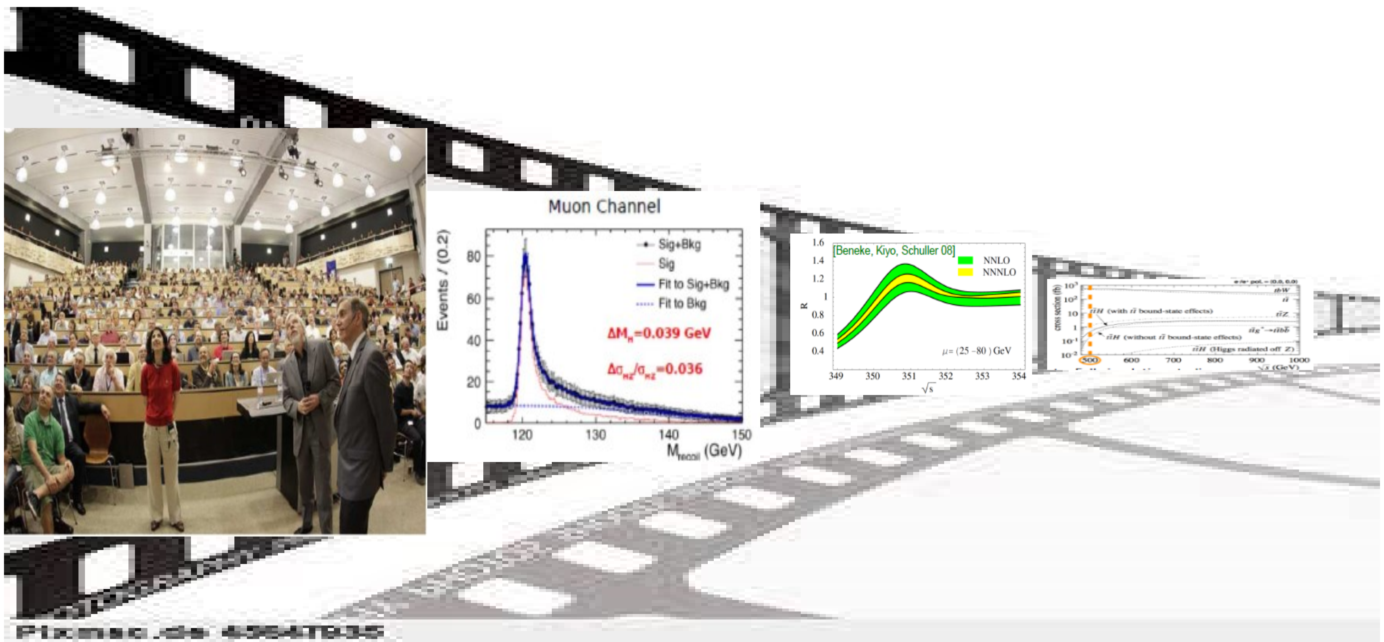
Spin treatment at the ILC: overview, status, needs and open questions

G. Moortgat-Pick
(Uni Hamburg/DESY)



LINEAR COLLIDER COLLABORATION

World-wide Event

- **On June 12th,2013, ILC TDR was published in Worldwide Event.**

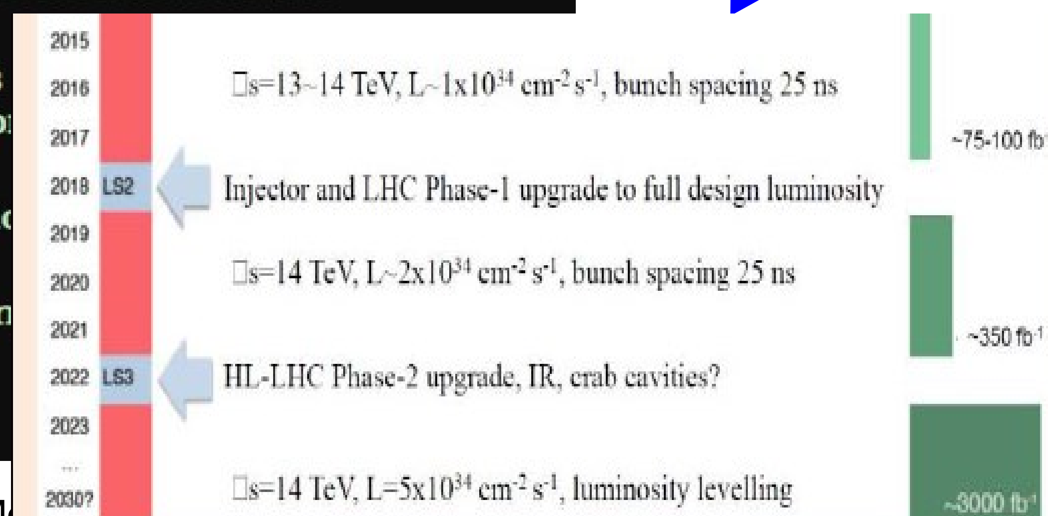
- **End of major phase in ILC development – now what?**

Very encouraging politics!

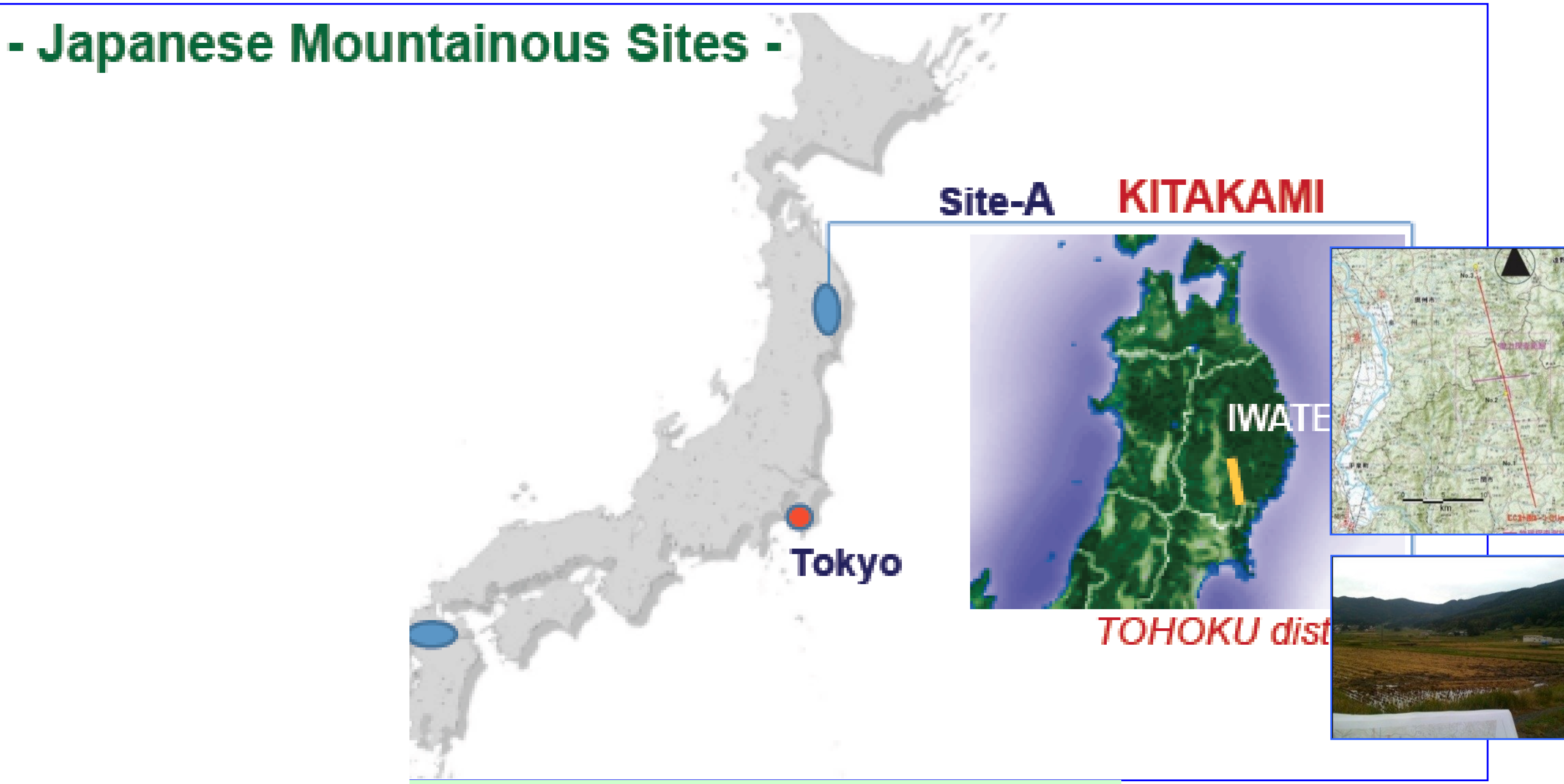
Possible Timeline

- July 2013
  - Non-political evaluation of 2 Japanese candidate sites complete, followed by down-selecting to one
- End 2013
  - Japanese government announces its intent to bid
- 2013~2015
  - Inter-governmental negotiations
  - Completion of R&Ds, preparatio
- ~2015
  - Inputs from LHC@14TeV, decisi
- 2015~16
  - Construction begins (incl. biddin
- 2026~27
  - Commissioning

LHC timeline



Japanese Site for ILC



- LCC Directorate official site visit Oct. 2013.

Brock Snowmass Summary

ILC, up to 500 GeV

1. **Tagged Higgs study in e+e–> Zh: model-independent BR and Higgs Γ, direct study of invisible & exotic Higgs decays**
2. **Model-independent Higgs couplings with % accuracy, great statistical & systematic sensitivity to theories.**
3. Higgs CP studies in fermionic channels (e.g., tau tau)
4. **Giga-Z program for EW precision, W mass to 4 MeV and beyond.**
5. Improvement of triple VB couplings by a factor 10, to accuracy below expectations for Higgs sector resonances.
6. Theoretically and experimentally precise top quark mass to 100 MeV.
7. **Sub-% measurement of top couplings to gamma & Z, accuracy well below expectations in models of composite top and Higgs**
8. Search for rare top couplings in e+e- -> t cbar, t ubar.
9. Improvement of α_S from Giga-Z
10. No-footnotes search capability for new particles in LHC blind spots -- Higgsino, stealth stop, compressed spectra, WIMP dark matter

Higgs EW Top QCD NP/flavor

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Brock Snowmass Summary

ILC 1 TeV

1. Precision Higgs coupling to top, 2% accuracy
2. **Higgs self-coupling, 13% accuracy**
3. Model-independent search for extended Higgs states to 500 GeV.
4. Improvement in precision of triple gauge boson couplings by a factor 4 over 500 GeV results.
5. **Model-independent search for new particles with coupling to gamma or Z to 500 GeV**
6. Search for Z' using e+e- -> f fbar to ~ 5 TeV, a reach comparable to LHC for similar models. Multiple observables for Z' diagnostics.
7. **Any discovery of new particles dictates a lepton collider program:**

   search for EW partners, 1% precision mass measurement, the complete decay profile, model-independent measurement of cross sections, BRs and couplings with polarization observables, search for flavor and CP-violating interactions

