DESY HERA 80/02
September 1980

COSTS OF "HERA" ELECTRON RING AS A FUNCTION OF APERTURE, CELL LENGTH AND e^+e^- LUMINOSITY

by

H.Kaiser and K.Steffen

"DIE VERANTWORTUNG FÜR DEN INHALT
DIESES INTERNEN BERICHTES LIEGT
AUSSCHLIESSLICH BEIM VERFASSER."

Summary

Responding to a suggestion by G. Voss[1)], we examined the cost dependance of the HERA electron ring on aperture and cell length and determined the optimum cell length which turned out to be about 20 m, not far from the HERA design. The aperture limited design luminosity of $4 \cdot 10^{31} cm^{-2} s^{-1}$ at 25 GeV (for $\Delta Q = 0.025$ and $\beta_z^* = 3$ cm) can be doubled for an added investment price of 44 MDM. For a factor of 4, the added investment price is 120 MDM.

Introduction

In the aperture and beam-beam limited energy region, the luminosity of an electron storage ring increases as the square of the aperture radius if the beam emittance and current are correspondingly increased. At high energy, however, a large focusing strength, i.e. a large quadrupole length or small aperture radius is needed for high luminosity. These conflicting aperture demands were analysed in a note by G. Voss[1)] where he also pointed out that, for given beam emittance and luminosity, the cell length, in principle, is a free parameter that can be chosen for minimum overall cost.

In this note we try to determine how the costs of the HERA electron ring depend on aperture radius and cell length, how the cell length should be chosen and how much more it would cost to increase the e^+e^- luminosity in the medium and lower energy region by a factor of 2 or 4.

Assessment of costs

Tab. 1 gives the investment and operating cost contributions that markedly vary with aperture radius R and cell length L. The costs are given in MDM for 4 different values of R and L in a 4x4 matrix using the following notations:

L		R = 3.5 cm		R = 4.9 cm		R = 7 cm		R = 9.9 cm	
L = 20.88 m	η =	0.768		0.686		0.549		0.326	
		Costs [MDM] Invest.	Oper.	Costs [MDM] Invest.	Oper.	Costs [MDM] Invest.	Oper.	Costs [MDM] Invest.	Oper.
	B	9.11	6.01	13.42	7.53	20.46	11.75	33.16	33.33
	Q	14.25	4.27	29.55	6.47	64.13	10.53	135.75	17.22
	S	4.50		12.08		29.85		76.88	
	PS	3.76		5.12		8.15		18.48	
	C	9.21		10.74		14.33		26.61	
	RF	16.17	67.25	18.10	75.29	22.62	94.07	38.10	158.42
	ΔT	0		8.76		21.15		38.66	
	V	27.80		30.91		34.97		39.84	
		84.80	77.53	128.68	89.29	215.66	116.35	407.48	208.97
		Invest.+Oper.	162.33	Inv.+Oper.	217.97	Inv.+Oper.	332.01	Inv.+Oper.	616.45
L = 15.66 m		Present HERA design							
	η =	η_o = 0.690		0.58		0.40		0.100	
		Costs [MDM] Invest.	Oper.	Costs [MDM] Invest.	Oper.	Costs [MDM] Invest.	Oper.		
	B	9.77	7.44	14.20	10.53	21.39	22.14		
	Q	19.00	5.69	39.40	8.62	85.50	14.04		
	S	6.00		16.10		39.80			
	PS	4.80		7.00		13.22			
	C	10.66		13.37		21.02			
	RF	18.00	74.85	21.41	89.05	31.05	129.12		
	ΔT	0		8.76		21.15			
	V	27.80		30.91		34.97			
		96.03	87.98	151.15	108.02	268.10	165.30		
		Inv.+Oper.	184.01	Inv.+Oper.	259.17	Inv.+Oper.	433.40		
L = 10.44 m	η =	0.534		0.372		0.098			
		Costs [MDM] Invest.	Oper.	Costs [MDM] Invest.	Oper.				
	B	11.08	12.42	15.74	25.60				
	Q	28.50	8.54	59.10	12.93				
	S	9.00		24.15					
	PS	7.66		14.08					
	C	14.83		22.87					
	RF	23.26	96.72	33.39	138.83				
	ΔT	0		8.76					
	V	27.80		30.91					
		122.13	117.68	209.00	177.36				
		Inv.+Oper.	239.81	Inv.+Oper.	386.36				
L = 7.84 m	η =	0.380		0.163					
		Costs [MDM] Invest.	Oper.						
	B	12.39	24.53						
	Q	38.00	11.37						
	S	12.00							
	PS	13.49							
	C	22.31							
	RF	32.68	135.91						
	ΔT	0							
	V	27.80							
		152.67	171.81						
		Invest.+Oper.	330.48						

