SC ACCELERATOR COMPONENTS FOR LIGHT ION LINACS

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Abstract

Our SRF related activities are mainly dedicated to two projects. One is connected with the LINAC system of the proposed European Spallation Neutron Source ESS which is supposed to deliver 1.3 GeV H$^-$ pulses of about 110 mA over 1.2 ms with a repetition rate of 50 Hz for injection into compressor/storage rings. Additionally H$^+$ pulses of 2.5 ms with the same current should be provided in interlaced operation with a repetition rate of 16.66.. Hz. In close co-operation with European partners, we work on selected items for the ESS LINAC. A superconducting (sc) test module with 5 elliptic cells is available for investigating stability effects i.e. microphonics and Lorentz Force Detuning (LFD) in pulse mode operation. For the medium energy segment spoke type cavities are under investigation. – Since May 2001 the realization of a low energy LINAC based on sc Quarter Wave Resonators (QWR) is pursued, which will serve as H$^-$ and D$^-$ injector for the cooler synchrotron COSY. For the design we found an experienced partner in INFN-LNL, Legnaro, Italy, were the ALPI heavy ion accelerator was constructed using sc QWR technology. Their resonator structures have to be modified to compensate the disturbing effects of non-symmetrical fields, which are especially important in light ion acceleration.

1 THE ESS CONCEPT

The European Spallation Neutron Source (ESS) aims to become the next generation regional neutron source for Europe. The proposed accelerator configuration of the ESS will start with two high intensity H$^-$ ion sources followed by radio frequency quadruple (RFQ) arrangements in series including beam chopping in a parallel configuration. After acceleration up to 20 MeV, the two separate beams with intensities of approximately 55 mA peak current each are combined to one beam by a funnelling system for further acceleration to about 90-100 MeV in a Drift Tube Linac (SDTL). Acceleration of the H$^-$ beam to the final energy of 1.334 GeV will be accomplished by Coupled Cavity LINAC systems (CCL) in a combination of normal conducting (nc) and sc sections.

After extensive investigation and consultations over the past years, consensus has been reached between the parties concerned that in addition to the short pulse target station also a long pulse target station has to be seriously considered. Thus the ESS LINAC is required to deliver 1.334 GeV H$^-$ beams in a sequence of pulses of about 110 mA peak current with a repetition rate of 50 Hz for injection into the storage rings. Assuming an interlaced operation for the long pulse mode (t_{PULS} =2.5ms) with 16.66.. Hz, an H$^+$ beam of equal intensity can be delivered from a single source. The peak current is made identical for all pulses to keep space charge forces constant. The average beam power is as high as 5 MW for both modes. The beam power required for short and long pulse application is made equal by adjusting the individual pulse duration.

Figure 1 shows one possible layout of the ESS linac system as it is presently discussed in the frame of the CONCERT project in France. Progress in sc accelerator technology in recent years has a significant impact on linac design. With higher accelerating gradients than possible with copper structures, the use of sc cavities reduces the linac length. Moreover, due to the high RF to beam power conversion rate, the operational costs are significantly reduced. Even if the advantages of
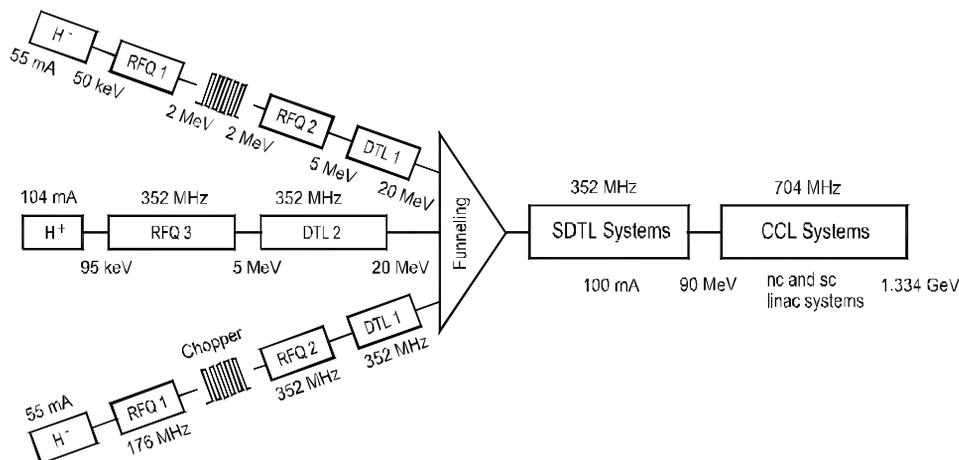

