Simulation and Measurement of Beam Halo at Accelerator Test Facility of KEK

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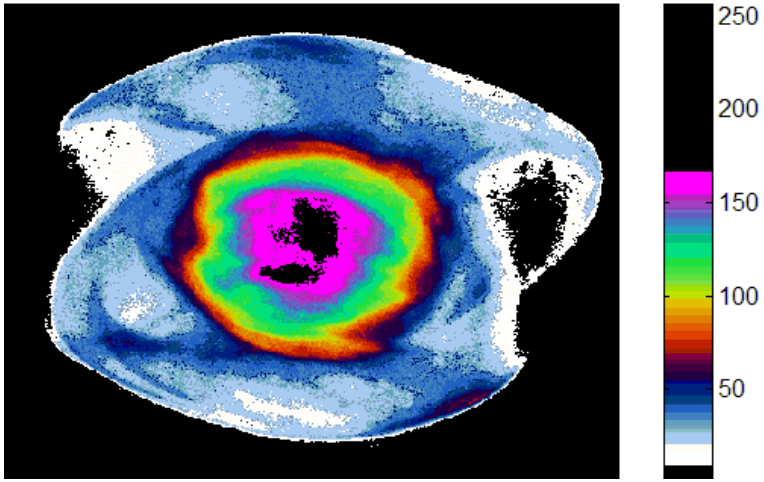
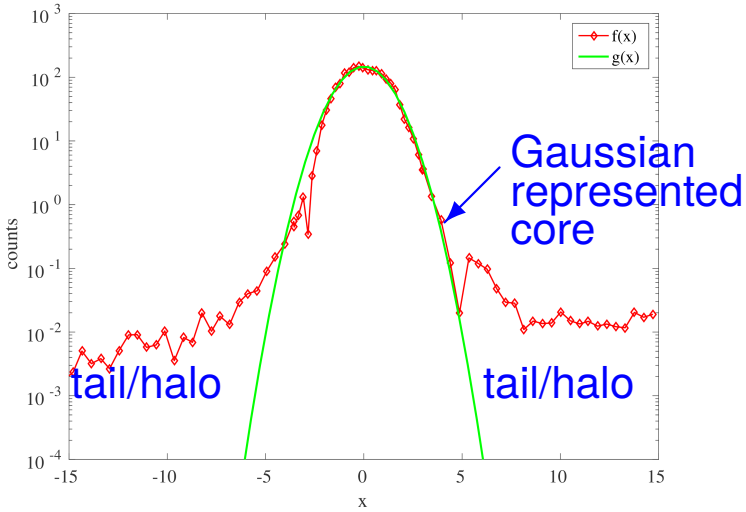
Introduction

What's Halo? Halo definition



"From the diagnostics point of view, one thing is certainly clear – by definition halo is low density and therefore difficult to measure . . ."
—Halo'03 Workshop

- Regarding the 'non-Gaussian' component of profile as halo, the '*Gaussian area ratio*' is also a quantification of halo

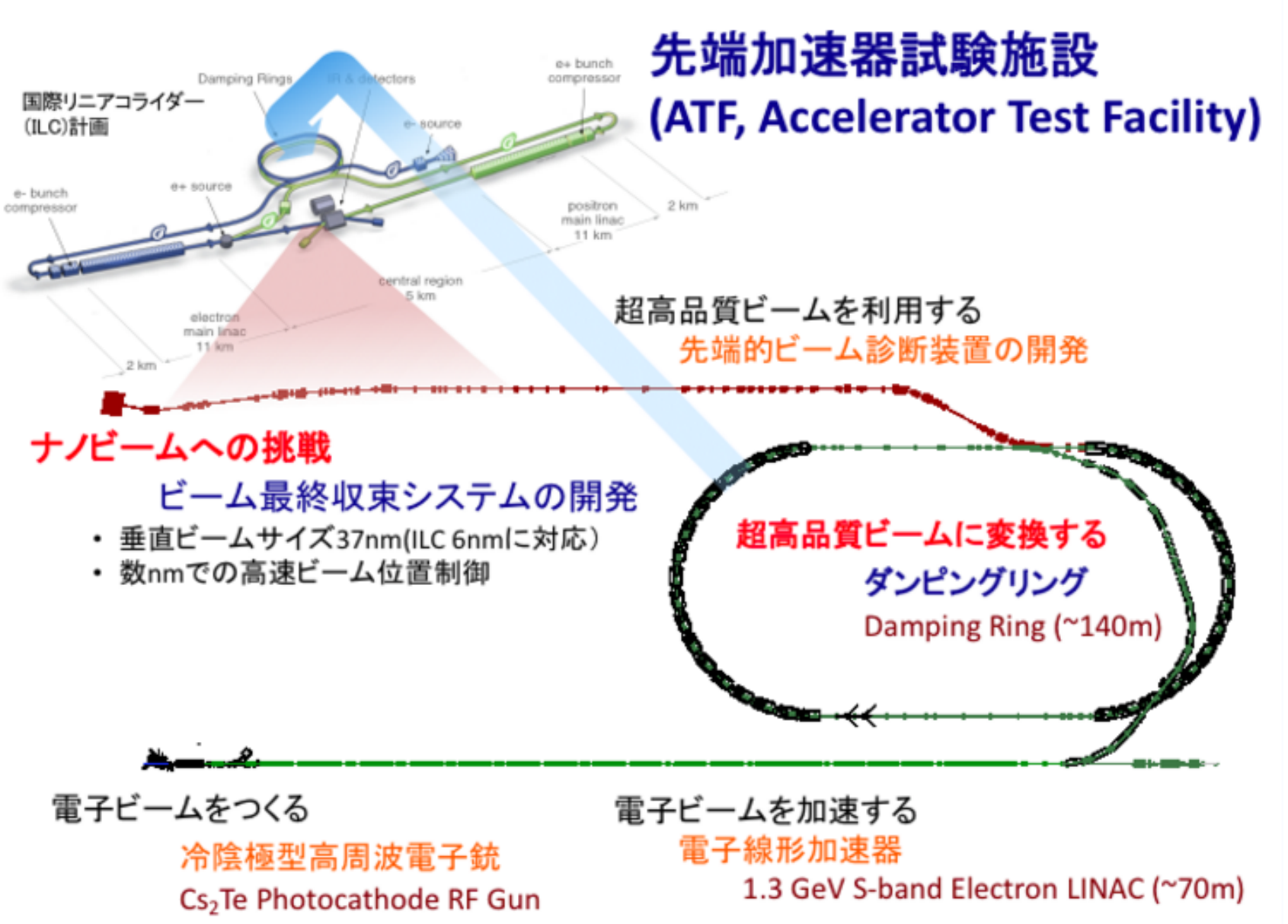


Negative effects:

- Increasing background level; influence precise particle physics experiments (gamma ray & muons from collimator)
- Second beam-beam limit of luminosity of future collider

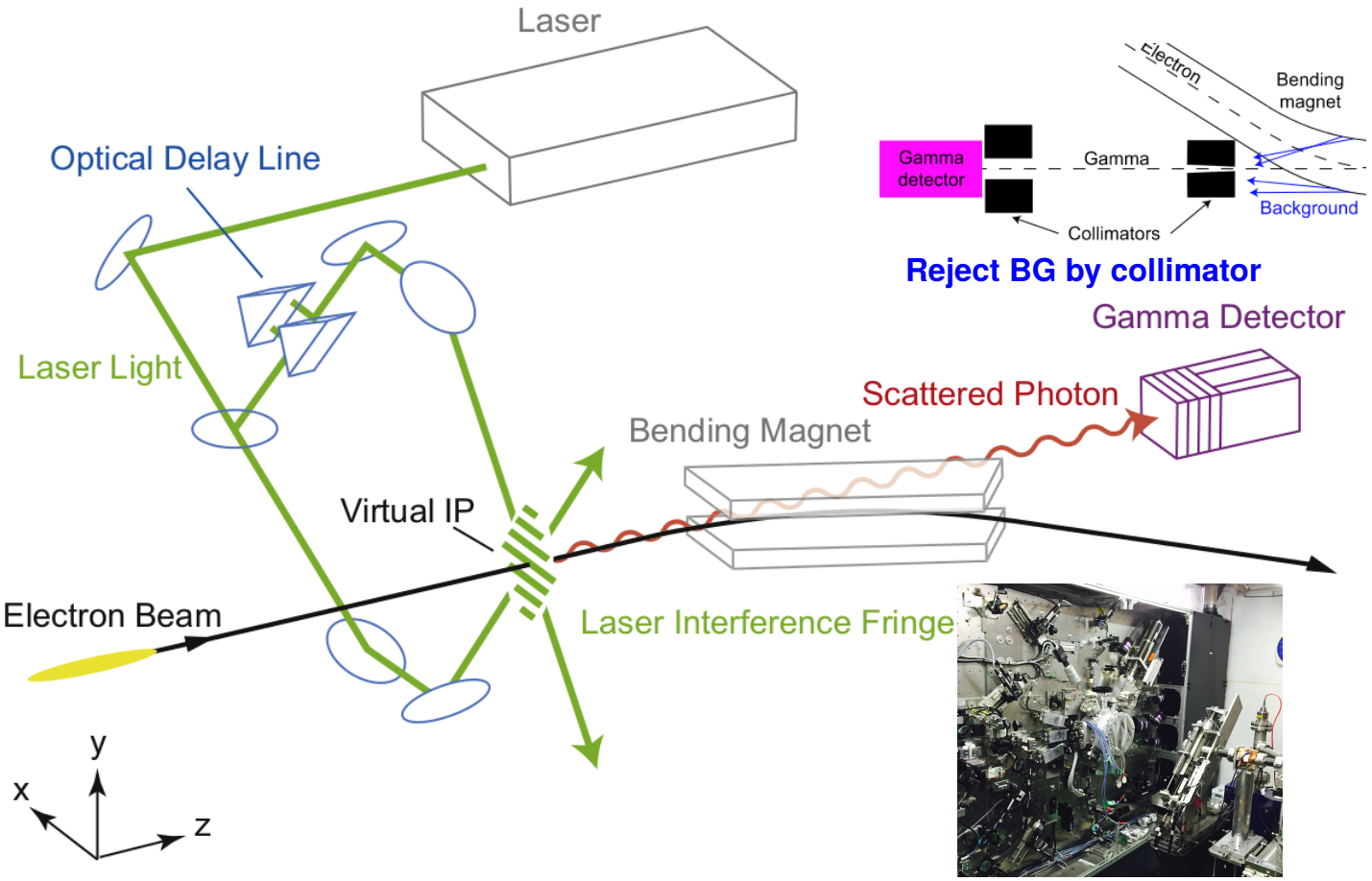
[1] K. Wittenburg, CAS (1992), 557-580
[2] H. Zhang, et al., PRST-AB, 15, 072803 (2012)