Table 1: Dependence of HERA cost contributions on cell length L and aperture radius R

R is the aperture radius of the cell quadrupole; its values are $(\sqrt{2})^n \cdot R_o$ with R_o = 3.5 cm (present HERA design) and n = 0, 1, 2, 3.

L is the cell length; its values are $\frac{4}{m} \cdot L_o$ with L_o = 15.66 m (present HERA design) and m = 3, 4, 6, 8. The 10 half cells we considered are shown to scale in Fig. 1. The quadrupole length is scaled as the aperture radius R in order to maintain the same focusing strength at high energy[1]. Similarly, the sextupole length is scaled as R^2. Maintaining the necessary gaps for vacuum equipment and coil ends, the bending magnet length, then, is taken as the remaining length within the half cell. Thus, the bending magnet filling factor gets rapidly worse for smaller cell length as well as for larger aperture radius, i.e. the bending field goes up and causes higher magnet power and radiation losses leading to higher costs for power installation and consumption.

B Invest. is the cost of bending magnets with cross section as shown in Fig. 2. Their good field aperture is matched to the quadrupole aperture for a height to width ratio of 2/3, and gap height and pole width scale as R. Maintaining an optimised magnet, the current density in the single conductor Al-"coil" is kept constant, i.e. the linear coil dimension scales as $\sqrt{R}$; a similar conductor for field compensation is assumed around the ring.

The cost breakdown for a single magnet of the present HERA design (5.4 m long with 5 cm gap) is shown in Tab. 2; the prices (in DM) are scaled from PETRA bending magnet prices assuming a 50 % cost increase (∿4 years). The underlined prices do not depend on individual magnet length; their contribution to the total cost B in Tab. 1 is proportional to 1/L or the number of magnets, while the contribution of the others is assumed to be constant. At first glance, this might not appear to be correct in view of the varying magnet filling factor η, but it is indeed a good assumption since the field strength and yoke thickness must be increased for smaller filling factor.

