KEK, High Energy Accelerator Research Organization

PEARL Photon Factory

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Beam halo study at the KEK Compact ERL

22/06/2017, Thursday,13:15 - 14:55

59th ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs (ERL17)

503-1-001 - Council Chamber, CERN

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High Energy Accelerator Research Organization, KEK

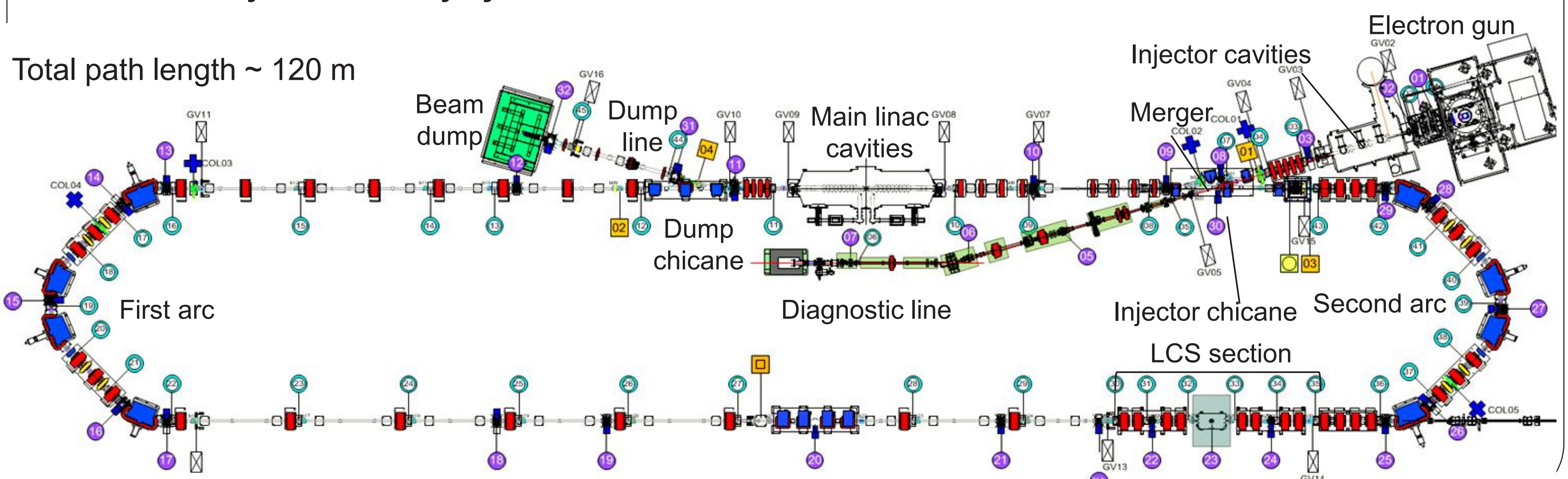
Contents

Introduction

Present status of cERL

- FY 2016 achievements:
  - Present status: “Update on the KEK ERL facility” by Prof. H. Kawata
  - Higher bunch charge operation (7.7 pC): “Higher bunch charge operation in compact ERL at KEK” by Dr. T. Miyajima

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)



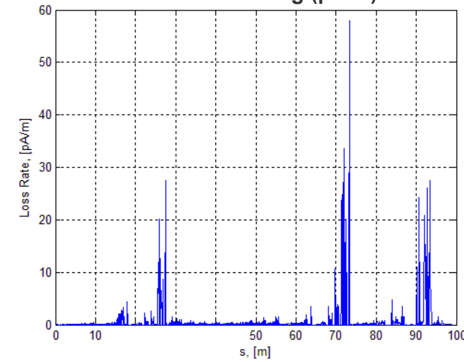
* For circulating 1-mA CW beam

Introduction

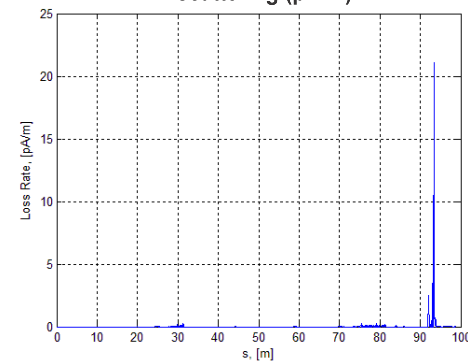
Possible beam halo & loss reasons in cERL

- **Beam dynamics:**
  - Space charge (negligible for 0.2 – 0.3 pC/bunch)
  - Intrabeam scattering
  - Touschek scattering (~0.04 pA/m)
  - CSR (negligible)
- **Design-related:**
  - Beam line elements misalignment
- **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

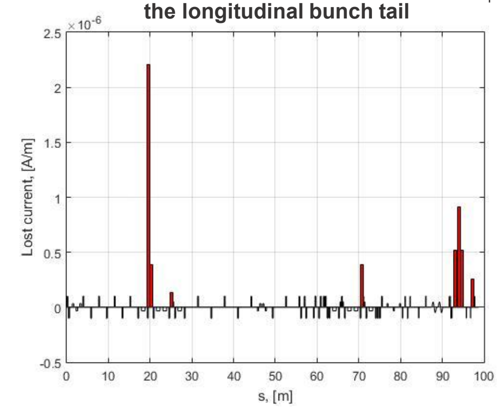
Loss distribution due to elastic scattering (pA/m)



Loss distribution of Touschek scattering (pA/m)



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



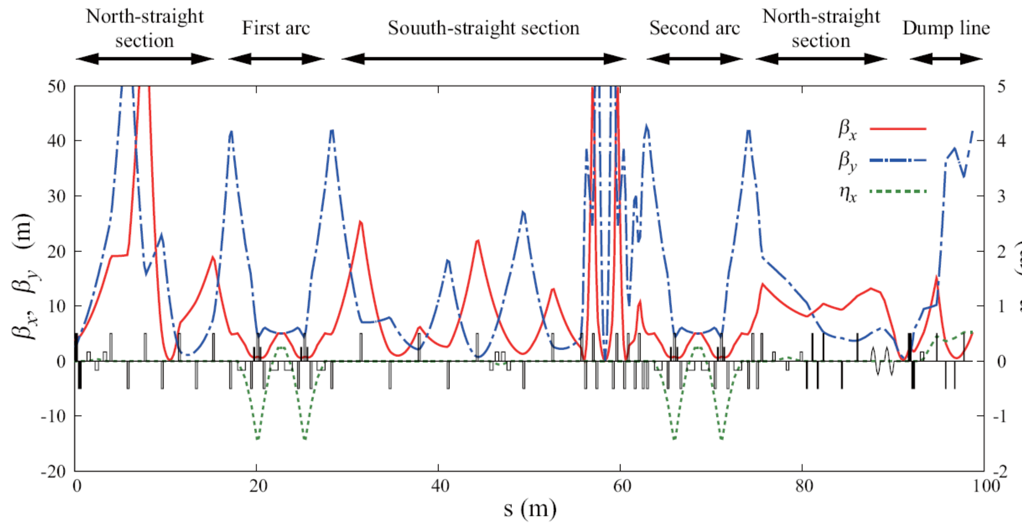
Introduction
Motivation

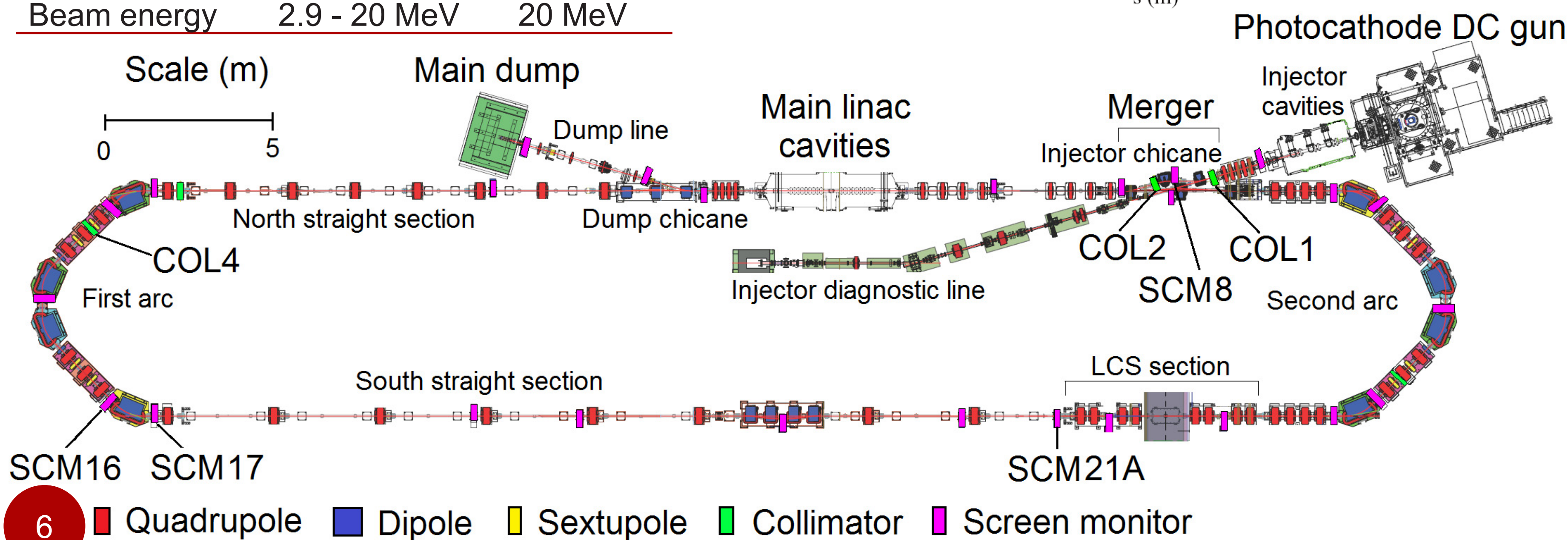
- To understand beam halo formation processes at cERL, we made some measurements during a machine study. **In this study, we found some beam losses in the recirculation loop, when the beam passes through it without collimation.** We activated COL1 and COL2 in the merger section, where the beam energy is low, to reduce the beam loss and to avoid collimators activation. It worked for the beam loss mitigation in the recirculation loop
- **We also found that we can even enhance the beam loss reduction when the beam enters the injector cavities with a slight angle from the central axis of the injector.** This is achieved by inclusion of the steering coils of the injector line. Once a transverse beam offset is created and the off-center beam experiences RF field kicks, it could be cut away by the collimation system
- **Since no transverse beam halo has been observed at the electron gun vicinity, we conjecture that the driving mechanism of the beam halo formation is transfer of the longitudinal bunch tail into the transverse plane in the rest of the machine.** The longitudinal bunch tail is assumed to be produced mainly by the cathode response on the laser excitation
- In this talk, I will show that beam halo simulations with this transfer mechanism can well reproduce observed beam halo profiles