Higgs EW Top QCD NP/flavor

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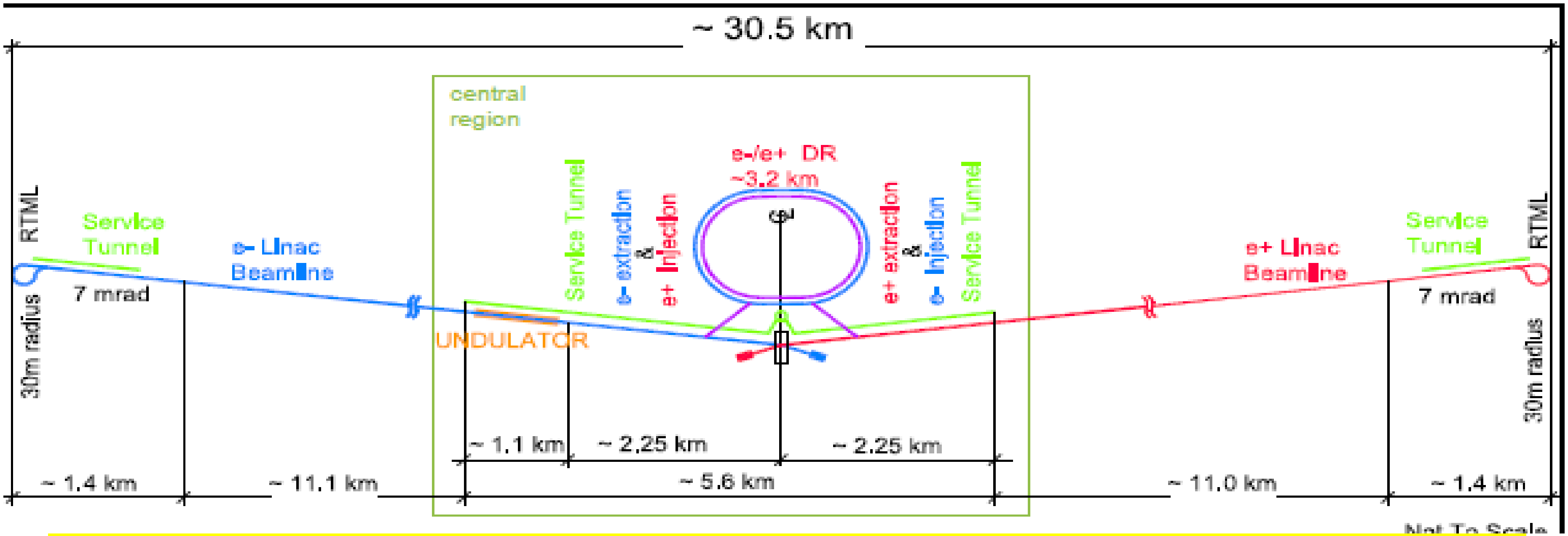
The LC physics offer and challenges

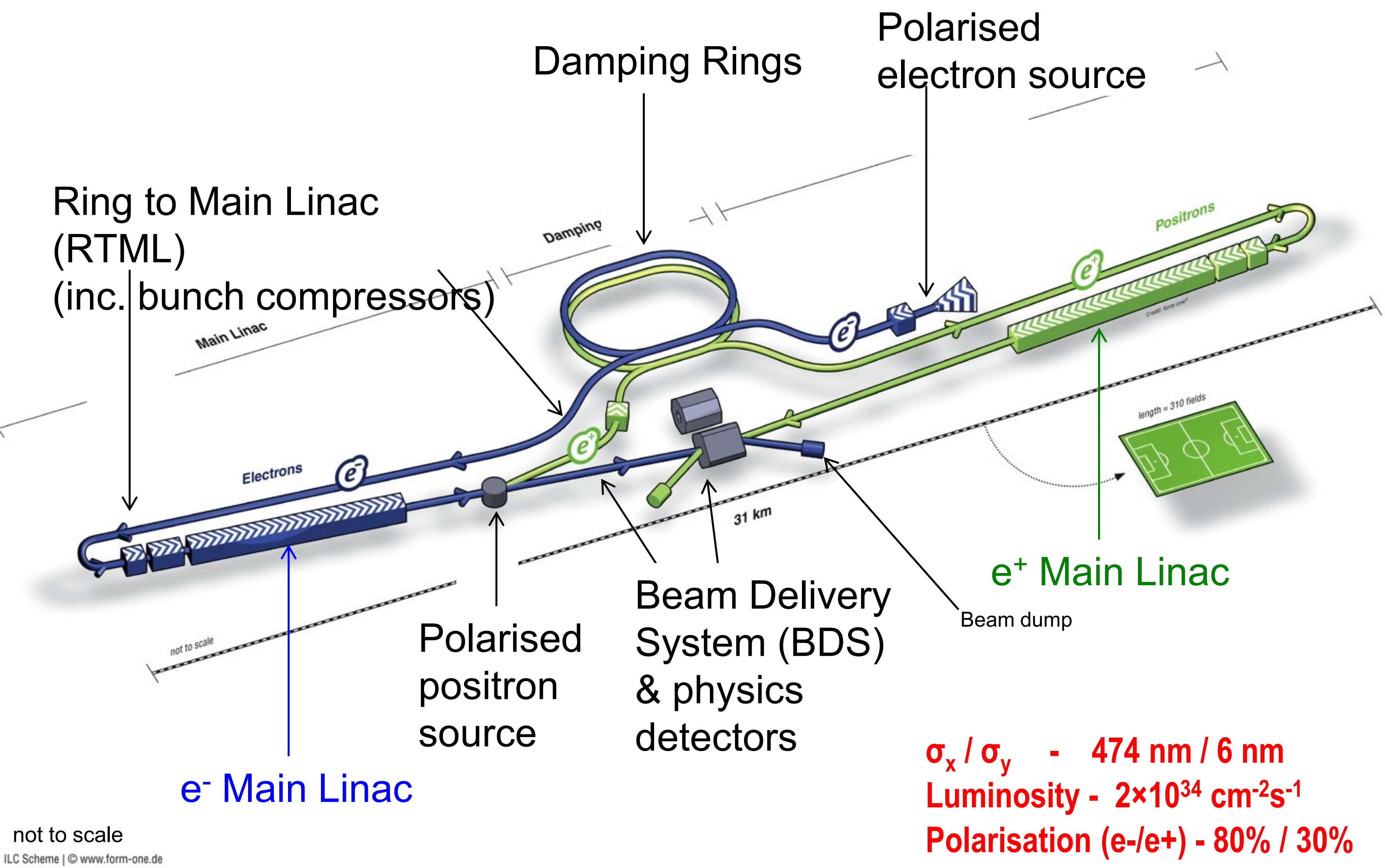
- Staged energy approach:
  - $\sqrt{s}$~240 GeV, `Higgs frontier‘
  - $\sqrt{s}$~350 GeV, `Top threshold‘
  - $\sqrt{s}$~500 GeV, `Top Yukawa‘
  - ($\sqrt{s}$=91 GeV, `EW Precision frontier‘)
  - $\sqrt{s}$~1000 GeV, `Higgs potential‘
- Polarized beams and threshold scans:
  - impact on ‘quality’ (and quantity)
  - Something ‘new’ comp. to LHC analyses
- Highest precision: precise spin treatment required

ILC Machine Lay-out



- **About 30 km in first stage √s=500 GeV, crossing angle 2x7 mrad**
- **High luminosity: $2x10^{34}cm^{-2}s^{-1}$**
- **Running time: 75% per year**
- **Beams: $2x10^{10}$/bunch, 1312 bunch/pulse, 5 Hz rep. rate for √s=350 and 500 GeV**

ILC Machine Overview



σ_x / σ_y - 474 nm / 6 nm

Luminosity - 2×10^{34} cm^{-2}s^{-1}

Polarisation (e-/e+) - 80% / 30%

ILC Parameters

Centre-of-mass energy	E_{CM}	GeV	200	230	250	350	500
Luminosity pulse repetition rate		Hz	5	5	5	5	5
Positron production mode			10 Hz	10 Hz	10 Hz	nom.	nom.
Estimated AC power	P_{AC}	MW	114	119	122	121	163
Bunch population	N	$\times 10^{10}$	2	2	2	2	2
Number of bunches	n_b		1312	1312	1312	1312	1312
Linac bunch interval	Δt_b	ns	554	554	554	554	554
RMS bunch length	σ_z	μm	300	300	300	300	300
Normalized horizontal emittance at IP	$\gamma\epsilon_x$	μm	10	10	10	10	10
Normalized vertical emittance at IP	$\gamma\epsilon_y$	nm	35	35	35	35	35
Horizontal beta function at IP	β_x^*	mm	16	14	13	16	11
Vertical beta function at IP	β_y^*	mm	0.34	0.38	0.41	0.34	0.48
RMS horizontal beam size at IP	σ_x^*	nm	904	789	729	684	474
RMS vertical beam size at IP	σ_y^*	nm	7.8	7.7	7.7	5.9	5.9
Vertical disruption parameter	D_y		24.3	24.5	24.5	24.3	24.6
Fractional RMS energy loss to beamstrahlung	δ_{BS}	%	0.65	0.83	0.97	1.9	4.5
Luminosity	L	$\times 10^{34}$ cm^{-2}s^{-1}	0.56	0.67	0.75	1.0	1.8
Fraction of L in top 1% E_{CM}	$L_{0.01}$	%	91	89	87	77	58
Electron polarisation	P_-	%	80	80	80	80	80
Positron polarisation	P_+	%	30	30	30	30	30
Electron relative energy spread at IP	$\Delta p/p$	%	0.20	0.19	0.19	0.16	0.13
Positron relative energy spread at IP	$\Delta p/p$	%	0.19	0.17	0.15	0.10	0.07

