Lattices for 8 and 30 GeV proton drivers

G.H. Rees

Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, UK

Abstract. Lattices for 8 and 30 GeV proton drivers are described. The former is for a potential upgrade of the ISIS facility at RAL, and the latter for a possible neutrino factory driver in the ISR tunnel at CERN.

1. Introduction

Lattices have been designed for 8 and 30 GeV proton synchrotrons, the former for a potential upgrade of ISIS at RAL, and the latter for a possible neutrino factory driver in the ISR tunnel at CERN [1]. Each lattice requires chromaticity correction sextupoles, a large dynamic aperture, and a transition gamma (γ_t) larger than the value of γ at its maximum energy.

In the ISIS proposal, the present, 160-240 kW, 0.8 GeV, 50 Hz ring is the injector for a new synchrotron of three times the radius (3×26.0 m). The new ring may operate at 3 GeV and 50 Hz for a 1 MW spallation neutron source, or at 8 GeV and 50/3 Hz as a source for neutrino factory R & D studies. It is also possible to have a second ring and a new, higher energy, dual-ring injector to create a 4 MW spallation source, or a 4 MW neutrino factory driver or a dual purpose 2 MW spallation source and 2 MW proton driver.

The 30 GeV ring in the ISR tunnel is one option for a CERN neutrino factory driver. Previous designs have struggled to reach the 30 GeV lattice design energy despite the ISR tunnel being 1.5 times longer than that of the 30 GeV PS ring. This is due to the need for γ_t to be greater than γ at 30 GeV. The new lattice achieves this, and 30 GeV, by making use of both quadrupole focusing cells and combined function bending magnet cells. Some aspects of the 30 GeV lattice are similar to those of the 8 GeV ring.

2. Basis of the lattice designs

It is desirable to have integer Q_h in all the arcs to obtain directly zero dispersion straight sections. High γ_t may be obtained by choosing a periodicity for the arc near to but larger than its horizontal tune and with bending or focusing perturbations in some of the cells. A suitable choice is to use groups of three cells in the arc with the centre one different from the outer two. Thus, use is often made of four groups of three, 90° cells to give an arc periodicity of four and a Q_h of three. The cells need not all have equal betatron phase shifts but the sum of the three should be 270°, horizontally and vertically, to give good cancellation within the arc of third order resonance effects due to chromaticity correction sextupoles. No cancelling in the arcs occurs, however, for fourth order sextupole effects, so care is needed in choosing the phase shifts in the adjacent straight sections.

Important features for the lattices are adequate space for the main and trim magnets and the large radio frequency (rf) systems, and long free straight sections to ease the designs of the injection, extraction and beam loss collector systems. To obtain such features, doublet cells are preferred to FODO units, despite their need for higher quadrupole gradients. There is also the possible benefit of using fewer bending magnets and hence less space for coil ends.

For the 8 and 30 GeV lattices, five groups of three arc cells give better lattice parameters than four groups of three. The group phase shifts of 270° must then be changed, and values giving good sextupole cancellation effects are 288° or 216°. The former is chosen for the horizontal plane but, because of the desirability of a tune split, the values of 180° and 216° are considered for the vertical plane. The choice of 180° leads to good sextupole cancellations for the three, main, third order and for three out of the four, main, fourth order resonances, while the 216° value is good for two of the three, third order and all four, fourth order resonances.

The choice of phase shifts for the 8 GeV lattice is 288° and 180°, while that for the 30 GeV ring is 288° and 216°. The former is of a racetrack design with 22 cells per superperiod, 15 in the arc and 7 in the long straight section; all cells have phase shifts close to 96° horizontally and 60° vertically so that the arc and ring betatron tunes are, respectively, $Q_h = 4$, $Q_v = 2.5$, and $Q_h \sim 11.7$, $Q_v \sim 7.32$. Trim quadrupoles in the long straight sections allow Q_v for the ring to be raised to 7.4, so as to keep well away from $2Q_v = 14$ and $4Q_v = 28$ resonances under space charge conditions. The lattice makes use of sector dipole magnets to avoid a significant ripple of the β_v values. Long sector dipoles are used in the outer, and short ones in the centre cells, of the arc groups. A similar lattice has been proposed for the 8 GeV FNAL booster but there, the arc groups have parallel edged dipoles and vertical phase shifts of 216° for an arc Q_v of 3; tunes are $(11.7, 8.65)$ and additive sextupole effects in the arcs for $2Q_v + Q_h = n$ are not dangerous unless space charge tune shifts are $\sim \frac{1}{3}$, when n drops from 29 to 28 for a structure resonance.

