F. Méot, BNL, Dec. 2011

TRANSPORT OF $\overrightarrow{^{3}\mathrm{He}}$ IN BOOSTER AND AGS

CONTEXT :

- **C-AD is exploring the possibility of polarized $^{3}\mathrm{He}^{2+}$ storage in RHIC, at time scale of a few years from now.**

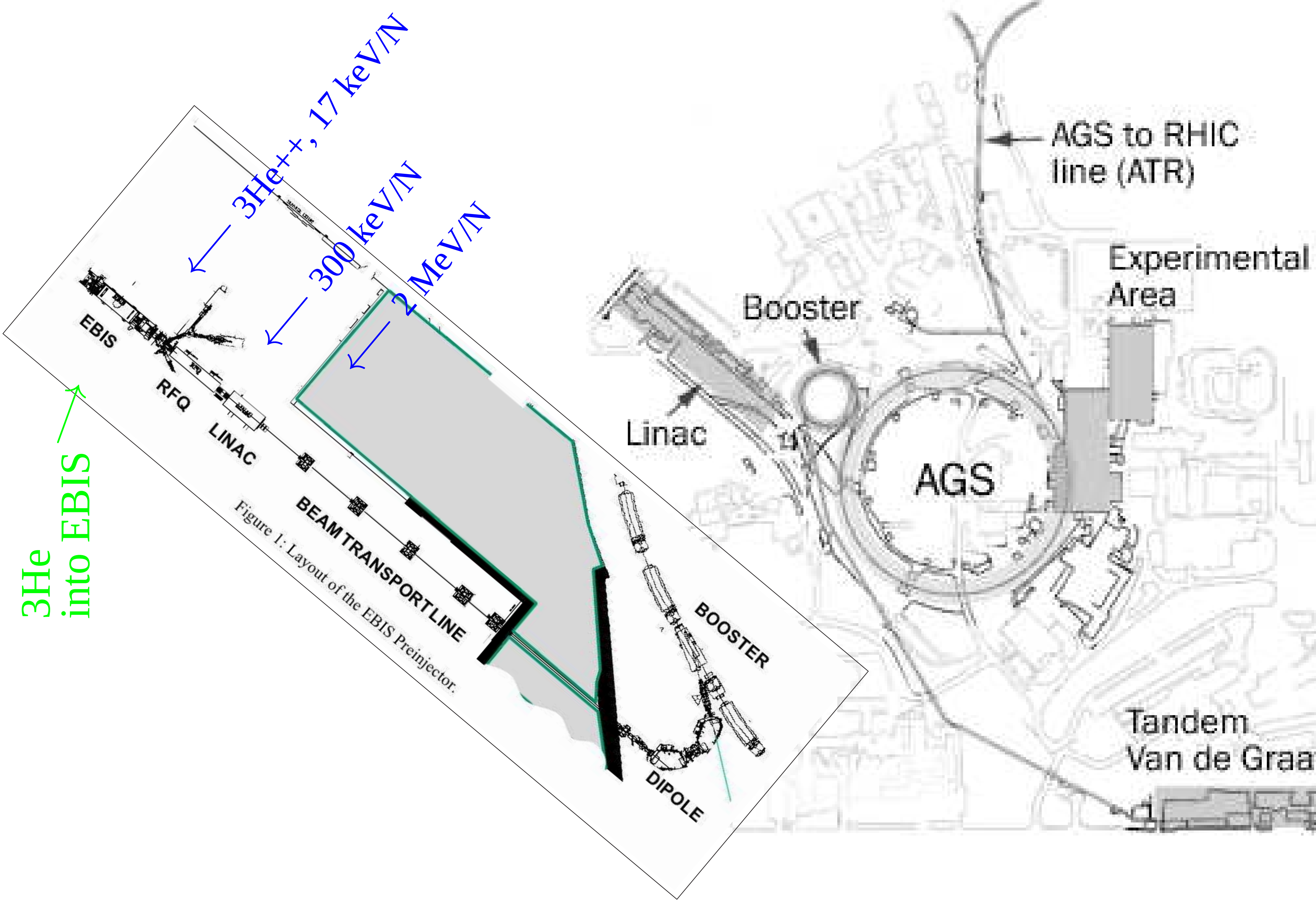
- **$\overrightarrow{^{3}\mathrm{He}}^{2+}$ provides the polarized neutrons in $\overrightarrow{^{3}\mathrm{He}}^{2+}$-$\overrightarrow{^{3}\mathrm{He}}^{2+}$ or p-$\overrightarrow{^{3}\mathrm{He}}^{2+}$ collisions, 500 GeV $^{3}\mathrm{He}^{2+}$, 170 GeV p.**

Contents

1 Layout

Reminder, RHIC at max. $B\rho$, 833.9 T.m :
proton : p=250 GeV/c, $G\gamma$=477.7
$^3He^{2+}$: p=500 GeV/c, $G\gamma$=-745, $\sim 10^{11}$ppb

APEX W



2 Particle data

	units	proton (for comparison)	$^3He^{2+}$
mass	MeV/c^2	**938.272046**	**2808.39148**
	10^{-27}**kg**	**1.672621777**	**5.00641234**
mass/amu	MeV/c^2	**1.00727646**	**3.0149322**
charge Q	$\|e\|$	**+1**	**+2**
number of nucleons, N		**1**	**3**
number of protons, Z		**1**	**2**
spin quantum number		**1/2**	**1/2**
magnetic moment, μ	μ_N	**2.7928474**	**-2.1276253**
gyromagnetic ratio $g = \frac{\mu}{\mu_N} \times 2\frac{m_p \mu_N}{Ze\hbar I}$	μ/μ_N	**2**	**2.99315281**
anomalous mag. moment $G = \frac{g-2}{2}$		**1.7928474**	**-4.18415382**
Imp. resonance interval $\|mc^2/G\|$	MeV	**523.3**	**671.2**

nuclear magneton unit, $\mu_N = \frac{e\hbar}{2m_p}$	**eV/T**	**3.1524512**$\times 10^{-8}$
atomic mass unit, amu	MeV/c^2	**931.494061**
elementary charge, e	**C**	**1.602176565**$\times 10^{-19}$
speed of light in vac.	**m/s**	**2.99792458**$\times 10^{8}$
$\hbar$	**J.s**	**1.054571726**$\times 10^{-34}$
	eV.s	**6.58211928**$\times 10^{-16}$

3 Booster and AGS energy ranges

Proton, for comparison

		Comments
BOOSTER INJECTION :		
kin-E (GeV)	0.2	Hyp. : Energy out of linac (Ref. CJG)
$B\rho$ (T.m)	2.1496	
γ	1.2132	
$\beta\gamma$	0.6868	
$G\gamma$	2.175	
BOOSTER EXTRACTION / AGS INJECTION :		
kin-E (GeV)	1.4167	
$B\rho$ (T.m)	7.2051	Max. $B\rho$ in Booster is 17 T.m
γ	2.5100	w/ Qx/y=4.73/4.82 optics
$\beta\gamma$	2.3021	
$G\gamma$	4.5	
AGS EXTRACTION :		
kin-E (GeV)	22.8738	
$B\rho$ (T.m)	79.3668	
γ	25.3786	
$\beta\gamma$		
$G\gamma$	45.5	Half-int. for AtR match ; not more due to AtR matching limitations.

