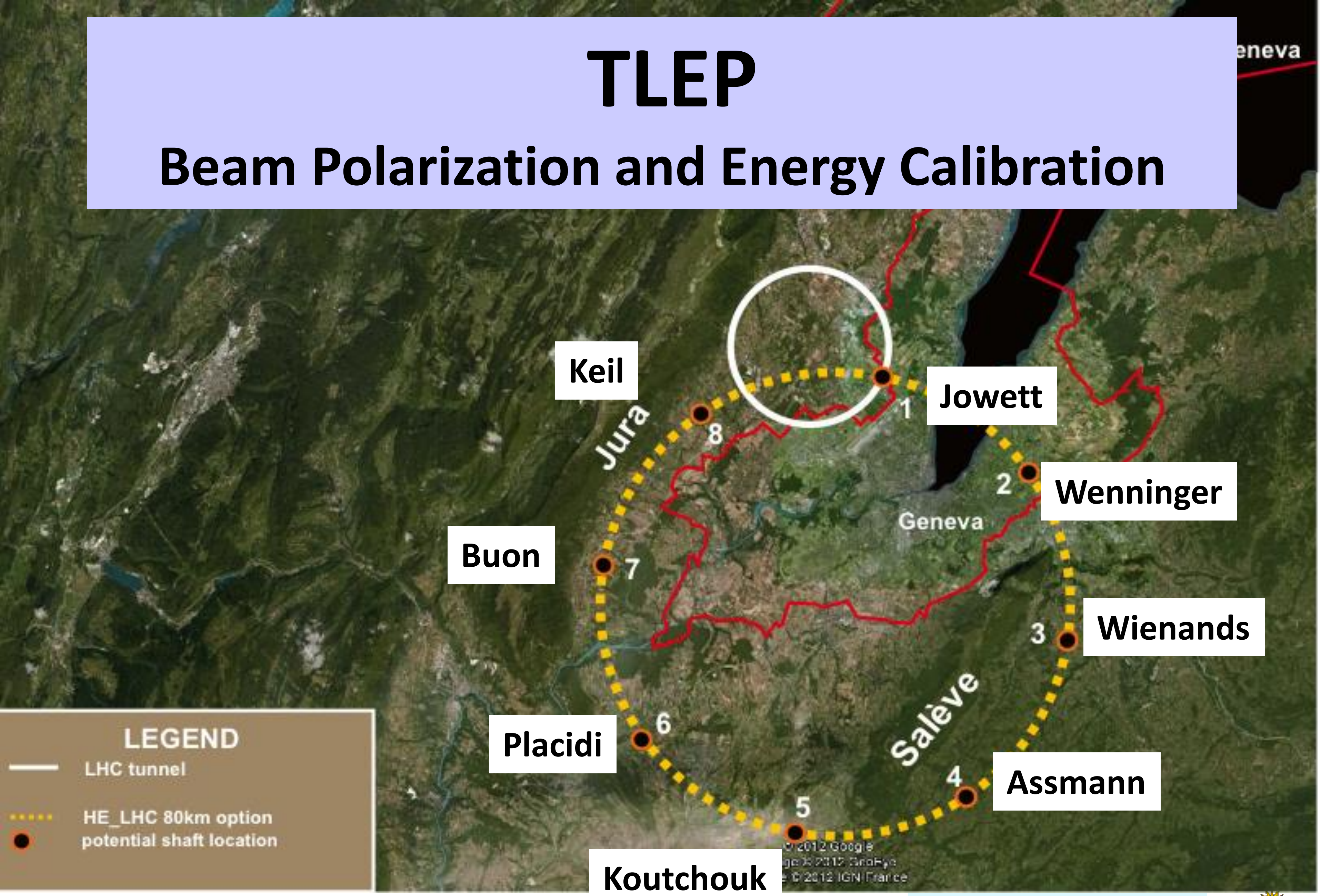
TLEP

Beam Polarization and Energy Calibration



Keil

Jowett

Wenninger

Buon

Wienands

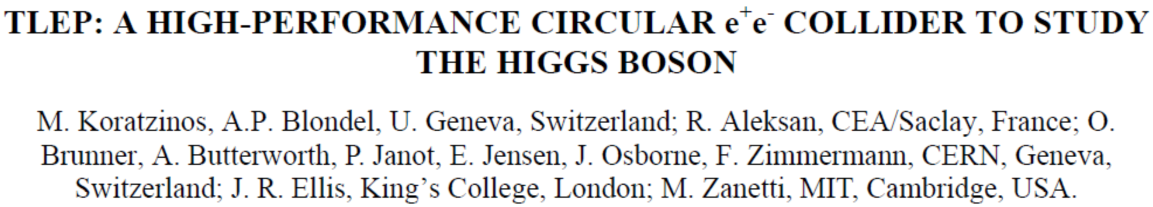
Placidi

Assmann

Koutchouk

and many others!

IPAC'13 Shanghai



TLEP: A HIGH-PERFORMANCE CIRCULAR e^+e^- COLLIDER TO STUDY THE HIGGS BOSON

M. Koratzinos, A.P. Blondel, U. Geneva, Switzerland; R. Aleksan, CEA/Saclay, France; O. Brunner, A. Butterworth, P. Janot, E. Jensen, J. Osborne, F. Zimmermann, CERN, Geneva, Switzerland; J. R. Ellis, King's College, London; M. Zanetti, MIT, Cambridge, USA.

http://arxiv.org/abs/1305.6498.

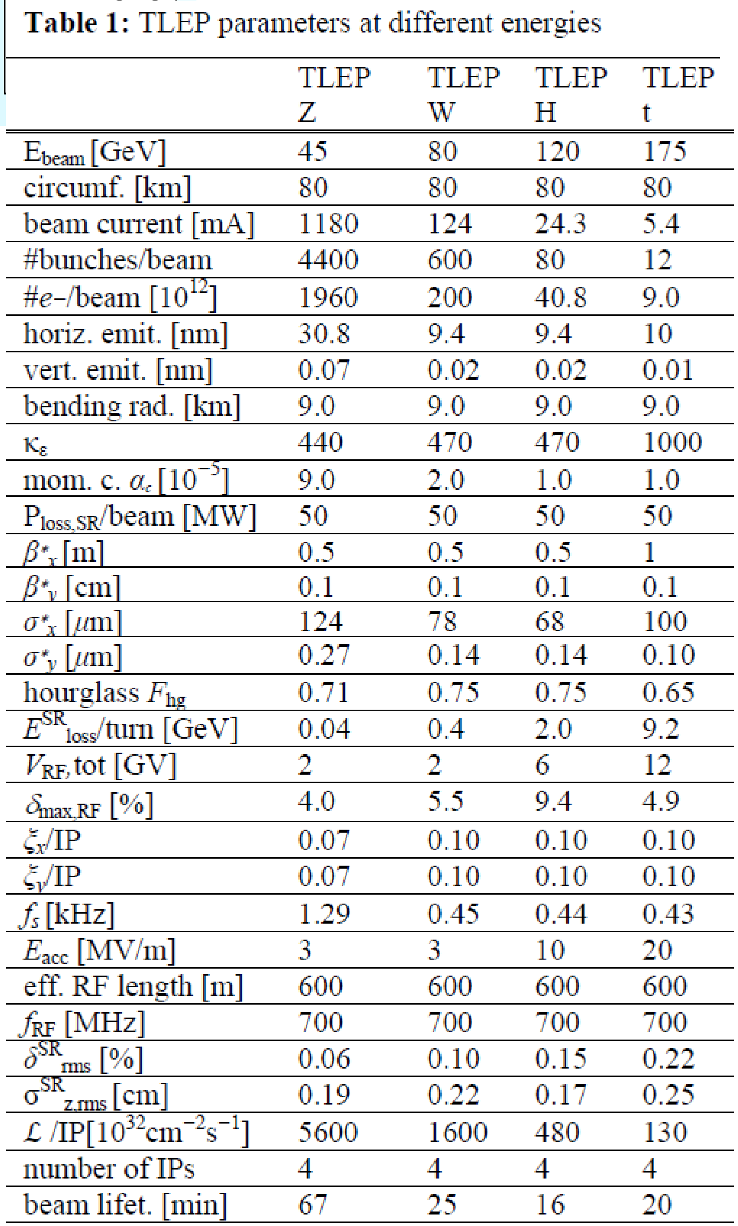
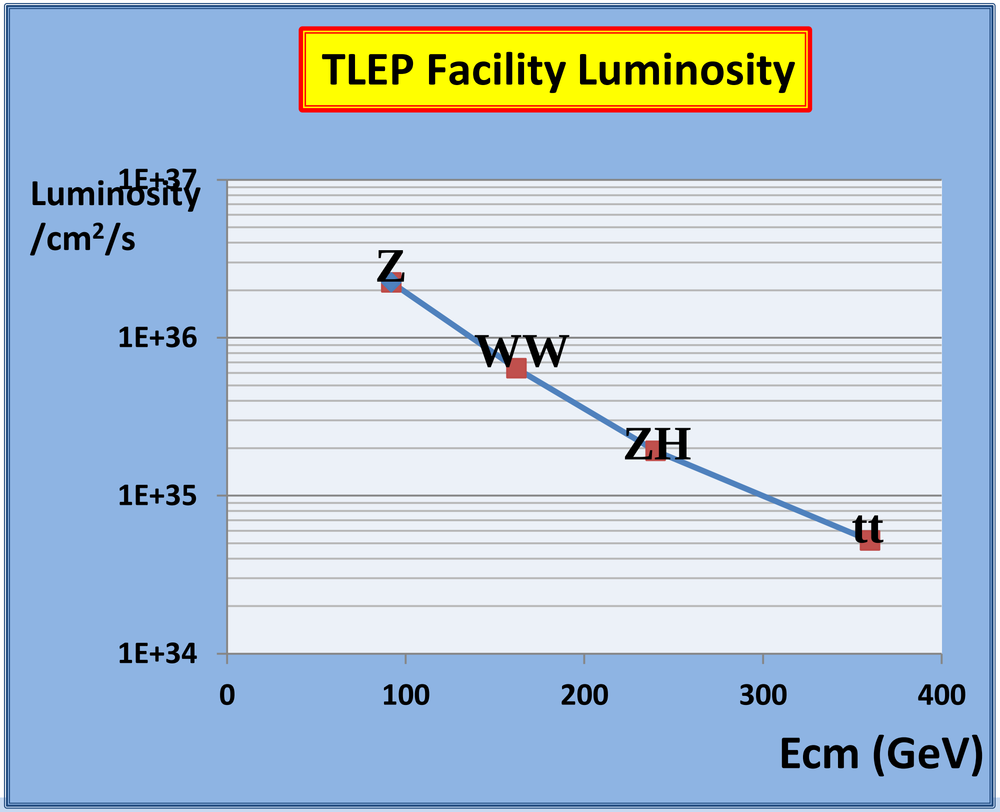


Table 1: TLEP parameters at different energies

	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



CONSISTENT SET OF PARAMETERS FOR TLEP TAKING INTO ACCOUNT BEAMSTRAHLUNG

Upgrades are being considered – charge compensation and/or faster fill-up time

A possible TLEP running programme

1. ZH threshold scan and 240 GeV running (200 GeV to 250 GeV)
   5+ years @2 10^35 /cm2/s => 210^6 ZH events
   ++ returns at Z peak with TLEP-H configuration
   for detector and beam energy calibration

Higgs boson HZ studies
+ WW, ZZ etc..

