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Design Study for a
Medium-Energy, Intense,
Proton-Storage Ring (WNR Ring)

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

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Compiled by

Ralph R. Fullwood

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FOREWORD

This report represents an overall view of the design of a medium-energy proton-storage ring for use at the Los Alamos Meson Physics Facility (LAMPF). It is not, by any means, a design report but does serve to point out areas of difficulty.

The consultants who supplied information that has been used verbatim, abstracted, or paraphrased are: R. T. Avery, A. A. Garren, J. T. Gunn, and K. Halbach (all of LBL), P. F. Meads, Jr. (Wm. Brobeck & Associates), C. E. Neilsen (Ohio State Univ.), and D. Norgren and F. S. Reinath (LBL). V. K. Neil (LLL) has been extremely helpful.

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DESIGN STUDY FOR A MEDIUM-ENERGY, INTENSE, PROTON-STORAGE RING (WNR RING)

compiled by

Ralph R. Fullwood

ABSTRACT

A design concept for a high-intensity, medium-energy proton storage ring to be used for weapons-related and basic physics research is presented. This racetrack-type, strong-focusing ring would accumulate 800-MeV protons up to currents of 100 A in the charge-exchange injection, low-duty mode. After bunching, this current would be extracted as a single 100-nsec pulse. The high-duty mode accepts 25 turns of injected protons by a combination of orbit and tune shifting to achieve 60% phase density. In one configuration, the beam would be bunched into five 5-nsec packets, each of which would be extracted separately at a rate of 600 pulses/sec. This design uses the sector magnets of the Cal-Tech synchrotron modified to be combined-function and strong-focusing. Each 180° bend is separated by a 15.74-m, π - 2π matched insert providing 7 m of clear drift. Extraction is by a 1° vertical kick of the beam into iron extraction septa. The design requires the particle energy to be less than the transition energy to avoid the "negative-mass" effect. An analysis of the ion-induced instability requires a vacuum of 10^{-9} Torr; aluminum vacuum chambers are specified to reduce the resistive-wall effects.

I. SUMMARY AND BACKGROUND

Future development of sophisticated nuclear weapons will require better knowledge of neutronics and hydrodynamics. In weapons effects, knowledge of the system's operation in radiation environments, as well as detailed understanding of the physics for the calculations will be required. These facts, coupled with possible constraints on nuclear-explosions testing, point to laboratory accelerator-based investigations.

It has been shown that medium-energy protons incident on heavy metal targets have an efficiency for neutron production exceeded only by (d,t) fusion.¹ This (p,xn) reaction which leads to 20-40 neutrons per incident proton has a spectrum bracketing that of nuclear weapons. The spectrum decreases at high energy as $E^{-1.9}$, compared with that from electron bombardment (e, γ ,xn), which decreases as $E^{-2.8}$ (where E is the neutron energy). The target heating is 56 MeV/neutron, compared with the 2000-MeV/neutron electron heating. This reduced target

heating results in a higher neutron burst capability than other methods of neutron production. The neutrons from the (p,xn) reaction have reduced gamma content because of the mode of production and target self-shielding. (Gamma production, if desired, can be achieved by loading the target with materials having strong gamma-production properties.)

To effectively support weapons research, however, requires a much larger pulse of protons for a shorter duration than the Los Alamos Meson Physics Facility (LAMPF) can provide. Therefore, the recent development of storage rings becomes important.

In 1956^{2,3} it was pointed out that for relativistic beams, the center-of-mass energy in reactions between identical particles does not increase linearly, but as the square root of the bombarding energy. This could be circumvented by having similar accelerators firing at each other, but such a procedure would be very inefficient because interactions would seldom occur and the beams would be wasted. Therefore the concept of storing beams of

particles and recirculating them to increase the reaction probability originated.

The reaction probability is proportional to the product of the interacting currents. This has led to intensive studies of beam-stability phenomena to try to raise the maximum current capability. The success of these efforts (as well as other technological developments) has led to the rapid progress in storage rings depicted in Table I and Fig. 1.

Design of the weapons neutron research (WNR) ring has been controlled primarily by the need to obtain the largest possible pulse of protons at a very low duty rate. This has led to adoption of charge-exchange injection^{4,5} to avoid the limitations on the amount of beam storage imposed by Liouville's theorem.

We do not visualize that this mode of operation will take a long time, partly for experimental setup reasons. Having designed for these large currents, we can certainly store less current. Therefore, a

high-duty, low-stored-current mode of operation is also planned. This mode would use conventional multiturn injection of the proton beam into radial and vertical betatron space and would be limited to 25 turns. Table II summarizes the design performance specifications for the WNR ring.

These specifications do not reflect the versatility of the ring, but rather represent certain extreme conditions. The design requires that rf bunching be used to provide a beam-free region to allow time for the extraction magnet to come on and stabilize (25 nsec). Within this constraint and the constraint that the bunching factor be no greater than 10, other pulse patterns are permitted up to 250 nsec, the period of the storage ring. We also intend to provide very long pulses, called a slow spill, by shifting the tune onto a resonance. There is a blank space in the performance between 250 nsec and the nearly dc operation of a slow spill which can be filled only by the direct LAMPF beam.

TABLE I
VARIOUS STORAGE RINGS THROUGHOUT THE WORLD

		Status	Particles	Energy (GeV)	Ring Current (A)	Size (M)
CANADA:	SASKATOON TORONTO	STUDY	e ⁺	0.1 - 0.3	0.5	
		STUDY	e ⁻	0.5		
CERN:	GENEVA, CESAR	1963, RETIRED	e ⁻	0.002	20.0 40 μ -/Pulse	7.6
	GENEVA, ISR	1971, OPERATING	p,p	28.0		300.0
	GENEVA, MSR	1965, OPERATING	μ ⁻	1.3 GeV/c		5.0
FRANCE:	ORSAY, ACO SACLAY	1966, OPERATING	e ⁻ ,e ⁺	0.5	0.5	100.0
		STUDY	e ⁻	0.045		7.0
GERMANY:	HAMBURG, DORIS	1973, CONSTRUCTION	e ⁻ ,e ⁺	3.5	6.0	55 x 110
ITALY:	FRASCATI, ADA	1961, RETIRED	e ⁻ ,e ⁺	0.25	0.001	3.0
	FRASCATI, ADONE	1967, OPERATING	e ⁻ ,e ⁺	1.5	0.04	33.5
USSR:	KHARKOV	1963, RETIRED	e ⁻ ,e ⁻	0.1	0.04 1.0 2, 0.02 0.5 10, 0.01	2.0
	NOVOSIBIRSK, VEP-1	1963, OPERATING	e ⁻ ,e ⁻	0.13		1.0
	NOVOSIBIRSK	1964, EXPERIMENT	H ⁺ $\rightarrow$ p	0.001		0.42
	NOVOSIBIRSK, VEPP-2	1966, OPERATING	e ⁻ ,e ⁻	0.7		3.5
	NOVOSIBIRSK, VEPP-3	1970, OPERATING	e ⁻ ,e ⁺	3.5		28 x 16
	NOVOSIBIRSK, VAPP	CONSTRUCTION	p, $\bar{p}$;e ⁻ ,e ⁺	13.6		90 x 125
USA:	CAMBRIDGE, BYPASS	1970, OPERATING	e ⁻ ,e ⁺	3.5	0.03	72.0
	LOS ALAMOS, WNR RING	STUDY	p, H ⁺ $\rightarrow$ p	0.8	100, 0.6	8.0
	LIVERMORE	1971, CONSTRUCTION	e ⁻	0.004	200.0	8.0
	WESTON, NAL	STUDY	p,p;p, $\bar{p}$	100.0	1450.0	100.0
	MADISON, MURA	1967, OPERATING	e ⁻ ,e ⁺	0.2	0.1	3.0
	PRINCETON/STANFORD	1961, RETIRED	e ⁻ ,e ⁻	0.5	0.1	4.0
	STANFORD, SLAC-SPEAR	1972, CONSTRUCTION	e ⁻ ,e ⁺	0.3	0.5	60 x 70

Fig. 1. Intensity evolution of various storage rings.

In studying the problems associated with achieving these specifications, we studied many different lattice configurations and performed perhaps a thousand parametric studies on them. This proposal would use the California Institute of Technology electron synchrotron⁶ modified to become an alternating-gradient machine in the form of a racetrack and using "invisible inserts"⁷ in the straight sections.

II. STORAGE-RING DESIGN

A. Lattice Design

The configuration of bending and focusing elements required to hold a circulating beam in a torus is central to the other problems of injection, extraction, and beam stability. The principal design characteristics for this ring are as follows.

1. Capability for storing 800-MeV protons having a γ of 1.86 (specialized terms are defined in the Glossary) and a magnetic rigidity, $B\rho$ of 4.88 Tm. Storage of lower energy particles to be possible, but perhaps at reduced intensity.

2. A 250-nsec period of revolution to be compressed by rf bunching into 100 nsec to allow turnon time for the beam extraction. A second mode of operation to be five 5-nsec bunches with individual pulse extraction.

	DESIGN-PERFORMANCE SPECIFICATIONS FOR WNR RING	
	Low-Duty Mode	High-Duty Mode
Peak Extracted Beam Current (A)	100	4
Pulse Duration for Above (nsec)	100	5
Maximum Number of Protons Stored	6×10^{13}	6×10^{11}
Maximum Repetition Rate	1/10 min	600/sec
Injected Particle Type	H^- Ions	Protons
Injection Current (mA)	1.7	17
Injection Time	0.1 sec	6.5 μ sec
Number of Turns Injected	2×10^4	25
Maximum Bunching Factor	10	10
Harmonic Bunching Number	1, 5	1, 5
Neutron Production (neutron/incident proton)	400	30
Instantaneous Neutron Production Rate (n/sec)	2×10^{23}	7×10^{20}
Neutrons/Pulse	2×10^{16}	1×10^{12}
Target Average Power (kW)	2	19
Beam Power (kW)	0.013	10

3. Injection in two modes: charge-exchange injection of 2×10^4 turns (100 A for 1.7-mA H^- beam). Injection into radial and vertical betatron phase space of 25 turns of 17-mA proton beam.

4. Injected beam characteristics assumed to be $\pi/3$ cm mrad in both planes with a $\Delta p/p$ of $\pm 0.2\%$.

5. From the bunching action, ring $\Delta p/p$ to be $\pm 2\%$.

6. Beam containment time to be 0.1 sec.

7. Design to employ high-conducting, low-impedance wall materials and inserts.

8. Aperture to be of the order of 10 x 20 cm or greater.

9. Tuning variability to be ± 0.25 .

Given these conditions, we conducted a survey of suitable existing designs. It soon became apparent that there was none that could be directly copied. There is only one operating proton storage ring, the CERN-ISR,⁸ whose design was governed by long storage time and the intersection of beam lines -- neither of which is involved in this design. At 28 GeV, the ISR particle gamma is well above its ring gamma, so it should have different instability problems. The ISR uses synchrotron

space injection; this was examined for the WNR ring and rejected in favor of charge-exchange injection for the high-current mode. For the low-current mode, it was rejected because of complexity and slowness compared with betatron-space injection.

Electron-storage ring designs were also studied, but the LAMPF proton gamma of 1.86 is very much lower than that of any electron ring. In fact, electrons of this gamma have only 440-keV energy, and it would be highly impractical to build an electron ring whose particle gamma is below the ring gamma.

The advantage (which may also be a disadvantage) of electron rings is that the particles radiate synchrotron light, causing damping of the betatron oscillations. For 800-MeV protons, the absence of dissipative forces leads to large aperture requirements. Electron cooling of the proton beam is being considered, but there are no plans for its use at an early phase.

From this review it was apparent that the general principles of previous designs were about all that could be directly employed, and we began a survey for a suitable lattice* for the WNR ring.

The programs used in the lattice search are all well tested and have been used for design of accelerators and beam-transport lines throughout the world. The three principal programs are as follows.

SYNCH -- a computer system⁹ for synchrotron design and orbit analysis. Much of the notation and technique is from Courant and Snyder which adds usefulness to the code and probably accounts for its wide acceptance. It computes the elements of the Twiss matrix, of which the most important is the beta function that relates the beam size in the synchrotron to the emittance of the injected beam. This permits parametric study of lattices without reference to the injected beam. It also calculates the quantity x_{eq} , which relates the equilibrium orbit shift to the momentum dependence. It treats drift spaces, bending magnets of uniform gradient, quadrupole magnets, misalignments, arbitrary elements specified by user-supplied matrices, and transformations not expressible in matrix form. It also provides matrix manipulation procedures and ray tracing.

4P -- a program^{10,11} like SYNCH, except that it does not work in the Courant and Snyder formalism. It can treat accelerators having 90 or fewer elements like those treated by SYNCH. Further, it can calculate the system to third-order aberrations. The principal reason for its use in this study is its comprehensive method of parametric adjustment

using a linear programming algorithm to satisfy up to 12 linear beam constraints and to minimize aberrations. Another reason for its use is its cathode-ray tube generated output plots.

TRANSPORT -- a program¹² that differs from the preceding two in that it uses seven-element rather than three-element matrix manipulation. It was not designed for synchrotron analysis, and is not basically in the Courant and Snyder formalism. Its seven-element matrix form makes it useful in study of second-order and sextupole effects, the use to which it was applied.

The first calculated lattice was a fourfold separated-function design (Fig. 2). Separated function is considered because it provides greater freedom and independence of adjustment than does combined function. [The National Accelerator Laboratory (NAL) accelerator, for example, is a separated-function machine.] The disadvantages of this lattice are high-field magnets and zero gamma transition. The latter fact means that the ring would exhibit the conventional negative-mass instability and no low-beam gamma advantage would be realized. Another design used eightfold symmetry (Fig. 3). It also used very high field bends (although not so high as NAL), but suffered from short (2.75-m), free-drift lengths.

Fig. 2. A separated-function lattice study. Design parameters are: $B = 20$ kG; quadrupole length $= 0.369$ m; $QF-B' = 1.325$ kG/cm; $QD-B' = -1.515$ kG/cm. Maximum betatron functions: $\beta_x = 2.954$ m, $\beta_y = 13.803$ m (bends); and $\beta_x = 7.471$ m, $\beta_y = 1.833$ m (quadrupoles); $x_{eq} = -0.685$ (bends), 1.833 m (quadrupoles); $\gamma_{tr} = 0$. Tunes: $\nu_x = 2.751$, $\nu_y = 2.750$.

*Others principally involved in the lattice selection were Philip F. Meads, Jr., of Wm. M. Brobeck & Associates, and Alper A. Garren of LBL.

Fig. 3. A low-gradient separated-function lattice study. Design parameters are: $B = 20$ kG; quadrupole length = 0.4 m; $QF-B' = 0.6$ kG/cm; $QD-B' = -0.2$ kG/cm. Maximum betatron functions: $\beta_x = 6.646$ m, $\beta_y = 7.603$ m (bends); $\beta_x = 8.043$ m, $\beta_y = 9.517$ m (quadrupoles); $x_{eq} = 1.738$ m (bends), 2.023 m (quadrupoles); $Y_{tr} = 2.474$. Tunes: $\nu_x = 2.446$, $\nu_y = 1.366$.

Early in the study, two problems became apparent. First, the ring period, which had been specified as 200 nsec, required compact, high-field bending and focusing magnets to provide space for injection, extraction, and rf bunching. Second, to achieve fairly long field-free regions for these operations requires a systematic, special design of these sections. The phase advance should be some multiple of π in these inserts so that the bending and focusing can be treated separately from the design of the drift sections.

The matching inserts known at this time were the Collins,¹³ which does not advance the phase by a multiple of π , and Garren's uncompensated $\pi-\pi$.¹⁴ Neither matches the closed orbit for off-energy particles. Other inserts are Garren's $\pi-\pi$ matched^{15,16} and Nakash's $2\pi-2\pi$.¹⁷ Both satisfy this closed-orbit criterion, but the former must be designed to a specific lattice and the latter divides the drift region more or less uniformly thus not allowing large, empty regions.

As part of the study for the WNR ring, Meads discovered the new $\pi-2\pi$ insert.⁷ (The 2π phase advance is in the radial plane.) This insert satis-

Fig. 4. A separated-function $\pi-2\pi$ lattice study. Design parameters are: $B = 20$ kG (edge focusing); quadrupole length = 0.4 m; $QF-B' = 1.00$ kG/m; $QD-B' = 0.4$ kG/m. Maximum betatron functions: $\beta_x = 4.769$ m, $\beta_y = 9.849$ m (normal cell); $\beta_x = 12.398$ m, $\beta_y = 33.107$ m (long straight section); maximum $x_{eq} = 1.291$ m. Tunes: $\nu_x = 4.375$, $\nu_y = 1.772$.

fies the requirement for invisibility in both planes and matching of the closed orbit for off-energy particles. The use of different phase advance in the two planes provides the freedom needed to group the magnetic lenses at each end of the drift region and thereby allow a large, empty space in the middle. Figure 4 shows an early study of a 16-cell separated-function racetrack with the $\pi-2\pi$ insert employed asymmetrically.

During the study, we learned that the Cal-Tech synchrotron, which started as a quarter-scale model of the Bevatron, was being decommissioned and was available. Because the rigidity of the electrons it had been accelerating ($B\rho = 5.8$ Tm) was about that of the protons from LAMPF (4.88 Tm), we recognized that these magnets were readily adaptable to the WNR ring. The most expeditious use of the Cal-Tech synchrotron would be to use the existing magnets and copper coils. This constrains the possible designs to those having twofold or fourfold symmetry.

Figure 5 shows a racetrack design using the modified Cal-Tech synchrotron for bending and focusing. The plan is to convert the weak-focusing synchrotron to a strong-focusing, combined-function ring by replacing the pole tips. (The vacuum chamber and rf systems would also be discarded.) The problem in this design is that the coils extend some distance beyond the steel, and it is deemed that the

Fig. 5. A combined-function π - 2π lattice study. Design parameters are: $B = 12.795$ kG; quadrupole length = 0.5 m. Maximum betatron functions: $\hat{\beta}_x = 3.54$ m, $\hat{\beta}_y = 5.71$ m (bends); $\gamma_{tr} = 1.95$. Tunes: $\nu_x = 4.069$, $\nu_y = 2.258$.

90° sectors can be placed no closer than about 1 m. This creates a very crowded situation for the triplet lens shown at the ends of the racetrack. There was also evidence that the triplets were not functioning well, and the beta functions were larger with than without the 1-m gap.

The next step was to expand the design to four-fold symmetry so that there would be adequate space for matching between the 90° sections. This design, shown in Fig. 6, indeed, was considered suitable for detailed cost estimation. The initial estimate was slightly more than \$2 million. The major cost reduction was realized by a change of power-supply design, but, on reexamination, the racetrack was reconsidered.

