Update on the ISOLDE Superconducting Recoil Separator

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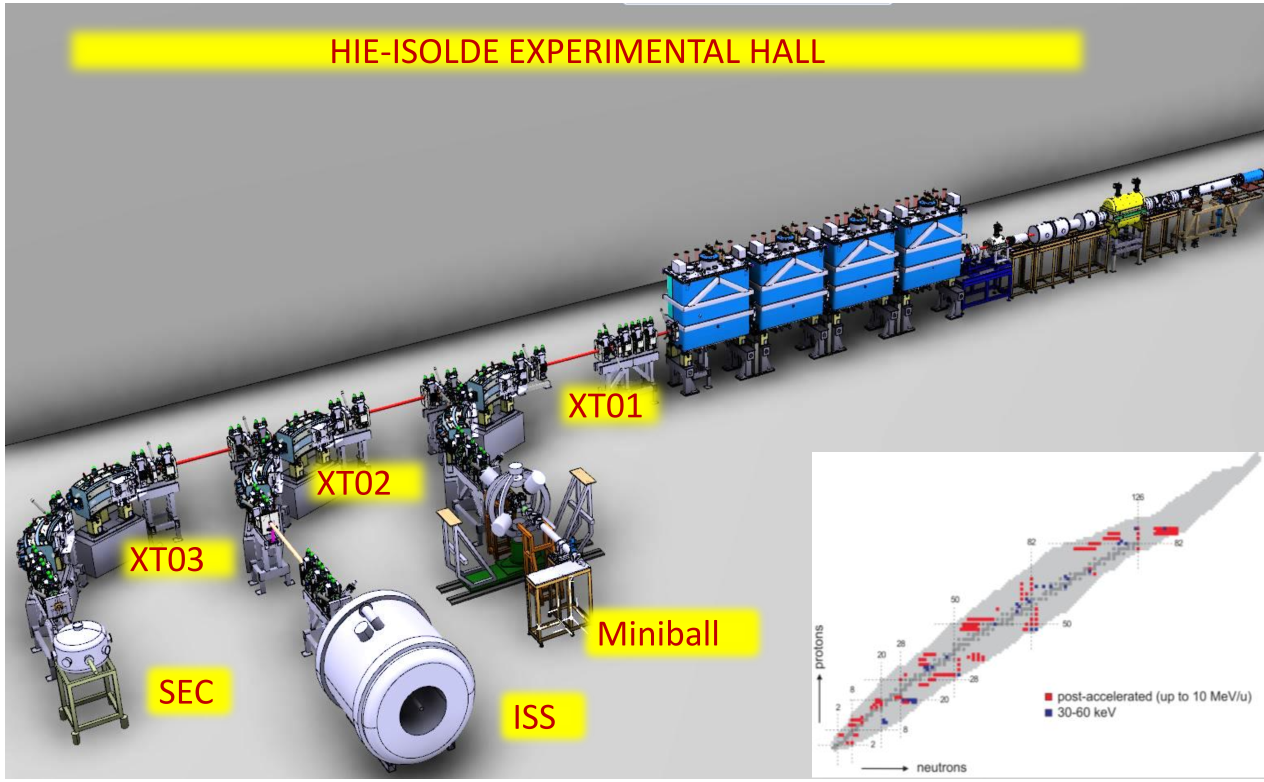
THE HIE-ISOLDE FACILITY AT CERN

World-leading facility in radioisotope production and acceleration

- Large range of radioactive beams: from ^{6}He – ^{234}Ra
- > 1000 isotopes, > 70 elements
- Wide energy range 0.45 -~ 10 MeV/A



- Broad research program with radioactive nuclei
- A Recoil Separator will greatly extend the ISOLDE physics program.
- Previous project: HIE-Isolde Fragment Identifier, using warm magnets (HIFI) – 2011-2017.

<u>Present :</u> ISOLDE Superconducting Recoil Separator (ISRS)

- First studies started in 2019
- LoI INTC-I-228 approved, INTC-2021.

LoI INTC-I-228: Design study of a Superconducting Recoil Separator for HIE-ISOLDE

Objective: carry out R&D program to study the possibility to develop a compact fragment separator using **innovative** concepts and technologies:

(1) Mini- particle storage ring

(2) Fixed Field Alternating Gradient

(3) Iron free combined-function Canted Cosine Theta magnets

(4) cryostats cooled by cryocoolers

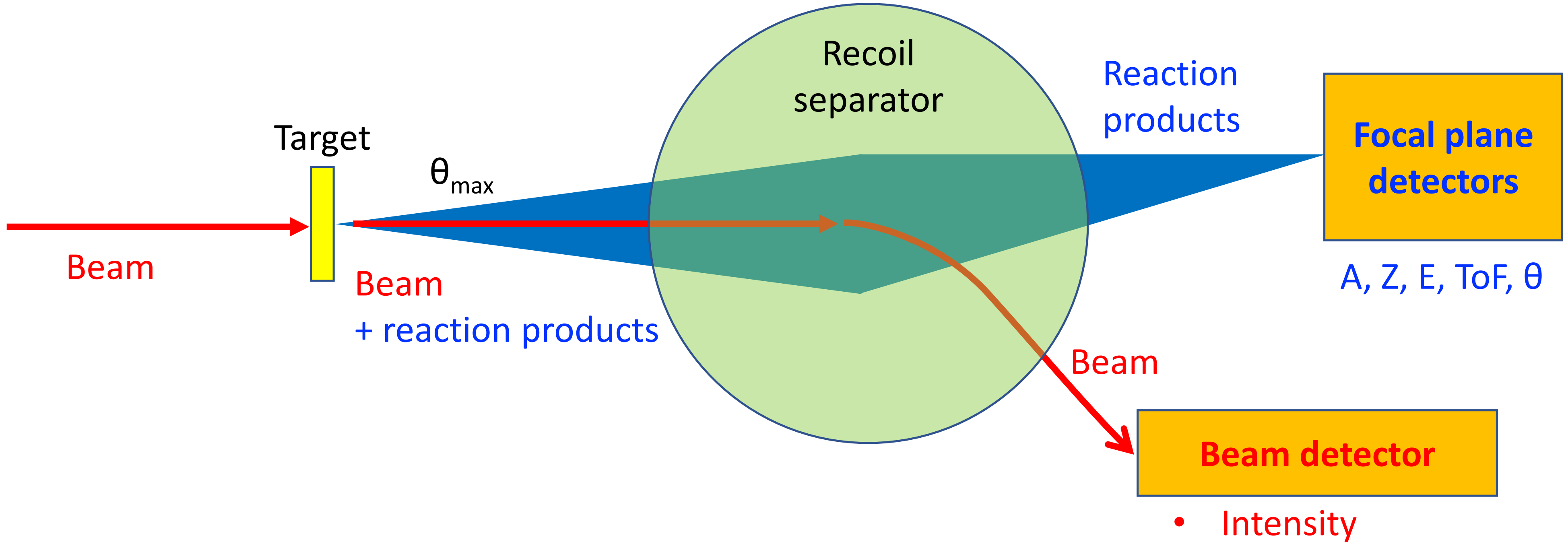
- **Technological breakthrough** for future fragment separators, mass spectrometers, recirculating targets (→TSR)
- **Construction** of mini-particle accelerators and ion-transport systems for societal applications → hadron-therapy, radioisotope production, gantries.

Main advantages:

- **Mini-RING particle storage system:** large flight path in small space → ToF, Q/A resolving power, …
- **RF system:** mass spectrometry → synchronous mode of operation.
- **FFAG:** allows storing particle beams of large momentum and energy acceptance using FIXED FIELDS.
- **Multifunction SC magnets:** Compactness; High B, Low power.
- **Iron-free SC CCT:**
  - ✓ CCT Versatility, high-order corrections
  - ✓ Lightweight systems
  - ✓ Avoid iron hysteresis/nonlinearities
  - ✓ Energy consumption
- **Cryostats cooled by cryocoolers:** portability, mobility and operation (rotations – complex if using LHe)

Recoil Separators

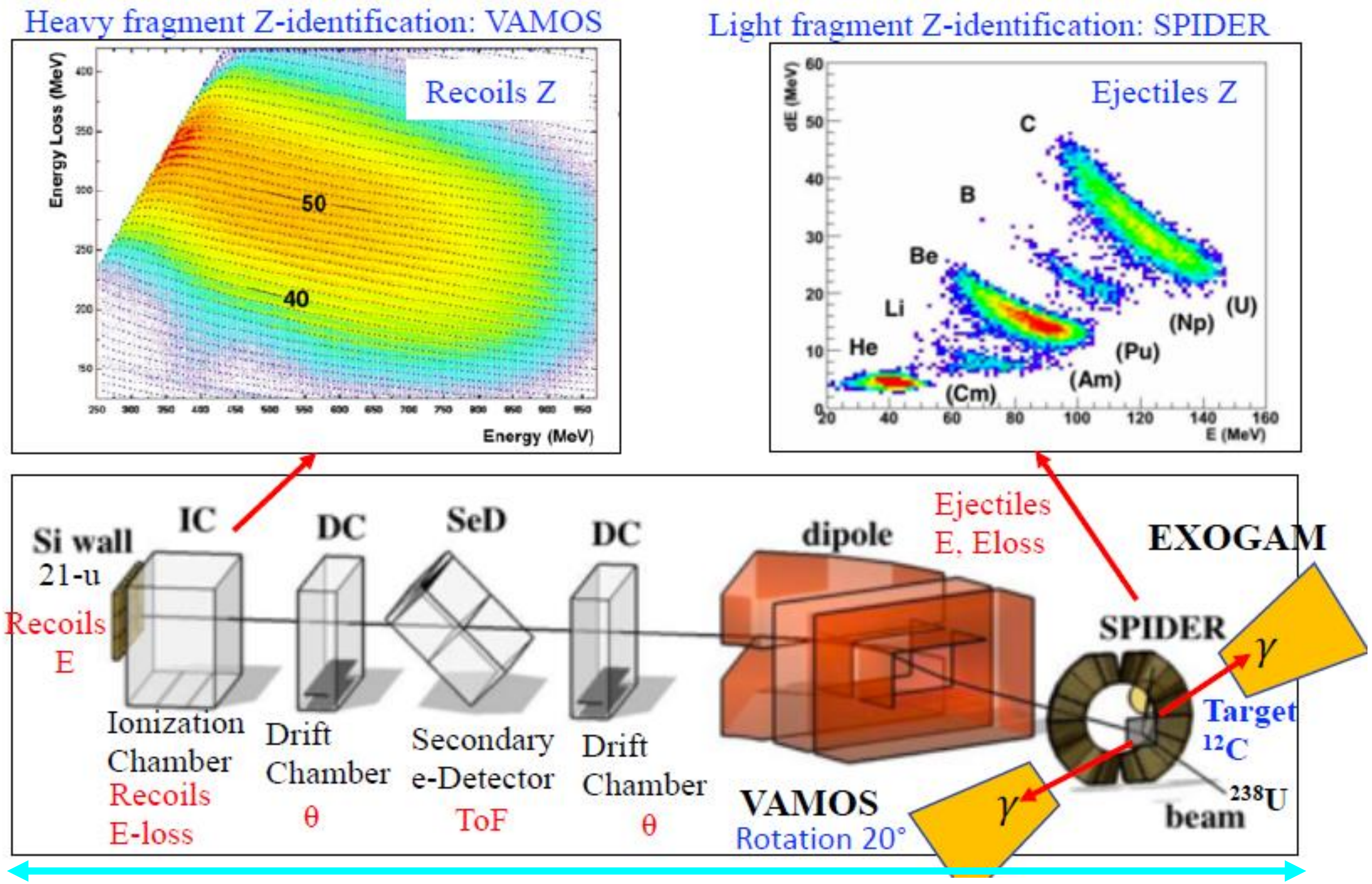
- Use to detect forward focussed reaction products (recoils): A, Z, E, ToF, θ
- Separate them from the primary beam.