2. Top threshold scan and (350) GeV running
   5+ years @2 10^35 /cm2/s ➔ 10^6 ttbar pairs ++Zpeak

Top quark mass
Hvv Higgs boson studies

3. Z peak scan and peak running , TLEP-Z configuration ➔ 10^12 Z decays
   → transverse polarization of ‘single’ bunches for precise E_beam calibration
   2 years

Mz, Γ_Z R_b etc…
Precision tests and
rare decays

4. WW threshold scan for W mass measurement and W pair studies
   1-2 years ➔ 10^8 W pairs ++Zpeak

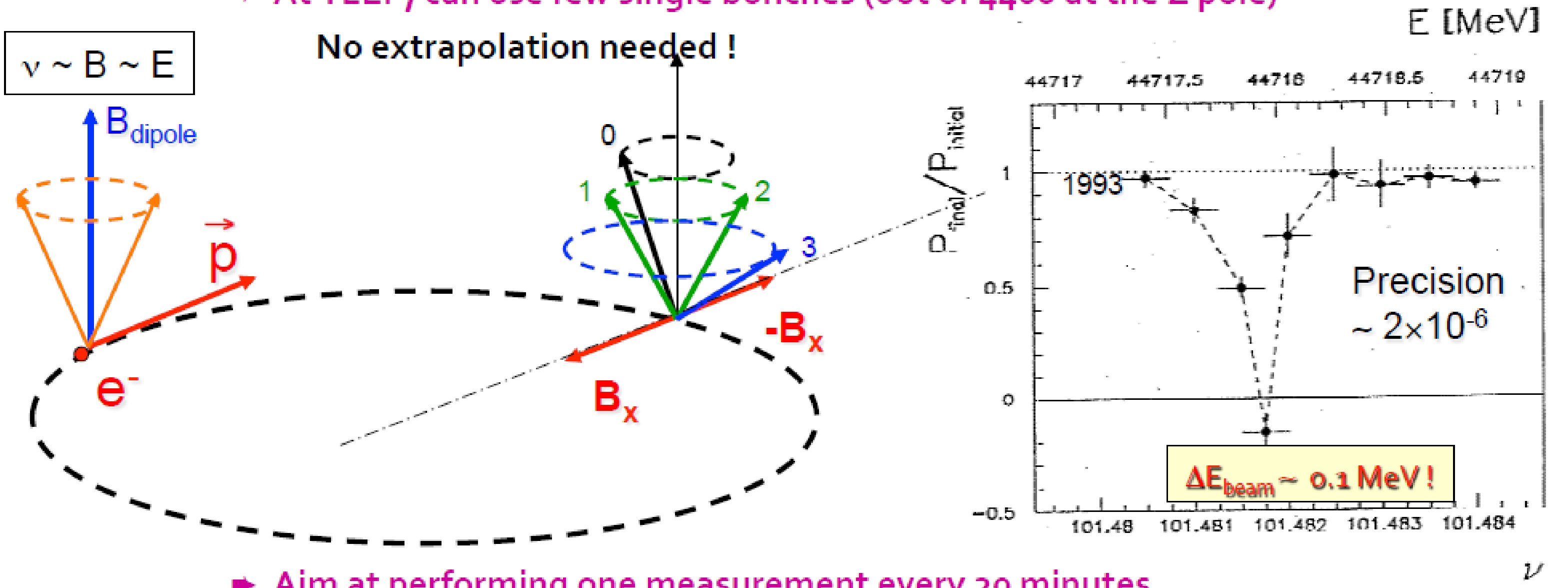
M_W, and W properties
etc…

5. Polarized beams (spin rotators) at Z peak 1 year at BBTS=0.01/IP => 10^{11} Z decays.

A_{LR}, A_{FB}^{pol} etc

- Natural beam transverse polarization up to $\sqrt{s} \sim 2\, m_W$
  - Exquisite beam energy measurement with resonant depolarization, unique to rings
    - Precision limited to 2 MeV at LEP1 by the extrapolation to collision conditions
      - At TLEP, can use few single bunches (out of 4400 at the Z pole)

... and no e+ polarimeter!



No extrapolation needed !

Precision ~ 2×10^{-6}

$\Delta E_{beam} \sim 0.1$ MeV !

- Aim at performing one measurement every 20 minutes

Ultimate precision better than 50 keV for m_Z and m_W measurements

- For $\sqrt{s}$ above $2m_W$: use accurate W or Z masses in $e^+e^- \to Z(\gamma)$, WW, ZZ

should revisit the uncertainty and the method to understand how much better we can do.

Also how practical is it to co-exist

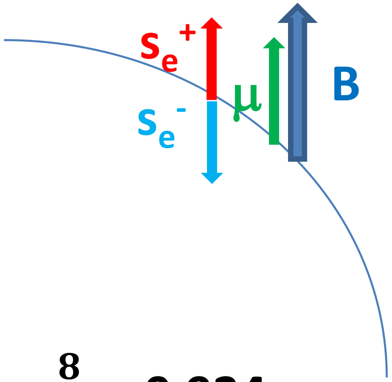
'polarized single bunches' with 'top-off injection'

To depolarize we must polarize

and *that* is the hard part.

Polarization basics

Polarization builds up by Sokolov Ternov effect
(magnetic moment aligns on magnetic field by emission of Synchrotron radiation)



- **-- spin of e+ and e- are transverse and opposite**
- **-- polarization growth is slow**

$$P_0 = \frac{8}{5\sqrt{3}} = 0.924$$

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

f_0 = revolution frequency = c/C
I_3 = 2π/ρ²

C : Circumference
ρ : bending radius

in other words, the polarization time scales as C³/E⁵

at given energy polarization time is ~27 times longer at TLEP than LEP
~ 150 hours at the Z peak (45.5 GeV)

Its all about depolarizing effects

depolarization occurs because the B field is not uniformly perpendicular to the storage ring plane. Transverse components ‘trip’ the spin by an amount

$$\delta\theta_{\text{spin}} = \nu\, \delta\theta_{\text{trajectory}}$$

$$\nu = \frac{E}{440.6486 \text{ MeV}} = 103.5 \text{ at the Z pole}$$

this is a problem because
1. the equilibrum spin is not the same for different energies in the beam
2. the equilibrium is not the same across the beam phase space

➔ spread of equilibrium direction and excitation of spin resonances.

Derbenev and Kondratenko [14] :

$$P_\infty = -\frac{8}{5\sqrt{3}} \frac{\left\langle |\rho^{-3}| \hat{\mathbf{b}} \cdot (\mathbf{n} - \boldsymbol{\Gamma}) \right\rangle}{\left\langle |\rho^{-3}| [1 - \frac{2}{9}(\mathbf{n} \cdot \hat{\mathbf{v}})^2 + \frac{11}{18} |\boldsymbol{\Gamma}|^2] \right\rangle},$$

Γ is the spin-orbit coupling i.e. the variation of the equilibrium spin direction upon a change of energy by SR in a magnet. The average can be expressed as a sum over the magnets.

$$P = -\frac{8}{5\sqrt{3}} \frac{\sum_j |\mathbf{B}_j|^3 L_j}{\sum_j \left[|\mathbf{B}_j|^3 L_j (1 + \frac{11}{18} |\boldsymbol{\Gamma}_j|^2) \right]}$$

$$= P_0 \frac{\frac{1}{\tau_p}}{\frac{1}{\tau_p} + \frac{1}{\tau_d}} \qquad P = P_0 \frac{1}{1 + \frac{\tau_P}{\tau_D}}$$

with

$$\frac{1}{\tau_p} \propto \sum_j |\mathbf{B}_j|^3 L_j \propto I_3,$$

$$\frac{1}{\tau_d} \propto \sum_j \frac{11}{18} |\mathbf{B}_j|^3 L_j |\boldsymbol{\Gamma}_j|^2.$$

