Acceleration of Polarized He-3 in Booster and AGS

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Table of Contents

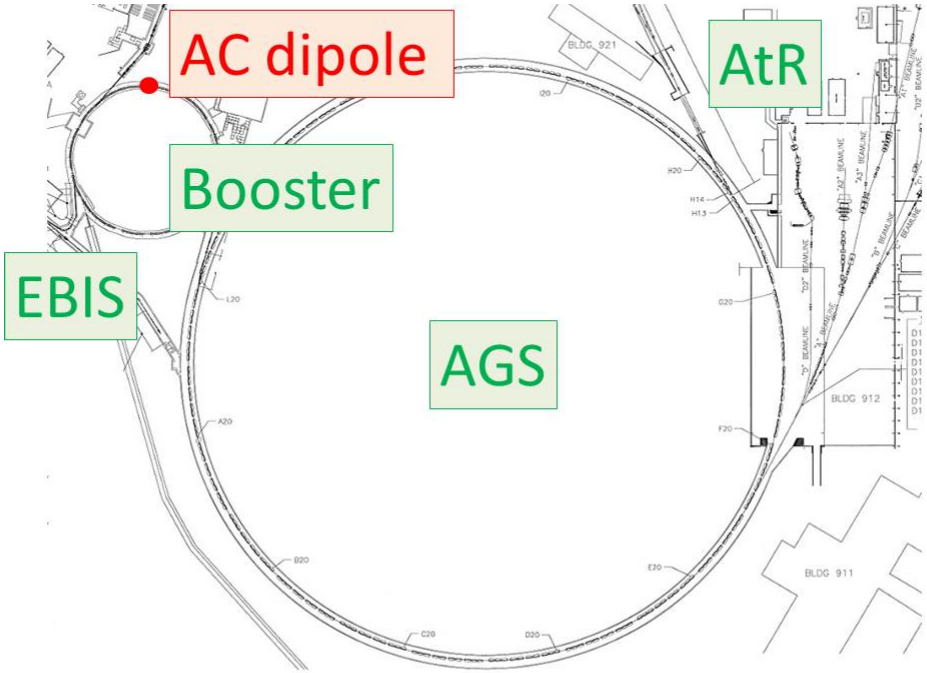
Introduction

Why He3?

He3 in Booster

Booster
- 36 Dipoles, 48 Quadrupoles, 6 superperiods, 12 drift sections.
- Intrinsic Resonances occur at $G\gamma = 6n \pm \nu_y$, n=0,1,2,...[1]

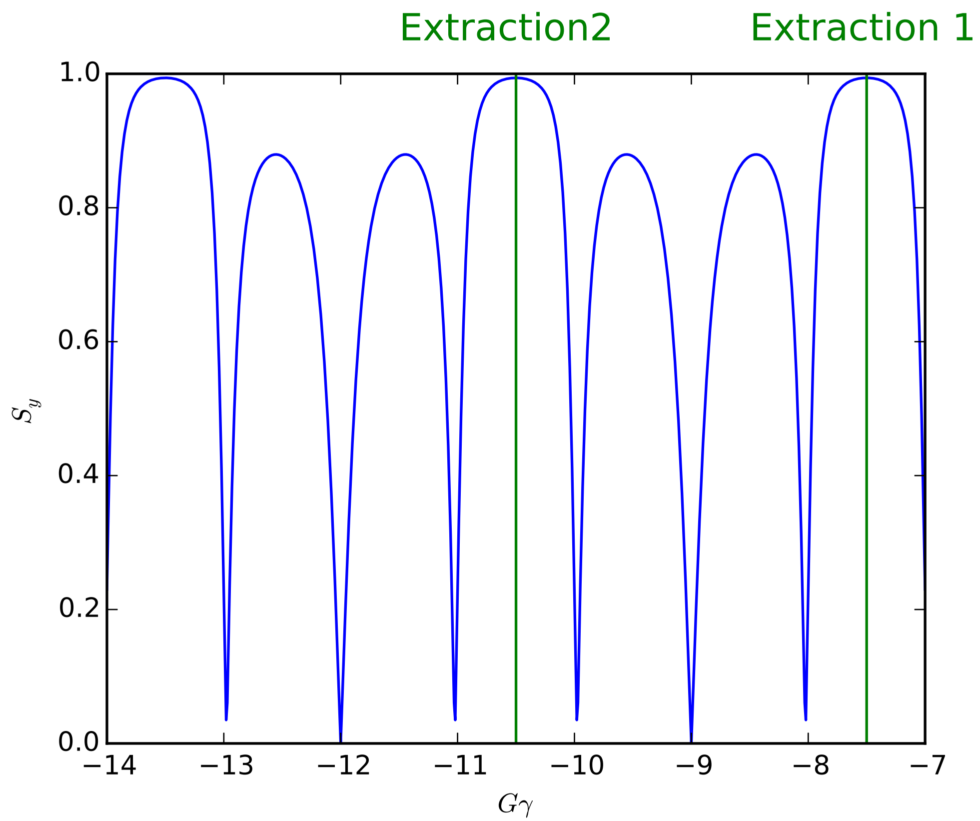
He3 in the Booster
- $G = -4.184$
- $G\gamma_{injection} = -4.193$
- $B\rho_{injection} = 0.306\ Tm$
- $97kHz < f < 1.4MHz$
- ν_y, ν_x typically vary between 4.0 and 5.0
- $\varepsilon_N = 4\pi mm\ mrad$ (From RHIC Run 14)



[1] S. Y. Lee. Spin Dynamics and Snakes in Synchrotrons. World Scientific 1997.

