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THE STANFORD STORAGE RING - SPEAR*

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I. GENERAL DESIGN FEATURES

SPEAR (Stanford Positron-Electron Asymmetric Ring) consists of a single ring of magnets threaded by an aluminum vacuum chamber in which counter-rotating beams of electrons and positrons will circulate. A high luminosity is achieved by making the beams collide in one of two long "low-beta" interaction regions.[1,2] The ring is composed of the two matched low-beta regions connected by nearly circular arcs of unequal length[3] (see Fig. 1). In its initial configuration SPEAR is limited to a maximum operating energy of about 2.5 GeV each beam by the rf voltage capability of the single cavity which will be installed in the ring. The magnets of the ring are however, designed to operate at energies up to 4.5 GeV, and an increase in the initial maximum operating energy thus requires an increase in the number of rf cavities and in the magnet power.

The ring will operate in the so-called one-bunch mode wherein a single circulating bunch of electrons and a single bunch of positrons will collide with zero crossing angle at one of the two low-beta regions. The other potential collision point, because of the asymmetric design of SPEAR, is not at the

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center of the second low-beta section, but is rather in a region where beta is rather large. Since a collision between the two beams at such a point would result in greatly exceeding the threshold for the incoherent two-beam instability, the beams will be made to miss each other by a local perturbation of equilibrium orbits generated by an electric field.

The limiting luminosity of SPEAR, as with other storage rings, is determined by the incoherent two-beam instability. This instability limits the current density in the beams in a manner which depends on the guidefield parameters β_x and β_y and the beam energy. For SPEAR the maximum design luminosity is 10^{32} cm^{-2} sec^{-1} at an energy of 2 GeV each beam. At energies above 2 GeV the circulating beam current is limited by the available rf power and is proportional to E^{-4}. Control of the transverse dimensions of the beam to maintain the limiting current density set by the incoherent limit results in a luminosity proportional to E^{-3}. Below 2 GeV the luminosity is limited by the aperture of the storage ring (the limiting aperture is outside the low-beta insertions). The beam current must be proportional to the beam energy if the limiting current density is not to be exceeded, resulting in a luminosity proportional to E^2.

The most difficult problem which most storage ring projects have faced in their early days of operation is the control of various kinds of instabilities. We are planning to equip the storage ring with various devices to aid in controlling these instability problems. These devices include a fast feedback system for the control of single-beam coherent oscillations; electric quadrupole lenses to split the betatron oscillation frequencies of the electron and positron beams; a special rf cavity to split the synchrotron frequencies of the two beams; sextupole lenses to control the tune-versus-energy characteristics of the lattice; and a set of octupole lenses to control the frequency spread in the beam and to vary the strength of the Landau damping.

The two interaction regions have been designed with a 5 meter drift space between the faces of the quadrupole magnets closest to the interaction point. We feel that these relatively long interaction regions will be required for the kinds of apparatus used for experimentation at the higher energies of which SPEAR is capable. The interaction point is above the center of a pit which is 40 feet long, 35 feet transverse to the beam, and gives a vertical clearance to the beam line of 10 feet. The interaction region buildings will also allow 10 feet of vertical clearance above the beam line.

II. MAGNET LATTICE

The SPEAR lattice is a separated function lattice composed of zero-gradient bending magnets and quadrupoles. The basic cell is composed of three quadrupoles and two bending magnets. (See Fig. 1.) The long arc connecting the two low-beta insertions is composed of six standard cells while the short arc is composed of five such cells. Figure 2 shows the structure, beta functions (β_x, β_y), and momentum vector (η) for a standard cell in the long arc. The short arc must have a smaller average radius than the long arc in order to close the ring. We have chosen to accomplish this by keeping the bending magnet and quadrupole fields and lengths identical in the two regions and shortening the three meter straight section in the standard cell by roughly one-half meter to make the cells for a short arc. Since the first and second derivatives of the beta function are very small at the center of the cell straight section, this makes a negligible perturbation on the transfer matrix of the cell.

Properties of the low-beta insertion are shown in Fig. 3. At the center of the interaction region, β_y is nominally 5 cm and is continuously adjustable up to a value of a few meters by varying the currents in Q1, Q2, and Q3. The momentum vector η has been made zero in the central region of the insert to allow this variation in β_y without spoiling the momentum match to the rest of the ring.

The normal tune of each ring is around $\nu_x = 5.2$, $\nu_y = 5.1$. These tunes can be varied from roughly 4.5 to 5.7 with little difficulty. To maintain a perfect momentum match over this region, the quadrupole QF1 in the insertion must be physically moved from its nominal position. However, over a region of $\Delta\nu \approx \pm 1/4$ the match is satisfactory without varying the position of QF1.