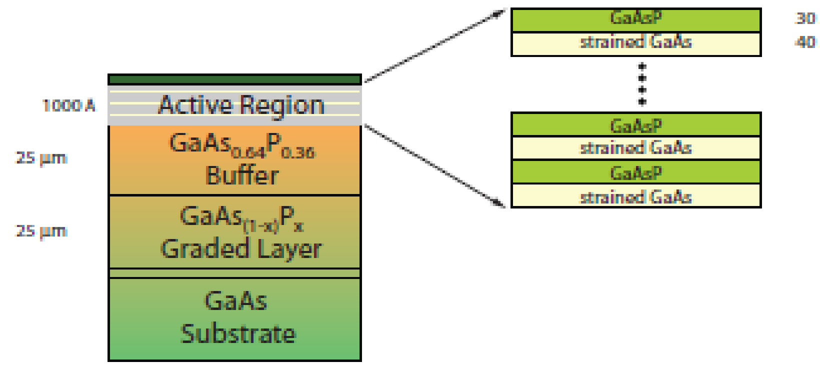
Scope requirements: ICFA LC Parameter

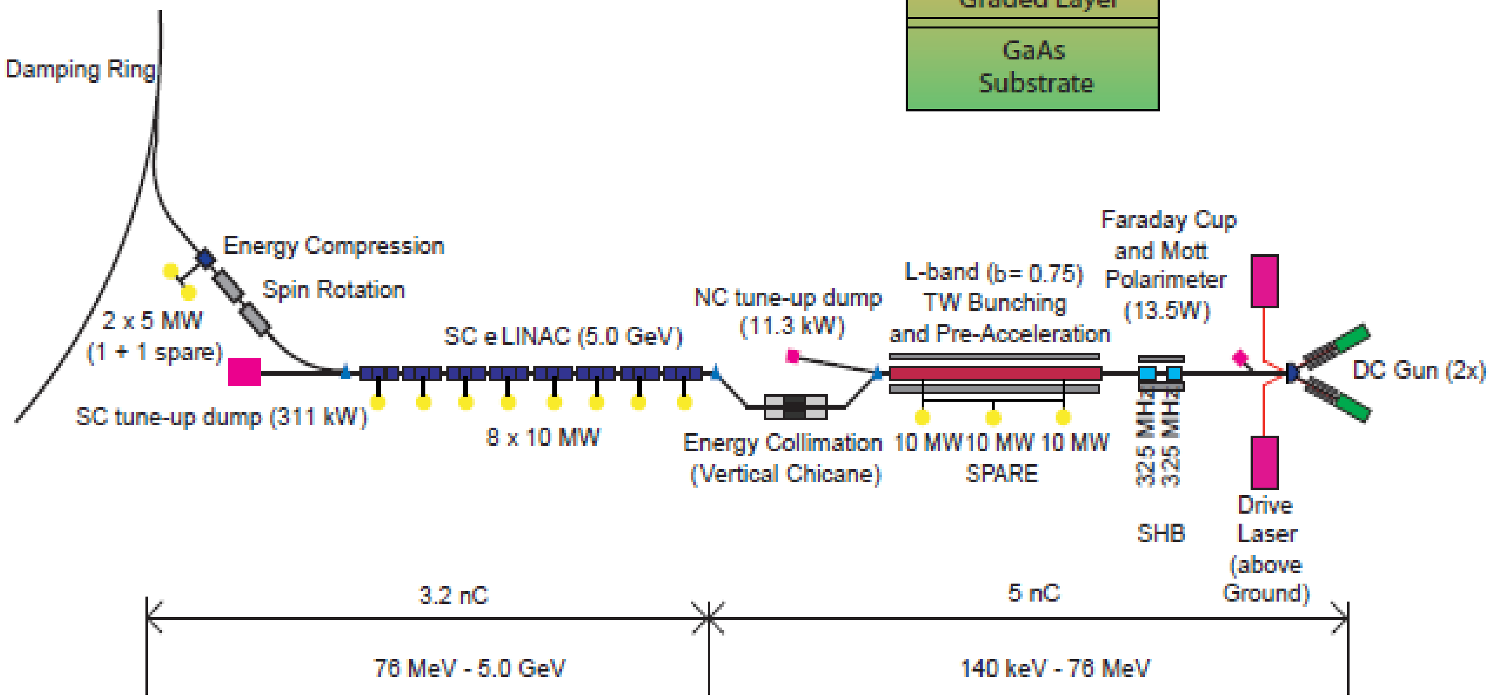
- **'Scope Document no.1' (2003) and 'no.2' (2006): baseline**
  - **Full luminosity of $2x10^{34}cm^{-2}s^{-1}$**
  - **Beam energy stability and precision below tenth of percent level**
  - **Machine interface must allow measurements of beam energy and differential luminosity spectrum with similar accuracy**
  - **Electron beams with polarization of at least 80% within whole energy range**
- **Options:**
  - **e+ polarization ~50% in whole energy range**
  - **GigaZ= high lumi run at the Z-pole/WW threshold: energy stability and calibration accuracy below tenth of percent level**

Exploitation of polarization needs particular treatment

Electron polarization

- **Similar as SLC e- source: but now for long trains and high RF power**
  - DC gun: e- with 200keV
  - Laser: λ=790nm , based on TiSapph,
  - cw. Nd:Yag laser provides power

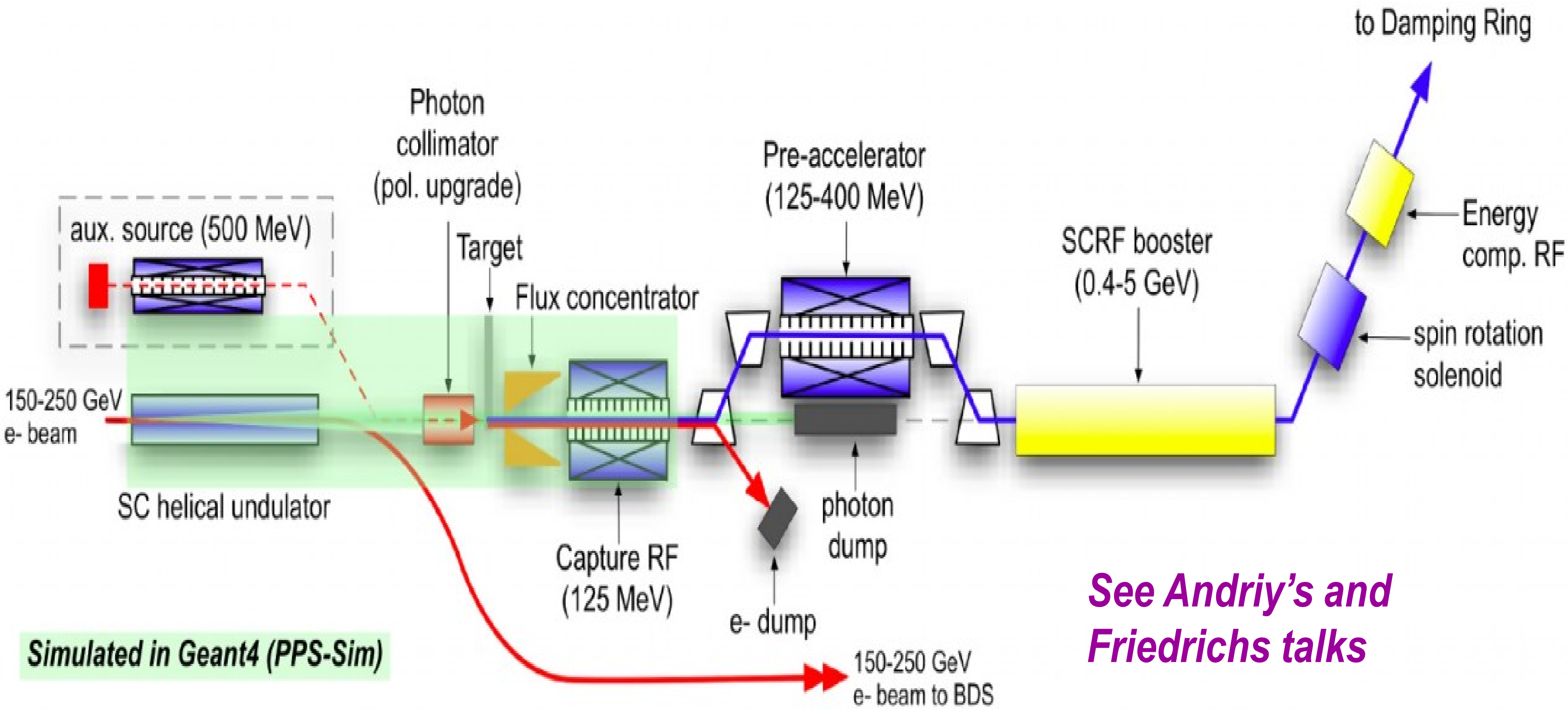




Positron source

- Choice: e+ via radiation from a helical undulator (because of higher yield, less rad. level, better DR accept., less target stress)

(Target processes: Olufemi Adeyemi)



See Andriy's and Friedrichs talks

Polarization:Technical facts I

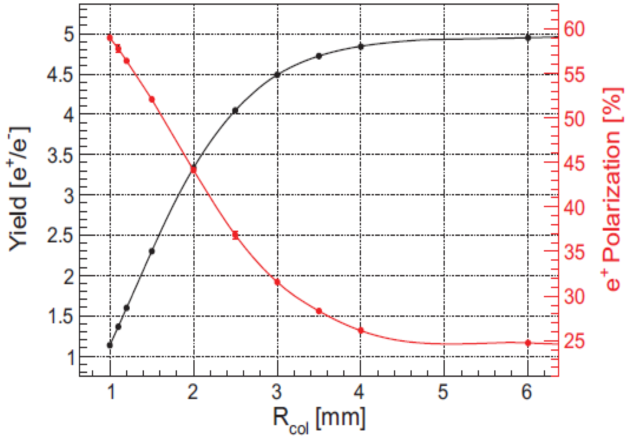
- P(e-) ~ 80-90%
- P(e+) (always yield ≥1.5 imposed):

Andriy Ushakov,

$\sqrt{s}$=240 GeV: 120 GeV e- drive beam

- Undulator with 231 m (K=0.92, λ=11.5 mm), collimator r=3.5 mm
- P(e+)~ 40%

Eb=175 GeV



$\sqrt{s}$=350GeV: 175 GeV e- drive beam

- Collimator with r=1.2 mm
- P(e+)~ 56%

$\sqrt{s}$=500GeV: 250 GeV e- drive beam

- Undulator with 144 m, collimator r=0.7mm
- P(e+)~59%

Technical facts II

- **P(e+) (always yield ≥1.5 imposed):**

  $\sqrt{s}$=1 TeV: 500 GeV e- drive beam

  - **Undulator with 176 m (K=2.5), collimator r=0.9mm**
  - **P(e+)~54%**

- **Measurent of polarization:**

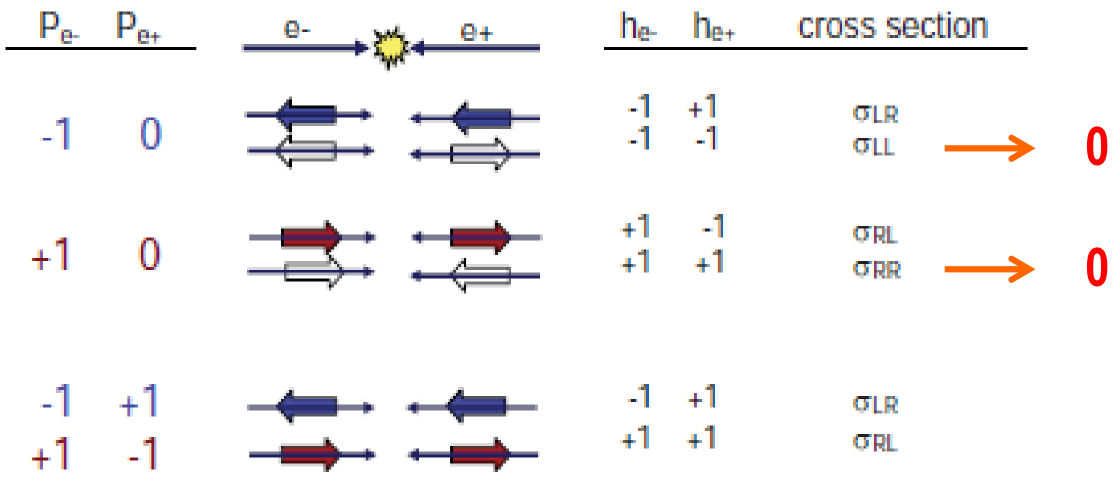
  See Annika's talk

  - **Compton polarimetry (up- and down-stream): δP/P=0.25%**
  - **Via WW-process (lumi-weighted!): δP/P(e-)~0.1%,**

    δP/P(e+)~0.2-0.3%

Spin sensitive components

- Spin rotator before / after damping rings
- (Fast) helicity flipping of the e+ required: *see Sabine's talk*



  – Apply kicker at the damping system

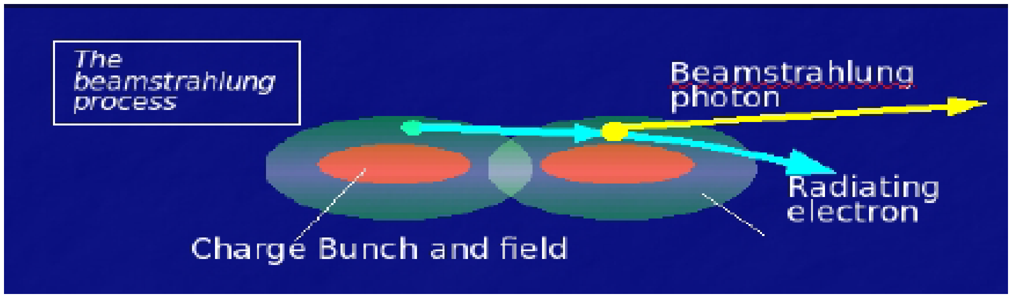
- Polarization measurement (polarimetry, lumi-weigthed)

see Moritz and Annika's talks

- QED processes at beam-beam interaction *see Tony's talk*

Beam-beam: strong fields in IR

Tony Hartin



$$\Upsilon = \frac{e|\vec{a}|}{mE_{cr}}(k \cdot p)$$

$$\Upsilon \approx \frac{5}{6}\frac{N r_e^2 \gamma}{\alpha \sigma_z(\sigma_x + \sigma_y)}$$

