He-3 polarization preservation in injectors

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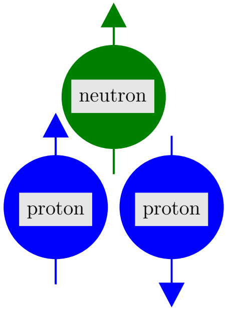
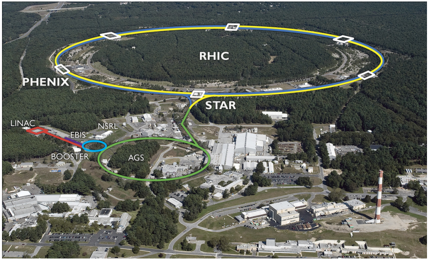
Table of Contents

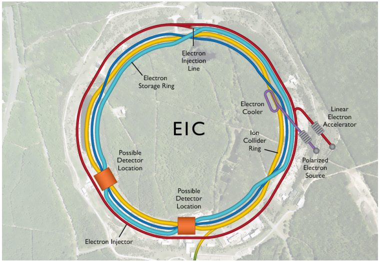
Why He-3?

- Polarized neutron collisions are part of the EIC physics program (q=0).
- Polarized neutron collisions will be facilitated with collisions of polarized He-3, where up to 86% of the polarization is accounted for by the neutron.
- Polarization scheme of He-3 provides polarized neutrons paired with two unpolarized protons, q=2.



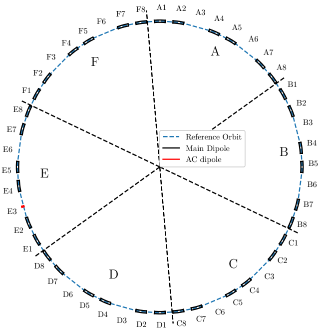
The RHIC and EIC Accelerator Complex





- RHIC scheduled to run until 2025.
- 2025 through 2032 is construction of EIC.
  - Installation of electron collider ring inside RHIC tunnel.
- EIC commissioning and physics program to follow.

Booster and AGS



The Booster will receive polarized He-3 from the EBIS at 2 MeV/u. The Booster:

- Has a superperiodicity of P=6, labelled A through F,
- Each superperiod contains 4 FODO cells and 6 main dipoles,
- Circumference of 201.78 m,
- $\nu_y < 4.5$ for polarized He-3 and $\nu_y > 4.5$ for polarized protons.
- Serves as the injector for the AGS.

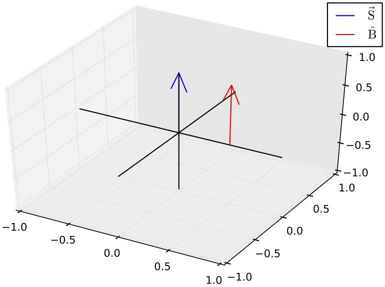
The AGS is the injector for RHIC

- Has a superperiodicity of 12 (labelled A through L) with a length of 807.12 m
- Tunes typically $\nu_y > 8.9$ for polarized protons.

Spin Dynamics

Torque on the magnetic moment from a magnetic field: $\vec{\Gamma} \propto \vec{S} \times \vec{B}$

- No torque if the two are parallel
- Maximum if the two are orthogonal



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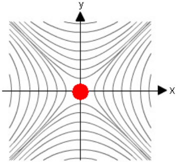
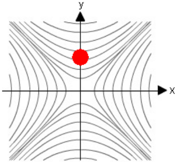
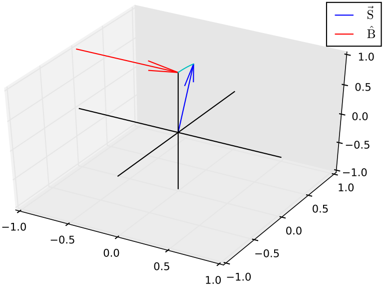


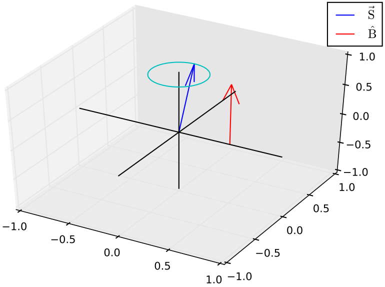




Spin Dynamics

Torque on the magnetic moment from a magnetic field: $\vec{\Gamma} \propto \vec{S} \times \vec{B}$

- No torque if the two are parallel
- Maximum if the two are orthogonal
- Beam now rotates in dipole field since they are no longer parallel.



Number of rotations the spin rotates in one turn is known as the spin tune: $\nu_s = G\gamma$, with G being the anomalous magnetic moment (G_{He-3}=-4.1842, $G_{protons}$=1.7928) and γ being the Lorentz factor.

Thomas-BMT

The Thomas-BMT equation is the equation of motion for a particle's spin vector, $\vec{S}$, in a synchrotron (neglecting effects of $\vec{E}$)

$$\frac{d\vec{S}}{dt} = \frac{q}{\gamma m}\vec{S} \times \left[(1 + G\gamma)\vec{B_\perp} + (1 + G)\vec{B_\parallel}\right] \tag{1}$$

- Term $\propto \vec{B}_\perp$ is strongest due to presence of strong focusing quadrupoles
- Terms $\propto \vec{B}_\parallel$ is small.

From this, the resonance strength can be calculated with the Fourier transform of spin perturbing fields

$$\epsilon_k = \frac{(1 + G\gamma)}{2\pi} \oint \left[\frac{\partial B_x/\partial y}{B\rho}\right] y e^{iK\theta} ds \tag{2}$$

Depolarizing Resonances

Depolarizing resonances are primarily caused by particles sampling the horizontal fields of quadrupoles.

This causes depolarization when the spin precession is in phase with the sampling of the fields. This occurs when:

1. Imperfection Resonances: $\nu_s = n$
   - Result of non-zero vertical closed orbits
2. Intrinsic Resonances: $\nu_s = nP \pm \nu_y$
   - The number of spin rotations in one turn of the ring is in phase with excursions into quadrupoles from betatron oscillations

where n is an integer and P is the superperiodicity.

Polarization preservation techniques in Injectors

Overview of polarization preservation techniques to be covered in detail:

In the AGS Booster

- Imperfection resonance crossing using orbit harmonic correction scheme
- Intrinsic resonance crossing using

In the AGS

- two partial snakes for overcoming imperfection and intrinsic depolarizing resonances.

The AGS snakes constrain our configurations and so will be covered first.

