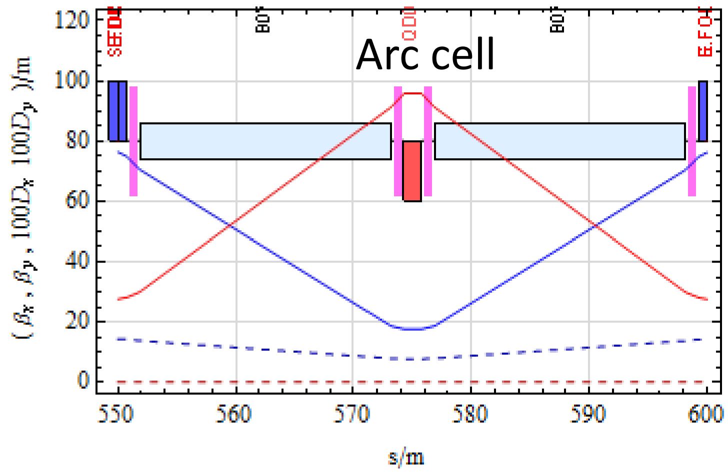
Polarization Wigglers for TLEP and Lessons from LEP

John Jowett

A quick look at some aspects of the TLEP optics and the wigglers that have also been considered by others (A. Blondel, …).

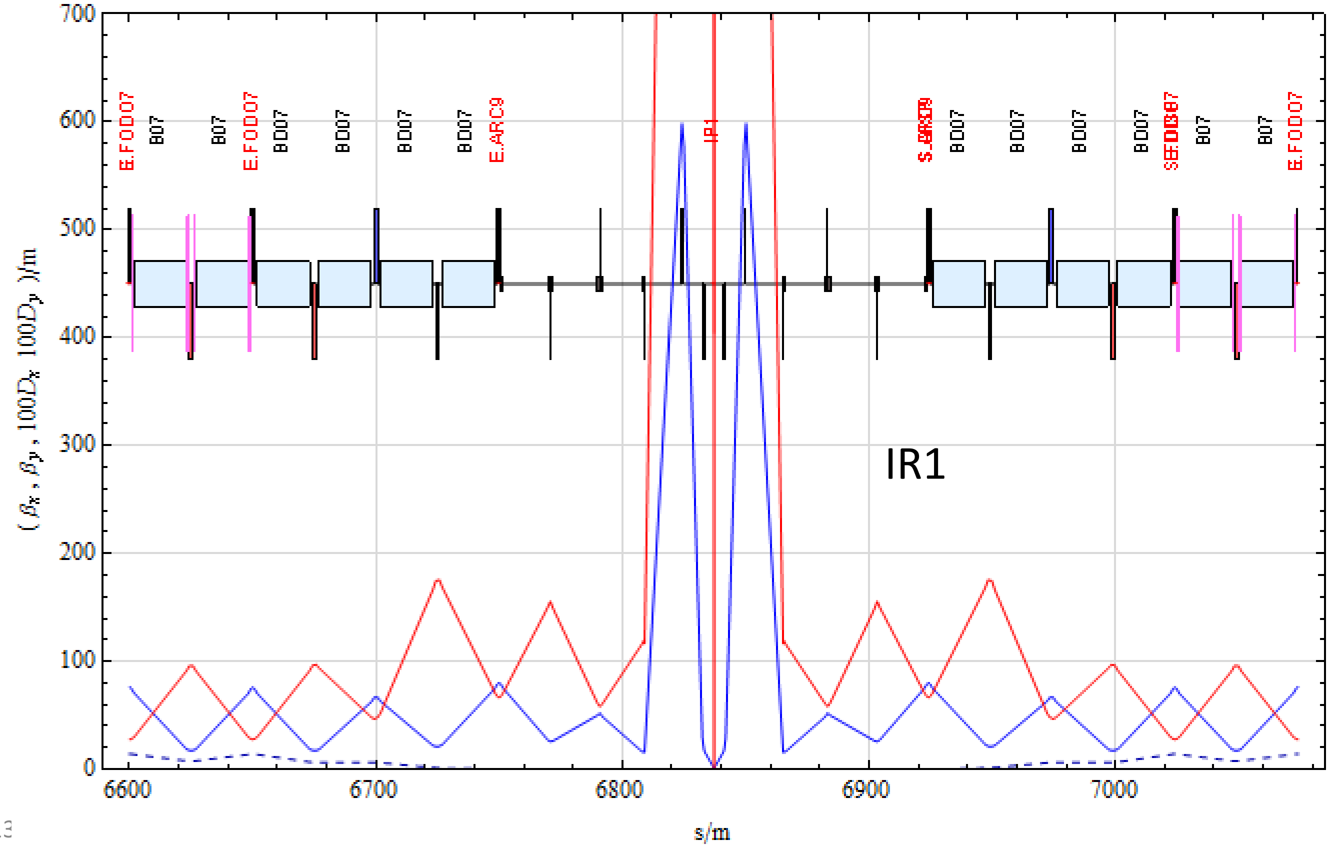
Apologies that I did no work on TLEP until yesterday.

TLEP optics



- TLEP optics (80 km) from Bernhard Holzer used in following

At first I thought the quadrupoles were too short for good damping aperture.

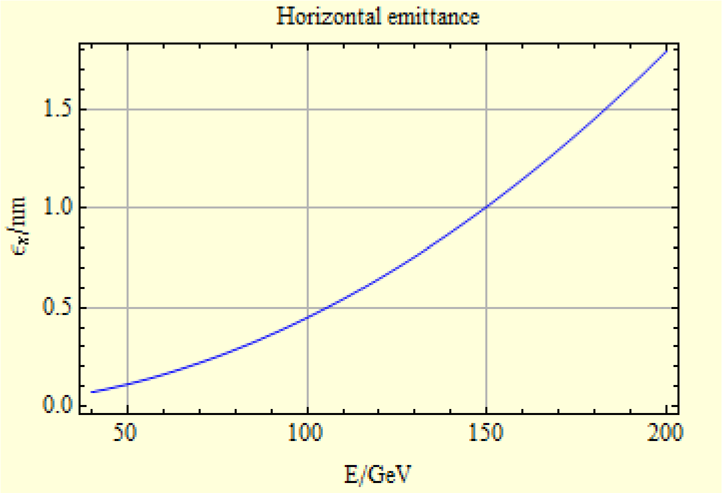


TLEP parameter lists and emittance

Table 1: TLEP parameters at different energies

	TLEP Z	TLEP W	TLEP H	TLEP t
E_{beam} [GeV]	45	80	120	175
circumf. [km]	80	80	80	80
beam current [mA]	1180	124	24.3	5.4
#bunches/beam	4400	600	80	12
#e−/beam [10^{12}]	1960	200	40.8	9.0
horiz. emit. [nm]	30.8	9.4	9.4	10
vert. emit. [nm]	0.07	0.02	0.02	0.01
bending rad. [km]	9.0	9.0	9.0	9.0
κ_ε	440	470	470	1000
mom. c. α_c [10^{-5}]	9.0	2.0	1.0	1.0
$P_{loss,SR}$/beam [MW]	50	50	50	50
β^*_x [m]	0.5	0.5	0.5	1
β^*_y [cm]	0.1	0.1	0.1	0.1
σ^*_x [μm]	124	78	68	100
σ^*_y [μm]	0.27	0.14	0.14	0.10
hourglass F_{hg}	0.71	0.75	0.75	0.65
E^{SR}_{loss}/turn [GeV]	0.04	0.4	2.0	9.2
$V_{RF,tot}$ [GV]	2	2	6	12
$\delta_{max,RF}$ [%]	4.0	5.5	9.4	4.9
ξ_x/IP	0.07	0.10	0.10	0.10
ξ_y/IP	0.07	0.10	0.10	0.10
f_s [kHz]	1.29	0.45	0.44	0.43
E_{acc} [MV/m]	3	3	10	20
eff. RF length [m]	600	600	600	600
f_{RF} [MHz]	700	700	700	700
δ^{SR}_{rms} [%]	0.06	0.10	0.15	0.22
$\sigma^{SR}_{z,rms}$ [cm]	0.19	0.22	0.17	0.25
$\mathcal{L}$/IP[10^{32}cm^{-2}s^{-1}]	5600	1600	480	130
number of IPs	4	4	4	4
beam lifet. [min]	67	25	16	20

