

ECOS-LINCE: A HIGH-INTENSITY HEAVY-ION FACILITY FOR NUCLEAR STRUCTURE AND REACTIONS*

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During the last years, the ECOS working group has been considering the construction of a new high-intensity accelerator of stable ion beams for the next Long-Range Plan of the nuclear physics community in Europe. The new facility (LINCE) will be a multi-user facility dedicated to ECOS science: fundamental physics, astrophysics, nuclear structure and reaction

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dynamics. In this paper, we summarize preliminary design studies of the low-energy part of this facility based on the use of a multi-ion superconducting linac.

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1. Introduction

In the latest report of ECOS (European Collaboration on Stable Ion Beams) — an expert working group of Nuclear Physics European Collaboration Committee (NuPECC) [1, 2], the construction of a high-intensity accelerator for stable beams at energies at and above the Coulomb barrier was proposed to be considered for the next Long-Range Plan of the nuclear physics community in Europe. This accelerator should be dedicated to experiments demanding higher intensities and/or longer beam times beyond the availability of present facilities. The ECOS report, published in July 2007 [3], identified several areas of research to be addressed by the new facility:

- Synthesis and spectroscopy of super-heavy nuclei.
- Nuclear structure studies at low, medium and high-spin.
- Ground-state properties.
- Near-barrier transfer and fusion reactions.
- Nuclear astrophysics.
- Ion-ion collisions in plasma.

During the years since publication of the ECOS report, new topics have emerged, covering the study of the equation of state of asymmetric nuclear matter, isoscalar and isovector resonances both spin-flip and non-spin-flip types, and precision measurements of nuclear matrix-elements for fundamental physics, which demand the use of high-intensity stable beams. Furthermore, interesting applications of heavy- and light-ion beams in different disciplines could be pursued with the proposed facility.

The wide range of experimental activity proposed for LINCE (European LINac CEnter) leads to consider a multi-ion accelerator (from protons to uranium) of variable energy, ranging from few A MeV up to about 200 A MeV, delivering a maximum heavy-ion intensity around 1 mA on target. The design of this facility can be based on a high-energy high-intensity continuous-wave (CW) superconducting (SC) heavy-ion linac. This option will benefit from the recent know-how acquired by the scientific community

during the upgrade of the ATLAS facility at the Argonne National Laboratory (ANL, USA), the Facility for Rare Isotope Beams at Michigan State University (FRIB, USA), and the superconducting linac of SPIRAL2 facility at the Grand Accélérateur National d'Ions Lourds (GANIL, France). Nevertheless, other configurations cannot be excluded. From a conceptual point of view, a low-energy linac can be coupled to a FFAG high-intensity synchrotron in a similar manner to the KURRY facility at Kyoto University (Japan) [4]. Another possibility can be based on the high-gradient CH superconducting resonators recently development at GSI (Germany) [5]. In any case, a detailed study of the LINCE facility must be launched in the nearest future to analyse the various technological solutions.

In this paper, we present a preliminary design of a multi-ion CW-SC linac as an option for building the future LINCE facility. We have considered a range of energies up to ≈ 10 A MeV, which can cover a major part of the physics topics addressed in the previous ECOS report. This accelerator can be regarded as the “low-energy” part of the facility, allowing for the ion energy to be extended using additional alternatives.

1.1. Beam dynamics calculations

The configuration of the linac and the detailed specifications of the main accelerator components (magnets, RFQ and SC cavities) depends on the choice of the mass-to-charge ratio, A/q . This factor determines space-charge effects and the maximum ion-energy gain per cavity. To achieve a compact design with a reduced number of cavities, we have chosen the range $1 \leq A/q \leq 7$. A selection of ion beams and intensities considered in this work is given in Table I. The design requirements are the following:

1. Energy range from protons (45 MeV) up to uranium (8.5 A MeV).
2. Maximum beam intensity of 1 mA.
3. Current stability $< 1\%$.
4. Beam structure — continuous wave.
5. Beam losses < 1 nA/meter.
6. Bunch length ≤ 100 ps.
7. Transverse emittance (norm, rms) $< 0.1 \pi$ mm mrad.
8. Longitudinal emittance (rms) < 4 nsec keV/ u .

