A VARIABLE, HIGH SPEED BEAM-POWER ABSORBER

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ABSTRACT

When operating ring cyclotrons at high beam currents, the frequently used flattopping cavities require special measures to handle the additional power induced by the beam. This problem is analyzed, some possible solutions are reviewed and a method of using an RF- power tube as a fast variable load (or reactance) is described.

The design concept, results from simulation as well as some experimental results for a prototype beam- power absorber are presented. The operating frequency is 151 MHz and absorption rates for the selected power tetrode (YD 1177) are up to 8 kW (CW) or 30 kW pulse power.

Furthermore, a control system for load tuning as well as control parameters and their characteristics are discussed. It can be seen that such a system could alternatively be used as a fast reactive tuning element of limited linear range.

1. INTRODUCTION

Flattopping reduces total energy gain per turn for particles of a certain phase range by decelerating them to a desired energy level; the energy difference is deposited in the cavity. Beam induced cavity voltage is therefore in phase with generator induced cavity voltage.

Beam induced power is proportional to beam current ($P_B = U_C \cdot n \cdot I_B$) and it is obvious that an I_B exists above which $P_B \geq P_L$, that is: beam induced power becomes greater than the cavity losses. Even before reaching this point, however, cavity voltage stability specifications can no longer be maintained due to 'loss of controllability'.

A common way out, used at higher frequencies, consists of placing a circulator in the transmission line between cavity and power amplifier (PA); unfortunately, at 150 MHz and power levels higher than a few kW, no commercial circulators are available anywhere. Nevertheless, several alternate solutions to this problem can be thougt of:

1.1 Lowering the Q of the Cavity

This is easiest done by adding load resistors either into the power feed line between RF-generator and cavity or with load resistors coupled directly to the cavity. Such a scheme has serious limitations, however; it requires more RF power for operation at low beam levels, just to be dissipated in loads. So, for P_G greater than say $2..3 \cdot P_L$ it becomes prohibitively expensive.

1.2 Load on Cavity, Variable in Steps

To alleviate the power demand on the driver amplifier, one can think of a system which only connects additional load to the cavity at beam currents above a predetermined value. This can be done in discrete load steps. Such a design is more power-efficient but the major problem will be power switching. During transients (e.g.: cavity spark, fast beam interlock) overload or mismatch of the final amplifier cannot be avoided; if it exceeds power level or duration limits, automatic protection circuits will turn off the amplifier. In case of multipacting, turn-on may be a time- consuming procedure (sec...min); therefore, shutting off amplifiers should be avoided.

From this, it can be seen that switching should be done very fast (within microseconds), which rules out electromechanical switching gear.

What remains then is electronic switching. A concept with coaxial switches has been described, based on high power PIN-diodes as switching elements in the inner conductor[1]. Switching times are approx. 1 μs. Some further work in this direction has been done at CERN and Karlsruhe. Unfortunately, no system has been developed beyond prototype status. Considerable development time can therefore be expected in view of known sensitivity of semiconductors to over-voltage and transients.

Another future solution might involve superconducting switches, at present, however, such systems are still far away from reliable operation; even under ideal conditions.

1.3 Power Amplifier Adapted to Operation in Absorbing Mode at Higher Beam Levels

Together with an additional load (lower effective Q, case 1.1) such a system can be operated from amplifier to absorber mode as a function of beam current. It requires an overrated power amplifier (plate dissipation, RF output power) but no additional high power components. It is therefore suitable only for a limited range of I_B, but for the anticipated max. beam current of I_B=2 mA in the SIN accelerators[2], it seems appropriate, particularly since the necessary (overrated) PA's already exist.