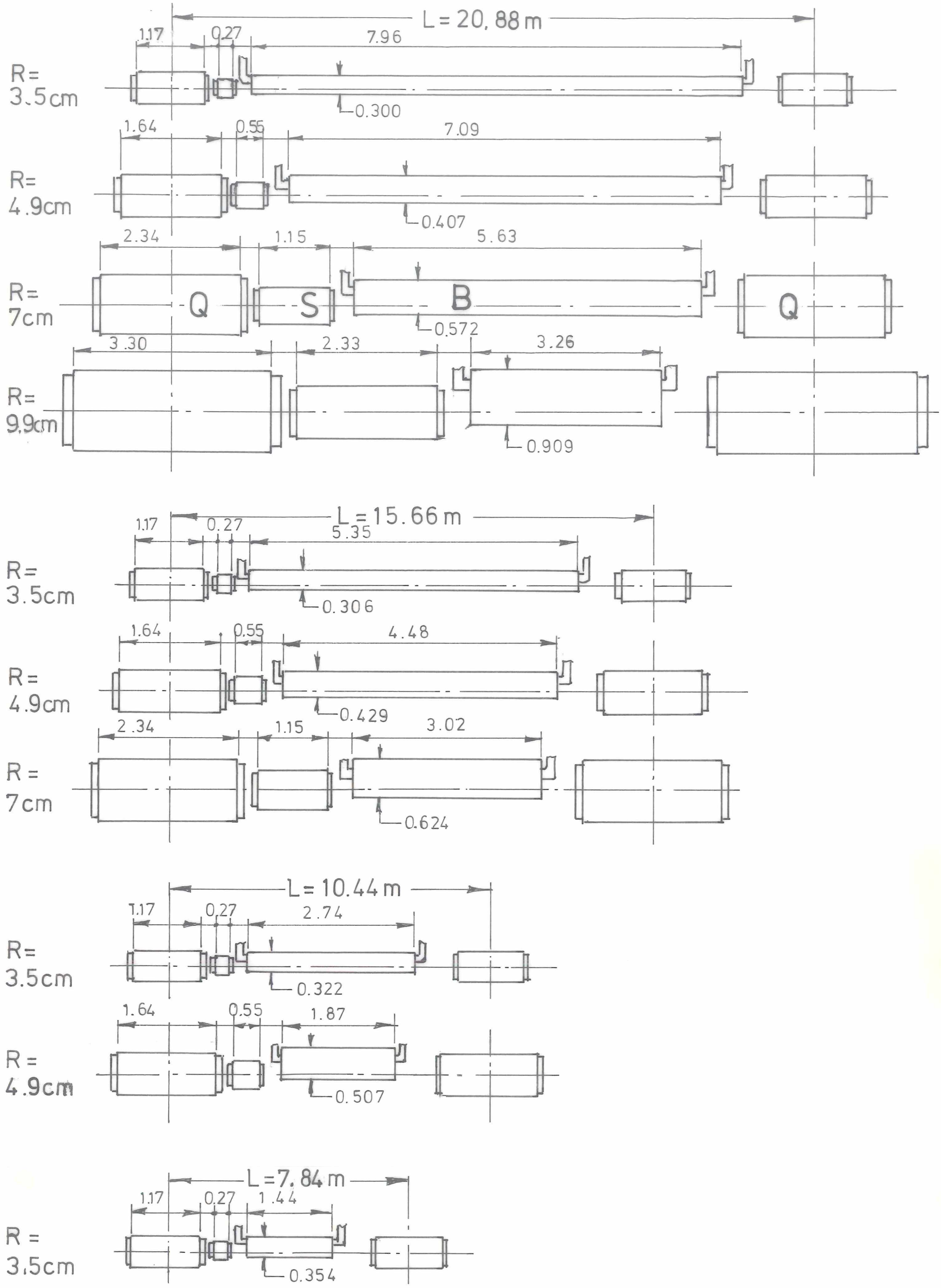


Fig. 1 Half cell structures