Accelerator Test Facility (ATF) at KEK



Motivation of halo study at ATF2

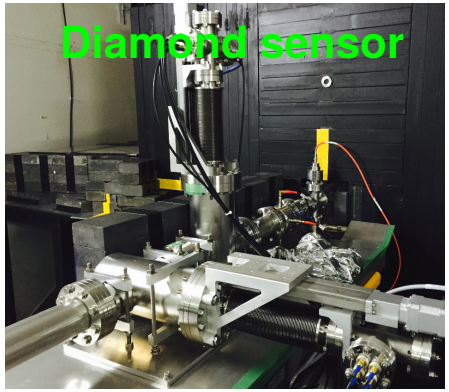
- Background induced by halo particles loss upstream of IP might reduce the modulation resolution of Shintake monitor
- To understand the genesis of halo and its distribution in storage ring

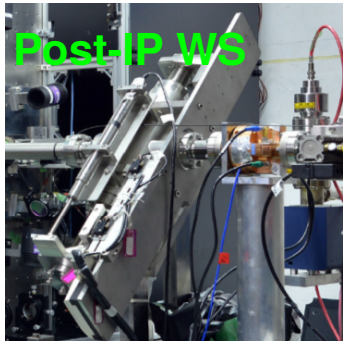


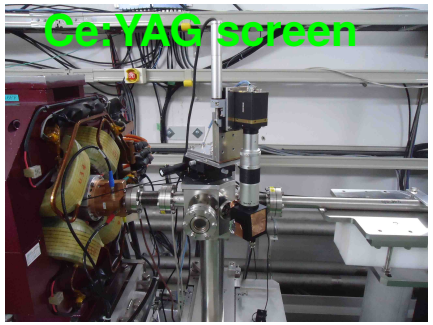
* Figures from [1] J. Yan, et al., NIMA 740(2014) 31-137; [2] T. Suehara, et al., NIMA 616(2010) 1-8

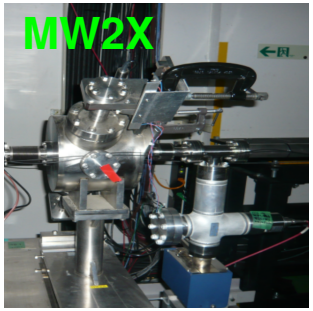
Past and present halo measurement at ATF2

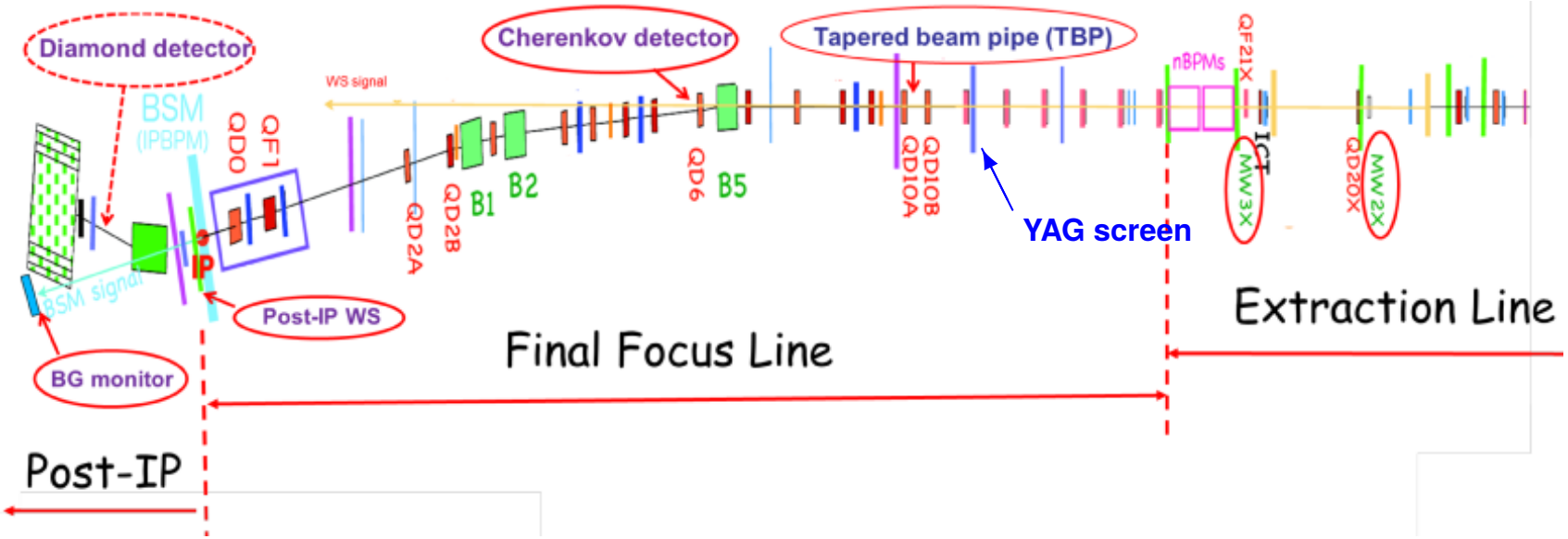
- Diagnostic of beam halo has started since 2005 with wire scanners at ATF EXT line
- New visualization of halo at EXT line and Post-IP of ATF2 were performed using Post-IP WS (2013), YAG screen (2015) and DS (2015)









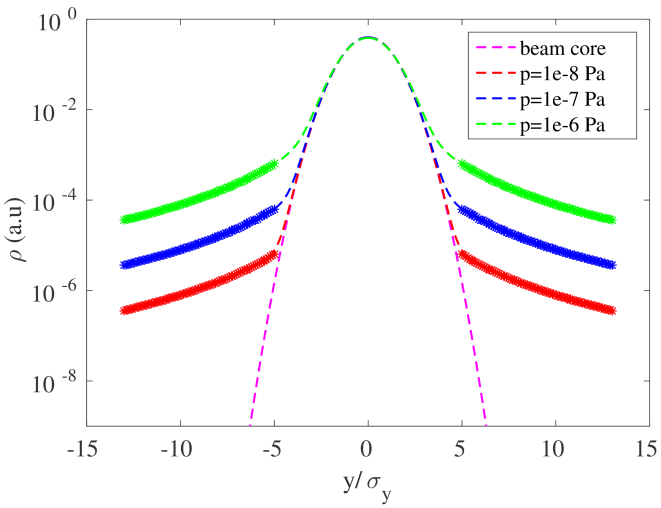


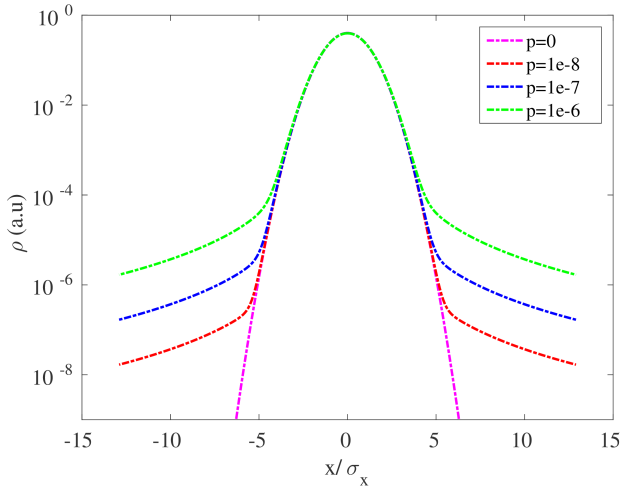
Candidate halo source

- Particles process (beam gas Coulomb scattering, Bremsstrahlung and intra beam scattering), mismatching, field errors,interactions with aperture limits and Potential Well Distortion (PWD)
- Beam halo from BGS at ATF damping ring was first studied by K. Hirata

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

$$\rho_{tail}(X) \simeq \frac{N_d\beta\theta_{min}}{8\sigma_0 X^3}, (X \to \infty)$$





[1] K. Hirata and K. Yokoya, *ParticleAccelerators* 39 (1992), 147-158

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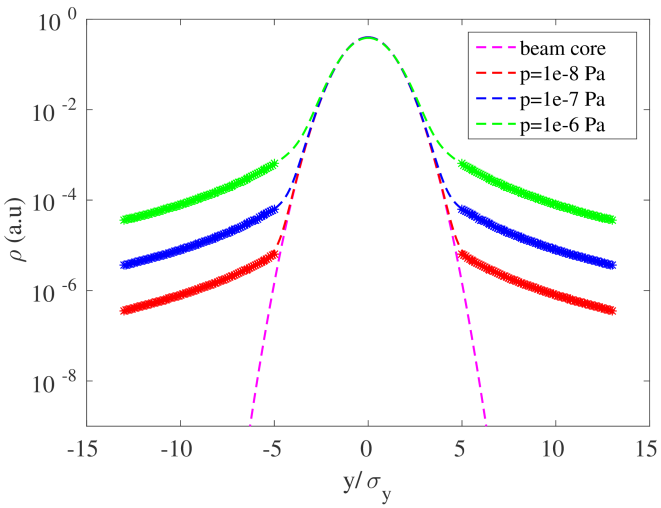
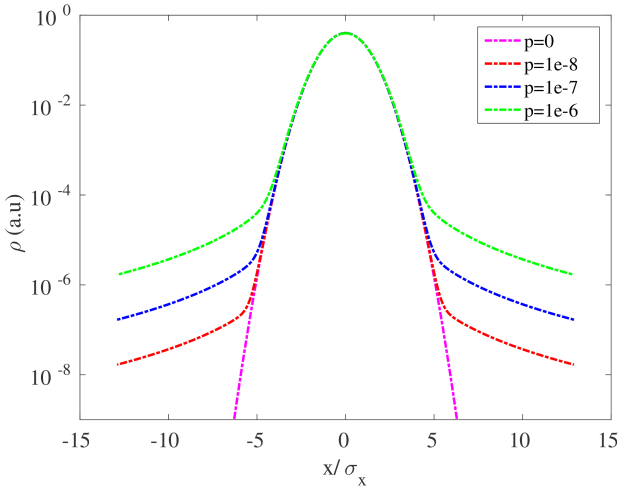




- More detailed and systematic simulation and experiment are essential !

