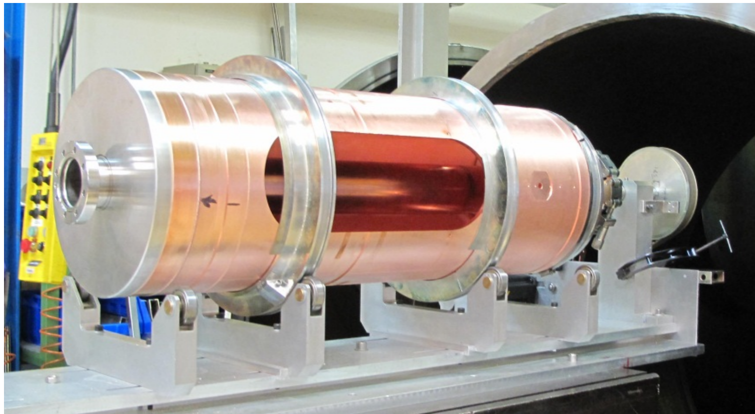
The high-β Cavities are based on 101.28 MHz niobium-sputtered copper (Nb/Cu) Quarter Wave Resonators.

Highly demanding: acceleration gradient 6 MV/m with power consumption of 10 W



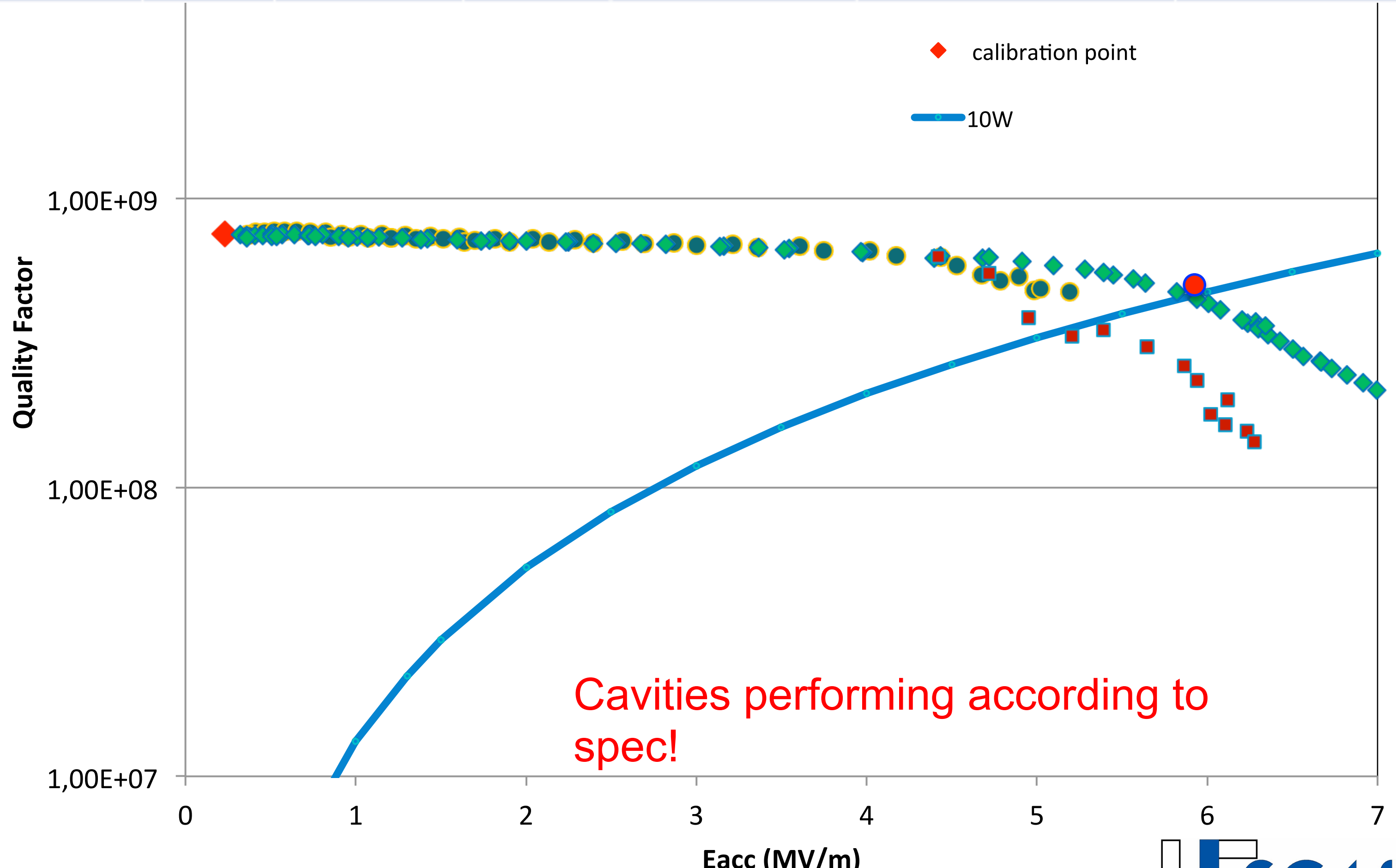


- 1 cavity (Q4) manufactured for sputtering tests on samples

