Particle Accelerators, 1970, Vol. 1, pp. 79–92

HEAVY IONS AND HIGHER PROTON CURRENTS PROPOSED FOR THE PRINCETON-PENNSYLVANIA ACCELERATOR

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The Princeton–Pennsylvania Accelerator (PPA), because of its original design specifications, is uniquely suited for use as a heavy ion accelerator. With the improvement of the vacuum system and other relatively minor modifications, very heavy nuclei could be accelerated to an energy of 6–8 MeV per nucleon and with currents sufficient for the search for the stable, superheavy transuranic elements predicted by theory. The addition of a small booster synchrotron (PPB) to inject protons at 75 MeV would raise proton currents by a factor of twenty to 10^{12} per pulse or 2×10^{13} per second. The same booster would make possible the acceleration of fully stripped ions to very high energies by two successive acceleration steps in the PPA. The PPA coupled with the presently designed booster could produce krypton with 900 MeV per nucleon or 76 BeV total. In principle the PPA could accelerate uranium to 191 BeV. At such high energies one may expect some coherent production of particles whose thresholds lie above the free nucleon–nucleon collision energies. Also one would expect the formation of shock waves in nuclear matter.

1. INTRODUCTION

When the Princeton–Pennsylvania Accelerator was first proposed in 1955 it was pointed out that eventually there would be interest in accelerating such ions as carbon to the multibillion volt range of energies. The reasoning behind this prediction was, simply, that depositing so much energy in a complex nucleus in this manner was quite different from the case where a single nucleon carries in the energy and therefore one might find new phenomena taking place. While we hope to try this experiment in the near future our ultimate goal is now much more ambitious. We would like to accelerate fully ionized heavy nuclei, e.g., xenon, uranium, to the highest energy attainable with the PPA which, for fully stripped xenon is 120 BeV and for uranium is 191 BeV. Even though the energy per incident nucleon for these heavy nuclei is only about 800 MeV, and therefore, at first glance, not high energy in the elementary particle sense, one may expect some collective effects, in addition to the much more probable single particle phenomena, which could prove to be of great interest. For example a shock wave in nuclear matter might be formed leading to the production and ejection of mesons by multiple collisions. To the extent that the nucleons in the heavy nucleus behave coherently one may hope to see new elementary particle phenomena with energy thresholds higher than anything thus far observed.

The deposition of 10–100 BeV in a nucleus by the almost simultaneous impact of many nucleons will heat up nuclear matter to temperatures and densities which are believed to have existed in the Primeval Fireball.(1) While the high temperature so induced will last only about 10^{-22} seconds, this is long enough to yield information about the behavior of matter in the primitive stages of our universe. One need not believe in the Big Bang theory to appreciate the importance of studying nuclear matter in a very highly excited state far removed from anything thus far produced in the laboratory.

An immediate, much lower, heavy ion energy goal, is set by the current interest in making the superheavy transuranic, stable elements predicted by theory, but thus far not observed. For this field of research one needs only modest energies sufficient to overcome the Coulomb barrier, e.g., around 6–8 MeV/amu. It is not clear which projectile and target nuclei would have the best chance of forming these superheavy nuclei in the region around $Z = 114$; so it is necessary to keep the accelerator parameters sufficiently flexible to accommodate everything from about calcium to uranium. Since neither the cross sections for formation, nor the lifetimes are precisely calculable, and estimates vary over a wide range, it is difficult to set a lower limit on the beam current which will be needed. However, one can show that 10^{10} particles per second is sufficient for many exploratory experiments. The proposed improvements to the PPA will provide 10–20 times this current.

Our plans call for boosting the PPA proton

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current by a factor of 20–30 and this also fits into our heavy ion planning, especially the acceleration of fully ionized krypton and eventually xenon and uranium. For some time it has been clear that the PPA would benefit greatly by a boost in proton current from the present 10^{12} per second to about 25×10^{12} per second. At this current, and at our proton energy of 3 BeV, our pion flux, even in the low energy range of 200–300 MeV, would be competitive with meson 'factories'. At higher pion energies the PPA flux would be much more intense than that of these low energy accelerators. Our method for increasing the PPA proton current, now limited by vertical instability due to space charge in the synchrotron, is to inject at 75 MeV rather than our present 3 MeV. The booster synchrotron which would accomplish this could also be used to inject heavy ions, in a partially stripped state, into the PPA. However, its main contribution to the heavy ion acceleration process would come later after the partially stripped ions are accelerated in the PPA to top magnetic field. At this point the ions would be sent through a stripping foil or gas to produce 100 per cent stripping. After full stripping the ejected ions would be sent back into the booster synchrotron for temporary storage before being reinjected into the PPA which, meanwhile, was recycled to low magnetic field.

An essential prerequisite for accelerating heavy ions in a synchrotron is a very good vacuum in the 10^{-9} torr range. Without this major vacuum improvement there would be an intolerably large loss of beam due to charge changing electron capture and loss phenomena during acceleration. Again there is a favorable interaction of our desire for higher proton currents and for heavy ions. The intense proton beam essentially requires us to replace our present epoxy-fibreglass chamber by a radiation hard, ceramic chamber, and this is also needed to reach the 10^{-9} torr range required by heavy ion acceleration. Furthermore, even without obtaining an increase in beam current we have already made lans to replace the original epoxy chambers by modern, more maintenance-free, ceramic chambers.

2. THE PPA AS AN ACCELERATOR OF HEAVY IONS

It is an inherent feature of a synchrotron that it is capable of accelerating a particle with any charge-to-mass ratio provided only that the rf system has a sufficiently flexible frequency range. Since the PPA was designed to accelerate protons from 3 MeV injection to 3 BeV final, the rf swing is already 12 : 1 and a modification for deuterons and α-particles now being installed will soon raise the swing to 24 : 1. The task of matching the rf swing to various values of charge-to-mass ratio is made much easier by the ability to use different harmonic ratios between the particle frequency and the acceleration frequency.

The ease of acceleration of any particle, regardless of charge state, coupled with the large $B \cdot \rho$ of the synchrotron magnet, simplifies the task of designing an ion source suitable for producing ions of a given type in a charge state high enough to reach the energy range of interest. For example, to attain an energy of 7 MeV/amu, which is suitable for the $Z = 114$ search, requires only Ca^{2+}, or Xe^{4+}, or U^{7+}, whereas most other accelerators typically require considerably higher charge states. In general the higher charge states are more difficult to produce at the desired intensities.

