FCC-ee

Beam Polarization and Energy Calibration

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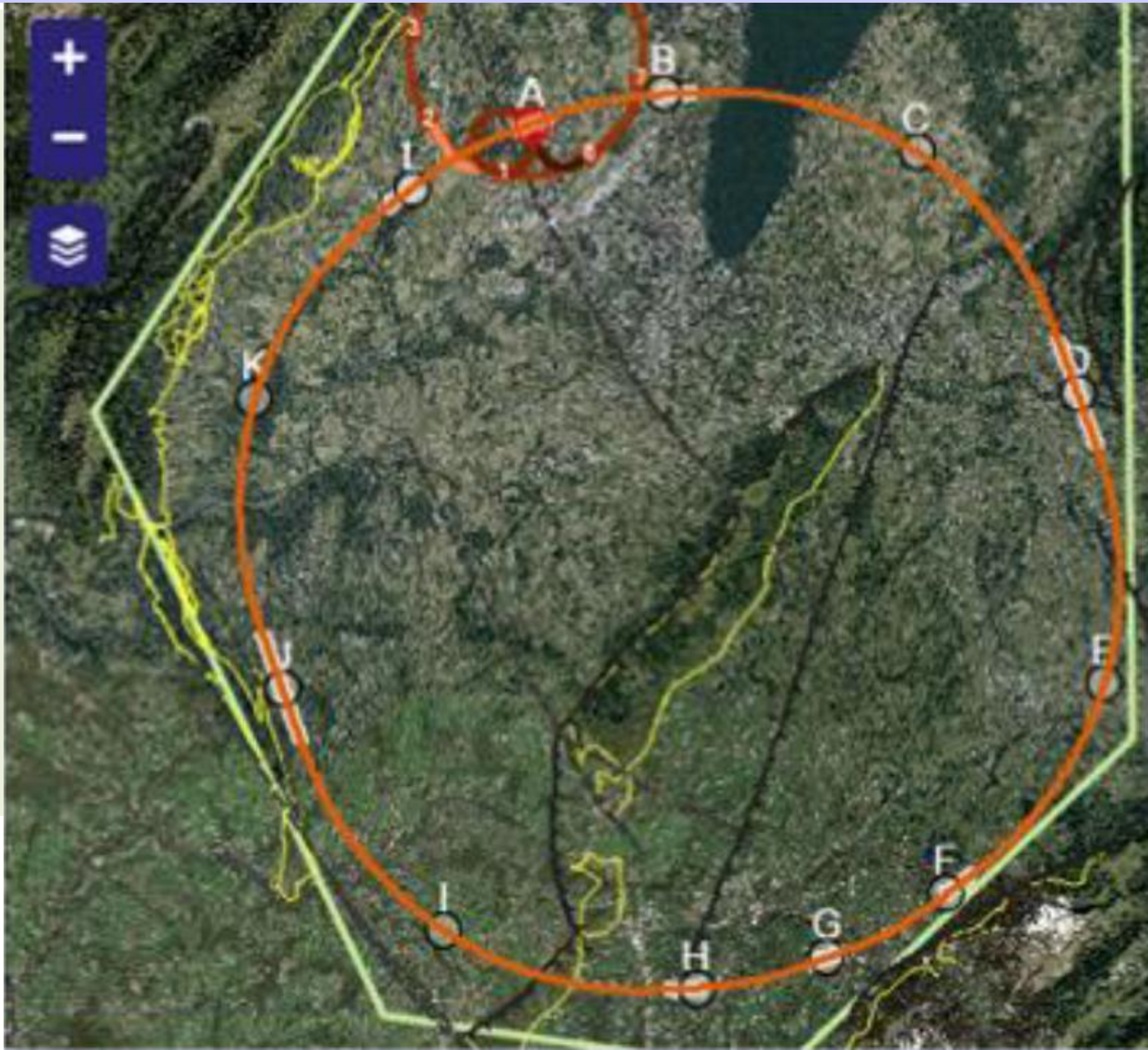


Priorities from Physics

We have concluded that first priority is to achieve transverse polarization
in a way that allows continuous beam calibration by resonant depolarization
(energy measurement every ~10 minutes on 'monitoring' single bunches)

- This is a unique feature of circular e+e- storage ring colliders
- baseline runnig scheme defined with monitoring bunches
- the question of the residual systematic error requires further studies of the relationship between spin tune, beam energy at IRs, and center-of-mass energy

➔ target is 100keV at Z and W pair threshold energies

'Do we want longitudinal polarization'?

lower priority

at Z, W, top: no information that we cannot obtain otherwise
from unpolarized A_{FB} asymmetries or final state polarization (top, tau)
+ too much loss of luminosity in present running scheme to provide gain in precision.

Baseline study:

-- transverse polarization for high precision measurements at Z and WW

-- polarization levels at : Z(91.2+-3), H(126), WW(161+-3) (E_{CM}) → Eliana

-- polarization wigglers → Eliana

-- polarization improvement tools (orbit, harmonic corrections) → Eliana

-- running scheme in physics ← main difference to LEP!

-- polarimeter design → Jorg

-- depolarization and syst. errors on energy determination → Anton

-- from beam energy to center-of-mass energy → Anton

-- ancillary instrumentation ! not adressed today

RF phases and position to IR

precise prediction of saw-toothing

properties of monitoring bunches vs colliding ones ← different from LEP!

relative position, beam size, dispersion, energy spread etc…

Beyond baseline

-- complementary monitoring (spectrometer, Moller scattering) → Jorg

Some Bibliography

[1] R. Assmann et al., "Calibration of centre-of-mass energies at LEP1," *Eur. Phys. J. C 6, 187-223 (1999).*

[2] L. Arnaudon et al., "Accurate Determination of the LEP Beam Energy by resonant depolarization," *Z. Phys. C 66, 45-62 (1995).*

[3] A.A. Sokolov, I.M.Ternov, "On Polarization and spin effects in the theory of synchrotron radiation," *Sov. Phys. Dokl. 8, 1203 (1964).*

[4] A. Blondel and J.M. Jowett, "Dedicated Wiglers for Polarization," *LEP note 606, CERN, 1988.*

[5] R. Assmann et al., "Spin dynamics in LEP with 40–100 GeV beams," in *AIP Conf. Proc. 570 , 169* , 2001.

[6] G. Wilson, "Prospects for Center-of-Mass Energy Measurements at Future e^+e^- Colliders" *talk in TLEP7, 19 June 2014*.

[7] M. Koratzinos, "Transverse polarization for energy calibration at Z-peak", *arXiv:1501.06856 [physics.acc-ph]*

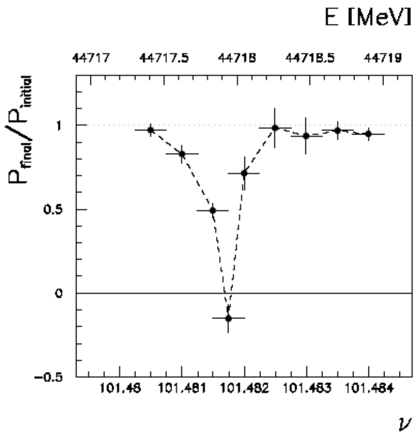
[8] M. Koratzinos, "Beam energy calibration: systematic uncertainties", *talk in TLEP8, 28 October 2014*

[9] *M. Koratzinos, "*FCC-ee: Energy Calibration Options"*, FCC week 2015, Washington.*

[10] *M. Koratzinos et al.,* "FCC-ee: Energy Calibration", *IPAC '15*

[11] *E. Gianfelice* 'Investigation of beam self-polarization in the future *e*+*e*− circular collider' Phys.Rev.Accel.Beams 19 (2016) no.10, 101005 **arXiv:1705.03003v1**

Beam polarization and E-calibration @ FCC-ee



Precise meast of E_{beam} by resonant depolarization

~100 keV each time the meast is made *LEP →*

At LEP transverse polarization was achieved routinely at Z peak.

instrumental in 10^{-3} measurement of the Z width in 1993

led to prediction of top quark mass (179+- 20 GeV) in Mar'94

Polarization in collisions was observed *(40% at BBTS = 0.04 at Z energy)*

At LEP beam energy spread destroyed polarization above 61 GeV

$\sigma_E \propto E^2/\sqrt{\rho}$ → *At FCC-ee transverse polarization up to at least 81 GeV (WW threshold)*

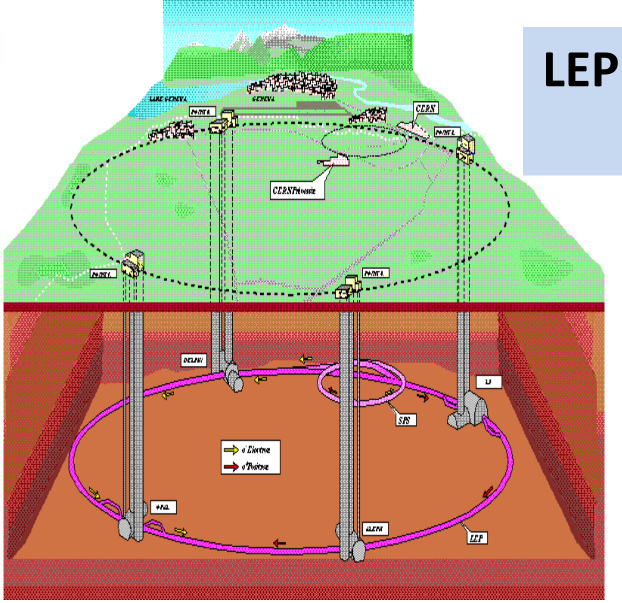
to go to higher energies requires spin rotators and siberian snake

FCC-ee: use 'single' bunches to measure the beam energy continuously

→*no interpolation errors due to tides, ground motion or trains etc…*

<< 100 keV beam energy calibration around Z peak and W pair threshold.

Δm_Z ~0.1 MeV, $\Delta\Gamma_Z$ ~0.1 MeV, Δm_W ~ 0.5 MeV



LEP (1989-2000) first observation of $P_\perp$ in 1990
first resonant depolarization in 1991

$$\tau_p = \left(\frac{5\sqrt{3}}{8} \frac{\hbar r_e E_{beam}^5}{m_e^6 \rho^3} \right)^{-1}$$

=310 minutes
at 45.6 GeV in LEP
250 hours in FCC-eeZ!
14 hours at WW

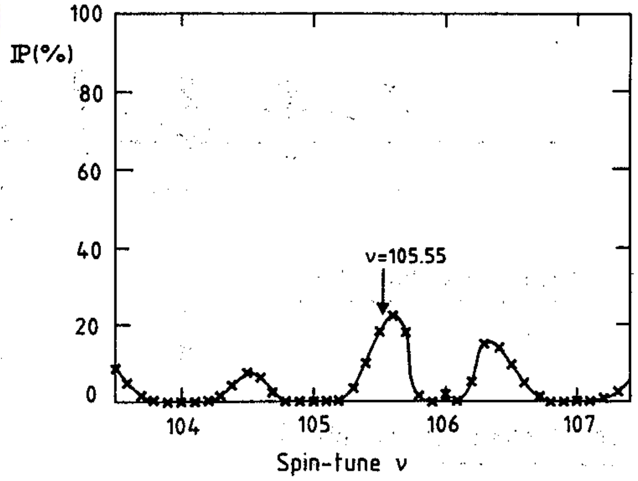
$$P_\infty = 0.924 \times \frac{1}{1+\frac{\tau_p}{\tau_d}} \qquad \frac{1}{\tau_p} \propto \sum_j |B_j|^3 L_j$$

$$\tau_p^{eff} = \tau_p \times \frac{1}{1+\frac{\tau_p}{\tau_d}}. \qquad \frac{1}{\tau_d} \propto \sum_j |B_j|^3 L_j \frac{11}{18} |\Gamma_j|^2$$

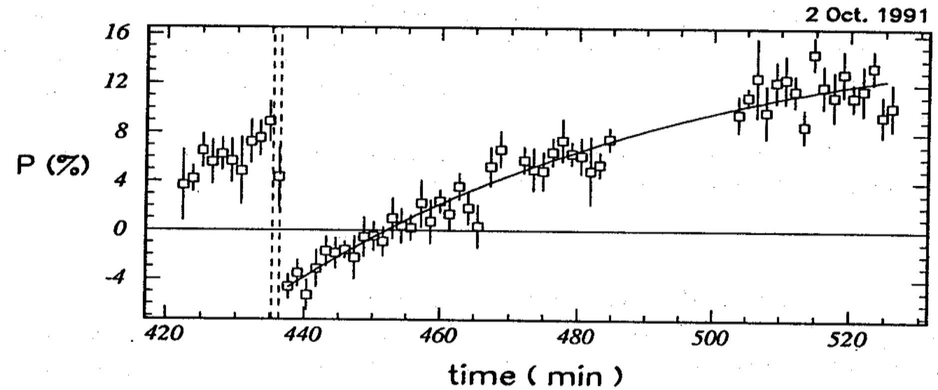
orbit imperfections

$$\nu = a_e \gamma = \frac{g_e - 2}{2} \frac{E_{Beam}}{m_e c^2} = \frac{E_{Beam}}{0.4406486(1)}$$