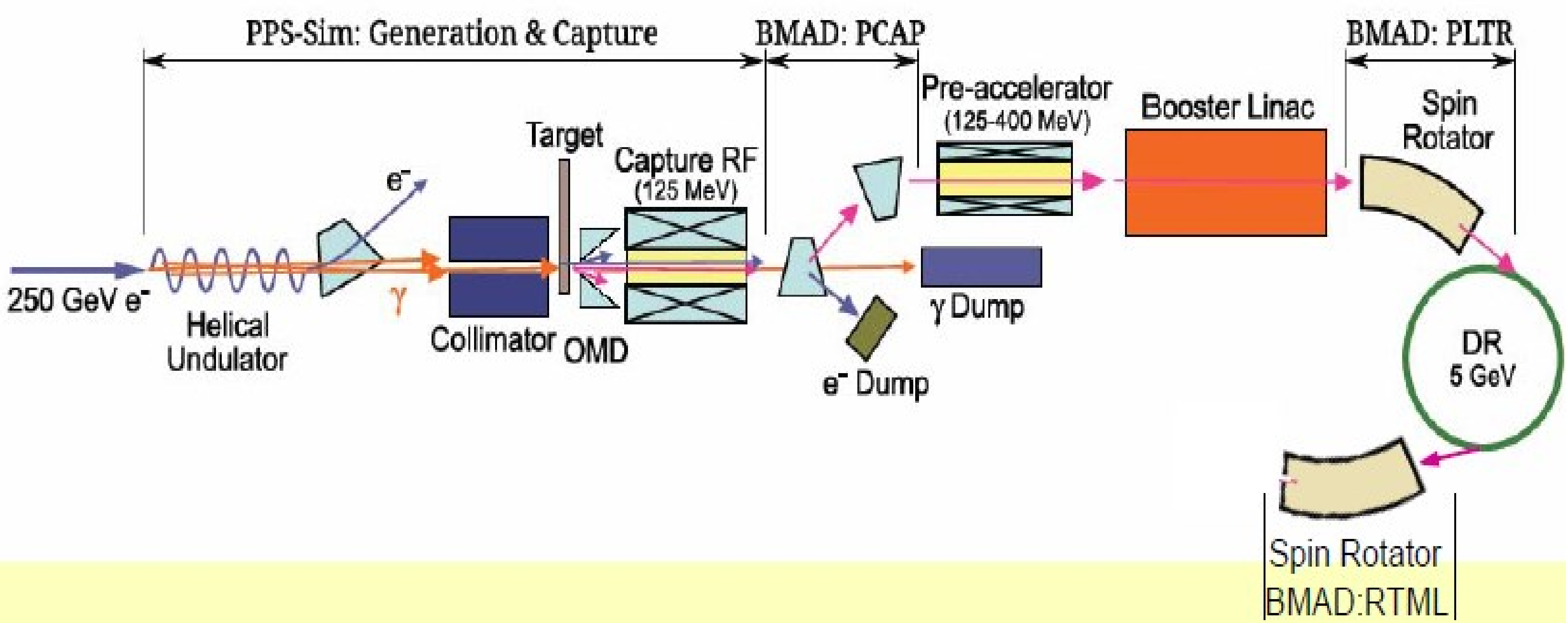
$\Upsilon > 0.1$ strong field regime

- Υ depends on collider bunch parameters and the pinch effect
- Future linear colliders will have "strong" IP fields
- For polarised particles, beamstrahlung entails "spin-flip"

Machine	LEP2	SLC	ILC	CLIC
E (GeV)	94.5	46.6	500	1500
$N(\times 10^{10})$	334	4	1.74	0.37
σ_x, σ_y (μm)	190, 3	2.1, 0.9	0.335, 0.0027	0.045, 0.001
σ_z (mm)	20	1.1	0.225	0.044
Υ_{av}	0.00015	0.001	0.2	4.9

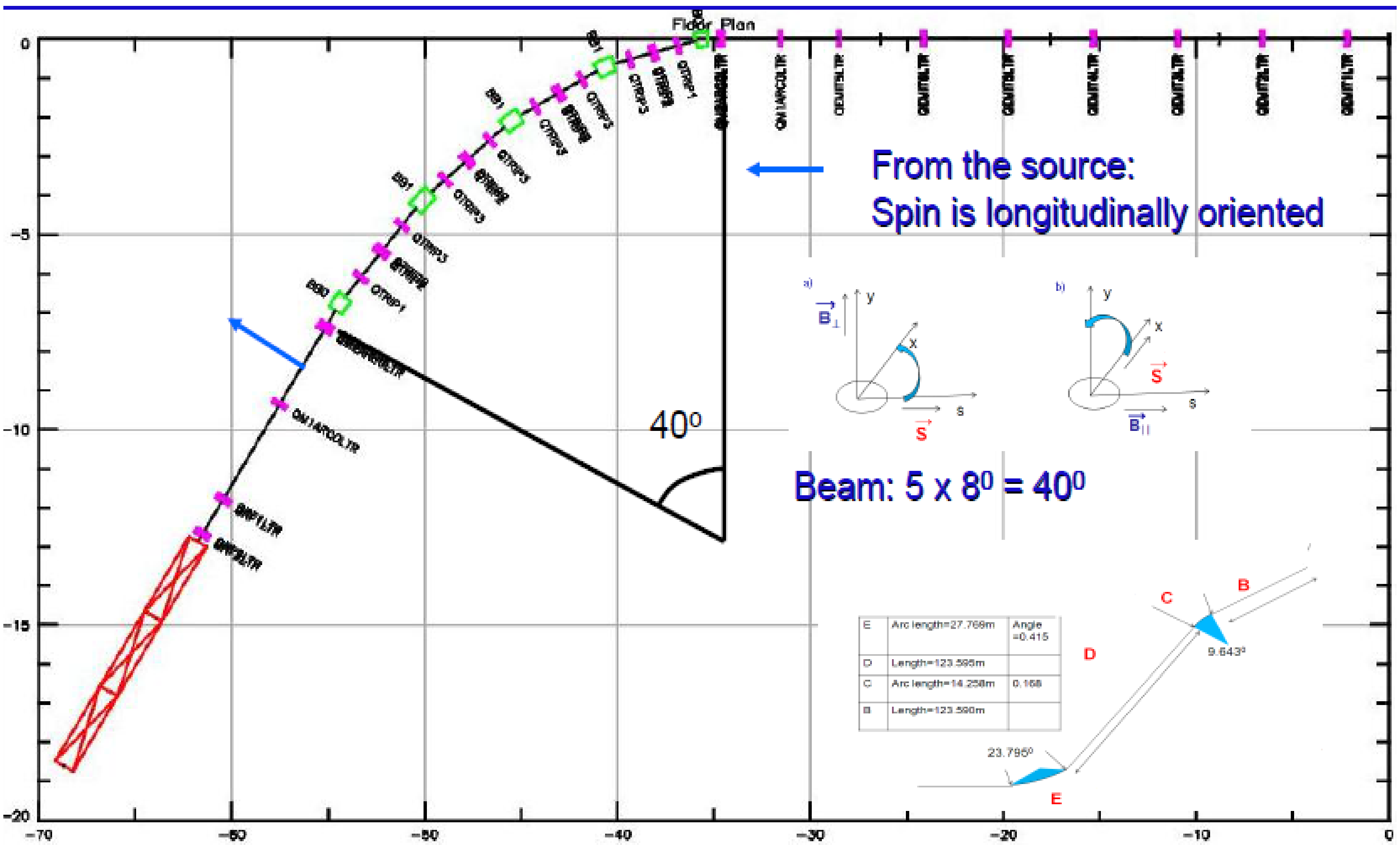
Spin Rotator System

Valentyn Kovalenko



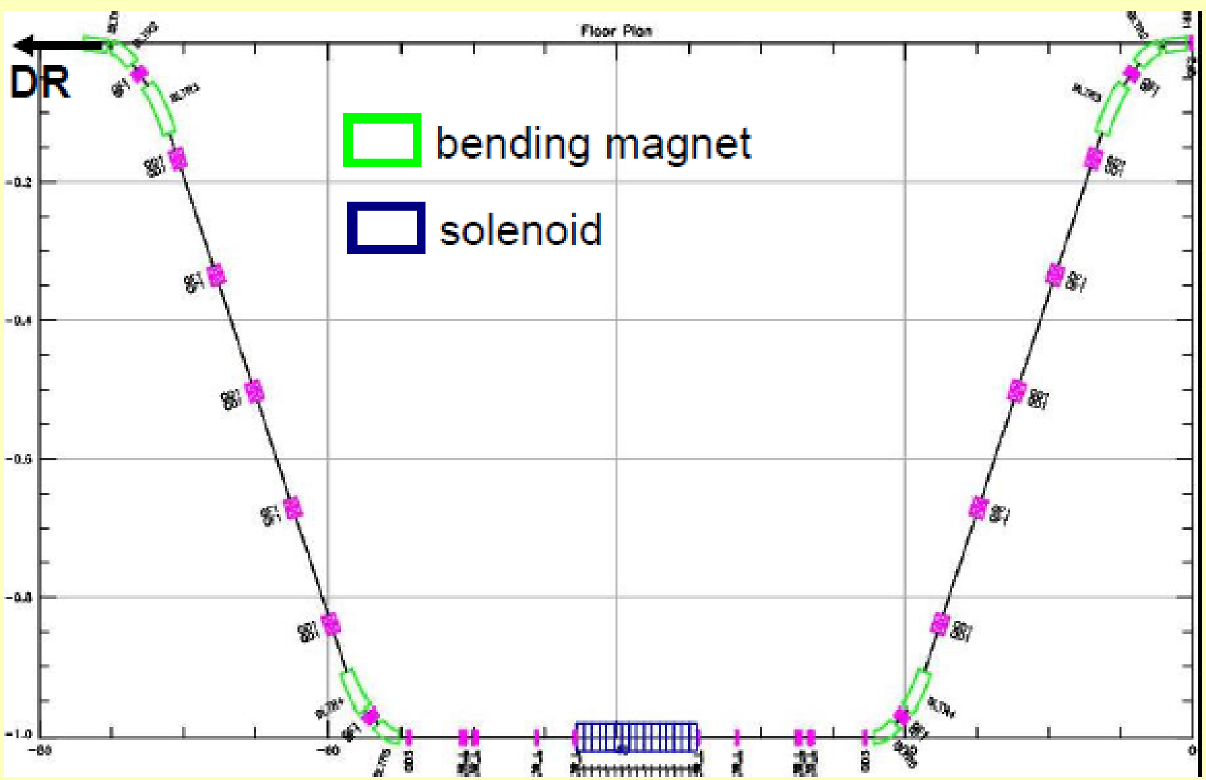
- The longitudinally polarized positron beam has to be rotated:
  - into ***vertical*** direction ***before*** the ***DR***.
  - ***after*** the ***DR*** into ***longitudinal*** direction.
- Spin tracking has to be included in all transport elements that are expected to contribute to a loss of polarization.