$^3\overrightarrow{\text{He}}^{2+}$, possible data :

		Comments
BOOSTER INJECTION :		
kinetic E (MeV/N)	2.0146	Hyp. : $\beta = 0.0655$ from EBIS IH DTL
$B\rho$ (T.m)	0.3075	Note : $B\rho_{inj,^3\mathrm{He}^{2+}} \ll B\rho_{inj,p}$
γ	1.0022	
$\beta\gamma$	0.0656	
$G\gamma$	-4.1932	
BOOSTER EXTRACTION / AGS INJECTION :		
kinetic E (GeV)	2.2256	0.74186 GeV/N
$B\rho$ (T.m)	6.9678	Consistent w/ p : $B\rho_{inj,^3\mathrm{He}^{2+}} \approx B\rho_{inj,p}$.
γ	1.7925	
$\beta\gamma$	1.4876	
$G\gamma$	-7.5	
	-10.5	Interest : injection into AGS beyond 0+.
AGS EXTRACTION :		
kinetic E (GeV)	30.4	
$B\rho$ (T.m)	55.2	$B\rho_{xtr,^3\mathrm{He}^{2+}} \ll B\rho_{xtr,p}$, whereas $B\rho = 79.36 \rightarrow G\gamma = -71$, this leaves room for extraction beyond 60-.
$G\gamma$	-49.5	
$\lvert G\gamma \rvert$	>51 ?	Higher injection E into RHIC

• **Note : Transition γ :**
Booster : 4.8 ; AGS : 8.4 ; RHIC : 23.6.

4 Depolarizing resonances in booster

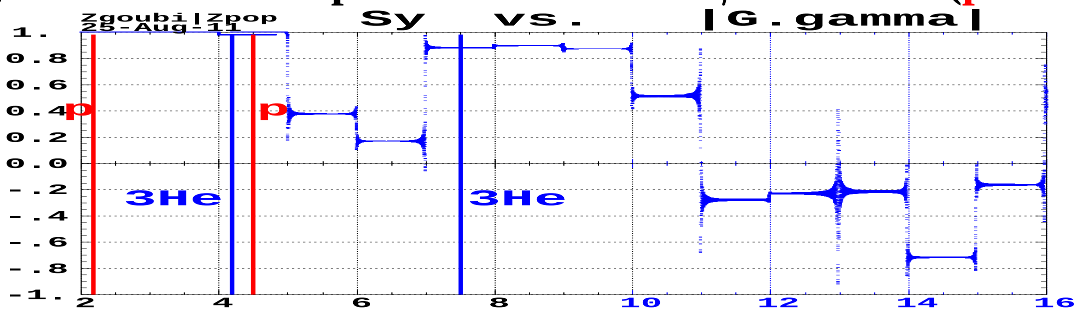
Imperfection resonances, $\boxed{G\gamma - n = 0}$**, induced by vertical closed-orbit**

- Acceleration range, $\vec{p}$ **:** $G\gamma\ : 2.175 \rightarrow 4.5$ **: 2 resonances, at** $G\gamma = \begin{cases} 3 : & \textbf{harm. orbit correction} \\ 4 : & \textbf{reinforced/spin flip} \end{cases}$

- Possible "conservative" $^3\overrightarrow{\mathrm{He}}^{2+}$ **range :** $G\gamma\ : -4.19 \rightarrow -7.5$ **: 3 resonances, at** $-G\gamma =$ **5, 6, 7.**

- **Example of** S_y **motion,** $^3\overrightarrow{\mathrm{He}}^{2+}$**,** $|G\gamma| : 4.19 \rightarrow 16$**.**

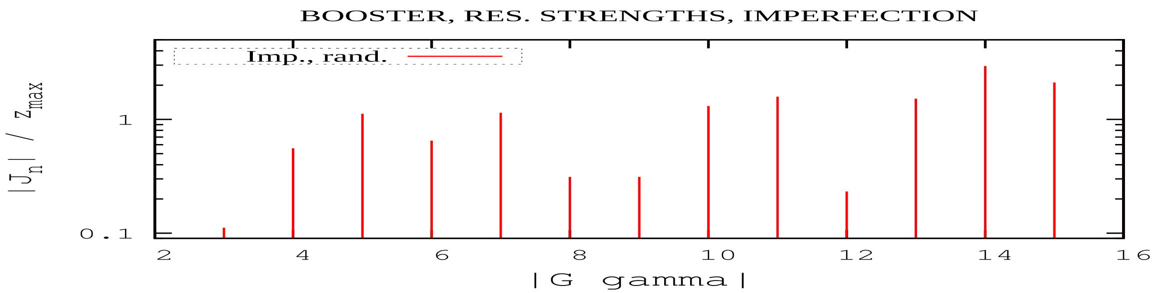
Range shown covers up to max. booster $B\rho \approx 17$ **T.m (proton** $G\gamma = 9.9$**,** $^3\overrightarrow{\mathrm{He}}^{2+}$ $G\gamma = -15.75$**) :**



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

Single $^3\overrightarrow{\mathrm{He}}^{2+}$ **on V c.o. (**$\hat{y}_{co} = 1$ **mm),** $\epsilon_x,\ \epsilon_y$ **zero.**

- **Strengths of imperfection resonances in Booster, Qx / Qy = 4.73 / 4.82 optics.**



Thin lens model :

$$\boxed{J_n = \frac{1+G\gamma}{2\pi}\Sigma_{Qpoles}\left(\cos(G\gamma\alpha_i) + i\,\sin(G\gamma\alpha_i)\right)(KL)_i\, z_{co,i}}$$

