LHeC Electron Ring Arc Design

Emittance and damping partition constrained by the hadron ring and magnet choices

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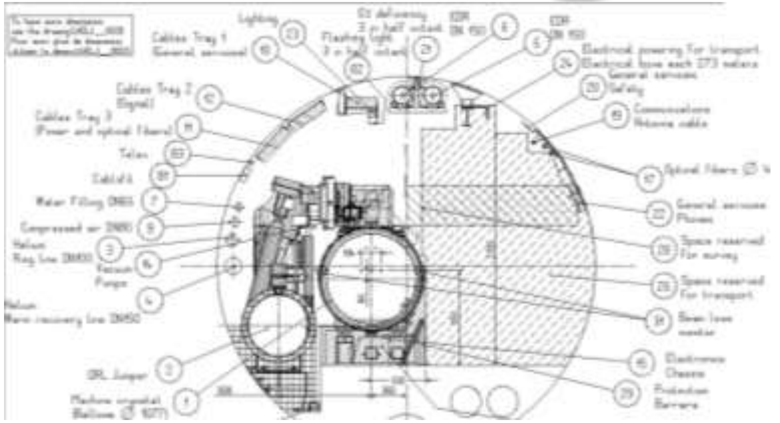
Magnet issues

Size & weight

The magnets must be compatible with the present LHC machine.



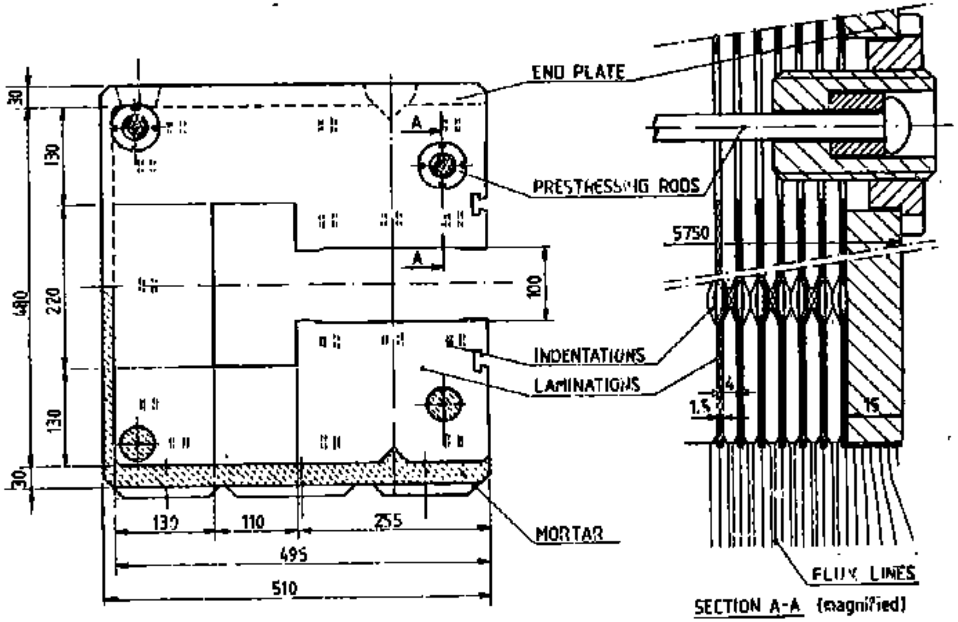
Field level

By filling all available arc space with magnets the required dipole field at an injection energy of 5 GeV is only about 60 Gauss !

Magnetic field quality & reproducibility at injection is an issue.

