

Understanding Lifetimes, Beam Sizes and Gas Scattering in IOTA

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FAST/IOTA Collaboration Meeting
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Goals and Objectives

■ Goals

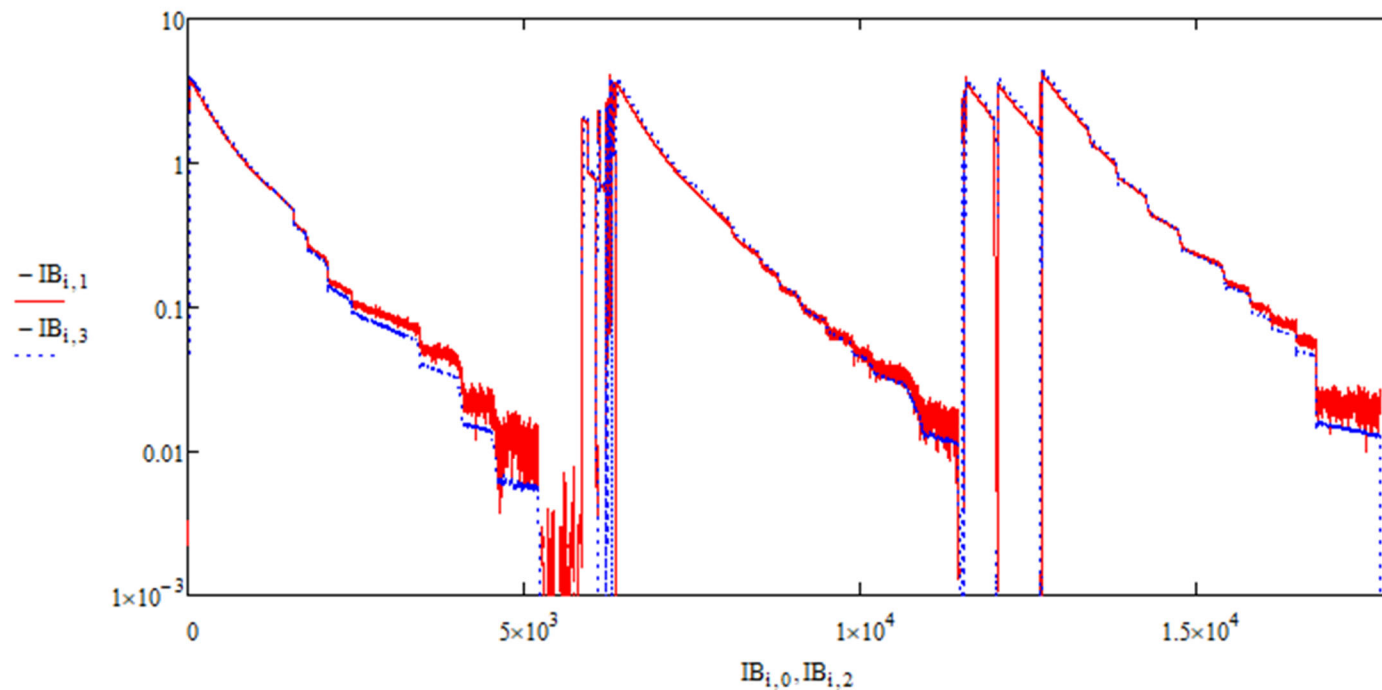
- ◆ Verify accuracy of our instrumentation
 - Beam emittances
 - Bunch length
 - Momentum spread
 - Bunch and beam current measurements
- ◆ Optics verification as a byproduct of beam size measurements
 - Coupling control
- ◆ Measurements and calibration of RF voltage
 - Beam deceleration due to interaction with vacuum chamber and RF
 - Characterization of longitudinal impedance
- ◆ Characterization of vacuum (very important for the OSC)

■ The above measurements/parameters are related through: IBS, Touschek scattering, scattering at the residual gas, longitudinal impedance, RF voltage calibration

- ◆ Verification of theory:
 - IBS
 - elastic and inelastic gas scattering

Acquired Data

- Two shifts of the IBS measurements
 - ◆ March 6, 2020: IBS in Uncoupled and 100% coupled lattice
 - ◆ March 17, 2020: IBS in Uncoupled lattice only
- 2 data sets for uncoupled measurements still have different coupling
- All data are logged and extracted later for the analysis
- Beam was scraped, time-to-time, to accelerate measurements



Beam current from DCCT & WCM for 3 measurement of March 6 (2 uncoupled & coupled)

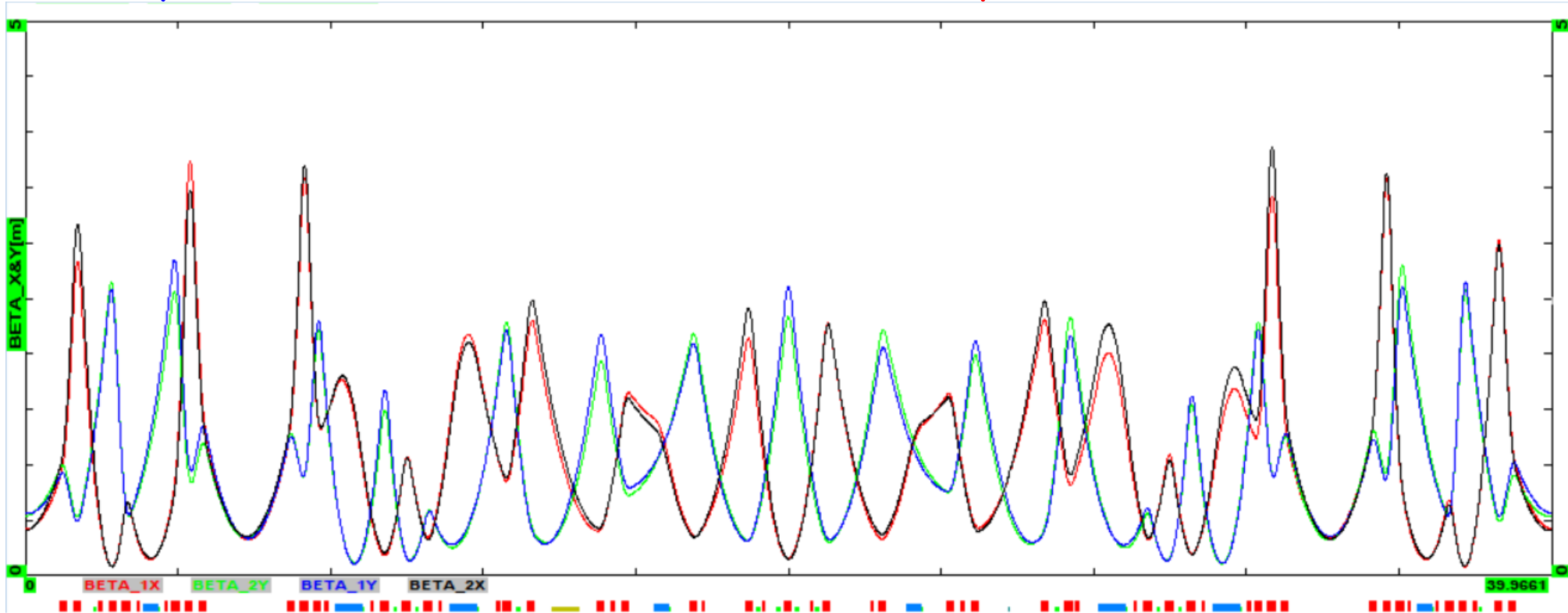
Simulations of Beam Parameters Evolution

- What is accounted
 - ◆ SR damping and heating
 - ◆ Single (Touschek) and multiple IBS
 - ◆ Single and multiple scattering at the residual gas
 - Elastic (Rutherford) scattering limits minimum achievable vertical emittance
 - Inelastic scattering
 - Energy loss due to residual gas ionization
 - negligible for our parameters
 - Bremsstrahlung (γ -radiation at collisions)
 - Suspected to be a major mechanism of particle loss at small current
- RF voltage was calibrated to good accuracy
- Machine acceptances are measured with the beam kicks
- Beam optics was measured and is in good shape

Measurements in x-y Coupled Beam Optics

Coupled Beam Optics

- Beam parameters evolution in coupled optics is more difficult for analysis but the model does not have free parameters!!!



After careful decoupling, the coupling was introduced by SQA1L, GdL= 200 G, Tune split: 0.015

Damping parameters: $g_1 = 0.685$, $g_2 = .678$, $g_z = 2.636$

Equilibrium rms emittances: $\varepsilon_x = 12.8$ nm, $\varepsilon_y = 13.8$ nm

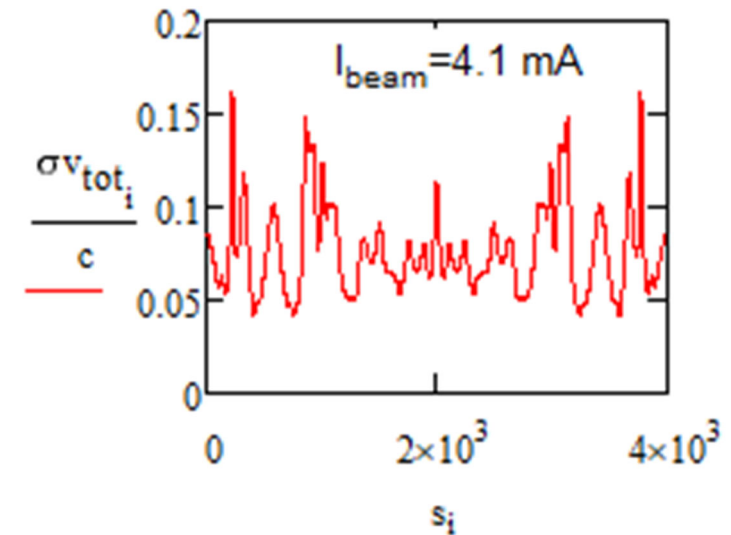
Equilibrium relative rms momentum spread: $\sigma_p = 8.75 \cdot 10^{-5}$

