EIC User Group Meeting July 2019 Paris

Optimizing the Electron Beam Polarization in High Energy Storage Rings w/ Special Emphasis Put on the EIC Electron Ring(s)

Mathias Vogt (DESY–MFL)

- Polarized Beams
- Treating Electrons like Protons?
- Design Optimization
- Operational Machine Optimization

FLASH
Free–Electron Laser
in Hamburg

What brought me here. . .

13 years ago:

Experience with HERA

(an Asymmetric High–$\mathcal{L}$ $e^\pm/p$–Collider with Polarized $e^\pm$)

17.07.2006

Mathias Vogt* (DESY–MPY) for the HERA Team

- **Overview**
- $e^\pm/p$–Collisions : "Two Worlds Collide"
- The HERA–II IRs
- **Luminosity** / **Lepton–Polarization** / **Experimental Backgrounds**

*: some slides stolen from F.Willeke

1.5 years ago:

eRHIC Injector Conceptual Review / 2018-01-29 / **contrib.:** M.Vogt (DESY/MFL)

eRHIC Injector Conceptual Review / 2018-01-29

contribution of M.Vogt (DESY/MFL)

- General Remarks
- Polarization transmission of the unperturbed RCS (design)
- A little bit on perturbed orbit
- Summary

What I'm really doing now:

Upgrade Plans for FLASH for the Years after 2020.

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FLASH
Free–Electron Laser in Hamburg

Motivation

The superconducting free-electron laser user facility FLASH at DESY in Hamburg routinely delivers several thousand high brilliance XUV and soft x-ray photon pulses per second. The user facility FLASH is in operation since 2005 and since 2015 the bunch train from the superconducting linac can be split between the original FLASH1 undulator beamline and a new second beamline FLASH2. In 2016 a significant *Mid Term Refurbishment Program* was started for FLASH. Its program will persist for the next years. As part of the DESY strategy process *DESY 2030* that was initiated 2016, a second substantial upgrade, FLASH2020+ was proposed. In April 2019 the internal conceptual design report (CDR) for FLASH2020+ was produced Here we will briefly summarize the accelerator related aspects of the CDR.

The Ongoing Mid Term Refurbishment Process

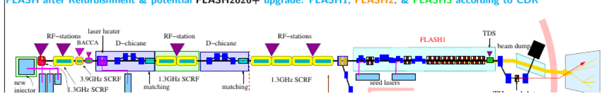
Already Implemented / Started

- BPM upgrade: better resolution $\rightarrow$ also at lower charge
- Optical synchronization upgrade $\rightarrow$
- $\rightarrow$ BAM upgrade (started): resolution & low charge
- Improve gain/bandwidth of intra-train BAM FB w/ norm.-cond. S-band cavity **BACCA**
- New RF coupler interlock electronics
- **PolariX-TDS** FLASHForward: 2019 / FLASH2: 2020
- **New independent bunch compression chicane for FLASH2 (2019)**

In Preparation / Planned

- **Replace oldest SC L-band modules w/ refurbished EU-XFEL prototypes**
- $\leftarrow$ 2nd & 3rd modules in injector
- $\rightarrow$ Move RF station closer to new modules $\rightarrow$ shorter waveguides $\rightarrow$ less resistive losses
- $\Rightarrow$ 2nd compressor chicane: E_{ref} from 450 MeV to 550 MeV
- Optimize waveguide distribution for 1st & 2nd L-band module in main linac
- $\Rightarrow$ **Maximum E_{ref} (post-linac) to 1350 MeV**
- **New injector laser system** parallel to three "old" injector lasers
- $\leftarrow$ new external laser hut
- New RF-gun w/ improved thermal properties + w/ **two** input couplers being built
- $\rightarrow$ Reliable operation at 800 μ usable RF flat top
- Screen station upgrade where applicable
- $\leftarrow$ space constraints
- FLASH2 helical after-burner : design started
- Intra-train orbit FB : new project

FLASH after Refurbishment & potential FLASH2020+ upgrade: FLASH1, FLASH2, & FLASH3 according to CDR



One of my scientific hobbies:

A Beam Dynamics View on a Generalized Formulation of Spin Dynamics, Based on Topological Algebra, with Examples

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Here I rephrase some of the results of work[1–6] performed in several collaborations with **K.Heinemann & J.A.Ellison***, **D.P.Barber**†, and **A.Kling**‡ on a generalized look on spin dynamics and beam polarization in storage rings. It is done in a way that emphasizes the applicability of the concepts to real world polarized beams rather than presenting the results in their most general form. The latter view can be found in several articles on the ArXiv and will be published in refereed journals soon. I will introduce several "spin-related" systems, state some selected main results of the above mentioned work and then recover and compare some basic (and some not so basic) findings for the various systems in the light of our generalized approach.

