CATHI Final Review Meeting

22-26 September 2014
Hotel H10 Marina in Barcelona - Spain
Europe/Zurich timezone

ECOS-LINCE: A proposal for a high-intensity stable beam facility for nuclear structure and reactions

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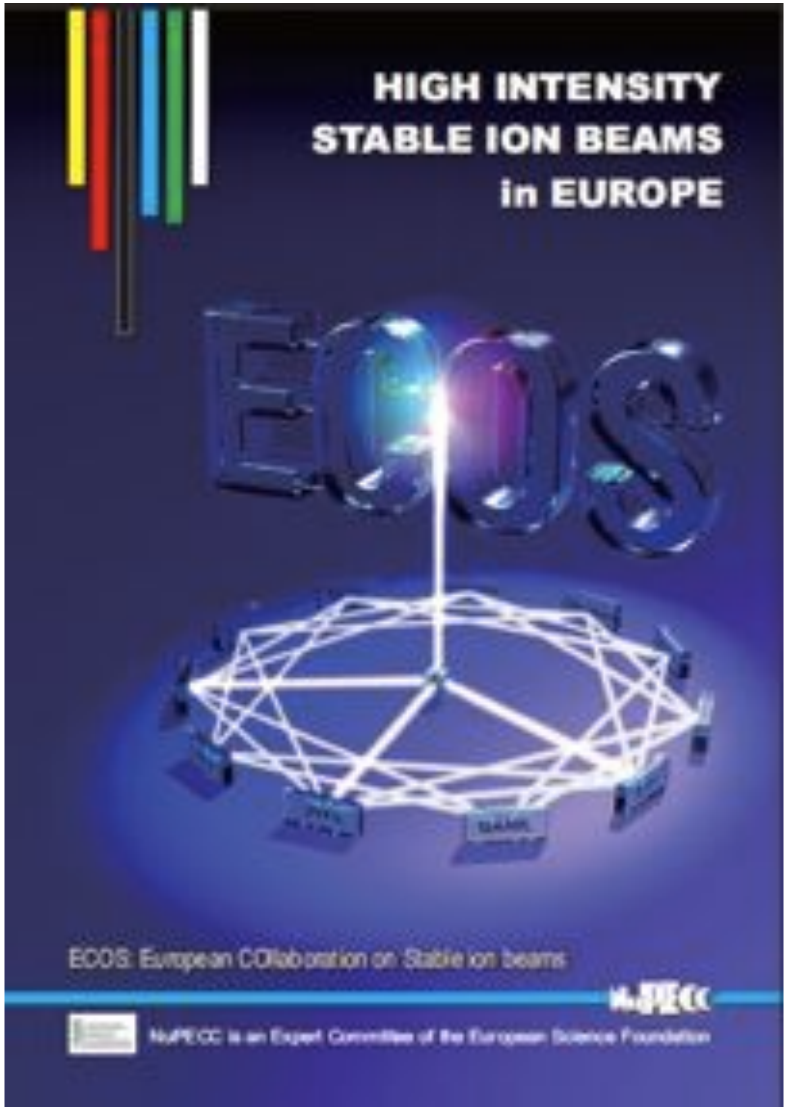
HIGH INTENSITY STABLE ION BEAMS IN EUROPE



ECOS: **E**uropean **Co**llaboration on **S**table ion Beams.
(http://www.ensarfp7.eu/project/ecos)

Expert working group of the Nuclear Physics European Collaboration Committee (NuPECC)

ECOS REPORT: Describe the research perspectives at EU with high intensity stable ion beams, categorize existing facilities and identify the opportunities for a dedicated new facility in EUROPE

ECOS Working group:

Faical Azaiez (Chair) (Orsay)
Giacomo de Angelis (Legnaro)
Rolf-Dietmar Herzberg (Liverpool)
Sigurd Hofmann (GSI Darmstadt)
Rauno Julin (Jyvaskyla)
Marek Lewitowicz (GANIL Caen)
Marie-Helene Moscatello (GANIL Caen)
Anna Maria Porcellano (Legnaro)
Ulrich Ratzinger (Frankfurt)
Adam Maj (Kracow)
Dieter Ackermann (GSI)
Ismael Martel (Huelva)

ECOS working group conclusions

IV: Concluding remarks and recommendations

…"The long-term goal for a new dedicated high intensity stable ion beam facility in Europe, with energies at and above the Coulomb barrier, is considered to be one of the important issues to be discussed in the next Long Range Plan of the nuclear physics community."…

ECOS-LINCE proposal

ECOS-LINCE facility: a FIRST CLASS High intensity heavy-ion accelerator for stable ions, with energies at and above the Coulomb barrier.

LINCE; high-intensity superconducting LINAC

- Wide range of ions, from protons to Uranium
- Wide range of energies, up to 10 A MeV for 238U
- High Intensity accelerator (1 mA light ions → 10 particle-microamp heavy ions)

LINCE: energy booster using heavy-ion synchrotron:

- 50 MeV/u for light ion species
- 200 MeV for p, d, t.

PROGRAM:

- Basic and fundamental science
- Applications of nuclear physics

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Basic Nuclear Physics

- The totality of the ECOS physics case

  - Nuclear structure, low medium and high spin
  - Reaction mechanisms
  - Charge exchange reactions
  - Isomers
  - Ground state properties
  - Astrophysics
  - Superheavies

Energy booster:

- Nuclear equation of state (EOS)
- Fundamental physics: neutrinoless double-beta decay

Main objective: provide a heavy-ion facility to carry out studies demanding high intensity stable beams and/or long run experiments (months of continuous beam time!)

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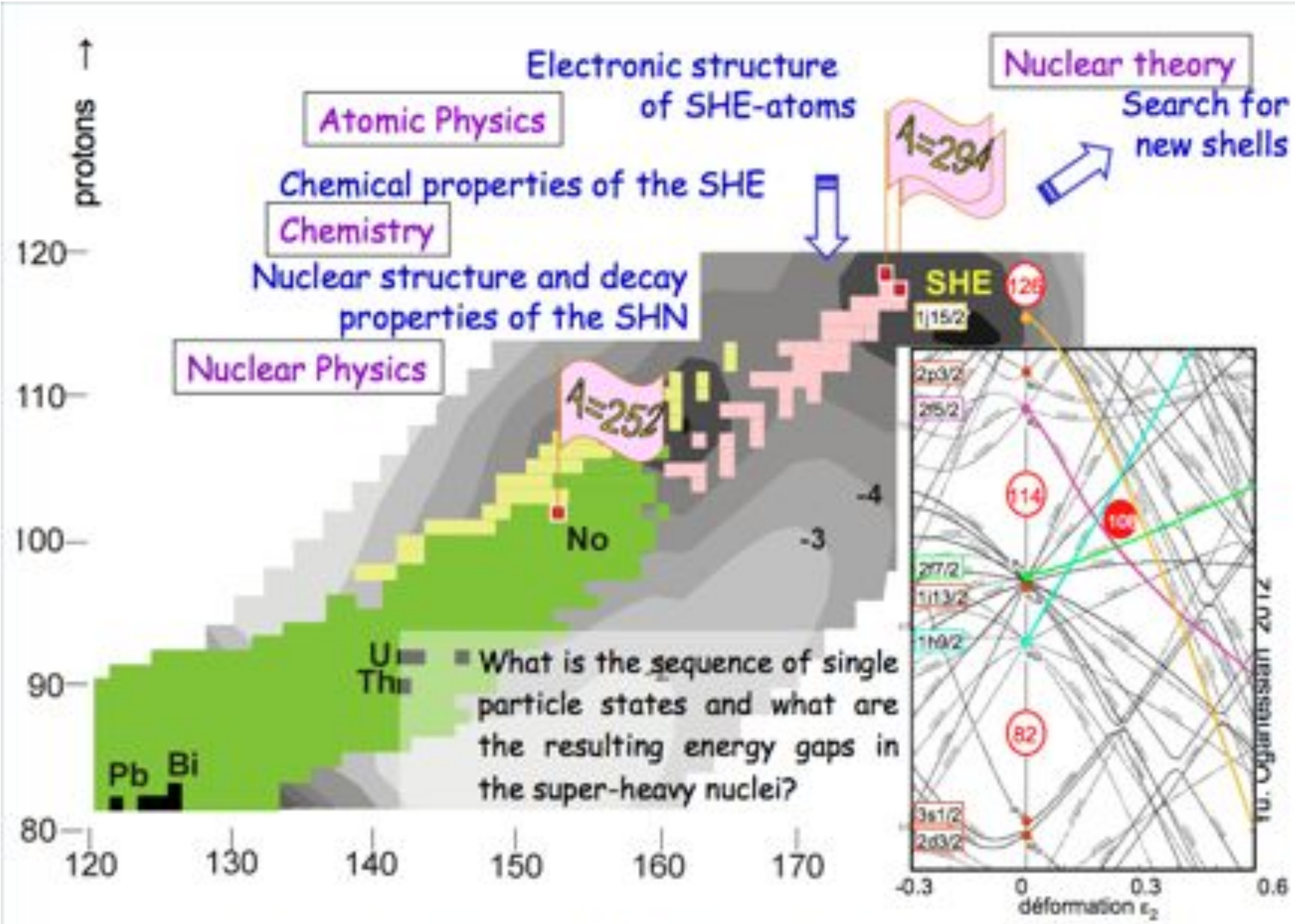
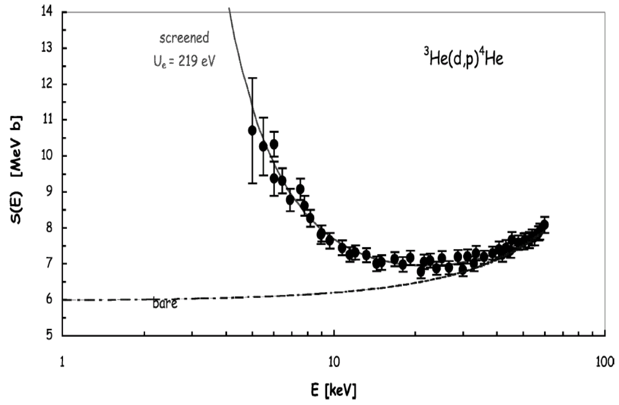
Superheavies