The AGS Snakes

The AGS has two partial helical dipoles (snakes) to preserve polarization through the vertical imperfection resonances. The two snakes are referred to as Cold and Warm, each rotate the spin a fixed amount (χ_C and χ_W) as particles transit the snakes on every turn.
The spin tune in this dual partial snake configuration is

$$\nu_s = \frac{1}{\pi}\cos^{-1}\left[\cos\frac{\chi_c}{2}\cos\frac{\chi_w}{2}\cos(G\gamma\pi) - \sin\frac{\chi_c}{2}\sin\frac{\chi_w}{2}\cos(G\gamma\frac{\pi}{3})\right] \quad (3)$$

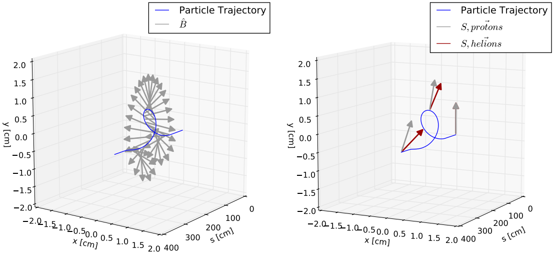
where the $\pi/3$ term is from the relative separation of the two snakes being one third of the ring. It is also important to note that $\nu_{\rm s} \neq {\rm G}\gamma$ with snakes.
The projection of the stable spin direction on the vertical axis is given by

$$\cos\alpha_3 = \frac{1}{\sin\ \pi\nu_s}\left[\cos\frac{\chi_w}{2}\cos\frac{\chi_c}{2}\sin(G\gamma\pi) - \sin\frac{\chi_w}{2}\sin\frac{\chi_c}{2}\sin(G\gamma\frac{\pi}{3})\right] \quad (4)$$

The vertical component of the stable spin direction, $\cos\alpha_3$, will be nearest vertical every

$$G\gamma = 3n + 1.5. \quad (5)$$

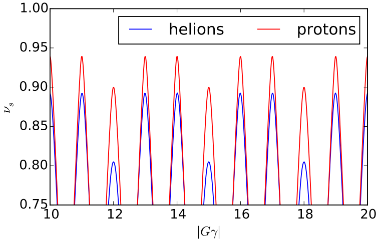
AGS Snakes

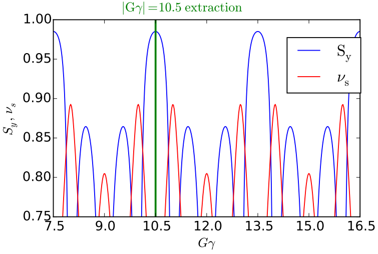


- This snake is a dipole magnet rolled into a helix.
- Direction of $\vec{B}$ sampled by particle and resulting spin rotation from vertical.
- The snakes are held at constant field.
- Due to horizontal component of stable spin direction, horizontal imperfection resonances are present.
- With the same field strength snakes, He-3 will rotate G_h/G_p more than protons.
- This gives χ_c=25% and χ_w=14% (in units of % of π)

ν_s and α_3 in the AGS

By having $\nu_s \neq G\gamma$, the criteria for imperfection resonance can no longer be satisfied.





This results in a substantial spin tune gap where both ν_x and ν_y can be placed. Having both tunes inside the spin tune gap means the horizontal imperfection resonances are also avoided.

- No emittance growth from many tune jumps
- No polarization loss from

AGS Snakes

To quantify the optical defects, particles are tracked through only the cold snake to calculate the transport matrix.
From the transport matrix, the total coupling (CP) and focusing (FC) are calculated from transport matrix elements m_{ij},[a]

$$CP = LL + UR \tag{6}$$

with

$$LL = m_{31}^2 + m_{32}^2 + m_{41}^2 + m_{42}^2 \tag{7}$$

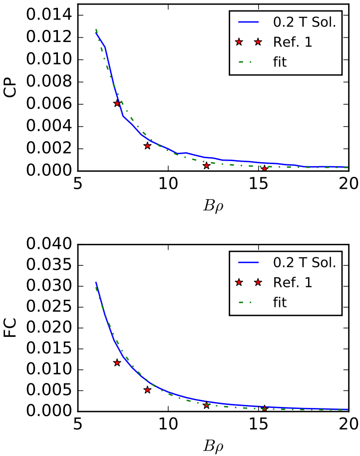
$$UR = m_{13}^2 + m_{14}^2 + m_{23}^2 + m_{24}^2. \tag{8}$$

and

$$FC = m_{12}^2 + m_{34}^2 \tag{9}$$

[a] Ref 1, C-A/AP 128, Cold Snake Optimization by Modelling

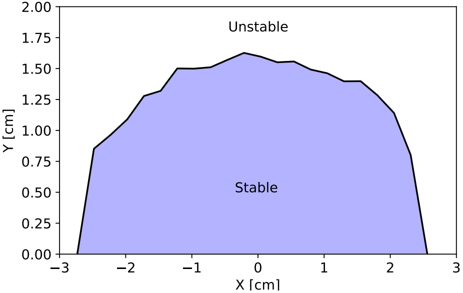
These optical distortions reduce exponentially with $B\rho$.



Admittance Calculation

Protons cannot fit inside the spin tune gap at injection due to the snake optical defects limiting the admittance.

Admittance is the stable area in X and Y for a given $[\nu_x, \nu_y]$. This shown for protons at $|G\gamma| = 4.5$ and $[\nu_x, \nu_y]$=[8.77, 8.88]



Compare admittance of protons at $|G\gamma| = 4.5$ ($B\rho = 7.2$ Tm) to He-3 at $|G\gamma| = 7.5$ and 10.5 ($B\rho = 7.0$ Tm and $B\rho = 10.8$ Tm).

pyZgoubi is used to handle particle coordinates and fitting algorithms,and creates a thread for each ν_y and ν_x configuration.

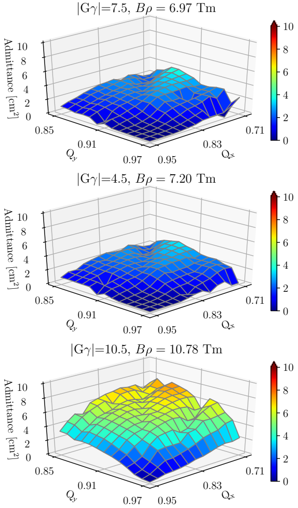
AGS Admittance Simulation Results

Simulations are performed at $B\rho = 6.968$ Tm, $B\rho = 7.203$ Tm, and $B\rho = 10.780$ Tm as seen in figure.

- There are subtle differences in the admittance between He-3 at $B\rho = 6.968$ Tm and protons at $B\rho = 7.203$ Tm
- A minimum factor of 2 gain in admittance in the $B\rho = 10.780$ Tm case.

The admittance calculations are done for 1,000 turns to minimize computing time.

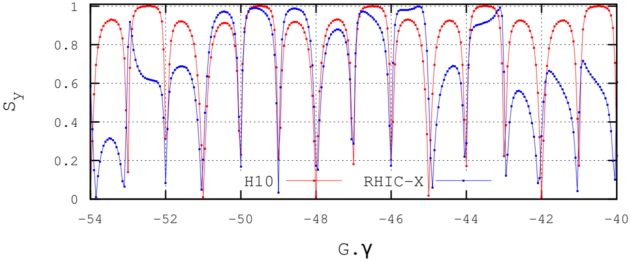
- Idealized admittance tracking would be for a number of turns equal to the time the particles are at injection energy.



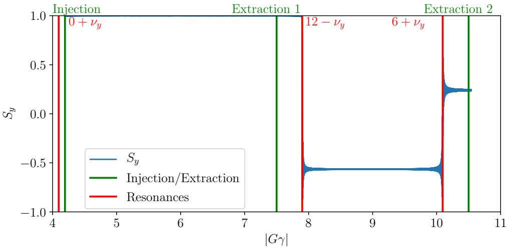
Extraction from AGS

He-3 will be extracted from the AGS at $|G\gamma| = 49.5$.

- Due to mismatch in stable spin direction between RHIC and AGS, extraction cannot occur above $|G\gamma| = 51.5$.
- This is lower in rigidity ($B\rho = 55.21\ Tm$) than protons which extract at $G\gamma = 45.5$ ($B\rho = 79.37\ Tm$).



