Simulations for FCC-ee polarization

E. Gianfelice (Fermilab)

Contents:

- Introduction
- Sokolov-Tenov polarization in a 100 km ring
- Polarization with wigglers
- Simulations at 45 GeV in presence of misalignments
- Highlights from alternative proposal by I. Koop
- Summary

FCC Week, Washington, March 2015

Introduction

- High precision beam energy measurement ($\ll 100$ keV) is needed for Z pole physics at 90 GeV CM energy and W physics at 160 CM energy.
- Z pole physics would profit from longitudinal beam polarization.
- Self-polarization through Sokolov-Ternov effect strongly depends on bending radius and beam energy: not obvious for FCC.
- Alternative proposals have been made by I. Koop at HF2014, not easy either.

Sokolov-Ternov polarization

Build-up rate

$$\tau_p^{-1} = \frac{5\sqrt{3}}{8}\frac{r_e\gamma^5\hbar}{m_0C}\oint\frac{ds}{|\rho|^3}$$

For FCC-e^+e^- with $\rho \simeq$ 10424 m, fixed by the maximum attainable dipole field for the hh case, it is

E (GeV)	U_0 (MeV)	$\Delta E/E$ (%)	τ_{pol} (h)
45	35	0.038	256
80	349	0.067	14

Effect of wigglers

τ_p may be reduced by introducing wigglers:

$$\tau_p^{-1} = F\left[\int_{dip} \frac{ds}{|\rho_d|^3} + \int_{wig} \frac{ds}{|\rho_w|^3}\right] \qquad F \equiv \frac{5\sqrt{3}}{8}\frac{r_e \gamma^5 \hbar}{m_0 C}$$

Polarization

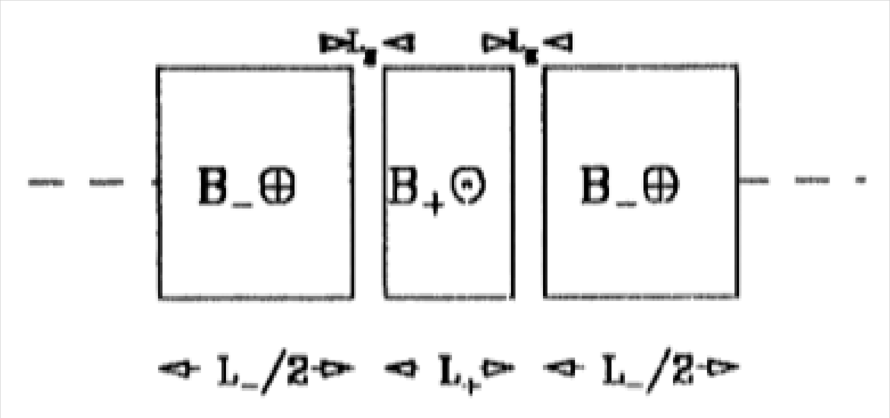
$$P = \frac{8}{5\sqrt{3}} \frac{\oint ds \frac{\hat{B}\cdot\hat{n}_0}{|\rho|^3}}{\oint ds \frac{1}{|\rho|^3}} \propto \tau_p \left[\int_{dip} ds \, \frac{\hat{B}_d \cdot \hat{n}_0}{|\rho_d|^3} + \int_{wig} ds \, \frac{\hat{B}_w \cdot \hat{n}_0}{|\rho_w|^3}\right]$$

$\hat{n}_0 \equiv \hat{y}$ in a perfectly planar ring.

Constraints:

- $x' = 0$ outside the wiggler $\Rightarrow \int_{wig} ds \, B_w = 0$ (vanishing field integral)
- $x = 0$ outside the wiggler $\Rightarrow \int_{wig} ds \, sB_w = 0$ (true for symmetric field)
- P large $\Rightarrow \int_{wig} ds \, B_w^3$ must be large

The LEP polarization wigglers have been considered



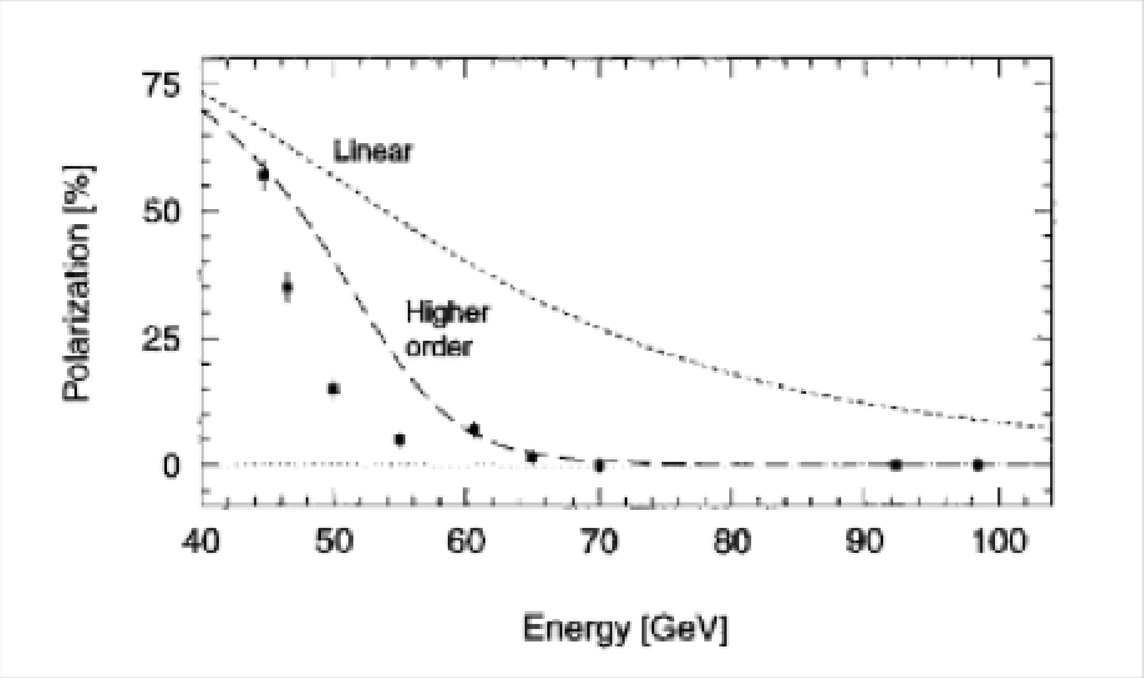
$$\int_{wig} ds\, \frac{1}{\rho_w^3} = \frac{L_+}{\rho_+^3}\Big(1 - \frac{1}{N^2}\Big) \qquad N \equiv L_-/L_+ = B_+/B_-$$

N should be large for keeping polarization high!

