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ACCELERATOR DEPARTMENT
Informal Report

SAWTOOTH VOLTAGE GENERATION FOR A POSSIBLE AGS BEAM
BUNCHING PREPARATORY TO INJECTION INTO ISABELLE

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December 9, 1971

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INTERSECTING STORAGE ACCELERATOR NOTES

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One of the possible methods for transferring the beam from the AGS and stacking it in Isabelle, is to form a single beam bunch in the AGS which is assembled in "box car" fashion in Isabelle. (See CRISP 71-14) Two methods of forming this single bunch have been discussed.

The first method is to adiabatically debunch the 12 beam bunches used in the AGS acceleration process and adiabatically rebunch into a single bunch at the fundamental frequency.

The second method is similar to the first except the beam is rebunched with a sawtooth waveform. Dr. Rena Chasman has examined this sawtooth rebunching process and has found that a ± 5 kV sawtooth waveform produces a final beam stack with the desired characteristic in about 65 milliseconds.

BEAM LOADING

The circuit system developing this ± 5 kV sawtooth waveform must be able to drive a beam load of 2×10^{13} protons. If a waveform shape change of 33% is allowed, the capacity of the accelerating gap can be determined.

$$\frac{dV}{dt}_{\min} = \frac{1}{C} (I_{\text{Circuit}} - I_{\text{beam}})$$

$$\frac{dV}{dt}_{\max} = \frac{1}{C} (I_{\text{Circuit}})$$

$$\text{if } \frac{dV}{dt}_{\min} = \frac{2}{3} \frac{dV}{dt}_{\max}, \quad I_{\text{Circuit}} = 3 I_{\text{beam}}$$

$$I_{\text{beam}} = \frac{Q}{\Delta t} \quad \text{where } Q = Ne = 2 \times 10^{13} \times 1.6 \times 10^{-19} = 3.2 \times 10^{-6} \text{ Coul.}$$

$$\Delta t = \text{final bunch width}$$

$$= 1/24 \text{ revolution period in AGS}$$

$$= 0.112 \mu \text{ seconds}$$

therefore $I_{\text{beam}} = 28.5 \text{ amp}$ and $I_{\text{Circuit}} = 85.5 \text{ amp}$.

$$C = \frac{I_{\text{Circuit}}}{\left(\frac{dV}{dt}\right)_{\text{max}}} = \frac{85.5 \text{ amps}}{10^4 \text{ volt}} \frac{2.7 \times 10^{-6} \text{ sec.}}{1} = .0230 \mu f$$

With slightly more gap loading, a $0.02 \mu f$ capacitor can be employed.

HARD TUBE MODULATOR

The hard tube modulator shown in Fig.1 can be engineered to develop the desired waveform. The hard vacuum control tube delivers a constant current of 85.5 amp to the coax system which forms the linearity rising voltage on the $0.02 \mu f$ gap capacitor. The deuterium thyratrons shown fires to reverse the voltage on the gap capacitor.

The gap capacitor and the inductance in series with the thyratron anode form a series resonant circuit which produce a half sine wave of anode current and a full voltage reversal of the gap potential.

$$I_{\text{peak}} = V \sqrt{\frac{C}{L}} \quad \text{and} \quad \omega = \frac{1}{\sqrt{LC}}$$

$$\text{therefore } I_{\text{peak}} = VC\omega =$$

$$I_{\text{average}} = \frac{\int i dt}{p} = \frac{I_{\text{peak}}}{\omega p} \int_0^{\pi} \sin \omega t d\omega t$$

where $p = \text{repetition period} = 2.7 \text{ microseconds}$

$$I_{\text{average}} = \frac{2 I_{\text{peak}}}{\omega p} = \frac{2 V C}{p}$$

(Note - I_{average} is independent of ω)

$$I_{\text{average}} = \frac{2 \times 5 \times 10^3}{2.7 \times 10^{-6}} = 74 \text{ amps}$$

For the purposes of thyratron ratings, the current should be averaged over a

one second period, therefore

$$\text{thyatron } I_{\text{average}} = 74 \times .065 = 4.8 \text{ amps}$$

While this is within the 6 amp average rating of current available deuterium thyratrons, I suggest that two be employed and fired alternately for reliable operation and a reduction of the average current to 2.4 amp each tube.

Omega (ω) can be chosen to limit the peak current to rated values (2500 amps)

$$\omega = \frac{I_{\text{peak}}}{V C} = \frac{2.5 \times 10^3}{5 \times 10^{-3} \times 2 \times 10^{-8}} = 25 \times 10^6 \text{ rad/sec}$$

$$\text{switching time} = \frac{\text{ringing period}}{2} = \frac{\pi}{\omega} = 125 \text{ nano sec.}$$

62.5 nanosec. from each of the two beam bunches (220 nano sec is the width of a beam bunch) adjacent to the step in the sawtooth will be lost. This represents about 5% of the total beam.

