The Possibility of Polarisation in the LHeC Ring-Ring Scenario

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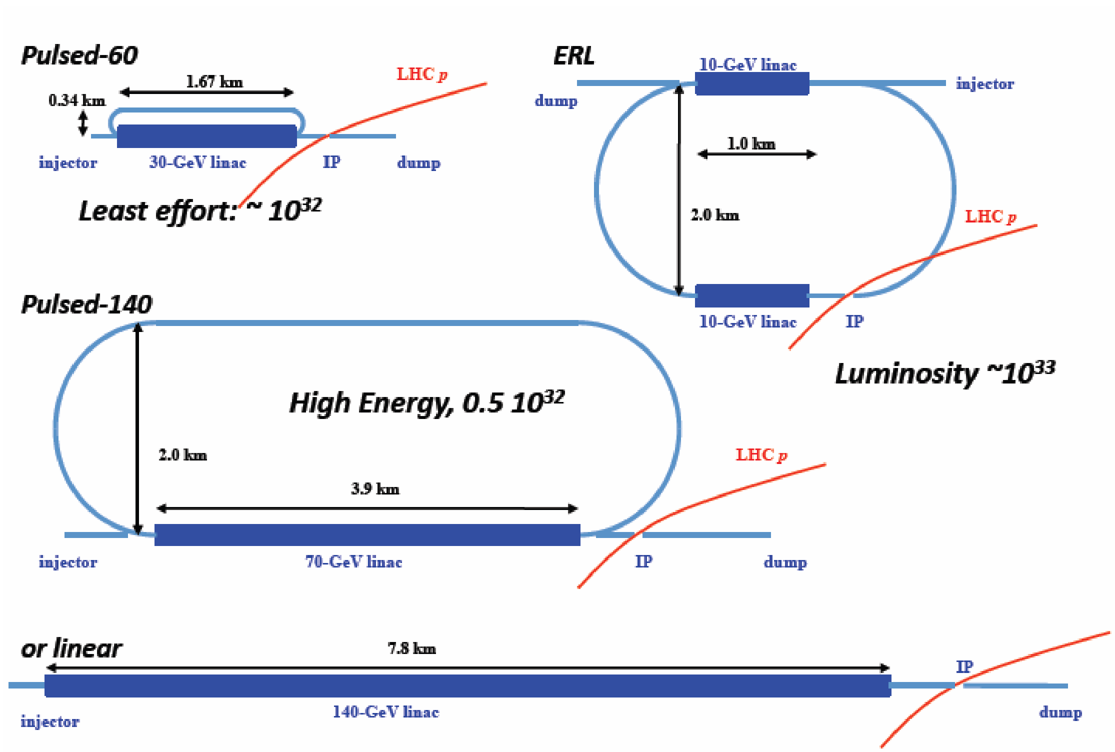
1 September 2010

See Kurt Aulenbacher's review of $e^{\pm} - p$ schemes: 27/09/2010

Linac/recirculator - ring schemes

Max Klein: at ICHEP Paris: Future Machines and Projects 24.7.2010



Linac/recirculator - ring schemes

Max Klein: at ICHEP Paris: Future Machines and Projects 24.7.2010

Based on SLC, ILC and LHC experience.

Workpackages for CDR

- Baseline Parameters [Designs, Real photon option, ERL]
- Sources [Positrons, Polarisation]
- Rf Design
- Injection and Dump
- Beam-beam effects
- Lattice/Optics and Impedance
- Vacuum and Beam Pipe
- Integration and Layout
- Interaction Region
- Powering Issues
- Magnets
- Cryogenics

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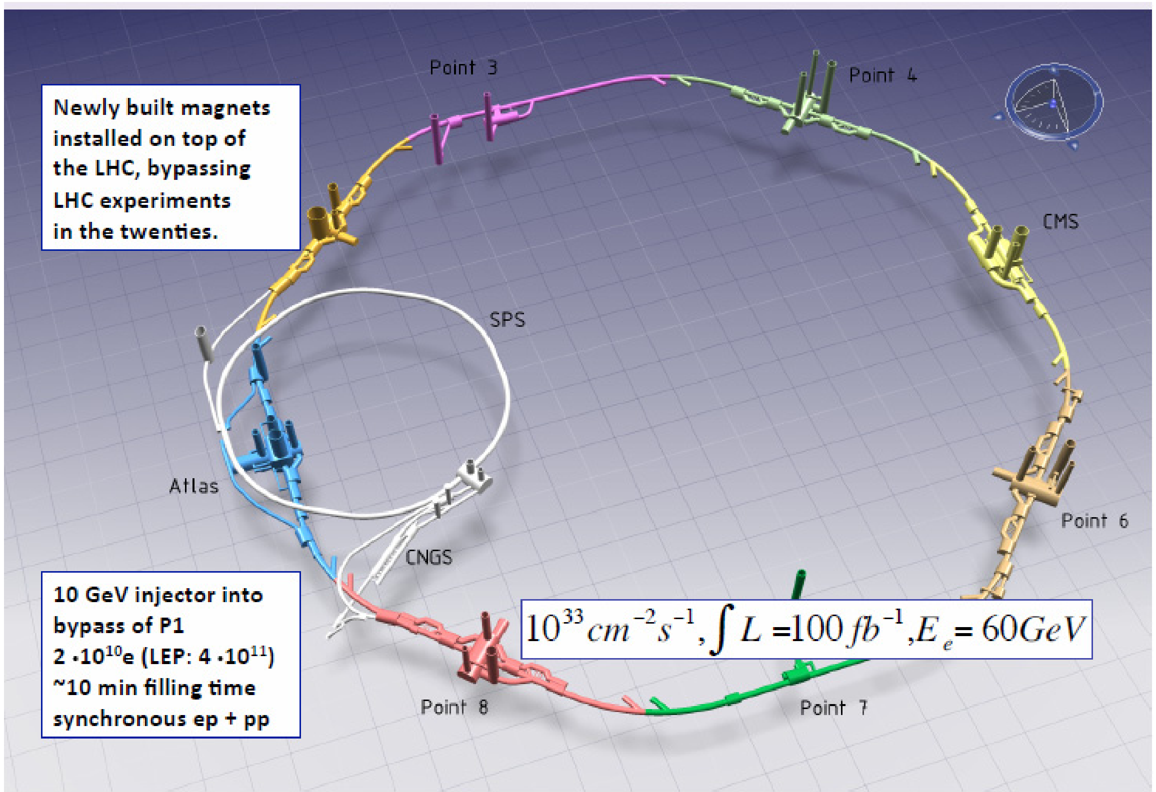
SLAC
TAC Turkey

The ring - ring option.

Max Klein: at ICHEP Paris: Future Machines and Projects 24.7.2010



The ring - ring option.

Max Klein: at ICHEP Paris: Future Machines and Projects 24.7.2010

Based on HERA, LEP, LHC experience.

Workpackages for CDR

- Baseline Parameters and Installation Scenarios
- Lattice Design [Optics, Magnets, Bypasses, IR for high L and 1°]
- Rf Design [Installation in bypasses, Crabs]
- Injector Complex [Sources, Injector]
- Injection and Dump
- Beam-beam effects
- Impedance and Collective Effects
- Vacuum and Beam Pipe
- Integration and Machine Protection
- Powering Issues
- e Beam Polarization
- Deuteron and Ion Beams

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Precision QCD and Electroweak Physics

Max Klein: at ICHEP Paris: Future Machines and Projects 24.7.2010

Structure functions [F_2,F_L,xF_3^{gZ},F_2^{gZ}; F_2^{cc},F_2^{bb},F_2^{ss}] in p/d and A
Quark distributions from direct measurements and QCD fits
Strong coupling constant α_s to per mille accuracy
Gluon distribution in full x range to unprecedented precision
Standard Model Higgs
Single top and anti-top quark production at high rate (5pb)
Electroweak couplings (light and heavy quarks and mixing angle)
Heavy quark fragmentation functions
Charm and beauty below and way beyond threshold at per cent accuracy
Heavy quarks in real photon-proton collisions [LR option]
Jets and QCD in photoproduction and DIS
Gluon structure of the photon
....

