Recent results for RHIC with frozen SC & BB (MADX-SC)

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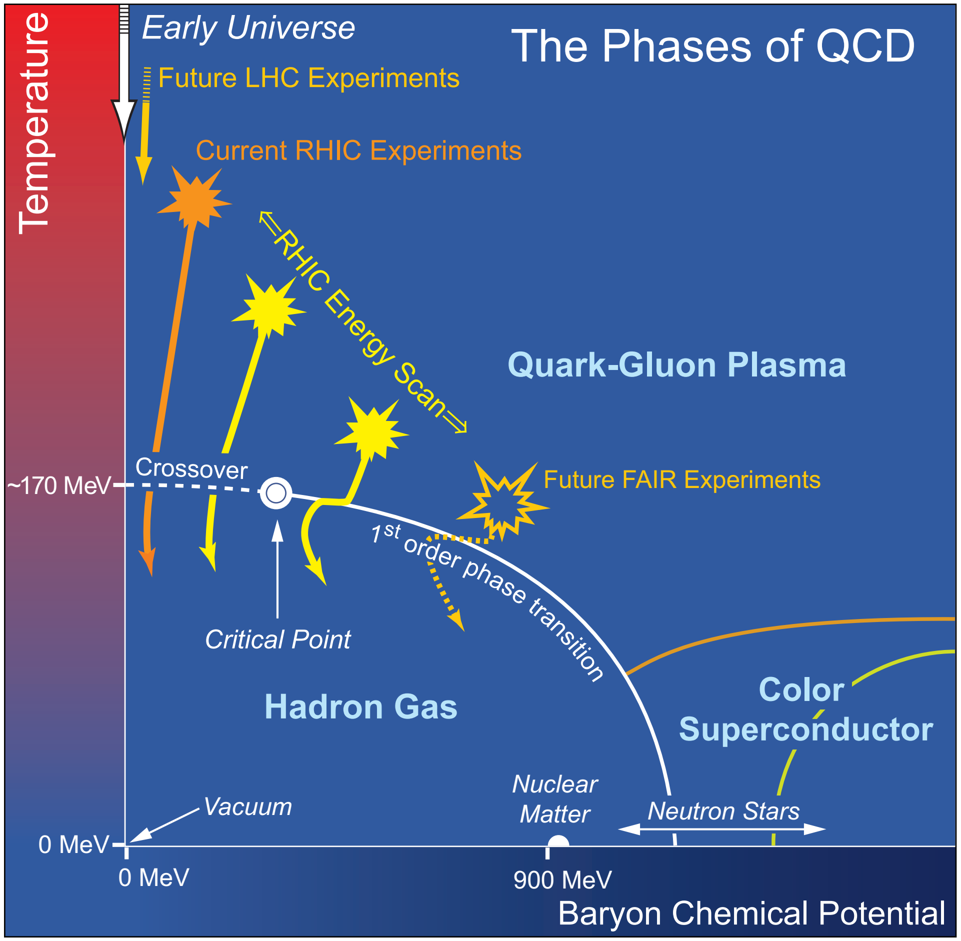
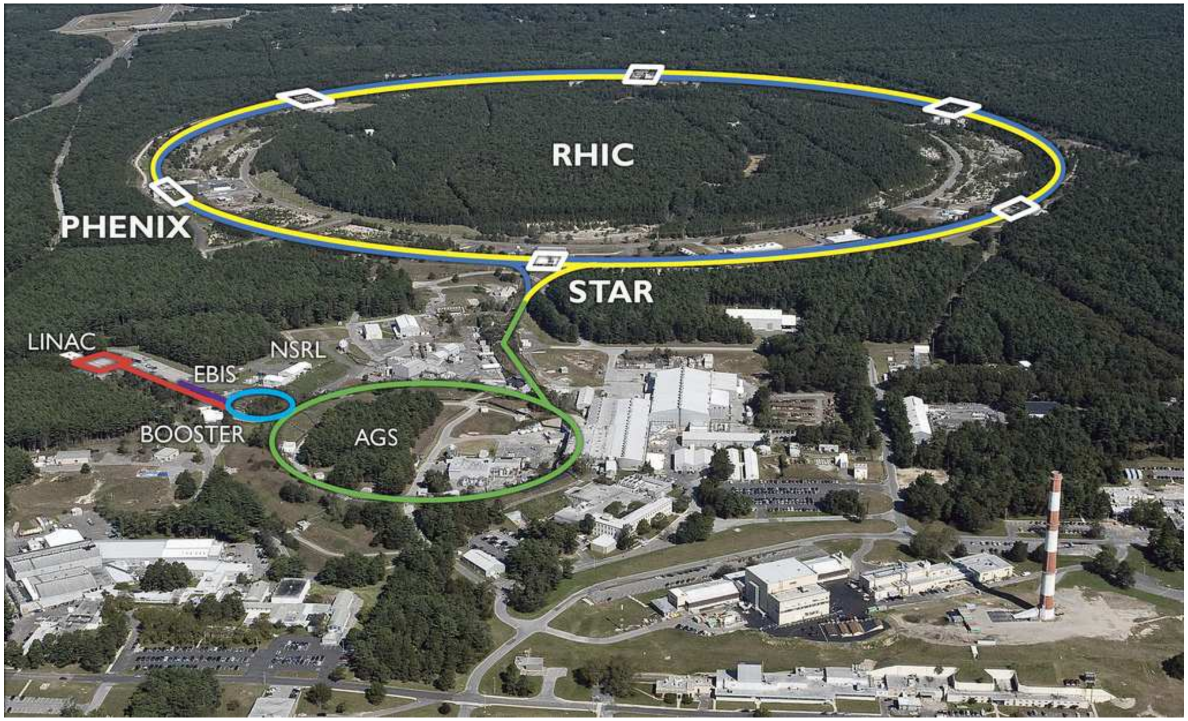
Motivation - Search for the QCD Critical Point



