A CW NON-SYNCHRONOUS TRAVELING WAVE STRUCTURE FOR A 300 MeV PULSE STRETCHER RING

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Abstract

The cw traveling wave RF cavity installed in the pulse stretcher ring at the Saskatchewan Accelerator Laboratory was designed to compensate for synchrotron radiation and parasitic losses while heavily beam loaded, and to control beam spill over a wide energy range. Design and construction aspects of this 2856 MHz, fast filling time (T_F = 19 ns), reduced phase velocity structure and its associated rectangular waveguide network and RF monitors are described. The relevance of the extremely low copper loss (<3%) to the fast control response, and the beam energy gain characteristics of this 12.8 MΩ total shunt impedance structure are discussed. Microwave measurement data are presented for the fundamental frequency and for higher order modes; and several techniques for reducing the effects of the BBU modes are described.

Introduction

The economic advantages of using a pulse stretcher ring (PSR) to extend the beam duty factor of conventional linac systems and the potential for attaining a high quality extracted beam has, in recent years, led to considerable activity — both in construction and in proposals to upgrade existing linac facilities. (A comparative listing of typical PSR parameters is given in Table I of Reference 1.)

For existing facilities, the PSR design parameters are strongly influenced by the characteristics of the linac beam and by the layout of the site, and this in turn places a variety of constraints on the design of the PSR RF system. Such was the case for the Saskatchewan Accelerator Laboratory EROS project (formerly named SORE[2]), wherein the minimum beam aperture, injected current, maximum circulating current and RF cavity voltage were all predetermined. The EROS ring is 108 meters in circumference; thus, with a peak current of 200 mA injected into the ring for a period of 1 μs, the beam will wrap around on itself approximately 2½ times to give a circulating current of 500 mA. In the normal pulse stretcher mode, all of the particles must be extracted before the next injected pulse.

With a suitably designed RF system, synchrotron radiation and parasitic losses can be accurately compensated, and the spill can be controlled over a wide range of operating energies and currents to maximize the effective duty cycle of the beam, while maintaining a very narrow energy spread and low emittance.

The proposed technique at EROS for controlling and smoothing the extraction process is to reduce the height of the RF bucket, causing electrons to spill from the trapped orbit region of stability. Control of the RF bucket for extraction shall be achieved by modulating the field strength of the RF cavity with a programmable waveform,[3,4] repeated at the pulse repetition rate of the linac, i.e., with a periodicity of a few milliseconds. It is perhaps of interest, at this stage, to mention that, consistent with the RF transmitter amplitude and phase controls, if the RF cavity could have a dynamic response of tens of nanoseconds rather than the usual microseconds, a highly advantageous means would then be available for controlling potentially serious beam dumping instabilities associated with the fast injection process.

RF System Considerations

Operational parameters having a major influence on the design of a suitable RF cavity include the maximum height of the desired RF bucket, the minimum beam aperture size, the maximum beam loading condition, and the system response requirements for dynamic control of the resultant RF field amplitude and phase. In addition to these factors, design emphasis should also be directed at preventing or strongly suppressing multi-turn beam induced higher order modes that cause beam instabilities, at minimizing the absolute level of (cw) RF power dissipated in the cavity walls, and at avoiding large changes in this dissipation during different modes of operation of the PSR.

The EROS RF system was planned as a two-stage program — an initial stage using a low level of RF power to enable operation up to 300 MeV with beams of moderate intensity, and a final stage using an RF transmitter of higher power to allow operation with beams of up to 500 mA. This plan presented an opportunity for performing useful physics experiments and for becoming familiar with the operating requirements of the ring at an early stage in the program, while minimizing expenditure for the RF power source. To avoid subsequent modifications of the main ring, however, it was considered highly desirable that the RF cavity and associated evacuated RF components be designed and constructed from the outset to satisfy the higher RF power and the heavy beam loading conditions of the final stage.