Beam halo measurement

Beam settings & measurement equipments

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

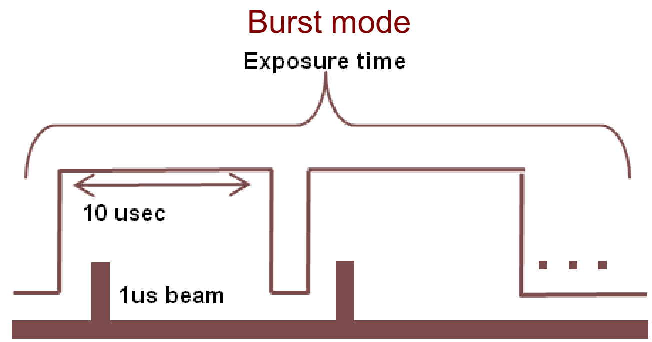


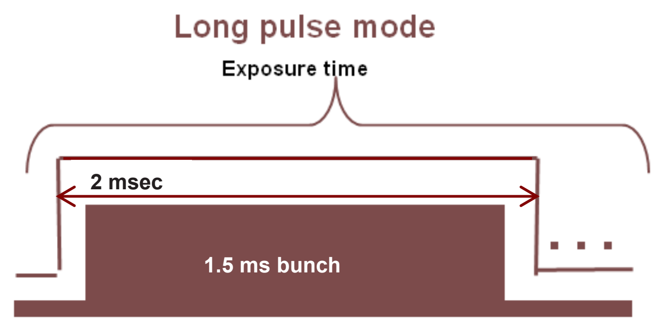


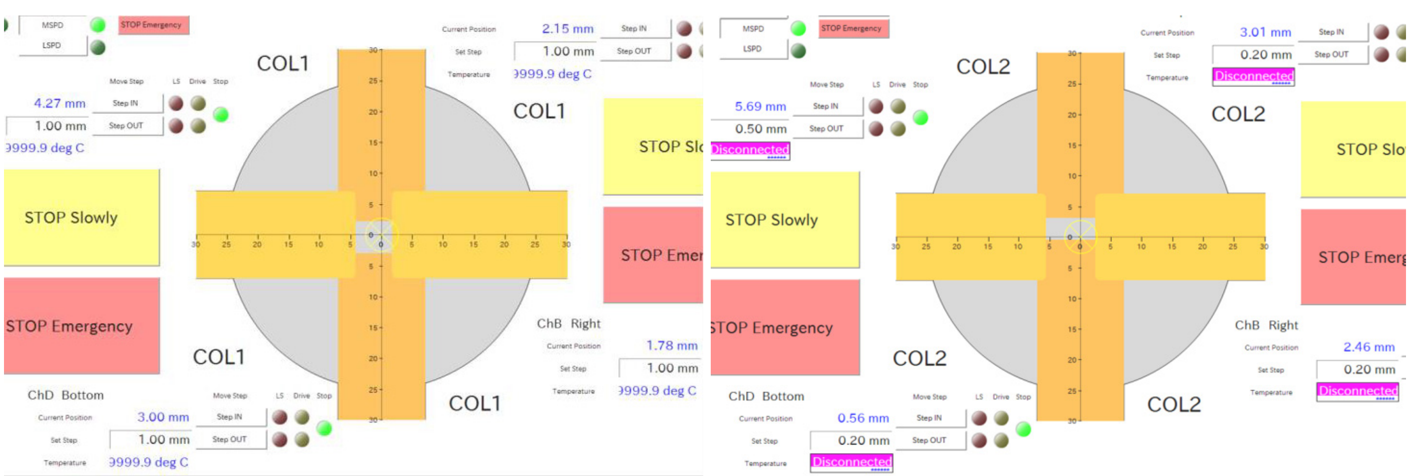
Beam halo measurement

Workflow

- Insert a screen. Set the exposure time of the camera to 10 μs (2 ms)[1] at least so that a 1 μs (1.5 ms)[1] beam is visible. 10 μs is minimum exposure time of the camera
- Adjust the trigger delay if needed. It allows capture of only one macro pulse during one camera shutter period. Set the camera gain to the maximum 22 dB
- Capture beam halo profiles for 10 seconds with 5 Hz (0.6 Hz)[1] macro pulse frequency. Thus, 50 profiles (1 profile)[1] are obtained by one take
- Insert the collimators to see effectiveness of the collimation system against the beam halo. Resulting particle losses in the recirculation loop are monitored by the loss monitors during the measurements
- Repeat the screen capture processes 1 and 2



