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ECOS-LINCE: A HIGH INTENSITY MULTI-ION SUPERCONDUCTING LINAC FOR NUCLEAR STRUCTURE AND REACTIONS

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Abstract

During the past years, ECOS working group strongly supported the construction of a dedicated high-intensity stable-ion-beam facility in Europe, with energies at and above the Coulomb barrier as part of the Long-Range Plan of the Nuclear-Physics community. LINCE will be a multi-user facility dedicated to ECOS science: fundamental physics, astrophysics, nuclear structure and reaction dynamics. Applied research is foreseen in the fields of medical physics, aerospace and material sciences with energetic heavy ions. The facility will produce a wide range of ions, from protons (45 MeV) up to Uranium (8.5 MeV/u) with 1mA maximum beam intensity. A very compact linac has been designed by using a HV platform with a double-frequency ECR ion source, multi-harmonic buncher, an innovative CW RFQ design ($1 \leq A/Q \leq 7$) and 26 accelerating cavities made of bulk niobium ($\beta = 0.045, 0.077$ and 0.15) working at 72.75 and 109.125 MHz.

INTRODUCTION

Present knowledge of subatomic degrees of freedom and nuclear structure has been exponentially growing during the last decades by the use of heavy ion facilities. A number of facilities are presently operating at the European Unión delivering ion beams with intensities of up to a few 10^{12} particles/sec, being recognized as leading European research infrastructures. As the understanding of the atomic nucleus has increased, new physics domains have emerged that require the construction of a dedicated European facility for providing higher intensity stable heavy-ion beams. In the latest report of ECOS (European Collaboration on Stable Ion Beams, an expert working group of NuPECC [1, 2]), the construction of a high-intensity accelerator for stable beams with energies at and above the Coulomb barrier, is considered as one of the most important issues for the next long term plan of the nuclear physics community in Europe. This accelerator should be dedicated to fundamental research proposals requiring long beam times and high intensities, which will not be feasible at existing or new planned facilities at EU. The ECOS report identifies several nuclear physics topics where investigations can be only addressed with high intensity stable beams:

- 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

Applied research should be also foreseen in the fields of medical physics, energy, aerospace and material sciences. In order to accomplish for a demanding program on fundamental and applied nuclear physics, we propose the construction of a high-intensity CW superconducting linac for light- and heavy-Ion beams: the ECOS-LINCE facility. The conceptual design should be based on a reliable design using well-established technologies, aiming to provide and effective beam time allocation of about 5000 h/y for fundamental physics and 2000 h/y for applications.

Table 1: Selected Beam Intensities and Energies

Ion	Q	A/q	E (Mev/u)	I (pμA) / I (eμA)
H	1	1	45	1000 / 1000
^{4}He	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

A sample of selected ion beams and intensities are listed in Table 1. The development of this new facility should benefit from the state-of-the-art technologies and expertise recently acquired in the construction of high intensity linacs for SPIRAL2 (Caen, France), FAIR (Darmstadt, Germany), SPES (Legnaro, Italy), ATLAS (Chicago, USA) and FRIB (Michigan, USA).

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OVERALL LAYOUT OF THE FACILITY

The proposed CW multi-ion superconducting linac should be able to accelerate a wide range of ions and energies, from protons up to Uranium in a wide range of energies. Overall design requirements imposed are the following:

1. Energy range from protons (45 MeV) up to Uranium (8.5 MeV).
2. High intensity beam of 1 mA for light ions and 10p μA for heavy ions.
3. Current stability: <1 %.
4. Current structure CW/macro-pulse
5. Beam loss < 1 nA/meter
6. Transverse emittance (norm, rms): < 1π·mm·mrad
7. Longitudinal emittance (rms): < 4 nsec·keV/u