For a given beam energy, the RF cavity field strength is determined by the ring harmonic number and momentum compaction parameter (α), as well as the RF bucket height which, in turn, is established by the injected beam energy and phase spread. An energy compression system,[5] installed between the linac and EROS, is arranged to provide a compression factor of 8 to 10 with a longitudinal phase dispersion of 1 radian/%. Thus, in compressing a ±1% linac beam energy spread, the RF bunch longitudinal phase is extended to approximately 120°. These PSR injection parameters define the height of the RF bucket ($\approx 0.12\%/\sin[\frac{1}{2}(180-60)] = 0.14\%$); and with a harmonic number of 1028 and α = 0.0483, for a 300 MeV beam, the EROS RF cavity must have a field gradient capable of providing a maximum energy gain of 45 kV. (Neglecting losses, this cavity field requirement is proportional to the beam energy and the square of the RF bucket height.) EROS synchrotron radiation losses of 720 eV/turn and parasitic losses at 500 mA of 650 eV are small; thus, for energy compensation of approximately 1.4 kV/turn, the bunch centroid should be phased close to the zero crossing.

Because a 4 cm diameter beam aperture was acceptable for the PSR, a frequency identical to that of the 2856 MHz linac was chosen for the RF cavity. This simplified the system, since linac injector and control modifications for subharmonic operation were no longer necessary, and an undesirable reduction in effective beam duty factor was avoided. However, because of the very large beam induced voltage, a disadvantage in this choice of frequency is that even with the best compromise of coupling coefficient (β) and cavity tuning angle (ψ),[6] the input cw RF power required to satisfy heavy beam loading conditions causes excessive levels of dissipation for an S-band standing wave cavity. Additional complexity is introduced with an array of cavities, and with the need to adjust cavity coupling and tuning angle to operate at light and heavy beam

E-bend directional coupler and a thick ceramic RF window and water load at the output. To assist in evaluating HEM_{11} modes, the directional couplers have relatively broad band characteristics with coupling ratios of 44 and 40 dB at 2856 and 3600 MHz, respectively.

A view of the overall system, including the input and output beam port vacuum nipples, the rectangular waveguide (RWG) network, and the mounting baseplate and support assembly, is shown in Figure 3, during preparation for shipment to Saskatchewan.

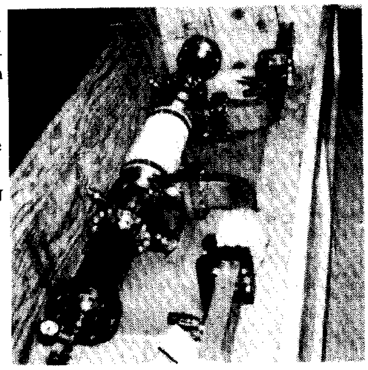


Figure 3. Final Assembly including RWG Network.

An input recirculator and load assembly is not required with this system because the very low level of reflected power (VSWR = 1.08) is independent of beam loading and remains essentially constant over the full operating range. A remnant RF high power load is necessary, however, because the structure has an extremely low insertion loss. Moreover, with a passive circuit and an RF bunched beam of 500 mA, the regenerated RF power[9] could attain a peak level of 21.1 kW.

The structure microwave parameters are listed below.

λ_0=0.105m	v_g/c=0.07	r_0=32.1MΩ/m on-axis,
β_w=0.9520	Q=12600	increasing off-axis by
L=0.4m	$f_\pi - f_0$=227MHz	2.1% and 5.2% at 5mm and
τ=0.0134Np	$d\theta/dT$=0.33°/°C	7.5mm radii, respectively.

After final matching and tuning of the RF coupler cavities and the re-entrant drift tubes, each body cavity was nodal tuned; and an accurate phase dispersion measurement of the centerline cavities gave $(d\theta/df)$=6.8°/MHz. Using the convenient relationship[10] $T_F=(d\theta/df)/(2\pi)$, an empirical confirmation of 18.9 ns was obtained for the filling time. This value was consistent with the high group velocity (0.07c) obtained earlier from resonant frequency measurements of large aperture cavity cold stacks; and the associated low attenuation coefficients $[I\propto(Q\ v_g)^{-1}]$ resulted in the extremely low copper loss reported above.

