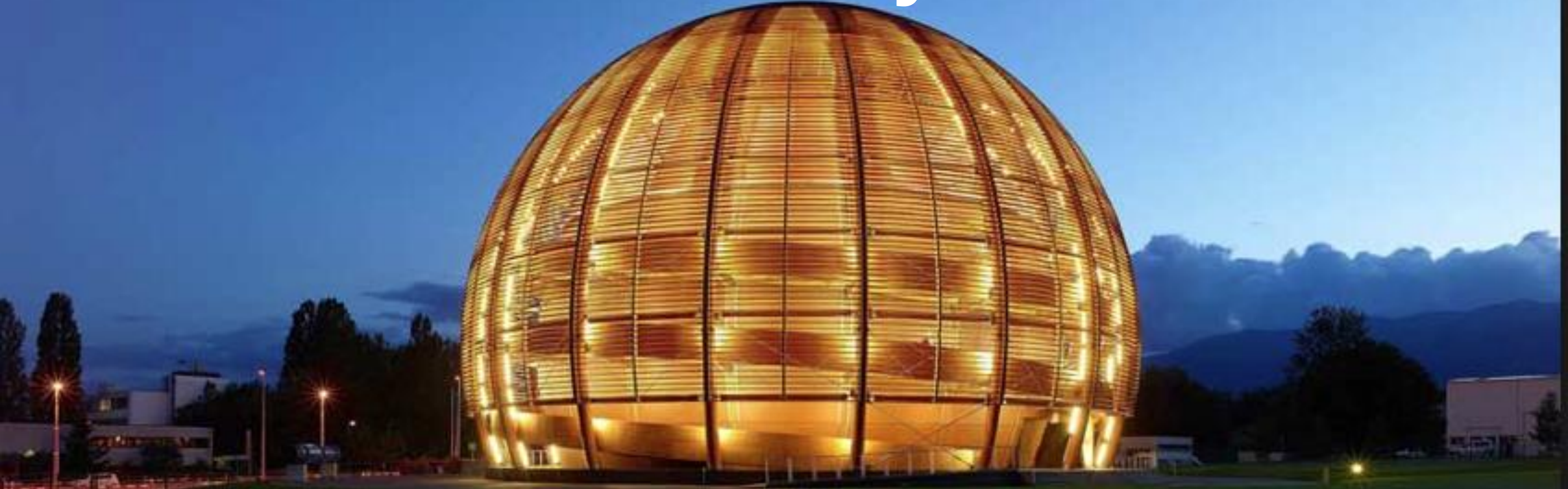
Accelerators for Nuclear Physics: ISOLDE Radioactive Ion Beam Facility



ASP18 – 5th African School of
Fundamental Physics and Applications
University of Namibia, and
Namibia University of Science and Technology
Windhoek, Namibia
June 24 – July 14, 2018

Yacine Kadi
CERN Experimental Area Group
Geneva, Switzerland

Who Am I !

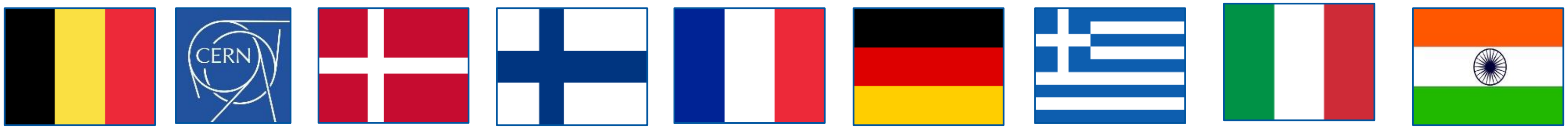
- **Nuclear Engineering (UK & F)**
- **Nuclear Physics** (**CH**, FEAT, TARC and nTOF, ISOLDE)
- **Applied Physics** (CERN)
- **Academia** (prof. SunKyunKwan Univ, Seoul, South Korea)

Who Am I !

- 1995 – 2004: Leading the simulation studies within the Energy Amplifier Conceptual Studies at CERN + TRADE (EUROTRANS FP6)
- 2005 – 2009: Leading the EURISOL-DS Multi-MW target project within FP6
- 2006 – 2009: Lead the AB/ATB-TD section – overseeing the design, construction, testing, installation, operation and maintenance of LHC Beam Intercepting Devices
- 2009 – 2018: Leading the HIE-ISOLDE project at CERN – which has as objective to increase the energy, intensity and quality of the radioactive ion beams at CERN-ISOLDE.
- 2018 – …: Leading the CERN SPS North Experimental Area Upgrade (Hadron Physics, ATLAS/CMS beam test facility) + Coordinating CERN Material Test Facility (HiRadMat)

ISOLDE Facility

- ISOLDE is the CERN radioactive ion beam facility
- Oldest experiment at CERN (approved > 50 y ago)
- Provides low energy and **post-accelerated beams**
- Run by an **international collaboration since 1965**

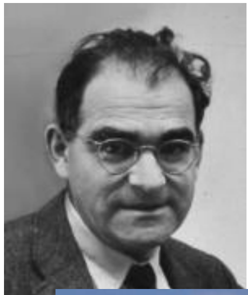


Belgium CERN Denmark Finland France Germany Greece Italy India

Ireland Norway Poland Romania Spain South Africa Sweden Slovakia United Kingdom

- **> 500 Users from 100 Institutions, 50 experiments / year**

ISOLDE brief History



The 1963 Conference on High Energy Physics and Nuclear Structure

Conclusions: Call for proposals in nuclear physics at CERN

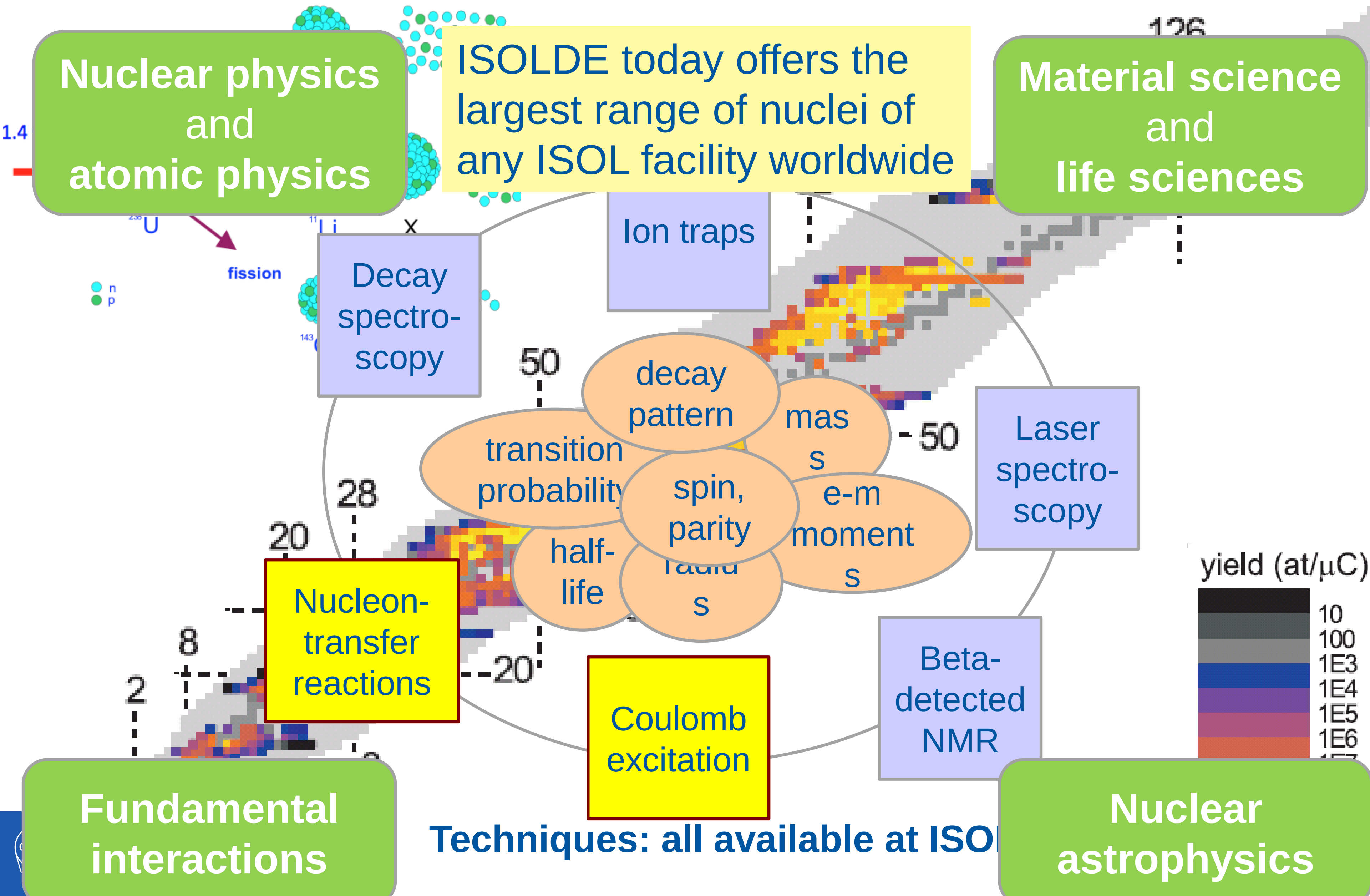
V.
(D

C. Rubbia
(DG 1989-93)

New Facility
June 1992 @ PSB

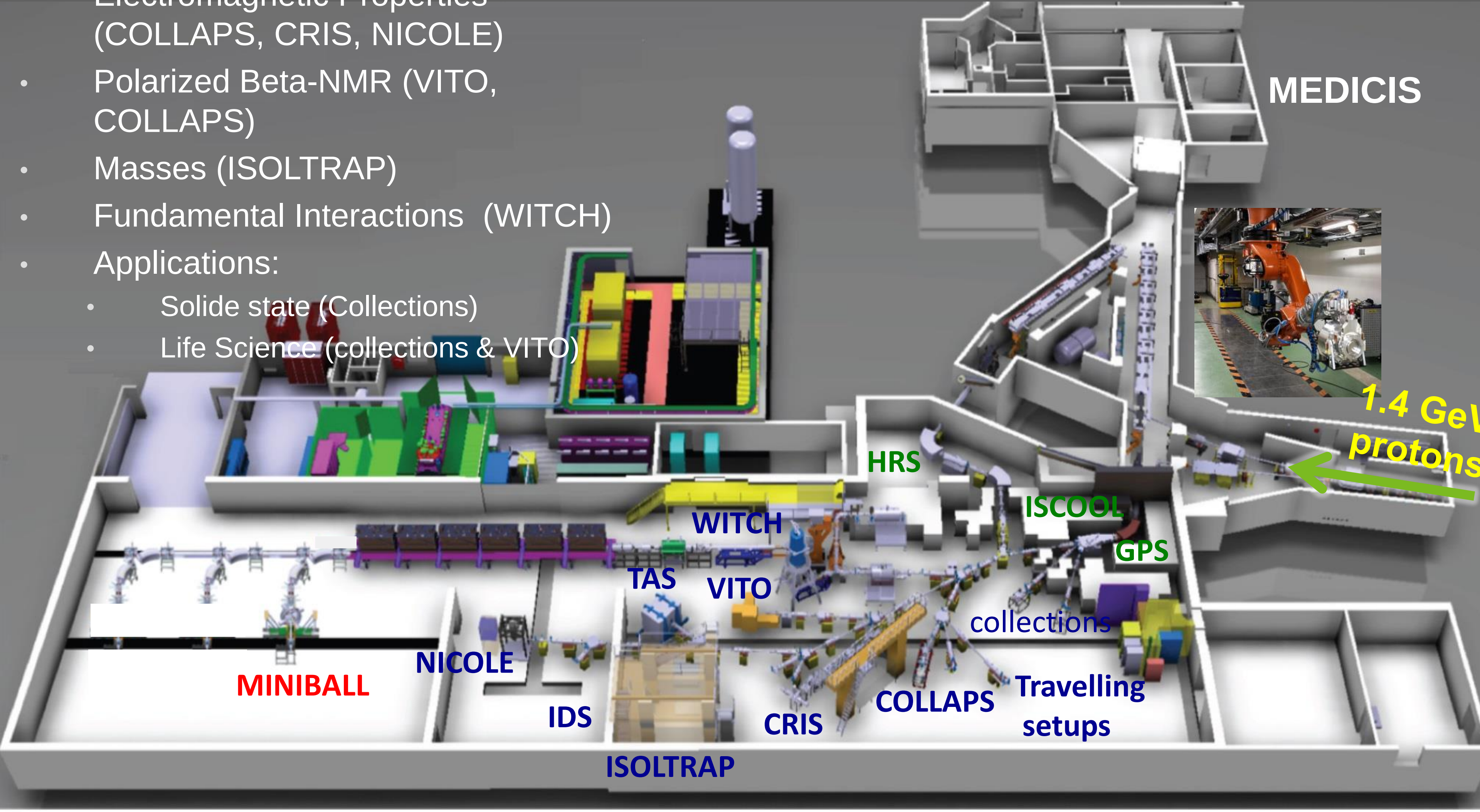
CERN Research Infrastructures

Research with radioactive nuclides @ ISOLDE



- Decay spectroscopy (IDS, TAS,..)
- Coulomb excitation (MINIBALL)
- Transfer reactions (T-REX, Scattering)
- Electromagnetic Properties (COLLAPS, CRIS, NICOLE)
- Polarized Beta-NMR (VITO, COLLAPS)
- Masses (ISOLTRAP)
- Fundamental Interactions (WITCH)
- Applications:
  - Solide state (Collections)
  - Life Science (collections & VITO)

ISOLDE



Low Energy (30-60kV) Exps, Post-accelerated Exps (10 MeV/u) Machine elements

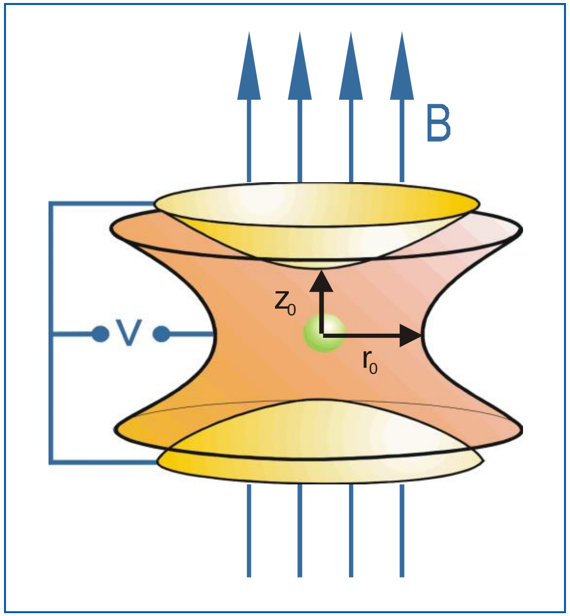
ISOLTRAP: principle

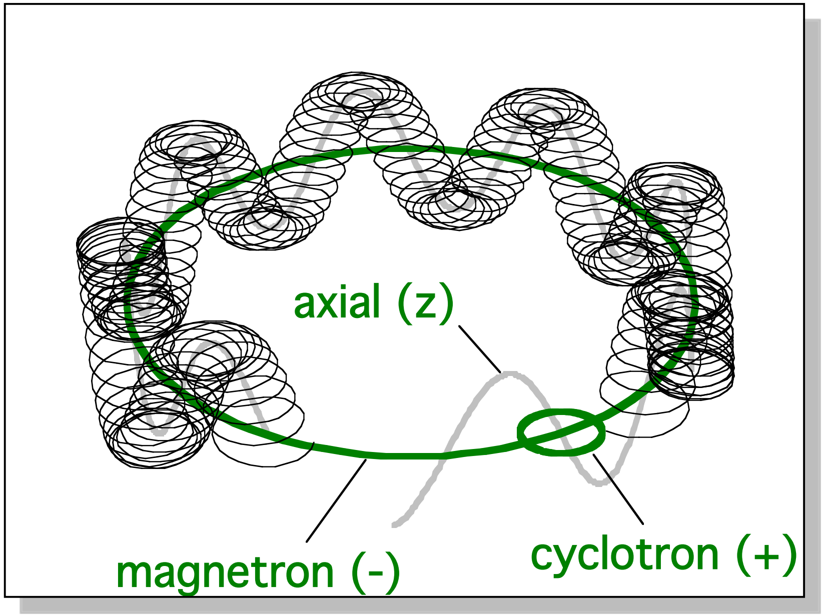
Determination of nuclear mass by measuring the cyclotron frequency:

Ions are trapped in crossed magnetic and electric field

The frequency of their motion is proportional to their mass

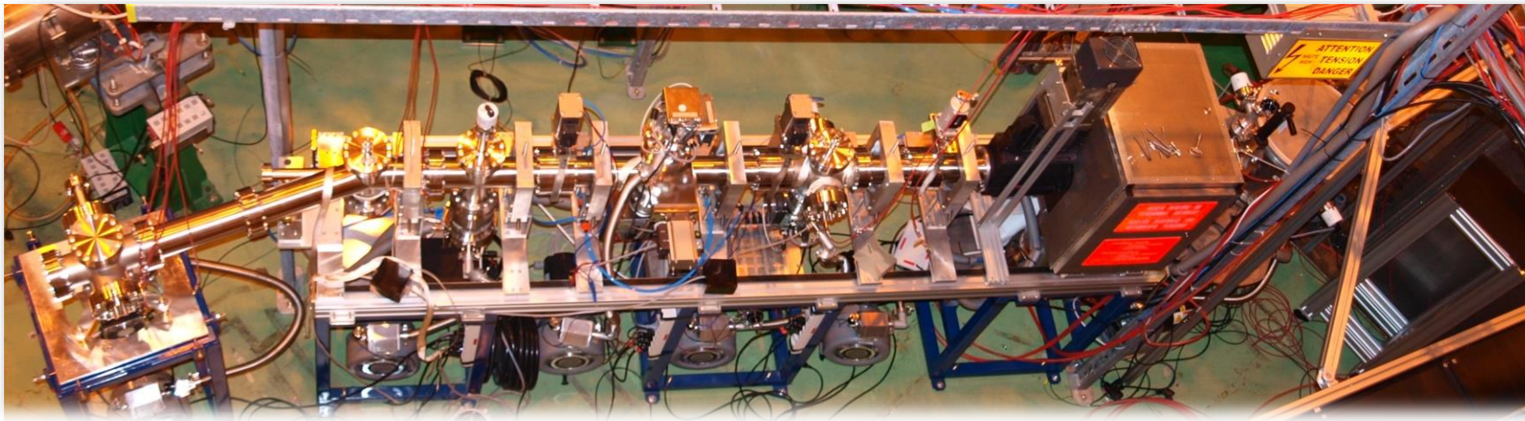
$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

