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## **Accelerating Polarized Beams in TEVATRON**

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Introduction

Polarization experiments at high energies continue to generate surprises. Many questions remain unanswered or unanswerable within the frame work of QCD, these include such simple basic questions as to why the polarization analyzing power in pp elastic scattering remains high, why hyperons are produced with high polarizations at high energies, etc. It is, therefore, interesting to investigate the possibilities of accelerating and storing polarized beams in the Tevatron.

On the technical side the recent understanding of the possibilities of turning on and off Siberian snakes without depolarizing the beam and of the effects of partial snakes, i.e. snakes with precession angles less than  $180^\circ$ , opened up new ways of dealing with depolarizing resonances. The tried and true method of a combination of jumping (rapid crossing), slow crossing (total flip), and de-exciting (reducing alignment errors) resonances are exacting, costly and time consuming. They can hopefully be replaced by the use of the much simpler "passive" partial snakes.

In this paper, we will examine the totality of equipment, manpower and cost necessary to obtain a polarized proton beam in the Tevatron. We will not, however, be concerned with the acquisition and acceleration of polarized  $\bar{p}$  beams. Furthermore we will consider only a planar main ring without overpass, although it is expected that Siberian snake schemes could be made

to apply equally well to non-planar machines. In addition to not wanting to tackle here the task of reformulating the theory for a non-planar closed orbit, we also anticipate that as part of the Tevatron upgrade the main ring will in the not too distant future, be replaced by a planar main injector situated in a separate tunnel.

### Polarized $H^-$ Source and Preaccelerator

The polarized  $H^-$  source consists of two main sections. The first section produces a polarized  $H^0$  beam. Many different schemes have been proposed and employed for this purpose. The most straightforward and traditional is the method of using the Stern-Gerlach mechanism to produce a neutral atomic hydrogen beam with electron spins polarized. The nucleus proton is then polarized through microwave transitions between hyperfine states in a magnetic field. In the second section, the  $H^0$  is transformed to  $H^-$  through electron pickup from Cs atoms. Figs. 1a and 1b give a schematic drawing of such a source used for the AGS polarized beam.<sup>1</sup>

The simplest preaccelerator is an RFQ linac as used for the AGS beam. The RFQ can accelerate the beam to higher energy ( $\sim 2$  MeV) than the Cockcroft-Walton (CW), thereby making the first section of the following drift-tube linac (DTL) more efficient. As a part of the Tevatron upgrade, the CW is to be replaced by a 2 MeV RFQ (Fig. 2). This can be used for accelerating polarized  $H^-$  as well. Otherwise one will have to build a dedicated RFQ and inject the 2 MeV  $H^-$  beam from the RFQ as an alternative branch into the present DTL.

### Acceleration through Linacs

The beam is A.G. focused in both the RFQ and the DTL. In the RFQ the focusing is electric which has little effect on the spin. In the DTL the transverse focusing is supplied by quadrupole magnets. The spin does precess about the magnetic field of the quadrupoles. However, the quadrupole polarities are alternated in such a way as to cancel out the first order orbital effect leaving only the second order effect which is focusing in both transverse planes. This also makes the spin precessional effect (which is linear) cancel in successive quadrupoles. Thus, the polarization will be preserved throughout both the RFQ and the DTL linacs.

The injection beam transport line may have to be modified. Depending on the design of the Siberian snake to be used in the booster ring, the eigen-direction of the spin at the injection point is uniquely determined. The injection transport line must precess the spin of the beam from the linac such that at the injection point, it points in the eigen-direction. The redesign and rebuilding of the transport line are straightforward.

### Depolarizing Resonance in Synchrotrons

Contrary to a linac, in a synchrotron the acceleration rate is much slower and the beam returns through the same quadrupoles sector after sector or at least, turn after turn. If the spin precession tune (precession per turn) runs into some rational relationship with the sector or revolution periodicity (resonance condition), the undesirable precession can accumulate and after many turns or sectors, may amount to a sizeable depolarization. The resonances must be avoided or eliminated.

More specifically, in a synchrotron (assumed planar), the main guide field is vertical (coordinate  $z$ ). Hence, the eigenspin direction is  $\pm\hat{z}$ . In the absence

of horizontal field component, a vertically polarized beam will retain its polarization forever. There are however two sources of horizontal field components on the particles. First, because of alignment errors the closed orbit will not be perfectly in a horizontal plane. The horizontal field component felt by a particle traveling on the closed orbit is proportional to the magnitude of the vertical distortion of the closed orbit. Second, all particles in the beam perform vertical oscillations. The incremental horizontal field on a particle straying vertically off the closed orbit is what imparts the restoring force to keep the particle focused toward the closed orbit. This second horizontal field component is clearly proportional to the amplitude of the vertical oscillation of the particle, or the vertical size of the beam. Both of these horizontal fields are oscillatory; the imperfection field having harmonics  $k$  ( $=$  integer) and the field due to vertical oscillation (intrinsic) having harmonics  $kP \pm \nu_z$  where  $P$  is the lattice sector periodicity. The resonant conditions are therefore

$$\text{Precession tune} = \nu_p = \gamma G = \begin{cases} k & \text{imperfection} \\ kP \pm \nu_z & \text{intrinsic} \end{cases}$$

where  $G = \frac{K-2}{2} = 1.793$  for proton, is the anomalous gyromagnetic ratio.

The strength  $\epsilon$  of these resonances depend, in addition to the amplitude of oscillation or orbit distortion, on the specific magnet lattice and can be calculated for a given lattice by a computer program DEPOL written by E.D. Courant. The amount of depolarization suffered in crossing a resonance is proportional to the strength  $\epsilon$  and inversely to the crossing speed  $\alpha$ . To reduce the depolarization effect, one must therefore either reduce  $\epsilon$  or increase  $\alpha$ . Both methods have been applied in practice.

The strength  $\epsilon$  increases with energy for both types of resonance such that at high energies

$$\epsilon \propto \begin{cases} \gamma & \text{imperfection} \\ \sqrt{\gamma} & \text{intrinsic} \end{cases}$$

(At low energies  $\gamma$  should be replaced by  $\beta\gamma$ .)

For imperfection resonances the orbit distortion is fixed and the horizontal field component is roughly proportional to  $\gamma$ . For intrinsic resonances the proportionality is softened because the amplitude of oscillation decreases as  $1/\sqrt{\gamma}$ . Thus for high energy machines, the stronger and more numerous resonances make the individual resonance jump and orbit correction method used so far, extremely unattractive. Fortunately, Derbenev and Kondratenko<sup>2</sup> proposed in 1977 an ingenious method of eliminating the resonances altogether using strings of dipoles to impart the equivalent of phase shifts to the vertical precession. This method has come to be called the Siberian snake.

#### Siberian Snakes - Full and Partial

If while an oscillation is being driven by a resonant force, its phase is periodically shifted by  $180^\circ$  the force will just periodically increase and reduce the oscillation amplitude leading to no net blow-up of the oscillation and the resonance is effectively eliminated. The phase of the vertical precession can be shifted  $180^\circ$  by a  $180^\circ$  precession about any horizontal axis. The Siberian snake is a series of moderate dipoles ( $\sim 10$  in number and  $\sim 1$  Tm each) installed in a straight section of the synchrotron ring lattice, which produce just such a horizontal precession while causing no net deflection of the orbit. The Type 1 (longitudinal) snake produces a precession about the longitudinal horizontal (tangent  $\hat{y}$ ) axis and the Type 2 (transverse) snake has a transverse horizontal (normal  $\hat{x}$ ) precession axis. They are shown in Figs. 3 and 4. They

differ in their closed spin or eigenspin trajectory (the equivalent of the closed orbit). For a perfect ring without snakes the closed eigenspin direction is a constant  $\hat{z}$  all around the ring. With a longitudinal snake the closed eigenspin orientation at a location diametrically opposite the snake is in the longitudinal direction  $\hat{y}$ . As the particle goes around the ring, the spin precesses in the horizontal plane to some angle, say  $\theta$ , from  $\hat{y}$  at the snake. The  $180^\circ$  flip by the snake brings the spin back to the horizontal plane at angle  $-\theta$  from  $\hat{y}$ . The continued precession in the horizontal plane around the remaining half-revolution will bring the spin back to  $\hat{y}$  at the diametrically opposite starting point to complete the closed eigenspin trajectory. With a transverse snake, the eigenspin orientation at the location diametrically opposite to the snake is in the transverse direction  $\hat{x}$ . More attractive is the arrangement with a pair of snakes, one longitudinal one transverse, placed at diametrically opposite locations in the ring. The eigenspin trajectory is along  $\hat{z}$  for one-half of the ring and along  $-\hat{z}$  for the other half. At the point of injection, the polarization of the injected beam should point along the eigenspin direction.