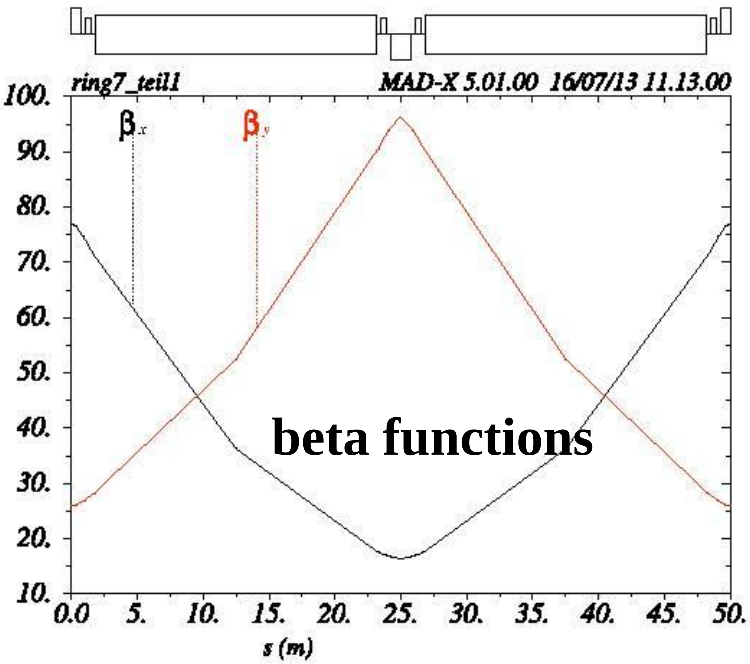
Natural emittance of TLEP lattice

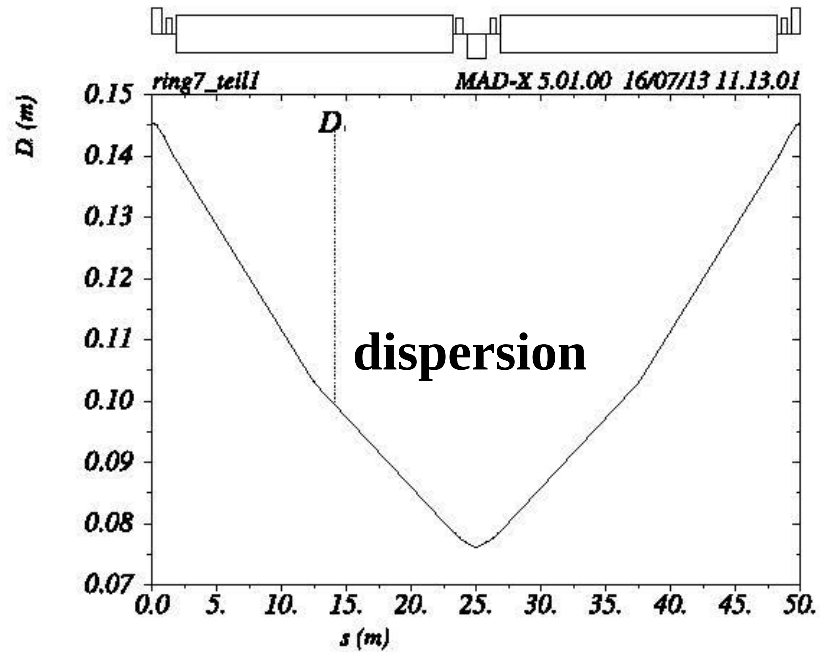


Must to do something to create much larger emittance at lower energies.

optics – TLEP arc cell

Y. Cai,
B. Holzer,
H. Burkhardt





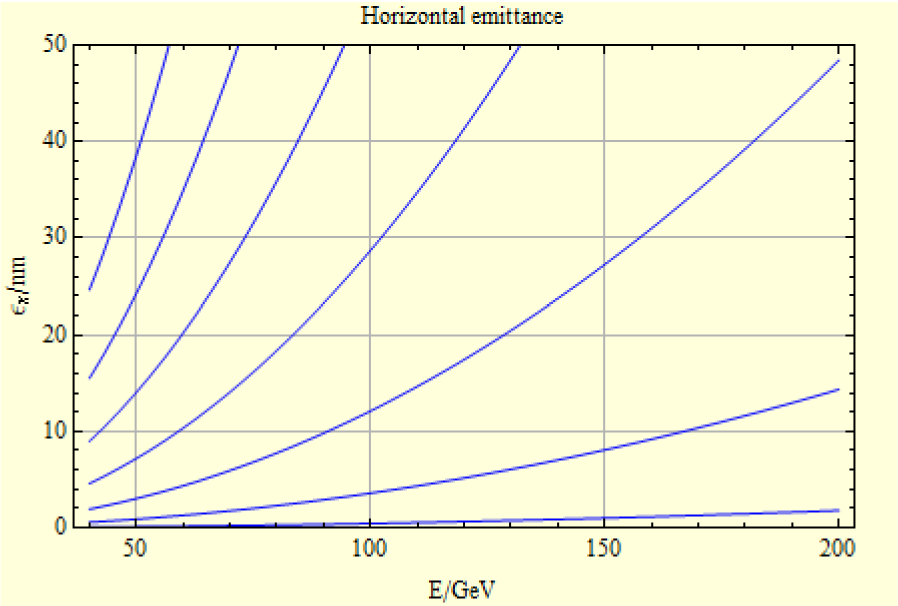
from LEP **to TLEP**

ρ=3100 m, L_{cell}=79 m **ρ=9100 m, L_{cell}=50 m**

ε_x=48 nm at 104.5 GeV → ε_x=1.5 nm at 175 GeV

$\varepsilon \propto \gamma^2 \theta^3$: **at lower beam energy increase cell length (“θ”) x2 or x6!**

Emittance control at lower energies



This will give β>500 m in arc cells 300 m long.

What are the aperture requirements?

Can the dispersion still be matched with the same dispersion suppressors? Of course one can also play with Jx and reduce the phase advance but this is a big factor.

Stop Press: since Bernhard's talk, I evaluated the vertical emittance from the opening angle of synchrotron radiation: 1.5 am

Damping aperture

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

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

Synchrotron integrals are well known, except maybe

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

Damping aperture limit is reached when either J_x or J_ε becomes zero.

