The Luminosity Upgrade at RHIC
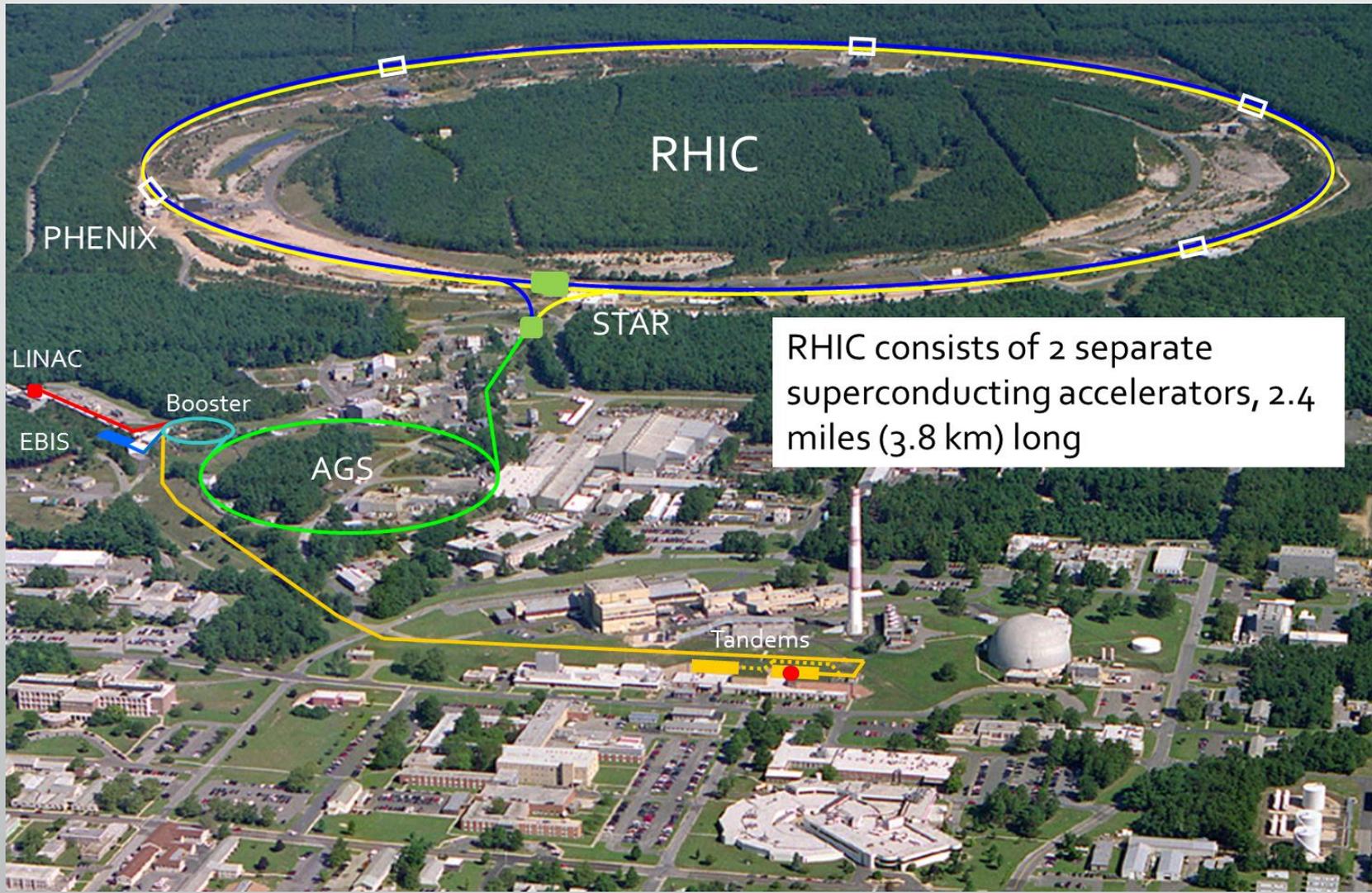
G. Robert-Demolaize, Brookhaven National Laboratory

- RHIC accelerator complex:

RHIC consists of 2 separate superconducting accelerators, 2.4 miles (3.8 km) long

- The Relativistic Heavy Ion Collider (RHIC) aims at recreating the quark-gluon plasma and study the rare processes R of cross-section σ_p associated with it:

$$\frac{dR}{dt} = L\,\sigma_p\,, \qquad L = \frac{N_1 N_2 f N_b}{4\pi\sqrt{\beta_x^* \epsilon_x}\sqrt{\beta_y^* \epsilon_y}}\;.$$

- For rare events, σ_p is usually very small therefore the luminosity L needs to be maximized, which requires:

  - increased per-bunch intensity;

  - beam lifetime dominated by burn-off;

  - smaller beam size at the interaction point (IP).

- Run7 marked the first efforts towards the **RHIC-II Upgrade** with the implementation of components aimed at improving the design average store luminosity by a factor of 20.

- Run14 featured the completion of the Upgrade: average store luminosities have been improved by a factor of 25 from Run4, reaching a **consistent L = 50.0x10^{26}cm^{-2}s^{-1}** while keeping the beams for physics for twice as long.

- Recent Performance Overview:

	Species	N_b	Intensity [10^9]	β* (IR6/8) [m]	ϵ_{rms} [μm]	L_{peak} [10^{26} cm^{-2}s^{-1}]	L_{avg} [10^{26} cm^{-2}s^{-1}]	L_{week} [μb^{-1}]	Store Length [h]
Design	A-A	55	1.0	2.0	2.5 → 6.7	9	2	50	
Enhanced	A-A	111	1.0	1.0	2.5 → 6.7	30	8	300	
Run4	Au-Au	45	1.1	1.0	2.5 → 6.7	15	5	160	5.0
Run7	Au-Au	103	1.1	0.83 / 0.77	2.8 → 5.8	30	12	380	5.0
Run10	Au-Au	111	1.1	0.75	2.8 → 3.3	45.3	20.0	670	4.0
Run11	Au-Au	111	1.3	0.75	2.5 → 1.7	52.6	30.0	1000	4.0
Run12	Cu-Au	111	4.0 / 1.3	0.7	4.1 → 1.2	120.0	100.0	3500	14.0
	U-U	111	0.3	0.7	2.2 → 0.4	8.8	5.6	200	7.5
Run14	Au-Au	111	1.6	0.7 → 0.5	2.5 → 0.65	84.0	50.0	2200	10.0

- The following reviews the upgrades brought to all three tiers of RHIC's activities: machine hardware, lattice design and operational efficiency.

INJECTORS
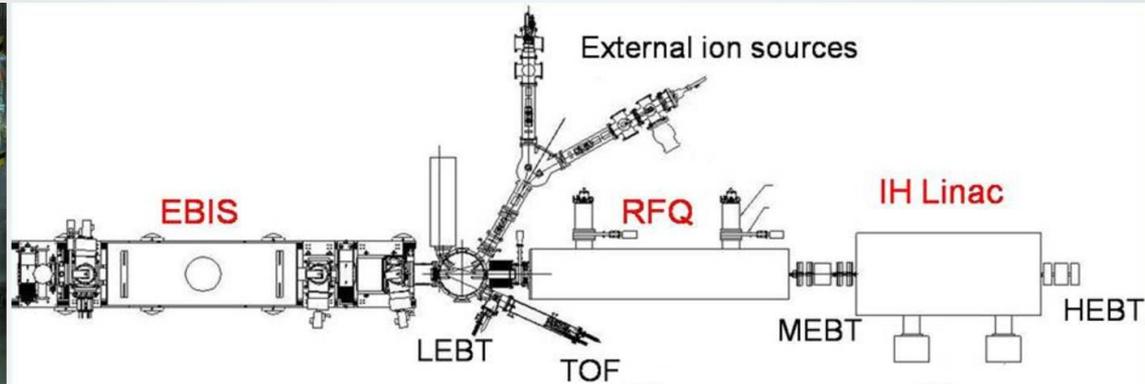
Courtesy of J. Alessi

- A new Electron Beam Ion Source (EBIS) followed by an RFQ and a short linac is now used instead of the Tandem Van de Graaf. It allows switching rapidly between various ion species while still providing high per-bunch intensities.

- Successfully commissioned in 2010 and has since delivered beams to both RHIC and the NASA facility without slowing down operations for either programs.

- The ion species other than Au that have been used for RHIC physics are (to date) Cu, U and ^{3}He.

STOCHASTIC COOLING
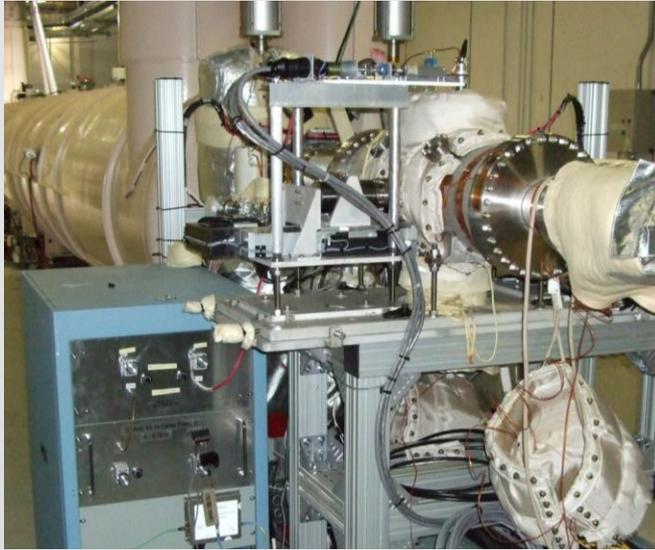
Courtesy of K. Mernick

- Main limitation to luminosity lifetime: emittance blowup from intrabeam scattering.

- The RHIC Stochastic Cooling system was designed to counter this mechanism and reduce the beam emittance: for each of the three planes of motion, it uses a pickup (left) and kicker magnet (right) pair separated by a multiple of π/2 phase advance.

- Installed in stages: longitudinal in Run7, vertical in Run10, full system in Run11.