It is intuitively reasonable that the accumulated horizontal (depolarizing) precession due to the resonance should not be as large as  $\pi$  between snakes (one full revolution if there is only one snake in the ring). This expectation has been shown to be approximately valid and since the resonance strength  $\epsilon$  is a measure of the depolarizing horizontal precession per turn in units of  $2\pi$ , for a single snake the condition can be written as

$$\epsilon < 1/2 .$$

Therefore, more snakes (or pairs of snakes, if vertical eigenspin orientation is desired) distributed around the ring are needed to cope with strong resonances at high energies.

Although the snakes produce no net distortion in the particle orbit external to the snakes, they unavoidably cause transverse (x and z) orbit excursions inside. Since the transverse precessions, hence the strengths of the dipoles are independent of particle energy, the excursions are larger at lower energies. From the expressions given in Figs. 3 and 4, we see that the excursions get uncomfortably large at proton energies below  $\sim 30$  GeV.

Fortunately, it has recently been realized<sup>3</sup> that for weak resonances which occur at low energies the phase shift produced by the snake could be less than  $\pi$ . As long as the depolarizing horizontal precession per turn is small, the repeated passage through the snake every revolution will result in continuous coherent accumulation of the snake precession and as long as the depolarizing horizontal precession is less than  $\pi$  when the snake precession has accumulated to  $\pi$ , further traversals will cause the depolarizing horizontal precession to decrease, thereby rendering the resonance harmless. This condition has also been confirmed semi-quantitatively and for one snake the condition on the snake precession  $\delta$  can be written as

$$\frac{\delta}{2\pi} > \epsilon$$

Since it is likely that the snake dipole could be weaker, hence, the orbit excursion could be smaller for partial snakes with  $\delta < \pi$ , it was hoped that in this manner one could use Siberian snake to eliminate depolarizing resonance even at energies much lower than 30 GeV. But first, one must invent snakes which can be powered to yield precession angle  $\delta$  continuously variable down to 0. This was done by D. Underwood<sup>4</sup> and shown in Figs. 5 and 6. All these continuously variable precession snakes have dipoles with fields rolled  $45^\circ$  from the vertical (or horizontal). This is shown in Figs. 5 and 6 by the



arrows in the squares which are end-views of the dipoles. The magnets are powered in two strings, A and B. Fig. 5 shows a transverse continuously variable partial snake with 12 dipole units (Some neighboring dipoles can naturally be combined to make one dipole two units in length.). The required precession angle  $\theta$  in each dipole unit for the two strings is plotted as function of the desired snake precession angle  $\delta$  in Fig. 7.

The precession angle  $\theta$  of the stronger A string dipoles is related to the total transverse precession  $\delta$  of the snake by

$$\theta^2 = \frac{\pi}{8} \delta \quad (\text{valid for } \delta = 0 \text{ to } \pi)$$

Fig. 6 shows a longitudinal continuously variable partial snake with eight dipole units. The required dipole precession angle  $\theta$  is plotted as function of the snake precession angle  $\delta$  in Fig. 8. The larger dipole precession angle is related to the snake precession angle also by the above equation except that its validity extends only over  $\delta = 0$  to  $\pi/2$ . To get  $\delta = \pi$ , one needs two snakes joined together. The orbit excursions are proportional directly to  $\theta$  and inversely to the particle momentum,  $\beta\gamma$ , and are given in Figs. 5 and 6 for 5.48-tesla superconducting dipoles.

#### Application to Tevatron

The resonance strengths  $\epsilon$  for the Tevatron Ring have been calculated using DEPOL and are shown in a log-log plot in Fig. 9. The black squares are those of the strongest intrinsic resonances and they all fall on the straight line with a  $\sqrt{\gamma}$  slope. An oscillation amplitude corresponding to a normalized emittance (invariant) of  $10\pi$  mm-mrad is assumed. The crosses lying on the straight line with a  $\gamma$  slope give the strengths of the strongest imperfection

resonances. An rms closed-orbit distortion of 0.1 mm and an rms quadrupole gradient error of 0.1% were assumed for this calculation.

Since the Main Ring has nearly the identical lattice to the Tevatron Ring (As mentioned in the introduction we consider here only the pre-overpassed planar Main Ring.), the resonance strengths are expected to be given with good approximate by extensions of the Tevatron Ring straight lines. When the present Main Ring is replaced, we will need to investigate the resonances in the new planar Main Injector. But since the circumference and the betatron tunes of the Main Injector are likely smaller than those of the Main Ring, one can expect with good assurance that the resonances in the Main Injector will not be stronger than those in the planar Main Ring.

Because of the high cell periodicity (24) of the Booster Ring, it has only one weak intrinsic resonance ( $\gamma G = \nu_z = 6.8$ ) shown as a circle in Fig. 9. The imperfection resonances shown as triangles are also weak.

In Table 1 we list the numbers of intrinsic and imperfection resonances and the upper limits of their strengths for the Booster Ring, the (planar) Main Ring and the Tevatron Ring. We propose to suppress all these resonances with full and partial Siberian snakes. The proposed configurations and modes of operation of the snakes for these three synchrotron rings are described in detail below.

Table 1 - Spin Resonances of the Tevatron

		<u>Booster Ring</u>	<u>Main Ring</u>	<u>Tevatron Ring</u>	
T (Gev)	0.2	8	150	900	
$\gamma G$	2.175	17.08	288.4	1722	
No. of resonances					
Intrinsic		1	90	476	
Imperfection		15	271	1433	
Max. strength of res.					
Intrinsic		$10^{-2}$	0.22	0.72	
Imperfection		$2 \times 10^{-3}$	0.10	0.77	

### 1. Booster

It is fairly clear from the resonance strengths given in Table 1 that one  $90^\circ$ -maximum partial snake (say, the longitudinal) alone will be adequate. We propose here a "fixed excursion" mode of operation. This mode of operation is possible and desirable for all machines with rather low resonance strengths over the entire range of acceleration. At the top energy of 8 GeV ( $\beta\gamma = 9.42$ ), the snake is turned on full which for a superconducting, Underwood's longitudinal partial snake means  $\delta = 90^\circ$ ,  $\theta = 45^\circ$  and  $a_{\max} = 3.48$  cm. At lower energies the snake dipole excitation  $B\ell$ , hence  $\theta$ , is reduced in proportion to  $\beta\gamma$  so as to keep the excursion  $a_{\max}$  fixed. This allows the dipole to be aligned on the distorted orbit. Since the orbit excursion is fixed, no allowance in the dipole aperture is needed to accommodate orbit displacements. With such an excitation program we have.

$$\frac{\theta}{45^\circ} = \frac{\beta\gamma}{9.42},$$

$$\delta = \frac{\theta^2}{22.5^\circ} = \frac{45^\circ{}^2}{22.5^\circ} \left( \frac{\beta\gamma}{9.42} \right)^2 = 90^\circ \left( \frac{\beta\gamma}{9.42} \right)^2$$

and the maximum resonance strength  $\epsilon_{\max}$  that can be suppressed is

$$\epsilon_{\max} = \frac{\delta}{360^\circ} = \frac{1}{4} \left( \frac{\beta\gamma}{9.42} \right)^2$$

This is plotted in Fig. 10 together with the expected strengths of the strongest intrinsic and imperfection resonances. We see that the "fixed excursion" program of excitation keeps the permitted maximum strengths comfortably above those expected.

