HIGH INTENSITY INJECTOR LINACS FOR SPALLATION SOURCES

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Abstract

A review is given of the layout and the design problems for recently proposed spallation neutron sources with up to 5 MW average beam power. The accelerator part consists of an H^- - injector linac followed by compressor rings. Different to the design of high intensity proton linacs are the low energy front end and the restrictions at high energy for loss free ring injection. The linac energy spread has to be reduced by a bunch rotator requiring an unfilamented beam in longitudinal phase space. Uncollected ring injection losses should be kept below 10^{-4}. Due to intensity limitations of the H^- ion source a funneling line is needed at the front end. For loss free ring injection the linac pulse has to be chopped after the first RFQ. Special emphasis is given to either transverse or longitudinal halo production due to mismatch of a high intensity bunched beam. Concerning particle loss in the linac itself the loss rate has to be smaller than 10^{-7}/m for unconstrained hands on maintenance. Design criteria are discussed for 10% pulsed RF systems. Comments are given about the use of pulsed superconducting cavities above 200 MeV beam energy.

1 PROPOSALS FOR HIGH POWER SPALLATION SOURCES

Recent proposals for spallation neutron source facilities require up to 5 MW average beam power. The accelerator part consists of a high intensity pulsed H^- linac followed either by a compressor ring or a rapid cycling synchrotron. The high intensity compressor rings are summarized in ref. [1,2]. Detailed proposals exist for the following projects :

1.1 Japanese Hadron Facility (JHF)

The JHF aims at an interdisciplinary facility based on a high intensity proton accelerator [3]. It is planned to replace the existing KEK 12 GeV booster synchrotron by a high intensity 3 GeV booster. A 3 GeV, 200 μA proton beam , upgradeable to 800 μA, can be sent either to a spallation source target or a muon production target or nuclear physics area. By adding a 50 GeV proton synchrotron an average current of 10 μA can be given to a Kaon area or a neutrino experimental hall.

The H^- - injector linac has to accelerate a 30 mA peak current beam up to 200 MeV in a first step. The repetition rate is 25 Hz and the pulse length 400 μ sec, leading to 200 μA average current [4]. This results in a 3 GeV, 0.6 MW spallation neutron source. The final goal is to accelerate 60 mA peak current up to 400 MeV, leading to 800 μA average beam current at 50 Hz rep. rate. This would lead to a 3 GeV, 2.4 MW spallation source facility.

Quite recently the Japanese government decided to provide an additional fund to supplement the KEK 1998 budget. With this additional fund the JHF project team is preparing to construct a high intensity linac up to 60 MeV.

1.2 Neutron Science Project (NSP) at JAERI, Japan

The Japan Atomic Energy Research Institute (JAERI) is proposing the Neutron Science Project NSP. The objective of the NSP is to explore technologies for nuclear waste transmutation and basic research science in combination with a high intensity proton storage ring [5]. The 1.5 GeV linear accelerator is required to operate with H^+ and H^- particles in a pulsed or CW mode. 5 MW average H^- power is envisaged for a spallation neutron source facility, whereas 8 MW CW H^+ beam can be provided for nuclear waste transmutation experiments.

Above 100 MeV a 5 cell superconducting (SC) cavity at 600 MHz is foreseen with 16 MV/m peak surface field. Single SC cavities at β=0.5 have reached peak surface fields of 44 MV/m at 2.1 K already [6].

1.3 Spallation Neutron Source (SNS) Project

Oak Ridge National Laboratory is coordinating for the Department of Energy in the US the SNS project [7]. As a first step a 1 MW beam power facility with one target is envisaged with a final energy of 1 GeV. The whole facility is upgradeable up to 4 MW beam power and a second target station.

Design parameters of the first step are for the H^- injector linac pulse current of 30 mA for 1 msec long pulses. The 4 MW upgrade will be achieved by doubling the ion source current and installing a funnel line at 20 MeV. The high energy part of the linac is a conventional room temperature 805 MHz coupled cavity linac (CCL).

The project will be built by a consortium of 5 DOE laboratories. Lawrence Berkeley National Laboratory (LBNL) is responsible for the SNS linac front end [9], Los Alamos National Laboratory (LANL) is designing the linac [8]. The transport line between linac and compressor rings and the compressor ring layout itself is the responsibility of Brookhaven National Laboratory (BNL).