An important advantage of this arrangement is that control loop performance (amplitude- and phase specifications) can be maintained over the entire operating range with only minor changes to low power level RF circuitry. Consequently, such a

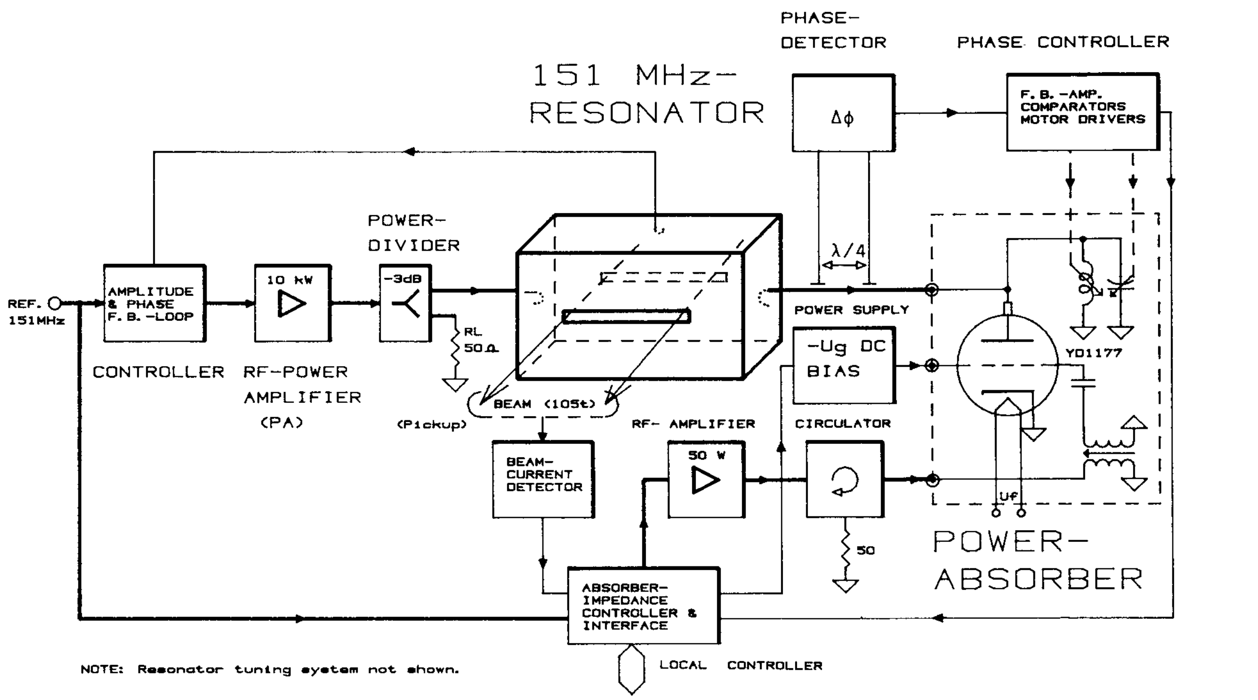

Fig. 1: Simplified block diagram of a flattopping resonator and beam power absorber.

system is implemented at the SIN injector (72 MeV p) and will be used in the ring cyclotron (580 MeV p) in the near future[3].

1.4 Variable Load, Coupled to Cavity

Finally, a universal solution can be thought of consisting of a continuously variable load coupled directly to the cavity. Separate coupling has the advantage that the coupling element and transmission line can be adapted to the maximum power level to be absorbed. The PA, its transmission line and coupling then only need to be specified for cavity loss power (P_L), which is important if the beam power level (P_B) is many times higher than P_L.(Figure 1)

Such a continuously variable attenuator should also respond rapidly (within μs) to beam intensity changes, such that no overload or shutoff of the PA can occur. Rapid intensity changes are typical in pulsed beam operating modes.

One of the most suitable electronic components to handle this task seems to be an electron tube; it can, at one and the same time, handle high power levels, respond fast (RF-tube), and is robust (short overvoltage conditions are not fatal).

2. CONCEPT OF PROTOTYPE

With an absorption rate of 4.5 kW/mA (see ref. 2) we obtain a maximum of 9 kW beam power (P_B) per cavity; not all of it has to be absorbed by the absorber stage, however. For low beam currents it is feasible to run without activated absorber at all and reduce the drive level of the PA first. Figure 2. shows corresponding RF- and beam power levels as functions of beam current in the resonator.

In general, we have: $P_L = 1/2\ \frac{U_{CP}^2}{R_s} = P_B + P_G - P_{ABS}$, with: U_C = const. (controlled parameter) and R_S = const.(loss).