Emittance damping time: $\tau_1 = 3.51$ s, $\tau_y = 3.54$ s, $\tau_s = 0.91$ s

Understanding Lifetimes, Beam Sizes and Scattering in IOTA, V. Lebedev

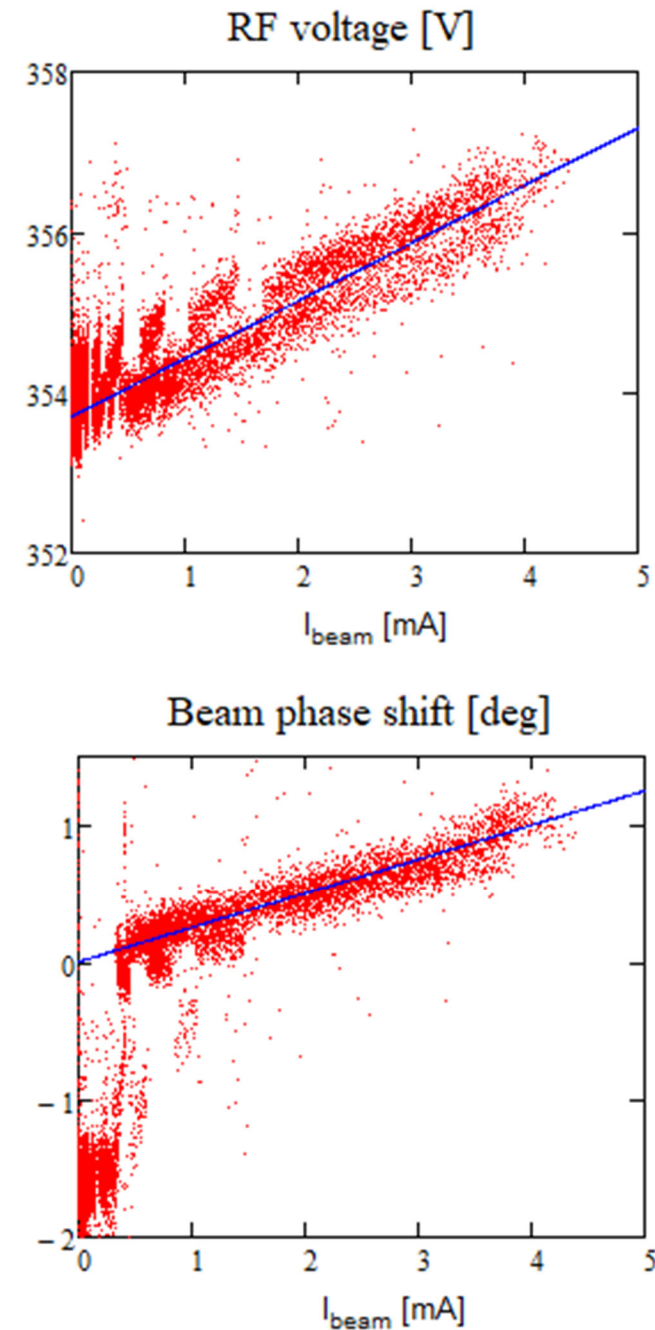
Theoretical Analysis Used in Coupled Optics

- 4D Twiss parameters used in computation of single and multiple IBS
 - ◆ Analysis assumes non-relativistic beam in the beam frame
 - Getting close to be incorrect at maximum current of 4 mA
 - ◆ Assume: $\text{momentum_spread} \ll \text{bucket_size}$ in Touschek rate computation
 - $\sigma_p / (\Delta p/p)_{\text{sep}} \in [0.04, 0.15]$ for beam current in the range $[0, 4]$ mA
 - Correction is computed separately
- The only unknown parameter is the effective pressure of residual gas
 - ◆ Emittances set by SR: $\varepsilon_{1\text{SR}} = 12.1 \text{ nm}$ $\varepsilon_{2\text{SR}} = 13.0 \text{ nm}$
 - ◆ Emittances set by the residual gas scattering: $\varepsilon_{1\text{gas}} \approx \varepsilon_{2\text{gas}} \approx 0.42 \text{ nm}$
 - These values are obtained from measurements with uncoupled optics
- The effective pressure does not play any role on the beam parameters evolution with exception of the beam lifetime set by gas scattering at small beam current when Touschek is negligible



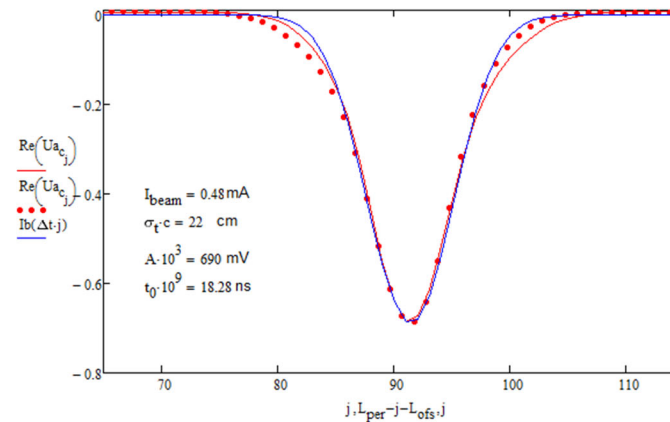
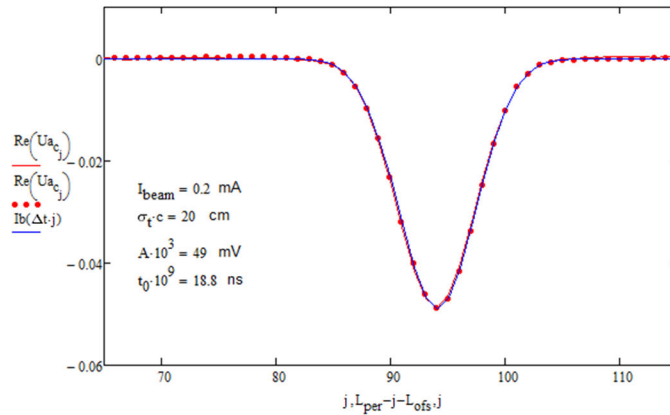
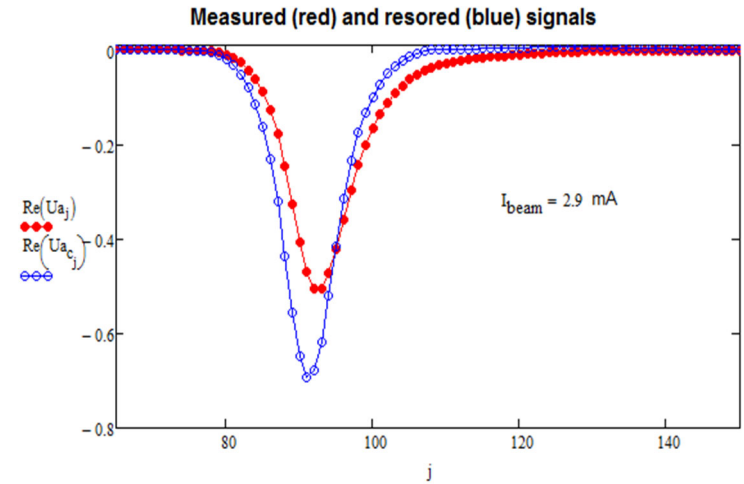
Beam Induced Voltage at RF Cavity

- RF voltage is measured by the RF cavity prob with online computation from the scope measurements
- Measurements show negligible effect of the beam current on the RF voltage and phase
 - ◆ The measurements yield:
 $dV_{RF}/dI_{beam}=0.72 \text{ V/mA}$
 - ◆ Measurements also show that the beam current shifts the RF voltage phase relative to the beam: 0.25 deg/mA



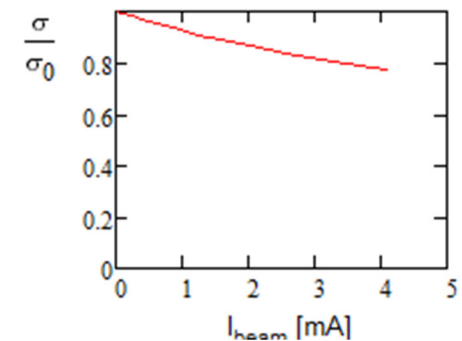
Beam Self-Compression

- We correct the dispersion and damping in the WCM monitor cabling
- At small current the bunch longitudinal distribution is Gaussian
- It starts getting non-gaussian tails and visible bunch self-compression with current increase