Yuri Oganessian. "Synthesis of SH-nuclei" FUSHE 2012, May14, 2012, Weilrod, Germany

Astropysics

σ ~picobarn!! at relevant energies < 1 MeV, few GK



Extrapolation from higher energies by using the astrophysical S(E) factor:

$$S(E) = \sigma(E)\, E \exp(2\pi\eta)$$

→ DIRECT & INDIRECT METHODS

DIRECT METHODS

-Increase number of detected particles ("brute force": → intensity, → detector eff.)

- Reduce the background

- Fight with electron screening: theory does not work!!

INDIRECT METHODS

Coulomb dissociation: Determine the absolute S(E) factor of a radiative capture reaction **A+x → B+γ** studying the reversing photodisintegration process **B+γ → A+x ~100 MeV/A**

Asymptotic Normalization Coefficients (ANC): Determine the S(0) factor of the radiative capture reaction, **A+x → B+γ** studying a peripheral transfer reaction into a bound state of the B nucleus.

Trojan Horse Method (THM): Determine the S(E) factor of a charged particle reaction **A+x→c+C** selecting the Quasi Free contribution of an appropriate **A+a(x+s)→ c+C+s** reaction.

Nuclear structure at low, medium and high spin

In-flight production of exotic nuclei at reaction targets

Typical beams

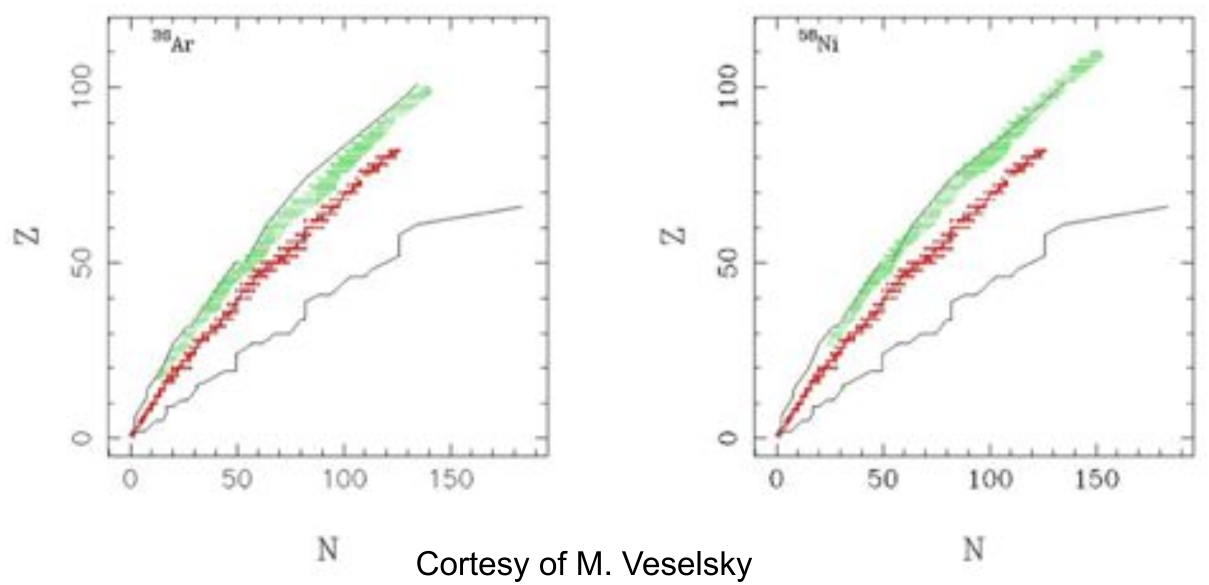
^{40}Ar ~ 14 MeV/u
^{86}Kr ~ 8.5 MeV/u
^{84}Kr ~ 10 MeV/u
^{136}Xe ~ 7 MeV/u

Exotic isotope production:

Height of the Coulomb barrier ~ 4 to 5 MeV/nucleon:

- → compound nucleus/fus.evap reactions, E ~ Eb → proton rich
- → reactions of nucleon exchange, E>> Eb → neutron rich

Compound nucleus/fus. evap reactions → Basic mechanism for production of proton rich nuclei de- excitation channels: 3-6n, p2-5n, a2-5n

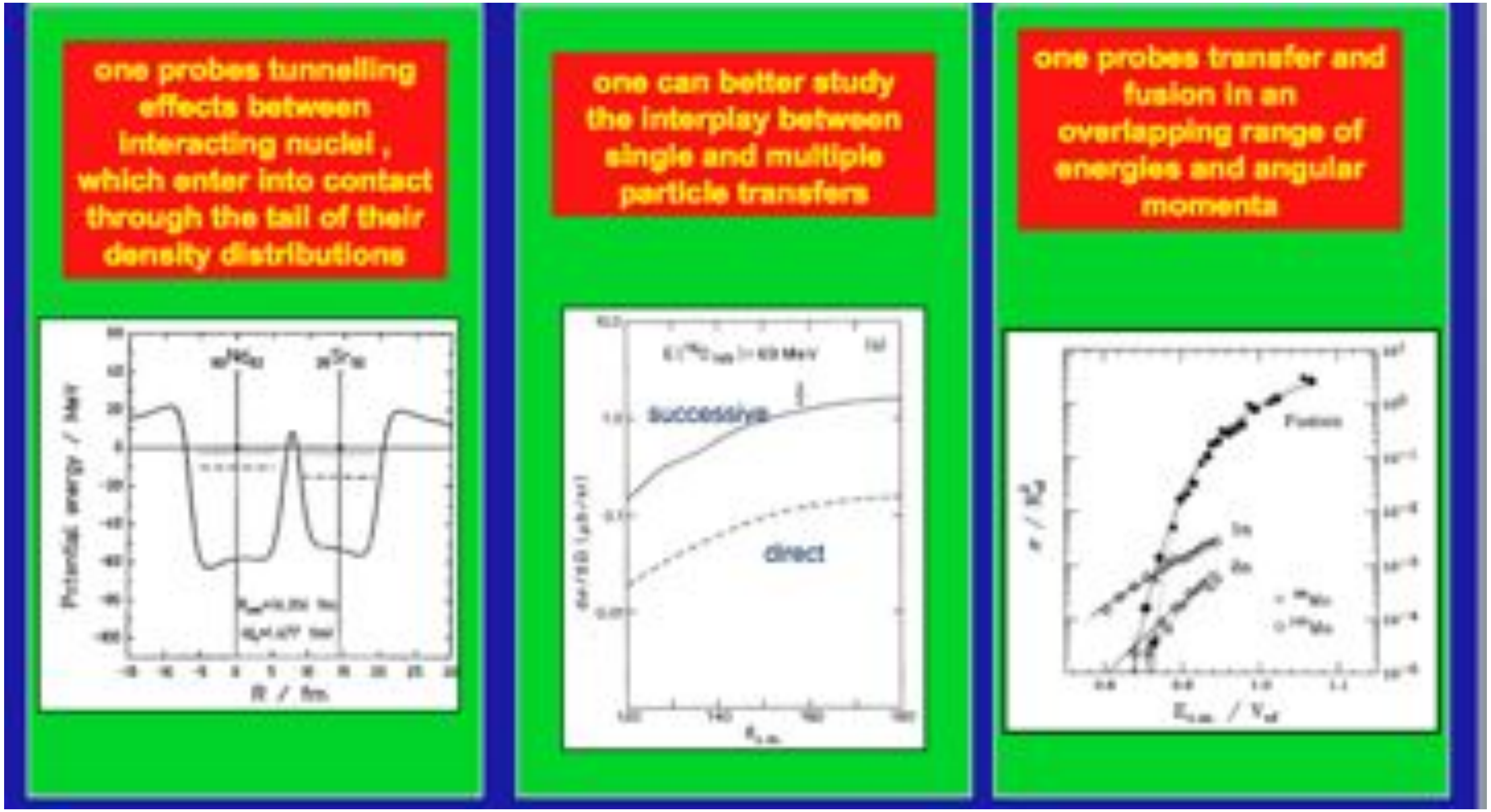


Cortesy of M. Veselsky

M. Veselsky, G.A. Souliotis, Nuclear Physics A 765 (2006) 252; A 781 (2007) 521.
G.A.Souliotis et al., PRC 84, 064607 (2011); M. Veselsky,et al., Nucl. Phys. A 872 (2011) 1.