Garren suggested that instead of trying to minimize the gap where the 90° sectors meet, we introduce the needed gap, but include another, half as wide, at the other end of the sector as part of the cell (Fig. 7). Because the π - 2π insert has unit-magnitude transfer matrices, the ring has fourfold symmetry. Only the off-energy, off-axis particle knows that it has twofold symmetry. Because of the invisible character of the insert, the sector lattice calculations proceeded in the usual fashion without the inserts, and the calculations for the inserts were studied and parametrized to discover the most economical design.

We observed that there is a trade-off between the betatron oscillation amplitude and the momentum compaction of the ring. If $\Delta p/p$ is 0.02 after bunching and we assume an emittance of 13.89×10^{-5}

Fig. 6. Foursquare combined-function π - 2π lattice study. Design parameters are: $B = 12.81$ kG; profile parameters: $k_F = 3.5/\text{m}$, $k_D = -4.5/\text{m}$; quadrupole length = 0.5 m; maximum betatron functions: $\beta_x = 3.697$ m, $\beta_y = 1.574$ m (F-F point in bends); $\beta_x = 20.54$ m, $\beta_y = 21.44$ m (long straight section); $x_{eq} = 1.0003$ (bends), -2.333 m (long straight section). Tunes: $\nu_x = 6.389$, $\nu_y = 3.408$.

Fig. 7. Cell symmetrization by introducing a gap into the long drift length.

$$\Delta x(\text{cm}) = 2 \hat{x}_{\text{eq}} + 1.179 \sqrt{\beta} \quad ,$$
$$\Delta x(\text{cm}) \approx 1.56 + 0.22(\hat{\beta} + 9 \times_{\text{eq}}).$$

We also tried to determine the relationships among central drift length, quadrupole gradients, quadrupole spacing, and minimum $\hat{\beta}_x$. Meads investigated this problem and determined that there are only two free parameters that can be taken to be the radial magnification, m , and the central drift length, $2L$. Because of reflection symmetry about the midpoint, the minimum apertures require that the endpoints be waist locations in both planes; also, the midpoint must be a double-waist location. Meads shows by general arguments that the minimum $\hat{\beta}_x$ is $2L$.

Further, attempts to increase the central drift length or reduce the magnification reduce the spacing between the second and third quadrupoles. This fact is the limiting physical parameter in the design. This spacing is therefore set to a minimum, and the insertion effects are studied by varying either the central drift length or the radial magnification. Furthermore, we decided to use identical quadrupoles in the design (for economy) and a magnification, m , of $-1/\sqrt{2}$. This causes $\sim 50\%$ of the drift to be in the central drift length. The final design constraint requires that the pole-tip field be less than 10 kG to avoid saturation.¹⁸

The diagram illustrates the Fermilab Main Ring, a circular particle accelerator. Key components and labels include:

- PROTON INJECTION**: The entry point for protons into the ring.
- INFLECTOR**: A device used to bend the beam into the ring.
- ORBIT SHIFT**: A mechanism for adjusting the beam's path.
- EXTRACTION SEPTUM**: A device used to extract the beam from the ring.
- VERT. KICKER**: A magnet used to kick the beam vertically.
- Magnets and Beam Positions**: Various magnets (labeled 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 112, 113, 114, 115, 116, 117, 118, 119, 120, 121, 122, 123, 124, 125, 126, 127, 128, 129, 130, 131, 132, 133, 134, 135, 136, 137, 138, 139, 140, 141, 142, 143, 144, 145, 146, 147, 148, 149, 150, 151, 152, 153, 154, 155, 156, 157, 158, 159, 160, 161, 162, 163, 164, 165, 166, 167, 168, 169, 170, 171, 172, 173, 174, 175, 176, 177, 178, 179, 180, 181, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191, 192, 193, 194, 195, 196, 197, 198, 199, 200, 201, 202, 203, 204, 205, 206, 207, 208, 209, 210, 211, 212, 213, 214, 215, 216, 217, 218, 219, 220, 221, 222, 223, 224, 225, 226, 227, 228, 229, 230, 231, 232, 233, 234, 235, 236, 237, 238, 239, 240, 241, 242, 243, 244, 245, 246, 247, 248, 249, 250, 251, 252, 253, 254, 255, 256, 257, 258, 259, 260, 261, 262, 263, 264, 265, 266, 267, 268, 269, 270, 271, 272, 273, 274, 275, 276, 277, 278, 279, 280, 281, 282, 283, 284, 285, 286, 287, 288, 289, 290, 291, 292, 293, 294, 295, 296, 297, 298, 299, 300, 301, 302, 303, 304, 305, 306, 307, 308, 309, 310, 311, 312, 313, 314, 315, 316, 317, 318, 319, 320, 321, 322, 323, 324, 325, 326, 327, 328, 329, 330, 331, 332, 333, 334, 335, 336, 337, 338, 339, 340, 341, 342, 343, 344, 345, 346, 347, 348, 349, 350, 351, 352, 353, 354, 355, 356, 357, 358, 359, 360, 361, 362, 363, 364, 365, 366, 367, 368, 369, 370, 371, 372, 373, 374, 375, 376, 377, 378, 379, 380, 381, 382, 383, 384, 385, 386, 387, 388, 389, 390, 391, 392, 393, 394, 395, 396, 397, 398, 399, 400, 401, 402, 403, 404, 405, 406, 407, 408, 409, 410, 411, 412, 413, 414, 415, 416, 417, 418, 419, 420, 421, 422, 423, 424, 425, 426, 427, 428, 429, 430, 431, 432, 433, 434, 435, 436, 437, 438, 439, 440, 441, 442, 443, 444, 445, 446, 447, 448, 449, 450, 451, 452, 453, 454, 455, 456, 457, 458, 459, 460, 461, 462, 463, 464, 465, 466, 467, 468, 469, 470, 471, 472, 473, 474, 475, 476, 477, 478, 479, 480, 481, 482, 483, 484, 485, 486, 487, 488, 489, 490, 491, 492, 493, 494, 495, 496, 497, 498, 499, 500, 501, 502, 503, 504, 505, 506, 507, 508, 509, 510, 511, 512, 513, 514, 515, 516, 517, 518, 519, 520, 521, 522, 523, 524, 525, 526, 527, 528, 529, 530, 531, 532, 533, 534, 535, 536, 537, 538, 539, 540, 541, 542, 543, 544, 545, 546, 547, 548, 549, 550, 551, 552, 553, 554, 555, 556, 557, 558, 559, 560, 561, 562, 563, 564, 565, 566, 567, 568, 569, 570, 571, 572, 573, 574, 575, 576, 577, 578, 579, 580, 581, 582, 583, 584, 585, 586, 587, 588, 589, 590, 591, 592, 593, 594, 595, 596, 597, 598, 599, 600, 601, 602, 603, 604, 605, 606, 607, 608, 609, 610, 611, 612, 613, 614, 615, 616, 617, 618, 619, 620, 621, 622, 623, 624, 625, 626, 627, 628, 629, 630, 631, 632, 633, 634, 635, 636, 637, 638, 639, 640, 641, 642, 643, 644, 645, 646, 647, 648, 649, 650, 651, 652, 653, 654, 655, 656, 657, 658, 659, 660, 661, 662, 663, 664, 665, 666, 667, 668, 669, 670, 671, 672, 673, 674, 675, 676, 677, 678, 679, 680, 681, 682, 683, 684, 685, 686, 687, 688, 689, 690, 691, 692, 693, 694, 695, 696, 697, 698, 699, 700, 701, 702, 703, 704, 705, 706, 707, 708, 709, 710, 711, 712, 713, 714, 715, 716, 717, 718, 719, 720, 721, 722, 723, 724, 725, 726, 727, 728, 729, 730, 731, 732, 733, 734, 735, 736, 737, 738, 739, 740, 741, 742, 743, 744, 745, 746, 747, 748, 749, 750, 751, 752, 753, 754, 755, 756, 757, 758, 759, 760, 761, 762, 763, 764, 765, 766, 767, 768, 769, 770, 771, 772, 773, 774, 775, 776, 777, 778, 779, 780, 781, 782, 783, 784, 785, 786, 787, 788, 789, 790, 791, 792, 793, 794, 795, 796, 797, 798, 799, 8

Figure 9 shows the beam envelope through one superperiod of the ring shown in Fig. 8. Figure 10 shows the beam envelope through a 90° bend. The $\Delta p/p = 2\%$ off-momentum orbit is also shown.

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TABLE III - WNR-RING LATTICE, BEST OF EACH TYPE

Description	Ref Date (1971)	Structure	K_f or B'_f	K_d or B'_d	Longest Drifts		v_x	v_z	Max Values in Bends			Max in Lattice			γ_{tr}
					No.	Length(m)			β_x (m)	β_y (m)	$ x_{eq} $ (m)	β_x (m)	β_y (m)	$ x_{eq} $ (m)	
4-cell, sep-func, 90°, 20-kG bends and doublets (Fig. 2)	4/12		1.325 kG/cm	-1.515 kG/cm	4	6.09	2.75	2.75	2.954	13.803	0.685	7.471	18.449	1.833	0
16-cell FOFOOD, 12-kG magnets	4/12	FOFOOD	8.823/m	-9.242/m	16	1.06	3.25	3.25	4.348	3.564	1.063				
4-cell, sep-func, 20-kG and triplets	4/12		1.229 kG/cm	-2.241 kG/cm	4	4.0	2.75	6.25	3.242	3.863	0.85	25.25	7.478	3.095	
FOFDOD Racetrack and π -2 π	4/24	FOFDOD			2	5.0	3.75	2.75	4.963	5.119	2.164	10.059	49.862	2.164	
FOFDOD Racetrack and π -2 π	4/24	FOFDOD			2	5.0	3.25	2.25	5.369	5.515	3.692	10.079	33.937	3.692	
12-cell FOOFDOD, 12-kG magnets	4/24	FOOFDOD	8.345/m	-7.9/m	12	1.58	4.25	4.25	4.154	8.534	0.637				
FDFD Racetrack, π -2 π	4/30	FDFD			2	5.0	4.25	2.25	4.253	7.051	1.346	10.199	37.2	1.346	
4-cell, sep-func, 90°, 10-kG bends and doublets	4/24		1.25 kG/cm	-1.5 kG/cm	2	6.09	2.52	2.89	3.722	13.01	0.413	6.801	17.378	2.042	
8-cell, low-gradient, separated-function	5/4		0.2 kG/cm		8	2.72	1.86	0.60	4.398	16.931	2.263	4.628	16.931	2.454	
8-cell, low-gradient, sep-func (Fig. 3)	5/4		0.6 kG/cm	-0.2 kG/cm	8	2.72	2.47	1.37	6.646	7.603	1.738	8.043	9.517	2.023	2.47
Cal-Tech 8-cell A.G.	5/10	FBDBF	7/m	-12/m				2.20+ N_{LSS}	0.868+ N_{LSS}	2.278	5.528	0.911			
Cal-Tech 8-cell A.G.	5/10	BFBDB	9/m	-8/m				1.708+ N_{LSS}	0.592+ N_{LSS}	2.648	7.570	1.423			
Cal-Tech 8-cell A.G.	5/10	BFBDB	13/m	-13/m				1.93+ N_{LSS}	1.64+ N_{LSS}	2.589	3.034	1.178			
Sep-func racetrack with LSS (Fig. 4) 20-kG bends	5/12		1 and 2.93 kG/cm	0.4 and -3.48 kG/cm	2	6.03	4.375	1.772	4.769	9.849	1.291	6.636	17.163	1.291	2.95
Cal-Tech A.G. race-track with LSS (Fig. 5)	5/27	FDFD	3/m	-4/m	2	6.254	4.069	2.258	3.54	5.71	1.23				1.95
Cal-Tech A.G. four-square with LSS (Fig. 6)	6/30	FDFD	3.5/m 1.42 kG/cm	-4.5/m -1.38 kG/cm	4	6	6.39	3.41	3.697	1.57	1.00029	20.12	2.924	2.33	
Cal-Tech A.G. racetrack 4-MHz (Fig. 7)	12/2	FDFD	3.2/m	-4/m	2	7	4.39	2.23	5.59	9.93	1.072	7.67	22.6	1.07	3.40

Fig. 10. Radial (upper) and vertical (lower) beam-oscillation amplitudes in the long straight section. Same emittance as Fig. 9.

B. Injection

1. General Discussion. Liouville's theorem¹⁷ states that in a conservative system, phase density is also conserved. Table IV shows an $a_x = 200$ cm mrad; $a_y = 67.8$ cm mrad phase space available in the drift region. The injected beam is expected to have emittances of $\epsilon_x = \epsilon_y = \pi/3$ cm mrad. Hence, within the bounds of Liouville's theorem, 192 turns could be injected into the radial betatron phase space and 65 turns into vertical betatron phase space, or 12,480 turns into the combined spaces. For a peak injected current of 17 mA, only 5900 turns (assuming 100% efficiency) need be injected to provide the 100 A of circulating beam. Previous accelerator experience, however, indicates that only a few turns can be injected in this manner. For the Omnitron study, an injection scheme was devised for stacking 30 turns in betatron space.

The CERN-ISR is loaded by injecting 800 turns into synchrotron space, i.e., injection by varying the energy between the incoming particles and the

TABLE IV

SUMMARY OF PROPERTIES OF PROPOSED WNR RING

Overall Properties

Max Dimensions: 21.2 x 10.94 m (69.6 x 35.9 ft)
 Period: 250 nsec
 Circumference: 63.01 m (206.7 ft)
 Equivalent Radius: 10.03 m (32.91 ft)
 Design Particle Kinetic Energy: 800 MeV
 Design Particle γ : 1.8526
 Design Particle β : 0.84181
 Design Particle Magnetic Rigidity (BP): 4.881 Tm
 Design Particle Momentum (pc): 1.4633 GeV
 Design Particle 1/velocity: 3.9625 nsec/m
 Ring Tune: $\nu_x = 4.39$, $\nu_z = 2.23$
 Ring γ Transition: 3.4023; $\eta = 1/\gamma^2 - 1/\gamma_{tr}^2 = 0.2050$
 Maximum Ring Momentum Spread: $\Delta p/p = \pm 2\%$
 Injection Emittance: $\epsilon_x = \epsilon_y = \pi/3$ cm mrad
 Injection-Momentum Spread: $\Delta p/p = \pm 0.2\%$
 Form Factor: $F_x = 3.36$, $F_y = 5.02$, $\langle F \rangle = 4.19$

90° Sector

Radius of Equilibrium Orbit: 3.7592 m
 Equilibrium-Orbit Guide Field: 12.9839 kG
 Gradient-Profile Parameters: $K_f = 3.2/\text{m}$; $K_d = -4/\text{m}$
 Magnetic Gradient: $n_f = -12.03$; $n_d = 15.04$
 Maximum β : $\hat{\beta}_x = 5.59/\text{m}$; $\hat{\beta}_y = 9.93/\text{m}$
 Maximum x_{eq} : 1.072 m
 Aperture: 10 x 20 cm (3.94 x 7.87 in., approximately elliptical)
 Magnet Power: 1 MW
 Magnet Weight: 155 tons of iron; 18 tons of copper
 Magnet Cooling: 92.1 gpm for $\Delta T = 40^\circ\text{C}$
 Pressure Differential: ~ 175 psi

$\pi-2\pi$

Insert Length: 17.74 m (58.2 ft)
 Center Drift Length: 7 m (23.0 ft)
 Quadrupole Gradients: 0.4419 kG/cm; -1.5192 kG/cm; 1.51424 kG/cm
 Quadrupole Magnetic Length: 10 cm (4 in.); 35.6 cm (14 in.); 35.6 cm (14 in.)
 Quadrupole Aperture: 15.24 (6 in.)
 Minimum Aperture: 13.97 cm (5.5 in.)
 Quadrupole Power: 30.8 kW each
 Quadrupole Cooling: 2.9 gal/min
 Admittance: $a_x = 200$ cm mrad; $a_y = 67.8$ cm mrad

stored beam. This can be done because the stored beam is out of synchronism with the rf voltages used to modify the energy of the particles being raised to a parking orbit. This injection scheme, which requires about 1 h to fill the storage ring, has an efficiency of 50%. This was the first injection scheme studied for the WNR ring, but it was rejected because of the 50% loss which would have created undesirable radioactivity in the ring, because of problems imposed in shifting the synchrotron frequency at the 120-pps rate of LAMPF, and because of expected poorer LAMPF beam quality compared with the CERN-PS which is the injector for the CERN-ISR.

Professor F. C. Shoemaker, of Princeton, after examining the various parameters and design goals, suggested two rings. The first would receive protons by storing in betatron space up to the limit of this technique. This would be done with a large enough rf voltage to contain the momentum spread. Then the rf voltage would be adiabatically decreased to homogenize the beam. A final momentum spread of $\Delta p/p \approx 0.01\%$ was expected (see Sec. IV.A). This very high-quality beam would then be stored by injection into synchrotron space of a second ring in the manner of the CERN-ISR. As beautiful as this scheme is, it was rejected because of complexity in favor of the charge-exchange injection technique advocated by Nagle. However, a variation is discussed in Sec. II.A.2.

2. Charge-Exchange Injection. In the same paper⁴ that established the principle of the tandem Van de Graaff, Alvarez also stated the principle of charge-exchange injection into a circular accelerator. The first known test of the scheme was the work of Budker and Dimov at Novosibirsk.⁵ A 1-MeV beam of H^- ions charge-exchanged into a ring of 100-nsec period for about 1000 turns resulted in 1-A circulating current. This circulating current is about 1/2 that allowed by incoherent space-charge effects. The stripping was accomplished by a pulsed nitrogen jet.

Argonne National Laboratories is working on charge-exchange injection into the Cornell synchrotron which is being remodeled into a storage ring.¹⁹ The beam from this ring would be used to inject into the Zero Gradient Synchrotron (ZGS) at a higher energy than the original design. Meanwhile, experi-

ments on charge-exchange injection directly into the ZGS are under way.

The Tri-Universities TRIUMPF sector-focused cyclotron, which should have nearly a tenth the intensity of LAMPF, will use H^- stripping to extract a proton beam with 100% efficiency.²⁰ The inefficiency of extraction from circular accelerators has been a primary reason for the linear accelerator design of LAMPF.

A stripper employing photons and electric or magnetic fields would be ideal. It could be pulsed, beam heating would not be a problem, and beam scattering would be minimized. However, direct electric stripping, even to H^0 , is not practical. Magnetic stripping to H^0 is very easy; a 5-kG field, equivalent to an electric field of 2.3 MV/cm, will strip H^- ions to H^0 ions in 2.2 μ sec. Because the binding energy of this electron is only 0.755 eV, impractically high magnetic fields would be required to strip H^0 ions to protons for which the binding energy is 13.5 eV.

A proposed initial experiment on LAMPF²¹ employs a 45-MW laser injecting into a mirror cavity to produce electric fields strong enough to strip H^- to H^0 . The laser pulse will be only of such duration that one micropulse will be affected. This neutralized bunch will be separated from the rest of the beam by magnetic selection, and the H^0 pulse will be stripped to protons in a foil.

