Fighting the Residual Polarization Loss in the AGS

1. **Depolarizing Resonances and Correction Schemes**
2. **Simulation and Analysis of Past Results**
3. **Strategy and Results of Run9**

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1. Depolarizing Resonances and Correction Schemes

Depolarizing Resonances in the AGS

Imperfection Resonances

$\nu_s = n$ (integer) $G\gamma = 5,6,\ldots 45$ partial snake(s)

Vertical Intrinsic Resonances

$\nu_s = kP \pm \nu_y$

Strong ones: $G\gamma = 0+\nu_y, 12+\nu_y, 36\pm\nu_y$ strong partial snakes

Note: with two partial snakes in the AGS, P=1. There are a lot weak intrinsic resonances as a result.

Horizontal Intrinsic Resonances

1. horizontal non-vertical stable spin direction due to strong partial snake interaction with horizontal motion.

2. betatron motion coupled to the vertical betatron motion by coupling elements: solenoid, helical magnet.

$\nu_s = k \pm \nu_x$ fast crossing speed, strong partial snakes

Partial Snake Resonances

strength proportional to nearby intrinsic resonance strength.

$\nu_s = kP \pm m\nu_y$, $m>1$ avoid the resonance tunes

Spin Dynamics

- Spin tune is given by

  $\cos\pi\nu_s = \cos(\delta/2)\cos G\gamma\pi$

  $\delta = 0.05\pi$ in AGS, ν_s can not be an integer, avoided all imperfection resonances;

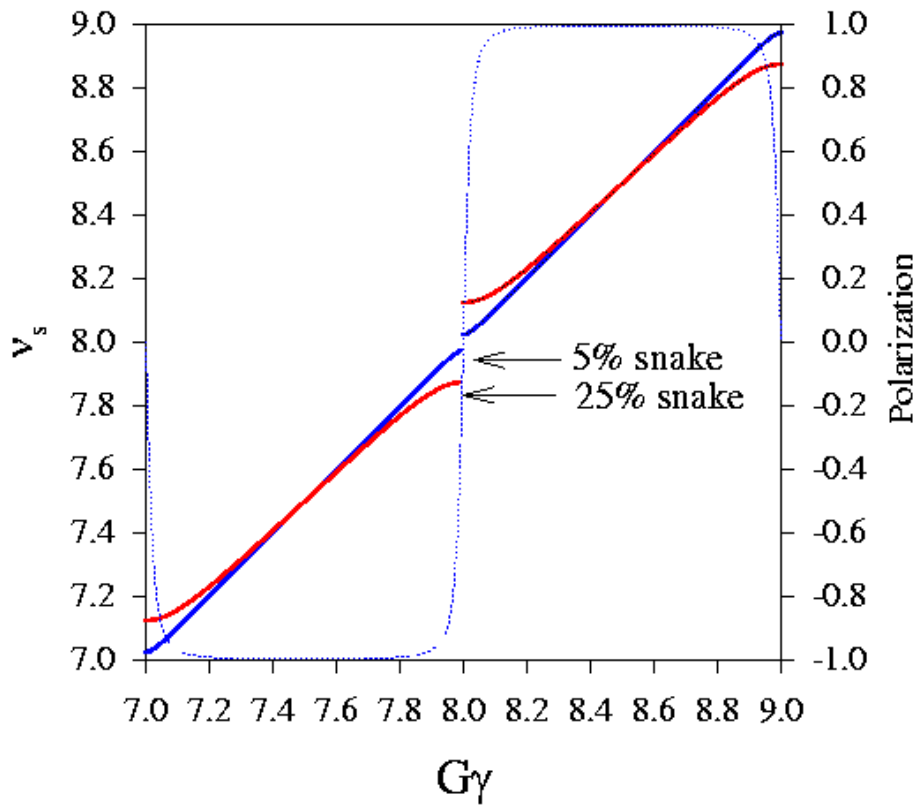
  $\delta = \pi$ in RHIC, $\nu_s = 1/2$, avoided all imperfection and intrinsic resonances.

- Polarization after passing an isolated resonance with strength ε and passing speed $\alpha = Gd\gamma/d\theta$ is given by Froissart-Stora Formula

  $P_f/P_i = 2\exp[-\pi|\varepsilon|^2/(2\alpha)]-1$

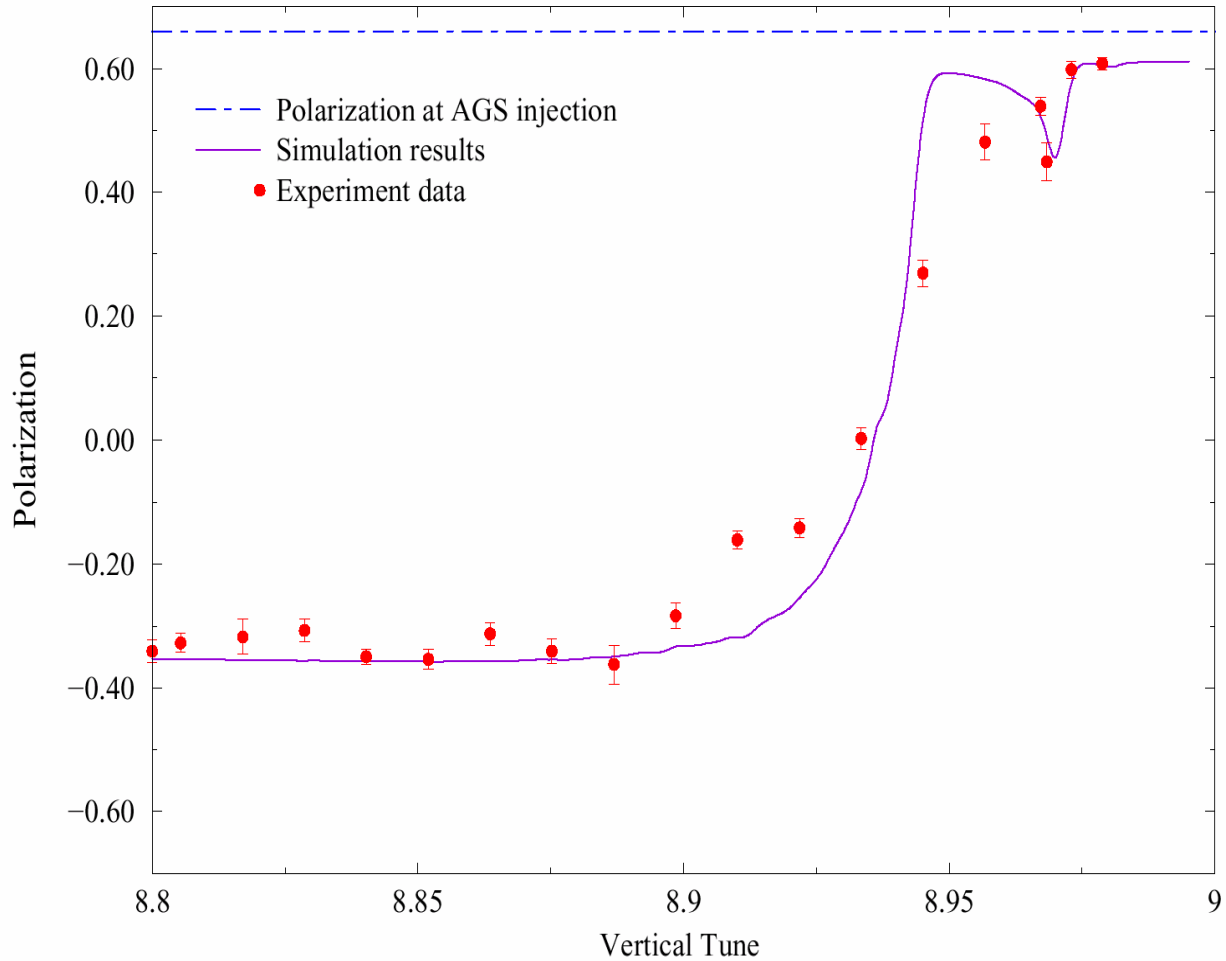
  $\pi|\varepsilon|^2/(2\alpha) \ll 1$, $P_f/P_i \to 1$;

  $\pi|\varepsilon|^2/(2\alpha) \gg 1$, $P_f/P_i \to -1$.