AGS Limitations on Booster

- Two partial siberian snakes stable spin direction perfectly matched for $G\gamma = 3n + 1.5$.[2, 3]
  - Extraction from Booster ideal at $G\gamma = -7.5$ *or* -10.5 or otherwise risk losing 10-100% polarization due to mismatch.[4]
- Partial siberian snakes are DC, have a large distortion of optics at low $B\rho$.[4]
- Extraction from Booster ideal at $G\gamma = -10.5$.



[2] H. Huang et al. Overcoming Depolarizing Resonances in the AGS with Two Helical Partial Siberian Snakes. Particle Accelerator Conference 2007 Proceedings June, 2007
[3]F. Lin. Towards Full Preservation of Polarization of Proton Beams in AGS. PhD Thesis, Indiana University December, 2007.
[4] F. Meot. Transport of Polarized He3 in Booster and AGS. BNL C-AD Spin Meeting November, 2015

Booster Limitations

- MMPS consists of 6 modules that provide 1000V.[5]
  - Only 2 modules capable of exceeding 3000A.
  - This limits fast ramp rate to 9.5 T m ($G\gamma = -10.5$ corresponds to $B\rho = 10.8$ Tm).
  - Extract at $G\gamma = -7.5$ with all 6 modules.
  - Extract at $G\gamma = -10.5$ with only 2 modules.
  - Crossing speed: $\alpha = 7.961 \times 10^{-6}$ (6 modules) or $\alpha = 2.654 \times 10^{-6}$ (2 modules)
- Booster extraction/AGS injection supplies designed for $B\rho = 9.5$ Tm.
- Saturation effects in Quadrupoles noticeable with $B\rho > 10$.[6]

[5] K. Gardner. Injector Setup for Helions in RHIC. BNL C-AD Spin Meeting November, 2015
[6] E. Bleser. Booster Short Quadrupole Measurements. Booster Technical Note no 174 September 12, 1990.

Spin Resonances in the Booster

0+

- Avoidable with $\nu_y < 4.1$ when injecting.
- Unvoidable with $\nu_y > 4.1$ when injecting.

12-

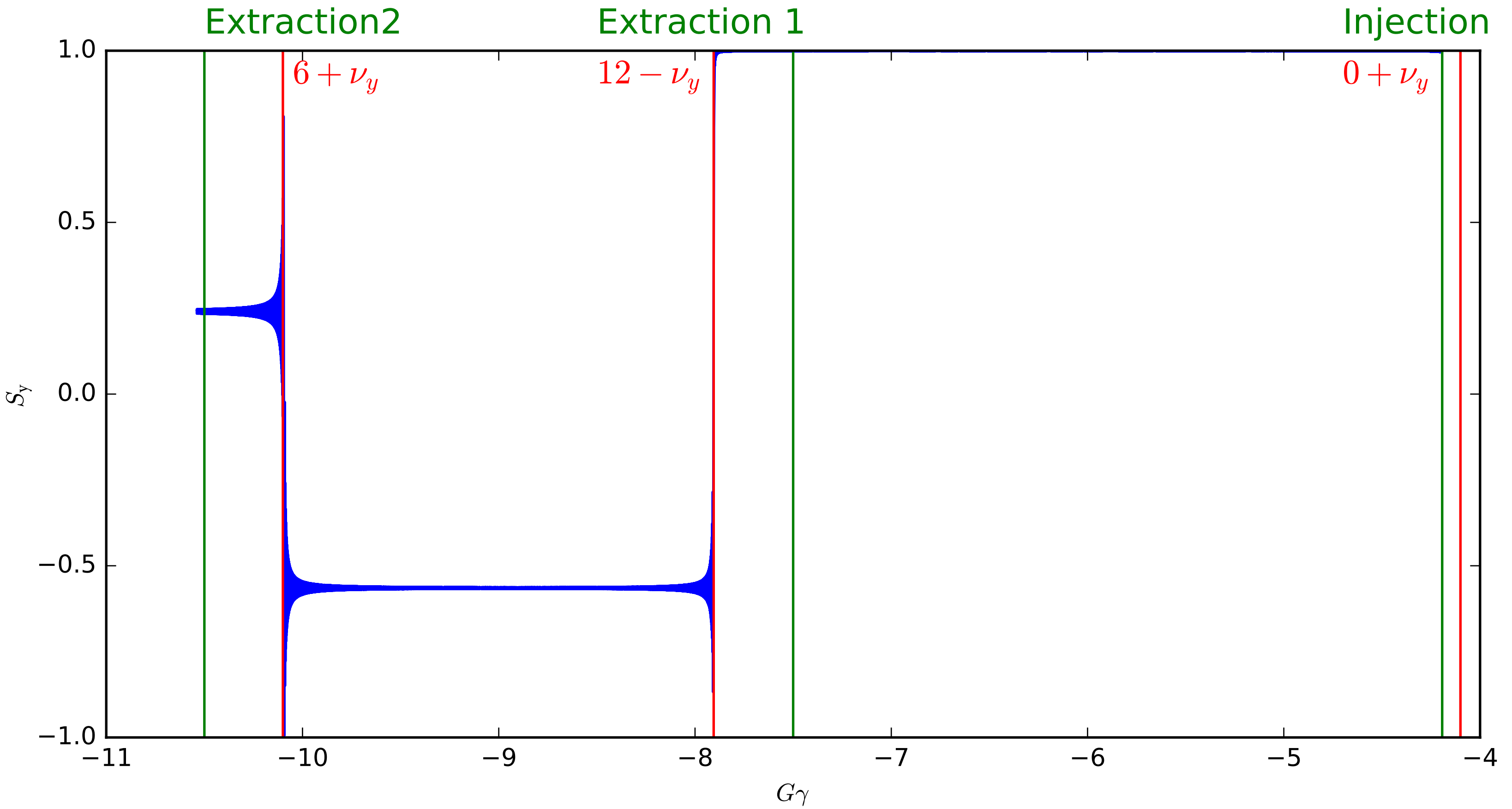
- Avoidable with $\nu_y < 4.5$ when extracting at $G\gamma = -7.5$
- Unvoidable when extracting at $G\gamma = -10.5$

