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LATTICE INSERTIONS FOR POPAE*

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Summary

Four types of insertions are described for the six 200-m straight sections of POPAE. All have dispersion matched to zero. (1) Injection-ejection insertion - This has proper high-β values and phase advances for horizontal injection and vertical ejection. (2) Phase-adjust insertion - The phase advance in this insertion is adjustable over a range of ~100°. (3) General-purpose insertion - The β^* is adjustable from 2.5 to 200 m and the crossing angle is adjustable from 0 to 11 mrad. (4) High-luminosity insertion - This gives an even lower β^* of 1 meter.

General Description of the Lattice

The design of POPAE[1] has evolved into a regular structure consisting of six, 720-m long curved sections, separated by 200-m long straight sections where the beams are focused and cross one another. Each sextant is composed of 12 lattice cells, having eight 6-m long bending magnets with a field of 60 kG at 1000 GeV. The two end cells of each sextant are modified to make the dispersion go to zero in the straight sections. One bending magnet is omitted from the end cells of the inner ring, achieving in a natural way the horizontal crossing of the beams at 11 mrad.

The regular cell is a separated-function FODO cell with 90° betatron phase advance. It consists of two quadrupoles and eight dipoles. Magnets are separated by 80-cm drift to accommodate cryostats and pump-out ports. One pair of beam-position sensing electrodes is located in the space immediately downstream of each quadrupole, and clearing electrodes are placed in all other spaces. Field-correction windings are located inside the magnets. The cold-bore vacuum is extended continuously through all regular cells in a curved section.

Dispersion Elimination

The end cells of each curved section have modified quadrupole strengths such as to set the horizontal dispersion in the adjoining straight section to zero. A single dipole has been removed from the end cells of the outer curved section, being necessary for the crossing geometry and to provide space for the injection kicker. Removal of these dipoles provides a horizontal crossing angle between the beams in the two rings equal to the bending of one dipole, 11 mrad. These cells are shown in Figs. 1 and 2. One could have alternatively produced zero dispersion by rearranging dipoles in several end cells, as in the ISABELLE design[2], but this leads to a lower packing factor and so was not done.

Injection-Ejection Insertion

The lattice insertion (I) in the injection straight section is shown in Fig. 3 together with the dispersion-eliminating cells C1 and C2 at the upstream and downstream ends, respectively. Also shown are the stacking rf cavity, the injection septum, the ejection kicker on the upstream side of the crossing point, and the ejection septum and injection kicker on the downstream side.

Phase Adjust Insertion

The quadrupoles in the phasing straight section insertion (P) are so arranged that by varying their strengths, the betatron phase advances across the insertion can be adjusted over a range of some 100°, while keeping the amplitude functions at the ends properly matched, This insertion for two examples with different phase advance is shown in Fig. 4.

General Purpose Insertion

A general-purpose insertion that is intended to serve a great variety of physics experiments should have a long central drift space. On the other hand, it should also be able to yield an amplitude function β^* at the crossing point that is small. A low β^* coupled with a long drift space leads to high maximum β-value (β_{max}) in the insertion, which is undesirable because it increases the variation of β with momentum. As a compromise, a central drift length of ±45 m was chosen. At a low β_v^* value of 2.5 m and a horizontal β_h^* of 13.5 m, β_{max} is about 800 m, and the variation β^* across the momentum spread in the stacked beam is quite tolerable and need not be corrected. The tuning range of β^* for this insertion extends from this low value to several hundred meters. Fig. 5 shows the insertion (E) with two sets of running parameters corresponding to the low β_v^* value of 2.5 m and a high β_v^* value of 200 m.

