コンパクトERLにおけるビームハローについて

cERLミニワークショップ

2016年5月31日（火）

10:55-11:15
4号館2階輪講室1・2

田中　オリガ

Contents

Introduction

Beam halo as a source of the beam loss

What to explore?

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*

- The beam halo is one of the main factors of the beam loss in cERL
- Therefore, experimental measurements and analytical evaluation of the halo distribution are very important to understand the way to minimize the number of halo particles and to reduce the beam losses

Motivation

The main goal is to understand the beam halo formation processes and give the realistic description of the corresponding beam losses in cERL

What is carried out?

- Beam halo observation:
  - Multi-profile beam halo measurement with CCD cameras at different locations of the beam line without and with collimators
  - HDR (High Dynamic Range) imaging method for data processing
- Beam halo simulation:
  - Probable beam halo reasons, obtained from the measurement results were included into the beam halo simulation to see its influence on the beam halo formation

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

Introduction

Reasons of the beam halo

- **Beam dynamics**:
  - Space charge
  - Intrabeam scattering*
  - Touschek scattering*
  - Kicks from steering coils***
- **Errors**:
  - Beam line elements misalignment**,***
  - Improper timing and synchronism
  - Shift in phase**
- **Laser system:**
  - Ghost pulses
  - Scattered light from lens defects
  - Ghost image from mirror surface
  - Diffraction at laser pinhole
- **Electron gun:**
  - Cathode temporal response**,***
  - Scattered light on cathode
  - Cathode damage
  - Field emission from the gun
- **Vacuum system:**
  - Residual gas scattering*
  - Ion trapping
- **SRF cavities**:
  - Dark current*
  - Kicks from input / HOM couplers
- **Beam monitor**:
  - CCD linearity
  - CCD saturation
  - YAG screen saturation

* O. Tanaka et al., “Beam Losses Study for KEK cERL”, MOPRO109, IPAC’14, Dresden, Germany (2014)
** O. Tanaka et al., “Simulation study of beam halo and loss for KEK compact ERL”, TUPWA068, IPAC’15, Richmond, USA (2015)
*** O. Tanaka et al., “Simulation study of the beam halo formation for beam loss estimation and mitigation at KEK compact ERL”, TUPOW039, IPAC’16, Busan, South Korea (2016)

Introduction

cERL operation conditions and beam halo reasons

- **Beam dynamics**:
  - **Space charge**
  - **Intrabeam scattering**
  - **Touschek scattering**
  - **Kicks from steering coils**
- **Errors**:
  - **Beam line elements misalignment**
  - **Improper timing and synchronism**
  - **Shift in phase**
- **Laser system:**
  - **Ghost pulses**
  - **Scattered light from lens defects**
  - **Ghost image from mirror surface**
  - **Diffraction at laser pinhole**
- **Electron gun:**
  - **Cathode temporal response**
  - **Scattered light on cathode**
  - **Cathode damage**
  - **Field emission from the gun**
- **Vacuum system:**
  - **Residual gas scattering**
  - **Ion trapping**
- **SRF cavities**:
  - **Dark current**
  - **Kicks from input / HOM couplers**
- **Beam monitor**:
  - **CCD linearity**
  - **CCD saturation**
  - **YAG screen saturation**

Red are taken into account
Green are negligible
Blue could present but not taken into account

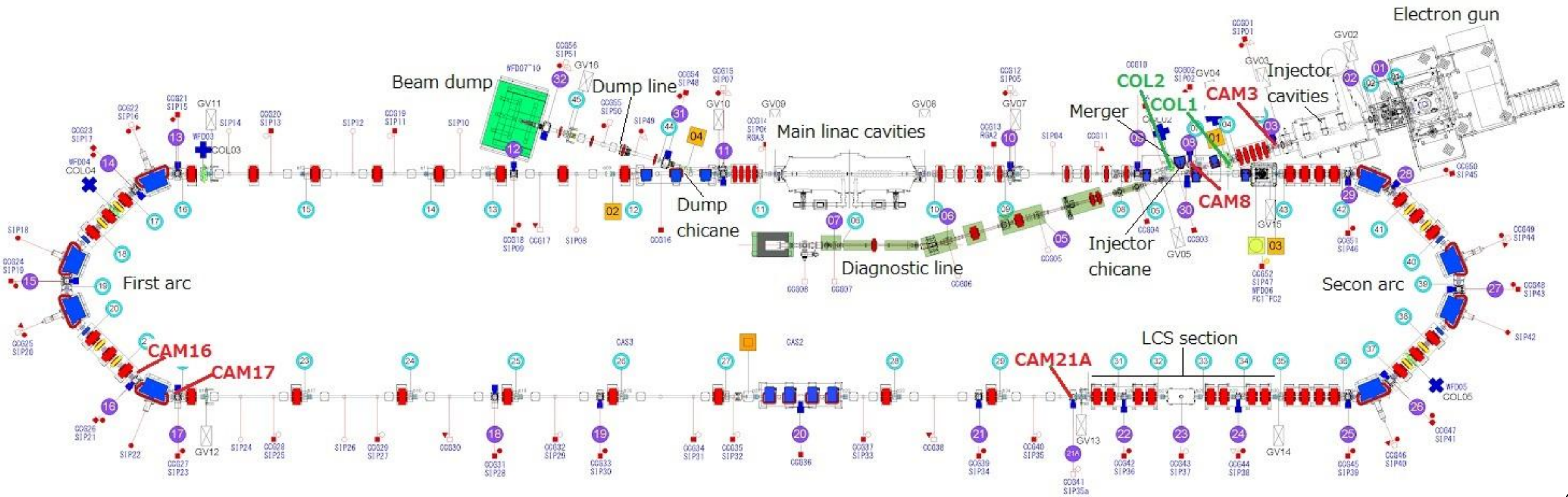
Beam halo measurement

Settings

To understand the beam halo formation mechanisms several CCD cameras at different locations of the beam line were chosen