The very strong quadrupoles Q2 and Q3 in the insertion next to the interaction region make the chromatic aberrations of the storage ring guidefield much larger than is usual in a strong focusing machine. These chromatic aberrations are sufficiently large so that it is impossible to inject the full ± 1/2% momentum spread for which the injection system is designed without corrections. Calculations have shown that the best way to correct this chromatic aberration is to distribute sextupole correction magnets throughout the normal cells of the guidefield. We have designed for three sextupole magnets per cell which allows both horizontal and vertical chromaticities to be reduced to zero.

III. DESIGN DETAILS

In this section some of the design details of the ring which may be of interest will be described.

A. Magnets

Both the bending magnets and the quadrupoles are of conventional design and will be machined from rolled steel plate. All magnet coils will be made of aluminum since we find fabrication of aluminum coils to be considerably cheaper than fabrication of copper coils. Each magnet will be provided with an auxiliary coil capable of handling about 1% of the ampere turns of the main coil. These coils can be used to eliminate the closed-orbit deviations by compensating for field errors and small quadrupole misalignments.

Calculations have shown that the tolerances on the sextupole magnets are extremely loose and the iron cores of these magnets will therefore, be made by casting. All magnets are capable of operating up to a maximum field equivalent to 4.5 GeV, but in the first stage of SPEAR power will be supplied to run the magnets only to about 2.5 GeV.

B. RF

The rf system will run at a frequency of about 42 megacycles on the 31st harmonic of the orbit frequency. Initially, there will be one rf cavity. Power available at turn-on is expected to be 160 kW to 200 kW total. The energy loss per turn in synchrotron radiation at 2 GeV is 110 kV and the maximum rf voltage available is 300 kV giving a quantum fluctuation lifetime considerably in excess of 10^{10} sec. At the injection energy of 1.5 GeV the momentum acceptance is ± 0.5%.

C. Injection

We plan to inject electrons and positrons into the storage ring at an energy of 1.5 GeV using the beams of the 20 GeV Stanford Linear Accelerator. In filling the ring in the one-bunch mode described above, we are limited to accepting particles in two 7-ns bursts during the nominal 1.5 μsec pulse of the 20 GeV linac. This bad duty cycle match can be only partially compensated by modulating the linac gun and increasing the instantaneous current during our acceptance time. With the 20 pps injection repetition rate determined by the radiation damping times in the storage ring, the positron filling rate is expected to be 6 min per circulating ampere. The injection system is a relatively standard beam-bump-and-septum design.

D. Vacuum

The vacuum chamber will be fabricated of aluminum extruded in a cross section of our design including the water passage to carry off heat generated by the absorption of synchrotron radiation. The vacuum chamber cross section is shown in Fig. 4. We chose aluminum over the more conventional stainless steel because an aluminum chamber is easier to fabricate and has a lower gas desorption coefficient and a lower x-ray reflection coefficient than steel. The inside surface of the vacuum chamber, where synchrotron radiation will strike, will be corrugated to further reduce the gas desorption rate.

We plan to use distributed ion pumps of our own design for most of the pump capacity required on the ring. These pumps use the relatively low quality magnetic field of the bending magnets near the pole edge for the magnetic field required on the pumps. The components of one of these pumps are shown in Fig. 5. The pump is made from pieces of stainless steel tubing spot-welded together and supported by insulators between two 0.080" thick titanium plates. In tests with ion pump cells 1/2" in diameter, we have achieved pumping speeds of about 500 liters/sec per meter of pump for nitrogen or carbon monoxide and 1200, 45, and 5 l/s/m for hydrogen, helium and argon, respectively. The pumping speed is nearly independent of magnetic field down to fields of about 1.8 kG which corresponds in our design to 0.75 GeV circulating beams. The ring will also be supplied with one 80 liter/sec conventional ion pump per straight section to hold the ring at high vacuum when no beams are stored and the magnets are off.

E. Assembly

We plan to preassemble the components of the ring into modules as shown in Fig. 6 before installation in the storage ring housing. Each module is composed of a 30-ft-long concrete support girder on which two bending magnets, three quadrupoles and three sextupoles are typically mounted. These are the elements of a normal cell, less the cell straight section. The magnets will be aligned with respect to the girder, the vacuum chamber installed and leak-checked and all power, water and control cabling installed as a part of module assembly. Installation of this module into the ring requires the alignment of the concrete support girder and the connection of one water pipe, 3 dc power cables and one multi-conductor control cable.

F. Status

We have recently completed an extensive research and development program emphasizing work on the ring magnets and on the vacuum chamber. We expect to begin fabrication of the storage ring itself in the second half of 1970 and to finish construction in 1972.

