Mitigation of Space Charge Effects in RHIC and its Injectors

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Overview

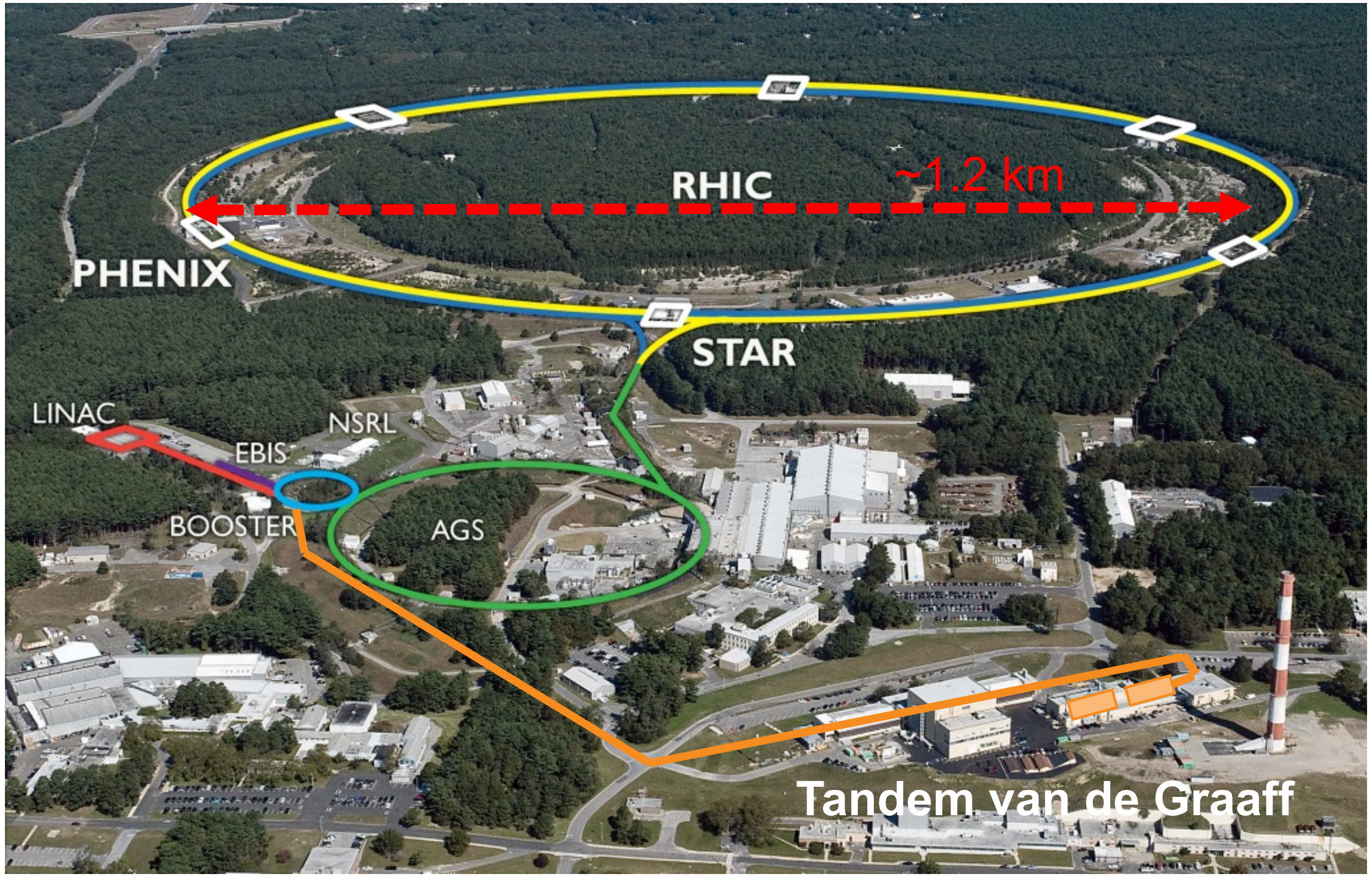
- RHIC complex and the need for space charge mitigation
- Survey of intensity dependent effects during:
    - Polarized proton operation
    - Gold beam operation
        - In the injectors
        - Low energy (3.85 GeV/n) colliding beam operation in RHIC

RHIC Accelerator Complex

Accelerator Rings	Circumference [m]
Booster	201
AGS	807
RHIC	3833

Typical Top Energies [Total, GeV/N]

	Au	Pol. Protons
Linac (H^-)	--	1.1
Booster	1	2.3
AGS	10	23.8
RHIC	100	255



Heavy Ions	Protons
E-beam Ion Source (EBIS)	OPPIS (polarized)
Tandem Van de Graaf	High-intensity H^- (unpolarized)

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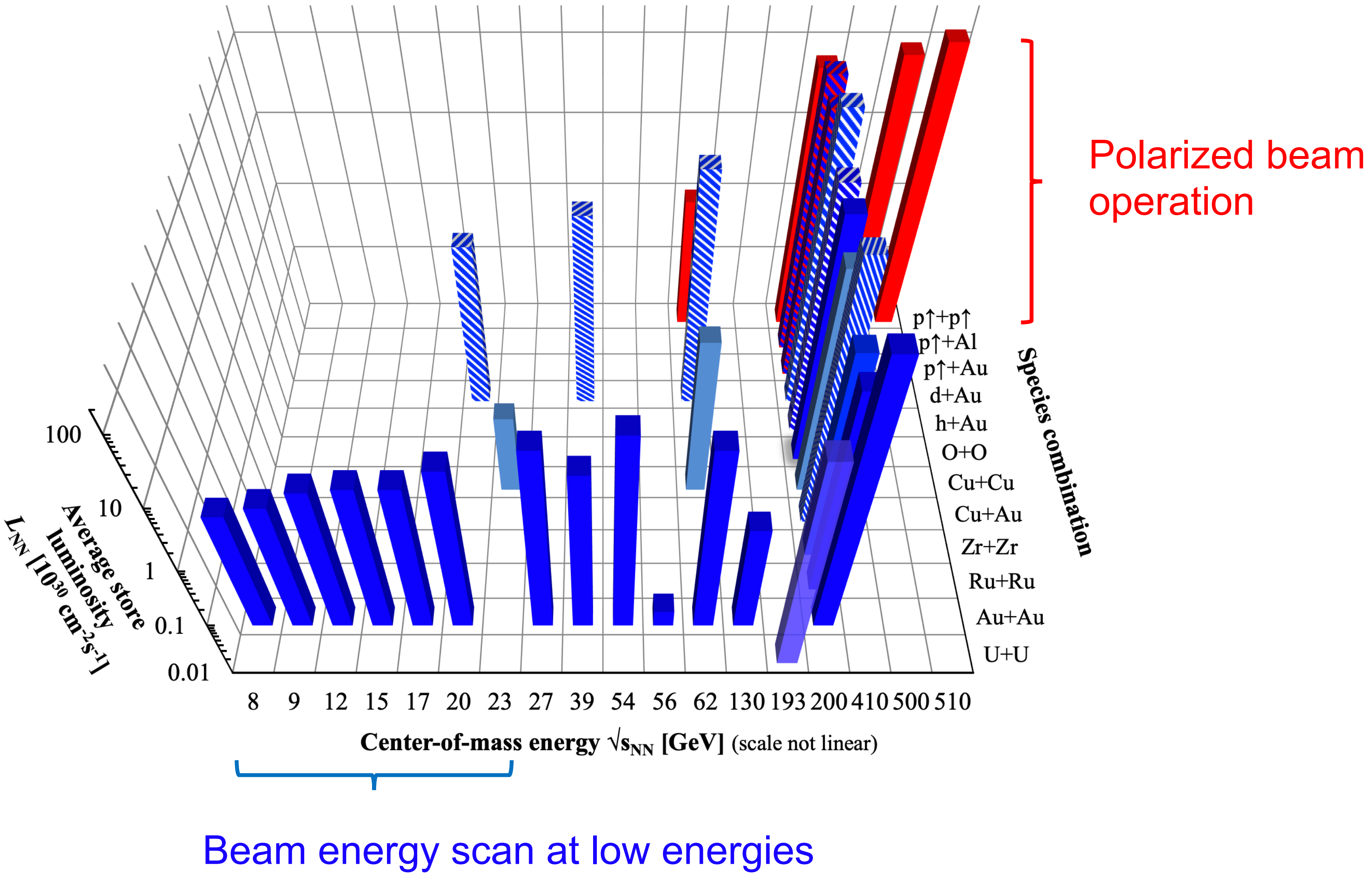
RHIC Physics Program

- To date: 12 different species combinations in collision
- Polarized p-p and p-ion collider operation
- Energy scan of Au-Au collisions from 100 GeV/N (max) down to sub-injection energies as low as 3.85 GeV/N

RHIC energies, species combinations and luminosities (Run-1 to 22)

