Depolarizer system concept for FCC-ee

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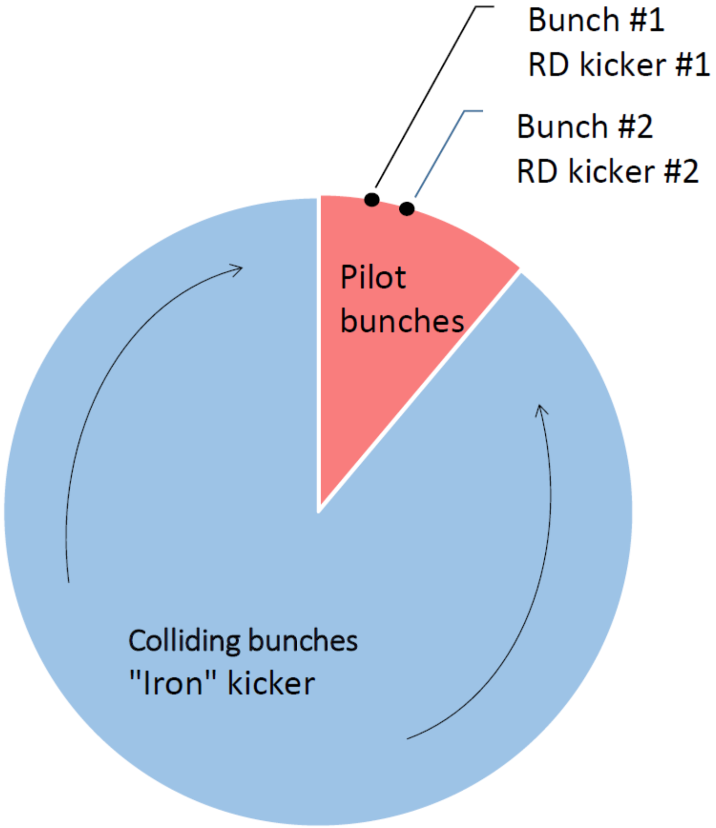
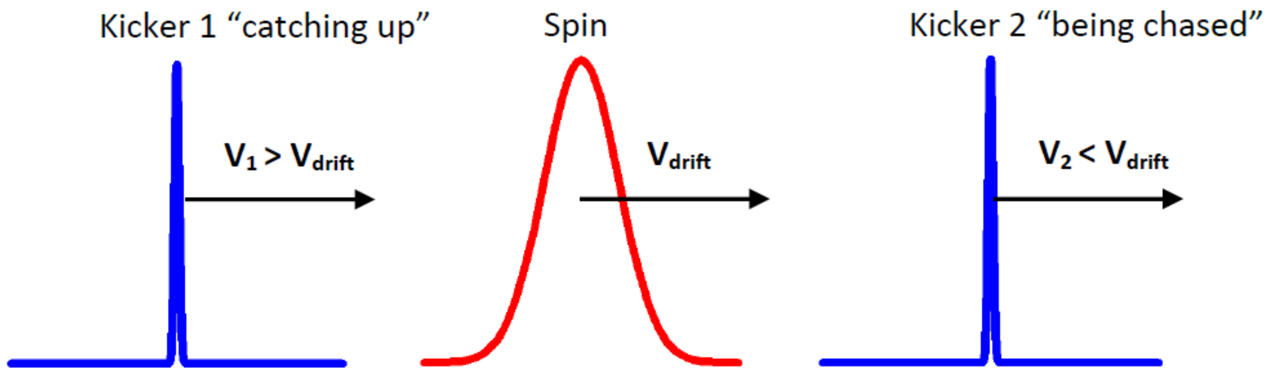
General view

Consider concept of three depolarizer system at FCC-ee:

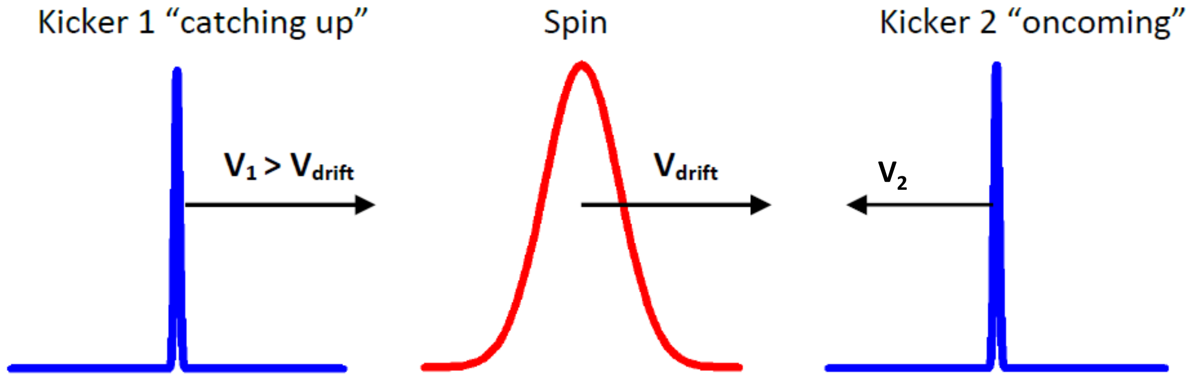
1. Two RD kickers are for energy calibration with resonant depolarization of pilot bunches ("pair scanning")
2. Third kicker, "Iron" kicker, is designed to eliminate the polarization of "physical" bunches
3. Each of RD kickers, simultaneously with another RD kicker, selectively affects one of two pilot bunches. Selectivity resolution is better than minimum bunch spacing (i.e. < 10 ns)
4. "Iron" kicker signal is strobbed in such a way that it affects all collidi bunches at once and doesn't affect pilot ones.
5. "Iron" frequency is regularly tuned in accordance with change of energy and its drift rate which are measured every ~15 minutes using RD kickers in "pair-scanning" mode
6. Attenuation of "Iron" signal in time intervals corresponding to pilot bunches at level of 10^{-2}



Pair scanning modes



Drive-by scanning. Most suitable if you already know the direction and approximate speed of the energy drift, as well as where the resonance might be. Kickers scan in the same direction relative to each other, but in opposite directions relative to the spin drift



Counter scanning . Suitable for preliminary determination of spin resonance position at certain time as well as direction and rate of drift. The result is needed to stabilize the energy using a feedback system based on tuning of RF resonator frequency . Kickers differ from each other in the direction of scanning.

