A Study of Beam Chopping Options for the ATLAS Positive Ion Linac

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Abstract

Unbunched beam components from the injection beam bunching system must be removed prior to acceleration in the ATLAS Positive Ion Injector Linac(PII). A sine-wave chopper has been used for this purpose up to now. Such a device can have a significant detrimental effect on the longitudinal and transverse beam emittance of heavy-ion beams which can be sufficiently severe to limit the overall beam quality from the ATLAS accelerator.

A study of the optimum chopper configuration and chopper type was undertaken as part of a new ion source project for ATLAS. A transmission-line chopper and a two-harmonic chopper were investigated as alternatives to the conventional sine-wave chopper. This paper reports the results of that investigation and discusses the design of the selected transmission-line chopper.

Introduction

The acceleration of heavy-ion beams in the ATLAS superconducting linac[1] is accomplished with a minimum of emittance growth. In order to achieve heavy-ion beams possessing the lowest possible emittance, a two-stage bunching system is used to convert the continuous (DC) beam from the ion sources into a sharply pulsed beam for injection into the linac. The bunching system is 60-70% efficient in this process. The remaining unbunched portion of the beam must be removed to avoid increased emittance and secondary partial bunches interspersed among the intended beam bunches.

Removing the unbunched beam components is presently accomplished with a ‘sine-wave’ RF chopper which deflects particles with significant time errors vertically, alternately ‘up’ and then ‘down’. The chopper is installed in the low energy beam transport section of the PII where the particle velocity is typically 0.0085c.

‘Sine-wave’ choppers introduce beam degradation by causing emittance growth through increased beam divergence in the deflection plane and by adding additional energy spread to the off-axis particles. Keeping the beam well bunched and physically small reduces these negative effects, but the reality of beam transport systems does not usually allow the chopper to be placed in the most desirable location from this viewpoint.

As part of a new ion source project for ATLAS[2], a design review of the injection bunching and chopping system for the ATLAS Positive Ion Injector(PII) has been undertaken with a goal of improved performance with regard to space charge limitations and to the performance of the chopping system. The bunching system study has been published previously[3]. In this paper, the present ‘sine-wave’ chopper performance is compared to what appears to be an attractive alternative - a segmented transmission-line square-wave chopper. The results of this study come from calculations of the chopper electric field components using the program POISSON[4] and ray-tracing particles through those fields using MATHCAD[5].

Chopper Options Considered

Sine-Wave Chopper

The resonant sine-wave chopper is a simple, cheap, low power alternative for such applications. In a number of situations, it is possible to find configurations which reduce the detrimental effects of the sine-wave deflection. In most applications, such as the present ATLAS implementation for the tandem and the PII injector, beam transmission occurs at the zero-crossing point of the waveform. The chopper operates at half the bunching frequency, alternately deflecting unwanted beam components in opposite directions. At ATLAS the deflection plane is the vertical plane.

Because of the finite size of the chopper plates and the continuous waveform of the resonant chopper, all particles see some electric field as they traverse the plate region. The result is that they emerge from the chopper with an additional divergence and position offset that is almost linearly proportional to time error relative to the bunch center. Since the initial divergence of a particle is assumed to be independent of time, this induced chopper divergence is uncorrelated with the transverse emittance and therefore adds in quadrature to the original value. For a well bunched beam, the divergence will be increased by from 10 to 40%. If the beam optics make it desirable to place the chopper far from a time waist, then the emittance, especially longitudinal, can be increased much more than this value.

Even more important than the transverse emittance growth, a significant increase in energy spread will generally occur for all particles which are off-axis. Since the chopper plates will not be at a waist, this effect can be quite significant. This growth results from the plate fringing fields yielding an accelerating /de-accelerating field component which is phased additively at the entrance and exit of the plates. In addition, alternate bunches are accelerated/de-accelerated doubling the effect when averaged over many bunches. For the ATLAS PII geometry, this effect can produce an energy spread at ±1 cm off-axis which is comparable to the bunching-induced energy spread and in total exceeds the buncher voltage when the effect from alternate bunches is considered. Since this energy spread is time correlated in a highly nonlinear manner and has a strong radial dependence, it functions as a longitudinal emittance growth.