The total length of the longitudinal Snake is only  $\sim 2.5$  m and can be accommodated easily in one of the many empty 6m straight sections of the Booster. The beam transport line from the linac must be redesigned to precess the polarization of the  $H^-$  beam to the specific eigen-orientation at the injection point. The electron stripping by the foil to convert  $H^-$  to p should not have any effect on the polarization of the beam.

## 2. Main Ring

Since the maximum resonance strength is  $\sim 0.22$ , we will need a  $180^\circ$ -maximum snake (one transverse snake as shown in Fig. 5 or two longitudinal snakes as shown in Fig. 6 or one of each). It is easy to see that a fixed excursion program will not cover the low energy end. Thus, we have to keep the full excitation down to some low energy, here chosen to be 30 GeV. Above 30 GeV the excursion is allowed to vary. The fixed excursion program is used from 30 GeV down to the injection energy of 8 GeV. With this hybrid program, the maximum allowable resonance strength is as shown in

Fig. 11. We see that it is now comfortably greater than the maximum computed strengths over the whole energy range of 8 GeV to 150 GeV.

The difference between the maximum excursions at 30 GeV and 150 GeV is 1.6 cm which must be accommodated in the enlarged aperture of the Snake dipoles. But this is small and creates only a minor demand on the aperture. A superconducting transverse partial snake of the type shown in Fig. 5 is about 3 m in length and can easily be accommodated in an empty mini-straight at station-48, a medium straight at station-17, or a long straight at station-0. Here also, the Booster-Main Ring transport line must be redesigned to match the eigenspin orientations.

### 3. Tevatron Ring

Since the maximum resonance strength is 0.77 we need, at the minimum, one pair of full longitudinal and full transverse snakes such as those shown in Figs. 3 and 4. To allow for some comfortable safety margin, one may want to use more than one pair. The six sector symmetry of the Tevatron Ring suggests the use of three pairs.

Here the snakes are constantly powered at full  $180^\circ$  precession and the orbit excursion from 150 GeV on up is only 5.5 mm which is quite negligible. With pairs of full snakes, the eigenspin orientation is always vertical. The present beam transfer line from the main ring to the Tevatron Ring is likely too short to carry out the proper spin orientation matching. But as mentioned earlier, most likely the Main Ring will be replaced by a planar Main Injector in a separate tunnel. In this case the eigenspin matched beam transfer lines can be designed ahead of time. The Main Injector will likely have a magnet lattice and a set of spin resonances quite different from those of the Main Ring, but the maximum strengths of these resonances should not be greater

than those of the Main Ring and the snake system described above for the Main Ring should still suffice.

It is possible only to make the crudest of cost estimate here. The following table should be considered only as a guess.

Source and Preaccelerator	M\$ 1.5
Linac-Booster line modification	0.5
Booster snake and power supply	1.0
Booster-Main Ring line modification	1.0
Main Ring Snake and power supply	1.5
Main Ring-Tevatron line addition	1.0
Tevatron snake (3 pairs) and power supply	5.0
Polarimeters, controls etc.	<u>2.0</u>
	M\$ 13.5

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3. T. Roser, Paper to be published in the Proc. of the 8th Int. Symp. on High Energy Spin Phys., Minneapolis, Sept. 1988.
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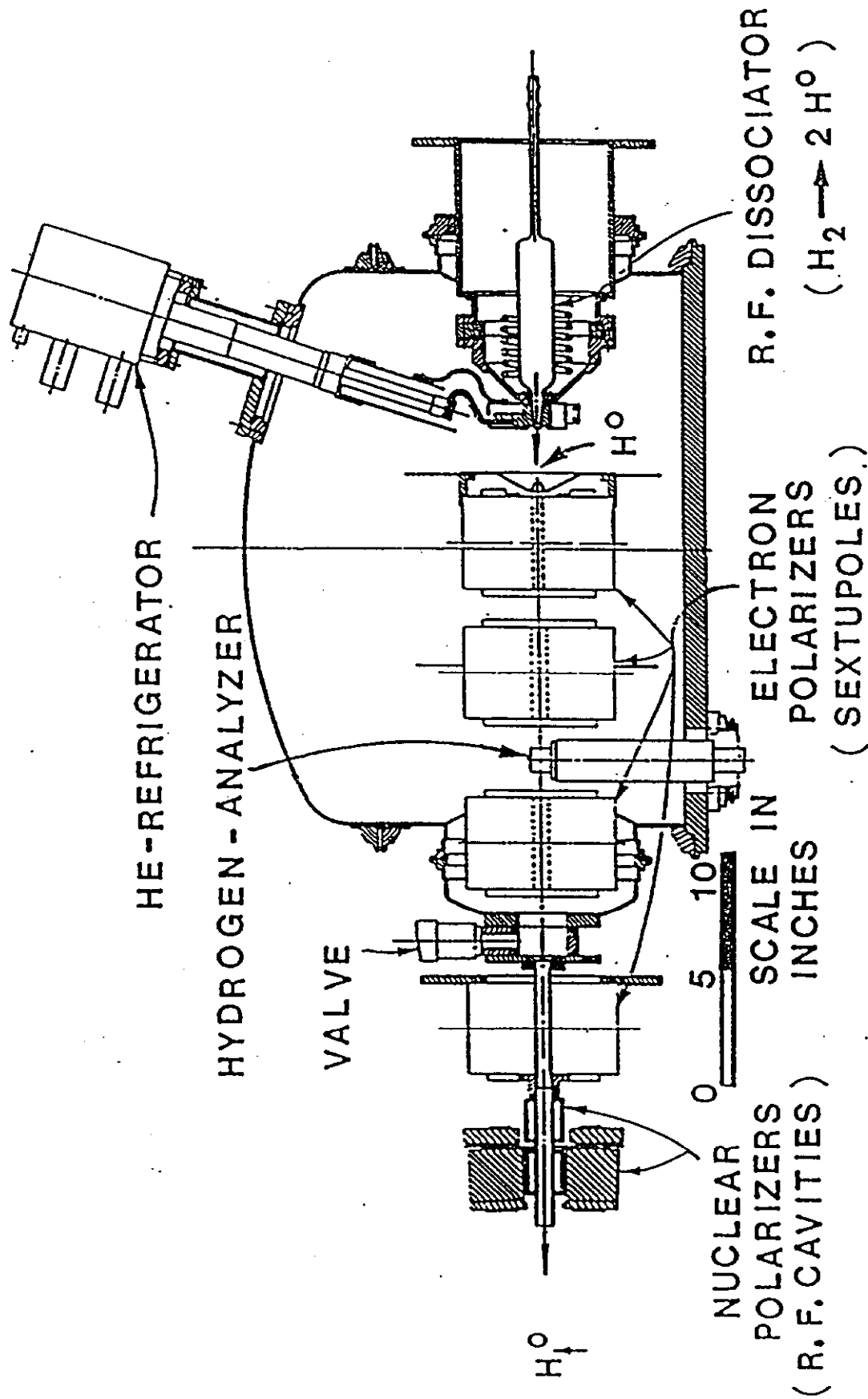


Fig. 1a Neutral atomic beam part of the polarized  $H^\circ$  source (producing polarized  $H^\circ$ )