VAMOS @ GANIL (Caen, France)

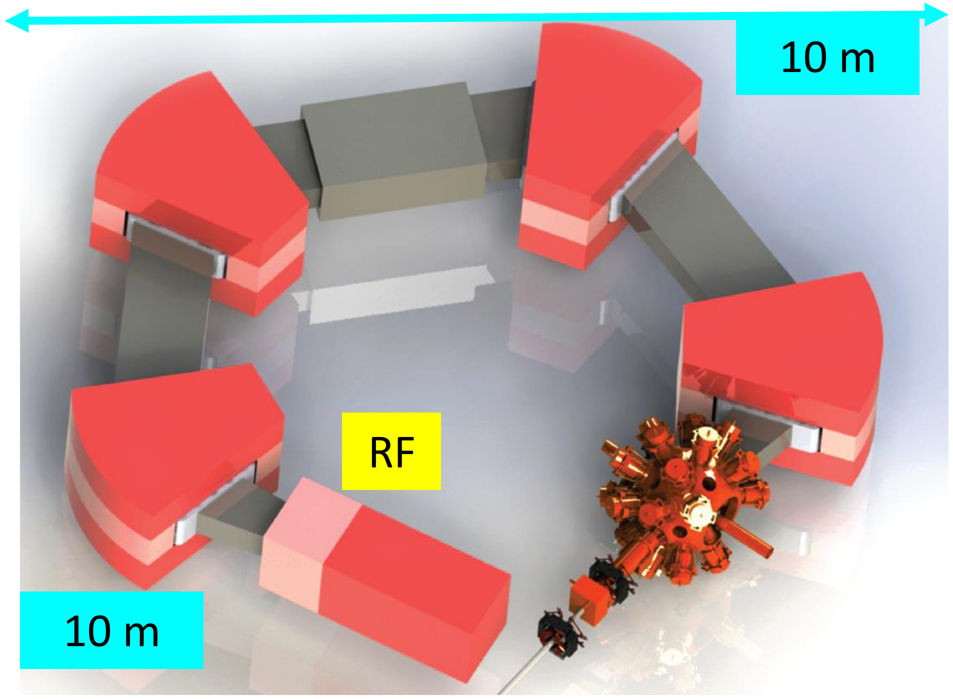
Selectivity on rigidity

Flight path ~ 10 m
R > 200



15 m

ISLA @ FRIB (Michigan, USA)



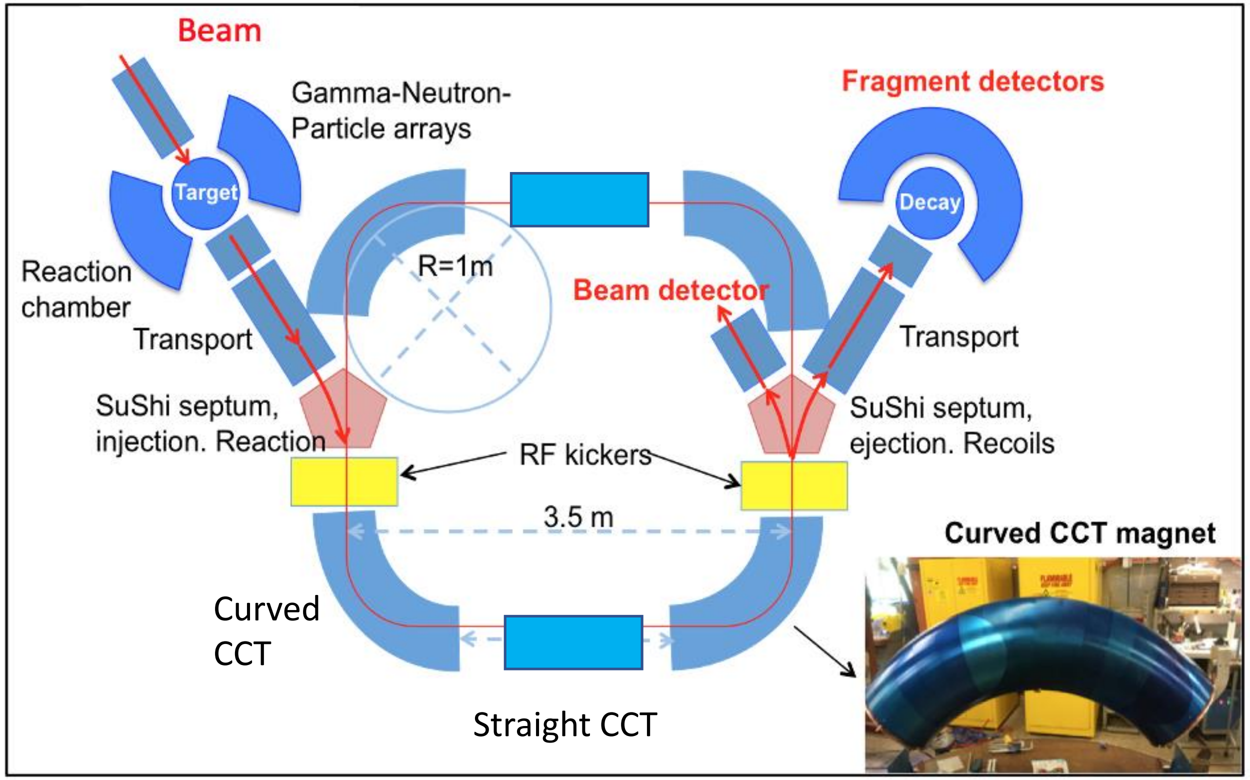
Selectivity on ToF:

Larger fight path ~ 20 m
γ-taggin on target with scintillators (<1ns)
MCP at focal point (0.1 ns)
RF system → select A/q and charge states
R > 1000

Nuclear Instruments and Methods in Physics Research B 317 (2013) 319–322

ISRS concept

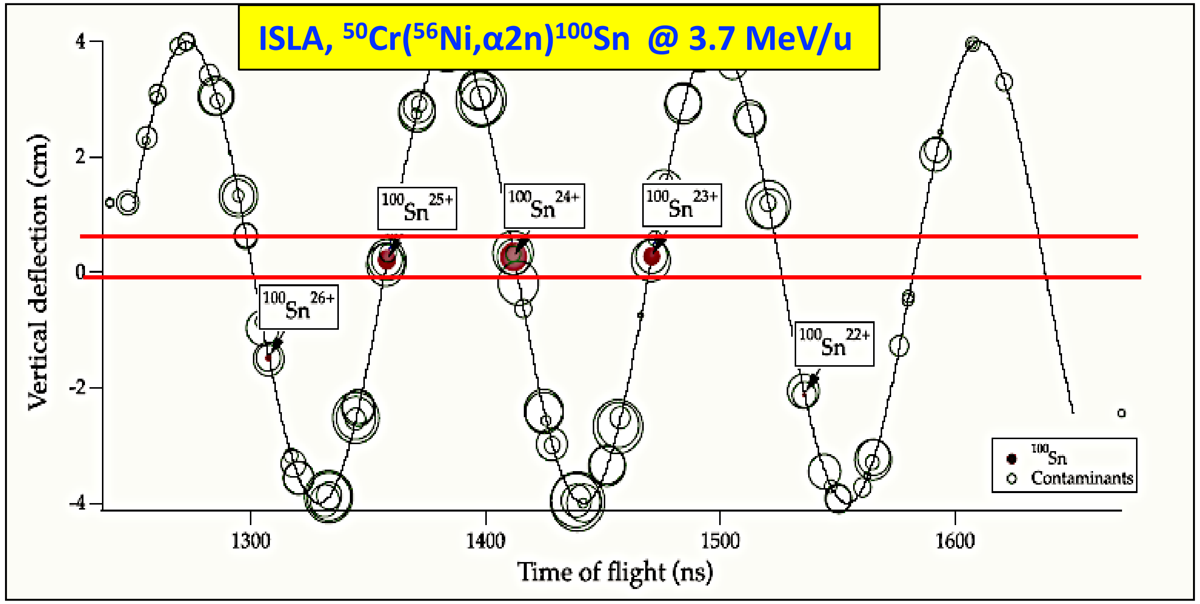
Nuclear Inst. and Methods in Physics Research, A 969 (2020) 164048



Large A/Q selectivity

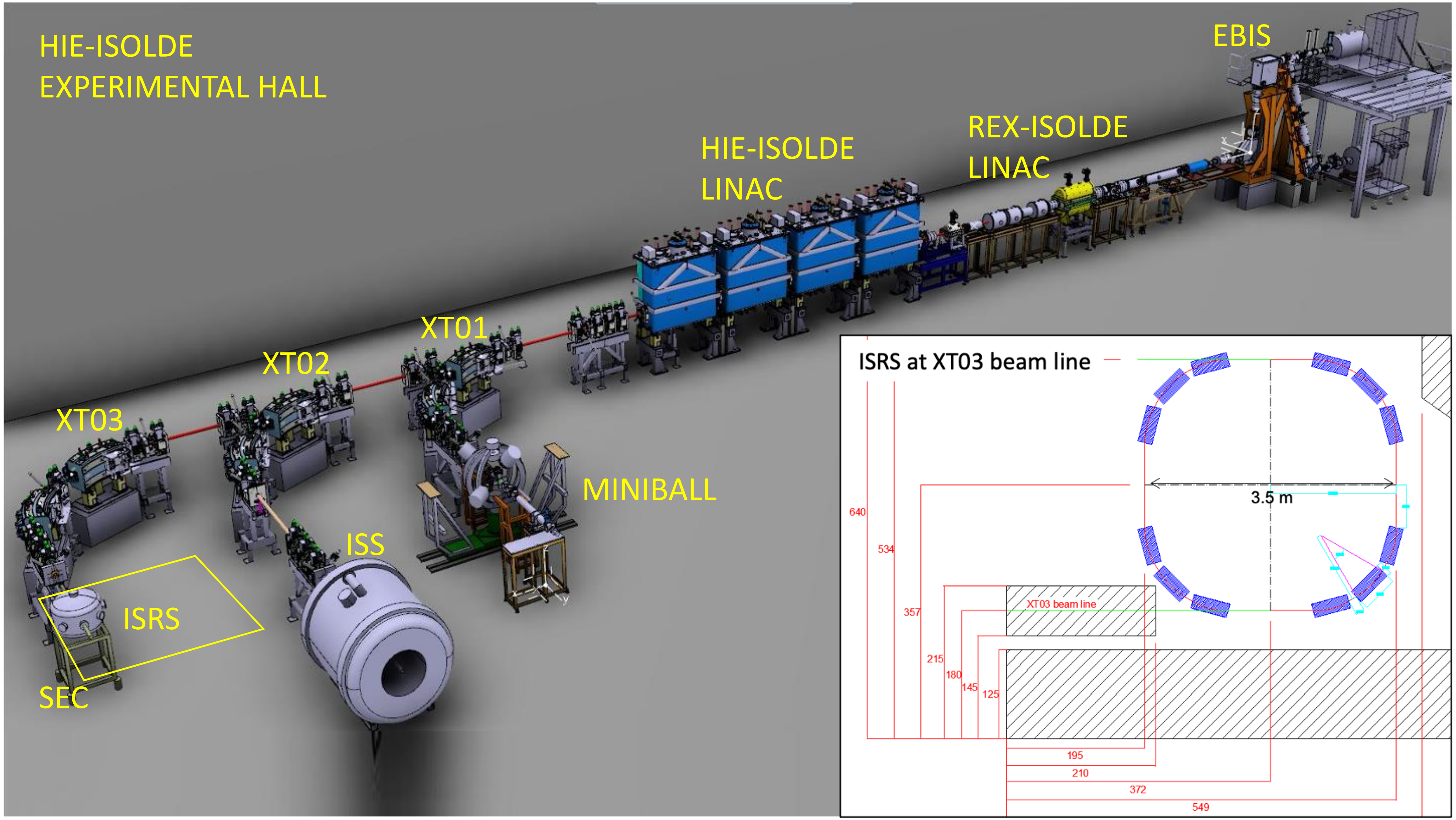
- Magnetic rigidity Bρ
- Cyclotron frequency ωc
- RF frequency ω_{RF}
- γ-taggin on target with scintillators (ToF <1ns)
- Eloss detectors (Focal Plane) → E, Q, A, ToF (<5ns)

