ISOLDE Collaboration Committee Meeting

19th March 2019

A Superconducting Recoil Separator for HIE-ISOLDE

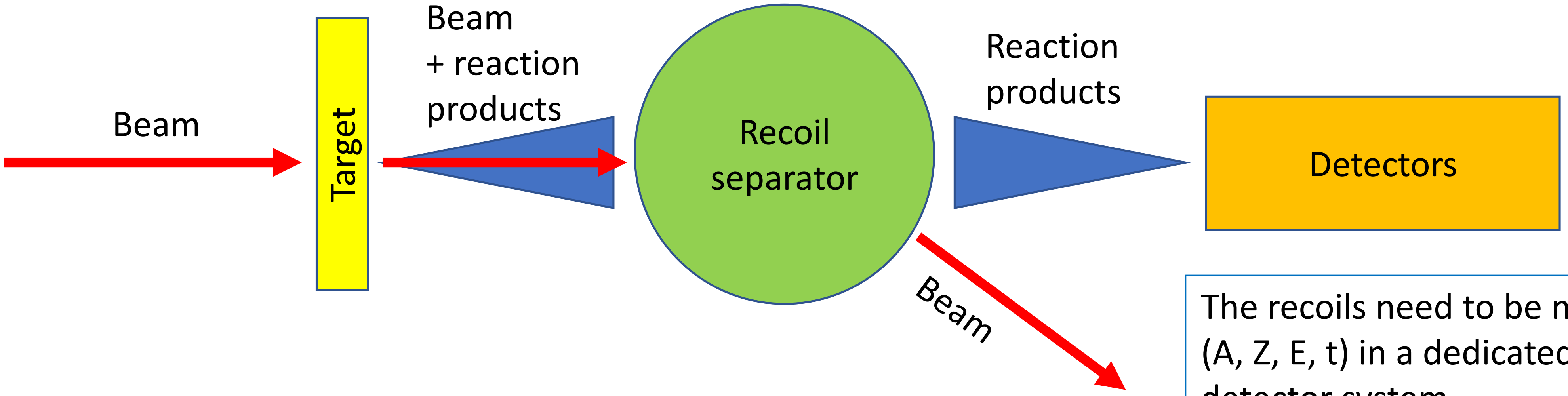
I. Martel

University of Huelva

Recoil Separators

Measurement of reactions products → main advantage when forward focussing recoils.

- Direct reactions, nucleon transfer in inverse kinematics, fusion-evaporation, Coulex (beam composition/ impurities), …



The recoils need to be measured (A, Z, E, t) in a dedicated detector system.

The primary beam needs to be separated from the reactions products (recoils).

Stand alone
In coincidence with other systems
HIE-ISOLDE low-energy beams (β ~ 0.05-0.15).

Simple experiments
High efficiencies

High cost of separator
Moderate cost of detectors

HIE-ISOLDE

International Nuclear Physics Conference 2010 (INPC2010) IOP Publishing
Journal of Physics: Conference Series **312** (2011) 052010 doi:10.1088/1742-6596/312/5/052010

The HIE-ISOLDE Project

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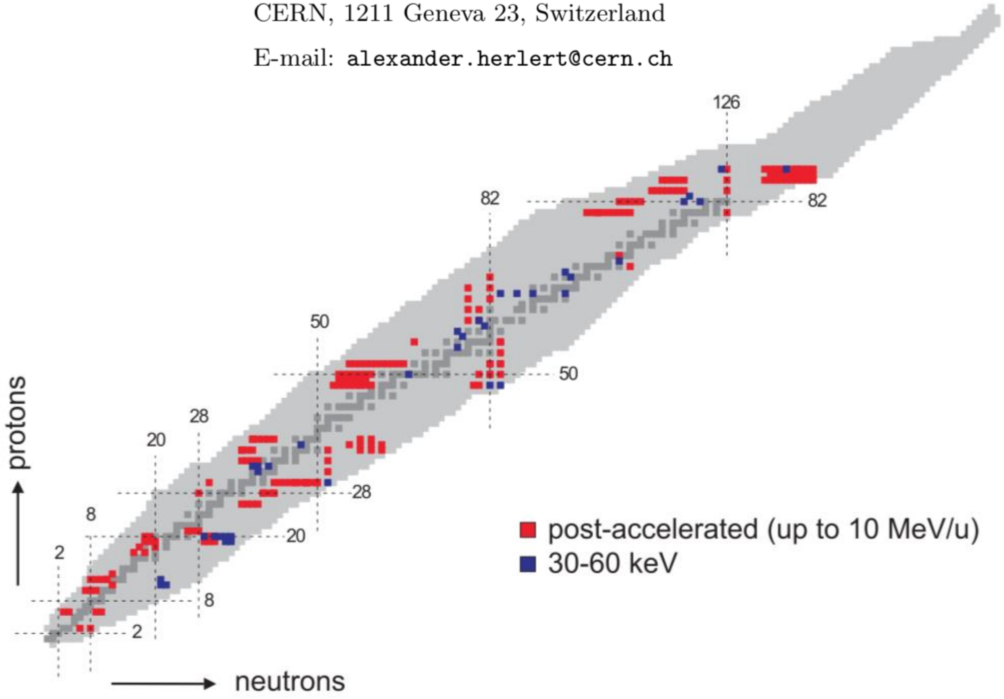


Figure 5. Isotopes requested by ISOLDE users for HIE-ISOLDE

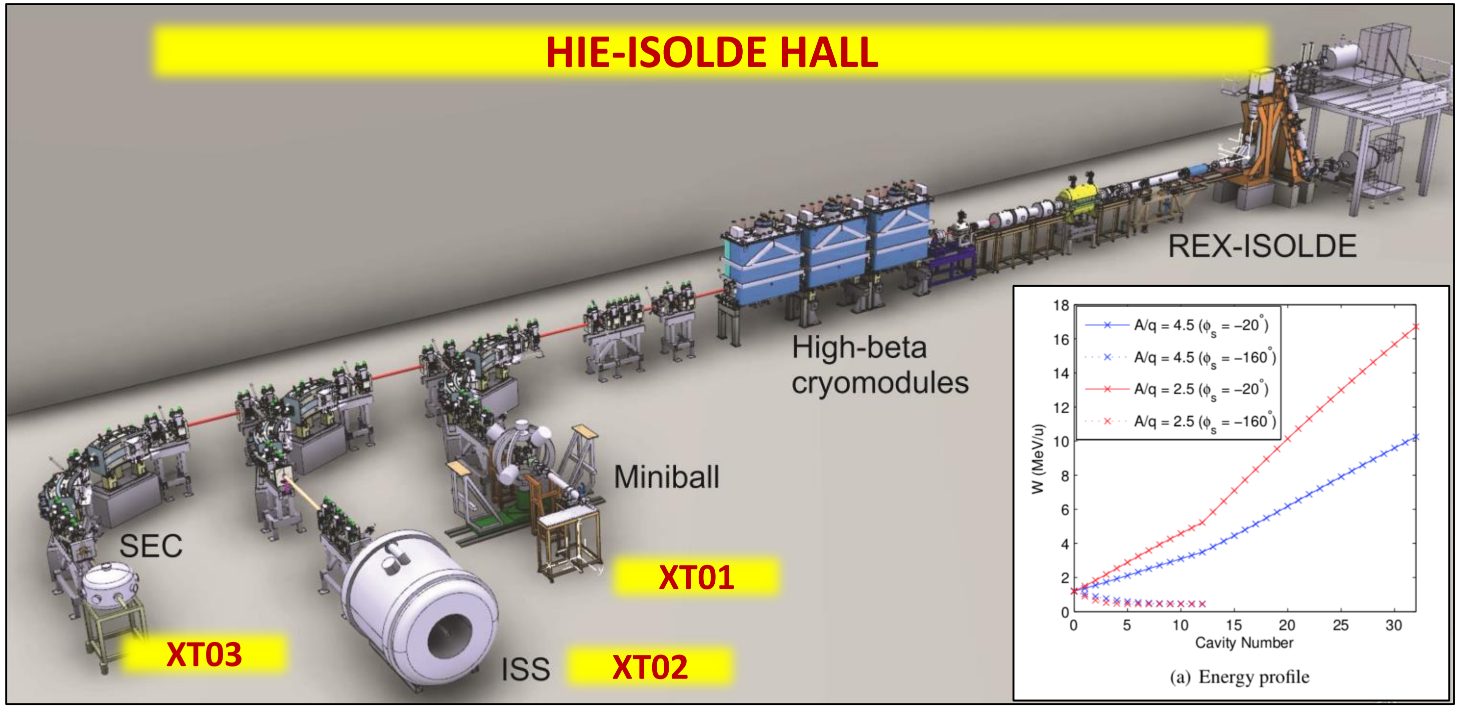


Table 17.1: Design parameters of dipole magnets.

