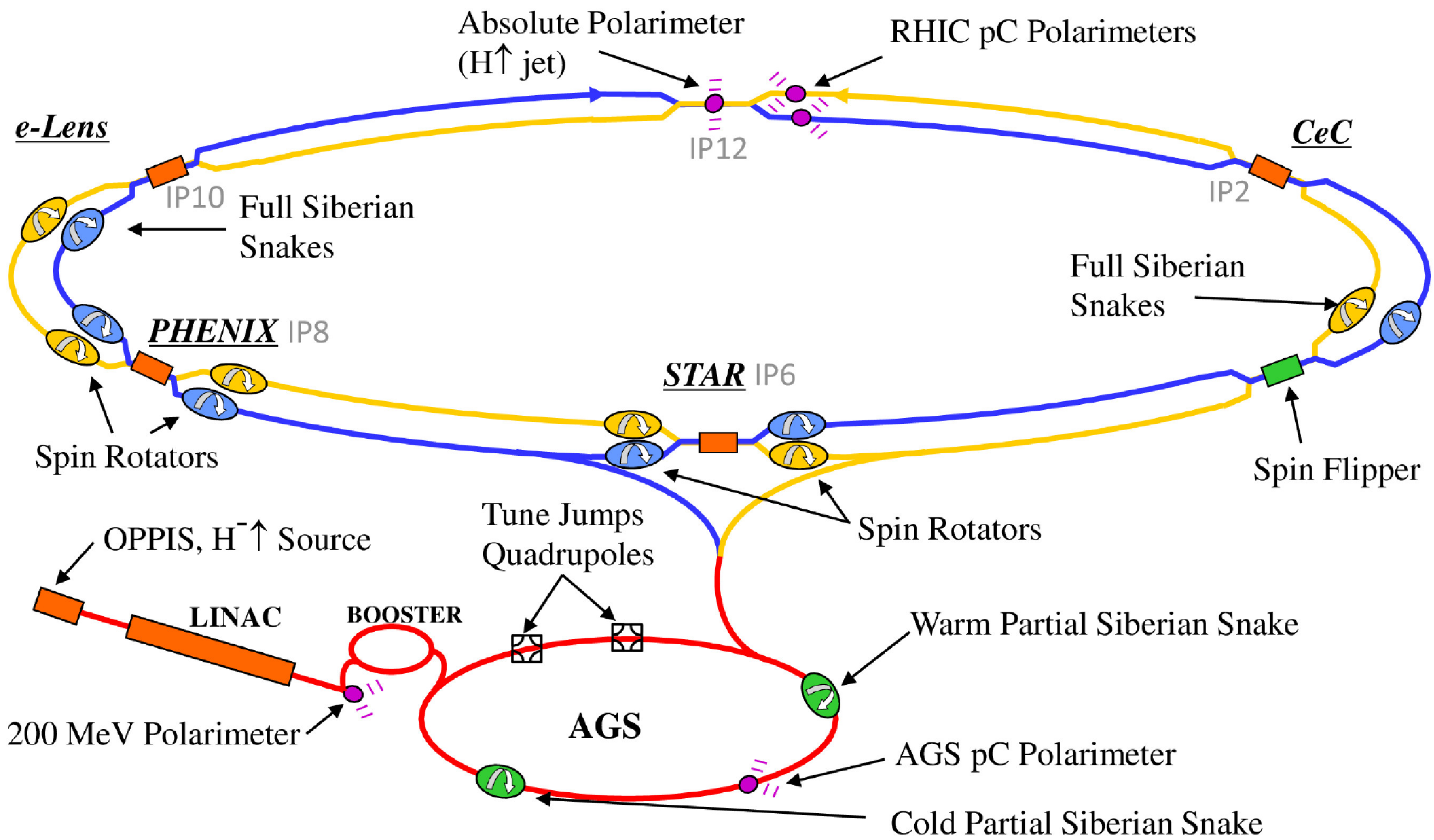
# TRANSPORT OF $^3\overrightarrow{He}^{2+}$, FROM SOURCE TO COLLISION