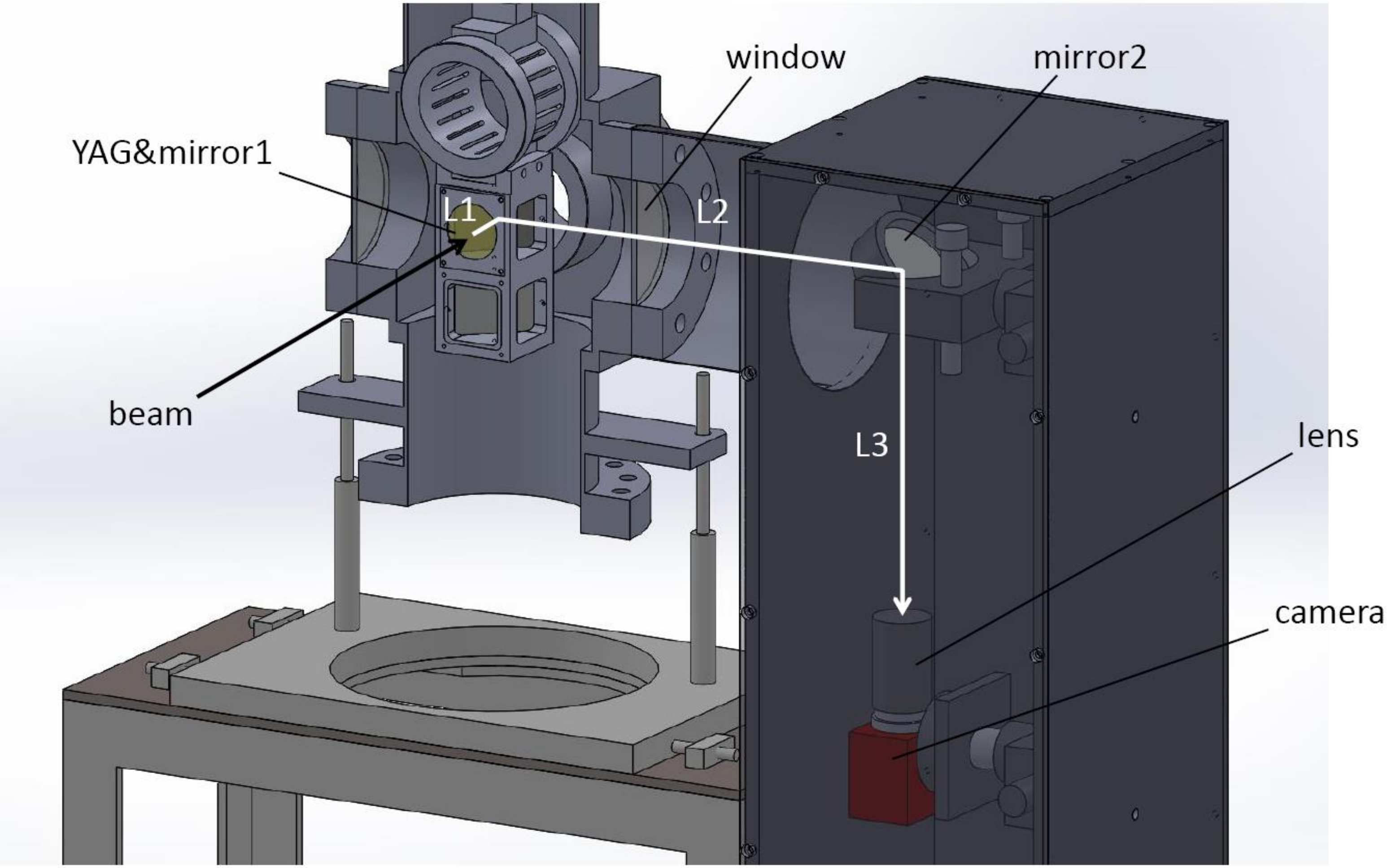




[1] For long pulse mode

Beam halo measurement

Screen monitor optics

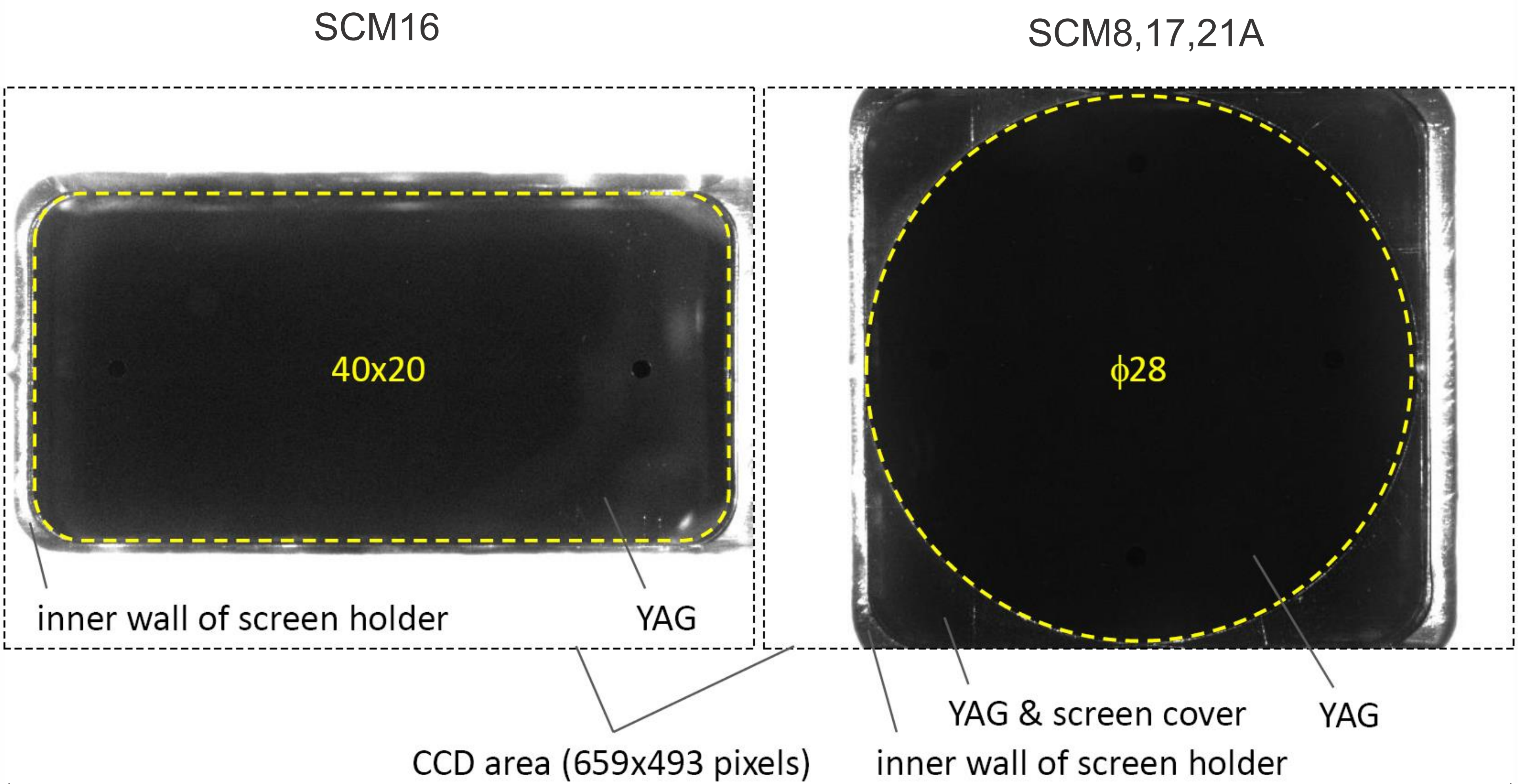


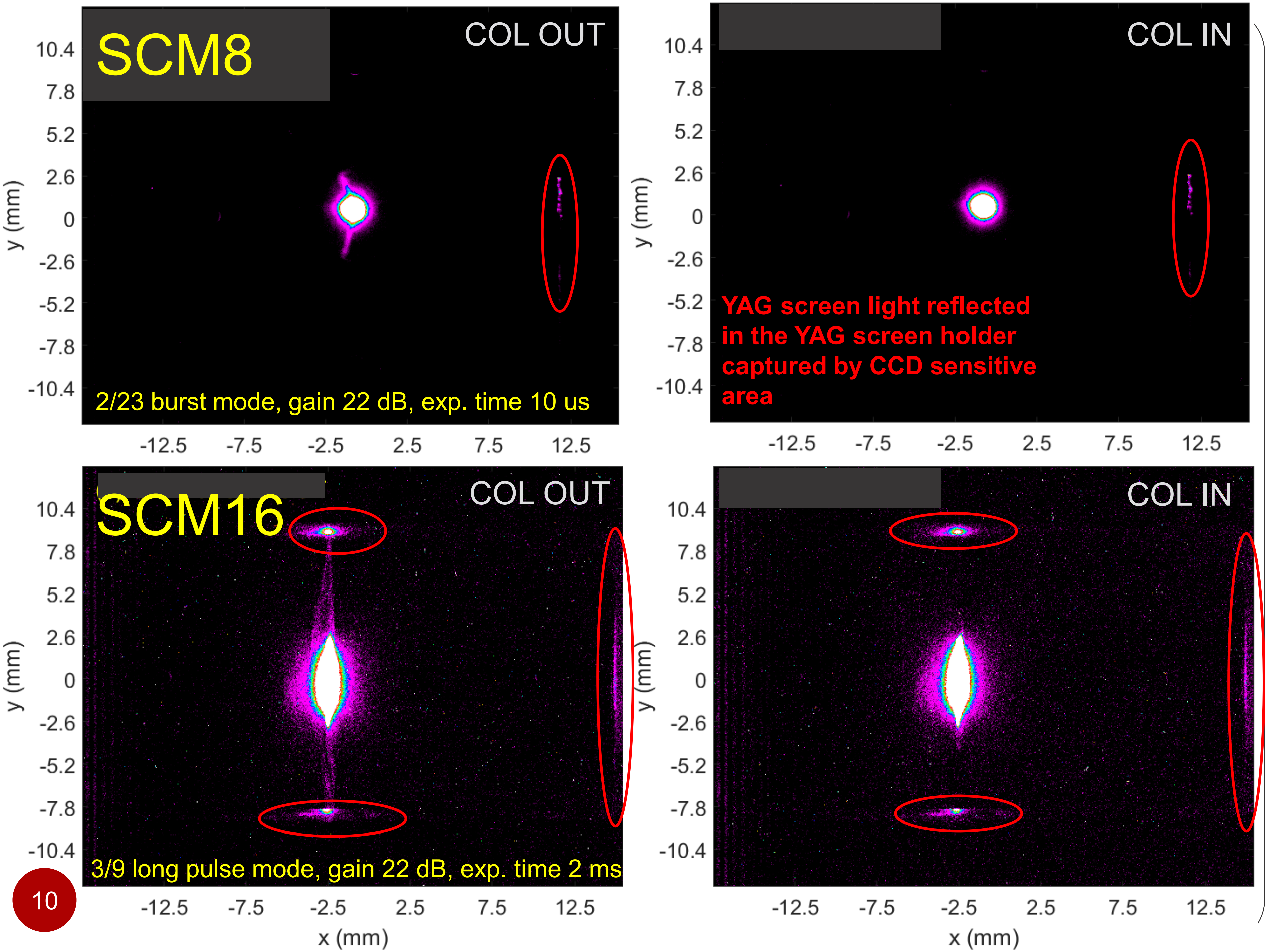
MS8) YAG: ϕ28, L1=21, L2=337, L3=420, mirror2: ϕ60, lens: f100-ϕ30

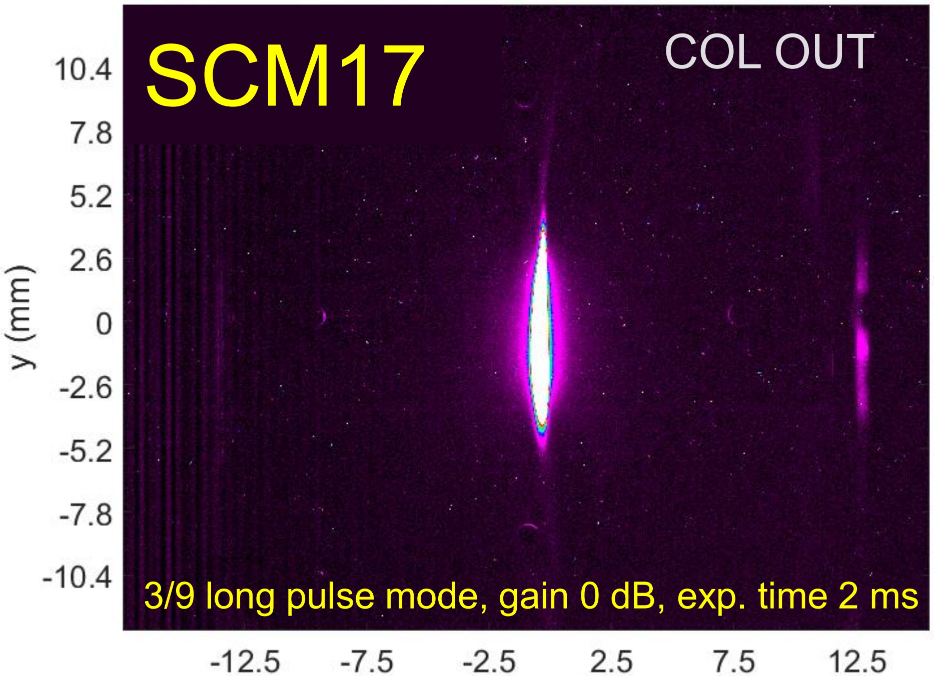
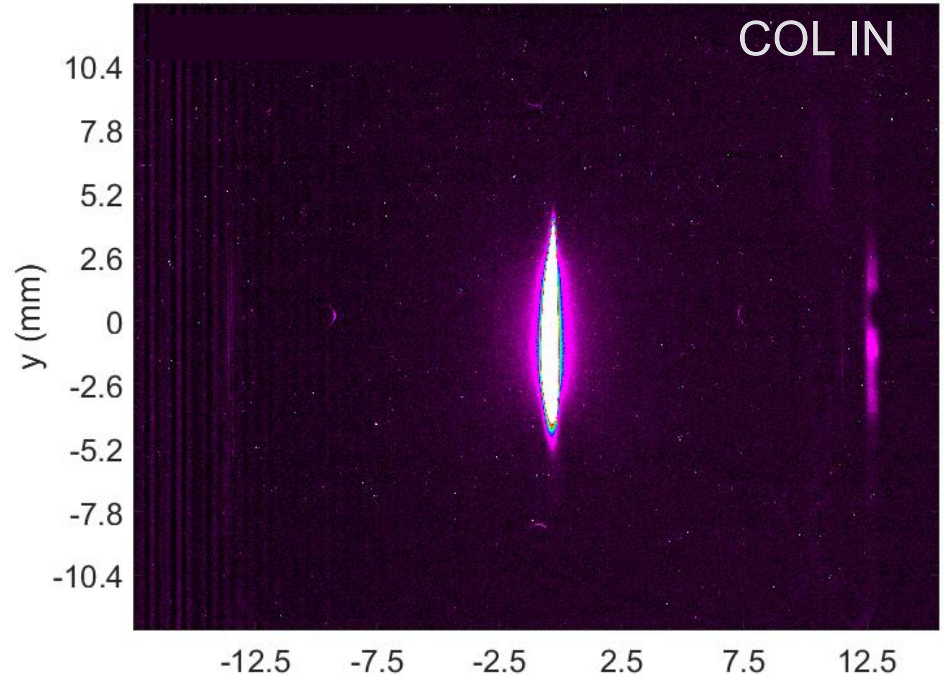
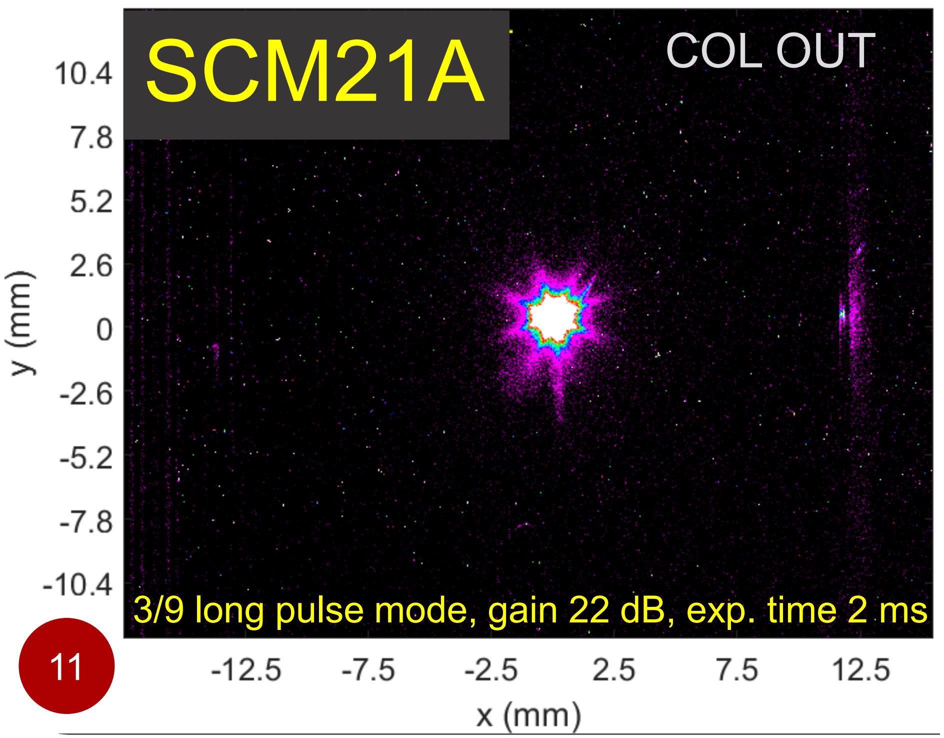
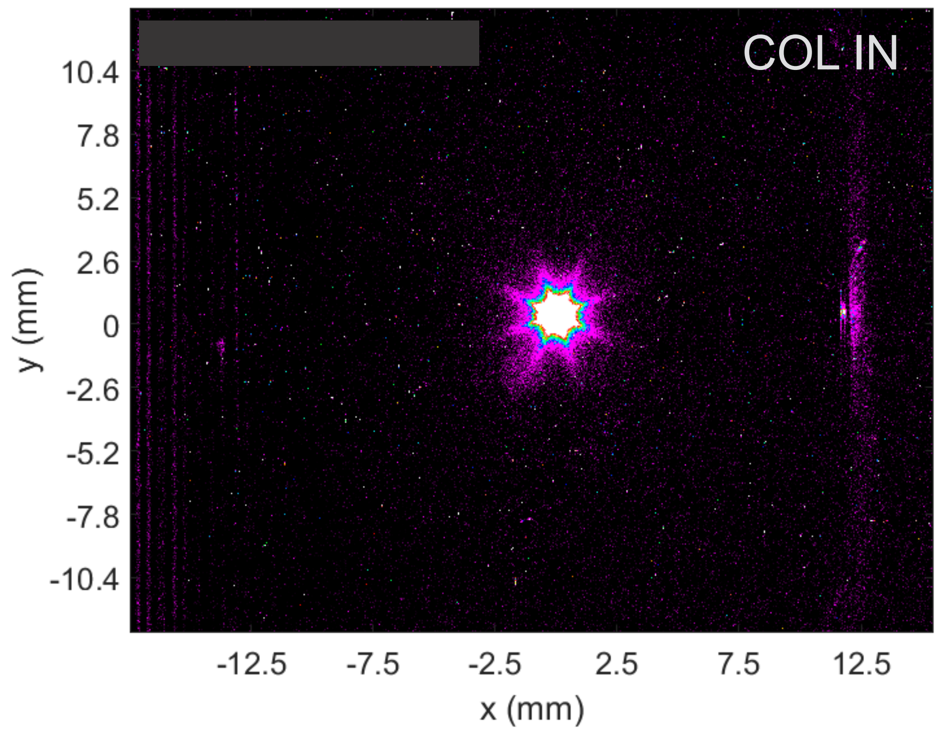
MS16) YAG: 40x20, L1=27, L2=229, L3=161, mirror2: ϕ50, lens: f50-ϕ28