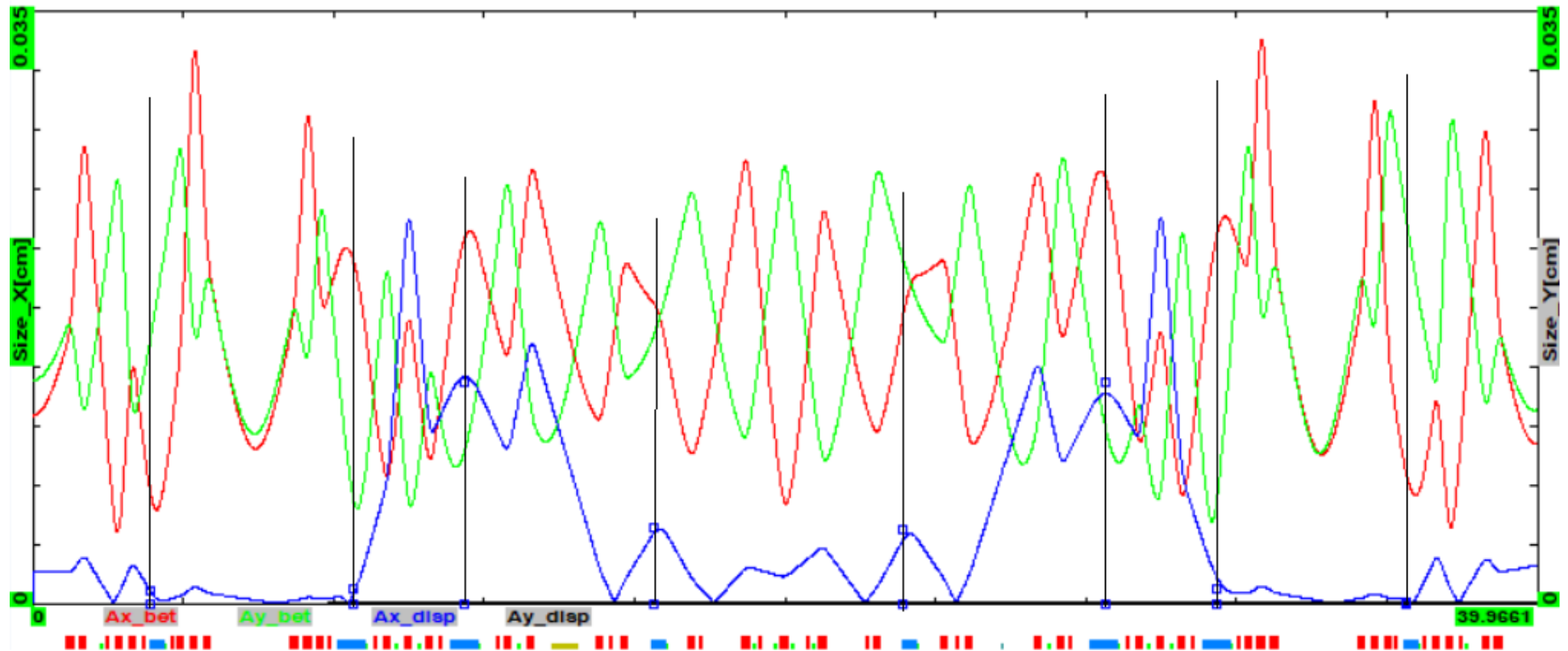


- Simple model for bunch self-compression

$$\sigma_s = \frac{\sigma_{s0}}{\sqrt{1 + WN_e}}, \quad \sigma_{s0} \propto \sqrt{V_{RF}}, \quad W = 2 \cdot 10^{-10}$$



Beam Size Measurements in Coupled Optics

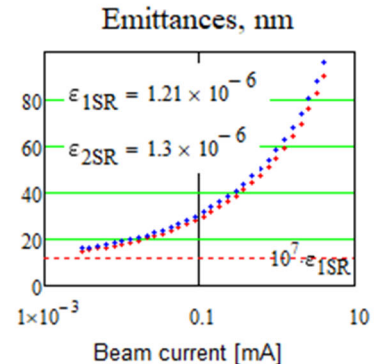
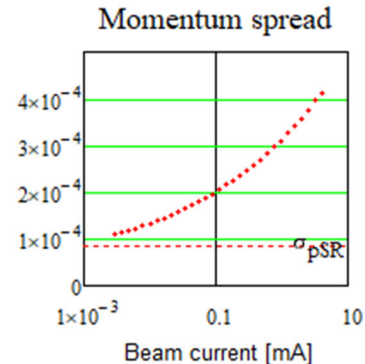
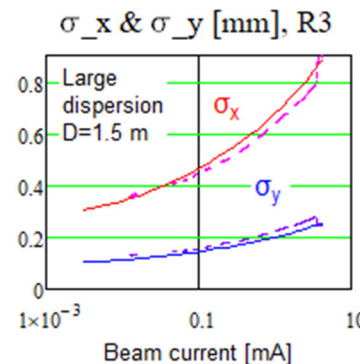
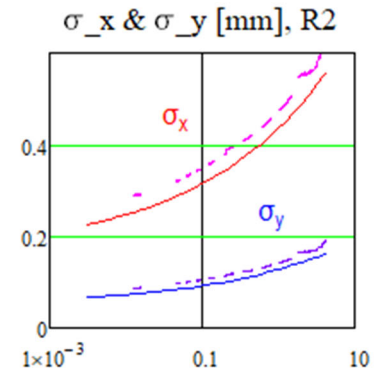
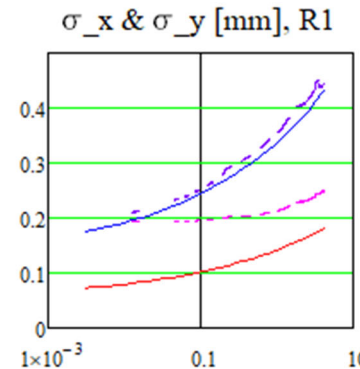
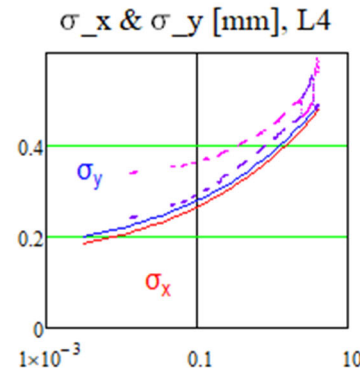
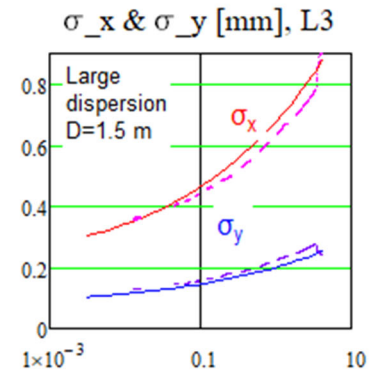
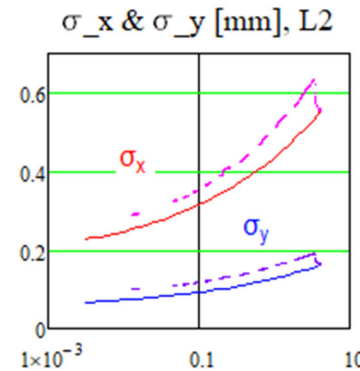
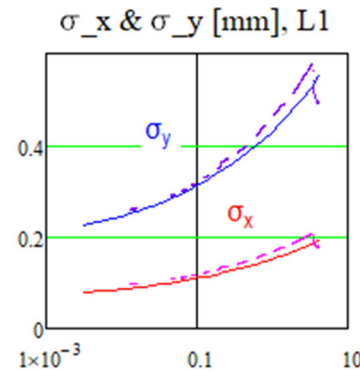


Rms bunch sizes for small beam current (SR driven, no IBS). Vertical lines mark sync-light locations

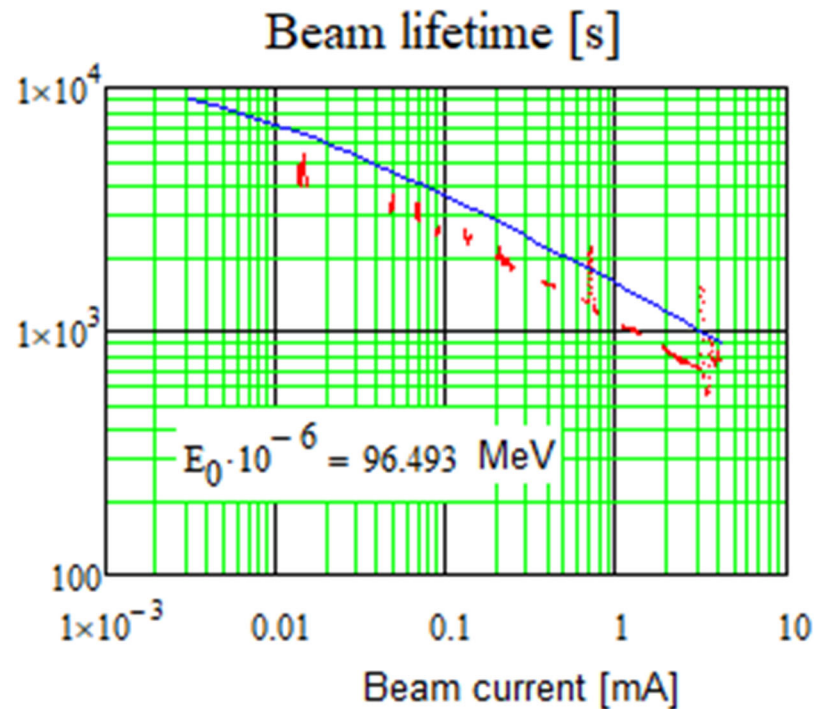
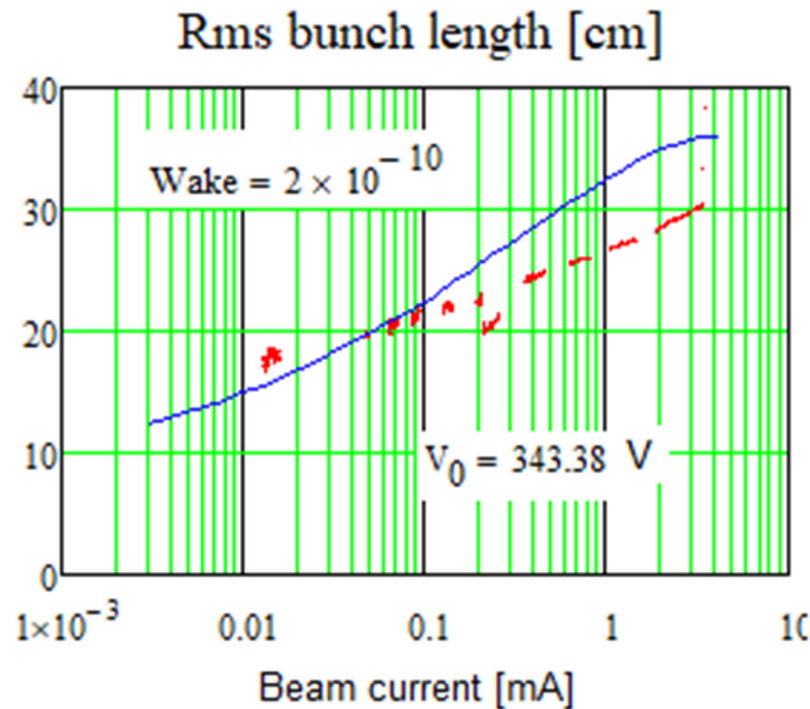
- 2 Sync-lights are at large dispersion
- Momentum spread makes contribution comparable to the betatron sizes

Beam Size Measurements in Coupled Optics (2)

- R1 camera looks poorly focused
- L4, R1, R2 did not have gain control properly operating
- Other cameras show decent coincidence of beam sizes
- Good coincidence for the high dispersion cameras
- Still they show smaller momentum spread at large current. Same as the bunch length monitor shows smaller bunch length