François Méot
BNL C-AD

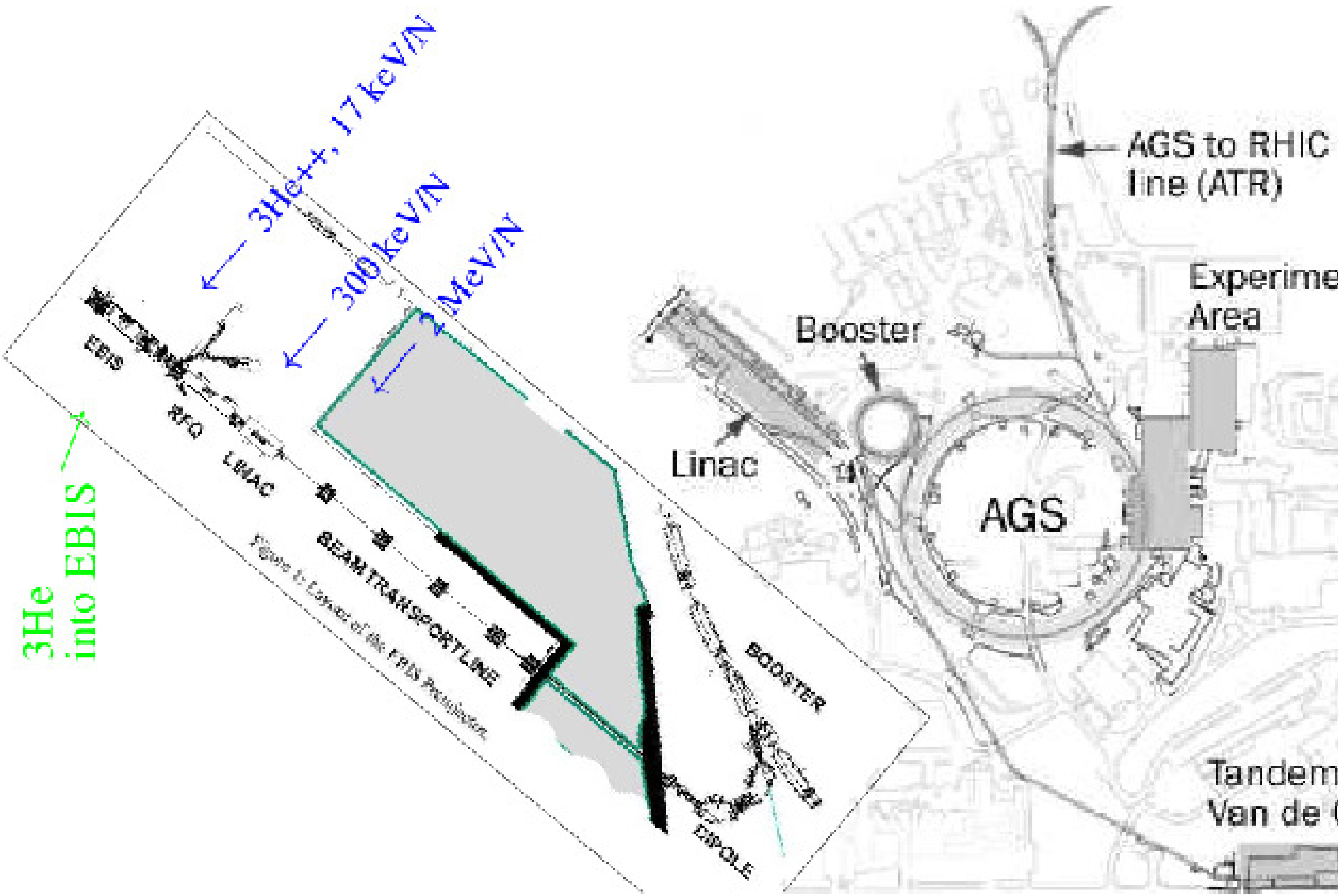
**RHIC INSTALLATION LAYOUT**




RHIC Run 14: collisions with Helium-3 for the first time, on Gold

*https://www.bnl.gov/rhic/news2/news.asp?a=5026&t=today*

# $^3He^{2+}$ SOURCE TO AGS



# PARTICLE DATA / POLARIZATION

| | units | proton | $^2H^+$ (for comparison) | $^3He^{2+}$ |
|---|---|---|---|---|
| mass | $MeV/c^2$ | 938.272046 | 1875.6128 | 2808.39148 |
| | $10^{-27}$kg | 1.672621777 | 3.34358348 | 5.00641234 |
| mass/amu | $MeV/c^2$ | 1.00727646 | 2.013553212 | 3.0149322 |
| charge Q | $\|e\|$ | +1 | +1 | +2 |
| Q/A | | 1 | 1 | 2/3 |
| number of nucleons, N | | 1 | 2 | 3 |
| number of protons, Z | | 1 | 1 | 2 |
| spin quantum number | | 1/2 | 1 | 1/2 |
| magnetic moment, $\mu$ | $\mu_N$ | 2.7928474 | 0.85743823 | -2.1276253 |
| gyromagnetic ratio $g = \frac{\mu}{\mu_N} \times 2\frac{m_p \mu_N}{Ze\hbar I}$ | $\mu/\mu_N$ | 2 | 1.99900759 | 2.99315281 |
| anomalous mag. moment $G = \frac{g-2}{2}$ | | 1.7928474 | -0.1429872 | -4.18415382 |
| Imp. resonance interval $\|mc^2/G\|$ | $MeV$ | 523.3 | 13117 | 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 | $6.58211928 \times 10^{-16}$ |

# SOME PARAMETERS OF RHIC AND INJECTORS

## Proton, for comparison

**BOOSTER INJECTION :**

| | | Comments |
|---|---|---|
| kin-E (GeV) | 0.2 | Hyp. : Energy out of linac (Ref. CJG) |
| $B\rho$ (T.m) | 2.1496 | |
| $\gamma$ | 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 |
| $\gamma$ | 2.5100 | w/ Qx/y=4.73/4.82 optics |
| $\beta\gamma$ | 2.3021 | |
| $G\gamma$ | 4.5 | |

**AGS EXTRACTION / RHIC INJECTION :**

| | | |
|---|---|---|
| kin-E (GeV) | 22.8738 | |
| $B\rho$ (T.m) | 79.3668 | |
| $\gamma$ | 25.3786 | |
| $\beta\gamma$ | | |
| $G\gamma$ | 45.5 | Half-int. for AtR match ; not more due to AtR matching limitations. |

## $^3$He$^{2+}$ data, best knowledge :

**BOOSTER INJECTION :**

| | | Comments |
|---|---|---|
| kinetic E (MeV/N) | 2.0146 | Hyp. : $\beta = 0.0655$ from EBIS IH DTL |
| $B\rho$ (T.m) | 0.3075 | Note : $B\rho_{inj,^3He^{2+}} \ll B\rho_{inj,p}$ |
| $\gamma$ | 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 : $B\rho_{inj,^3He^{2+}} \approx B\rho_{inj,p}$. |
| $\gamma$ | 1.7925 | |
| $\beta\gamma$ | 1.4876 | |
| $G\gamma$ | -7.5 | Requires $Q_y < 4.5$ so to escape $12 - Q_y$ |
| Alternate possibility under development | -10.5 | Interest : injection into AGS beyond 0+; requires $Q_y > 4.5$ so to avoid $6 + Q_y$ |

**AGS EXTRACTION / RHIC INJECTION :**

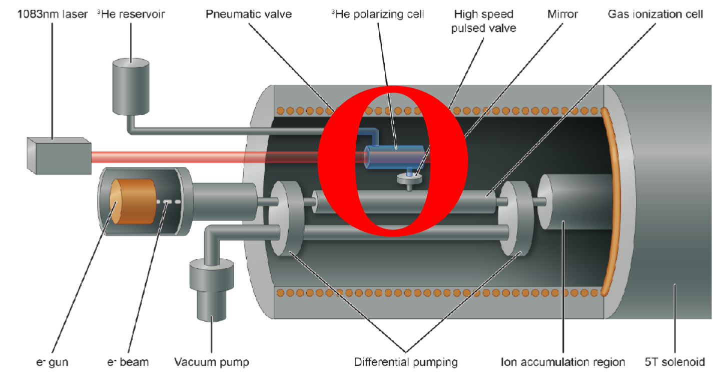
| | | |
|---|---|---|
| kinetic E (GeV) | 27.7311 | 9.24369 GeV/N |
| $B\rho$ (T.m) | 50.7185 | $B\rho_{xtr,^3He^{2+}} \ll B\rho_{xtr,p}$, whereas $B\rho = 79.36 \rightarrow G\gamma = -71$, this leaves room for extraction beyond 60-. |
| $\gamma$ | 10.8743 | |
| $\beta\gamma$ | 10.8282 | |
| $G\gamma$ | -45.5 | |
| Other possibilities? | | |
| $B\rho$ 55 T.m | -49.5 | Better spin match to vertical $\vec{n}_0$ in RHIC; plateau is further away from 36+, 36+ crossed faster. |
| $B\rho \rightarrow$ 79 T.m | $< -51$ ? | -60+$Q_y$ is a strong depolarizing resonance |

# 3He SOURCE

• EBIS has provided He2+, Ne5+, Ar10+, Fe20+,Ti18+, Cu11+, Au32+, U39+ ... for NSRL or RHIC.

**Helion adds to the list ... polarization requires dedicated developments.**

• High polarization of optically-pumped 3He cell requires the latter to be placed inside the solenoid. The second solenoid, part of EBIS upgrade.



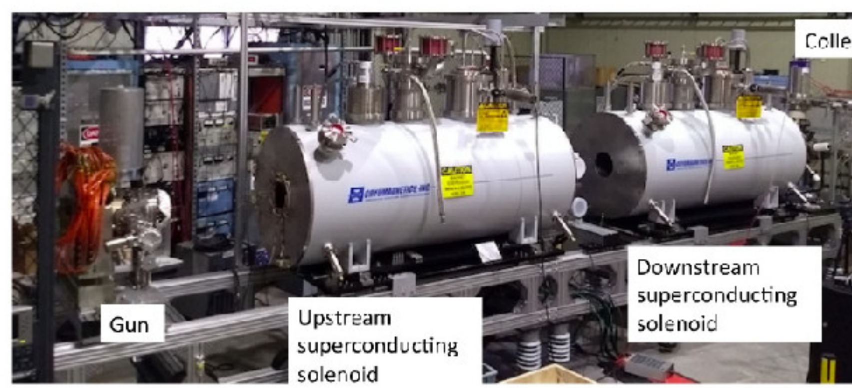

• Requirements:

◇ $2 \times 10^{11}\ {}^3\overrightarrow{\mathrm{He}}^{2+}$ in a $2\mu s$ pulse (4 mA)

◇ spin-flip every pulse

◇ compatibility with regular EBIS operation

**Current Setup of Extended EBIS Solenoids**




• Plans:

◇ EBIS upgrade, on-going

◇ Installation 2022 - 2023

◇ Expected polarization 80%

# BOOSTER

**OPTION 1/2: Extract at Gγ=-7.5 / acceleration to $B\rho \approx 7$ (today's proton)**

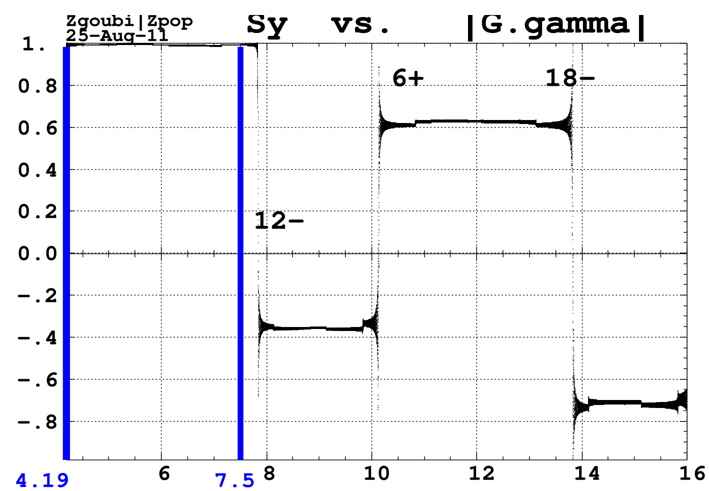
◇ **Imperfection resonances**, $G\gamma - n = 0$

- **proton range :** $G\gamma\ :\ 2.175 \to 4.5$
- **2 resonances,**
- **at** $G\gamma = 3,\ 4$

- $^{3}He^{2+}$ **:** $G\gamma\ :\ -4.19 \to -7.5$
- **3 resonances, at** $G\gamma = 5,\ 6,\ 7$

- **Correction method: orbit harmonic correction or excitation (spin flip)**

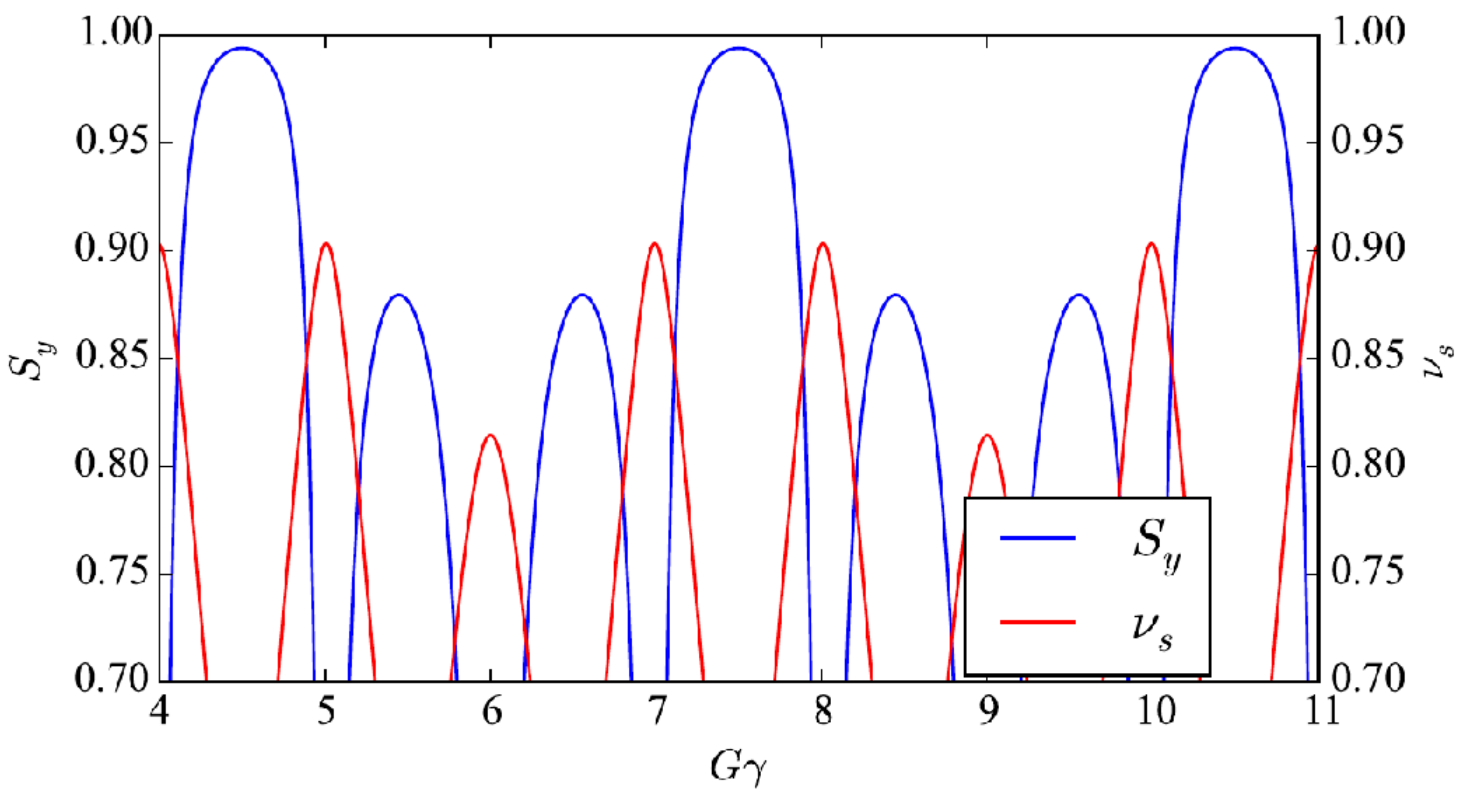
◇ **Intrinsic resonances**, $G\gamma - n = \pm Q_y$




$$\begin{cases} \text{set injection } Q_y \approx 4.11 \text{ to avoid } 0 + Q_y\ (< \text{injection } G\gamma = 4.19) \\ \text{maintain } 12 - Qy \text{ beyond extraction } G\gamma = -7.5,\ \text{using } Q_y < 4.5 \end{cases}$$

## OPTION (2/2)

- ◇ **Extract at a higher G$\gamma$**
- ◇ **G$\gamma = -10.5$ is the next best match to AGS $\vec{n}_0$ beyond G$\gamma = -7.5$:**



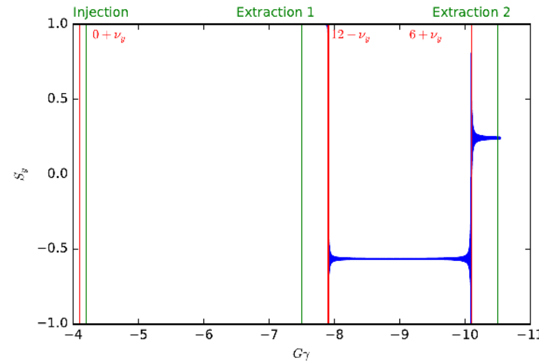

**blue: vertical component of the stable spin direction $\vec{n}_0$ in the AGS**

**red: spin tune**

◇ **Exraction $G\gamma = -10.5$ imposes crossing** $G\gamma = -12 + Q_y \approx -8^+$