[1] K. Hirata and K. Yokoya, *ParticleAccelerators* 39 (1992), 147-158

Simulation of beam halo from BGS

Method of BGS simulation in SAD

- Represent equilibrium beam parameters by inducing alignment errors to quads and sext.
- Identify ϵ_x, ϵ_y, σ_z and σ_p at the moment of BGS events happened
- Generate N_j random BGS events in each j-th turn, with varying Twiss parameters according to the position (including multi-BGS)
- Track N_j particles from scattering to common observation point, to be combined with N_{j-1} scattered particles accumulated from previous turns and tracked to observation point
- Repeat the above process until extraction

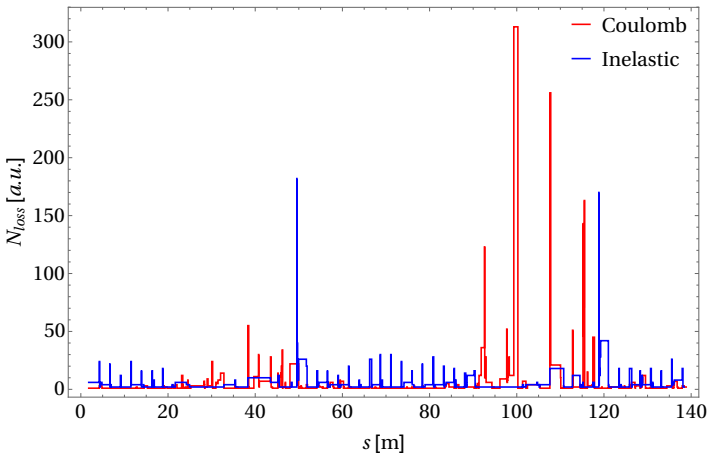
† Core/BGS particles are tracked separately

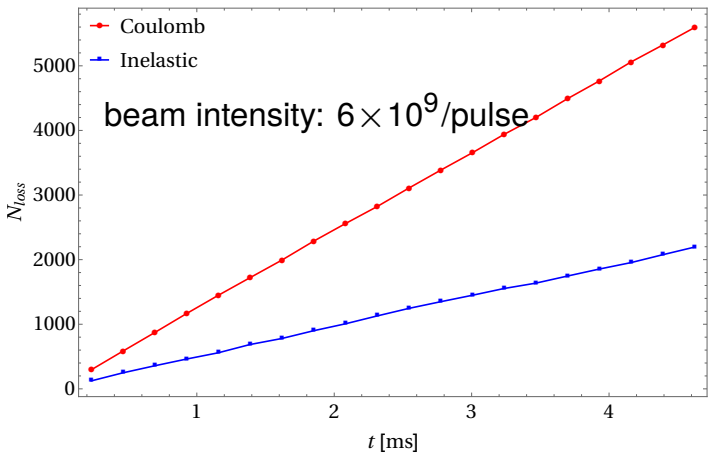
† Common beam parameters at injection ($t = 0$)

E (GeV)	$\epsilon_{x,0}$ (nm)	$\epsilon_{y,0}$ (nm)	σ_l (ps)	σ_p	RD/QE
1.282	14	14	15	0.4%	only at Dipoles

Benchmark of BGS simulation

- Benchmarking by vacuum lifetime τ_v prediction, comparing with analytic estimation
- Elastic BGS and Brems. are considered in simulation
- Simulation parameters:
  E=1.3 GeV, $P = 1 \times 10^{-6}$ Pa, pipe aperture 7.5/12 mm and $\delta_{acc} = 1\%$





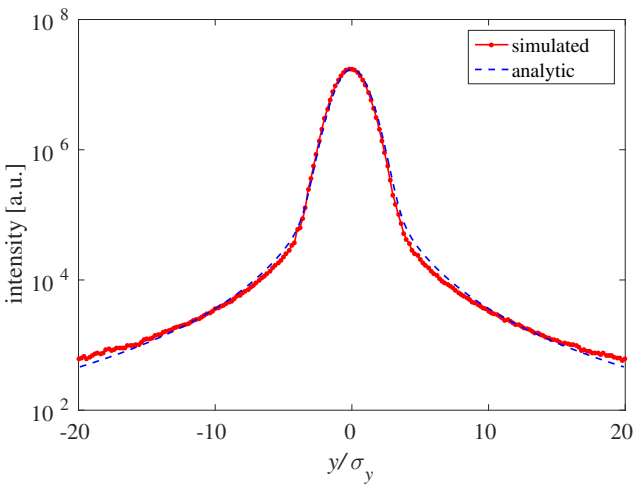
- Vacuum lifetime (1×10^{-6} Pa):
  analytic, 71 mins; simulated, 78 mins;

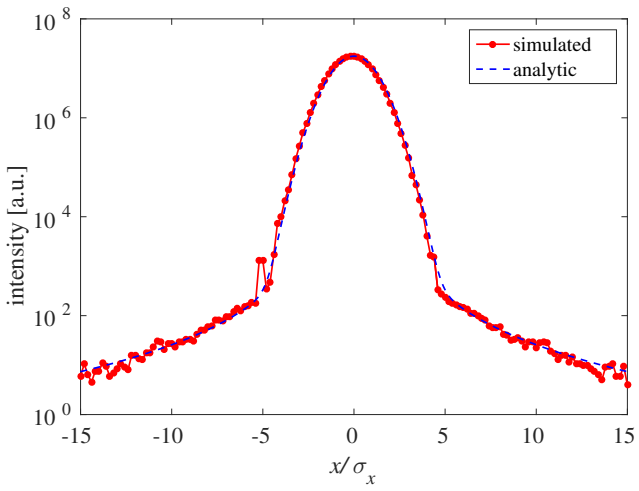
[1] T. Okugi, et al., NIMA 455(2000) 207-212

Comparison of theoretical/tracking results

- Theoretical estimation is based upon the equilibrium parameters

ϵ_x (nm)	ϵ_y (pm)	$\bar{\beta}_x$ (m)	$\bar{\beta}_y$ (m)	τ_x (ms)	τ_y (ms)	gas
1.2	12.8	4	4.6	20	27.6	CO

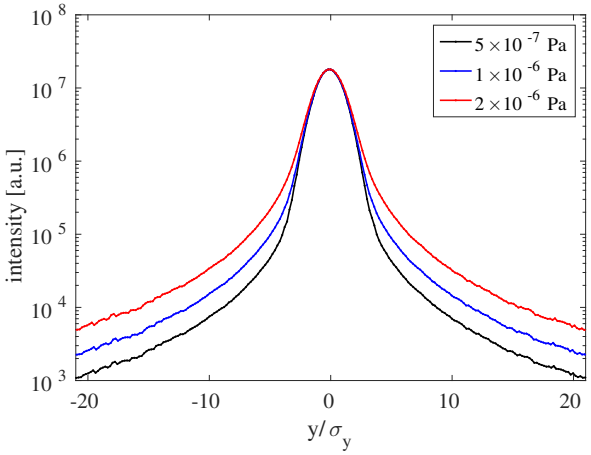


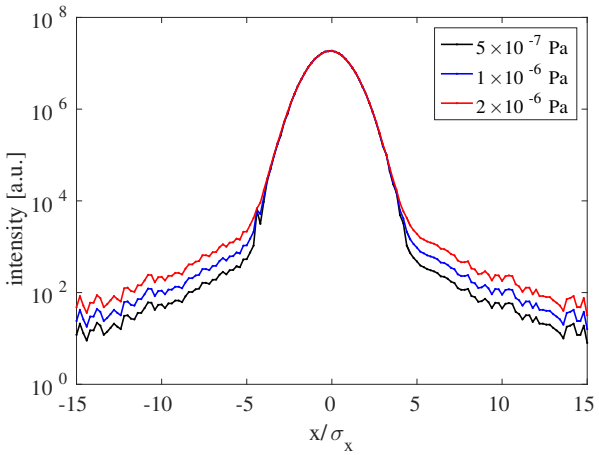


- Vertically, tracking result ($t_n \geq 2\tau_y$) is coincident with the theoretic prediction
- Horizontally, less beam halo comparing with vertical one, and the quantity is consistent with theoretic estimation!

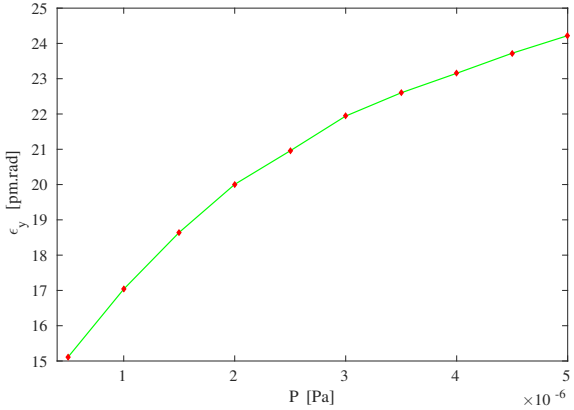
Vacuum dependence of beam halo

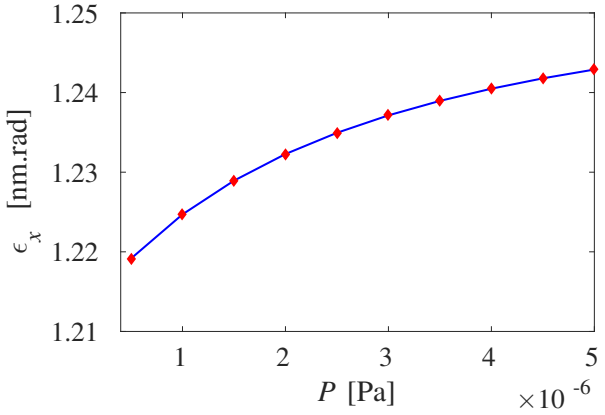
- Beam halo varies corresponding to P_{ave}, vertically and horizontally