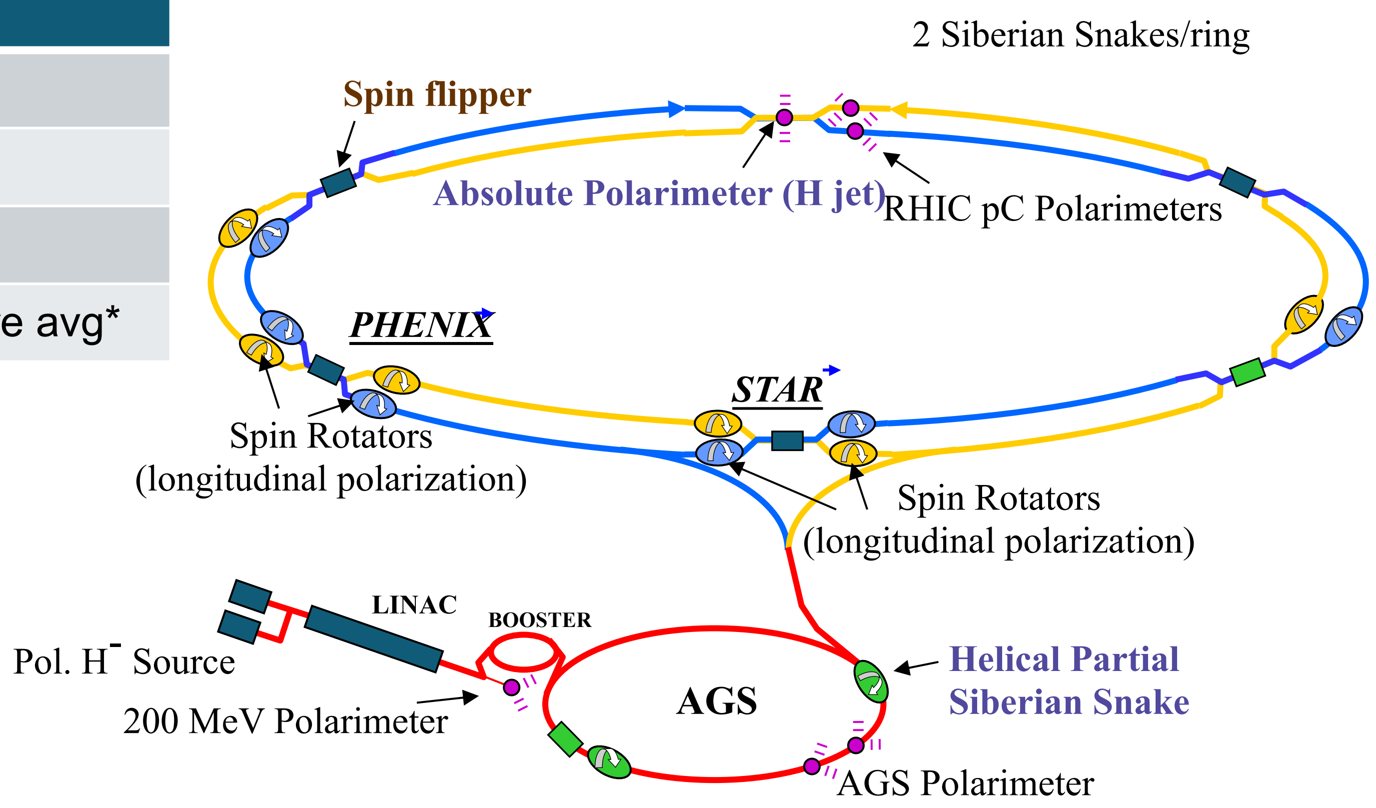


Polarized proton operation

RHIC Polarized Beam Complex

	Max Energy [GeV]	Pol. At Max Energy [%]	Polarimeter
Source+Linac	1.1	82-84	
Booster	2.5	~80-84	
AGS	23.8	67-70	p-Carbon
RHIC	255	55-60	Jet, full store avg*

* Includes both ramp loss and store decay



	Relative Ramp Polarization Loss (Run 17, full run avg)
AGS	17 %
RHIC	8 %

Depolarizing resonances

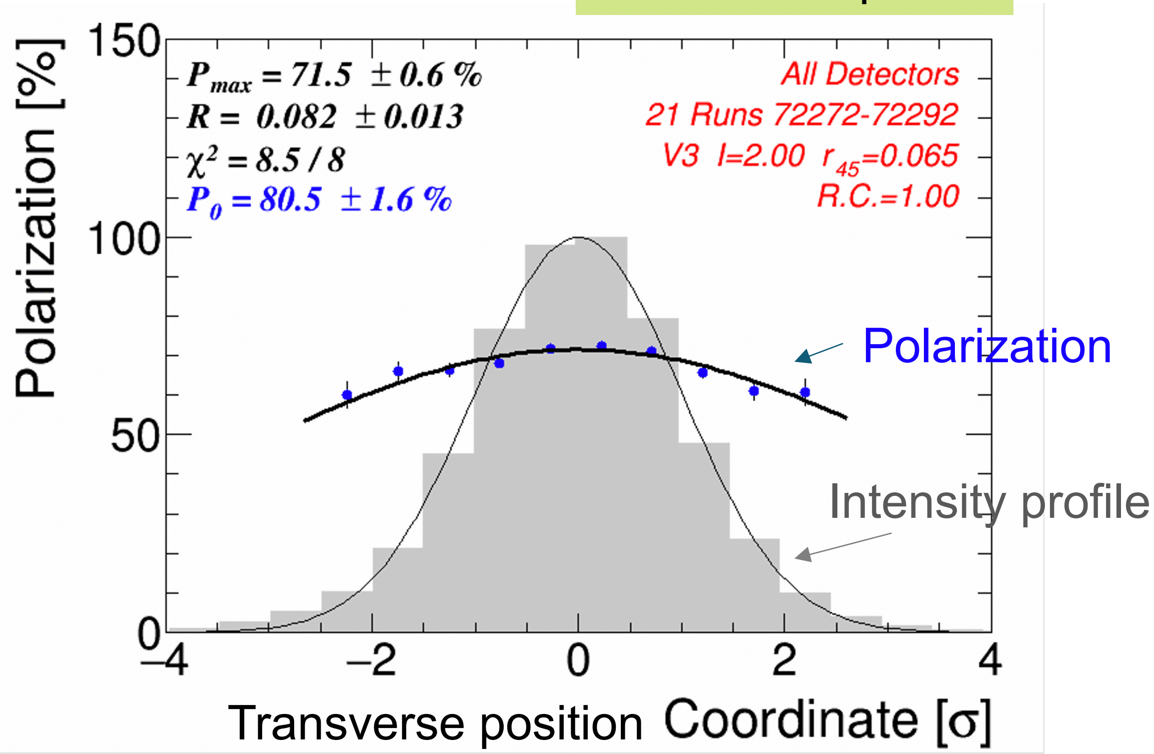
- Most remaining depolarization between the source and RHIC is from intrinsic resonances
  - High amplitude particles sample higher focusing fields in quads
  - More depolarization at higher betatron amplitude

Polarization transmission through single resonance (gaussian beam, emittance *I*):

$$\frac{P_f}{P_i} = \frac{1 - \frac{\pi I}{\alpha I_o}|\varepsilon(I_o)|^2}{1 + \frac{\pi I}{\alpha I_o}|\varepsilon(I_o)|^2} \approx 1 - \frac{2\pi}{\alpha}|\varepsilon(I_o)|^2 \frac{I}{I_o}$$

P_f, P_i = final, initial polarization
I = rms transverse emittance
I_0 = reference emittance
$\varepsilon(I_o)$ = resonance strength at ref emittance
α = resonance crossing rate

Polarization profile



Measured with transversely thin (~10 um) carbon target inserted at varying transverse locations in beam

Polarized collider performance

Collider luminosity, $\mathcal{L}$

$$\mathcal{L} \propto \frac{N^2}{\varepsilon}$$

N = intensity/ bunch
ε = tran. emittance

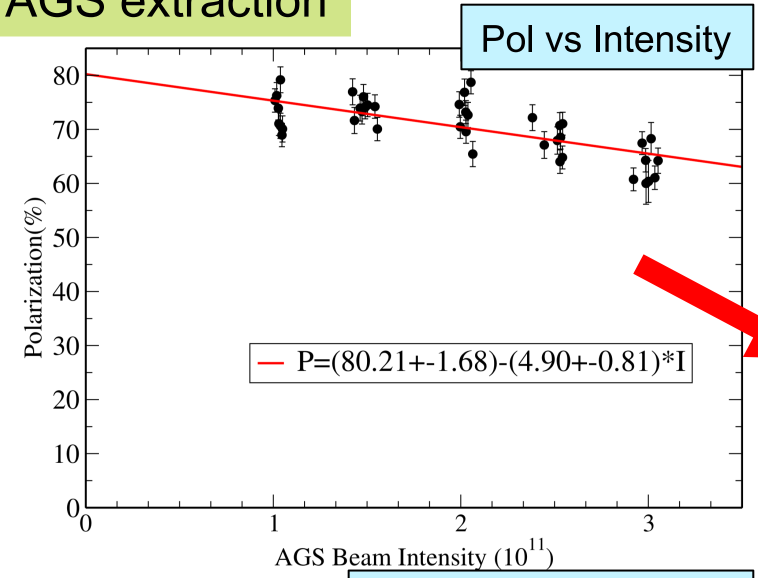
Polarized collider figure of merit (for polarization P):

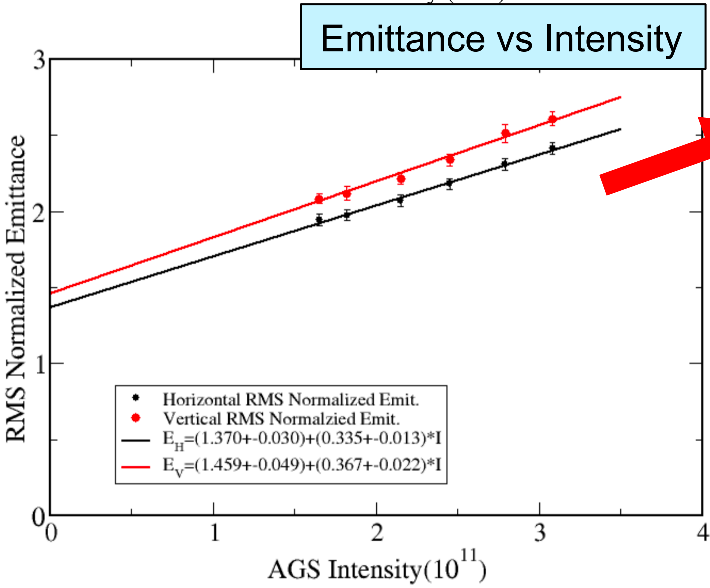
$$\text{FOM} = \begin{cases} \mathcal{L}\, P^2 & \text{transverse spin} \\ \mathcal{L}\, P^4 & \text{longitudinal spin} \end{cases}$$

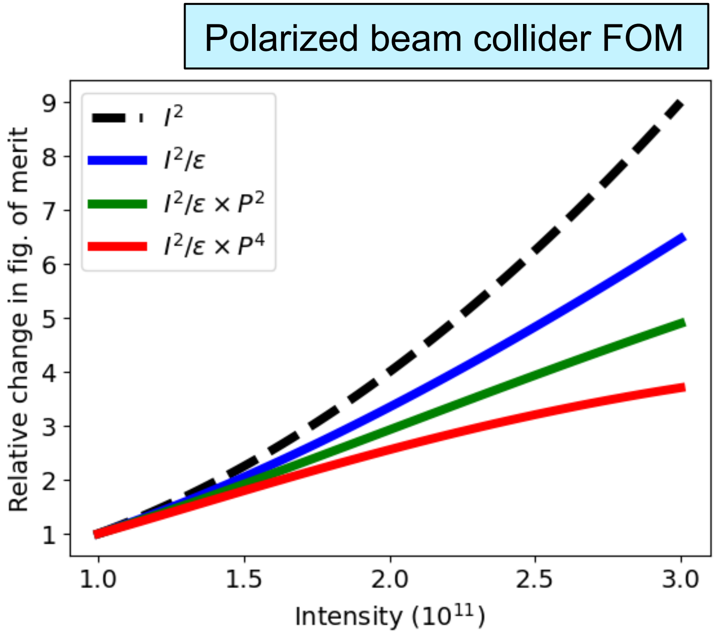
Since both emittance and polarization degrade with intensity figure of merit decreases rapidly

FOM dependence on intensity closer to linear in N than quadratic.