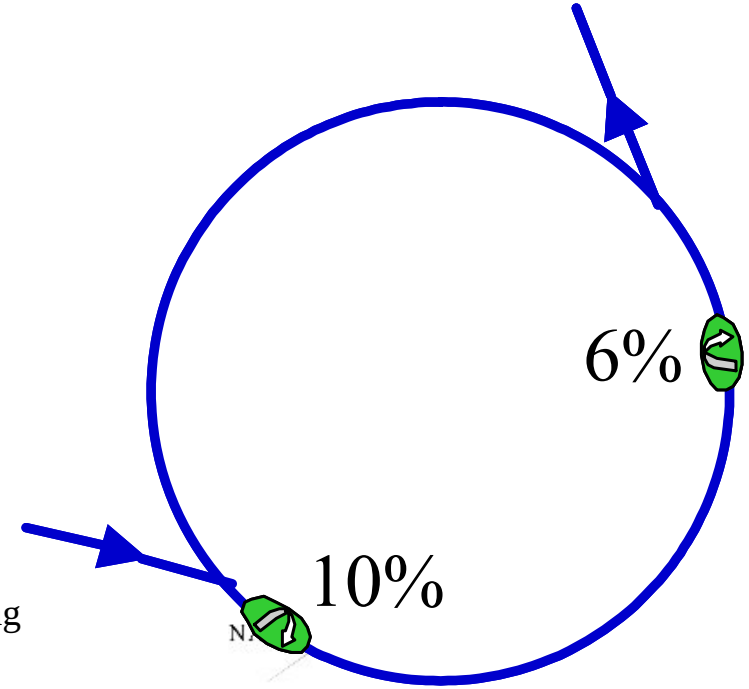
Simulation and Experiment Results

- A simple model simulation shows that 20% snake is needed to overcome the strongest resonance 36+ν. Snake resonances occur when fractional betatron tune equals 1/2, 1/3 of spin tune.
- The blue line is the injected beam polarization. The difference between the red dots and blue line is due to the coupling resonance and tilted stable spin direction.

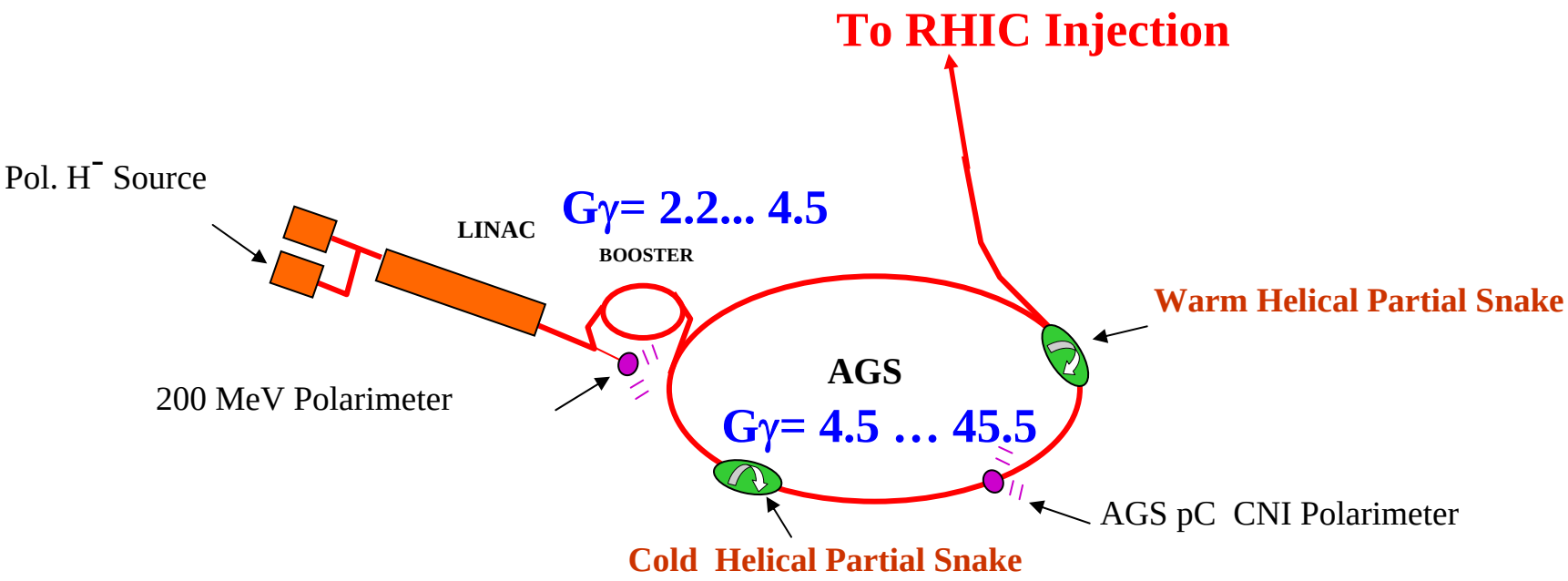


AGS Dual Partial Snake Scheme

The dual-partial-snake solution provides better spin match at injection and extraction.



AGS as RHIC Polarized Proton Injector



AGS has been running as RHIC polarized proton injector with dual partial snakes since 2006. It has delivered 65% polarization with $1.5*10^{11}$/bunch intensity with 82% as input polarization.

H. Huang, et al., *PRL*. **99**, 154801 (2007).

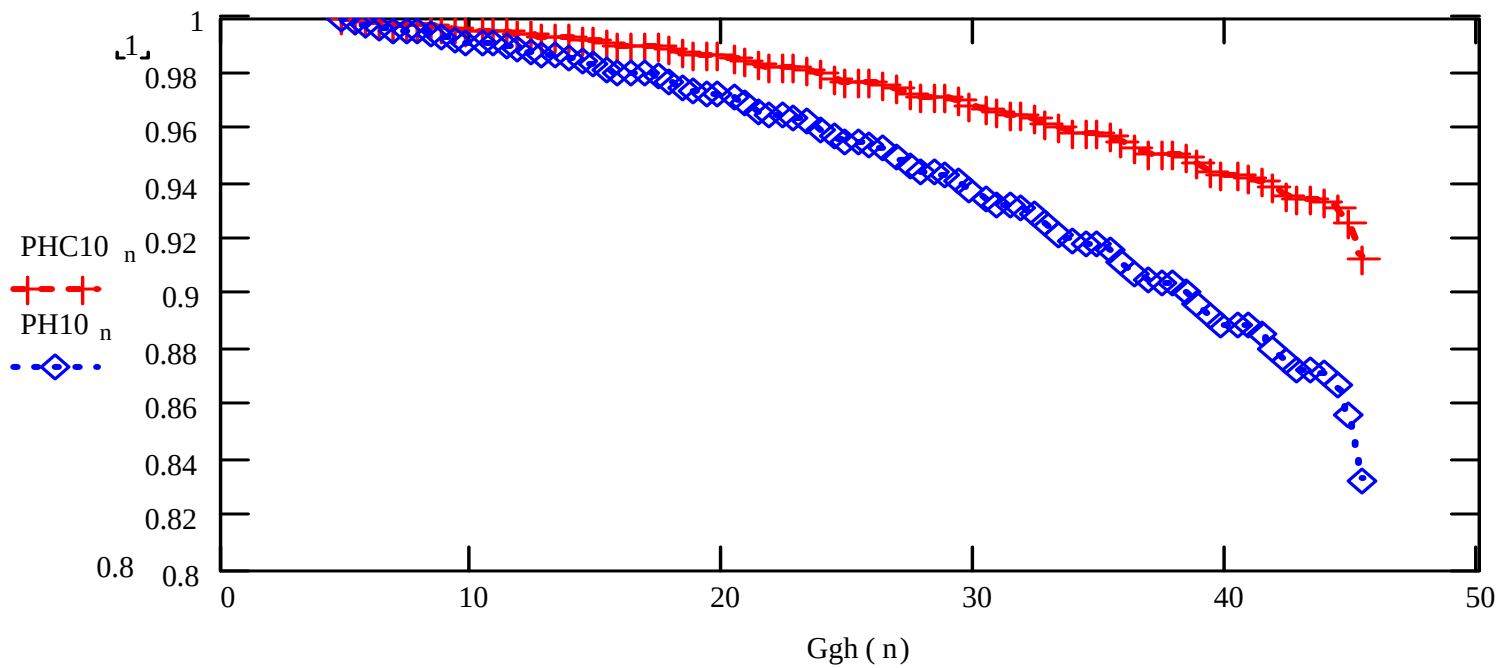
2. Simulation and Analysis of Past Results

