

SC PROTON LINAC FOR THE CONCERT MULTI-USERS FACILITY

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Abstract

The 1.3 GeV Linac of the CONCERT multi-users facility [1] has to accelerate protons and H^- ions in a series of current pulses distributed over each 20 ms period. The peak current is identical for all pulses to keep the space charge forces about constant apart from a slight emittance change between H^+ and H^- bunches. The beam power required for a given application is then obtained by adjusting the pulse duration. Because of their high acceleration efficiency, superconducting cavities of elliptical shape and working at 704 MHz have been selected. The overall architecture - transition energy, number of cavities per module, cavity design and number of families - results from linac length/cost optimisation and does not depend on the duty cycle which can vary from 5% to 25%, typical values for a stand-alone and multi-users facilities, respectively. RF power generation is based on individual klystrons and pulsed IGBT high voltage power supplies. Each cavity is fed by two symmetrical couplers to achieve the required peak power and to reduce the RF kicks. With adequate beam matching between the different sections, beam dynamics 3D simulations in the absence of errors and with various realistic errors show stable beam behaviour, as well as moderate halo enhancement and emittance growths.

1 LINAC LAYOUT

The transition energy between NC and SC structures has been fixed at 185 MeV. Below 200 MeV, the energy gain per real-estate of SC cavities is lower than 2 MeV/m, which can be obtained by warm Coupled Cavity Linac (CCL) structures. Besides, the design of SC cavities for beta values lower than 0.6 is complicated by stiffness and microphonics issues. The achievable gradient in SC cavities is determined by the maximum peak surface field that we can expect at the niobium cavity walls in a reproducible way and without resorting to sophisticated surface treatment. However, the lower the "beta" value of the cavity, the larger the ratio of surface field over accelerating gradient. From cavity code computations, an empirical law for the setting of gradient in proton linac as

a function of the cavity "beta" can be inferred. Figure 1 shows for example the expected gradients for two values of peak magnetic field, as well as the data of the cavities designed in the context of the French-Italian collaboration [2] and for the SNS Linac [3], when the peak surface fields are set to 50 mT (magnetic) and 27.5 MV/m (electric), respectively.

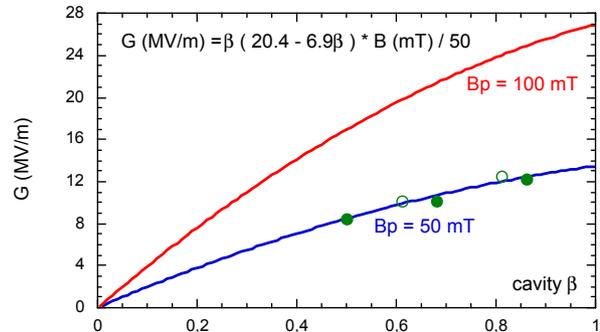


Figure 1: Expected gradients as a function of the beta-value (full circles: French-Italian collab.; empty circles: for SNS)

For the present CONCERT Linac, a 50 mT magnetic field has been selected, a conservative factor of two lower than the surface field aimed at for the TESLA project. Taking into account 3 fundamental constraints (maximum accelerating field below a prescribed value, which depends on the cavity "beta" to keep a moderate peak surface field; longitudinal phase advance per cell, which depends on the accelerating gradient, the beam energy and the lattice length, below 90° for stability reasons; beam power per cavity below the input coupler capability) the entire SRF linac architecture (in terms of number of cavity families, number of cells per cavity and number of cavities per cryomodule) was inferred from an optimisation of the linac length, which makes efficient use of the SC cavities. The total SRF linac length is lower than 300 m, and a schematic layout is shown in Figure 2. Realistic dimensions of cryostat and warm section for doublet focusing and diagnostics have been assumed.