1.4 European Spallation Source (ESS)

The 5 MW beam power short pulse ESS facility [10] consists of a 6% duty cycle H^- linac with 1.334 GeV final energy. The pulse compression to less than 1μ sec is achieved by two compressor rings in a shared tunnel. Various R+D work is going on, especially for building an ESS test stand with ion source, chopper and RFQ at Rutherford Appleton Laboratory (RAL) U.K. and continuing beam loss studies [11].

2 BASE LINE LAYOUT OF HIGH INTENSITY INJECTOR LINACS

The dominating design feature of a high intensity injector linac is to bring particle losses down to about 1 W/m and to guarantee less than 10^{-4} uncollected ring injection losses. All accelerator sections have to be designed to be far away from the space charge limit.

As an example, the layout for the 5 MW H^- injector linac of ESS is shown in Fig. 1. Both RFQs operate at 175 MHz followed by a conventional 350 MHz drift tube linac (DTL) up to 70 MeV. The high β CCL operates at 700 MHz. Different from a proton linac is a bunched beam chopping line at 2 MeV between two 175 MHz RFQ structures and a 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 reduced by the bunch rotator.

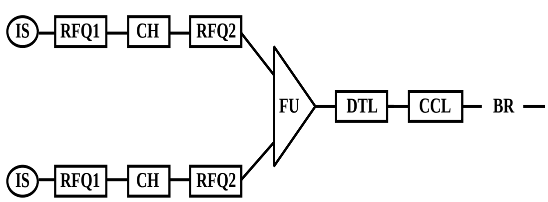

Figure 1: ESS linac layout: IS: I ion source, CH: chopper, FU: funneling, BR: bunch rotator

2.1 Low Energy Front End

Ion source requirements of more than 100 mA, 10% duty cycle H^- currents cannot be met with existing ion sources. R and D prototype programs are going on for all the above mentioned spallation source projects. For ceasiated RF-driven H^- volume sources a current of 70 mA at 7% duty cycle will be reached soon [9,12].

The beam transport between the H^- ion source and the first RFQ can be space charge compensated or uncompensated [9]. Integrated ion source RFQ test stands are set up for both possibilities.

Cooling problems for a 10% duty cycle RFQ are not so severe as for a CW H^+ RFQ, but more demanding than in RFQ structures built up to now. Field stability at 10% duty cycle can be achieved by 'π-mode stabilization loops' (PISL) for 4 vane structures [13]. Less than 1% unwanted field contamination has been experimentally verified. The 4-rod RFQ offers some advantage over the 4-vane design in terms of RF properties and ease of manufacture. The limited cooling capacity of a conventional 4-rod RFQ can be overcome [14], allowing up to 10% duty cycle. New RFQ-codes are available, taking into account rod or vane shaped electrodes, 8 term potential function, dipole components and complete 3d space charge subroutines [15].

A bunched beam transfer line at about 2 MeV is a good solution for a clean chopped beam with sharp edges and small longitudinal emittance increase. Chopping efficiencies of about 60% are required for loss free ring injection. Fast traveling wave choppers with 3 nsec rise time are under development [16]. Layouts of a chopping line with regular betatron oscillations as equal as possible in both planes results in quite small rms emittance growth [2].

The use of a funneling scheme implies a second bunched beam transfer line, but relaxes the constraints on the chopping line and on the ion source considerably. The peak current per ion source is halved and the first RFQ can operate at lower frequency. In a funneling section with conventional elements the two beams are merged together by an arrangement of septum magnets and an array of RF deflection elements. Care has to be taken to match the dispersion and its angle to zero even under space charge conditions [2]. By implementing a Two-Beam Funnel RFQ [17] lower energies for the funneling section seem to be possible.

2.2 Halo Production due to Mismatch in Bunched Beams

The major problem of the design in high current proton linacs is the loss of particles at higher energies. Particle loss leads to activation of accelerator components and reduces the flexibility of hands on maintenance. As a rule of thumb, hands on maintenance is possible if the loss is less than 1 W/m. In a linac losses occur radially due to the formation of a beam halo. The beam halo consists of a 'small' number of particles which oscillate around the beam core. In addition filamentation of the particle distribution in the longitudinal phase space can cause activation problems when injected into compressor rings. The design goal is less than 10^{-4} uncollected lost particles at ring injection.