Detailed beam-dynamics and beam-transport calculations [7, 8] have been carried out with the codes TRACK [9], GPT [10] and MADX [11], including the space-charge effects and realistic electromagnetic fields obtained by the numerical codes CST [12], HFSS [13] and COMSOL Multiphysics [14]. The final configuration proposed for LINCE is shown in Fig. 1.

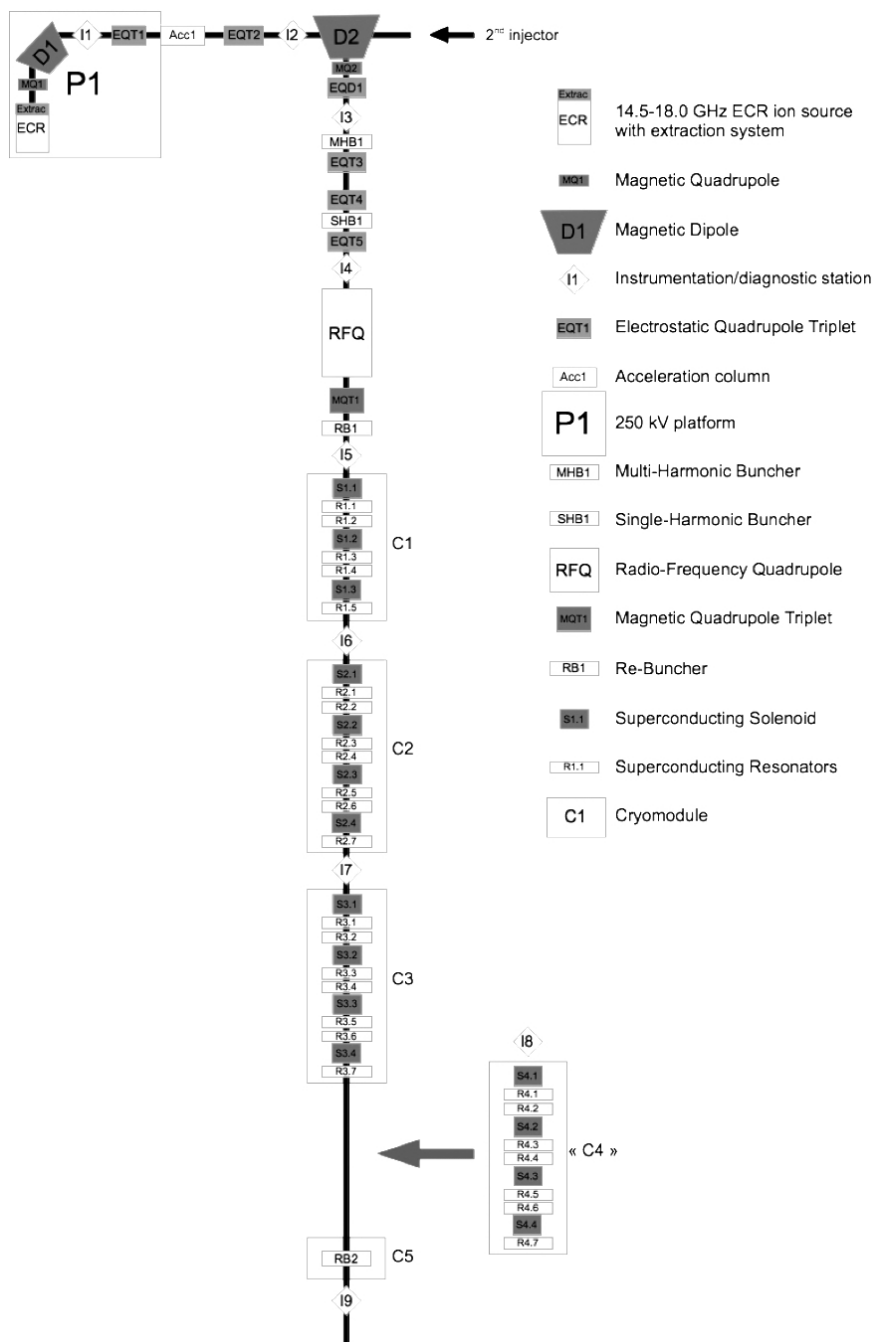


Fig. 1. Configuration of the superconducting linac proposed for LINCE.

