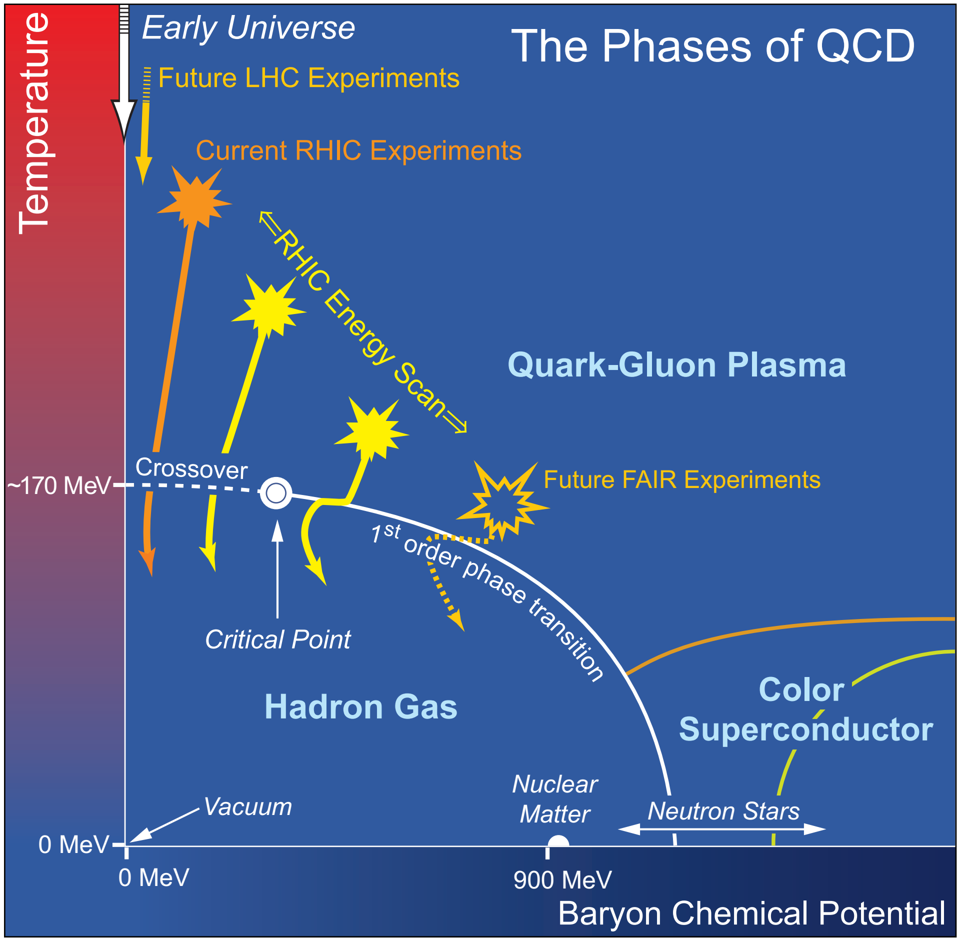
$\sqrt{s} = 5\,\text{GeV/n}$ Au Studies

Christoph Montag

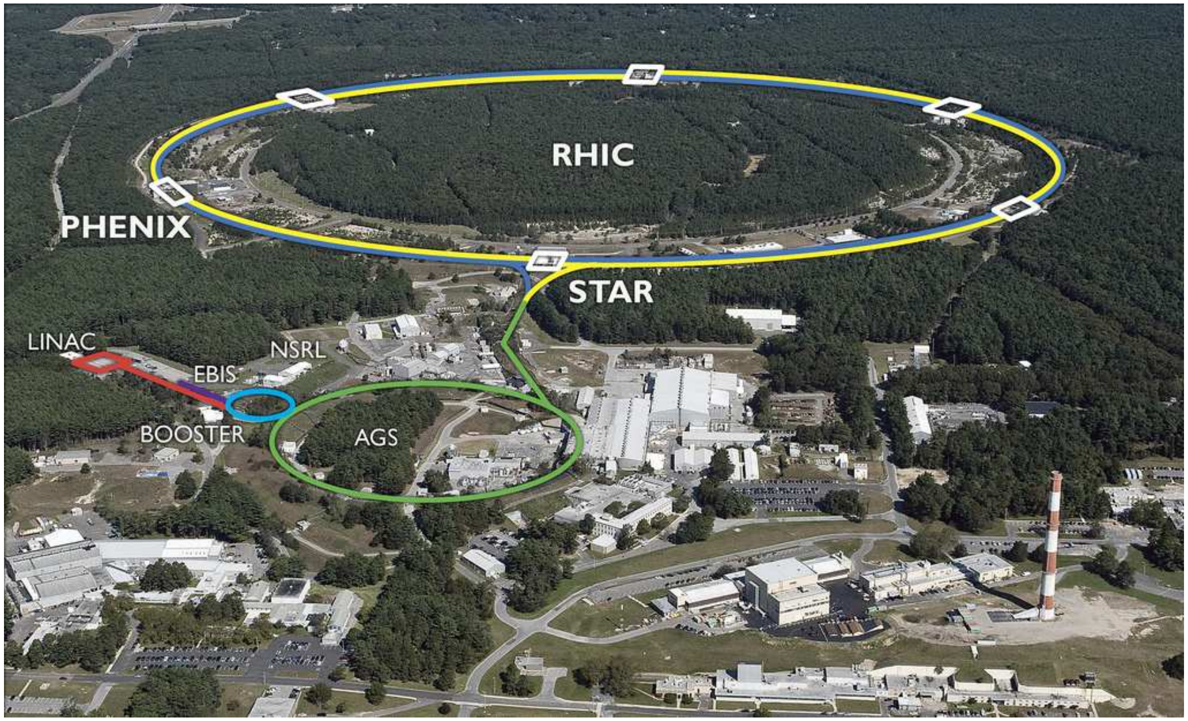
Brookhaven National Laboratory