Kicker linewidth is known and less than assumed linewidth of spin (Fine scanning).
Spin linewidth is much less than distance between synchrotron modulation resonances ("isolated resonance").
Spin linewidth and other sought parameters is determined from fitting model curve to measurement data.

- Compared to the use of a single depolarizer, pair scanning will make it possible to determine the direction and drift rate of the spin resonance, while its position at a certain moment of time is found with an error (< 10 keV) much smaller than the spin half- line width of ~100 keV at Z pole.

- The measured paired RD diagrams are fitted with curves obtained on the basis of an analytical model that takes into account the shapes of the spin and depolarizer spectra, as well as the scanning and energy drift processes. The sought quantities are the parameters of the model

- The model uses the solution of the Froissart-Stora equation for the case of fast uncorrelated spin resonance crossings. In this sense the model is not phenomenological

- At drift rate << 1 keV/s (for example, ~ 100 keV/h) the Pair-Scanning method becomes practically model independent: depolarization diagrams at counter scanning are mirror symmetrical and the spin resonance position is found as an average between them

- The possibilities of Pair Scanning are explored using Monte Carlo simulations taking into account the possible errors in polarization measurement

LINE WIDTH IN SPIN AND DEPOLARIZER SPECTRA (partially renewed)

$\varepsilon_\nu \sim \nu\langle H''(\sigma_{x\beta}^2 + \sigma_{x\gamma}^2)\rangle$ broadening of spin line due to sextupoles [turn^{-1}]

$\varepsilon_{diff} \sim \frac{\sigma_\nu}{\nu_\gamma}\frac{\lambda_\gamma}{2\pi}$ broadening of spin line due to radiative diffusion of spin phase [turn^{-1}]

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	E GeV	f_0 kHz	σ_ν spin tune spread due to energy spread [turn^{-1}]	ν_γ synchrotron tune [turn^{-1}]	σ_ν/ν_γ modulation index	$\lambda_\gamma/2\pi$ radiation decrement [rad^{-1}]	ε_ν due to non-linearity [turn^{-1}]	$\varepsilon_{\text{diff}}$ due to radiative diffusion [turn^{-1}]	$\frac{\sqrt{\varepsilon_\nu^2+\varepsilon_{\text{diff}}^2}}{\nu}$	Spin line half- width [keV]
VEPP-4M	1.85 4.73	820	0.0015 0.0098	~0.01 0.015	~0.015 ≈0.7	1.8e-6 3.0e-5	~4e-6 ~1e-4	2.7e-7 2.1e-5	≈1e-6 ≈1e-5	≈2 ≈40
LEP	45.6	11	0.061	0.083	0.73	4.7e-4	-	3.4e-4	~3e-6	~140
FCC-ee	45.6 80	3	0.039 0.120	0.025 0.051/0.080	1.56 2.37/1.50	1.25e-4 6.8e-4	~7.3e-5 -	2e-4 1.6e-3/1.0e-3	≈2.3e-6 8.8e-6/5.6e-6	≈108 705/450

Frequency resolution of the FCC-ee depolarizer synthesizer should be not worse than 10^{-4} Hz

$\delta f_d \sim \sqrt{df_d/dt}$ [Hz] broadening of depolarizer line when scanning rate of df_d/dt

$\varrho = \frac{\Delta f_d}{\Delta E} = \nu\frac{f_0}{E} = 0.007$ [Hz/keV] ratio of frequency interval to energy interval ($\nu = \gamma a$)

$df_d/dt \ll (100\,\varrho)^2 \approx 0.5$ [Hz/s] needed rate to provide depolarizer linewidth much smaller than that of spin

If necessary, depolarizer line can be expanded in artificial way using synthesizer, maintaining rate of scanning

ANALYTICAL MODEL OF FINE SCANNING

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Based on the Froissart–Store equation as applied to the case of fast uncorrelated intersections of the isolated spin resonance, taking into account the shape of spin and depolarizer spectra as well as the time dependence of resonance detuning because of scanning and energy drift

Spin spectrum

$$g(q) = \frac{1}{\sqrt{2\pi}\sigma_s}\exp\left(-\frac{q^2}{2\sigma_s^2}\right)$$

Depolarizer spectrum

$$h(q) = \frac{1}{\sqrt{2\pi}\sigma_d}\exp\left(-\frac{q^2}{2\sigma_d^2}\right)$$

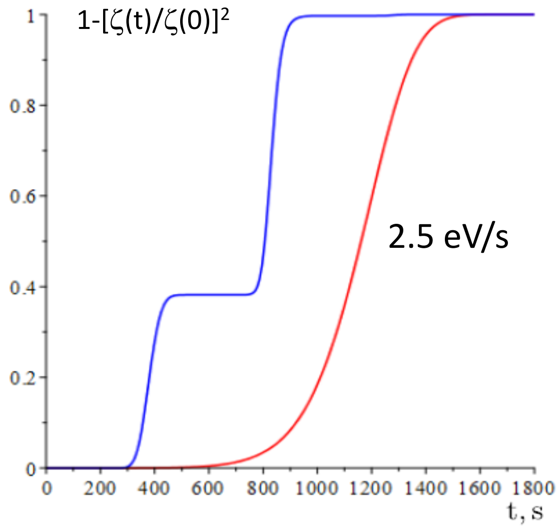
- Quantity q is detuning in relative to center of spin spectrum written in energy units
- Ratio of half-widths of spectral lines recommended for scanning: σ_s (spin) $\geq \sigma_d$ (depolarizer)
- Convolution of spectral distribution functions: $G(q) = (g * h)(q)$
- Time parameter used is $\tau_d \sim \frac{\pi\Delta f_{spin}}{|w_k|^2\omega_0^2}$, depolarization time in specific case when narrow depolarizer line is inside spin spectrum band of width $\Delta f_{spin} = 2\sigma_s \cdot \varrho$; $\varrho = \nu\frac{f_0}{E} = 0.007$ [Hz/keV] ratio of frequency and energy intervals ($\nu = \gamma a$); $\omega_0 = 2\pi f_0$ revolution frequency; $|w_k|$ spin harmonic amplitude
- When detuning changes with rate of $\dot{q} = dq/dt$, polarization ζ decreases according to equation

$$\frac{d\zeta}{dq}\frac{dq}{dt} \approx -\zeta\frac{\pi\sigma_s}{\tau_d}G(q(t)) \quad \text{so} \quad \zeta(q(t)) \approx \zeta_0\exp\left[-\pi\sigma_s\left(\frac{dq}{dt}\tau_d\right)^{-1}\int_{-\infty}^{q} G\,dq'\right]$$