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: $C = 3833.845\,\text{m}$

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

Required beam energy range for critical point search:

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

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

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

Challenges Encountered

1. Unexpectedly poor lifetime at lowest energy (2.5 GeV/n)

2. Strong lifetime deterioration due to beam-beam in presence of space charge

Studied through experiments and MADX-SC tracking

Tracking Method

- Frozen space charge model in MADX-SC (V. Kapin, F. Schmidt), parallelized at BNL (K. Yu, N. D'Imperio) using OPEN MP

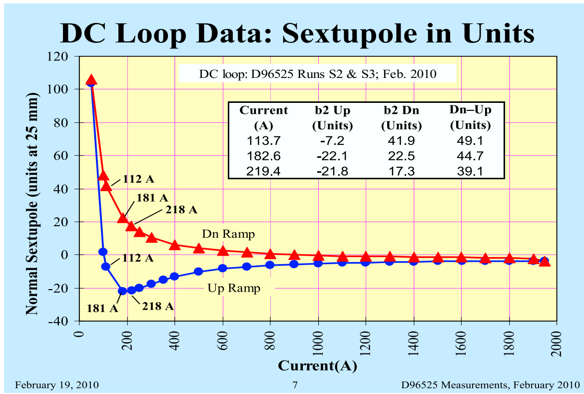
- Dynamic aperture studies to compare with experimental results

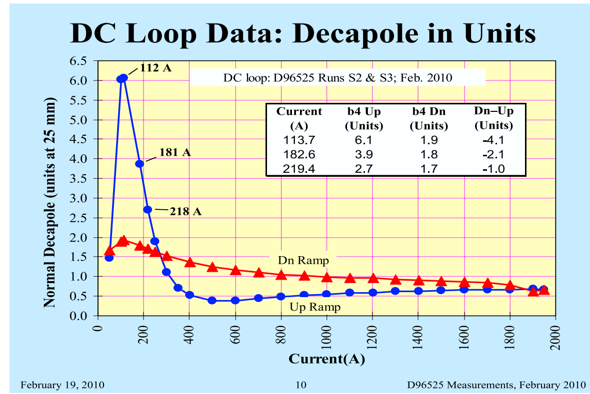
- Multipole errors in all magnets (sextupole and decapole in dipoles, 12- and 20-pole in quadrupoles)

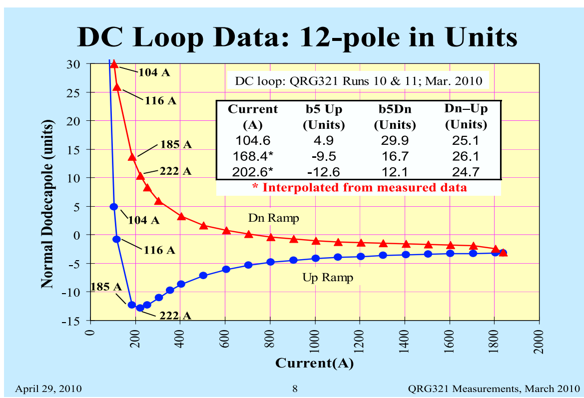
- Tracking with momentum error at $3\,\sigma_p$

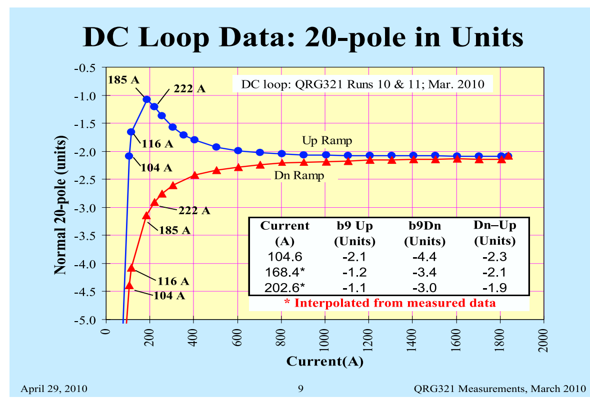
- Dynamic aperture (DA) scaled to wire scanner (polarimeter) location ($\beta = 25\,\mathrm{m}$), using average measured $\sigma = (\sigma_x + \sigma_y)/2$ as reference