4 such wigglers with $N = 6$ and L_{+}=1.3 m have been introduced in dispersion free regions of a simplified FCC ring (*"toy ring"*). At 45 GeV:

B_{+} (T)	U_0 (MeV)	$\Delta E/E$ (%)	ΔE (MeV)	ϵ_x (μm)	τ_x (s)	P (%)	τ_{pol} (min)
0	37	.04	18	.8e-3	.82	92.4	14e3
1.3	64	.22	99	.5e-2	.48	87.6	247
2.6	144	.41	184	.070	.21	87.6	31
3.9	278	.55	247	.274	.11	87.6	9
5.2	466	.65	292	.691	.06	87.6	4

LEP measured polarization



(R. Assmann et al., SPIN2000, Osaka)

Polarization strongly depending on energy and no polarization observed above 65 GeV.

$$P_{DK} = \frac{8}{5\sqrt{3}} \frac{\oint ds < \frac{1}{|\rho|^3} \hat{b} \cdot (\hat{n} - \frac{\partial \hat{n}}{\partial \delta}) >}{\oint ds < \frac{1}{|\rho|^3} \left[1 - \frac{2}{9} (\hat{n} \cdot \hat{s})^2 + \frac{11}{18} (\frac{\partial \hat{n}}{\partial \delta})^2 \right] >}$$

with

$$\hat{b} \equiv \vec{v} \times \dot{\vec{v}} / |\vec{v} \times \dot{\vec{v}}|$$

$\partial \hat{n} / \partial \delta$ ($\delta \equiv \delta E / E$) quantifies the depolarizing effects resulting from the trajectory perturbations consequent to photon emission.

In a perfectly planar machine $\partial \hat{n} / \partial \delta = 0$. In presence of quadrupole vertical misalignments (and/or spin rotator) $\partial \hat{n} / \partial \delta \neq 0$ and large when

$$\nu_{spin} \pm m Q_x \pm n Q_y \pm p Q_s = \text{integer} \qquad \nu_{spin} \simeq a\gamma$$

Usually the dominant higher order resonances are the *synchrotron sidebands* of the first order resonances.

Distance between *imperfection* (or zeroth) order resonances: $\Delta E = 440$ MeV.

LEP lack of polarization at high energy is understood as due to the larger beam energy spread. Wigglers are going to introduce a large energy spread in FCC-e+e- beams!

	E (GeV)	$\Delta E/E$ (%)	ΔE (MeV)
HERA-e	27	0.1	27
LEP	40	0.06	26
LEP	100	0.16	160

A decrease of $\Delta E/E$ by constant τ_p is possible at expenses of U_0 and P_{nom} by choosing a smaller N [a]:

N	B_+ (T)	U_0 (MeV)	$\Delta E/E$ (%)	ΔE (MeV)	P (%)	τ_{pol} (min)
6	5.2	466	0.65	292	87.6	4
2	3.6	654	0.53	238	55	4.1

[a] L_w=const.

Resonances are awakened by imperfections!

Question: how *perfect* the ring must be for keeping resonances "sleeping"?

Simulations in presence of realistic errors and corrections are needed.

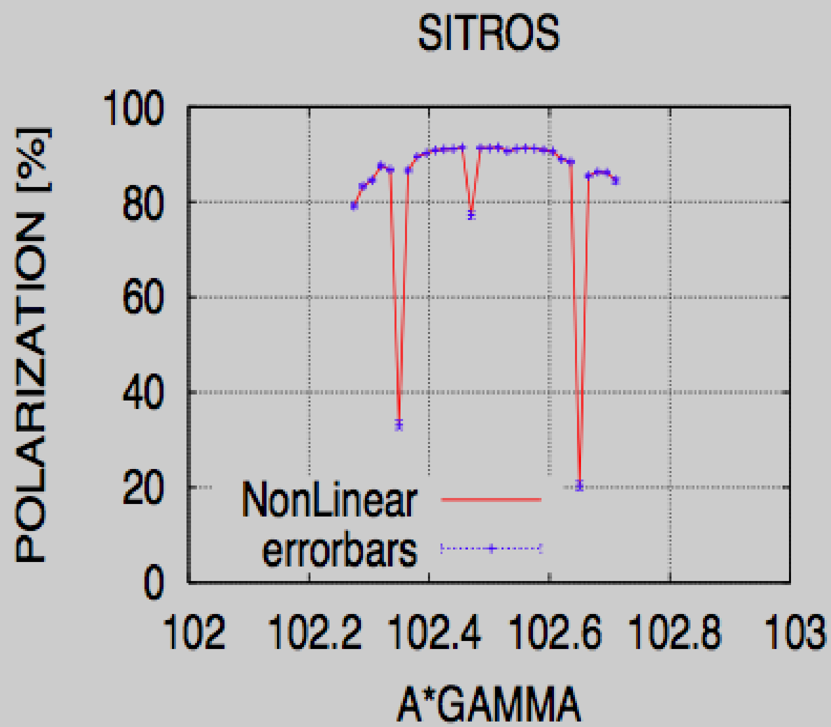
- MAD-X used for simulating quadrupole misalignments and orbit correction
- SITROS (by J. Kewish) used for computing the resulting polarization. It is a tracking code with 2th order orbit description and non-linear spin motion. It has been used for HERA-e in the version improved by M. Böge and M. Berglund.
  - HERA-e like *Harmonic Bumps* optimization for $\boldsymbol{\delta \hat{n}_0}$ correction in the FCC-e+e- ring implemented.