RF cavity at the isochronous focus → deflection & Q/A
RF harmonic and phase → charge states of the same isotope

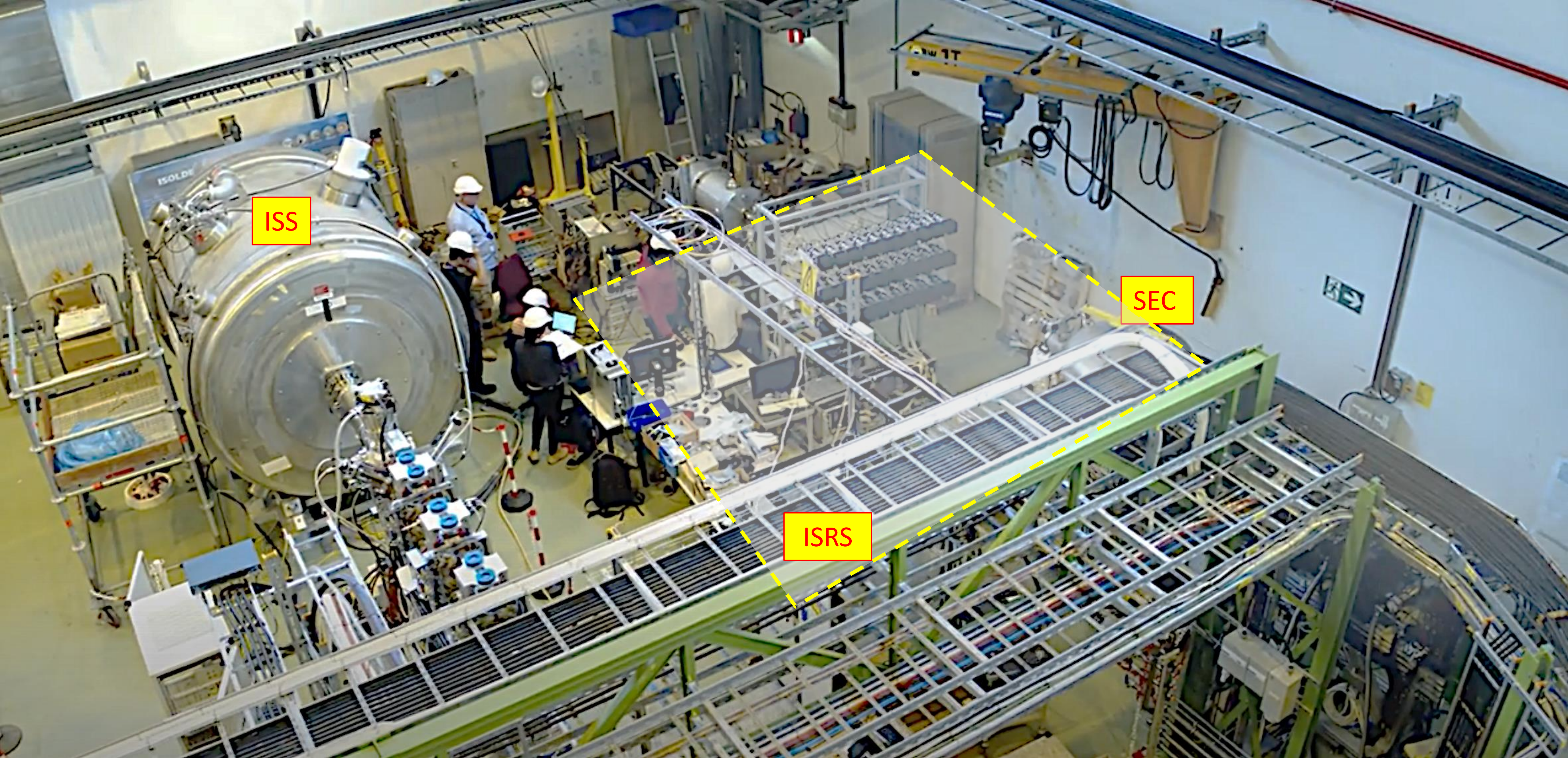


Nuclear Instruments and Methods in Physics Research B 317 (2013) 319–322

- Large acceptance particle storage system (FFAG optics)
- Mini-ring ~ 3.5 m diameter (CCT comb. function magnets)
- Increased flight path ~ 200 m
- 100% storage efficiency (from ^{11}Li to ^{234}Ra @ 10 MeV/u)
- R >> 1000