Parameter	Value
Number of magnets	6
Peak field in centre [T]	1.2
Allowed integrated field error	$\pm 5 \cdot 10^{-4}$
Magnetic aperture [mm]	50
Magnetic length [mm]	1414
Bending radius [m]	1.8
Bending angle [deg]	45
Conductor dimensions [mm]	□10;
Nominal current [A]	423
Magnet resistance (20°C) [mΩ]	100
Magnet inductance [mH]	113
Cooling flow (Δp = 10 bars) [l/min]	23

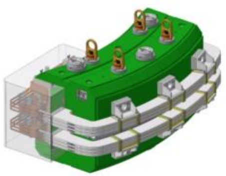
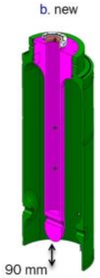


Table 2. Main design parameters of high-beta cavities.

Design parameter	Value
F_0 (MHz)	101.28
β_g (%)	10.3
E_{acc} (MV m^{-1}) = V_0/L_a	6
L_a (m)	0.3
R_{shunt}/Q_0 (Ω)	550
E_{peak}/E_{acc}	5.6
H_{peak}/E_{acc} (G (MV m^{-1})$^{-1}$)	100
Q_0 (at 6 MV m^{-1}, P = 10 W)	5×10^8
$\Gamma = R_s Q_0$ (Ω)	31
U/E^2_{acc} (mJ (MV m^{-1})$^{-2}$)	210
T (K)	4.5



The need of recoil separators at HIE-ISOLDE: the HIFI Project

March 10-11, 2011 | Spectrometer at HIE-ISOLDE, Workshop, Lund (Sweden)

Request from Letters of Intend = 43%

- identify beam-like particles
- light particle spectrometer
- MINIBALL, SEC

Other set-ups

- GASPARD
- ACTAR
- Fission fragments
- ISS: challenging due to fringe fields

Beams

Full range of isotopes available at HIE-ISOLDE (Li to Ra)

Coupling to other particle detectors

- SEC, MINIBALL, ISS
- Plunger (under construction)
- e-spectrometer (SAGE-type)

Types

Ray-tracing spectrometer: VAMOS, PRISMA...
Mass spectrometer: EMMA, MARA, RITU ...

Physics cases

- *Direct reactions studies, Transfer reactions*
  - Energy: 5.5 - 10 MeV/u
  - Intensities: > 10^5/s
  - Small scattering angles around 0°
  - Event-by-event PID
  - Identification of heavy transfer product
  - Reactions of beam contaminants
  - Angular distribution
  - Fusion-evaration reactions with target / carrier
  - Beam composition for normalisation
- *Coulomb excitation*
  - 4 - 5.5 MeV/u, Intensities: > 10^2/s ... 10^8/s
  - A and Z determination for scattered particles using large area Bragg detector
  - Beam composition for normalisation
- *Deep inelastic reactions*
- *Fusion-evaporation reactions*
- *Astrophysics*

Coordinators: Olof Tengblad; Wilton Catford; Joakim Cederkäll

Specifications of the recoil separator

Physics		
E [MeV/u]	0.45	10
A	7	234
A/Q	2.5	4.5
P [MeV/c]	1	30
Bρ [Tm]	0.25	2.16

Timing

Slow extraction from EBIS useful for TOF

Linac f = 101.28 MHz → rebuncher down to ~ 10 MHz.

Intensity

10^5/s for heavy beams, but 10^9/s instantaneous rate.

→ debuncher

Multi-harmonic buncher (M. Fraiser et al. LINAC2014, THPP030)

Size of the HIE-ISOLDE hall

Separator

- Rejection: ~10^{-12}
- 100 % transport efficiency
- Mass resolution > 1/300
- Large acceptance ~ 100 mrad
- Gas-filled mode

Focal plane detector

- Position sensitivity ~ 1 mrad (scattering angle)
- Particle identification (A, Z)
- Eloss, Time of Flight, Pulse shape
- Time resolution ~ ns
- Energy resolution < 100 keV
- 100% efficiency

Simulations

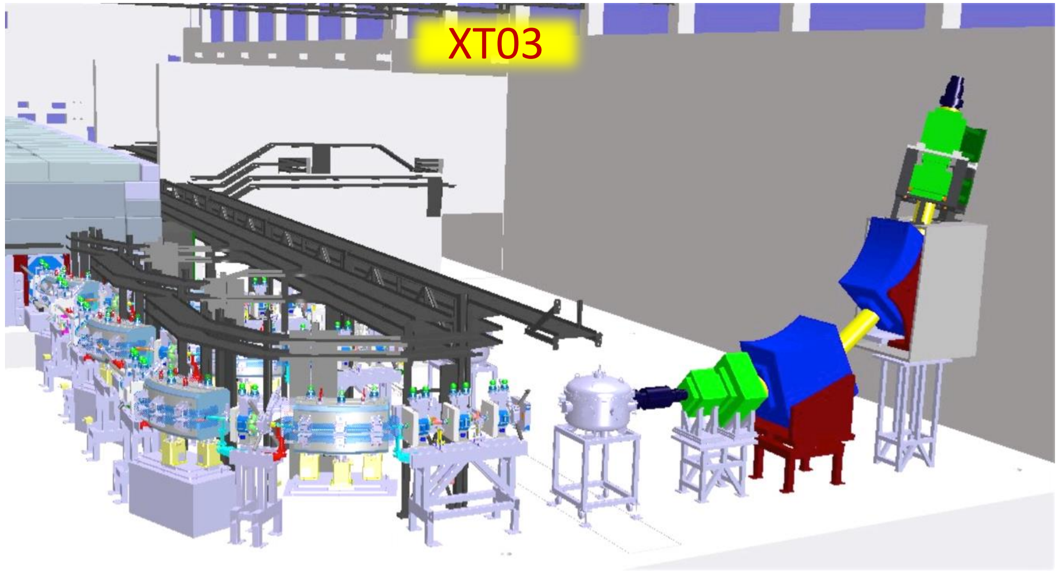
EMMA, MARA, PRISMA

- ^{9}Li(d,n)^{10}Be
- ^{22}Mg(d,n)^{23}Al
- ^{68}Ni(d,n)^{69}Ni
- ^{132}Sn(d,p)^{133}Sn
- ^{184}Hg(3He,n)^{186}Pb

Traditional system based on warm magnets

- Simple and experienced.
- Little space available but could fit.
- ToF – space limitations. Δt [s/m] ~ 15/A
- Not easy to move from one line to the other.

Layout for SEC



Layout for MINIBALL

Courtesy of J. Cederkall

Proposal for a design study using SC elements

- Explore new design concept using SC coils and RF cavities.
- Produce a compact, efficient and high-selectivity recoil separator.
- Design study including beam dynamics, mechanics, size, weight, efficiency, selectivity, construction and running costs.

SC solenoids

- Combined function magnets for bending and focussing
- High fields ~ 8 T

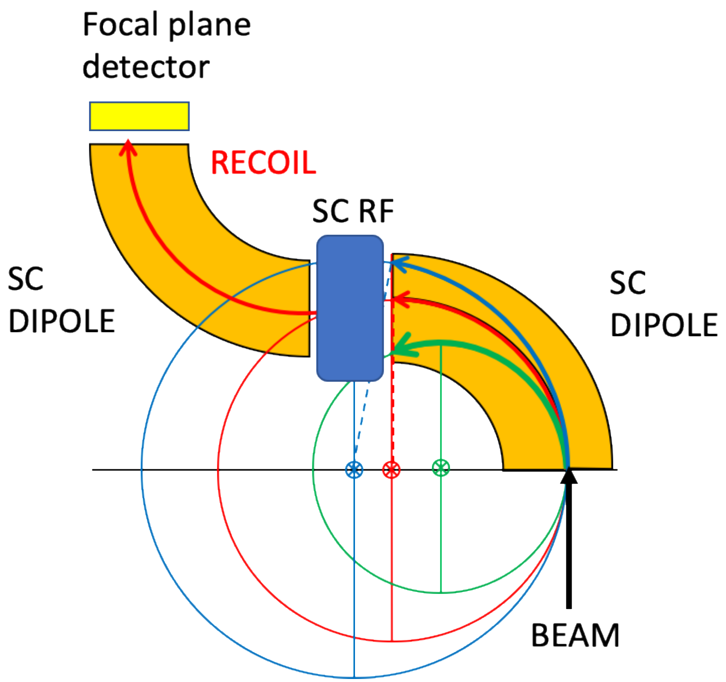
SC RF cavities

- High gradients ~ 10 MV/m
- Rebuncher ~ 10 MHz

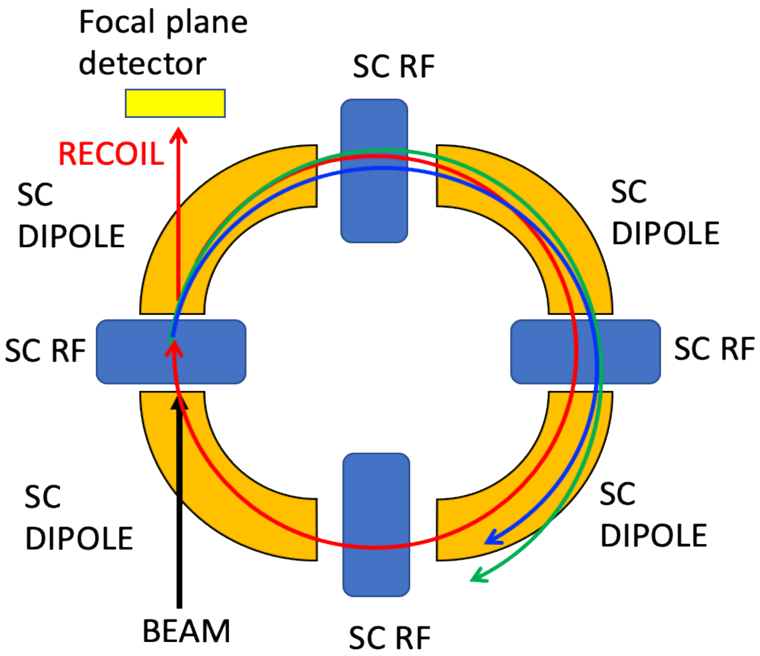
Hight temperature SC

FFAG

(EMMA project at Daresbury Laboratory)