Having found that a material stripper is necessary to extract the last electron, we must decide where this will be done in the ring and just what form this stripper must take. A further condition is that the stripping must occur in the circulating beam region because stripping before the beam has reached this region is tantamount to proton injection.

In the injection shown in Fig. 11, advantage is taken of two facts: H^- ions follow the mirror-image trajectory of protons in the same magnetic field, and the 2π radial phase advance in the straight section allows the type of injection shown. The equilibrium-orbit deflectors are shown causing the phase to advance by π , and the H^- beam is injected on a mirror-image trajectory. This requires a very shallow angle of injection. An alternative would be to cause the first equilibrium-orbit deflector to over-deflect so that the beam would be

Fig. 11. H^- injection using a mirror-image path and the orbit-shift magnets. Q1, 2, 3 are half the quadrupoles for a π - 2π insert. OS is the orbit-shift magnet.

Fig. 12. H^- injection using a mirror-image path, excessive orbit shifting, and a wedge magnet.

Fig. 13. H^- injection using magnetic stripping to H^0 . S is the stripping magnet.

bending slightly outward (Fig. 12). A mixer magnet would cause an equal inward trajectory for the protons. The H^- ions following the mirror image of the protons would merge with them on leaving the mixer magnet.

The techniques shown in Figs. 11 and 12 have the following problems: (1) The H^- beam must be small and must enter very near the center of Q_4 to avoid being magnetically stripped, (2) both techniques complicate the injection-extraction region which is already fairly crowded, and (3) both reduce the latitude on stripper types. The method shown in Fig. 12 may introduce a superperiod of one into the ring. In spite of these objections, either scheme could be added later without a major redesign.

Figure 13 shows the H^- beam being focused and magnetically stripped, and entering the ring on the equilibrium orbit in the straight section. Magnetic stripping is used because Allison and Emigh's data²² show that, at the optimum thickness for material stripping, the ratios for $H^-:H^0:p$ are 20:60:20%. This 40% beam loss would be inefficient and would produce radioactive buildup.

To use magnetic stripping, it must be shown that neither the statistical nature of the stripping nor the effects of the stripping magnet's fringing field will cause an undesirable increase in beam emittance.

We begin by assuming that the decay from H^- to H^0 in a magnetic field²³ is represented by

$$f^- = e^{-t/\tau}, \quad (1)$$

where f^- is the fraction of the original H^- beam after time (t);

$$\tau(\text{sec}) = \frac{7.96 \times 10^{-14}}{\epsilon} e^{42.56/\epsilon}, \quad (2)$$

and

$$\epsilon = 0.3 \beta \gamma B, \quad (3)$$

where ϵ is the electric field gradient in megavolts per centimeter, β and γ have the usual meanings, and B is the magnetic field in kilogauss.

The rate of formation of H^0 ions is obtained by differentiating Eq. (1).

$$\frac{df^0}{dt} = \frac{1}{\tau} e^{-t/\tau}. \quad (4)$$

Time is not of direct interest, but the spatial distribution of H^0 formation, obtained from $x = \beta c t$ where x is the depth of penetration of the fringing field, is. With this change of variables,

$$\frac{df^0}{dx} = \frac{1}{\tau \beta c} e^{-\beta c x / \tau}. \quad (5)$$

We will now assume that the fringing field is zero one gap distance away and increases linearly in the direction of the magnet; i.e., $B = B_0 x/g$ (note that time is also taken to be zero at $x = 0$). Using these assumptions; Eqs. (2), (3), and (5); and reasonable values for $B_0 = 20$ kG and $g = 6$ cm, we show the distribution function df^0/dx in Fig. 14.

The differential angular deflection of the H^- ion in the fringing field is

$$d\theta = \frac{B_0 x dx}{(B\rho) g}, \quad (6)$$

where the same linear assumption on the fringing field has been used. The angular deflection of the H^- ion in this field before it strips is

$$\theta = \int_0^x \frac{B_0 x dx}{(B\rho) g} = \frac{B_0 x^2}{2 (B\rho) g}; \quad (7)$$

Fig. 14. Fraction of H^- ions stripped to neutrals as a function of depth (df/dx) in the magnetic-stripping field and of deflection from the beam axis (df/dl).

however, we need not the angle, but the deflection (l) of the H^- beam on the stripper located at distance L inside the lattice.

$$l = L \theta, \quad (8)$$

so

$$l = \frac{L B_0 x^2}{2(B\rho) g}. \quad (9)$$

Equation (9) can be used to change the variables of Eq. (5) to l and df^0/dl , using $L = 7$ m. Figure 14 which also shows this functional dependence, indicates that the beam would be broadened by about 1 cm if magnetic stripping were used as outlined. [Logarithmic differentiation of Eq. (9) shows that the magnetic dispersion due to the beam-momentum spread is an insignificant effect compared with the stripping dispersion.] Hence, the 1-cm angular deflection at 7 m is slightly less than a milliradian, so

Fig. 15. Stripping cross section for various materials as a function of energy.

one can safely assume that the beam emittance in the radial plane will be increased 1 cm mrad by magnetic stripping.

Having injected an H^0 beam into the ring with little emittance degradation, we must now indicate a method for conversion to protons. The first problem is to determine the quantity of material required to perform the conversion with 1% or less H^0 contamination. Cross sections, σ_{01} , for stripping H^0 ions to protons are available mostly at energies below 1 MeV and are summarized in S. K. Allison's review papers.^{24,25} Above 1 MeV and below 18 MeV, there are some data by Smythe and Toevs;²⁶ at 50 MeV there is an unpublished datum from TRIUMPF.²⁷ Considering the paucity of appropriate data, extrapolation schemes had to be developed. These were reviewed by Thiessen²⁸ who proposes using Bethe's primary specific ionization j_p ²⁹ as the scaling factor. This is the same as P. W. Allison's last suggestion of energy scaling by dE/dx . Figure 15 shows this energy scaling (solid line) normalized to the data of Smythe and Toevs. The ordinate is plotted as σ_{01}/Z where Z is the atomic number of the target atom, because this seems to remove much of the atomic dependence, as demonstrated by S. K. Allison's data at 1 MeV. The Smythe and Toevs hydrogen data do not scale as $1/E$

as they should for low energy according to Wright's theory³⁰ and from the dE/dx postulated energy dependence. Note that the Smythe and Toevs point for argon does not extrapolate back to S. K. Allison's data at 1 MeV. Despite these apparent inconsistencies, we use a single curve,

$$\frac{\sigma_{01}(E)}{Z} = \frac{1.41 \times 10^{-18} (dE/dx)_E}{(dE/dx)_{10 \text{ MeV}}},$$

for all elements. This is the curve for nitrogen and oxygen in Fig. 15. This choice extrapolates well to S. K. Allison's nitrogen, argon, and hydrogen data at 1 MeV.

The fraction of protons after the beam has penetrated a stripper δ atoms/cm² thick²⁴ is

$$F_p = \left(1 - e^{-\delta \sigma_{01}} \right),$$

where the cross section, σ_{10} , is assumed to be zero. For $F_p = 0.99$, $\delta \sigma_{01} = 4.6$. From Fig. 15, $\sigma_{01}/Z = 5.83 \times 10^{-20} \text{ cm}^2$; hence, for 1% H⁰ contamination the stripper must have a thickness of $\delta \approx 7.89 \times 10^{19}/Z \text{ atoms/cm}^2$.

Table V presents thicknesses and other parameters for various solid strippers. Important criteria are high melting points, low energy loss, and low multiple scattering. Boron, although attractive, is not readily fabricated, whereas carbon is fabricated in 5- $\mu\text{g/cm}^2$ thicknesses, 1-cm square.³¹ Nickel is readily fabricated in thin sheets. There may be considerable latitude in the choice of a solid stripper, but for our immediate purposes, we will use carbon as an example.

The best location for the stripper is the off-momentum crossover (Fig. 10) with $\beta_x = 5.79 \text{ m}$ and $\beta_y = 14 \text{ m}$, which will be considered later for a vapor stripper. However, to reduce stripper heating, the equilibrium orbit-shift magnets will be used to shift the beam away from the foil. Thus a location immediately after Q_3 is selected for the carbon stripper; here $\beta_x = 7.67 \text{ m}$ and $\beta_y = 5.79 \text{ m}$. We will assume that the injected H⁰ beam has an emittance of $\epsilon_x = 2\pi/3 \times 10^{-5} \text{ mrad}$, or is doubled by the magnetic stripping. The least beam enlargement results from matching the injected beam $\hat{\beta}$ to the ring β at this location.¹⁷ With this assumption, the beam size should be 1.54 and 1.16 cm in the x and z planes, respectively

TABLE V
PROPERTIES OF VARIOUS SOLID ELEMENTS FOR 99% STRIPPING
OF H⁰ IONS BY ONE STRIPPER TRAVERSAL

Element	Melting Point(°C) ^a	$t(\mu\text{g/cm}^2)$	$t(\mu\text{m})$	$\Delta E(\text{keV})^b$	$\sqrt{\theta^2}(\mu\text{rad})^c$	Work Function(eV) ^a
Al	660.2	272	101	508	17.5	4.08
B	2300.	283	121	563	10.1	4.5
C	2355.	262	131	563	10.8	4.6
Cr	1083.	287	32	472	27.6	----
Ni	1453.	275	31	473	27.1	5.03
Os	3000.	328	14.5	420	48.8	4.55
Pt	1769.	328	15.3	420	49.8	5.36
Ag	960.8	301	28.7	443	36.7	4.56
Ta	2996.	325	19.7	420	46.2	4.19
Ti	1675. (3260 b.p.)	285	62.8	476	23.4	3.95
W	3460.	326	16.9	420	47.5	4.52
Zr	1452.	299	45.8	465	33.2	4.21

^aRef. 32.

^bRef. 33.

^cRef. 34.

The required low-duty beam requires 10 macro-pulses of the LAMPF H^- beam, or 2×10^4 turns. The beam's angular divergence will increase as $\sqrt{N}$ where N is the number of foil traversals. Using the carbon data from Table V, we find the angular spread from 2×10^4 traversals to be 1.4 mrad. Toward the end of the injection, the circulating current is 34 A, which if it all intercepted the stripper would be 1.91×10^4 W. The problem is to reduce this power dissipation so that it will not destroy the stripper.

The mechanisms of stripper cooling are conduction, radiation, and thermionic emission (a type of evaporation). Conduction is easily shown to be insignificant. Northcliffe³⁵ and Mackenzie³⁶ have analyzed radiation cooling of strippers. The Stefan-Boltzmann equation is

$$W_T = \epsilon \sigma (T^4 - T_o^4) ,$$

where T_o is the ambient temperature, $\epsilon = 0.81$ for carbon (Table V), and $\sigma = 5.67 \times 10^{-12}$ W/cm² - °K⁴ (Ref. 32). The radiative power density for carbon is presented graphically in Fig. 16.

Fig. 16. Power dissipation and thermionic current density from a carbon stripper as a function of temperature.

Vacuum-tube emitters are often cooled when heavy currents are drawn; a related phenomenon is ionic cooling of electronic components.³⁷ In the development of direct-power converters using thermionic emission, the power removed by this cooling must be replaced by the heat source.³⁸

Each electron emitted carries an energy of $\phi_E + 2$ kT, where ϕ_E is the work function of the emitter (stripper, in this case) and 2 kT is the average kinetic energy of the evaporated electrons. The current density is obtained from a modified form of the Richardson's Equation to give a rate of

$$W_e = 1.2 \times 10^2 (\phi_E + 8.62 \times 10^{-5} T) T^2 e^{-1.16 \times 10^4 \phi_E / T} \quad (W/cm^2) ,$$

where ϕ_E for carbon (Table V) is 4.7 eV and T is the emitter temperature in °K. This also is plotted in Fig. 16 as well as the sum $W_e + W_T$.

Stripper heating can be reduced by use of the beam's betatron oscillations. Figure 17 shows the beam being injected 0.96 cm below the equilibrium orbit and 2.49 cm to the right of center. If the equilibrium orbit were held fixed in the center of the vacuum pipe as shown, the beam would fill the aperture as shown, but the current density would not be uniform. We will therefore have to inject in conjunction with equilibrium shifting to obtain a

Fig. 17. Beam dispersion by betatron oscillations and stripper changer.

uniform current distribution. If this is done, the ratio of current intercepting the stripper to that of the whole beam is 1:12.93; therefore, the peak heat dissipation in the stripper is $1.9 \times 10^4 / 12.93 = 1.477$ kW. The stripper area is 2.66 cm^2 (the stripper has two sides) resulting in a power density of 555 W/cm^2 . Figure 16 shows the temperature at this power density to be 3100°K . Table VI gives the final temperature as a function of macropulse number.

TABLE VI

CARBON STRIPPER TEMPERATURE AS A FUNCTION OF INJECTION-CYCLE NUMBER

Injection-Cycle Number	Max Power Density (W/cm^2)	Max Temperature ($^\circ\text{K}$)
1	55.5	1750
2	111	2200
3	166.5	2400
4	222	2600
5	277.5	2750
6	333	2850
7	388.5	2900
8	444	3000
9	499.4	3050
10	555	3100

Note that if electron-emission cooling were not used the peak temperature would be 3350°K . By the same token, use of a stripper with a smaller work function would considerably reduce the temperature. Thoriated tungsten might, therefore, be a useful stripper material if it can be fabricated thin enough. Table V indicates a very high rms scattering for tungsten; however, when the dilution factor from off-axis injection is used, the total rms scattering is only 1.86 mrad .

These high temperatures require investigation of the stripper evaporation rate. Figure 18 shows data from the Smithsonian Physical Tables³⁹ adjusted to express the percent of evaporation per second. At the final temperature (3100°K) of Table VI, the target is evaporating at $60\%/ \text{sec}$; however, because the whole injection cycle requires only 0.1 sec (the beam is on for only 5 msec), less than 6% of the target evaporates during one injection. Note that there has been no allowance for stripper cooling due to the heat of vaporization removed by evaporation, because of the absence of data.

Fig. 18. Carbon target evaporation as a function of temperature.

From the foregoing arguments, carbon is a possible stripping material but it seems to have a short lifetime. There may be better materials, especially those with a lower work function so that thermionic cooling can become effective at a lower temperature.

Before leaving the discussion of solid strippers, we note that there is a useful procedure whereby a carbon stripper can be held at 1750°K . This method is very similar to Shoemaker's suggestion: a macropulse of H^- is injected using a carbon foil to strip. A 201-MHz cavity operating in phase-lock with LAMPF would be operated at such voltage that the micropulses could be accepted. During the LAMPF off cycle, the rf voltage would be adiabatically decreased, homogenizing the energy. This method produces the necessary packing density for synchrotron space. Next, or concurrently, the beam energy would be shifted so that on the next injection cycle the previously stored beams would not intercept the stripper. To estimate the energy gain or loss needed per turn, x_{eq} is 1.072 m ; to shift the beam by 1.54 cm (the width of the stripper) requires a momentum shift of 1.44% and an energy shift of 2.21% . This is 17.71 MeV occurring in $7730 \text{ } \mu\text{sec}$, or $30,920$ revolutions of the beam in the ring; hence, the

energy change per turn is 572.9 eV. This is easily done, and we give further analysis in Sec. IV.

Vapor stripping is an attractive alternative to solid stripping because of the possibility of rapid insertion and removal of the stripper and because the heating problem is ameliorated. A gas-jet stripper was used in the charge-exchange-injection Novosibirsk storage ring;⁵ a sodium-vapor beam is used for beam-profile scanning in the ISR storage ring;⁴⁰ and a supersonic lithium jet is used for stripping cross-section measurements.⁴¹

The vapor stripper required for the WNR ring differs from those just cited in that a much larger amount of material is required in the beam. Smith⁴² describes a titanium getter pump using electron-beam evaporation of 500 g/h of titanium. The mean velocity of these atoms is

$$\bar{v} = 0.22 \sqrt{\frac{T(^{\circ}\text{K})}{A \cdot 300}} \text{ cm}/\mu\text{sec} ,$$

where A is the atomic number of titanium, and T is the vapor temperature which, because the atoms lose 7.02 eV in evaporating, is not the same as the temperature of the sputtering surface. As a working number, assume that T is 900°K; then $\bar{v}$ is 55 cm/msec. The number density of titanium atoms is

$$N(\text{atoms}/\text{cm}^3) = j(\text{atoms}/\text{cm}^2\text{-sec})/\bar{v}(\text{cm}/\text{sec}) ,$$

where j is the current density of the stripper beam.

A reasonable location for this stripper is at the off-momentum crossover following Q_1 . Here the β functions are $\beta_x = 0.579$ m and $\beta_z = 1.40$ m. Again, if the injected beam of $\epsilon = 2\pi/3 \times 10^{-5}$ mrad is matched to the lattice, the beam will be 3.92 mm wide and 6.11 mm high. Assuming that a suitable ventura can be designed so that the vapor is this wide, then for the 500-g/h pump and a 10-cm-long vapor, the current, j , is 4.46×10^{20} atom/cm²-sec. Thus, the thickness is 8.1×10^{16} atoms/cm², but the required thickness for 99% stripping is 3.58×10^{18} atoms/cm². This factor of 44 density increase can possibly be achieved by a 1-kG longitudinal magnetic field that would cause 0.345-cm spirals (assuming that the ions are singly charged and much smaller if multiply charged). Unfortunately, the electron beam must be about 100 keV to penetrate this mag-

netic field. To avoid this problem, we could use laser heating of the titanium.

P. W. Allison has suggested the hydrocarbon tran-Decalin ($\text{C}_{10}\text{H}_{18}$). It vaporizes at room temperature, so it would not require a boiler; also, it freezes out easily to a low vapor pressure. Its large molecule results in low velocity at room temperature such as is needed to increase the density. Unfortunately, there are no valves fast enough to admit the vapor with a short rise time compared with 500 μsec . Another problem is the probable radiation damage to the molecules.

Therefore, presently, radiation- and thermionic-cooled strippers with rf beam-orbit shifting seem the most satisfactory approach to this method of injection. Besides maintaining a satisfactory stripper temperature, this approach permits current storage that is not limited by the stripper.

Before discussing proton injection, we must examine the question of particle loss in the targets due to nuclear interactions. The cross section is about 50 mbar/nucleon, and the stripper attenuation is 7.88×10^{-6} after 20,000 traversals. Using the dilution factor of 0.077 due to injection as shown in Fig. 17, we find that the loss is 1.2% which is comparable to the 1% loss from not stripping all of the H^0 ions. Again, rf orbit shifting will reduce this loss to 0.12%.

3. Proton Injection. The problem of injecting particles into a closed ring designed to contain them seems insurmountable because, if time reversal is invoked, there is no particular reason why the particles would come out of the ring and go back up the injection channel.

