An overview of RHIC beam-beam experiments

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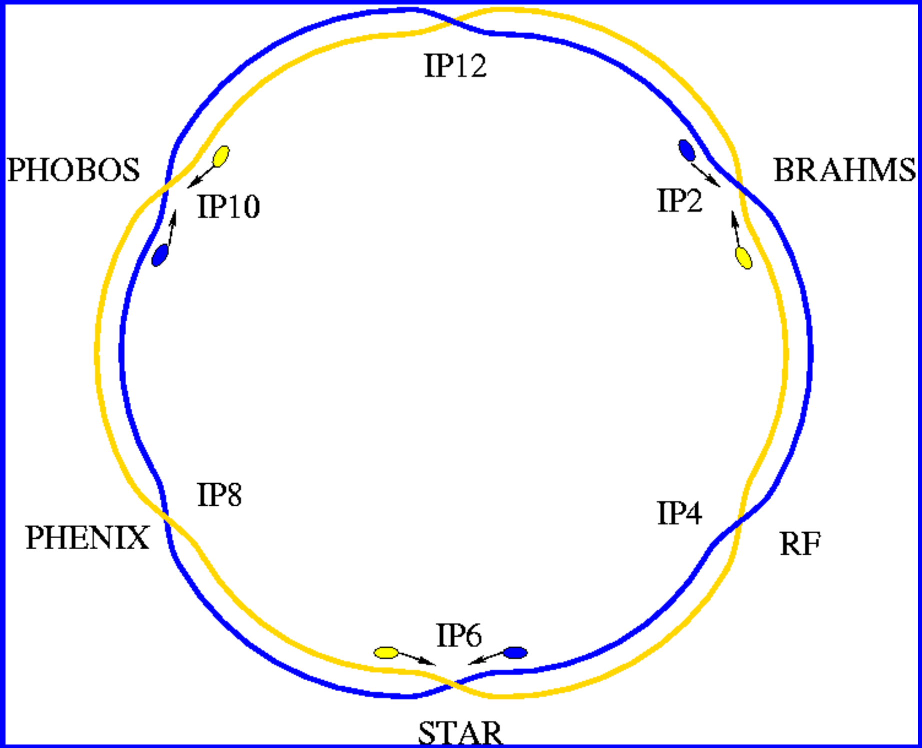
BROOKHAVEN
NATIONAL LABORATORY

CARE-HHH working meeting
LHC beam-beam effects and beam-beam compensation
28 August 2008

Outline

1. Recent polarized proton operation
   (beam-beam limited)
2. Experiments with wires
3. Other experiments
4. E-lens simulations
5. Summary

RHIC layout



– Two independent rings

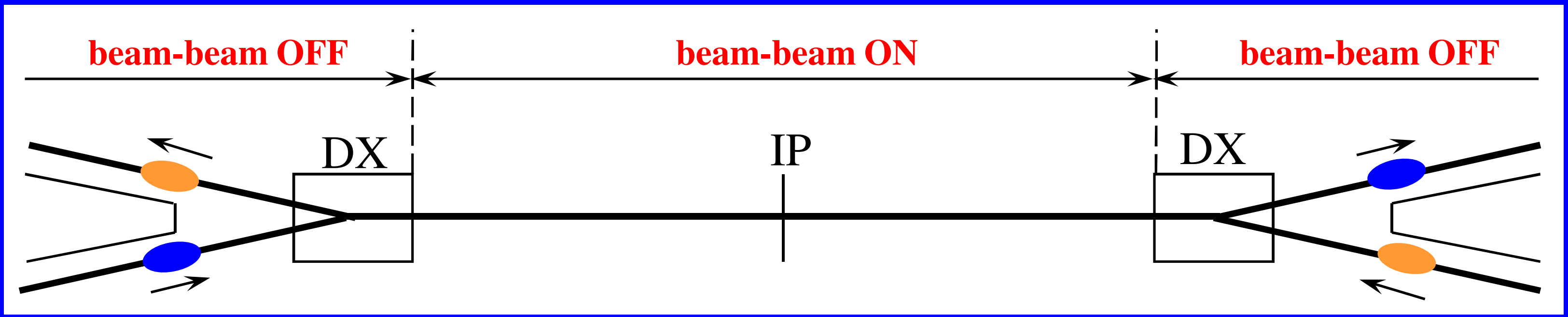
– Nominally no crossing angle

– No parasitic collisions in stores

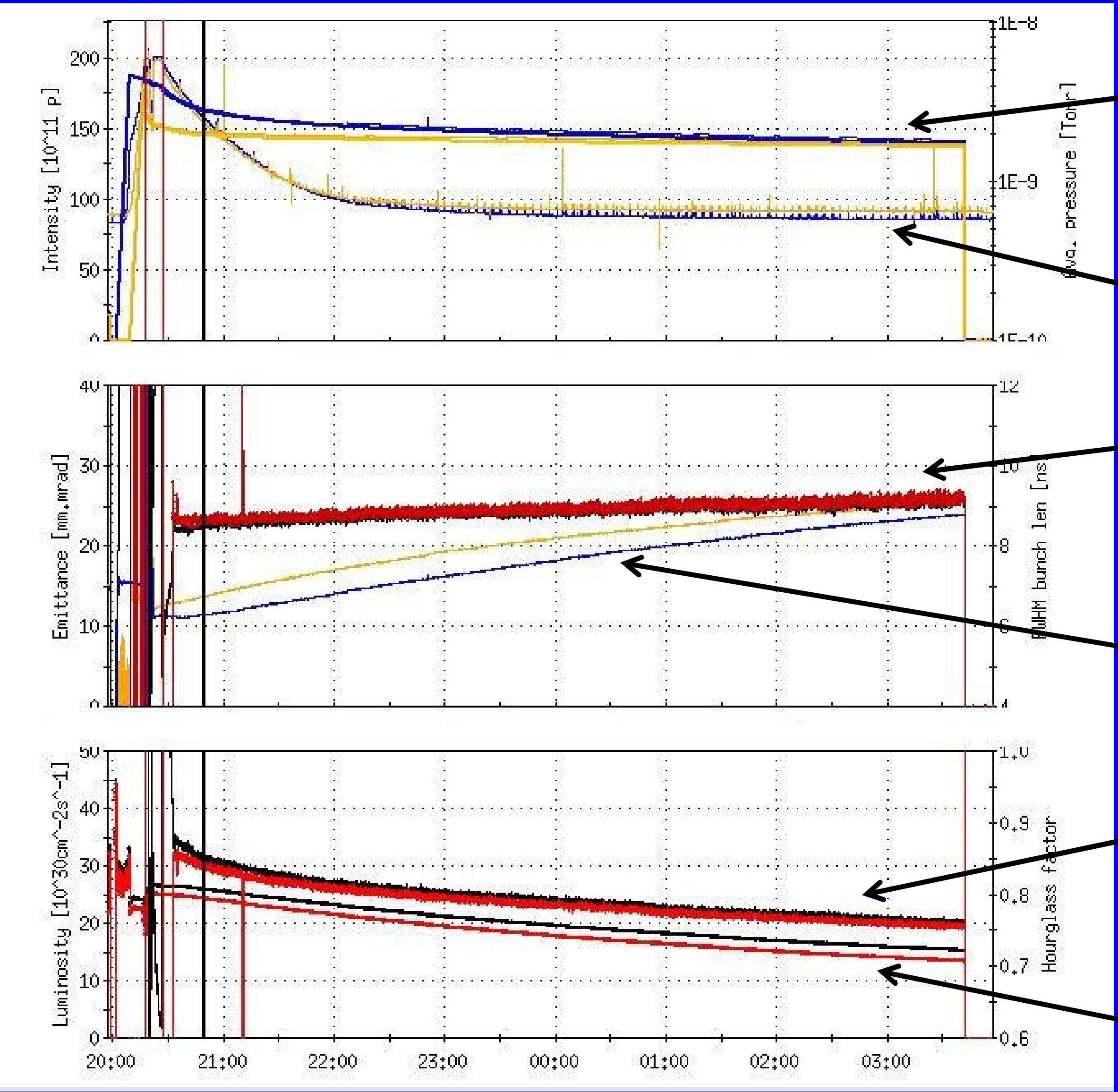
(15σ vertical separation in non-collision IPs)

– Beam-beam couples 6 bunches

(3 Blue and 3 Yellow)



2008 polarized proton performance



intensities

pressure (warm regions)

emittances

bunch lengths

luminosity

hourglass factors

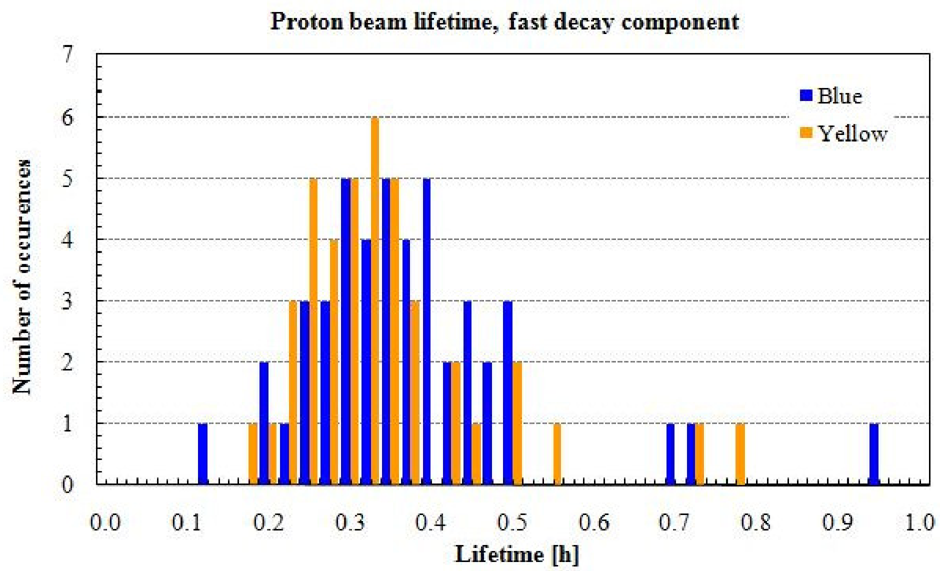
(Store 9989)

