RHIC Machine Studies Towards Improving the Performance at 2.5 GeV

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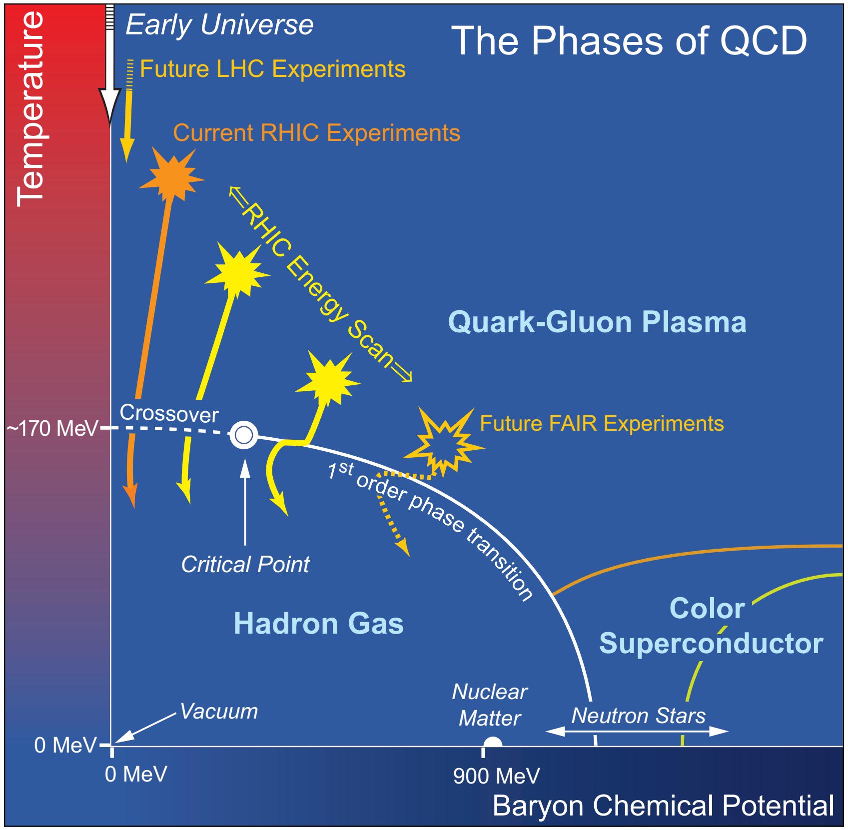
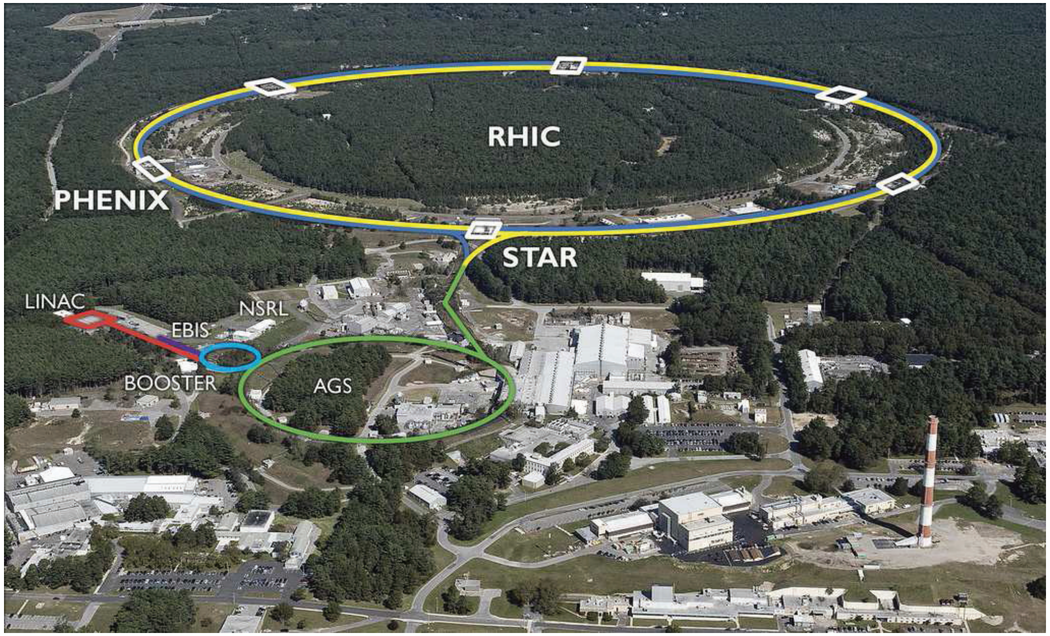
Motivation - Search for the QCD Critical Point