Ring-ring design parameters

Max Klein: at ICHEP Paris: Future Machines and Projects 24.7.2010

electron beam	RR	LR	LR
e- energy at IP[GeV]	60	60	140
luminosity [10^{32} $cm^{-2}s^{-1}$]	17	10	0.44
polarization [%]	40	90	90
bunch population [10^9]	26	2.0	1.6
e- bunch length [mm]	10	0.3	0.3
bunch interval [ns]	25	50	50
transv. emit. $\gamma\varepsilon_{x,y}$ [mm]	0.58, 0.29	0.05	0.1
rms IP beam size $\sigma_{x,y}$ [μm]	30, 16	7	7
e- IP beta funct. $\beta^*_{x,y}$ [m]	0.18, 0.10	0.12	0.14
full crossing angle [mrad]	0.93	0	0
geometric reduction H_{hg}	0.77	0.91	0.94
repetition rate [Hz]	N/A	N/A	10
beam pulse length [ms]	N/A	N/A	5
ER efficiency	N/A	94%	N/A
average current [mA]	131	6.6	5.4
tot. wall plug power[MW]	100	100	100

proton beam	RR	LR
bunch pop. [10^{11}]	1.7	1.7
tr.emit.$\gamma\varepsilon_{x,y}$ [μm]	3.75	3.75
spot size $\sigma_{x,y}$ [μm]	30, 16	7
$\beta^*_{x,y}$ [m]	1.8,0.5	0.1
bunch spacing [ns]	25	25

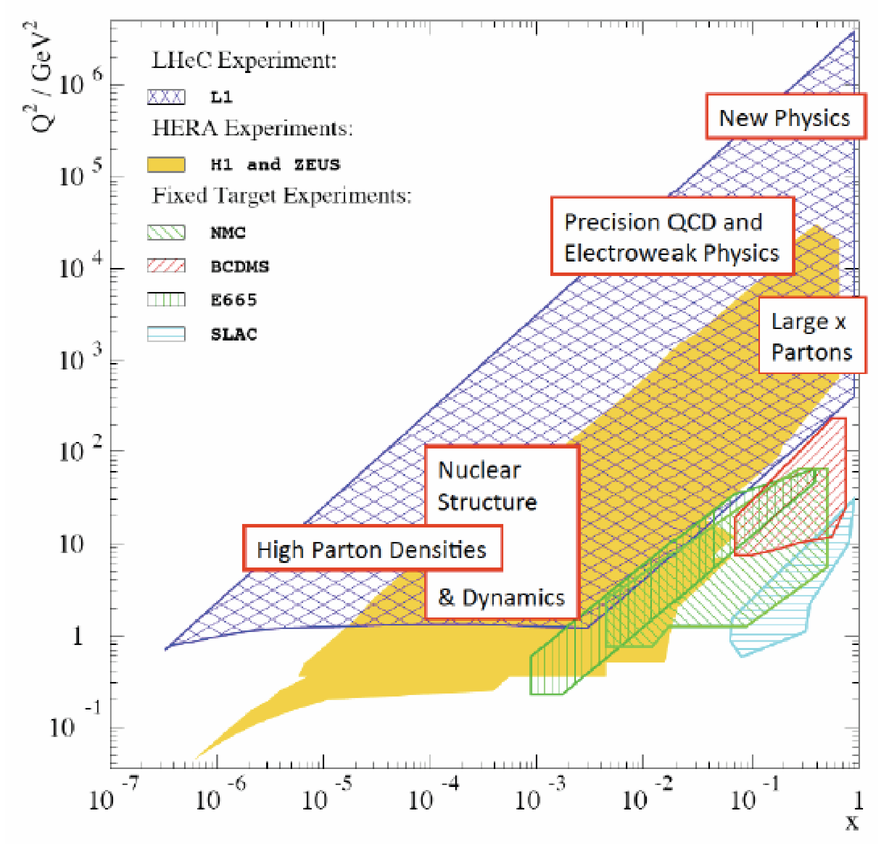
“ultimate p beam”
present record N_p=1.3 10^{11}
1.7 probably conservative

Design also for deuterons (new) and lead (exists)

RR= Ring – Ring
LR =Linac –Ring

Tentative: 8.7.2010

Max Klein: at ICHEP Paris: Future Machines and Projects 24.7.2010

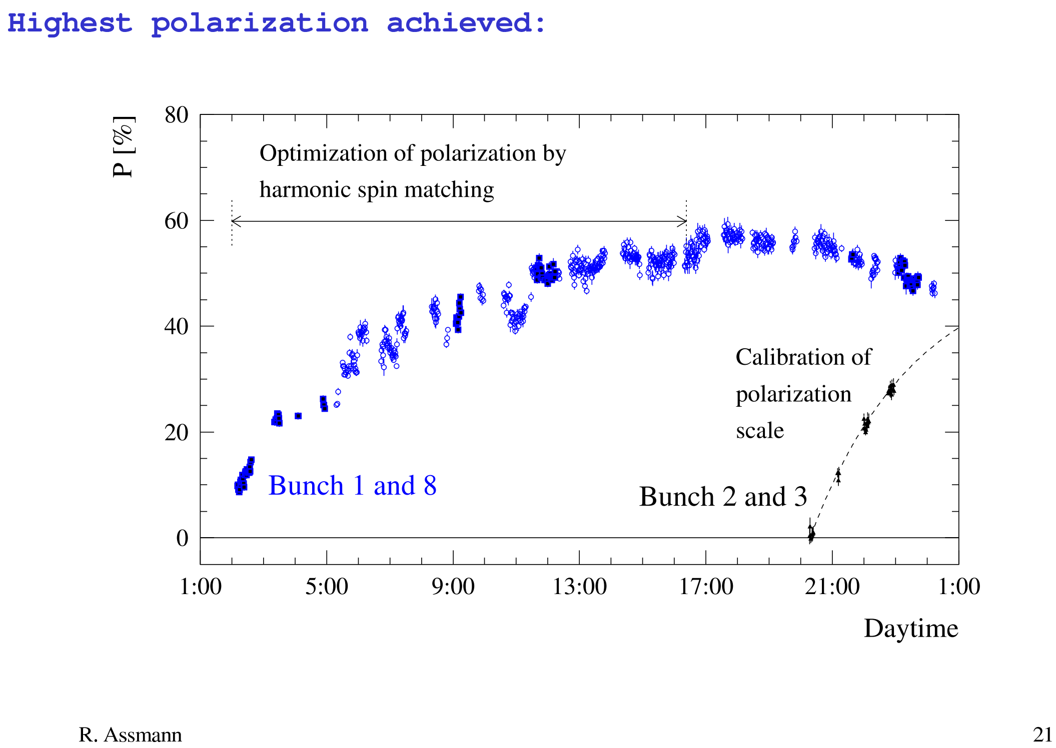


**For this talk, the ring-ring option:
a super HERA...**

The ring-ring option would use conventional technology and would provide both polarised electrons **and** positrons.

LEP

Polarisation from the Sokolov-Ternov effect at 46 GeV and above – the highest energy so far!



Vertical polarisation by the S-T effect, no rotators. "Deterministic" harmonic orbit correction.

46 GeV, $\tau_{st} \approx 5$ hours

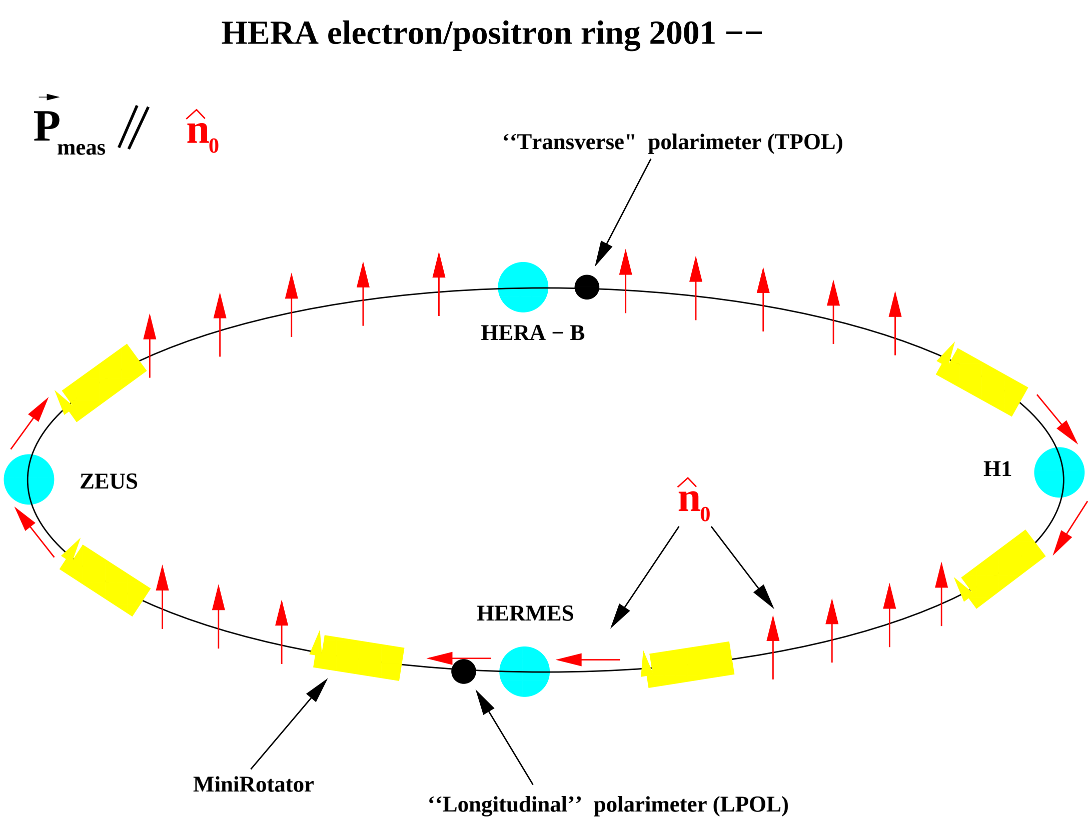
HERA

The first and only $e^{\pm}$ ring to supply longitudinal polarisation at high energy

— via the Sokolov-Ternov effect – also at 3 IP's simultaneously!