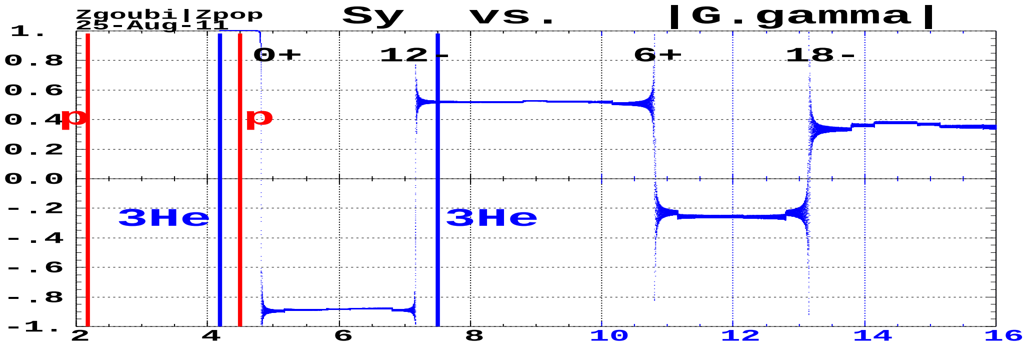
- **Means for correction of imperfection resonances, *practical feasibility to be explored* : harmonic orbit correction, helical partial snake.**

Intrinsic resonances, $\boxed{G\gamma \pm Q_y - n = 0}$**, induced by betatron motion**

- Acceleration range, proton : $G\gamma\ : 2.175 \to 4.5$ **: no systematic (n=6×integer) resonance.**

- Possible range, $^3\overrightarrow{\mathrm{He}}^{2+}$: $G\gamma\ : -4.193 \to -7.5$ **: 2 systematic resonances, at** $G\gamma = 0 + Q_y,\ 12 - Q_y$**.**

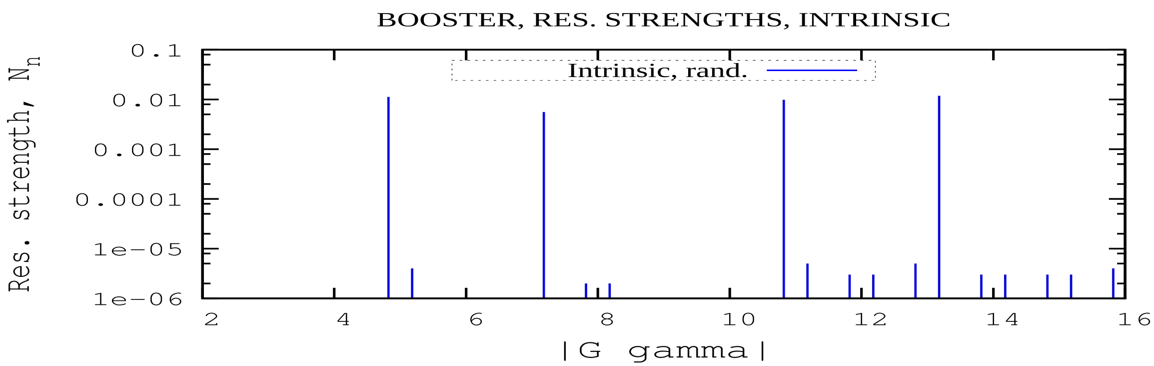
• **S_y motion for $^3\overrightarrow{\mathrm{He}}^{2+}$ in** $|G\gamma| : 4.19 \to 7.5$**. Vertical lines show $G\gamma$ ranges for p and for $^3\overrightarrow{\mathrm{He}}^{2+}$.**



$$\frac{P_f}{P_i} = 2\exp\left(-\frac{\pi}{2}\frac{|J_n|^2}{\alpha}\right) - 1, \quad \dot{\gamma} = 16.$$

Single $^3\overrightarrow{\mathrm{He}}^{2+}$ on zero vertical orbit with $\epsilon_y \approx 0.6\,\pi$mm.mrad invariant.

• **Strengths of intrinsic resonances in Booster, Qy = 4.82.**
Major lines are at $G\gamma = 0 + Q_y,\ 12-,\ 6+,\ 18-$**.**



$$\boxed{\begin{aligned} N_n^{\pm} &= \frac{1+G\gamma}{4\pi}\Sigma_{Qpoles}\left(\cos(G\gamma\alpha_i \pm \psi_i)\right. \\ &+ \left. i\sin(G\gamma\alpha_i \pm \psi_i)\right)(KL)_i\sqrt{\beta_{z,i}\epsilon_z/\pi} \end{aligned}}$$

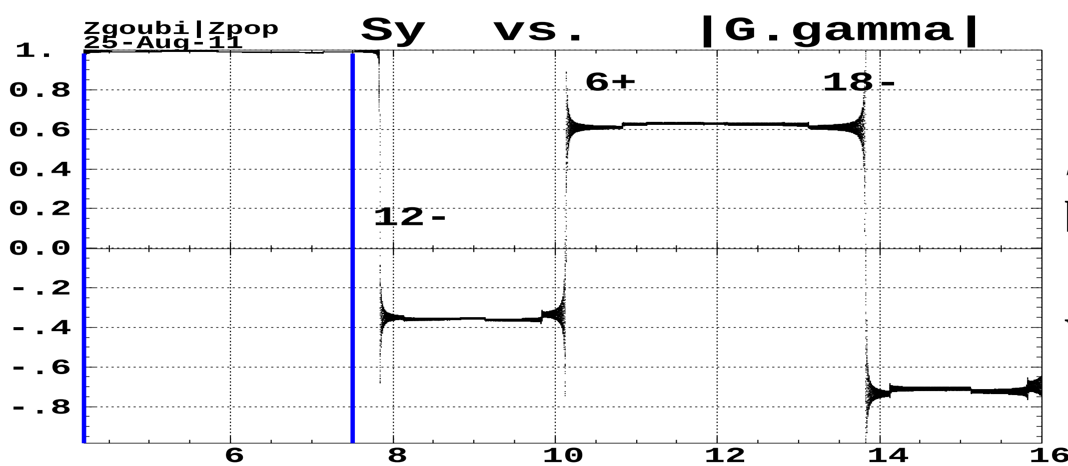
• **Foreseen means for overcoming intrinsic resonances, to be assessed : AC dipole (was done in AGS).**

- **Possible different settings for $^3\overrightarrow{\mathrm{He}}^{2+}$ – to be assessed:**

(i) Could foresee pushing both $\begin{cases} 0+Qy \\ 12-Qy \end{cases}$ resonances beyond [4.19,7.5] range.
Hence, no systematic resonance in acceleration range, no compensation needed.