The polarization time is reduced in the same way as the asymptotic polarization

$$\tau_P{}^{eff} = \tau_P \frac{1}{1 + \frac{\tau_P}{\tau_D}}$$

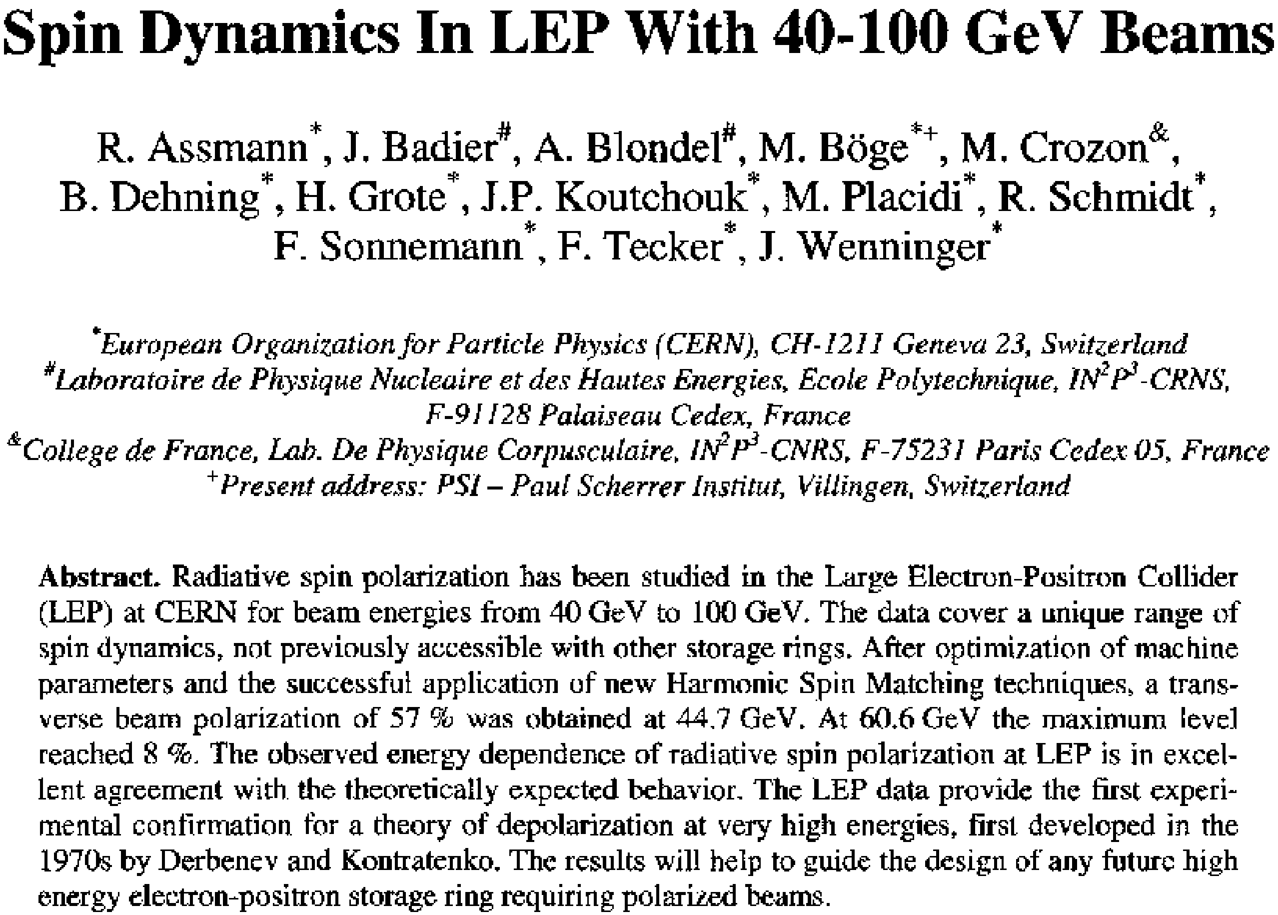
P=92.4% and τ = 150hrs

then for $\frac{\tau_P}{\tau_D}$=9

P = 9.2% and τ = 15hrs.

What we know from LEP on depolarizing effects

http://dx.doi.org/10.1063/1.1384062 AIP Conf. Proc. 570, 169 (2001) Spin 2000 conf, Osaka



Spin Dynamics In LEP With 40-100 GeV Beams

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Abstract. Radiative spin polarization has been studied in the Large Electron-Positron Collider (LEP) at CERN for beam energies from 40 GeV to 100 GeV. The data cover a unique range of spin dynamics, not previously accessible with other storage rings. After optimization of machine parameters and the successful application of new Harmonic Spin Matching techniques, a transverse beam polarization of 57 % was obtained at 44.7 GeV. At 60.6 GeV the maximum level reached 8 %. The observed energy dependence of radiative spin polarization at LEP is in excellent agreement with the theoretically expected behavior. The LEP data provide the first experimental confirmation for a theory of depolarization at very high energies, first developed in the 1970s by Derbenev and Kontratenko. The results will help to guide the design of any future high energy electron-positron storage ring requiring polarized beams.

$$\frac{1}{\tau_p} \propto \sum_j |\mathbf{B}_j|^3 L_j \propto I_3,$$

$$\frac{1}{\tau_d} \propto \sum_j \frac{11}{18} |\mathbf{B}_j|^3 L_j |\mathbf{\Gamma}_j|^2.$$

can be improved by increasing the sum of |B|^3 (Wigglers)

can be improved by 'spin matching'

the sources of depolarization can be separated into harmonics (the integer resonances) and/or into the components of motion:

horizontal betatron: $|\mathbf{\Gamma}_x|^2 \propto (\eta_x^W + \delta\eta)^2 \delta\mathbf{n}^2,$

vertical betatron: $|\mathbf{\Gamma}_y|^2 \propto \delta\eta^2,$

synchrotron: $|\mathbf{\Gamma}_z|^2 \propto A\delta\eta^2 + B\delta\mathbf{n}^2,$

receipes:

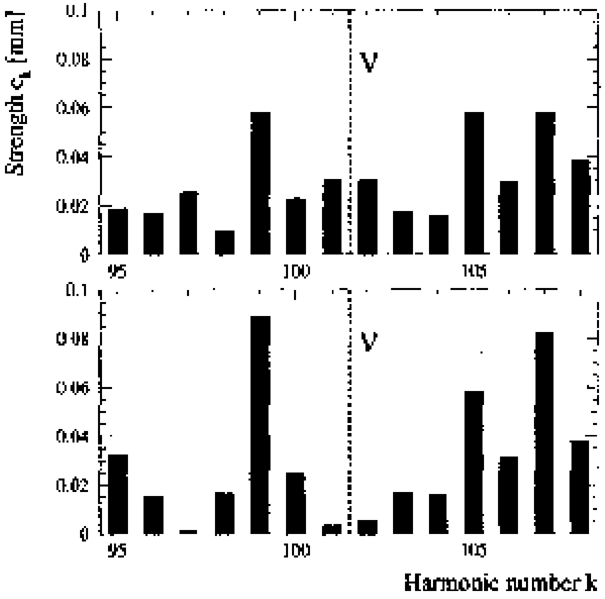
-- reduce the emittances and vertical dispersion δη

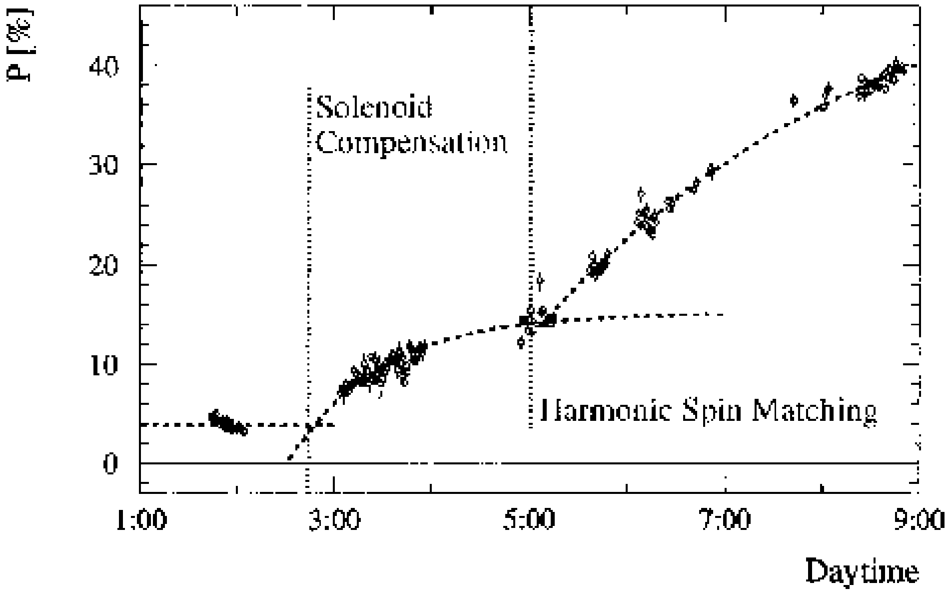
→ this will be done at TLEP to reduce beam size!

-- reduce the vertical spin motion δn →harmonic spin matching

-- do not increase the energy spread

examples of harmonic spin matching (I)





Deterministic Harmonic spin matching :

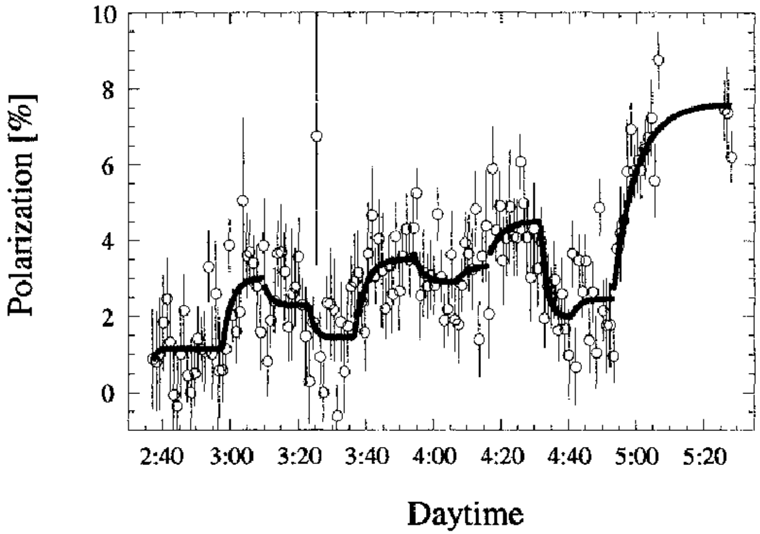
measure orbit, decompose in harmonics, cancel components near to spin tune.

☺ NO FIDDLING AROUND.