AGS extraction



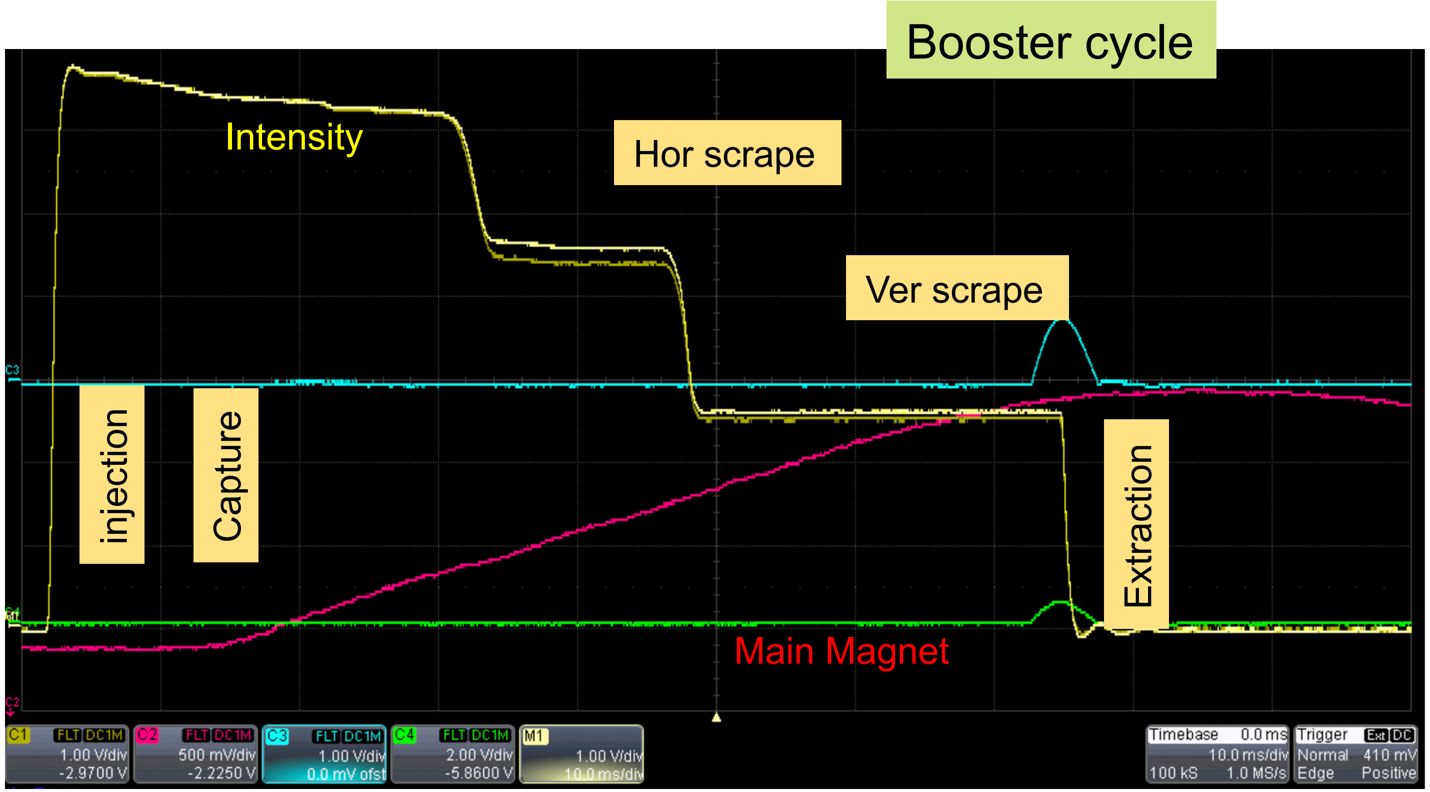




Impact of intensity increase on FOM given emittance and polarization dependence at AGS extraction

Proton Acceleration in Booster

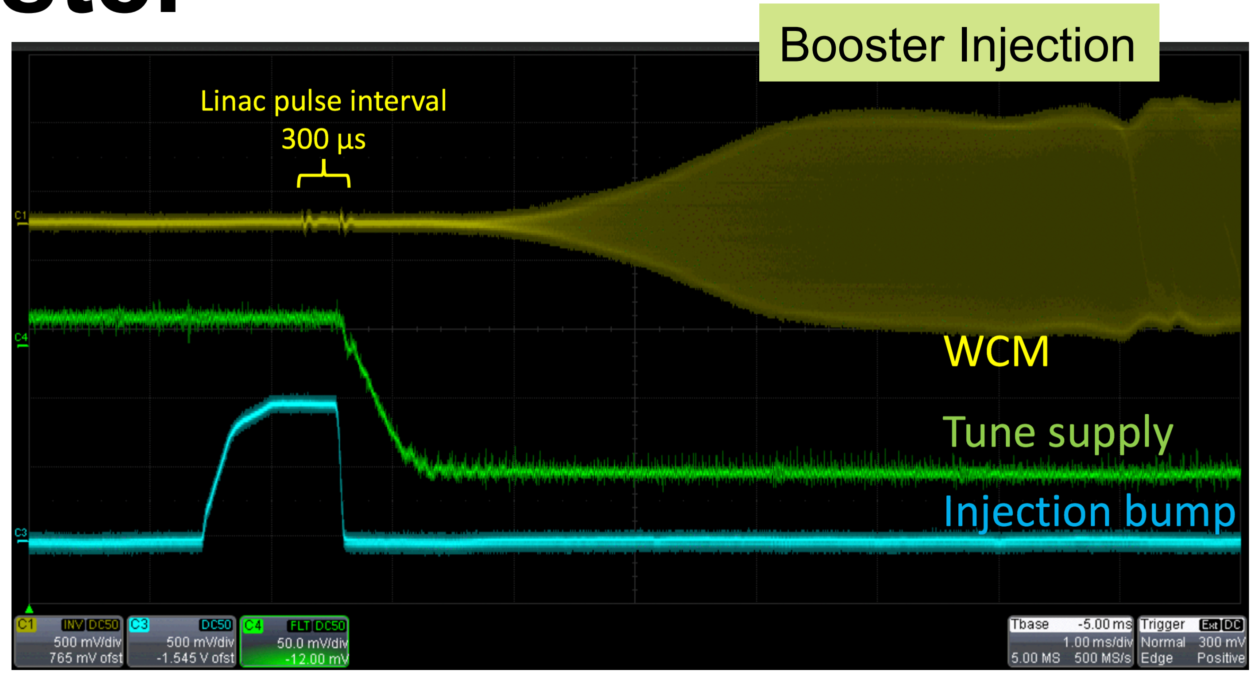
- H- Linac delivers up to 1×10^{12} in 300 us pulse
- Adiabatic RF capture (h=1,2)
- Acceleration ~70 ms
- Transverse scrapes
  - Orbit bumps against apertures
  - Reduce intensity and emittance to RHIC requirements
  - Generally more vertical scraping than horizontal (strong intrinsic resonances are vertical)

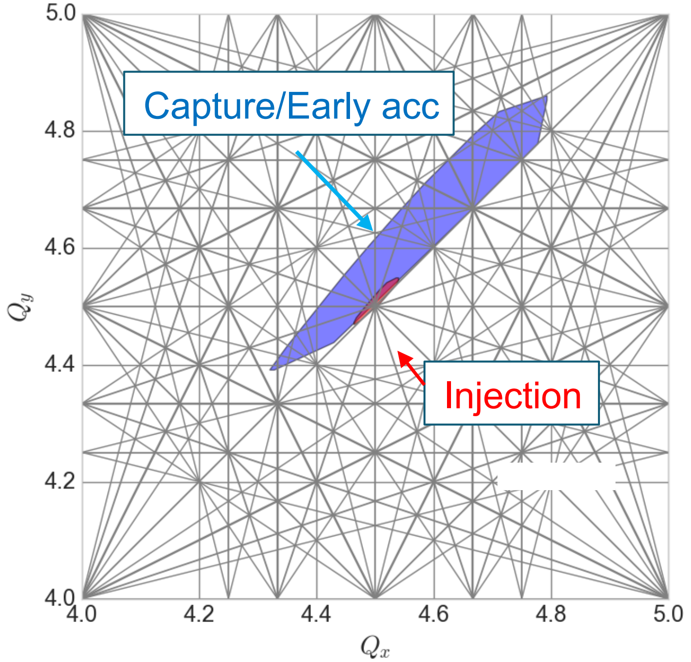


	Energy (Kin. GeV)	Intensity (10^{11})
Injection	0.2	6-8
Extraction	1.416	2.5

Injection of H^- into Booster

- Injection of coasting beam with tunes *near and just above ½*
  - Coasting beam has small space charge
  - Half-integer tune + half integer stopband correction quads minimize beta at stripping foil location
    - Minimizes scattering due to foil
- Tunes pulled up away from half before bunching
  - Max space charge tune shift $dQ_{sc} = -0.4$
- Injection tune: empirical tradeoff between scattering and proximity to half integer