Beam Lifetime in Coupled Optics

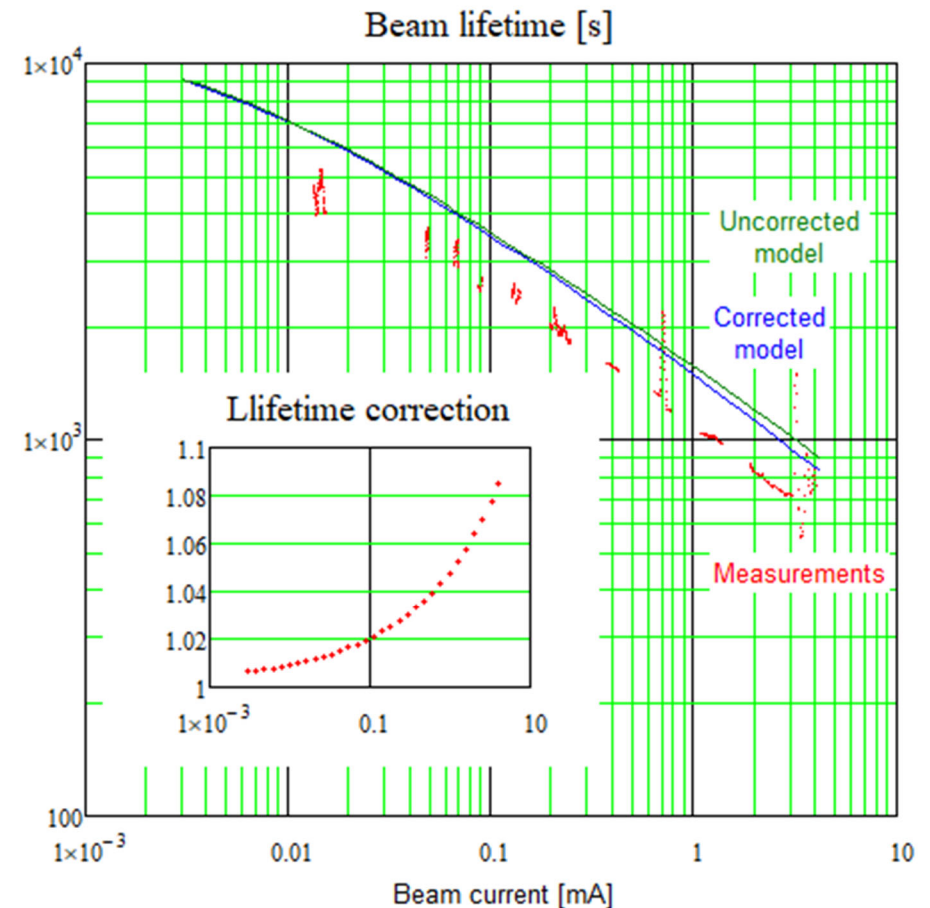


- Measured L_{bunch} at small currents is larger than the model predicts
 - ◆ Present speculation is that it is a result of trigger jitter at the data acquisition
 - Averaging is performed at the scope (~100 acquisitions)
 - Required rms jitter ~0.3 ns (sampling rate 1 Gsample/s)
 - ◆ Additional studies are required to find the actual reason
- Measured loss rate ~40% below model (reason unknown)

Correction of Touschek Lifetime in Coupled Optics

- Correction of Touschek lifetime for a finite momentum spread in the bunch resulted in minor improvement => discrepancy between measured and predicted lifetimes came to 1.35 times
- The reason is unknown
- If it is due to reduction of longitudinal acceptance it should be decreased by 0.87 times

- ◆ From $(\Delta p/p)_{\text{accept}} = 2.75 \cdot 10^{-3}$ (set by RF bucket height)
- ◆ To $(\Delta p/p)_{\text{accept}} = 2.39 \cdot 10^{-3}$



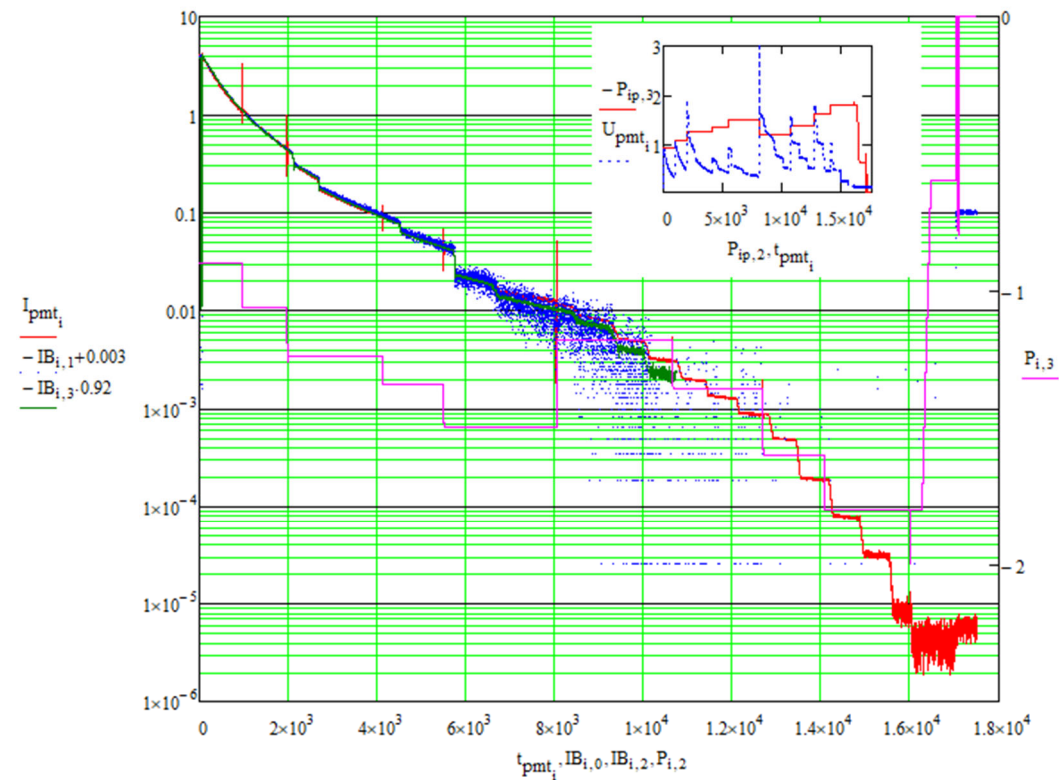
Conclusions to the Coupled Optics Measurements

- Calculated \perp beam sizes are quite close to the measured ones
 - ◆ ~10%
- Significant discrepancy for the bunch length
 - ◆ Measured sizes are longer at small current (+10%)
 - Looks like a problem with the measurements (-20%)
 - ◆ Measured sizes are shorter at large current
 - Looks like incorrect description of bunch self-compression
 - ◆ Accuracy of \perp beam sizes at dispersive places is insufficient to extract momentum spread with comparable accuracy
- The measured lifetime is 35% below predicted
 - ◆ Origin is unknown
 - ◆ There are no free parameters in the theory to change it

Measurements in Uncoupled Beam Optics

Measurements in Uncoupled Optics

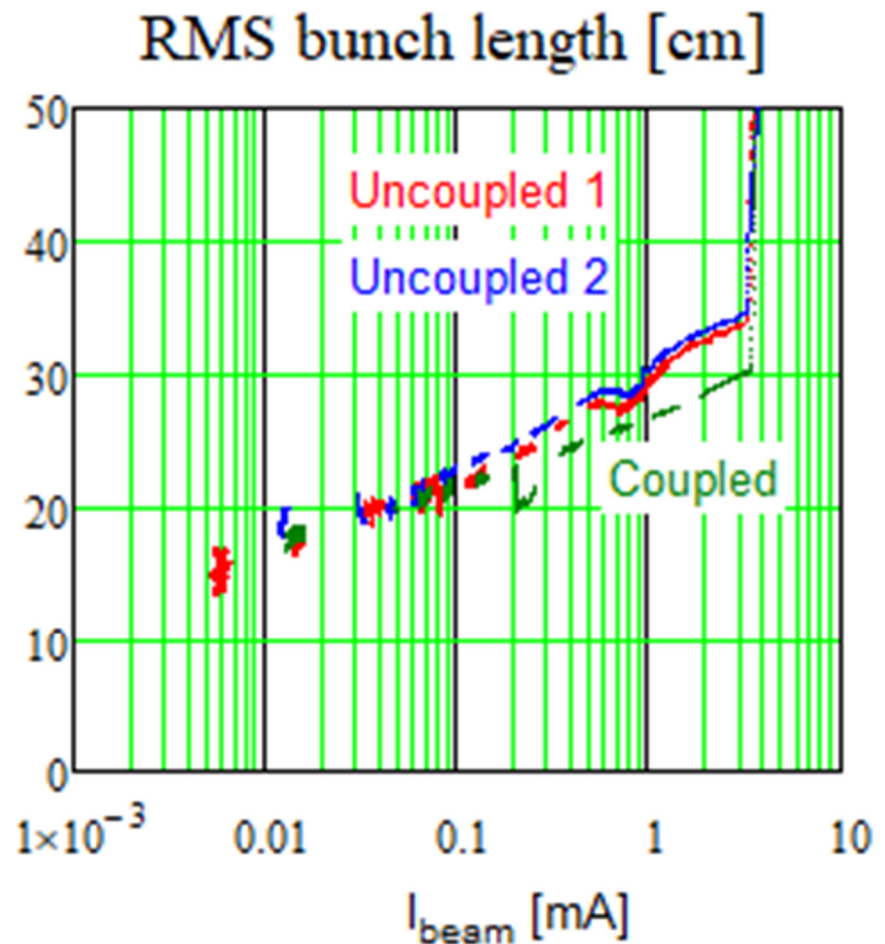
- There are two measurements performed at different days:
 - ◆ March 6&17 of 2020
- The second measurement was carried out in very large range of beam currents [5 nA - 4 mA]
- 3 current monitors were used
 - ◆ DCCT:
 $I_{\text{beam}} \in [0.1 - 5] \text{ mA}$
 - ◆ Wall Current Monitor:
 $I_{\text{beam}} \in [0.005 - 5] \text{ mA}$
 - ◆ Photomultiplier:
 $I_{\text{beam}} \in [\text{single el.} - 5] \text{ mA}$
- Auto-adjustments of sensitivity allowed us to use sync-light cameras in the entire current range



