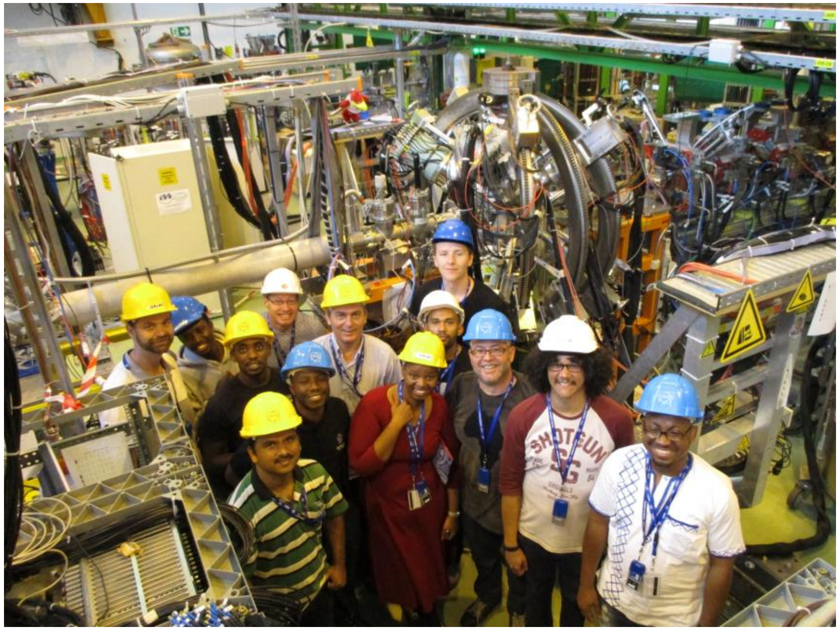
Nuclear Physics with radioactive beams

J. Cederkall for the ISOLDE collaboration

For more info about ISOLDE experiments also contact:



Krish Bharuth – Ram et al.
UKZN/DUT
Solid state physics spec. Mössbauer spectroscopy.

Nicolas Orce et al.
University of Western Cape, SA
Experiments at HIE-ISOLDE spec. concerning nuclear shape studies.

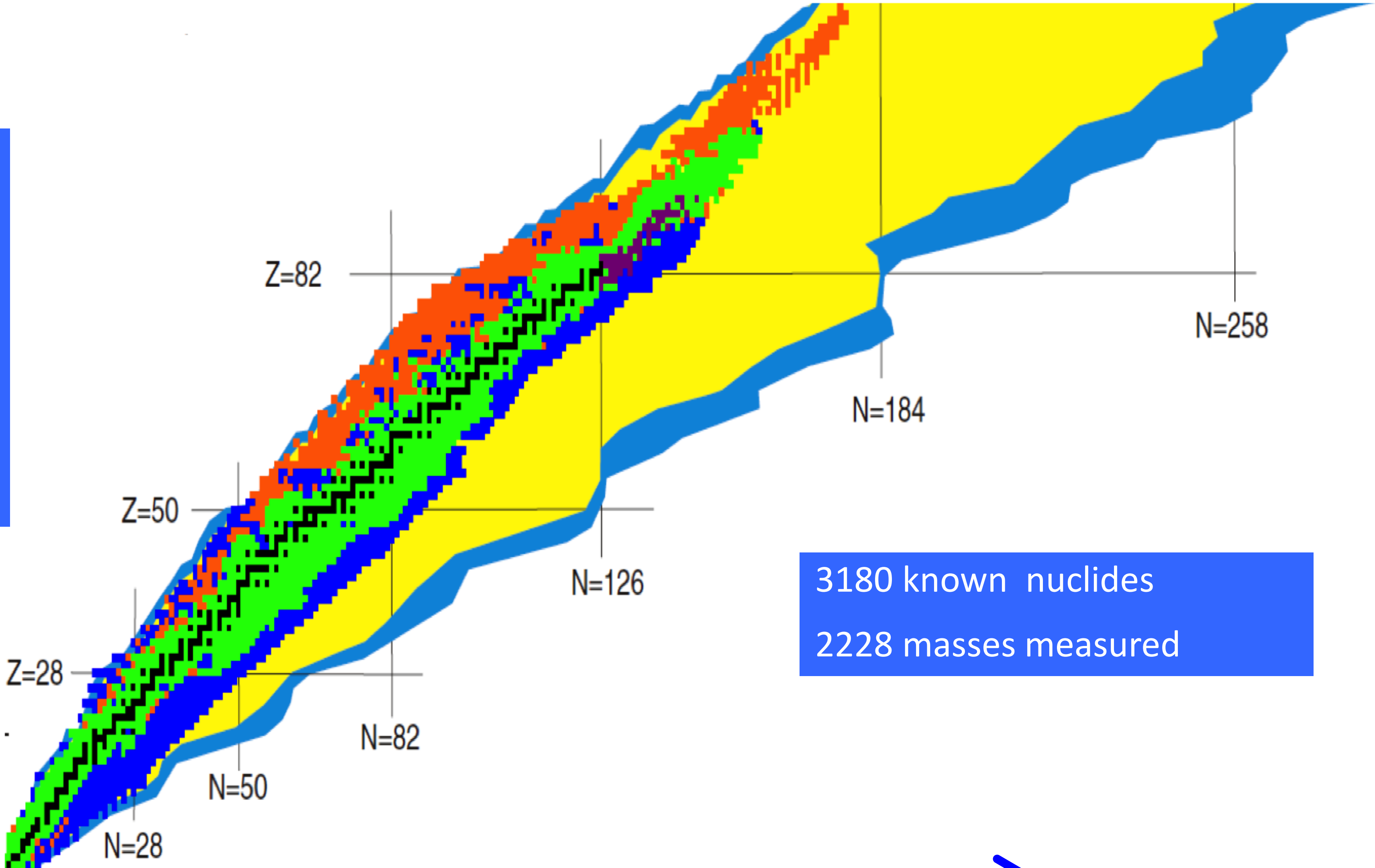
ISOLDE

LUND UNIVERSITY

Nuclear Physics - current questions

- **How are nuclei built from their constituents?**
  - nuclear interaction in the medium
- **Where are the limits of nuclear existence?**
  - location of the driplines, existence of superheavy elements
- **Do nuclear shells change far from stability?**
  - shell evolution and changes of the potential
- **How can we relate and connect collective phenomena to the motion of individual nucleons**
  - interplay between single particle and collective motion
- **How were and are the elements formed?**
  - reaction rates, masses, astrophysical sites and observations

Nuclear Physics far from stability



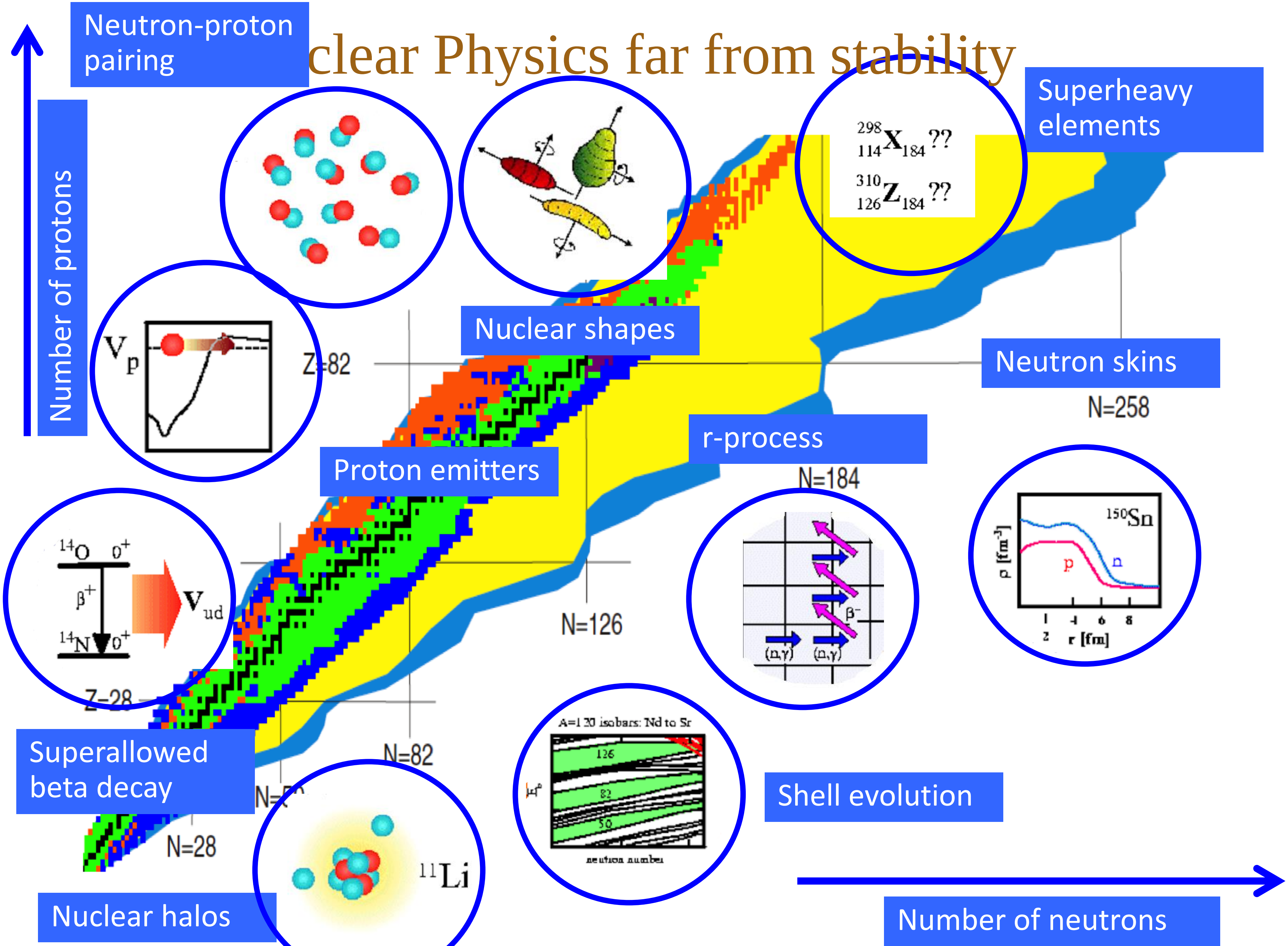
Number of protons

3180 known nuclides

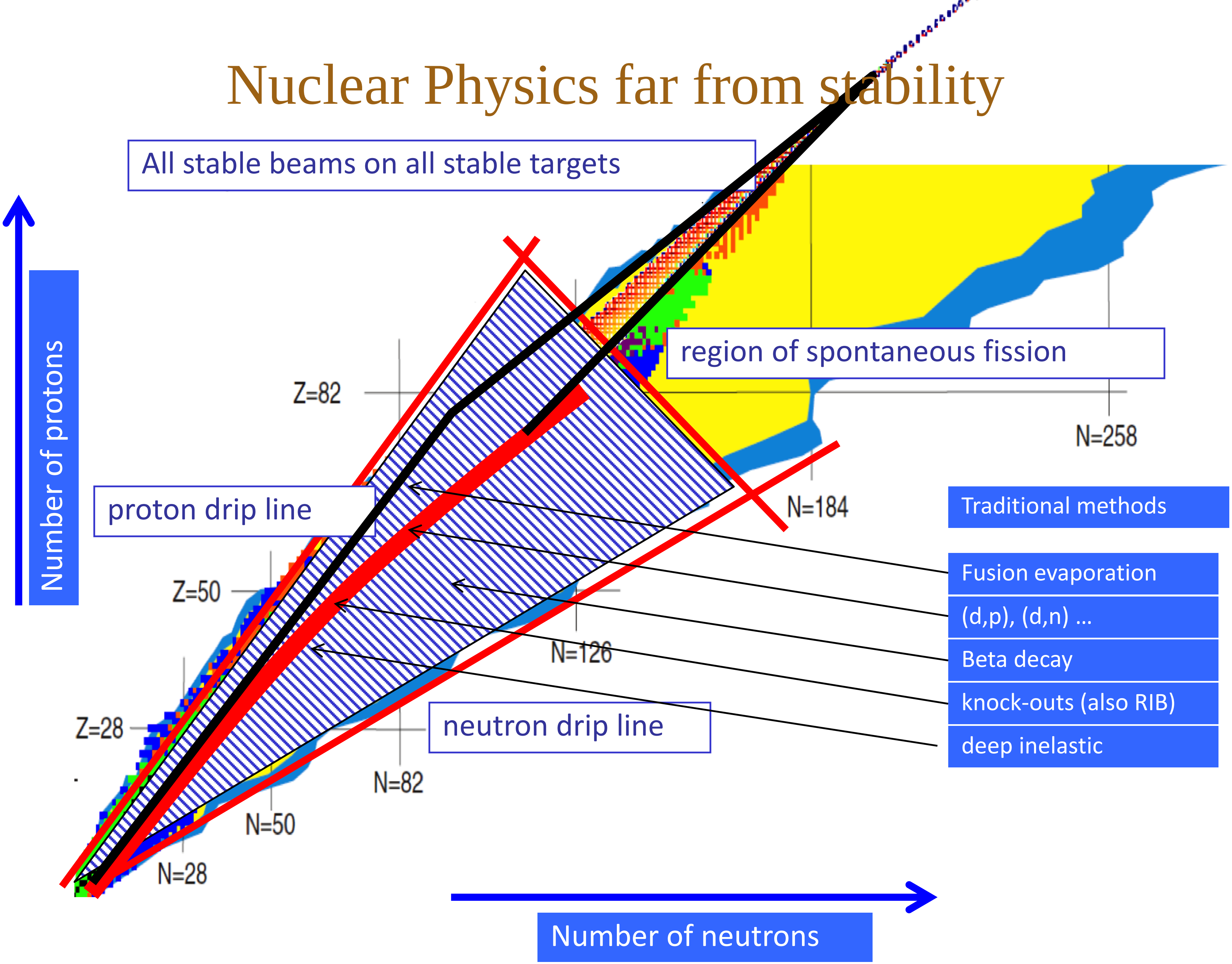
2228 masses measured

Number of neutrons

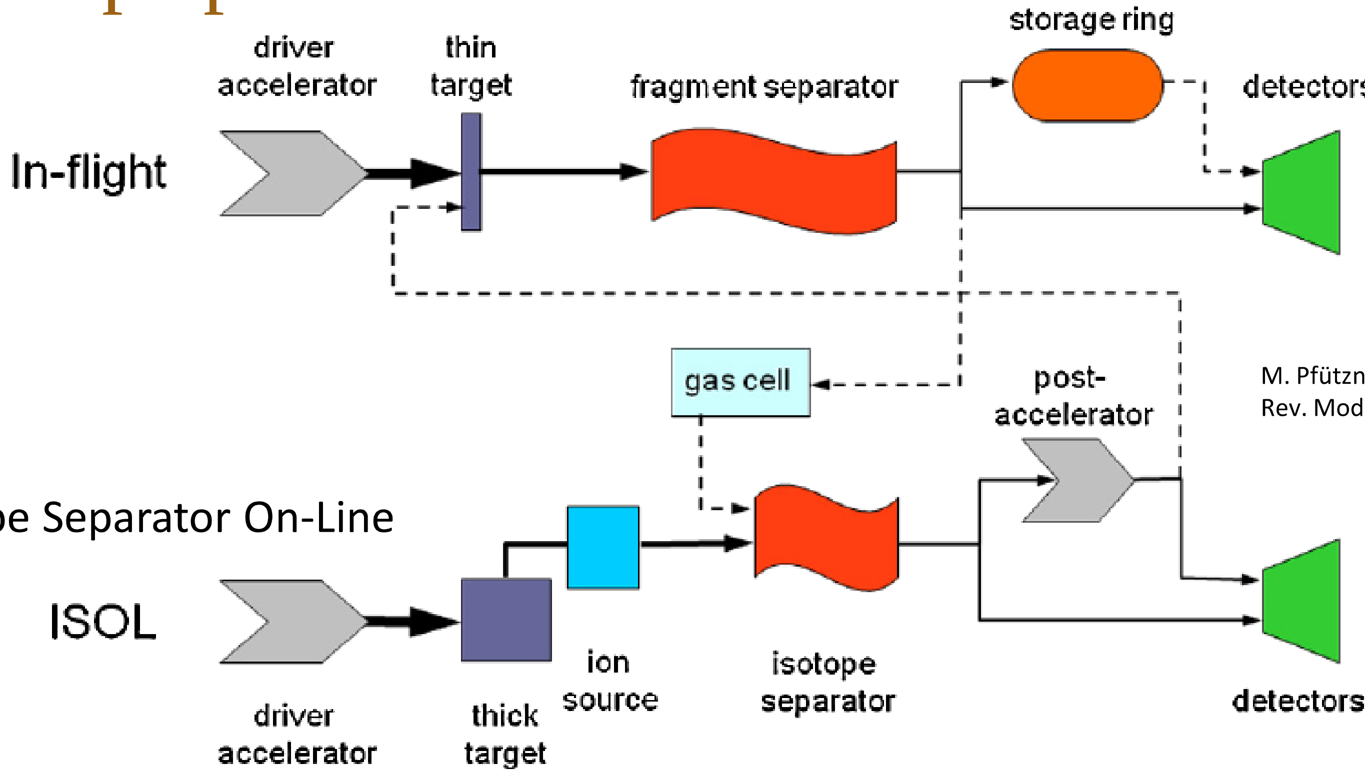
clear Physics far from stability



Nuclear Physics far from stability



Isotope production



M. Pfützner et al.,
Rev. Mod. Phys. 84, 567 (2012)

Isotope Separator On-Line

	ISOL	In-flight
Production rate	Slow	Fast
Beam intensity	High	Low
Beam energy	Low	High
Beam quality/purity	Good	Poor
Beam chemistry	Selective ionization	Independent

Nuclear reaction types:
Fragmentation
Fission
Spallation
Fusion
Coulomb dissociation