    Reference: M.Blaskiewicz,J.M.Brennan,and K.Mernick,Phys.Rev. Lett. 105, 094801(2010)

STOCHASTIC COOLING

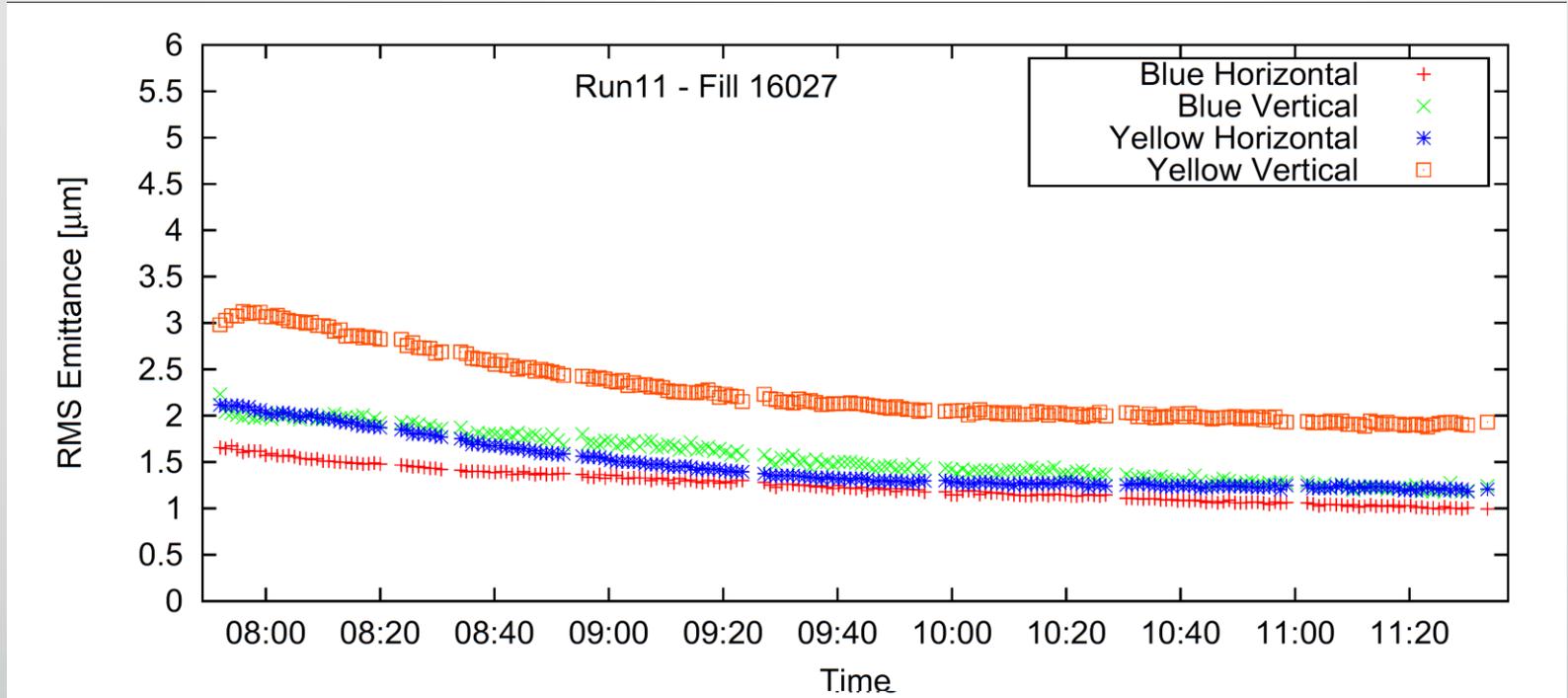- Schematic view of the installation:
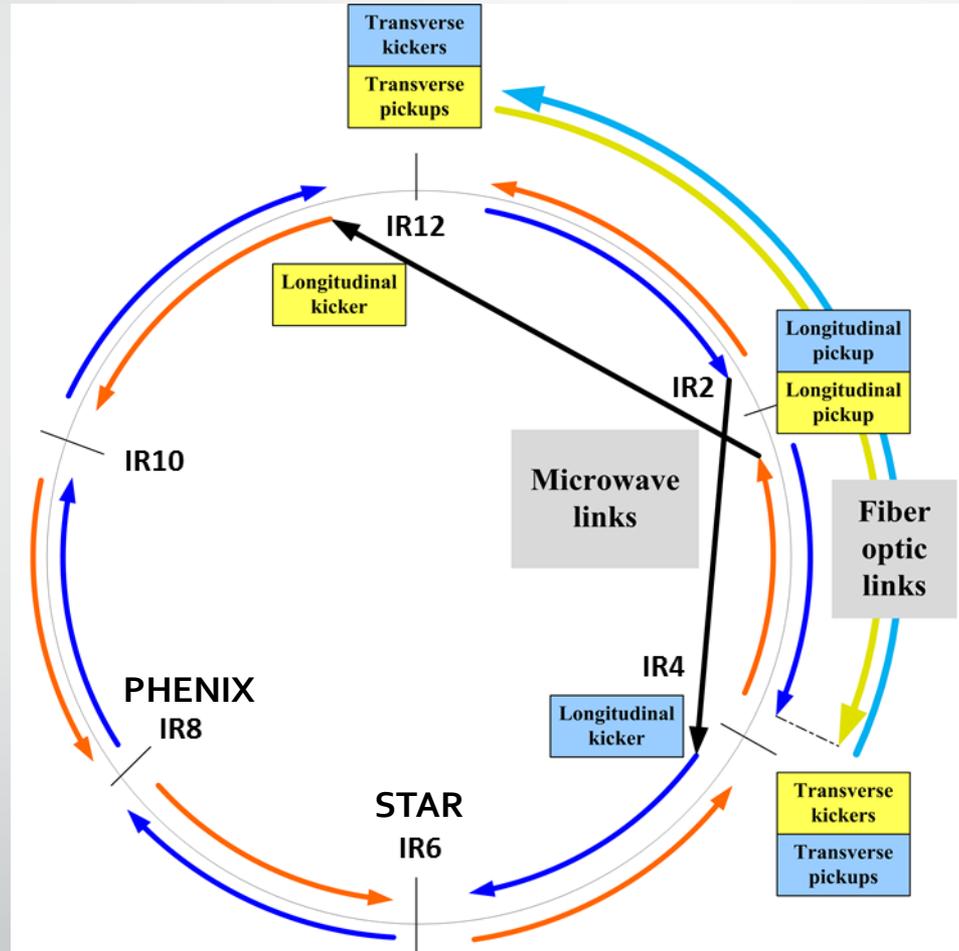
STOCHASTIC COOLING
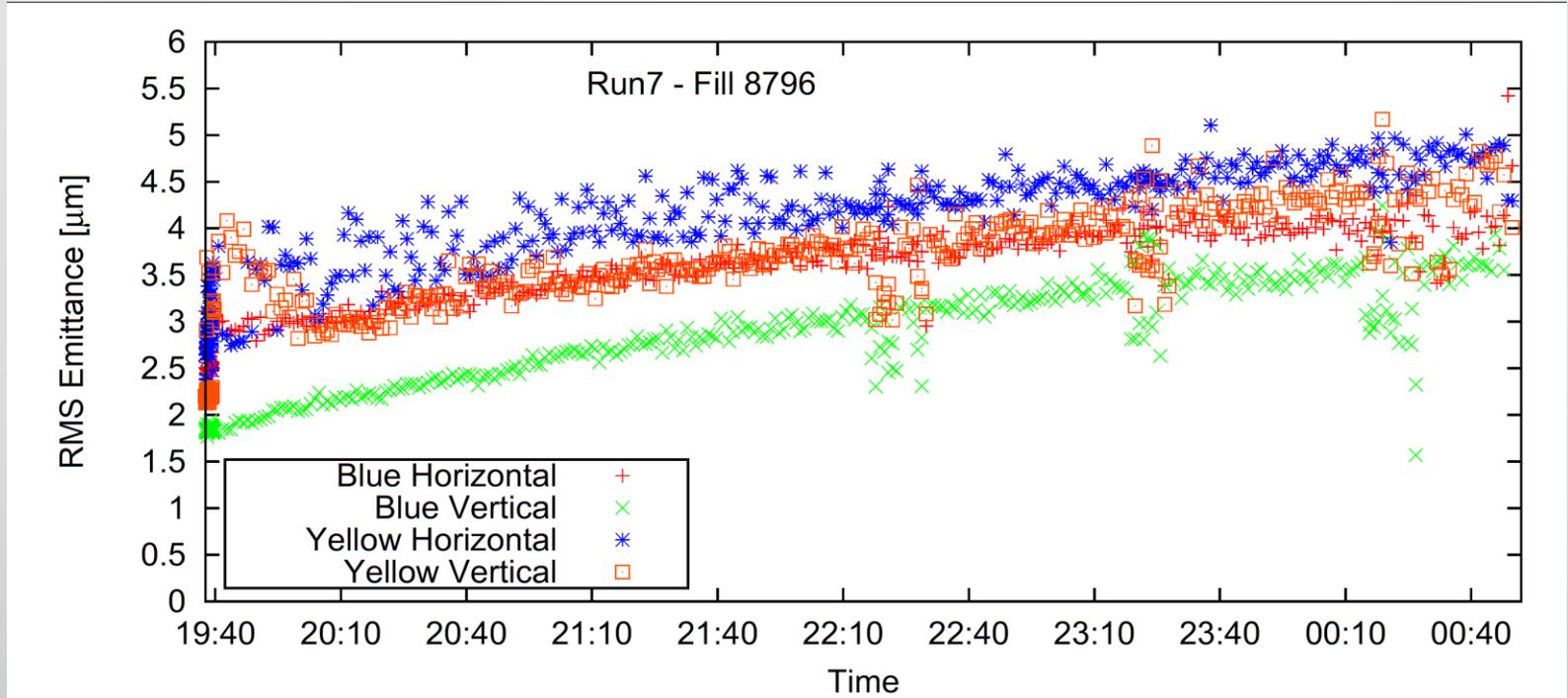
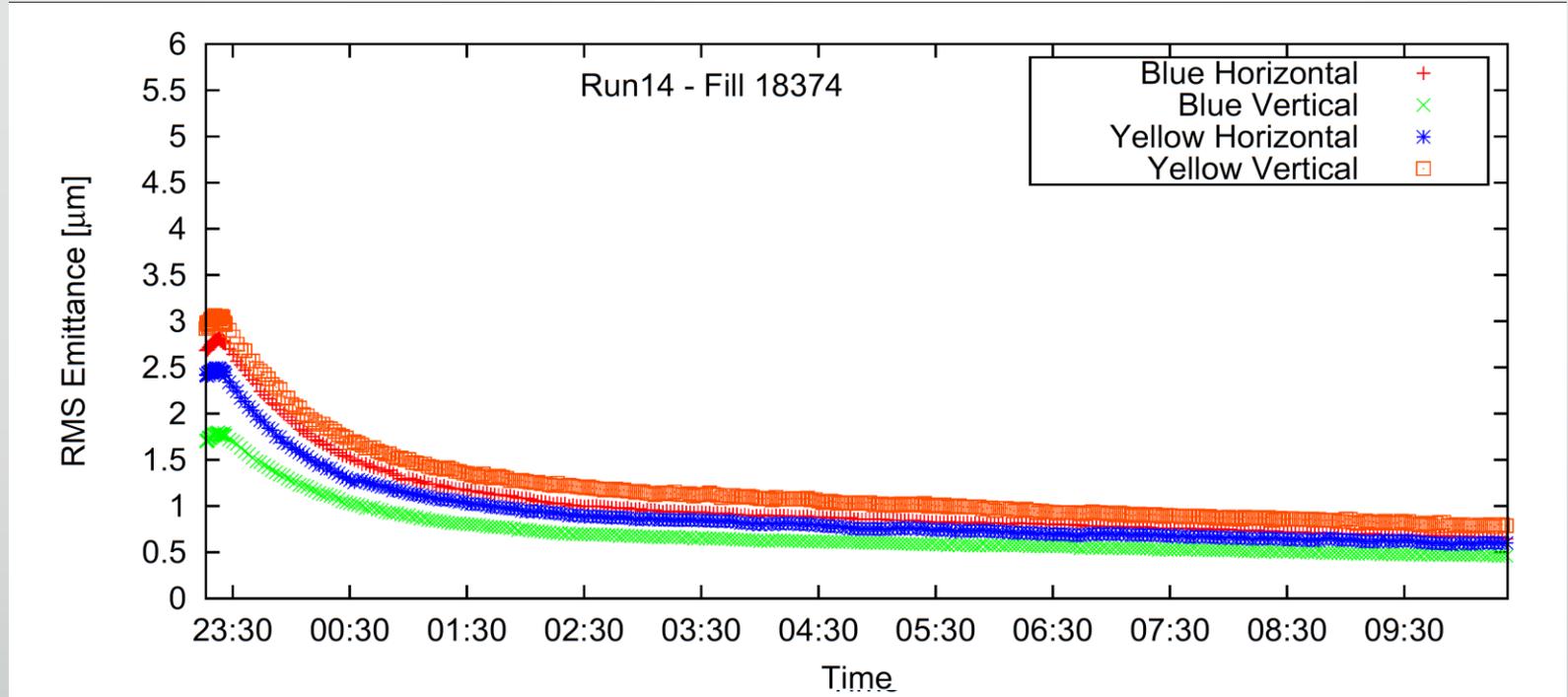- System performance:

STOCHASTIC COOLING

- System performance:

- With a full 3D system in Run11, transverse RMS emittances were reduced by **up to 30%**.