Burst mode (1 μs width)	
Macro pulse duration	1 μs
Macro pulse frequency	5 Hz
Integration time	10 μs
Bunch charge	0.2-0.3 pC / bunch
Average current	1.5 nA
Peak current	300 μA
Repetition rate	1.3 GHz
Beam energy	2.9 - 20 MeV

Long pulse mode (1.5 ms width)	
Macro pulse duration	1.5 ms
Macro pulse frequency	0.6 Hz
Integration time	2 ms
Bunch charge	6 nC / pulse
Average current	3 nA
Peak current	15 nA
Repetition rate	1.3 GHz
Beam energy	20 MeV

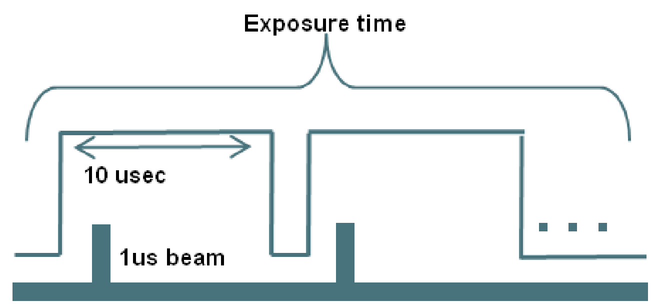


Beam halo measurement

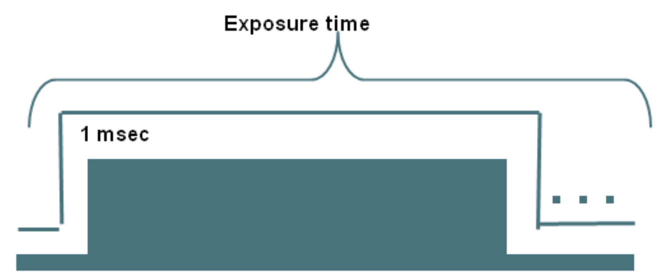
Workflow

1. Insert a screen.
2. Check whatever the 1 μs (1-10 ms[1]) beam is visible while setting the integration time of the camera to 10 μs (1-10 ms[1]), which is the least value. Adjust the trigger delay if needed. It allows capture only one macro pulse during one camera shutter pulse. We set the gain to maximum to see the beam halo better.
3. Capture the beam halo profiles during 10 s automatically with 5 Hz (0.1 Hz[1]) macro pulse frequency. Thus, the data obtained contain 50 profiles (1 profile[1]).
4. Insert the collimators (see Fig. 1) to check the effectiveness of the collimation system against the beam halo. It also allows to estimate the beam loss rate using loss monitors.
5. Perform the screen capture described in 3 above once again.

Burst mode



Long pulse mode



[1] For long pulse mode.

Data processing

Simple approach

- To obtain for the total beam halo image, all the profiles of one capture were summarized
- The sharp saturated peak of the beam core is cut on the acceptable level to recognize the beam halo easily

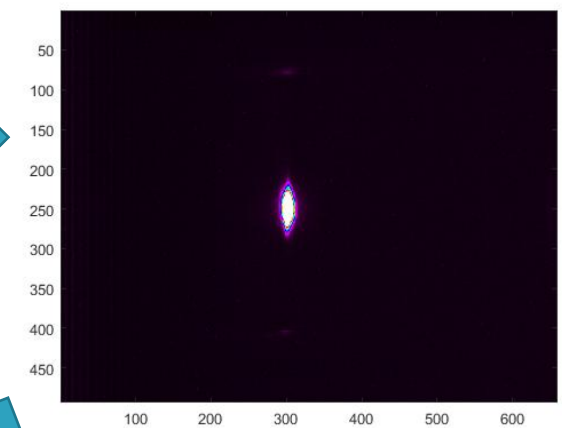
run1_cam1_gain22.dat

	A	B	C	D				
	VarName1	VarName2	VarName3	VarName4				
	NUMBER	TEXT	TEXT	NUMBER	NUMBER	NUMBER	NUMBER	NUMBER
1	CERL:MON:SC:rotate:cam1	2016-03-02	15:02:31.579259	324887	0	0	0	0
2	CERL:MON:SC:rotate:cam1	2016-03-02	15:02:31.778682	324887	0	0	0	0
3	CERL:MON:SC:rotate:cam1	2016-03-02	15:02:31.977953	324887	0	0	0	0
4	CERL:MON:SC:rotate:cam1	2016-03-02	15:02:32.178291	324887	0	0	0	0
5	CERL:MON:SC:rotate:cam1	2016-03-02	15:02:32.378121	324887	0	0	0	0
6	CERL:MON:SC:rotate:cam1	2016-03-02	15:02:32.578042	324887	0	0	0	0
7	CERL:MON:SC:rotate:cam1	2016-03-02	15:02:32.778586	324887	0	0	0	0
8	CERL:MON:SC:rotate:cam1	2016-03-02	15:02:32.978019	324887	0	0	0	0
9	CERL:MON:SC:rotate:cam1	2016-03-02	15:02:33.179298	324887	0	0	0	0
10	CERL:MON:SC:rotate:cam1	2016-03-02	15:02:33.377916	324887	0	0	0	0
11	CERL:MON:SC:rotate:cam1	2016-03-02	15:02:33.578197	324887	0	0	0	0
12	CERL:MON:SC:rotate:cam1	2016-03-02	15:02:33.779428	324887	0	0	0	0
13	CERL:MON:SC:rotate:cam1	2016-03-02	15:02:33.980006	324887	0	0	0	0
14	CERL:MON:SC:rotate:cam1	2016-03-02	15:02:34.177959	324887	0	0	0	0
15	CERL:MON:SC:rotate:cam1	2016-03-02	15:02:34.378329	324887	0	0	0	0
16	CERL:MON:SC:rotate:cam1	2016-03-02	15:02:34.578136	324887		0	0	0

