Electron/positron Polarisation?

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D.P. Barber

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Deutsches Elektronen–Synchrotron (DESY), Germany

University of Liverpool, UK

Cockcroft Institute, Daresbury, UK

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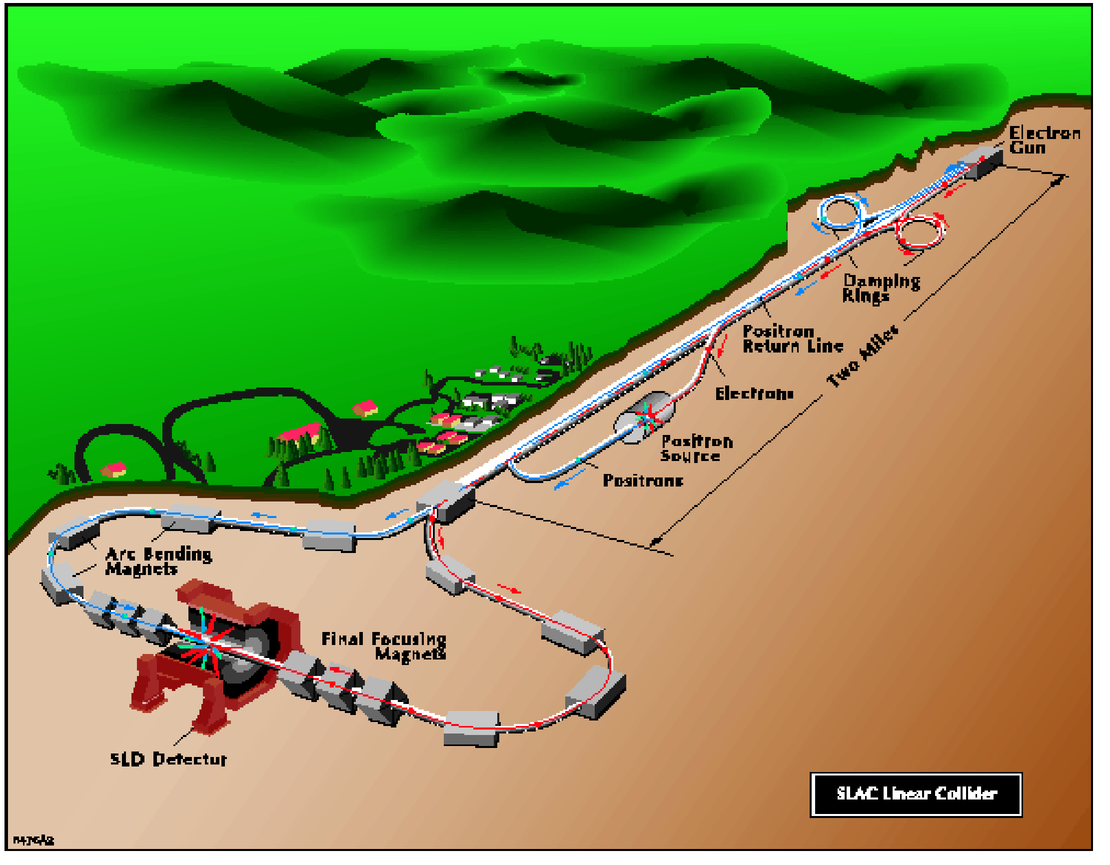
Plan

- SLC – a reminder
- LEP – a reminder
- HERA – a reminder
- Options
- Some theory and phenomenology
- Ring-ring
- Linac-ring and recirculator-ring
- Strategy

SLC

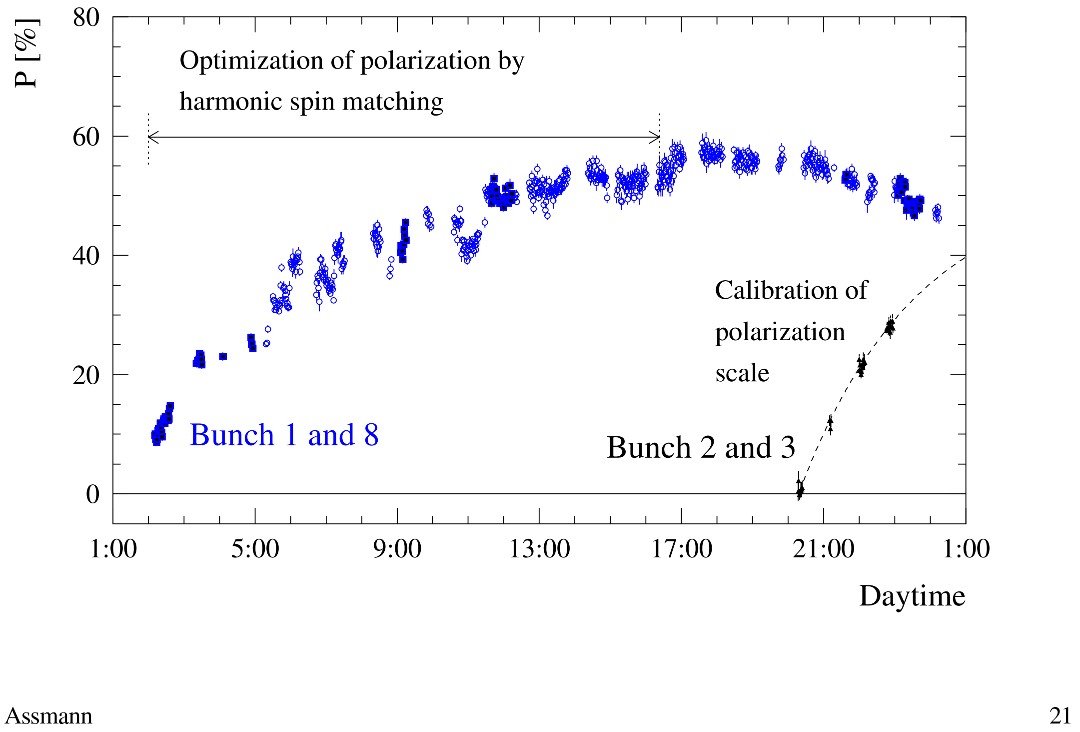


≈ 50 GeV polarised electrons, ≈ 80 percent

LEP

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

Highest polarization achieved:



Vertical polarisation by the S-T effect, no rotators. "Deterministic" harmonic orbit correction.
46 GeV, $\tau_{st} \approx 5$ hours

LEP features.

