RHIC instabilities at transition crossing

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Thanks to the Committee for invitation!

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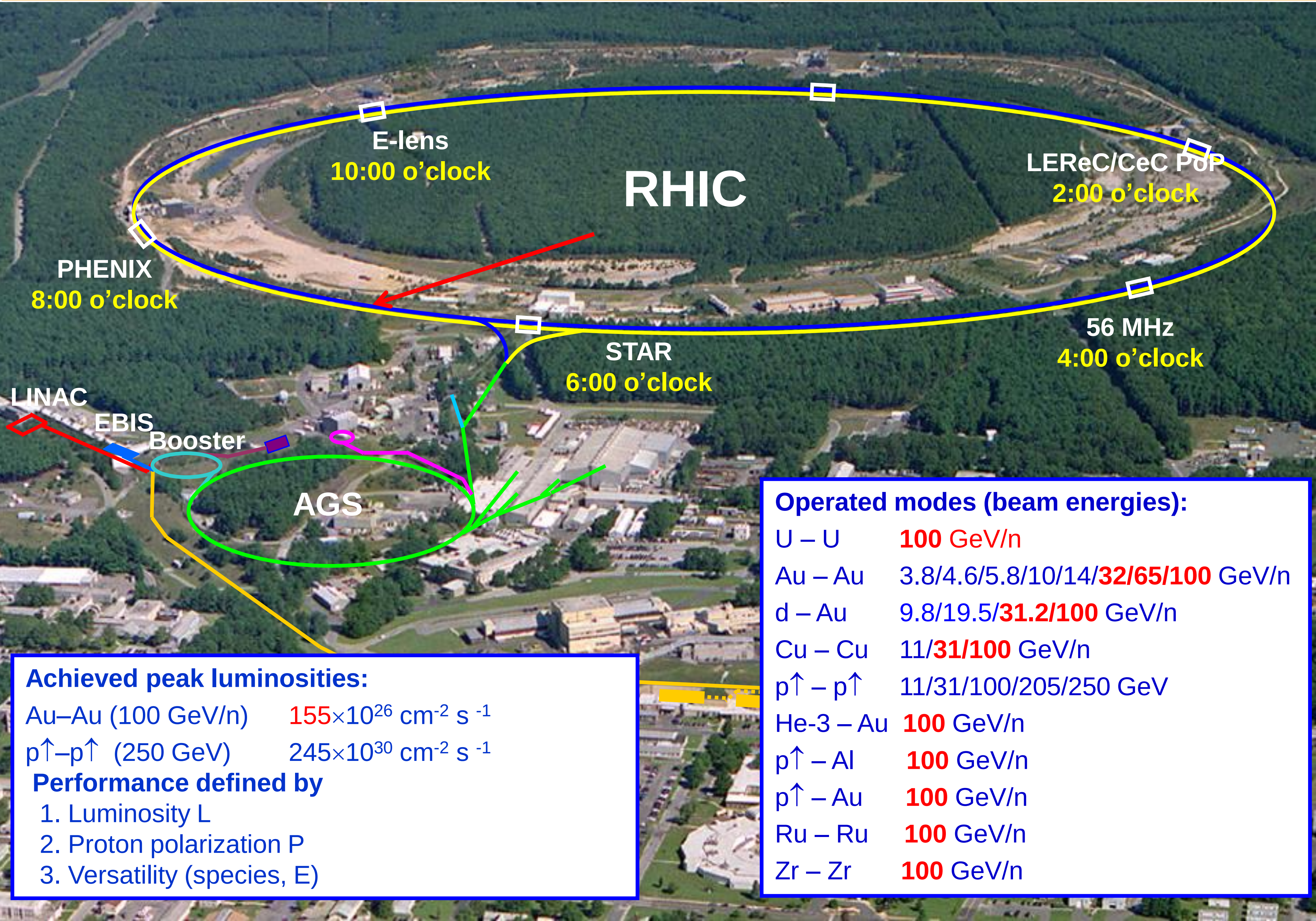
Outline

- Introduction
- Observation
- Methods
- Summary

RHIC – a High Luminosity (Polarized) Hadron Collider



Achieved peak luminosities:

Au–Au (100 GeV/n) 155×10^26 cm^-2 s^-1

p↑–p↑ (250 GeV) 245×10^30 cm^-2 s^-1

Performance defined by

1. Luminosity L
2. Proton polarization P
3. Versatility (species, E)

Operated modes (beam energies):

U – U	**100** GeV/n
Au – Au	3.8/4.6/5.8/10/14/**32/65/100** GeV/n
d – Au	9.8/19.5/**31.2/100** GeV/n
Cu – Cu	11/**31/100** GeV/n
p↑ – p↑	11/31/100/205/250 GeV
He-3 – Au	**100** GeV/n
p↑ – Al	**100** GeV/n
p↑ – Au	**100** GeV/n
Ru – Ru	**100** GeV/n
Zr – Zr	**100** GeV/n

Instability during Transition

→ In RHIC, all ions above 23 GeV except proton have to cross transition energy, with slow superconducting magnet ramping rate

→ **Single particle effects** -> chromatic non-linearity -> different momentum particle to cross transition at different times

→ **Multi-particle effects** -> bunch shape mismatch to RF bucket (induced by low frequency self fields) and microwave instability (higher frequency self fields)

→ These multi-particle effects will increase the momentum spread, enhancing the chromatic nonlinear effect and leading to particle loss

→ **Electron clouds** -> bunches are short at transition triggering e-cloud formation -> e-clouds lower the stability threshold given by the machine impedance and enhanced by electron clouds

→ In RHIC, instability has limited total bunch intensities in the past (not presently)

Time scales Characterize transition crossing

→ Two time scales to characterize transition crossing

→ The non-adiabatic time: not described by adiabatic Hamiltonian (longitudinal)

$$T_c = \left(\frac{A E_T}{ZeV|\cos(\emptyset_s)|} \cdot \frac{\gamma_T^3}{h\gamma'} \cdot \frac{C_0^2}{4\pi c^2} \right)^{1/3}$$

→ The non-linear time: single particle non-linearity chromatic effect (transverse)

$$T_{nl} = \left|(\alpha_1 + 1.5 \cdot \beta_T^2)\right| \cdot \delta_{max} \cdot \frac{\gamma_T}{\gamma'}$$

	FNAL Booster	FNAL MI	AGS	RHIC	KEKPS	CPS
C (m)	474.2	3319.4	807.12	3833.8	339.29	628.32
V (kV)	950	4000	300	300	90	200
h	84	588	12	360	9	6-20
γ_T	5.4	20.4	8.5	22.5	6.76	6.5
$\dot{\gamma}$ (s^{-1})	200	190	70	1.6	40	60
$\mathcal{A}$ (eVs/u)	0.04	0.04	1.	0.3	0.3	0.5
$\hat{\delta}$ ($\times 10^{-3}$)	6.4	2.5	6.7	4.5	5.4	6.6
τ_{ad} (ms)	0.2	2.0	2.5	36	1.8	1.5
τ_{nl} (ms)	0.13	0.19	0.61	63	0.7	0.5

S.Y. Lee, Accelerator Physics, p302

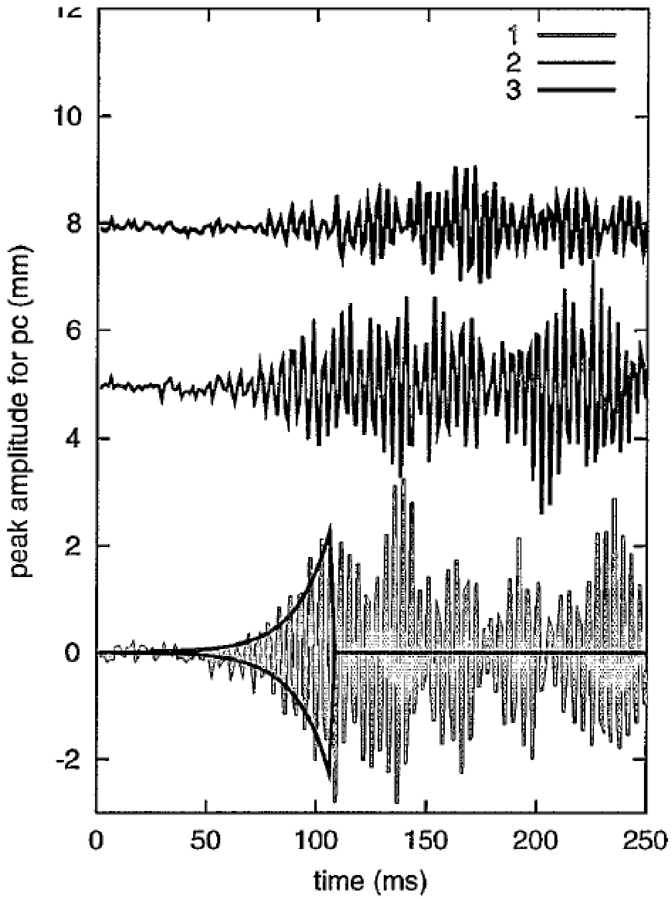
		Design	2004	2007	2016
Transition Lorentz Factor		22.80	22.80	22.91	23.95
Acceleration rate	/s	1.60	0.50	0.40	0.36
Maximum off-momentum parameter		0.00	0.00	0.01	0.00
C ircumference	m	3833.85	3833.85	3833.85	3833.85
Atomic Number		79.00	79.00	79.00	79.00
Atomic Weight		197.00	197.00	197.00	197.00
Transition Energy per nucleon	GeV	21.40	21.40	21.50	23.33
phase	rad	0.16	0.08	0.08	0.07
Peak rf Voltage	kV	300.00	300.00	300.00	200.00
rf Voltage during transitiion	kV	296.17	299.04	299.04	199.51
Harmonic number		342.00	360.00	360.00	360.00
Nonlinear momentum compaction parameter		0.60	-0.54	-0.30	-2.64
beta_T		1.00	1.00	1.00	1.00
non-adiabatic time	ms	**37.02**	**53.45**	**57.95**	**74.00**
nonlinear time	ms	**128.50**	**187.67**	**356.54**	**306.62**

Instrumentation for Transition Crossing Instabilities in RHIC

1. Beam Decay and BBB beam loss
2. IPM for Emittance
3. Coherence signal
4. Electron cloud detector
5. Longitudinal Bunch length & Shape
6. Vacuum
7. 10Hz & TBT BPM
8. Longitudinal phase tomographic reconstruction

