## Beam Polarization in Future Colliders: FCC-ee and eRHIC

Outline

- FCC-ee
- Polarization wigglers
- Polarization in presence of misalignments
- eRHIC storage ring
- Sokolov-Ternov effect and eRHIC storage ring
- Polarization in presence of misalignments

Eliana GIANFELICE-WENDT (Fermilab)
HKIAS mini-workshop on Polarization in Future Colliders
January 18, 2019

## FCC: a brief introduction

CERN is planning its future at the energy frontier after the completion of the LHC program.

Following 2013 recommendations of the Council on European Strategy for Particle Physics, CERN has launched a 5 years international design study for a Future Circular Collider (FCC).

Future Circular Collider Study


CERN is undertaking an integral design study for post-LHC particle accelerator options in a global context. The Future Circular Collider (FCC) study has an emphasis on protonproton and electron-positron (lepton) high-energy frontier machines. It is exploring the potential of hadron and lepton circular colliders, performing an in-depth analysis of infrastructure and operation concepts and considering the technology research and development programs that would be required to build a future circular collider. A conceptual design report will be delivered before the end of 2018, in time for the next update of the European Strategy for Particle Physics.

A $\boldsymbol{p} \boldsymbol{p}$ circular collider with a center of mass energy of about 100 TeV is believed to have the necessary discovery potential.


(N. Arkani-Hamed, Geneva 2014 Kick-off meeting)

The c.m. energy reachable by re-placing LHC dipoles with 20 T dipoles is 33 TeV .

- For 100 TeV a new tunnel is needed.
- It could first host a $e^{ \pm}$collider.
- Further options: ions, ep collider.
- Site: Geneva, it would use existing accelerators as injectors and exploit existing technical and administrative infrastructures.


FCC-ee parameters

| parameter | $Z$ | $W$ | $H(\mathrm{ZH})$ | $t \bar{t}$ |
| :--- | :---: | :---: | :---: | :---: |
| beam energy $[\mathrm{GeV}]$ | 45.6 | 80 | 120 | 182.5 |
| circumference $[\mathrm{km}]$ | 97.8 | 97.8 | 97.8 | 97.8 |
| beam current $[\mathrm{mA}]$ | 1390 | 147 | 29 | 5.4 |
| bunches / beam | 16640 | 2000 | 328 | 48 |
| part./bunch $\left[10^{11}\right]$ | 1.7 | 1.5 | 1.8 | 2.3 |
| hor. emittance $[\mathrm{nm}]$ | 0.3 | 0.8 | 0.6 | 1.5 |
| vert. emittance $[\mathrm{pm}]$ | 1.0 | 1.7 | 1.3 | 2.9 |
| hor IP beta $[\mathrm{m}]$ | 0.15 | 0.2 | 0.3 | 1 |
| vert. IP beta $[\mathrm{mm}]$ | 0.8 | 1.0 | 1.0 | 1.6 |
| lum. $\left[10^{34} \mathrm{~cm}^{-2} \mathrm{~s}^{-1}\right]$ | $>200$ | $>25$ | $>7$ | $>1.3$ |

(from M. Benedikt and F. Zimmermann, IPAC2018)

## Polarization in FCC-ee

- Resonant de-polarization has been proposed for accurate beam energy calibration ( $\ll 100 \mathrm{keV}$ ) at 45 and 80 GeV beam energy. It relies on the relationship $\nu_{\text {spin }}=\boldsymbol{a} \gamma^{\text {a }}$.
- Beam polarization is obtained "for free" through Sokolov-Ternov effect. The effect is in practice restricted to a limited range of values of machine size and beam energy because
- of the build-up rate
- it is jeopardized by machine imperfections (spin/orbital motion resonances) which affects the reachable level of polarization in particular at high energy.
- $10 \%$ beam polarization is estimated to be enough for the purpose of energy calibration.

[^0]Build-up rate

$$
\tau_{\mathbf{S T}}^{-1}=\frac{5 \sqrt{3}}{8} \frac{r_{e} \hbar}{m_{0}} \frac{\gamma^{5}}{|\rho|^{3}} \rightarrow \tau_{p}^{-1}=\frac{5 \sqrt{3}}{8} \frac{r_{e} \hbar \gamma^{5}}{m_{0} C} \oint \frac{d s}{|\rho|^{3}} \text { for an actual ring }
$$

For FCC-ee with $\rho \simeq 10424 \mathrm{~m}$,it is

| $\boldsymbol{E}$ | $\boldsymbol{\tau}_{\text {pol }}$ | $\boldsymbol{\tau}_{\mathbf{1 0 \%}}\left(^{*}\right)$ |
| :---: | :---: | :---: |
| $(\mathrm{GeV})$ | $(\mathrm{h})$ | h |
| 45 | 256 | 29 |
| 80 | 14 | 1.6 |