In the 30 GeV ring, the phase shifts of 288° and 216° lead directly to a third order structure sum resonance. Four superperiods of 15 arc and 3 straight section cells lead to tunes of $Q_h = 19.2$ and $Q_v = 14.4$, and to $2Q_v + Q_h = 48$. Quadrupoles are thus adjusted to raise the straight section tunes from $(0.8, 0.6)$ to $(0.83, 0.71)$, for $2(0.71) + 0.83 = 2.25$, and hence cancellation for sextupole effects over the four superperiods. The structure sum resonance is then avoided as $Q_h = 19.32$ and $Q_v = 14.84$ so that $2Q_v + Q_h = 49$, not 48, unless the tune shifts reach $\sim \frac{1}{3}$, as before.

To achieve the energy of 30 GeV, combined function bending magnets are used in the outer cells of the groups of three in the arcs. The central cell quadrupoles focus differently from the outer cell gradient magnets and so they are adjusted in strength and position to obtain satisfactory lattice parameter and γ_t values. Straight sections must also be matched to the arcs, causing more complexity than for the 8 GeV lattice. The integer Q_h values of the arcs give zero dispersion straights in the 30 and 8 GeV rings, but the dispersion oscillates more in the arcs of the former than of the latter. For the chromaticity correction of both rings, sextupoles are located in the central cells of the arc groups, one on each side of both the F and D quadrupoles.

3. Parameters for the 8 GeV lattice

The main requirements for the 8 GeV lattice are a mean radius of 78.0 m, $\gamma_t > 12.5$, peak dipole and quadrupole fields < 1.5 T and 10 T/m, respectively, space for momentum and betatron collimation systems and zero dispersion regions for fast injection, fast extraction and high power radio frequency systems. In addition, trim quadrupoles, dipoles, sextupoles and, possibly, octupoles are needed, respectively, for tune control, orbit corrections, chromaticity and error correction, and instability cures.

Studies of lattices with two, three and four superperiods showed that the first gave the most straight section space and the most arc design flexibility. A racetrack ring is thus chosen, and it uses three doublet cells, C1, C2 and C3, assembled in five groups of (C1,C2,C1) cells in each arc, and seven, missing dipole, C3 cells in adjacent straight sections. This leads to 44 cells in total, with 22 per superperiod. C1, C2 and C3 have the respective forms FBD, FbD and FOD, where F or D, B or b, and O represent F or D quadrupoles, long or short sector dipoles, and straight sections, respectively. Table 1 gives the cell parameters and Figure 1 the dispersion and β values.

Table 1. 8 GeV Cell Parameters

Unit	Length (m)	Angle (deg)	Gradient (m^{-2})
B	2.97	8.25	0.00
b	1.08	3.00	0.00
B,b end	0.50	0.00	0.00
F	1.20	0.00	-0.33
D	1.036	0.00	0.33
FT2/3	0.20	0.00	0.00 / -0.01
DT2/3	0.20	0.00	0.0025 / 0.02
O1	0.20	0.00	0.00
O2	0.562374	0.00	0.00
O3	0.80	0.00	0.00
O4	3.23	0.00	0.00
O5	2.97	0.00	0.00

C1:	F,	O1,	O1,	O3,	BE,	B,	B,	BE,	O3,	O1,	O1,	D,	O2;
C2:	F,	O1,	FT2,	O4,	bE,	b,	bE,	O4,	DT2,	O1,	D,	O2;	
C3:	F,	O1,	FT3,	O3,	O5,	O5,	O3,	DT3,	O1,	D,	O2:		

Lattice cell structure: 2×[5×(C1,C2,C1),7×C3]

Sector dipoles are preferred to parallel edge units as the vertical, end field focusing of the latter creates a ripple in the lattice β_v-waveform. The use of a short, central, b dipole in C2 limits the fields to $\sim$ 1.44 T at 8 GeV and also adjusts dispersion so that each cell group (C1, C2, C1) is approximately an achromat (when $Q_h = 4$ for each achromatic arc). All main quadrupoles have field gradients of $\sim$ 9.78 T/m at 8 GeV, with the F unit longer than the D for $Q_h > Q_v$. Tunes in the arcs and straights are varied by the C2 and C3 trim quadrupoles, respectively. In the arcs are 20, 3.23 m free straights and in C3, between trim quadrupoles, are 14, all of length > 7.5 m. Betatron acceptances are $304\,\pi$ mm mr for a momentum spread of $\pm 0.8\%$.

