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FORMATION AND ACCELERATION OF NANOSECOND BEAM PULSES IN AN ISOCHRONOUS CYCLOTRON

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Summary

Use of cyclotron beams for time-of-flight experiments requires the production of high-intensity ion bursts of very short time duration. A lower limit for obtaining short pulses of a defined energy spread is set by the intrinsic energy-time spread of the ion beam. The factors determining this spread are investigated. Central-region design features facilitating the formation of nanosecond pulses in the NRDL cyclotron are discussed, and results of detailed calculations on the magnitude of the intrinsic energy-time spread are presented.

Introduction

The pulsed nature of cyclotron beams can be utilized advantageously in experiments where time-of-flight techniques are employed. Pulse durations observed are typically between 20° and 60° of the rf period, i.e., about 3 to 9 nsec for a frequency of 20 Mc/sec. The 70-inch sector-focused cyclotron now under construction at this Laboratory will be used for neutron time-of-flight work in one of its modes of operation, and a detailed investigation aiming at an optimum design of the cyclotron for this purpose has been carried out. The objectives of this design program were threefold: (1) formation of a short ion pulse having small intrinsic energy-time spread and traveling on distinct and well separated orbits; (2) selection of individual "fish" out of the continuous pulse train by means of a beam pulse selector located on the first turn; (3) careful control of the energy-time relations within the selected pulse during the subsequent acceleration process and through the extraction system to achieve additional time compression on the external beam path between cyclotron and target via the klystron effect. The present paper deals with part (1) of this program while parts (2) and (3) are discussed in two other conference contributions.[1,2]

Central Geometry and Operating Conditions

The NRDL 70-inch cyclotron is a 4-sector spiral machine with 35° dees in two opposite valleys. It is a variable-frequency machine (range 11 to 33 Mc/sec) and accelerates protons and alphas up to 100 MeV, deuterons to 50 MeV. Injection and acceleration of the ions will be accomplished in three different modes of operation each of which has a constant orbit geometry or constant number of turns: (1) protons from 16 to 100 MeV, high-energy deuterons, and alphas are accelerated in a first-harmonic mode (rf operates with ion cyclotron frequency) with large duty factor; the number of turns in this mode is about 830, the frequency ranges from 24.4 Mc/sec down to 11 Mc/sec; (2) protons below 16 MeV are accelerated in a third-harmonic mode (rf frequency is three times the cyclotron frequency) with only 50 turns, i.e., very large turn separation; in this mode the cyclotron will be used for neutron time-of-flight work; (3) deuterons below 32 MeV are accelerated in a third-harmonic mode with 100 turns.

The central geometry is shown schematically in Figs. 1 and 2. The dee tips are broadened to obtain sufficient energy and radius gain on the first turns in the first-harmonic mode where the ions are injected at a very small radius. Source and puller are adjustable over a large range. A water-cooled, electrically insulated and movable slit for coarse beam selection, removal and measurement of unwanted ions is located in the valley to the right. A phase-selection slit with adjustable jaws in the lower dee serves to define the pulse length and radial width of the beam. The beam pulse selector is in the valley to the left of the ion source. The figures show the situation in the third-harmonic mode of proton acceleration which will be discussed here only from the point of view of short pulse formation. Other features of the central-region design for the NRDL cyclotron, in particular the situation in the first-harmonic mode of operation, will be described in detail in a future report.

Factors Determining the Pulse Shape and Energy Spread

The pulse length of the ion beam in the cyclotron is limited by the rf phase angle, during which the ions can be successfully accelerated, and is proportional to the rf oscillation period. Operating the rf on the third harmonic of the orbital frequency, as is planned for the NRDL cyclotron, reduces the pulse duration by a factor of three compared to first-harmonic acceleration. The acceptable phase angle, as well as the actual spatial shape and time structure of each ion "fish", are strongly determined by conditions in the center of the cyclotron. Major factors are the number of ions injected (per cm^2 sterradian) as a function of time, the initial energy spread and emittance characteristics (width and divergence) of the ion beam, space-charge effects, phase bunching,[3] energy gain versus time, and the ion-optical properties of the electric and magnetic fields (focusing conditions). The interplay of these factors is very complicated, and the theoretical analysis has to depend on single-particle dynamics as the current-density distribution, and hence space-charge effects, are not known exactly and difficult to calculate.