for various aperture parameters R and cell lengths L

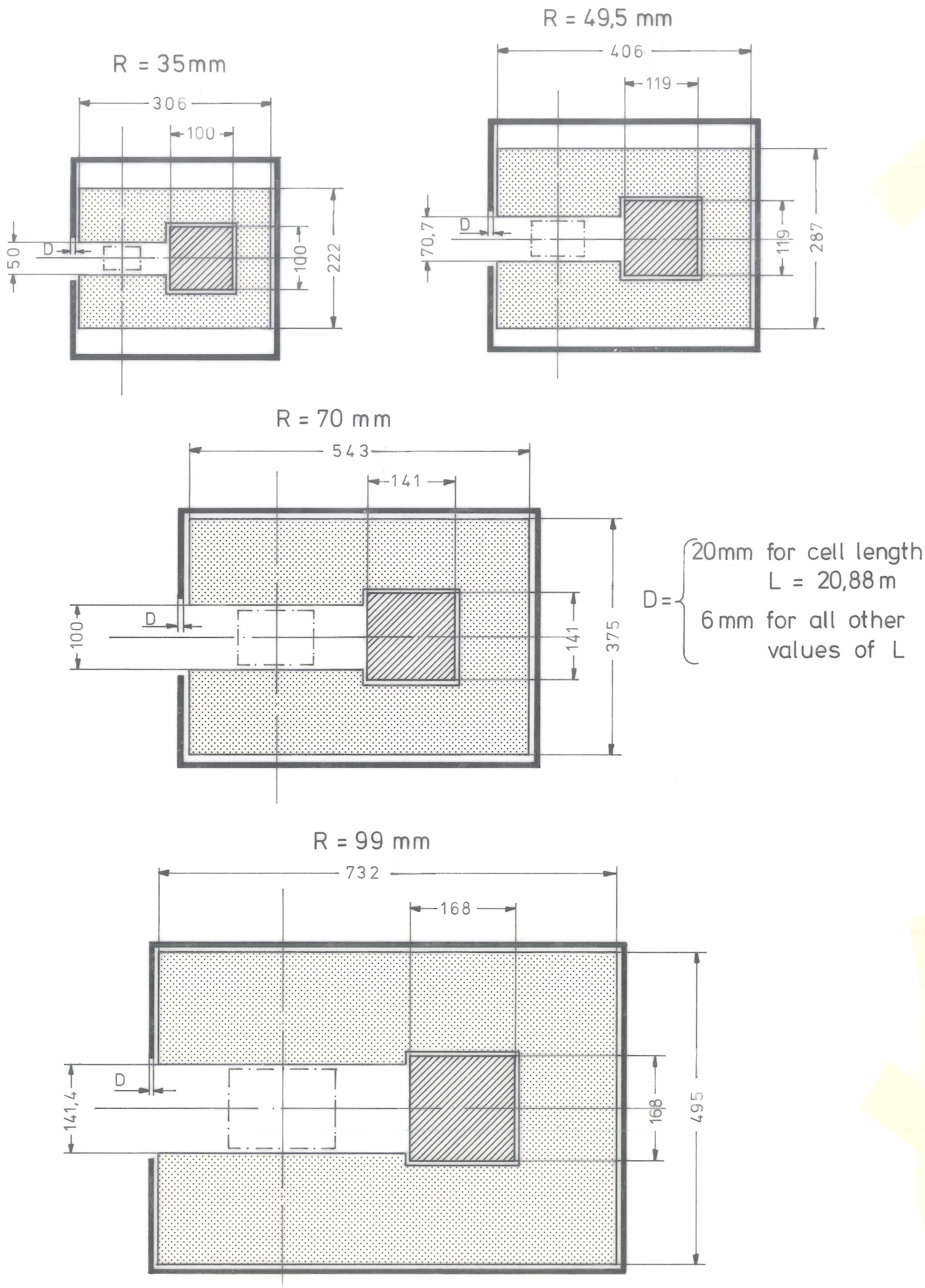
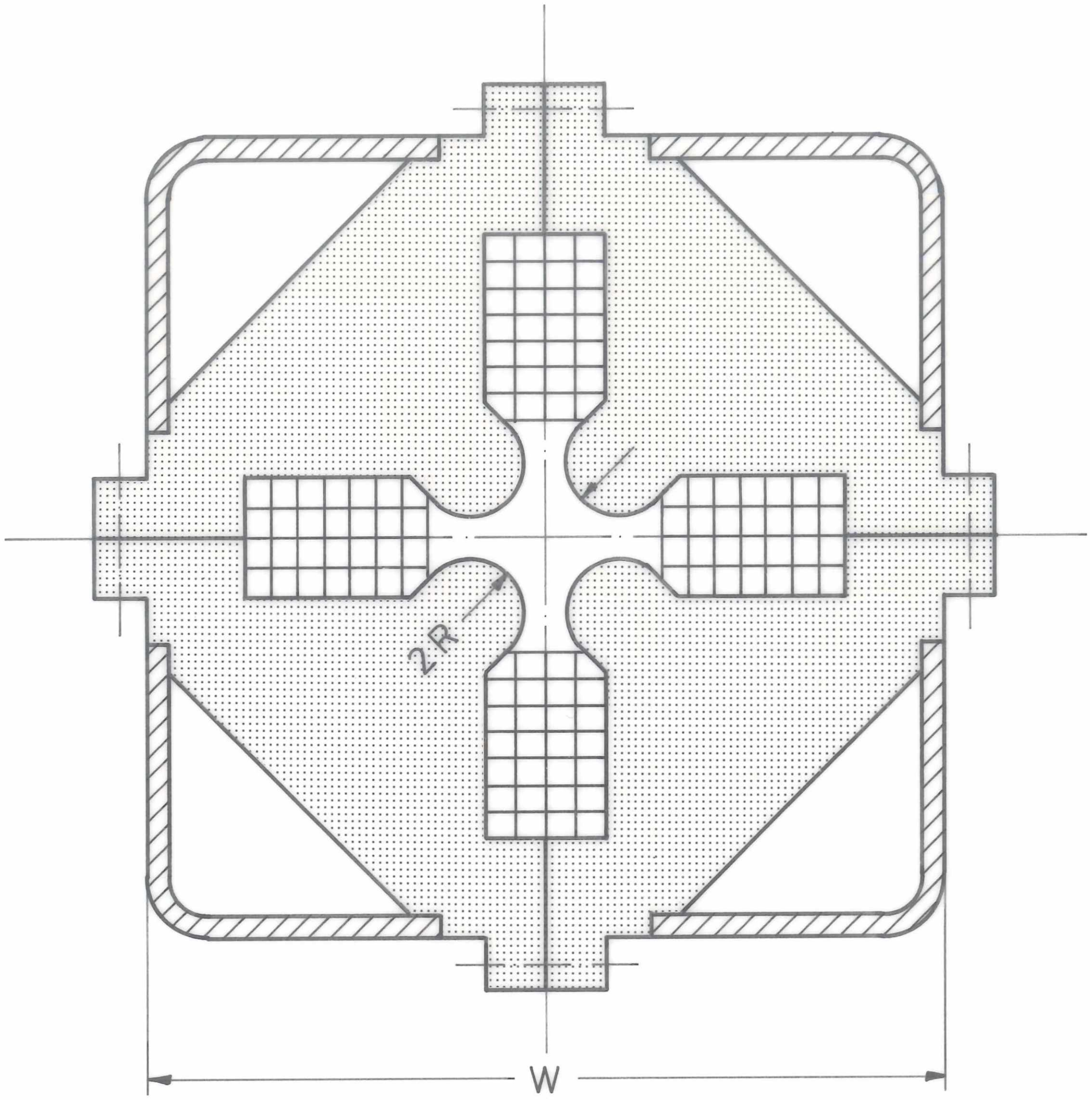