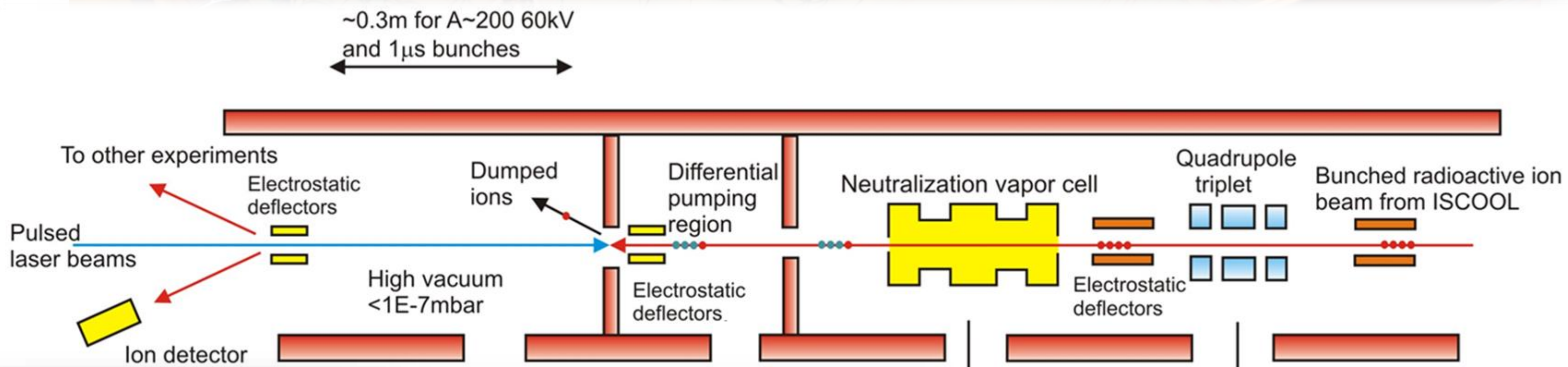


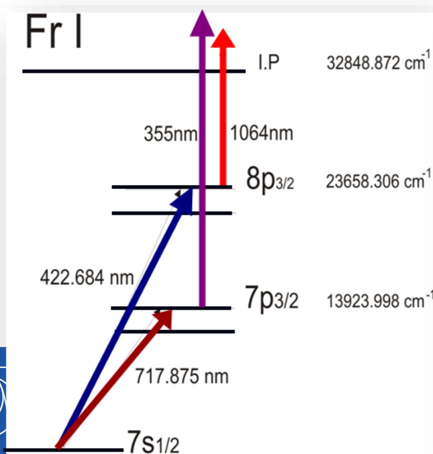


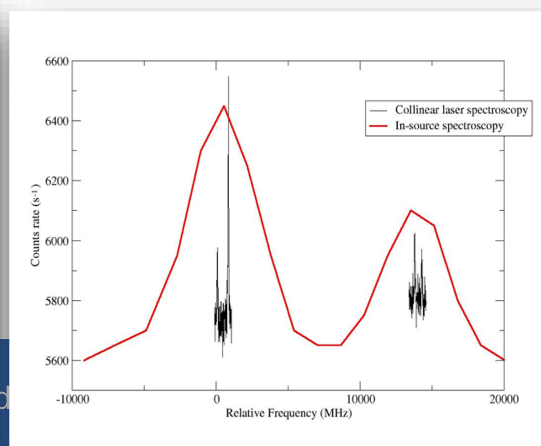
A=100, B=6T

- $\nu_+ \approx 1$ MHz
- $\nu_- \approx 1$ kHz
- $\nu_z \approx 44$ kHz







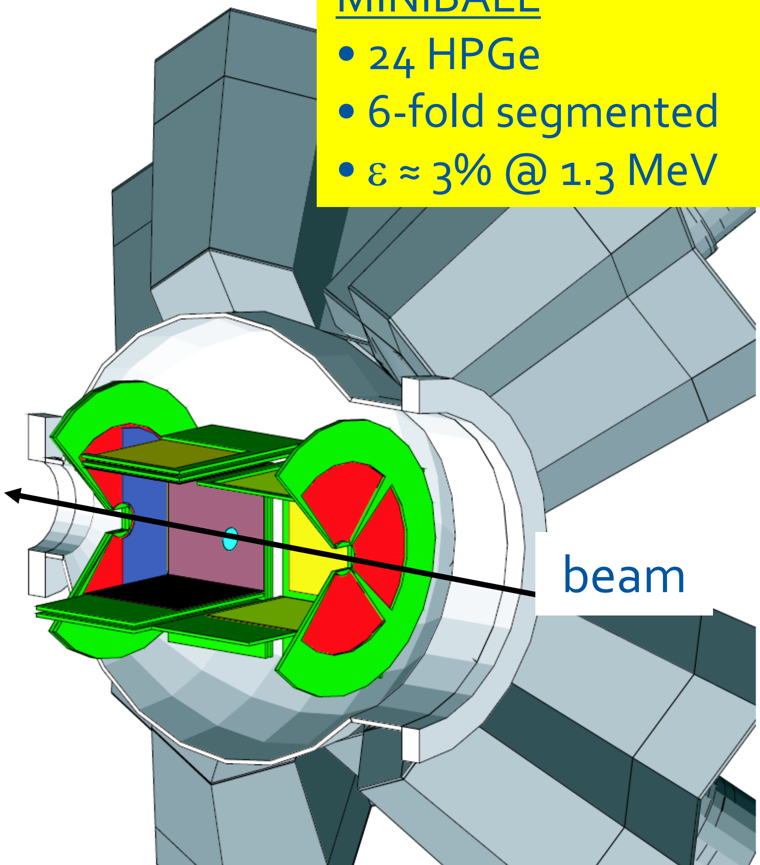


Combining high resolution nature of collinear beams method with high sensitivity of in-source spectroscopy. Allowing extraction of B factors and quadrupole moments.

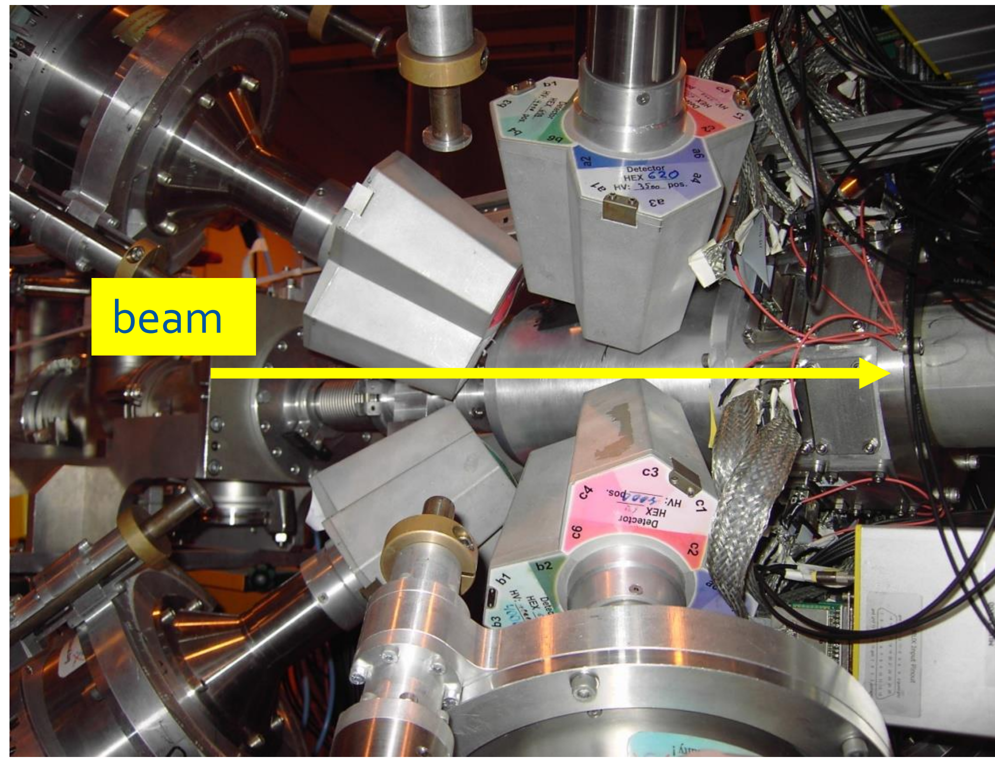
Experimental set-up: T-REX & MINIBALL

December 8 - 10, 2010 | ISOLDE Workshop 2010 | Thorsten Kröll | TUD - Institut für Kernphysik | 11

MINIBALL
- 24 HPGe
- 6-fold segmented
- ε ≈ 3% @ 1.3 MeV



... shown is GEANT4
Implementation of set-up



TDPAC and Mössbauer Spectroscopy

Nuclear probes as sensors inside the nanoworld

- **Nanopartices, Nanowires, nm-sized layered thin films,**
  Nanocomposite Materials, Macromolecules
- **Probe atoms at surfaces and interfaces**

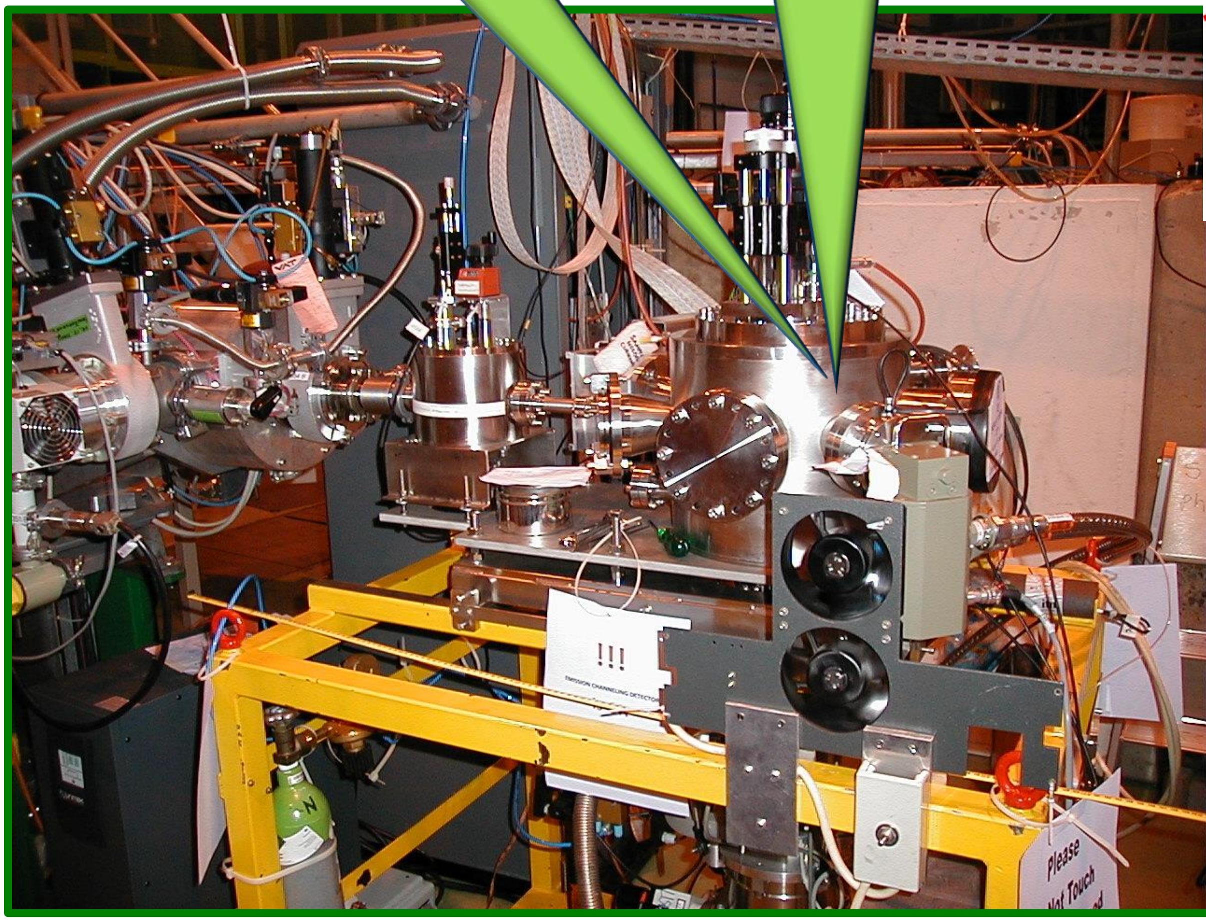
Nuclear probes as local magnetic field sensors

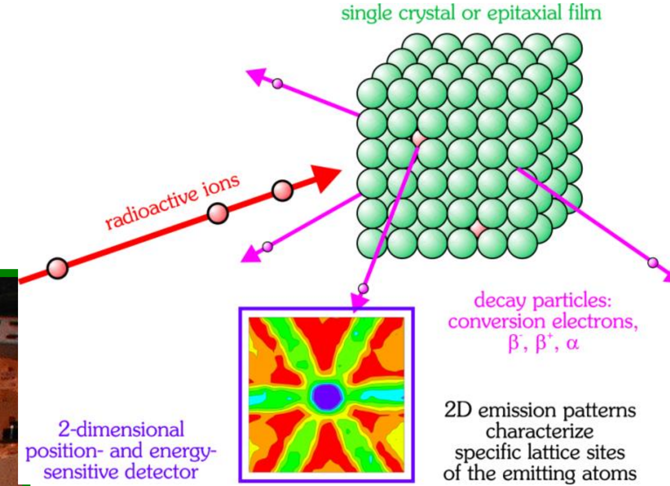
- **Magnetic properties of clusters and nanocrystalline films**
- **Heavy fermion systems, Magnetoresistive materials**
- **Understanding magnetic hyperfine fields in solids**

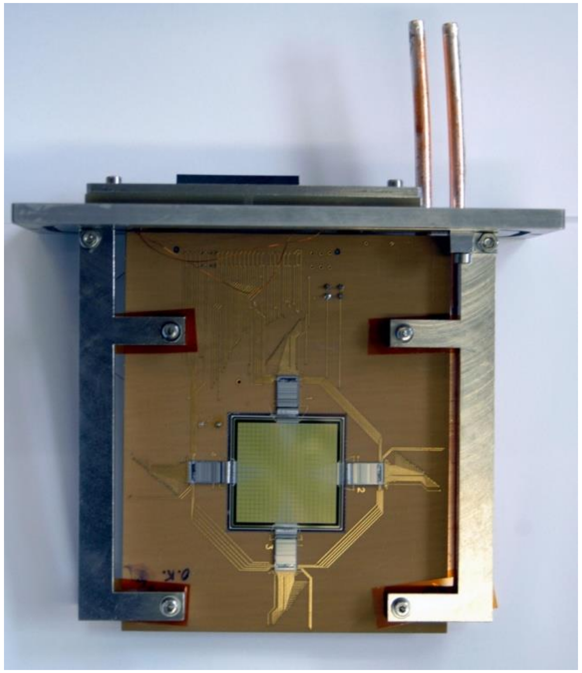
New online Emission Channeling

NEW pad-Si FAST 2D electron detector

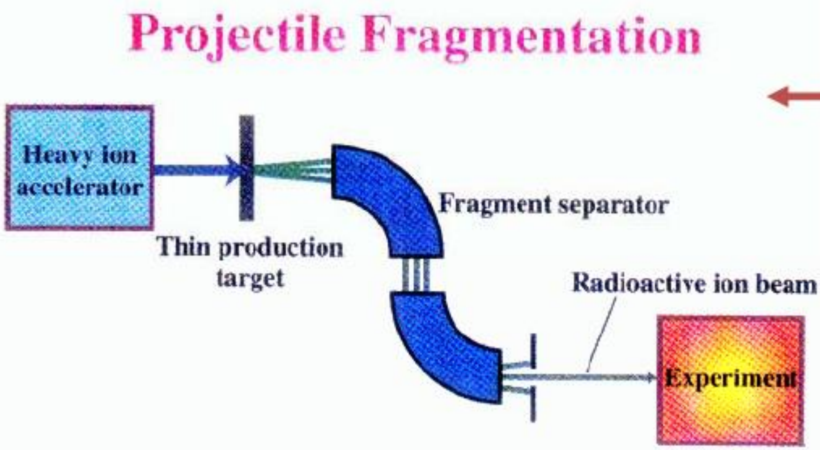
NEW cooling system down to 50K







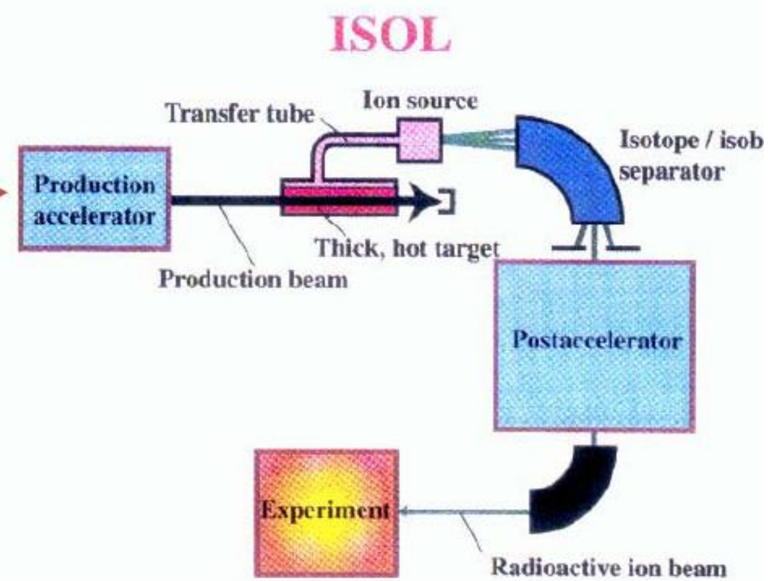
Radioactive Beam Production: Two Complementary Methods