Classical design concept



Ring design concept

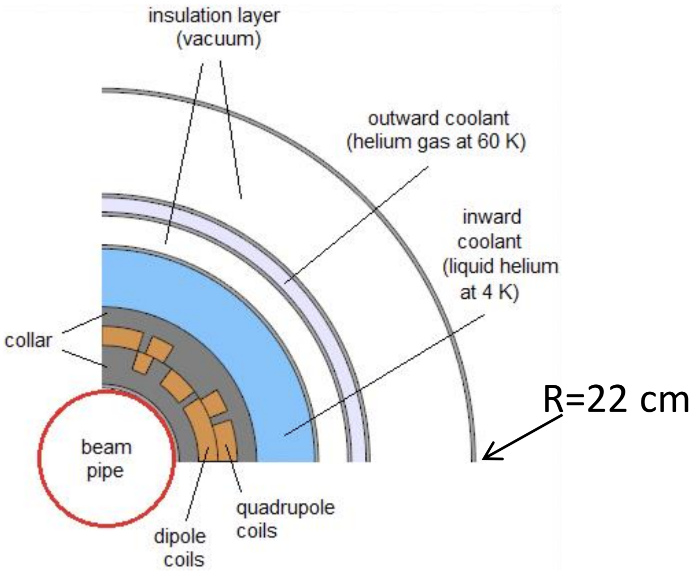
Example – Combined function magnets

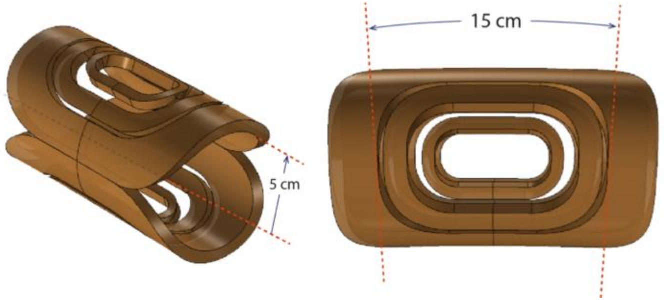
“Design of a superconducting Gantry cryostat”

C. Bontoiu, et al., IPAC2015, doi:10.18429/JACoW-IPAC2015-WEPMN051

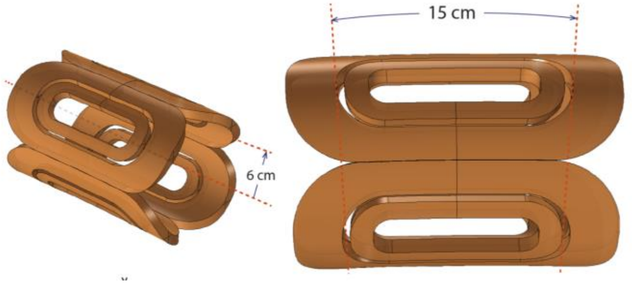
- Design study of a SC Gantry for protontherapy
- Protons of 175 MeV ± 20% (large acceptance); R= 2.5 m
- Bmax = 2.195 T
- Dipoles Bρ = 5.47 Tm
- Quads gradient = 90 T/m
- Small magnets Length x Diameter ~ 20 cm x 15 cm
- 36 magnets, FFAG