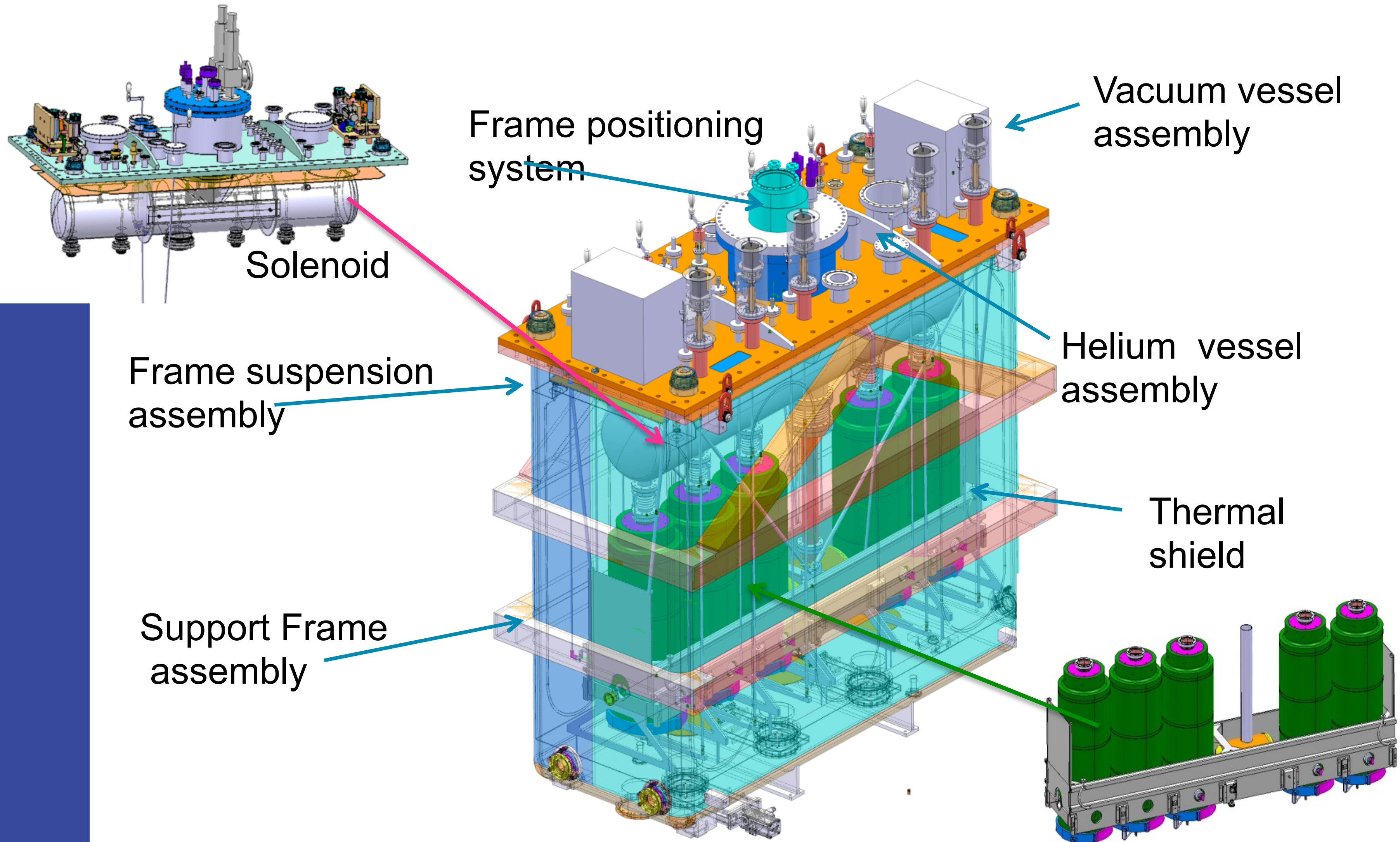


Q3-4 coating (April 2013)

Date	Total dep. Energy [kWh]	Sputtering Pressure [mbar]	Average Power [kW]	Max Temp Thermocouple8 (top of the cavity) [°C]	Max Temp Thermocouple10 (bottom of the cavity) [°C]	Max Temp Thermocouple10 (middle of the cavity) [°C]
25-02-2013	45.7	2.22E-01	8	380	418	427

