Investigation of the beam halo and momentum tail at the ATF

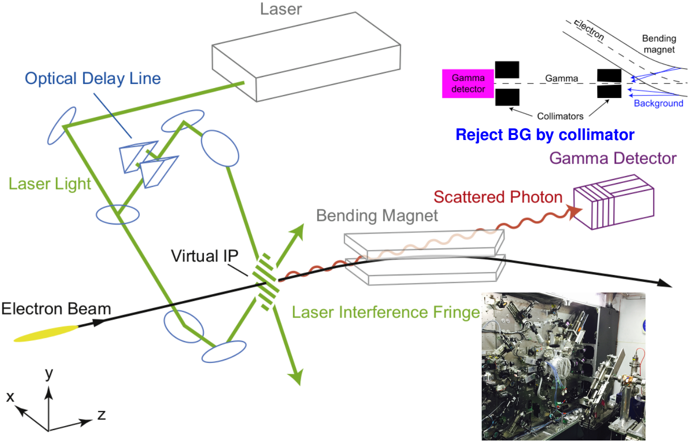
R. Yang[1], P. Bambade[1], A. Faus-Golfe[1], V. Kubytskyi[1], S. Wallon [1], A. Aryshev [2], K. Kubo [2], T. Naito[2], T. Okugi [2], N. Terunuma[2], M. Bergamaschi [3] and N. Fuster-Martínez[3]

1. Laboratoire de l'Accélérateur Linéaire (LAL), Orsay, France
2. High Energy Accelerator Research Organization (KEK), Tsukuba, Japan
3. CERN, Geneva, Switzerland

May 28, 2018

Motivations

- Background induced by halo particles loss upstream of IP might reduce the modulation resolution of $Shintake$ monitor
- To understand the genesis of halo and its distribution !

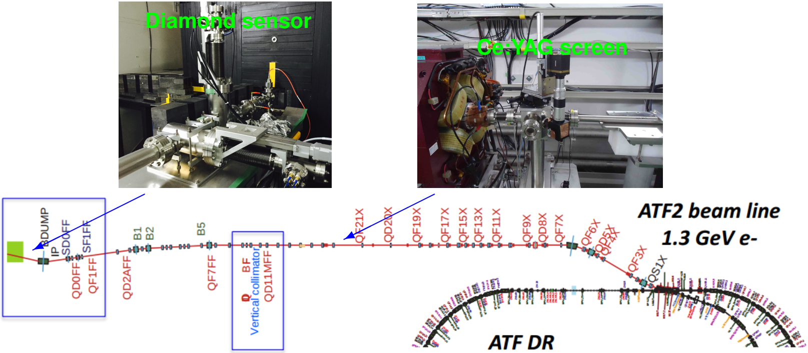


* Figures from [1] J. Yan, et al., NIMA 740(2014) 31-137; [2] T. Suehara, et al., NIMA 616(2010) 1-8

- Instrumentations for halo diagnostic: DS and YAG/OTR
- Vertical beam halo formation: BGS process
- Horizontal halo/momentum tail:Touschek scattering?
- Conclusion

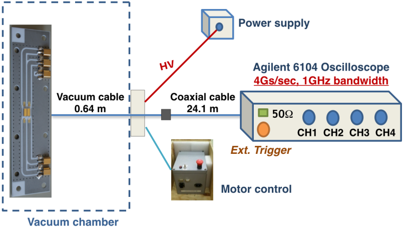
Instrumentations for beam halo diagnostics

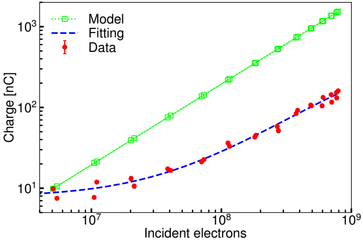
- First measurement: wire scanners at the previous EXT line, 2005
- New diagnostics: diamond sensor (DS) detector and YAG/OTR monitor



DS: η_x ≈1 m, η_y ≈0; YAG/OTR: η_x ≈0, η_y tunable!

in vacuum diamond sensor detector



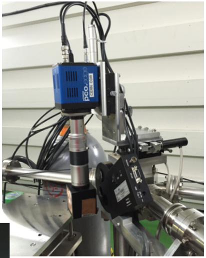


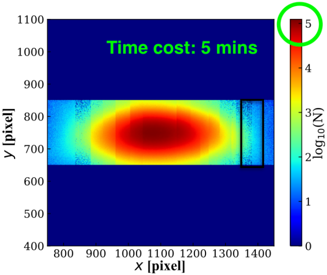
- Two 1.5 mm×4 mm and two 0.1 mm×4 mm sCVD DS strips
- Dynamic range $d_R \approx 10^5$
  * Lower limit: induction current/noise level
    $> 2 \times 10^{-3}$ nC (>1×$10^3 e$)
  * Upper limit: charge collection saturation
    $\sim 1 \times 10^2$ nC
- Signal of core is re-scaled by "self-calibration" thanks to WS upstream of DS
  * Approximating charge collected in the core by extrapolating WS measurement
  * Re-scaling factor
    $$\kappa(n_e) = Q_{exp}/Q_{meas}$$

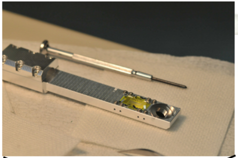
[1] S. Liu, $et\ al.$, NIMA, 832 (2016)