Overview of He-3 in the Booster



- He-3 are injected into the Booster at $|G\gamma| = 4.19$
- At injection, $\nu_y < 4.1$ to avoid the $|G\gamma| = 0 + \nu_y$ resonance
- Extraction possible at $|G\gamma| = 7.5$ and $|G\gamma| = 10.5$

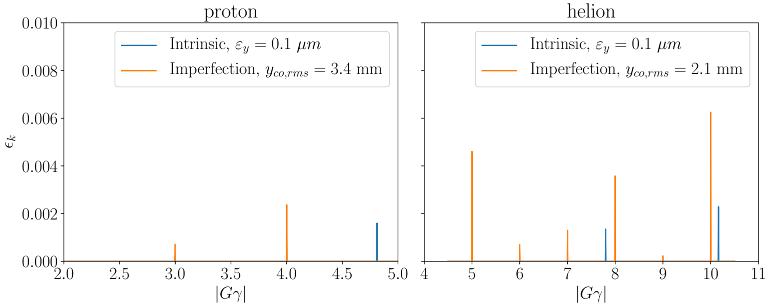
Extraction at $|G\gamma| = 10.5$

- Crossing $|G\gamma| = 5$ through 10 imperfection resonances
- Crosses $|G\gamma| = 12 - \nu_y$ and $|G\gamma| = 6 + \nu_y$
- Avoids $|G\gamma| = 0 + \nu_y$ in AGS
- Minimizes optical defects from AGS cold snake
- Vertical tune can be placed inside spin tune gap in AGS at injection

Booster Resonance Strengths

The resonance strengths are calculated using the Zgoubi and MADx models.

Intrinsic and imperfection resonance strength spectra in the Booster for protons and He-3 in the $|G\gamma|$ range of interest:



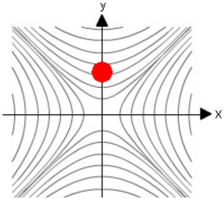
Intrinsic Resonance Crossing with an AC Dipole

An AC dipole works by forcing all particles to undergo large amplitude vertical betatron oscillations.

- This is done with a horizontal magnetic field that oscillates in phase with the vertical betatron motion, at tune $\nu_m = f_m / f_{rev}$.
- The amplitude of these coherent oscillations is

$$Y_{coh} = \frac{B_m l}{4\pi B\rho\delta_m}\beta_y \tag{10}$$

  where $B_m l$ is the integrated strength of the dipole kick.
- The separation between the tune of the AC dipole, ν_m, and ν_y is the resonance proximity parameter, $\delta_m = \nu_y - (n + \nu_m)$.
- This creates a driven resonance at ν_m.

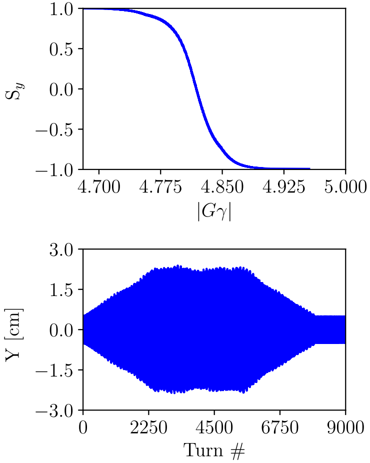


As f_m is fixed, ν_m can change as much as $\Delta\nu_m = 0.0028$ for He-3 crossing $|G\gamma| = 12 - \nu_y$ due to rapid change in f_{rev}

Intrinsic Resonance Crossing with an AC Dipole

Protons crossing the $|G\gamma| = 0 + \nu_y$

- Spin-flip observed as the projection of spin on the vertical axis transitions from +1 to -1 before and after the resonance.
- Spin-flip achieved with $\mathrm{B_m l} = 15.5\ \mathrm{G \cdot m}$.



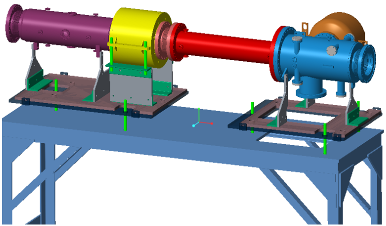
Summary of AC dipole Simulations

	Protons	He-3	
Resonance	$0+\nu_y$	$12-\nu_y$	$6+\nu_y$
ϵ_K	0.00246	0.00304	0.00440
σ_y [mm]	1.83	2.75	2.31
δ_m	0.01	0.01	0.01
$B_m l$ [Gm]	15.5	16.5	20.5
ν_y	4.809	4.192	4.174
ε_{ratio}	1.03	1.02	1.00
$N_{scraped}/N_{total}$[%]	0.0	1.2	0.0

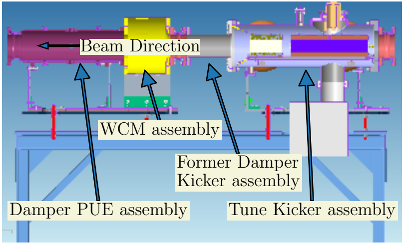
where σ_y is the RMS width of the beam, ε_{ratio} is the comparison of σ_y at the start and end of the tracking, and $N_{scraped}/N_{total}$ monitors particle loss.

AC Dipole Upgrade

Old

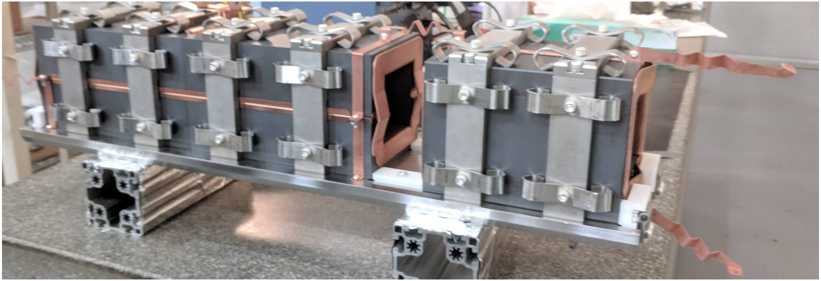


New



- Vertical kicker magnet length increased from 12 cm to 50 cm.
- Horizontal kicker magnet length increased from 12 cm to 20 cm.
- Damper kicker was removed to accommodate larger tunekicker assembly (had not been used since high intensity protons)
- Vertical limiting aperture was measured with beam to be ± 3.5 cm.

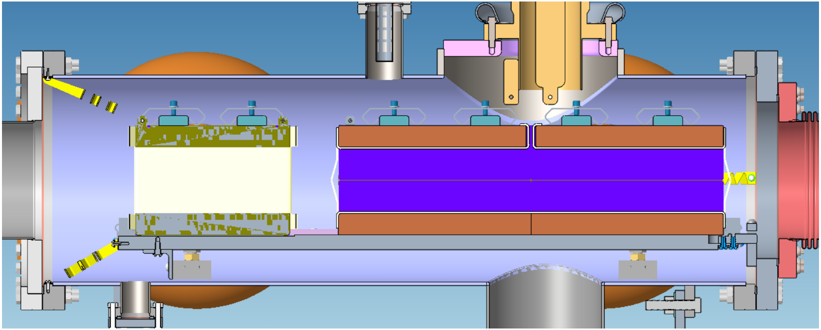
Physical magnet parameters



	Vertical Magnet	Horizontal Magnet
l [cm]	50	20
Opening[cm] (H×V)	8.6×8.2	9.6×8.6

These dimensions were chosen so magnet would not become limiting aperture of the machine.