6+

- Avoidable with $\nu_y > 4.5$ when extracting at $G\gamma = -10.5$
- Unvoidable with $\nu_y < 4.5$ when extracting at $G\gamma = -10.5$

Overview of Possible Booster Configurations

- Extract at $G\gamma = -7.5 or - 10.5$
- Avoid 6+ by ramping ν_y above 4.5



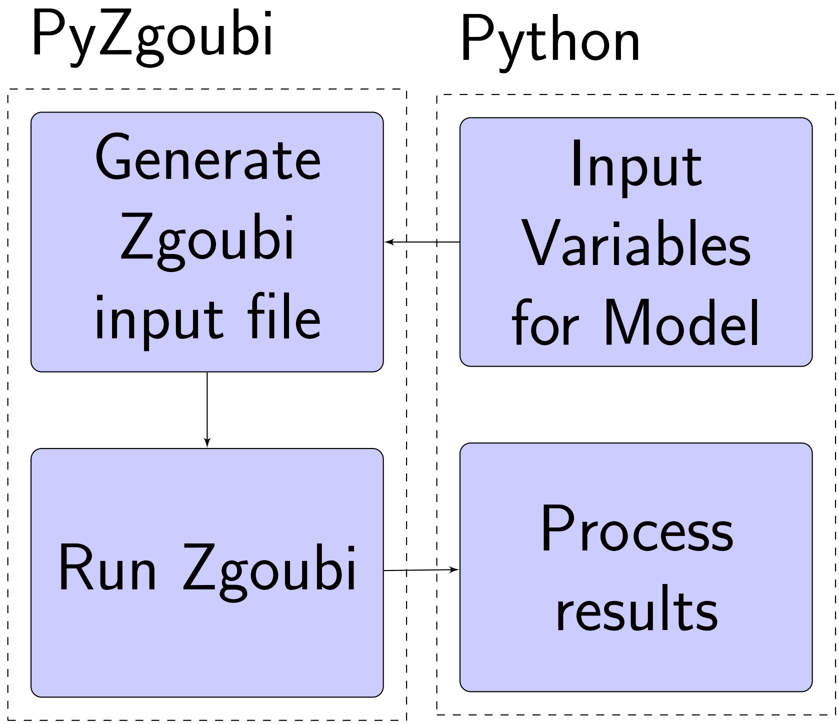
PyZgoubi

Zgoubi[7]

- Powerful and versatile accelerator simulation engine.
- Well established and widely used.

PyZgoubi[8]

- Python wrapper for Zgoubi.
- Uses the same Zgoubi engine but with python syntax at the top level.
- Access to Python modules and packages.

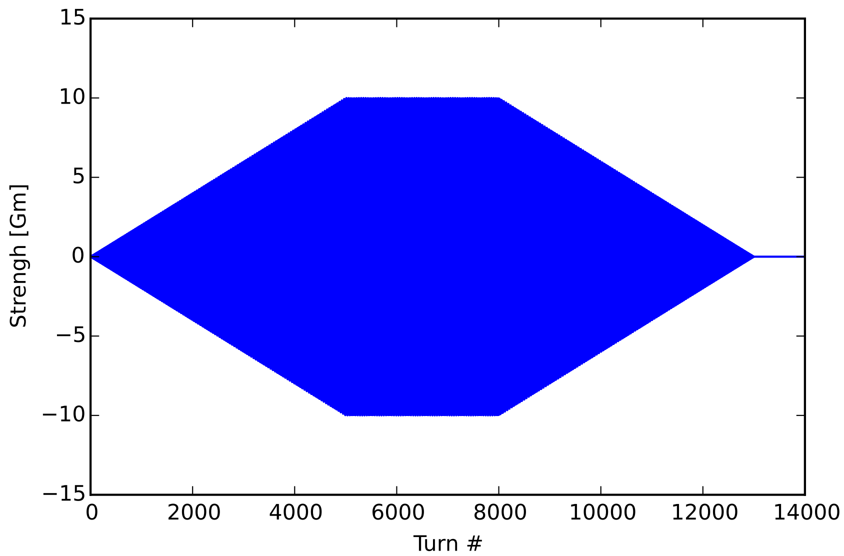


[7]F. Meot. Zgoubi User's Guide. CA/AP Note no 470. October, 2012.
[8] S. Tygier et al. The PyZgoubi Framework and the Simulation of Dynamic Aperture in Fixed-Field Alternating Gradient Accelerators. Nuclear Instruments and Methods in Physics. Volume 775, pages 15-26. March, 2015.