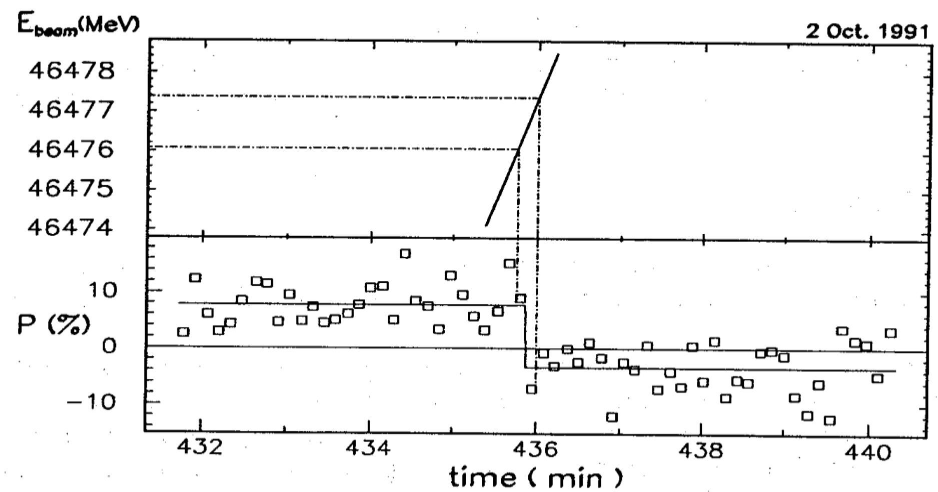
Spin tune at the Z peak : 103.5
The scan points 101.5 / 103.5 / 105.5 are perfect optimum for Z width meast
scan points at 100.5 and 106.5 are good for $\Delta\alpha_{QED}$ measurement
Spin tune for W threshold 180.5 -- 183.5



Self polarization @LEP :
expectations at LEP were O(5-20%)depending on imperfections *(including estimate of energy spread effect) (Koutchouk, 1988)*



10% level sufficient
for resonant depolarization
→ E_{beam}calibration at ±100keV



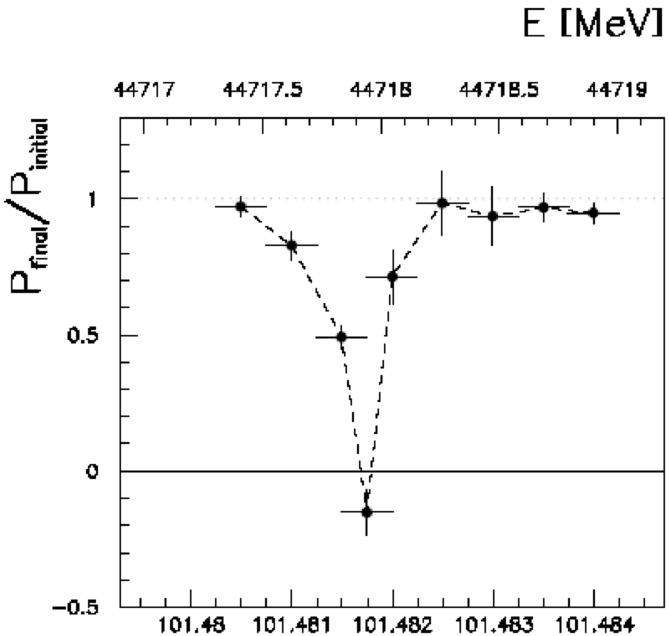
effective polarization time
is also 10% of polarization time

$$P_\infty = 0.924 \times \frac{1}{1+\frac{\tau_p}{\tau_d}}$$

$$\tau_p^{eff} = \tau_p \times \frac{1}{1+\frac{\tau_p}{\tau_d}} .$$

$E_{beam} = 46{,}466.6 \pm 0.6$ MeV, e.g. precise to $\pm 1.5\ 10^{-5}$.

Figure 20: Polarization signal on 2 October 1991, showing the localization of the depolarizi
within the sweep



in 1995 we pushed the measurement to «high precision» (100 keV)

spin tune

SOURCE	ΔE Theoretical estimates	ΔE Experimental upper bound
Electron mass		13 keV
Revolution frequency		<1 keV
Depolarizer frequency		100 keV
Width of excited resonance		100 keV
Interference of resonances		< 100 keV
Quadratic nonlinearities	< 5 keV	< 500 keV
ν_s-shifts from long. fields	< 5 keV	< 500 keV
ν_s-shifts from rad. fields	< 100 keV	< 800 keV
Total systematic error	**100 keV**	
Total upper bound		**< 1.1 MeV**

Table 1: Systematic errors in the measurement of the beam energy by resonant depolarization assuming a well corrected vertical orbit. Quoted errors, evaluated at $E = 45.6$ GeV, are understood to be Gaussian and refer to the energy of a single beam. The contributions in the third column are experimental upper bounds used to compute the total upper bound on the systematic error.

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

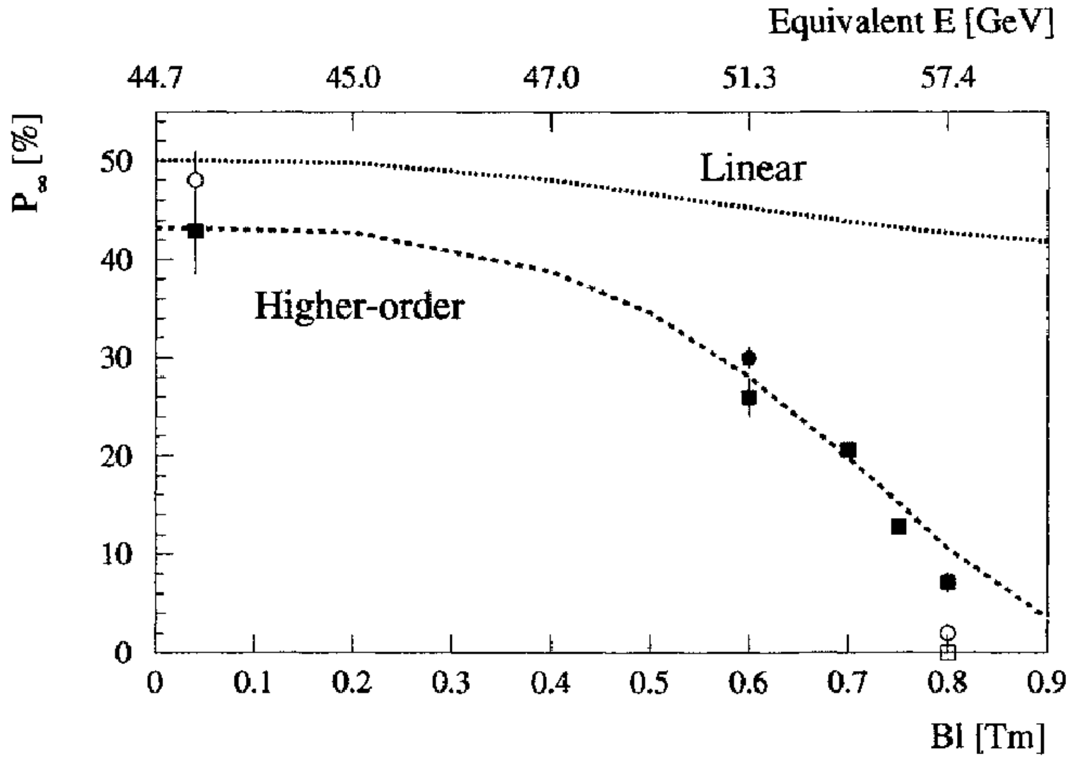
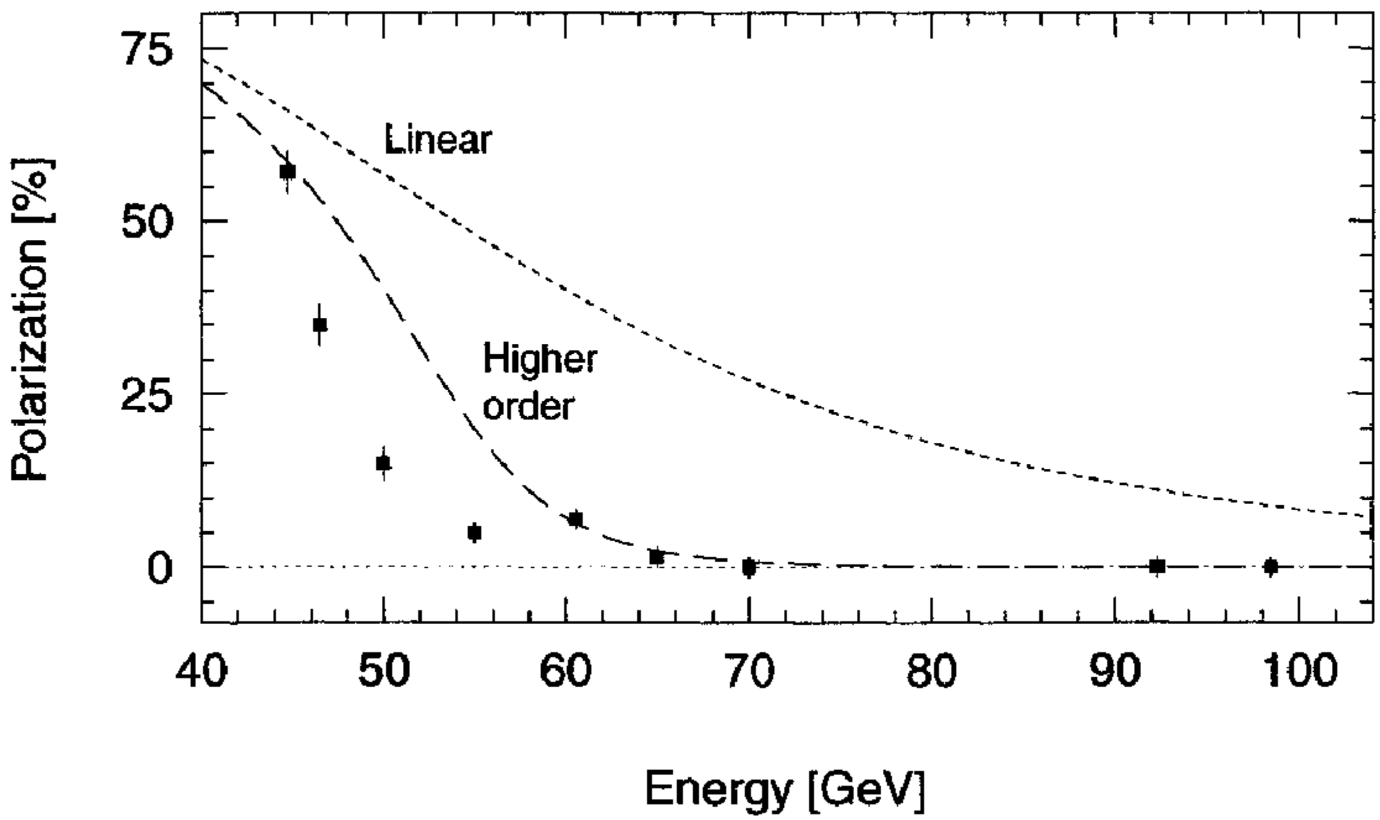


FIGURE 8. Observed polarization level at 44.7 GeV for different excitations Bl of the LEP damping wigglers. The upper scale indicates the beam energy that would produce the same spin tune spread. The polarization measurements are compared to the expectations from linear and higher-order theory.

Energy spread should not exceed ~55 MeV

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



The good news is that polarization in LEP at 61 GeV corresponds to polarization in FCC-ee at >80 GeV

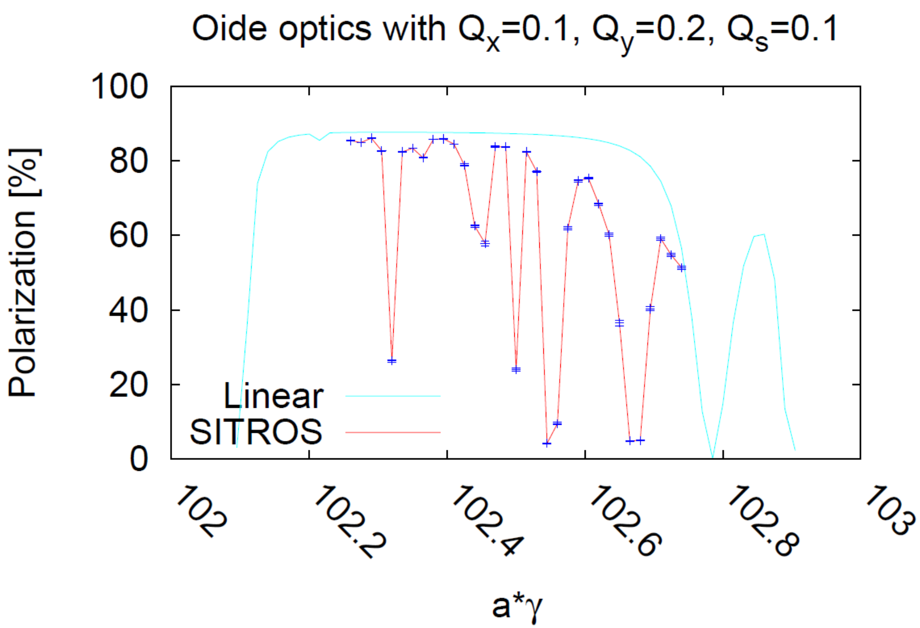
➔ Good news for M_W measurement (see E. Gianfelice's presentations)

These observations were consistent with the hypothesis that energy spread drives the synchrotron resonances.
We were able to keep the polarization as long as $\sigma_E < 56$ MeV.