Search for the QCD critical point requires beam energy scan in gold-gold collisions at center-of-mass energies between 5 GeV/nucleon and 30 GeV/nucleon

The Relativistic Heavy Ion Collider



Circumference: $C = 3833.845\,\mathrm{m}$

Nominal Au beam energy range: $E = 10\,\mathrm{GeV/nucleon} - 100\,\mathrm{GeV/nucleon}$

Required beam energy range for critical point search:

$E = 2.5\,\mathrm{GeV/nucleon} - 15\,\mathrm{GeV/nucleon}$

Energy range for critical point search extends well below RHIC design energies

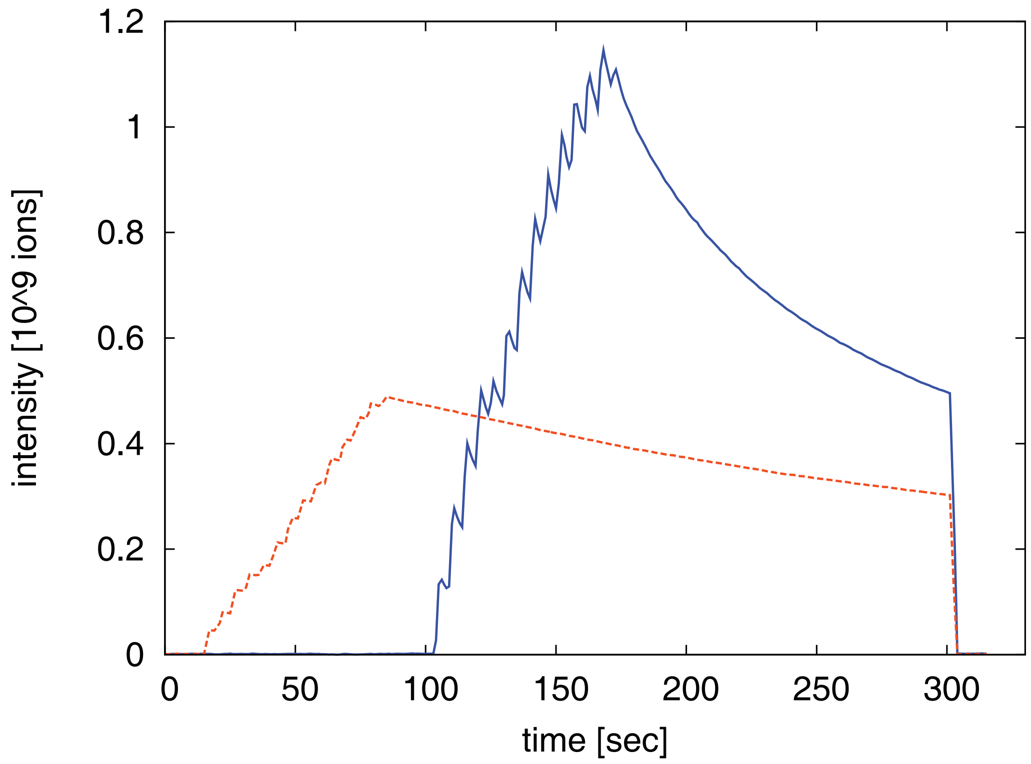
Challenges: large emittance, magnet nonlinearities, space charge, IBS