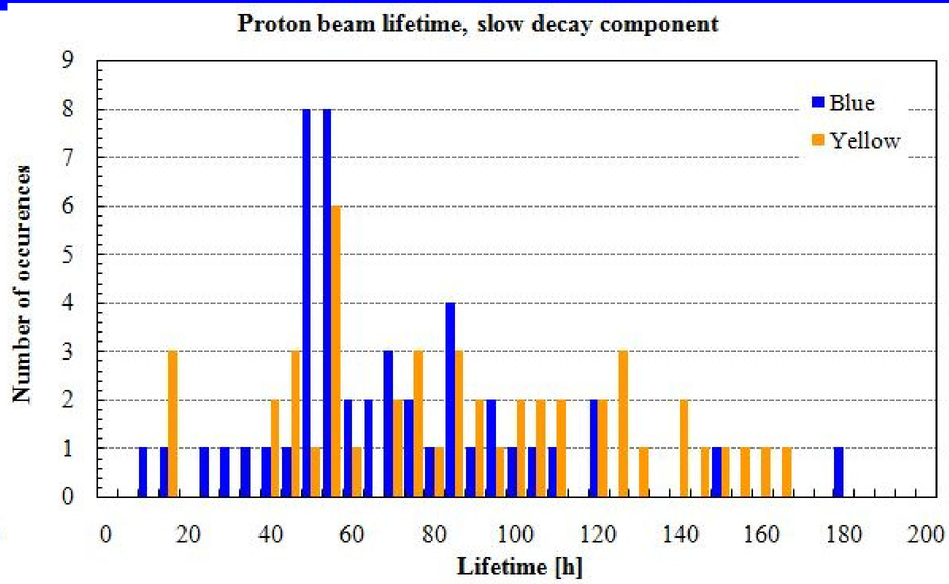
Beam lifetimes 2008

Beam intensities fitted to

$$N = A_1 \exp(-t/\tau_1) + A_2 \exp(-t/\tau_2)$$

$A_1 \approx$ 6% of (A_1+A_2)	**Blue**	$A_2 \approx$ 94% of (A_1+A_2)
3%	**Yellow**	97%
$\tau_1 \approx 0.35$ h		$\tau_1 \approx 50$ h



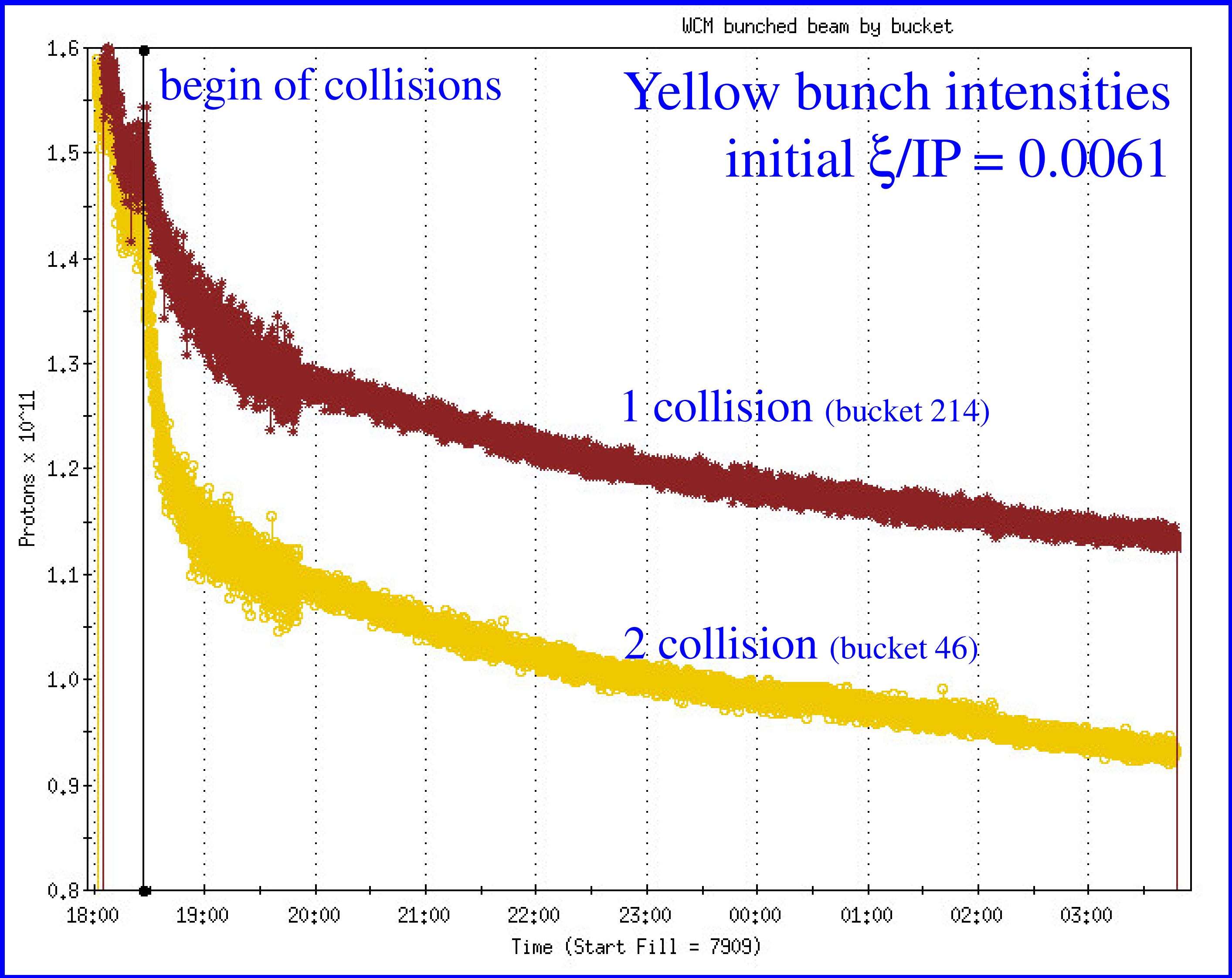


Initial beam lifetime from non-beam-beam effects is **≈700 h**

(calculated, including burn-off, residual gas interactions, IBS, elastic beam-beam).

Beam losses are dominated by beam-beam in conjunction with other effects.

Beam lifetimes with 1 and 2 collisions (2006)



Luminosity lifetimes 2006

Luminosities fitted to

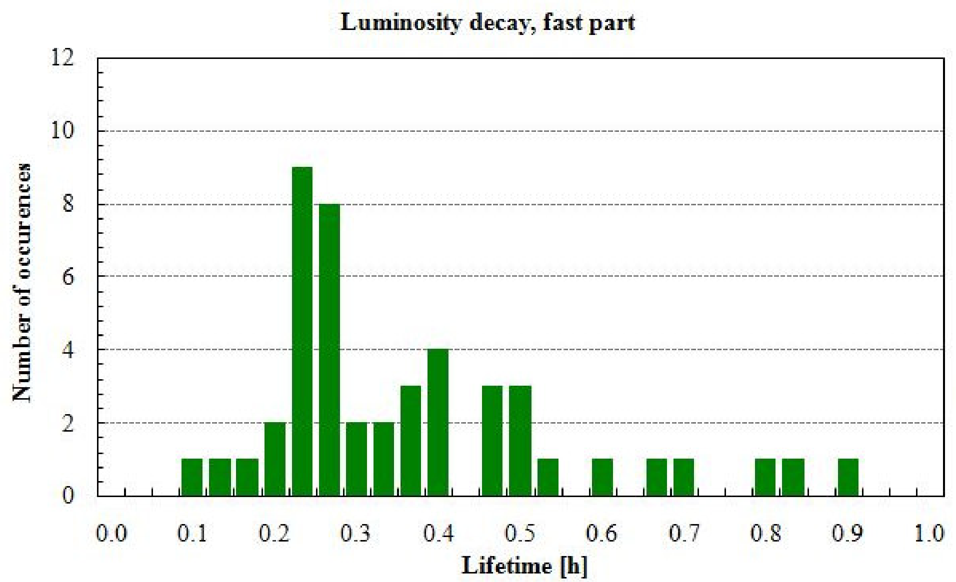
$$N = A_1 \exp(-t/\tau_1) + A_2 \exp(-t/\tau_2)$$