AC-Dipole

Make a large betatron oscillation at frequency near resonance to induce full spin-flip.
$\delta = \nu_y - (k - \nu_m)$, l=20 cm, AC dipole field and frequency are B_m and ν_y.[9]

$$Z_{coh} = \frac{B_m l}{4\pi\delta \ B\rho}\beta_z \tag{1}$$



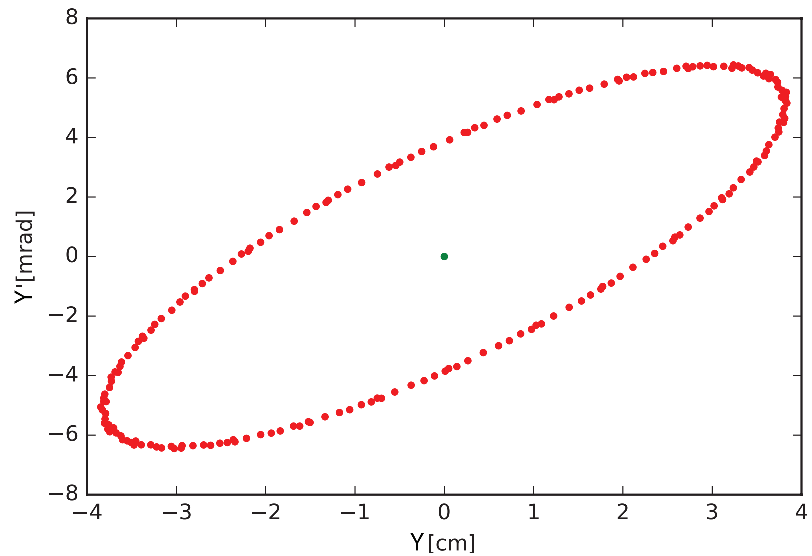


Figure : Left: Ramp used for the AC-dipole. $\delta = -0.01$. Right: Center of bunch prior to AC dipole turning on (green). Center of bunch for 200 turns with AC dipole at full strength.

Ramp rate is chosen to provide $G\gamma = -(12 - \nu_y - 0.1)$ at start of ramp.

AC-Dipole expected results

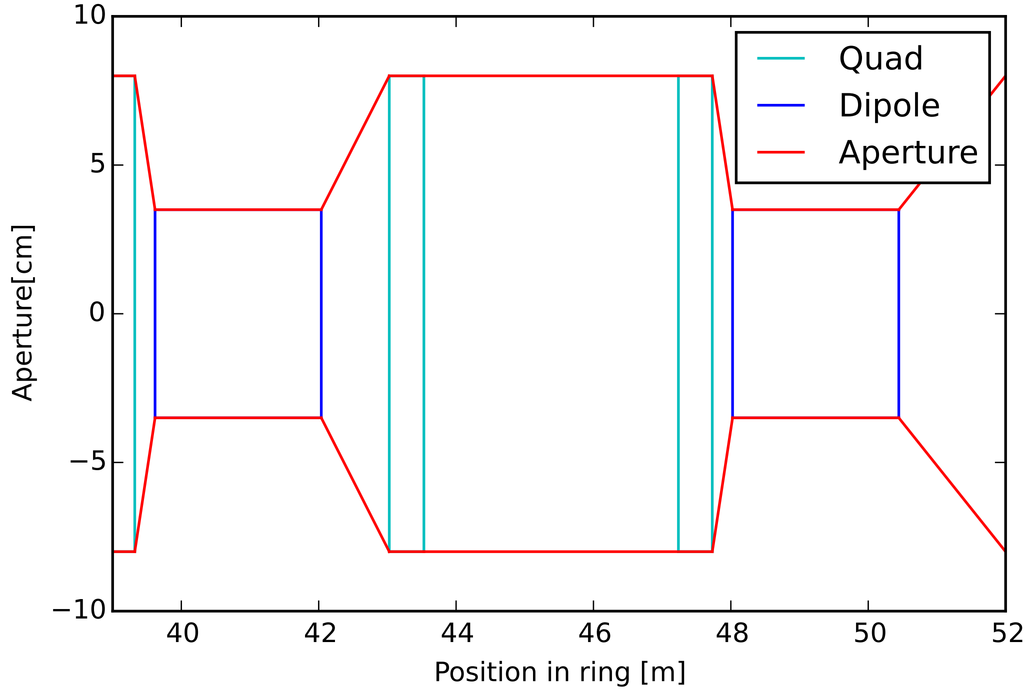
Expected requirements of AC-dipole when using analytical results.[9]

	0+	12-($\nu_y > 4.5$)	12-($\nu_y < 4.5$)	6+
$G\gamma$	-4.7	-7.3	-7.8	-10.4
$B\rho$ [$T\ m$]	2.37	6.69	7.36	10.6
ϵ [$\varepsilon_N = 4\pi$]	0.0171	0.0096	0.0103	0.0170
$B_m l$ [Gm]	21.6	32.2	34.46, 30.6	46.7, 42.2

[9] M. Bai, S. Y. Lee, H. Huang, T. Roser, M. Syphers. Overcoming the Intrinsic Spin Resonance using Resonance Island created by RF Dipole. AGS/RHIC/SN no 055 May 5, 1997.