Specs must be scaled down for HIE-ISOLDE



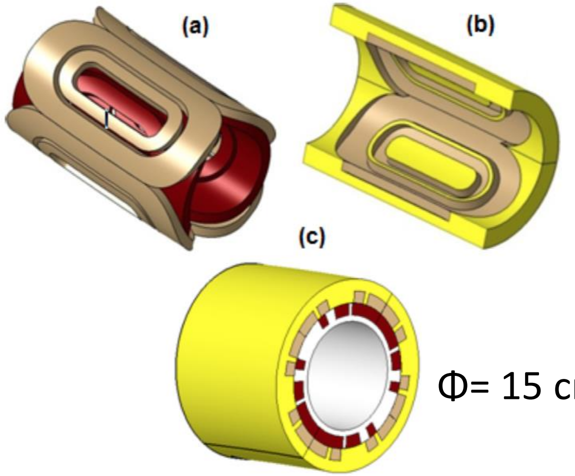


SC Dipole



SC quadrupole

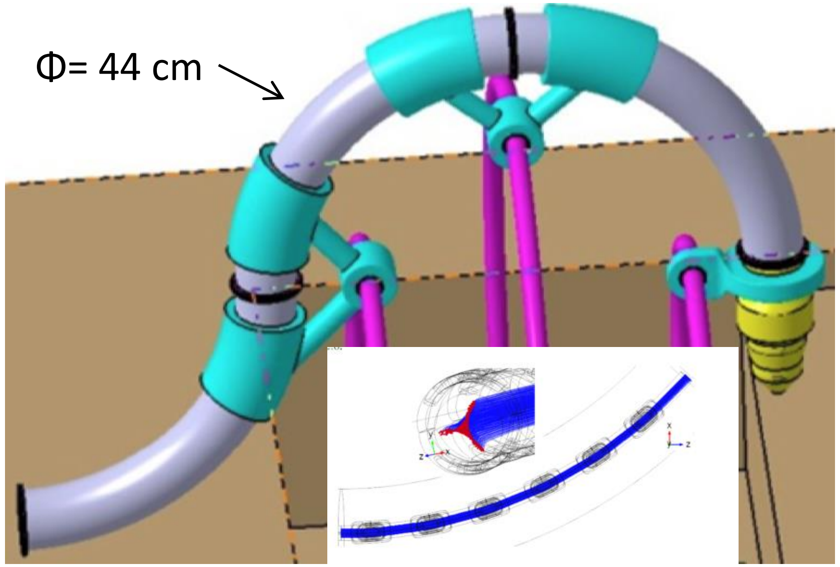
Combined function magnet



Φ= 15 cm

L=20 cm

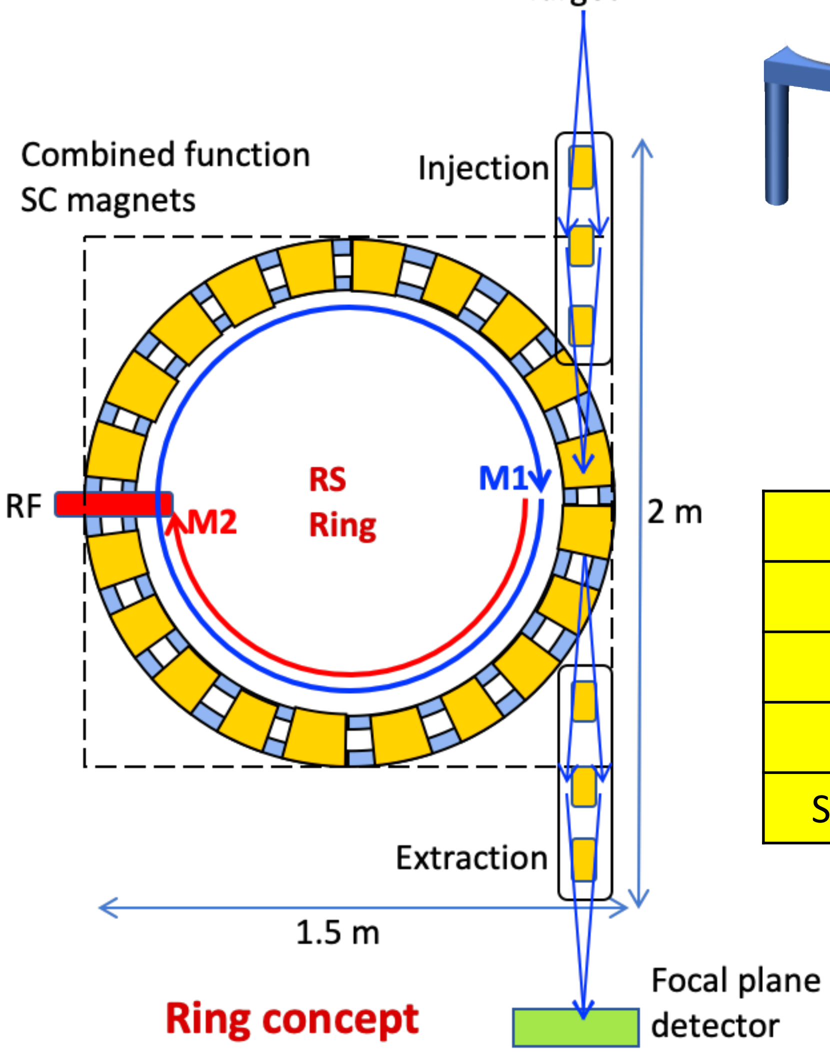
Φ= 44 cm



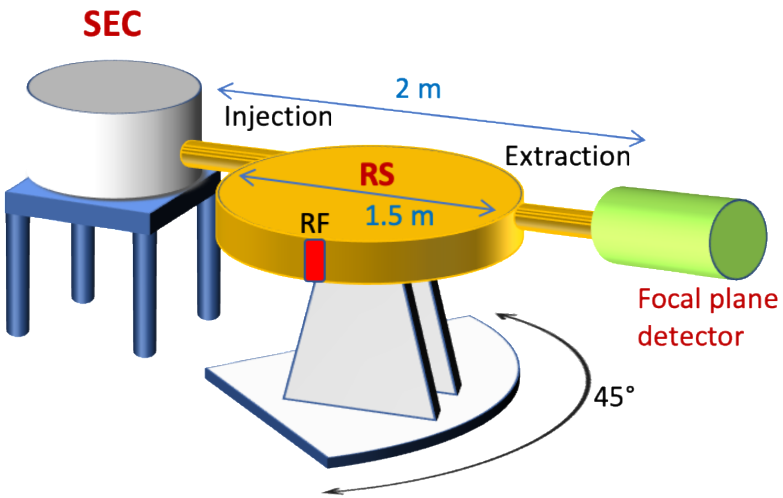
Gantry layout

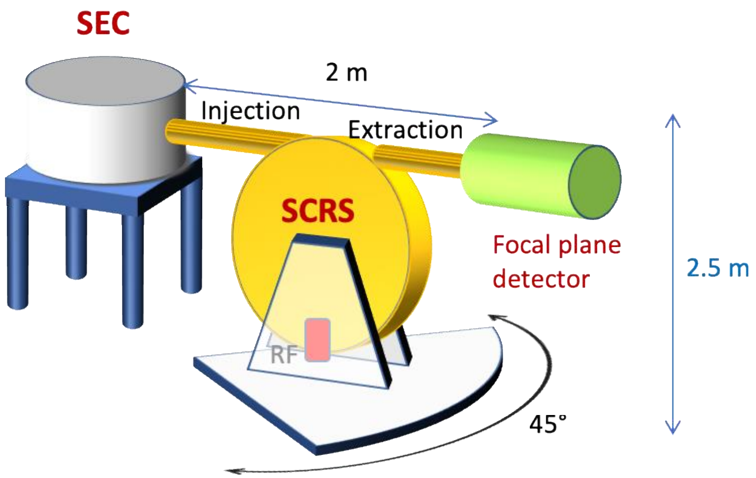
Example – Ring concept

- Remove only primary beam

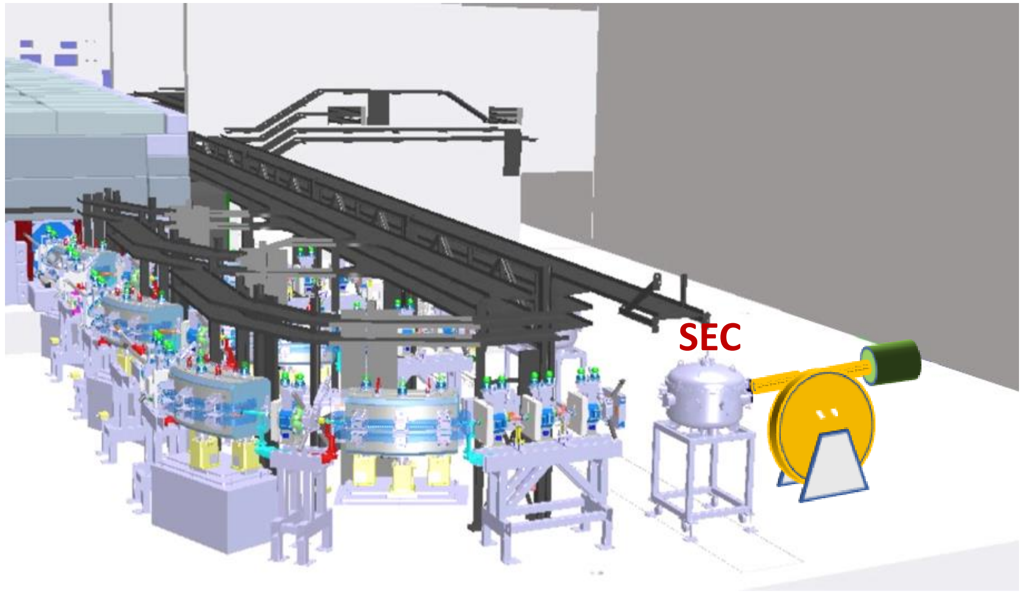


Ring concept



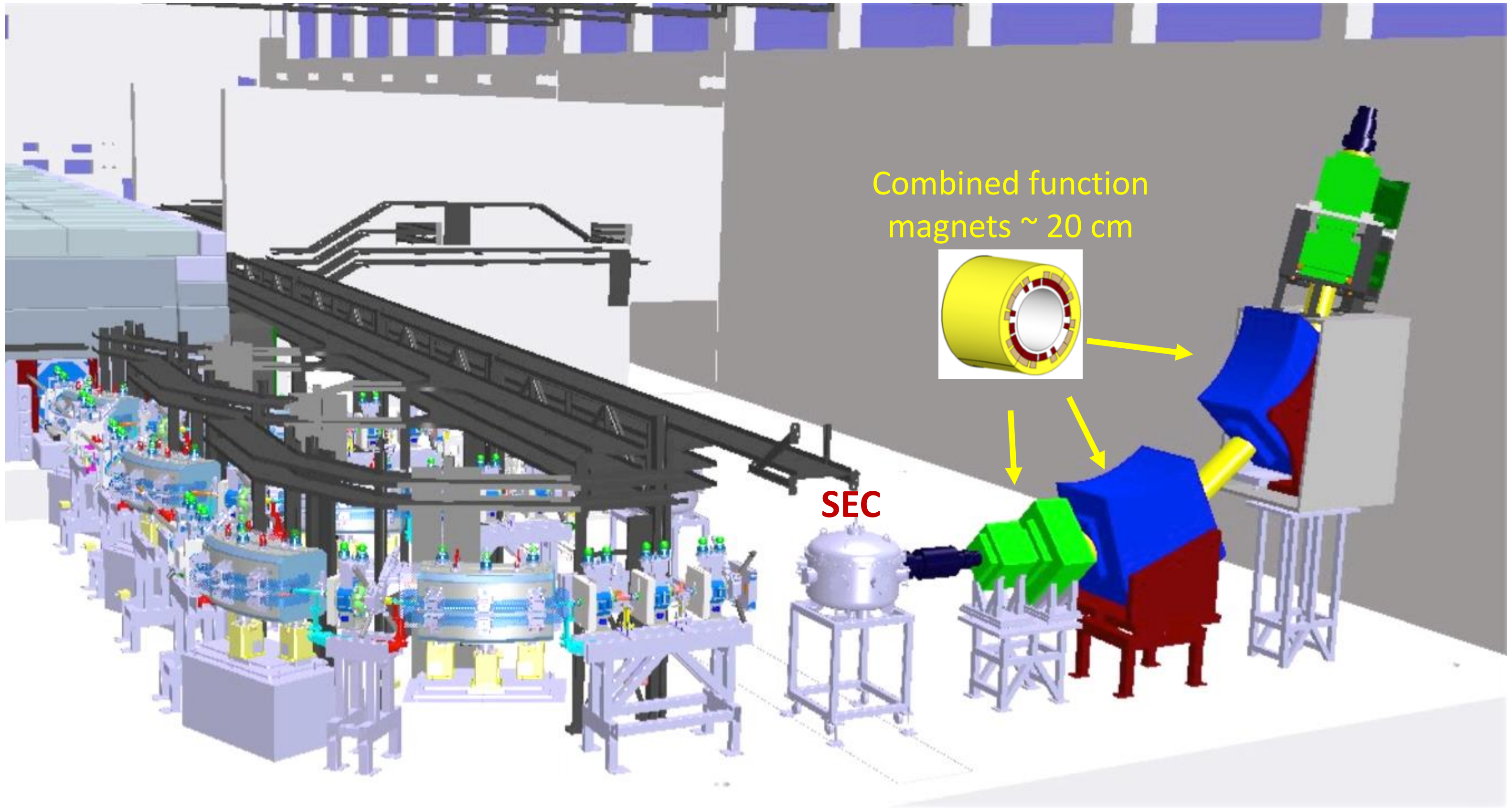


R [m]	0.5 - 1
B [T]	2 - 6
f_0 [MHz]	10 - 40
f_k [kHz]	100 - 3000
Storage t [µs]	0.5 - 10



