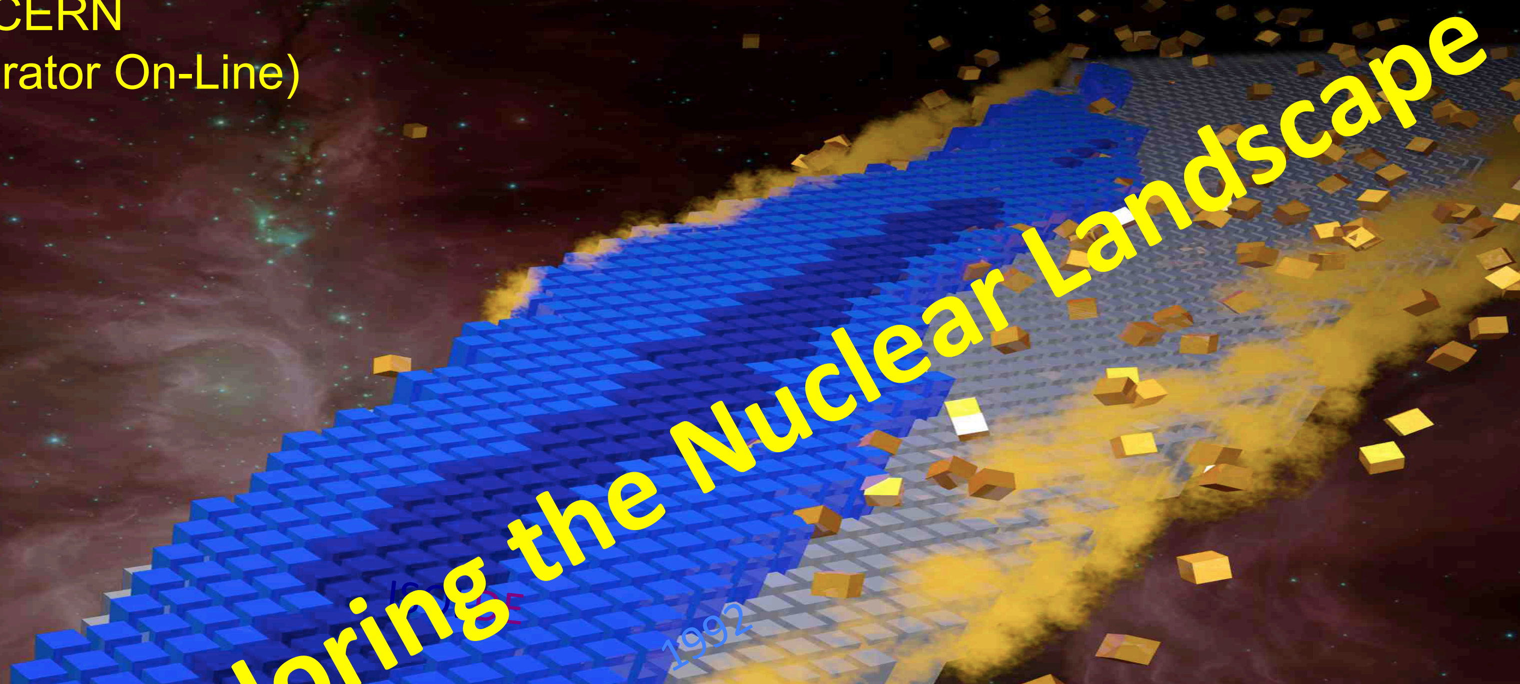
Maria J. G. Borge
ISOLDE-PH, CERN
(Isotope Separator On-Line)

Exploring the Nuclear Landscape



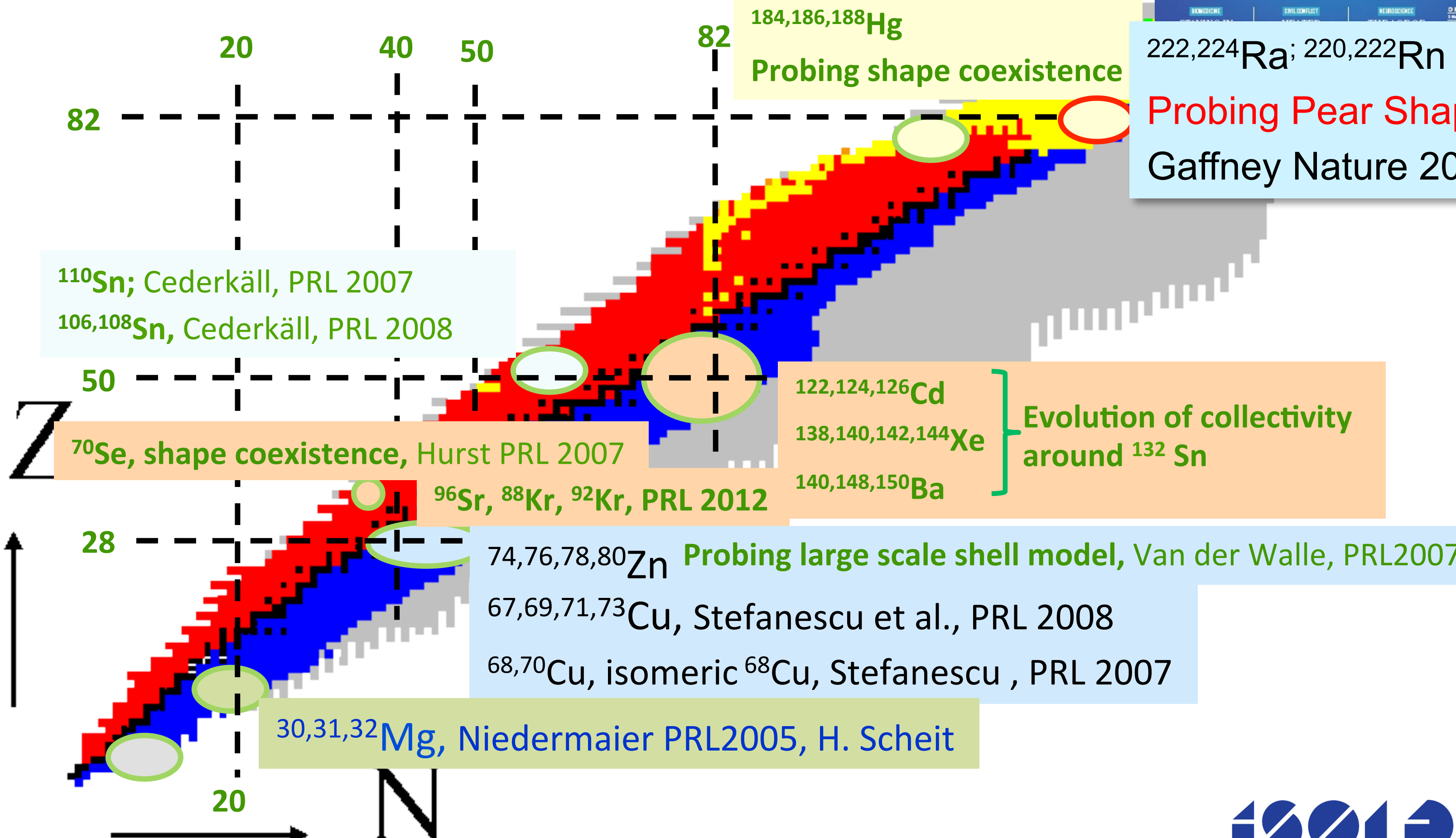
Physics program @ REX

REX-ISOLDE started in 2001

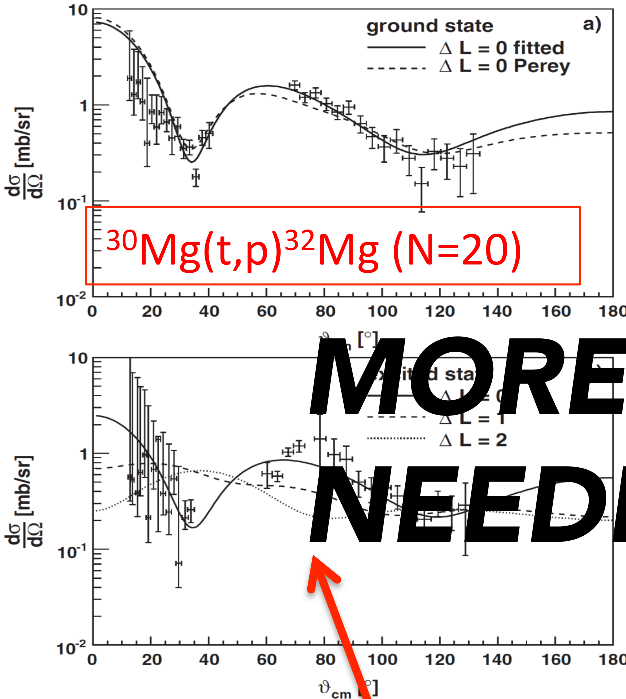
72 different beams already used at REX- ISOLDE of 700 available!

Coulomb excitation with Miniball:

- collectivity versus individual nucleon behaviour

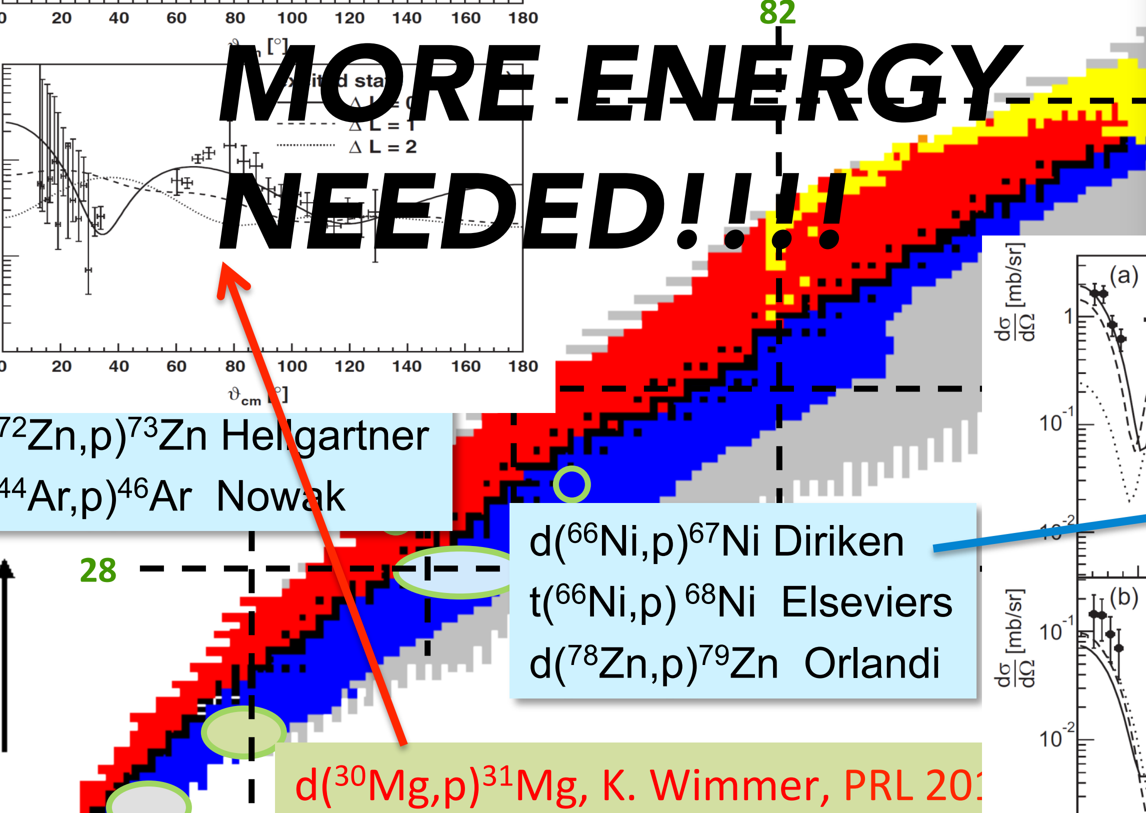


Transfer Reactions @ REX



- …reaction studies:
- …operties
- …structures

MORE ENERGY NEEDED!!!!