Beam Polarization Dynamics vs. Particle Scattering Process

- Beam → Density Matrix $\underline{\rho}_N := \Psi_N(\vec{z})\,\frac{1}{2}\left(\underline{1} + \underline{\vec{\sigma}}\cdot\vec{P}_N(\vec{z})\right)$ (at IP & turn N)
- Process → Observable $\mathcal{O}$: $\langle|\,\mathcal{O}\,|\rangle_N = \int_{\mathbb{R}^6} \mathrm{trace}(\underline{\rho}_N\mathcal{O})\, d\vec{z}$ (at IP & turn N)
- Collisions → $\underline{\rho}_N^{\mathrm{ion}}$ & $\underline{\rho}_N^{\mathrm{ele}}$ (slightly more intricate)

- Ψ: **Liouville PSD**
  ← phase fluid ($6d$ not $6dN_{\mathrm{part}}$)
- Stationary: level curves ≡ invariant curves $\vec{J} = \mathrm{const}$
- Extension to FP for damping & QExcitation and/or Vlasov for collective effects

- $\vec{P}$: **T-BMT Polarization Field**
- Stationary: ISF × dyn pola
  $\vec{P} = P(\vec{J})\,\hat{n}(\vec{J},\vec{\psi})$
- Extension : Sokolov-Ternov, spin diffusion, kinetic pola. ...

→ Bloch Eqn.
(for polarization **Density**:
$(\Psi\,\vec{P})$)

$\underline{\rho}$: interface between class. kinetic theory (beam) and QM/QFT scattering process!

Since we have users here...

Glossary of Some Commonly* Used Terms and Symbols

- $\vec{z} \in \mathbb{R}^6$: point/trajectory in (orbital) phasespace: $\vec{z}^{\mathrm{T}} = \Big(x, a := \frac{p_x}{p_0} =_1 x', y, b := \frac{p_y}{p_0} =_1 y', \tau = (t_0 - t)\frac{T_0}{p_0}, \eta = \frac{T - T_0}{T_0}\Big)$ where $T := \sqrt{p^2 + m^2} - m$
- $\vec{x}$: a 6- or 3-vector
- $\underline{X}$: a matrix, for any vector field $\vec{X}$, $\underline{X}$ is its Jacobian matrix
- $\|\vec{x}\| \equiv \|\vec{x}\|_2$: Euclidean norm
  $\|\vec{x}\|_1$: taxi-cab norm
  $|x|$ real or complex modulus

$\star$: in my talk!

- $\hat{x}$: a **unit** vector, i.e. if $\|\vec{x}\| \neq 0$, then $\hat{x} := \vec{x}/\|\vec{x}\|$
- $\hat{S} \in \mathbb{S}_3$: "spin" $\rightarrow$see next slide
- s : the distance along the design orbit of an accelerator: $\rightarrow$ our version of "time" :-)
- $c = 1$:-)
- C : circumference of the ring $\rightarrow s$ and $s + nC$ mean the same position in the ring
- $\vec{Q} := (Q_x, Q_y, Q_\tau)$: orbital tunes, ν : spin tune
- $X =: \{X\} + [X]$: integer + fractional part of X

The Invariant Spin Field (1)

- Today only spin-$\frac{1}{2}$ **($\leftarrow$ electrons!)**
- "Spin" $\hat{S}$: (normalized) single particle expectation value of $\underline{\vec{\sigma}}$ $\leftrightarrow$ unit 3-vector in (Lorentz) rest frame of particle
- T-BMT equation:
  $\frac{d}{dt}\hat{S} = \vec{\Omega}(\vec{B}(\vec{z}), \vec{E}(\vec{z}), \vec{z}(t)) \times \hat{S}$
- Principal Solution
  (in accelerator coordinates):
  $\hat{S}(s_f)|_{\vec{z}_f} = \underline{R}_{s_f \leftarrow s_i}(\vec{z}_i)\, \hat{S}(s_i)|_{\vec{z}_i}$
  where $\underline{R} \in \mathbf{SO(3)}$, and
  $\vec{z}_f := \vec{M}_{s_f \leftarrow s_i}(\vec{z}_i)$, $\underline{M} \in \mathbf{Sp(6)}$
- One Turn Maps (OTMs) :
  $\vec{\mathcal{M}}_s := \vec{M}_{s+C \leftarrow s}$,
  $\underline{\mathcal{R}}_s(\vec{z}) := \underline{R}_{s+C \leftarrow s}(\vec{z})$

- **Liouville evolution** :
  $\Psi_{s_f} = \Psi_{s_i} \circ \vec{M}^{-1}_{s_f \leftarrow s_i}$

$\rightarrow$ stationary iff $\Psi \overset{!}{=} \Psi \circ \vec{\mathcal{M}}^{-1}$