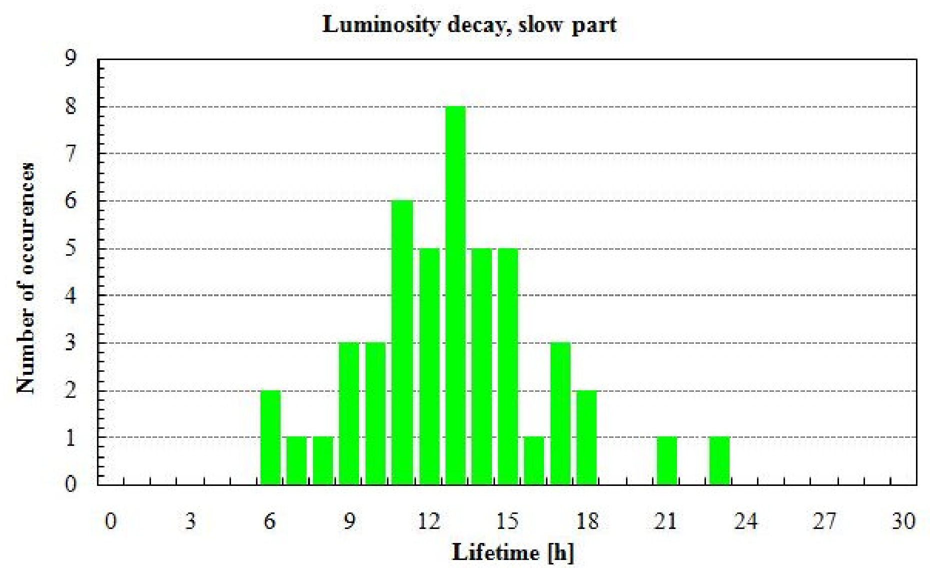
$A_1 \approx 10\%$ of (A_1+A_2)

$\tau_1 \approx 0.3$ h

$A_2 \approx 90\%$ of (A_1+A_2)

$\tau_1 \approx 12$ h





Initial luminosity lifetime from non-beam-beam effects is **≈40 h**

(calculated, including burn-off, residual gas interactions, IBS, elastic beam-beam).

Luminosity lifetime is dominated by beam-beam effects.

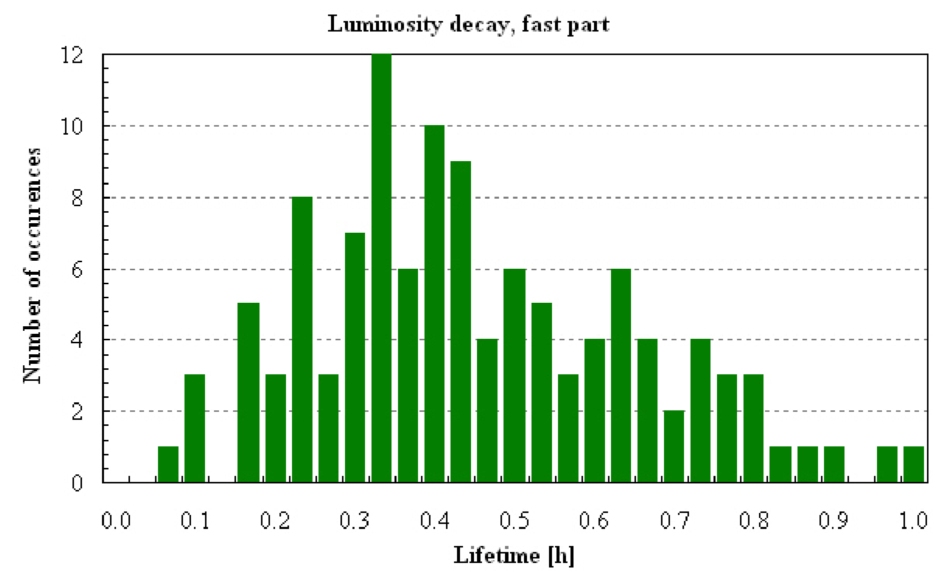
Luminosity lifetimes 2008

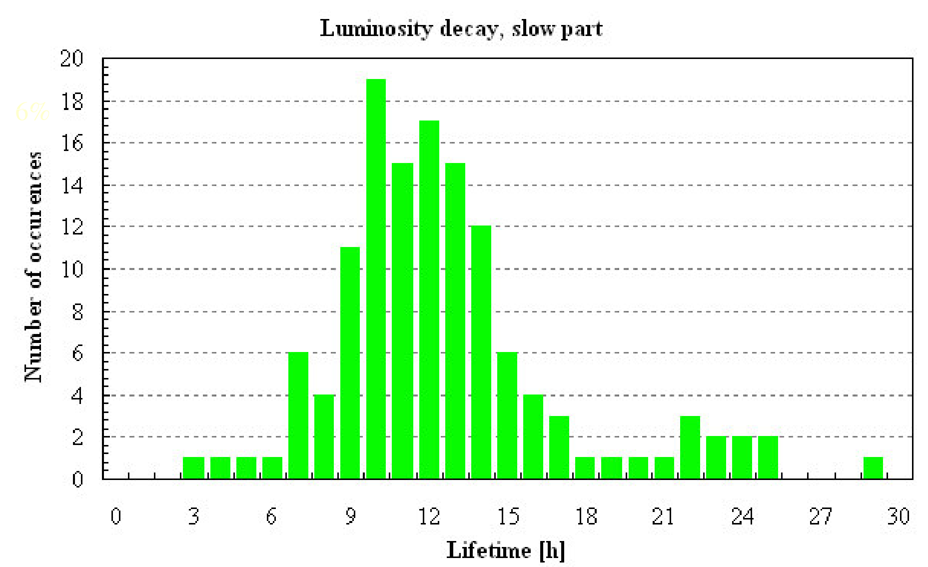
Luminosities fitted to

$$N = A_1 \exp(-t/\tau_1) + A_2 \exp(-t/\tau_2)$$

$A_1 \approx 12\%$ of (A_1+A_2)
$\tau_1 \approx 0.4$ h

$A_2 \approx 88\%$ of (A_1+A_2)
$\tau_1 \approx 12$ h





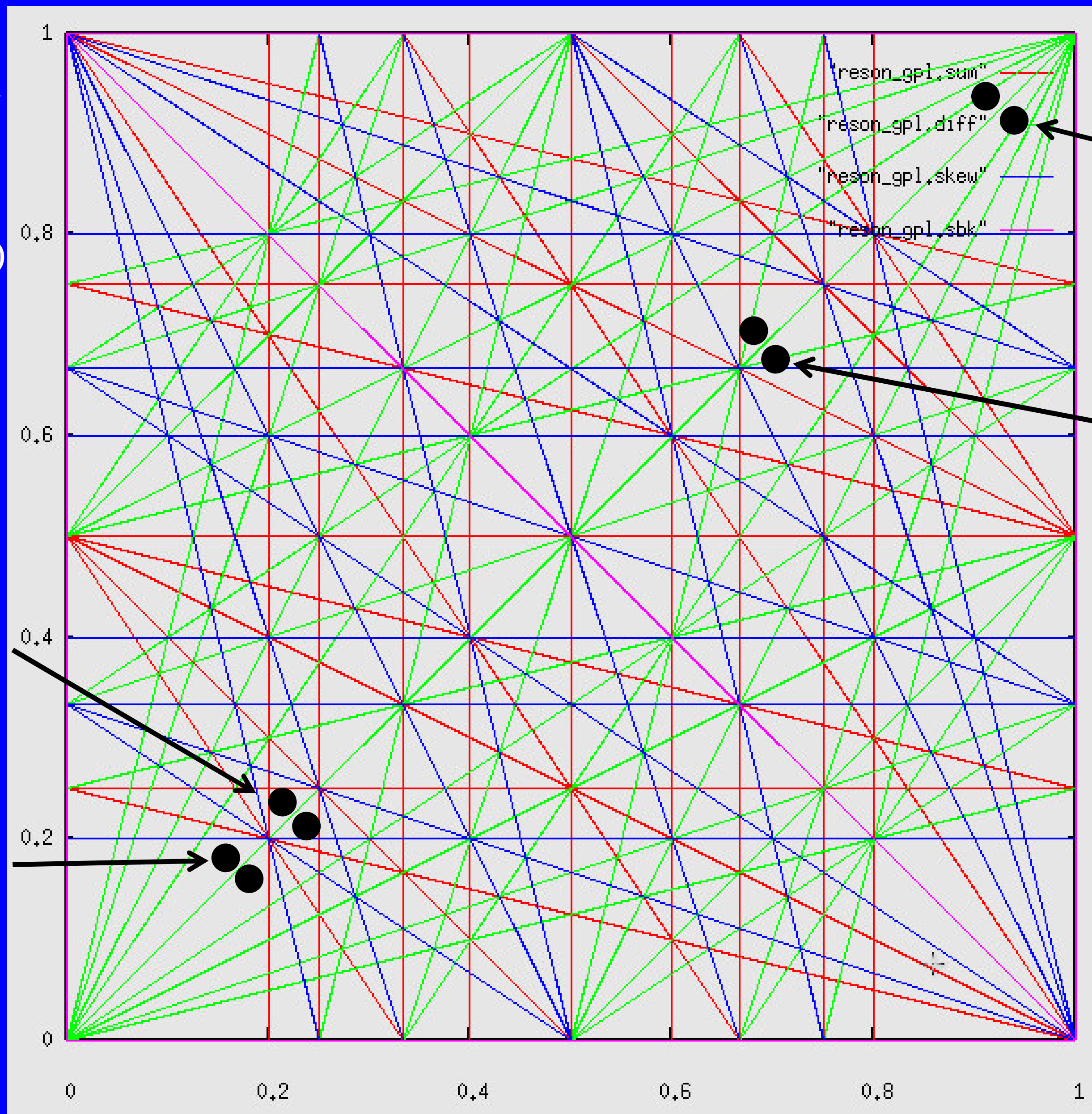
Initial luminosity lifetime from non-beam-beam effects is **≈40 h**
(calculated, including burn-off, residual gas interactions, IBS, elastic beam-beam).
Luminosity lifetime is dominated by beam-beam effects.