Available Aperture

Limiting aperture in vertical plane is from the dipole vacuum pipe, $\pm 3.5cm$.



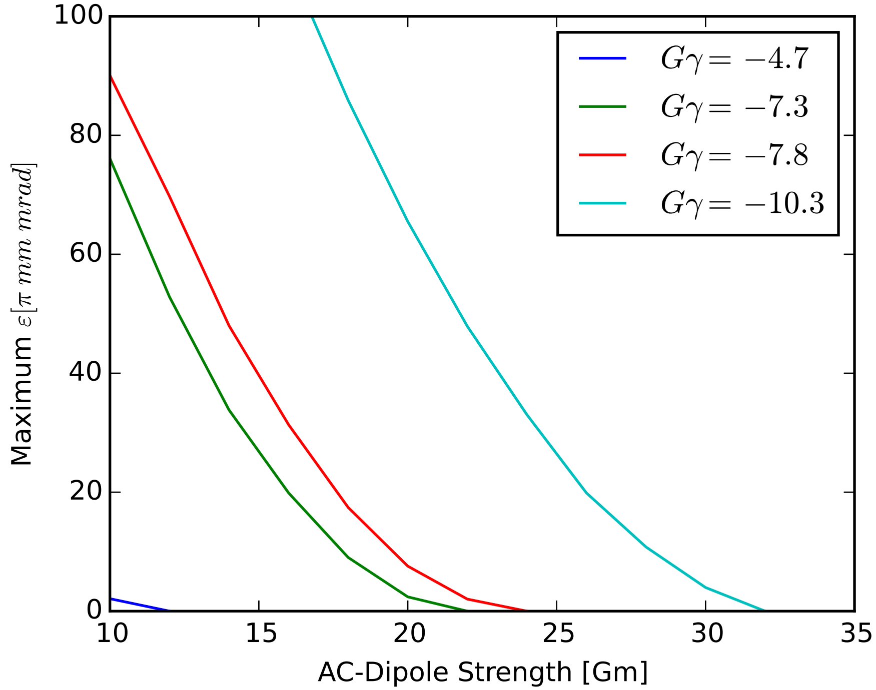


Figure : Left: Cartoon showing available aperture in the Booster over a small area. Right: Image showing the maximum allowed emittance particle for various AC Dipole strengths.

Spin Tracking Results

Two sets of bunched beam tracking, Gaussian and truncated Gaussian.

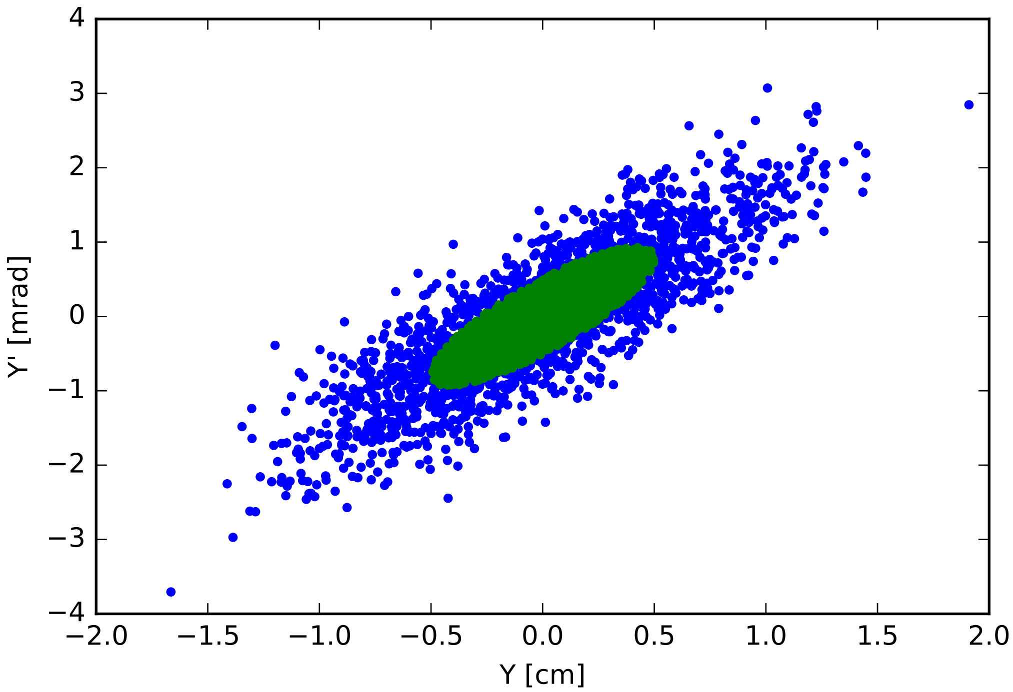


Figure : Gaussian bunch (blue), truncated Gaussian bunch (green), $\varepsilon_N = 4\pi$.