Review of Observations for March 6 Data

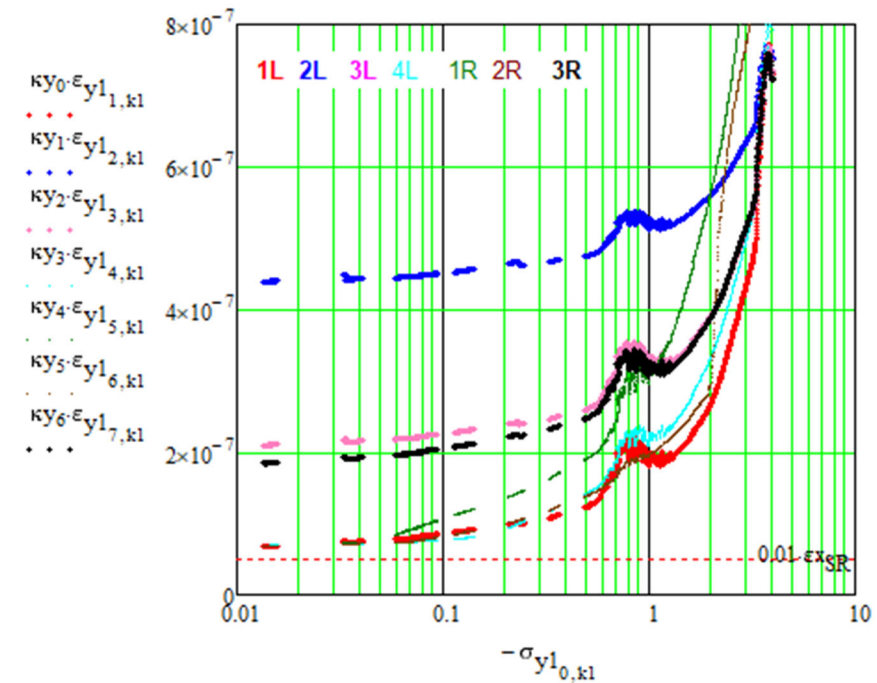
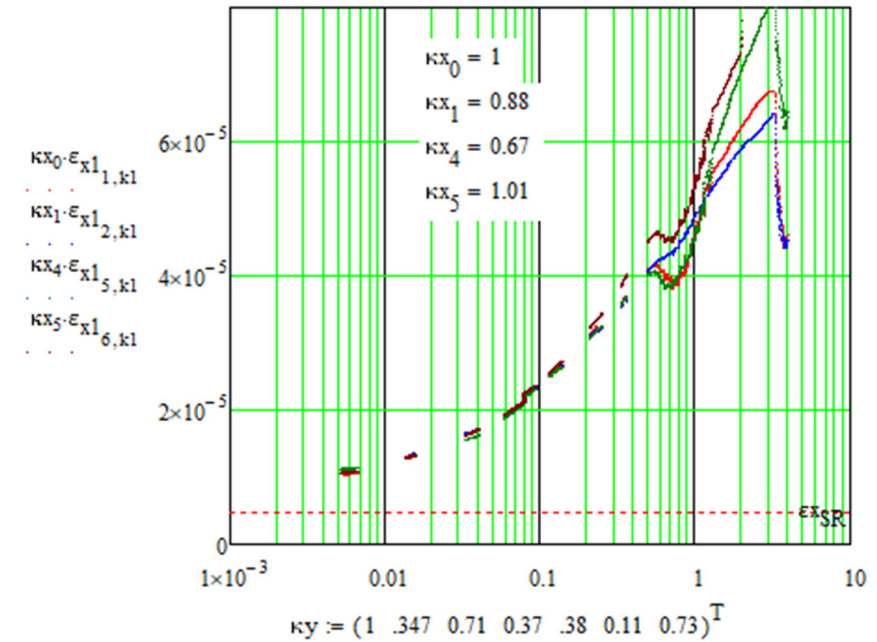
■ Bunch length

- ◆ Grows fast with current
- ◆ Longitudinal instability for $I > 3.3$ mA
- ◆ A dip at 0.8 mA
 - Absent for coupled measurements
 - Also absent for March 17 where coupling was larger
 - Correlates with horizontal size
 - Anticorrelates with vertical size
 - **Stored ions?**
 - ⇒ We need independent verification



Review of Observations for March 6 Data (2)

- Beam sizes and emittances
 - ◆ Hor. Emittances for 1L & 2L correlate well
 - ◆ 1R & 2R are saturated at large current
 - ◆ For most sync. lights the vert. emittances have large contribution from diffraction
 - ◆ The smallest vert. emittance is measured by 1L and 4L (large β_y)
- For uncoupled optics the momentum spread makes small contribution to the hor. beam size even at high dispersion points
 - ◆ Momentum spread cannot be extracted from sync. lights

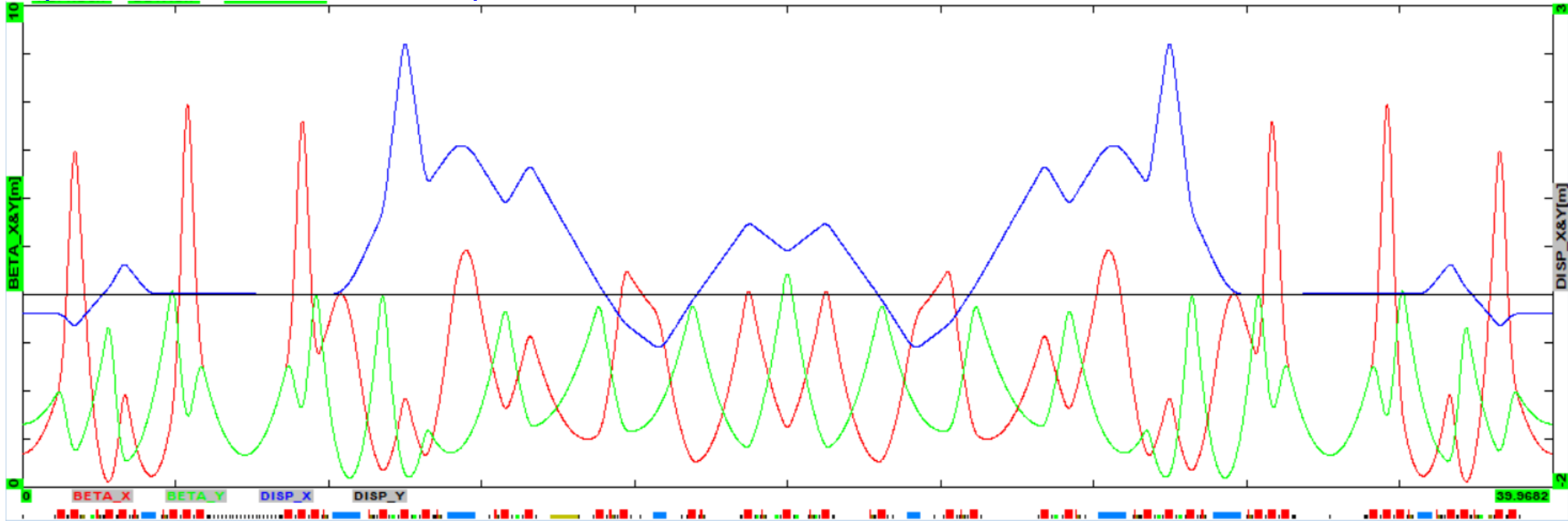


Longitudinal Damper and Dynamics

- Longitudinal damper was used in March 6 measurements
 - ◆ It introduced some noise and had small effect on the emittance growth. It is not accounted in the model
- Longitudinal damper was not used in March 17 measurements
 - ◆ For unknown reason the beam was stable without the damper
- Bunch self-compression was present and was simulated the same way as for the coupled optics

Uncoupled Beam Optics

Optics was well decoupled before measurements were started



Total Length=3996.82

Tunes: $Q_x=5.30$ $Q_y=5.30$

Momentum compaction=0.07198 Natural chromaticity: $p \cdot dv_x/dp = -10.4708$ $p \cdot dv_y/dp = -7.45$

Beam Energy = 100 MeV

SR losses: VSR = 12.8963 eV/per turn

Damping parameters: $g_x = 0.345$ $g_y = 1$ $g_z = 2.65$

Equilibrium rms emittances: $\varepsilon_x = 5.95e-06$ cm $\varepsilon_y = 0$

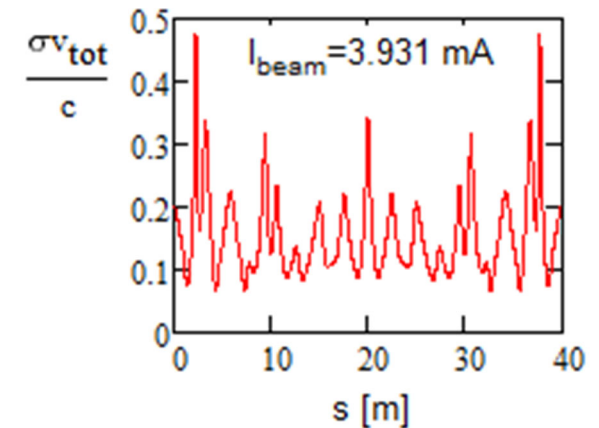
Equilibrium relative rms momentum spread: $\sigma_p = 8.95e-05$

Amplitude damping decrement per turn: $\lambda_x=2.22e-08$ $\lambda_y=6.44e-08$ $\lambda_s=1.711e-07$

Theoretical Analysis Used in Uncoupled Optics

■ Uncoupled optics used in computation of single and multiple IBS

- ◆ For multiple IBS, analysis assumes non-relativistic beam in the beam frame. It is not quite accurate at large beam current (~4 mA)
 - Applicability of this choice is discussed later
- ◆ Full relativistic treatment is used for computation of Touschek scattering
 - Momentum spread \ll Bucket size in Touschek rate computation



Same as for coupled optics: $\sigma_p / (\Delta p/p)_{sep} \in [0.04, 0.15]$ for $I_{beam} \in [0, 4]$ mA