This worked very well at LEP-Z

and should work even better at TLEP-Z if orbit is measured better.

examples of harmonic spin matching (II)

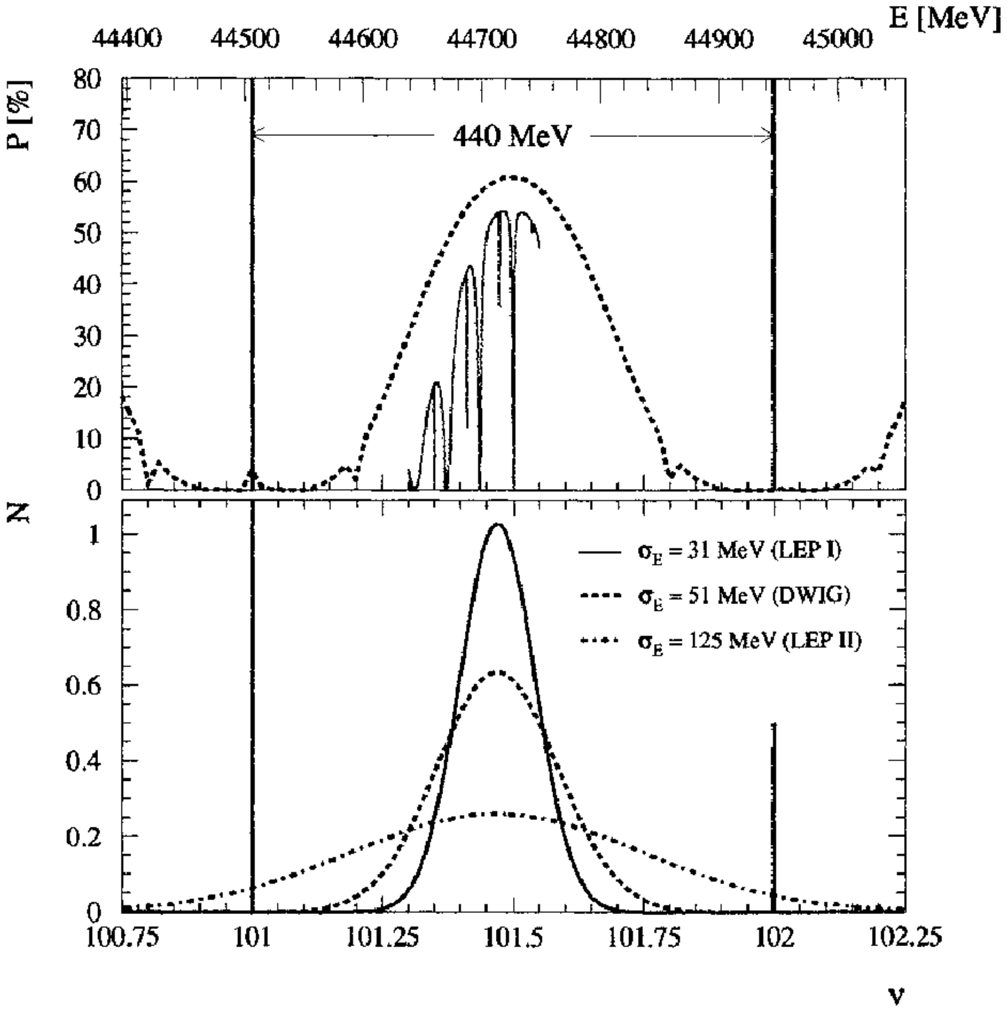


	HSM bumps settings				Fit results
Time hr:min	137 (cos)	137 (sin)	138 (cos)	138 (sin)	P_1 (%)
02:35	0.0	0.0	0.0	0.0	1.15 ± 0.23
02:58	2.0	0.0	0.0	0.0	3.03 ± 0.37
03:10	2.0	0.0	2.0	0.0	2.28 ± 0.30
03:23	2.0	0.0	2.0	2.0	1.45 ± 0.27
03:36	2.0	2.0	2.0	0.0	3.51 ± 0.28
03:54	2.0	2.0	2.0	-2.0	2.88 ± 0.25
04:06	2.0	2.0	2.0	0.0	3.33 ± 0.40
04:16	4.0	2.0	2.0	0.0	4.53 ± 0.34
04:33	6.0	2.0	2.0	0.0	1.86 ± 0.27
04:41	3.0	4.0	2.0	0.0	2.66 ± 0.35
04:53	3.0	2.0	0.6	-0.6	7.69 ± 0.36

When all else fails, empirical spin matching: excite harmonics one by one to measure directly their effect on polarization and fit for pole in 4-D space.
Here 8% polarization at 61 GeV.

$$P_{asym} = \frac{92.4\ \%}{1+\left(\tau_p/\tau_d\right)_0 + \sum_i \gamma_i \left(a_i - a_i^{bump}\right)^2}$$

The energy spread really enhances depolarization



effect of energy spread on Polarization in a given machine was studied using the damping wigglers

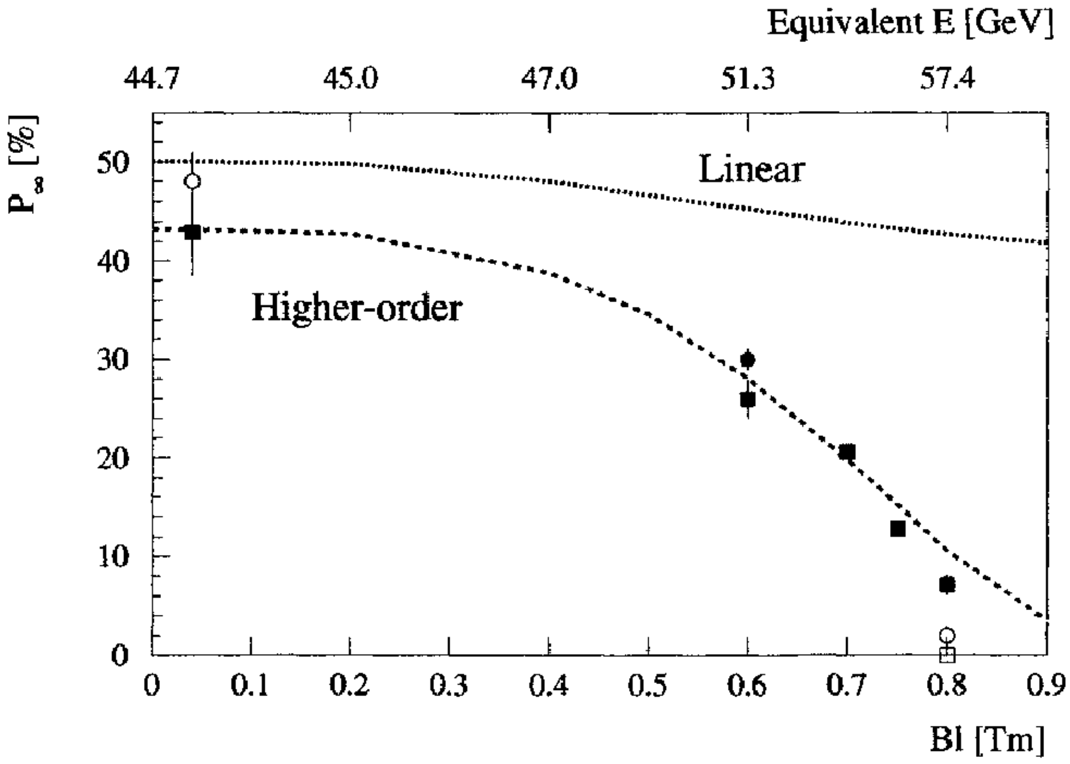
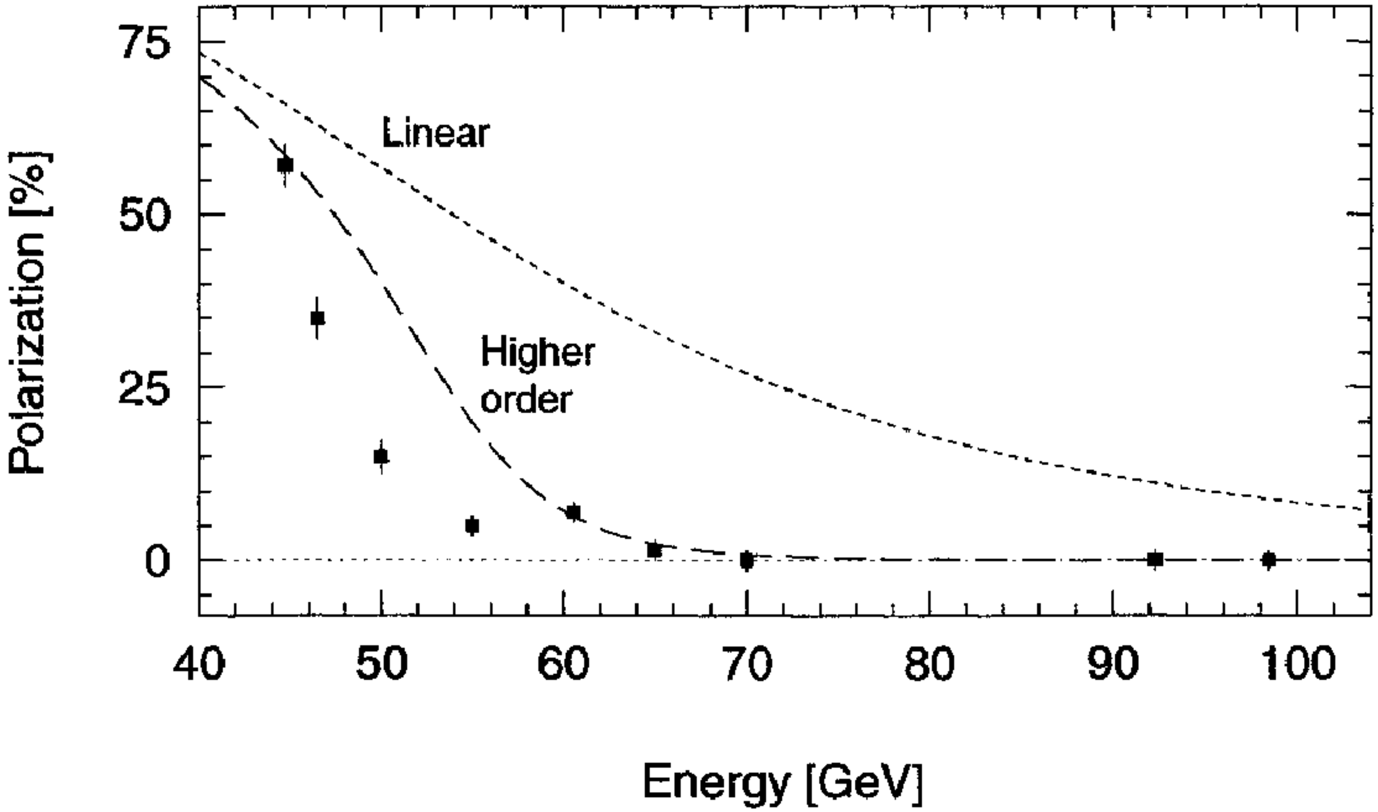


