DESIGN CRITERIA FOR HIGH INTENSITY H^- – INJECTOR LINACS

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All proposed pulsed spallation source projects include a high power H^- – linac followed by one or more compressor rings [1] or a rapid cycling cyclotron [2].. A key issue for the whole accelerator facility is the loss free ring injection which can be achieved by H^- – H^+ charge exchange. The design of an H^-– injector differs remarkably from the layout of an high intensity H^+– linac [3]. At the low energy end a fast chopper operating at the ring revolution frequency has to be installed. No partly filled bunches are allowed. Funneling of two beams is preferred as it relaxes the conditions for the chopping system. The linac itself has to be designed for no emittance growth and small halo production. In order to ensure a loss free injection into the rings, the linac pulse has to be limited in energy and truncated transversely. The energy spread reduction is made by a bunch rotator after the linac. A cost saving option is to use pulsed superconducting cavities for the high β linac [4].

INTRODUCTION

All proposed pulsed spallation source projects consists of a high power H^- – linac, followed by one (or more) compressor rings or rapid cycling synchrotrons. In Fig. 1, as a typical example the layout of the ESS linac is shown [5]. The low energy part consists of two H^-– ion sources with 70 mA peak current each, a 2 MeV bunched beam transfer line between two RFQs for installing a fast chopping device and a 5 MeV funneling line afterwards. The drift tube linac (DTL) operates at 350 MHz, the coupled cavity linac (CCL) at 700 MHz. The transition energy is 70 MeV. In the 1.334 GeV high energy transfer line, a 4 m long 700 MHz cavity is positioned after 75 m, acting as a bunch rotator. The linac operates at 50 Hz with 6% duty cycle. All the mentioned parameters are more or less typical for high intensity H^-- injector linacs.

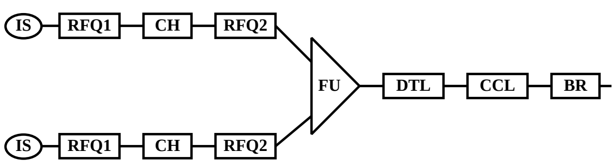

Fig. 1 ESS linac layout: IS: ion source, CH: chopper, FU: funneling, BR: bunch rotator

Different from high intensity proton linacs is the injector part; two H^-– sources and the two bunched beam transfer lines and the bunch rotation cavity at the linac end. For achieving loss free ring injection, the linac pulse has to be chopped at the ring revolution frequency and the energy spread has to be limited [6]. Energy ramping of the injected pulse is also foreseen for most scenarios.

FRONT END OF THE H^-– INJECTOR LINAC

For any loss free ring injection scheme at about 1.3 GeV, the number of injected turns is limited to about 1000. As in addition the linac pulse has to chopped with about 60% chopping efficiency, the required peak current from the H^-– source has to be about 100 mA. Even at 50 mA peak current a cesiated source is not available at this moment [7].

Due to the strict loss limitation in the following rings, a 'clean' pulse has to be provided, including sharp voids created by the chopping system. After each void the beam current is built up in about 50 μsec depending somewhat on the source parameters. The leading edge particles can be seen at ring injection, even with an RFQ as the first accelerator. This is absolutely unwanted for a typical tolerable loss rate of 10^{-4} at ring injection. Switching on the RFQ sometimes later, may not remove this 'leading' edge problem completely due to the RFQ filling time. A similar argument holds for chopping the ion source. For a clean chopped beam, the rise and fall time must be shorter than the RFQ bunching time, typically about 5 nsec. Large distortions of the beam emittance, due to chopping in space charge neuralized transport system, have been observed[8]. Increasing the extraction voltage might overcome some of the problems, but it is not in favour of the required energy spread limitation at the linac end, as it increases the longitudinal emittance drastically.

An achievable solution for getting a beam with no 'leading' edge particles, sharp edges created by the chopper and a small longitudinal emittance is the design of a bunched beam transfer line. The fast chopping element [9] and the mandatory collector afterwards are located in drift spaces, obtained by a triple waist design in all 3 directions [10]. Prechopping of the ion source reduces the heat load at the collector. The beam is kept bunched in order to maintain the small output RFQ-emittance. The correct phasing of independent bunching cavities is routine at the Fermilab 400 MeV linac upgrade [11] and was also demonstrated successfully with beam at the 5 MeV Los Alamos single leg funnel experiment [12].