Polarized proton luminosity goals

Parameter	unit	**Achieved (2006/08)**	**Next $\mathcal{L}$ goals (≥2011)**
Energy	GeV	100	100 (250)
No of bunches	…	111	111
Bunch intensity, initial	10^{11}	1.5	2.0
Emittance, initial	mm.mrad	20	20
Beam-beam parameter ξ/IP	…	0.0056	0.0075
β^*	m	1.0	0.7 (0.5)
Hour-glass factor	…	0.76	0.76
Peak $\mathcal{L}$	**10^{30}cm^{-2}s^{-1}**	**35**	**90 (300)**
Average $\mathcal{L}$	**10^{30}cm^{-2}s^{-1}**	**23**	**60 (200)**
Polarization $\mathcal{P}$	**%**	**60**	**70**

RHIC tunes tested so far

ΔQ = space between limiting resonances (disregarding resonance width)



Proton tunes (4)
(0.96,0.95)
ΔQ = 0.1

Proton tunes (3)
(0.695,0.685)
ΔQ = 0.033

Ion tunes (2)
(0.235,0.225)
ΔQ = 0.022

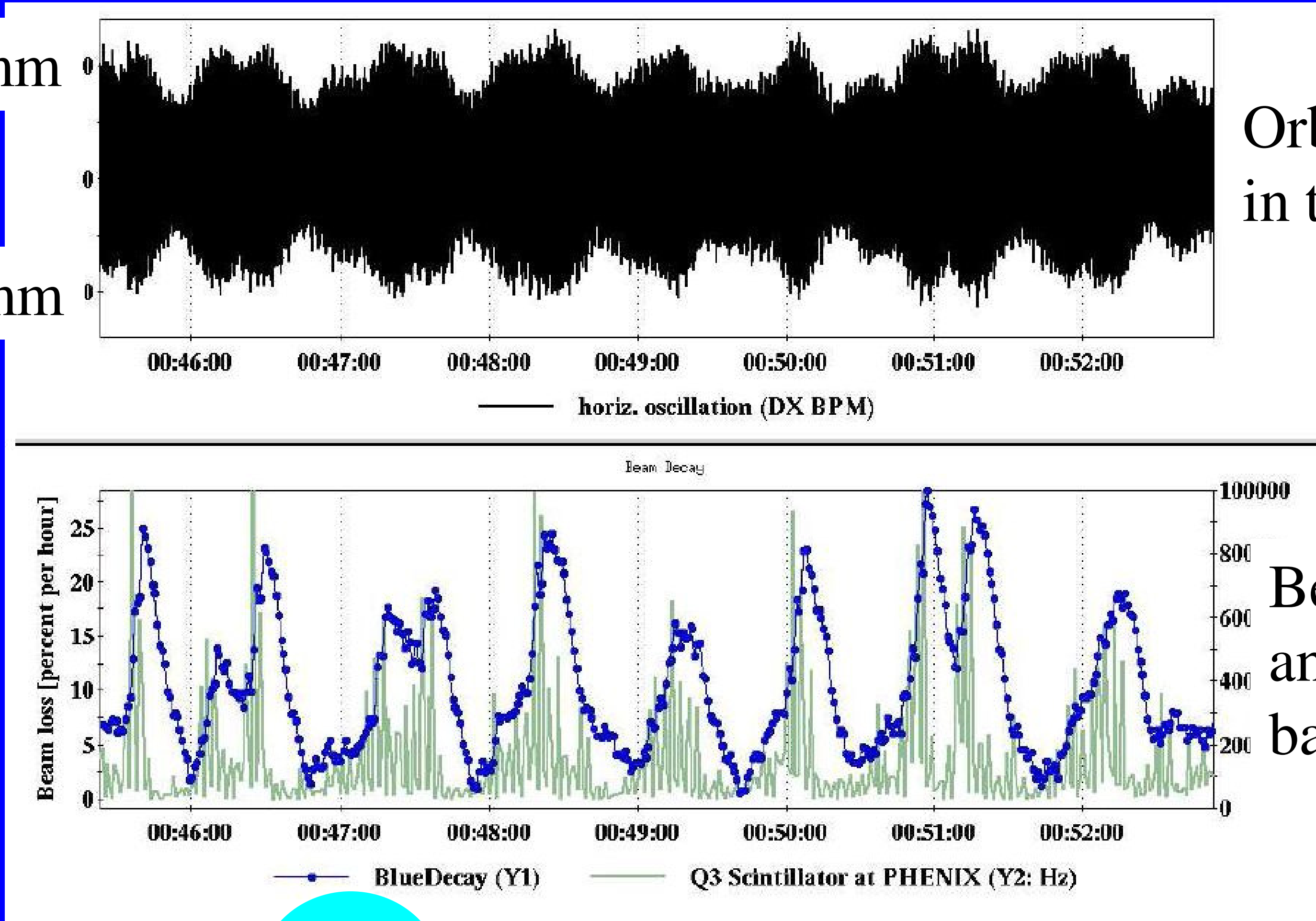
Design tunes (1)
(0.19,0.18)
ΔQ = 0.033

(also constraints from polarization)

Effect of 10 Hz triplet vibrations at near-integer WP

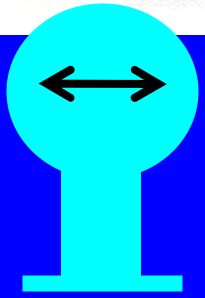
5 mm

-5 mm



Orbit motion in triplet

Beam loss rate and experimental background

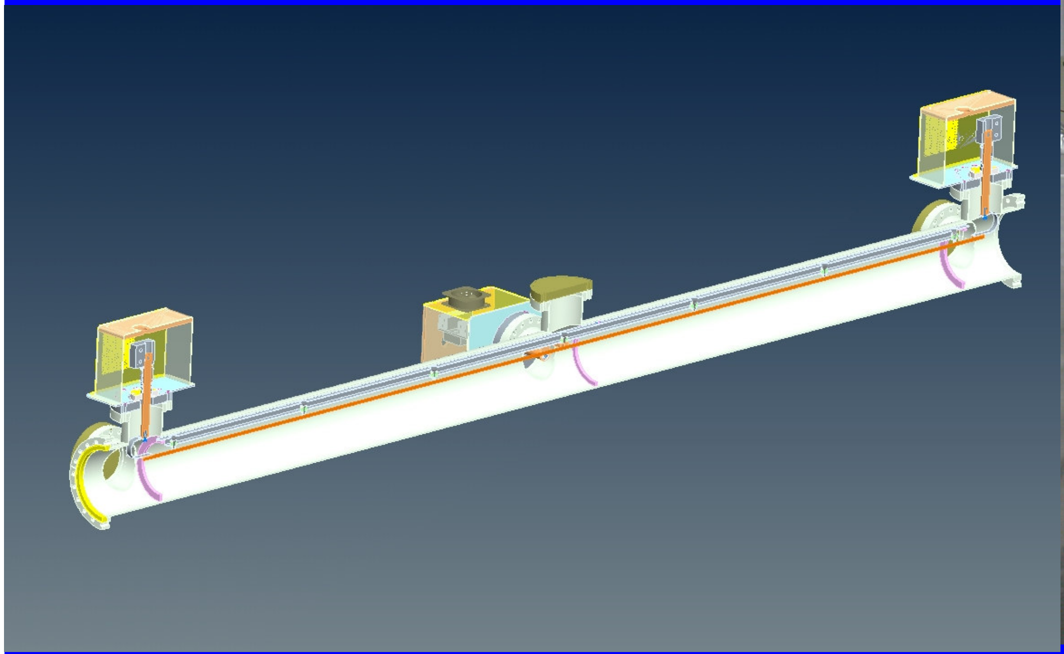


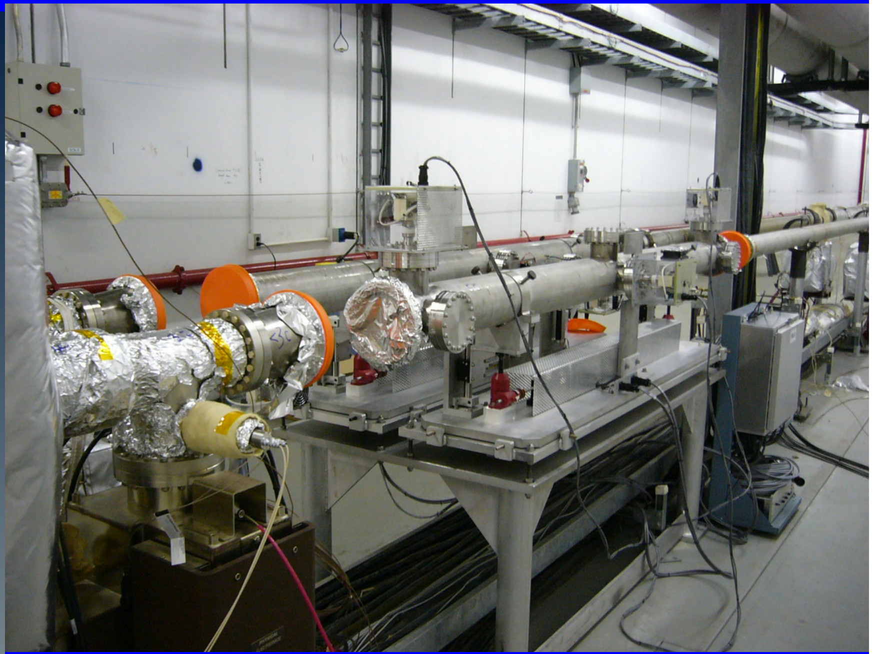
Triplet magnets are inverted pendulums with 10 Hz eigenfrequency

Cryo line decoupled, cold-mass feedback test installed this shut-down

Long-range experiments with wire

- Long-range beam-beam effects in RHIC only on ramp, possibly with upgrades
- 2 wires installed to study long-range effect (collaboration within U.S. LHC Accelerator Research Program)





Vertically movable wires, maximum integrated strength of 125Am (~13 LR interactions with $N_b=2\times10^{11}$).