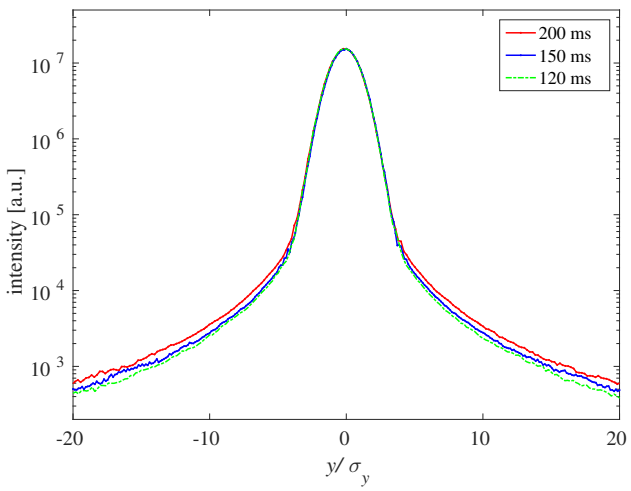
- Vertical emittance ϵ_y grows from 15 pm to 24 pm, and ϵ_x increase from 1.18 nm to 1.23 nm, if P_{ave} increase to 5×10^{-6} Pa

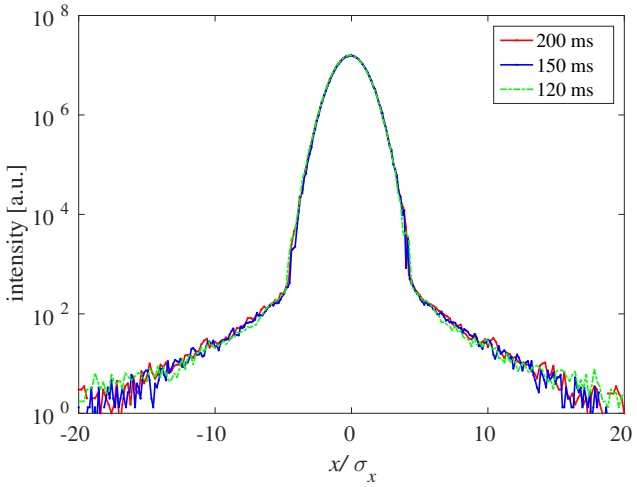




Halo evoluation with storage time

- Theoretical formulas assumes equilibrium beam parameters, without radiation damping and quantum excitation
- Tracking simulation of beam extraction at 120 ms, 150 ms and 200 ms

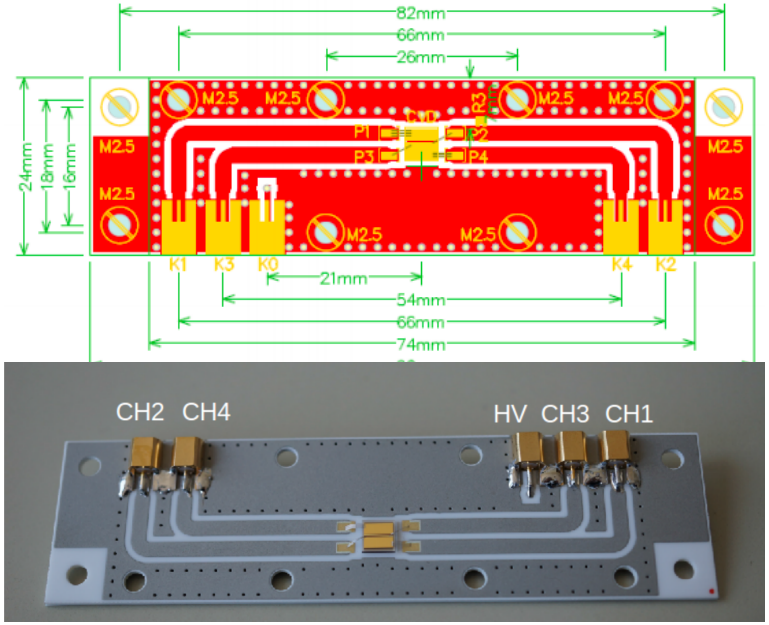




- Lower halo level is observed at 120/150 ms (in normalized coordinate), vertically, since ϵ_y hasn't reach equilibrium status
- Horizontal halo keeps in constant (ϵ_x is equilibrium)

Visualization of beam halo using DS at Post-IP

Halo measurement by *in vacuum* diamond sensor



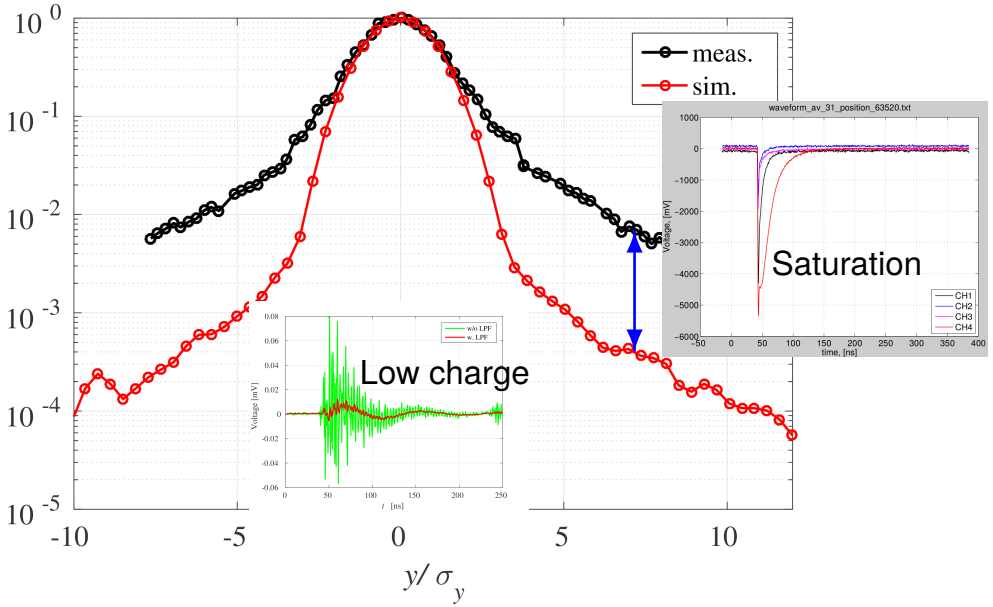
Test of DS

- Leakage current: $\sim$ pA
- Integrated charge by an MIP: 2.88 fC
- Charge collection efficiency: 100 % @ 400 V (small signal)
- Dynamic range $d_R = 10^6$

• Errors: high charge signal reduced by charge collection saturation, and sensitivity limited by induction current

• Reducing d_R and cause profile distortion

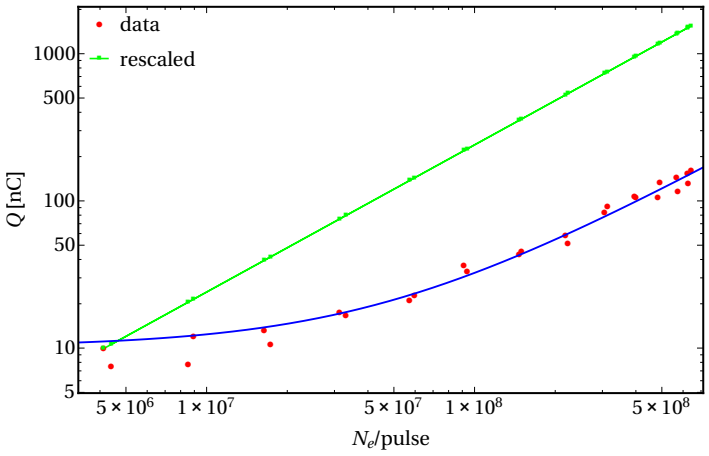
• Solutions: carefully alignment, 1 Ω resistor, calibration of DS signal and RF-finger/LPFs

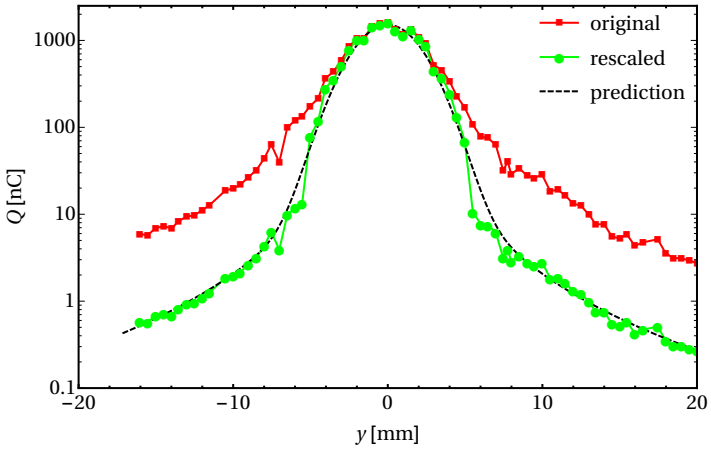


[1] S. Liu, et al., NIMA, 832 (2016)

Rescaling based on self-calibration

- Method to rescale data using profile given by broad DS stripe:
  - Fit $\sigma_{x,y}$ from WS data
  - Predict the expected charge Q_{exp} within Gaussian core region, using the charge collection factor given by low charge data
  - Fit $Q_{meas} \propto n_e$ predicted based on beam intensity and $\sigma_{x,y}$
  - Calculate rescaling factor $\kappa(n_e) = Q_{exp}/Q_{meas}$
  - Rescale charge collected within core region using $\kappa(n_e)$