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

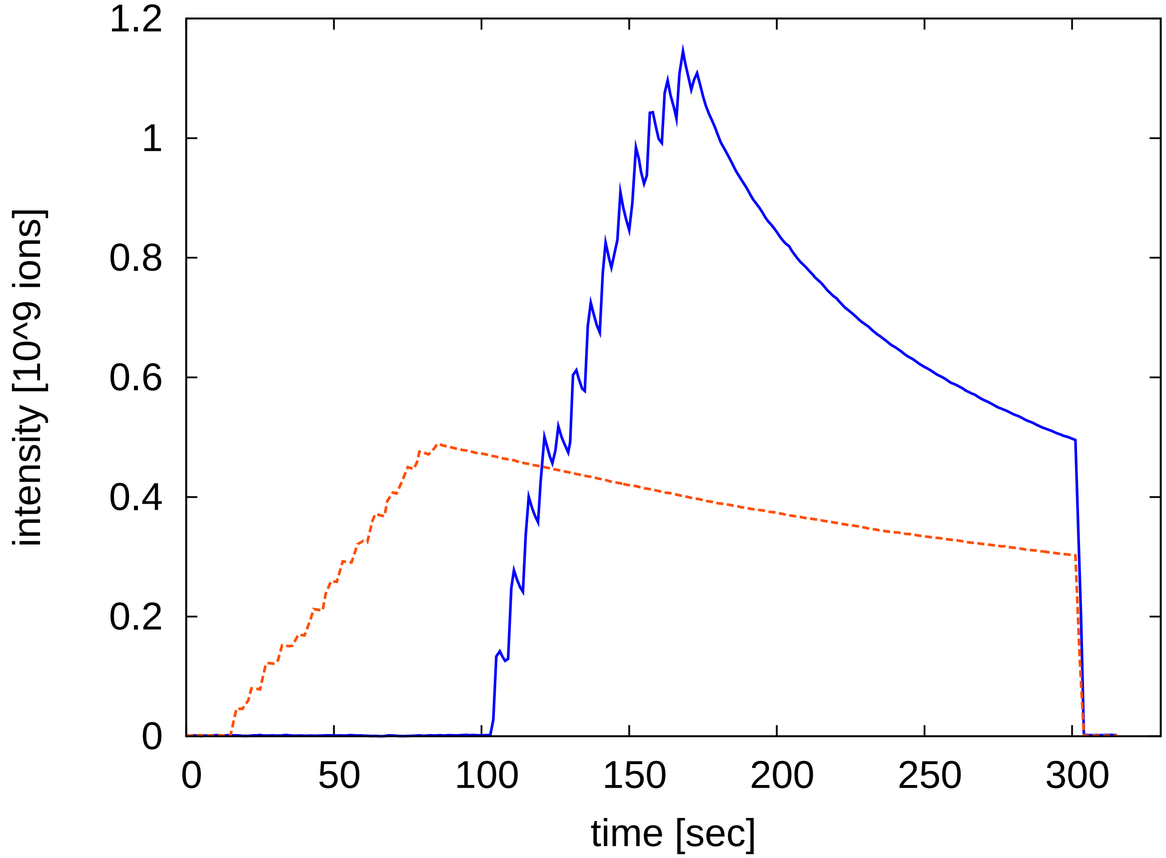
- No information about magnet-to-magnet variations available

- Unknown whether measured magnets are good representatives

- As a baseline, assigned the same multipole coefficients to ALL magnets

Understanding the Lifetime at 2.5 GeV/n

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:

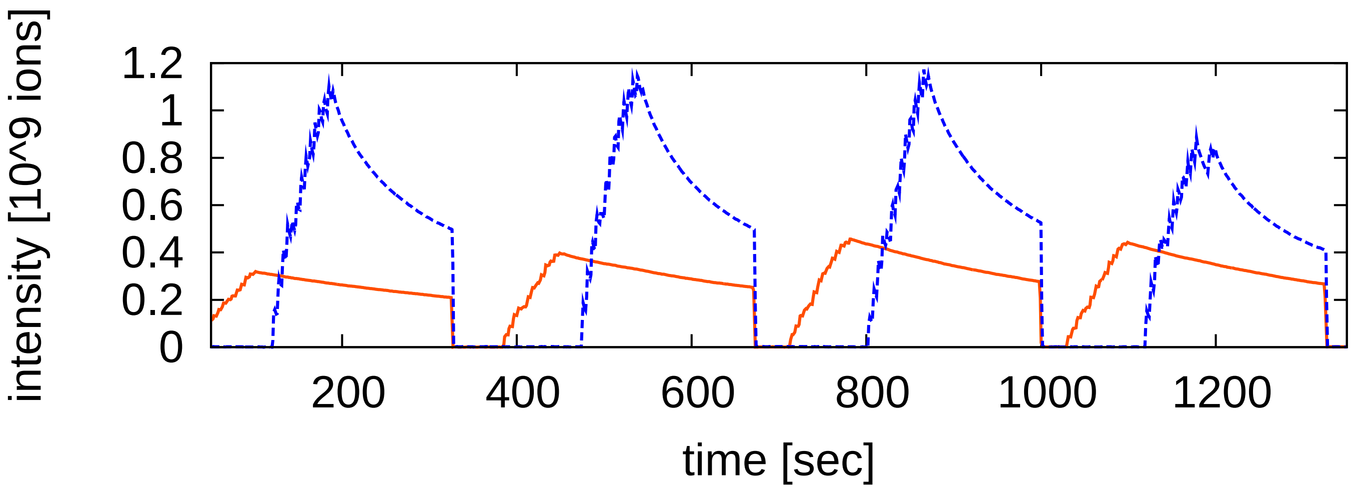
ramp	pp13-6GeV
$B\rho$	19.3 Tm
E	5.86 GeV
E_{kin}	4.92 GeV
γ	6.25
p	5.79 GeV/c
f_{rev}	77.187 kHz
h	363
tunes	28.17/30.13

