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HIGH INTENSITY HADRON ACCELERATORS*

L. C. Teng

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*Presented at the Conference on the Intersections between Particle and Nuclear Physics, Steamboat Springs, Colorado, May 23-30, 1984.

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INTRODUCTION

When one talks about intersections between particle and nuclear physics one cannot help talking about the intersections of facilities and budgets. Actually the energies of the accelerators proposed now for nuclear physics were in the frontiers of particle physics only a few years ago, but of course, we are now talking about much higher intensities. In this paper we give an introductory discussion of high intensity hadron accelerators with special emphasis on the high intensity feature. The topics selected for this discussion are the following:

- o Types of accelerator - We are reminded that the principal actions of an accelerator are to confine and to accelerate a particle beam.
- o Focusing - This is a discussion of the confinement of single particles.
- o Intensity limitations - These are related to confinement of intense beams of particles.
- o Power economics - Considerations related to acceleration of intense beams of particles.
- o Heavy ion kinematics - The adaptation of accelerators to accelerate all types of heavy ions.

The discussions will necessarily be sketchy, but will hopefully be clear and illuminating.

TYPES OF ACCELERATOR

This is tabulated below:

- Circular
  - Fixed field (Cyclotron)
    - CW (Isochronous cyclotron) (1)
    - FM (Synchrocyclotron) (2)
  - Pulsed field (Synchrotron)
    - CG synchrotron (3)
    - AG synchrotron
      - Resonant excitation (4)
      - Ramp excitation (5)
- Linear
  - Accelerating structure - different for different velocity ranges (6)
  - RF source - different for different frequency ranges (7)

Each parenthesized number corresponds to the following itemized discussions.

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1. For the isochronous field (revolution time independent of energy) it is difficult to provide adequate axial focusing at high energies. This generally limits the top energy of a continuous-wave (CW) cyclotron which gives a continuous beam, to ~1 GeV. This will be discussed more in detail later.

2. If the isochronous field cannot be maintained because of axial focusing one has to frequency modulate the accelerating RF to keep in step with the revolution of the beam. The beam will have to be accelerated in pulses. It is then more economical to use a synchrotron which also gives a pulsed beam. There are now only about half a dozen synchrocyclotrons still in operation, the highest energy being the 1000 MeV machine at the Gatchina Institute in the USSR. It is safe to say that no new FM cyclotron will be built in the future.

3. All constant gradient (CG) or weak focusing proton synchrotrons have been either decommissioned or converted to AG focusing or accelerating heavy ions. These include PPA, Cosmotron, ZGS, Nimrod, Saturne, Bevatron, Synchrophasotron, Birmingham machine, etc. It is even more certain that no new CG synchrotrons will be built in the future.

4. By adding capacitors and inductors to the magnets, to form a resonating circuit, the magnets can be excited at the resonant frequency. Together with a proper DC bias the magnet excitation is then a biased sine wave. The highest frequency that has been used is 60 Hz. In principle there is no upper limit in frequency, except that more RF is required for faster acceleration. The only operating proton synchrotron with resonant excitation is the 15 Hz Fermilab Booster shown in Figures 1 and 2.

5. Most synchrotrons are ramp-excited. This gives the capability of a flat-top hence a long beam spill for electronic counter and chamber experiments.

6. The accelerating structure of a linac is a loaded wave guide which supports either a travelling wave or a standing wave. The desired characteristics of the wave guide are that the shunt impedance should be high so that the cavity power loss is low and that the separations between the wanted accelerating mode and all other unwanted modes should be sufficiently large so that the accelerating mode alone is excited. Thus, for different velocity ranges different electrode structures (cell structures) are needed. Starting from the low velocity end we have: radiofrequency quadrupole structure (RFQ), Wideröe structure. Alvarez (drift tube) structure, disk-and-washer structure, side-coupled cavity structure, axial coupled cavity structure, annular coupled cavity structure, etc. The last four high velocity structures are for velocities higher than ~½ c and are shown in Figure 3. The Wideröe and the Alvarez drift tube structures are familiar to everyone. The RFQ structure is shown in Figure 4. The four rippled electrodes produce an electric quadrupole field in addition to a longitudinal field. The structure is, therefore, self-focusing. (All other structures use separate quadrupole magnets for focusing.) Furthermore, the electric focusing in an RFQ is most effective for low velocity particles.