Lattice functions are $\alpha_p \sim 2.5$ m, $\beta_h \sim 16$ m, and $\beta_v \sim 20$ m, maximum, with the β-functions almost periodic from cell to cell. The nominal working point is $Q_h = 11.7$, $Q_v = 7.35 \pm 0.05$, and $\gamma_t = 13.78$. Dispersion is zero in the long straight sections, and approximately periodic in the arc groups, which are almost achromatic. Sextupoles are placed in the C2 cells, one on each side of both F and D. The lattice has a large dynamic aperture on setting of sextupoles for zero chromaticity, at least in the absence of space charge forces, whose effect has yet to be evaluated.

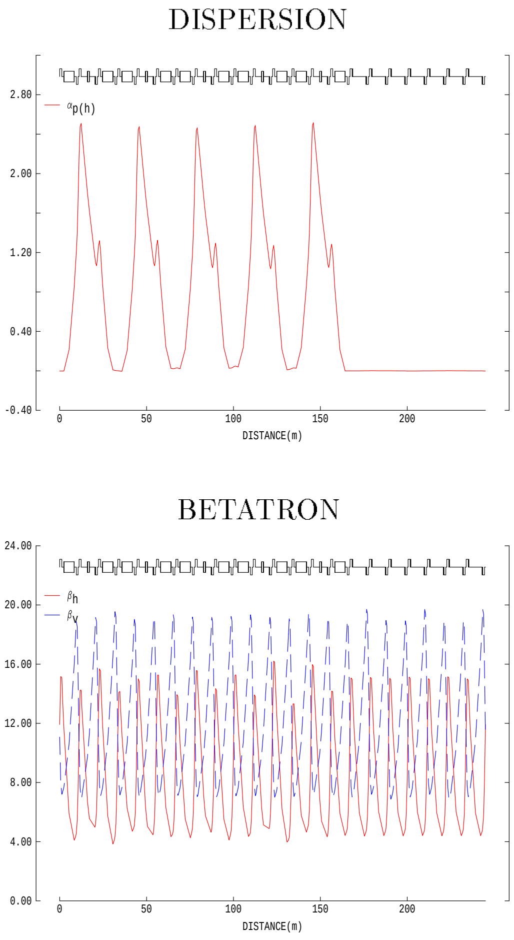

Figure 1. 8 GeV Lattice

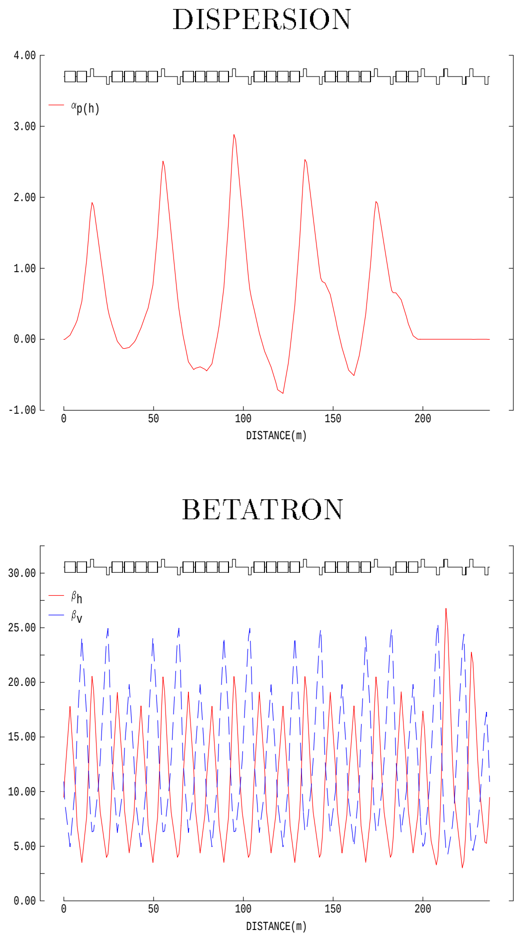

Figure 2. 30 GeV Lattice

4. Parameters for the 30 GeV lattice

The main requirements for the 30 GeV ring are a mean radius of 151.0 m, a γ_t of at least 40, peak centre and edge fields for the combined function bending magnets < 1.46 and