- **Polarization Field / BMT evol.**:
  $\vec{P}_{s_f} =$
  $(\underline{R}_{s_f \leftarrow s_i} \circ \vec{M}^{-1}_{s_f \leftarrow s_i})\, (\vec{P}_{s_i} \circ \vec{M}^{-1}_{s_f \leftarrow s_i})$

$\rightarrow$ Stationary iff
$\vec{P} \overset{!}{=} (\underline{\mathcal{R}} \circ \vec{\mathcal{M}}^{-1})\, (\vec{P} \circ \vec{\mathcal{M}}^{-1})$

$\rightarrow$ Invariant Polarization Field (IPF)

($\vec{0}$ is always a trivial IPF)

$\rightarrow$ Iff **normalizable**

$\rightarrow$ **Invariant Spin Field (ISF)**

$$\boxed{\hat{n} \overset{!}{=} (\underline{\mathcal{R}} \circ \vec{\mathcal{M}}^{-1})\, (\hat{n} \circ \vec{\mathcal{M}}^{-1})}$$

The Invariant Spin Field (2)

- **Spin action** $I := \hat{S} \cdot \hat{n}$ is adiabatic invariant along orbital traj. $\vec{z}(s)$
- $\vec{P} \to \hat{n}$ maximizes polarization (at s e.g. at IP)
- $\hat{n}$ is local (in PS $\times$ s) quantization axis for spin operators
- When does $\hat{n}$ exist ??
- *specialized* analytical Model (**SRM**) $\to$ always!
- Linearized s-o coupling (see below) $\to$ unless on 1st order resonance
- Non-lin pert. theo.$\to$ unless on *some* resonance
- Non-pert. methods $\to$ often codes suggest numerical convergence to smth. behaving like an ISF for many-many turns...
- **Spin-Orbit Resonance**???
  quasi-periodic orbit motion w/ orbital tunes $\vec{Q}$ and spin precession around local $\hat{n}$ w/ spin tune ν:
  $\exists$ integer k_0, $\vec{k}$ so that
  $$\boxed{k_0 = \vec{k} \cdot \vec{Q} \pm \nu}$$

The ISF and the Spin Tune (3)

- In general, i.e. if orbit motion is non resonant ($l_0 \neq \vec{l} \cdot \vec{Q}$, $\forall\ l_0$, $\vec{l}$) ν can only depend on $\vec{J}$ (orbital actions!) called amplitude dependent spin tune
- **On the design orbit** (or perturbed closed orbit), orbital motion is 1-turn-*periodic*

$\rightarrow$ $\boxed{\hat{n}(\vec{z}; s) \rightarrow \hat{n}_0(s)\ \&\ \nu(\vec{J}) \rightarrow \nu_0}$

- $\hat{n}_0$: eigenvector to eigenvalue 1 of $\underline{\mathcal{R}}$
- ν_0 : other two eigenvalues are $\exp(\pm i 2\pi \nu_0)$
- $\hat{n}_0$ & ν_0 always exist !

- Most essential s.-o.-resonances w/ $\vec{k} = \vec{0}$ $\rightarrow$ integer or imperfection resonances (n_0 becomes **non-unique**), and $k_y = 1 \rightarrow$ **linear vertical** or **intrinsic**
- *Flat* (midplane-symmetric) ring w/o solenoids & spin rotators: $\nu_0 = a\gamma$, $a := \frac{g-2}{2}$

  $\Rightarrow$ an integer resonance occurs every 440 MeV ($e^{\pm}$) or 523 MeV (p, $\bar{p}$)
- *On* orbital resonance :

  $\hat{n}$ becomes eigenvector of $\underline{R}_{s+\mathbf{k}C \leftarrow s}$ for some integer $\mathbf{k}$

  ν much more complicated: might not exist, might depend on orbital phases mod some k' (resonantly reduced phase tori)

Why are the ISF and the Spin Tune so Essential ???

- **Protons**

... or ramped polarized electrons to be stored only for a short time

- Ramp up polarized beam from the source (at rest)
- Encounter* spin-orbit resonances every 523 (440) MeV

→ $\hat{S} \cdot \hat{n}$ is **adiabatic** invariant, w/ **potential depolarization** on crossing resonances not fast or not slow enough
→ **Froissart-Stora**

⋆ or avoid crossing them!

- **Electrons**

... or protons to be stored at some fantastically high energy in the **far** future :-)

(a) **Radiative polarization (Sokolov-Ternov)** only efficient if $\hat{n}$ tightly bundled ($\hat{n} \approx \hat{n}_0$) and $\hat{n}_0 || \vec{B}_{\text{dipoles}}$

(b) **Spin diffusion** (depolarizing the beam) if $\hat{n}$ has some noticeable angular spread

- (a) is most efficiently perturbed and (b) enhanced on or close to **spin-orbit resonances**

Sokolov-Ternov Radiative Polarization vs. Derbenev-Kondratenko Spin Diffusion

- HE electrons in storage ring ⇒ **SynRad!**
- Primitive ring: only dipoles in *const.* bending plane ⇒ Sokolov-Ternov (ST) build up → 0.9238
- Still prim. ring (w/o focusing 'n' stuff)) but w/ more complex geometry ⇒ Baier-Katkov-Strakhovenko (BKS) corrections.