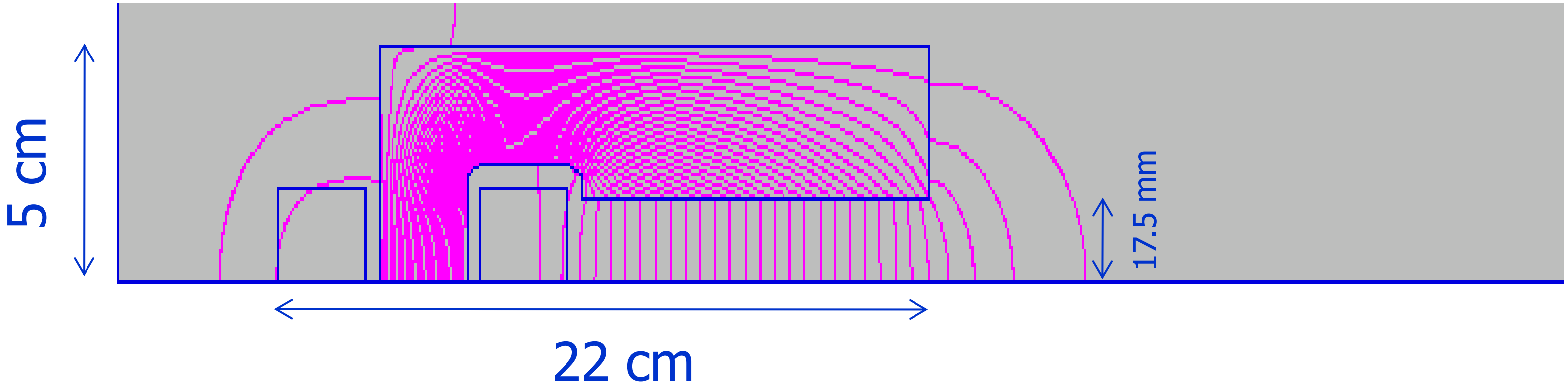
Low field bending : LEP

- Main bending magnets were made of "steel-concrete" cores
  - 5.75 m length, 100 mm vertical aperture
  - 6×2 cores per 79 m long regular FODO cell
- Peak magnetic field was very low (1100/215 G at 100/20 GeV).
  - To provide adequate field reproducibility at injection and limit the magnet weight, the magnet cores were manufactured as stacks of 1.5 mm thick low carbon steel laminations, spaced by 4 mm and embedded in a cement mortar.
- Each 5.75 m long core weighed 4.6 tonnes.



Guidelines for magnet work

- With respect to LEP dipoles we want:
  - smaller, lighter, lower injection field
- Directions to explore :
  - smaller magnet aperture (smaller, lighter)
  - shorter magnets (increase injection field)
  - materials-compounds-composites (ferrites, resin-diluted ferromagnetic powders, plastic of foams fillers …)
  - iron-less designs, possibly using iron to reclose the flux lines.



Pictured : ½ compact C-shaped dipole supplied by a single turn conductor I = 3750 A, B=1350 Gauss, Gap = 35 mm vertical

Living with weak magnets

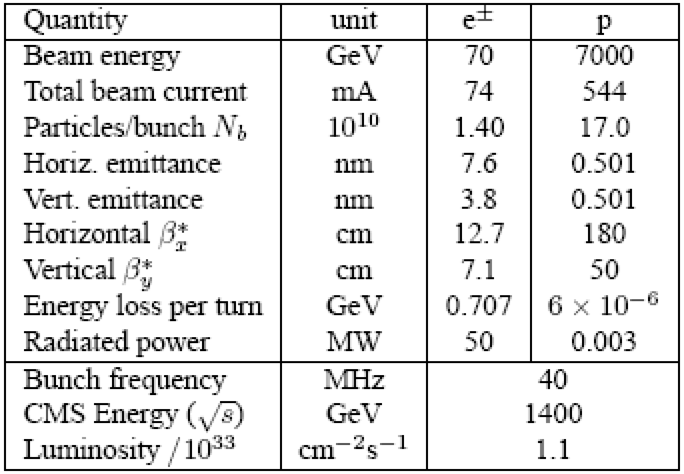
- High injection energy
  - Helps with this and many other things, but is expensive.
- Non-reproducible injection conditions ?
  - Study operational ways to do very fast first-turn steering, optics corrections and optimization for intensity on every fill?
  - Merge these into ramp, leading to reproducible conditions at collision energy where field is higher.
  - Unconventional, messy, but not obviously impossible.

Arc cell design

- Normal approach to electron ring design:
  - Fill all available arc space with the weakest possible dipoles (gives max energy for given RF power)
- Discussed on basis of analytical thin-lens theory in last year’s Divonne workshop
- My proposal then was to use a FODO cell with half the length of the LHC cell, favourable phase advances based on LEP experience, together with some variation of the damping partition numbers.
- We are now pushed, with great reluctance, to consider cells with shorter, stronger magnets.
- No reason to consider other than FODO cells.