Fortunately the problem is not this simple. It is possible to inject off the equilibrium orbit, and the normal betatron oscillations then cause the injected beam to miss the inflector for several turns (depending upon the tune). Most proton-injection methods have used this betatron injection for only a few turns, during which time the magnetic field or particle energy was changing; hence, further turns would miss the inflector. References to past work are contained in Kolomensky and Lebedev,⁴³ Livingood,⁴⁴ and the Green and Courant "Handbuch" article,⁴⁵ but perhaps the most advanced concepts are in the Omnitron Study⁴⁶ and the AGS Improvement Study.⁴⁷ The

scheme proposed here is an extension of this previous work.*

A plot of $\sqrt{\beta} x'$ or $x/\sqrt{\beta}$ transforms the elliptical acceptance volume of the ring into a circle with oscillations described as polar rotations. The problem is to pack the injected phase volumes (ellipses) into this circle most efficiently. It can be shown that if $\theta\beta = \text{Modulo}(2\pi \nu_x)$ and ρ is the equilibrium-orbit deflection in units of $x/\sqrt{\beta}$, then $\rho\theta\beta$ is constant and we find a hyperbolic relationship.

A physical realization of this type of injection is shown in Fig. 19. Note that the 27th turn would hit the inflecting septum. However, the injection shown is into radial betatron space, whereas vertical off-equilibrium-axis injection will produce oscillations that will cause the inflector to be missed. Indeed, a plot like Fig. 19 could also be devised for vertical space injection, but we have no plans for programmed injection into this space. Figure 19 also points up another problem of multi-turn injection; the filling efficiency is greatest at midcycle. Initially the inefficiency arises from packing ellipses using small off-axis injection; toward the end of the cycle, the inefficiency arises because the large radius of curvature does not allow the preceding turn to miss the inflector.

Fig. 19. Normalized betatron phase-space injection for 28 turns.

*The proton-injection method proposed here is by P. F. Meads of William Brobeck and Associates.

Fig. 20. Proton injection from outside the ring (Scheme A).

Fig. 21. Proton injection from inside the ring (Scheme B).

Fig. 22. Proton injection from outside the ring (Scheme C).

The hardware details of the preceding design,* except for the tune-shifting ferrite quadrupoles, have been investigated. Such devices have been used at CEA for Landau damping by tune shifts during the passage of the bunch.

Figures 20 through 22 show possible injection methods. The first two require that the injection and extraction septa be close together and enclosed in one vacuum box. Figure 22 places the injector just before the sector magnet and requires special quadrupole-magnet designs for compactness. The method shown in Fig. 21 is the most conservative but requires a beam-handling system for proton injection

*This study is by Robert T. Avery, LLL.

quite separate and distinct from that for H^- injection. However, unless indicated otherwise, it is the method being discussed. Central to all these techniques are the injection septa, SM-1 and SM-2.

Septum magnets^{48,49} are usually dc magnets of special shapes for production of ideally discontinuous magnetic field conditions. The dividing wall referred to in the name is typically millimeters thick and may be either current-carrying or ferromagnetic.

Figure 23 shows the design of SM-1 and its relation to the beam in the lattice. It is a one-turn magnet, with the square water-cooled copper bar being one of the conductors and the 3-mm water-cooled copper strip being the other conductor and the septum. The pertinent design parameters are abstracted in Table VII. This picture of a septum assumes that the field vanishes at the outer boundaries of the conductors and that there are no fringing fields at the gap ends. Both of these assumptions are untrue, so compensation by correcting windings is necessary. To a first order, both effects can be compensated for by a "back-leg" winding that shunts 1 to 3% of the current from either the septum or return conductor to produce $\oint \mathbf{B} \cdot d\mathbf{l} = 0$ along all trajectories. It may not be possible to make this integral vanish everywhere, and some trim windings along the iron core may be necessary.

Figure 24 shows the conceptual design of SM-2. Here greater distance from the circulating beam permits three turns of copper, but the gap is larger (0.560) than in SM-1 because of the assumption that the beam is brought to a small-diameter focus

Fig. 23. Current septum magnet SM-1 conceptual design.

TABLE VII
SEPTA DESIGN PARAMETERS

	SM-1	SM-2
Field	3.9 kG	7.8 kG
Length	60 cm	60 cm
Deflection Angle (800-MeV protons)	48 mrad	96 mrad
Gap	0.375 in.	0.56 in.
Magnetic Efficiency	99.4%	99.3%

Septum Values

Turns	1	3
Current Density	14 kA/cm ²	5.25 kA/cm ²
Resistance	0.67 mΩ	0.25 mΩ/turn
Voltage	2.0 V	0.75 V/turn
Current	3.0 kA	2.95 kA
Power	6.0 kW	2.2 kW
Cooling	0.7 gpm	0.7 gpm
Pressure Drop	68 psi	---

Septum and Return

Resistance	1.5 mΩ	1.5 mΩ
Voltage	4.5 V	4.5 V
Current	3 kA	3 kA
Power	13.5 kW	13.5 kW
Temperature Rise	30°C	---
Cooling	1.9 gpm	2.1 gpm
Pressure Drop	91 psi	69 psi

Fig. 24. Current septum magnet SM-2 conceptual design.

Fig. 25. Relationship of the septa to the injected and stored beams (not to scale).

immediately after SM-1. The design parameters of SM-2 are also summarized in Table VII. The relationship between the septa and the injected and circulating beams is shown in Fig. 25.

C. Extraction*

1. Fast Extraction. Having filled the ring with protons by charge exchange or direct proton injection into betatron space, we must now extract the beam in a fraction of the rotational period.

As guides to extractor design there are reviews by Reich⁵⁰ and Forsyth and Fruitman,⁵¹ as well as many unpublished documents. Extraction from the WNR ring poses an unusual high-duty problem by requiring that the "kicker" (fast-deflection magnet) have not only a fast rise time but also a fast fall time with essentially full recovery after the pulse. These conditions are posed by the desire to remove a single bunch, leaving the other four bunches undis-

*The designs discussed in this section are primarily those of Avery and Faltens, LBL.

Fig. 26. Kicker pulses. High-duty mode (top), low-duty mode (bottom).

turbed and circulating in the ring. These two mode requirements are shown in Fig. 26.

To minimize costs and satisfy the stringent requirements for high-duty operation, the flatness of the beam (Fig. 27) suggests a vertical kick. This requires less deflection angle, hence less kicker field, than any other scheme studied.

Because of WNR architecture and the shielding thickness above the ring, an iron septum in the long straight section is used to intercept the beam and deflect it horizontally (Fig. 28). The kick in the vertical plane is shown in Fig. 29.

Fig. 27. Beam shape at the extraction septum.

Fig. 28. Horizontal-beam extraction with an iron septum.

Fig. 29. Vertical kick into the iron septum. 0: 1 m from sector magnet exit; 1: kicker midlength at $s = 6$ cm; 2: start of septum at $s = 4.87$ m; 3: center of insert at $s = 7.87$ m.

Using this conceptual design, the first step will be to determine the deflection sensitivity when deflecting through the quadrupole lenses. Next, the septum design must be established, and, finally, we return to the design of the kicker and its pulsing circuitry.

We assume that the kicker is a short distance (location 1 in Fig. 29) downstream from the entrance (location 0) of the π - 2π insert. The transfer element from location 0 to the midpoint of the long drift (location 3) is especially simple:

$$\begin{pmatrix} y \\ y' \end{pmatrix}_3 = \begin{pmatrix} 0 & f \\ -1/f & 0 \end{pmatrix} \begin{pmatrix} y \\ y' \end{pmatrix}_0,$$

where f , the focal length, is 2.928 m.

The matrices for the drift spaces (0) to (1) and (2) to (3) are:

$$\begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix}_{01} ; \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}_{23}$$

Hence, the transfer matrix is

$$\begin{pmatrix} y \\ y' \end{pmatrix}_2 = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 0 & f \\ -1/f & 0 \end{pmatrix} \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix} \begin{pmatrix} y \\ y' \end{pmatrix}_1.$$

This is evaluated numerically to give

$$\begin{pmatrix} y \\ y' \end{pmatrix}_2 = \begin{pmatrix} 1.0246 & 2.866 \\ -0.3415 & 0.02049 \end{pmatrix} \begin{pmatrix} y \\ y' \end{pmatrix}_1,$$

for $l = 6$ cm and $L = 3$ m. Hence, $y_2 = 2.866 y'_1$, and to get a 3-cm displacement of the beam at the septum entrance requires 10.5 mrad of kick. The beam angle in the septum will be 0.225 mrad. If the septum is 3.25 m long, the height gain therein will be 0.7 mm. Referring to Fig. 10, note that the vertical envelope decreases from 0.93 cm at the entrance to 0.80 cm at the exit. These effects provide an additional 2-mm clearance at the exit.

Figure 30 shows the iron extraction septum and how the kicked and unkicked beam would fit. This 3.0-cm deflection is $\sim 20\%$ more than the minimum needed for extraction. Figure 31 shows the appearance of the full septum in 1/4 scale. The parameters are listed in Table VIII.

Fig. 30. Iron horizontal-extraction septum.

Fig. 31. Full drawing of the iron horizontal-extraction septum.

TABLE VIII

WNR-RING EXTRACTION-SEPTUM PARAMETERS

Magnetic Field:	1200 G
Deflection Angle:	80 mrad (4.6°)
Septum at Thinnest:	0.3 mm
Leakage Field:	~ 3 G
Steel:	1010 Annealed at 1500°F
Length:	3.25 m
Turns:	8
Current:	550 A
Conductor:	Copper, 0.340-in.^2 , 0.1835-in. -diam cooling hole
Resistance:	$18.4\text{ m}\Omega$ for each of the two coils
Total Voltage:	22 V
Total Power:	12.1 kW
Water Flow:	2.4 gpm
Pressure Drop:	80 psi (no manifold allowance)
Weight:	130 lb copper; 2950 lb steel
Special Requirements:	Because the coil is in vacuum and the desired vacuum is $< 10^{-8}$ Torr, inorganic insulation will be required. Because of the low coil voltage, glow discharge should not be a problem.

This design uses back-leg coils in preference to saddle coils which might adversely affect the beam owing to stray fields.

We now consider the kicker used to deflect the beam into this extractor. The high frequencies involved rule out the use of steel to shape the field. Figure 32 shows a conceptual design formed of two conductors. Heavy currents flow in opposite directions, so the B field is horizontal and the kick is vertical.

To achieve the necessary 10.5 mrad of kick, 512 G are needed for 1 m (at 800-MeV proton energy). 8000 A will create a 570-G field to give a safety factor of 11%. The characteristic impedance of these plates in the geometry shown is $21.4\ \Omega$, and the voltage needed is 10^5 V.

Conceptually the driving pulses for such a kicker could use lumped constants; but, considering the pulse flatness, the rise time and fall time, and the

Fig. 32. Vertical kicker using flat conductors.

Fig. 33. Vertical kicker using capacity loading.

short pulse requirements, a distributed-constant pulse-forming network would probably be the most reasonable approach. However, 10^5 V on the conductor means, for a simple circuit, 2×10^5 V on the pulse-forming network before discharge. Usual high-voltage cables such as RG 19 or RG 222 are charged to only about 25 kV, so clearly something must be done.

At this point the design closely follows that of Brückner^{52,53} for the CERN-PI extractor; parallel-plate capacitive loading is used to reduce the transmission line impedance to $1.56\ \Omega$. This is the impedance of 32 RG 19 coaxial cables in parallel, and the 8000 A will be attained with 12,480 V or, using simple techniques, 24,960 V for charging the lines.

The most important design parameters are presented in Table IX, and the kicker is shown conceptually in Fig. 33.

TABLE IX

PARAMETERS FOR THE CAPACITY-LOADED VERTICAL KICKER

Deflection Angle:	10.5 mrad (0.6°)
Magnetic Field:	570 G
Effective Kicker Length:	1 m
Conductor Width:	12 cm
Required Current:	8000 A
Required Voltage:	12,480 V
Impedance:	1.56 Ω
Gap Width:	4 mm
Capacitor Plate:	55 x 24 cm ² , 0.6 cm thick
Number of Plates:	400 (both conductors and ground)
Propagation Velocity:	2.19 cm/nsec ($\beta = 0.073$)
Rise and Fall Times:	≤ 30 nsec

This β value would result in a kicker-filling time of 46 nsec. To handle the high-duty requirements, this must be shortened. Dividing the kicker in half and driving the halves separately shortens this time to 23 nsec.

There may be some question as to whether 4 mm of vacuum will hold off 25 kV. (If the kicker is not part of the pulse-forming network, this number is reduced to 12.5 kV.) LBL design data give the following dc breakdown voltages in vacuum (for a 4-mm gap).

Material	Voltage (kV)
316 Stainless Steel	360
Inconel	260
Copper	148
Aluminum	114

The paper by Bolin et al.⁵⁴ lists materials of increasing desirability as: carbon, beryllium, lead, aluminum, copper, nickel, iron, stainless steel, titanium, tantalum, molybdenum, and tungsten. They indicate that this gradient is satisfactory but close to marginal. They also present data indicating very substantial improvements (2x) from anodizing of the aluminum electrodes. They include data for metal oxides, fluorides, organic films, and epoxies. A dielectric coating on the cathode acts to inhibit field emission; a coating on the anode is usually detrimental. Hold-off voltage is improved

by conditioning the electrodes in vacuum under voltage. This application, however, is for short pulses, and the data on time-dependent effects are not conclusive; hence, dc values are assumed to apply.

The WNR extraction kicker is compared to others in Table X (other entries are from Ref. 51). This table shows that the problems are comparable to those of some very large accelerators. Note that both the present AGS kicker and the present CERN-PS kickers are capable of multishot operation like that required for the WNR ring, except that they have less stringent rise-time requirements and their recovery time is 150-200 msec, compared with the WNR-ring kicker-recovery time of 1.67 msec (or 25 nsec for the magnet).

Thus we come to the difficulties suggested above. The problem is that the best-known thyratrons (CX 1174) are rated for only 10,000 A/ μ sec; the present kicker design requires 100,000 A/ μ sec. We present various solutions, none of which can be guaranteed to be a solution, let alone the optional solution.

(1) Pushed Thyratrons

Apparently the anode rise-time current ratings are very conservative. Fudin⁵⁵ states that 20-nsec rise times to full current can be achieved. He cites data from CERN for a CX 1157 which indicate that the time to full current as a function of reservoir heater currents is 50 nsec at 5.8 V, 25 nsec at 6.2 V, 14 nsec at 6.6 V, and 12 nsec at 6.8 V. This application was for a spark-chamber pulser, and repetition rate information is unavailable. Fudin also refers to O'Hanlon and Zadasco's work (CERN)⁵⁶ using the CX 1168 at 50 kV and 1800 A. They find for the rise time as a function of reservoir voltage: 120 nsec at 5.0 V, 60 nsec at 5.5 V, and 40 nsec at 6.0 V. It is significant that the increase in reservoir pressure did not cause breakdown at 50 kV, which is the general effect of increasing the reservoir temperature. Time jitter cited in both of these reports is under 2 nsec. The data presented in Table XI compare various potential thyratrons for this application.

TABLE X

WNR-RING KICKER COMPARED WITH KICKERS OF REF. 51

Installation	Max Proton Energy (GeV)	Magnet Type	Individual Magnet Aperture w x h x L (cm ³)	No. of Magnet Sections	Total Deflect- ing Force (T-m)	E Max Charge (kV)	Z ₀ per Magnet (Ω)	Bunch Separation (μsec)	W _s (μW)	Switches	Comments
LASL WNR Ring	0.8	Trans- mission Line, Full Aperture	12 x 2 x x 50	2	0.058	25	1.56	50	128	Deuterium Thyratron?	Requires clean recovery for multiple pulse extraction.
CERN Booster Extraction Kicker	0.8	Trans- mission Line, Full Aperture	11.5 x 7 x 48	4	0.04	33	25 (produces E on ter- mination)	50	106	Deuterium Thyratron plus spark gap	Part of complex four- ring injection system.
Postconversion AGS Kicker	30	Lumped Magnet, Full Aperture	15.3 x 7 x 38	4	0.2	100	14	200	1240	4-Deuterium Thyratrons	Under development -- Blumlein circuit used.
Present AGS Kicker	30	Lumped Magnet, Full Aperture	15 x 6.7 x 38	4	0.08	40	7	200	170	2-Deuterium Thyratrons	Capable of full beam ex- traction or multiple single-bunch extractions 100 msec apart.
NAL Booster Extractor	8	Unloaded Trans. Line	6.9 x 6.9 x 100	4	0.03	70	50	45	19	4-Deuterium Thyratrons	No extra capacity needed to operate at this impedance.
CERN-PS Extraction	25	Trans. Line	15 x 5.5 x 23	12	0.17	80	15	100	750	36-Deuterium Thyratrons	Under development.
Present CERN-PS Kicker	25	Trans. Line Mobile	2.2 x 2 x 28	2	0.14	70	10	100	110	6-Spark Gaps	Capable of multislot operation after 150- to 200-msec recharge.

TABLE XI

POSSIBLE KICKER THYRATRONS

Tube Type	Peak Voltage (kV)	Forward Current (kA)	Peak Anode Cost	Remarks
CX 1174	40	6.0	\$2500	Ceramic deuterium tetrode
CX 1154	40	2.5	1590	Ceramic deuterium tetrode
CX 1159	33	1.0	590	Glass deuterium tetrode
7384	25	1.0	425	Glass hydrogen tetrode
CX 1180	25	1.0	985	Ceramic hydrogen tetrode

(2) Corrective Networks

A kicker is ideally a magnetic switch, and conditions intermediate to OFF or ON are not of interest except for the problems they present. Therefore, the use of capacitors, inductors, and stub lines at various places in the circuit to correct the performance is quite appropriate. Such trimming, although guided by theory, cannot be assured of success beforehand and is more suitable for model adjustment.

(3) Flux Concentration

The kicker shown in Figs. 32 and 33 uses no ferromagnetic materials. Ferrites have the necessary high-frequency properties and permeabilities of ~ 100 , and can, literally, be fabricated in any shape. It may be possible to design a ferrite-loaded kicker, conceptually shown in Fig. 34.

This concept has not been developed; it might provide a factor of 1.5 flux concentration that, in conjunction with solutions (1) and (2), would probably meet the requirements. The closed box as shown is probably not suitable because of possible leakage currents in the ferrite caused by the high electric fields. However it should be possible to introduce gaps across which the field could be developed with only negligible reluctance increase.

Fig. 34. Ferrite box loading of the kicker.

(4) Shock Lines

In the original planning for the kicker, we thought that the use of shock lines^{52,57} would keep the rate of current rise from posing a problem. Shock lines are transmission lines whose propagation velocity is a function of the voltage or current transmitted. Thus the "top" of the pulse goes faster than the "bottom," and a shock front with a rise time of ~ 1 nsec develops. In this application, the problem arises in trying to get fast turnoff at the trailing edge; the shock line tends to slow the fall times. Brückner⁵² uses a "tail-biting" spark gap to achieve fast turnoff. Objections to spark gaps are given in the next section.