Fig. 2 Bending magnet cross sections for various radii R and filling factor $\eta = 0.69$



R [mm]	W [mm]
35	470
49.5	664.7
70	940
99	1329.4

FIG. 3 QUADRUPOLE CROSS SECTIONS

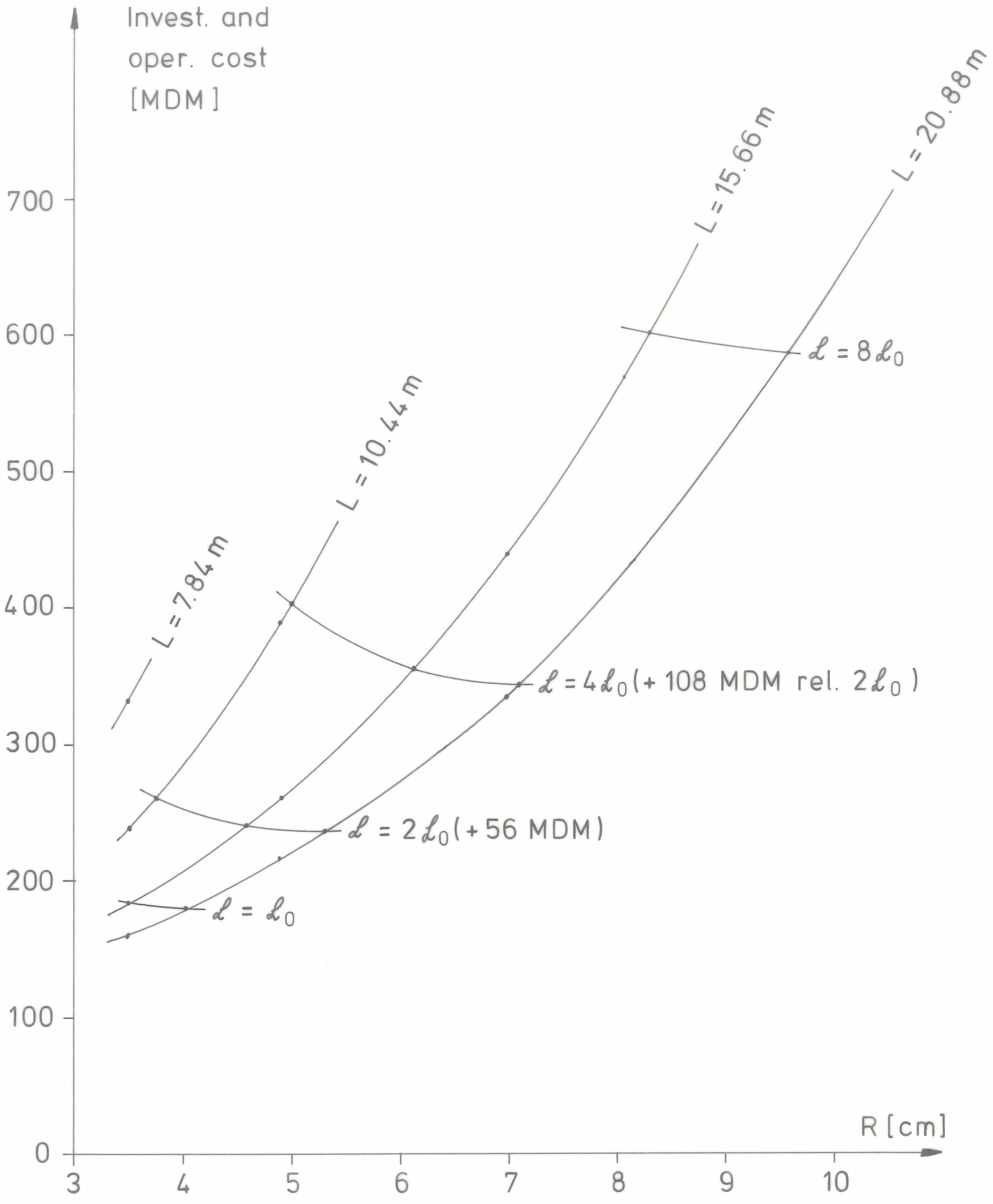


Fig. 4 Sum of the HERA invest. and oper. cost contributions that depend on aperture radius R and cell length L, with curves of constant luminosity $\mathcal{L}$

Tab. 2: Cost breakdown for HERA bending magnet
(5.4m long, 5cm gap height; prices in DM)

gap height	50mm	71mm	100mm	141mm
corresponding to R	3.5cm	4.9cm	7cm	9.9cm
iron (all costs included)	5002	8598	15000	26699
– scrap iron	– 150	– 258	– 450	– 801
punching (∝ weight)	740	1272	2220	3952
assembly { fixed	1294	1294	1294	1294
assembly { variable (∝ weight)	108	185	323	575
reinforcing profiles { fixed	400	400	400	400
reinforcing profiles { variable	415	545	722	965
end plates (2)	778	1021	1352	1807
accessories (fixed)	482	482	482	482
magnet supports	650	919	1300	1838
transportation	331	569	992	1766
magnet yoke Σ	10050	15027	23635	38977
Al coil conductor	3713	5258	7381	10488
insulation within magnet	1000	1190	1410	1680
connections + expansion loops	500	707	1000	2828
coil Σ	5213	7155	9791	14996

B Oper. is the cost of bending magnet power for an operation of 25 000 h at 30 GeV, assuming a price of 0.11 DM/kWh.

Q Invest. is the quadrupole magnet cost which is taken to be 19 MDM for the present HERA design and is scaled as $R^{1.61}$ and $L^{0.56}$. These scaling laws were extracted from commercial offers for PETRA quadrupoles[2), assuming for all values of R the similar shape of cross section as is shown in Fig. 3.

S Invest. is the sextupole magnet cost, scaled with R and L as the quadrupoles.

Q+S Oper. is the cost of quadrupole and sextupole magnet power for an operation of 25 000 h at 30 GeV.

PS Invest. is the cost of power supplies for all magnets, taken from the HERA proposal and scaled linearly with the sum of magnet power.

C Invest. is the cooling water installation cost for the sum of rf and magnet power.

Rf Invest. is the cost of rf klystrons with high voltage power supplies, assuming 13.2 MW for the present HERA design and scaling inversely with the magnet filling factor.

Rf Oper. is the electricity and klystron replacement cost for an rf operation of 25 000 h at full power (assumed klystron values: output power 550 kW, efficiency 65 %, life 10 000 h, price 317 kDM).

T Invest. is the increase in ring tunnel cost with tunnel radius (9 MDM for Δr = 10 cm). We assumed Δr to be equal to the increase of the outer quadrupole radius.

