Experience and Projections for Low-Energy RHIC Operations

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Motivated by discussions at the

"Can We Discover the QCD Critical Point at RHIC?"
RIKEN Workshop, March 9-10 2006

- Background, parameters, challenges
- 22 GeV proton test run preliminary findings
- Performance projections and plans

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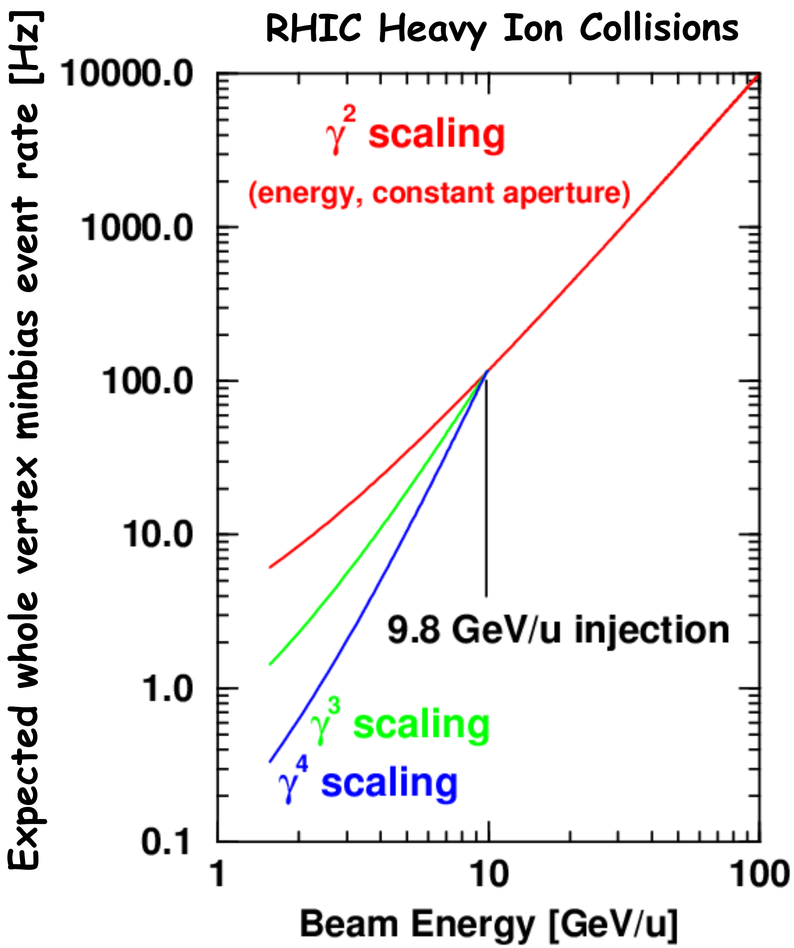
- There is substantial and growing interest in RHIC heavy ion collisions with c.m. energy in the range $\sqrt{s_{NN}}$= 5-50 GeV/n
  - Corresponds to Au beams in RHIC of γ=2.68 to 26.8
  - Nominal Au injection is γ=10.52, already below design γ=12.6
  - Krishna Rajagopal's Thursday talk, RIKEN workshop energies:
    $\sqrt{s_{NN}}$ = 5, 6.3, 7.6, 8.8, 12.3, 18, 28 GeV/n

- Operational and strategic challenges
  - How does RHIC magnetic field quality degrade at lower currents and energies?
  - Can we correct all necessary machine parameters with the existing power supply configuration?
  - What are short- and long-term facility improvements?
  - Can we collide ^{32}Au to lower Z/A, and run with higher fields/currents? (Workshop short answer: unfortunately not.)

RIKEN Workshop Accelerator Summary

- No apparent show-stoppers for RHIC collisions at E_{cm} = 5-50 GeV/n
  - Only equal energies
  - Unequal species possible only if minimum rigidity > 200 T-m
  - Without cooling → long vertex distribution
- Small set of specific energies (and species?) should be a workshop deliverable for planning:
  - 2.5,3.2,3.8,4.4… GeV/n total beam energy
- Studies that should be done soon:
  - *A ~1 day study period at low total beam energy to identify power supply, lifetime, tuning issues/limitations*
  - Low-current superconducting magnet measurements
- Pre-cooling in AGS → 10x luminosity ?
- Electron beam cooling would make this a fantastic facility: ~100x luminosity, small vertex distribution, long stores.