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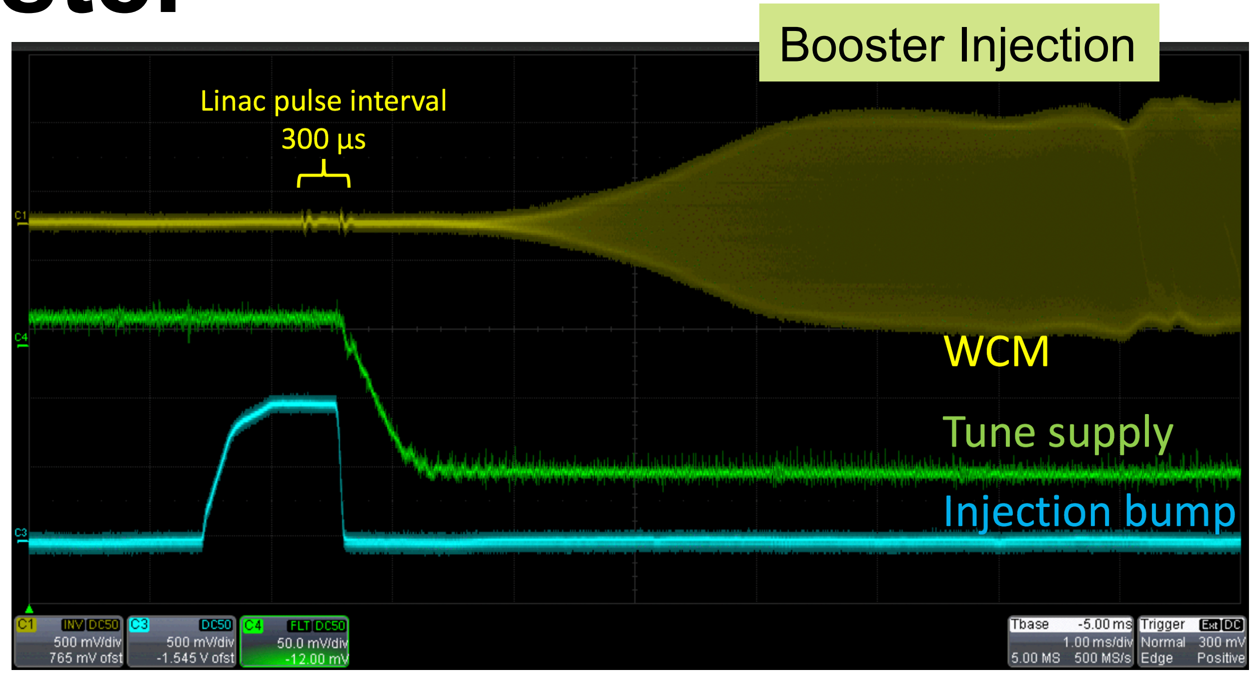
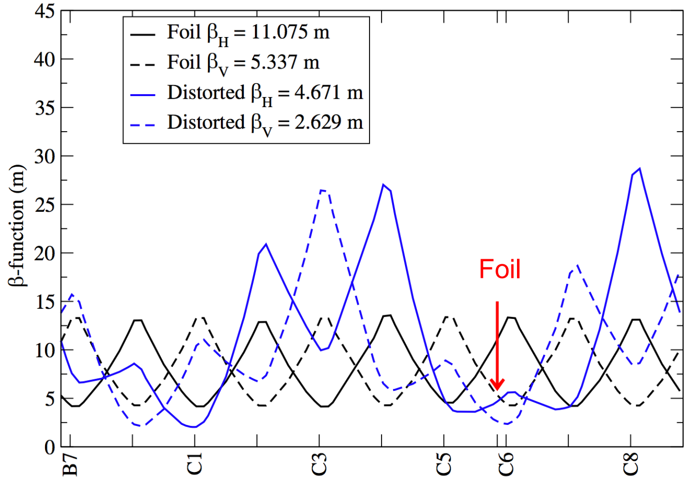
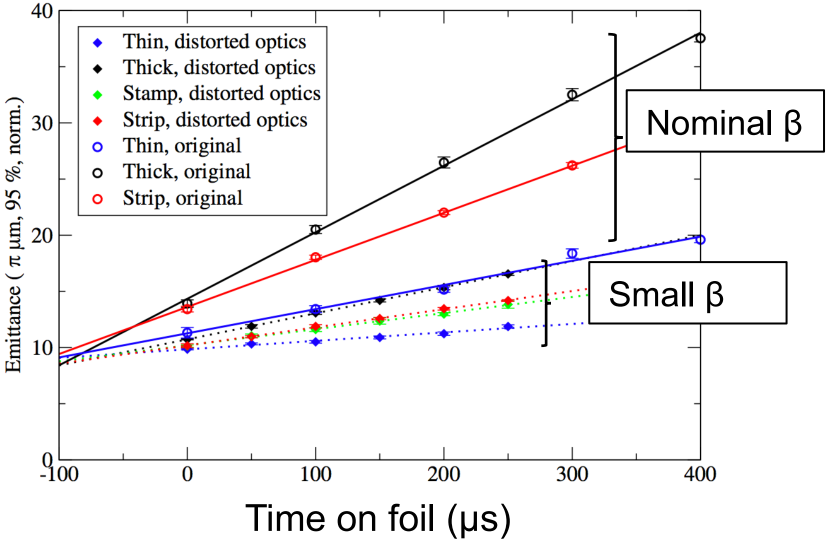




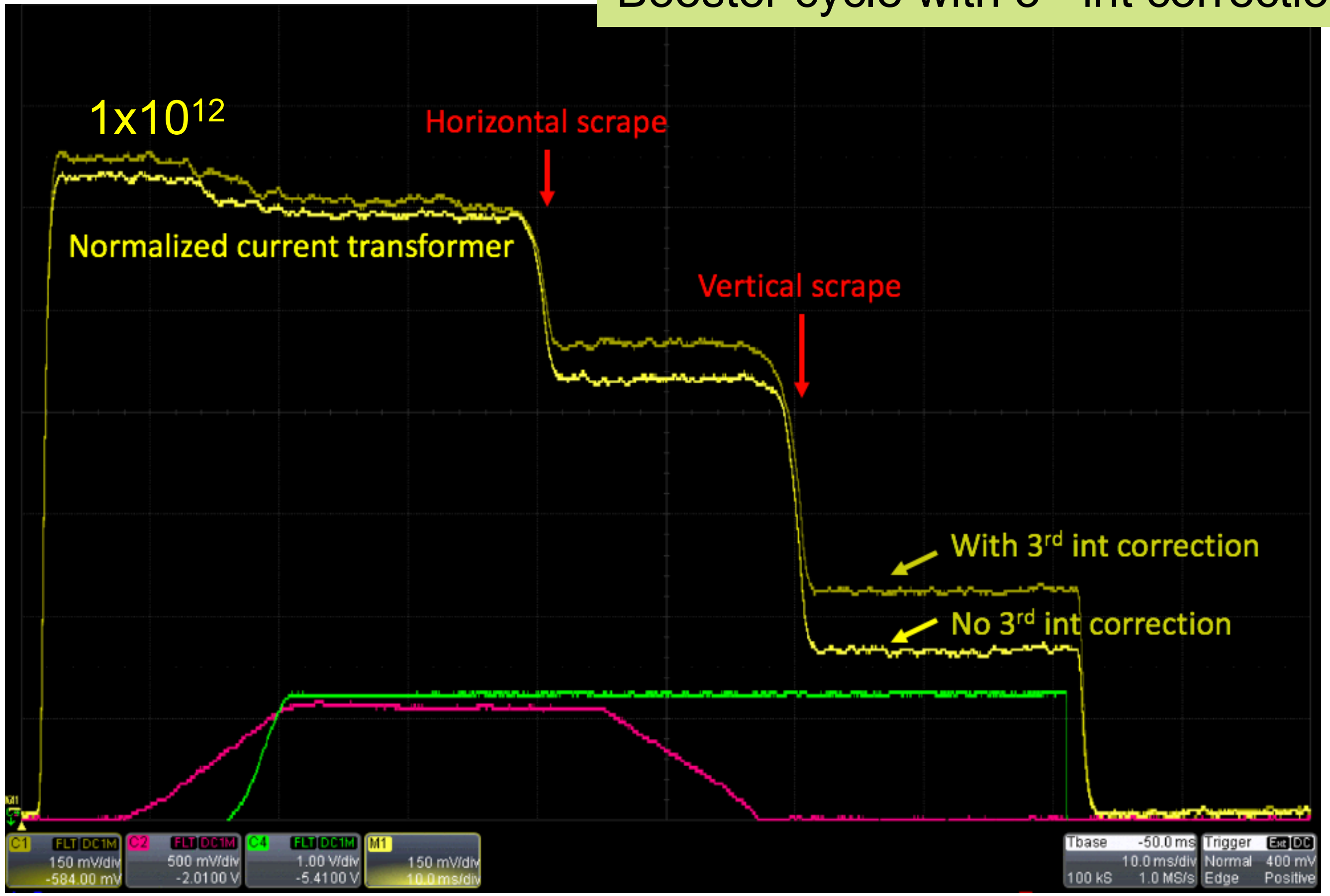
β-functions near the injection foil.



Booster Stopband Correction

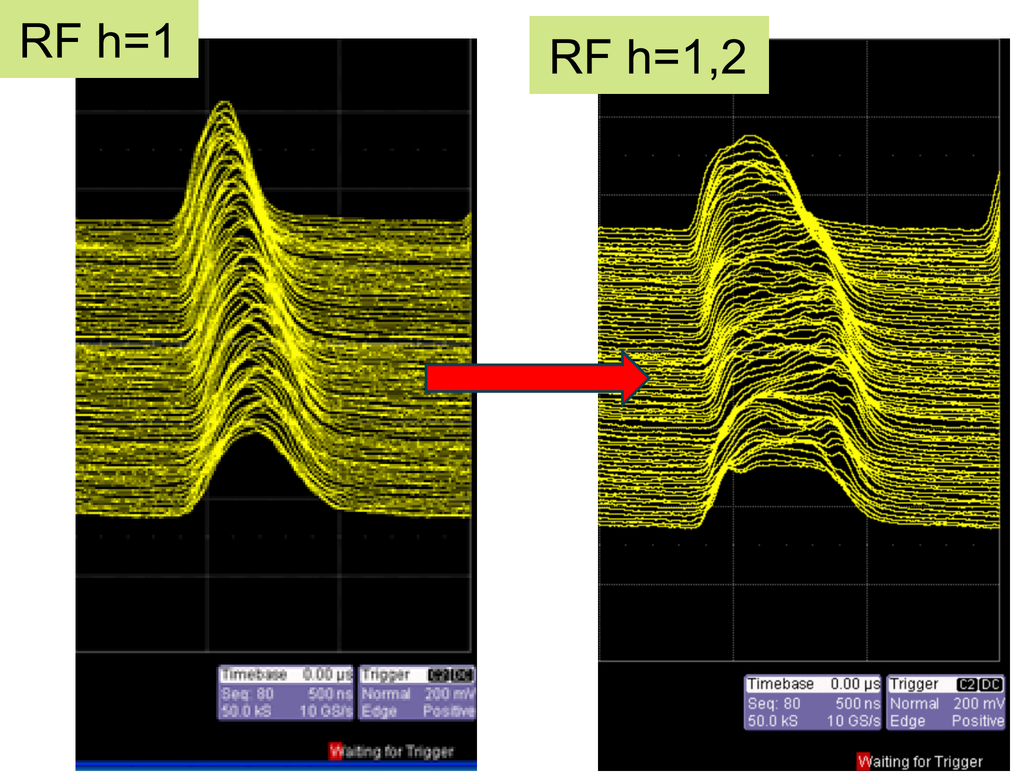
- Higher order multipoles available in Booster
  - In use since high intensity (>10^{13}/pulse) operation
- No direct measurement of beam size in Booster
  - Transverse sizes gauged by intensity through scrapes
- Third integer stop band correction applied at injection energy +30% better transmission to Booster extraction