■ Effective pressure of residual gas plays major role at small current

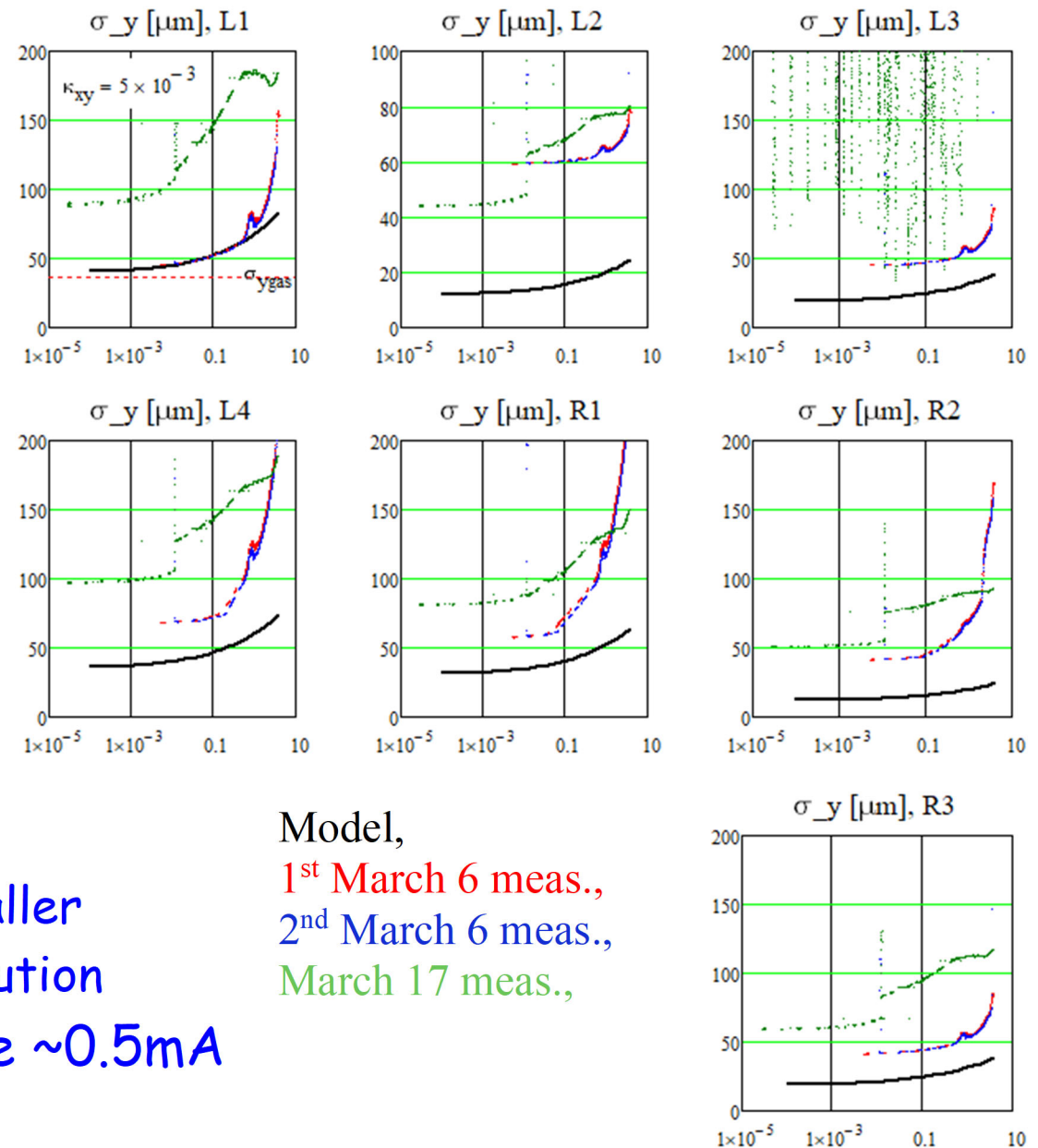
- ◆ Together with SR sets vertical emittance: $\varepsilon_{xgas} \approx \varepsilon_{ygas} \approx 0.42$ nm
- ◆ Sets the beam lifetime to ~200 min

■ In the absence of coupling for both SR and IBS $d\varepsilon_y / dt = 0$

- ◆ The best we can assume that there is the same coupling coefficients for both SR and IBS: $d\varepsilon_y / dt = \kappa d\varepsilon_x / dt$
- ◆ Coupling coefficient for the IBS is determined uniquely at large I_{beam}

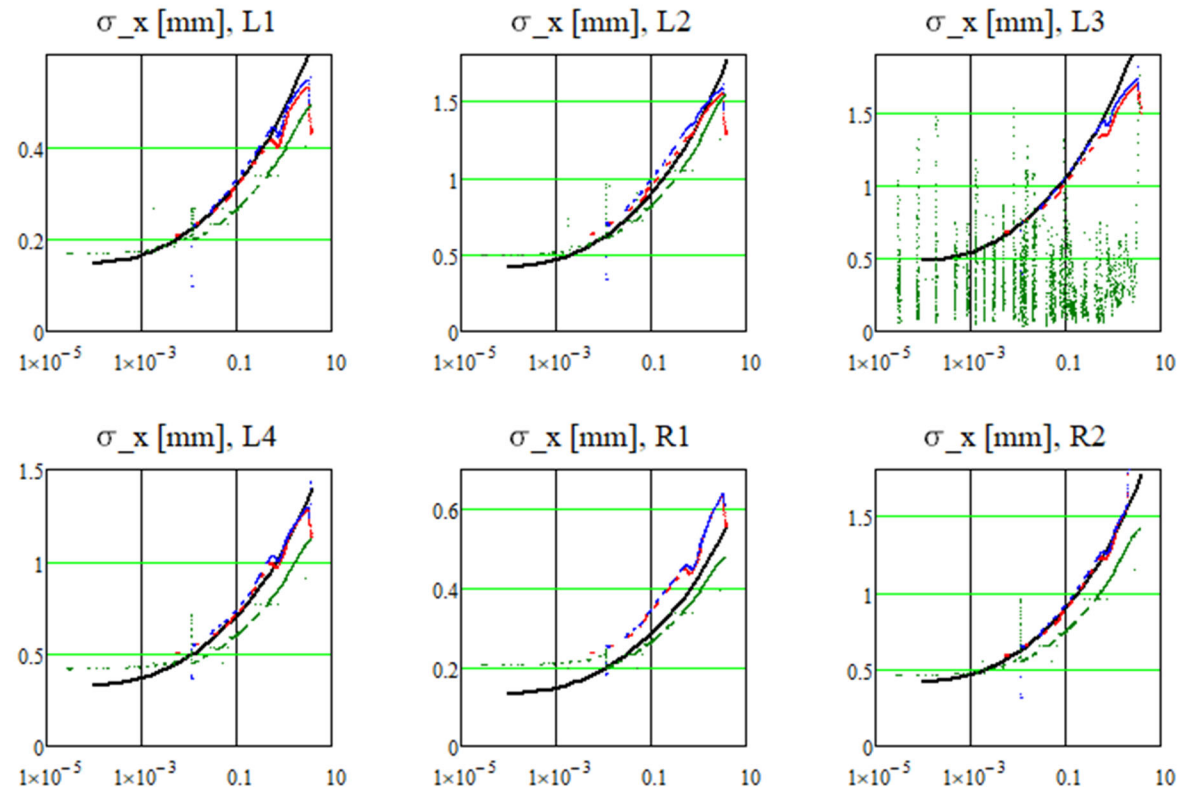
Vertical Beam Sizes for Uncoupled Optics

- The smallest ε_y is achieved at L1 measurements for both March 6 measurements
 - ◆ March 17 measurements had larger coupling and ignored
- That sets the coupling coefficient: $\kappa_{xy}=5 \cdot 10^{-3}$
- To fit to measured ε_y at small I_{beam} we set $\varepsilon_{y_gas}=0.42 \text{ nm}$
 - ◆ Actual value should be smaller due to diffraction contribution
- Fast emittance growth above $\sim 0.5 \text{ mA}$
 - ◆ Looks as stored ions