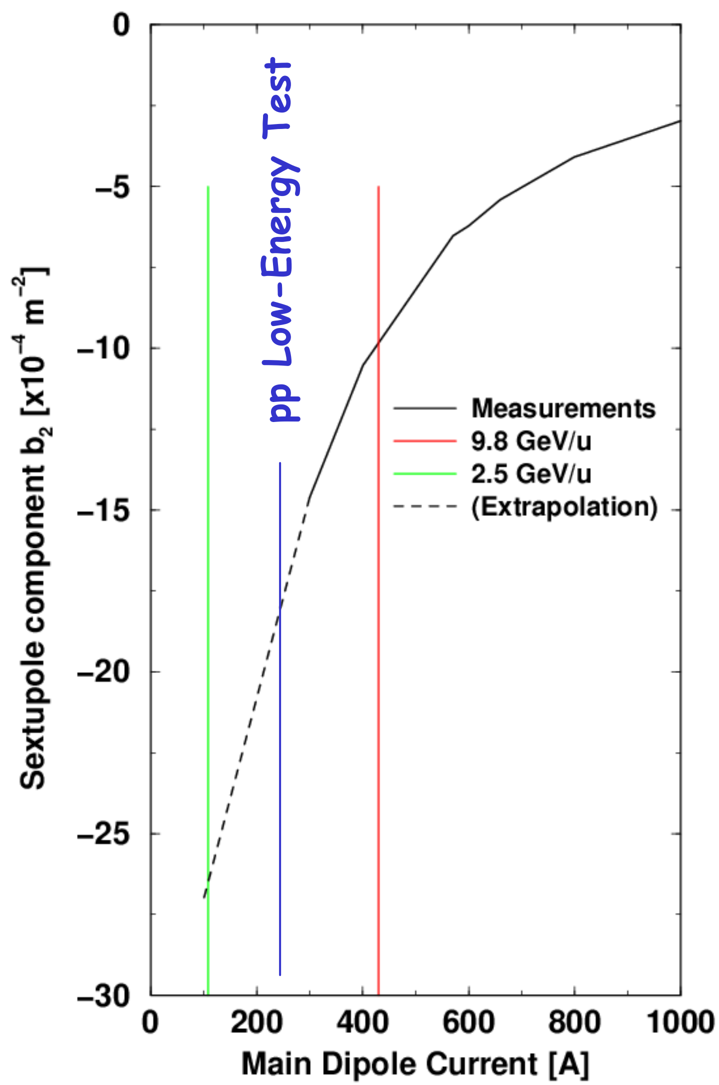


T. Roser, T. Satogata

Low-Energy Magnetic Field Quality

Total Energy	γ	$B\rho$	Dipole Current
9.8 GeV/u	10.52	81.11	430 A
2.5 GeV/u	2.68	20.69	110 A

- Magnet currents scale with rigidity $B\rho$ which scale with γ
- Field quality deteriorates rapidly at very low currents
- Currently have some magnet measurements at very low currents, enough for simulations
  - Extrapolating low-field behavior from simulations



Proton/Gold parameters tested at Bρ=37.4 T-m

	Protons	Gold (eq)
$\sqrt{s}$ [GeV]	22.5	9.18
Beam energy [GeV]	11.25	4.59
Beam kinetic energy [GeV]	10.312	3.660
Relativistic γ	11.99	4.93
Relativistic β	0.997	0.979
Momentum [GeV/c]	11.211	4.496
$B\rho$ [T-m]	37.40	37.40
Injection current scaling	0.471	0.384
Main dipole current [A]	217.7	217.7
Main quad current [A]	202.6	202.6
Revolution frequency [Hz]	77924	76571
RF frequency [MHz, h=360]	28.053	27.566