Radioactive beams world wide

Z. Meisel, Jour. Phys. Conf. Ser. 742, 012019 (2016)

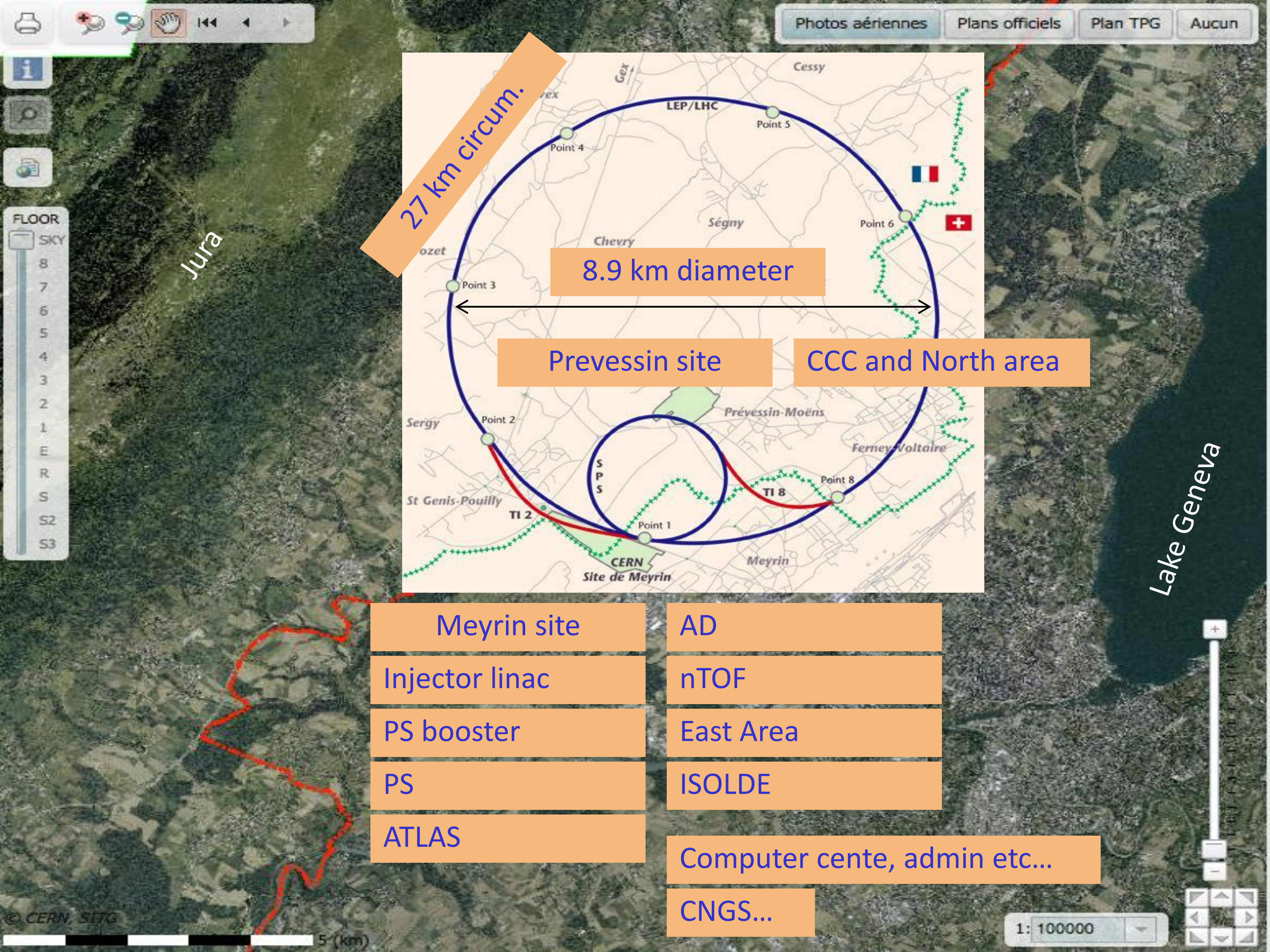
Facilities recently built, under construction or planned

FAIR(GSI, Germany)
FRIB(NSCL, USA)
HIAF (IMP, China)

RAON (S. Korea)
ARIEL (TRIUMF, Canada)
ANURIB (India)

CERN

ISOLDE



Photos aériennes
Plans officiels
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S2
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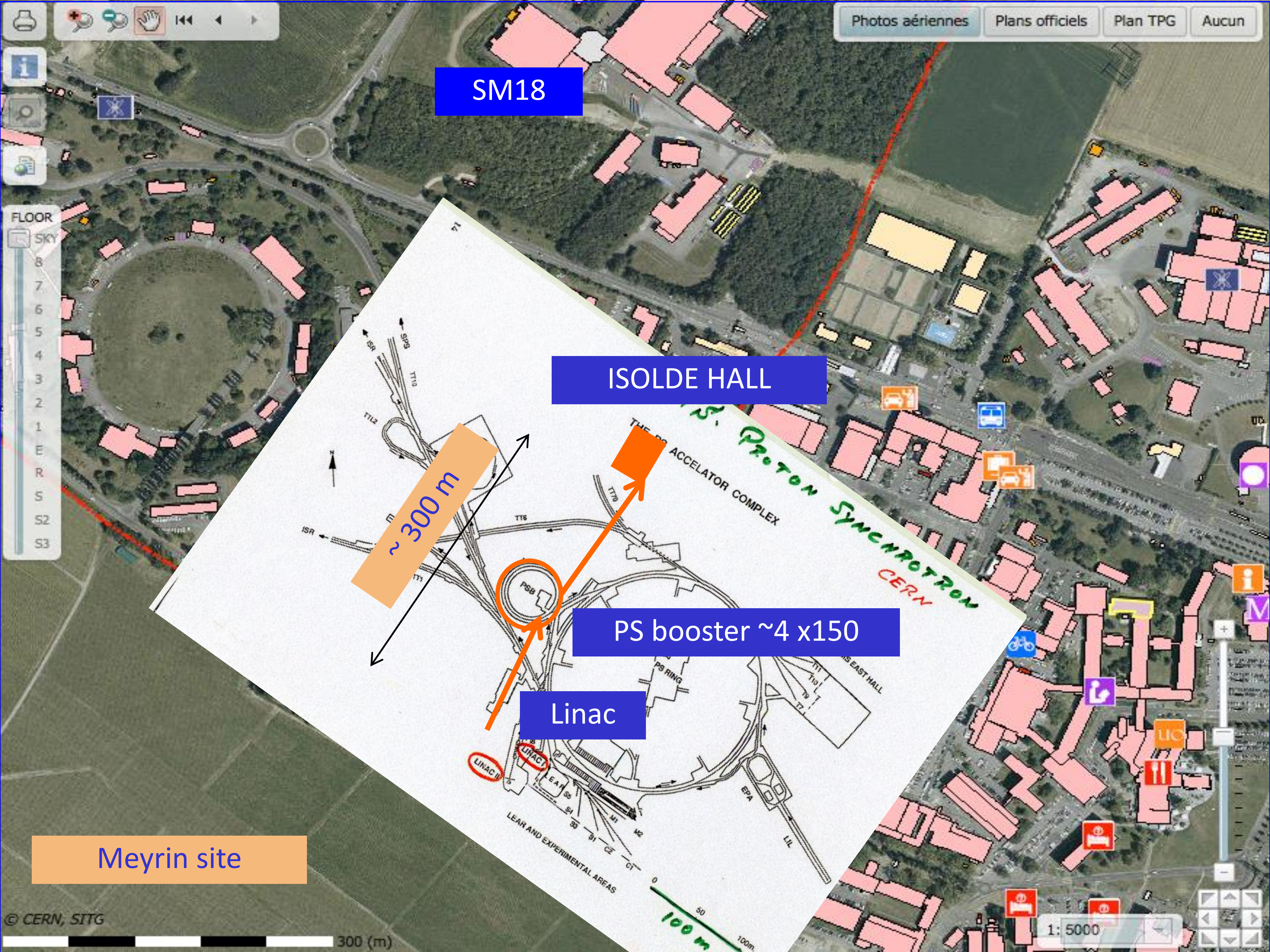
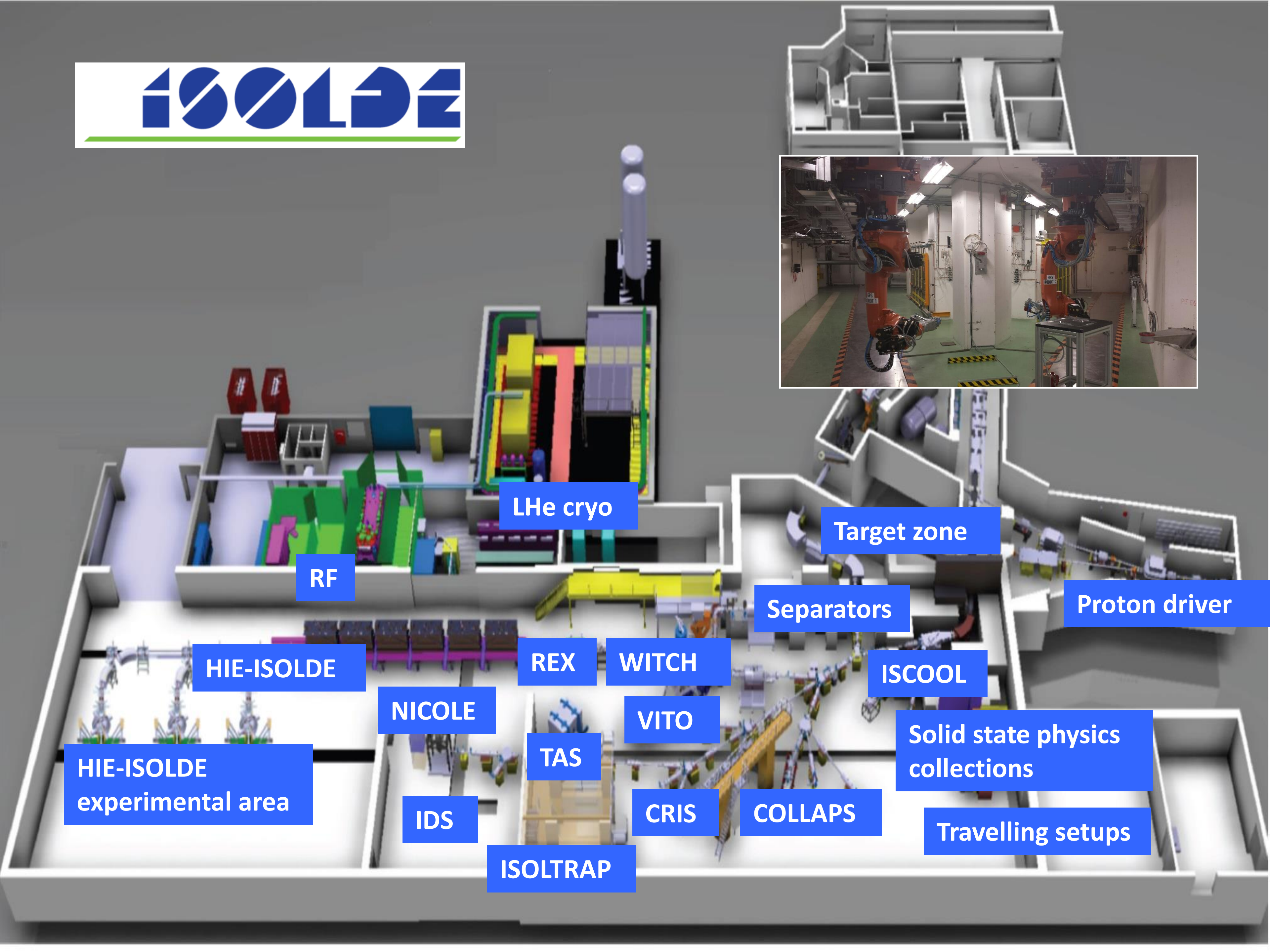
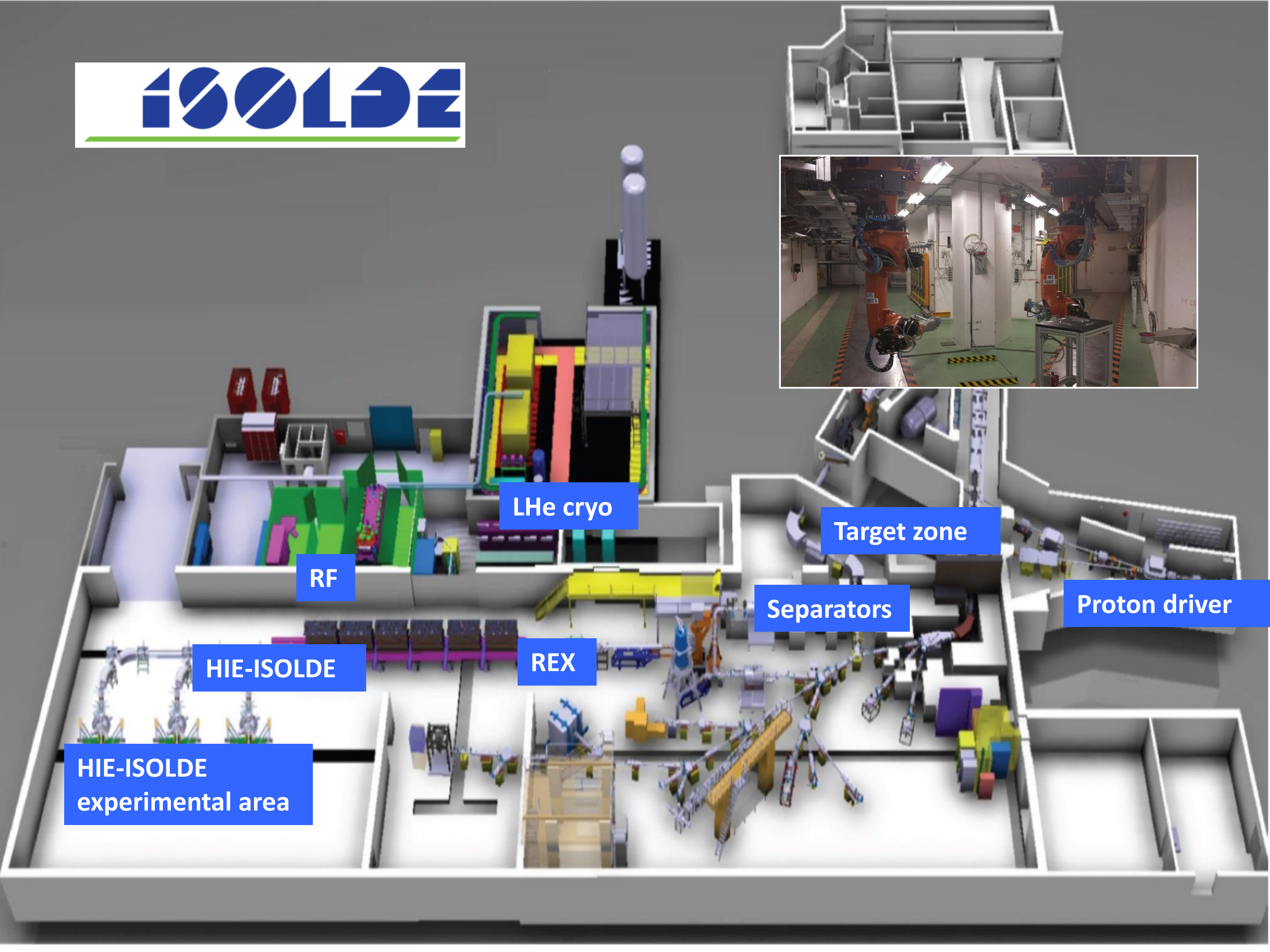
Jura
27 km circum.
Cessy
Gex
LEP/LHC
Point 5
Point 4
Point 6
Ségny
Chevry
8.9 km diameter
Point 3
Prevessin site
CCC and North area
Prévessin-Moëns
Sergy
Point 2
Ferney-Voltaire
SPS
Point 8
TI 8
St Genis-Pouilly
TI 2
Point 1
CERN
Site de Meyrin
Meyrin
Lake Geneva
Meyrin site
Injector linac
PS booster
PS
ATLAS
AD
nTOF
East Area
ISOLDE
Computer cente, admin etc…
CNGS…
© CERN, SITG
5 (km)
1: 100000



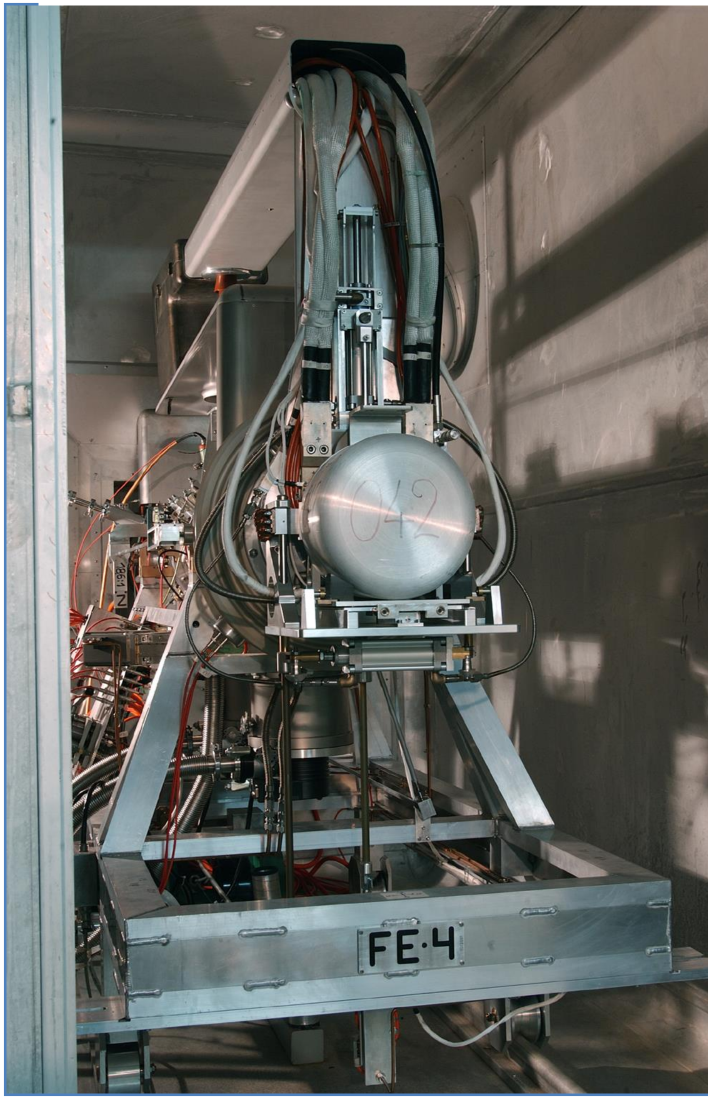
SM18
ISOLDE HALL
~ 300 m
PS booster ~4 x150
Linac
Meyrin site
THE PS ACCELERATOR COMPLEX
Proton Synchrotron
CERN
LINAC
LINAC II
PSB
PS RING
LEAR AND EXPERIMENTAL AREAS
100 m
© CERN, SITG
300 (m)
1: 5000
Photos aériennes
Plans officiels
Plan TPG
Aucun
FLOOR

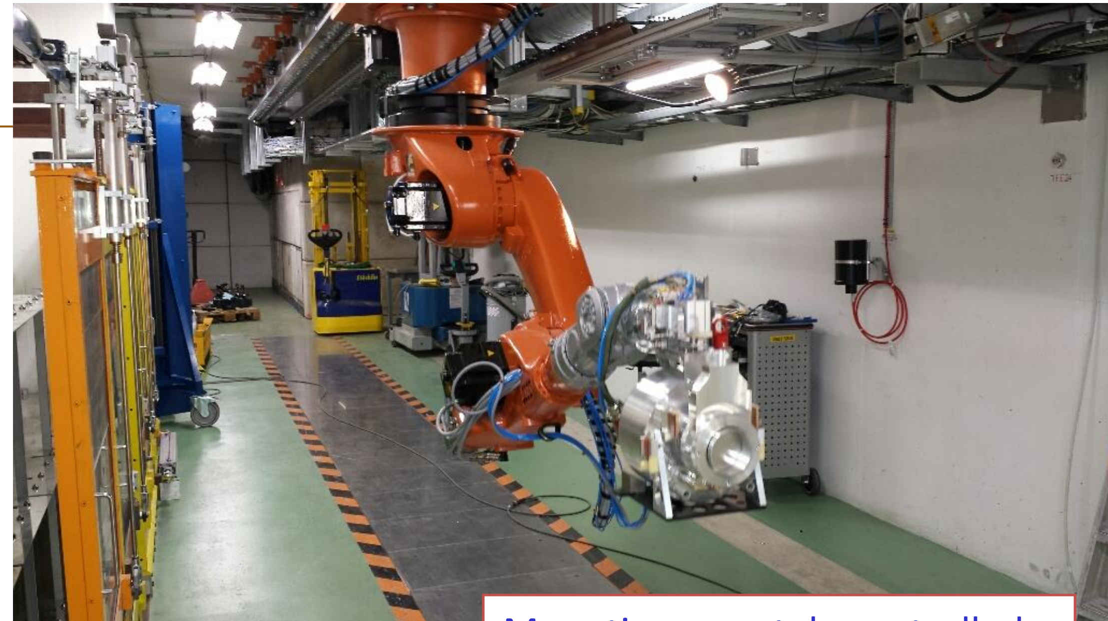

LHe cryo
Target zone
RF
Separators
Proton driver
HIE-ISOLDE
REX
WITCH
ISCOOL
NICOLE
VITO
Solid state physics collections
TAS
HIE-ISOLDE experimental area
IDS
CRIS
COLLAPS
Travelling setups
ISOLTRAP



ISOLDE
LHe cryo
Target zone
RF
Separators
Proton driver
HIE-ISOLDE
REX
HIE-ISOLDE experimental area

Targetry





Mounting remotely controlled via robots.