High-Luminosity Insertion

To achieve very high luminosities the crossing angle can be reduced down to 0° by the insertion of four beam steering dipoles, EB1 to EB4, in the central drift space. In this case, the clear length is reduced to ±10 m. The symmetry in geometry guarantees that, although the angle dispersion becomes finite, the displacement dispersion remains zero at the crossing point. The two inner dipoles are used in common by the two beams and hence must have a rather wide horizontal aperture of 18 cm. By adjusting β^* and the crossing angle, the luminosity can be varied over a wide range. As an example, high-luminosity insertion (H) with a central drift space of ±10 m is shown in Fig. 6. This insertion can be tuned to the vertical values of β^* = 1 m and β_h^* = 3 m and still has a tolerable β_{max} of less than 1100 m.

Operational Considerations

Overall lattice characteristics with a variety of insertions were studied using the computer program SYNCH.[3] Those for a typical mix are given in Table 1.

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Table 1. Orbit Characteristics for a Typical Mixture of Straight-Section Insertions

Straight Section	G	H	I	J	K	L
Insertion	Inj.(I)	Exp.(E)	Exp.(E)	Exp.(E)	Phase(P)	Hi-lum.(H).
Crossing Angle (mrad)	11	11	11	11	11	1
Central drift space (m)	±28	±45	±45	±45	±34.8	±10
β_v^* (m)	219	2.5	131.5	131.5	25	1.0
β_h^* (m)	81	13.5	25	25	86.7	3.0
$\beta_{v,max}$	553	813	169	179	231	901
$\beta_{h,max}$(m)	213	781	420	420	251	1082

Betatron Tunes
Horizontal $\nu_h = 21.84$
Vertical $\nu_v = 22.36$

Transition Energy $\gamma_t = 19.59$

Chromaticity
Horizontal $\Delta\nu_h / \frac{\Delta p}{p} = -44.0$
Vertical $\Delta\nu_v / \frac{\Delta p}{p} = -43.4$

We choose to operate in a region of the tune diagram between the fifth and the integer resonances on a line parallel to and 0.02 away from the difference diagonal. This region is free of all resonances below sixth order and is large enough to accommodate tune spreads of at least 0.1 in both planes. At injection the chromaticity is tuned to a small positive value to suppress the head-tail effect. The tune spread in the stacked beam needed to suppress all other transverse instablities by the Landau-damping mechanism is generally small enough so that the operating point on the injection orbit can also be accommodated in this region. Thus, only resonances higher than fifth need be crossed during stacking.

1. D. Ayres, et al., "A 1000-GeV on 1000-GeV Proton-Proton Colliding Beam Facility", Fermilab and Argonne National Laboratory Joint Proposal (May 1976)
2. "A Proposal for Construction of a Proton-Proton Storage Accelerator Facility ISABELLE", BNL 20161 (June 1976)
3. A.A. Garren and A. Kenny, notes dated Feb. 1974

STRUCTURE $(QF/2)^{-1}$(QF1)SBSBSBSBS
(QD1)SBSBSBSBS

[$(QF/2)^{-1}$ removes QF/2 in the adjoining cell]

ELEMENTS

		Length (m)	Field (kG) or Gradient (kG/m)
Dipole	B	6.170	59.649
Quadrupole	QF	1.320	1208.6
	QF1	1.600	1199.1
	QD1	1.600	-974.1
Drift	S	0.800	

AMPLITUDE FUNCTIONS AT END

Horizontal $\beta_{h,end}$ = 198.2 m
Vertical $\beta_{v,end}$ = 21.26 m

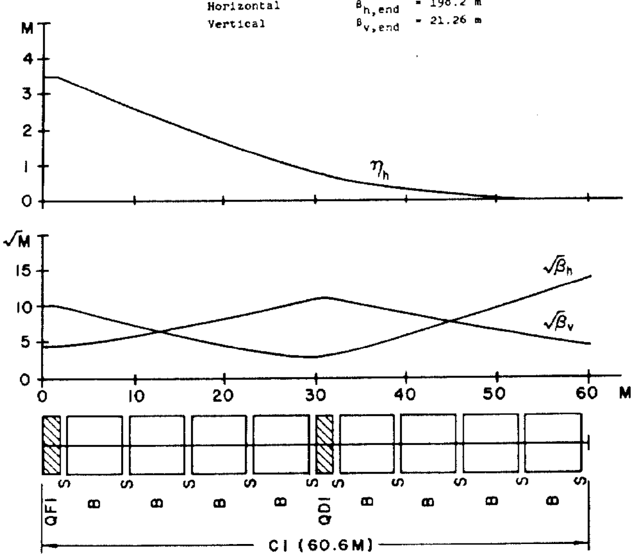

Fig. 1 Dispersion-eliminating cell C1.

