KEK, High Energy Accelerator Research Organization

ID: MOOL03

コンパクトERLにおけるビームロス低減のためビームハロー観察及び解析

Beam halo observation and examination for beam loss reduction at the Compact ERL

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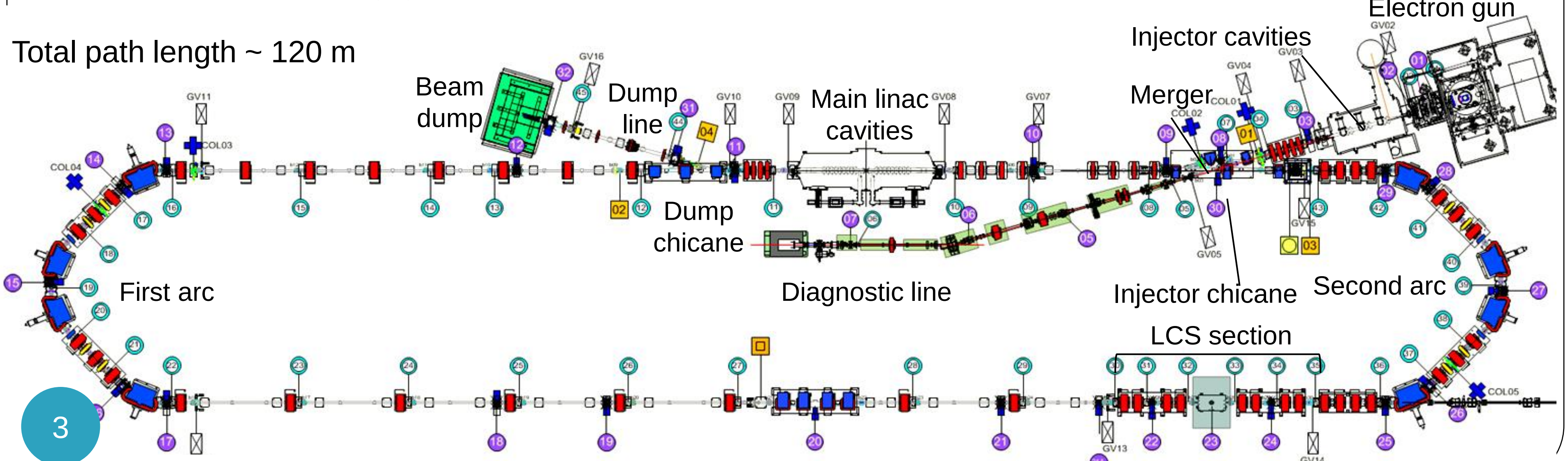
Introduction

Current status of cERL

- FY2015 achievements
  - ☑ 1 mA high-average-current operation
  - ☑ Total beam losses less then 0.1%*
  - ☑ Successful bunch compression
  - ☑ Successful commissioning of laser Compton Scattering (LCS) system
- For detailed information refer to:
  - S. Sakanaka, 1 mA operation, WEOM15
  - M. Shimada, beam optics, TUP062 and TUP063
  - T. Miyajima, orbit correction, TUP064
  - K. Harada, rastering system, MOP079

Typical parameters	Design	In operation
Beam energy	35 MeV	19.9 MeV
Injector energy	5 MeV	2.9 – 6.0 MeV
Gun high voltage	500 kV	390 – 450 kV
Maximum current	10 mA	1 mA
Bunch length	1 – 3 ps	1 – 3 ps (usual) 0.15 ps (compressed)
Repetition rate	1.3 GHz	1.3 GHz (usual) 162.5 MHz (for LCS)

Total path length ~ 120 m



* For circulating 1-mA CW beam

Introduction

Future plan and nearest R&D of cERL

- **1st stage** of the future light source at KEK is a low-emittance electron storage ring of energy 3 GeV (KEK-LS) [more detailes K. Harada, WEOM16]
- **2nd stage** of the plan is linac-type light source establishment:
  - CW-XFEL (high-repetition-rate FEL linac)
- **Industrial application**
  - EUV-FEL (FEL for Extreme Ultraviolet lithography) [see N. Nakamura, TUP074]

R&D of ERL technologies in KEK is still very urgent task!

- **Possible applications of cERL:**
  - High-power THz light source [see Y. Honda, MOP076]
  - High-flux LCS facility [see T. Akagi, MOP057]
- **Nearest R&D include:**
  - Lower emittance (< 1 mm mrad) establishment at higher bunch charges (7.7 pC)
  - Beam current increase up to 10 mA
- **Current increase scheme:**
  1. Beam repetition rate increase
  2. Accelerator adjustment (optics tuning, orbit corrections (especially in the injector line), radiation surveys, beam loss estimation)
  3. Beam halo collimation (to reduce the beam losses along the beam line)

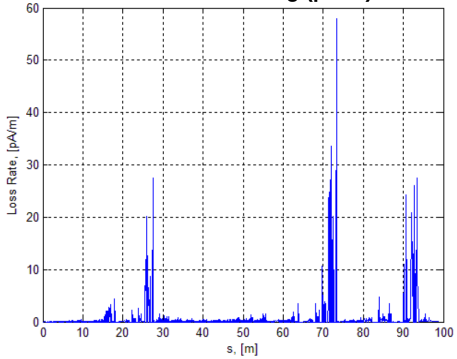
Beam loss mitigation is indispensible for the current increase!

Introduction

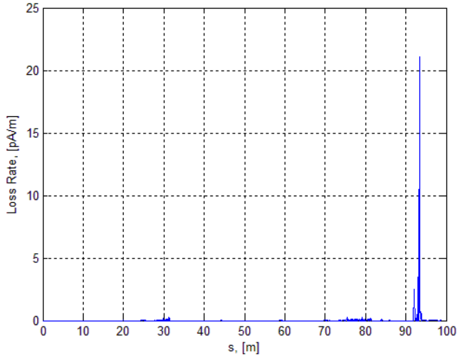
Reasons of the beam loss in cERL

- **Beam dynamics:**
  - Space charge (negligible for 0.2 – 0.3 pC/bunch)
  - Intrabeam scattering
  - Touschek scattering (~0.04 pA/m)*
- **Design-related:**
  - Beam line elements misalignment
  - Kicks from steering coils
- **Errors:**
  - Improper timing
  - Laser or RF cavity phase shift
- **Electron gun:**
  - Longitudinal bunch tail (order of a few uA/m)**
  - Scattered light on cathode
  - Field emission from the gun
- **Vacuum system:**
  - Residual gas scattering (~0.76 pA/m)*
  - Ion trapping
- **SRF cavities:**
  - Dark current
  - Kicks from input / HOM couplers

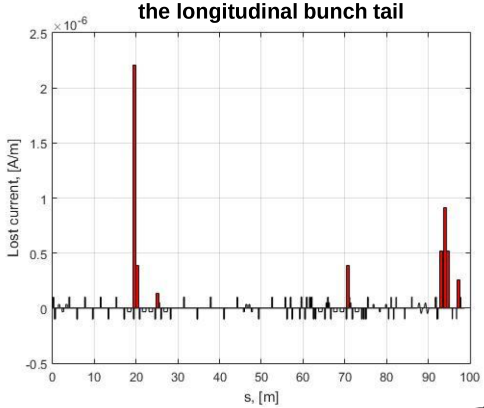
Loss distribution due to elastic scattering (pA/m)



Loss distribution of Touschek scattering (pA/m)



Lost current (A/m) due to the longitudinal bunch tail



* O. Tanaka *et al.*, "Beam Halo Propagation and Mitigation for Beam Loss Study at KEK Compact ERL", in Proceedings of PASJ2015, THP020.