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: $E = 10\,\mathrm{GeV/nucleon} - 100\,\mathrm{GeV/nucleon}$

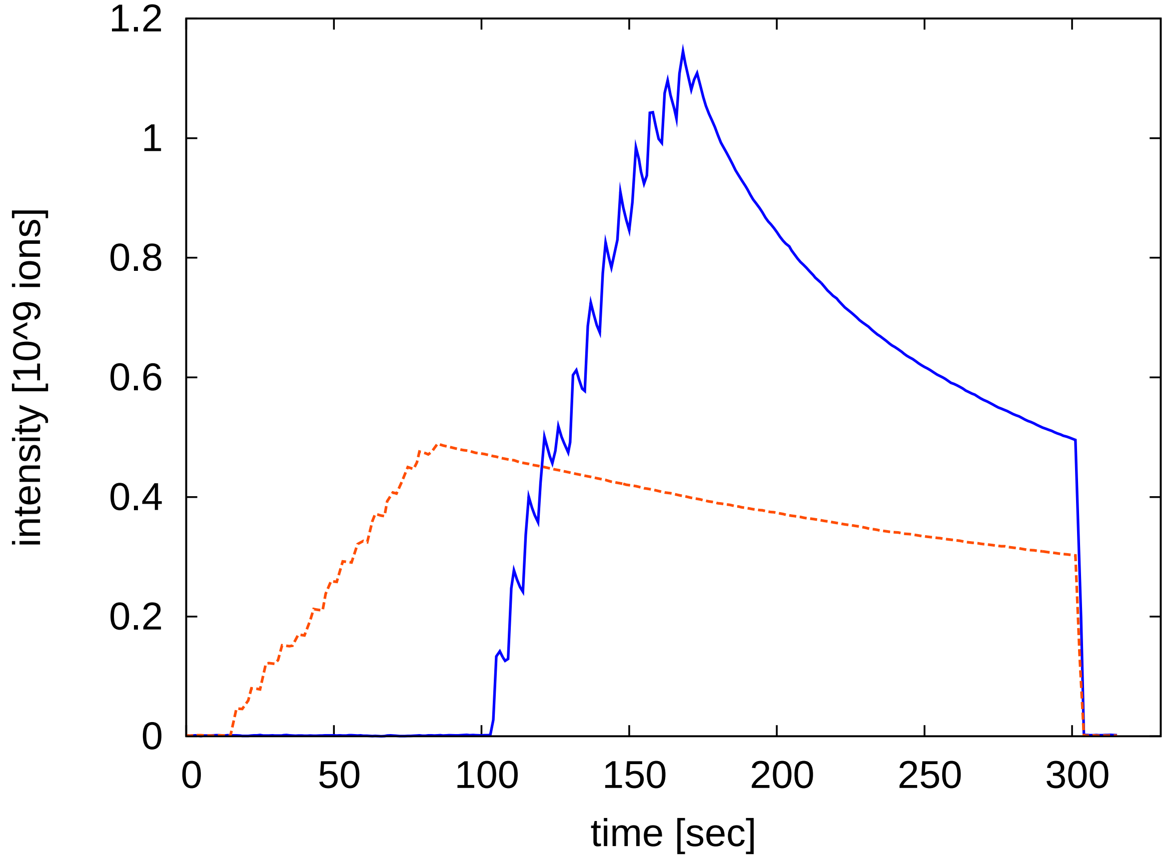
Required beam energy range for critical point search:

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

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

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

Typical Store During Test Run with 2.5 GeV/nucleon Gold in FY2012



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:

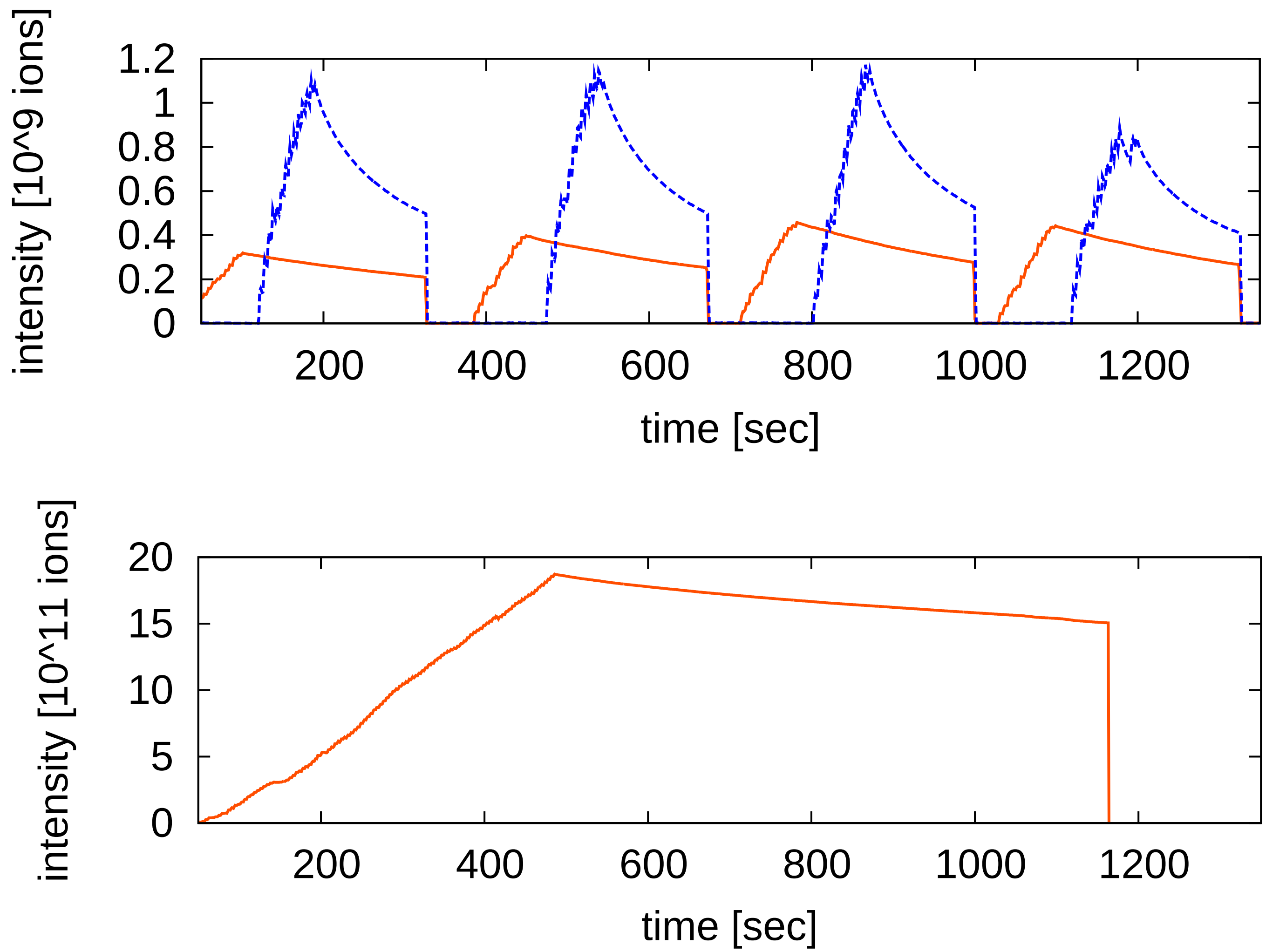
ramp	pp13-6GeV
$B\rho$	19.3 Tm
E	5.86 GeV
E_{kin}	4.92 GeV
γ	6.25
p	5.79 GeV/c
f_{rev}	77.187 kHz
h	363
tunes	28.17/30.13