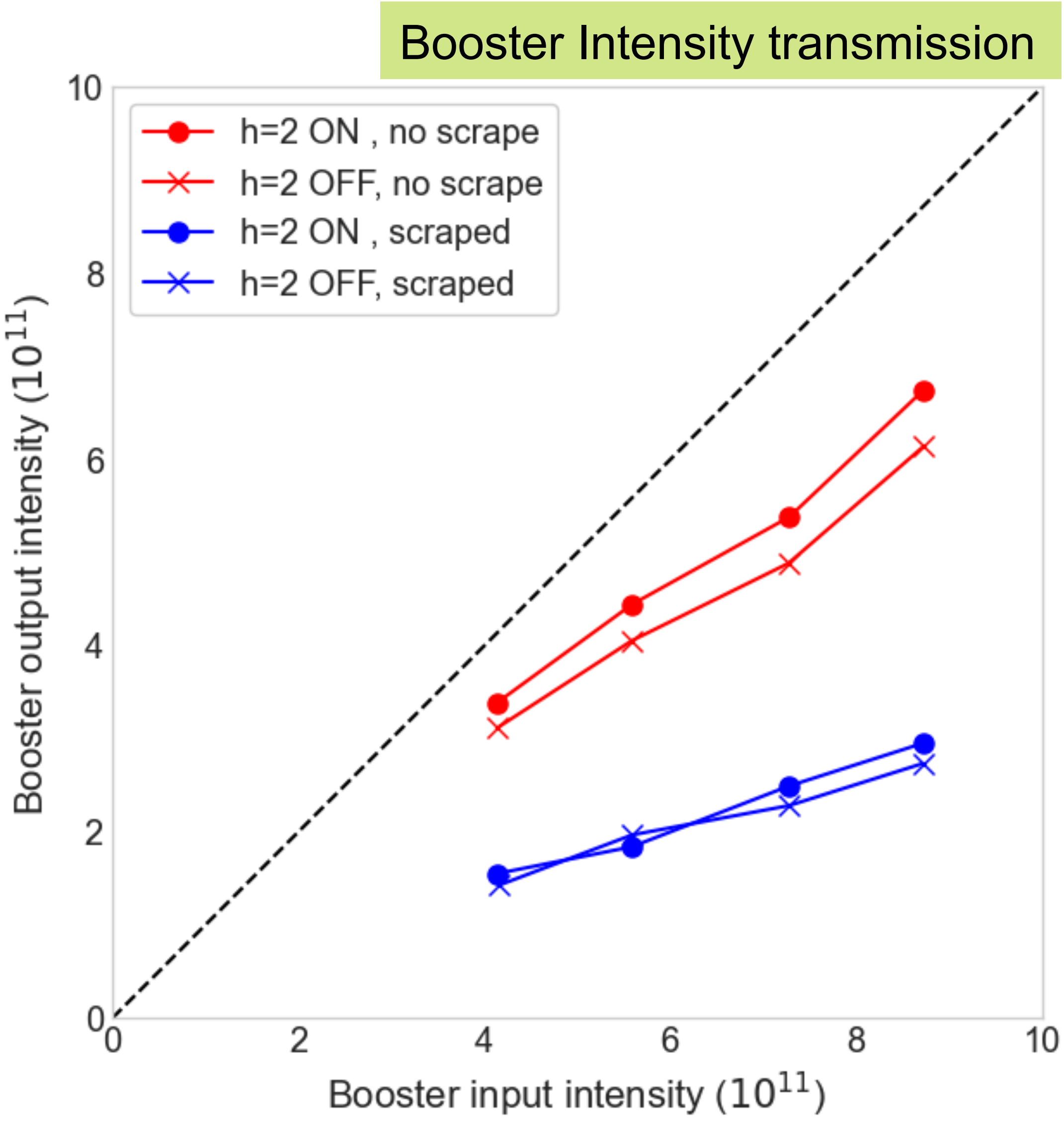
Booster cycle with 3rd int correction



Dual Harmonic RF in Booster

- Reduction of peak intensity with second harmonic RF defocusing
- Adiabatic capture of injected coasting beam with h=1 and h=2
- 25% reduction of peak current
- +15% transmission at typical operating intensity with scraping present
- More improvement without scraping
  - Implies some particle blown out to high amplitude and lost in the scrape





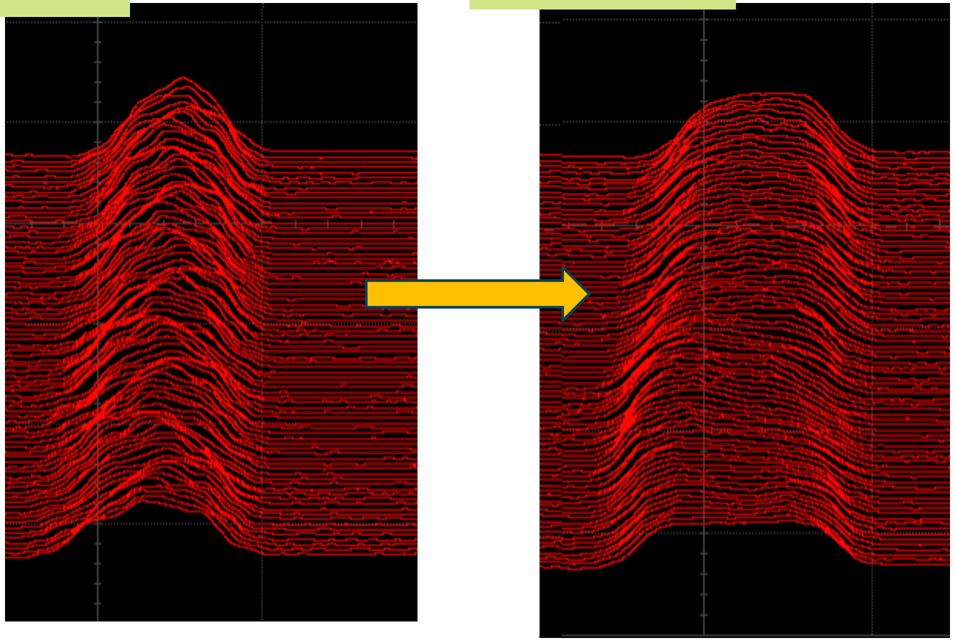
Dual Harmonic in AGS

Space charge tune shift at AGS injection: $dQ_{sc,x,y}$ = -0.11, -0.23

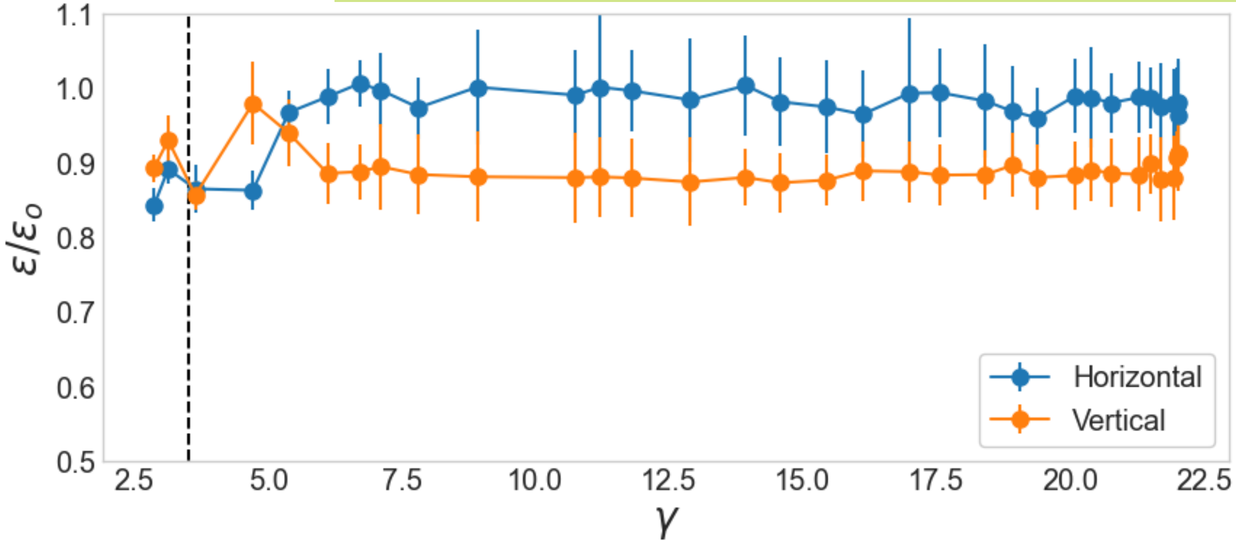
Larger dQ_{sc} in vertical due to preferentially vertical scraping: $\varepsilon_{x,y}$ = 1.4, 0.6 μm (rms norm)

With dual harmonic 10% reduction of vertical emittance, horizontal unchanged (consistent with larger vertical dQ_{sc})

RF h=6 RF h=6,12



Relative change in AGS emittance (IPM)