Since in a synchrotron there is no unique momentum or velocity requirement for injection, a variety of injectors may be used ranging in energy from a few to many MeV, provided that the emittance and energy spread are suitably small. The present PPA injector is a 3 MV Van de Graaff. We are planning on inserting a small, fast cycling booster synchrotron between the dc injector, e.g., the Van de Graaff, and the PPA. The booster, used as a heavy ion injector into the PPA permits the ion source to be as low as 750 kV from ground, a voltage low enough to make feasible the construction of a very large, air insulated, high voltage terminal within which a large, heavy, high power ion source could be located. The space and power available for the ion source would be sufficient to accommodate almost anything thus far proposed for making highly stripped heavy ions. Also an ion source to produce polarized protons and deuterons could be accommodated.

3. THE VACUUM REQUIREMENTS AND DESIGN OF THE VACUUM SYSTEM

3.1. *Vacuum required for heavy ion acceleration*

The vacuum requirements of a heavy ion synchrotron are more demanding than those of linear accelerators because of the greater distance travelled by the ions in reaching high energy. Unless the vacuum is very good an ion can pick up, or lose, one or more electrons from the residual gas thus abruptly changing its charge state. The PPA, being fast cycling at 10–20 Hz, gets the ions up to full energy in about 2 per cent the distance typically encountered in the more conventional slow cycling proton accelerators. For this reason the PPA can tolerate a vacuum about 50 times poorer than can these accelerators. As shown in Sec. 3.2, at 10^{-9} torr in the PPA, there will be at least 50 per cent survival of the heaviest ions to full energy. While this is not an easy vacuum to attain it is feasible in the PPA because the chamber cross section is only about 6 × 29 cm, a size which lends itself to the use of ceramic sections.

3.2 *Calculation of heavy ion transmission efficiency*

Beam losses due to a change of charge of an ion when passing through the residual gas in the vacuum chamber have to be estimated so that vacuum requirements can be established. The beam transmission is given by the expression(2)

$$\frac{n}{n_0} = \exp\left[-10^{27} p \int_0^T \sigma_{\text{tot}}(\beta)\beta \, dt\right]$$

where p = pressure in torr
$\sigma_{\text{tot}}(\beta)$ = sum of the cross sections for electron loss and electron capture, in cm^2/atom
$\beta = v/c$
T = acceleration time.

As there are no available data at our energies for electron loss and capture cross sections, semi-empirical expressions have to be used based on experimental results at lower energies (up to 1 MeV/amu) and assuming that the charge distribution in a beam when passing through a stripping medium is known. Calculations have been performed for some heavy ion species; results show that the average value of the product $\sigma_{\text{tot}} \cdot \beta$ is not larger than a few times 10^{-17} cm^2. Beam transmissions at different pressures in the vacuum chamber have been estimated from the expression above by using the value $T = 20$ msec for the acceleration time in the PPA and an average value of $2 \cdot 10^{-17}$ cm^2/atom for $\overline{\sigma_{\text{tot}} \cdot \beta}$. Taking into account unavoidable errors in the calculation of the electron loss and capture cross sections, it follows that an average pressure of 10^{-9} torr in the vacuum chamber should assure heavy ion beam transmission efficiencies of at least 50–80 per cent; for many ions transmission efficiency would be even higher.

3.3. *The vacuum system design*

A vacuum, averaged around the 24 m diameter ring, of 10^{-9} torr would not be too difficult if we could rebuild everything. However, this being impracticable we must consider what minimum changes will achieve the desired result. Experience has shown that the main problem is the outgassing of water vapor from all surfaces, assuming that the system uses only ceramics, metal and metal gaskets. Obviously a liberal use of liquid nitrogen cooled surfaces is essential and possibly even gaseous helium cooled (20 °K) surfaces in certain situations. Outgassing by heating all surfaces to 125 °C will substantially shorten the pumpdown time. Ideally it would be worthwhile to replace our present oil diffusion pumps, of which there are 30, 6-inch CEC using Santo-Vac No. 5 pump fluid, by sputter ion pumps. These 'dry vacuum' pumps are not only more foolproof than oil diffusion pumps, but they have no oil backstreaming problem. However, in our experience over 5 years, we have never had either a catastrophic or a slow deterioration of vacuum in the 10^{-7} torr range due to backstreaming. It is our belief that inserting liquid nitrogen 'opaque' baffles between pumps and chambers will reduce the backstreaming problem, if there is one, to negligible proportions, even in the 10^{-9} torr region. Nevertheless, if funds become available in time we would prefer to use only dry vacuum pumps.

Since the 16 vacuum chambers within the magnet pole tips constitute 70 per cent of the total circumference of 75.5 m, it is essential that they achieve as good a vacuum as possible, preferably in the 5×10^{-10} torr region. The problem is made difficult by the necessity to avoid large metal areas in which strong eddy currents would be induced by the rapidly changing synchrotron magnetic field. Even stainless steel 0.002 cm thick, in large areas, would run very hot and, even worse, drastically perturb the magnetic field shaping.

We have solved our problem by building a ceramic chamber composed of 11 sections, each 30 cm long, joined together by a metal ring which is furnace brazed to the end of each ceramic section. This joint is vacuum tight and slightly flexible. These 11 sections are clamped to a curved, stainless steel support, taken from the old epoxy chambers, which also serves as the front spacer for the magnet pole tips. A photograph is shown in Fig. 1. This chamber has been pumped on the test stand to $5 \pm 3 \times 10^{-10}$ torr using a single 6-inch CEC oil diffusion pump and a liquid nitrogen 'cold finger'. Only 4 days 'baking' at 125 °C were required to reach this vacuum. Mass spectrometer analysis of the residual gas showed it