In TLEP lattice $J_\varepsilon' = 2\frac{I_8}{I_2} = 219 \Rightarrow$ damping aperture 1.3% in δ_e.

With $6\times$ longer cells, this will be reduced to $\approx 0.2\%$ in $\delta_e \Rightarrow$ possible concern?

May be very difficult to find an initial damped closed orbit.

Solution may be to lengthen quadrupoles and or
reduce betatron phase advance.

History of the wigglers in LEP

- In 1983 we proposed an installation of 16 asymmetric wigglers in LEP to control emittance (luminosity at beam-beam limit), increase radiation damping and enhance the Sokolov-Ternov polarization rate.
- At the time, polarization was considered a chimera *(plus ça change …)* and money was scarce, so we got only 8 wigglers, enough to serve the first two purposes reasonably well.
- There were then 2 families of wigglers in the LEP design:
  - The 4 Emittance Wigglers, located in missing-dipole space in the dispersion suppressors where $D_x>0$.
  - The 4 Damping Wigglers, located in matching sections where $D_x=0$.

LEP Emittance and Damping Wigglers

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WIGGLERS FOR CONTROL OF BEAM CHARACTERISTICS IN LEP

J.M. Jowett and T.M. Taylor
LEP Division
CERN

http://accelconf.web.cern.ch/AccelConf/p83/PDF/PAC1983_2581.PDF

Well-thought out integral magnet design

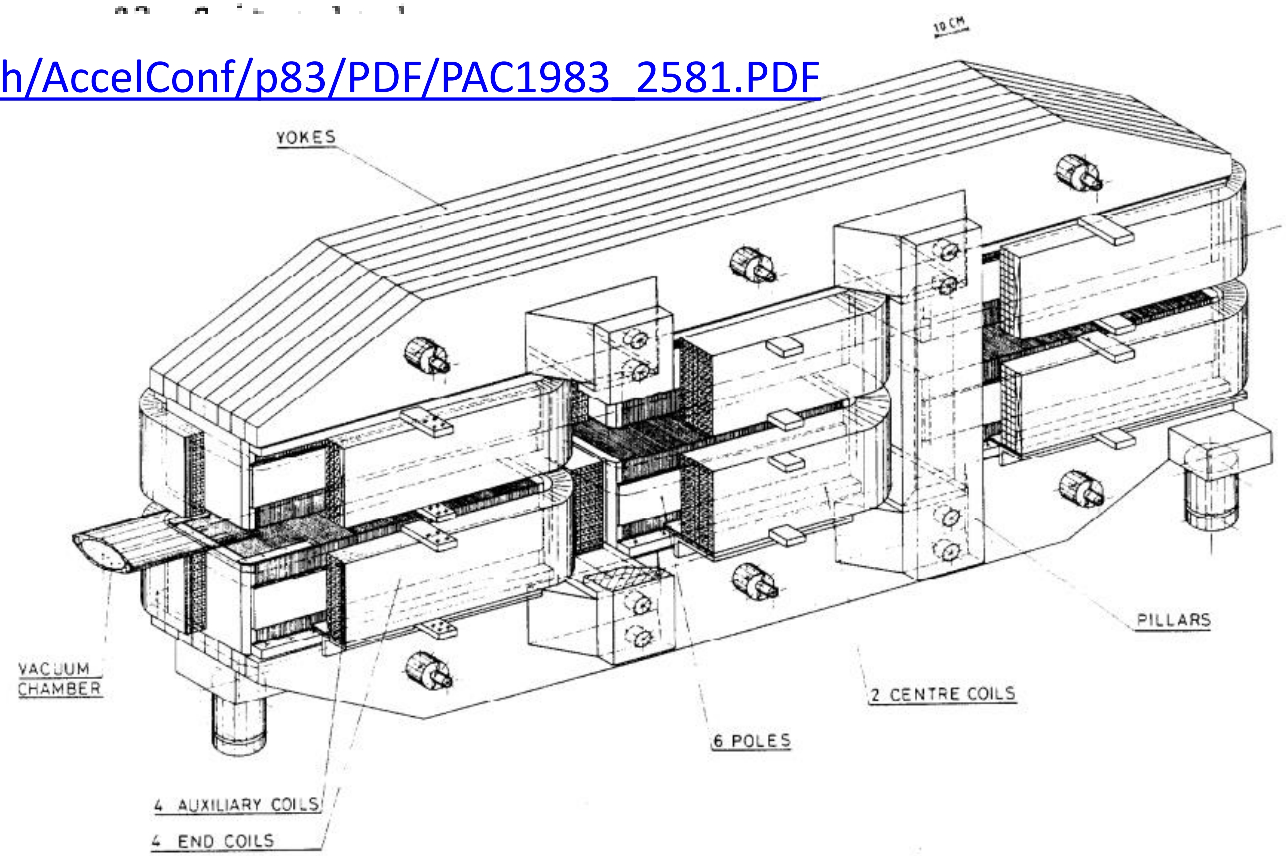


Fig. 3 Proposed LEP wiggler magnet

Ideal polarization performance of LEP E- and D-wigglers

We nevertheless managed to include a moderate asymmetry parameter (2.5) so that the polarization would have a chance.

We did all this shortly before the Z-boson, the particle of the moment, was discovered at a relatively low mass *(plus ça change …)* and when there was little quantitative information on depolarization effects.

This plot shows the wiggler field necessary to keep emittance constant.