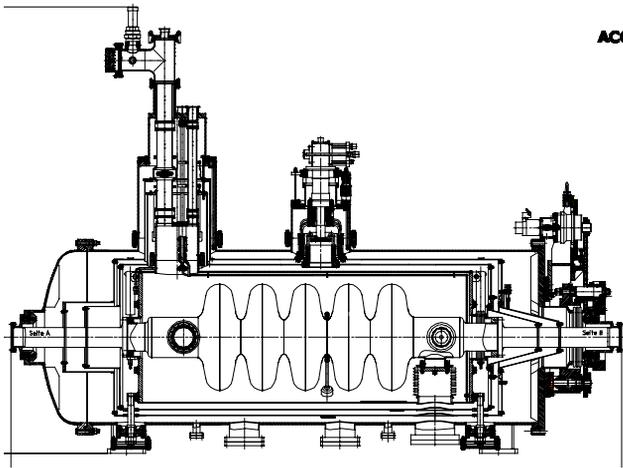Figure 1: Schematic layout of the modified ESS linac concept for short and long pulse operation.

Figure 2: Superconducting test module, 5 elliptic cells, f = 500 MHz, β = 0.75, E_{acc} ~ 11 MV/m, 2 thermal shields at 20 K and 80K, combined frequency tuning system (coarse by motor driven gear, fine/fast by piezo elements).

superconductivity are more pronounced for the high duty cycle mode as in case of long pulse operation of ESS, the final decision for a nc or sc version of the high energy part is still pending.

Our contribution to the accelerator system of ESS includes design and R&D work for the low and high energy LINAC part. We are investigating RF and mechanical characteristics of elliptic cells and try to design a system for amplitude and phase control, which allows active compensation of LFD. For the low energy part of the LINAC (i.e. the regime from 20 MeV to ~150 MeV), we are investigating sc multi-gap H-type structures which promise to be an attractive alternative for operation with high duty cycles.

2 SUPERCONDUCTING TEST MODULE

In order to supplement design work by experimental investigations a test module was realized in co-operation with industry [1]. The sc cavity (5 elliptic cells, f=500 MHz, β=0.75) is operational for tests with RF-power up to 40 kW. Figure 2 shows the module which is designed for test purposes only and not anticipated to work with beam. It allows the investigation of important effects like LFD or microphonics and is an excellent test bench for an advanced control system of amplitude and phase, especially in pulse mode operation. The module is equipped with a coarse frequency tuning system working with a stepper motor and gear. A superposed fast frequency tuning system comprising piezo elements supports the idea to implement an active compensation of LFD. Experimental results concerning the analysis of mechanical resonances and first attempts to control LFD are discussed in [2].

3 LOW-β SC CAVITY INVESTIGATIONS

For many accelerators operating in cw or long pulse mode, like in transmutation facilities or long pulse

