Low Energy Au Ions in RHIC

Christoph Montag
Brookhaven National Laboratory

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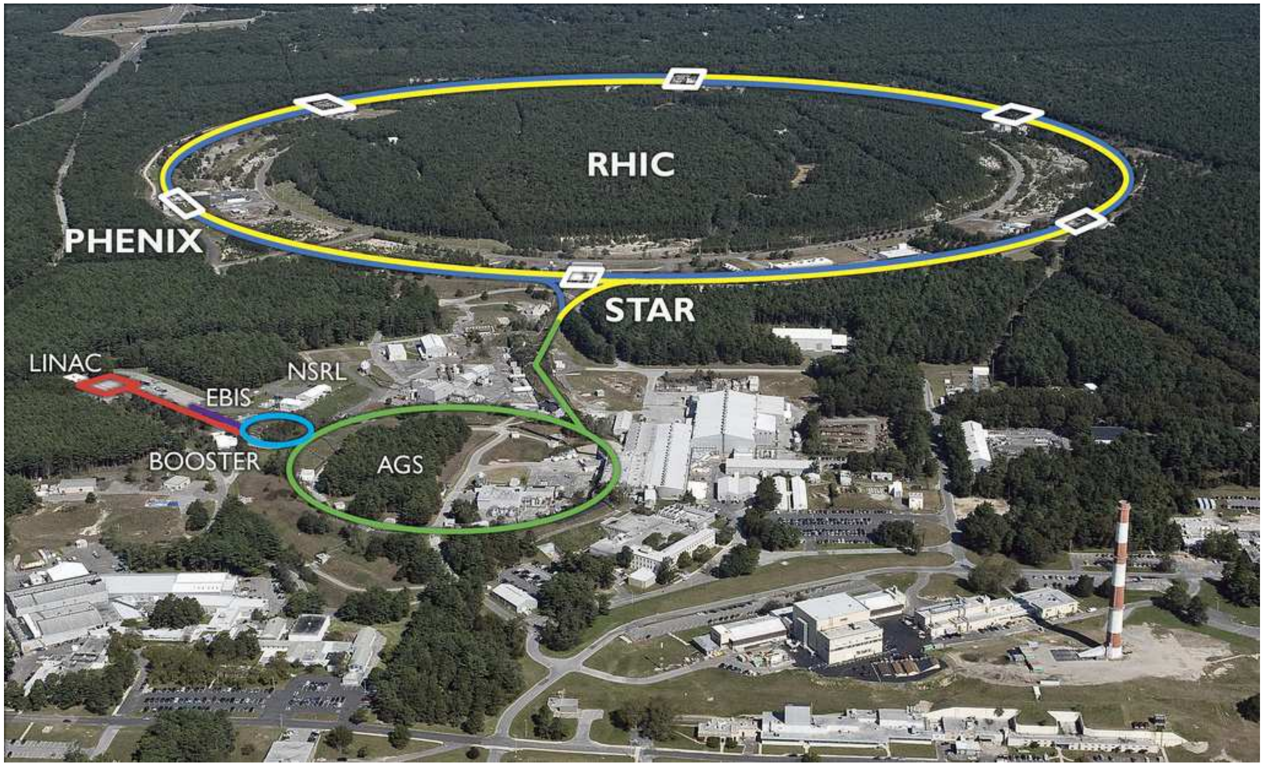
The Relativistic Heavy Ion Collider



Circumference: $C = 3833.845\,\mathrm{m}$
Nominal Au beam energy range: $E = 10\,\mathrm{GeV/n}$–$100\,\mathrm{GeV/n}$
Energy range for critical point search is (well) below design energies

Known Challenges at Low Energy

- Transverse beam size
- Space charge
- Intrabeam scattering
- Magnet nonlinearities

Transverse Beam Size

At any location s around the circumference of the machine, the rms transverse beam size is calculated as

$$\sigma = \sqrt{\epsilon\beta(s)},$$

with

$$\epsilon\gamma = \epsilon_N \qquad \text{(normalized emittance)}$$

The lower the energy, the larger the beam size – aperture problem!

$$\text{Luminosity } L \propto \beta_{\text{IP}}$$

$$\beta_{\text{IP}} \cdot \beta_{\text{triplet}} \approx \text{const.}$$

Luminosity limit

Space Charge

Consider a round beam with radius a and uniform charge density η, moving at velocity $v = \beta c$.