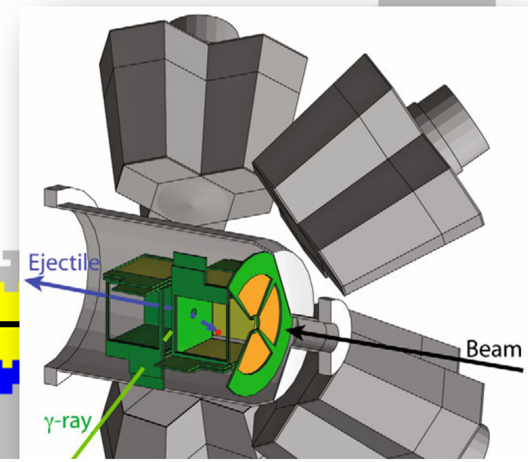


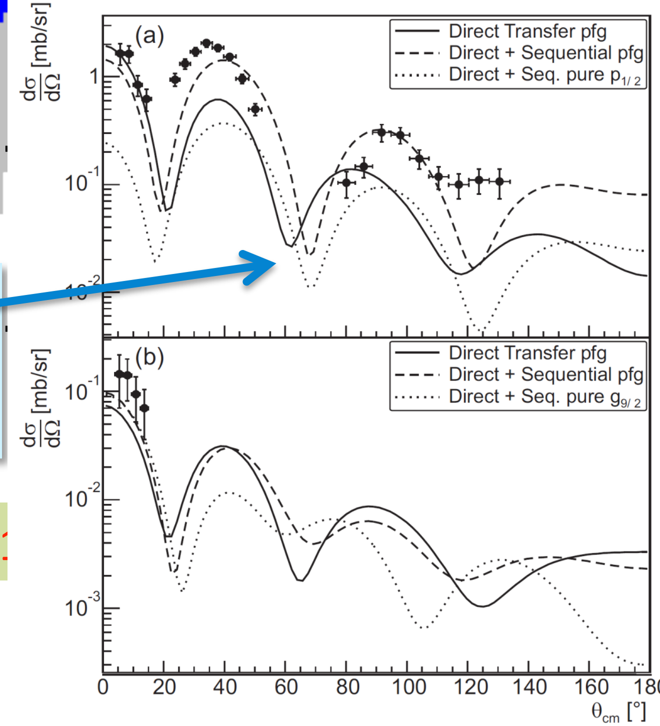
t(^{72}Zn,p)^{73}Zn Hellgartner
t(^{44}Ar,p)^{46}Ar Nowak

d(^{66}Ni,p)^{67}Ni Diriken
t(^{66}Ni,p) ^{68}Ni Elseviers
d(^{78}Zn,p)^{79}Zn Orlandi

d(^{30}Mg,p)^{31}Mg, K. Wimmer, PRL 20…

Light nuclei, halos & clusters
d(^{8}Li,p)^{9}Li*; Tengborn PRC (2011) d(^{9}Li,p)^{10}Li
d(^{11}Be,p)^{12}Be Johansen PRC (2013)





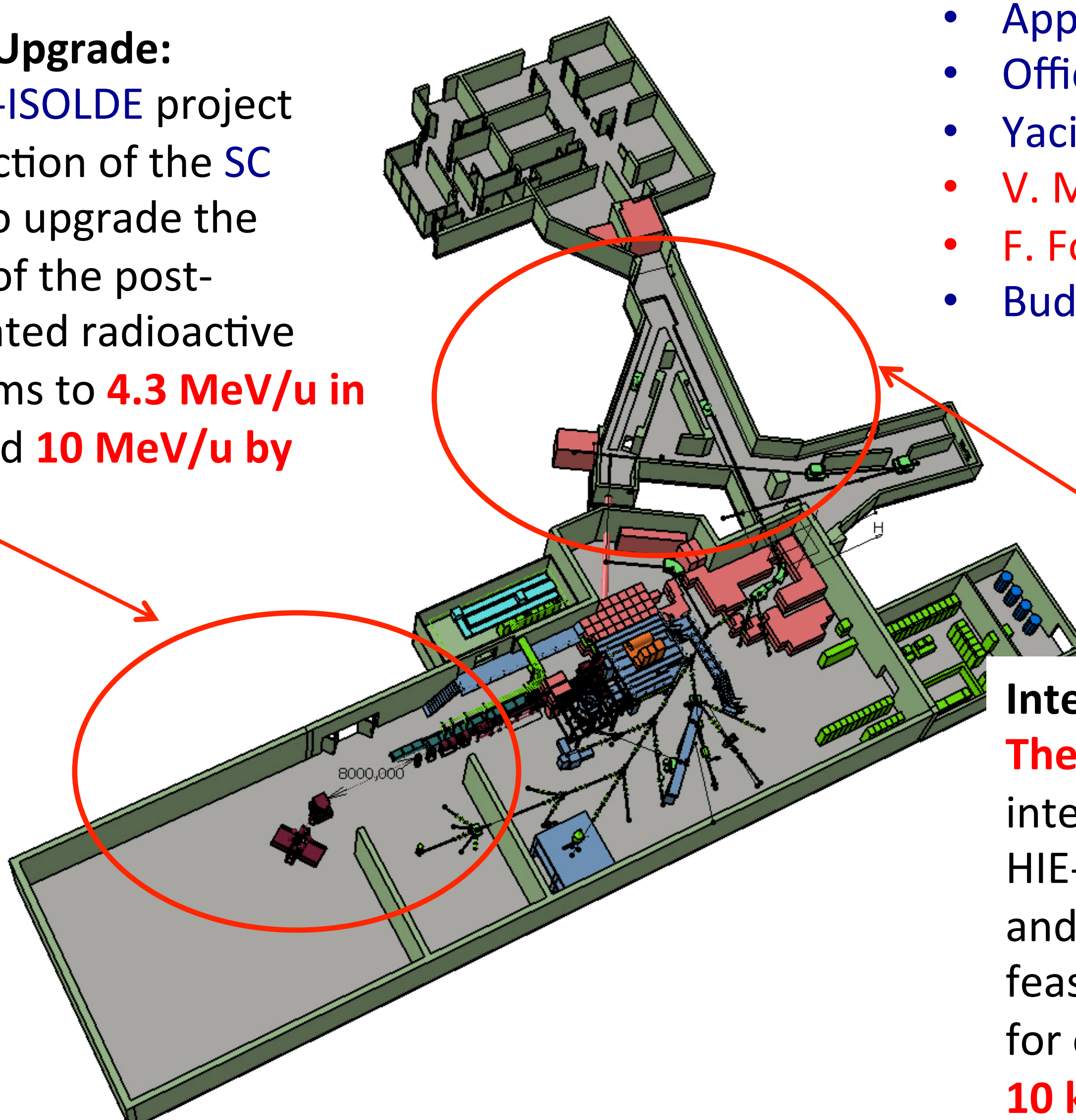
HIE-ISOLDE Opportunities:

Reaction	Physics	Optimum energy
(d,p), (^{3}He,α), (^{3}He,d), (d,n),… transfer	Single-particle configurations, r- and rp-process for nucleosynthesis	10 MeV/u
(^{3}He,p), (d,α), (p,t), (t,p)	pairing	5-10 MeV/u
Few-nucleon transfer	Structure of neutron-rich and proton-rich nuclei	8 MeV/u
Unsafe Coulomb excitation	High-lying collective states	6-8 MeV/u
Compound nucleus reactions	Exotic structure at drip line	5 MeV/u
Coulomb excitation, g-factor measurements	Nuclear collectivity and single-particle aspects	3-5 MeV/u
(p,p'γ), (p,α), …	nucleosynthesis	2-5 MeV/u

Near Future: HIE-ISOLDE project

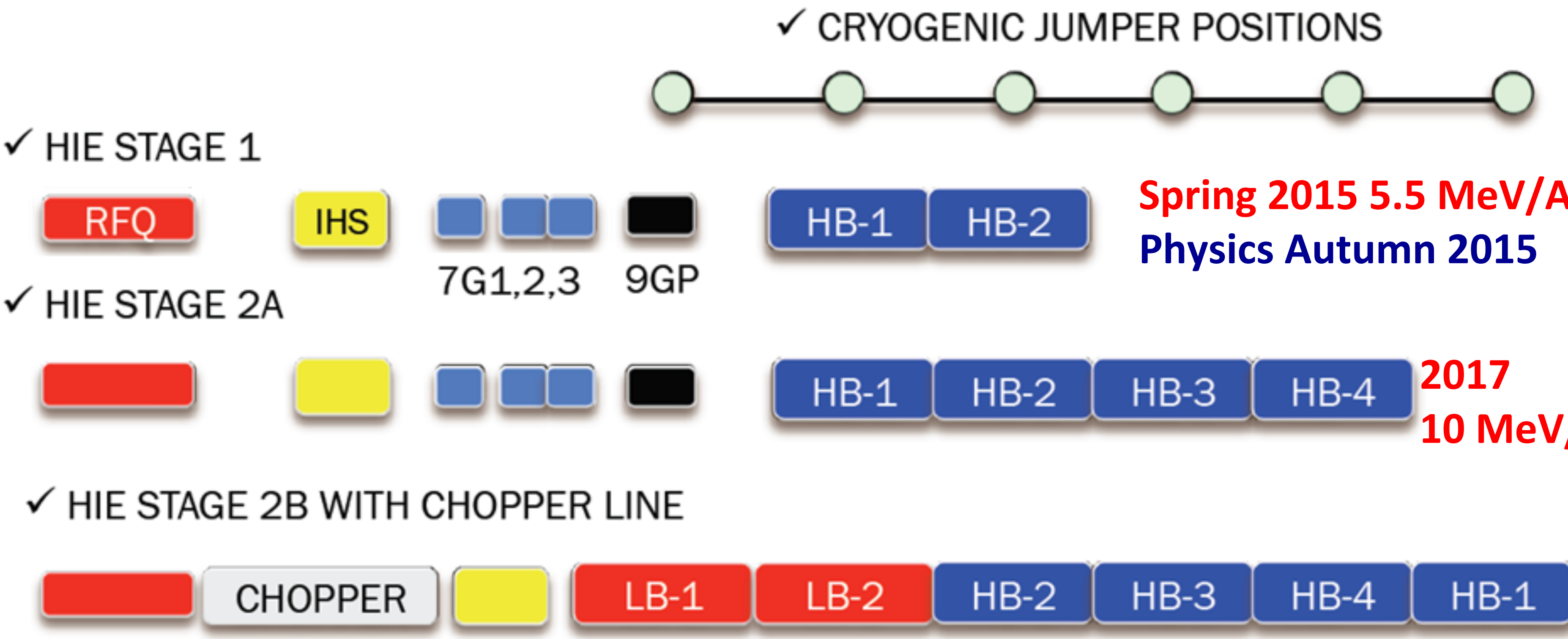
Energy Upgrade:
The HIE-ISOLDE project construction of the SC LINAC to upgrade the energy of the post-accelerated radioactive ion beams to **4.3 MeV/u in 2015** and **10 MeV/u by 2017**

- Approved Dec 2009
- Offically started Jan 2010
- Yacine Kadi project Leader
- V. Mertens Project Monitoring
- F. Formenti Technical Coord.
- Budget 43 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 are online.

SC-LINAC Installed in 3-phases



Spring 2015 5.5 MeV/A

Physics Autumn 2015

2017

10 MeV/A

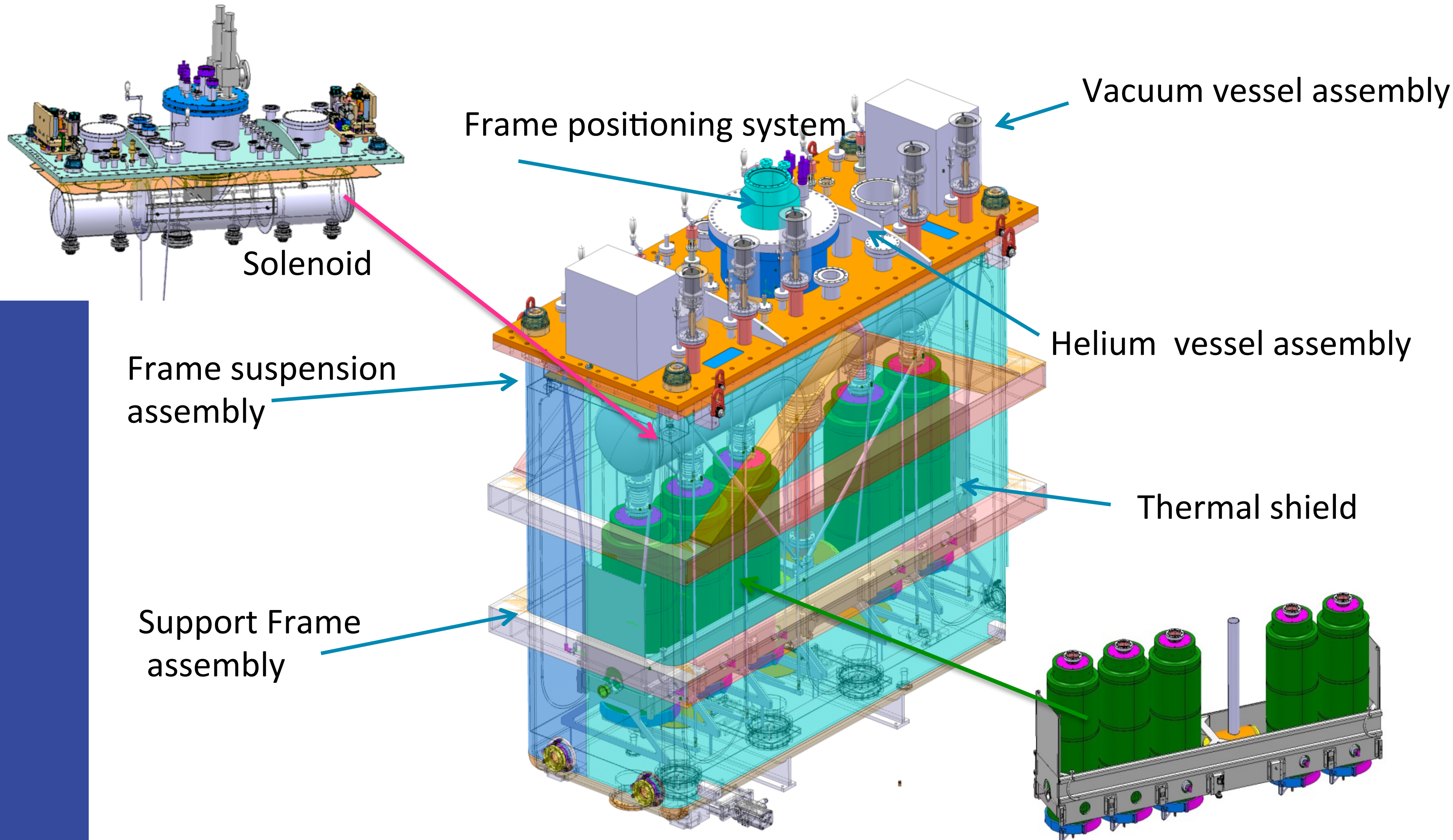
2018 (LS2)

