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THE LATTICE OF THE SPS

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After reviewing many alternatives, the SPS design team selected a FODO separated function lattice for the SPS. Periodicity and Q were chosen bearing in mind cost of construction, space for major accelerator components, extraction and the provision of adequate beam acceptance in spite of the influence of non-linear stop-bands.

General Description

The 1964 design study[1] of the 300 GeV machine was based upon a combined function lattice rather similar to that of the 25 GeV CERN PS. The mean radius at a field of 1.2T was 1200 m. In 1967[2] Fermilab decided to adopt a separated function lattice for their main ring. Simple dipole magnets were designed to operate at 1.8T and a peak energy of 400 GeV was quoted for a ring only 1000 m in radius.

CERN made a detailed reappraisal[3] of both types of lattice and decided to change to a separate function configuration, not because there was any significant cost saving to be had but because there was a certain flexibility in the separate function design. Space for major accelerator components, such as injection and extraction systems could be provided simply by leaving out bending magnets, this without either interrupting the regular focussing properties of the machine or introducing special matched insertions. Apart from these minor conviences which tipped the scales in favour of the new lattice, the separate function machine had two attractive features which proved crucial when later approval for the project was sought.

This comparison had shown that all other things being equal separated function machines were more compact. Their window frame bending magnets could operate at a field 50% higher than the gradient magnets of a combined function machine. Even allowing space for the quadrupoles of the separate function machine one saved several hundred metres radius. It was possible to propose a 400 GeV machine which fitted the limited confines of the CERN - Prevessin site, taking advantage of CERN's existing infrastructure and resolving the site selection controversy.

The other advantage of the separate function principle was that construction could start with the modest intention of filling half of the space in each cell with bending magnets and later, once the major component costs and construction schedules became clear one might exercise the option to install the missing magnets bringing the energy to 400 GeV.

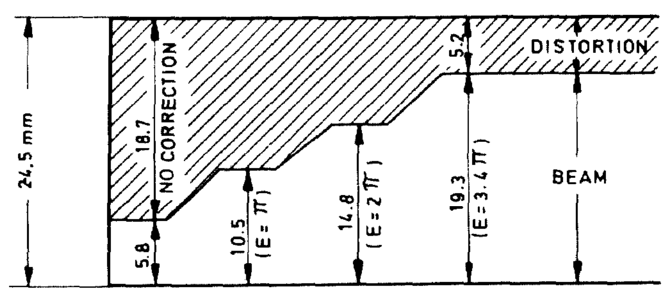
The only disadvantage for the separated function lattice, which became apparant during running-in, is the need for very careful regulation of the two quadrupole and dipole circuits, but this difficulty has been overcome and is by far outweighed by the freedom to move the Q values at will.

The similarity between the SPS and its elder sister at Batavia is no accident. Many alternatives were studied, but, given similar boundary conditions it was not unnatural to arrive at a similar optimum.

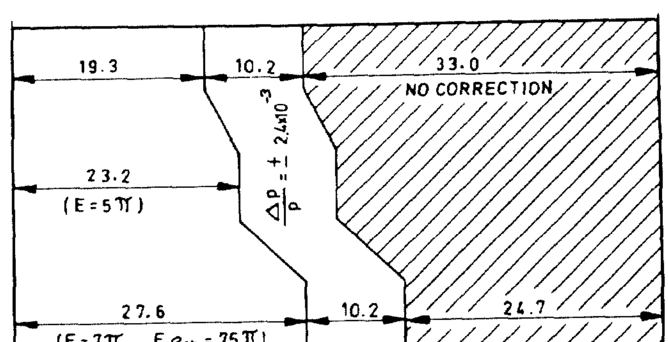
Aperture Requirements

The SPS was the first CERN machine to rely on closed orbit correction to achieve the full acceptance needed for the design intensity. It was thought, that with careful magnet design, remanent and stray field orbit distortions would be smaller than about 30 mm horizontally, and could then be corrected at injection with a small dipole at each quadrupole. Provided the alignment errors could be kept within tolerances met at the ISR, distortions present at high field would be less than 15 mm and be corrected by moving a few selected quadrupoles.

Having used this procedure to arrive at magnet apertures the SPS designers checked that there was sufficient horizontal aperture for the resonant growth of slow extraction needed to reduce losses at the septum and pondered whether magnet pole edges and coils were far enough from the beam to ensure the field tolerances necessary to avoid betatron resonances in a large accelerator. An extra 10 mm was added to the horizontal aperature, a measure which in retrospect seems to have had a beneficial effect at very little extra cost. Fig. 1 shows how apertures were finally defined[4].



a) Vertical semi-apertures



b) Horizontal semi-apertures

Fig. 1 Breakdown of SPS injection apertures

Measurements of closed orbit without correction lie within these predictions and correction procedures are even more effective than had been hoped.