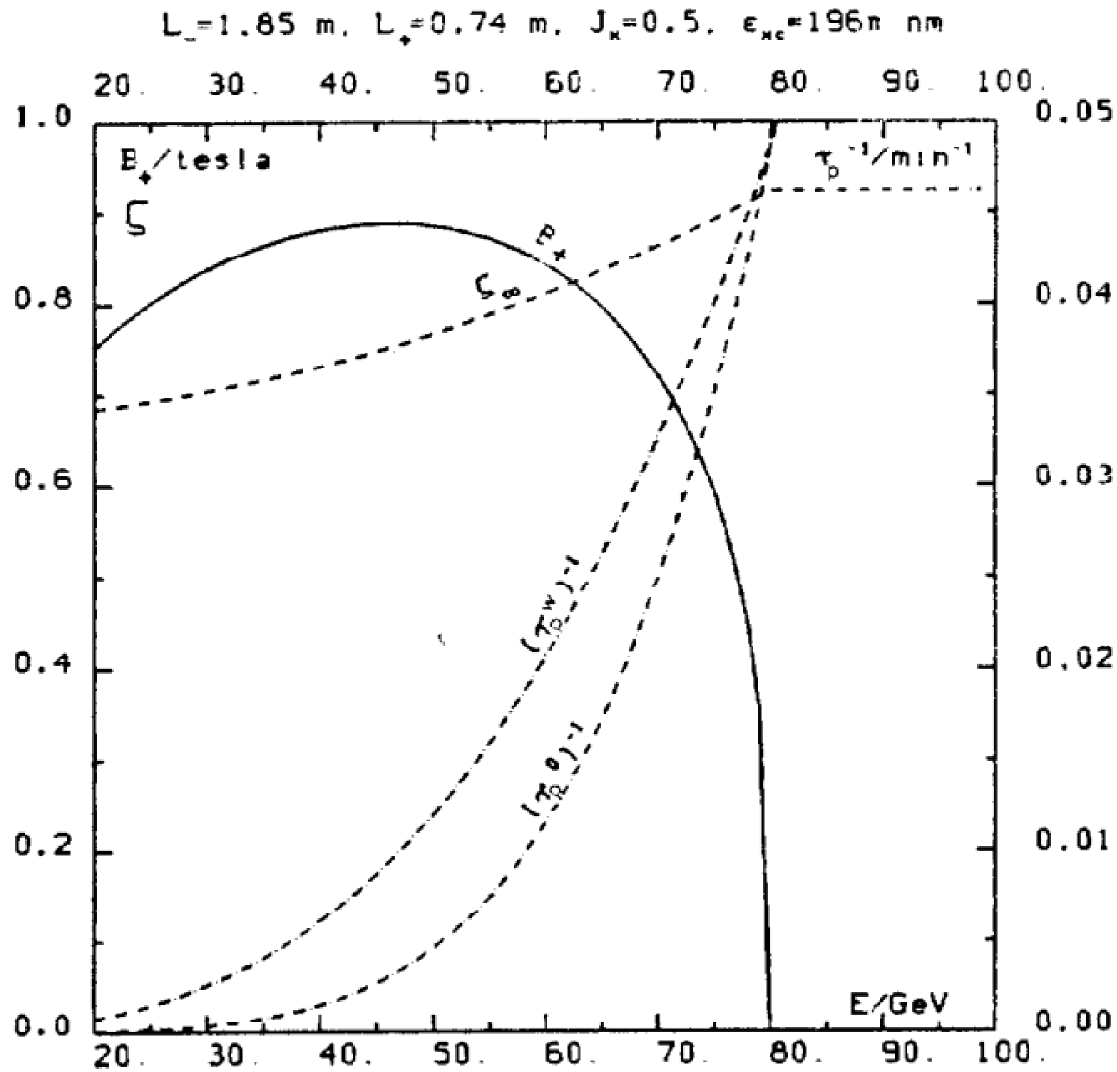


Fig. 2 Typical curves of required wiggler excitation and corresponding polarization

Wiggler compensation

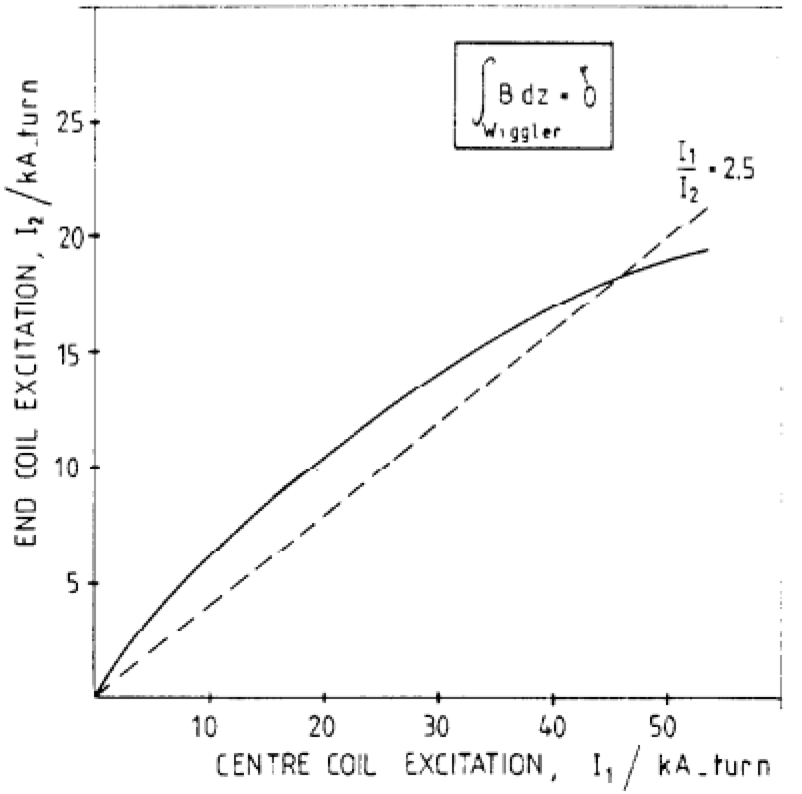


Fig. 5 End coil vs. centre coil excitation for no net effect on the closed orbit.

Integral magnet design,
Field integral well cancelled by built-in trims.

Wigglers excitations were the only non-linear knobs in LEP.
Wiggler field was accompanied by approximately quadratic shifts in nearby quadrupole strengths designed to match out tune changes from weak-focusing in wiggler dipoles. Worked perfectly from theory.

- By 1988, the prospect of longitudinally polarized e+e- collisions at the Z-pole was taken seriously thanks, in particular, to the advocacy of Alain Blondel *(plus ça change …)* who stressed the need for faster polarization.
- Hence more, stronger wigglers …

LEP Note 606

http://cds.cern.ch/record/442913

DEDICATED WIGGLERS FOR POLARIZATION

A. Blondel and J.M. Jowett

3 May 1988

Summary

We propose that LEP should be equipped with additional wigglers, dedicated to improving the beam polarization. The main arguments for them are as follows:

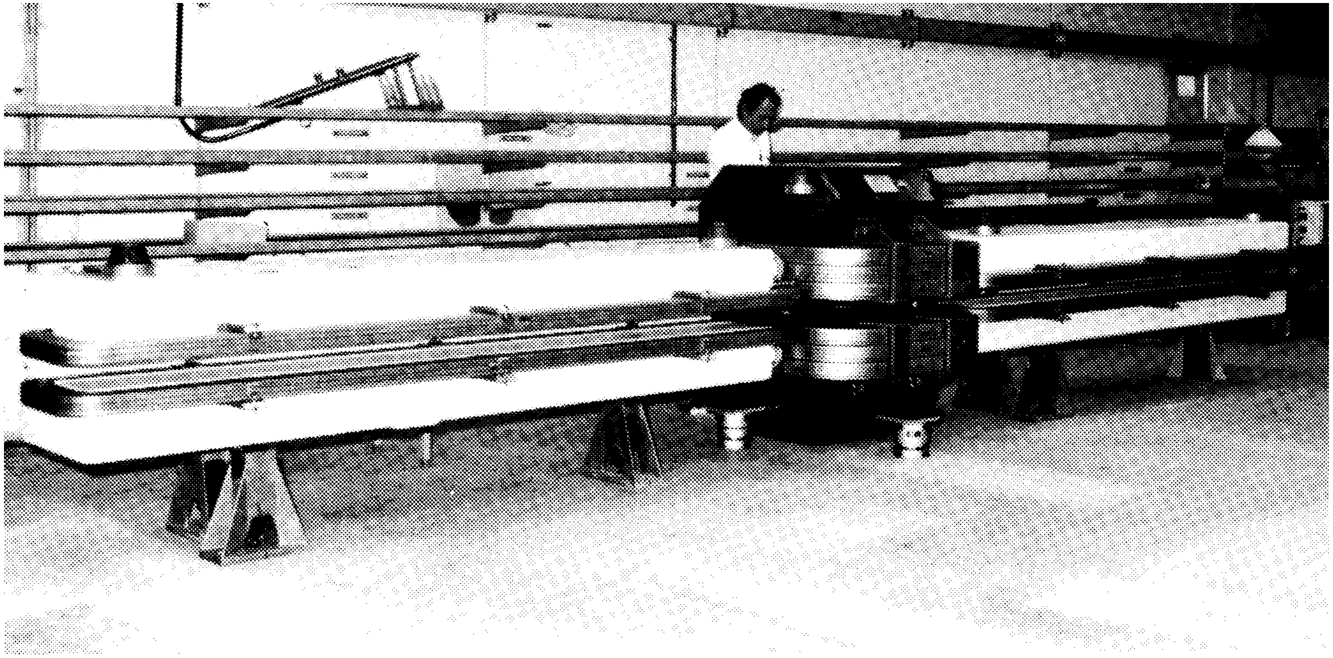
- The new wigglers can be made much more "asymmetric" than the existing ones, leading to an ideal asymptotic polarization degree of 88 % instead of 74 % at the Z energy.
- With additional wigglers installed in low-β straight sections, the polarization time can be reduced to 36 minutes, still respecting aperture constraints. This makes empirical correction of depolarizing effects feasible in a reasonable time and improves the effective polarization degree during a physics run.
- Since the dispersion is nominally zero in low-β straight sections, these wigglers reduce the depolarizing effects of horizontal betatron oscillations.
- These powerful wigglers dominate the rest of the machine as far as *both polarizing* and *depolarizing* effects are concerned, bringing substantial simplification to their analysis and correction. Beneficial effects on the asymptotic polarization degree have been found in *first*-order simulations.
- Although neither theory nor simulation have yet given us definitive estimates of the higher-order effects related to the beam energy spread, powerful wigglers give us flexibility in studying these effects.