Electrical field inside beam ($r < a$):

$$E_r = \frac{\eta}{2\epsilon_0} r$$

Magnetic field inside beam ($r < a$):

$$B_\Phi = -\frac{\beta\eta}{2\epsilon_0 c} r$$

Resulting net defocusing force:

$$\vec{F} = e(\vec{E} + \vec{v} \times \vec{B}) = \frac{e\eta}{2\epsilon_0}(1 - \beta^2)\vec{r} = \frac{e\eta}{2\epsilon_0 \gamma^2}\vec{r}$$

The lower the beam energy, the stronger the space charge force

Space charge force causes a tune shift

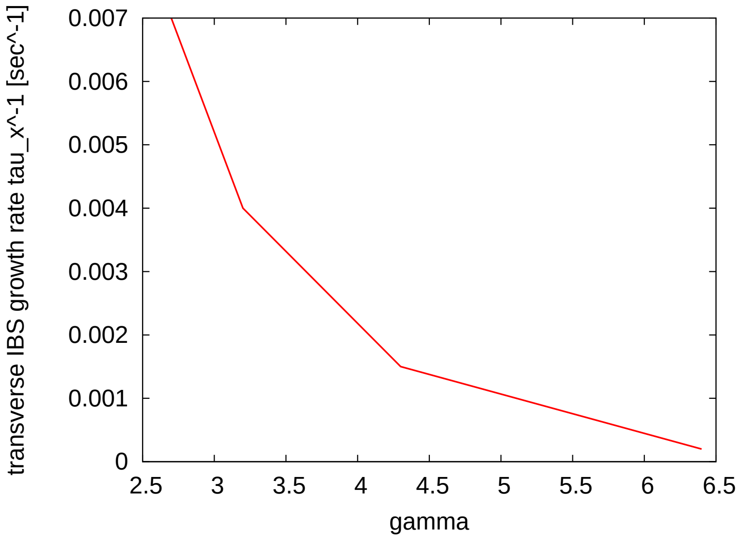
$$\Delta Q_{sc} = -\frac{Z^2 r_p}{A} \frac{N}{4\pi\beta\gamma^2\epsilon_N} \frac{C}{\sqrt{2\pi}\sigma_s}$$

Since the tune shift is largest in the center of the beam and vanishes in the tails, this results in a tune spread that needs to fit in-between low-order resonances (similar to beam-beam tuneshift).

The larger the machine circumference C, the larger the space charge tune spread; the greater the bunch length σ_s, the smaller

Intrabeam Scattering

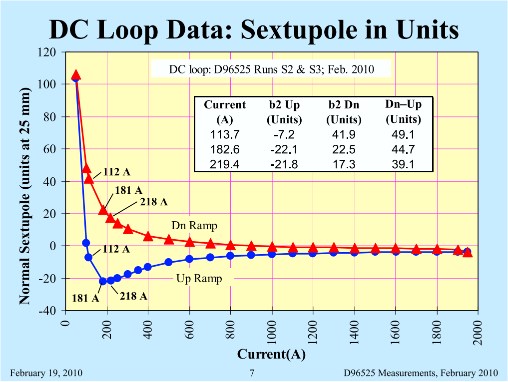
Focusing forces (transverse and longitudinal) cause individual ions to scatter off each other, leading to beam heating (emittance growth)



Emittance growth rates increase rapidly at low beam energies

Can be counteracted with electron cooling

Magnet Nonlinearities

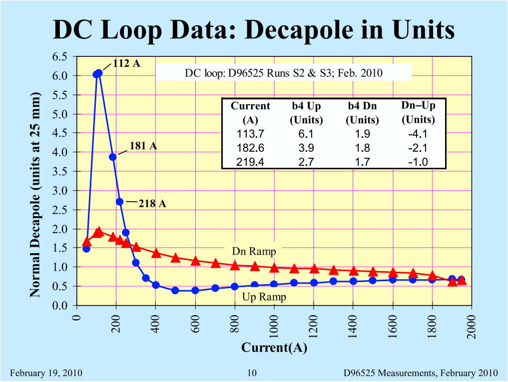


DC Loop Data: Sextupole in Units

DC loop: D96525 Runs S2 & S3; Feb. 2010

Current (A)	b2 Up (Units)	b2 Dn (Units)	Dn–Up (Units)
113.7	-7.2	41.9	49.1
182.6	-22.1	22.5	44.7
219.4	-21.8	17.3	39.1

February 19, 2010 7 D96525 Measurements, February 2010

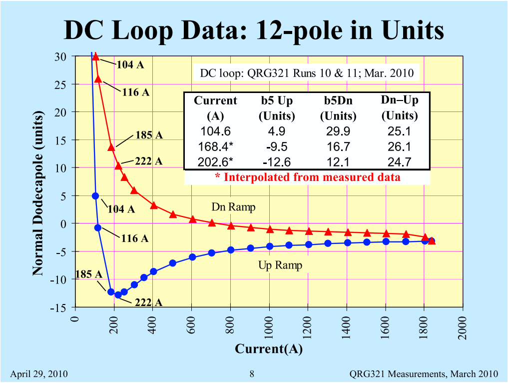


DC Loop Data: Decapole in Units

DC loop: D96525 Runs S2 & S3; Feb. 2010

Current (A)	b4 Up (Units)	b4 Dn (Units)	Dn–Up (Units)
113.7	6.1	1.9	-4.1
182.6	3.9	1.8	-2.1
219.4	2.7	1.7	-1.0