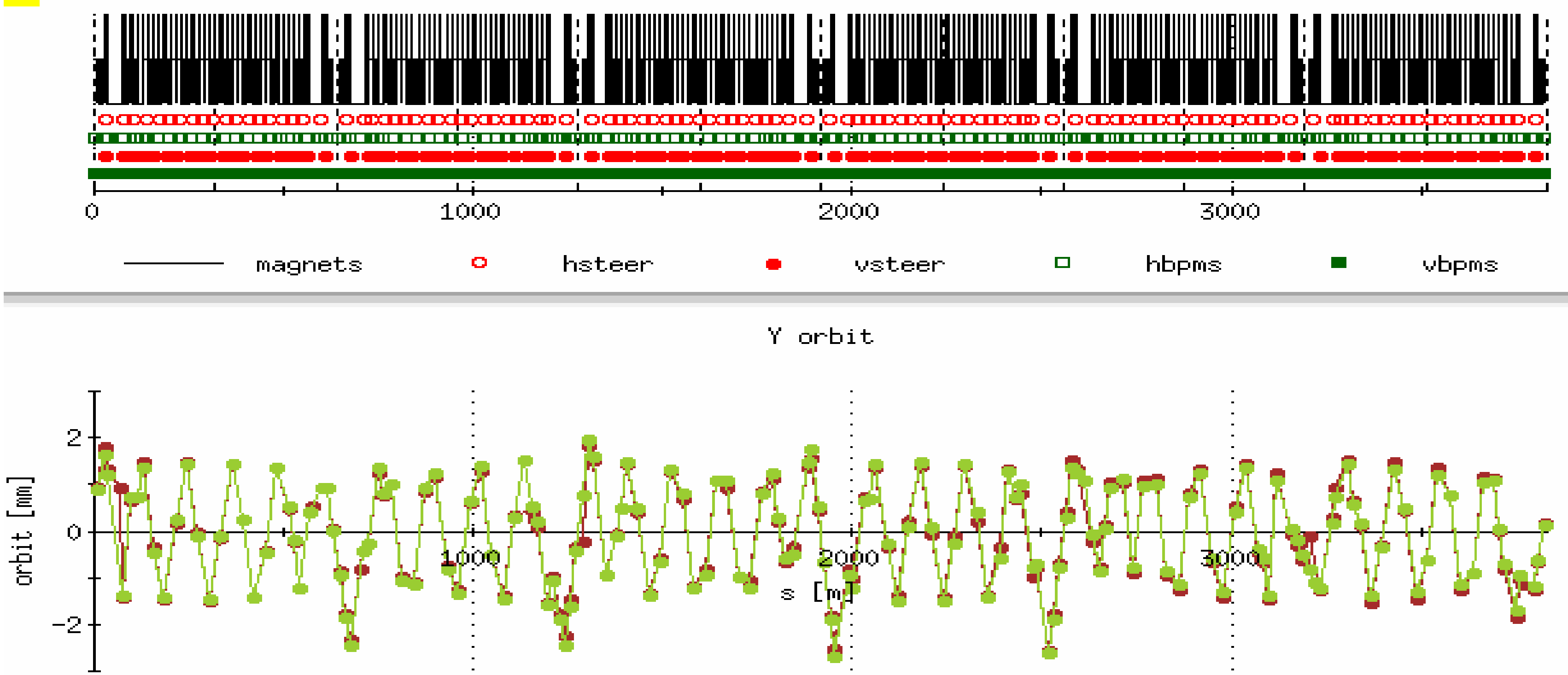
RHIC RF frequency range is 28-28.17 MHz

- Gold energy ($\sqrt{s_{NN}}$=9.2 GeV/n) is near middle of preferred energy list
- Tested magnets and power supplies at less than half of normal injection current
  - Reasonably balance for initial testing, performance extrapolation
- Did NOT require change to RHIC harmonic number or substantial reconfiguration of RHIC RF
  - Au h=366 gives RHIC RF frequency of 28.03 MHz

Low-Energy Proton Test Run Results (June 5-6 2006)

- First injection to circulating beam in about 30 minutes (both rings)
- Circulating beam to RF capture in under 3 hours.
- Single bunch intensities up to about 8e10 protons.
- Injection efficiency was about 70-80%.
- Beam lifetimes of 5-10h (not in collision) and 4-5h (in collision) achieved.
- Chromaticities and instabilities can barely be controlled with existing power supplies at this energy. For this and lower energies, we should rewire unipolar sextupoles for future operations.
- Proton emittances out of AGS were very good (<10 π mm mrad normalized) Measured emittances in RHIC are being analyzed, but appear to be comparable as long as beams did not go unstable.
- Optics measurements and correction data were taken in both rings, and will be analyzed to compare to tests. Initial analyses show that optics (beta functions, phases, dispersions) are surprisingly close to the model, so linear field quality is not limiting performance.
- Two hours were spent performing vernier scans in PHENIX and STAR with beam-beam counters. These data are currently being analyzed.

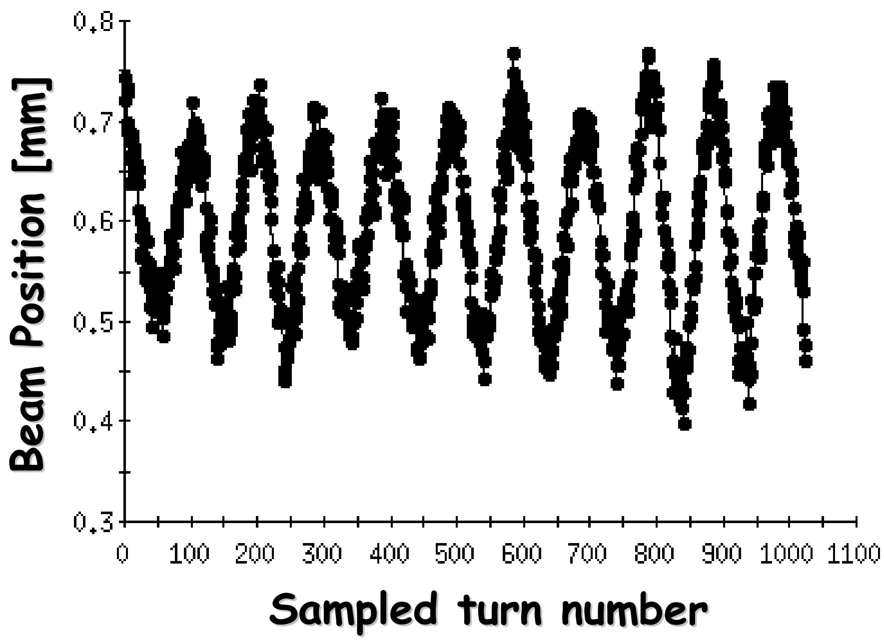
Low-Energy Test Run Optics

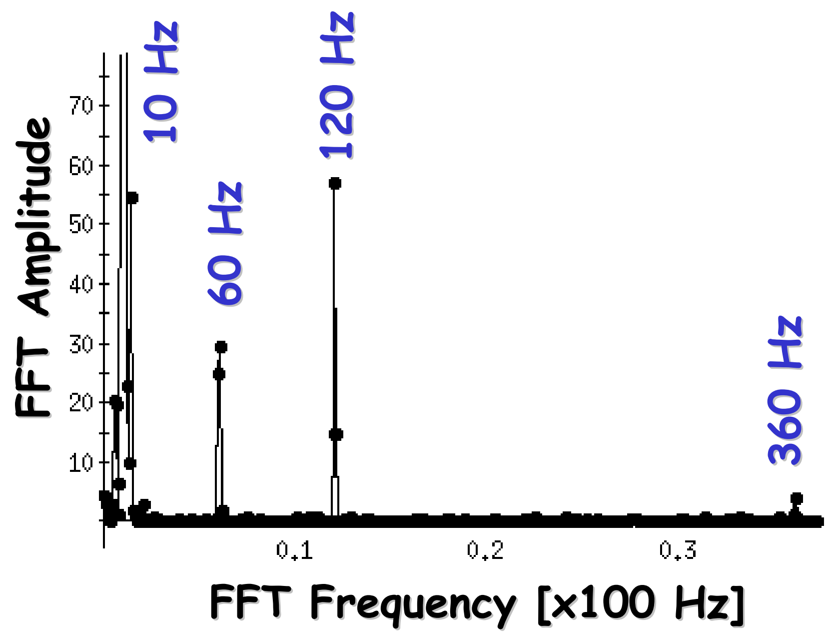


S-coordinate [m]