◇ **That also requires crossing** $G\gamma = -6 - Q_y \approx -10^-$

**as extracting before -6-Qy would require moving $Q_y > 4.5$ and we do not like that!**

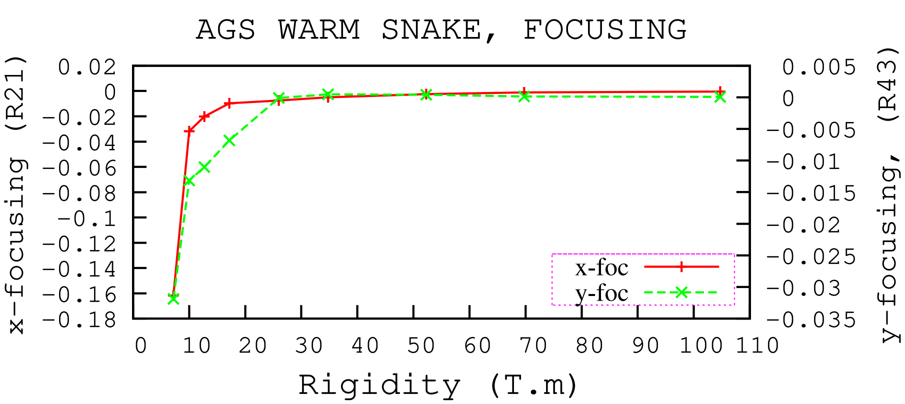


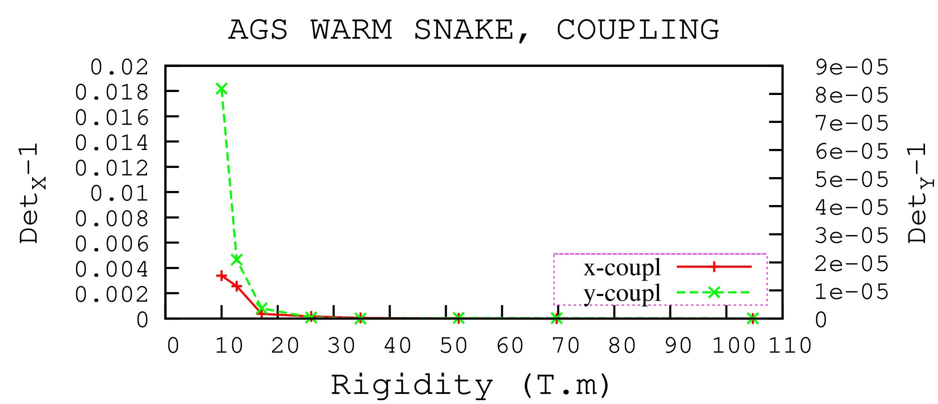

• **Interest of extraction $|G\gamma| > 7.5$ :**

**- $G\gamma = -7.5$ is $B\rho = 6.97$ T.m, even lower than proton's at $B\rho = 7.21$ at $G\gamma = 4.5$ ;**

**- this low-rigidity region is one of substantial optics perturbations in the AGS :**

**strong betatron distortion, and coupling .**



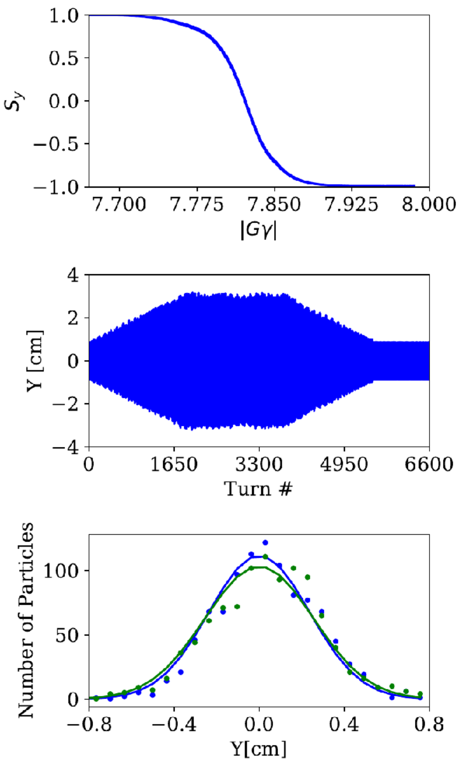

• **Higher extraction rigidity from booster requires visiting capabilities: Booster MM power supplies; booster extraction kicker (9.5 T m); injection system limits in AGS ...**

*[C. Gardner, Injector setup for Helions in eRHIC, Spin Meetings, Nov. 18, 2015]*

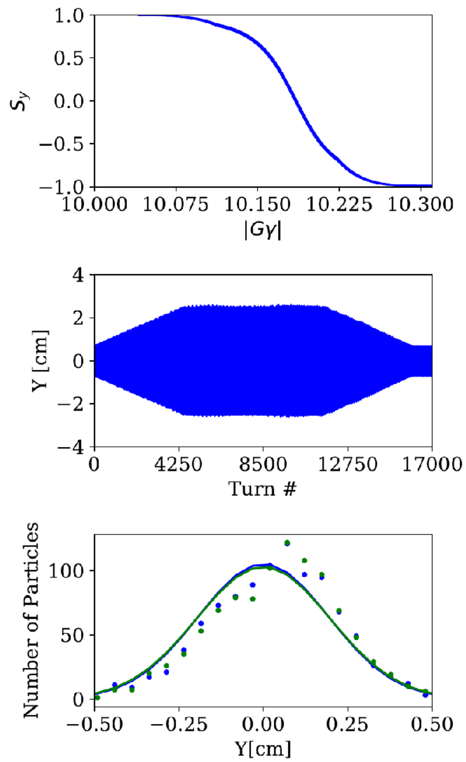
# • AN AC DIPOLE

**Has been installed in Booster.**

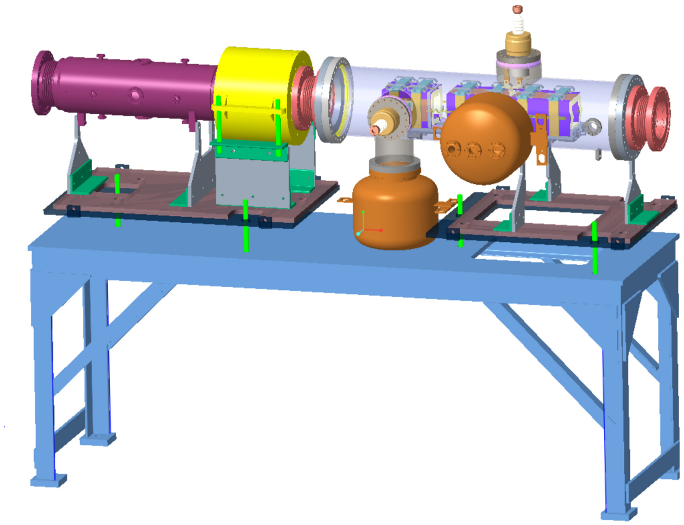
$G\gamma = -12 + Qy$




$-6 - Qy$




◇ **AC dipole & tune kicker at booster E3 straight:**



◇ $f_{osc} \approx 250\,kHz$

• **Plans:**

◇ **Next Fall: Establish beam dynamics and acceptance upon wide vertical beam shaking**