$\left.{ }^{*}\right)$ Time needed to reach $\boldsymbol{P}=10 \%$ for energy calibration

$$
\tau_{10 \%}=-\tau_{p} \times \ln \left(1-0.1 / P_{\infty}\right)
$$

## Polarization wigglers

At low energy the polarization time may be reduced by introducing properly designed wiggler magnets i.e. a sequence of vertical dipole fields, $\overrightarrow{\boldsymbol{B}}_{\boldsymbol{w}}$, with alternating signs. Constraints for $\boldsymbol{x}=\mathbf{0}$ outside the wiggler

- $\int_{w i g} d s B_{w}=0$
- $\int_{w i g} d s s B_{w}=0$
$\Rightarrow$ a symmetric field configuration fulfills both conditions. From Baier-Katkov-Strakhovenk expressions

$$
\begin{gathered}
\tau_{p}^{-1}=F \gamma^{5}\left[\int_{d i p} \frac{d s}{\left|\rho_{d}\right|^{3}}+\int_{w i g} \frac{d s}{\left|\rho_{w}\right|^{3}}\right] \quad F \equiv \frac{5 \sqrt{3}}{8} \frac{r_{e} \hbar}{m_{0} C} \\
P_{\infty}=\frac{8}{5 \sqrt{3}} \frac{\oint d s \frac{\hat{B} \cdot \hat{n}_{0}}{|\rho|^{3}}}{\oint d s \frac{1}{|\rho|^{3}}} \propto \tau_{p}\left[\int_{d i p} d s \frac{\hat{B}_{d} \cdot \hat{n}_{0}}{\left|\rho_{d}\right|^{3}}+\int_{w i g} d s \frac{\hat{B}_{w} \cdot \hat{n}_{0}}{\left|\rho_{w}\right|^{3}}\right]
\end{gathered}
$$

Small $\tau_{p} \rightarrow\left|B_{w}\right|$ large.
$\boldsymbol{P}_{\infty}$ large $\rightarrow \int_{w i g} d s B_{w}^{3}$ must be large too.

With $\hat{\boldsymbol{n}}_{\mathbf{0}} \equiv \hat{\boldsymbol{y}}$ and a piecewiseconstant field in the wiggler

$$
\begin{gathered}
P_{\infty}=\frac{8 F \gamma^{5}}{5 \sqrt{3}} \tau_{p}\left[\int_{d i p} d s \frac{\hat{B}_{d} \cdot \hat{n}_{0}}{\left|\rho_{d}\right|^{3}}+\frac{L^{+}}{\left|\rho^{+}\right|^{3}}\left(1-\frac{1}{N^{2}}\right)\right] \\
\tau_{p}^{-1}=F \gamma^{5}\left[\int_{d i p} \frac{d s}{\left|\rho_{d}\right|^{3}}+\int_{w i g} \frac{d s}{\left|\rho_{w}\right|^{3}}\right]=F \gamma^{5}\left[\int_{d i p} \frac{d s}{\left|\rho_{d}\right|^{3}}+\frac{L^{+}}{\left|\rho^{+}\right|^{3}}\left(1+\frac{1}{N^{2}}\right)\right]
\end{gathered}
$$

where $\boldsymbol{N} \equiv \boldsymbol{L}^{-} / \boldsymbol{L}^{+}=\boldsymbol{B}^{+} / \boldsymbol{B}^{-}$(6 for FCCee wiggler, as LEP).
The presence of wigglers increases $\boldsymbol{U}_{\text {loss }}$ and $\sigma_{E} / \boldsymbol{E}$. The particle energy lost per turn and the energy spread are

$$
U_{l o s s}=\frac{C_{\gamma} E^{4}}{2 \pi} \oint \frac{d s}{\rho^{2}} \quad\left(\sigma_{E} / E\right)^{2}=\frac{C_{q}}{J_{\epsilon}} \gamma^{2} \oint \frac{d s}{|\rho|^{3}} / \oint \frac{d s}{\rho^{2}}
$$

The generally valid relationship

$$
\left(\sigma_{E} / E\right)^{2}=\frac{C_{q} C_{\gamma} E^{4}}{2 \pi J_{\epsilon} F \gamma^{3}} \frac{1}{\tau_{p} U_{\text {loss }}}
$$

shows that a small $\tau_{p}$ is at price of a higher $\boldsymbol{U}_{\text {loss }}$ and/or $\sigma_{E}$.

