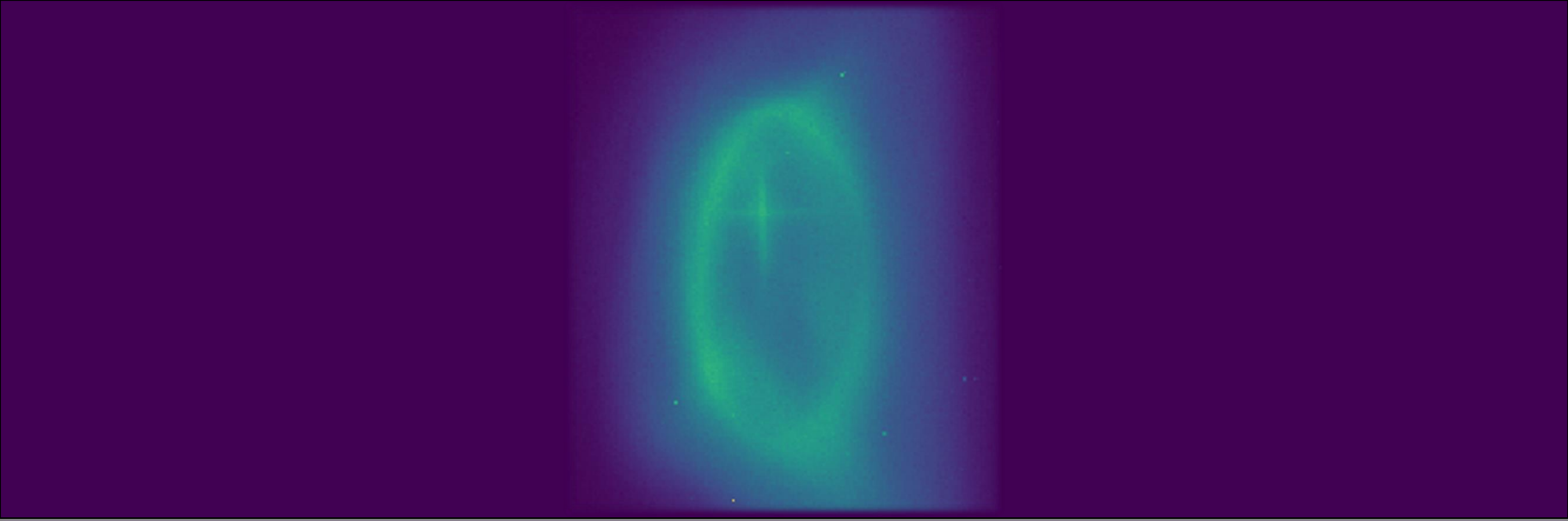


Beam Halo in Energy Recovery Linacs

Olga Tanaka on behalf of the cERL team (KEK, Japan)

Workshop on Energy Recovery Linacs

September 17, 2019

WISTA - Bunsen Saal

10:45 – 11:10

bERLin 2019

Outline

Introduction

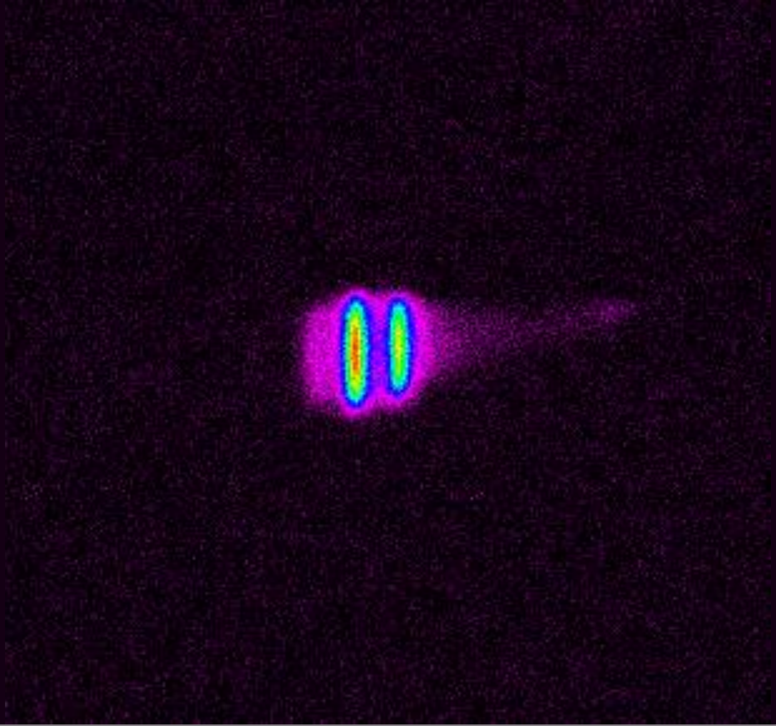
- Beam halo in ERLs: an overview
- Present status of cERL
- Collimator study

Conclusion & outlook

Introduction

- In ancient times, the appearance in the sky of the solar halo caused genuine fear. People considered the halo effect as a harbinger of destructive wars, famines, great troubles etc.
- Nowadays beam dynamics physicist have no room to be scared by the electron halo. We need to fight against it.

Stockholm, 20th April, 1535.



Beam halo in ERLs: an overview

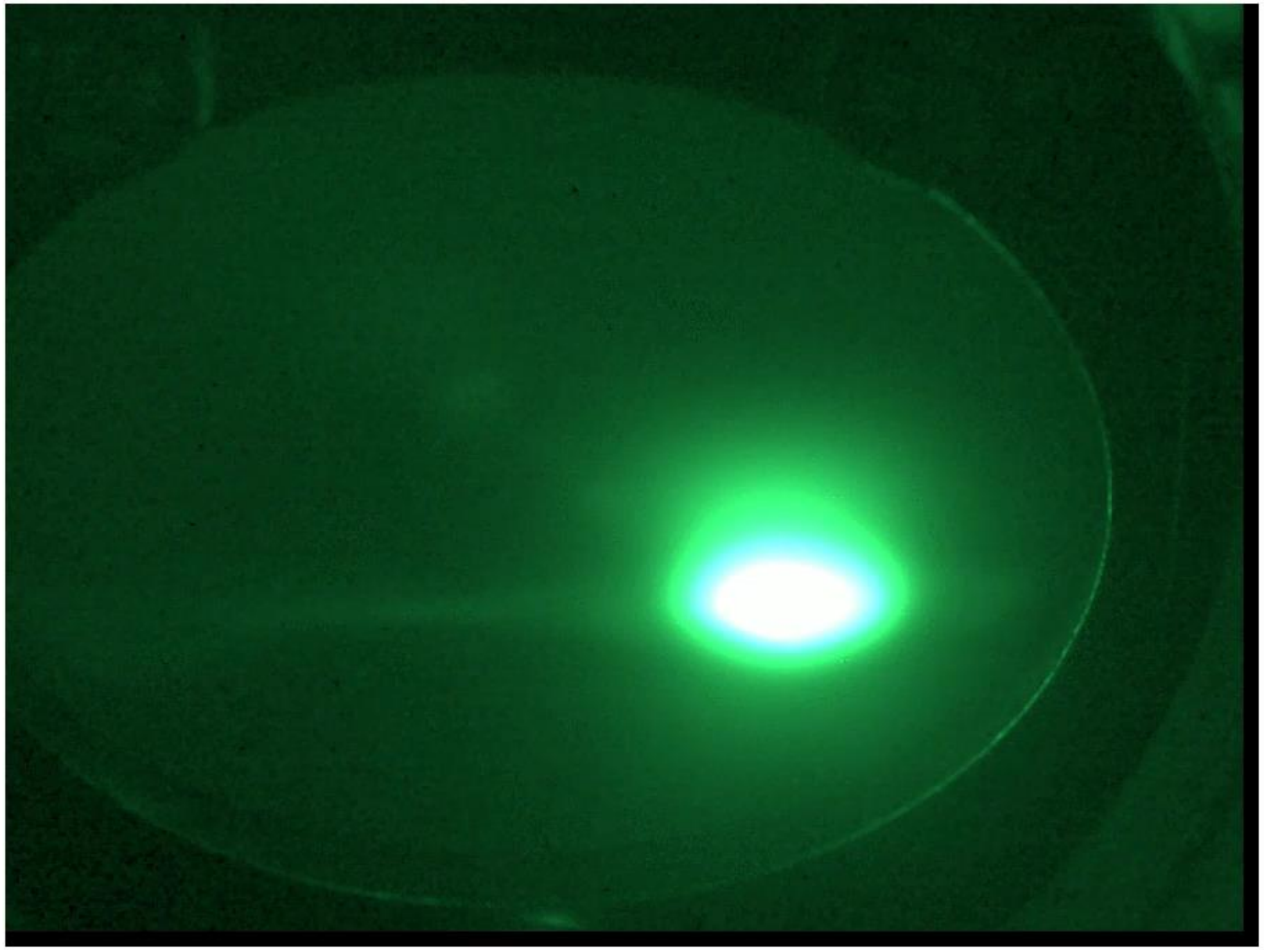
Beam halo investigations: reasons

- Poster WEPNEC02 “Investigation and Mitigation of the Mie-Scattering on the Surface of the First Objective Lens for Coronagraph-Based Halo Monitor” by *J.-G. Hwang* from HZB

- The **following mechanisms** are known to be typical for ERL machine:
    1. **Beam dynamics** (space charge effects, Touschek, and intrabeam scatterings);
    2. **Machine imperfections** (defects of components, machine nonlinearities and misalignments);
    3. **Errors** (improper beam timing of laser or rf cavity phase shifts);
    4. **Electron gun** (dark current, longitudinal tails);
    5. **Vacuum system** (residual gas scattering and ion trapping);

- In addition to these well-known sources of halo formation, there are also some mechanisms **unique to each machine** that can generate beam halo.

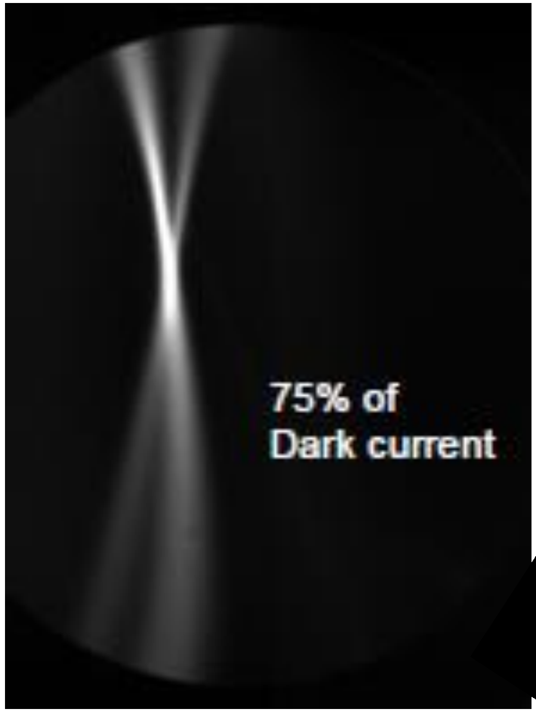
Example#1: observation of beam halo in the CBETA



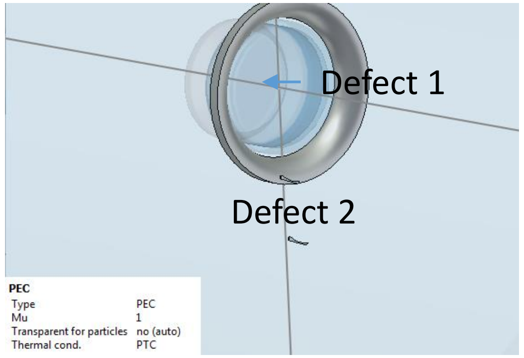
Changed a quad just upstream of the screen. Halo **changes shape** like a beam, camera/lens/bloom effect would not.
Conclusion: this is halo is real electrons.

Courtesy of S. Brooks, Cornell, 20.04.2019.