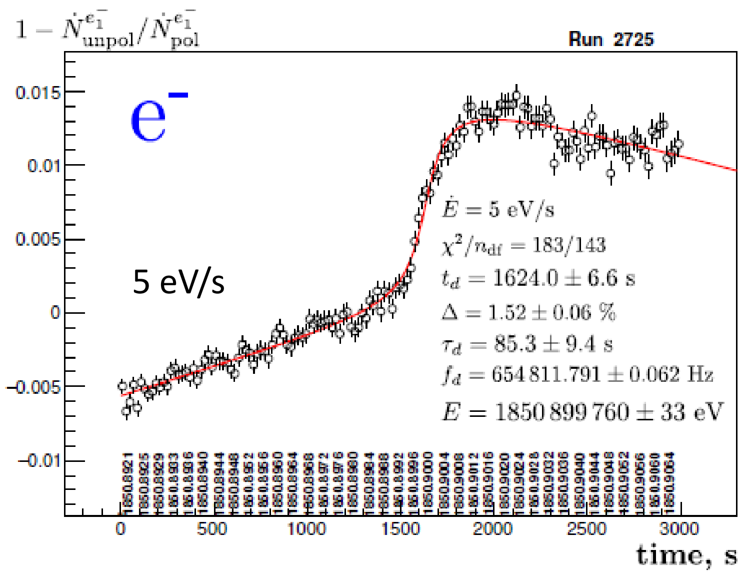
- Accounting for both scan rate and energy drift: $q(t) = q(0) + \int_0^t(\dot{q}_{\mathrm{dep}} + \dot{q}_{\mathrm{drift}})dt$

MODEL VS FINE SCANNING EXRERIMENTS AT VEPP-4M

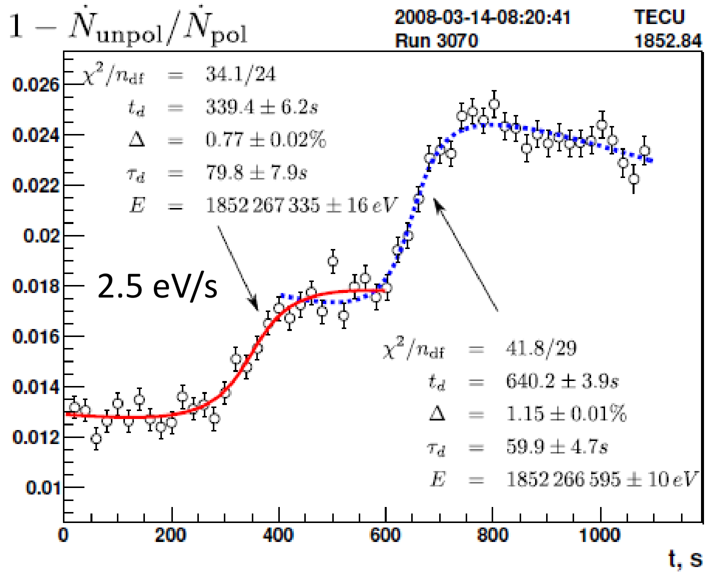
Simulation model taking into account spin line half-width estimated as 1 keV at 1.85 GeV VEPP-4M (due to sextupoles) reasonably corresponds to results of Fine-Scanning (high resolution) experiments using Touschek polarimeter



Model: spin half-linewidth 1 keV; $|w_k|=10^{-7}$; depolarizer half-linewidth = 0 keV .
Blue: with energy oscillations of 2 keV and 500 s



The typical experimental result on FS ($|w_k| \sim 5\cdot10^{-8}$). Depolarizer half-linewidth ~0.06 keV .