Button BPM for coherence measurement

3 components for fast instability



M. Blaskiewicz et al, PAC 2003

2 components for slow instability

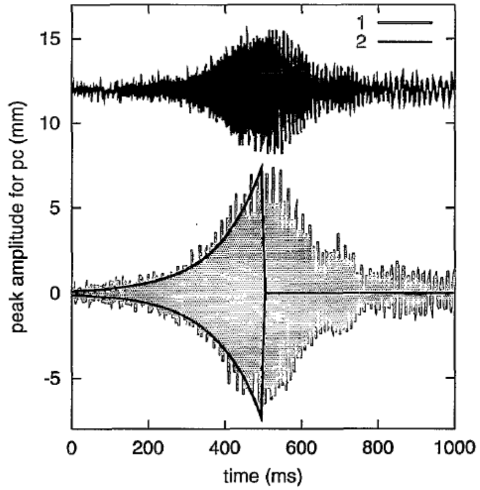
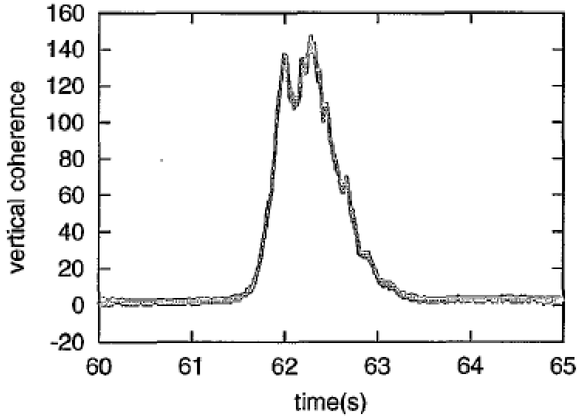
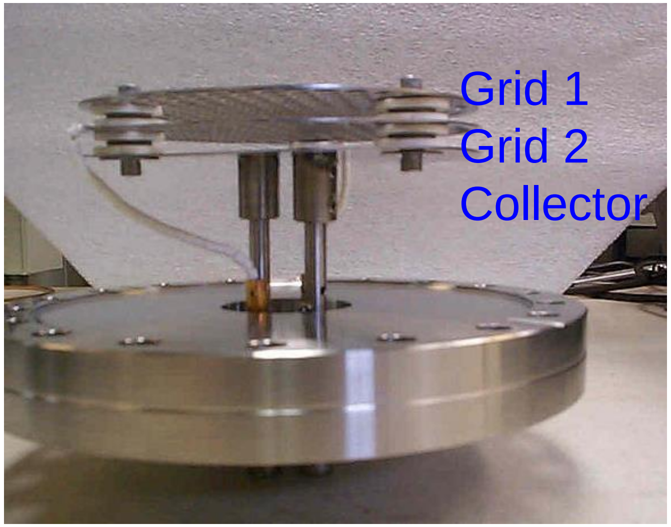


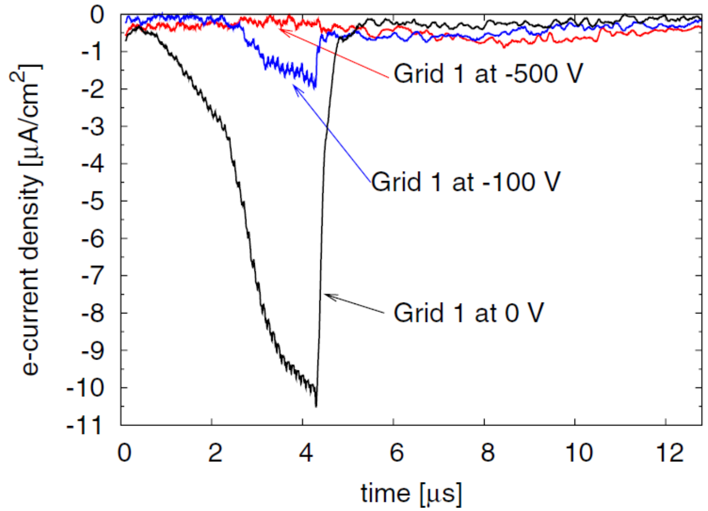
Figure 6: Time series of the 2 strongest principle components for a slower instability. The traces are offset vertically to improve clarity.



Signal used in MCR

Electron Cloud Detector





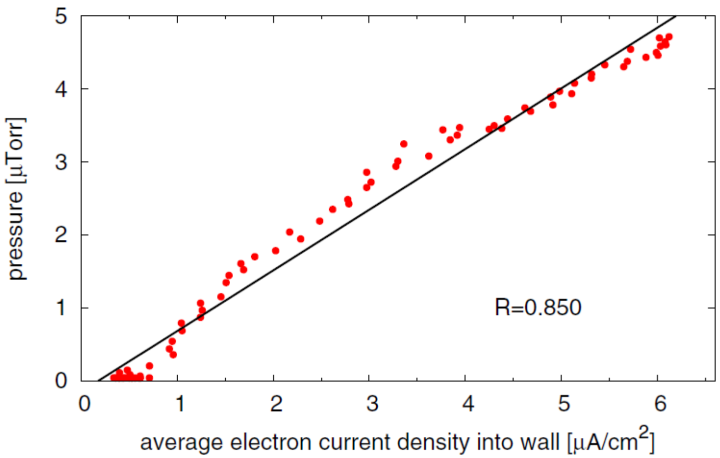
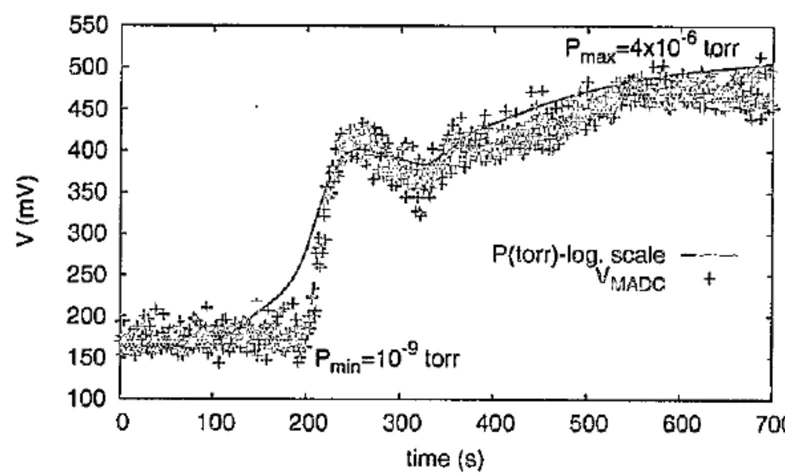


FIG. 10. (Color) Pressure increase vs time-averaged electron current density into the wall. Red dots are measured values, the black line is a linear fit [21,22].

U. Iriso and W. Fischer, PRST-AB 8, 113201 (2005).



EC signal used in MCR

U. Iriso-Arizo, et al, 2003, PAC

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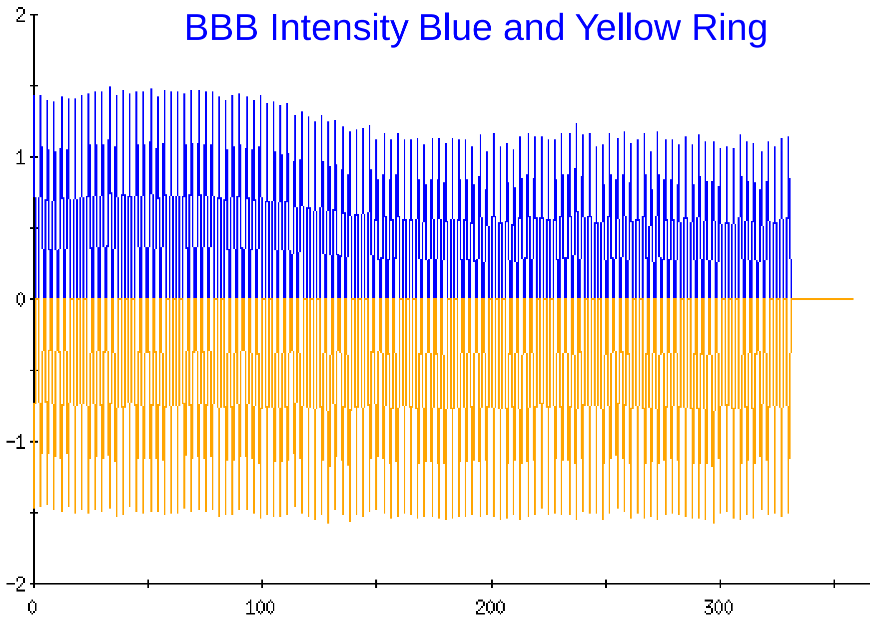
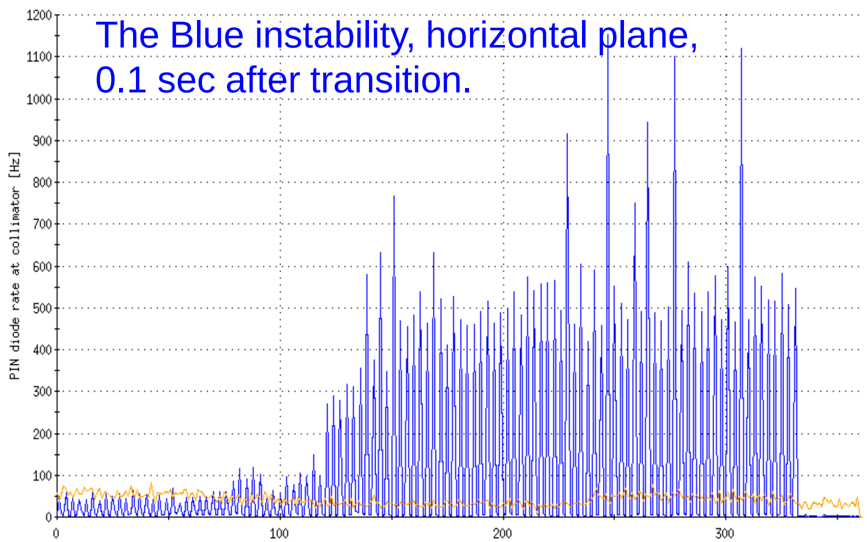
BBB Beam Loss During Transition (Fill18176, 4/6/2014)





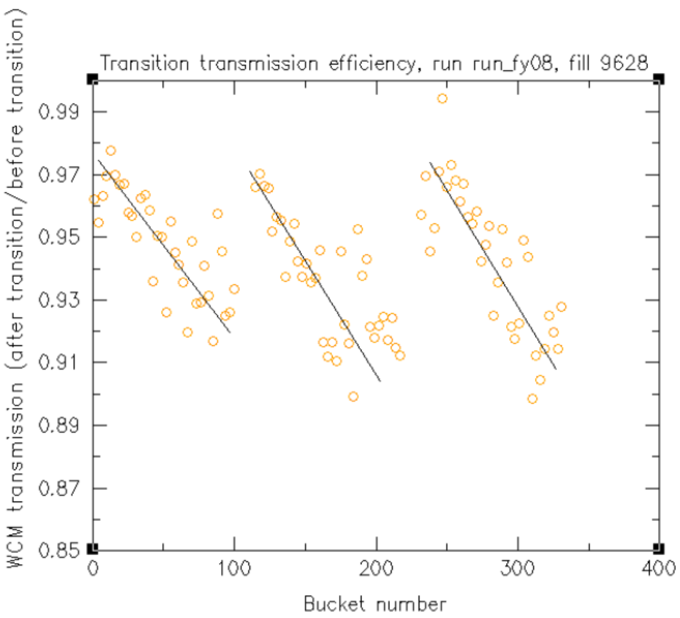
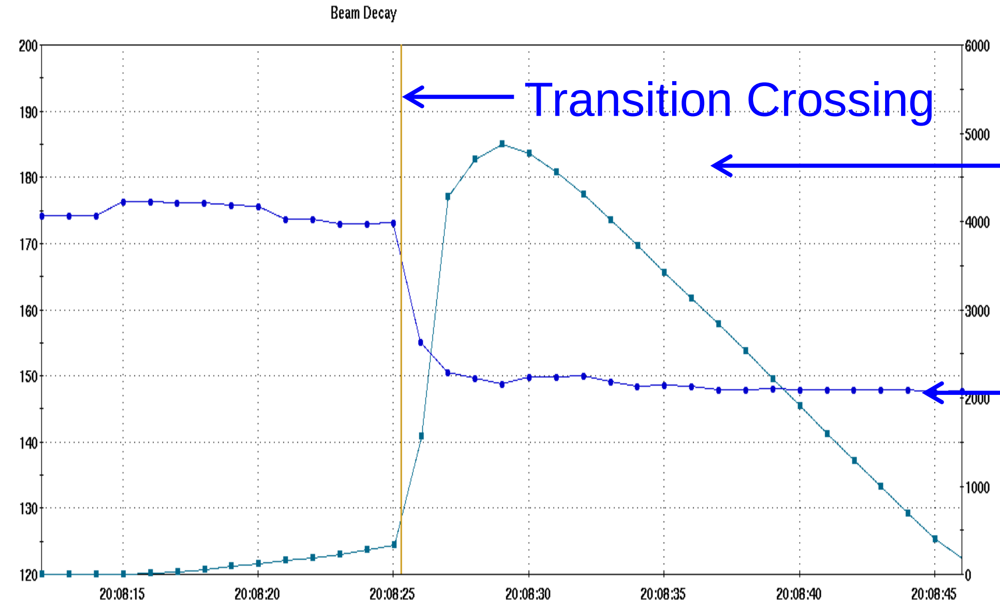


Figure 2: Bunch intensity transmission through the transition in dependence on bunch position in the train.