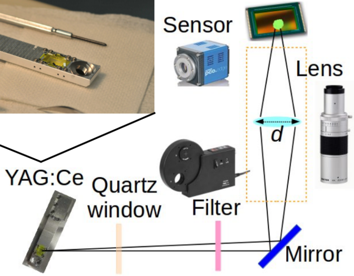
A novel Ce:YAG/OTR monitor

- YAG —> core/halo; OTR —> core (saturation-free)
- Collaboration among KEK, CERN and LAL
- Critical Performance:
  DNR > 10^5 and resolution < 10 μm
- Scanning (x or y) using YAG + ND filter
  —> avoiding the blooming effect
- Multi-shot measurements
  —> Position/beam size jitter < 5%







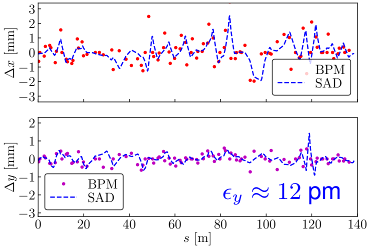


Monte Carlo simulation of BGS

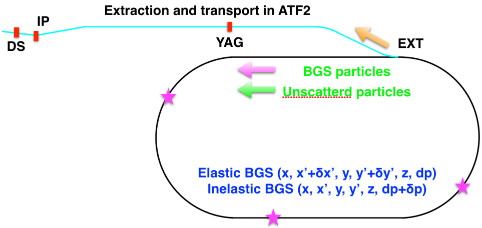
- Analytical approximations based on K. Hirata's model
- Realistic COD in the DR
  $\rightarrow$ approach the operation ϵ_y
- Two atoms per molecule with A=$\sqrt{50}$
  $\rightarrow$ represent residual gas
- Tracking scattered & unscattered particles separately

Main parameters of ATF DR

Beam energy [GeV]	1.282
Circumference [m]	138.56
Ver. emittance [pm]	12
Hor. emittance [nm]	1.17
Energy spread [%]	0.056
Bunch length [mm]	5 .3
Damping time [ms]	27.0/19.8/20.6



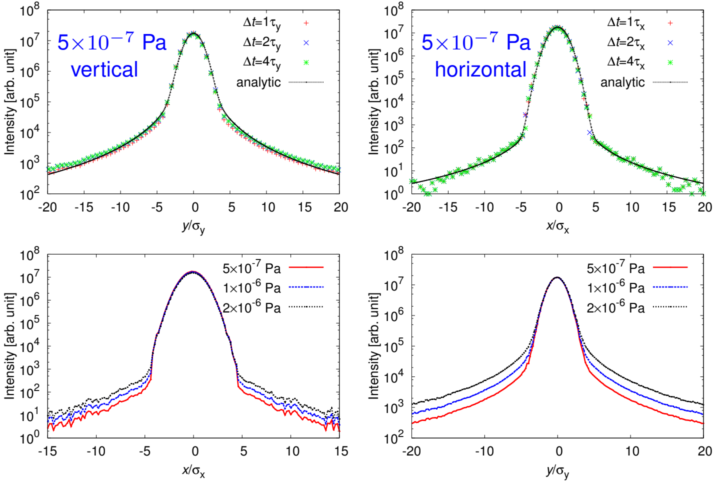
Script developed in SAD



[1] K. Hirata and K. Yokoya, Part. Accel. 39, 147 (1992)

Numerical predictions from two methods

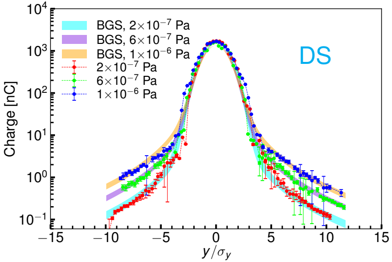
- Two predictions agree well: vacuum pressures $< 2 \times 10^{-6}$ Pa
- Vertical tail is more significant, in the y/σ_y coordinate

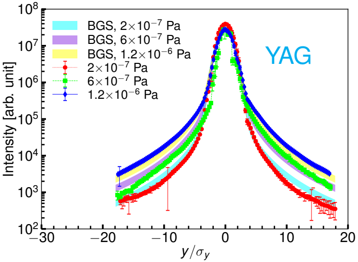


- So, how about the halo distribution in the real world...

Vertical beam halo due to BGS

- Beam profiles measured by DS after re-scaling and that by YAG monitor are in good agreement with the numerical predictions
- Higher tail for the worsened vacuum: 2$\times 10^{-7}$ Pa$\rightarrow$ 1$\times 10^{-6}$ Pa
- Vertical beam halo is dominated by elastic BGS[1]!

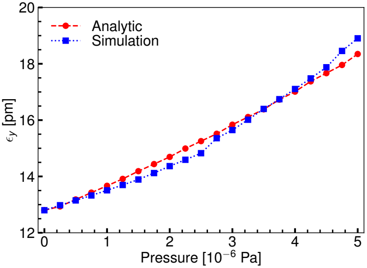




[1] See, R. Yang, $et\ al.$, Phys. Rev. Accel. Beams 21, 051001 (2018)

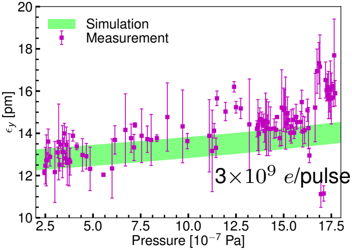
Vertical emittance growth due to BGS

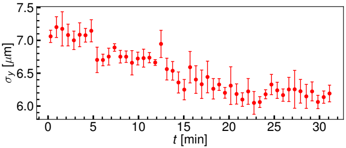
- Small-angle beam-gas scattering –> ver. emittance dilution
- Long ver. damping time (27 ms)
- Numerical estimations predict a ϵ_y growth from 12.8 pm to 18.7(18.9) pm for a vacuum pressure of 5×10^{-6} Pa



Measurable and significant!