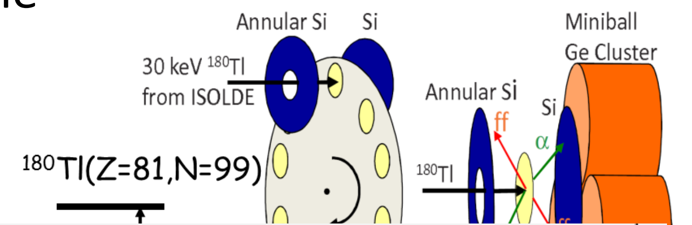


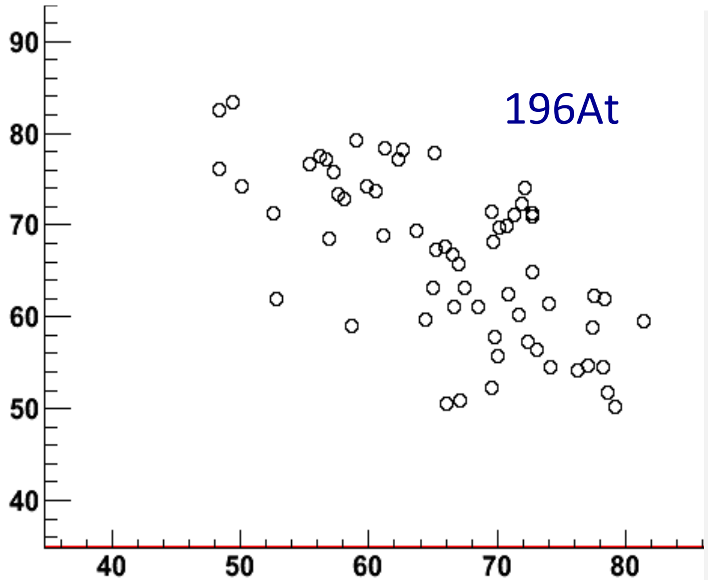
High-β Cryomodule sub-elements

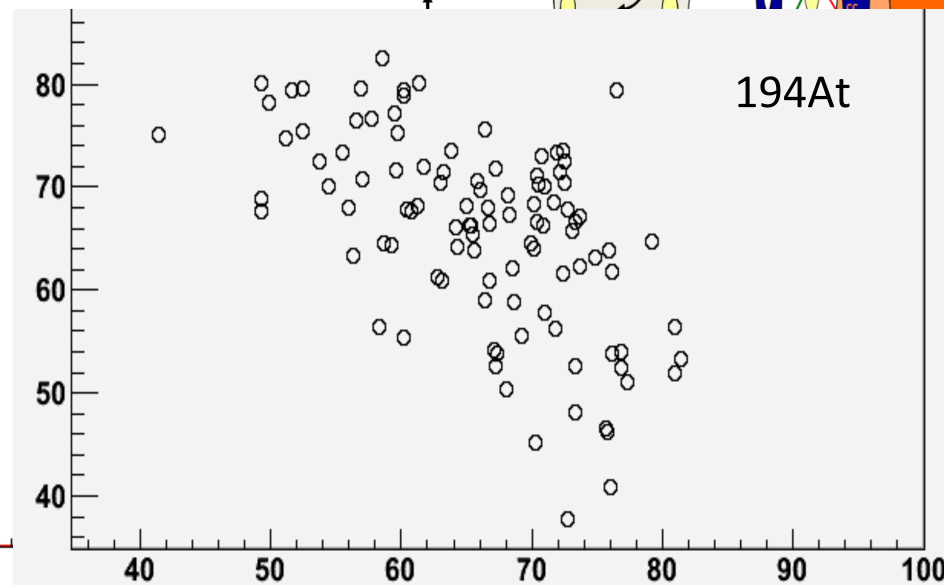


Beta-delayed fission

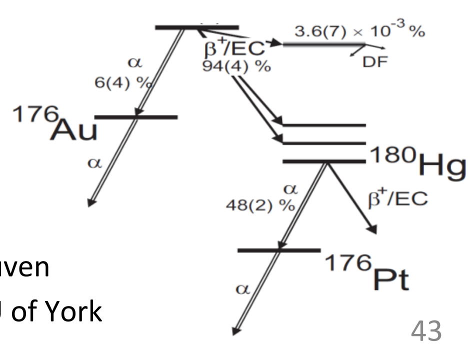
- Beta-delayed fission is believed to affect the abundance of heavy elements as it contributes to recycling heavy elements in the course of the r-process.

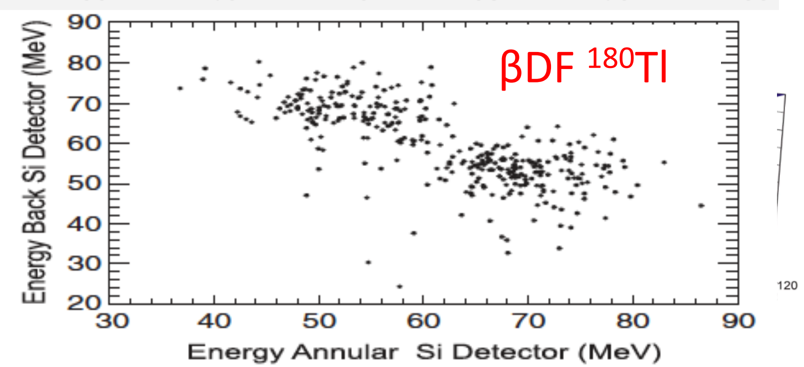






^{180}Hg* ➔ ^{90}Zr+^{90}Zr (?)





Fr: L.Ghys, Ph.D thesis KULeuven
At: V. Trusdale, Ph.D thesis U of York
Tl: PRL 105 (2010) 252502

Motivation for the TSR

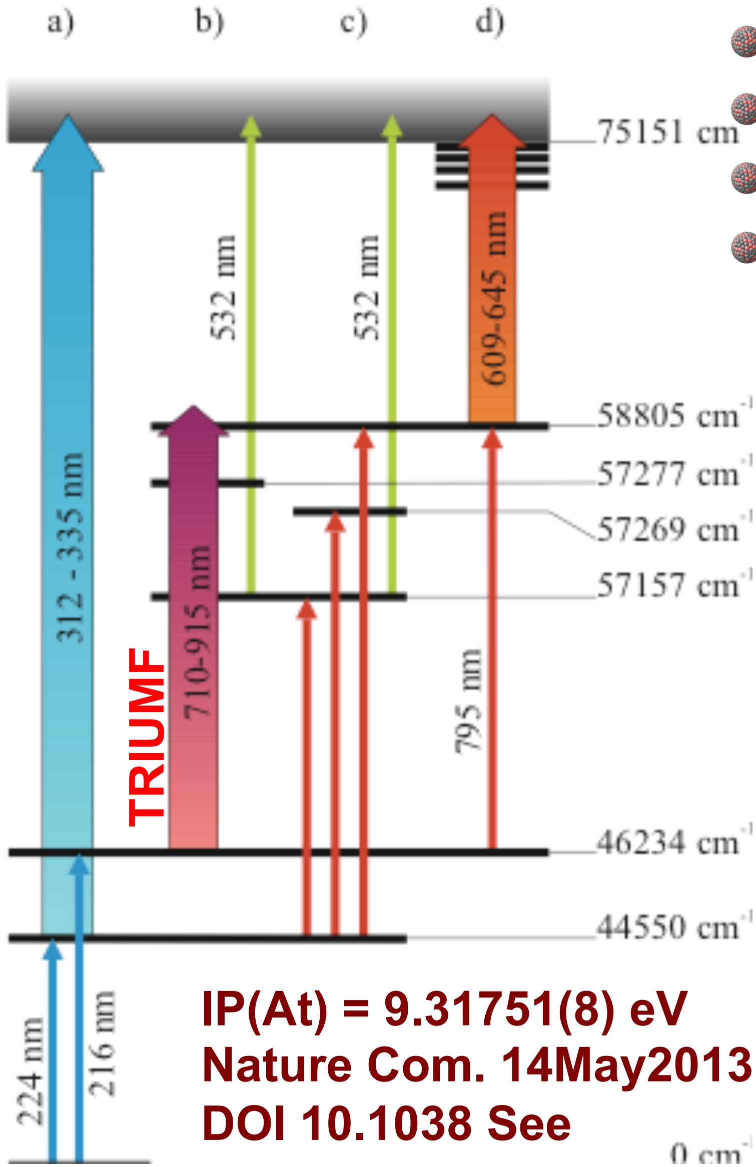
- 1. Higher intensities and cooler beams than in-flight storage rings
- 2. Compared to thick experimental target and direct beam from the post-accelerator:
- + no background from a target container or a beam dump
- + reduced energy straggling for projectile and reaction products in thin target
- + smaller beam size -> improved kinematic corrections for reaction products
- + decreased detector dead-time as CW beam (REX and HIE-ISOLDE pulsed)
- Possibility to use extracted beam with excellent optical qualities