Achieved Beam Parameters During Low Energy Physics Runs

	3.85 GeV/n	5.75 GeV/n	9.8 GeV/n
γ	4.1	6.1	10.7
σ_s [m]	1.5	1.5	1.5
ϵ_n (rms) [mm mrad]	3	2.5	2.5
ϵ (rms) [mm mrad]	0.73	0.41	0.23
I_{bunch} [1e9]	0.5	1.1	0.9
N_{bunches}	111	111	111
β^* [m]	6.0	6.0	2.5
ΔQ_{bb}	$1.2 \cdot 10^{-3}$	$1.7 \cdot 10^{-3}$	$1.4 \cdot 10^{-3}$
ΔQ_{sc}	0.035	0.047	0.012
τ_{beam} [sec]	1000	1500	3000

Bunch intensity at lowest energies limited by space charge tune shift limit, $\Delta Q_{\text{sc}} \approx 0.05$

Typical Store During Test Run with 2.5 GeV/nucleon Gold



27 bunches, $\approx 4\,\mathrm{min}$ lifetime

Blue bunch intensity $N = 4 \cdot 10^7$ - factor ten less than at 3.85 GeV/nucleon

Most RHIC instrumentation did not work at these low intensities - how can we improve the performance?

Understanding the Performance at 2.5 GeV

Objective: Test single-particle effects by using protons instead of gold in the same lattice

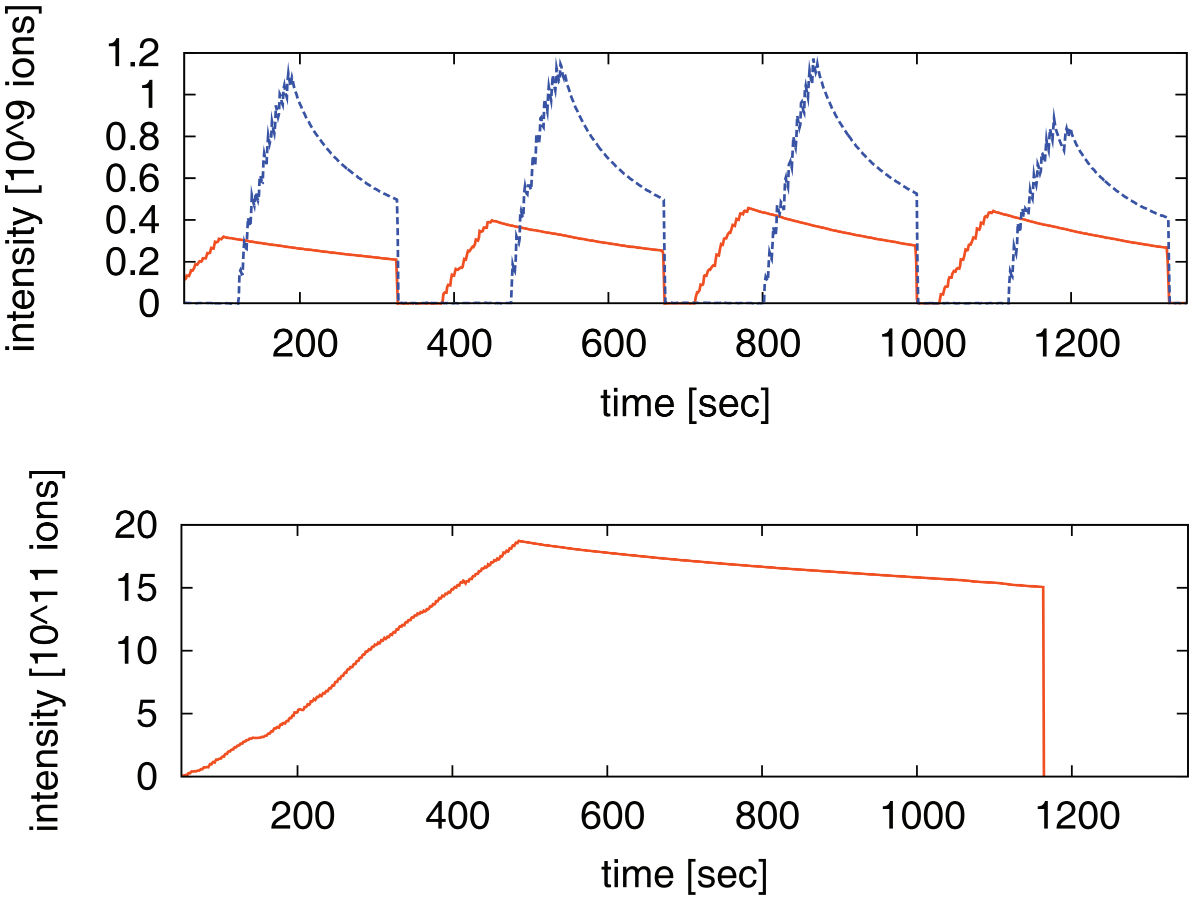
Parameters:

ramp	pp13-6GeV
$B\rho$	19.3 Tm
E	5.86 GeV
E_{kin}	4.92 GeV
γ	6.25
p	5.79 GeV/c
f_{rev}	77.187 kHz
h	363

Higher γ at the same $B\rho$ as gold results in smaller beam sizes, less space charge and IBS

Single particle effects can be studied with protons

Beam Intensities with Gold (top) and Protons (bottom)



Stores during 22 min of beam operation

50 percent injection efficiency with protons, vs. 10 percent with gold

Proton intensity is sufficient for instrumentation to work reliably

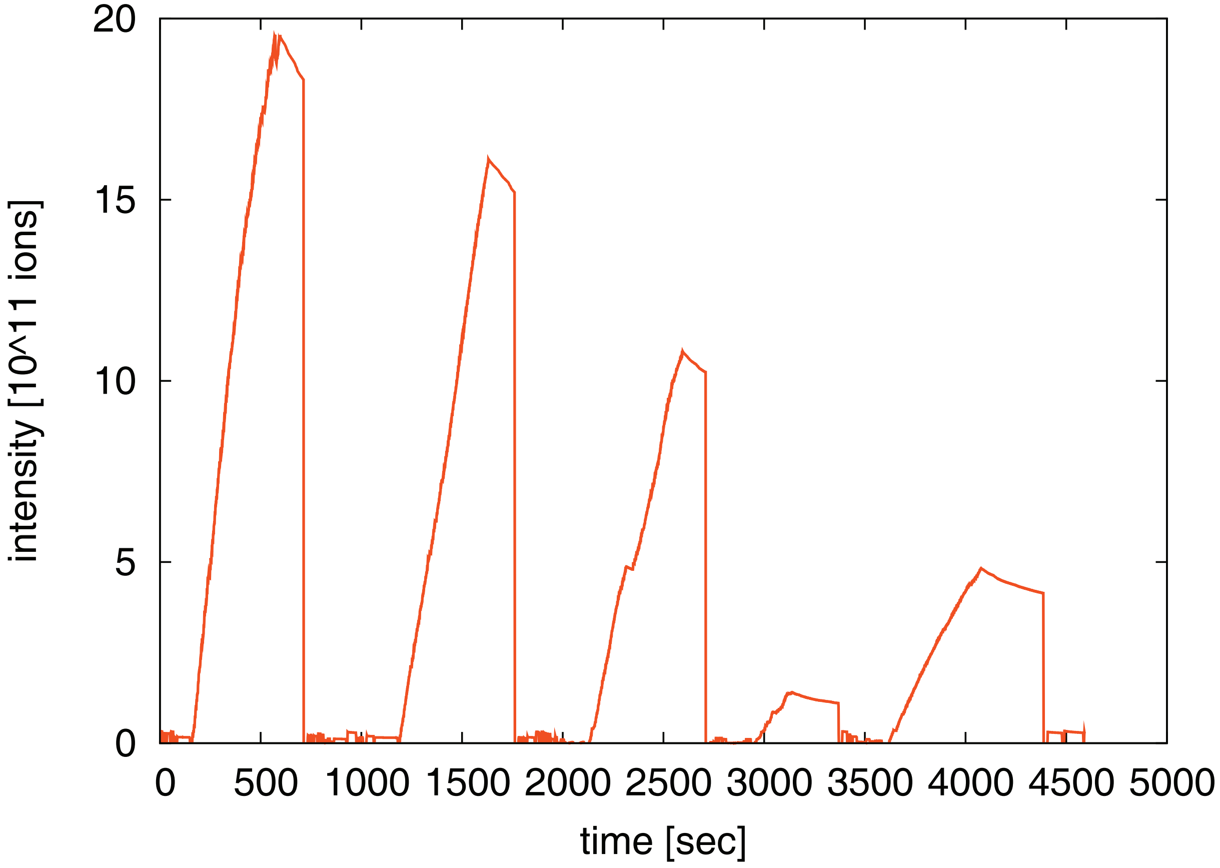
Dynamic Aperture Measurements

Two methods:

- Inject beam with intentional offset, measure acceptance with wire scanner

- Blow-up emittance with tunemeter, measure maximum beam profiles with wire scanner

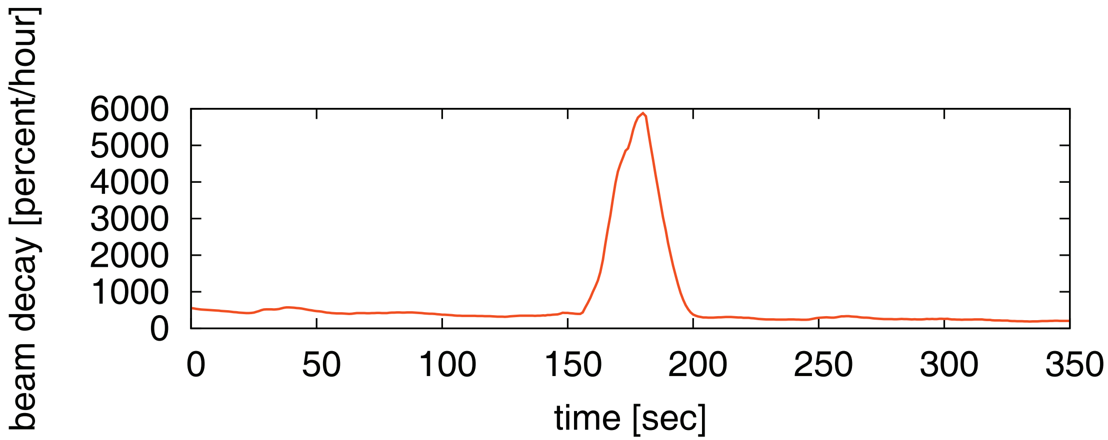
Intensities With Mis-steered Injection

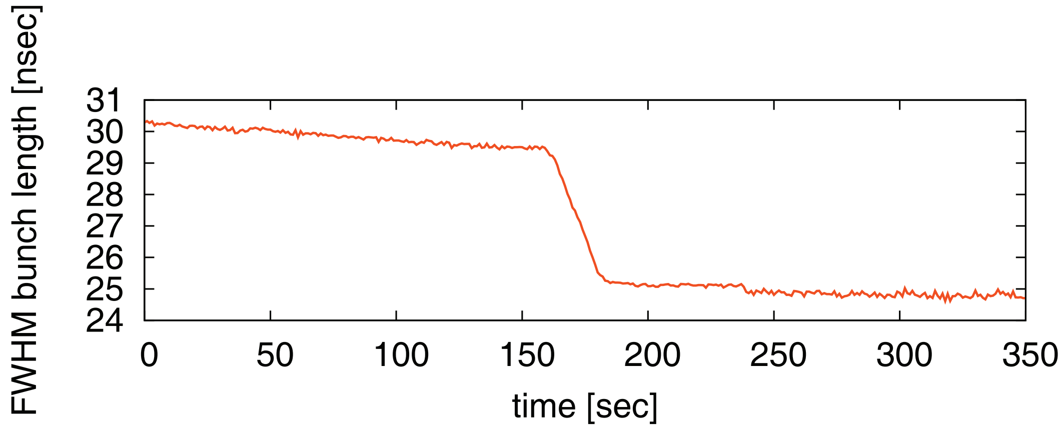


Reduced injection efficiency due to mis-steering

Dynamic aperture limit is reached

Beam Decay and Bunch Length During Blow-up with Tunemeter



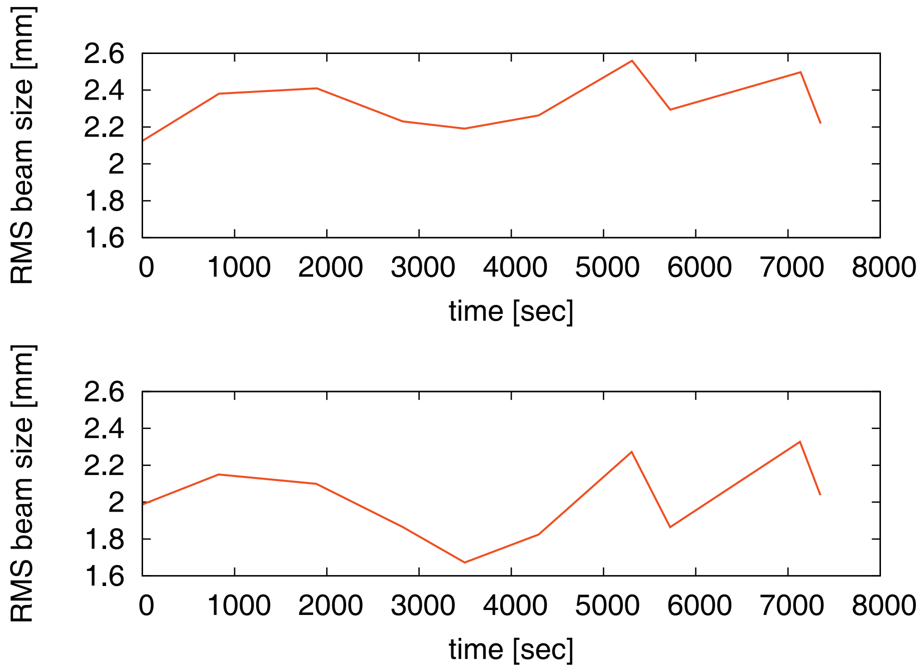


Beam decay immediately recovers when tunemeter is turned off

Bunch length shrinks during kicking

$\Rightarrow$ transverse dynamic aperture limitation for off-momentum particles

RMS Beam Sizes During DA Measurement



RMS beam size remains unchanged regardless of mis-steering and tunemeter blow-up efforts - independent of intensity

$\Rightarrow$ Dynamic aperture is already filled anyway, allowing for maximum RMS emittances of $\epsilon_x = 0.23\,$mm mrad $\epsilon_y = 0.16\,$mm mrad

At 3.85 GeV/n, beams with $\epsilon = 0.73\,$mm mrad were routinely stored

Dynamic aperture is dominatd by single-particle effects

Space Charge

Space charge tune shift:

$$\Delta Q_{\mathrm{sc}} = -\frac{Z^2 r_p}{A}\frac{N}{4\pi\beta\gamma^2\epsilon_n}\frac{C}{\sqrt{2\pi}\sigma_s}$$

With $Z = A = 1$, $N = 4 \cdot 10^{10}$, $\epsilon_n = 1\,\mathrm{mm\,mrad}$, and $\sigma_s = 3\,\mathrm{m}$, this results in a space charge tune shift of