GANIL/SISSI, GSI,
RIKEN, NSCL/MSU

High energy, large variety of species,
Poor optical qualities

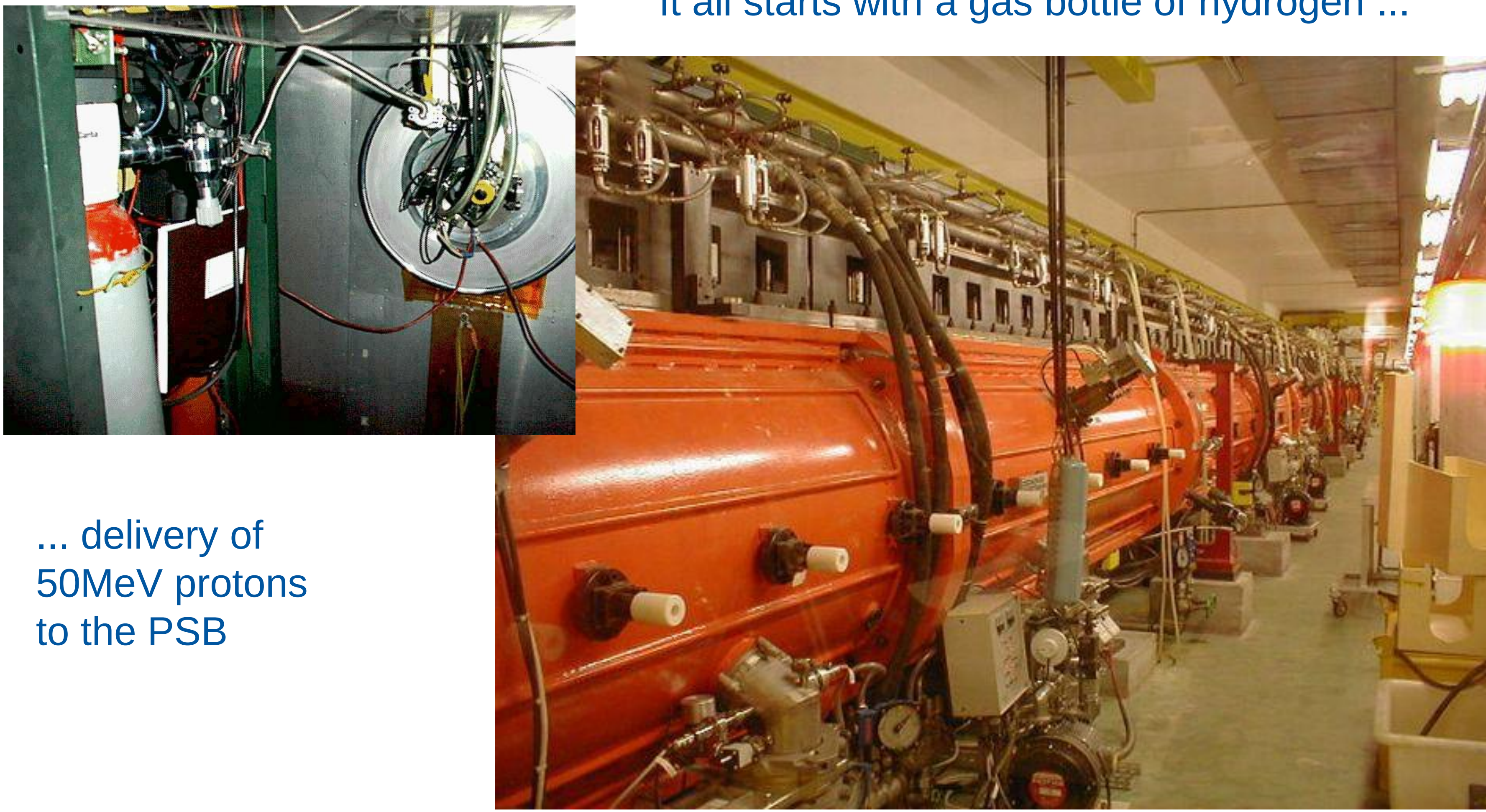
GANIL/SPIRAL, REX/ISOLDE,
ISAAC/TRIUMF



Low energy, chemistry is difficult,
good beam qualities

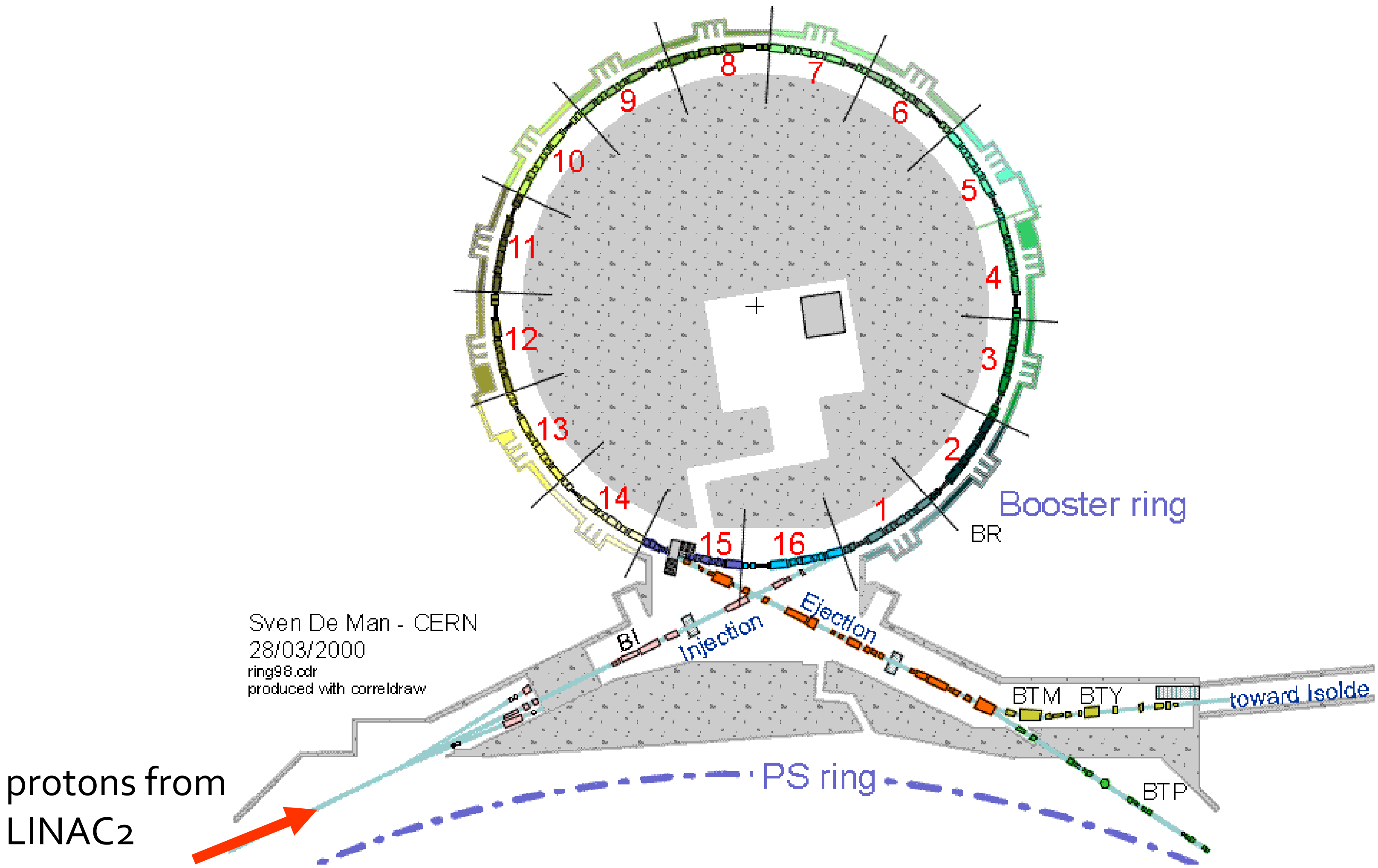
The Proton Driver: LINAC 2

It all starts with a gas bottle of hydrogen ...

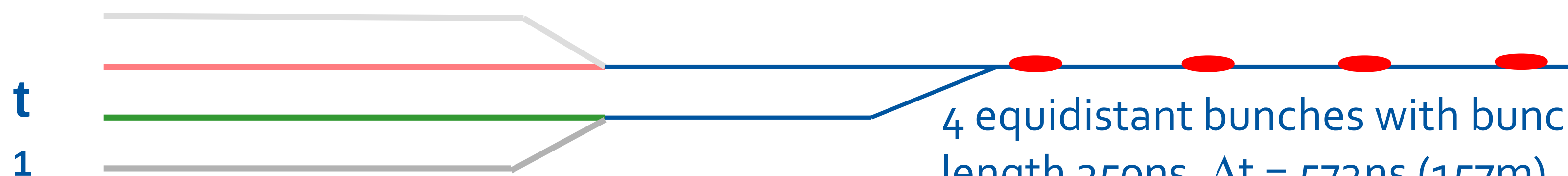


... delivery of
50MeV protons
to the PSB

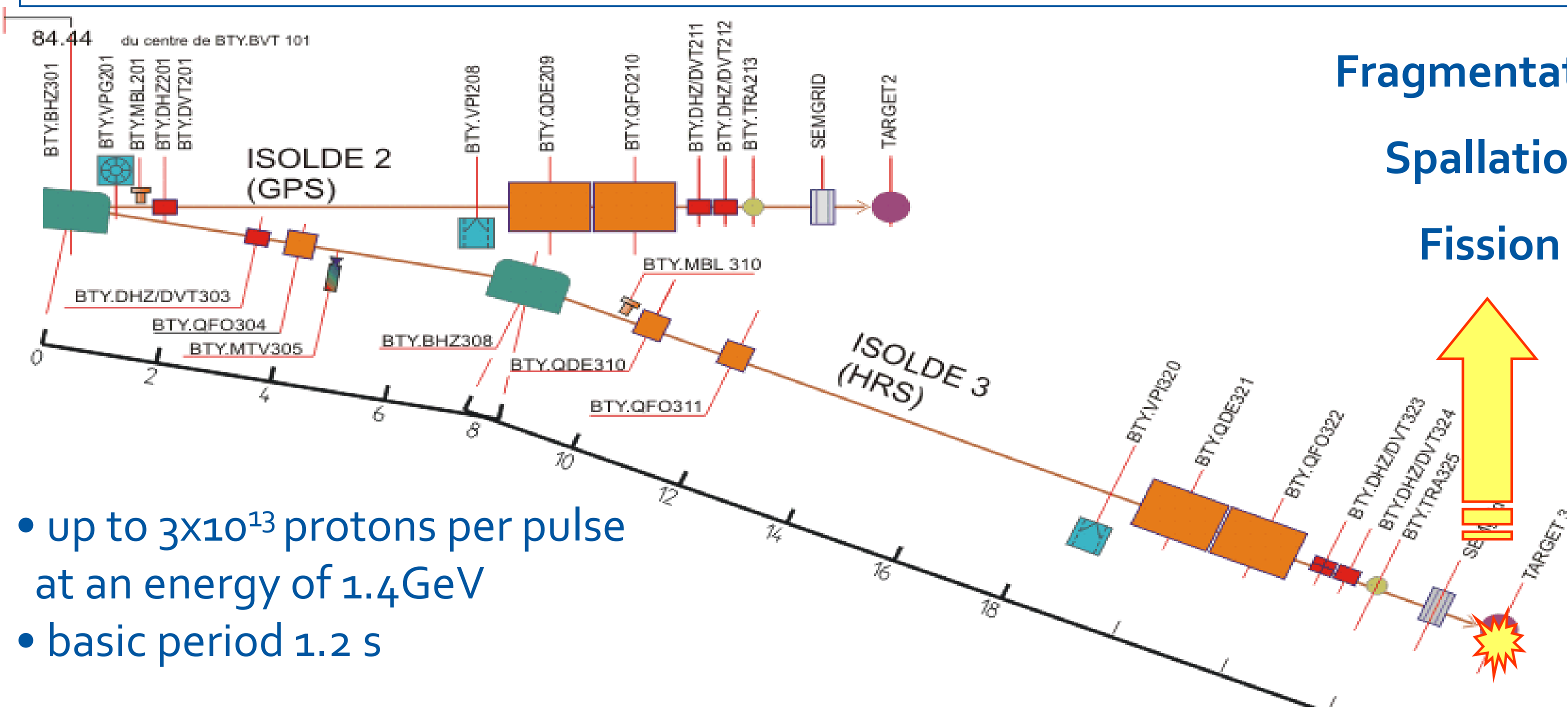
Proton Synchrotron Booster



Delivery of protons to ISOLDE Targets



4 equidistant bunches with bunch length 25ons, Δt = 572ns (157m)



Fragmentation

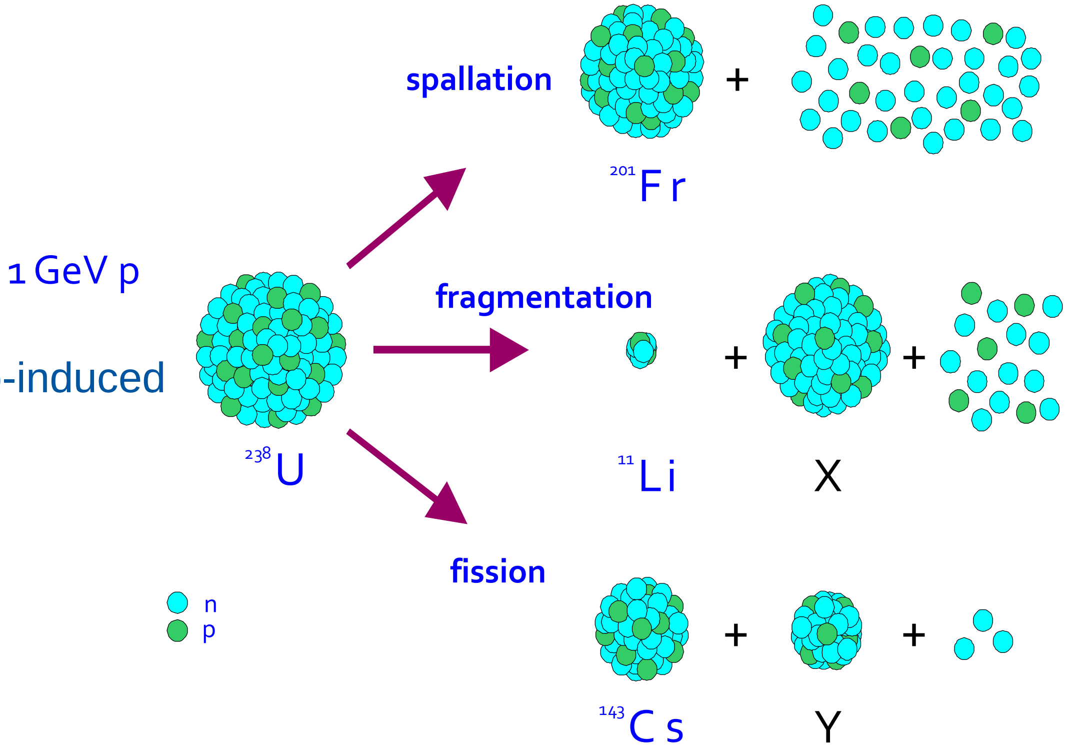
Spallation

Fission

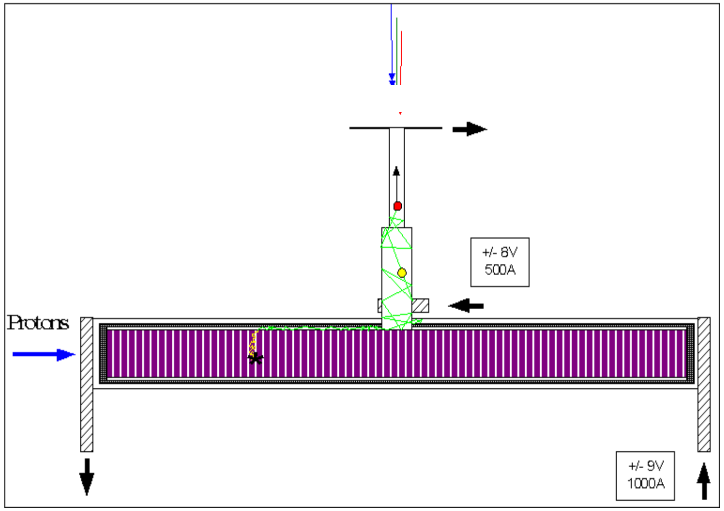
- up to $3x10^{13}$ protons per pulse at an energy of 1.4GeV
- basic period 1.2 s

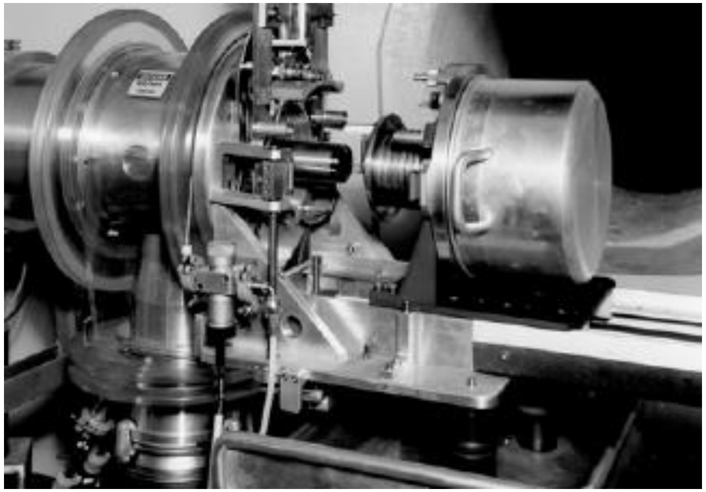
RIB - Production reactions

- Spallation
- Fragmentation
- Fission
  - n- (thermal or energetic), p-induced
  - Photofission (e-beam)
- Fusion



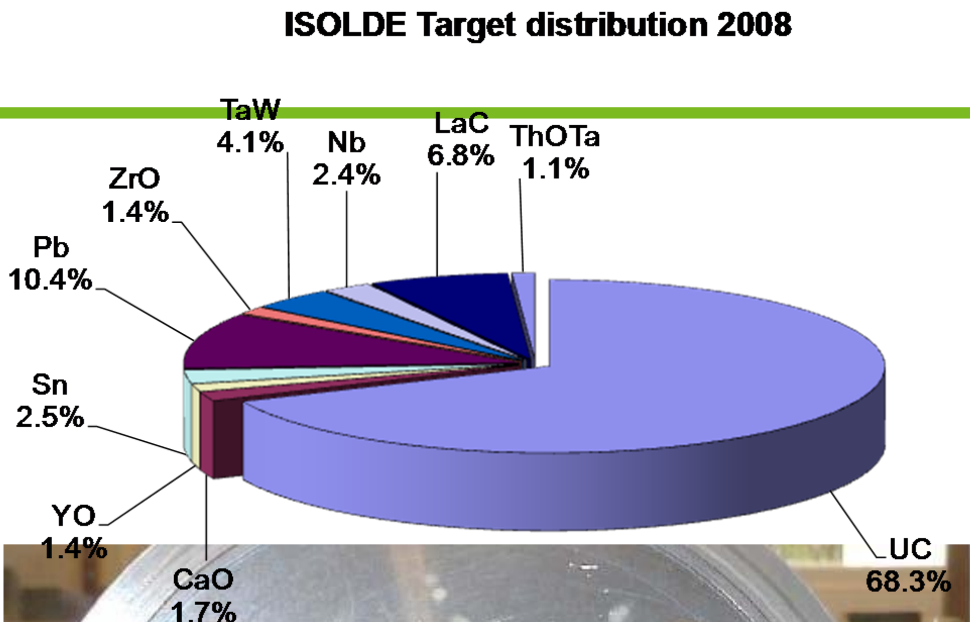
Target – Ion-source matrix

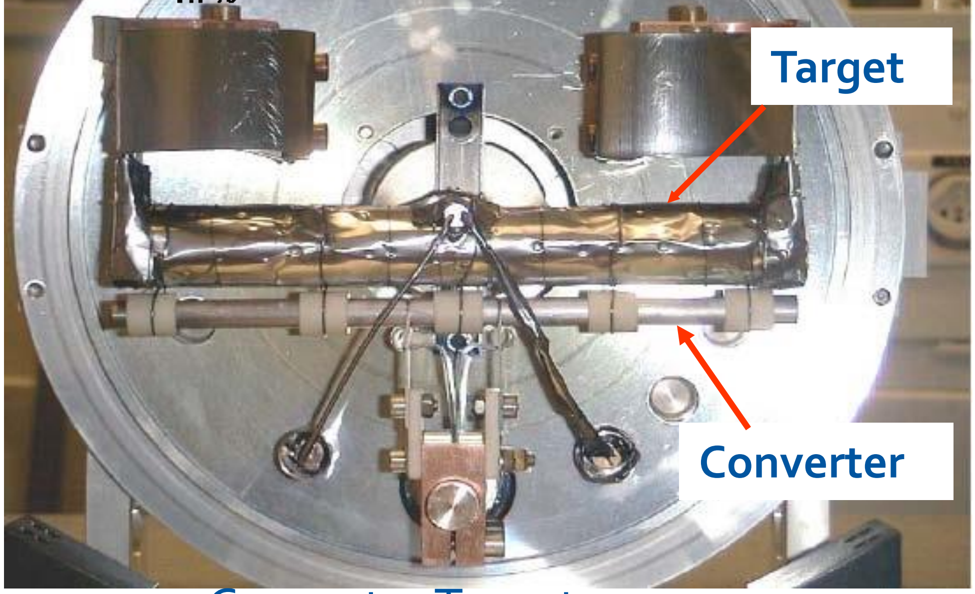




- Container: 20 x 2 cm cylinder of Ta
- Material:
  - Liquid La, Pb, Sn
  - Metal foil/powder Nb, Ti, Ta..
  - Oxides CaO, MgO
  - Carbides SiC, UC, ThC
- Ion-source
  - Surface
  - Plasma
  - Laser
- Fluorination CF4 or SF6