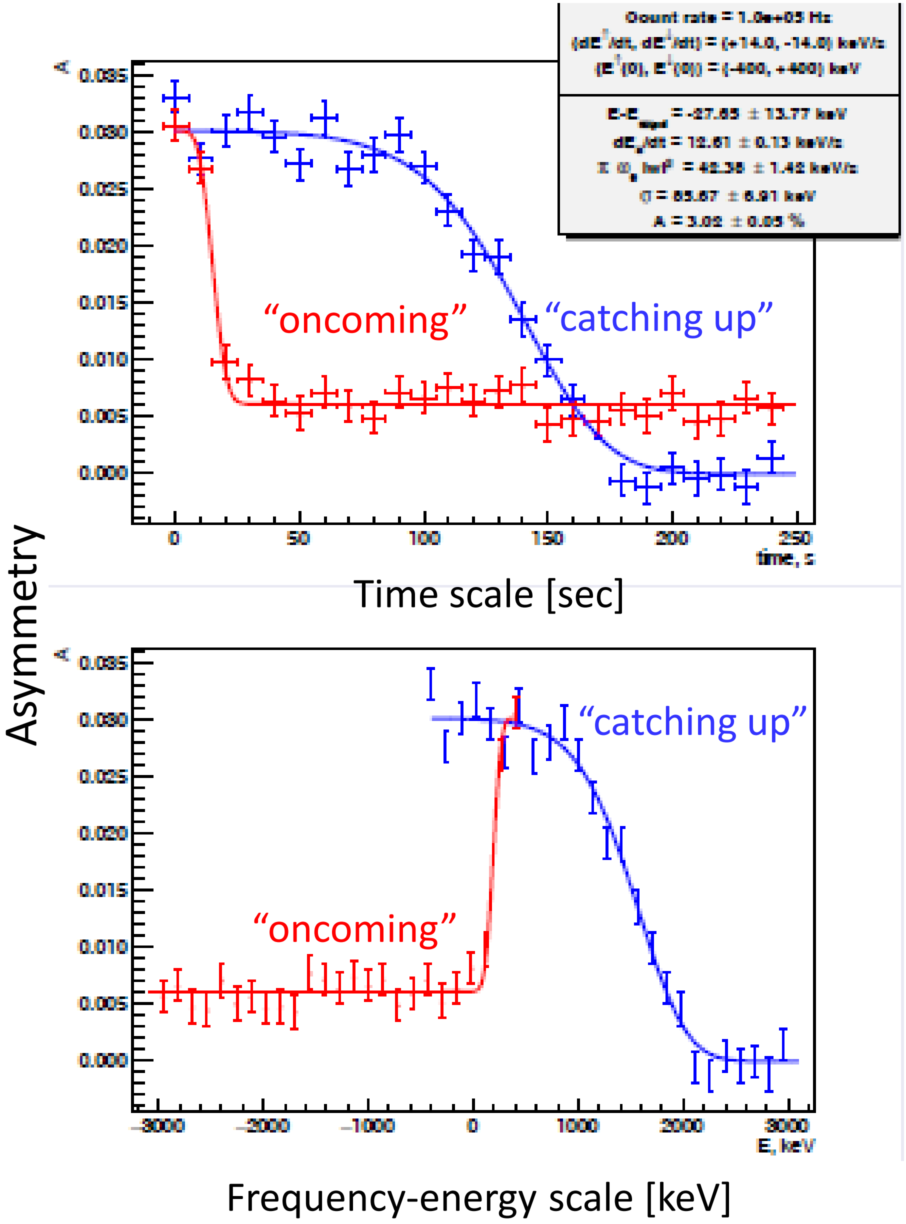


Presumably, slow field oscillations of 1 keV and a period of a few hundred seconds.

Conditions of polarization “measurement” with laser polarimeter in Monte – Carlo simulation

- E=45 GeV
- Number of electrons in pilot bunch =10^{10}
- Counting rate $\dot{N}$ =10^5 Hz
- Beam polarization degree 10%
- Polarization effect (asymmetry) A=0.3×10% = 3%
- Total measurement time $t_{max} \approx 1000$ s
- Count time per point T = 10 s

“Counter” scanning under extreme energy drift



Setting:

Energy drift rate = +12.5 keV/s

“Catching up” kicker: $dE^{\uparrow}/dt=+14$ keV/s, $|w|=4\cdot10^{-5}$

“Oncoming” kicker: $dE^{\downarrow}/dt= -14$ keV/s, $|w|=4\cdot10^{-5}$

Spin spectrum line width sigma = 100 keV (0.7 Hz)

Kicker spectrum line width sigma = 24 keV (0.17 Hz)

Start positions: $E^{\uparrow}(t=0)= -400$ keV; $E^{\downarrow}(t=0)= +400$ keV

Fit:

Deviation of result from expected energy = **-27.65 ± 13.77 keV**

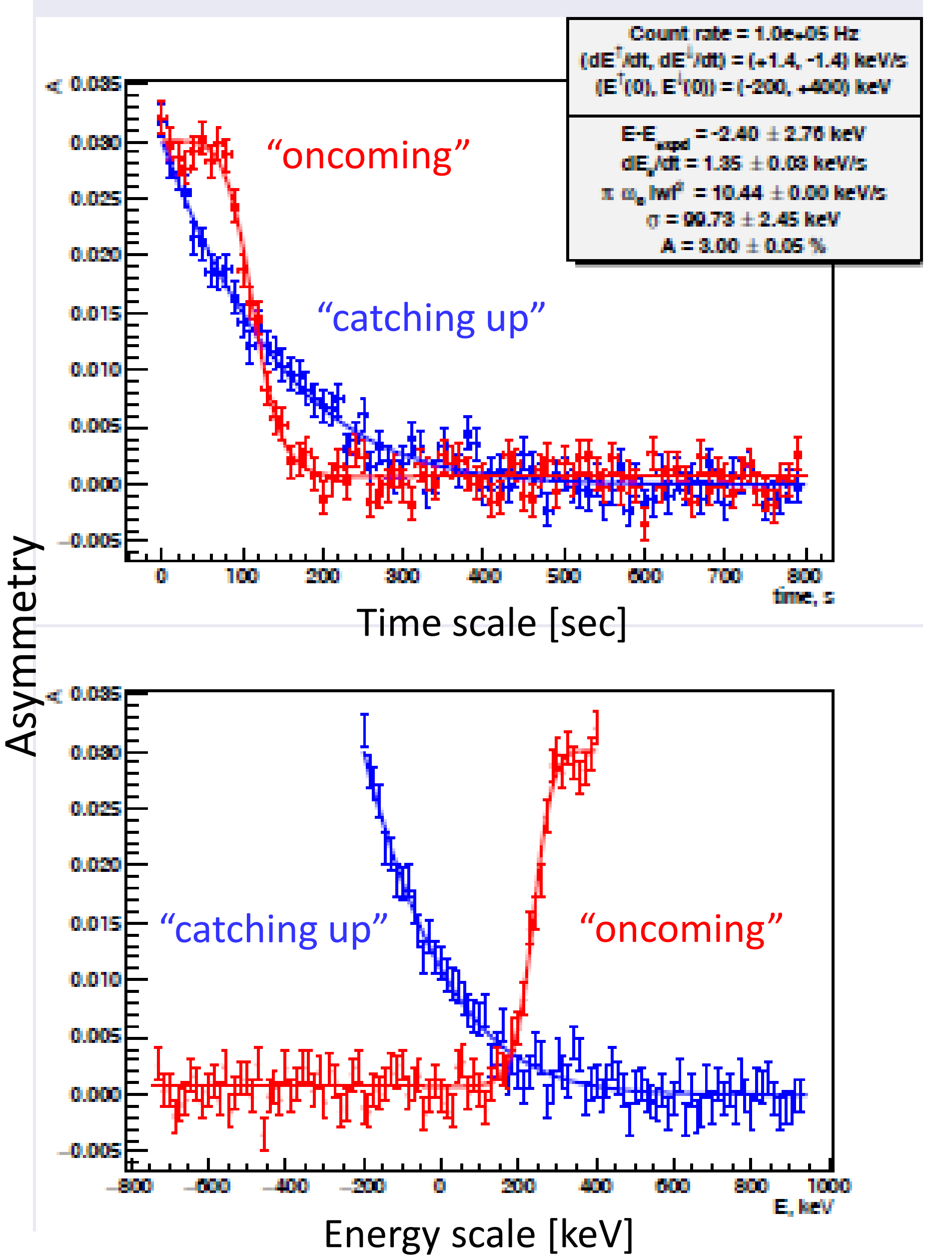
Energy drift rate = 12.61 ± 0.13 keV/s (vs setting 12.5 keV/s)

Sigma of spin linewidth = 85.67 ± 6.91 keV (vs setting 100 keV)

Note:

Due to too fast relative oncoming scanning (14+12.5=26.5 keV/s vs 14-12.5=1.5 keV/s for catching-up), the depolarization is incomplete. It indicates the direction of drift. In realty, the found drift parameters can be used for stabilizing energy through the RF-based feed back