AC Dipole On vs Off

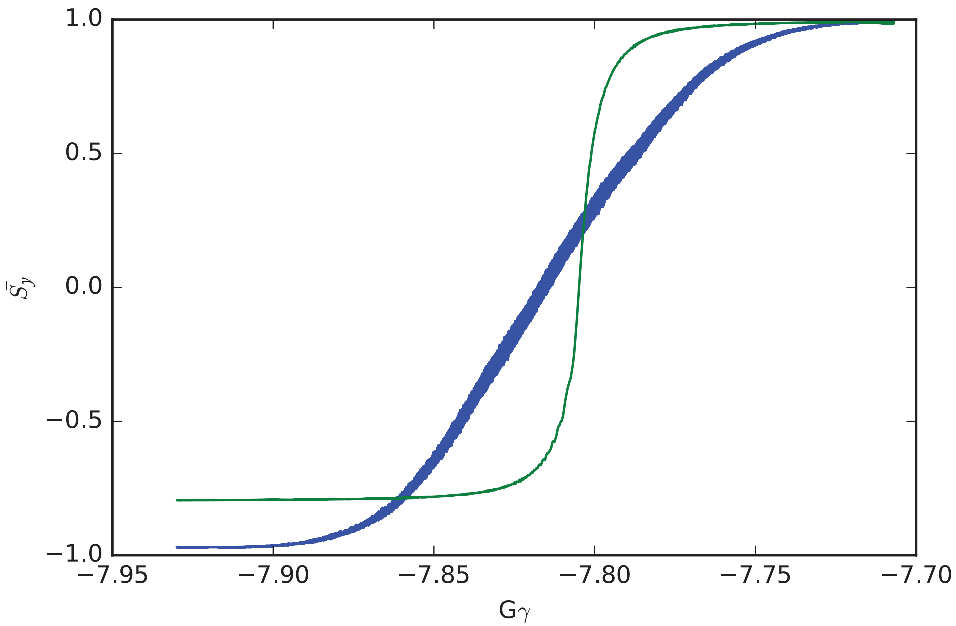


Figure : Example for 12- resonance. AC dipole off (green) $P_{f,ACoff} = -80\%$, AC Dipole on(blue) $P_{f,ACon} = -99\%$.

Spin Tracking Results 0+

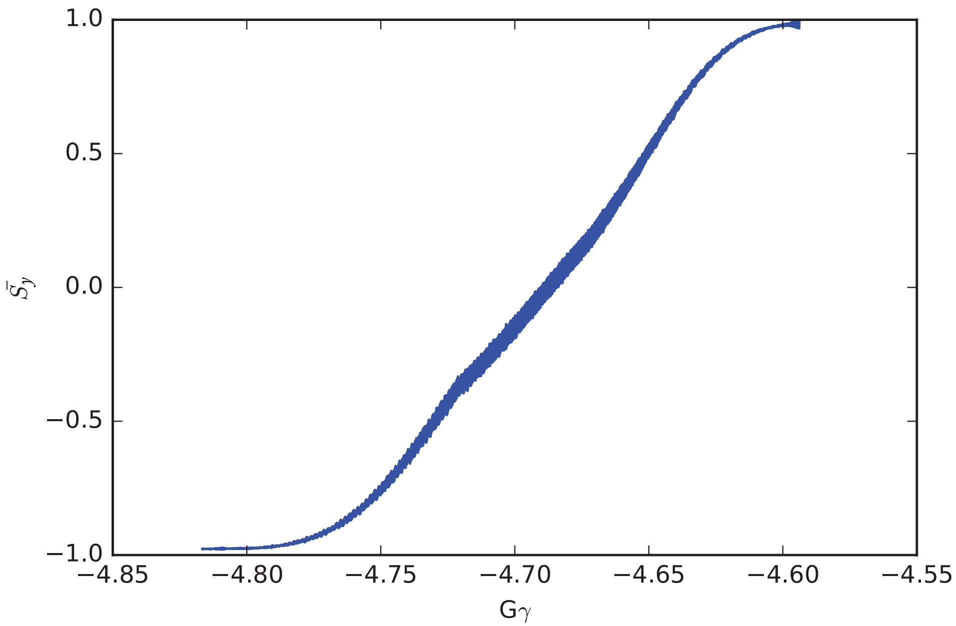


Figure : Example for 0+ resonance. Ensemble average of S_y with Gaussian bunch, $B_m l = 21.6\ Gm$, $P_f = -99\%$.