The use of a funneling scheme implies a second bunched beam transfer line, but relaxes the constraints of the chopping line considerably. The peak current is halved and the first RFQ operates at a lower frequency. Both bunched beam lines are emittance dominated and not space charge dominated. Therefore, the energy spread is almost constant between two bunching cavities. The phase width must be limited to 40^{o} in order to avoid filamentation in the longitudinal phase space. This limits the free drift space to the value of the longitudinal betafunction at the buncher position, proportional to the bunching wavelength. Low frequencies and high energies, obtainable by using segmented RFQs [13], are preferred for both lines. Due to the pulsed operation, the thermal layout of the rf-deflector cavity and a two gap, two hole bunching cavity is quite relaxed compared to cw operation [14].

As both bunched beam lines are emittance dominated, they are very insensitive against operation at reduced current levels during a start-up period [10,15]. Variable electromagnetic quads allow current depending matching.

NORMALCONDUCTING HIGH β LINAC

The most cost expensive and on the other hand most sensitive part of any injector linac is the high β one. A frequency jump and operating at higher gradient is preferred in order to reduce the capital and operating costs. But this can cause longitudinal halo production due to mismatch, absolutely unwanted for the required energy spread limitation afterwards. Both conflicting requirements can be overcome by an almost optimized layout, emphasizing the high quality design [16].

A new developed cost effective, reduced in size, high efficient modulator system can be used for the pulsed operation [17]. This modulator has delivered 10 MW peak power for 2 msec with 85% efficiency. Together with a cathode modulated klystron, this results in a high overall rf–efficiency even for pulse length up to 2 msec. Based on this assumption, in Fig. 2 the investment and operating costs for the normal conducting ESS high β linac are plotted as a function of the accelerating gradient. For 50.000 h or 10 years operating time, about the lifetime of a pulsed klystron, the cost optimum is shifted considerably towards a lower gradient.

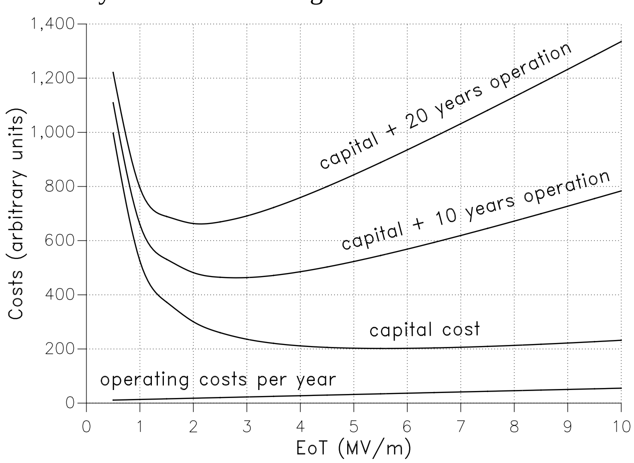

Fig. 2 Costs for the ESS 700 MHz normalconducting coupled cavity linac. Capital costs include structures, rf and buildings without extensive shielding

The rf-control system has to be designed for beamloading parameters up to 3 and an abrupt change of beam current due to chopping. About 30% additional power of the generator power, applied for reducing the cavitiy filling time, seems to be adequate to control 1% amplitude and 1^o phase stability [18]. These are the upper limits for keeping the fluctuation of the mean beam energy below the rms energy spread [16].

Operating the high β linac at higher frequencies is not in favour from the beam dynamics point of view. It increases the bunch current without substantial gain in rf-efficiency, as the shunt impedance is almost constant for constant aperture radius. The effective longitudinal emittance is increased too, absolutely unwanted for the energy spread limitation in the high energy transfer line.

BEAM COLLIMATION IN THE HIGH ENERGY TRANSFER LINE

In order to ensure a loss free injection scheme, the outcoming linac pulse has to be limited in energy spread and truncated in both transversal planes. Energy ramping during the injection time is also foreseen for most scenarios.