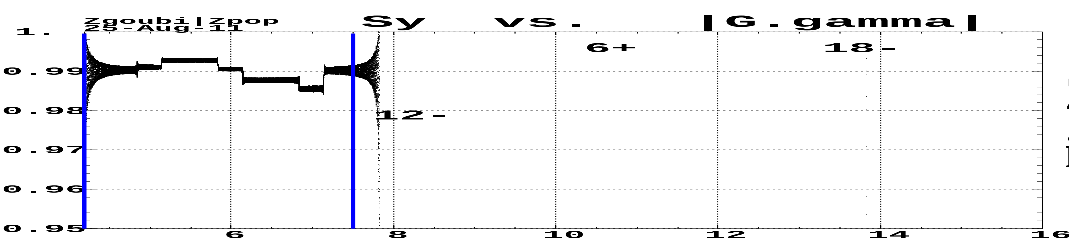
How that works :

- **Strength of 0^+ for $\epsilon_y = 2.5\pi$mm.mrad, norm., is $N_n \approx 0.012$.**
- **Take distance to the resonance $\Delta = |G\gamma + Q_y - n| > 7 \times N_n$, then**
- **given $n = 0$ here, then tune at injection should satisfy $Q_y < -G\gamma|_{inj} - 7 \times N_n \approx 4.11$.**



S_y motion. $^3\overrightarrow{\mathrm{He}}^{2+}$ is on zero vertical orbit with non-zero vertical invariant.

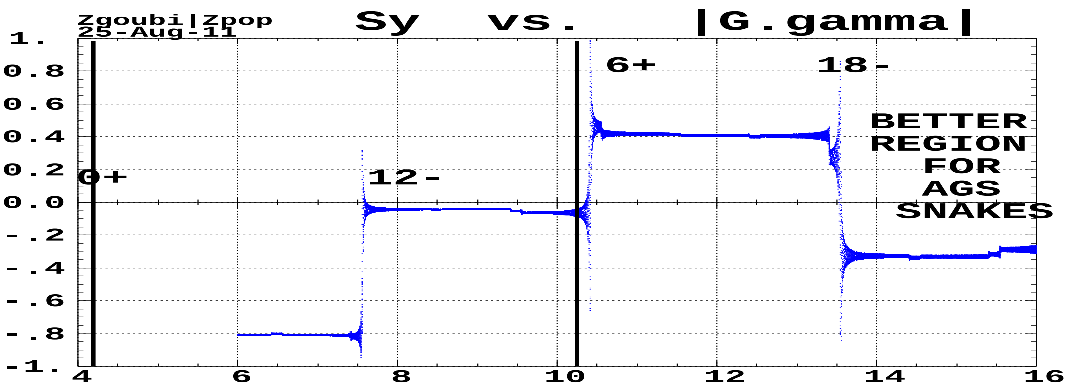
Vertical lines show $G\gamma$ range for $^3\overrightarrow{\mathrm{He}}^{2+}$.



Zoom on *random* intrinsic resonances in acceleration range.

(ii) Could foresee extracting at higher rigidity.

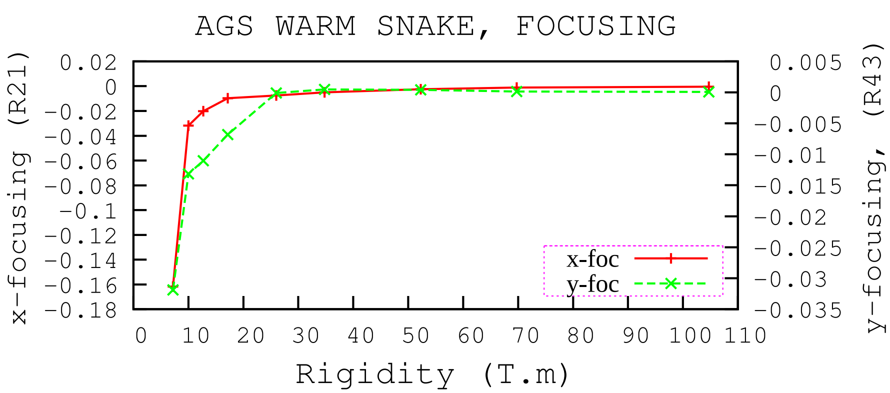
- **For instance, below 6+Qy and beyond AGS[0+], e.g.,** $G\gamma = -10.5$ **(**$B\rho = 10.8$ **T.m, needs** $Q_y > 4.5$**).**
- **Or even further,** $B\rho \to 15$ **T.m (**$G\gamma \to -14$**).**
- *Note : still below transition* γ *(*$|G\gamma|_{tr} > 16$*), and below max.* $B\rho = 17$ *T.m.*

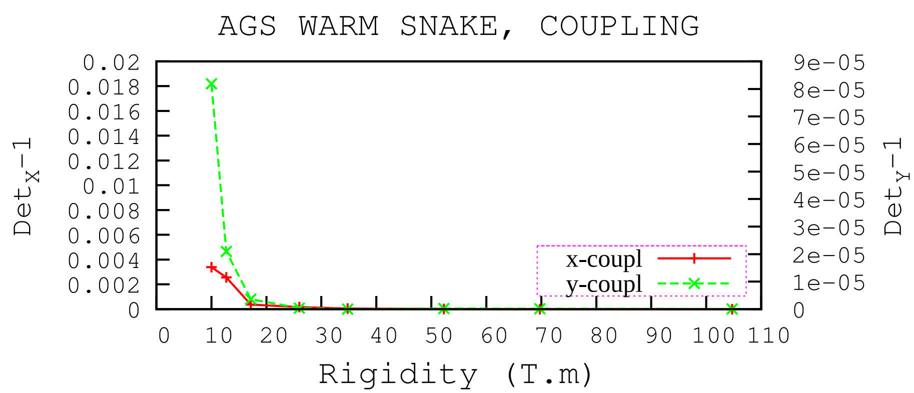


Strengths (Qx/Qy=4.73/4.82) :

$G\gamma$	0+	12-	6+	18-
N_n **at 2.5**π	**0.011**	**0.0006**	**0.010**	**0.012**

- **Interest : improved optics in AGS with snakes if rigidity is higher :**
- $G\gamma = -7.5$ **is** $B\rho = 6.97$ **T.m, even lower than proton** $G\gamma = 4.5$**,** $B\rho = 7.21$ **;**
- **lower rigidity is less favorable as to snake optics : focusing perturbed, coupling.**