Working point identical to Au test run

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

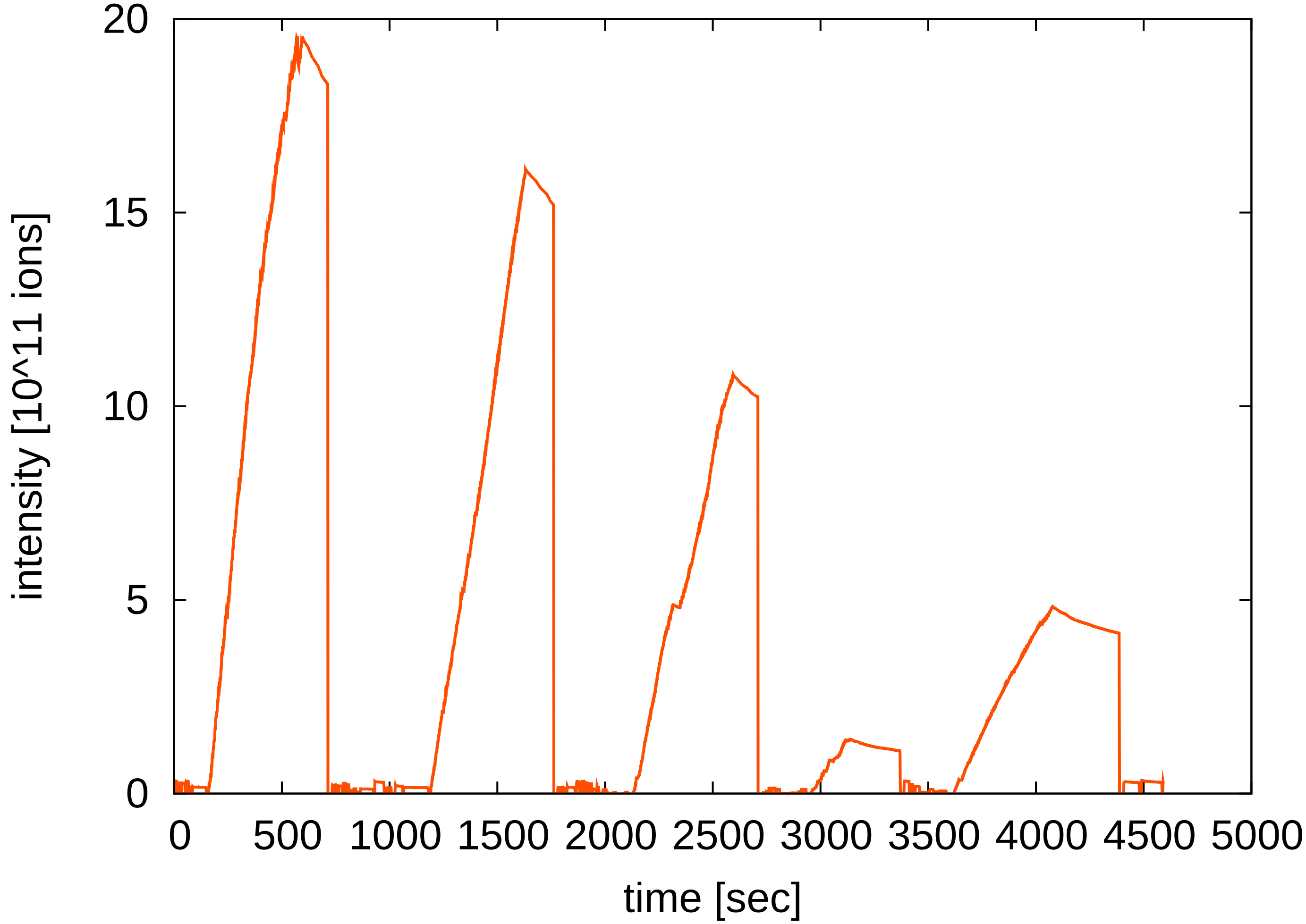
Dynamic Aperture Measurements

Two methods:

- Inject beam with intentional offset, measure acceptance with wire scanner (polarimeter)