Targetry

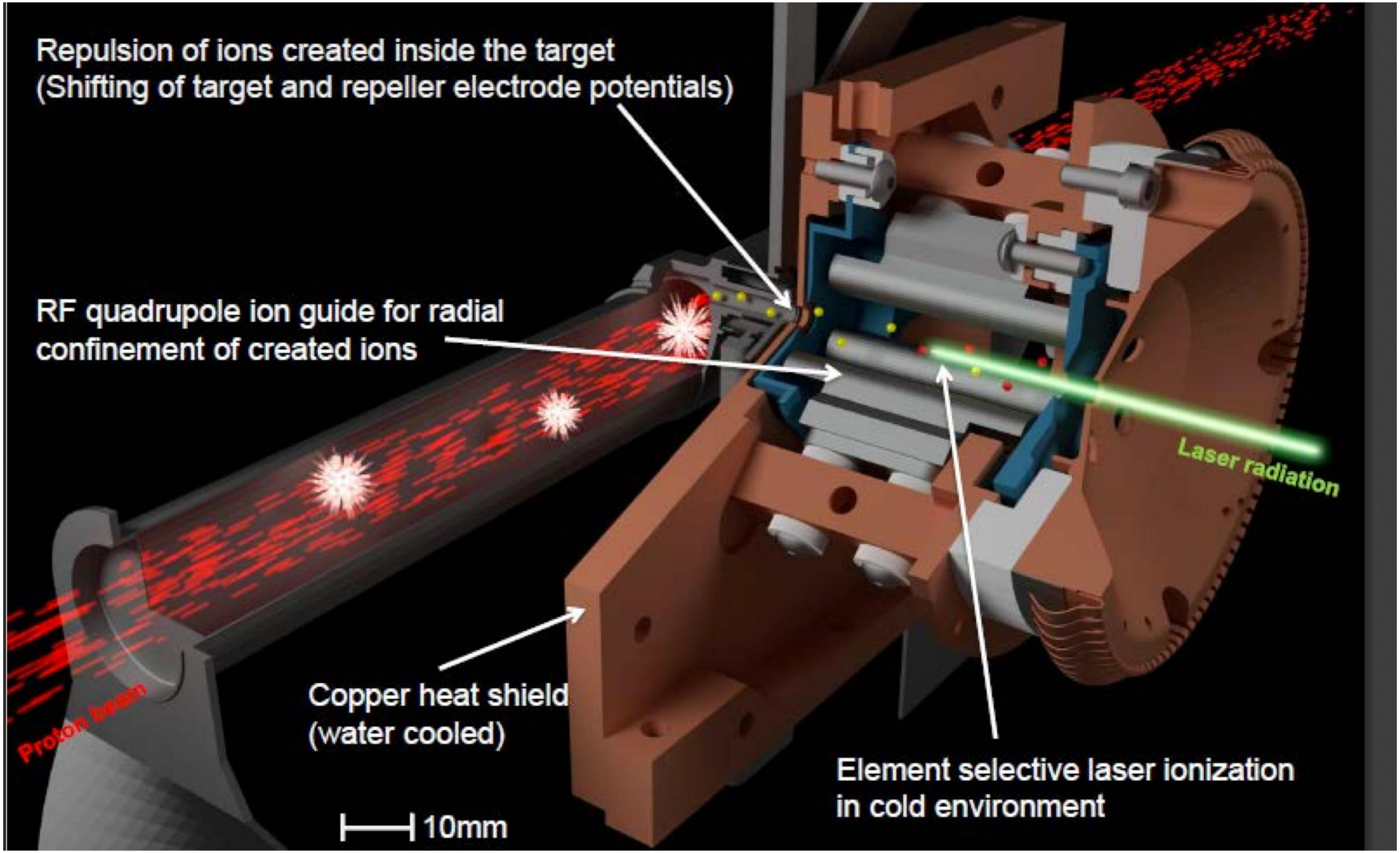
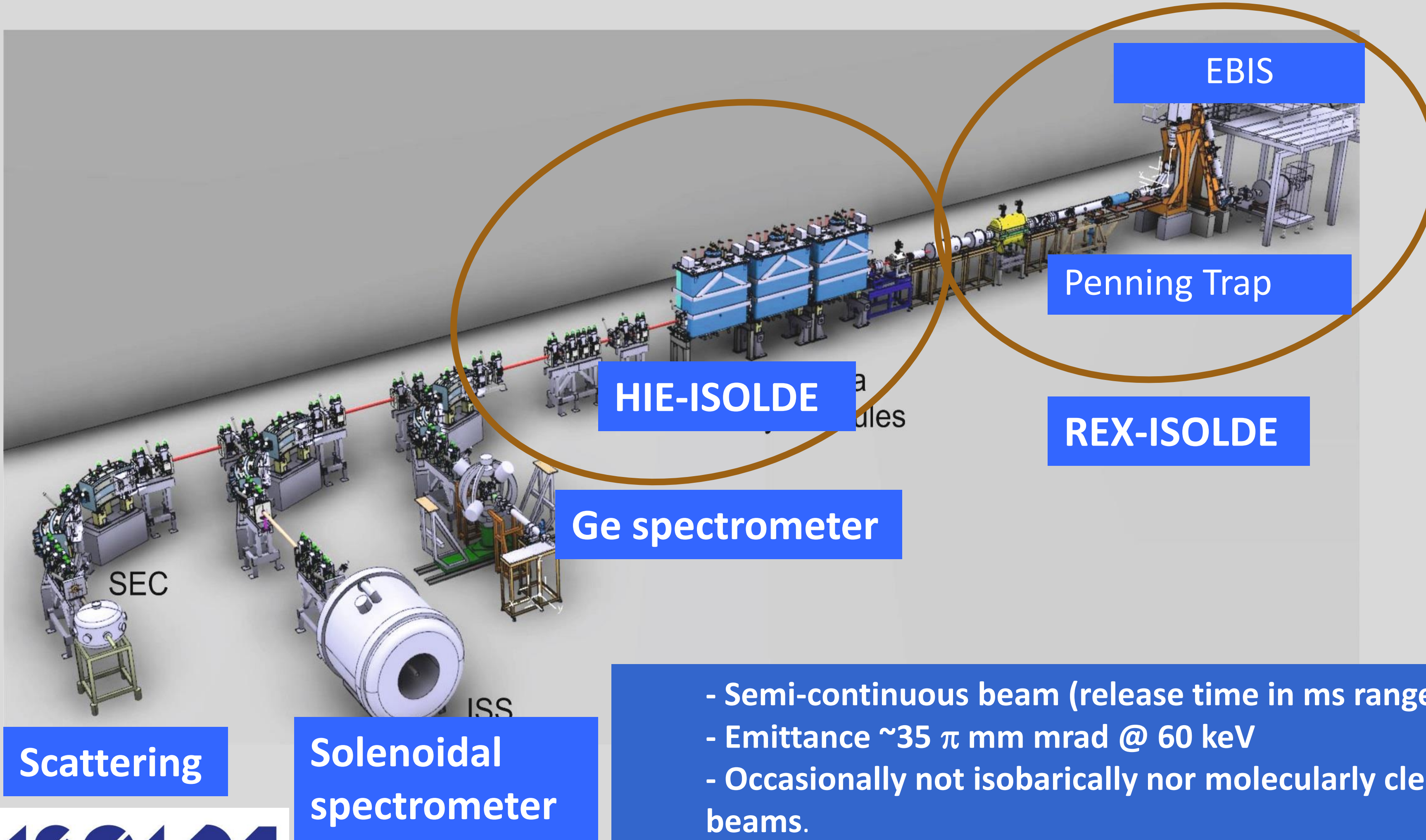


Illustration: Triumf radioactive beam facility

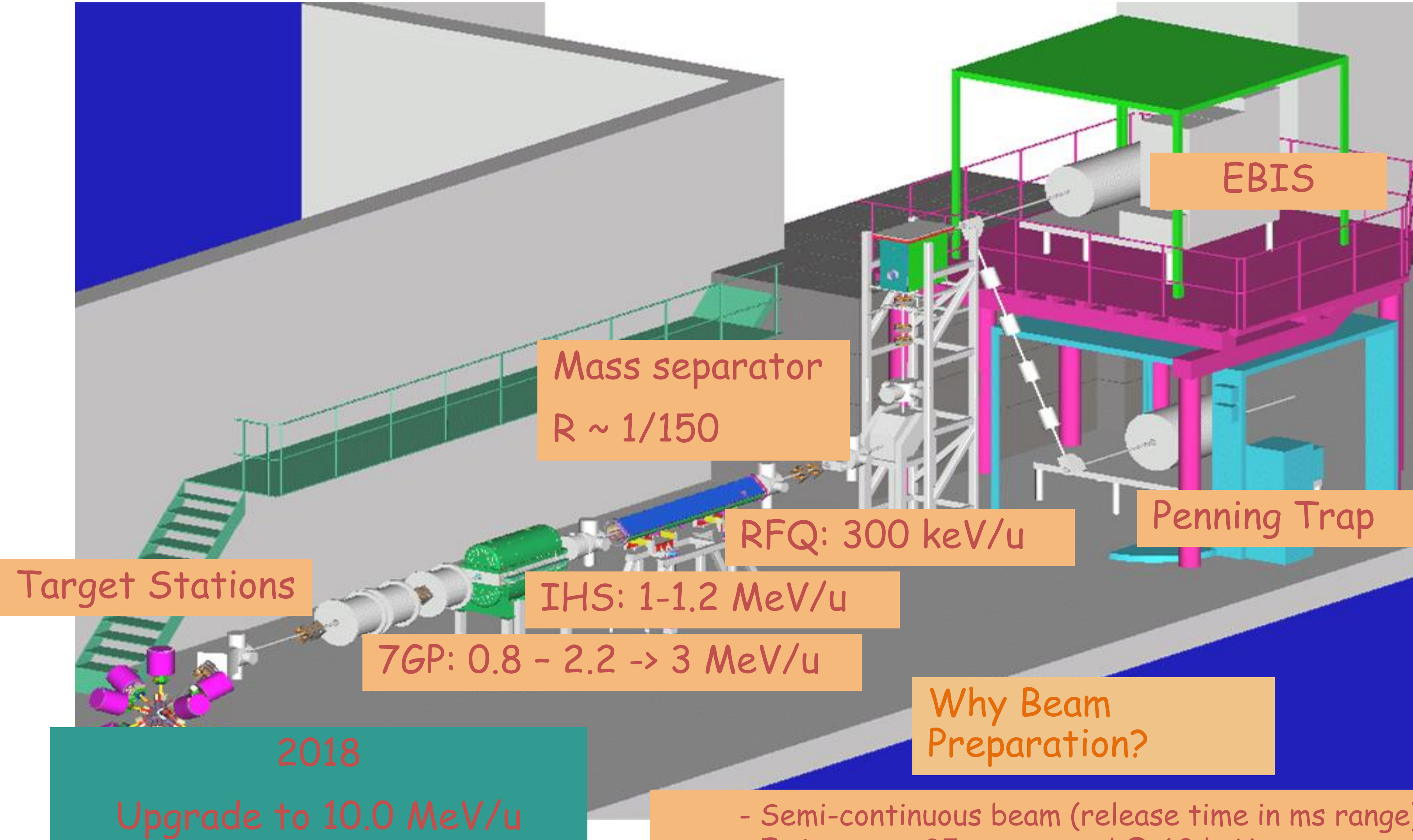
REX-ISOLDE and HIE-ISOLDE



- Semi-continuous beam (release time in ms range)
- Emittance ~35 π mm mrad @ 60 keV
- Occasionally not isobarically nor molecularly clean beams.

ISOLDE

REX and HIE-ISOLDE



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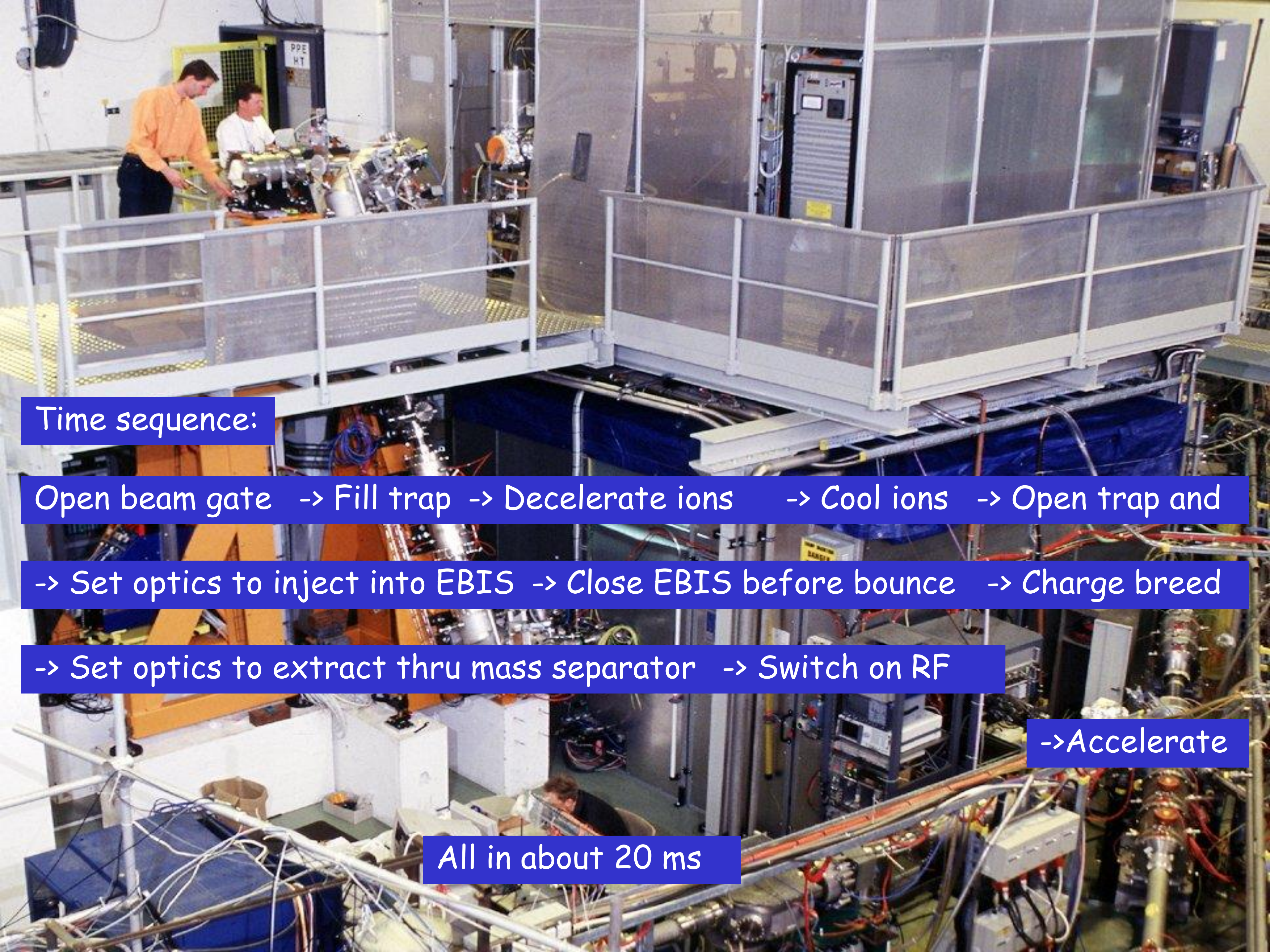


Time sequence:

Open beam gate -> Fill trap -> Decelerate ions -> Cool ions -> Open trap and

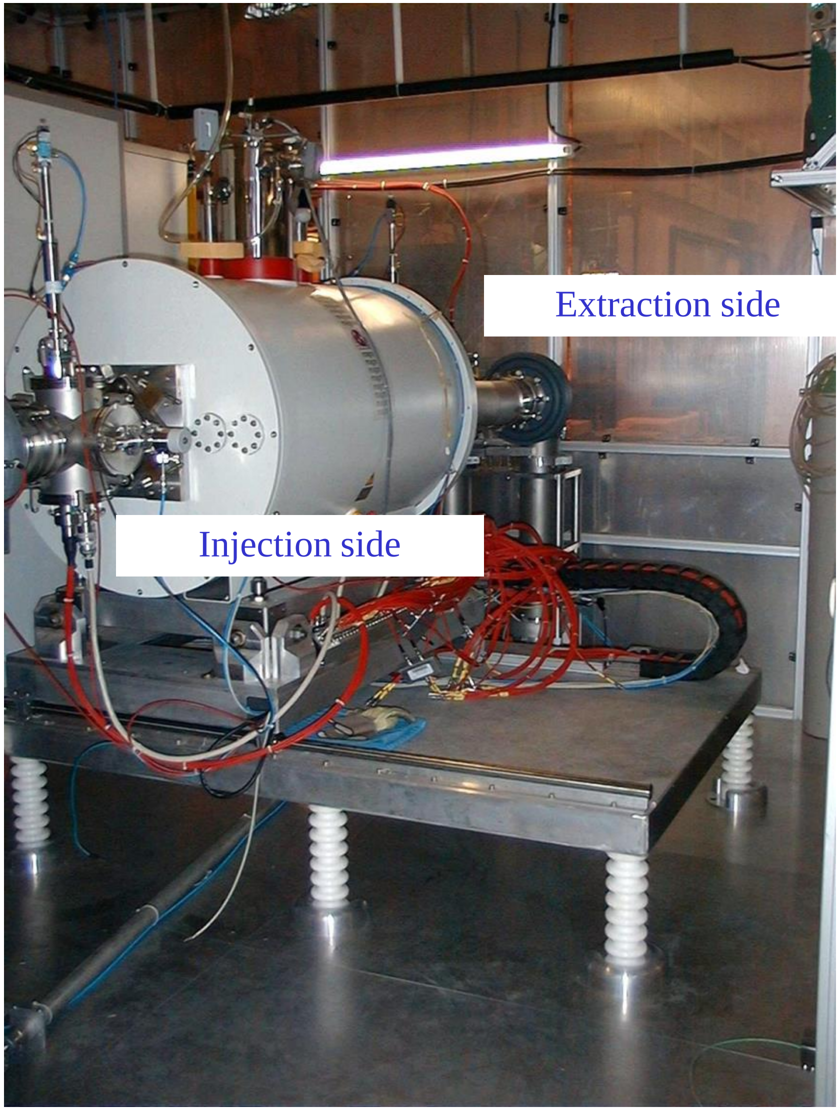
-> Set optics to inject into EBIS -> Close EBIS before bounce -> Charge breed