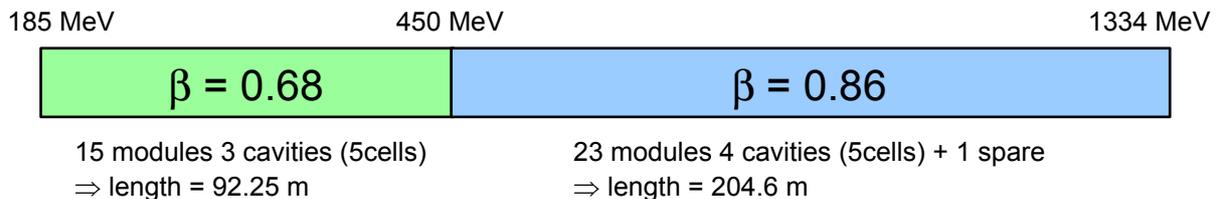


Figure 2: Schematic linac layout

Prototype couplers have transferred RF power of 1 MW on teststands at different places. Half of this value has been chosen for the SNS coupler [3], a derived version from the KEK-B coupler. Assuming that two couplers are feeding each cavity, a maximum beam power of about 1 MW per cavity is then chosen. Since the optimal “beta” values are very close to the ones of French-Italian collaboration cavity designs [2], we adopted these shapes, but with identical end-cells. The symmetry will preserve field flatness over a wide tuning range, and the risk of inadequate damping for dipole higher order modes is minimized. One full 4-cavity module has been added at the linac end for redundancy purpose. This will provide additional acceleration should a problem during operation make it necessary to lower the performance of some couplers or cavities. The synchronous phase is set at -25° all along the linac. The energy gain per cavity along the linac, shown in Figure 3 as a function of the beam energy, was calculated with the actual cavities, by integration in the exact electric field, including the fringe RF field at both ends. Longitudinal matching was performed by adjusting the synchronous phase for the cavities of the two cryomodules located just before and after the “beta” transition.

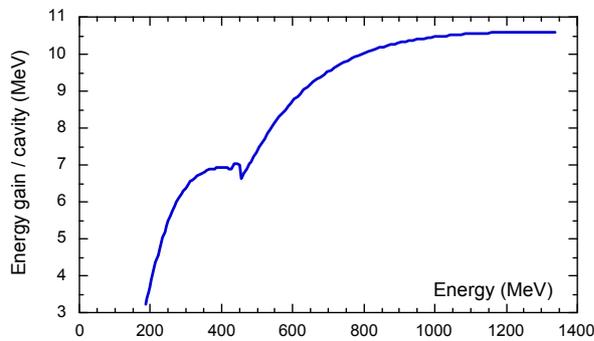


Figure 3: Energy gain per cavity along the linac.

2 RF SYSTEM

The RF system is required to transfer RF power from the klystron to the successive beam pulses over each 20 ms cycle. In order to keep the space-charge forces constant so that the settings of the linac components do not need to be changed from pulse to pulse, the bunch charge is kept constant for all current pulses. The average intensity of chopped H^- beams is then about 70% lower than that of unchopped H^+ beams. In case of multiple pulses at each cycle, it is better to group them with minimal spacing than to distribute them regularly along the entire period. The pulse spacing has to be larger than the rise (fall) time of the pulsed dipole, which switches the different beam pulses towards the different users, and is fixed at 100 μ s. The field in the cavity is maintained at constant phase and amplitude between the current pulses in such a way that the cavity pulsing rate is not higher than 50 Hz. Thanks to the “feedforward” technique, the RF control system is capable of injecting the correct input power, by a fast change in phase and in amplitude at low

level, during the H^- and H^+ beam pulses, which differ in intensity, and during the beam gaps, when the intensity is null. Since the RF power needed greatly varies, from 500 kW at the low-energy end to 1400 kW at the high-energy end, different klystron types can be considered because the efficiency depends on the output power. The optimisation was performed by using known klystron efficiency curves, when the output RF power is changed by adjustment of the high voltage setting. An initial efficiency of 65% at RF power saturation, which is now achievable with standard and mature klystron technology, was assumed. With two klystron families, maximum efficiency is achieved when the klystron change coincides with the change from medium- to high-beta cavity. The two families consist of 45 klystrons with 950 kW saturation power and 96 klystrons with 1400 kW saturation power. The optimum high voltage power supplies configuration, including a 95% efficiency value and a 0.90 power factor value, consists of 5 units of 3.7 MVA each and 15 units of 4.2 MVA each, feeding 6 to 11 klystrons. The beam power per cavity for a current of 100 mA, the klystron saturation power as well as the resulting electric power are shown in Figure 4. The klystron power includes a total of 32% extra power, to make up for circulator, waveguide losses (6%), waveguide distribution and coupler mismatches (6%) and to allow for cavity field control (20%). The overall efficiency, the beam- to ac-power ratio, is then about 45%.

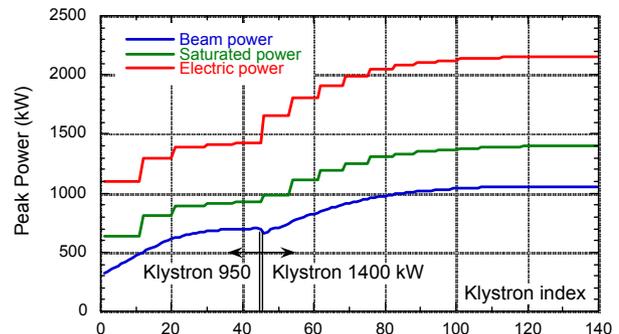


Figure 4: Beam, saturation and electric powers.

Various power systems have been evaluated to provide, with very high efficiency, the pulsed high peak power at a 50 Hz repetition rate. The combination of long pulses (5 ms pulse length capability with fast switching times) with high repetition rates (25% maximum duty cycle) favours power supplies made of series-connected modules with IGBT switches operating in pulse width modulation (PWM) mode. With a lower duty cycle, the DC-DC high frequency converter using an IGBT inverter, adopted for SNS [4] could be also chosen.