“Counter” scanning under moderate energy drift



Setting:

Energy drift rate = +1.3 keV/s

“Catching up” kicker: $dE^{\uparrow}/dt=+1.43$ keV/s, $|w|=2\cdot10^{-5}$

“Oncoming” kicker: $dE^{\downarrow}/dt= -1.43$ keV/s, $|w|=2\cdot10^{-5}$

Spin spectrum linewidth sigma = 100 keV (0.7 Hz)

Kicker spectrum linewidth sigma = 7.1 keV (0.05 Hz)

Start positions: $E^{\uparrow}(t=0)= -200$ keV; $E^{\downarrow}(t=0)= +400$ keV

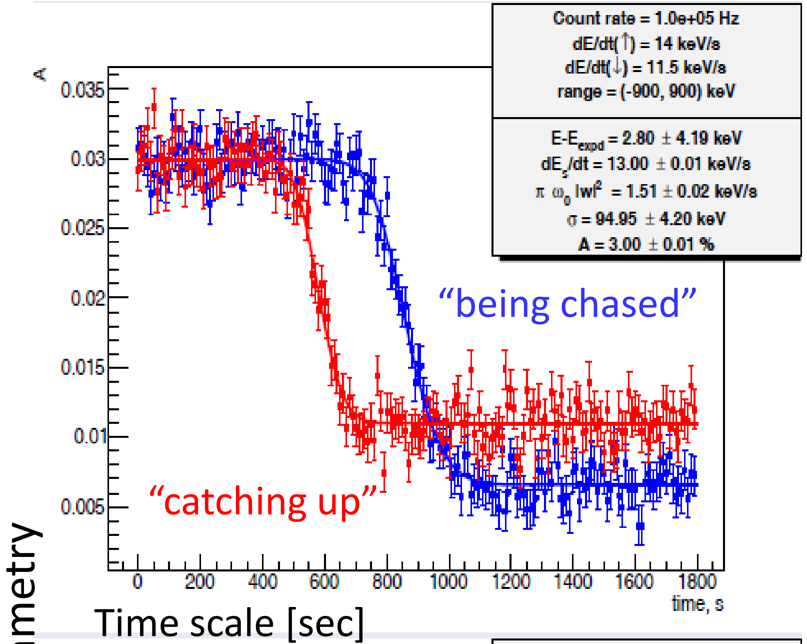
Fit:

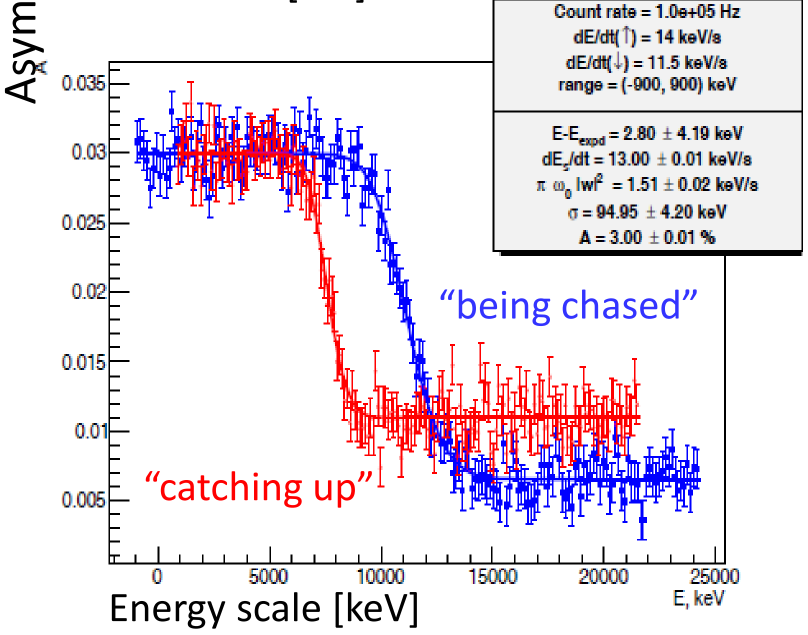
Deviation of result from expected energy = **-2.40 ± 2.76 keV**

Energy drift rate = 1.36 ± 0.03 keV/s (vs setting 1.3 keV/s)

Sigma of spin linewidth = 99.73 ± 2.46 keV (vs setting 100 keV)

“Drive-by” scanning under extreme energy drift





Setting:

Energy drift rate = +13 keV/s

“Catching up” kicker: dE_1dt = +14 keV/s, $|w|=2\cdot10^{-5}$

“Being chased” kicker: dE_2/dt= -11.5 keV/s, $|w|=2\cdot10^{-5}$

Spin spectrum linewidth sigma = 100 keV (0.7 Hz)

“Catching up” kicker linewidth sigma = 24 keV (0.17 Hz)

“Being chased” kicker linewidth sigma = 22 keV (0.15 Hz)

Start positions: E_1 (t=0)= - 900 keV; E_2 (t=0)= + 900 keV

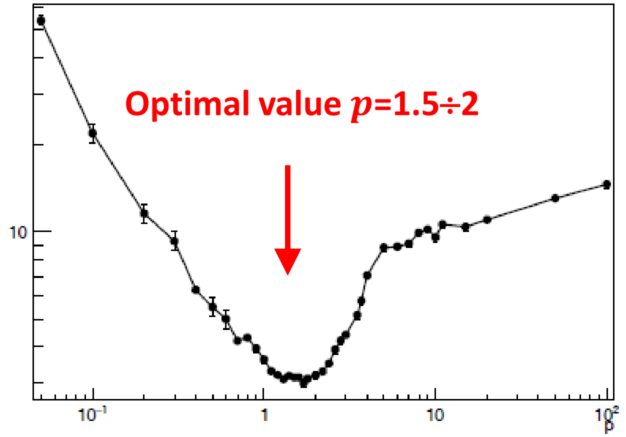
Fit:

Deviation of result from expected energy = **-2.80 ± 4.10 keV**

Energy drift rate = 13.0 ± 0.01 eV/s (vs setting 1.3 keV/s)

Sigma of spin linewidth = 94.95 ± 4.20 keV (vs setting 100 keV)

Error in energy [keV] vs parameter *p* of depolarizer efficiency at scanning



Error is minimized at a certain ratio of harmonic squared and relative scan rate in the parameter