MS21A) YAG: ϕ28, L1=21, L2=229, L3=139, mirror2: ϕ50, lens: f50-ϕ28

Beam halo measurement
YAG screen geometry




SCM8
COL OUT
COL IN
2/23 burst mode, gain 22 dB, exp. time 10 us
YAG screen light reflected in the YAG screen holder captured by CCD sensitive area
SCM16
COL OUT
COL IN
3/9 long pulse mode, gain 22 dB, exp. time 2 ms
y (mm)
x (mm)
10.4
7.8
5.2
2.6
0
-2.6
-5.2
-7.8
-10.4
-12.5
-7.5
-2.5
2.5
7.5
12.5


SCM17
COL OUT
3/9 long pulse mode, gain 0 dB, exp. time 2 ms
y (mm)
10.4
7.8
5.2
2.6
0
-2.6
-5.2
-7.8
-10.4
-12.5
-7.5
-2.5
2.5
7.5
12.5

COL IN
y (mm)
10.4
7.8
5.2
2.6
0
-2.6
-5.2
-7.8
-10.4
-12.5
-7.5
-2.5
2.5
7.5
12.5

SCM21A
COL OUT
3/9 long pulse mode, gain 22 dB, exp. time 2 ms
y (mm)
10.4
7.8
5.2
2.6
0
-2.6
-5.2
-7.8
-10.4
-12.5
-7.5
-2.5
2.5
7.5
12.5
x (mm)

COL IN
y (mm)
10.4
7.8
5.2
2.6
0
-2.6
-5.2
-7.8
-10.4
-12.5
-7.5
-2.5
2.5
7.5
12.5
x (mm)

Beam halo measurement

Lessons learned from beam halo measurements

- After the proper data processing, vertical halos emerge at the all camera locations. On the contrary, there weren't any vertical halos at the profiles, captured when collimators were in
- We allow the saturation of the core part (ND filters taken out), because the shape of the halo can be captured clearly at the maximum gain
- The collimation systems are effective to remove vertical beam halos. The elimination of the vertical halo by the collimation system and the reduction of particle losses in the recirculation loop are synchronized. We believe it is a good indication of the effectiveness of the beam based tuning

Longitudinal bunch tail

Photo-cathode temporal response

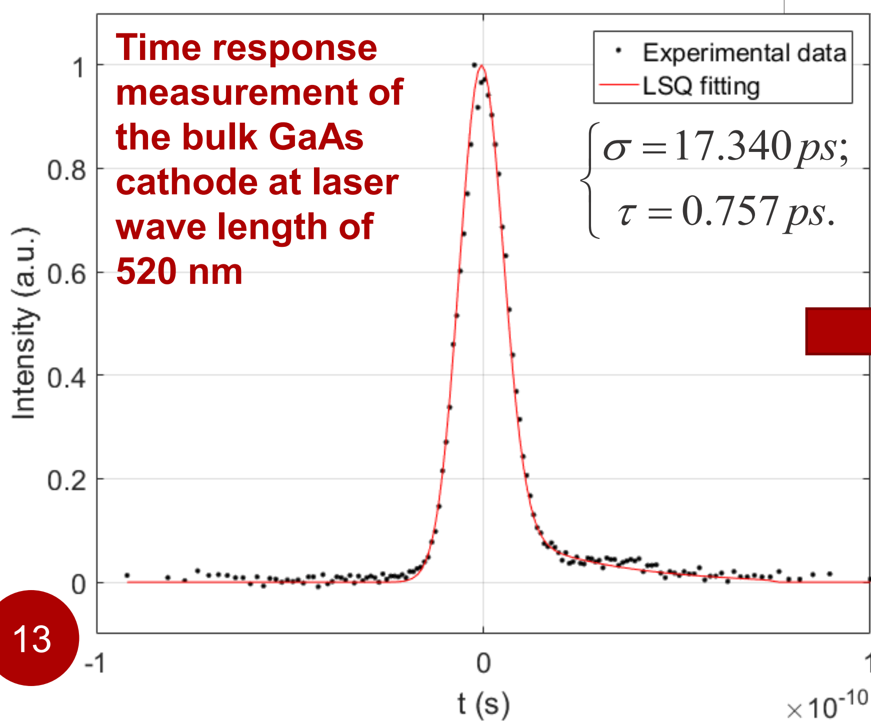
- A model function used in the fitting procedure is a convolution integral

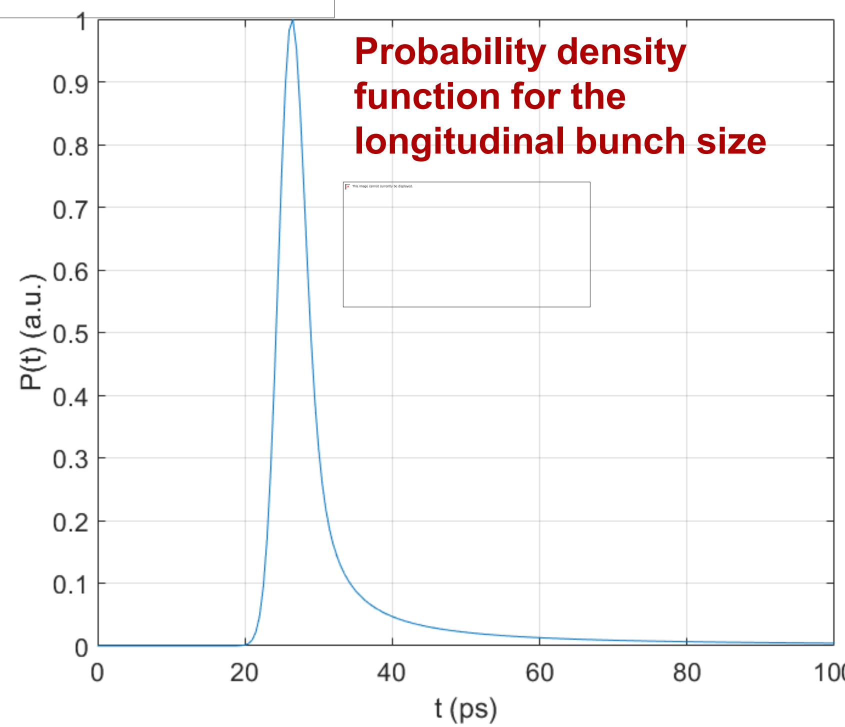
$$(f*g)(k)=\int_{-\infty}^{\infty} f(k)g(k-s)\,dk=\int_{-\infty}^{\infty} f(k-s)g(s)\,ds,$$