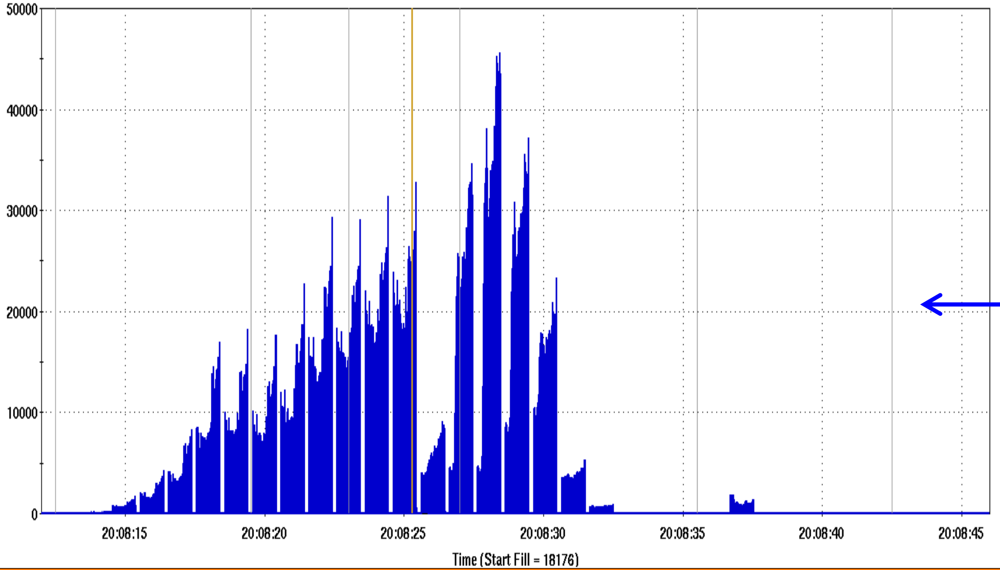
BBB Beam Loss with Gap (Fill9628, 01/23/2008) V. Ptitsyn, et al, HB 2008 WGA04,

Total Beam Loss (Fill18176, 4/6/2014)