What Are the Sources of the Polarization Loss?

- Imperfection and vertical intrinsic resonances have been taken care of by the dual partial snakes (except a few vertical ones near injection as vertical tune is outside the spin tune gap).
- The sources of polarization losses:
  - due to horizontal intrinsic resonances along the ramp.
  - the snake resonances associated with strong vertical intrinsic resonances, mostly at the strongest resonance $36+\nu_y$.
  - With the insertion of partial snakes, the super-periodicity P is one. The slow ramp rate and large lattice distortion near injection result polarization loss due to both horizontal and vertical intrinsic resonances.
- Spin tracking is very useful to identify these losses and give direction for cures.
- The emittances measured in the AGS are larger than the ones from linac. If we can find ways to reduce the emittance growth, it is going to affect polarization positively.

Horizontal Intrinsic Resonances

- Driven by vertical oscillating fields (horizontal focusing) with horizontal stable spin direction from partial snake
- 82 weak resonances between 4.5 and 45.5
- Leads to horizontal polarization profile
- For 10% and 5.9% partial snakes and 15 π horizontal emittance polarization transmission is predicted to be 91% in beam center (red), 83% for average (blue)



F. Lin, et al, *PR*. STAB **10**, 044001(2007).

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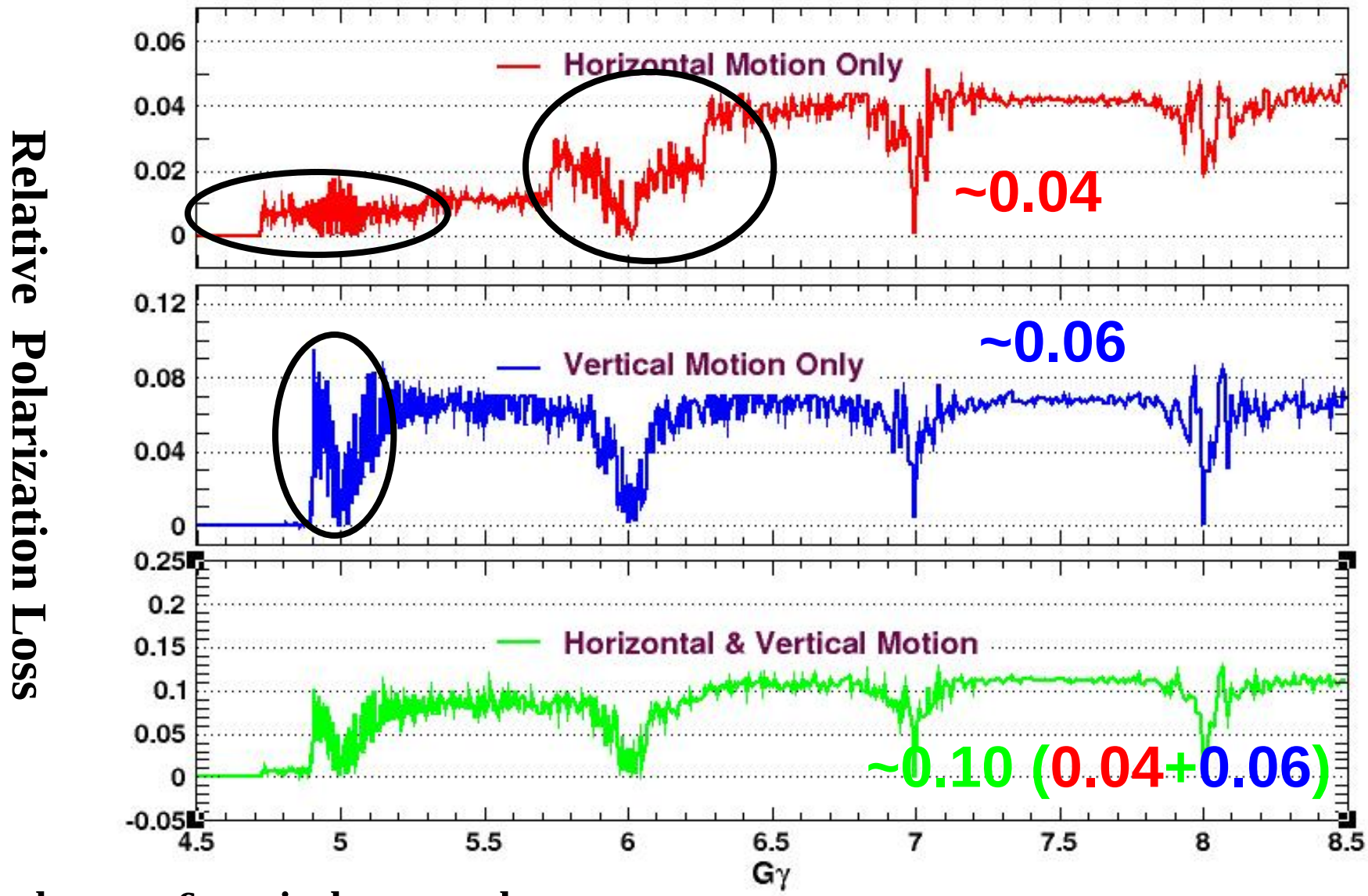
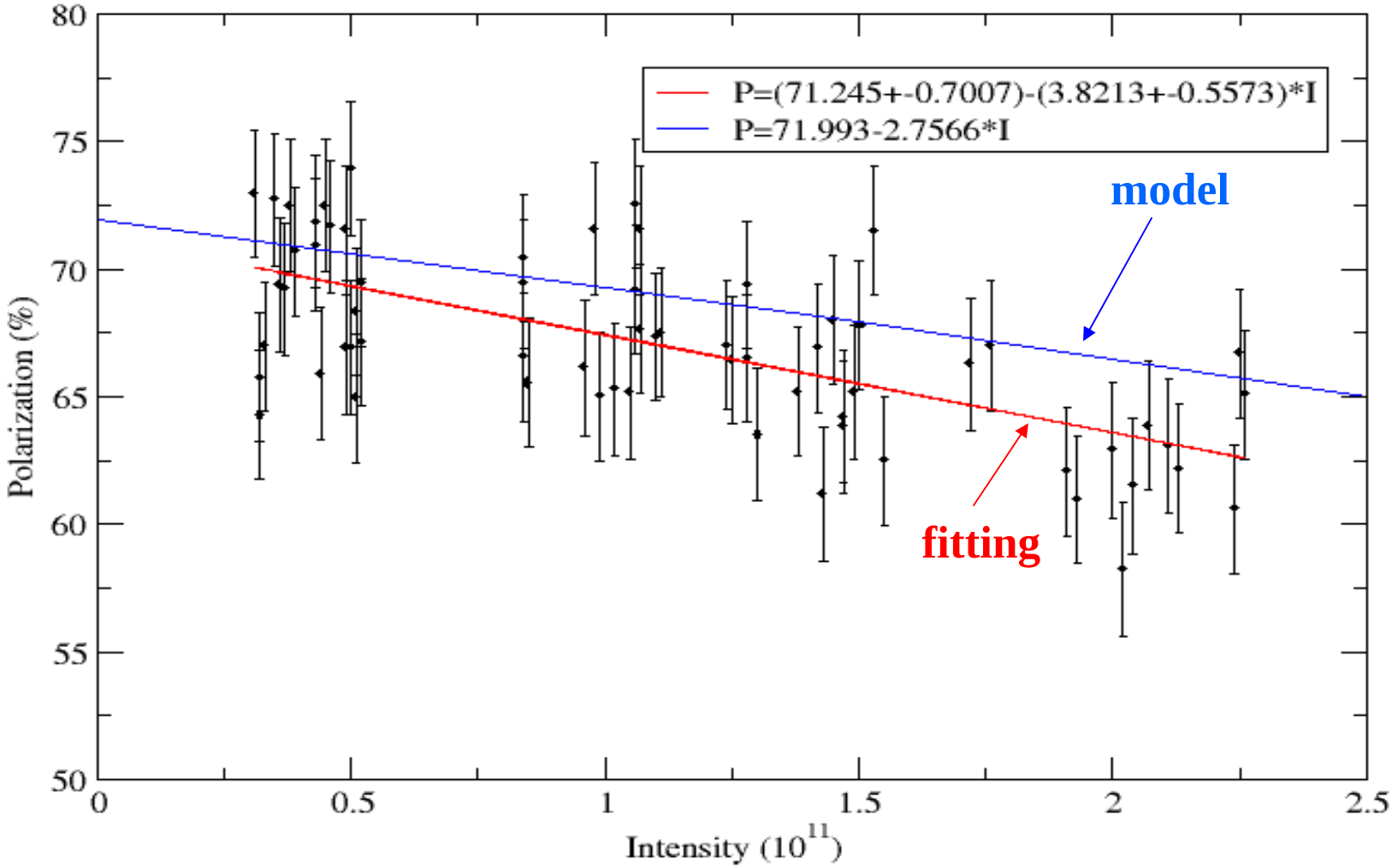
Polarization Loss Near Injection



