Title

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SPILL CONTROL AND INTENSITY MONITORING FOR THE BEVATRON-BEVALAC EXTERNAL PARTICLE BEAMS*

by

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I. SUMMARY

Time-intensity modulation in beam spill can be of primary concern in some experiments. The major source of this beam structure is from main-guide field-magnet power supply ripple. If the time constants are appropriate, then final control of beam structure can be accomplished by closed loop control of the intensity of beam spill. The response characteristics of the feedback system will determine the final structure. At high beam fluxes signal to noise ratio of beam detectors, in the feedback loop, can be improved by at least four orders of magnitude by using photomultiplier tubes and a water Cerenkov counter in place of the normal secondary emission monitor.

At beam fluxes below 10^{10} particles per second (PPS), a plastic scintillator and photomultiplier tube are used in the feedback system. A plastic scintillator and photomultiplier are also used in the beam as intensity monitors. At intensities below about 10^7 PPS standard counting techniques are used. For intensities between 10^6 to 110^9 PPS, the photomultiplier is used as a current source driving an integrating circuit which is then calibrated to read the number of particles per pulse.

II. Introduction

A. Experimental Requirements

The major purpose of a particle accelerator is to deliver high energy particles to an experimenter in a mode that is compatible with the needs of his experiment. The quantities of concern to the experimenter are:

1. The total number of particles delivered to his experiment. This determines the length of time to complete the experiment to the desired statistical accuracy.
2. The average rate of particles during the beam spill. This is the envelope of the spill and is determined by the method used to spill beam and the spill feedback control system if one is used.
3. The instantaneous peak rates during the spill. This is determined by the method used to spill beam and the variation of parameters that affect it such as main magnet field ripple or rf structure from the accelerating electrode. This fine structure except rf structure is hopefully controlled by the feedback system used to spill beam. However, as will be seen, the feedback system may introduce some fine structure of its own.
4. Beam spot size, spatial density and beam emittance.
5. Energy and energy spread; momentum and momentum spread.

Monitoring and control the first three quantities are discussed in this paper. Essentially all experimenters are interested in the number of particles per pulsed (ppp) and the pulse rate. The average and instantaneous rates of beam spill are mainly of interest to the experimenter doing a counting experiment. However a biological experiment which uses beam position scanning to get controlled dose distribution is also vitally interested in average and instantaneous rates (time intensity modulation) of beam spill.

The structure associated with the number of particles per pulse and the pulse rate constitutes the macrostructure of the beam. The instantaneous pulse rate is the beam microstructure.

One final point, I would like to define, is the concept of "DC" beam spill and the structure associated with individual particles in the beam. For convenience let's define the beam pulse width associated with a single particle as the width of the pulse from the particle detector. In our case, using a scintillator and a photomultiplier with a clipping line, this width is 10 ns. A preliminary definition for "DC" beam is uniform rate of particle spill. If we consider the spill over a period of one second, then we have one particle every 10^{-12} s for a spill of 10^{12} particles and one particle every 10^{-6} s for a spill of 10^6 particles. For the case of 10^{12} ppp, we will have 10^6 particles per 10 ns the width of our beam detector. We obviously cannot resolve this detail. However any counter experiment taking 10^{12} is counting the secondary particle flux from a target, so his flux is of the order of 10^4 to 10^6 ppp. With a counter pulse width of 10 ns, we could theoretically count 10^8 ppp for a uniform beam spill. With particles flux of 10^6 ppp we would only be counting one one hundredth of the time. This is for an ideal counter and ignores statistical fluctuations. We can therefore allow some variation in the arrival time between individual particles as long as we don't get two particles within our 10 ns counter resolution.

Each experimenter has a resolution time associated with his experiment. The beam can be considered "DC" as long as two beam particles do not appear within the resolution time of the experiment. A "DC" beam therefore appears as a picket fence with some modulation of space between pickets allowed. With this picture of a "DC" beam, we can talk meaningfully of a "DC" beam from 2 ppp to 10^{12} ppp or above. This concept will be considered when discussing closed loop spill control.