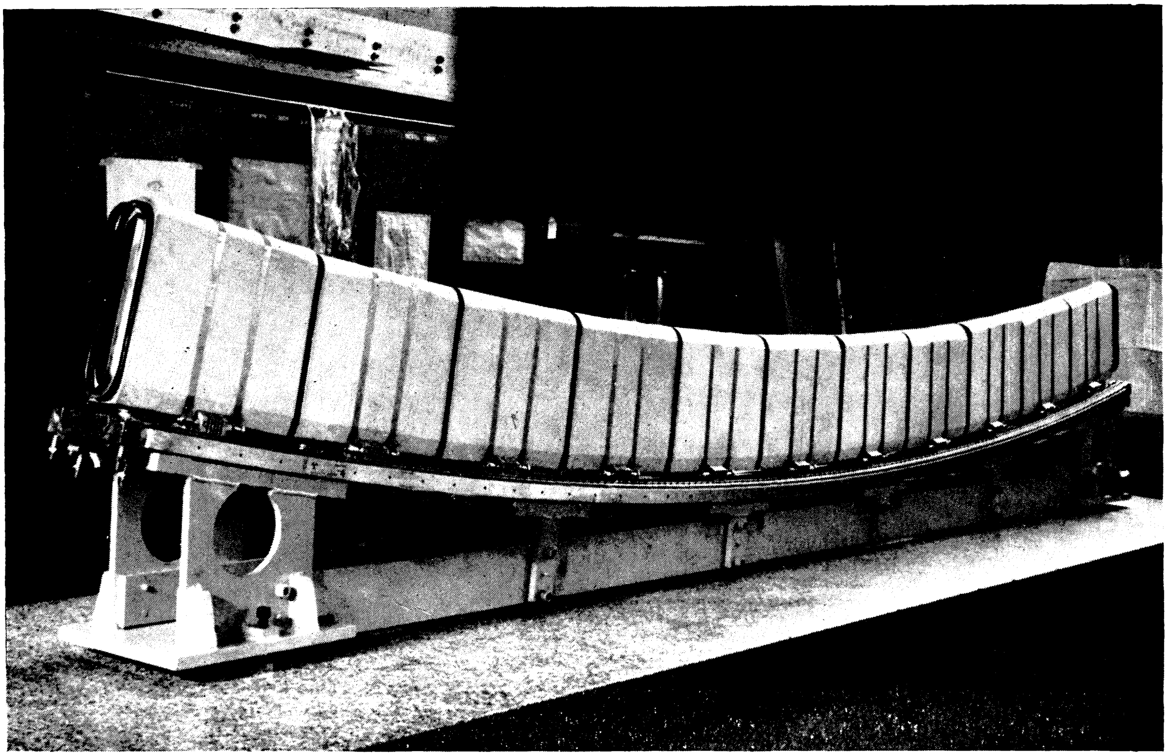

FIG. 1. Ceramic vacuum chamber with the support.

to be mass 28, probably CO; all other partial pressures were below the detection limit of the instrument, which is about 3×10^{-10} torr. It therefore would appear that we have a practicable solution to this section of our vacuum problem. The first chamber is now installed in the synchrotron where it has operated with no difficulties. No attempt has been made to reach 10^{-10} torr however. The remaining parts of the synchrotron vacuum chamber consist largely of metal boxes with metal 'O' rings, as in the injection and target sections, or ceramic and metal tubes as in the rf cavities. Perhaps the most troublesome section, at present, is the external beam extraction magnet which exposes to the vacuum considerable area of magnet laminations and epoxy insulated, water cooled current conductor. A new and simpler magnet has been designed which gets around all these problems while at the same time eliminating the radiation damage which might occur at high proton currents.

4. ION SOURCES AND INJECTOR

4.1. *Requirements for a heavy ion source*

The present proton ion source in the Van de Graaff is capable of delivering pulsed beam currents of 10–20 mA, although only a few mA are enough to fill the PPA up to its incoherent space charge limit. The proposed booster will require a more intense proton beam at injection. Space charge calculations have shown that 350 mA turns would be necessary to fill the booster to the limit of the vertical incoherent instability. At present, reliable and compact proton sources are available which can produce pulsed proton beam currents of up to 50 mA, with a pulse duration of 10 μsec, corresponding to a 10-turn injection. More advanced types of duoplasmatrons can yield up to 500 mA, enough for single turn injection into the booster. Very low values of the beam emittance have been reported, so that a good match to the booster acceptance should be expected.

Heavy ion source requirements are more complex. They will be determined by the usual injection parameters of the preinjector, the booster, the PPA, space charge limit, six-dimensional phase space acceptance, and by additional factors, such as ion species, final ion energy, mode of operation, etc. The heavy ion space charge limit of the PPA, defined as the number of charges in the machine, will roughly be proportional to the effective injection voltage. An ion source in the terminal of the Van de Graaff should be capable of delivering pulsed, heavy ion beam currents in the range of a few hundred μA to about 1 mA, depending basically on $\epsilon^{1/2}$ (where ϵ is the ratio of charge state q of the ion to the atomic number A for the particular ion).

The PPA space charge limit for heavy ions with higher ϵ values could be substantially increased by accelerating them in the booster before injection into PPA (same operating mode as for protons). The gain, however, would be smaller than for protons and will decrease with the ϵ of the particle. (See Sec. 7.3.2.) It is worth mentioning that an ion source with a small current, but high brightness, can be used for multiturn injection into a synchrotron thereby increasing its effective output manyfold. Thus the PPA and the proposed booster synchrotron can be used to store particles from a weak ion source.

4.2. *Helium and xenon in the present* PIG *ion source*

Pulsed discharges of the PIG type with either cold or hot cathodes are frequently used as sources for heavy ions. Although our present cold-cathode PIG source, with axial extraction, in the terminal of the Van de Graaff, was developed specifically as a proton source (low, 1500 gauss magnetic field, low arc discharge power), successful operation has been achieved with helium and xenon. The beam of the Van de Graaff was analyzed in the $\mathbf{E} \times \mathbf{B}$ separator and the different ion components measured by means of a current transformer. With helium as the operating gas a very good quality beam of He^{+} was obtained ($\sim$5 mA). After passing this beam through a nitrogen stripper about 600 μA of He^{++} were obtained and successfully injected and accelerated in the PPA. An experiment with xenon was equally successful. A total beam current of about 2.3 mA was measured, with 200 μA of Xe^{4+} being obtained at the entrance to the synchrotron.

Side extracted PIG sources are reported to yield(3) higher currents of multiply charged ions, but a high magnetic field is necessary, the reported values being between 4 and 6 kG. Because of the limited space available in the Van de Graaff terminal a 3 kG permanent magnet, instead of an electromagnet, was used with a side extracted source. In terms of Xe^{4+} output there was no improvement compared to the axially extracted source at low magnetic field. Development of both side and axial extraction sources with pulsed magnetic fields up to 7 kG is in progress. Preliminary results with an axial PIG using a 5 kG pulsed field do show enhanced xenon currents and also the production of N^{3+} and C^{2+} looks very encouraging.

4.3. *Proposed supplementary heavy ion preinjector*

A full utilization of PPA capabilities in terms of different ion species and final energies would probably not be possible without an additional dc preinjector to supplement the present Van de Graaff. Its accelerating voltage could be as low as 750 kV, but a higher voltage, e.g., 2 MV, would be preferable from space charge considerations. The important thing is to provide sufficient space, weight supporting capability, power and cooling to accommodate all types of ion sources. Incidentally, the PPA can, in principle, accelerate polarized particles without encountering depolarization phenomena; so it is highly desirable that the new preinjector be large enough to accommodate such ion sources. While a 750 kV, air insulated Cockcroft–Walton can readily be designed to the above criteria it is also possible to build a 2 MV, pressurized, SF_6 insulated injector with a large, high voltage terminal and an adequately short tank-on, tank-off time for easy accessibility. As mentioned, the higher voltage is advantageous from the space charge point of view and also the larger synchrotron acceptance.

5. RADIO-FREQUENCY SYSTEM

5.1. *Existing* rf *system*

The present rf system used for proton acceleration is dual, having 4 drift tubes for beam capture and initial acceleration up to 20 MeV and 4, double-gap, resonant cavities for the final acceleration to 3 BeV. Each drift tube is coaxial with a resonant cavity in order to save space. However, drift tubes and cavities are made independently resonant by appropriate ferrite loading rings whose permeability can be varied by a programmed biasing current.