Basis of FODO cell design (1)

- Design emittance taken from our EPAC 2008 paper, to be achieved at top energy.
- Damping partition, Robinson Theorem. Change RF frequency to vary J_x, extensively used in LEP, HERA.



Quantity	unit	e$^{\pm}$	p
Beam energy	GeV	70	7000
Total beam current	mA	74	544
Particles/bunch N_b	10^{10}	1.40	17.0
Horiz. emittance	nm	7.6	0.501
Vert. emittance	nm	3.8	0.501
Horizontal β_x^*	cm	12.7	180
Vertical β_y^*	cm	7.1	50
Energy loss per turn	GeV	0.707	6×10^{-6}
Radiated power	MW	50	0.003
Bunch frequency	MHz	40	
CMS Energy ($\sqrt{s}$)	GeV	1400	
Luminosity / 10^{33}	cm^{-2}s^{-1}	1.1	

See last year's talk for more details.

Note that thinner quads give more rapid damping partition change.

$$\varepsilon_x = \frac{55}{32\sqrt{3}} \frac{\hbar c}{m_e c^2}^{3} E_e^{\,2} \frac{I_5}{J_x I_2}$$

$$J_x + J_y + J_\varepsilon = 4, \qquad J_\varepsilon = 2 + 2\frac{I_8}{I_2}\,\delta_e, \quad J_y = 1$$

Synchrotron integrals are well known, except maybe

$$I_8 = \int K_1^{\,2} D_x^{\,2}\,ds \approx -\frac{81 L_{\mathrm{FODO}} \quad -9 + \cos\ \mu_{\mathrm{FODO}} \quad \csc\left[\frac{\mu_{\mathrm{FODO}}}{2}\right]^2}{200 L_Q} I_2$$

Match to proton beam size at IP at lower electron energy by detuning IR.

Basis of FODO cell design (2)

- Assume we can adjust betatron coupling to get vertical emittance, taking account of sum rule for quantum excitation

$$J_x \varepsilon_{xc} + J_y \varepsilon_{yc} = J_x \varepsilon_x$$

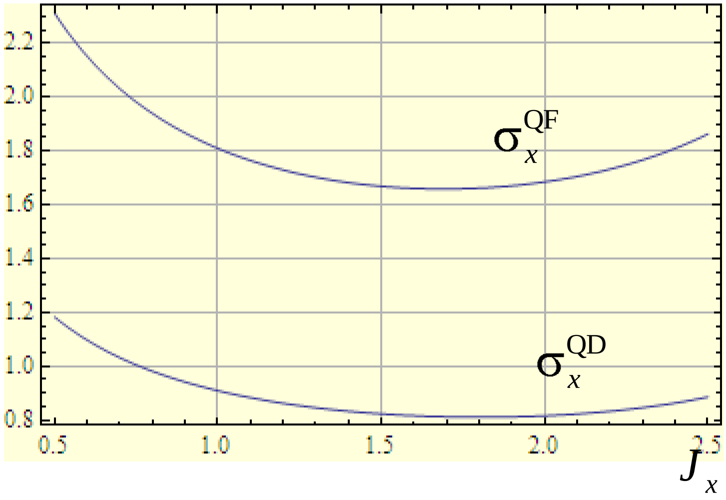
- Build parametrised thick-lens model of FODO cell with
  - Given bend angle per cell
  - Thick quadrupoles
  - Dipoles that only fill a fraction of available space, even after allowance for sextupoles, BPMs, pumps, etc.
  - Centres of dipoles can slide around in available space
  - Independent horizontal and vertical betatron phase
  - Compute many beam parameters, some linked to hadron beam
- Not treated at this level (just for lack of time)
  - Matching to IRs, bypasses, other straight sections
  - Sextupoles, chromaticity, non-linear behaviour but draw on LEP experience of many phase advances.
  - RF, longitudinal phase space

Basis of FODO cell design (3)