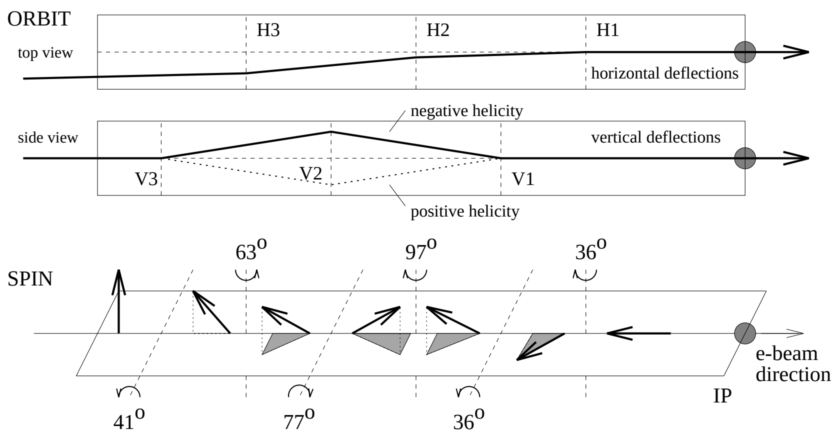
$\approx$ 30 GeV, $\tau_{st} \approx$ 30 mins. Depolarisation not too strong.

Perfectly balanced parameters



Polarisation vertical in the arcs – to drive the Sokolov-Ternov effect

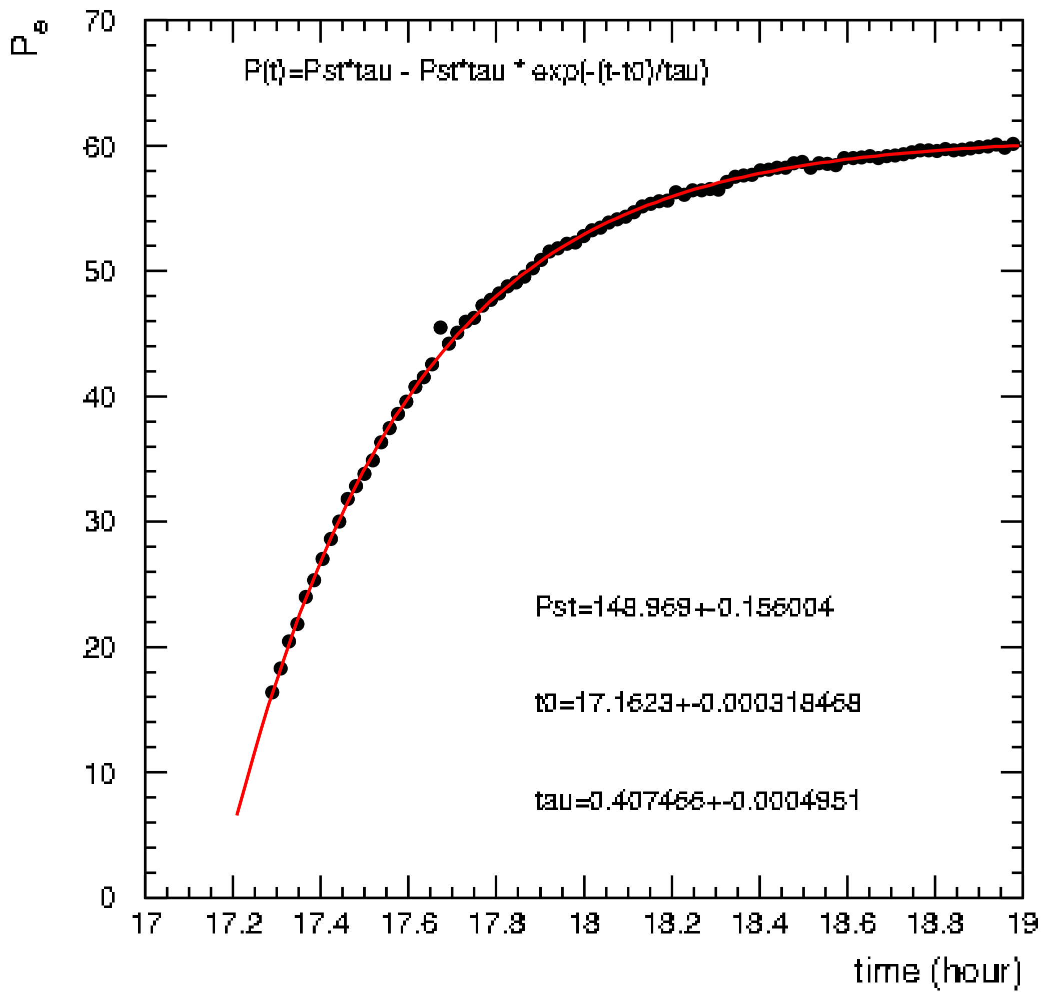
HERA MiniRotator: Buon + Steffen



56 m ("short") → no quads.

27 – 39 GeV, both helicities, variable geometry

NO INTERNAL QUADRUPOLES!



3 pairs of rotators (so max. Sokolov-Ternov polarisation = 83 %), solenoids on, no beam-beam

Some theory and phenomenology

- Electrons (positrons) in storage rings can become spin POLARISED due to emission of synchrotron radiation: Sokolov–Ternov effect (1964).

- The polarisation is perpendicular to the machine plane in simple rings.

- The maximum value is then $P_{st} = 92.4\%$.

BUT!

- Sync. radn. also excites orbit motion. This leads to DEPOLARISATION!
- In any case, the **value** of the polarisation is the same at all azimuths — time scales.

The T-BMT equation.

$$\frac{d\vec{S}}{ds} = \vec{\Omega}(\gamma, \vec{v}, \vec{B}, \vec{E}) \times \vec{S}$$

Periodic solution $\hat{n}_0$ on closed orbit.

The real unit eigenvector of:

$$R_{3\times 3}(s+C, s)\hat{n}_0 = \hat{n}_0$$

$\hat{n}_0$ is 1–turn periodic: $\hat{n}_0(s+C) = \hat{n}_0(s)$

$\hat{n}_0$: direction of measured equilibrium radiative polarisation.

Closed orbit spin tune ν_0: number of precessions per turn around $\hat{n}_0$ for a spin on the closed orbit. Extract from the eigenvalues of $R_{3\times 3}(s+C, s)$

Spin motions

- Protons: largely deterministic — unless various noise (e.g.IBS).
- Electrons/positrons:
  If a photon causes a spin flip, what are the other $\approx 10^{10}$ photons doing? ===>

  Stochastic/damped orbital motion due to synchrotron radiation
  + inhomogeneous fields
  + spin–orbit coupling via T–BMT
  ===> spin diffusion i.e. depolarisation!!!

  Self polarisation: Balance of poln. and depoln. ===>

  $$P_\infty \approx P_{BK} \frac{1}{1 + (\frac{\tau_{dep}}{\tau_{BK}})^{-1}} \qquad (P_{ST} \to P_{BK})$$

  In any case:

  $\tau_{dep}^{-1} \propto \gamma^{2N} \tau_{st}^{-1}$ (actually a polynomial in γ^{2N})

  ===> Trouble at high energy!

Spin–orbit resonances

$$\nu_{\rm spin} \;=\; k + k_I\nu_I + k_{II}\nu_{II} + k_{III}\nu_{III}$$

$\nu_{\rm spin}$: amplitude dependent spin tune ≈ closed orbit spin tune = precessions /turn on CO

- Orbit "drives spins" ===> Resonant enhancement of spin diffusion
  AT FIXED ENERGY EVEN AWAY FROM RESONANCES!
- Resonance order: $|k_I| + |k_{II}| + |k_{III}|$
- First order: $|k_I| + |k_{II}| + |k_{III}| = 1$ e.g. SLIM like formalisms.
- Strongest beyond first order:
  synchrotron sidebands of first order parent betatron or synchrotron resonances

$$\nu_{\rm spin} \;=\; k + k_i\nu_i + k_{III}\nu_{III}, \quad i = I, II \text{ or } III$$

- Proton-style resonances strengths are NOT helpful for estimating depolarising rates!