B. Bevatron-Bevalac Facility

The Bevatron is a weak focusing synchrotron with four 90 degree curved sections of 15.22 meter radius of curvature (gap ℄) and four straight sections 6.1 meters long. There are three injectors: a 19 MeV proton linac (5 MeV/u for heavy ions e/m = 0.5); a 50 MeV proton linac; and the SuperHILAC for heavy ions from carbon through argon with eventual operation planned up to Krypton. (8 MeV/u). These facilities have been described previously.[1]

A peak magnetic field of 15.5 kG, yields of 6.2 GeV kinetic energy and heavy ions (e/m = 0.5) of 2.7 GeV/u. The normal operating peak magnetic field of 12.8 kG allows operation with a two second flat top at a kinetic energy of 4.9 GeV for protons and 2.1 GeV/u for heavy ions (e/m = 0.5) at 10 pulses per minute. The type of particles accelerated and the peak number per pulse are shown in Table I.

Table I. Number of ions per pulse available in external beam channel from 20 MeV proton linac and projected levels from SuperHILAC.

Ion	20-MeV Proton Linac	SuperHILAC Bevalac Mode
^{1}H	710^{12}	——
^{4}He	2×10^{10}	——
^{12}C	10^8	3×10^{10}
^{14}N	10^7	2×10^{10}
^{16}O	1.5×10^7	1.5×10^{10}
^{20}Ne	10^5	10^{10}
^{40}Ar	——	4×10^8
^{56}Fe	——	7×10^4

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Essentially all the experiments are now done in the External Particle Facility.[2] Beam is extracted from the synchrotron using a $\nu_R = 2/3$ extraction system.[3,4]

III. Beam Detectors

In normal operation of the Bevatron-Bevalac, we span a kinetic energy range from 250 MeV/u for biomedical experiments to 4.9 GeV protons or 2.1 GeV/u heavy ions for nuclear science and high energy physics. The number of particles varies from about 10^3 to 10^{13} ppp depending on the nature of the experiment. This ten orders of magnitude change in intensity required substantial changes in beam detection equipment both for intensity measurement and for feedback control of the resonant extraction system from the original secondary emission monitors (SEM) used for high intensity proton beams.

If the detector is to be placed directly in the beam, then four problems must be considered. First the detector must be linear over at least three or four decades of beam intensity to be useful. Second at high beam fluxes radiation damage and auto-activation determine useful life times of the detector. Third background radiation in the area can create both lifetime problems (radiation damage) and signal to noise ratio problems. Fourth the detector must be thin enough to minimize energy spread increase and secondary particle contamination of the beam.

The SEM has been the standard beam detection device in most high intensity proton accelerators. The nominal secondary electron production is 2 percent per surface ($\beta \sim 1$, $e/m = 1$). The SEMS at the Bevatron have five collecting foils or ten surfaces. For 10^{12} protons over a one second spill, this gives an average current of 3.2×10^{-8} A. If the particle flux is reduced an order of magnitude the current from the SEM is reduced an order of magnitude.

A photomultiplier (PM) tube, such as the RCA 8575, can deliver an average current of between 1×10^{-6} A to 200×10^{-6} A depending on stability required and still remain linear. This current can be increased by an order of magnitude by the use of "after burners" or separate high current source for the final four stages of the photomultipliers. A self tracking solid state modification of the P.M base circuit is under trial at the Bevatron and hopefully will eliminate the operational problems of having to have and adjust two power supplies.

The high current capability of the P.M over the SEM made it highly attractive as a device to monitor beam intensity with a much improved signal to noise ratio. Preliminary tests were made using a liquid Cerenkov counter and P.M looking at secondary particles from the septum of the first magnet in the extraction channel. The duty factor (microstructure) for the experiment being run at the time, went from 10 percent with the SEM to 50 percent using the P.M signal to control beam spill. This improvement provided sufficient incentive to start a development program using a P.M in the beam monitoring circuits. An additional advantage of the P.M. is that the same current output can be maintained over the full range of intensities by adjusting the P.M high voltage and by suitable choice of particle detectors.

Polyvinyl toluene plastic (Pilot "F") scintillators, 0.125 in thick, are used up to beam fluxes of 10^{10} ppp. At about 10^8 ppp the photocathode saturates and the P.M output becomes non-linear. The P.M can be made linear again by restricting the light reaching the photocathode. This has been done by irising the light pipe. Neutral grey filters have been considered but have not as yet been tried.

At fluxes above 10^{10} ppp radiation damage to the scintillator starts to be of concern. Both reduced light output and radiation damage were solved by constructing a thin 0.125 in. thick water cell with 0.003 in. thick aluminum windows. The Cerenkov light from the water is collected from the edge of the cell by multiple reflection. The light outputs is down by about 10^6 compared to an 0.125 in. plastic scintillator.