STOCHASTIC COOLING

- System performance:

- With a full 3D system in Run11, transverse RMS emittances were reduced by **up to 30%**.

- Additional upgrades for reliability in Run14 allowed lowering emittances by **a factor 3**.

FEEDBACK SYSTEMS

- Goal of RHIC Operations: deliver high luminosities to experiments with great store-to-store reproducibility => need state-of-the-art control of all beam parameters!

- Improved measurement precision has contributed to improved control of the beam's properties and to the successful application of routine orbit, energy, tune, and coupling feedback in RHIC:

| Parameter	Stability, no feedback	Stability, w/ feedback
rms beam position	1 mm	20μm
betatron tunes	0.02	0.001
coupling coefficients	0.04	0.01
beam energy	250μm	15μm
chromaticity	10	3

- Ramp development efficiency has been reduced from several days (Run8 and prior) down to 1 ramp or about 2 hours (as of Run11).

- Overall accelerator availability is estimated to be increased by ~ 1 week per fiscal year due to the improved reproducibility afforded by use of feedback-based beam control.

FEEDBACK SYSTEMS

- Highlight reel:

Courtesy of M. Minty

Average orbit measurements (vertical plane) with and without improved data processing algorithm
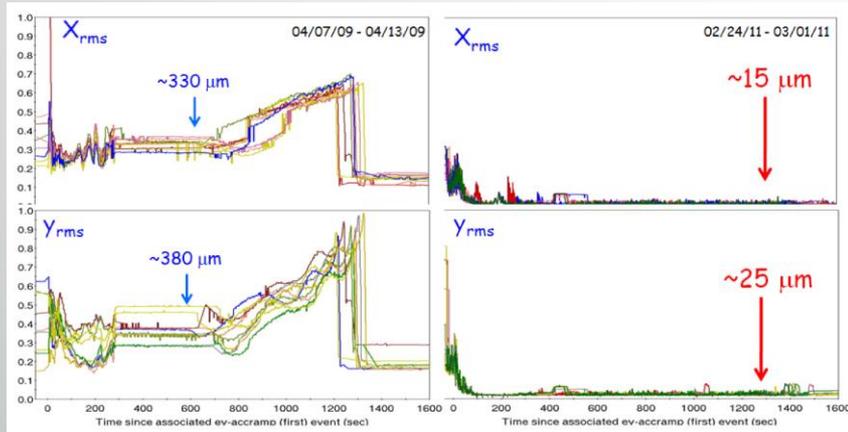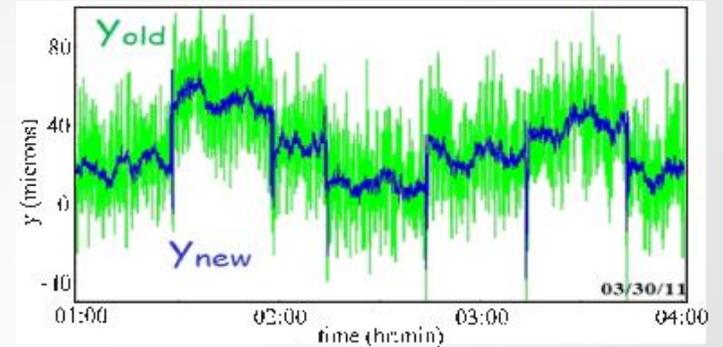
Superposition of measurements from multiple ramps of horizontal (top) and vertical (bottom) orbit rms measured without (left, Run9) and with (right, Run11) orbit feedback.

Measured RHIC betatron tunes (top) and chromaticity (bottom) with (blue) and without (red) tune/coupling feedback during the energy ramp and beta-squeeze during Run11.
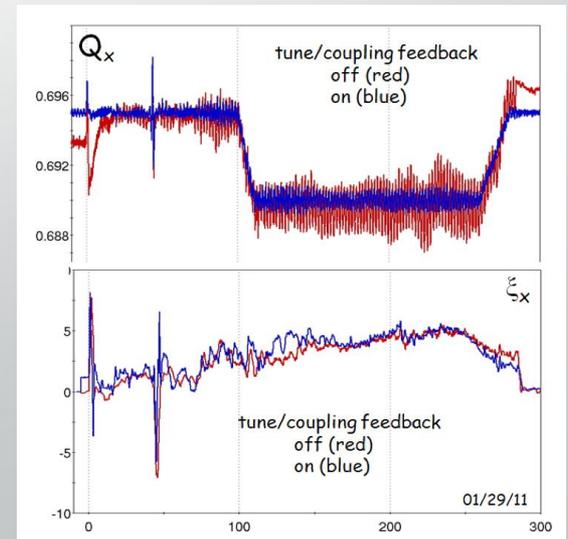
RF SYSTEMS

- A new Low-Level RF Upgrade Platform has been deployed across the entire RHIC accelerator complex in both operational as well as R&D applications:

  - improved flexibility and precision of bunch merging gymnastics in the Booster and AGS;

  - improved stability of synchronization and bunch to bucket transfers between Booster, AGS and RHIC;

  - bunch by bunch longitudinal damping and transient beam loading compensation in RHIC;

  - improved flexibility and precision in the RHIC store rebucketing gymnastic;

  - development of a RHIC bunch by bunch transverse damper.

- During Run14, a 56 MHz SRF cavity was installed and commissioned with beam, providing additional longitudinal focusing in complement to what is achieved by the longitudinal Stochastic Cooling
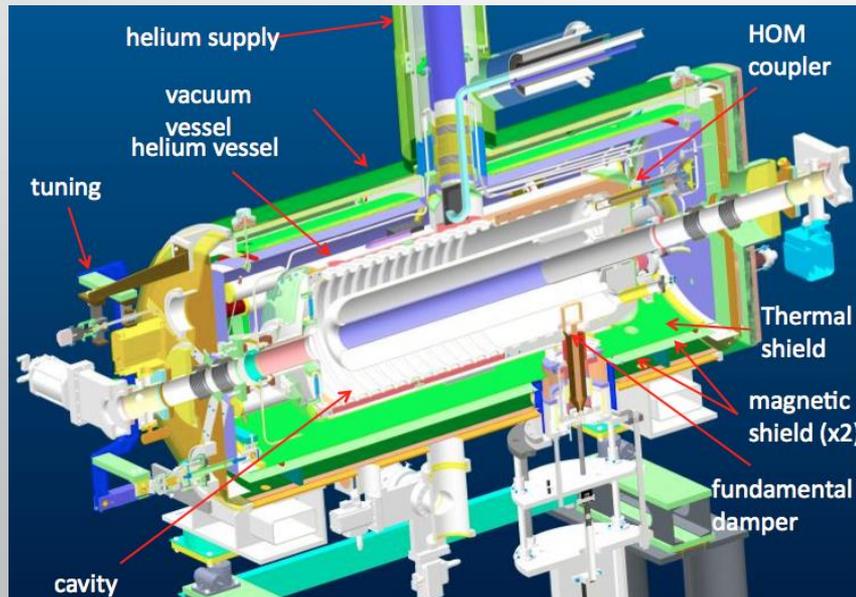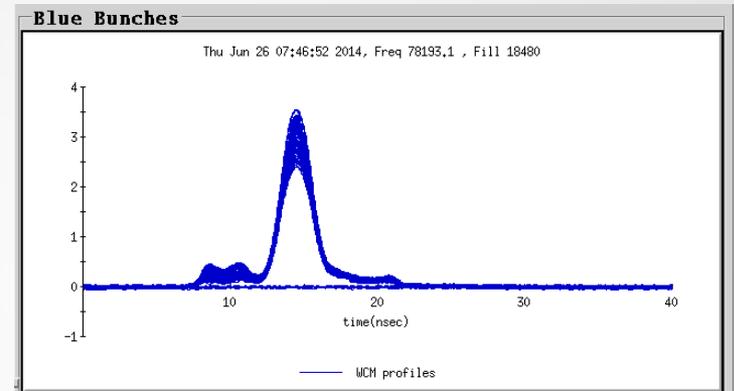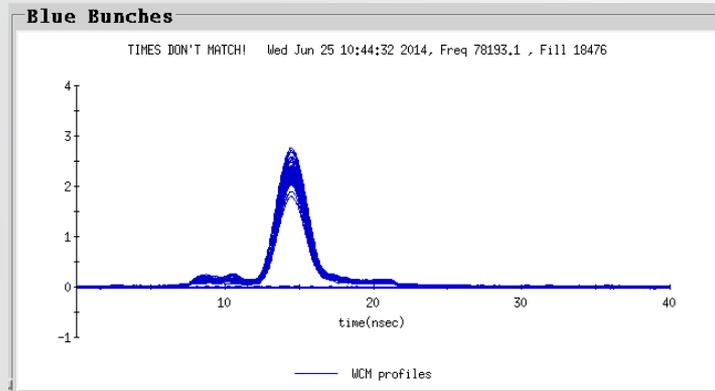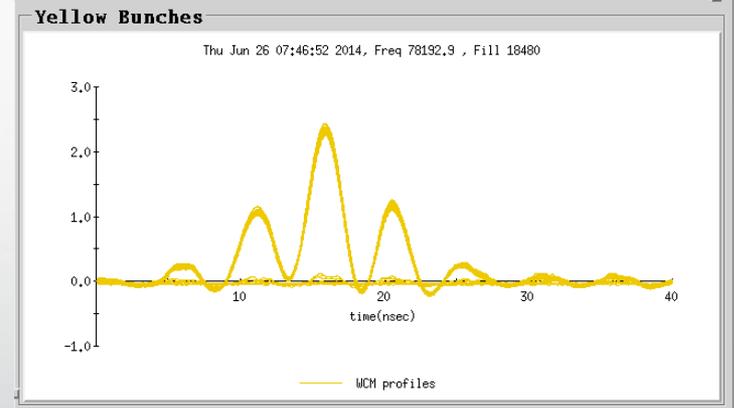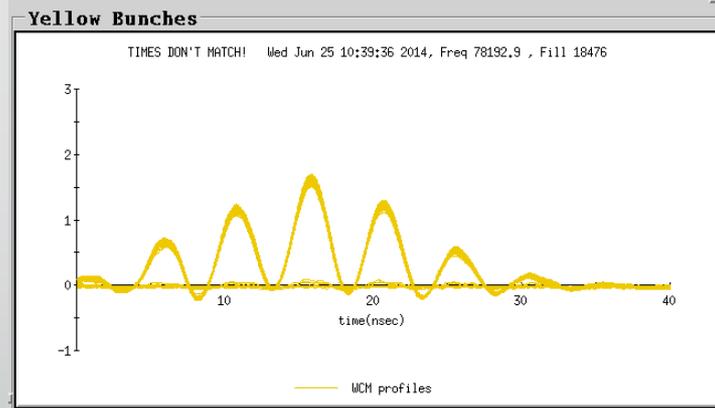
Courtesy of Q. Wu

RF SYSTEMS

- Longitudinal focusing from Run14 operations with 56 MHz SRF cavity:

Courtesy of Q. Wu

^{3}He

Au

Fill 18476 - no 56 MHz cavity

Fill 18480 - with 56 MHz cavity

=> the population of Au beam in the satellite buckets is squeezed towards the center.