- Energy calibration by measuring $\gamma(g-2)/2$ with RF depolarisation.

  Error of $\approx$ 1.6 MeV on the Z^0 mass.

- Detection of energy changes due to gravitationally induced changes in the size of the ring: $\approx$ 8 MeV.

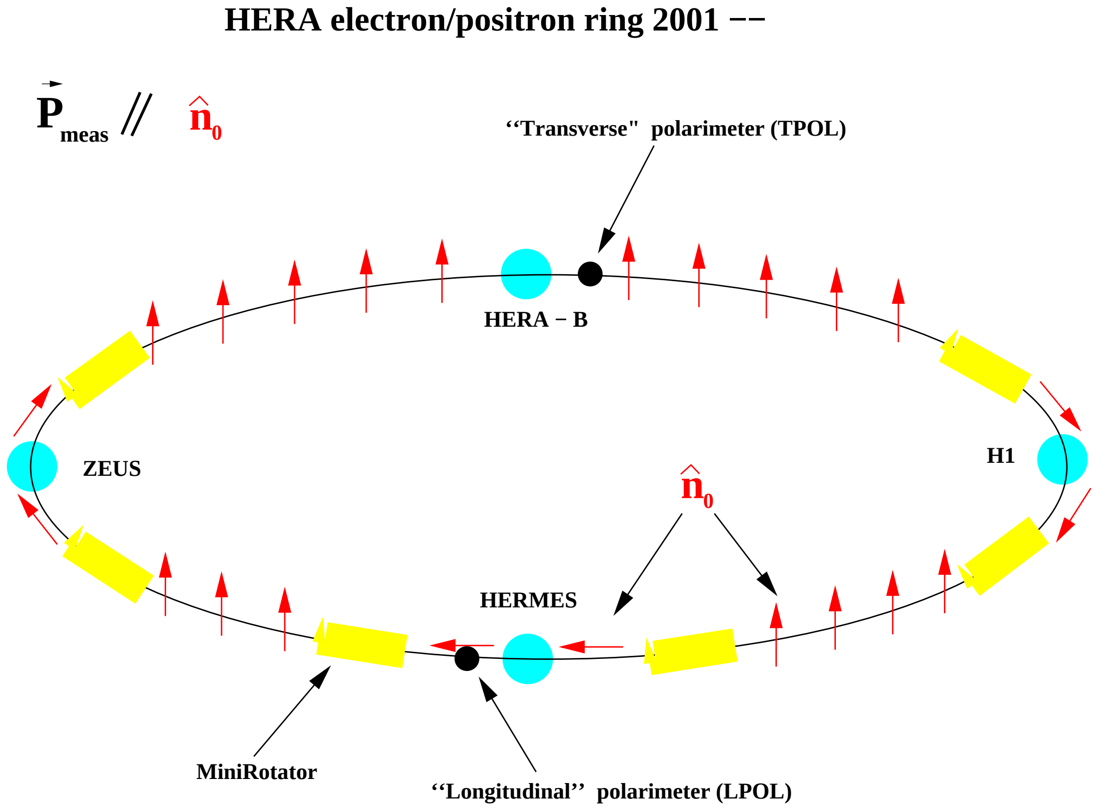
- Some spin flip even in that environment.

- Checking the punctuality of the TGV.

HERA

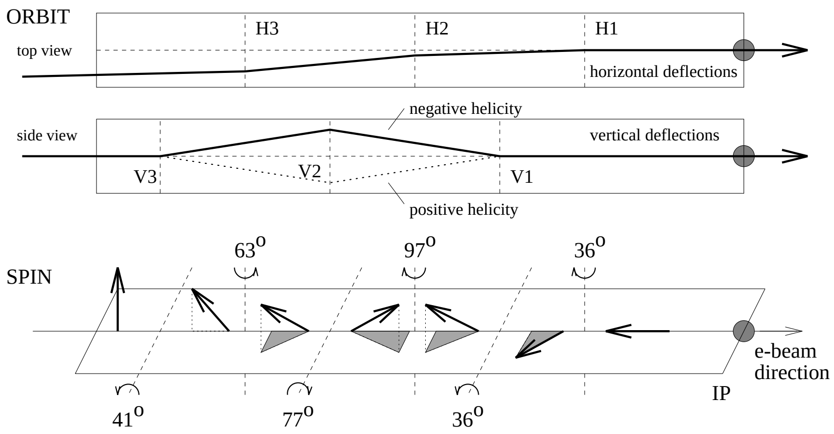
The first and only $e^{\pm}$ ring to supply longitudinal polarisation at high energy
— via the Sokolov-Ternov effect – also at 3 IP's simultaneously!
≈ 30 GeV, $\tau_{st} \approx 30$ mins. Depolarisation not too strong.
Perfectly balanced parameters

LHeC: 70 GeV, $\tau_{st} \approx 30$ mins. Depolarisation strong.
A very exciting challenge for polarisation aficionados!