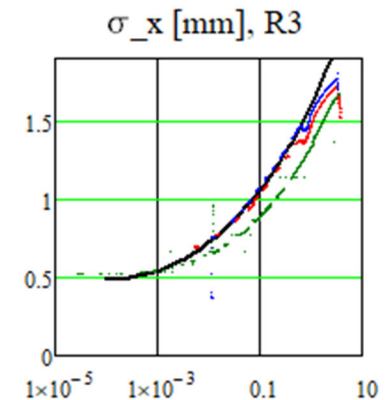


Horizontal Beam Sizes for Uncoupled Optics

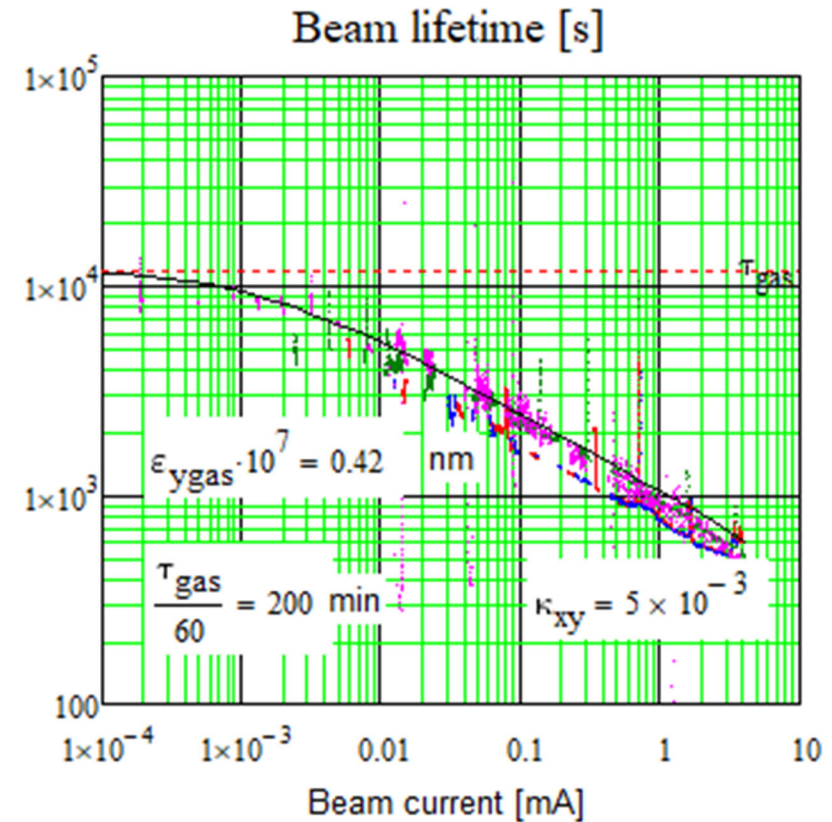
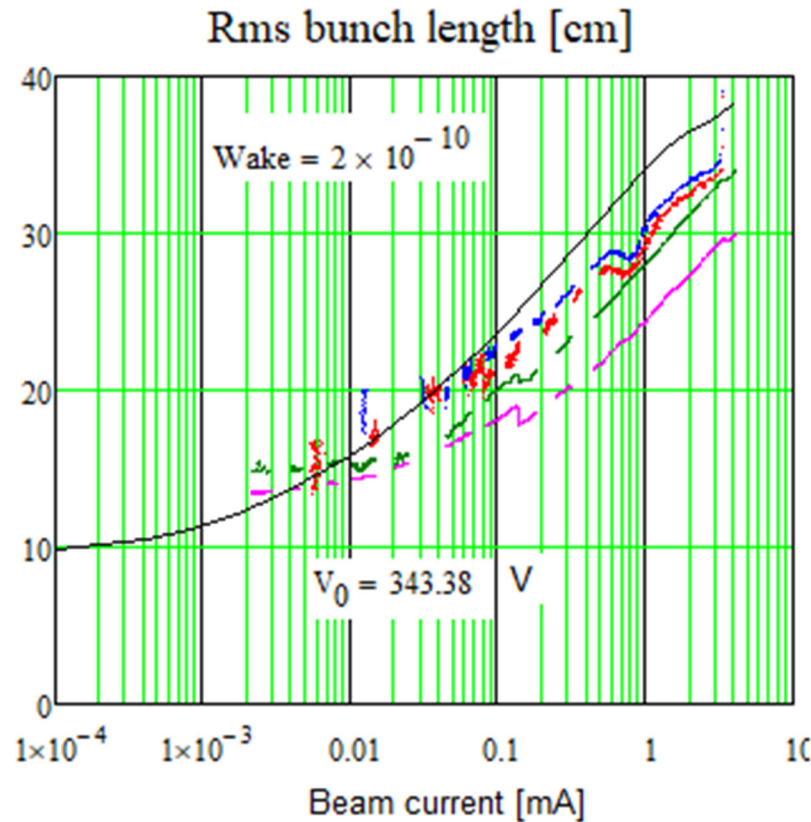
- Good agreement for March 6 data
- March 17 data show smaller ε_x because larger value of ε_y due to larger coupling
- Ions bump up vertical emittance above 0.5 mA resulting horizontal emittance reduction



Model,
 1st March 6 meas.,
 2nd March 6 meas.,
 March 17 meas.,



Lifetime and Bunch Length for Uncoupled Optics



Model, 1st March 6 meas., 2nd March 6 meas., March 17 meas., March 17 meas. Gaussian fitting

- Good coincidence for lifetime - still measured lifetime is ~30% smaller at large beam current for March 6 data (where model parameters tuned)
- Predicted bunch length is shorter at small currents and larger at large currents: Gaussian fit is even shorter => non-Gaussian tails at large I_{beam}

Effective Vacuum

- There are two independent ways to obtain effective vacuum

- ◆ From beam lifetime at small current

$$\tau_{gas}^{-1} = \frac{2\pi c r_e^2}{\gamma^2 \beta^3} \left\langle \left(\frac{\beta_x(s)}{\varepsilon_{xm}} + \frac{\beta_y(s)}{\varepsilon_{ym}} \right) n_{eff}(s) \right\rangle_s, \quad n_{eff}(s) = \sum_k \text{over atoms} Z_k (Z_k + 1) n_k(s)$$

- ◆ From minimum measured vertical emittance at small current

$$\frac{d\varepsilon_y}{dt} = \frac{\varepsilon_y}{2\tau_{ySR}} = \frac{2\pi c r_e^2}{\gamma^2 \beta^3} \left\langle \beta_y(s) n_{eff}(s) \right\rangle_s, \quad n_{eff}(s) = \sum_k \text{over atoms} Z_k (Z_k + 1) n_k(s) \ln \left(\frac{204}{\sqrt[3]{Z_k}} \right)$$

- For estimate we assume uniform gas distribution over ring

Other parameters:

measured acceptances: $\varepsilon_{xm}=22 \mu\text{m}$, $\varepsilon_{ym}=40 \mu\text{m}$

averaged beta-functions: $\beta_{xa}=2.16 \text{ m}$, $\beta_{ya}=1.94 \text{ m}$

$\Rightarrow P_{eff}=4.2 \cdot 10^{-8}$ Torr of atomic hydrogen equivalent for $\tau_{gas} = 200 \text{ min}$

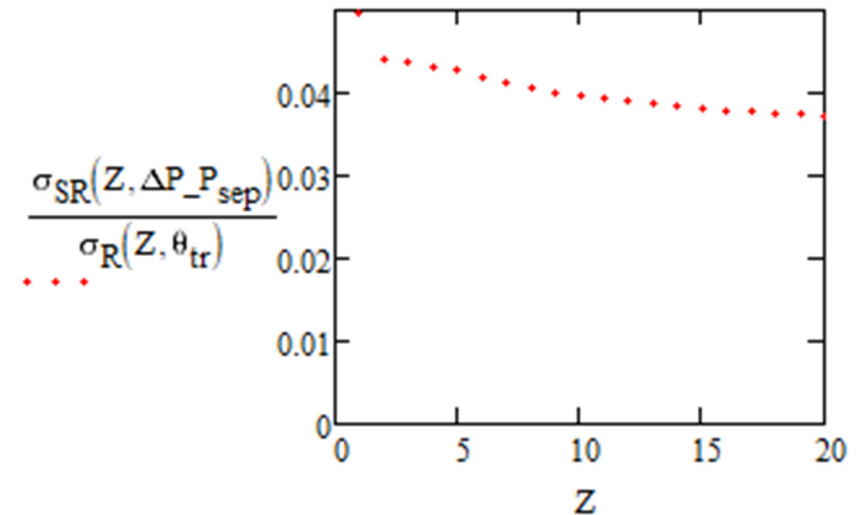
This value is close to what we should expect \Rightarrow looks trustable

- ◆ Using this P_{eff} we obtain equilibrium vertical emittance of 5.6 nm
 - That is 13 times smaller than 0.42 nm measured

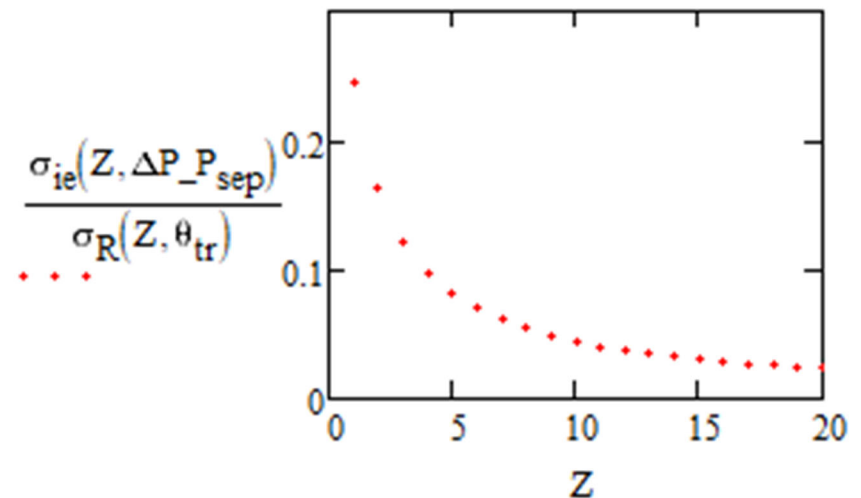
Actually, it will be larger because we include diffraction contribution the vertical beam size at L1)

Other Contributors to Particle Loss

- Bremsstrahlung increases particle loss by about ~4%



- Inelastic scattering on atomic electrons adds 3-25% (depending on Z)