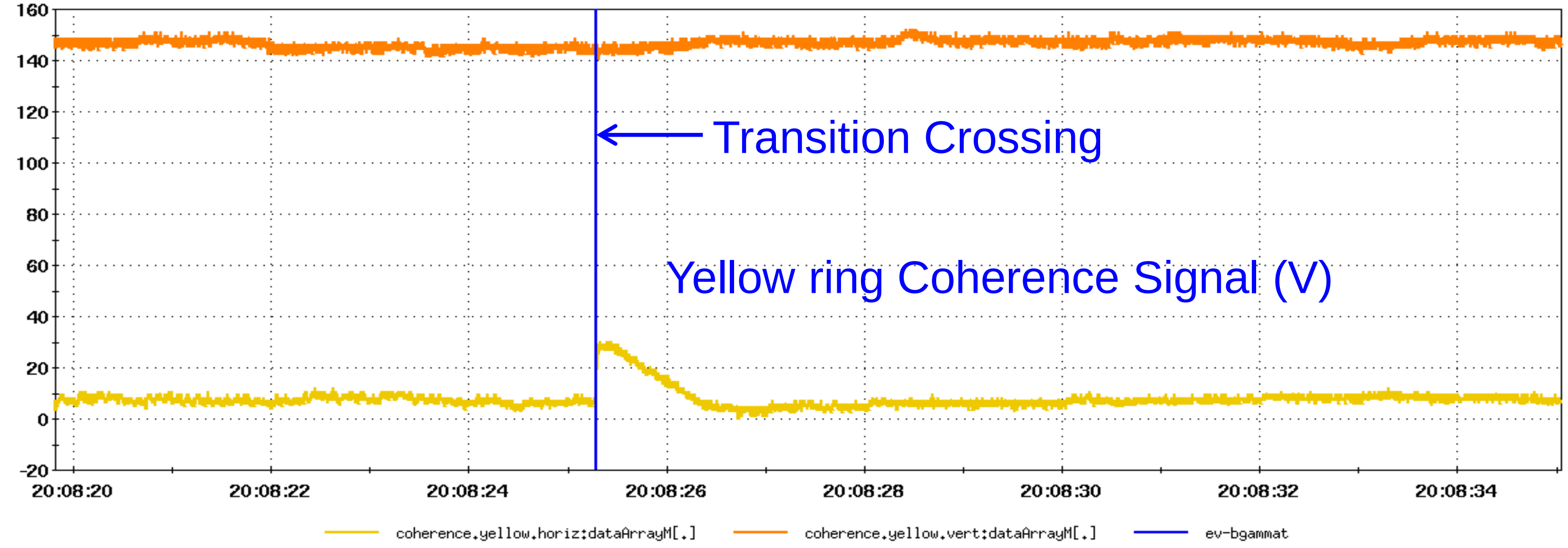
Beam Decay: 4500%/hour

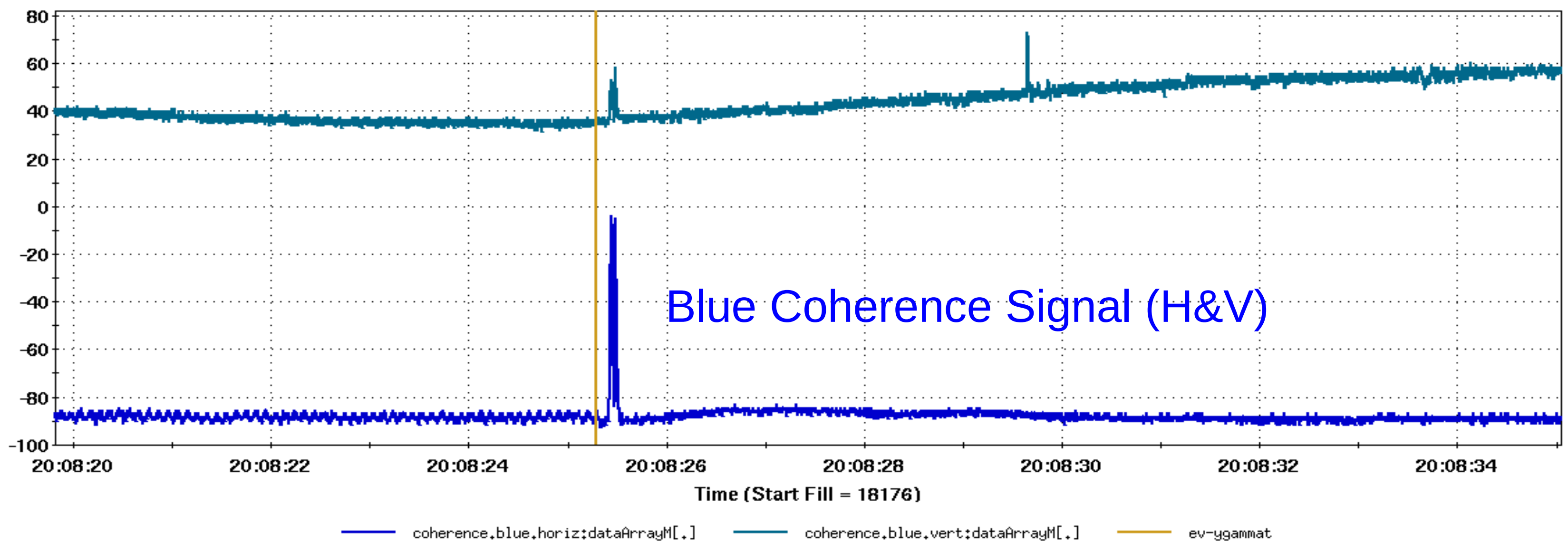
Bunched Intensity:13%



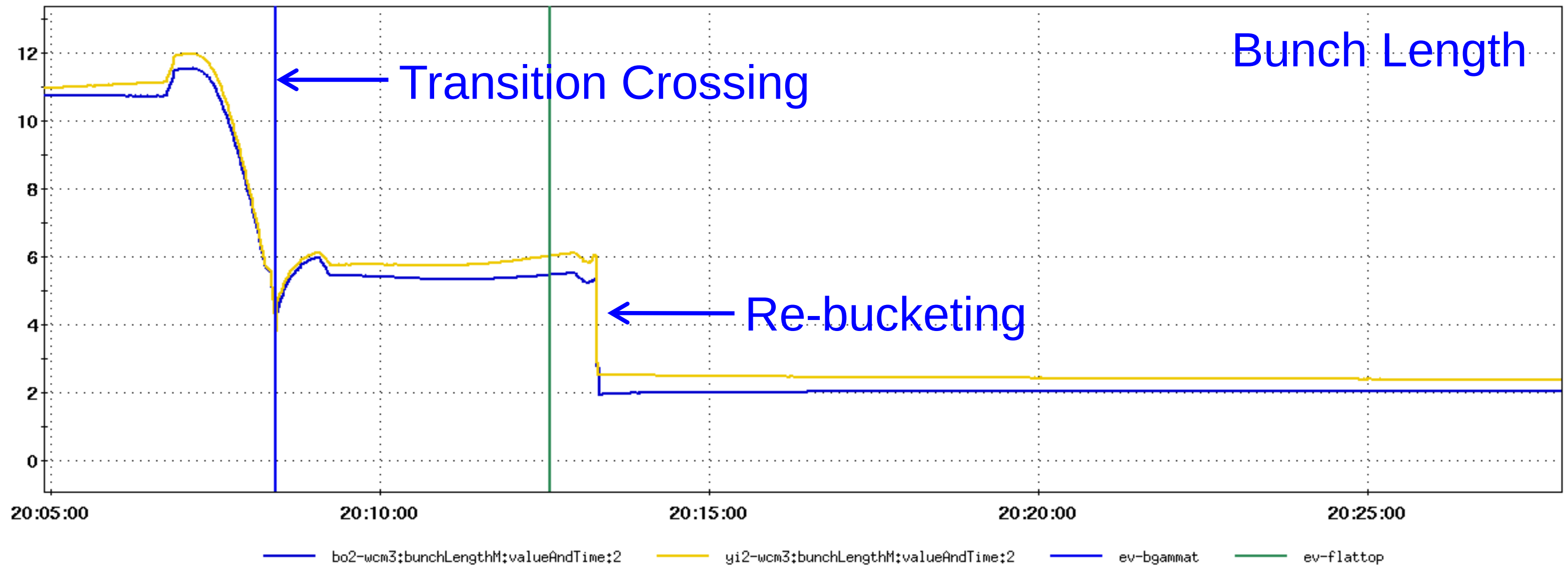
BBB Beam Loss

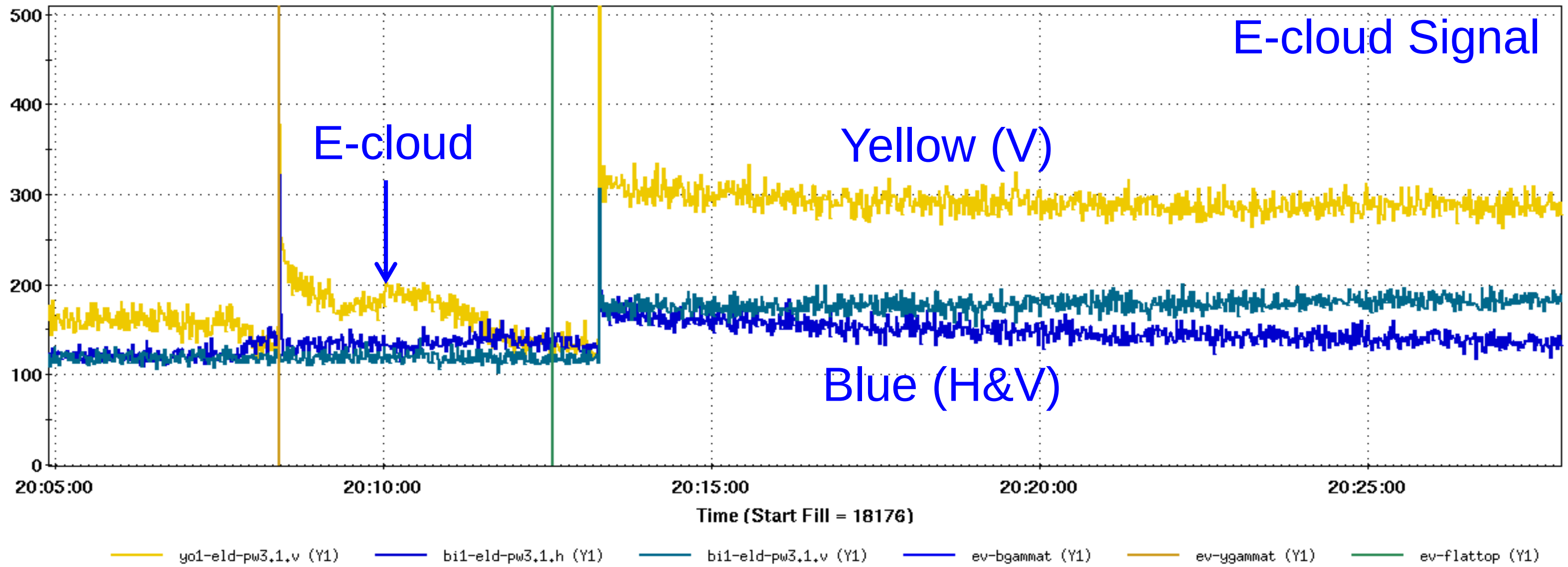
Coherence Signal (Fill18176, 4/6/2014)



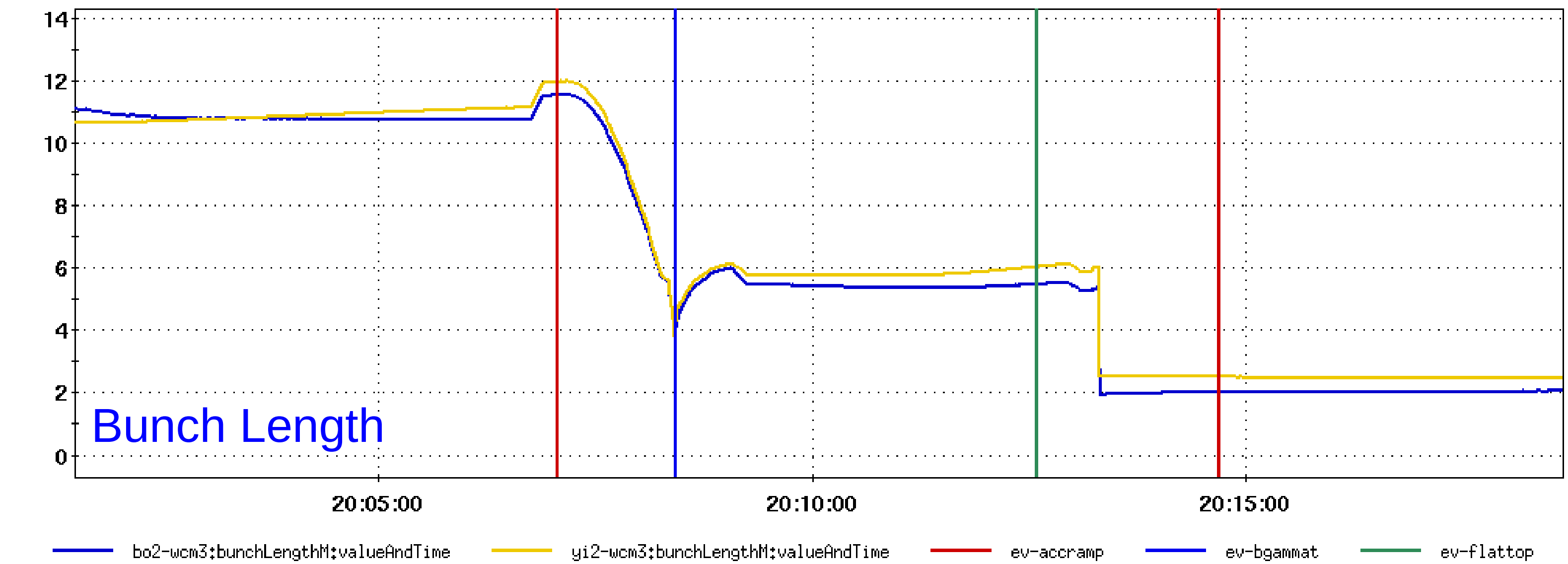


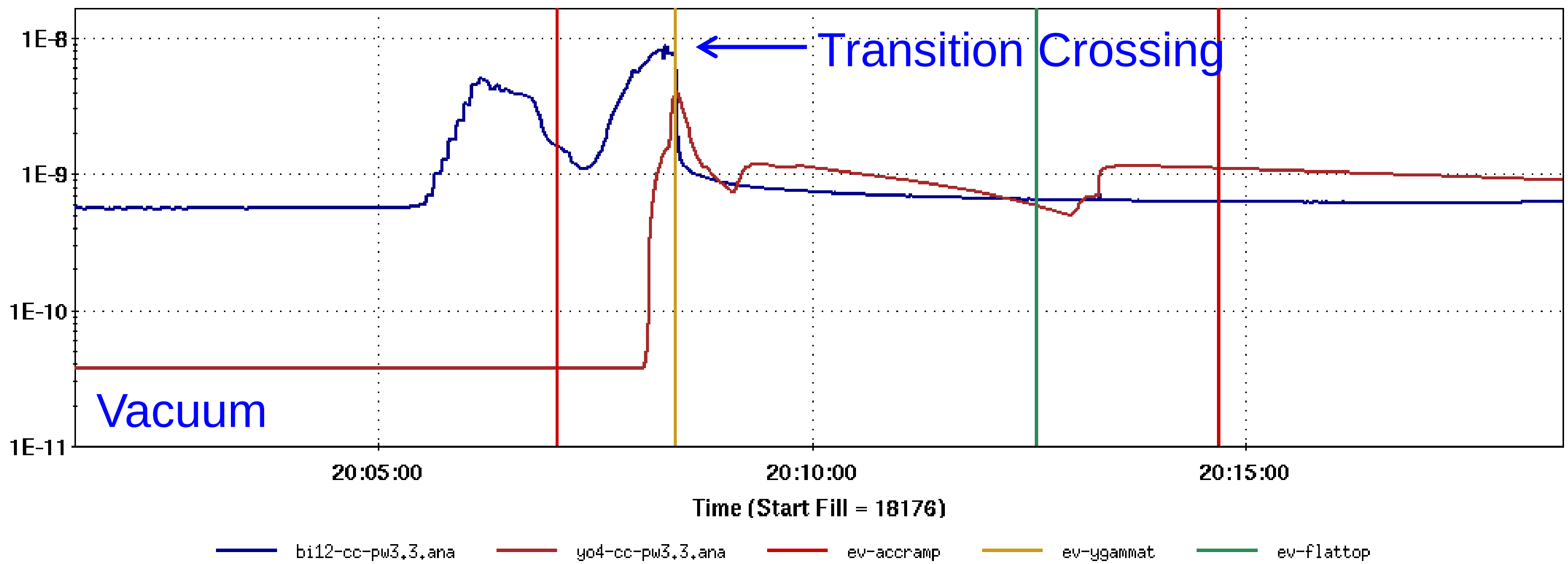
Electron Cloud Signal (Fill18176, 4/6/2014)



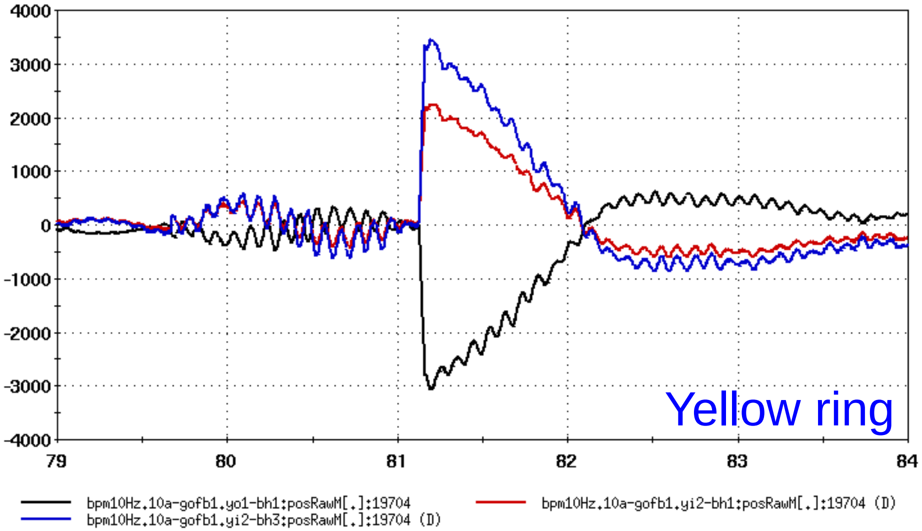


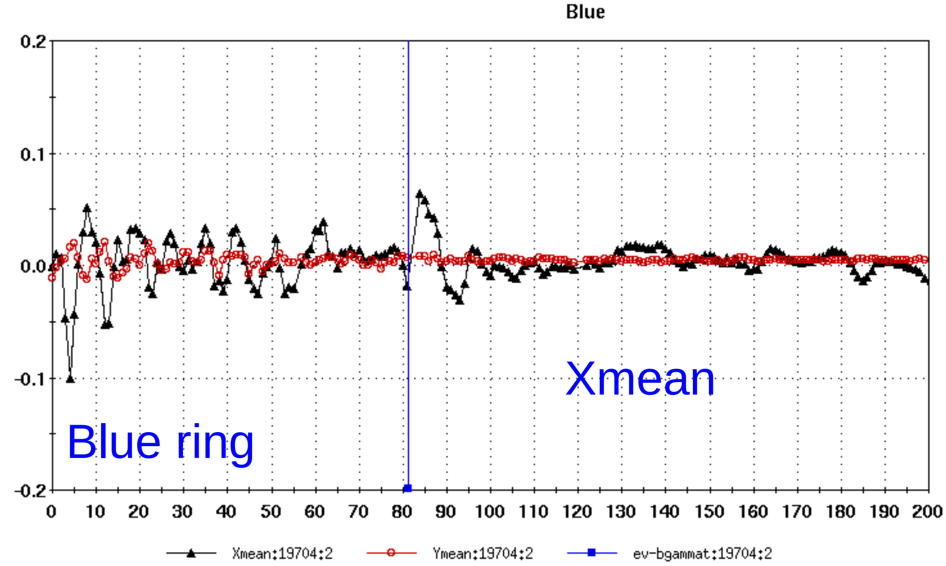
Vacuum (Fill19704, 3/17/2016)