3 ENERGY STABILITY

The “one klystron per cavity” scheme, where each cavity has its own feedback/feedforward RF control system, has been chosen because it provides the best RF stability for proton beams, the simplest operation procedure and the greatest flexibility in the event of a

sudden RF failure. Due to the narrow bandwidth of superconducting cavities, field fluctuations originate mainly from any slight detuning, induced by the so called Lorentz forces or by microphonics. In addition, any bunch phase oscillation, induced for example by energy or phase error of the incoming beam, will upset the cavity voltage via beam-loading. A low level RF system with fast feedback loops has been designed and numerical simulations performed with the code PSTAB showed that the cavity voltages can be efficiently controlled. Figure 5 shows for example the effect of Lorentz forces (4 and 2 Hz/(MV/m)² for the medium- and high-beta cavities) and microphonics (amplitude of 100 Hz equivalent to phase fluctuations of $\pm 8^\circ$) on the energy of a single chopped H⁻ pulse. In all cases, the maximum deviation is much smaller than ± 0.1 MeV and the maximum extra peak power needed for field control is less than 2.5%.

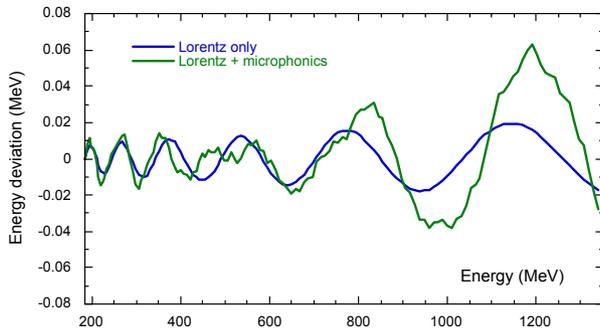


Figure 5: Energy deviation of the last bunch of the H⁻ pulse along the linac (with Lorentz forces and microphonics).

4 BEAM DYNAMICS

The design objective is to restrict beam losses to very low levels, usually to 1W/m, that will allow hands-on maintenance throughout the linac. Besides, to inject the beam into a compressor ring with acceptable losses, the rms transverse emittance and energy spread have to be of the order of 0.5π mm.mrad and a few tenths of MeV at the linac exit. Some basic rules have been observed to minimise the risk of halo formation and emittance growth (phase advance per lattice below 90° ; minimum energy exchange by avoiding any resonance excitation; careful rms beam matching at every change of linac section; phase advance per unit length kept as continuous as possible through the transitions). Multiparticle simulations were carried out in the error free machine first with a matched input beam to check the overall architecture as well as beam matching, and second with a strongly mismatched input beam (30%-20% mismatch in transverse-longitudinal plane) to test the “robustness” of the linac design. In the calculations, a beam of 100,000 particles is tracked from an initial 6-D waterbag distribution with a transverse normalized emittance of 0.35π mm mrad and a longitudinal emittance of 0.4π deg MeV. The bunch charge is 0.3 nC, corresponding to a beam current of 100 mA with a bunch frequency of 352.2

MHz. Figure 6 shows the final beam distributions in longitudinal and transverse planes.

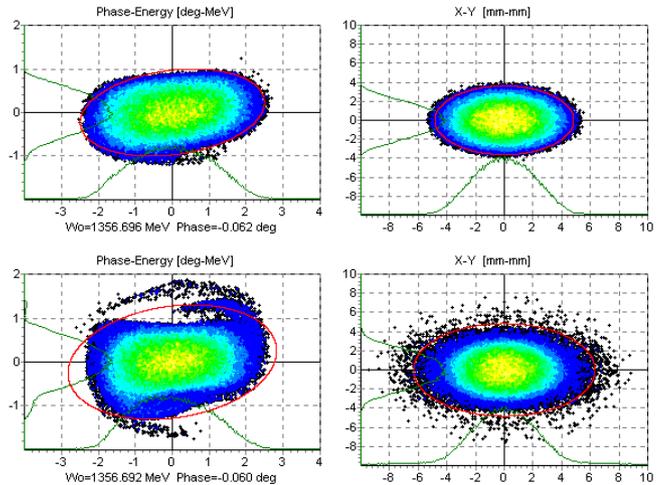


Figure 6: Beam distributions for matched (top) and mismatched (bottom) input beam at the linac exit.

The transverse emittance growths are lower than 5% and 20% for the matched and mismatched case. Whereas the beam distribution in phase space at the linac exit does not exhibit any tail or halo without mismatch (the total emittance is 10 times the rms value keeping in mind that it would be 8 times for the initial waterbag distribution), some halo formation in all planes is now clearly visible for the mismatched input beam: The beam tails are lower than 5 times the rms size of the beam and about 10^{-3} particles are outside 16 times the rms emittance. Besides, end-to-end simulations without errors didn't show excessive beam halo.

5 REFERENCES

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