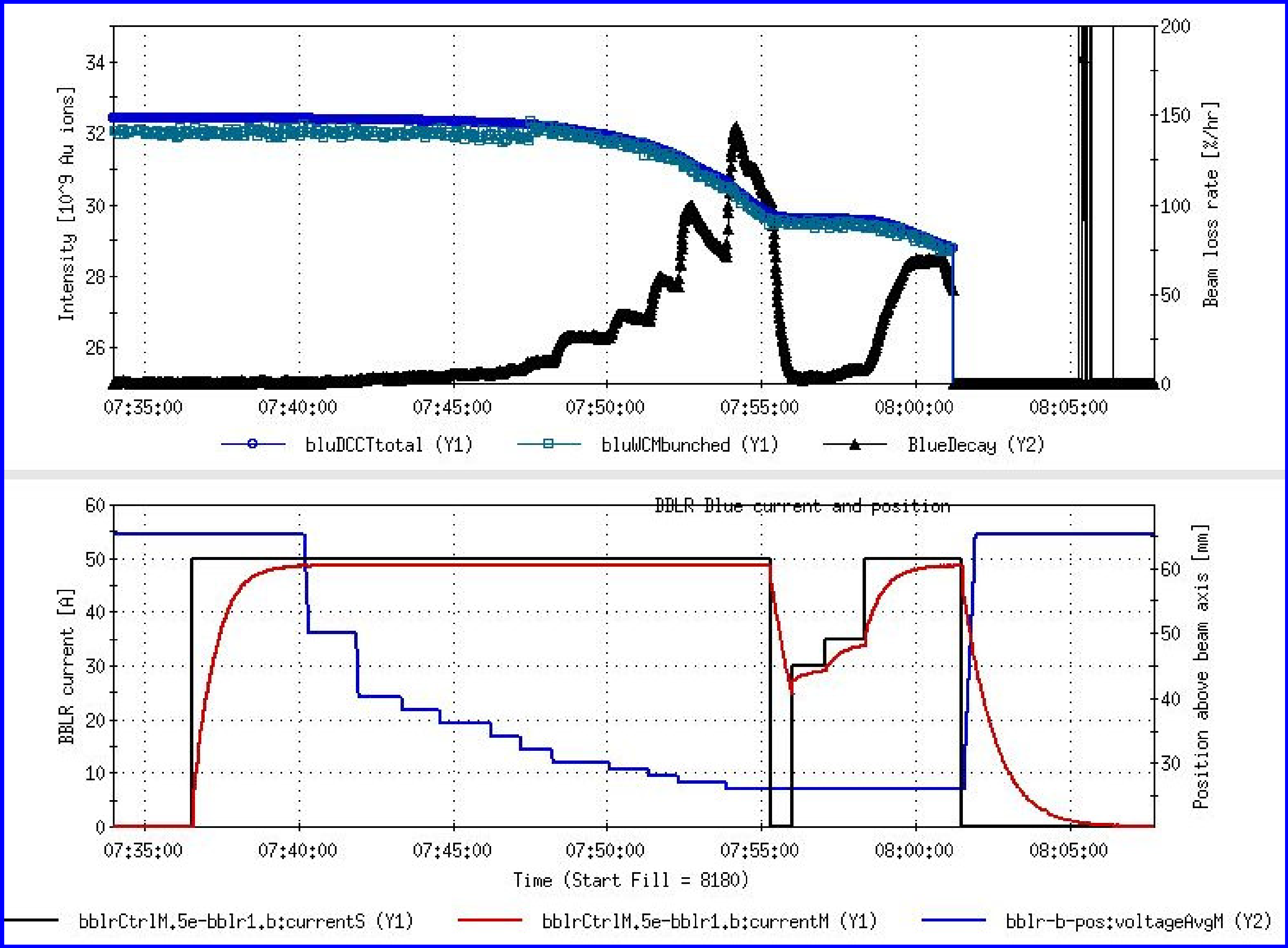
Long-range beam-beam experiments in RHIC

Measurements are

beam lifetime observations with variations in separation, strength (wire), and other parameters (tune, chromaticity)

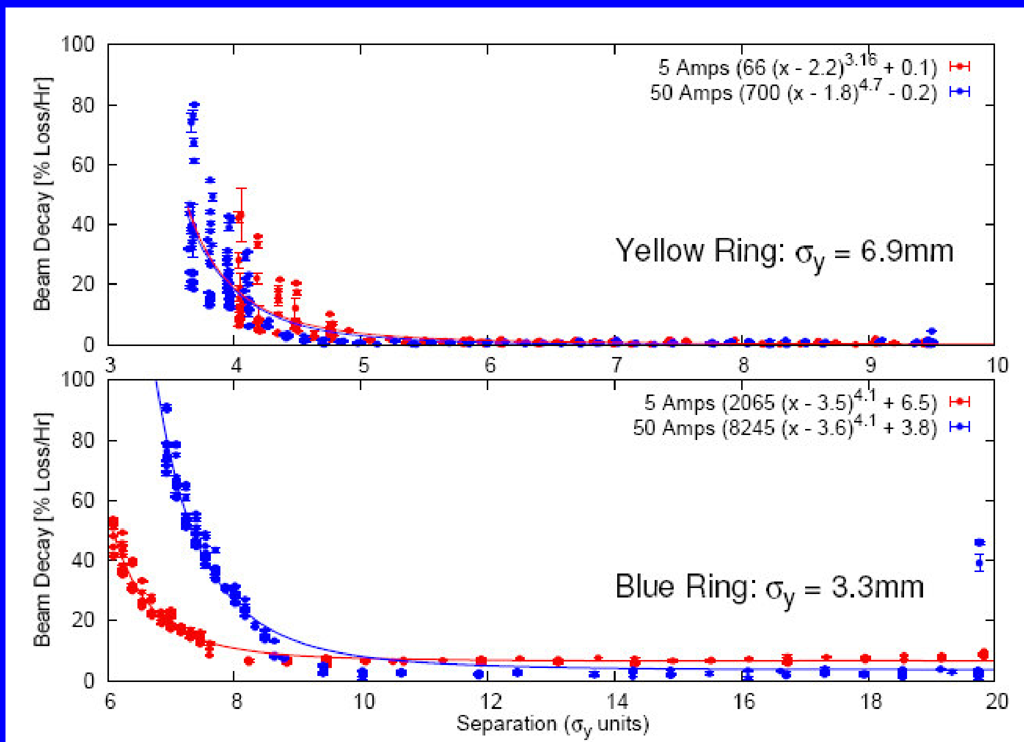
- 2005: long-range with p-beam at injection
- 2006: long-range with p-beam at store
- 2007: long-range with Au-beam & wire at store
- 2008: only (parasitic) test d-beam & wire (short p-run)
- 2009: likely to have p-beam available

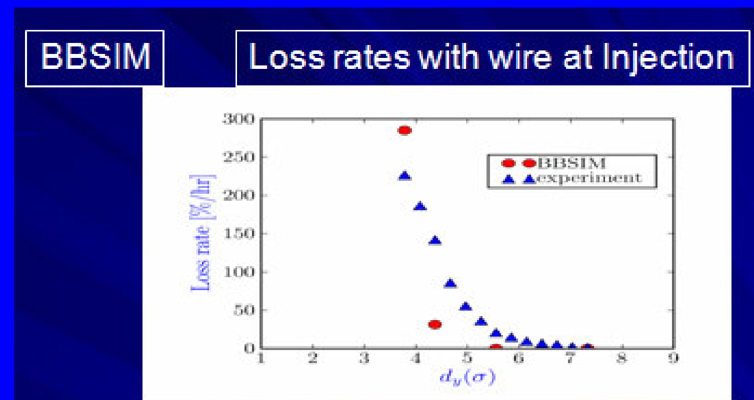
Scan with d-beam in 2008 (01/28/08, fill 9664)