## Horizontal emittance

$$
\begin{gathered}
\epsilon_{x}=C_{q} \gamma^{2} \frac{\mathcal{I}_{5}}{J_{x} \mathcal{I}_{2}} \quad \mathcal{I}_{2} \equiv \oint d s \frac{1}{\rho^{2}} \\
\mathcal{I}_{5} \equiv \oint d s \frac{\beta_{x} D_{x}^{\prime 2}+2 \alpha_{x} D_{x} D_{x}^{\prime}+\gamma_{x} D_{x}^{2}}{|\rho|^{3}}
\end{gathered}
$$

Even if located where nominally $\boldsymbol{D}_{\boldsymbol{x}}=0$, wigglers may increase the horizontal emittance

$$
\Delta \mathcal{I}_{5} \simeq \frac{1}{15 \pi^{3}} \frac{<\beta_{x}>_{w} \ell_{w}}{\rho_{w}^{5}} \lambda_{w}
$$

The emittance increase can be mitigated by choosing a shorter wiggler period, $\boldsymbol{\lambda}_{\boldsymbol{w}}$.



LEP wigglers
LEP-like wiggler orbit (shown for $\boldsymbol{B}^{+}=5.2 \mathrm{~T}$ )


3 periods, orbit shown for $B^{+}=0.7 \mathrm{~T}$

With 8 of such wigglers and $B^{+}=0.568 \mathrm{~T}$

- $\tau_{10 \%} \simeq 2.7 \mathrm{~h}$
- $\boldsymbol{\sigma}_{\boldsymbol{E}}=50 \mathrm{MeV}$
- For the $90 / 90$ deg optics $\epsilon_{x}$ increases from 90 pm to 120 pm with 3 periods (field for $\tau_{10 \%}=2.7 \mathrm{~h}$ ).

Accurate simulations are necessary for evaluating the polarization level in presence of misalignments when direct evaluation of Derbenev-Kondratenko expression is prohibitive.

- MAD-X used for simulating quadrupole misalignments and orbit correction.
- SITROS (by J. Kewish) used for computing the resulting polarization.
- Tracking code with 2th order orbit description and non-linear spin motion.
- Used for HERA-e in the version improved by M. Böge and M. Berglund.
- It contains SITF (fully 6D) for analytical polarization computation with linearized spin motion.
* Useful tool for preliminary checks before embarking in time consuming tracking.
* Computation of polarization related to the 3 degree of freedom separately: useful for disentangling problems!

More recently Bmad by D. Sagan and the PTC software by E. Forest have become available for polarization calculations.

## Simulations for a toy ring

Preliminary studies with a simplified optics (FODO cells and dispersion-free regions for wigglers) have shown that large polarization could be achieved at 45 GeV (even with very large wiggler fields, if orbit very well corrected!) and at 80 GeV .


## Simulations for the "actual" FCC-ee

FCC- $e^{ \pm}$design relies on ultra-flat beams

|  | $\boldsymbol{Z}$ | $\boldsymbol{W} \boldsymbol{W}$ |
| :---: | :---: | :---: |
| Beam energy [GeV] | 45.6 | 80 |
| FODO | $60^{\mathbf{0}} / 60^{\mathbf{0}} /$ | $60^{\mathbf{0}} / 60^{\mathbf{0}}$ |
| $\boldsymbol{\epsilon}_{\boldsymbol{x}}[\mathrm{nm}]$ | 0.27 | 0.84 |
| $\boldsymbol{\epsilon}_{\boldsymbol{y}}[\mathrm{pm}]$ | 1 | 1.7 |
| $\boldsymbol{\beta}_{\boldsymbol{x}}^{*}[\mathrm{~m}]$ | 0.15 | 0.2 |
| $\boldsymbol{\beta}_{\boldsymbol{y}}^{*}[\mathrm{~mm}]$ | 0.8 | 1 |
| $\boldsymbol{\sigma}_{\boldsymbol{x}}^{*}[\boldsymbol{\mu \mathrm { m } ]}$ | 6.4 | 13 |
| $\boldsymbol{\sigma}_{\boldsymbol{y}}^{*}[\mathrm{~nm}]$ | 28 | 41 |

For squeezing $\boldsymbol{\beta}_{y}^{*}$ strong quadrupoles are needed in the IR where $\boldsymbol{\beta}_{\boldsymbol{y}}$ is large.
$\sim$ Large chromaticity and response to misalignments in the vertical plane.
Additional related problems

- Beam offsets in the strong IRs sextupoles, produce tune shift and betatron coupling.
- Small offsets of the IRs quads may lead to an anti-damped machine.