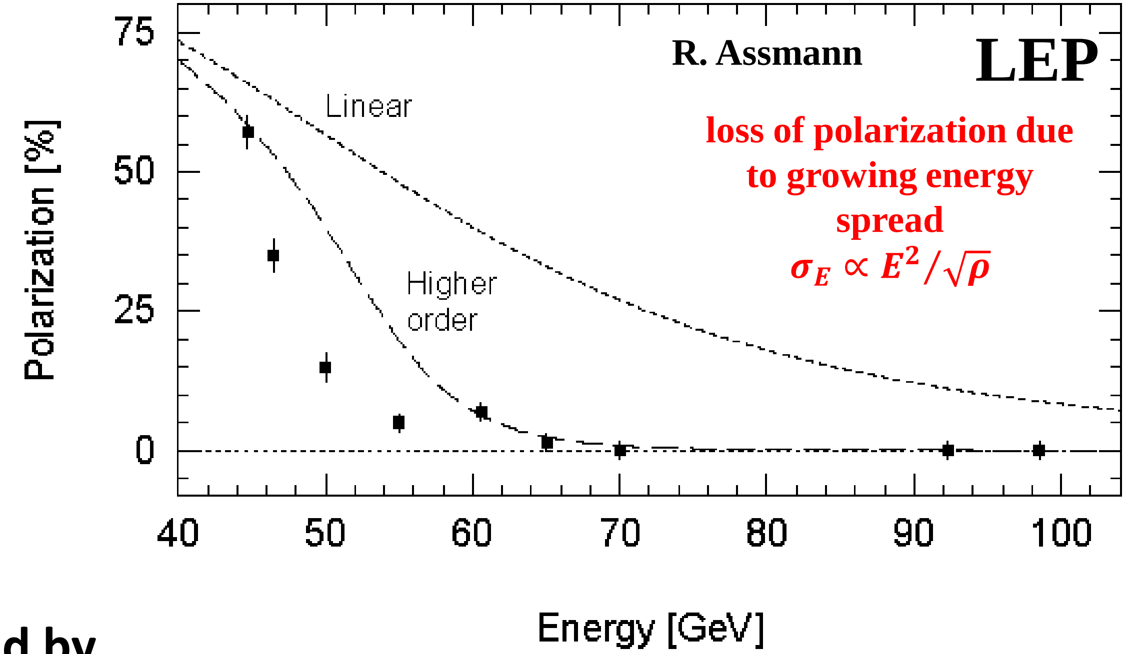
FIGURE 8. Observed polarization level at 44.7 GeV for different excitations Bl of the LEP damping wigglers. The upper scale indicates the beam energy that would produce the same spin tune spread. The polarization measurements are compared to the expectations from linear and higher-order theory.

$\sigma_E \propto E_b^2 / \sqrt{\rho}$



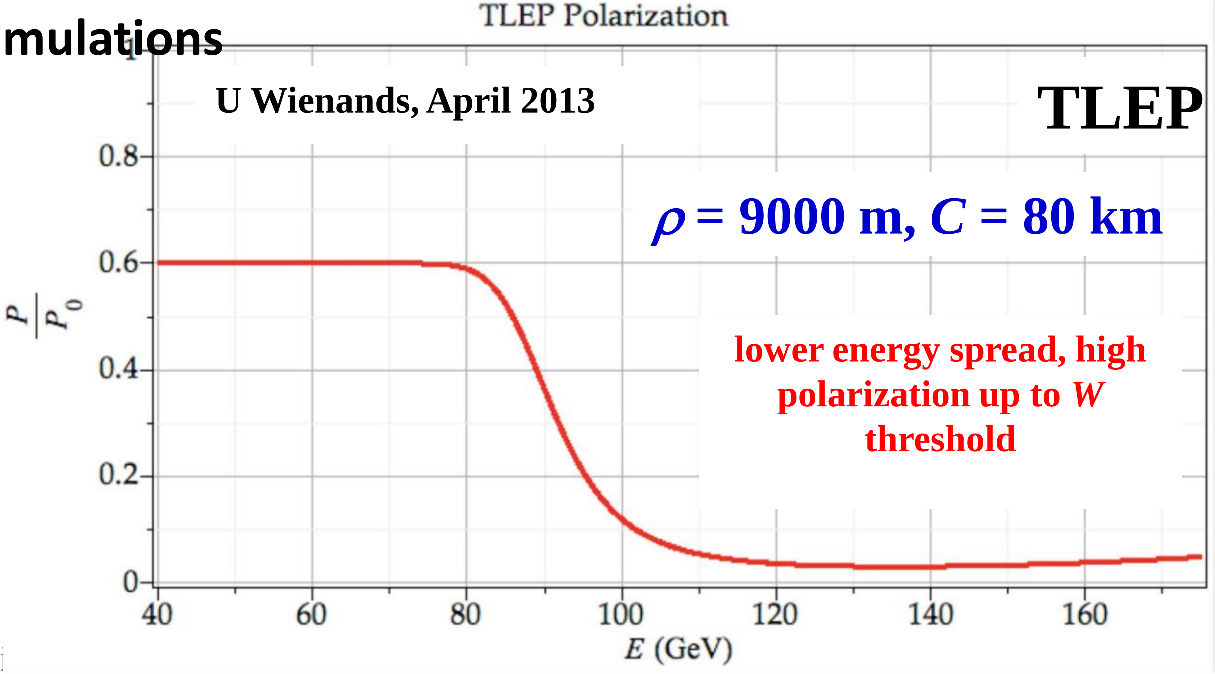
The good news is that polarization in LEP at 61 GeV corresponds to polarization in TLEP at 81 GeV

➔ Good news for M_W measurement



loss of polarization due to growing energy spread
$\sigma_E \propto E^2/\sqrt{\rho}$

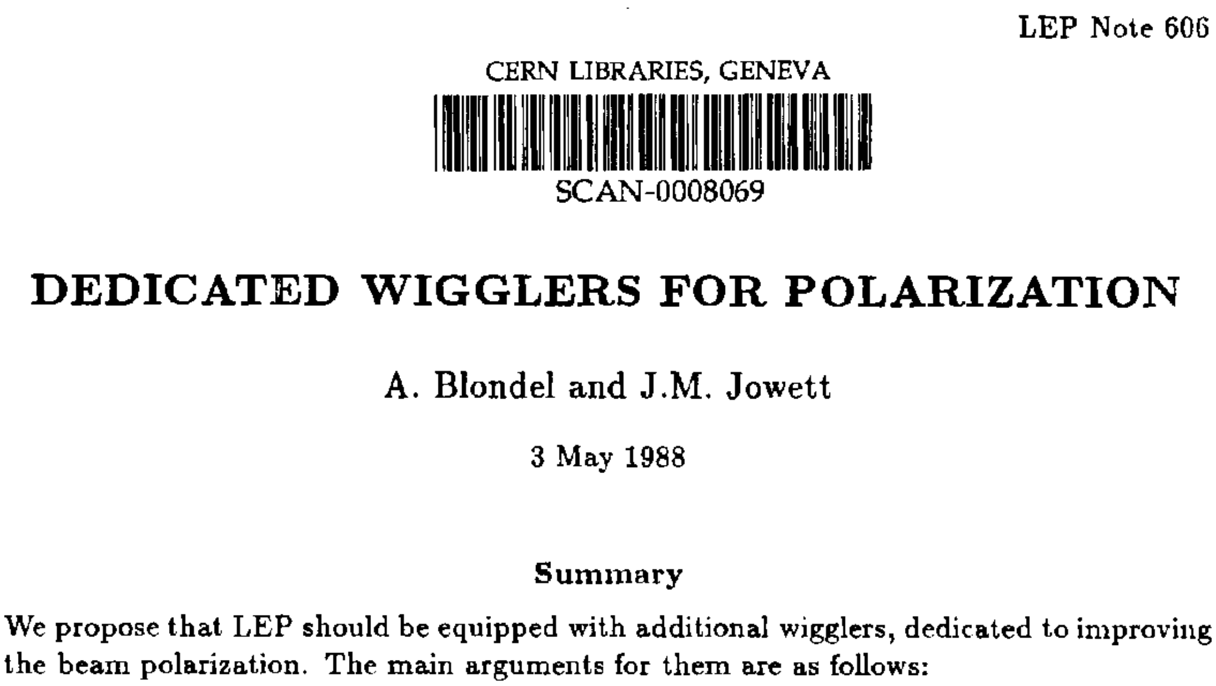
this is confirmed by higher order simulations



ρ = 9000 m, C = 80 km

lower energy spread, high polarization up to W threshold

Use of polarization wigglers at TLEP



LEP Note 606

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:

FOREWORD How the sausage was made...

In order to evaluate the effect of wigglers and top-up injection on TLEP polarization performance, I have generated two spread sheets

1. the first one calculates the energy pread and polarization time in TLEP assuming a bending radius of 10km for a circumference of 80km, and the presence of the 12 polarization wigglers that were built for LEP as calculated in LEP note 606 (Blondel/Jowett)

2. the second one folds the achived polarization performance with top up injection, given the luminosity life time and the regular injection of unpolarized particles.

The variable parameters are
-- B+ : field in the positive pole of the wigglers
-- beam energy
-- luminosity lifetime
-- and of course Jx but I have refrained to play with it. (one would want it as small as possible)

Energy spread (Jx=1)

beam energy		LEP sigma(E)	LEP tau_P	TLEP sigma(E)	TLEP tau_P
45 GeV	no wiggs	32 MeV	5.5 hrs	18 MeV	167 hrs
45 GeV	wigglers	46 MeV	2.4 hrs	58 MeV	12 hrs
55 GeV	no wiggs	48 MeV	1.96 hrs	26 MeV	61 hrs
61 GeV	no wiggs	59 MeV	1.1 hrs	33 MeV	36 hrs
81 GeV				58 MeV	8.9 hr

➔ ☹ annoyingly: with wigglers at TLEP, the energy spread is larger than at LEP, for a given polarization time.