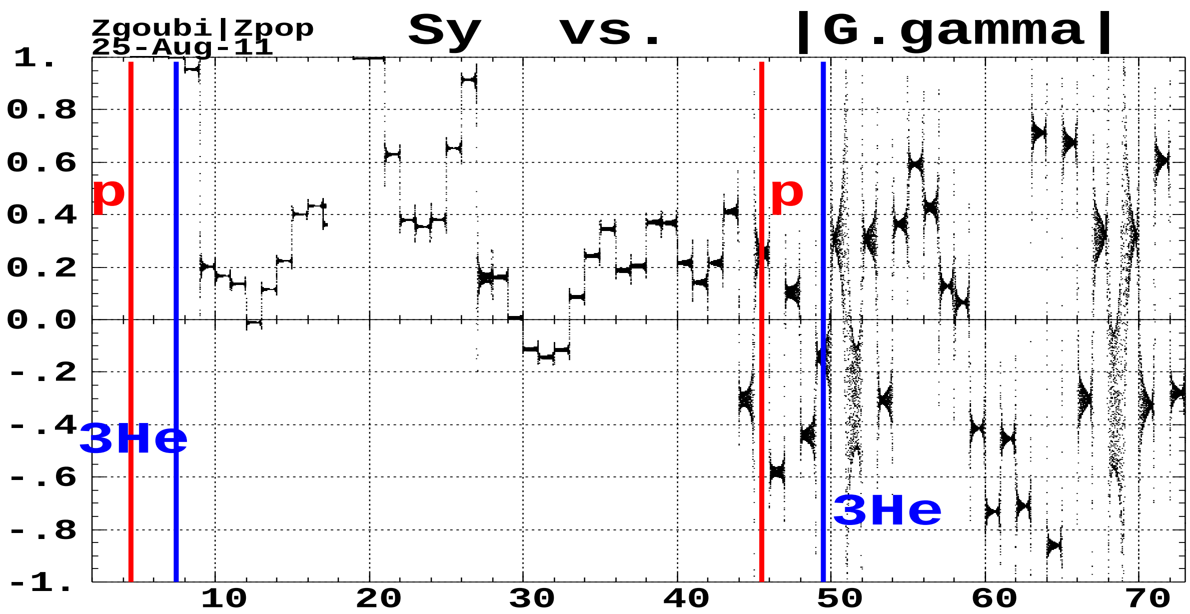


5 Depolarizing resonances in AGS

Imperfection resonances, $\boxed{G\gamma - n = 0}$

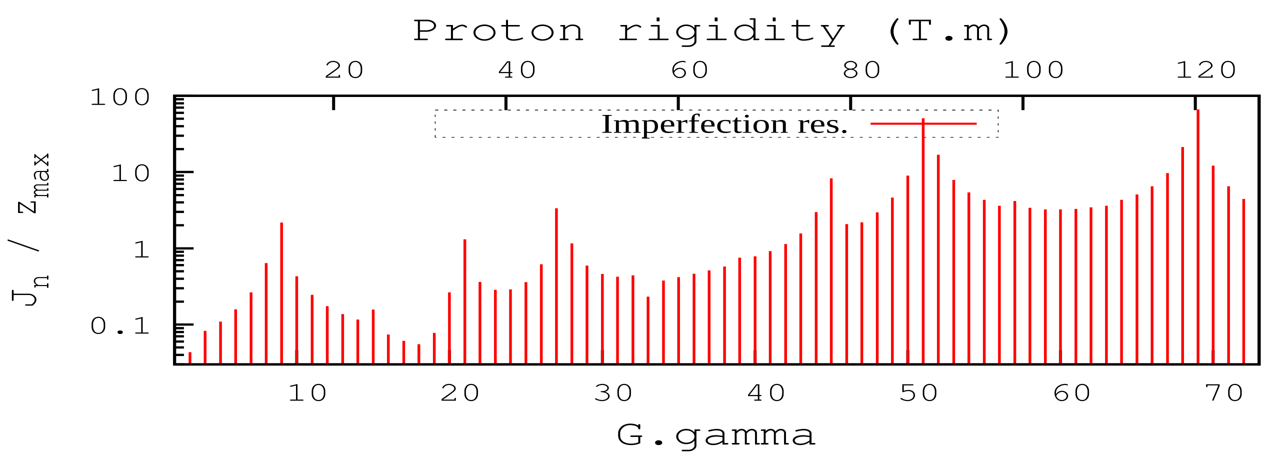
Spin motion, typical :

- Proton, acceleration range :
$G\gamma \ : 4.5 \to 45.5$,
41 integer resonances crossed.

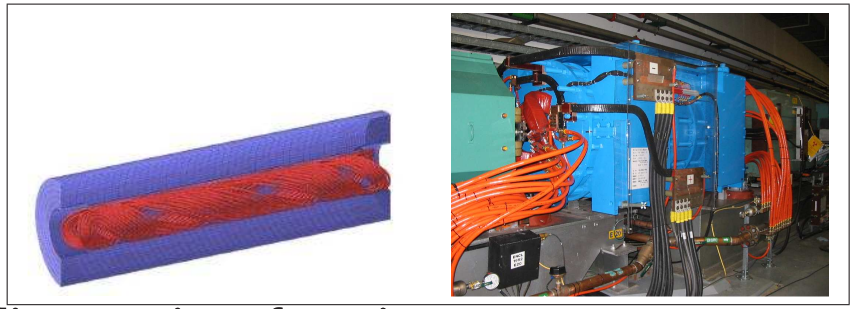


- $^{3}\overrightarrow{He}^{2+}$**, possible range :**
$G\gamma \ : -7.5 \to -49.5$,
42 resonances crossed.