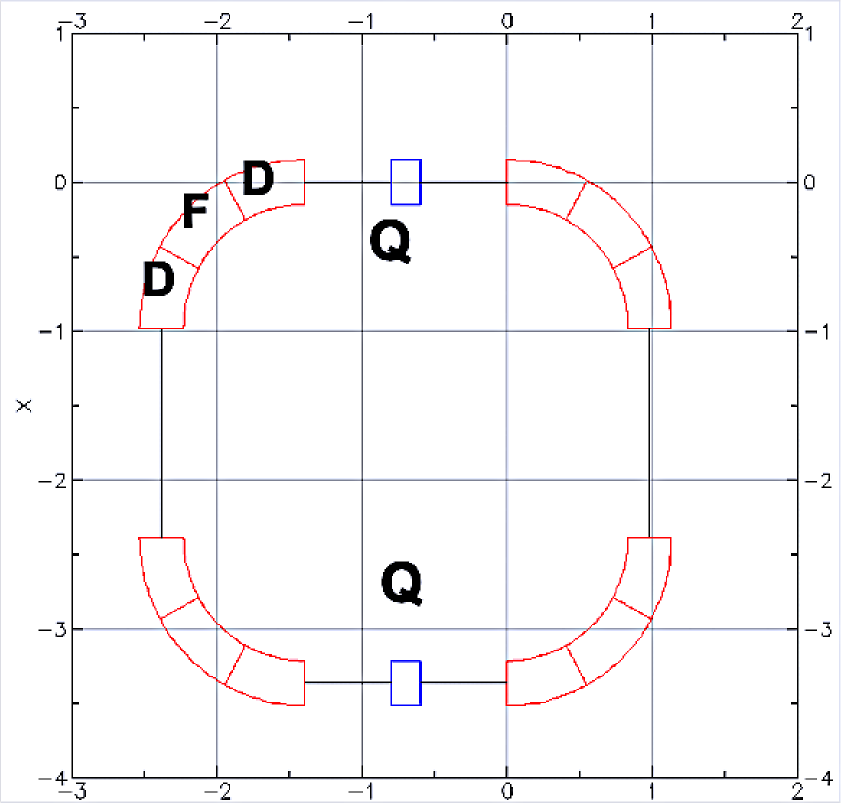
Courtesy of A. Rodríguez, CERN



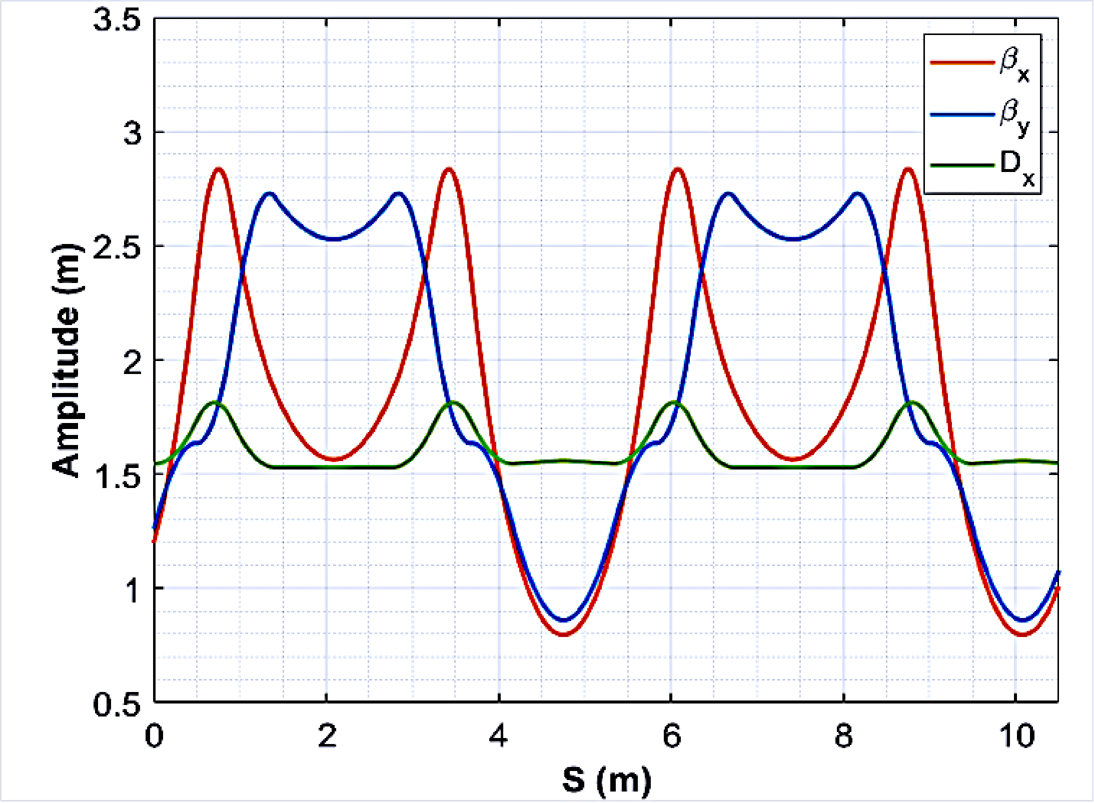
ISOLDE
ISS
SEC
ISRS

ISRS BEAM DYNAMICS

Study for isochronous optics solution



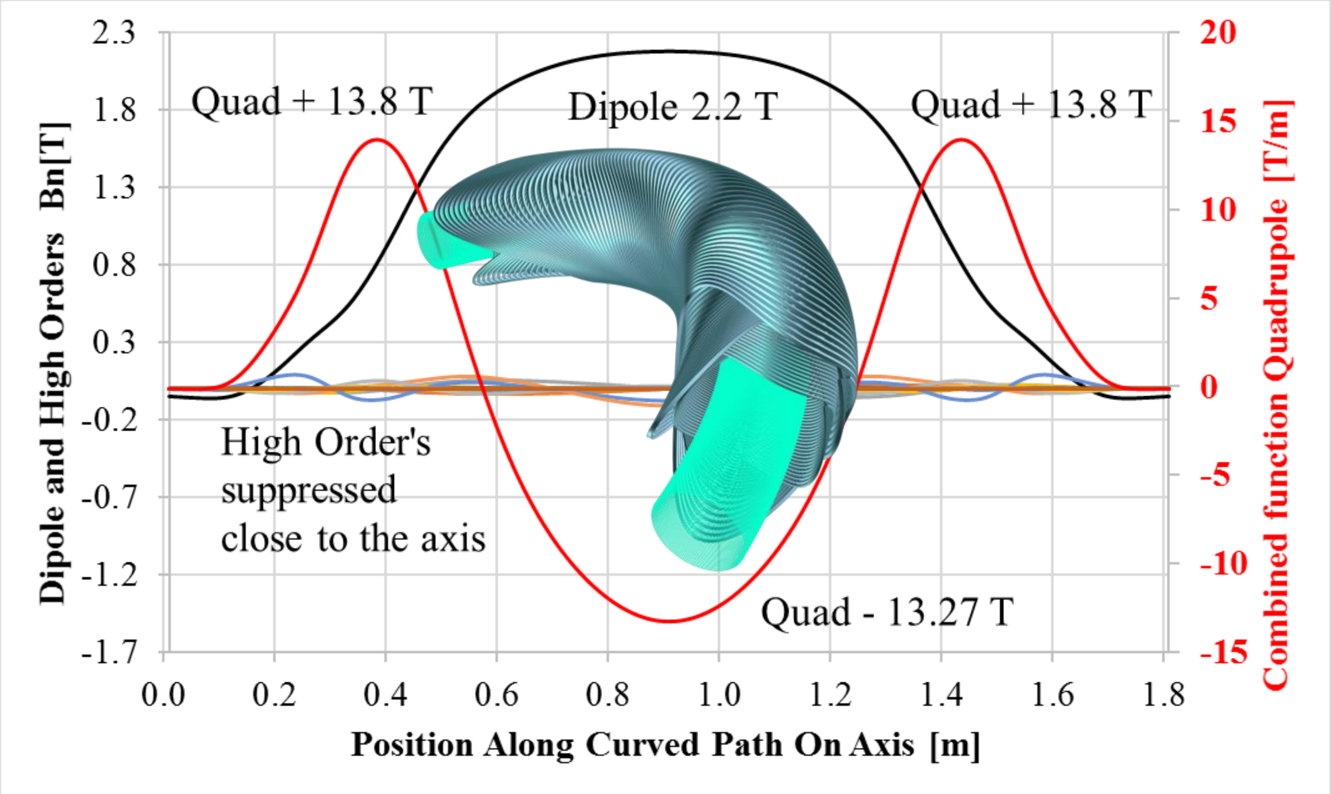
Floor plan of the ISRS ring consisting of four 90° CCT magnets with a DFD alternating quadrupolar sequence and two additional quadrupoles (Q) to facilitate optical matching.



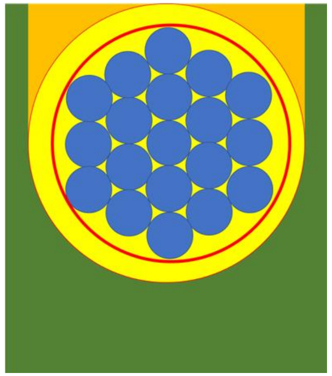
Twiss parameters (betatron functions $\beta_{x,y}$ and first order dispersion function D_x) of the ISRS lattice for an isochronous optics solution.

Courtesy of J. Resta, Univ. Valencia

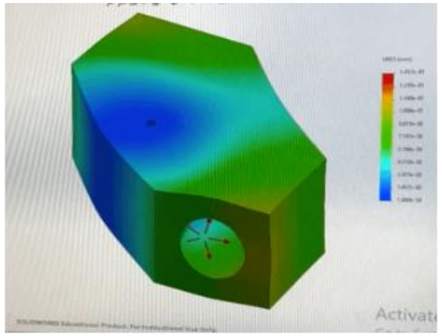
CCT DIPOLE + TRIPLET DESIGN & CONSTRUCTION



Resins investigation

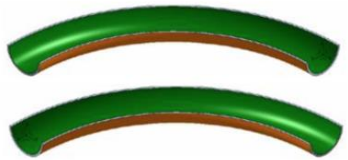


Channel layouts

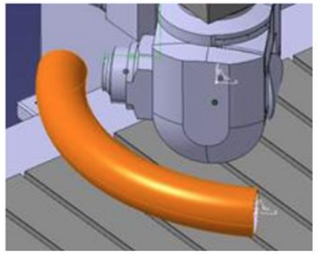


Deflection stress

Machining → formers



Two halves



e-welding + machining

Full HIE-ISOLDE combo coil Dipole 2.2T- Quad 15 T/m 200 mm aperture 1 m curvature radii 90 deg = 1570 mm arc length 24 wires in 4x6 channel

9 km wire, 710 A 4.1 T peak field 2 layers – formers Inductance 768 mH Stored Energy 193.5 kJ Load line fraction 79.8%

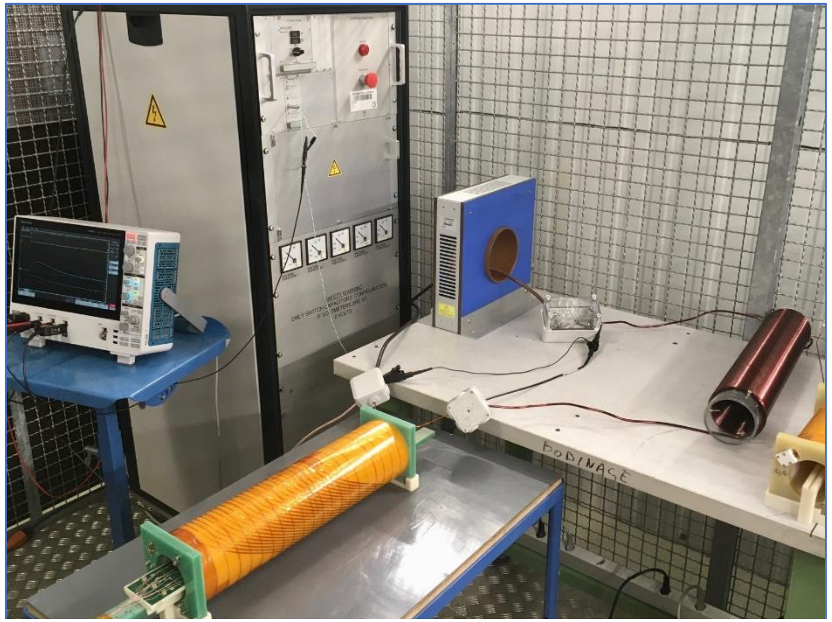
- CCT Protection,
- Impregnation,
- Winding force on channel walls,
- etc

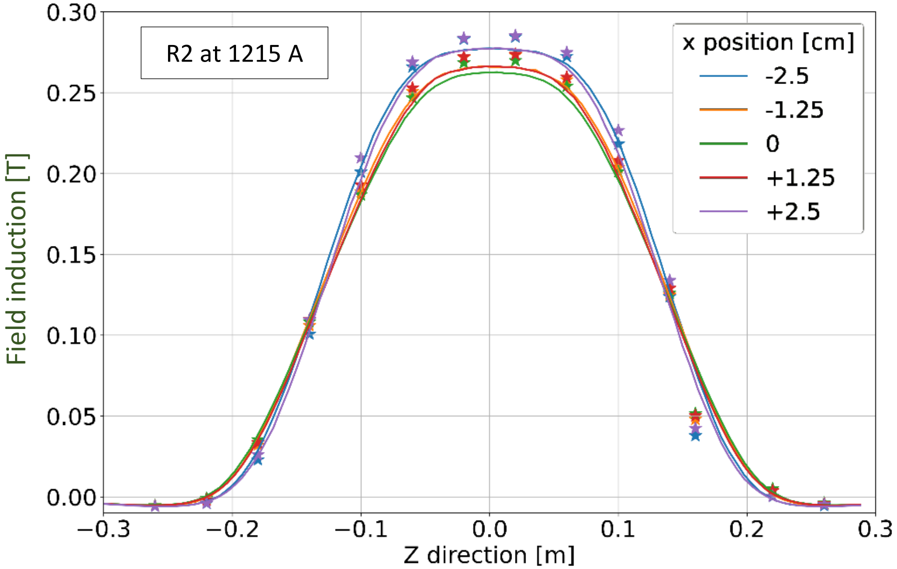
G. Kirby et al., IEEE Transactions on Applied Superconductivity 23(2022)1-5, 10.1109/TASC.2022.3158332