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

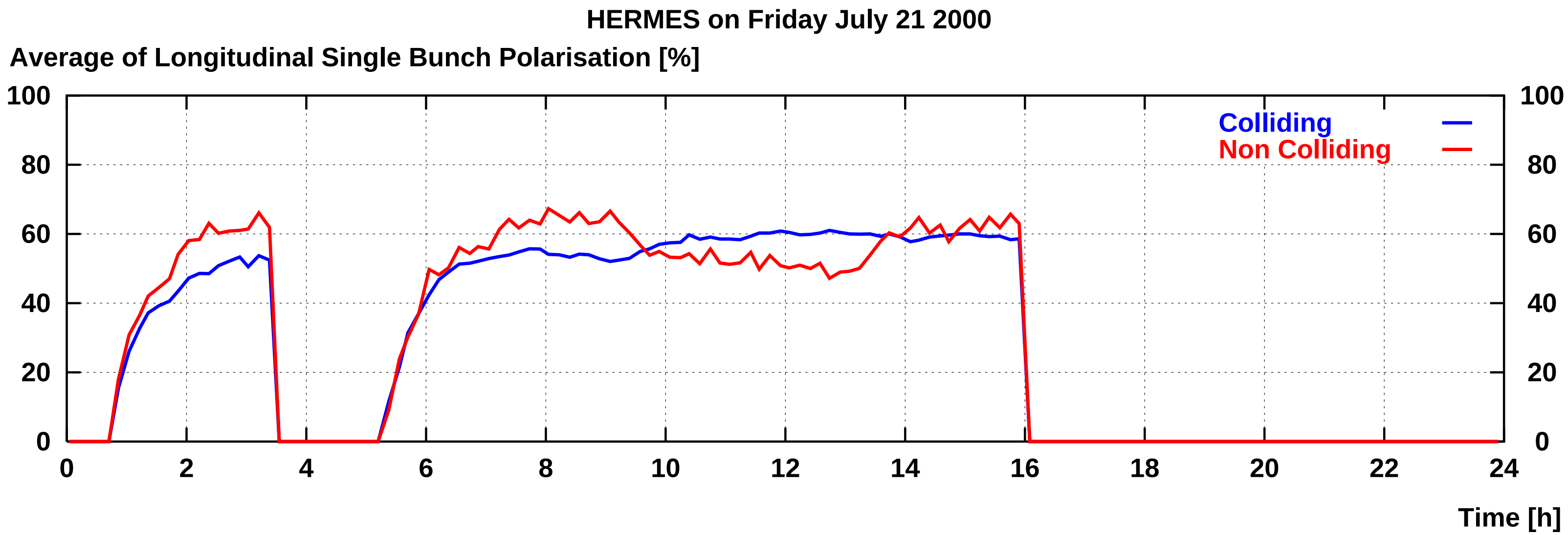
HERA MiniRotator: Buon + Steffen



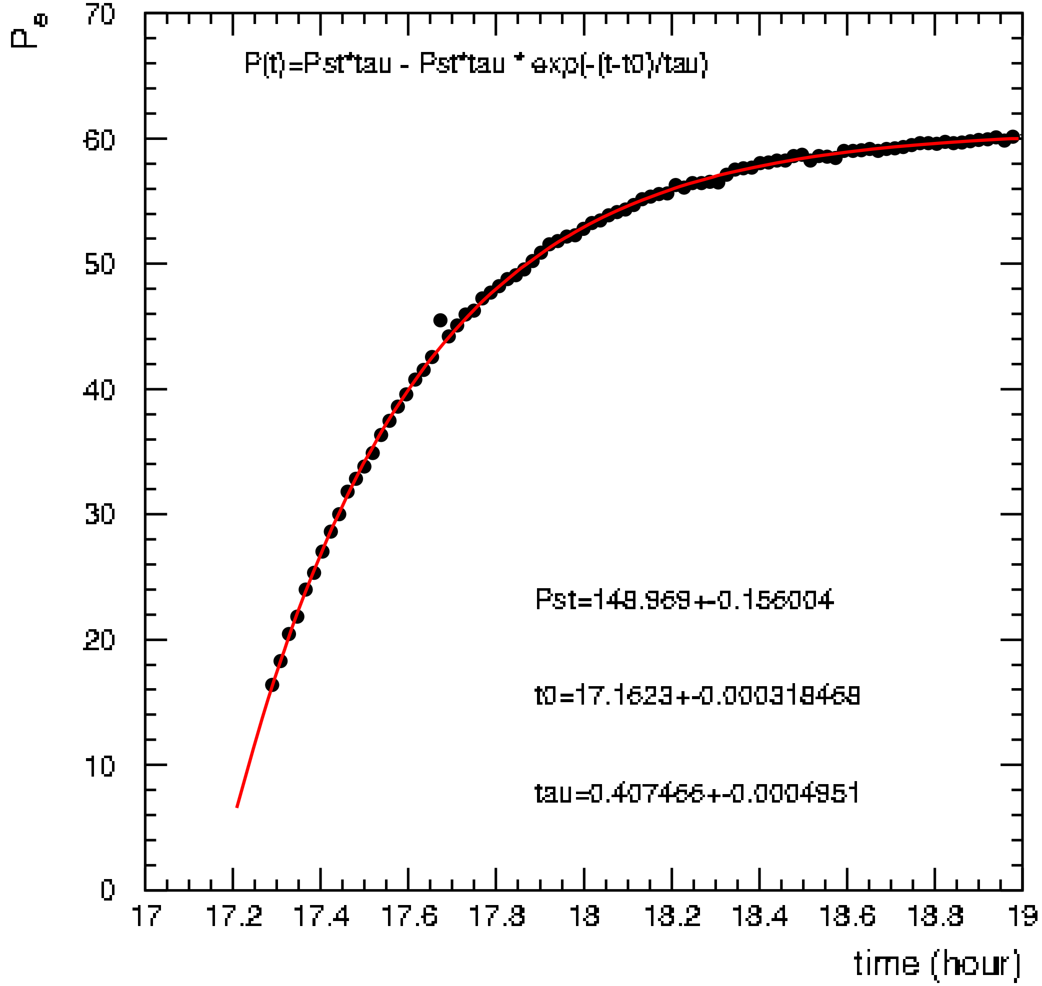
56 m ("short") → no quads.