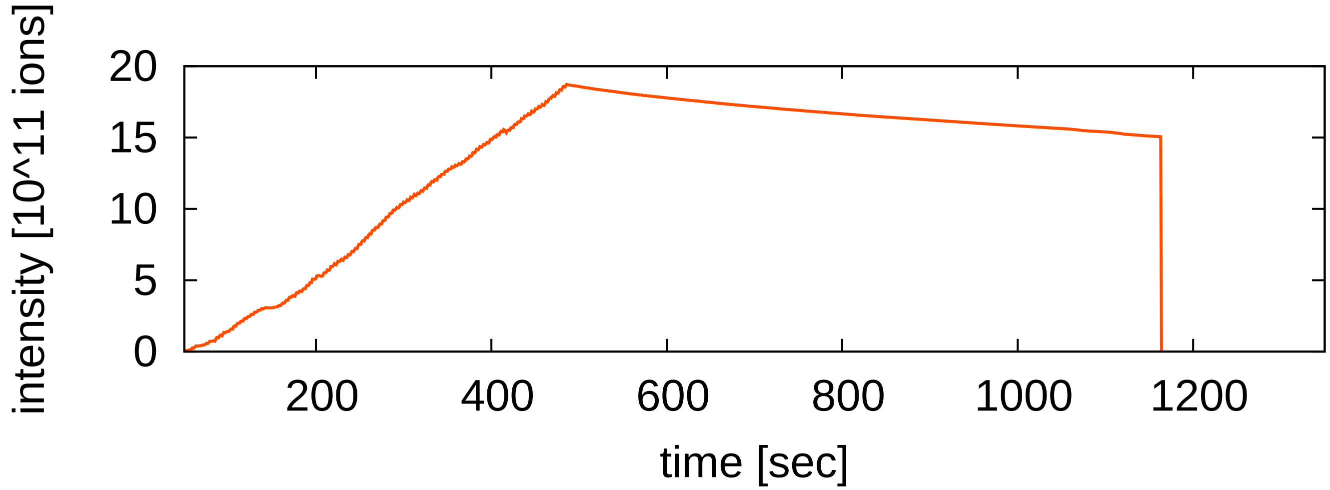
Working point identical to Au test run (as found)

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

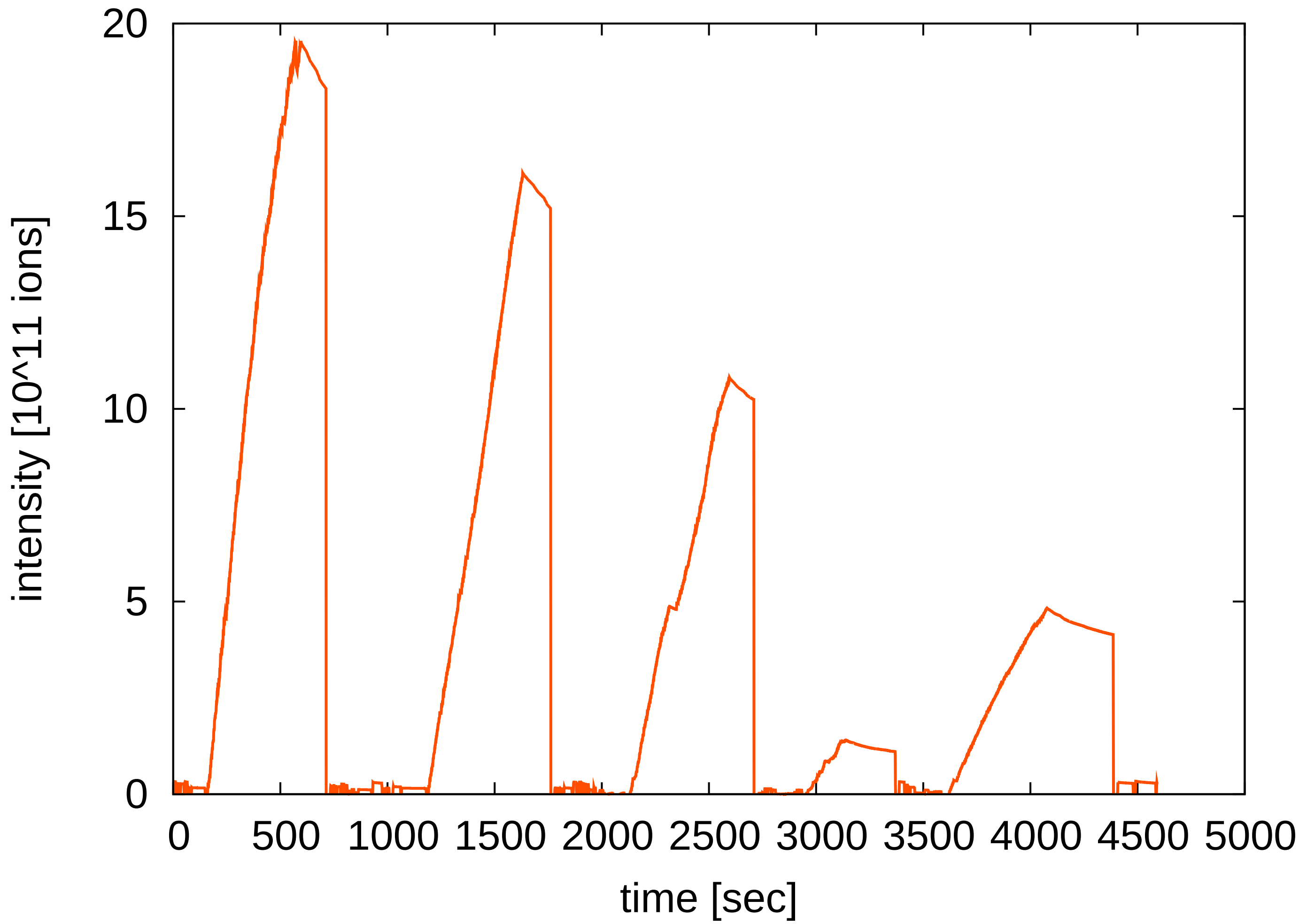
Proton intensity is sufficient for instrumentation to work reliably