V Invest. is the total cost of the HERA vacuum system. Half of this cost is assumed to be independent of R and the other half is scaled as $R^{0.6}$.[3)]

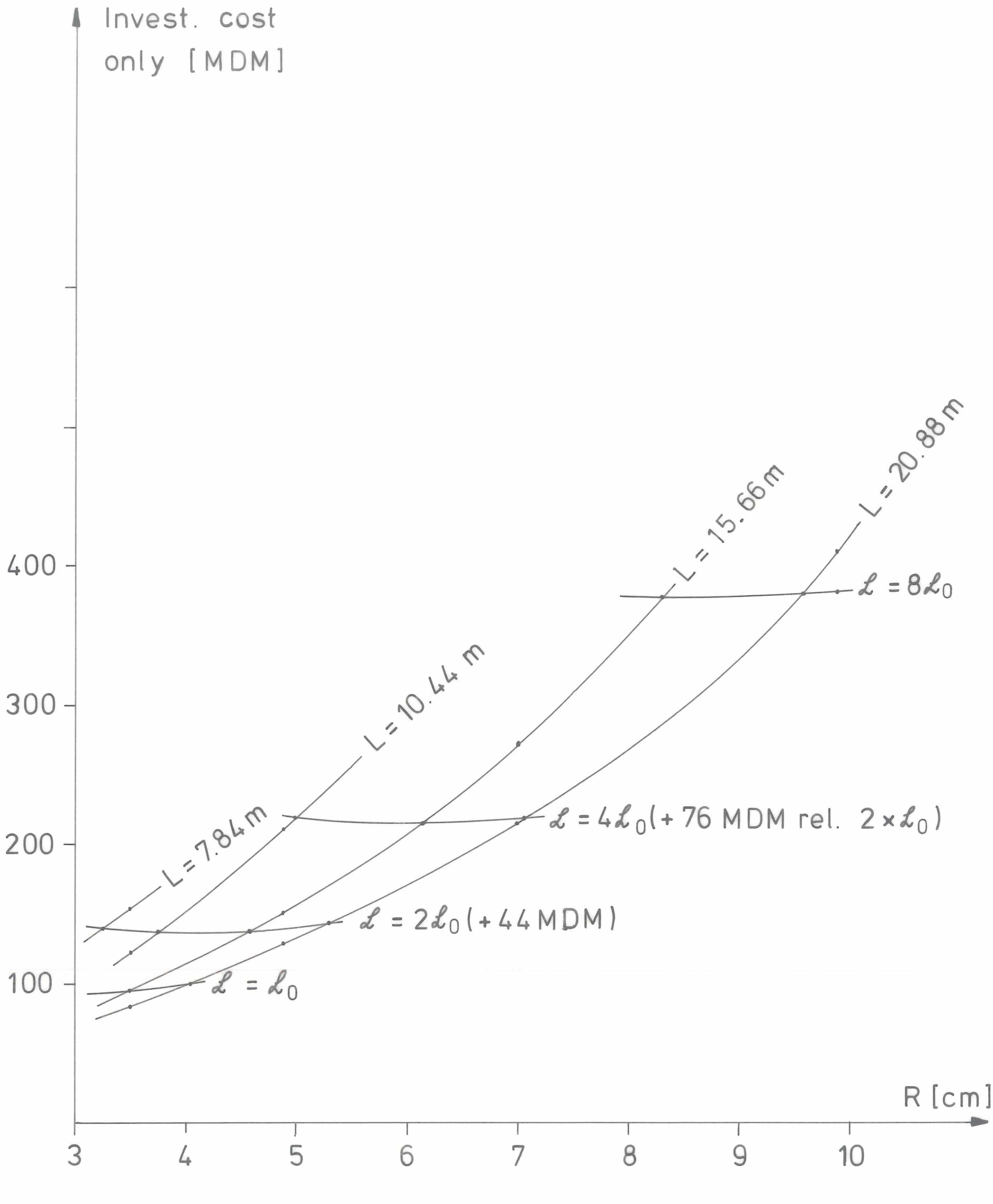


Fig. 5 Sum of the HERA invest. cost contributions only, with curves of constant luminosity $\mathcal{L}$