-> Set optics to extract thru mass separator -> Switch on RF

->Accelerate

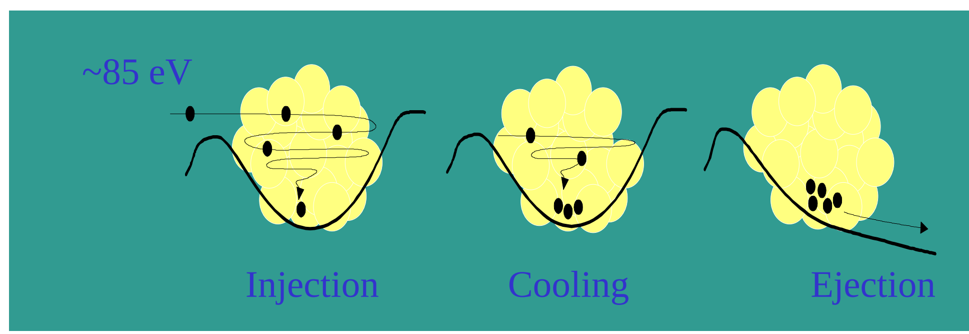
All in about 20 ms

Trapping and Cooling



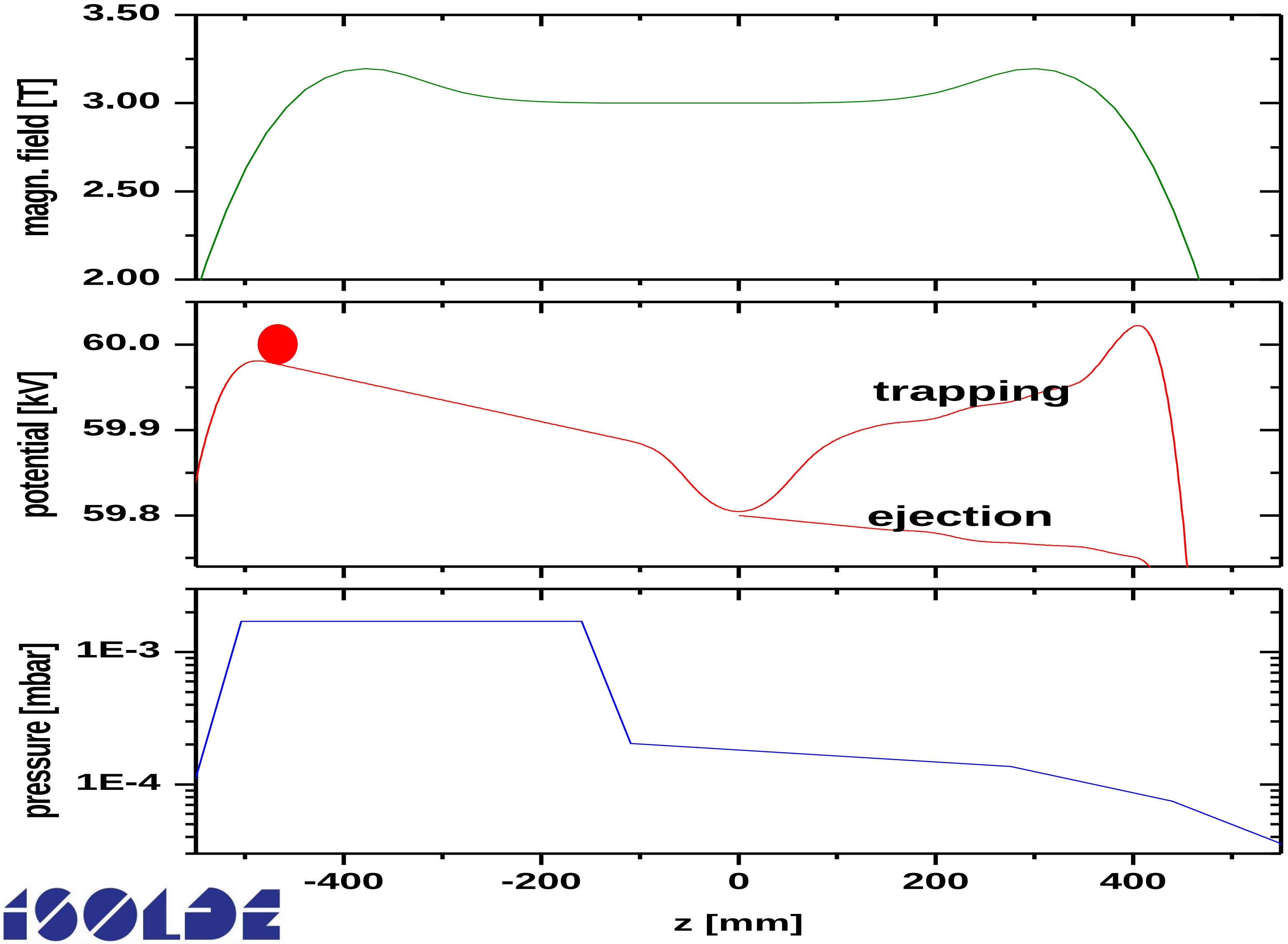
Cylindrical Penning Trap

- 3T Super conducting magnet
- 2.0 cm axial x 2.5 cm radial trapping region
- 1E-6 field homogeneity
- 1E-3 mbar trapping pressure
- Buffer gas: Argon, Neon
- 1E-7 mbar exit pressure
- Efficiency ~ 30 % >> 50% (Na)

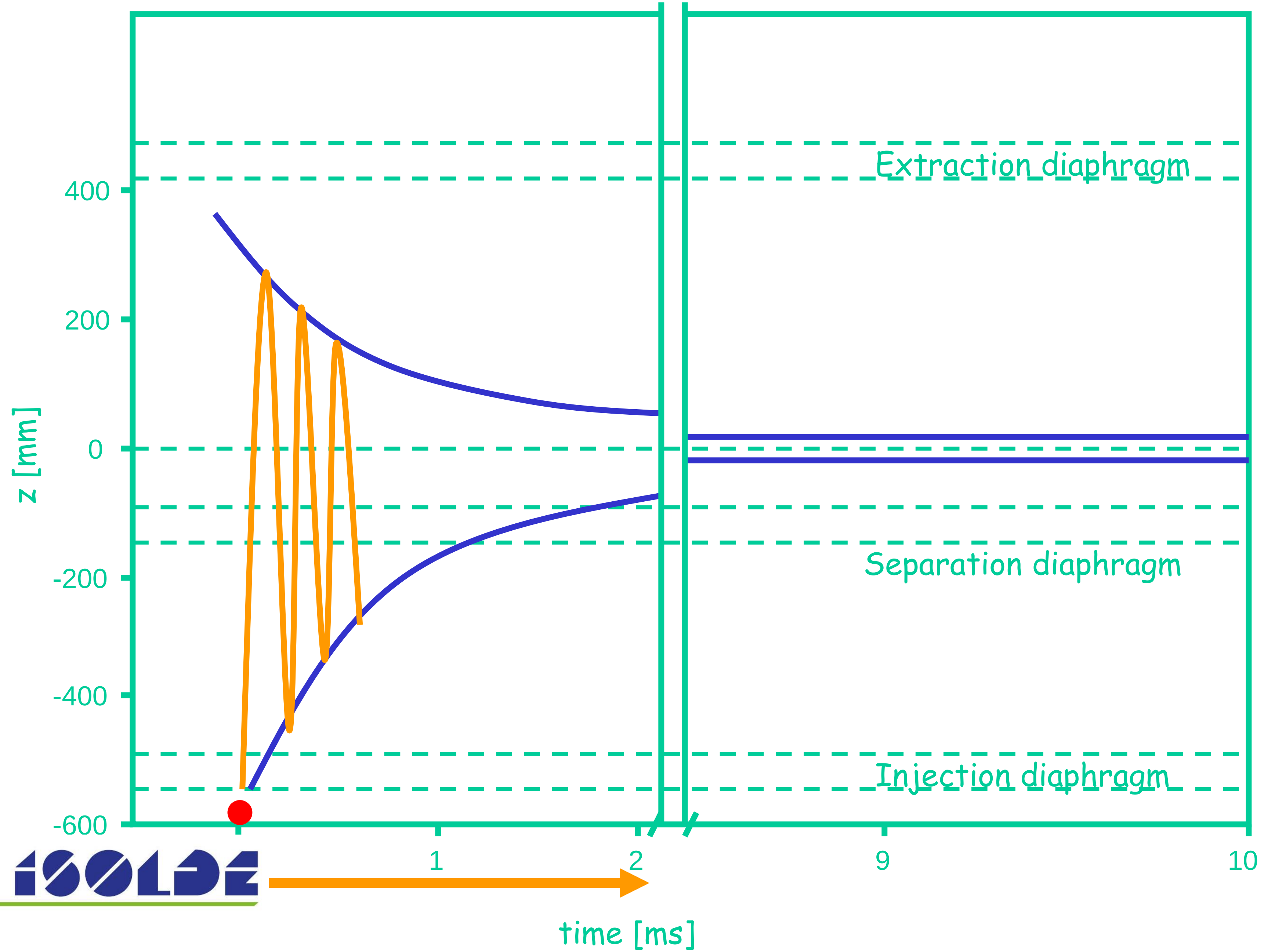


ISOLDE

Trapping and Cooling



Trapping and Cooling



Trapping and Cooling

Eigenmotion consists of:

Axial, Cyclotron and Magnetron motions

Stable | Unstable

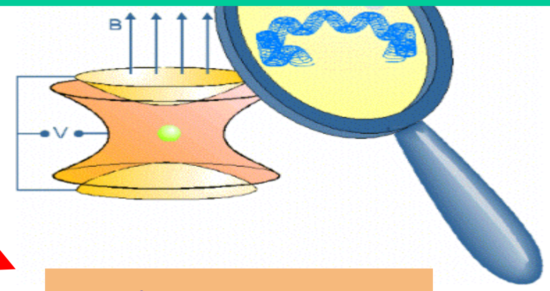
Couples with rf Q-field

Stability by applying:

1. Electric Quadrupole field.

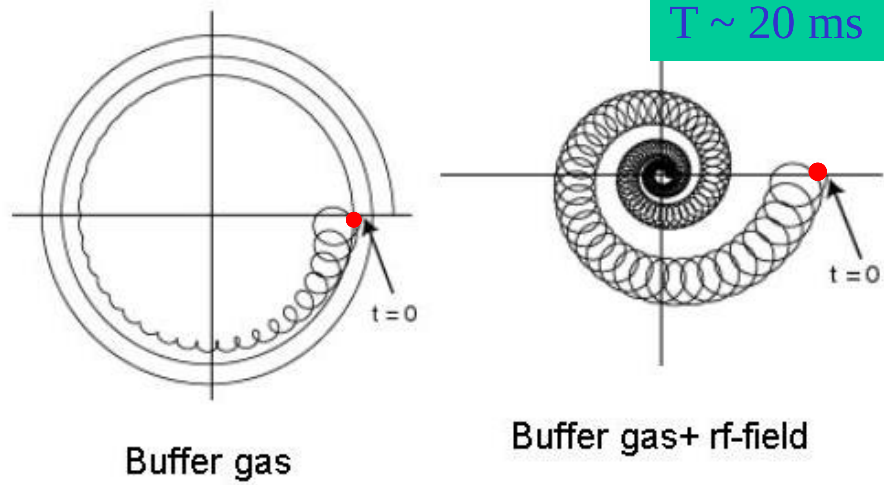
2. Magnetic Field (radial confinement)

Split central ring in 4 in azimuth

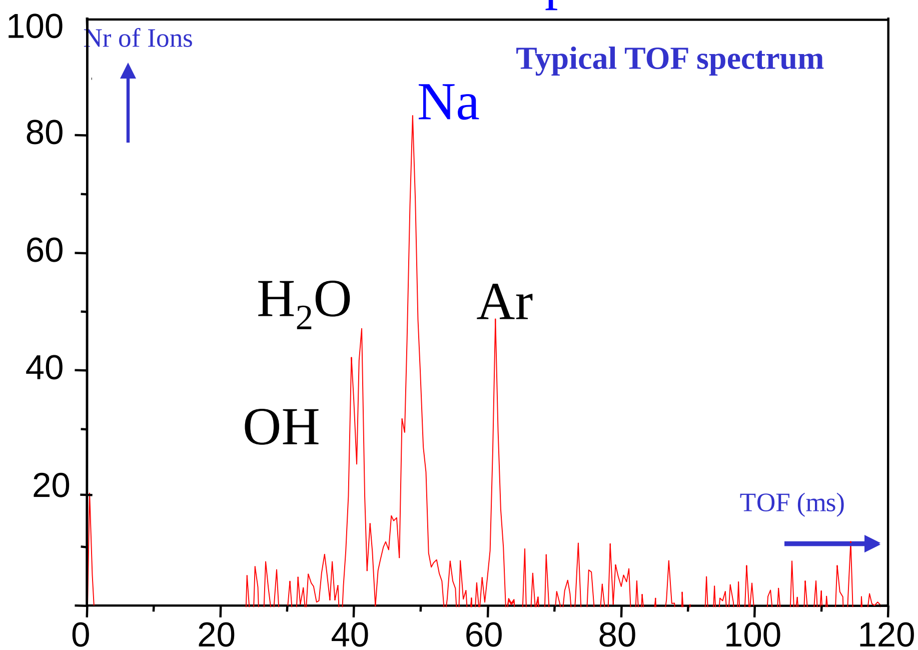


Excite at ω = qB/m

T ~ 20 ms



600 ^{26}Na ions/pulse



G. Bollen, G. Savard >> ISOLTRAP

The flight time for ions defined as the time from extraction time until they hit a micro channel plate detector.

Charge breeding

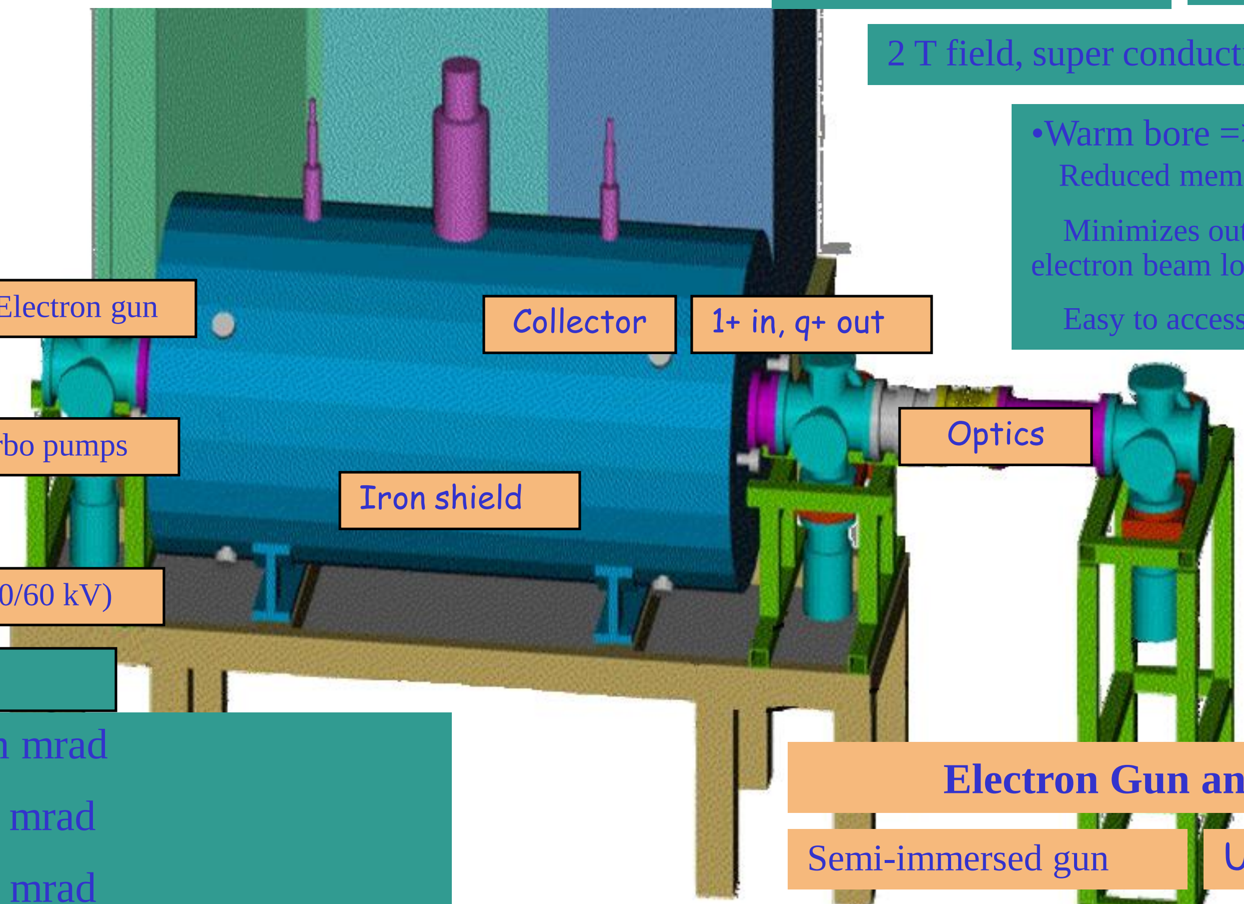
Solenoid

~0.8 m trap length

Iron shielded

2 T field, super conducting winding

- Warm bore =>
  - Reduced memory effects
  - Minimizes out-gassing from electron beam load
  - Easy to access inner structure



Emittance (at 30keV)