One solution is to use a shock line with a clipping stub so that the fast rise is reflected and used to turn off the kicker (Fig. 35). The undesirable aspects come from the pulses that reflect from the end of the pulse-forming network (PFN) and travel back to the magnet. It may be possible to absorb these pulses in the charging network by switching in a load. Another problem is that the reverse wave brings the shock line out of saturation, causing impedance mismatch.

Katayev⁵⁷ shows an elegant solution using biased double shock lines (Fig. 36). The operation is substantially as follows.

Fig. 35. A shock line and clipping stub.

Fig. 36. Biased double shock line (Ref. 57).

The two PFN generate identical pulses; the two shock lines are prebiased with equal currents of opposite polarity but variable magnitude. If the pre-bias current is zero, the output pulse is zero. However, prebiasing oppositely causes more energy to be absorbed from the leading edge of one pulse than from the other, so it arrives later. The kicker is pulsed during the time between the arrival of these two shock fronts. The delay interval is controlled by the prebiasing currents used.

In principle, there should be no secondary pulses, both shock lines should stay in saturation, and the load resistors (Z_0) should absorb the reverse waves; however, such ideal operation would probably not be realized.

A decided disadvantage of this design is its complexity. Further, the thyatron has to carry four times the current required for the kicker. Because the deflectors are split to reduce the filling time, and because there are two conductors per deflector, 32 thyatrons each carrying 4 kA would be required. The operation of thyatrons in parallel requires balancing networks that add to the complexity.

(5) Spark Gaps

Spark gaps can readily achieve the required current rise times. They were used in the Stanford Mark III Linac and are used in the LBL Electron Ring Accelerator (ERA). The ERA experience is that after 5×10^5 shots at 10 kA, the gaps require processing. At the 600 pps of the high-duty mode, this is only 14 min of operation. To operate through 1 week (100 h) at high duty requires a spark gap life of 2×10^8 .

A possible approach suggested by Faltens⁵⁸ is the use of mercury-wetted iron-sponge spark gaps developed during World War II. Glasoe and Lebacqz⁵⁹ report operation of two such gaps in series at 24.5 kV, 925 A, 2 μ sec, and 240 pps with a lifetime in excess of 4×10^8 .

Spark gaps are commercially available only for "crowbar" applications, so lifetimes of 10^4 are satisfactory. Any designs embodying spark gaps would be a development task.

(6) Empty Bucket

It is certainly possible to devise an rf system or LAMPF injection-blanking system that would

leave one rf bucket empty, thereby doubling the time allowed to operate the kicker. This is an option that can be used at any time and which would reduce the intensity by 20%. It therefore seems unnecessary to use this recourse until the other options are shown to be infeasible.

(7) More Thyatrons

Certainly this approach is possible, but it is economically questionable and requires balancing networks.

(8) Hard-Tube Pulser

This approach is considered prohibitively expensive in view of the 100 MW to be switched, and there is no history of similar applications.

In conclusion, combinations of solutions (1), (2), and (3), being the least expensive, should be investigated first.

2. Slow-Spill Extraction. A storage ring is basically a duty-cycle manipulator; besides the requirement for pulse compression and, hence, fast extraction, there are applications for which slow extraction is desirable. One of the earliest schemes, the energy-loss target method,⁵⁰ is not suitable for the present design because of the vertically located extraction system.

A generally more efficient method that appears applicable to the WNR ring is resonance extraction. Resonance extraction seems to provide the advantages of efficient long-burst ejection with practically no increase in circulating-beam emittance. The basic idea is to shift the tune onto a betatron resonance that will cause large enough beam oscillation to enter the extraction system.

In the theory of resonance extraction,⁵⁰ the harmonic equation describing the beam motion is driven by a force represented by a harmonic expansion. For slow extraction resonances, one should use the nonlinear resonances above the second order because the betatron frequency is a function of amplitude which makes it possible to resonate the outer extremities of the beam while the rest is stable. Once the beam is unstable, the growth rate is faster than exponential.

Fig. 37. Quarter-scale bevatron (Cal-Tech synchrotron) during assembly.

No design work has been done on this type of extraction for the WNR ring, but it seems that with the fast tune control needed for the betatron injection and with the various trimming fields, this type of extraction is possible. A rather distressing point is that only about 70% efficiency has been achieved. This may cause an intolerable radioactive buildup in the storage ring and require modification of past techniques.

D. Sector Magnets

A key economy aspect of this proposal is the use of the quarter-scale bevatron/Cal-Tech synchrotron for the bending magnets. Figure 37 shows these 4-90° bending sectors during assembly at Berkeley. Figure 38 shows a sector with the placement of the F and D pole tips providing the strong focusing, and Fig. 39 gives more detail of the iron as well as a possible concrete supporting structure. Figure 40 shows details of the extruded vacuum chamber located between

these pole tips, and Fig. 41 shows the details of the pole tips.*

The Cal-Tech synchrotron as presently available is a weak focusing accelerator. It will be necessary to replace the present vacuum chamber and pole tips to adapt it for use as a strong-focusing, high-intensity storage ring.

Given the values for the profile parameters from Table IV, we must devise appropriately shaped pole tips for the magnets to realize these parameters. The design in Fig. 41 is not final; it was calculated on the basis of real, nonlinear iron in the pole tips and infinitely permeable iron in the return legs. The forward problem was calculated for the vector magnetic potential using the program POISSON; the inverse or synthesis was calculated using SMIRT.⁶⁰

The program POISSON originated with the two-dimensional weapons-diffusion code by Winslow (LLI).

*The present pole-tip design is by K. Halbach (LBL) assisted by S. Magary (LBL).

Fig. 38. Ninety-degree-sector magnet showing placement of F and D pole tips. Cross-section view of a sector.

Colonius (LBL) rewrote it into the program that solves Poisson's equation in vector-potential form using a triangular mesh along which the permeability is assumed constant. A new vector potential is expressed as a summation over old values plus an inhomogeneous current-source term and equals the old vector potential plus an over-relaxation term. About 200 iterations are required for a problem in infinitely permeable iron.

The synthesis programs, SMIRT or PISA,⁶⁰ invert the forward program by finding the parameter set that minimizes a weighted sum of the squares of the deviations between the desired and accomplished performance of a system. This is done subject to the restraining conditions that require certain perfor-

mance specifications to be met exactly. PISA is written in a general form for use on a variety of problems, but it is especially suitable for magneto-statics. The secondary variable (extensive parameter) is expressed as a weighted least-squares sum in which the weighting can be used advantageously when certain secondary variables (the magnetic potential) must be fitted more accurately than at other locations. The least squares are minimized using Lagrange multipliers subject to the restraining conditions that must be met exactly. The numerical solution of the problem follows from a Taylor's series expansion of the secondary parameters. The system parameters such as the permeability result from a solution by standard matrix methods.

Fig. 39. Ninety-degree-sector magnet and support stand.

Vogel and Yound⁶¹ have compared POISSON using the previously described triangular mesh with the program LINDA (by R. Christian, Purdue) which uses a quadrilateral mesh. If the boundaries are curved, the POISSON mesh triangles become severely distorted and accuracy is lost. If the magnet can be conformally mapped into a dipole, the mesh is fairly symmetrical and good accuracy is achieved. This was the procedure followed by Vogel and Yound who found good agreement between the two computational procedures. It seems from the foregoing that the pole-tip design should be recalculated for real iron and that results calculated by POISSON should be checked using LINDA before actual machining begins.

E. Vacuum System

Storage rings operate at $\sim 10^{-9}$ Torr vacuum without beam,⁶² and in electron storage rings the vacuum may deteriorate to $\sim 10^{-8}$ Torr with beam

owing to photo-gas desorption. In the CERN-ISR the vacuum is 10^{-9} Torr in the rings⁸ and 10^{-11} Torr in the interaction region. In that ring, the vacuum criterion is set by the requirement that the beam coast for > 10 h; in the interaction region, the criterion is set by the ratio of events due to beam-beam interaction and those due to beam background. In the specifications for the WNR ring, we assume that a vacuum of $\sim 10^{-9}$ Torr is required on the basis of the other storage rings; it is, however, interesting to apply some standard criteria to estimating the vacuum requirements.

Molière has obtained a formula for atomic scattering using a Fermi-Thomas potential which Courant⁶³ has applied to the problem of beam scattering. Using his formulae for 800-MeV protons and nitrogen as the residual gas, we find a cross section of

$$\sigma = 4.17 \times 10^{-33} \text{ m}^2,$$

Fig. 41. Strong-focusing pole tips.

vacuum chamber wall and the only effect of the wall is caused by the variation of beam radius in azimuthal position around the ring. Hence, unstable monopole oscillations caused by the walls grow very slowly. In contrast, the motion of an ion inside the beam is affected by the beam radius and can produce unstable monopole oscillations because of the memory field left behind.

Following their analysis, we find an electron oscillation frequency of 0.909 rad/nsec and an ion e-folding rate of 0.887 μ sec. In the low-duty bunched mode before ejection, the time between the head and tail is 150 nsec, so the electrons execute 136 rad while the ion undergoes 0.85 of an e-folding. Thus the electrons are not captured by the beam as assumed in the derivation, and the ions undergo nearly an e-folding in contradiction to the assumption of the derivation.

Ignoring this problem and continuing with their theory, in Table XII we indicate the growth rates for the fastest modes, $n = 7$ and 8 in the radial plane and $n = 3$ and 4 in the vertical plane. This table indicates that a vacuum of 10^{-8} Torr must be attained, but that 10^{-9} Torr should be sought because of the experience of others and some questions

of the strict applicability of Hereward, Morton, and Schindl's theory to this problem.

TABLE XII
ION-PRODUCED THROBBING-BEAM GROWTH RATES
(IN SECONDS) FOR THE FASTEST MODES

Pressure (Torr)	Tune: $v_x = 4.39$		Tune: $v_y = 2.23$	
	$n = 7$	$n = 8$	$n = 3$	$n = 4$
10^{-7}	0.142	0.0775	0.0775	0.037
10^{-8}	6.775	1.42	0.775	0.37
10^{-9}	7.75	14.2	7.75	3.7

For the WNR vacuum system, we selected aluminum as the vacuum-chamber material primarily for the efficacy of its high conductivity in suppressing the resistive wall instability (see Sec. III). Secondary reasons are low cost and ease of fabrication. The SLAC-SPEAR uses aluminum primarily to achieve the heat conductivity necessary to carry off the 50 kW of power resulting from synchrotron light.

The decision to use aluminum carries with it certain problems. It limits the bake-out temperature to about 200°C, and all-metal demountable aluminum flanges create some problems.

Fig. 42. Hall seal (upper), Varian seal (center), Danielson seal (bottom).

Roth⁶⁵ presents a review of metal-to-metal seals but none specifically for joining aluminum to aluminum. A metal-to-metal technique for joining stainless steel to aluminum is the Hall⁶⁶ seal (Fig. 42, upper). SLAC reports⁶⁷ 1254 bake-out cycles (20-180°C) on an 11- by 4-in. seal using half-hard copper gaskets with 57 gasket changes. Presumably the same seal would be satisfactory for joining aluminum to aluminum.

Another approach is Danielson's,⁶⁸ also for joining aluminum to stainless steel. A Varian seal of the type used for joining stainless steel to stainless steel (Fig. 42, center) is modified by replacing the usual copper gasket with a copper gasket coated with an uncured silicone called "Panshield"

(Dow Corning Corp.). This material is brushed on and cured at 250°C for 8 h. After curing, the coating is ~ 0.00025 in. thick (Fig. 42, bottom). With use, the aluminum surface becomes slightly flattened, but its sealing ability is not impaired. Such a seal between aluminum and stainless steel was baked overnight at 250°C, with a vacuum of 2×10^{11} Torr being achieved. The same seal was leak tested at 250°C and liquid nitrogen temperature with no leaks detected.

Other techniques are explosive bonding of stainless steel flanges to aluminum,⁶⁹ which is a form of pressure bonding. Roth⁶⁵ does not give any welding techniques for joining stainless steel to aluminum but does indicate that aluminum can be bonded to tantalum, platinum, iron-nickel, and iron by resistance welding. Roth (Ref. 65, p. 265) describes soft-soldering of aluminum to stainless steel but calls for a transition section of brass or copper. A final approach is the use of Vitron "O" rings; we believe that this method should be adopted only if metal-to-metal seals are found unsatisfactory. The reasons are radiation damage and outgassing. [Apparently, however, Vitron can be baked to about as high a temperature (200°C) as aluminum.]

The proposed vacuum chamber, shown in Fig. 43, is formed by welding together two extruded sections. Using mirror-image extrusions involves only one die cost. The water passage shown is used to dissipate the I²R heating from the trim coils in the extruded fins. The water passage could be used as a steam passage for bake-out. The bake-out can also be done by simply removing the water and using the trim coils as heating elements. The extrusion for the SLAC-SPEAR design does not involve welding, but uses blends for the die supports. The integrity of the flows at the blends was tested by driving wedges into the ends. They report that in most cases rupture occurred, not at the blends, but in other areas. It may be possible to use their techniques to eliminate the welds altogether.

Also shown in Fig. 43 is a chamber for distributed sputter-ion pumps pioneered by SLAC-SPEAR. These pumps provide the advantages of operating with the magnetic guide field and being located so close to the pumped volume that the coupling impedance is negligible. Any conventional pump would have to be located far enough away that the pump's magnetic

APPROX. AREA OF EXTRUSION (HALF-SECTION) = 3.6 SQ. IN.

Fig. 43. Proposed vacuum-chamber cross section.

field did not perturb the orbit. The SLAC-SPEAR design⁶⁷ consists of a cathode of 185 tubular cells, 1/2 in. in diam by 1.1 in. high, formed of 16-mil type 304 stainless-steel tubing welded to make a two-cell-wide array. The cathodes are upper and lower titanium plates, 90 mils thick by 1.4 in. wide. A screen (Fig. 43) must be used as a sputter shield to protect the vacuum chamber from titanium deposits, but perhaps more important for a high-intensity storage ring, it prevents beam-produced electromagnetic fields from penetrating to the vacuum pump. The pumping speed is constant for fields at above 3.5 kG, and the voltage for constant pumping speed is 7.3 kV.

Under these conditions, the nitrogen pumping speed is 600 liters/sec with a hydrogen speed of about 200 liters/sec. It has been stated that noble-gas pumping for sputter-ion pumps can be improved greatly by using some tantalum cathodes,⁷⁰ but this was not done in the SLAC-SPEAR design.

The long π - 2π straight sections of the WNR ring constitute $\sim 1/2$ of the circumference. Figure 44 shows conceptually how distributed sputter-ion pumps could be located in quadrupole magnets to provide low-impedance pumping in this region.

Another type of pump planned for the straight sections is the SNECMA turbomolecular pump. SNECMA, the largest French manufacturer of jet engines, is the developer of the vertical-axis, multistage turbomolecular pump. One of the SNECMA designs consists of an 11-in.-diam rotor spinning at 12,000 rpm

Fig. 44. Conceptual location of distributed sputter-ion pumps in a quadrupole magnet. DP, distributed pumps; C, exciting coils; PT, pole tips.

and having a tip velocity of 580 ft/sec. The pump consists of 4 low-pressure stages with a 4.4:1 compression ratio and 10 high-pressure stages with a 2.1:1 pressure ratio for a total of 14 stages.

Turbomolecular pumps have the following advantages.

1. The vacuum is extremely clean (10^{-11} Torr ultimate vacuum). The rotating vanes provide a trap for back-streaming fore-pump oils. This serves to protect sputter-ion pumps which tend to be poisoned by pump oils.
2. There is no need for LN_2 traps.

3. They pump all gases.
4. Rough pumping can be through the turbomolecular pump.
5. The pumping speed is essentially constant for all gases over a pressure range of 10^{-1} to 5×10^{-8} Torr.
6. The pump is not harmed by catastrophic venting to atmospheric pressure, nor by accidental loss of the roughing pump.
7. There are no rotating seals between the atmosphere and vacuum, nor any belts or gears.

Table XIII presents the performance of several models of the SNECMA pumps, which are sold in the U.S. by Airco-Temescal, Berkeley, CA.

TABLE XIII

PERFORMANCE OF VARIOUS MODELS OF SNECMA PUMPS

Model	9016	614	314	114
Pumping Speed (liters/sec)	9000	650	400	100
Voltage (V)	200	220	220	220
Starting Current (A)	16	3.2	0.7	0.7
Running Current	4	0.8	0.1	0.08
Approximate Price	\$47,500	\$8833	\$4500	\$7750

Two vacuum systems* were designed for the WNR ring. System 1 was designed when the lattice had the superperiod of four (Fig. 6). The present lattice has been changed somewhat, and, in fact, system 2 also does not calculate the present design exactly. We will follow design 1 closely, but with corrections for numerical differences. Table XIV presents the distribution of surface areas identified in Fig. 45.

The rough pumping of this volume is by liquid nitrogen-cooled sorption pumps. This volume requires about 200 lb of molecular sieve; six commercial sorption pumps** are located in the two short section and at each end of the long straight sections. The pump-down time to reach 10^{-3} Torr would be 10-20 min. Then two 100-liter/sec sputter-ion pumps** in the short straight section and three 400-liter/sec turbomolecular pumps would be turned on. Two of these turbomolecular pumps would be in the extraction straight section; the other would be in the rf straight section. The total pumping speed would then be 1400 liters/sec.

*System 1 was designed by Reinath and Gunn, and system 2 by Norgren and Gunn, all of LBL.

**Ion Equipment Corporation pumps, for example.

TABLE XIV

TOTAL VACUUM-SURFACE AREAS OF THE WNR RING

Vacuum Chamber	Cross-Section Perimeter (m)	Length (m)	Area (m ²)	Volume ^b (liters)
A (elliptical)	0.414	23.62	9.78	121
B (round)	0.478	4.0	1.91	73
C (round)	0.478	17.74	8.48	323
RF cavities (line C) ^a	4.52	1	4.52	88
D (round)	0.478	13.74	6.57	251
Vertical Kicker ^a	1.4 (box only)	1.91	15.47	500
Injection Septa ^a		1.4	2.3	27.7
Extraction Septum ^a		3.25	12.4	273
Total			61.43	1657

^aWe assume that all these items will be in the vacuum systems (no ceramic sections).

^bNo subtraction for volume displacement by hardware.

Fig. 45. Vacuum system for the WNR ring.