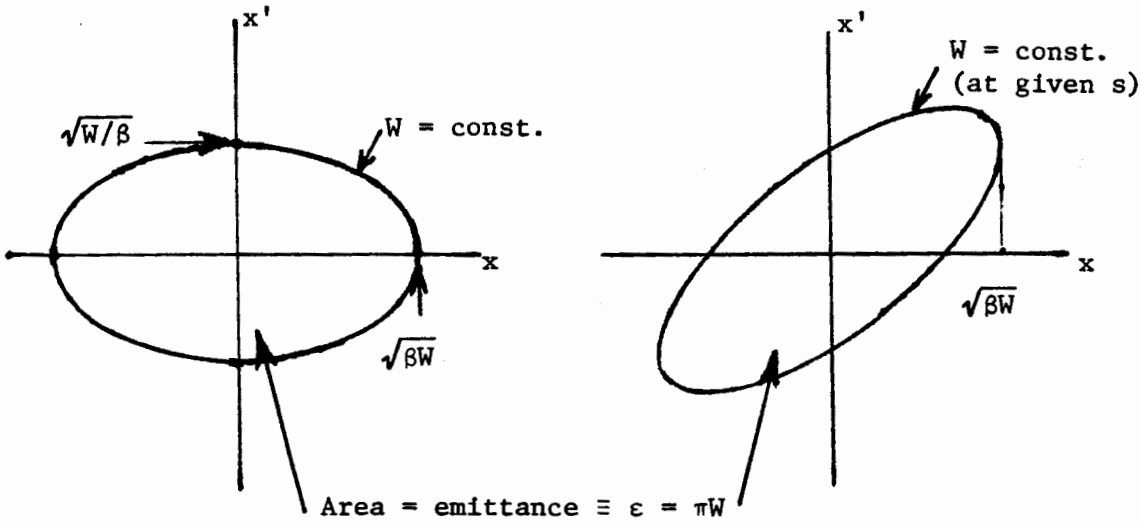
7. For frequencies below ~200 MHz the gridded tubes are effective and efficient. Above ~400 MHz klystrons are appropriate. Efficiencies (DC to RF) of these sources range from ~50% to ~70%. High efficiency sources, the gyrotron and the gyrocon are being developed. Both are invented in the USSR and are capable of efficiencies beyond 90%. The R&D of high efficiency RF sources over all frequency ranges is of paramount importance for all types of accelerators.

FOCUSING-CONFINEMENT OF SINGLE PARTICLES

1. Linac and Synchrotron

In contrast to the cyclotron the orbits in these types of accelerator are fixed spatially. Thus, the magnetic field is shaped only to provide proper focusing. Because of the divergence equation obeyed by the magnetic field a quadrupole magnet acts like an extreme astigmatic linear lens, having equal and opposite focal actions in the two orthogonal transverse planes. It was, however, discovered by Courant, Livingston and Snyder in 1952 that overall focusing in both planes can be obtained by alternating the focusing and defocusing actions. This is shown in Figure 5 where the rectangles between the lenses represent accelerating cavity structures for the linac or bending dipole magnets for the synchrotron. The resulting stable (linear) transverse oscillations of a particle are called the betatron oscillations. It differs from a harmonic oscillation in that its force factor instead of being a constant is a periodic function of the distance s along the (closed) orbit. We exhibit below the betatron oscillation side by side with the harmonic oscillation.

Harmonic Oscillation	Betatron Oscillation
o Equation	o Equation
$x''+kx = 0$	$x''+k(s)x = 0$
k = constant	$k(s) =$
o Solution	o Solution
$x = Ae^{\pm is/\beta}$	$x = A\sqrt{\beta(s)}\, e^{\pm i\int ds/\beta(s)}$
$\beta = \frac{1}{\sqrt{k}} \equiv \frac{\lambda}{2\pi}$	$\beta = \frac{1}{\sqrt{k}}\sqrt{1-\frac{1}{2}\beta\beta''+\frac{1}{4}\beta'^2}$
o Invariant	o Invariant
$W = \frac{A^2}{\beta} = \frac{x^2}{\beta} + \beta x'^2$	$W = \frac{1+\frac{1}{4}\beta'^2}{\beta}x^2 - \beta' xx' + \beta x'^2$