• **Strengths of imperfection resonances in AGS :**



- **Imperfection resonances in AGS are overcome by spin-flipping, using two helical partial snakes**



- **A partial snake forces polarization to flip : at Xing of any integer resonance one gets**

$$\frac{P_{final}}{P_{initial}} = \left(2\exp\left(-\frac{\pi}{2\alpha}\left|\frac{\phi}{2\pi}+J_n\right|^2\right) - 1\right) = -1 \qquad \textbf{\textit{at better than}}\ 10^{-3}$$

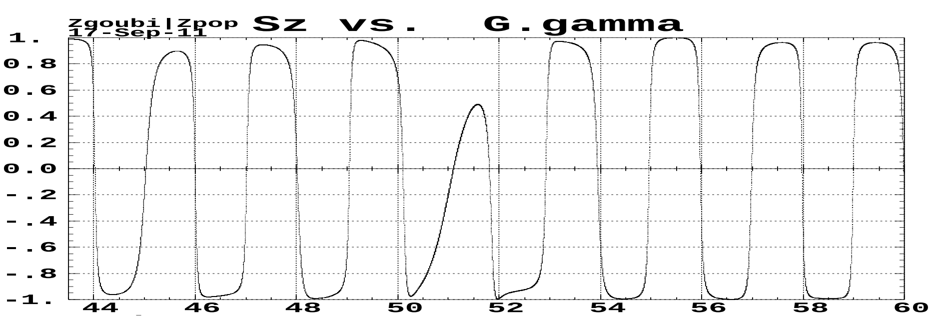
if snake strength $\phi/2\pi$ dominates over strength of imperfection resonances : $\frac{\phi}{2\pi} \gtrsim |J_n| + 2\sqrt{\alpha}$.

- **In the AGS, snakes ensure spin rotations** $\phi = \begin{cases} \textbf{proton : Cold/2.1T/21}^o\textbf{, Warm/1.5T/11}^o \\ {}^3\overrightarrow{\textbf{He}}^{2+} \textbf{ : Cold/2.1T/-44}^o\textbf{, Warm/1.5T/-26}^o \end{cases}$

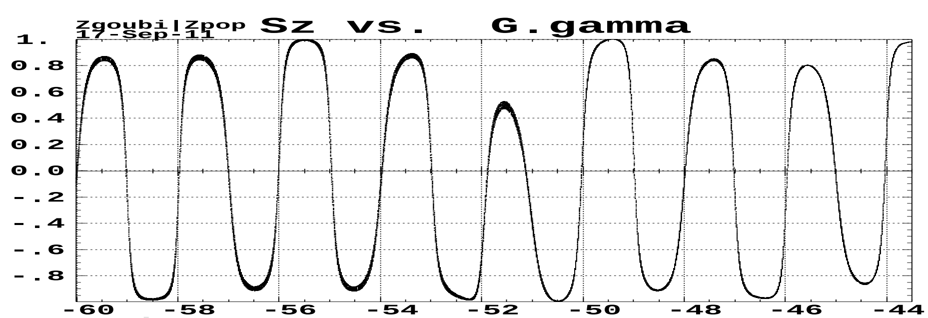
- **Example spin flip, below :** $G\gamma\ :\ 43.5 \to 60$, **rigidities :** $\begin{cases} \textbf{proton :}\ 75.9 \to 104.7\ \textbf{T.m} \\ {}^3\overrightarrow{\textbf{He}}^{2+}\ \textbf{:}\ 48.47 \to 67.0\ \textbf{T.m} \end{cases}$,

- Single particle ; vertical orbit : $\begin{cases} \textbf{proton :}\ \hat{y}_{co} \approx \textbf{8 mm} \\ {}^3\overrightarrow{\textbf{He}}^{2+}\ \textbf{:}\ \hat{y}_{co} \approx \textbf{5 mm} \end{cases}$ **;** $\epsilon_x,\ \epsilon_y \approx 0$**,** $\delta p/p|_{synch.} < 10^{-4}$**.**

Proton **snakes 12% + 6%**



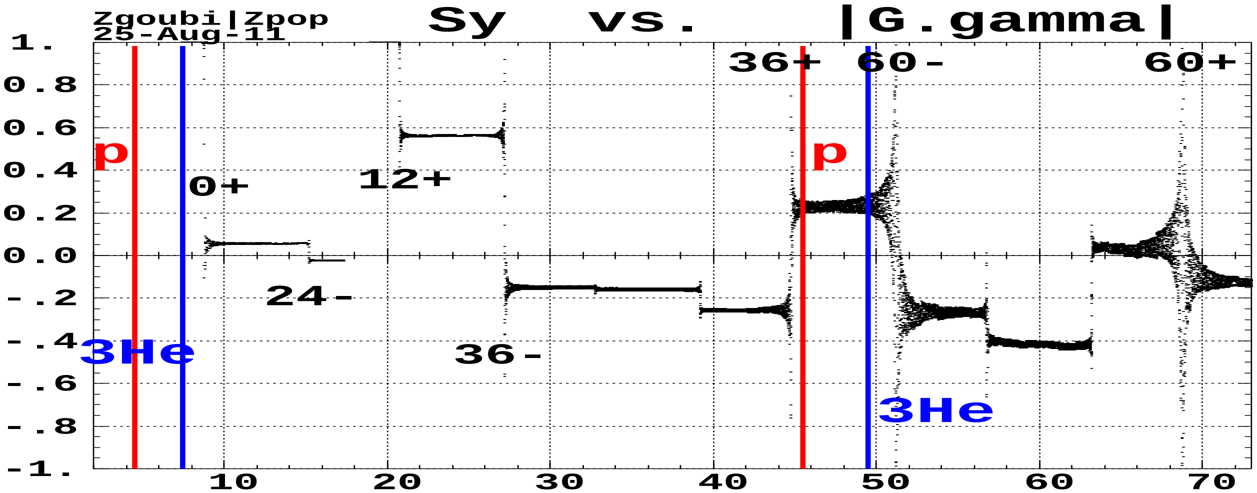
${}^3\overrightarrow{\textbf{He}}^{2+}$, snake settings as p's, i.e. 25% + 15%



Intrinsic resonances, $G\gamma \pm Q_y - n = 0$:

• S_y **motion, typical :**

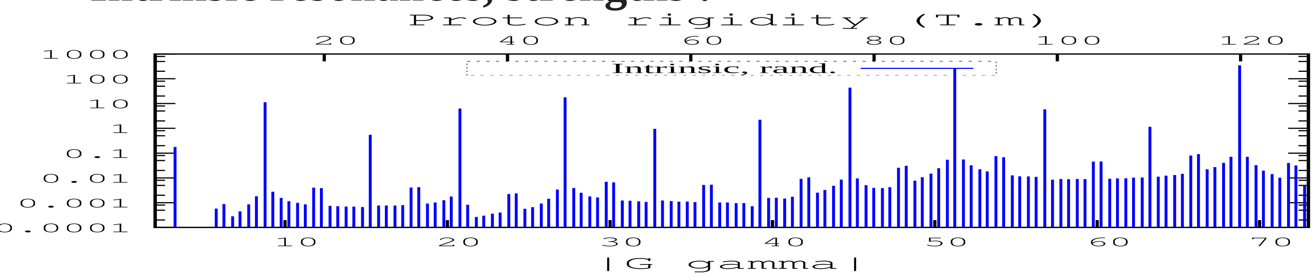
Major lines are systematic resonances (n=12×integer), at $G\gamma$ = 0+Q_y, 12+Qy, 36-Qy, 36+Qy, 60-Qy



- **Proton, acceleration range :**
$G\gamma$: $4.5 \to 45.5$,
4 strong resonances crossed.