Parameters of a Normal Period

A FODO configuration was chosen because of its simplicity, because the beta values at the quadrupoles are very different, an important consideration if one wants correction magnets to act orthogonally, and because the fraction of the circumference devoted to quadrupoles is smaller than in other configurations.

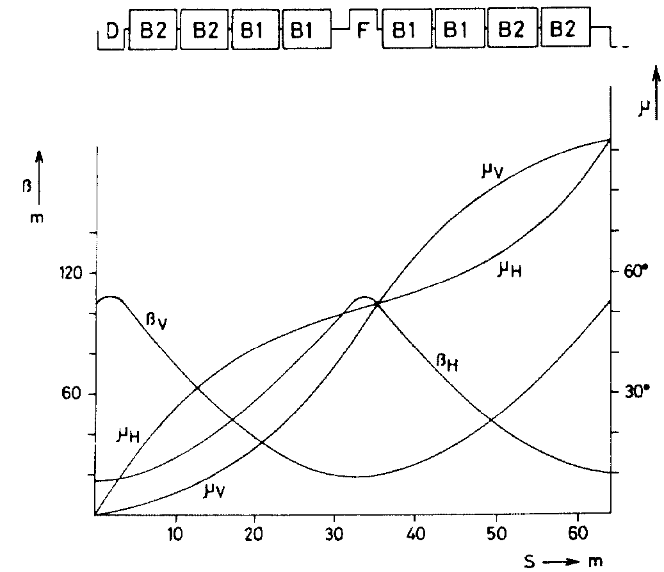


Fig. 2(a) Lattice functions

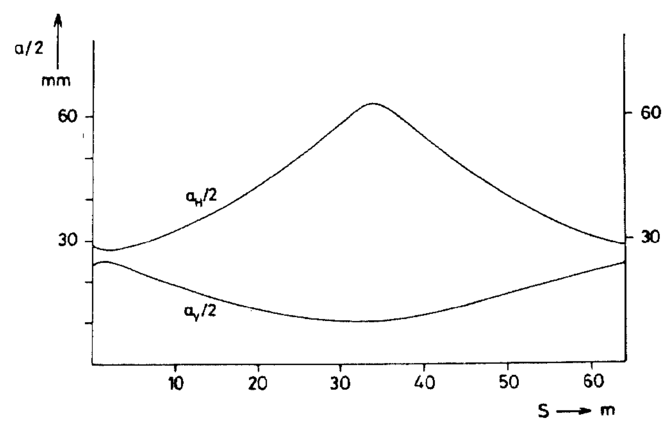


Fig. 2(b) Beam envelope fitting mechanical apertures

Fig. 2(a) shows the lattice functions. After a careful cost optimisation which included coefficients for magnet aperture, stored energy of the power supply, tunnel circumference and running costs, a periodicity of 108 and a phase advance of 92^{o} per period were chosen. Lattices with fewer periods and lower Q tended to have large lattice functions and apertures. Those with larger numbers of periods required more focussing and bending magnets. The many factors of 108 left several options open in the symmetrical arrangement of correction magnets and a phase advance of almost 90^{o} was a considerable conceptual simplification.

In retrospect the rather high Q had another advantage, it tended to reduce α_p which has a direct influence on the chromaticity Q spread caused by sextupole guide field imperfections.

Fig. 2(b) shows the envelope of a beam which just fits the mechanical apertures. The cost saving to be had from matching two types of dipole apertures to the envelope outweighed the extra tooling and development costs.

On the other hand although the beam has a very different aspect ratio at F and D quadrupoles both sections fit well into a single symmetrical quadrupole design. Of course the F and D quadrupoles are powered by independent power supplies to allow Q tuning but are otherwise identical.

Long Straight Section Insertions

The machine is divided into six identical superperiods. Each superperiod is composed of fourteen normal periods and a sequence of four special periods which form the long straight section insertion. Bending magnets are omitted from the special periods to make room for the more bulky components of the machine but the regular spacing of quadrupoles is preserved throughout the superperiod.

The sequence of special periods in the insertion is shown in Fig. 3. The pattern is mainly determined by the design of the extraction channel.

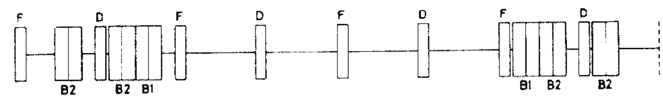


Fig. 3 Long straight section insertion

The six long straight sections of the machine are equally spaced around the ring. Straight section number 1 is assigned to the injection system for the input beam from the CPS, the second to an extraction system to the North Experimental Area, a third to the r.f. accelerating system, a fourth to a beam dump and the fifth reserved for future developments. Straight section 6 is used for the extraction system to the West Hall.