Period 100ns

Resolution 1-2 ns

Background < 1%

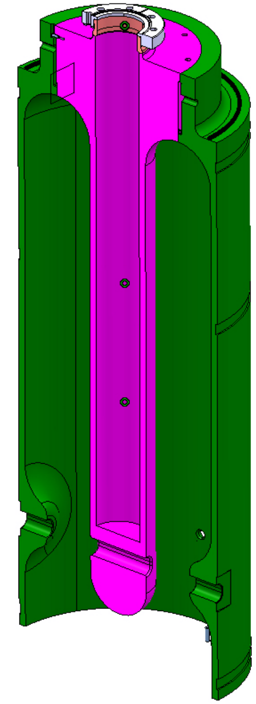
High-β Cryomodule sub-elements



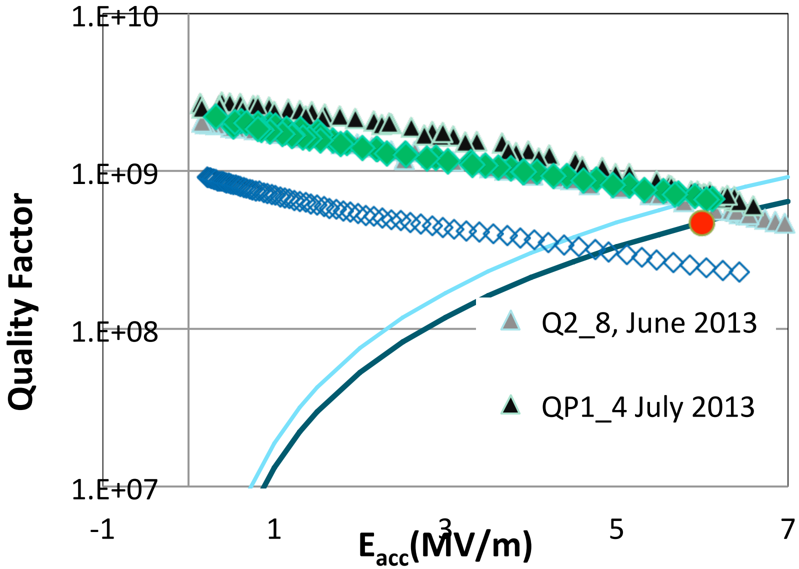
Cavity prototypes designed & built @ CERN

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

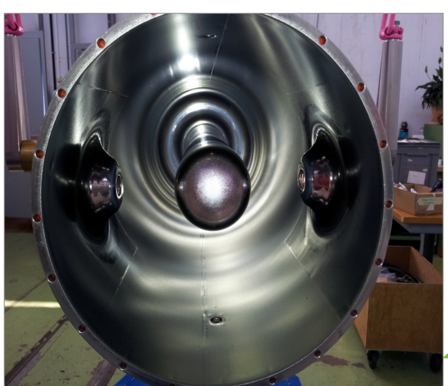
Highly demanding: acceleration gradient 6 MV/m with power consumption of 10 W

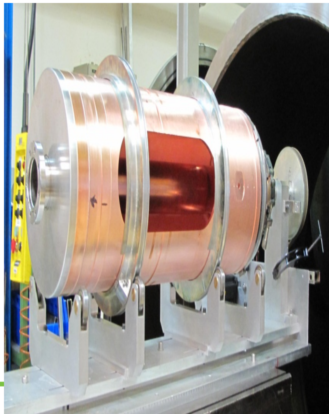


¾ Cavities performing beyond spec

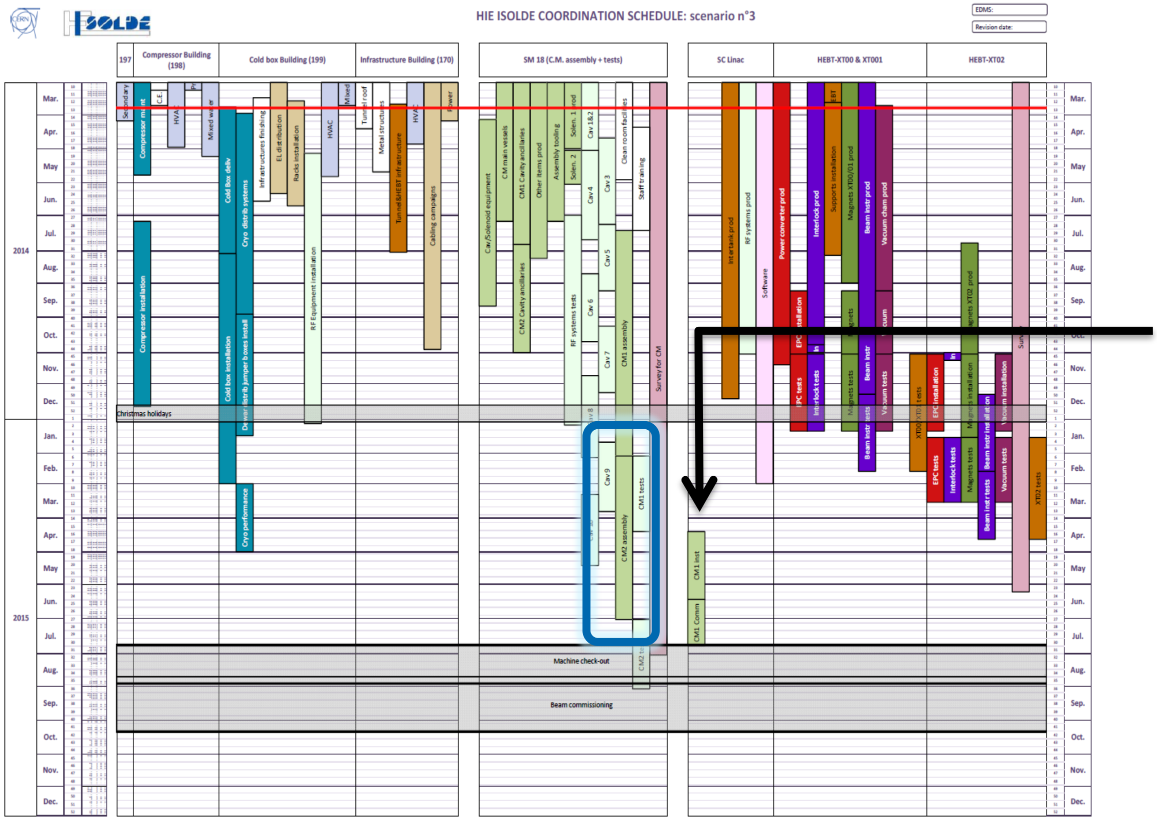


- 1 cavity (Q4) manufactured for sputtering tests on samples





Present Status

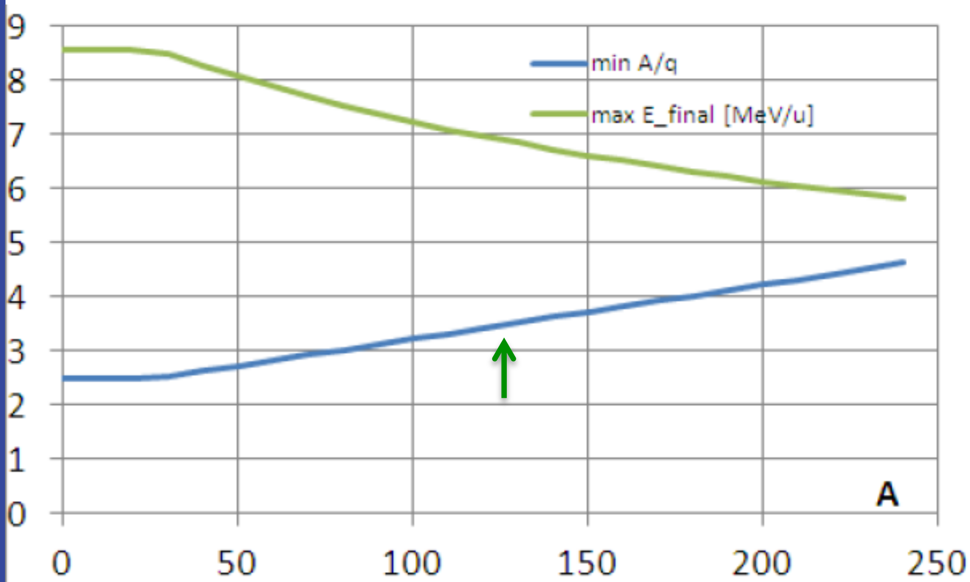


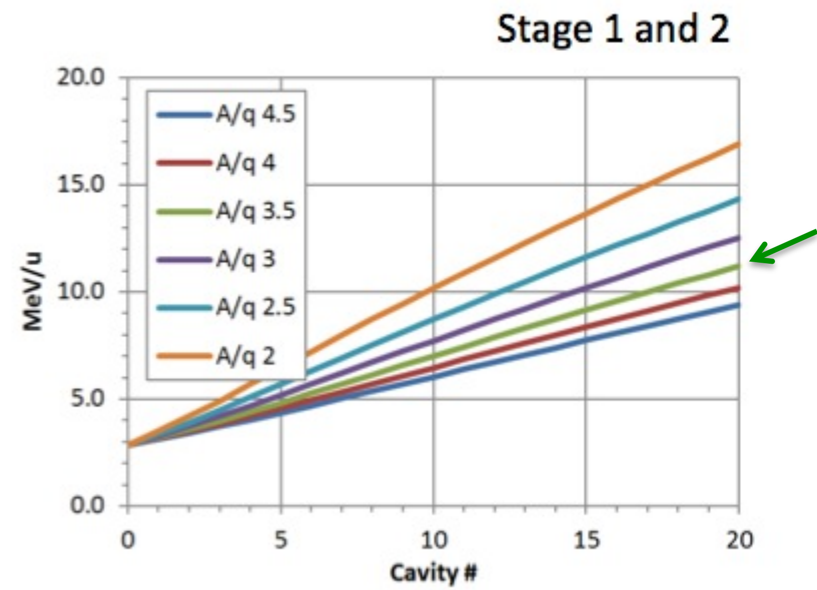
One cryo module installed to ensure physics in October 2015

is compatible with the layout and the initial requirements for physics (4.3 MeV/u)

Beam Parameters

- A/q = 4.5 and energy 5.5 MeV/u are the nominal parameters of the facility.
- Higher energy and lower A/q → Decrease in efficiency
  Increase in breeding time





E_final = 2.9 + 14/(A/q) [MeV/u]