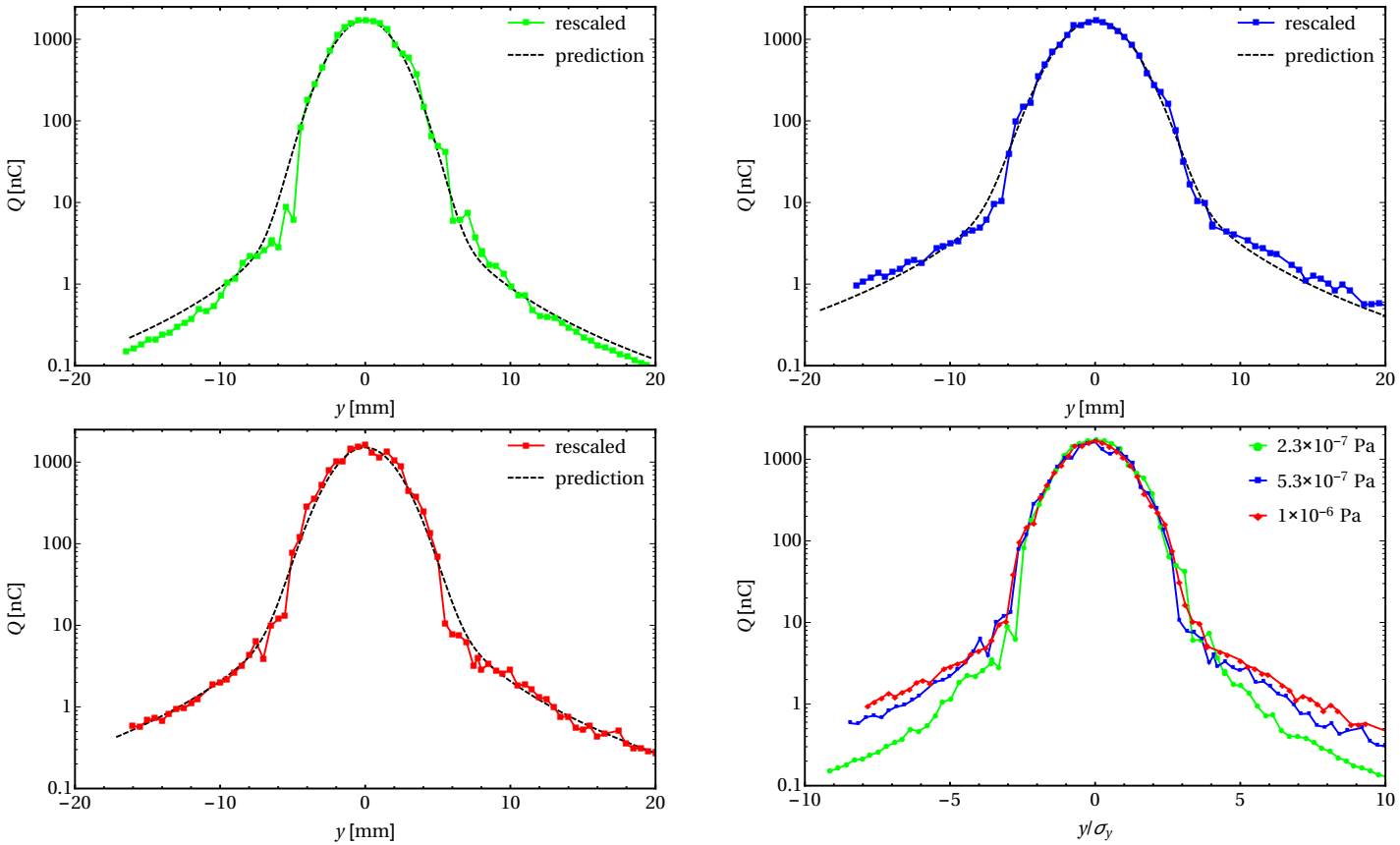




- Beam profile after rescaling is comparable with estimation, which is predicted by BGS theory/simulation!

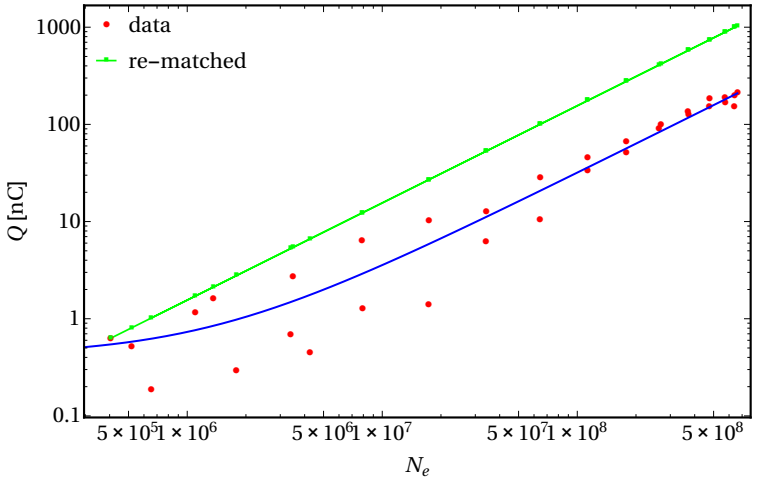
Vacuum dependence of vertical beam halo

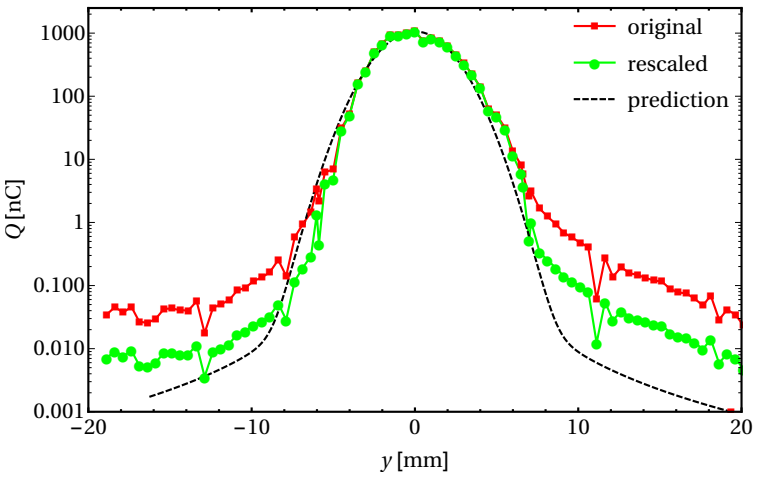
- Halo profiles rescaled based on self-calibration, with P_{aver} are $2.3 \times 10^{-7} \sim 1 \times 10^{-6}$ Pa, agree well with BGS theoretic prediction!
- Vertical beam halo is dominated by beam gas Coulomb scattering



Optimization of horizontal profiles

- Halo measured by DS after rescaling is higher than BGS prediction!
- Asymmetric beam profile is observed, more particles in high energy side





- Reasons: systematic errors of experiment or rescaling, other possible halo source (IBS and PWD?)

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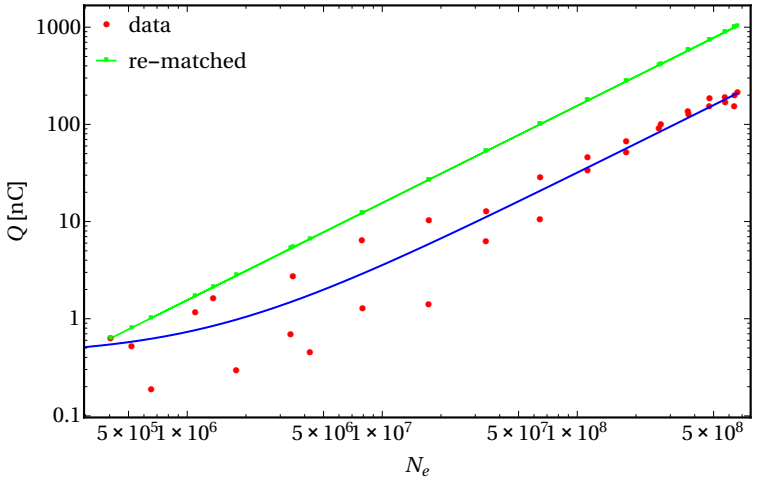
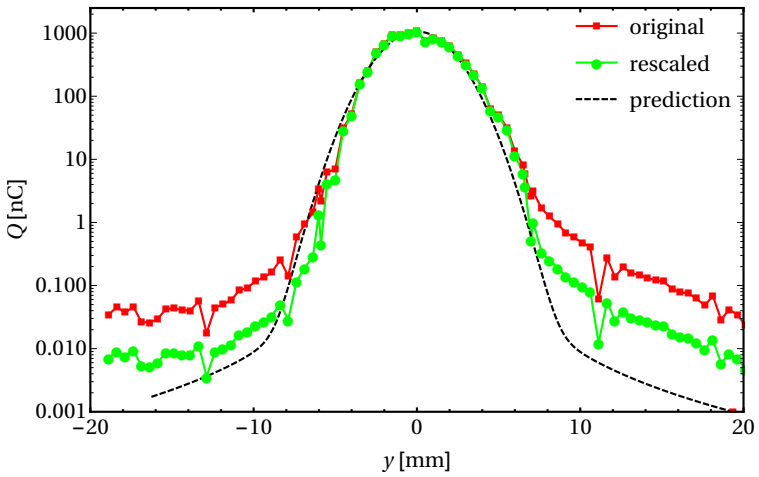
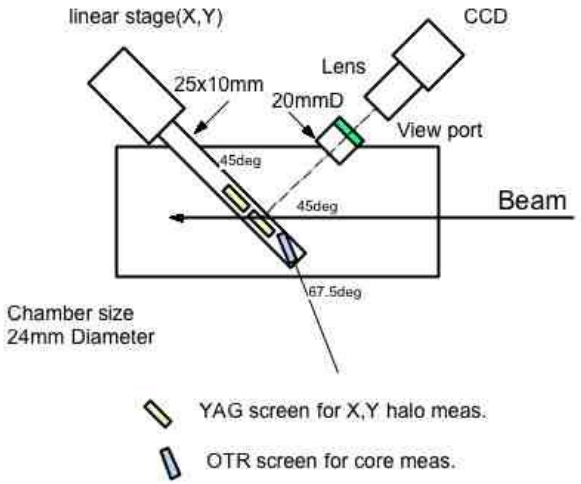