Sidebands of parent first order betatron resonances: a useful **approximation**

$$\tau_{_{dep}}^{-1} \propto \frac{A}{(\nu_0 \pm Q_y)^2} \quad \rightarrow \quad \tau_{_{dep}}^{-1} \propto \sum_{m_s=-\infty}^{\infty} \frac{A\, B(\xi; m_s)}{(\nu_0 \pm Q_y \pm m_s\, Q_s)^2}$$

A is an energy dependent factor

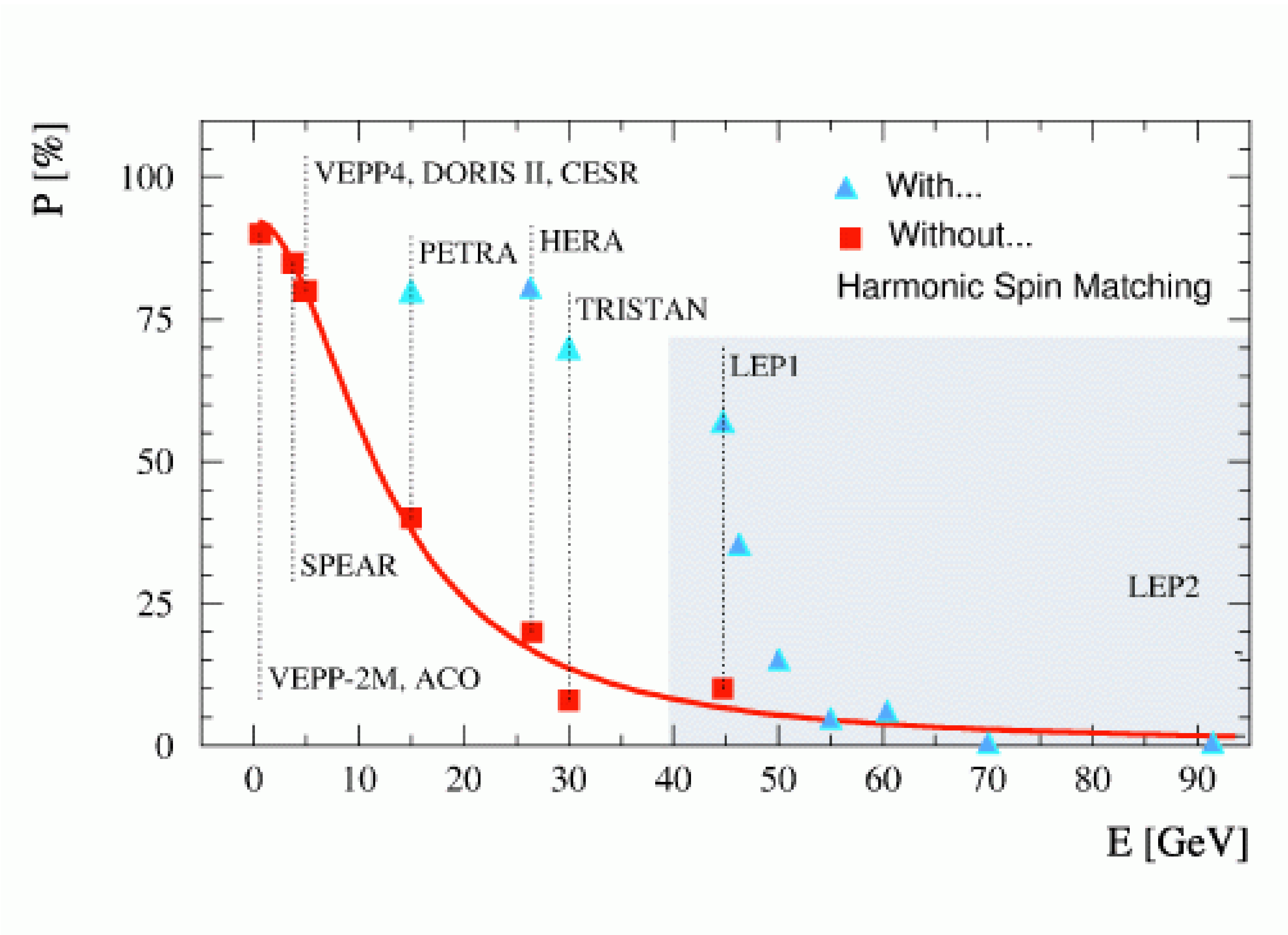
$B(\xi; m_s)$'s: *enhancement factors*, contain modified Bessel functions $I_{|m_s|}(\xi)$ and $I_{|m_s|+1}(\xi)$ depending on the *modulation index*

$$\xi = (\frac{a\gamma\ \sigma_\delta}{Q_s})^2$$

in a simple flat ring.

===> very strong effects at high energy — dominant source of trouble

Analogous formula for sidebands of first order synchrotron resonances.



R. Assmann, SPIN2000, Osaka, Japan

- For longitudinal polarisation the polarisation vector must be rotated into the longitudinal direction before an IP and back to the vertical afterwards ===> spin rotators.
- Vertical bends must be neutralised – otherwise $\hat{n}_0$ is not vertical $\Longrightarrow$ strong depolarisation
- Depolarisation can be strongly enhanced by misalignments, regions where the polarisation vector ($\hat{n}_0$) is horizontal between spin rotators etc, etc.....

$\Longrightarrow$ **Linear spin matching**

Skip the invariant spin field and the Derbenev-Kondratenko formula for today!

Heuristics instead!

N.B. this is not the trivial business of ensuring that a spin behaves as required in a string of dipoles!!

$$\vec{S} \approx \hat{n}_0(s) + \alpha\hat{m}_0(s) + \beta\hat{l}_0(s)$$

α, β: 2 small spin tilt angles — have subtracted out the big rotations!

$$\hat{\mathbf{M}}_{8\times 8} = \begin{pmatrix} \mathbf{M_{6\times 6}} & \mathbf{0_{6\times 2}} \\ \mathbf{G_{2\times 6}} & \mathbf{D_{2\times 2}} \end{pmatrix}$$

acting on $\vec{u} = (x,\ x',\ y,\ y',\ l,\ \delta)$ and α, β

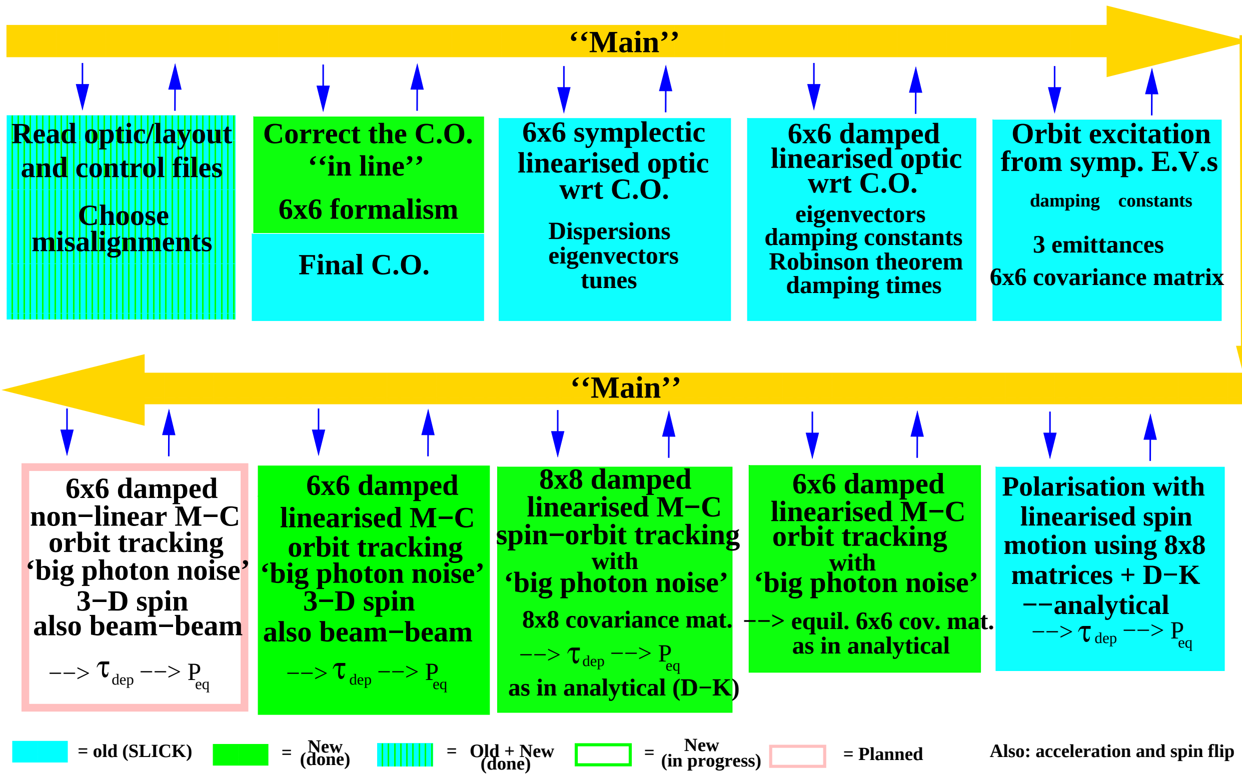
This is the SLIM formalism for estimating depolarisation analytically at first order (Chao 1981).

To minimize depolarisation:

minimize appropriate bits of $\mathbf{G_{2\times 6}}$ for appropriate stretches of ring

===> lots of independent quadrupole circuits.