February 19, 2010 10 D96525 Measurements, February 2010



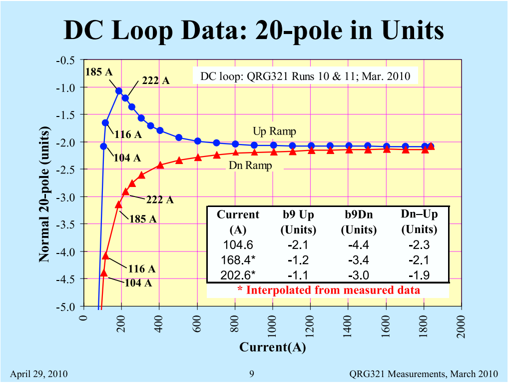
DC Loop Data: 12-pole in Units

DC loop: QRG321 Runs 10 & 11; Mar. 2010

Current (A)	b5 Up (Units)	b5Dn (Units)	Dn–Up (Units)
104.6	4.9	29.9	25.1
168.4*	-9.5	16.7	26.1
202.6*	-12.6	12.1	24.7

* Interpolated from measured data

April 29, 2010 8 QRG321 Measurements, March 2010



DC Loop Data: 20-pole in Units

DC loop: QRG321 Runs 10 & 11; Mar. 2010

Current (A)	b9 Up (Units)	b9Dn (Units)	Dn–Up (Units)
104.6	-2.1	-4.4	-2.3
168.4*	-1.2	-3.4	-2.1
202.6*	-1.1	-3.0	-1.9

* Interpolated from measured data

April 29, 2010 9 QRG321 Measurements, March 2010

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

Achieved Beam Parameters at Low Energy

	2.5 GeV	3.85 GeV	5.75 GeV
γ	2.68	4.1	6.1
σ_s [m]	2.5	1.5	1.5
ϵ_n [mm mrad]	20 (?)	20	15
I_{bunch} [1e9]	0.05	0.5	1.1
N_{bunches}	27	111	111
β^* [m]	8.5	6.0	6.0
ΔQ_{bb}	1.2e-4	1.2e-3	1.7e-3
ΔQ_{sc}	0.005	0.035	0.047
$\tau_{\text{IBS}}(x/s)$ [sec]		475/525	4350/330
τ_{beam} [sec]	250	1000	1500
τ_{lumi} [sec]	?	400	1500
L_{peak} [cm^{-2}sec^{-1}]	> 0	3.1e24	3.3e25
$L_{\text{store avg.}}$ [cm^{-2}sec^{-1}]	> 0	1.25e24	1.5e25

Without electron cooling, BES-II would take about 70 weeks

RF Frequency and Harmonic Number

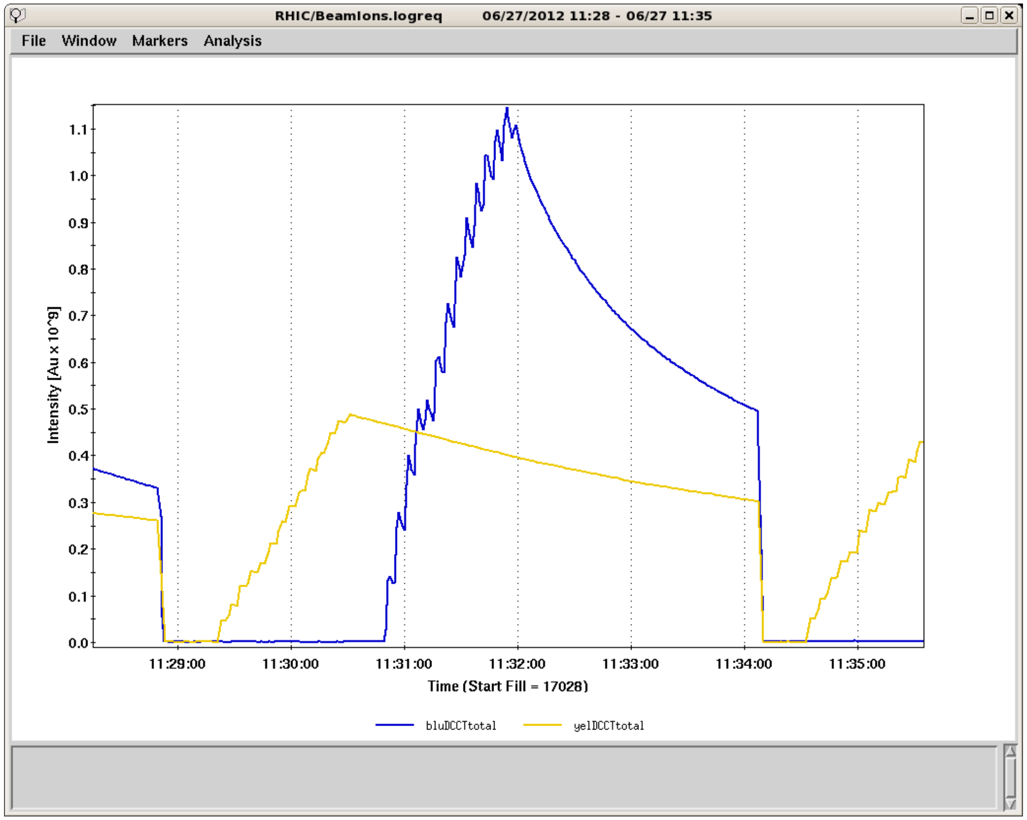
E_{tot} [GeV/nucleon]	$\sqrt{s_{\text{NN}}}$ [GeV]	Harmonic number	No of simultaneous experiments
2.42-2.55	4.84-5.10	387	2
2.55-2.67	5.10-5.34	384	1
2.67-2.84	5.34-5.68	381	1
2.84-3.08	5.68-6.16	378	2
3.08-3.32	6.16-6.64	375	1
3.32-3.69	6.64-7.38	372	1
3.69-4.33	7.38-8.66	369	2
4.33-5.17	8.66-10.34	366	1
5.17-7.30	10.34-14.60	363	1
7.30-100	14.60-200	360	2