Transfer and fusion reaction studies

- Pair correlations (nn,pp,np channels) in transfer reactions at sub-barrier energies
- Charge exchange reactions
- Multinucleon transfer reactions (neutron rich nuclei) and effects on induced fission and quasi fission processes
- Hindrance phenomenon in sub-barrier fusion reactions



Physics beyond the Standar Model

Search for 0νββ decay. A worldwide race

Completed experiments:
- Gotthard TPC
- Heidelberg-Moscow
- IGEX
- NEMO1, 2 and 3

Experiments currently taking data:
- COBRA
- CUORICINO and CUORE
- DCBA
- EXO
- GERDA
- MOON
- KamLAND-Zen

Proposed/future experiments:
- CANDLES and XMASS at Kamioka Observatory
- MAJORANA
- NEXT
- SNO+
- SuperNEMO

$$T^{0\nu}_{1/2}(0^+ \to 0^+) = G_{01}\left|M^{\beta\beta 0\nu}\right|^2 \left|\frac{\langle m_\nu \rangle}{m_e}\right|^{-2}$$

Xsections: ~nanobarn!! → High intensity ion beams

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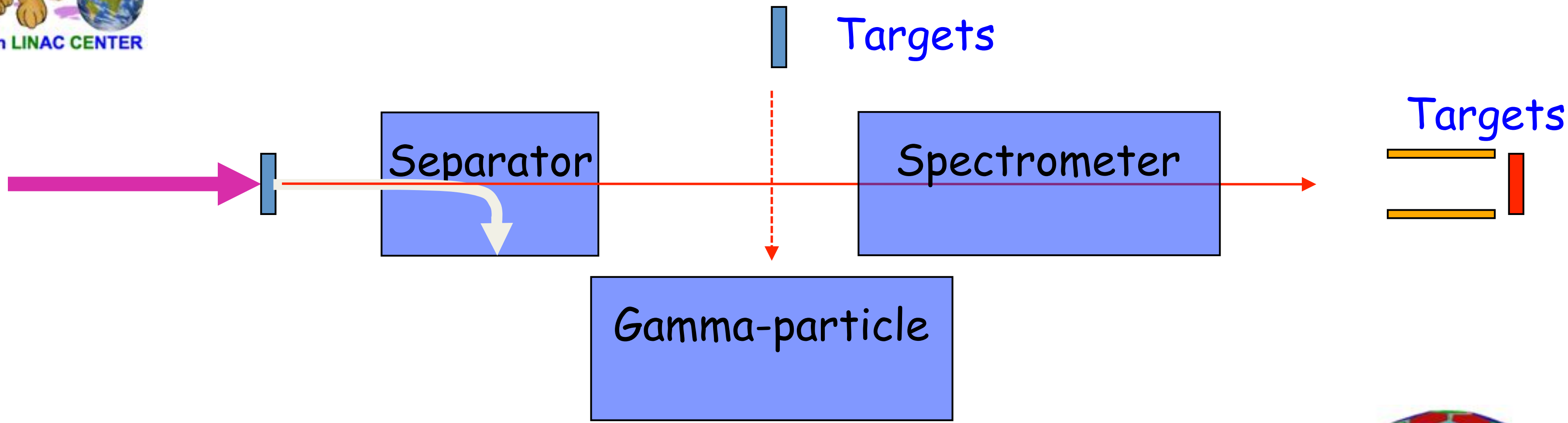
Typical experimental setup

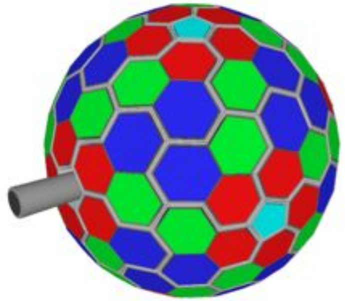


SPECIFIC DEVELOPMENTS

- High resolution spectrometers and recoil separators with high rejection power (MAGNEX, VAMOS, PRISMA,…)

- High power targets

- New generation of gamma & particle detectors (FAZIA, AGATA,…) with new generation electronics and data correlation systems.



Advanced GAmma Tracking Array

AGATA will be able to handle 10 - 100 times more beam

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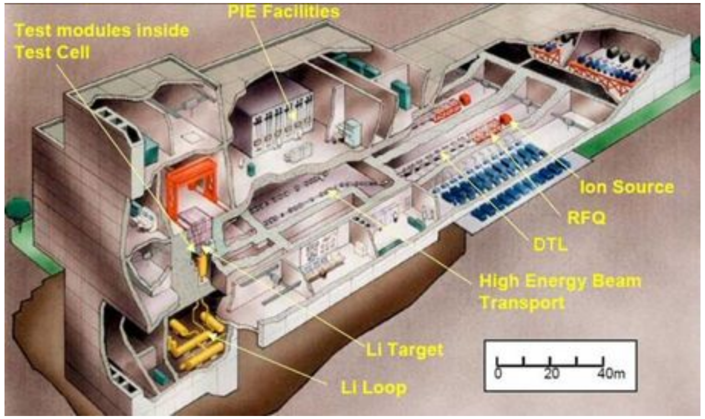
Fusion energy research

Material research for energy production

Fusion energy research: aiming at qualifying advanced materials resistant to extreme conditions, specific to fusion reactors like ITER. Intense ion beams of moderate energy are needed to simulate fusion reactor conditions. (CIEMAT)



IFMIF project: a 40 MeV, 125 mA deuteron + lithium target → neutrons to test materials for first generation of fusion reactors

→ the DEMO reactor

Cocktail beams à la JANNUS

Double, triple charged ions

Condition: Same A/q

EX: ^{56}Fe (14+) + ^{4}He(1+)

	A	Z	E (MeV)
C	12	4	146,7
Si	28	9	318,2
Fe	56	14	385,0
W	184	25	373,6
H	1	1	up to ~ 40

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Radioisotope production

Modern radioisotopes are currently investigated/used to treat in a more efficient way the different tumours and cancer disease of our society.

What LINACs can do better (than cyclotrons)

Radio-nuclide	Target	Reaction	Projectile	Energy (MeV)
F-18	O-16	$(\alpha,pn)\&(\alpha,2n)$	^{4}He	40
F-18	Ne-20	(d,α)	d	15
Sc-43	Ca-40	$(\alpha,n)\&(\alpha,p)$	^{4}He	24
Cu-61	Co-59	$(\alpha,2n)$	^{4}He	40
Cu-64	Ni-64	(d,2n)	d	30
Cu-67	Ni-64	(α,p)	^{4}He	40
In-111	Ag-109	$(\alpha,2n)$	^{4}He	40
Sn-117m	Cd-116	$(\alpha,3n)$	^{4}He	42
I-124	Sb	(α,xn)	^{4}He	42
At-211	Bi-209	$(\alpha,2n)$	^{4}He	29
Rn-211	Bi-209	$(^{7}Li,5n)$	^{7}Li	≈60

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Aerospace

High intensity ion beams are used in **aerospace programs** for radiation resistant electronics and in nuclear energy applications. Quality tests are required in order to accomplish with UE safety regulations for energy control and aerospace on-board electronics. Research can be centred on the impact of radiation on the response of new device technologies and single-event effects in new technologies and ultra-small devices.

Highly demanded ions & energies ~10 MeV/u

Ion	Energia [MeV/u]	LET^{MEAS} @superficie [MeV/mg/cm^2]	LET^{MEAS} @Pico de Bragg [MeV/mg/cm^2]
$^{15}N^{+4}$	139	1.87	5.92 (@191 um)
$^{20}Ne^{+6‡}$	186	3.68	9.41 (@138 um)
$^{30}Si^{+8}$	278	6.74	13.7 (@114 um)
$^{40}Ar^{+12‡}$	372	10.08	18.9 (@100 um)
$^{56}Fe^{+15}$	523	18.84	29.7 (@75 um)
$^{82}Kr^{+22}$	768	30.44	41.7 (@68 um)
$^{131}Xe^{+35}$	1217	54.95	67.9 (@57 um)