Dayton⁷¹ gives an outgassing rate of

$$q(t) = \frac{a}{t} + b,$$

where t is in hours, a is the 1-h outgassing rate, and b is the ultimate outgassing rate. Using the center of Dennis and Heppell's⁷² band of data for aluminum, we find that $a = 2 \times 10^{-8}$ Torr·liter·h/sec·cm² and $b = 10^{-9}$ Torr·liter/sec·cm². Then the pressure after a time t is

$$P(t) = \frac{A}{s} q(t),$$

where A is the surface-area outgassing and s is the pumping speed. Thus

$$\begin{aligned} P(t) &= \frac{61.43 \times 10^4 \text{ cm}^2}{1400 \text{ liter/sec}} \left(\frac{2 \times 10^{-8}}{t} + 10^{-9} \right) \frac{\text{Torr} \cdot \text{liter}}{\text{cm}^2 \cdot \text{sec}} \\ &= \frac{8.77 \times 10^{-6}}{t} (1 + 0.05 t). \end{aligned}$$

After 1 h, the pressure is about 8.8×10^{-6} Torr; after 4 h, it is 2.63×10^{-6} Torr, and baking at 200°C begins. During this bake cycle, we assume that the pressure rises by one order of magnitude.

After 16 h of baking, the heat is turned off and the outgassing rate is assumed to be reduced by one order of magnitude from its value at the start of the baking. The transient outgassing is assumed to be a function of time⁷³ such that

$$q(t) = \frac{2 \times 10^{-9}}{t^{1.5}} + 10^{-10} \text{ Torr} \cdot \text{liter/cm}^2 \cdot \text{sec}.$$

About 5 h after baking, hence after considerable cooling, the distributed sputter-ion pumps are turned on. Assuming the performance of these pumps to be the same as that reported,⁶⁷ the maximum nitrogen speed is 520 liters/sec/r. The outer circumference of the bends (A) is 24.2 m, so the pumping speed is

12,000 liters/sec. Four sputter-ion pumps are installed in each quadrupole; assuming the above pumping speed, each set of four pumps has a combined pumping speed of 620 liters/sec. Because there are 12 quadrupoles in the two straight sections, the total pumping speed is 7440 liters/sec to give a combined total of 20,840 liters/sec in the bends, straight sections, and conventional sputter-ion and turbomolecular pumps.

The pressure-time relationship is

$$P(t) = \frac{61.43 \times 10^4 \text{ cm}^2}{2 \times 10^4 \text{ liter/sec}} \left(\frac{2 \times 10^{-9}}{t^{1.5}} + 10^{-10} \right) \frac{\text{Torr} \cdot \text{liter}}{\text{cm}^2 \cdot \text{sec}}$$

This indicates a limiting pressure of 3×10^{-9} Torr and a pressure of 6×10^{-9} Torr after 1 h. in the above, we have assumed that the pumping impedances are negligible because of the use of distributed pumps.

Reinath and Gunn's and Norgren and Gunn's estimates did not include the gas load of the last five items in Table XIV, so the pumping speed requirement was lower. Note also that the above estimate does not include the vacuum equipment for delivering the beam to the ring or transporting it away.

F. Alignment, Geodetics, and Errors

The small apertures associated with strong-focusing accelerators usually impose stringent construction and installation tolerances. Because of its large aperture and comparatively small radius, the WNR ring is not subject to such severe requirements as high-energy synchrotrons like the AGS or the CERN-PS. Nevertheless, the requirements must be analyzed and criteria must be established.

In the analysis of the effect of errors on the closed orbit, errors in magnet placement and magnetic field errors enter similarly. Bruck¹⁷ integrates the error equation and assumes that the magnet is composed of M units independently aligned and of equal length. Inside the magnet, β is assumed constant, and no correlations between alignment errors and field errors are assumed. With these assumptions, the maximum closed-orbit displacement where $\beta = \beta_{\text{max}}$ is

$$\langle y_F \rangle = \frac{\pi |n| R F^{1/2}}{|\sin \pi \nu| M^{1/2} \nu \rho}$$

$$\cdot \sqrt{(\delta y)^2 + \frac{\rho^2}{n^2} \left(\frac{\delta B}{B} \right)^2 + \frac{M(R-\rho)}{M_{ss} \rho} \left(\frac{\delta B_{ss}}{B} \right)^2},$$

where M is the number of units, n is the field index, R is the equivalent radius, ρ is the magnetic radius, and M_{ss} is the number of straight sections. B_{ss} is the stray field in the straight sections (est < 0.5 G), and F is the average form factor ($F_f = 1.074$; $F_d = 1.092$). The remaining numbers are given in Table IV. This gives

$$\langle y_F \rangle_x = 6.478 \sqrt{(\delta y)^2 + 0.078 \left(\frac{\delta B}{B} \right)^2 + 8.34 \left(\frac{\delta B_{ss}}{B} \right)^2}.$$

This shows that an error in $\delta B/B$ is only about 30% as effective in shifting the equilibrium orbit as is an error in placement ($\delta y/y$). It also shows that stray fields in the straight sections produce negligible effects on the beam because of the high operating energy. Assuming that the alignment and magnetic errors are the same: $\delta \omega^2 = \delta y^2 = 0.078 (\delta B/B)^2$, and $\langle y_F \rangle_x = 9.16 \delta \omega^2$. The beam extent shown in Fig. 27 is 11 cm. If 10% of this, or 1.1 cm, is considered a negligible beam shift, then $\delta y = 0.35$ cm, $\delta B/B = 1.2\%$, and $\delta B = 163$ g.

Although these tolerances do not require it, Collins' technique¹⁷ can be used to reduce the closed-orbit excursion. This method has been used at CEA and Hamburg to correct the residual fields at injection. It uses cell-length trim coils dispersed about the ring to compensate errors affecting the closed orbit.

Errors in δn of the field index cause deformation of the beam envelope, a change of tune, and expansion of the unstable half-integer tunes into unstable bands. Bruck¹⁷ gives

$$\begin{aligned} \left(\frac{\delta y_e}{y_e} \right)_{\text{extr}} &= \pm \frac{4}{\pi} \frac{|n|}{M^{1/2}} \frac{R}{\nu \rho} \left(\frac{\delta n}{n} \right)^2 \\ &= \pm 2.37 \left(\frac{\delta n}{n} \right)^2, \end{aligned}$$

for the effect of random gradient errors on the extremities of the envelope. The CERN-PS has an error of $(\delta n/n) \approx 1\%$. If we assume that the WNR ring machining is done equally well, then $(\delta y_e/y_e)_{\text{extr}} =$

$\pm 2.37\%$. This seems a bit large and should be investigated further. One big difference, however, is that the WNR ring will be dc instead of pulsed like the CERN-PS. So, tolerance on the gradient probably can be kept much tighter and further reduced with trimming coils.

A gradient error can produce a change of tune. Bruck¹⁷ analyzes this problem for quarter-integer tune such that $2\nu = r + 1/2$ where r is an integer. Then

$$\nu^2 \approx \nu_0^2 - 1/2 \frac{2R\sqrt{(\delta n)^2}}{(4\nu^2 - r^2)^{1/2} \rho}$$

approximately where a summation over r has been restricted to the r value such that $(4\nu^2 - r^2)$ is minimum ($r = 9$). This gives

$$\Delta\nu = 0.067 \frac{\delta n}{\rho}$$

Thus for $\overline{\delta n} = 0.12$, $\Delta\nu = 0.0081$.

Errors in δn also cause bands of instability centered on integer and half-integer tune values. Bruck¹⁷ analyzes this problem in analogy with the band structure of semiconductors and shows that the full width of the band is approximately

$$\Delta\nu = \sqrt{\frac{R}{\rho} \frac{(\delta n)^2}{M}}$$

or

$$\Delta\nu = 0.77 \sqrt{\frac{\delta n}{\rho}}$$

Thus for errors of $\overline{\delta n}/n = 0.01$, $\Delta\nu = 0.28$. This is a significant bandwidth and should be examined further. As stated previously, because the ring is dc, it should be possible to trim the magnets so that $\delta n/n$ is considerably less than 1%.

Having explored the effects of positioning and magnet errors on the beam, we turn to specific alignment techniques, in particular those requiring only distance measurements. Gervaise,⁷⁴ and the 200-BeV study⁷⁵ explore various survey techniques and conclude that angular measurements are difficult to make to the accuracy (~ 0.1 mm) required for high-energy accelerators. Surveying procedures to determine the locations of points on a geometrical figure employ redundant techniques. The data are normally processed by the method of least squares (with appropriate weights assigned according to the precision

of various measurements) to determine the best estimate of the desired coordinates. From the relationship between the inferred coordinates or related quantities and the individual measurements, one can determine how much statistically distributed errors in the measurement will affect the beam characteristics. Laslett and Smith⁷⁶ have examined how the errors in various surveying techniques propagate, and especially how radial errors in the primary survey affect the equilibrium orbit in the horizontal plane. The effect of these errors is dominated by the Fourier component of the monument error for which the harmonic number is closest to the natural betatron frequency. In fact, Laslett⁷⁷ has shown that for a 200-BeV synchrotron of the NAL type and a 30-BeV synchrotron of the AGS type, approximately 90% of the closed-orbit response is due to one harmonic of the perturbation.

The alignment techniques developed for high-energy synchrotrons^{74,75} are designed for a tunnel architecture for which radial measurement to the center of curvature are not possible. It might appear that the best way to survey a torus would be a series of distance and angle measurements. However, the development of precision distance-measuring equipment using the time-of-flight of light has given the superiority to distance measurement. This device, called a Mekometer,^{74,75} uses a Kerr cell driven by a precision oscillator to modulate a light beam. By reflecting the beam and determining maxima, distances can be measured to about ± 0.001 in. There are no angular measuring instruments that provide comparable accuracy for this purpose. Laslett and Smith⁷⁶ assume that the azimuthal error is negligible because it is directly determined, and determine the radial position by the perpendicular displacement from the m monument to a chord from the $m-1$ to the $m+1$ monuments. As the m index changes to encompass the ring, the triangles overlap, resulting in redundant measurements. The most probable location of the benchmarks result from least-squares fitting of all the data.

The WNR ring's comparatively small size and racetrack geometry suggest that a much simpler alignment procedure be used. It must be recognized that symmetry is all-important.

Figure 46 shows the survey pattern. A single rigid radius vector, possibly made of Invar, sets the equalities $\overline{AB} = \overline{AC} = \overline{AD} = \overline{AE}$. The posts on

Fig. 46. Survey monument placement for the WNR ring.

Monuments B, C, D, and E will be equipped with transverse mechanisms to permit motion only perpendicular to this radius vector once this radial distance is fixed. If this device is realized using straight ways, there will be a slight sagitta effect. If the motion of adjustments is ± 1 cm, then using a radial length of 8.93 m, one finds a displacement of ± 0.007 in. It may, therefore, be necessary to iterate on the radial adjustment as the net becomes symmetrized.

With the radial distances of B, C, D, and E established, the figure may have a hinge error near A. Taut wires are stretched from $\overline{BE}$ and $\overline{CD}$, and the perpendicular distances from these wires to A are measured and set equal using another Invar bar with, possibly, a traveling microscope to sight on the wire. This adjustment is performed at constant radius so that upon completion $\overline{BE} = \overline{CD}$ and $\overline{BC} = \overline{DE}$. The primary net is now measured, possibly using a Mekometer.^{74,75} The distances measured are $\overline{AB}$, $\overline{AC}$, $\overline{AD}$, $\overline{AE}$, $\overline{BC}$, $\overline{CD}$, $\overline{DE}$, $\overline{EB}$, and the perpendicular chord from A to the segments $\overline{BC}$, $\overline{CD}$, $\overline{DE}$, and $\overline{EB}$. This rigid-bar technique should give 0.001-in. radial symmetry with possibly greater hinge-type error.

The vertical elevation of the center of curvature monuments B, C, D, and E must be established. Here again, the absolute value is unimportant, and even a plane tilt is not significant, but the planarity is all-important. The method for setting the elevation is that of liquid levels.⁷⁵ A system of tubes connecting wells at A through U is proposed. If mercury or water in 3-in.-deep wells is used, a 1°C temperature gradient would cause a 0.0005-in. error. We may therefore insulate the connecting

pipes and close the loop so that the fluid can be circulated slowly to average out gradients. An advantage of mercury over water as the fluid is the possibility of electrically sensing the surface level. Optical methods probably can be used with water, so this advantage may be only apparent. A system similar to that just described was tested at LBL and appears to be as good as or better than optical leveling ($< \pm 0.001$ in.). These wells are used to establish the level of all the monuments.

With the monuments leveled,* a Wild Heerbrugg Instruments, Inc. T-3 or equivalent theodolite is mounted on one of the center-of-curvature posts, say E, and adjusted so that it scans a plane intersecting the levels at Q and J. The lower iron poles of the magnet are installed using the leveling screws to bring their upper surfaces to approximately the correct height so that the top of the pole tip will be at its design location. The steel is also located in approximately the correct radial location. (Great precision is not required for the return-leg steel.) One of the lower pole tips is installed approximately, the lower return-steel leveling screws are adjusted so that the pole tip rests evenly on each of the return legs it encompasses, and the vertical elevation is properly adjusted with the theodolite. The theodolite is removed, an Invar radius vector and traveling microscope are installed on post E, and the pole tip is adjusted radially by sighting on a fiducial mark machined into each of its ends when it was manufactured. An alternative method is to use a machinists' indicator on the radius vector. This method accurately locates each end of the pole tip. The radius vector is removed, the theodolite is installed, and the elevation is checked again. Probably leveling all the lower pole tips of a sector at once would be more efficient. After several permutations of leveling and radial locating, the lower pole tips of all sectors are located to the desired tolerances and rigidly secured to the lower return legs by bolts. Nonmagnetic spacers (Fig. 41) are installed, and the upper pole tips are mounted on them. Thus, the accuracy of locating one pole-piece relative to the other is determined by machining tolerances which can be < 0.001 in.

*This alignment procedure is primarily due to J. Gunn, LBL.

We have not mentioned leveling the surface the lower pole tip rests upon. This is necessary because rotation of the pole tip tends to couple vertical and horizontal betatron oscillations. Leveling can be either by precision level, such as a Wild Heerbrug Instruments, Inc. N-2, or by distance-transfer blocks, such as Johansen blocks, and sightings taken with the theodolite from one radial end of the support base to the other.

With both pole tips, the vacuum chamber, the upper and lower exciting coils, and the inner and outer return steel properly installed, the upper return steel is finally installed. The figure, however, is over-determined, and there is no assurance that the upper steel will close the box without air gaps. At this point, a meticulous fitting procedure is necessary to fill the air gap with steel whose magnetic characteristics are similar to that of the pole tip.

As the magnets are being assembled and hence getting heavier, the level must be monitored continually with the theodolite. Although the alignment may be correct during initial assembly, there is no assurance that foundation shifts will not cause long-term problems.

The Los Alamos Meson Physics facility is located on a small mesa called "Mesita de los Alamos". This area has experienced volcanic activity for several million years, culminating in the cataclysmic eruptions that produced the welded tuff of the Bandelier formation which will be the foundation for the WNR ring. Welded tuff is a low-density rock sometimes exhibiting 400-ft high escarpments, but soft enough to be cut with a bulldozer. Moduli of elasticity over 150,000 psi are common. A recent 2-1/2-yr study of seismicity indicated high stability compared with such regions as southern California. The boulder-capped conglomerate pinnacles seen in Rendija Canyon are cited as evidence of the ground stability.

The four sectors of the WNR ring weigh 173 tons and have a 907-ft² bottom face area. This weight is primarily borne by leveling jacks, but if the foundation (Fig. 39) uniformly disperses the load, the pressure is 0.2 ton/ft². In Keller's extensive study of the weight-bearing characteristics of the welded tuff at Mesita de los Alamos,⁷⁸ he cites deformation characteristics using missile-silo

counterweights. At loadings of 4.05 ton/ft², he measures, for the maximum of several experiments, a deformation of 6 cm, 5 ft from the steel mass and essentially vanishing at 40 ft. He observed very little creep during 6 weeks of observation. Some of the experiments showed much less loading deformation. When the load was removed, the point of observation returned to 0.006 ± 0.006 of its original location and exhibited no long-term creep.

Similar observations were made on a water tower located on a nearby mesa. The water level cycled, depending upon demand, and deflected the benchmarks, but no long-term deformations were observed. It therefore seems reasonable that the Mesita de los Alamos provides such a firm foundation for the WNR ring that frequent realignment will be unnecessary.

III. BEAM STABILITY

A storage ring is a nondissipative mechanical system and, as such, is prone to resonances. Indeed, the principal beam-loss mechanism (neglecting gas scattering) is resonance-beam excitation. In this section, we first explore the resonance structure and then investigate phenomena known to be capable of shifting the betatron frequency onto one of these resonances. In the following, Bruck's work¹⁷ is principally used.

A. Field Error

In practice, the guide field contains some error $\delta B_x(\theta)$ or $\delta B_z(\theta)$, because of magnetic imperfections or magnet misplacement. These errors may be represented in a Fourier series. When the beam tune coincides with a harmonic of the error, the effects begin to reinforce, the oscillations grow, and the beam is lost. Analysis of this problem indicates that the beam tune in either plane must not have integral values. This is a very strong resonance that normally leads to full beam loss.

B. Gradient Error

An error in field gradient may also excite beam resonances. If the error is expanded in a Fourier series and inserted in the Kerst-Serber equation, a Mathieu equation results, and, hence, stable oscillations correspond to stable solutions of the Mathieu equation. This gives rise to the requirement that ν cannot be integer or half-integer.

When the integer is equal to the number of cells (eight for the WNR ring) or the superperiod (two), the prohibition is especially strong.

C. Linear-Coupling Error

If there is coupling between the vertical and radial betatron oscillations, as, for example, a twisted quadrupole, then the two modes may interact, leading to beam loss. This effect leads to the interdiction against $\nu_x + \nu_z = n$, where n is an integer.

D. Nonlinear Resonances

The trajectory equations are not actually linear, but are made so by the neglect of nonlinear terms. A driving term may be included to describe the nonlinear coupling by powers of x and z and include a harmonic term having the periodicity of the lattice. This analysis leads to the prohibition of $\nu = kN/2$, where k, l are integers and N is the number of lattice cells per revolution.

All of the various resonances may be summarized by the prohibition $2\nu_x + m\nu_z = n$; $l, m, n = 0, \pm 1, \pm 2, \dots$, and $|l| + |m| = p$, the order of the resonance. For $p > 4$, theory and experience indicate that the resonances are weak. Figure 47 shows the anticipated resonance structure of the WNR ring. The classification of the prohibitions is indicated as (l, m, n) where these are the indices used above.

Fig. 47. WNR-ring resonance structure.