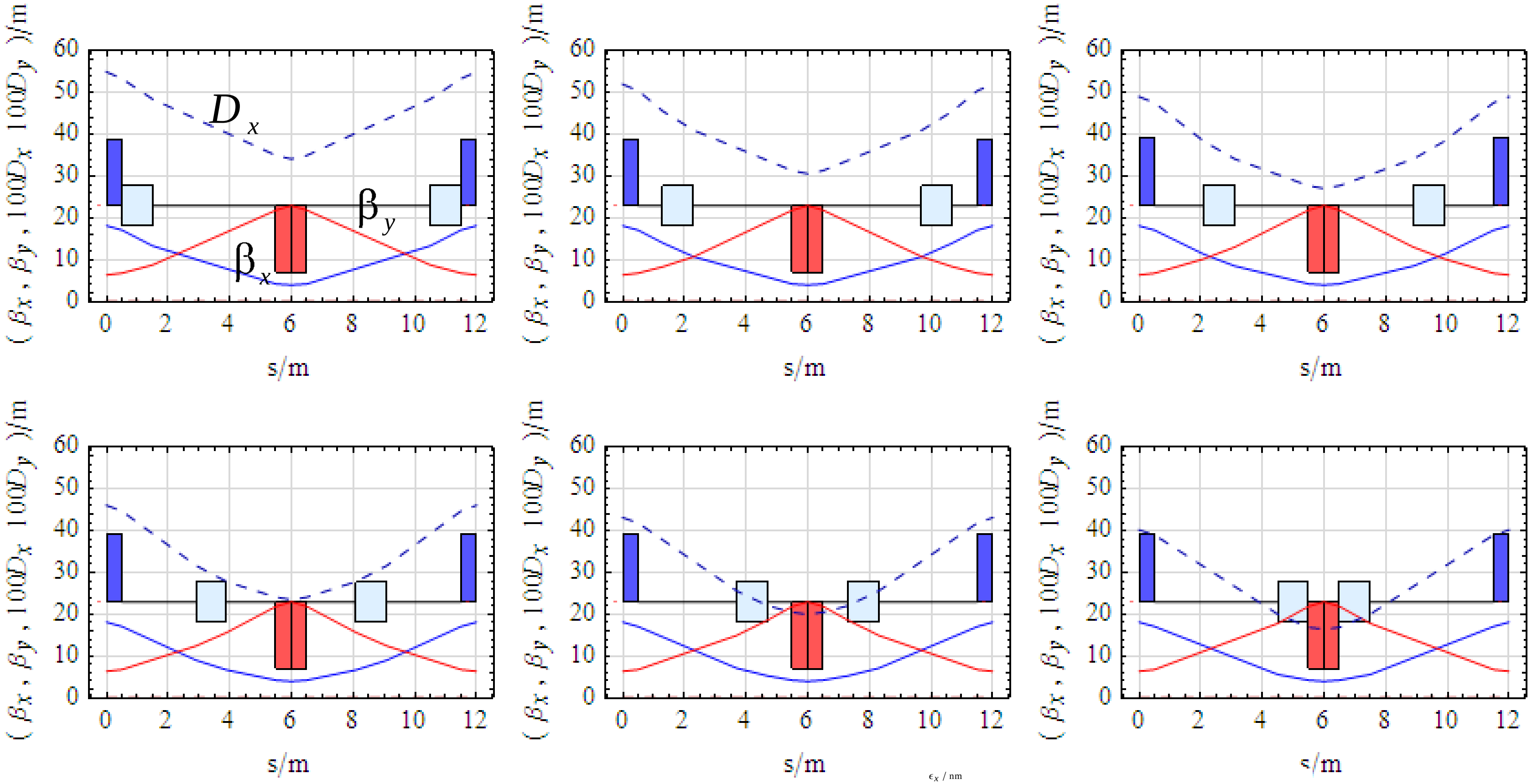
- To minimise horizontal aperture requirement, choose

$$J_x \approx 1.5$$

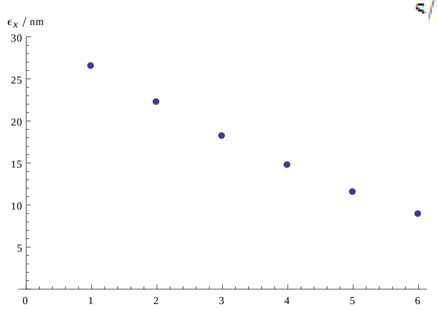
- Plot of horizontal beam size in QF and QD (in mm) in a LEP-like cell