The proposed iron-cored dipole wigglers would consist of 0.65 m long central sections between two weak sections, each 2 m long. Twelve such units, installed around P3 and P7 would cost approximately SFR 2 M, including cabling and power converters.

Concept for Polarization Wigglers in LEP

Innovative (=cheap, quick) magnet design. Left-over LEP concrete dipoles were sawn in half to make the weak outer poles.
Separate short dipole for strong centre pole.

Operationally very troublesome orbit effects despite special trim coils.
Large energy spread and betatron tune spread.



The Polarization Wigglers in LEP

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EPAC 1992

http://accelconf.web.cern.ch/AccelConf/e92/PDF/EPAC1992_0649.PDF

Parameters, vacuum effects

Centre magnet peak field	1.359	Tesla
End magnet peak field	0.168	Tesla
$\int B_y \, ds$ in centre magnet	1.016	Tm
$\int B_y^2 \, ds$ in centre magnet	1.237	T^2m
$\int B_y^3 \, ds$ in centre magnet	1.600	T^3m
Effective length ratio L-/L+ (B)	8.01	
Centre pole length	0.62	m
End pole length	2.88	m
Centre-end pole separation	0.37	m
Closed orbit displacement (20 GeV)	14	mm
Pole gap height in centre magnets	94	mm
Pole gap height in end magnet	100	mm
Total length of wiggler	7.25	m
Total power per wiggler	42	kW
Nominal main coil current	500	A
Maximum current in trim coils	±55	A
Mass of central magnet	4.9	t
Mass of one end magnet	2.5	t

Table 1: Parameter list for polarization wiggler magnets

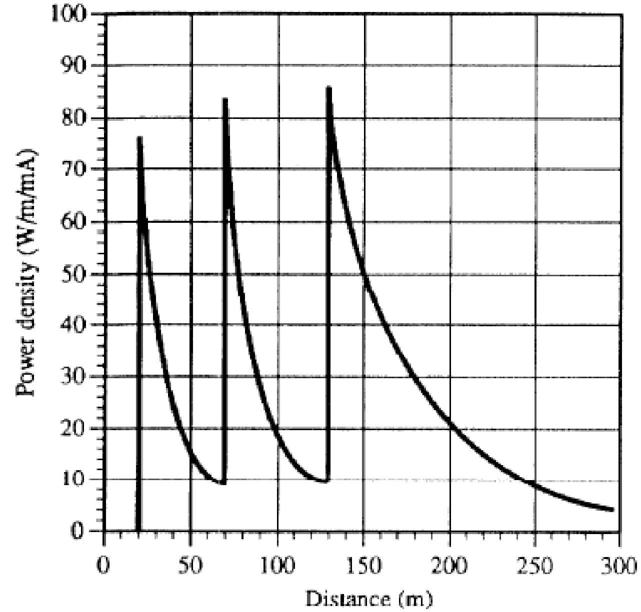
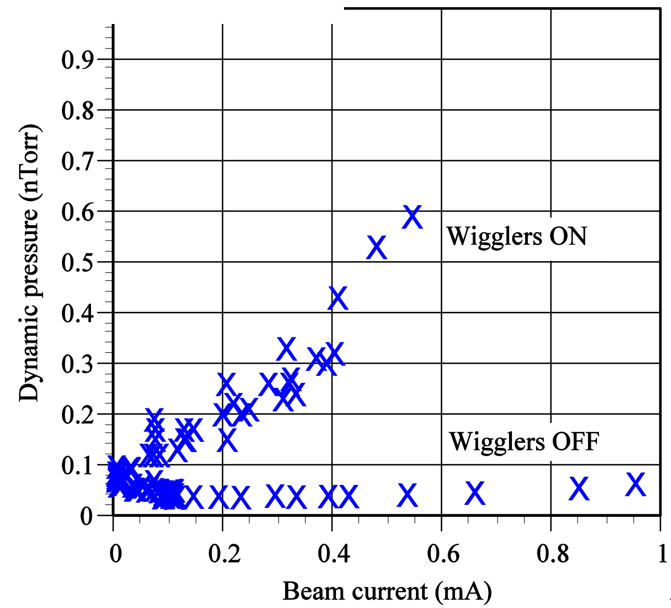


Figure 3: Power density (W/m/mA) along one side of the vacuum chamber downstream of a set of 3 wigglers, calculated for one beam of 47 GeV, 1mA beam current and 1.3T central field.

Had to remove collimators away from wigglers.
Later, the radiation from these wigglers caused significant damage to vacuum chambers.



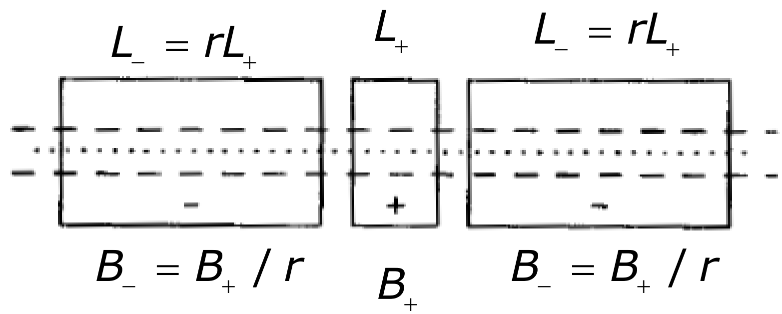
Benefits of the Polarization Wigglers in LEP

- As polarization levels were relatively low (but enough for energy calibration), the effective growth time of transverse polarization was acceptable and wigglers were *not* needed at 46 GeV.
- Bunch-lengthening and enhanced damping at injection mitigated the Transverse Mode-Coupling Instability (TMCI), allowed record single-bunch currents, raising luminosity for LEP2.
- Spin-rotators were never installed … if you ever want them, make sure they are NOT AN AFTERTHOUGHT, but worked into the basic design of the interaction regions.