Area = emittance $\equiv \varepsilon = \pi W$

Beam width = $\sqrt{\beta\varepsilon/\pi}$

o Tune

$$\nu = \frac{2\pi R}{\lambda} = \frac{R}{\beta}$$

o Tune

$$\nu = \frac{1}{2\pi}\int^{2\pi R} \frac{ds}{\beta(s)} = R\left[\frac{1}{2\pi R}\int \frac{ds}{\beta(s)}\right] \equiv \frac{R}{<\beta>}$$

o Resonances

o Resonances

These are given by $\nu = m/n$. If not crossed in less than ~20 revolutions, the integer (n=1) and the half-integer (n=2) resonances should be avoided. The tune spread in the beam should, therefore, be $\Delta\nu \lesssim 0.4$.

2. CW (Isochronous) Cyclotron

The field must be shaped for isochronism. The orbit expands when accelerated. We denote the orbit length by $2\pi R$ and the magnetic field averaged over the orbit by B. Then, for the isochronism condition

$$R \propto \beta \quad (\beta \equiv \frac{v}{c} \text{ in this and all subsequent sections})$$

and for the bending condition

$$BR \propto \text{momentum} \propto \beta\gamma.$$

Hence $B \propto \gamma$ and rises sharply with increasing R for relativistic energies. For a B rising with R the average effect is axial defocusing. Other axial focusing forces must be derived to overcome this average axial defocusing force. L.H. Thomas proposed in 1938 to construct the magnetic field in sectors and obtain axial focusing from the fringe fields at sector edges. This can be seen from Figure 6. Away from the mid-plane the fringe field denoted by the arrow has a horizontal component perpendicular to the particle orbit, thus producing an axial force. It can be seen that this axial force is focusing at all the sector edges. It is also clear that the strength of this axial focusing is limited. In 1955, D.W. Kerst et. al. proposed a spiral-sector geometry (Figure 7) for

which the axial actions of the fringe fields at the entrances and the exits of sectors are alternately focusing and defocusing. The net effect is, of course, focusing and can be made rather strong by using a large spiral angle. However, for $\gamma >> 2$ (proton energy >>1 GeV) the axial defocusing effect due to the radially rising average field becomes so strong that it is difficult to override even with the largest practical spiral angle. Thus, the practical top energy of a cyclotron is limited at best to a few GeV for protons.

INTENSITY LIMITATIONS-CONFINEMENT OF INTENSE BEAMS OF PARTICLES

For an intense beam both the interactions among the beam particles and the self-field of the beam become important. They act to limit the maximum beam current that can be obtained. These are discussed, here, in a physically descriptive manner without mathematical derivation.

1. Space Charge Tune Spread

   This is given for a synchrotron by

$$\Delta\nu = \frac{3}{2} \frac{r_o}{\beta^2\gamma^3} \frac{N}{\varepsilon}$$

where

$r_o = \frac{e^2}{mc^2}$ = classical radius of particle

N = total number of particles in the uniform beam

ε = emittance of beam

and where the factor 3/2 is for a Gaussian distribution and should be replaced by other values for other distributions of particles in the beam. Particles with small oscillations sample the dense core of the beam and have their tunes depressed by the value $\Delta\nu$ shown above. Particles with very large oscillations sample the whole beam with an average density much lower than that of the core and hence have very small tune depressions. Thus, the spread of the tunes of all particles in the beam is approximately equal to $\Delta\nu$ given above. As mentioned earlier, in order to avoid beam-losing resonances $\Delta\nu$ should be $\lesssim 0.4$. The proportionality of $\Delta\nu$ to $r_oN = e^2N/mc^2$ and the inverse proportionality to the energy factor $\beta^2\gamma^3$ and the emittance ε are all easy to understand qualitatively.

There is no resonance for a linear accelerator. In a linear transport the beam intensity can be so high that the focusing action of the quadrupoles is almost totally overcome by the space charge defocusing action. The tune spread formula given above applies, in principle, also to the cyclotron. But because there is no longitudinal focusing in a CW cyclotron the beam current is almost always limited to a much lower value by the longitudinal space charge force which lengthens the beam bunches until the momentum spread becomes

unacceptably large.