spallation neutron sources, sc technology might be the only choice. In the high energy part of such accelerators the well-developed multi-cell elliptic cavities are most suitable. For the low energy part, such elliptic structures cannot be used because of their mechanical characteristics. There is a choice of different, already proven low-β sc cavities. We investigate multi-gap (up to ten) H-cavities (700 and 320 MHz, β=0.2 to 0.5) based on spoke type geometry [3]. All cavities are optimized to reach the maximum possible accelerating electric field. Electrodynamic and structural analyses are provided for the cavity design. Simulations for various vacuum and coupling port positions are in progress. Different cavity tuning schemes are under investigation. A 4-gap 700 MHz, β=0.2 superconducting H-cavity is being designed (see Figure 3). A copper model of such an H-cavity has been constructed and measured. First experimental results indicated excellent agreement with calculations.
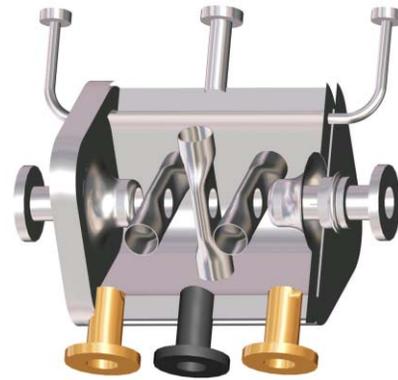

Figure 3: A four-gap niobium spoke-type cavity for β = 0.2. Frequency tuning is done by axial displacement of the end caps.

4 SC LINAC INJECTOR FOR COSY

The cooler synchrotron COSY is in operation at Forschungszentrum Jülich since 1993 and up to now provides polarized and unpolarized proton beams for internal and external experiments [4]. The isochronous cyclotron JULIC serves as injector delivering H⁻ beams at 45 MeV for the stripping injection into the COSY ring. JULIC was originally designed as a variable energy deuteron accelerator for up to 90 MeV. To serve as injector it had to be converted into a machine providing extracted beams of negative ions, which for high energy negative deuterons was a challenge. Last year a 10 µA D⁻ beam could be successfully extracted and injected into COSY [5]. Deuteron beams from a cooler synchrotron will open a new attractive field for experimental research in Hadron physics.

Operational experience at COSY with JULIC as injector shows that up to 2×10^{11} particles can be accumulated in the ring during injection, but the values achieved for polarized proton beams are at best an order of magnitude lower. In order to fill the ring up to its space

charge limit with polarized particles, the beam intensity from the injector has to be at least 10 times but preferably 100 times higher, which is completely out of range for JULIC. To fully exploit the unique experimental opportunities of COSY, the facility has to provide sufficiently intense beams of polarized protons and deuterons by means of a new pre-accelerator replacing the cyclotron JULIC as injector.

Several alternatives for a new injector were considered and evaluated in more detail. Our aim was to find an optimum solution in terms of justifiable resources, available space, accessibility, minimum interference with the ongoing experimental programme at COSY, as well as recent developments in the field of accelerators. As a result, the option of a superconducting LINAC is favored. The project of the new COSY injector is fully approved by the authorities, i.e. by the supervisory board of Forschungszentrum Jülich, and construction has already begun.

4.1 General Layout

The proposed injector is designed to deliver both polarized and unpolarized H⁻ and D⁻ beams at an energy of approximately 50 MeV. Beam currents up to 2 mA should be provided in pulses lasting up to 500 μs with a maximum repetition rate of 2 Hz. Hence the duty factor of beam in the new injector will not exceed a value of 10^{-3}.

By installing the new injector in a service area close to COSY, it can be linked most directly and economically to the existing injection path into the ring. Preserving accessibility to all important parts, this choice minimizes interference with the operation of COSY during the construction period. The available space for the LINAC is not more than 6 m wide and approximately 40 m long, including support equipment and shielding.

For a conventional LINAC, the most reasonable method to accelerate both types of ions in the same accelerating structure would be to use the βλ-mode for H⁻ and the 2βλ-mode for D⁻ beams. Unfortunately this implies that the maximum energy for D⁻ would be at best not more than half that of H⁻.. Moreover, the required RF power in the order of 7 MW has to be delivered by 4 to 5 Klystrons. In case of failure of only one Klystron there would be no beam available for several days. Reliability is of prime concern as the injector LINAC is expected to deliver beam at least 7.500 h/year.

The concept of a sc LINAC with individually powered Quarter Wave Resonators (QWR's) changes the situation drastically. RF power is generated in 3 kW solid state modules and in the case of failure such modules can be quickly replaced. As each resonator can be controlled individually in amplitude and phase, it is possible to reach a final energy of approximately 50 MeV for H⁻ as well as D⁻ ions.