The cell is constructed by making a picture frame of 0.125 in. thick lucite. Aluminum foil is then glued to the frame and backed with 0.062 in. aluminum window frame as a structural clamp. The edges of the frame are polished. One edge can be cemented to a light pipe and then to the P.M. Thin tubes enter the cell through the edge, one at the top and the other at the bottom of the cell. These provide water flow in and out of the cell for filling and for thermal expansion and contraction of the water. Plastic tubes attach the cell to two water bottles. This also allows for removal of gas from hydrolysis of the water. A circular cell is shown in Fig. 1. This cell was designed to work in a reflective box rather than being attached to a light pipe. In this case the edges must be bevelled to allow light to escape from the cell (critical angle of refraction).

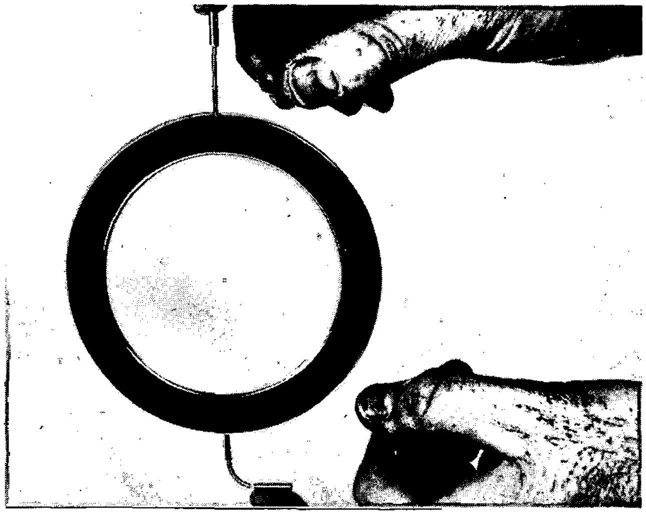


Fig. 1. Thin water Cerenhov cell.

The plastic scintillator and water cell provide adequate beam detectors over the full operating range of the Bevalac. We have some remaining problems that are associated with our specific machine operations and the confined space in which to place the detectors. If the plastic scintillator and light pipe are pulled back out of the beam but left in place, the plastic light pipe will brown from background radiation when we operate at high proton fluxes ($> 10^{12}$ ppp). Tests with a lightly browned T.V. camera lens showed a 20 percent reduction in transmission of white light but a 90 percent reduction in transmission of blue light which is the region of operation of T.V. vidicons and P.M. tubes.

To eliminate the light pipe problem, a reflective box has been constructed. The P.M. tubes then collect light from direct and multiple reflection within the box. Only the plastic scintillators and water cell have to be moved in and out of the beam. This installation will be tested when machine operation is resumed.

IV. MONITORING THE PHOTOMULTIPLIER SIGNAL

A. Intensity Monitoring

The P.M. signal is used in two modes of operation. At low fluxes 10^3 to 10^7 ppp, standard counting techniques are used for beam intensity monitoring. The P.M. output goes to a 300 MHz Mecl discriminator and then to a times 10 prescaler. The discriminator is placed as close to the P.M. as possible to minimize pluse width broadening. A clipping line at the P.M. clips the pulse to 10 ns base width at the discriminator. The prescaled by 10 signal is then sent to a scaler in the main control room (MCR). If unclipped and sent directly to the MCR, the pulse would be about 40 ns wide. The signal cables and H. V. cables are run together in a special cable run to the MCR to minimize noise pickup. The signal cables are RG 213 u to minimize pulse width broadening.

We have achieved counting of nearly 10^7 ppp over a 1500 ms beam spill. Depending on beam spill length and microstructure, the scaler counting of beam particles usually goes non-linear at between 2×10^5 to 10^7 ppp.

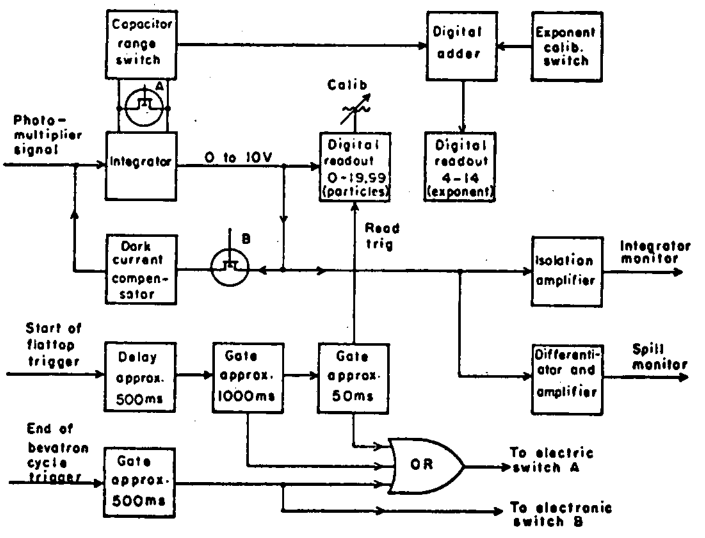
Our SEM produces a usable output at about 10^9 protons per pulse. The usable output from the SEM for various ions assuming a z^2 relationship and constant β is shown in Table II.