For protons, injected at 4 MeV and using a harmonic number of 8, the total frequency swing is 2.8–29.8 MHz with drift tube to cavity crossover at 5.8–6.0 MHz. At the synchronous phase angles usually employed the peak voltage across the gaps is of the order of 10 kV for both drift tube and cavity.

5.2. *Changes in* rf *system required by heavy ions*

In the case of heavy ion acceleration such parameters as harmonic number and frequency range have to be chosen in a manner to keep the required drift tube and cavity voltages within safe limits. Table I shows, for a wide selection of ions, the appropriate injection magnetic field, harmonic number and frequency range to produce final energies (total and per nucleon) as given in the first two columns. A 4 MV injector is assumed but helium and carbon will be accelerated as He^+ and C^{3+} by 4 MV before stripping to He^{2+} and C^{6+}.

In order to accomplish the above the cavities and associated rf drive will require no changes provided we do not exceed 30 MHz. The dual cavity gaps impose a limitation on the highest useable harmonic since at $h = 48$ the gap voltages turn out to oppose each other. For this reason we will not be able to exceed a harmonic number of about 24 since we do not wish to increase the gap voltage by more than 20 per cent over our present figure.

The drift tubes will require considerable modification in order to accelerate all ion types, especially in view of the above cavity limitations. A larger frequency swing, larger duty cycle, and larger gap voltage will be necessary. This work is already under way as a part of the project to accelerate He^{2+} to 4.8 BeV and C^{6+} to 14 BeV. Drift tube resonator tanks are being enlarged and a new Japanese ferrite, Tohoku ACL 200-R, has been tested, and is now under procurement, which allows a wider frequency swing than the present Phillips IV-C ferrite. The increase in gap voltage and duty cycle presents no serious problem beyond the need for an additional 50 kW rectifier.

In order to change quickly from one ion type and final energy to another it will be necessary to provide a programmed computer which automatically adjusts the many machine parameters. A PDP-9 computer is now being connected to the present accelerator system and should be suitable for the more complex heavy ion program.

All of the above remarks were based on the assumption of a 4 MV Van de Graaff feeding directly into the PPA synchrotron. When the booster synchrotron is operating it is generally true for all ions that the rf problems in the PPA become simpler since the ions enter at a higher velocity. As a result, the drift tube system will be operated at a matching harmonic number and a frequency range which turn out to be always well within the design range. The rf design for the booster is discussed in Sec. 7.1.

6. TARGETING AND EXTRACTION

The PPA operates, at present, with both internal targets and a slow-extracted external beam. It is possible to switch between them on a pulse-to-

TABLE I

The following definitions and parameters are used: 4 MV injection directly into PPA: ion species assumes C^{12}, A^{40}, Kr^{84}, Xe^{136}, U^{238}; T_{total} is the kinetic energy imparted to c.m. of nucleus; T_{amu} is $T_{\text{total}}/\text{At. No.}$; B_{inj} is magnetic field at injection; h is harmonic number of the rf; f_{inj} and f_{final} are initial and final rf frequencies; R_{fi} is ratio $f_{\text{final}}/f_{\text{inj}}$. In all cases the upper limit of drift tube frequency is 6.0 MHz and the lower limit of the cavity is 5.8 MHz.

Ion	T_{total}	T_{amu}	B_{inj}	h	f_{inj}	f_{final}	R_{fi}
	BeV	MeV	gauss	harmonic	MHz	MHz	
p	3.0	3000	314	8	2.81	29.67	10.5
He^{2+}	4.8	1200	314	8	1.41	27.5	19.5
C^{6+}	14.4	1200	314	8	1.41	27.5	19.5
A^{5+}	4.67	117.0	886	16	2.00	28.04	14.0
A^{6+}	6.75	169.0	810	12	1.64	25.2	15.4
Kr^{7+}	4.54	54.0	1085	16	1.63	19.8	12.1
Kr^{8+}	5.87	70.0	1015	16	1.74	22.48	12.9
Xe^{4+}	0.923	6.78	1827	20	1.21	9.17	7.58
Xe^{8+}	3.65	26.8	1291	16	1.37	14.36	10.5
Xe^{11+}	6.82	50.1	1101	16	1.61	19.28	12.0
U^{7+}	1.61	6.8	1827	20	1.21	9.15	7.5
U^{8+}	2.10	8.8	1709	20	1.29	10.43	8.1
U^{9+}	2.66	11.0	1612	20	1.37	11.70	8.5

pulse basis. With the magnet cycle flat topped, it will be possible to switch between external and internal targets within one pulse.

The internal targets are located in a field-free straight-section, so that secondary beams of either sign may be obtained. The minimum production angle is 13°. The control of the spill is, at present, by rf steering. This provides a very tight rf bunch time-structure in the beams (see Sec. 8.6). With flat top operation, the spill will be controlled by a programmed orbit distortion.

There is, at present, one beam extraction point. It is possible to add an extraction magnet in the internal target straight-section so that the present internal target experimental area may be used with an external beam. The primary objective of this change would be to reduce the amount of beam deposited in the accelerator proper, to extend its life. The properties of the external beam are detailed in Sec. 8.7.

7. BOOSTER INJECTOR

7.1. *Booster parameters and general design*

The booster as designed may be described as a general purpose, alternating gradient magnet ring, capable of ac excitation at 20 Hz with a maximum $B \cdot \rho$ of 12.9 kG meters. Figure 2 shows a plan view. Though the design emphasis has been on a 3 MeV to 75 MeV booster synchrotron capable of