Luminosity and Lattice Implications

- For Gaussian shaped bunched beams colliding head-on, the luminosity is given by:

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi \sigma_x^* \sigma_y^*}$$

with:

$$\sigma_x^* = \sigma_y^* = \sqrt{\beta_x^* \cdot \epsilon_x} = \sqrt{\beta_y^* \cdot \epsilon_y} = \sqrt{\beta^* \cdot \epsilon}$$

=> two ways to maximize luminosity: **higher beam intensity** in **smaller transverse beam sizes**!

- For RHIC physics runs:

  - the revolution frequency f is given;

  - the number of bunches N_b is already maximized – 111 per ring;

  - the number of particles per bunch $N_{1,2}$ can be improved with better lifetime;

  - the transverse $\beta_{x,y}^*$ functions at each experimental insertion can be reduced ("squeezed").

  => goal of RHIC-II Upgrade: beam lifetime dominated by burn-off + collisions at $\beta_{x,y}^* < 0.7$ m.
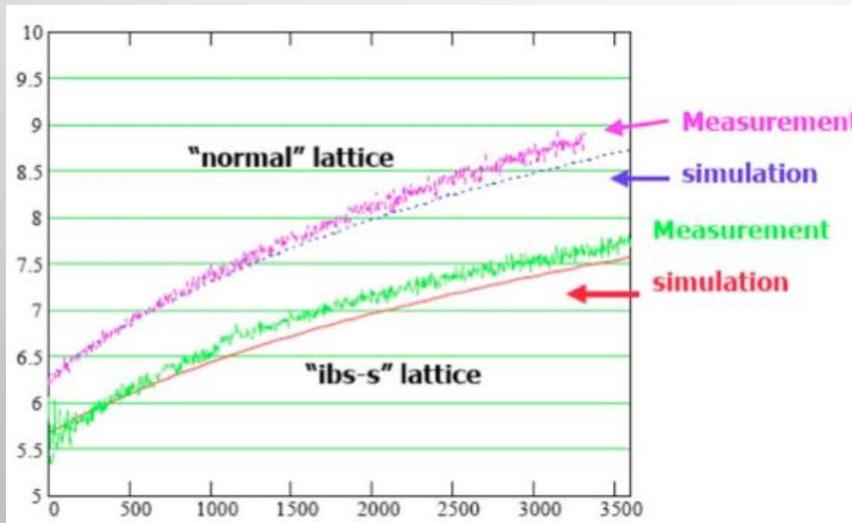
Beam lifetime – Off-Momentum Dynamic Aperture

- Main limitation to high luminosities in RHIC: emittance blowup from Intrabeam Scattering (IBS).

- Potential solution: change the design lattice to reduce the contribution of longitudinal IBS diffusion to the transverse planes:

$$\frac{d\epsilon_z}{ds} = H(s)\frac{d\delta_E^2}{ds},\ H(s) = \gamma_z D_z^2 + 2\alpha_z D_z D_z' + \beta_z D_z'^2$$

=> need higher integer tunes to lower the average dispersion function $D_z(s)$ in the arcs!

- For RHIC Run8, the Au lattice featured for the first time $(Q_x, Q_y) = (31, 32)$, 3 units larger than before:


Courtesy of V. Litvinenko

=> phase advance per cell: 84° -> 95°;

=> **30% reduction in emittance blowup**;

=> **large beam losses after RF rebucketing**.

Beam lifetime – Off-Momentum Dynamic Aperture

- RF rebucketing at RHIC is the process by which bunches are transferred from the 28 MHz acceleration system to the 197 MHz storage system.

- This process involves compressing bunches down to 5 ns, but it also increases the momentum spread, with $\delta p/p_{max}$ going from 0.9×10^{-3} to 1.7×10^{-3}.

- Tracking studies show that IBS suppression lattice has a reduced off-momentum dynamic aperture:
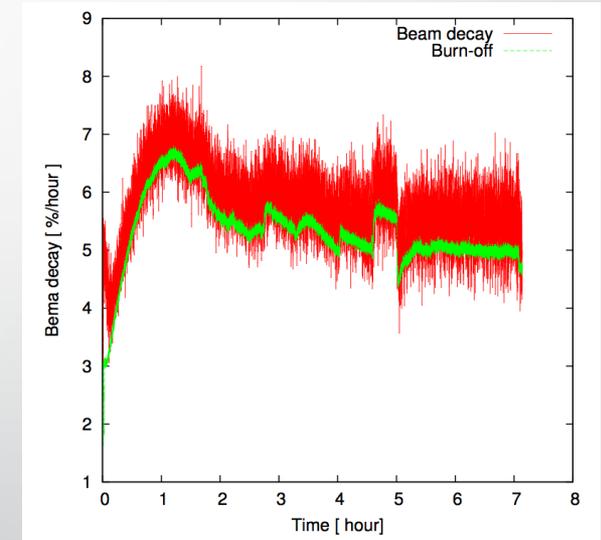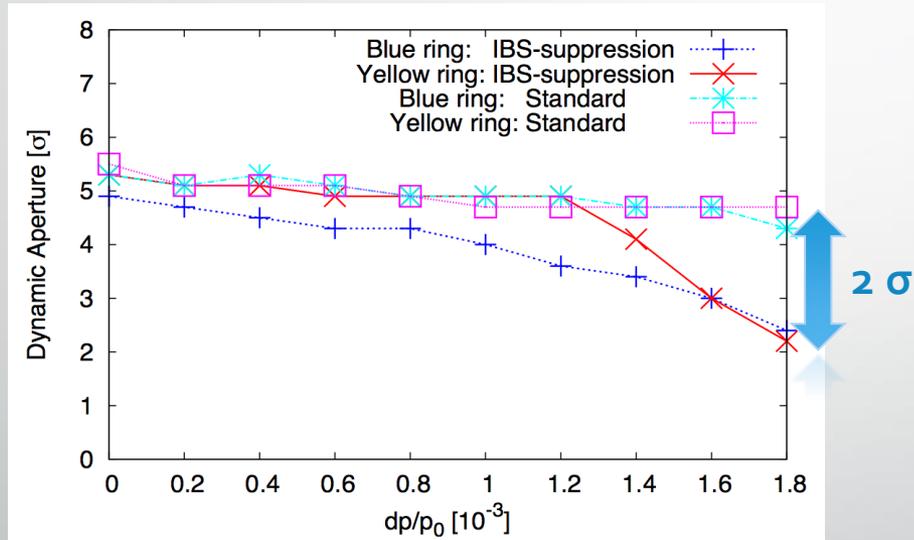

Courtesy of Y. Luo

=> successful implementation of Stochastic Cooling system allows reverting to Standard lattice!!
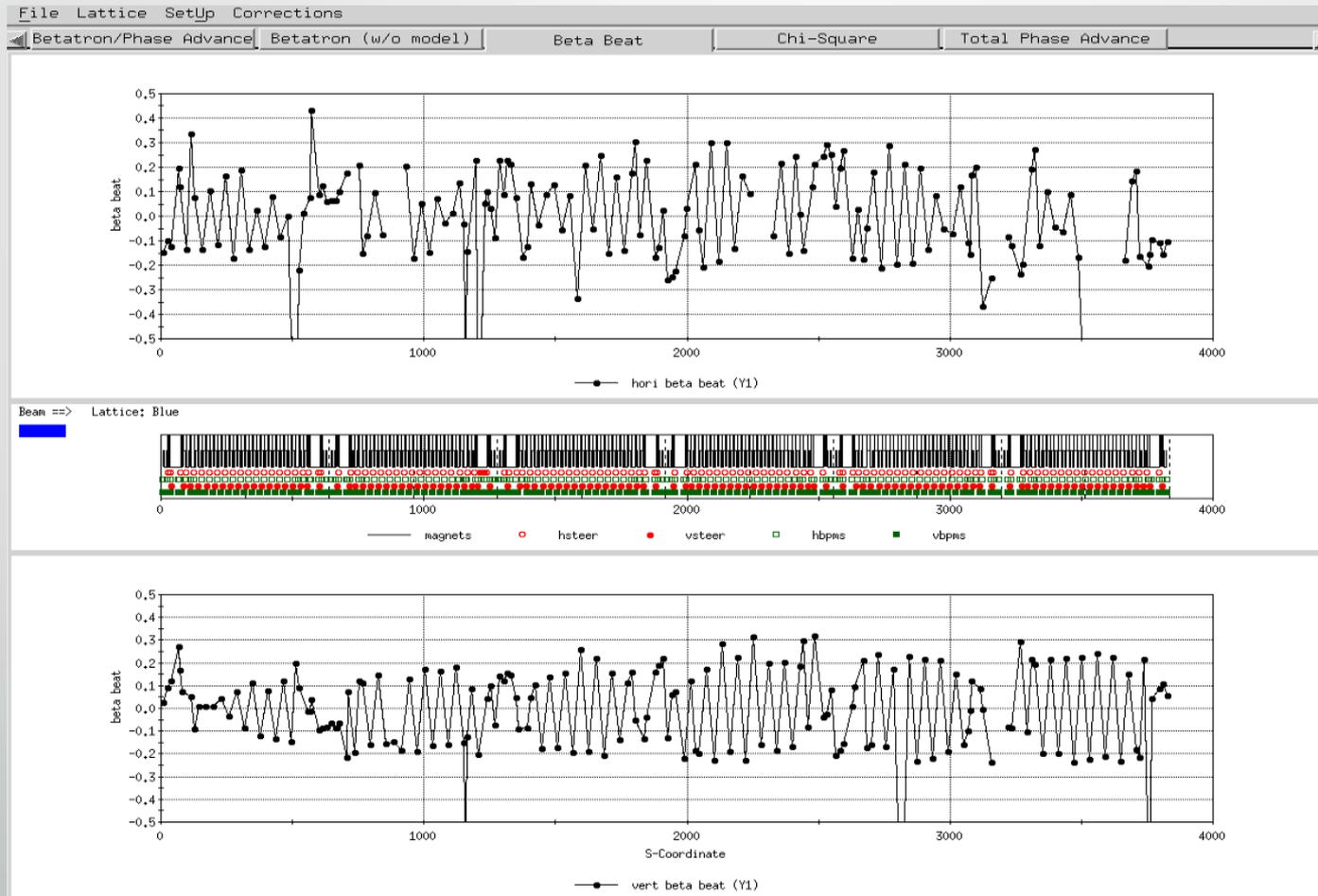
Luminosity Leveling with Dynamic β* Squeeze

- End of Run11: first attempt to reduce the transverse beam size at the collision point of one of RHIC's experimental insertions

  => served as a good proof of principle, but also highlighted some limitations to the method.