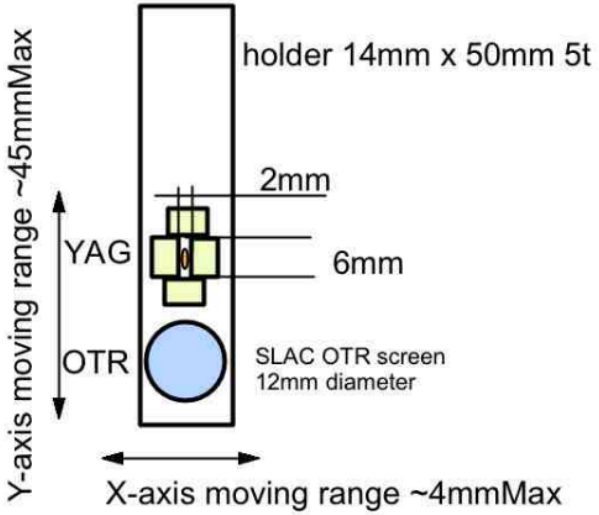


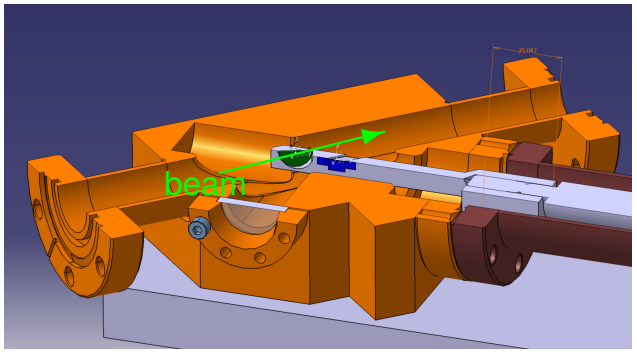
- Reasons: systematic errors of experiment or rescaling, other possible halo source (IBS and PWD?)
- Strategies:
  - Another halo monitor (OTR/YAG screens) at EXT line
  - Simulation of beam distortion due to IBS and PWD

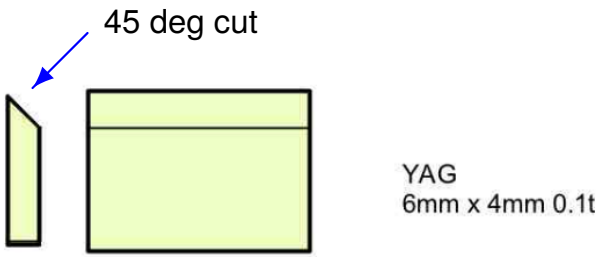
Upgrading of OTR/YAG screens monitor

- Motivation: fast diagnostic of beam halo at dispersion free region
- Idea: 3 screens(2 YAG screens for halo and 1 OTR screens for beam core) are combined to realize high dynamic range 2D profile imaging









- Horizontal slices are cut by 45 deg to avoid edge effects (horizontal insert)

Conclusion

- Simulation of BGS halo in damping ring indicate
  - Good agreements are observed between simulation and theoretic estimation of beam halo
  - Simulation and theory both predict much less halo in $\vec{x}$ than $\vec{y}$
- Thanks to rescaling of DS data, vertical beam halo (and vacuum dependence) are observed and consistent with theoretical prediction
- Proposing to study halo at dispersion-free region, upgrading of OTR/YAG screens monitor is underway (plan to install in May)
- Understanding and validating of halo model at ATF is beneficial to the realism and feasibility of future lepton collider and synchrotron radiation source!

Many thanks to for ATF collaboration!

Thank you for your attention!

Back up...

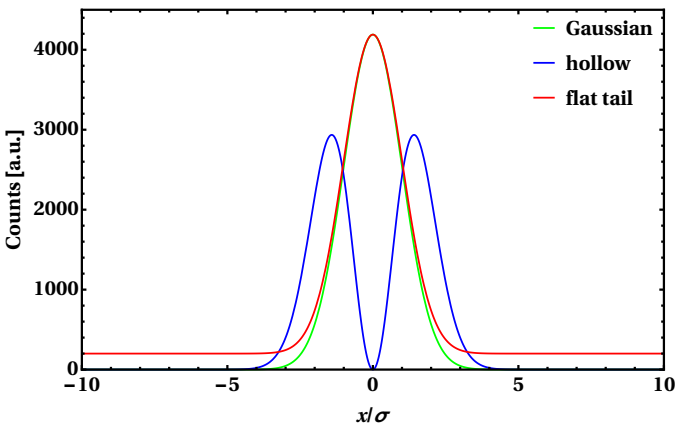
Quantification of 1D beam halo

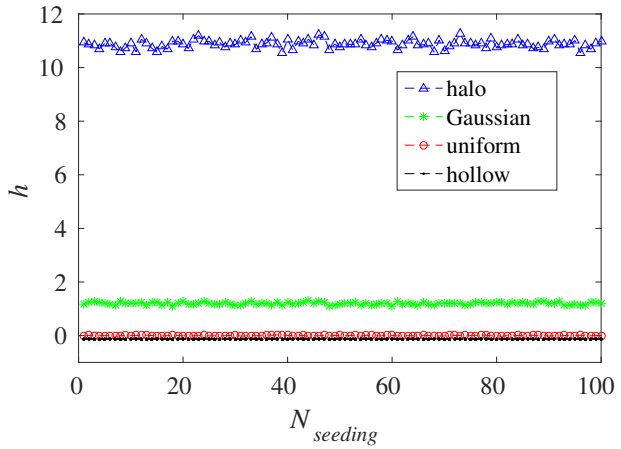
- Kurtosis is used to quantify 1D beam profile (for simulation), normalizing to K-V distribution

$$h(x) = \frac{1}{N}\sum_{i=1}^{N}[\frac{x_i - \bar{x}}{\sigma_x}]^4 - \frac{9}{5}$$

- Significant halo when $h > 1.2$, and quite sensitive

	Hollow	Uniform	Gaussian	Gaussian core + flat tail
h	-2/15	0	6/5	11

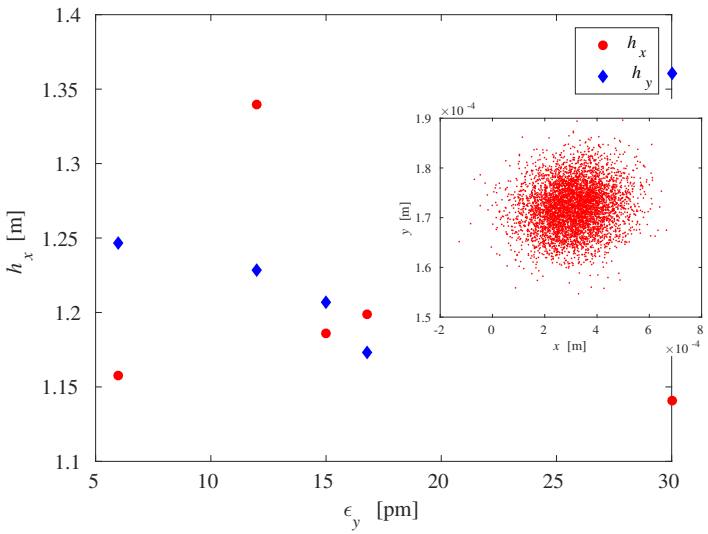


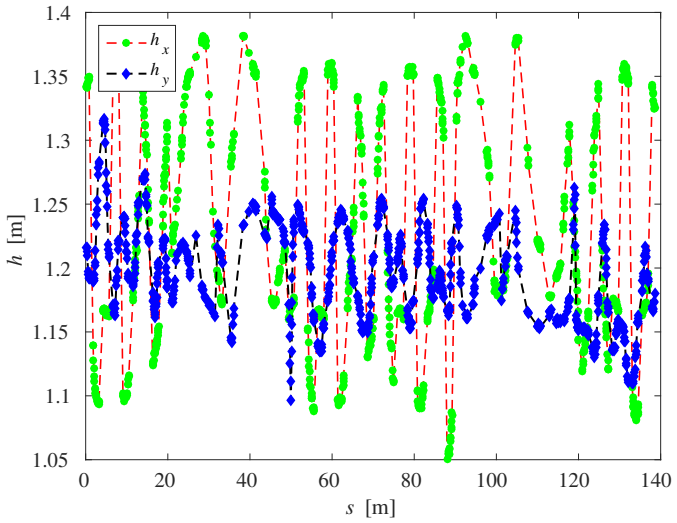


[1] C. Allen, et al., PRST-AB, 2002, 5(12):124202

Beam distorsion from alignment errors

- Tracking of macro-particles (2×10^4) from injection to extraction
- Several seedings of errors are considered, to represent different ϵ_y
- Gaussian transverse beam profiles, and few halo particles, with 20/70 μm alignment errors
- h_x/h_y oscillate around $1.2^{+0.3}_{-0.1}$ along the whole ring (due to η and statistical errors?)



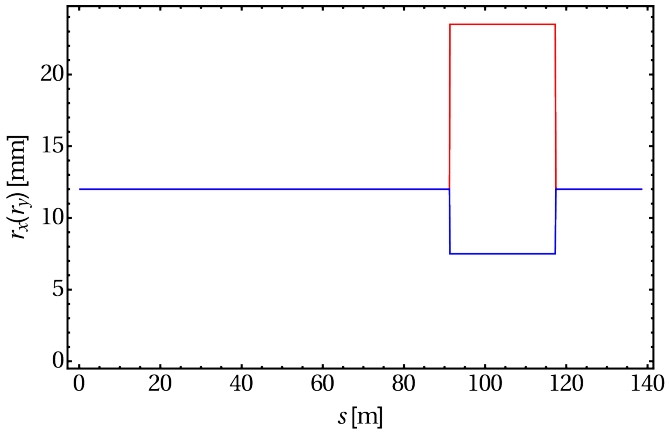


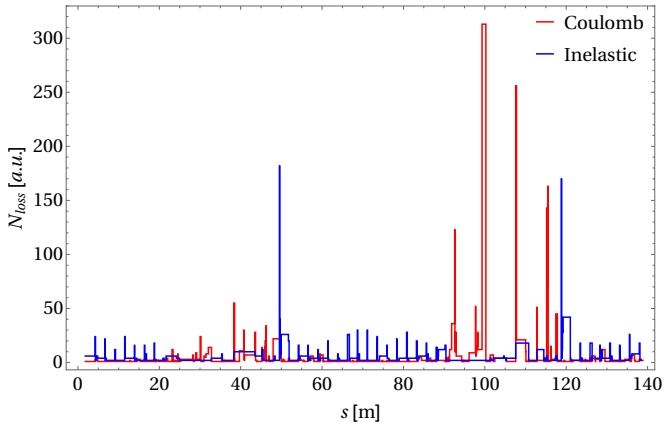
Simulation of vacuum lifetime

- Assuming BGS only includes elastic Coulomb scattering and Brems., tracking study based on the nominal parameter of DR