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)

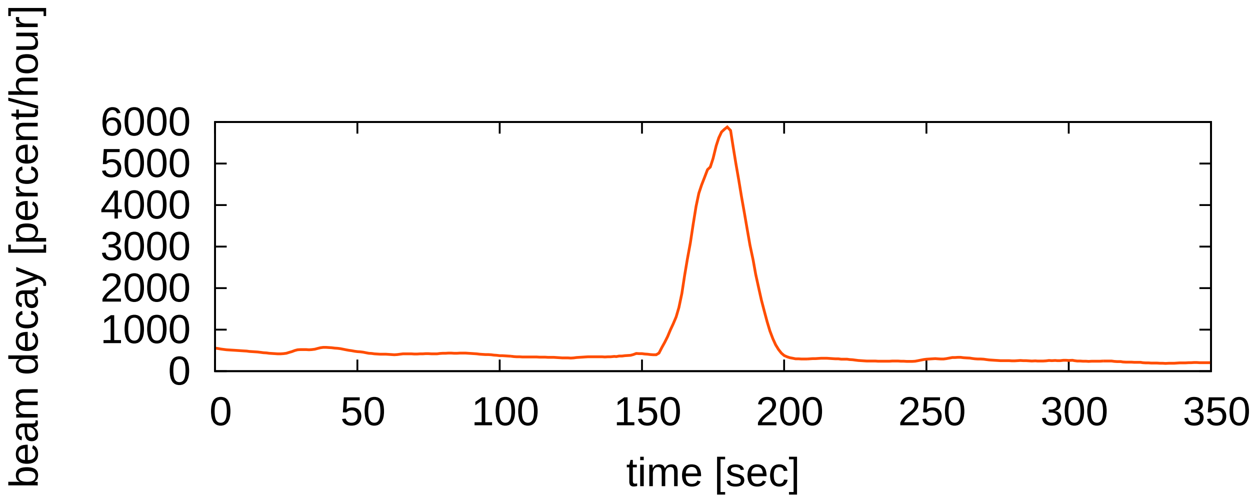
Intensities With Mis-steered Injection

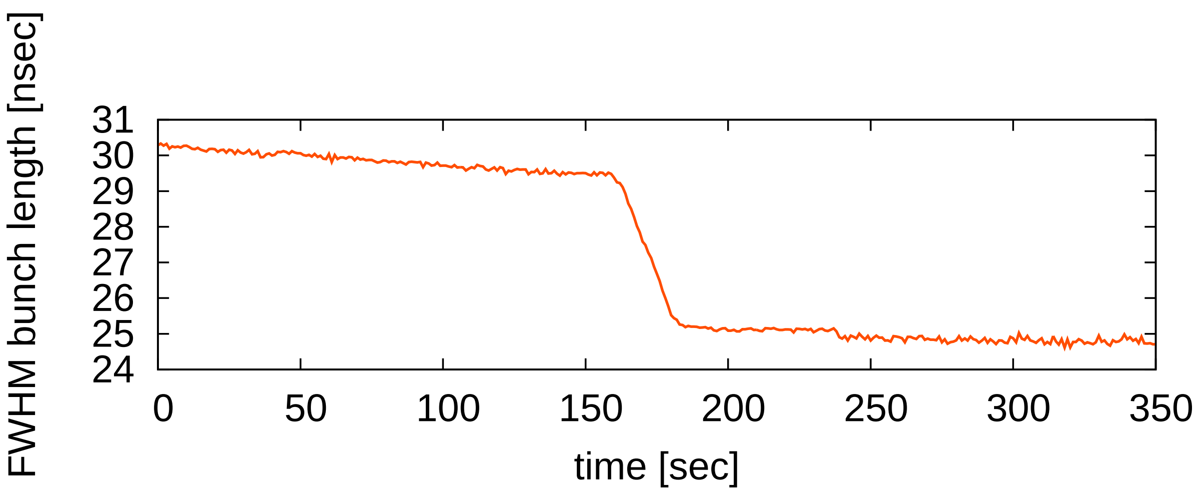


Reduced injection efficiency due to mis-steering

Dynamic aperture limit is reached

Beam Decay and Bunch Length During Blow-up with Tunemeter



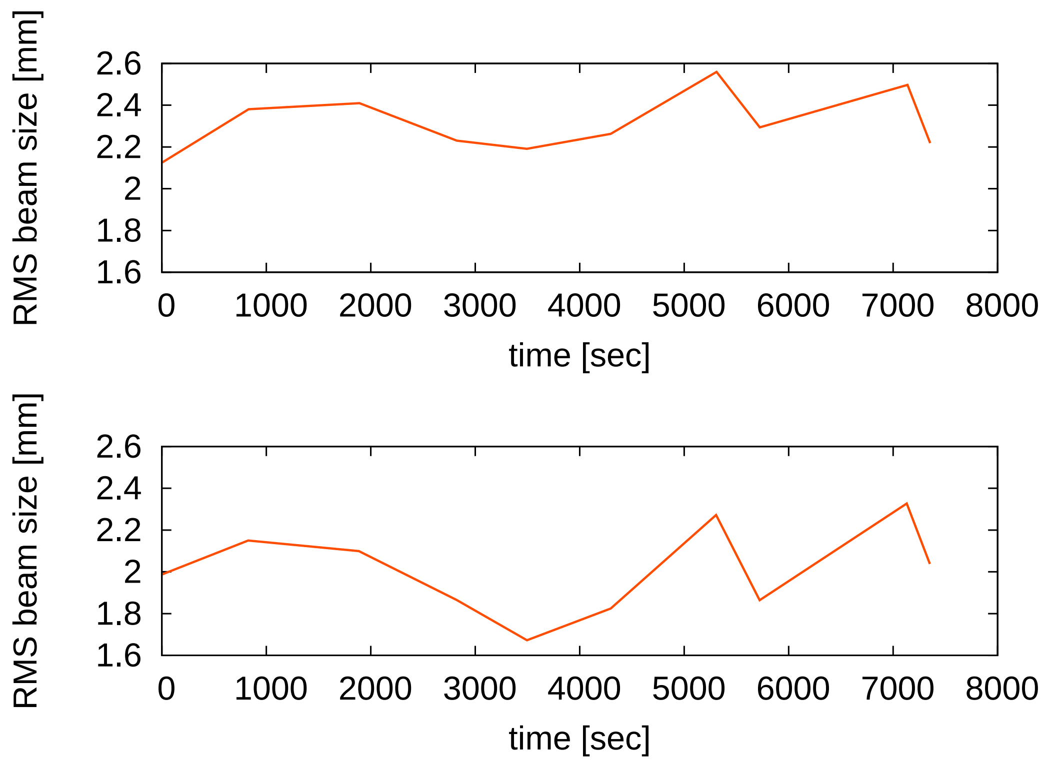


Beam decay immediately recovers when tunemeter is turned off

