Investigation of beam tail/halo at Accelerator Test Facility of KEK (Japan)

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August 23, 2016

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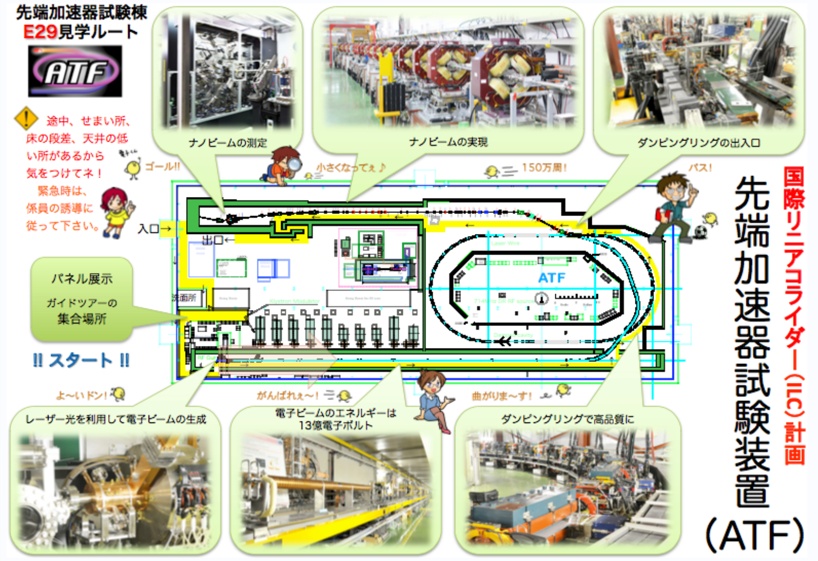
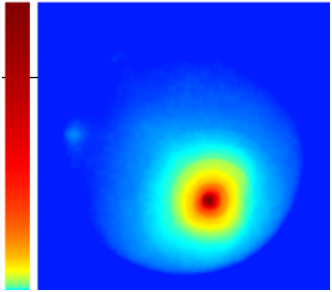
Introduction

Accelerator Test Facility, KEK



[1] http://atf.kek.jp/twiki/bin/view/Public/ATFaccelerator

Motivation



"From the diagnostics point of view, one thing is certainly clear by definition halo is low density and therefore difficult to measure "
— Simulation/visualization with a high dynamic range ($> 10^6$)

Negative effects:

- Nuclear activation of beam transport channel;
- Increasing background level;
- Influence on detector (gamma ray & muons from collimator)

Evaluation of beam tail/halo in one bunch

Beam tail/halo should be increased particles comparing with the distribution of beam core...

- Kurtosis (1D)

$$k = \frac{< (x - x_0)^4 >}{< (x - x_0)^2 >^2}$$

- Halo parameter H (2D)

$$H_i = \frac{\sqrt{3 < x_i^4 >< x_i'^4 > +9 < x_i^2 x_i'^2 >^2 -12 < x_i x_i'^3 >< x_i^3 x_i' >}}{2 < x_i^2 >< x_i'^2 > -2 < x_i x_i' >^2} - 2$$

$H_i > 1 \Rightarrow$ significant halo

- Ratio of beam core to offset

$$f(x) = g(x) \cdot l(x)$$

where $g(x) = A\frac{(x-x_0)^2}{2\sigma^2}$ and $l(x) = a_0 x + b_0$

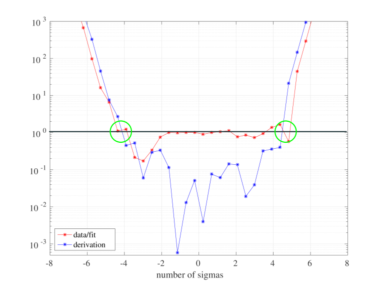
Definition of beam tail/halo

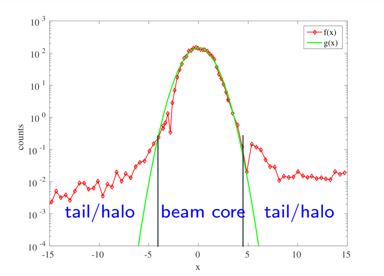
Definition used in our case

- Considering tail/halo particles together and assuming a Gaussian beam core;
- Beam tail/halo are defined as an increasing population of particles comparing with Gaussian beam core.