Two Harmonic Chopper

The effect of adding an additional frequency to the sine-wave chopper was investigated. This approach can be beneficial to limiting emittance growth when the transit time of a particle is a small fraction of the chopper period and when the beam is well bunched in the chopper plates. Neither situation is realized for the ATLAS PII injector. The beam transit time through the buncher field is a total of 65° and we wish to use the chopper at a location some distance from the buncher waist, so the time width of the transmitted beam will be the equivalent of 30° in chopper phase. Under these conditions flattening of the sine-wave at 90° cannot be extended over a sufficiently large phase range to significantly alter the effect on emittance of the chopper. Ray-tracing calculations showed no significant reduction in emittance growth compared to the single frequency chopper.

Transmission-line Chopper

The transmission-line chopper is a series of short pairs of electrodes which can be biased to a high voltage, deflecting all ions sufficiently to be stopped on a downstream aperture or slit system. The electrodes are arranged in a 'parallel strip-line' configuration allowing an impedance matched system for fast time response. When transmission of a beam bunch is desired, the electrode voltage is pulsed to zero while the beam bunch traverses the electrode. The voltage pulse transmits downstream to the other electrodes in the chopper system delayed sufficiently so as to stay in phase with the beam bunch. Similar chopper electrode systems have been employed by others[6,7] but with different transmission requirements and electronic implementations.

The transmission-line chopper is a non-resonant system, so the details of the waveform can be varied with a sufficiently sophisticated pulse generator. This allows the function of a chopper, described in the introduction, to be combined with that of a beam sweeper - a device which removes some bunches from the bunch train created by the injection bunching system. This feature is needed for some of the experimental program supported by ATLAS and is now accomplished with a separate set of deflection electrodes and electronics.

The attractive feature of this implementation of the transmission-line chopper is that the electrode geometry indicated in figure 1 can be chosen, in the limit of a sharp field boundary, so that the main body of the transmitted particles see no deflecting field. Therefore, the emittance growth in transverse and longitudinal phase space can be significantly reduced. Only the fringe particles of a bunch, which constitute the transition region from full transmission to full cut-off, experience a transverse kick or an energy change.

The angular deflection which particle 'i' in the transition group with charge q, mass A, and velocity β_i experiences is given simply by:

$$q_i = 0.322 \cdot \left(\frac{q}{A \cdot b_i} \right) \cdot E_y \cdot dt_i \qquad 1$$

where dt_i (which is designed to be less than $l_e/ß_i$) is the time spent in the field region of length l_e. The number of electrode pairs is chosen so that the maximum deflection is similar to the maximum deflection in the present sine-wave chopper: 6 to 8 mr. The detrimental effect on the beam emittance is much reduced because the deflection is in only one direction, not equally in two directions, and the chopper geometry can be designed so that dt is zero for the main transmitted body of the ensemble. As an example when using a cutoff point of ±5 ns, the deflection seen by particles at ±2.5 ns is only 35% to 50% in a transmission-line chopper compared to a sine-wave chopper.

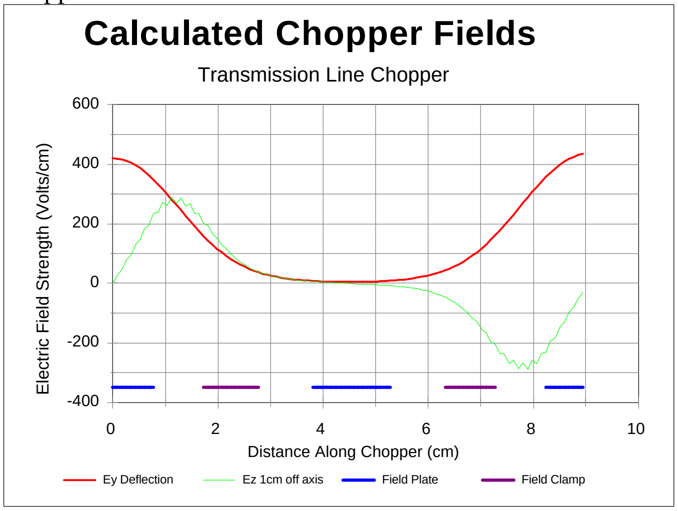

Fig. 1. Calculated transmission-line chopper electric field profile for pulse transmission condition. The biased DC clamp electrodes limit the extent of the fringing fields. The blue lines show the strip-line geometry assumed.

The induced energy spread from the transmission-line chopper is significantly less than that seen in the sine-wave chopper. There is no phase flip while the particles are in the chopper plates nor do alternate bunches see opposing field patterns which double the ensemble effect compared to any one bunch. The main component of the ensemble sees little or no electric field; only a small acceleration from the residual fringe field is observed.

