ACCELERATOR PHYSICS OF HIGH INTENSITY PROTON LINACS

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Abstract

The accelerator physics of high intensity linacs, either pulsed H^- or cw proton facilities, is presented. Existing proposals for such facilities are described. A base line layout of high intensity linacs is presented. Special emphasis is given to halo calculations. Comments are given for the RF system and superconducting linac options are described for cw or pulsed operation.

1 PROPOSALS FOR HIGH INTENSITY LINACS

High intensity proton linacs can either be pulsed H^- – accelerators up to 5 MW average beam power or cw H^+ – accelerators up to 130 MW beam power. A pulsed H^- – linac is part of the accelerator facility [1] of a short pulse spallation source. They inject either into a compressor ring [3] or into a rapid cycling synchrotron [4]. Designs of a spallation source target station are given in ref. [2]. CW proton linacs are designed for tritium production or waste transmutation [5].

Detailed proposals exist for the following high intensity linear accelerators:

1.1 Japanese Hadron Project (JHP)

The JHP aims at an interdisciplinary facility based on a high intensity proton accelerator [6]. It is planned to replace the existing KEK 12 GeV proton synchrotron by a high intensity 3 GeV booster. A 3 GeV, 200 μA proton beam can be sent either to a spallation source target or to a muon production target or nuclear physics area. By adding a 50 GeV proton synchrotron later on, an average current of 10 μA can be given to a Kaon area or to a neutrino experimental hall.

The H^- – injector linac has to accelerate a 30 mA peak current beam up to 200 MeV. The rep. rate is 25 Hz and the pulse length 400 msec. Above 100 MeV, an annular-ring coupled cavity structure is proposed [7].

1.2 National Spallation Source Project at Oak Ridge

Oak Ridge National Laboratory is coordinating for the Department of Energy in the U.S. an R and D study for a short pulse spallation source [8]. As the 1st step, a 1 MW beam power facility with one target station is envisaged. The whole facility is upgradable to 4 MW beam power and a second target station.

Typical parameters for the H^-- injector linac are pulse currents of 30 mA and 1 GeV final energy. The rep. rate is 60 Hz, the duty cycle about 4 %.

Various options for the accompanying circular accelerators are under discussion.

1.3 High Intensity Proposals at Los Alamos

It is proposed to change the LAMPF 1 MW proton beam dump into a long pulse spallation neutron target. At the front-end of the 60 Hz, 20 mA, 800 MeV LANSCE, formerly LAMPF, linear accelerator, it is foreseen to install a 201 MHz RFQ up to 5 MeV, replacing the existing first DTL tank. An improved longitudinal matching at 105 MeV into the 805 MHz coupled cavity linac is also envisaged [9]. With these improvements the particle loss rate at high energy can be drastically decreased.

High power proton linear accelerators up to 130 MW beam power in the 1st step are suggested for tritium production [10], accelerator driven transmutation technology [11] and other applications [12]. The base line design starts with a 350 MHz resonantly coupled RFQ structure up to 7 MeV [13]. If funneling is not required, the particles are injected into a 700 MHz Coupled Cavity Drift Tube Linac (CCDTL) [14]. If funneling is necessary, each funnel leg consists of a 350 MHz RFQ followed by a 350 MHz CCDTL. The combination of the two beams is done around 20 MeV. The particles are then accelerated in a 700 MHz CCDTL, as for the unfunneled case. Above 100 MeV on, a conventional 700 MHz coupled cavity linac will accelerate the particles up to about 1 GeV. The attraction of this base line design is that there is no frequency jump at high energies and no abrupt change of the quadrupole spacing. In addition a singlet focusing system can be used all for the linac above 7 MeV.

Especially for cw operation, quite a lot of rf power is dissipated in the high β part of the linac. A feasibility study examines iris loaded 700 MHz, 4 cell, superconducting cavities at 2 K operating temperature [15], see chapter 4.

1.4 French TRISPAL Project

Facility studies started in France several years ago for tritium production with a proton accelerator, the TRISPAL proposal [16]. This is a 40 mA cw proton linear accelerator with one frequency of 350 MHz all along the linac. The final energy is 600 MeV, the average beam power 24 MW. The chosen high β structure is a slot coupled π mode structure, similar to the LEP or ESRF cavities [17].