In recent years substantial progress has been achieved by identifying the parametric resonance condition as a major source of halo production of DC and bunched beams. For realistic particle distributions with nonlinear space charge forces particles even inside the core have a tune spread. Parametric resonances can occur between single particle tunes and the frequency of the oscillating mismatched beam core [18].

Due to the two transverse and one longitudinal bunch dimensions 3 eigenmodes exist for a bunched beam. The frequencies of these modes can be approximately expressed by the full and zero current transverse and longitudinal tunes only. There exists a pure transverse quadrupolar mode and high and low modes which couple the transverse and longitudinal directions. The high mode represents a 'breathing' of the ellipsoidal bunch. For the low mode the bunch breathes in transverse direction but the oscillation in the longitudinal direction is of opposite phase. For exciting the high or low mode only, the longitudinal mismatch is normally different in amplitude than the transverse ones [18,19].

For a mismatched bunched beam a 1/2 parametric resonance between a single particle tune and the frequency of an eigenmode is always excited radially by the quadrupolar mode. The high or low mode can excite a parametric resonance in the transverse and/or the longitudinal direction.

Fig. 2 and Fig. 3 show Monte Carlo simulations with 20000 particles which interact in full 3d for a 70 MeV bunched beam transfer line. A 6d waterbag distribution is used as input. The transverse and longitudinal tune depressions are 0.7 and 0.8 respectively. The transverse temperature is 1/3 of the longitudinal temperature. Shown is the 99.9% total to rms emittance ratio in the x-direction. In Fig. 2 the matched case is compared to a 20% quadrupolar mode excitation. A substantial increase of the 99.9% emittance is visible due to the 1/2 parametric resonance excitation. In Fig. 3 the same emittance ratio as in Fig. 2 is shown but comparing the matched case with a 20% radially and 30% longitudinally excited high mode. Here, no single particle tune is as large as half the high mode frequency and, as predicted, no resonance effect can be seen [18,19].

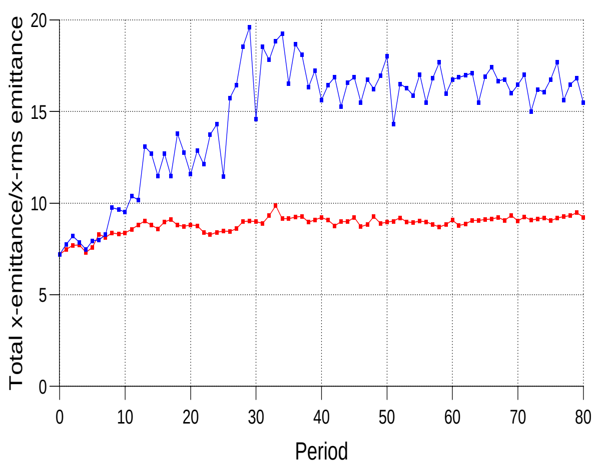

Figure 2: 99.9% total to rms emittance ratio for a matched (bottom) and a quadrupolar mode excited case (top)

During the startup period of high intensity linacs more than 20% initial mismatch is expected especially in the longitudinal plane. For a spallation source linac with its additional restriction on loss free ring injection a design is required where the transverse and longitudinal halo production is insensitive to all kinds of mismatch. Linac designs with both transverse and longitudinal tune depressions above 0.8 and transverse to longitudinal temperature ratios between 1/3 and 2 fulfill these conditions if no high mode envelope instability is excited [18]. The 214 mA ESS CCL has design parameters which meet these conditions for most of it's length and transverse and longitudinal halo formation is acceptable for a 20% initial mismatch. Space charge dominated designs with tune depressions below 0.4 [20] or large temperature anisotropy [21] can lead to chaotic single particle motion [22] and enormous halo production due to mismatch which is absolutely unwanted for high intensity injector linacs.