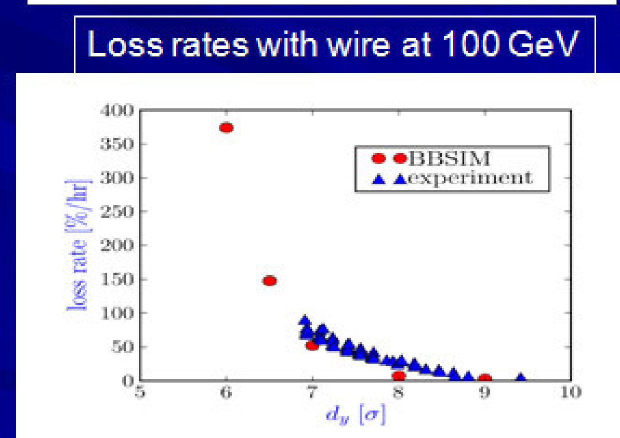


Long-range measurement and simulation

Experiments so far: distance, current and chromaticity scans with Au, for comparison with simulations





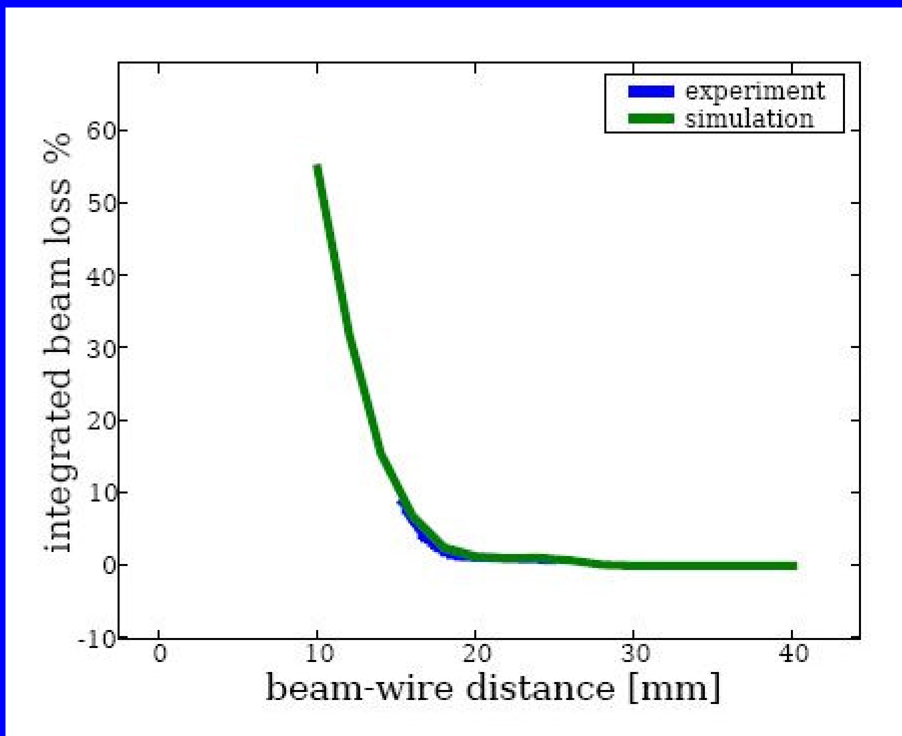


H.J. Kim, T. Sen, FNAL →

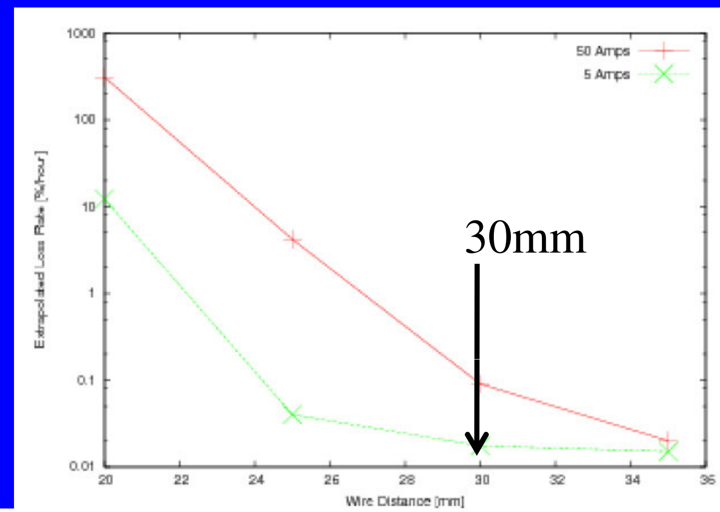
Onset of large losses reproduced within 1σ.

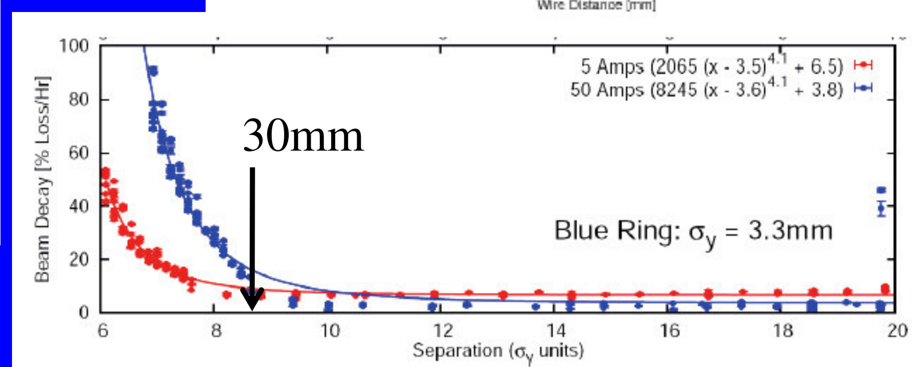
Long-range measurement and simulation

Simulation by U. Dorda for
Au beam with wire 12.5Am



Simulation by A. Kabel for
Au beam with wire 12.5 & 125Am

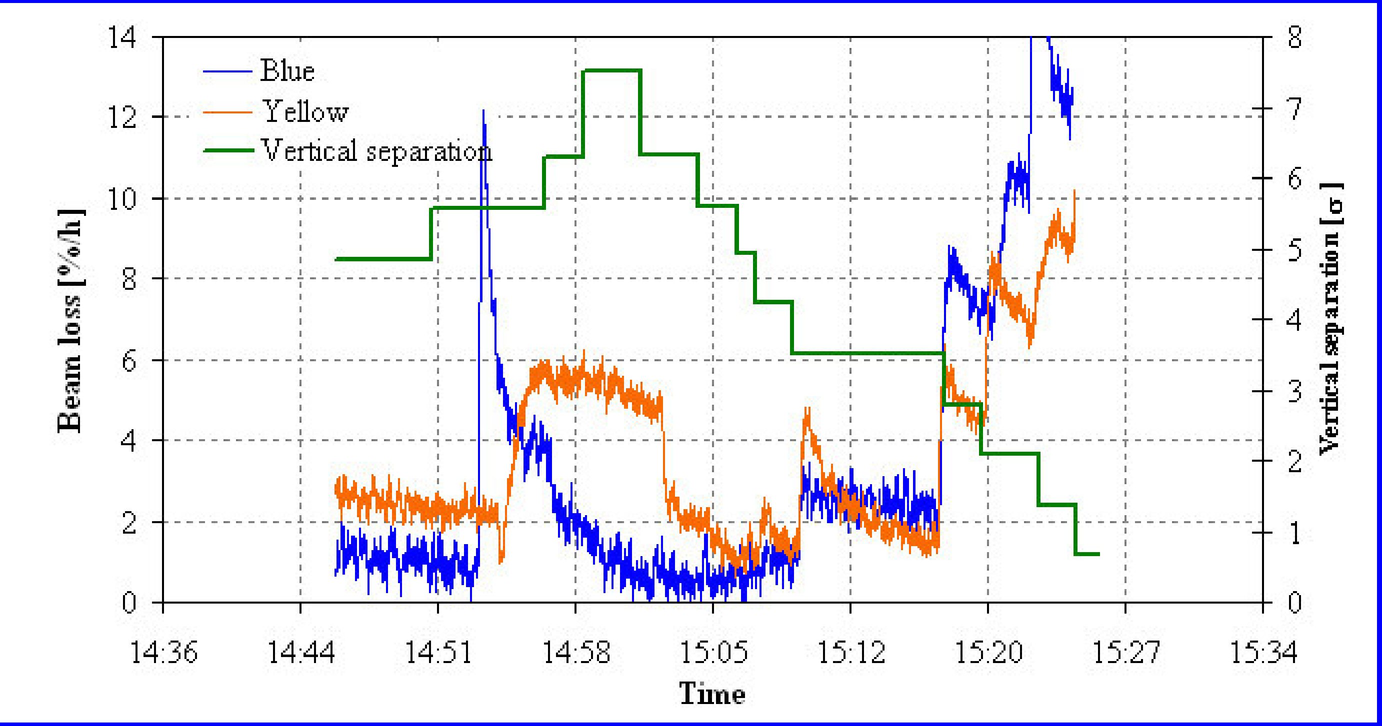




Onset of large losses reproduced within 1σ.

Minimum beam separation

Collision at s = 10.6 m, Yellow beam moved vertically (after 15:00)
Tunes B (0.739,0.727) Y (0.727,0.738)



Onset of losses from long-range interaction seen in experiments:

- at 4σ for single beam LR interaction (picture above)
- between 5-9σ with wire (strong dependence on WP and chromaticity)

[N. Abreu, "Beam-beam with a few long-range encounters at long distance", BEAM'07.]