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

⇒ 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 Results and Intensity Dependence

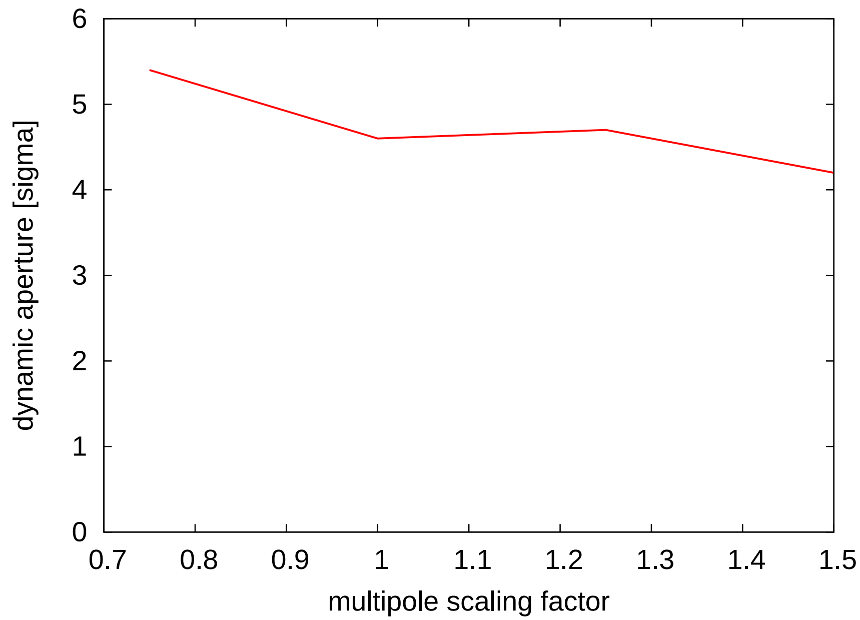
- DA measurements with protons showed no intensity dependence
- Though the bunch intensity varied by a factor 3-4, dynamic aperture remained practically constant
- Tracking results (10^5 turns):

bunch intensity	$2 \cdot 10^{10}$	$4 \cdot 10^{10}$
minimum DA	$4.9\,\sigma$	$4.6\,\sigma$