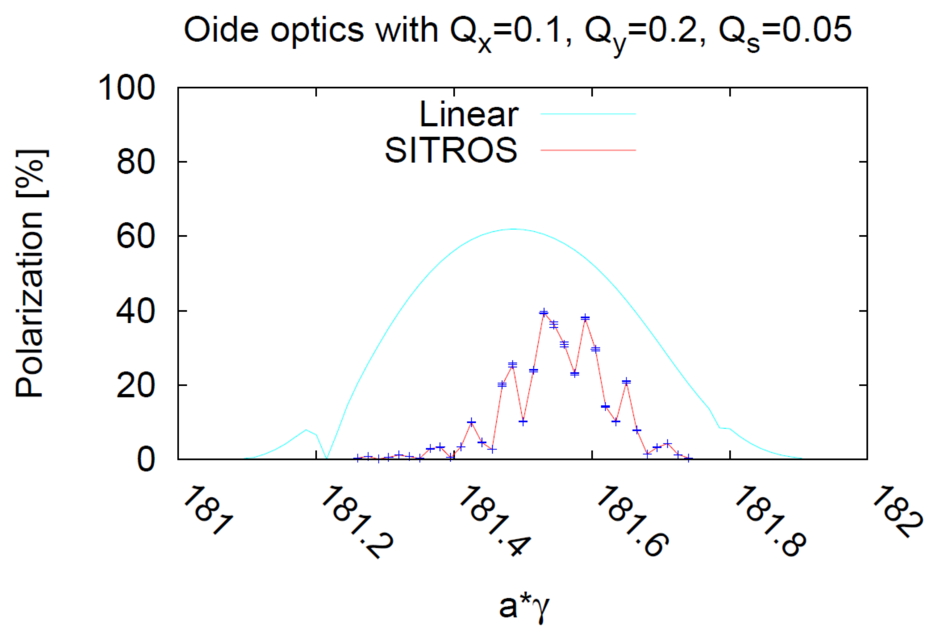
In a larger ring the energy spread is smaller ☺

But the polarization time is much longer
→ need to use wigglers within limit of energy spread.

45 GeV



80 GeV



At the Z obtain excellent polarization level but too slow for polarization in physics need wiggler for Energy calibration

At the W expecation similar to LEP at Z → enough for energy calibration

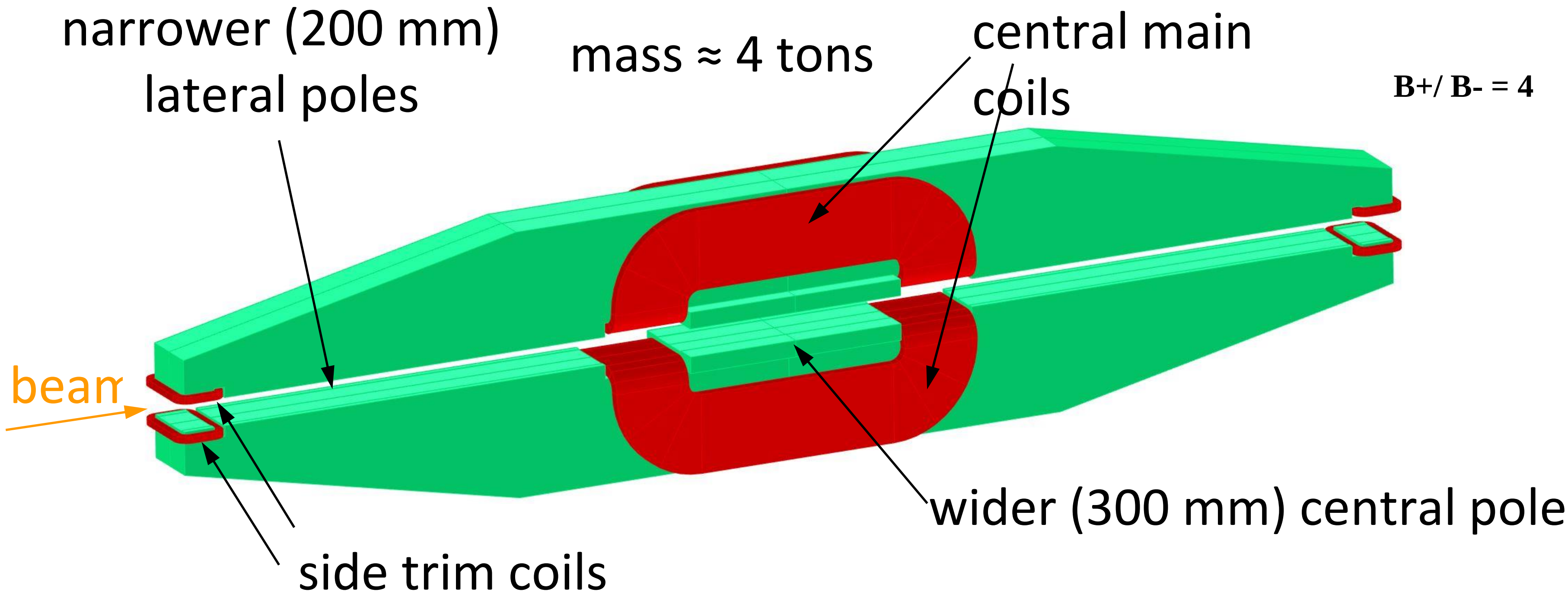
Simulations by Eliana Gianfelice

Running mode

- The process is e+/e- symmetric and independent
- Inject 300 (out of 30,000 - 75,000 at the Z), 50 out of 5260 at the WW

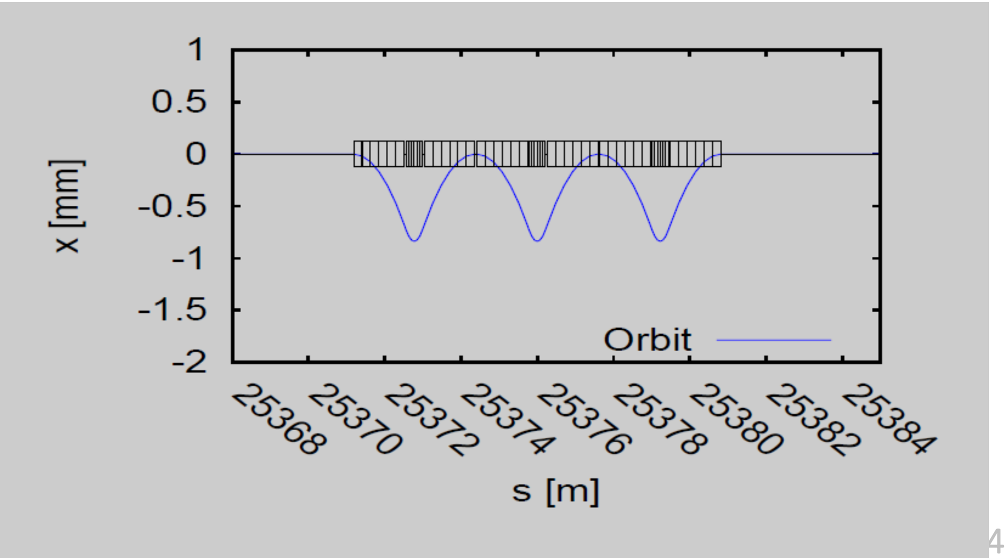
  non- colliding bunches in each beam (1%)
- Use wigglers to achieve polarization of these bunches at a level of 9%, adequate for depolarization measurements – a 50-100 minute dead-time is introduced where no line shape physics can take place. Fills need to be long to compensate
- Switch off wigglers and start line shape physics data taking with colliding bunches, which are continuously filled up (and therefore build up no polarization)
- Perform a depolarization measurement every 10 minutes – 6 per hour.
- When all non-colliding bunches will be exhausted, the new non-colliding bunches would have achieved a meaningful natural polarization.
- Similar procedure at the Z and W energies, no wigglers are needed at the WW

A first magnetic concept of the FCC-ee wigglers *(A. Milanese)*



8 such magnets per beam with B=0.7T will shorten life time to 25hrs at the

However smaller magnets in series → lead to smaller horizontal excursion smaller emittance blow-up
(Gianfelice)



Wigglers

- Wigglers are essential since natural polarization time is long but have two undesired effects:
- They increase the energy spread
- They contribute to the SR power budget of your machine
- Strategy is to use them is such a way that
  - The energy spread is less than some manageable number (so that no resonances are encountered).
  - Switch them on only where necessary and only on the monitoring bunches

Machine	Energy	No. of wigglers	B+	Polarization time to 9%	Energy spread	Wiggler SR power
FCC-ee	45	0	0	25 hours	17MeV	0
FCC-ee	45	8	0.7T	2.1 hours	52MeV	20MW*1%
FCC-ee	45	1	1.35T	2.4 hours	52MeV	9MW*1%

Lose ~2h at the beginning of (hopefully) very long fills – can reduce this if lower polarization levels could be distinguished by the polarimeter

Systematic Errors

– **Resonant depolarization errors**

theoretical estimates
design test experiments

– **Energy spread error (for Z width)**

Cannot use the bunch length at IP
needs measurement of energy spread

– **IP specific correction (RF) errors**

requirements on RF distance to IR and phases

– **Beam energy to IR errors**

saw-tooth small at Z

– **Energy difference of colliding and non-colliding bunches**

BPM, etc… must have differential position meast capabilities

-- **Relationship between spin-tune and beam energy at IPs**

need dedicated simulation tools
e.g. spin tracking including FFT
(D. *Barber*)

FCC-ee Center-of-mass Energy Calibration and Beam Polarization

authors

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CONCLUSIONS

-- A beam Energy Calibration and Polarization (EPOL) was created 6 mo. ago

-- There is a straightforward baseline running mode for the Z and W (poss. H(126))
with continuous Energy Calibration on 1% non-colliding bunches
in order to aim at $\pm$100 keV beam energy calibration

-- Polarization prospects for Z and WW are good, sufficient for the energy calibration,
Experiments can calibrate at higher energy with WW, γZ events (~$\pm$5-10 MeV)
this is sufficient for top and Higgs mass measurements

-- final word on precision requires much further work on systematic effects

-- a list of required hardware and instrumentation will be produced
essential to ensure continuity and some redundancy

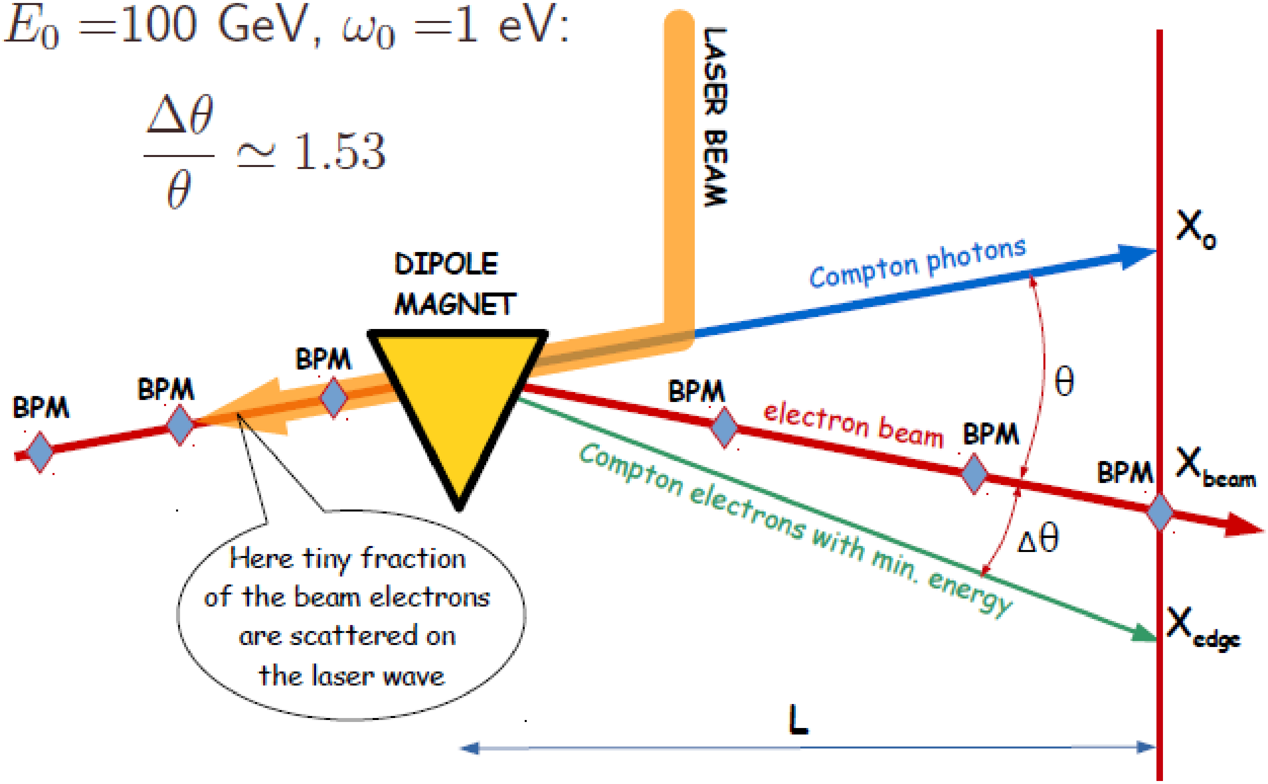
-- Computing tools for beam polarization (presently approximate)
will need to be further developped

SPARES

Spectrometer with laser calibration (suggestion)