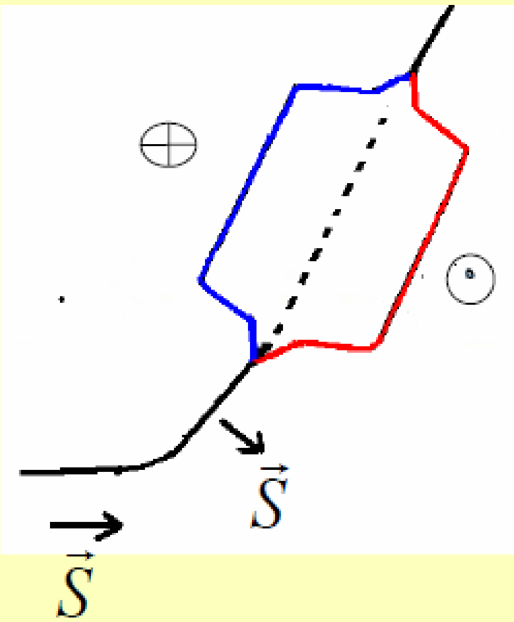
Positron Linac to Ring Beamline



Lattice Spin Flipper

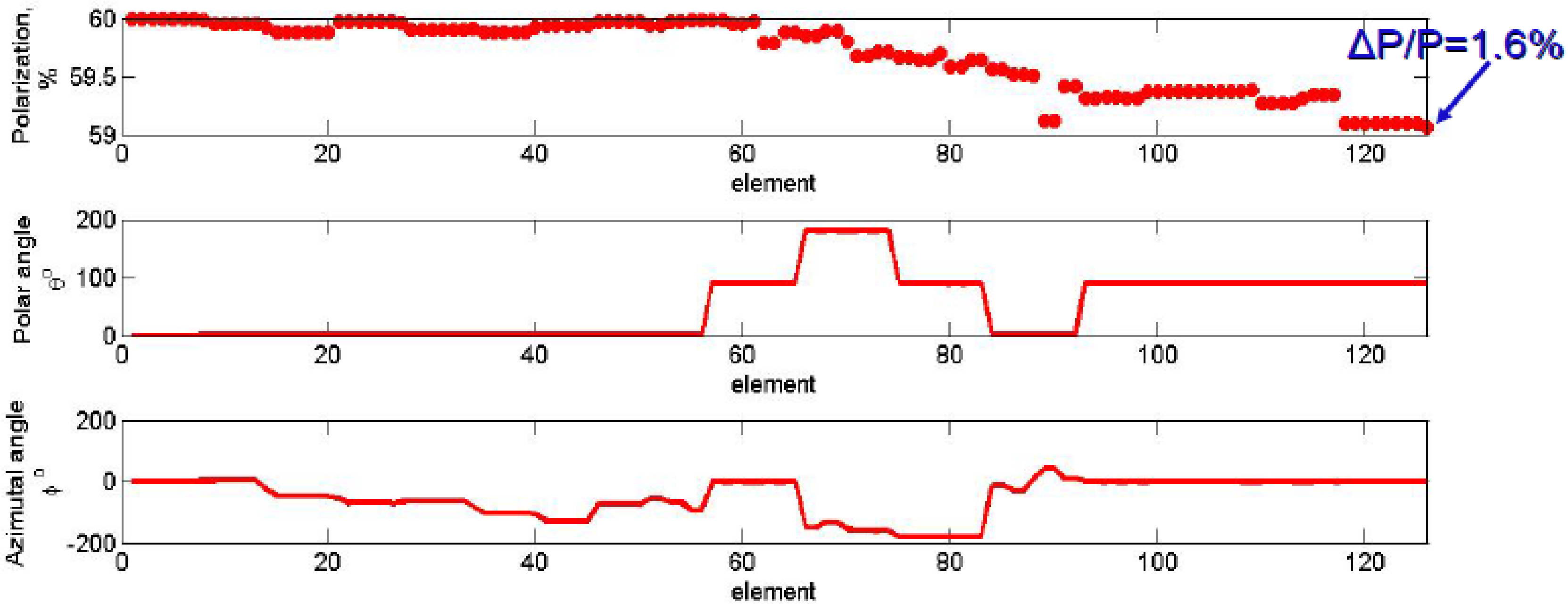
Larisa Malysheva





- Total length <80m.
- ***First cell*** is irregular FODO cell which should include ***fast kicker***.
- At the parallel section the branch separation is about 2 m.

BMAD: Spin Tracking in PLTR (up to spin flipper)



Initial energy spread ΔE/E=3.5%

$\varepsilon_{nx} = \varepsilon_{ny}$ = 0.05 rad m

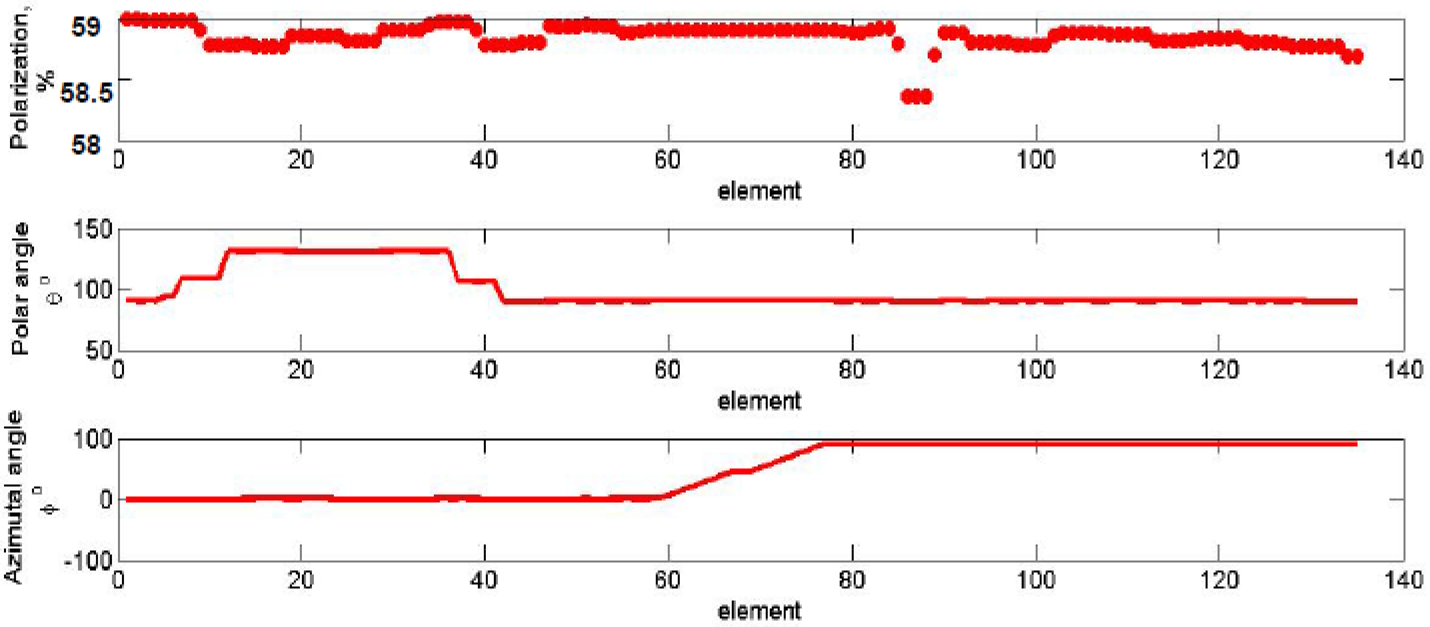
$\varepsilon_{nx} = \varepsilon_{ny}$ = 0.05 rad m

In the beginning positron beam is longitudinally polarized:

Polar angle $\theta = 0^0 \rightarrow 90^0$

Azimutal angle $\varphi = 0^0 \rightarrow 0^0$

Spin tracking: spin flipper



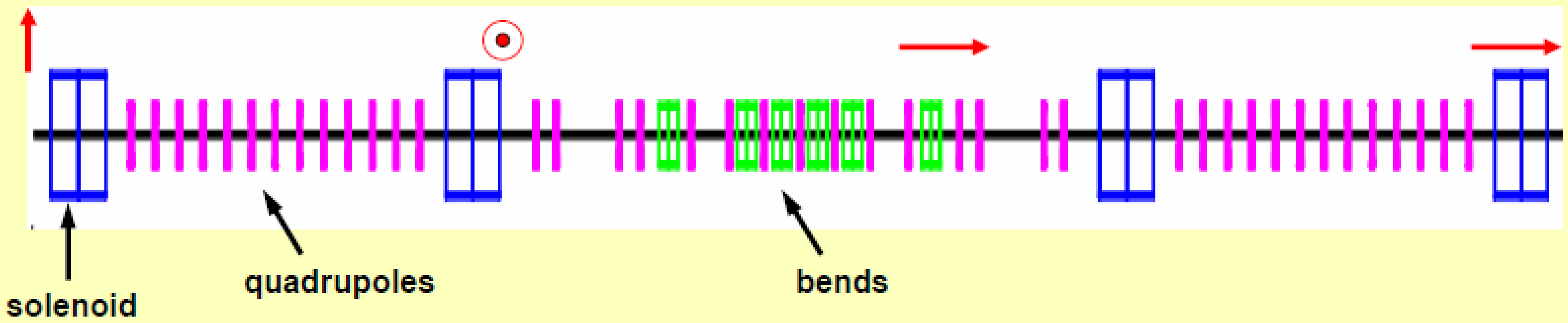
Relative depolarization is 1.7%

Positron beam has a vertical polarization at the end of beamline.

Polar angle $\theta = 90^0 \rightarrow 90^0$

Azimutal angle $\varphi = 0^0 \rightarrow 90^0$

Post DR Spin Rotator

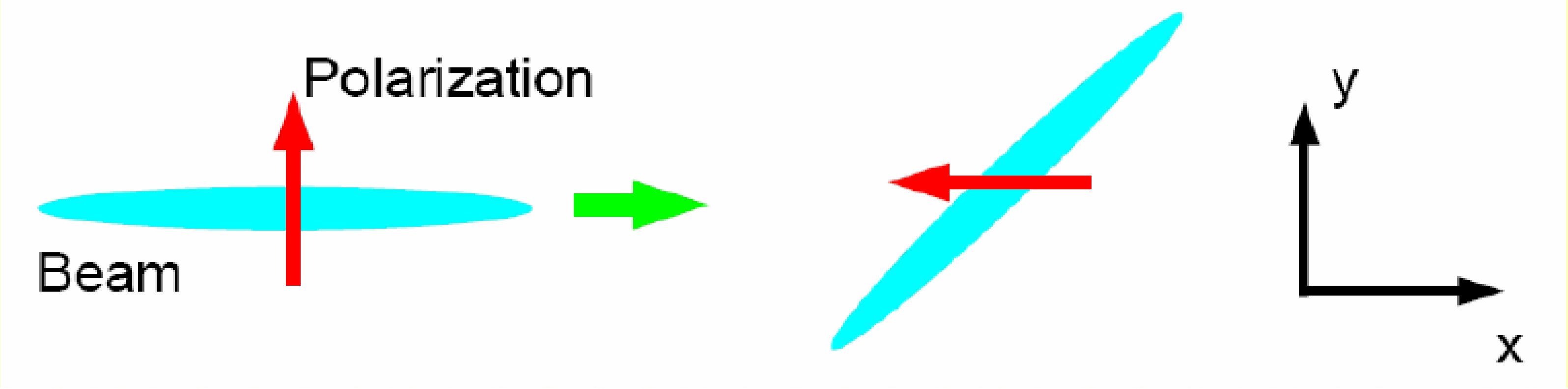


Spin rotator design requirements:

- spin rotator must preserve both vertical and horizontal emittance (dilution < 2%)
- emittance increase caused by synchrotron radiation should be negligible at 5 GeV beam energy
- the system must preserve the beam polarization
- the system should be short (≤100 m)