Tracking reproduces measured intensity (in)dependence well

Scaling All Multipole Errors

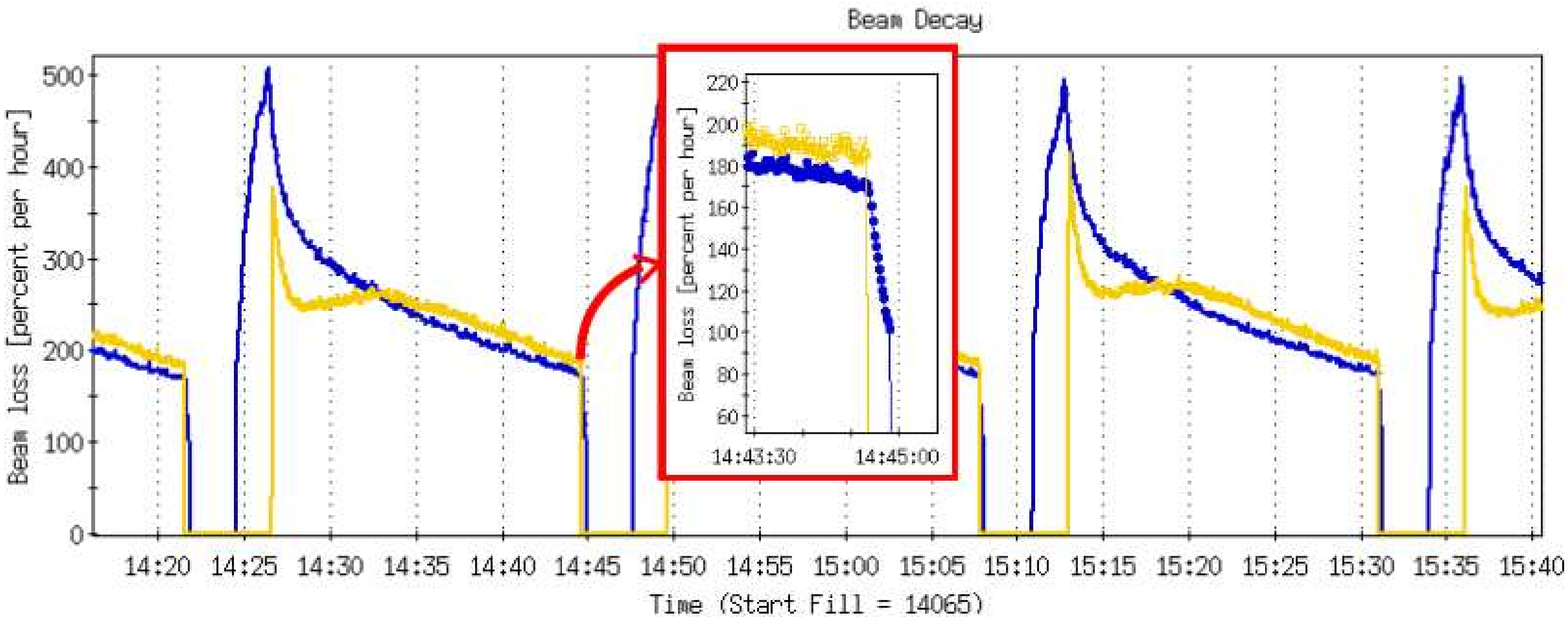
Single magnets measured at low field may not be good representatives of those installed in the machine. Scaled all multipole errors to study the dependence of dynamic aperture on these multipoles



Minimum DA drops from 4.6σ to 4.2σ when all multipole errors are increased by 50 percent
(Note that increasing b_2 changes the machine sextupoles, which may explain the plateau)

Beam-beam in the presence of space charge

Beam Decay Rate at 5.75 GeV During Run-10



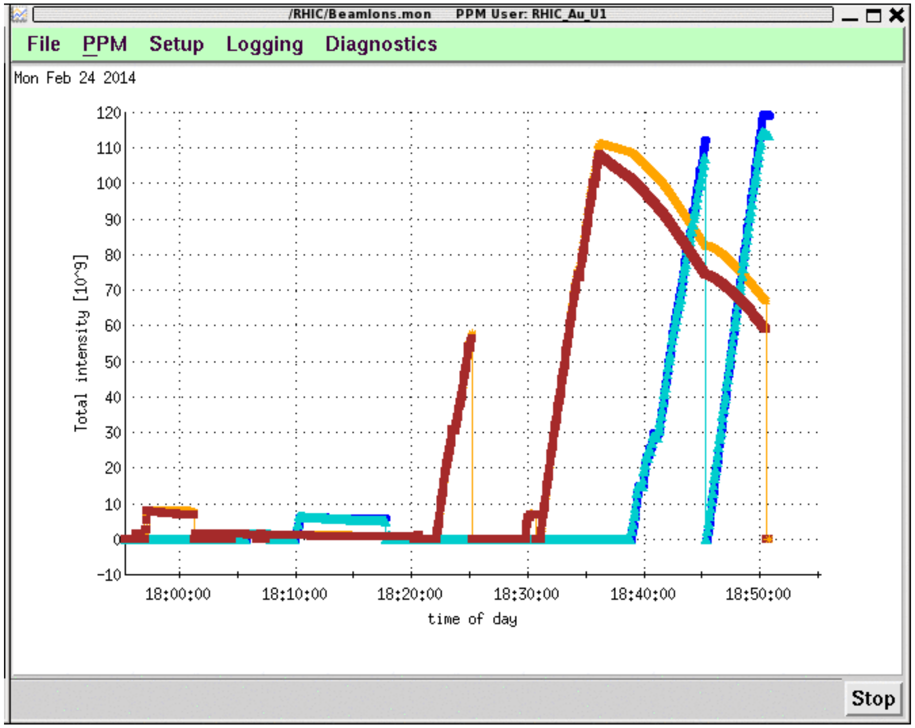
Blue beam decay improves dramatically as soon as Yellow is dumped at the end of store