E_0 =100 GeV, ω_0 =1 eV:

$$\frac{\Delta\theta}{\theta} \simeq 1.53$$

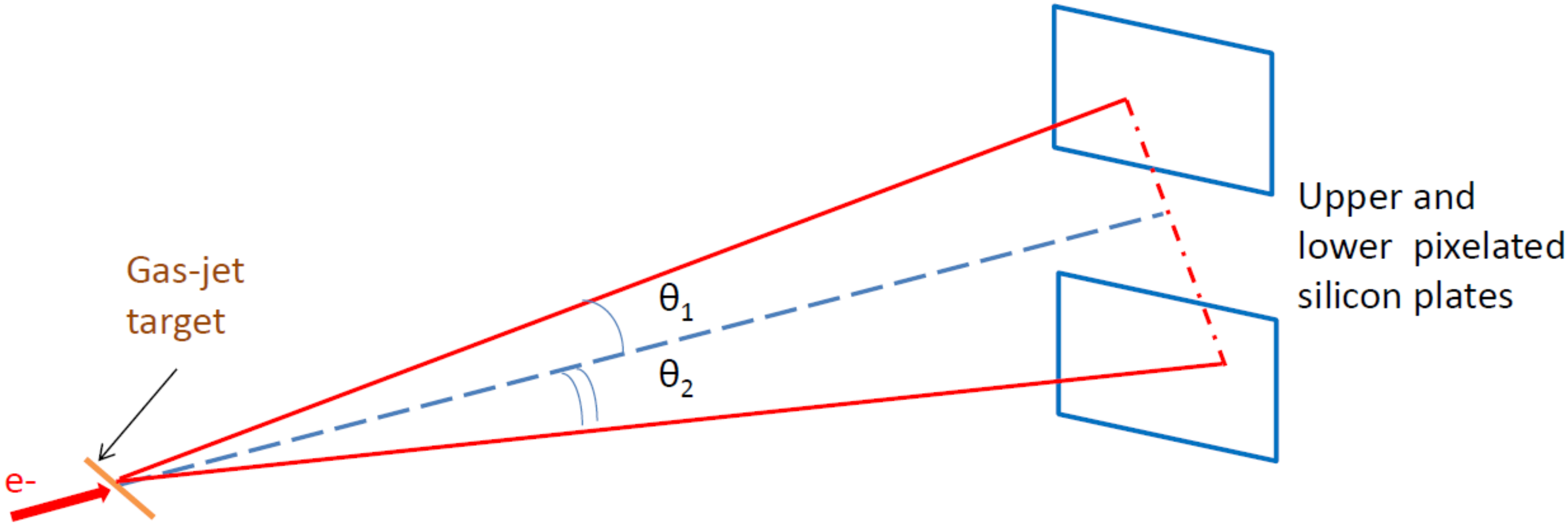


Access to the beam energy: $E_0 = \frac{\Delta\theta}{\theta} \times \frac{m^2}{4\omega_0}$

Koop, Munchnoi

Möller scattering spectrometer

ee-scattering spectrometer setup



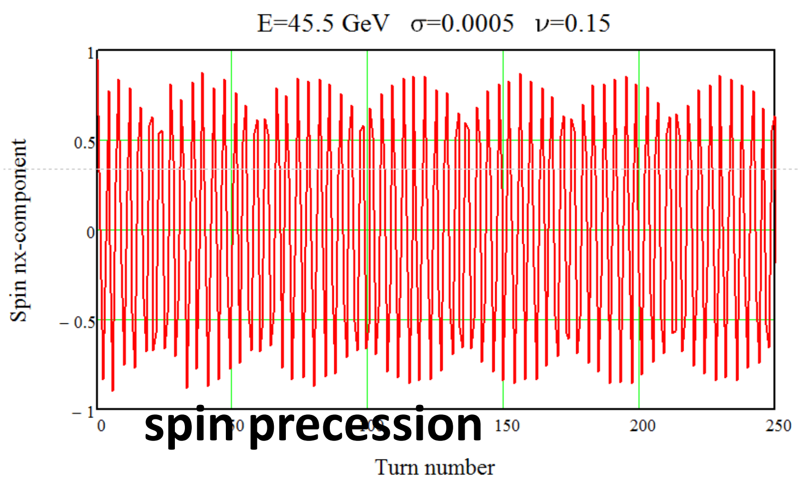
$$\min \quad \frac{\tan(\theta_1)+\tan(\theta_2)}{2} \rightarrow x_0 = \frac{1}{\gamma_{cm}} = \sqrt{\frac{2}{\gamma+1}}$$

Injection of polarized e- or e+ beams → precession in horizontal plane (Koop)

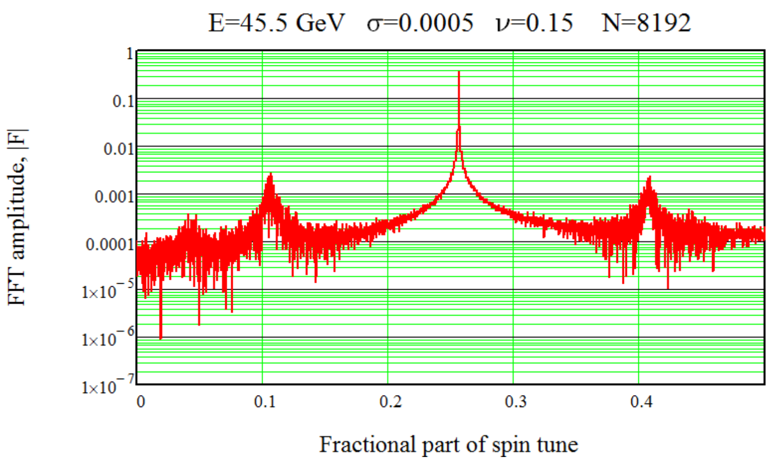
- Production of polarized electrons from a laser photocathode
- Production of polarized positrons in a small energy damping ring (1-2 GeV), with polarization time in the order of 10 min
- Acceleration of polarized beams via linac, SPS , booster storage ring (100 km) using Siberian Snakes. → 8000T.m of SC solenoids
- Injection of polarized bunches into the collider rings with the horizontal spin orientation.
- Measuring turn by turn free precession frequency using the longitudinal Compton polarimeter.

3kHz

beautiful! but
.... lots of hardware



spin precession



Resonant depolarization accuracy at FCCee – goal

Per beam, not ECM

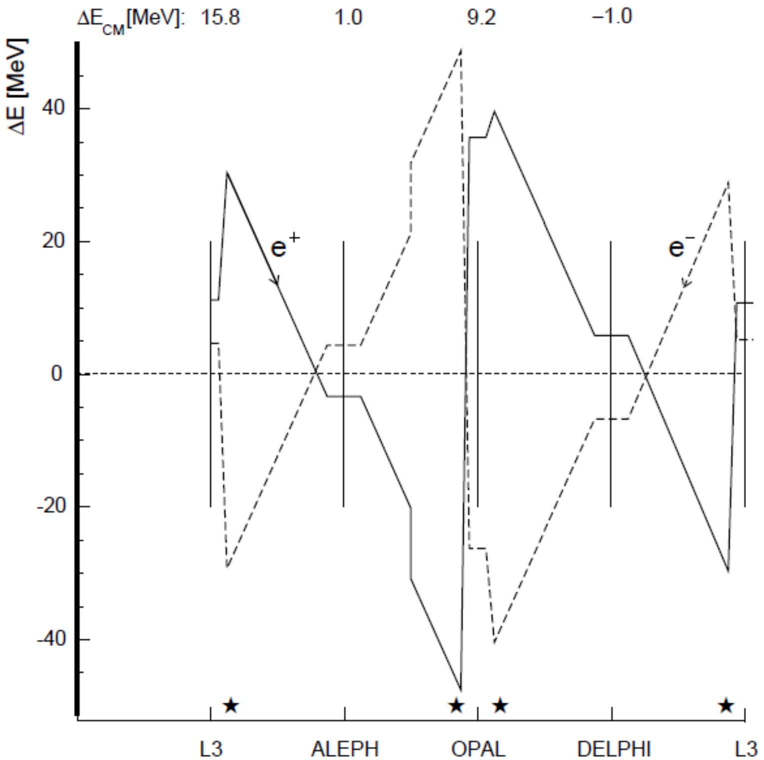
Source	$\Delta E/E$	ΔE (E=45.6 GeV)	Correlated/Z mass	Uncorrelated / Z width
Electron mass	$3 \cdot 10^{-7}$	15 keV	15keV	0keV
Revolution frequency	10^{-10}	0 keV	0keV	0keV
Frequency of the RF magnet	$2 \cdot 10^{-8}$	1 keV	1keV	0keV
Width of excited resonance	$2 \cdot 10^{-6}$	90 keV	1keV	1keV
Interference of resonances	$2 \cdot 10^{-6}$	90 keV	9keV	9keV
Spin tune shifts from long. fields	$1.1 \cdot 10^{-7}$	5 keV	5keV	5keV
Spin tune shifts from hor. fields	$2 \cdot 10^{-6}$	100 keV	3keV	1keV
Quadratic non-linearities	10^{-7}	5 keV	5keV	5keV
Total error	$4.4 \cdot 10^{-6}$	200 keV	~20keV	~12keV
IP specific errors			~40keV	~20keV
total			~45keV	~23keV

- Statistical errors are divided by sqrt(10,000) - negligible
- This is a first attempt at quantifying the errors and can be considered as a wish
- The table should eventually also include effects that were negligible at the time of LEP

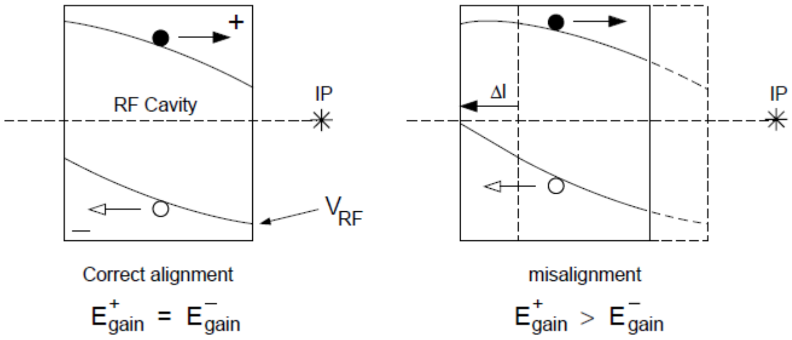
Energy spread

- Total error at LEP was 1000keV translating to 200keV for the Z width
- The method used at LEP (which was measuring the bunch length at the IP) cannot be used at the FCC-ee due to the crab waist scheme being used
- another method should be used: for instance an SR camera at a place of large known dispersion (in the arcs)
- Energy spread at the Z is 17MeV. We need a system that can measure this to 0.1% (not the accuracy of individual measurements, but the accuracy of the method) → 20keV per beam translating to 7keV for the Z width (numbers need to be checked)

IP specific (RF) corrections



Errors arise due to cavity misalignments primarily:



- At LEP cavity misalignment was assumed to be 1.4mm in 1995

Work is needed to reduce this error. For LEP the error was of the order of 500keV (leading to an error of 400/200keV for the mass/width of the Z. Need to reduce this error by (more than) a factor of 10!

This might be the dominant error at FCC-ee

Beam energy to E_{CM}

- $E_{CM} \neq E_{e^+} + E_{e^-}$! (in general)
- At LEP, opposite sign vertical dispersion introduced a correlation between ECM energy and bunch collision offset
- Dispersion difference at the IP was ~2mm

$$\Delta E_{\mathrm{CM}} = -\frac{1}{2} \cdot \frac{\delta y}{\sigma_y^2} \cdot \frac{\sigma_{E_b^2}}{E_b} \cdot \Delta D_y^* \qquad (18)$$

Collision offsets were sub-micron!

Table 13. The luminosity-weighted collision offsets $\langle \delta y \rangle_{\mathrm{lum}}$

	$\langle \delta y \rangle_{\mathrm{lum}}$ (μm)			
	IP2	IP4	IP6	IP8
P−2	0.43±0.17	0.53±0.19	0.34±0.24	0.18±0.16
P+2	−0.05±0.17	−0.36±0.19	0.15±0.30	−0.16±0.24

Table 15. The centre-of-mass energy correction ΔE_{CM} due to dispersion effects. The error is due to the error on the determination of the collision offset δy

	ΔE_{CM} (MeV)			
	IP2	IP4	IP6	IP8
P−2	−0.99±0.39	0.69±0.24	−0.48±0.33	0.29±0.25
P+2	0.12±0.39	−0.47±0.24	−0.21±0.41	−0.26±0.38

To avoid the problem, we should run with zero OSVD!

LEP error (ECM) ~400keV

Non-colliding to colliding bunch energy difference

- At FCC-ee we are obliged to routinely measure non-colliding bunches
- These have a different tune shift and do not suffer from beamstrahlung
- We should model any systematic average energy difference…
- …but also measure this difference in a dedicated MD where we polarize all bunches, switch top-up injection off and then measure (quickly!) the difference in energy between colliding and non-colliding bunches

W physics

$$\sigma_E \propto \frac{E^2}{\sqrt{\rho}}$$

- In contrast to LEP, adequate polarization levels are expected to exist at the FCC-ee since the energy spread decreases in a larger ring (to be verified)
- Analysis will be similar to the Z, and resulting error much smaller than what was achieved at LEP (that had to rely on large extrapolation)
- The statistical error is expected to be 0.3MeV (which is much larger than what can be achieved at the Z), so we can be fairly confident that the systematic error due to the energy uncertainty will not be a limiting factor

Issues - summary

- Hardware:
  - Develop a performant polarimeter
    - Need at least 2
    - Aim to be able to perform a measurement with precision of <1% in one minute.
  - Develop a beam size measuring device at a place of known dispersion for energy spread measurements
  - Develop (polarization) wigglers
- Software: full polarization simulation software analysis
- RF system errors: investigate what positioning accuracy is needed, if it is achievable and how we can independently verify.
- Model energy difference of colliding/ non-colliding bunches and perform a verification measurement
- …

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)

80 km machine!)

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.

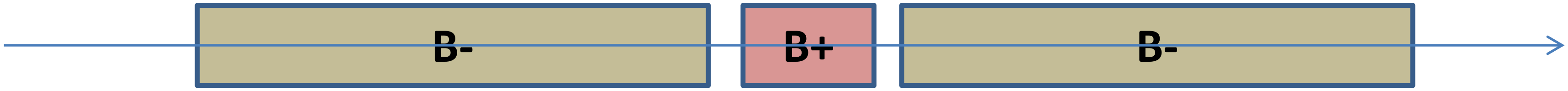
consider somewhere between 48 and 58 MeV as maximum acceptable for energy spread*). Take 52 MeV for the sake of discussion.
Note that wigglers make energy spread worse faster at TLEP (damping is less)
☺ There is no need for wigglers at 81 GeV.