Physical magnet parameters II



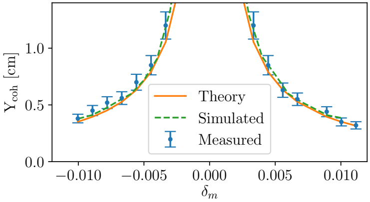
The AC dipole is powered as part of a resonant LC circuit

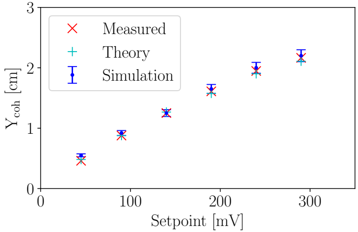
A drive frequency of $f_m = 250\ kHz$ is the maximum supported frequency for the power amplifier used in this beam test.

The design strength is $\mathrm{B_m l} = 25\ \mathrm{G \cdot m}$ providing $\sim 25\%$ margin from simulation.

Beam Dynamics with an AC dipole

Beam dynamics studies with unpolarized protons showed strong agreement between measurements, theory, and simulations.

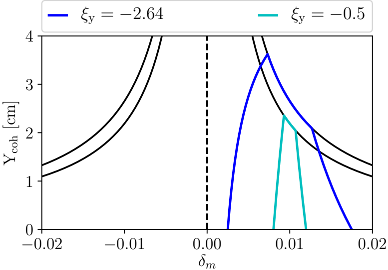


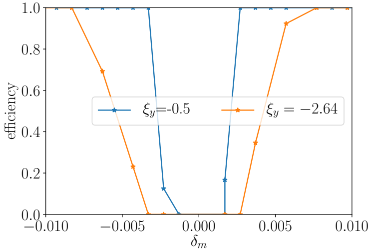


- Protons at this time were injected at 116 MeV, not nominal 200 MeV.

AC dipole results, pre experimental period II

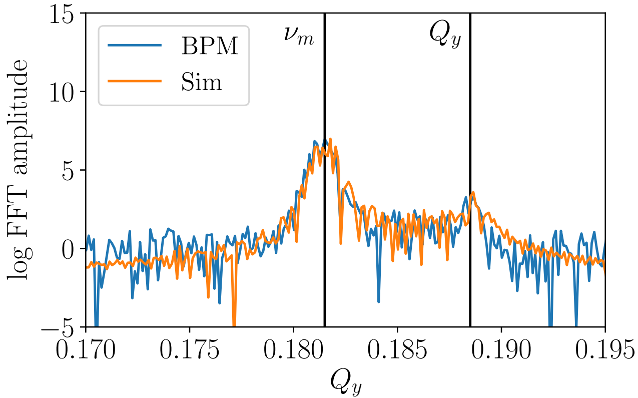
Chromaticity near zero shows narrow δ_m which minimizes losses when compared to natural chromaticity,





Minimizing ξ_y minimizes the spread in ν_y and thus minimizes the achievable $\delta_m$without beam loss.
Mechanism for loss generation shown on left where the natural chromaticity occupies a wide range of δ_m.

Fourier analysis of BPMs



- Comparison of FFT confirms measurement of δ_m=0.008.
- FFT of simulation and measurements show good agreement.

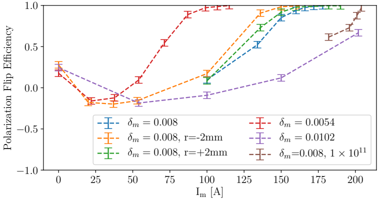
Configuration for Proton Beam Tests

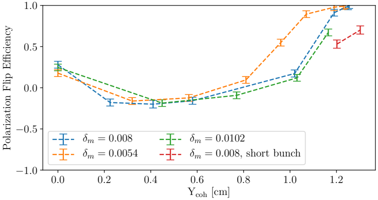
Protons are injected into the Booster from the 200 MeV LINAC

- $|G\gamma|_{injection} = 2.18$
- $\nu_y > 4.5$
- $|G\gamma_{extraction}| = 4.5$, avoiding the $|G\gamma| = 0 + \nu_y$ intrinsic resonance.
- Crosses the $|G\gamma| = 3,\ 4$ imperfection resonances.
- $|G\gamma|_{extraction}$ moved to $|G\gamma|_{extraction} = 4.93$ to cross $|G\gamma| = 0 + \nu_y = 4.81$.
  - Turn off AGS snakes so stable spin directions are matched.
  - Use AC dipole to preserve polarization across resonance.

Experimental Results

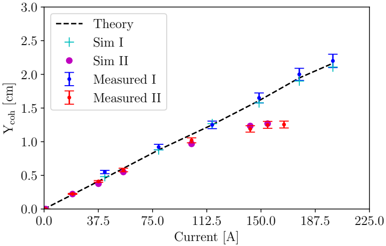
- Were able to spin flip with multiple measurements on the asymptote.
- Due to limited beam time, the operation condition was tuned for 0.5×10^{11} protons.
- More details to follow.





Results and Issues

BPM data shows reduced Y_{coh} vs I_m:



The RF operated in a fixed f_{rev} mode:

- which is the synchronization of RF for extraction from Booster to AGS (synchro) beginning 15 ms before extraction,
- it caused a change in radius to maintain the predetermined f_{rev},
- the change in radius caused feed-down in the sextupoles which resulted in a change of δ_m and a reduction of Y_{coh}.

The change in radius is

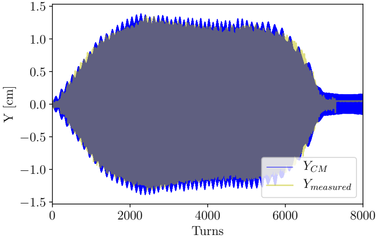
$$\Delta r = \frac{1}{2}\left\langle \frac{1+\alpha_y}{\beta_y} \right\rangle \frac{Y_{coh}^2}{2\beta_y} r. \tag{11}$$

This is implemented in Zgoubi with a radial change at turn 1200 to match experimental data.

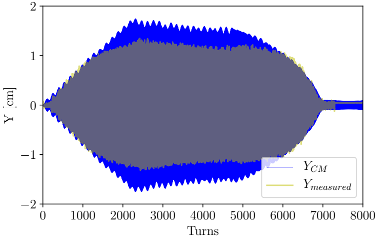
Simulations of Δr at 136 A

Comparison of 136 A setpoint with and without radial change.

Radial change

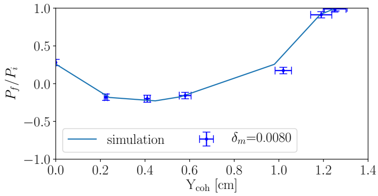


No radial change



Here, Y_{CM} is simulation and $Y_{measured}$ is the measurement. The $Y_{measured}$ is semi-transparent to not obscure Y_{CM}.

Comparison of Experimental and Simulation Results



- Simulations show good agreement with measurements.
- Improvements between simulations and experimental data were achieved by mimicking the real beam conditions in detail.