SLIM by A. Chao is used for linear calculations.

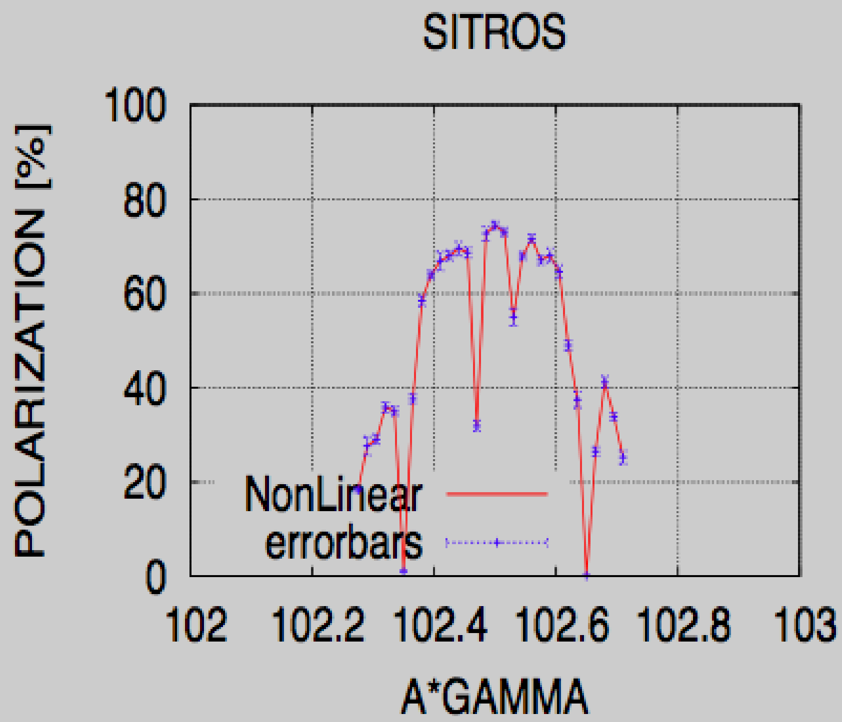
SLICKTRACK by D. Barber is available too, but it needs extra work to avoid using the costly NAG library.

SITROS: Polarization in presence of vertical misalignments w/o wigglers (no corrections!)

B_+=0, δ_y^Q=10 μm, y_{rms} 0.4 mm



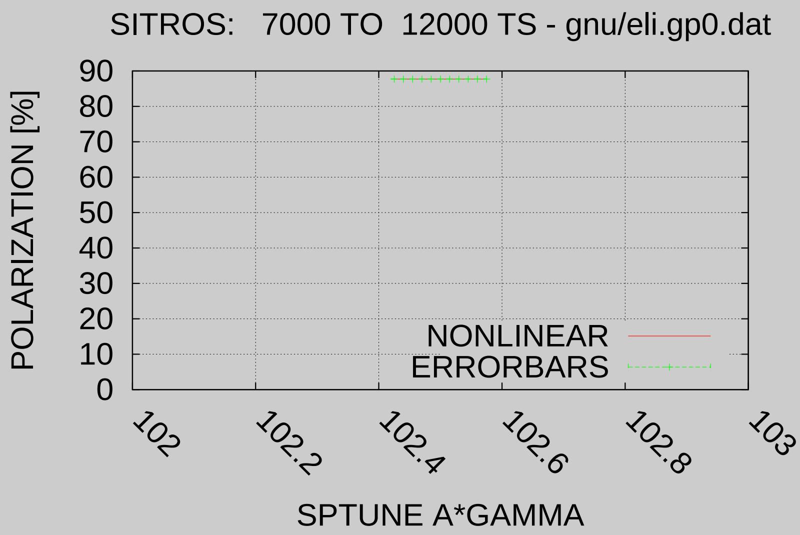
B_+=0, δ_y^Q=50 μm, y_{rms} 2 mm



(from HF2014, Beijing)

Polarization for the toy ring with

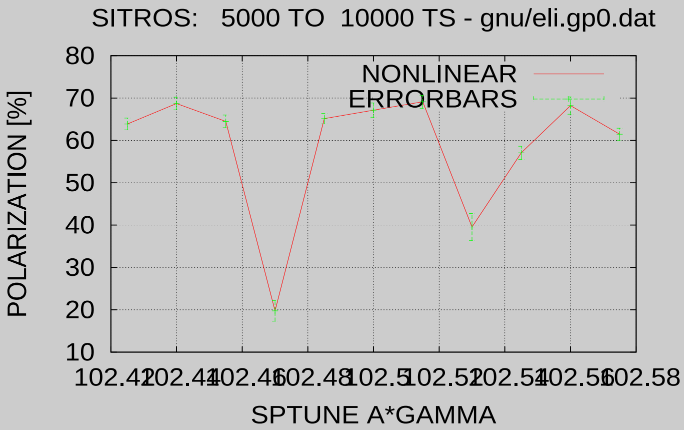
- Q_x=0.1283
  Q_y=0.2085
  Q_s=0.1168 (U_{rf}=594 MV, h=201000, f_{RF}=600 MHz) [a]
- no misalignments
- B_+= 1.29 T