$$R(x) = f(x)/g(x) > 1$$

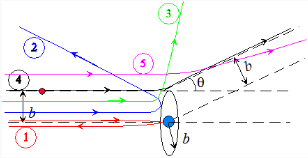
$$d(R(x))/dx > c_0$$

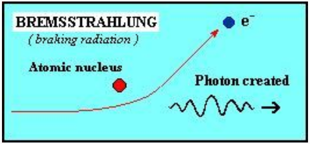




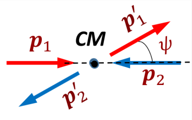
Particles process

- Scattering by residual gas (elastic, inelastic)





- Scattering between particles within bunch (intrabeam and Touschek scattering)



$$\frac{dP}{dt} = \frac{1}{2}\int dr \frac{dP_1}{\gamma_1}\frac{dP_2}{\gamma_2} P(\gamma, P_1)P(\gamma, P_2)|M|^2 \frac{dP_1'}{\gamma_1'}\frac{dP_2'}{\gamma_2'}\frac{\delta^2(P_1' + P_2' - P_1 - P_2)}{(2\pi)^2}$$

Others

- Mismatching/misalignment/dispersion/energy halo/wakefield..

Reconstruction of beam tail/halo at ATF2

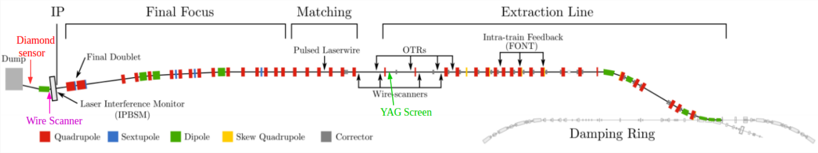
Realist beam tail/halo generator for ATF2

Beam tail/halo at EXT line could be measured using Wire Scanner. With a Gaussian beam core, beam tail/halo could be described as

$$\rho_H = 2.2 \times 10^9 X^{-3.5} \tag{1}$$

$$\rho_V = \begin{cases} 2.2 \times 10^9 X^{-3.5} & 3 < X < 6 \\ 3.7 \times 10^8 X^{-2.5} & X > 6 \end{cases} \tag{2}$$

where ρ_H and ρ_V are the horizontal and vertical distributions, $X = x/\sigma_x$ is the number of sigmas.



Realistic beam tail/halo generator for ATF2

Defining the normalized variables $\tilde{x} = \frac{x}{\sqrt{\beta}}$ and $\tilde{x}' = \frac{d\tilde{x}}{d\phi} = \sqrt{\beta}x' + x\frac{\alpha}{\sqrt{\beta}}$, The Courant-Snyder invariant can be expressed as

$$\tilde{x}^2 + \tilde{x}'^2 = \gamma x^2 + 2\alpha x x' + \beta x'^2 = \frac{\varepsilon}{\pi} \tag{3}$$

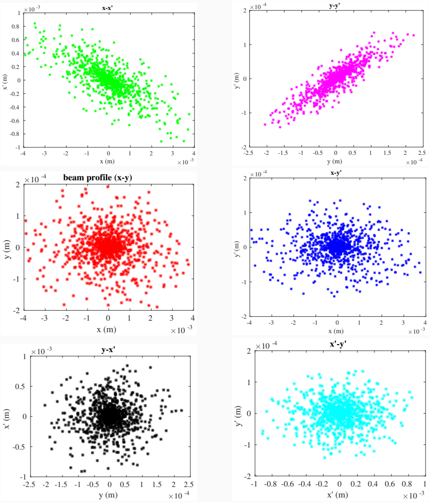
Assuming the vertical tail/halo distribution to be same as the horizontal one, the distributions of $(\tilde{x}, \tilde{x}', \tilde{y}, \tilde{y}')$ will be independent and share the same shape. The 4D distribution can be described as

$$f(r) = \begin{cases} \frac{N}{\sqrt{2\pi}\sigma_r} e^{-\frac{r^2}{2\sigma_r^2}} & |r| \leq 3\sigma_r \\ NK_1 \cdot r^{-3.5} & 3\sigma_r < |r| < 40\sigma_r \end{cases} \tag{4}$$