STRUCTURE $(QF/2)^{-1}$(QF2)LBSBSBS
(QD2)SBSBSBSBS

[$(QF/2)^{-1}$ removes QF/2 in the adjoining cell]

ELEMENTS

		Length (m)	Field (kG) or Gradient (kG/m)
Dipole	B	6.170	59.649
Quadrupole	QF	1.320	1208.6
	QF2	1.600	1143.8
	QD2	1.600	-1026.2
Drift	S	0.800	
Long drift	L	7.770	

AMPLITUDE FUNCTIONS AT END

Horizontal $\beta_{h,end}$ = 155.9 m
Vertical $\beta_{v,end}$ = 15.67 m

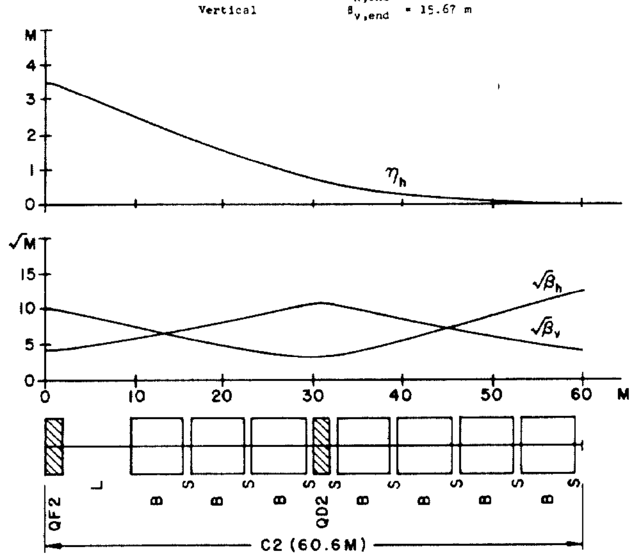

Fig. 2 Dispersion-eliminating cell C2.

STRUCTURE (IQ1)IS1(IQ2)IS2(IQ3)IS3 (IQ4)IS4(IQ5)IS5(IQ6)

ELEMENTS

		Length (m)	Gradient (kG/m)
Quadrupoles	IQ1	1.320	1188.4
	IQ2	1.320	-945.5
	IQ3	1.320	601.5
	IQ4	1.320	-703.1
	IQ5	1.320	582.2
	IQ6	1.320	528.8
Drift	IS1	20.000	
	IS2	50.000	
	IS3	55.000	
	IS4	50.000	
	IS5	16.472	

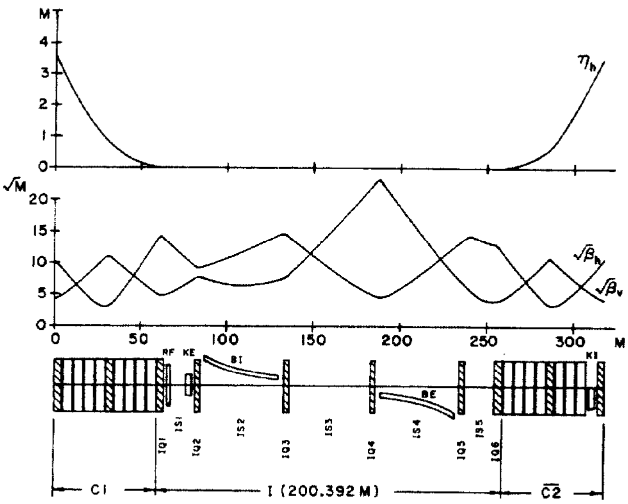

Fig. 3 Injection straight-section insertion I, together with cells C1 and $\overline{C2}$, showing injection, stacking, and ejection elements.