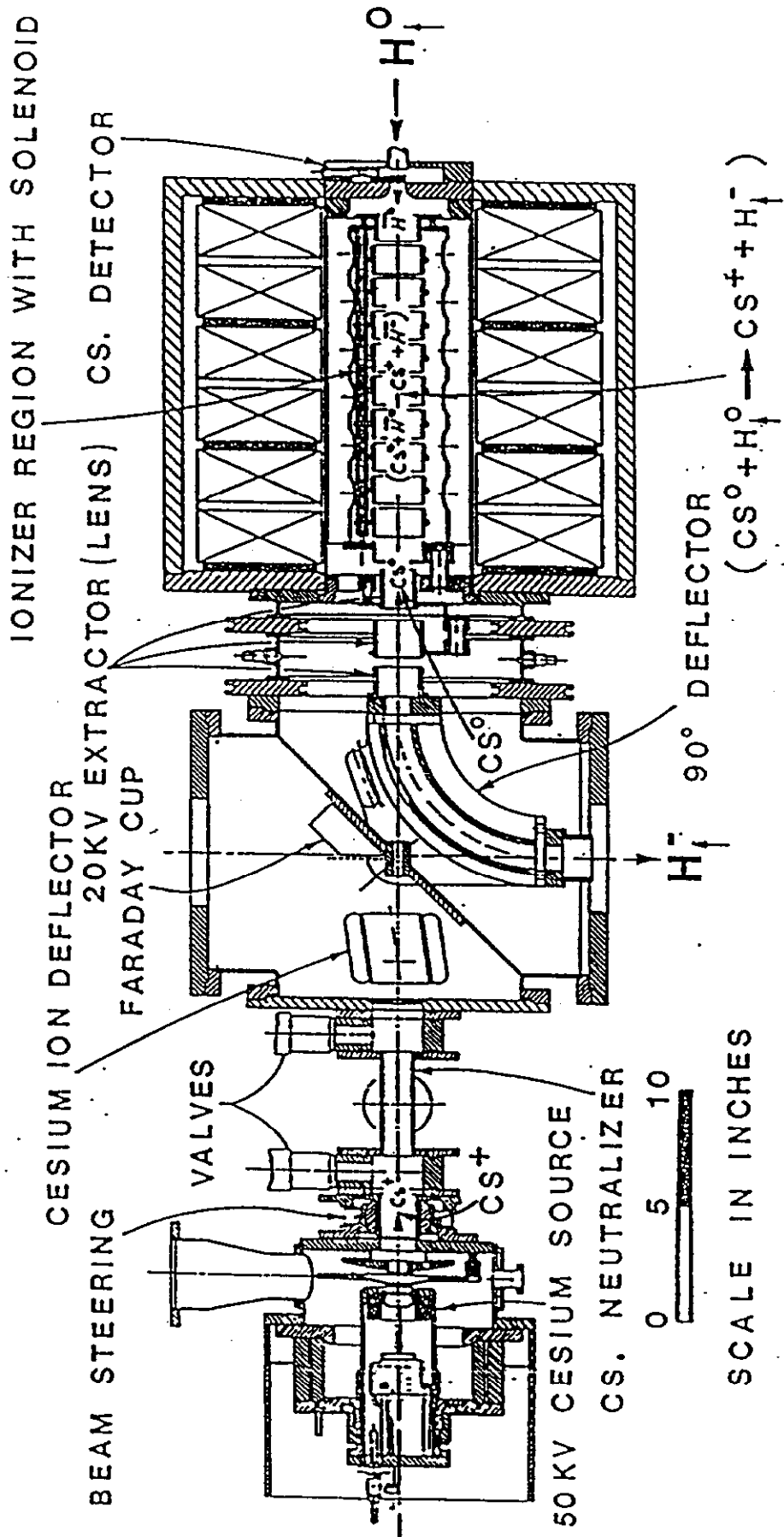


Fig. 1b Electron exchange part of the polarized  $H^-$  source.

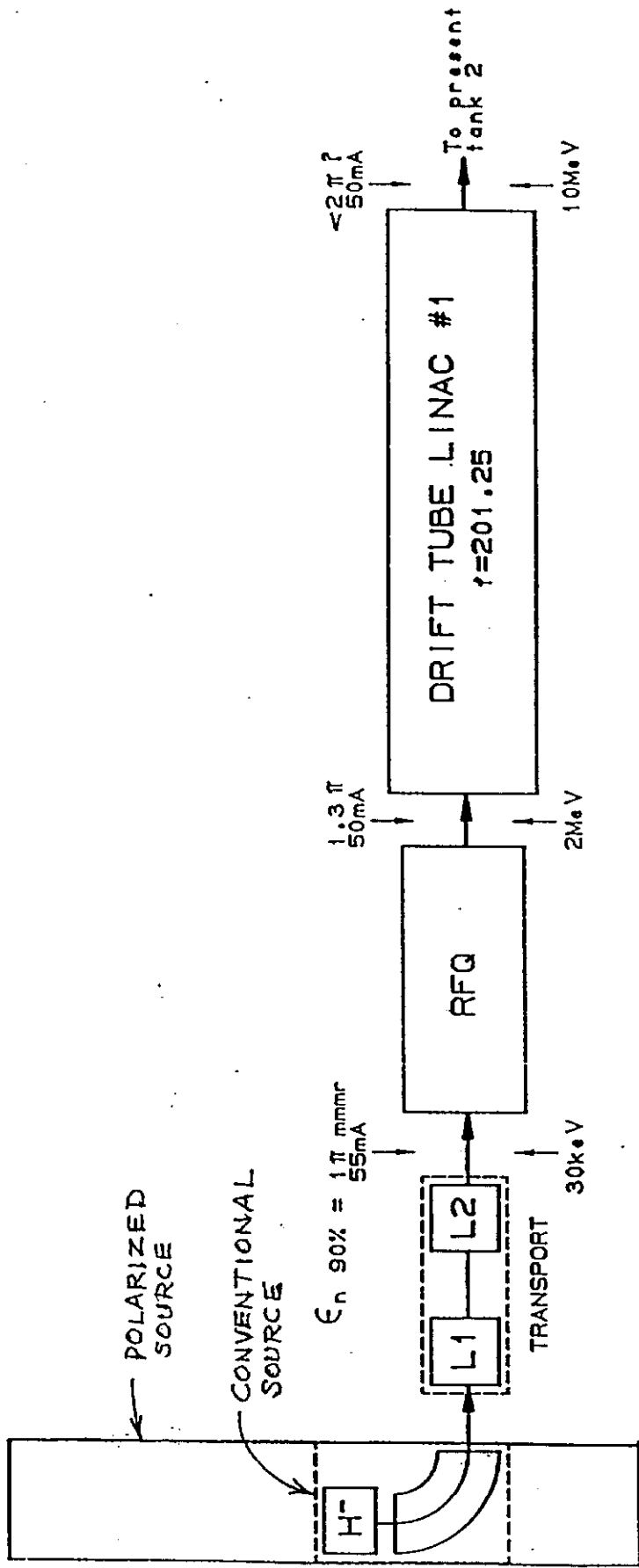
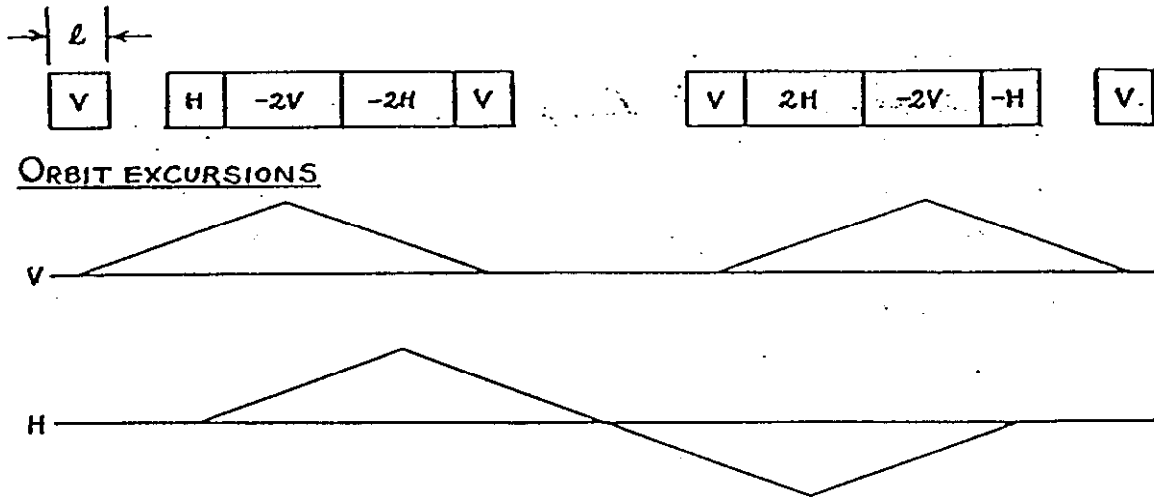
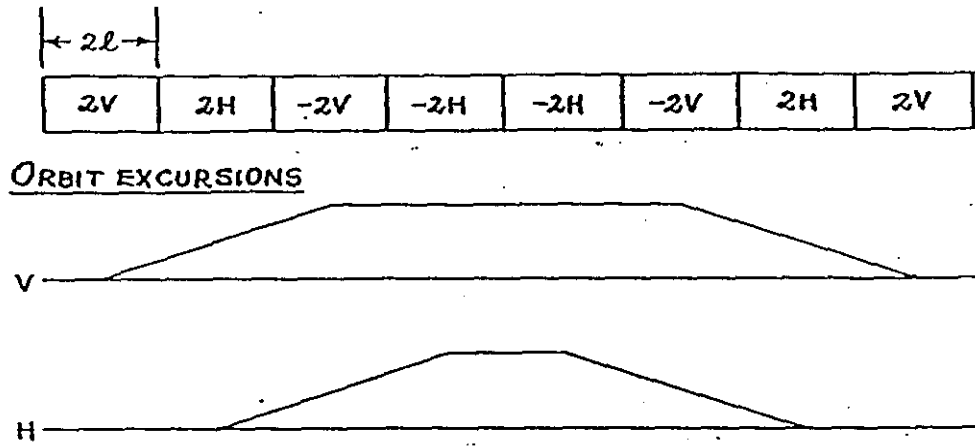