Sliding dipoles around the cell



Modification of dispersion by putting dipoles near QDs gives > factor 2 in emittance



Revolution periods of LHeC beams

Revolution periods depend on fractional magnetic rigidity (momentum) deviations of each beam:

$$\delta = \frac{p - p_0}{p_0}$$

Electrons: $T_e(\delta_e) = \frac{C_e}{c}(1 + \alpha_e C_e)$

Hadrons: $T_p(\gamma_p, \delta_p) = \frac{C_p}{c} \frac{1}{\sqrt{1-\gamma_p^{-2}}} \left[1 + \left(\alpha_p - \frac{1}{\gamma_p^{2}} \right) \delta_p \right]$

where C_e, C_p are the circumferences of the central orbits passing on average through centres of quadrupoles.

Suppose there is some difference between circumferences:

$$\Delta C = C_e - C_p \approx \Delta C(\text{intended}) \pm 15\text{ mm}$$

Last year, we measured the error on the LHC circumference to be about -12 mm with respect to design.

Similar values were found at LEP.

Expect an error of this magnitude when we build electron ring.

Condition for stationary IP

If bunches are to collide at the same IP on every turn, RF systems of the two rings must be locked in an appropriate frequency ratio so that:

$$T_e(\delta_e) = T_p(\gamma_p, \delta_p)$$

which can be solved to give δ_p as a function of δ_p and ΔC, the other quantities in the equation being given by the chosen operating conditions.

Somewhat similar to injection and ramp considerations for p-A mode of LHC

It is easy to solve the equations exactly. For exposition, we expand the solution in an appropriate ordering scheme of small quantities $(\Delta C^{1/3}, \gamma_p^{-1/2}, \delta_p)$

$$\delta_e \approx \frac{\alpha_p}{\alpha_e}\delta_p - \frac{\Delta C}{\alpha_e C_p} + \frac{1}{2\alpha_e \gamma_p^2}$$

Thus, the damping partition and emittance become functions of $\delta_p, \Delta C, \gamma_p$.

Limits on hadron beam momentum

- At HERA, electron beam momentum was deliberately varied and caused proton beam to move by some mm in the arcs.
- At LHC, we are *much* more restricted for machine protection reasons *and* because the tune is larger

With normal beam intensities:

$$-0.0005 < \delta_p < 0.0005 \quad \text{(gives 1 mm orbit shift in arc QFs)}$$

With very low intensity pilot beams:

$$-0.003 < \delta_p < 0.003 \quad \text{(gives 6 mm orbit shift in arc QFs)}$$

$$\alpha_e \sim \frac{1}{Q_x^{\,2}}$$

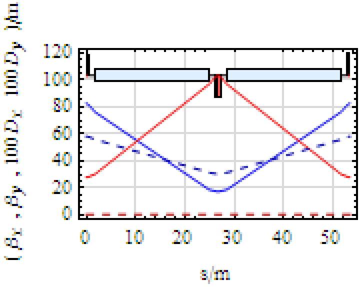
Constraint probably *not* relaxed with experience.

- Together with the revolution period constraint, this fixes the range of damping partition and emittance accessible with a given optics.

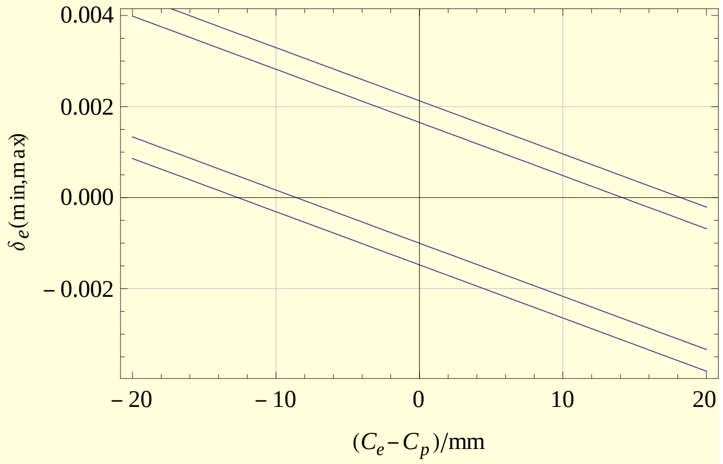
Weak bend solution (1)