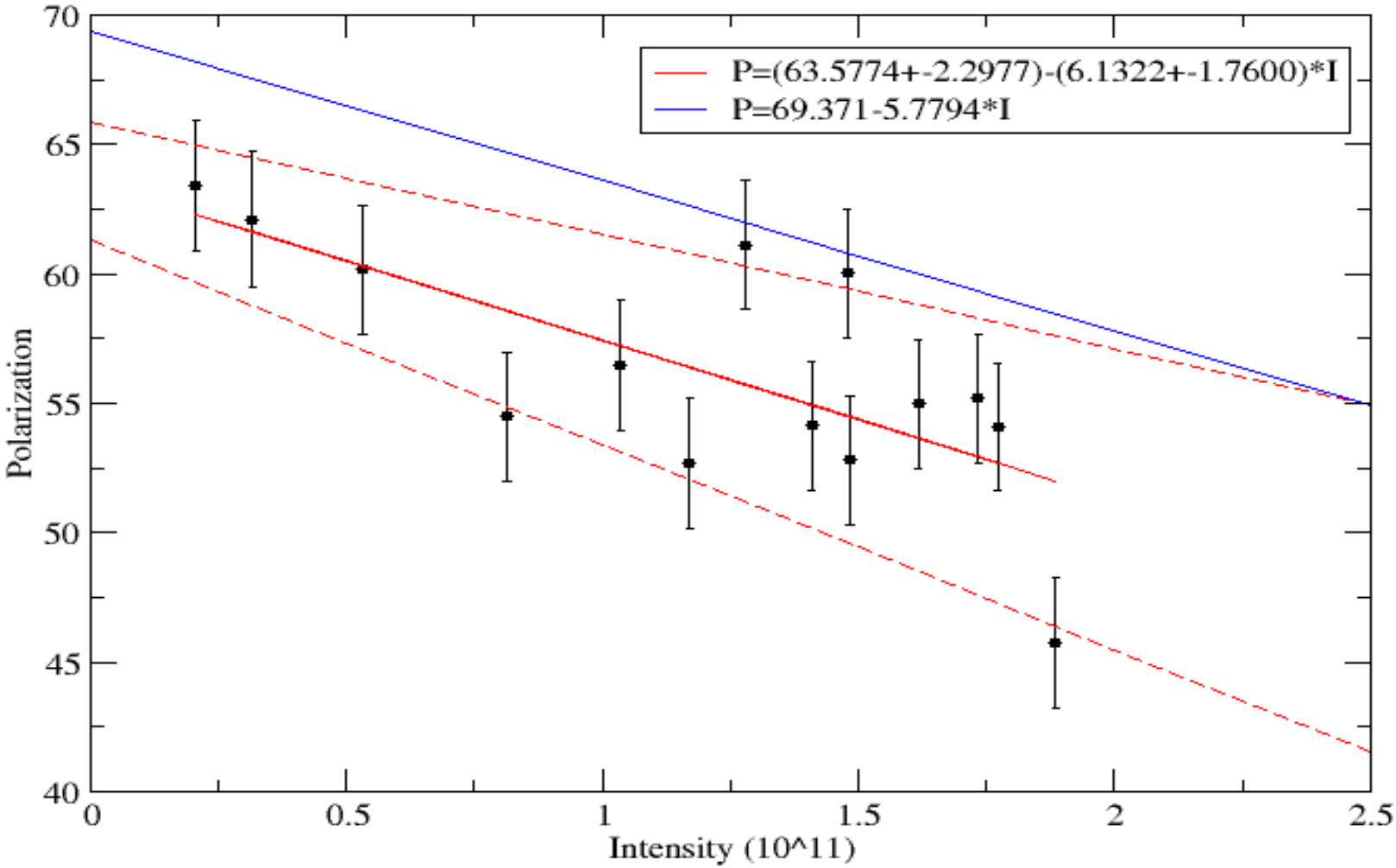
Based on run6 vertical tune path

Polarization vs. Intensity in Run6



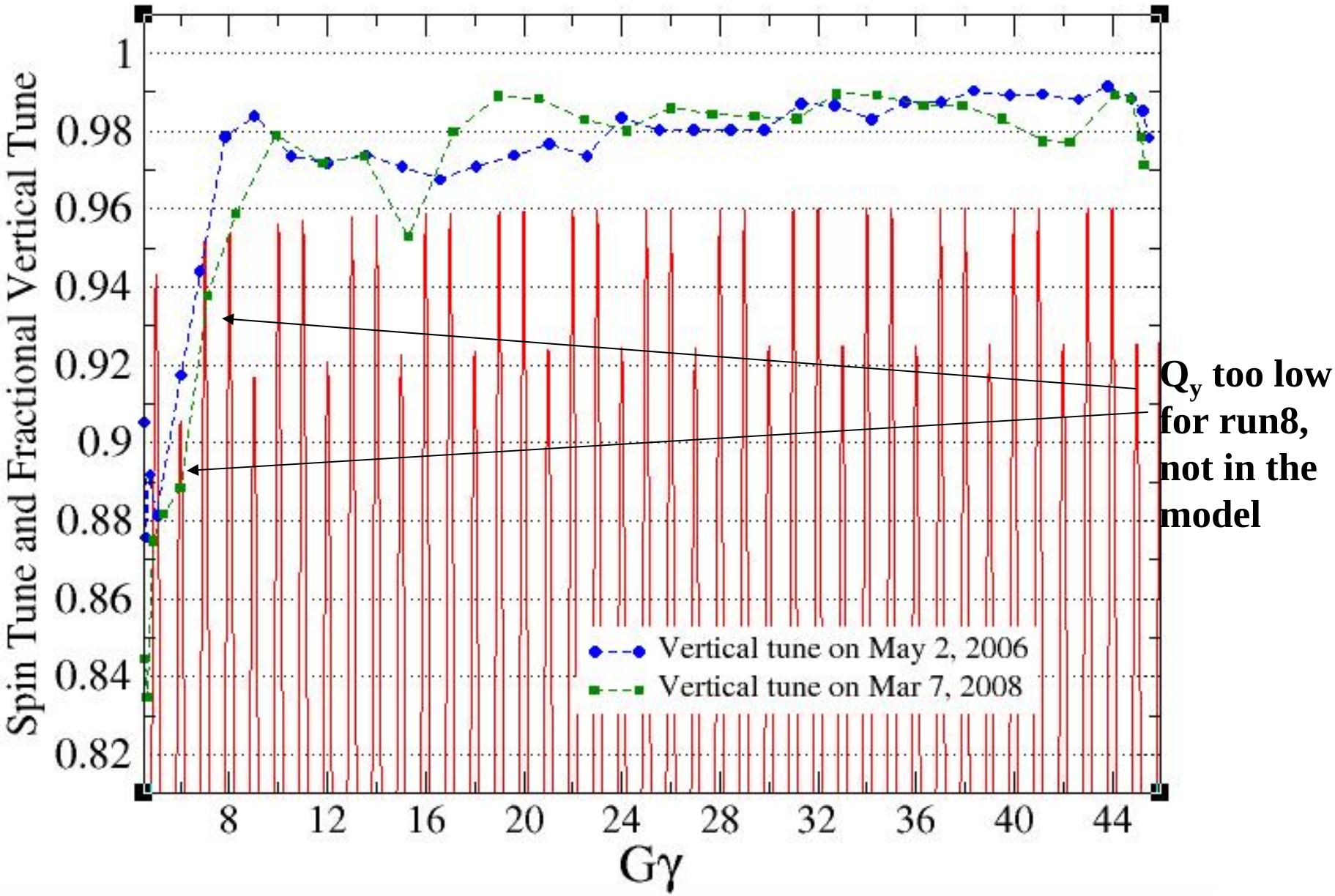
Experimental data are normalized to the 200MeV polarization and then assuming 82% AGS input. Model prediction: taken into account AGS input as 82%. The emittance dependence