$r = \sqrt{\tilde{X}^2 + \tilde{X}'^2 + \tilde{Y}^2 + \tilde{Y}'^2}$, N is the quantity of particles and K_1 is a matching factor.

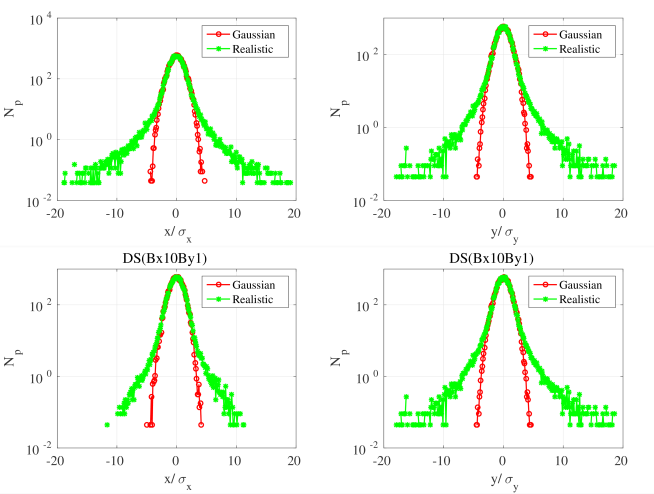
Realistic beam tail/halo generator for ATF2

- Calculate the number of particles in beam core and beam halo regions;
- Generate the beam core and beam halo particles r_j respectively, as normalized coordinates using a Monte Carlo algorithm;
- Assign each r to $(\tilde{X}, \tilde{X}', \tilde{Y}, \tilde{Y}')_j$ randomly;
- Convert the normalized distributions $(\tilde{X}, \tilde{X}', \tilde{Y}, \tilde{Y}')$ to the physical phase space distribution (x, x', y, y').



Realistic beam tail/halo generator for ATF2

- Visualize profile to more than 10 σ_x and 20 σ_y with realistic model, but only 5σ with gaussian model, at start/end of ATF2 (MADX)
- Application: beam loss/background study and beam profile measurement
  $\rightsquigarrow$ for beam after damping ring?



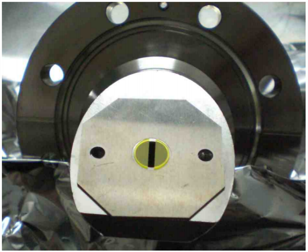
Experimental studies of transverse beam tail/halo

Devices for beam tail/halo visualization

- In EXT line: Ce:YAG screen, Wire Scanner (removed now)
- At Post-IP: Wire Scanner, Diamond Sensor

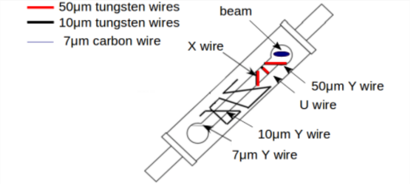
Ce:YAG screen

- 1 mm slit in the center and only the beam halo is imaged
- Dynamic range $\sim 10^3$



Wire Scanner

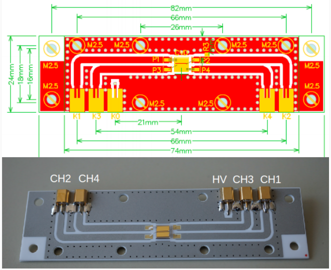
- Dynamic range $\sim 10^4$



[1] T. Naito and T. Mitsuhashi, in *Proc. IBIC'15*. [2] M. Matsuda et al., ATF-02-04-2002