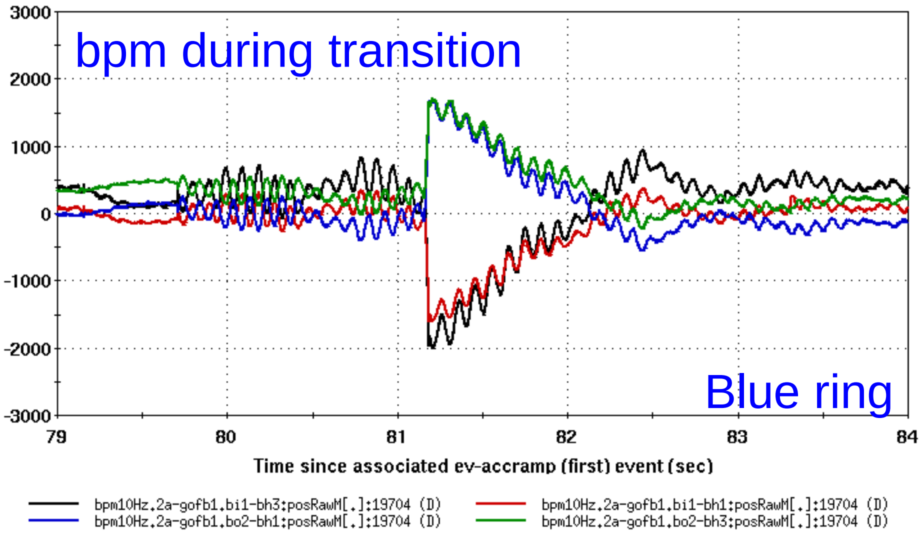


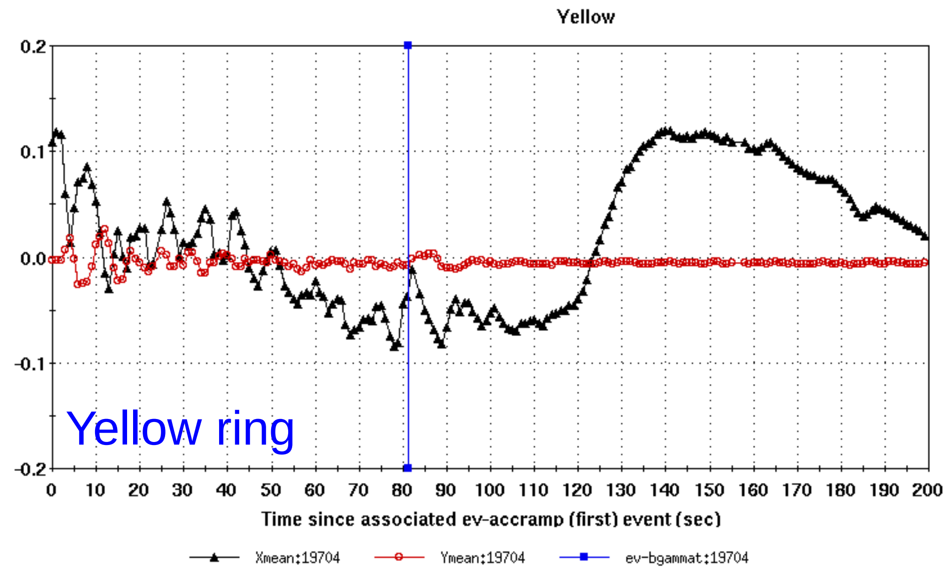


10Hz BPM and Mean Orbit (Fill19704, 3/17/2016)



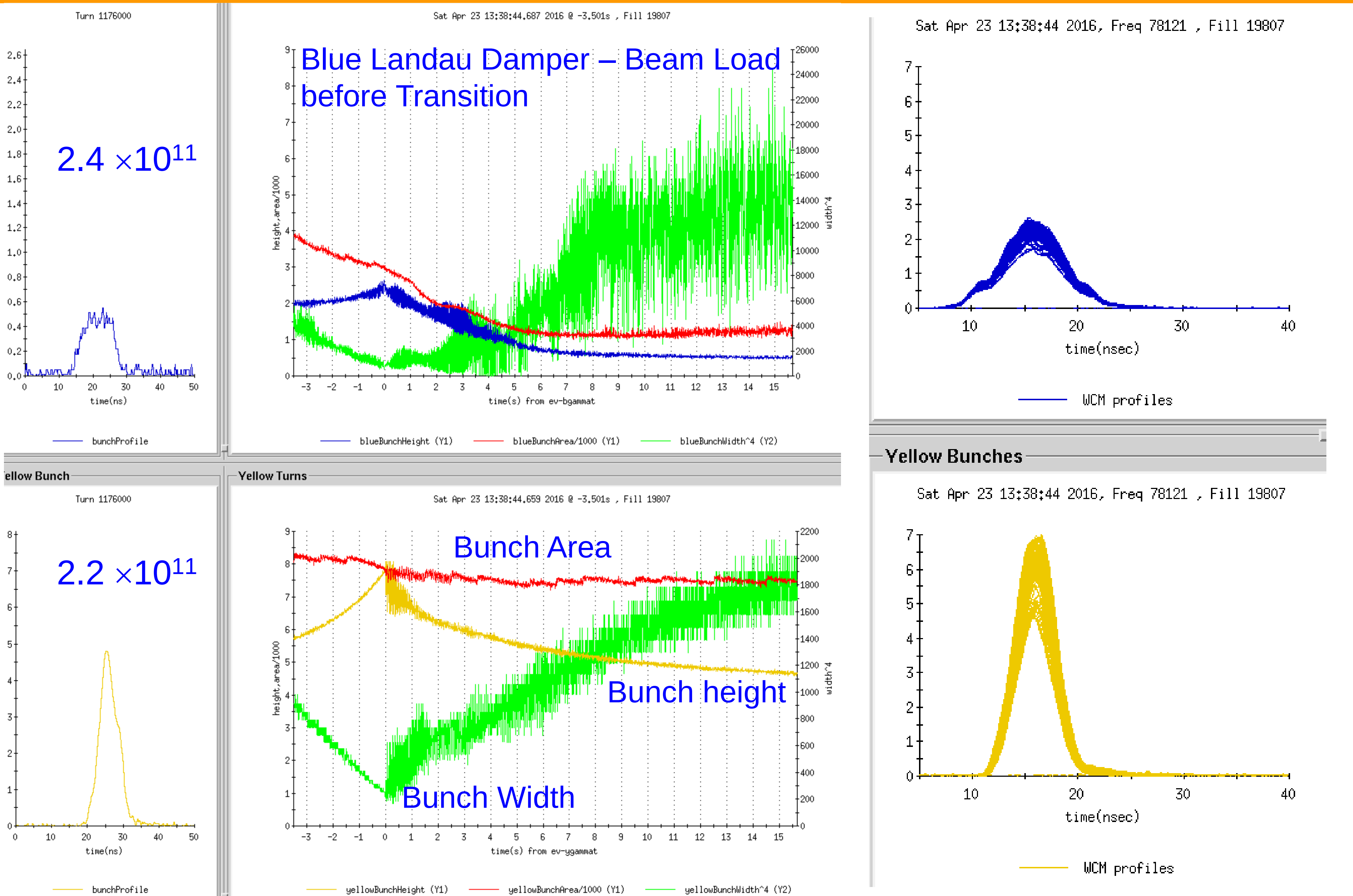






Minty Michiko 2016-03-17elog

WCM and Landau Damping (Fill 19807)



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Used Methods in RHIC for Transition Crossing Control

1. gt-jump implemented
2. Octupoles control
3. Chromaticity control
4. Lower Accelerator RF voltage
5. Landau Cavity for shape Oscillations after Transition
6. Split transition lattice
7. Feedback of quadrupole oscillations