on intensity was taken from fitting of measurements: ε_x=9.21+2.30*I; ε_y =7.90+4.13*I, where I is intensity in unit of 10^{11}.

Polarization vs. Intensity in Run8 (a Short Run)

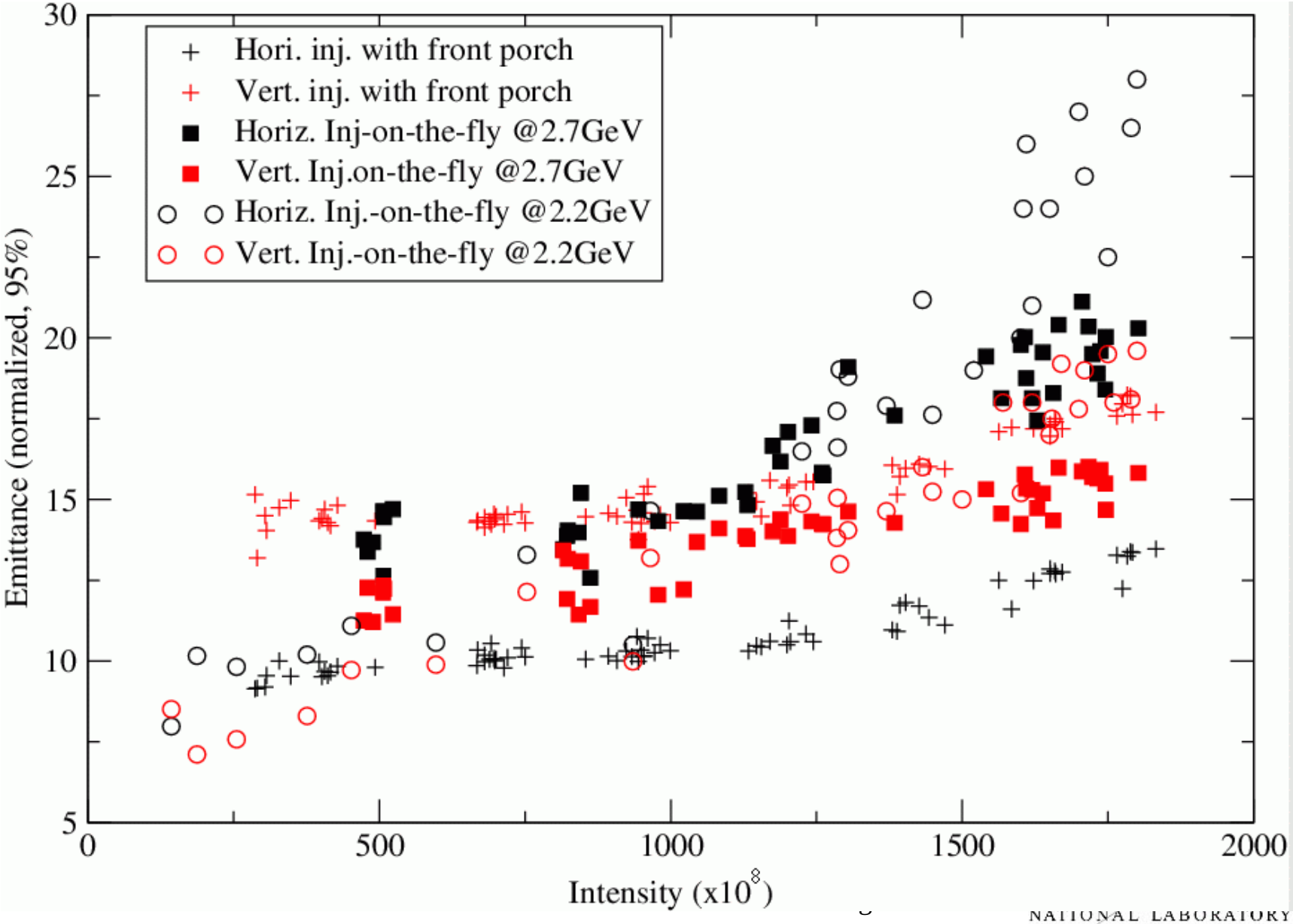


Larger discrepancy between model and experimental data. What are the other sources of the loss?