Example#2: dark current analysis of defects at bERLinPro injector

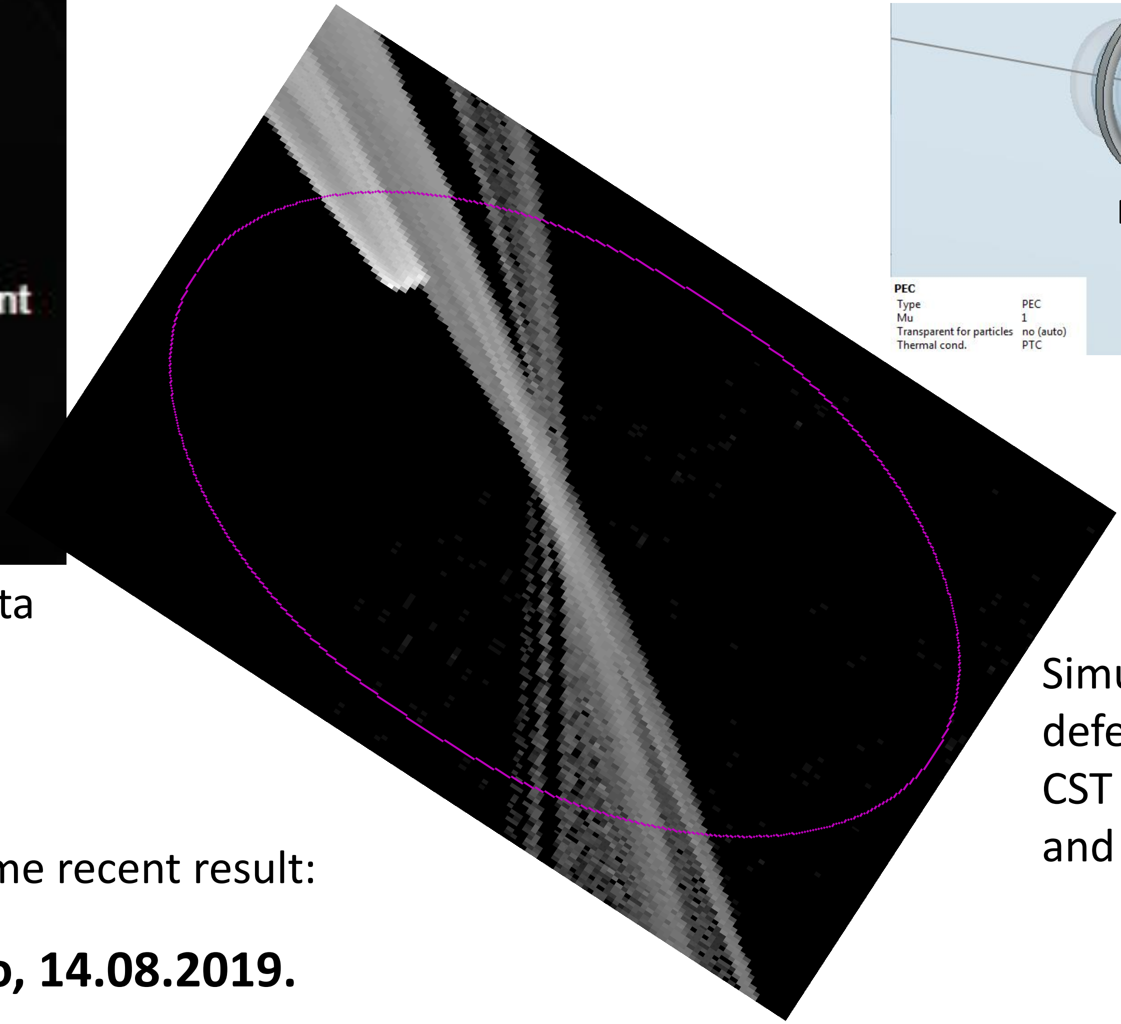


Dark current measured at FOM2, main emitter cross-like structure. Caused by defects?



At E_0= 7MV/m momenta measured were 0.86 and 0.89 MeV/c (E_{kin}=0.35 MeV)

Some recent result:



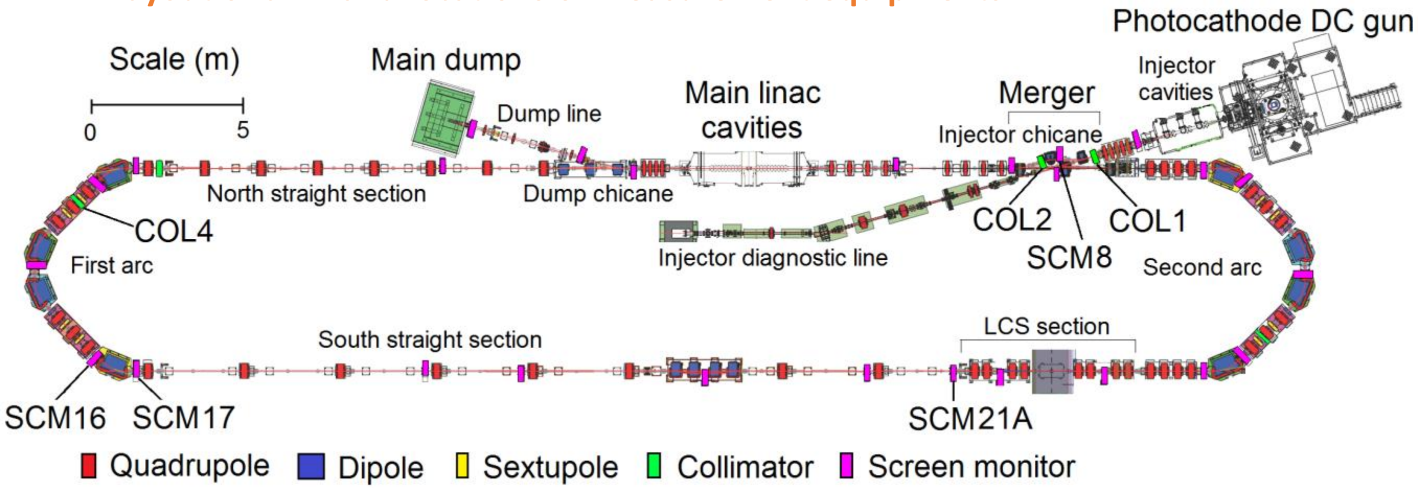
Simulation of defect 1 using CST MWS and PS PIC.

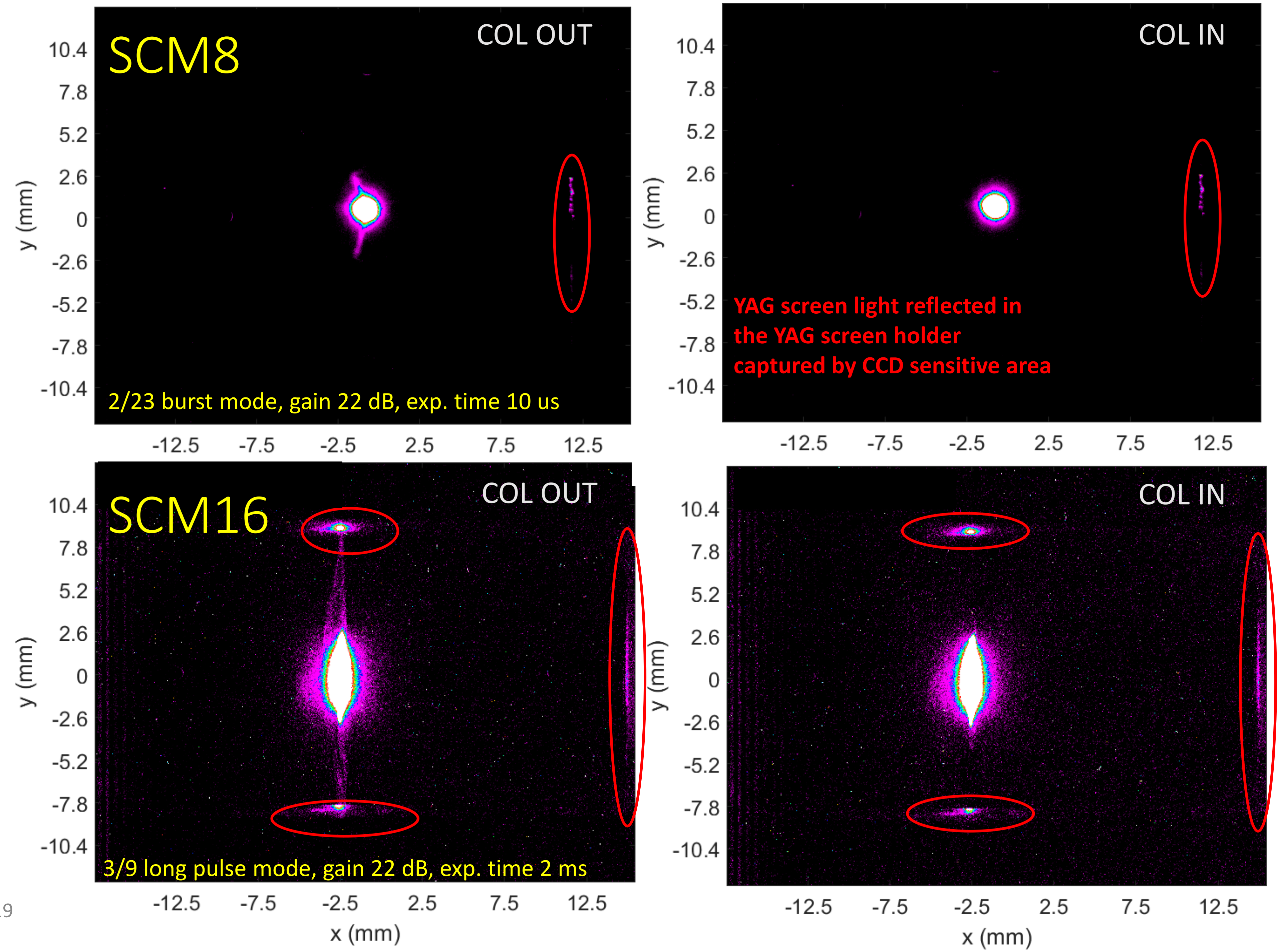
Courtesy of A. Neumann, bERLinPro, 14.08.2019.

Example#3: beam halo in cERL (I)

- Non-negligible particle losses were observed in the recirculation loop due to a halo during a common operation.
- The beam halo formation is usually related to non-linear effects such as the space-charge, Coherent Synchrotron Radiation (CSR) effects, and diffusion effects.
- These are not the case at the cERL injector due to its low intensity beam.
- I had to find a new mechanism to explain the halo formation in the "semi" linear cERL injector.

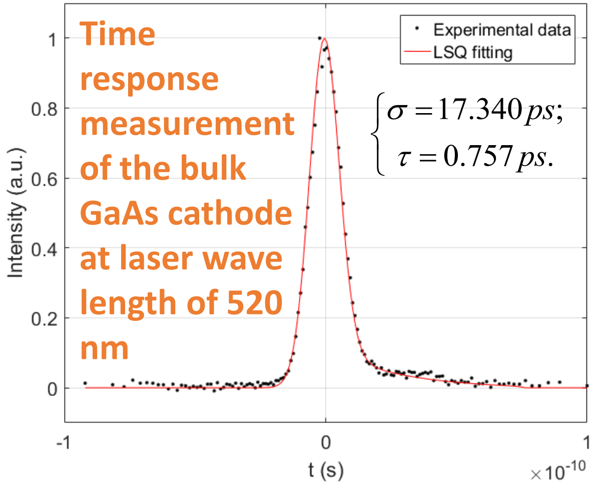
Layout of cERL and locations of measurement equipments

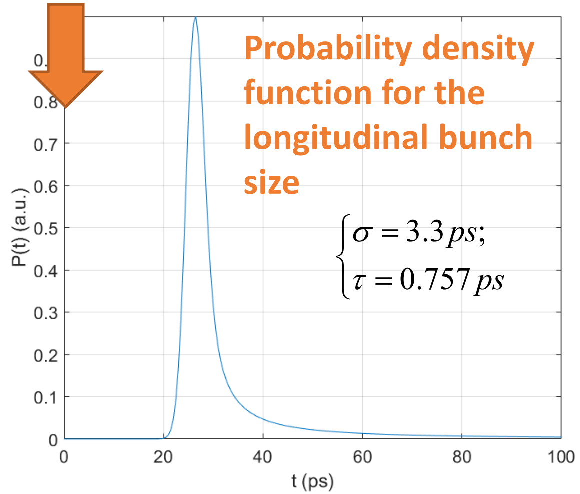



SCM8
COL OUT
COL IN
2/23 burst mode, gain 22 dB, exp. time 10 us
YAG screen light reflected in
the YAG screen holder
captured by CCD sensitive area
SCM16
COL OUT
COL IN
3/9 long pulse mode, gain 22 dB, exp. time 2 ms
y (mm)
x (mm)
10.4
7.8
5.2
2.6
0
-2.6
-5.2
-7.8
-10.4
-12.5
-7.5
-2.5
2.5
7.5
12.5

Example#3: beam halo in cERL (III)

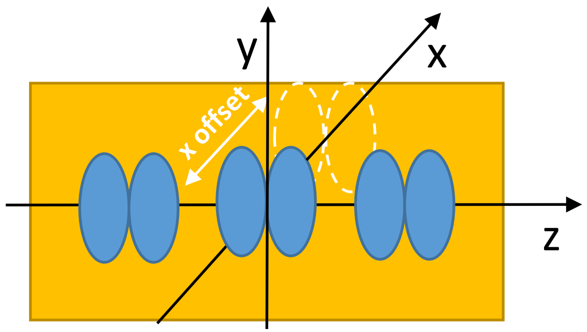
- Beam studies show that we can reduce the beam loss when the beam enters the injector cavities with a slight angle from the central axis of the injector.
- Since no transverse beam halo has been observed at the electron gun vicinity, we conjecture that the driving mechanism of the beam halo formation is transfer of the longitudinal bunch tail into the transverse plane in the rest of machine.
- The longitudinal bunch tail is created at the photocathode.