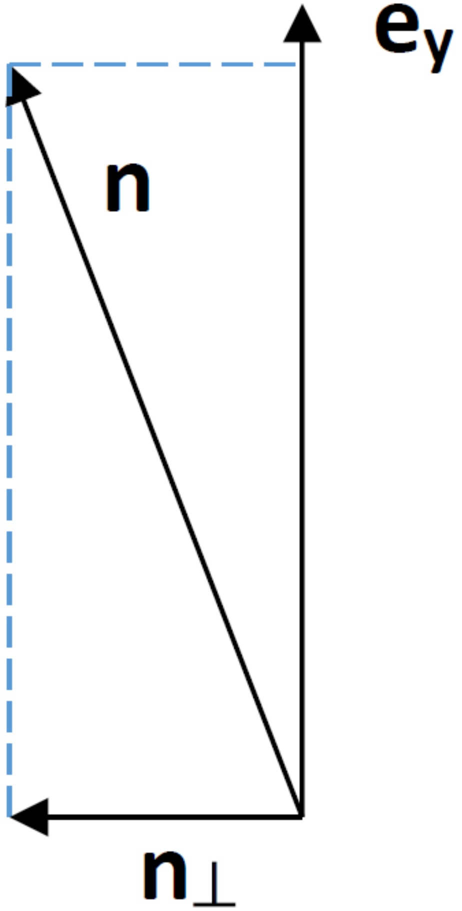
$$p = \frac{2\pi^2|w^2|\cdot f_0[\mathrm{Hz}]\cdot 440648\ [\mathrm{keV}]}{|\dot{E}_{drift}-\dot{E}_{kicker}|[\mathrm{keV/s}]}.$$

The kickers have the same harmonics and relative scan rates. Example: p=1.5 at $|\dot{E}_{drift}-\dot{E}_{kicker}|$=1 keV/s, $|w|$=7.6e-6.

“Iron”. How strong?

Transverse component of polarization axis in order of magnitude due to vertical CO distortions ($\nu = \gamma a$; $w_k^{(CO)}$, k amplitude and number of main spin harmonic):

$$n_\perp \sim \left| \frac{w_k^{(CO)}}{k-\nu} \right| \quad .$$



Longitudinal polarization at IP:

$P_\parallel \sim P \cdot n_\perp, \quad P \sim g \cdot 0.92,$

$g < 1$ – natural depolarization factor of magnetic structure with imperfections.

At Z-pole, $|k - \nu|$~0.5 and $P \sim 0.5$ at critical resonant harmonic $\left|w_k^{(CO)}\right| \sim 10^{-3}$.

S. Nikitin. Polarization issues in circular electron–positron super-colliders, International Journal of Modern Physics A 35(15n16):204100 (2020) DOI: 10.1142/S0217751X20410018

Expected “natural” $P_\parallel \sim 0.001$.

To reduce this value to the level $P_\parallel \sim 10^{-5}$, it is necessary to apply the "Iron" kicker, which reduces the total equilibrium degree of polarization to P ~10^{-3}. "Iron" acts immediately on all "physical" bunches in two possible options:

a) during full time in <u>collision ON</u> mode

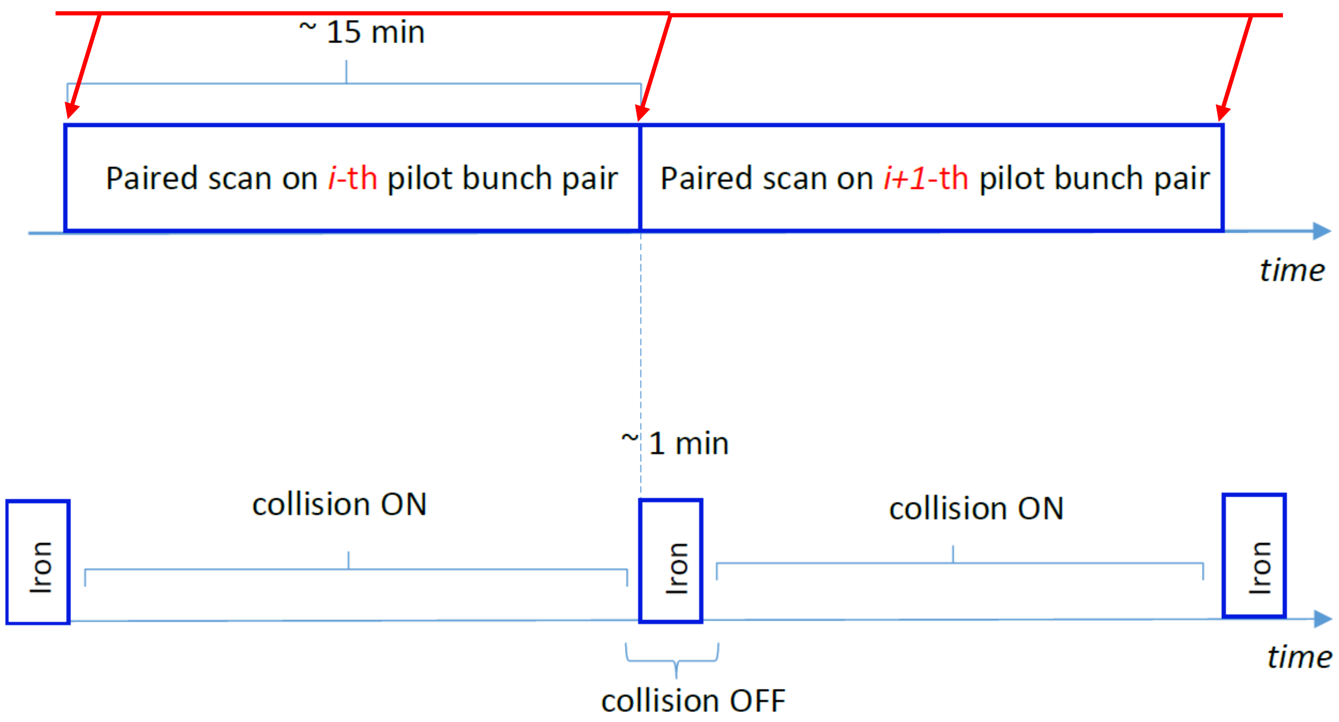
b) during short time ~ 1 min in <u>collision OFF</u> mode in pauses between collision runs .