The layout of the proposed injector is shown in Fig. 4. The ion source section includes one source for polarized H⁻ and D⁻ ions (CIPIOS type) and a commercial multi-cusp source for unpolarized H⁻ and D⁻ ions. The
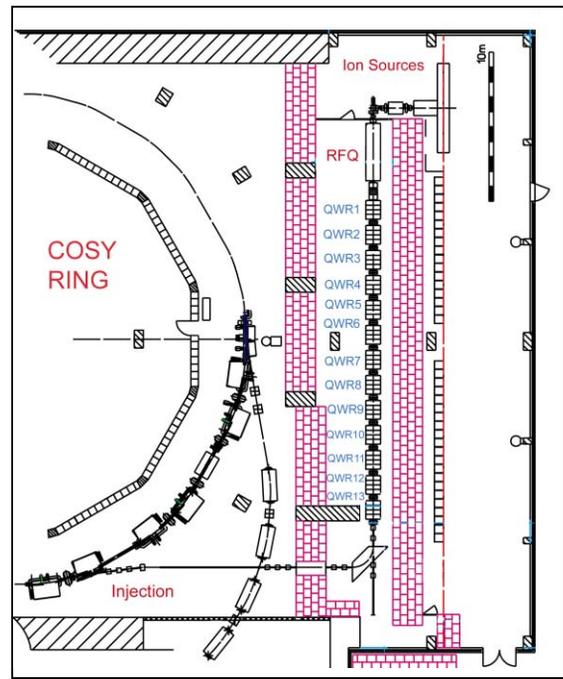

Figure 4: Schematic layout of the sc injector LINAC for COSY. Beams are bent by 90° for injection.

following RFQ section has to be designed individually for H⁻ and D⁻ ions according to the particular velocity profile of these particles, which is mainly dictated by the performance of the polarized source. As a consequence the RFQ structures must be easily interchangeable in a short time when the ion species is changed.

4.2 LINAC Configuration

To achieve maximum energy gain for both H⁻ and D⁻ ions, it is necessary to use independently phased resonators as early as possible in the LINAC. The required peak beam current of 2 mA allows to start the QWR LINAC after a 160 MHz RFQ stage at the relative low energy of 2.5 MeV/A, without expecting severe space charge problems. 2-gap resonators matched to this energy and up to about 20 MeV can be derived with minor modifications from 160 MHz QWR's that exist at LNL. Above 20 MeV energy, efficient acceleration can be achieved with resonators working at 320 MHz without modifying the resonator shape except for its length. Experience with existing sc QWR structures and test results obtained with laboratory devices indicate that peak accelerating gradients of about 8 MV/m should be possible without forsaking the magnetic and electric field limits. Design values of up to 8.2 MV/m are therefore considered acceptable.

The present LINAC design comprises a total number of 44 QWR's grouped in 11 cryostats of which the first 14 operate at 160 MHz and the remaining 30 at 320 MHz. The different QWR structures used can be distinguished by the distance between their two accelerating gaps, usually expressed as the optimum ion velocity β_S for

maximum acceleration in the structure. The specifications are summed up in Table 1.

Table 1: QWR Specifications of the sc LINAC

	Type I	Type II	Type III
f [MHz]	160	160	320
β_S	0.092	0.118	0.224
E_{acc} [MV/m]	7.2	8.2	7.6
number	2	12	30

The operational characteristics of the LINAC injector, with low duty cycle, very high accelerating gradient, pulsed operation, H⁻ and D⁻ beams, define some unique requirements for the cavities:

- good mechanical stability to reduce microphonic effects and minimize LFD,
- large velocity acceptance for different beams,
- capability of reaching the specified 8.2 MV/m field within (RF) pulses in the order of 1 ms.

On the other hand, a high quality factor Q, commonly considered very important, is (even if desirable) not really indispensable in our case. The cryogenic power dissipation is anyway low for operation at < 0.3 % RF duty cycle, and the installed RF power is dominated by beam loading. For example, a low Q superconducting resonator requiring 100 W to reach the specified gradient, would load the cryogenic system by only 0.3 W, which is insignificant for the 3 kW RF amplifier.