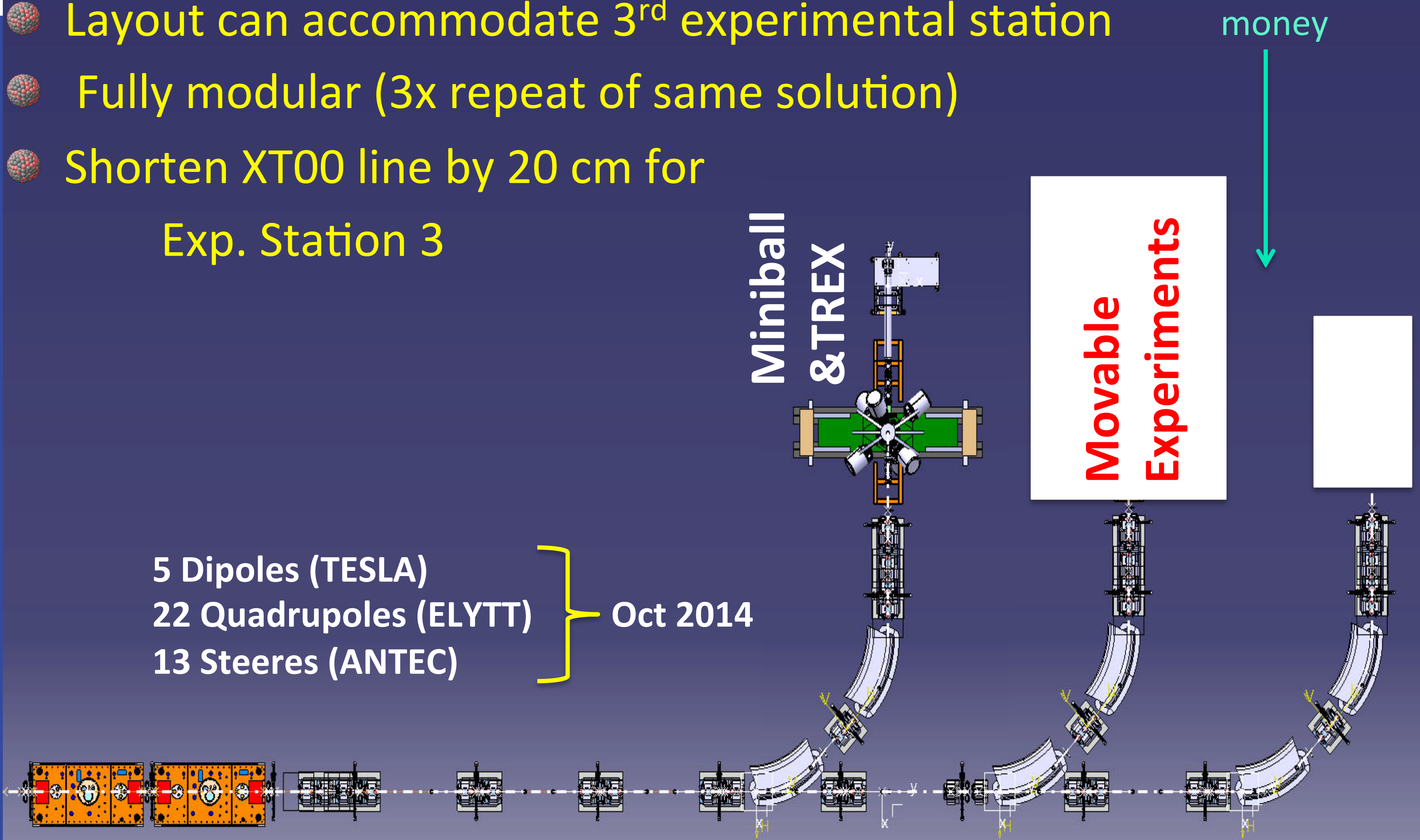
Assuming 6 MV/m

A/q = 4.5 E =1. 2 – 5.5 MeV/u
A/q = 2.4 E= 1.2 - 8.6 MeV/u

Proposed three beamlines

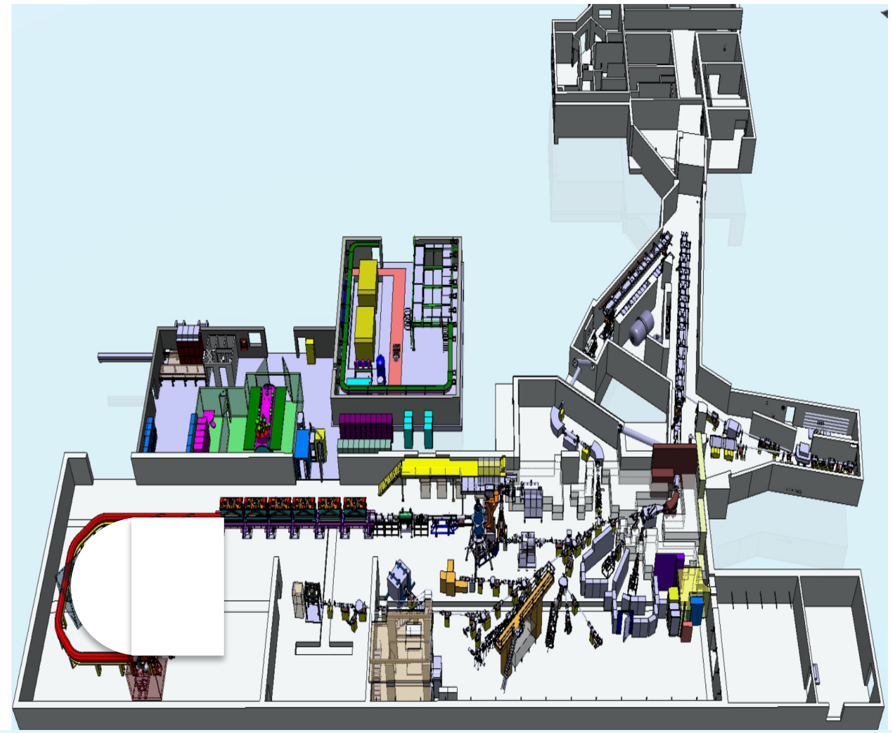
- Layout can accommodate 3rd experimental station
- Fully modular (3x repeat of same solution)
- Shorten XT00 line by 20 cm for

  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 ($3.3x10^{13}$)

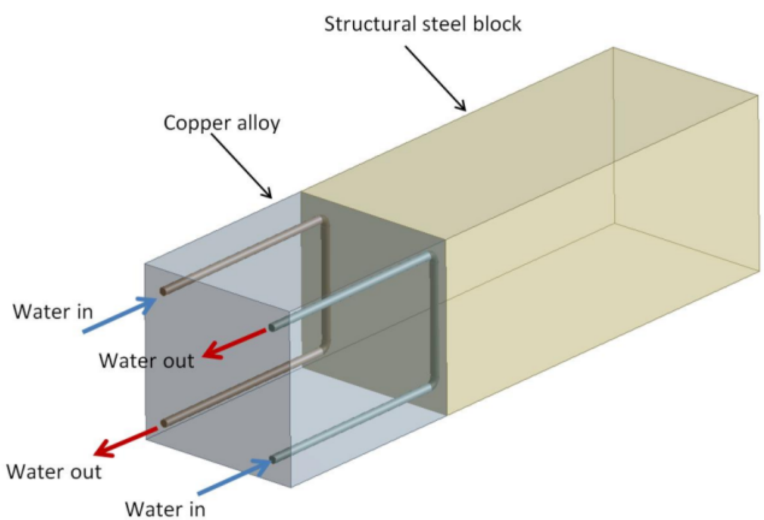
2GeV beam energy (1.4GeV)

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

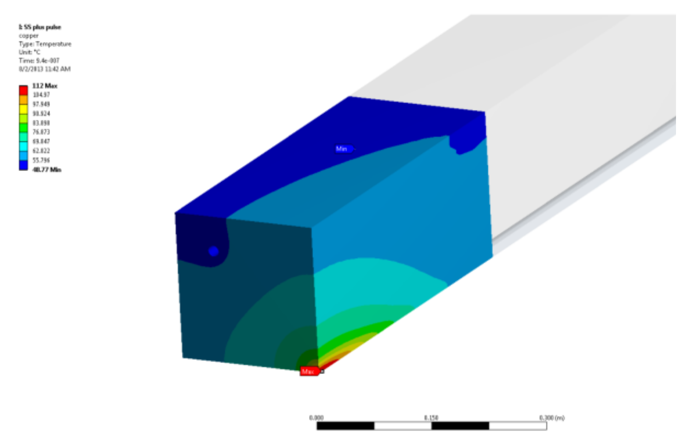
HRS and GPS dumps

- Present design study → beam upgrade will damage the dump
- Design proposed → active cooled CuCrZr block in front of old dump
- Max temperatures and stresses are below the material limits for a 2.0 GeV beam

New Design



Thermal Analysis

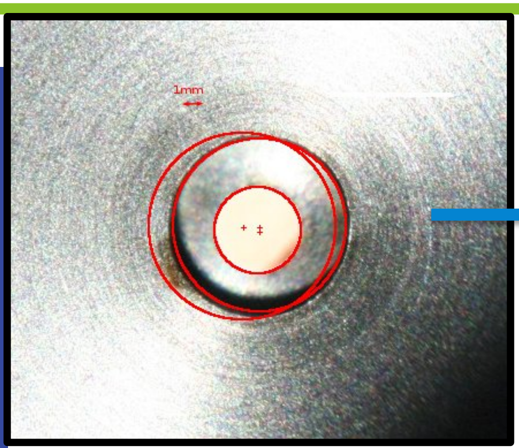


High Energy Compression and Current (HEC²) EBIS

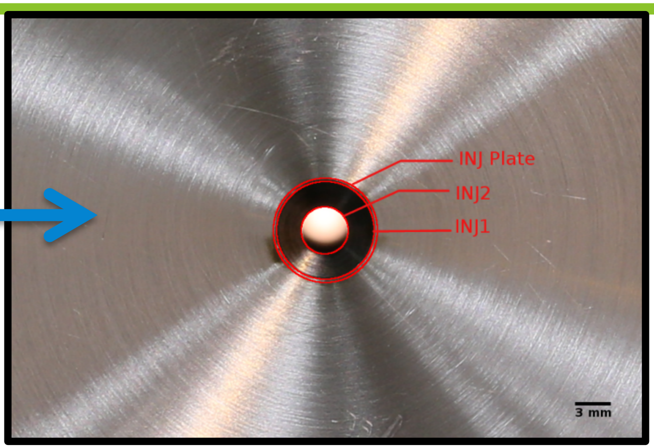
EBIS parameters	REXEBIS (Now)	HEC² for HIE-ISOLDE	HEC² II for TSR@ISOLDE	Demonstrated (Nov 2013)
Electron energy [kV]	5	60	150	30
Electron current [A]	0.2	3-4	4-5	1.54
Electron current density [A/cm²]	100	$1\text{-}2 \times 10^4$	$1\text{-}2 \times 10^4$	NA

- HEC² gun built at CERN, shipped to BNL and installed on Test EBIS
- HEC² gun first operated at BNL in Nov 2013 on the real EBIS
- Energy up to 30 keV and current up to 1.54 A were achieved in ~ 10 ms pulses
- Diagnostic tools to measure the current density were set up for the next visit
- The test stand is upgraded to enable higher current
- Extended set of diagnostic tools is in production at CERN

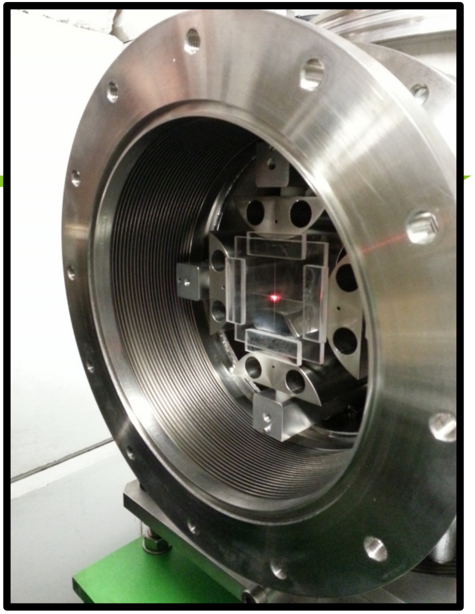
ISCOOL



Measured misalignment of the injection (top) and extraction electrodes was 0.75mm



Results of the internal realignment for the injection and extraction electrodes to a precision of 0.1mm

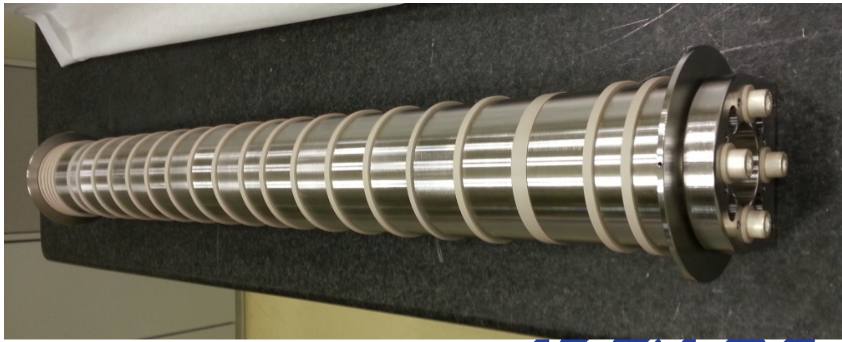


External alignment was done by aligning both sides of ISCOOL to the beamline quadrupole triplets, using a RILIS laser and the target

- **Construction of new RFQCB:**

✓ All parts needed for setup in the test stand have been received, or are in the workshop.

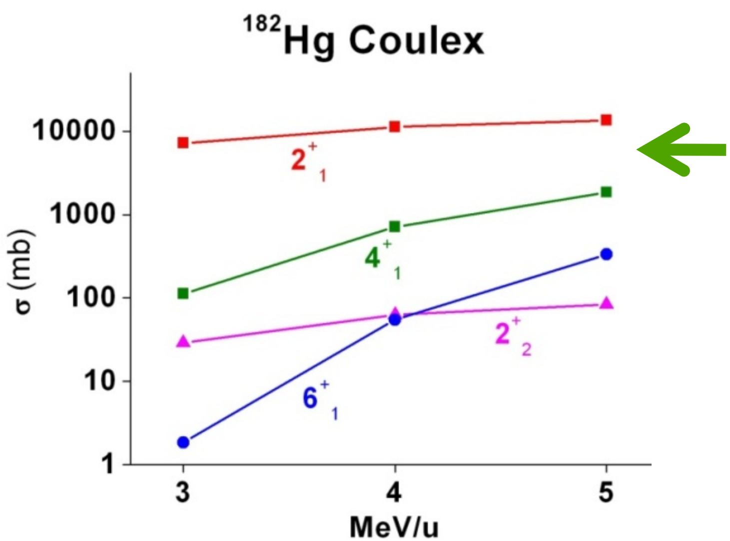
Installation will begin in the next months.