27 – 39 GeV, both helicities, variable geometry

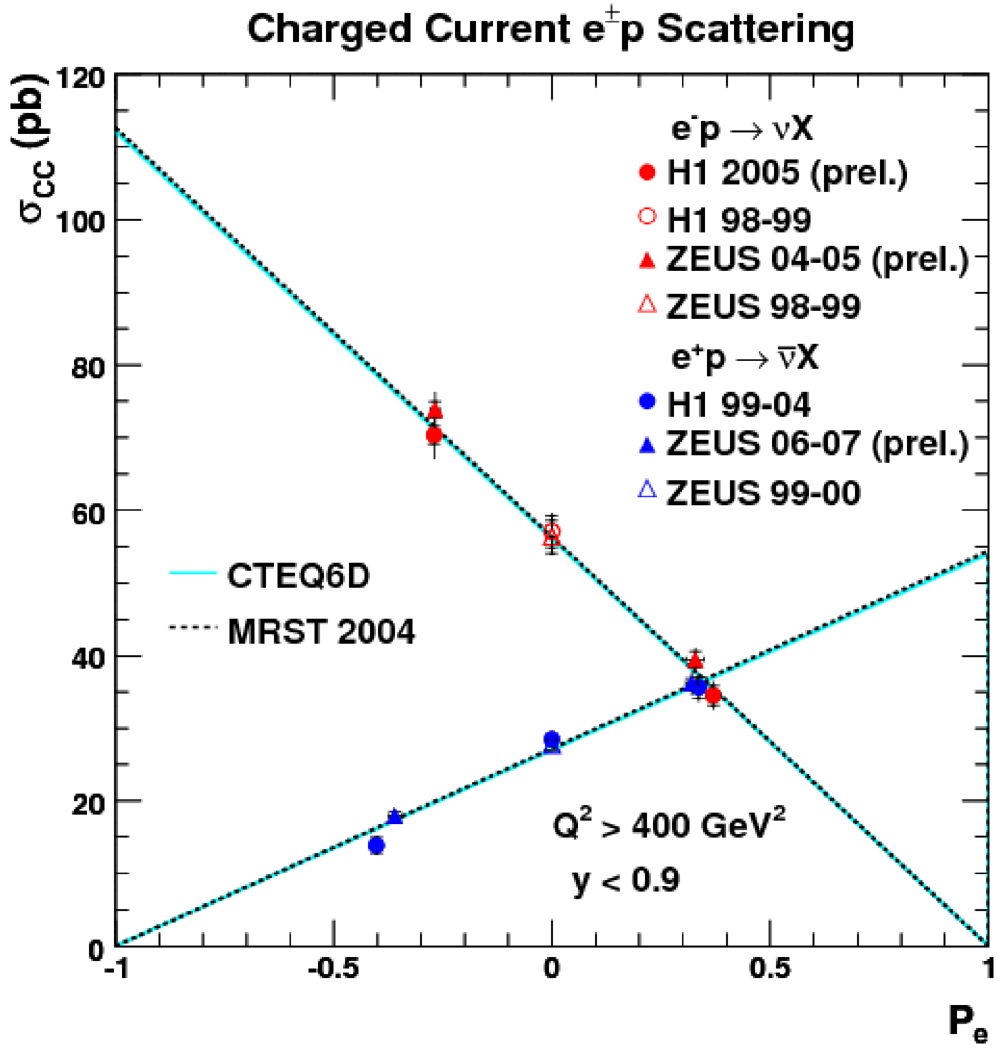
NO INTERNAL QUADRUPOLES!


HERMES on Friday July 21 2000
Average of Longitudinal Single Bunch Polarisation [%]
Colliding
Non Colliding
Time [h]
0
20
40
60
80
100
0
2
4
6
8
10
12
14
16
18
20
22
24

June 2007, the Fabry-Perot-Compton polarimeter of the POL2000 Project: Calibrating polarimeters



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


Charged Current e±p Scattering
σCC (pb)
120
100
80
60
40
20
0
-1
-0.5
0
0.5
1
Pe
e-p → νX
H1 2005 (prel.)
H1 98-99
ZEUS 04-05 (prel.)
ZEUS 98-99
e+p → ν̄X
H1 99-04
ZEUS 06-07 (prel.)
ZEUS 99-00
CTEQ6D
MRST 2004
Q2 > 400 GeV2
y < 0.9

The options

Option	Source	Polarisation loss	Comment
Linac-ring	????	Small	No spin-orbit resonances
Linac-ring multi turn	????	Small	No spin-orbit resonances
Recirculator	????	Probably small	No spin-orbit resonances
Pre-accelerator ring		Large! –unless snake(s) to suppress spin-orbit resonances	Probably strong stochastic depolarisation at 70 GeV
Ring-ring with Sokolov-Ternov effect		$\Longrightarrow$	Probably strong stochastic depolarisation at 70 GeV

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:

$$R_{3\times3}(s + C, s)\hat{n}_0 = \hat{n}_0$$

$\hat{n}_0$ 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 $R_{3\times3}(s + C, s)$

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:

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

  ===> Trouble at high energy!