Courtesy of G. Kirby, CERN

CCT Technology development

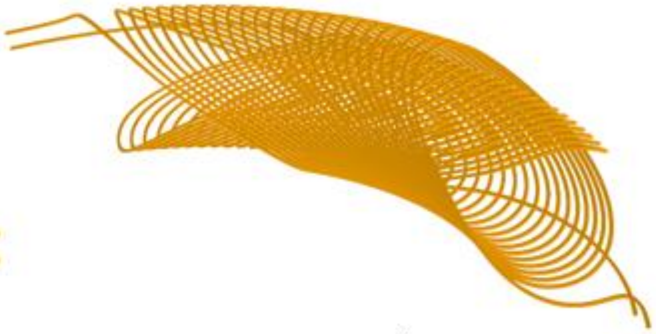
First step: pulsed resistive models



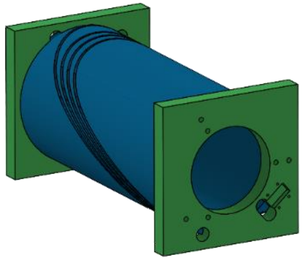


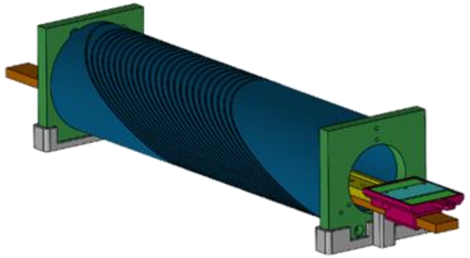
Short Straight - R1

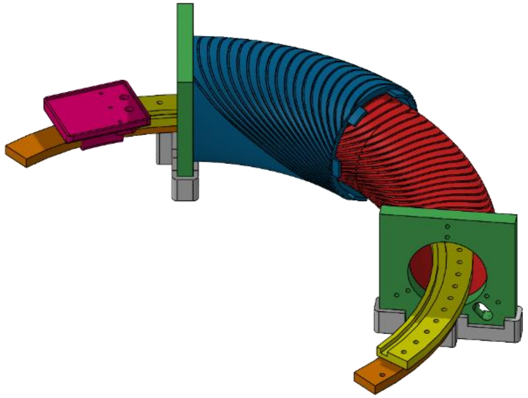
Long Straight - R2

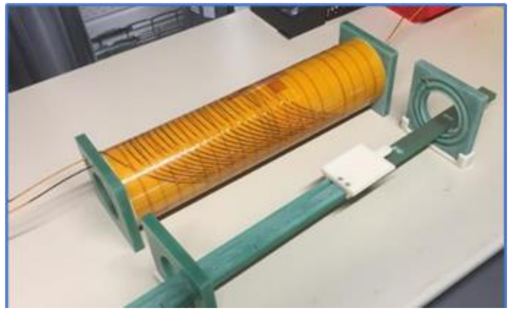


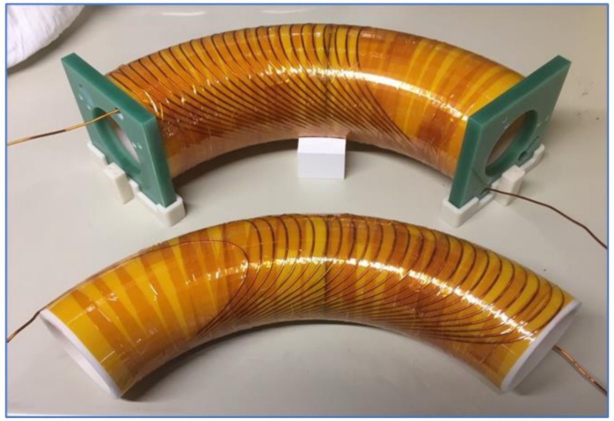
Long Curved - R3





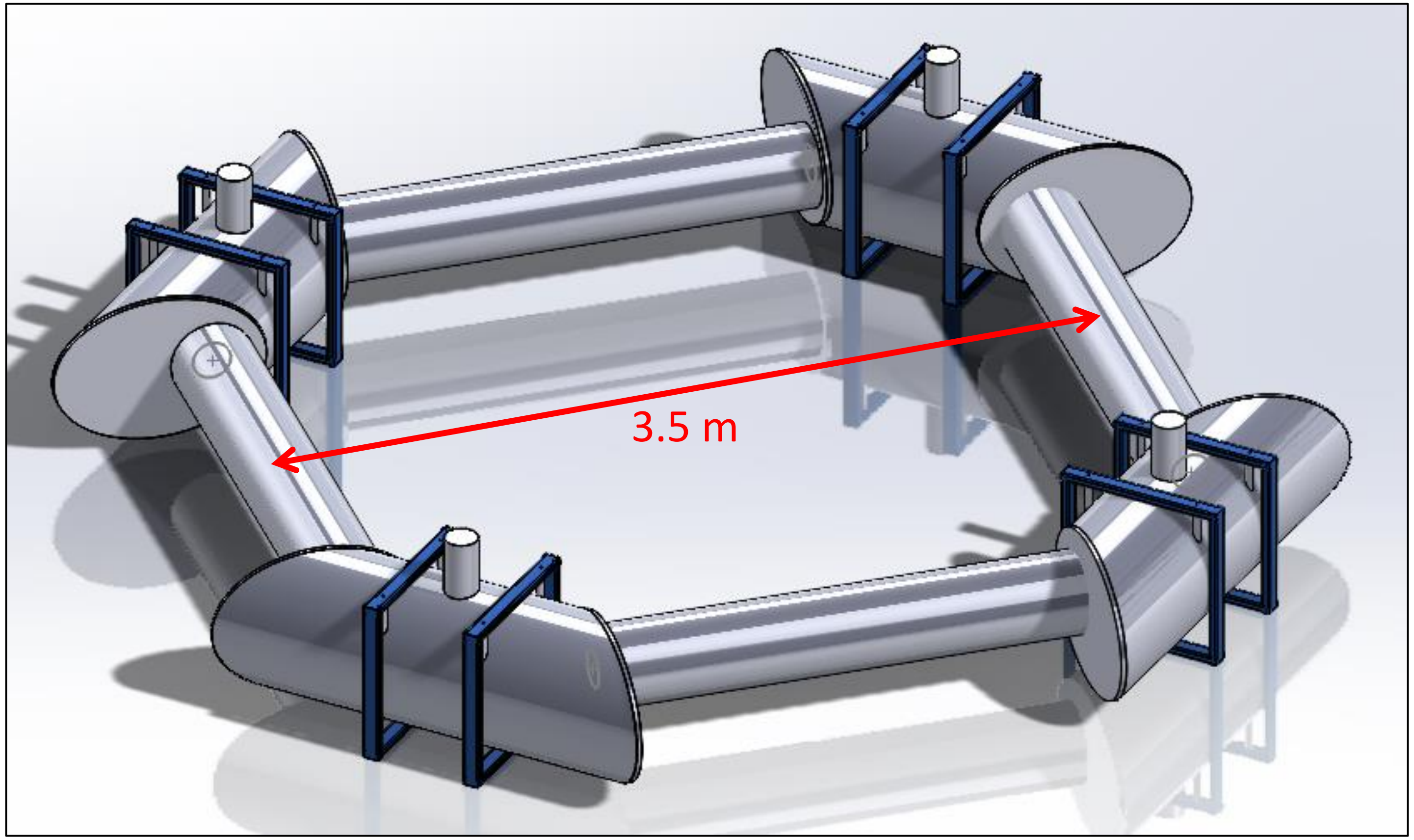




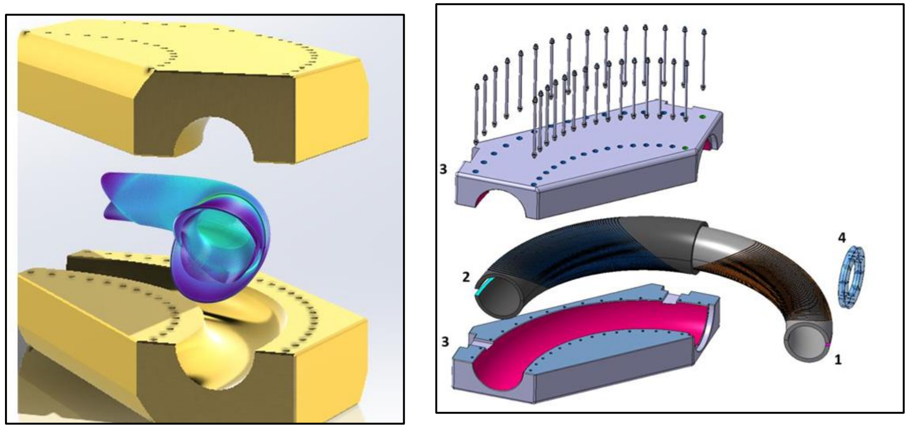


Courtesy of D. Tommasini, CERN

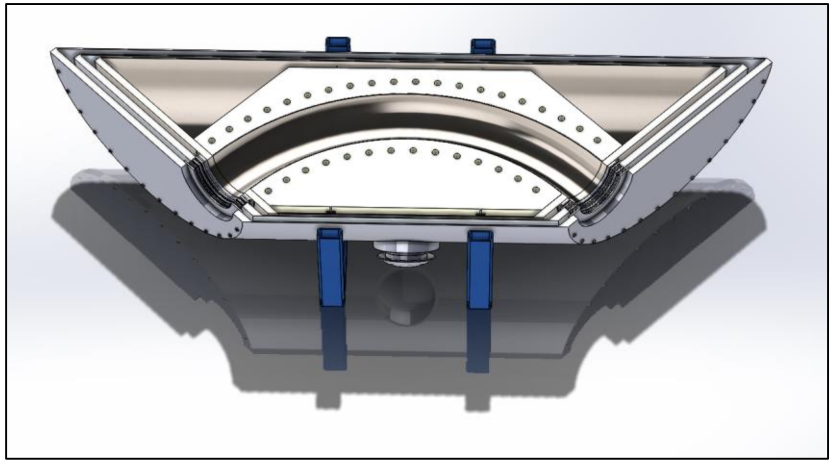
ISRS PRELIMINARY DESIGNS



MINI-RING



CCT Dipole

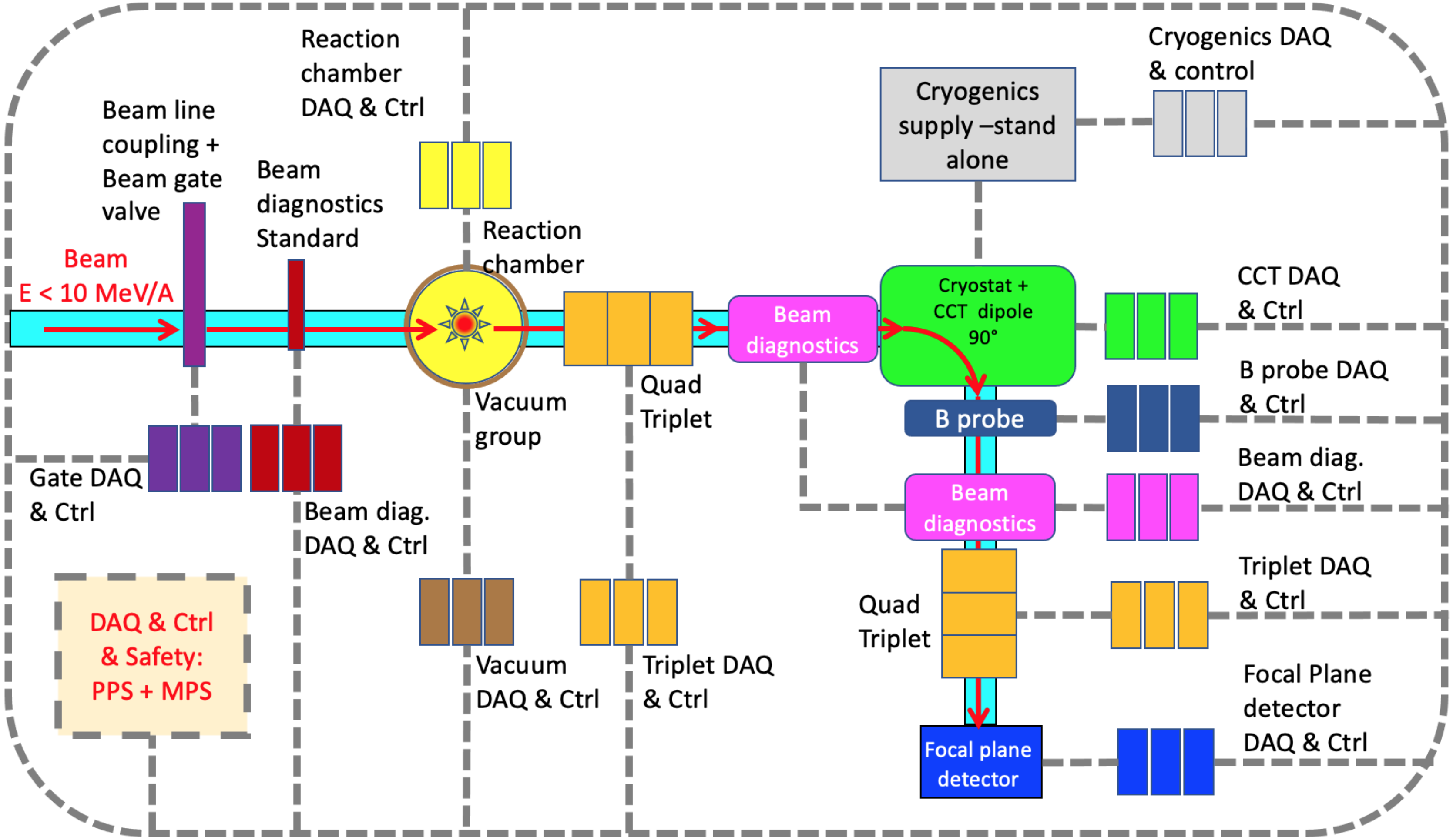


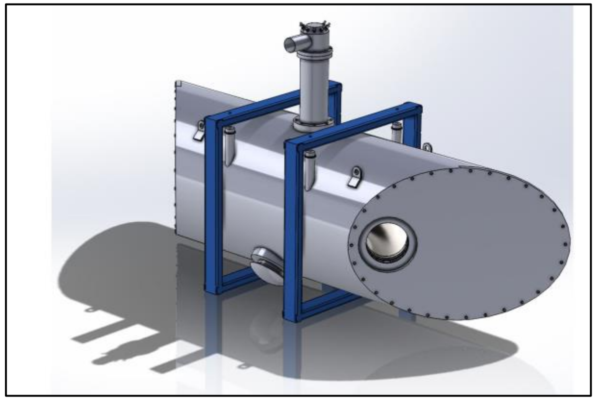
CRYOSTAT