E (GeV)	P (Pa)	$\bar{\beta}_x/\bar{\beta}_y$ (m)	$\beta_{x,m}/\beta_{y,m}$ (m)	b_x/b_y (mm)	δ_{acc}
1.3	1×10^{-6}	4/4.6	22.5/23.4	7.5/12	0.01
ϵ_x (pm)	ϵ_y (nm)	σ_p	τ_{Coul} (min)	τ_{Brem} (min)	τ_v (min)
13.7	12	5×10^{-4}	101	341	78

- τ_v corresponds to transverse acceptance $\epsilon_A = 2 \times 10^{-6}$ (physical aperture)

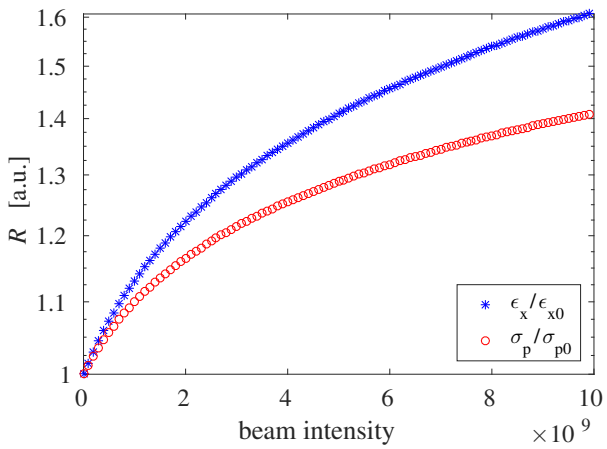


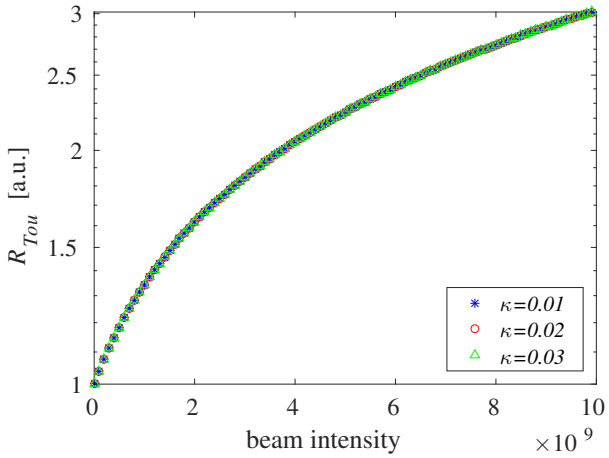


- More loss at the western arc section (min. A/β), especially region around the 1*nd* quad. entering the arc section (QM22R.1, QM22R.2)

Vacuum lifetime experiment in Jan. 2017

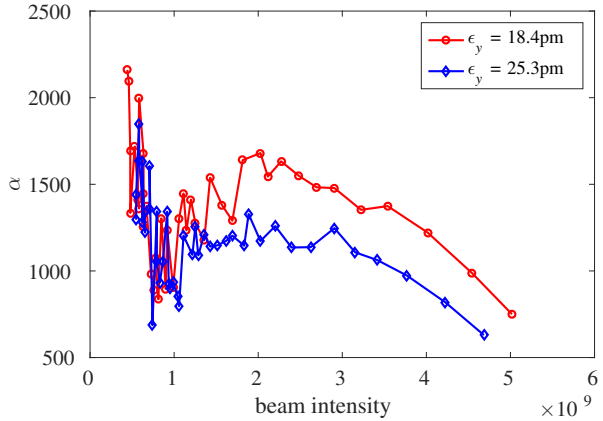
- Vertical emittance is variated by tuning SF1R magnet
- Two vacuum levels are considered ($2.3\times10^{-7}/1\times10^{-6}$ Pa)
- Bunch volume (σ_s,σ_p,ϵ_x and ϵ_y) evolution with beam intensity is included in analysis
- Current dependence of σ_s,σ_p,ϵ_x due to IBS is calculated by SAD
- ϵ_y is determined by $x-y$ coupling

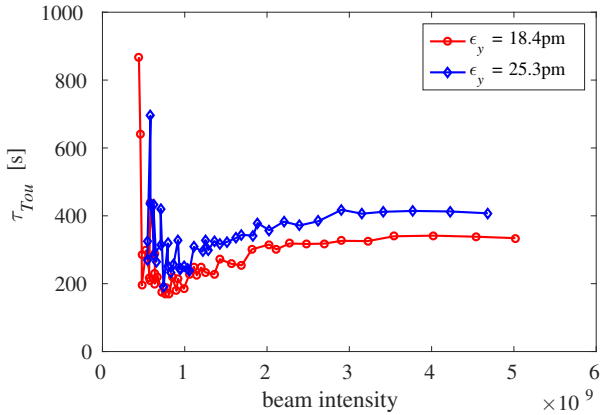




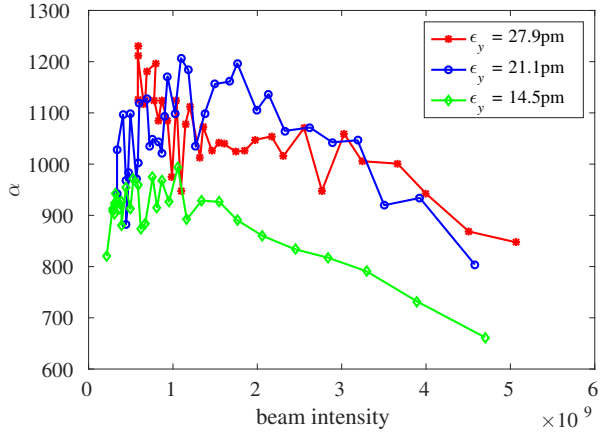
Vacuum lifetime experiment in Jan. 2017

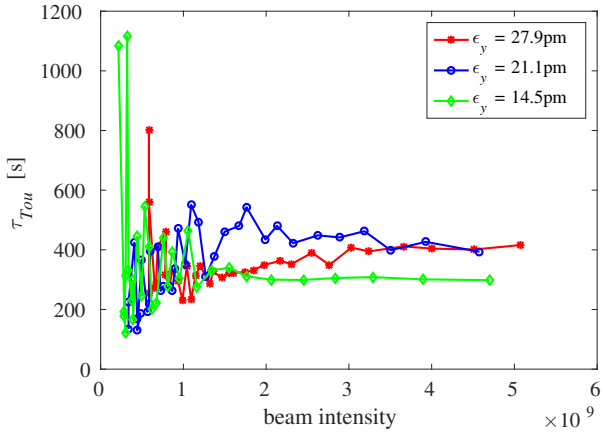
- α and τ_{Tou} measured are different for variate vacuums
- $P \approx 2.3 \times 10^{-7}$ Pa: $\alpha \in$ [1000,1500] $\mathrm{Pa}^{-1}\mathrm{s}^{-1}$, $\tau_{Tou} \approx$400/370 s





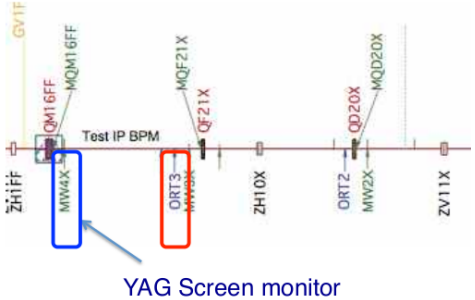
- $P \approx 1 \times 10^{-6}$ Pa: $\alpha \in$ [1000,1200] $\mathrm{Pa}^{-1}\mathrm{s}^{-1}$, $\tau_{Tou} \approx$400/300 s

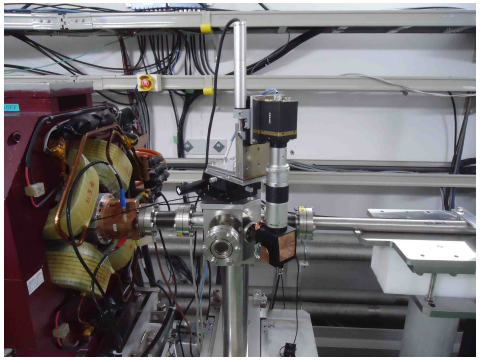


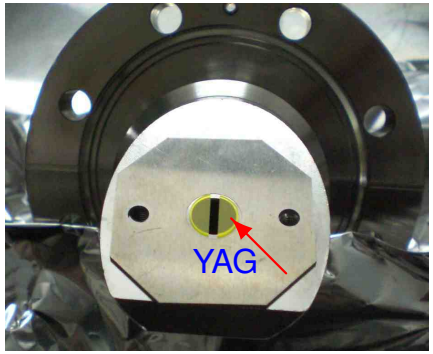


Present Ce:YAG screen monitor

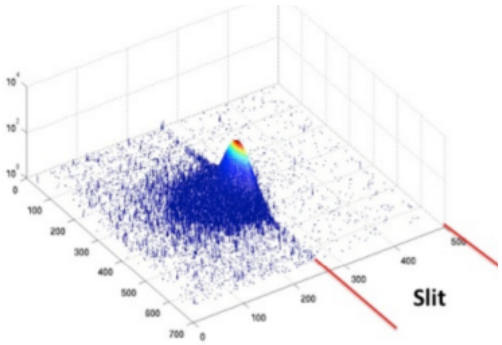
- Present YAG screen has two separated screens with 1 mm slit and can visualize vertical halo at 0.3 m upstream of QM16