If particle interaction is neglected, Liouville's theorem can be applied in simple form stating that the volume occupied by the ion "fish" in phase space - defined by the space and momentum coordinates of the particles - remains constant; in particular, if only median-plane motion in the cyclotron is considered, the volume of a given small element $\Delta\Omega = \Delta r \Delta p_r \Delta\varphi \Delta p_\varphi$ does not change throughout the motion of the beam, even though its shape may change considerably. If no coupling exists between radial and azimuthal motion, the areas filled by the beam in the r-p_r and φ-p_φ plane, are each separately preserved. For a well-centered cyclotron beam the average azimuthal position, φ, is proportional to the time, t, and the kinetic energy, E_k, is essentially determined by the azimuthal momentum, p_φ; hence a small element $\Delta\varphi\Delta p_\varphi$ can be approximately transformed into an equivalent product $\Delta E_k \Delta t$.

With respect to formation of short pulses it is important to know the size (and shape) of the area the beam occupies in the energy-time plane as it represents, according to Liouville's theorem, an intrinsic limitation to the minimum pulse length obtainable (for a given energy spread). This intrinsic energy-time spread results from the finite width, divergence, and energy spread of the injected beam. Two particles leaving the source at the same time but differing in initial position and direction move on slightly different orbits, and, as a result, they may be separated in time (and differ in energy) at some later point along the trajectories, as is illustrated in Fig. 1. A displacement in the r-p_r plane is thus transformed into a spread in the E_k-t (or φ-p_φ) plane; a separation Δr in a uniform magnetic field, for example, produces a time difference of magnitude $\omega_e \Delta t = \Delta\varphi = \Delta r/r$, where ω_e is the electric angular frequency. This coupling effect between radial and azimuthal motion is of an oscillatory nature and, since it is roughly proportional to $1/r$, it is most pronounced in the central region and diminishes as the particles are accelerated to higher energies.

The coupling effect, in addition to the fact that the radial momentum may be quite large in the center, poses a limit to the applicability of Liouville's theorem in the E_k-t plane. For an estimate of the intrinsic energy-time spread evolving during the initial acceleration process the calculations must therefore be extended over a sufficient number of turns to the point where these effects have tapered off.

Results of the Computer Studies

The central-region calculations were carried out with the "Pinwheel" computer program which had been developed at Michigan State University.[4] Magnetic-field data used was obtained from model-magnet measurements and isochronized for the calculations. The field is practically uniform to a radius of 2 in. at which point the flutter amplitude starts to build up reaching 10% at 4 in. and leveling off to 40% at a radius of 8 in.; the spiral in this region is very small (only about 5°). The approximate electric field distribution, shown partially in Fig. 1, was obtained graphically by fitting together the known equipotentials of a standard dee gap and conducting-paper measurements in regions where two-dimensional approximation is allowed (source-puller gap). The spiral curvature of the dees was neglected and the acceleration gap was assumed to continue in straight fashion (see dashed lines in Fig. 2). The critical source-puller region, which determines the subsequent history of the beam, was studied separately using enlarged conducting-paper models (scale factor 20:1) with measured data points spaced close enough to avoid inaccuracies in the interpolation process. The ion trajectories were calculated from the source slit to the field-free region inside the puller and the final values of position, momentum, and time were then used as starting conditions for the subsequent motion in the main field. By suitable transformations (rotations and translations) any desired position of the source-puller system within the main field could be simulated.