$k=t/\tau$ is normalized time
$\tau=\alpha^{-2}D^{-1}$ is photoemission
$\tau\le 1$ characteristic time
D is the electron diffusion constant
α is the optical absorption coefficient

of the normal distribution $f(k)=\dfrac{1}{\sqrt{2\pi\sigma^2}}e^{-\frac{k^2}{2\sigma^2}}$,

with the photoemission current function



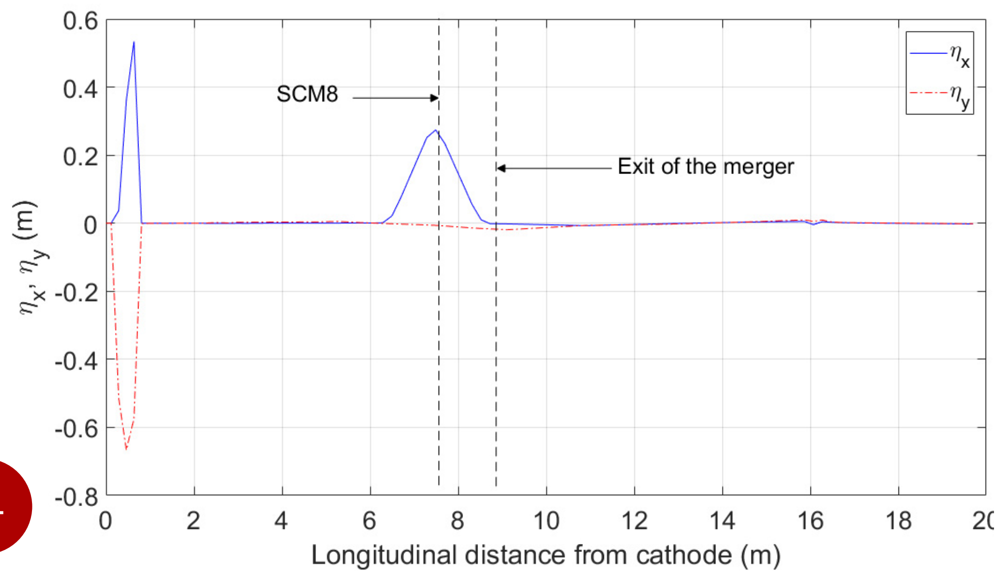


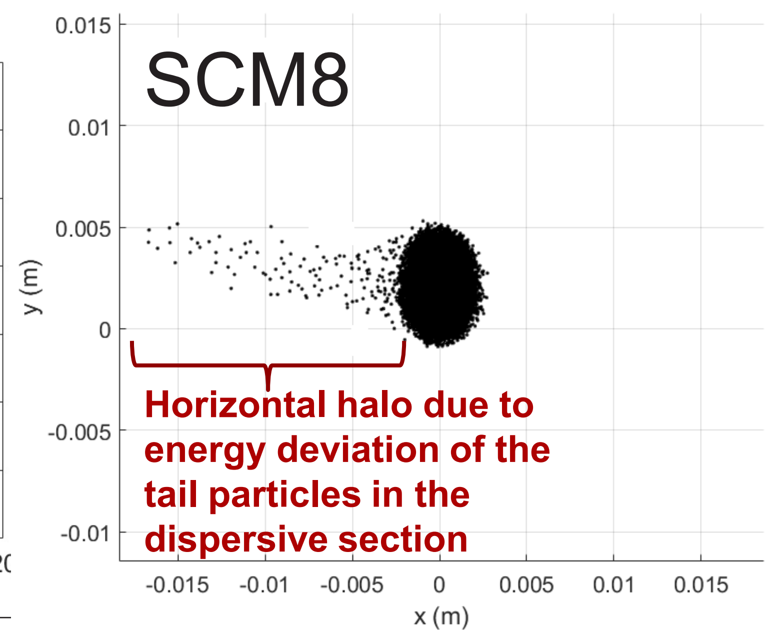
Longitudinal bunch tail

Tail tracking

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	
default	3.3 ps
with bunch tail	100 ps
Transverse distribution (uniform)	φ = 1.2 mm

- Electrons at the 3.3 ps Gaussian core are accelerated on-crest by the injector cavities up to energy 2.9 MeV
- Electrons at the tail experience off-crest acceleration due to its time retardation
- Tail electrons exit the cavities with a large energy deviation of 0.64 MeV
- The energy deviation of electrons at the longitudinal tail results in a horizontal halo (from the low energy side) in the dispersive sections





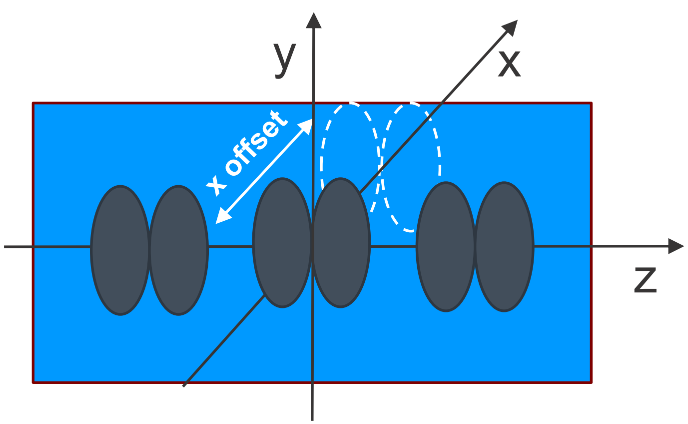
Longitudinal bunch tail

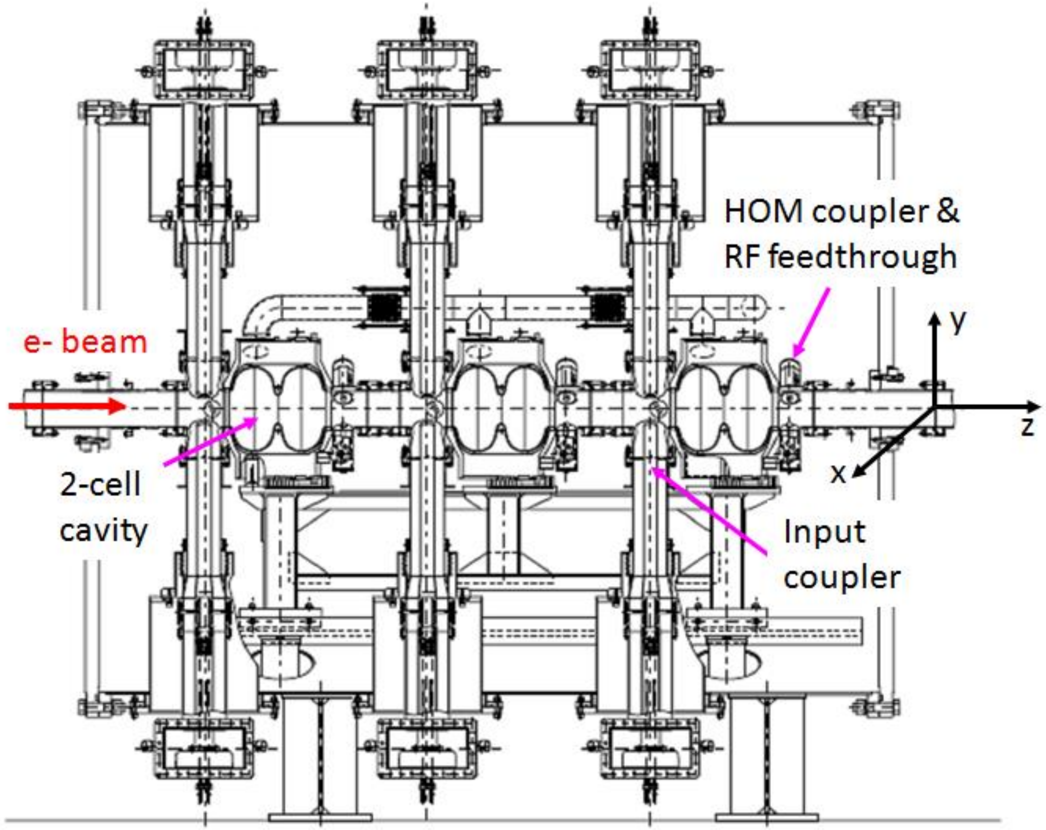
Lessons learned from tail tracking

- At the presence of the longitudinal bunch tail the energy deviation of tail electrons can create a horizontal halo through the horizontal dispersion
- However, the vertical dispersion exists only in the photo-cathode vicinity, while the large vertical halo is observed at screen monitor SCM8 where there is no vertical dispersion
- Thus, this mechanism alone (the transformation of the longitudinal bunch tail to a transverse halo through the dispersion) may not be sufficient to explain the vertical halo formation observed at cERL

Effects of injector cavity RF kicks
cERL injector cryomodule

- The transverse RF kicks at the injector cavities are a possible mechanism to enhance the transformation of the longitudinal bunch tail to the transverse halo. Transverse kicks on the beam arise when the beam trajectory has an offset due to some reasons inside the cryomodule
- It was found that the middle cavity has a relative horizontal offset of 2.6 mm
- No significant relative offsets were found for the vertical alignment of the three cavities