Preliminary beam dynamic studies have been performed with the code TRACK [3] using realistic electromagnetic fields obtained from HFSS and COMSOL Multiphysics, including the space-charge effects. These studies have provided optimum configuration using realistic working parameters, minimizing the length and complexity of the accelerator. A layout of the full accelerator system is presented in Fig. 1. The solution combines two frequencies for the RFQ and SC cavities (72.75 and 109.12 MHz), limiting the beam repetition rate at a RF sub-harmonic of both frequencies (18.1875 MHz). The main LINCE subsystems considered are the following:

- Superconducting ECR with extraction voltage of 30 kV and focusing solenoid.
- High-voltage platform from 10kV to 280kV
- Low Energy Beam Transport line (LEBT).
- A Multi-harmonic buncher at the fundamental frequency F= 18.1875 MHz.
- A Single Harmonic Buncher (SHB) at a frequency of 36.37 MHz will be used for protons and He beams.
- RFQ to accelerate pre-bunched ions up to 500 keV/u (1≤A/q≤7) operated at 72.75MHz.
- Four accelerating cryomodules (C1 to C4) housing superconducting quarter wave resonators (QWR) and solenoids.
- Rebuncher section (C5).

A major issue in this design is the choice of the factor q/A (charge state /atomic mass) characterizing the heavy ion beam. In principle, the design of main components (RFQ and SC cavities) is strongly related to this choice. The final beam energy per atomic mass unit (MeV/u) is proportional to both the total accelerating available voltage and the q/A factor. For any configuration it is required to adopt a compromise for the q/A value. Low charge state ions, are obviously easier to obtain with an ECR Ion Source, but it leads to lower q/A factors decreasing the final energy per unit mass.

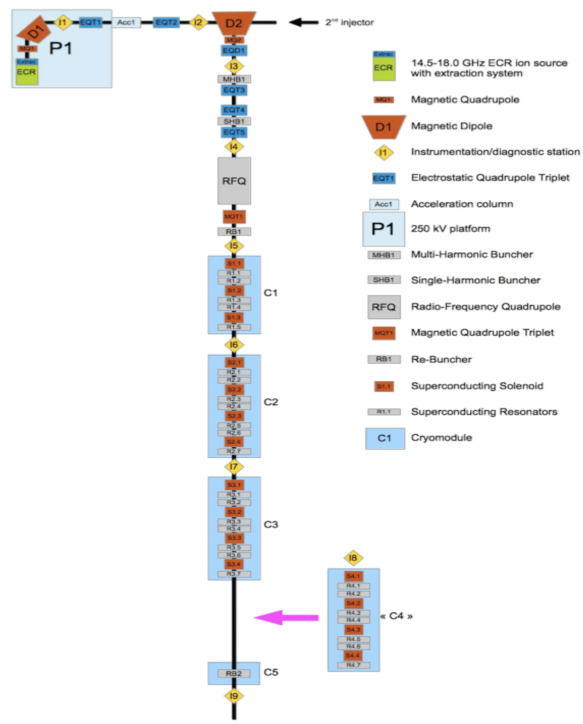

Figure 1: Proposed layout of the ECOS-LINCE superconducting linac.

The design goal chosen in this work is q/A covering the range between 1 (protons) and 1/7 (heavy ions). It corresponds to accelerated beams of H+, C3+, Ar8+ and Kr20+, for example. Commercial Electron Cyclotron Resonance (ECR) ion sources can deliver high currents of several pμA for many heavy-ion species and charged states. A convenient choice is an ECR with full permanent magnet construction, and therefore reducing the power needs of the system at the HV platform. However, no commercial option is available at present for achieving highly-charge states up to U30+ at high currents of 10 pμA, and a dedicated superconducting ECR working at double frequency (14/18 GHz) is under study [4]. The fundamental working frequency of F=18.1875 MHz is an appropriate choice for achieving a minimum bunch spacing of 50 ns need in time-of-flight applications using commercial RF amplifiers. For proton and helium beams, a second buncher working at the first harmonic F = 36.375 MHz is needed due to the space-charge effects.