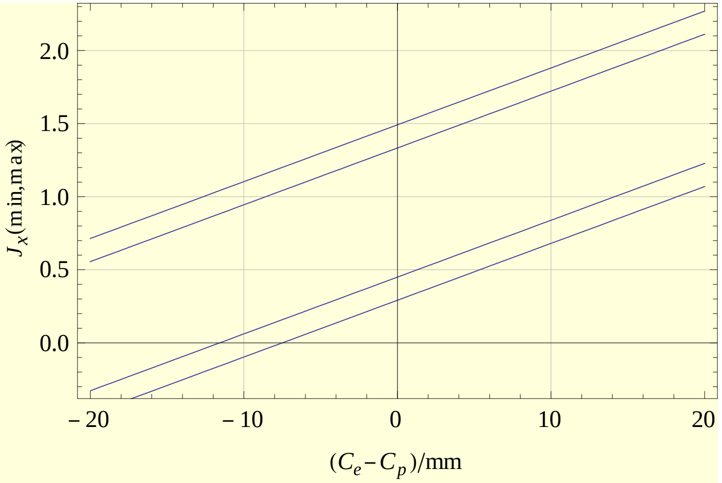
- This is similar to the solution proposed in last year's talk on the basis of thin-lens analytical theory.
- Cell length is half of LHC's – only way to get the emittance.
- Consider the limits on emittance for electrons constrained by collisions with both protons and $^{208}Pb^{82+}$ nuclei (deuterons are in-between).
- This solution gives the maximum energy for given RF power but has problems of very weak fields at injection discussed earlier.

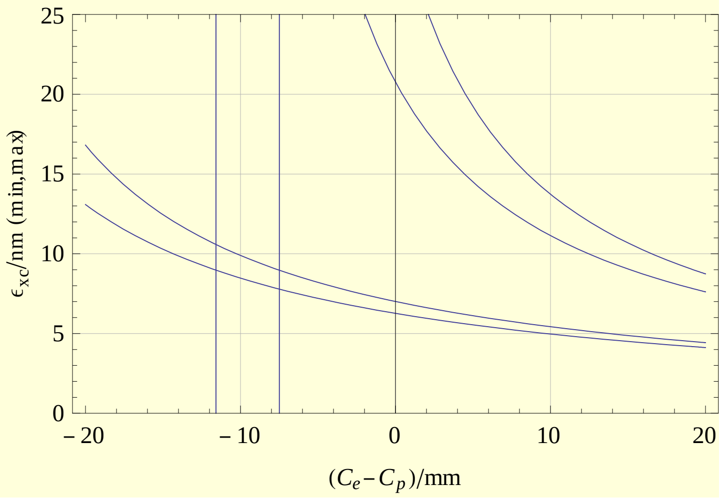
Weak bend solution (2)

OpticsPlot		OpticsFile	FODO-2009-09-02-04-06-12.tfs	
MADfile	FODO-2009-09-02-04-06-12.madx	MADTerminalOutput	FODO-2009-09-02-04-06-12.mou	
LFODO	53.4515 Meter	phiFODO	0.0170739	
fB	0.9	gB	0.5	
mux	90 °	muy	60 °	
Ncell	368.	Lcells	19 670.1 Meter	
KQF	0.0513543	KQD	-0.0419588	
Lbend	23.1532 Meter	Lquad	1. Meter	
Brho	233.495 Meter Tesla	ρBend	2712.12 Meter	
Bbend	0.0860933 Tesla	dBdxQF	$\frac{11.991\ \text{Tesla}}{\text{Meter}}$	
dBdxQD	$-\frac{9.79716\ \text{Tesla}}{\text{Meter}}$	betxQF	82.5598 Meter	
DxQF	0.581358 Meter	betyQF	27.7087 Meter	
betxQD	17.2616 Meter	DxQD	0.302629 Meter	
betyQD	103.345 Meter	I1	0.00743455 Meter	
I2	$\frac{6.29541\times10^{-6}}{\text{Meter}}$	I3	$\frac{2.32121\times10^{-9}}{\text{Meter}^2}$	
I5	$\frac{1.0909\times10^{-11}}{\text{Meter}}$	I8	$\frac{0.00104772}{\text{Meter}}$	
alphac	0.000102627	deltas	-0.00150216	
deltaep	$-0.0014772 - \frac{0.116796\ \delta C}{\text{Meter}}$		$0.00165227 - \frac{0.116796\ \delta C}{\text{Meter}}$	EGeV	70.
kappa	0.5	Je	1.5	
Jx	1.5	Jy	1	
Jep	332.854	U0	783.15 ElectronVolt Mega	
taux	0.0105977 Second	tauy	0.0158966 Second	
taue	0.0105977 Second	Ex	8.30703 Meter Nano	
Exc	6.23027 Meter Nano	Eyc	3.11514 Meter Nano	
sigE	0.0013295	sigxQF	0.0010544 Meter	
sigxQD	0.000519062 Meter	sigyQF	$0.000293797\sqrt{\text{Meter}^2}$	