Spin–orbit resonances

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

ν_{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

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

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

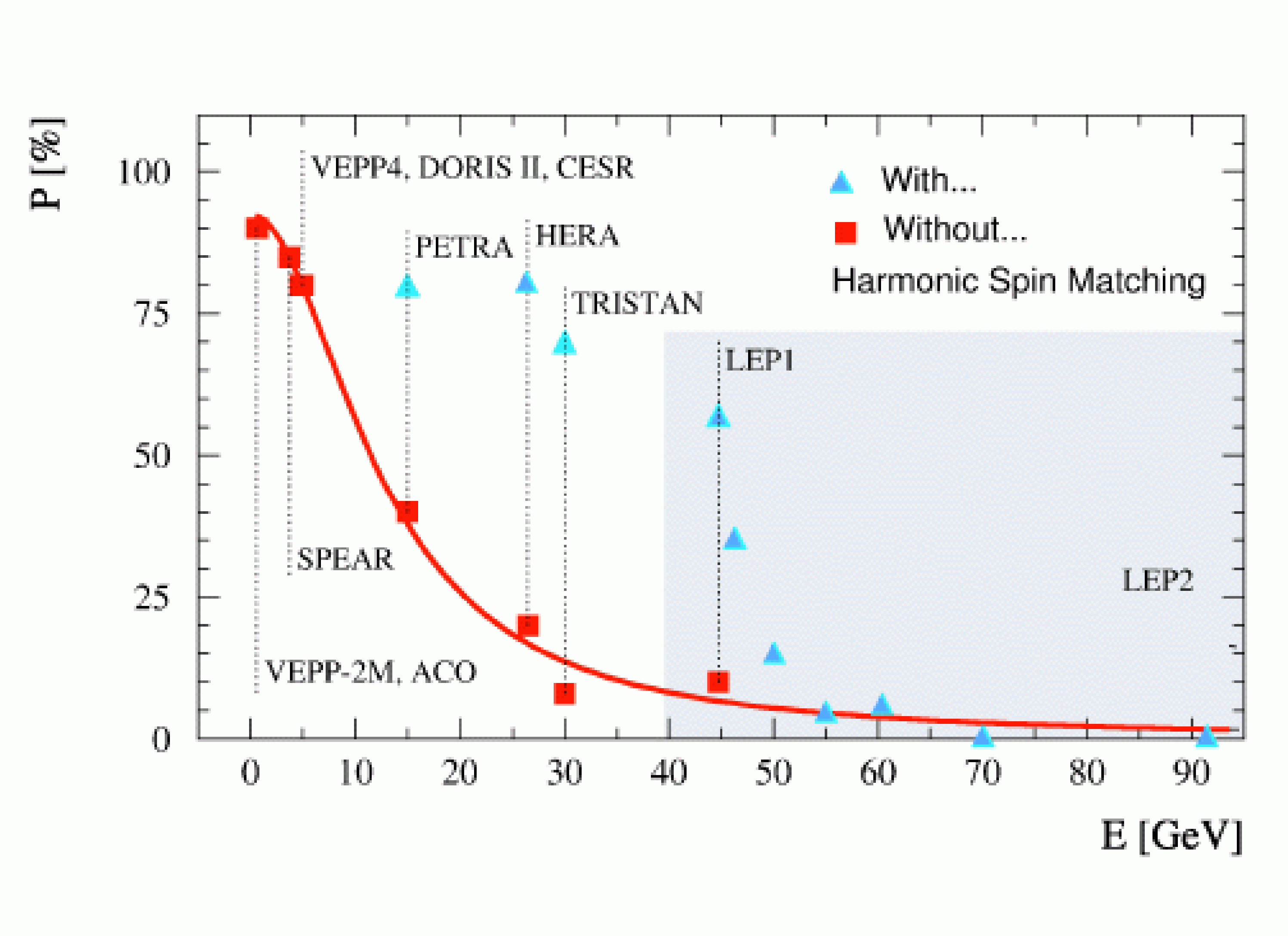
$B(\xi; m_s)$'s: *enhancement factors*, contain modified Bessel functions $I_{|m_s|}(\xi)$ and $I_{|m_s|+1}(\xi)$ depending on the *modulation index*

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

in a 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!

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

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

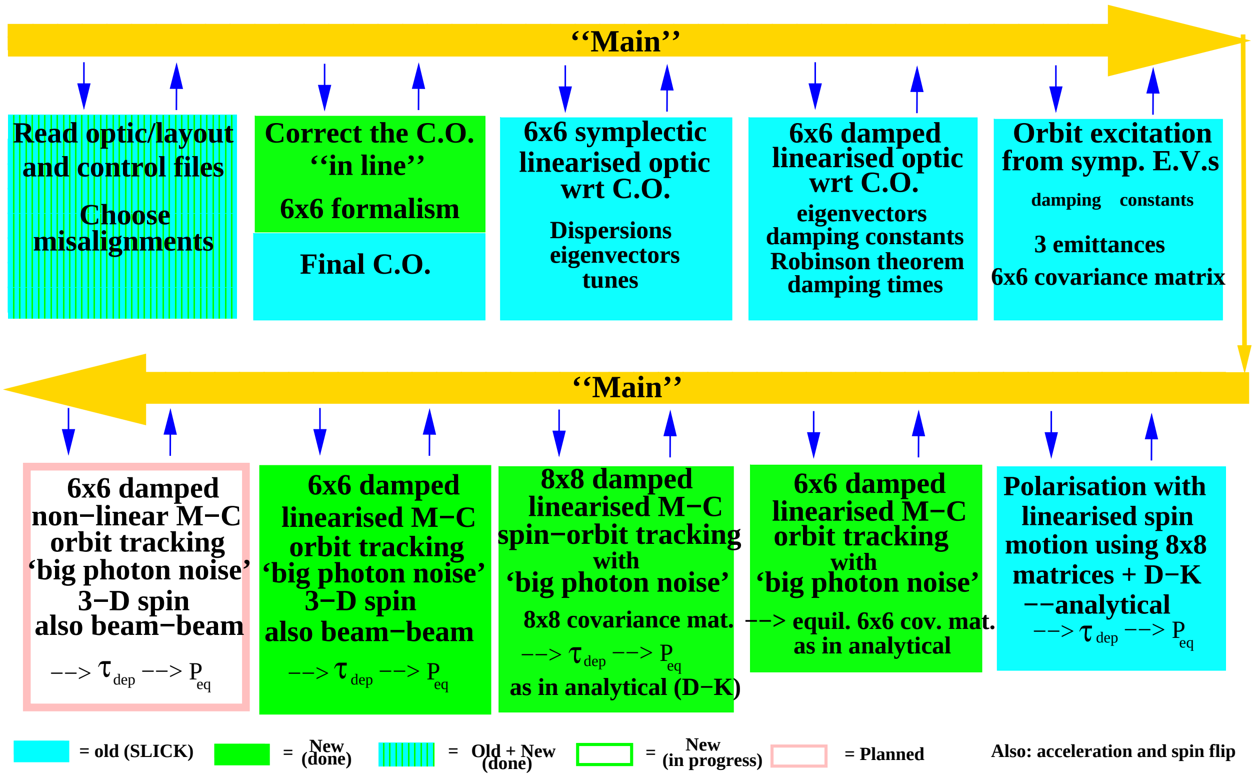
$$\hat{\mathbf{M}}_{8\times 8} = \begin{pmatrix} \mathbf{M_{6\times 6}} & \mathbf{0_{6\times 2}} \\ \mathbf{G_{2\times 6}} & \mathbf{D_{2\times 2}} \end{pmatrix}$$