The structure of SLICKTRACK



Spin coordinates

$$\hat{S} = \sqrt{1 - \alpha^2 - \beta^2}\ \hat{n}_0 + \alpha\hat{m} + \beta\hat{l}$$

Estimating depolarisation by M-C simulation $\alpha^2 + \beta^2 << 1$

$$\Delta P \approx -\frac{1}{2}\Delta(<\alpha^2 + \beta^2>) = -\frac{1}{2}\Delta(\sigma_\alpha^2 + \sigma_\beta^2) \quad \Longrightarrow \frac{dP}{dt} \approx -\frac{1}{2} = -\frac{1}{2}\frac{d}{dt}(\sigma_\alpha^2 + \sigma_\beta^2)$$

Spin–orbit covariance matrix

$$\begin{pmatrix}
\sigma_x^2 & \sigma_{xx'} & . & . & . & . & | & . & . \\
\sigma_{x'x} & \sigma_{x'}^2 & . & . & . & . & | & . & . \\
. & . & . & . & . & . & | & . & . \\
. & . & . & . & . & . & | & . & . \\
. & . & . & . & . & . & | & . & . \\
. & . & . & . & . & \sigma_\delta^2 & | & . & . \\
- & - & - & - & - & - & - & - & - \\
. & . & . & . & . & . & | & \sigma_\alpha^2 & \sigma_{\alpha\beta} \\
\sigma_{\beta x}. & . & . & . & . & . & | & \sigma_{\beta\alpha} & \sigma_\beta^2
\end{pmatrix}$$

Spin–orbit maps for sections

For linearised spin motion (SLIM/SLICK):

$$\hat{\mathbf{M}} = \begin{pmatrix} \mathbf{M_{6\times6}} & \mathbf{0_{6\times2}} \\ \mathbf{G_{2\times6}} & \mathbf{D_{2\times2}} \end{pmatrix}$$

The $\mathbf{G_{2\times6}} \times (\mathbf{x}, \mathbf{x}', \mathbf{y}, \mathbf{y}', \mathbf{\Delta l}, \delta)^{\mathbf{T}}$ delivers changes to the 2 small angles α and β

For full 3–D spin motion:

$$\hat{\mathbf{M}} = \begin{pmatrix} \mathbf{M_{6\times6}} & \mathbf{0_{6\times3}} \\ \mathbf{G_{3\times6}} & \mathbf{D_{3\times3}} \end{pmatrix}$$

The $\mathbf{G_{3\times6}} \times (\mathbf{x}, \mathbf{x}', \mathbf{y}, \mathbf{y}', \mathbf{\Delta l}, \delta)^{\mathbf{T}}$ delivers rotations around $\hat{n}_0,\ \hat{m}_0,\ \hat{l}_0$

The beam–beam (non–linear) kicks are applied at single points

Some advice to calculaters:

Software, for linearised spin motion, that does not intrinsically include synchrotron motion and which does not include misalignments and orbit correction is useless above a couple of GeV.

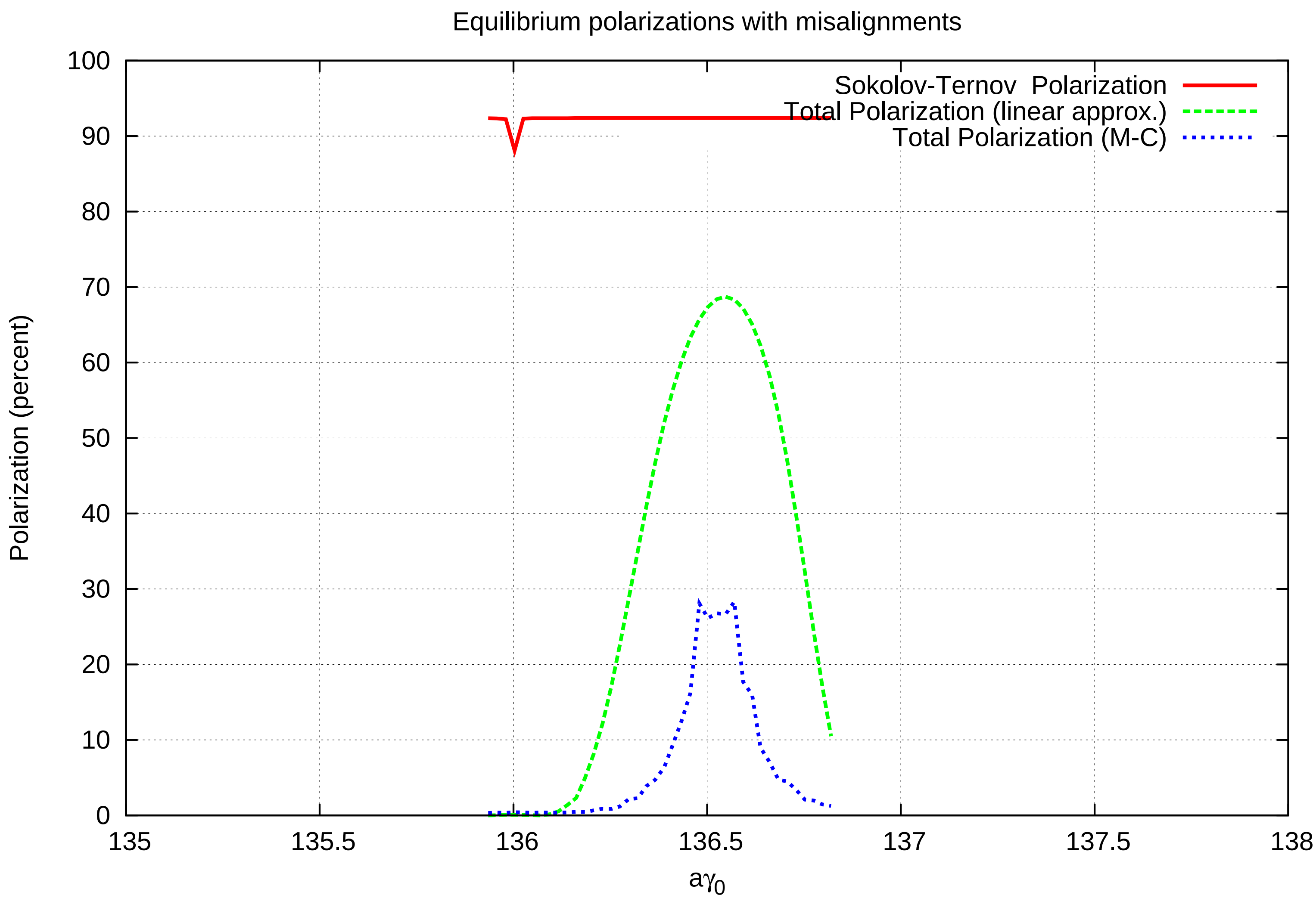
Software that cannot, in addition, account for full 3-D spin motion, and which therefore cannot consistently account for synchrotron sidebands, is useless above about 10 GeV.

A first look!!

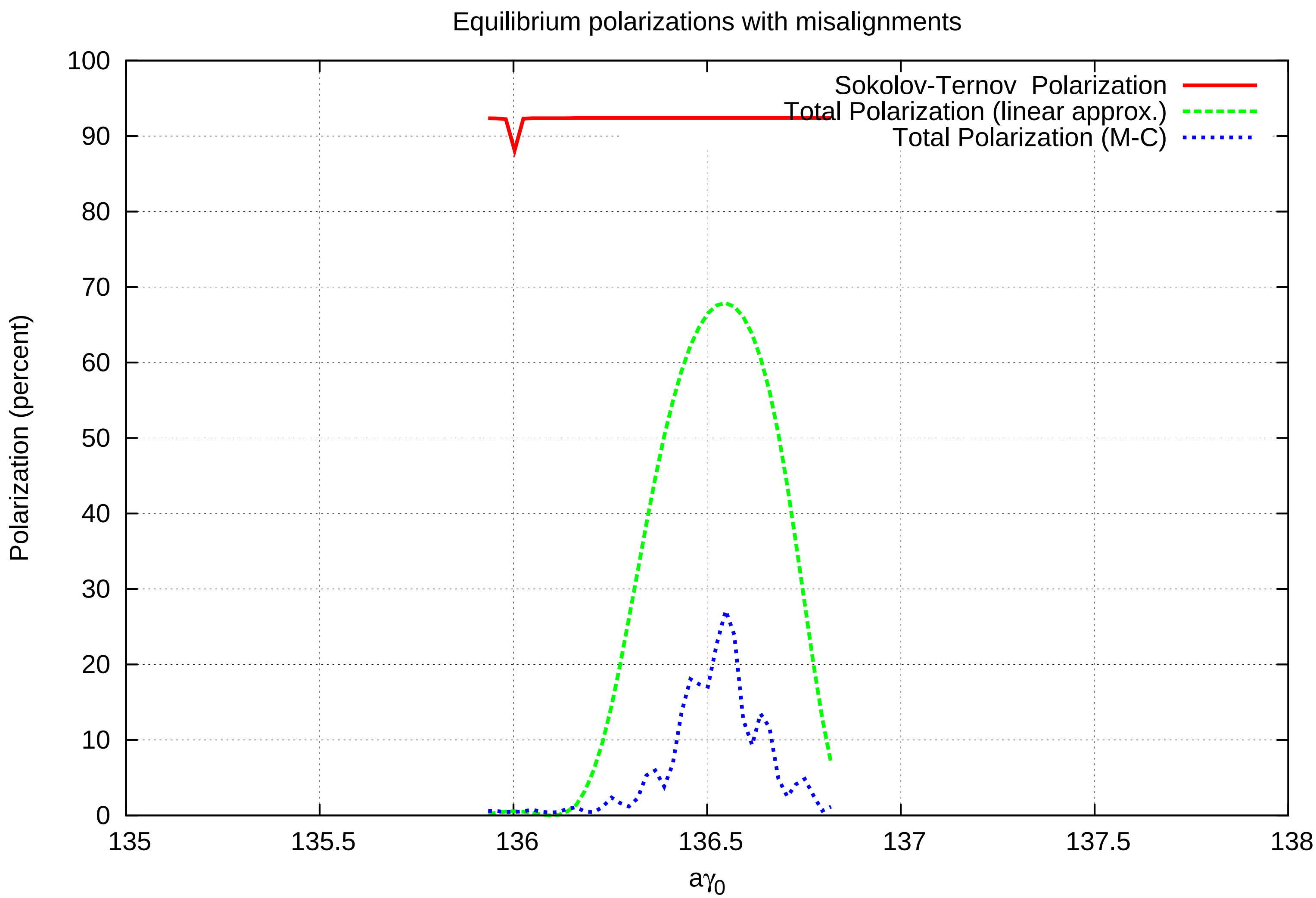
Flat ring with vertical polarisation near 60 GeV