Spin Tracking Results 12-

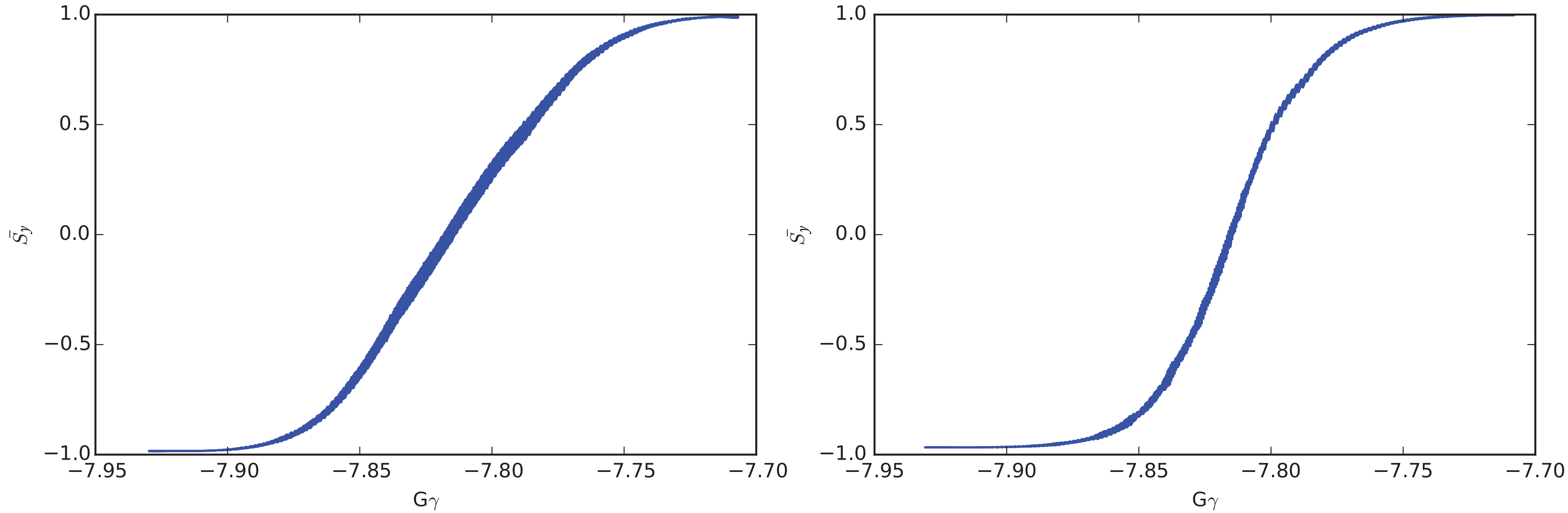


Figure : Example for 12- resonance. Left: Ensemble average of S_y with Gaussian bunch, $B_m l = 34\ Gm$, $P_f = -99\%$. Right: Ensemble average of S_y with truncated Gaussian bunch, $B_m l = 18\ Gm$. Beam was cut to 1σ to simulate scraping, $P_f = -98\%$.

Spin Tracking Results 6+

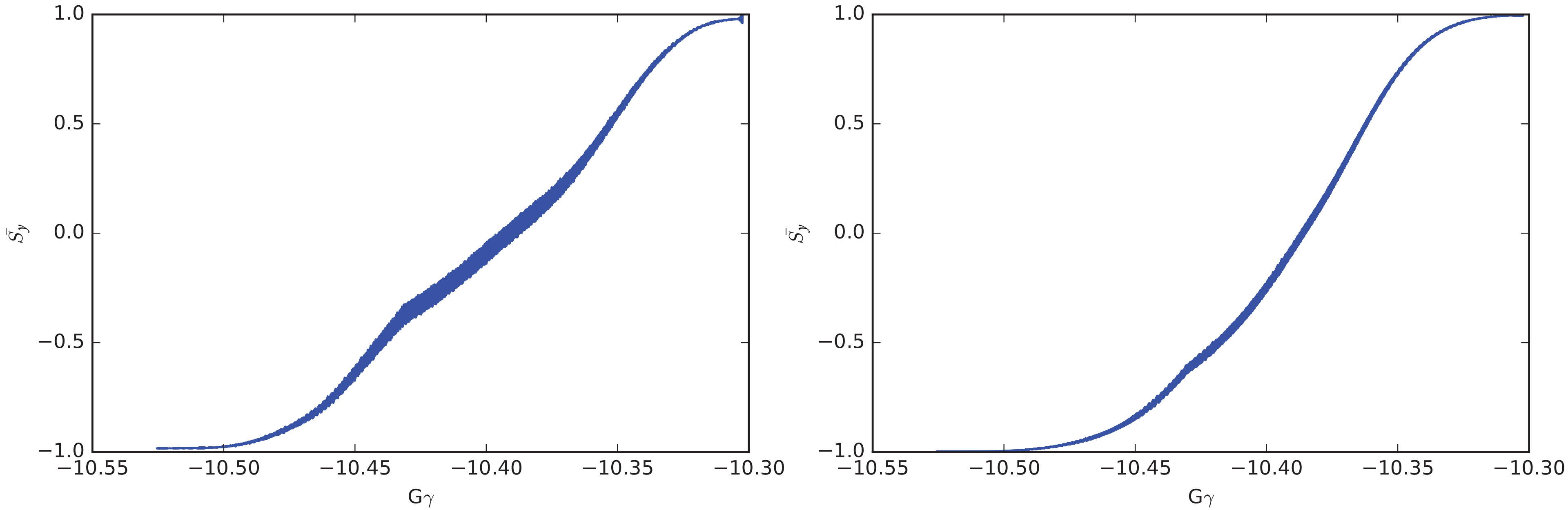


Figure : Examples for 6+ resonance. Left: Ensemble average of S_y with Gaussian bunch, $B_m l = 44.0\ Gm$, $P_f = -99\%$. Right: Ensemble average of S_y with truncated Gaussian bunch, $B_m l = 24\ Gm$. Beam was cut to 1σ to simulate scraping, $P_f = -99\%$.