Physics Cases discussed for the TSR

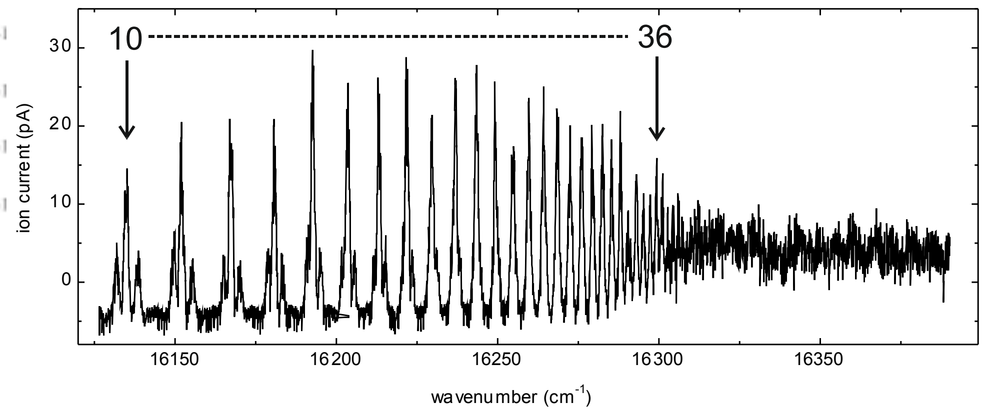
1. Half-life measurements of ^{7}Be in different atomic charge states
2. Capture reactions for astrophysical p-process
3. Nuclear astrophysics through transfer reactions
4. Nuclear structure through transfer reactions
5. Long-lived isomeric states
6. Atomic effects on nuclear half-lives
7. Di-electronic recombination on exotic nuclei
8. Atomic physics experiments
9. Neutrino physics
10. Laser spectroscopy experiments in the storage ring

ISOLDE

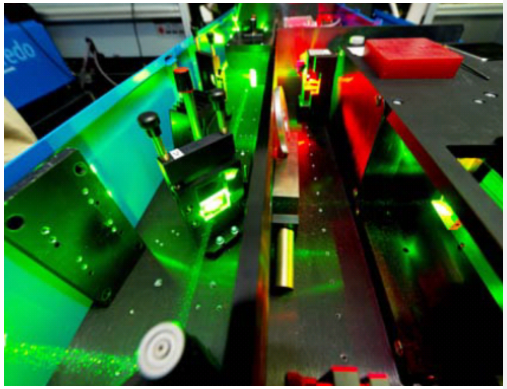
Determination of Atomic properties of Astatine

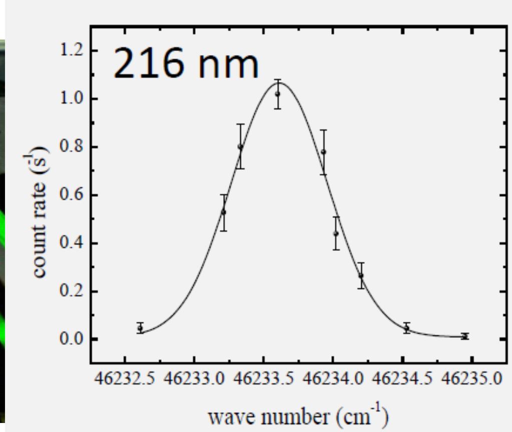


- Determination of ionising potential
- Identification of new atomic transitions
- Comparison with atomic theory
- Scan of ionizing laser: converging Rydberg levels allow precise determination of the IP