2. Intrabeam Scattering

In a dense bunch of beam the scattering between beam particles becomes significant and causes emittance growth. The growth rate of the 6-dimensional phase space volume of the beam bunch Γ (6-D emittance), is given by

$$\frac{1}{\Gamma}\frac{d\Gamma}{dt} = \frac{\pi^2}{\gamma}\frac{c\, r_o^2 N(\log)}{\Gamma}\left\langle H(\lambda_1, \lambda_2, \lambda_3)\right\rangle_{2\pi R}$$

where log = Coulomb logarithm $\cong$ 20, and $H(\lambda_1, \lambda_2, \lambda_3)$ is a dimensionless and homogeneous "momentum shape factor". $1/\sqrt{\lambda_1}$, $1/\sqrt{\lambda_2}$, $1/\sqrt{\lambda_3}$ measure the principal axes of the momentum ellipsoid of the beam bunch. $\langle\ \rangle_{2\pi R}$ denotes averaging around the orbit. H can be expressed, in general, in terms of elliptic integrals and H = 0 if $\lambda_1 = \lambda_2 = \lambda_3$, namely when the momentum spread is isotropic. In an alternating gradient lattice the λ's cannot be equal everywhere, hence the emittance will always grow.

The dependence of the emittance growth rate on $r_o^2 N$ is expected because it is the result of scattering reactions. The e^4 dependence indicates that for (and only for) high charge-state heavy ions the intrabeam scattering is likely to impose the most stringent limitation. For proton synchrotrons the intensity is generally limited by other phenomena. Even more so for linacs and cyclotrons, the intrabeam scattering effect never needs to be considered.

3. Coherent Instabilities

The high current beam travelling inside the vacuum pipe induces a voltage through an "impedance" of the pipe. This voltage, in turn, acts back on individual particles in the beam. Depending on the phase of the feedback and the coherence of the motions of the particles such a mechanism can cause instabilities and the beam can stray or blow up. The obvious "cures" of these instabilities are the following:

o One should keep the "impedance" of the beam pipe as low as possible. This is done by keeping the inner surface of the beam pipe as smooth as possible. All discontinuities and intrusions in the pipe should be avoided and all devices which must be exposed electromagnetically to the beam such as the beam monitor should be designed so that they are flush with the interior wall of the beam pipe.

o For low frequency (low mode number) instabilities, one can sense the beam motion by a pick-up electrode and use the signal properly processed by an electronic circuit to drive the beam in a negative feed-back. Available electronics, however, limit the effectiveness of this "cure" to frequencies less than ~1 GHz.

o The high frequency modes can only be stabilized through Landau damping due to a spread in the oscillation frequencies of individual particles in the beam. The frequency spread "decoherentizes" the motion and washes out the effect of the induced voltage on individual particles. To increase the spread in longitudinal oscillation frequency one increases the momentum spread in the beam and to increase the spread in transverse oscillation frequency one

increases the tune spread by introducing an octupole field. But, of course, the tolerable magnitudes of these spreads are all limited and they must be introduced judiciously.

The coherent instabilities are caused by the field due to the upstream part of the beam affecting the motion of the downstream part of the beam and hence affect linear and circular accelerators alike. The dependence on beam parameters is, again, r_oN.

One can summarize the intensity limitations of different types of accelerator as follows:

o The cyclotron, because of the absence of longitudinal focusing, is limited by longitudinal space charge forces to a beam current of the order of 100 μA.

o The synchrotron is usually limited to a beam current of several hundred mA by the tune spread due to transverse space charge forces at injection, when the beam energy is lowest. Coherent instabilities do arise, but can usually be taken care of by various "cures". The intrabeam scattering is troublesome only for high charge-state heavy ions.

o The linac is limited by the coherent instability (beam breakup phenomenon) and by the transient effect of beam loading on the RF. The limit is generally of the order of 500 mA.

POWER ECONOMICS-ACCELERATION OF INTENSE BEAMS OF PARTICLES

In this section we will make some observations related to power consumption, efficiency and cost in accelerating a high current beam of particles.