Continuous “Iron” at Z pole (collision ON)

- Enforced depolarization time τ=1000 sec
- Steady-state polarization degree $P \sim 10^{-3}$
- Longitudinal polarization $P_{||} \sim 10^{-5}$
- Spectrum line is of order of uncertainty in position of spin resonance which is due to energy drift and broadening of spin line (σ_s half-width). For example, $\sim 3\sigma_s$ =300 keV or $\Delta f_{.} \sim 2.1$ Hz
- Kicker harmonic amplitude $|w| \approx (\Delta f_{.} / 2\pi\tau_{.})^{1/2} / f_0 \sim 5 \cdot 10^{-6}$
- From time to time frequency of “Iron” is tuned in accordance with the energy and its drift rate measured with help of RD kickers
- In continuous mode, “Iron” eliminates polarization, but may spoil luminosity (needs to clarify).

Pulse-periodic “Iron” (collision OFF mode)

Spin resonance position refined after every scan



~ 15 min

Paired scan on *i*-th pilot bunch pair

Paired scan on *i+1*-th pilot bunch pair

time

~ 1 min

Iron

collision ON

Iron

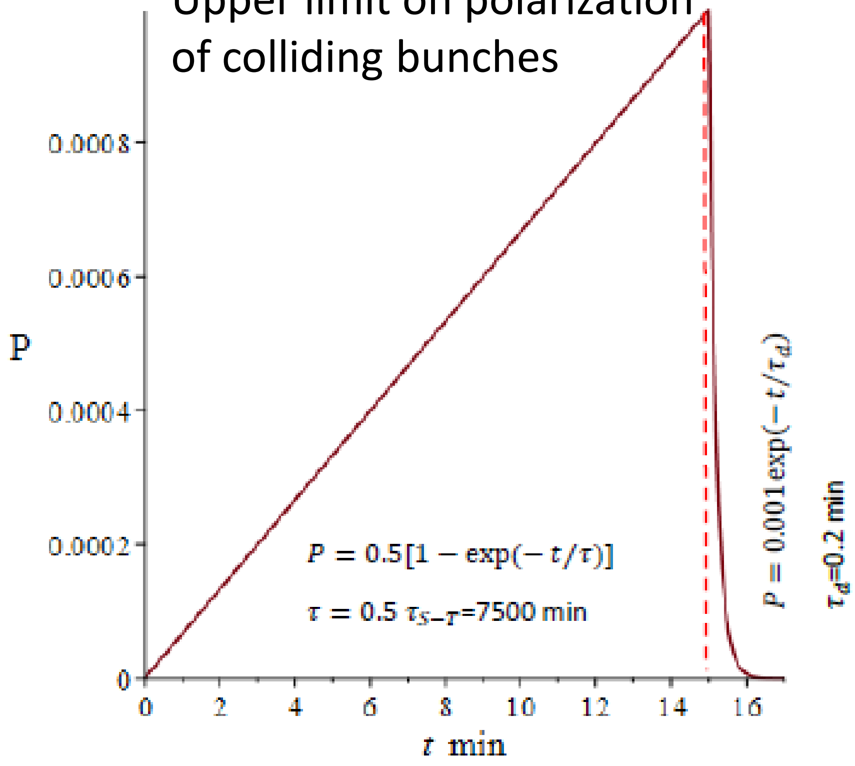
collision ON

Iron

time

collision OFF

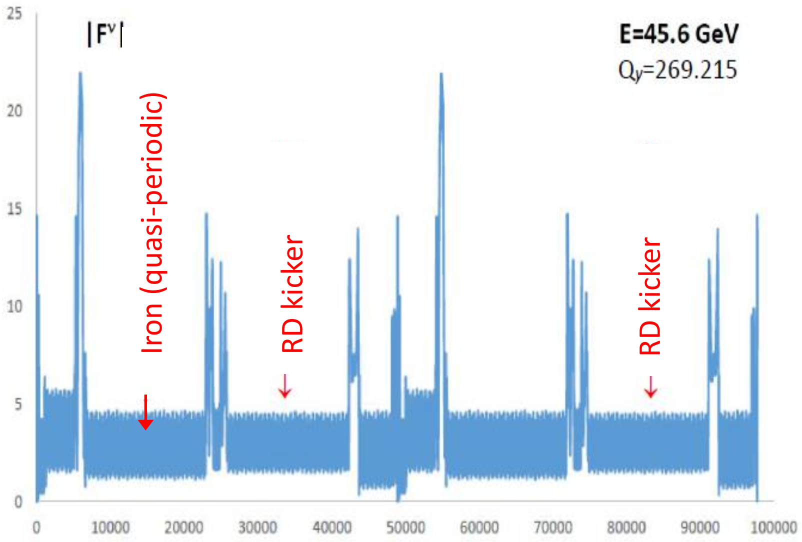
Upper limit on polarization of colliding bunches

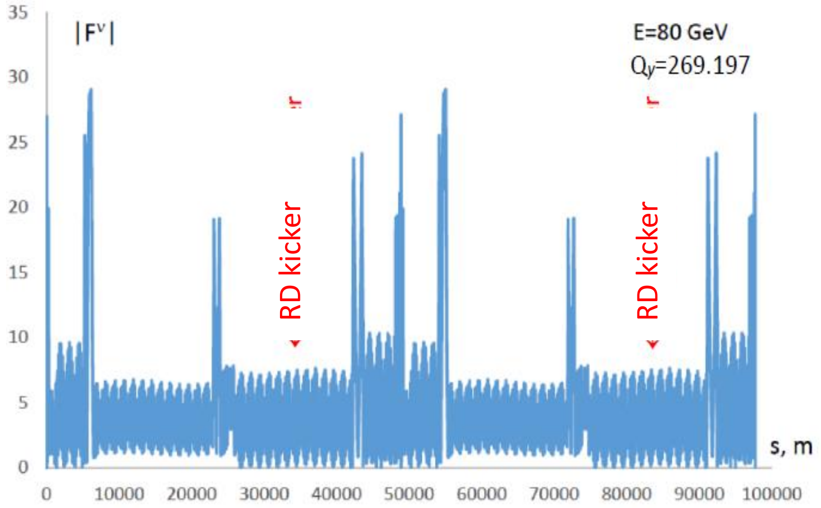


Width of “Iron” spectral line is of order of uncertainty in position of spin resonance which is due to energy drift and broadening of spin line.
For example, ~300 keV (or Δf ~ 2.1 Hz);
effective “Iron” harmonic amplitude $|w| \approx (\Delta f / 2\pi\tau_{d.})^{1/2} / f_0$~ $5\cdot10^{-5}$;
characteristic depolarization time assumed is $\tau_d \approx 12$ second.