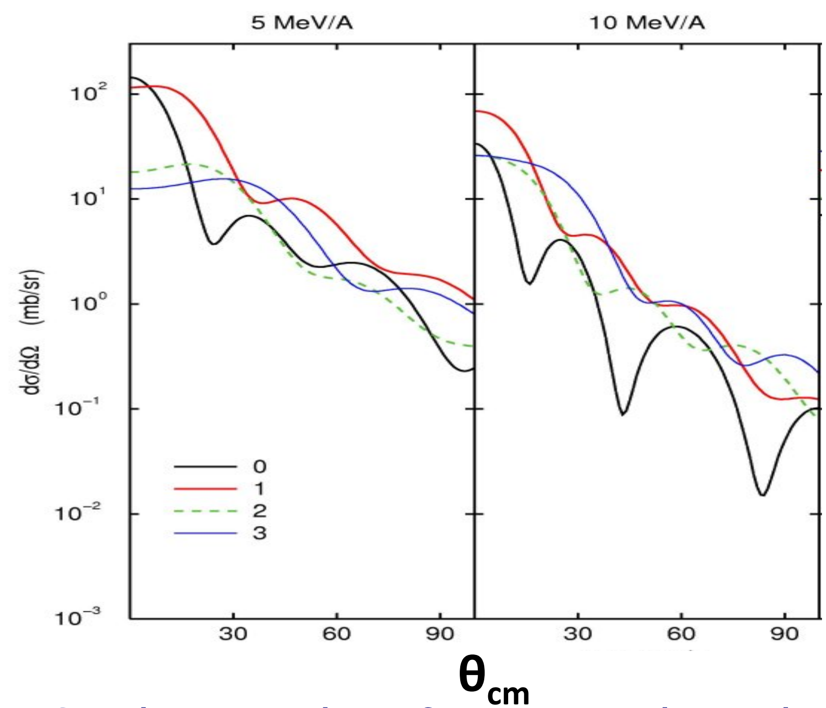
Advantages of HIE-ISOLDE

Intensity & Selectivity & Beam quality & Efficiency

Energy upgrade to 5.5 MeV /A → 10 MeV /A



$^{32}Mg(d,p)^{33}Mg$



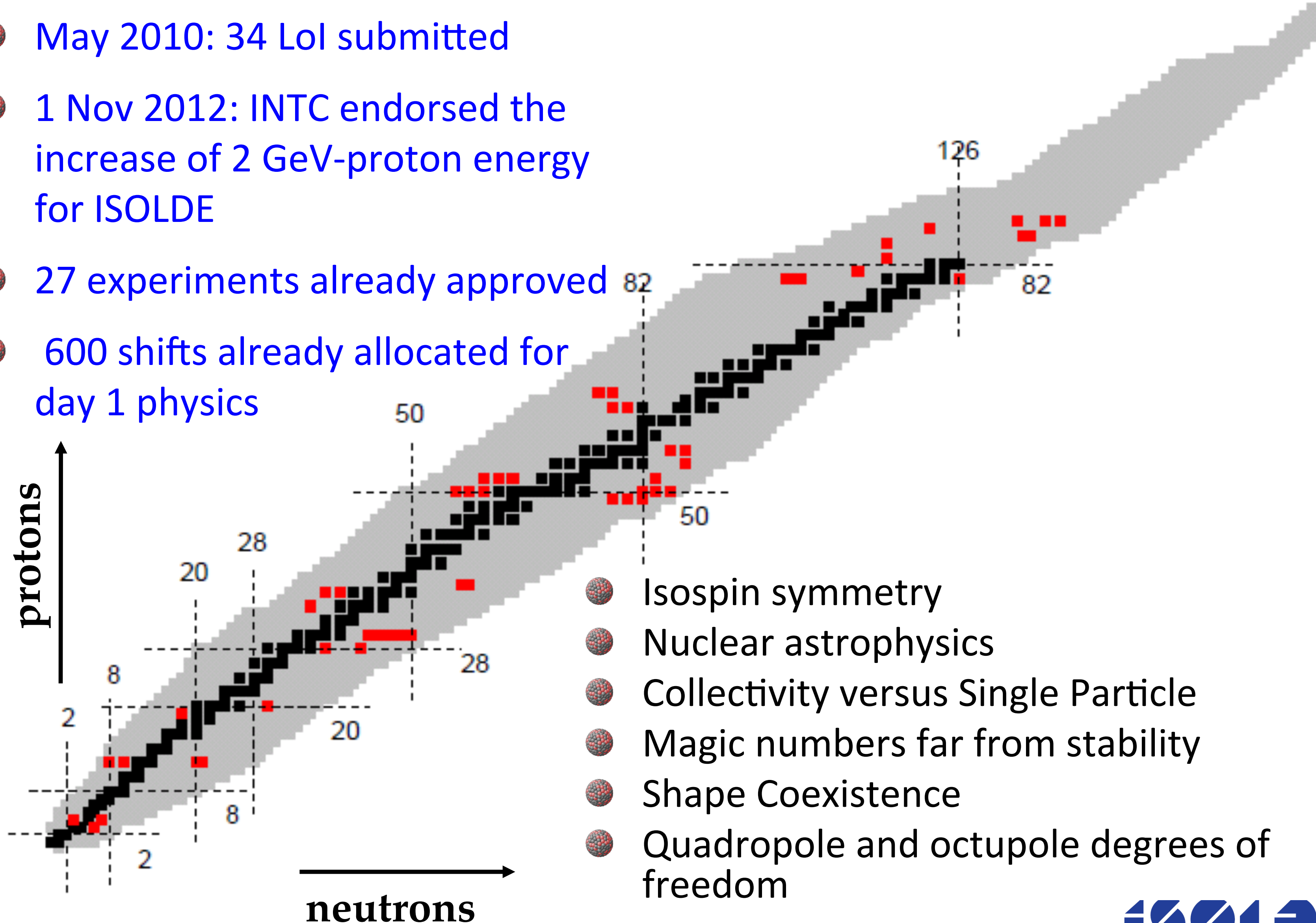
- ❑ Access to a wealth of spectroscopic information
- ❑ From the absolutes intensities of $4^+/2^+$ (multistep coulex)

⇒Access to the sign of deformation

- ❑ Single particle information through the spectroscopic factors
- ❑ High energy needed to learn about the "l" transfer

Physics @ HIE-ISOLDE

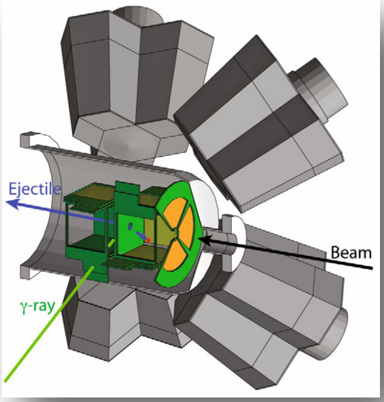
- May 2010: 34 LoI submitted
- 1 Nov 2012: INTC endorsed the increase of 2 GeV-proton energy for ISOLDE
- 27 experiments already approved
- 600 shifts already allocated for day 1 physics

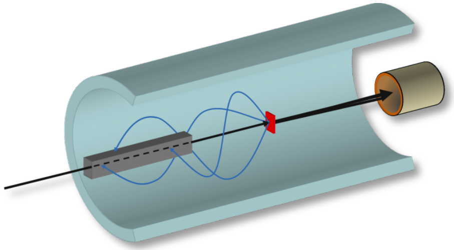


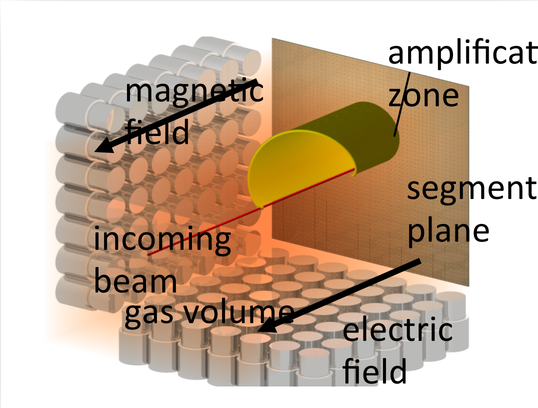
- Isospin symmetry
- Nuclear astrophysics
- Collectivity versus Single Particle
- Magic numbers far from stability
- Shape Coexistence
- Quadropole and octupole degrees of freedom

Instrumentation

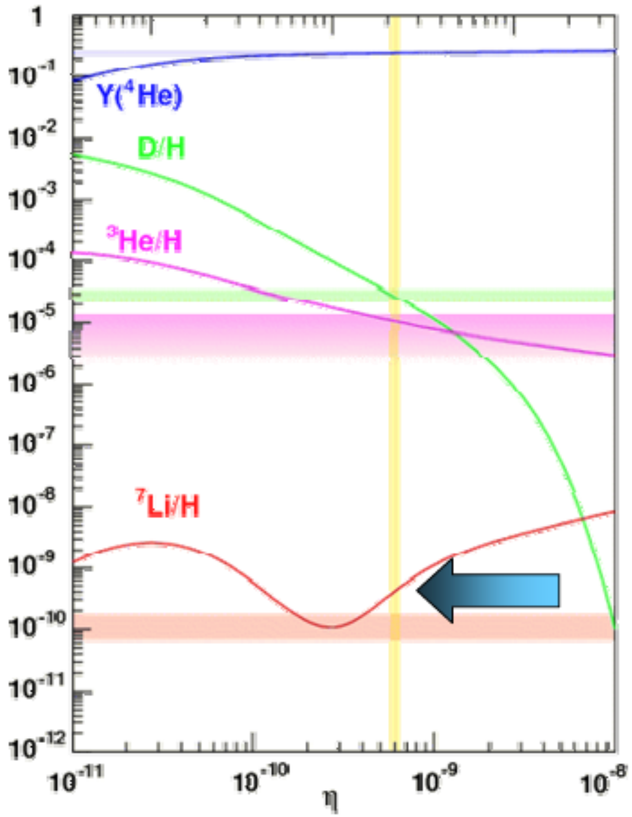
- Miniball + T-ReX (upgrade planned) : COULEX + Transfer 22
- Multipurpose reaction chamber 2
- CORSET chamber for Fusion-fission reactions 1
- SPEDE: added to Miniball+T-REX 1
- Helios type device: transfer @ TSR
- MAYA/ACTAR: resonant scattering + transfer. 1
- For 2016: TSR storage ring,







Adressing the ^{7}Li cosmological Problem (IS554)



Observed values represented by bands, predicted values represented by lines.

A factor of 4 in abundance of primordial ^{7}Li abundance while good agreement od D, ^{3,4}He.

Theory $\quad {}^7\mathrm{Li/H} = 5.12\,_{-0.62}^{+0.71} \times 10^{-10}$

Observation $\quad {}^7\mathrm{Li/H} = 1.23\,_{-0.16}^{+0.34} \times 10^{-10}$

Explore the alternative of resonance enhancement of nuclear reactions ➔Via the ^{7}Be(d,p)2α

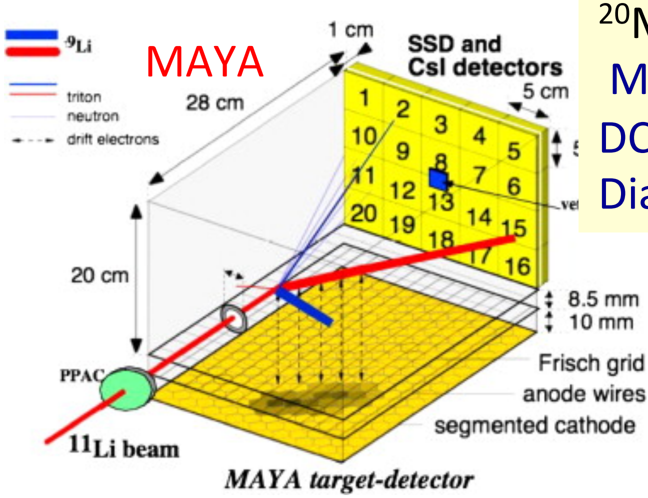
The destruction of ^{7}Be can be high due to the narrow resonance in ^{9}B at 16. 7MeV (5/2$^+$)

- This resonance can be very strong
- At the limit of quantum mechanically allowed value for the deuteron separation width
- Er = 170 -220 keV ;
- Deuteron Separation width Γ_d = 20 – 40 keV
- Achieved if the interaction radius for deuterium > 9 fm

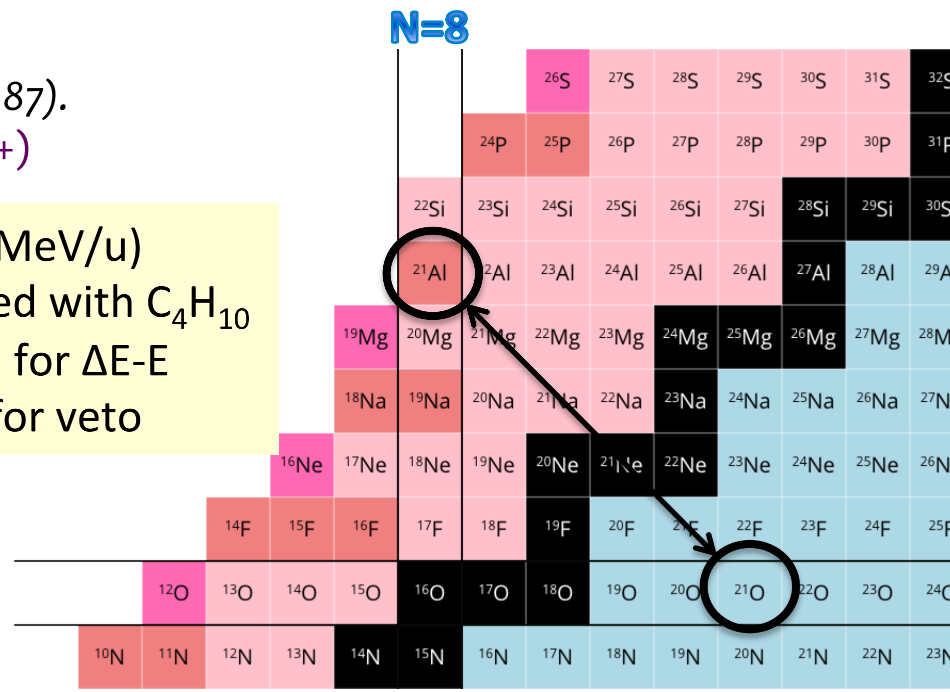
- Experiment ^{7}Be(d,p) and (d,d) at 35 MeV at T-REX

Study of n=8 gap beyond stability (IS564)

- **Study of the unbound proton-rich nucleus ^{21}Al with resonance elastic and inelastic scattering using an active target**
- The N=8 shell gap at the proton-drip line known up to ^{20}Mg
- The next isotope in the chain is ^{21}Al -> no experimental data
  - -Upper limit of $T_{1/2}$<35 ns
    M. G. Saint-Laurent, et al., PRL 59, 33 (1987).
  - Unknown Spin and Parity -> ^{21}O (5/2+)



^{20}Mg (5.5 MeV/u)
MAYA filled with C_4H_{10}
DC+Si+CsI for ΔE-E
Diamond for veto