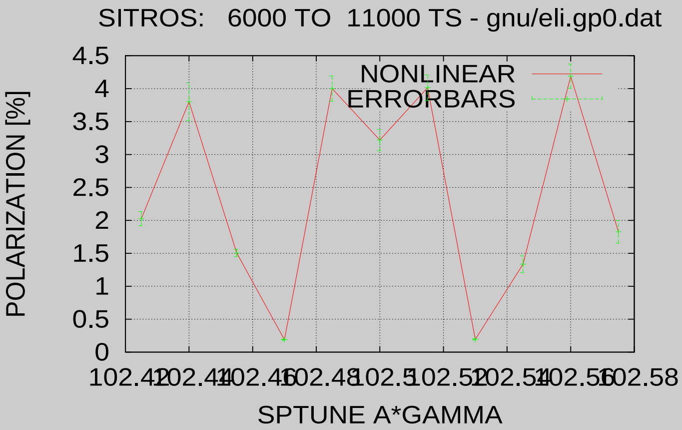
[a] The RF voltage is adapted to the wiggler field for keeping Q_s constant

Polarization for the toy ring with

- Q_x=0.1283
  Q_y=0.2085
  Q_s=0.1168 (U_{rf}=594 MV)
- δ_y^Q= 50 μm → y_{rms}= 2 mm, no corrections applied

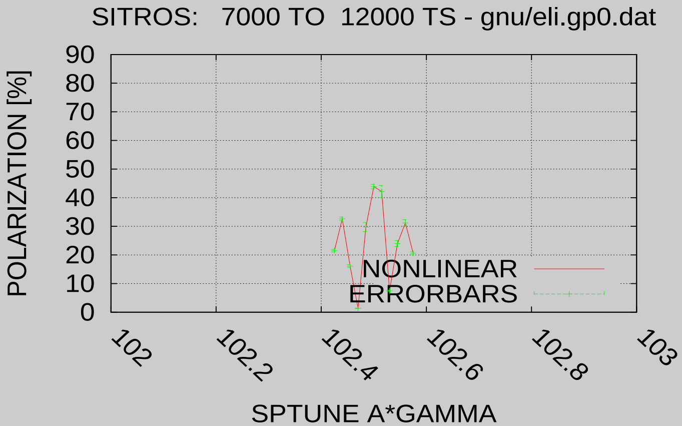


B_w=0

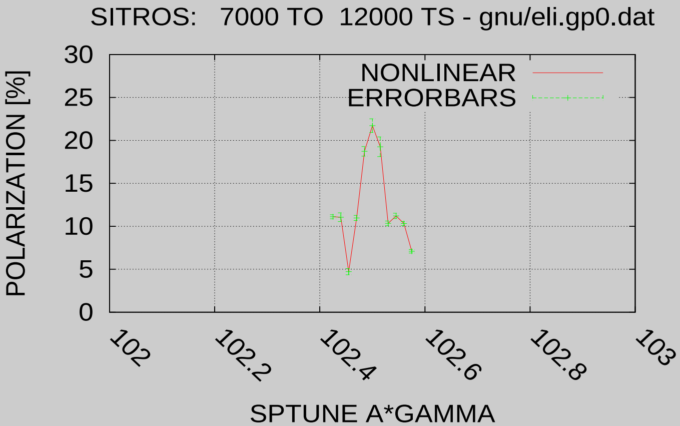


B_+=1.29 T

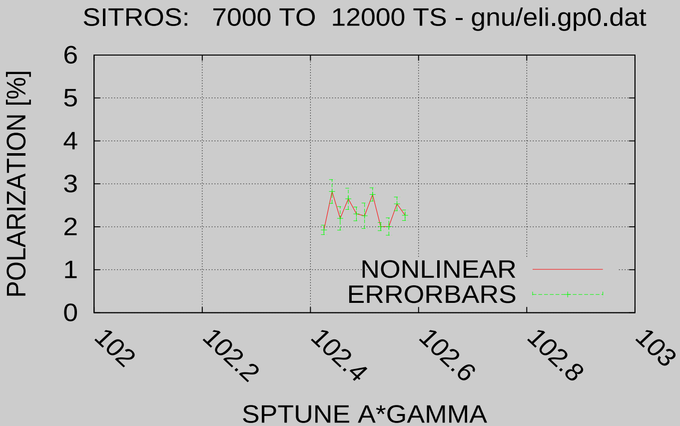
$\delta_y^Q = 25\ \mu\text{m} \rightarrow y_{rms} = 0.8\ \text{mm}$



$B_+ = 1.29$ T



$B_+ = 2.6$ T

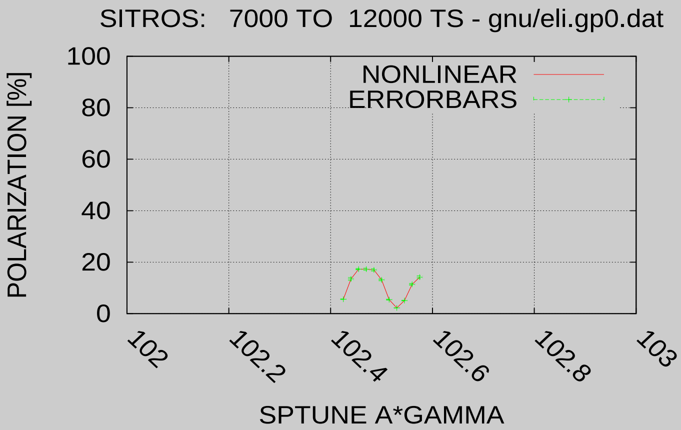


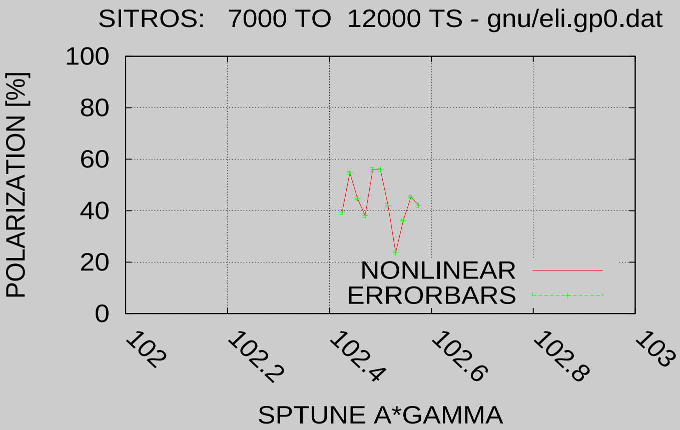
$B_+ = 3.9$ T

Closed orbit correction scheme: one vertical corrector + BPM introduced close to *each* vertical focusing quadrupole.