- Power supply wiring scheme: "nested" shunt supplies control both sides of each insertion region
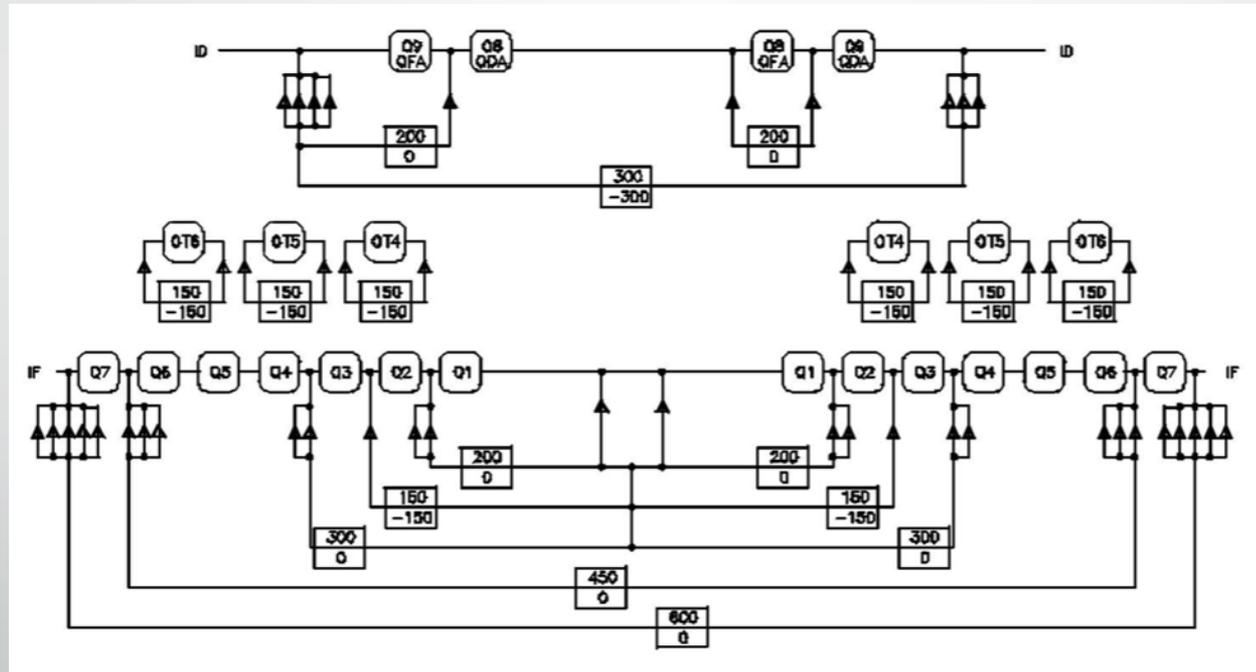
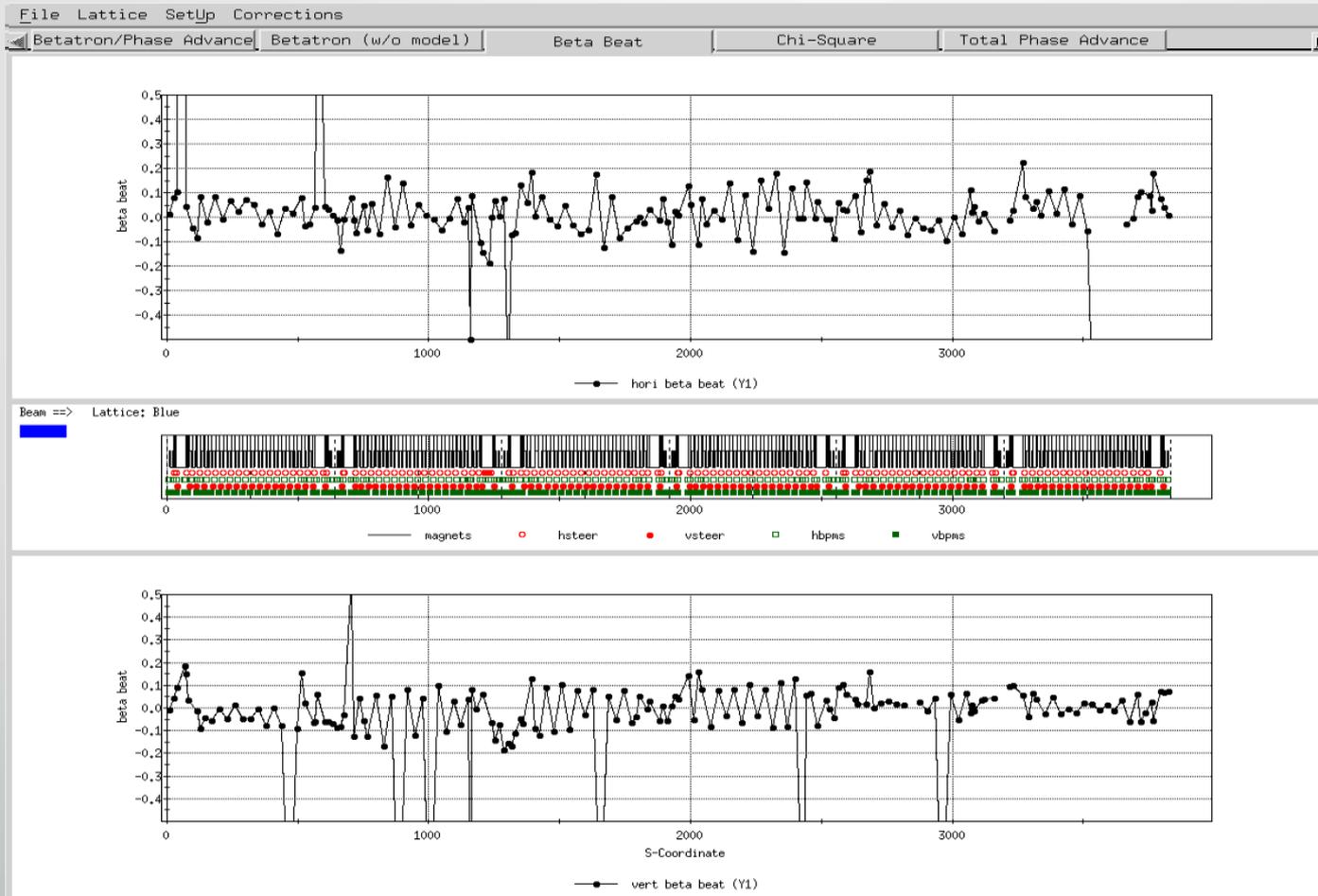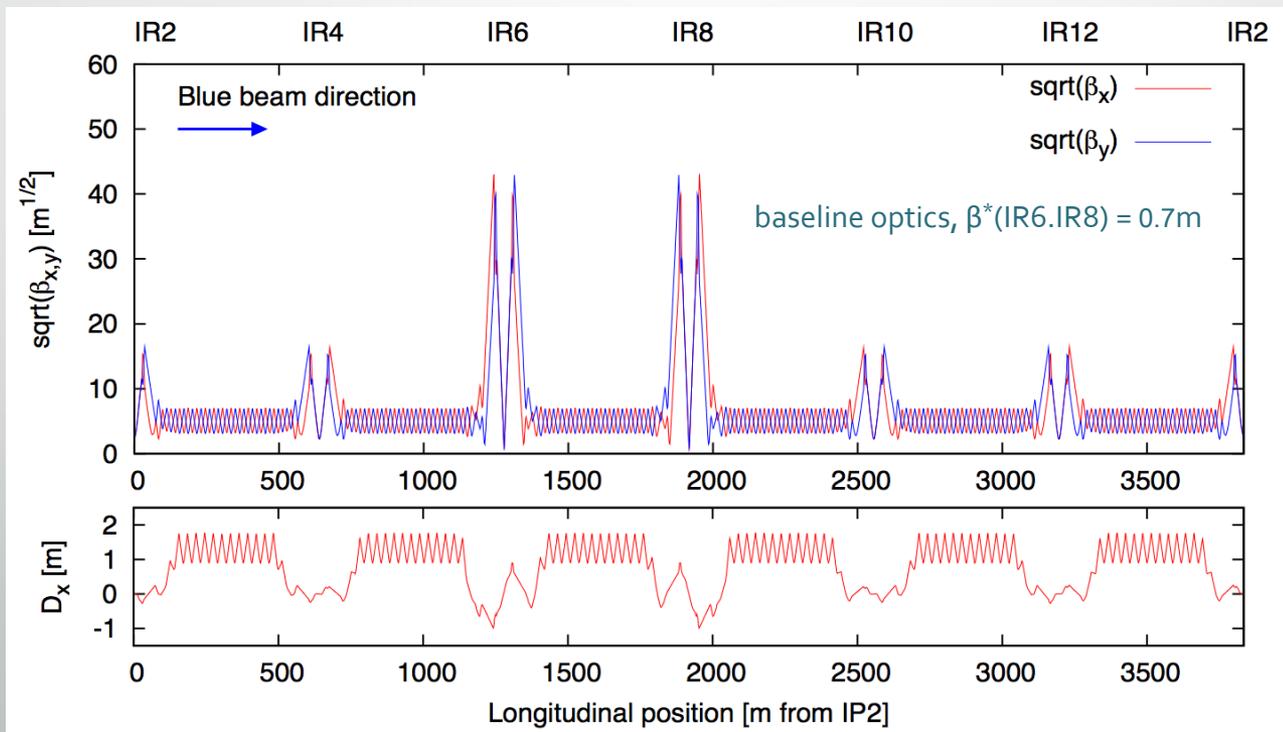=> limits in current prevent from reaching β* lower than 0.55 m!

Luminosity Leveling with Dynamic β* Squeeze

- New magnet strengths from squeezing algorithm need to be implemented after the linear optics have been corrected:

Luminosity Leveling with Dynamic β* Squeeze

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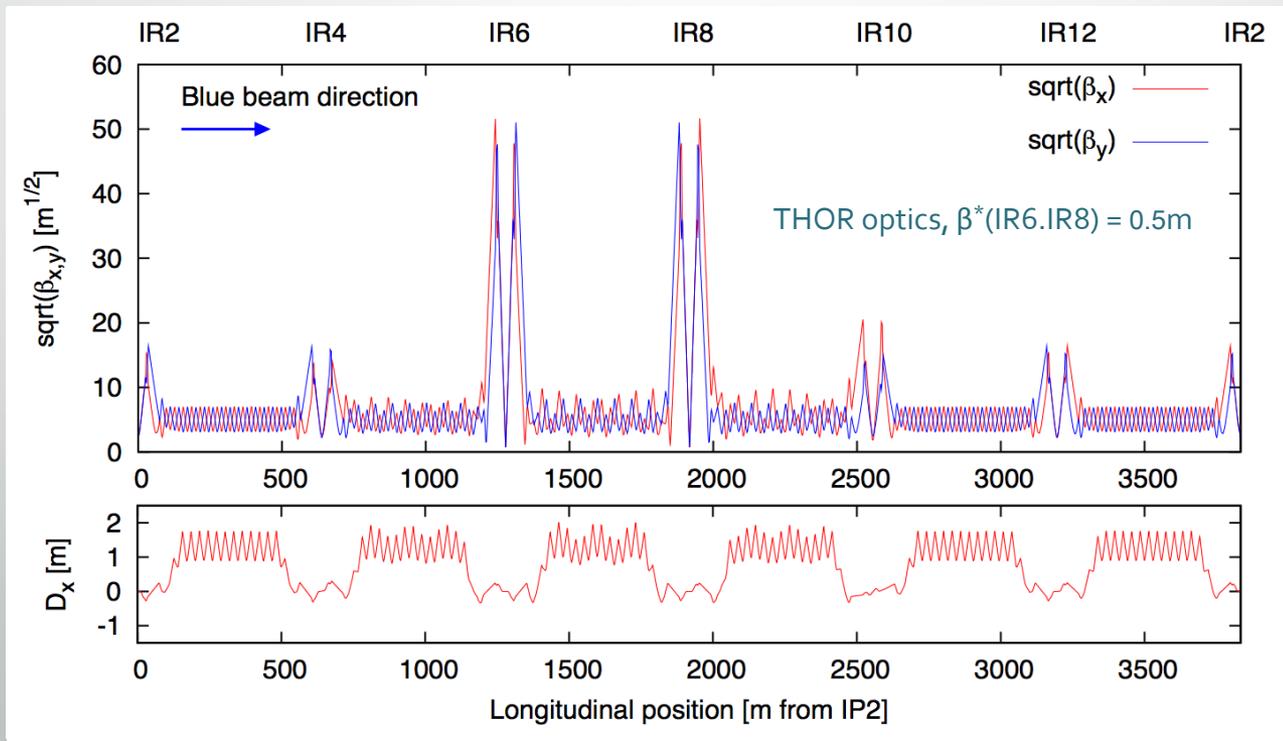
Luminosity Leveling with Dynamic β* Squeeze

- A new technique, the Achromatic Telescopic Squeeze (ATS), was developed at CERN for LHC studies and uses the insertions around the targeted IP to launch and close a β-beat wave to allow reducing β* further with little to no change to the chromatic functions.