COLLIDING BEAM STORAGE RINGS -- SUMMARY TABLE

GENERALITIES

Name	SPEAR
Institute	SLAC
Place	Stanford
Construction started	1970
First beams or goal	1972
Colliding particles	e^+, e^-
Max. energy	2.5 GeV
Possible extension	4.5 GeV
No. of rings	1
Approx. shape	ovoid
Dimensions	60 m × 74 m
Orbit length	220 m
No. of orbit intersections	2
No. of experimental zones	2
Approx. area for experiments	2 × (11 m × 12 m)
Straight sect. for experiments	5m

BEAM PARAMETERS

Reference energy	2 GeV
Relative energy spread	5×10^{-4}
Luminosity $\mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$	10^{32}
Beam life	> 2 hr.
Half crossing angle (vert/horiz)	0
Beam current (each beam)	0.5 A
No. of particles per beam	2×10^{12}
No. of bunches per beam	2
No. of particles per bunch	10^{12}
Bunch to bunch time	0.7 μs/24 ns
Half bunch length	14 cm
Half bunch width at I.P.	0.32 cm
Half bunch height at I.P.	0.008 cm

MAGNET LATTICE

Name	SPEAR
Total no. of bending magnets (B)	34
Max. bending field	6.3 kG (2.5 GeV)
Radius in bending magnets	12.72 m
Total no. of quadrupoles (Q)	51
Max. field gradient	590 g/cm
Total weight of Fe	230 tons
Total weight of Cu	---
No. of identical superperiods	1
No. of magnet periods	11
Composition (0 = straight), (F, D, = synchr. mag.)	Q/2 BQ0QB Q/2
Low-beta insertion (no. x length)	2 × 48 m
Experimental straight section	2 × 5 m
Ev. third type	---
Magnet power available	---
Possible extension	---
Machine acceptance horiz.	$\pi \times 6$ cm × 4.5 mr
Machine acceptance vertic.	$\pi \times 1$ cm × 3 mr
Horiz. ampl. funct. at int. point	1.6 m to 8 m
Vert. ampl. funct. at int. point	5 cm to 1 m

RF SYSTEM

Frequency (rf)	42.35 MHz
Revoltuion frequency	1.36 MHz
Corresponding revolution time	0.73 μs
No. of transmitters (total)	8
No. of cavities (total)	1
Max. rf power (total)	200 kW
Max. peak rf voltage (per beam)	300 kV
Max. rf power on the beams	180 kW

Summary Table (cont'd.) - 3

VACUUM SYSTEM

Name	SPEAR
Roughing pumps (no. x type)	---
Total pumping speed	---
UHV pumps (no. x type)	34 × ion
Total pumping speed	1.7×10^4 l/sec
Pressure without beam	$< 10^{-9}$ torr
Pressure with beam	$< 5 \times 10^{-9}$ torr

INJECTION SYSTEM

Reference injection energy	1.5 GeV
Accelerators used	linac
Filling speed	6 min/A
Ev. filling speed for opp. sign	2 min/A
Total time for fill. process (Imax)	6 min
Acceptance	2mm × 3 mr
Acceptance energy spread	± 1/2%

REFERENCES AND FOOTNOTES

1. K. W. Robinson and G. A. Voss, CEAL-TM-149 (1965) unpublished.
2. P. L. Morton and J. R. Rees, IEEE Trans. Nucl. Sci. NS-14, 630 (1967).
3. This configuration is derived from a previous SLAC design which used two intersecting asymmetric rings designed to produce higher luminosity in the energy range below 2 GeV than this project. The single ring described here is one of the two rings of this previous design and allows high energy physics experiments to begin with a facility of lower cost while preserving the option of adding the second ring at a later date.

FIGURE CAPTIONS

1. Schematic layout of SPEAR.
2. Betatron functions (left scale) and momentum function (right scale) in a standard cell of large arc.
3. Betatron functions (left scale) and momentum function (right scale) in the low-beta insertion.
4. Cross section of the extruded aluminum vacuum chamber.
5. The components of the distributed ion pump.
6. The standard SPEAR assembly module.