*) 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 $\tau_P{}^{eff}$ = 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

D. Brandt, O. Gröbner, J.M. Jowett, T.M. Taylor, T. Tortschanoff, CERN
CH-1211 Geneva 23

EPAC 1992

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

The LEP damping and emittance wigglers are a better model.

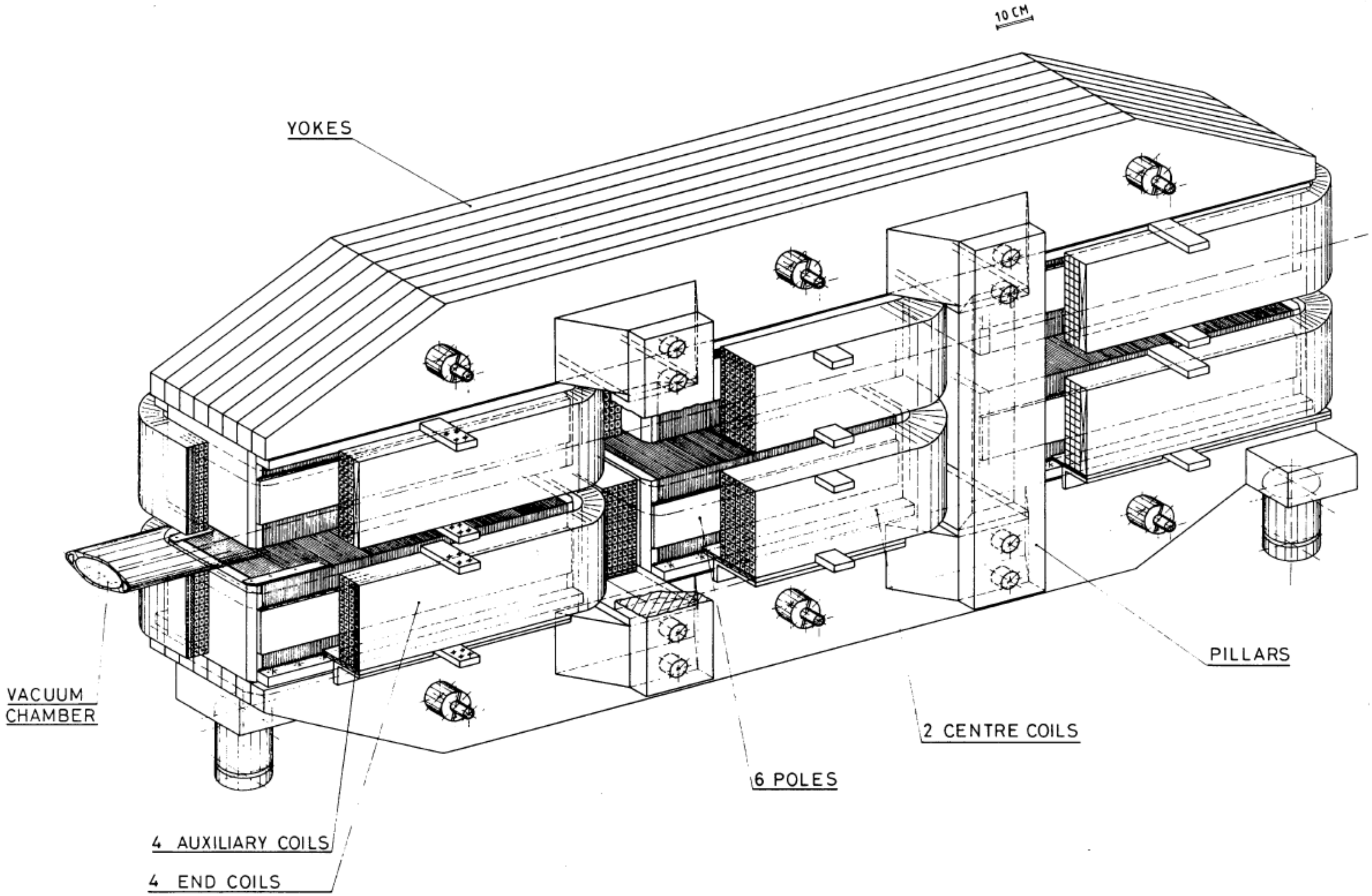
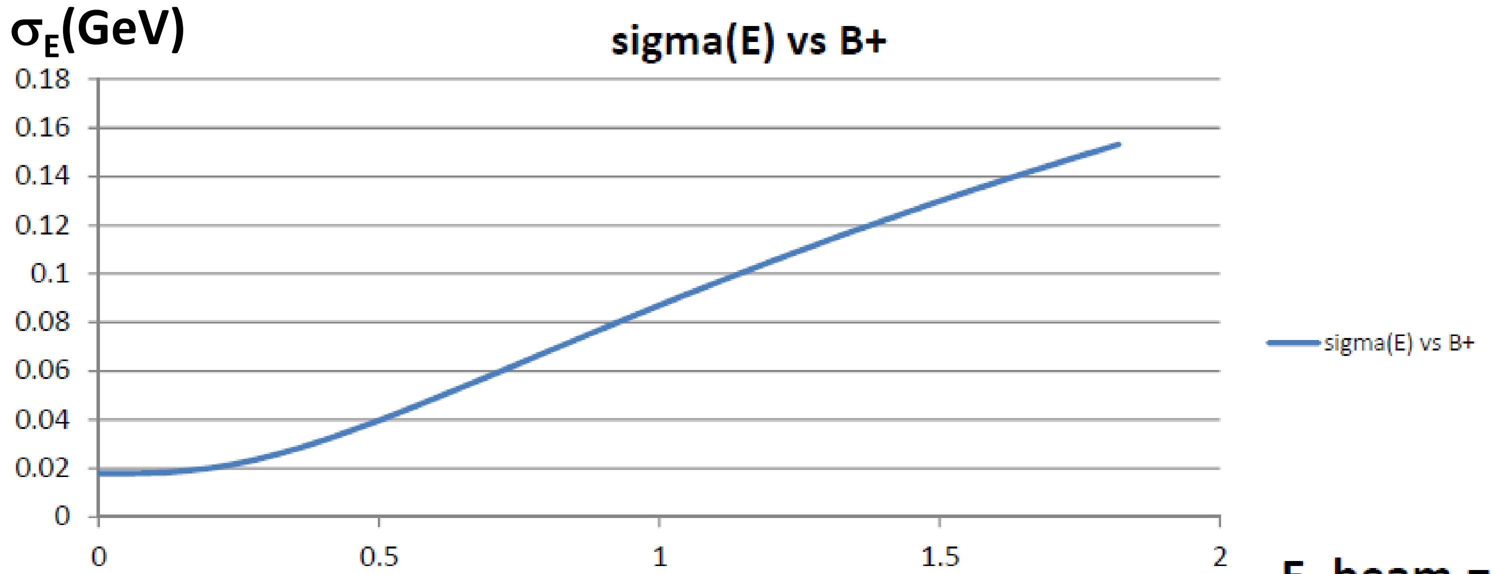
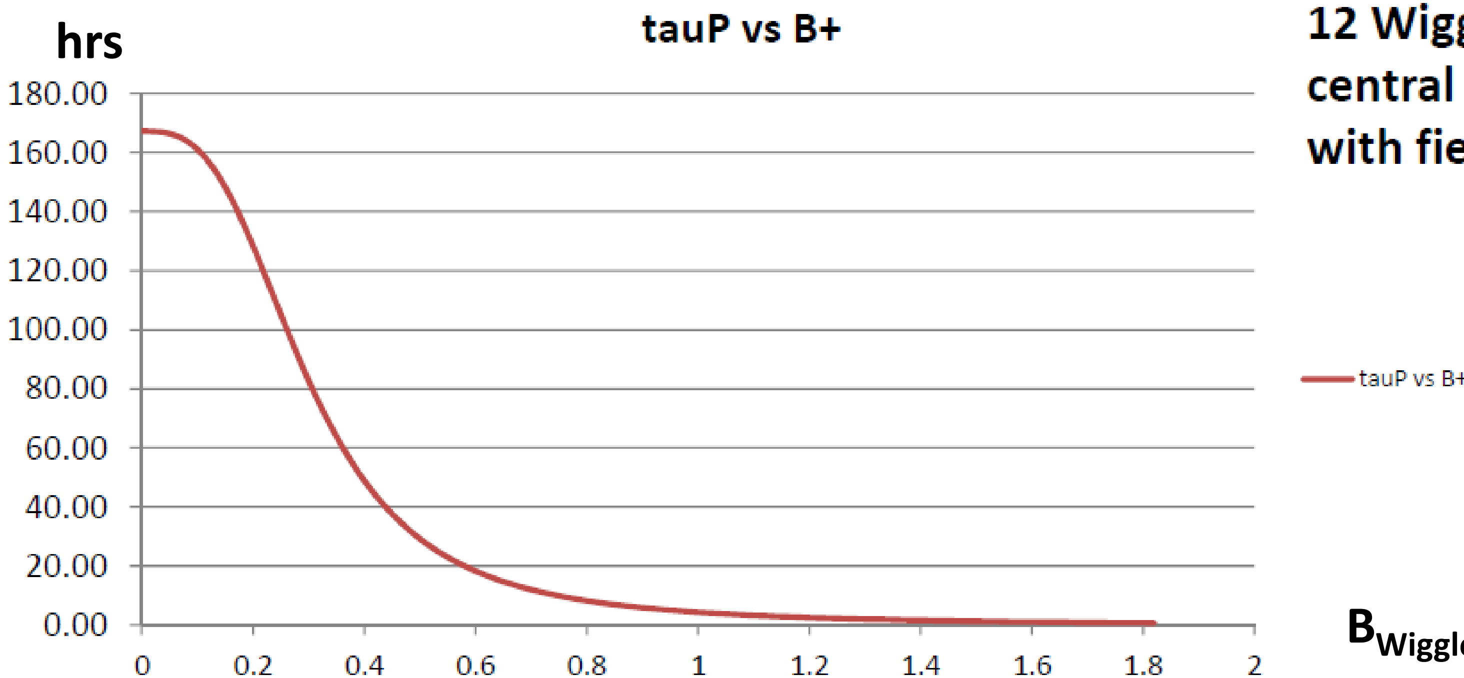


Fig. 3 Proposed LEP wiggler magnet

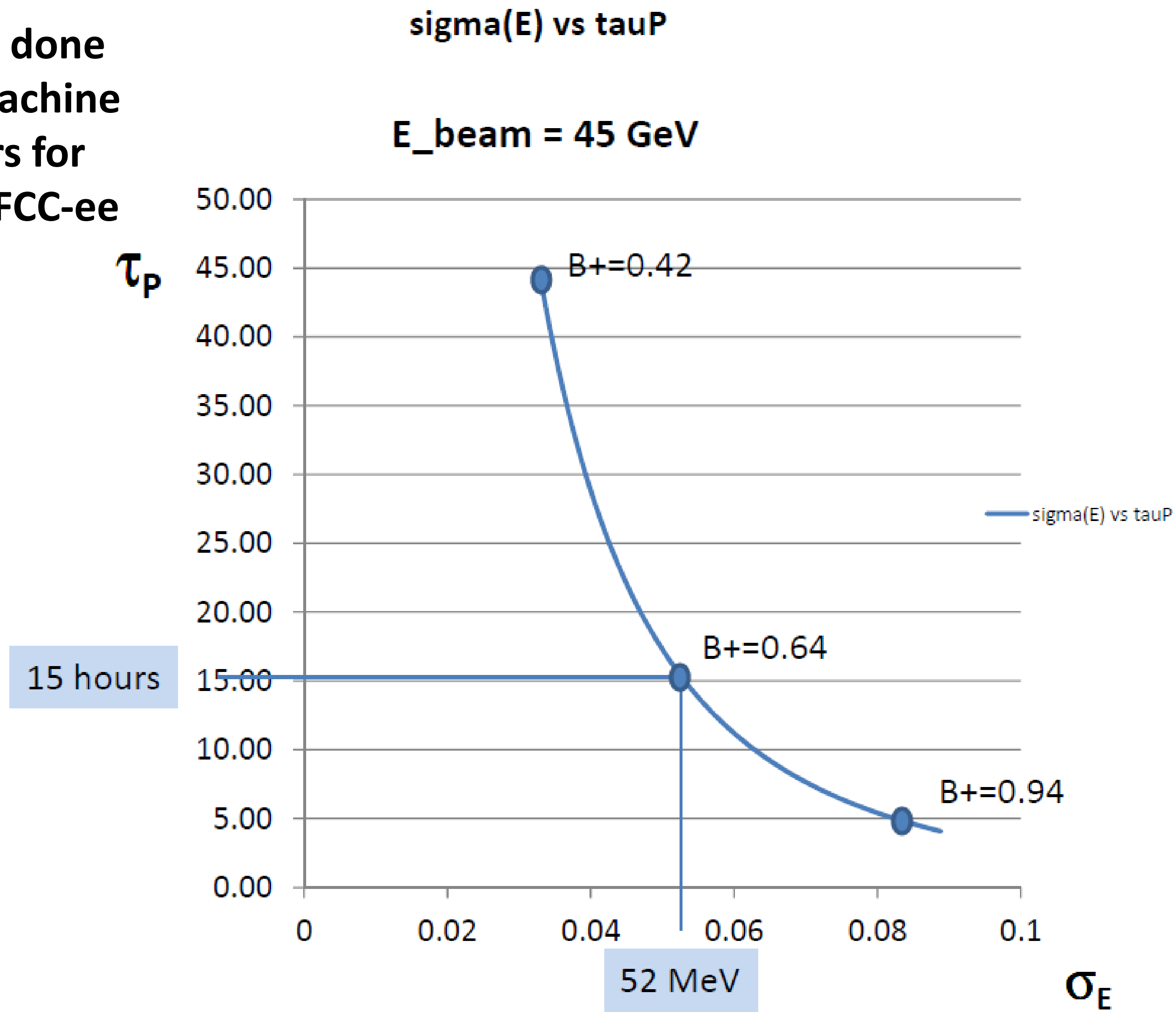




E_beam = 45 GeV
12 Wigglers
central pole is 65 cm
with field B+

$B_{Wiggler}$(T)

NB this was done for 80km machine itsa 25 hours for the 100km FCC-ee



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.