Table II. Detectable ion threshold of LBL SEM in particles per pulse (ppp).

	Particle					
	Ne	O	N	C	He	H
Charged (+)	10	8	7	6	2	1
ppp($\times 10^7$)	1	1.6	2.0	2.7	50	100

To cover the region of 10^5 to 10^9 ppp, we have chosen to use P.M. and integrator circuits. The P.M. is now looked at as a current source rather than a pulse out for a particle through. As a current source, the output is no longer calibrated but can be made proportional to the number of particles.

The integrator provides six decades of range by switching the integrator capacitor. The output of the integrator is read by a digital voltmeter. A separate two digit readout gives the scale of ten the integrator is set to read. This is set to read the correct range at the calibration point and then tracks range scale when the integrator capacitor is switched. (See block diagram below).



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Calibration is accomplished at the low intensity end by reducing the beam level until the scaler P.M. signal is linear. The HV on the integrating P.M. is then adjusted until the digital voltmeter readout corresponds to the scaler read out. The integrater output now reads particles per pulse. The output from the integrator will now be linear until the P.M. saturates; either current saturation in the final stages or saturation at the photocathode.

The integrating P.M. can be calibrated at the upper end in the same manner by comparing it with the SEM reading.

B. Beam Shape Monitoring and Spill Control

For beam shape monitoring and spill control, the P.M. are operated as current sources for all intensity levels of beam.

Beam extraction from the Bevatron is from radial betatron phase space using the two thirds resonance. The resonance is driven by a two part perturbation. a time constant part P1 and a time variable part S1.. The value of S1 determines what fraction of radial space is still stable for betatron oscillations. If the radial distribution of particles is the same at 10^3 ppp as at 10^{12} ppp, then for a given value of S1 current the same fraction of beam will have been extracted for either case. The output signal level from the P.M. to the spiller control chassis which controls S1 current must therefore be the same value independent of the total number of particles accelerated. This P.M. output level is controlled by adjusting the P.M. high voltage and by appropriate selection of beam detector. Plastic scintillators are used for beam levels from 10^3 to about 10^{10} ppp. The range from 10^{10} to 10^{13} ppp is spanned by using the thin water Cerenkov counter.

If the charge (ϕ) from the P.M. is proportional to the number of primary particles (N) passing through the detector we have $\phi = KN$. In the region of 10^5 to 10^8 ppp K is a constant for our P.M. and plastic scintillators. Between 10^8 and 10^{10} ppp K is a slowly decreasing function unless we attenuate the light. In the region where K is slowly changing the detector is unsuitable as a beam intensity monitor. It is however quite usable as a signal monitor for the closed loop spill control as dQ is still proportional to dN.

One final point should be made regarding background radiation and light attenuation to the P.M. At the Bevatron we have a general background radiation flux near the accelerator of the order of 10^5 particles per cm^2 for 10^{12} protons extracted. In going from a plastic scintillator at 10^6 ppp to a water Cerenkov counter for 10^{12} ppp we have provided a light attenuation of about 10^6 to maintain the same output current from the photomultiplier. At the same time we have raised the background radiation flux by 10^6. The background flux through the P.M. and light pipe now give a current output that is approaching the P.M. current output from the Cerenkov light. The best signal to background ratio we have been able to achieve is ten to one. Radiation shielding of the P.M. can improve this but is very inconvenient. However it is not as bad as it may seem because the background flux rate is proportional to the beam extraction rate so even the background is a usable signal for closed loop control. However the background rate may change near the detector because of beam scraping in the transport channel caused by changes in beam position. The feedback system will then convert this to a real intensity modulation.

V. BEAM SPILL STRUCTURE

The radial extraction system is sensitive to radial position changes of the order of 0.001 in. Changes in the reference voltage from the spiller control chassis to S1 magnet of the order of 0.001 mv correspond to changes to position of radial stability of the order of 0.001 in.