◇ **January 2021: polarized proton beams will allow establishing spin flipping**

**Resonance crossed will be $G\gamma = 0 + Q_y$ ($Q_y \approx 4.2$)**

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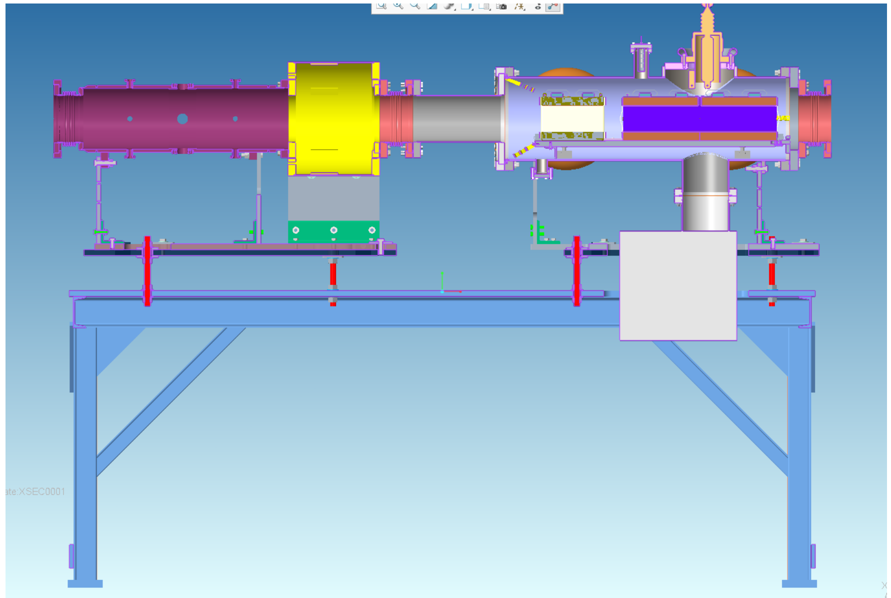
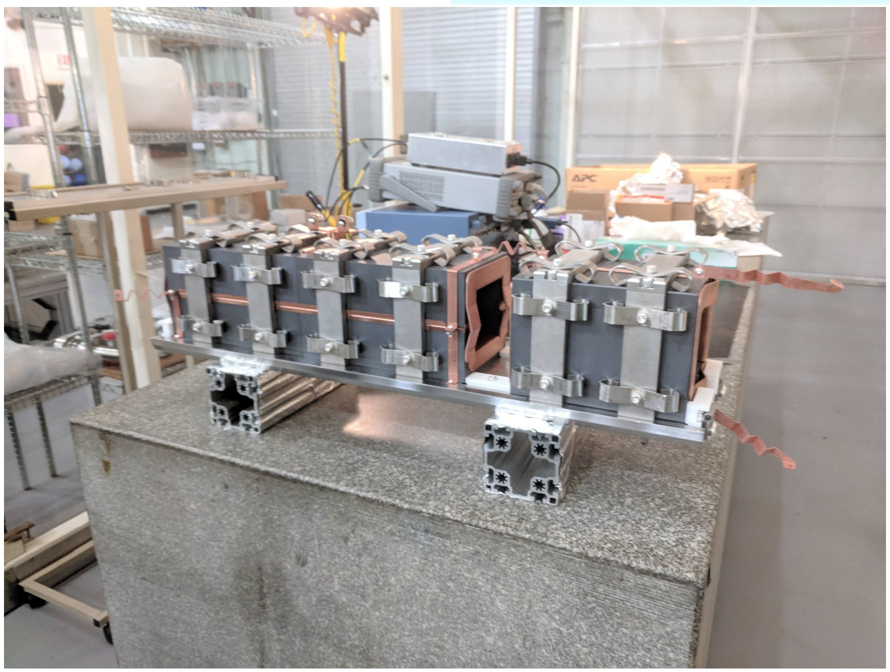
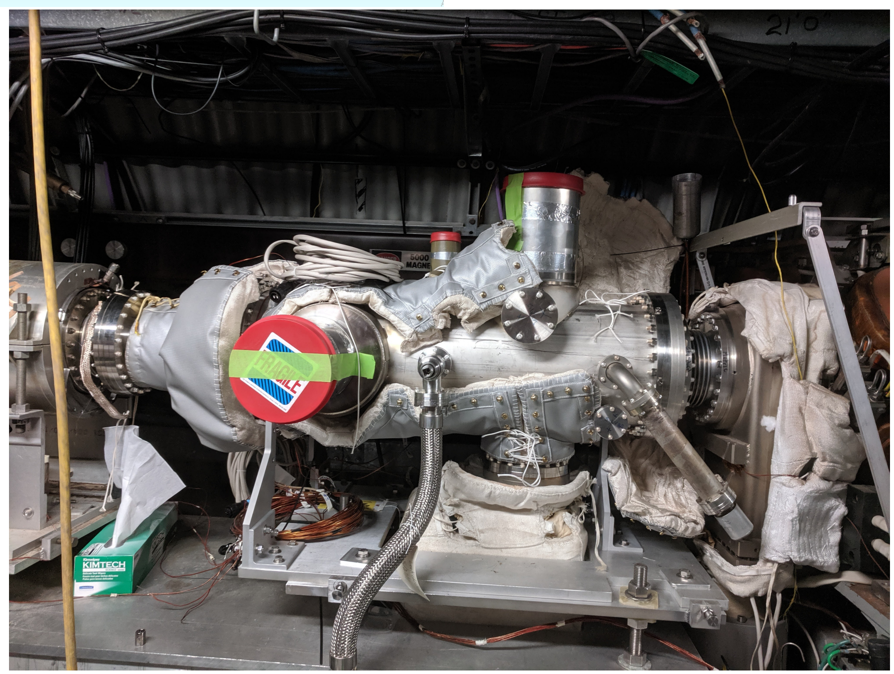
*Refs.: Kiel Hock et als., BNL C-AD: https://technotes.bnl.gov/PDF?publicationId=209028; https://technotes.bnl.gov/PDF?publicationId=203600*

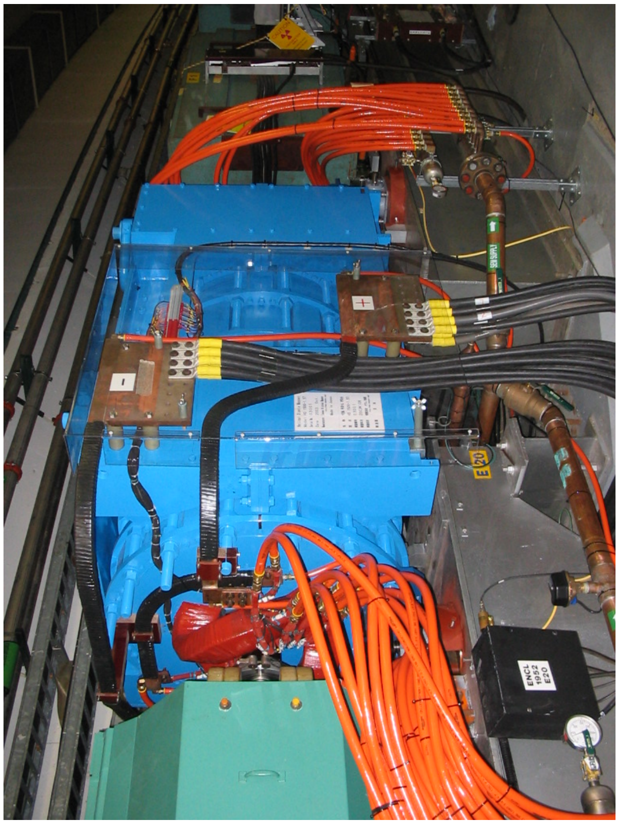
# AN AC DIPOLE IN BOOSTER (cont'd)