- Measured optics in both rings are surprisingly good
  - No indications of linear optics problems, quadrupole magnet or power supplies with aberrant low-current behavior

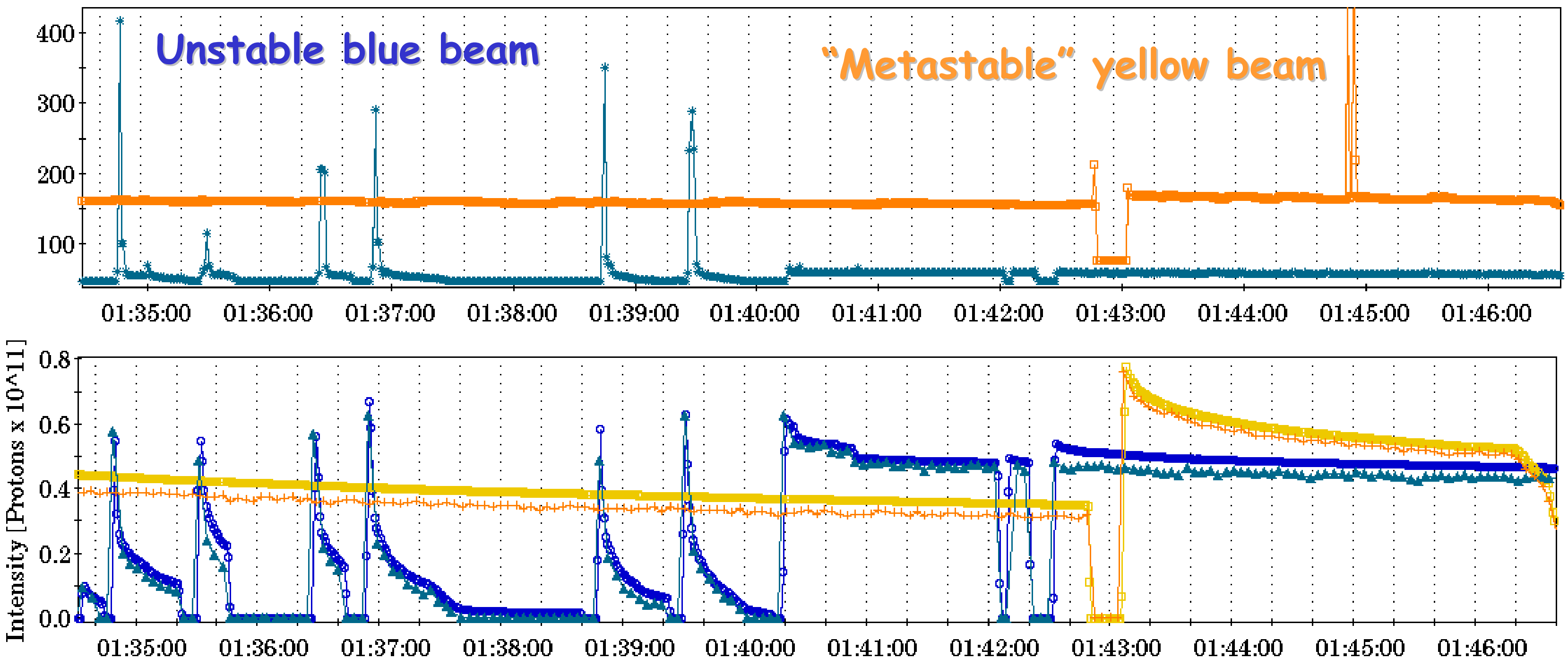
Low-Energy Test Run Beam Ripple





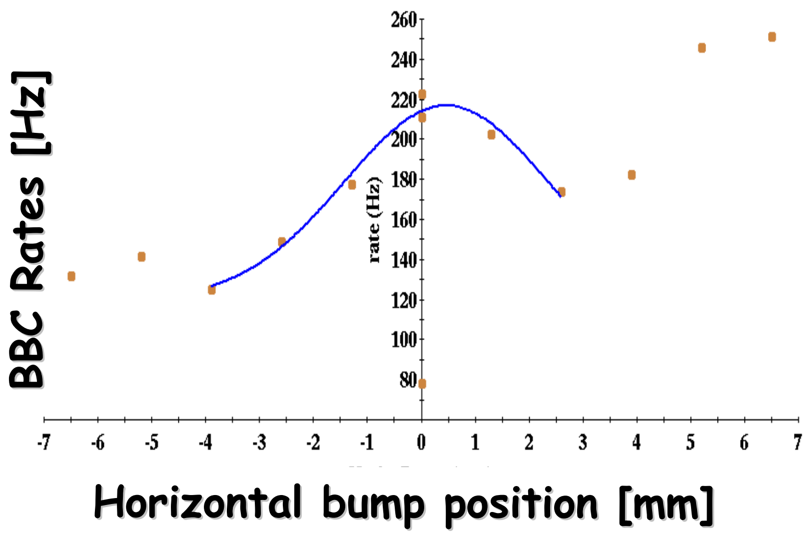
- Measured beam ripple in both rings is also good
  - No indications of major coherent ripple from power supplies
  - Coherent beam oscillation spectrum comparable to injection at nominal energies
  - Should still dwell AGS Booster during low-energy stores