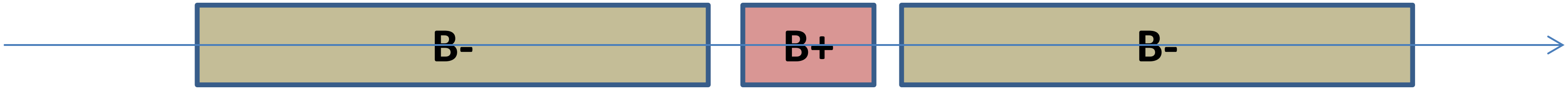
consider somewhere between 48 and 58 MeV as maximum acceptable for energy spread*). Take 52 MeV for the sake of discussion.
Note that wigglers make energy spread worse faster at TLEP (damping is less)
☺ There is no need for wigglers at 81 GeV.

*) The absolute value of energy spread corresponds to an absolute value of spin-tune spread

$$\nu = \frac{E_{beam}}{0.44065}$$

Hypothetical scenario

Insert in TLEP the 12 Polarization wigglers that had been built for LEP (B-=B+/6.25)



Use formulae given in TLEP note 606 to determine as a function of B+ excitation

1. the energy pread σ_E
2. the polarization time τ_P

then set an uppper limit on energy spread ...
and see what polarization time we get

for 10% polarization the time is $\tau_P^{eff} = 0.1\ \tau_P$

for 52 MeV energy spread at TLEP Z we get τ_P = 15hrs or τ_P^{eff} = 90 minutes

-- lose 90 minutes of running , then can depolarize one bunch every 10 minutes
if we have 9 'single bunches' per beam. (will keep a few more to be sure)

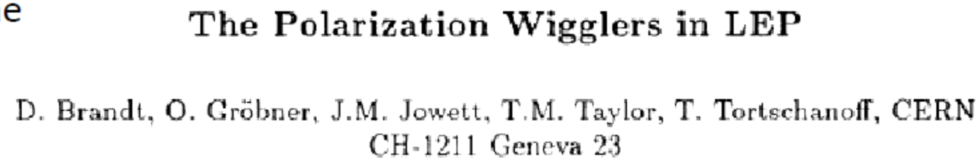
Changing the wigglers (e.g. more, weaker) makes little difference

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.

Jowett: were not easy to use (orbit distortions) and should probably be better designed



The Polarization Wigglers in LEP

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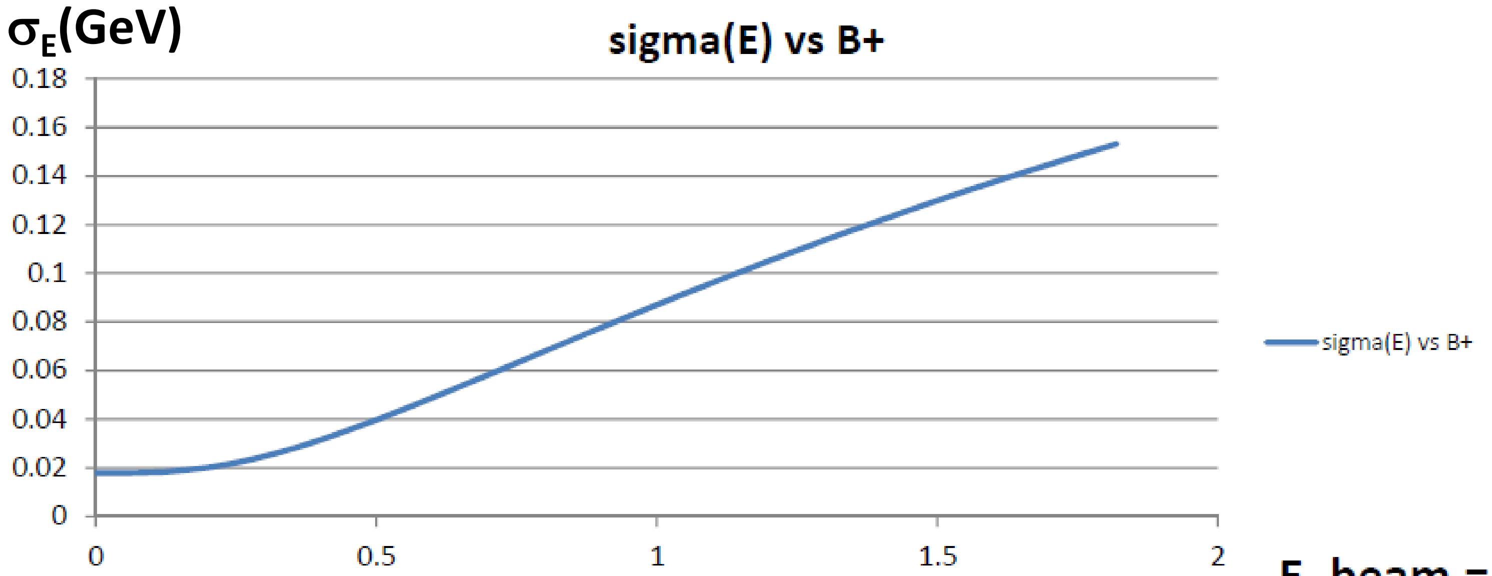
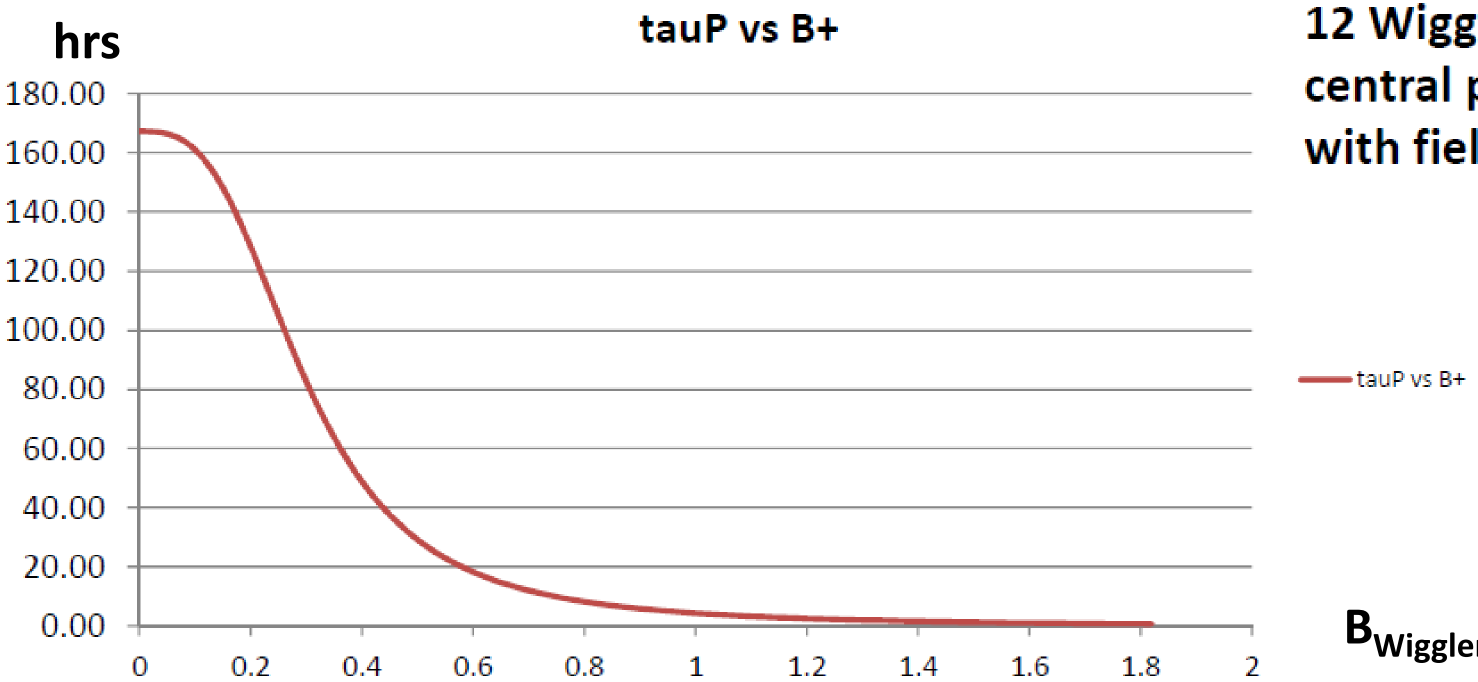
CH-1211 Geneva 23