Though $\xi_{\text{beam-beam}} << \Delta Q_{\text{SC}}$, beam-beam has a strong effect on beam lifetime

This effect has been observed at other low energies as well, with tunes set to .13/.12

Tune Scan at 7.3 GeV in Run-14

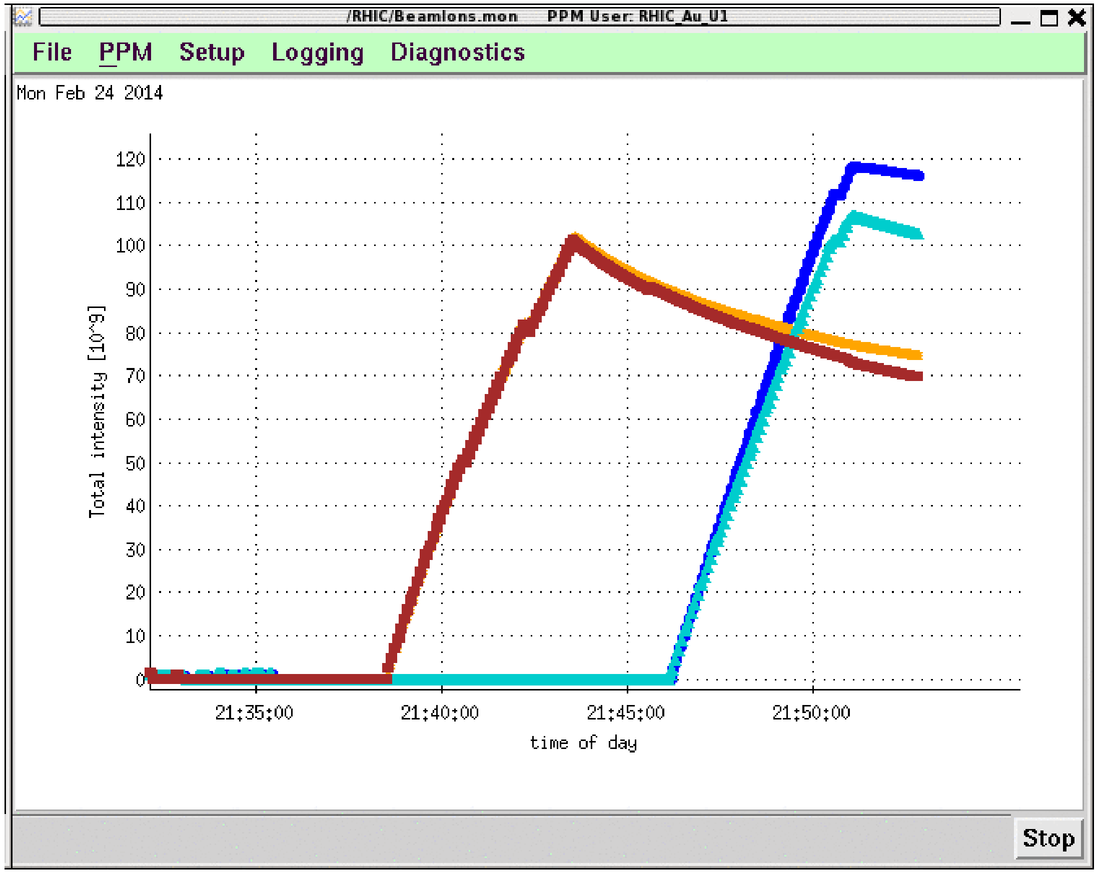
Working point: .13/.12



Yellow lifetime deteriorates as soon as Blue is injected

Dynamic aperture from tracking (10^5 turns):
$5.5\,\sigma$ without beam-beam, $4.5\,\sigma$ with beam-beam

Working point: .095/.085



No effect on Yellow lifetime when Blue is injected

Dynamic aperture from tracking (10^5 turns):
5.4 σ without beam-beam, 5.5 σ with beam-beam

Summary

- Desired energy range for the QCD critical point search extends far below the RHIC design energy range

- Dynamic aperture is limited by single-particle effects, most likely magnet nonlinearities

- Tracking studies reproduce experimental results reasonably well

MADX-SC is a useful and reliable tool to understand and improve RHIC performance at low energies