TABLE I

Selected LINCE beam intensities and energies. The expected uranium intensity could be increased. Recent results obtained at Riken (Japan) showed 200 $\epsilon\mu\text{A}$ for $^{238}\text{U}^{34+}$ [6].

Ion	Q	A/Q	E [MeV/ u]	I [$p\mu\text{A}$]/ I [$e\mu\text{A}$]
H	1	1	45	1000/1000
^4He	2	2	10	500/1000
^{28}Si	9	3.1	12	10/90
^{48}Ca	8 or 10	6 or 5	7.5	10/80 or 100
^{184}W	27	6.8	2.5	1/27
^{238}U	34	7	8.5	0.5/17

The initial 40 A keV ion beam is produced on a high-voltage platform (250 kV max.) by a high-intensity electron-cyclotron resonance ion source (ECRIS) using a 30 kV extraction system. The low-energy beam transport system [8] transfers the ions to a multi-harmonic buncher (MHB) working at 18.1875 MHz, which defines the fundamental frequency of the accelerator. This frequency corresponds to about 55 ns between ion bunches, which is appropriate for time-of-flight experiments. We also found that, for H and He beams, an additional single-harmonic buncher (SHB) working at 36.375 MHz (2nd harmonic) is needed to reduce the space-charge effects.

The Radio-Frequency Quadrupole (RFQ) works at 72.75 MHz (4th harmonic), delivering a bunched beam around 100 ps width and an energy of 500 A keV.

The designed linac system is composed of 26 SC-QWR with only three beta values (0.045, 0.077 and 0.150). The operational frequency of the first group of 19 cavities will be 72.75 MHz (4th harmonic), delivering a maximum energy of 25 MeV for $A/q = 1$, and 5 A MeV for $A/q = 7$. The last group of

TABLE II

Beam energy (in MeV) for selected A/q values obtained from present design study.

A/q	E/A	Example	Charge state
1	45	H	1+
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	8.5	^{238}U	34+

7 cavities working at 109.12 MHz (6th harmonic) must be included to reach the design energy goal, 45 MeV protons ($A/q = 1$) and 8.5 A MeV $^{238}\text{U}^{(34+)}$ ($A/q = 7$). Maximum energies for typical ion beams are shown in Table II. The total length of the linac accelerator is 17 m.

1.2. The ECRIS ion source

In order to carry out long beam-time experiments, a very reliable and stable ion source must be provided. The maximum beam intensity considered at present design study is of 1 mA, meaning a range of 10–100 μA for heavy ions up to $A/q = 7$. These beams can be produced by commercial 28 GHz ECRIS, although operating at its limits of performance (see *e.g.*, [15]) so that beam stability for long uninterrupted operation is not guaranteed.

We have carried out a preliminary study of a superconducting double-frequency ECRIS [16] able to fulfil these requirements. The superconductivity option is more convenient as the source has to be used in conjunction with a HV platform, and a reduced power consumption is needed. On the other hand, the variety of ions at high charge states precludes the use of a permanent magnet option.

The ECRIS design has been based on the Geller's scaling laws [17]. Our study, including the magnetic and thermo-mechanical modelling, and the beam extraction, has been performed using COMSOL Multiphysics [14]. The final configuration is shown in Fig. 2. The radial magnetic field is created by using an external SC dodecapole structure surrounding the triplet of SC solenoids that induce the axial magnetic field. The working parameters are given in Table III. The performance of this source is expected to be similar to SERSE [18], which has similar size and magnetic fields.