4.3 Beam Dynamics

The new COSY injector has to accelerate particles that differ in mass by a factor of 2. There are two preferable types of LINAC structures appropriate for this purpose:
(a) multi-gap structures with internal synchronization of gaps, such as an Alvarez structure;
(b) systems with external synchronizing of the different groups of structures, where each of them has a number of gaps, for instance sc coaxial structures.

For our purpose the second option is more appropriate. In this case both types of particles with masses m_1 and m_2 are instantaneously not in synchronism in each resonator ($\beta_{part1,2} \neq \beta_{str}$), but in total we have a stable motion in the whole accelerator. The integral

$$\varphi = \frac{\omega}{c} \int_0^z \left[\frac{1}{\beta_{str}} - \frac{1}{\beta_{part}} \right] d\varsigma - \Delta\varphi_{RF}$$

is almost never equal to zero, which means absence of synchronism, but due to a proper choice of the RF phase shift $\Delta\varphi_{RF}$ between the cavities we can create a quasi-synchronous motion for both types of particles in the whole accelerator. In reality, we should prepare individual maps of RF phases for H⁻ and D⁻ operation and retune the accelerator completely when changing from one particle to the other. Hence both types of particles can be accelerated up to the same final energy.
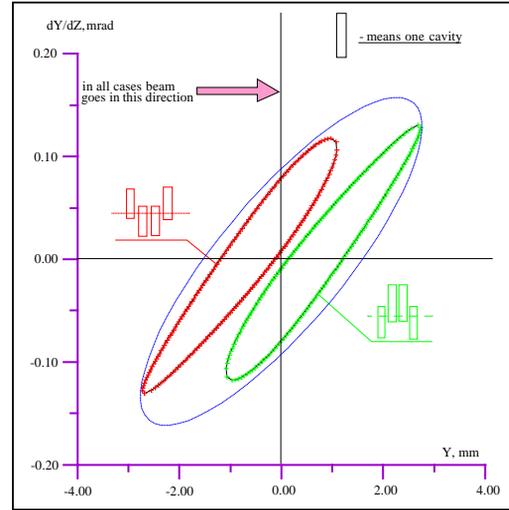

Figure 5: Effect of electromagnetic fields on protons at the end of the QWR-LINAC. Results are shown for the most effective correction scheme. The surrounding (dotted) ellipse corresponds to an increase in the effective normalized emittance of 10%.

We have simulated the motion for both particles in electromagnetic fields obtained by HFSS calculations. The field data for this purpose were supplied by LNL, as we had no precise information about the resonator geometries at that time. Initially we optimize the time of flight factor of each resonator for both types of particles and determine the RF phase. Then we investigate the motion of particles through the chain of individual separatrices. This is a very important step, since the particles are starting to be accelerated with an energy lower than the synchronous energy level of the separatrix but finish with a higher energy. In this stage we avoid the possibility, that one part of the bunch appears inside the separatrix, while another part is outside. Under such circumstances the bunch could be split into two parts assuming that one of them will be lost.

In the third stage we analyze the parametric action of drift space to the longitudinal motion. The parametric resonance arises, when the frequency perturbation ν is near to the double longitudinal frequency Ω, i.e.

$$\nu = 2\Omega + \varepsilon,$$

where the width of the resonance is determined by

$$-e_1 \frac{\Omega}{2} < \varepsilon < e_1 \frac{\Omega}{2}.$$

This effect strongly restricts the drift space length between modules. We have done numerical calculations for the LINAC using different drift spaces. The appropriate value of the drift space is about 0.7 to 0.8 m. When the drift is longer, the separatrix becomes significantly smaller.