Fig. 2 Upgrade of the low-energy end of the Tevatron linac showing the RFQ as preaccelerator. For polarized beam, one can simply replace the unpolarized source (dashed line) by the physically larger polarized  $H^-$  source (solid line).



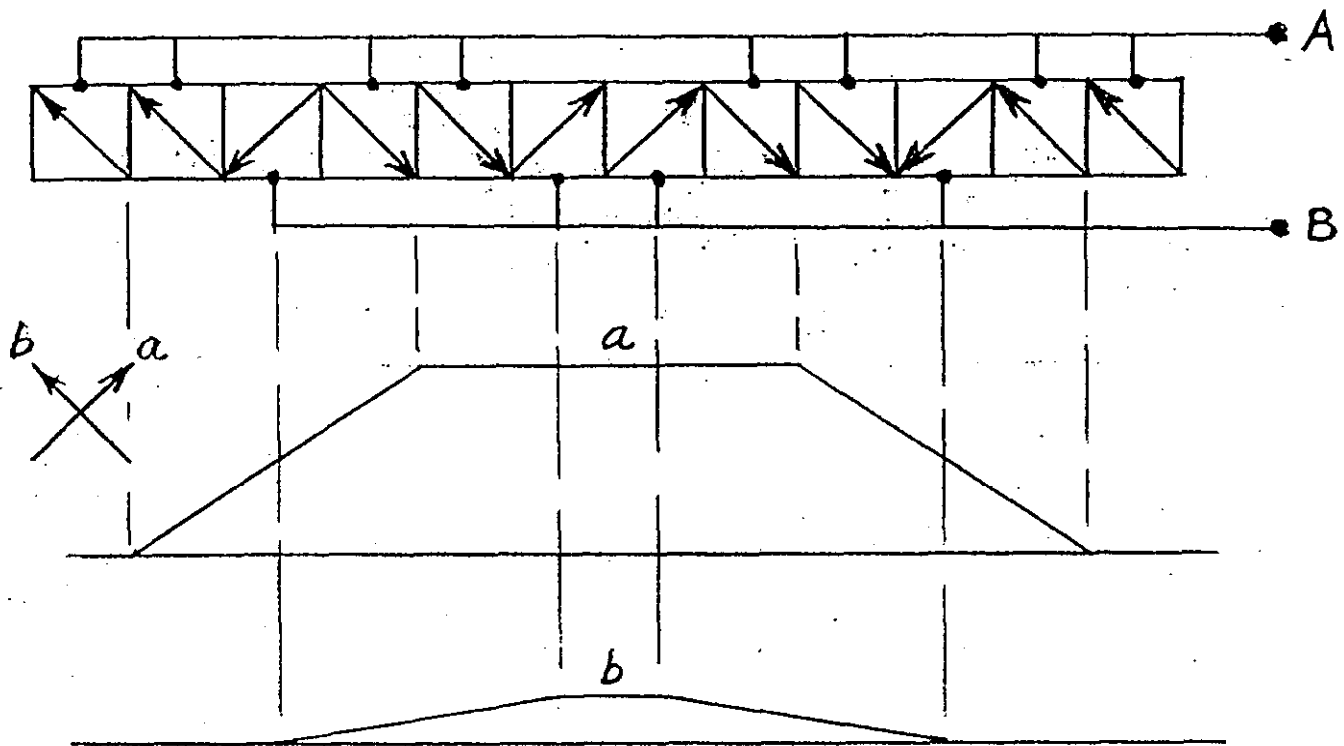
	Conventional dipole	Superconducting dipole
Field B	1.83 T	5.48 T
Unit length $\ell$	0.75 m	0.25 m
Total length 19 $\ell$	14.25 m	4.75 m
Orbit excursion $\Delta x = \Delta z$	1.15 m/ $\beta\gamma$	0.38 m/ $\beta\gamma$

Figure 3. Longitudinal rotator (Type 1 Siberian snake) precesses the spin  $180^\circ$  about the longitudinal ( $\hat{y}$ ) axis. For the proton each unit has  $B\ell = 1.37 \text{ Tm}$  and precesses the spin  $45^\circ$ . H and V denote horizontal and vertical orbital deflections.