Wigglers and radiation integrals

$$G(s) = \frac{eB_y(s)}{p_0 c},$$

$$\mathcal{H} = \frac{\eta_x^2 + \left(\beta_x \eta_x' - \frac{1}{2}\beta_x' \eta_x\right)}{\beta_x}.$$



Each of these integrals includes a contribution from the wigglers. Making the approximation that, apart from some asymmetric wigglers with $r = B_+/B_- = L_-/L_+ > 1$, the storage ring has an isomagnetic bending strength, $G_0 = 1/\rho_0$ we may evaluate these as

$$I_2 \simeq 2\pi G_0 + N_{\rm W}|G_+|^2 L_+ \left(1 + \frac{1}{r}\right), \tag{2.7}$$

$$I_3 \simeq 2\pi G_0^2 + N_{\rm W}|G_+|^3 L_+ \left(1 + \frac{1}{r^2}\right), \tag{2.8}$$

$$I_{3a} \simeq 2\pi G_0^2 + N_{\rm W}|G_+|^3 L_+ \left(1 - \frac{1}{r^2}\right), \tag{2.9}$$

$$I_5 \simeq 2\pi \langle\mathcal{H}\rangle_{\rm B} G_0^2 + N_{\rm W}|G_+|^3 L_+ \langle\mathcal{H}\rangle_{\rm W} \left(1 + \frac{1}{r^2}\right). \tag{2.10}$$

Emittance, energy spread

At low intensity, the uncoupled horizontal emittance of a storage ring is given by the familiar formula

$$\epsilon_x = \frac{55}{32\sqrt{3}}\frac{\hbar}{m_e c}\left(\frac{E_0}{m_e c^2}\right)^2 \frac{1}{J_x}\frac{I_5}{I_2},$$

$$\simeq \frac{55}{32\sqrt{3}}\frac{\hbar}{m_e c}\left(\frac{E_0}{m_e c^2}\right)^2 \left(\frac{1}{J_x}\right)\frac{2\pi\langle\mathcal{H}\rangle_B G_0^2 + N_W|G_+|^3 L_+\langle\mathcal{H}\rangle_W\left(1+\frac{1}{r^2}\right)}{2\pi G_0 + N_W|G_+|^2 L_+\left(1+\frac{1}{r}\right)}, \quad (2.11)$$

The r.m.s. energy spread σ_ϵ is given by what starts off looking like a very similar formula:

$$\sigma_\epsilon^2 = \frac{55}{32\sqrt{3}}\frac{\hbar}{m_e c}\left(\frac{E_0}{m_e c^2}\right)^2 \left(\frac{1}{3-J_x}\right)\frac{I_3}{I_2} \quad (2.14)$$

$$= \frac{55}{32\sqrt{3}}\frac{\hbar}{m_e c}\left(\frac{E_0}{m_e c^2}\right)^2 \left(\frac{1}{3-J_x}\right)\frac{2\pi G_0^2 + N_W L_+|G_+|^3\left(1+\frac{1}{r^2}\right)}{2\pi G_0 + N_W L_+|G_+|^2\left(1+\frac{1}{r}\right)}. \quad (2.15)$$

A quantity very closely related to the energy spread is the Sokolov-Ternov polarization rate:

$$\alpha_p = \frac{1}{\tau_p} = \frac{5\sqrt{3}}{8}\frac{\hbar r_e}{m_e c}\left(\frac{E}{m_e c^2}\right)^5 f_0 I_3 \quad (2.18)$$

$$= \frac{5\sqrt{3}}{8}\frac{\hbar r_e}{m_e c}\left(\frac{E}{m_e c^2}\right)^5 f_0\left[2\pi G_0^2 + N_W|G_+|^3 L_+\left(1+\frac{1}{r^2}\right)\right]. \quad (2.19)$$

Faster polarization increases energy spread

2.3 Polarization rate *vs.* energy spread

From (2.16) and (2.20), we can derive a relationship giving the *price paid in increased energy spread* for a given increase in the polarization rate:

$$\frac{\mathcal{F}\{\alpha_p\}}{\mathcal{F}\{\sigma_\epsilon\}^2} = 1 + \left(\frac{N_W L_+ G_0}{2\pi}\right)^{1/3} \frac{\left(1+\frac{1}{r}\right)}{\left(1+\frac{1}{r^2}\right)^{2/3}} \left(\mathcal{F}\{\alpha_p\} - 1\right)^{2/3}. \qquad (2.25)$$

Given that the wigglers occupy only a small fraction of the circumference of LEP, we may roughly estimate the increase in energy spread with

$$\mathcal{F}\{\sigma_\epsilon\} \simeq \sqrt{\mathcal{F}\{\alpha_p\}} - \left(\frac{N_W L_+}{16\pi\rho_0}\right)^{1/3} \left(1+\frac{1}{r}\right) \left(\mathcal{F}\{\alpha_p\}\right)^{1/6} \left(\mathcal{F}\{\alpha_p\} - \frac{2}{3}\right), \qquad (2.26)$$

In the cases of interest to us, the first term on the right-hand side is several times larger than the second. The weak dependence of the second term on the wiggler parameters

Once the energy spread becomes comparable with 440 MeV, the spacing between the integer spin resonances, strong depolarization occurs.

Polarization level

In an *ideal, absolutely planar* machine the asymptotic polarization level is given by

$$P_\infty^I = \frac{8}{5\sqrt{3}} \frac{I_{3a}}{I_3} \tag{2.22}$$

which is just a special case of (5.1) with all depolarizing effects neglected. Using the wigglers to increase the rate of polarization reduces P_∞^I by a factor

$$\mathcal{F}\left\{P_\infty^I\right\} \stackrel{\text{def}}{=} \frac{P_\infty^I(\text{wigglers})}{P_\infty^I(\text{no wigglers})} = \frac{1 + \frac{N_W L_+ |G_+|^3}{2\pi G_0^2}\left(1 - \frac{1}{r^2}\right)}{1 + \frac{N_W L_+ |G_+|^3}{2\pi G_0^2}\left(1 + \frac{1}{r^2}\right)} \tag{2.23}$$

In the limit of a wiggler-dominated machine, (2.21), this becomes

$$P_\infty^I(\text{wigglers}) = P_\infty^I(\text{no wigglers})\frac{(r^2 - 1)}{(r^2 + 1)} \tag{2.24}$$

Low polarization level is "better"

In the presence of depolarizing effects, the asymptotic level is

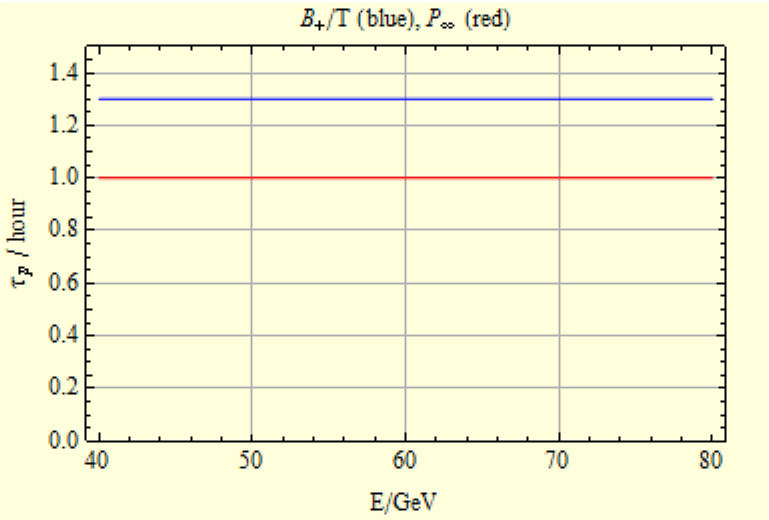
$$P_\infty = \frac{8}{5\sqrt{3}} \frac{1}{1 + \tau_p / \tau_d}$$