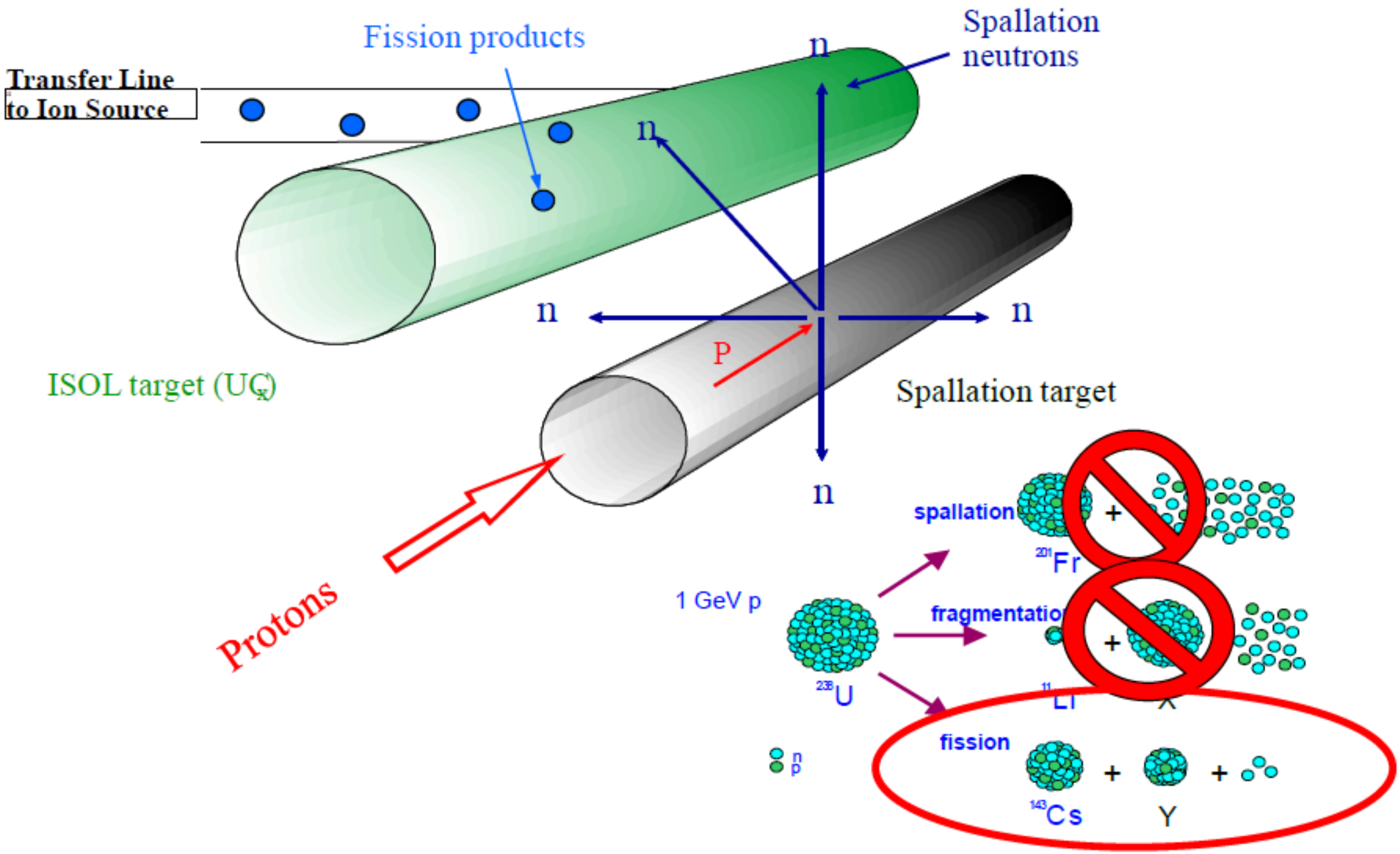


IP(At) = 9.31751(8) eV
Nature Com. 14May2013
DOI 10.1038 See



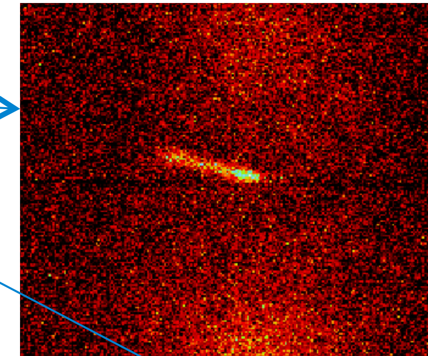


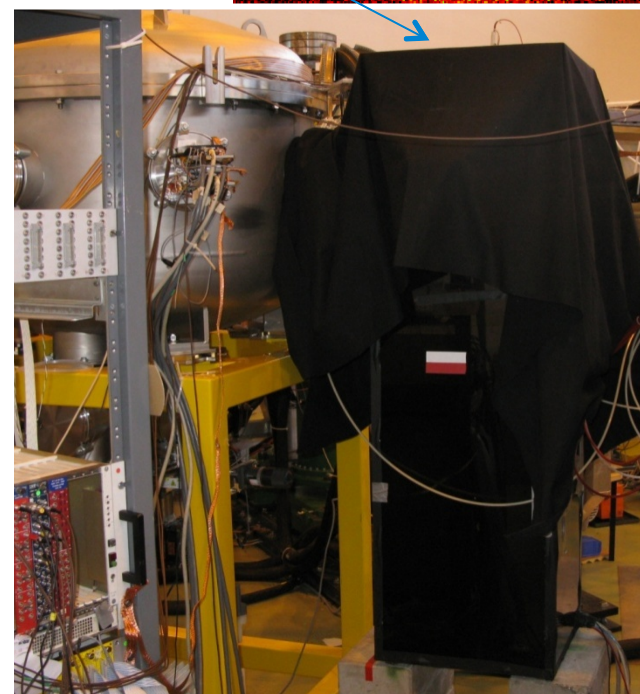
Converter target

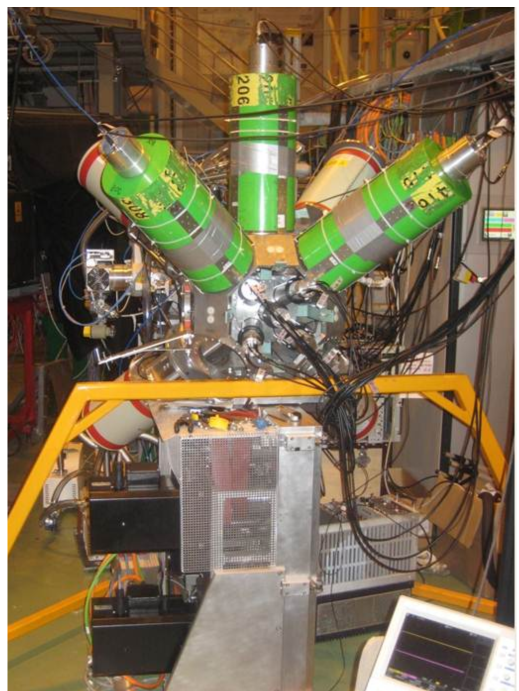


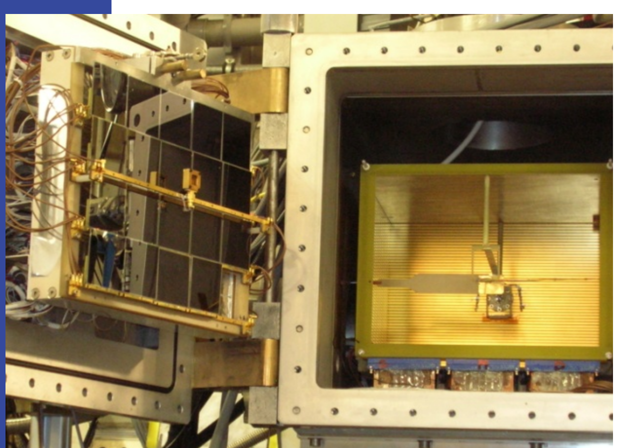
New setups in the summer

- Successful experiments with new setups & by new groups:
  - 6He with opt. time-proj. chamber (Warsaw);
  - 21Na and 31Mg with REX scattering chamber (Lund and Tokyo);
  - 34Mg with fast tape-station (Bucharest)
  - 12 Be with active target MAYA (Leuven, GANIL);