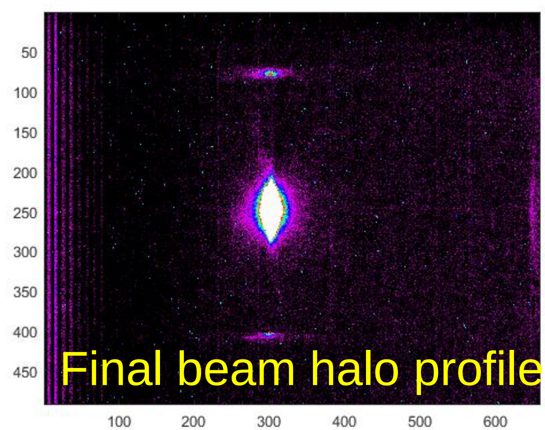
324887 columns

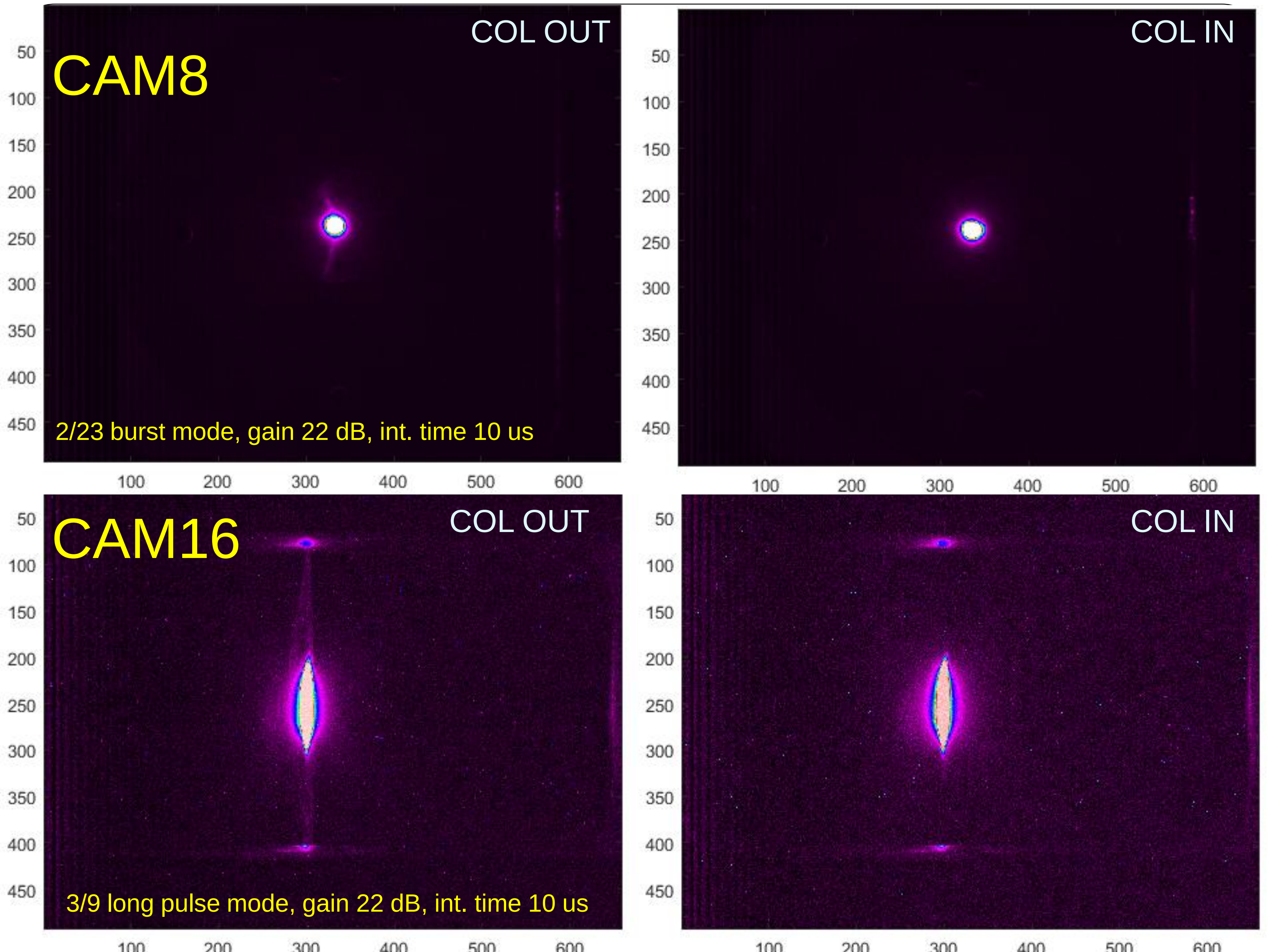
50 strokes