1.8 T, respectively, maximum quadrupole fields < 1.05 T, and space requirements as for the 8 GeV ring.

Table 2. 30 GeV Cell Parameters

Unit	Length (m)	Angle (deg)	Gradient (m^{-2})
BF	5.91	4.76608	-0.0558
BD	5.25	4.23392	0.0558
BF, BD end	0.50	0.0	0.0
F2	1.80	0.0	-0.143794
F3/4	1.90	0.0	-0.143794
D2	1.57	0.0	0.143794
D3/4	1.758	0.0	0.143794
FT4	0.20	0.0	-0.0153637
DT4	0.20	0.0	0.0184866
O1	0.50	0.0	0.0
O2	1.017238	0.0	0.0
O4/O5	0.200/2.66	0.0	0.0
O32	0.73	0.0	0.0
O33/34	0.442/0.86	0.0	0.0
O62	3.47	0.0	0.0
O63/64	2.921/4.44	0.0	0.0
O72	0.13	0.0	0.0
O73/74	0.000/0.10	0.0	0.0

C1: O1, BFE, BF, BFE, O2, BDE, BD, BDE, O1;
C2: O1, O32, FT2, O4, F2, O5, O2, O62, D2, O4, DT2, O72, O1:
C3: O1, O33, FT3, O4, F3, O5, O2, O63, D3, O4, DT3, O73, O1:
C4; O1, O34, FT4, O4, F4, O5, O2, O64, D4, O4, DT4, O74, O1:

Lattice cell structure: 4×[5×(C1,C2,C1),C3,C4,C3]

Since the ISR tunnel is nearly circular, lattices of four, six and eight superperiods have been considered and the foremost is chosen as it allows most design flexibility. Design for the lattice is similar to that of the 8 GeV ring, with five groups of (C1,C2,C1) cells in the arcs, as discussed, but followed by a (C3,C4,C3) unit, where C2, C3 and C4 have missing magnets and C1 uses combined function magnets only. There are 72 cells in all, with 18 per superperiod. Cells C1 and C2/C3 have the respective forms: BFoBD and FOD, where BF/BD, F/D and o/O represent, respectively, BF or BD combined function units, F or D quadrupoles, and short or long straight sections.

The BF and BD units are of a sector design, again to avoid vertical end field focusing. Fields on the centre and outer orbits are 1.452 and 1.8 T at 30 GeV, respectively, with the same maximum field gradient, 5.756 T/m and with BF longer than BD, for $Q_h > Q_v$. Quadrupoles all have maximum gradients of 14.833 T/m, again with the F longer than the D, and with the lengths of F3/4 > F2 and D3/4 > D2. Tunes in the arcs and straights are varied, respectively, by the C2 and C3/4 trim quadrupoles, and FT4/DT4 units assist with the arc-straight betatron matching. In each arc are five C2 cells with free straight sections of length ~ 7.15 m, and the long (C3,C4,C3) units have two lengths of ~ 6.6 m and one of ~ 8.1 m. The transverse acceptances assumed are $176\,\pi$ mm mr for the fractional beam momentum spread of $\pm 1\%$. Table 2 gives the cell parameters and Figure 2 the dispersion and β values.

Lattice functions are $\alpha_p \sim 2.9$ m, $\beta_h \sim 27$ m and $\beta_v \sim 25$ m, maximum, with matched β-functions periodic for the arc groups. The nominal operating point is $Q_h = 19.32$, $Q_v = 14.84$ and $\gamma_t = 40.94$. The dispersion is not periodic in the arc groups, and the α_p maxima vary from ~ 1.9 m to 2.9 m. Sextupoles for chromaticity control are located in the C2 cells, and resulting dynamic apertures are expected to be similar to those of the 8 GeV lattice. The sextupoles are also required to correct the non-linear component of the momentum compaction (α_1) at the top energy of 30 GeV, and this is a topic for future study. The combined function magnets complicate the ring design but their use appears unavoidable in order to achieve 30 GeV.

Acknowledgements

Collaborations with W. Chou (FNAL), D. Ritson and A.A. Garren on the 8 GeV lattice and with H. Schönauer (CERN) on the 30 GeV lattice are gratefully acknowledged.

References

[1] H. Schönauer, Proton drivers for neutrino factories: The CERN approach, Nuclear Instruments and Methods, Volume 472, No. 3, October 2001, Proceedings of NuFact'00, p. 504-510.