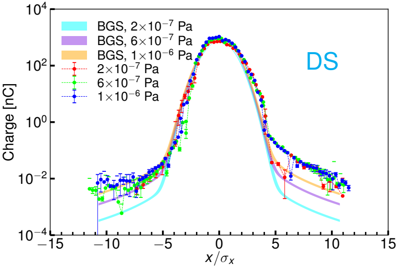
- Ver. emttance obtained using an X-ray SR monitor; 2×10^{-7} Pa to 1.75×10^{-6} Pa
- More than 10% emittance growth!

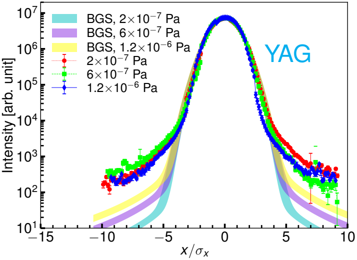




Horizontal profile measurements

- Measurements are higher than the numerical predictions (BGS)
- Asymmetric distribution, more particles on the high energy side
- No significant change for the degraded vacuum
- Other dominating mechanisms (Touschek scattering?)



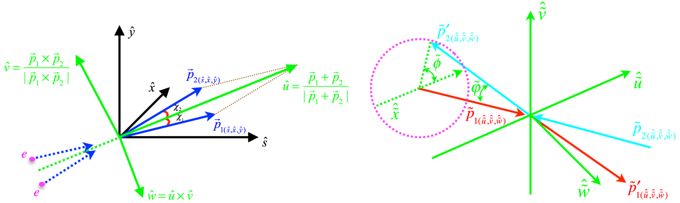


PS: Optical aberration and secondary emission in ATF2, and the imperfect extraction kicker field –> demonstrated to be small

Tail from Coulomb scattering of particles?

- IBS/Touschek scattering is very strong in the ATF DR
- Large-angle collisions result in large δ_p –> Touschek lifetime
- Particles after large-angle θ collisions and remain within the separatrix –> Momentum tail and hor. tail (?)

$$\Delta\vec{p}_{1,2} = \pm p_{1,2} \begin{pmatrix} \gamma_t[\gamma_t(\cos\chi_{1,2} - \beta_t/\beta_{1,2})\cos\tilde{\varphi} + \sin\chi\sin\tilde{\varphi}\cos\tilde{\phi}] - \gamma_t\bar{p}_s/p_{1,2} \\ \sqrt{\gamma_t^2(\cos\chi_{1,2} - \beta_t/\beta_{1,2})^2 + \sin^2\chi}\,\sin\tilde{\varphi}\sin\tilde{\phi} \\ \sin\chi(\cos\tilde{\varphi} - 1) - \gamma_t(\cos\chi_{1,2} - \beta_t/\beta_{1,2})\sin\tilde{\varphi}\cos\tilde{\phi} \end{pmatrix}_{\hat{u},\hat{v},\hat{w}}$$



Momentum tail is more "clean", i.e., less influence from transverse non-linearity
–> Momentum tail imaging

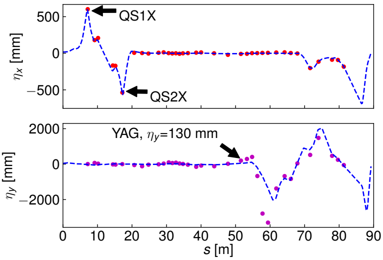
[1] M. Martini, CERN-2017-006-SP

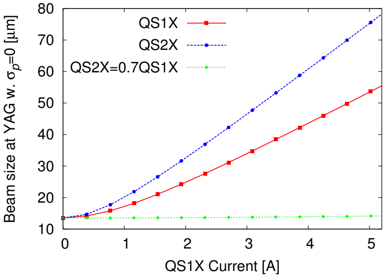
Design of energy spectrum measurement (1)

- Min. distinguishable energy deviation

$$\delta_{m,\mathrm{sep}} \geq 2\sqrt{\epsilon\beta}/\eta$$

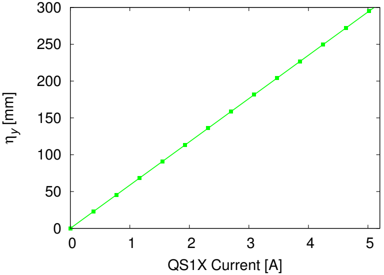
- Small β and large η, but $\epsilon_x \approx 100\epsilon_y$ –> vertical observation is superior!
- Vertical dispersion blowing up:
  - Adjusting η_y by tuning QS1X/QS2X with specific ratio, e.g., 10:7
  - Ver. profile <— energy spectrum if η_y is large enough (>150 mm)

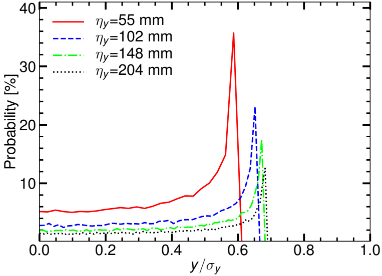


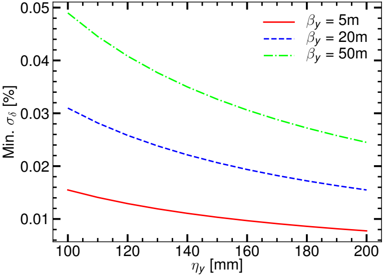


Design of energy spectrum measurement (2)