1.5 European Spallation Source (ESS) Facility

The 5 MW beam power short pulse ESS facility [18] consists of a 6 % duty cycle H^- - linac [19] with

1.334 GeV final energy. Two 70 mA H^- – sources are funneled together at 5 MeV into a 350 MHz DTL. From 70 MeV on a 700 MHz coupled cavity linac (CCL) will accelerate the beam up to the final energy. The superconducting high β option is described below. The pulse compression to less than 1 μsec is achieved by two compressor rings in a shared tunnel. A liquid mercury target with horizontal beam injection is foreseen as reference design [2]. About 80 people, working part time, from 6 European countries and 11 participating laboratories are involved in this study, financed for 2 years by the European Community. The final report will be ready by fall '96.

2 BASE LINE LAYOUT OF HIGH INTENSITY LINACS

The dominating design features of a high intensity linac, either pulsed or cw, is to bring particle losses at high energy down to about 1 W/m. This corresponds to loss rates below 10^{-7}/m, exceeding the presently achieved figures by orders of magnitude. Therefore the linac design is determined by approaching this loss figures, not by minimizing either capital cost and/or operating cost. All accelerator sections have to be designed to be far away from the space charge limit.

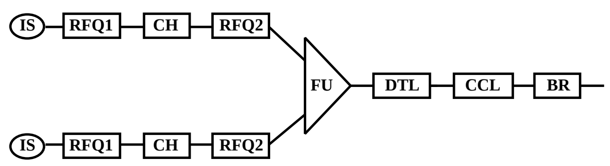

Fig. 1 ESS linac layout: IS: ion source, CH: chopper, FU: funneling, BR: bunch rotator

As an example, the layout for the ESS 5 MW H^- - injector linac is shown in Fig.1. Both RFQs operate at 175 MHz followed by a conventional 350 MHz drift tube linac up to 70 MeV. The high β coupled cavity linac 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 [20].

2.1 Low Energy Front End

The ion source requirements of up 100 mA cw proton current or 70 mA, 10 % duty cycle H^- current cannot be met with existing ion sources. R and D prototype programs are going on worldwide [21]. For negative ions, neutralization effects in the beam transport system between the ion source and the 1st RFQ also have to be considered [22]. 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. The fast chopping element [23] and the mandatory collector afterwards are located in drift spaces, obtained by a triple waist design in all 3 directions [24].

The use of a funneling scheme at somewhat higher energies implies a second bunched beam transfer line, but relaxes the constraints on the chopping line and the ion sources considerably. The peak current per ion source is halved and the 1st RFQ operates at a lower frequency. Low frequencies are preferred for both lines, as the available free drift space without bunching is proportional to the bunching wavelength. If there is no frequency jump envisaged for the high β structure [10], special attention has to be given to both bunched beam transfer lines, now at higher frequencies.

2.2 High β Accelerating Structures

The high linac is the most expensive part of the whole linac for both the capital cost and the operating cost. Optimization of the accelerating gradient leads to about 1.3 MV/m for cw operation [5] and about 2.8 MV/m for pulsed operation at 10 % duty cycle [25]. For technical designed linacs, including focusing quads and diagnostic elements, these values correspond to an average energy gain of 1 MeV/m and 2 MeV/m respectively. The corresponding RF system is described below.

2.3 ESS Beam Loss Calculations

The high β linac is on the other hand the most sensitive part concerning particle losses. One way to avoid the generation of halo particles outside the dense beam core is to design the linac in a non space charge dominated regime [26], proposed for the ESS coupled cavity linac. Transverse focusing is provided by doublets after every second tank. By decreasing the transverse tune, even for 214 mA bunch current at 700 MHz, the transverse and longitudinal tune depression are about 0.8. Less than 10 % rms emittance growth is observed. More important for beam losses are the reduced number of halo particles outside the dense core.

Fig. 2 displays the ratio between the total emittance and the rms emittance in one transverse direction along the ESS coupled cavity linac from 70 MeV to 1.334 GeV. Based on 50000 fully interacting particles, the input distribution with a 'hard' edge develops along the linac into a distribution with some 'soft' edge. Less than 10^{-3} particles are outside this 'soft' edge. The observed oscillations are probably due to mismatch caused by the change of the cell length and the number of cells per tank. These halo particles are oscillating radially through the core. Their number is constant and their phase space trajectories are bounded after 500 MeV. Therefore, use of scrapers seems possible at intermediate energies. For a matched input beam to the ESS coupled cavity linac, 10^{-5} particles are expected outside 1 cm radius after scraping. The aperture radius is 2.2 cm for the ESS coupled cavity structure.