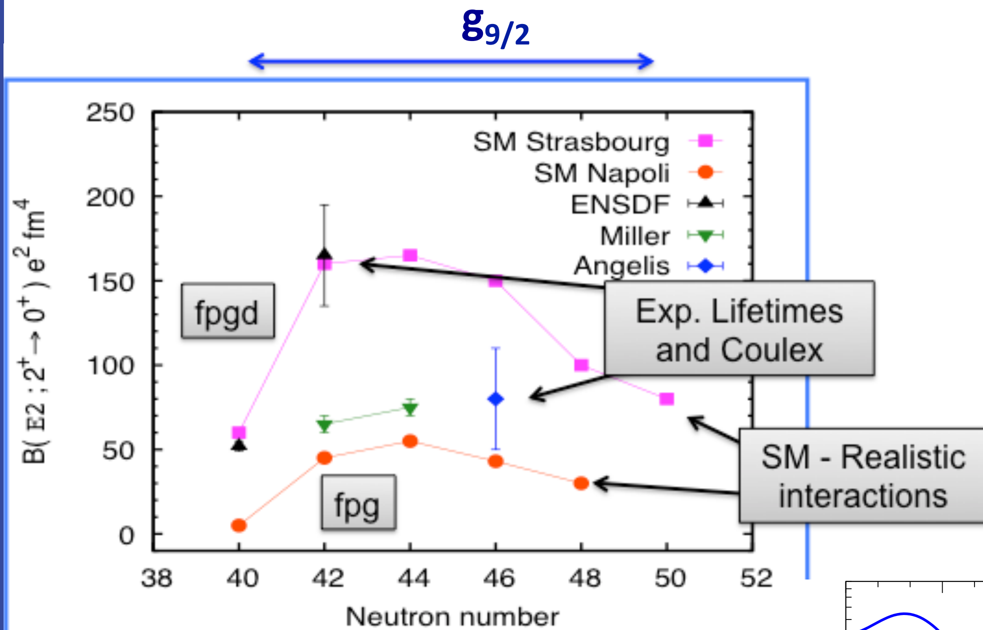


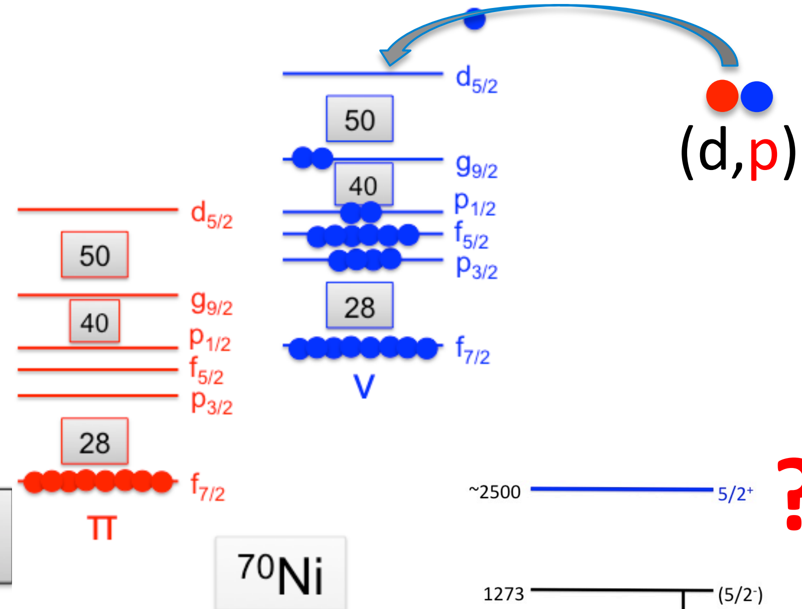
ADVANTAGES compared to conventional thick target method:

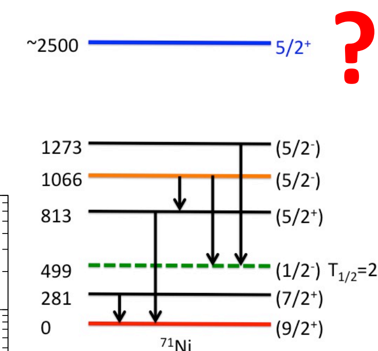
1) Background from C can be discriminated.
2) Inelastic and elastic can be separated.

Shell Evolution in Ni-isotopes (IS555)

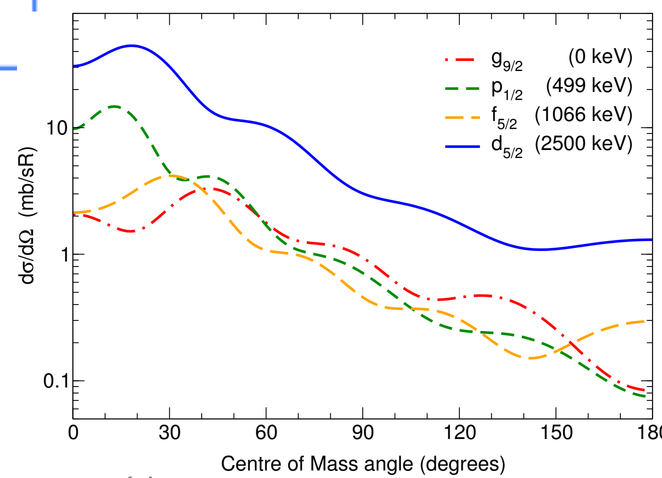
- Large theoretical and experimental discrepancies. For Ni –isotopes beyond N= 40.



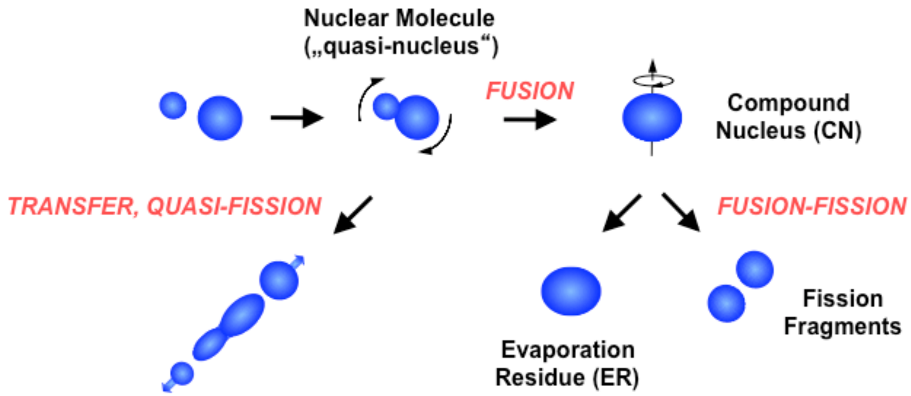




- Transfer reaction to characterize the 5/2+ state in ^{71}Ni by looking to proton angular distribution with T-REX



Search for the new magic numbers above ^{208}Pb?(IS550)



- **Nuclei with N ≈ 184 are still far**
- **Nuclei with Z > 118 are still unknown**

- Study of quasi-fission and fusion-fission with ^{94,95}Rb projectiles with Corset
- $^{95}\text{Rb} + {}^{209}\text{Bi} \rightarrow Z_1 + Z_2 = \mathbf{120}, \; N_1 + N_2 = \mathbf{184}$

Asymmetric component → transfer, quasi-fission

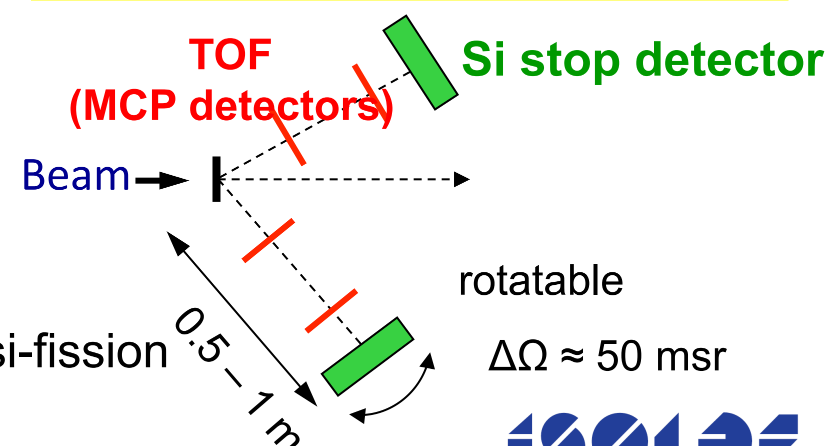
Symmetric component → fusion-fission

Z = 114, 120 or 126

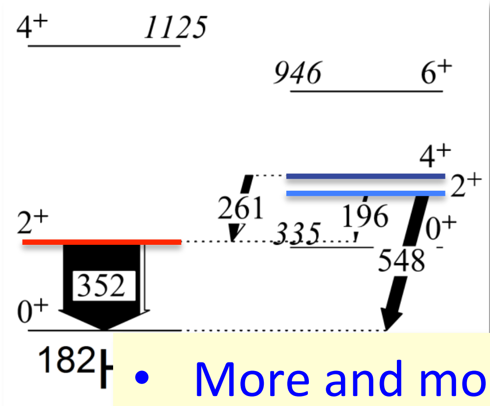
N = 184 ?

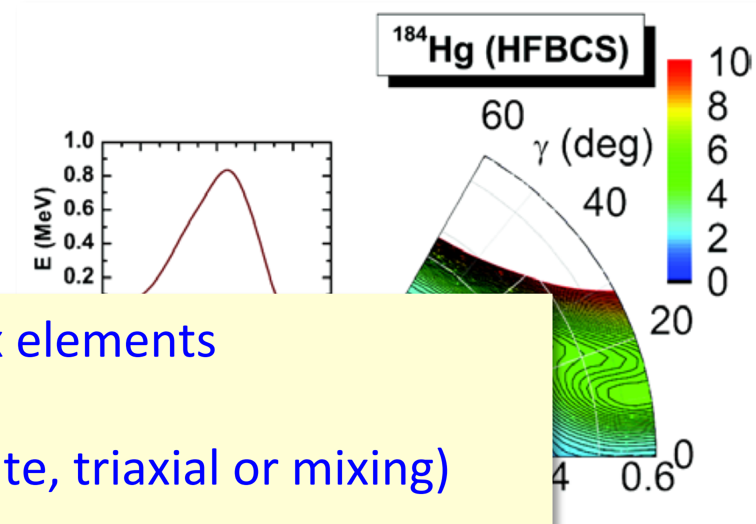
- Shell closures indicated by an increase of fission barriers and half-lives
- **Influence expected in *quasi-nuclei***

$$\sigma_{ER} = \sigma_{capture} \times P_{CN} \times P_{survival}$$

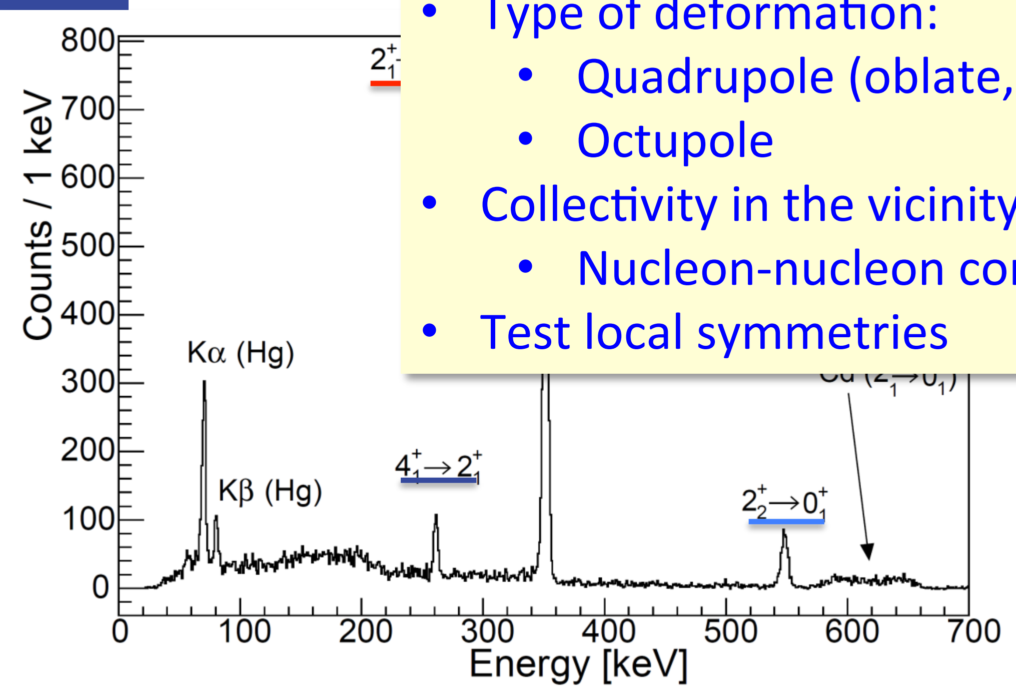


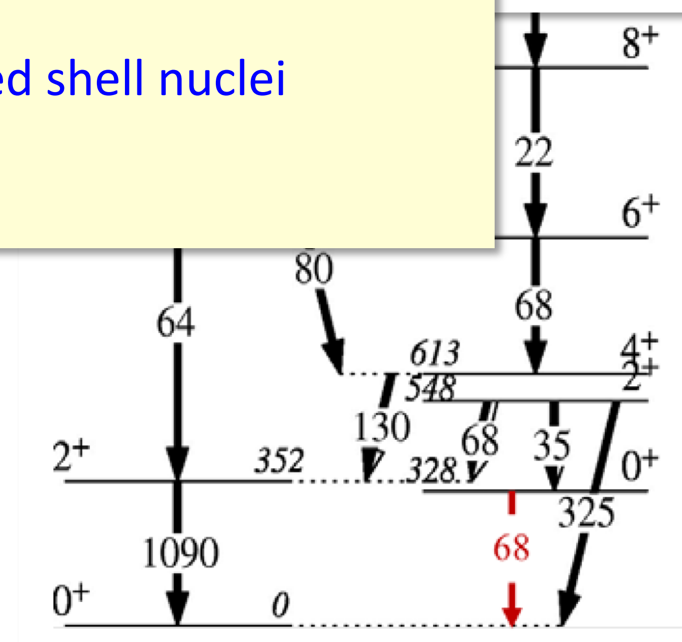
Coulomb excitation of ^{182}Hg



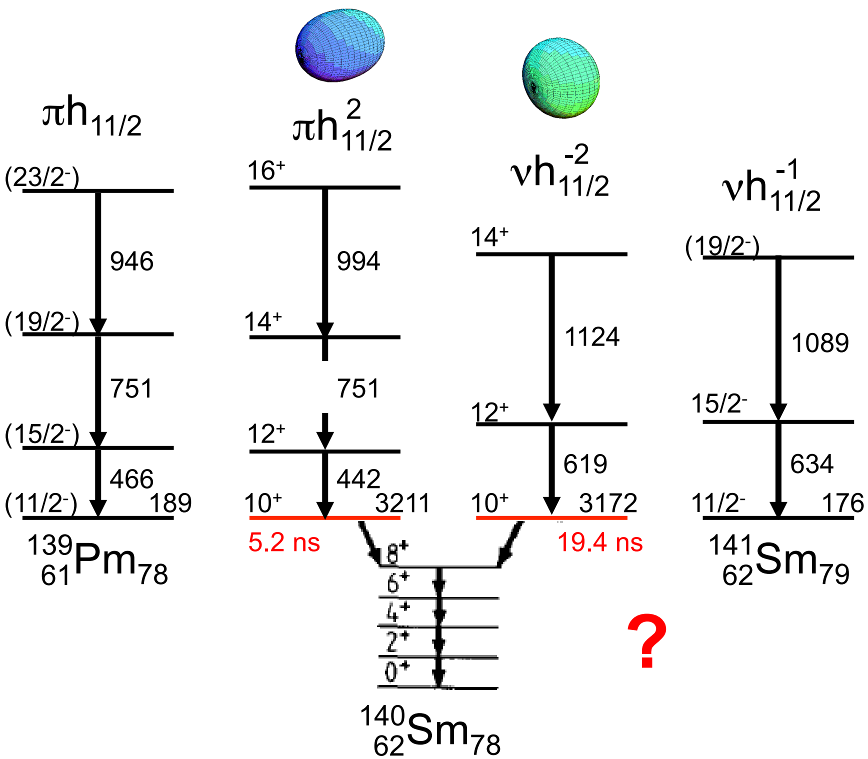


- More and more precise matrix elements
- Type of deformation:
  - Quadrupole (oblate, prolate, triaxial or mixing)
  - Octupole
- Collectivity in the vicinity of closed shell nuclei
  - Nucleon-nucleon correlation
- Test local symmetries