Isolde: ~ 35 p mm mrad

Rextrap: ~ 7p mm mrad

EBIS: < 10 p mm mrad

Acceptance

Mass separator: ~ 40 π mm mrad

RFQ acceptance: ~ 180 p mm mrad

Electron Gun and Beam

Semi-immersed gun

U = 5 keV

j >200 A/cm^2

Adjustable

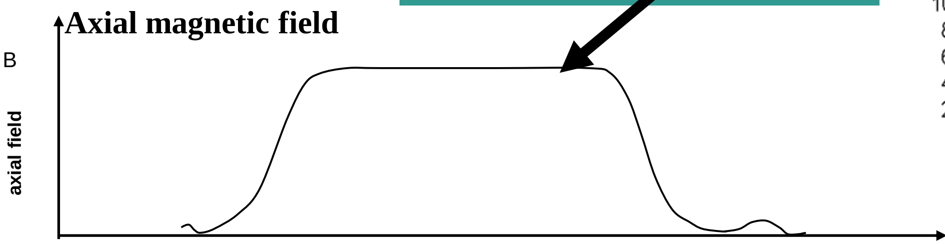
Capacity: 1E10 charges

10% compensation (filling)

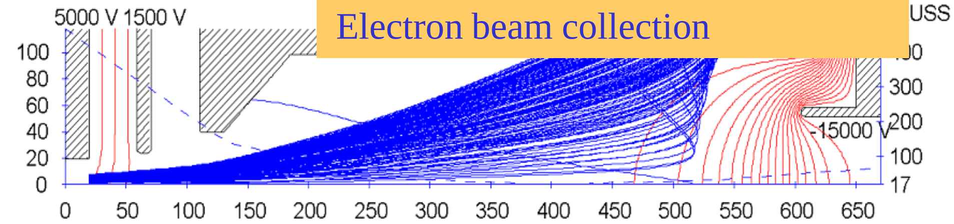
Pressure: 1E-11 region (UHV system)

Charge breeding

Homogeneity +-0.25%

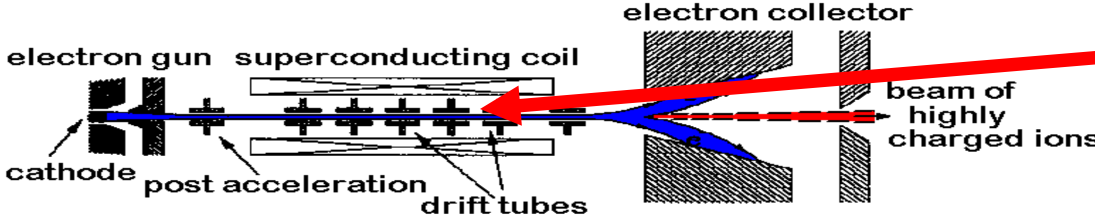


Electron beam collection



Inside REX-EBIS

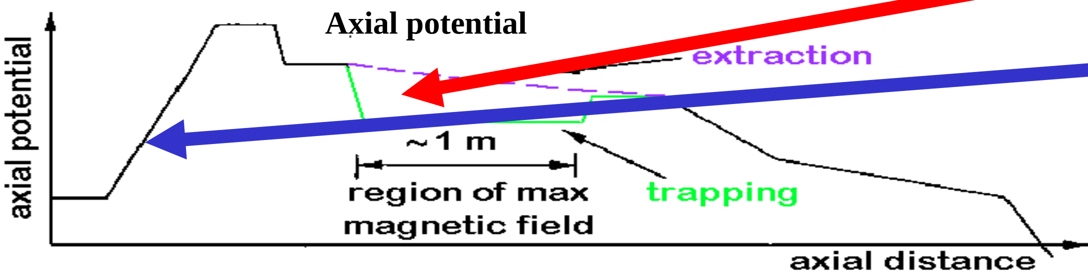
EBIS cross-view



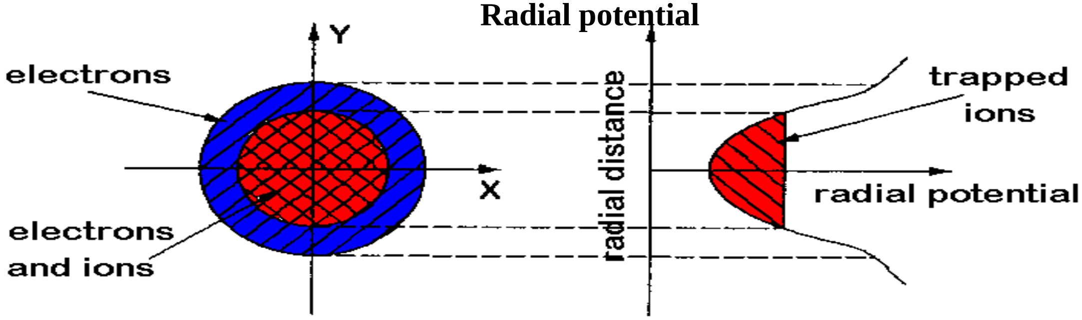
Titanium inner structure

Drift tubes form a cylindrical ion trap and reflects rest-gas ions produced in the electron gun region.

Axial potential

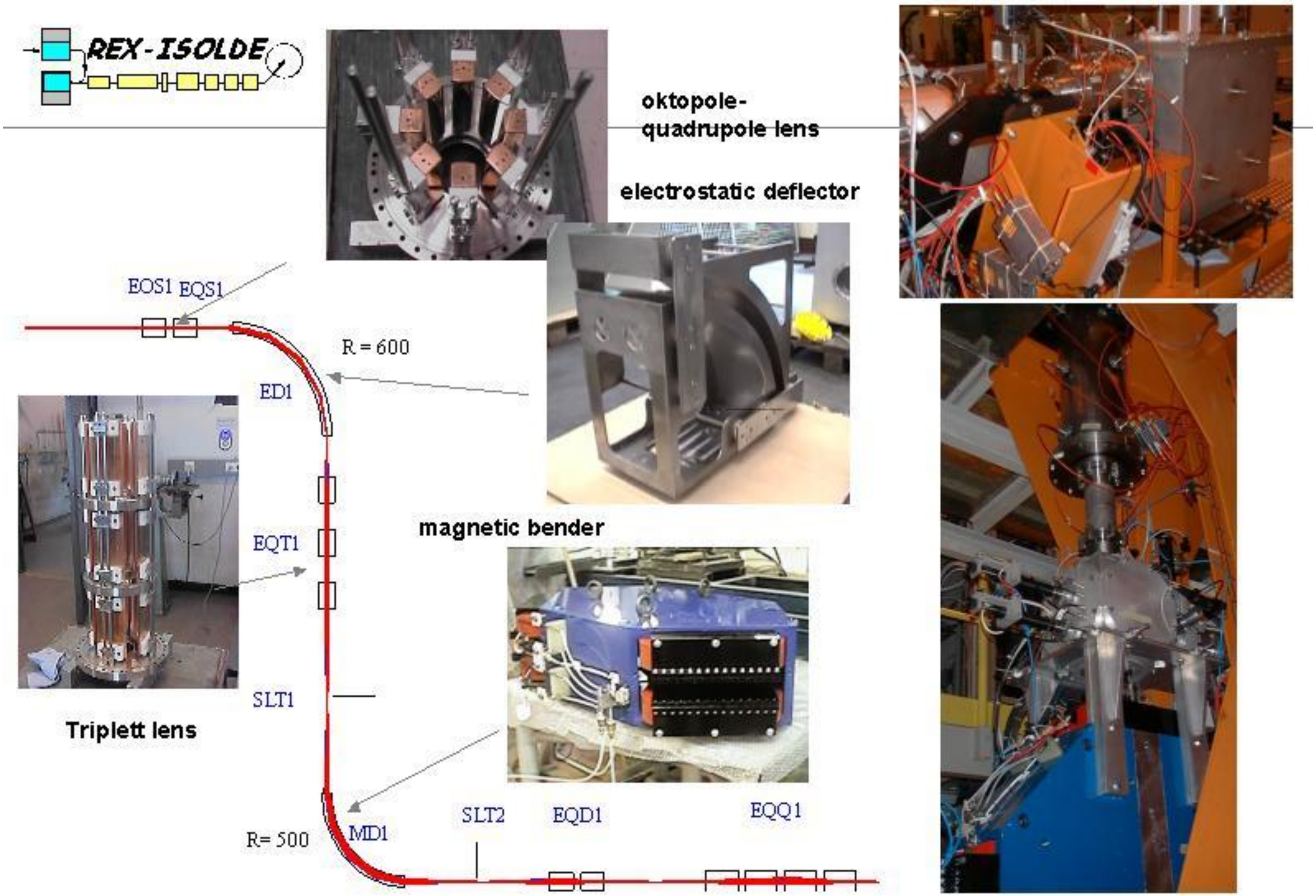


Radial potential



Electron beam compensation

Final mass separation



Our main analysis tool for analyzing injected beam

Low resolution: ~ 200

HIE-ISOLDE

- **Approved by CERN management in September 2009**
- **Staged project:**
  - **Phase 1: Two cryomodules completed 2016 to give 5.5 MeV/u**
  - **Phase 2: Two additional modules for 2018 to give 10 MeV/u**
- **Trap cooling & charge breeding system, and normal conducting LINAC from REX-ISOLDE to give 2.8 MeV/u remains.**
- **Acceleration over full mass range possible**
- **Intensity upgrade study for targetry etc. part of the project**

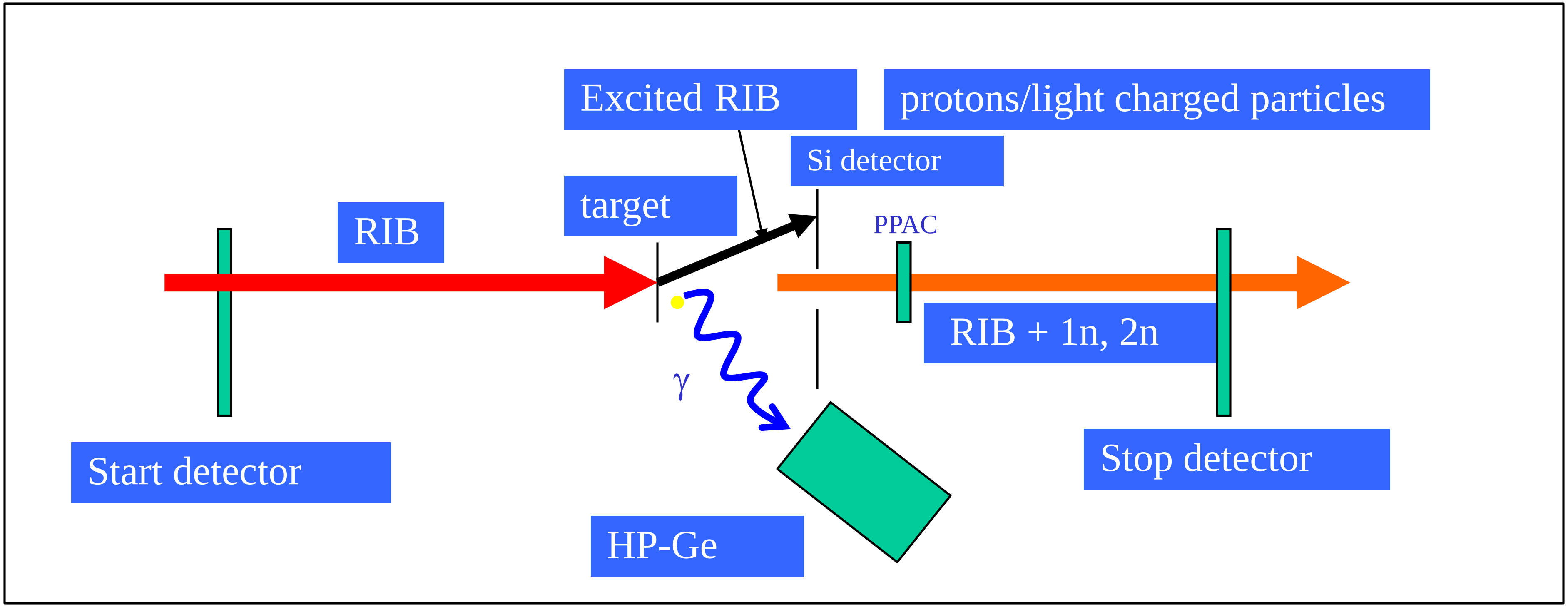
Physics: Transfer reactions and multistep Coulomb excitation

HIE - ISOLDE – accelerator structures

Experimental principle

Experimental information:

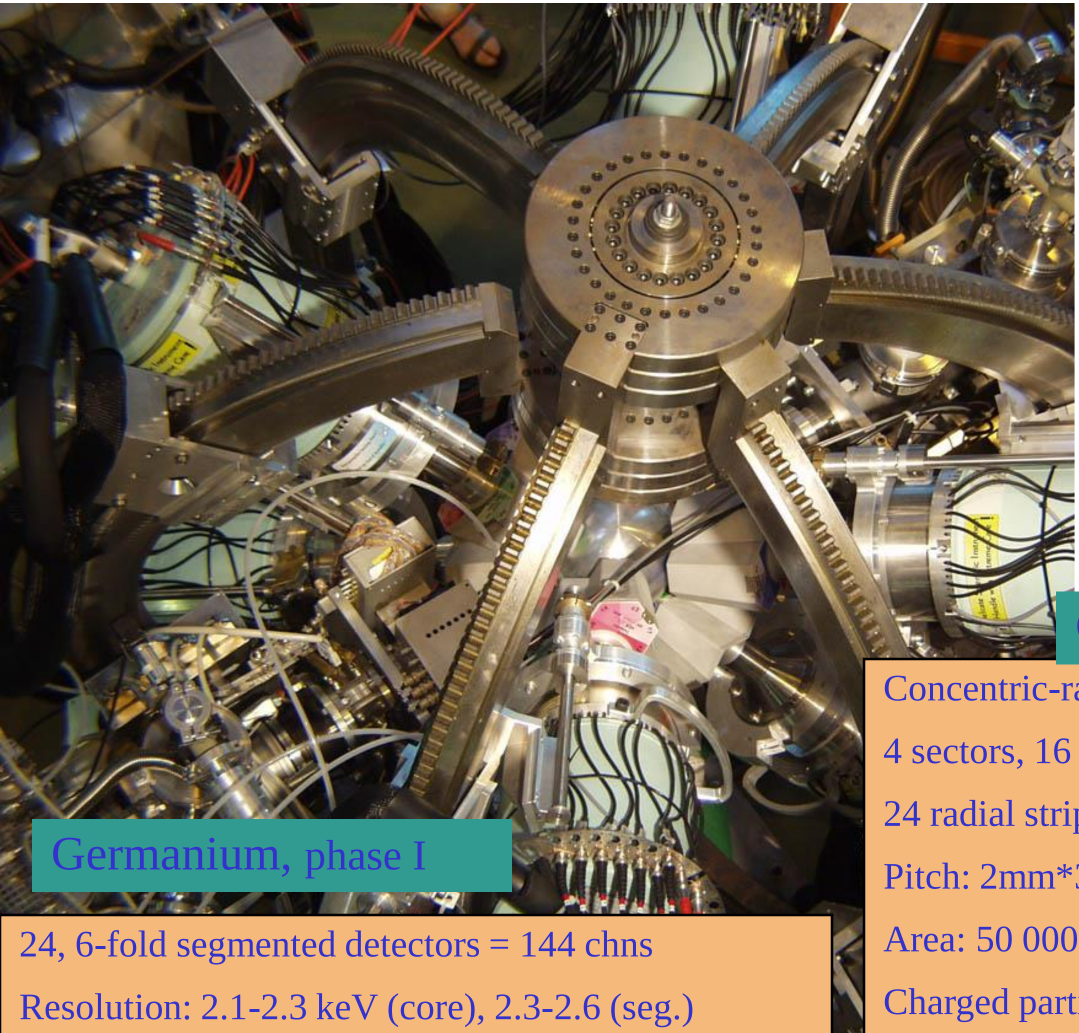
Transition probabilities, magnetic moments, spectroscopic factors, new levels…



Targets: Coulex ^{58}Ni…

Transfer PE(D), ^{3}H etc

Detectors



Germanium, phase I

24, 6-fold segmented detectors = 144 chns

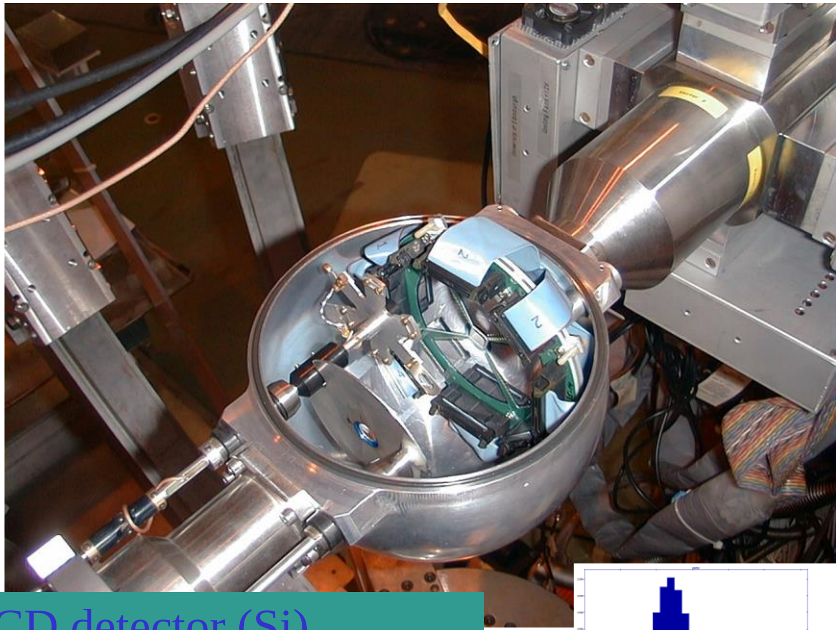
Resolution: 2.1-2.3 keV (core), 2.3-2.6 (seg.)

Photo Peak efficiency: 9.5%, (11.3% with AB)

Completely digital electronics after Pre-amp.