E. Space-Charge Effects

The space-charge forces combine with the magnetic-guide field forces to change the frequency of betatron oscillation. These forces are brought into the Kerst-Serber equation as a perturbation on the stiffness term resulting from electric and magnetic forces in the relativistic beam. From these considerations for a round beam, it can be shown¹⁷ that

$$N = \frac{2|\delta\nu|\beta^2\gamma^3 A}{r_p}, \quad (10)$$

where N is the total number of particles; $|\delta\nu|$, the maximum allowable tune shift, is $1/4$; r_p is the classical proton radius; and the remaining terms are given in Table IV. Substituting into Eq. (10) and using $\langle A \rangle = 133.9$ cm mrad for the admittance; and $N = 1.93 \times 10^{15}$ particles for the total charge gives a current of 3000 A if it is bunched into 100 nsec.

Rather than using a SYNCH-derived value for the admittance, Bruck¹⁷ gives it as $A = \pi v a^2 / RF$. Substituting this into Eq. (10),

$$N = \frac{2\pi v |\delta\nu| \beta^2 \gamma^3 a^2}{r_p RF}, \quad (11)$$

where R is the ring radius, F is the form factor which averaged between the two planes is $\langle F \rangle = 4.19$, v averaged is $\langle v \rangle = 3.31$, and a^2 is taken to be the sum of the squares of 1-cm vertical half-height and 5-cm horizontal half-height. This gives $N = 1.79 \times 10^{14}$ protons and a current of 285 A. The reason for this much lower second result is that a beam of the given dimensions is far from filling the ring admittance.

Equation (10) shows that the maximum current-holding capabilities of a ring are a function only of the admittance and the particle mass and energy. However, when the admittance is considered, the maximum current scales with the beam area and inversely with the ring radius and form factor.

Laslett⁷⁹ and Laslett and Resegotti⁸⁰ have studied the more realistic problem of a bunched elliptical beam in a perfectly conducting elliptical chamber with a dipole magnet outside the chamber (Fig. 48). In this analysis, Eq. (11) is modified to describe the effect on a single particle as

Fig. 48. Elliptical beam in an elliptical vacuum chamber.

$$N_{\text{incoh}} = \frac{\pi v |\delta v| \beta^2 \gamma^3 b(a+b) B}{R r F} \quad (12)$$

where B is the bunching factor and the electrostatic and electromagnetic effects are contained in F .

$$F = 1 - \gamma^2 \eta + \frac{b(a+b)}{h^2} \left[\epsilon_1 (1 - \eta + B \beta^2 \gamma^2) + \epsilon_2 B \beta^2 \gamma^2 \left(\frac{h^2}{g^2} \right) \right] \quad (13)$$

For the WNR ring, $B = 0.4$, $b = 1$ cm, $a = 2$ cm, $h = 5$ cm, $w = 10$ cm, $g = 7.08$ cm, and η is the clearing field ($\eta < 1$). For this case, the electrostatic image factors are $\epsilon_1 = 0.172$ and $\epsilon_2 = 0.41$, and the magnetostatic image factor is $\xi = 0.6$. As the neutralization factor $\eta \rightarrow 1$, F goes to zero and even becomes negative, allowing very large currents. Conservatively, we take the case of $\eta = 0$. From Eq. (12), $N_{\text{incoh}} = 6.03 \times 10^{14}$ R/F. Substituting into Eq. (13), we find that $F = 1.04$; that is, the image forces constitute only 4% effect on the space-charge limit. Using $B = 0.4$ gives $N = 2.32 \times 10^{14}$ protons, or 371 A. This calculation does not consider the nonsinusoidal character of the betatron oscillations. If this is included, $F = 4.36$ and $N = 5.53 \times 10^{13}$ protons or 88 A, indicating that incomplete neutralization is probably needed to meet the design goals.

F. Negative-Mass Instability

The charged particles of the beam exert a mutual azimuthal force. If the linear density is not uniform, the particles upstream of the maximum are accelerated and those downstream are decelerated. If the beam energy is above the transition energy, an increase in energy is accompanied by reduced

angular velocity. Under the action of this density maximum, the particles paradoxically converge on this maximum and further increase the current density. This is the qualitative description of the negative-mass instability.

In the work of Nielsen, Sessler, and Symon,⁸¹ the Hamiltonian for the azimuthal motion with space charge is formed. This is solved in the linear approximation for a propagating wave of frequency ω .

$$\omega = \pm \omega \left[\frac{g \lambda r_p}{\gamma^2 \beta^2} \eta + \frac{\eta^2}{4 \beta^4} \left(\frac{\Delta E}{E} \right)^2 \right]^{1/2} \quad (14)$$

where λ is the linear charge density, g is a geometry factor > 1 , $\eta = 1/\gamma^2 - 1/\gamma_{\text{tr}}^2$ where γ_{tr} is the γ corresponding to the particle energy at which phase stability is lost, and ω is the particle angular frequency. For the WNR ring, $\eta = 0.205$, but the important point is that $\eta > 0$; hence, ω is real and the solution is harmonic. The beam stability indicated by Eq. (14) for positive η values (below γ transition) is in accord with the physical description previously presented.

From this picture of the negative-mass instability, it seems that for situations below γ transition the effect of longitudinal space-charge is to debunch the beam, which does not lead to instability.

C. Longitudinal Resistive-Wall Effect*

Neil and Sessler⁸² have applied the concepts of the resistive-wall traveling-wave tube to analysis of longitudinal-beam instabilities such as those observed at MURA.⁸³ These longitudinal bunching effects were observed at low energy, below the γ transition, and, until the work of Neil and Sessler, presented a quandary inasmuch as they appeared to be a manifestation of negative-mass instability occurring below transition, which should be impossible.

Their analysis begins with the assumption of a uniform, unbunched beam having a particle-density perturbation of the form $\exp(in\theta - \omega t)$, where n represents the mode number of the instability. Two cases are considered: a circular beam centered inside a circular vacuum chamber of finite conductivity, and a ribbon beam of finite extent centered inside a

*The analysis in the next three sections, for which we are grateful, is primarily by V. K. Neil, LLL.

rectangular vacuum chamber of finite conductivity at top and bottom but with perfectly conducting side walls. In both cases, the chamber curvature is ignored and the longitudinal wavelength of the perturbation is assumed to be much longer than the vacuum-chamber dimensions. Here we apply only the first case to the storage ring.

By solving Maxwell's equations, introducing the electric field into a linearized Vlasov equation, and assuming that all particles have the same angular momentum, we find an e-folding growth rate of

$$t_0 = \frac{b}{\beta\gamma} \left\{ \frac{2\sigma E [1 + 2\ln(b/a)]}{R N e^2 F^3 \xi} \right\}^{1/2}, \quad (15)$$

where

N = total number of particles in the ring
(6×10^{13} , low-duty mode)

R = equivalent ring radius (10.03 m)

F = particle-circulation frequency (4×10^6)

σ = conductivity in cgs units (4×10^{17} sec⁻¹ for aluminum)

a = beam radius (1 cm); b = chamber inner radius (5 cm).

The other symbols have the meanings given in Table IV. This leads to a growth rate of 0.411 sec for $n = 1$ and indicates that the longitudinal resistive-wall effect should not be troublesome. Further refinements such as including Landau damping only tend to slow this growth time.

The longitudinal instabilities, even if they occur, do not lead to catastrophic consequences; they only produce local densities in excess of the space-charge limit and hence some particle loss. However, before investigating the transverse resistive-wall effect, we will investigate another longitudinal effect.

H. Beam-Cavity Interaction

As the beam circulates through rf cavities or other electrical inserts in the vacuum system, density fluctuations may excite electrical oscillations that interact with the beam to produce more bunching and possibly lead to longitudinal instability. In the ISR design,⁸⁴ the shunt impedance of each cavity was held to 6.5 Ω at 10 MHz. Because there are six cavities, the total impedance is 39 Ω , less than the estimated 50 Ω needed.⁸ In the ISR, this is achieved

by nearly class-A operation of the final power tubes using strong negative feedback. Faltens et al.⁸⁵ give a method for measuring this coupling impedance with a given structure. However, we use Laslett, Neil, and Sessler's stability criteria⁸⁶ here to estimate the maximum accumulated impedance of the inserts. They consider the problem of a rectangular vacuum chamber with an undriven cavity and find

$$Z_c < \frac{Z_0 n c \eta}{r_p N F \beta^2} \left(\frac{\Delta E}{E_0} \right)^2, \quad (16)$$

where $Z_0 = 377 \Omega$, the impedance of free space, and the other terms are conventional or as given in Table IV. The criterion is

$$Z_c < 47 n \left(\frac{\Delta E}{E_0} \right)^2 \text{ M}\Omega. \quad (17)$$

For the 2.2% energy spread needed to miss the stripper, the cavity impedance, Z_c is less than 23 k Ω , which should not be difficult to satisfy for cavities or other inserts such as clearing electrodes.

I. Transverse Resistive-Wall Instability

In the MURA 50-MeV electron accelerator, transverse beam oscillations with a frequency $f = (n - \nu)f_c$ were observed, where n is an integer $> \nu$, ν is the tune, and f_c is the circulation frequency. The effect can be understood in terms of a traveling wave in a resistive wall interacting with the beam to cause beam translational oscillations. Conceptually, we see that if the particle velocity is greater than the phase velocity, the effect is capacitive; the force is 90° out of phase, and the work done on the particles is zero. If, however, the wall conductivity is finite, the charges lag and work is done on the beam.

This problem was analyzed by Laslett, Neil, and Sessler⁸⁷ for cylindrical and slab geometry. In cylindrical geometry, they find that the vertical oscillations grow exponentially with a time constant

$$t_g = \frac{4\pi^2 \nu_z \gamma b^3 \sqrt{(n - \nu_z) f_c \sigma}}{r_p c^2 N \beta}, \quad (18)$$

where $n > \nu_z$. Using $\sigma = 4 \times 10^{17}$ /sec as the

conductivity of aluminum, $N = 6 \times 10^{13}$ and $n = 3$ gives $t_g = 1.15 \times 10^{-5} b^3$ sec. The value of b in the sectors is least at 5 cm, giving 1.43-msec growth time.

They also analyze a ribbon beam of width Δ in a rectangular chamber of width w and height h having a growth time of

$$t_g = \frac{6v_z \gamma h^3 F_3 (h/w, \Delta/h) \sqrt{(n-v_z) f_o} \sigma}{r_p c^2 N E} \quad (19)$$

For the values $h/w = 1/2$ and $\Delta/h = 1/2$, Fig. 5 of Ref. 87 gives $F_3 = 0.95$. For $N = 6 \times 10^{13}$, the growth time is 3.72 msec.

The vertical instabilities due to the transverse resistive-wall effect were stabilized in the 50-MeV MURA electron accelerator by feedback. Narrow-band feedback had been used previously to stabilize the Cosmotron, but with an unbunched beam, wide bandwidth feedback is needed. Pruett, Otte, and Mills⁸⁸ present an analysis indicating that an odd number of betatron quarter-wavelengths should separate the beam position-sensing electrodes and the correcting electrodes. Furthermore, the time delay in transmitting the correction signal should be an integral multiple of the beam transit time between these locations. The technique used at MURA and at Argonne⁸⁹ was to use parallel-plate beam-elevation sensors operating differentially to reject the intense common-mode pulse from a bunched beam. This was amplified by a wide-band chain amplifier in the former case and by a more conventional compensated amplifier in the latter case. The maximum signal delivered to the electrostatic correction plates was 1.5 V at MURA and 20 V at Argonne to stabilize growth rates of milliseconds. The problem at Argonne was made difficult by the need to correct during the acceleration cycle when the particle velocity is not constant. In the WNR ring, this problem will not arise; however, the need for feedback beam stabilization is indicated.

The amount of system gain needed to give stabilization has been 100-1000. In Richter's⁹⁰ analysis of the problem for SLAC-SPEAR, he arrives at a gain of 1000 and points out the need for servoing the vertical position on the media plane. Very slight shifts of the average beam elevation will saturate

the sensing system unless ac coupling, which may have detrimental effects on the phase shift, is used.

The bandwidth for the WNR ring does not seem to impose serious requirements. In the low-duty case for which the previous transverse resistive-wall calculations were made, only one 100-nsec bunch is planned. This seems to require only a 10-MHz bandwidth. If the instability should, however, be an interbunch instability, such as the head-tail, then wider bandwidth would be necessary.

J. Head-Tail Instability

The interaction of a beam of charged particles with its environment produces an electromagnetic wave that can interact with the beam. This wave's decay rate determines whether the interaction occurs from one revolution to the next, as for the transverse resistive-wall effect, or has decayed by the next revolution. In the latter case, the head of the bunch of particles produces an electromagnetic wake that affects the tail of the bunch symmetrically or antisymmetrically. If the bunch were rigid, this would change only the restoring forces and hence the tune; however, the bunch is not rigid and particles circulate within it. Pellegrini^{91,92} and Sands⁹³ consider a magnetic-wake field produced by charge displacement by betatron oscillations which causes a radial displacement force on the tail of the bunch. Sands applied Robinson's analysis⁹⁴ of the electromagnetic wake in a cylindrical, resistive-wall vacuum chamber to the head-tail instability.⁹⁵

Zotter⁹⁶ applied Sands' analysis to the ISR proton-storage ring by numerically evaluating the wake integral instead of using the power-series expansion that is valid for electron storage rings. The following analysis for the WNR ring is for the low-duty mode, 6×10^{13} protons in a single 100-nsec bunch. Two cases are considered: Case I, conserved phase density for which the energy spread, $\Delta E/E_0$, is 6.25×10^{-4} ; and Case II, diluted phase density for which $\Delta E/E_0$ is 7.75×10^{-3} .

The variable that determines whether the wake integral can be expanded or numerical integration is needed is

$$x = \frac{2\Delta v f_o \xi}{\alpha} ,$$

where A is the synchrotron amplitude in time units

$$A = \frac{\alpha \Delta E_{\max}}{\gamma E_0 \omega_s},$$

and the synchrotron frequency is

$$\omega_s = 2\pi f_0 \left(\frac{h\nu}{\beta^2 2\pi \gamma E_0} \right)^{1/2}$$

The rotational frequency is f_0 ; ν is the average tune; ξ is the chromaticity, $(d\nu/\nu)/(dE/E)$; α is the dispersion, $-\eta/\beta^2$; and the bunching voltage (see Sec. IV) is 84 V for Case I and 13 kV for Case II. The other values are given in Table IV, except for the chromaticity which is assumed to be $-1/2$. When this is used with an α of -0.0864 , because the energy is below transition, positive x values result.

The chromaticity is varied readily using sextupole magnets; hence, it may have positive or negative values. Changing the sign of the chromaticity changes from growing to damping instability modes, and vice versa. It may be desirable to design for zero chromaticity.

Following Zotter's notation, the exponential growth rate is

$$\beta_m = -0.0808 \left(\frac{r_0 c}{b^3 \sqrt{\mu_0}} \right) \left(\frac{N E_0 \sqrt{A}}{\alpha r} \right) F_m(x),$$

where the first parenthesis is $5.35 \times 10^{-7} \text{ sec}^{-3/2}$ assuming an aluminum wall of radius $b = 5 \text{ cm}$, and

$$F_m(x) = 2 \int_0^\pi d\psi \cos m\psi \left\{ \frac{\pi}{\sqrt{2x} \sin(\psi/2)} \sin [x \sin(\psi/2)] - 2 \int_0^{x \sin(\psi/2)} \frac{du}{\sqrt{x \sin(\psi/2) + u}} \cdot \left[\cos u - \frac{\sin u}{2(x \sin \frac{\psi}{2} + u)} \right] \tan^{-1} \sqrt{\frac{u}{x \sin(\frac{\psi}{2}) - u}} \right\}$$

was numerically evaluated for the Case I and II x values. The growth rates are summarized in Table XV. These growth or damping times are of the order of a millisecond, so further consideration should be given to suppressing this head-tail effect. This is most easily done using sextupole fields.

TABLE XV

HEAD-TAIL GROWTH RATES FOR THE WNR RING

Mode Number	Case I (sec^{-1})	Case II (sec^{-1})
0	-129.8	+ 838.8
1	+351.4	+1091.0
2	+798.1	+1178.0

K. Resistive-Wall Effect for a Bunched Beam

We conclude this section on instabilities by calling attention to Courant and Sessler's paper⁹⁷ on resistive-wall effect on bunched beams. This paper assumes that the bunches are rigid and obtains the rule that for a single bunch, the tune ν should be $N < \nu < N + 1/2$ where N is an integer. This rule, which is the reason for the tune selection in the WNR ring, is without experimental confirmation. In fact, the ACO and Adone storage-ring experience is just the opposite. It is generally held that the assumption of rigid bunches is not true and so this rule should not be applied. Probably a more successful approach would be to allow freedom of tune manipulation and explore the most favorable tunes experimentally.

IV. BUNCHING

The WNR-ring design involves various requirements for debunching, energy shifting, and bunching. These concepts are not frozen, but we should estimate the problems involved.

A. Capture and Adiabatic Debunching

The beam from LAMPF is designed to have a momentum spread of $\pm 0.2\%$ averaged over a micropulse and leaving the accelerator with a phase-angular spread of 36° . For bunching ratios of 10, excessively large bunching voltages are required. If the beam is just injected into the ring, the beam ellipse will shear and there will be large phase dilution just as for a beam in a drift region. What is required is a method to preserve the phase density while distorting the ellipse to occupy 360° of phase space (Fig. 49). Upright ellipses represent the injected beam that is modulated at 201 MHz, and flattened ellipses represent the desired deformation. The shear lines show what would happen if the bunches were not captured.

Fig. 49. Synchrotron-space beam ellipse and adiabatic deformation.

Symon and Sessler⁹⁸ give a general discussion of rf beam manipulation. They cast the acceleration equations in a Hamiltonian form so that phase-space density is conserved during adiabatic deformation (Liouville's theorem). The area occupied by the injected beam will be $A_1 = \Delta\theta_1 \Delta E_1 / f_1$ where $\Delta\theta_1$ is the phase angular spread, ΔE_1 is the energy spread, and f_1 is the circulation frequency. The LAMPF microstructure bunch width is 0.12 nsec, which, following a 500-ft transport line, is broadened to 0.4 nsec or $\Delta\theta = (0.08)2\pi$. This number is probably an upper limit because the energy spread in a single bunch is probably much less than average. If we now assume that phase area is conserved as $\Delta\theta \rightarrow 2\pi$, the resulting energy spread is

$$\frac{\Delta E_2}{E_0} = \frac{(2\pi)(0.08)\Delta E_1}{(2\pi)E_0} = \pm 0.025\% \quad (20)$$

The problem is to devise a procedure to bring about this energy homogenization. The voltage required to contain a bunch whose maximum angular extent (the separatrix) ϕ , relative to the rf, is

$$V = \frac{2\pi h \gamma E_s \eta}{\beta^2} \left[\frac{(E_m - E_s)/\gamma E_0}{2 \sin \phi/2} \right]^2, \quad (21)$$

where h is the number of buckets around the circumference, E_m is the maximum particle energy, E_s is the synchronous energy, and E_0 is the rest energy. Equation (21) for the WNR ring is written as

$$V = 196.2 h (\Delta E/E_0)^2 \frac{1}{\sin^2 \phi/2} \text{ (MV)}, \quad (22)$$

where $\Delta E = E_m - E_s$.