Weak bend solution (3)







Limited range of Jx variation, shifts down for Pb ions.

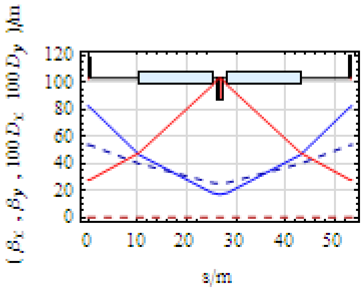
To get design emittance, need ~ 15 mm circumference difference.

How do we arrange that ?

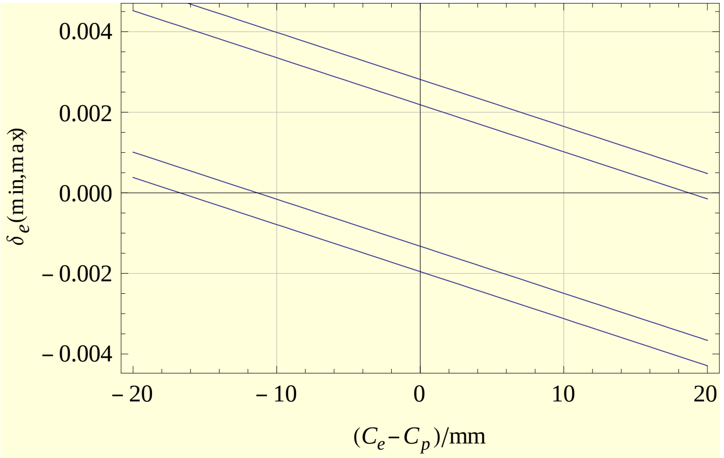
Medium strength bends (1)

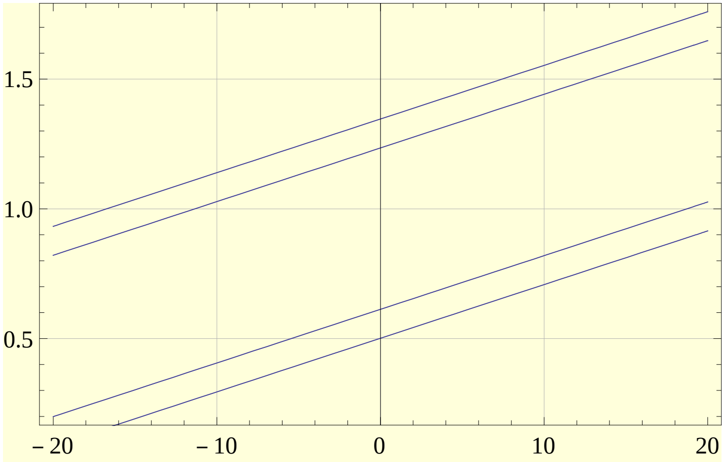
- Field of 0.135 T at 70 GeV.
  - Basis of preliminary specification we sent to colleagues at BINP.
- Use empty spaces for synchrotron radiation absorbers decoupled from magnets ?
  - Power distribution and feasibility to be studied