Limitations
and
Possible Improvements

2.5 GeV

- Tiny intensity due to poor injection efficiency - only 90 percent. Not understood yet.
- Bunches out of AGS are extremely long, even longer than the injection kicker pulse
- Transverse beam sizes are unknown; RHIC instrumentation does not work properly at these intensities
- 4 min beam lifetime is reasonable, but space charge effects at nominal intensity may change that

Typical store at 2.5 GeV



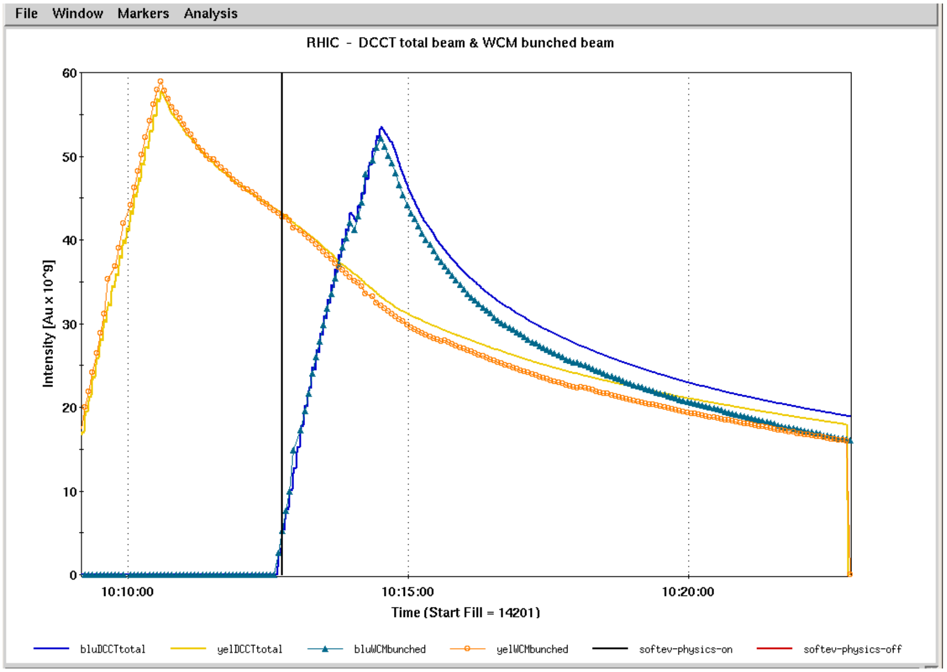
27 bunches, $\approx 4\,\text{min}$ lifetime
Filling 111 bunches takes about $2\,\text{min}$ per beam – need 3 times longer lifetime to be efficient

Proposed beam studies during Run-13

- Extract 2.5 GeV Au from AGS to W-dump, measure transverse emittances to understand injection efficiency problem. Parasitic to proton operation.