STRUCTURE (PQ1)PS1(PQ2)PS2(PQ3)PS3(PQ4)PS4 PS4(PQ5)PS3(PQ6)PS2(PQ7)PS1(PQ8)

ELEMENTS

		Length (m)	Gradient (kG/m) Expl. 1	Gradient (kG/m) Expl. 2
Quadrupole	PQ1	1.600	616.1	161.5
	PQ2	1.600	332.1	835.4
	PQ3	1.600	-943.8	-1075.9
	PQ4	1.600	553.1	190.7
	PQ5	1.600	250.5	207.3
	PQ6	1.600	-851.5	-1029.9
	PQ7	1.600	352.0	719.3
	PQ8	1.600	762.8	367.7
Drift	PS1	22.000		
	PS2	19.000		
	PS3	18.000		
	PS4	34.796		

PHASE ADVANCES

		Expl. 1	Expl. 2
Horizontal	ϕ_h	140.00°	115.00°
Vertical	ϕ_v	218.75°	310.00°

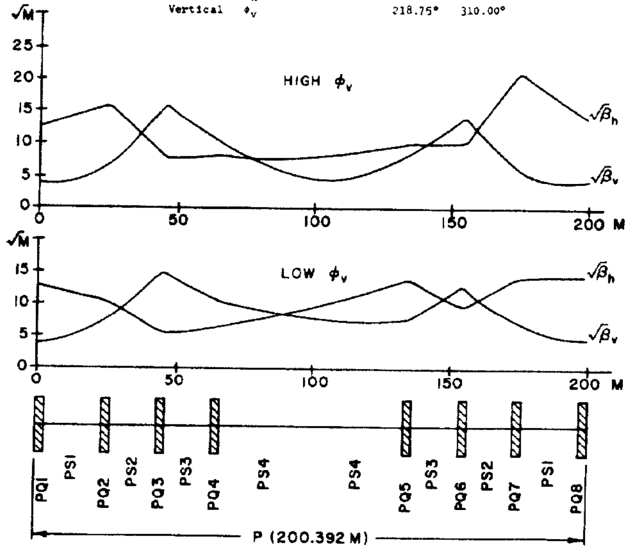

Fig. 4 Phasing straight-section insertion P.

STRUCTURE (EQ1)ES1(EQ2)ES2(EQ3)ES3 (EQ4)ES4(EQ5)ES5(EQ6)ES6 ES6(EQ7)ES5(EQ8)ES4(EQ9) ES3(EQ10)ES2(EQ11)ES1(EQ12)

AMPLITUDE FUNCTIONS

		Expl. 1	Expl. 2
Crossing-point, Horizontal	β_h^*	13.5 m	17.4 m
Crossing-point, Vertical	β_v^*	2.5 m	200.0 m
Maximum	β_{max}	812.5 m	681.8 m

ELEMENTS

		Length (m)	Gradient (kG/m) Expl. 1	Gradient (kG/m) Expl. 2
Quadrupole	EQ1	1.600	-1107.4	596.0
	EQ2	1.600	875.3	-822.3
	EQ3	1.600	33.8	-1252.9
	EQ4	1.600	68.5	1067.3
	EQ5	1.600	857.1	[illegible]
	EQ6	1.600	-1212.6	-811.5
	EQ7	1.600	-1228.3	-785.7
	EQ8	1.600	953.3	652.6
	EQ9	1.600	68.9	1062.6
	EQ10	1.600	20.9	-1355.3
	EQ11	1.600	637.4	-674.5
	EQ12	1.600	-903.5	748.2
Drift	ES1	5.596		
	ES2	6.000		
	ES3	7.000		
	ES4	14.000		
	ES5	13.000		
	ES6	45.000		