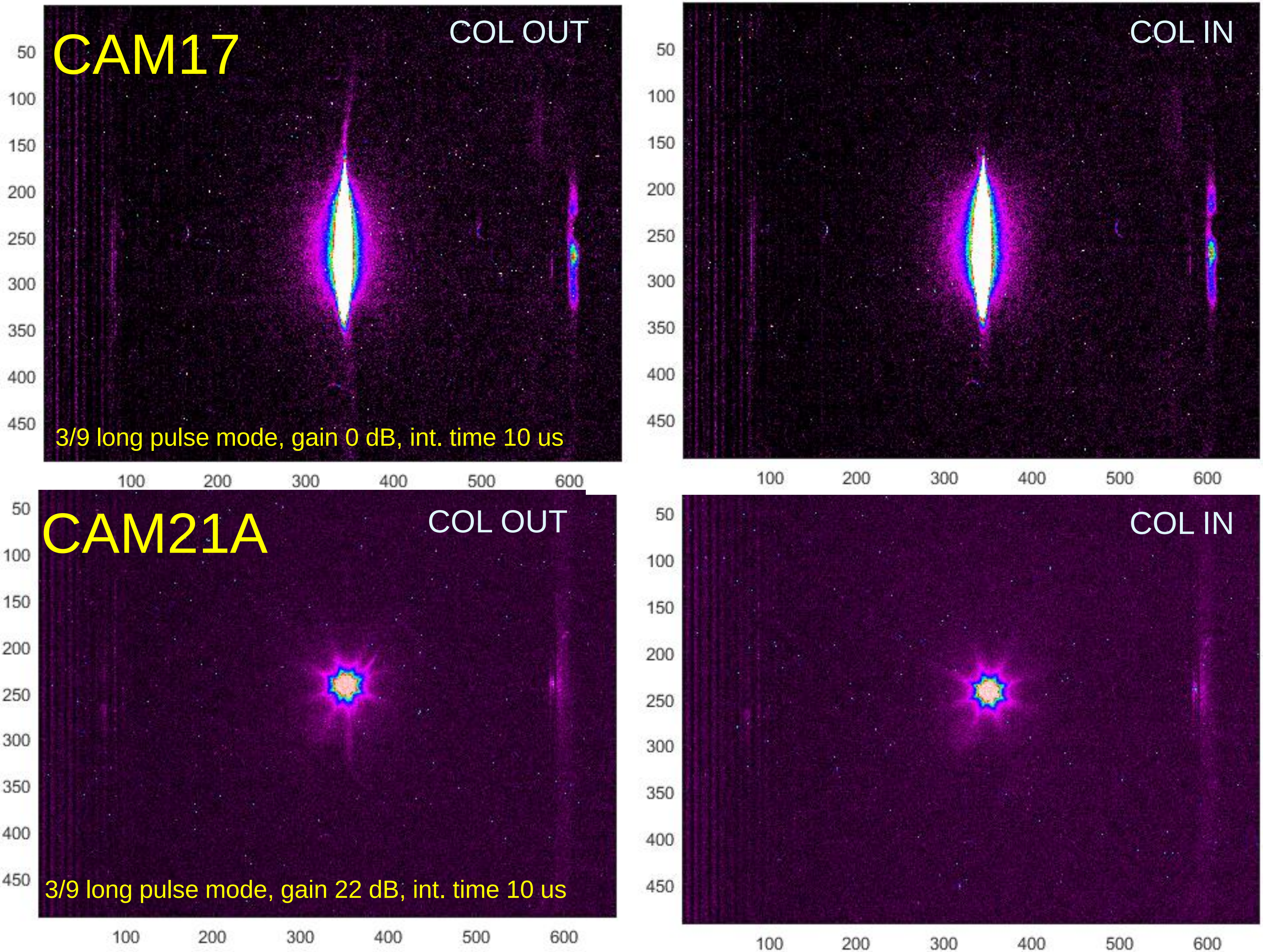
1. Sum all strokes
2. Reshape summarized stroke to 493x659 matrix (screen size in pixels)



