ENERGY REGULATION OF A 3 Mv VAN DE GRAAFF POSITIVE ION ACCELERATOR BY MODULATION OF THE ION SOURCE DARK CURRENT

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Abstract

As a result of work on a scheme to regulate the energy of the 3 Mv, Van de Graaff injector at this installation, it was found that several disturbing effects were produced upon closing the energy control feedback loop using a beam derived signal for modulation of the corona current.

These undesirable effects, which are mainly a result of the long ion transit time and ion dispersion in the high pressure gas, seriously limited the manipulation and the analysis of the regulation problem.

To circumvent these difficulties, it was decided to modulate the dark current (D. C. beam current) of the pulsed positive ion source by means of a variable intensity light signal transmitted to a photomultiplier tube in the high voltage terminal through a plexiglass pipe.

This approach provided a rational transfer function permitting a more straight forward analysis of loop operation, a higher frequency response and greater reliability of operation all of which resulted in improved energy regulation from about ± 1.5 KV to about ± 500 V. The existing servo loop on the corona current was retained as a back-up element and it continues to handle the major portion of the slow energy regulation.

Brief Summary on P. P. A. Injector

The Princeton-Pennsylvania Accelerator, a 3 BeV weak focusing proton synchrotron with a repetition rate of 19 pulses per second, has a 3 MeV pulsed positive ion Van de Graaff Accelerator as an injector. This is a horizontal machine that injects protons into the synchrotron vacuum chamber through a seventy foot long beam transport system which includes a double deflection of the 3 MeV proton beam using an electrostatic deflector and inflector. (Figure 1)

A single programable 50kV power supply with a long-term regulation and stability of ± 0.01% is the voltage source for the deflecting electric fields in both devices.

In normal operation, the output beam from the Van de Graaff consists of a 50 microsecond long, 8-9 milliampere pulse of positive ions triggered by a peaker coil in the synchrotron magnet at the injection field of 272 gauss. Between pulses, the Penning Ion Gauge (PIG) ion source provides a continuous low intensity positive ion beam of about 40 microamperes, also referred to as D. C. beam, or dark current.

The D. C. beam is focused to a width of about 0.1 inches at a point about 40 inches down beam from the deflector where it passes between a pair of insulated slits which are adjustable and have a normal separation of about 0.1 inches. A deviation in proton beam energy will tend to change the beam charge stripped off on one or the other slit. Each slit is grounded through a two megohm resistor and the difference between the voltages produced is fed back to control the potential of the high voltage terminal. Originally, this signal, after suitable electronic manipulation, was used to control the grid bias of the corona current control tube, a tetrode located on the side of the pressure tank with its plate connected through a high pressure bushing, to the corona points within the tank, which are some 18 inches from and directed toward the high voltage terminal.

The electric field between corona points and terminal produces an ionization path through the mixture of N_2 and CO_2 gas at 300 psig. The modulation of the current conducted by the tube changes the rate of flow of charge along this path and consequently the potential of the high voltage terminal with respect to the tank which is at ground potential.

Some Disadvantages of Corona Current Regulation

Because of the finite drift velocity of the ions between corona points and terminal, modulating this current has the unpleasant feature of introducing a delay of several milliseconds into the feedback path. In addition, there is a smearing due to normal diffusion in the gas and the combination of these two effects seriously limits the frequency response of this method of control. The capacitive coupling between the shield which supports the corona points and the high voltage terminal is sufficiently small (less than 1% of terminal to ground capacity) that the instantaneous displacement current is not able to contribute significantly to the terminal voltage regulation for any reasonable voltage swings on the corona terminal. Therefore, at frequencies above several cycles per second, there is no effective control using the corona current. Another handicap associated with corona current regulation is a noise component presumably due to changing discharge patterns.

General Description of Dark Current Regulation Approach

The above-mentioned considerations led us to search for another approach to the problem and a try at regulating the terminal voltage by modulating the D. C. beam emitted by the source. Ions from the source will leave the base of the Van de Graaff within less than one microsecond; thus, making the delay time negligible. A command signal is transmitted to a photomultiplier in the high voltage terminal by means of a neon lamp and a lucite light pipe. The photomultiplier output controls the D. C. beam intensity by controlling the D. C. bias on the ion source anode through a pentode tube. This setup allows the transmission to the terminal of signals with cutoff frequencies in excess of 3 kilocycles. With a possible D. C. beam intensity modulation of 40 microamps and a fixed terminal capacity to ground of about 60 pf, the system is capable of a maximum rate of change of voltage of about ± .66 kilovolt/millisecond.

During the high intensity injection pulse the terminal voltage sags some 4 kilovolts and thus it takes several milliseconds to restore the terminal voltage to its nominal value. It should only be mentioned that a liner enveloping the high voltage terminal is being pulsed simultaneously to compensate for this voltage sag and, in the case of P. P. A., to also increase the pulsed beam energy to match the rise in magnetic field during injection time. As indicated in (Figure 1) slit amplifiers are placed in immediate vicinity of the control slits in order to reduce the input capacitance. High input impedances are necessary because of the small currents intercepted by the slits, thus making small input capacitances mandatory.