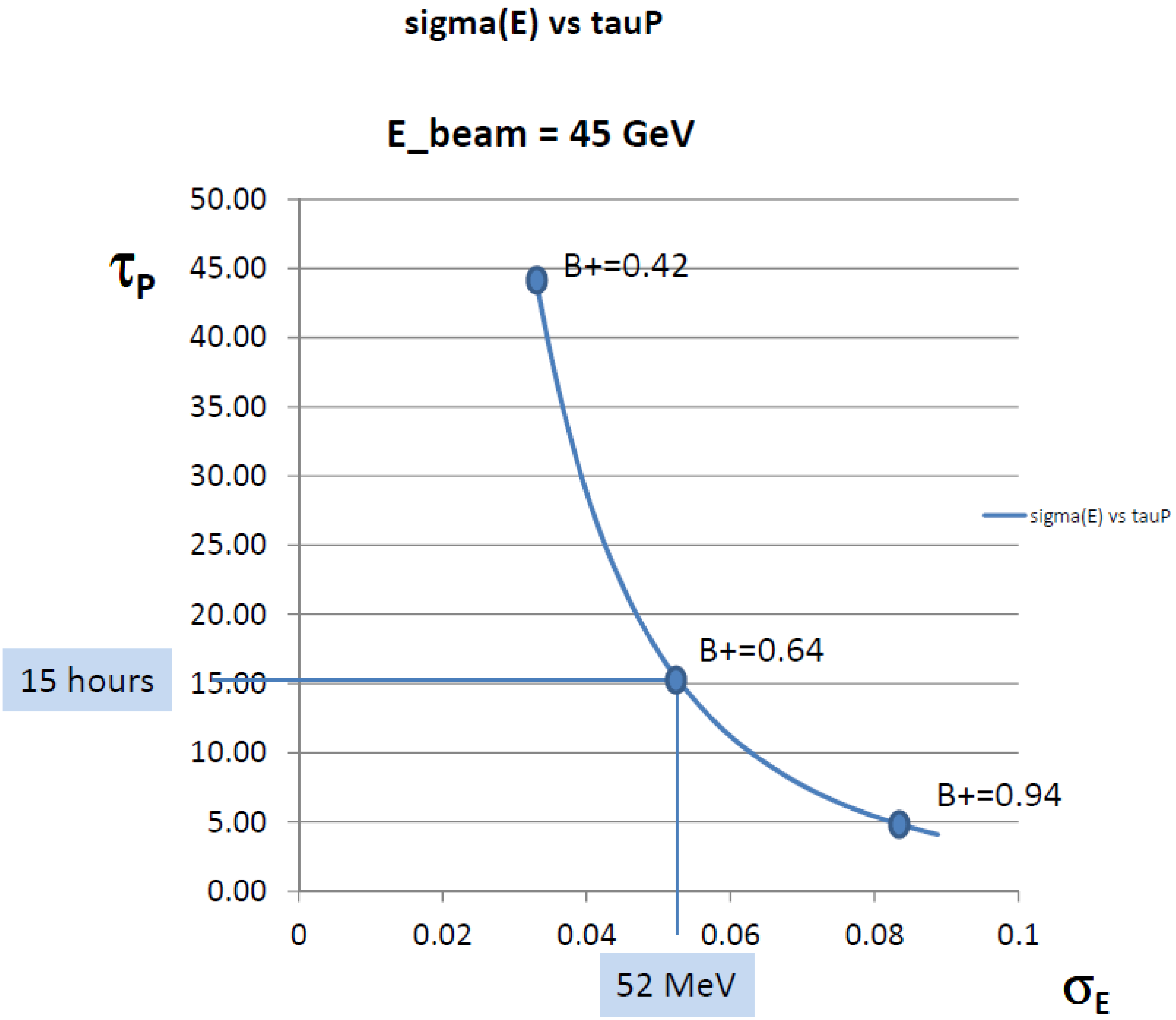
EPAC
1992

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



E_beam = 45 GeV
12 Wigglers
central pole is 65 cm
with field B+





we can reasonably expect to have 15hrs (900 min) polarization time for 52 MeV energy spread

Synchroton radiation power in the wigglers

Synchrotron radiation power by particles of a given energy in a magnet of a given length scales as the square of the magnetic field.

The energy loss per passage through a polarization wiggler was calculated in LEP note 606 (see next page). It is 3.22 MeV per wiggler or 38.6 MeV for the 12 wigglers.

At LEP the energy loss per particle per turn is 117 MeV/turn in the machine with no wiglers and becomes 156 MeV per turn with the 12 wigglers at full field. From this it follows that in the machine running at 45 GeV and wigglers at full field the radiation power in the wigglers would have been 25% of the total power dissipated around LEP.

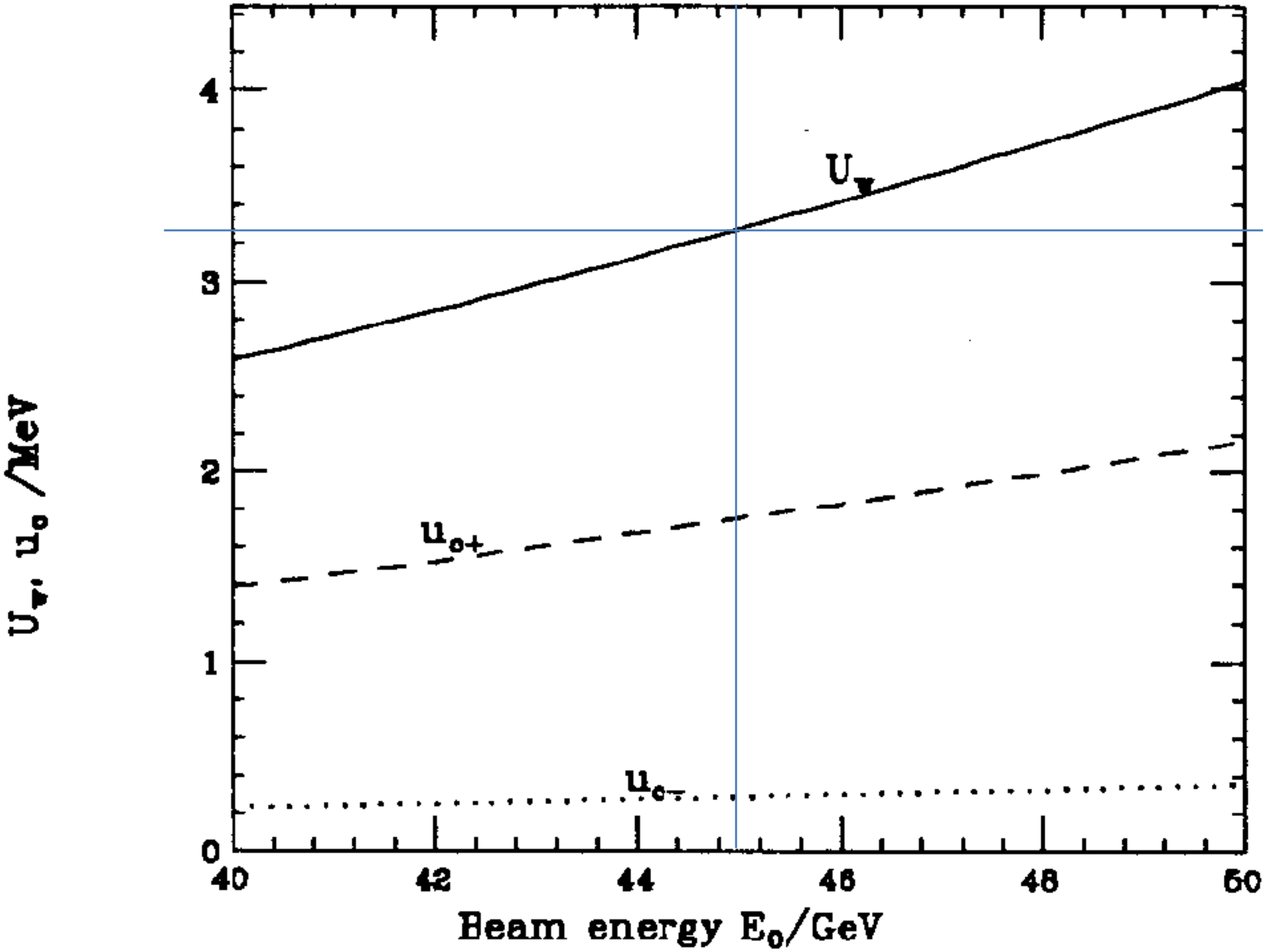
In TLEP now, the energy loss per turn in the ring is 36.3 MeV while, in the wigglers at 0.64T, the energy loss in the wigglers is approx. a quarter of the above or 9.4 MeV.

The fraction of energy lost in the wigglers is then 9.4/(36.3+9.4) or 21%.

For a total SR power of 100MW,

21 MW will go in the wigglers.

ENERGY LOSS PER PARTICLE PER WIGGLER



3.22MeV at 45 GeV

Figure 2: Energy loss per particle per wiggler unit, U_w, and critical energies, $u_{c\pm}$, in the wiggler blocks; here the wiggler field is a constant $B_+ = 1.3\,\mathrm{T}$.

TOTAL ENERGY LOSS PER TURN PER PARTICLE WITH 12 WIGGLERS

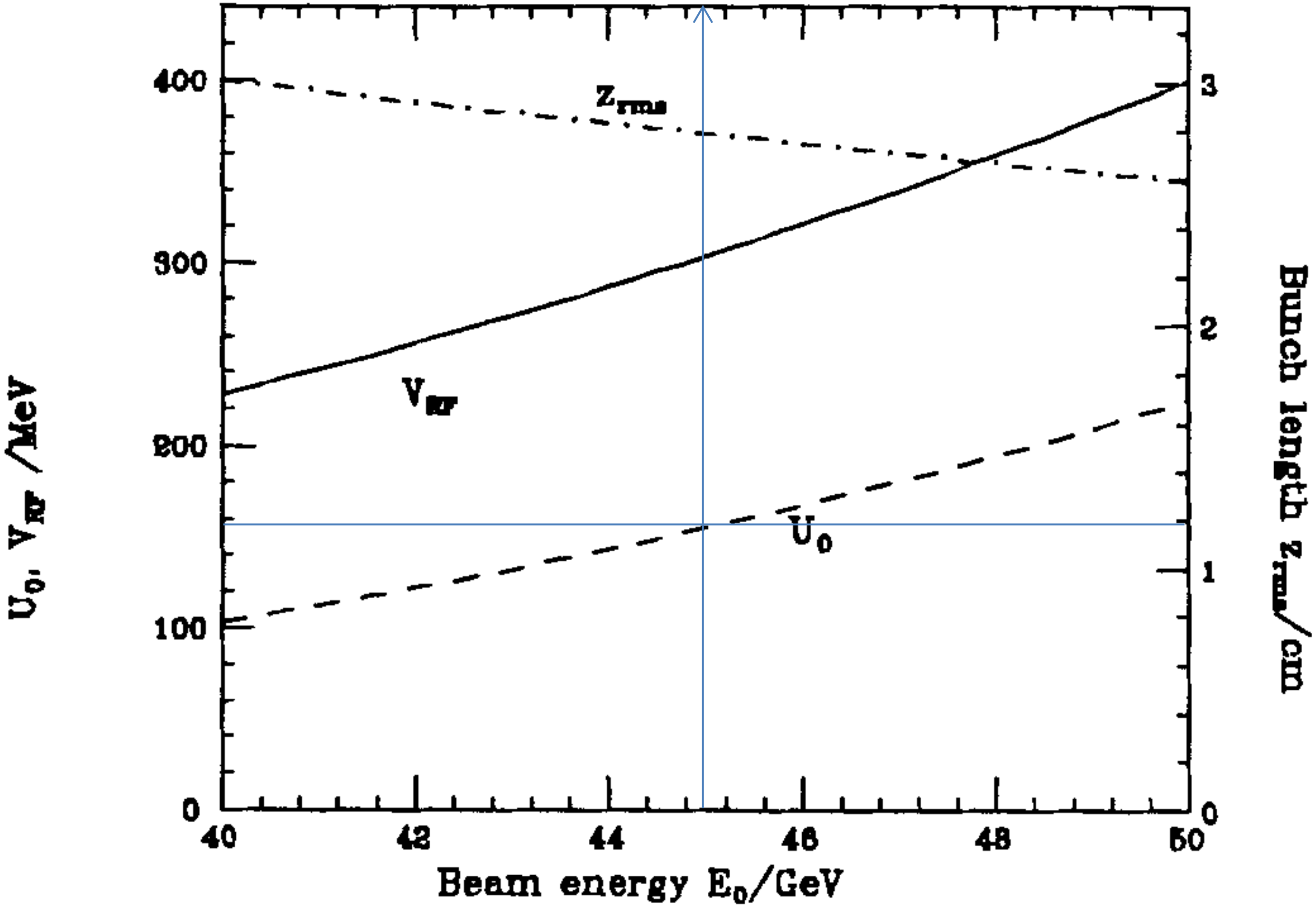


Figure 7: Longitudinal parameters with $B_+ = 1.3\,\mathrm{T}$; the RF voltage is adjusted to maintain 15 h longitudinal quantum lifetime. The bunch length and total radiative energy loss per turn are also shown.