For the transition group particles, the leading particles see an accelerating (let us say) field, while the those trailing see a de-accelerating field. These residual acceleration fields act as additional bunching components but they have an undesirable radial dependence (essentially a spherical aberration). Overall the energy spread increase in a typical case is less than 25% of that experienced in a sine-wave chopper.

The most compact geometry which gives the minimum emittance growth to the beam is one in which each electrode is approximately the width of an individual bunch and is separated by a similar width field-free (nearly) gap which serves as a 'staging' region for the bunch while the previous electrode turns 'on' and the next electrode turns 'off'. Multiple sections of parallel strip-line deflectors are arranged transverse to the beam path. Figure 2 is a cartoon schematic of the geometry and electrical properties of the transmission-line chopper. Each strip-line section will be 1.5 cm wide in the beam direction by 5.0 cm long transversely with 3.6 cm total vertical gap required by the beam size in the chopper region. Between the strip-line sections will be 1 cm wide DC biased, or grounded, electrodes which will serve to clamp the fringing fields as indicated in Figure 1. The physical strip-line period is 4.5 cm long.

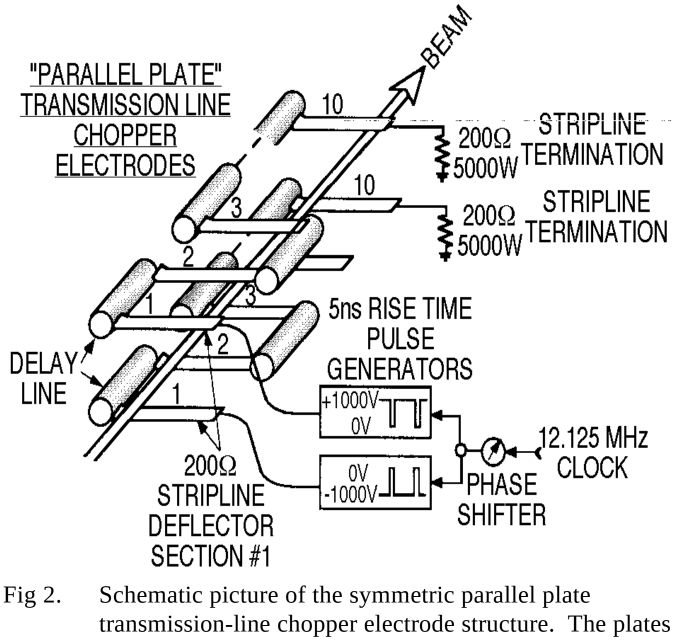

Fig 2. Schematic picture of the symmetric parallel plate transmission-line chopper electrode structure. The plates will be driven symmetrically by separate pulse generators synchronized off the master oscillator. The transmission-line will consist of ten deflection regions spaced as indicated in figure 1 requiring a pulse delay of approximately 17 ns.

Strip-line sections terminate in a delay line which matches the deflection pulse propagation to the arrival time of 0.0085c velocity beam bunch at the next strip-line section. The complete traveling wave deflector will have 10 sections and operate at a pulse rate of 12.125 MHz and a maximum voltage of ±1000 volts. Frequency response will have to be better than 100 MHz to produce pulse rise times of 5 ns.

The deflector sections have an extreme geometry which results in a large vertical space between two narrow strip-line halves. Transmission-line impedance is therefore dominated by edge effects and surrounding structures. A test strip-line has been constructed with the requisite dimensions, but 46 cm long. Measurements indicate each strip-line half has an impedance of 200Ω and overall bandwidth of 3.0 GHz.

Each strip-line deflector is connected in series to the next deflector through an impedance matched delay line section that provides the strip-line propagation delay of 17.6 ns required to match the bunch arrival time at the next section. The construction of the deflection plates as segments of a strip line which is impedance matched to the connecting delay lines is the qualitative distinction from previous implementations. The voltage-off pulse width has been chosen, at this time, to also be 17.6 ns. This means the transition to the transmission state for the next deflector section occurs when the pulse is at the midpoint between deflectors. Shorter voltage-off times are possible, narrowing the pulse acceptance, but with some additional detrimental effects on beam emittance and energy spread. The coaxial spiral delay line[8] chosen is a coaxial transmission-line with a helical inner conductor. The axial wavelength is very long compared to the diameter which produces the desired compact length necessary for this application. The entire strip-line and delay line system will be mounted in the beam vacuum.

Construction of a prototype chopper electrode structure is underway. Beam tests of the structure are expected to occur in the coming year. This work was supported by U.S.DOE Nuclear Science Division under contract W-31-109-ENG-38.

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