	<u>Conventional dipole</u>	<u>Superconducting dipole</u>
Field B	1.83 T	5.48 T
Unit length $\ell$	0.75 m	0.25 m
Total length $16 \ell$	12 m	4 m
Orbit excursion $\Delta x = \Delta z$	$2.63 \text{ m}/\beta\gamma$	$0.88 \text{ m}/\beta\gamma$

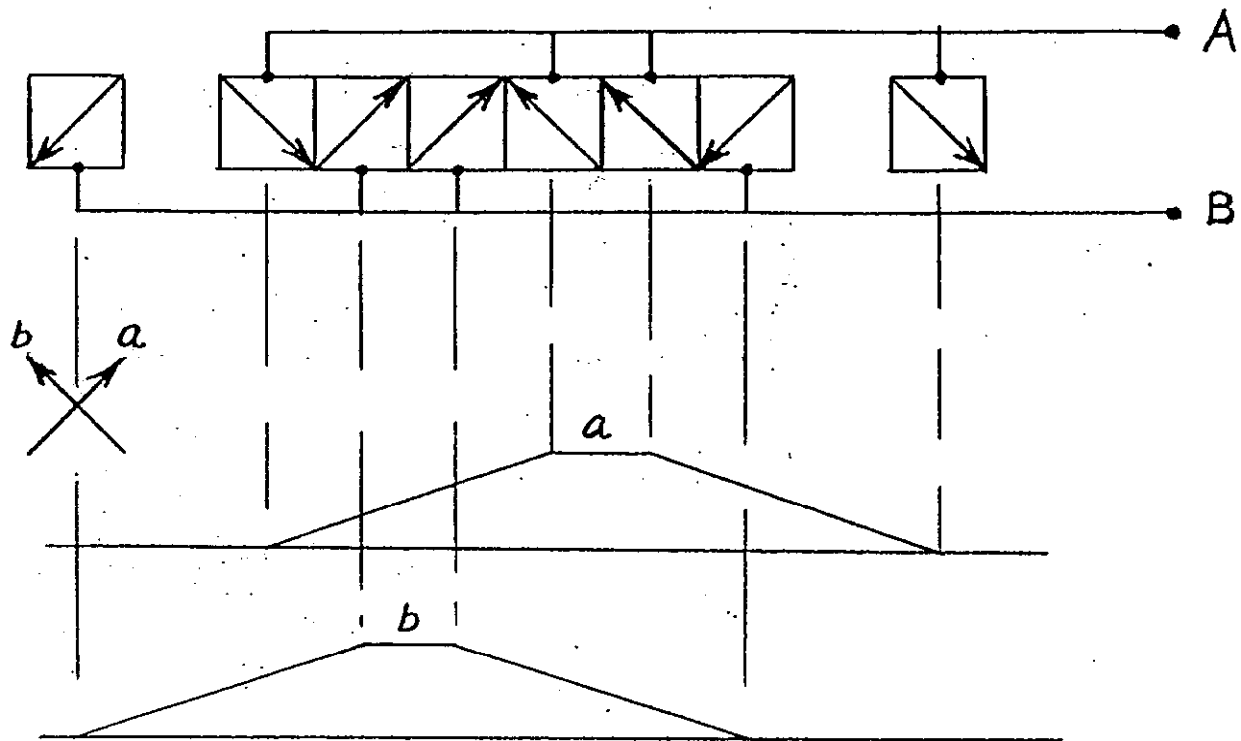
Figure 4. Transverse rotator (Type 2 Siberian snake) precesses the spin  $180^\circ$  about the transverse ( $\hat{x}$ ) axis. For the proton each unit has  $B\ell = 1.37 \text{ Tm}$  and precesses the spin  $45^\circ$ . H and V denote horizontal and vertical orbit deflections.



Half Excitation Parameters

Snake Precession	90° (180° Full)	
	<u>A String</u>	<u>B String</u>
Precession per dipole unit	45°	22.5°
Field	5.48T	2.74T
Unit length $\ell$		0.25m
Total length $12\ell$		3m
Orbit excursion	$a = \frac{0.656m}{\beta\gamma}$	$b = \frac{0.164m}{\beta\gamma}$

Fig. 5 Transverse continuously variable precession partial snake designed by D. Underwood. The snake has 12 skew (45°-roll) dipoles powered in two strings A and B, and has a precession range of  $\delta = 0^\circ$  to  $180^\circ$ .



Full Excitation Parameters

Snake precession (Full)	90°
(A and B strings identical at full excitation)	
Unit precession	45°
Field	5.48T
Unit length $\ell$	0.25m
Total length, $10\ell$	2.5 m
Orbit excursion	$a = b = \frac{0.328m}{\beta\gamma}$

Fig. 6 Longitudinal continuously variable precession partial snake designed by D. Underwood. The snake has 8 skew (45°-roll) dipoles powered in two strings A and B, and has a precession range of  $\delta = 0^\circ$  to  $90^\circ$ .

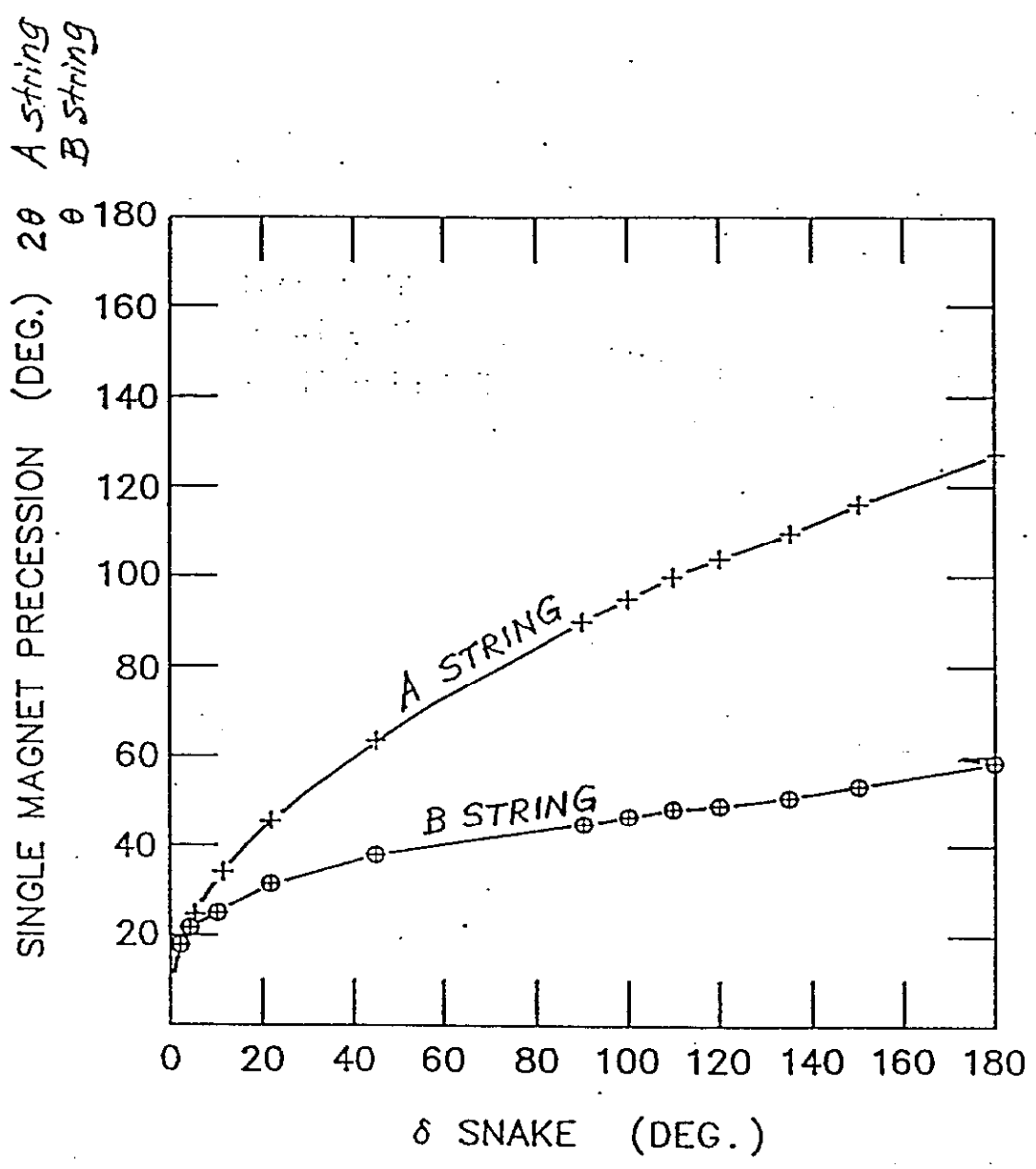


Fig. 7 Unit dipole precession angle  $\theta$  in the A and B strings as functions of the snake precession angle  $\delta$  for the transverse partial snake of Fig. 5. The function of the stronger string A is given by  $\theta^2 = (22.5^\circ)\delta$  over the range of  $\delta = 0^\circ$  to  $180^\circ$ .