** O. Tanaka *et al.*, "Beam loss studies for the KEK compact ERL", in Proceedings of PASJ2014, SAP018.

Introduction

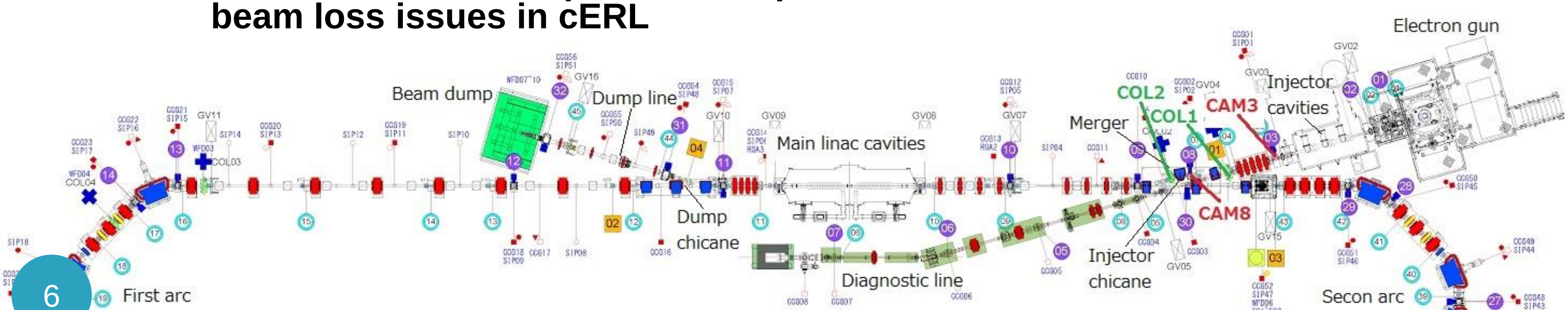
Beam halo formation mechanism

- **Subject:** beam halo as a source of the beam loss. The beam halo is known to be a collection of particles of any origin and behavior which lies in the low density region of the beam distribution far away from the core*
- **Reason:** longitudinal bunch tail originated at the photocathode transferred into the transverse plane
- **Mechanism:** we guess it occurs due to rf field kicks. These kicks are a complex effect of:
  - Injector cavities misalignment
  - Steering coils influence on the beam trajectory inside the cavity

Transverse offset at the collimators

Beam loss reduction in the recirculating loop

- **Goal of the beam halo measurements and simulations reported here is to check and to confirm the tail transformation hypothesis of beam halo formation and to explore other possibilities of beam halo formation and beam loss issues in cERL**



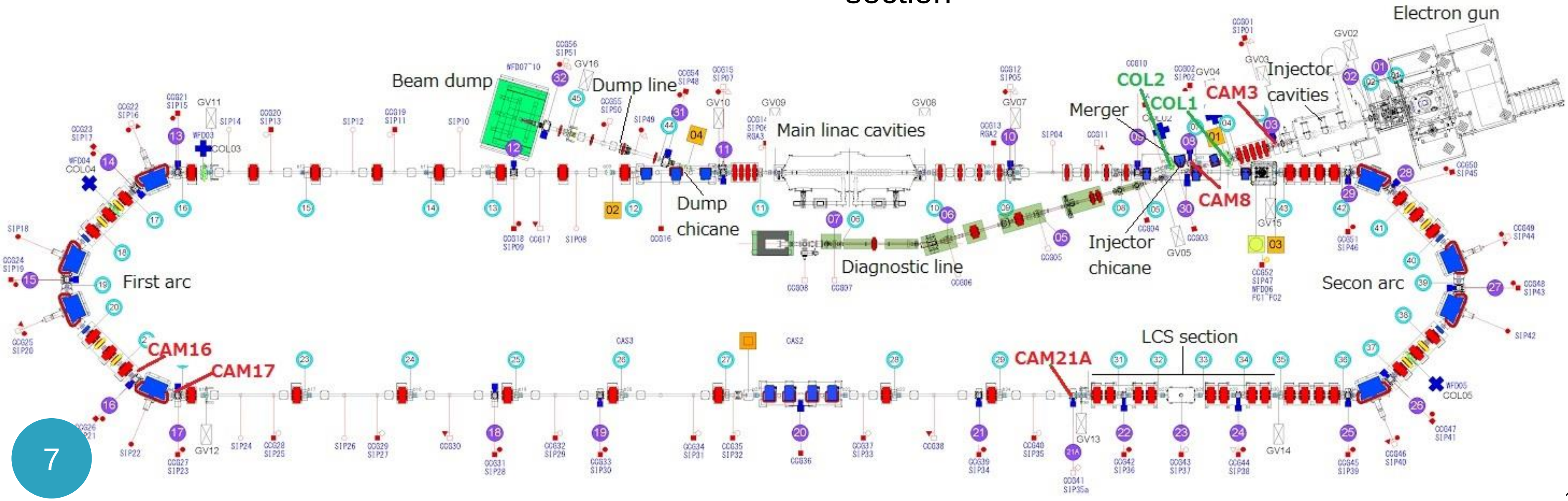
* A. V. Fedotov, Nucl. Instrum. Methods Phys. Res. A557 (2006).

Beam halo measurement

Settings

Settings	Burst	Long pulse
Macro pulse duration	1 µs	1.5 ms
Macro pulse frequency	5 Hz	0.6 Hz
Integration time	10 µs	2 ms
Bunch charge	0.2-0.3 pC	2.6 fC
Average current	1.5 nA	3 nA
Peak current	300 µA	15 nA
Repetition rate	1.3 GHz	1.3 GHz
Beam energy	2.9 - 20 MeV	20 MeV

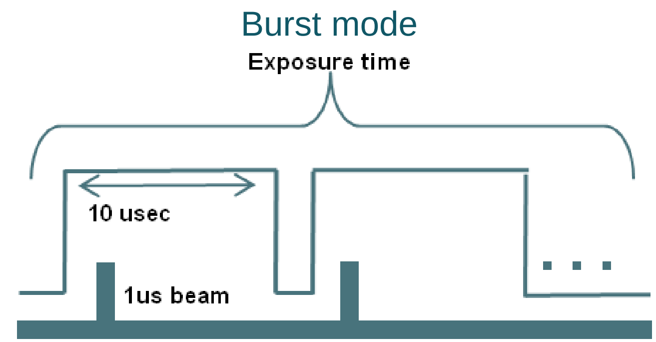
- CAM8 placed in the merger section, where the dispersion impacts to the halo formation
- CAM 16 of the 1st arc is also located in the dispersive section. Therefore, some particles with an energy spread could be observed
- CAM17 picks up the beam profiles in the place with big betatron oscillations
- Location of CAM21A (before the LCS system) coincides with the loss point
- COL1, 2 helpful to reduce the beam loss in the recirculating loop, are in the merger section