- Q_x=0.1283
  Q_y=0.2085
  Q_s=0.1168 (U_{rf}=594 MV with B_w=0)
- δ_y^Q= 50 μm $\rightarrow$ y_{rms}= 2 mm
  orbit corrected down to y_{rms}= 0.2 mm with 40 correctors by MICADO
  $\delta\hat{n}_0$=1.5 mrad

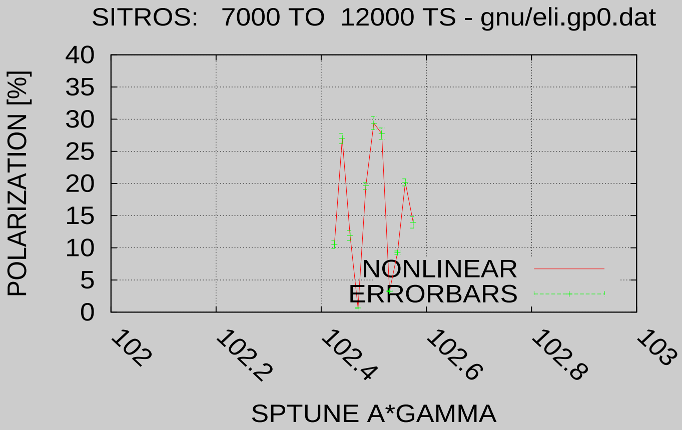
$$B_+\text{=3.9 T } (U_{rf}\text{=653 MV})$$



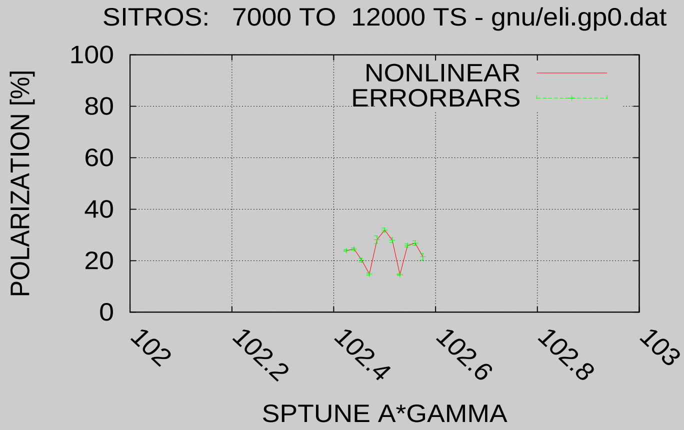


$\delta\hat{n}_0$=0.8 mrad with harmonic bumps

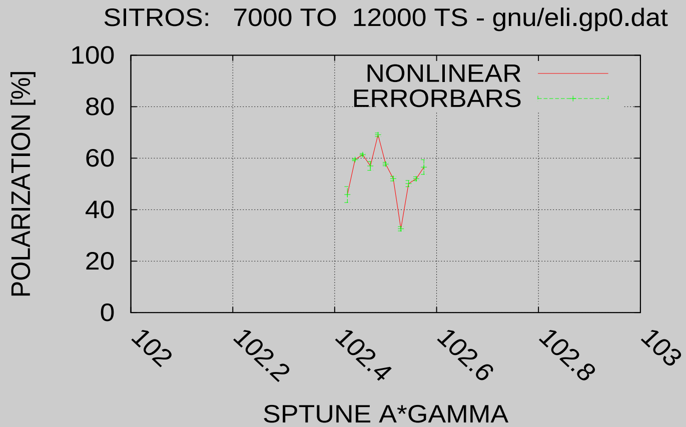
- δ_y^Q= 50 μm $\rightarrow$ y_{rms}= 2 mm
- orbit corrected down to y_{rms}= 0.1 mm with 100 correctors by MICADO
- $\delta\hat{n}_0$=0.8 mrad



B_+=1.3 T



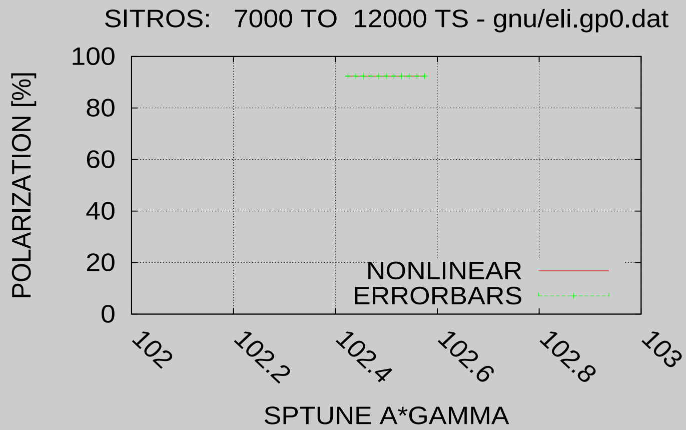
B_+=3.9 T



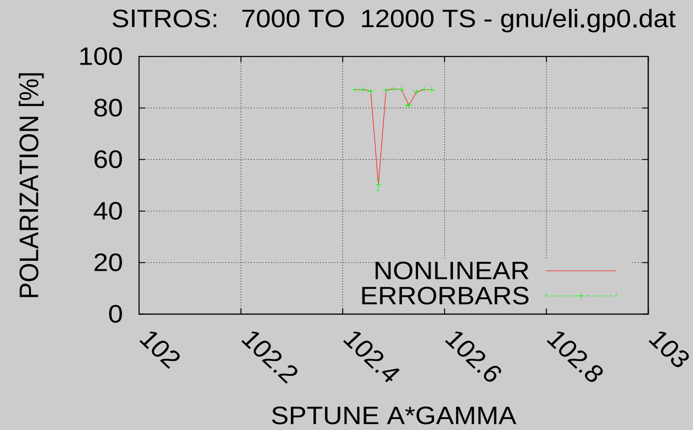
B_+=3.9 T, $\delta\hat{n}_0$=0.6 mrad with harmonic bumps