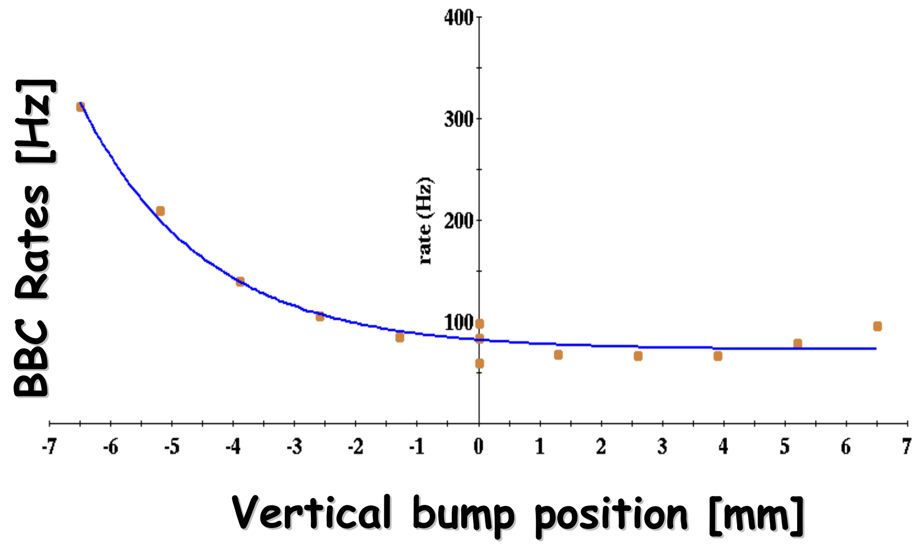
Low-Energy Test Run Instabilities



- Beam stability was a problem through the low-energy test
  - Power supply configuration did not permit necessary chromaticity control
  - Yellow beam was metastable at best
  - Some instabilities damped with strong octupoles in both rings

Low-Energy Test Run Vernier Scans (STAR)





- Collision steering attempted at STAR and PHENIX
  - Mostly background, likely driven by unstable (large) yellow beam
  - Some apparent real rates in STAR, though very low
  - Rates consistent with luminosity down by factor 2500 from 100 GeV (1.7×10^{28})
  - Expected reduction from beam parameters is closer to 4000
    - Difficult to justify one-day 22 GeV pp run this year from this data
    - Luminosity monitoring will be a challenge for low-energy program
    - Beam-beam tune shift may be one of our best luminosity observables

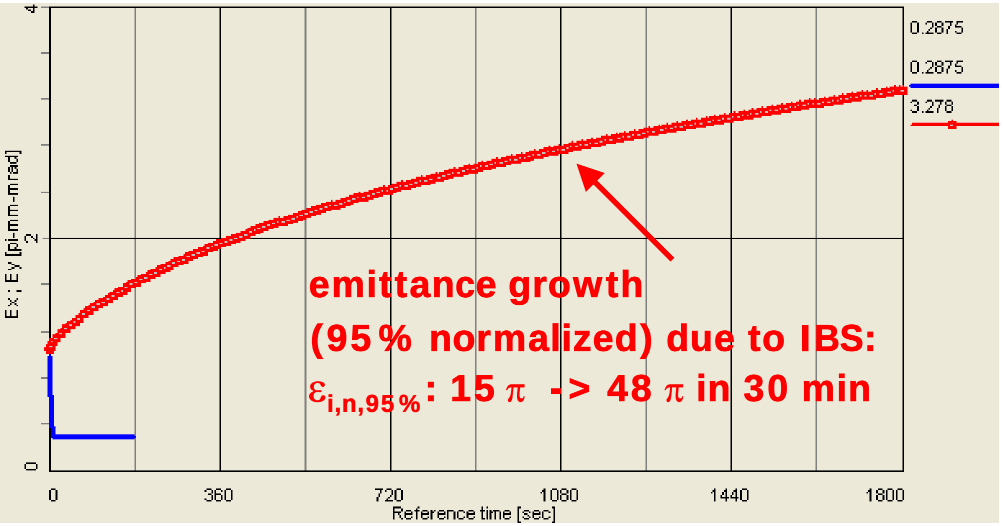
- IBS will make ion lifetimes worse than protons (A. Fedotov)

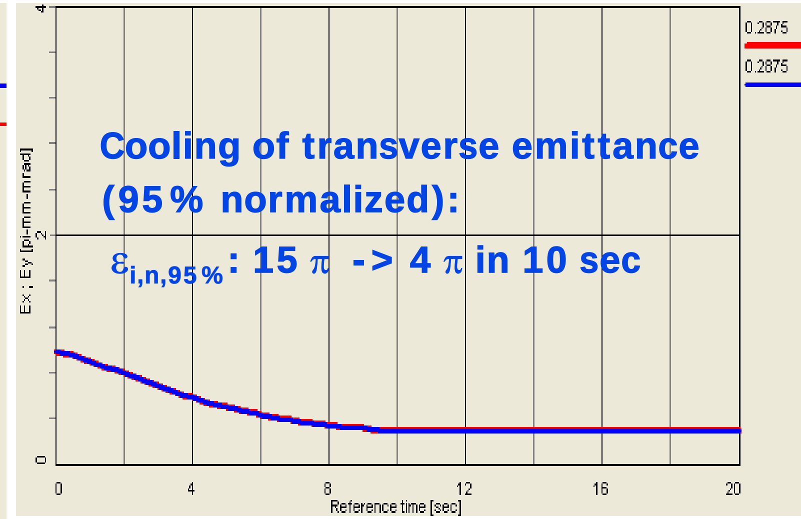
Beam Energy [GeV/u]	IBS growth time [s]
2.5	250
5	1800
9	5000 (horizontal)

  - Consistent with 15- to 30-minute stores at 5 GeV/u
  - Lower energies likely require cooling or lattice modifications

- Recommend ~1 week of low-energy Au setup and operations
  - Between maintenance days to swap power supply polarities
  - CERN data suggests $\sqrt{s_{NN}}$=7.6 GeV/u; leverage 9.2 GeV/u done
  - Gain experience with IBS, low luminosity, fast refills
  - Produces definitive luminosity for performance extrapolations
  - Tests at multiple energies? One day at $\sqrt{s_{NN}}$=5 GeV/u?