An in vacuum diamond sensor

- Why diamond?
  Band gap (5.48 eV)⇒ lower noise level/quasi negligible leakage current (pA)
  High mobility ($1300 \sim 4500$ $cm^2 \cdot V^{-1} \cdot s^{-1}$) ⇒ fast data acquisition (100 MHz)
  High displacement energy (43 eV) ⇒ High radiation hardness
- Design of diamond sensor (designed by LAL)



Test of DS

- leakage current: $\sim$ pA @ 400 V
- integrated charge by an MIP: 2.88 fC
- charge collection efficiency (CCE): 100 % @ 400 V
- dynamic region: $\sim 10^7$

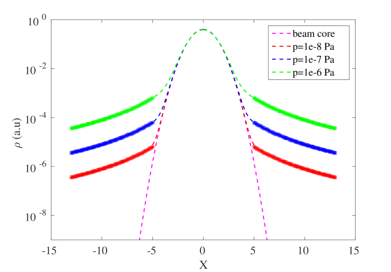
[1] S. Liu, PhD Thesis, 2015

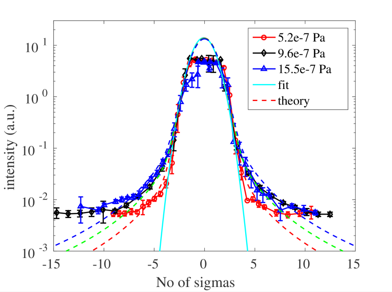
Vertical beam tail/halo at EXT line

- Beam tail/halo is assumed to be as same as that in the exit of DR, which could be predicted by elastic beam scattering theory[1]

$$\rho(X) = \frac{1}{\pi}\int_0^{\infty} \exp[-\frac{1}{2}k^2 + \frac{N_t}{d}\cdot\frac{2}{\pi}\int_0^1 (\frac{KX}{\sigma_0'}\theta_{min}\cdot K_1(\frac{KX}{\sigma_0'}\theta_{min})-1)/X\cdot arcos(X)]dXdK]$$

- Higher beam tail /halo level was observed clearly when the DR vacuum increased with low beam intensity (0.1×10^{10}/bunch)

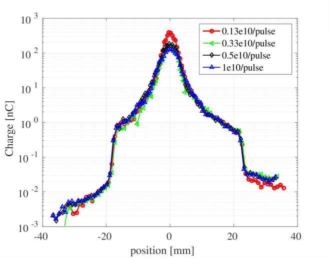




[1] H. Kohji, "Non-Gaussian distribution of electron beams due to incoherent stochastic processes",1992.

Vertical beam tail/halo at Post-IP

- Beam optics: Bx10By1
  Beam intensity: 0.1×10^{10}/pulse$\sim 1\times10^{10}$/pulse
  DR vacuum: 10×10^{-7} Pa



Beam size measured by Diamond Sensor

	0.1e10	0.3e10	0.5e10	1.0e10
CH1/mm	1.530	1.491	1.463	1.662
CH2/mm	1.815	1.589	1.626	1.800
CH3/mm	2.046	2.025	2.055	2.081
CH4/mm	2.612	2.338	2.301	2.258

- Vertical beam tail is proportional to the beam intensity (elastic/inelastic beam-gas scattering, intra-beam scattering)
- Larger σ_y measured by DS with higher beam intensity

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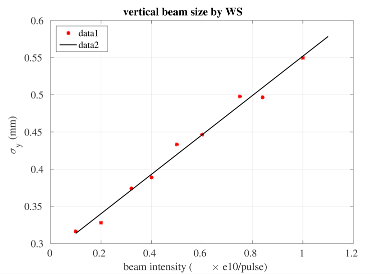
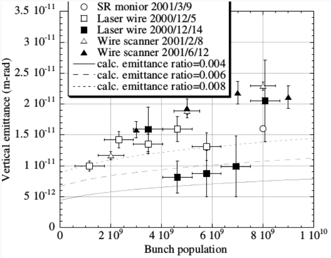
  DR vacuum: 10×10^{-7} Pa