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

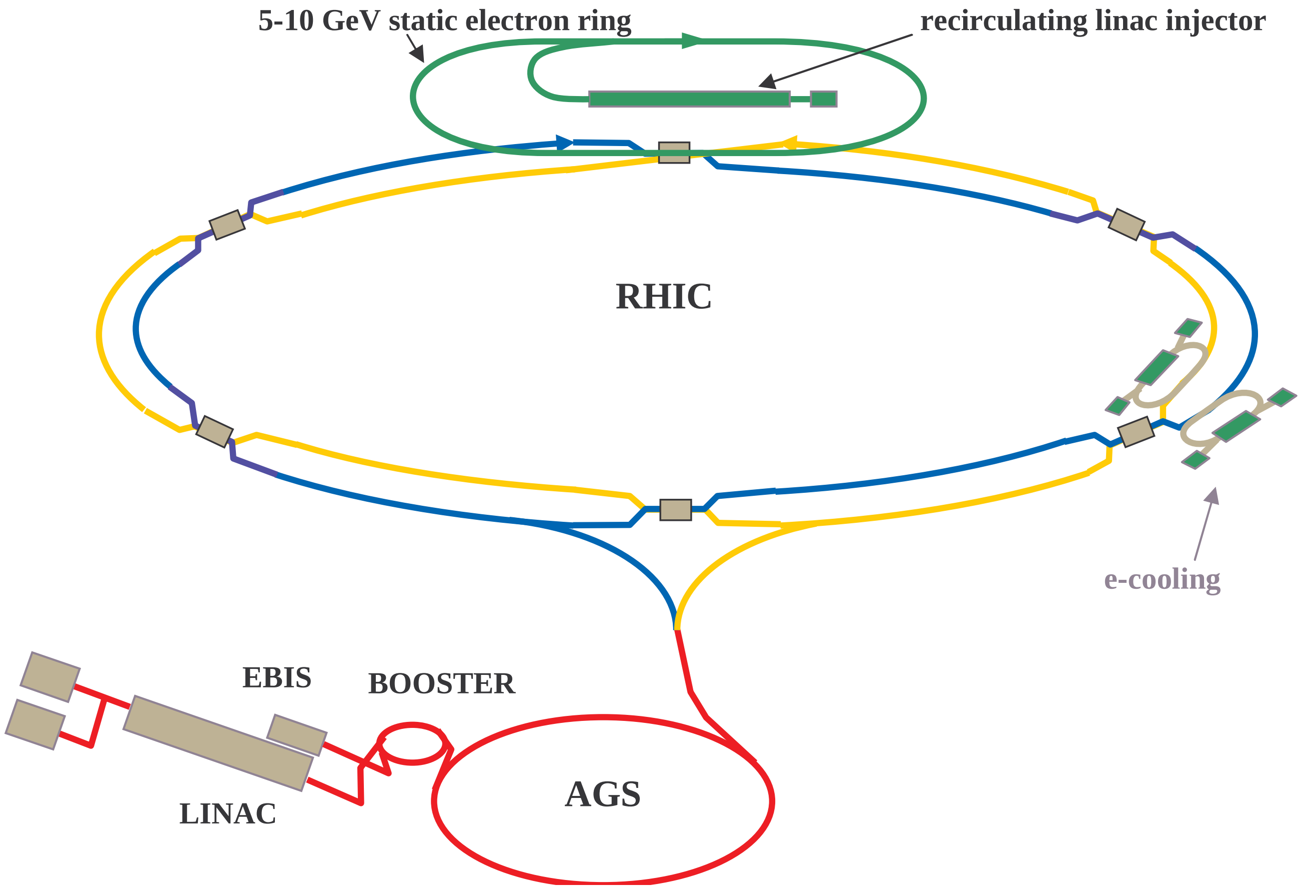
For full 3–D spin motion:

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

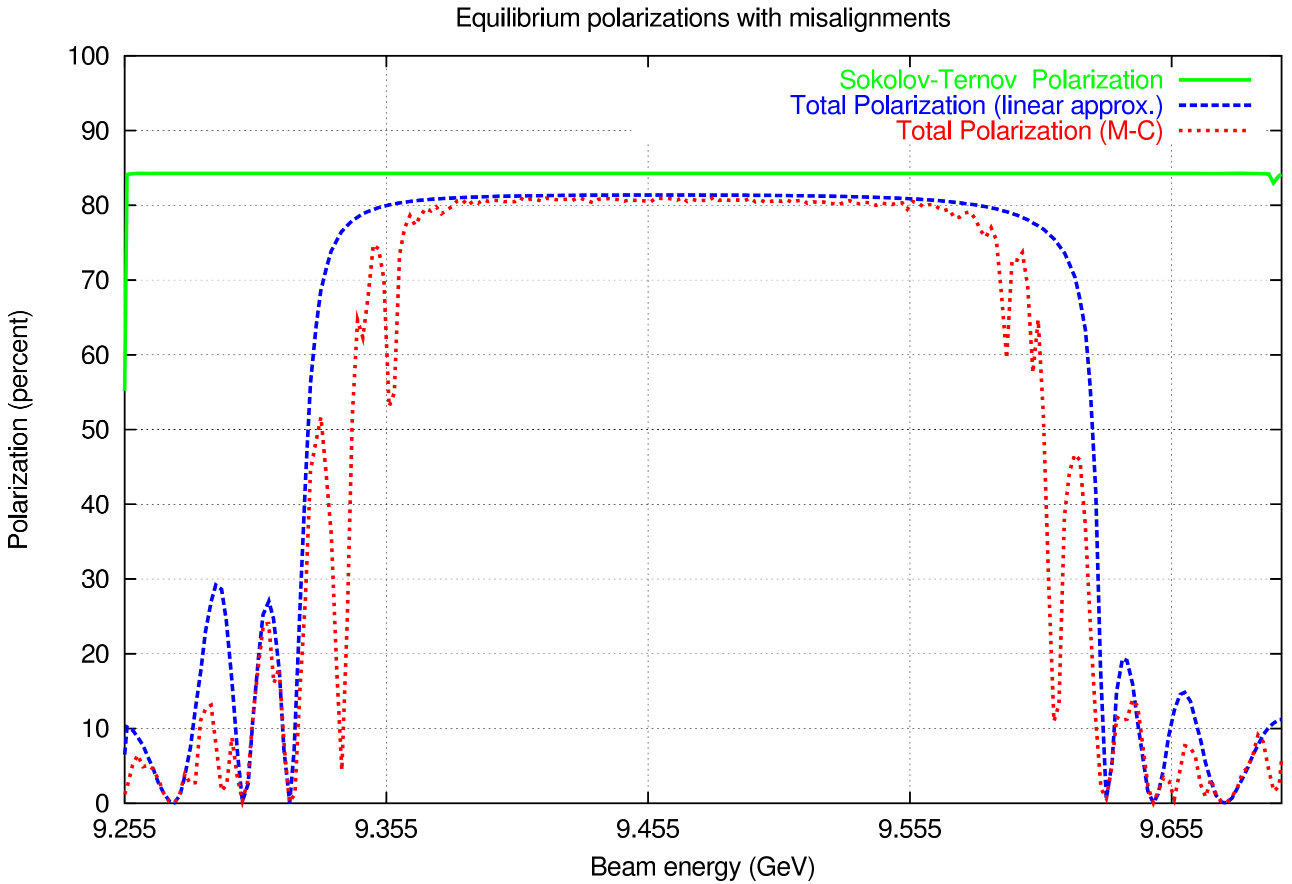
The $\mathbf{G_{3\times6}} \times (\mathbf{x}, \mathbf{x'}, \mathbf{y}, \mathbf{y'}, \mathbf{\Delta l}, \delta)^{\mathbf{T}}$ delivers rotations around $\hat{n}_0,\ \hat{m}_0,\ \hat{l}_0$

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

eRHIC ring-ring option

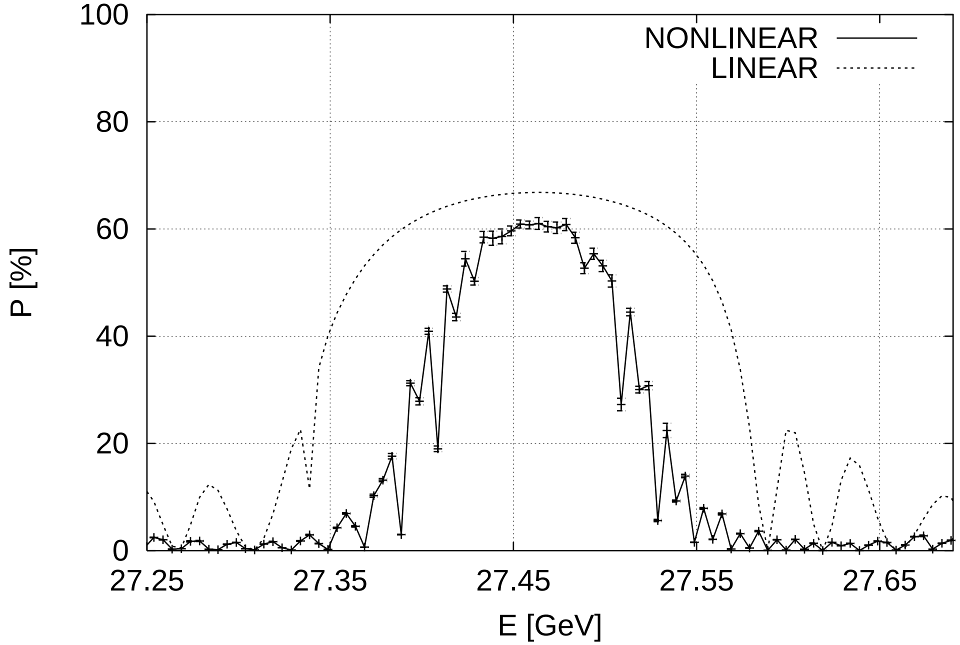


Full 3–D spin motion: eRHIC ≈ 9 GeV



SLICKTRACK

Full 3–D spin motion: HERA-II ≈ 27.5 GeV



SITROS: M. Berglund, DESY–THESIS 2001–044 (2001)

Diagnostics! Diagnostics! Diagnostics!

Switch spin-orbit coupling off/on to see what does what.

Recommendations for obtaining high self polarisation or large lifetime for stored injected polarisation in rings

- Include polarisation in the design (lattice, rotators, optic, spin matching) from the start — it should not be an "add on".
- Pay particular attention to:
  - alignment control and beam position monitoring
  - $\longrightarrow$ deterministic harmonic C.O. spin matching?
  - facilities for beam–based monitor calibration.
  - careful solenoid compensation $\longrightarrow$ locally with anti–solenoids if possible.
- Use spin transfer matrix formalism for spin matching in exotic machines and understand the physics of the spin–orbit coupling of each section of the ring. Ensure that there are enough independent quadrupole circuits.
  See D.P. Barber and G. Ripken in *"Handbook of Accelerator Physics and Engineering"*, Eds: A.W. Chao and M. Tigner, World Scientific, 3rd edition (2006).
- There is plenty of software available for detailed numerical calculations of linearized spin motion. The theory for linear orbit motion is well established.
- Very interesting depolarisation effects due to beam–beam forces have been seen at HERA and LEP. For future high luminosity ring–ring colliders it will be very important to have a good understanding of these effects and to be able to carry out reliable simulations with tracking codes. This could become a high priority for running in the presence of intense proton beams.