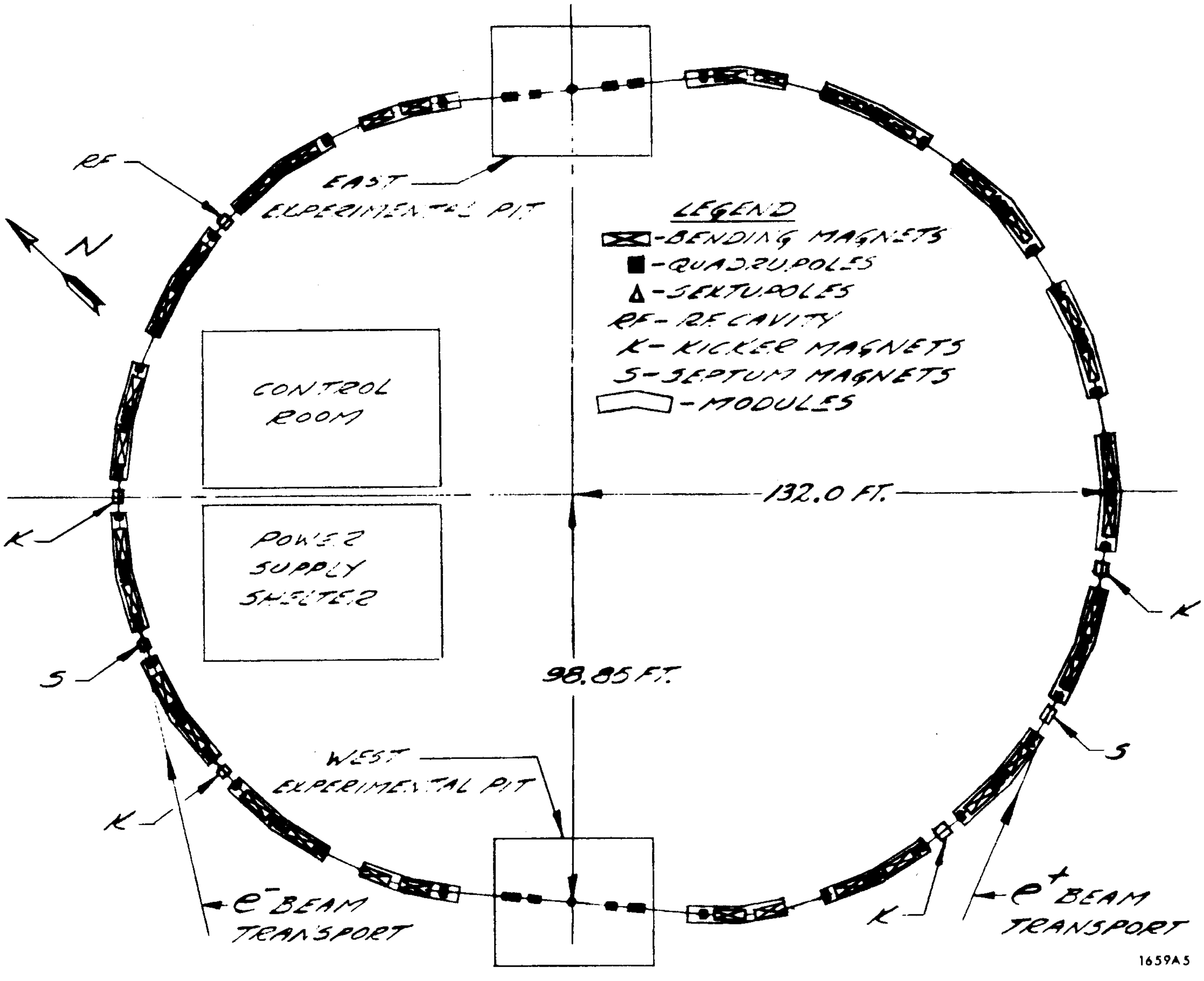
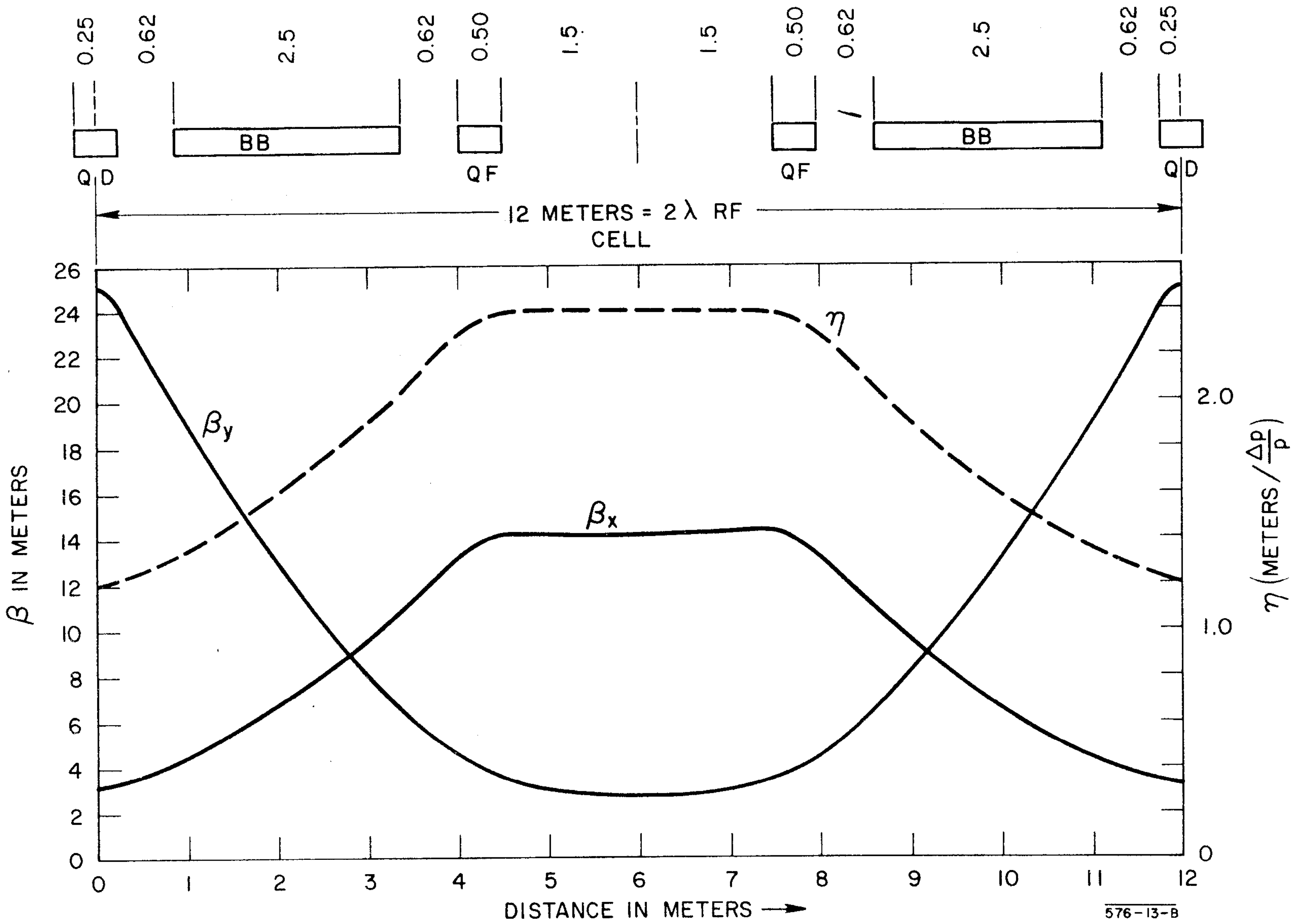