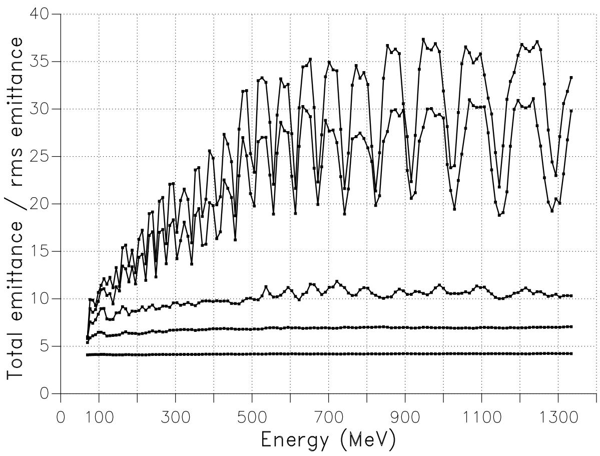

Fig. 2 Ratio between total emittances and rms emittances in one transverse plane. Curves (top to bottom) correspond to 100%, 99.99%, 99.9%, 99%, 90% emittances.

The injection energy energy into the ESS CCL is chosen equal to 70 MeV, well below the neutron production threshold of about 120 MeV. Longitudinal halo particles created by the frequency jump between DTl and CCl, will have more than one synchrotron oscillation up to 120 MeV.

Halo studies and chaotic beam behavior for space charge dominated designs are discussed in [27].

2.4 High β Transfer Line

The transfer line after a high intensity proton linac can be quite long and complicated due to either target illumination requirements [5,10] or to matching conditions for loss free ring injection [20]. In most cases it is neither possible nor necessary to keep the beam bunched. Space charge forces are small but still effective in a long transfer line. For loss free injection into a circular machine, the energy spread of the linac bunches has to be reduced by placing a bunch rotator some distance behind the linac.

Due to space charge forces, the rms energy spread is increased by a factor of 2 along the 130 m long 1.334 GeV ESS transfer line with 214 mA bunch current. A bunch rotator is positioned after the first 70 m. Some filamentation in the longitudinal and transverse planes is observed. For loss free ring injection into the ESS compressor rings, there should be less than 10^{-4} particles outside an energy spread of ±2 MeV. Uncorrelated amplitude and phase of ±1 % and ±1° respectively will cause an oscillation of the beam center of 0.6 MeV [25]. As the energy spread collimation has to be guaranteed for all bunch currents including much larger RF tolerances during the start-up period, an achromatic bending system is installed after the bunch rotation cavity [18,20].

Without a bunch rotator, due to the continuous increase of the bunch length, the influence of a conducting pipe has to be considered for a bunch length larger or equal to the pipe radius. The conducting pipe slows down the debunching process, but enhances longitudinal filamentation. Space charge forces are getting less and less important. The starting distributions by are effected by space charge along the 1st part of the transfer line.

3 RF SYSTEMS

For cw and for pulsed operation, R and D work is going on to establish more efficient rf amplifiers and power supplies. For frequencies above 700 MHz, Multi Beam Klystrons with about 6 MW rf peak power and more than 65 % rf efficiency are proposed [28].

A new developed cost effective, reduced in size, high efficient power supply known as a bouncer modulator can be used for pulsed operation [29]. This modulator has delivered 10 MW dc power for 2 msec, 1 Hz repetition rate with 85 % efficiency. Two of these modulators are used for the 500 MeV electron beam TESLA Test Facility at DESY [30].

Based on this design, a layout is made for a modulator delivering 3 MW dc power for 1.2 msec at 50 Hz repetition rate. The ac to dc efficiency is about 85 %, the pulse flatness better than ±0.5 % [31]. This relatively small in size modulator is connected to a 2 MW peak rf power klystron. Very cost attractive is the possibility of connecting two of the klystron to one 6 MW dc power modulator. If one klystron fails, the pulse flatness is still better than ±1 % after reconnecting the damaged transmitter. For spallation sources, this type of modulator also allows a dual mode operation. Here e.g. every fifth pulse is enlarged in time and the 60 % beam chopping is not applied. Such a 'double' bouncer modulator has two independent bouncer circuits, but one common high voltage platform. The pulse flatness is about ±1.5 % for the large pulse, which is acceptable as this pulse is sent directly from the linac to a 'long' pulse target station without being compressed.