Typical figures from RADEF, Finland

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LINCE working parameters

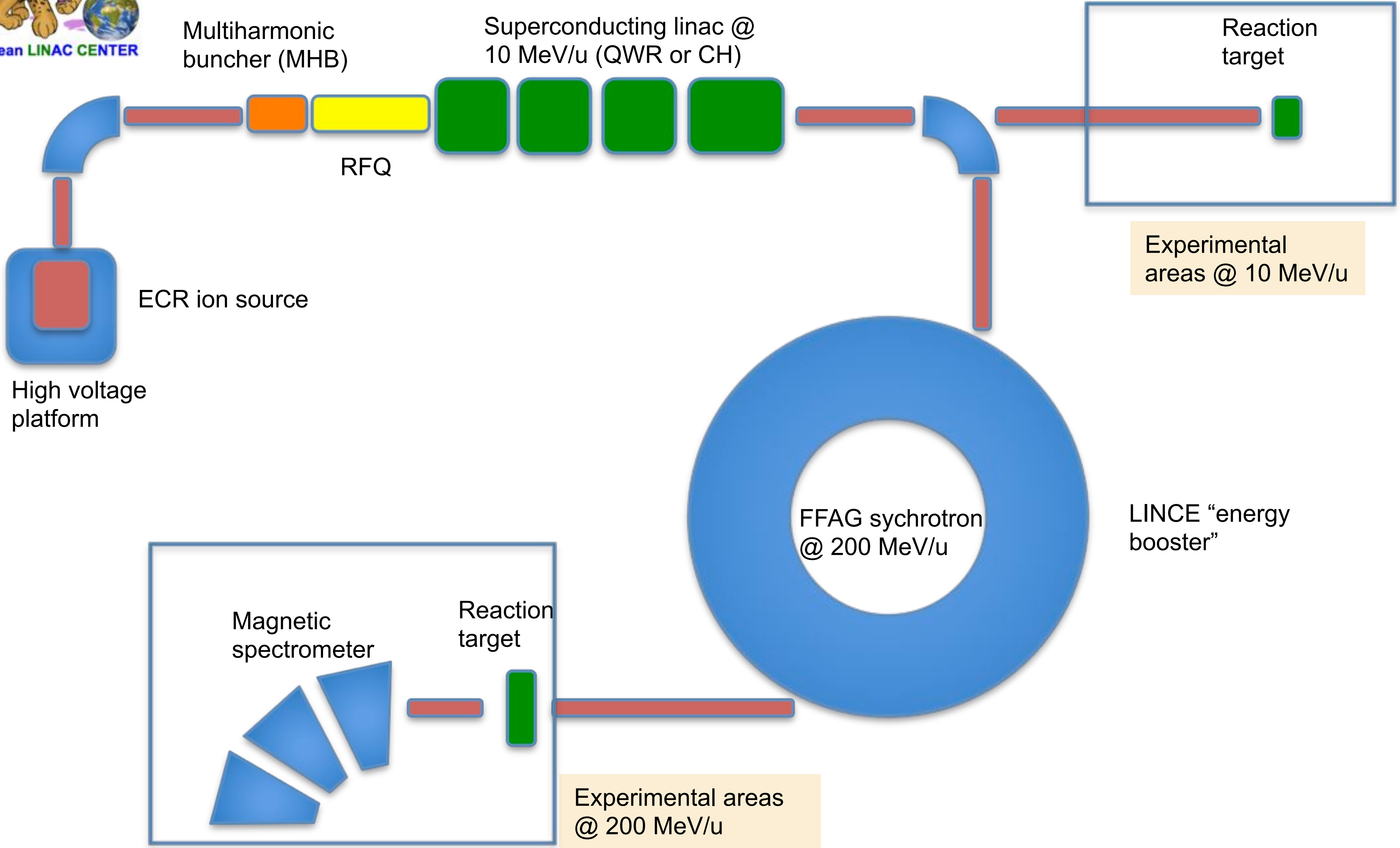
LINCE must provide 7000 hours of availability/year, with high stablity and reliability for long run experiments: 5000 hours for **ECOS science** and 2000 hours for Applications.

Main parameters:

- Protons to Uranium: 1 mA max intensity at target → eg., ^{48}Ca (8+) > 10 pμA
- CW LINAC, energy up to 10 MeV/u (protons 45 MeV, ^{238}U @ 8.5 MeV/u). Based on superconducting QWR cavities and/or CH structures.
- SYNCHROTON, energy up to 50 MeV/u for light ion species & 200 MeV for d, t. Based on FFAG (superconducting cavities, magnets).
- Full-SC ECR ion source for high-charged & high-intensity ion beams (eg, ^{238}U @ 34+). High stability and reliability.
- CW RFQ for $1 \leq A/q \leq 7$.
- High resolution magnetic spectrometer. Based on superconducting magnets.

TAKE ADVANTAGE OF RECENT DEVELOPMENTS FOR HIGH INTENSTY LINACS (SPIRAL2, FAIR, FRIB, ATLAS upgrade)

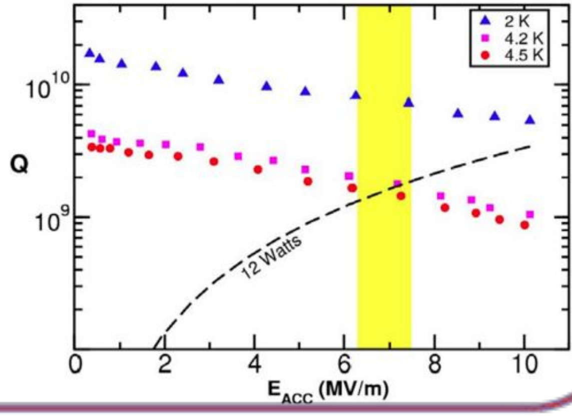
LINCE CONCEPTUAL LAYOUT



LINCE LINAC

Synergies with HEAVY-ION LINAC developments at ATLAS upgrade (ANL), FRIB (MSU), SPIRAL2(GANIL), SPES (LNL) and IAP/GSI.

Superconducting QWR and cryomodules ATLAS (ANL)



CW RFQ: SPIRAL2(GANIL)

Figure 6: RFQ prototype 1 meter module

Table 1: RFQ main parameters

Parameter	*Value*
Length	5.077m
Mean aperture R_0	8.1 – 10.0 mm
Vane voltage	100 – 113 kV
Modulation	1 – 1.99
Input rms emittance (π.mm.mrad)	0.2 (D$^-$) / 0.4 (1/3)
Transverse emittance growth	0
Peak electric field	1.65 kp
Transmission w/o errors	>99.9%
Transmission with errors	99.87%
Input energy	20 keV/u
Output energy	0.75 MeV/u

CH cavities: IAP-GSI

Table 1: Parameter range for the CH cavity

Frequency (MHz)	200 - 800
Particle velocity (v/c)	0.05 - 0.5
Gap number	10 - 25
Accelerating gradient (MV/m)	5 - 8
Length of the cavity (m)	0.5 - 1.5
Drift tube aperture (mm)	10 - 60
Tank radius (mm)	185 - 130
E_{max}/E_{acc}	3.9 - 6.2
B_{max}/E_{acc} (mT/(MV/m))	3.7 - 8.8
R/Q_0 (kΩ/m)	2.6 - 4.7

Figure 3: Photo of the CH copper model cavity. The end cells and part of the tank housing is removed

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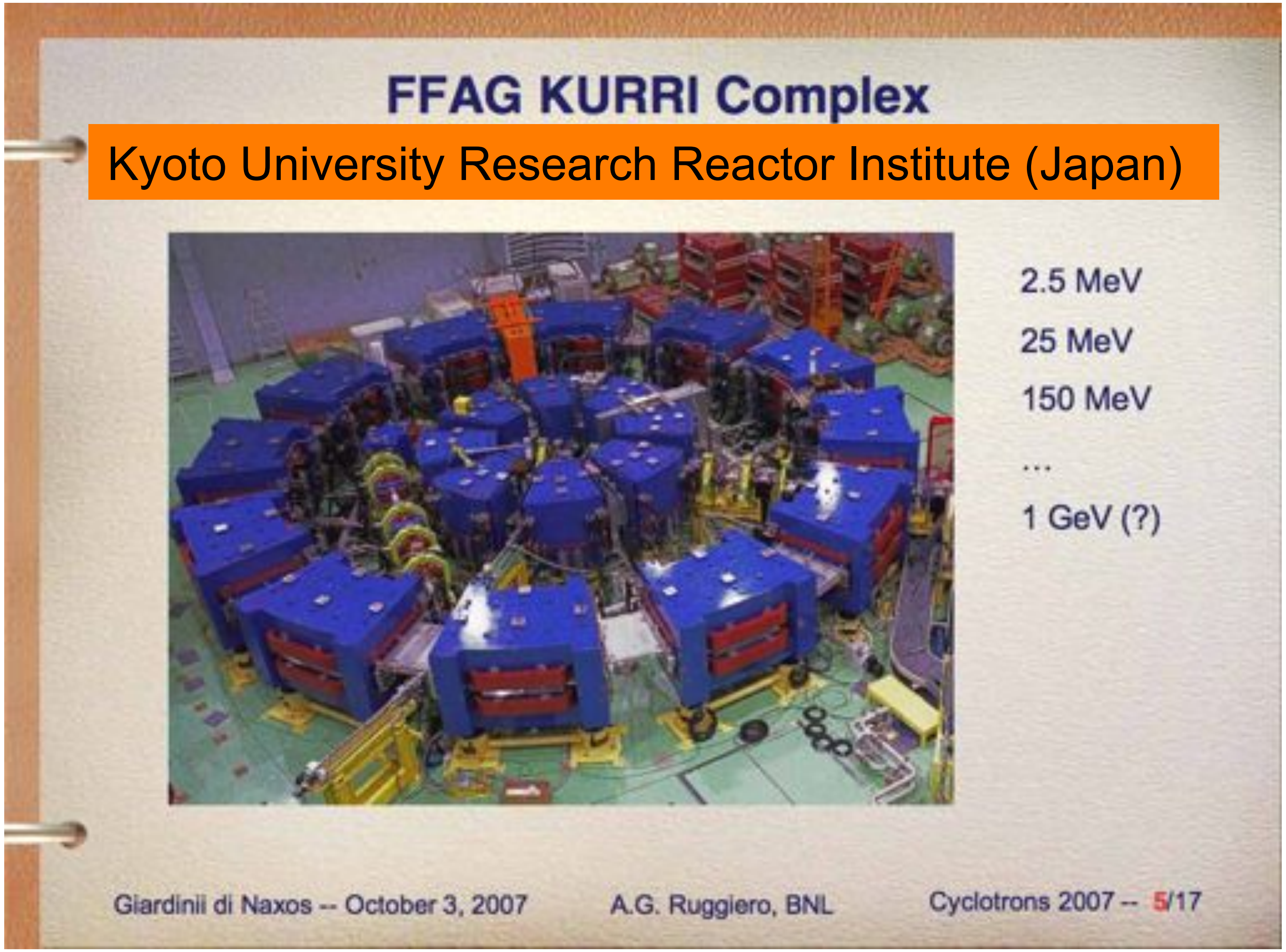
LINCE "energy booster"