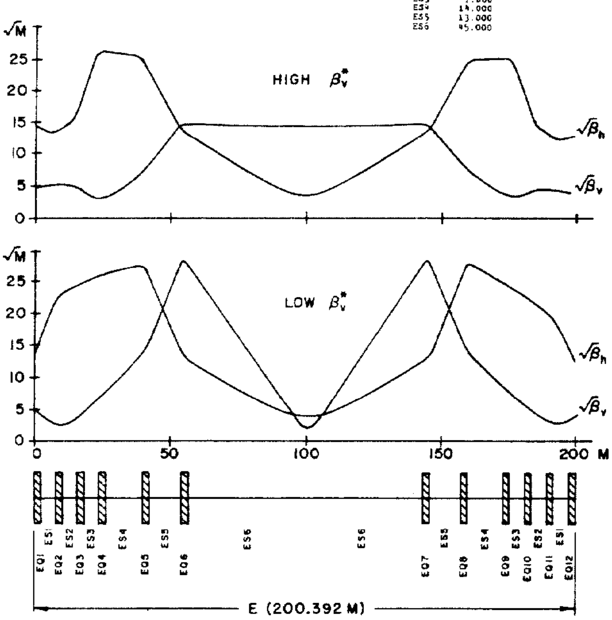

Fig. 5 General-purpose experimental straight-section insertion E.

STRUCTURE (HQ1)HS1(HQ2)HS2(HQ3)HS3(HQ4)HS4 (HQ5)HS5(HQ6)HS6(HB1)HS7(HB2)HS8 HS8(HB3)HS7(HB4)HS6(HQ7)HS5(HQ8) HS4(HQ9)HS3(HQ10)HS2(HQ11)HS1(HQ12)

AMPLITUDE FUNCTIONS

Crossing-point, Horizontal $\beta_h^* = 3.0$ m
Crossing-point, Vertical $\beta_v^* = 1.0$ m
Maximum $\beta_{max} = 1382$ m

CROSSING ANGLE

Dipole fields given are for 0° (head-on)

ELEMENTS

		Length (m)	Field (kG) or Gradient (kG/m)
Quadrupoles	HQ1	1.600	-667.7
	HQ2	1.600	679.2
	HQ3	1.600	-124.7
	HQ4	1.600	141.2
	HQ5	3.000	956.9
	HQ6	3.000	-1155.8
	HQ7	3.000	-1165.6
	HQ8	3.000	987.8
	HQ9	1.600	144.3
	HQ10	1.600	181.4
	HQ11	1.600	504.5
	HQ12	1.600	-477.4
Dipoles	HB1	2.643	59.649
	HB2	5.728	-59.649
	HB3	5.728	59.649
	HB4	2.643	-59.649
Drift	HS1	5.396	
	HS2	14.000	
	HS3	14.000	
	HS4	21.600	
	HS5	2.800	
	HS6	0.800	
	HS7	10.829	
	HS8	10.000	

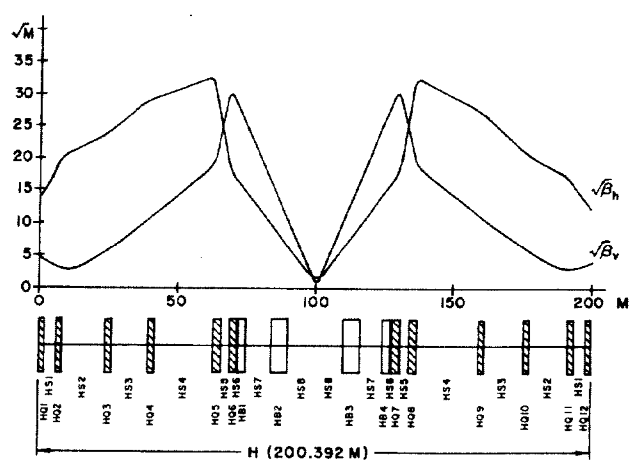

Fig. 6 High-luminosity insertion H.