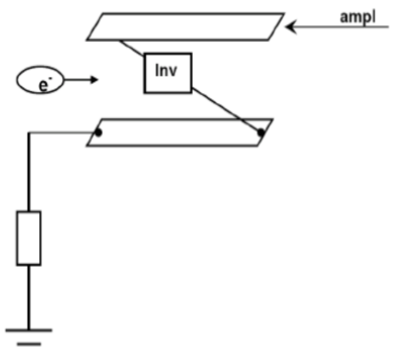
TEM-BASED DEPOLARIZER

Spin response factor vs azimuth at Z pole and WW threshold.
Lattice option with two IPs





Strip-line-based kicker



$$|w_k| = \frac{\nu \hat{B}_\perp l_d}{2\pi B\rho}|F^\nu| = \frac{\nu\varphi_\perp}{2\pi}|F^\nu|$$

$$\tau_d = \frac{\pi\Delta f}{\omega_0^2 |w_k|^2}$$

The parameter τ_d is the depolarization time for the two selected cases with no scanning. In one case (RD kicker), after turning on the depolarizer, its line is inside the band Δf of the spin spectrum. In the other, ("Iron") the spin line is inside the kicker spectrum band. ($\omega_0 = 2\pi f_0$ angular frequency of particle revolution).

Conceptual parameters for scaling

Beam energy	$E = 45.6$ GeV
spin harmonic amplitude	$\lvert w_k \rvert \propto \frac{\nu U l_d \lvert F^\nu \rvert}{E \cdot d}$
strip-line length	$l_d = 1$ m;
verticalgap between plates	$d = 20$ mm
amplitude of signal from amplifier	= 100 V
amplitude of voltage between plates	$U = 200$ V
spin response factor	$\lvert F^\nu \rvert = 5$
deflection angle in one passage	$\varphi_\perp = 2.2 \cdot 10^{-7}$
spin rotation in one passage`	$\nu\varphi_\perp = 2.3 \cdot 10^{-5}$
spin harmonic amplitude	$\lvert w_k \rvert = 1.8 \cdot 10^{-5}$
spin spectral band	$\Delta f = 1.4$ Hz
characteristic relaxation time	$\tau_d \approx 38$ second

The conceptual data shown are for scaling. For example, with $l_d \approx 3$ m, $|w_k|^2$ is 10 times larger. Our conditions are for complete or partial depolarization (without adiabatic spin flip). This is the case of fast uncorrelated crossings in spectral band. We studied it in the Fine-Scanning experiments at VEPP-4:

$\nu^2 \geq \tau_p(\Delta f)^3/f_0^2$, "uncorrelatedness" (τ_p= S-T time);

$(\Delta f/f_0)^2 \gg |w_k|^2$, "rapidity" of resonance crossing.

Note that for the same $|F^\nu|$ and voltage *U*, amplitudes of spin harmonics $|w_k|$ at 45 and 80 GeV are equal

ON INFLUENCE OF SYNCHROTRON MODULATION ON DEPOLARIZER STRENGTH

Without diffusion, modulation gives a line spectrum. As a consequence, the depolarization rate at the main spin resonance with allowance for synchrotron modulation ($\kappa = \sigma_s/\nu_\gamma$, modulation index) Derbenev et al. Part.Acc. V.8, n.2 (1978)

$\frac{1}{\tau_d} \propto |w_k|^2 I_0\left(\frac{\sigma_\nu^2}{\nu_\gamma^2}\right)\exp\left(-\frac{\sigma_\nu^2}{\nu_\gamma^2}\right)$ where

$|w_k| = \frac{\nu\varphi_\perp}{2\pi}|F^\nu|$, determined by kicker parameters;

$|w_k|_{eff} = |w_k|\sqrt{I_0\left(\frac{\sigma_\nu^2}{\nu_\gamma^2}\right)\exp\left(-\frac{\sigma_\nu^2}{\nu_\gamma^2}\right)}$, this “works”.

E [GeV]	ν_γ	σ_s	$\kappa = \sigma_s/\nu_\gamma$	$\|W_k\|_{eff}/\|W_k\|$
45	0.025	0.039	1.56	0.53
80	0.08	0.120	1.50	0.54

True if the condition $\kappa^2\lambda_\gamma \ll \nu_\gamma$ is met. This condition is fulfilled well on FCC-ee in the mode of physical experiments::

E=45 GeV, $\kappa = 1.56$, $\lambda_\gamma = 1/1273$ turns^{-1}, $\nu_\gamma = 0.025 \rightarrow 0.0019 << 0.025$

E=80 GeV, $\kappa = 1.50$, $\lambda_\gamma = 1/236$ turns^{-1}, $\nu_\gamma = 0.080 \rightarrow 0.0096 << 0.080$

Compare: E=80 GeV, $\kappa = 2.45$, $\underline{\nu_\gamma = 0.051}$ $\rightarrow 0.0254 < 0.051$

Conclusions

System of three kickers seems to fully meet task of precision measurement of masses on FCC-ee using RD.
Two kickers are to exclude influence of energy drift and decrease uncertainty in position of spin resonance.
At Z pole, the maximum achievable accuracy is of the order of several keV with reference to a certain point in time.
Scan cycle is about 15 minutes.
Third kicker (Iron) suppresses possible parasitic longitudinal polarization of physical bunches to level of 10^{-5}.
The **continuous mode of Iron** operation requires a voltage amplitude an order of magnitude smaller than the **pulse-periodic mode**. But it still requires periodic frequency adjustment. It is necessary to study its influence on luminosity. **Pulse-periodic mode** seems to be more reliable (total polarization killed just after calibration does not grow higher 10^{-3} in next 15 min) .
Estimated parameters of kickers on Z pole are in Table:

Type		l_d m	**$U/2$ Volt**	$\|F^\nu\|$	$\|w_k\|$	$\|w_k\|_{\text{eff}}$	**E GeV**	**d cm**
Iron	Pulse-periodic	3	≈180	5	$9.6\ 10^{-5}$	$5\cdot10^{-5}$	45	2
	Continuous	3	≈20	5	$1.1\cdot10^{-5}$	$5.6\cdot10^{-6}$		
RD kickers		5	≈10÷200	5	$10^{-5}\div2\cdot10^{-4}$	$5\cdot10^{-6}\div10^{-4}$		