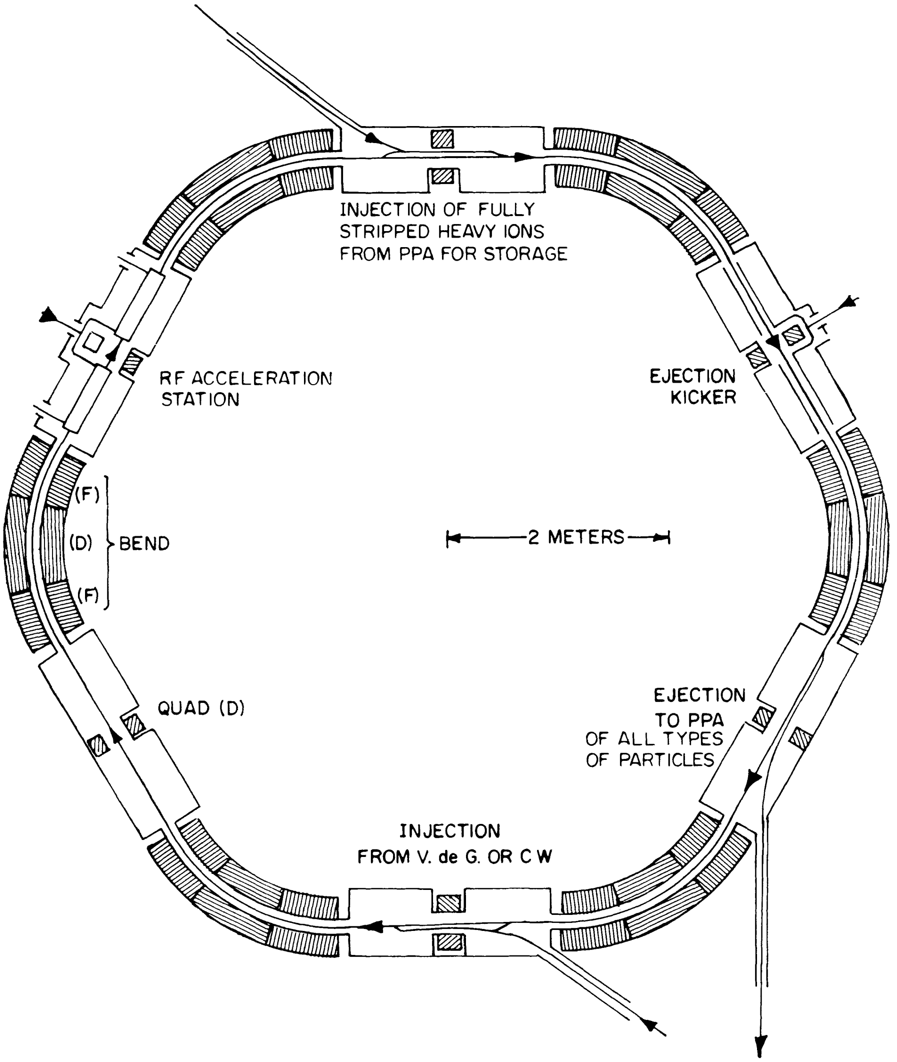

FIG. 2. PPB plan layout.

increasing the proton beam intensity of PPA by a factor of 20 to 1×10^{12} protons per pulse or 2×10^{13} per second, it adds significantly to the scope of the PPA's heavy ion capability. General parameters of the PPB are given in Table II.

TABLE II

General parameters for booster synchrotron

Average radius	3.66 m
Orbit radius	1.72 m
Lattice type	*FDFODO*
Number of superperiods	6
Cells per superperiod	2
Peak momentum	382 MeV/c
Peak magnetic field (central orbit)	7.5 kG
Magnet aperture (useable)	5.5×10 cm^2
ν_y (vertical)	1.79
ν_x (radial)	1.80
β_{min}, β_{max} (vertical)	1.42 m, 4.37 m
β_{min}, β_{max} (radial)	0.95 m, 3.61 m
Betatron acceptance (vertical and radial)	28 π cm-mrad
K bending magnets	± 2.772/m
Bending magnet length	1.8 m
Peak bending magnet gradient	208 G/cm
K quadrupole	-7.0/m
Quadrupole magnet length	0.22 m
Peak quadrupole gradient	515 G/cm
Number of straight sections	6
Length of straight sections	2.02 m (quadrupole in center)

The PPB may be employed in three ways:

(a) As a booster synchrotron to raise the proton energy from 3 MeV to 75 MeV thereby raising the space charge limited current by a factor of 20.

(b) As an accumulator ring to store partially stripped heavy ions from the dc preinjector before injection into the PPA. In some cases the PPB would actually accelerate the heavy ions and there could be some stripping before injection into the PPA. This mode would be useful in producing heavy ions with an energy of 6–8 MeV/amu.

(c) As a storage ring for fully stripped heavy ions produced by stripping after acceleration in the PPA to 10–15 MeV/amu. Ions stored would be reinjected in the PPA at low field and then carried to top energy. For the PPB parameters chosen the method should work for all nuclei up to krypton. Heavier nuclei would require a separate storage ring with a larger $B \cdot \rho$ (see Sec. 7.2).

Consider first those design aspects of the PPB which would be common to all three uses. The general bending magnet parameters are shown in Table III. Injection into the PPB would be done with an inflector and rapid, closed orbit distortion.

TABLE III

Mechanical and electrical parameters for booster magnet

Number of bending magnets	6
Magnet weight each	1134 kg
Magnet type	*H* (NAL Booster D laminations)
Lamination thickness	0.035 cm
Magnet peak stored energy each	5 kJ
Magnet size	33 cm × 46 cm × 184 cm
Coil cross section	9 cm × 4.5 cm (2 coils/magnet)
Peak I	940 A
Turns per magnet	36 (18 turns/coil)
Inductance per magnet	11.4 mH each
Resistance per magnet	0.020 Ω each

Injection would be multiturn with the number of turns depending on the particular use of the PPB.

The magnet powering system would be of the resonant type first developed for the PPA. Magnet flat top and flat bottom switches will be installed in order to be able to match the repetition rate of PPA which is now being converted to a variable flat top. The peak I^2R of the magnet system would be 120 kW.

The vacuum chamber of the PPB would be formed of titanium with a wall thickness of 0.015 cm. Such a chamber would have sufficient resistivity to have minimal eddy current effects and would make possible the 10^{-9} torr vacuum required for heavy ion acceleration.

The rf system, requiring 7 kV gap voltage and a 5 : 1 frequency range, would consist of a single drift tube which would be driven by an untuned, broadband amplifier capable of being programmed over a wide frequency range.

The beam would be extracted from the PPB with an electrostatic deflector and dc septum magnet. The electrostatic deflector would be driven by a high voltage pulse train which would, in general deflect every third beam pulse past the septum until all the beam bunches were extracted. This method is used to match the circumference of PPA which is approximately three times the circumference of PPB.

7.2. *Applications of booster*

In order to further specify operating parameters consider one case of each type of machine operation. The possible number of cases is very large with the variables being: injection energy, charge state, pre-stripping, post-stripping, ion type, and final energy desired.

CASE I: The PPB will be used to increase the energy of protons into PPA from 3 MeV to 75 MeV

CASE II: The PPB will be used to accumulate U^{7+} ions injected from a relatively low voltage dc injector, e.g., 750 kV, accelerate the ions to 0.065 MeV/amu (after which there could be stripping to U^{8+} or possibly higher) and inject them into PPA for acceleration to 6.8 MeV/amu.

CASE III: Here the PPB will be used to store fully stripped krypton ions which have previously been accelerated as Kr^{4+} to 13 MeV/amu in PPA and then fully stripped when leaving PPA. Storage in the PPB is necessary in order to allow the PPA to return to low field for a second acceleration cycle to the top energy of 76 BeV.