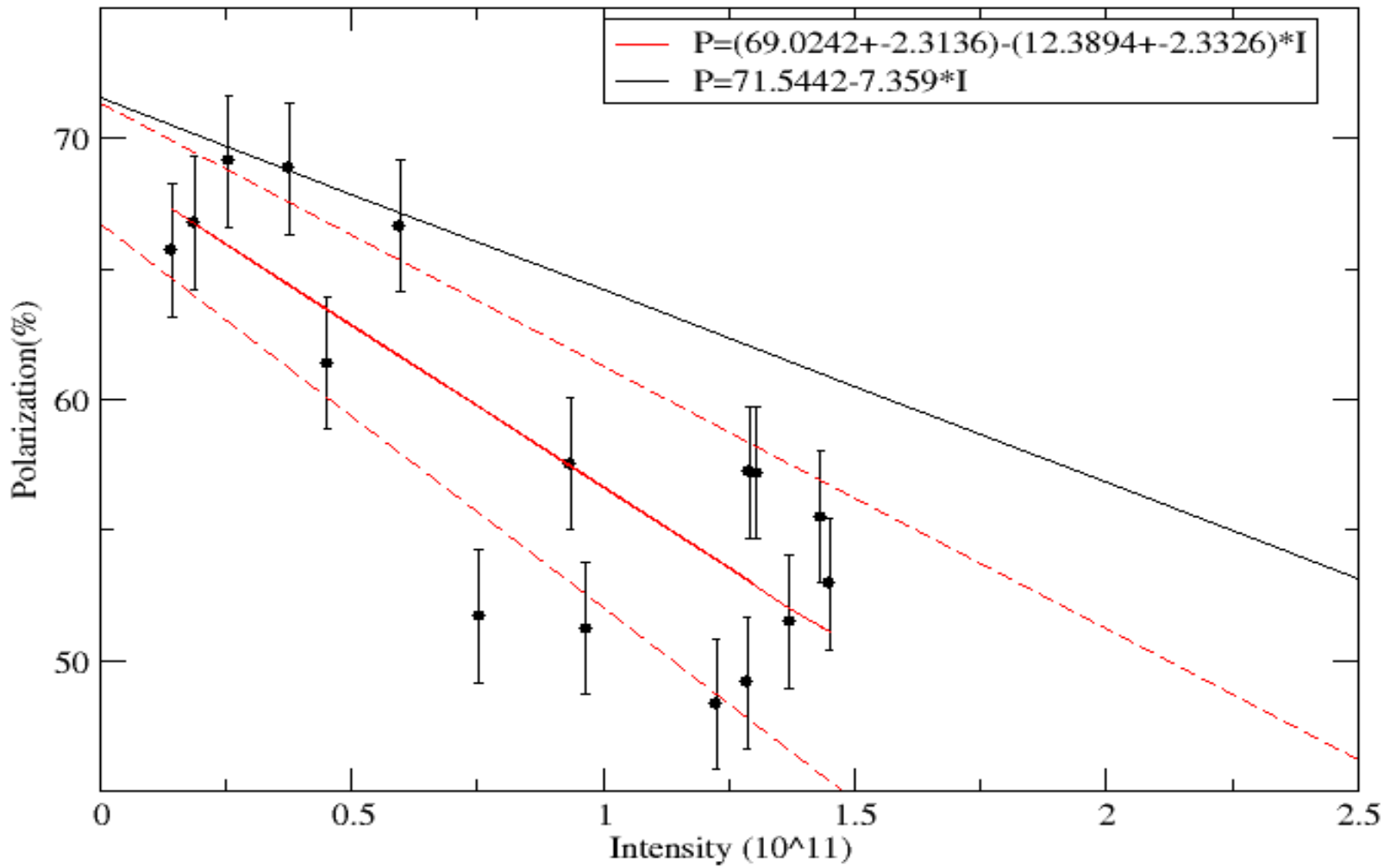
Additional Polarization Losses due to Vertical tune Path



Emittances Show Dependence on Intensity



Polarization vs. Intensity for Injection-on-the Fly



Prediction did not agree with experimental data.

3. Strategy and Results of Run9

Strategy to Overcome Polarization Loss

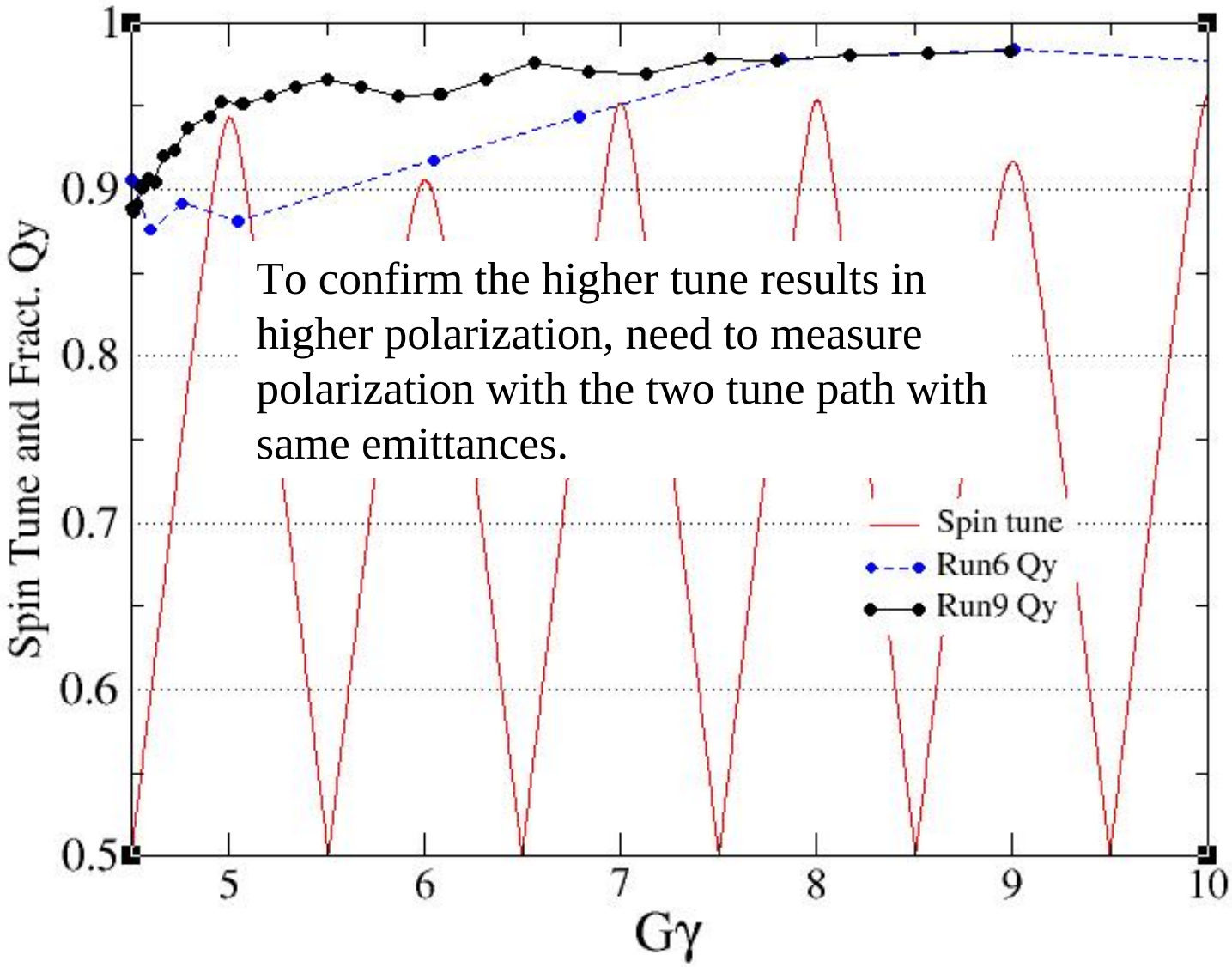
- There are significant emittance growth in the injector chain:
  - Emittance growth in the LEBT/MEBT of linac.
  - Multiple scattering at stripping foil at LtB.
  - BtA optics mismatch.
- The plan is to solve these emittance growth problem one by one:
  - LEBT/MEBT upgrade
  - Change the LtB foil; manipulate beta function at the foil to reduce the emittance growth
  - BtA study to better understand the BtA line and AGS optical model.
- Setup AGS injection with vertical tune in the spin tune gap (>8.95).
- Use two tune jump quads to mitigate the polarization loss due to horizontal resonances. It will be commissioned after mid-March. The gain on polarization during 250GeV run is hoped from smaller emittance out of linac and better matching at AGS injection.
- Change RF setup from h=12 to h=6 to reduce space charge effect (more important due to expected smaller emittances).