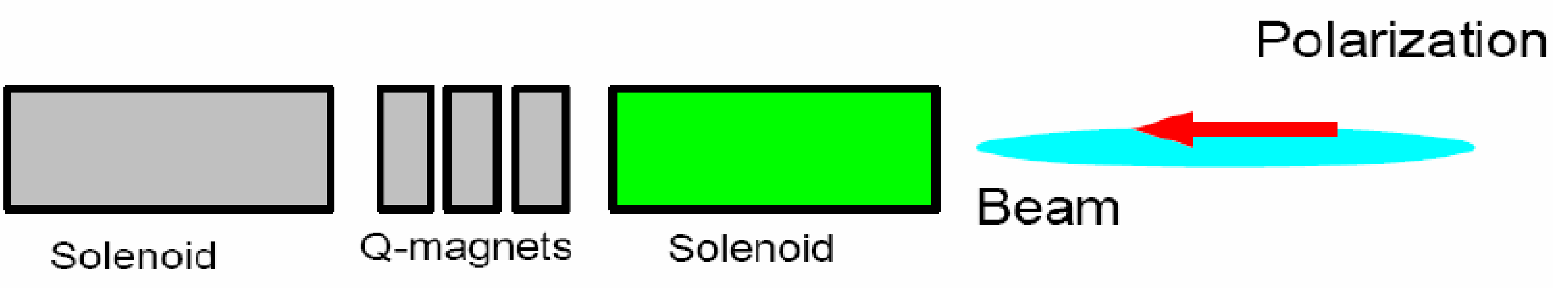
X-Y Coupling

- Solenoid field rotates not only the spin, but also transverse phase spaces
  - Solenoid increases the vertical emittance via the coupling between horizontal and vertical motion (x-y coupling)
  - If the spin must be rotated by 90 degrees then the orbit would roll by 45 degrees ⟶ this would be disastrous if the x-y coupling was not removed



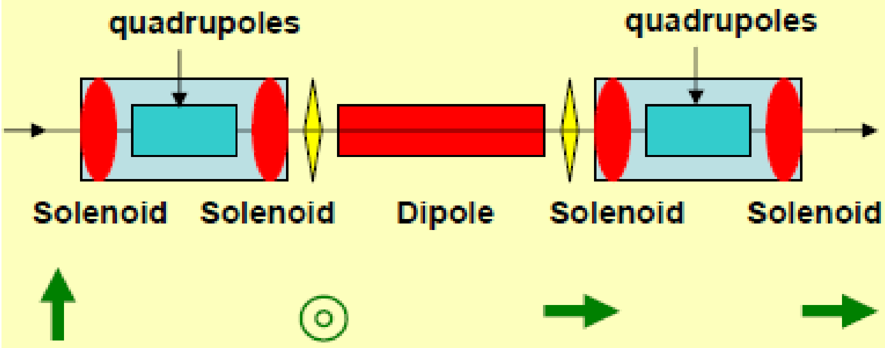
Emma Rotator: phase space

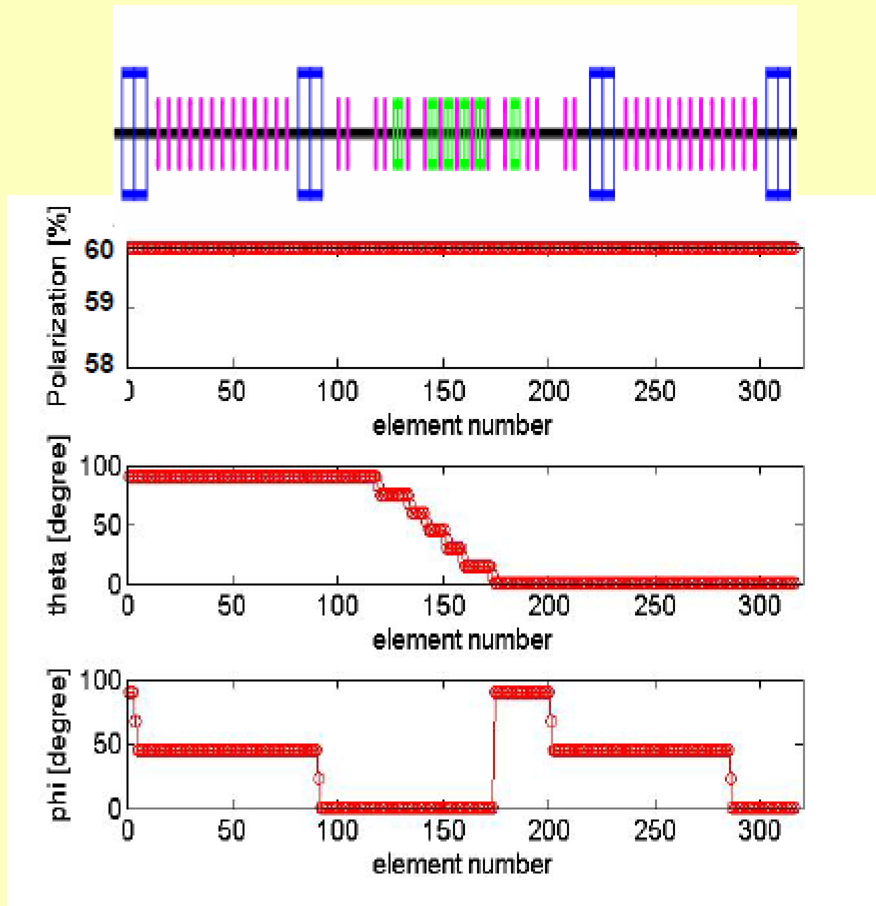
- Is it possible to rotate only the spin and do not roll the particle phase space? -> Yes, that is Emma rotator = Solenoid + Quadrupoles + Solenoid
- The first solenoid rotates the spin by half the desired total. At the same tine it also rotates the beam by a quarter the same amount.
- The center of the Emma Rotator is a FODO cell transfer line which reflects the beam about Y-axis.
- The second solenoid of equal strength to the first, will rotate the spin the rest of way as it rotates the beam back to the flat state. Rotation by the two solenoids are canceled out (no emittance growth)



Spin rotator and emittance preservation

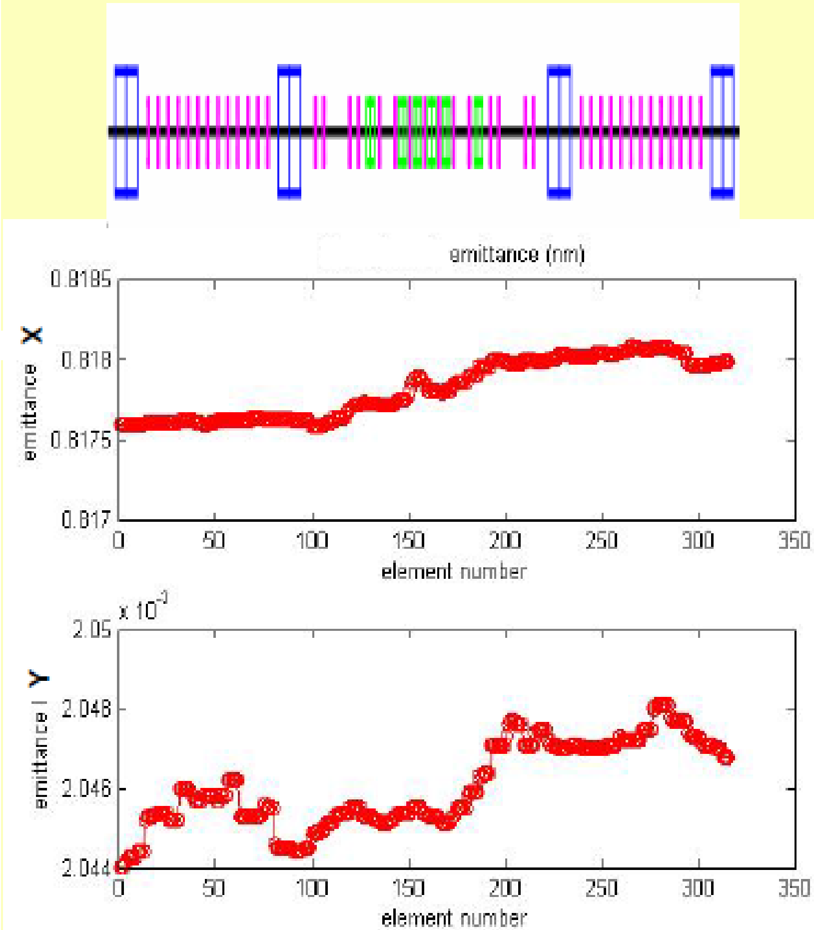
- Spin Rotator = Emma Rotator + Dipole Rotator + Emma Rotator
  - Emma rotator consists of two solenoid magnets and one reflector between them
- Any desirable spin orientation could be achieved





- Depolarization <0.1%

Emittance preservation



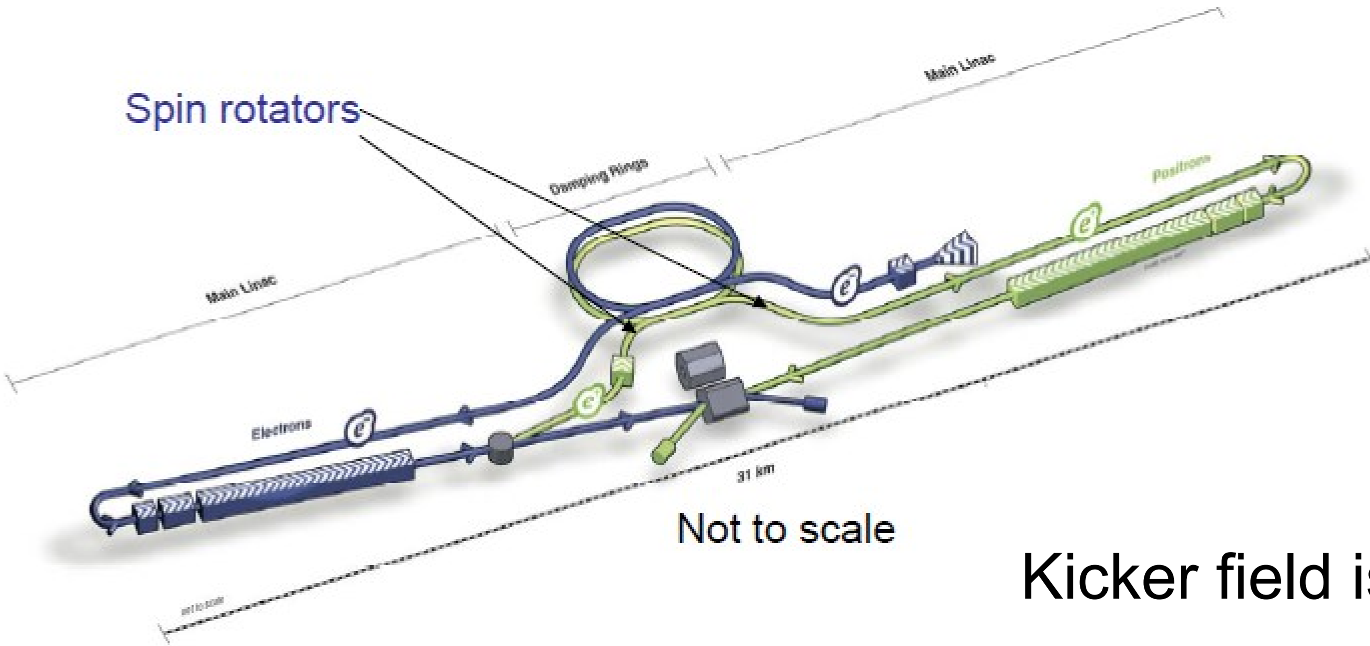
- Emittance dilution 0.3% and satisfy the spin rotator requirements

Resonant Depolarization

- **Unpolarized configuration highly desirable**
  - Get systematics under control, etc.
- **Helical undulator radiation: always polarized**
  - Question: if only medium/low polarization available
    possible to destroy polarization if no spin rotators are used before the DR?
  - No, since no complete decoherence! *See study of Barber/ Malysheva*
- **Proposal: use RF kickers to get resonant depolarization**
  - Study done by Valentyn Kovalenko within this BMBF project together with M. Vogt, A. Wolski
  - Simple spin model used so far, but looks promising

Resonant Depolarization

Valentyn Kovalenko



Use oscillating magnetic field (kicker)

Kicker field is ⊥ beam axis

- A resonance occurs when the rf magnetic field's frequency f_r is synchronized with the spin tune v_s and the circulation frequency f_c:

$$f_r = f_c(n \pm \nu_s)$$

When the kicker frequency is close to the resonant frequency, the kicks add up coherently, and the cumulative effect of the kicks is to tilt the spins strongly away from the vertical.