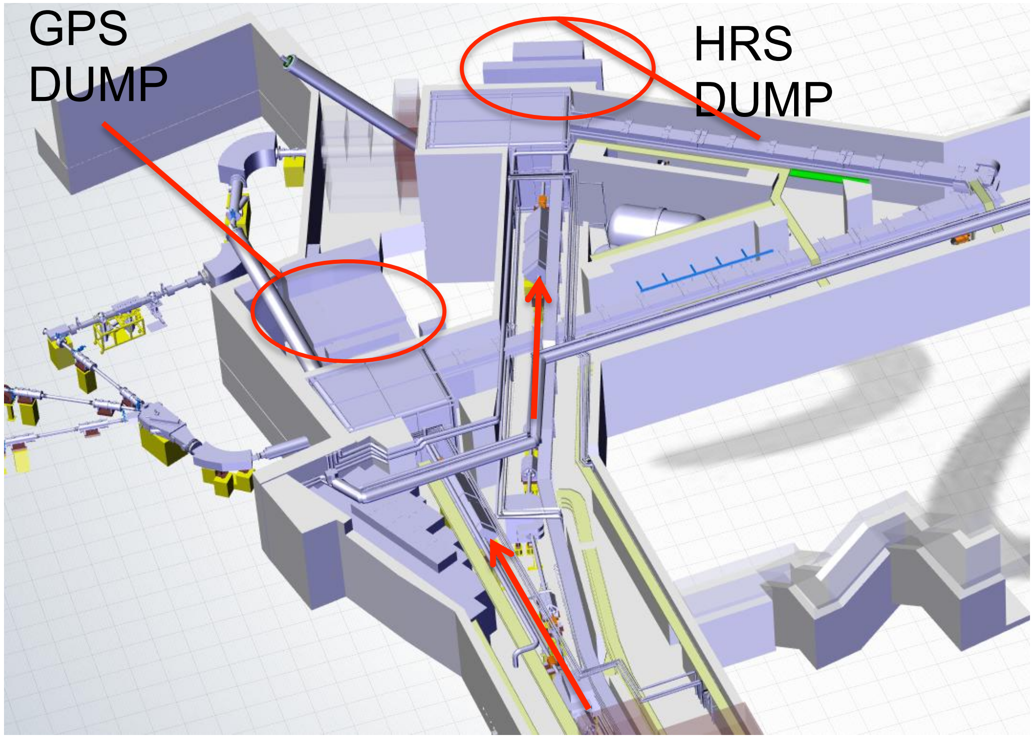


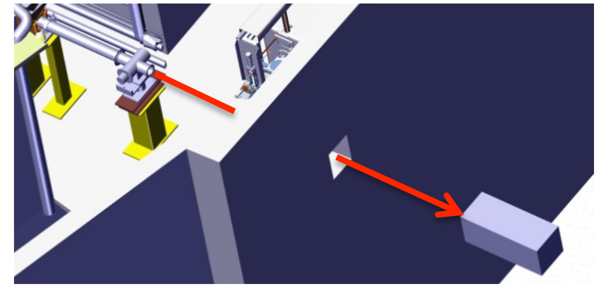




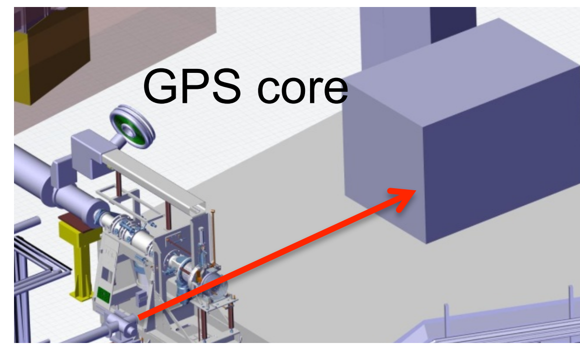


ISOLDE Beam Dumps





0.4 x 0.4 x 1m



1.6 x 1.6 x 2.4m
Off centre

Two options

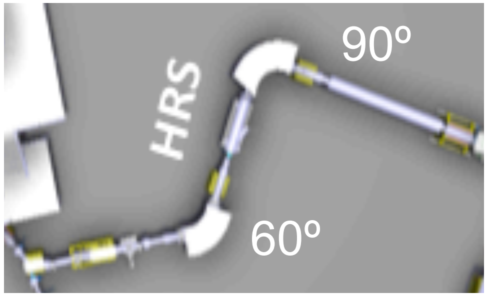
- Remove all the earth to replace the beam dumps and shielding
- Insert a second **cooled beam dump** in front of existing dumps

  Attention: back scattering and air activation need to be assessed

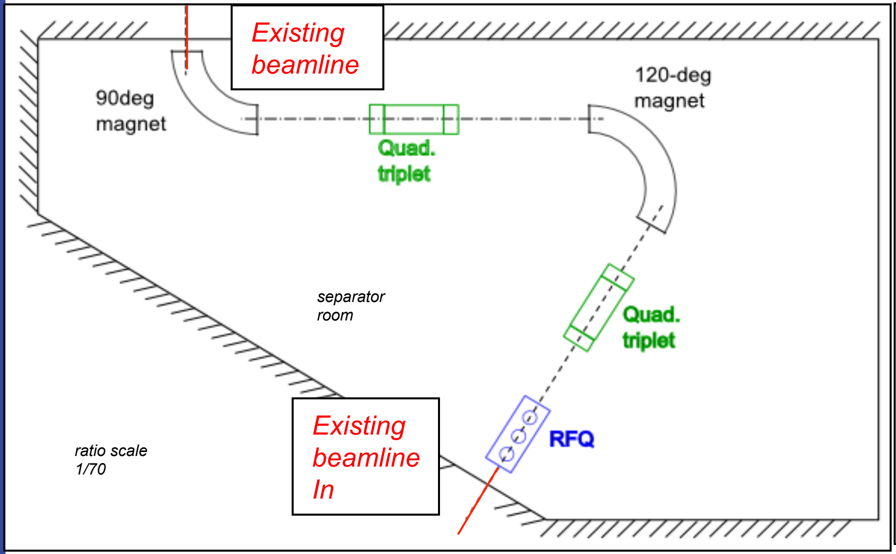
  Conceptual design of cooled beam dump required.