Optics changed over the years as a result of the feasibility studies.

$$
\text { January } 2018 \text { Optics }\left(60^{\circ} / 60^{\circ}\right)
$$

| Optics |  | $\boldsymbol{\xi}_{\boldsymbol{x}}$ | $\boldsymbol{\xi}_{\boldsymbol{y}}$ |
| :---: | :---: | :---: | :---: |
| 45 GeV | all sexts off | -361 | -1540 |
|  | IR setxs off | +3.5 | -1230 |
| 80 GeV | all sexts off | -359 | -1331 |
|  | IR setxs off | +3 | -1017 |


| Optics |  | $\boldsymbol{F}_{\boldsymbol{y}}$ |
| :---: | :---: | :---: |
| 45 GeV | all quads | 665 |
|  | w/o IPs quads | 124 |
| 80 GeV | all quads | $\boldsymbol{F}_{\boldsymbol{y}}$ |
|  | w/o IPs quads | 127 |

with

$$
\begin{gathered}
F \equiv \frac{1}{2 \sqrt{2}\left|\sin \pi Q_{z}\right|} \sqrt{\left\langle\beta_{z}>\right.} \sqrt{\Sigma_{i=1}^{N Q} \beta_{z, i}(k \ell)_{i}^{2}} \\
\\
<z_{r m s}>=F \delta z_{r m s}^{Q} \quad z=x, y
\end{gathered}
$$

## Simulations of orbit distortions

Correction scheme:
a BPM close to each quad and IR sextupole;
a horizontal (vertical) corrector close to each horizontal (vertical) focusing quadrupole; horizontal + vertical corrector close to each IR quadrupole.
"Tricks" needed for introducing misalignments errors in the simulation (!):

- Move tunes away from integer ("set up" tunes)
$-\boldsymbol{q}_{\boldsymbol{x}}: 0.1 \rightarrow 0.2$
$-\boldsymbol{q}_{y}: 0.2 \rightarrow 0.3$
- Switch sextupoles off (linear machine).
- Add errors to "arc" quads in steps of 5-10 $\boldsymbol{\mu} \mathrm{m}$ and correct by each step with large number (some hundreds) correctors.
- Add errors to the IR quadrupoles in steps of $5 \mu \mathrm{~m}$ and correct with close by correctors.
A lengthy procedure not feasible in a real machine. In practice: use "relaxed" optics and one-turn steering through correction dipoles for establishing a closed orbit.


## 2017 90/90 deg optics

45 GeV case with 4 wigglers (LEP-like).
$\delta y_{r m s}^{Q}=200 \mu \mathrm{~m}$, no BPMs errors
$\boldsymbol{y}_{r m s}=0.049 \mathrm{~mm}$
$|\boldsymbol{\delta} \hat{\boldsymbol{n}}|_{0, r m s}=0.4 \mathrm{mrad}$, no harmonic bumps

Same error realization at 80 GeV
$|\boldsymbol{\delta} \hat{\boldsymbol{n}}|_{\mathbf{0}, \text { rms }}=2 \mathrm{mrad}$
Oide optics with $\mathrm{Q}_{\mathrm{x}}=0.1, \mathrm{Q}_{\mathrm{y}}=0.2, \mathrm{Q}_{\mathrm{s}}=0.1$



## with harmonic bumps

Oide optics with $\mathrm{Q}_{\mathrm{x}}=0.1, \mathrm{Q}_{\mathrm{y}}=0.2, \mathrm{Q}_{\mathrm{s}}=0.1$


Introducing BPM errors and quadrupole radial offsets and roll angles, misalignments had to be decreased! Set of errors assumed (but no statistics)

|  | IR Quads | IR BPMs | other Quads | other BPMs |
| :---: | :---: | :---: | :---: | :---: |
| $\boldsymbol{\delta} \boldsymbol{x}(\boldsymbol{\mu \mathrm { m } )}$ | 10 | 10 | 30 | 30 |
| $\boldsymbol{\delta} \boldsymbol{y}(\boldsymbol{\mu \mathrm { m } )}$ | 10 | 10 | 30 | 30 |
| $\boldsymbol{\delta} \boldsymbol{\theta}(\boldsymbol{\mu r a d})$ | 10 | 10 | 30 | 30 |
| calibration | - | $1 \%$ | - | $1 \%$ |

- Although the resulting orbit after correction is in the order of few microns, the vertical emittance may result above specs.
- Skew quadrupoles used for minimizing spurious vertical dispersion and betatron coupling.
- Many seeds give no stable optics when sextupoles are turned on: the beam position at the sextupoles must be extremely well controlled!
- Some seeds give anti-damped machine when synchrotron radiation is turned on: the beam position at the IR quadrupoles must be extremely well controlled too!