← Since spins precess around $\hat{n}_0$ which is not always $\| \hat{b}$ (Frenet-Serret co-normal vector, typically $\sim \vec{B}_{\rm dip}$) anymore.

- I.p. **figure-8-ring**: ST → 0 (← that needs not be bad!)

- Most photons do not contribute to ST/BKS
- But recoil makes particle jump in phase space
- Spin stays const., but potentially

$$\boxed{I_+ \equiv \hat{S} \cdot \hat{n}(\vec{z}_+; s) \neq \hat{S} \cdot \hat{n}(\vec{z}_-; s) \equiv I_-}$$

$-$: before / $+$: after photon emission

→ **Random walk of spin action** and thus polarization $P(\vec{J}) \approx \left\langle I \right\rangle^{[\text{ensemble}]}(\vec{J}) \left\langle \hat{n}(\vec{\psi}, \vec{J}) \right\rangle^{[\vec{\psi}]}$

→ **Spin Diffusion** driven by **stochastic nature of photon emission** & **opening of ISF**

Radiative Polarization: Short Summary

- $P_{\rm st} := \frac{8}{5\sqrt{3}}$, $\quad F_\gamma := \frac{r_e \hbar \gamma^5}{m_e}$
- $A_0 := \frac{1}{C}\oint ds \frac{\hat{n}_0(s)\cdot\hat{b}(s)}{|\rho(s)|^3}$
- $A := \frac{1}{C}\oint ds \frac{\left\langle \hat{n}\cdot\hat{b}\right\rangle^{[\rm ps]}(s)}{|\rho(s)|^3}$
- $B_0 := \frac{1}{C}\oint ds \frac{1-\frac{2}{9}\hat{n}_0(s)\cdot\hat{t}(s)}{|\rho(s)|^3}$
- $B := \frac{1}{C}\oint ds \frac{\left\langle 1-\frac{2}{9}\hat{n}\cdot\hat{t}\right\rangle^{[\rm ps]}(s)}{|\rho(s)|^3}$
- $D := \frac{1}{C}\oint ds \frac{\left\langle \frac{11}{18}\|\partial_\eta \hat{n}\|^2\right\rangle^{[\rm ps]}(s)}{|\rho(s)|^3}$
- $K := \frac{1}{C}\oint ds \frac{\left\langle (\partial_\eta \hat{n})\cdot\hat{b}\right\rangle^{[\rm ps]}(s)}{|\rho(s)|^3}$

- $\tau_{\rm st}^{-1} = \frac{F_\gamma}{P_{\rm st}|\rho|^3}$
- $\vec{P}_{\rm bks} = \hat{n}_0 P_{\rm st}\frac{A_0}{B_0}$, $\quad \tau_{\rm bks}^{-1} = \frac{F_\gamma}{P_{\rm st}} B_0$
- $P_{\rm dk} = P_{\rm st}\frac{K-A}{D+B}$,
  $\vec{P}_{\rm dk}(\vec{z};s) = \hat{n}(\vec{z};s) P_{\rm dk}$
  $\tau_{\rm dk}^{-1} = \frac{F_\gamma}{P_{\rm st}}(D+B)$
- iff $(A \approx A_0$ & $B \approx B_0) \Rightarrow$
  $\tau_{\rm dk}^{-1} \approx \frac{F_\gamma}{P_{\rm st}}(D+B_0)$
  $= \tau_{\rm bks}^{-1} + \tau_{\rm dep}^{-1}$ where $\tau_{\rm dep}^{-1} := \frac{F_\gamma}{P_{\rm st}} D$
  $P_{\rm dk} \approx P_{\rm st}\frac{K-A_0}{D+B_0}$
- iff furthermore $K \approx 0 \Rightarrow$
  $P_{\rm dk} \approx P_{\rm bks}\frac{\tau_{\rm dk}}{\tau_{\rm bks}} \approx P_{\rm bks}\frac{\tau_{\rm bks}^{-1}}{\tau_{\rm bks}^{-1}+\tau_{\rm dep}^{-1}}$

Radiative Polarization: Some Comments

- Integrals (last slide) all contain $\frac{1}{|\rho(s)|^3}$

$\leftarrow$ Assumption that radiation happens primarily in **dipoles**!

$\rightarrow$ In reality dipole-rad dominates by far!

$\Rightarrow$ For high ST build-up avoid bending the beam in other than ring plane

$\Rightarrow$ For moderate depolarization avoid $\partial_\eta \hat{n}$ large in dipoles!