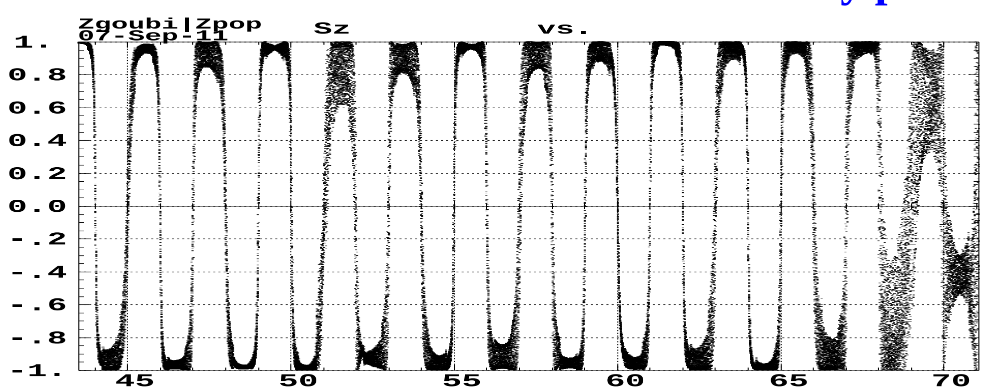
- $^3\overrightarrow{\mathrm{He}}^{2+}$**, possible range :**
$G\gamma$: $-7.5 \to -49.5$,
4 strong resonances crossed.

• **Intrinsic resonances, strengths :**



$^3\overrightarrow{\mathrm{He}}^{2+}$ **resonance strengths are sronger than p's , in the ratio** $\sqrt{|G_{^3\mathrm{He}^{2+}}| \,/\, G_p} \approx 1.5$

• **Intrinsic resonances in AGS are overcome by pushing Q_y in the snake-induced, forbiden Q_s band**



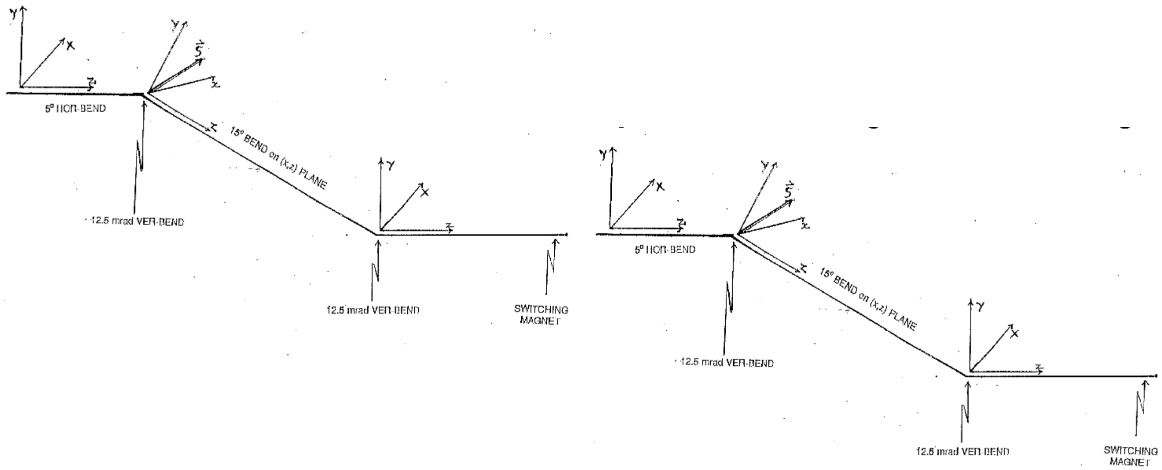
However, non-zero ϵ_x excites

$$G\gamma = integer \pm Q_x$$

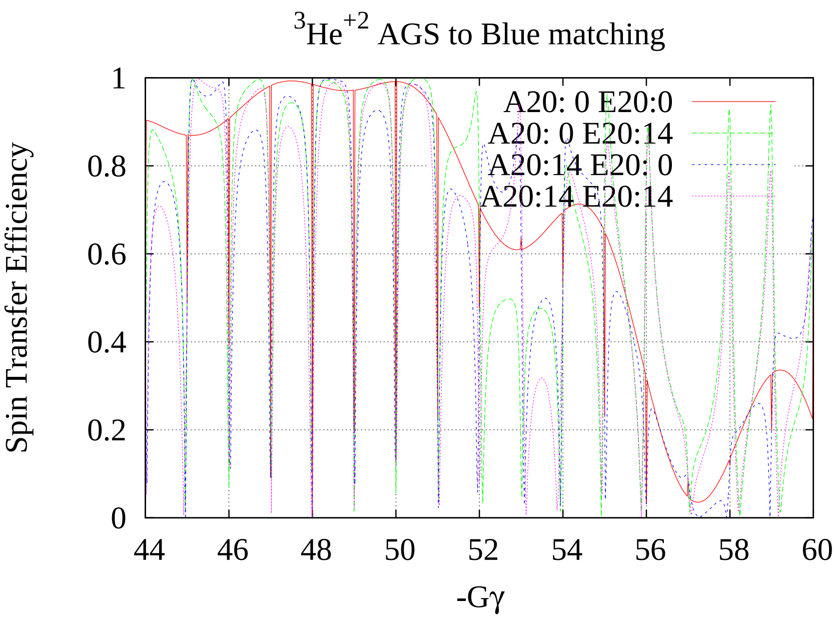
($\vec{p}$, $\epsilon_x \approx 15\,\pi\,10^{-6}$ norm., $\epsilon_y \approx 2\,\pi\,10^{-6}$ norm., here)