HEAVY-ION SYNCHROTON:

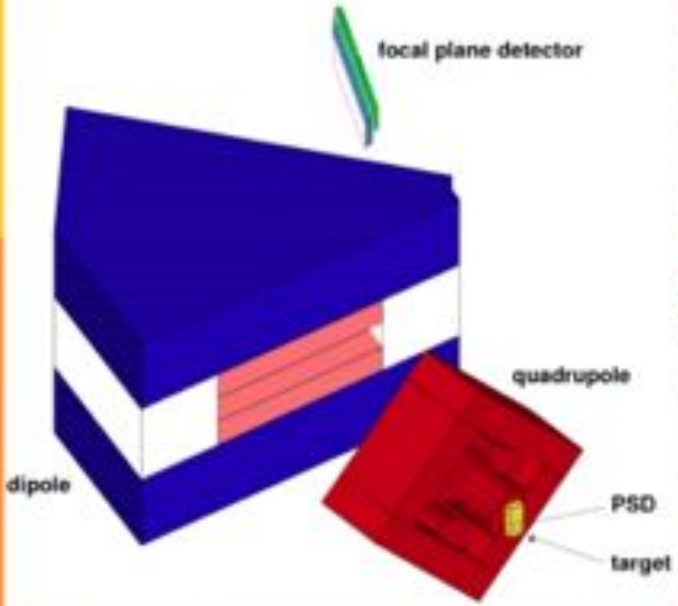
- LINAC injection
- OUTPUT: 50 MeV/u for light ion species & 200 MeV for deuterons
- Technology available in EU at STFC-Oxford (UK)



LINCE "high-resolution spectrometer"

Superconducting version of MAGNEX (LNL, Catania) → increase B > 2 T

MAGNEX



Maximum magnetic rigidity	1.8 T• m
Solid angle	51 msr
E_{max}/E_{min}	1.5
Total energy resolution (target 1 mm²) (90% of full acceptance)	~1000
Mass resolution	250

A.Cunsolo et al., NIMA 481 (2002) 4

A.Cunsolo et al., NIMA 484 (2002) 5

F. Cappuzzello, INFN-Catania

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Pre-design studies/LINCE-LINAC

On-going actions at University of Huelva

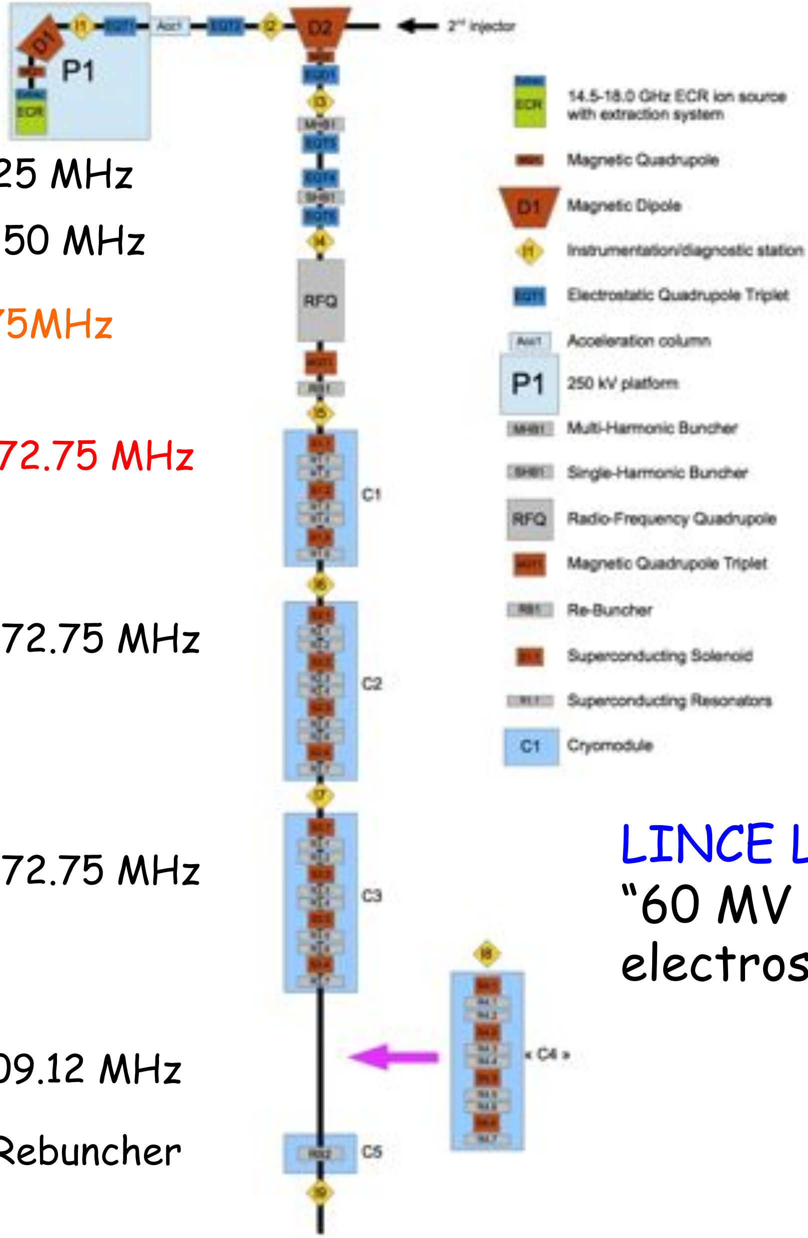
- Choice of 1^{st} harmonic (fundamental) → defined minimum time of flight: 50 ns

→ 18.1875 MHz (54.98 ns) from RF amplifier market → HI-buncher

- For protons and alphas need second buncher @ 36.375 MHz (space charge effects)
- Frequency of RFQ, F = 72.75 MHz (4^{th} harm.)
  - E in/out = 0.04 A MeV / 0.5 A MeV
- Frequency of SC cavities : 72.75 MHz (4^{th} harm.) and 109.125 MHz (6^{th} harm.)
- 26 x SC-QWR cavities and 4 cryostats: β = 0.045 (5), 2 x β = 0.77 (7), β = 0.15 (7)

A/Q	E/A	Example	Charge state	
1	42	H	1+	**Intensity: < 1mA**
2	25	D	1+	
3	18	^{18}O	6+	
4	14	^{32}S	8+	
5	12	^{48}Ca	10+	
6	10	^{48}Ca	8+	
7	8	^{238}U	34+	

Pre-design studies



MHB1 f = 18.125 MHz

MHB2 f = 36.250 MHz

RFQ f = 72.75MHz

C1: β = 0.045, f = 72.75 MHz

C2: β = 0.077, f = 72.75 MHz

C2: β = 0.077, f = 72.75 MHz

C3: β = 0.15, f = 109.12 MHz

Rebuncher

LINCE LINAC:
"60 MV equivalent electrostatic accelerator"