Comparison of ϵ_k from simulation and experimental results:

	Simulation (2017)	Experiment
σ_y [mm]	1.83	1.23
$\epsilon_k(\sigma_y)$	0.002460	0.001905
$\epsilon_k(1.83\ mm)$	-	0.002324

Reflection on He-3 with an AC dipole

- The model proved to accurately determine AC dipole requirements for polarized protons

He-3 crossing $|G\gamma| = 6 + \nu_y$ will occur 14.4 ms before extraction.
To avoid interference with synchro, there are several options:

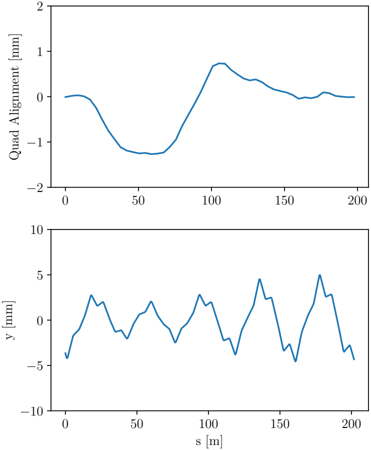
- Study the synchro process to determine if it can be shortened.
- Reduce the pulse length so normal variation is still accommodate with minimal buffer
- Reduce the acceleration ramp rate after crossing the AC dipole pulse to ensure no interference from synchro.

Imperfection Resonances

For correcting the $|G\gamma| = k$ resonance, the h=k harmonic of the corrector dipoles is used.
Harmonic h=k can be:

- corrected so no polarization is lost,
- or enhanced to induce a full spin-flip.

The vertical closed orbit error is introduced by misaligning quadrupoles in the Zgoubi model according to survey data.



Imperfection Resonances: Harmonic Orbit Correction

The Booster has 24 vertical orbit correctors placed adjacent to vertically focusing quadrupoles, and are used for creating and correcting orbit harmonics. These correctors are powered according to

$$B_{j,h} = a_h \sin(h\theta_j) + b_h \cos(h\theta_j) \tag{12}$$

where j is corrector number, θ_j is the location in the ring, a_h and b_h are the amplitudes for harmonic h.
The total current on corrector j is

$$I_j = \sum_h I_{h,S} \sin(h\theta_j) + I_{h,C} \cos(h\theta_j) \tag{13}$$

where $I_{h,S}$ and $I_{h,C}$ are the corrector currents for the Sine and Cosine components. The maximum current of all correctors is

$$I_{max} = \max[|I_j|]. \tag{14}$$

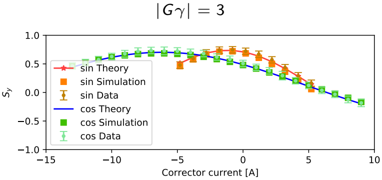
This is an important parameter so as to avoid exceeding the maximum current of the supplies, 25 A.

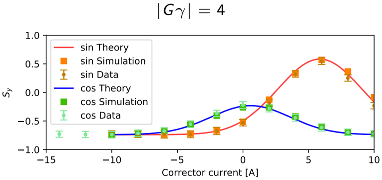
Protons Harmonic Scan at $|G\gamma|$=3,4

The Froissart-Stora formula at a given resonance k, and harmonic h=k, as a function of corrector current is given by,

$$\frac{P_f}{P_i} = 2e^{-\frac{(I_{k,S}-I_{k,oS})^2}{2\sigma_{k,S}^2}} e^{-\frac{(I_{k,C}-I_{k,oC})^2}{2\sigma_{k,C}^2}} - 1 \qquad (15)$$

where $I_{k,oS}$ and $I_{k,oC}$ are the optimal corrector currents, and $\sigma_{k,S}$ and $\sigma_{k,C}$ the widths. Harmonic scan of protons crossing $|G\gamma| = 3,\ 4$ with a comparison between theory, simulations, and experimental data,





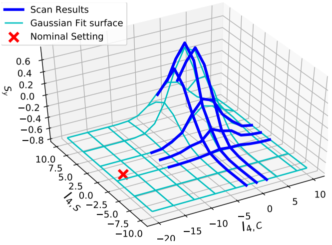
Proton Harmonic Scan summary

Summary of fit data to proton harmonic scans.

k	source	$I_{k,oS}$ [A]	$\sigma_{k,S}$ [A]	$I_{k,oC}$ [A]	$\sigma_{k,C}$ [A]
3	scan data	-1.1821	3.8390	7.5322	6.1607
3	simulation	-1.2997	3.5643	7.8536	6.2140
4	scan data	5.8646	3.2160	0.5740	3.2160
4	simulation	6.0330	3.2482	0.7019	3.3593

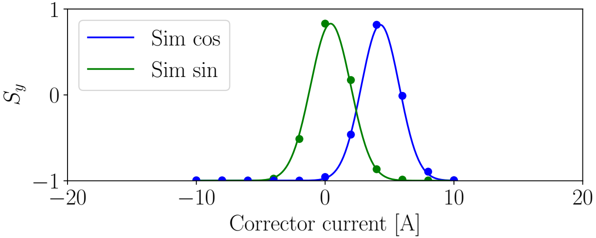
A scan using Zgoubi at various initial currents of the sine and cosine corrector families shows the reliance on initial currents in the scan shown on right:

- The light blue surface grid is reconstructed by fitting to the experimental data and extrapolating it to a larger range.
- The red 'X' marks corrector currents used in Run17, $I_{4,S}$, $I_{4,C}$ =[0 A, -18 A].



He-3 Crossing $|G\gamma|$=5

With the experimental data of protons being well matched with simulation, the treatment is extended to He-3. Figure below shows a harmonic scan for He-3 crossing $|G\gamma| = 5$.



To correct the orbit harmonic h=4, [$I_{4,S}$, $I_{4,C}$]=[2.797 A, 0.669 A] and to spin-flip: h=5 currents are [$I_{5,S}$, $I_{5,C}$]=[10.0 A, -18.0 A] and I_{max}=23.086 A. Harmonic scans for the remaining imperfection resonances and fit results are summarized in Table and corrector family currents and corresponding I_{max} on next slides.

He-3 Harmonic Scan Summary

To allow all He-3 imperfection resonances to be studied with the same orbit, the h=4 and h=5 harmonic corrections are scaled to all higher order resonances by the ratio of rigidity. That is

$$I(h=5, |G\gamma|=k) = I(|G\gamma|=5)\frac{B\rho(|G\gamma|=k)}{B\rho(|G\gamma|=5)} \tag{16}$$

These corrector currents are

$[I_{4,S},\ I_{4,C},\ I_{5,S},\ I_{5,C}]$=[2.797 A, 0.669 A, 0.520 A, 4.296 A]

Table: Summary of fit data for He-3 harmonic scans.

k	$I_{k,oS}$ [A]	$\sigma_{k,S}$ [A]	$I_{k,oC}$ [A]	$\sigma_{k,C}$ [A]
5	0.5200	1.5750	4.2955	1.5288
6	1.2226	3.6268	-0.2896	2.7384
7	3.1077	4.4358	1.8801	4.5166
8	-4.8460	4.8366	10.6646	5.5313
9	-1.1232	5.2331	-0.3165	3.9495
10	-23.6518	5.5783	-0.4287	5.4708

These fit parameters are used to determine optimal correction currents.