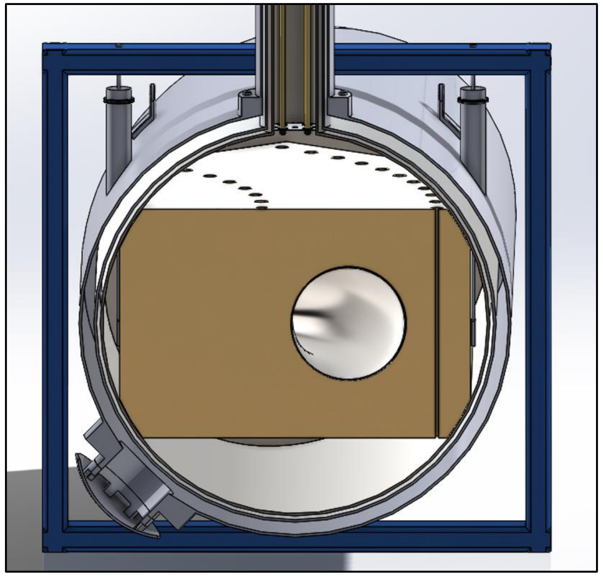
Courtesy of G. Kirby, CERN

CCT test bench

- Test the CCT magnet with ion beams
- Obtain data to validate beam dynamics
- Preliminary concepts, technical drawings, definition of subsystems

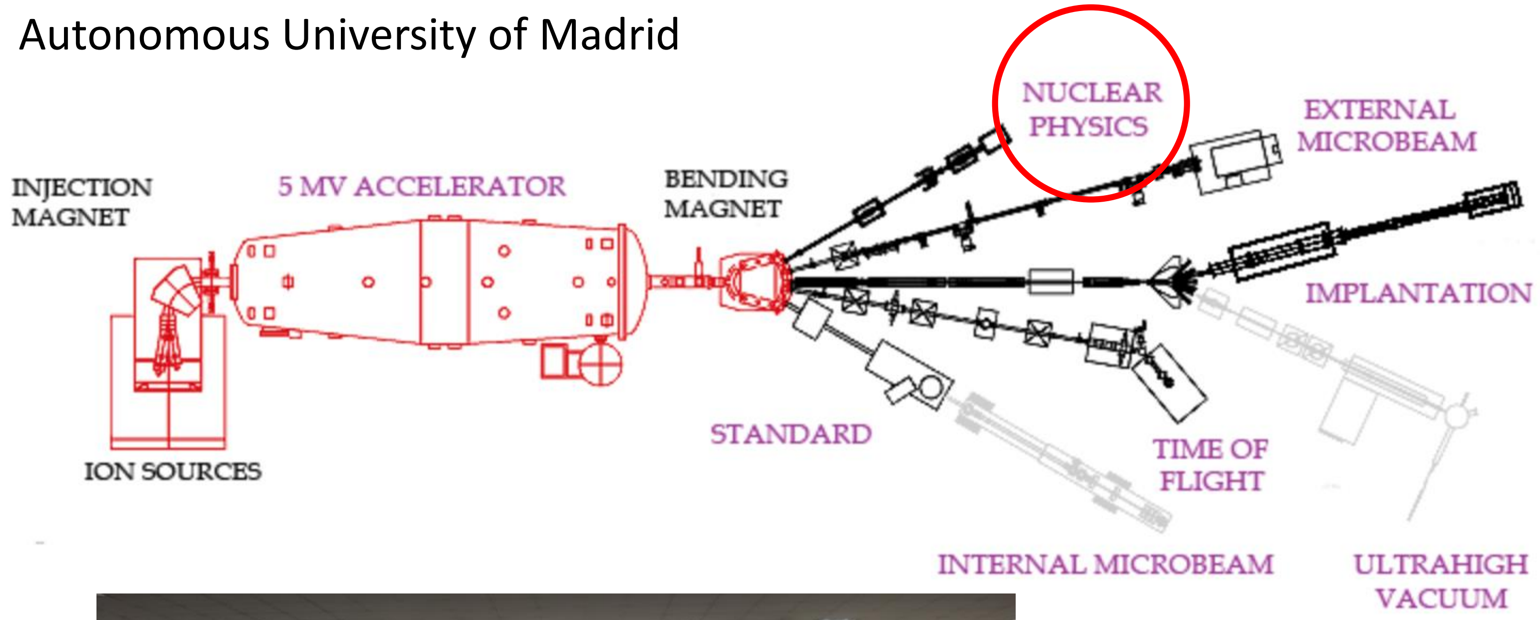






CMAM (Centro de Micro-Análisis de Materiales)

Autonomous University of Madrid



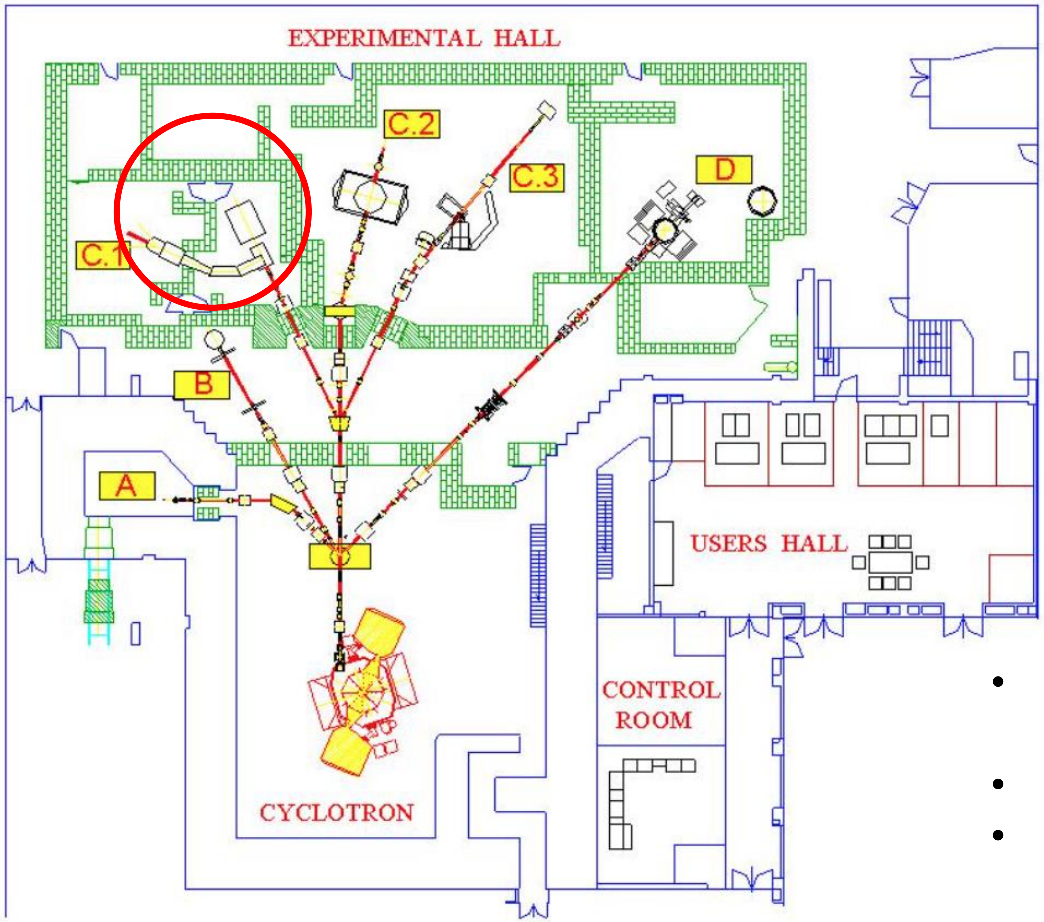
- 5MV terminal voltage tandem accelerator (Tandetron)
- Duoplasmatron Ion Source
- Sputtering Ion Source
- Buncher system (on going)

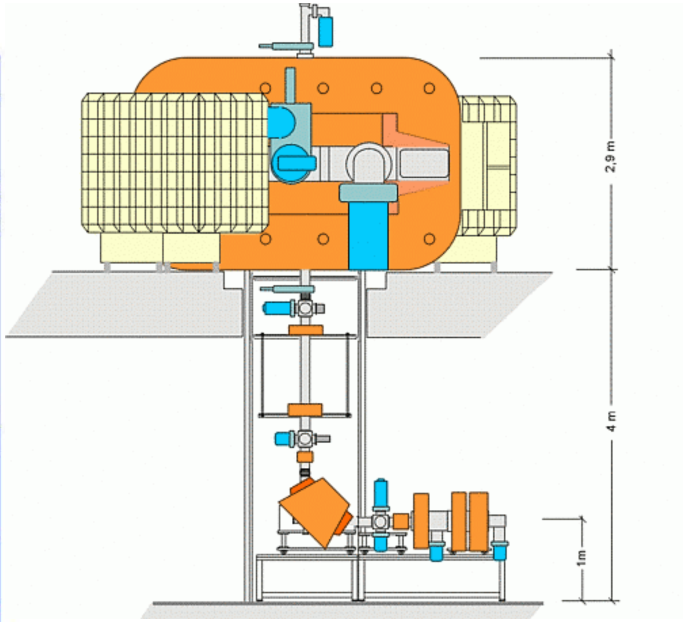
A	Q	E (MeV)	E/A (MeV)
1	1	10.00	10.00
6	3	20.00	3.33
9	4	25.00	2.78
10	5	30.00	3.00
12	6	35.00	2.92

Preliminary tests of CCT Test Bench

Heavy Ion Laboratory (HIL)