- Constraints for RHIC:

  - initial lattice design does not feature the required phase advance of 90°/cell;

  - STAR and PHENIX experiments are next to each other.

- Solution: use a global rematching algorithm over a larger section of the machine that includes STAR & PHENIX:

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Luminosity Leveling with Dynamic β* Squeeze

- After commissioning the new lattice in dedicated beam experiment time, it was made operational for the last two weeks of Run14.

- Luminosity as a function of time during one of the Run14 stores featuring dynamic β* squeeze:
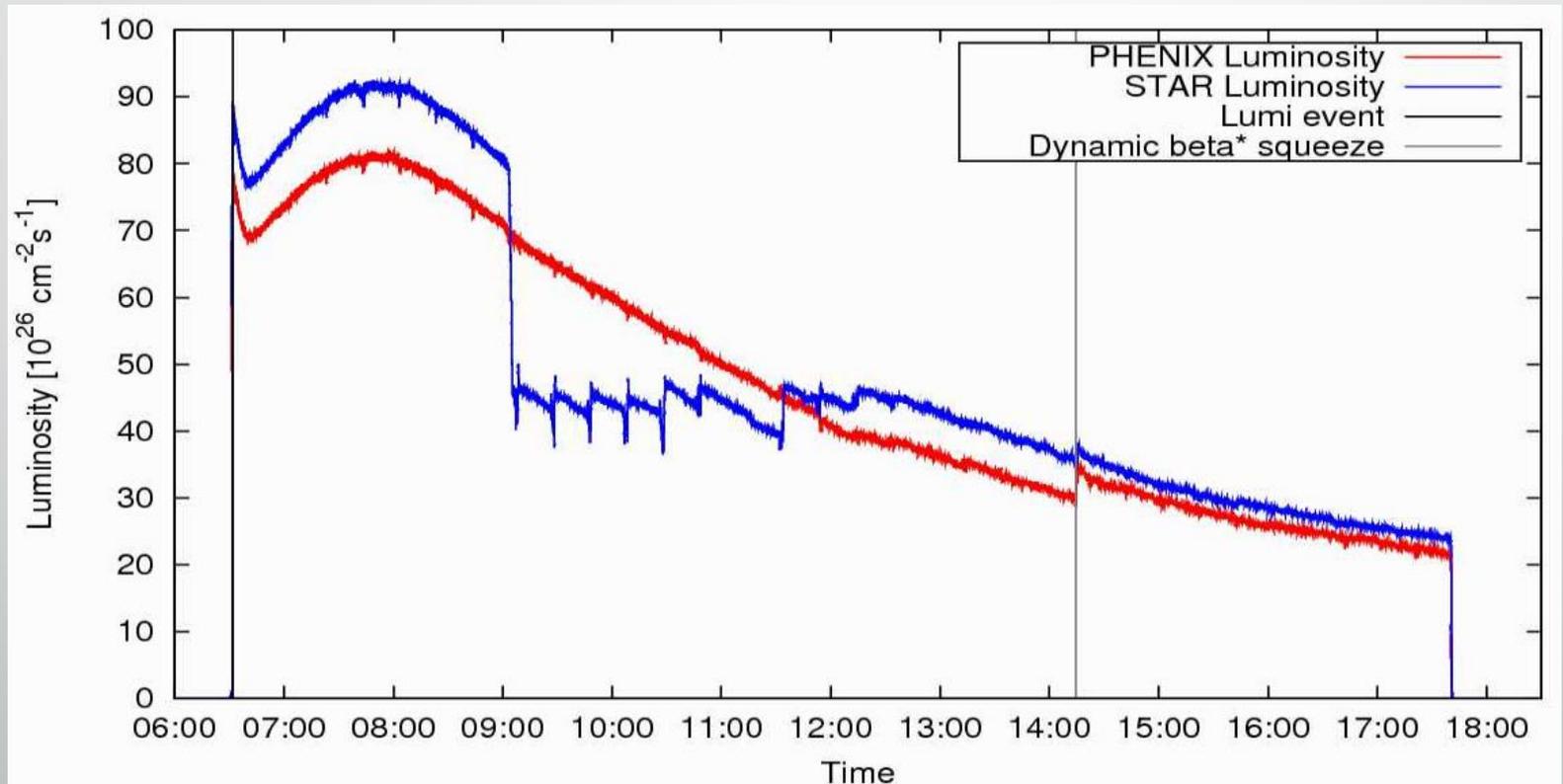
# Luminosity Leveling with Dynamic β* Squeeze

- After commissioning the new lattice in dedicated beam experiment time, it was made operational for the last two weeks of Run14.

- Zoom on the luminosity jump at the time of the β* squeeze:
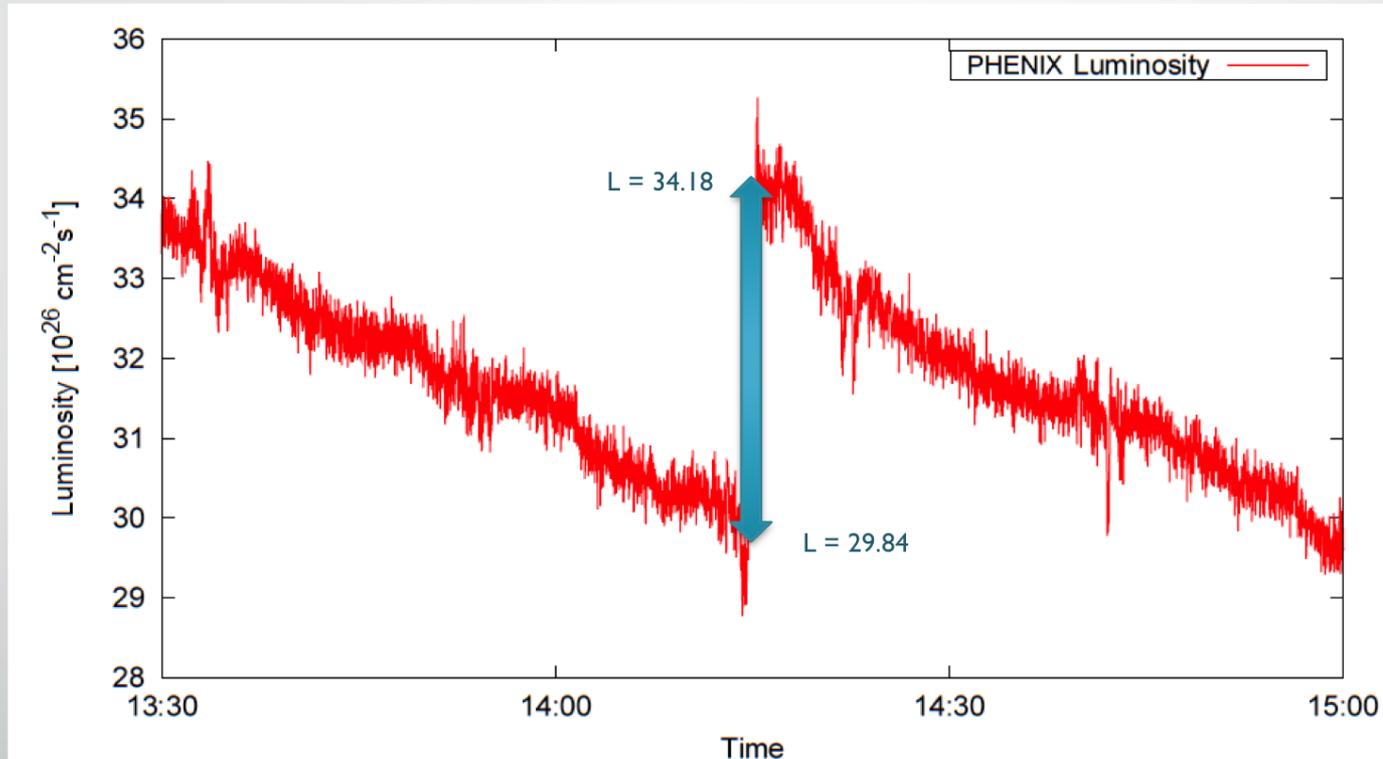
- Measured luminosity gain: $\Delta = 14.54\%$

- Predicted: $(\text{hourglass}/\beta)_{THOR}/(\text{hourglass}/\beta)_{classic} = 14.47\%$ (using APEX optics measurements and assuming stable bunch length).

Luminosity Leveling with Dynamic β* Squeeze

- Effect on integrated luminosity for PHENIX:
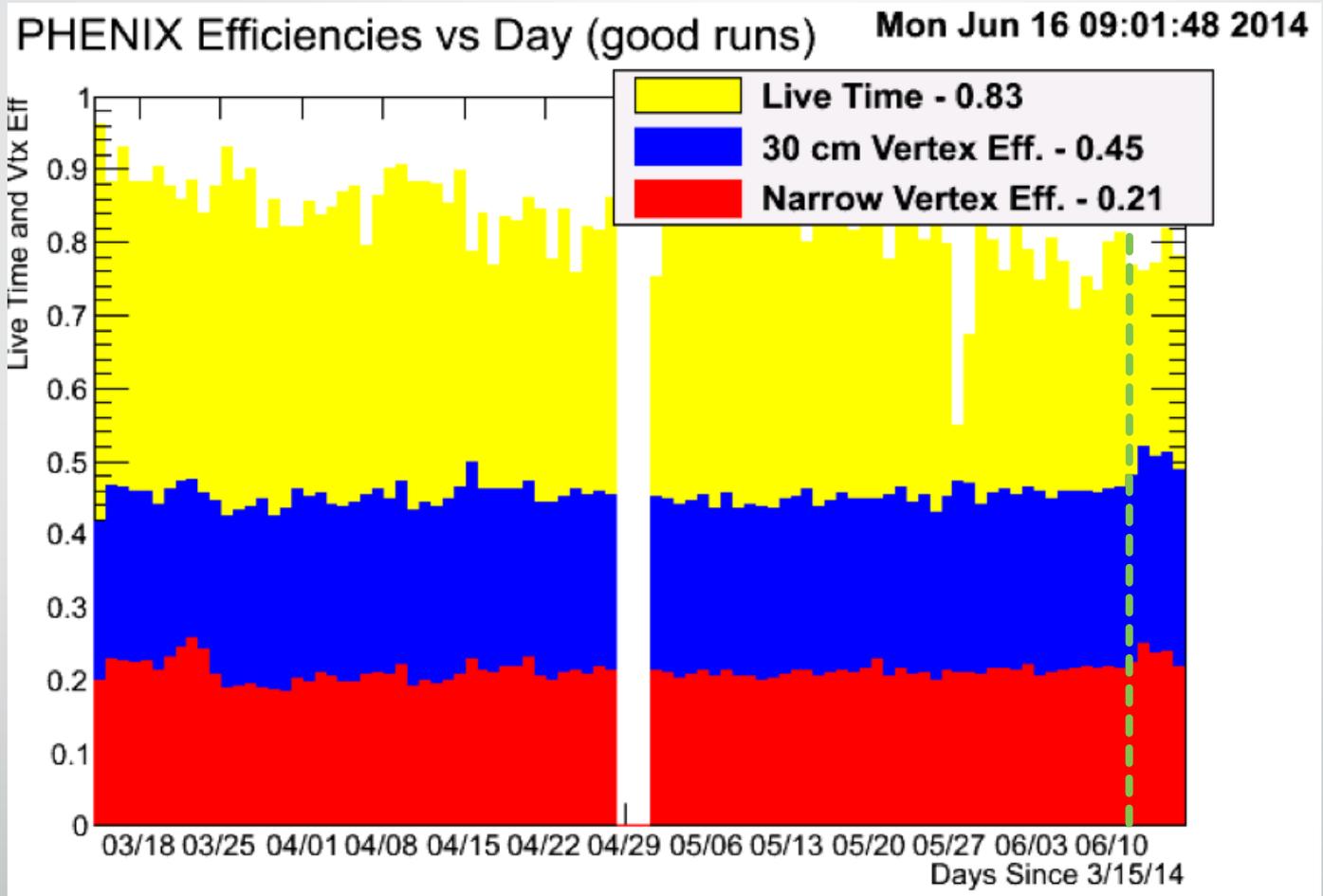
RHIC as a Versatile Collider