All 1096 vertical correctors used for orbit correction through SVD with $\delta_y^Q = 50\ \mu$m

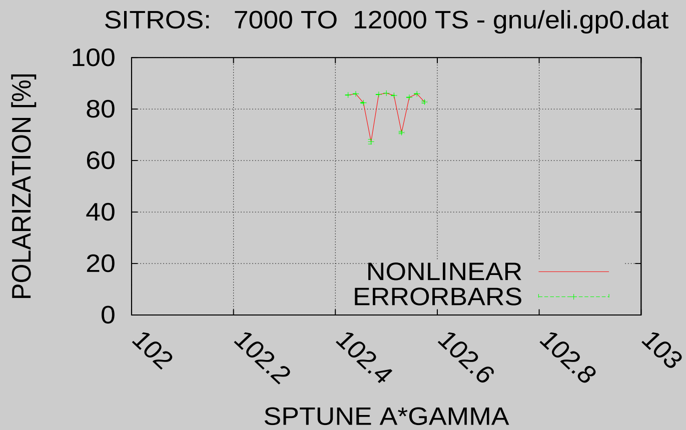
- $y_{rms} = 0.04$ mm
- $\delta\hat{n}_0 = 0.1$ mrad



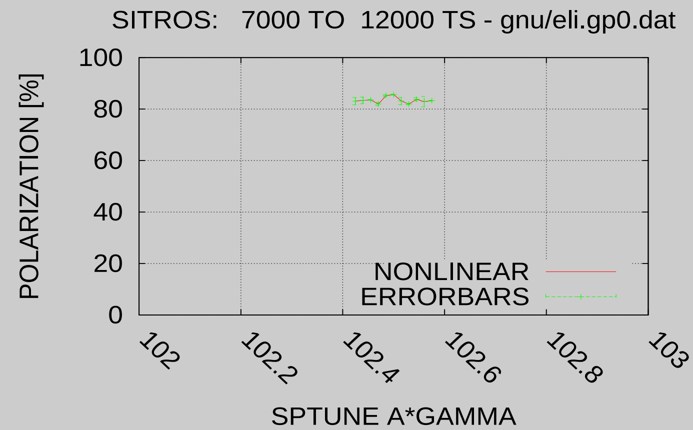
$B_+ = 0$ T



$B_+ = 1.3$ T



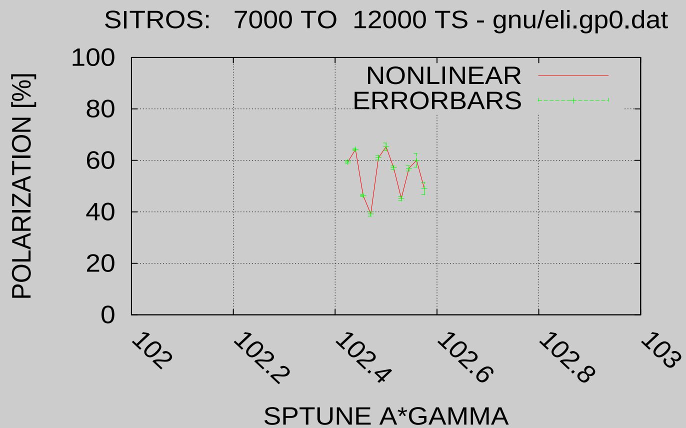
$B_+ = 2.6$ T



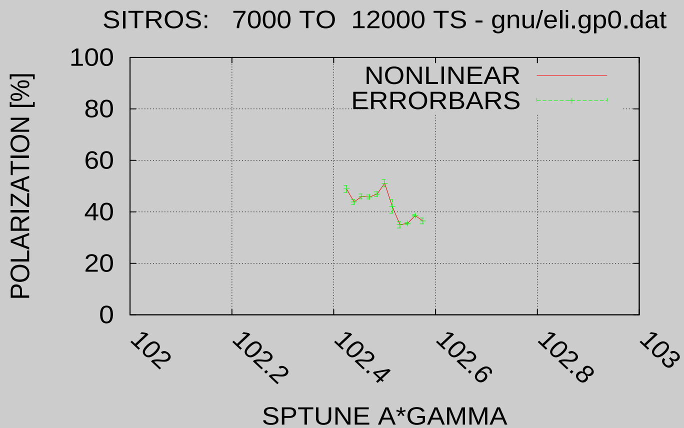
$B_+ = 3.9$ T

Increasing quadrupole vertical misalignments to something more realistic:

- δ_y^Q= 200 μm $\rightarrow$ y_{rms}= 15 mm, with B_+=3.9 T :
  - * orbit corrected down to y_{rms}= 0.04 mm with 1096 correctors (SVD)
    * $\delta\hat{n}_0$=0.3 mrad
  - * orbit corrected down to y_{rms}= 0.4 mm with 110 correctors (MICADO)
    * $\delta\hat{n}_0$=2.9 mrad reduced to 1.6 mrad by harmonic bumps