- Vertical dispersion at the YAG can be increased to around 300 mm
- Impact of the betatron xy coupling (R_{31}, R_{32}) is small, e.g., <0.6 σ_y for $2J_x = 400\epsilon_x$
- Min. distinguishable momentum deviation: around 3×10^{-4} for $\eta_y > 160$ mm

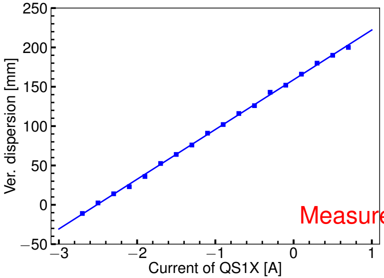




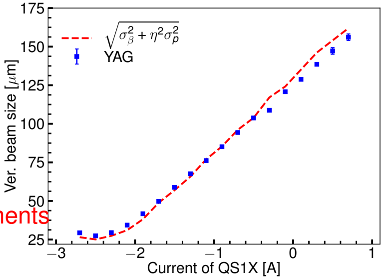


Increase of the vertical dispersion

- Residual ver. dispersion –> non-zero current of QS1X/QS2X
- Dispersion at YAG is approached by that measured by a BPM attached to QM16 quad. ($\Delta s \approx 30$ mm)
- $\beta_y \approx 50$ m; Dispersion domain for $\eta_y > 160$ mm
  –> Measurements for $\eta_y \approx 200$ mm @ YAG

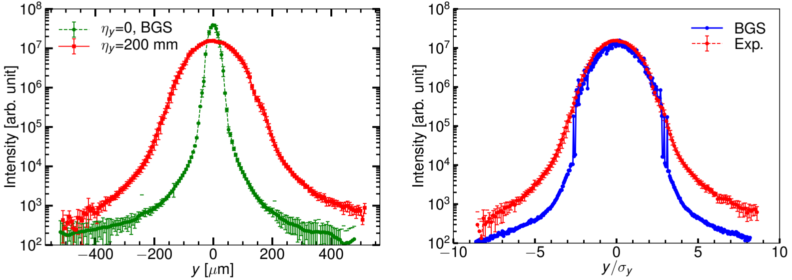


Measurements



First observation of energy spectrum

- Simulations with the measured vertical betatron profile at EXT kicker
- For $\eta_y = 200$ mm, the measured vertical tail is higher than the prediction by at least a factor of 4 –> Momentum profile!?



- Influence of the betatron halo (BGS) and xy coupling terms? Due to Touschek scattering?

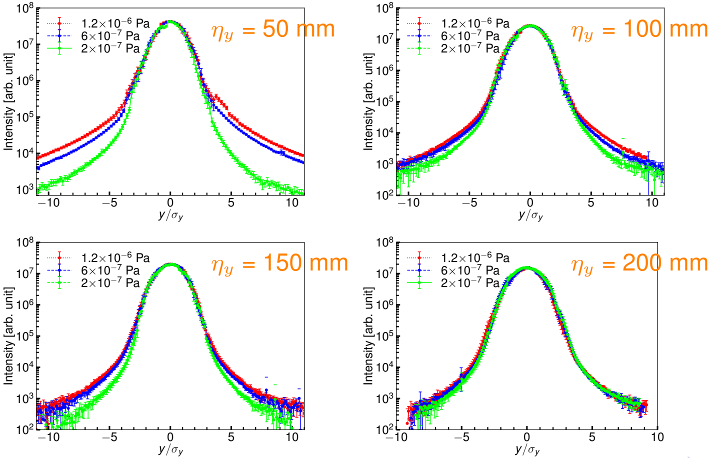
Energy spectrum - vacuum dependence

- BGS process results in the vertical betatron halo

–> Variation of vertical tail/halo for various vacuum pressures ?

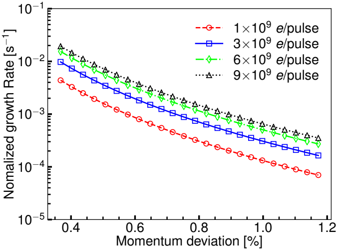
- $\eta_y = 50$ mm –> 200 mm

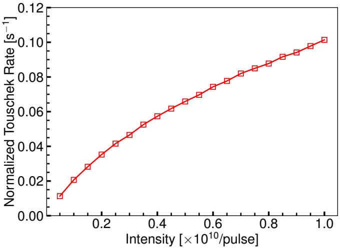
Betatron distribution + momentum deviation –> momentum distribution



Energy spectrum - intensity dependence

- Touschek scattering depends on beam intensity and emittances
- Higher beam intensity –> higher Tous. scattering rate –> higher tail (?)
- Analytical estimation based on Piwinski's model
  –> Intensity from 1×10^9 e/pulse to 6×10^9 e/pulse, the scattering rate increase from 2×10^8/s to 4×10^9/s for 0.35%$<\delta<$1.2%

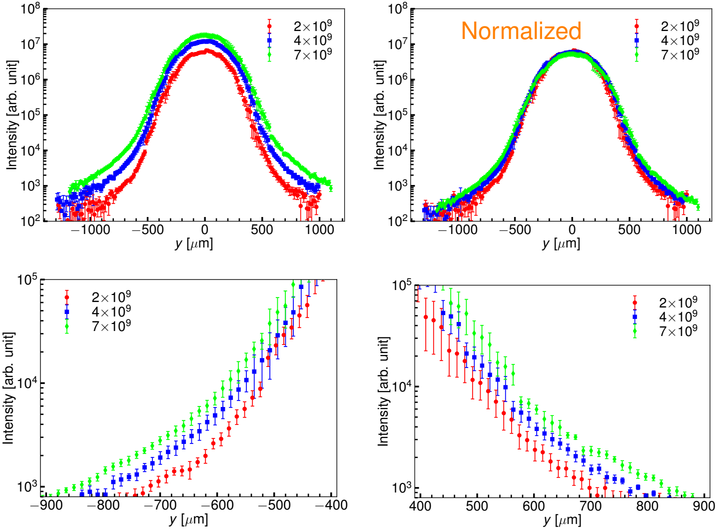




- Wake potential distortion is not included and can further weaken the intensity dependence