For adiabatic damping, the bucket catching the pulse must not be completely filled, but if the bucket is too empty, excessive capture voltages

will be required. We will capture the beam with an 804-MHz cavity; hence, ϕ is 116° and h is 4. Thus the capture voltage is 10.5 kV. This voltage is lowered until the separatrix is π , the energy spread is reduced by 3.1 to 0.1%, and the capture voltage is 7.54 kV. If the voltage were further reduced, the particles would escape and the ellipse would shear.

At this point the 201-MHz cavity is turned on to capture the bunch on the fundamental. Hence h is 1 and ϕ is $\pi/2$, giving a capture voltage of 393 V. This is lowered to zero, and, presumably, the energy spread is $\pm 0.025\%$, a lower limit (assuming LAMPF beam values). For stability, it may be desirable to keep the spread broader. This can be done at any time by simply turning off the voltage used for a adiabatic damping and allowing the ellipse to shear.

B. Energy Shifting

In the discussion of the stripper design, we indicated a need to shift the beam energy by 1.44% in 7.73 msec so that the previously injected beam would miss the stripper on the next injection cycle. This requires an energy shift of 573 V per turn, which allows no time for adiabatic damping (unless it continues concurrently). We will therefore assume that the time interval is broken into thirds so that 2.58 msec and 1720 V per turn are allowed for energy shifting. This is added to the capture voltage to give 40.2 kV, and the synchronous phase angle is 2.45° . Substituting into Bruck's¹⁷ Eq. (16.32) gives $\Delta E/E = \pm 0.34\%$, indicating that the assumed bucket is somewhat deeper than need be, but still reasonable.

The fractional cavity-frequency shift needed to provide this energy gain is $df/f = (dE/E)(\eta/\beta^2) = 0.289 \Delta E/E = 0.416\%$. The fractional bandwidth of a cavity is approximately $1/Q$, so the Q need be no greater than 240 to accommodate this frequency shift. This seems to place a severe restriction on the cavity and to cause excessive power loss, but on this time scale it is quite possible to modulate the cavity mechanically.

C. Bunching

There are many combinations of pulse widths and repetition rates, but we will consider only two, the low-duty and high-duty modes.

1. Low-Duty Mode. This mode requires the beam to be a single 100-nsec bunch. This can be done in two steps, bunching with the fundamental, followed by the second harmonic. However, it is more conservative to consider only fundamental bunching.

Assuming that the homogenized beam ($\Delta E/E_0 = 2.5 \times 10^{-4}$) is increased in energy spread by the bunching factor (2.5), $h = 1$, and $\phi = 144^\circ$, Eq. (22) gives 85 V for bunching at 4 MHz.

2. High-Duty Mode. This mode requires five 5-nsec bunches. Here the bunching factor is 10; hence, $\Delta E/E_0 = 2.5 \times 10^{-3}$, $h = 1$, and $\phi = 36^\circ$, and we find a bunching voltage of 12.8 kV at 20 MHz. This voltage could be considerably reduced by only partially bunching on the fundamental and finishing on the second or higher harmonic.

In the previous example, if phase density had not been preserved (there was no adiabatic damping), 2 MV of bunching voltage would have been required.

D. An Alternative to Debunching

Equation (21) shows that the voltage needed for bunching or debunching depends on $\eta = 1/\gamma_{tr}^2 - 1/\gamma_{tr}^2$ which has been a free parameter in the design of the WNR ring except for the requirement that it be positive to avoid the negative mass instability. If $\delta = \gamma_{tr} - \gamma$, then a power series expansion gives

$$\eta = 2\delta/\gamma_{tr}^3 + 3\delta^2/\gamma_{tr}^4 \quad (23)$$

Presently, $\gamma_{tr} = 3.402$ and $\eta = 0.205$. If $\gamma_{tr} = 2$, then $\eta = 0.047$, a reduction of 4.34 in the bunching-voltage requirements.

It seems that this could be an alternative to debunching and would allow the bunching to take place with the present LAMPF energy spread (increased by the bunching factor). We do not know what difficulties⁹⁹ may be encountered as $\eta \rightarrow 0$, but the freedom of this parameter should be kept in mind.

V. MEDIUM-ENERGY PROTON-STORAGE RING APPLICATIONS

All previous work with storage rings has been with colliding beams; the use of a storage ring as a duty-cycle manipulator is a new application. Here we outline various possible usages but do not develop them in depth.

A. Defense Applications

A storage ring used in conjunction with a neutron-chain multiplying target should be capable of total neutron output approaching 10^{17} n. This is roughly the output of a bare critical reactor (Godiva), but our interest is in the fact that the burst duration is only several tenths of microseconds. Thus, the first applications to come to mind are those for which Godivas have been used in the past. Some uses have been suggested in conference proceedings^{100,101}; however, probably the most extensive use has been in the investigation of transient radiation effects of electronics (TREES) as a result of neutron and secondary-gamma irradiation. The advantages afforded by the storage ring are: (1) The pulse is of much shorter duration than is possible with a supercritical multiplier. (2) The irradiation volume is larger because the target is only a multiplier and does not go critical. A target study involving a 7-cm-diam by 10-cm-long central cavity in ^{238}U predicted a neutron fluence of 0.063 n/cm² proton. For 6×10^{13} incident protons and a target multiplication of 20 through the use of ^{235}U , a fluence of $\sim 7 \times 10^{13}$ n/cm² will result. The hollow beam for this design could be achieved by a pulsed-wire septum or a high-frequency rotating field. (3) The hard neutron spectrum and small gamma production provide a good simulation of degraded nuclear weapon spectra. It should be superior in total output to Gulf General Atomics' EPFA,¹⁰⁰ an electron-linac-pulsed supercritical assembly (4×10^{13} n) and in reduced gamma production. For experiments requiring a high neutron production rate, the proton-storage ring booster rate of 3×10^{23} n/sec is significantly greater than EPFA's 4×10^{18} n/sec.

In achieving these high production rates, severe booster mechanical-design problems are anticipated. The total neutron output is comparable to a Godiva, but the pulse is so short that shock waves will be produced throughout the material. This seems to indicate that a solid-metal booster would crack under the rarification wave, and some other design is needed. One concept is to make the fuel in the form of very small pellets held together in a container. A second thought along the same line is to use a uranyl-sulphate solution in the KING concept.¹⁰⁰ This approach is particularly interesting because much of the energy goes into the heat of

vaporization, not into translational motion. Unfortunately, uranyl-sulphate tends to be a comparatively slow reactor because of the hydrogen in the water; an alternative might be condensed uranyl-hexafluoride.

The very fact that booster damage is anticipated suggests that the storage ring could be used for the study of material properties under extreme conditions. This and many other defense-related applications are discussed elsewhere.¹⁰²

B. Neutron-Pulse Radiolysis

Pulse radiolysis is a technique for direct study of transient, radiation-produced chemical and biological species. These metastable molecules are detected by fast-responding optical or spectrophotometric time analyses of the species population.

Neutron radiolysis is an interesting approach because its linear-energy transfer (LET) is about 4 eV/Å in typical tissue as compared with the LET of 0.02 eV/Å for 1-MeV electrons.¹⁰⁰ This high LET for neutrons resulting from the proton recoil is sufficient to dissociate the hydrogen-oxygen bond along the path it traverses. Further, the energy is sufficient to ionize one molecule of each pair along the path. The result is a cylindrical volume containing closely spaced ions, electrons, and free radicals. The recoil of nuclei of oxygen, carbon, and other atoms will produce tracks of even higher ionization density.

As an aside, it may be possible to study the recombination of the transient species resulting from π^- -produced stars in tissue and thereby gain some fundamental insight into the basis of pion cancer therapy.

The lack of neutron sources of sufficient intensity and short duration has prevented investigations of this sort. Some investigations were performed using the APFA pulsed-neutron source; however, the storage ring and subcritical booster could provide a neutron-source increase of 1000 times the total neutron output and nearly 5 orders of magnitude in the production rate.

It seems that a special booster design would be necessary to accommodate the spectrophotometer beam, but this does not seem difficult. Depending upon the progress of the work, it might be desirable not

to use a booster because of the fairly long time response, but to use a nonmultiplying target with the storage ring in the high-duty 5-nsec burst mode. Then we could study short-lived species.

C. Polarized Proton-Storage Ring

Polarization experiments have been significant in physics for distinguishing between competing theories, stimulating new research, determining nuclear spin and parity, testing invariance principles, and measuring off-diagonal elements of the S matrix.

The fact that protons are contained in a storage ring for some time suggests that operations such as beam polarization by multiple target traversals are possible. Csonka¹⁰³ considers this problem particularly for the CERN-ISR for the purpose of colliding polarized proton beams. He suggests three methods for polarizing the beam in each ring: (1) Polarization by beam transmission through a polarized proton target. In this case, if the total cross section for scattering a proton beam polarized along the target-polarization vector differs for parallel and antiparallel spin orientation, the net result is a beam whose polarization increases with target traversals. (2) Introducing an unpolarized hydrogen target into the beam so that particles scattered to the right and left are captured in separate satellite orbits, causes the two beams to have opposite polarization. This approach depends upon the ability of the lattice to hold three separate orbits. (3) Introducing a polarized hydrogen target, but capturing scattered protons within the acceptance of the storage ring, results in a beam of scattered and original protons of gradually increasing polarization.

We will not try here to design the experiment, only to point out its possibility. If direct comparisons with the ISR were possible, then using Csonka's numbers and the fact that the WNR ring has 40 times more circulation frequency, the beam should be 10% polarized in 45 sec and 30% polarized in 2.25 min. This, combined with the ring's capabilities for long or short extraction and the ability to reduce the energy spread below that of LAMPF, could make this a valuable experimental tool.

D. Counting Experiments

A storage ring may be considered a duty-cycle manipulator. We have been interested mostly in pulse compression, but it can also be used with slow beam extraction to provide a practically dc beam. This is especially true if charge-exchange injection is used, for then it is possible to inject and extract at the same time. The micropulses, as well as the macropulses, would be smoothed. Thus, if the microstructure is 0.4 nsec after traveling 500 ft this microduty is 8%. The macroduty is 6%. So, in this sense, the LAMPF duty is 0.5%. This is probably overly severe because in most experiments the microduty would be smeared in the secondary beam line.

Suppose an experiment has an accidental counting rate of

$$T = 2\tau \frac{R^2}{D^2},$$

where τ is the resolving time, R is the true counting rate, and D is the beam duty. Then if we wish that the fraction of accidentals be 10% or less,

$$\frac{R-T}{R} = 0.1 = 1 - \frac{2\tau R}{D^2}.$$

Hence,

$$R = \frac{0.1 D^2}{2\tau}.$$

For this situation in which the counting rate is limited by accidentals, the data rate could be increased 278 times by smoothing the macrostructure or 40,000 times by smoothing both the micro- and macrostructures.

Admittedly these advantages are realized for only some experiments but for those, the rewards of slow extraction from a storage ring are great indeed.

E. Pulsed Source for an Unstable Particle-Storage Ring

1. Muon-Storage Ring. One of the fundamental unknowns in physics today is the difference between an electron and a muon. The precision measurement of the difference between the observed magnetic moment of a Fermion and the Dirac predicted value of 2 (the so-called $g-2$ experiment) is very important. Because the interaction should be purely electromagnetic, an

alternative way of viewing the experiment is to search for a coupling to another field that would explain the muon-electron mass difference.

One method for this measurement is a counting experiment involving measurement of the precession frequency in a precise, well-known, magnetic field.¹⁰⁴ This technique could profitably use the storage ring in a slow-spill mode to improve the counting rate.

Another, perhaps potentially more accurate, method uses a muon storage ring.¹⁰⁵ The weak-focusing storage ring operated at CERN is 5 m in diameter. The muons are injected into the ring as a result of the decay of pions formed by proton bombardment of an internal target. The muons are formed polarized by the forward decay of the pions, and the polarization direction as a function of time is determined by recording the electrons emitted in muon decay. The experiment consists of comparing the frequency of muon revolution to the spin-precession frequency in the ring's magnetic field. Because of radiative corrections, the muon spin precesses faster than the state of polarization and this gives a direct measurement of the $g-2$ factor.

The CERN-PS proton pulse for forming the muons consists of three 10-nsec microstructure pulses, 105 nsec apart. Therefore, about 10^{11} protons are injected every 3 sec. The WNR ring in the high-duty mode would inject 6×10^{11} protons 600 times a second. Thus, on the basis of incident-particle flux, the WNR ring should be about 1800 times better than the CERN-PS for this purpose. In actual fact, the energies are so different that they do not compete, but supplement each other. The short (5-nsec) proton-burst width will implement the turn-counting method of measurement.

One might wonder if the muons could be formed and circulate in the WNR ring itself. This point has not been investigated, but, off hand, it seems that a strong focusing storage ring is not suitable. However, because of the long drift distances, the period of rotation may be relatively independent of momentum and could be useful.

2. Colliding Unstable-Particle Storage Ring.

Macek and Maglic¹⁰⁶ have proposed a weak-focusing, superconducting storage ring in which unstable particles such as pions and muons would precess and interact with each other. This "Precetron" requires

very intense proton bursts of short duration compared with the pion lifetime. Using their Table I, we conclude that the WNR ring using the full LAMPF H^- beam, i.e., the low-duty mode but at a 10-pps repetition rate, could drive the Precetron to produce about 100 interactions per hour. This is a very low counting rate, and perhaps future improvements in the Precetron design, such as strong focusing, could increase the interaction efficiency.

F. Beam Dynamics

Advancement of the understanding of beam dynamics comes with each advanced accelerator or storage ring, and this will be true for the WNR ring. The results of this study will be used to improve the performance of the WNR ring and assist in future circular-accelerator designs. In the design of the WNR ring, there are new concepts and applications of theoretical principles not experimentally tested. Particular interest is in the advantages of operating below the transition energy of the storage ring.

From the instability studies in this report, we see that the head-tail and transverse resistive-wall effects are most likely to be troublesome. Both effects result from the interaction of a beam with its environment which can be changed to affect the electromagnetic field. Thus, Sessler and Vaccaro¹⁰⁷ suggest the use of a helical insert (like that used in traveling-wave tubes) to slow the wave. Briggs¹⁰⁸ and Briggs and Neil¹⁰⁹ suggest the use of dielectric wall coatings. Inductive or iris-loading of the walls, like that used in linear microwave accelerators, or impedance matching of the walls to absorb the radiation¹¹⁰ may be future developments that could be explored with the WNR ring.

Besides these passive techniques, there are active approaches to stabilizing the beam at high currents. We have already referred to the wide-band feedback stabilization systems used at MURA and on the ZGS. Another active technique used at Cambridge involved rf quadrupoles to cause different parts of a bunch to have different tunes.

An electron-storage ring property that would be advantageous for proton-storage rings is radiation damping of the betatron oscillations. A method proposed to accomplish this is to mix electrons of similar velocity with the protons so that electron-proton

Coulomb interactions occur. The electrons take up some of the proton energy, thus cooling the protons. Budker,¹¹¹ a strong exponent of this technique, has calculated the relativistic case for equal proton and electron velocity. Maurer has calculated both the nonrelativistic¹¹² and relativistic¹¹³ cases for dissimilar particle velocities. Using Hereward's Debye length technique,¹¹⁴ we find a damping time of 1.7 sec using 1 A of electrons in the interaction region if the beam has a 2% momentum spread.

Use of electron cooling in conjunction with adiabatic compression of the energy spread could produce extremely high-density beams. This would be useful for storage-ring applications and would improve the ring performance through the use of many stacked, high-density orbits.

G. Neutron Time-of-Flight Spectrometer

Neutron resonance spectroscopy is the oldest application of pulsed-neutron research. The literature is voluminous, and a recent survey is recommended.¹¹⁵

The WNR ring in the high-duty mode would constitute the best neutron time-of-flight spectrometer in the world. In terms of neutron intensity, the Columbia University Improved Nevis Cyclotron is the closest competition. The higher repetition rate and greater target flexibility give the WNR ring advantages that in practice yield much higher counting rates than are reflected in the direct-intensity comparison.¹

VI. GLOSSARY OF SPECIALIZED TERMS

Admittance: the maximum emittance an accelerator or storage ring can accept.

B: the magnetic field intensity, unless stated otherwise, in units of kilogauss.

Betatron Space: the phase space representing radial and vertical oscillations.

Bucket: a bounded region of synchrotron space in which particles can be held.

Cell: a repeating element.

Charge Exchange: the removal of one or more electrons from an ion.

Chromaticity: the variation of tune with momentum: pdv/vdp .

Closed Orbit: the orbit for which the restoring forces are zero, i.e., the orbit for which the betatron amplitude is zero; hence, the equilibrium orbit.

Dispersion: the fractional variation of period with momentum, $pdT/Tdp = 1/\alpha - 1/\gamma^2$.

Emittance: the area of canonical phase space that represents the beam. Practically, the emittance is the product of the beam diameter and the angular divergence in that plane.

Field Index: the ratio of the logarithmic derivative of the magnetic field with radius $n = -RdB/BdR$.

Insert: a separation in a lattice. A matched insert would have a unit transfer matrix.

Kicker: a fast-response deflection element.

Lattice: the configuration of elements that provides the beam-restoring forces for a circular accelerator or storage ring.

Liouville's Theorem: the statement that the area representing a collection of particles in phase space is preserved if the energy is constant.

Momentum Compaction: see α .

Phase Advance: the change of phase angle of a particle traversing an accelerator element $\mu = \int ds/\beta(s)$.

Profile Parameter: $1/B (dB/dR) = -n/R$.

Rigidity: the product of magnetic field times radius of curvature.

Sector Magnets: those magnets used to bend a particle through some angle. They may also provide restoring forces, in which case they are called combined-function magnets.

Septum: a thin element located close to a beam for injection or extraction.

Shock Line: a delay line having nonlinear properties.

Stripper: an element used to remove electrons from ions.

Strong Focusing: the use of restoring forces so great that convergence in both planes cannot be achieved simultaneously.

Synchrotron Space: energy phase space.

Tune: the number of betatron oscillations per turn.

Weak Focusing: focusing in two plane simultaneously. It is characterized by $0 < n < 1$ for magnetic forces.

x_{eq} : the shift of orbit radius with momentum $= \alpha R$.

α : momentum compaction factor, $\alpha = Rdp/pdR = 1/\gamma_{tr}^2$.

β : ratio of particle velocity to that of light.

β -function: upper right-hand element of the Twiss matrix. The average beta function is the betatron wavelength.

γ : the ratio of the particle total energy to its rest energy.

γ_{tr} : the γ of a particle in a storage ring or circular accelerator having no phase stability; i.e., $\eta = 0$.

$\eta = 1/\gamma^2 - 1/\gamma_{tr}^2$.

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