IBS and Electron Cooling at 2.5 GeV/u





- IBS growth times for low-energy gold ions are short, o(4 minutes)
  - Correspondingly short luminosity lifetimes, need to constantly refill
- Electron cooling with a modest electron beam can help
  - Cooling times are a few seconds, dramatically improves emittances and lumi lifetime
  - Electron beam from simulation: q=5nC, RMS $\varepsilon_{e,n}$=10μm, σ_p=1e-3, L=10m (Figs: plotted emittance is rms unnormalized)
  - Might be done with prototype ERL gun currently in design

A. Fedotov

Summary and Recommendations

- There is substantial and growing interest in RHIC operations at low energies ($\sqrt{s_{NN}}$= 5-50 AGeV)
  - Discovery of the QCD critical point would be another major discovery at RHIC

- There are (still) no show-stoppers to a low-energy program
  - Low-energy ($B\rho$=37.4 T-m) test run occurred June 5-6 2006
  - Injection efficiency 70-80%, lifetimes up to 5-10h, good optics
  - Addressable issues: sextupoles, instabilities, lumi monitoring
  - Difficult to justify one-day $\sqrt{s}$ = 22 GeV run this year

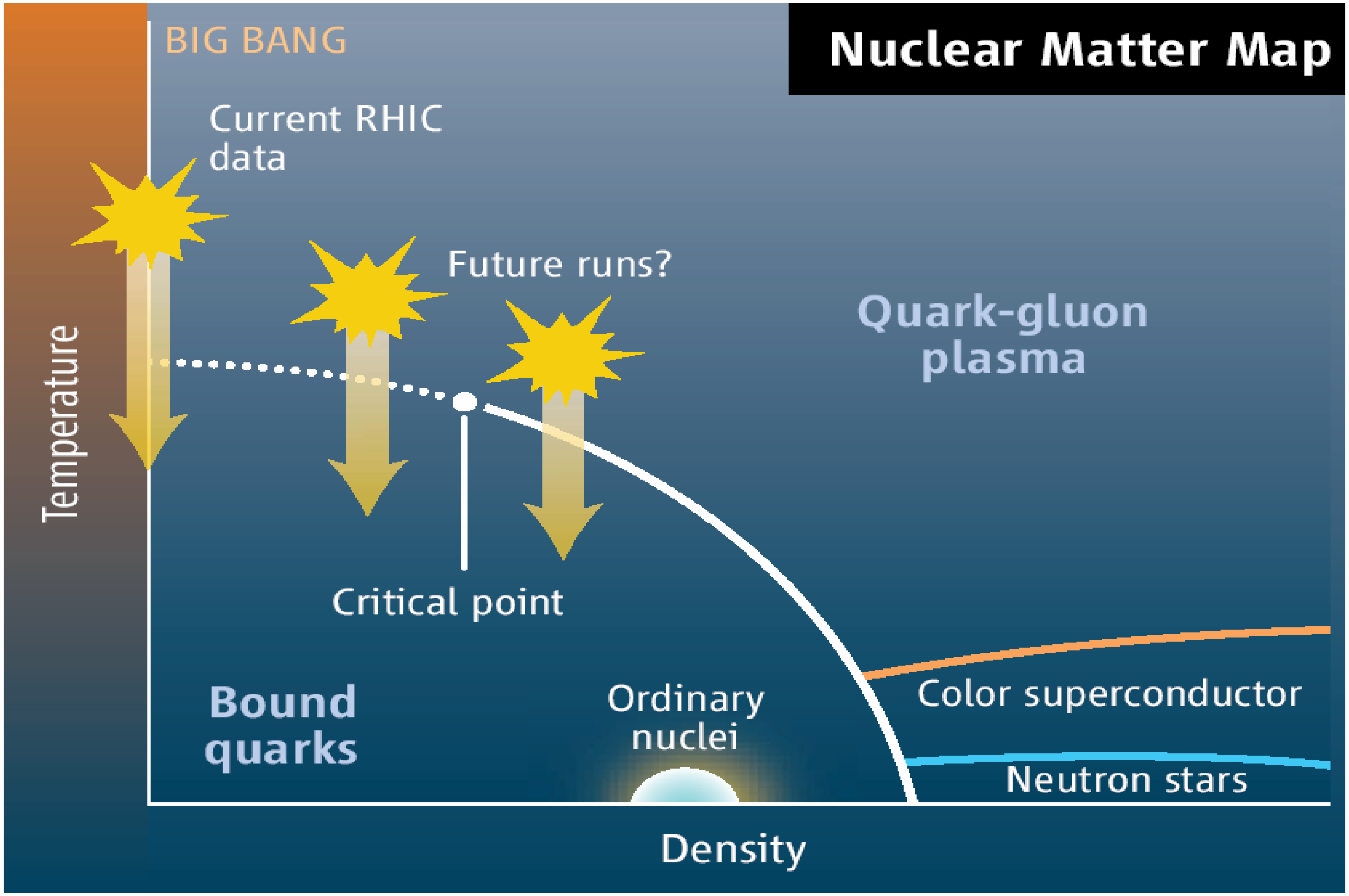
- Future planning
  - One week of 1-2 energies in 2007 with ions is natural next step
  - Recommended energies: $\sqrt{s_{NN}}$=7.6 GeV/u, test at $\sqrt{s_{NN}}$=5 GeV/u
  - Low-energy electron cooling looks very beneficial in longer timescale (Compatible with STAR TOF upgrade?)