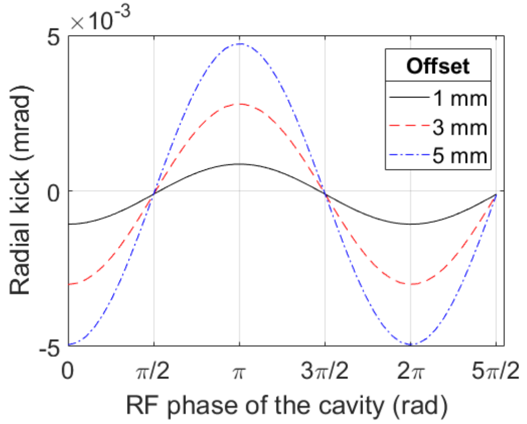


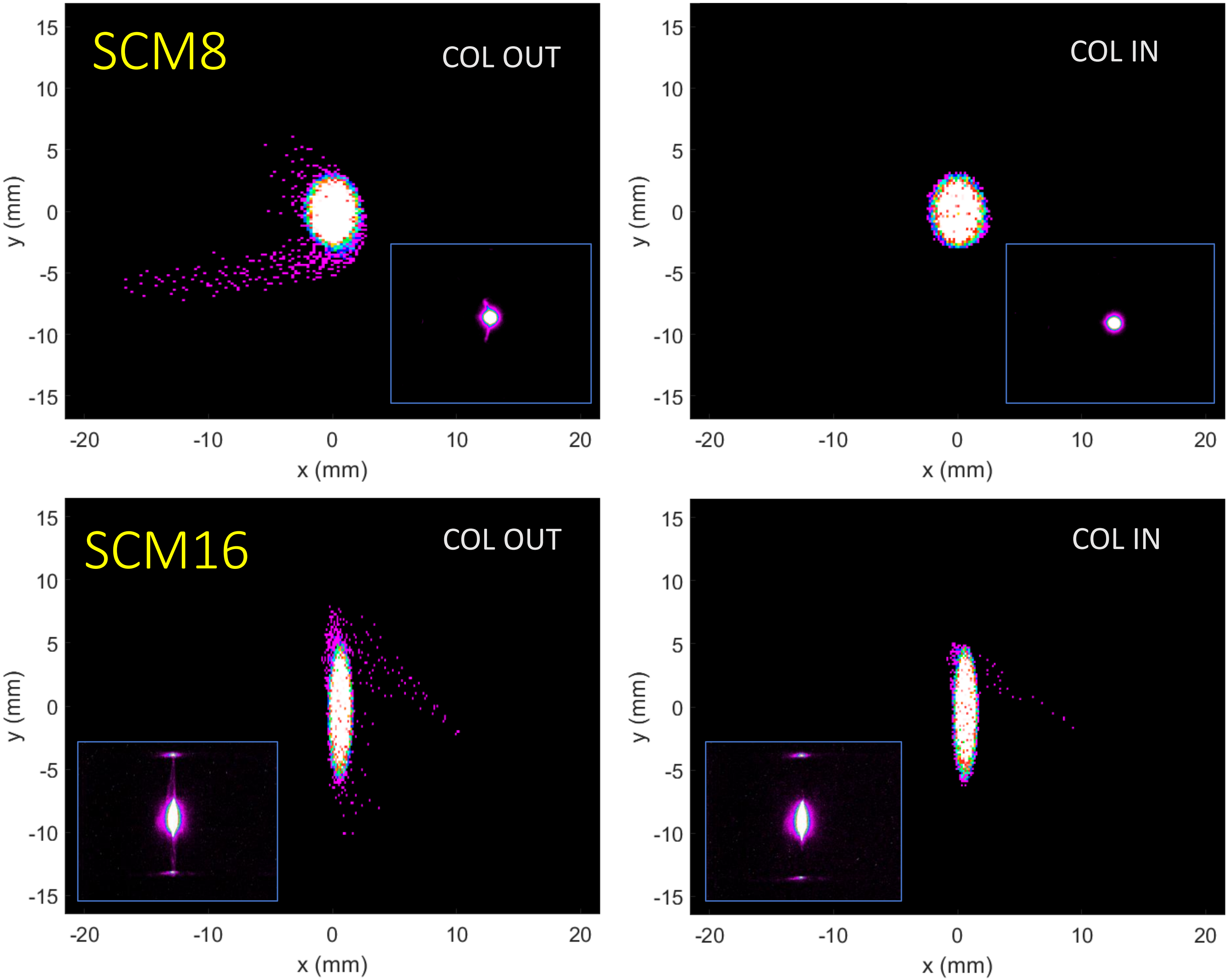


Example#3: beam halo in cERL (IV)

- The key elements causing this transformation are:
  - The injector cavities;
  - The displacement of the beam orbit inside them.
- The accelerating mode of the injector cavities can produce transverse RF kicks to non-relativistic particles when the beam enters with a transverse offset.
- The strength and the direction of those kicks are different for particles in the core and the tails, and thus some particles in the tail start to deviate transversely from the core, resulting in a halo.
- In addition, particles receive different transverse kicks from the accelerating cavities depending on their relative longitudinal position from the core, since they enter the accelerating cavities at different RF phases.






SCM8
COL OUT
COL IN
SCM16
COL OUT
COL IN
y (mm)
x (mm)
15
10
5
0
-5
-10
-15
-20
-10
0
10
20

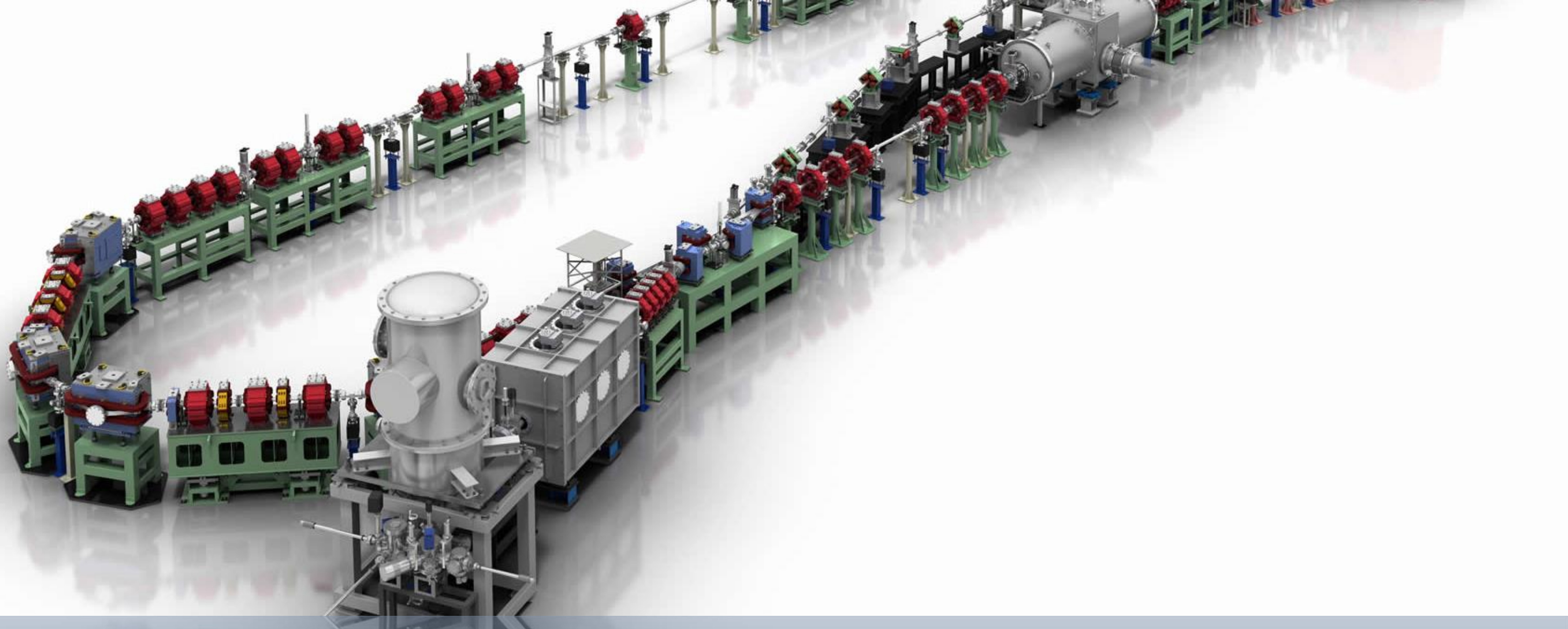
Lessons learned from beam halo study at cERL:

- ✓We guess that the transverse beam halo could occur from the **longitudinal bunch tail** arising at the photocathode.
- ✓The **mechanisms** transferring the longitudinal bunch tail into the transverse plane are: rf field kicks, due to injector line elements misalignments and an effect of the steering on the beam trajectory.
- ✓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.

But, it is all for 1 pC per bunch!

PhysRevAccelBeams.21.024202

O. Tanaka et. al. "New halo formation mechanism at the KEK compact energy recovery linac"



Present status of cERL

Presentations about cERL at ERL’19

- **Monday, 16th September 2019**
    1. ”Compact ERL (cERL), stable 1 mA operation with a small beam emittance at KEK” by *T. Miyajima.*
    2. “Industrial Applications of cERL” by *H. Sakai.*
- **Tuesday, 17th September 2019**
    1. “KEK ERL SRF Operation Experience” by *H. Sakai*.
    2. “Characterization of Microphonics in the cERL main linac superconducting cavities” by *F. Qiu*
- **Wednesday, 18th September 2019**
    1. “High-Efficiency Broadband THz Emission via Diffraction-Radiation Cavity” by M. *Shimada*.
- **Thursday, 19th September 2019**
    1. “Degradation and Recovery of Cavity Performance in Compact-ERL Injector Cryomodule at KEK” by *E. Kako.*
    2. ”Injector development at KEK” by *T. Miyajima.*
    3. “Development of HOM coupler with C-shaped waveguide for ERL operation” by *M. Sawamura*.
- **Poster**
    1. WEPNEC11 “Beam Optics of Bunch Compression at Compact ERL” by *M. Shimada*.

Motivation

- The Compact ERL at KEK is planned to be upgrade to a **mid-infrared Free Electron Laser** (IR-FEL) in May 2020.
- Toward the IR FEL test, we designed a beam transport condition in an injector beamline for 60 pC bunch charge, and operated the cERL accelerator to confirm the designed beam performance and to develop the method of beam tuning **to control space charge effect**.
- During the operation in June 2019, we optimized injector to 4 MeV energy. *→ see the Thursday's talk by T. Miyajima on the injector development*
- To meet the IR-FEL requirements, we had to tune the beam to **4 ps RMS bunch length and < 3 πmm· mrad normalized emittance**.

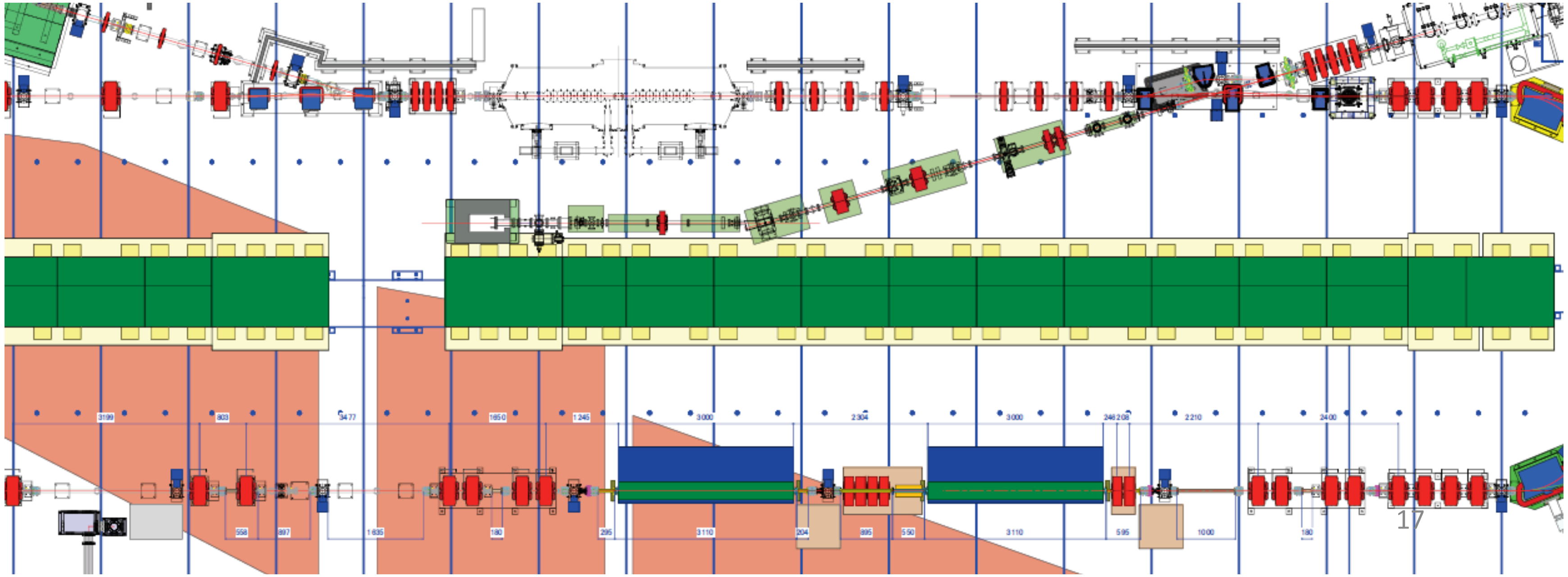
cERL beam parameters

- In June 2019 the main purpose of the cERL beam tuning was to control space charge effect.
- We achieved the following beam parameters:
  - The **emittance** at the ML entrance obtained by Q-scan is 2.89/1.99 πmm · mrad (design emittance ε_{nxy} = 2.26/1.86 πmm · mrad).