Cut the peak



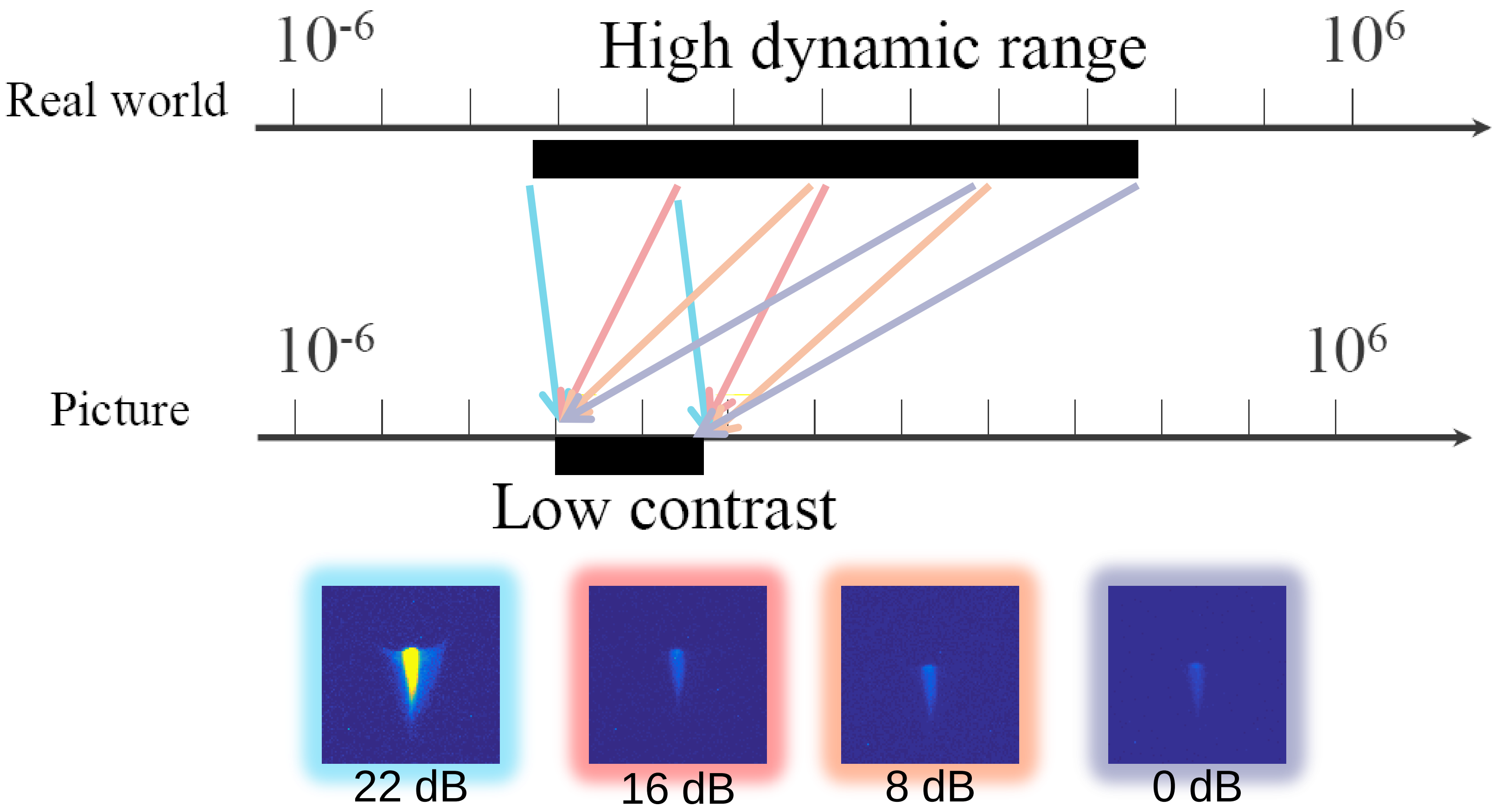

CAM8
COL OUT
COL IN
2/23 burst mode, gain 22 dB, int. time 10 us
CAM16
COL OUT
COL IN
3/9 long pulse mode, gain 22 dB, int. time 10 us


CAM17
COL OUT
COL IN
3/9 long pulse mode, gain 0 dB, int. time 10 us
CAM21A
COL OUT
COL IN
3/9 long pulse mode, gain 22 dB, int. time 10 us

Data processing

HDR imaging approach

Idea: (from the field of professional photography) to combine pixels from different exposures directly into a final composite*

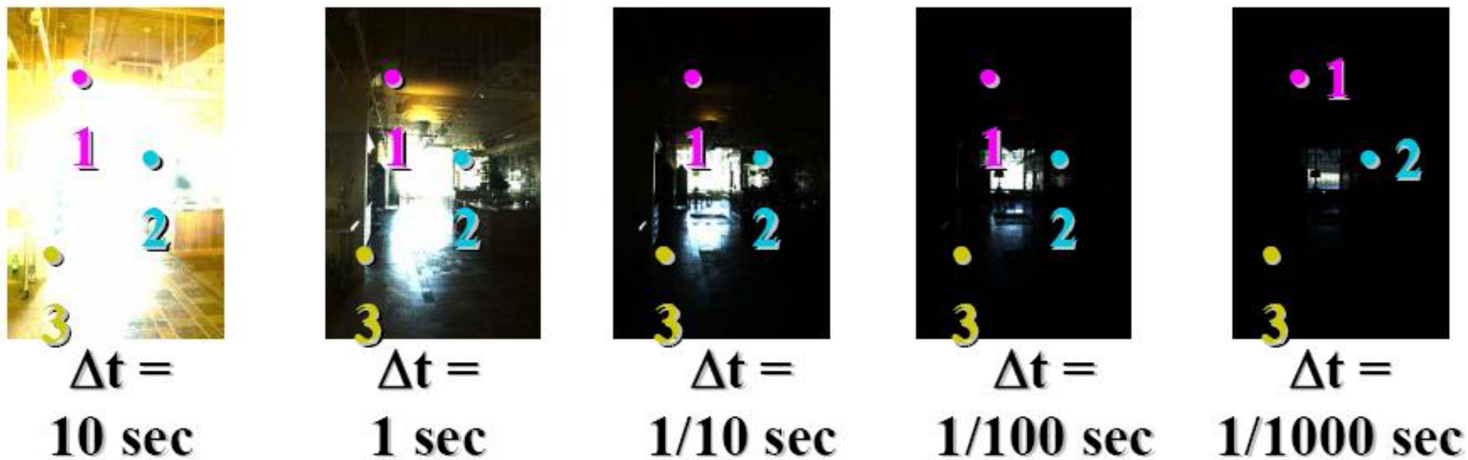


* P. E. Debevec and J. Malik, “Recovering high dynamic range radiance maps from photographs ”. In SIGGRAPH, pages 369-378, (1997).

Data processing

HDR imaging algorithm*

Image series



$$\text{Pixel Value } Z = f(\text{Exposure})$$

$$\text{Exposure} = \text{Radiance} \times \Delta t$$

$$\log \text{Exposure} = \log \text{Radiance} + \log \Delta t$$

* B. Freeman, “HDR imaging and the Bilateral Filter ”.