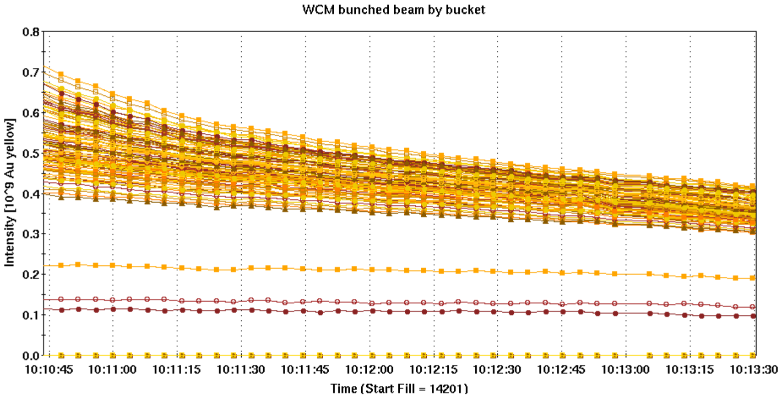
- Inject protons at same rigidity as 2.5 GeV Au into RHIC, to understand RHIC lattice nonlinearities. Requires dedicated machine setup and significant amount of time ($\approx$24 h)

3.85 GeV



- Intensity limited to $0.7 \cdot 10^9$ per bunch by poor lifetime at full intensity; likely space charge limit

Lifetime dependence without collisions



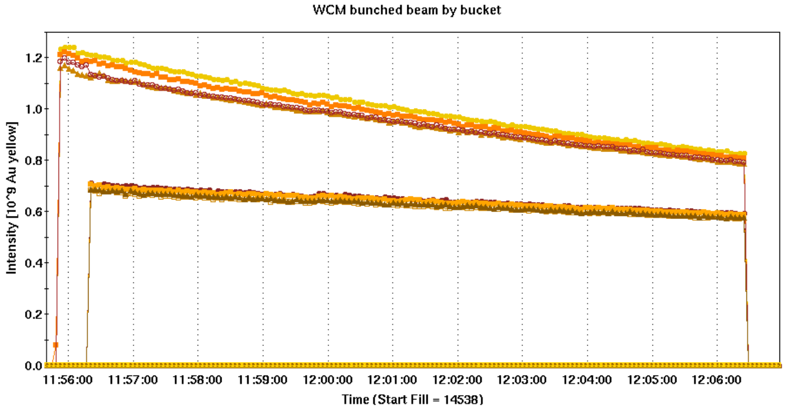
Double-exponential fit:

- $\tau_{\text{fast}} = 30\,\text{sec}$ for 18 percent of the beam, $\tau_{\text{slow}} = 500\,\text{sec}$ for 82 percent of the beam, at $N = 0.73 \cdot 10^9$, $\Delta Q_{\text{sc}} = 0.1$
- $\tau = 1000\,\text{sec}$ at $N = 0.26 \cdot 10^9$, $\Delta Q_{\text{sc}} = 0.04$ (single exponential fit)

Good agreement with IBS simulations; strong dependence on collimator setting (aperture)