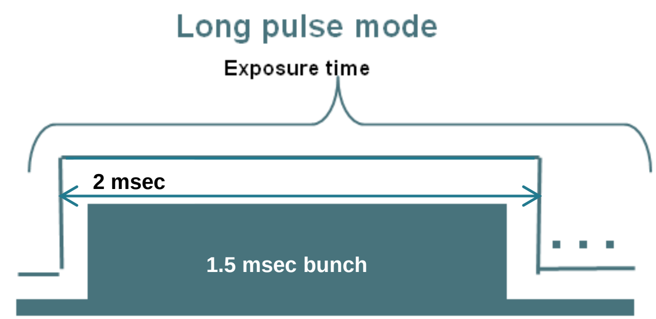


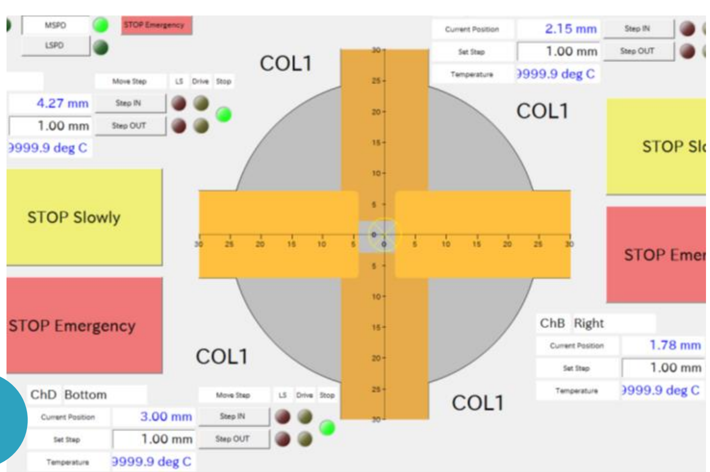
Beam halo measurement

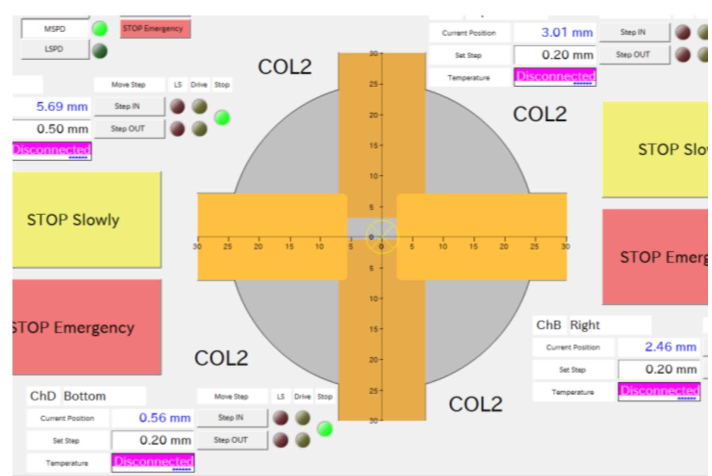
Workflow

1. Adjust the trigger delay so that only one macro pulse 1 μs (1.5 ms[1]) could be captured during one camera shutter pulse 10 μs (2 ms[1])
2. Set the camera gain to maximum (22 dB)
3. Then the sets of beam halo profiles are collected automatically with macro pulse frequency 5 Hz (0.6 Hz[1])
4. Insert the collimators
5. Repeat steps 1 – 3