Summary of Corrector Strength Requirements

The set of $I_{k,S}$ and $I_{k,C}$ are able to correct the harmonic
($|G\gamma| = 3$ and 9)
or enhance it
($|G\gamma| = 4,\ 5,\ 6,\ 7,\ 8,\ 10$)

K	μ_S [A]	μ_C [A]	$I_{S,K}$	$I_{C,K}$	$I_{M,F}$	$I_{M,C}$
5	0.322	2.105	0.35	-1.71	4.33	6.44
6	0.567	-0.189	1.78	9.65	17.77	9.19
7	1.425	0.847	10.02	-8.14	22.4	13.95
8	-2.463	5.242	2.75	-9.39	21.98	22.37
9	-0.614	-0.222	-1.17	-14.35	29.71	17.59
10	-23.669	-0.477	-3.67	-0.477	22.86	39.43

To improve the margin here, the existing Booster Corrector supplies will be modified to allow 40A of maximum current.

Upgrades, Caveats, and Unknowns

The BtA transfer line is designed for a maximum $B\rho = 9.5\ Tm$ which is primarily limited by the kicker magnets.

- These will need to be upgraded to support higher extraction energy.

The Booster Main Magnet power supply only has two of six modules capable of going beyond $B\rho = 9.5\ Tm$

- The slower ramp rate from having lower voltage does not adversely effect polarization transmission in the booster.

Unknown how much intesnity the polarized He-3 source will provide

- If intensity from the source is low, multiple pulses will be needed from booster and then merged in AGS at injection.
- This is more reason to have the stronger snake configuration to support polarization lifetime.

Summary I

On AGS

- Simulations showed that the available admittance increases with magnetic rigidity due to reduced optical defects from the AGS snakes.
- Extraction for He-3 at $|G\gamma| = 10.5$ provide a larger admittance that would allow both betatron tunes to be put within the spin tune gap at injection.
- This extraction energy also allows the $|G\gamma| = 0 + \nu_y$ resonance to be avoided in the AGS.

On Imperfection Resonances

- Simulations of imperfection resonances using misaligned quadrupoles from survey data match experimental scan data for protons crossing $G\gamma$=3 and $G\gamma$=4.
- This method was extended to simulate these resonances for He-3.
- These simulations determined there is sufficient corrector current to correct each of the imperfection resonances crossed as He-3 is accelerated to $|G\gamma|$=10.5.

Summary II

On Intrinsic Resonances and the AC dipole experiment

- Able to demonstrate full spin-flip of protons using AC dipole.
- Reduced Y_{coh} from x_{co} changes and feed-down in sextupoles prevented spin-flipping for nominal emittance beam.
- Simulations are able to replicate experimental data by modulating the radius.
- He-3 crossing the $|G\gamma| = 6 + \nu_y$ resonance should be fine as the AC dipole pulse would be 14.4 ms away from extraction.

Thank you

Thank you and questions.

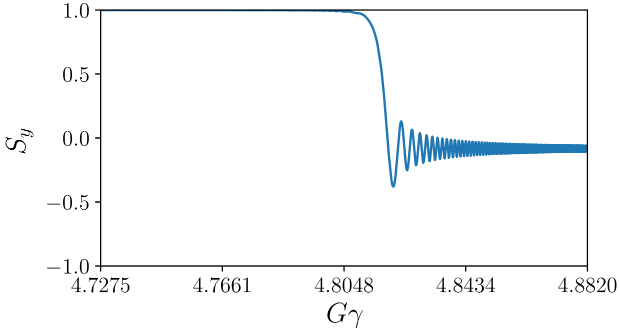
Extra Slides

Resonance Strength Calculations I

Froissart-Stora formula has a single particle accelerated through resonance.

$$\frac{P_f}{P_i} = 2exp(-\frac{\pi|\epsilon|^2}{2\alpha}) - 1 \quad (17)$$

This case is for a single proton,



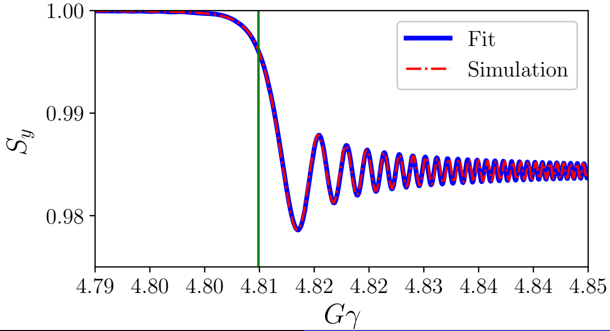
Resonance Strength Calculations II

Fresnel Integral

$$Upstream(\theta < 0) : (P(\theta)/P_i)^2 = 1 - \frac{\pi}{\alpha}\epsilon^2 \left[(0.5 - C(-\theta\sqrt{\frac{\alpha}{\pi}}))^2 + (0.5 - S(-\theta\sqrt{\frac{\alpha}{\pi}}))^2 \right]$$
$$Downstream(\theta > 0) : (P(\theta)/P_i)^2 = 1 - \frac{\pi}{\alpha}\epsilon^2 \left[(0.5 + C(\theta\sqrt{\frac{\alpha}{\pi}}))^2 + (0.5 + S(\theta\sqrt{\frac{\alpha}{\pi}}))^2 \right] \quad (18)$$

$$C(x) = \int_0^x cos(\frac{\pi}{2}t^2)dt, \;\; S(x) = \int_0^x sin(\frac{\pi}{2}t^2)dt \quad (19)$$

θ is the distance to the resonance.



Resonance Strength Calculations III

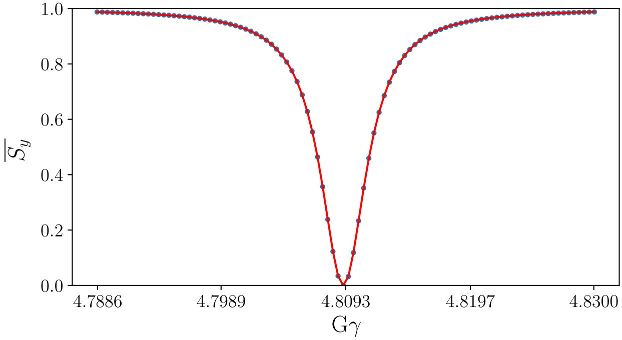
Static depolarization A particle is allowed to freely oscillate at $G\gamma$ values neighboring the resonance.

$$\bar{S_y^2} = \frac{1}{1 + |\epsilon|^2/\Delta^2} \tag{20}$$

$$\Delta = G\gamma - (n\ m - \nu_y) \tag{21}$$

A good place to start trying to preserve the spin is around $G\gamma_o = G\gamma_R - 7\epsilon_k$

derived from $|\varepsilon_k|$, $\Delta = \sqrt{\frac{S_y^2}{S_y^2 - 1}}\epsilon_k$ for $S_y = 99\%$.



Summary of Intrinsic Resonance Crossing

The three methods are compared with results from DEPOL which use a MADx output optics file to calculate the Fourier amplitude, ϵ_k.

	K	Froissart-Stora		Fresnel Integral		Static		DEPOL
$\varepsilon_y(\mu m)$		ϵ_K	P_f	ϵ_K	ν_y	ϵ_K	ν_y	ϵ_0
Protons								
0.001	$0+\nu_y$	0.000160	0.984	0.000160	4.8091	0.000161	4.8091	0.000161
0.234						0.002463	4.8091	0.002469
He-3								
0.001	$12-\nu_y$	0.000135	0.993	0.000135	7.8079	0.000132	7.8082	0.000130
0.535						0.003037	7.8082	0.003013
0.001	$6+\nu_y$	0.000229	0.933	0.000238	10.1739	0.000226	10.1742	0.000224
0.369						0.004396	10.1742	0.004294

These methods from the preceding slides are also used for imperfection resonance crossing.