High Resolution Separator (HRS) upgrade design study

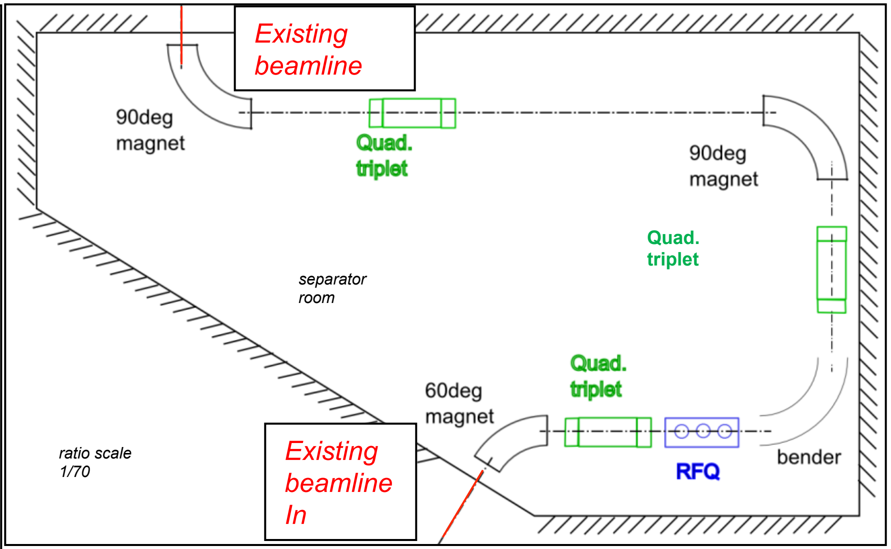
Constraints
- ➔ available space in separator room
- ➔ positioning of already existing beamlines upstream and downstream



From target Beam In



Scheme of layout 1



Scheme of layout 2

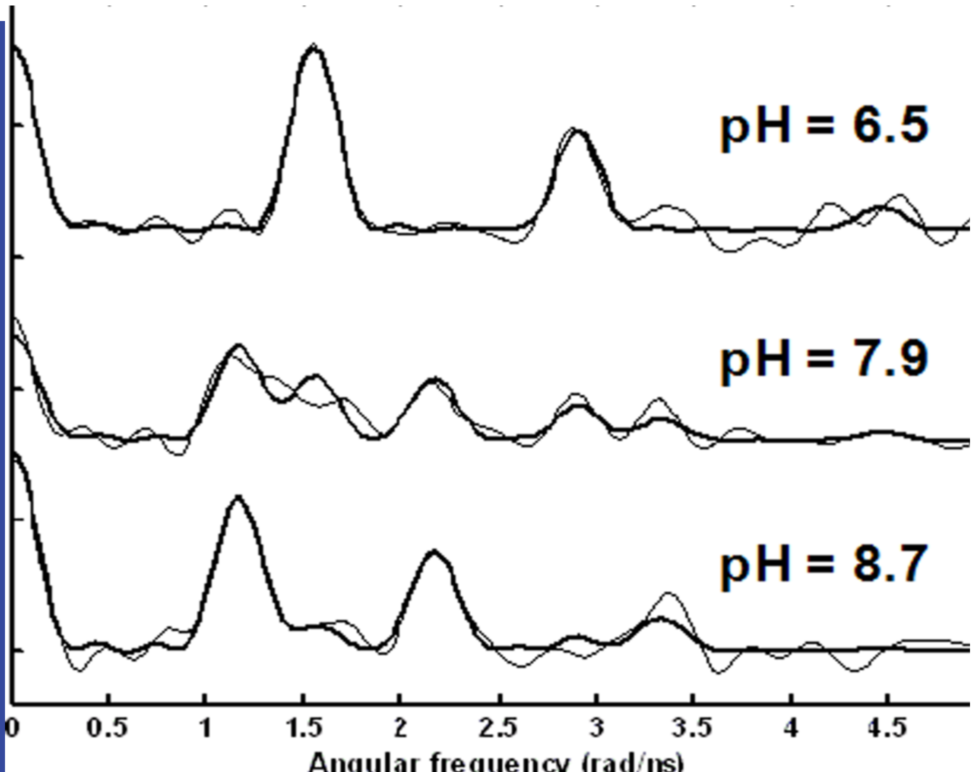
- Beam bunching and cooling directly after extraction from the front end
- Beam shaping (defocusing) prior to first magnetic stage (120 ° dipole magnet) and prior to 90 ° second magnet

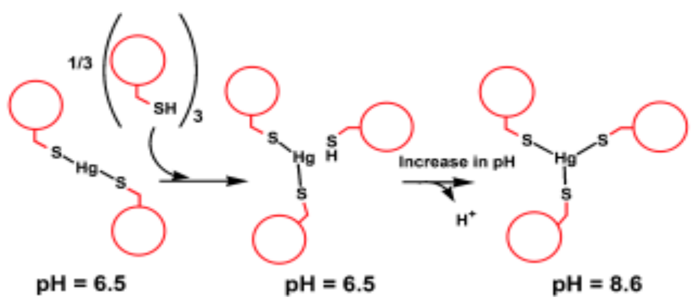
- Use of a 60° dipole magnet to clean the beam coming from the front end from its contaminants prior to cooling
- Necessity of a quadrupole triplet after the first magnetic stage to shape the beam prior to injection in the RFQBC

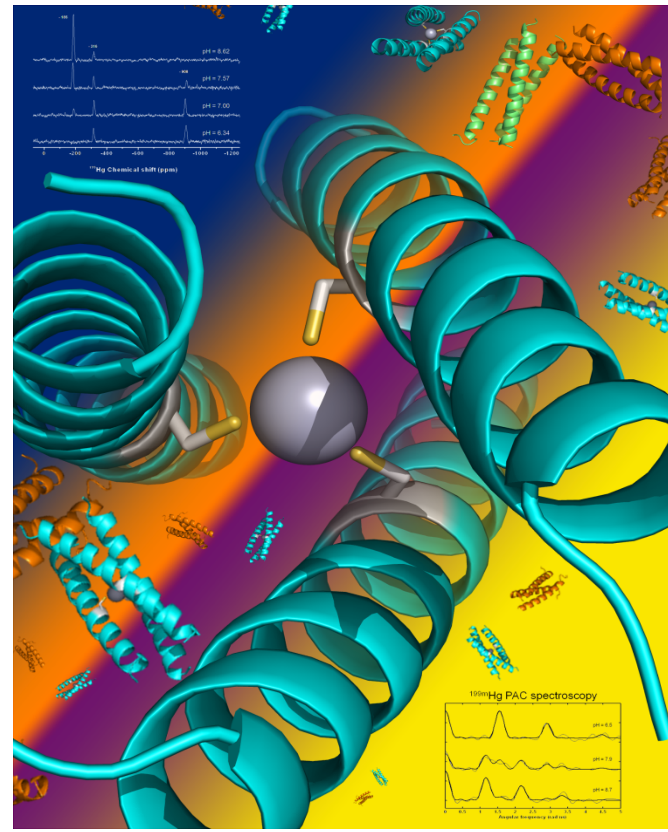
A Few Facts

- ISOLDE is the CERN radioactive beam facility
- In operation since 45 years
- The largest selection of isotopes of any ISOL facility worldwide
- Provides low energy or post-accelerated beams
- Run by an international collaboration
- Open to users from around the world