- RHIC can routinely produce collisions for multiple physics programs during one calendar year, often for only a few weeks in each running mode.

- Each program can include symmetric or asymmetric collisions, for heavy ions and/or polarized protons, and for a wide range of energies.

- Generic, highly configurable tools for sequencing accelerator task have been developed, along with software for saving and restoring many accelerator configuration parameters that allow fast switching between operating modes and/or species. The generic nature of the tools allows new equipment to be integrated and reconfigured on the fly.
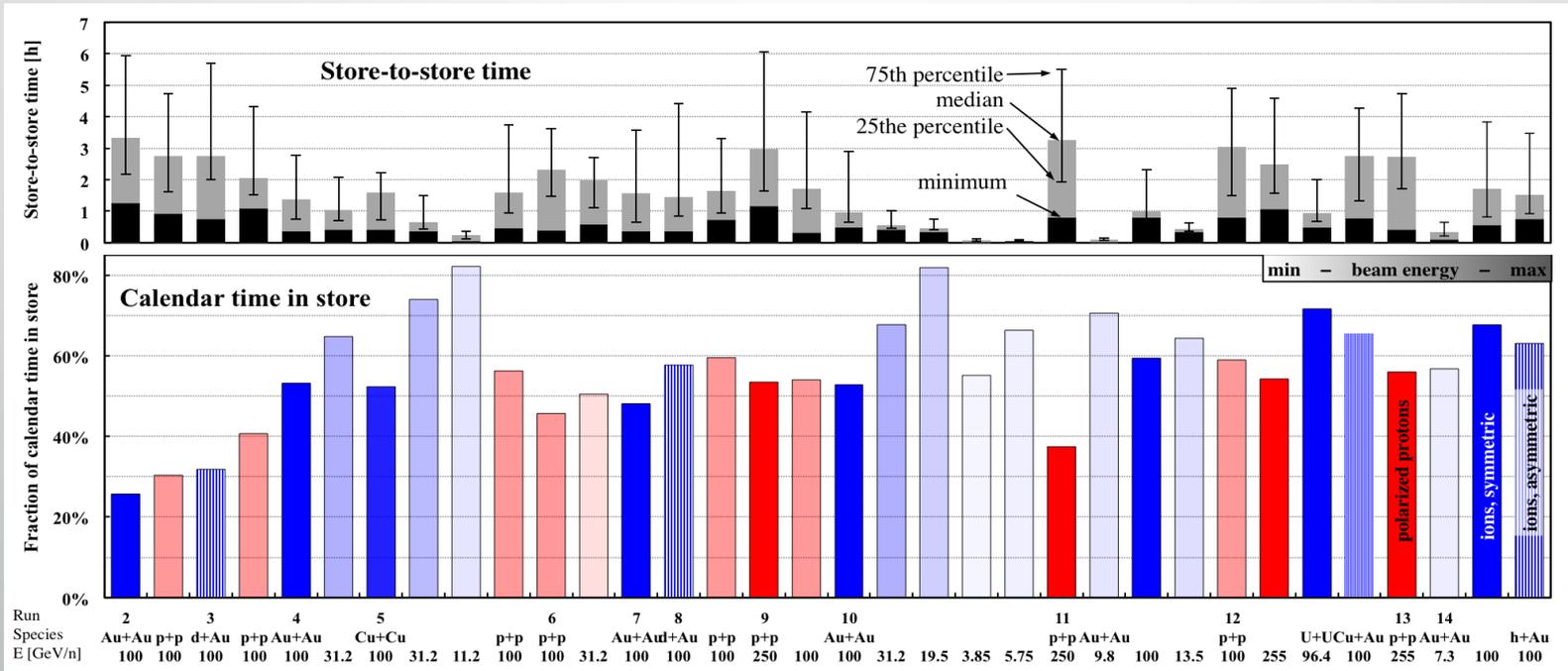
Courtesy of W. Fischer

Looking Back – Looking Forward

- With the RHIC-II upgrade now completed, there is a significant increase of all performance indicators of the entire accelerator complex:

  - solutions against intrabeam scattering, which limited the delivered luminosity to STAR and PHENIX, have been successfully implemented: the Stochastic Cooling system is reducing the transverse emittances by more than a factor 3, allowing for new mechanisms for luminosity leveling to be commissioned for the first time with beam;

  - a new, superconducting 56 MHz RF cavity was also installed to help focusing the beam longitudinally;

  - upgrades to the instrumentation and feedback systems introduced state-of-the-art beam control tools.

- All of those factors contributed to making the Au-Au run of Run14 the most successful heavy ion physics run to date, with a record average luminosity of $50.0 \times 10^{26} \text{cm}^{-2}\text{s}^{-1}$. Run14 is now the staple for all coming RHIC runs with heavy ions, with the goal of pushing the most recent tools (dynamic β^* squeeze and 56 MHz SRF cavity) to their limit in order to achieve flat, high level luminosity for Run16.
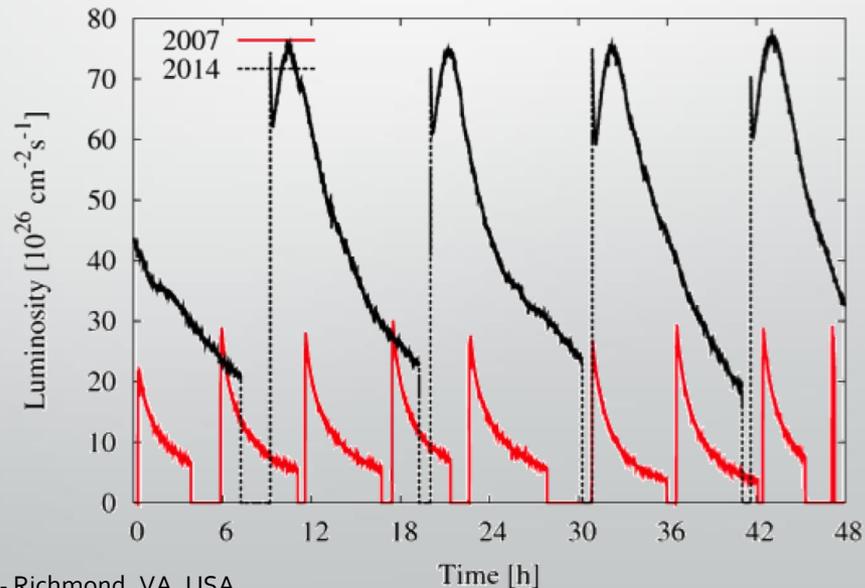
Many Thanks…

- … to all members of the Collider-Accelerator Department at Brookhaven National Laboratory whose collective accomplishments are reported here …

- … and in particular to J. Alessi, W. Fischer, P. Ingrassia, V. Litvinenko, Y. Luo, M. Minty, V. Schoefer, K. Smith, Q. Wu for sharing material for this report …