$$\Delta Q_{\mathrm{sc}} = -0.065$$

For 2.5 GeV/n gold at the same emittances ($\epsilon_n = 0.4\,\mathrm{mm\,mrad}$ due to smaller γ), this tune shift would be reached at $N_{\mathrm{Au}} = 8 \cdot 10^7$ - still factor 5 less than at 3.85 GeV/n

Beam-beam tuneshift would be $\xi_{\mathrm{IP}} = 8 \cdot 10^{-4}$

This would allow for a peak luminosity of $2 \cdot 10^{22}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ - factor 10 less than required for physics

Summary

- Desired energy range for the QCD ciritical point search extends far below the RHIC design energy range
- Dynamic aperture measurements with protons at same rigidity as 2.5 GeV/n gold show factor 3 smaller dynamic aperture than at 3.85 GeV/n.
- Dynamic aperture is limited by single-particle effects, most likely magnet nonlinearities
- Filling this small dynamic aperture with gold ions would provide a maximum luminosity of $2 \cdot 10^{22}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ at the space charge limit - factor 10 too low
- Improving dynamic aperture is key to higher intensity (space charge limit)
- Next step: Study performance with gold beam, with injected emittances tailored to measured small dynamic aperture
- Tracking studies are underway to understand small dynamic aperture. Multipole errors at these low fields are known only for a single dipole and a single quadrupole

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