5.75 GeV

Lifetime without collisions

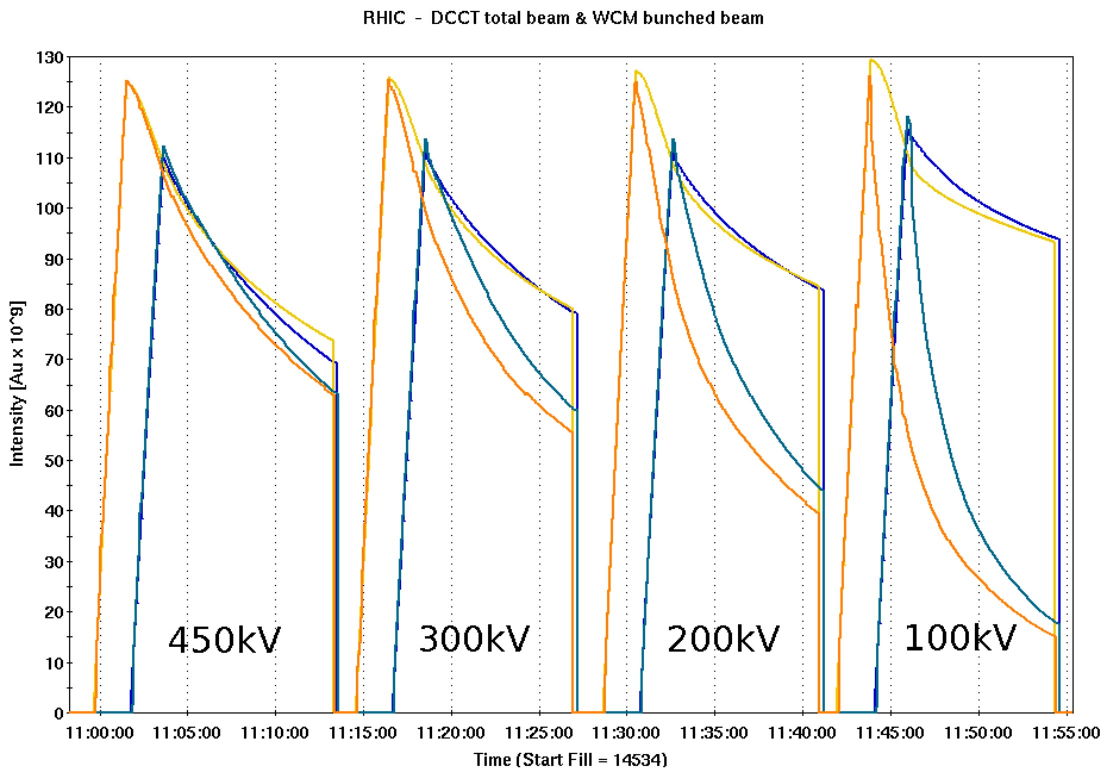


- 1600 sec lifetime for 98 percent of the beam at $1.1 \cdot 10^9$

- 4200 sec lifetime for 93 percent at $0.7 \cdot 10^9$

Very good agreement with IBS simulations

RF voltage scan



Lower RF voltage causes more debunching, but better overall lifetime

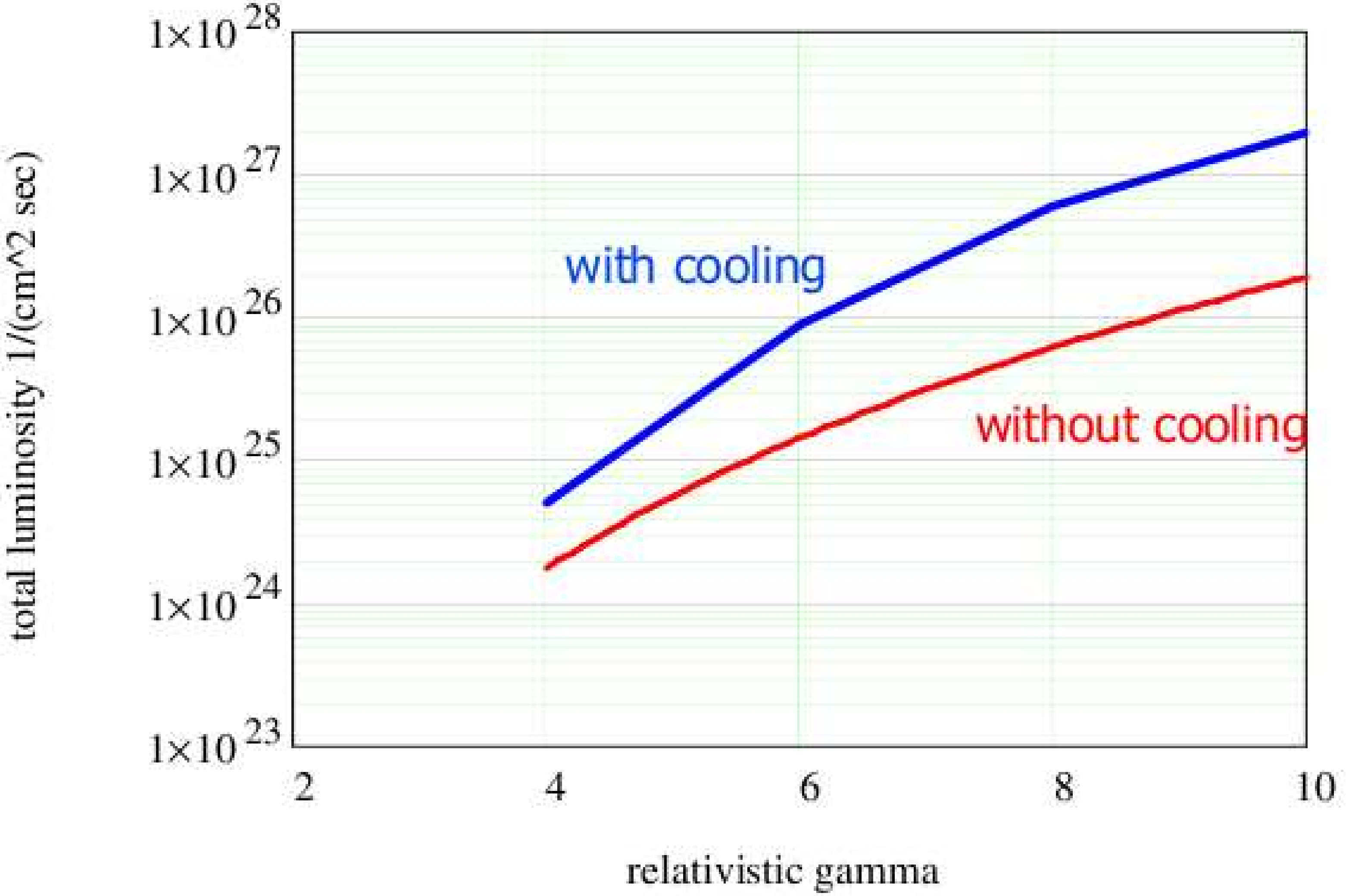
Electron cooling would counteract debunching from IBS