- … and finally,

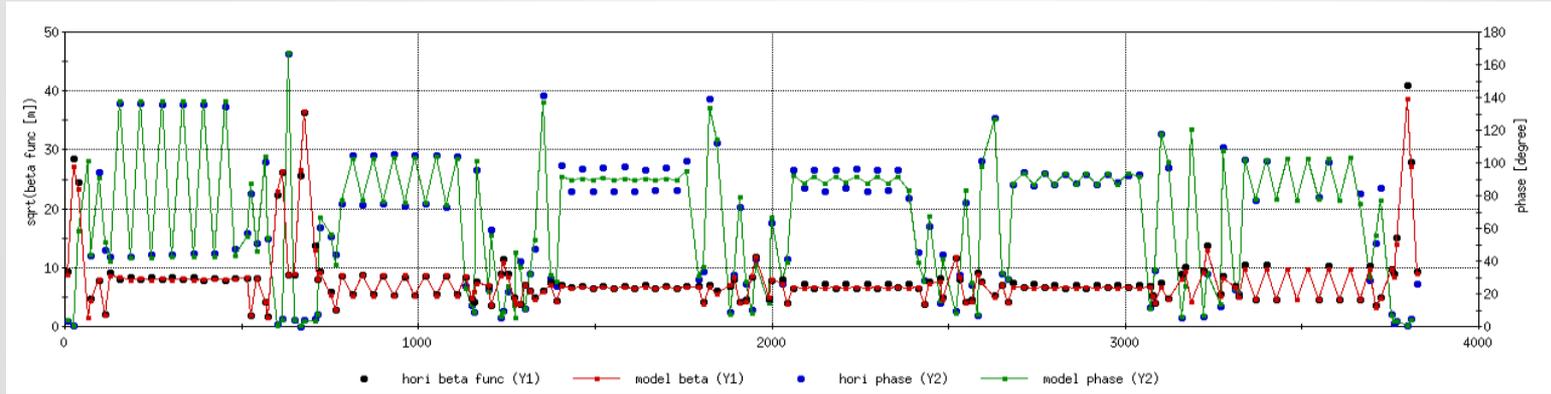# *YOU, FOR YOUR ATTENTION!*

Backup Slides

RF SYSTEMS

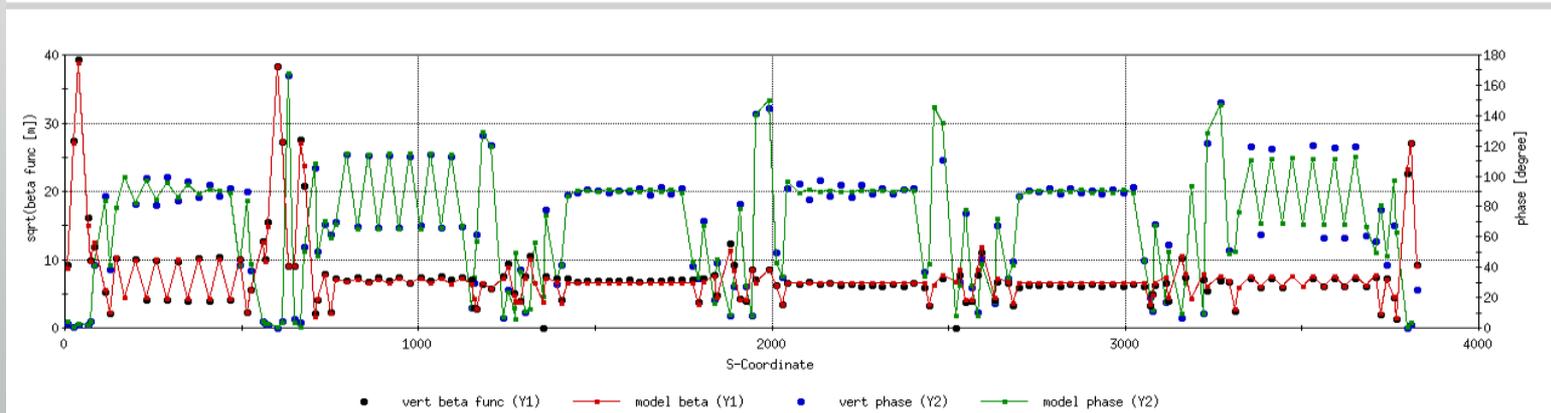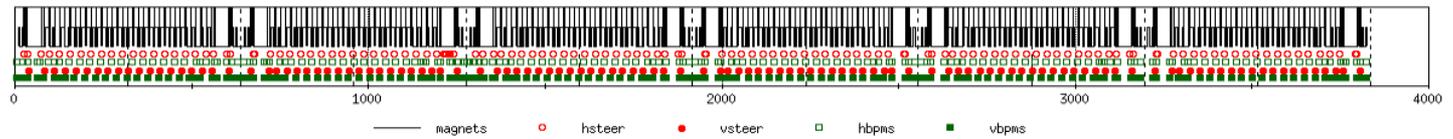- Impact of 56 MHz SRF cavity on delivered luminosity:
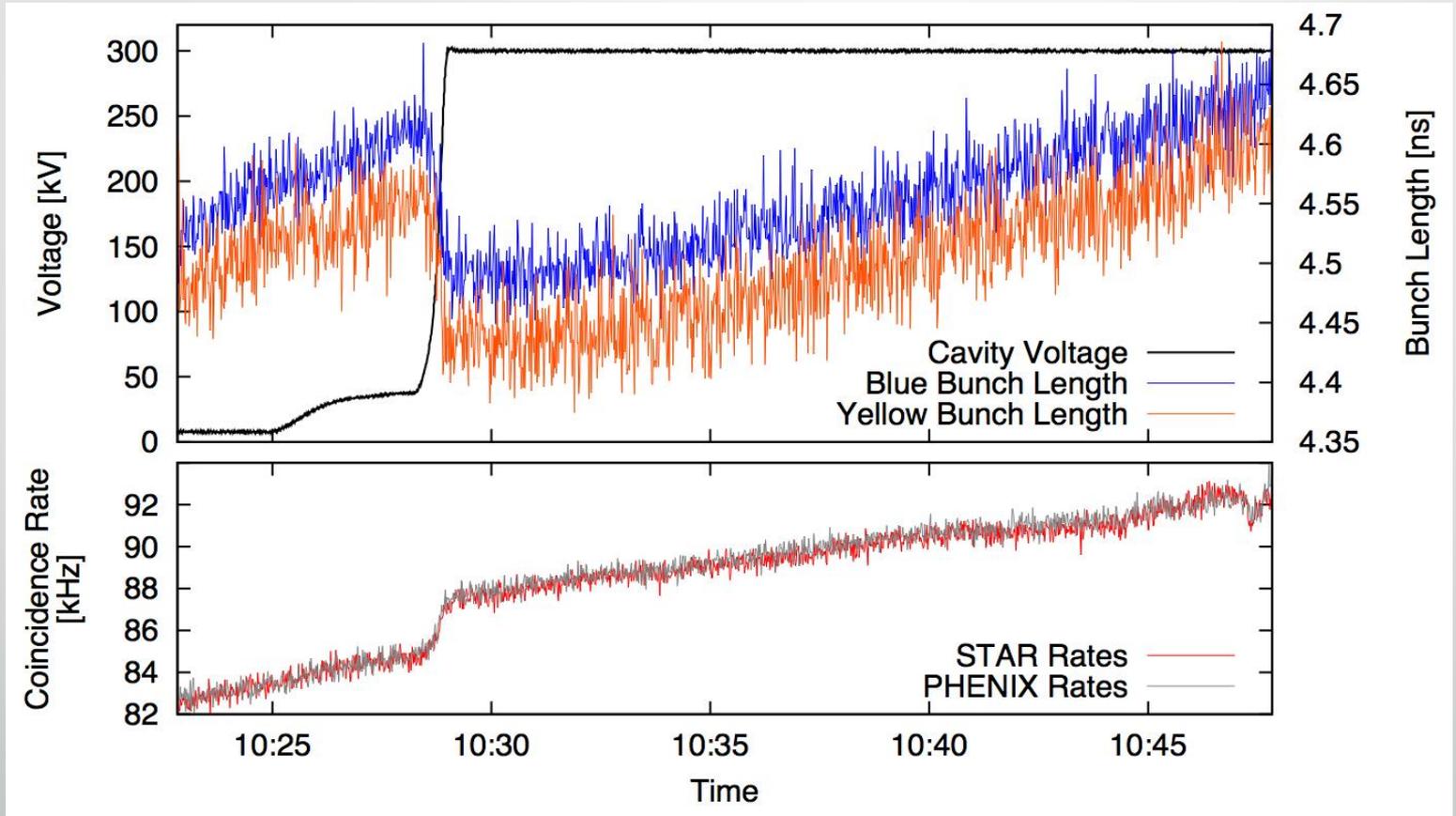
Backup Slides
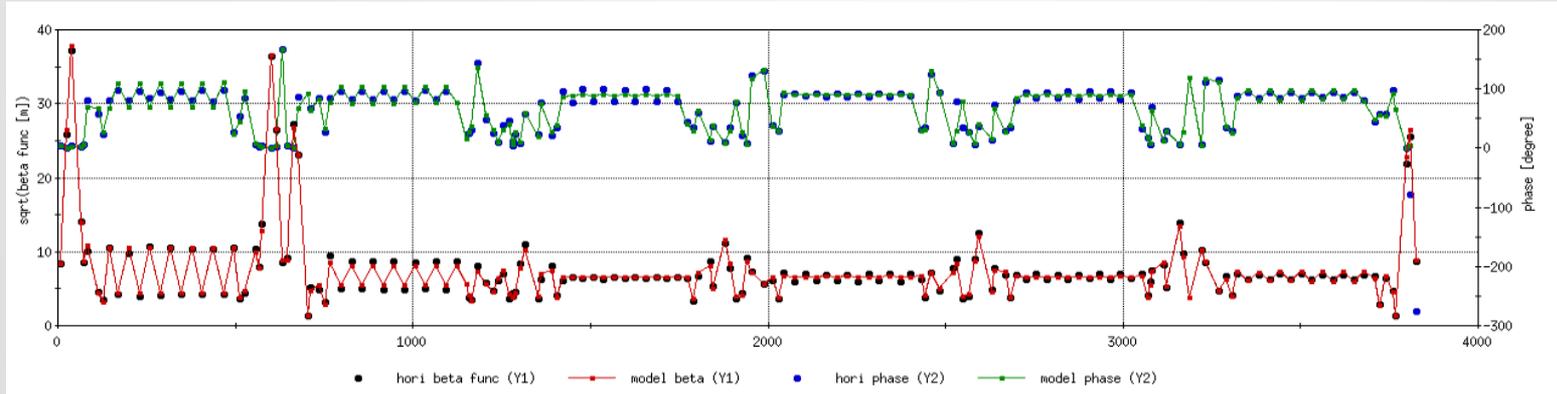
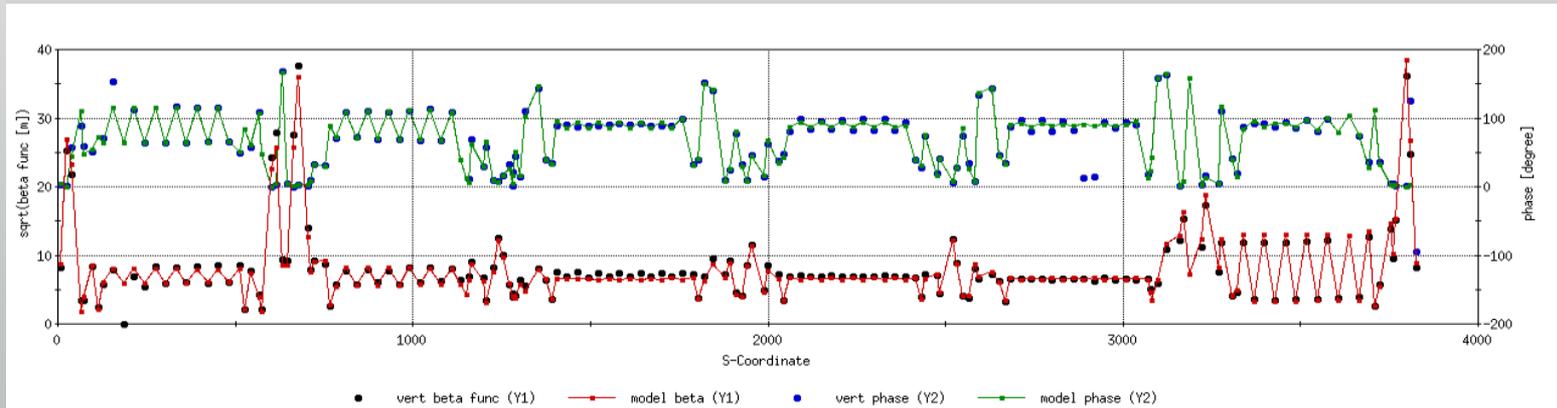- <u>Run15 pp lattice w/ ATS scheme:</u>

Blue lattice

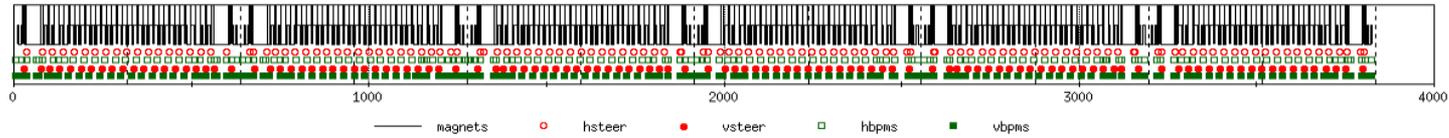# Backup Slides

- <u>Run15 pp lattice w/ ATS scheme:</u>

Yellow lattice

Highly Trained Operators

Courtesy of Y. Dutheil

- Since Run4, the rate of operations personnel replacement has been halved. The increased stability in the number of operators is beneficial in that more operators are experienced in accelerator operation.

- Operations group was expanded to include accelerator specialists who could be relied upon to train operators and others and solve accelerator performance problems. Accelerator specialists were also charged with managing the cold restart of RHIC following each yearly shutdown.

- In spite of automation via software, operators were encouraged to explore parameter changes at appropriate times in the cycle: this tuning of the parameter space paid dividends, as evidenced by the successful commissioning and operation of Stochastic Cooling during Run10 and Run11.