Position sensitivity increases granularity ~10

Used for low M (<10) events, d=10.3 cm



CD detector (Si)

Concentric-radial DSSSD

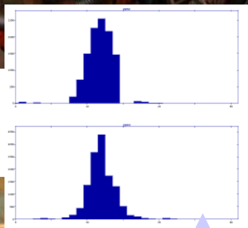
4 sectors, 16 concentric,

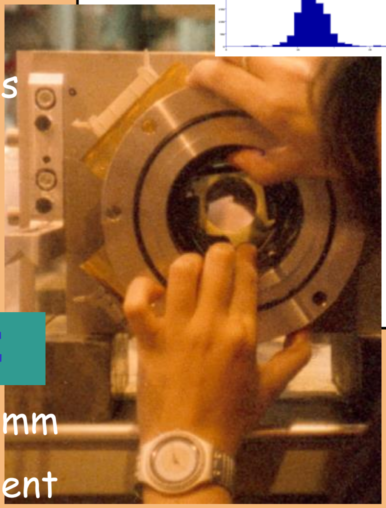
24 radial strips. 0.5mm thickness

Pitch: 2mm*3.5 deg

Area: 50 000 mm^2 (93% active)

Charged particle detection





PPAC

25*25 metal strips

Active agent isobutane, Pitch 1.25 mm

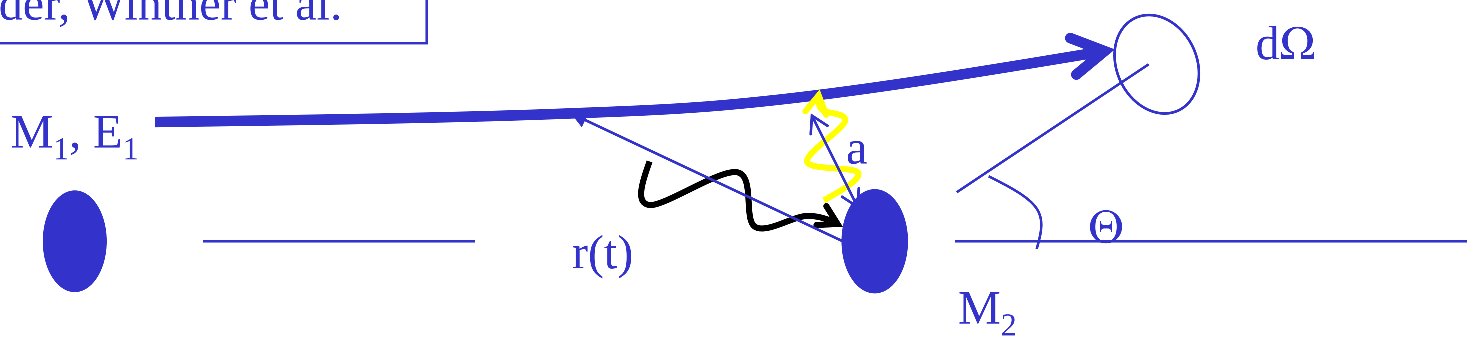
Operates in single particle or current

mode for background reduction and beam monitoring

Coulomb excitation

Well established theory:

Alder, Winther et al.



$$d\sigma/d\Omega = P \;\; d\sigma_R/d\Omega$$

Well known

Time dependent problem: Potential V(r(t)).

Time dependent Schrodinger equation:

$$i\hbar(\partial/\partial t)\,|\Psi(t)> = H(t)\,|\Psi(t)> \; ; \;\; \text{where } H(t) = H_0 + V(t)$$

$$H_o|n> = E_n\,|n>$$

Introduce time dependent excitation amplitudes: $a_n(t) = <n|\Psi> \exp(iE_n t/\hbar)$

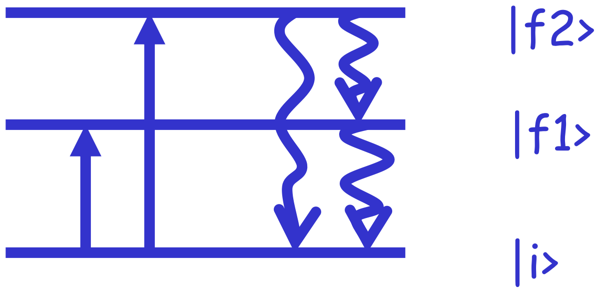
(the time evolution operator to describe a states time dependence)

The result is a set of coupled differential equations for the amplitudes:

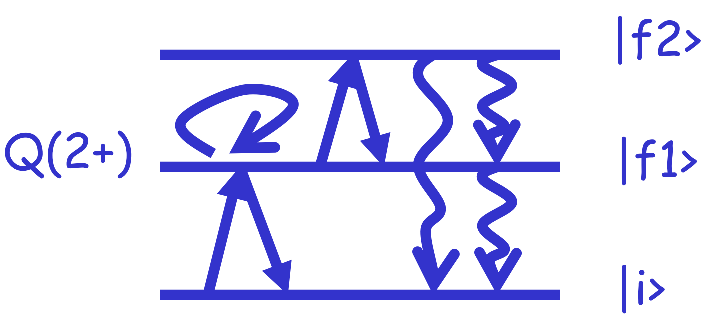
$$i\hbar\,(\partial/\partial t)\,a_n(t) = \sum_m <n|V|m> \;\; \exp[i(E_n - E_m)t/\hbar]\;a_m(t)$$

$$a_n(-\infty) = \partial_{0n},\; P_n = |a_n|^2$$

Coulomb excitation: Perturbation theory



Single step
excitations



multi step
excitations

Amplitudes and cross sections

$$a_{i\to f} = \frac{1}{i\hbar}\int_{-\infty}^{\infty} e^{i\omega_{fi}t}\langle f|V(\vec{r}(t))|i\rangle dt$$

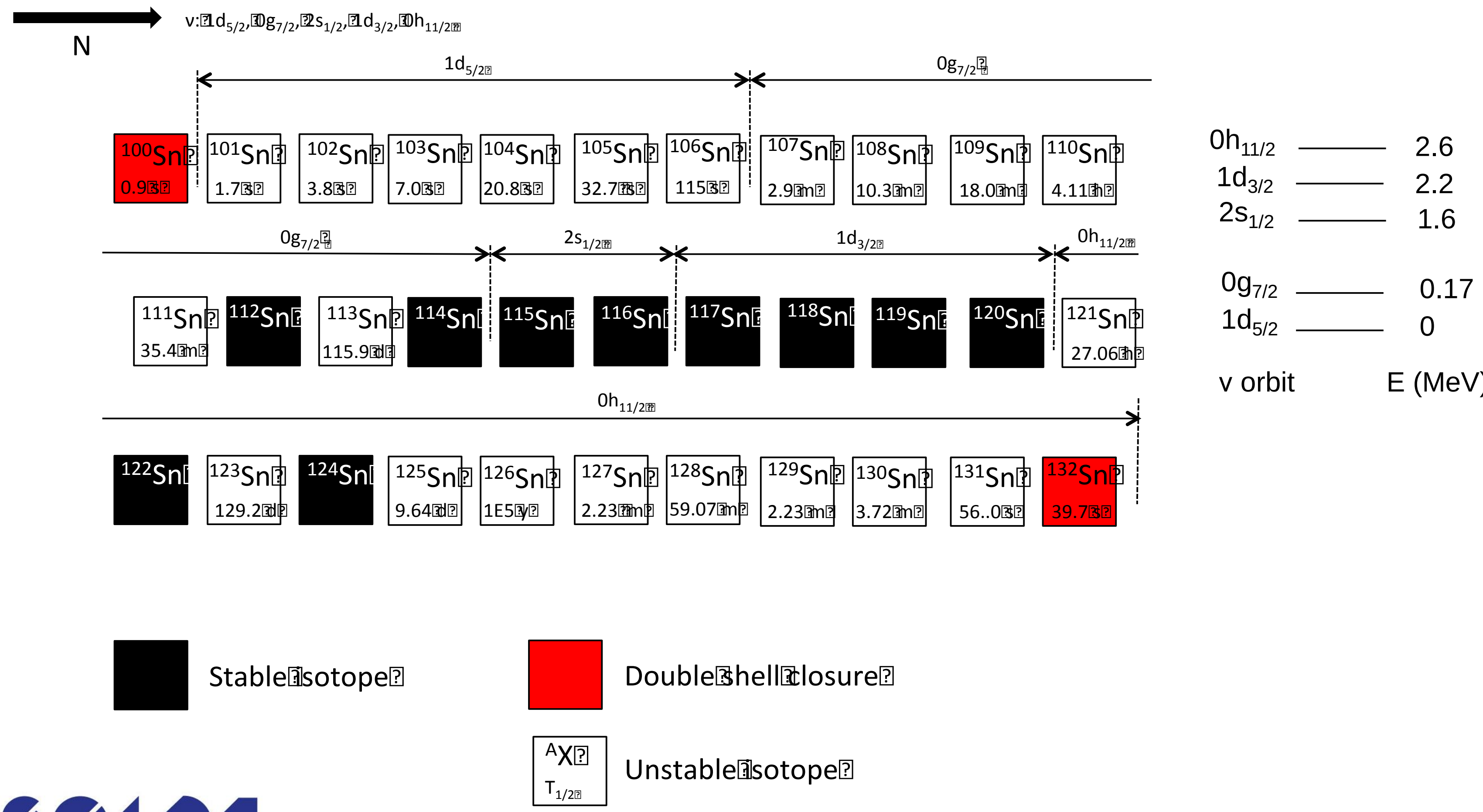
$$\sigma_{E\lambda} = \left(\frac{Z_t e}{\hbar v}\right)^2 a_0^{-2\lambda+2} B(E\lambda) f_{E\lambda}(\xi)$$

$$f_{E\lambda}(\xi) = \int_{\Theta_1}^{\Theta_2} \frac{df_{E\lambda}(\Theta,\xi)}{d\Omega} d\Omega \ ,$$

$$\begin{aligned} B(\pi\lambda; I_i \to I_f) &= \sum_{\mu M_f} |\langle I_f M_f|\mathcal{M}(\pi\lambda\mu)|I_i M_i\rangle|^2 \\ &= \frac{1}{2I_i+1}|\langle I_f||\mathcal{M}(\pi\lambda)||I_i\rangle|^2 \end{aligned}$$

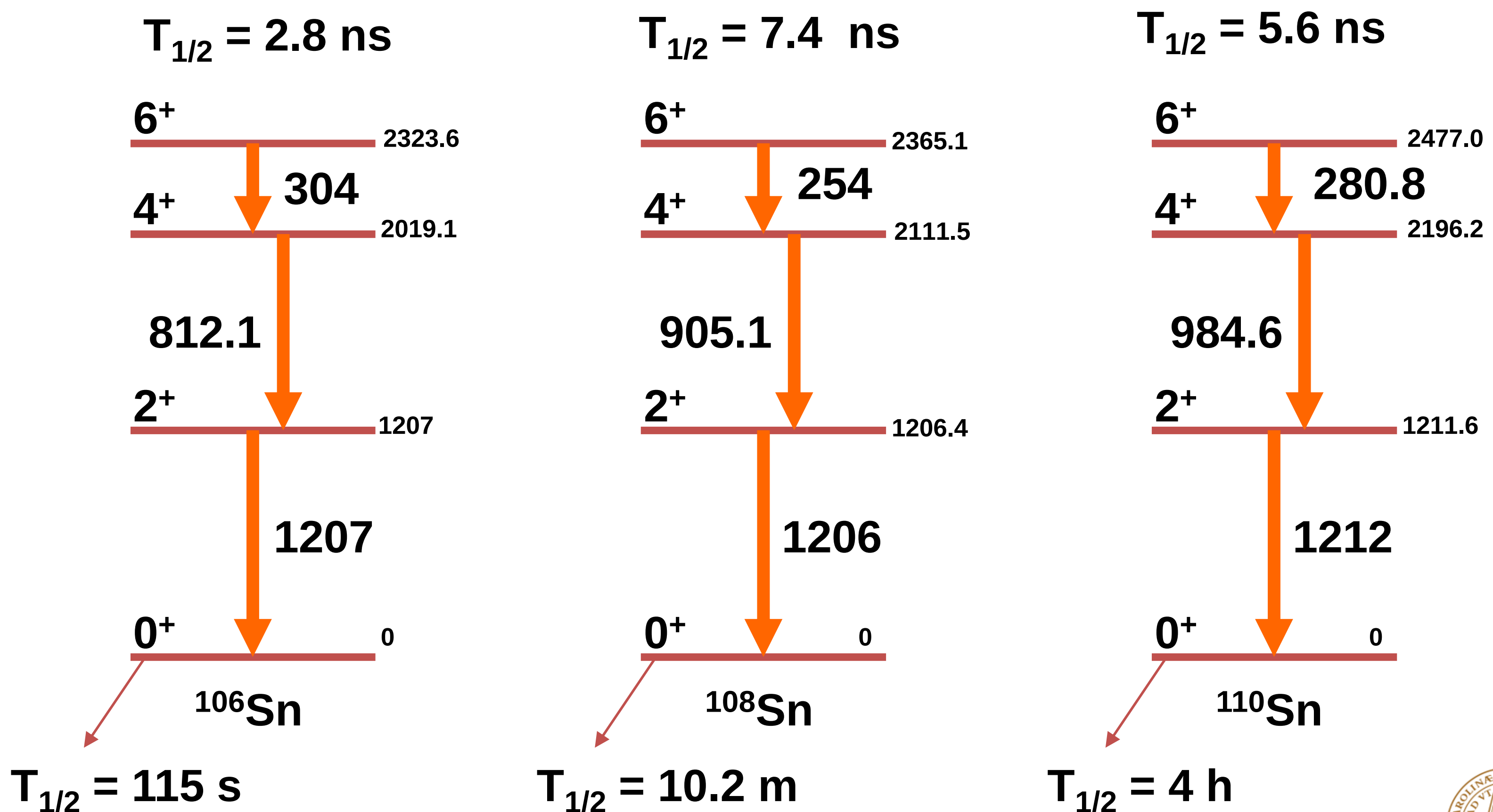
Magnetic transitions reduced: $(v/c)^2$

The Sn chain



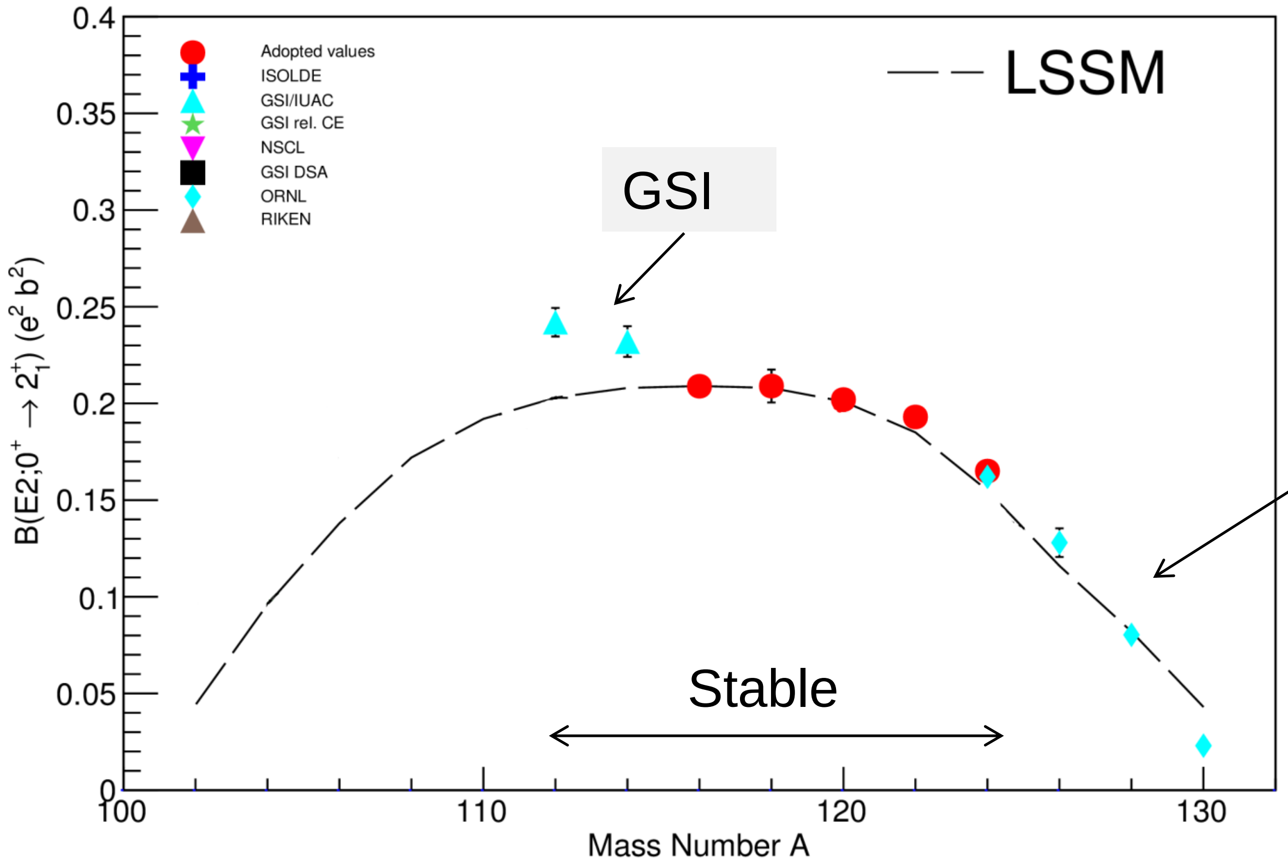
N
v: 1d5/2, 0g7/2, 2s1/2, 1d3/2, 0h11/2
1d5/2
0g7/2
100Sn 0.9 s
101Sn 1.7 s
102Sn 3.8 s
103Sn 7.0 s
104Sn 20.8 s
105Sn 32.7 s
106Sn 115 s
107Sn 2.9 m
108Sn 10.3 m
109Sn 18.0 m
110Sn 4.11 h
0g7/2
2s1/2
1d3/2
0h11/2
111Sn 35.4 m
112Sn
113Sn 115.9 d
114Sn
115Sn
116Sn
117Sn
118Sn
119Sn
120Sn
121Sn 27.06 h
0h11/2
122Sn
123Sn 129.2 d
124Sn
125Sn 9.64 d
126Sn 1E5 y
127Sn 2.23 m
128Sn 59.07 m
129Sn 2.23 m
130Sn 3.72 m
131Sn 56..0 s
132Sn 39.7 s
0h11/2 2.6
1d3/2 2.2
2s1/2 1.6
0g7/2 0.17
1d5/2 0
v orbit
E (MeV)
Stable isotope
Double shell closure
AX T1/2
Unstable isotope

Why Coulomb excitation?