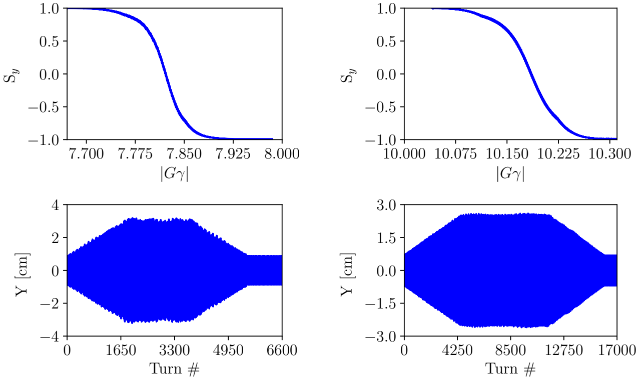
Imperfection Resonance Strengths

The imperfection resonance strengths are calculated for protons and He-3 after including quadrupole alignment data.

Species	k	$B\rho$ $[T \cdot m]$	ϵ_k	
			Simulation	Calculation
Protons	3	4.198	0.000714	0.000644
	4	6.240	0.002367	0.002396
He-3	5	3.064	0.004605	0.004492
	6	4.814	0.000701	0.000716
	7	6.282	0.001299	0.001158
	8	7.633	0.003582	0.003834
	9	8.920	0.000226	0.000239
	10	10.167	0.006252	0.006646

Intrinsic Resonance Crossing with an AC Dipole

He-3 crossing the $|G\gamma| = 12 - \nu_y$ (left) and $|G\gamma| = 6 + \nu_y$ (right)



Full spin-flip achieved with $\mathrm{B_m l} = 16.5\ \mathrm{G \cdot m}$ ($|G\gamma| = 12 - \nu_y$) and $\mathrm{B_m l} = 20.5\ \mathrm{G \cdot m}$ ($|G\gamma| = 6 + \nu_y$).

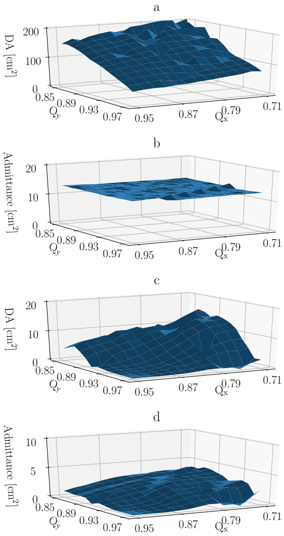
Simulation Results I

A comparison of the DA and admittance is made for the AGS in the absence and presence of snakes. This is shown for He-3 at $|G\gamma|=7.5$ in Figure on right:

- a snakes off, no limiting aperture;
- b snakes off with limiting aperture;
- c snakes on, no limiting aperture;
- d snakes on, with limiting aperture.

Key observations:

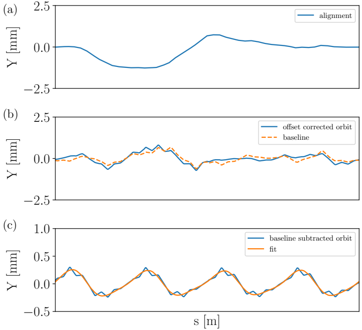
- the snakes severely reduce the DA and admittance of the machine,
- the DA is larger than admittance of the machine,
- the strong optical defects cause a further reduction in the admittance.



Booster Alignment Errors

Quadrupole alignment errors from survey seen in (a) and placed into the Zgoubi input files using PyZgoubi using the CHANGREF keyword.

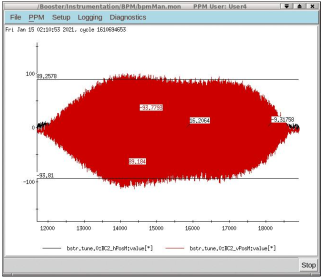
- a Vertical quadrupole misalignments in the Booster are scaled to 65% to match h=4 data;
- b Orbit after incorporating misalignments with $I_{4,S}$=5.22 A and baseline orbit with $I_{4,S}$=6.97 A, and all other harmonic strengths being the same;
- c Baseline subtracted orbit for He-3 crossing the $|G\gamma| = 8$ resonance.

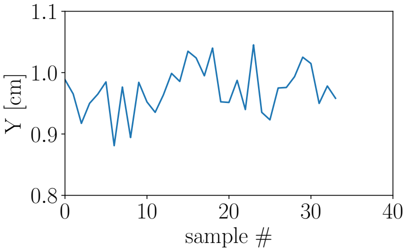


This example orbit at $|G\gamma| = 8$ has a corrector current with respect to h=8 of cos8v=5 A, sin8v=13 A. The components of the fit results are: [sin4, cos4, sin5, cos5, sin8, cos8]=[0.1997 mm, 0.07796 mm, 0.01137 mm, 0.00031849 mm, -0.01263 mm, -0.04177 mm].

BPM Analysis

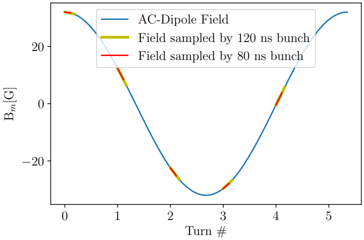
- Each polarization measurement took ∼10 minutes with many cycles.
- Y_{coh} is measured at the midpoint of the pulse.
- The archives are read and analyzed for each pulse logged to get Y_{coh}
- Example shown below for 100 A setpoint with $Y_{coh} = 0.972 \pm 0.038$ cm

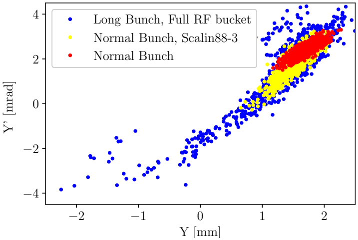




Bunch Length II

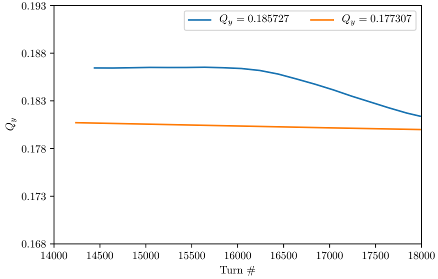
- Bunch length can cause filamentation in phase space due to different arrival times of particles vs AC dipole phase.
- Simulations showed no change in P_f with the same bunch parameters.

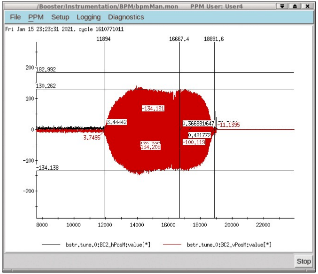




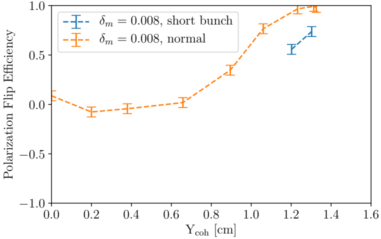
Operating AC dipole with Extraction Bumps

- Ramp up of extraction bumps cause vertical tune to start decreasing at turn $\sim$16250
- Ramp down of AC dipole begins at turn $\sim$16667
- This results in δ_m decreasing as the AC dipole amplitude is ramped down, causing a non-adiabatic ramp down of Y_{coh}
- Tune measurement on left taken @2200 01/15/2021.
- Sine fit is performed for 200 turns every 200 turns through the duration of the oscillations.