Magnetic field ripple in the main guide field is controlled by passive filters in the M.G. Room and dynamic ripple reduction[5] windings on the pole tips.

Because of asymmetries in the ripple components in the four main magnet quadrants, there is a distortion of the closed orbit as well as a simple change in radius of curvature.

Betatron acceleration from ripple in the net enclosed magnetic flux causes additional changes in particle radius. As a result of these two effects, changes in radial beam position at the location of the perturbation magnet are a complex function of the main magnet ripple field. To correlate ripple structure with main magnet ripple, it is more fruitful to check for coherence with main magnet current than detailed comparisons by harmonic analysis of the signals. This is accomplished by putting the beam monitor signal, showing the beam structure, on an oscillascope and using M. G. synchronized multiple triggers. Pictures of multiple sweeps are then checked for co-herrent structure. Figure 2. When the gain of the closed loop feedback is sufficiently high, there is no structure that is strongly coherent with the M.G. power supply. Figure 3. The remaining structure is not coherent with line frequency[5] so cannot come from the other power supplies associated with the extraction system. The remaining structure is then characteristic of the spill control system.

Budgetary restrictions on Bevatron operation have made it difficult to collect consistent sets of data. Much of the data has been collected during normal operation for experiments. The freedom to vary parameters controlling the beam spill was therefore very

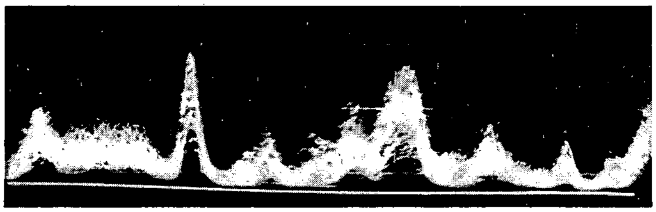

Fig. 2. Beam structure coherent with main magnet field ripple sweep 1 ms/cm.

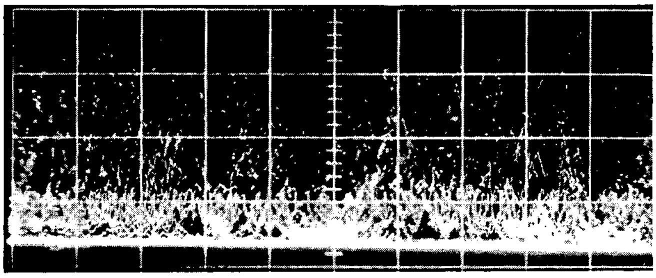

Fig. 3. Coherent beam structure removed by closed loop spill control sweep 1 ms/cm.

limited. The following discussion on beam structure and control is therefore a composite picture rather than the result of a series of carefully controlled experiments. Those experiments are scheduled and will be done when machine operation time is available.

At low energy operation, such as for the Bio-medical runs, the radial width of the beam is too great to allow for normal resonant extraction using S1 currents to control the spill rate. An operating mode was found that allows the beam to be moved radially into the perturbation. This radial shift as a function of time is normally done by ramping the main guide field with the rf voltage turned off. Macrostructure for this spill mode is shown in Fig. 4. The macrostructure for a beam spilled with closed loop feedback is shown in Fig. 5.

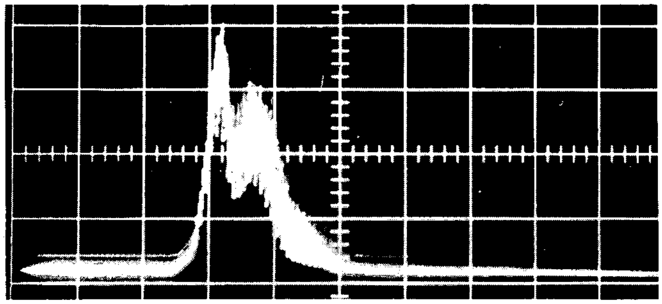

Fig. 4. Beam spill shape with ramped main guide field.