On the basis of measurements by Murray, who found that the energy spread of the beam from a cyclotron-type ion source is of the order of a few electronvolts,[5] initial energies of 0 and 5 eV were assumed in the computer studies. The emitting surface of the plasma was considered to be flat and of the same potential as the surrounding source wall. Groups of four particles were started from each of several points across the slit aperture (see legend in Figs. 3 and 4): one with zero initial energy, the other three with 5 eV and initial directions of 0°, 45° and -45°, respectively. In a typical computer run five points were chosen (i.e., a total of twenty initial conditions), and starting phases with respect to the rf voltage were varied in 5° steps from -90° to 0° (peak-voltage phase). The distance between source slit and puller was kept constant at .5 in., the dee voltage was 100 kV, the central magnetic field 7 kG, the electric frequency 33 Mc/sec (these conditions correspond to the upper limit of the third-harmonic, low-energy proton mode).

The major results of the computer studies, which cannot be discussed in detail here, can be summarized as follows:

(1) Radial beam quality and energy-time spread of a group of particles are strongly influenced by the electric field between ion source and puller, in particular by the field gradient at the source output slit.[6] As seen in Fig. 1 and 2 the slit is slightly recessed and the source structure facing the puller forms a concave surface. Optimum conditions were achieved with a recess angle of 10° which produces a smooth, almost parallel, beam in the source-puller region with a focus in the

accelerating gap following the puller.

(2) The energy-time spread increases with the initial width of the beam; reduction of source slit width from .080 in. to .040 in. brought an improvement by a factor of 2. Under the conditions investigated .040 in. was about the optimum slit size as ions initially displaced by this amount experience energy-time spreads comparable to particles starting at a single point with $\pm 45^{\circ}$ divergence.

(3) The initial energy has only a small effect, if one compares ions of same starting position and direction: particles starting with zero energy experience practically the same motion as those starting with 5 eV in forward direction.

(4) A crucial parameter is, as one expects, the starting phase with respect to the rf during traversal of the accelerating gaps. Best behaved in every respect are the particles starting between -90° and -60° which are accelerated in the phase interval of maximum energy gain.

(5) Phase bunching occurs in the source-puller gap for ions starting close to -90°. Particles leaving the source in the time interval between -90° and -60° are compressed to 12° behind the puller slit. However, this compression does not prevail and during the subsequent motion the total pulse length for this group increases again to about 25°. Nevertheless, this portion of the beam was selected for final acceleration as the ions starting at later times suffer intolerable distortions in radial motion and, as a result, excessive intrinsic energy-time spreads.

The final computer results obtained for the optimum conditions are illustrated in Figs. 2, 3, and 4. In Fig. 2 the first three turns of the beam are traced schematically. Location and shape of the ion pulse transmitted through the slit system are marked at time intervals corresponding to a quarter of a revolution. The "beam" path and width is defined by the inner and outer envelopes of the pulse. The total radial cross section of the selected pulse varies between .050 in. and .200 in. on the two revolutions shown; the intrinsic radial width within the pulse is about a factor of two smaller. At the phase selector slit the location of the groups of particles starting at -90°, -60°, and -30° is indicated. Fig. 3 shows the radius (a) and energy (b) of the particles versus the rf phase, $\omega_e t$, at which they cross the x-axis, and the radial intensity distribution (c) at the end of the first turn. The groups starting at the same time are encircled, and the symbols mark the initial conditions as explained in the legend. The "shape" of the pulse as a whole (if no selector slits are employed) is schematically outlined, and the two horizontal lines at radii 4.600 in. and 4.725 in. represent the selecting action of a radial slit, .125 in. wide. The shaded lines define the approximate contours of the selected pulse, which has a total length of about 20° and a maximum energy spread of 13 keV. The intrinsic energy-time spread, i.e., the area occupied by this pulse in the E_k-t plane is approximately 80 keV deg. During the subsequent motion the spread increases to a value of about 140 keV deg on the third turn (reference time $\omega_e t = 2520^{\circ}$), as is shown in Fig. 4. The shape of the pulse as a whole in the energy-time diagram of Fig. 4. reflects the sinusoidal character of the energy gain as a function of time; the selected "fish" is riding on the peak of this sine wave. During subsequent acceleration to full energy this pulse in the energy-time diagram stretches out considerably: the particles which are 10° off the peak-energy phase end up with 1.5% (or 240 keV at 16 MeV) less energy than those riding at the peak. To the extent that Liouville's theorem applies in the energy-time plane the total "volume" of this stretched, thin filament, however, would still be about 140 keV deg as it was on the third turn.