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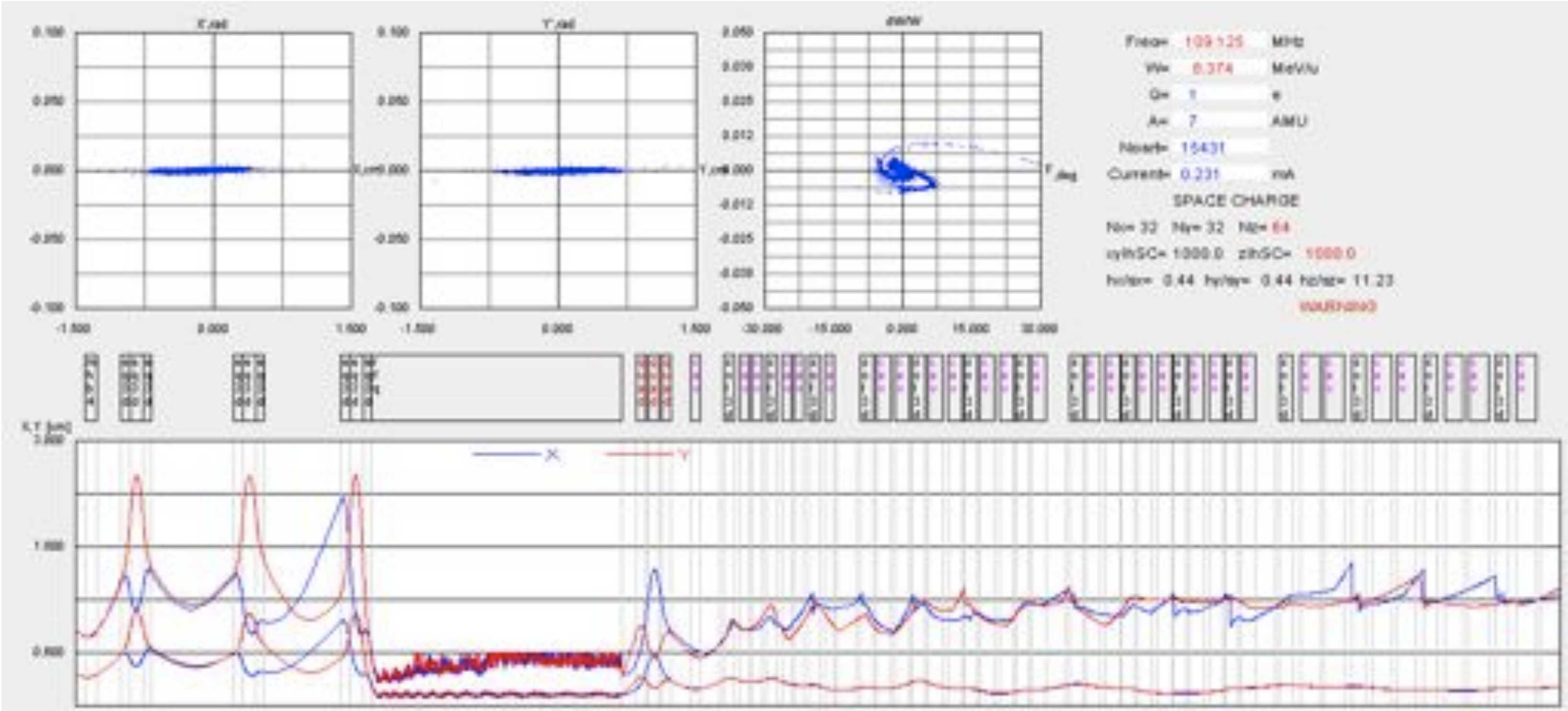
Pre-design studies

TRACK 3D (P. Ostroumov, A. Villari, I. Martel)

Reliable beam dynamics with low beam losses



Calculated full transmission for H-I > 75%

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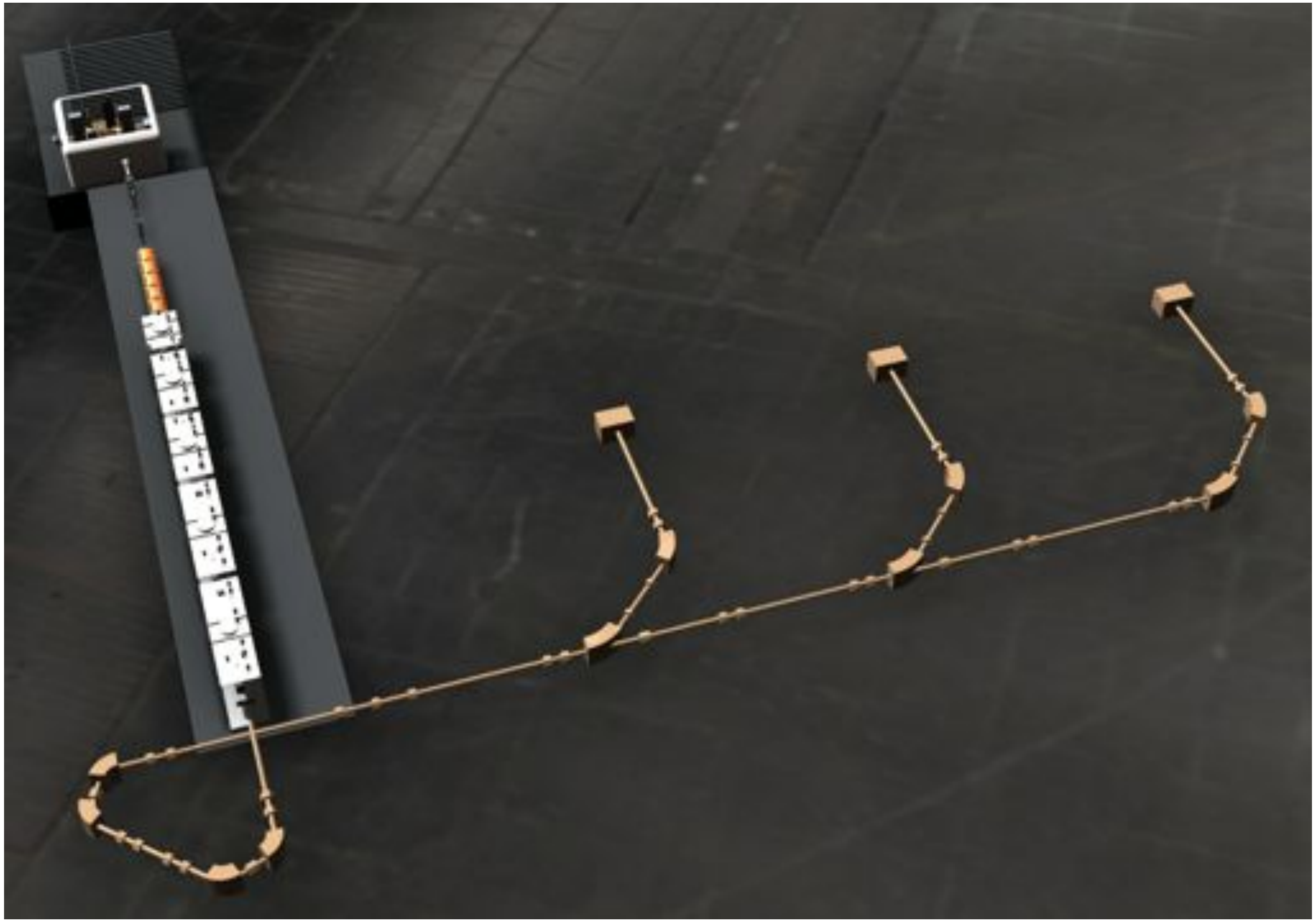
Pre-design studies

LINCE LINAC layout



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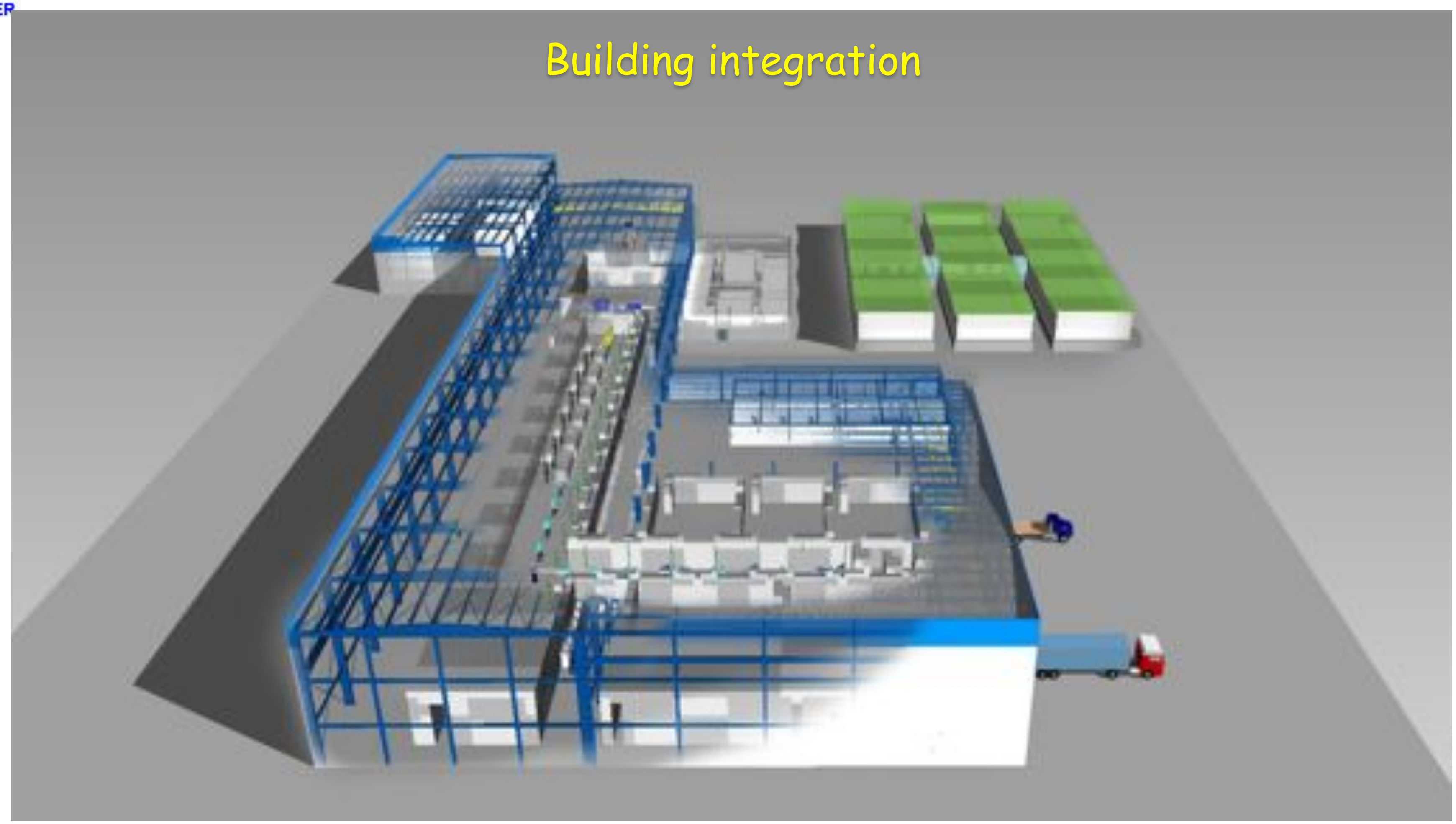
Pre-design studies