2.1 Absorber Model Design

Since we did not want to install the absorber right on the resonator, the electrical length l between coupling point and equivalent absorber resistance R'_A was chosen to be exactly $l = n \cdot \lambda/2$ (requires tunable line length!). This permits the use of a model with a real, varying resistor R_A connected in parallel to the cavity shunt resistance R_S via a coupling loop.

It should be noted that this concept operates **without DC power-supply** for the anode tank circuit, thus allowing a much simpler and cheaper absorber design and avoiding stability problems usually associated with amplifier tubes.

In order to make the absorber as simple as possible, a **triode** was chosen as an absorber tube, eliminating the need for a separate screen supply. Such a triode must have minimal internal capacitance C_{AG} to minimize 'Durchgriff' $D = \delta U_G/\delta U_A$ ($=1/\mu$), that is: power feed-through from anode to grid. A suitable tube is the YD 1177, available from Philips, as can be seen from data sheets.

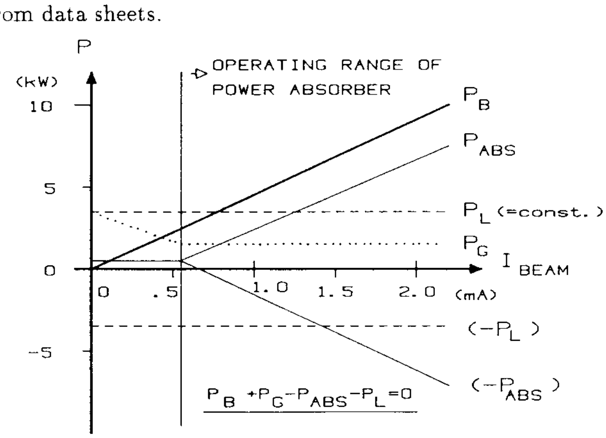

Fig. 2: Power levels as fct. of beam current.

Several tube circuit arrangements are possible, but two are the most prominent: grounded grid and grounded cathode configurations. High frequency applications usually call for grounded grid circuits, the main advantage beeing good input-output insulation, better stability and lower input impedance. If one uses a grounded cathode concept, especially at RF- frequencies, neutralisation schemes have to be applied to obtain good insulation and stability. As our experience has shown, such neutralisation at 150 MHz can be very tricky. The big advantage of the grounded cathode concept lies in the fact that very little grid drive power is needed (this configuration has voltage gain!), thus saving additional amplifier stages in the grid drive. Estimates show that $\approx$ 25 W should suffice vs. 500..700 W needed in a grounded grid configuration.

It was therefore decided to use the **grounded cathode** scheme first for a simple prototype and proof of principle.

2.2 Tube Operating Parameters

The DC-grid bias voltage (the only external DC-source required) was chosen to be adjustable from -180 V to -50 V, with RF-drive (U_G) added as an absorber power level control parameter. The phase of U_G can also be modulated; this allows for proper tuning of the absorber impedance such that it stays purely resistive ($Z_{ABS} \approx R_A$).

Figure 3 shows the effect of the grid phase shift angle α on anode current I_A, the resulting current angle Φ is identical to the phase angle Φ of the absorber impedance vector:

$$\mathbf{Z}_{ABS} = Z\underline{/\Phi} = \frac{|U_A|}{|I_A|}\,\underline{/\Phi_U - \Phi_I} \quad .$$

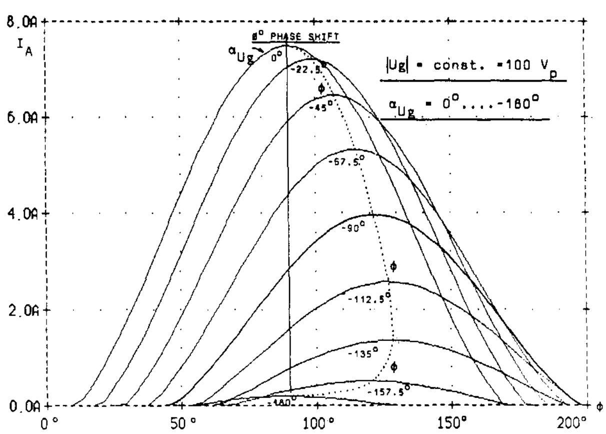

Fig. 3: Anode current angle (ϕ) vs. grid drive angle (α).