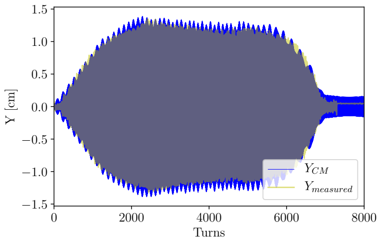
Short Bunch



- Simulations showed a longer bunch would improve AC dipole performance due to smaller dp/p.
- Long Booster bunches require lengthy setup time where short bunches are quick.
- To prove effect of bunch length on polarization, a comparison between a normal and short bunches are made.
- Short bunch showed reduced AC dipole performance vs normal bunch.

Simulations at high I_m

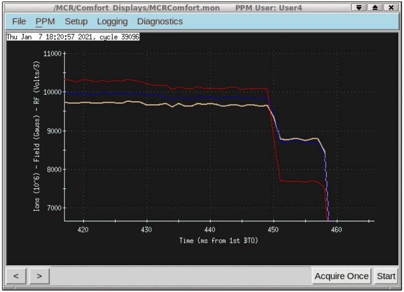
Y_{coh} = 1.19 cm, I_m=136 A



- $Y_{coh,theory}$=1.41 cm, $Y_{coh,measured}$=1.186 cm, $Y_{coh,sim}$=1.198 cm
- Radius changed by Δr=0.8 mm by scaling the momentum of all particles up to dP/P=1.0003 between turns 1200 and 5800.
  - Main dipoles already scaling for acceleration so radius changes are done by manipulating the momentum.
- Changing the radius in this way causes the beam to undergo synchrotron motion.
  - Need to look into updating circumference in CAVITE.
  - Sufficient for matching experimental data

Emittance Growth

During beam dynamics studies, scraping was setup after the AC dipole pulse so any emittance growth would show increased losses.



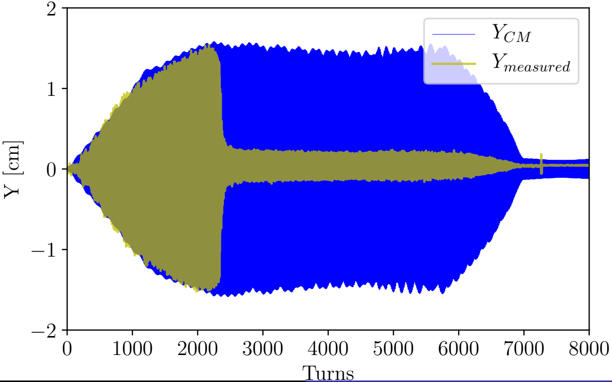
- Red- AC dipole on
- Blue- AC dipole off
- Yellow?- AC dipole on after tuning (conditions used for experiment)

- During experimental period, emittance was measured on BtA MW006 and showed negligible emittance growth for most configurations.
  - Given $C_y \sim 0$, there would possibly be emittance dilution in AGS. The IPM was unable to be configured for this intensity.

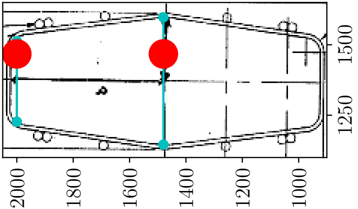
Comparison with Beam Loss

$Y_{coh,peak} = 1.45$ cm results in ∼40% beam loss and a reduction in the BPM signal.

Note given σ_y=1.23 mm and Y_{coh}=1.45 cm, these losses are below the aperture of 3.5 cm and inconsistent with previous experiments.



Beam Loss notes



- Vertical aperture at center of beam pipe is ± 3.49 cm.
- Vertical aperture at x=± 8.255 cm from center of beampipe is ± 2.22 cm.
- Horizontal scraping and adjustment of horizontal tunes improved AC dipole losses.
- Plot shows 1.23 mm beam with $Y_{coh} = 1.5\ cm$ at center of beampipe and with a large horizontal excursion.

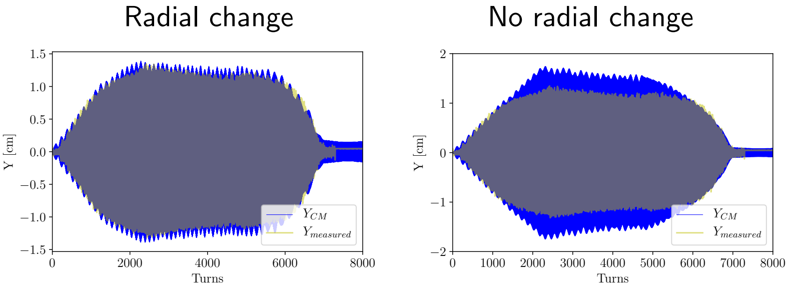
With a Y_{coh}=2 cm there is a corresponding radius change of Δr=0.18 mm. This is following

$$\Delta r = \frac{1}{2}\left\langle \frac{1+\alpha_y}{\beta_y} \right\rangle \frac{Y_{coh}^2}{2\beta} r \tag{22}$$

- For the detuning observed in the experiment and matched with simulation, a radius change of $\Delta r \sim 1$ mm would be needed.
- Change in radius is not entirely contributed to Y_{coh}'s path length increase.
- Radius change from RF logs show additional 0.5 mm change

Simulations of Δr at 136 A

Comparison of 136 A setpoint with and without radial change.



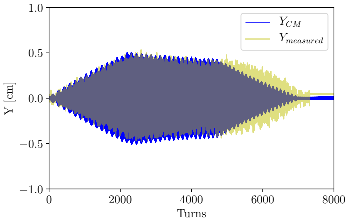
Here, Y_{CM} is simulation and $Y_{measured}$ is the measurement. The $Y_{measured}$ is semi-transparent to not obscure Y_{CM}.

Simulations: AC dipole with extraction bumps on

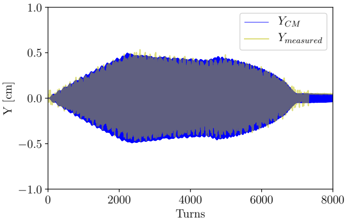
- Ramp up of extraction bumps causes large residual horizontal orbit.
- Horizontal orbit causes feed-down from sextupoles and a reduction in δ_m.
- Reduction of δ_m as the AC dipole ramps down causes a non adiabatic ramp down.
- Non-adiabatic ramp down causes oscillations to continue after AC dipole is ramped down.
- Resolved by separating the AC dipole pulse from the extraction bumps with a scan of the pulse start time and adjusting the extraction bump pulse.

$Y_{coh} = 0.36$ cm

Extraction bumps off:



Extraction bumps on:



$G\gamma$=5.1 extraction

- Would give a better comparison to He-3 data.
  - Sufficient separation from extraction bumps and improved separation for synchro.
- Determined time to tune h=5 would be too lengthy.
  - -8 A change in sin5v resulted in polarization +1%.
- Would be worthwhile to pursue in future when more time is available.

Future Prospects:
Extraction at higher $|G\gamma|$ to allow separation between synchro and AC dipole

- Extraction at $|G\gamma|$=5.5 has the AC dipole pulse ending at $|G\gamma|$=4.93.
- With $t_{extraction} - t_{synchro}$=15 ms, need $\dot{B}$=5.095 T/s instead of nominal 6.5 T/s to have complete separation.