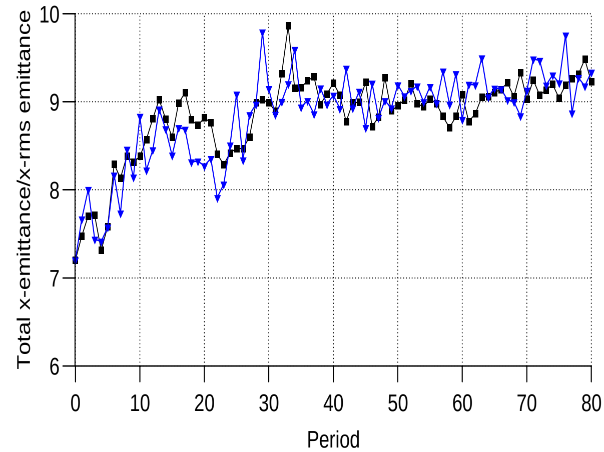

Figure 3: 99.9% total to rms emittance ratio for a matched (squares) and a high mode excited case (triangles). Please note the enlarged scale

2.3 High β Transfer Line

The transfer line from the H^- linac to the compressor rings differs in some respects from the H^+ transferline between a high intensity H^+ linac and a high power target station either for tritium production or waste transmutation. In both lines the linac beam is not kept bunched. Space charge forces are small but still effective, especially in the longitudinal plane [23] resulting in an increase of the energy spread.

For loss free ring injection into a circular machine the energy spread of the linac bunches has to be reduced by placing a bunch rotator at some distance behind the linac. After bunch rotation there should be less than 10^{-4} particles outside an energy spread of $\pm$ 2 MeV as a typical figure. For the ESS bunch rotation system there are less than 10^{-4} particles outside $\pm$ 0.8 MeV for the matched case, but more than 10^{-4} outside $\pm$ 1 MeV for the mismatched case. Longitudinal space charge effects are still visible after the bunch rotation system.

Uncorrelated RF amplitude and phase errors of $\pm$ 1% and $\pm$ 1^o respectively can cause an oscillation of the beam center by as much as 1 MeV [24]. As the energy spread collimation has to be guaranteed for all bunch currents including much larger RF tolerances during the start up procedure achromatic bending systems have to be installed in the high β transfer line. The influence of a conducting pipe has to be considered as the bunch length is equal or larger than the pipe radius. [23]

3 PULSED RF SYSTEM

The high β section from about 100 MeV onwards is the most expensive part of the whole linac for both the capital cost and the operating cost. Typically operating frequencies are between 600 and 800 MHz. Cost optimization of the accelerating gradient leads to about 2.8 MV/m for 10% duty cycle pulsed operation. Including focusing quadrupoles and diagnostic elements this value corresponds to an average real estate energy gain of 2 MeV/m for a room temperature linac design.

The layout of the RF system is a trade off between capital cost and overall RF efficiency. Conventional 2.5 MW peak power klystrons at 805 MHz, 8% duty cycle, with a modulating anode and a floating deck modulator are proposed for the SNS [25]. Such a RF system is expected to be very robust, can almost be built today and does not need circulators for protecting the klystron. The klystron efficiency is 60% at 100 kV beam voltage.

Prototyping is necessary for a 2.5 MW peak power, 7% duty cycle cathode modulated klystron with a transformer coupled bouncer type modulator. More than 65% RF efficiency is expected for 120 kV beam voltage at 1.4 msec pulse duration. No circulator is required. The modulator cost can be substantially decreased by connecting 2 klystrons to one modulator. The modulator efficiency is about 85%, the pulse flatness better than $\pm$ 0.5% [26]. A test stand with commercially available IGBT switches (EUPEC FF 800) mounted on individually water cooled boards has been set up in order to study temperature rise and life time problems at 50 Hz repetition rate for ESS.

Low voltage 2 MW peak power HOM-IOT (higher order mode inductive output tube) without a modulator are expected to be an attractive solution in the near future due to their smaller size and lower production costs compared to high power klystrons. Prototyping is needed therefore. A 1MW CW, 700 MHz HOM-IOT is under development for the Los Alamos APT project [27] requiring only 40 kV beam voltage for an anticipated RF efficiency $>$ 70% [28]. For a 700 MHz HOM-IOT with 2 MW peak power pulsed at 7% duty cycle, only 65 kV beam voltage is required and an efficiency of $>$ 70% is expected [29].