Since $|I_A|$ decreases if α differs from 0, Z_{ABS} increases, causing the absorbed power to decrease; therefore the drive level $|U_G|$ would have to be raised to compensate for this effect. This interdependence of phase and amplitude levels is shown in Fig. 3. For the chosen operating mode, we see that: $I_{A\ peak}$ = 7A.

We calculate absorbed power:

$$P_A = \frac{1}{T}\int_o^T u_A(t) * i_A(t) * dt = 7.4\ kW;$$

this result has been obtained by numerical integration for:
U_{Ap} = 5 kV_p, U_{Gp} = 100 V_p, U_{DC} = -50 V.

Given P_A and U_A, we determine an rms value for I_A:

$$I_A(rms) = P_A\frac{\sqrt{2}}{U_{Ap}} = \frac{7.4\ kW * \sqrt{2}}{5\ kV} = 2.1\ A \quad .$$

This value is well within the safe operating range of **4.0 A** given in the tube specs.

3. ABSORBER DESIGN

The absorber consists of the following elements:

- a foreshortened $\lambda/4$ coaxial line resonator functioning as an anode tank circuit with a coupling point (loop) to obtain impedance transformation between input and anode impedance R'_A.
- a grid circuit with a variable char. impedance (Z_0) coaxial line of length $\lambda/4$ to match the grid load to the output of the drive amplifier (50Ω).
- Neutralisation circuitry, with the purpose of injecting an anode voltage signal, shifted in phase by 180°, into the grid to compensate for feedthrough from the anode caused by capacitance C_{GA}. This circuitry is composed of an anode voltage pickup capacitor C_N, a tuning capacitor C_T (equal to C_{GK}), and a $\lambda/4$ transmission line (Z_0=1.1Ω) intended to match the dynamic grid input capacitance one-to-one to the node with C_N and C_T.
  This circuit is a variation of the single- ended neutralisation by Bruene (compare ref. 4). Neutralisation, that is: total calculated attenuation from anode voltage to the grid terminal of the tube is: A_N=−34 dB.
  The equivalent power level [@ U_a = 3.5 kV_{rms}] into 50 Ω on the grid terminal would then be 100 W. Using a properly terminated circulator with 500 W power rating on the grid input terminal, feedthrough can be lowered to A=-57 dB into 50 Ω (measured), which corresponds to a power feedthrough of 0.5 W to the output of the grid drive amplifier at full operating anode voltage.

3.1 Absorber-Resonator Transmission Line, Coupling Loop

When specifying the transmission line between absorber and resonator, the following points have to be taken into account:

- To achieve a 1:1 transformation of R_A into the cavity (parallel to R_S), a line length of exactly n·λ/2 must be maintained between the two impedances.
- Z_{ABS} has to be adjusted such that its reactive component X approaches zero by shifting the grid drive signal in phase, otherwise, tranformation ratios change!
- Except at **one** operating point, the line will always be operated in a **mismatched** mode, that is: SWR > 1.
- To allow the use of a minimal-size coaxial line, maximum power (P_{Amax} = 8 kW), should be obtained with: $R_{ABS} < Z_0$ = 50 Ω.

4. CONTROL LOOPS OF THE ABSORBER STAGE

Two main control loops have to be designed around the absorber stage. They are:

- Absorber **power level** control (=amplitude control)
- Absorber **impedance phase angle** (=tune)

These control loops should not interfere with the resonator accelerating voltage amplitude- and phase controls. This is achieved by letting the absorber act as a disturbance of the cavity voltage, with limited bandwidth (compared to the A/Φ-control bandwidth of the cavity voltage controller).

4.1 Amplitude Control

In a strict sense, amplitude control is not a closed loop system, since beam intensity I_B is to control the power absorption level and is itself not directly dependent on P_A.
As a consequence, this control parameter cannot cause instability of the resonator amplitude control system; it can only degrade its performance. Not surprisingly, a suitable control parameter for P_{ABS} is U_G.