- Subtle effect (kinetic polarization: K) $\rightarrow$ interference effect (DK'75)

$\Rightarrow$ Pot. non-vanishing equilibr. pola. even if ST $\equiv$ 0

$\leftarrow$ ST/BKS/DK: assumption of linear dynamics $\rightarrow$ diffusion w/ *const.* rates!

$\Rightarrow$ $P(t) = P_0 e^{-t/\tau_{\rm dk}} + P_\infty (1 - e^{-t/\tau_{\rm dk}})$

$\Leftarrow$ More rigorous (but less predictive, so far) treatment: Bloch equation for polarization *density* $\Psi(\vec{z};s)\vec{P}(\vec{z};s)$

- Also other mechanisms can drive spin diffusion (IBS, residual gas scattering (incoherent or via cloud effects), RF- & power converter noise), but with different stochastic dynamics (RF/PC's: SRN; QE/scattering: MRN iid, IBS/cloud: MRN correlated,. . .)

$\rightarrow$ even for protons/ions. . .

EIC: Electrons as Protons ???

- There is no noticeable ST for protons ...and no other convincing polarization mechanism at typical collider energies

$\Rightarrow$ polarize p's at the source and accelerate $\rightarrow$ res. $\rightarrow$ losses ($\leftarrow$ FS)

- Electrons **traditionally** polarized radiatively at collision energy during the store:
  $\rightarrow$ decent $\tau_{\rm bks}$, $\tau_{\rm dep}$ needed
  $\rightarrow$ $\vec{P}_\infty$ same $\forall$ bunches

- EIC users want alternating helicity at the IP(s) $\rightarrow$

- **eRHIC**: kick-out injection every some minutes
  $\leftarrow$ ST is (m.o.l. slowly) depolarizing one spin orientation

- **JLEIC**: continuous top-up over decaying polarization
  $\leftarrow$ fig-8 ring $\Rightarrow$ no net-ST but spin diffusion!

- For **both rings**: spin diff. (& ST) is only an issue at highest electron energies

- RCS at HE: potential **resonance crossing** w/ (!!!) **radiative spin diffusion** if too slow (seems not the case!)

Linearized Spin Orbit Coupling : $\tilde{n}$

- assume linear orbital motion
- transform spin motion to *periodic* frame $(\hat{n}_0, \hat{m}_0, \hat{l}_0)$ rotating *around* $\hat{n}_0$, making spin motion a *uniform* rotation with angle $2\pi\nu_0$ per turn.
- then study deviation $\hat{S} - \hat{n}_0$ and linearize in plane containing North-pole

$\Rightarrow$ LinSpin: $\tilde{S} := \begin{pmatrix} \alpha \\ \beta \end{pmatrix} =_1 \begin{pmatrix} \hat{S} \cdot \hat{m}_0 \\ \hat{S} \cdot \hat{l}_0 \end{pmatrix}$ w/ linearized BMT evolution: $\tilde{S}_f = \underline{G}_{s_f \leftarrow s_i} \vec{z}_i + \underline{D}_{s_f \leftarrow s_i} \tilde{S}_i$

- define **linear spin field**: $\tilde{f}_s(\vec{z}) := \underline{F}_s \vec{z}$
- reminder: std spin field evolution over one turn: $\hat{n}(\vec{z}; s + C) = \underline{\mathcal{R}}_s \hat{n}(\underline{\mathcal{M}}_s^{-1} \vec{z}; s) \stackrel{!}{=} \hat{n}(\vec{z}; s)$

- LinSF: $\tilde{f}_{s+C}(\vec{z}) = \underline{F}_{s+C} \vec{z} = \underline{\mathcal{G}}_s \underline{\mathcal{M}}_s^{-1} \vec{z} + \underline{\mathcal{D}}_s \underline{F}_s \underline{\mathcal{M}}_s^{-1} \vec{z}$

$\Rightarrow$ $\underline{F}_{s+C} = (\underline{\mathcal{G}}_s + \underline{\mathcal{D}}_s \underline{F}_s) \underline{\mathcal{M}}_s^{-1}$

$\Rightarrow$ i.p. for LinISF $\tilde{n}_s(\vec{z}) := \underline{N}_s \vec{z}$:

$\boxed{\underline{N}_s \stackrel{!}{=} (\underline{\mathcal{G}}_s + \underline{\mathcal{D}}_s \underline{N}_s) \underline{\mathcal{M}}_s^{-1}}$

or $\underline{N}_s \underline{\mathcal{M}}_s - \underline{\mathcal{D}}_s \underline{N}_s = \underline{\mathcal{G}}_s$

- can be solved using **eigensys of $\underline{\mathcal{M}}$** (**drop** s) : $\underline{\mathcal{M}} \vec{v}_k = \lambda_k \vec{v}_k$, $k = \pm 1, \pm 2, \pm 3$, $\lambda_{\pm k} = \exp(\pm i 2\pi Q_k)$, $\vec{z} = \sum_k a_k(\vec{z}) \vec{v}_k =: \underline{V}\, \vec{a}(\vec{z})$