Pre-design studies

ECR with **reliable** parameters

- ECR Double frequency 14.5-18.GHz
- Reference performance attainable: > 1.5 mA ^{16}O (6+)
- Maximum field needed in Injection = 2.5 T
- Full Super-Conducting, He recycling
- **Dodecapole "**external magnet" (à la SECRAL)
- Chamber φ = 100 mm, L = 700 mm
- Reasonable operation cost for rare isotopes

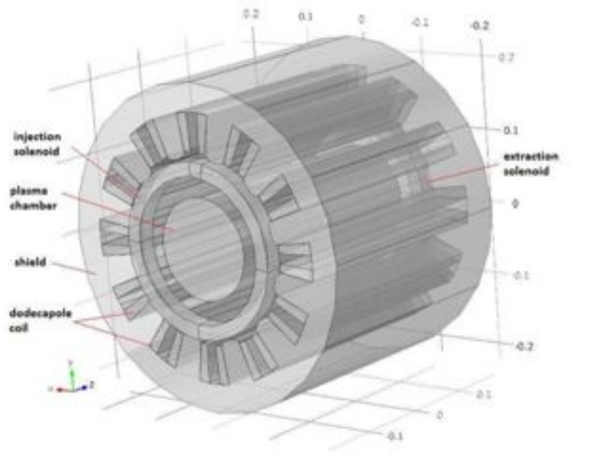
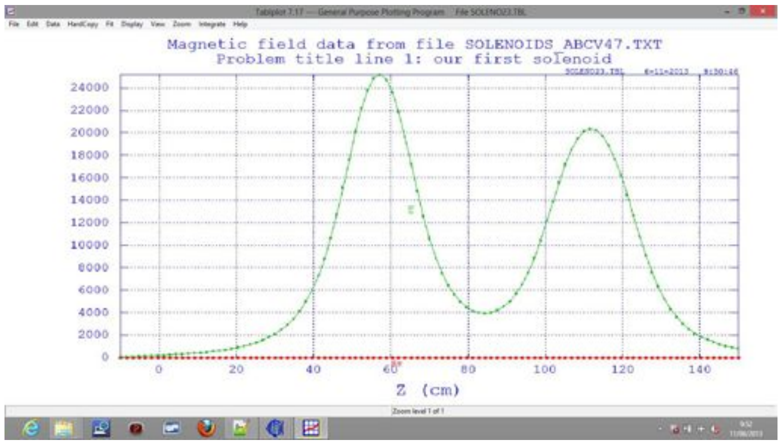


Ilustración 1.15 Región central de la fuente de iones ECR con los solenoides de inyección y extracción, la cámara de plasma y las partes lineales de las bobinas del dodecapolo.



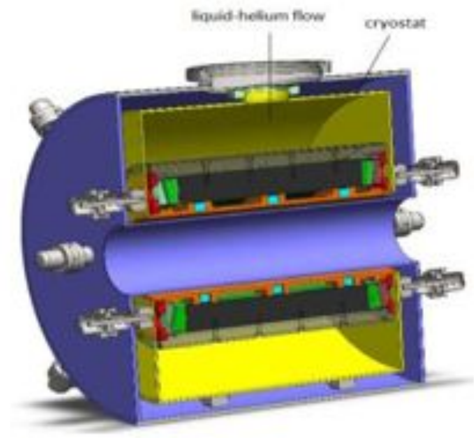


Ilustración 1.28 Diseño del criostato de la fuente de iones ECR.

ECRIS-LINCE (CARMEN)

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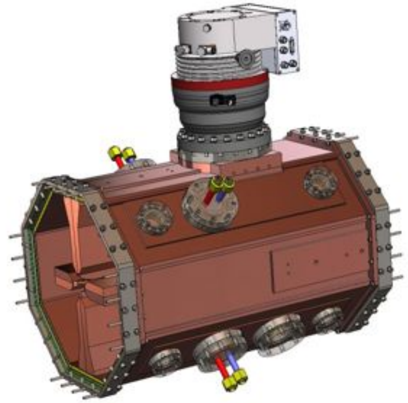
Pre-design studies

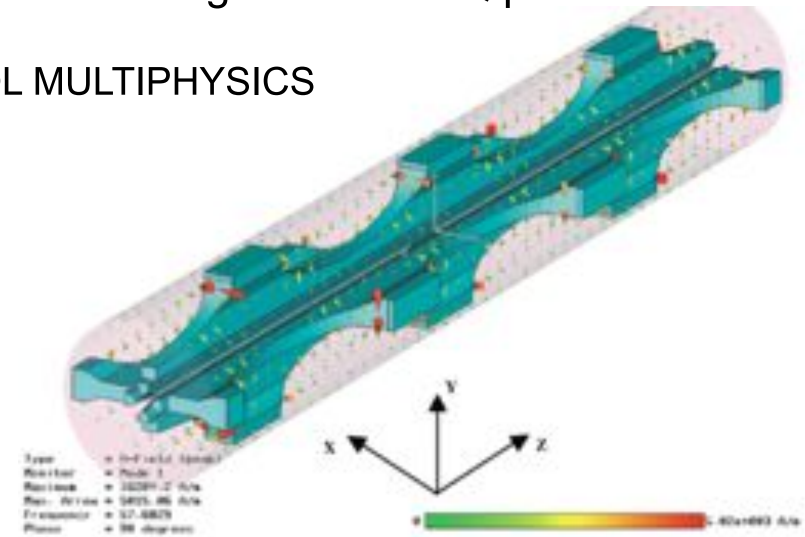
RFQ with proven design

- F = 72.75 MHz
- A/q = 7 (85 kV), down to A/q = 1 (12 kV)
- Injection energy: 40 A keV (280 kV for A/q=7)
- Output energy: 500 A keV
- Brazing concept proven technology
- M-H Buncher (4 H) fundamental: 18.188 MHz corresponding to 55 ns
- Double Buncher for protons and f = 36.37 MHz
- Manufacturing tests of RFQ parts