Improvement from electron cooling

1. Significant improvement expected at 5.75 GeV and above

2. Below 5.75 GeV
   - need larger apertures (retract collimators)
   - space charge tune shift limit at $\Delta Q_{sc} = 0.05$
   - reduce $\Delta p/p$ by using low-frequency RF system - either 9 MHz or new AGS-type 4.5 MHz cavity
   - even with the present 28 MHz system, factor 2-3 luminosity improvement seems feasible

Expected Luminosity Improvement from Electron Cooling



Challenges for electron cooling

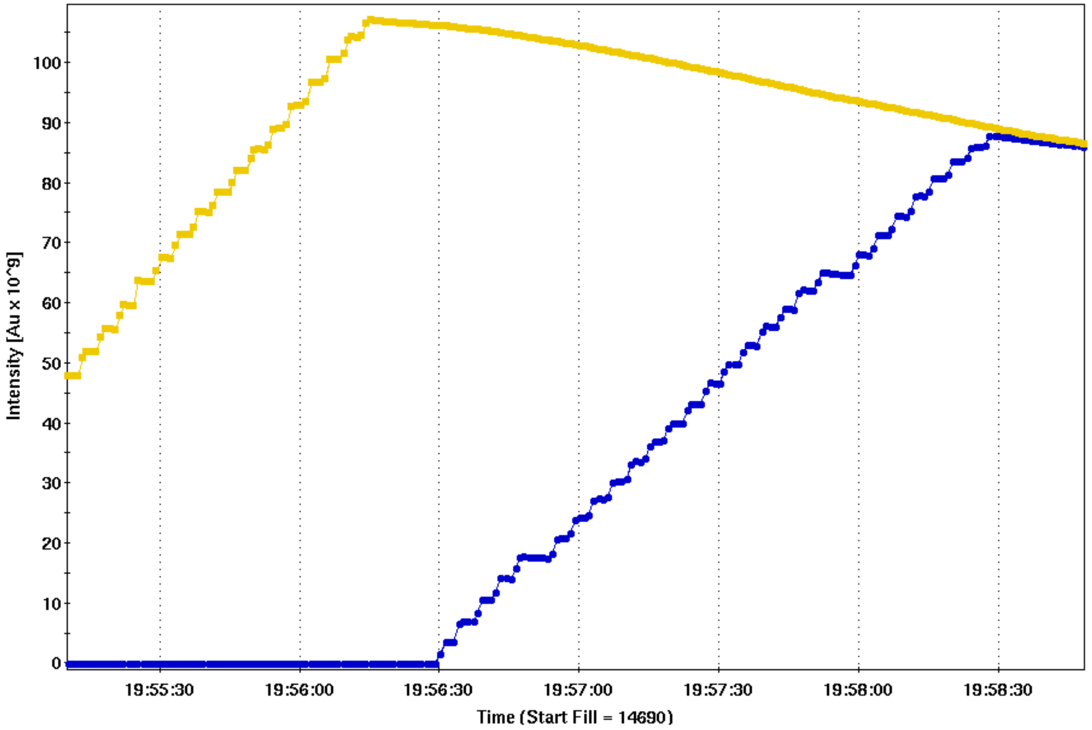
- Lower-frequency RF systems increase longitudinal IBS rates

- Need shorter cooling times to counteract

- With SRF-gun based electron cooler, cooling longer bunches requires larger number of electron bunches