Analytical approach

Froissart and Stora (1960)

$$\frac{P_f}{P_i} = 2\exp\left\{\frac{-\pi|\varepsilon|^2}{2\alpha}\right\} - 1$$

$$\varepsilon = \frac{(1+G\gamma)\int B_\perp dl}{4\pi B_0 \rho_0}$$

is resonance strength of one rf dipole.

α is the rate of resonance crossing (crossing speed).
If the rf dipole tune is swept across an interval ΔQ in N turns, then $\alpha = \frac{\Delta Q}{2\pi N}$

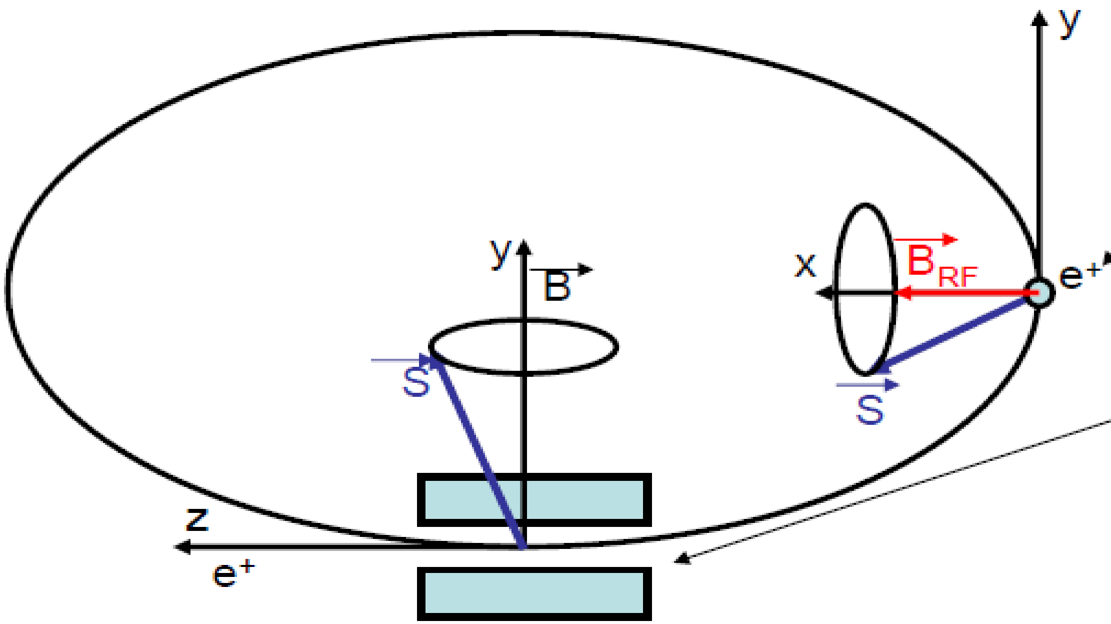
Three distinct conditions for the variation rate crossing ΔQ are:

Rate	Polarization	Effect
Fast crossing	$P_f = P_i$	No depolarization
Medium crossing	$P_i > P_f > -P_i$	Partial depolarization
Slow crossing	$P_f = -P_i$	Spin-flip

Used (simple) spin model

- The model consists of an RF dipole followed by continuous bending magnet.

- Spin behaviour of bunch of particles is described by applying rotation matrices at each revolution turn.



RF Dipole

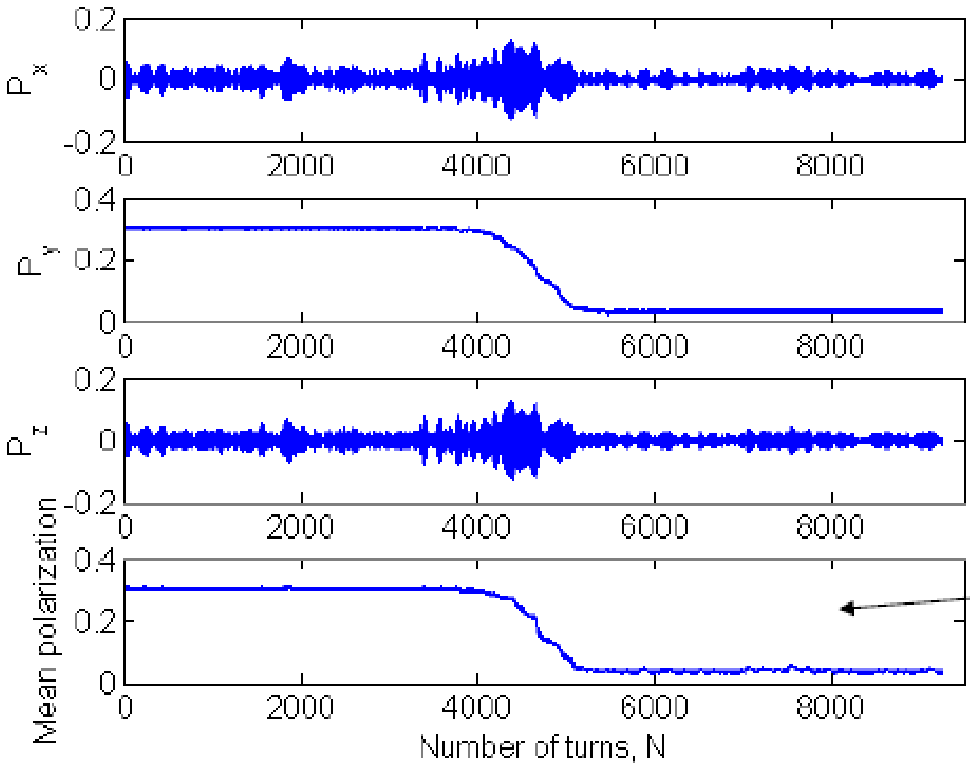
$$R_x(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix}$$

Dipole Magnet

$$R_y(\theta) = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix}$$

Principal feature

- Initial polarization (vertical): 30%
- Spin tune Gγ=11.35
- Revolution frequency=92.5 kHz
- Resonance frequency=60.17 kHz
- Number of turns=9256



Integrated field of rf dipole:

$$\int B_\perp dl = 0.01\ T\cdot m$$

Energy spread: 0.5%

Resonance strength:

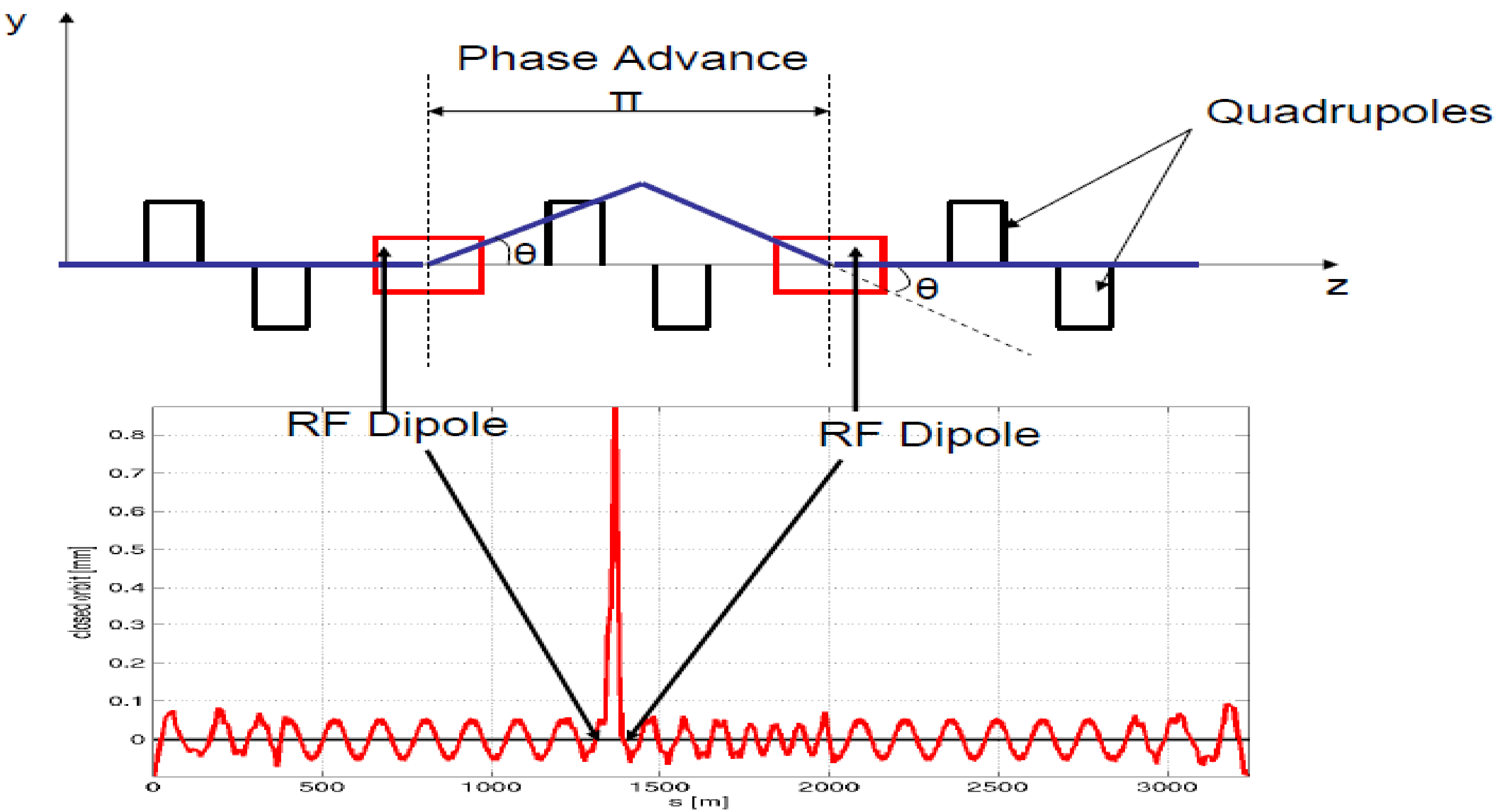
$$\varepsilon = \frac{(1+G\gamma)\int B_\perp dl}{4\pi B_0 \rho_0} =$$