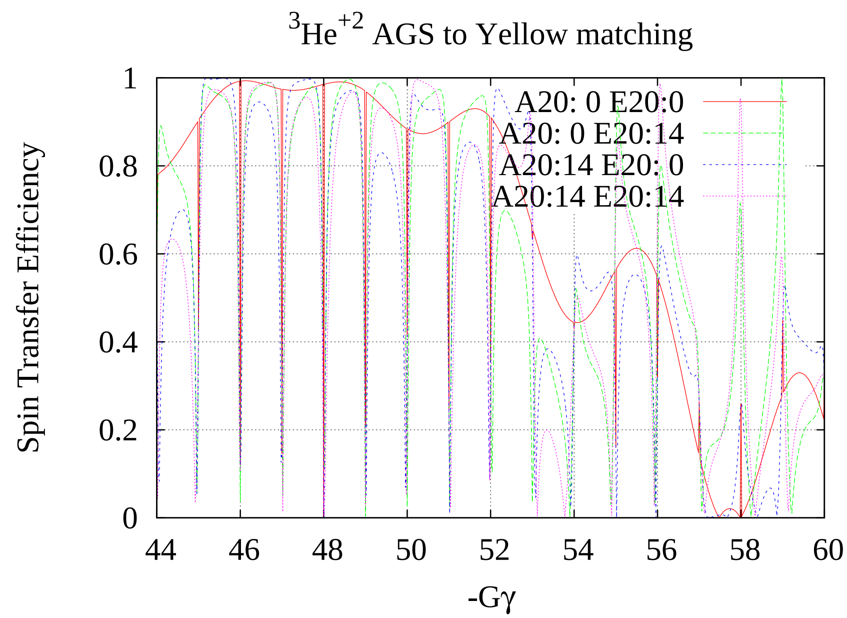
6 AtR matching

• Horizontal bends interleaved with vertical deviations in AtR cause the line to be non-transparent to spin motion.
Hence matching between AGS and RHIC stable spin directions is necessary



(i) Matching to vertical $\vec{n}_0$ in RHIC is achievable in the range $G\gamma \simeq 45.5 - 49.5$ – depending on snake settings [Ref. W. MacKay] :



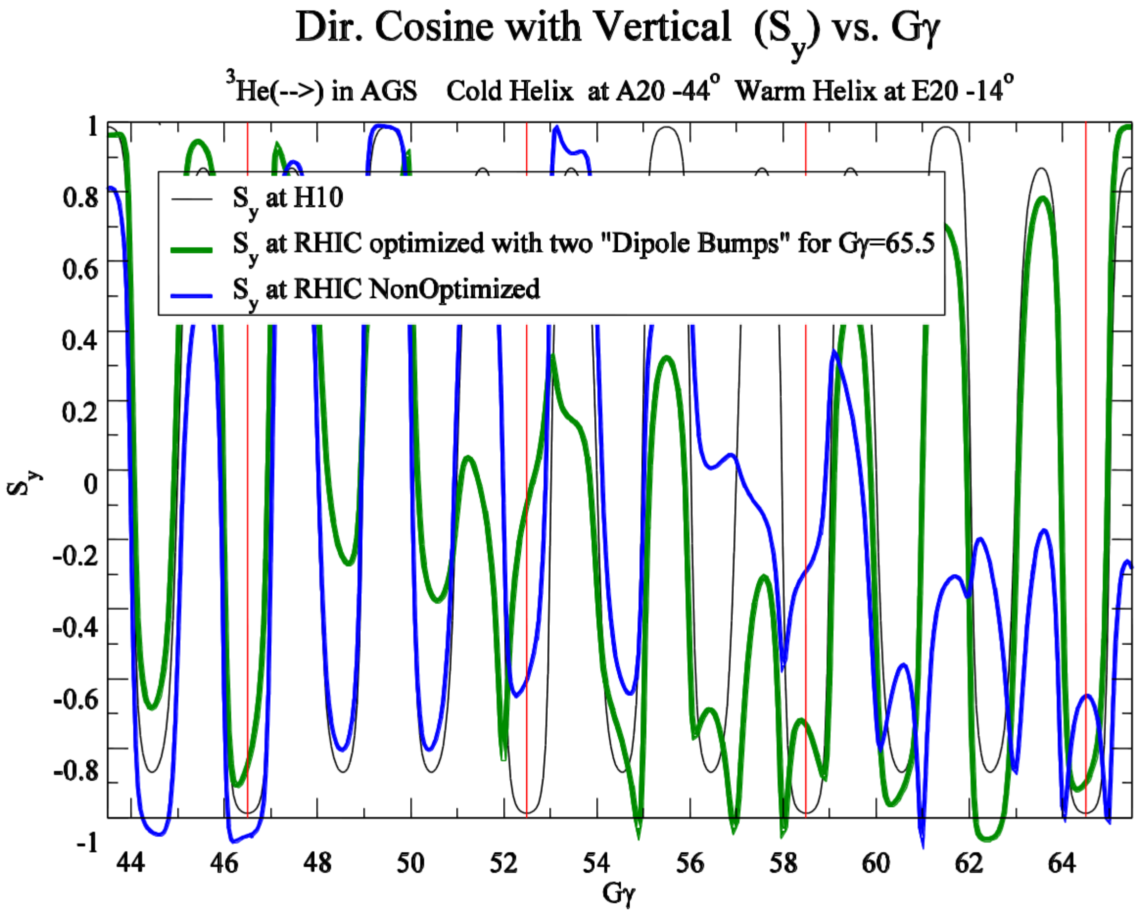


AtR matching

(ii) Extracting $^3He^{2+}$ at higher $B\rho$ from AGS ? (this requires overcoming $G\gamma$ =60-Qy and higher $G\gamma$ resonances in AGS - to be assessed)

- **That raises the question of extending the AtR matching to higher $G\gamma$.**

- **Matching is possible using two horizontal dipole bumps located at vertical deviations in the line [ref. Nick Tsoupas] :**



7 Comments

• In view of preparing future acceleration of $^{3}\overrightarrow{\mathrm{He}}^{2+}$ in RHIC, we might plan the following experiments, in booster and AGS :

(i) Assess operation of Booster at Q_y close to ≈ 4 : $G\gamma_{^3He^{2+}} span\ 4.19 \rightarrow 7.5$ *is then free of intrinsic resonances.*

(ii) Acceleration in booster beyond $B\rho = 7$ T.m : *in view of*

- *higher rigidity in AGS snakes,*
- *bringing $G\gamma_{^3He^{2+}}$ at AGS injection beyond $0 + Q_y$ AGS depolarizing resonance.*

(iii) AGS : investigate use of warm snake at higher field.

Possible APEX :

• $^{3}\mathrm{He}^{2+}$ in RHIC :
Demonstration of feasibility : accelerate (non polarized) $^{3}\mathrm{He}^{2+}$ up to 500GeV in RHIC.

THANK YOU