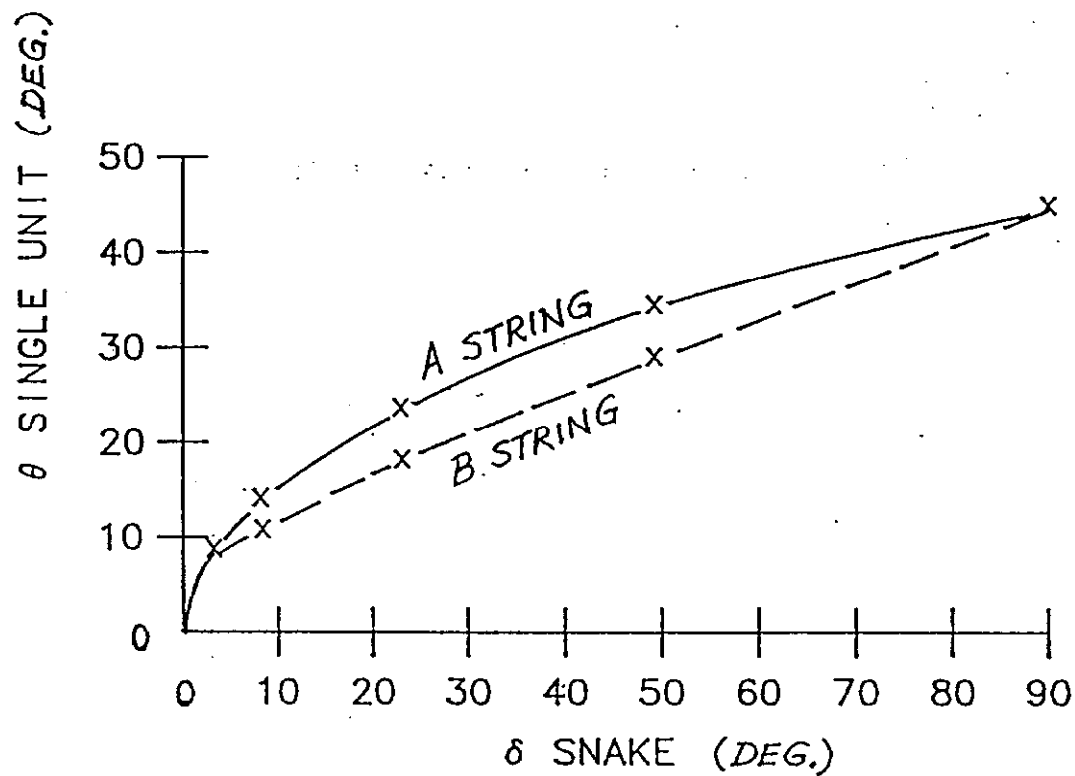


Fig. 8 Unit dipole precession angle  $\theta$  in the A and B strings as functions of the snake precession angle  $\delta$  for the longitudinal partial snake of Fig. 6. The function of the stronger string A is given by  $\theta^2 = (22.5^\circ)\delta$  over the range of  $\delta = 0^\circ$  to  $90^\circ$ .



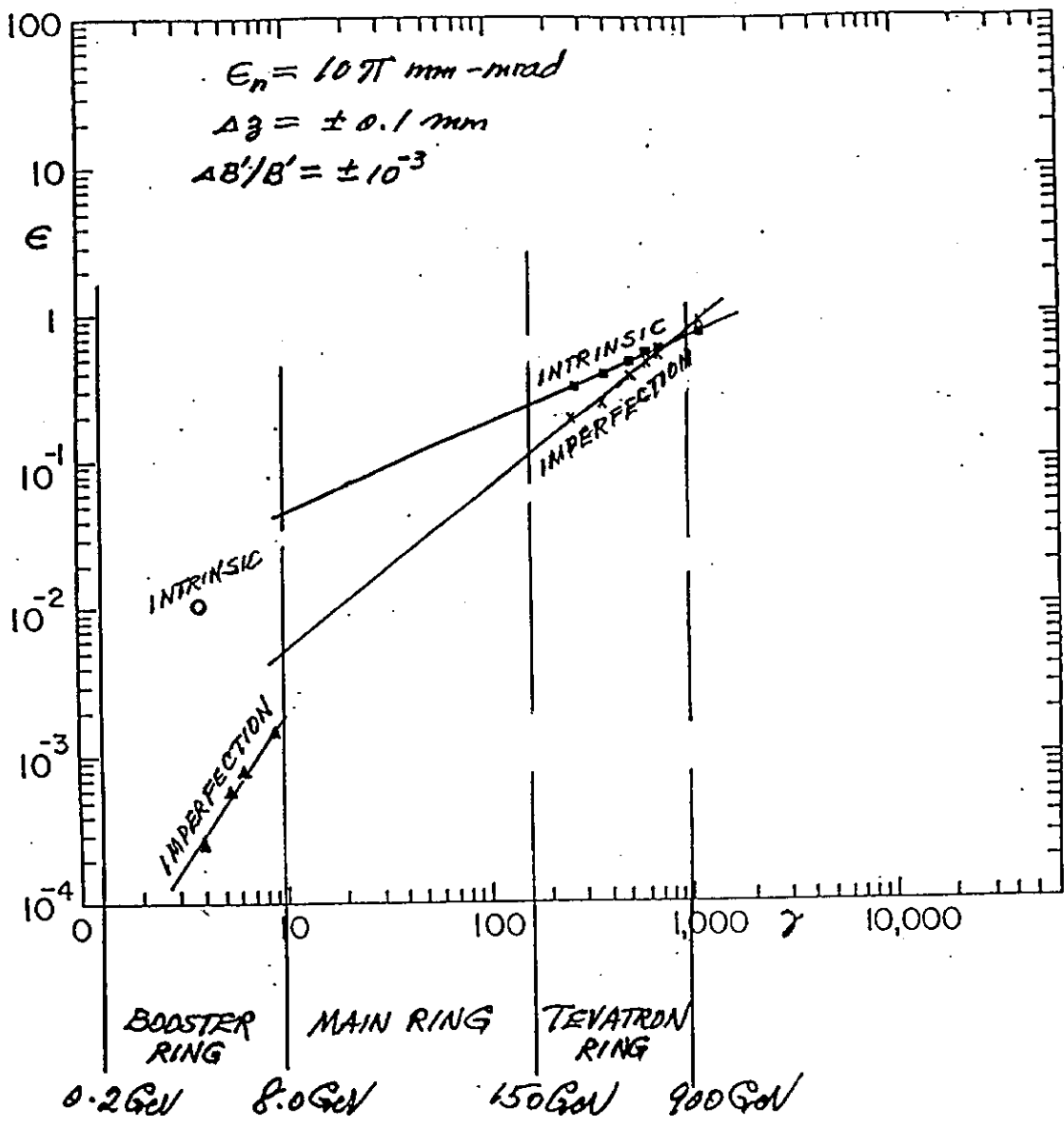


Fig. 9 Strengths  $\epsilon$  of the intrinsic and imperfection resonances in the Booster Ring, the (planar) Main Ring and the Tevatron Ring as computed using the program DEPOL.