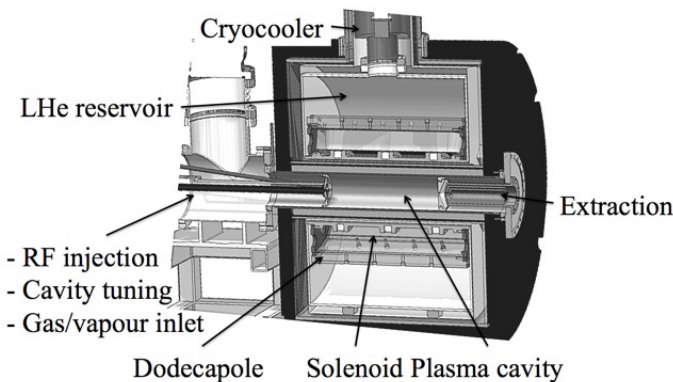


Fig. 2. Sketch of the main elements of the ECRIS proposed for LINCE.

TABLE III

Main parameters of the double-frequency LINCE ECRIS.

Parameter	Value
Working frequency	14.5 GHz and 18 GHz
RF power	1 kW (14.5 GHz) and 2 kW (18 GHz)
B injection	Variable < 2.6 T
B extraction	Variable < 2.0 T
B min.	Variable $0.22 \text{ T} < B < 0.5 \text{ T}$
B radial in the wall of the chamber	Variable < 1.8 T
Diameter of the chamber	100 mm
Internal diameter of solenoid coil	200 mm
Length of the chamber	700 mm
SC-coil working temperature	4.5 K
Yoke diameter/length	800 mm/800 mm
Neutral injection	Gas, oven and sputtering
Injection-extraction coil distance	336 mm
Coil mechanical support	Aluminium
Extraction voltage	30 kV
Extraction focussing	Einzel lens
X-ray shielding	Lead (1 cm)

1.3. The RFQ

The initial acceleration of the heavy-ion beam will be achieved using a room-temperature RFQ operating at 72.75 MHz. In this work, we have considered a four-vane resonator of octagonal shape, and the detailed design has been based on the system currently operating at ANL [19]. The model includes the so-called “RF windows”, a series of characteristic openings at the body of the vane structure as shown in Fig. 3 (left). In our case, the design covers a mass-over-charge ratio in the range $1 \leq A/q \leq 7$, with the entrance and exit energies of 40 A keV and 500 A keV, respectively.

In this work, the vane structure was generated using the code DESRFQ [20]. The beam dynamics simulations were carried-out using TRACK [9] and GPT [10]. A realistic physics model of the complete RFQ structure was implemented in COMSOL Multiphysics [14] by coupling the relevant physics modules (Electromagnetic, RF, Heat Transfer, Thermo-Mechanics, Fluid Dynamics and Particle Tracking), obtaining a total beam transmission close to 80%. The main working parameters obtained after the optimisation process are given in Table IV, and the final mechanical realization is shown in Fig. 3 (right). A more detailed discussion of the design process can be found in [7, 21, 22].

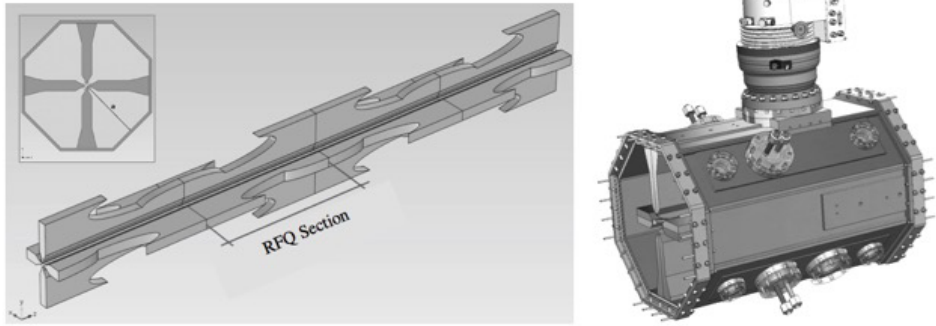


Fig. 3. Left: COMSOL model of the vane structure of LINCe RFQ, showing the RF windows and sections. Right: Mechanical construction of the first RFQ section.

TABLE IV

Main parameters of the room-temperature LINCe RFQ.