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

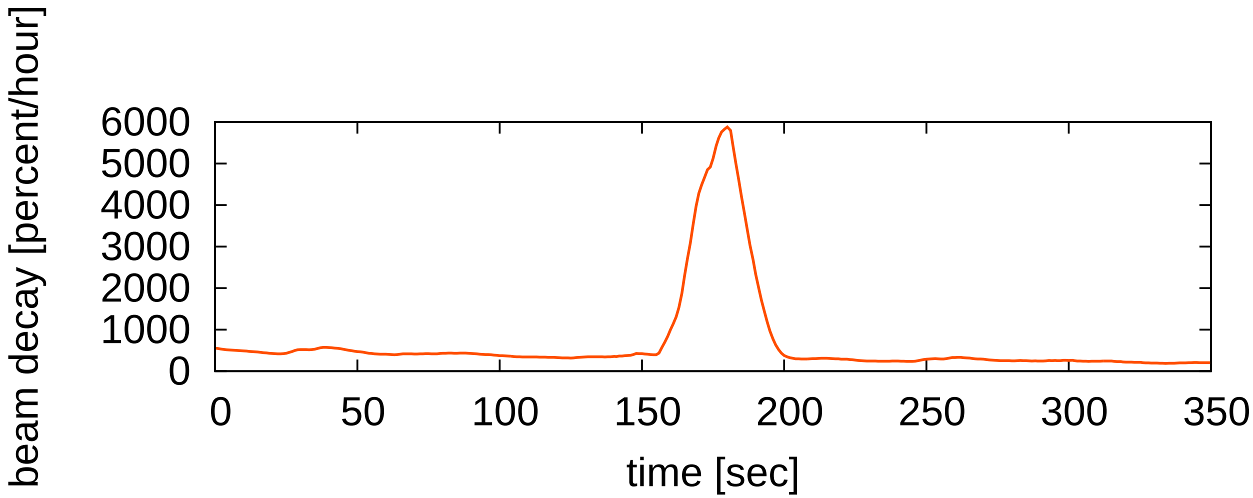
Intensities With Mis-steered Injection

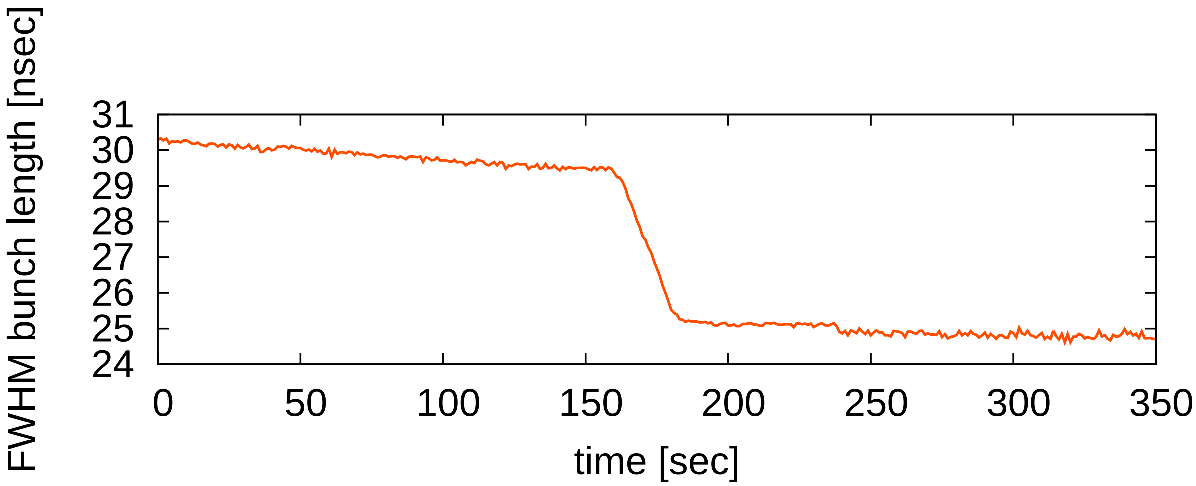


Reduced injection efficiency due to mis-steering

Dynamic aperture limit is reached

Beam Decay and Bunch Length During Blow-up with Tunemeter



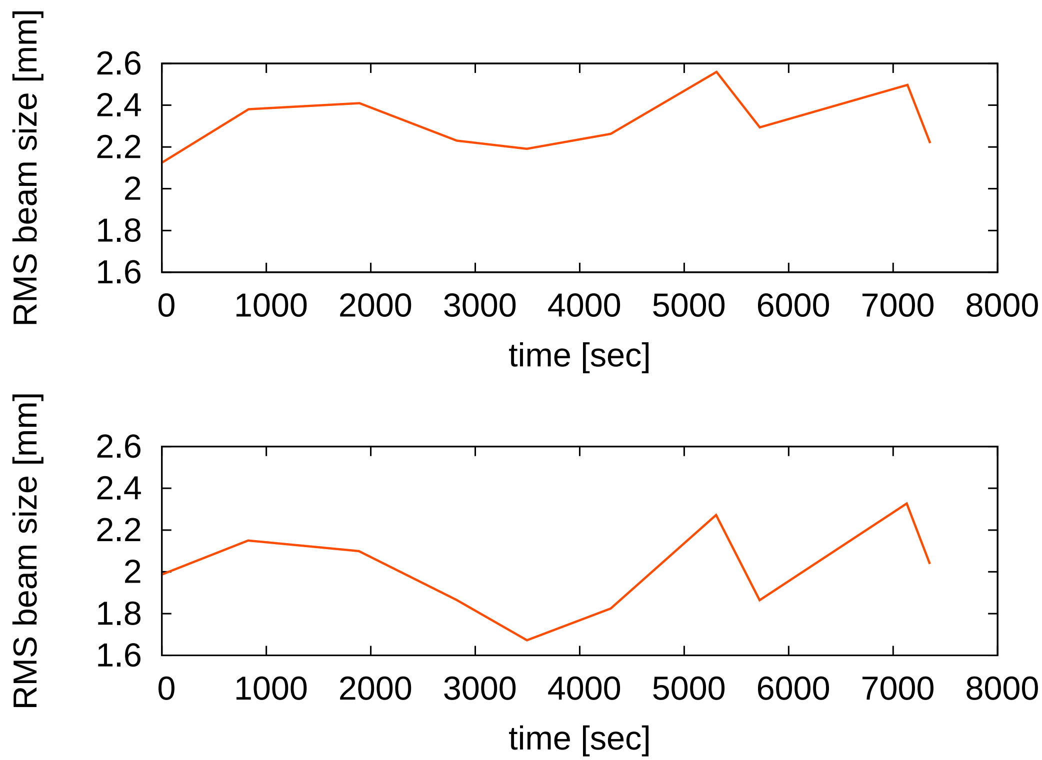


Beam decay immediately recovers when tunemeter is turned off

Bunch length shrinks during kicking

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

RMS Beam Sizes During DA Measurement



RMS beam size remains essentially 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 $\epsilon_x = 0.23\,\mathrm{mm\,mrad}$ $\epsilon_y = 0.16\,\mathrm{mm\,mrad}$