Higher Order Mode Considerations

The TM_{01} and HEM_{11} dispersion curves for this large aperture structure, indicating both the upper and lower passbands of the lowest order angular dependent mode, are shown in Figure 4. It should be especially noted that the HEM_{11} lower passband exhibits a forward traveling wave characteristic having a group velocity of 0.017c at v_p=c and a π cut-off frequency of 3731 MHz. Also, for the upper passband, the zero mode frequency is 4090 MHz, and at approximately 5350 MHz, the phase velocity of the first backward space harmonic equals the velocity of light.

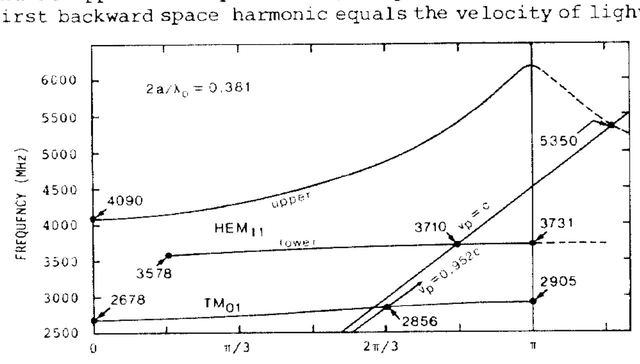


Figure 4. RF Cavity Propagation Characteristics.

A variety of Q-spoiling techniques were devised to minimize the HEM_{11} field intensities caused by (a) resonant buildup due to imperfectly matched terminations and (b) excitation of backward space harmonic resonances. These techniques included the use of termination cavities fabricated and matched with tunable re-entrant, large aperture, RF lossy (high ρ and μ) drift tube assemblies, having a cut-off frequency of approximately 3470 MHz; the use of slotted beam drift tubes with externally loaded probes, in two orthogonal planes oriented azimuthally at 45° to the S-band couplers; and the previously mentioned broad band HOM extraction circuits, coupled into cell numbers 6 and 7. These impedance transformed WR187 RWG circuits, and the loaded drift tube probes, are shown in Figure 5.

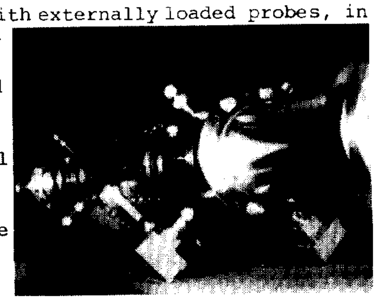
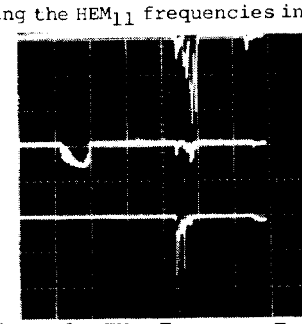


Figure 5. EROS RF Cavity HOM Q-Spoiling Circuits.

The highest $r_\perp/Q$ values of 10 to 12 Ω/cm (1/3 to 1/2 the value for normal size apertures) occurred in the vicinity of the lower branch v_p=c intercept at 3670 to 3730 MHz, and accordingly, the WR187 circuit coupling was optimized for this frequency range. Overall Q-spoiling, including compression nodal tuning of the structure to optimize HEM_{11} coupling to the external S-band load,[11] resulted in a substantial reduction of transverse shunt impedance with HEM_{11} maximum $R_\perp$ values of between 0.1 and 0.16 MΩ.

Cold test measurements of simulated beam tube reflections and a HOM characterization up to 8.2 GHz were carried out on the final assembly, with RF injection and detection at different combinations of the ten available ports. A typical set of HEM_{11} detection signals, shown in Figure 6, for the case of a 2.5 to 4.05 GHz swept frequency injection at the input coupler, illustrates the effectiveness of coupling the HEM_{11} frequencies into the selected external loads.



(a) Detector in WR187 extraction circuit: HOM peaks at 3692 and 3719 MHz.

(b) Detector at S-band Output Load: TM_{01} pass band and HOM peaks from 3571 to 3695 MHz.

(c) Detector in Beam Drift Tube (Probe #4): HOM peaks at 3579 and 3593 MHz.

Figure 6. HEM_{11} Frequency Transmission into External Loads.

References

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