- $Q_x = 123.83$
- $Q_y = \ 85.62$
- $\sigma_{\rm vco} = 75$ microns
- R.m.s. tilt of $\hat{n}_0 \approx 4$ mrad near the peak polarisation.
  No harmonic closed-orbit spin matching so far.
- Radiative energy loss: 430 MeV per turn
- $a\gamma_0 \frac{\sigma_{\gamma_0}}{\gamma_0} \approx 0.13$.

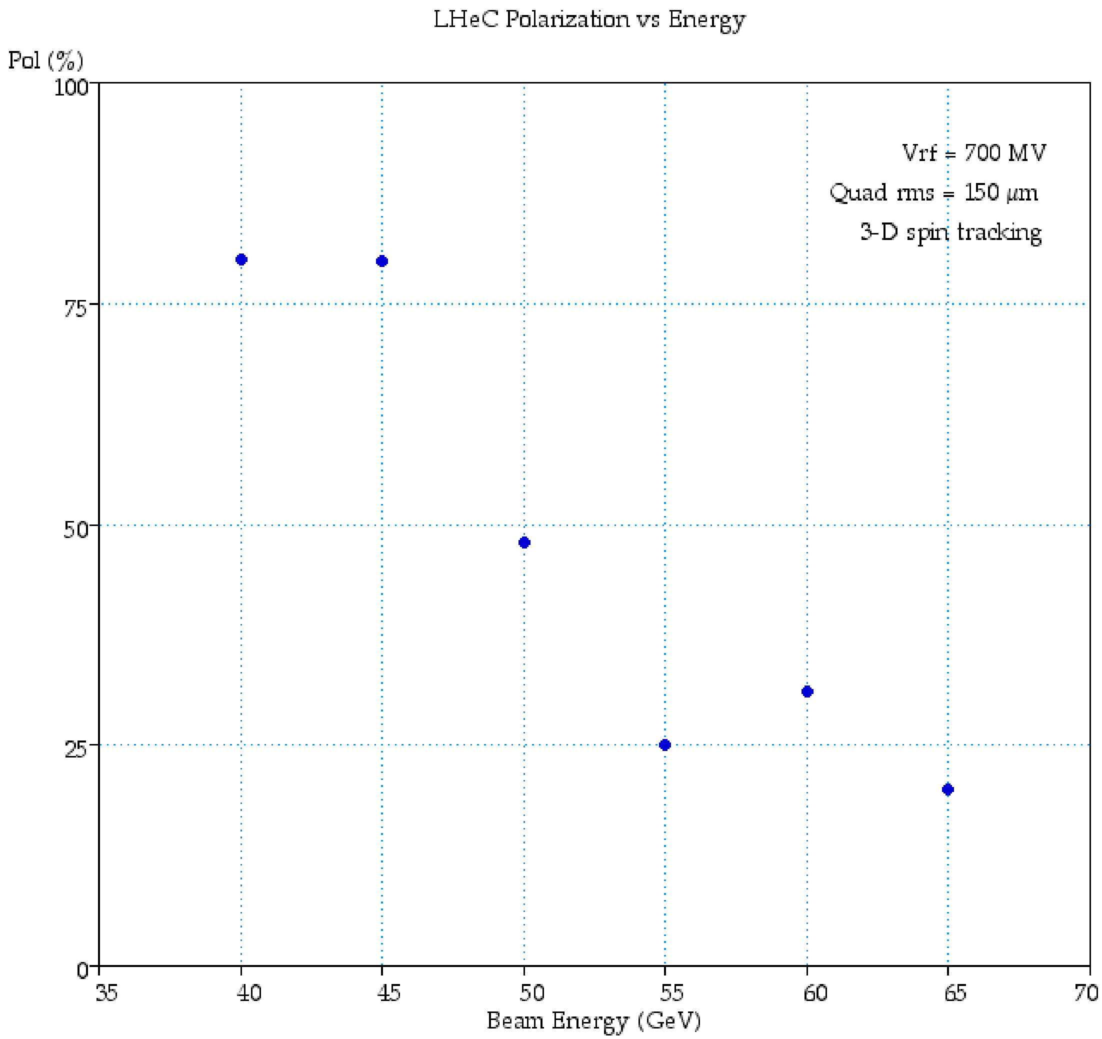
$Q_s = 0.06, \xi \approx 5$ **An example of just one misalignment**



$Q_s = 0.1, \xi \approx 1.9$. **An example of just one misalignment**



Energy dependence of maximum polarisation — an example of just one misalignment



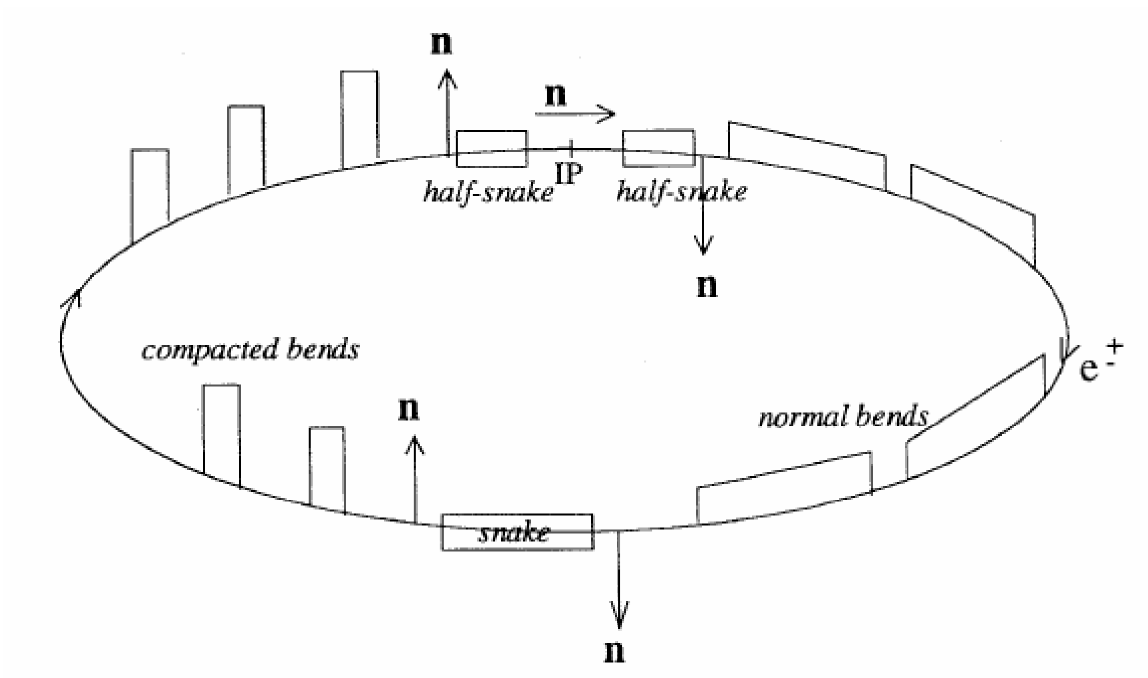
Summary on the flat ring

- Initial calculations suggest that vertical polarisation would not be impossible with modern very good alignment.
- The dependence on Q_s is qualitatively as expected.
- The attainable equilibrium polarisation is highest at low energy as expected.