Targets

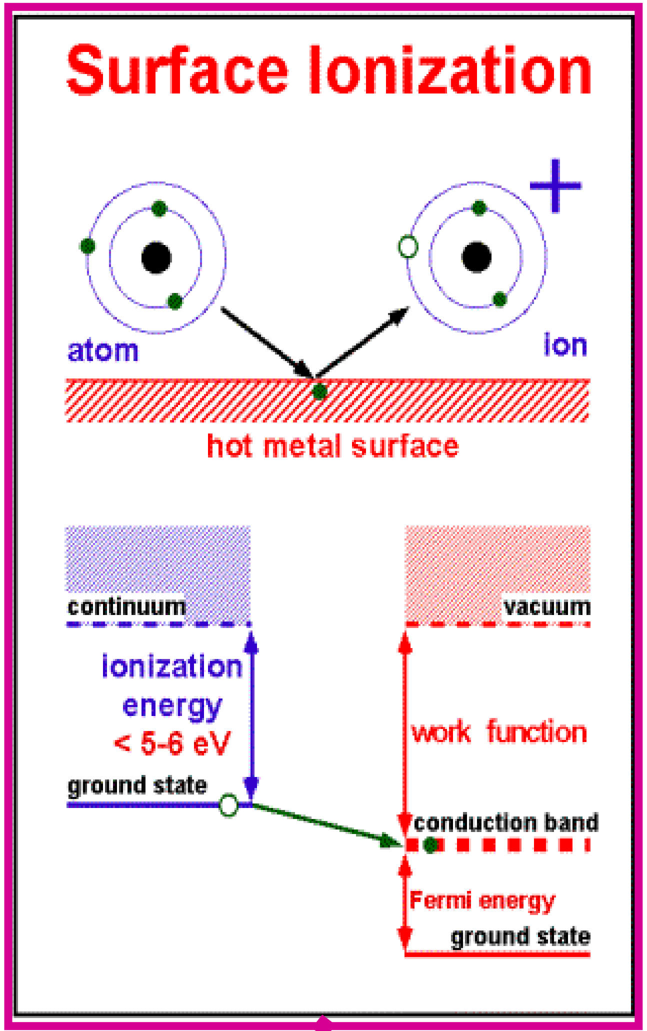


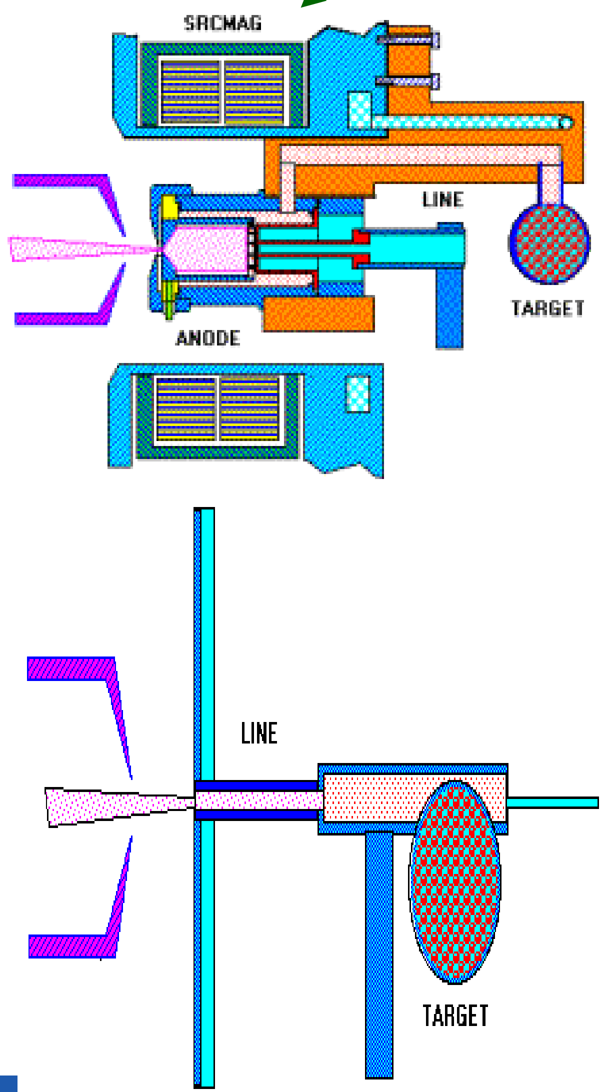


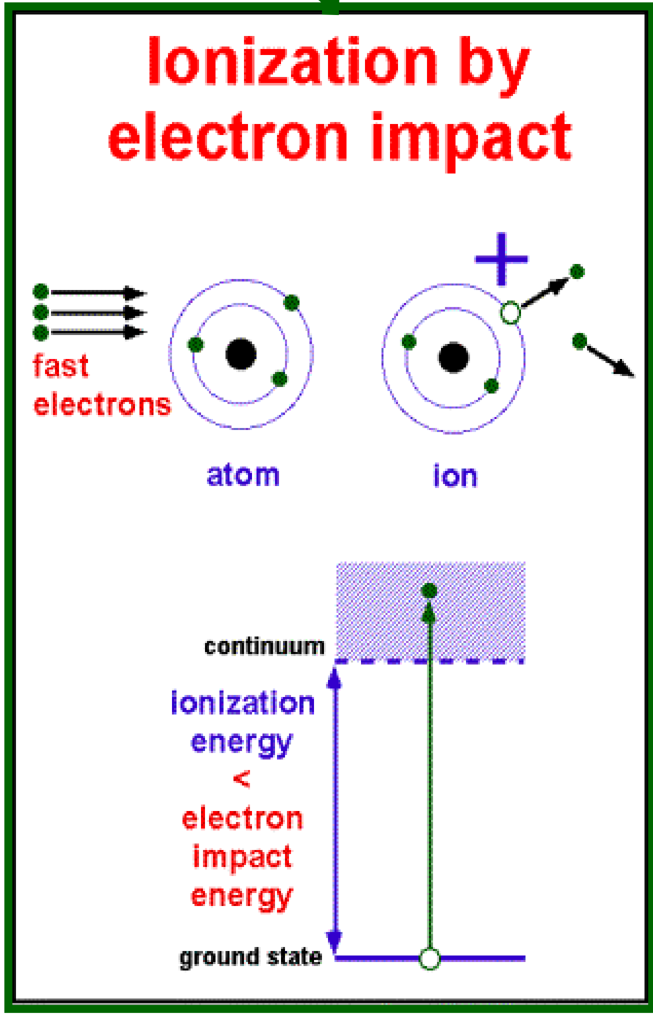
Converter Target

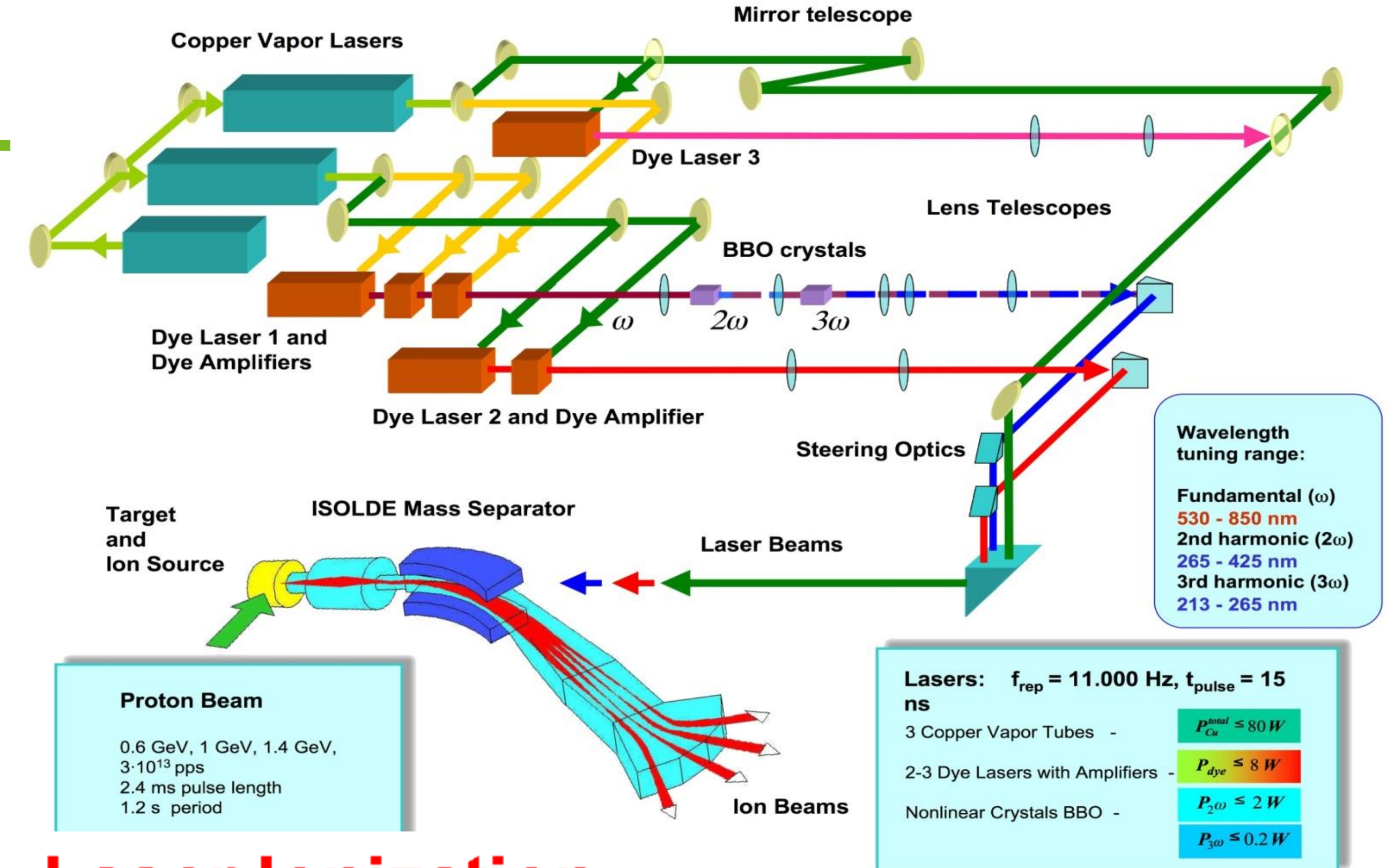
Standard

Surface & plasma ionization

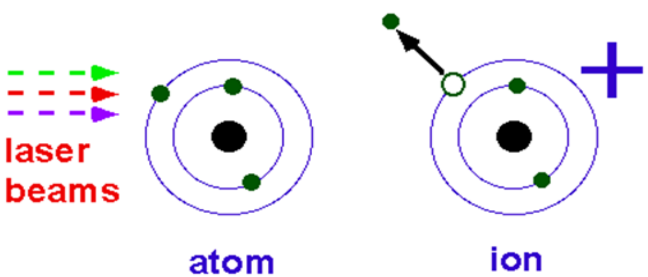


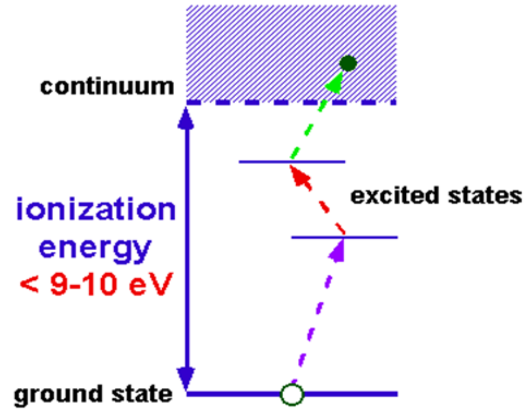




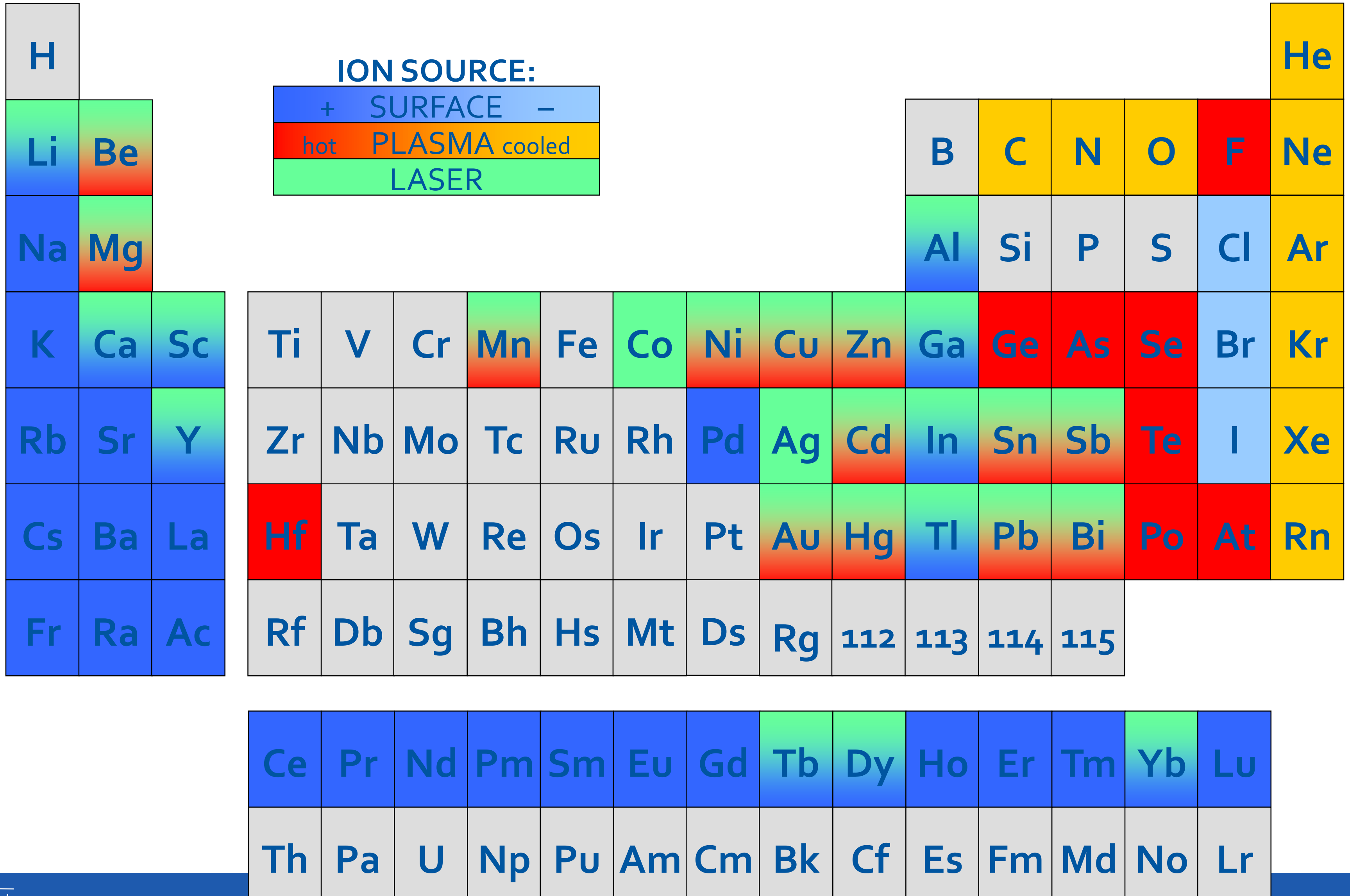


Laser Ionization

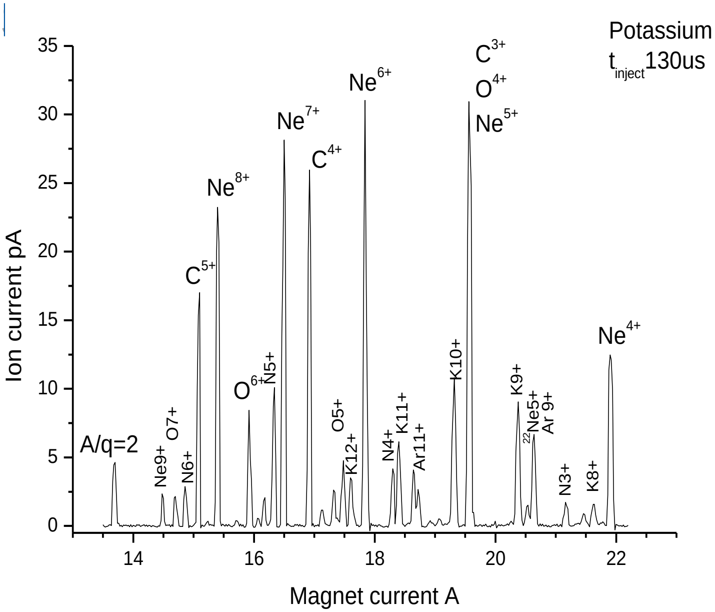




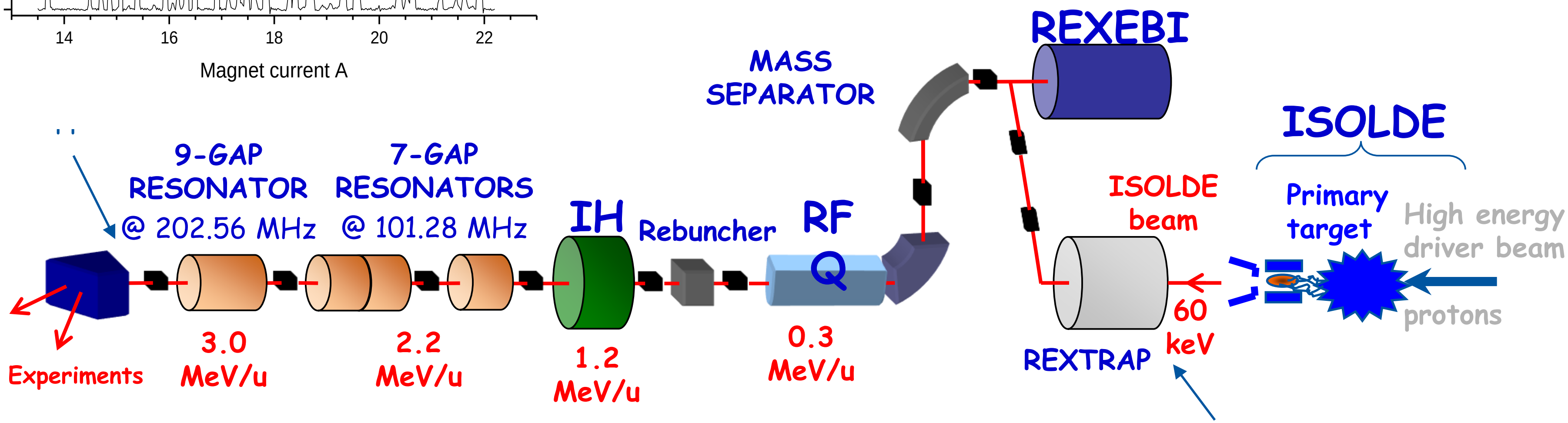
ISOLDE Table of elements



REX-Isolde

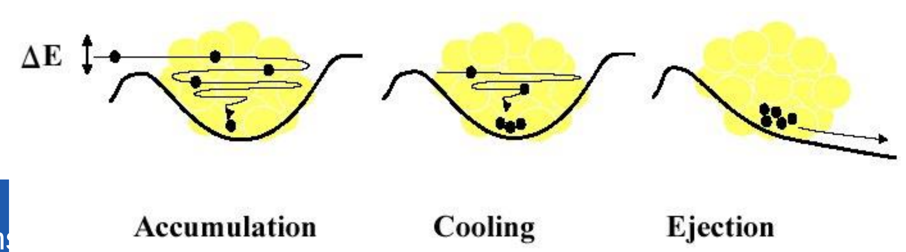


* charge breeding
* 1+ ions to n+



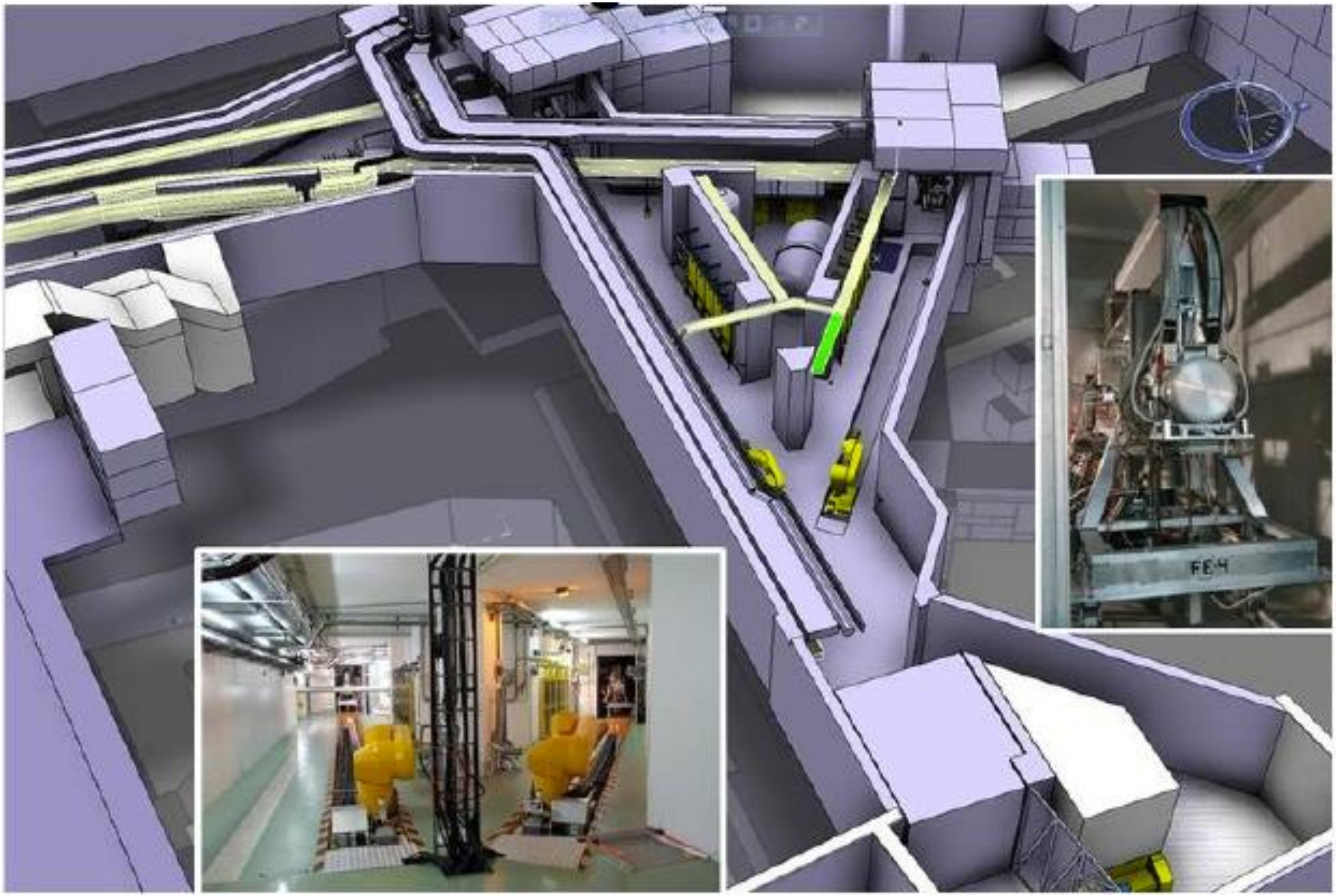