$\Rightarrow$ $\boxed{\tilde{n}(\vec{z}) = \underline{N} \vec{z} = \sum_k a_k(\vec{z}) (\lambda_k - \underline{\mathcal{D}})^{-1} \underline{\mathcal{G}} \vec{v}_k}$

$\leftarrow$ resonance denominator $(\lambda_k - \underline{\mathcal{D}})^{-1}$ $\Rightarrow$ intrinsic res.: $k_0 = \vec{k} \cdot \vec{Q} \pm \nu$, $||\vec{k}||_1 = 1$

Linearized S-O Coupling : Strong Spin Match (at the Design Level!)

- $\tilde{n}(\vec{z}) = \sum_k a_k(\vec{z})(\lambda_k - \underline{\mathcal{D}})^{-1}\underline{\mathcal{G}}\vec{v}_k$ is a linear form in $\vec{z}$ (of course!)

$\Rightarrow$ $\boxed{\partial_\eta \tilde{n} \equiv \partial_6 \tilde{n} = -2\Im \sum_{k=1,2,3} v^*_{k,5}(\lambda_k - \underline{\mathcal{D}})^{-1}\underline{\mathcal{G}}\vec{v}_k}$ is independent of $\vec{z}$

$\rightarrow$ PS average is easy for τ_{dep} :-)

- At linear order, given enough (non-degenerate) quadrupole "knobs", one may enforce (match) $\partial_\eta \tilde{n} \rightarrow \tilde{0}$ i.p. at locations s where $\rho(s)$ is finite (bends)

$\rightarrow$ Strong Spin Match

- $v_{k,5}$: sensitivity of k-th orbital eigenmode on recoils through photon emission $\rightarrow$ k-dispersion

- $\tilde{w}_k := (\lambda_k - \underline{\mathcal{D}})^{-1}\underline{\mathcal{G}}\,\vec{v}_k$: sensitivity of $\tilde{n}$ on k-th orbital eigenmode

$\leftarrow$ main knob : $\underline{\mathcal{G}}\,\vec{v}_k$. (and of course stay far away from intrinsic resonances)

- $\boxed{\text{general strategy for mode } k\text{: minimize } \underline{G}_{s_{j+1}\leftarrow s_j}\vec{v}_k(s_j) \text{ for dipoles } 1 < j < N_{\mathrm{dip}} \text{ for which } |v_{k,5}(s_j)|^2/|\rho(s_j)|^3 \text{ is significant}}$

uncoupled/weakly coupled machine: mode $1 \rightarrow$ mainly x, x' (hor.), $2 \rightarrow$, mainly y, y' (vert.), $3 \rightarrow$ mainly τ, η (long.)

Strong Spin Match : Some Strategies

($\rightarrow$ D.P.Barber, G.Ripken in Handbook of Acc Phys & Eng [Chao/Tigner])

- **Flat** (no vertical bends), **midplane-symmetric** (no transverse coupling, i.p. no solenoids) ring, no spin matching is needed (on the linear level!)
  On the design level! Spurious vertical dispersion and spurious coupling can not be accounted for by matching, but must e carefully controlled during operation

- Spin rotators containing only hor. & vert. dipoles **w/o quads** break the spin match **only weakly**, since $\underline{G}$ stronger in quads (it's about $\hat{n}$, not $\hat{n}_0$!). **With quads**, they do require spin matching!

- Spin rotators containing dipoles & solenoids require explicit spin matching, while at the same time the coupling introduced by the solenoids has to be locally compensated or the spin transparency other sections will potentially be severely degraded.

- If a **mirror symmetric** straight section with longitudinal polarization does **not contain dipoles)**, the spin match can be given purely in terms of Twiss parameters: let $s = 0$ be the IP, and the straight section range from $-s$ to $+s$, then
  $-\alpha(s) \stackrel{!}{=} \tan(\phi(\phi(s) - \phi(0))$ for both x and y.

- Sometimes symmetries allow a clever choice of the initial $\hat{m}$, $\hat{l}$ to number of independent $\underline{G}$ elements. ($\tilde{w}_k$ is a two component vector and only $\|\tilde{w}_k\|$ matters.)

Harmonic Orbit Match (During Set-Up/Tuning)

- In perfectly aligned flat ring $\hat{n}_0 = \pm\hat{y}$ in arcs $\Rightarrow$ $\hat{l}$, $\hat{m}$ have no vertical component $\Rightarrow$ many $\underline{G}$ elements vanish automatically $\rightarrow$**good!**
- Perturbed closed (vertical) orbit $\Rightarrow$ tilt of $\hat{n}_0$
  typically several tens of mrad at HE, linearly increasing w/ $a\gamma$

$\leftarrow$ not ST, but τ_{dep} suffers!