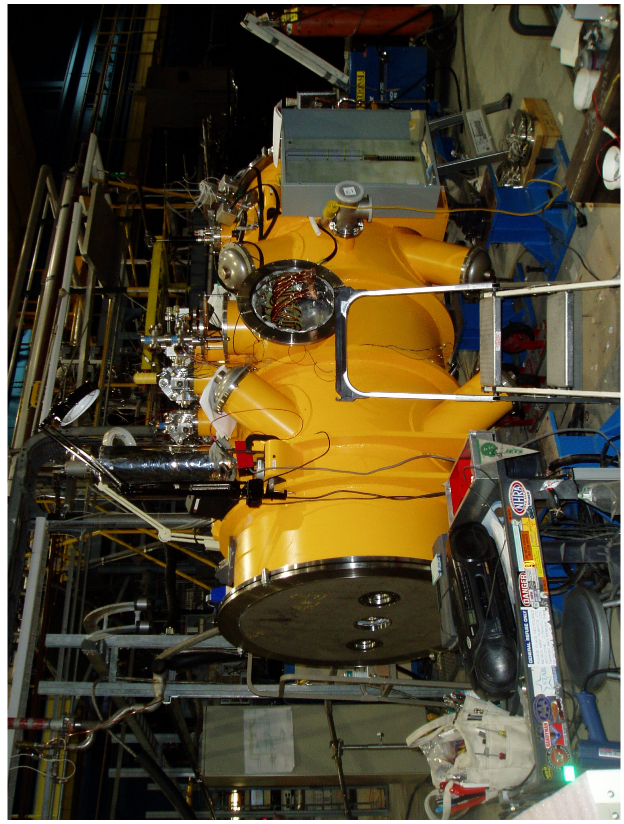


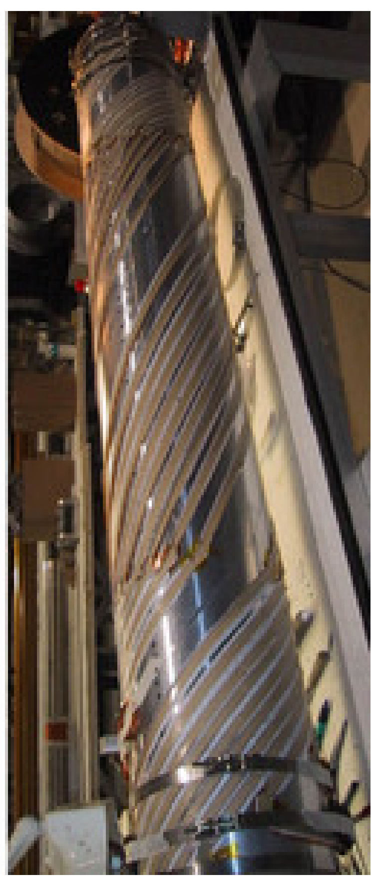




- $^3$**He in AGS**







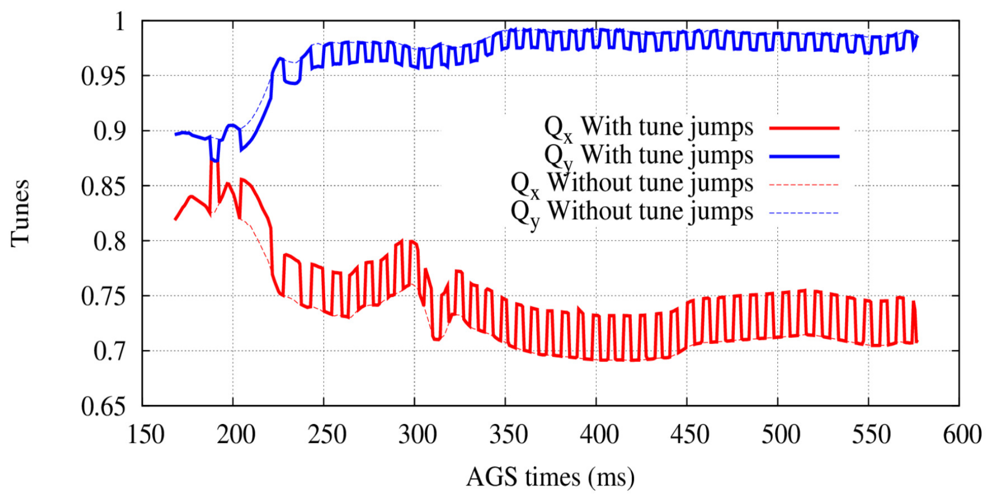
*Ref.: https://www.riken.jp/en/news_pubs/research_news/rr/5162/*

# • $^{3}$He in AGS (cont'd)

◇ G$= -4.18$: AGS partial snakes are 2.3 times stronger than for protons

⋄ This is ok for overcoming 1.5 times stronger resonances.

◇ Issue however : snakes induce $\vec{n}_0$ tilt resulting in harmful 81 resonance series $G\gamma = \text{int.} \pm Q_x$, stronger with $^{3}$He.

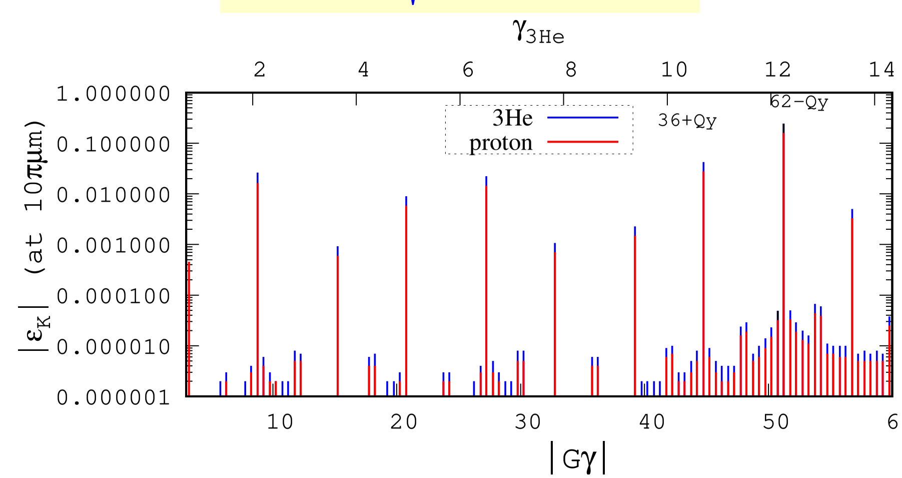



◇ *With $^{3}$He, snakes are $\frac{|G_{^3He}|}{G_p} = 2.3$ times stronger than for protons :*

| | Warm snake | Cold snake |
|---|---|---|
| B max (T) | | 3 |
| B nominal (T) | 1.5 | 2.1 |
| snake angle (deg.) proton : | ≈ 11 | ≈ 21 |
| snake angle (deg.) $^3He^{2+}$ : | 26 | 44 |
| "% snake" proton : | 6 | 12 |
| "% snake" $^3He^{2+}$ : | 15 | 25 |

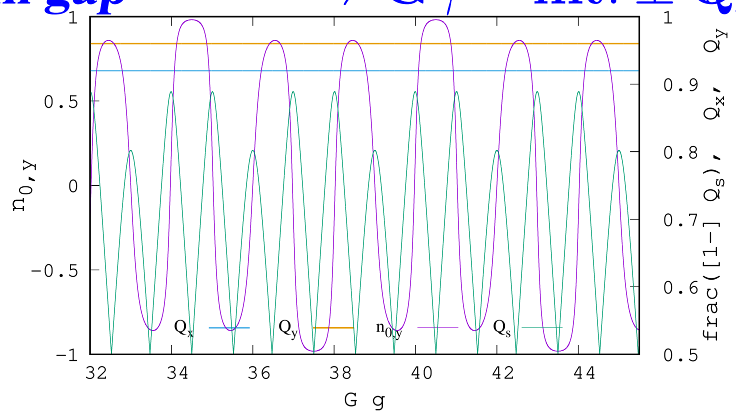
◇ *At identical normalized emittance, strengths of intrinsic resonances satisfy*

$$\frac{|\epsilon_{^3He}|}{|\epsilon_p|} = \sqrt{\frac{|G_{^3He}|}{G_p}} \approx 1.5$$