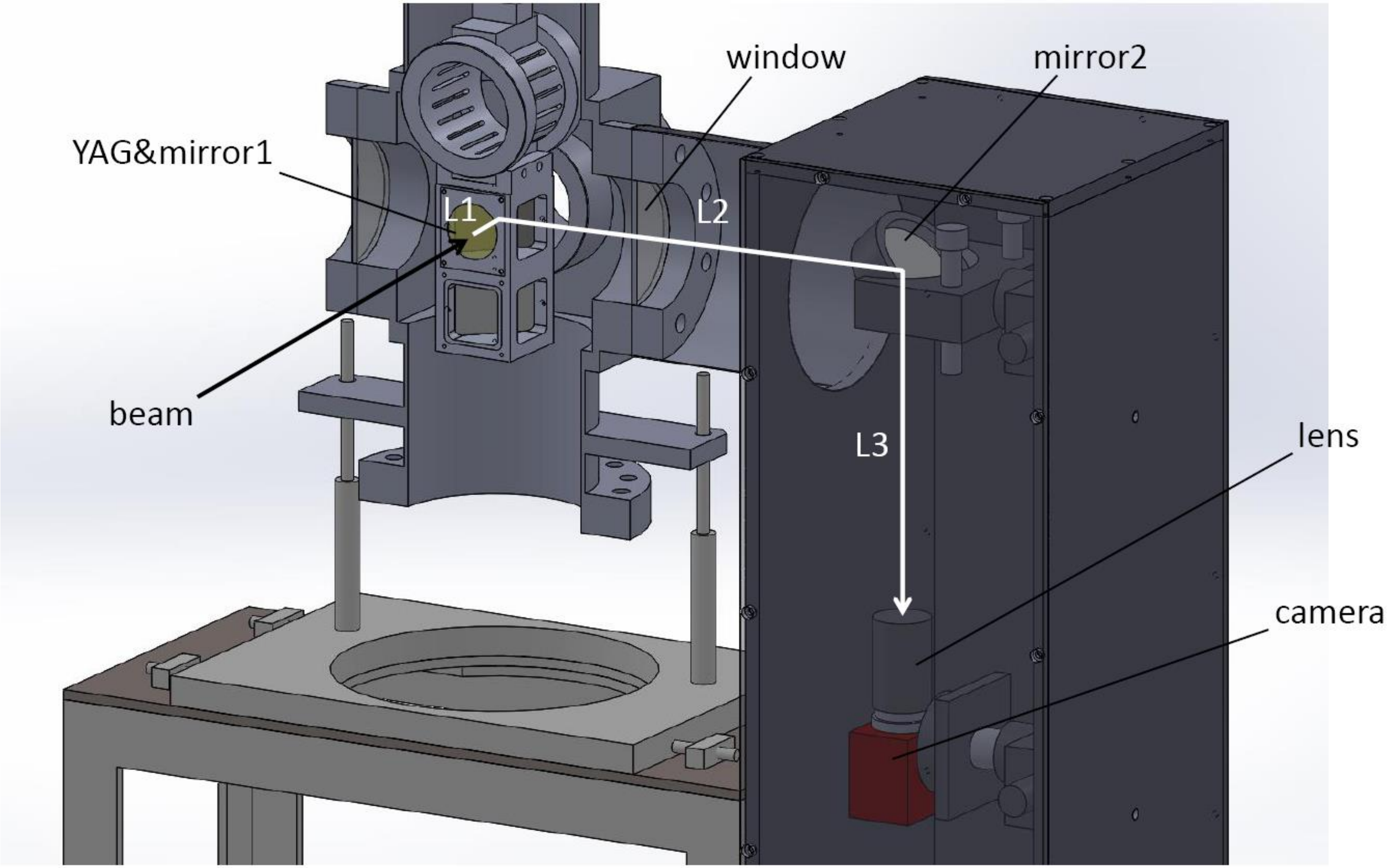




[1] For long pulse mode

Beam halo measurement

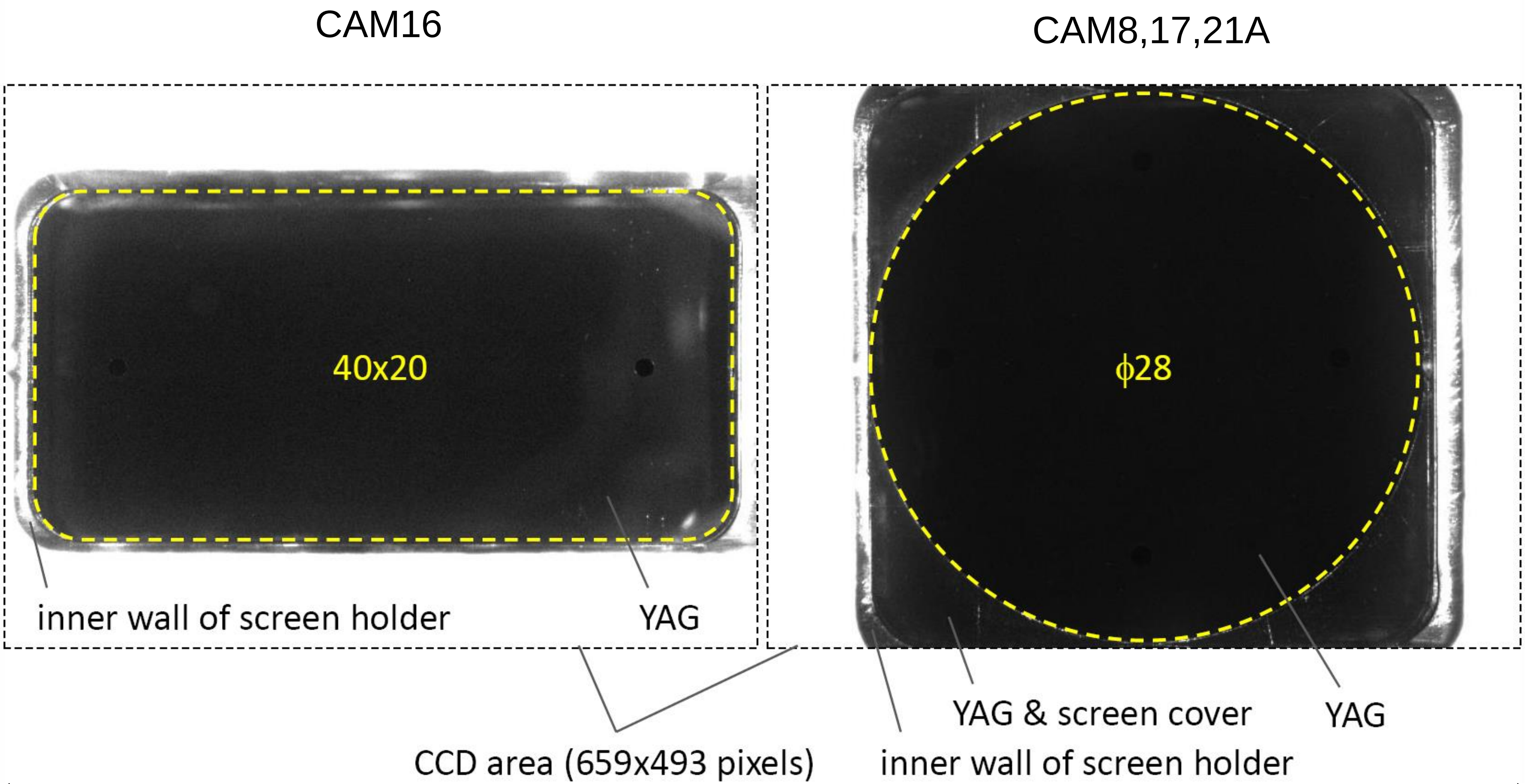
CCD camera optics

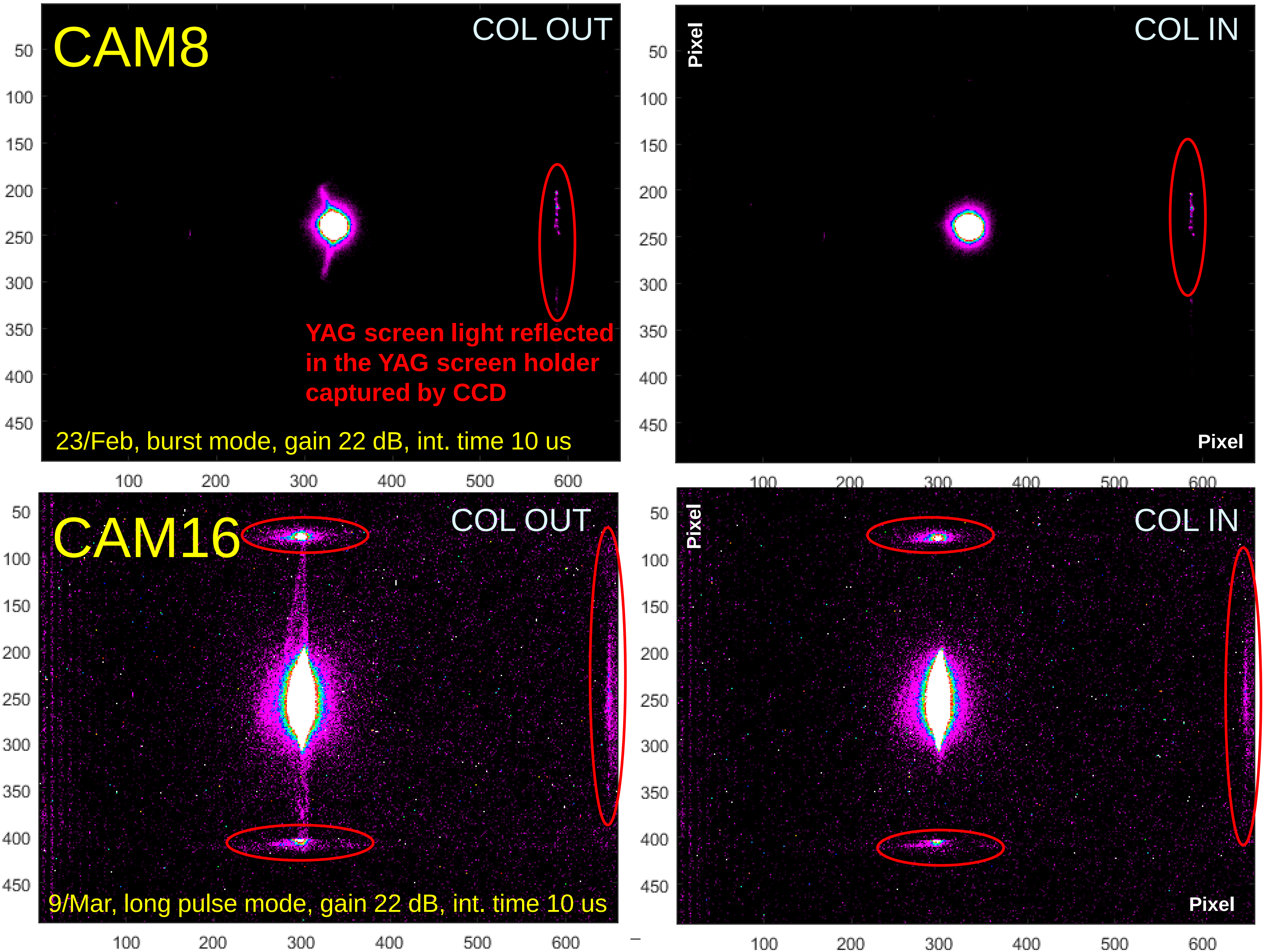


- CAM8 YAG: ϕ28, L1=21, L2=337, L3=420, mirror2: ϕ60, lens: f100-ϕ30
- CAM16 YAG: 40x20, L1=27, L2=229, L3=161, mirror2: ϕ50, lens: f50-ϕ28
- CAM21A YAG: ϕ28, L1=21, L2=229, L3=139, mirror2: ϕ50, lens: f50-ϕ28