Initial Machine Projections

Mode	Beam Energy [GeV/u]	$N_{bunches}$	Ions/bunch [10^9]	β^* [m]	Emittance [μm]	L_{peak} [$cm^{-2}s^{-1}$]
Au-Au 2001-2	9.8	55	0.6	3	15	8.0×10^{24}
Au-Au 2003-4	31.2	45	1.0	3	15-30	1.2×10^{26}
Au-Au	9.8	55	1.2	10	15-40	1.0×10^{25}
Au-Au	2.5	55	1.0	10	15-30	1.1×10^{23}
Au-Au	25	55	1.2	3	15-40	2.0×10^{26}

- Assumes expected luminosity scaling as γ^3 below 9.8 GeV/u
- β^*/aperture and integrated luminosity tradeoffs must be studied
- Projections do not include potential improvements
  - Electron and stochastic cooling (peak and integrated luminosity)
  - Lattice modifications to mitigate IBS (integrated luminosity)
  - Total bunch intensity from vacuum improvements (peak luminosity)

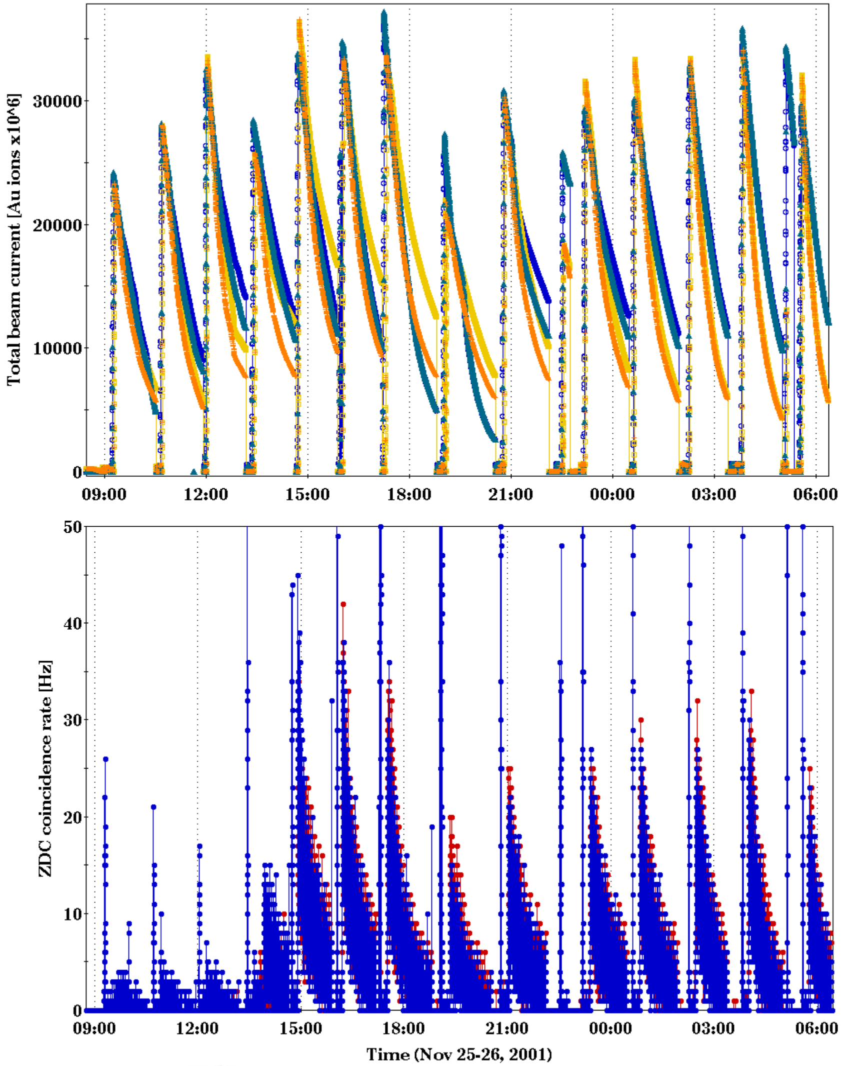
Searching For The QCD Critical Point



Landmark study. Physicists have seen a smooth transition from bound quarks to quark-gluon plasma (dotted line). They now hope to find the point beyond which the transition becomes violent (white line).