- Quad misalignment & enough well placed steerers
  $\rightarrow$ kick minimization e.g. BBA
  $\rightarrow$automatically minimizes spurious dispersion
  $\leftarrow$does not help for dipole tilts

$\leftarrow$ Residual orbit might still perturb spin transparency

- Harmonic Bumps:
  $\longrightarrow$ linear combination of short 3-bumps, allowing to manipulate the harmonic content of the (vertical) orbit at harmonics close to the integer part of the closed-orbit spin tune ν_0

$\leftarrow$ effect on $\hat{n}_0$ is strongest for close-by harmonics.

- HERA-e: typically sufficient:
  $(\{\nu_0\}, \{\nu_0\}+1)$ w/ $|\Delta| = 1$ and
  $(\{\nu_0\}-1, \{\nu_0\}+2)$ w/ $|\Delta| = 2$

  . . . each w/ $\Re$ and $\Im$ unfortunately

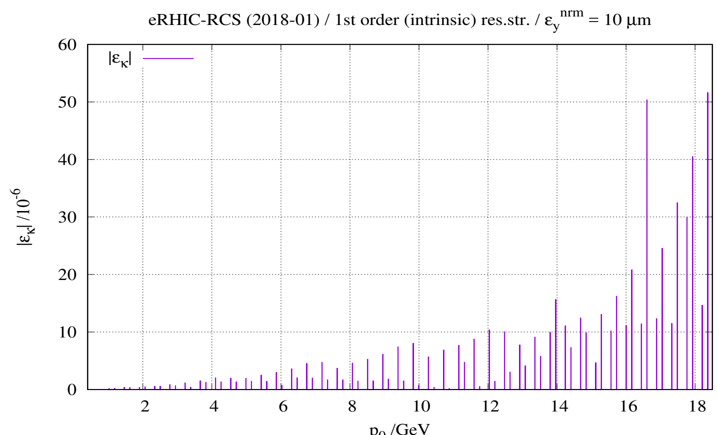
The 2 EIC PreAcc Chains at the Design Level

- **Both** JLEIC & eRHIC require:
  $\rightarrow$ **full energy injector**
  $\rightarrow$ **highly polarized beams**
- JLEIC: tunable $\vec{P}$ from photo injector & acceleration in CEBAF recirc. linac $\rightarrow$ $\pm$ vertical $\vec{P}$ at JLEIC injection point $\rightarrow$ **well established**. . .
- eRHIC: Rapid Cycling Synchrotron (RCS): $\rightarrow$ **clever trick to push depol. resonances out of the relevant E-range**:
- In **superperiodic** (w/ period M), **flat** ring (w/o solenoids & spin rotators). . .

. . . not all integers are allowed: for vertical intrinsic res.:

$$\boxed{a\gamma_{\rm res} = kM \pm Q_y}$$

- RCS: *approximate* sperperiodicity $M = 96$, $\{Q_y\} = 50$
  $\rightarrow$ save until ≈ 20 GeV