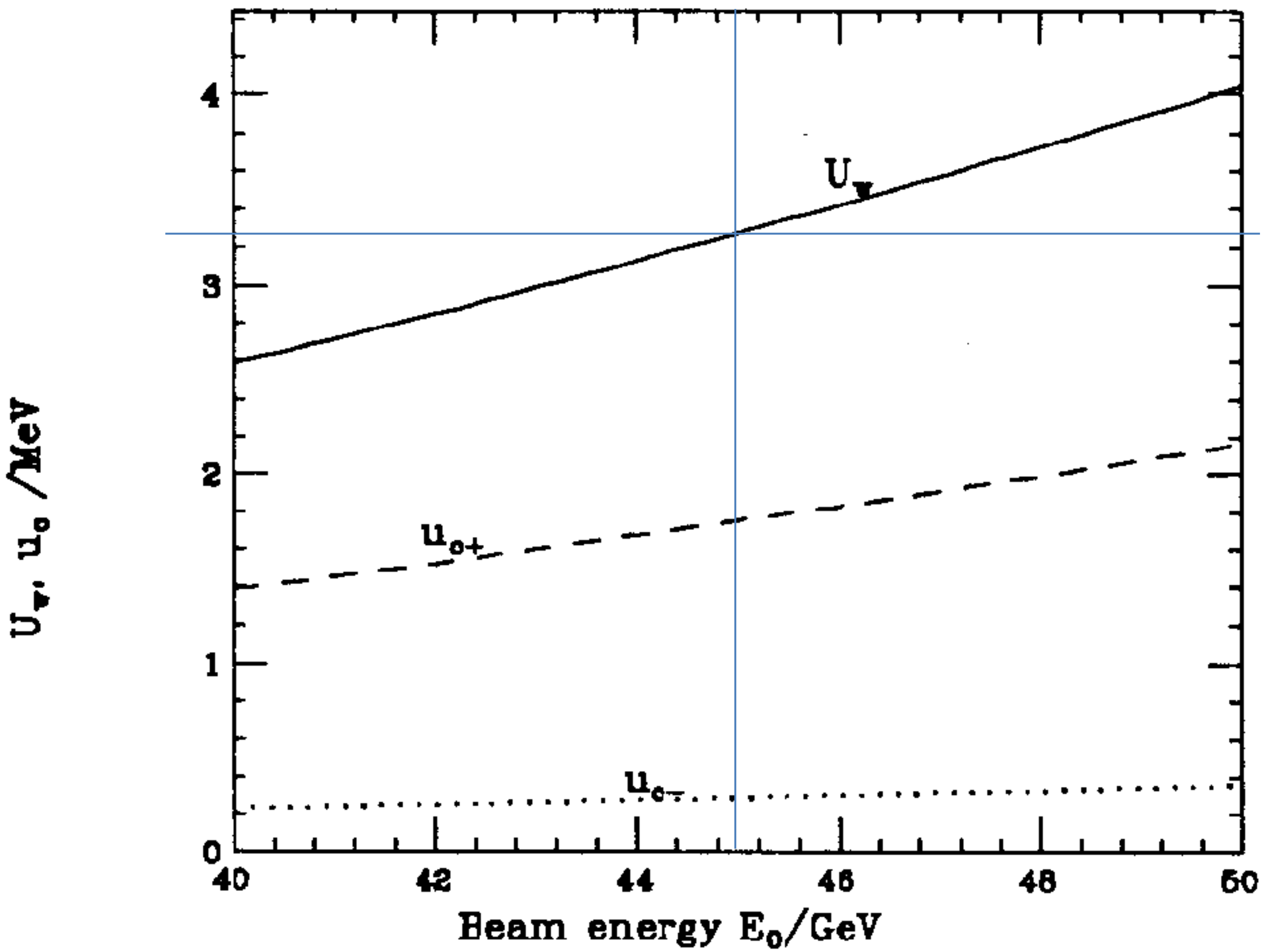
At LEP the energy loss per particle per turn is 117 MeV/turn in the machine with no wiglers and becomes 156 MeV per turn with the 12 wigglers at full field. From this it follows that in the machine running at 45 GeV and wigglers at full field the radiation power in the wigglers would have been 25% of 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 go in the wigglers. (if we use it on full current)

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

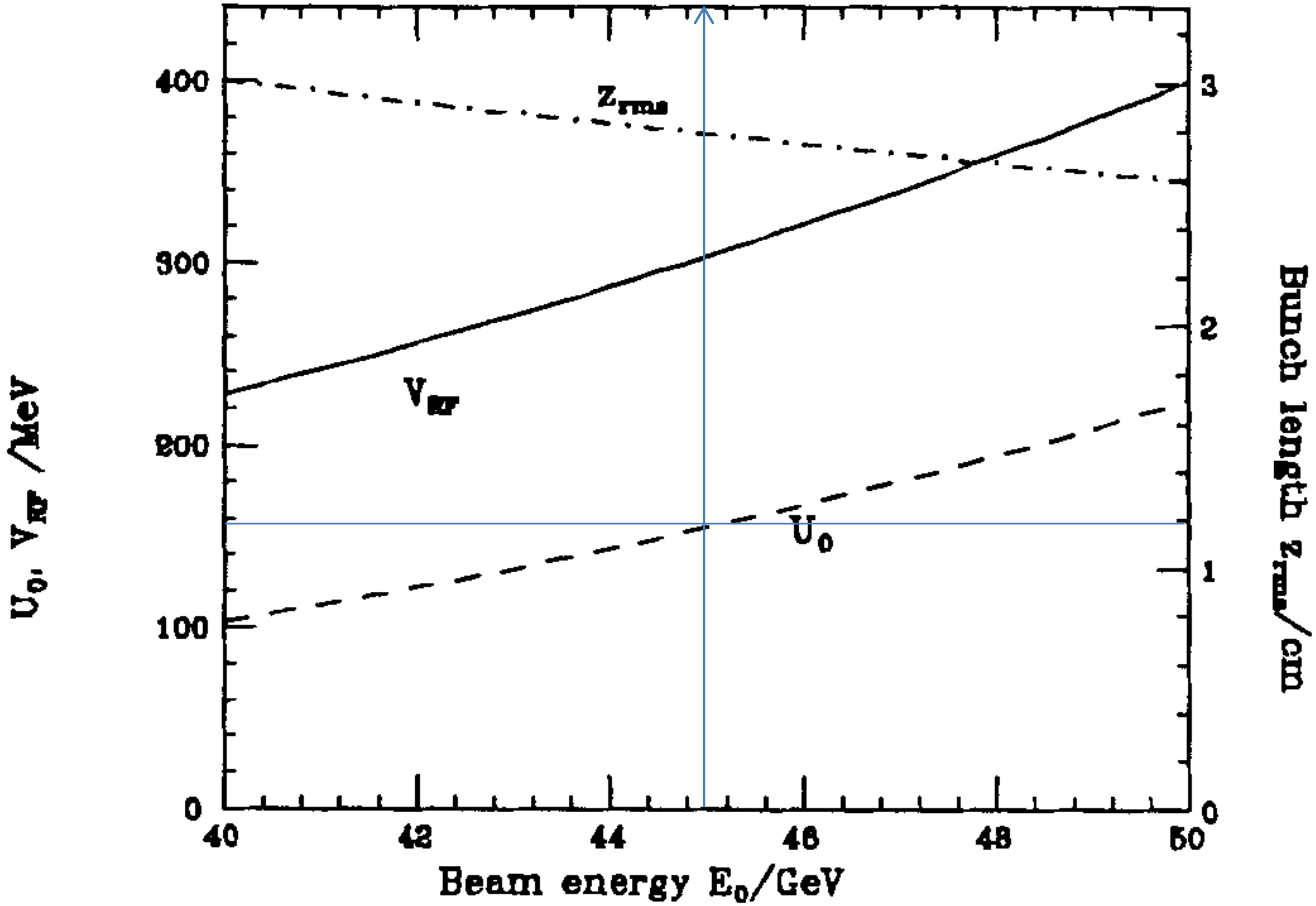


Figure 7: Longitudinal parameters with $B_+ = 1.3\,\mathrm{T}$; the RF voltage is adjusted to maintain 15 h longitudinal quantum lifetime. The bunch length and total radiative energy loss per turn are also shown.

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.

TLEP

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?

Polarization in collisions

$$P_{\perp}^{\infty} = \frac{8/5\sqrt{3}}{1 + \left(\frac{\tau_p}{\tau_d}\right)_{orbit} + \left(\frac{\tau_p}{\tau_d}\right)_{BB}}$$

CERN-SL-26-021

v = 101.5
11-1994
ξ_y = 0.04

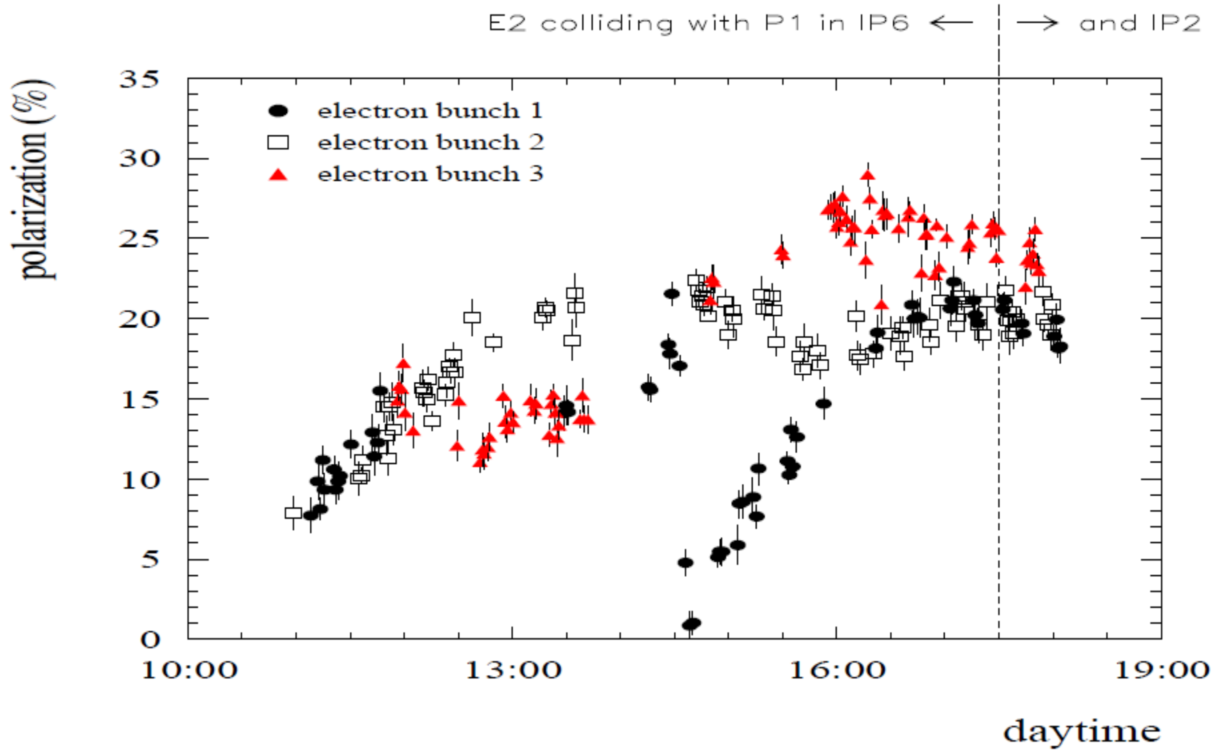


Figure 5: Polarization with colliding beams. With the adoption of a purely Deterministic *HSM* scheme the maximum polarization level attained by the non–colliding electron bunch *E*3 was about 25% while the colliding bunch *E*2 reached a maximum of ~20%. The electron bunch *E*1 was depolarized on purpose to calibrate the polarimeter scale through the Sokolov-Ternov polarization rise time.