* longitudinal accumulation and bunching
* transverse phase space cooling

* 6 cavities
* 100 and 200 MHz, ~100 kW
* 300 keV/u to 3 MeV/u

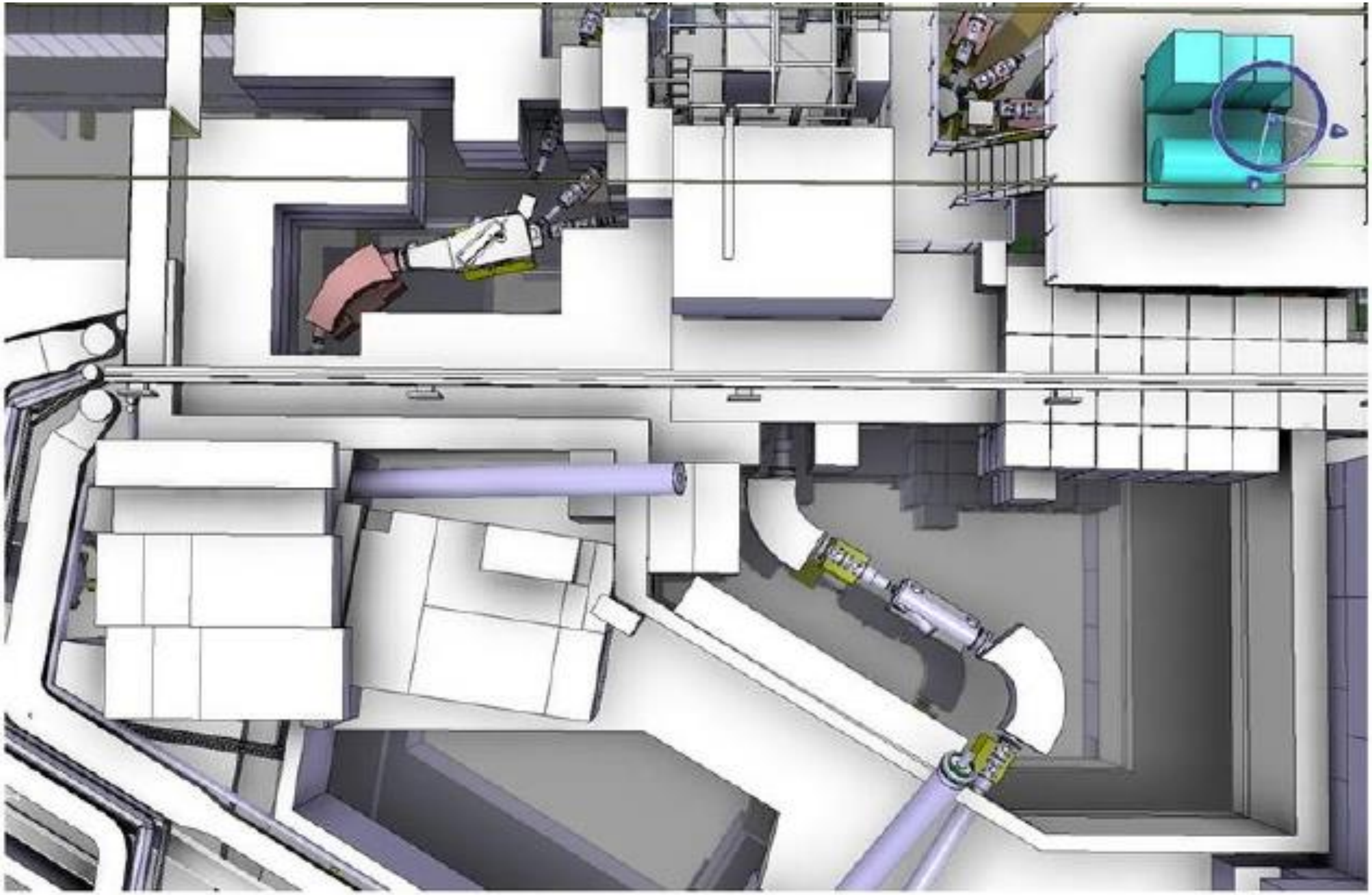


ISOLDE Experimental hall

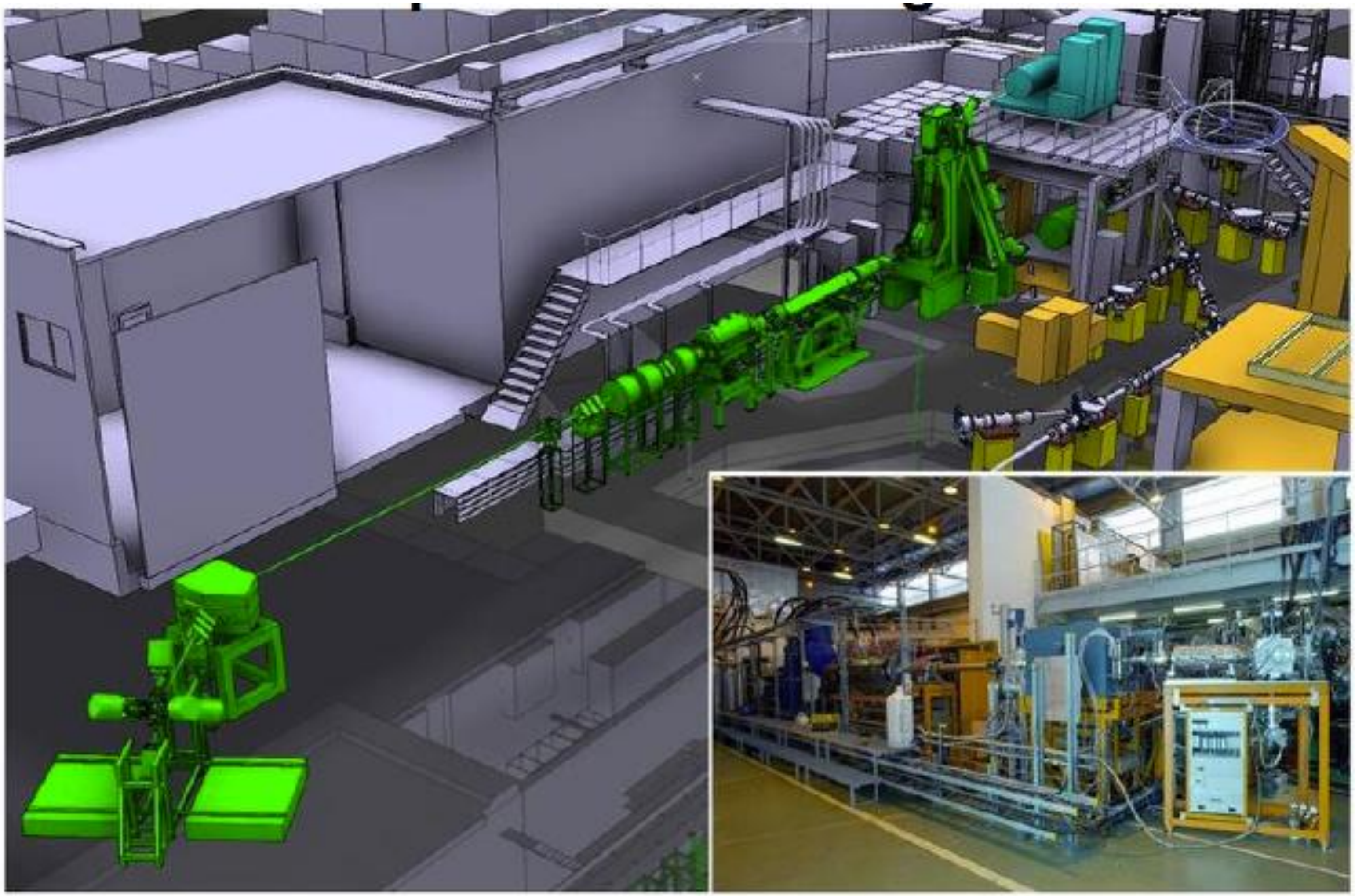
Target Zone



GPS and HRS Separators

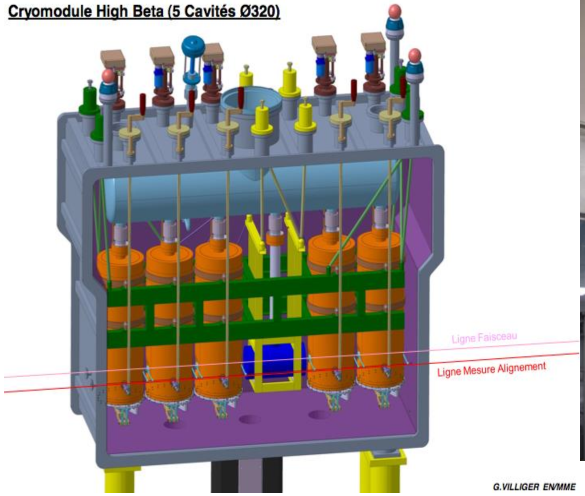


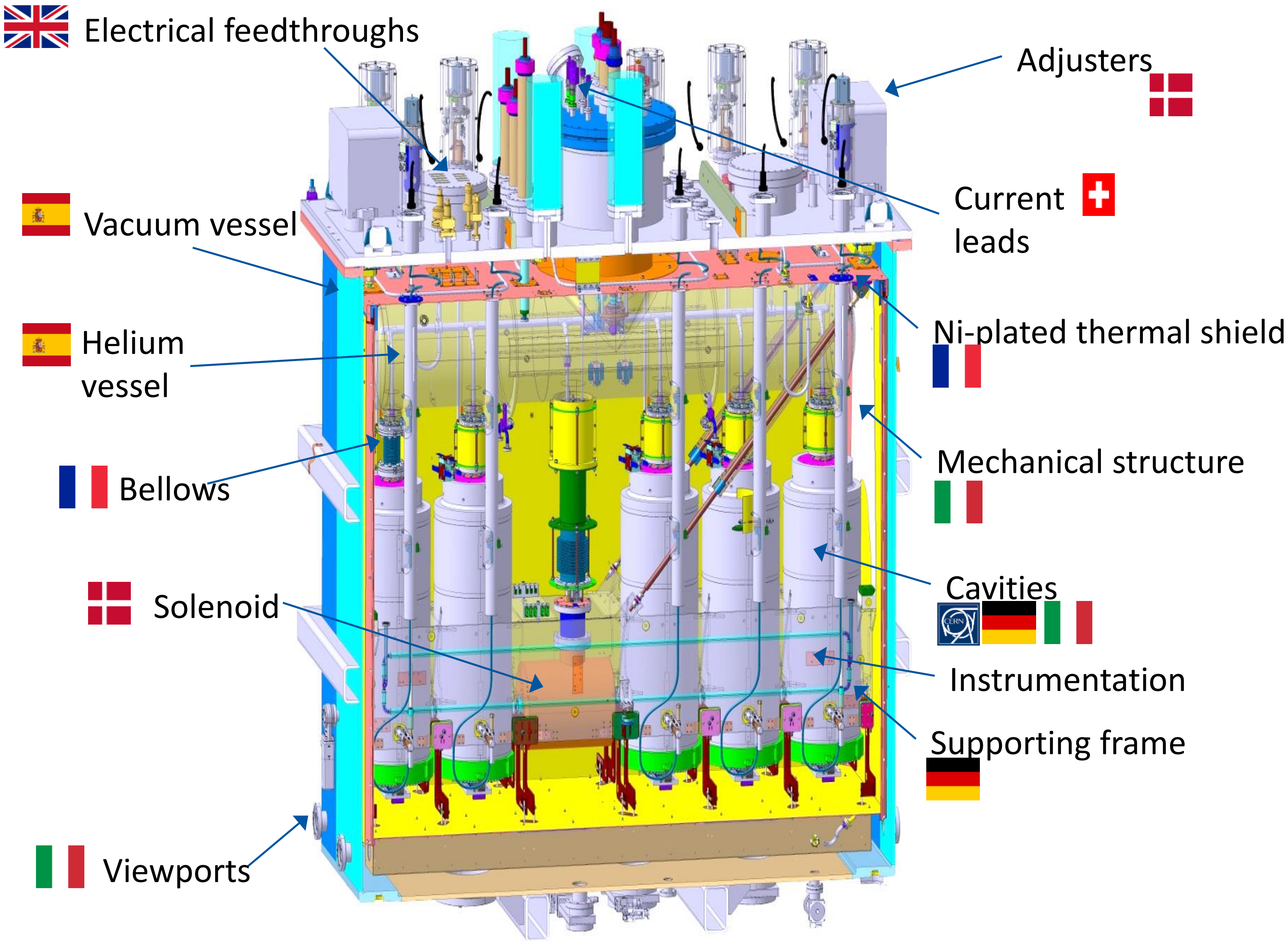
REX Post-Accelerator Linac



Miniball experiment

Key Technologies




Electrical feedthroughs
Adjusters
Vacuum vessel
Current leads
Helium vessel
Ni-plated thermal shield
Bellows
Mechanical structure
Solenoid
Cavities
Instrumentation
Supporting frame
Viewports