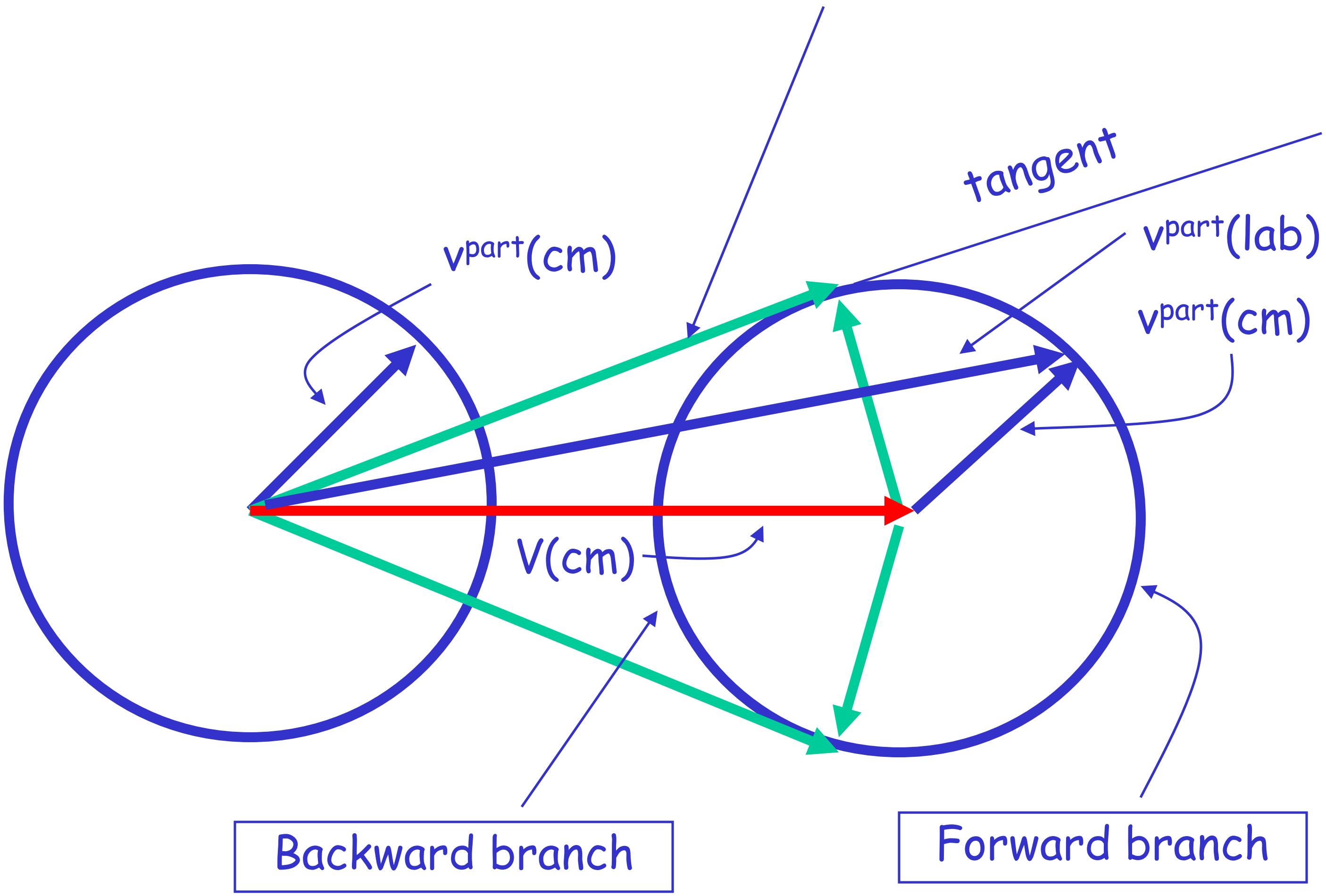
Lund University

B(E2) – evolution of data 2005 to 2017



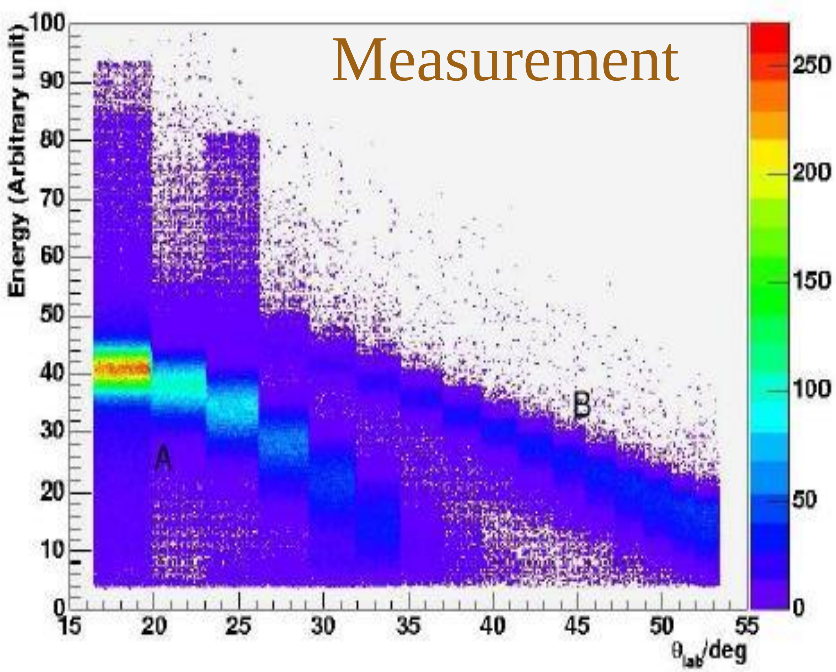
Kinematics – channel identification

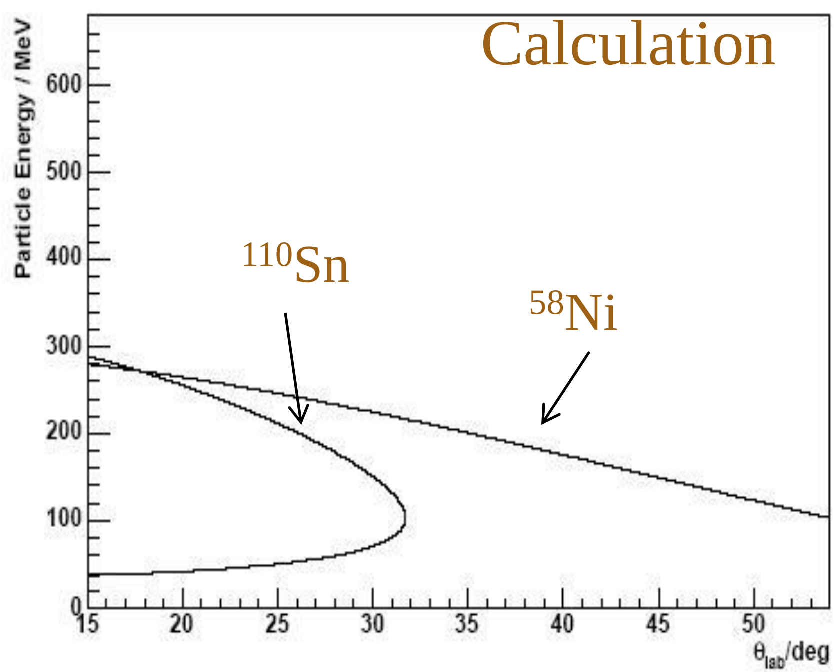
Galilean transformation → Max scattering angle



Kinematics - compared to calculation

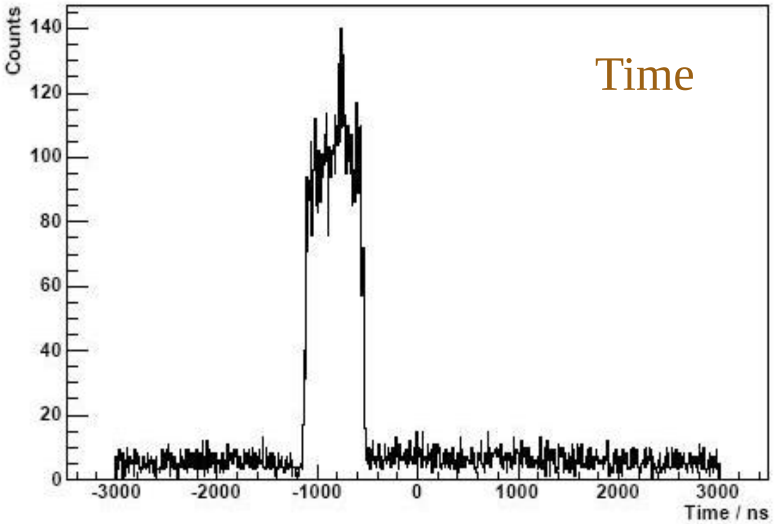
^{110,108,106}Sn on ^{58}Ni at 2.8 MeV/u

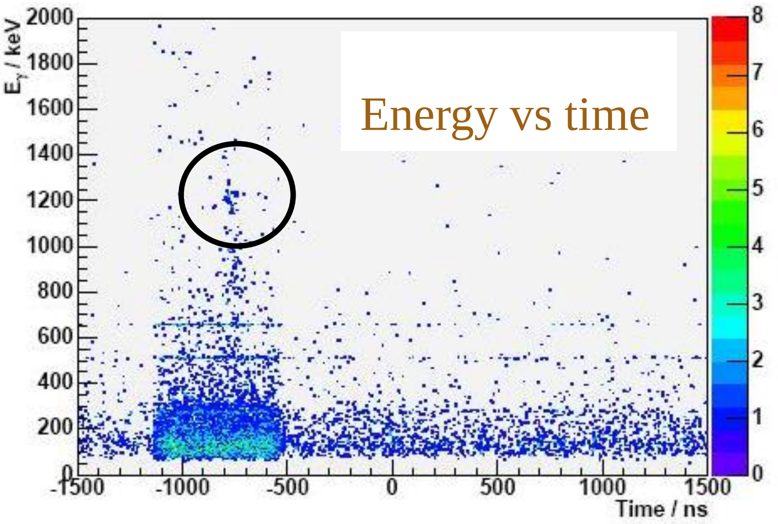


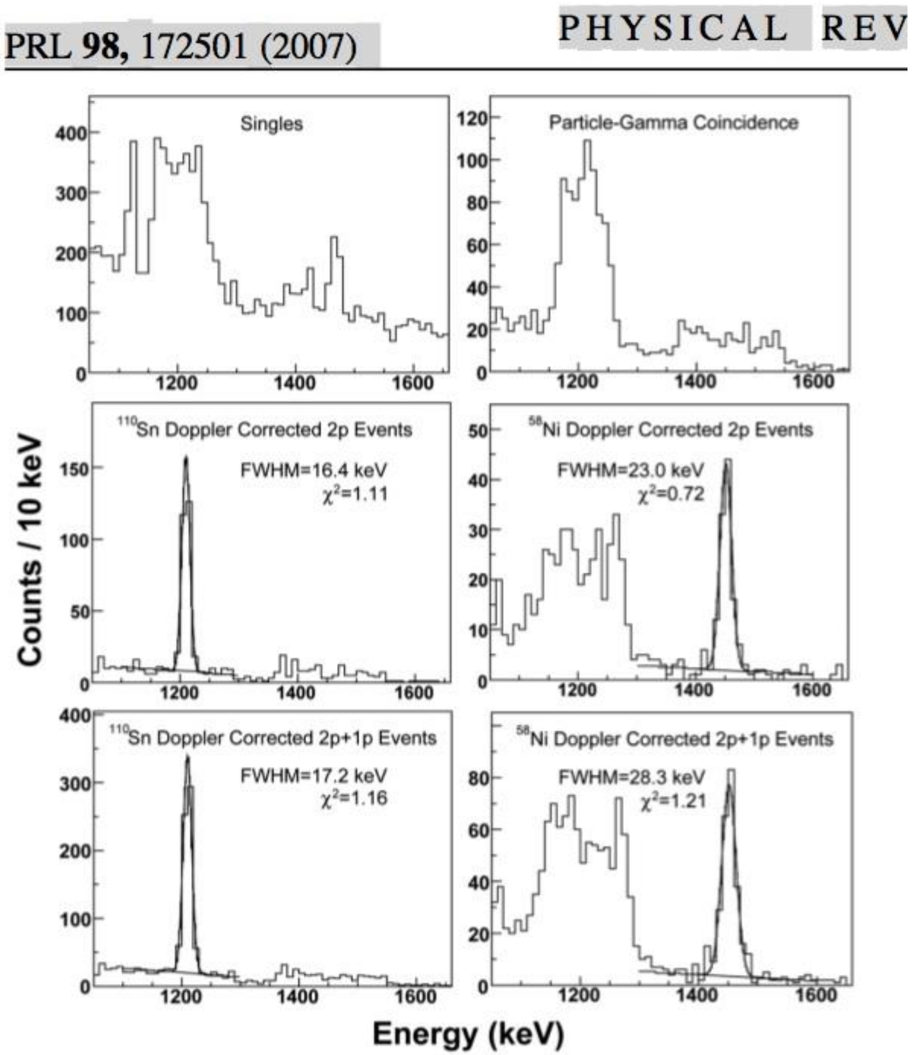


Energy in lab vs scattering angle

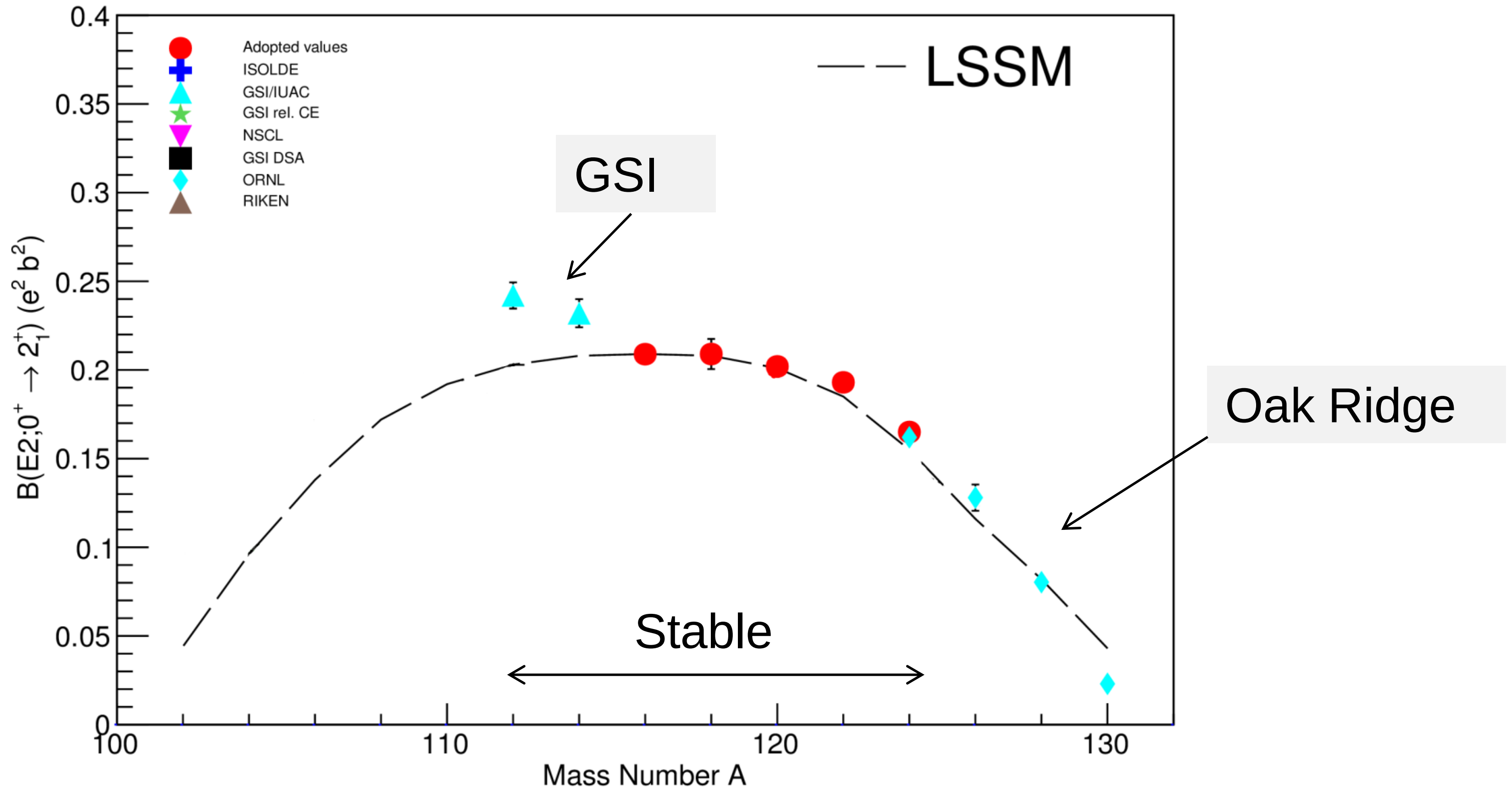
Particle – γ coincidence and Doppler shift