An important question is how much current one can expect for operation with such short pulses. Cyclotron-type ion sources produce current densities of the order of a few hundred milliamperes per cm^2 of output slit aperture under dc conditions. If, for example, one takes a figure of 360 mA/cm^2 and assumes that the number of particles leaving the source in each accelerating half period of the rf is independent of the starting phase (saturated source output) one gets 36 mA peak current for a $.1 \times 1.0$ cm^2 slit and 3 mA average current for a pulse of 30° width. Selecting every hundredth pulse, as planned with the beam pulse selector, reduces this figure to 30 μA. Assuming a square-wave time distribution of the current density one can also determine the time-averaged radial density distribution along the beam path. Azimuthal "alignment" of the beam pulse and/or radial focusing produce peaks in the density curve, large radial amplitudes or defocusing would tend to "smear" out the intensity. Fig. 3c shows the current distribution at the end of the first turn. The shaded area marks the portion of the "beam" which is within the selected pulse. Fig. 4c illustrates the current distribution (of the selected pulse only) on the third turn.

The vertical motion of the ions has also been investigated. The calculations, which cannot be discussed in this short paper, showed that electric focusing is very effective and that no ion losses due to defocusing or overfocusing do occur within the selected pulse.

Conclusions

The theoretical investigations discussed in this paper indicate that it is possible to produce short ion pulses of high intensity, small intrinsic energy spread and good radial (as well as vertical) beam quality. Pulses of 20° (or 1.8 nsec at 33 Mc/sec) total length can be formed in the center of the cyclotron. The intrinsic energy-time spread of the beam emerging from the initial acceleration process is of the order of 150 keV deg (or about 12×10^{-9} keV sec for a frequency of 33 Mc/sec), allowing a time compression of the extracted pulse to fractions of a nanosecond by means of klystron bunching, as discussed in reference 1.

These calculations are in agreement with measurements at the Karlsruhe cyclotron where acceleration is accomplished in a third-harmonic mode at 33 Mc/sec, similar to the case discussed in this paper. The pulse length of the Karlsruhe cyclotron beam was found to be between 20^{o} to 30^{o} (total width) in the center,[7] and neutron pulses produced by the extracted beam had a half width of .9 nsec.[8]

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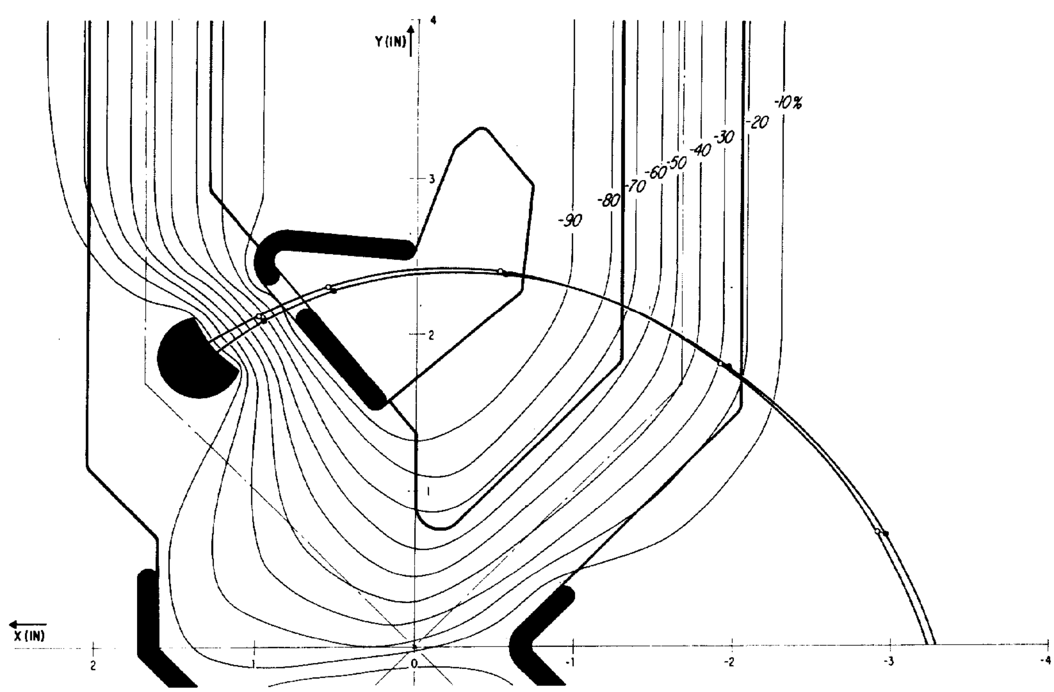