Warsaw University



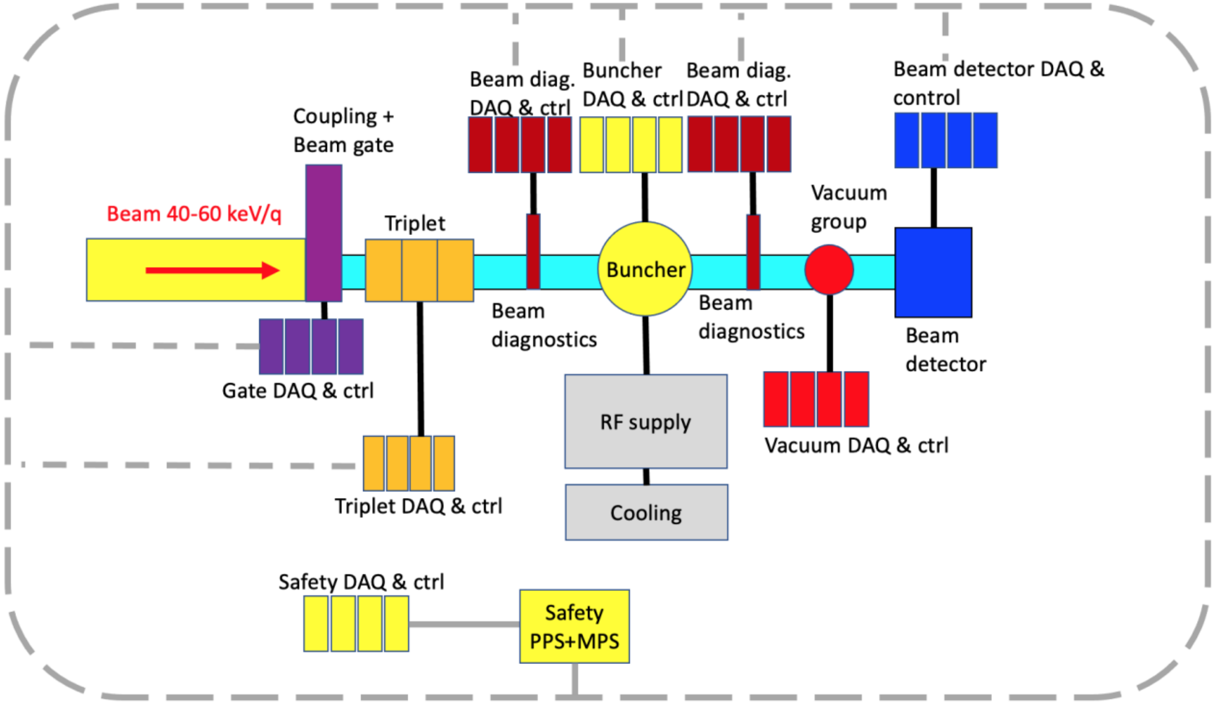


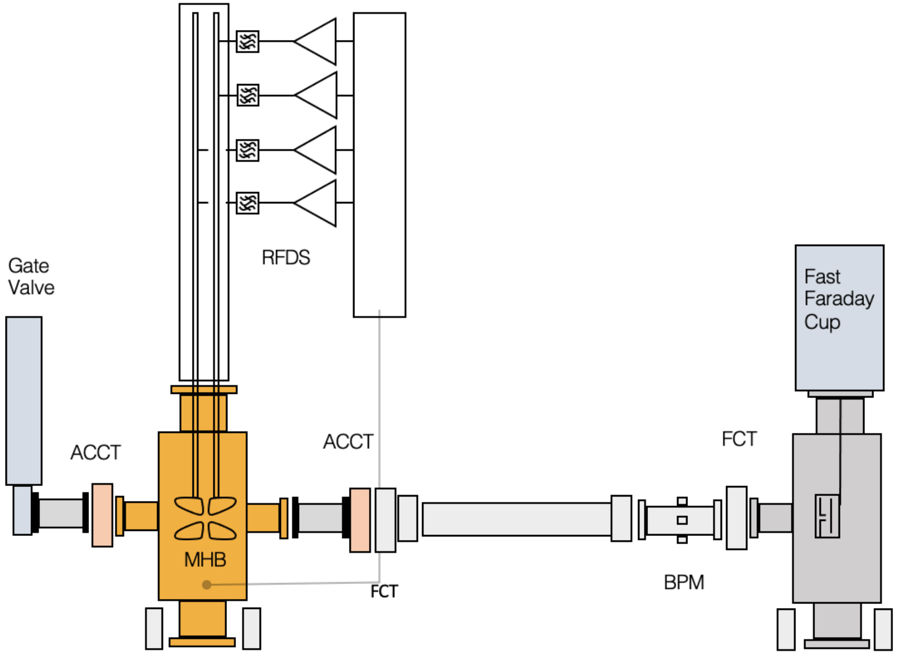
- Isochronous heavy-ion cyclotron (K=160)
- Two ECR sources
- Beams from He up to Ar, (and Xe) up to 10 MeV/A
- ~ 5 ns pulse width
- 12 - 21 MHz

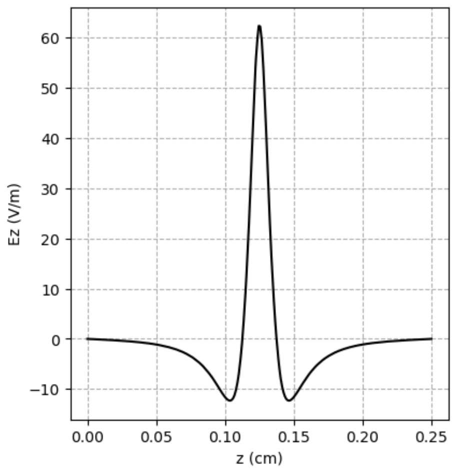
Ion	Energy min [MeV]	Energy max [MeV]	Energy max [MeV/nucl.]
$^{10}B^{+2}$	51	55	5.5
$^{11}B^{+2}$	40	50	4.5
$^{12}C^{+2}$	38	50	4.2
$^{12}C^{+3}$	53	92	7.7
$^{13}C^{+3}$		90	6.9
$^{14}N^{+2}$	32	50	3.6
$^{14}N^{+3}$	57	91	6.5
$^{15}N^{+3}$		43	2.9
$^{16}O^{+3}$	46	80	5.0
$^{16}O^{+4}$	80	120	7.5
$^{18}O^{+4}$	100	120	6.7
$^{19}F^{+3}$	50	66	3.5
$^{20}Ne^{+3}$	45	68	3.4
$^{20}Ne^{+4}$	68	115	5.8
$^{20}Ne^{+5}$	130	160	8.0
$^{22}Ne^{+3}$	44	55	2.5
$^{24}Mg^{+4}$		77	3.2
$^{32}S^{+5}$	79	110	3.4
$^{32}S^{+6}$	*120(*)*	150	4.7
$^{32}S^{+7}$	*120(*)*	225	7.0
$^{40}Ar^{+6}$	*90(*)*	132	3.7
$^{40}Ar^{+7}$	*130(*)*	164	4.1
$^{40}Ar^{+8}$	*180(*)*	200	5.0

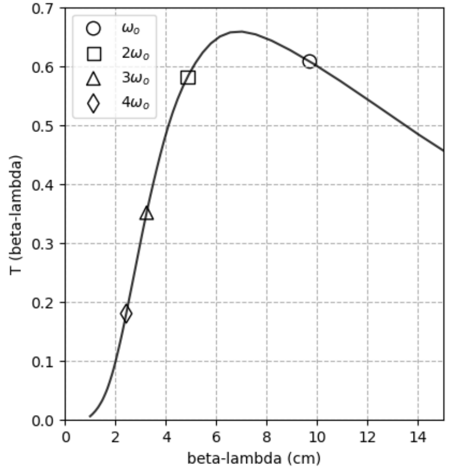
Buncher test bench

- Test the CCT magnet with ion beams
- Obtain data to validate beam dynamics
- Preliminary concepts, technical drawings, simulations, subsystems









Courtesy of I. Bustinduy, ESS-Bilbao

Simulations based on the M.A. Fraser great reports. HIE-ISOLDE-PROJECT-Note-0035

High current Multi-Specimens Ion Source

Number	Symbol	Name	Atomic Weight (A)	1st (eV)	2nd (eV)	3rd (eV)
1	H	Hydrogen	1.008	**13.59844**		
2	He	Helium	4.003	**24.58738**	54.41776	
7	N	Nitrogen	14.01	**14.53414**	29.6013	47.44924
8	O	Oxygen	16	**13.61806**	35.11730	54.9355
10	Ne	Neon	20.18	**21.5646**	40.96328	63.45
18	Ar	Argon	39.95	**15,75962**	27.62967	40.74
36	Kr	Krypton	83.8	**13,99961**	24.35985	36.950
54	Xe	Xenon	131.3	**12.1298**	21.20979	32.1230

The MHB Team

- Tests of Buncher Test Bench

Courtesy of I. Bustinduy, ESS-Bilbao

Funding

- Recently (December 2021): MoU CERN – Spain: funds CERN experiments with active participation of Spanish groups.
- Complementary: PATHFINDER EU call (application) → more oriented to general applications

MoU CERN – Spain: ISRS (2022-2025)

- Detailed beam dynamics of the ISRS ring
- CCT Dipole test bench
  - ✓ CCT Dipole protype (2 nested CCT coils)
  - ✓ Mini-RING cryostat protype (LHe)
  - ✓ Magnetic measurement system
- Multi-harmonic buncher + ion test bench
- Preliminary study of diagnostics and focal plane detectors.
- Tests with stable heavy ion beams

- Letter to ISCC with project details is in preparation: activity review/endorsement
- Spanish contribution to ISOLDE

Pathfinder (SPRINGS) – Submitted (2023-2026)

- Detailed study of the injection extraction system
- FFAG test bench – MAGDEM demostrator
  - ✓ CCT Triplet protype (2 nested CCT coils)
  - ✓ + CCT Dipole → complete ISRS magnet system
  - ✓ Magnetic measurement system
  - ✓ Mini-RING cryostat protype (Cryocoolers)
- Design study of SC re-buncher system
- Prototypes of diagnostics and focal plane detectors
- MAGDEM experimental program

SUMMARY & CONCLUSIONS

- MoU CERN – Spain / ISRS (2022-2025) – funded → administration
- EU Call Pathfinder / ISRS (2023-2026) - submitted
- Detailed beam dynamics of the ISRS ring
- CCT Dipole test bench
  - ✓ CCT Dipole protype (2 nested CCT coils) → Reduced size (warm) prototypes of Cu
  - ✓ Mini-RING cryostat protype (LHe) → first concepts/technical drawings
  - ✓ Magnetic measurement system → first protypes / reduced size
  - ✓ Subsystems
- Multi-harmonic buncher + ion test bench
  - ✓ First concepts/technical drawings
  - ✓ Simulations
  - ✓ Subsystems
- Letter to ISCC with project details is in preparation: activity review/endorsement

ISRS COLLABORATION

Inst. de Física, UNAM, ***México.***
Univ. Huelva, ***Spain.***
IJCLab-Univ. Paris-Sud, ***France.***
Dpt. of Physics, Univ. Liverpool, ***UK****.*
Wigner Research Centre for Physics, Budapest, ***Hungary****.*
*TTI Norte, Santander****, Spain.***
Inst. de Estructura de la Materia, CSIC, Madrid, ***Spain****.*
ESS-BILBAO, Bilbao, ***Spain.***
CERN, Geneva, **Switzerland.**
Univ. Surrey, **UK.**
Lund University, **Sweden.**
Götenborg University, **Sweden.**
Univ. Edinburgh, **UK.**
LNL INFN, **Italy**
Uppsala Univ., ***Sweden.***
Aarhus Univ., ***Denmark.***
Chalmers Univ. of Technology, ***Sweden.***
ACS, Orsay, ***France.***
CENGB, Gradignan, ***France.***
Univ. York, ***UK.***
Univ. of West Scotland, ***UK.***
ICMUV-Univ. de Valencia, ***Spain.***
The Cockcroft Institute, ***UK.***
Astroparticule et Cosmologie-Univ. Paris Diderot, ***France.***
Univ. Jyvaskyla, ***Finland.***
IMIS Univ. Riyadh, ***Saudi Arabia.***
IFIN-HH, Bucharest, ***Romania.***
*Politecnico di Milano-DEIB & INFN****, Italy.***
HIL-Warsaw University, ***Poland.***

THANKS!