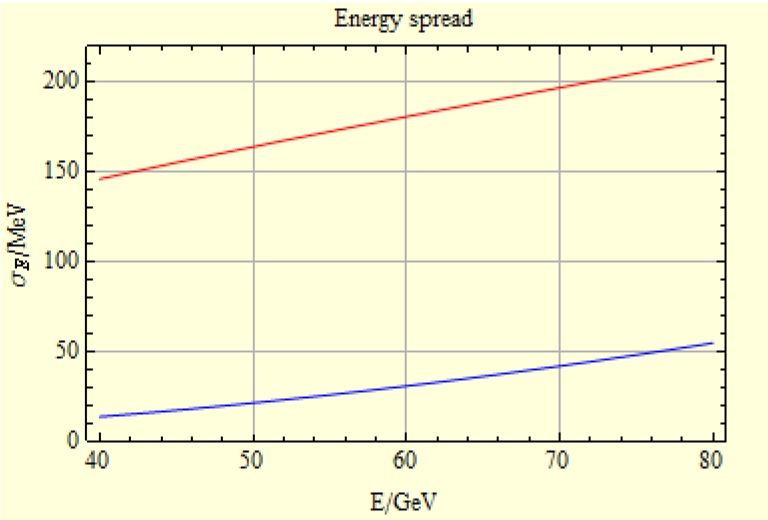
and the effective polarization time is given by

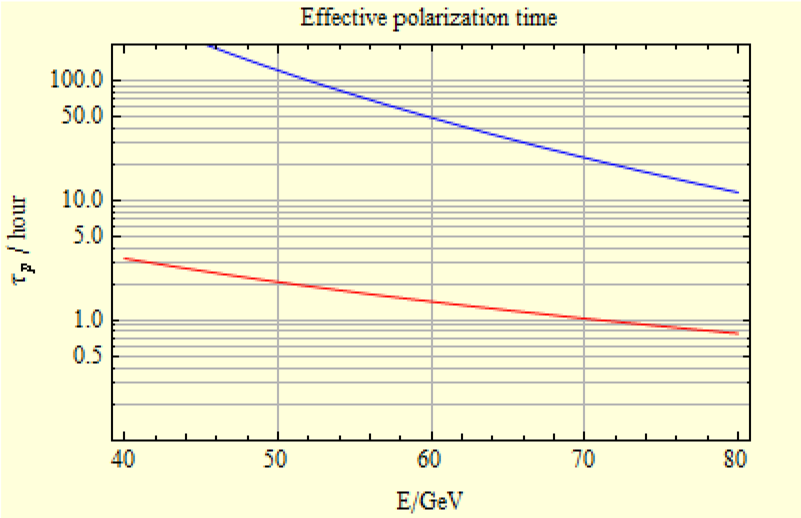
$$\tau_{peff}^{-1} = \tau_p^{-1} + \tau_d^{-1}$$