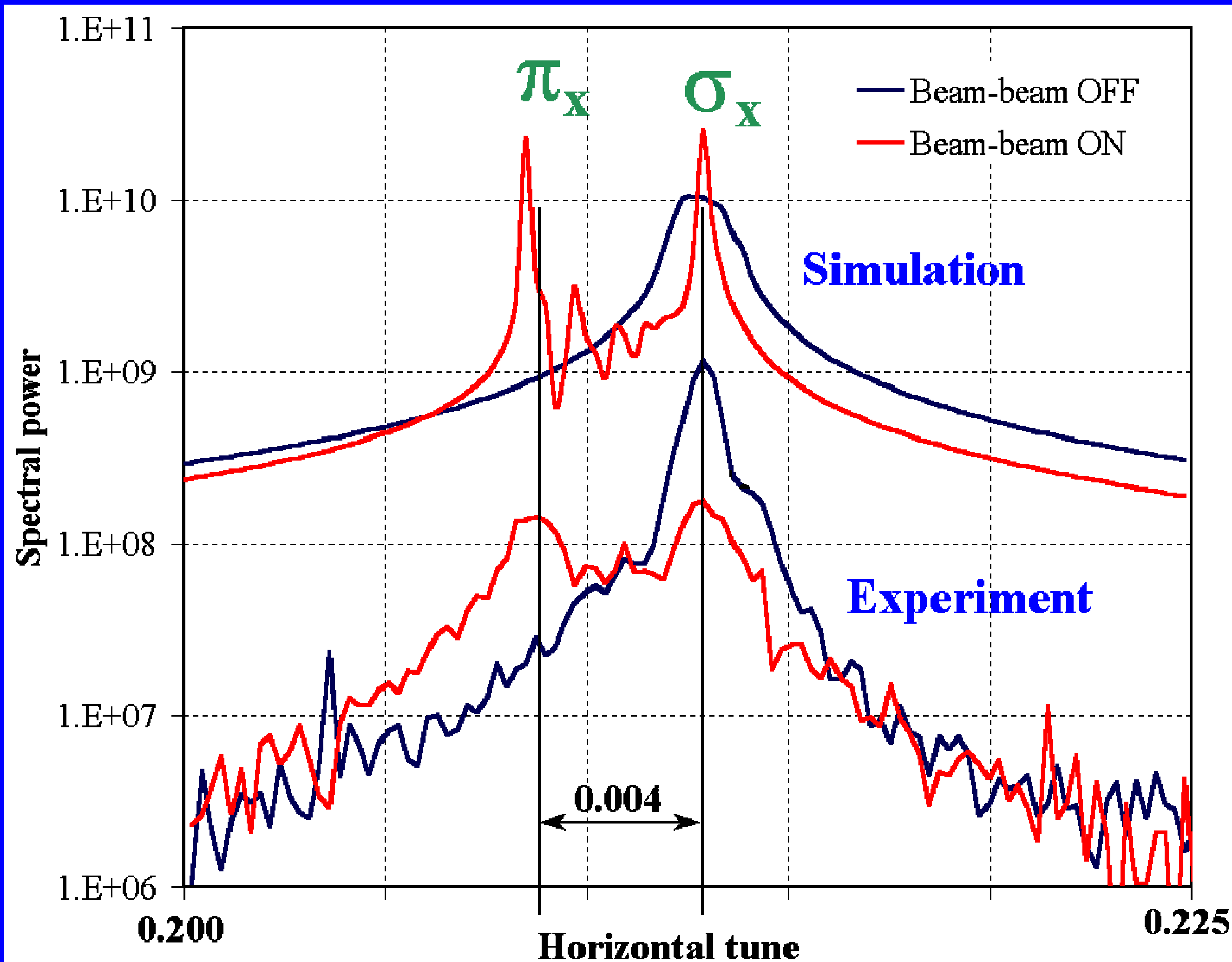
Planned test with RHIC BBLR wires in 2009

- Will ask for 3×3 hr dedicated time again
- Would like to test effect on background with protons too (parasitic)
- Parameter scans (distance, strength) with protons
  - Including head-on
  - Different working points than for Au (LHC working point mirrored at 0.5)
- Attempt to compensate one long-range interaction

Other beam-beam experiments in previous years

- Coherent π-mode generation and suppression
- Resonance driving terms with beam-beam
  (planned with AC dipole, not yet carried out)
- Lifetime and background as function of (Q_x,Q_y)
- Tunes scans at injection and new WP (R. Tomas)
- Near-integer WP (C. Montag)
- BTF measured and simulated (T. Pieloni)

Coherent effects – π– and σ–modes with excitation



Experiment:
- single p bunch/ring
- **ξ = 0.003**
-$|Q_{x,B}–Q_{x,Y}| < 0.001$

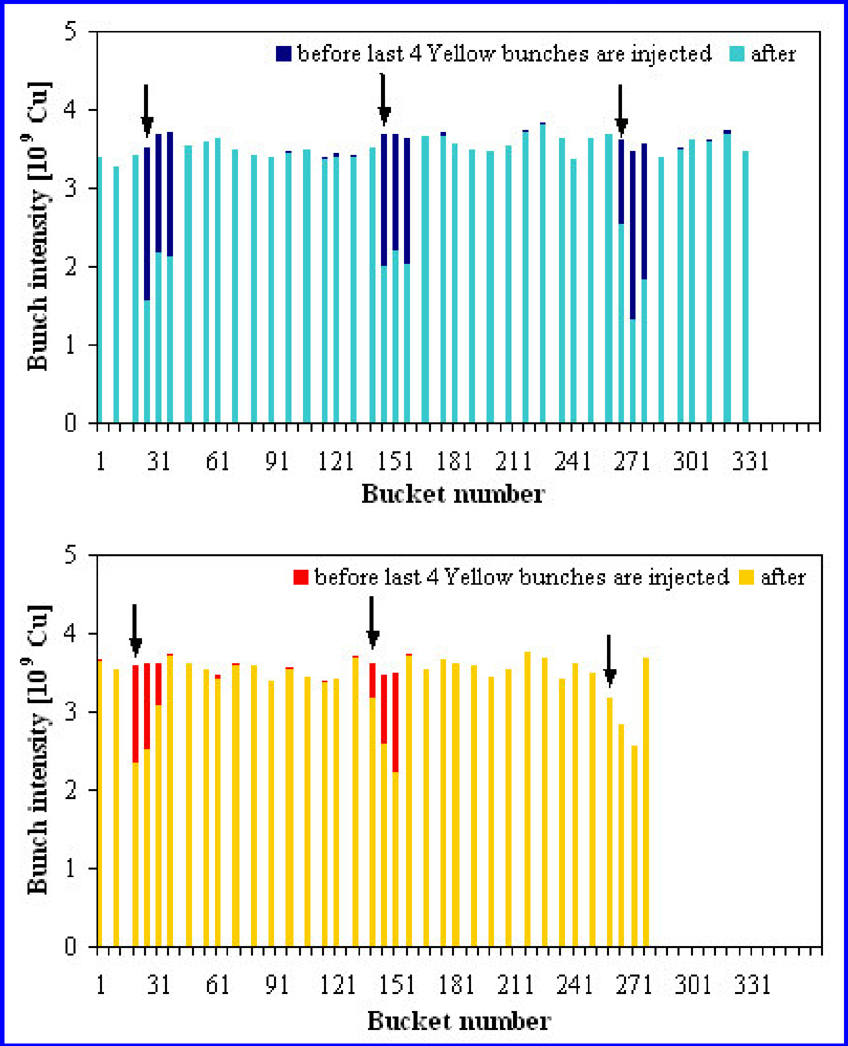
Observation:
- π_x-mode shift: 0.004
- expectation:
  $1.21 \cdot \xi = 0.0036$
  [Yokoya, Meller, Siemann]

[Simulation: M. Vogt et al., DESY, “Simulations of coherent beam-beam modes at RHIC”, EPAC02]

Coherent effects – bb coupled bunches unstable

- Instability triggered by strong-strong beam-beam interaction with Cu^{29+} at injection (right)
- Also observed with Au^{79+} at low energy, possibly with p
- Can be suppressed with tune and chromaticity changes
- Not an operational problem currently, but keep Blue and Yellow tunes apart as a precaution