Parameter	Design	In operation
Beam energy [MeV]:		
• Injector	4	4.05
• Recirculation loop	17.6	17.5
Bunch charge [pC]	60	60
Repetition rate [GHz]	1.3	1.3
Bunch length (rms) [ps]	4	4.5
Energy spread [%]	<0.06	0.21
Normalized emittance (rms) in injector [μm·rad]:		
• Horizontal	< 3	2.89±0.09
• Vertical	< 3	1.99±0.20

- The **RMS bunch length** measurement result was 4.5 ps (design value is 4.1 ps).
- The **energy spread** was measured as <0.21% (design value of 0.062%).

→ *For details see talk by T. Miyajima on the injector development*



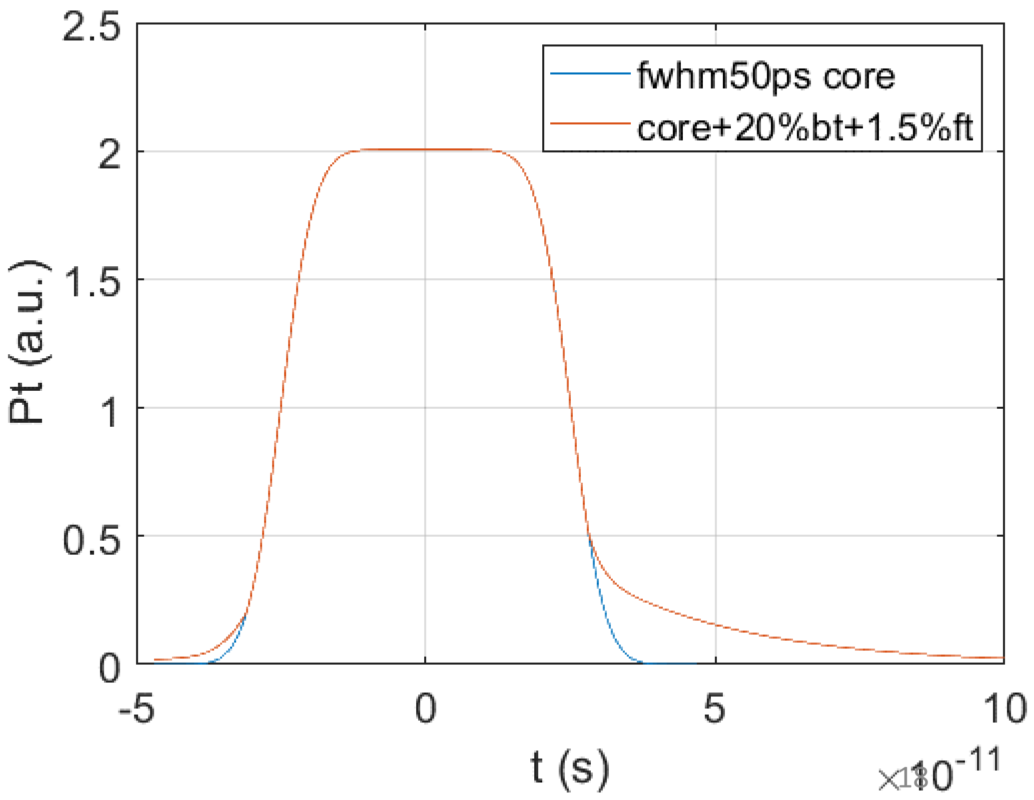
Halo tracking through the injector

GPT simulation input parameters	
Number of particles	25000
Beam energy	4 – 17.5 MeV
Total charge	60 pC / bunch
RF frequency	1.3 GHz
Longitudinal distribution: • Core • Tail	• FWHM 50 ps flat-top Gaussian • Back & forward tails of 100 ps length
Transverse distribution	Uniform ϕ= 2 mm

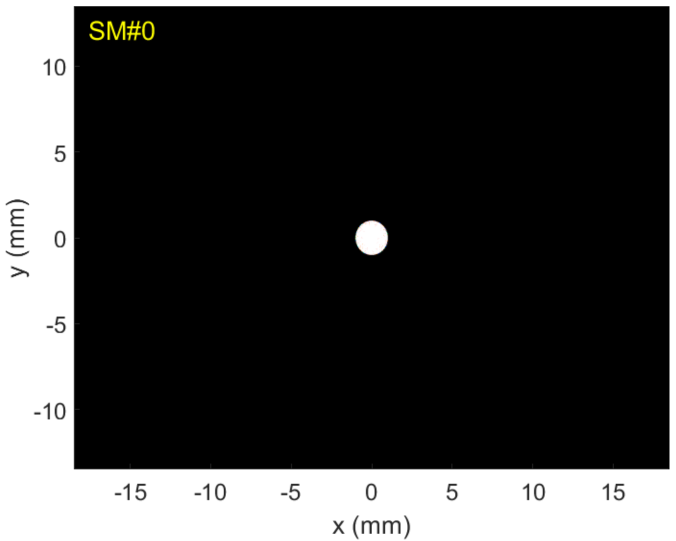
Longitudinal distribution

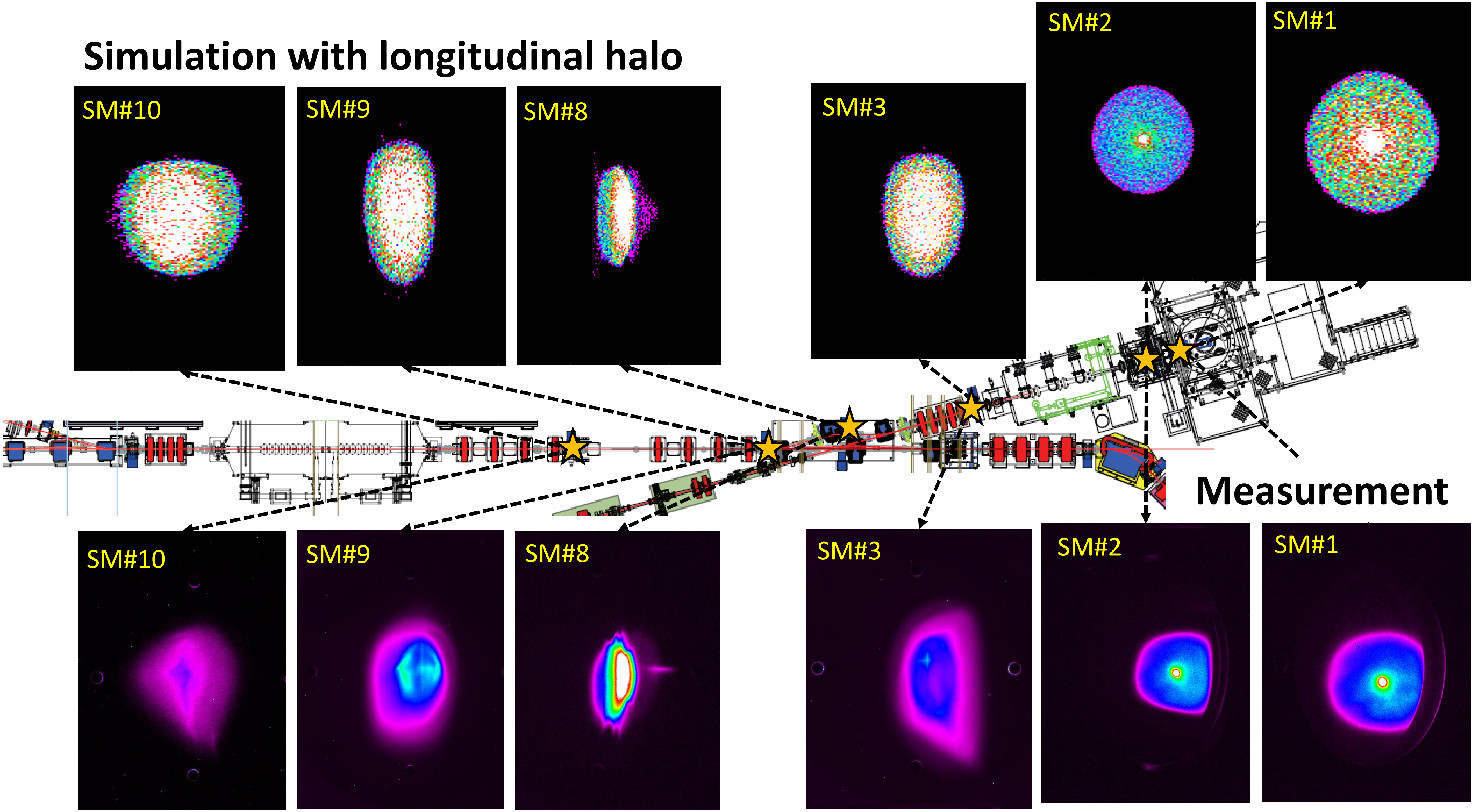
Back tail ~ 20% of core

Forward tail ~ 1.5% of core

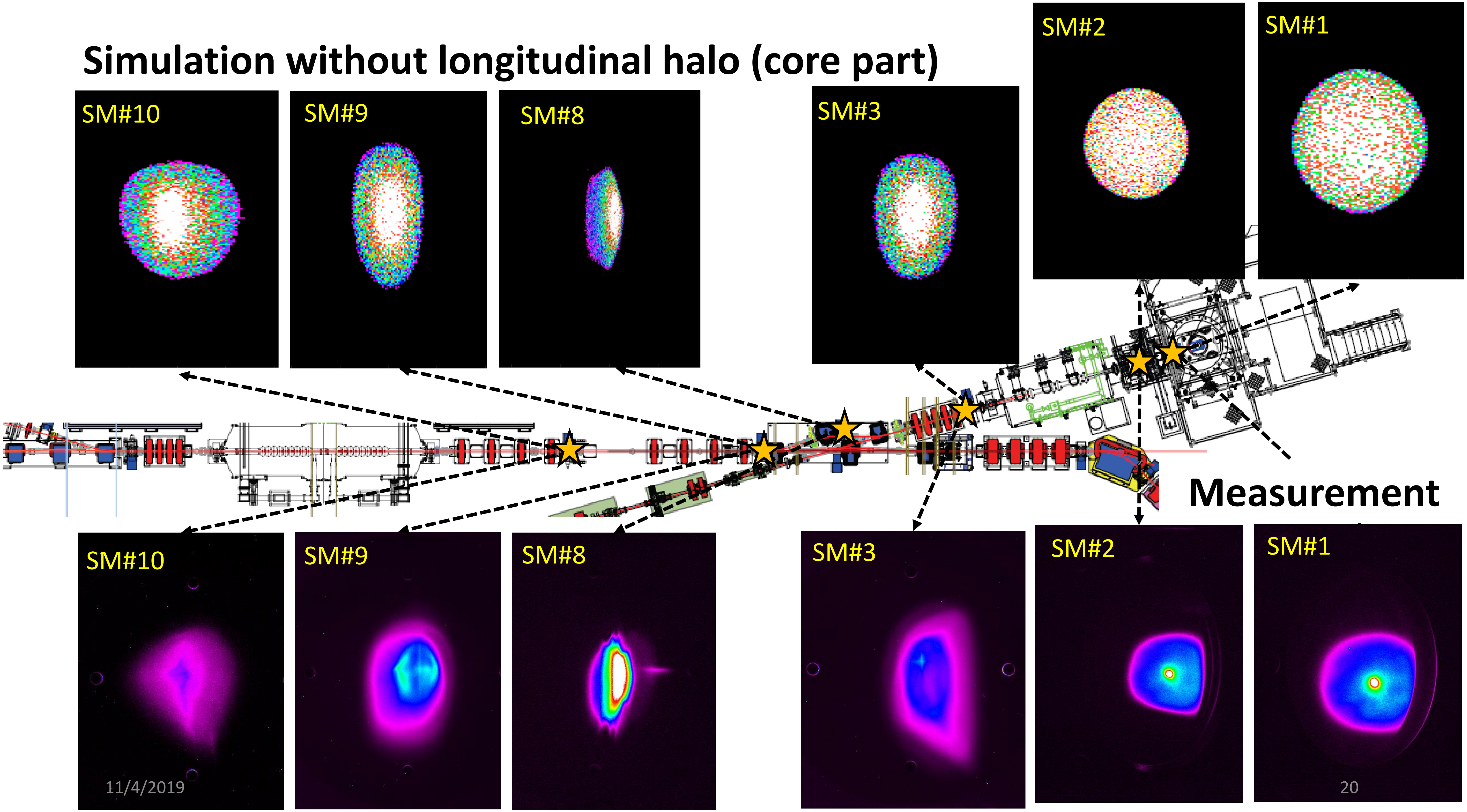


Transverse distribution




Simulation with longitudinal halo
SM#10
SM#9
SM#8
SM#3
SM#2
SM#1
Measurement
SM#10
SM#9
SM#8
SM#3
SM#2
SM#1

Simulation without longitudinal halo (core part)



Lesson learned from the high bunch charge operation:

For a bunch charge of 60 pC, the **space charge effect is dominant**.