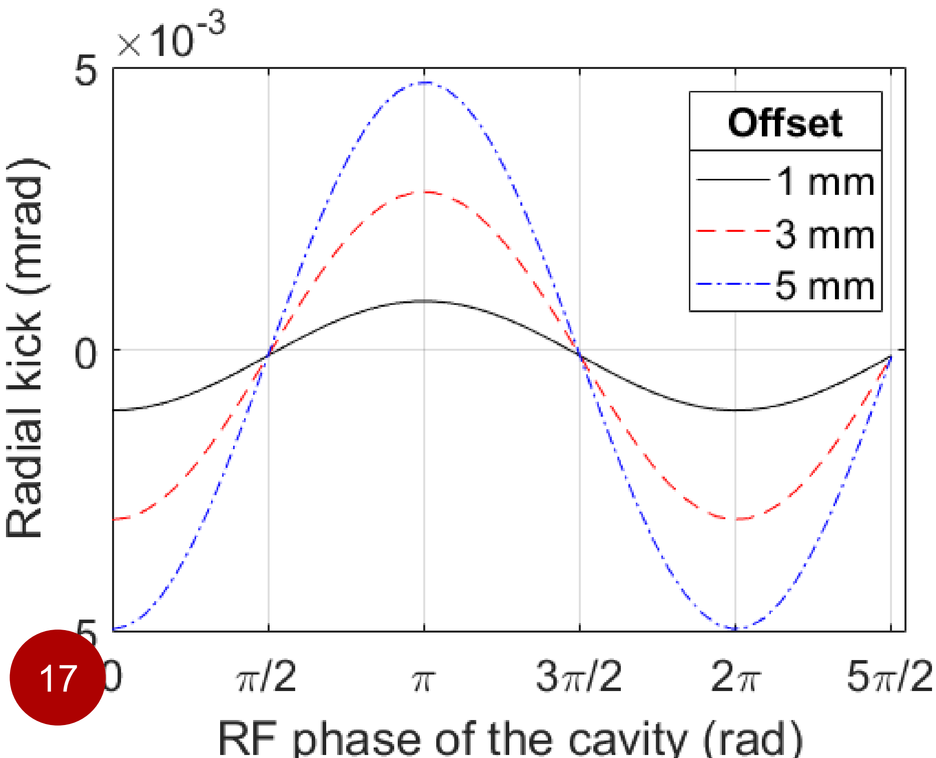
Effects of injector cavity RF kicks

cERL injector cryomodule

- The value of the transverse kick depends on the RF cavity phase and of the value of beam trajectory offsets inside the cavity

$$\begin{cases} x'_{out} = \dfrac{(\gamma\beta)_{in}}{(\gamma\beta)_{out}} x'_{in} - \dfrac{1}{(\gamma\beta)_{out}} \dfrac{x}{r} \dfrac{qV_0}{mc^2\beta\gamma} I_1\left(\sqrt{k^2-k_0^2}\,r\right)\left(T(k)\sin\phi + S(k)\cos\phi\right); \\ y'_{out} = \dfrac{(\gamma\beta)_{in}}{(\gamma\beta)_{out}} y'_{in} - \dfrac{1}{(\gamma\beta)_{out}} \dfrac{y}{r} \dfrac{qV_0}{mc^2\beta\gamma} I_1\left(\sqrt{k^2-k_0^2}\,r\right)\left(T(k)\sin\phi + S(k)\cos\phi\right). \end{cases}$$

- We assume that particles are moving in parallel to *z* axis
- All the energy-dependent parameters are fixed at their initial values
- Equations are valid only at low energy



x_{off}(mm)	y_{off} (mm)	Δx'(mrad)	Δy' (mrad)
2.6	2	-0.2916	0.2837
2.6	0	-0.2916	0.0018
2.6	-2	-0.2916	0.2825
0	2	0.0003	0.2837
0	0	0.0003	0.0018
0	-2	0.0003	0.2825
-2.6	2	-0.2915	0.2837
-2.6	0	-0.2915	0.0018
-2.6	-2	-0.2915	0.2825

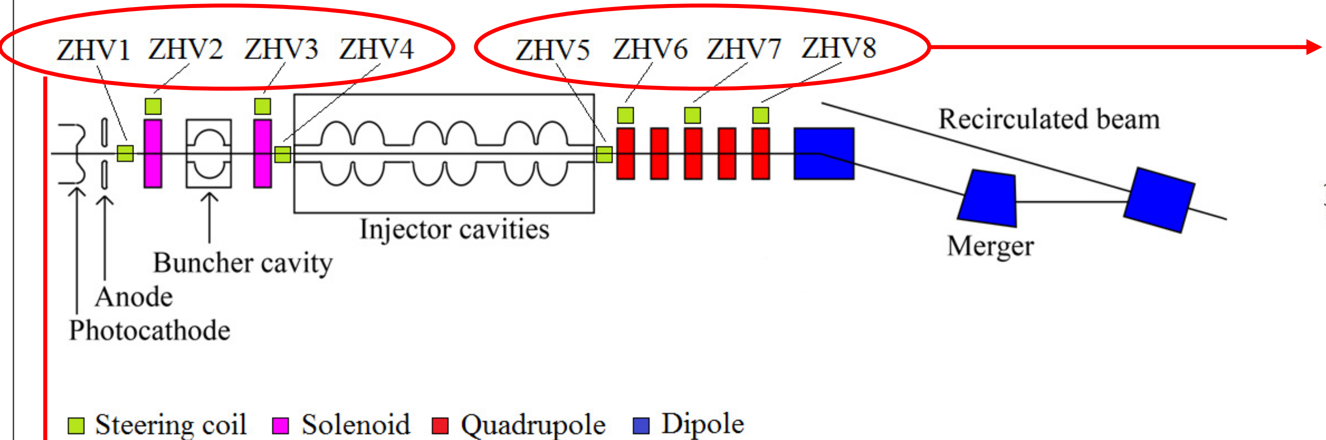
Effects of injector cavity RF kicks

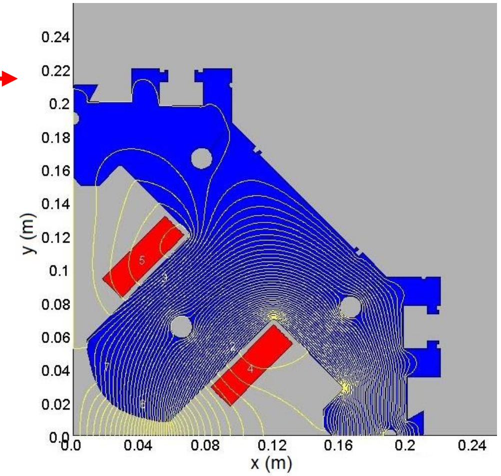
Lessons learned from cavity RF kicks

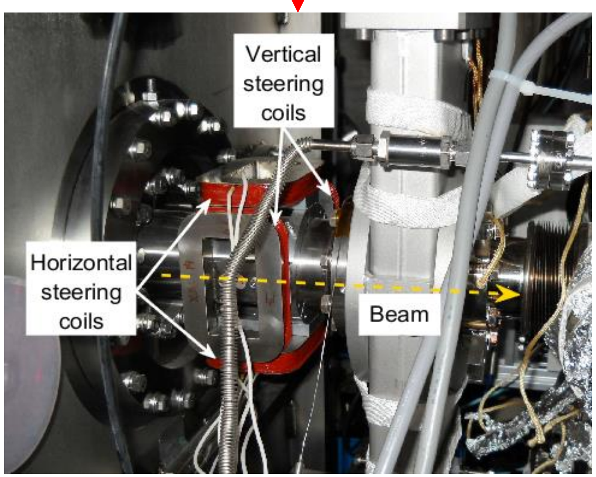
- We have learned that a reasonable amount of the beam orbit displacement (a few mm) inside the injector cavities can excite strong enough transverse RF kicks to particles, and the strength of those kicks largely depends on the particle’s longitudinal position in a bunch
- Particles in the core receive more or less similar amount of transverse RF kicks from the cavity accelerating mode due to their vicinity in the longitudinal position. Therefore, they move together transversely
- Particles in the tail receive quite different transverse RF kicks, sometimes even in the opposite direction, from those for the core, depending on their longitudinal distance from the core. Therefore, they start to deviate transversely from the core, creating a halo
- This transformation of a longitudinal bunch tail to a transverse beam halo by the beam orbit displacement inside a cavity can be a new mechanism of the halo formation

Steering coils effects on the beam trajectory

Layout & geometry of the steering coils







Steering name	Current (A)	ItoBL (T m/A)	Lenth (mm)	Gap (mm)	Width (mm)	Turns / coil
ZH1	-0.30	$3.42\ 10^{-5}$	59	133	95.5	90
ZV1	-0.90	$3.23\ 10^{-5}$				
ZH2	0.06	$5.93\ 10^{-5}$	63	132	66	122
ZV2	-0.18	$6.07\ 10^{-5}$				
ZH3	0.00	$5.93\ 10^{-5}$	63	132	66	122
ZV3	0.00	$6.07\ 10^{-5}$				
ZH4	0.71	$3.21\ 10^{-5}$	59	133	95.5	90
ZV4	-3.18	$3.57\ 10^{-5}$				
ZH5	-0.82	$7.07\ 10^{-5}$	79	143	95.5	150
ZV5	0.25	$7.48\ 10^{-5}$				
ZH6	-4.90	$1.83\ 10^{-5}$	100	60	140	240
ZV6	1.70	$1.73\ 10^{-5}$				
ZH7	-0.43	$1.83\ 10^{-5}$	100	60	140	240
ZV7	0.005	$1.73\ 10^{-5}$				
ZH8	0.00	$1.83\ 10^{-5}$	100	60	140	240
ZV8	-0.58	$1.73\ 10^{-5}$				

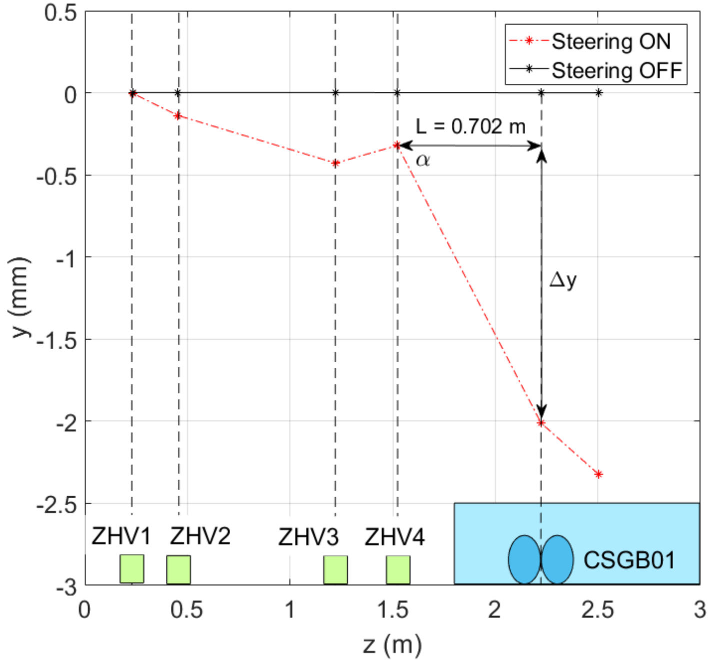
Steering coils effects on the beam trajectory

Orbit displacement estimation

- The Integral of magnetic fields $B_x(z)$ is equal to the incremental of the beam tilt α:

$$\int_0^z B_x(z)dz = \frac{\gamma mc\beta_z}{e}\alpha = \frac{\gamma mc\beta_z}{e}\frac{\Delta y}{L}.$$

- The simulation yields a small entry angle of α = 0.138º to the injector cavities from the central axis of the injector and a vertical offset of Δy = 1.67 mm at the first cavity location.