Longitudinal polarisation

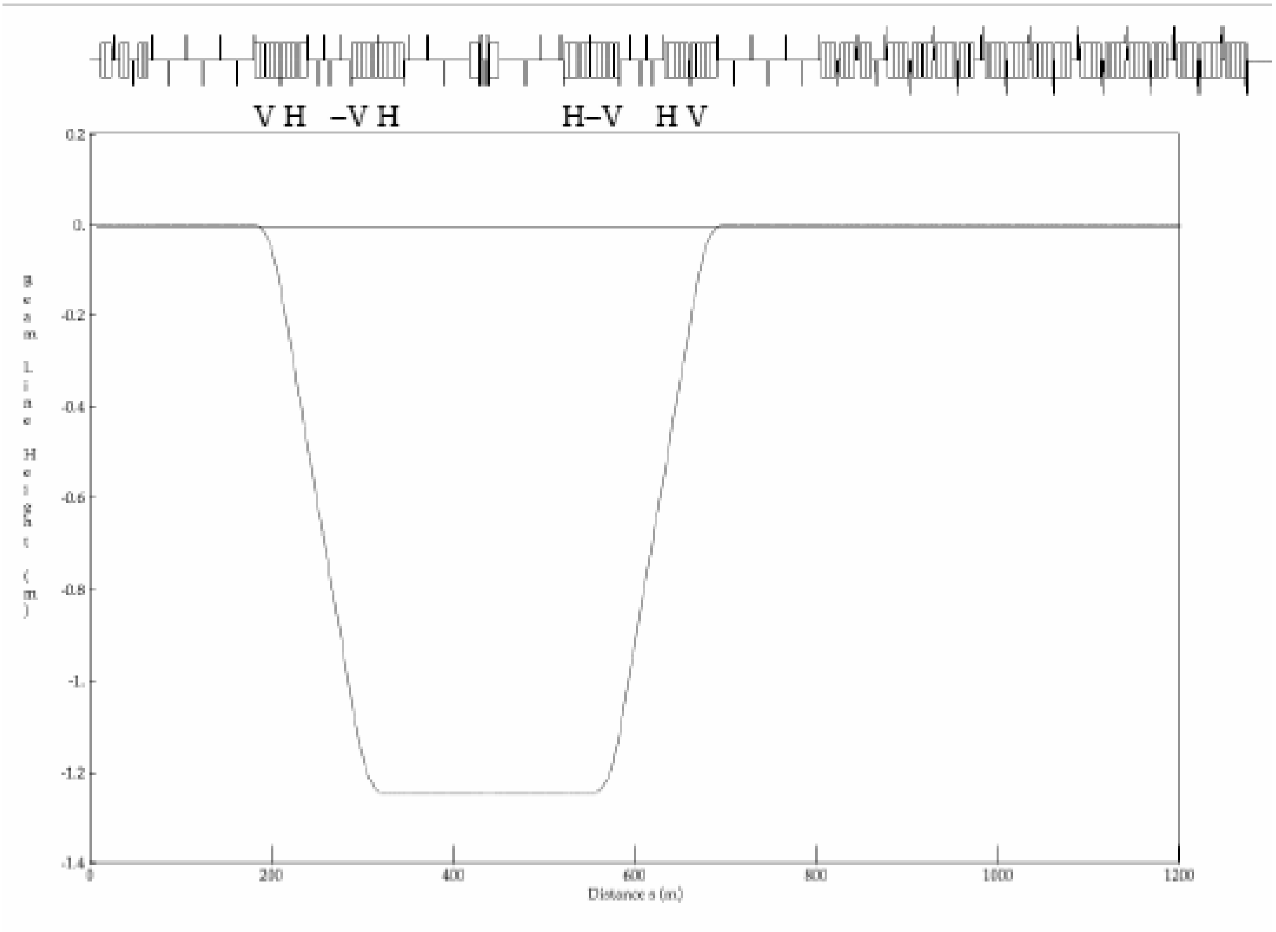
- Need rotators ==> need serious spin matching.
- Rotators must be compatible with the contraints of the environment.
- Do Siberian Snakes help to suppress the effect of synchrotron sidebands by suppressing the oscillations of $a\gamma$?
- Naive use of snakes kills the Sokolov-Ternov polarisation!
- So need asymmetric distribution of radiation.
- Try the Derbenev-Grote scheme (1995).

A suggestion by Ya. Derbenev and H. Grote



n means $\hat{n}_0$ here !!!

LHeC rotators



$\Longrightarrow$ very strong depolarisation – of course!

But we can switch spin-orbit coupling off/on to see what does what: the G matrix

So make the interaction region and rotators spin transparent in software.

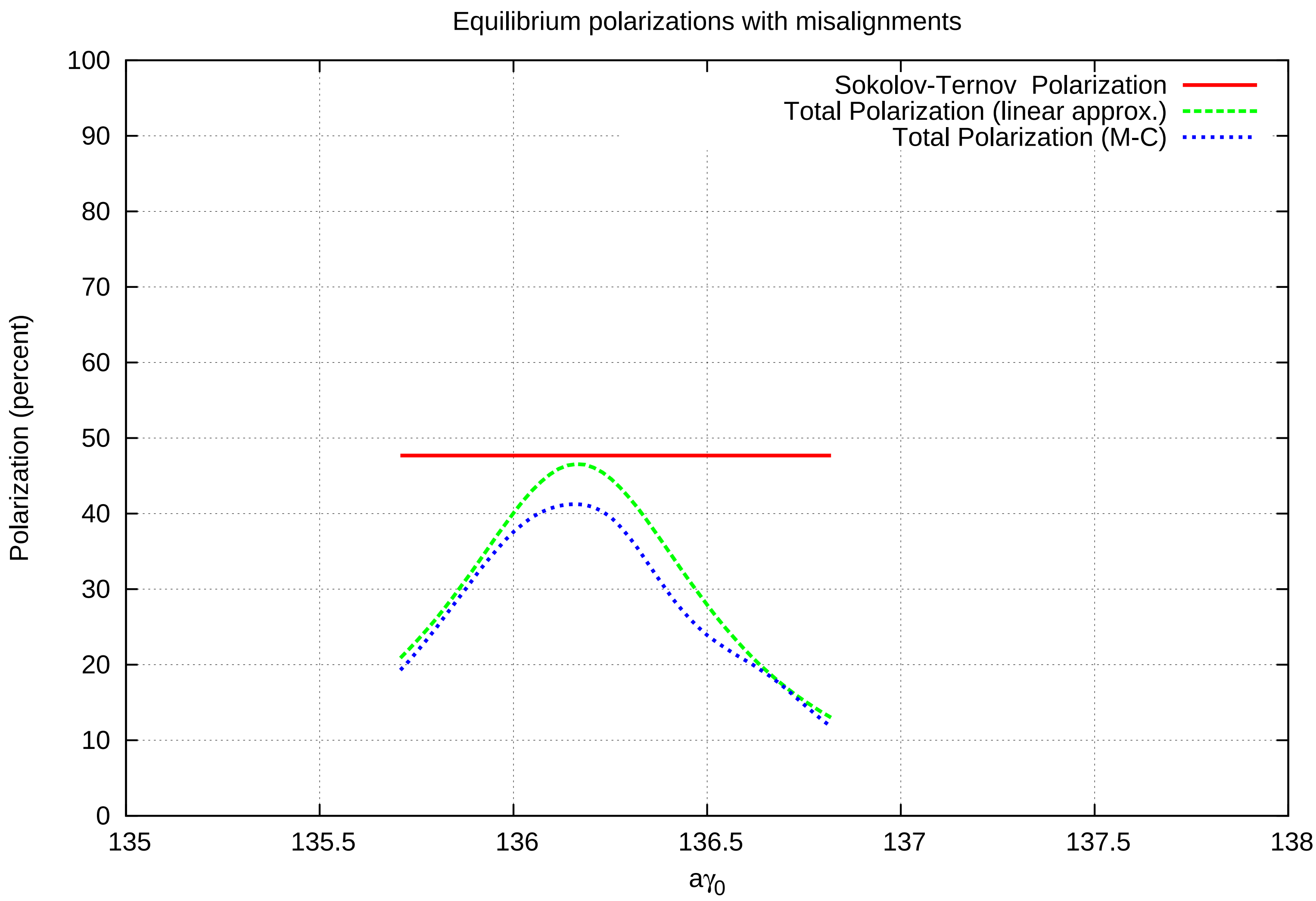
Diagnostics! – since 1982

The D–G set-up near 60 GeV

- $Q_x = 124.36$
- $Q_y = 88.80$
- $\sigma_{\rm vco} = 75$ microns
- R.m.s. tilt of $\hat{n}_0 \approx 8$ mrad near the peak polarisation. No harmonic closed-orbit spin matching so far.
- Radiative energy loss: 586 MeV per turn
- $a\gamma_0 \frac{\sigma_{\gamma_0}}{\gamma_0} \approx 0.13$.
- An ideal thin lens snake which is transparent for orbital motion.
- ν_0 is almost independent of machine energy: around 0.41 (not 0.5 – because of the rotators).