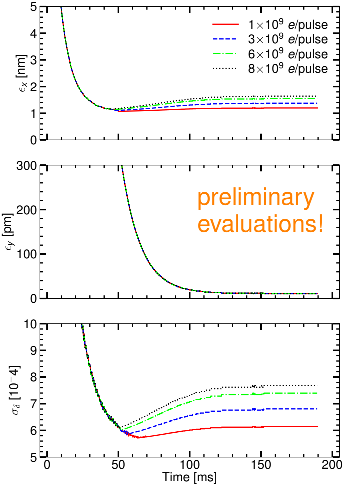
Energy spectrum - intensity dependence

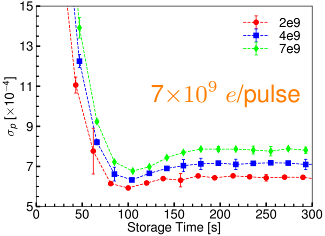
- Experiment conditions: $\eta_y \approx 200$ mm, DR vacuum 2$\times 10^{-7}$ Pa
- Significant dilution of the rms energy spread and increase of momentum tail

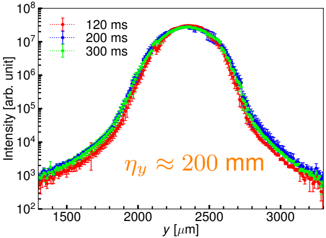


Energy spectrum vs. extraction time

- Emittances and Touschek scattering rate $\sim$ the storage time (damping, IBS)
- Evolution of σ_p and momentum tail seems consistent !

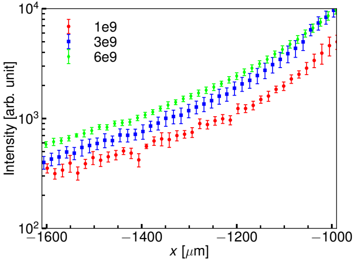


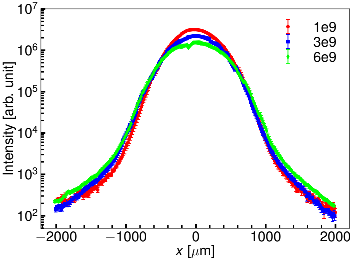




Touschek scattering –> Horizontal tail?

- Measurements of the momentum tail indicate a highly possible influence of Touschek scattering
- Tous. scattering induce also horizontal tail/halo due to a large η_x?
- Increased hor. tail/halo for a higher beam intensity –> consistent with the intensity dependence of momentum tail





- Detailed simulations of Touschek scattering are of critical importance!

Summary

- DS detector and a novel YAG/OTR monitor has been developed and operated for beam halo studies
- Vertical halo is mainly induced by elastic BGS in the damping ring, demonstrated by numerical estimations and measurements
- Momentum tail was visualized through a proper adjustment of the vertical dispersion. Evolutions of momentum tail as a function of intensity, gas pressure and extraction time are qualitatively consistent with the presence of Touschek scattering
- Monte Carlo simulations of Touschek scattering is underway...

Many thanks to ATF collaboration!

Thank you for your attention!

Back up...

Numerical approximation of BGS halo

- Solving the diffusion equation in the presence of RAD, QE and IBS

$$\frac{d\vec{x}}{ds} = -[H(\vec{x}, s), \vec{x}] + \xi(\vec{x}, s)$$

- Distribution function of normalized coordinate $u = x/\sqrt{\beta}$:

$$\psi(u) = \frac{1}{2\pi} \int e^{i\omega u} \tilde{\psi}_t(\omega) \tilde{\psi}_f(\omega) d\omega$$

- Final expression derived using Campbell's theorem

$$\psi(x_i) = \frac{1}{\pi} \int_0^\infty \cos(\omega x_i) \exp(-\frac{\omega^2 \sigma_{x_i}^2}{2} + \frac{N}{\alpha} \hat{f}(\omega \sqrt{\bar{\beta}\beta_i})) d\omega$$

with

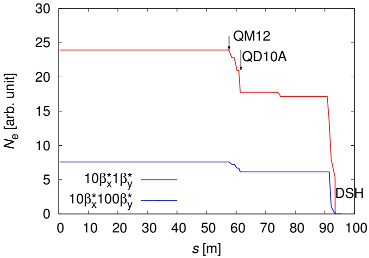
$$\hat{f}(\tilde{\omega}) = \frac{2}{\pi} \int_0^1 d\zeta \frac{\Re[\tilde{f}(\tilde{\omega}\zeta)] - 1}{\zeta} \cos^{-1} \zeta$$

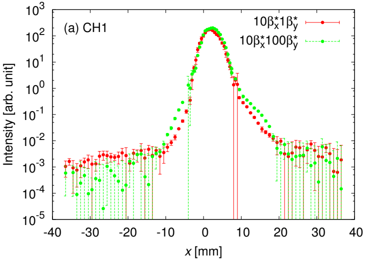
$$\tilde{f}(\tilde{\omega}) = \int d\theta_x f(\theta_x) \cos(\tilde{\omega}\theta_x)$$