/cont.

- Pay close attention to polarimetry: backgrounds!! $\longrightarrow$ build the machine around the polarimeter(s)! Fast precise polarimeters are essential for facilitating fast adjustment of the orbit or tunes. Build the machine around the polarimeter(s) so that bremsstrahlung and synchrotron radiation backgrounds are avoided
- Don't try to calibrate polarimeters during beam–beam collisions and be careful about the effects of kinetic polarisation if the ring is not flat.

The linac - ring option

Comments by Evgeni Tsentalovich on sources, August 2008

- Polarisation of 80 percent is certain. 90 percent might be possible.
- A peak current from of 10-20 Amps is feasible. Anything higher is very difficult – mainly because of space charge-related problems.
- Attaining high average current is the most difficult problem. The best existing sources produce routinely around 200 μA. In some tests - up to 1 mA with rather low lifetime. In one test - 10 mA with very low lifetime. Any gun with more than 1-5 mA must have active cathode cooling – none of the existing sources does.
- I am trying to build a source with active cathode cooling, large area cathode and ring-shaped emission. The hope is to boost the average current to tens of mA. Perhaps even hundreds —

High-Current Polarized Source Developments

Evgeni Tsentalovich
MIT

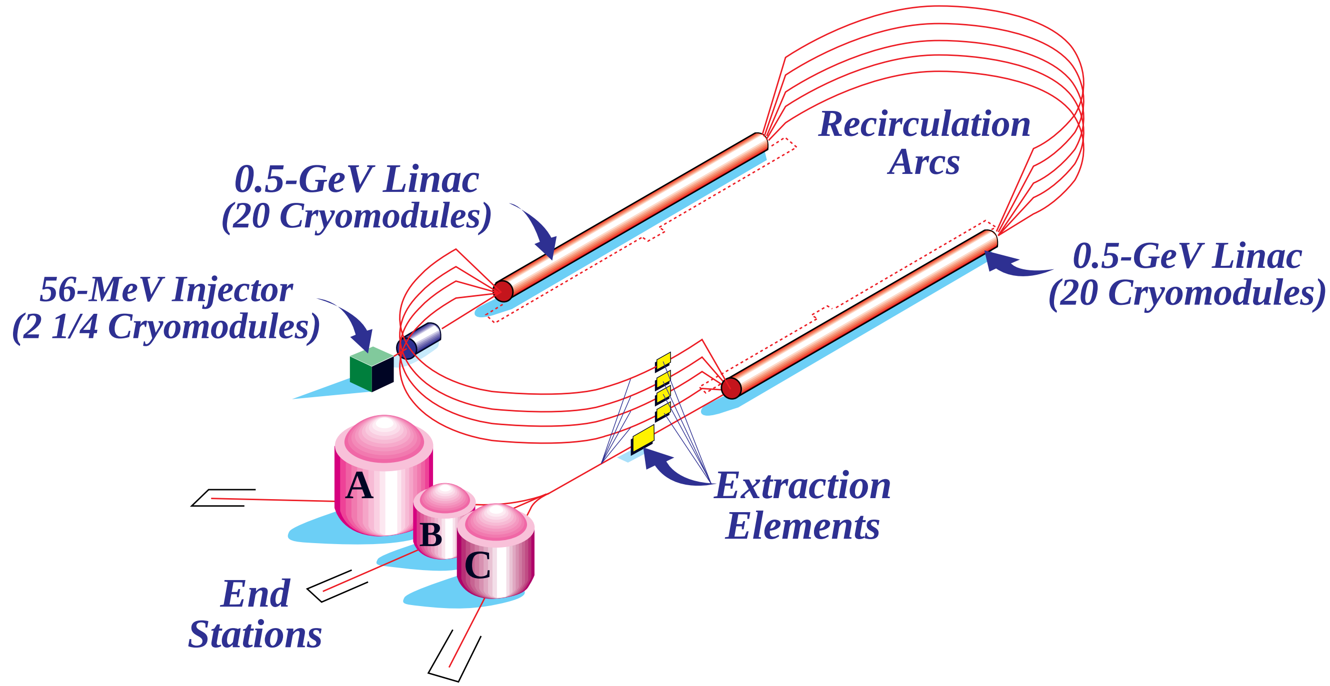
05/20/2008 1

Electron-Ion Collider Collaboration Meeting Hampton University, May, 2008
http://web.mit.edu/eicc/Hampton08/index.html

Recirculators for acceleration

Accelerate very quickly: no chance for resonance phenomena to develop.
– or “Froissart-Stora” depolarisation is very small.

CEBAF


Recirculation
Arcs
0.5-GeV Linac
(20 Cryomodules)
56-MeV Injector
(2 1/4 Cryomodules)
0.5-GeV Linac
(20 Cryomodules)
A
B
C
Extraction
Elements
End
Stations

ELFE@CERN

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THE WAY FORWARD

Plan for polarisation from the start! Polarisation can never be an after thought!

Begin NOW with intense careful study based on experience to investigate tricks.

For the ring-ring option:

- Need very good alignment – better than at LEP.
- Siberian Snakes to suppress the effect of energy spread and synchrotron motion on spin motion?
  These are essential in proton rings to suppress depolarising resonances during acceleration (e.g., RHIC).
  But in electron rings they kill the S-T effect if the synchrotron radiation is evenly distributed around the ring!!!
- Can an arrangement be found based on a correct snake layout combined with uneven synchrotron radiation from super bends?

For the linac-ring or recirculator-ring option:

- Continue with intensive high-current source development.

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