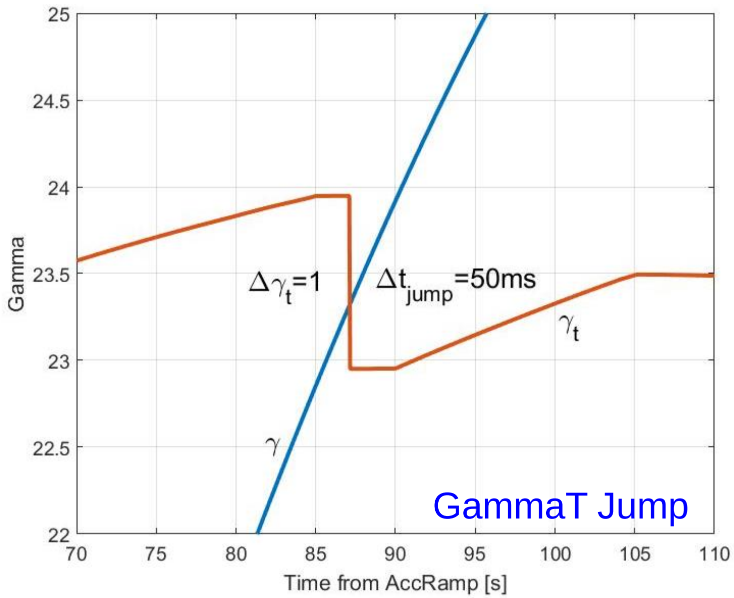
1.In-situ baking

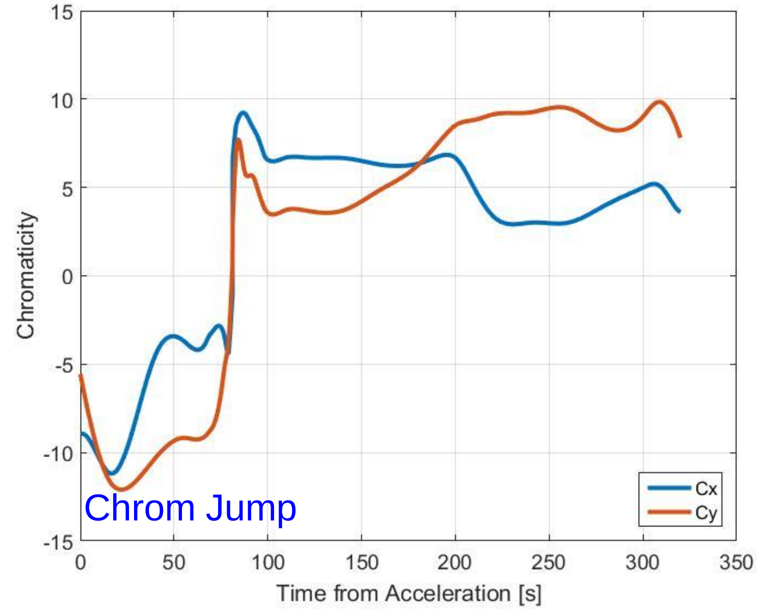
2.NEG

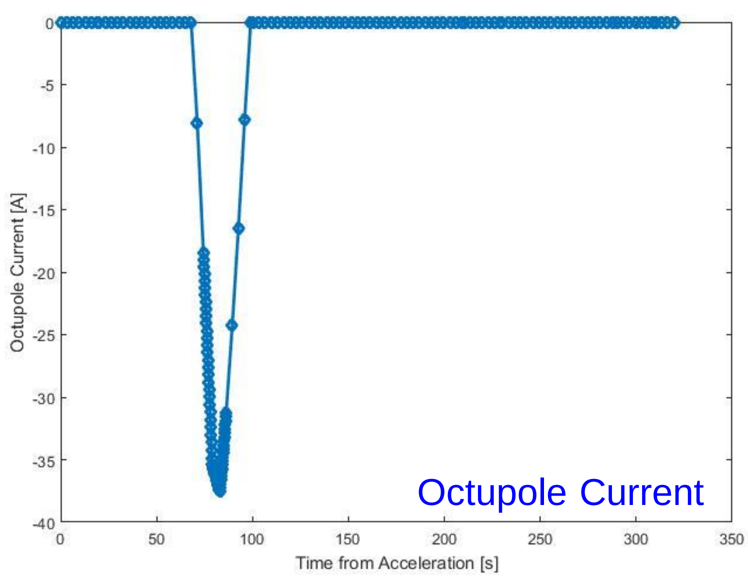
3.Scrubbing

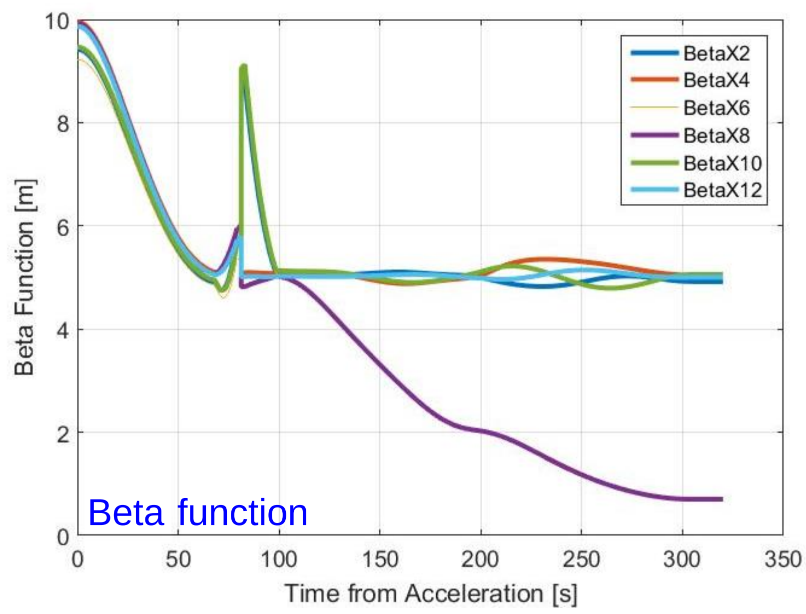
4.Solenoid, anti-grazing rings ….

GammaT Jump and Transition Crossing

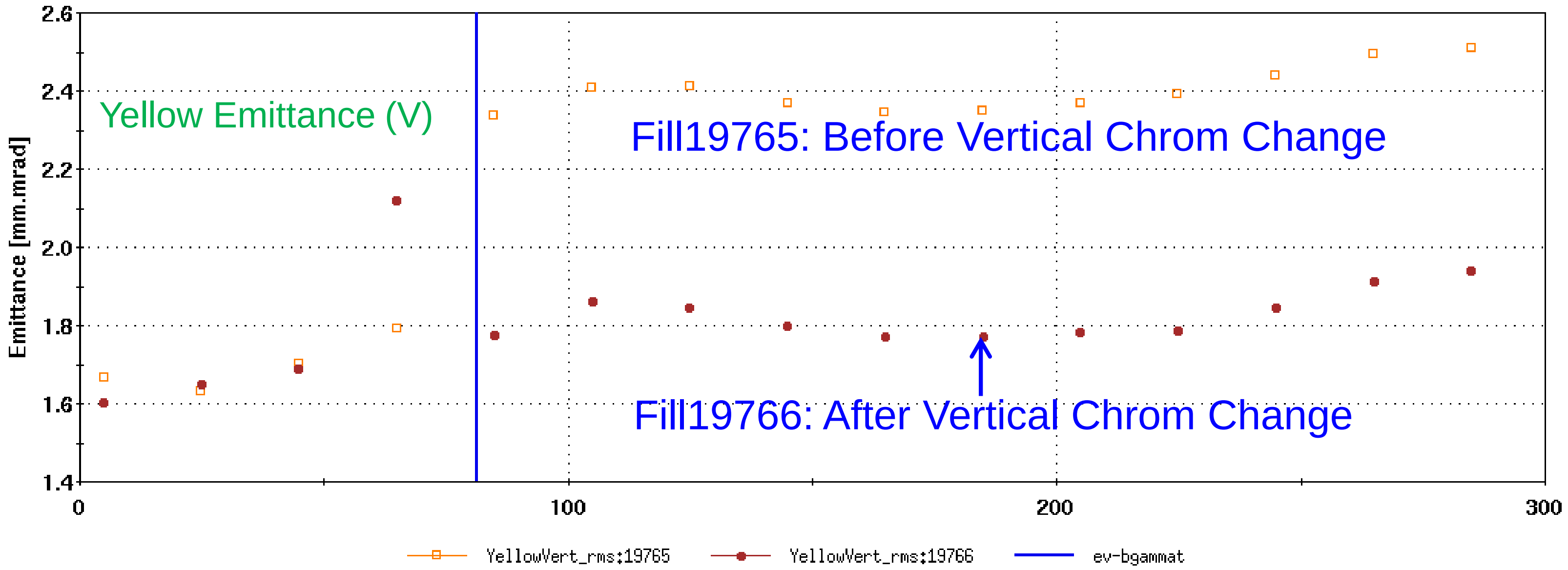


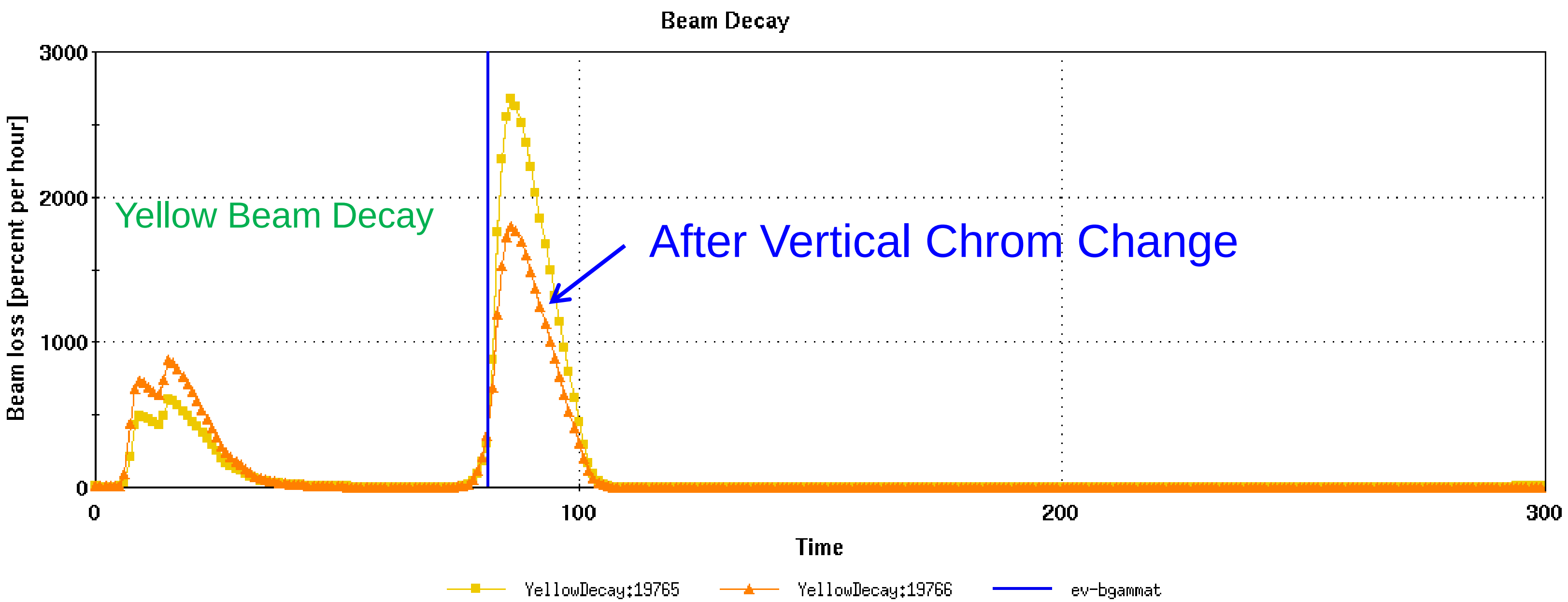




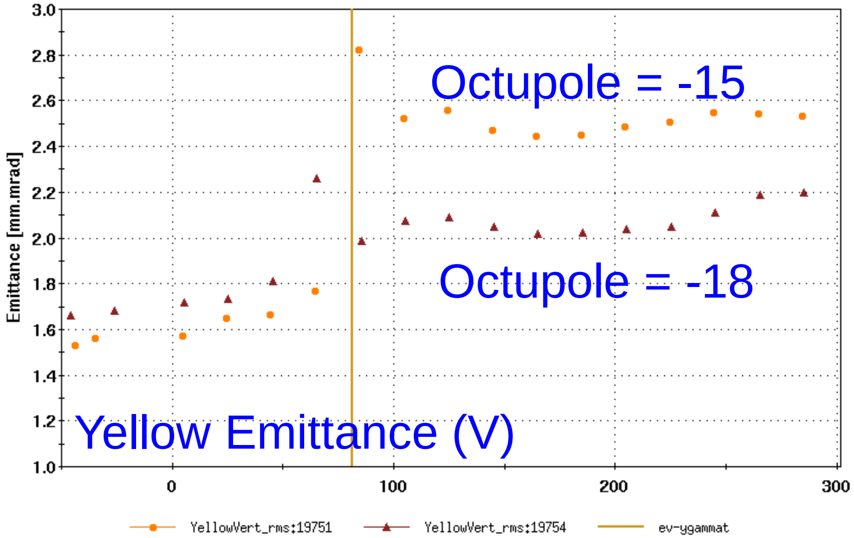


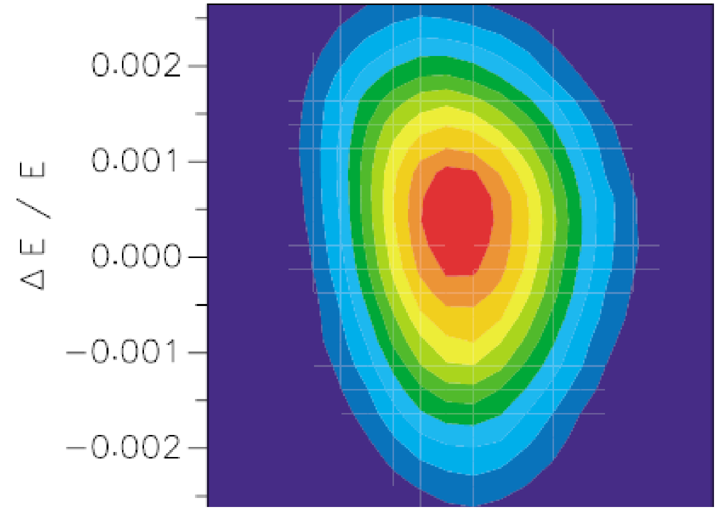
Chromaticity --- Sextuple (Fill19765~19766, 4/13/2016)