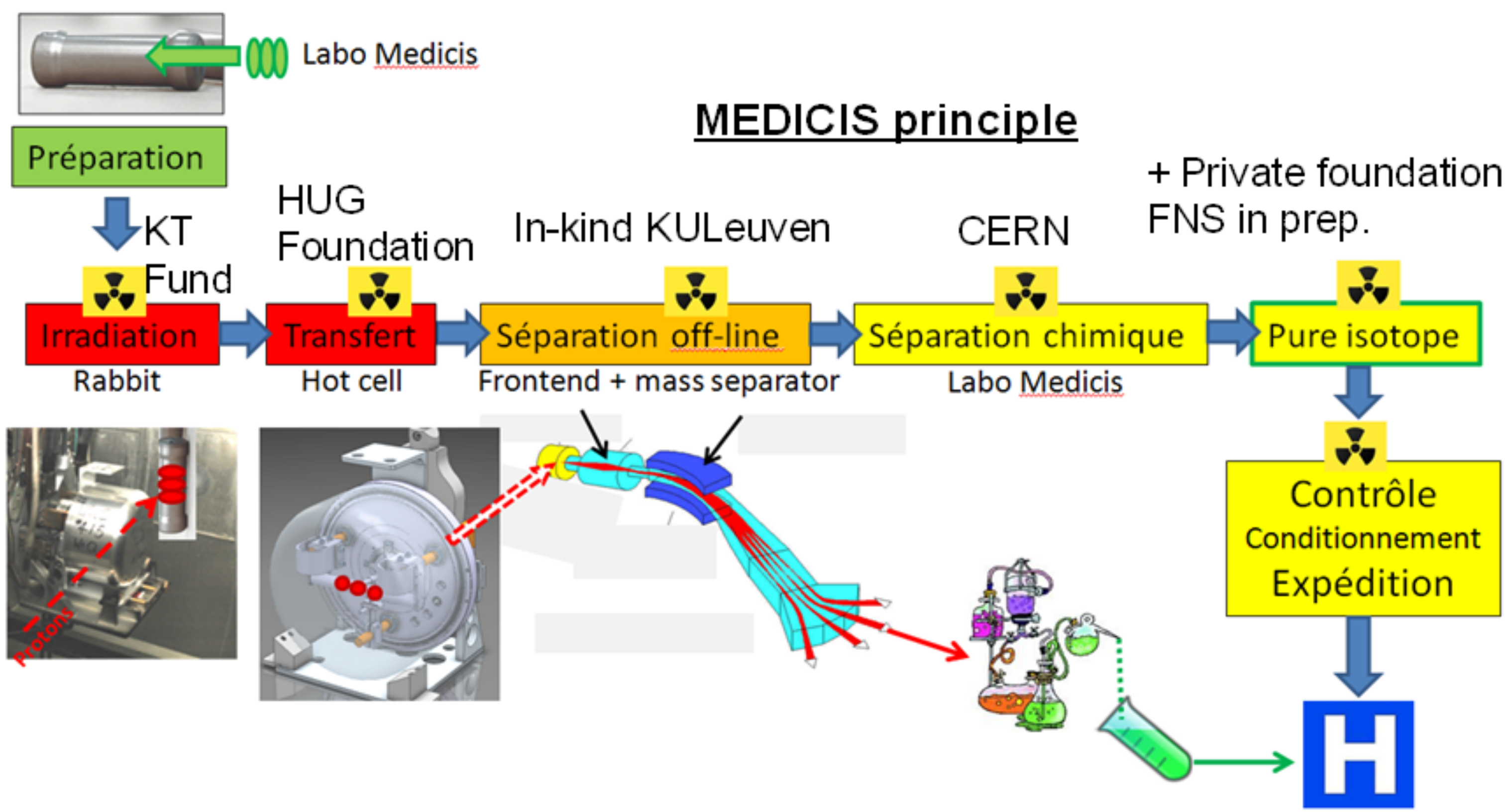
Metal binding to proteins



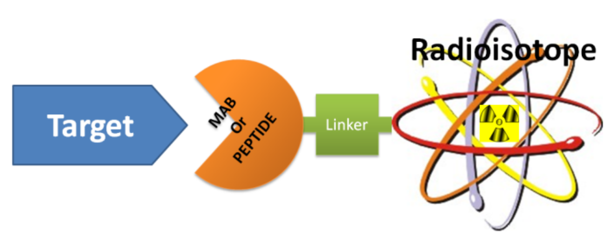




152Tb MEDICIS test batch shipped in August to Lausanne



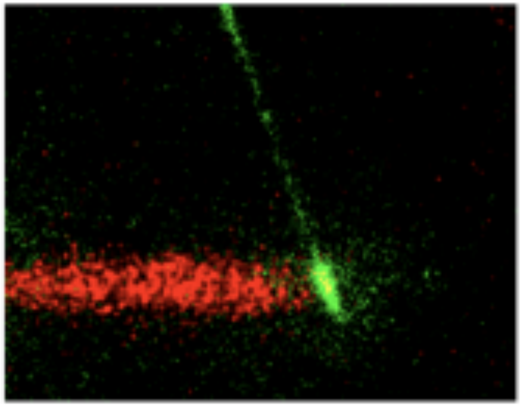
Prostate Cancer cells



152Tb From ISOLDE

Probing the neutron halo of ^{6}He using the Warsaw Optical Time Projection Chamber (OTPC)

- Weak decay branch ($\approx 10^{-6}$) $^6He \rightarrow \alpha + d$ provides insight into the 2n halo of ^{6}He
- Bunches of ^{6}He ions were delivered by REX-Isolde and implanted into the OTPC
- Clear images of decay events with tracks of an α particle and a deuteron were recorded by a CCD camera
- Detailed analysis is in progress



A CCD image showing a bunch of implanted ^{6}He ions (red) and a $^6He \rightarrow \alpha + d$ decay (green)