Fig. 1 Electric field configuration and typical particle trajectories near the ion source.

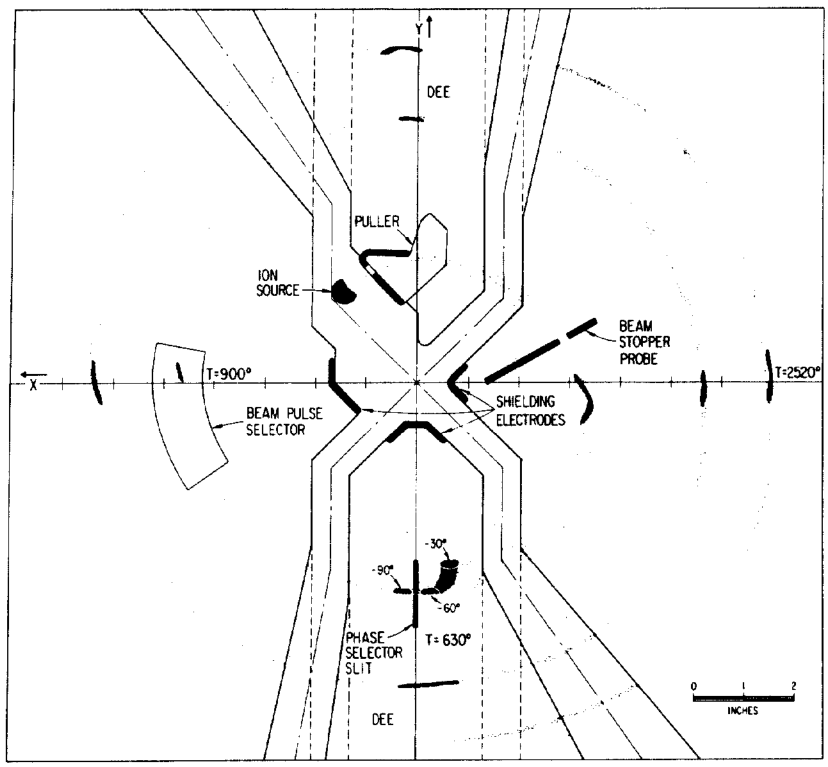

Fig. 2 Central geometry, beam defining system, and initial orbits of the ion pulses.