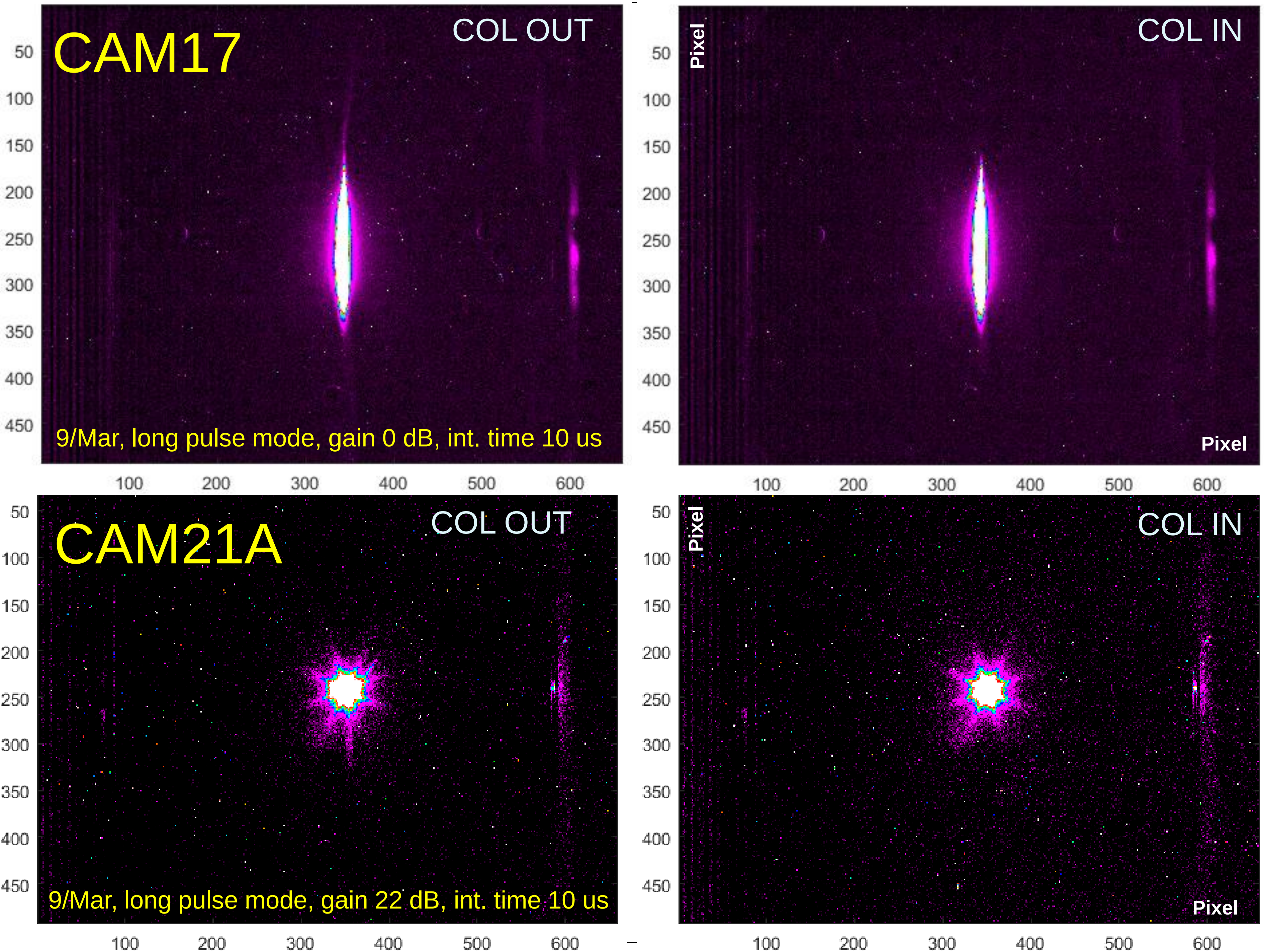
Beam halo measurement

YAG screen setup





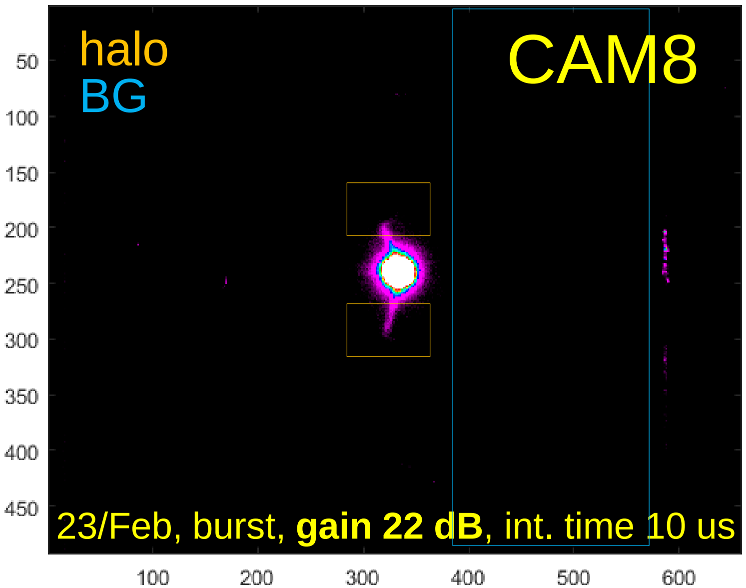
CAM8
COL OUT
COL IN
YAG screen light reflected in the YAG screen holder captured by CCD
23/Feb, burst mode, gain 22 dB, int. time 10 us
CAM16
COL OUT
COL IN
9/Mar, long pulse mode, gain 22 dB, int. time 10 us
Pixel
Pixel
50
100
150
200
250
300
350
400
450
100
200
300
400
500
600

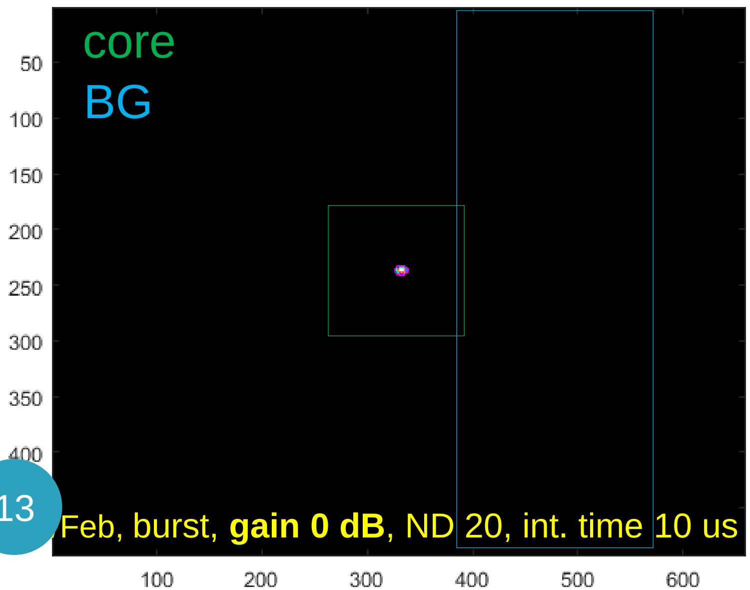


CAM17
COL OUT
COL IN
9/Mar, long pulse mode, gain 0 dB, int. time 10 us
CAM21A
COL OUT
COL IN
9/Mar, long pulse mode, gain 22 dB, int. time 10 us
Pixel
Pixel
Pixel
Pixel
50
100
150
200
250
300
350
400
450
100
200
300
400
500
600

Beam halo measurement

Core-halo ratio estimation





- Core / halo / background area selection (manually)
- Scaling

Intensity(halo) = 12.5893*20*Intensity(core)

Gain 22 dB vs Gain 0

ND filter 20

Place of observation	Core,%	Halo, %
CAM8 (merger)	99.45	0.55
CAM16 (1st arc)	99.37	0.63
CAM17 (straight sect.)	99.64	0.36
CAM 21A (before LCS)	99.48	0.52
Average	**99.49**	**0.51**

Beam halo measurement

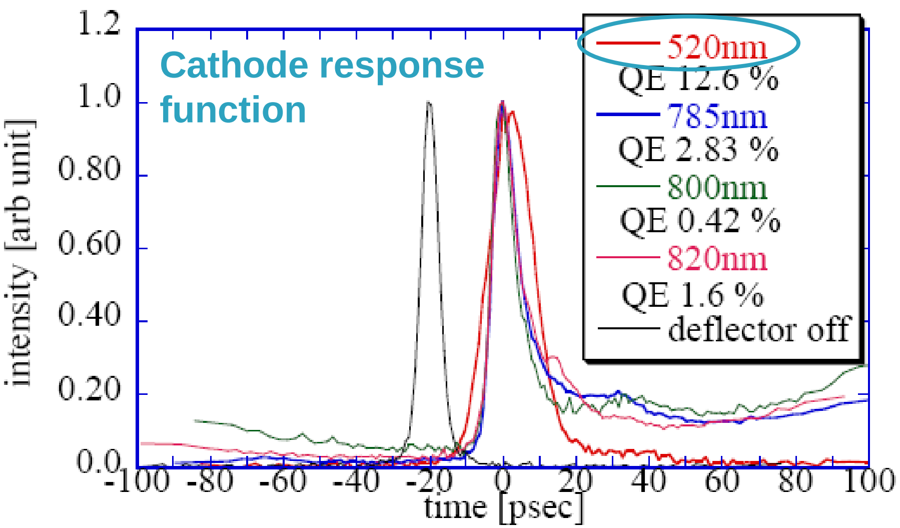
Lessons learned from beam halo measurements