1. Historically as the energies of accelerators went higher the accelerated beam currents decreased. Superficially, this trend appeared to be the consequence of the acceleration schemes or the accelerator types used. But in a total analysis one finds that the evolution of higher energy accelerator types is necessitated by the economy of both the construction cost and, most of all, the power consumption. For example, to obtain a 10 mA beam at even the modest energy of 10 GeV will require 100 MW of power to the beam or about 400 MW from the power main. With 5000 operating hours per year and an electricity cost of 10 ¢/kwh this represents an annual power bill of $200 million!

2. In actuality all accelerating cavity structures operate more efficiently at high beam currents. A typical RF cavity with some ferrite loading for frequency modulation might have peak voltage $V_o \cong 100$ kV and shunt impedance $Z_s \cong 100$ kΩ. The cavity power consumption is, therefore,

$$P_{cav.} = \frac{V_o^2}{2Z_s} = 50 \text{ kW}.$$

For good efficiency the power imparted to the beam should not be much less than this value. Even if the beam is accelerated on the peak cavity voltage to 100 keV this corresponds to a beam current of ~500 mA. Thus, for beam currents much less than 100 mA the cavity is not utilized efficiently.

3. In a synchrotron although the average beam current is low the accelerating cavities are efficiently used by recirculating the beam. The duty factor of the cavities is generally 50% or better and the beam current handled by the cavities is generally several hundred milliamps. The same is true in a cyclotron except the beam current loaded on the accelerating Dee system is only of the order of 10 mA (tens of μA times hundreds of turns).

In contrast, for the usual pulsed operation of a linac, the accelerating structure is operated at a duty factor of anywhere from a few percent (LAMPF) down to less than 10^{-5}, although the peak beam current during the pulse is hundreds or, at least, tens of milliampere. In view of the fact that linac structures are designed to efficiently accelerate hundreds of milliamps of beam continuously (CW operation and no recirculation) it appears that linacs are commonly used in an inefficient mode at very low duty factors. This is also the reason for the general feeling that linacs are expensive. We summarize as follows:

o For average beam currents up to 0.1 mA the cyclotron (< a few GeV) and the synchrotron (> a few GeV) are the appropriate accelerators.

o For average beam currents higher than 10 mA the CW linac is most efficient and cost effective. Such linacs have been proposed as neutron generators for materials studies (FMIT) and for breeding fissile fuels.

o For in-between average beam currents, there is no appropriate accelerator. One can only use the linac operated at low efficiency in the pulsed mode.

4. To illustrate the comparison of cost and efficiency we consider the example of a 50 GeV Kaon Factory with an average beam current of 100 μA. For a synchrotron, assuming a 5000-fold beam recirculation through the accelerating cavities we get the following parameters:

Recirculation = 5000 fold (assumed)
RF-loading beam current = 5000 x 100 μA = 500 mA
Accelerating voltage = (50 GV)/5000 = 10 MV
RF power = 2x(50 GV x 100 μA) = 10 MW
(DC to RF efficiency = 50%)
Revolution time = 5 μsec (assumed)
Pulse time = 2x(5000 x 5 μsec) = 50 msec
Pulse rate = 20 sec^{-1}
No. of protons/pulse = $3x10^{13}$
Cost of synchrotron ≅ M$ 200 (estimated)

For a linac the cost of the accelerating structure alone is about M$ 20/GeV or a total of about G$ 1. To obtain the specified performance with a linac appears, therefore, to be very expensive. However, if the desired beam current were 100 mA (leaving aside the question of the operating cost) the total linac cost would be:

RF power required = 2x(50 GV x 100 mA) = 10 GW
Cost of RF supply = G$ 20 (at $2/W)
Cost of accelerating structure = G$ 1
Total cost of linac = G$ 21

which is much less than the G$ 200 obtained by scaling the synchrotron

cost up by the 1000-fold increase in beam power. This simply demonstrates that most of the cost of the synchrotron is in the magnet system which effects the recirculation and which is, of course, absent in the linac.

HEAVY ION KINEMATICS

Finally, we give here a summary of the possibilities of and the modifications necessary for using proton accelerators to accelerate heavy ions.