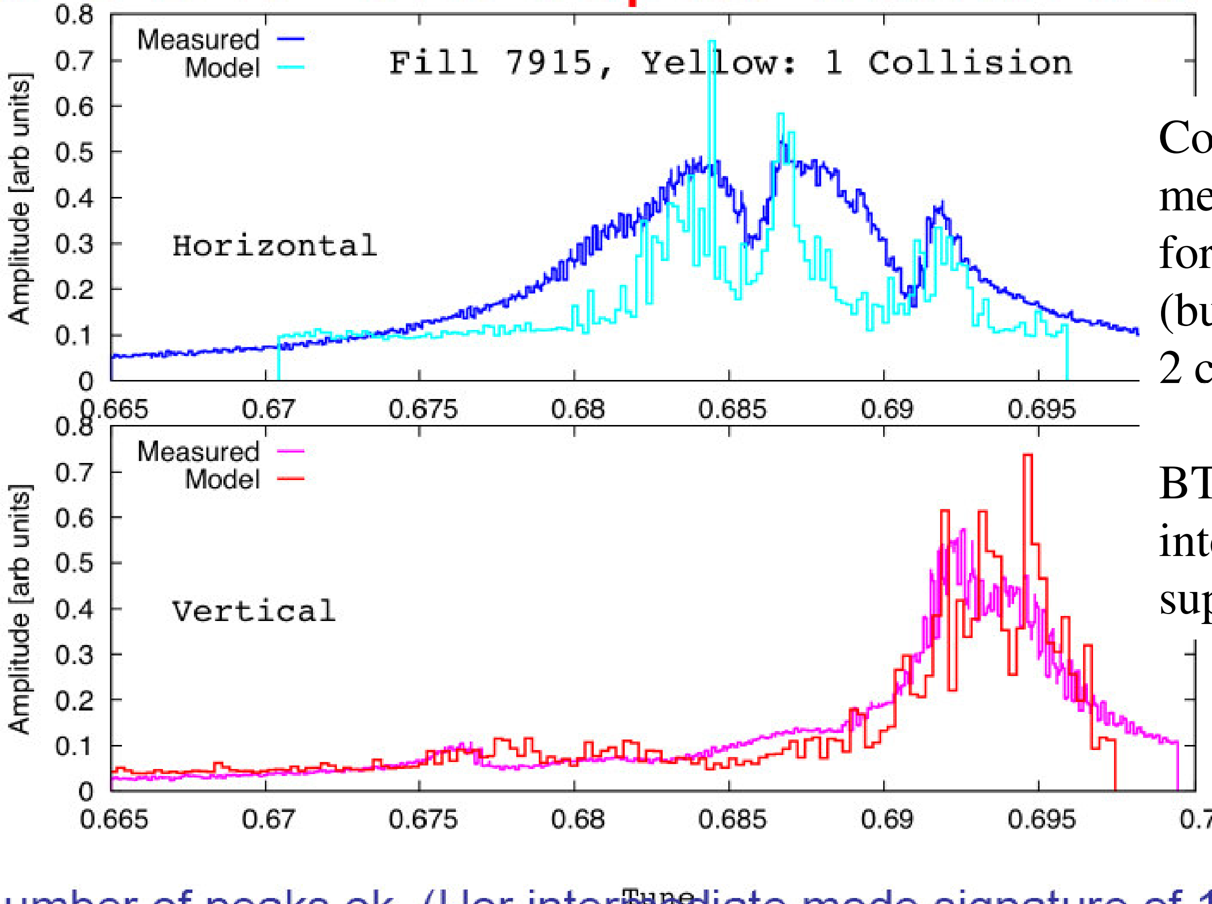
Bunch intensity before and after last 4 bunches are injected.



Observation of tune distributions with BTFs

Simulations with COMBI by T. Pieloni, EPFL/CERN

MPS BTF ON: SuperPacman bunch



Comparison between measurement and simulation for super-pacman bunches (bunches with only 1, not 2 collisions)

BTF detector sees most intense bunches, i.e. super-pacman bunches

1) Number of peaks ok, (Hor intermediate mode signature of 1 HOcoll)
2) Location of peaks ok, (tune distribution shift to higher freq)

BB & e-lens simulations in US

- **BNL**
  Y. Luo, N. Abreu, W. Fischer,
  G. Robert-Demolaize, C. Montag
- **FNAL**
  H.-J. Kim, T. Sen, A. Valishev
- **LBNL**
  J. Qiang
- **SLAC**
  A. Kabel

E-lens simulation Lyapunov map (Y. Luo)

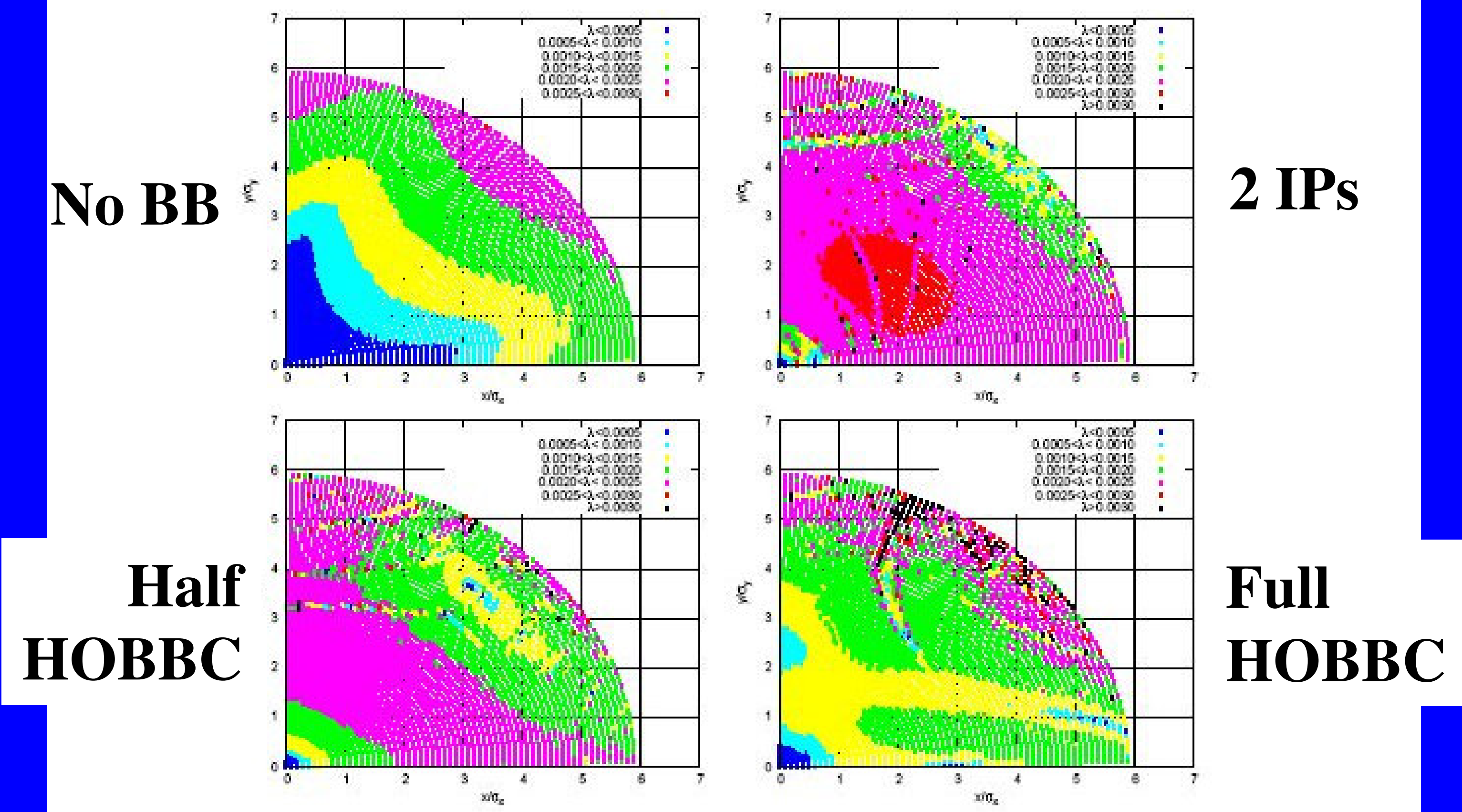


Figure 7: Lyapunov exponent maps of on-momentum particles for working point (28.685, 29.695): Top-left: without BB; Top-right: with BB; Bottom-left: with BB and half BB compensation; Bottom-right: with BB and full BB compensation.

Y. Luo, W. Fischer, and N. Abreu, **"Stability of single particle motion with head-on beam-beam compensation in the RHIC"**, BNL C-A/AP/310 (2008), also EPAC08.

(My) conclusions from e-lens simulations so far

1. Established methods used to evaluate magnet errors fail for electron lenses:
   - All particles are chaotic (i.e. no chaotic boundary)
   - DA not a good measure for bb since bb force becomes small at large amplitudes

2. None of the short-term evaluations gives a reliable answer for long-term behavior
   - Tune footprints, tune diffusion maps and Lyapunov exponent maps

3. Simulations generally show improvements in particle behavior below 3σ and deterioration above 4σ
   - not clear if this is acceptable in reality

(My) conclusions from e-lens simulations so far

4. Emittance growth is too noisy in simulations and not useful as a figure of merit

5. Electron lens benefits should be evaluated with beam lifetime simulations

6. Beam lifetimes can be simulated
   - over a few minutes with standard tracking models and large numbers of particles (BOINC, **many thanks to E. McIntosh and F. Schmidt**)
   - over longer periods with other models (LIFETRAC, diffusion models)

7. Beam lifetime simulations must be
   - benchmarked with measurements
   - tested for robustness of results due to small parameter changes (for example phase advance between IP and e-lens)

Summary

- Recent proton operation (2006/08) with
  - $\mathcal{L}_{peak} = 35\times10^{30}cm^{-2}s^{-1}$ and $\mathcal{L}_{avg} = 23\times10^{30}cm^{-2}s^{-1}$
  - ξ/IP = 0.006 and $\Delta Q_{bb,tot} = 0.012$
  - Luminosity lifetime of 12 h, dominated by bb effects
- Long-range experiments
  - Beam lifetime measurements with p-beam and wire still outstanding
  - Onset of large losses reproduced within 1σ for a number of measurements and with different programs
  - Onset of losses from long-range interaction seen in experiments:
    - at 4σ for single beam LR interaction
    - between 5-9σ with wire (strong dependence on WP and chromaticity)
- E-lens simulations are under way
  - Methods used to evaluate magnets not usable
  - Need to rely on beam lifetime simulations (covering a few minutes real time)