In order to apply the general method to the production of fully stripped ions heavier than krypton it would be necessary to reach energies in the PPA of up to 100 MeV/amu (for uranium) on the first acceleration cycle. The effects of this design are two-fold: First, the ion, e.g., uranium, must be ionized to U^{27+} before acceleration in the PPA in order to reach this energy; second, the $B.\rho$ of the storage ring must be 38 kGm. On the assumption that eventually ways will be found to reach U^{27+}, there still remains the storage ring problem. This ring could be a 7.2 m diameter, dc, weak focusing magnet with 16.5 kG field. An aperture of 3 cm × 8 cm would have an acceptance equal to that of the PPA vacuum chamber. While the proposed PPB could be designed with the required 16.5 kG field it is probably technically simpler and more economical to keep the PPB field at 7.5 kG and use a dc ring for the storage of fully stripped, very heavy ions. This could be added after a way is found to ionize uranium to U^{27+}. At the present writing we are proposing to implement Case III only as far as krypton. As funds become available the dc storage ring could be added.

Table IV shows specific operating parameters for each of the typical cases chosen.

7.3. *Effect of booster on space charge limitations*

7.3.1. *Effect for protons.* Incoherent space charge limit of a synchrotron is usually estimated with the help of Laslett's formula,[(4)] which relates the number of particles, machine and kinematic parameters and the shift in the betatron frequency

$$N \approx B \cdot \frac{\pi}{r_p} \cdot \frac{1 + a/b}{1 + [b(a+b)/h^2]\,[\epsilon_1(1 + B\beta^2\gamma^2) + \epsilon_2 B\beta^2(h^2/g^2)]} \cdot \Delta\nu\left(1 - \frac{\Delta\nu}{2\nu_{y0}}\right) A_y\beta^2\gamma^3$$

where

N = number of particles in the machine
B = bunching factor
r_p = classical proton radius
a, b = major and minor semi-axis of the beam
ϵ_1, ϵ_2 = image coefficients
ν_{y0} = vertical ν value without space charge
A_y = betatron phase space acceptance; $A_y = b^2\nu_{y0}/R$
β = v/c
γ = m/m_0
h = vertical semiaperture of the vacuum chamber
g = vertical semiaperture of the magnet.

A final proton energy of 75 MeV has been chosen for the booster. If it is assumed that at the higher energy the same incoherent space charge effects will again be the limiting factors, an increase in the injection energy from 3 MeV to 75 MeV would be followed by an increase in the space charge limit of the PPA by a factor

$$\frac{N_{75}}{N_3} = \frac{B_{75}}{B_3} \cdot \frac{(\beta^2\gamma^3)_{75}}{(\beta^2\gamma^3)_3} \approx 55.$$

However, the acceptance of the booster cannot be chosen arbitrarily large because the emittance of the booster beam at 75 MeV has to be matched to the PPA acceptance. Since by Liouville's theorem the momentum normalized emittance of any beam is constant, the betatron acceptance of the booster at 3 MeV can be larger only by the ratio of momenta at 75 MeV and at 3 MeV,

$$A_{y,\mathrm{PPB}} \approx 5A_{y,\mathrm{PPA}}.$$

Calculations of the synchrotron phase space acceptance in the PPA and the PPB have shown that the bunching factor B in the booster would be higher by a factor of about 6 for a combined increase of 30. (The bunching factor of the PPA is limited to about 0.1 by the small relative radial aperture.) Contributions of the remaining factors in Laslett's formula have proven to be much smaller; so, with an assumed overall efficiency of beam transmission from PPB to PPA of about 70%, a net gain of 20 in the PPA beam intensity should be expected.

7.3.2. *Effect for heavy ions.* The proposed booster has been designed for proton acceleration from 3 MeV to 75 MeV, with a proper match to PPA in betatron and synchrotron phase space for

TABLE IV

Booster operating parameters for three typical modes of operation: I Proton Acceleration; II Acceleration of U^{7+} by booster and PPA to 1.66 BeV; III Acceleration of Kr^{4+} by booster and PPA to 13 MeV/amu followed by complete stripping, storage in booster and subsequent acceleration in PPA to 76.0 BeV.

	Case			
	I	II	III	
Ion type	*p*	U	Kr	
Mass number *A*	1	238	84	
Charge state	1	7	36	
Injector voltage	3	0.75	0.75	MV
Injection energy/amu	3	0.02	13	MeV/amu
Injection momentum	76	1610	13,800	MeV/c
Injection field	1.5	4.5	7.5	kG
Final energy/amu	75	0.65	13	MeV/amu
Final momentum	382	2680	13,800	MeV/c
Final magnetic field	7.5	7.5	7.5	kG
rf harmonic number	7	28	7	
rf frequency range	7–35	2.4–4.1	15–15	MHz
Peak rf voltage	7	3.5	1	kV
β injection	0.08	0.007	0.17	
β final	0.4	0.012	0.17	
Injection current	50	1	—	mA
Injection turns	10	10	3	
Injection emittance	2.4π	2.4π	—	cm-mrad
Magnet peak VA	0.9	0.25	0.12	MVA
Magnet power	60	100	120	kW
Ejection voltage	100	2.7	43	kV
Over-all system particles/cycle	10^{12}	3×10^9	2×10^9	particles
Over-all system space charge limit/cycle	1.5×10^{12}	4×10^9	10^{10}	particles
Final beam energy/amu after acceleration in PPA	3000	6.8	900	MeV/amu
Final beam energy/particle after acceleration in PPA	3	1.61	76	BeV

the proton beam. A considerable increase in the PPA space charge limit is possible for many heavy ion species as well, if particles are accelerated in the booster before being injected into the PPA. As in the case with protons, the gain in the PPA space charge limit will consist of two contributions, a larger betatron phase space acceptance and a higher bunching factor. The gain in the betatron phase space acceptance will be equal to the ratio of the final momentum of particles in the booster to the injection momentum, limited however to the design value of 5. Calculations of the synchrotron phase space acceptance and bunching factors have been performed for a few ion species. Results show that the gain in the bunching factor depends on many factors—ion species, ratio of the final to the injection momentum in the booster, PPA magnet program, PPA harmonic number—and that generally it will be about equal to the ratio of momenta, with somewhat lower values for heavy ions with a low ϵ. A reasonable estimate for the total gain can be made by assuming that it is equal to about $\frac{2}{3}$ of the ratio of the final PPB energy to the injection energy.