[1] K. Hirata and K. Yokoya, Part. Accel. 39, 147(1992)

Horizontal halo at DSh for $1\beta_y^*$ and $100\beta_y^*$ optics

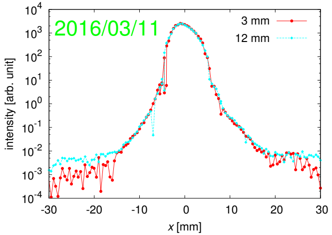
- Few influence of chromaticity and aberration in FF, and less beam loss in high β_y region for $10\beta_x^* 100\beta_y^*$ optics
- Higher horizontal tail/halo when $1\beta_y^* \to 100\beta_y^*$ observed by DS.
  - Effect of chromaticity and abberation in FF was negligible for nominal optics!

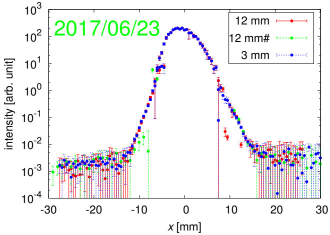




Influence of secondary emission in FF

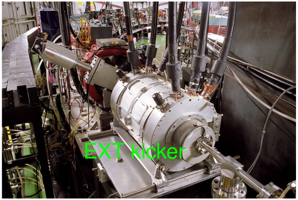
- Beam loss at FF and BDUMP and secondary particles shower are controlled by a vertical collimator upstream (12 mm/3 mm half-aperture)
- Experiment in 2016 shows observable effect of secondary shower
- Insignificant influence due to larger fluctuation in June, 2017



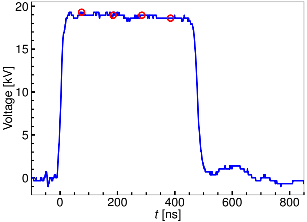


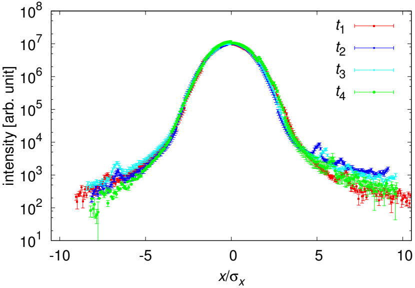
- Horizontal halo at Post-IP seems not dominated by aberration or secondary emission in FF. But, we should avoid their influences! -> YAG

Halo from imperfect EXT kicker field



- Imperfection of extraction kicker field will drive particles to be large amplitude, and it is difficult to simulation thus influence
- Horizontal profile was measured for several locations of kick timing (difference larger than 28 ns) using YAG/OTR monitor
- Horizontal tail/halo was slightly changed!

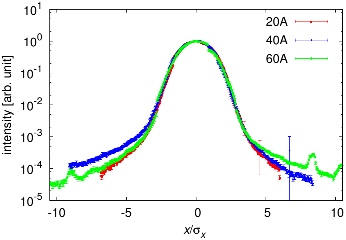


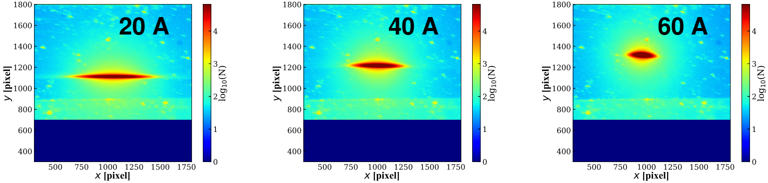


[1] M.N. Nguyen, ATF–06–04, 2006.12.15

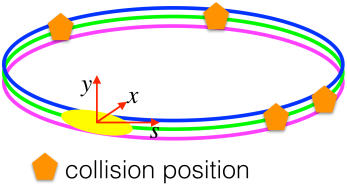
Influence of optical focusing

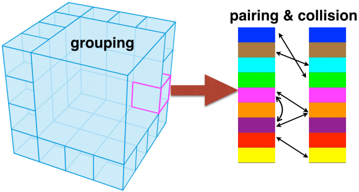
- Beam profile is modulated by varying the strength of quad. QF21 upstream of YAG/OTR monitor
- Horizontal dispersion has been corrected
- Horizontal halo and its asymmetry depend on the optical focusing!





Monte Carlo simulation with SIRE





- T & A binary collision model (BCM)
- Routine:
  - Generate particles in action-angle frame (J, Φ)
  - Track particle element-by-element, $J =$ const and random phase advance
  - Perform grouping, pairing and collision at each element
    The variance of polar angle $< \theta^2 >$ is expressed as

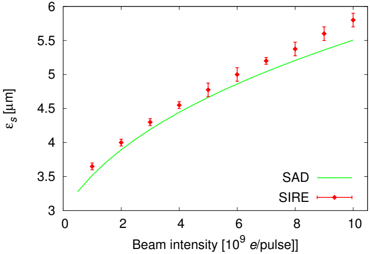
$$< \theta^2 > = \frac{4\pi \rho_v r_e^2 c_0 \Delta t}{\beta_{cm}^3} (\log)$$

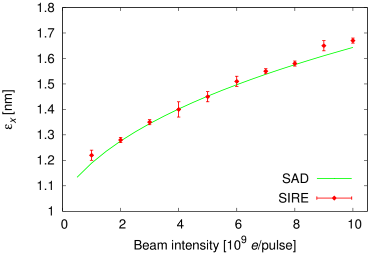
  - Damping and quantum excitation are considered in each turn