Some seeds show a small $\boldsymbol{P}_{\boldsymbol{y}}$ although $\boldsymbol{\epsilon}_{\boldsymbol{y}}$ and $\boldsymbol{D}_{\boldsymbol{y}}$ are small. Some examples



| $\boldsymbol{x}_{\boldsymbol{r m s}}$ | $\boldsymbol{y}_{\boldsymbol{r m s}}$ | $\boldsymbol{D}_{\boldsymbol{r m s} \boldsymbol{s}}^{\boldsymbol{y}}$ | $\boldsymbol{\epsilon}_{\boldsymbol{x}}$ | $\boldsymbol{\epsilon}_{\boldsymbol{y}}$ | $\left\|\boldsymbol{C}^{-}\right\|$ |  | $\boldsymbol{x}_{\boldsymbol{r m s}}$ | $\boldsymbol{y}_{\boldsymbol{r m s}}$ | $\boldsymbol{D}_{\boldsymbol{r m s}}^{\boldsymbol{y}}$ | $\boldsymbol{\epsilon}_{\boldsymbol{x}}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $(\boldsymbol{\mu \mathrm { m }})$ | $(\boldsymbol{\mu \mathrm { m } )}$ | $(\mathrm{mm})$ | $(\mathrm{nm})$ | $(\mathrm{pm})$ |  |  | $\boldsymbol{\epsilon}_{\boldsymbol{y}}$ | $\left\|\boldsymbol{C l}^{-}\right\|$ |  |  |
| 26 | 11 | 2 | 0.222 | 0.5 | 0.0014 |  | 144 | 11 | 2 | $(\boldsymbol{\mu m})$ |

Very small $\epsilon_{y} w /$ resorting to skew quadrupoles, but $\boldsymbol{P}$ few percent at 80 GeV in linear approximation, limited by the vertical motion... Is this an artifact?

Spin-orbit coupling integrals relating spin diffusion to orbital motion in linear approximation (Chao, Yokoya):

$$
\frac{\partial \hat{n}}{\partial \delta}(\vec{u} ; s)=\vec{d}(s)=\frac{1}{2} \Im\left\{\left(\hat{m}_{0}+i \hat{l}_{0}\right)^{*} \sum_{k= \pm x, \pm y, \pm s} \Delta_{k}\right\}
$$

with

$$
\begin{gathered}
\Delta_{ \pm x, \pm y}=(1+a \gamma) \frac{e^{\mp i \mu_{x, y}}}{e^{2 i \pi\left(\nu \pm Q_{x, y)}-1\right.}} \frac{\left.-D \pm i\left(\alpha D+\beta D^{\prime}\right)\right]_{x, y}}{\sqrt{\beta_{x, y}}} J_{x, y} \\
\Delta_{ \pm s}=(1+a \gamma) \frac{e^{ \pm i \mu_{s}}}{e^{2 i \pi\left(\nu \pm Q_{s}\right.}-1} J_{s} \\
J_{ \pm x, \pm y}=\int_{s, y}^{s+L} d s^{\prime}\left(\hat{m}_{0}+i \hat{l}_{0}\right) \cdot\left\{\begin{array}{l}
\hat{y} \sqrt{\beta_{x}} \\
\hat{x} \sqrt{\beta_{y}}
\end{array}\right\} K e^{ \pm i \mu_{x, y}} \\
J_{s}=\int_{s}^{s+L} d s^{\prime}\left(\hat{m}_{0}+i \hat{l}_{0}\right) \cdot\left(\hat{y} D_{x}+\hat{x} D_{y}\right) K
\end{gathered}
$$

Plotting $f_{y}$ vs. position for the perturbed optics, we notice that in some short regions $f_{y}$ is much larger than in the rest of the ring.

- Attempts of correcting the $f_{y}$ spikes with the skew quadrupoles were unsuccessful $\rightarrow$ vertical correctors used instead.
$\Re\left(f_{y}\right)$


$$
\Im\left(f_{y}\right)
$$


s[km]

After $f_{y}$ correction

80 GeV optics with $\mathrm{Q}_{\mathrm{x}}=0.11, \mathrm{Q}_{\mathrm{y}}=0.22, \mathrm{Q}_{\mathrm{s}}=0.049$
with tapering

with $\delta \hat{\boldsymbol{n}}_{0}$ correction in addition

80 GeV optics with $\mathrm{Q}_{\mathrm{x}}=0.11, \mathrm{Q}_{\mathrm{y}}=0.22, \mathrm{Q}_{\mathrm{s}}=0.049$ with tapering


$\mathrm{a}^{*} \gamma$

## Summary for FCCee

- Due to the demanding IR optics design and the machine size, establishing a closed orbit and keeping a stable machine look challenging.
- Even for an extremely well corrected orbit polarization may reserve surprises, however means have been found for meeting polarization requirements at 45 and 80 GeV beam energy.
- The long $\tau_{p}$ at 45 GeV and short lifetime in collision call for a strategical plan for polarization measurement (see M.Koratzinos IPAC15 contribution):
- Use of non-colliding bunches.
- Wigglers turned on for the time needed for polarizing the non-colliding bunches while the machine is filled.
- Exhausted pilote bunches must be immediately replaced (top-up injection needed anyway) so that they get naturally polarized.
- It must be proven that the required calibration precision can be reached. This implies a careful review of all possible biases (see Amsterdam FCC week contributions by A.Bogomyagkov and T.Tydecks):
- Experiment solenoids, vertical closed orbit and electric fields break the $\nu_{s}=a \gamma$ relationship.
- Sawtooth effect.
- Difference between the energy of non-colliding and colliding bunches.
- Difference between measured energy and CM energy.
- Energy needs to be monitored routinely.
- Double ring $\rightarrow$ both beams energy needs to be monitored.