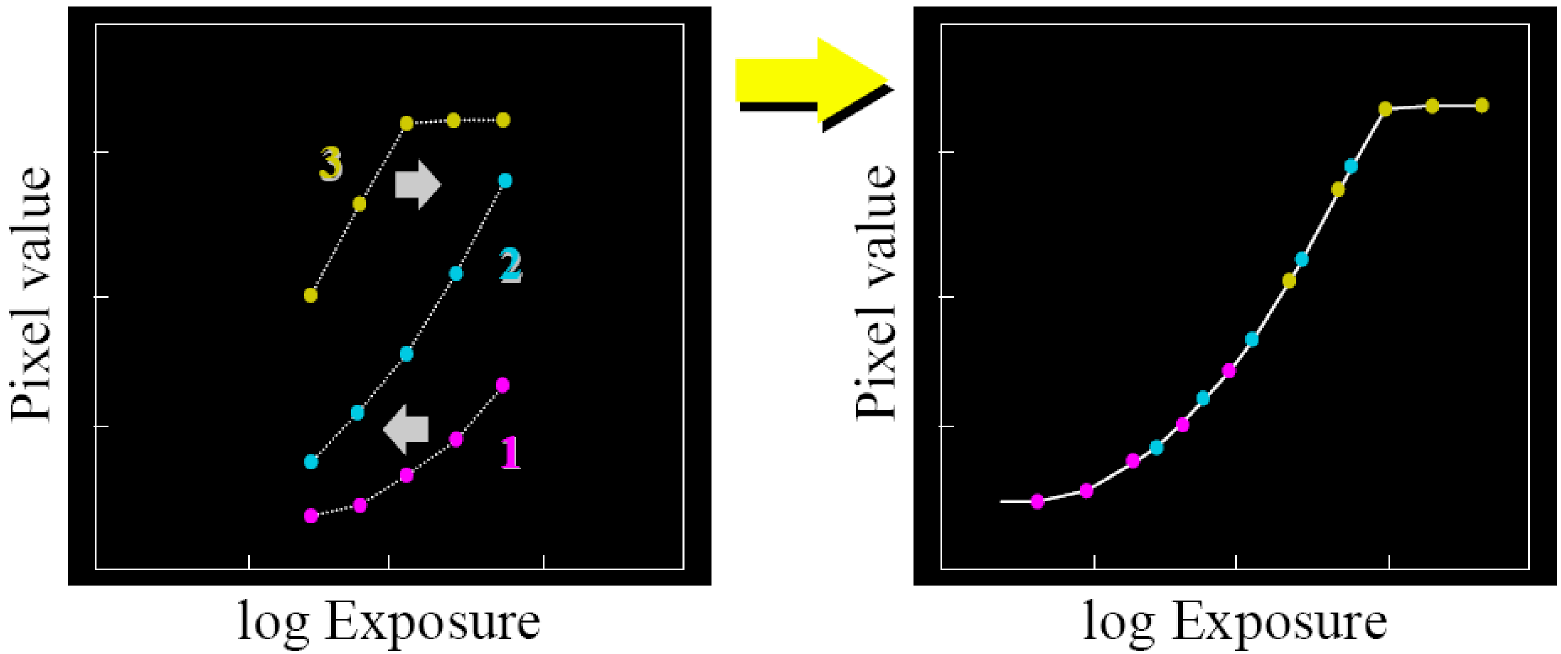
Data processing

Camera response curve*

- **Exposure is unknown, fit to find a smooth curve**

Assuming unit radiance for each pixel

After adjusting radiances to obtain a smooth response



* B. Freeman, “HDR imaging and the Bilateral Filter ”.

Data processing

Mathematical formulation*

- **Let *g(z)* be the *discrete* inverse response function**
- **For each pixel site *i* in each image *j*, want:**

$$\log Radiance_i + \log \Delta t_j = g(Z_{ij})$$

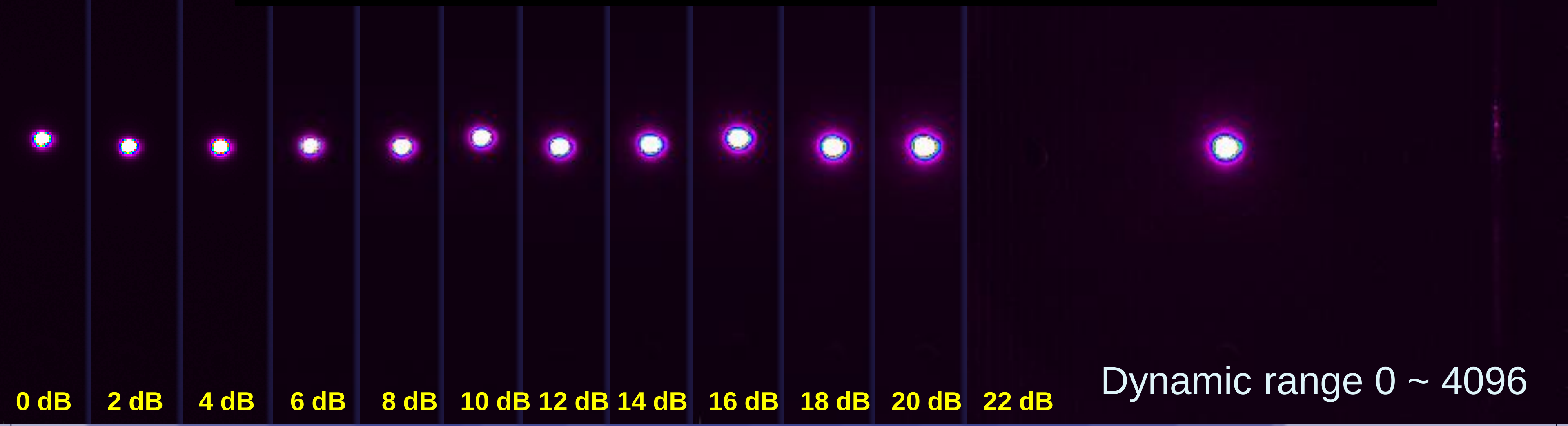
- **Solve the overdetermined linear system:**