Attention has to be given to the RF control system. For H^- injector linacs uncorrelated amplitude and phase errors have to be limited typically to $\pm$ 1% and 1^o respectively in order to prevent intolerable oscillation of the beam centre at the linac end. The strict amplitude and phase tolerances counteract in some respects the use of high peak power multi beam klystrons (MBK) as power splitting is mandatory here. Circulators are necessary for protecting the MBK. Doubling the number of cells per tank is not recommended as the field flatness is proportional the square of the cell number.

4 SUPERCONDUCTING HIGH β LINAC

Superconducting cells are a very interesting option for the high β linac. Superconducting cavities are now being routinely used in many accelerators. Experience gained during building these machines strongly suggests that RF superconductivity is approaching mature technology, even if it is still far from its limit. In order to accelerate a high intensity proton beam from 100 MeV to about 1.3 GeV, various technical and physical difficulties have to be overcome, which do not exist in the acceleration of low intensity relativistic electron beams.

For the 100mA CW APT proton linac a 5 cell 700 MHz superconducting cavity at 2 K is proposed from 217 MeV on [27]. Focusing is provided by conventional quadrupole doublets located in the warm region between cryomodules. Only 2 different cavity length are foreseen with an on axis accelerating gradient of about 5 MV/m. The real estate energy gain in the SC linac is 1.5 MeV/m. Each 5 cell SC cavity is equipped with 2 power input couplers, limited to 210 kW each. The 5 cell cavities are arranged in cryomodules fed by 1 MW DC klystrons. About $\pm$ 3% amplitude and $\pm$ 5% phase errors in each cavity are tolerable caused by the power splitting procedure.

The layout of a SC high β linac for 10% pulsed H^- injector differs in some respects from the layouts for a CW proton linac. Normal conducting, 700 MHz, 10% pulsed coupled cavity linacs for energies from 100 MeV on have an real estate energy gain of 2 MeV/m. For msec long pulses the achievable accelerating gradient in a SC cavity is almost the CW value limited by the peak surface field especially at β values below 0.5, corresponding to 150 MeV proton energy. Peak surface field values of 25 MV/m for a 2 K 5 cell cavity around 600 MHz are expected to be reached quite soon. The corresponding accelerating gradients inside the SC cavity are 6 MV/m at 200 MeV and 10 MV/m from 900 MeV on leading to a real estate energy gain of 3 MeV/m. 5 different geometries are needed for such a SC linac. 240 kW and 600 kW peak power is needed for a 5 cell cavity at 200 MeV and 900 MeV respectively. Substantial R+D is needed for developing input couplers at about 600 MHz, capable of handling 1 MW peak reflected power during the 100 μsec long filling time, corresponding to 4 MW peak forward power. Circulators are mandatory for klystron protection.

The input coupler power limitation can in principle be overcome by having 2 couplers per cavity. As pointed out before power splitting is a problem for a high intensity H^- linac due to the $\pm$ 1% and $\pm$ 1^o amplitude and phase error limits in each cavity. Another difficulty for the RF control system is the field stabilization at the beam arrival time, complicated due to microphonic noise varying from cavity to cavity and pulse to pulse. The startup cavity frequency can oscillate by $\pm$ 30 Hz, intolerable with $\pm$ 1^o phase error. Unlike electron linacs phase errors in different cavities connected to one klystron do not add up to a common energy fluctuation [30]. Large but predictable RF errors due to Lorentz force detuning may be compensated by stiffening the cavities and applying digital feedback and feedforward from lookup tables [31].

Below 200 MeV or β = 0.6 elliptical shaped SC structures suffer from mechanical instability problems [5]. The real estate energy gain is lower compared to a 10% pulsed room temperature linac due to the uneconomic use of space in a low β cryomodule. Also the RF control problems are more severe here due to the reduced cavity bandwidth.

Different groups have R+D plans to study β=0.5 cavity structures [5], new fabrication techniques [32] and pulsed RF control problems including power splitting [33].

For a 10% pulsed H^- injector linac limiting the peak surface gradient to 25 MV/m in the SC cavity for an energy range from 200 MeV to 1.5 GeV, the SC linac has 2/3 of the length of a competitive room temperature one. The capital costs are expected to be equal or even slightly higher for the SC option. A 5 MW average beam power spallation neutron source needs about 75 MVA AC power where about 12 MVA can be saved with such a superconducting linac

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