Refer to the Monday's talk about 1 mA operation by T. Miyajima.

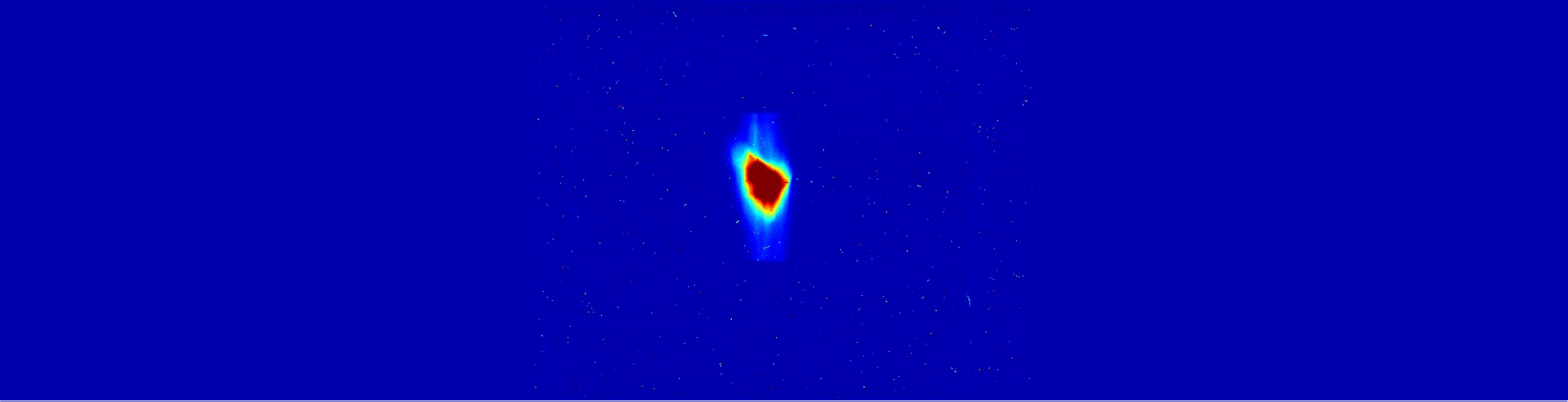
We need to tune the beam to be close to the design conditions → Further investigations (analytic, simulations, beam tests) are planned during the next operation in October, 2019.

For the optics matching for the bunch compression refer to poster WEPNEC11 by M. Shimada.

IR-FEL upgrade requires a high bunch charge CW operation:

- **Energy spread** should be minimized to improve the FEL-light quality → Investigate the halo influence on the energy spread.
- **Bunch length** and **beam emittance** should be controlled to meet the FEL requirements → Exclude the beam halo impact (or reduce as much as possible).
- A reasonable **collimation** is needed to protect the beam line components from its unnecessary irradiation and to lower the beam losses → Approve the usage of collimators.

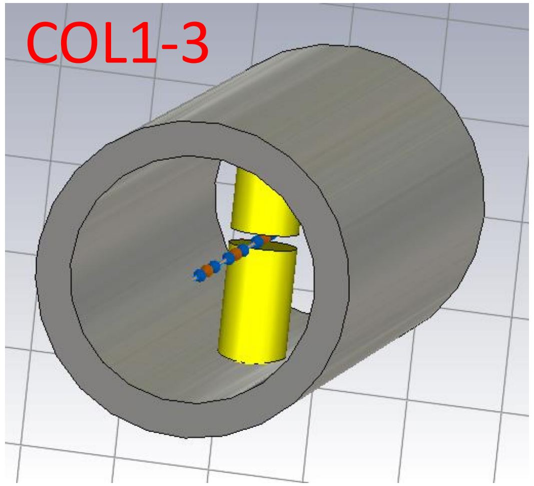
Industrial application of cERL were described in Monday's talk by H. Sakai.

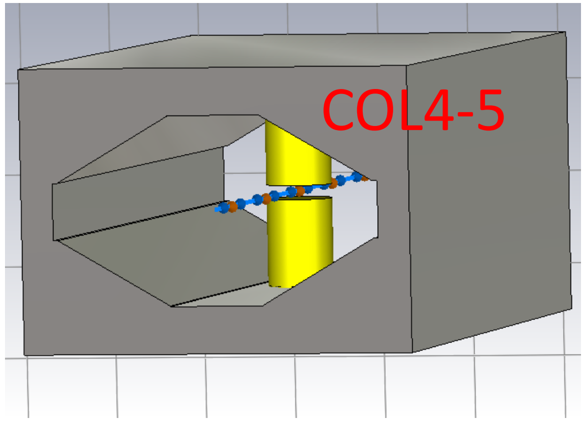


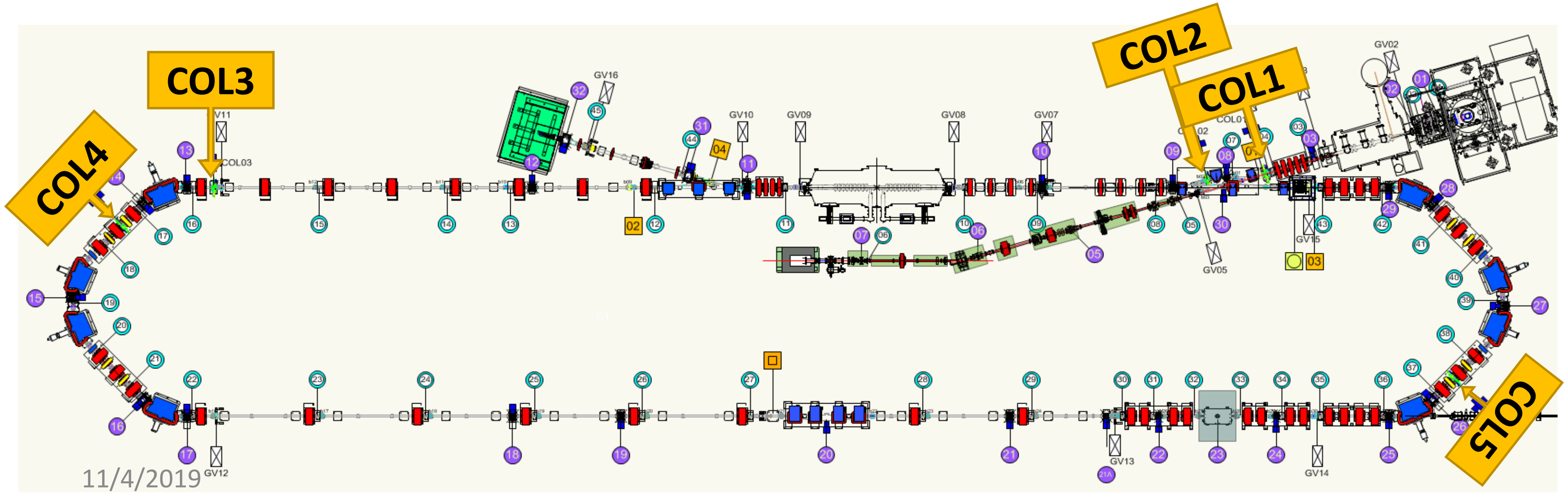
Collimator study

Motivation

- When the high intensity particle beam passes through locations with **narrow apertures** such a collimator’s rods, it leads to the creation of the unwanted **wakefields**.
- The **transverse** wake field may affect the **beam emittance** and the **longitudinal** wake field can cause the **energy loss** and the **energy spread**.







Influence of the transverse kick

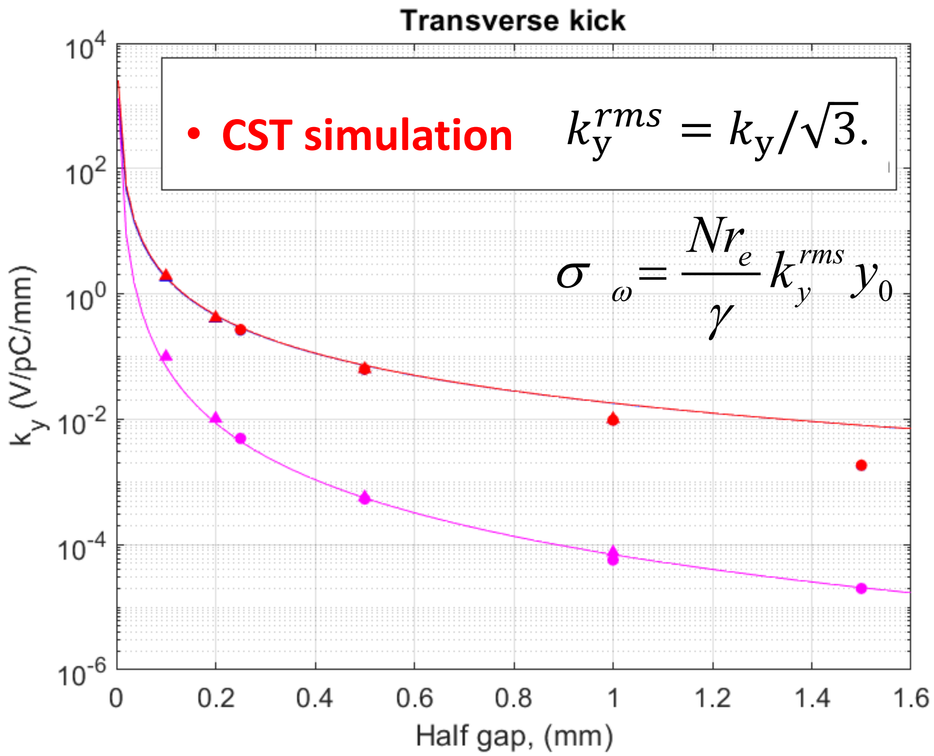
- **Transverse kick** was simulated with CST studio suite. Then it was cross-checked analytically.

- The **transverse emittance growth** with respect to the initial emittance:

$$\frac{\Delta\varepsilon_y}{\varepsilon_{y0}} = \sqrt{1+\frac{\beta_y \sigma_\omega^2}{\varepsilon_{y0}}} - 1,$$

- Expected values of the emittance blow-up due to the **collimator half gap 1.5 mm:**

Collimator	Init. emit. [µm×rad]	Beta func. [m]	**Emit. growth [%]**
COL1 E=2.9 MeV	1.15	27.47	**1.05**
COL2 E=2.9 MeV	1.25	19.23	**0.84**
COL3 E=17.6 MeV	0.954	34.76	**3.82**
COL4 E=17.6 MeV	0.954	6.99	**1.61**
COL5 E=17.6 MeV	0.954	6.99	**1.61**



- For 60pC per bunch and burst mode of the operation the emittance growth effect is expected to be small → **treat longitudinal wake**

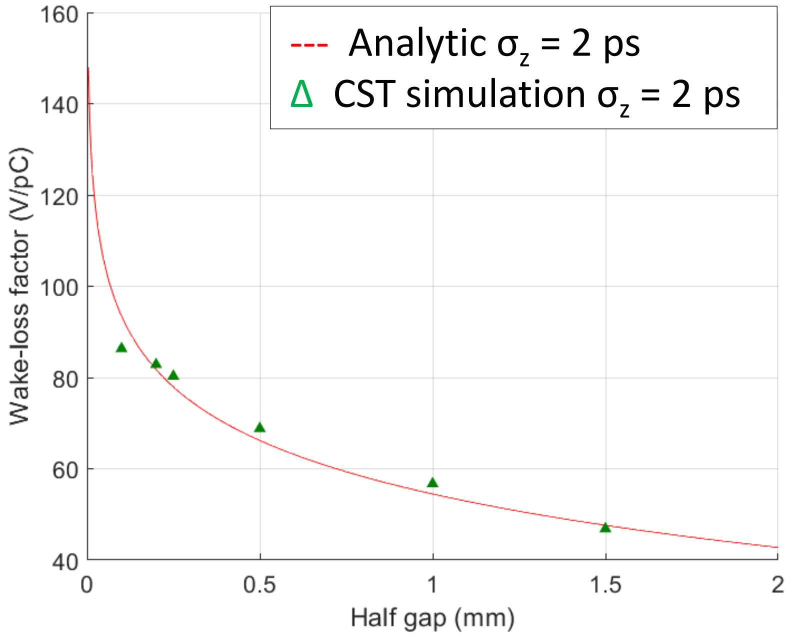
Influence of the longitudinal kick

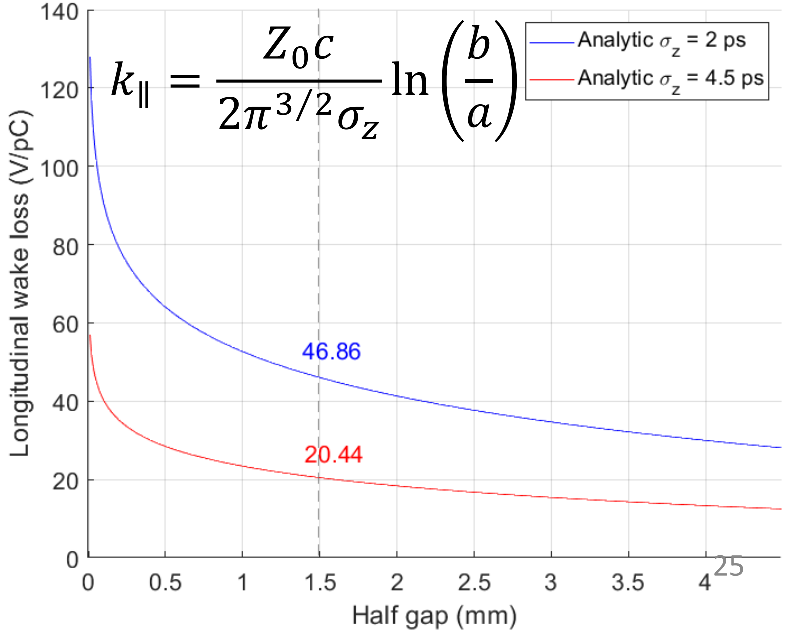
- **Longitudinal wake** was simulated with CST studio suite.
- The **energy loss per whole bunch** at one collimator for the 60 pC / bunch burst mode, bunch length 2 ps, and for the collimator half gap 1.5 mm:

$$\Delta E = k_{\parallel} Q^2 =$$

$$= 46.86 \frac{V}{pC} \times (60pC)^2 = \mathbf{168.7nJ}.$$

- The voltage received by the electrons is ΔV = $k_{||}$ x Q = 2812 V.
- The energy change in one electron is reduced by eΔV = 2812 eV.
- If E = 17.6 MeV, the **change of energy peak** is eΔV / E = 2816 eV / 17.6 MeV = 0.016%





Wake-induced energy spread

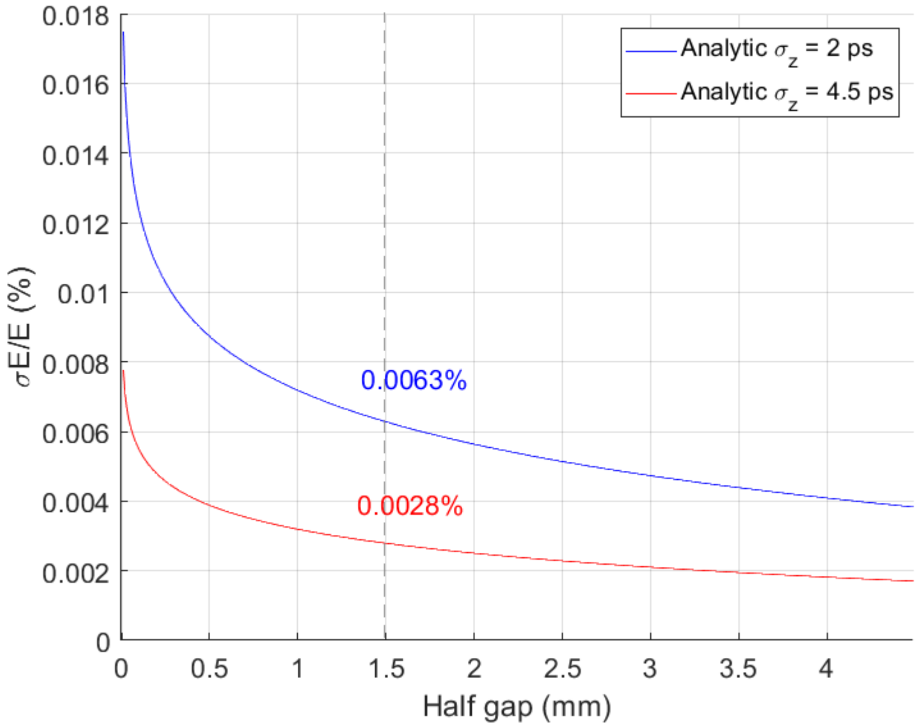
- For Gaussian bunch the energy spread due to one collimator is:

$$\sigma E = 0.4 \times k_{\parallel} \times Q = 1124\text{V}.$$

- Or with respect to the beam energy E = 17.6 MeV:

σE/E = 1124 eV/17.6 MeV = 0.0063%.

→Seems like the resolution of our monitors can not allow to measure it!

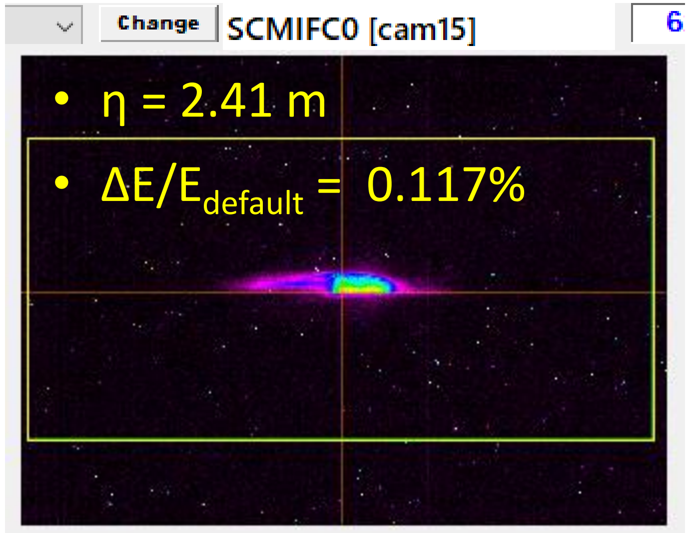


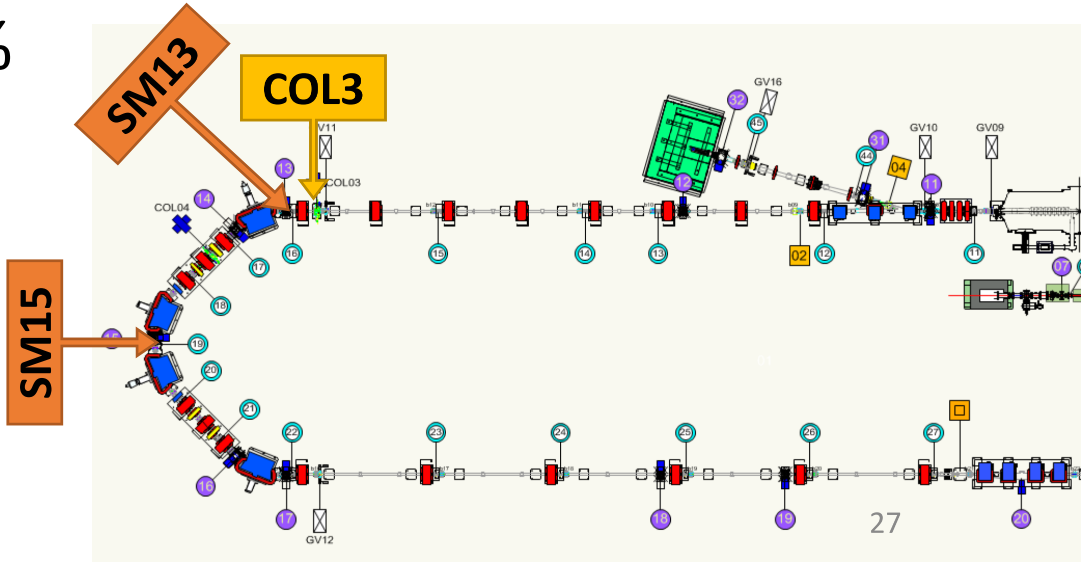
Energy spread measurement on 2019/06/26

1. Start dispersion measurement at CAM15：
   - Calculation with respect to the centroid shift
     - $\Delta E/E = 1\%$
     - $\Delta x = 374$ pixel
     - 1 $\text{pixel}_{CAM15} = 64.4\ \mu m$
   - **η = 2.41 m**

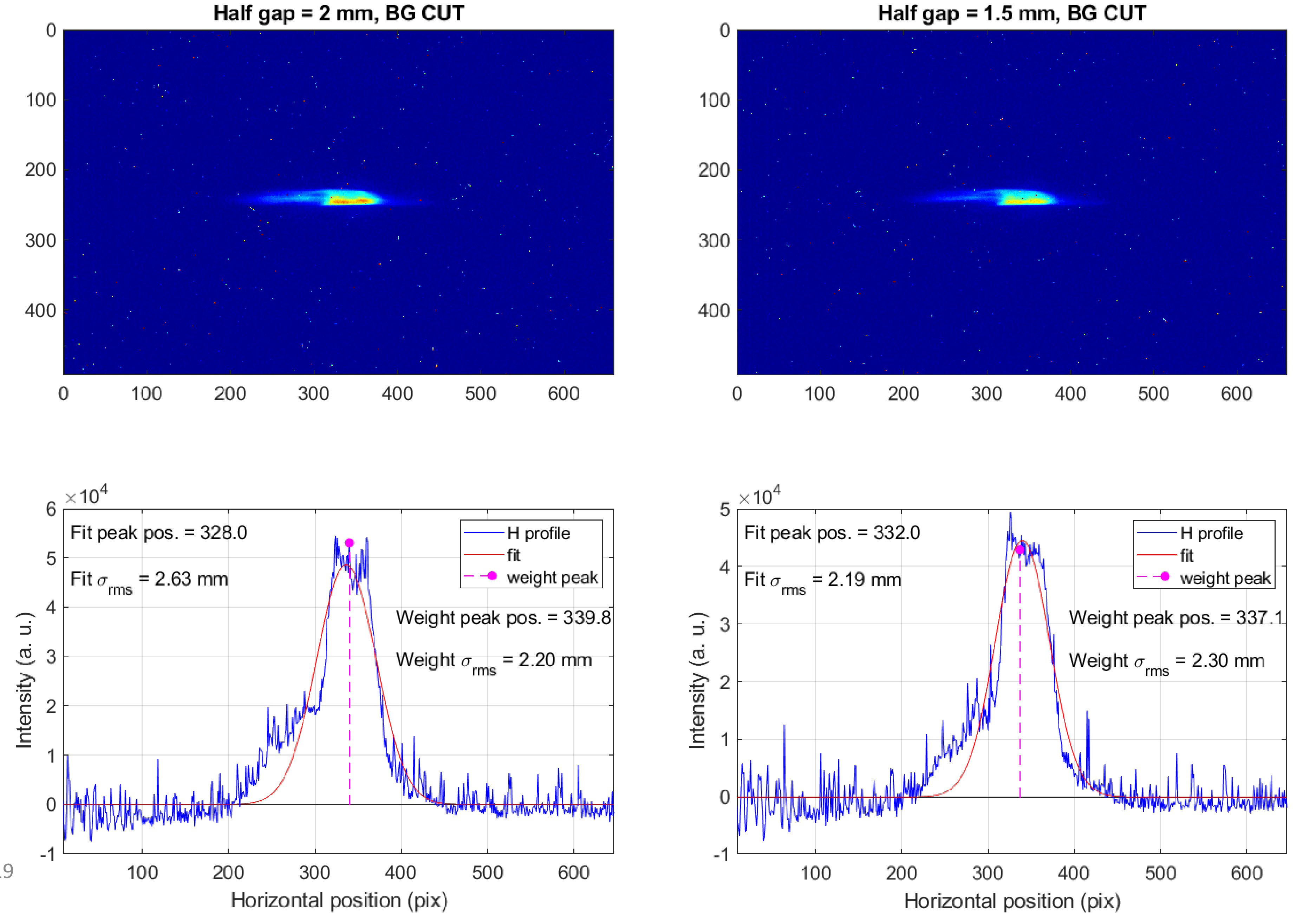
$$\Delta x = \eta \cdot \frac{\Delta E}{E}$$