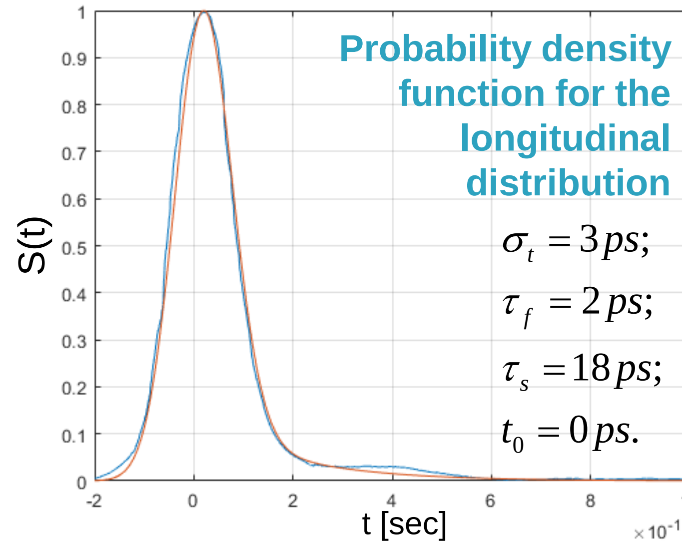
- After the proper data processing, vertical halos* at all camera locations were observed clearly. On the contrary, there weren't any vertical halos at the profiles, captured when collimators were in
- Vertical beam halo can be truncated using collimation system effectively. The beam loss reduction in the recirculating loop was simultaneous with the vertical halo truncation. We believe it is a good confirmation of the effectiveness of the beam tuning together with the collimation system
- Core-halo ratio estimation, based on the profiles measured at different CCD camera gain settings, gives about 0.5% for vertical beam halo

* Note, that only vertical halos issues observed during the measurement are discussed in this study. Of course, there could be any other unobserved beam halos at any other beamline locations

Beam halo simulation

Cathode temporal response





- The probability density function of longitudinal distribution is obtained from the GaAs bulk photocathode measurement*
- The measurement data is fitted by the convolution integral of Gaussian core with one or more electron retardation mechanisms

$$S(t) \propto \exp\left(\frac{\sigma_t^2}{2\tau^2}\right) exp\left(-\frac{t-t_o}{\tau}\right) \mathrm{erfc}\left(\frac{\sigma_t}{\sqrt{2}\tau} - \frac{t-t_o}{\sqrt{(2)}\sigma_t}\right),$$

$$S_{fast}(t) = \exp\left(\frac{\sigma_t^2}{2\tau_f^2}\right) \exp\left(-\frac{t-t_0}{\tau_f}\right) erfc\left(\frac{\sigma_t}{\sqrt{2}\tau_f} - \frac{t-t_0}{\sqrt{2}\sigma_t}\right),$$

$$S_{slow}(t) = \exp\left(\frac{\sigma_t^2}{2\tau_s^2}\right) \exp\left(-\frac{t-t_0}{\tau_s}\right) erfc\left(\frac{\sigma_t}{\sqrt{2}\tau_s} - \frac{t-t_0}{\sqrt{2}\sigma_t}\right),$$

$$S(t) = S_{fast}(t) + S_{slow}(t).$$

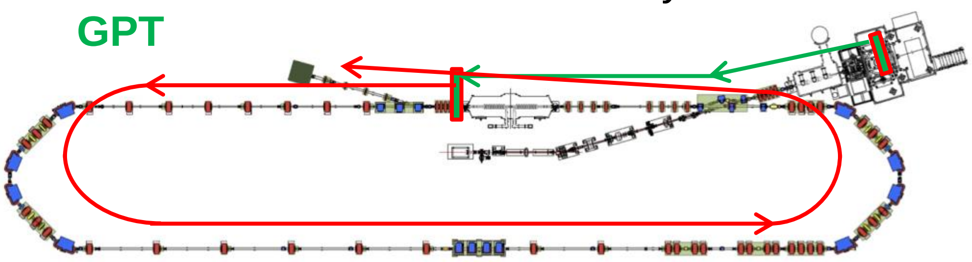
* S. Matsuba et al., “Initial Emittance and Temporal Response Measurement for GaAs Based Photocathodes”, IPAC’12, New Orleans, (2012)

Beam halo simulation

Initial particle distribution

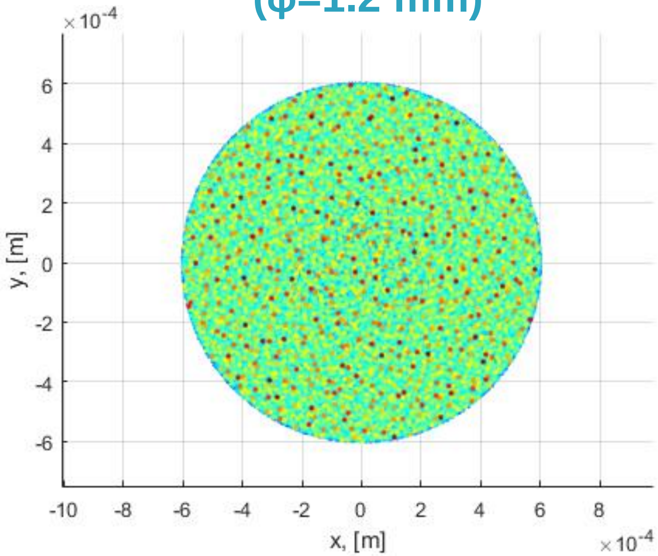
Simulation input parameters	
Number of particles	1E4
Beam energy	2.9 – 20 MeV
Total charge	0.3 pC / bunch
RF frequency	1.3 GHz
Laser spot diameter	1.2 mm
Bunch length	3 ps

From cathode to main RF cavity exit → **GPT**

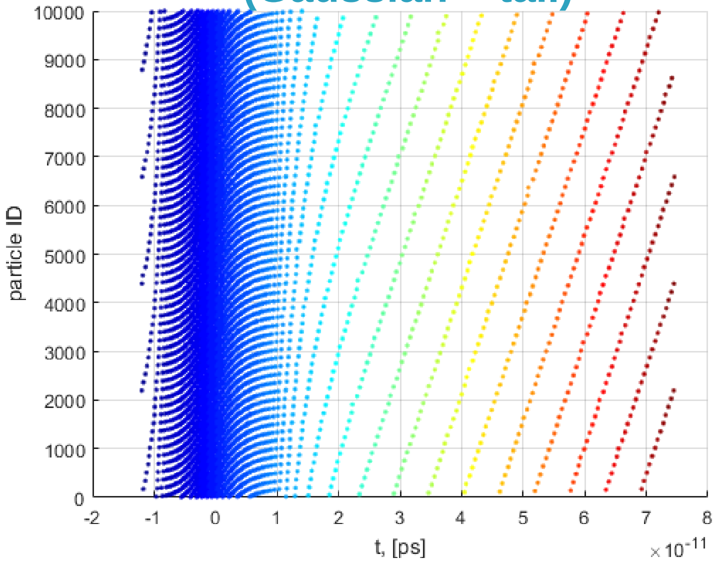


From main RF cavity exit to dump → **ELEGANT**

Transverse distribution (φ=1.2 mm)



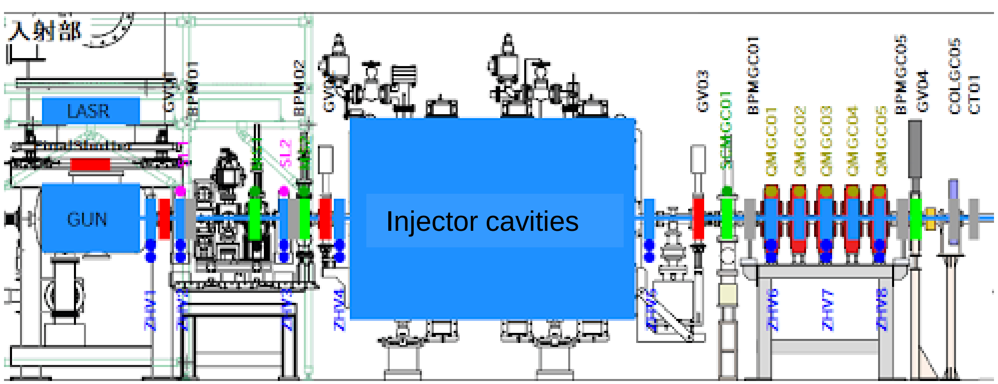
Longitudinal distribution (Gaussian + tail)