The energy spread reduction can be done by placing a dephasing section, consisting of a coupled cavity after the linac. Due to, still present, longitudinal space charge forces the energy spread is not constant. We have a space charge dominated motion instead of a emittance dominated one in this high energy transfer line [19].

Most of the spallation source facilities require a curved transfer line from the linac to the rings. The dipoles should be placed only after the bunch rotation cavity, where the energy spread is changing slowly. The dipole field has to be limited in order to avoid Lorentz dissociation of the H^-– particles. Due to the increased bunch length, image forces are more dominant than the direct Coulomb forces. They can lead to an increased number of particles outside the energy limit at the stripping foil. To overcome this difficulty, a two stage collimation system is proposed for the ESS facility. At the first stage, the combination of energy ramping and bunch rotation cavity, as many particles as possible are brought within the ±2 MeV collimation limit at the stripping foil. The few ones, still remaining outside the limit, are scraped away by a stripping foil at a position of large normalized dispersion in an achromatic collimation section [20].

SUPERCONDUCTING HIGH β LINAC

Especially for accelerator layouts with a long linac and compressor ring, superconducting cells are a very interesting option for the high part. In the normal conducting ESS high β linac the total rf power is 2.4 times the beam power cw. Superconducting cavities are now being routinely used in many accelerators. Experience gained during the building of these machines strongly suggests that rf superconductivity is approaching already mature technology, even if it is still from its limit.

For accelerating a high intensity pulsed H^-– beam from 100 MeV to about 1.3 GeV various technical and physical difficulties have to overcome which aren't existing in the acceleration of low intensity, cw, relativistic electron beams.

Superconducting iris loaded cavities can operate at the low DTL frequency of about 350 MHz with aperture openings of 5 cm radius [21]. This is certainly an advantage for reduced activation by particle losses. The accelerating gradient can be substantially higher than in a normalconducting cell, but the available space is used less effectively. A bunched beam transfer line between the DTL and the SC linac is required, as the transverse and longitudinal focusing parameters differ substantially in both sections.

Due to pulsed operation, the rf pulse length has to be increased by the filling time. If the rf input coupler is matched to have no power reflections during acceleration, then the filling time is proportional to the accelerating gradient/bunch current.

A higher gradient means a shorter linac, less investment costs, but increased operating costs. For a constant average current, the increase in rf pulse length is independent of the bunch current. During the start-up period with reduced current, and therefore reduced power, the filling time for half the current is 30% larger than the filling time at full current. For an optional ESS 350 MHz superconducting high β linac the rf-pulse length is increased by 50% for full intensity.

Due to the high effective pulse current of up to 65 mA, the input coupler requires special attention. Peak power levels can be greater than 400 kW, exceeding the present performance data obtained so far with beam [22]. The multipactor threshold is proportional to the 4th power in frequency [23]. As the filling time is not negligible compared to the pulse length, the behaviour of the high power input coupler under various load conditions must be studied, including the start-up period with 50% current only.

The arrangement of cells and rf units must be solved for cell length varying with β. For a constant number of cells/input coupler and a constant number of input couplers/klystron, the accelerating gradient must be ramped down with β. This increases the linac length substantially. By operating at higher frequencies, solutions can be found with increasing gradient, but decreasing number of cells/input coupler [24]. This is more favourable, as it keeps the peak surface field below its critical value all along the linac.

Most attention has to be given to the dynamic behaviour of the radiation pressure or Lorentz force detuning. With a time constant of 1 msec, measured at the MASCE accelerator at Saclay, the caused phase deviation is not constant during the beam pulse [25]. Even for stiffened cavities, where the static detuning is well inside the loaded cavitiy bandwidth, the dynamic effect must be examined in great detail. For a spallation source linac with energy spread limitation requirements, the accelerating phase has to be stabilized within 1^o over the beam pulse. If more than one cryomodule are connected to a klystron, microphonic noise must be considered too.

A 8 mA, pulsed, 500 MeV electron linac with 1,3 GHz superconducting cells, the TESLA test facility, is under construction at DESY [26]. The first beam is expected at end of 95. 16 power couplers are connected to one klystron. At the design gradient of 25 MW/m, the peak power per input coupler is 200 kW. As a SASE FEL is foreseen afterwards, controlling the dynamic Lorentz force detuning and microphonic noise is of great importance.

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