On-going Cu prototype

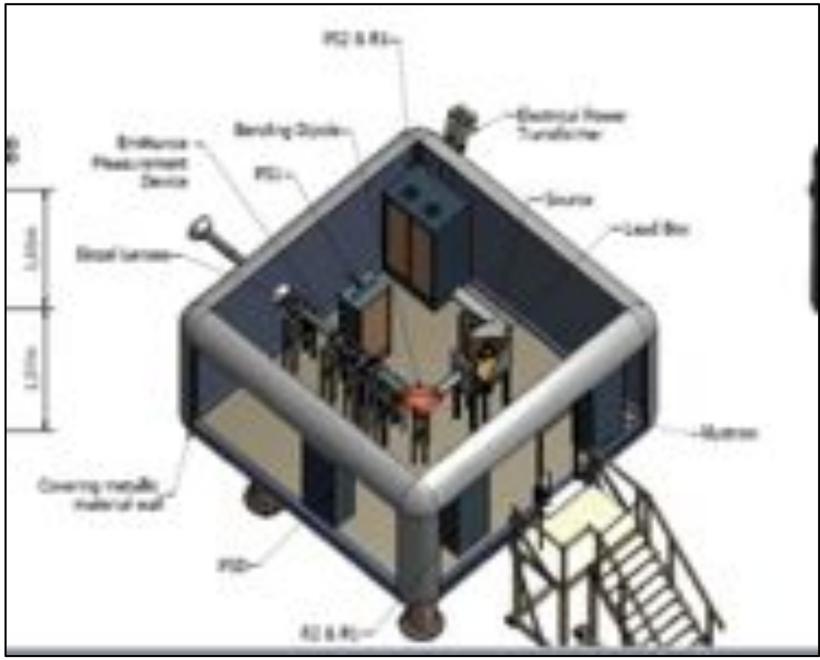
COMSOL MULTIPHYSICS



Cold model Aluminium

Pre-design studies

HV platform and LEB



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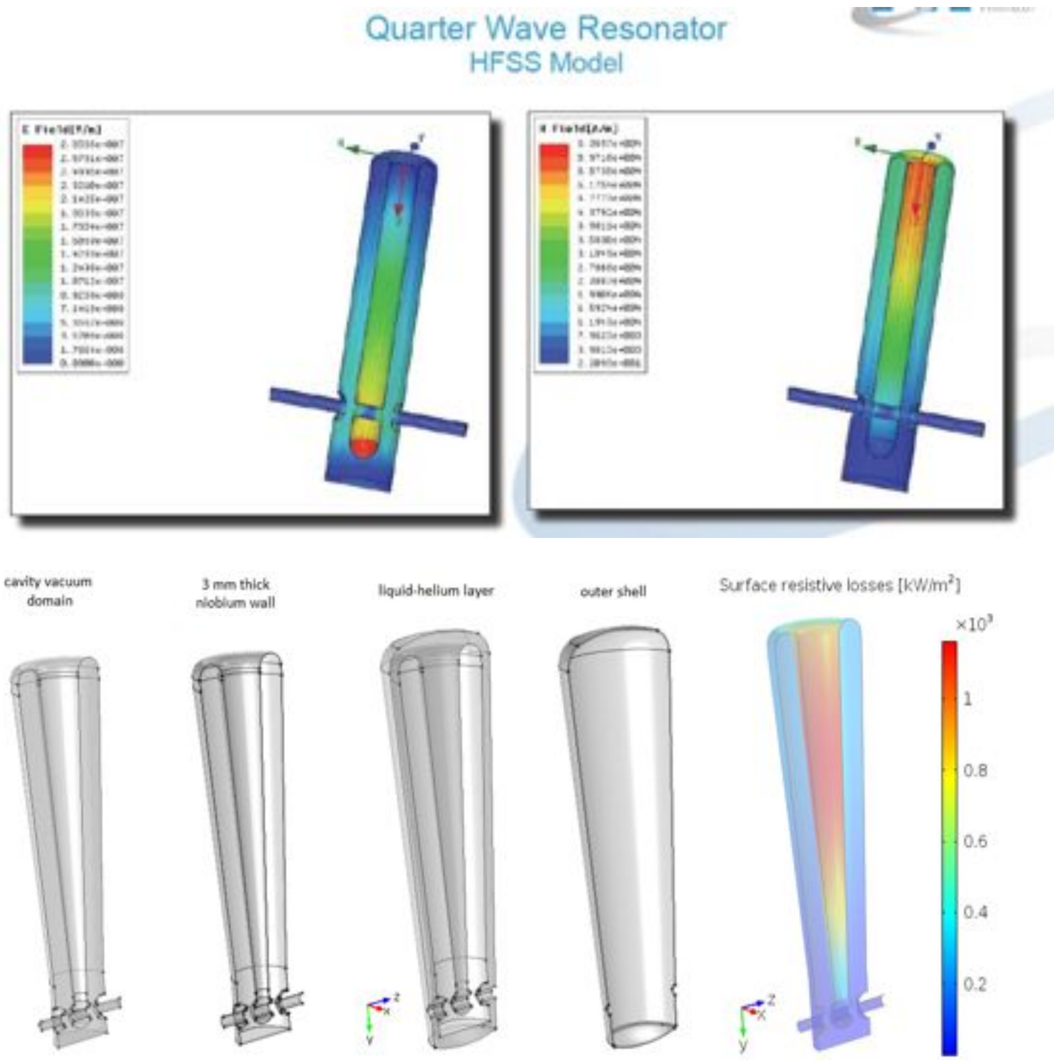
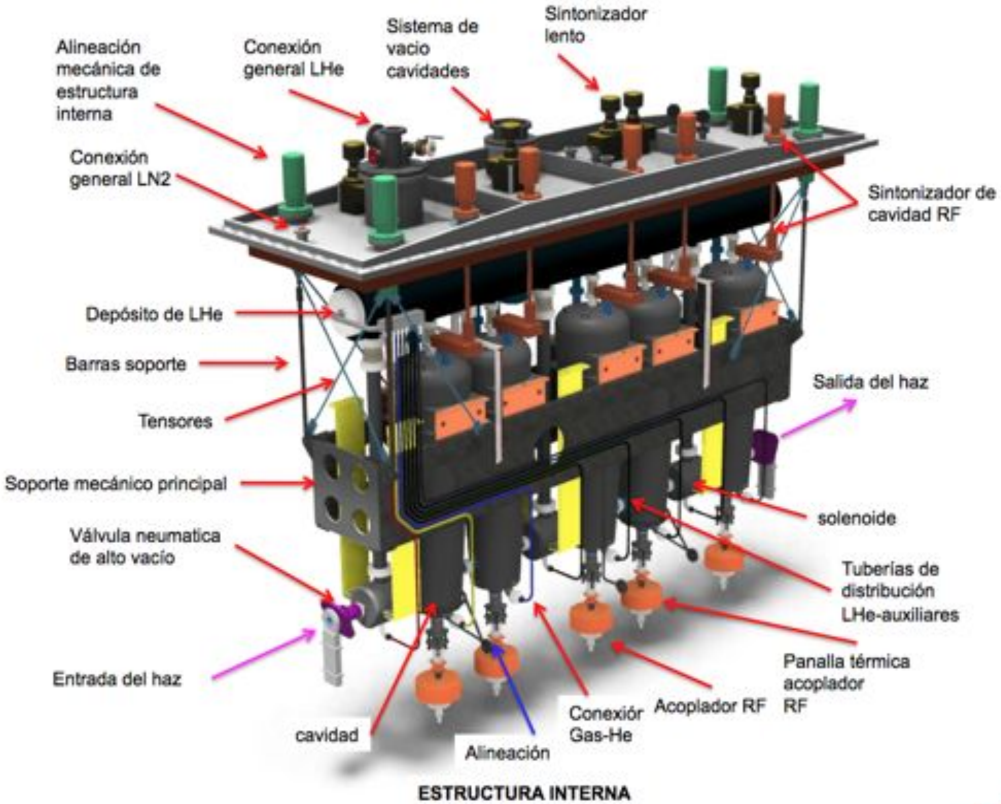
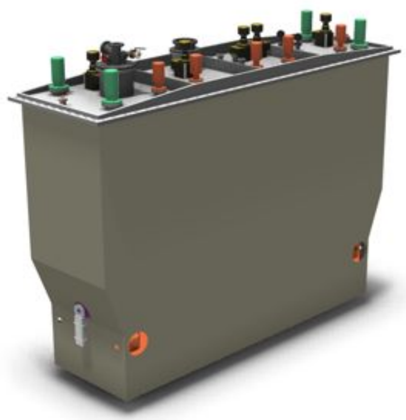
Pre-design studies



Simple test prototype

Pre-design studies





Cryomodule C1

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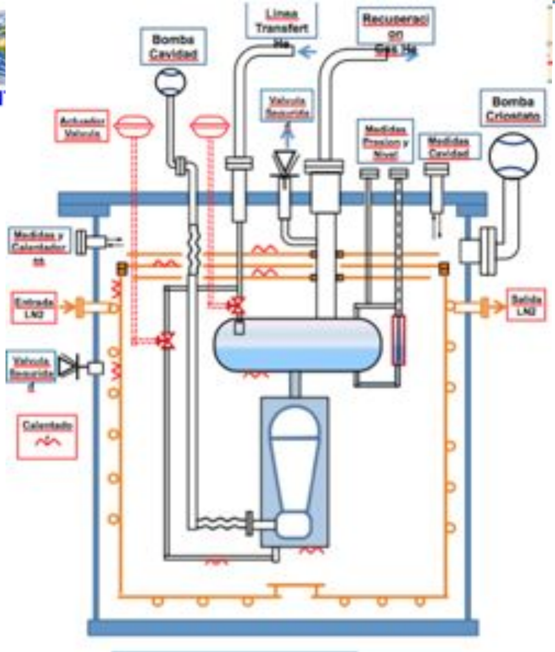
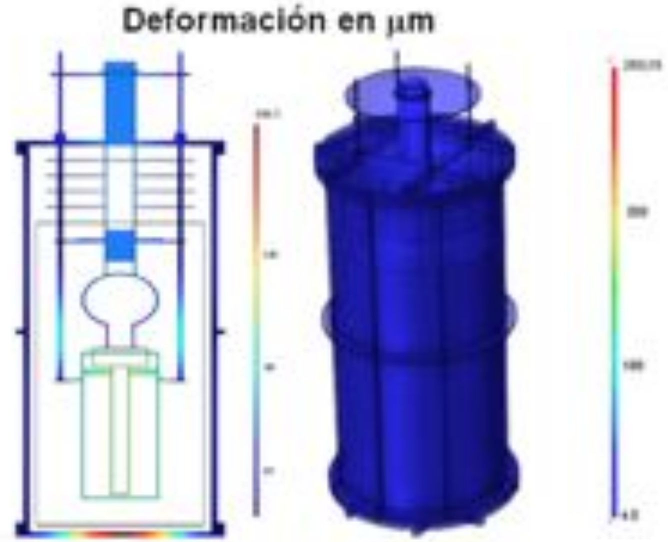
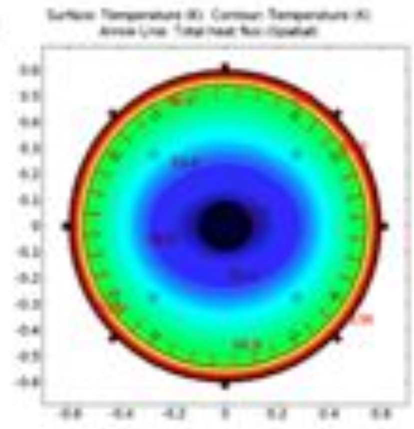
Cavity test cryostat







Prototype at UHU

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Possible planning

Pre-design	Detailed design (INFRADEV)	Construction	Commissioning
2012-16	2017/18	2019/22	2023

ECOS-LINCE:
Possible European Sites

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SPAIN

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PARQUE CIENTÍFICO TECNOLÓGICO DE HUELVA (PCTH, Aljaraque)

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Thanks for your attention!