Parameter	Value
Frequency	72.75 MHz
Total length	5040 mm
Input velocity	0.00926 c
Output velocity	0.03275 c
Input kinetic energy	40 A keV
Output kinetic energy	500 A keV
Design mass-to-charge ratio	$1 \leq A/q \leq 7$
Maximum vane voltage	82 kV
Maximum field strength	1.5 (Kilpatrick units)
Average inner radius	6 mm
Bunch length input/output	1 ns/200 ps
Maximum RF power	150 KW

1.4. Superconducting cavities and cryostats

Superconducting (SC) cavities represent the best choice to reach high energies using compact accelerator systems, with the advantage of requiring low RF power levels. Using present technologies, it is possible to develop SC quarter-wave (QWR) and half-wave (HWR) resonators with peak fields up to 60 MV/m at $T = 4.5$ K, a very low power consumption below 10 W per cavity, and high quality factors ($Q \approx 10^9$ typical). To provide the highest acceleration voltages, the resonators should be built using pure Nb bulk material. The results obtained recently for the QWR structures at ATLAS upgrade and SPIRAL2 projects [23, 24] confirm the possibility to obtain an accelerating voltage per cavity V_{acc} up to at least 4 MV.

For the present work, we have used a conservative V_{acc} value between 1.2 and 3.5 MV. The design of the QWR resonators has been carried out using CST [12], HFSS [13] and COMSOL Multiphysics [14]. The SC cavities have been grouped in separate cryostats hosting a maximum of 7 units of same beta value and frequency, allowing for easier operation and maintenance, as shown in Table V. Inter-cavity beam focussing is achieved by using compact SC solenoids with a maximum on-axis field of $B = 9$ T. The cavities have been grouped in 4 cryomodules (C1–C4) and one re-buncher (C5) (Table V). The maximum energy obtained at the exit of each cryomodule is given in Fig. 4. A more detailed description of the design process can be found in [25].

TABLE V

Configuration of SC QWR of the LINCE linac proposed at present design study.

Cryomodule	Type	Freq. [MHz]	Harmonic	Beta	V_{acc} [MV]	N cavities
C1	QWR	72.75	4	0.045	1.39	5
C2	QWR	72.75	4	0.077	2.38	7
C3	QWR	72.75	4	0.077	2.38	7
C4	QWR	109.125	6	0.150	3.30	7
C5	Re-buncher	109.125	6	0.150	3.30	1

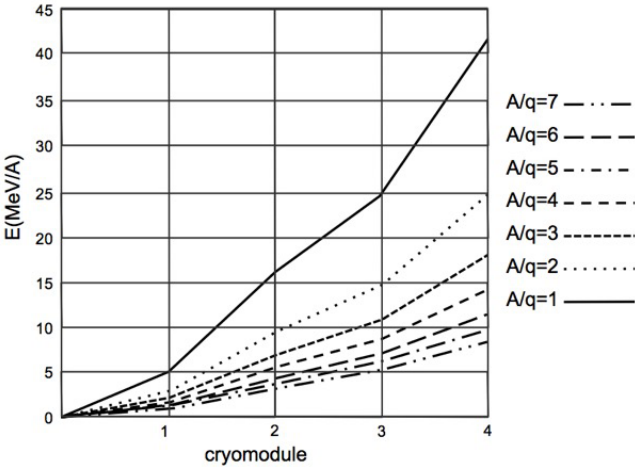


Fig. 4. Beam energy as a function of A/q at the exit of each cryomodule.

In Fig. 5, the general structure proposed for the C1 cryomodule is shown together with the main subsystems. We have chosen to separate the vacuum systems of the beam and cryostat vessel to avoid degradation of the Nb superconducting cavities. With this configuration, a static thermal load

of 24.2 W is expected. The dynamic heat load will depend on operation, and it is estimated around 80 W based on the projects at ANL (USA) and SPIRAL2 (France).