Attention has to be given to the rf control system. For H^- – injector linacs uncorrelated amplitude and phase errors have to limited typically to ±1 % and ±1° respectively, due to intolerable oscillation of the beam centre at the linac end. In addition transient effects at high beam loading and field drop due to beam chopping have to be considered. By applying a fast feedback and feed forward system, the rf-system of the Los Alamos Ground Test Accelerator (GTA) has achieved the quoted values [32,33]. Similar rf tolerances have to be fulfilled for the high intensity upgrade of the GSI accelerator facility [34].

The strict amplitude and phase tolerances are counteracting in same respect the use of high power Multi Beam klystrons, as power splitting is mandatory here. For the ESS linear accelerator, a more conservative approach is chosen of using a large number of small conventional 2 MW peak power klystrons. Only 2 accelerating tanks are connected to one klystron. 30% additional RF power is foreseen for control purpose. Under discussion are also solution for a 4 MW peak power klystron feeding for four accelerating cavities. Doubling the number of cells per tank is not recommended, as the field unflatness is proportional to the square of the cell number.

For cw proton accelerators up to 100 MW beam power cooling problems and rf feeder line arrangements have to be considered in addition [5,11].

For the Los Alamos cw APT linac, a 700 MHz 1 MW klystrode with more than 65 % rf efficiency is developed together with industry and patented at this moment [10]. A front-end 40 MeV test facility is proposed for cw operation up to 100 mA [12]. Evaluated will be the reliability and availability of components and systems.

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 [35]. Experience gained during building these machines strongly suggests that rf superconductivity is approaching mature technology, even if it is still 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 are not existing in the acceleration of low intensity relativistic electron beams [25].

The cell length varies by a factor 2.5 along the high β proton linac. For a technical linac layout without any abrupt change of the focusing structure, the average filling factor is less than 0.5. As the pulse current can be around 100 mA for high intensity proton linacs, the input power coupler requires special attention. Peak power levels can be greater than 400 kW, exceeding the present performance data obtained so far with beam [35].

For the 100 mA cw APT proton linac, a 4 cell 700 MHz superconducting cavity at 2 K is proposed [10,15]. Cold singlet focusing quads are placed after each cavity inside the cryostat. By limiting the accelerating gradient to 5 MV/m, which corresponds to 120 kW power per coupler, the average energy gain is 1 MeV/m. Only three different cavity length are suggested which require transverse and longitudinal matching sections in between. Four cavities, with two input couplers each, connected to a 1 MW klystron, still met the ±3% amplitude and ±5° phase error requirements. A detailed comparison with a 700 MHz, cw, room temperature coupled cavity linac is given in ref. [37].

The shape of a unstiffened superconducting iris loaded cavity at β = 0,4, corresponding to 85 MeV kinetic energy, is not optimised for vacuum requirements [36]. A stiffened 4 cell 700 MHz cavity has sufficient strength to resist vacuum load and has a minimal mechanical resonant frequency of 110 Hz. Los Alamos plans to build single cell superconducting cavities for β=0.48 and β=0.71 for the APT project. The objective is to demonstrate the physics performance of the cavities and to develop fabrication and joining techniques applicable to multi cell cavities.

For the high β part of the 10 % duty cycle ESS linac, a more advanced 5 cell 700 MHz superconducting structure is proposed [38]. Transverse focusing is applied by doublets after every second cavity. The cell length varies according to the β value. For an accelerating gradient of 10 MV/m inside the cavity, the average energy gain is about 4 MeV/m compared to 2 MeV/m for a conventional room temperature linac. The peak power per coupler is about 400 kW at the high β end. The number of cavities, with two input couplers each, connected to one klystron is under discussion. Due to the pulsed operation, special attention has to be given to the dynamic Lorentz force detuning. For a gradient of 10 MV/m, we have 4 % amplitude and 9° phase error in open loop response during the 1.2 msec long beam pulse. A 100 μsec long gap between the two beam pulses for filling the two ESS accumulator rings causes further complications. Multi coupler systems need attention for frequency shift due to microphonic noise of the connected cavities.

A 8 mA, pulsed 500 MeV electron linac with 1.3 GHz superconducting cells, the TESLA test facility, is under construction at DESY [30]. The first beam is expected at the end of 1996. 16 power couplers are connected to one klystron. At the design gradient of 25 MV/m, the peak power per coupler is 200 kW. Analog and digital feedback and feedforward systems are designed to keep amplitude and phase errors within an acceptable limit [39].

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