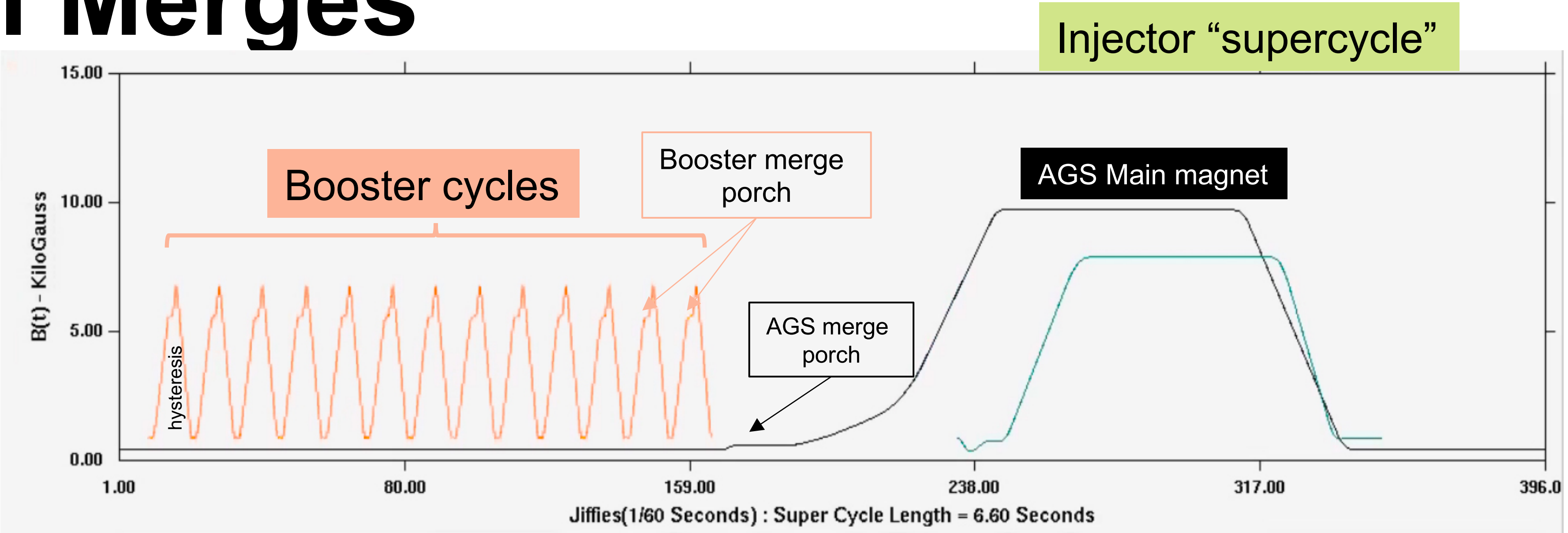
Dashed line marks end of h=12 (freq limited)
Some apparent early cycle changes (γ < 5) due to changes in dp/p, beam centroid motion, instrumental errors

Gold beam operation

Longitudinal Merges

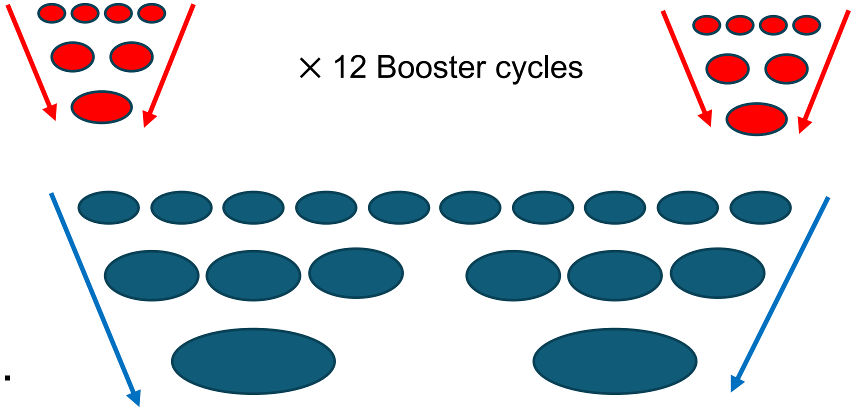
RHIC heavy ion physics per bunch intensity needs merging several cycles of ion source pulses

RHIC operation: N ~2-3x10^9

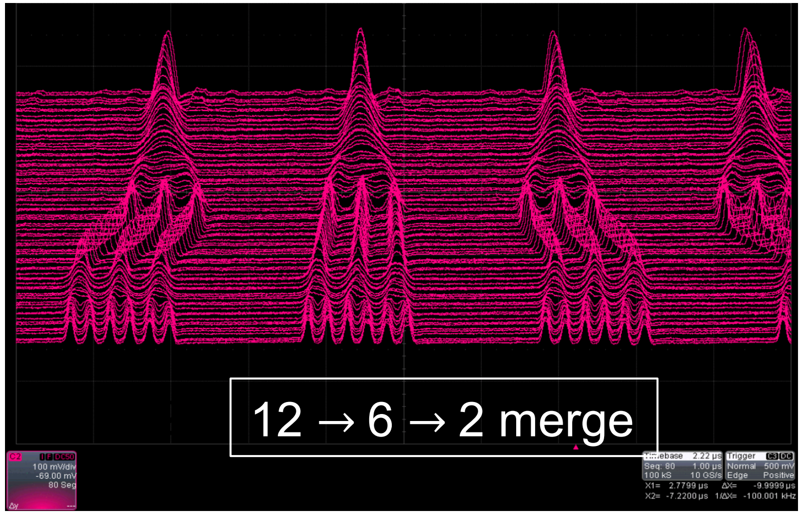


Booster: 4 → 2 → 1
In 12 separate cycles

AGS: 12 → 6 → 2
Final 2 bunches extracted to RHIC.



AGS extraction 2.5-3 x 10^9 / bunch



Longitudinal Merges: AGS injection

Space charge bottleneck in AGS comes after second merge (6 → 2 bunches)

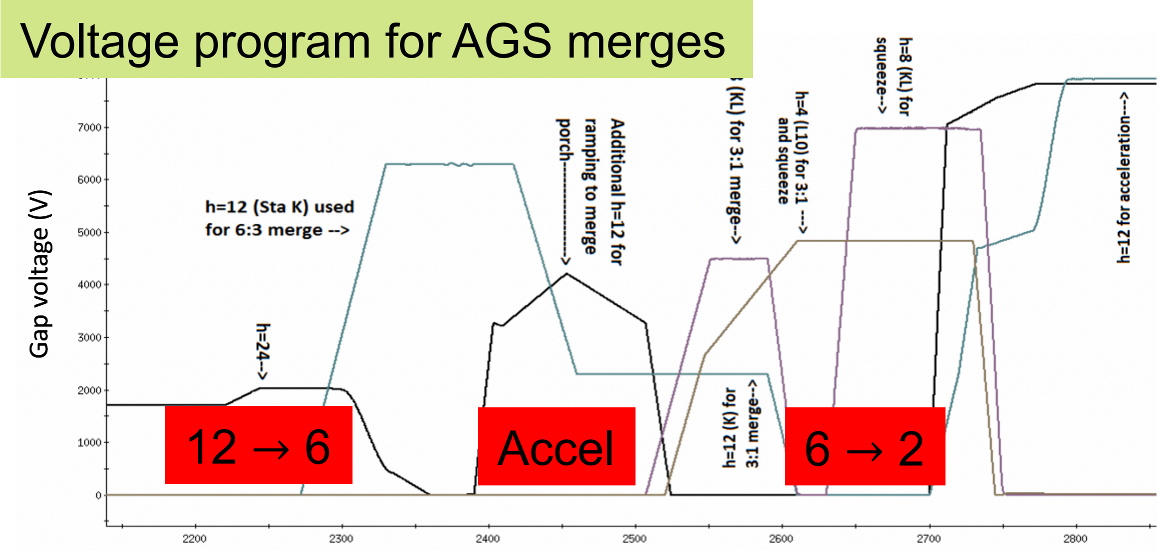
- dQ_{sc} ~ -0.4 in both planes

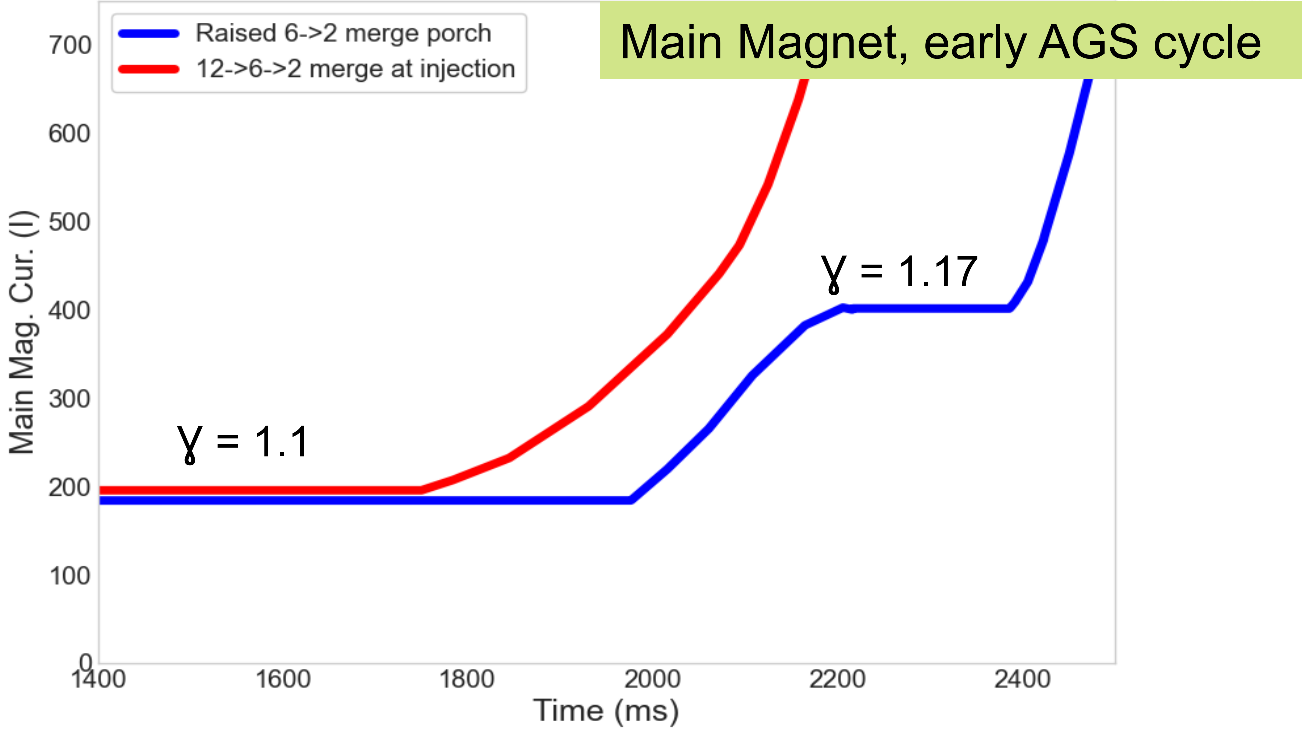
Merges occur at low energy due to frequency range limitations on lower harmonic cavities (h=4, 8)