8. FINAL BEAM PARAMETERS

8.1 *Energy vs particle and charge state*

The relationship between the energy per nucleon of an ion, its charge state and the rigidity $B.\rho$ is best represented by a $B.\rho$ vs energy per nucleon, T/amu diagram (Fig. 3). The parameter for one set of curves is ϵ; the other set of curves consists in the low energy region of lines corresponding to

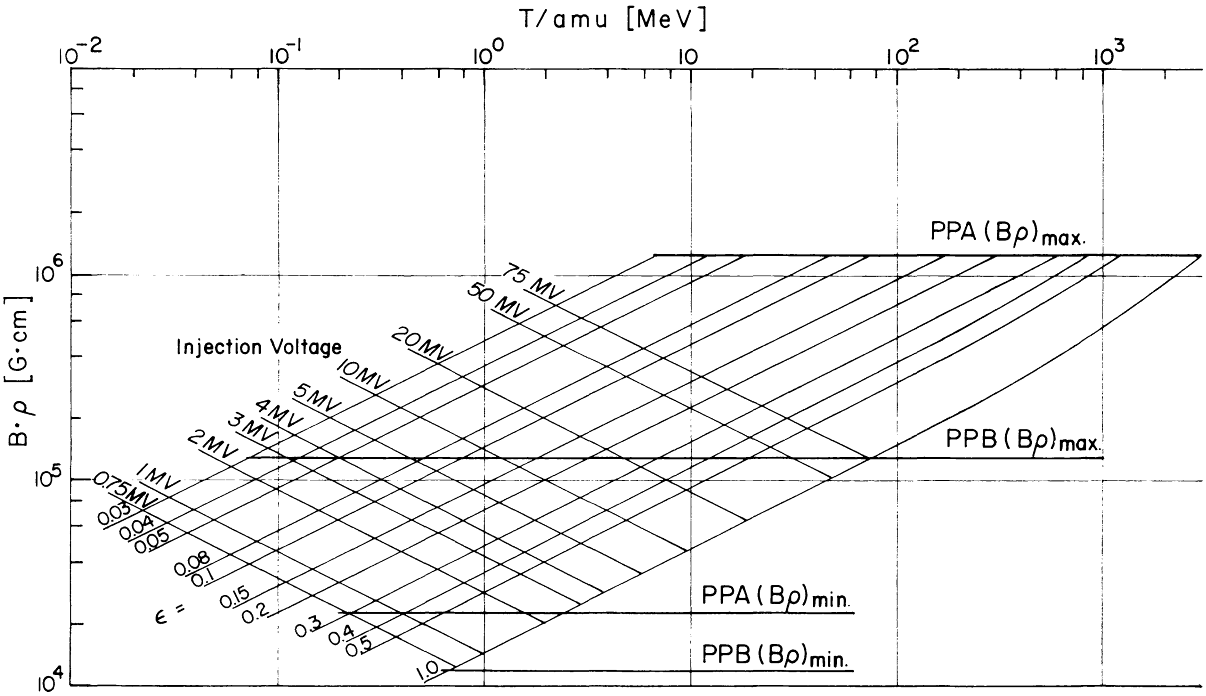

FIG. 3. Diagram of the magnetic rigidity $B \cdot \rho$ vs energy per nucleon T/amu.

constant effective injection voltages. Lower and upper limits of $B \cdot \rho$ for the booster and the PPA are also indicated. The diagram is self-explanatory —the acceleration of a particle is represented by moving on an ϵ = const. curve, the stripping by moving from one ϵ = const. curve to a higher one with T = const.

8.2. *Currents vs particle and charge state*

As it has been mentioned before, the final beam currents will depend on the ion species and the mode of operation. A few different modes will be considered and estimates for beam currents given relative to the present space charge limit for protons of $N_{p0} = 10^{12}$ per second.

(a) If ions are injected directly from the Van de Graaff or some other preinjector into the PPA, the space charge limit N_i will approximately be equal to

$$N_i \approx \frac{N_{p0}}{q} \cdot \frac{\mathrm{V}}{\mathrm{V}_0}$$

where q is the charge state of the ion, V_0 the Van de Graaff voltage and V the voltage of the other preinjector if used instead of the Van de Graaff.

(b) If ions are stripped between the preinjector and the PPA, the space charge limit will approximately be

$$N_i \approx N_{p0} \cdot \frac{\mathrm{V}}{\mathrm{V}_0} \cdot \frac{q_1}{q_2{}^2}$$

where q_1 and q_2 are charge states of the ion before and after stripping, respectively.

(c) If ions are accelerated in PPB and then injected into PPA, the gain relative to the mode (a) would be about 20 for protons, and for heavy ions roughly $\frac{2}{3}$ of the ratio of the final to the injection energy of the PPB.

(d) If ions are fully stripped after the acceleration in the PPA, then stored in PPB and again accelerated in PPA, the currents will be about an order of magnitude lower than in modes (a) and (c).

8.3. *Energy variability*

The energy of the ion beam from a synchrotron may be changed at will by changing the peak magnetic field. The upper limit of the energy is set either by the maximum value to which the field may be set, or, in some cases, by the upper frequency limit of the rf accelerating system. The useful lower limit is determined by considerations of beam size (or emittance) and percentage energy spread. With the control system available, the range of settings is continuous, with a reset precision and stability of better than one part in 10^4. At the present time, each change in peak field requires some adjustment of the rf program, a somewhat time consuming operation if the change in energy is large. A control computer now being installed will make this operation automatic.

8.4. *Energy spread*

The lower limit to the energy spread is given by the energy spread of the injector, multiplied by the ratio of the final particle velocity to the initial (injection) velocity. For this to be true, both the capture of the beam by the rf accelerating system, and the release of it at the end of the acceleration period, must be adiabatic. There must be no remanent bunch structure in the beam after rf turn-off, and there must be no dilution of the phase space caused by noise or transients in either the frequency or amplitude of the accelerating voltage. In practice, this lower limit could only be approached at very low intensities. Space charge effects set an upper limit to the linear density of the circulating beam, so that an appreciable intensity may be realized only if the beam bunches have an appreciable length which in turn implies an energy spread. One may calculate, then, the upper limit to the energy spread by using the acceptance of the accelerator at injection, i.e., the maximum value of energy spread and bunch length which may be contained. The product of these factors is proportional to the phase space area, and, in turn, properly normalized, proportional to the energy spread of an adiabatically debunched beam. The energy spread could be reduced below this level but with a proportionate decrease in the intensity. If the bunched beam is desired for time-of-flight measurements, the rf system must be left on. The bunch length and energy spread both depend on the voltage. With the voltage adjustment set as it is for proton acceleration at present, the energy spread is about 6 times as large as that of an adiabatically debunched beam. The dilution of phase space density for synchrotron oscillations in the PPA is, at worst, a factor of 2. This results in an energy spread in the full energy beam twice as large, for an unbunched beam, as that calculated from adiabatic theory. Using this figure, and the theoretical maximum acceptance of the accelerator at injection, we calculate the energy spread for several representative cases. The energies referred to are kinetic energies.