## eRHIC

- A hadron/lepton collider with polarized beams has been under consideration by the scientific community since some years, in the U.S. and Europe.
- Its realization has been recognized by the Nuclear Science Advisory Committee (NSAC) in its 2015 Long Range Plan as the highest priority for nuclear science following the completion of the Facility for Rare Isotope Beams (FRIB).
- Two different EIC designs under studies in the US: eRHIC (BNL) and JLEIC (JLab).
- The BNL based EIC design exploits the already existing (polarized) hadron complex.
- Polarized electrons will be generated by a polarized electron source, accelerated in a 400 MeV Linac and in a Rapid Cycling Synchrotron (RCS) to 5, 12 and 18 GeV and injected at full energy into the electron storage ring.
- RCS and storage ring will be both accommodated into the 3835 m long RHIC tunnel.
- The longitudinal polarization of the electron bunches generated by the source is brought in the vertical direction by a spin rotator prior being injected into the RCS.
- Single bunches with $\approx 85 \%$ polarization, either up or down, are injected from the RCS into the storage ring where polarization is brought into the longitudinal direction at the Interaction Point (IP) through a couple of solenoidal spin rotators.

Schematic view of the eRHIC electron accelerators chain


Sokolov-Ternov effect tends to polarize upwards the clockwise rotating electrons.

## Radiative polarization and the eRHIC storage ring

Experiments require

- Large proton and electron polarization ( $\gtrsim 70 \%$ )
- Longitudinal polarization at the IP with both helicities within the same store
- Energy

e p
- protons: between 41 and 275 GeV
- electrons: between 5 and 18 GeV

High proton polarization is already routinely achieved in RHIC.
Studies are needed instead for the electron beam.

Because the experimenters call for storage of electron bunches with both spin helicities Sokolov-Ternov effect is not an option but rather a nuisance!


In the eRHIC energy range the minimum polarization time nominally is $\tau_{p} \simeq 30^{\prime}$ at 18 GeV . At first sight a large time before Sokolov-Ternov effect reverses the polarization of the down-polarized electron bunches...

However the machine imperfections may quickly depolarize the whole beam.

Polarization builds-up exponentially

$$
P(t)=P_{\infty}\left(1-\mathrm{e}^{-t / \tau_{p}}\right)+P(0) \mathrm{e}^{-t / \tau_{p}}
$$

In the presence of depolarizing effects it is

$$
P_{\infty} \simeq \frac{\tau_{p}}{\tau_{\mathrm{BKS}}} P_{\mathrm{BKS}} \quad \text { and } \quad \frac{1}{\tau_{p}} \simeq \frac{1}{\tau_{\mathrm{BKS}}}+\frac{1}{\tau_{\mathrm{d}}}
$$

$\boldsymbol{P}_{\text {BKS }}$ and $\boldsymbol{\tau}_{\text {BKS }}$ are the Baier-Katkov-Strakhovenko generalization of the SokolovTernov quantities when $\hat{\boldsymbol{n}}_{\mathbf{0}}$ is not everywhere perpendicular to the velocity.
They may be computed "analytically"; for eRHIC storage ring at 18 GeV it is

- $\boldsymbol{P}_{B K S} \simeq 90 \%$
- $\tau_{B K S} \simeq 30$ minutes.
$\boldsymbol{P}$ for bunches polarized parallel or anti-parallel to the bending field



For instance, with $\boldsymbol{P}_{\boldsymbol{\infty}}=30 \%$, after 5 minutes $\boldsymbol{P}$ decays from $85 \%$ to

- $60 \%$ for up polarized bunches

$$
\rightarrow<\boldsymbol{P}>=73 \%
$$

- $-39 \%$ for down polarized bunches

$$
\rightarrow<\boldsymbol{P}>=-61 \%!
$$

$<\boldsymbol{P}>\left(5^{\prime}\right)=-70 \% \rightarrow \boldsymbol{P}_{\infty}=80 \%$ !!!


| $\boldsymbol{P}(\mathbf{0})$ | $\boldsymbol{P}_{\infty}[\%]$ | $<\boldsymbol{P}\rangle[\%]$ | $\boldsymbol{t}[\mathrm{min}]$ |
| :---: | :---: | :---: | :---: |
| -85 | 50 | 70 | 4 |

## Simulations for the eRHIC storage ring

- Energy: 18 GeV , the most challenging.
- Simulations shown here are for the "ATS" optics with
$-90^{\circ}$ FODO for both planes;
$-\boldsymbol{\beta}_{\boldsymbol{x}}^{*}=0.7 \mathrm{~m}$ and $\boldsymbol{\beta}_{y}^{*}=9 \mathrm{~cm}$.
- Working point for luminosity: $\boldsymbol{Q}_{\boldsymbol{x}}=60.12, \boldsymbol{Q}_{\boldsymbol{y}}=56.10, \boldsymbol{Q}_{\boldsymbol{s}}=0.046$



For comparison: Hera-e with 3 rotators

Bmad (by D.Sagan) implemented on a MAC laptop for cross-checking SITROS results. 300 particles tracked over 6000 turns (typical SITROS parameters) with SR and stochastic emission with Bmad "standard" tracking.