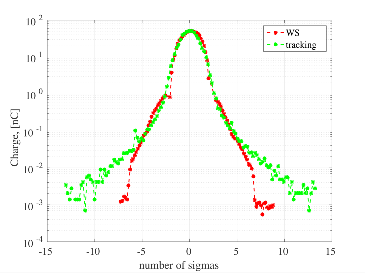


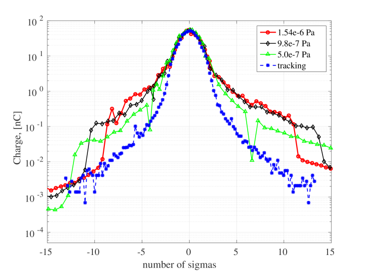
- Larger vertical beam size with higher beam intensity tends to be similar to the emittance grown due to IBS in ATF DR[1].

[1]Kubo, K., et al. Physical Review Letters 88.19 (2002): 194801

Vertical beam tail/halo at Post-IP

- Beam core/tail measured by WS agrees well with tracking results (MADX)⇒ No significant enhancement of beam tail/halo along ATF2 (optics related source is quite little)
- The beam tail/halo measured by DS is higher than the tracking result (might be due to misalignment of beam-DS), however it does follow the DR vacuum





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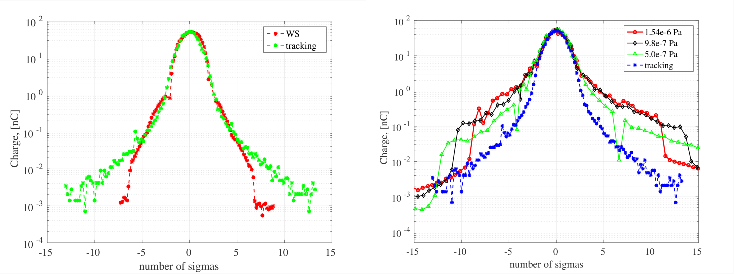


- Main source of vertical beam tail/halo is elastic beam-gas scattering in DR!

Horizontal beam tail/halo at Post-IP

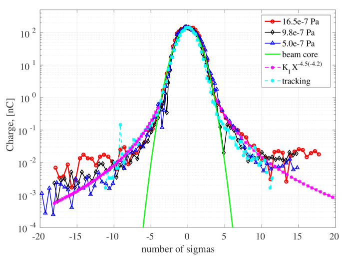
- Beam optics: Bx10By1
  Beam intensity: 0.5×10^{10} /pulse
  DR vacuum: 5×10^{-7} Pa, 10×10^{-7} Pa, 16.5×10^{-7} Pa
- Boundary of beam core/tail is $\pm4\sigma_x$ which is defined by

$$f(x)/g(x) \geqslant 1 \qquad d(f(x)/g(x))/dx \geqslant 0$$

- Beam profile is fit to

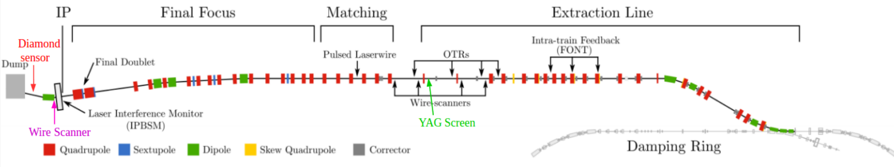
$$f(X) = \begin{cases} \frac{N}{\sqrt{2\pi}} e^{-\frac{X^2}{2}} & 0 < X < 4 \\ N K_x X^{-4.5(-4.2)} & X > 4 \end{cases}$$

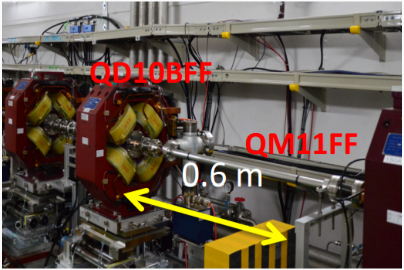
where $X = x/\sigma_x$, K_x is the matching factor.