Brief Analytical Description

In the following, let -K represent the transfer function through the regulation slits (the ratio of control voltage to terminal voltage), G represent the transfer conductance (the ratio of D. C. beam current to control voltage), C represent the terminal capacity to ground, I_{sat} represent the saturation D. C. beam current amplitude, V_0 represent the steady state terminal voltage, and V represent the instantaneous terminal voltage. The relation describing the terminal voltage for the linear case is as follows:

$$(1) \quad V = V_0 - \frac{I_{sat}}{GK} \exp\left(-\frac{GK}{C}\right)t$$

The above-mentioned is true in the range of frequencies where GK, which is a function of $j\omega$, can be still considered constant. In practice, this applies quite well as (Figure 2) shows, since the time constant of the high voltage terminal itself is orders of magnitude larger. From (Figure 1) and the following relations (2-4) we obtain for our system a lateral beam deflection of ± .0006 inches for an energy variation of ∓ .1 kV.

$$(2) \quad d = (\ell + \tfrac{S}{2}) \tan\Theta$$

$$(3) \quad \tan\Theta = \frac{S}{\delta}\,\frac{eV_D}{2T}$$

$$(4) \quad \Delta d = d(1 \mp \epsilon)$$

Where:

d = total beam deflection.

Δd = deflection fluctuation for energy fluctuation T.

ℓ = distance from output of deflector to slits.

S = length of deflector.

Θ = deflection angle.

V_D = deflector voltage.

δ = deflector plate separation.

e = proton charge.

In the case of our injection system Θ is 24°, ℓ is 1 meter and S is 1.26 meter. The present slit separation being about .15 inches with a D. C. beam current of 40 microamps and an assumed gaussian distribution having a standard deviation of 0.050 inches, each slit will intercept 2.8 microamps and produce 5600 millivolts across the two megohm input impedances of the slit amplifiers.

The differential voltage will be about ± 15 millivolts for a ± 1 kev energy variation. The slit amplifiers have input noise levels of less than ± .1 mV, providing an adequate signal to noise ratio. Careful consideration has been given to grounding and shielding. A ground from the Van de Graaff tank has been connected as the reference ground throughout the system including the slits and slit amplifier chassis. The several local power supplies are operated through low capacity isolation transformers. Upon amplification of the difference signal to the ± 10V level, a K of about 10^{-2} is obtained. The parameters of our system give a G value of about 4×10^{-6} mhos. This makes the value of C/GK of the order of 1.5 milliseconds which corresponds reasonably well with the observed data. (See Figure 2)

The overall attenuation and phase characteristics of the feedback loop have the usual 20 db/decade roll off with one phase advance network of 10 db attenuation producing a 53° phase advance at 6 cps to suppress a belt ripple voltage of approximately this fundamental frequency. The corner frequency of the high voltage terminal is below 1 cps.

The original corona current feedback loop produced a terminal voltage regulation of about ± 1.5 kV. By adding the D. C. beam feedback path the energy regulation was improved by a factor of two to three. The stability of the energy lock is quite good, since during the five-day 112 hour weekly operation only a minimum of operator attention is necessary.

Limitations on Energy Resolution

1. Tight mechanical specifications require freedom of mechanical vibrations all along the beam path before it strikes the slits. The sensitivity can be improved by increasing the distance between the deflector and the slits.

2. The transfer function K may vary with beam intensity, thus varying somewhat the open loop gain. This does not seem to be a serious limitation and could be removed by normalizing the signals.

3. There are influences on energy from variation of beam shape due to focusing and variations within the ion source plasma.

4. Loading effects and voltage fluctuation of the deflecting fields also produce energy fluctuations.

It seems reasonable to assume that some effort along each of these lines will be able to produce an additional improvement in the energy regulation.

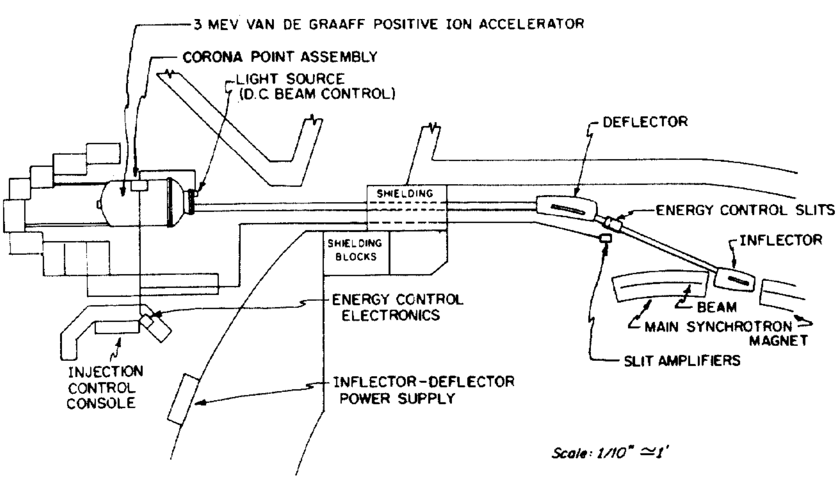

Fig. 1. Block diagram of Van de Graaf energy control system.

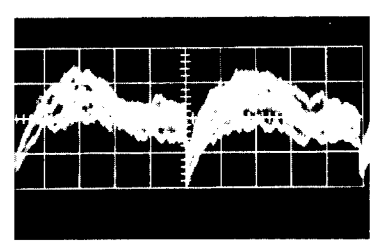

Fig. 2. Van de Graaf terminal voltage. Horizontal sweep: 10 msec per cm Vertical deflection: 1.2 kV per cm.