Example- Classical design concept

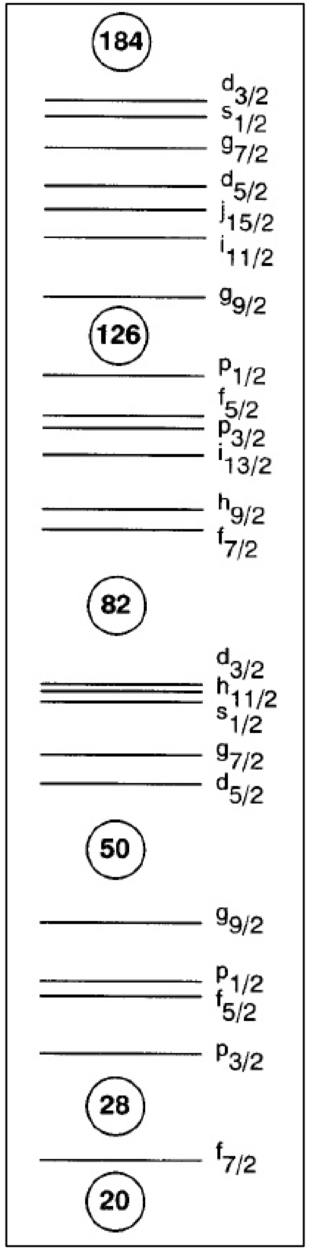
Reduction in size of dipoles and quadrupoles ~ factor 5.



Summary and conclusions

- Design study of a recoil separator using SC coils and RF cavities to produce a compact, efficient and high-selectivity instrument. Different options to be considered including combinations with warm magnets in ring and classical configurations.
- Proposal for funding to EU - under discussion (ERC, SINERGY, etc) within the international collaboration.
- Studentship U. Liverpool – CERN advertised.
- Collaboration meeting at Liverpool end of April/beginning of May.

- Request to ISCC: renewed support for HiFi and the SC design study of the recoil fragment separator.



Physics with RS at HIE-ISOLDE

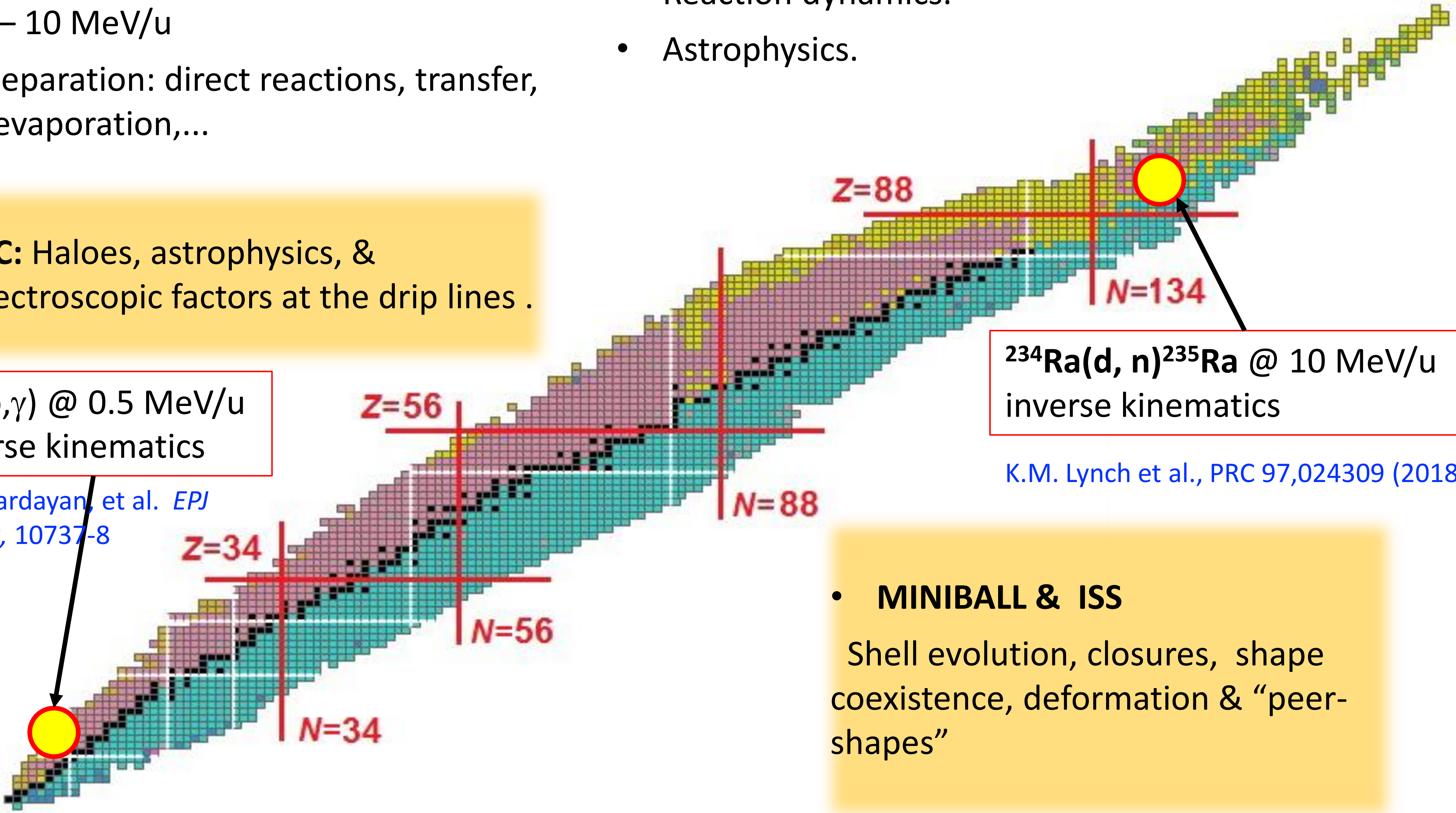
Complement experiments at SEC, MINIBALL and ISS.

E ~ 0.5 – 10 MeV/u

Recoil separation: direct reactions, transfer, fusion-evaporation,...

- Shell evolution and nuclear structure far from stability.
- Reaction dynamics.
- Astrophysics.

- **SEC:** Haloes, astrophysics, & spectroscopic factors at the drip lines .



$^{17}F(p,\gamma)$ @ 0.5 MeV/u
inverse kinematics

D. W. Bardayan, et al. *EPJ A, 2009*, 10737-8

$^{234}Ra(d, n)^{235}Ra$ @ 10 MeV/u
inverse kinematics

K.M. Lynch et al., PRC 97,024309 (2018)

- **MINIBALL & ISS**

Shell evolution, closures, shape coexistence, deformation & "peer-shapes"

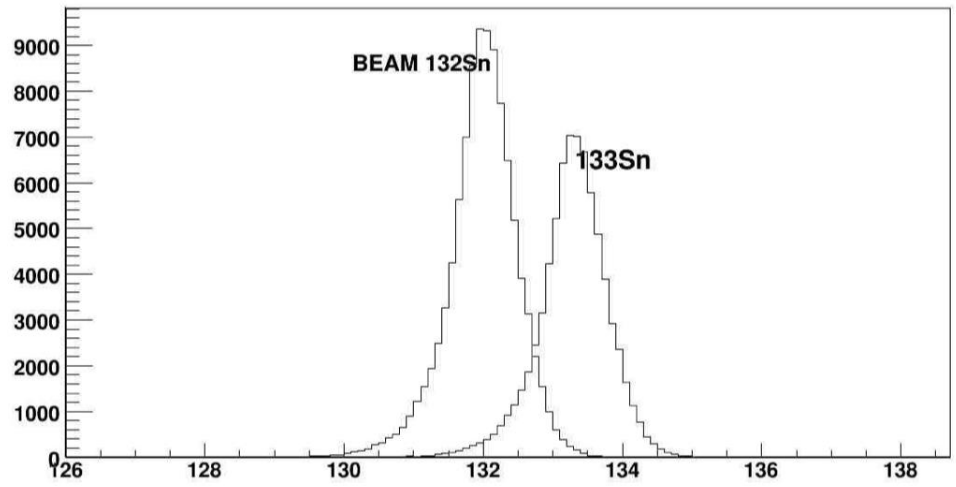
Spectrometer design for HIE-ISOLDE

Gry Tveten

Advisors:
Joakim Cederkall (Lund University) and Sunniva Siem (University of Oslo)