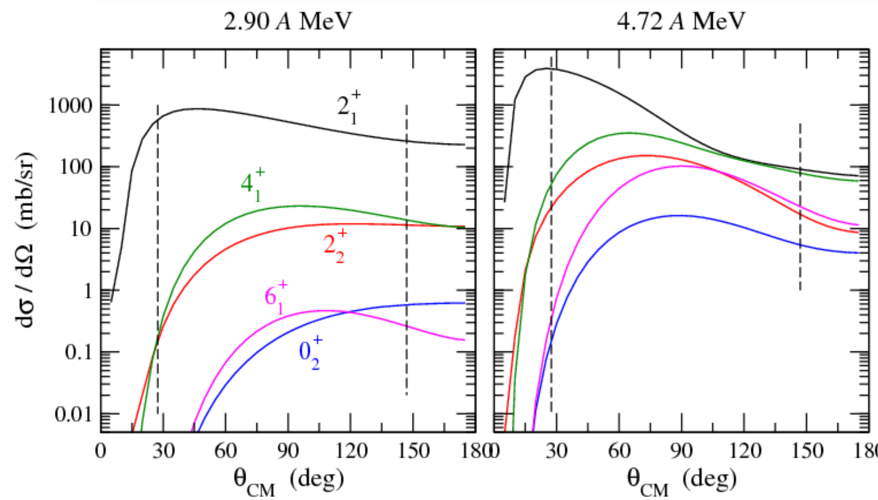


Shape transition & shape Coexistence in neutron deficient ^{140}Sm



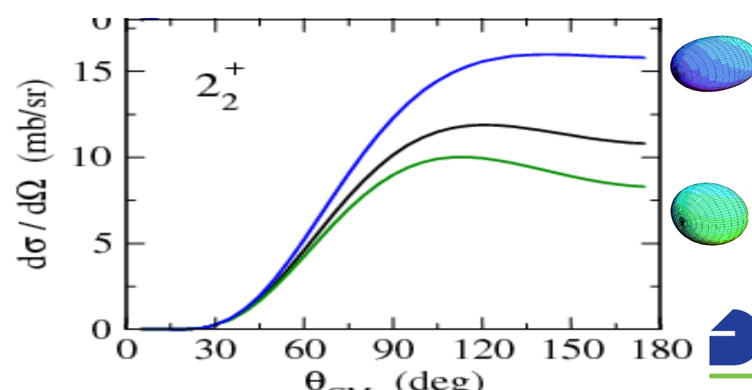
no experimental B(E2) values
low-lying (0⁺) state
⇒ indication for
shape coexistence ?
⇒ excited band built on
different shape ?

large gain for multi-step excitation for higher beam energies from HIE-ISOLDE



excitation cross sections for ^{140}Sm + ^{208}Pb

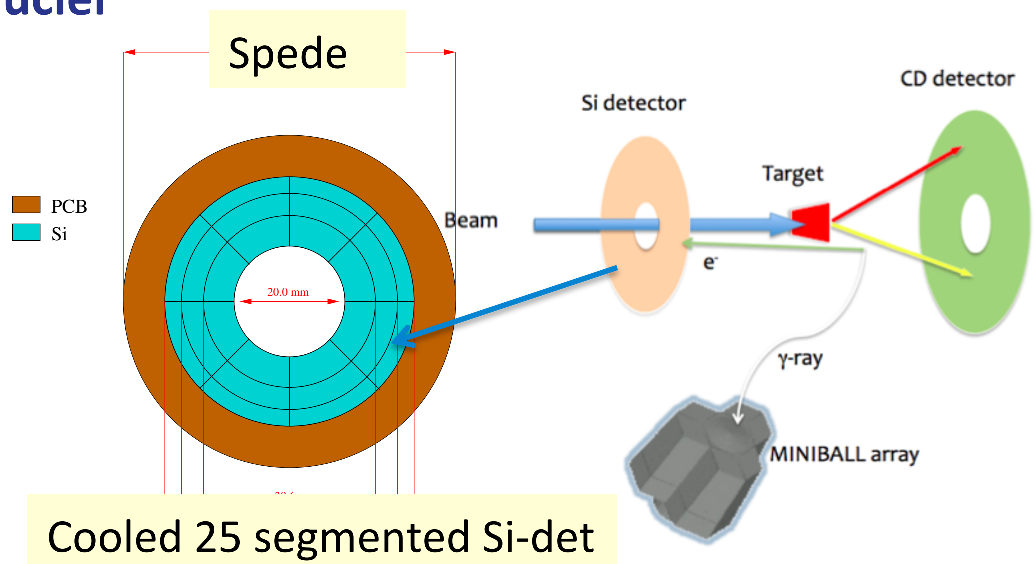
- experimental excitation energies
- matrix elements from theory



New candidates for EDM Measurements (IS552)

- The observation of a non-zero EDM indicates T-violation beyond the Standard Model.
- Octupole-deformed nuclei will have enhanced nuclear “Schiff” moments due to the presence of nearly degenerate parity doublets (seen in odd mass nuclei) and large collective octupole deformation.
- Presently **|d(^{199}Hg)| < 3.1×10^{-29} e.cm,** ***PRL 102 (2009) 101601***
- ***Octupole deformed nuclei will have 100-1000 higher* sensitivity compared with stable nuclei**

- Characterization of ^{221}Ra
- increased of a factor of 5 from 3 to 5,5 MeV/u
- Measurements of γ and e-conversion to determine the ΔE of parity doublet.



Conclusions

- Plenty of challenging physics waiting for the starting of HIE-ISOLDE!
- Many new groups and devices have been attracted by the increase of energy of the post-accelerated beams.
- **Phase 1: Start of the 4.3 MeV/u, physics program in 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 in this period.

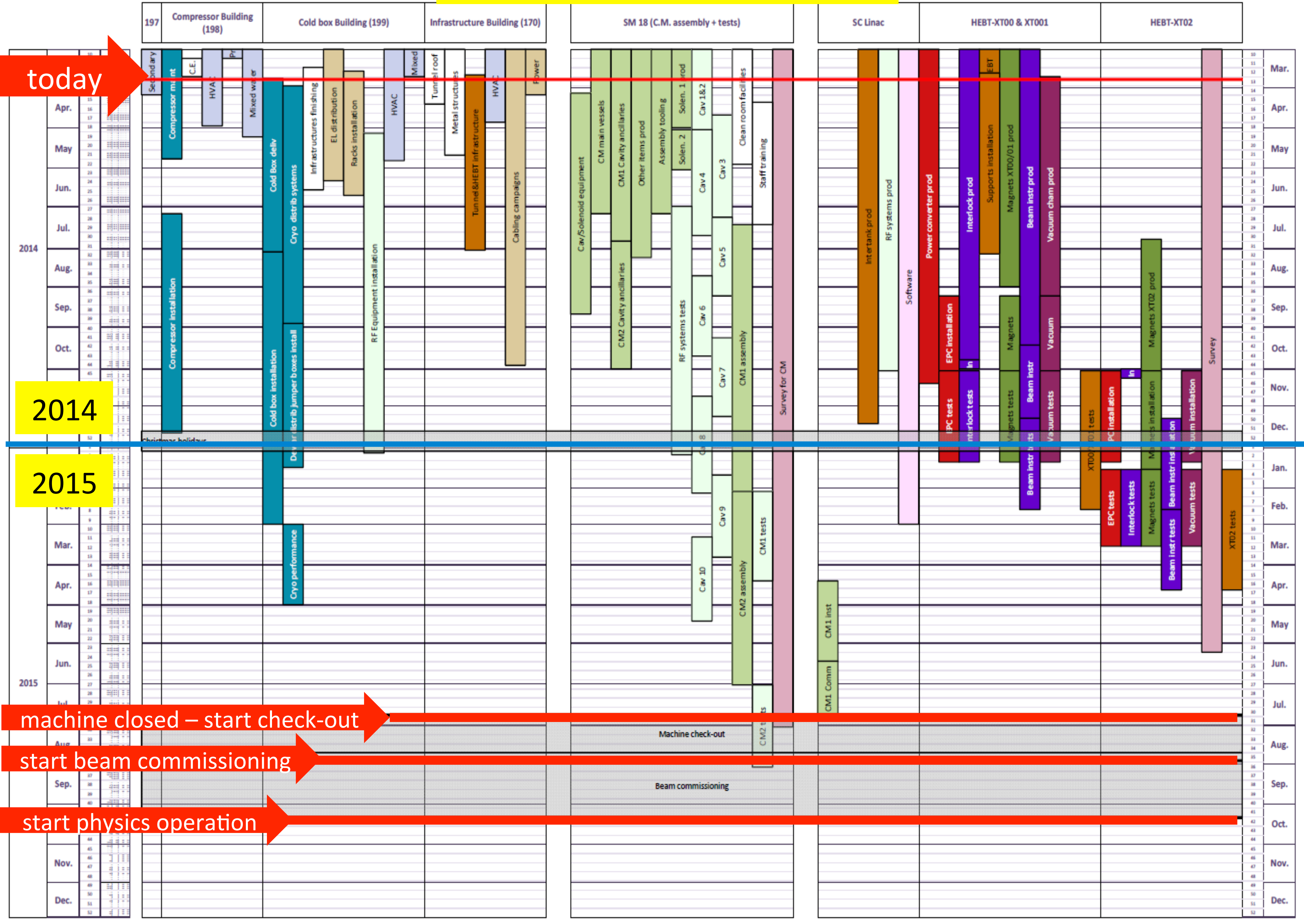
Thanks for your attention !

9Li	(p,2p), (d,pn)	Multitransfer reaction		
20Mg	MAYA/elastic	21Al last n=8		
66Ni	Miniball	G-strength enhancement		
68Ni	Miniball+T-REx	Transfer reactions		
70Ni	T-REX, (d,p)	Roll of d5/2 and g9/2		
70Se	Miniball	Multistep Coulomb around N=50		
74-80Zn	Miniball	Proving Shell Modela round N=50		
80Zn	T-REX, (d,p)	Single part orbits in N=50		
94Rb	T-REX, 208Pb-target	Multinucleon transfer		
^{A}Rb	CORSET, Bi-target	Quasi-fission, Fusion-fission for superheavies (Z=120)		
106,108,110Sn	Miniball	B(E2) deviation from predictions		
132Sn	Miniball	2p2h cross Shell configuration		
132Sn	Miniball	Moments of single part.		
134,136Sn	Tilted-foil	B(E2)		
142Xe	Miniball	B(E2), B(E3)		
142,144Ba	Miniball	B(E3)		
140Nd, 142Sm	Miniball	2+, stabilization of collective balance in N=80		
140Sm, 142Gd	Miniball	Shape coexistence		
182,184Hg	Miniball	Shape coexistence		
186,188Pb	Miniball	Coulomb excitation		
206Hg	Miniball	Multistep Coulomb 2+,3-		
222,224,226Rn	Miniball	Octupole Collectivity		

HIE-ISOLDE Beam parameters

Parameters HIE-ISOLDE Stage1	Value	Units
Mass to charge ratio A/q	2.5 to 4.5	
Output kinetic energy for A/q 4.5	1.2 – 5.5	MeV/u
Output kinetic energy for A/q 2.5	1.2 – 8.6	MeV/u
RF base frequency	101.28	MHz
RF period	9.87	ns
Max. rep. rate (NC linac)	50	Hz
Max RF pulse length (NC linac)	2	ms
EBIS pulse length	50 – 500	us
Transverse normalised emittance (90%)	0.07 (rms), 0.3 (90%)	mm.mrad
Longitudinal emittance (86%)	0.35 (rms), 1.5 (86%)	ns.keV/u
Energy spread	< 0.6 % (FWHM)	

New Baseline Schedule



The resources

- Changes after the Cost & Schedule Review in 2012
  - 2.56 MCHF for the Infrastructure Systems were added to the MTP.
  - 0.7 MCHF for the Machine as a CERN loan to the HIE-ISOLDE Collaboration.
  - A staff position was opened for three years for one Mechanical Engineer for TE/MSC-CMI.