Modification of h=4,8 cavity capacitance allowed second merge from 6 → 2 bunches at higher ɣ

γ^{-2} ~= 10% reduction in dQ_{sc}

Peak intensity with the higher merge porch ~12% higher (commensurate with reduction in peak current)





Low Energy Au RHIC collisions

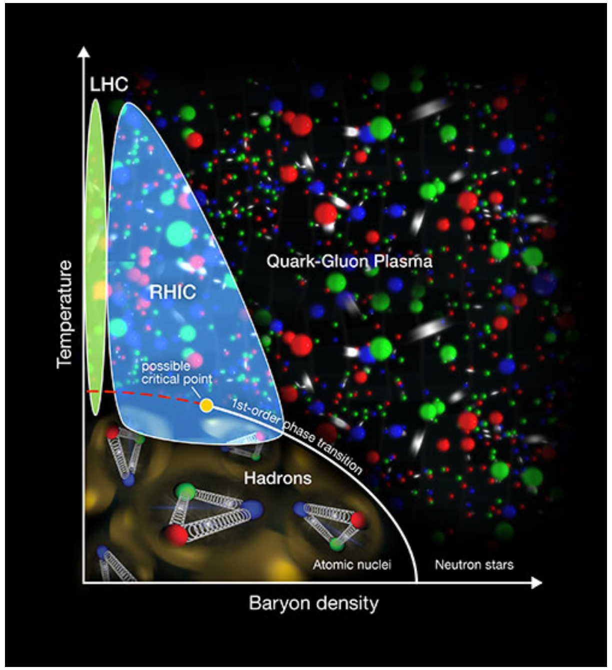
- Space charge at normal collision energy (100 GeV/N) typically negligible

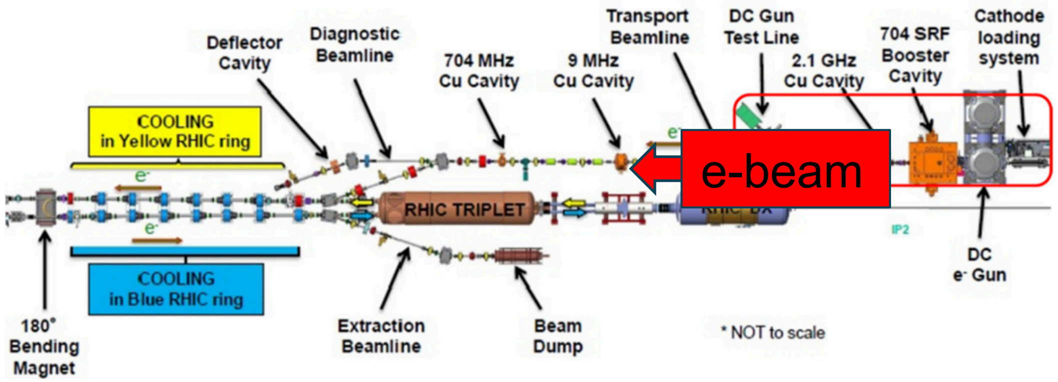
- Search for QCD critical point required collisions at beam energies at or below nominal injection (9.8 GeV/N)
  - 9.8 , 7.3, 5.75, 4.6, 3.85 GeV/N

- Initial attempts ~2010 “Beam Energy Scan I” (BES-I) successful, but luminosity seriously limited by beam lifetime
  - Dominated by intrabeam scattering (IBS time of order minutes)
  - Also includes effects of space charge up to $dQ_{sc} = 0.1$ at lowest energy in steady state collider mode

- 2019-2021: BES-II
  - Repeat energies from BES-I
  - Now with Low Energy RHIC Electron Cooling (LEReC) facility
    - Counteracts IBS, but adds new optimization challenges

BES-I,II Energy [GeV/N]
9.8
7.3
5.75
4.59
3.85





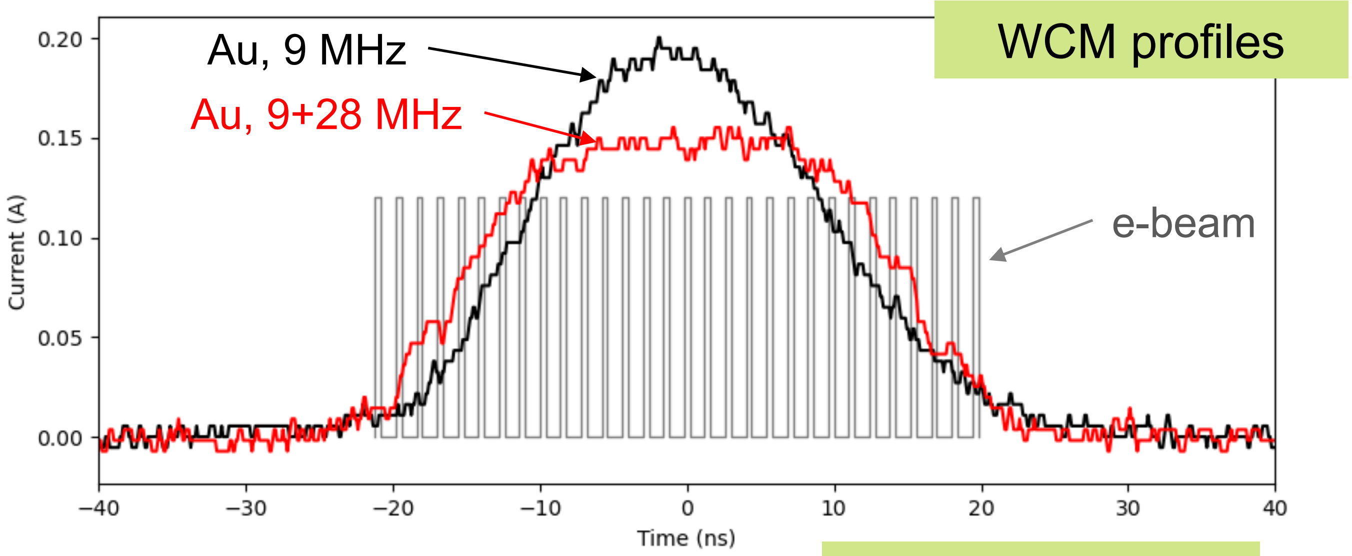
Low Energy RHIC collisions: Bunch lengthening

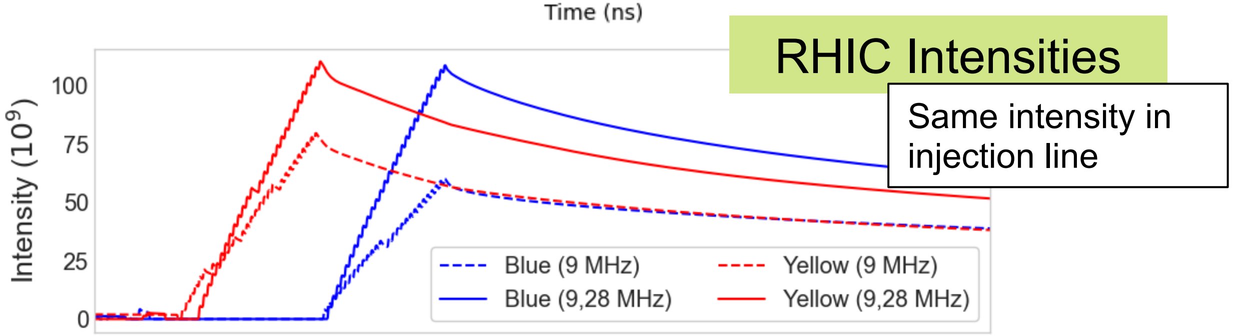
- At 3.85 GeV, per bunch intensity as high as N =1.5x10⁹
  - Modest compared to ordinary RHIC intensity
  - Low energy means dQ_{sc} ~ 0.1 while in collision
- Space charge kicks: ions ←→electrons
  - Tune working point $Q_{x,y}$ ~ 0.12

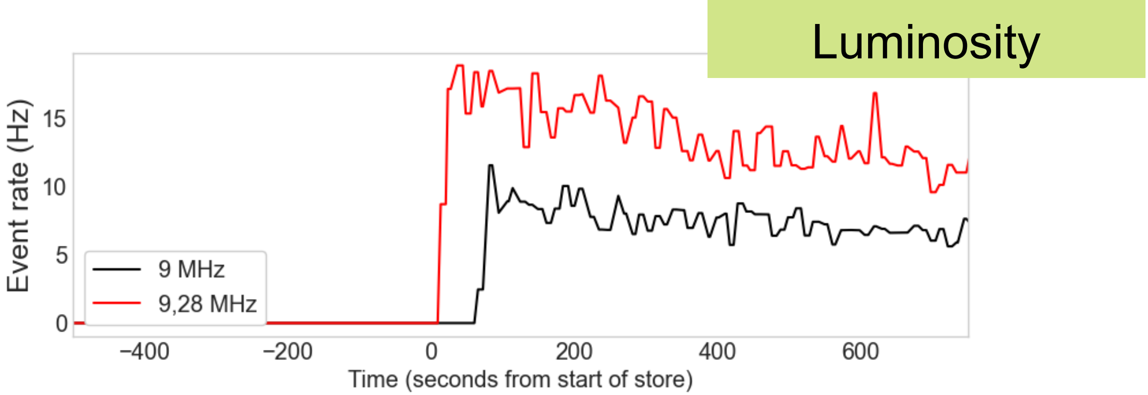
- Capture at 3.85 GeV/n in 9 MHZ RF (h=120)
  - 28 MHz (normally used for high energy acceleration) used to defocus, reduce peak current ~20%

- Factor 2 increase in luminosity (peak and integrated)

- Secondary benefit: space charge focusing of the ions on the electron is more uniform
  - Optimization for the 'average' electron bunch more closely reflects the group optimum