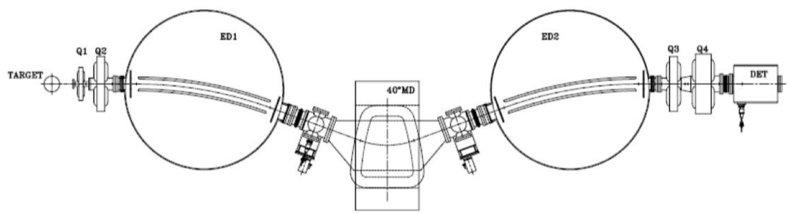
SIMULATIONS

$^{132}Sn(d,p)^{133}Sn$

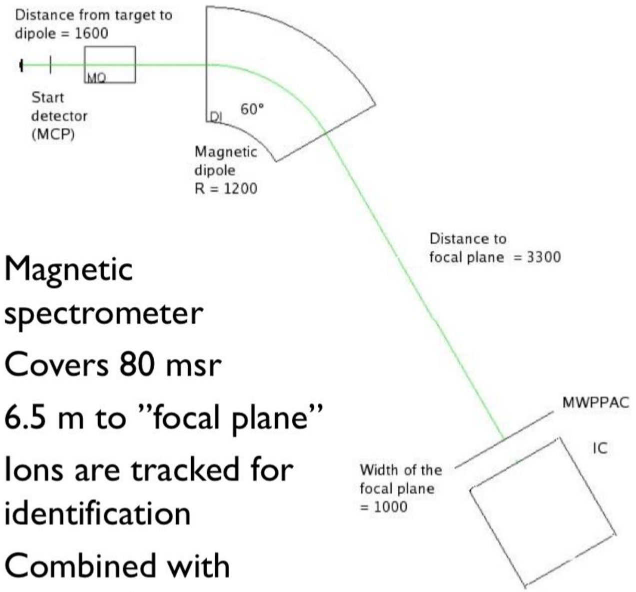


EMMA@TRIUMF

B. Davids, C.N. Davids / Nuclear Instruments and Methods in Physics Research A 544 (2005) 565–576

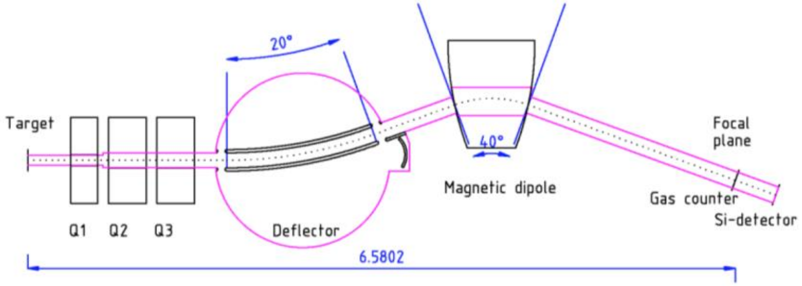


PRISMA@LNL



- Magnetic spectrometer
- Covers 80 msr
- 6.5 m to "focal plane"
- Ions are tracked for identification
- Combined with gamma-detectors

MARA @ JYFL



SIMULATIONS
Test cases

$^{9}Li(d,n)^{10}Be$

$^{22}Mg(d,n)^{23}Al$

$^{68}Ni(d,n)^{69}Ni$

$^{132}Sn(d,p)^{133}Sn$

$^{184}Hg(3He,n)^{186}Pb$

Courtesy of J. Cederkall

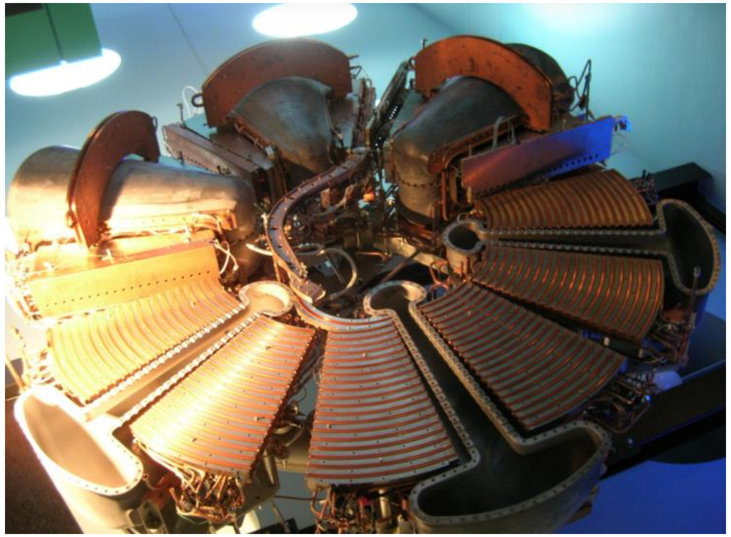
The TRITRON: Separated Sector Cyclotron

The TRITRON. U. TRINKS (1990)

Accelerator Laboratory of both Universities of Munich, D-85748 Garching, Germany.

- Superconducting separated-orbit cyclotron.
- Injection of from the Munich MP-tandem.

- Ion beam guided by 241 SC channel magnets
- AFG along fixed spiral orbits 40 mm width.
- 12 straight sectors per orbit.
- 12 intermediate gaps: SC cavities(170 MHz) & beam diagnostics, extraction, etc.



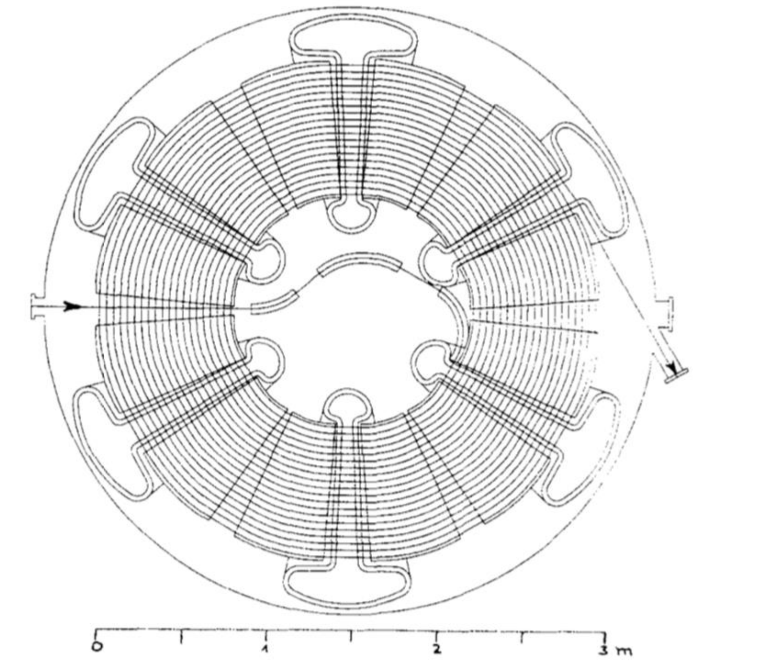
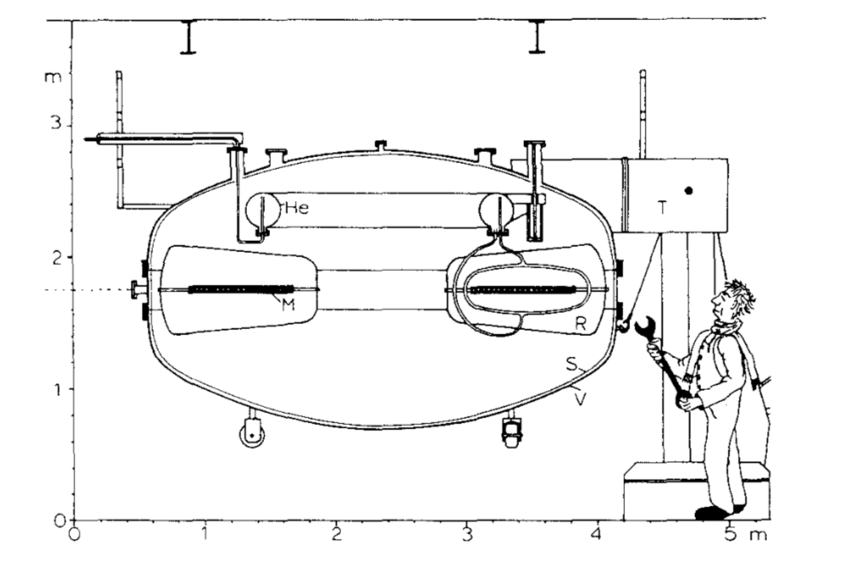


Figure 2: Horizontal cross section of the Tritron. The diameter of the vacuum vessel is 3.6 m.