Spin Tracking Results

	$12\text{-}\nu_y$	$6+\nu_y$
$\epsilon[\varepsilon_N = 4\pi]$	0.0103	0.0170
$\sigma_y[mm][Gaussian]$	5.87	4.88
$B_m l$ $[G\ \ m][Gaussian]$	33.9 (34.5)	44.0 (46.7)
$\varepsilon_{ratio}[Gaussian]$	1.00	1.06
$B_m l$ $[G\ \ m][Truncated]$	16.0	24.0
$\varepsilon_{ratio}[Truncated]$	1.00	1.00

Table : $B_m l$ shows strong agreement with theory (values in ()).

Conclusion

- Manageable hurdles that can be overcome.
  - Booster extraction + AGS injection power supplies.
    - Need to increase range 14%.
  - Negligible difference between AC-dipole requirements for 6 and 2 modules with the BMMPS.
    - BMMPS has exceeded design by 10% with 2 modules. Might be possible with 6.
  - AC-dipole is effective.
    - Can we improve the emittance?
  - Extraction at $G\gamma$=-10.5 is ideal to minimize optics distortions at low $B\rho$ and inject above 0+ in AGS.
  - Can we ramp from $\nu_y < 4.5$ to $\nu_y > 4.5$ to avoid 6+ all together?

Questions

Questions?

- S. Y. Lee. Spin Dynamics and Snakes in Synchrotrons. World Scientific 1997.
- H. Huang et al. Overcoming Depolarizing Resonances in the AGS with Two Helical Partial Siberian Snakes. Particle Accelerator Conference 2007 Proceedings June, 2007
- Lin. Towards Full Preservation of Polarization of Proton Beams in AGS. PhD Thesis, Indiana University December, 2007.
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- E. Bleser. Booster Short Quadrupole Measurements. Booster Technical Note no 174 September 12, 1990.
- F. Meot. Zgoubi User's Guide. CA/AP Note no 470. October, 2012
- S. Tygier et al. The PyZgoubi Framework and the Simulation of Dynamic Aperture in Fixed-Field Alternating Gradient Accelerators. Nuclear Instruments and Methods in Physics. Volume 775, pages 15-26. March, 2015.
- M. Bai, S. Y. Lee, H. Huang, T. Roser, M. Syphers. Overcoming the Intrinsic Spin Resonance using Resonance Island created by RF Dipole. AGS/RHIC/SN no 055 May 5, 1997.

Extra Slides

Abilitiy to recover emittance with AC-Dipole

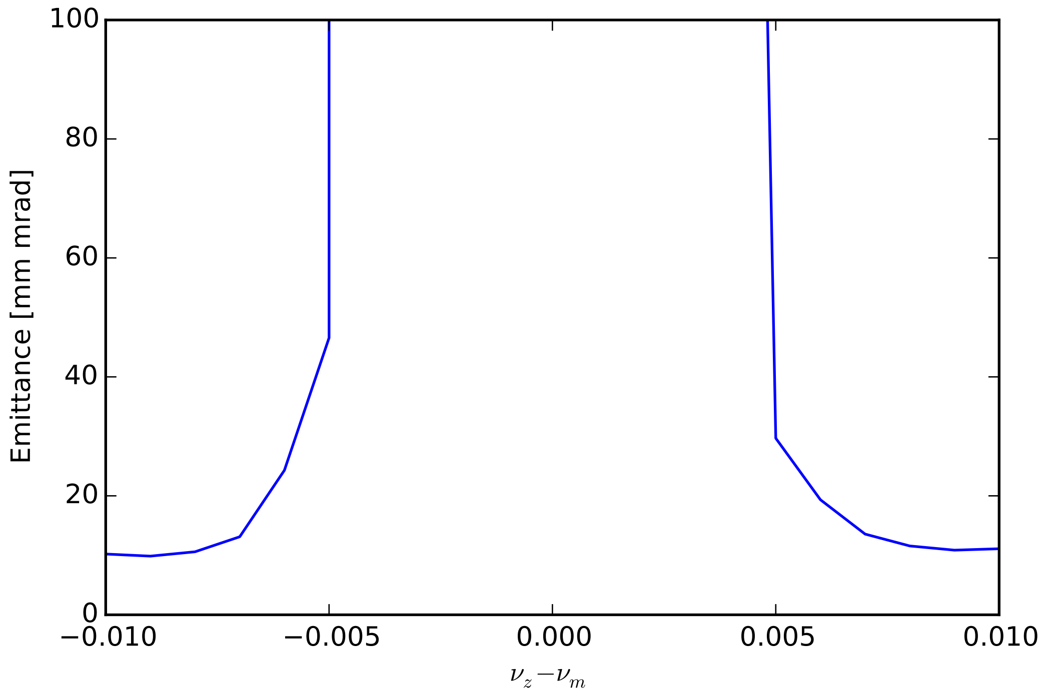

Figure : $B_x L = 14 Gm$ for a $\varepsilon = 10\pi$ particle. This data justifies a separation of 0.01 from ν_y.