2. RMS beam size $\sigma_x = 2.82$ mm
3. Default energy spread is $\sigma_x/\eta = 0.117\%$





Examples of measured profiles at SM#15



Data analysis

- **Weight analysis**
  - Peak position is:

$$x_c = \frac{1}{N}\sum_{i=1}^{659} x_i N_i,$$

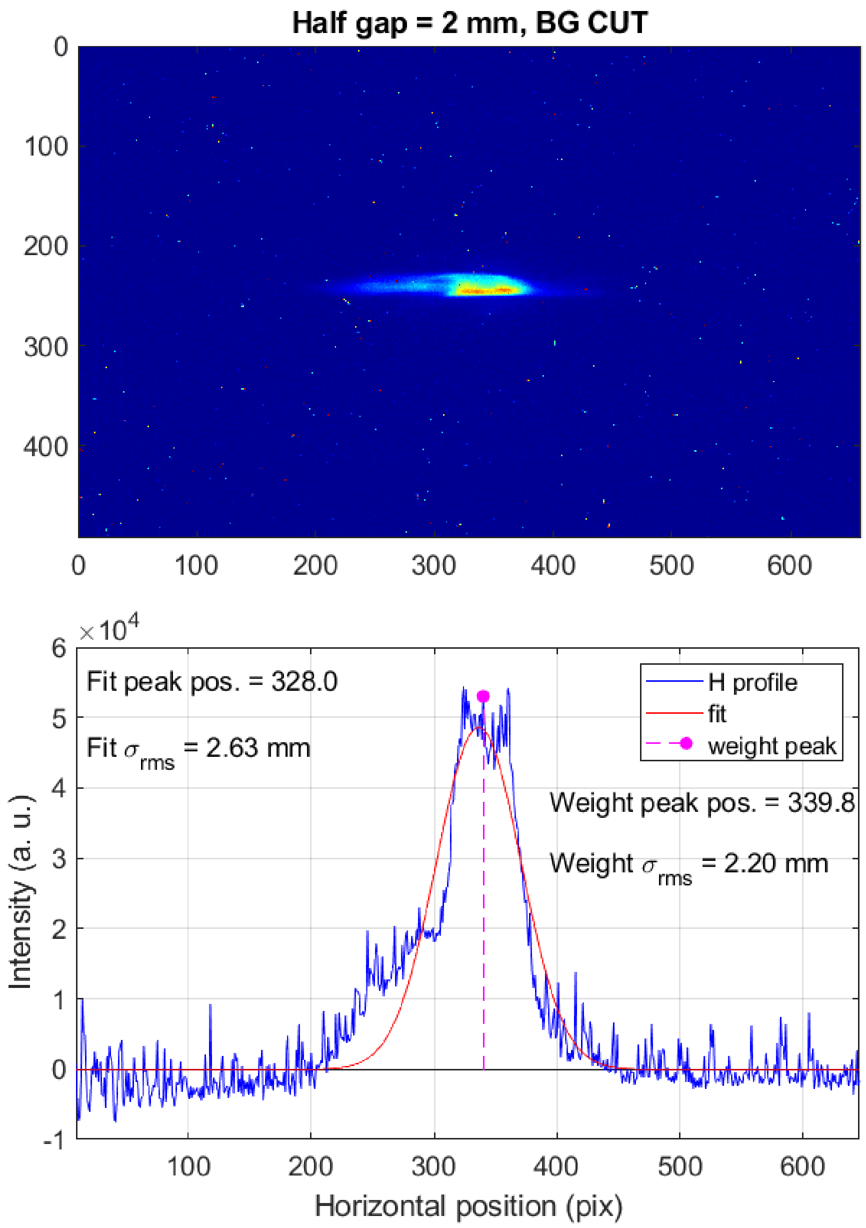
where

$$N = \sum_{i=1}^{659} N_i.$$

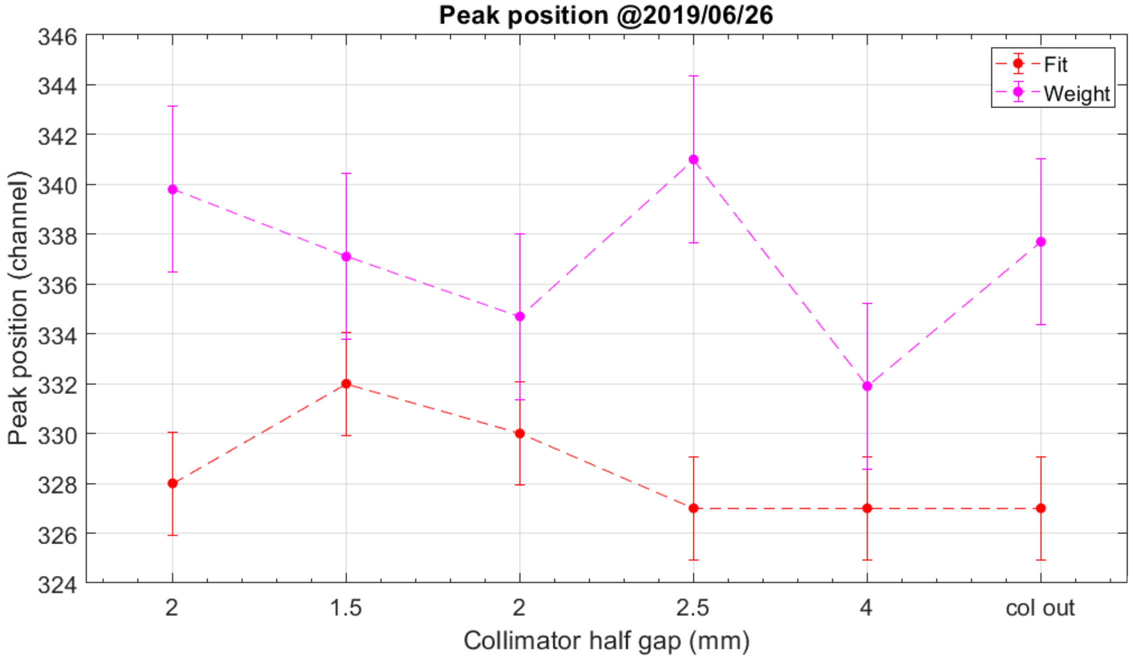
  - RMS sigma is:

$$\sigma_x = \sqrt{\frac{1}{N}\sum_{i=1}^{659} N_i \left(x_i - x_c\right)^2}.$$

* 1 pixel_{CAM15} = 62.7 μm

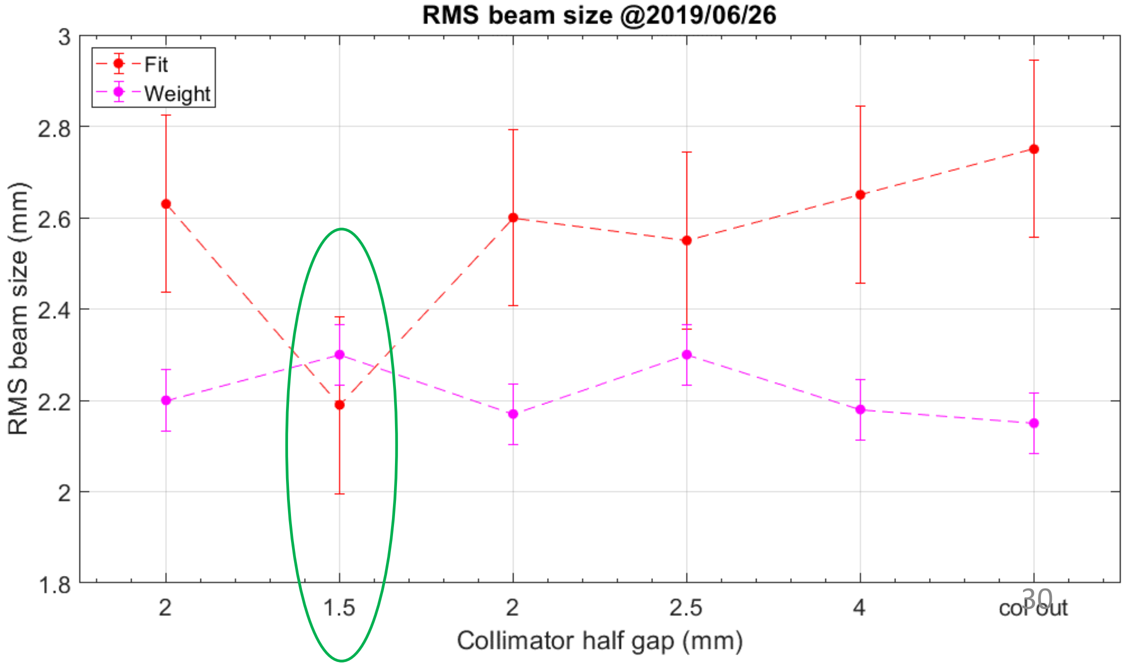


2019/06/26 measurement results

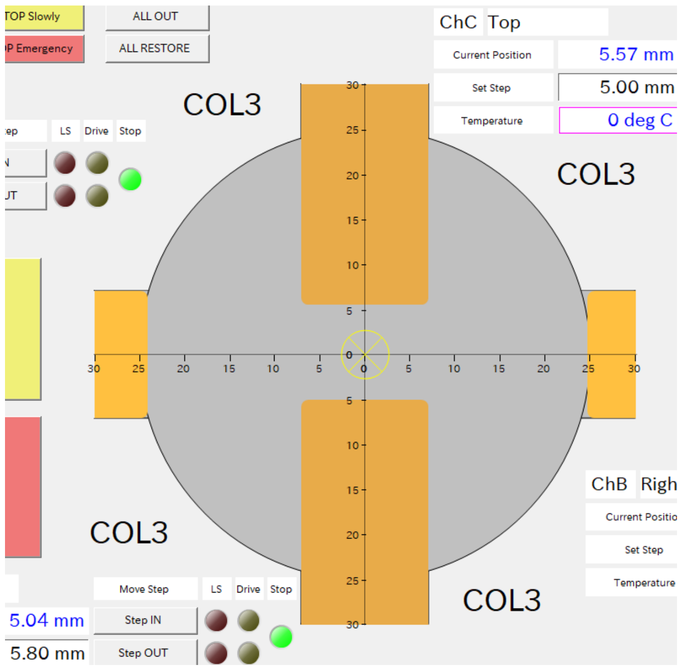


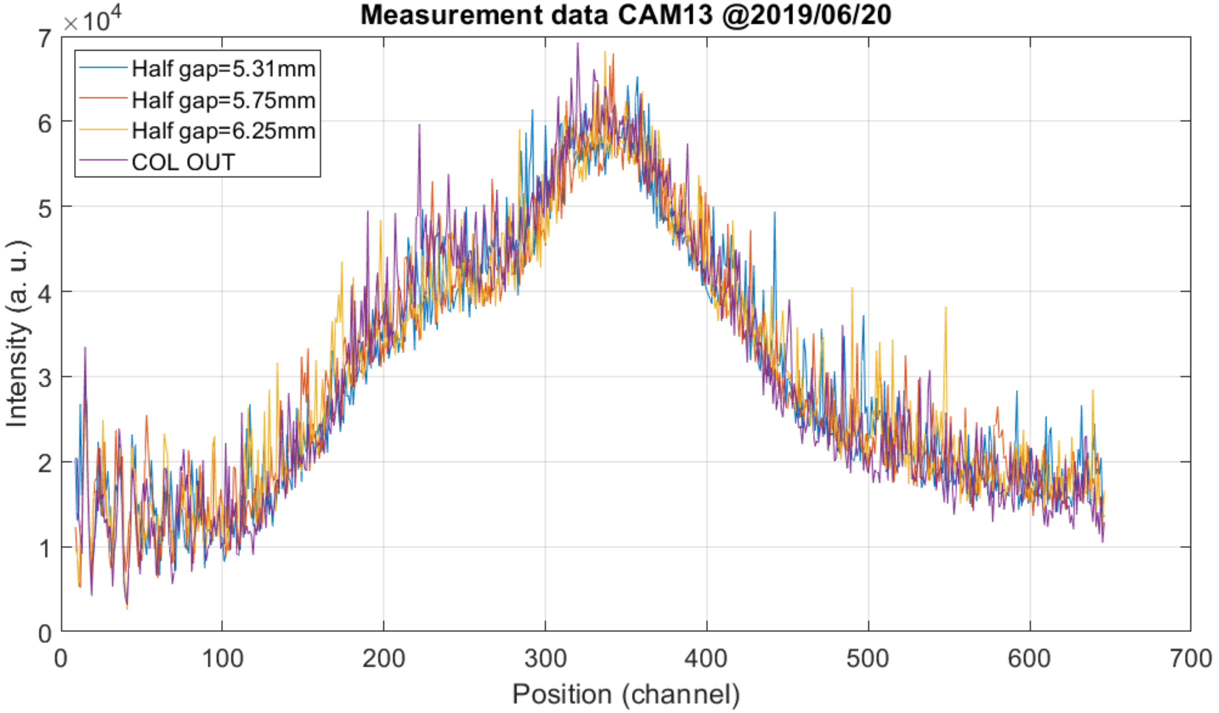
- The measurement is consistent with the simulation(calculation).

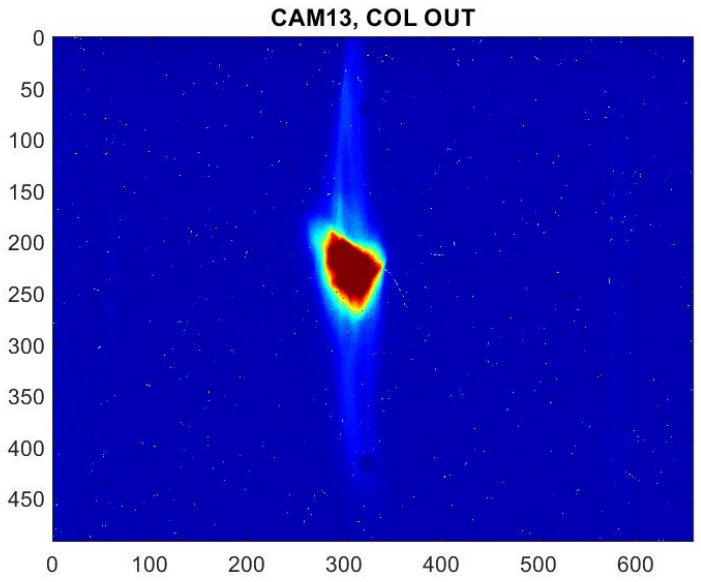
- Drop at collimator half gap 1.5 mm demonstrates that the beam core was damaged by the collimator's rod.