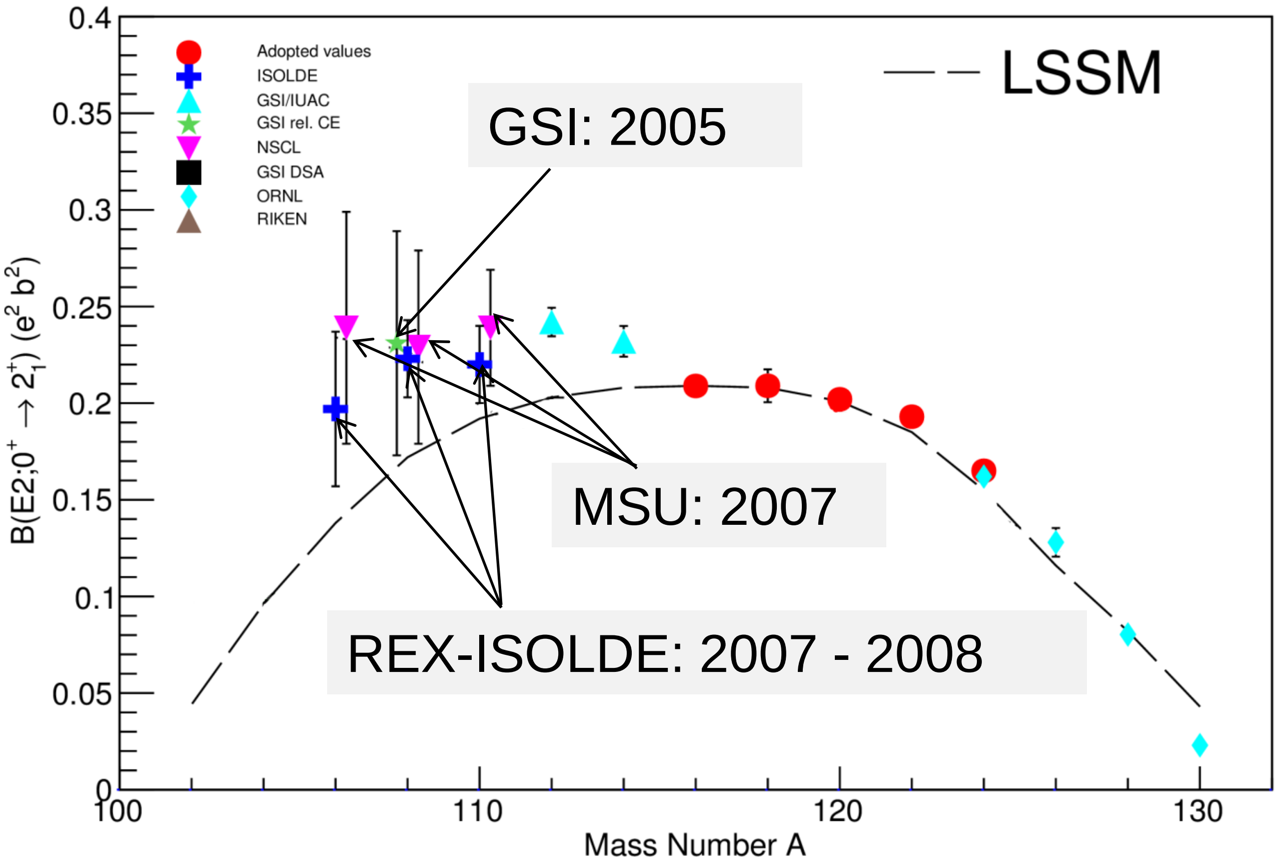




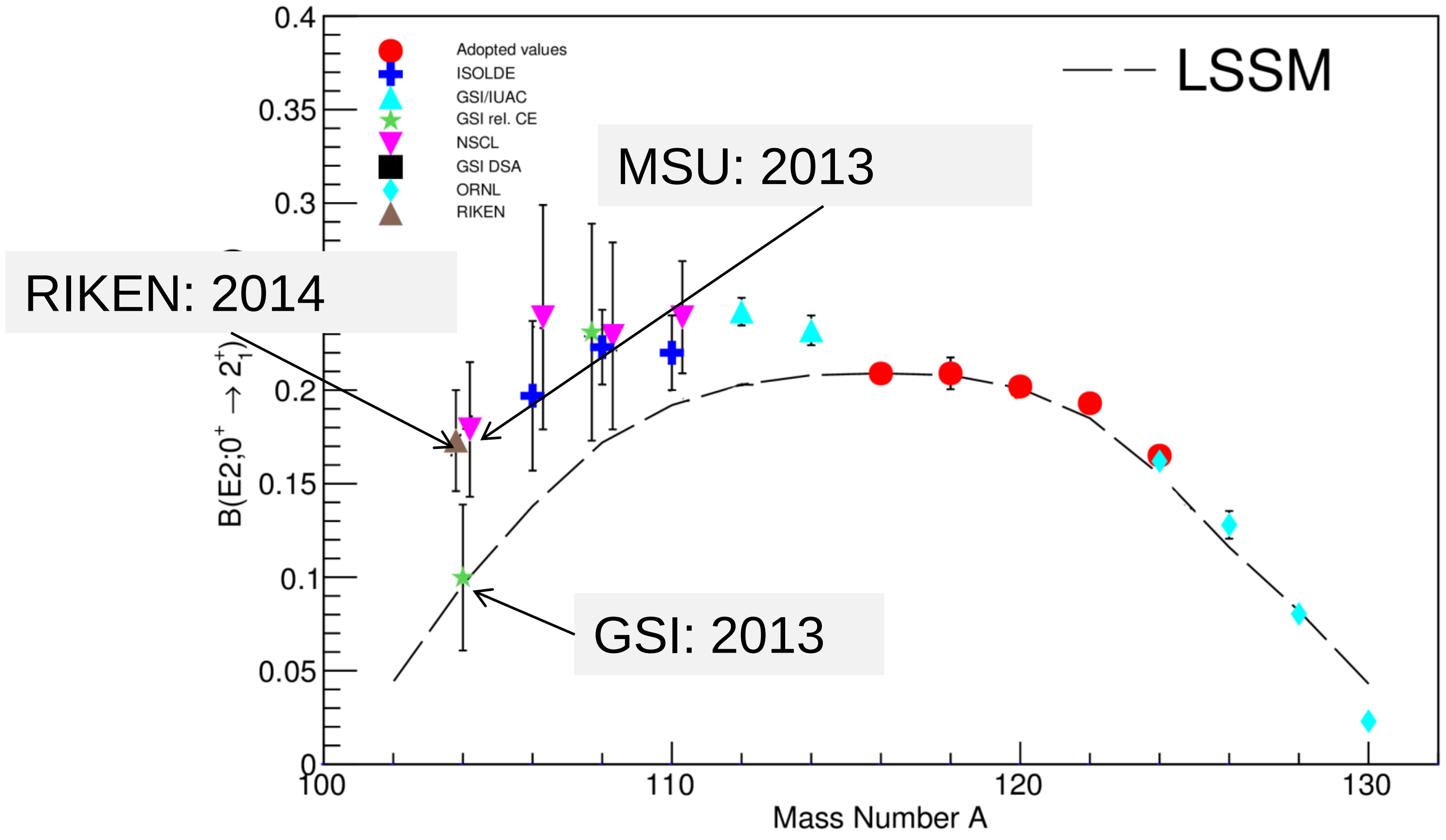
B(E2) – evolution of data 2005 to 2017



B(E2) – evolution of data 2005 to 2017

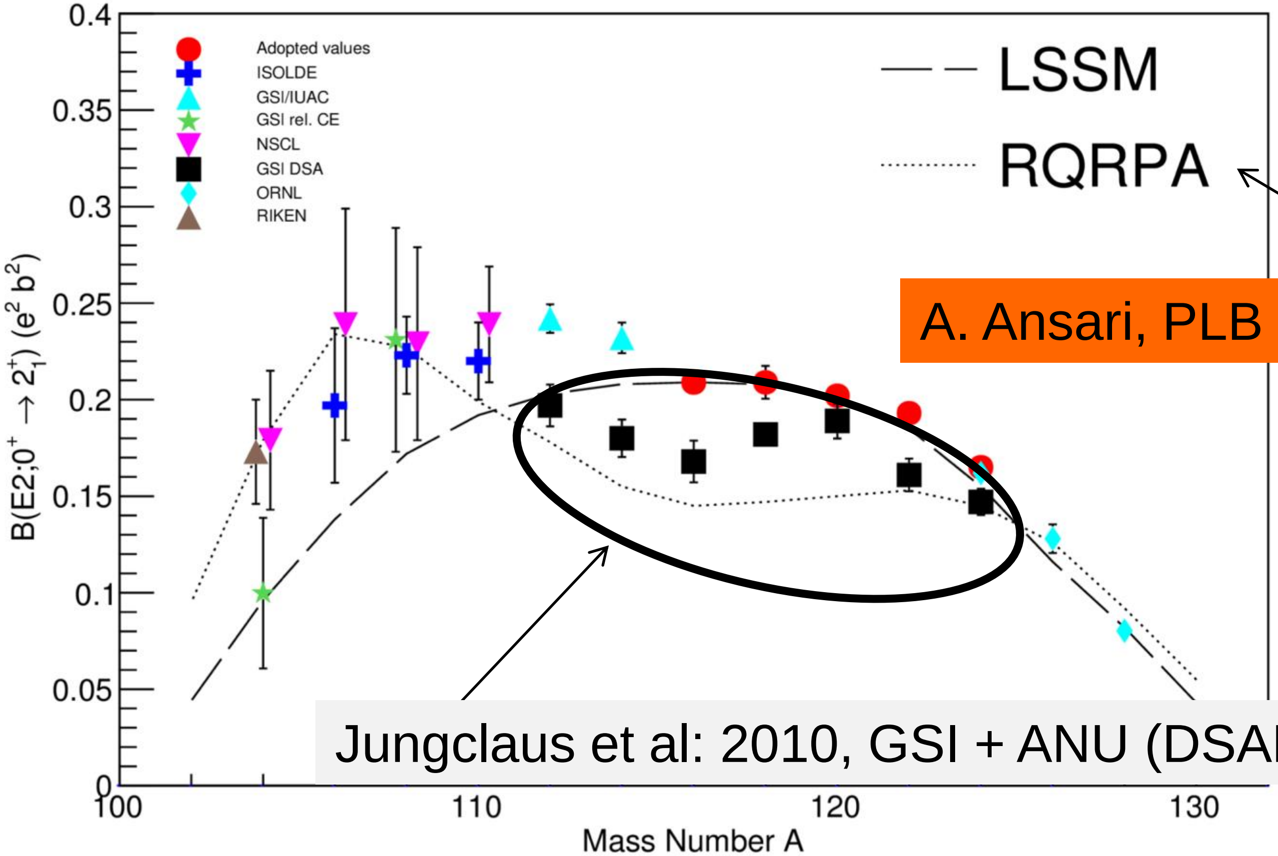


B(E2) – evolution of data 2005 to 2017



2016: Multinucleon transfer at GANIL (J. J. Dobon Valiente)
Experiment for ^{102}Sn approved at RIKEN (L. Cortes et al.)

P A Butler et al 2017 J. Phys. G: Nucl. Part. Phys. 44 044012



A. Ansari, PLB 623 (2005) 37

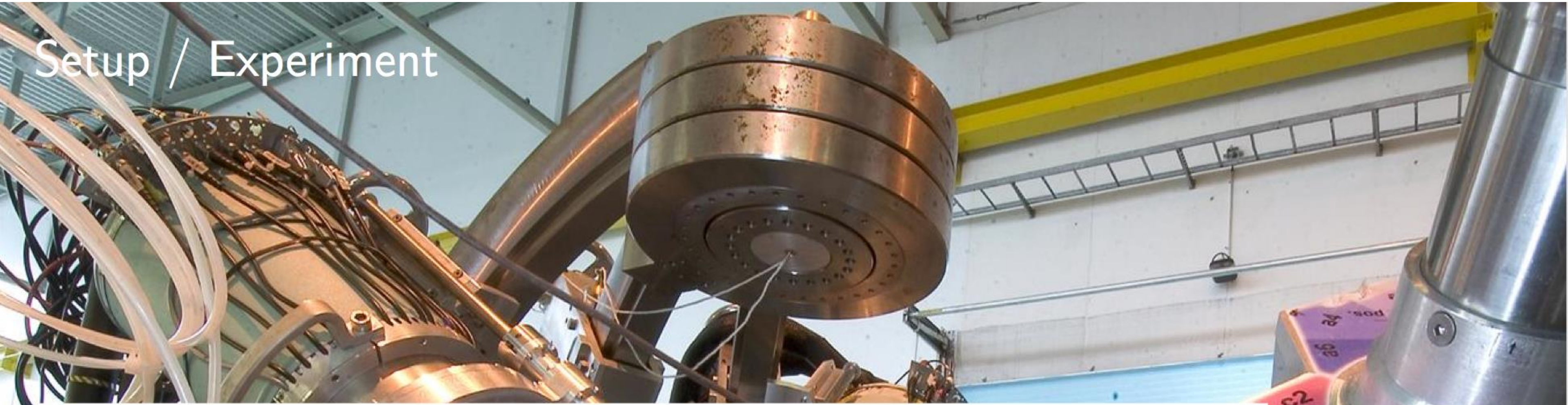
Jungclaus et al: 2010, GSI + ANU (DSAM)

General seniority:
I. Morales et al , PLB 703 (2011) 606

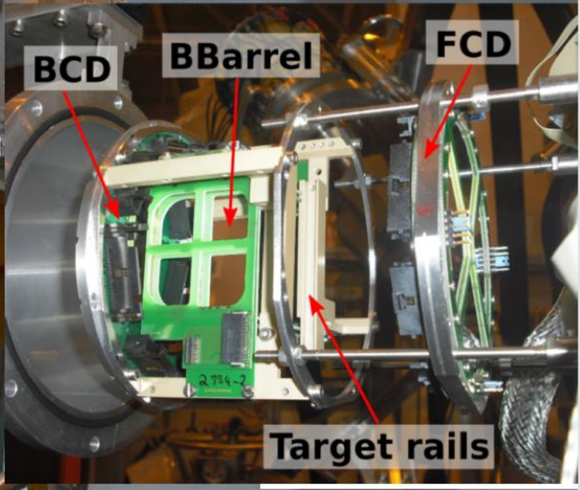
What to do to improve?

- **Reduce statistical error to be in line with stable beam Coulomb excitation.**
- **Try to measure life times using Doppler shift methods and compare for unstable isotopes**
- **Expand life times measurements to higher lying states**
- **Investigate influence of $Q(2^+)$ (if possible)**

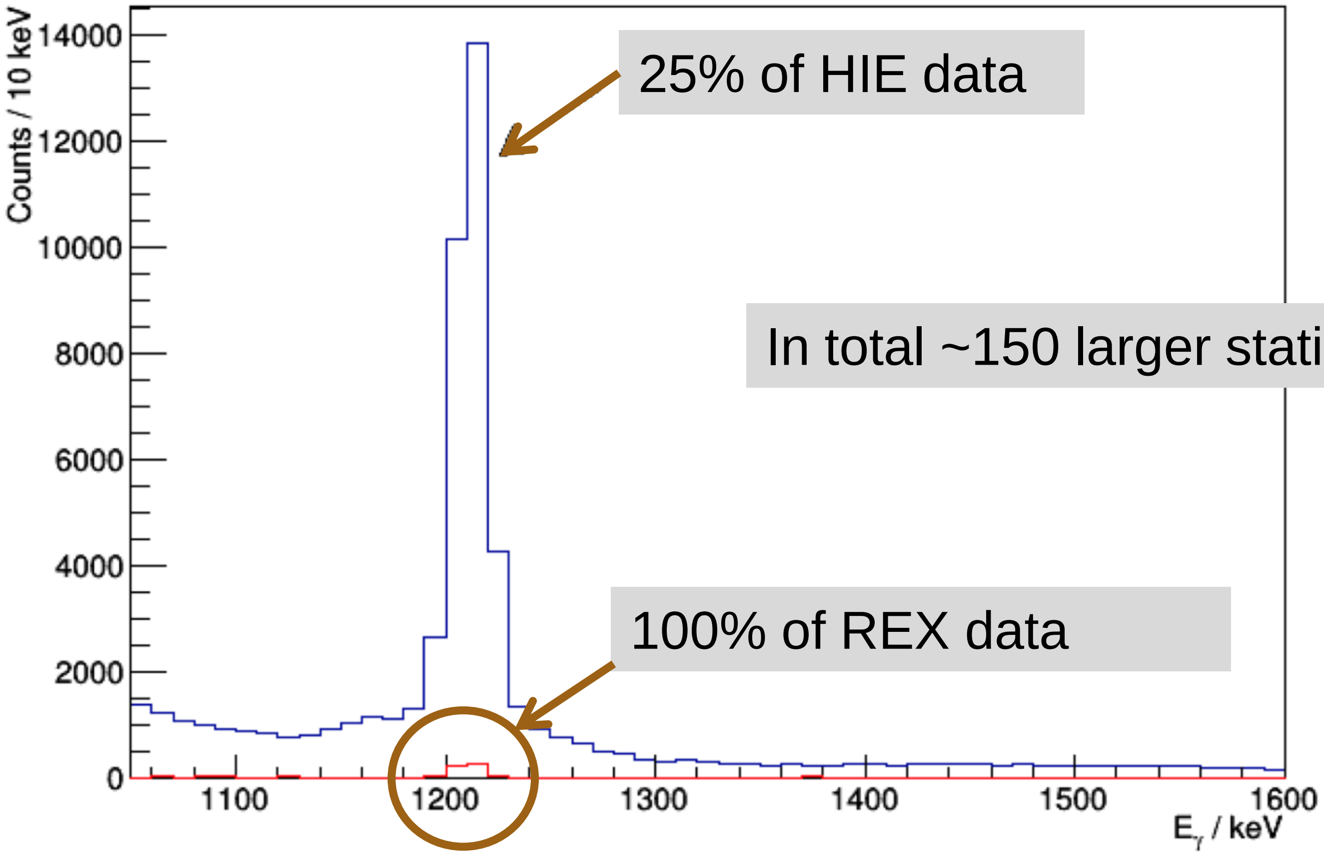
Setup / Experiment



- MINIBALL (24 active crystals)
- C-REX, forward DSSSD covering $20^\circ - 60^\circ$
- ^{110}Sn beam 4.4 MeV/u
- 4 mg/cm^2 ^{206}Pb target ($E_{2^+} = 805$ keV)



Sn-110: 2^+ to 0^+ compared to REX-ISOLDE?



25% of HIE data

In total ~150 larger statistics

100% of REX data

Conclusions (specific)

- **Reduce statistical error to be in line with stable beam Coulomb excitation.**
- **Try to measure life times using Doppler shift methods and compare for unstable isotopes**
- **Expand life times measurements to higher lying states**
- **Investigate influence of $Q(2^+)$ (if possible)**

Conclusions

- **Radioactive beam physics covers a wide spectrum of physics cases from nuclear astrophysics to fundamental symmetries**
- **Two main methods exist to produce isotopes far from stability for reaction studies: the ISOL and in-flight methods**
- **New in-flight facilities include FAIR in Europe, FRIB in the USA and RIBF in Japan**
- **New ISOL facilities includes HIE-ISOLDE at CERN, ISAC2 and Ariel at TRIUMF, Canada.**

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Collaboration

Christoph Berger, Christian Berner, Tom Berry, Maria J. Borge, Joakim Cederkall, Daniel Cox, Hilde de Witte, Liam Gaffney, Roman Gernhauser, Tobias Habermann, Anna-Lena Hartig, Corinna Henrich, Andres Illana Sisón, Jedrek Iwanicki, Thorsten Kröll, Paweł J. Napiorkowski, Georgi Rainovski, Peter Reiter, Sudipta Saha, Marcel Schilling, Michael Seidlitz, Jacob Snäll, Christian Stahl, Piet van Duppen, Nigel Warr, Fredrik Wenander et al.

TU München, Germany - University of Surrey, United Kingdom - TU Darmstadt, Germany - CERN-ISOLDE, Switzerland - KU Leuven, Belgium - UW HIL Warsaw, Poland - University of Jyväskylä, Finland - SU Sofia, Bulgaria - University of Cologne, Germany - Lund University, Sweden - CSIC Madrid, Spain

Yacine Kadi, Valter Venturi with the HIE-ISOLDE team and the ISOLDE collaboration

CERN

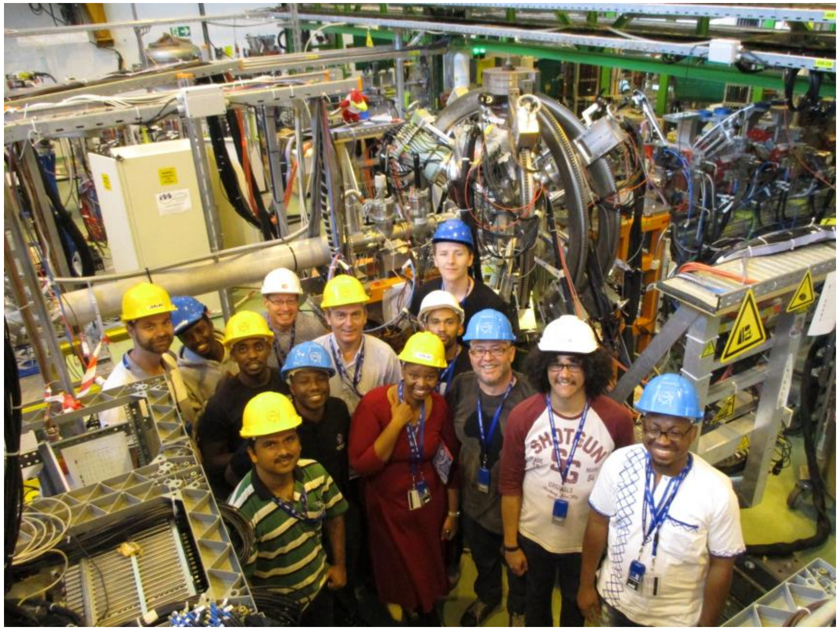
ISOLDE

MINIBALL

LUND UNIVERSITY

For more info about ISOLDE experiments also contact:

Krish Bharuth – Ram et al.
UKZN/DUT
Solid state physics spec. Mössbauer spectroscopy.



Nicolas Orce et al.
University of Western Cape, SA
Experiments at HIE-ISOLDE spec. concerning nuclear shape studies.

ISOLDE

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