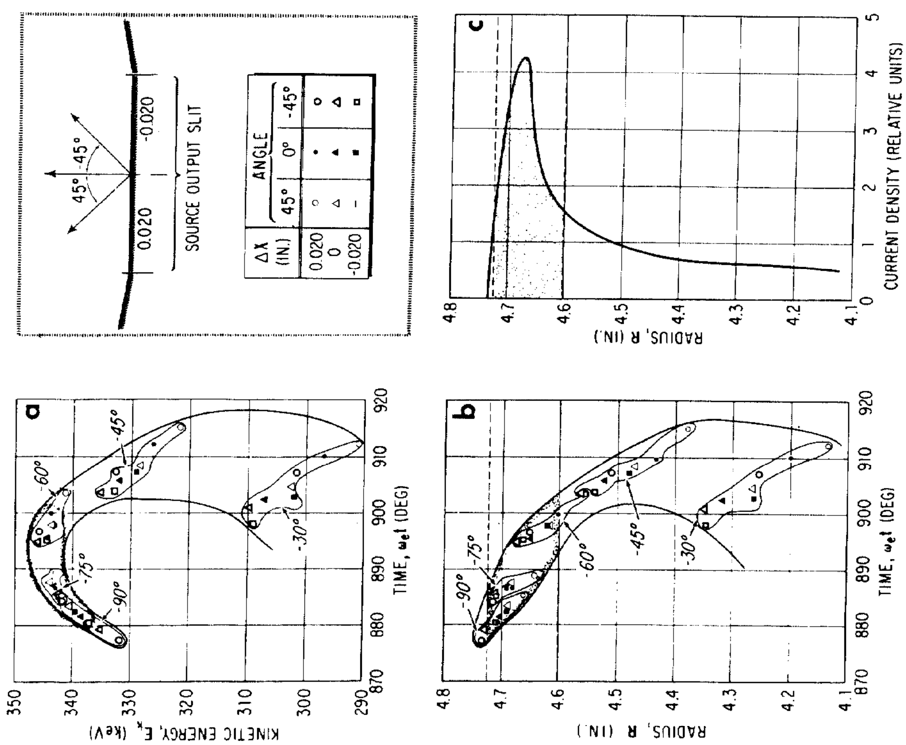

Fig. 3. Radius (a) versus RF phase, energy (b) versus RF phase, and radial intensity distribution (c) of the ion pulse at the end of the first turn.

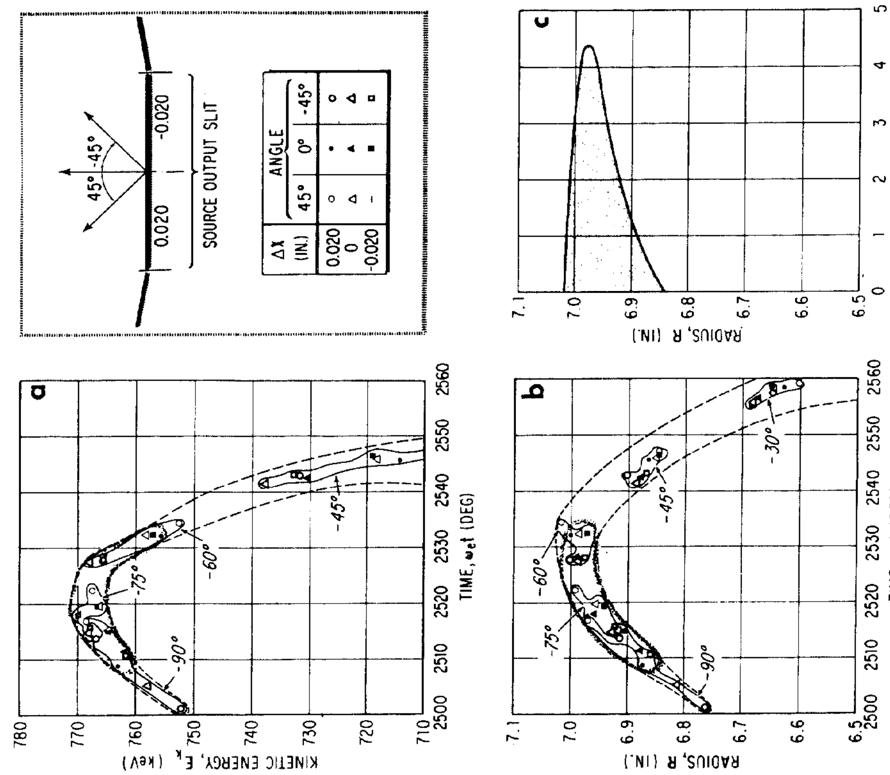

Fig. 4 Ion pulse characteristics on the third turn.