- Preparation of Cost & Schedule Review in October 2013
- Manpower: Resources added to help bolster areas under stress

  Volker Mertens (DDH of TE) for Project Monitoring

  Fabio Formenti (TE) for Technical Coordination

  Technical & Engineering teams augmented

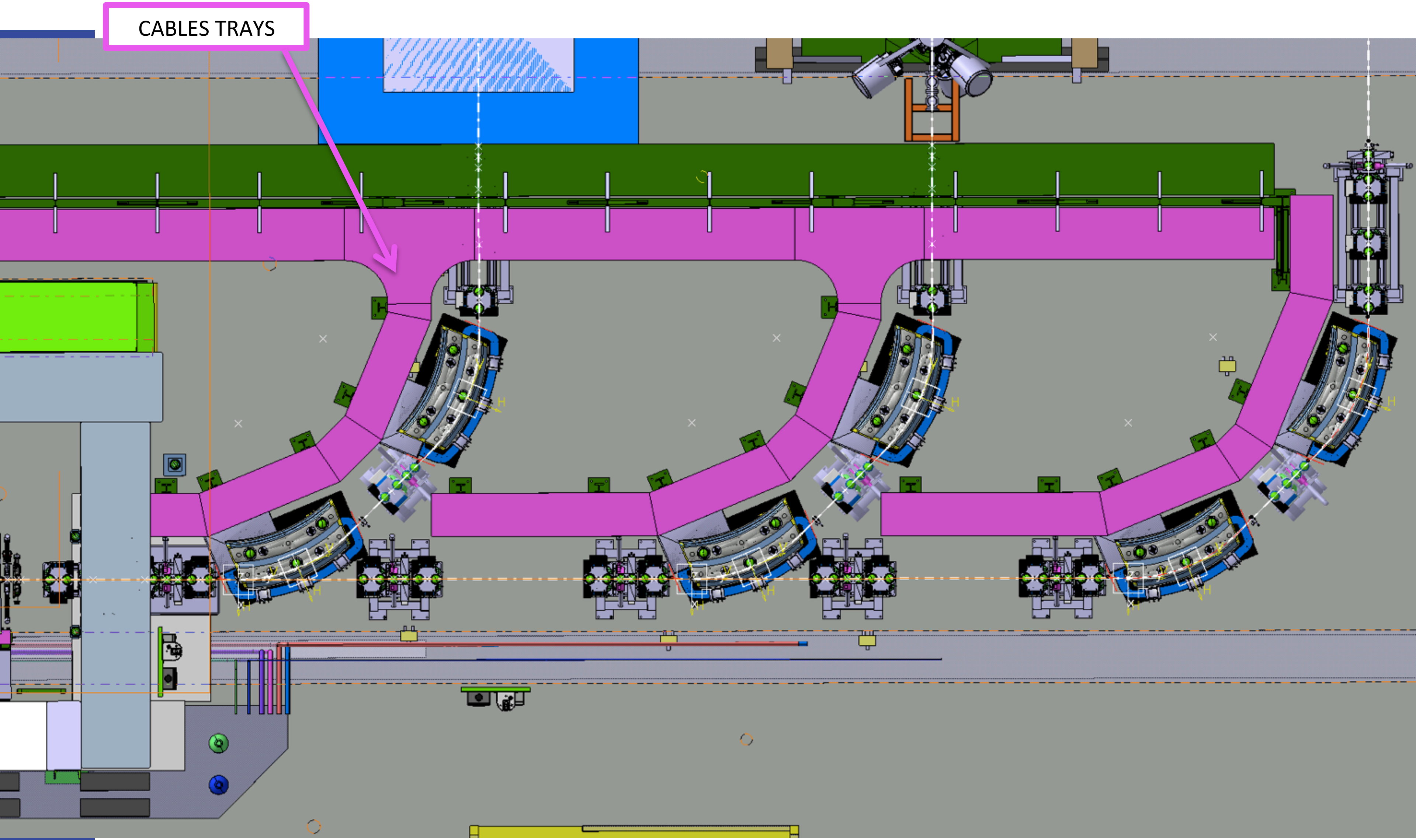
  A shortfall for the Phase 1 was identified in the machine part. Of 4.5 MCHF

  - ✓ The shortfall of 4.5 MCHF has been included in the MTP to be approved by Council in June 2014.

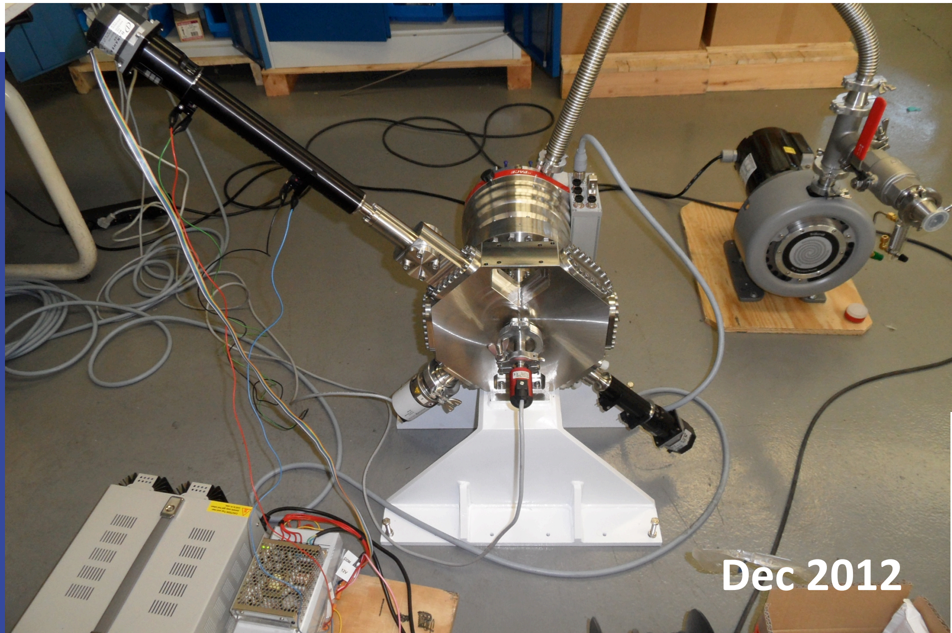
The reinforced project team judges

- ✓ that the resources for the design and procurement are adequate,
- ✓ a considerable part of the assembly and installation are adequate, while for other parts of the equipment assembly and tests as well as for the commissioning, need still to be confirmed.

Beam Lines &Cable Traces



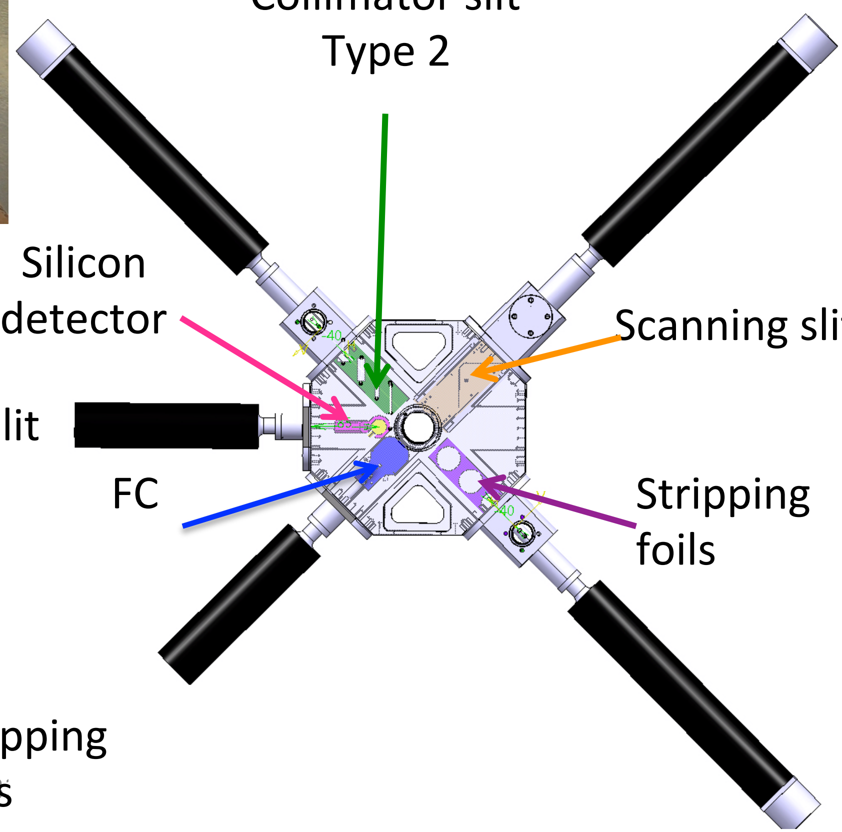
Diagnostic box

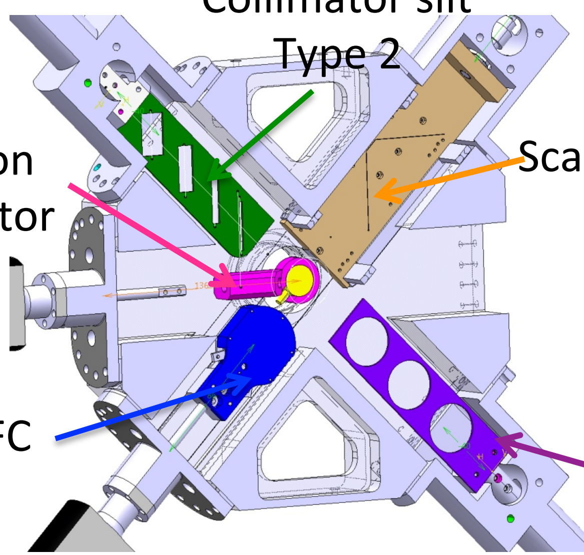


Highly demanding due to the reduce space

Prototypes already tested.

Call for tender launched.





Accepted HIE-ISOLDE experiments

title	EXP #	setup	shifts approved	isotopes approved	energy MeV/u
Study of the effect of shell stabilization of the collective isovector valence-shell excitations along the N=80 isotonic chain	IS546	MINIBALL + CD-only or MINIBALL + T-REX	42	140Nd, 142Sm	3.62; 4.5
Coulomb excitation of the two proton-hole nucleus 206Hg	IS547	MINIBALL + CD-only	15	206Hg	4.1 ?
Evolution of quadrupole and octupole collectivity north-east of 132Sn: the even Te and Xe isotopes	IS548	MINIBALL + T-REX	30	142Xe	4.50
Coulomb Excitation of Neutron-rich 134;136Sn isotopes	IS549	MINIBALL + T-REX	30	134;136Sn	4.40
Study of the Dinuclear System ARb + 209Bi (Z1 + Z2 = 120)	IS550	CORSET: 2-arm TOF spectrometer	12	95Rb	4.5-5.5
Coulomb excitation of doubly magic 132Sn with MINIBALL at HIE-ISOLDE	IS551	MINIBALL + T-REX	18	132Sn	5.50
Measurements of octupole collectivity in Rn and Ra nuclei using Coulomb excitation	IS552	MINIBALL + CD-only; MINIBALL + SPEDE	17	222Rn, 222,226,228 Ra	4-5
Determination of the B(E3,0+->3-) strength in the octupole correlated nuclei 142,144Ba using Coulomb excitation	IS553	MINIBALL + T-REX	30	142,144Ba	3.32, 4.1
Search for higher excited states of 8Be* to study the cosmological 7Li problem	IS554	MINIBALL + T-REX	15	7Be	?
Study of shell evolution in the Ni isotopes via one-neutron transfer reaction in 70Ni	IS555	MINIBALL + T-REX	36	71Ni	5.50
Spectroscopy of low-lying single-particle states in 81Zn populated in the 80Zn(d,p) reaction	IS556	MINIBALL + T-REX	36	80Zn	5.50
Coulomb excitation 74Zn-80Zn (N=50): probing the validity of shell-model descriptions around 78Ni	IS557	MINIBALL + CD-only	30	74-80Zn	4.55
Shape Transition and Coexistence in Neutron-Deficient Rare Earth Isotopes	IS558	MINIBALL + CD-only	12	140Sm	4.70
Statistical properties of warm nuclei: Investigating the low-energy enhancement in the gamma strength function of neutron-rich nuclei	IS559	MINIBALL + CD-only + LaBr3	21	66Ni	5.50

title	EXP #	setup	shifts approved	isotopes approved	energy MeV/u
Nuclear-moment studies in the odd-mass In isotopes up to N=82 using the Tilted Foils technique	IS560	tilted-foils + beta-NMR	13	129In	0.30
Transfer reactions at the neutron dripline with triton target	IS561	Si and SAND arrays	30	9Li	7 for A/q=3, 5.5 for A/q=4.5
Transfer Reactions and Multiple Coulomb Excitation in the 100Sn Region	IS562	MINIBALL + CD-only	30	110,108,106 Sn	5.50
Coulomb excitation of 182-184Hg: Shape coexistence in the neutron-deficient lead region	IS563	MINIBALL + CD-only	*12*	182,183,184 Hg	4.00
Study of the unbound proton-rich nucleus 21Al with resonance elastic and inelastic scattering using an active target	IS563	MAYA detector	43	20Mg	5.50
Probing intruder configurations in 186,188Pb using Coulomb excitation	IS566	MINIBALL + SPEDE	10	188Pb	<4.2
Solving the shape conundrum in 70Se	IS569	MINIBALL+CD	15	70Se	5 or 5.5
Study of shell evolution around the doubly magic 208Pb via a multinucleon transfer reaction with an unstable beam	IS572	MINIBALL	27	94Rb	5.50
Measurement of octupole collectivity in Rn and Ra nuclei using Coulomb excitation	IS552	Miniball+Spede+ CD	18	22,226,2214 Rn	4-5
Characterising excited states in and around the semi-magic nucleus\n 68 Ni using Coulomb excitation and one-neutron transfer	IS587	Miniball+T-REX	9	70Ni	5.00
(d,p)-transfer induced fission of heavy radioactive beams	IS581	ACTAR + (Ge detectors)	28	193Tl, 199Bi, 201At, 209Fr	5.00
18N: a challenge to the shell model and a part of the flow path to r-process element production in Type II supernovae	IS591	Miniball +T-REX	21	17N	5.00