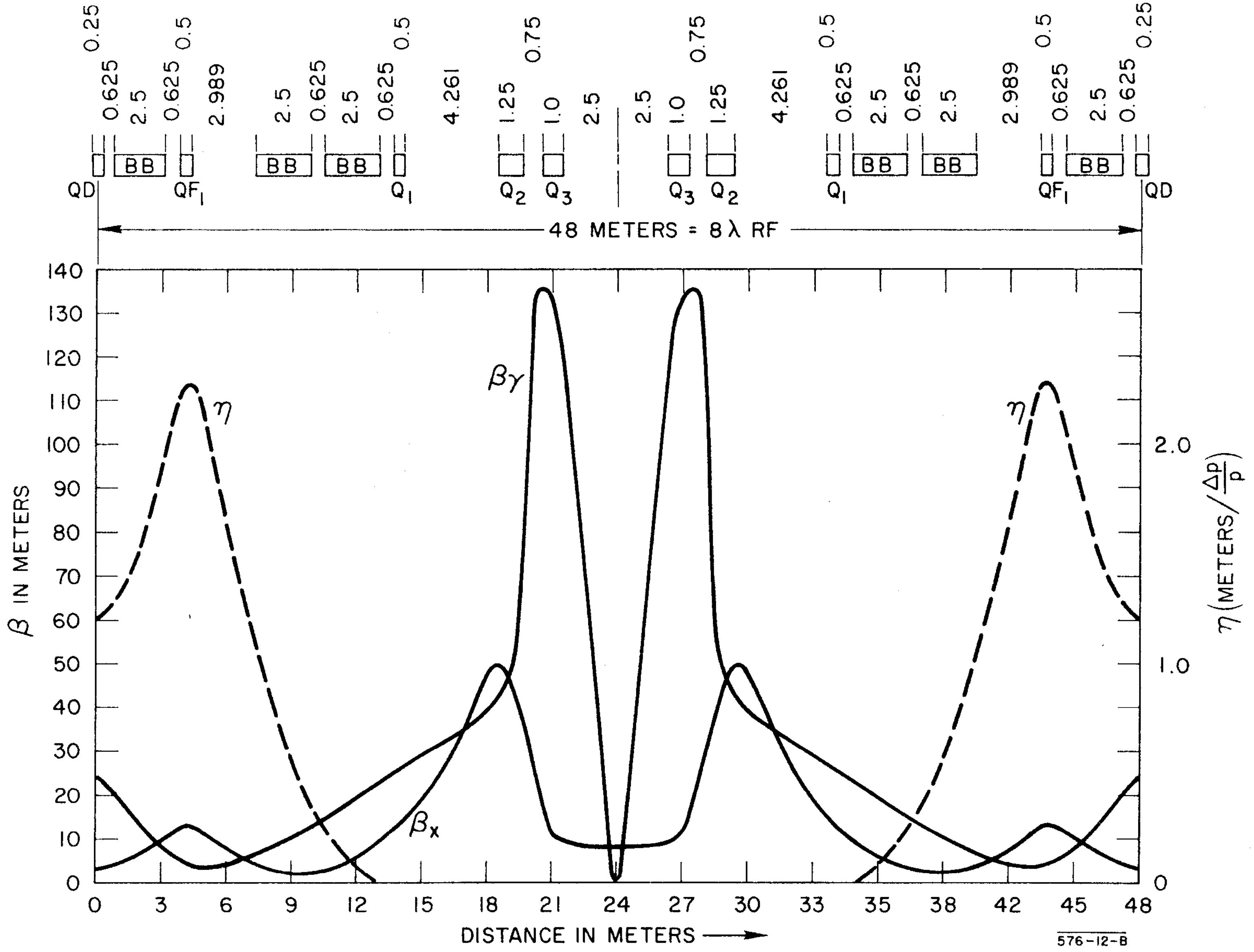