HIE-ISOLDE Cryomodule # 1

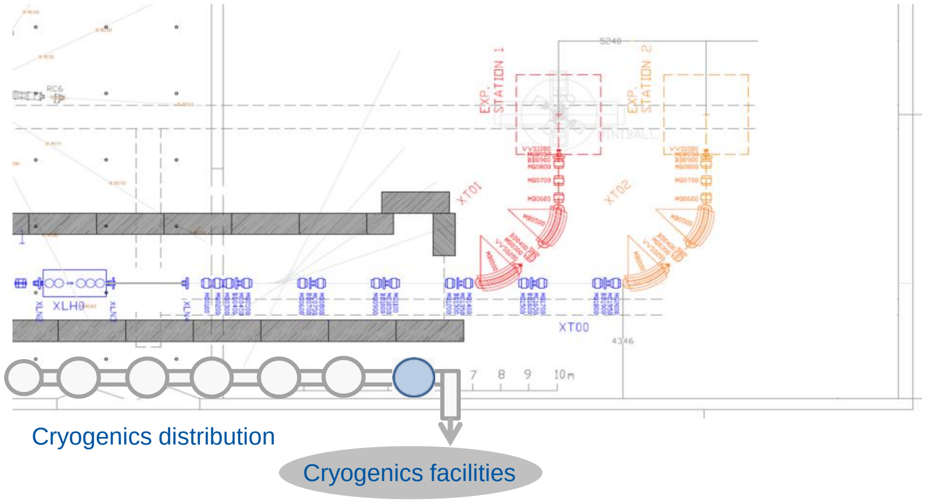
Late August 2014: Assembly start

Assembly time of CM1: 30 weeks
Baseline : 27 weeks

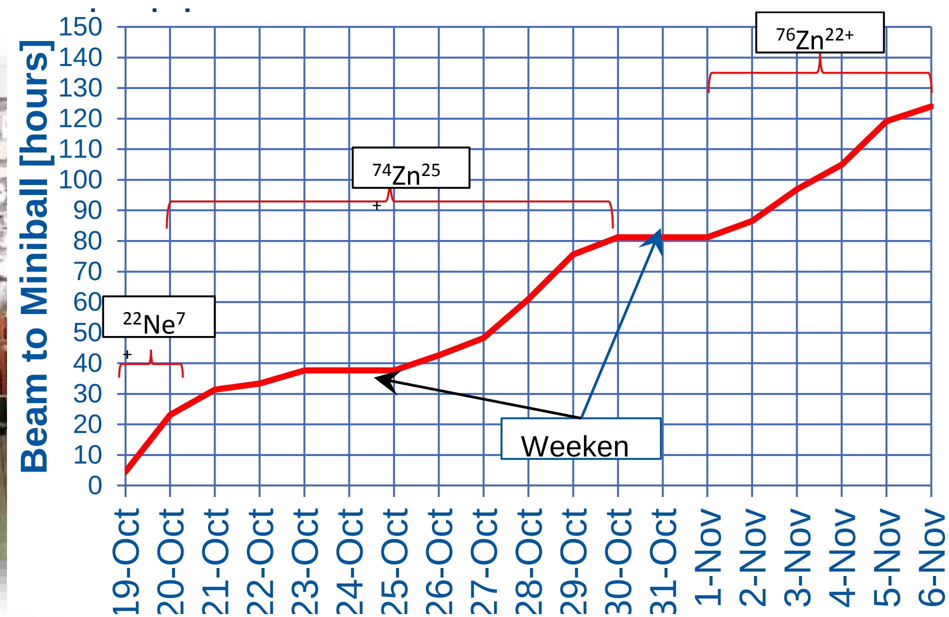
1 May 2015: Assembly completed

Mid-June 2015: Successfully cooled to 4.5K

2015 Commissioning Campaign



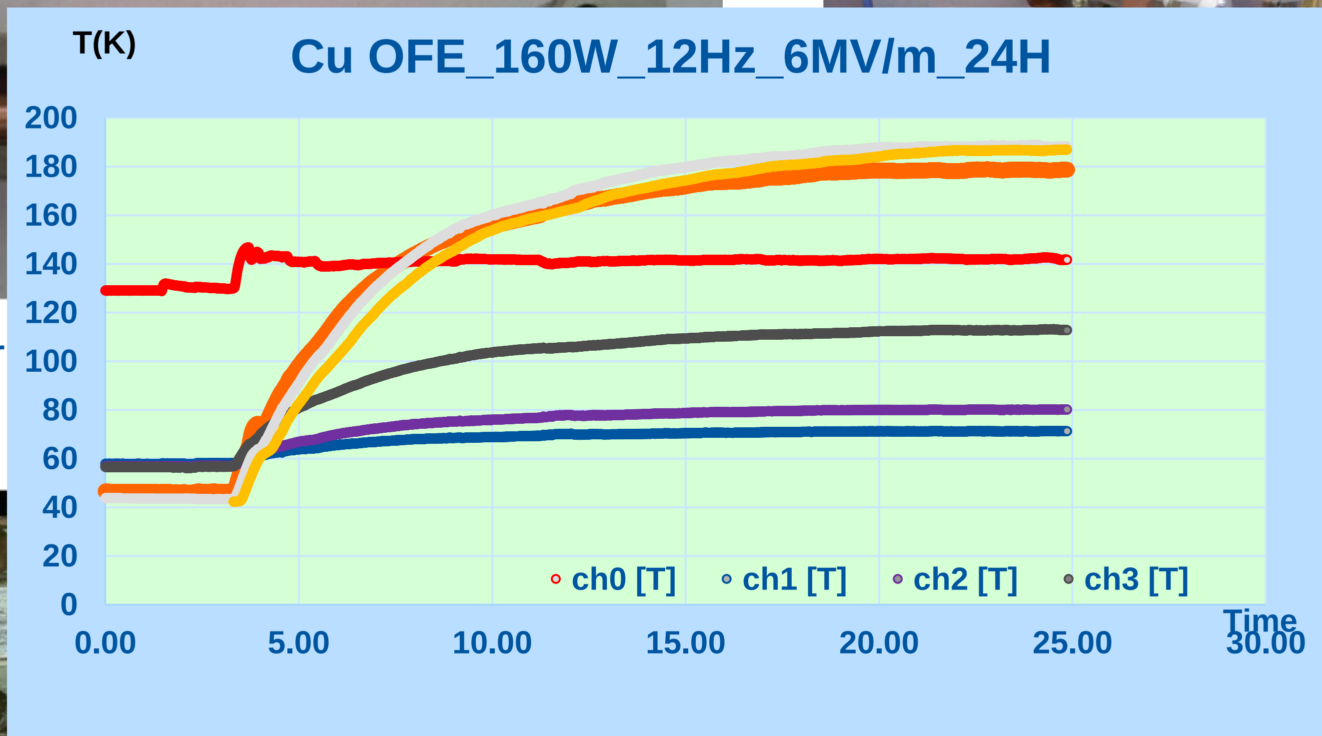
- The 2015 Commissioning campaign achieved its goals
- CM design choices validated
- SC cavities performance were confirmed with beam
- RF coupler problem identified (overheating)
- Physics run started on 19th October, on

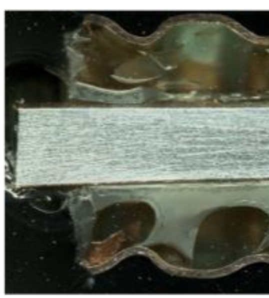


RF Coupler Heating

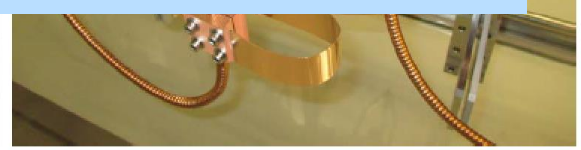
Coupler fully IN

RF short pr

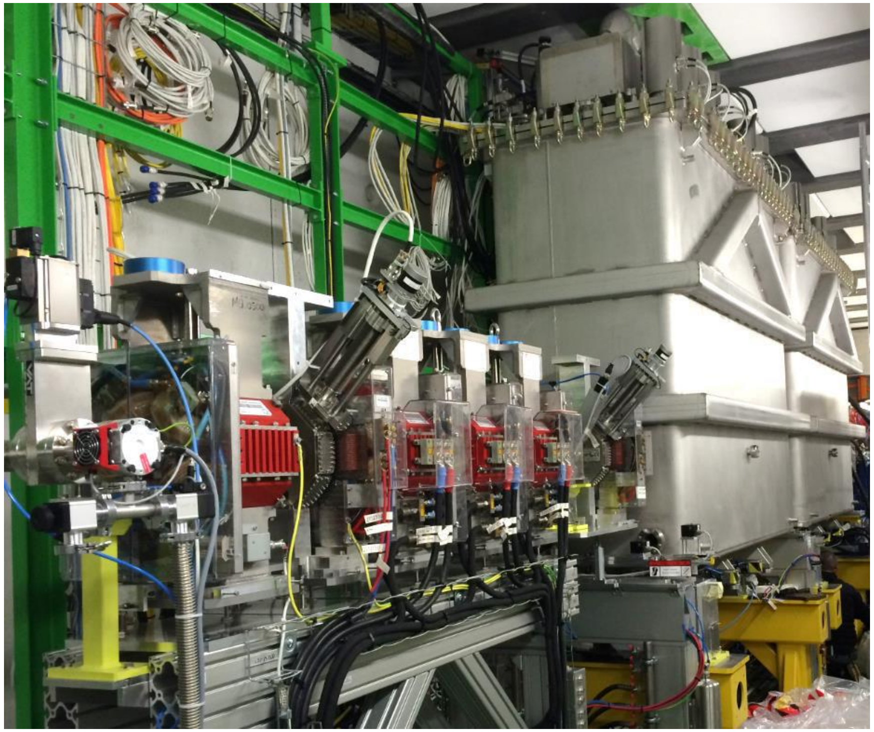


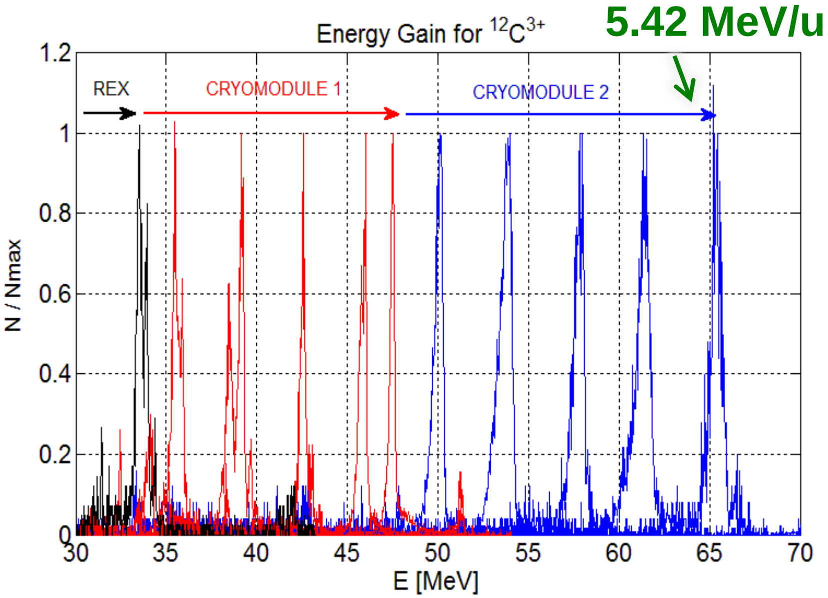


RF cable insulation melt and polymerized



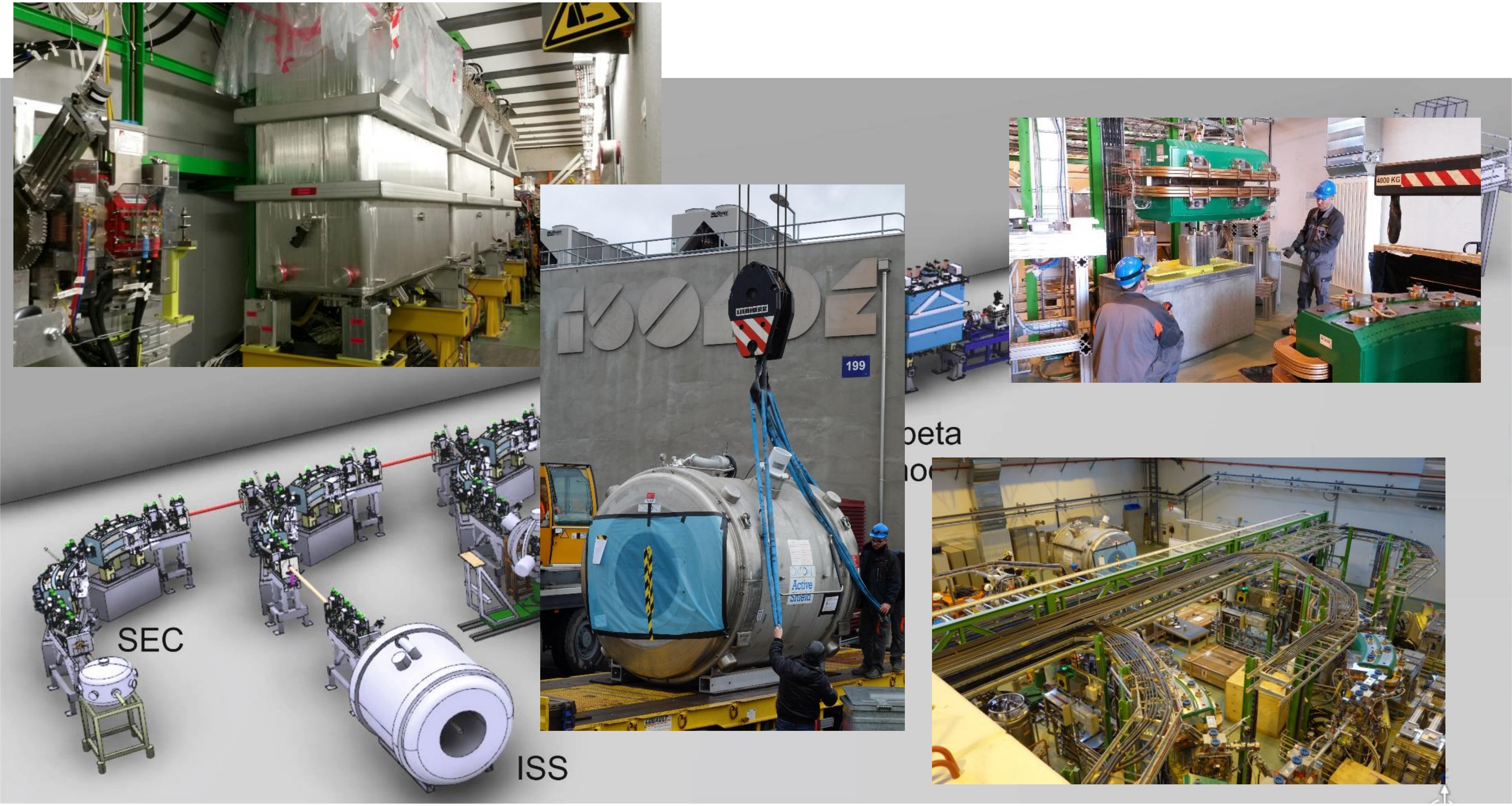
Phase 1: Commissioning & Operation (2016)



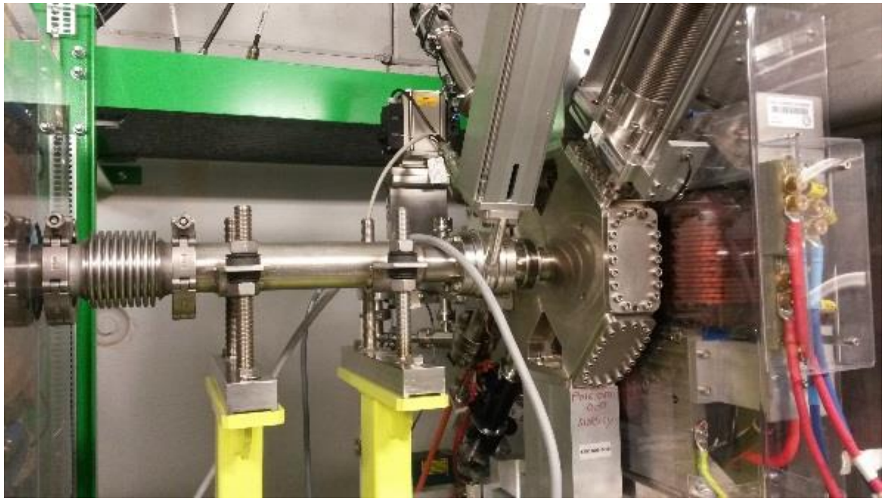


Experiment	Isotope	HEBT	Destination	Energy [MeV/u]	Shifts
IS-562	^{110}Sn	XT01	Miniball Spectrometer	4.5	12
	^{108}Sn			4.5	12
IS-548	^{142}Xe	XT01	Miniball Spectrometer	4.5	30
IS-557	^{80}Zn	XT01	Miniball Spectrometer	4.0	12
	^{78}Zn			4.0	12
IS-551	^{132}Sn	XT01	Miniball Spectrometer	5.5	18
IS-561	^{9}Li	XT02	Scattering Chamber	6.9 (7.2 req.)	15
IS-559	^{66}Ni	XT01	Miniball Spectrometer	5.5	24

Phase 2: Installation & Commissioning (2017)



Phase 2: Completion (2018)