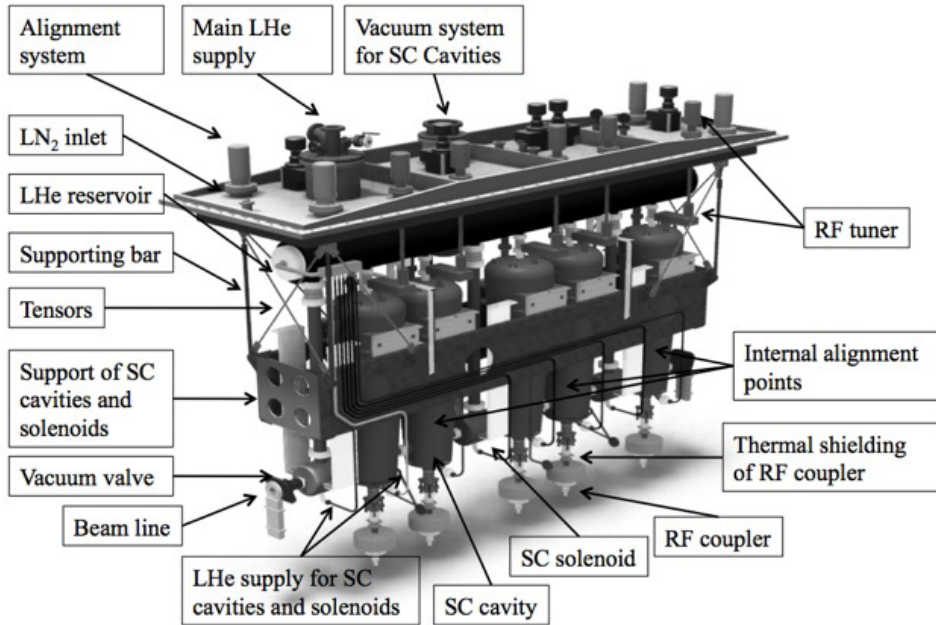


Fig. 5. Structure of the first cryostat C1 composed by 5 QWR and 3 SC solenoids.

2. Estimated cost

The cost of building for the proposed superconducting accelerator is summarized in Table VI. The figures were estimated from offers received from providers and from the costs of similar linac projects at ANL (USA) and SPIRAL2 (France). The present budget does not include the construction of the building.

The estimated funding needed for operation, assuming an annual beam time allocation of 7,000 h, will be around 5,000 k€ per year. This includes the salary of operators, technical staff, maintenance, electricity, and the replacement of damaged equipment (3% of the initial investment). It does not include the research and administration staff. The construction of LINCE would require approximately 6 years, including a commissioning period of 6 months. This estimate is based on previous experience from the construction of HIE-ISOLDE (CERN, Switzerland) and SPIRAL2 (GANIL, France).

TABLE VI

Estimated cost of LINCE superconducting linac.

Item	Cost (k€)
HV platform with ECRIS, beam line and vacuum	3,000
Low-energy beam transport	600
RFQ with auxiliary components	6,500
Cryo-module 1 complete, including man-power and power supplies	5,000
Cryo-modules 2, 3, 4 and 5, including man-power and power supplies	20,000
Cryogenics plant/installation (4.5 K, 1.5 kW)	7,000
Vacuum components for LINAC and beam lines	400
Command and control and software development	1,800
Radio-protection, safety and authorisations	650
Water, air and services	250
Diagnostics and beam instrumentation	800
Factory tests of components	200
Shipment costs and travel	700
Mechanical assembly	300
Cabling and racks	250
Detailed drawings and complementary studies	350
TOTAL	47,800

3. Summary and conclusions

In this work, we present a preliminary design study of a superconducting CW linac working at the fundamental frequency of 18.1875 MHz, that could fulfil the needs of the physics proposed for the ECOS-LINCE facility. This study is based on the ideas and concepts developed for the last upgrade of the ATLAS facility currently in operation at ANL (USA). Detailed beam dynamics and ion transport calculations have been performed by the use of the codes TRACK, MADX and GPT. Electromagnetic and thermo-mechanical studies of the critical subsystems were carried out by using CST, HFSS and COMSOL Multiphysics, which allowed to produce a realistic model of the full facility. A detailed design study should be launched in the nearest future considering other acceleration schemes, like the use of a high-intensity synchrotron and/or CH cavities.

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