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

Dynamic aperture is dominated by single-particle effects

Space Charge

Space charge tune shift:

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

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

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

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

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

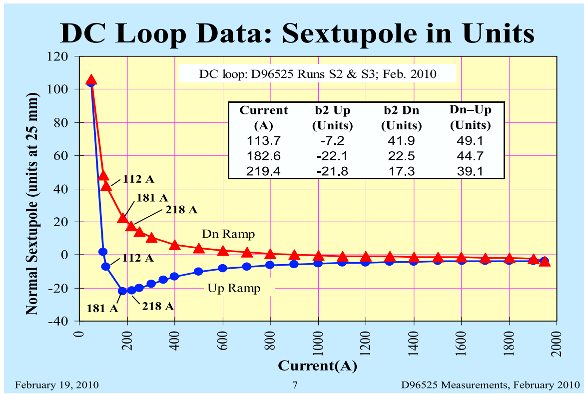
This would allow for a peak luminosity of $2 \cdot 10^{22}\,\text{cm}^{-2}\text{sec}^{-1}$ - factor 10 less than required for physics

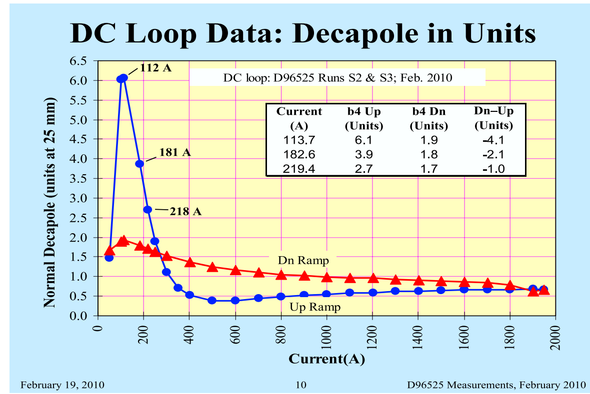
Tracking Studies and Beam Experiments

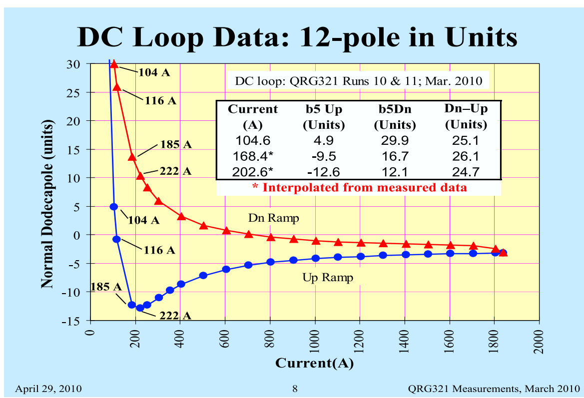
Tracking:

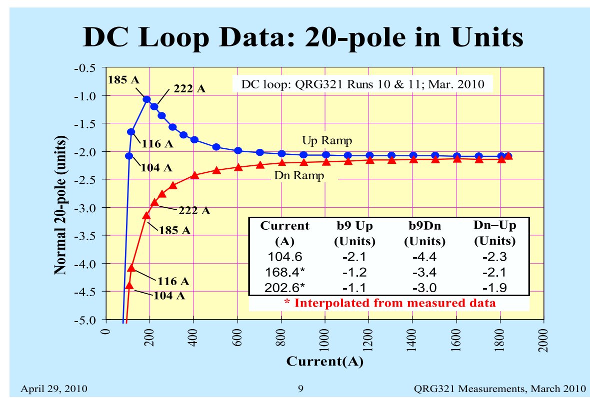
- Frozen space charge model (constant emittance, Gaussian distribution - equivalent to weak-strong beam-beam model) in SC MAD-X (V. Kapin, F. Schmidt)
- Dynamic aperture studies to compare with experimental results
- Multipole errors in all magnets (sextupole and decapole in dipoles, 12- and 20-pole in quadrupoles)
- Tracking with momentum error at $3\,\sigma_s$
- Dynamic aperture (DA) scaled to wire scanner (polarimeter) location ($\beta = 25\,\mathrm{m}$), using average measured $\sigma = (\sigma_x + \sigma_y)/2$ as reference

Magnet Nonlinearities









Magnets are optimized at full field; nonlinearities are worst in region interesting for critical point search

Multipole Errors in Tracking

- Below regular injection energy, multipole errors are only known for a single dipole and a single quadrupole
- No information about magnet-to-magnet variations available
- Unknown whether measured magnets are good representatives
- As a baseline, assigned the same multipole coefficients to ALL magnets

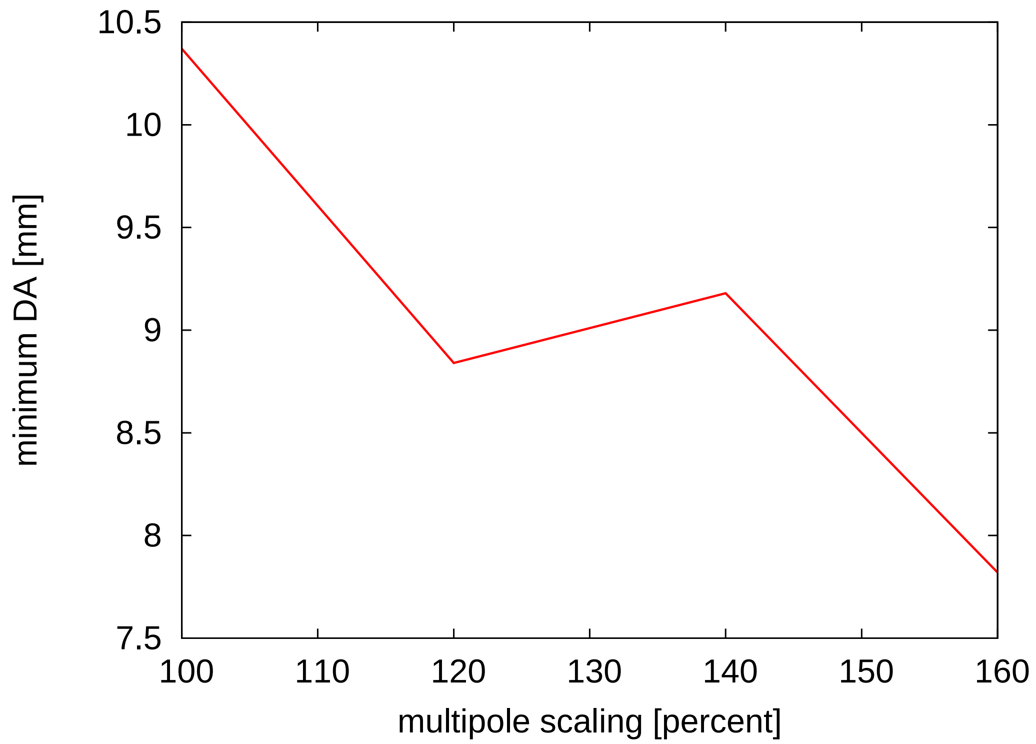
Intensity Dependence

- DA measurements with protons showed no intensity dependence
- Though the bunch intensity varied by a factor 3-4, dynamic aperture remained practically constant
- Tracking results:

bunch intensity	$2 \cdot 10^{10}$	$4 \cdot 10^{10}$
minimum DA	$4.7\,\sigma$	$4.9\,\sigma$