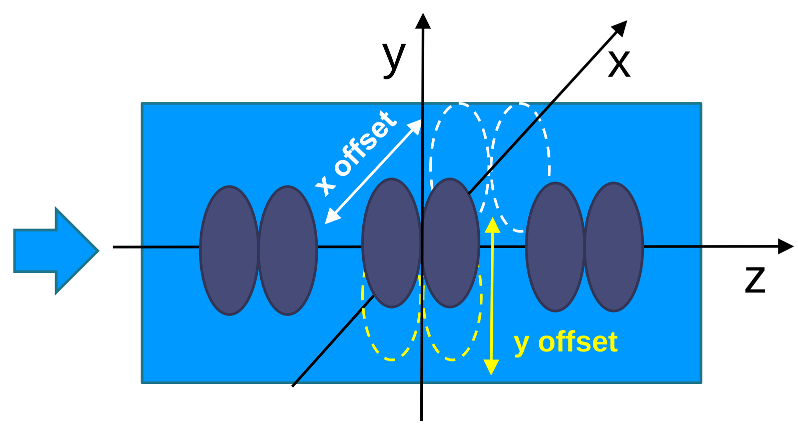
Beam halo simulation

Simulation conditions

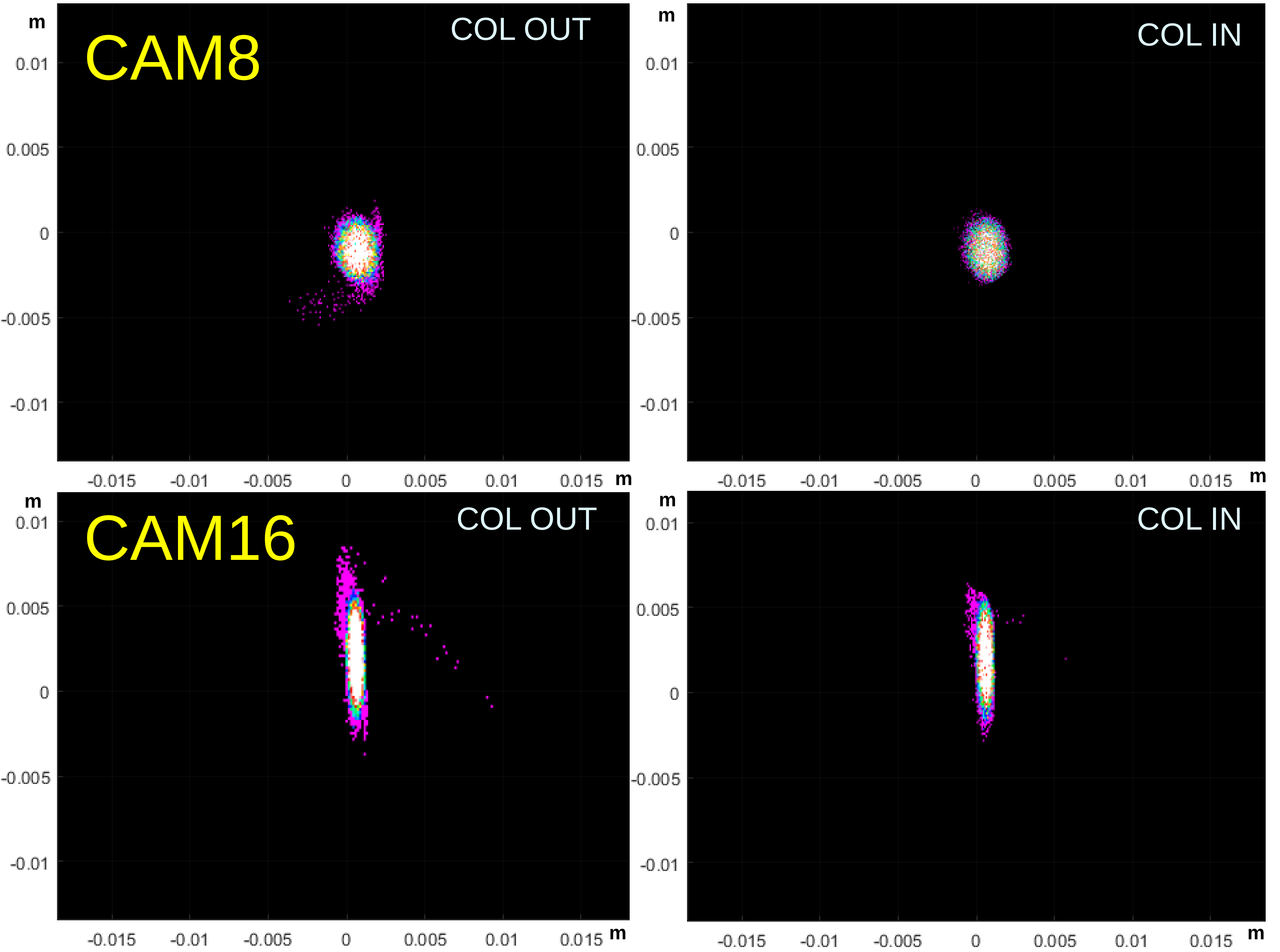
- To reproduce the rf field kicks in the simulation:
  1. Set up the optics (e.g. the K values of the quadrupole magnets)
  2. Set up the fields of steering coils
  3. Set up the injector cavities offset