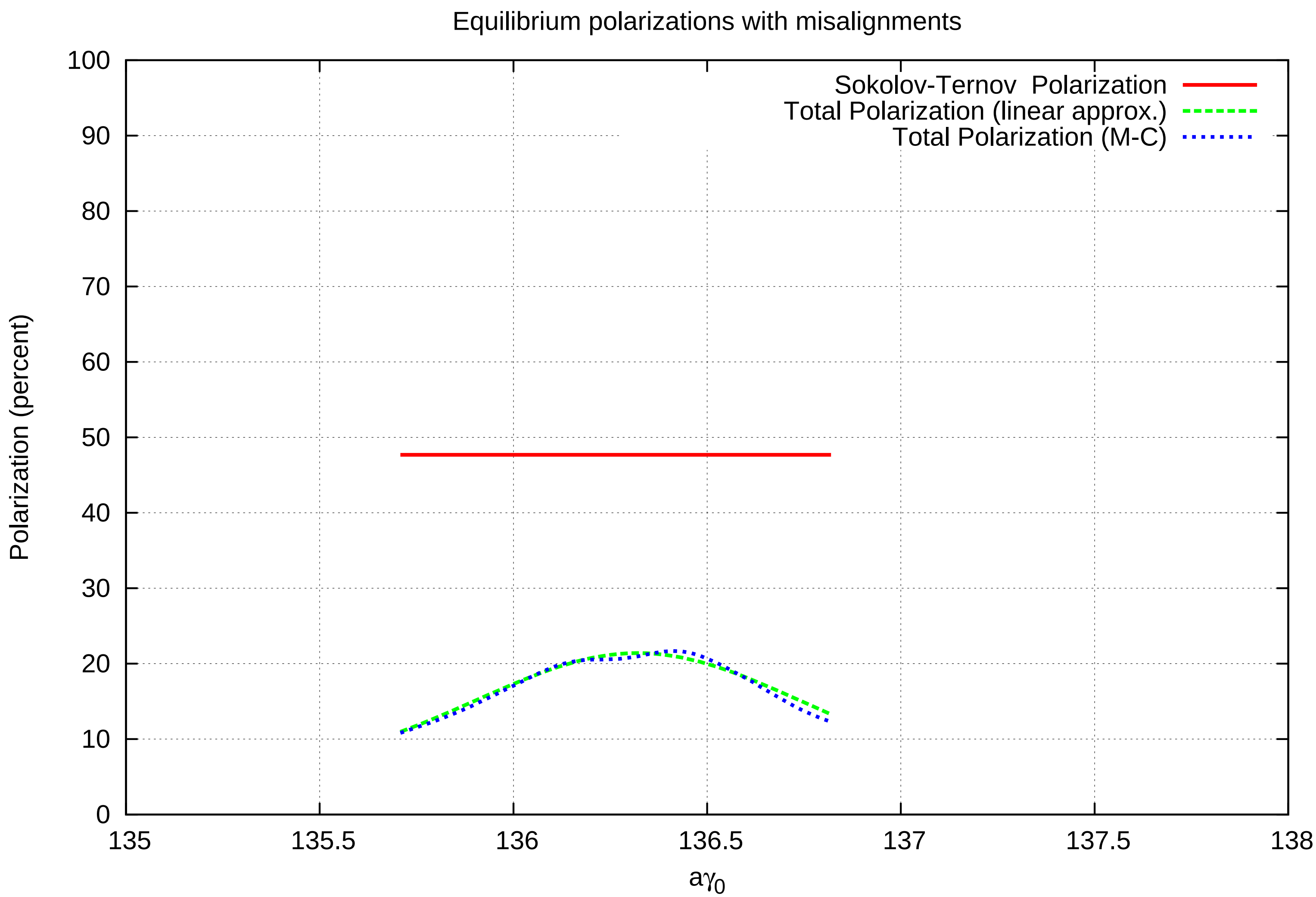
Perfect alignment and with the IR G matrix off

$Q_s = 0.1$



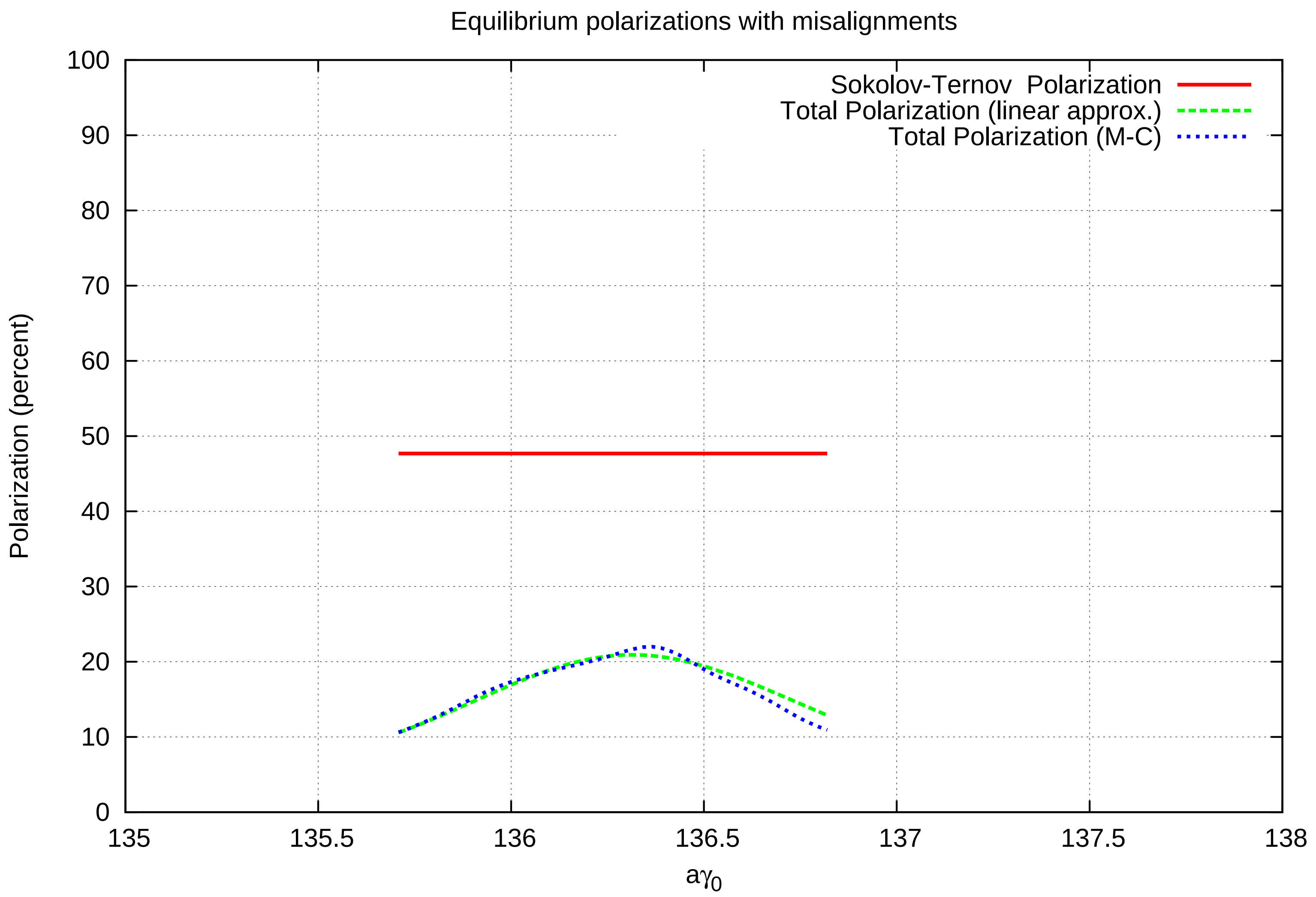
An example of just one misalignment and with the IR G matrix off

$Q_s = 0.06$



An example of just one misalignment and with the IR G matrix off

$Q_s = 0.10$



Summary on the model ring with rotators and a snake

- The maximum S-T polarisation is limited by the need for the asymmetric radiation distribution.
- In these calculations $\hat{n}_0$ is tilted from the vertical twice as much as for the flat ring $\Longrightarrow$ lower polarisation compared to the maximum S-T polarisation.
- With this rotator, $\hat{n}_0$ is tilted in the arcs away from design energy.
- Initial indications that the snake supresses the synchrotron sidebands. Much more investigation needed.
- —- the first time in the field that this topic has been invstigated.
- Essential to provide optical spin matching of the IR and arcs — obviously!.
- The dogleg rotator fits the need to bring the electron beam down to the proton beam.
- A practical snake design is needed.
- Optical spin matching is a big but necessary challenge.
- Harmonic closed orbit spin matching should be tested.
- In any case it would be essential to align the ring extremely well – but modern rings do have good alignment.

This has been a very first look but:

with modern alignment and the use of the Derbenev-Grote scheme,

optical spin matching will be well worth pursuing as the next step.

By Brian Montague during the lead-up to LEP and HERA polarisation.