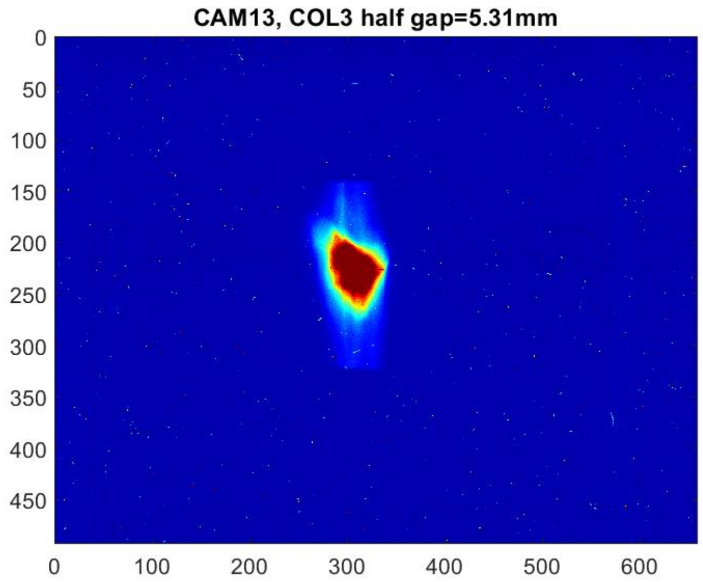


Beam halo influence

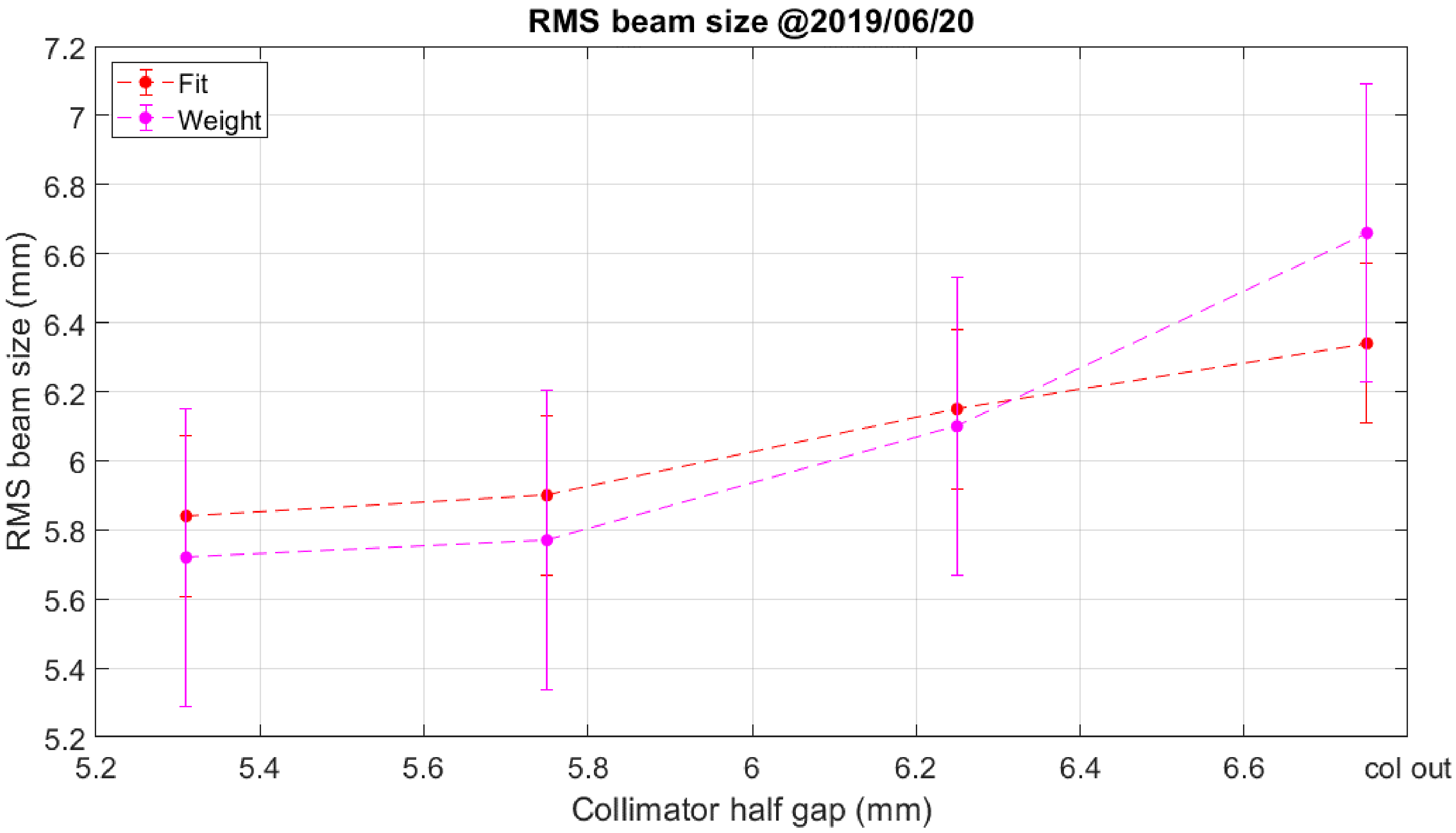


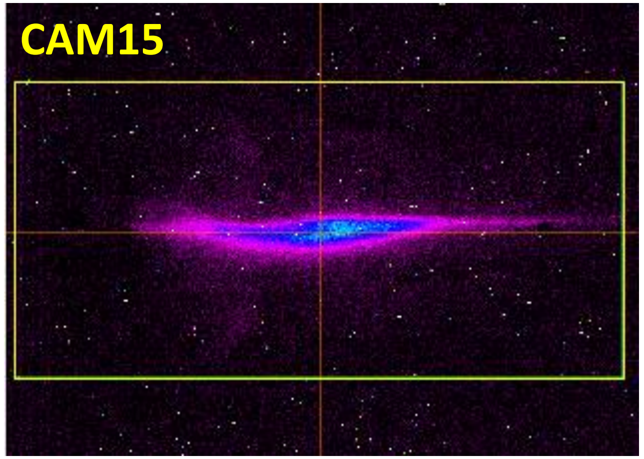






Results for the RMS beam size from 2019/06/20





- If we cut the halo with a collimator, the screen looks clean and horizontal beam size becomes smaller → coupling?!
- Energy spread becomes smaller.

Lessons learned from the collimator study:

"You cannot collimate them, you can only make them angry." ©

1. With the current beam parameters:
   1. Qtot = 60 pC burst mode
   2. Bunch length = 4.5 ps
   3. Energy spread ~ 0.1%
   4. Beam energy = 17.5 MeV (E_{inj} = 4 MeV)

   Even if one closed the collimator's **half gap** up to **2 mm**, it will not affect the **emittance** and **energy spread** so much.
2. It was confirmed by measurement that the **energy spread was reduced** when the upper and lower halos were removed with a collimator.
3. For the CW mode operation the power loss is:
   - $f_{rep} = 1.3\ GHz$, power loss → **219.3 W**

   Considering FEL mode, the repetition rate is $f_{rep} = 81.25\ MHz$, and the power loss is **13.7 W**

Conclusion & outlook

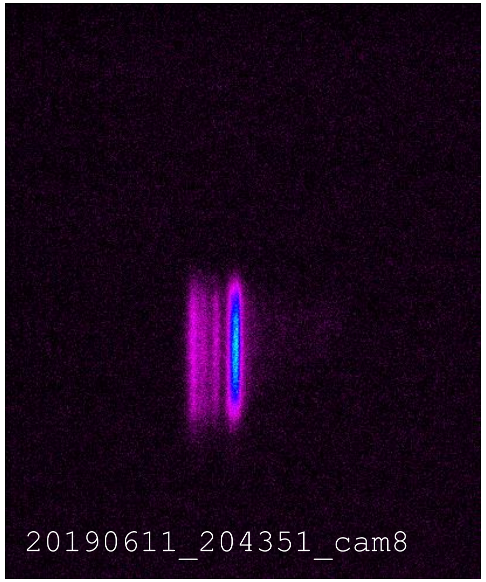
- Halo related discussion does not seem to be a trend nowadays.
- Nevertheless, the problem of the beam halo addresses to a numerous issues at all stages from the design process to the operation and beam tuning of a machine. These issues are:
    - The beam losses, activation of beam line components, machine protection;
    - Space charge effect, emittance growth, coupling;
    - Machine imperfections, misalignments, improper timing;
    - Etc.
- Therefore one important thing is to keep the mechanisms of beam halo formation in mind at every stage of the accelerator R&D.
- Another thing is that there are a lot of correlated processes in beam dynamics. One can start with a collimator wake and concluded with a halo-related energy spread and so on.

➢ At cERL like at any other ERL facility, we have to consider the halo seriously for the **beam current increase** (up to 10 mA at cERL).

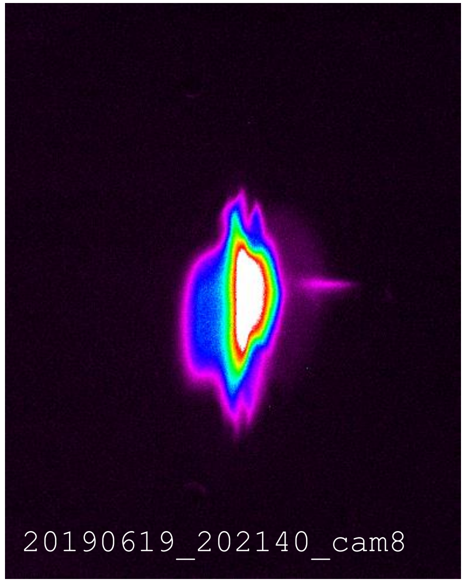
Postscript

- Halo (from Greek ἅλως) means **circle, disk**. When dealing with high charged electron bunches, this definition becomes incorrect. See real examples above:

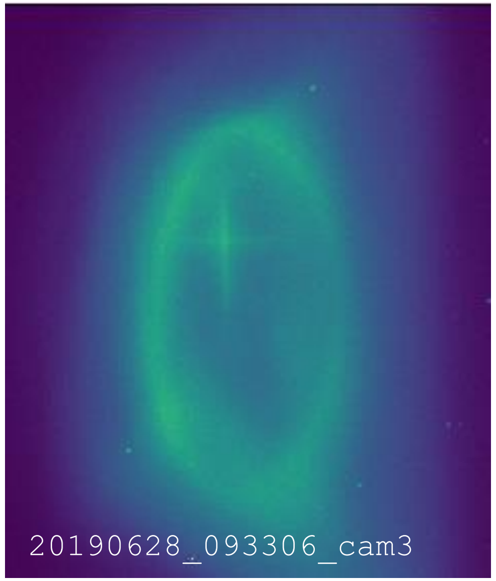
Three ghosts



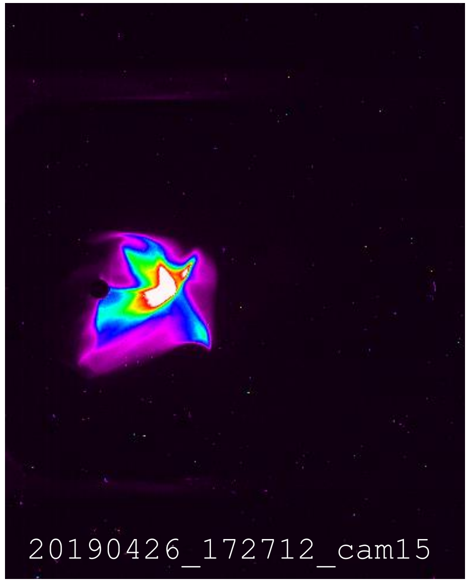
UFO on its side



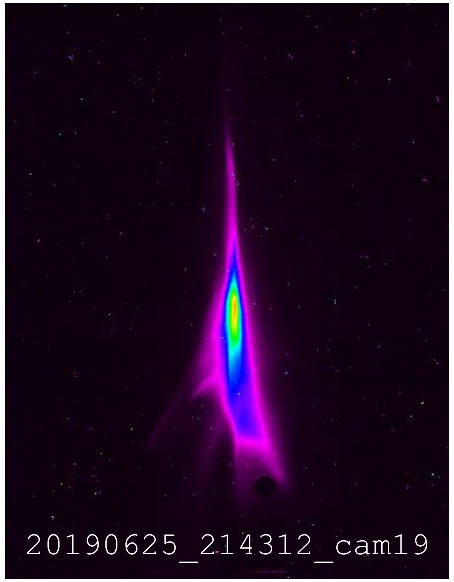
Star in egg



Flying angel



Sward fish



Courtesy of T. Obina, July 2019

Thanks for your attention!