Steering coils effects on the beam trajectory

Lessons learned from orbit displacement estimation

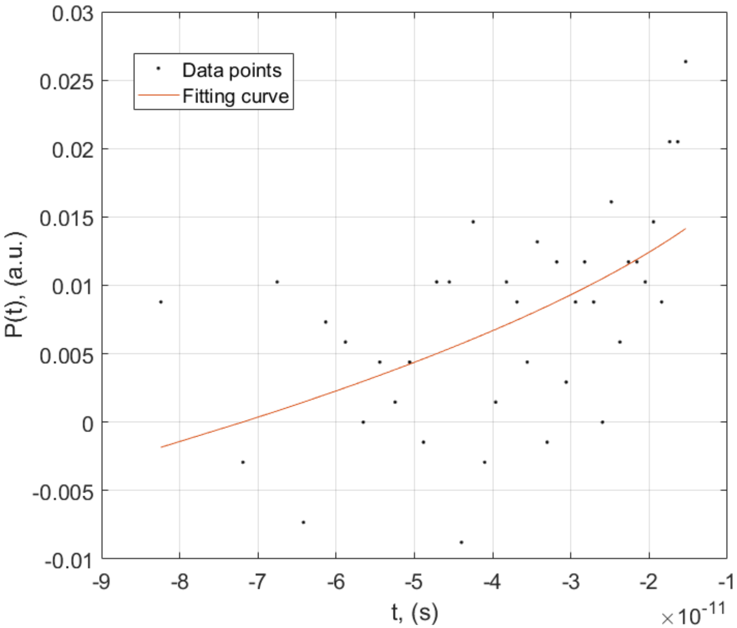
- Parameters of some devices that create transverse beam offsets in the injector cavities are already known
- The currents values of the steering coils ZHV1 – 8 are known from the operation log
- The relative horizontal offset of the injector cavity #2 is measured to be 2.6 mm
- As other possible effects on the beam orbit displacement, we can think of 1) collective horizontal and/or vertical displacements of all the three cavities, 2) ambient magnetic fields

Now let's consider all 3 effects combined together:

1. Longitudinal bunch tail
2. Effects of injector cavity RF kicks
3. Steering coils effects (and other possible effects) on the beam trajectory

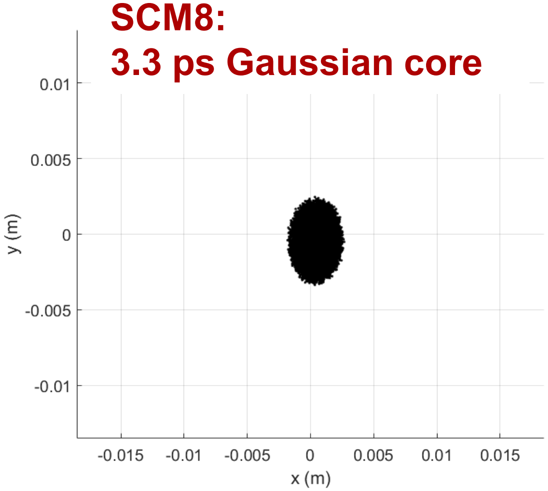
Simulations with 3 effects combined together

Forward tail

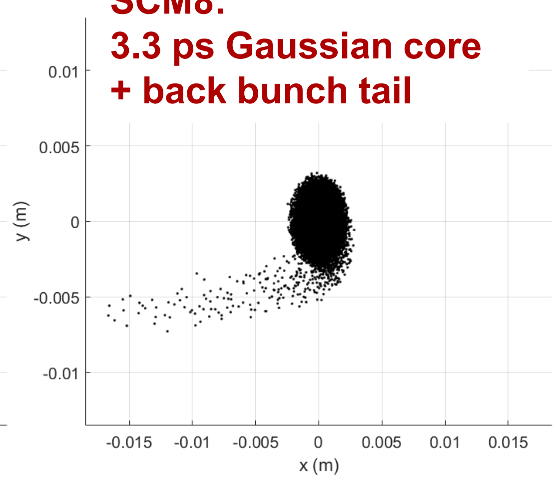


- The first step is to find a right combination of the halo formation factors, which reproduces well the measured profiles of vertical halo
- If one considers the longitudinal bunch tail alone, only one part of halo distribution (upper or lower, it depends on the observation point location) can be reproduced
- Upon closer examination a small percentage of particles (about 1.5% of the beam) outstripping the beam core in time was detected

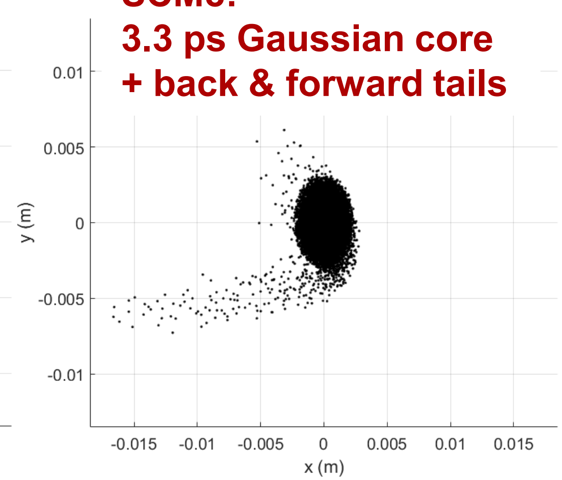
SCM8:
3.3 ps Gaussian core



SCM8:
3.3 ps Gaussian core
+ back bunch tail



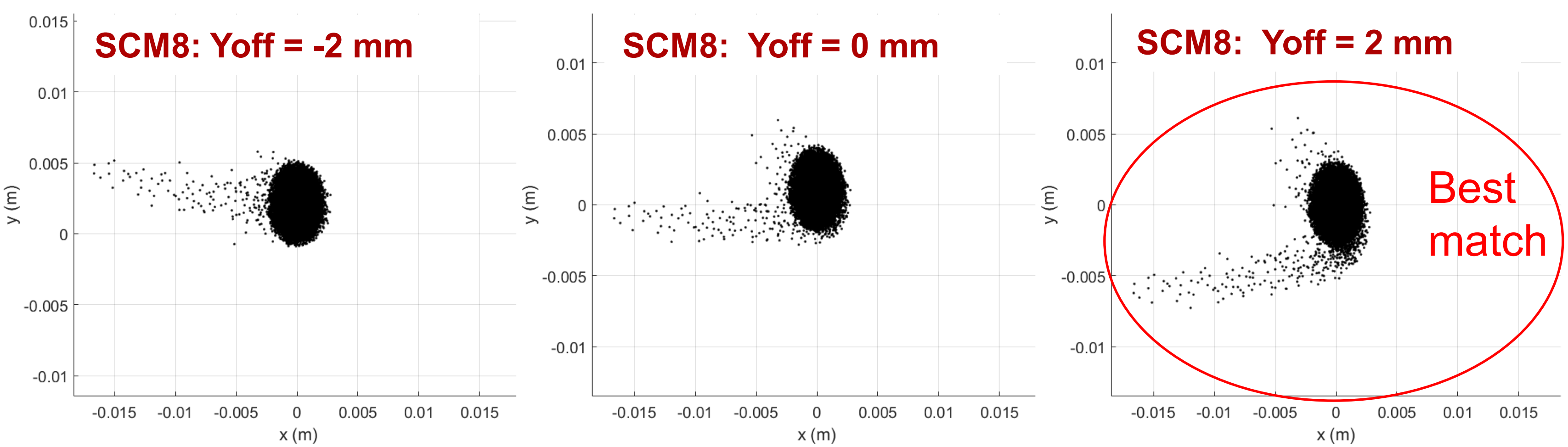
SCM8:
3.3 ps Gaussian core
+ back & forward tails