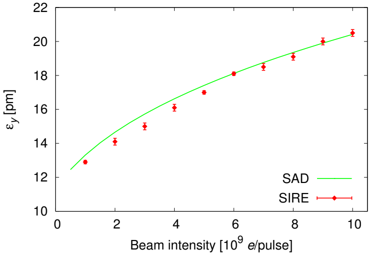
[1] A. Vivoli, IPAC'10, WEPE090

Emittance dilution due to IBS

- Equilibrium emittance could be calculated by envelope matrix method (multi-iteration) in SAD Gaussian phase-space distribution, including dispersion, xy coupling and tail cut (log)≈10
- Good agreement for ϵ_x and ϵ_s with varying (log) in simulation, but larger ϵ_y predicted by simulation

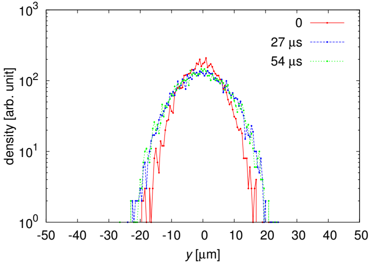


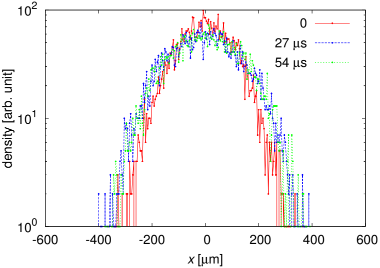


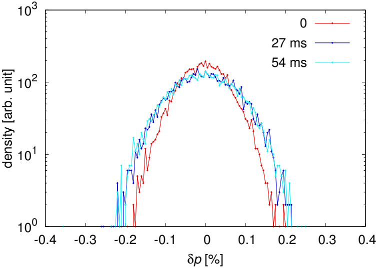


Evolution of beam profiles with IBS diffusion

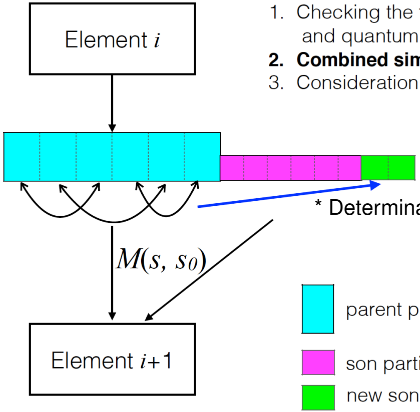
- Diffused transverse and momentum profiles remain Gaussian distribution
- To observe the possible tail from large angle collisions, we attempt to combine IBS & Touschek scattering in simulation...







Simulation of tail from large angle collisions



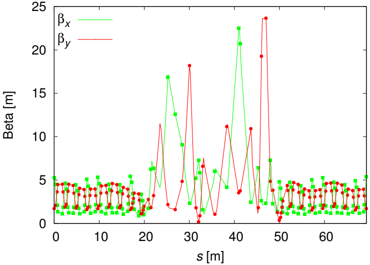
1. Checking the treatments of radiation damping and quantum excitation
2. **Combined simulation of IBS and Touschek scatterings**
3. Consideration of non-linear components (sext.)

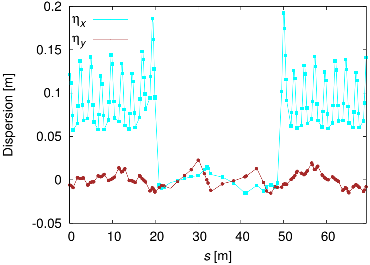
* Determination of "large" scattering angle

- Meanwhile, we also attempted to find evidence of halo from IBS by the measurement of momentum tail

Twiss parameters of ATF ring in SIRE

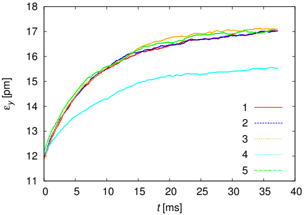
- 250 observation points after lattice compression (Δz>10 cm)



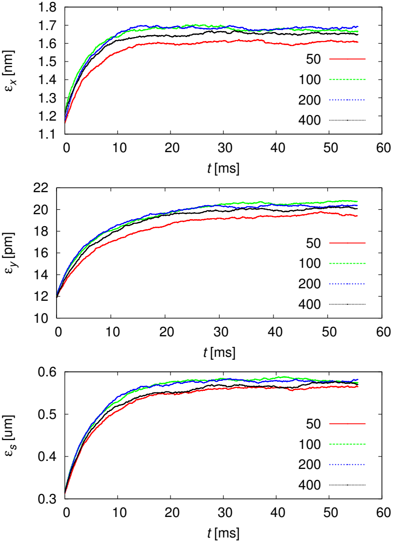


Emittance growth due to IBS

- Multiple tracking are essential for Monte Carlo simulation (large deviation)

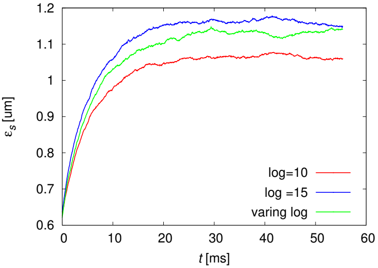


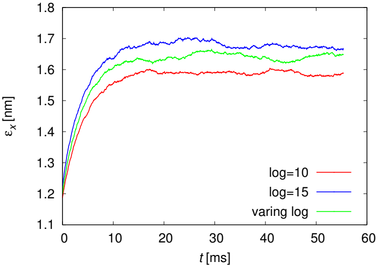
- Diffusion process and equilibrium are affected by cell density
- Cell density of 100/100/100 and 200/200/100 seems acceptable (1 % unscattered)