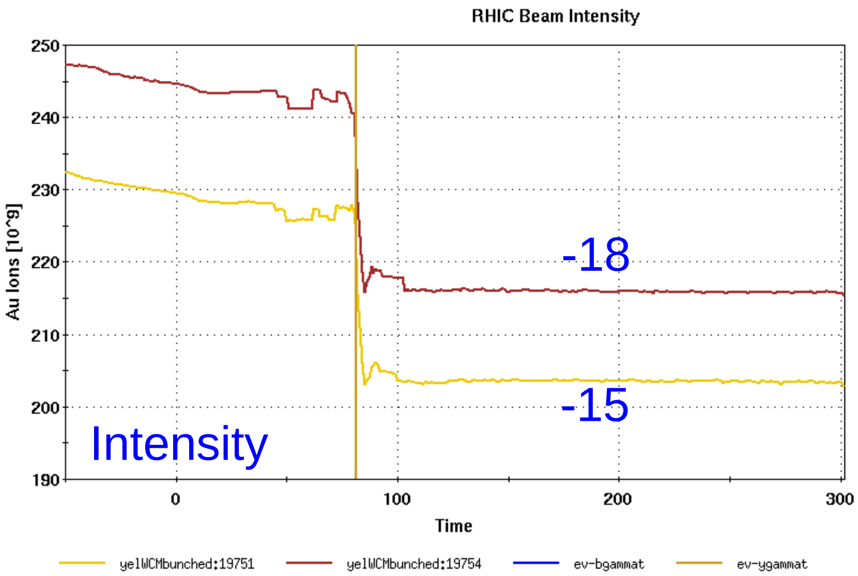


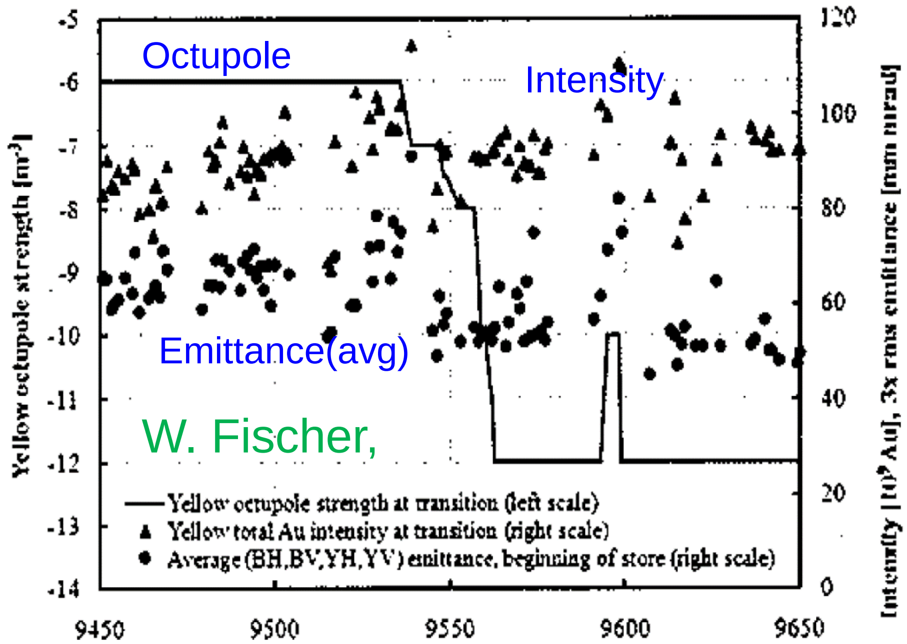


Octupole for tune spread (2002, Fill9450~9650,2008 and 19751-19754, 2016)



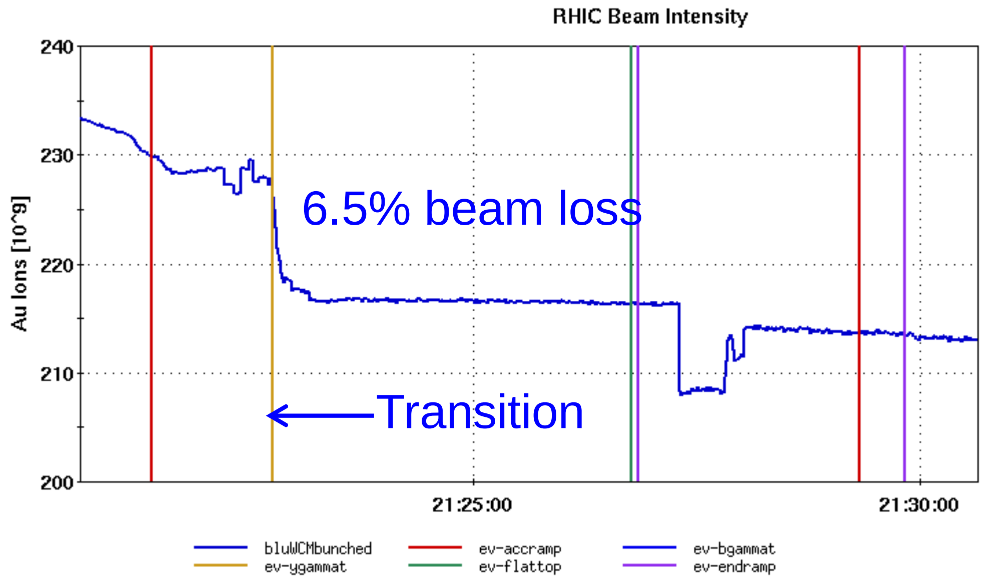






C. Montag, J. Kewisch, D. Trbojevic and F. Schmidt, PRST-AB 084401 (2002)

Accelerator Cavity Voltage (Fill 19679)



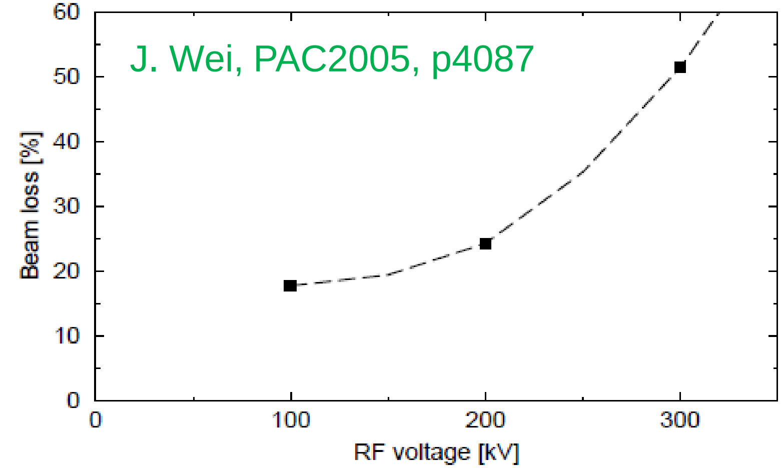
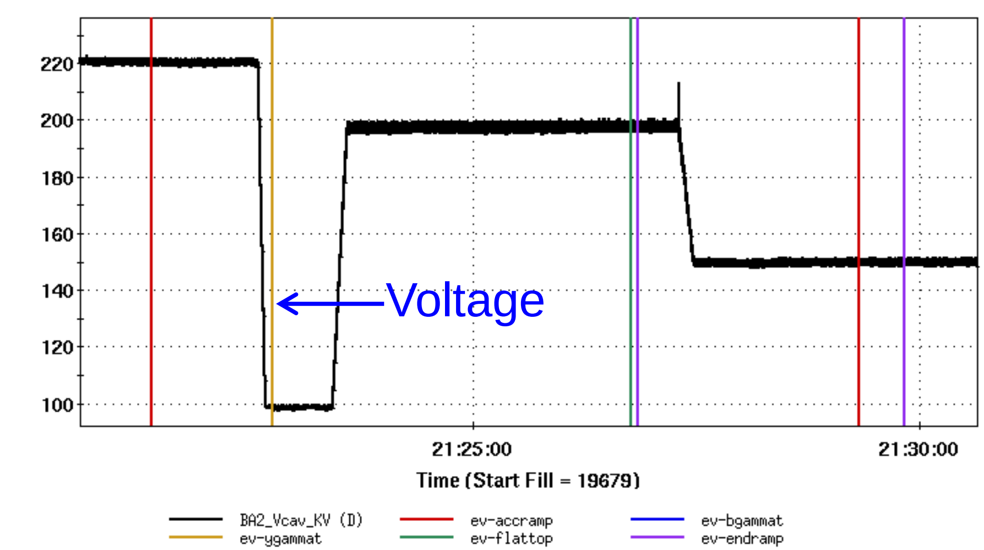
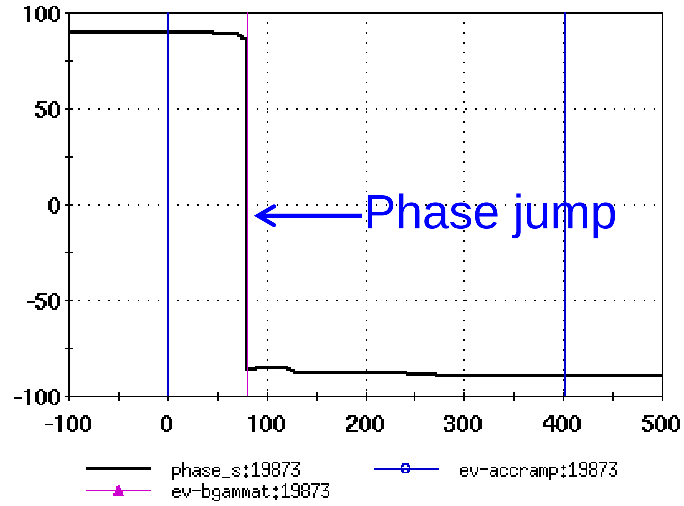


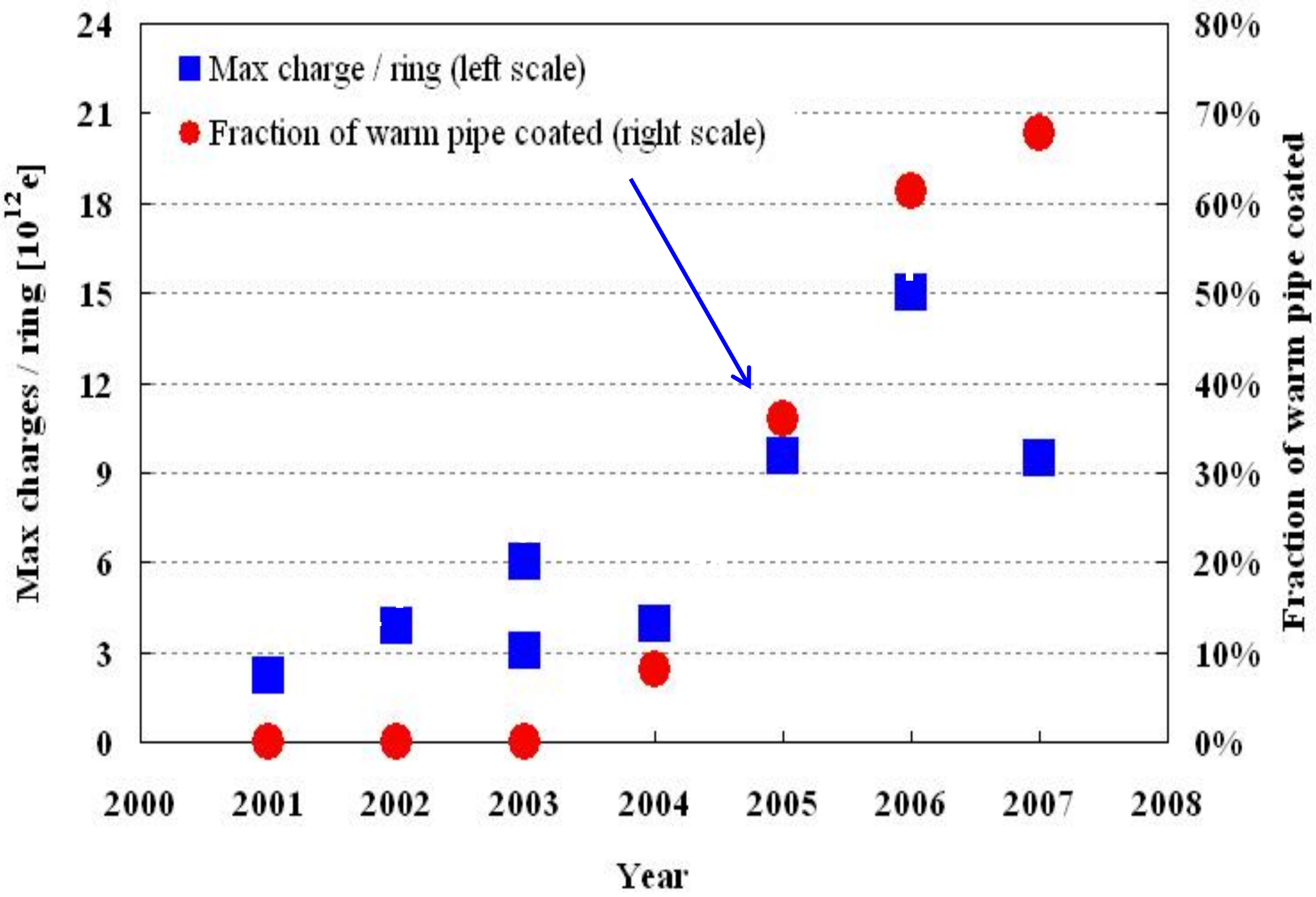
Figure 4: Average beam loss at transition as a function of the RF voltage with $b_{oct} = -3$ unit.