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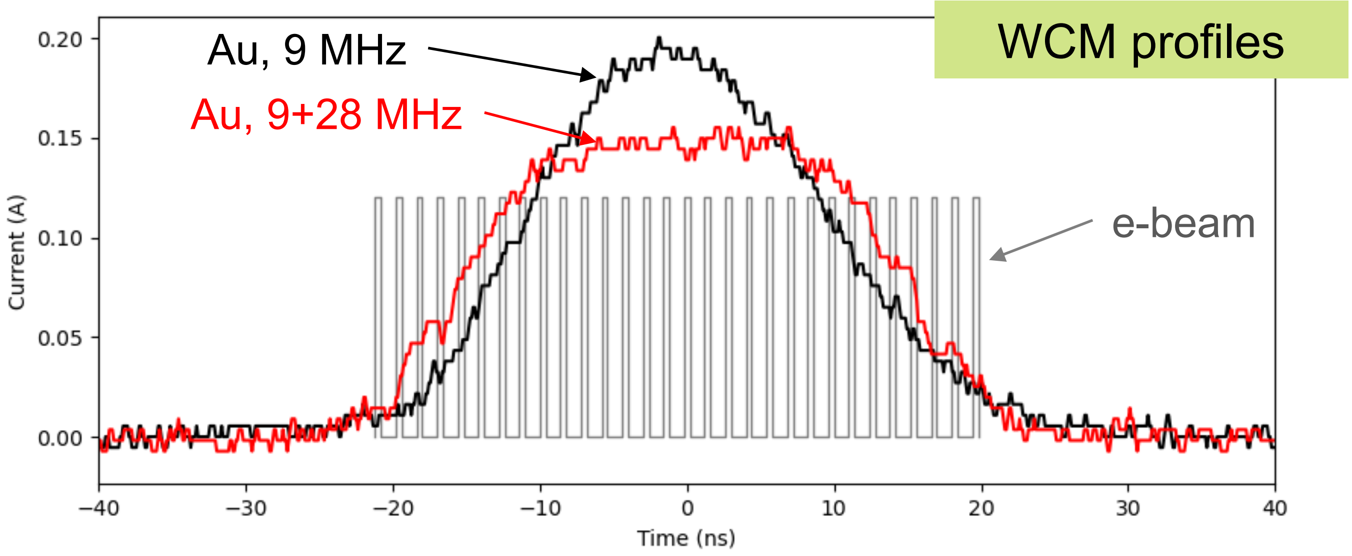
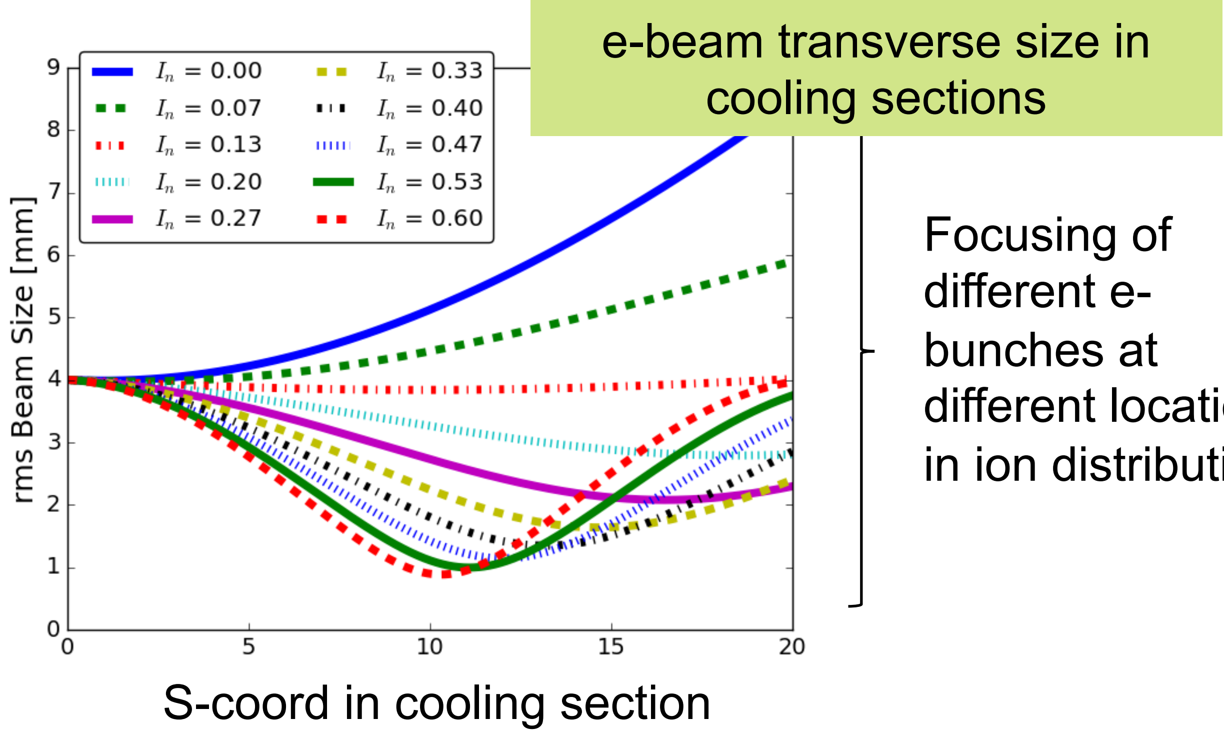




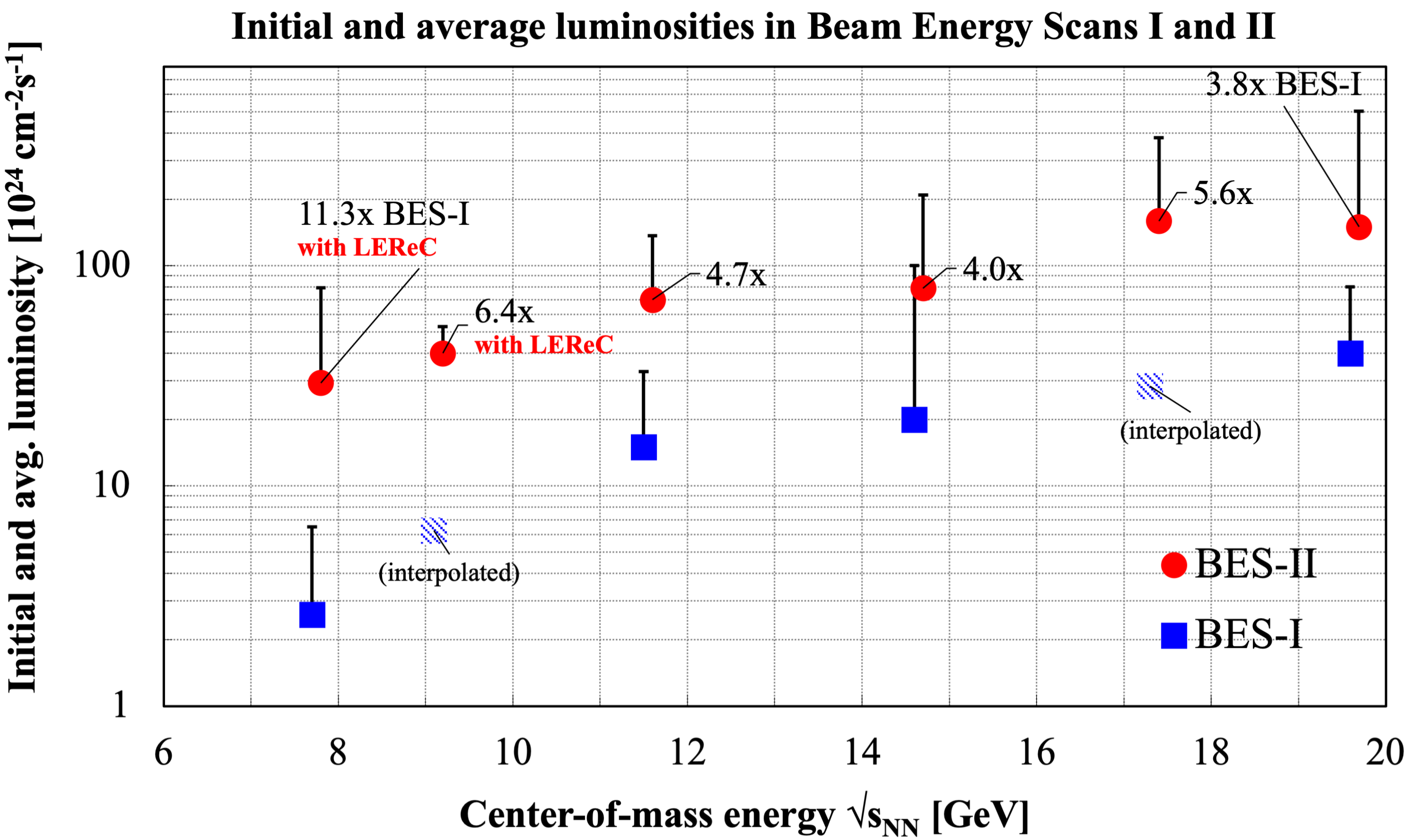
Focusing of different e-bunches at different locations in ion distribution

Luminosity in BES-II

BES-II shows x4-10 gain in average luminosity over BES-I

- LEReC and space charge effects most important for lowest two energies

- Full story involves more optimizations see:
  - C. Liu et al, Phys. Rev. Accel. Beams **25**, 051001



Future work

- Most space charge/collective effects work in RHIC era injectors is empirical “tuning”
  - Space charge ‘whack-a-mole’
  - Studies have primarily focused on polarization directly (helical dipoles, tune jumps…)
- Limited recent dedicated studies of intensity effects
  - M. Balcewicz et al, *Space charge driven third order resonance at AGS injection, NAPAC’22*
  - F. Meot, AGS resonance driving term studies (2014, unpublished)

- EIC era calls for N > $3x10^{11}$ from AGS with high polarization- Motivates a dedicated simulation/measurement campaign
  - Is observed stopband correction consistent with understanding of lattice? (e.g. why is the 3rd integer in Booster particularly strong)
  - Do the complicated helical dipole fields in AGS present high order driving terms relevant to intensity dependent effects? Is the beta distortion important?
  - Is the instrumentation sufficient to detect all likely effects?

Summary

- Both the heavy ion and proton RHIC programs benefit from compensation of space charge effects
  - The polarized beam program performance has particularly high sensitivity to emittance growth

- Bunch lengthening and stopband correction have been successfully used to improve performance

- The low energy RHIC collider program was a unique experience in collider operations under conditions of large space charge

- We look forward to making a comprehensive push to understand intensity dependent effects to make more progress on highly polarized bright beams into the EIC era