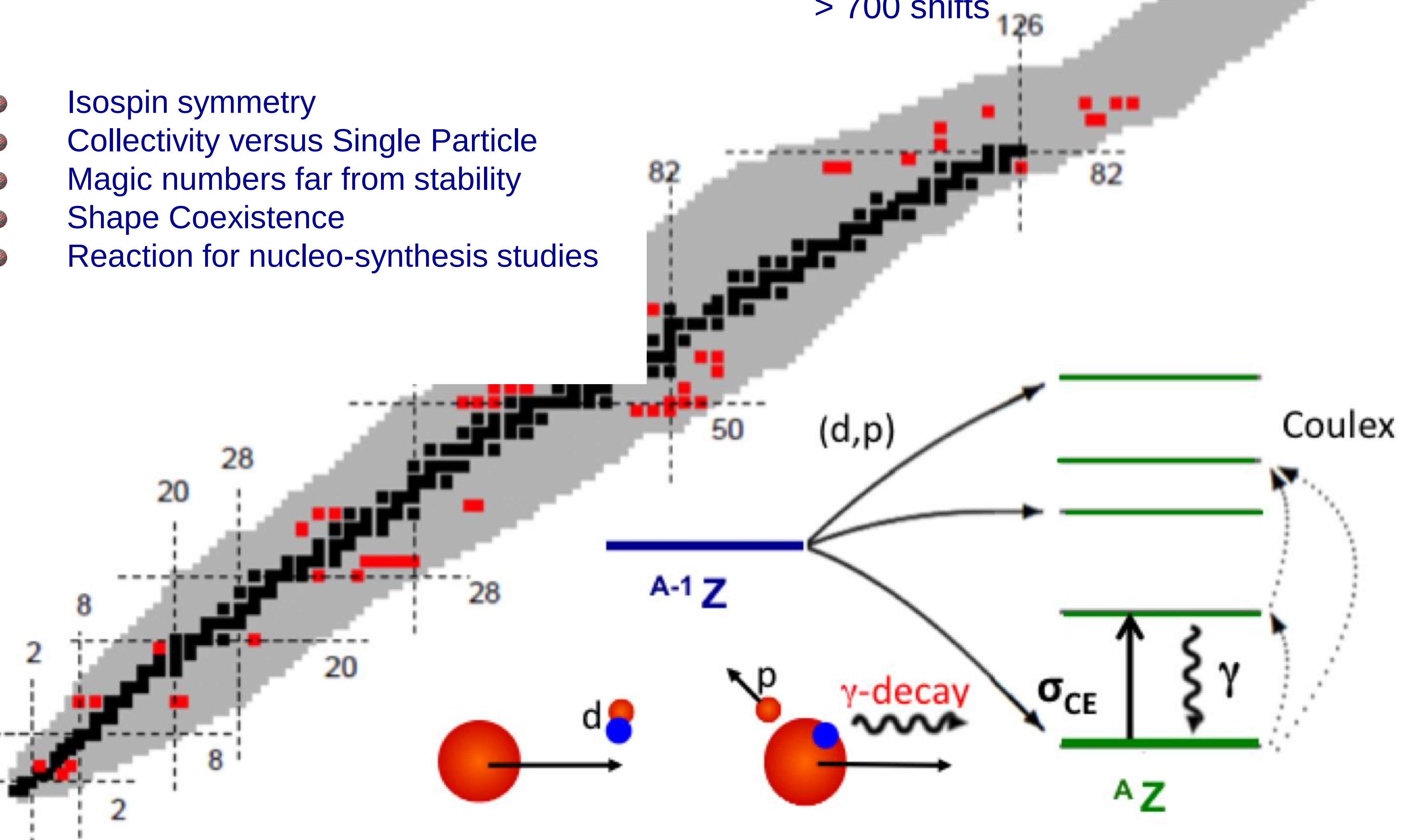


Physics at HIE-ISOLDE

The new energy window gives the opportunity to address new physics questions:

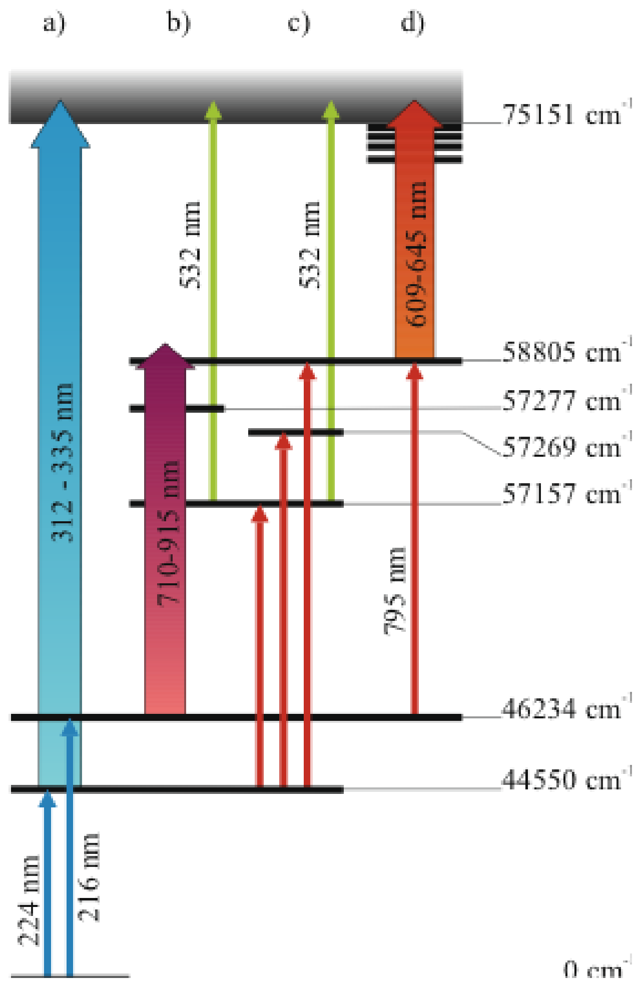
> 30 Exp approved
> 700 shifts

- Isospin symmetry
- Collectivity versus Single Particle
- Magic numbers far from stability
- Shape Coexistence
- Reaction for nucleo-synthesis studies



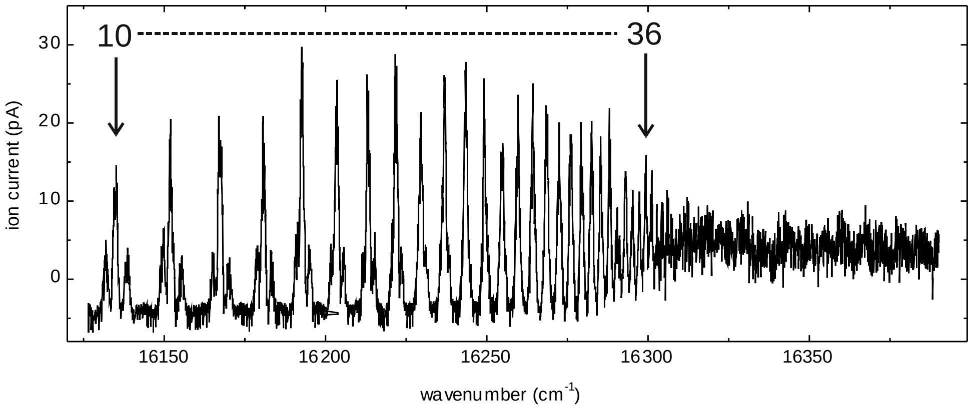
THANK YOU

Determination of the atomic properties of Astatine



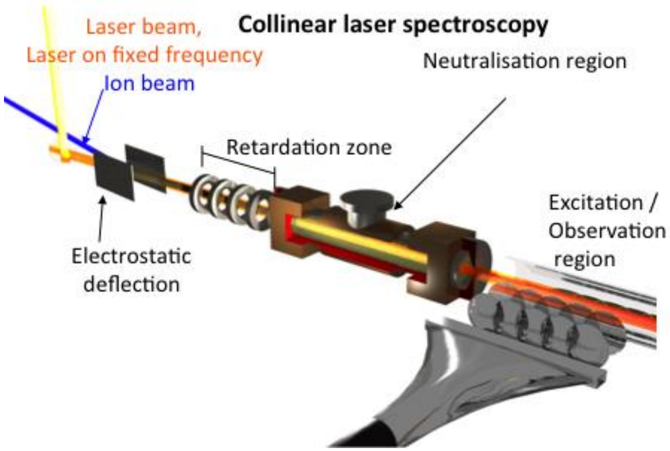
IP(At) = 9.31751(8) eV
Nature Com. 14 May 2013
DOI 10.1038

- Astatine rarest on Earth 29 g, (Guinness record)
- Identification of new atomic transitions
- Scan of ionizing laser: converging Rydberg levels allow precise determination of the IP
- Determination of ionising potential

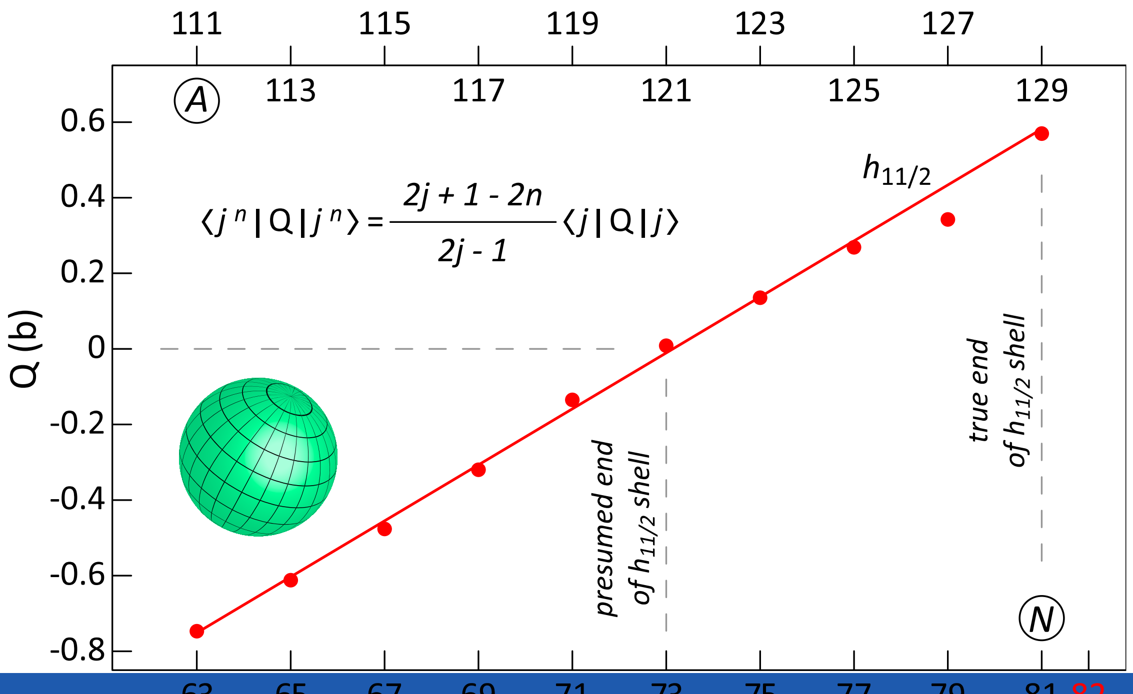


- Test of Atomic theory and Quantum Chemistry
- New beams / exotic decay modes: β-fission
- Potential interest for the development of ^{211}At as a medical radioisotope

Surprising simplicity in Cd-isotopes



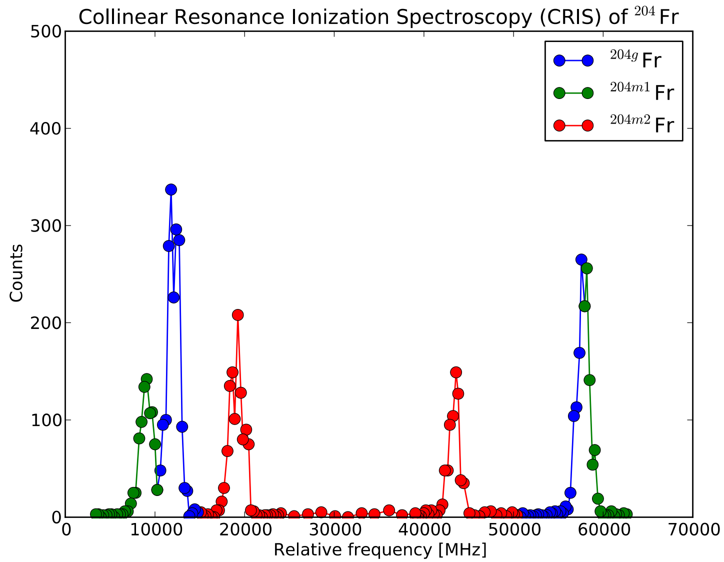
- ✓ Study of neutron-rich Cd-isotopes up to N= 82
- ✓ Long leave isomers in ^{127}Cd and ^{129}Cd observed for first time
- ✓ Spherical shell model confirmed by linear behaviour of the 11/2 quadrupole moments
- ✓ Remarkably mantained beyond $h_{11/2}$.



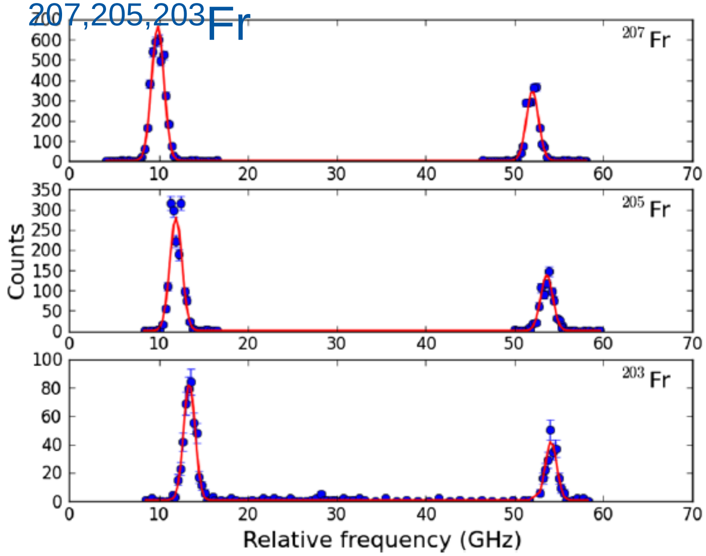
Iordanov et al, PRL 110 (2013) 192501

Hyperfine-structure and Radioactive-decay studies francium isotopes (CRIS)

Hyperfine structure of the 3 isomeric states of ^{204}Fr



Hyperfine structure of ^{207,205,203}Fr

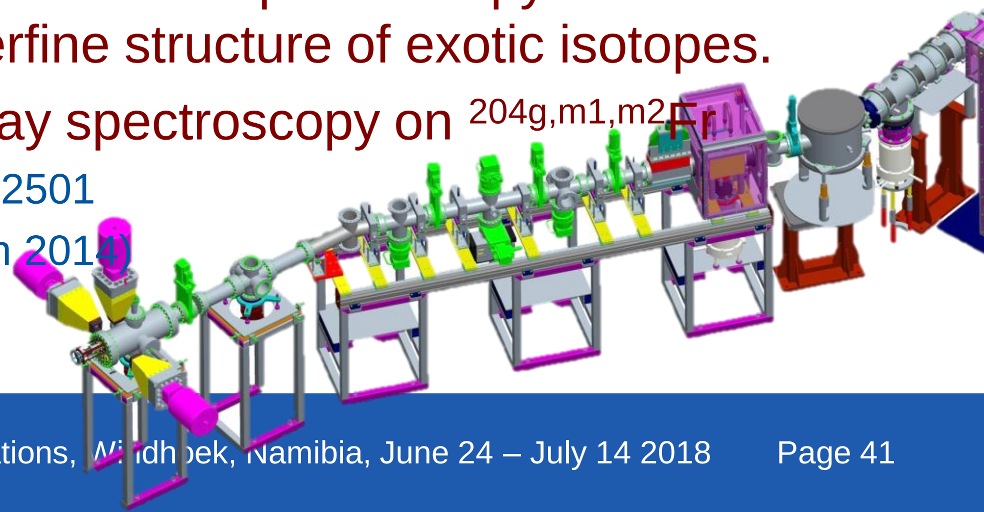


- The high resolution of collinear laser spectroscopy + ion detection to probe the hyperfine structure of exotic isotopes.
- Laser assisted nuclear decay spectroscopy on ^{204g,m1,m2}Fr

K.T. Flanagan et al., PRL 111 (2013) 212501

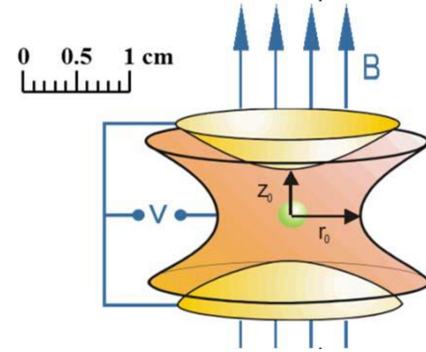
K. Lynch, Accepted Phys. Rev X (March 2014)

(Price IOP 2013 & Springer 2014)



ISOLTRAP:

High-precision mass of ^{82}Zn



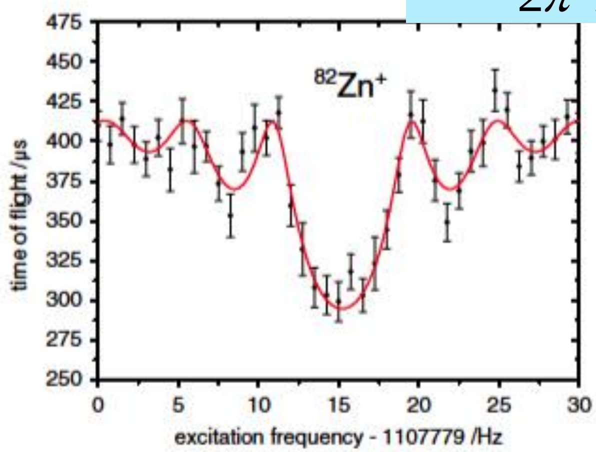
Combined ISOLDE technical know-how:
neutron-converter, quartz transfer line, laser ionis

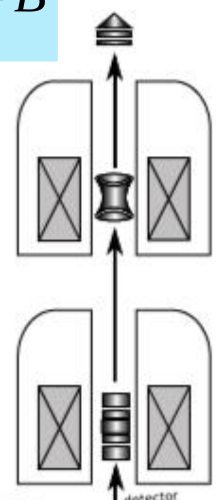
Nuclear structure:
N=50 shell closure

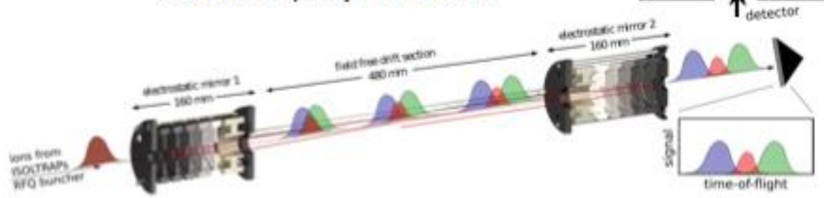
Astrophysics:
r-process path

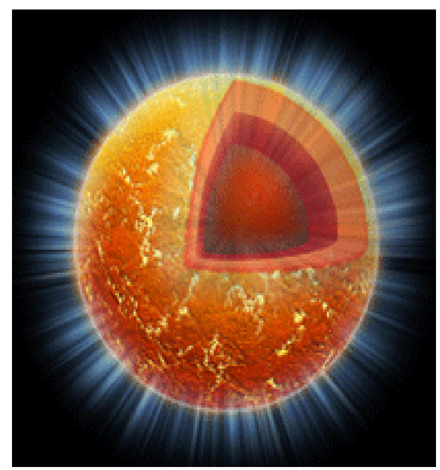
Astrophysics:
neutron star structure

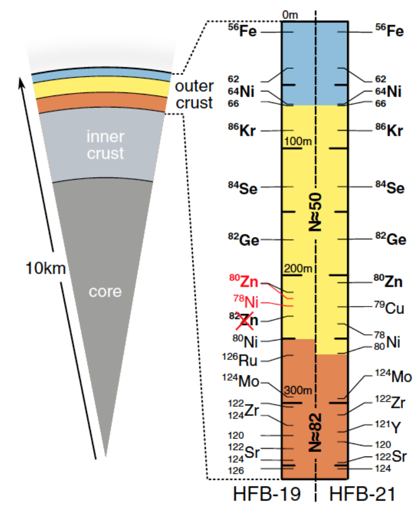
$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$