Preliminary conclusions:

1. ☹ the wigglers increase energy spread in TLEP faster than in LEP

2. ☺ a workable point can be found for the 'energy calibration mode' at the Z pole or W threshold, assuming no better performance than in LEP for depolarizing effects.

3. ☺ things should get better with lower emittance and lower vertical dispersion.

4. !!! A very careful design of the SR absorbers is required, as the SR power in the wigglers is very large (20% of the total in the ring) !!!

5. reducing the luminosity for polarization runs can be envisaged, since the statistical precision on m_Z and Γ_Z is very small (<10 keV) and probably smaller than systematics.

A Sample of Essential Quantities:

X	**Physics**	**Present precision**		**TLEP stat** **Syst Precision**	**TLEP key**	**Challenge**
M_Z MeV/c2	**Input**	91187.5 ±2.1	Z Line shape scan	**0.005 MeV** **<±0.1 MeV**	E_cal	QED corrections
Γ_Z MeV/c2	**$\Delta\rho$ (T)** **(no $\Delta\alpha$!)**	2495.2 ±2.3	Z Line shape scan	**0.008 MeV** **<±0.1 MeV**	E_cal	QED corrections
R_ℓ	α_s, δ_b	20.767 ± 0.025	Z Peak	**0.0001** **± 0.002** **- 0.0002**	Statistics	QED corrections
N_ν	**Unitarity of PMNS, sterile ν's**	2.984 ±0.008	Z Peak Z+γ(161 GeV)	**0.00008** **±0.004** **0.001**	->lumi meast Statistics	**QED corrections to Bhabha scat.**
R_b	δ_b	0.21629 ±0.00066	Z Peak	**0.000003** **±0.000020 - 60**	Statistics, small IP	Hemisphere correlations
A_{LR}	**$\Delta\rho$, ε_3, $\Delta\alpha$** **(T, S)**	0.1514 ±0.0022	Z peak, polarized	**±0.000015**	4 bunch scheme	Design experiment
M_W MeV/c2	**$\Delta\rho$, ε_3, ε_2, $\Delta\alpha$** **(T, S, U)**	80385 ± 15	Threshold (161 GeV)	**0.3 MeV** **<1 MeV**	E_cal & Statistics	QED corections
m_{top} MeV/c2	**Input**	173200 ± 900	Threshold scan	**10 MeV**	E_cal & Statistics	Theory limit at 100 MeV?

Longitudinal polarization operation:

Can we operate routinely with longitudinal polarization in collisions?
Polarization in collisions was observed in LEP
the following must be satisfied (in addition to spin rotators):

0. we have to take into account the top-off injection of non-polarized particles

1. random depolarization must be reduced wrt LEP by a factor 10 to go from 10% to 55% P with life time of 15hrs=900 minutes (i.e with wigglers ON as before)
This is beyond what was achieved at LEP but there is hope that it can be done with improved optics at TLEP, given better dispersion corrections (➔ simulation job to do)

2. luminosity lifetime must be reduced to 900 minutes as well. This means reducing luminosity by a factor 10 down to 6 10^34/cm2/s/IP , or increase the number of bunches (NB luminosity lifetime is sensitive to the momentum acceptance of the machine ➔ check!)

3. then the top up will reduce polarization further, to reach an equilibrium value of 44%

4. the effective polarization over a 12 hours stable run is then 39%

EXPERIMENTS ON BEAM-BEAM DEPOLARIZATION AT LEP

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PAC 1995

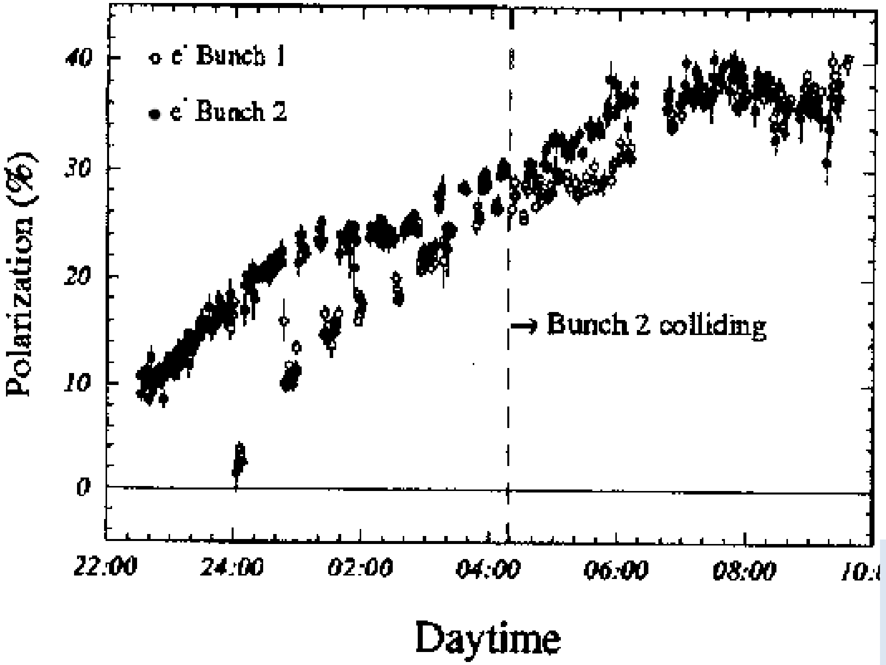

Figure. 3. Polarization level during third experiment

- With the beam colliding at one point, a polarization level of 40 % was achieved. The polarization level was about the same for one colliding and one non colliding bunch.
- It was observed that the polarization level depends critically on the synchrotron tune : when Q_s was changed by 0.005, the polarization strongly decreased.

experiment performed at an energy of 44.71 GeV the polarization level was 40 % with a linear beam-beam tune shift of about 0.04/IP. This indicates, that the beam-beam depolarization does not scale with the linear beam-beam tune shift at one crossing point. Other parameters as spin tune and synchrotron tune are also of importance.

LEP:
This was only tried 3 times!
Best result: P = 40% , ξ^*_y = 0.04 , one IP

TLEP
Assuming 4 IP and ξ^*_y = 0.01 ➔
reduce luminositiy somewhat, 10^{11} Z @ P=40%

Obtaining longitudinal polarization at higher energies requires a cancellation of depolarization effects by reducing the spin-tune spread associated with the energy spread. Siberian snake solutions [11] invoking combinations of spin rotators situated around the experiments and polarization wigglers are being discussed. They take advantage of the fact that the TLEP arcs have very low fields and can be overruled by polarization wigglers suitably disposed around the ring. These schemes will need to be worked out and simulated before the feasibility of longitudinal polarization in high energy collisions can be asserted.

AB, U. Wienans)

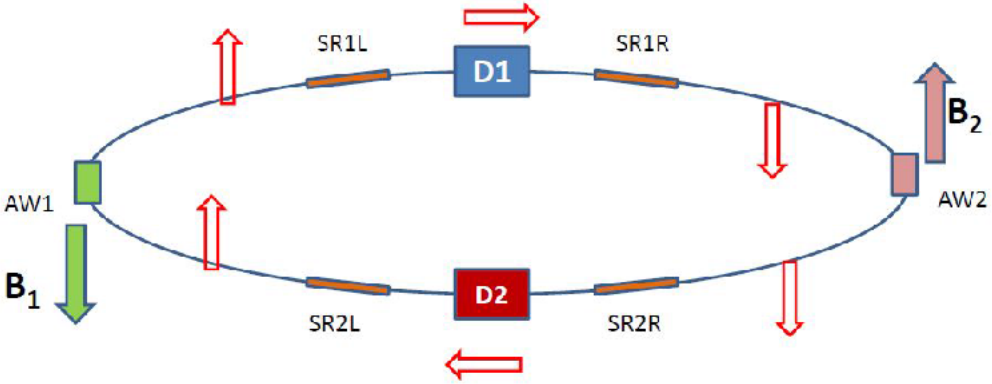

Figure 6: A possible scheme to obtain longitudinal beam polarization at high energies ($E_{beam} >> M_Z/2$) with TLEP: taking advantage of the weakness of the magnetic field in the arcs, the polarization is generated dominantly by strong asymmetric wigglers of opposite polarities (AW1 and AW2) in two halves of the ring. The transverse polarization obtained this way is rotated to longitudinal in the experimental straight sections in detector D1, by 90 degrees spin rotators (SR1L, etc..), and brought back to vertical (but reversed) in the following arc, and similarly for the next experimental straight section, D2. The scheme easily generalizes to the situation with four IPs. This scheme generates a spin transport with an integer part of the spin tune equal to zero. The spin polarization of the electrons is shown. Given separated beam pipes for the e^+ and e^- beams, they can be exposed to wigglers of opposite polarity, providing polarization of positrons can be chosen parallel to that of the electrons. In this way highly polarized e^+e^- systems at the collision point can be obtained. Polarization can be reversed by reversing the wiggler polarity. The possibility of depolarizing a fraction of the bunches in this scheme, to provide a normalization of polarimetry from the measured cross-sections, is being investigated.