$$= 8.8\cdot 10^{-4}$$

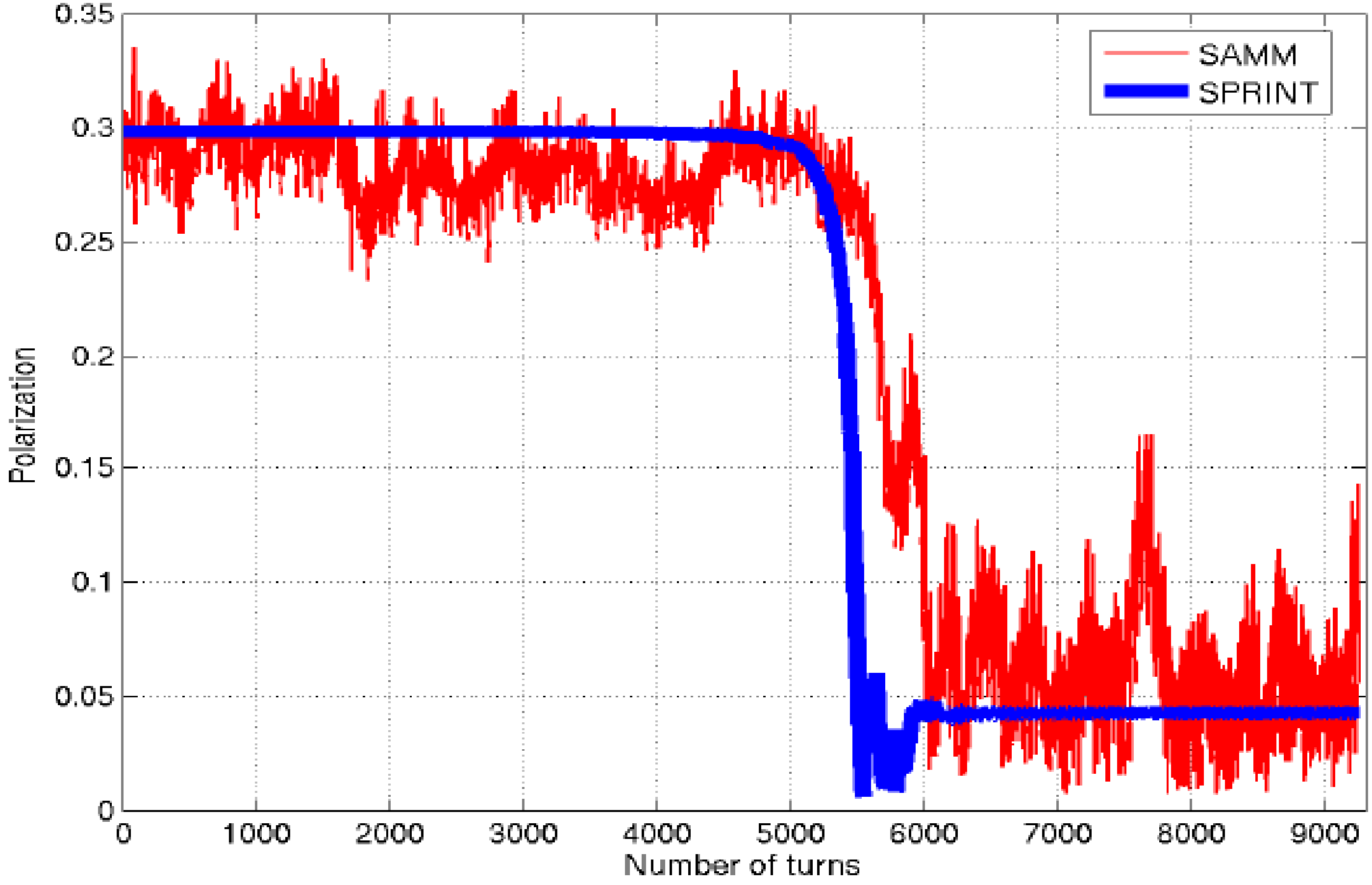
Mean polarization goes to 0

$$\sqrt{P_x^2 + P_y^2 + P_z^2}$$

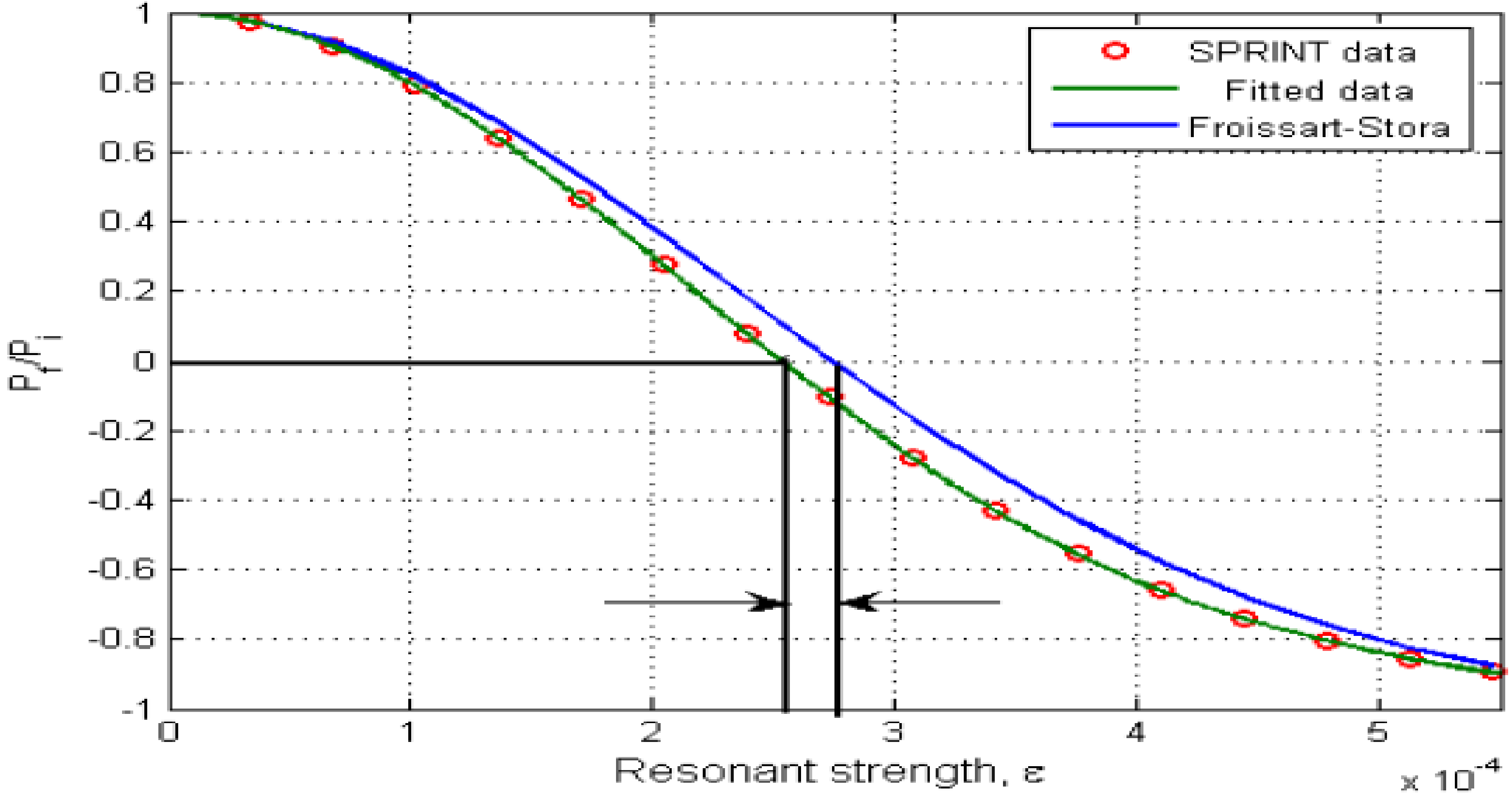
Application to Real lattice



Comparison codes SAMM+SPRINT

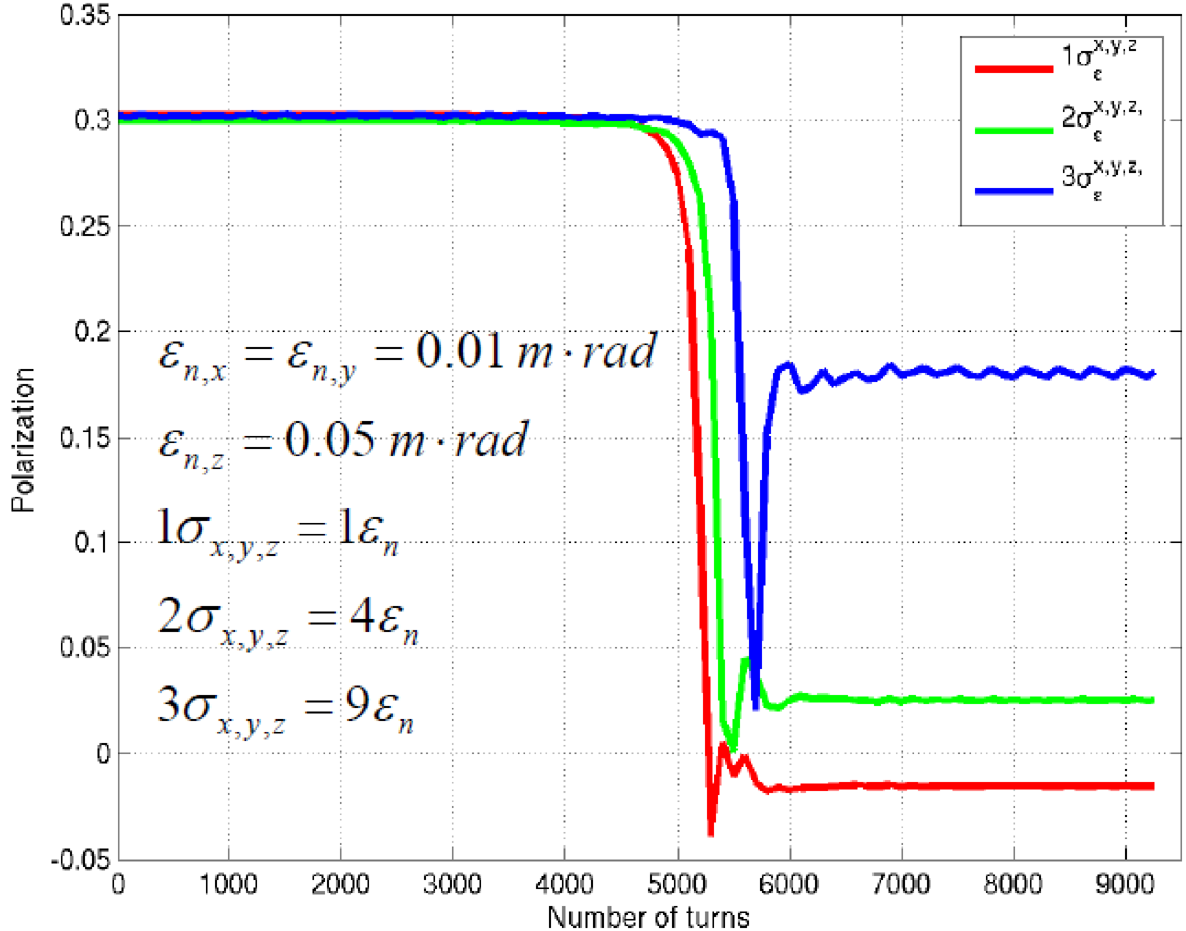


Comparison with analytical approach



$\Delta\varepsilon/\varepsilon = 0.2\cdot 10^{-4} / 2.5\cdot 10\text{-}4 = 8\%$

Influence of beam geometry



First results indicate:

- Feasibility of resonant depolarization technique at ILC

Open issues

Not a complete list (just as proposals for ‘To-do-list):

- Inclusion of effects of synchrotron radiation and radiation damping
- Test of different spin models (?)
- Inclusion of accurate spin tracking in damping ring
- Linking different codes for different sections to provide full cradle-to-grave tracking code
- Inclusion of non-Gaussian beams in beam-beam studies
- ….

Conclusions

- Beam polarization gives 'added-value' to ILC
  - Provides 'new' analysis tools comp. with LHC and highest precision
  - Requires complete spin control
- Positron polarization
  - Enhances eff. Lumi, provides higher prec.
  - full energy range: $\sqrt{s}$=92,…,1000 GeV !
  - Fast helicity reversal is required
- Spin tracking from source to downstream polarimeter
  - Spin rotator system
  - RF kicker for 'unpolarized' option
  - Depolarization and strong field effects in IP region