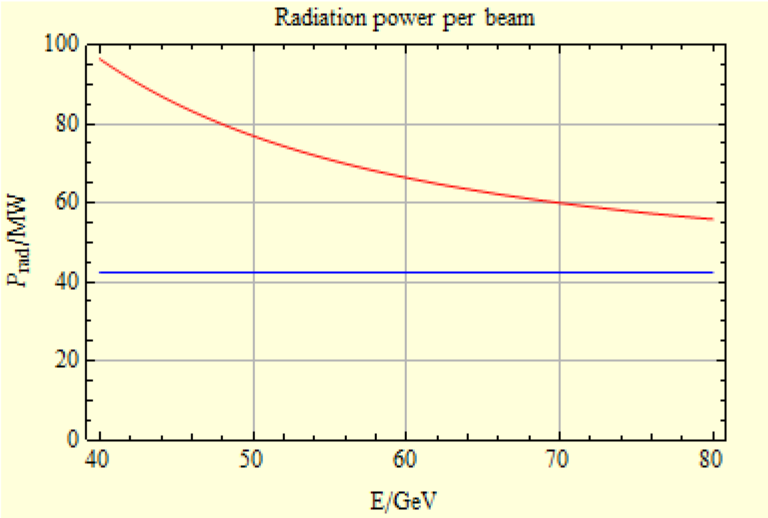
Go to CDF file …

12 wigglers flat-out, ideal polarization

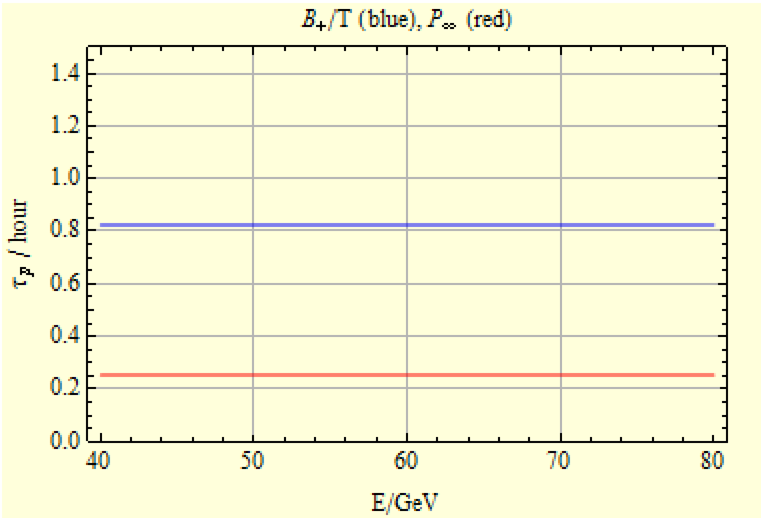


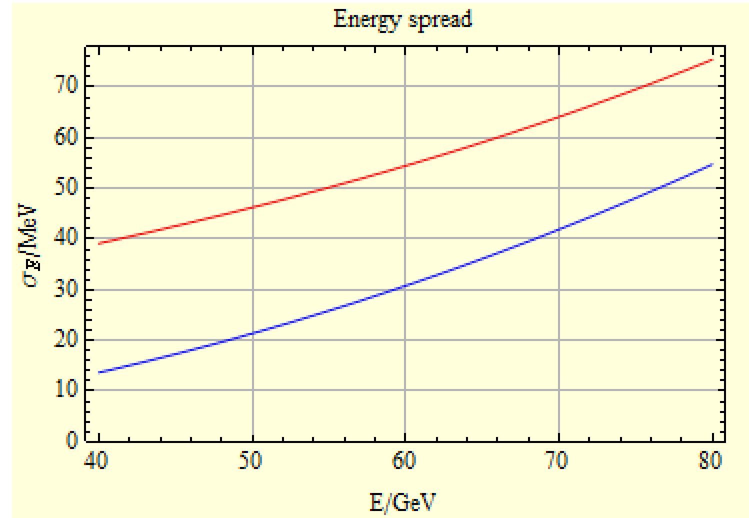






Possible solution, reduced field, 3 wigglers





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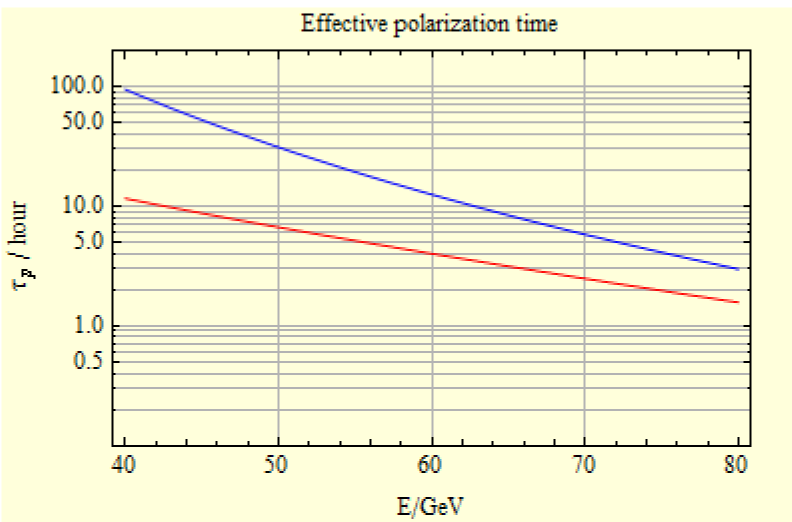
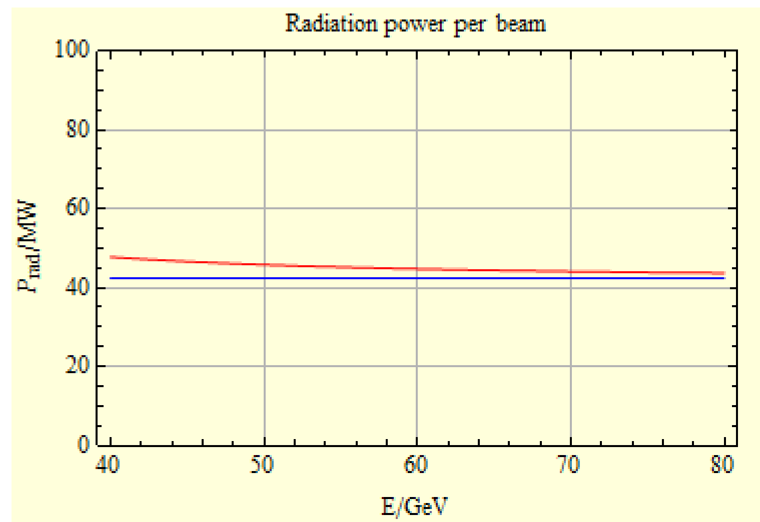




Residual dispersion at wiggler

Ideal

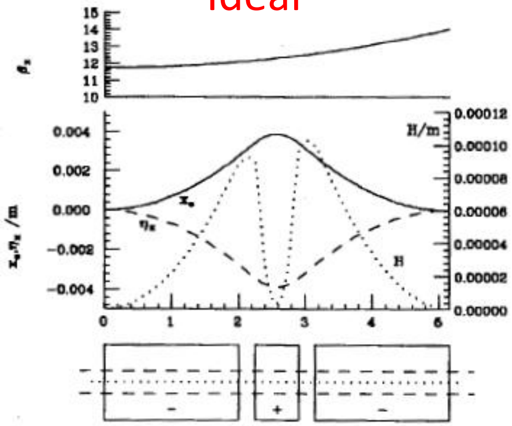


Figure 11: Horizontal closed orbit displacement and optical perturbations in the ideal case $\eta_x = 0$ at the entrance of the wiggler

Dispersion error

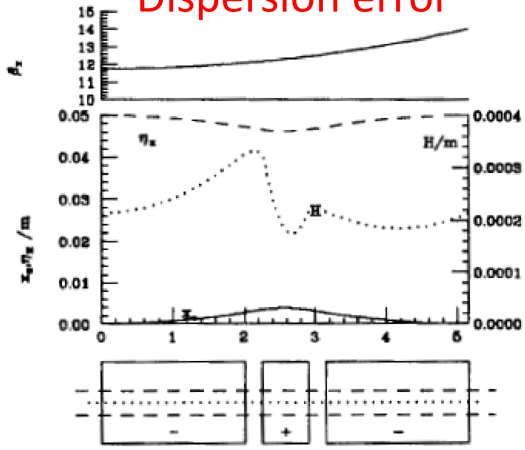


Figure 12: Horizontal closed orbit displacement and optical perturbations in a wiggler with residual $\eta_x = 5\,\mathrm{cm}$ because of machine imperfections

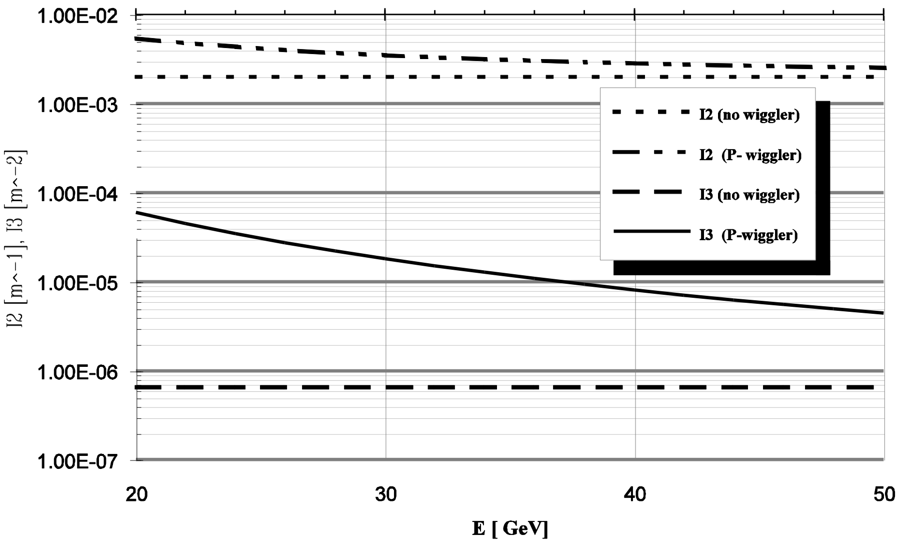
May increase emittance a bit (not a problem).

May also depolarize/complicate spin-matching of wigglers.

Conclusions

- The FODO cell design of the TLEP arcs may need longer quadrupoles to allow operation at Z energy.
  - Might also need to review dispersion suppressors?
- Wigglers can be used to enhance polarization rate but the available parameter space is very limited (low polarization levels, moderate wiggler fields and lengths).
- Huge flux of synchrotron radiation from wigglers.
- Emittance wigglers might be useful, if so leave some missing dipoles in Dispersion suppressors.

BACKUP SLIDES


1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
I2 [m^-1], I3 [m^-2]
20
30
40
50
E [GeV]
I2 (no wiggler)
I2 (P- wiggler)
I3 (no wiggler)
I3 (P-wiggler)