The normal conducting LINCE RFQ should operate at 75.72 MHz (4th harmonic) and is designed for q/A=1-1/7, with input energy of 40 keV/u. It is composed of a total of eight oxygen free electronic (OFE) copper structures brazed in a high-temperature hydrogen atmosphere furnace, with total length of 5.04 m. Each section has 624 mm length, and should be machined with a high mechanical precision below 100 um. The RFQ delivers a final energy of 500 KeV/u with RF power consumption below 150 KW [5].

For Heavy Ions accelerators superconducting (SC) cavities represent the best choice to reach high energies

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with reasonable accelerator sizes and RF power levels. The critical performance is the accelerating gradient, which is obtained with present state-of-the-art technologies, in a reproducible way, between 5 - 10 MV/m. All these performances are the result of many recent technological developments, improving fabrication techniques and preparation of the surfaces. Three Heavy Ion Linacs have been recently designed with associated detailed studies and R&D programs: ATLAS upgrade phase (ANL, USA), Spiral 2 (GANIL, France), FRIB (Michigan, USA). Construction of LINCE resonators can take advantage of these best well-known performance cavities.

To provide the needed acceleration voltages the SC QWR resonators should be built using pure Nb bulk material, working a T=4.5 K. The different parts of each resonator are produced primarily by Nb sheet forming and precision machining while the resonator is to be assembled by using electron beam welding. Appropriate RF surface processing including buffer chemical polishing, electropolishing and high pressure water rinsing are required prior the installation of resonators into the cryomodule. The results obtained recently for the QWR structures at ATLAS and SPIRAL2 project [6, 7] confirm the possibility to obtain an accelerating total voltage for the cavity up to 4 MV, operating in a safe nominal point between 1.2 and 3.5 MV with Qo values > 10^9.

Only 26 superconducting QWR cavities with three values of β = 0.045, 0.077, 0.15, working at 72.75 and 109.125 MHz, are required to reach the design energy goal and are summarized in Table 2. The SC cavities have been organized in four accelerating cryomodules, providing reasonable compactness, construction complexity and maintenance.

Table 2. Configuration Used for the Design Study

Cryo-module	Type	Freq. (MHz.)	Har-monic	Beta	V_{acc} (MV)	Nº Reso nators
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	0,15	3,30	7
C5	Rebuncher	109,125	6	0,15	3,30	1

Beam dynamics calculations have been performed with the code TRACK [3]. With the present structure of the accelerator, all ion beams with mass to charge ratio from 1 to 7 can be accelerated with maximum overall efficiencies. We continue optimization design of the linac to minimize beam losses below the acceptable level in the presence of machine errors.

The SC cavities operate within cryostats fed with Liquid Helium at 4.5 K. Dimensioning the installed cryogenic power consists to add the static losses, the dynamic losses and the margin for possible operation with higher voltages (power is proportional to V^2). The expected dynamic cryogenic load is below 10 W per cavity (total of 260 W). The static losses depend strongly on the cryostats design and the distribution of infrastructure installation, and a typical margin level installed in other similar linacs is about 30 %. Therefore the cryogenic system should be designed for a minimum 1kW at 4.5 K.

SUMMARY AND CONCLUSIONS

In this paper we present an overview of the ECOS-LINCE facility, a high-intensity facility for basic nuclear physics and applications. The design is based on a CW superconducting heavy-ion linac for q/A=1/7, working at the fundamental frequency of 18.1875 MHz and 26 superconducting quarter wave resonators, with three beta values β = 0.045, 0.077, 0.15. The choice of a double frequency superconducting ECR should allow to achieve beam intensities up to 1 mA for light ions and 10 puA for heavy-ions, with energies up to 45 MeV for protons and 8.5 MeV/u for ^{238}U. The conceptual design is fairly advanced, and will continue in nearest future with extensive end-to-end beam dynamics simulations iterated with the engineering design of the various accelerator elements.

ACKNOWLEDGMENTS

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