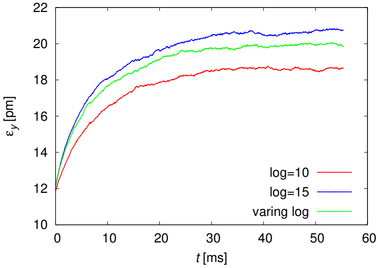


Determination of (log) factor

- Diffusion from IBS depends on $<\theta^2> \propto$ (log)
- Varying (log) is used in IBS simulation







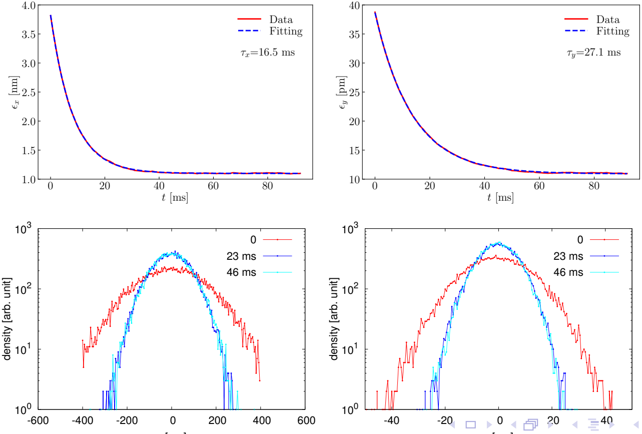
Transverse radiation damping and fluctuation

$$Jx_{i+1} = Jx_i e^{-2T_0/\tau_x}$$

$$Jy_{i+1} = Jy_i e^{-2T_0/\tau_y}$$

$$x_{i+1} = x_i + \sqrt{\epsilon_{eq} * \beta_x (1 - e^{-2T_0/\tau_x})} * w_i$$

$$x'_{i+1} = x'_i + \sqrt{\epsilon_{eq} * \beta_x (1 - e^{-2T_0/\tau_x})} * (1 - \alpha_x)/\beta_x * w_i$$



Longitudinal radiation damping and fluctuation

Synchrontron phase ϕ_s and radiation energy loss per turn U_0 is

$$\phi_s = \pi - \omega_{RF} \cdot z_s / c0$$
$$U_0 = V_{RF} \cdot \sin\phi_s$$

Particle energy change per turn is

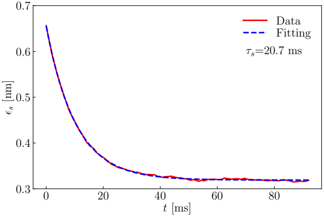
$$\delta p_{i+1} = \delta p_i + V_{RF} \sin(-z\omega_{RF}/c_0 + \phi_s)/E - U_0/$$

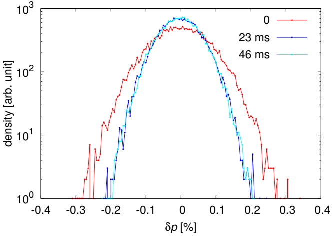
Energy change due to damping and excitation is

$$\delta p'_{i+1} = \delta p_{i+1} e^{-2T_0/\tau_s} + \sigma_{p,eq}\sqrt{4T_0/\tau_s} w_i$$

Longitudinal position shift above transition energy is

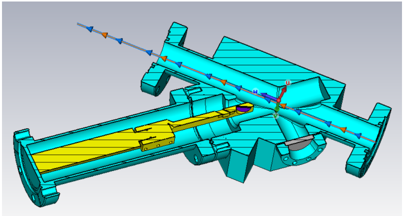
$$z_{i+1} = z_i - \delta p'_{i+1} T_0 \alpha_c c_0$$



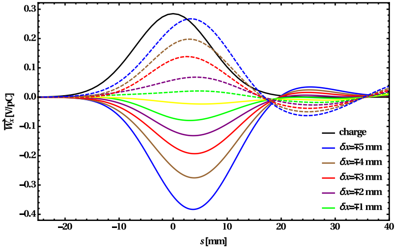


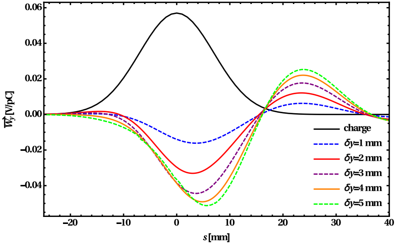
Wakefield property of OTR/YAG monitor

- Benchmarking based upon Ref. cavity (thanks to A. Lyapin)
- Simulation of wakefield with a simplified chamber/holder model
- Simulation parameter: $\sigma_z = 7$ mm, $Q = 1$ pC



- $A_{wy} \approx 0.05$ V/pC and $A_{wx} \approx 0.4$ V/pC, with beam is displaced by 5 mm





Effect of WK at YAG monitor to nanometer beam size

- Orbit change and beam size growth at IP can be estimated by linear calculation

$$\Delta y \approx R_{34} \frac{ed_y}{E} \int_{-\infty}^{\infty} W_T(z)\rho(z)dz$$

$$\Delta \sigma_y \approx \sqrt{R_{34}^2 (\frac{ed_y}{E}) \sigma_w^2}$$

- Assuming beam offset 3 mm at YAG and beam intensity as 3×10^9/pulse
- Effects: $\Delta y = 0.9$ nm, $\Delta \sigma_y = 0.5$ nm; $\Delta x = 0.87$ μm, $\Delta \sigma_x = 0.02$ μm