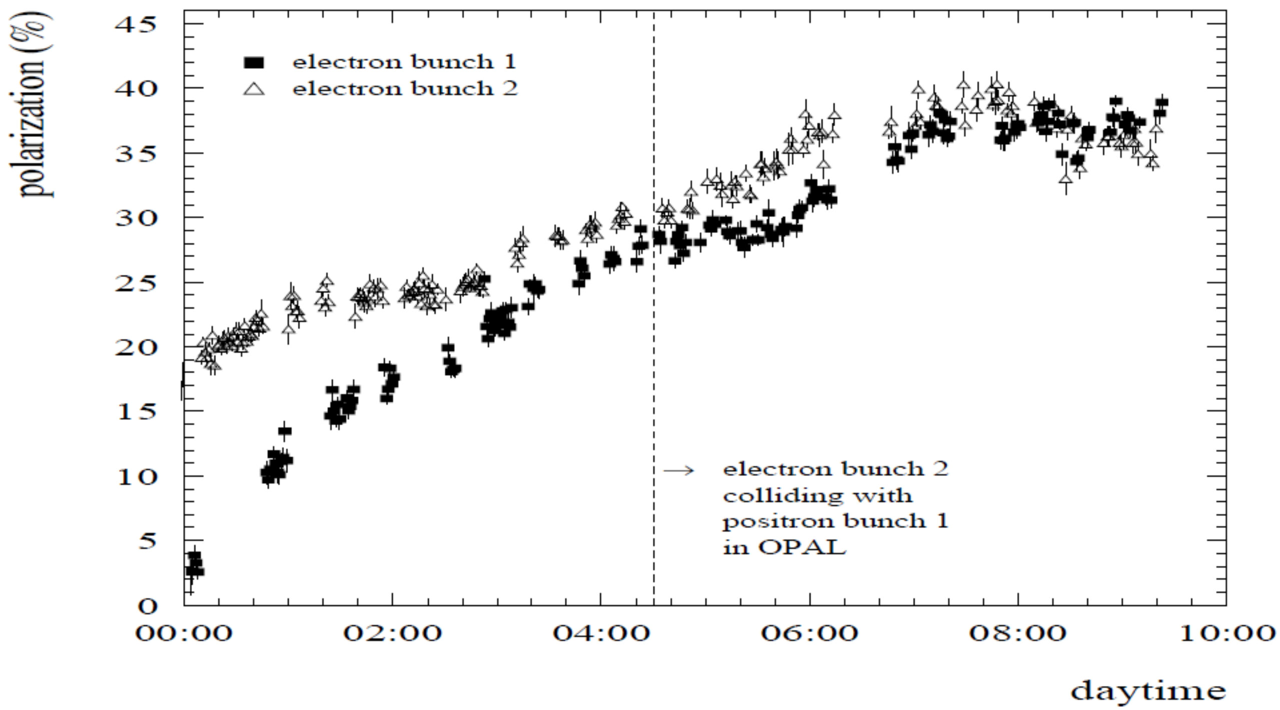


Figure 6: Polarization for colliding and non–colliding electron bunches was raised up to a 40% level during the last experiment in the 1994 LEP Run with the adoption of Empirical and Deterministic *HSM* which allowed for polarization to keep rising after the $E2$ electron bunch was made to collide with the positron bunch $P1$ in the OPAL experiment.

Date	MODE	P_∞	$(\tau_p/\tau_d)_{orbit}$	$(\tau_p/\tau_d)_{BB}$	y_{rms}/mm	ξ_y
23.08.93	1 beam	57%	0.62	–	0.33	–
16.11.94	2 beams, Sep.	26%	2.55		0.45	
	Colliding	22%		0.65		0.037
05.12.94	2 beams, Sep.	40%	2.7		0.36	
	Colliding	38%		≤ 0.3		0.040

Table 3: Comparison between the experiments 1994 and the High Polarization experiment in 1993. All experiments performed at PEAK-2 CM energy and with *HSM* .

Beam beam depolarization is not very large. $(\tau_p/\tau_d)_{BB}$ **< 0.65**

Alone, and for one exp. it would have limited the polarization to ~55%

Predictability is low.

Longitudinal polarization at LEP?

scheme developed in 1988 see A.B. CERN-PPE-93-125

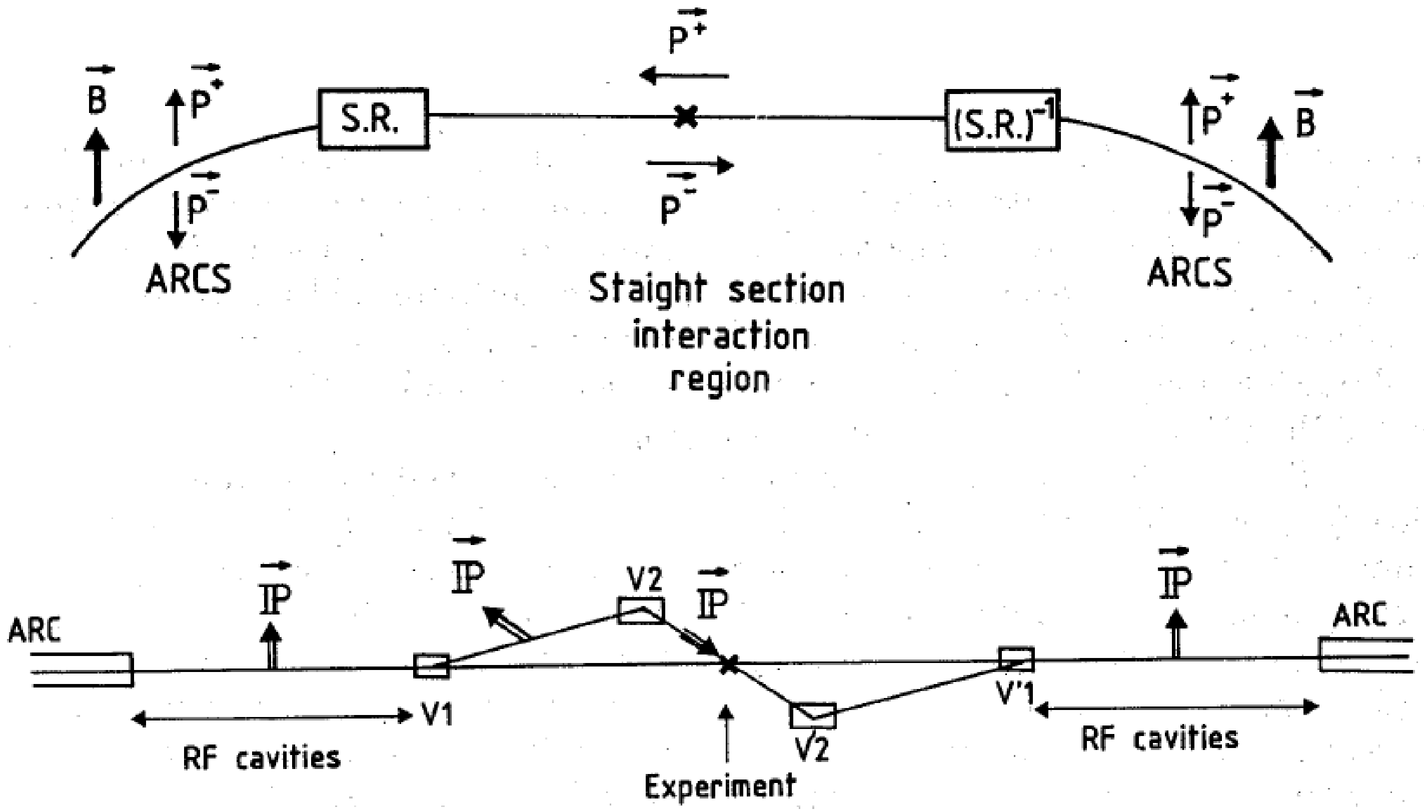
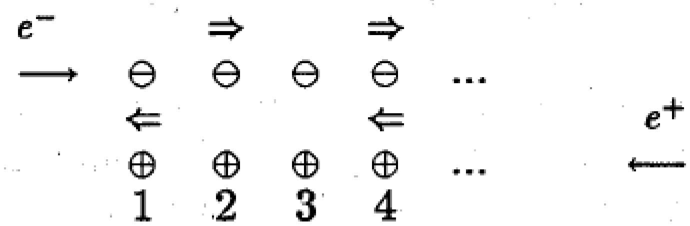


Figure 31: Top: principle of spin rotators for LEP. The spin orientation of electrons (P^-) and positrons (P^+) is indicated.
Bottom: the Richter-Schwitters spin-rotator, showing the direction of the positron spin and the location of the radio-frequency cavities.

measuring the polarization asymmerty:



The comparison of the four respective total cross-sections:

$$\sigma_1 = \sigma_u(1 + P_{e^+} A_{LR}) \quad (58)$$

$$\sigma_2 = \sigma_u(1 - P_{e^-} A_{LR}) \quad (59)$$

$$\sigma_3 = \sigma_u \quad (60)$$

$$\sigma_4 = \sigma_u(1 - P_{e^+} P_{e^-} + (P_{e^+} - P_{e^-}) A_{LR}) \quad (61)$$

allows a measurement of A_{LR} but also of P_{e^+} and P_{e^-} from the data. The role of the polarimeter is to monitor the evolution of the polarization with time and the possible differences between one bunch and an other, but its absolute calibration is obtained from the data.

requires (continuous) depolarization of selected bunches
e+ and e- polarimeter
bb tune shift not too large. → probably at least factor 4 loss in Luminosity.
Did not happen under pressure from LEP2, then LHC

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

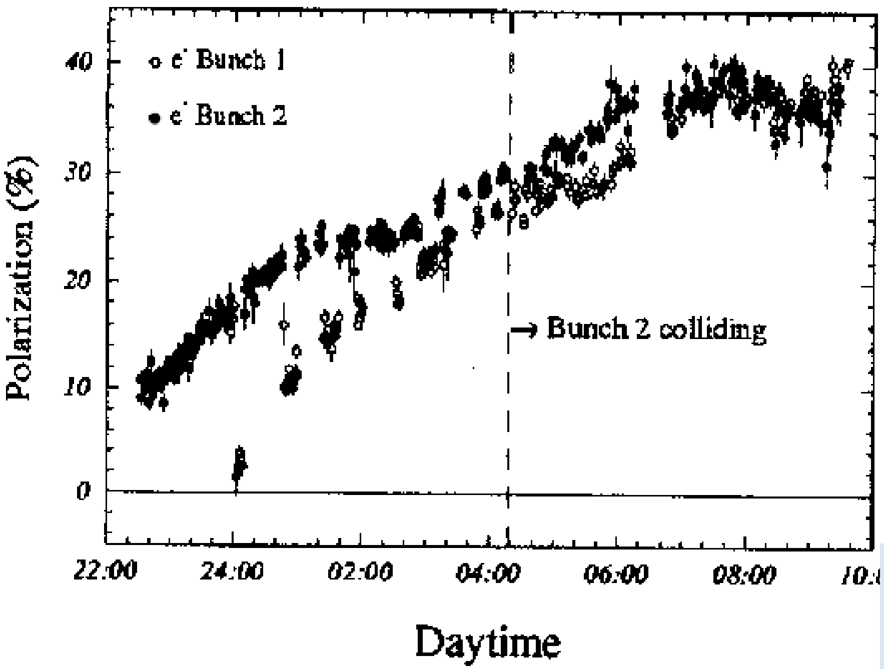


Figure. 3. Polarization level during third experiment

- 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. Wienands)

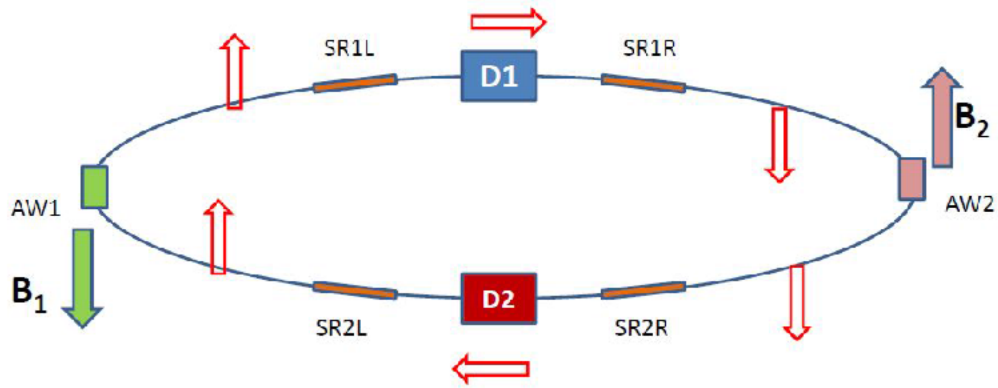


Figure 6: A possible scheme to obtain longitudinal beam polarization at high energies ($E_{beam} >> M_Z/2$) with TLEP: taking advantage of the weakness of the magnetic field in the arcs, the polarization is generated dominantly by strong asymmetric wigglers of opposite polarities (AW1 and AW2) in two 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.