The length of the feed coax going through the radiation shield must be small so that the reflections of the thyatron switching step occur during the 125 nano sec switching interval. If they occur after this, additional beam is lost.

$$d = v t \quad v = 2/3 \text{ velocity of light}$$

$$t = 62.5 \times 10^{-9} \text{ sec}$$

$$d = 41 \text{ ft.}$$

This is less than our normal sleeve penetration to the AGS tunnel and therefore will require a local house and a special short penetration of the AGS ring shield at the location of the sawtooth device.

Summation of sine waves

A sawtooth waveform can be generated by summing the Fourier components. Fig.2 shows the step edge of a sawtooth and the waveforms generated by summing the Fourier components to the integer indicated. For reference on the time scale, a beam bunch is sketched (after adiabatic debunching). From this figure, it can be seen that Fourier components through the 6th are required for any reasonable approximation to the sawtooth, but to obtain a good representation, components beyond the 12th will be required. This is a large number of cavities and does not appear to be a practical method.

Summation of "switched" sine waves

Fig.3A shows a sketch of the "switched" sine wave to be considered. The switching action reverses the polarity of each component at the fundamental sawtooth period. When these waveforms are summed, the result converges to the desired sawtooth much more rapidly. Fig.4 again shows a reference sawtooth and the waveforms that result by summing "switched" sine waves to the integer indicated. (Note, the even numbered integers are not required.) The wave form resulting from summing of the 1st and 3rd is a reasonable approximation of the sawtooth and the approximation improves rapidly with 5th and 7th. Thus, only 2 to 4 systems are required and the later system employs only small voltages. Following is a list of the amplitude coefficients of the "switched" sine wave components required to generate a ± 5 kV sawtooth waveform.

<u>Integer</u>	<u>Amplitude Coefficient</u>
1	4052 volts
3	450
5	162
7	82
9	50
11	33
13	24

Generation of "Switched" sine waves

"Switched" sine waves are easily generated by the circuit shown in Fig.3B. The action of the thyratrons and their anode inductor is the same as that described under "Hard Tube Modulator". Each firing reverses the voltage polarity across the gap capacitor. The thyatron ratings and circuit consideration are identical to those described before.

The relationship between E_{bb} and the gap voltage is determined by equating input energy to energy dissipated.

$$\int (\text{input per switching}) = \int_0^{\pi} e i dt = \frac{2 E_{bb} I_{\max}}{\omega_1}$$

where $I_{\max}$ is the peak current during switching, ei 2500 A

ω_1 = radial frequency of the switching process = 25×10^6 rad/sec

The energy dissipated at the planned magnetic flux level in the 3B7 ferrite of 500 gauss max is 0.2 watts per cubic centimeter. The design described later contains approximately $130,000 \text{ cm}^3$. Therefore, the power to excite to this flux level is 26 kW.

$$\int (\text{dissipated per switching}) = \frac{P}{2f_2} = \frac{P\pi}{\omega_2}$$

where P = dissipation power

$$\omega_2 = 2\pi f_2 = \text{radial frequency of the LC system} = 1.165 \times 10^6 \text{ rad/sec.}$$

equalizing these two energies

$$\frac{2E_{bb} I_{\max}}{\omega_1} = \frac{P\pi}{\omega_2}$$

$$\text{therefore } E_{bb} = \frac{\omega_1}{\omega_2} \frac{P\pi}{2I_{\max}} = 350 \text{ volts}$$

Thus, the supply source is only 350 volts and 74 amperes.

Cavity Design

The following is an outline of a ferrite loaded cavity for the "switched" sine wave first harmonic component. Other cavities are similar but much smaller.

$$E = 4.053 \text{ volts}$$

$$f = 185 \text{ kc}$$

$$\omega = 1.165 \times 10^6 \text{ rad/sec}$$

$$N = \text{one turn}$$

$$E = N \frac{d\theta}{dt} = NA \frac{dB}{dt}$$

$$\text{Cross-sectional area} = \frac{E}{B_{\max} \omega} \approx 700 \text{ cm}^2, B_{\max} = 500 \text{ gauss}$$

$$I_{\text{peak}} = E_{bb} C = 94.4 \text{ amps, } C = .02 \mu\text{f}$$

$$B_l = \frac{4\pi I_{\text{peak}}}{10} \text{ therefore } l = .24 \text{ cm (total air gap)}$$

This cross-sectional area is typically satisfied by 2 cores 18 x 20 cm in cross-section. The perimeter to enclose the AGS vacuum chamber is estimated to 180 cm. Volume of ferrite is approximately $130,000 \text{ cm}^3$.

Conclusion

The "switched" sine wave method for generating the desired sawtooth waveform is simple and much easier to build than the other methods studied.

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Fig. 1

Fig. 2

Fig. 3-A

Fig. 3-B