The TRITRON - project: general design data

TRITRON system

Injector	MP-Tandem (14MV)
Energy gain factor	~ 4.9
Injection radius	0.66 m
Extraction radius	1.45 m
Turn separation	40 mm
Number of turns	20

Magnets

Number of magnet sectors	12
Number of magnet channels/sector	20 (19)
Bending angle per channel	30°
Sector angle	20°
Bending radius	430 mm ... 942 mm
Increment of bending radius per turn	29.94 mm
Geometrical aperture	10 mm
Maximum magnetic induction:	
sector channels	1.7 T
90° - injection channel	2.4 T
Normalized radial gradients	3.6 m^{-1} bzw. -4.9 m^{-1}
Radial betatron oscillation number	1.2 - 1.6
Axial betatron oscillation number	0.8 - 1.7
Synchrotron oscillation number	0.2

Accelerating structures

Number of cavities	6
RF-frequency	170 MHz
Harmonic numbers	~ 14 ...~ 55
Total radial length	1233 mm
Radial gap length	~ 0.85 m
gap width: injection/ extraction	62 mm / 128 mm
Aperture of the beam holes	13 mm
Maximum gap voltage (design)	0.53 MV
Maximum electric field (design)	4.7 MV/m
Peak field to maximum gap field	< 1.5
Unloaded quality factor	500 000 000
Dissipated heat per cavity	6 W

Cryostat

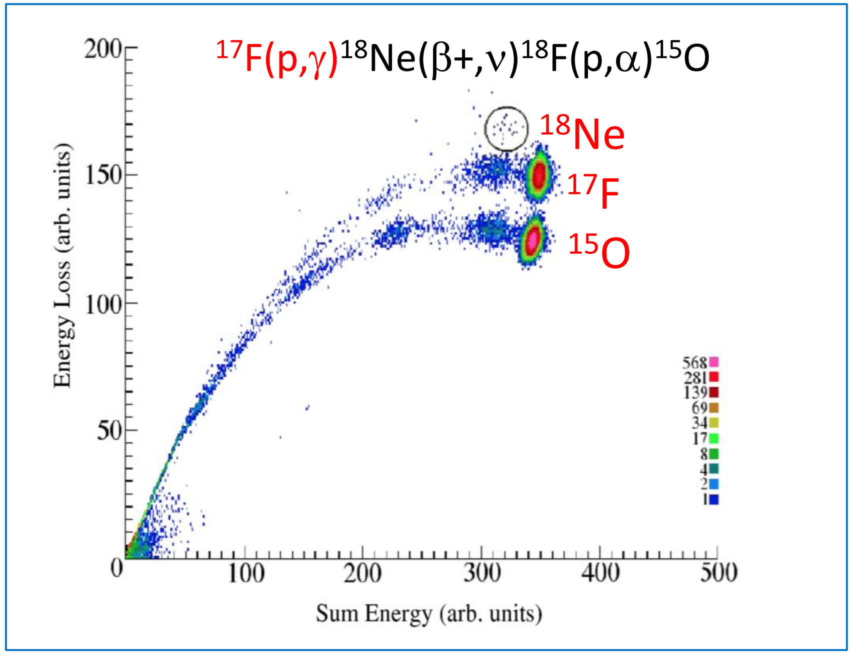
Diameter	3.6 m
Height	~ 3 m
Cold mass	7 000 kg
Refrigerator power at 4.6 K	155 W

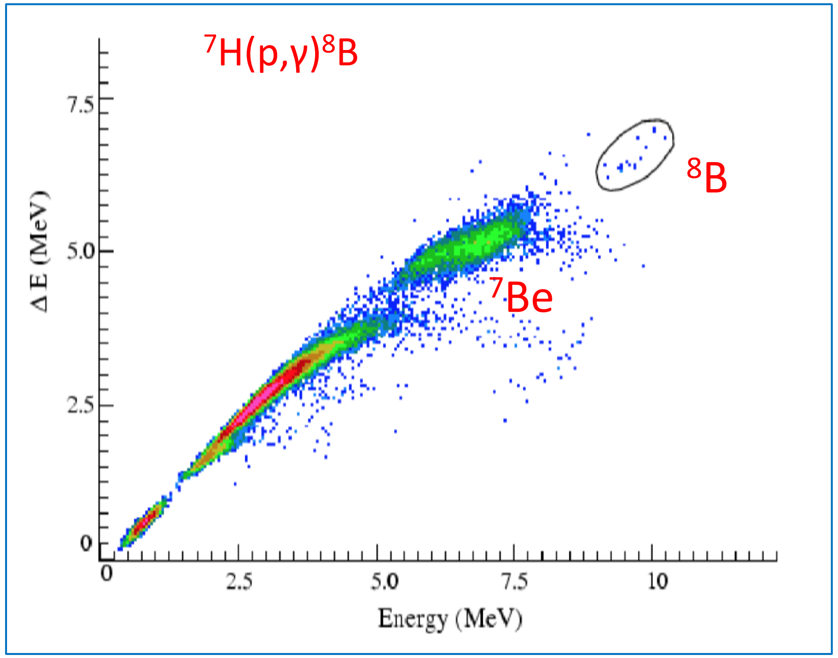
Direct measurements of (p,γ) cross sections at astrophysical energies using radioactive beams and the Daresbury Recoil Separator

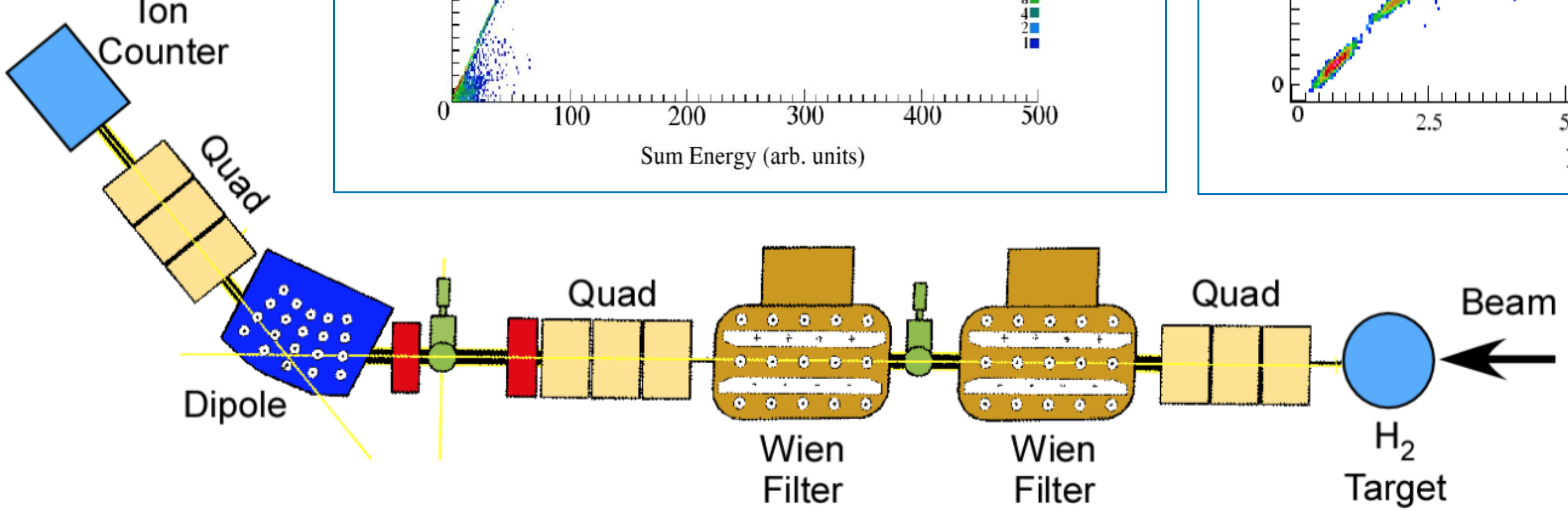
D. W. Bardayan, et al. *European Physical Journal A, 2009.* DOI: 10.1140/epja/i2008-10737-8

HRIBF (Oak Ridge) using the Daresbury Recoil Separator (DRS)

Explosive nucleosynthesis/X-ray bursts/Supernovae







Dedicated experiments with **γ, n** at exit channel

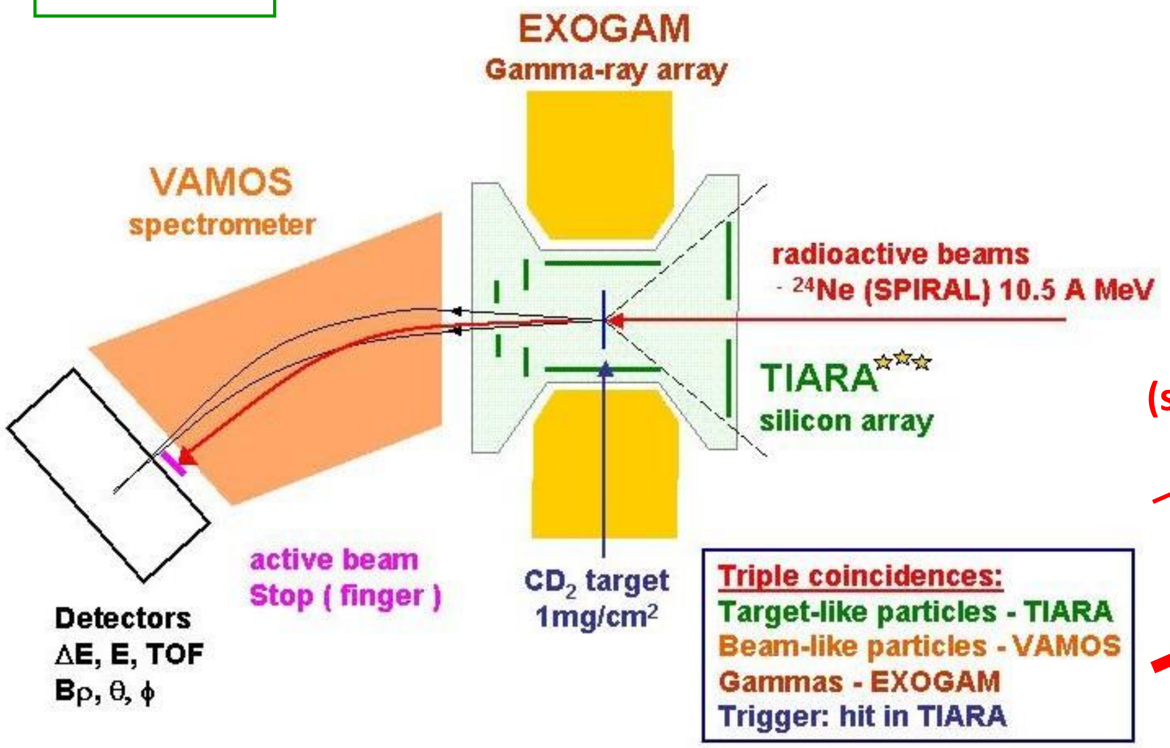
Study of $^{24}Ne(d, p\gamma)^{25}Ne$

GANIL - SPIRAL W.N. Catford *et al.*, Eur. Phys. J. **A25**, Suppl. 1, 245 (2005).