Polarization measurement with a back scattered frequency doubled Nd-Yag laser (528 nm)

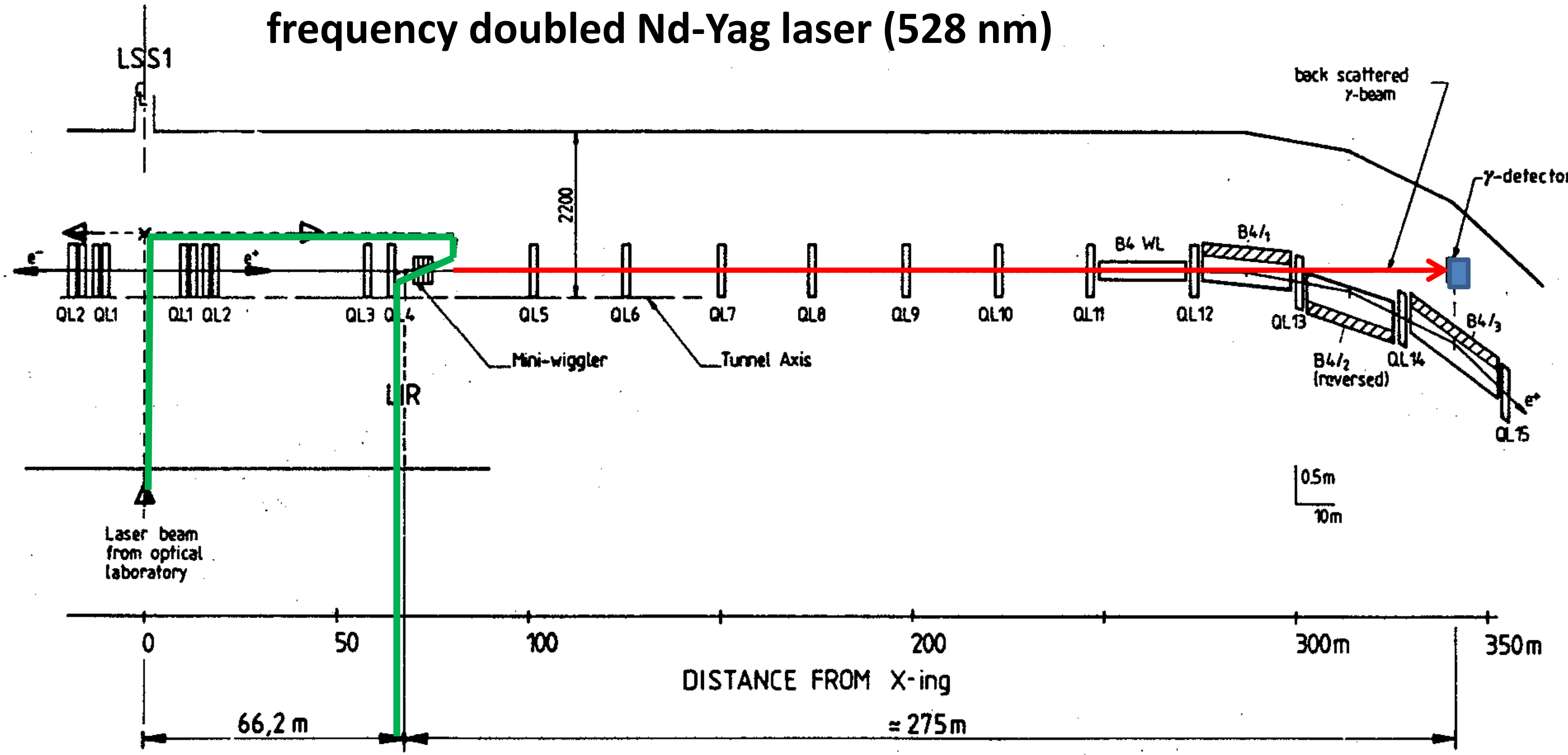


Figure 4: Set-up of the LEP polarimeter in LEP straight section 1. The laser beam is guided to the Laser Interaction Region (LIR) where it interacts with an angle of 3 mrad. The backscattered photons are separated from the electron beam 254 meters downstream at the beginning of the arc, and detected in a silicon strip calorimeter. (From [17]).

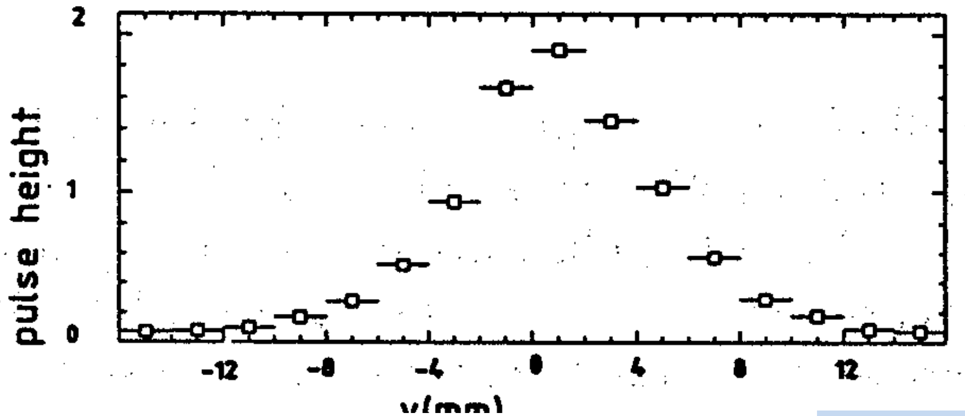
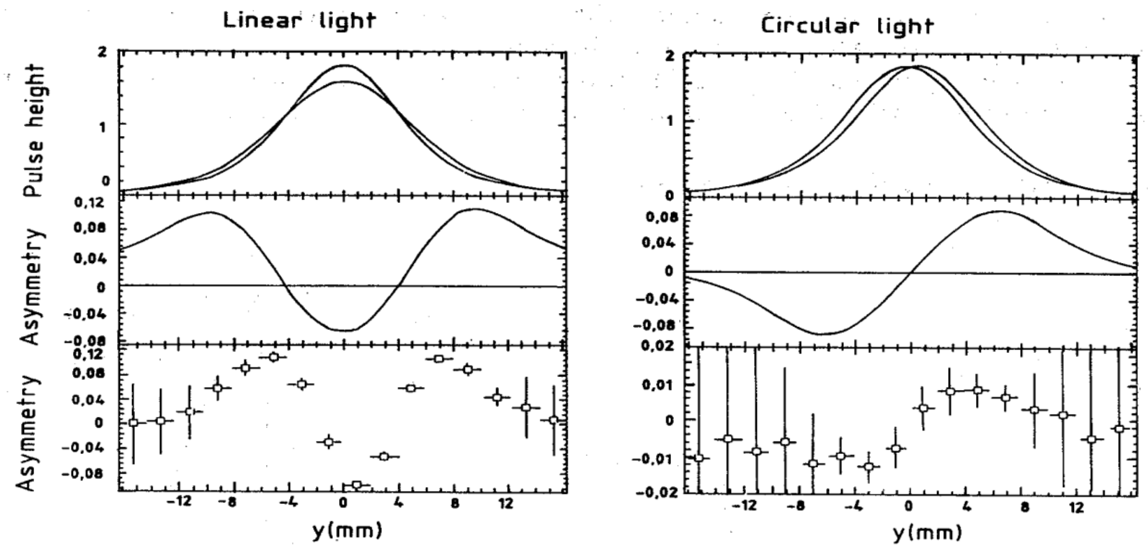


Figure 6:
Measured vertical profile in the photon detector of the LEP polarimeter. The profile is measured with a 2 mm pitch silicon strip detector after 2.5 radiation lengths of tungsten.

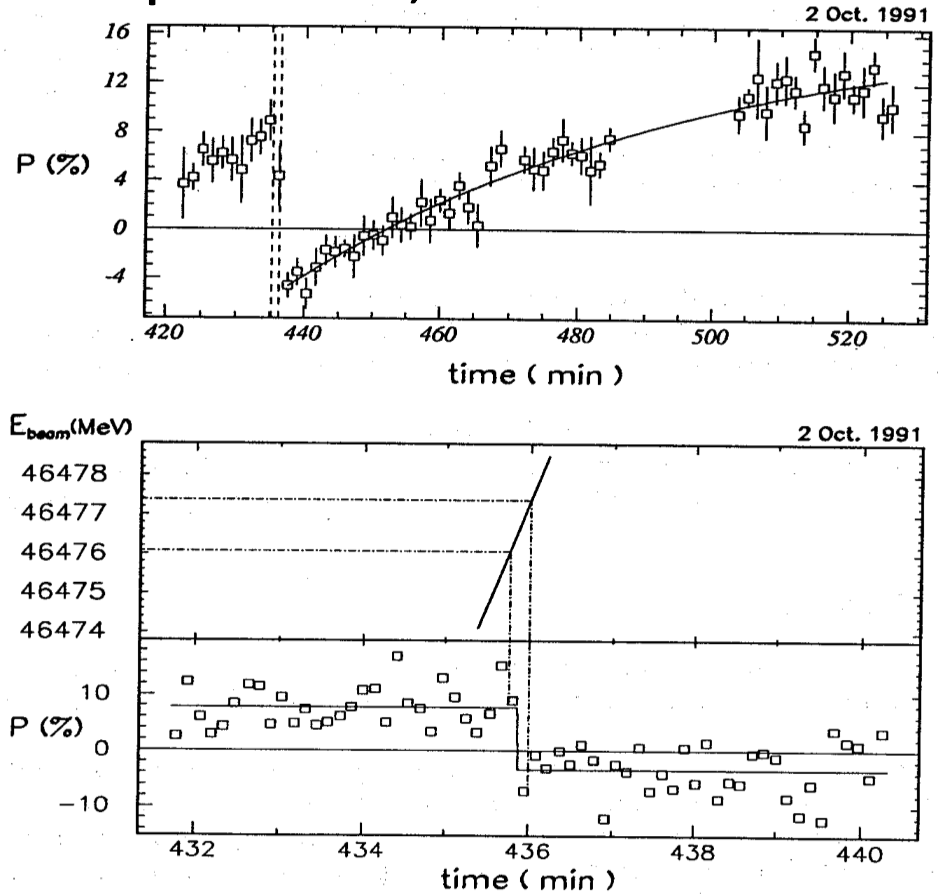
in FCC-ee emittances are much smaller and profile should be narrower.

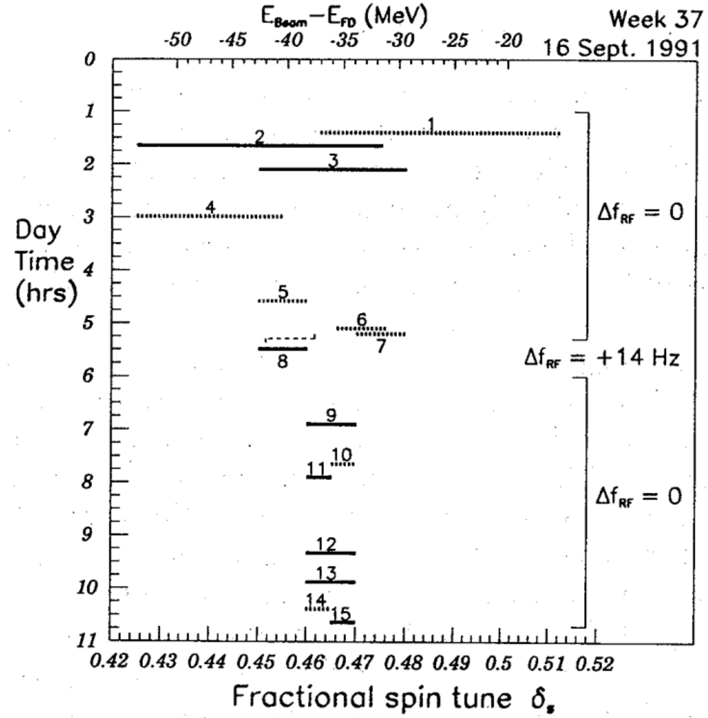


displacement upon inversion of circular light is a measure of the vertical polarization

Figure 7: Simulated and measured asymmetries in the vertical profiles of backscattered photons.
Top left: simulated profile and asymmetry for linear light;
Bottom left: measured asymmetry for linear light;
Top right: simulated profile and asymmetry for circular light on 100% polarized electrons;
Bottom right: measured asymmetry for circular light. The beam polarization is 10%. From [19].

Resonant depolarization, 1991





variation of Rf frequency to eliminate half integer ambiguity

$E_{beam} = 46{,}466.6 \pm 0.6$ MeV, e.g. precise to $\pm 1.5\ 10^{-5}$.

Figure 20: Polarization signal on 2 October 1991, showing the localization of the depolarizing frequency within the sweep.
Top: display of data points, with the frequency sweep indicated with vertical dashed lines. The full line represents the result of a fit with starting polarization $(-4.9 \pm 1.)\%$, polarization rise-time (60 ± 13) minutes, asymptotic polarization $(18.4 \pm 4.1)\%$.
Bottom: expanded view of the sweep period, with the individual data sets displayed (there are 10 sets per point); The frequency sweep lasted 7 data sets. The corresponding beam energy is shown in the upper box. Spin flip occurred between the two vertical dash-dotted lines.

depolarization by a static harmonic bump and polarization rise.

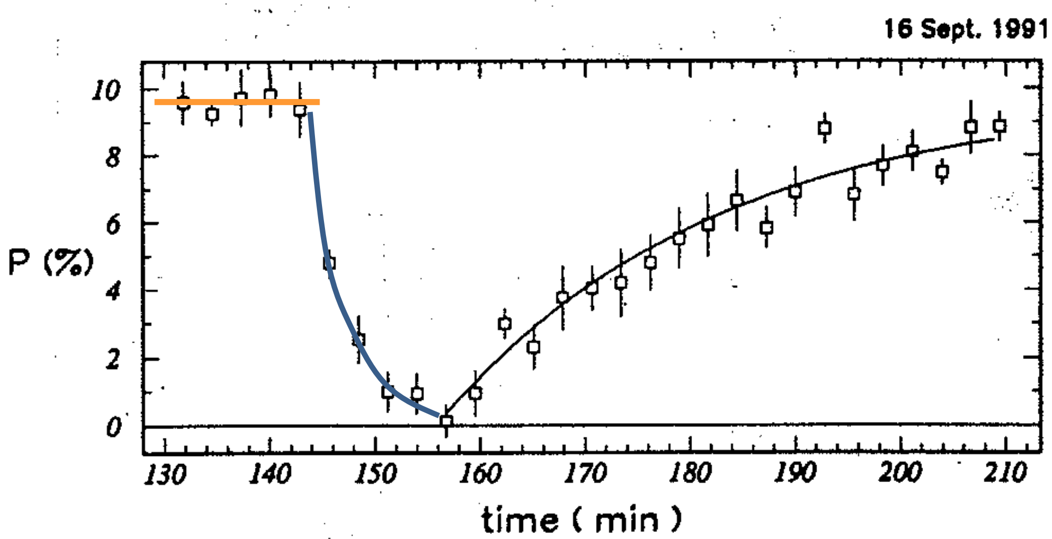


Figure 11: Polarization signal in LEP showing three consecutive phases:
1) stable polarization $P \simeq 9.6\%$;
2) depolarization by a static harmonic bump $\nu = 106$;
3) polarization rise.
The solid curve shows a fit to the polarization rise time of 35±10 minutes corresponding to $P_\infty = (10.7 \pm 3.1)\%$.