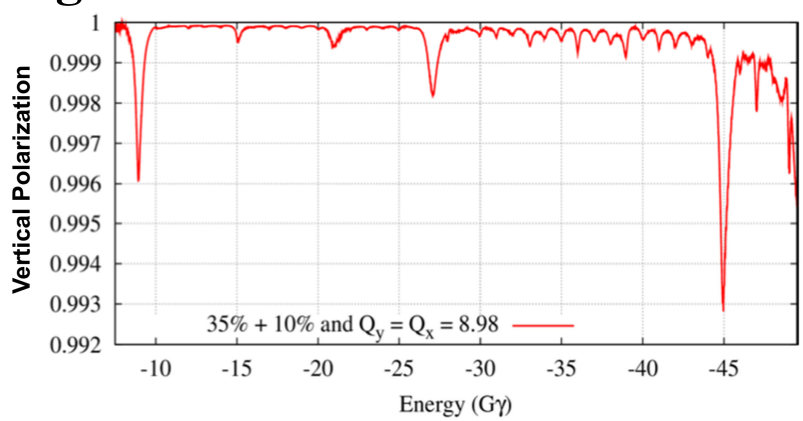


- **Foreseen: two 35%+15% partial snakes generate a large spin tune gap.**
- **Both betatron tunes can be put into gap to avoid all depolarizing resonances.**

◇ $Q_x$ ***and*** $Q_y$ ***in spin gap*** $\Rightarrow$ $\mathrm{G}\gamma = \mathrm{int.} \pm \mathrm{Q}_{\mathrm{x,y}}$ ***never happens :***



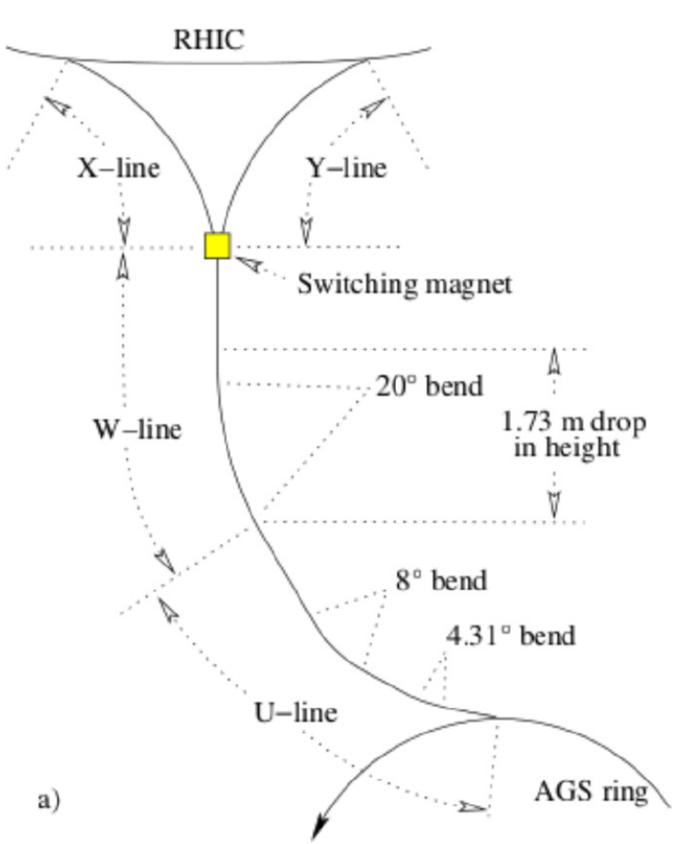

◇ **Proof-of-principle tracking simulation : a 2000-$^3$He bunch,** $\mathrm{G}\gamma = -7.5 \rightarrow -45.5$ **:**



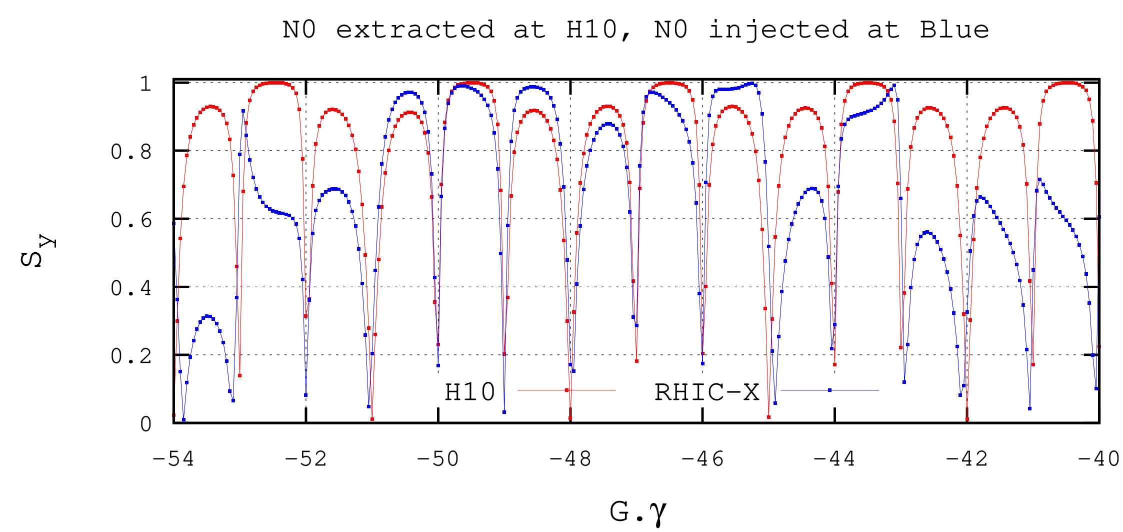

- **Higher injection rigidity from booster requires visiting capabilities: injection system limits in AGS; RF systems/frequencies ...**

*[C. Gardner, Injector setup for Helions in eRHIC, Spin Meetings, Nov. 18, 2015]*

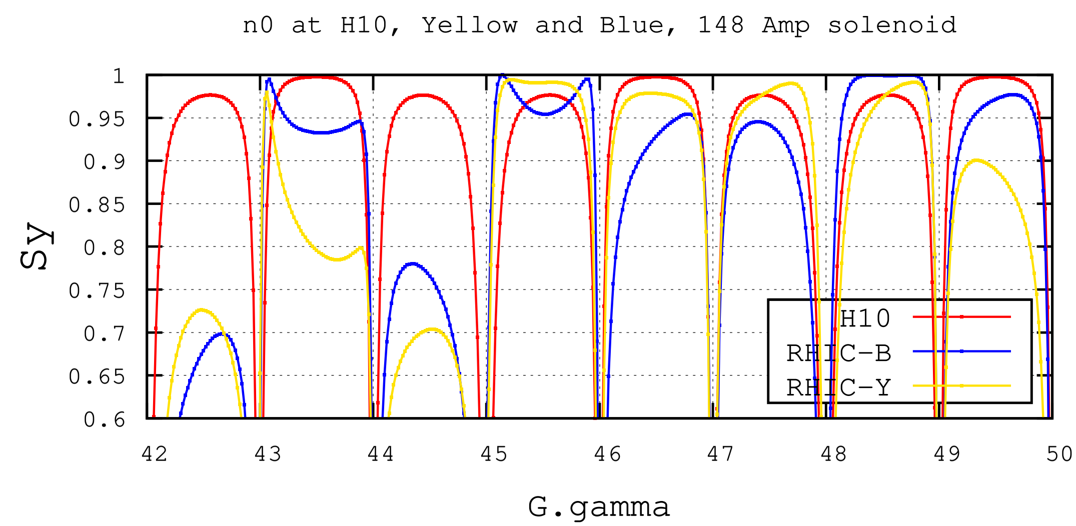
# • AtR




The AtR line.




Vertical component of $\vec{n}_0$ at AGS extraction septum (red) and at RHIC Blue injection kicker (blue curve). Snakes 6% and 15%




Proton case for comparison

# RHIC / EIC PLANS

- Todays 100% transmission to 100 eV and 15% loss to 255 GeV indicate a resonance compensation threshold (by the pair of full snakes) in 0.18-0.45.

- Resonances with $^3He^{2+}$ are stronger by $\left(\frac{|G_{^3He}|}{G_p}\right)^{1/2} = 1.53$, snakes are $\frac{G_{^3He}}{G_p} = 2.3$ as strong.