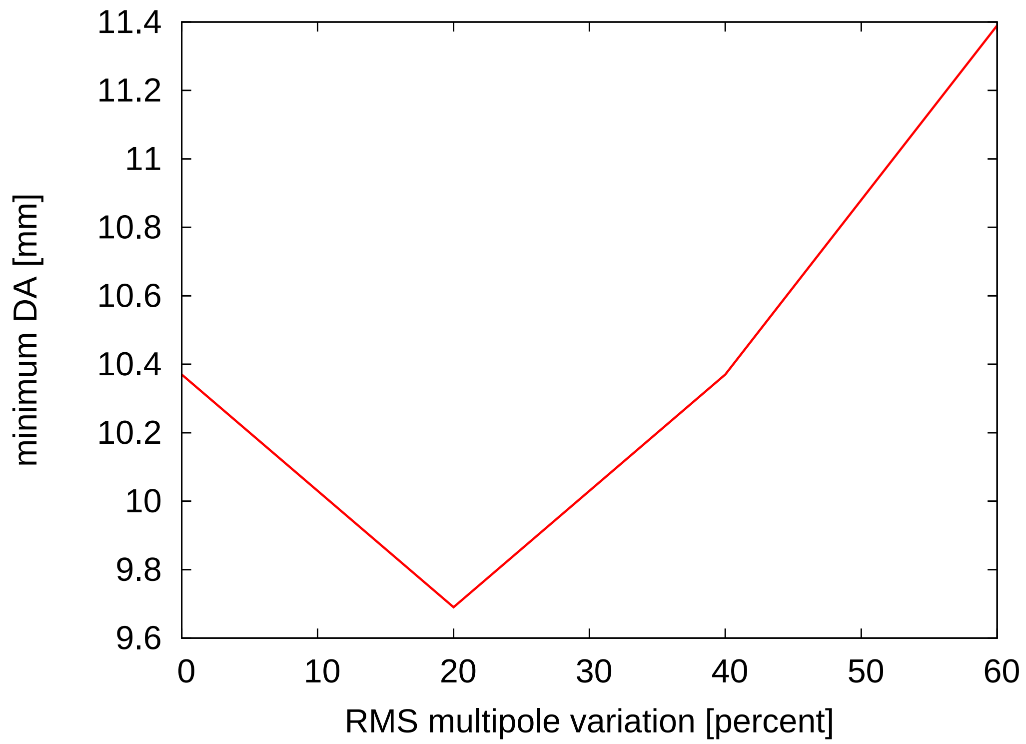
Tracking reproduces measured intensity (in)dependence well

Scaling All Multipole Errors



Minimum DA drops from 4.7σ to 3.5σ when all multipole errors are increased by 60 percent
(Note that increasing b_2 changes the machine sextupoles, which may explain the plateau)

Random Multipoles



Mean multipole coefficients unscaled

Little effect of randomizing multipole errors

Need to run with different random seeds

Comparison with Regular Injection

Measured multipole coefficients:

	2.5 GeV	9.8 GeV
b_2	-7.2	-10
b_4	6.1	0.4
b_5	4.9	-7.0
b_9	-2.1	-1.9

- Multipole errors at 2.5 GeV are comparable to those at regular injection
- b_4 at 9.8 GeV seems extremely small (order of magnitude compared to other multipoles)

DA tracking with these multipoles in the same 2.5 GeV lattice shows minimum DA of 5.8 $sigma$, vs. 4.7 σ with 2.5 GeV multipoles
Could the culprit be the working point (.17/.13)?
APEX: Measure DA at injection energy at this working point

Beam Studies at 2.5 GeV

- Pending a positive outcome of the DA measurements at injection, setup RHIC at 2.5 GeV/n Au at a better (to be determined by tracking and/or during injection energy experiment) working point

- Measure DA at this better working point

- Ideally, perform a tune scan (time consuming)

- Experiment may be better performed with 5.86 GeV protons (higher intensity, better instrumentation). Can we do that in Run-14?

Summary

- Desired energy range for the QCD critical 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
- Tracking studies reproduce experimental results reasonably well
- Using injection energy multipole errors in tracking points at working point choice as possible culprit for small DA - to be tested at injection energy during APEX
- Need to repeat low energy (proton?) test, including tune scan

Thanks to:

F. Schmidt, V. Litvinenko, K. Smith, T. Hayes, F. Severino, M. Costanzo, R. Schoenfeldt, K. Hartmann, J. Adessi, W. Dartiguenave, R. Michnoff, J. Jamilkowski, K. Mernick, M. Harvey, C. Liu, C. Harper