SVD

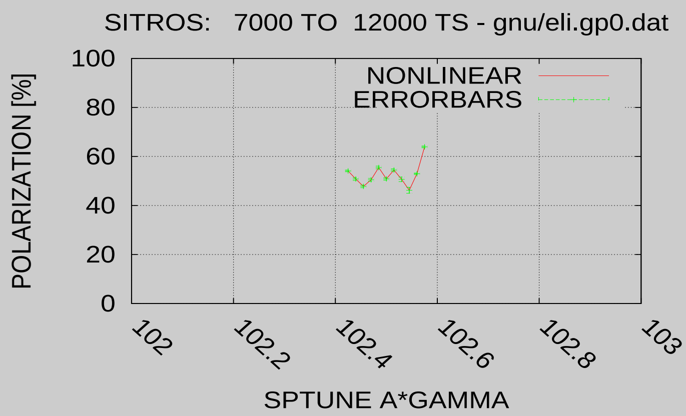


MICADO + harmonic bumps

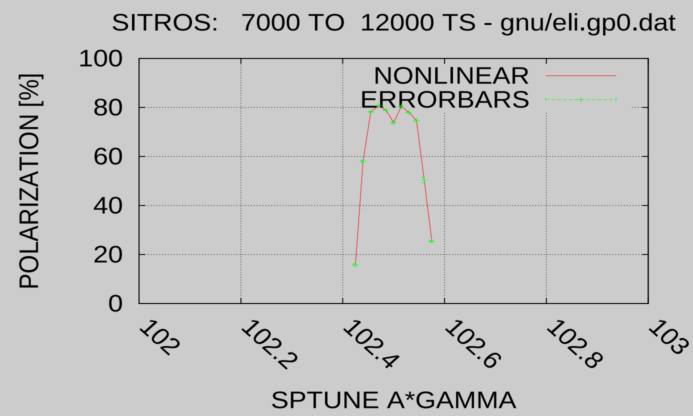
It is expected the strength of the sidebands to be proportional to the parent resonances through the factor

$$\xi = \left(\frac{a\gamma}{Q_s}\frac{\Delta E}{E}\right)^2$$

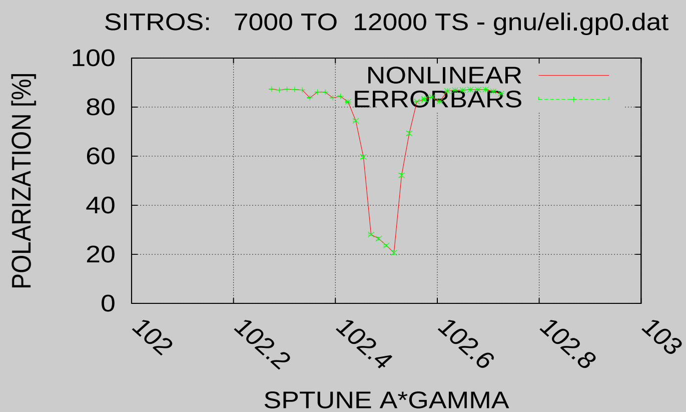
B_+=3.9 T , δ_y^Q= 200 μm, SVD correction



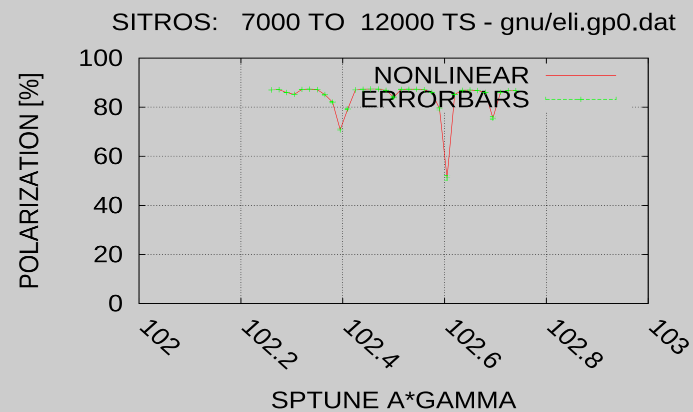
Q_s=0.08



Q_s=0.21



Q_s=0.48

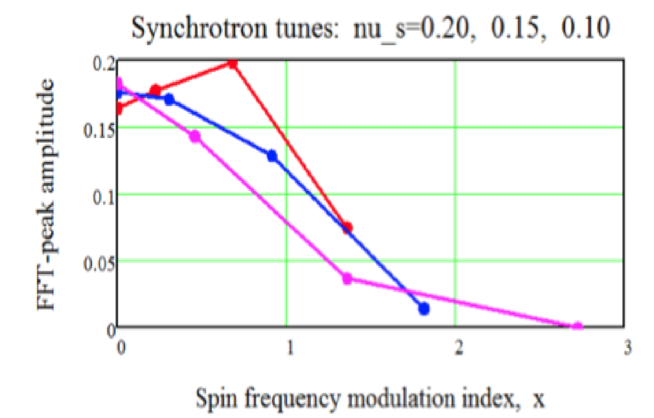


Q_s=0.80

Alternative Proposal[a]

Energy calibration

- Horizontally polarized beams are injected into the collider
  - Polarized e^- must be transported from source to collider
  - e^+ would get self-polarized in a low energy damping ring
    - Siberian Snakes needed in the pre-accelerators
  - Polarization brought into the horizontal plane prior to injection: spin rotators in the FCC transfer line
- Polarization is measured turn by turn right after injection by a longitudinal Compton polarimeter and ν_{spin} inferred from the polarization signal spectrum
- Signal decoherence depends on $\chi \equiv \sigma_e \nu_{spin} / Q_s$

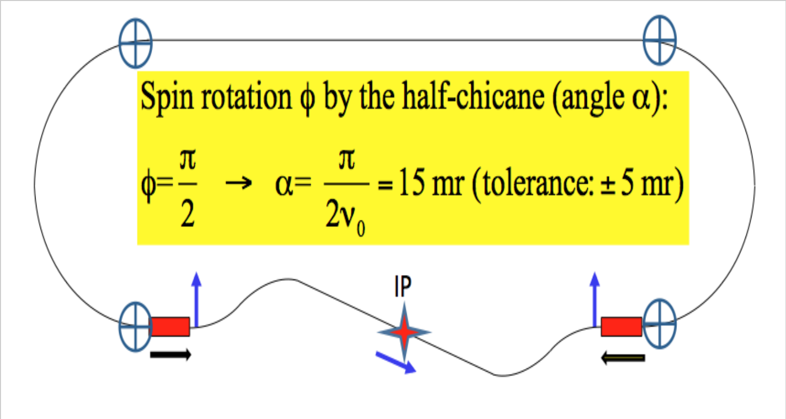


[a] from I. Koop HF2014 presentations

Longitudinal Polarization [a]