Although the magnetic field component B is shifted relatively to the E field by 90° in phase, the particles are getting an uncompensated transverse kick of about 1 mrad per resonator due to the asymmetric geometry of the

QWR [6, 7]. The total effect dramatically influences the beam emittance and without compensation the bunch would be shifted in a not acceptable way off the axis. In principle there are several possibilities for correction. One method which helps to compensate this dipole mode, is based on the RF field. We suggest the geometrical rotation of cavities in a sequence of -90°, +90°, +90°, -90° (or inversely), which results in minimum deviation of the bunches from the axis (see Fig.5). The effective non-normalized emittance around the two phase portraits equals 0.4 mm mrad. This value is 10% of the normalized emittance of the beam for the case of a zero dipole B component.

Other compensation schemes are also possible but have to be evaluated carefully. Compensating the kick by a modified E field in the accelerating gap is difficult to accomplish. For optimum cancellation different shapes of the electrodes are required according to the velocity profile of particles. In our case the two particles differ in mass by a factor of 2, which additionally complicates the solution. - Half wave resonators of course have no intrinsic transverse asymmetry, but so far they are not widely used for such applications because frequency tuning and chemical surface treatment seem to be difficult. This type of resonator together with other advanced structures (multi-gap spoke types a.o.) have to be seriously investigated as a possible alternative.

The proposed method of alternate orientation of resonators seems to be the most suitable solution at present, but it will introduce some technical problems. The LHe cooling concept has to be modified for the upside-down mounted resonators [8]. The cryostat has to be modified accordingly.

Figure 7: Separatrix for deuterons (left) an transit time factor versus energy for deuterons (right).

We also analyzed different schemes for the focusing system, based on quadrupole singlets, doublets and triplets. The first option is not satisfying due to the large beam envelope. The triplet system gives the minimum beam size, but requires too much space between the cryostats. So we selected the doublet system as a good compromise. The results show that we need field gradients up to 60 T/m with an effective length of 7 cm for the quadrupoles. The beam size is such that an aperture of 30 mm is sufficient for the resonators.

The beam dynamics computations were carried out using a three-dimensional code integrating the motion in arbitrary electrical and magnetic fields [9].

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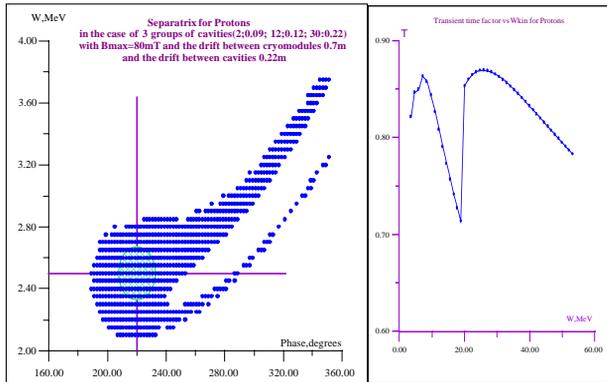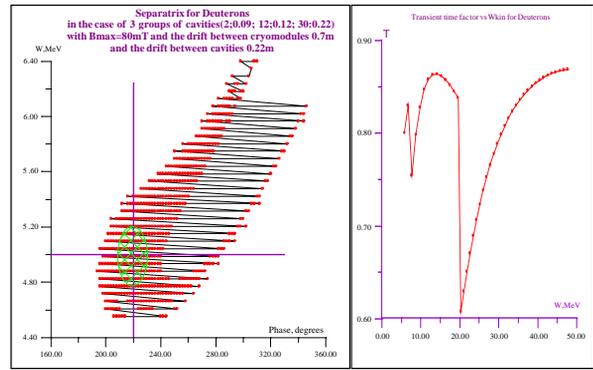
Figure 6: Separatrix of the LINAC for protons (left) and transit time factor versus energy for protons (right).

Another problem is to achieve the specified accelerating rate in the different groups of cavities. The calculations refer to the LINAC arrangement defined in Table 1. Figure 6 shows the separatrix of the whole LINAC for protons together with the function of transit time factor versus energy. It appears that the separatrix is quite roomy and that an initial bunch with W_{kin} = 2.5 ± 0.2 MeV and $\Delta\varphi$ = ± 10° can be accelerated without losses. Deuterons have a similar separatrix as it appears from Figure 7.