If: $P_{ABS}=P_B=f(I_B)|_{n,U_C=const.}$, then: $P_B \sim I_B$. And if: $P_{ABS}=U_A \cdot I_A=f(I_A)|_{U_A}=const.$, then: $P_{ABS} \sim I_A$, such that: $\underline{I_B \sim I_A}$. Applying curve – fitting to the I_A-U_G-characteristics of the YD1177, we find a second-order polynomial to fit nicely, with a dominant linear term k_1. Hence, we use a linear approximation:

$$U_G \approx k_o + k_1 \cdot I_A \,|_{\mu=const.} \quad ,$$

such that a simple linear controller of the type: $\underline{U_G = k_o + k_1 \cdot I_B}$ can be used.

4.2 Absorber Impedance Tuning

A suitable concept for obtaining information about absorbed power and impedance has to be found. A directional coupler could be used to measure absorbed power, for measuring impedance, however, one needs phase information over the entire operating range which is planned to cover:
$40\Omega < Z_A < 250\Omega$. Since the reflected power signal will be zero around $Z_A=50\Omega$, no phase relation between incident and reflected wave signal exists there!

Another method for determining impedance and phase angle of $\mathbf{Z}_{ABS}$ consists of placing two capacitive pick-up probes in the transmission line; spaced $\lambda/4$ apart and $n(\lambda/4)$ away from the absorber impedance $\mathbf{Z}_{ABS}$.

Two voltages $\mathbf{U}_1$ and $\mathbf{U}_2$ are generated and we wish to express: $\mathbf{Z}_A \underline{/\Phi} = f(\mathbf{U}_1,\mathbf{U}_2)$. Phase angle Φ can then be used to tune the absorber impedance to resistive values (jX=0).

Solving transmission-line voltage equations and using the special case $x=\lambda/4$ and $y=\lambda/2$, we obtain:

$$\mathbf{Z}_A = Z_o * \frac{U_2}{U_1}\underline{/\theta - \pi/2}; \quad \rightarrow \quad Z_A = Z_o * \frac{U_2}{U_1} = 50\Omega * \frac{U_2}{U_1}; \qquad \Phi = \theta - \pi/2.$$

A purely resistive absorber tune is reached if:
$\Phi = \theta - \pi/2 = 0$, that is $\underline{\text{if: } \theta = \pi/2}$

With $\mathbf{Z}_A = \frac{\mathbf{U}_A}{\mathbf{I}_A} = \frac{U_A}{I_A} \underline{/\Phi}$, our control parameter will be the phase angle Φ between plate voltage and the fundamental frequency component of the plate current $\mathbf{I}_A$. $\mathbf{I}_A$ is controlled by $U_G\underline{/\alpha}$, α beeing the phase angle between grid voltage $\mathbf{U}_G$ and plate voltage $\mathbf{I}_A$.

We linearize: $I_A = K(U_G \cdot \sin[\omega t] + \frac{1}{\mu} U_A \cdot \sin[\omega t+\alpha])$ assume constant U_G and U_A, solve for Φ, and we get:
$tg\ \Phi \approx \frac{U'_A * \sin\alpha}{U'_G + U'_A * \cos\alpha}$, and approximately: $\Phi \leq \frac{\alpha}{2}$ for $\alpha < \frac{\pi}{2}$; or, for the control vector α: $\underline{\alpha > 2\Phi}$ (compare Fig. 3).

5. CONCLUDING REMARKS

It has been demonstrated that it is possible to use a triode without plate power supply as a modulated load (variable resistor) at 150 MHz.

Since electronic grid voltage control is possible, modulation bandwidths of several MHz are reasonable; limited only by anode- and grid circuit Q-factors. This translates into response times well below the 1 μs range.

Since good neutralisation at 151 MHz will be very difficult to achieve, it should be avoided by using a different tube configuration from 'grounded cathode'.

The problem of electron backheating of the cathode has not been addressed seriously; literature and tube manufacturer data is relatively vague about this point (see ref. 4, p.142 ff). All we know by now is that we carried out all our tests with **one** tube, which has not shown any measurable change in characteristics compared to the beginning of our tests.

6. REFERENCES

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