Beam size

|  | $\sigma_{\boldsymbol{x}}$ | $\sigma_{y}$ | $\sigma_{\ell}$ | $\sigma_{\boldsymbol{E}}$ |
| :---: | :---: | :---: | :---: | :---: |
|  | $[\boldsymbol{\mu \mathrm { m } ]}]$ | $[\boldsymbol{\mu \mathrm { m } ]}]$ | $[\mathrm{mm}]$ | $[\%]$ |
| analytical (Bmad) | 123 | 0.4 | 7.0 | 0.1 |
| Bmad tracking | 120 | 2.0 | 6.7 | 0.1 |
| SITROS | 136 | 1.8 | 7.0 | 0.1 |

The large $\epsilon_{y}$ is not a SITROS artifact.

Add spins following SITROS path:

- Once equilibrium is reached particles coordinates are dumped on file.
- Spins parallel to $\hat{\boldsymbol{n}}_{\mathbf{0}}(0)$ are added and tracking re-started.

The spin tracking is very slow: 300 particles and 3000 turns take over 24 hours for one single energy point!
Zhe Duan kindly cross checked results with his PTC code.

D. Sagan is trying speeding up the tracking with spin.

## Machine with misalignments

- 494 BPMs ( $\mathrm{h}+\mathrm{v}$ ) added close to each quadrupole.
- $2 \times 494$ correctors ( $\mathrm{h}+\mathrm{v}$ ) added close to each quadrupole.
- Magnet misalignments and orbit correction simulated by MAD-X.
- Optics with errors and corrections dumped into a SITROS readable file.


## Strategy

Assumed quadrupole RMS misalignments

| horizontal offset | $\boldsymbol{\delta} \boldsymbol{x}^{\boldsymbol{Q}}$ | $200 \boldsymbol{\mu} \mathrm{~m}$ |
| :---: | :---: | :---: |
| vertical offset | $\boldsymbol{\delta} \boldsymbol{y}^{\boldsymbol{Q}}$ | $200 \boldsymbol{\mu} \mathrm{~m}$ |
| roll angle | $\boldsymbol{\delta} \boldsymbol{\psi}^{\boldsymbol{Q}}$ | $200 \boldsymbol{\mu} \mathrm{rad}$ |

- switch off sextupoles;
- move tunes to 0.2/0.3;
- introduce errors;
- correct orbit (MICADO/SVD);
- turn on sextupoles;
- tunes back to luminosity values.

MAD-X fails correcting the orbit! Example with only $\delta y^{Q} \neq 0$ and sexts off. Large discrepancy between what the correction module promises...

CORRECTION SUMMARY:

|  | average [mm] | std.dev. [mm] | RMS [mm] |
| :--- | :--- | :---: | :---: | peak-to-peak [mm]

...and the actual result!


Orbit is well sampled


Separate horizontal and vertical orbit correction inadequate in the rotator sections $\rightarrow$ "external" program used for correcting horizontal and vertical orbits simultaneously.

One error realization

- after orbit correction
- with $\boldsymbol{Q}_{\boldsymbol{x}}=60.10, \boldsymbol{Q}_{\boldsymbol{y}}=56.20$ (HERA-e tunes).



Same error realization, betatron tunes moved to $\boldsymbol{Q}_{\boldsymbol{x}}=60.12, \boldsymbol{Q}_{\boldsymbol{y}}=56.10$ for luminosity operation; w/o skew quads, $\left|C^{-}\right| \approx 0.01$.



Same error realization, luminosity tunes with 46 skew quads for correcting $\Delta D_{y}$ and coupling ( $\left|C^{-}\right| \approx 0.002$ ).