$$\sum_{i=1}^{N}\sum_{j=1}^{P}\left[\log Radiance_i + \log \Delta t_j - g(Z_{ij})\right]^2 + \lambda \sum_{z=Z_{min}}^{Z_{max}} g''(z)^2$$

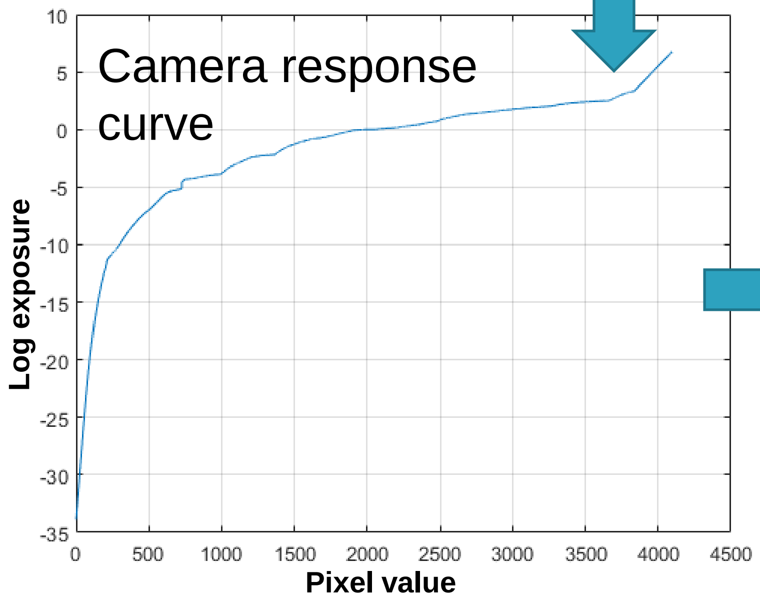
fitting term — smoothness term

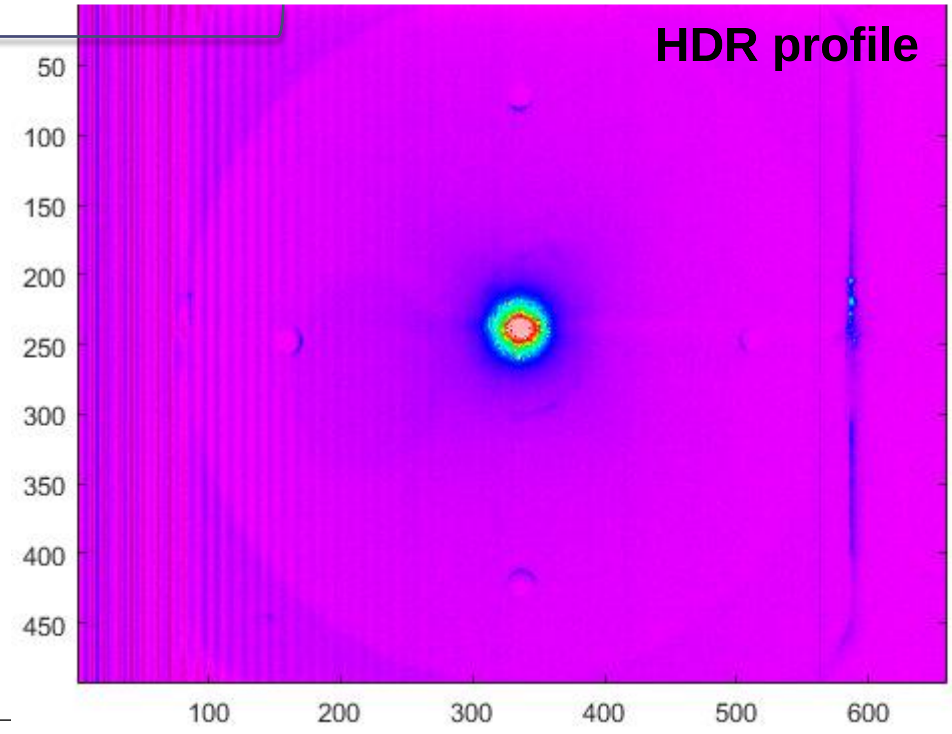
* B. Freeman, "HDR imaging and the Bilateral Filter ".