1. Circular Accelerators

The bending magnetic field strength B, the accelerating RF frequency F, and the harmonic number h for a proton (subscript o) and for a heavy ion with charge number q and mass number A, must satisfy the following relations:

$$\frac{q}{A}\,\frac{B}{B_o} = \frac{\beta\gamma}{\beta_o\gamma_o} \qquad \text{Magnetic field relation}$$

$$\frac{h_o}{h}\,\frac{F}{F_o} = \frac{\beta}{\beta_o} \qquad \text{RF frequency relation.}$$

For a synchrotron the same magnetic field program is appropriate for the confinement of a heavy ion with momentum-per-nucleon equal to q/A times that of the proton. The β of the heavy ion will be different from that of the proton, but the same RF frequency range can usually be used to accelerate the heavy ion on some appropriate harmonic number over, at least, a limited β range. To continue acceleration one will have to pass on to another smaller harmonic number.

For a cyclotron the RF frequency is fixed. One will have to choose an h such that β ($= \beta_o h_o/h$) when substituted in the field relation gives a field strength B not too different from B_o. Trim coils installed on the magnet poles are used to change $B_o(R)$ to $B(R)$. Aside from the proton, the q/A values of most fully stripped ions fall in the small range of 0.50 to 0.39. It is, therefore, relatively easy to adapt a cyclotron (or a synchrotron) for accelerating all ions other than the proton.

2. Linear Accelerator

For a linac the corresponding relations are

$$\frac{q}{A}\,\frac{E}{E_o} = \frac{\gamma-1}{\gamma_o-1} \qquad \text{Electric field (E) relation}$$

$$\frac{1}{h}\,\frac{F}{F_o} = \frac{\beta}{\beta_o} \qquad \text{RF frequency relation,}$$

the harmonic number for the proton being usually $h_o = 1$. Again, the RF frequency is fixed. One, therefore, tries to choose h such that β ($= \beta_o/h$) when substituted in the field relation gives a value for E not too different from E_o. Even though, it is rather difficult to adjust to the required $E(\ell)$ as function of the distance ℓ along the linac. (E_o is generally designed to be independent of ℓ.) The only possibility is to build the linac in short and independently tuned

sections. One such heavy ion linac, the RILAC, has been constructed and operated at RIKEN in Tokyo. At non-relativistic energies the field relation can be approximated by

$$\frac{q}{A}\frac{E}{E_o} = \frac{\gamma-1}{\gamma_o-1} \cong \frac{\beta^2}{\beta_o^{\ 2}} = \frac{1}{h^2}$$

where for the last expression we have substituted $\beta = \beta_o/h$ from the frequency relation. This gives a required E which is also independent of ℓ. There is, thus, no difficulty in retuning a conventional proton linac for accelerating any heavy ion to non-relativistic energies.

Figure 1 A photograph of the Fermilab 8-GeV proton Booster synchrotron showing the magnets. Underneath the magnets are the capacitors and inductors forming the 15-Hz resonating circuit with the magnets.

Figure 2. Photograph of the Fermilab Booster showing the accelerating cavities.