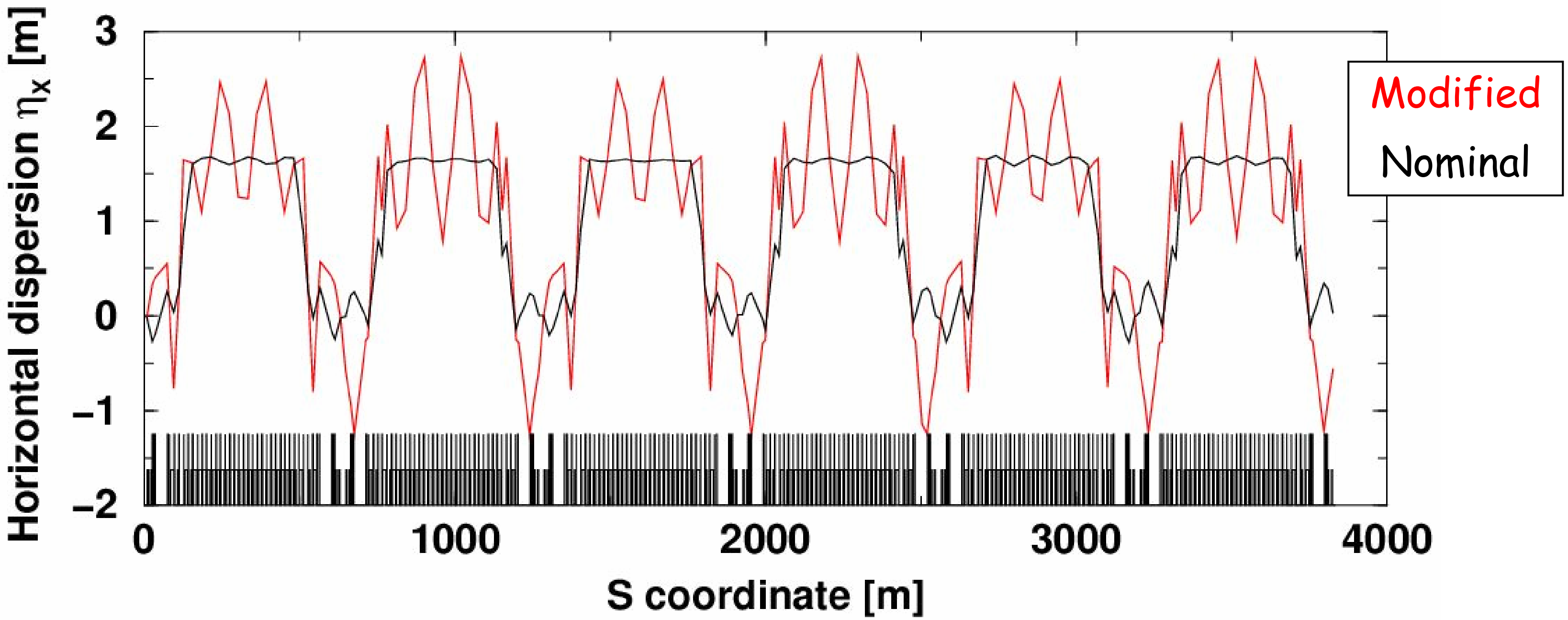
A. Cho, Science, 312 (14 Apr 2006)

2001 9.8 GeV/u Au collisions



- 2 days of 9.8 GeV/u collisions
  - 0.4 μb^{-1} integrated luminosity
  - β^*=3m by necessity
  - 60-90 minute stores
  - 56 Au bunches, 0.6×10^9/bunch
  - 10-30 Hz ZDC rates
  - IBS and aperture dominated beam and luminosity lifetime
- Another run at this energy may improve this by factor of 2-5
  - $1.0^+\times10^9$/bunch
  - Raise β^* to improve lifetime
- RHIC is best used as a storage ring collider below beam energies of ~12 GeV/u

Transition Energy Modification



- For Run 6, transition energy was successfully modified
  - Lowering polarized proton injection energy for spin matching
  - Nominal γ_T=23.5, modified γ_T=22.8
  - Primarily changes horizontal dispersion, momentum aperture
  - No effort to tune dispersion matching, limit triplet dispersion

- Stochastic cooling is feasible but requires development
  - Different mixing regime than high-energy stochastic cooling
  - Cannot use filter cooling, as Schottky bands overlap
  - Higher cooling rates at lower energies, but requires different method
    - Cooling rate estimates under development
- Palmer cooling
  - Under active development at C-AD as frontier of cooling
    - Will test cutting chord from pickup to kicker in Run 7
  - Requires new cold pickup in arc (high dispersion, low beta)
  - Concerns about 10 Hz coherenct signal rejection
- Electron cooling discussed in Alexei's talk

Beam Parameters for ^{79}Au

	Test Run	Au store	Au injection	Krishna's energies from workshop					
sqrt(s) [AGeV]	9.183	201.87	23.47	5	6.27	7.62	8.77	12.3	50
Brho [T-m]	37.39847	839.5406	97.303849	19.29881	24.90015	30.73055	35.64258	50.56592	207.8055
main dipole [A]	217.7156	4887.394	566.45538	112.3482	144.9565	178.8982	207.4937	294.37	1209.742
main quad [A]	202.6357	4548.873	527.22037	104.5665	134.9162	166.507	193.1218	273.9808	1125.95

main dipole [A]	537.4854	12065.75	1398.4367	277.3596	357.8613	441.655	512.25	726.726	2986.55
main quad [A]	500.2569	11230.03	1301.5753	258.1486	333.0744	411.0642	476.7695	676.39	2779.689

Beam Parameters for ^{32}Au

- Using ^{32}Au for low-energy heavy ion collisions reduces Z/A and increases required magnet fields by almost factor 2.5
  - Lowest main dipole/quad currents are above those already tested with protons on June 5 during low-energy test setup
  - Likely limited to below $\sqrt{s_{NN}}$=10 GeV/n by injection kicker strength
  - Most energies of interest could still run as storage ring
  - Many uncertainties: backgrounds, lifetime, emittance, dissociation cross section, IBS reduction… but still appealing if feasible.