E-cloud: NEG coating in RHIC

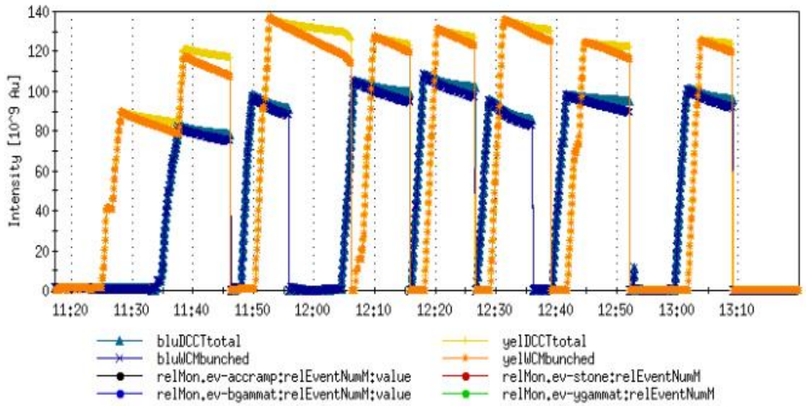
NEG coating started from 2005, increased the total stored charge in operation

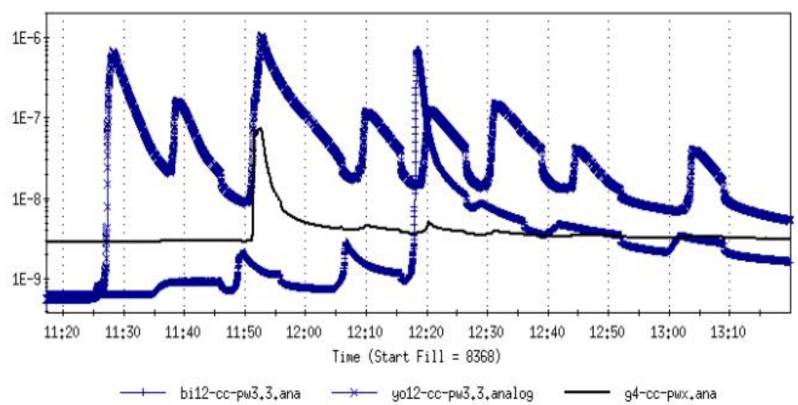


Notes: charge also limited by effects other than total charge (injectors, transition), dynamic pressure can be limited by single location (experiment).

Ecloud: scrubbing with Au and Proton

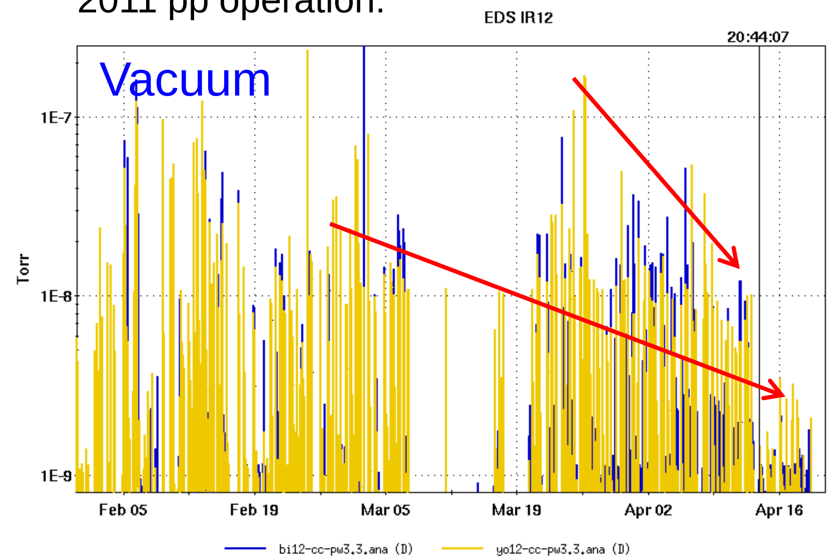
Scrubbing used in 2007 Au-Au operation:

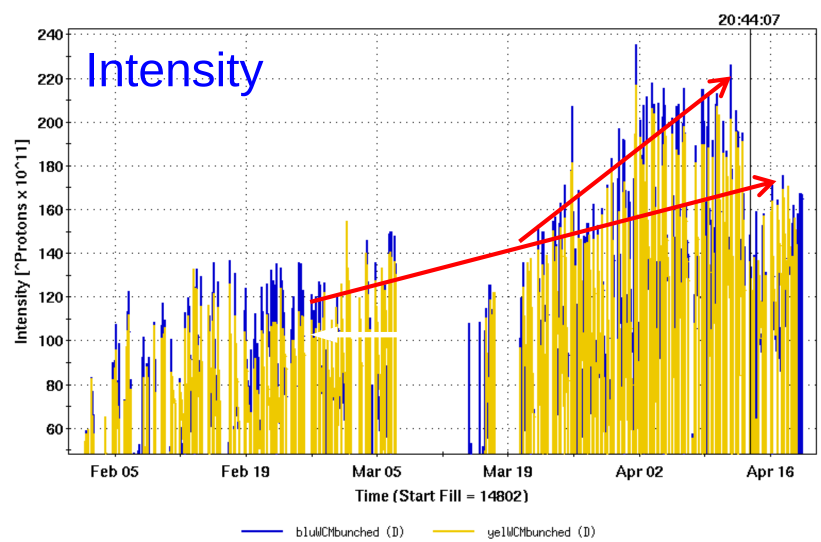




7 high intensity fills in about 2 h, Reduced dynamic pressure in worst location by more than 1 order of magnitude

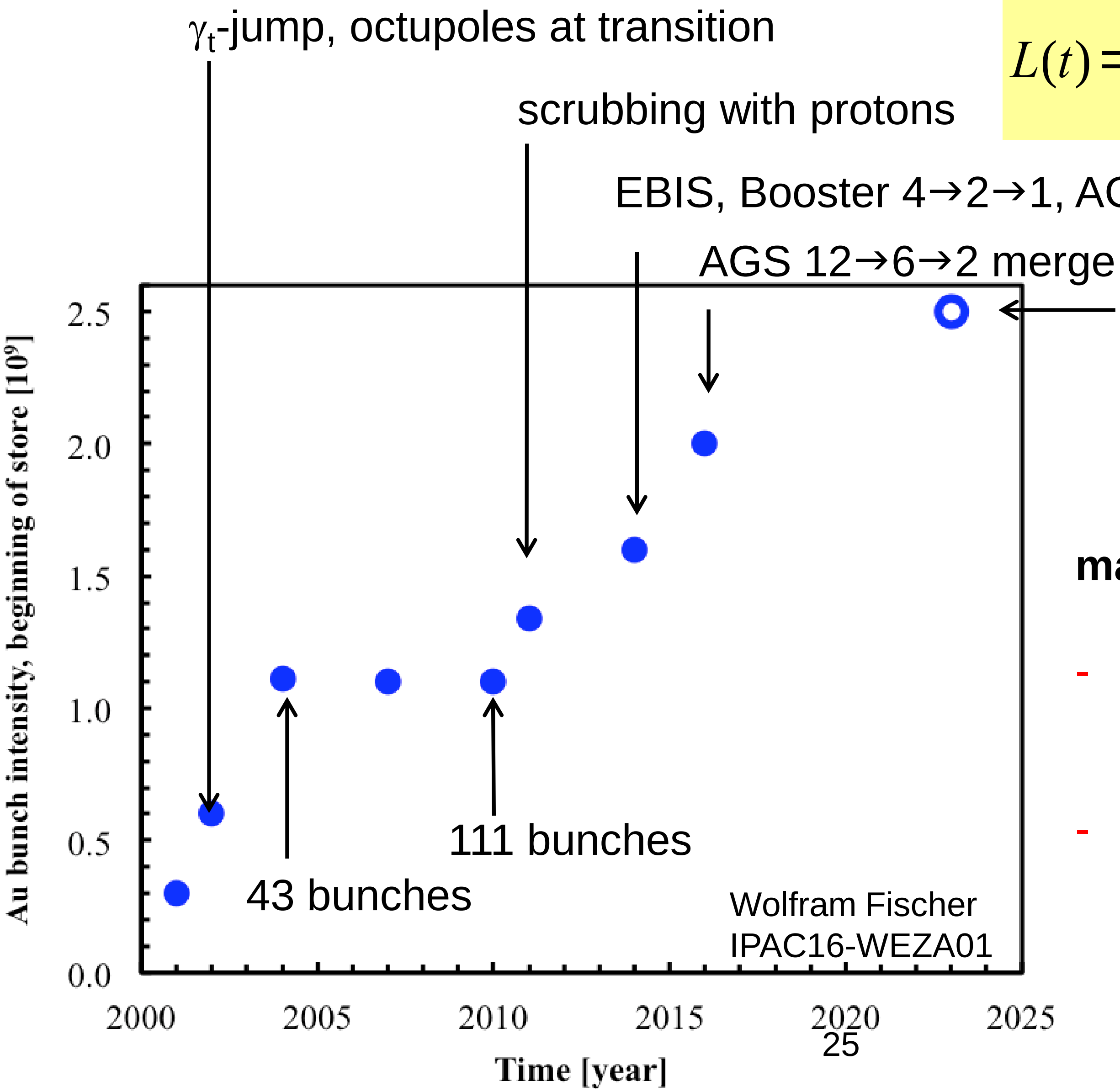
2011 pp operation:





Au Bunch Intensity Evolution

$$L(t) = \frac{1}{4\pi} f_0 N \frac{N_b^2(t)}{\epsilon(t)\beta^*(t)} h(\beta^*, \sigma_s, \theta)$$



main limits:

- **transition instability in RHIC (e-clouds)**
- **Machine protection**

H. Huang, K. Gardner, K. Zeno, RF, et al.

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Summary

- all ions excepts protons cross transition in RHIC, a relatively slow ramping sc machine
- observed transition instabilities with rise time as fast ~15 ms in the past
- clearly driven by electron clouds
- presently not limiting operations after implementation of a number of mitigation measures
- Used methods include gamma-t jump, octuples, fast chromaticity change, RF voltage, tune and orbit control, NEG coating of warm pipes, scrubbing over several years

More Methods for Transition Crossing Control

1. Reactive loading for less impedance
2. Rf system feedback
3. Avoiding phase jump by continuously varying phase and voltage
4. Artificial blow up longitudinal emittance
5. Using flattened rf (9MHz and 28MHz)
6. Temporarily changing the orbit circumference using programmed V and phase
7. Rf manipulation to eliminate bunch length oscillation.
8. Reduce rf voltage
9. Simulation?

Handbook of Accelerator Physics and Engineering, 2nd print. J. Wei, p286

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Thank you.