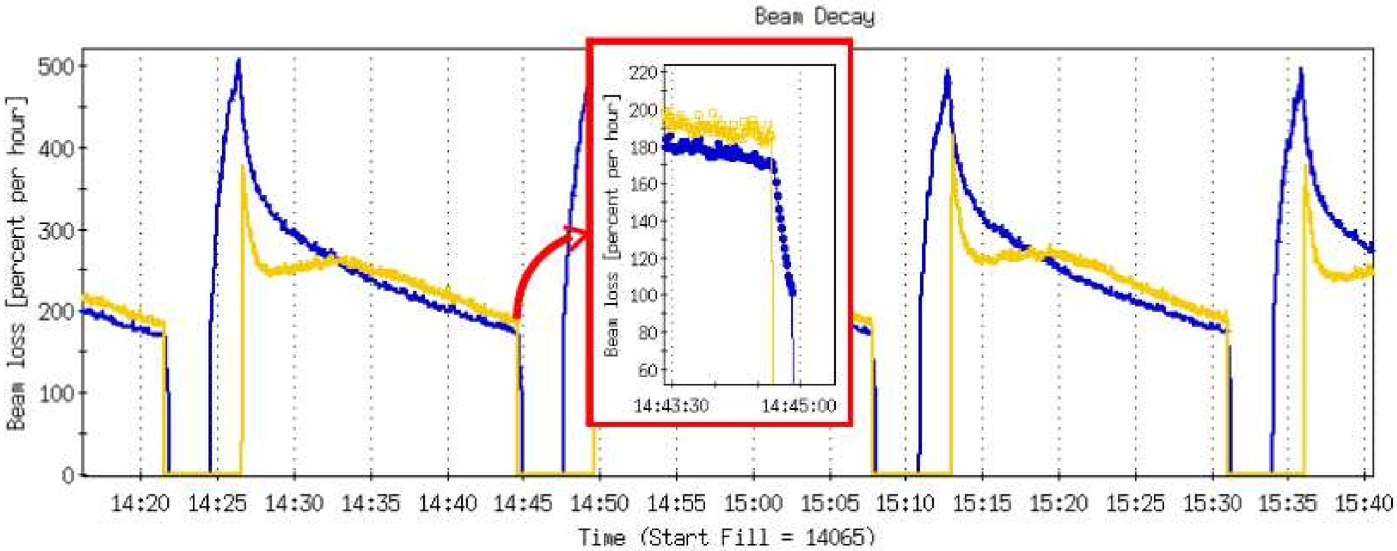
Beam-beam

Beam intensities at the start of a 5.75 GeV store



Yellow lifetime deteriorates as Blue is filled (beams are always in collision)

Beam decay rate at 5.75 GeV

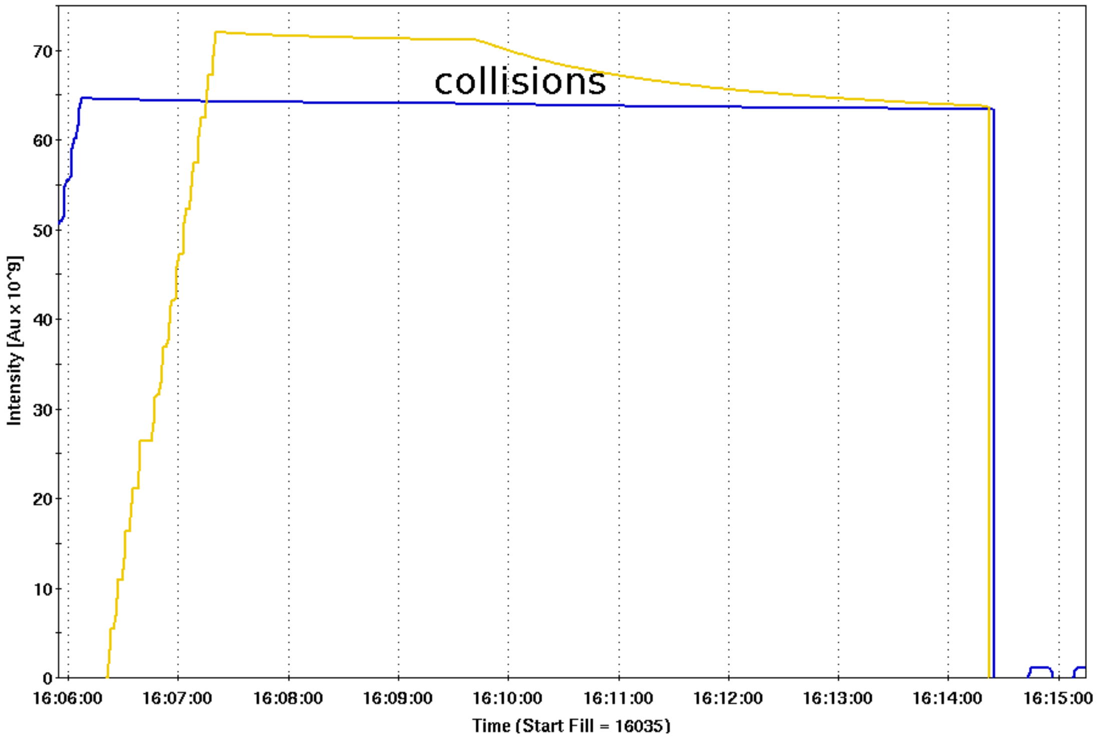


Blue beam decay improves dramatically as soon as Yellow is dumped at the end of store

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

Intensities at near-integer tunes (APEX)

Near the integer, spacing between nonlinear resonances is largest



No observable beam-beam effect in the Blue ring

Summary

- Factor 6 and higher luminosity improvement due to e-cooling seems feasible at 5.75 GeV and above, with somewhat retracted collimators, $\Delta Q_{sc} = 0.05$, and proper working point to reduce beam-beam effect
- At least factor 2-3 improvement expected at 3.85 GeV due to cooling, using low frequency RF system and/or improving (dynamic) aperture
- Understanding 2.5 GeV performance requires beam time (APEX)
- With electron cooling, BES-II would take about 20 weeks