EAST EXPERIMENTAL PIT
RF
N
LEGEND
-BENDING MAGNETS
-QUADRUPOLES
-SEXTUPOLES
RF- RF CAVITY
K- KICKER MAGNETS
S- SEPTUM MAGNETS
-MODULES
CONTROL ROOM
POWER SUPPLY SHELTER
132.0 FT.
K
K
S
98.85 FT.
S
WEST EXPERIMENTAL PIT
K
e^- BEAM TRANSPORT
K
e^+ BEAM TRANSPORT
1659A5

Fig. 1



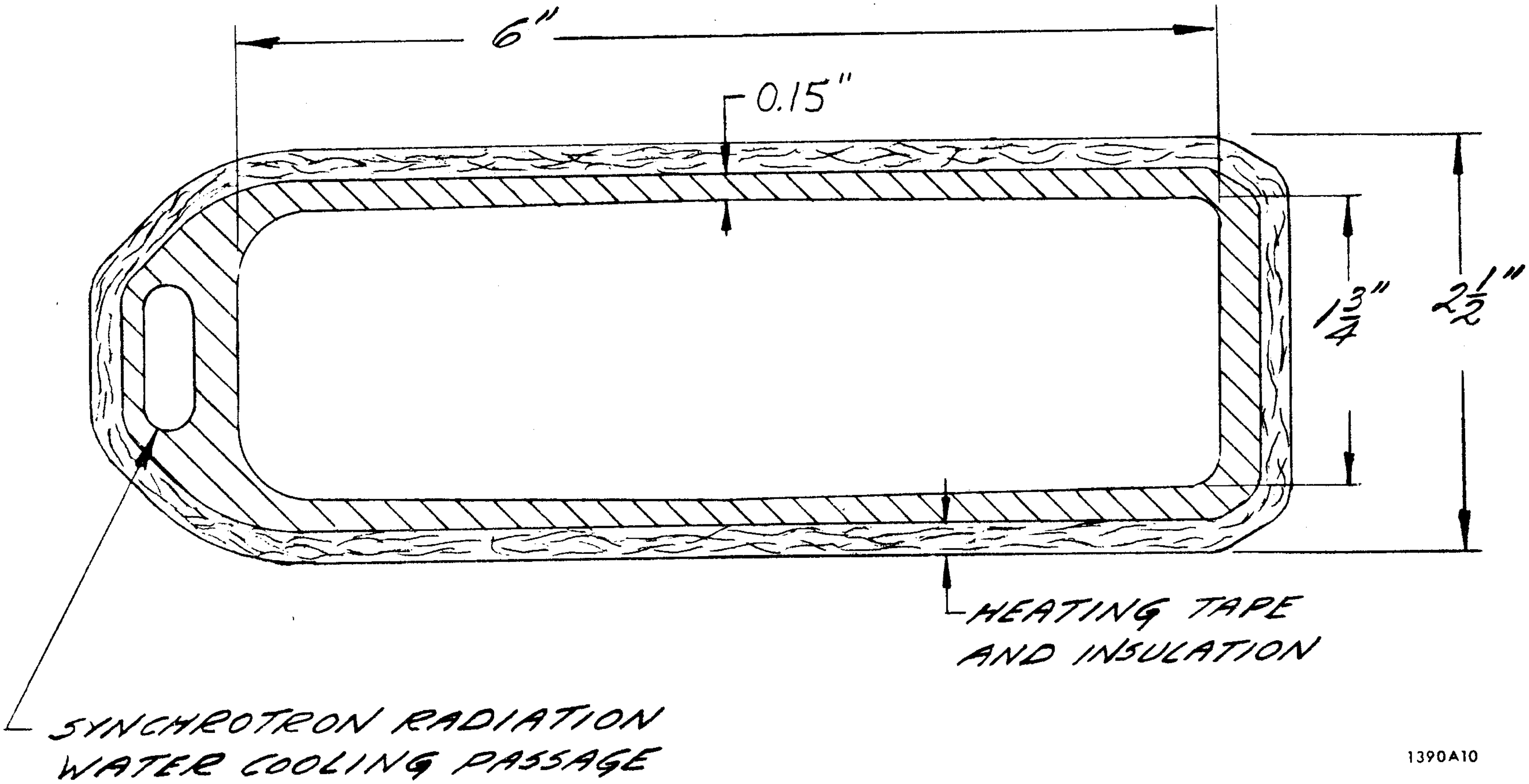
0.25
0.62
2.5
0.62
0.50
1.5
1.5
0.50
0.62
2.5
0.62
0.25
BB
BB
QD
QF
QF
QD
12 METERS = 2 λ RF CELL
β IN METERS
η (METERS / Δp/p)
DISTANCE IN METERS →
β_y
β_x
η
0
2
4
6
8
10
12
14
16
18
20
22
24
26
0
1.0
2.0
0
1
2
3
4
5
6
7
8
9
10
11
12
576-13-B