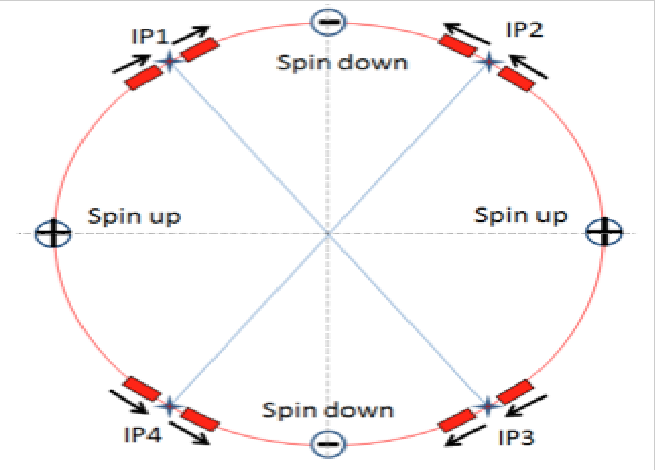
- Beams are vertically polarized prior to injection into the collider (see previous slide)

- Solenoid type spin rotators (solenoid + h-bend) bring $\hat{n}_0$ in the longitudinal direction at the IP



- It requires large solenoid integrated field: $\gamma\times$ 27 Gauss m for 90^0 rotation

- By arranging the polarity of the solenoids and assuming even number of IPs they act as Siberian Snakes



- Energy calibration is through resonant depolarization

[a] from I. Koop HF2014 presentations

Summary and outlook.

Studies for the 45 GeV case has been presented.

- The large bending radius inflates the polarization time at low energy.
- Wigglers may be designed for reducing the polarization time keeping a high asymptotic polarization level in *absence* of errors.
- In presence of errors, in particular the vertical misalignment of quadrupoles, depolarizing resonances appear. Synchrotron side-bands become more dangerous with increasing energy spread. Their importance can be quantified only by non-linear calculations, like in SITROS.
- The large energy spread introduced by the wigglers calls for well planned correction schemes.
- With a corrector + BPM close to each quadrupole scheme it seems that maintaining polarization for energy calibration is not a *mission impossible*! Most of the results presented here are for $\boldsymbol{B_+}$=3.9 T ($\boldsymbol{\tau_{pol}}$ =9').
  - Error on BPMs readings must be considered and the reach of beam-based alignments techniques simulated.

- Results need to be cross checked
  - Robustness wrt tracking parameters (number of particles and turns).
  - By using different codes.
- The effect of the synchrotron tune has been explored and analytical predictions seem confirmed.

End of the Episode

Thanks!

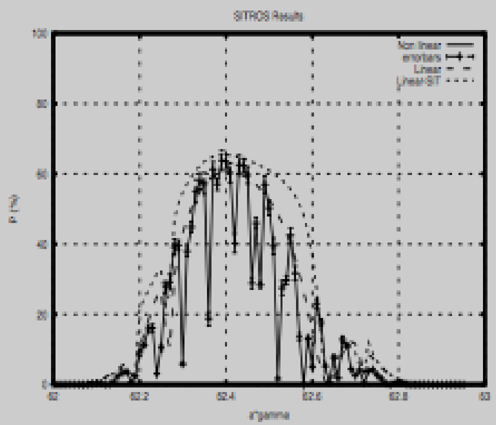
- Polarization first observed at ACO (Orsay) in 1968.
- The self polarization mechanism has been exploited at
  - HERA-e which provided *longitudinal* polarization for HERMES, H1 and ZEUS by using *spin rotators*.
  - LEP for energy calibration through RF resonant depolarization.

High level of polarization was obtained through

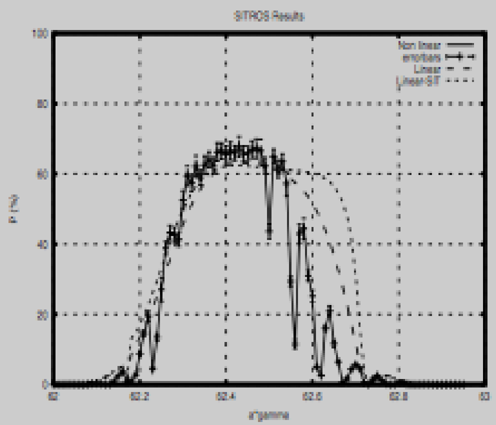
- Beam energy optimization: with ν_s half-integer the working point is halfway from all resonances.

HERA-e

- Small fractional part of orbital tunes



q_x=.2, q_y=.3, q_s=.05



q_x=.1, q_y.=2, q_s=.05

Setting the geometry

Assuming: B_{max}=16 T, E^p_{beam}=50 TeV and L_{tot}=100 Km

$$\rho_b = \frac{p}{e} B = 10423.6 \text{ m} \quad L_{bends} = 2\pi\rho_b = 65493.5 \text{ m} \quad \frac{L_{bends}}{L_{tot}} = 0.655$$

Maximum dispersion (FODO):

$$\hat{D} = \frac{L_{cell}\phi_b}{2} \frac{1 + 0.5 \sin \mu/2}{\sin^2 \mu/2} \qquad 2\phi_b \equiv \text{cell bending angle}$$

ϕ_b and thus ℓ_b [a] should be large for avoiding too small dispersion (chromaticity correction!)

Attempt: ℓ_b=30 m $\phi_b = \ell_b/\rho_b$=0.00287808 rad and $\mu = 60^o$

Number of cells:

$$n_{cells} = \frac{2\pi}{2\phi_b} \simeq 1090$$

[a] $L_{cell} = 0.655 L_{bends}/2\pi/\phi_b$