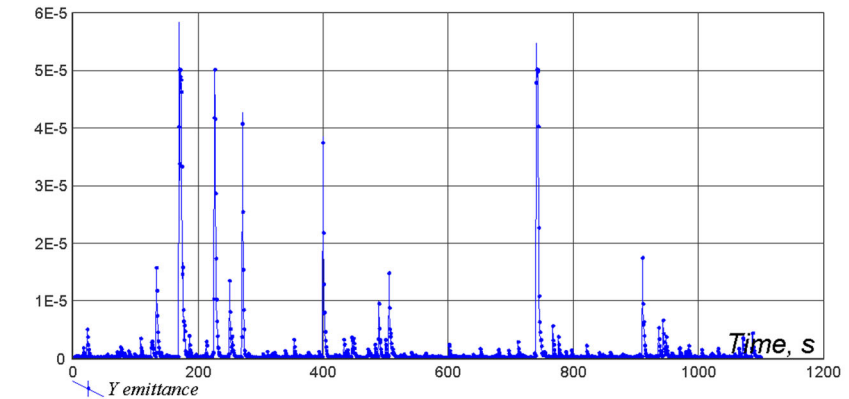
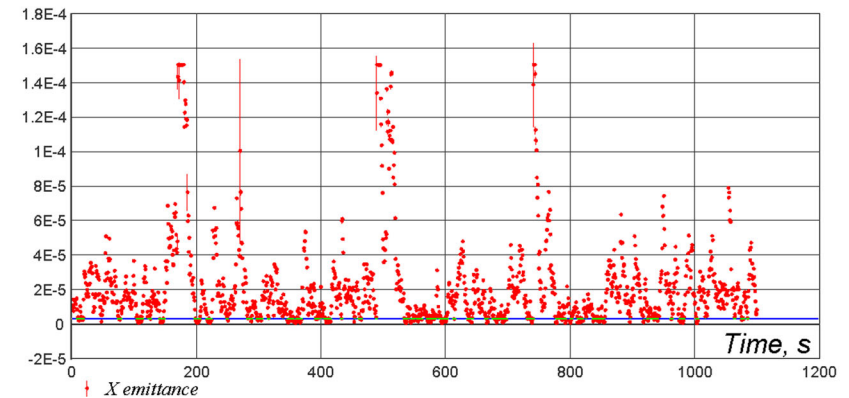
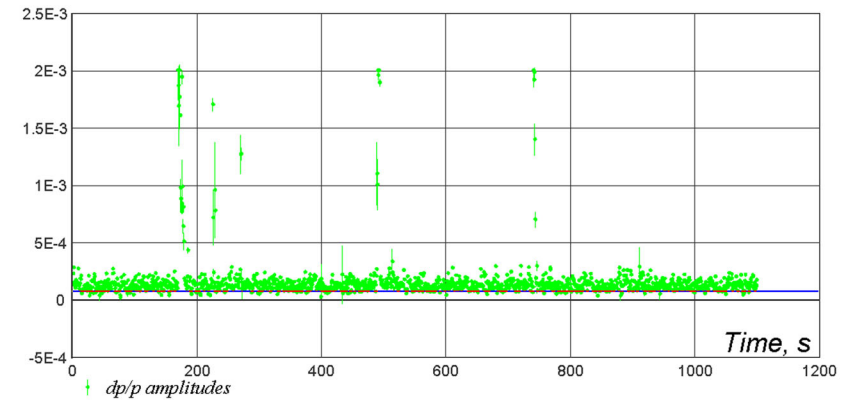
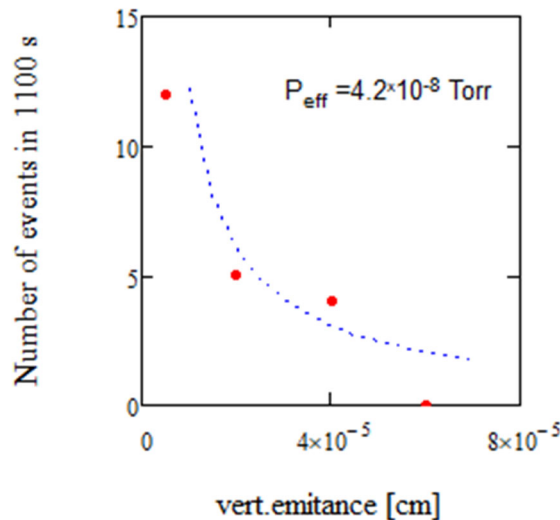


- That decreases the effective vacuum pressure to $\sim 3.5 \cdot 10^{-8}$ Torr

But still leaves at least an order of magnitude difference between two ways of vacuum computation

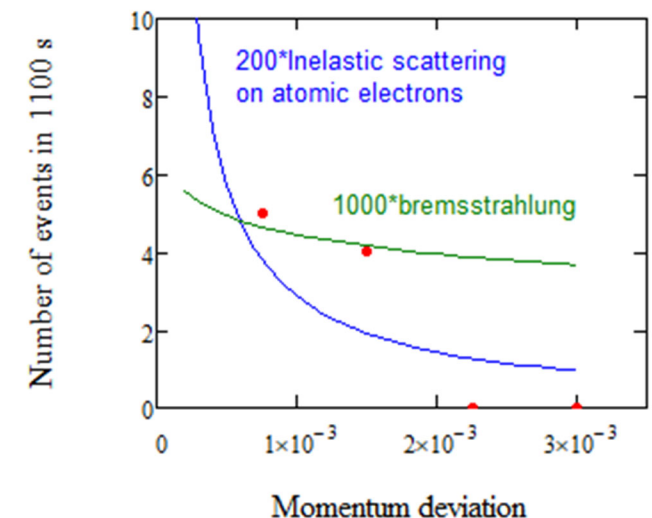
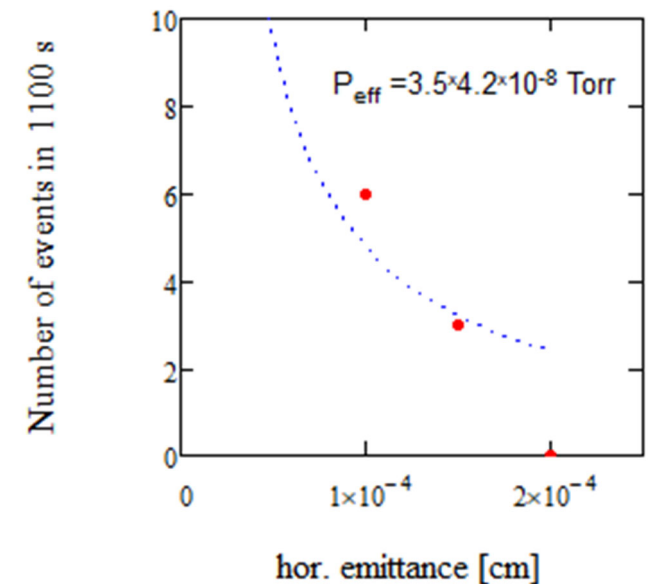
Vacuum Estimate from Single Electron Measurements

- Single electron measurements acquired in Run I allow us to see how many scatterings happened in each of three planes at different amplitudes
- The vertical plane is preferred because it is insensitive to the momentum change
 - ◆ Data analysis shows decent agreement with vacuum value discussed above



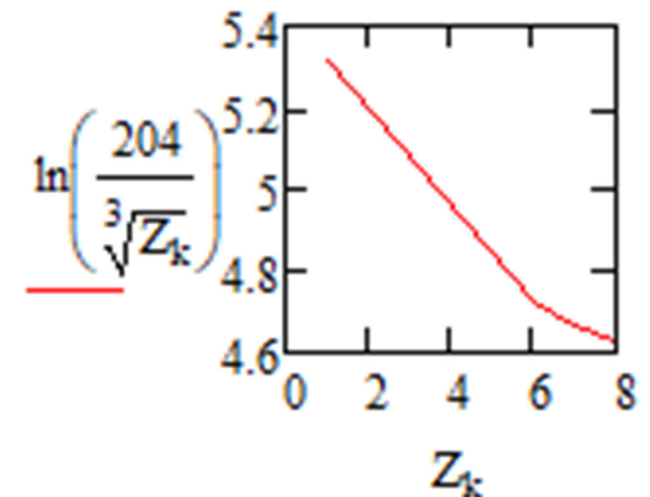
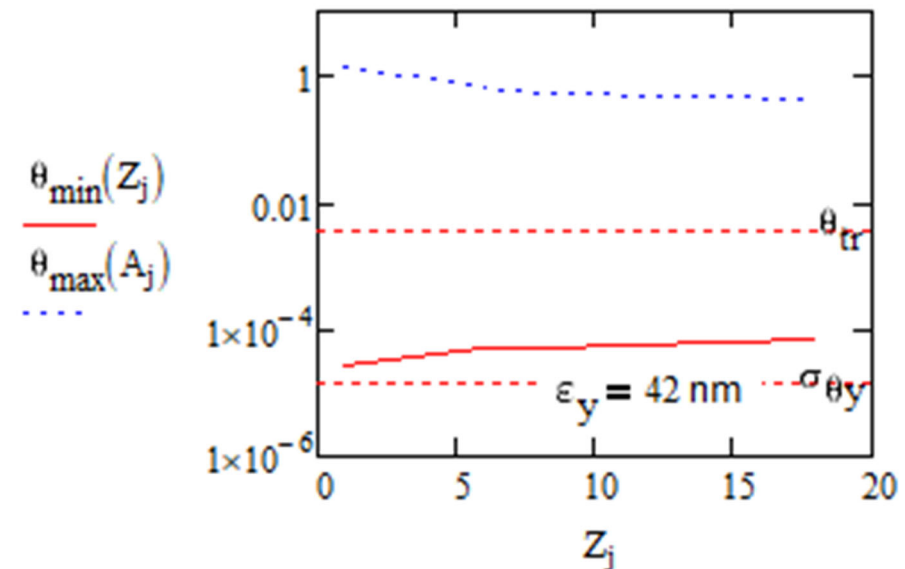
Vacuum Estimate from Single Electron Measurements (2)

- While number of events in the horizontal plane ~ 2 times smaller the observed emittance variations are larger
 - ◆ That requires vacuum to be worse by ~ 3.5 times
 - ◆ Other possible reason that there is local pressure bump in the place where difference between β_x and β_y is large
- Number of events in the longitudinal plane is much larger than can be supported by bremsstrahlung or inelastic scattering at the atomic electrons
 - ◆ Most possible reason it is Rutherford scattering at the nuclei
 - Perturbation in x and s coincide in time



What is Wrong with Vertical Emittance Measurements?

- Equations deal with the rms value of vertical emittance, but they do not assume that the distribution is Gaussian
- Logarithmic approximation is not applicable because θ_{\min} is larger than the measured vertical angular spread on the beam; i.e. $L_c < 1$
 - ◆ That reduces Coulomb logarithm: 5 \rightarrow ~ 1 ,
 - ◆ and creates non-Gaussian distribution with bright center and long tails
- Sinc-light monitor makes Gaussian fit resulting in much smaller beam size



Conclusions

- Many questions are still not answered
 - ◆ Additional measurements should be planned
- For both coupled and uncoupled optics the measurements show ~30-40% smaller lifetime than the model predicts
 - ◆ The reason is unknown
- We need to find out why L_{bunch} is smaller than the model predicts
 - ◆ Self-compression due to impedance?
 - ◆ Non-Gaussian momentum distribution due to single scattering?
- For coupled optics the model predicts well both emittances
- For uncoupled optics
 - ◆ Horizontal emittance is predicted well for $I_{\text{beam}} < 0.5 \text{ mA}$
 - ◆ Looks like we have ions stored in the beam for $I_{\text{beam}} > 0.5 \text{ mA}$
- Coming OSC run
 - ◆ Instrumentation is mostly ready
 - ◆ We need to add a preamp to measure small beam current with WCM
 - ◆ Sync light limit in resolution is $\leq 50 \text{ } \mu\text{m}$. It fits our immediate needs
 - ◆ **Significant vacuum improvement is required!!!**