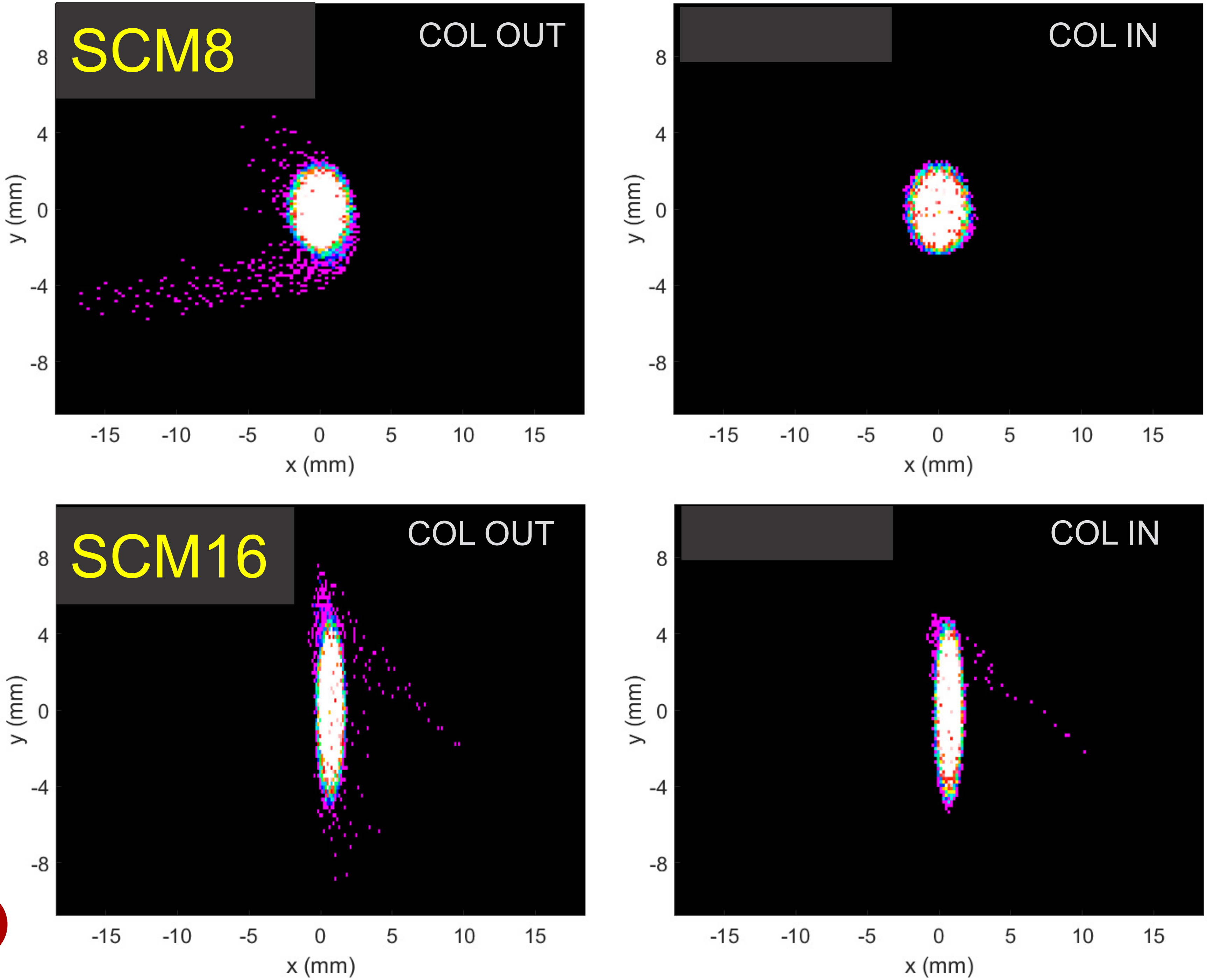


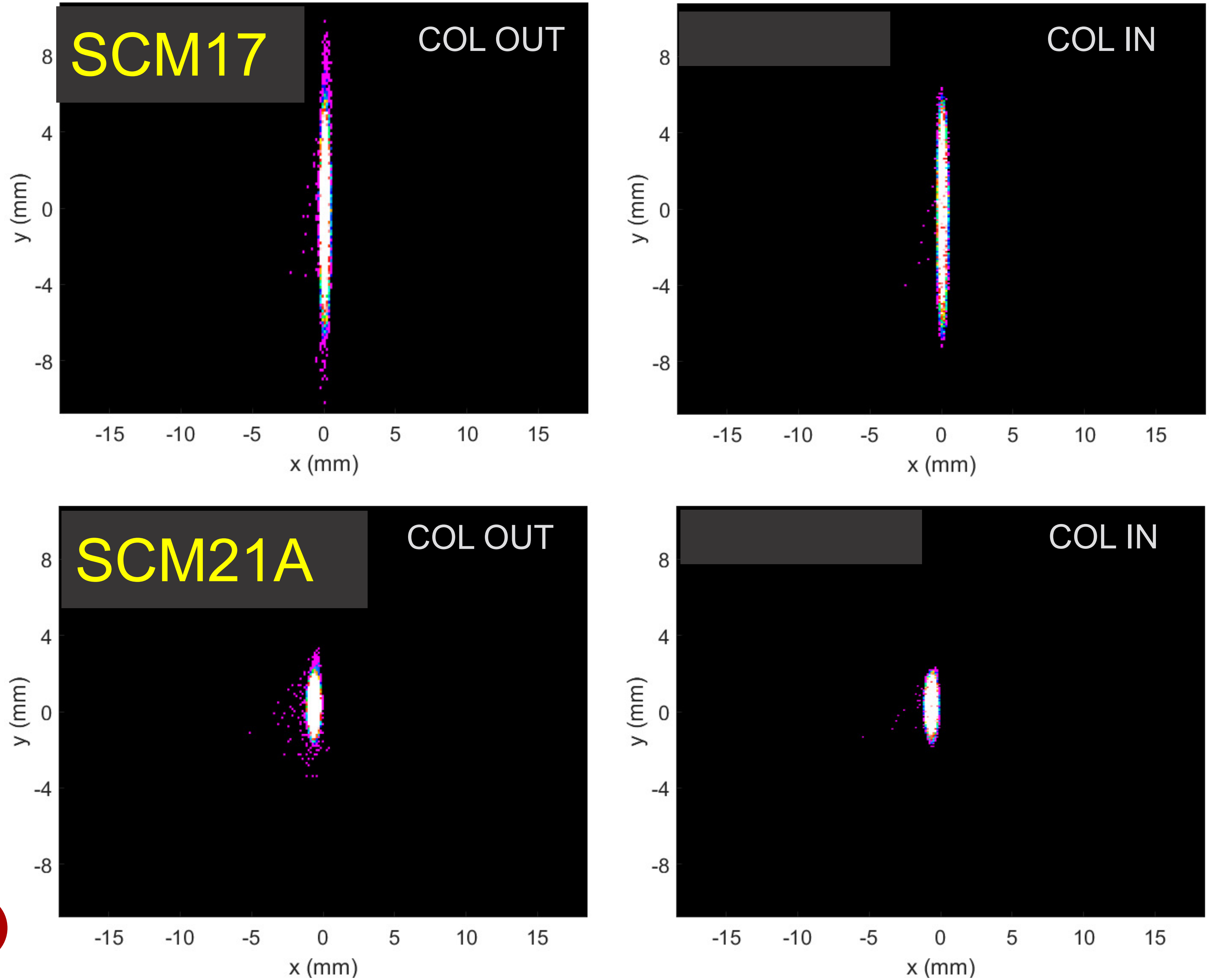
Simulations with 3 effects combined together

Beam trajectory displacement due to various effects

- It is essential to consider the beam orbit displacement inside the cryomodule and assume that there are additional beam orbit displacements there (on top of the steering coil effect), notably due to the collective cavity offset and possibly due to the ambient magnetic fields
- Let us use the collective cavity offset as a free parameter in simulations and find the optimum value which reproduces the measured beam halo profiles at the different locations
- The values -2 mm, 0 mm, 2 mm were tested for the collective horizontal and vertical offsets of cavities #1 – 3
- It is very likely that a collective vertical offset of the beam trajectory, due the misalignment of the injector cryomodule, or due to the ambient magnetic fields, exists and it is about 2 mm

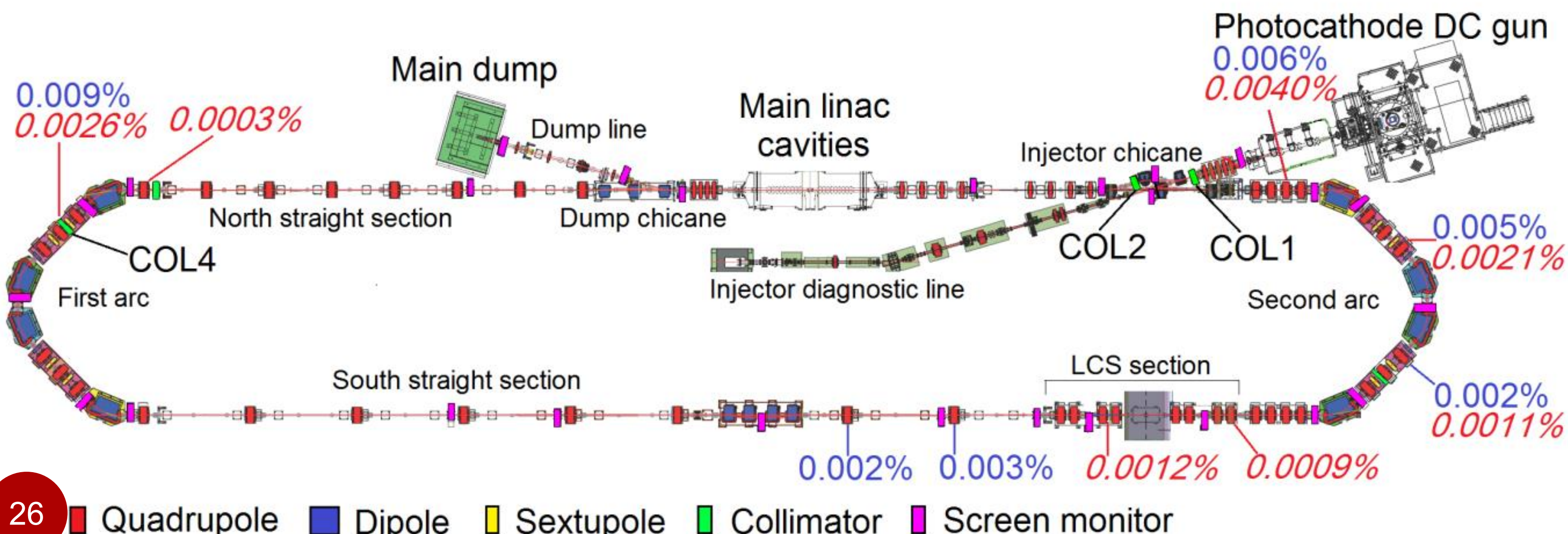



SCM8
COL OUT
COL IN
SCM16
COL OUT
COL IN
y (mm)
x (mm)
8
4
0
-4
-8
-15
-10
-5
0
5
10
15


SCM17
COL OUT
COL IN
SCM21A
COL OUT
COL IN
y (mm)
x (mm)
8
4
0
-4
-8
-15
-10
-5
0
5
10
15

Beam loss estimation
Loss rates comparison

- To simulate beam loss rates we change some input parameters:
  - The number of particles $N = 10^6$
  - The beam current J = 0.95 mA and the corresponding bunch charge Q = 0.73 pC
  - Collimators COL1, 2 and 4 inserted in
- Effects of the injector steering coils were also included in the beam loss simulation
- The measured horizontal offset of the injector middle cavity (2.6 mm) is included
- The common vertical offset of the three injector cavities (2 mm) Then the beam distribution with 3.3 ps Gaussian core with the back and forward tails was tracked



Simulations with 3 effects combined together

Lessons learned from the simulation study

- **Based on the experimental data, we made a conjecture that the most likely cause of the beam halo at cERL is the longitudinal bunch tail originated at the photocathode, and its transfer to a vertical halo in the rest of the machine**
- **The accelerating mode of the injector cavities can produce transverse RF kicks to particles when the beam orbit has a transverse offset.** The strength (and even the direction in some cases) of those kicks are different for particles in the core and those in the tails, and thus some particles in the tail start to deviate transversely from the core, resulting in a halo
- We found that the steering coils, (and possibly the ambient magnetic fields) produce substantial beam displacement in the injector cavities
- The present halo simulations also show a possibility that all the three injector cavities are shifted up together by 2 mm due to a vertical shift of the entire cryomodule
- **It may be the first time to prove that the transverse halo can be formed from the longitudinal bunch tail**
- We found that the inclusion of the forward tail in simulations significantly improves agreements between experimental data and simulation results

Summary & prospect

- Non-negligible transverse halos have been experimentally observed at cERL. It seems that halo formation mechanisms generate transverse offsets of a beam at the collimators COL1 and COL2 in the injector line since they are quite effective in cutting the beam halo
- The simulated beam losses show the reasonable agreements with the measured values for both the loss rates and the beam loss distribution along the beam line
- The next step of cERL R&D is the operation with the low-emittance and the high bunch charge (or high average beam current). For this end, more operational studies on the mechanisms of the beam halo formation are required to achieve overall beam loss reduction
- The most likely cause of the beam halo at cERL is the longitudinal bunch tail generated at photo-cathode. Therefore, we may need to consider a different-type of photocathode material such as multi-alkali to mitigate the beam loss further.
- The space charge effect will be another important factor in a higher bunch charge operation. They should be subjects of the further study

Thank you for your attention!
Nous vous remercions de votre attention!