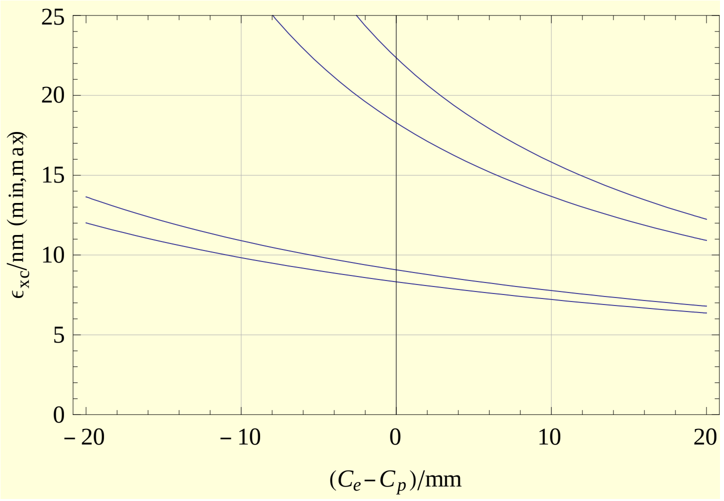
Medium strength bends (2)

OpticsPlot		OpticsFile	FODO-2009-09-02-01-10-35.tfs	
MADfile	FODO-2009-09-02-01-10-35.madx	MADTerminalOutput	FODO-2009-09-02-01-10-35.mou	
LFODO	53.4515 Meter	phiFODO	0.0170739	
fB	0.573955	gB	0.9	
mux	90 °	muy	60 °	
Ncell	368.	Lcells	19 670.1 Meter	
KQF	0.0513539	KQD	-0.0419586	
Lbend	14.7654 Meter	Lquad	1. Meter	
Brho	233.495 Meter Tesla	ρBend	1729.59 Meter	
Bbend	0.135 Tesla	dBdxQF	$\frac{11.9909\ \text{Tesla}}{\text{Meter}}$	
dBdxQD	$-\frac{9.79713\ \text{Tesla}}{\text{Meter}}$	betxQF	82.5562 Meter	
DxQF	0.539359 Meter	betyQF	27.7088 Meter	
betxQD	17.262 Meter	DxQD	0.251433 Meter	
betyQD	103.345 Meter	I1	0.00561837 Meter	
I2	$\frac{9.87162\times10^{-6}}{\text{Meter}}$	I3	$\frac{5.70748\times10^{-9}}{\text{Meter}^2}$	
I5	$\frac{2.05071\times10^{-11}}{\text{Meter}}$	I8	$\frac{0.000874169}{\text{Meter}}$	
alphac	0.0000775562	deltas	-0.00282314	
deltaep	$-0.00195472-\frac{0.116796\ \delta C}{\text{Meter}}$	$0.00218638-\frac{0.116796\ \delta C}{\text{Meter}}$	EGeV	70
kappa	0.5	Je	1.5	
Jx	1.5	Jy	1	
Jep	177.108	U0	1228.03 ElectronVolt Mega	
taux	0.00675847 Second	tauy	0.0101377 Second	
taue	0.00675847 Second	Ex	9.95865 Meter Nano	
Exc	7.46899 Meter Nano	Eyc	3.73449 Meter Nano	
sigE	0.00166483	sigxQF	0.00119286 Meter	
sigxQD	0.000551497 Meter	sigyQF	$0.000321681\sqrt{\text{Meter}^2}$	

Medium strength bends (3)







Limited range of Jx variation, shifts down for Pb ions.

To get design emittance, need ~ 25 mm circumference difference.

How do we arrange that ?

~ 12% loss in max energy w.r.t. weak bend solution

Fixing the e-ring circumference ?

Other machines have considered path-length chicanes.

Looks very difficult for LHeC – shift whole e-ring by ~ 4 mm radially!

Incorporate something variable in by-pass schemes ?

We categorically deny that there was an unsuccessful attempt to implement a path-length chicane in the LHC last year.

Summary

- We have considered normal (weak) and stronger dipole magnets for e-ring arcs despite loss of energy reach.
- Solutions given for weak and medium strength bends (stronger seems unacceptable).
  - Half-apertures ~(40 mm, 15 mm)
- Coupling to hadron ring puts severe constraints on e-ring circumference.
  - Circumference errors may shift the accessible range of emittances
  - Earth tides ?
  - Use of damping partition limited
  - Strong interest in making shorter, stronger quadrupoles also – more magnet studies.

Backup slides