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- ✓Igor Tsekhanovich LP2I Bordeaux
- ✓Marlene Assié IJCLAB
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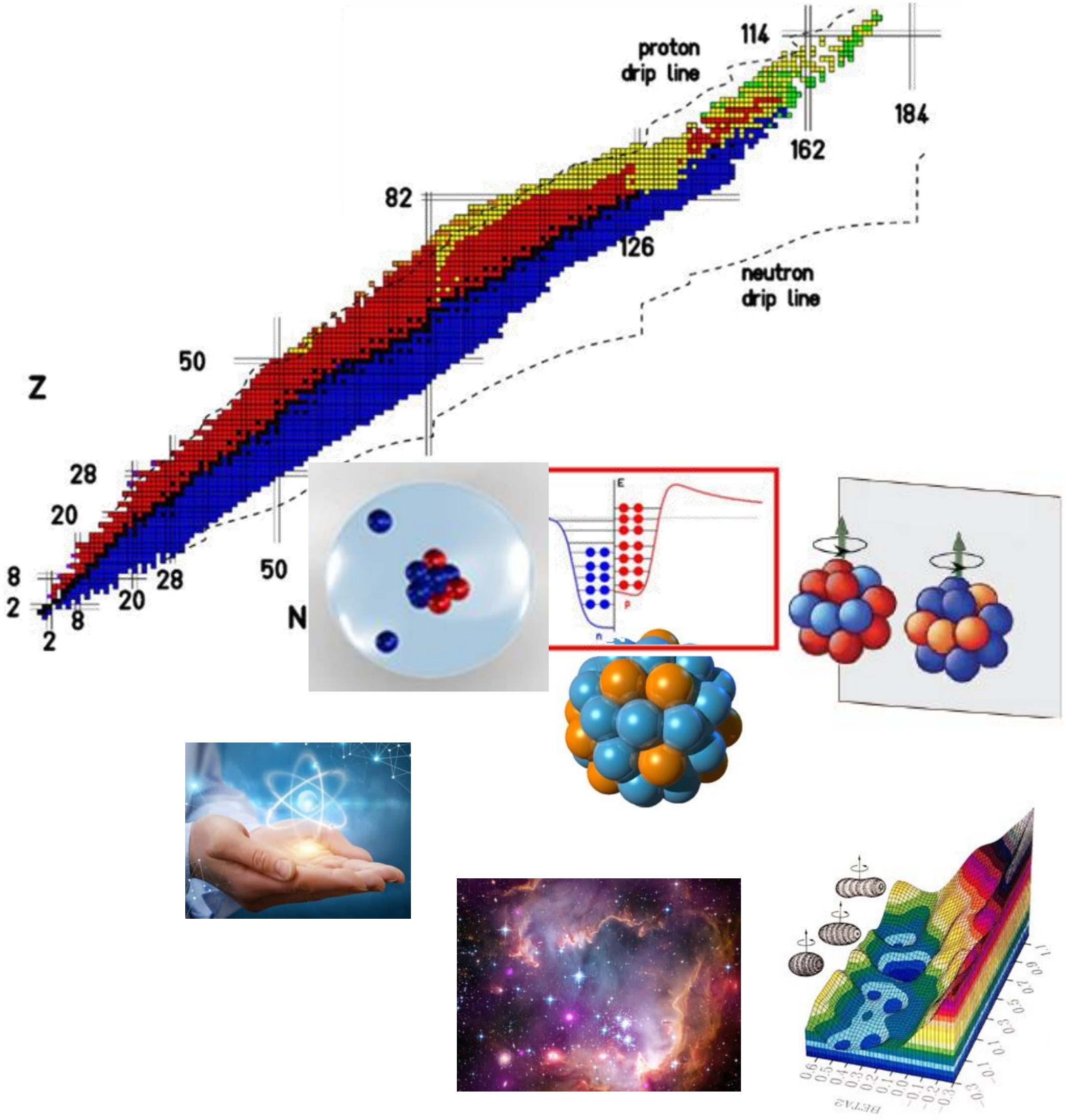
- ✓Joakim Cederkall Lund Univ.
- ✓Nara Singh U. West Scotland



PHYSICS OPPORTUNITIES

- ISRS as a stand-alone detector
- In coincidence with complementary detector arrays:
  - gamma- particle array Miniball + T-REX
  - Particle array GLORIA
  - Neutron array SAND
  - Multi-purpose reaction chamber SEC
  - Spectrometer ISS
  - Storage Ring TSR

Benefit from the plans for a future extension of the HIE-ISOLDE experimental hall.

- ***Coulomb dissociation*** at a few MeV/u has rarely been used despite having much high cross sections
  - ✓ Core fragments ~15°
  - ✓ Coincidence with the neutrons, particles and gammas ejected in the breakup.

- ***Direct transfer reactions*** *in inverse kinematics*
  - ✓ Mainly when light outgoing particle is a neutron
  - ✓ Cone ranges from ±15° for light projectiles
  - ✓ About ±1° for heavy beams
- Nuclear structure studies around N≈82, 126
- Reactions relevant for the s, p and rp process nucleosynthesis around Z ≈ 50 and Z ≈ 82

- ***Multinucleon transfer reactions***, via *deep inelastic, quasi-elastic and quasi-fission reactions*
  - ✓ Analyse individual exit channels.
  - ✓ Production of exotic nuclei and states so far unobserved
  - ✓ Coincidence with gammas and neutrons from decay.
  - ✓ Direct or inverse kinematics with light or heavy targets
  - ✓ The spectrometer should be able to rotate to cover the grazing angle
- Neutron-rich nuclei in Terra Incognita (^{78}Ni, r-nuclei ~N=126)
- Shell-quenching and the r-process

Fusion-evaporation *reactions in inverse kinematics*
- Selection of fusion evaporation residues
- lifetime measurements using standard and triple foil plungers

Low energy transfer, breakup and fusion reactions
- Reaction dynamics studies at low energies ~5 MeV/A
- Emphasize collective behaviour associated with nucleon correlations.
- Beam-like fragments in coincidence with neutrons and gammas

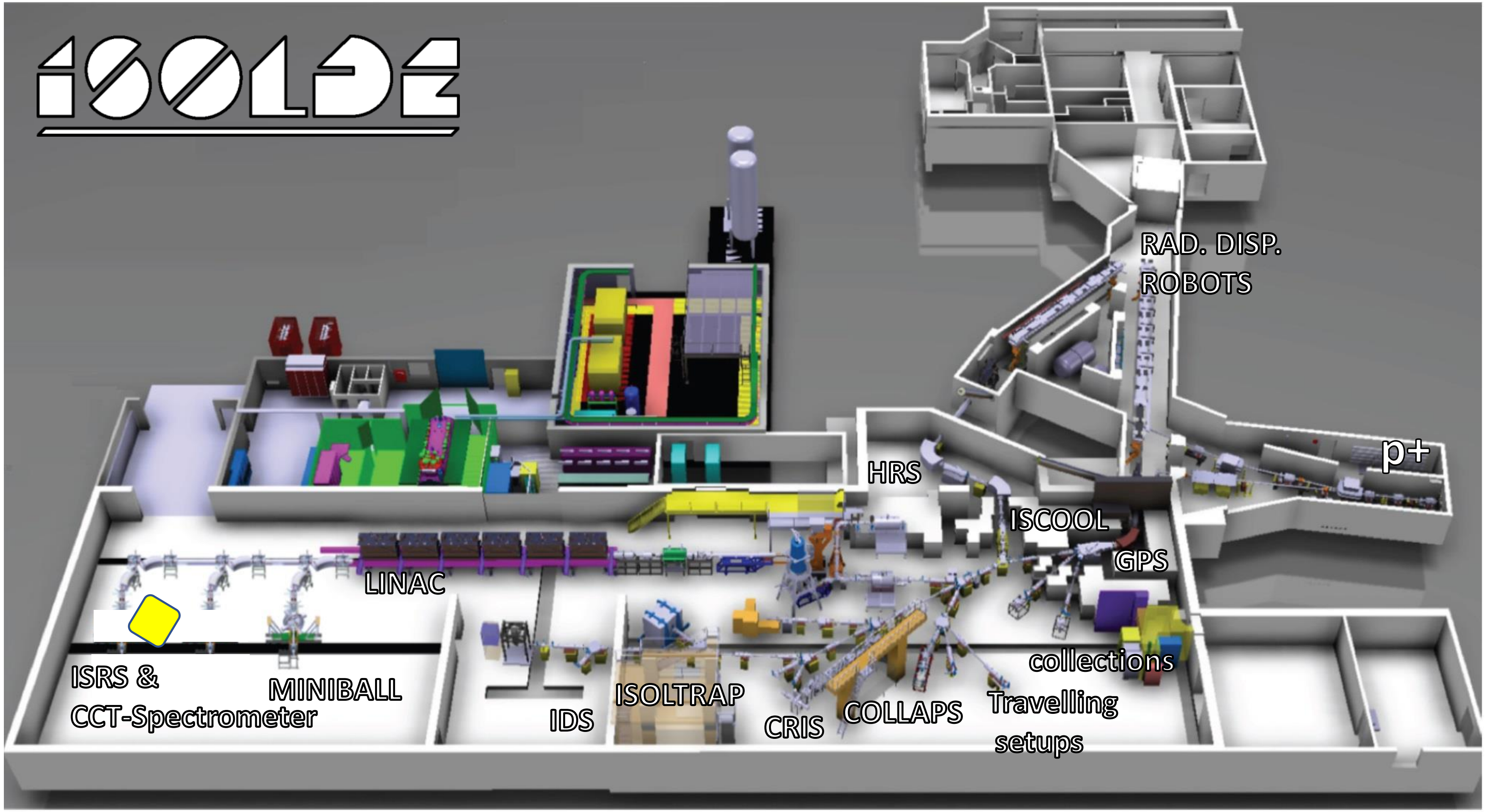
ISRS: performance request

- Energy: $4 \leqslant E/A \leqslant 10$ MeV
- Large acceptance (> 15 degrees, > 100 msr)
- Energy resolution < 100 keV
- Time resolution ~ 100 ns (coincidences)
- Excellent angular resolution (to allow kinematic reconstruction and Doppler correction) ~ 0.1 degrees.

- Event-by-event PID for :
  - physical separation of reaction products of interest
  - beam and isobaric beam contaminants and others
  - fusion-evaporation reactions with target
- At least VAMOS-like $\Delta Q/Q$ ~1/70 (FWHM), $\Delta M/M$~1/200 (FWHM) $\Delta Z/Z$~1/60 (FWHM).
- Couple with a MR-TOF.

Ancillary detectors and special equipment

- Targets : solid (also implanted) and cryogenic targets.
- Detectors for particle, gamma, neutron coincident measurement (like T-Rex-Miniball+ 0-deg detection)



ISOLDE
RAD. DISP.
ROBOTS
p+
HRS
ISCOOL
GPS
LINAC
collections
Travelling
setups
ISRS &
CCT-Spectrometer
MINIBALL
IDS
ISOLTRAP
CRIS
COLLAPS