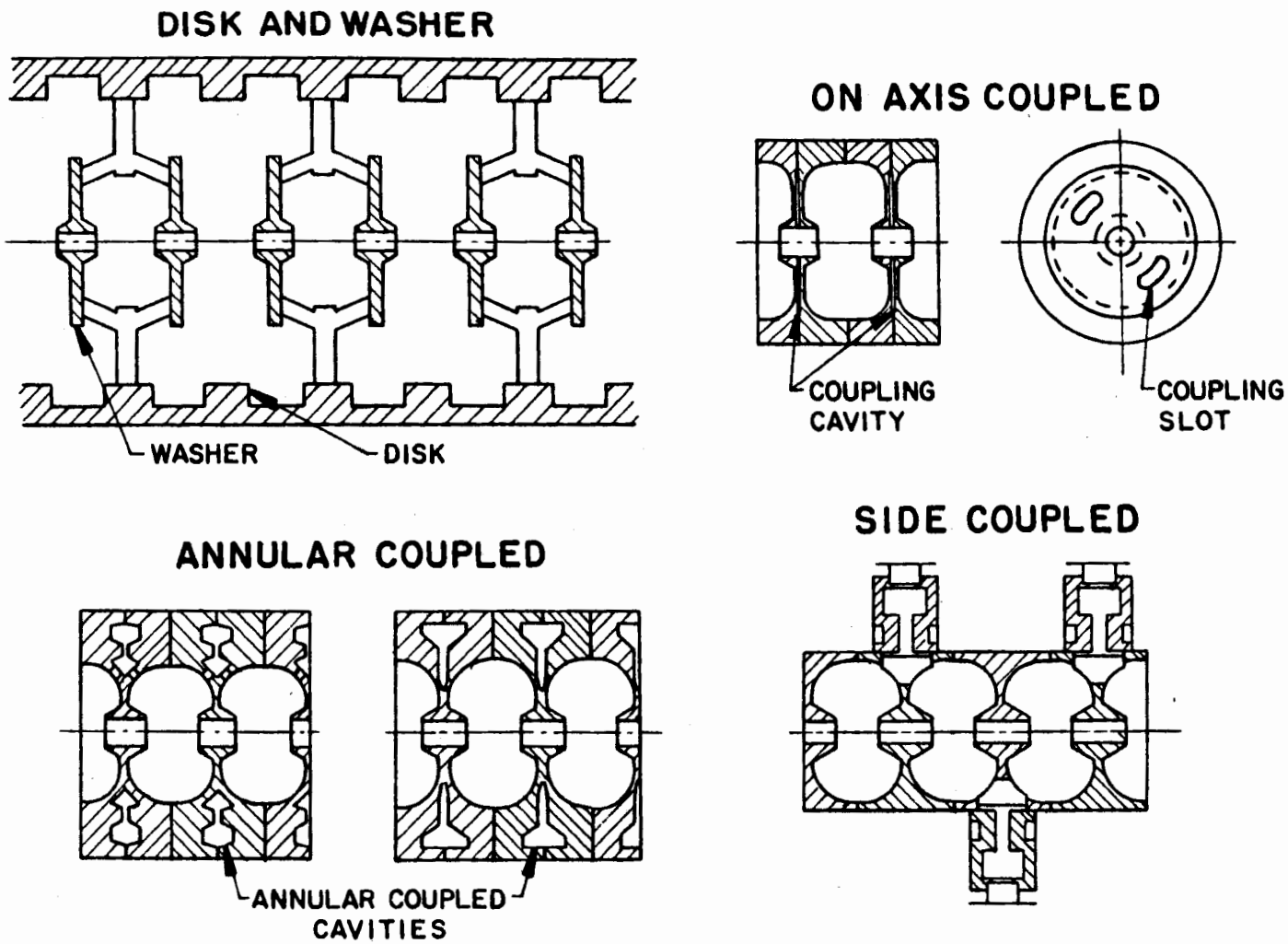


Figure 3. Four types of high-velocity standing-wave accelerating structures.

TM-1262

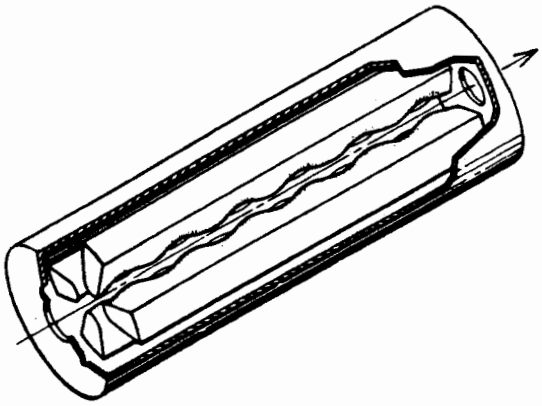


Figure 4 Illustrative drawing of one type of the radiofrequency quadrupole accelerating structure.

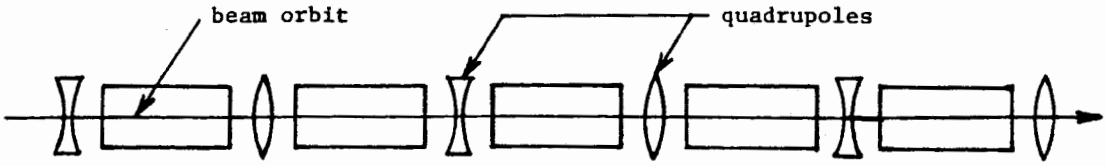


Figure 5 Diagram illustrating the principle of alternating gradient focusing. The lenses indicate the focal actions of the quadrupoles. In the orthogonal transverse plane the focal actions are reversed. The rectangles represent accelerating cavity structures for the linac or bending dipoles for the synchrotron.