- On the other hand:

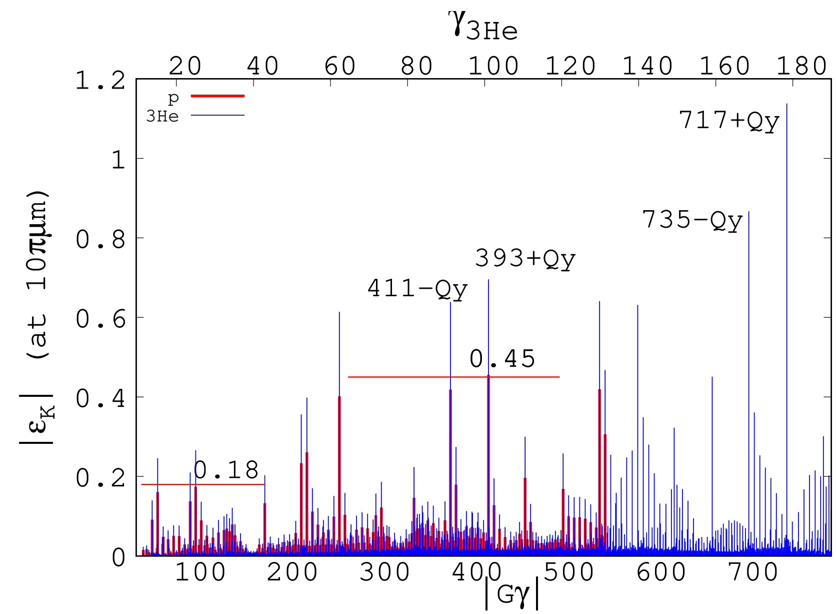
- resonance spectrum is denser

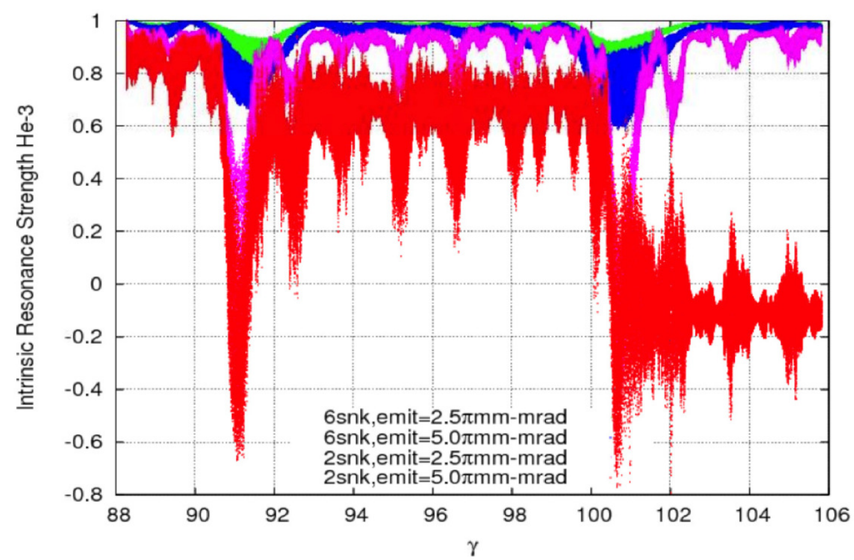
- imperfection and intrinsic resonances overlap, this affects polarization (excites snake resonances)

- Simulations show that 2 snakes do not maintain polarization upon crossing of

$G\gamma$ = -411 + Qy ($\gamma$ = 91) or

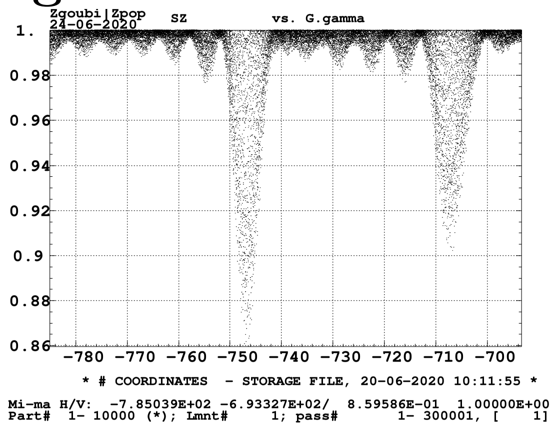
$G\gamma$ = -393-Qy ($\gamma$ = 101) ...



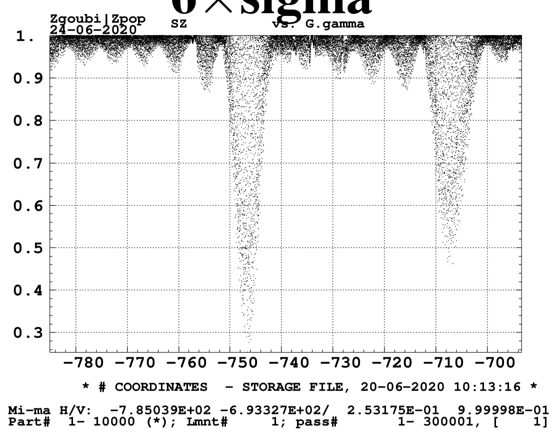



- **Whereas 6-snake do ... and beyond $G\gamma$ = 717 + Qy ($\gamma \approx$170)**

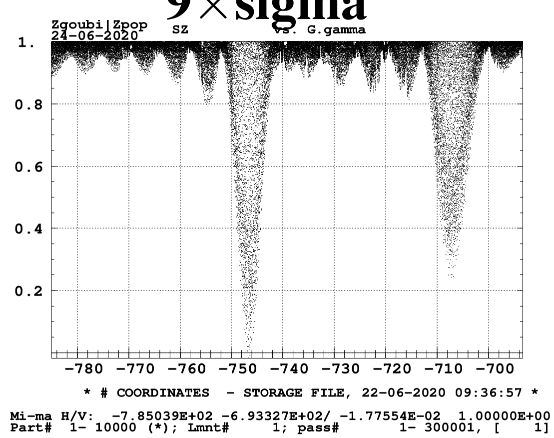
$1 \times$ sigma invariant $= 0.75\,\mu$m

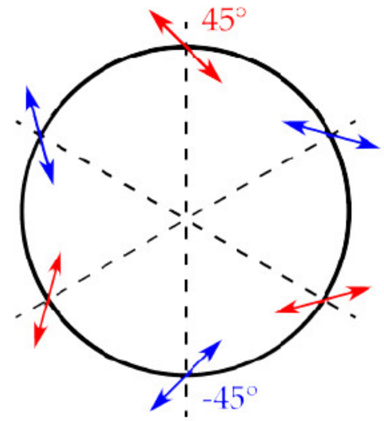



**6$\times$sigma**




**9$\times$sigma**




- **Foreseen scheme :**

**- 6 snakes ensure $\mathrm{N_{snakes}} > 5 \times \mathrm{Max}[\epsilon_{\mathrm{int}}] \approx 5$,**

**- $2\pi/6$ distance ensures energy-independent $\mathrm{Q_s}$,**

**- snake axes at $\phi_k = \pm 45^o$ yield**

$$Q_s = \frac{1}{\pi}\sum_{k=1}^{6}(-)^k\phi_k = 3/2$$

**- build 4 additional snakes from existing, like-helicity, rotator modules**

# In Summary:

- **No showstopper**
- **Substantial amount of work left to converge on design and parameters:**

  **- conclude on possible options**

  **- settle questions related with higher rigidity out of Booster / into AGS**

  **- complete whatever work is needed to assure $> 70\%$ at store ...**
- **... for real soon, 2023+ ?**

**Thank you for your attention**