Fig. 2



0.25
0.625
2.5
0.625
0.5
2.989
2.5
0.625
2.5
0.625
0.5
4.261
1.25
0.75
1.0
2.5
2.5
1.0
0.75
1.25
4.261
0.5
0.625
2.5
0.625
2.5
2.989
0.5
0.625
2.5
0.625
0.25
BB
QD
QF1
Q1
Q2
Q3
48 METERS = 8 λ RF
β IN METERS
η (METERS/Δp/p)
βγ
βx
η
DISTANCE IN METERS
0
3
6
9
12
15
18
21
24
27
30
33
35
38
42
45
48
10
20
30
40
50
60
70
80
90
100
110
120
130
140
1.0
2.0
576-12-B

Fig. 3



1390A10

Fig. 4

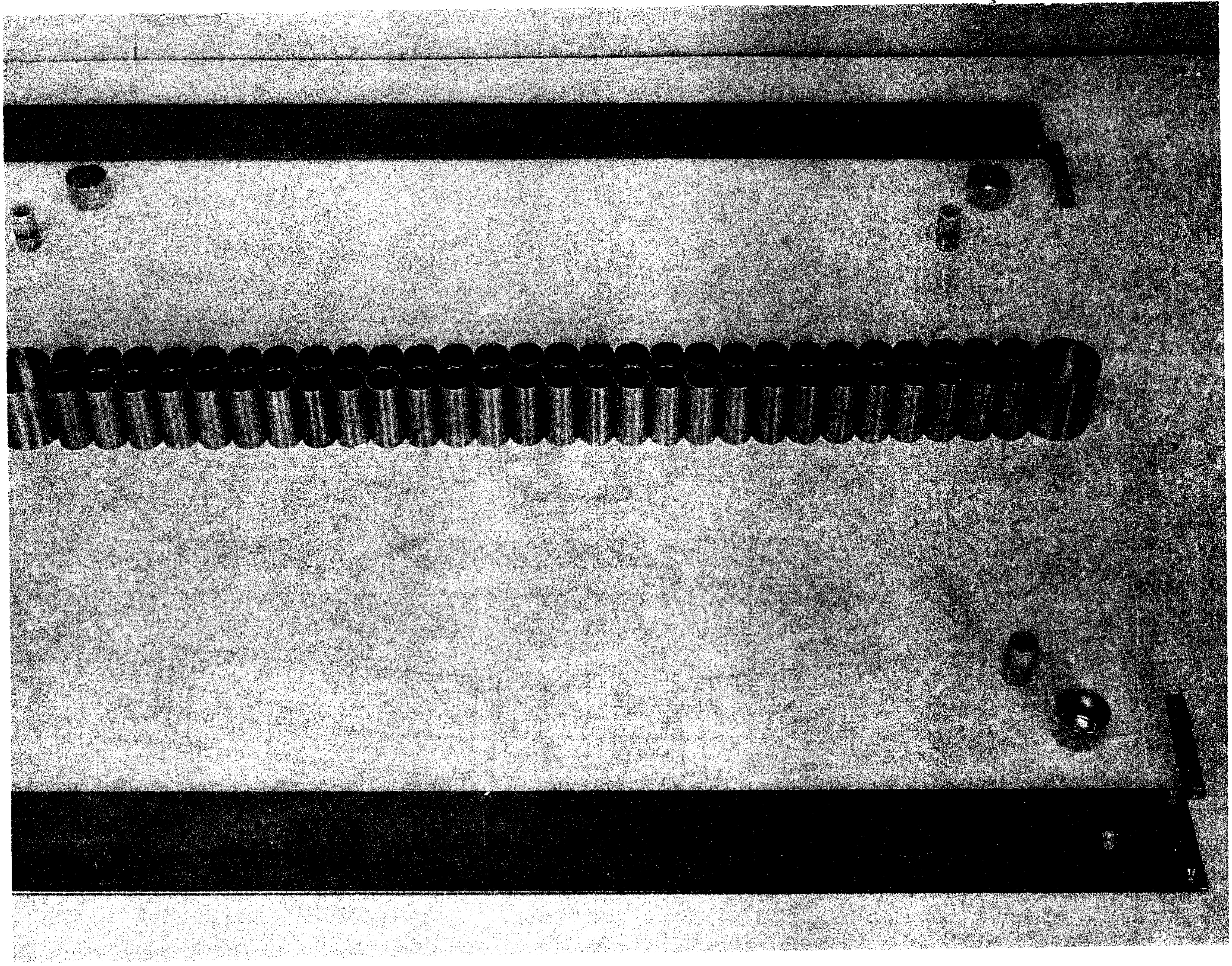


Fig. 5

1383A6

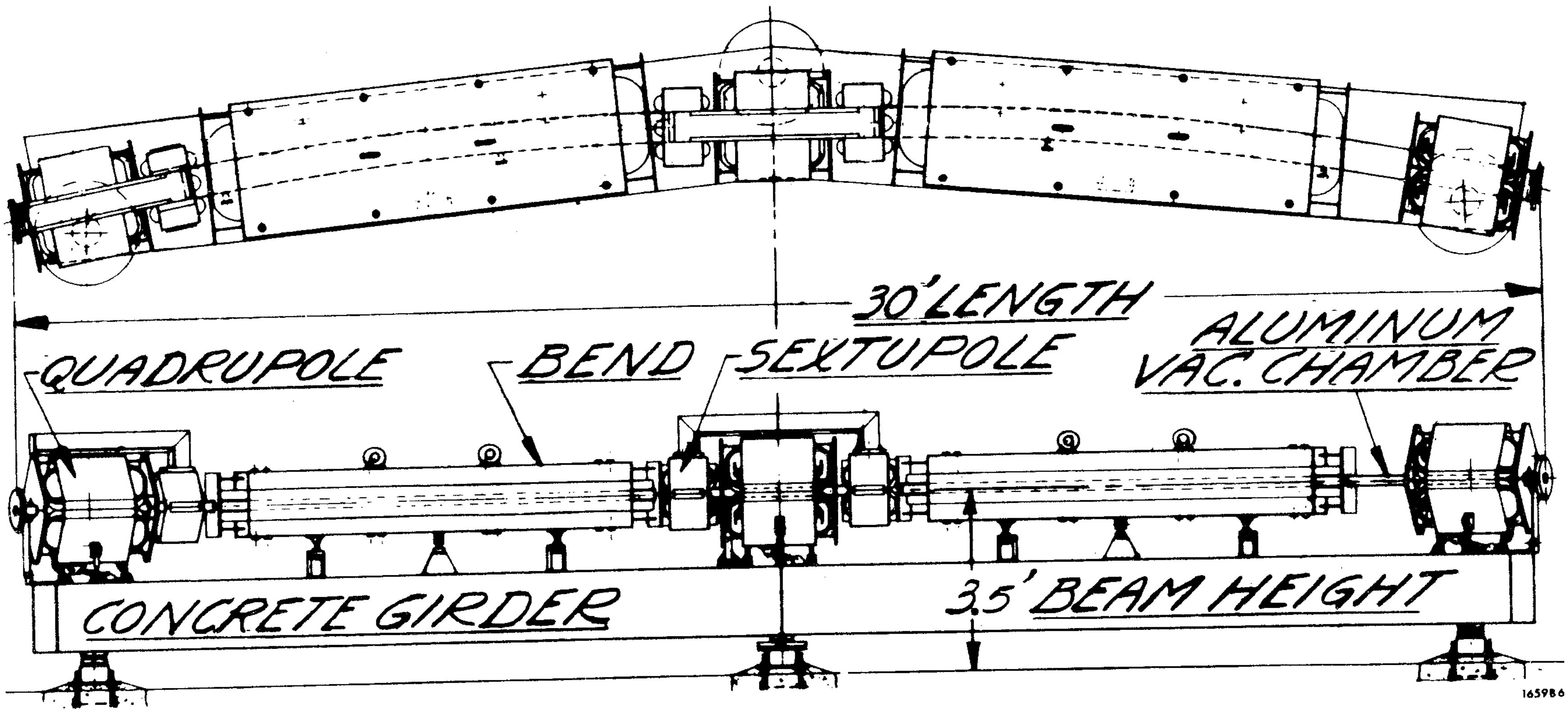

30' LENGTH
QUADRUPOLE
BEND
SEXTUPOLE
ALUMINUM VAC. CHAMBER
CONCRETE GIRDER
3.5' BEAM HEIGHT
165986

Fig. 6