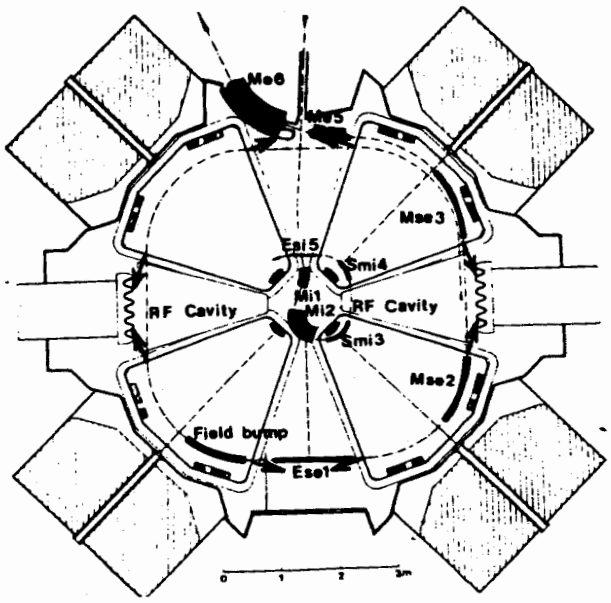


Figure 6 Diagram of the cyclotron GANIL in Caen showing the four radial sectored magnet.

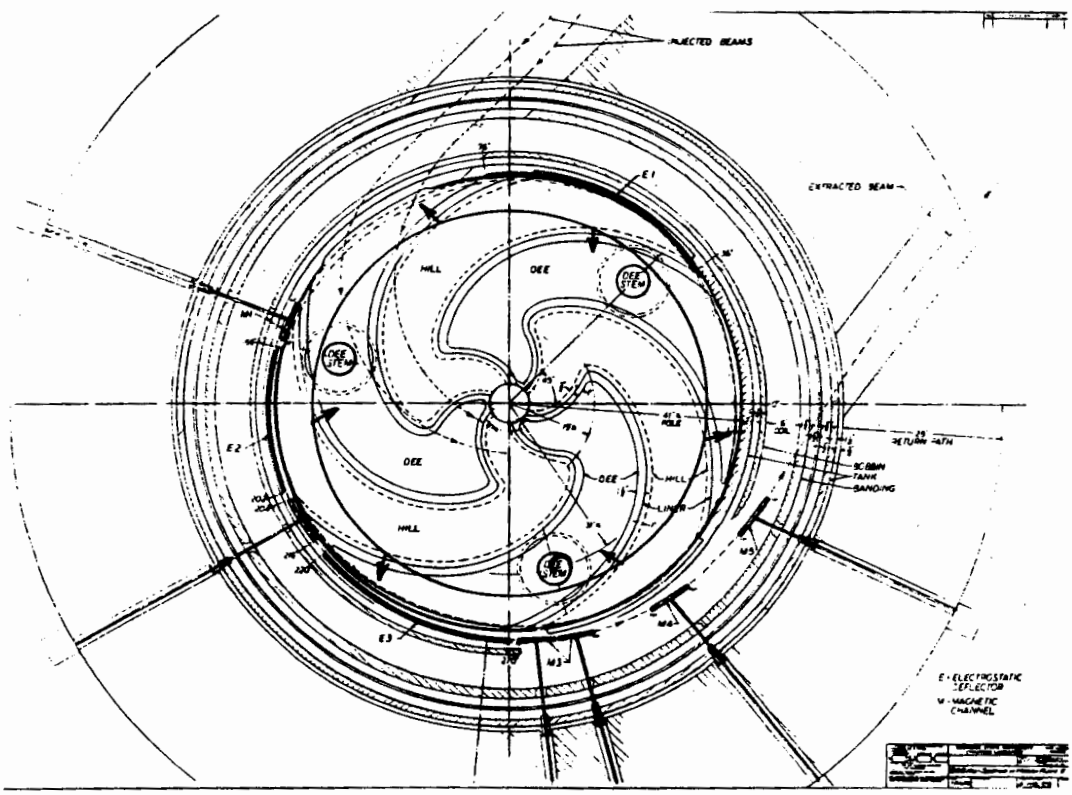


Figure 7 Plan view of the Michigan State University superconducting cyclotron magnet showing the three spiral sectors.