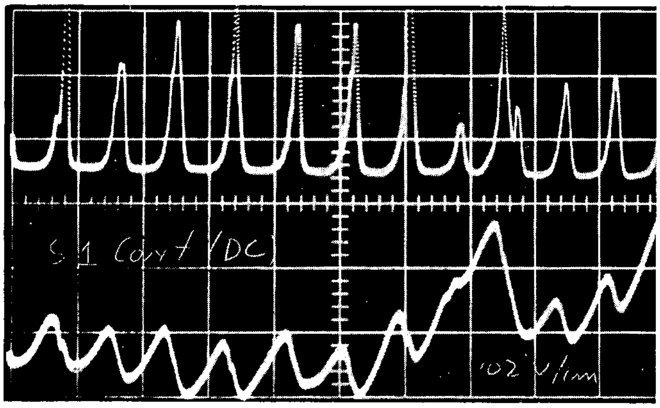

Fig. 5. Correlation of beam spill structure (upper trace) with s1 control signal (lower trace) sweep 1 ms/cm.

The beam spill feedback system can eliminate M.G. synchronized ripple structure. However, it does not always control the ripple. It is not clear at present whether there is a malfunction in the dynamic ripple reduction circuits which we have not as yet located or whether the ripple reduction equipment must be balanced against the betatron effect to minimize beam structure.

When the spill feedback system is able to control M.G. ripple structure, we have structure as shown in Fig. 6. Here the spill tracks the request for spill as shown by comparing spill structure with the lower trace which is S1 control signal. The spill continues after S1 has reached its peak value and contues as S1 tries to turn the spill off. If the gain in the spill control circuit is increased the spill gets higher and shorter. The times between pulses remaining the same.

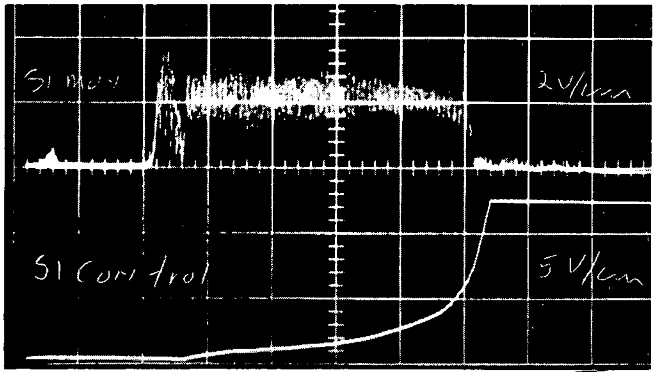

Fig. 6. Beam spill off the base line (upper trace) s1 control signal (lower trace) sweep 200 ms/cm.

At this stage one might become discouraged and feel that there is a basic mechanism in the extraction system that produces this structure. Similar structure has been observed at the Bevatron when extraction from rf phase space, into the Piccioni extraction system, by lowering the rf voltage. However as can be seen in Fig. 5. we can at times achieve good spill with little microstructure. Beam spills for normal operation a few years ago had less microstructure than we have today. Recent experiments have been operated in the primary beam while previous experiments have been done predominantly in secondary beams. The major change between these two modes of operation is that experiments operating directly in the primary beam are much more concerned with positional stability of the beam. This has been accomplished in general by lowering current in the perturbation magnet P1. Preliminary tests show different structure as the value of current in P1 is varied. Presumably the net slope of the perturbation at the point of extraction is going to control the rate of extraction: This effect is under study, both with more detailed calculations around the point of extraction and more machine measurements.

References

1. A. Ghiorso, H. Grunder, W. Hartsough, G. Lamberton, E. Lofgren, K. Lou, R. Main, R. Mobley, R. Morgado, W. Salsig, F. Selph, The Bevalac - An Economical Facility for Very Energetic Heavy Particle Research, presented at Particle Accelerator Conference, March 5-7, 1973, San Francisco, Ca.

2. T. Elioff, K. H. Lou, R. C. Sah, Bevatron External Proton Beam Facilities, Proc. of the 1971 Particle Accelerator Conference, Chicago, Ill., pg. 795, 796.

3. Y. M. Baconnier and G. R. Lambertson, Resonant Extraction Studies for the Bevatron, Lawrence Radiation Laboratory Report UCRL-17604, presented at Sixth Internation Conference on High Energy Accelerators, Cambridge, Mass., 1967.

4. R. W. Allison, Jr., H. A. Grunder, and G. R. Lambertson, Handling Field Nonlinearities in the Bevatron Resonant Extraction, Lawrence Radiation Laboratory Report UCRL-19213, presemted at 7th International Conference on High Energy Accelerators, Yerevan, Armenia, USSR, 1969.

5. K. C. Crebbin, W. A. Wenzel, W. H. Vogel, H. D. Lancaster R. M. Johnson, Bevatron Operation and Development XXXIV, May, June 1962, April 4, 1963, UCRL-10613.

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