Emittance Comparison

- Linac upgrade should leads to smaller emittance at Booster entrance. A better linac setup has been used for Booster injection.
- A matched BtA optics has been used for BtA.
- No scraping in Booster this year.
- Larger beam loss near transition when Qy is raised.
- The beam emittance (rf off at flattop) are comparable to run6:

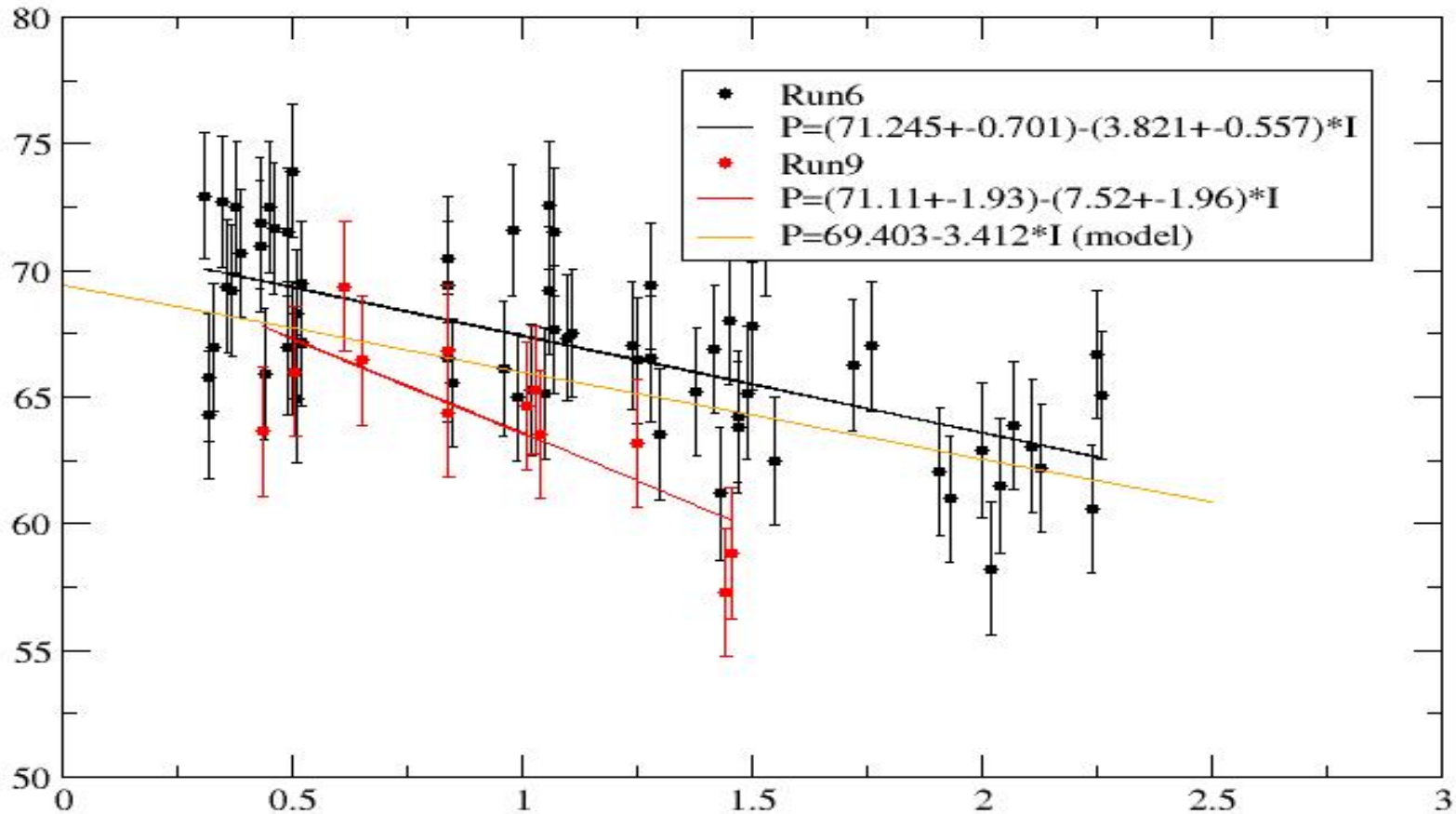
  5/11/06 H 11.4π V 16 π with $1.6*10^{11}$
  5/12/06 H 10.4π V 15.2π with $1.36*10^{11}$
  3/06/08 H 13π, V 17π with $1.4*10^{11}$
  2/10/09 H 11.2π, V 16.2 π with $1.44*10^{11}$

Higher Q_y Near Injection: within Spin Tune Gap



To confirm the higher tune results in higher polarization, need to measure polarization with the two tune path with same emittances.

Intensity Scan: Run9 vs. Run6



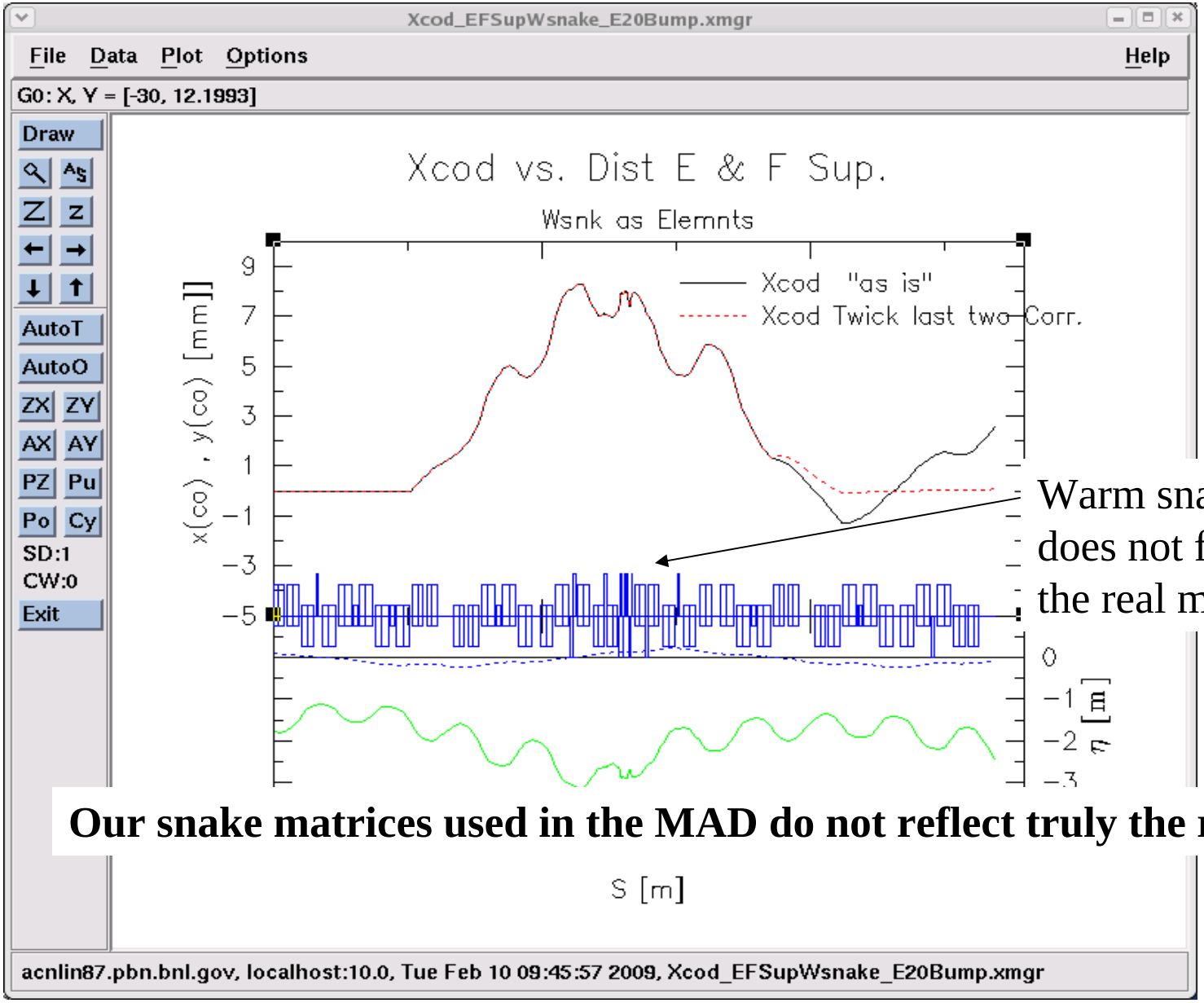
Model prediction: taken into account AGS input as 82%, spin mismatch at injection and C15. The emittance dependence on intensity was taken from fitting of measurements with IPM: ε_x =6.48+3.21*I; ε_y =9.82+4.63*I, where I is intensity in unit of 10^{11}.