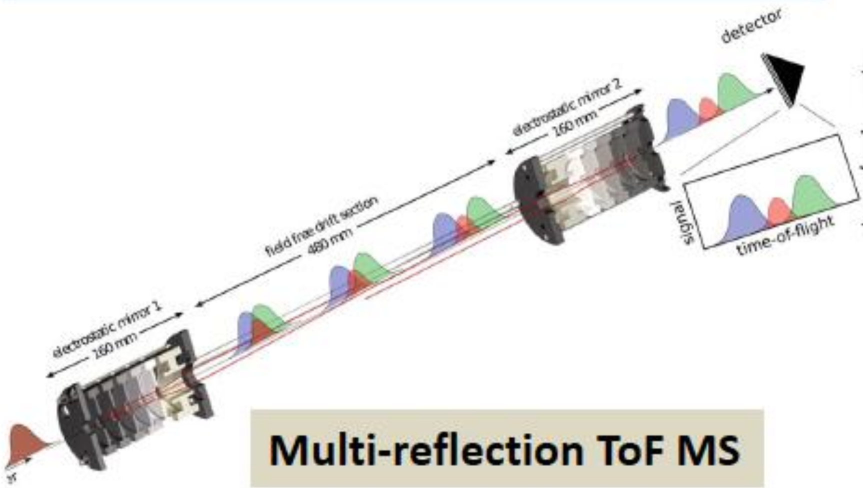


- Its determination is important for modelling of the crust of neutron stars , PRL110 (2013) 04110

CERN Courier, 53, n 3, 2013

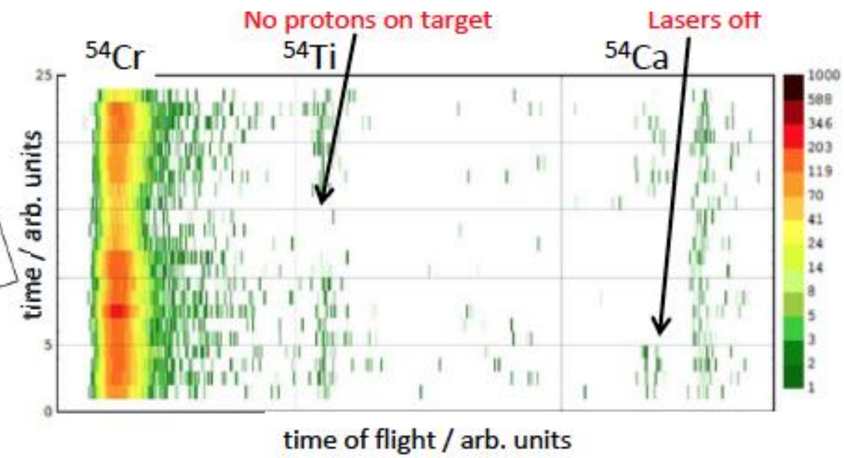
The Magic Number N=32

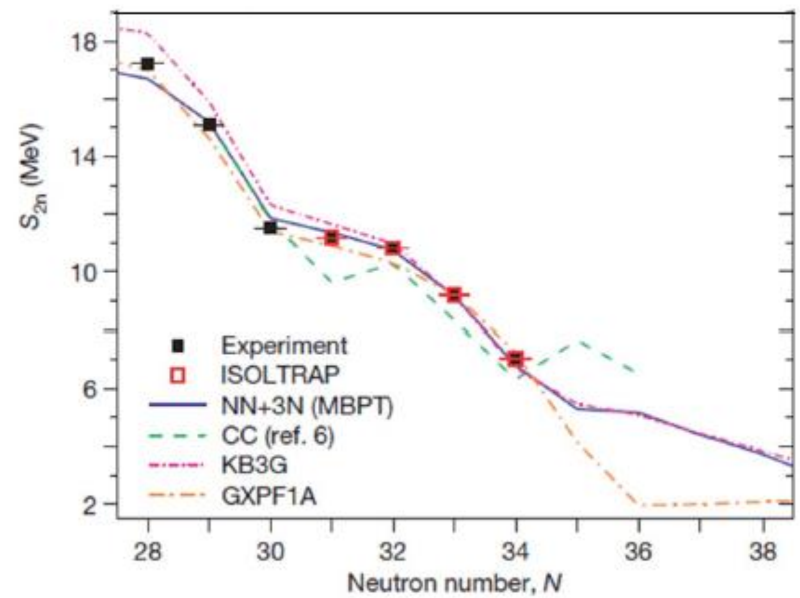
Magic number probed with n-rich Ca



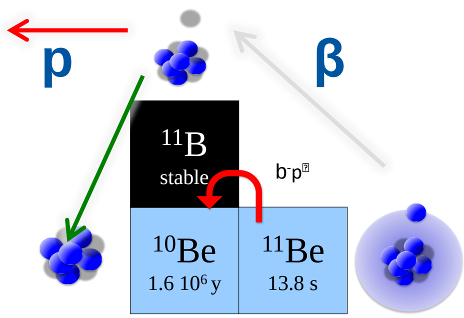
- Mass measurements via S_{2n} establish magic number at N=32
- Correct prediction from 3N-forces

F. Wienholtz *et al.*, Nature 498 (2013) 346





βp in halo ^{11}Be nuclei: Quasi-free n → p decay



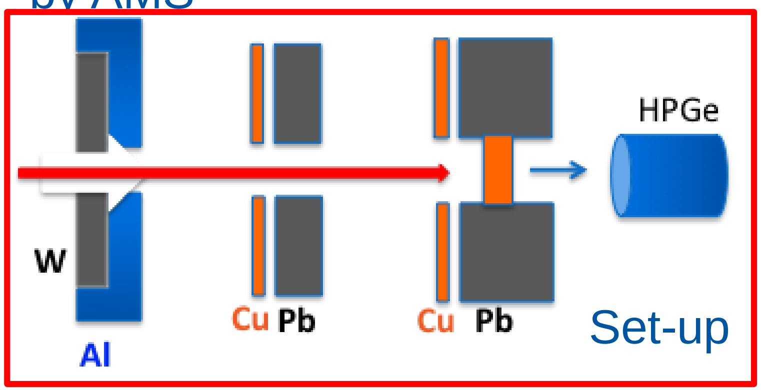
Aarhus-Goteborg-Madrid-Vienna Collaboration

- ✓ βd observed in ^{6}He & ^{11}Li halo nuclei decay directly to the continuum→ simpler mode in 1n-halo nuclei
- ✓ ^{11}Be best case to search for βp, $Q_{\beta p}$ = 280.7 keV
- ✓ Expected B.R. 10^{-8} assuming direct decay

  D. Baye & Tursonov, Phys. Lett. 696 (2011) 464
- ✓ Previous attempt gave unconclusive result with

BR = 2.5(25)x10^{-6}; Borge et al., J. Phys G 40 (2013)

A 200 keV 10^{-8} proton branch is challenging to detect → Detect ^{10}Be daughter by AMS



- Contaminations measured to be negligible.
- B.R. = 8.4(6) x 10^{-6} Consistent with previous results
- New Resonance identified in ^{11}B

❖ The new decay mode is consecuence of halo structure, peripheral decay of the neutron halo + intense super allowed transition near Q-value observed in other nuetron rich drip line nuclei. Riisager et al, Phys Lett. B732 (2014)305

Searching for pear-shaped nuclei at REX-ISOLD

Quadrupole deformation

Coulomb excitation to directly

acc

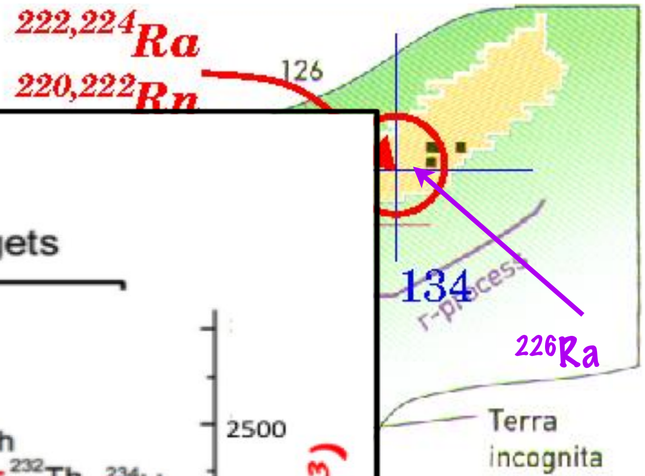
$B(E3; I_i \rightarrow$

Oblate (Ear

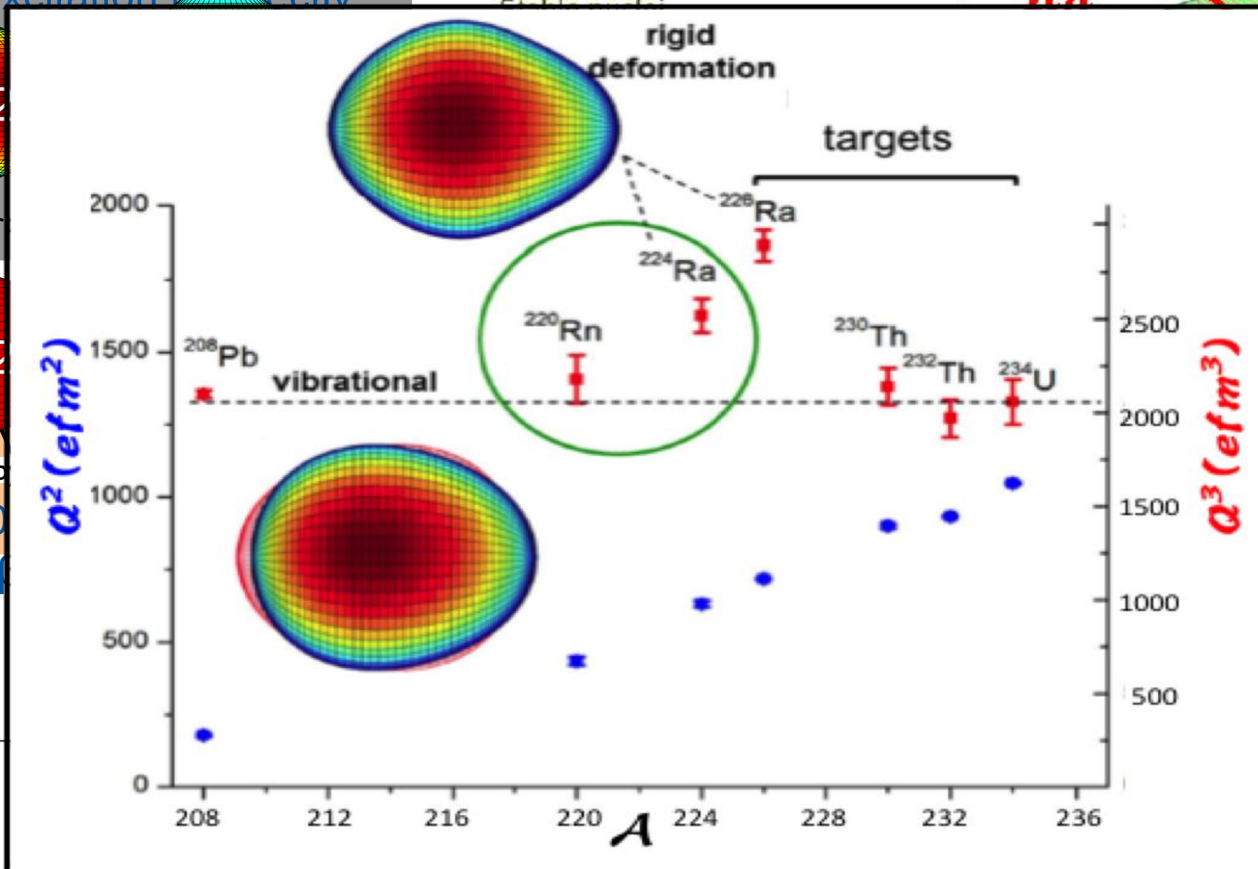
Prolate (Rugb

B(E3) ≳ 30

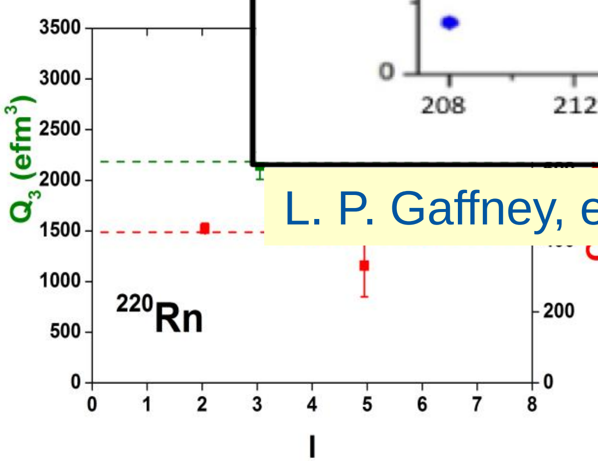
significant

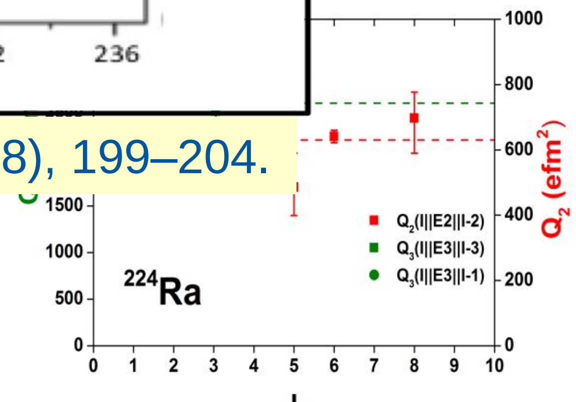


ns



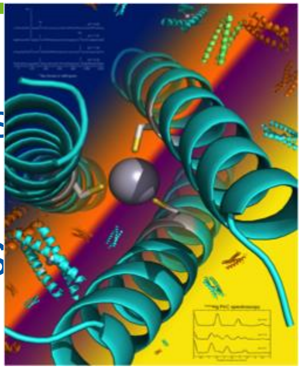
L. P. Gaffney, et al. (2013). Nature, **497**(7448), 199–204.





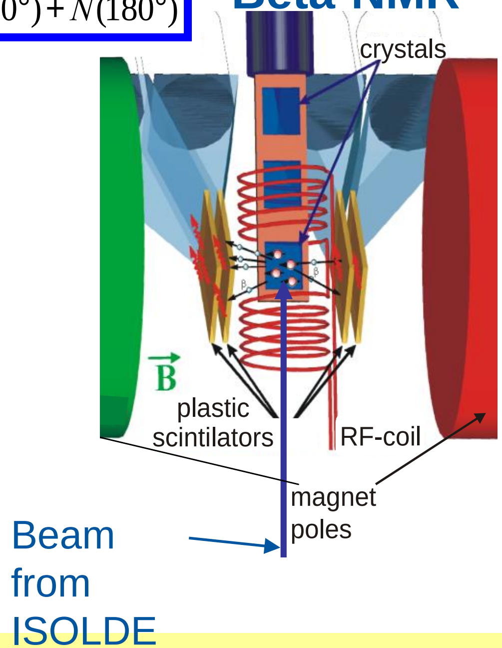
First β-NMR in a liquid sample: Study of metal-Ions in Biology

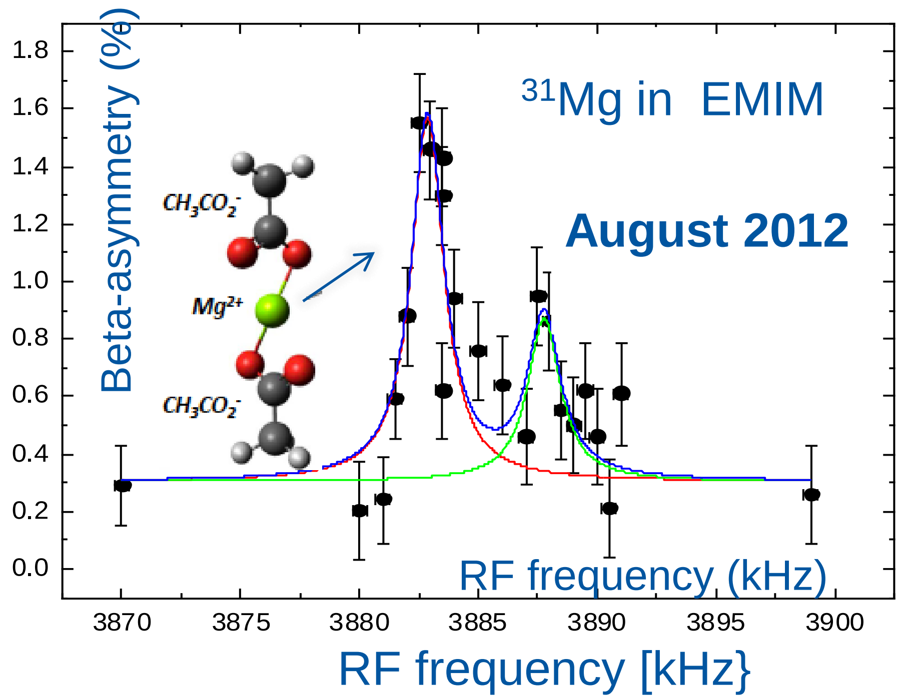
- Study of metal-ion interaction with biomolecules
- Probe nucleus: $^{31}Mg^{+}$ -> spin 1/2, half-life 230 ms, ca. 5*10^{5} ions
- Sample: ionic liquid (EMIM= 1-ethyl-3-Methyl-Imidazolium)
- Spin polarization via optical pumping with lasers from COLLAPS



A. Gottberg, et al., Submitted to Nature

$$A = \frac{N(0°) - N(180°)}{N(0°) + N(180°)}$$





β-NMR is a billion times more sensitive than conventional NMR spectroscopy