SITF - . 12/.10/.046


ATS $-\mathrm{Q}_{\mathrm{x}}=0.12, \mathrm{Q}_{\mathrm{y}}=0.10, \mathrm{Q}_{\mathrm{s}}=0.046$


SITF - . 12/.10/.046


Beam size at IP


|  | $[\mathrm{mm}]$ | $[\boldsymbol{\mu}]$ | $[\mathrm{mm}]$ |
| :---: | :---: | :---: | :---: |
| SITF | 0.121 | 1.718 | 6.984 |
| SITROS | 0.138 | 3.126 | 6.969 |

Adding $\hat{\boldsymbol{n}}_{0}$ correction by harmonic bumps


SITF - . 12/.10/.046


Effect on vertical orbit

SITF - . 12/.10/.046


ATS - $\mathrm{Q}_{\mathrm{x}}=0.12, \mathrm{Q}_{\mathrm{y}}=0.10, \mathrm{Q}_{\mathrm{s}}=0.046$


Beam size at IP

|  | $\sigma_{x}$ | $\sigma_{y}$ | $\sigma_{\ell}$ |
| :---: | :---: | :---: | :---: |
|  | $[\mathrm{mm}]$ | $[\mu \mathrm{m}]$ | $[\mathrm{mm}]$ |
| SITF | 0.121 | 3.151 | 6.985 |
| SITROS | 0.139 | 4.402 | 7.004 |

ATS $-Q_{x}=0.12, Q_{y}=0.10, Q_{s}=0.046$
 $\mathrm{a}^{\star} \gamma$
Level of polarizations similar to unperturbed optics, but BPMs errors to be still included and statistics needed!

The beam vertical emittance is 1.7 pm , corresponding to $\sigma_{y}^{*} \simeq 0.4 \mu \mathrm{~m}$. A larger beam size at the IP may be needed.

The $\boldsymbol{e}$-beam $\boldsymbol{\epsilon}_{y}$ may be efficiently increased by anti-symmetric bumps around low $\boldsymbol{\beta}_{\boldsymbol{y}}$ locations.

As a test such a bump has been introduced around the IP.
For the wished $\epsilon_{y}=3 \mathrm{~nm}$ there is no polarization!



## Two pairs of skew quads

Instead of blowing up the vertical emittance use betatron coupling for increasing vertical beam size at IP only:

$$
\boldsymbol{y}_{\max }=\sqrt{\epsilon_{I} \boldsymbol{\beta}_{y I}+\epsilon_{I I} \boldsymbol{\beta}_{y I I}}
$$

For $\boldsymbol{\epsilon}_{\boldsymbol{y}}=3.3 \mathrm{~nm}$ the wished $\sigma_{\boldsymbol{y}}$ is

$$
\sigma_{y}=\sqrt{\beta_{y} \epsilon_{y}}=\sqrt{0.09 \times 3.3 \times 10^{-9}}=17.2 \mu \mathrm{~m}
$$

( $\boldsymbol{\beta}_{\boldsymbol{y}}$ unperturbed vertical $\boldsymbol{\beta}$ at IP).
Two pairs of skew quads introduced left and right of IP (closed coupling bump).
The strength of the "leading" skew quad is changed in MADX until $\boldsymbol{y}_{\max }=17.2 \boldsymbol{\mu} \mathrm{~m}$ is reached.

Effect of the 2 pairs of skew quadrupoles from SITROS tracking of 10000 particles.
No skews



With skews



Beam size with 2 pairs of skews

|  | $\boldsymbol{\sigma}_{\boldsymbol{x}}$ | $\boldsymbol{\sigma}_{\boldsymbol{y}}$ | $\boldsymbol{\sigma}_{\ell}$ |
| :---: | :---: | :---: | :---: |
|  | $[\boldsymbol{\mu \mathrm { m } ]}]$ | $[\boldsymbol{\mu \mathrm { m } ]}$ | $[\mathrm{mm}]$ |
| analytical (SITF) | 121 | 17.6 | 6.97 |
| SITROS | 143 | 21.1 | 6.98 |




Polarization with 2 pairs of skews for $\sigma_{y}=21 \mu \mathrm{~m}$


- Other possibilities of tuning $\epsilon_{y}$ by $\boldsymbol{D}_{y}$ closed bumps are under study.

Polarization studies for the eRHIC storage ring are going on.

- With conservative errors $\boldsymbol{P}_{\infty} \approx 50 \%$ seems within reach:
- for upwards polarized bunches (anti-parallel to the guiding field), $\langle\boldsymbol{P}\rangle \approx 80 \%$., over 5 minutes if $\boldsymbol{P}(0)=85 \%$;
- for bunches polarized downwards the average polarization drops to $67 \%$ : they must be replaced more often.
- Luminosity working point requires linear coupling correction. Here the benefits of a local correction using 46 skew quadrupoles have been shown, but
- the use of correctors for dispersion and of (fewer?) skew quads for betatron coupling correction is an alternative to be tried;
- implementation of a knob for controlling the vertical beam size at IP w/o affecting polarization seems feasible.
- Comparisons with different codes (Bmad, PTC) are going on.
- Beam-beam effects need to be addressed.


[^0]:    ${ }^{\mathrm{a}} \boldsymbol{a}=$ gyromagnetic anomaly