AGS Setup Status

- $1.4*10^{11}$ intensity and ~60% polarization achieved with high vertical tune injection. Source polarization measurements is ~ 75% after reducing the background to the level never been seen before.
- BtA "matched" optics was put in last Thursday. No harm seen at IPM flattop emittance measurements. Polarization does not hurt either.
- Linac user5 tune was copied to user1 for AGS yesterday. No harm seen on emittance (BtA multiwire).
- Experienced intensity related beam loss at transition. Waiting for gamma_t quads for better transition crossing. Chromaticity around transition has been adjusted to cure it.
- An intensity scan is done. Slightly lower polarization than run6(due to lower source polarization?).
- Vertical tune on the ramp is pretty good. The strong intrinsic resonance locations should be similar to the run6 within one ms.
- Booster: no scraping yet. The beam is shaved off at AGS injection due to higher vertical tune now.

Snake Model Limitation

(courtesy of Nick)

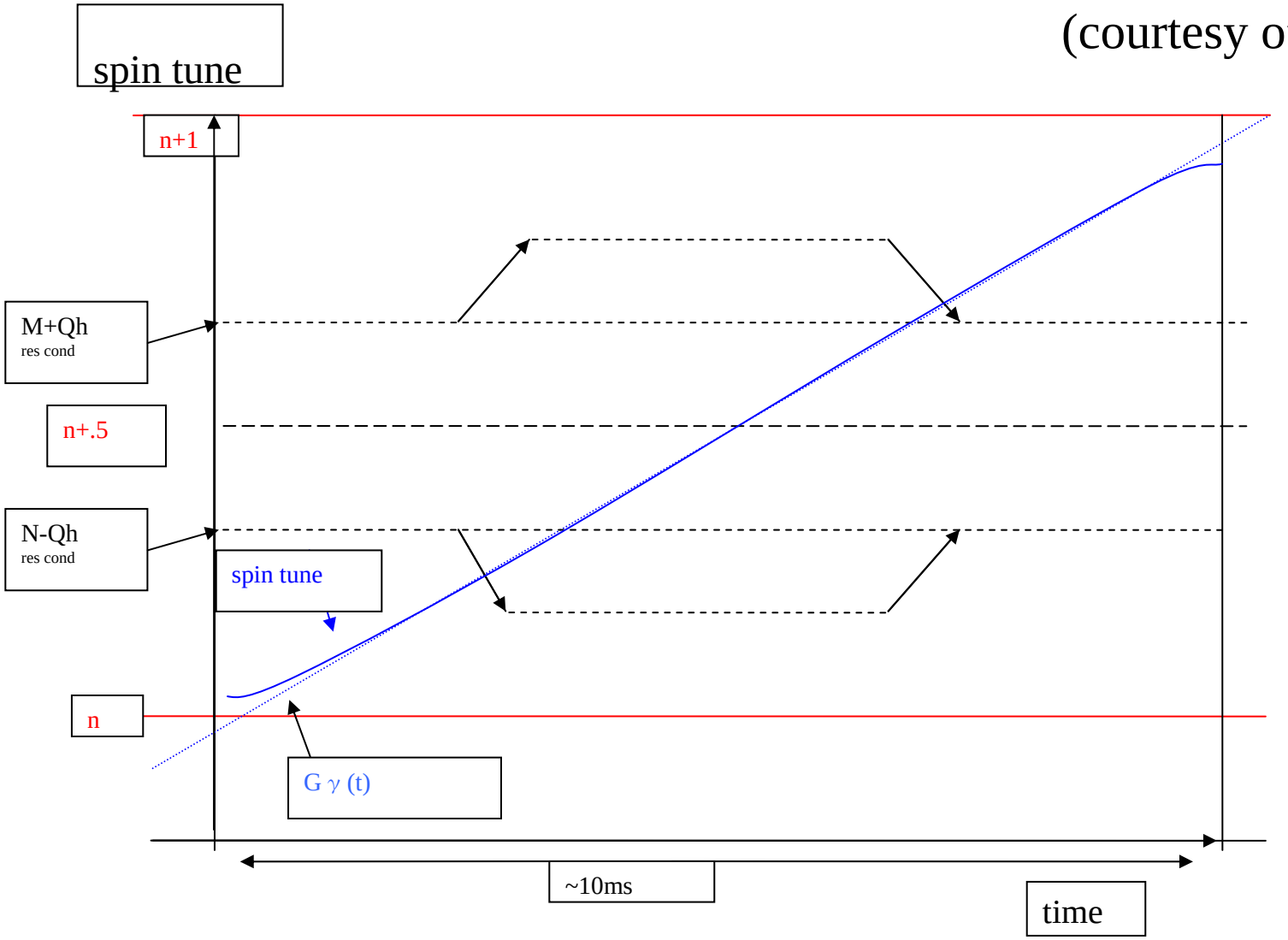


Warm snake matrix does not fully represent the real magnet.

Our snake matrices used in the MAD do not reflect truly the reality.

Horizontal Tune Jump

(courtesy of Leif)



The two resonances between two integers of Gγ will be "paired": the tune is jumped up then down.

Tune Jump for Horizontal Resonances

- Add two fast quad for this purpose.
- Minimum change of ν_x 0.04 in 100 μs. This increases the crossing speed by about 4 times.
- Operation issue: has to be dead-reckoning of timing. For practical operation, we need to maintain the horizontal tune and radius constant throughout the ramp.
- Benefit on polarization transfer efficiency (horizontal 15π beam):

Crossing	P_f/P_i(peak)	P_f/P_i(whole)
regular speed	0.912	0.832
Double speed	0.955	0.912
4X speed	0.977	0.955

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AGS Remaining Job List

- Horizontal tune jump study. It will not be ready until late March.
- Beta function manipulation at Ltb foil. It requires Qy=4.52 at injection without losing efficiency. The Booster ramp probably needs to be changed, too.
- Tune scan (polarization vs. vertical tune) at various intrinsic resonances to make sure they are all optimized.
- Harmonic scan (polarization vs. the sin9v harmonic amplitude) at 36+.
- Horizontal polarization profile measurement to evaluate the strength of horizontal resonances.
- User2 model testing experiment (warm snake only or cold snake only).
- Ramp measurement near injection to clarify the AGS injection polarization.
- Lower vertical tune near injection to check any impact on polarization.
- H=6 setup to reduce peak current—mitigate space charge effect.