(a) Protons (present operation). $E_{\text{inj}} = 3$ MeV,
$E_f = 3$ BeV
$\Delta E/E_{\text{bunched}} = 0.03\,\%$
$\Delta E/E_{\text{unbunched}} = 0.005\,\%$

(b) Protons (with booster synchrotron and increased intensity)
$\Delta E/E_{\text{bunched}} = 0.1\,\%$
$\Delta E/E_{\text{unbunched}} = 0.015\,\%$

(c) Carbon, accelerated by 4 MV in the 2^+ state and injected after stripping to 6^+. $E_{\text{inj}} = 8$ MeV, $E_f = 14.4$ BeV
$\Delta E/E_{\text{bunched}} = 0.027\,\%$
$\Delta E/E_{\text{unbunched}} = 0.004\,\%$

(d) Xenon, accelerated by 4 MV and injected and accelerated in the PPA, all in the 4^+ state.
$E_{\text{inj}} = 16$ MeV, $E_f = 925$ MeV
$\Delta E/E_{\text{bunched}} = 0.33\,\%$
$\Delta E/E_{\text{unbunched}} = 0.053\,\%$

(e) Uranium, injected into the booster from a 750 kV Cockcroft–Walton accelerator in the 7^+ state.
$E_{\text{transfer}} = 13.5$ MeV, $E_f = 1610$ MeV
$\Delta E/E_{\text{bunched}} = 0.011\,\%$
$\Delta E/E_{\text{unbunched}} = 0.0016\,\%$

(f) Krypton, accelerated in the 7^+ state by 4 MV, injected into the PPA, accelerated to 4.5 BeV, completely stripped, stored in the booster ring, reinjected into the PPA, accelerated to 75 BeV.
$\Delta E/E_{\text{bunched}} = 0.075\,\%$
$\Delta E/E_{\text{unbunched}} = 0.011\,\%$

8.5. *Duty cycle*

The PPA has operated for many years without the benefit of flat top, so that a suitable duty-cycle for counter or spark-chamber experiments could be realized only by accepting a considerable spread in energy of the particles striking the primary target. This energy spread was strongly time-correlated—it is more of an energy scanning than a true energy spread—so that experiments which needed the knowledge of the proton energy could acquire this data from the event timing. The duty factor in this mode of operation has been about 10 per cent, if one disregards the effect of the rf bunched structure, a reasonable approximation due to the higher than usual operating frequency of the accelerating system. The equipment for flat topping is being completed as this is written. It will offer a flat top with a duty-cycle of up to 50 per cent. The repetition rate will be halved in this case, with a consequent 50 per cent reduction in average accelerated intensity. For experiments which do not require a large duty-cycle, such as radiochemical activations, the magnet cycle may be operated without flat top, and therefore, at maximum average intensity. If desired, the rf structure may be removed during the targeting period by adiabatically reducing the accelerating voltage to zero. At the same time the energy spread will be reduced by a factor of 5–10. Since the external beam is slow-extracted, both internal and external beams can have an essentially dc beam for 50 msec.

8.6. *Time-of-flight*

Many experiments at the PPA have made use of the rf bunched structure of the beam. With the internal target, the secondary beams are produced in bunches less than 1.0 nsec long, spaced 33 nsec apart, with the option of suppressing alternate bunches with a corresponding factor of 2 reduction in average intensity. This provides a bunch spacing of 67 nsec. It is also possible to achieve 134 nsec or even 268 nsec bunch spacing.

This feature will remain as an option on flat top. It is most valuable for experiments with neutral particles, but has proved useful for other experiments where time-of-flight from the target is an aid in particle identification.

8.7. *External beam characteristics*

It is expected that most experiments with high proton intensities, and most experiments with heavy ions would use the external beam. This beam is directed into a 20,000 sq. ft. (approximately square) experimental hall served by a 40-ton crane. Magnets are under construction which will allow the beam to enter this hall at two alternative points to increase the flexibility of the staging of the experiments. The beam extraction system uses a nonlinear, resonant radial blowup and a septum magnet—a completely magnetic system which is inherently capable of extracting any beam which can be accelerated. The observed emittance of the proton beam is about $0.05\,\pi$ cm-mrad in the vertical plane and $0.2\,\pi$ cm-mrad in the horizontal plane. These parameters allow the beam to be focused to a 3 mm diameter spot with ordinary quadrupoles. The booster will cause a somewhat increased beam size—the emittance being increased by a factor of about 5.

The emittance of heavy ion beams will depend on details of the injection system used. Assuming ions are injected as in Sec. 8.4 the following can be said: The 14.4 BeV Carbon beam should be identical to the present proton beam in shape and emittance. The 925 MeV Xenon beam will have an emittance about 6.5 times as large. Therefore, to achieve a small target spot, stronger quadrupoles will be needed. The Uranium beam will have about 5 times the emittance of our present proton beam, and the ultra-high-energy Krypton beam should have a lower emittance than the present proton beam provided that dilution of phase space does not occur in the beam transfer operations. In any case, its emittance should be comparable to our present beam.

The present extraction efficiency is 60–70 per cent, and the external beam must be heavily shielded. A modification to the extraction system is nearing completion which should raise the efficiency to above 90 per cent—a badly needed step before the booster increases the intensity. The external heavy ion beams should require less shielding, as there is, in most cases, less beam power, and the primary particles are less penetrating.

If the energy of the ion beams is varied over a wide range, it will affect the beam emittance. The actual spot size may be held constant if desired but the angular spread in the beam will change.

APPENDIX

Some typical secondary beam properties

The yield of secondary particles depends on the properties of the beam and target used. Internal targets have usually been $1\frac{1}{2}$ inch platinum, to minimize the source size for large angle beams. Some beams from this target have been:

(1) At a production angle of 90°, about 2×10^4 K_L° per sec through a 12 × 12-in aperture at 20 ft, with 'chopped' beam, i.e., 67 nsec bunch spacing, and therefore, $\frac{1}{2}$ peak internal beam intensity.

(2) At a production angle of 13°, about 5×10^4 π^- with a ± 1 per cent momentum bite, about 1 BeV/c central momentum.

(3) At a production angle of 34°, about 500 K_L° per sec through a 4 × 4-in aperture 50 ft from the target, with 'chopped' beam.

In the external beam, a variety of targets have been used. Some sample beam properties include:

(1) A stopping K^+ beam from a 2-in platinum target with a 0° production angle yielded about 2000 stopped K^+ per sec.

(2) A π^+ beam produced at 8° from a 4-in platinum target, ± 4 per cent momentum bite, at 1200 MeV/c yielded 2.5×10^5 per sec.

(3) A π^- beam produced at 0° from a 4-in

beryllium target, ± 1/2 per cent momentum bite at 700 MeV/c yielded 1.3×10^5 per sec.

(4) A 250 MeV/c π^+ beam, used to generate stopping μ^+, yielded 10^6 π's/sec in a ± 3 per cent momentum bite from a 3-in platinum target.

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Received 27 February 1970.