N=16 replaces broken N=20

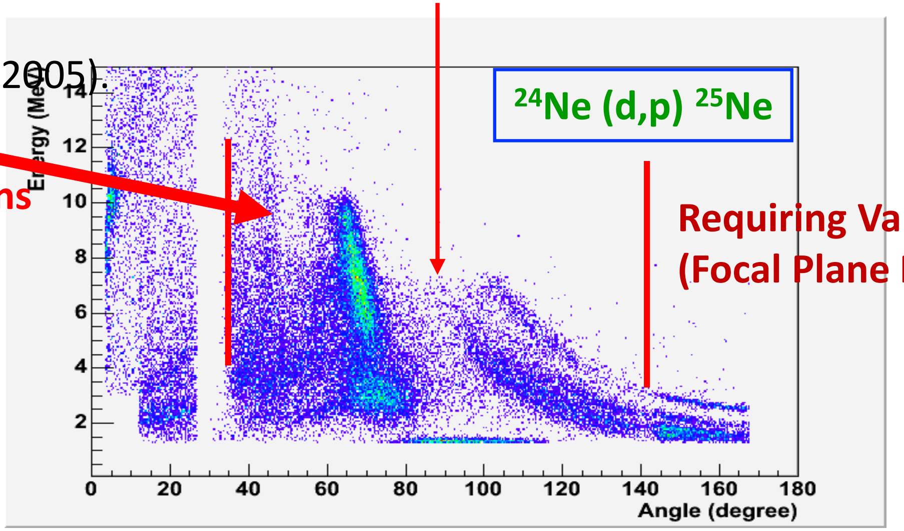
Target 1.0 mg/cm^2 of $(CD_2)_n$

~ 10 A.MeV



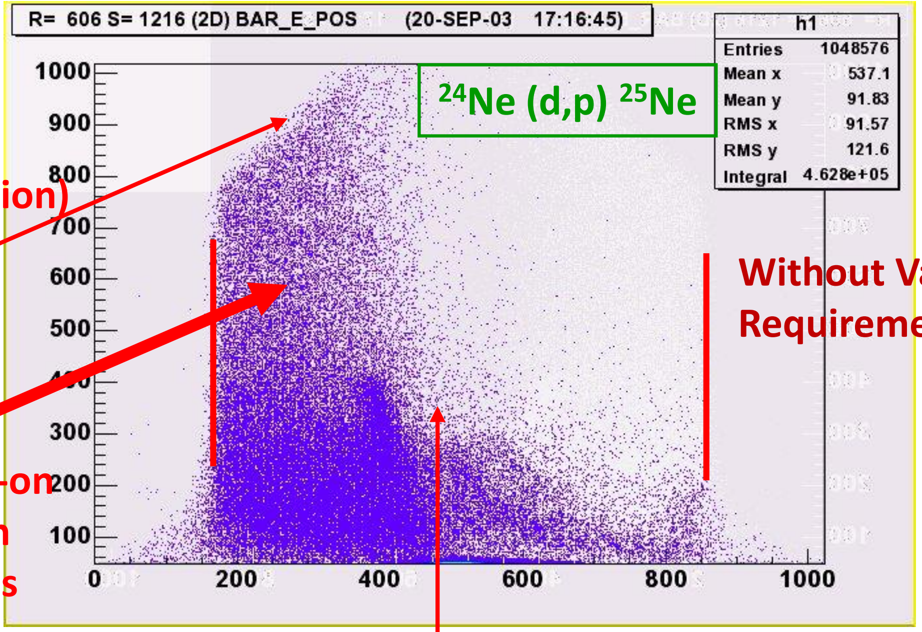
(90 degrees)

(d,t) tritons



Requiring Vamos (Focal Plane Plastic)

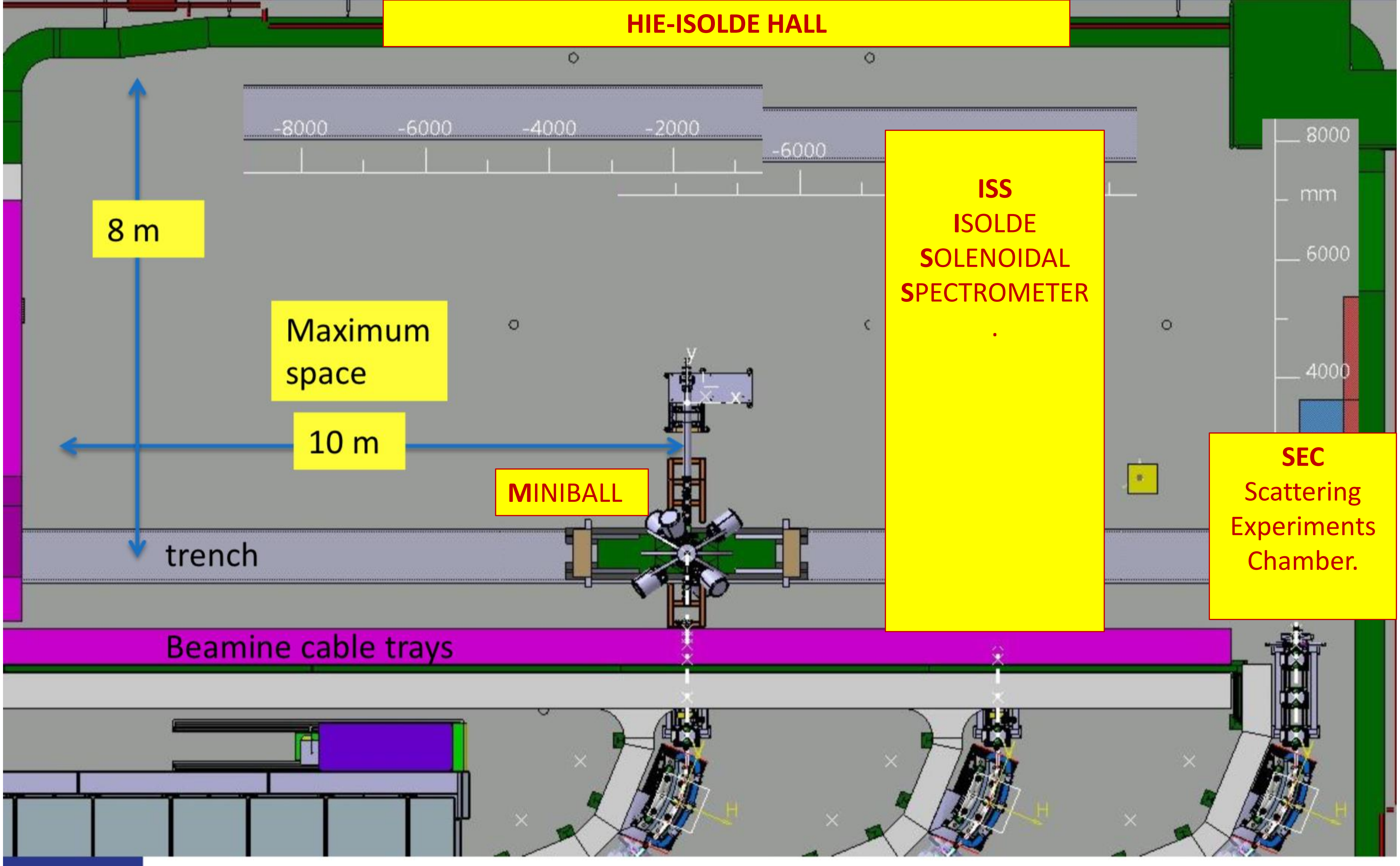
(saturation)



Without Vamos Requirement

Knock-on carbon elastics

(90 degrees)


HIE-ISOLDE HALL
-8000
-6000
-4000
-2000
-6000
8000
mm
6000
4000
8 m
Maximum space
10 m
MINIBALL
trench
ISS
ISOLDE
SOLENOIDAL
SPECTROMETER
SEC
Scattering
Experiments
Chamber.
Beamine cable trays