Evaluation of results

The results are presented in Figs. 4 and 5. Figure 4 shows the investment plus operating cost variation as a function of aperture radius R for the 4 different values of cell length L, while Fig. 5 show the investment cost variation only. Both figures also show curves for constant machine acceptance and constant maximum luminosity $\mathcal{L}$ which are obtained by varying R porportional to $\sqrt{L}$. For constant phase advance per cell, this variation is not immediately obvious since the orbit errors resulting from quadrupole errors in the cell structure are proportional to beta, divided by the focal length of these quadrupoles, and are thus independent of L. A numerical estimate for the e^+e^- HERA ring however shows that the expected orbit error caused by misalignment of the interaction region quadrupoles is larger than the error from the cell quadrupoles (see appendix). In view of this dominant contribution, which is proportional to $\sqrt{\beta}$, we have scaled R as $\sqrt{L}$ along the curves of constant luminosity. When, on the other hand, going from one of these curves to the next one that corresponds to twice the luminosity we must, for constant L and optics, multiply only the aperture fraction filled by the beam by a factor of $\sqrt{2}$. Assuming that, at R_o = 3.5 cm, 3/4 R_o is filled by the beam, only this part is increased while the remaining part (1/4 R_o), which is provided for orbit deviations, is kept constant.

It appears from Figs. 4 and 5 that, regarding total costs, the curves for constant luminosity have a fairly flat minimum at or slightly above L = 20 m while, regarding investment costs only, the curves are much flatter and have their minimum at about L = 15 m. We might therefore conclude that with respect to costs any cell length between 15 m and well over 20 m would be a good one. The final choice then, will depend on the focal strength required at high energy, and on technical aspects concerning lattice construction, installation and alignment.
The aperture limited HERA e^+e^- design luminosity at 25 GeV, with ΔQ = 0.025 and β_z^* = 3 cm, is $\mathcal{L}_o = 4 \cdot 10^{31} cm^{-2} s^{-1}$. It

can be doubled by increasing the quadrupole aperture radius from 3.5 cm to 4.6 cm, and this will cost additional 44 MDM for investment and 12 MDM for operation. For a luminosity increase by a factor of 4, the cost increment will be 120 MDM for investment and 44 MDM for operation. In other words: the first factor of two in e^+e^- luminosity can be had for 56 MDM total, and the second for 164 MDM.

Appendix: Estimated closed orbit errors

For the closed orbit deviations due to a mean random quadrupole misalignment $\langle \Delta y \rangle$ we have from ref. 4) p.7 (considering focusing quads. only):

closed orbit deviation

- caused in normal cell only: $$\langle y_{cell} \rangle = \frac{\sqrt{N}}{2|\sin \pi Q|} \beta_{cell} \frac{\langle \Delta y \rangle}{f_{cell}}$$
- caused in interaction region: $$\langle y_{I.R.} \rangle = \frac{\sqrt{M}}{2|\sin \pi Q|} \sqrt{\beta_{IR} \cdot \beta_{cell}} \frac{\langle \Delta y \rangle}{f_{IR}} \sqrt{\frac{L}{L_o}}$$

With e.g. $$\frac{1}{2|\sin \pi Q|} = 0,7$$

no. of cells	N	$= 320$
focal length of cell quads	f_{cell}	$= \frac{1}{2} L_o = 7.5$ m for $\Delta\phi = 60°$ per cell
max. beta in cell	β_{cell}	$= \sqrt{3} \cdot L_o = 26$ m
no. of high beta IR quads	M	$= 8$
focal length of IR quad.	f_{IR}	$= 1.5$ m (see HERA example in ref.5))
max. beta in IR	β_{IR}	$= 100$ m (see HERA example in ref.5))
mean quad. misalignment	$\langle \Delta y \rangle$	$= 0.2$ mm

we have the c.o. deviations

$$\langle y_{cell} \rangle = 8.7 \text{ mm}$$

$$\langle y_{IR} \rangle = 13.5 \sqrt{\frac{L}{L_o}} \text{ mm}$$

Acknowledgements

We wish to thank G. Voss for stimulating this study and furthering it with his suggestions and critical comments, and J. Kouptsidis and H. Wümpelmann for their contributions on vacuum and magnet cost scaling.

References

1) G.A. Voss: "Aperture considerations for HERA", Aug. 1980 unpublished
2) H. Wümpelmann: priv. comm., Sept. 1980
3) J. Kouptsidis: priv. comm., Aug. 1980
4) K. Steffen: "Effect of errors in large electron storage rings",Internal Report DESY PET-78/02 (Jan. 78)
5) K. Steffen: "e^+e^- luminosity and chromaticity in the aperture limited mini beta section", Internal Report HERA-80/03 (Sept.1980)