No special measures were taken to reduce the beat of the momentum compaction function Fig. 4. It is a convenience to have rather small α_p in the long straight sections.

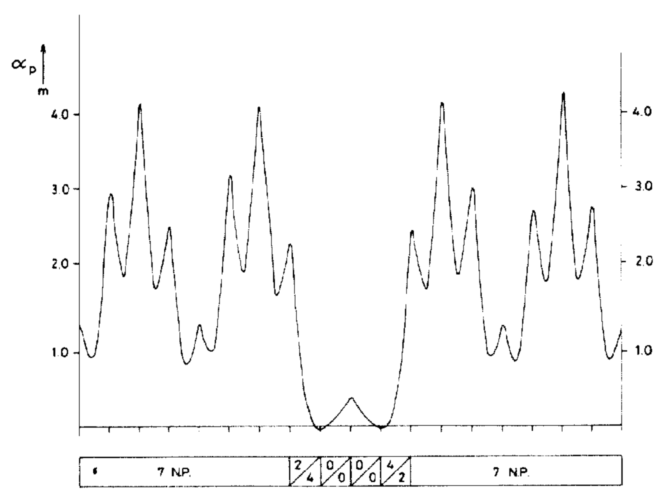


Fig. 4 Momentum compaction function in one superperiod

As the design progressed it was decided to enlarge the four central quadrupoles in the three symmetrically spaced straight sections for extraction and beam dumping. By scaling both length and aperture by the same ratio 11:9, no first order perturbation is made to the dynamics and the larger quadrupoles have space between their coils for the emerging extracted beam.

Choice of Working Point

One of the advantages of the separate function machine is that one has the freedom to explore various Q values with the beam. Nevertheless certain elementary precautions must be taken and a nominal Q value must be chosen as a basis for the specification of other components.

Fig. 5 shows the numerology of systematic sum resonances generated by multiples of 6, the superperiodicity of the SPS. The spacing of these lines becomes closer the smaller the superperiodicity but for s = 6 none fall within half integer squares. At the extremities of the diagram where Q is a multiple of s the momentum compaction function beats violently. A nominal Q value just above 27.5 was chosen remembering that the flexibility could be exploited to change Q if necessary.

In addition to the structure resonances there are of course the more numerous but weaker stopbands driven by random multipole errors and which have the same pattern in each integer square. It seemed prudent to have a small Q split to avoid the diagonal coupling resonance $Q_H = Q_V$ and preferable to be close to the half integer rather than the integer where closed orbit magnification factors become large, thus arriving at $Q_H = 27.6$, $Q_V = 27.55$.

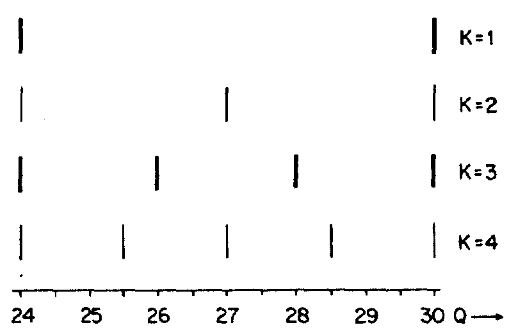


Fig. 5 Numerology of structure resonances

During construction Fermilab found empirically that fifth order structure resonances, contrary to widely held beliefs, are destructive to a beam when synchrotron motion or magnet ripple causes repetitive crossing. It therefore was no surprise to find that it was better to work the SPS at 27.4 rather than the nominal 27.6 which is a fifth order structure resonance.

Running-in Experience

In general the design calculations of beam sizes and orbit distortions for the SPS have proved valid and the lattice has no unexpected vices. Designers of other machine components have managed to fit into the straight sections available - there is even room to augment some systems. The separated function principle and the flexibility it gives in choice of Q has already proved its worth in avoiding one of the unexpected pitfalls of an extrapolation in accelerator design of a factor 10. Some pointers to how one might approach the design of an even larger ring emerge rather clearly.

(i) Steering the first turn and correcting closed orbit distortion to a few millimetres can be assumed from the first days of running-in.

(ii) The control of the chromatic Q spread with sextupoles is both essential and not very difficult in a machine of this size. The high Q of the SPS is an advantage in this respect.

(iii) The SPS though constructed to very fine tolerances must be tuned carefully if beam loss due to non-linear resonances is to be avoided. Future machine designing would do well to weigh this fact strongly in their lattice optimisation and choice of aperture.

(iv) Fifth and higher order stopbands are not stable when crossed repetitively.

References

1. CERN 300 GeV Design Study, CERN/563 (1964).

2. Design Report, National Accelerator Laboratory, FNAL (1968).

3. J.B. Adams, E.J.N. Wilson, Nuc. Inst. Meth., 87 (1970), p.157.

4. The 300 GeV Programme, CERN/1050 (1972).