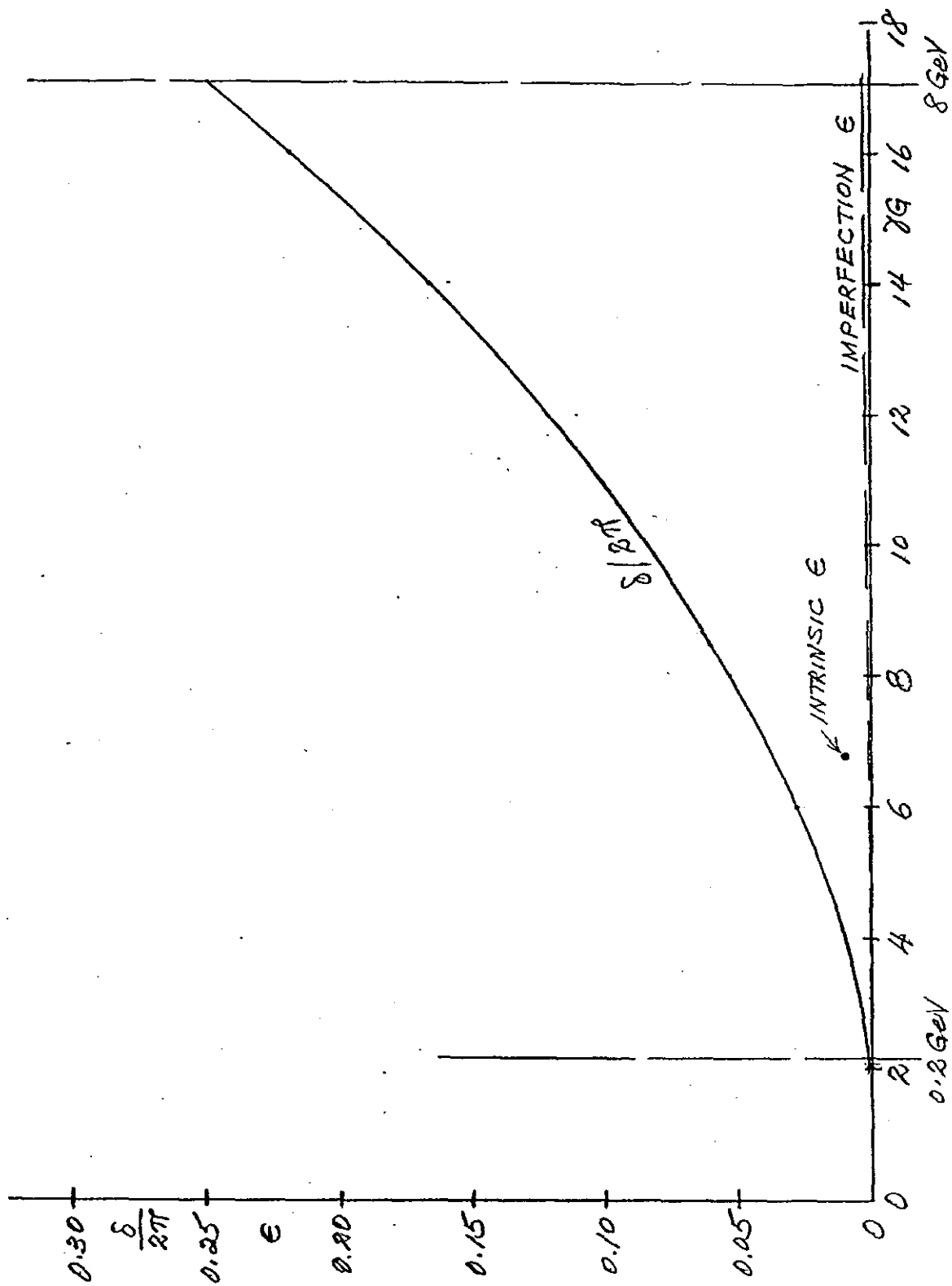


Fig. 10 The "fixed excursion" excitation program for the single Booster longitudinal partial snake. Plotted are the snake precession angle  $\delta/2\pi$  (maximum allowable resonance strength) and the strengths of the resonances against the spin tune  $\gamma G$ .

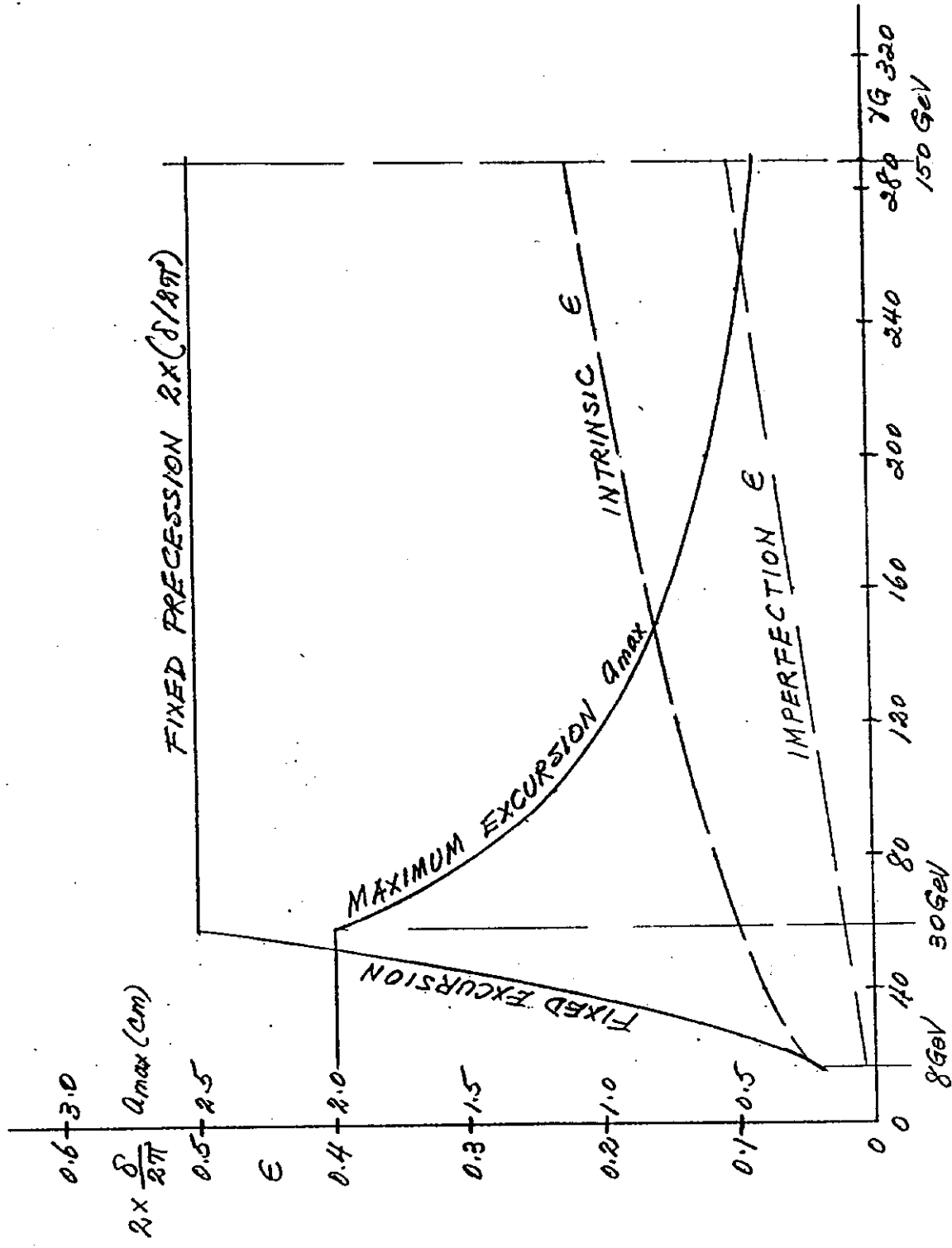


Fig. 11 The hybrid excitation program for the pair of partial snakes of the Main Ring. The "fixed excursion" program is followed from injection at 8 GeV reaching full excitation at 30 GeV which is then maintained until extraction at 150 GeV. Plotted are the snake precession angle  $\delta/2\pi$ , the strengths of the resonances and the maximum orbit excursion  $a_{max}$  against the spin tune  $\gamma G$ .