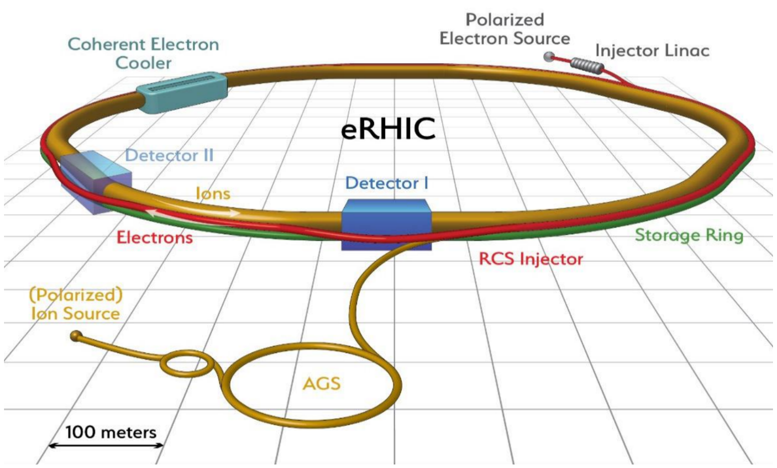


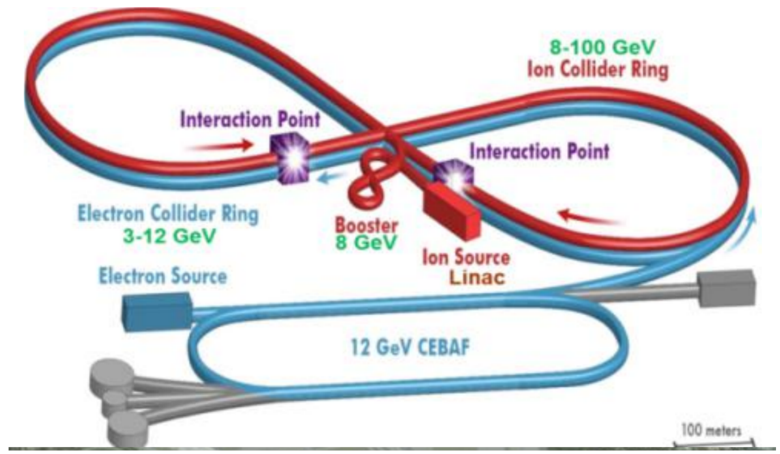
$\uparrow$ intrinsic (vertical spin orbit resonances in RCS from 1 to 18.5 GeV: on the 10^{-5} level (easily **jumpable!** non-adiabatic FS)

The EIC e^-–Storage Rings at the Design Level

Both: full-energy injector: presumably **off**–resonance !!!

Both: all this is only relevant at the HE-end of operations!





- "Traditional" storage ring
- ST has preferred direction
- Optimum (↑ + ↓) for P_∞ not much above 50%
- Kick-out injection every ≈ 3-6min

- Figure-8 "ring" w/ tuning-sol.
- ST build-up cancels

… but 2 counteracting half-8's drive spin diffusion

- Continuous top-up from CEBAF

The EIC e^-–Storage Rings at the Design Level (2)

- For enabling highest average Polarization at the high energy regime of both rings:
- Both designs contain spin rotators w/ interleaved solenoids and horizontal bends.

$\Rightarrow$ **Spin matching of straight sections seems advisable**

- Even though high P_∞ is not necessary (or not even desirable), τ_{dep} must not become too small! (can become seconds!)
- The working points (here: $\vec{Q}$ and $\nu(\gamma)$) must be chosen compatible for polarization, including the **beam-beam footprint**
- Diagnostics and “knobs” must be integrated to allow $\vec{P}$ optimization during operation (see next slides)
- In order to achieve high average (time-integrated) polarization during operation, spin issues have to be considered early on in the design phase! (Which they seemingly are!)

Operational Polarization Optimization : PreAcc Chain

- For JLEIC I would assume that optimizing e^- polarization in CEBAF is standard
- For eRHIC's RCS it is clear that potential issues, if at all, may only arise at the HE end of the cycle.

$\rightarrow$ Excellent orbit control is necessary and potentially even correction of the last imperfection resonances by rampable harmonic bumps.

$\rightarrow$ Good control over the tunes and coupling is essential — not only for polarization.

$\rightarrow$ Coherent instabilities: should not be allowed to blow up the beam, even though it's going to be damped back to equilibrium later in eRHIC

$\leftarrow$ Feedbacks (dampers): experience from HERA: as long as the keep instabilities ($\rightarrow$amplitudes) under control, they don't affect $\vec{P}$ strongly

Operational Polarization Optimization : e^-–Storage Rings (1)

- *initial* orbit & dispersion optimization / kick-minimization (BBA) $\leftarrow$ needs **enough** & **high-resolution** BPMs and enough steerers

$\star$ Optimize ν_0 !
$\rightarrow$ eRHIC : E-scan
$\rightarrow$ JLEIC : scan tuning solenoid

- Scan **harmonic bumps**

- Optimize tunes: generate space for beam-beam footprint away from spin-orbit resonances (HERA: this might cost some lumi!)

$\leftarrow$ These tunes might be quite different for eRHIC and JLEIC
$\rightarrow$ eRHIC: center of bunch (largest b-b tune shift & highest density) should be close to integer
$\rightarrow$ standard $(0 < [Q] < \frac{1}{2})$ vs. mirror $(\frac{1}{2} < [Q] < 1)$

- IF(P too small) GOTO $\star$ (iterate!)

Operational Polarization Optimization : e^-–Storage Rings (2)

1. Carefully watch the effect of dispersion bumps for "other" optimization $\leftarrow$ (lumi/background/lifetime/ldots)

$\rightarrow$ they might add xtra vertical dispersion & change the harmonic content

2. Same w/ coupling bumps (y-orbit through sextupoles / skew-quads) employed for "other" optimization

$\rightarrow$ they might change the harmonic content, add xtra vertical dispersion & affect the spin match

3. Same w/ optics bumps employed for "other" optimization

$\rightarrow$ they might strongly affect the spin match

- General wisdom on instabilities vs. FB-dampers $\rightarrow$ same as in PreAcc chain

Summary

- Polarization optimization must be thought off from the very beginning of design
- Polarization is generally in competition with luminosity and beam energy:
  "Meet the enchanting Spinderella and her two ugly sisters Luminosia and Energencia"
- Even w/ a proper, polarization-friendly design, optimization tuning can become tedious
- From my point of view both e-storage rings, eRHIC as well as JLEIC-e, have the potential for delivering highly polarized electron beams under collision

Thank you for Listening !!!