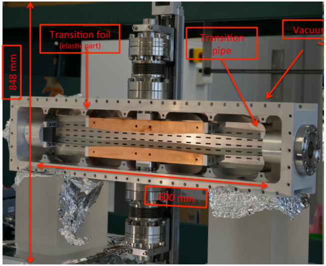


- Beam tail (halo) density didn't increase with a worse damping ring vacuum! ⇒ Main source of halo formation might not be beam gas scattering!

Beam halo suppressed by a vertical collimator



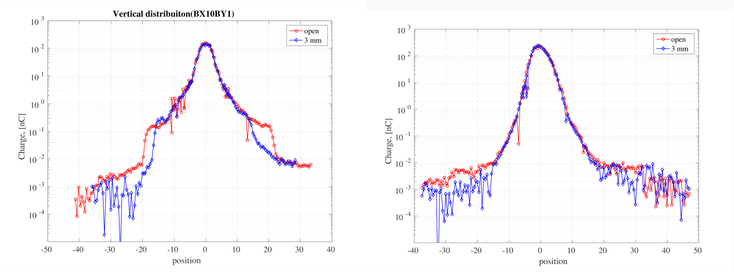




[1] Designed by N. Fuster-Martínez, IFIC, Spain

Beam halo suppressed by a vertical collimator

- Beam optics: Bx10By1
  Beam intensity: 0.3×10^{10} /pulse
  DR vacuum: 5.07×10^{-7} Pa
- Collimator setting: open (red line)and closed to 3 mm (blue line)



1) Vertically, symmetric cuts by vertical collimator are observed
2) In vertical plane, less residual halo beyond cut by collimator (fewer secondary particles when closing collimator)
3) Horizontally, less residual halo on low energy side when collimating vertically

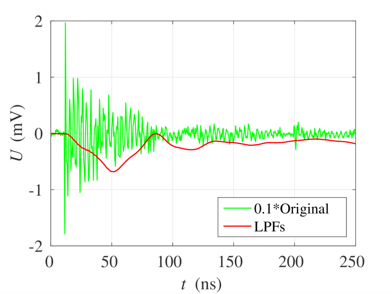
Recent status and prospects

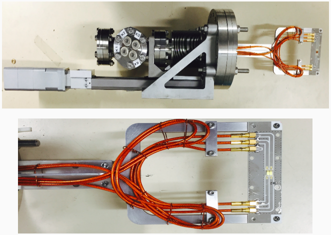
Experiments of DS at PHIL (LAL, Orsay)

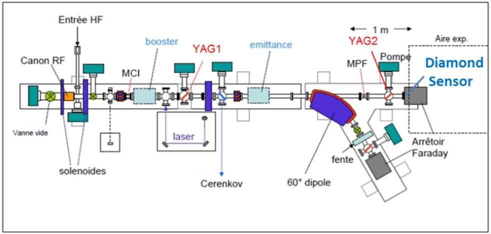
Goals: 1) test of diamond sensor, including linearity, HV dependence, pick-up level and dynamic range

2) study beam halo formation for photocathode RF-Gun

Status: installed in May and test is on going







Conclusion

Summary

- A realistic beam tail/halo generator is developed, which can approach realistic distribution without coupling between (x, x') and (y, y') plane
- Beam tail/halo at ATF2 were measured using YAG, WS and DS. For the vertical case, the main source of beam tail/halo should be elastic beam- gas scattering. Beam halo enhancement along ATF2 beamline is negligible. But, for the horizontal case, need more studies
- For a e+e- collider, beam tail/halo formation in the DR and in other systems must be considered carefully
- Theoretical studies of beam tail/halo sources in ATF DR, including elasitc/inelastic beam gas scattering and IBS, is in process

Thank you!

Questions?