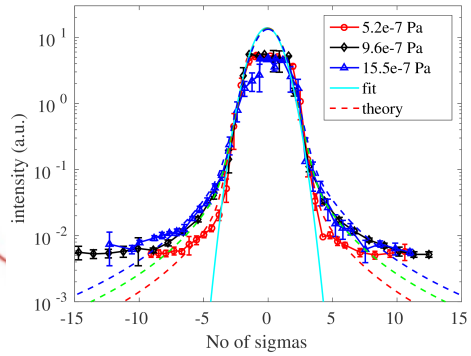


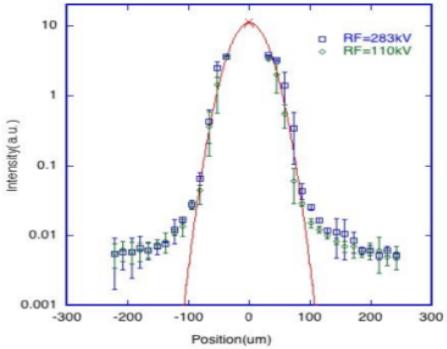




- Dynamic range $d_R < 10^4$, resolution $< 10\mu$m, satur. level 0.25 pC/μm^2
- YAG screen has been applied for vacuum dependence and RF voltage dependence of vertical beam halo



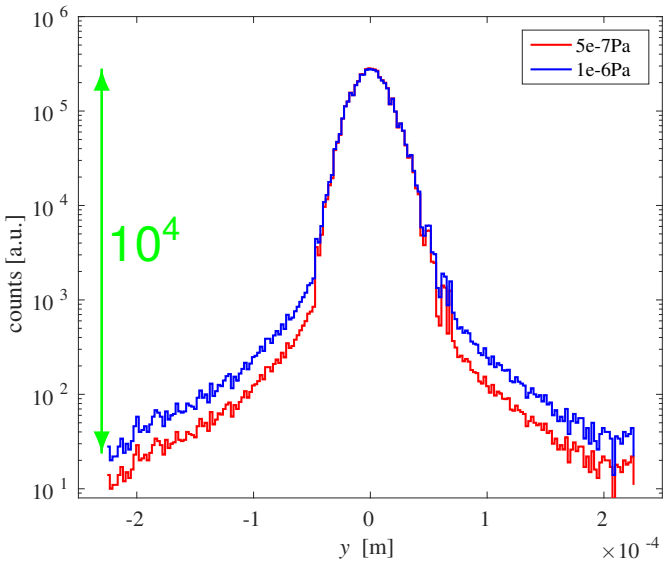


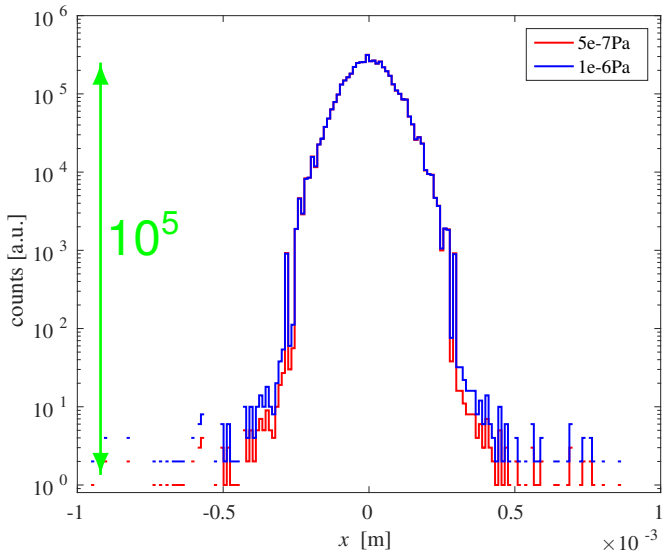


[1] T. Naito, IBIC15,TUPB024 (2015)

Expected performation and applications

- Resolution: OTR (from SLAC): 5∼10 μm , Ce:YAG: less than 10 μm
- Dynamic range: $< 10^4$ with present CCD , and hope to reach 10^5 with Hamamatsu 5985 CCD (sensitivity improved by 10^3)
- Application: Vacuum dependence, variation with extraction time for BGS halo and momentum diffusion study

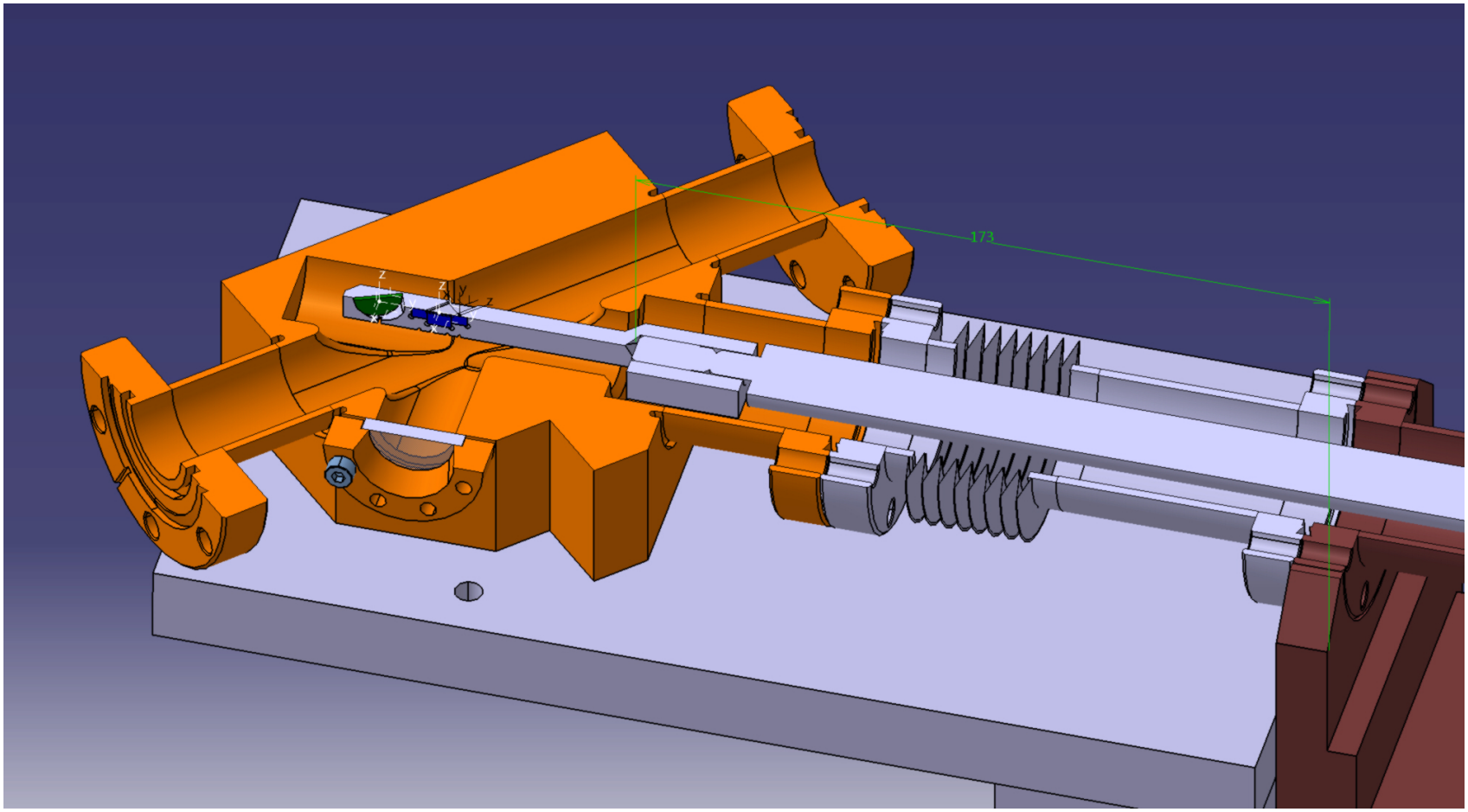




[1] M. Ross et al., SLAC-PUB-9280(2002)
[2] T. Naito, IBIC14,TUPD08 (2014)

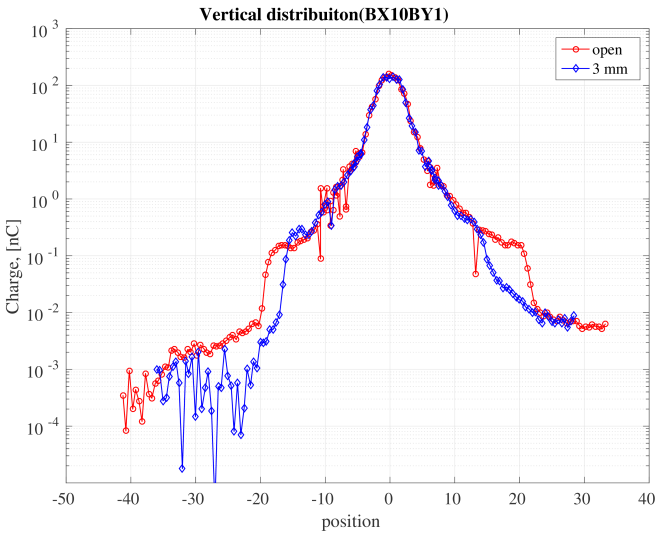
Mechanism design of YAG/OTR chamber and holder

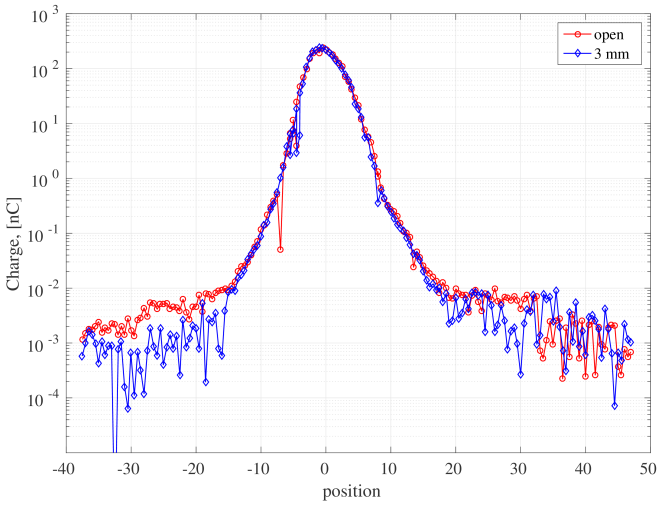
- Bellow at the holder pipe enables angle adjustment
- Indium seal is used for view window



Mitigation halo by a vertical collimator

- Location of collimator: QM10
  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)





- Vertically, symmetric cuts by vertical collimator are observed
- Horizontally, less residual halo on low energy side when collimating vertically