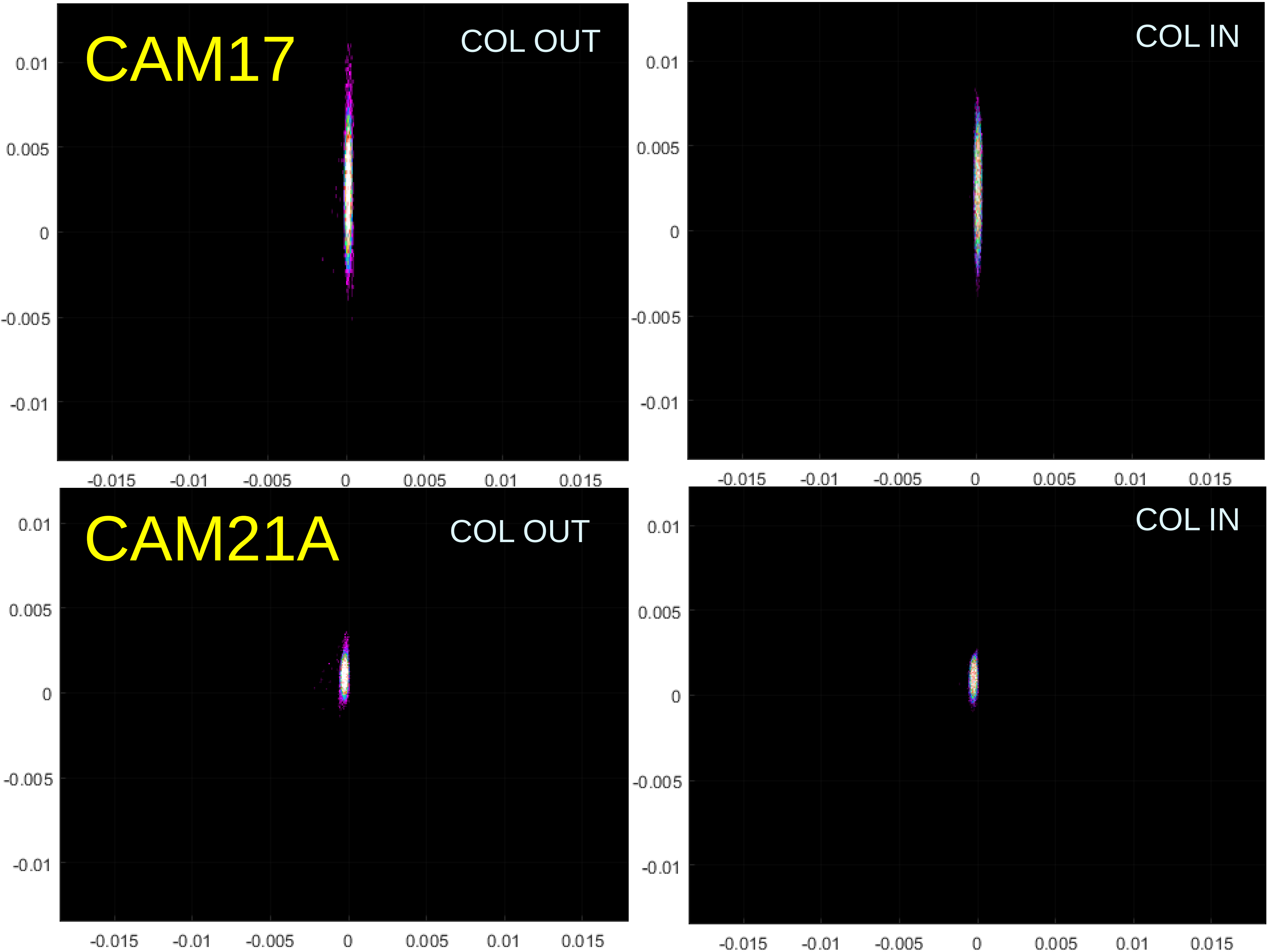
Layout of cERL injector



Injector cavities offset

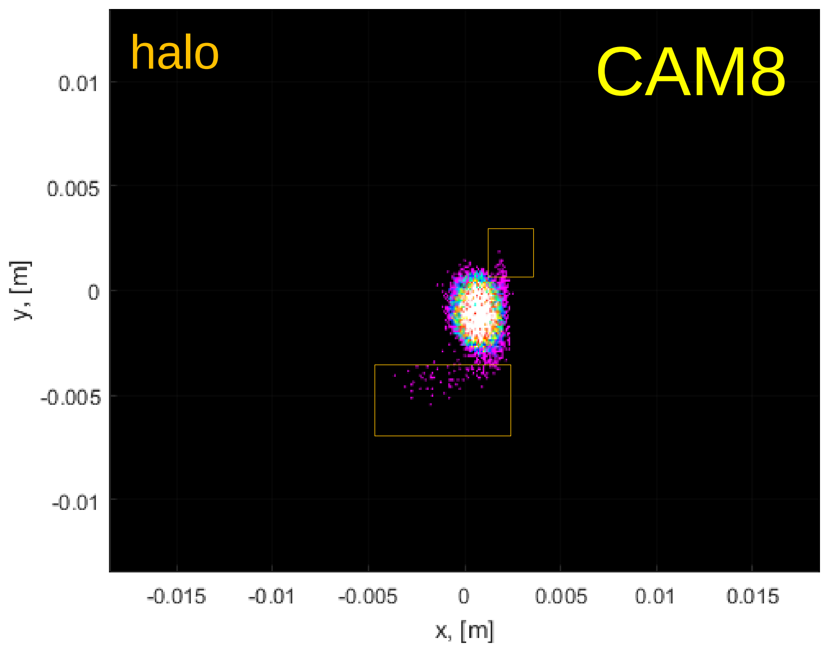


CAM8
COL OUT
COL IN
CAM16
COL OUT
COL IN
m
0.01
0.005
0
-0.005
-0.01
-0.015
-0.01
-0.005
0
0.005
0.01
0.015
m

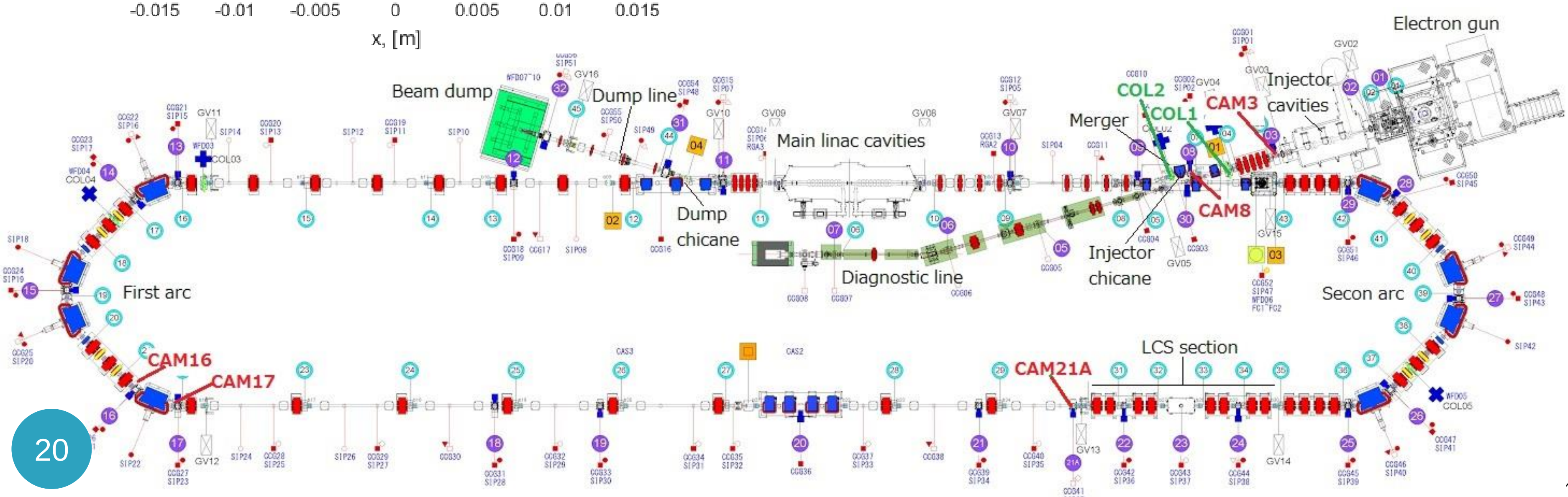

CAM17
COL OUT
COL IN
CAM21A
COL OUT
COL IN
0.01
0.005
0
-0.005
-0.01
-0.015
-0.01
-0.005
0
0.005
0.01
0.015

Beam halo simulation

Core-halo ratio estimation



Place of observation	Core,%	Halo, %
CAM8 (merger)	99.07	0.93
CAM16 (1st arc)	99.43	0.57
CAM17 (straight sect.)	99.50	0.50
CAM 21A (before LCS)	99.48	0.52
Average	**99.37**	**0.63**



Beam halo simulation

Lessons learned from beam halo simulation

- The lower part of the halo at CAM8 is very likely caused by longitudinal bunch tail transferred into transverse plane
- Upper part of this halo seems to be due to the injector cavities rf field kicks
- The statement above is opposite for CAM16, 17, and 21A (the upper part is due to the tail and lower part due to the rf field kicks)
- The beam core-halo ratio estimations from the simulated profiles yield the values of almost the same order with estimations from the measured profiles. That once again confirms the correctness of our halo formation hypothesis

Summary & prospect

- ☑ The next step of cERL R&D is low-emittance and high bunch charge operation, while the average beam current is increased. Thus, the study of the beam halo formation mechanisms is indispensible for overall beam loss reduction
- ☑ As we learned from the beam tuning experience, the most likely cause of the beam halo in cERL is longitudinal bunch tail originated at photocathode transferred into the transverse plane
- ☑ Our guess, that it occurs due to rf field kicks, find the experimental and computational evidences. Therefore we succeed in beam loss mitigation utilizing the collimation system
- ☒ However, a further beam loss elimination with achieving extremely low emittance is inextricably linked to the reduction of the longitudinal bunch tail originating in the photocathode
- ☒ One more possible but still unexplored halo reason is an influence of the input coupler of injector cavity
- ☒ Due attention should be paid to space charge effect when the bunch charge will be increased

御静聴ありがとうございました