Example: 2/23@CAM8, COL in



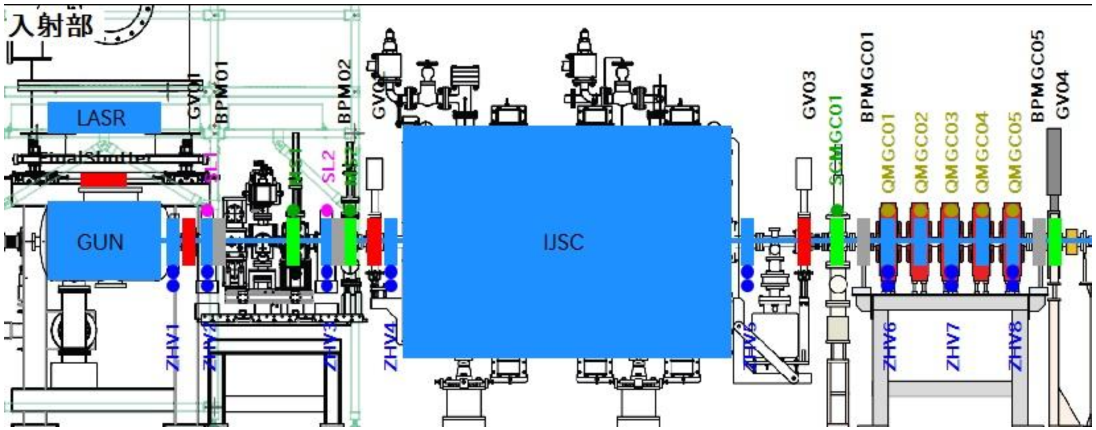
Set of 12 images with different exposures





Beam halo simulation

Kicks from steering coils

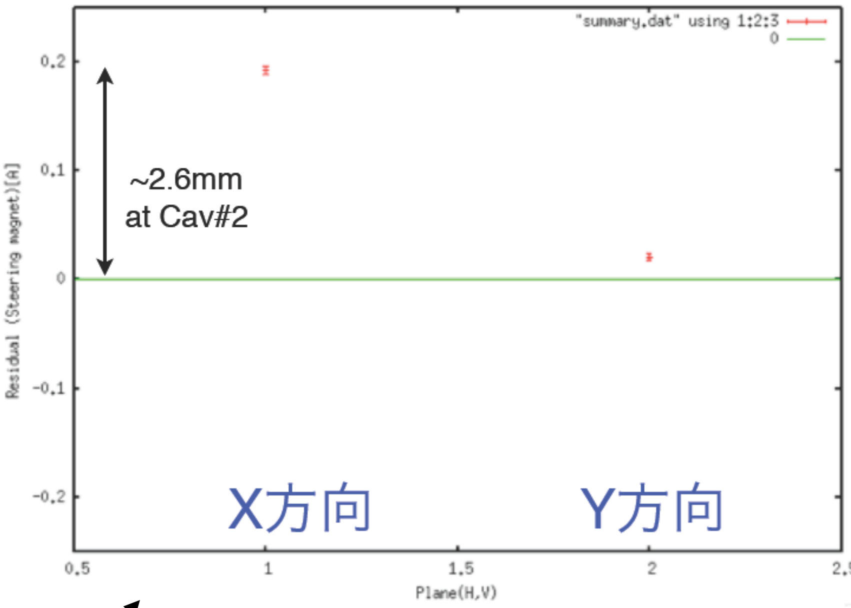


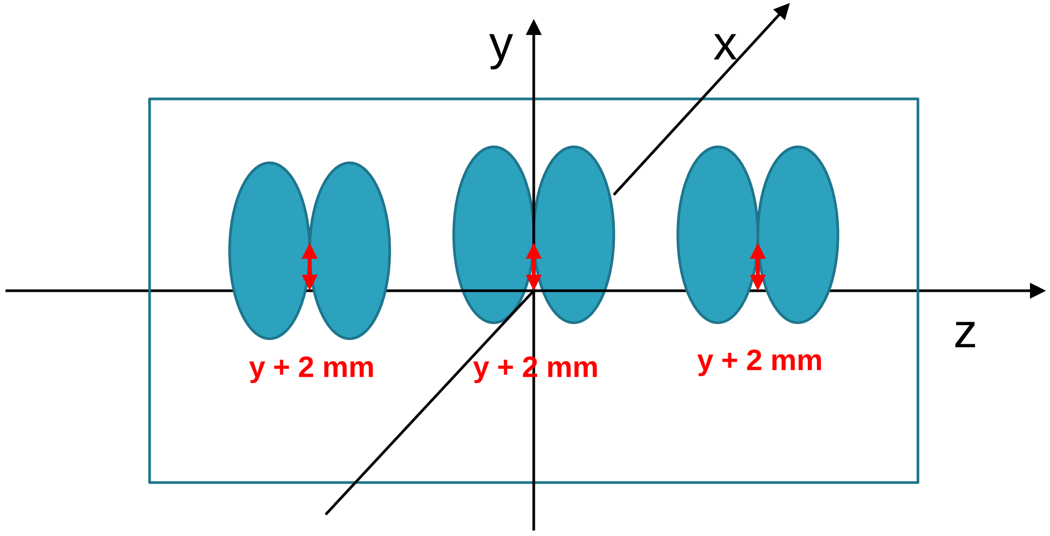
Steering name	Current [A]	ItoBL [T*m/A]	BL [T*m]	Z position [m]	Length [m]	Gap [m]	Width [m]
ZV01	-0.9	3.22710E-05	-2.904E-05	0.233000	0.059	0.133	0.0955
ZV2	-0.18	6.07777E-05	-1.094E-05	0.448791	0.059	0.132	0.0660
ZV3	0.0	6.07777E-05	0.0	1.219791	0.059	0.132	0.0660
ZV04	-3.18	3.57141E-05	-11.36E-05	1.518800	0.059	0.133	0.0955
ZV05	0.25	7.47835E-05	1.8696E-05	4.081800	0.079	0.143	0.0955
ZV06	1.7	1.73268E-04	29.456E-05	4.854474	0.100	0.060	0.1400
ZV07	0.0	1.73268E-04	0.0	5.254474	0.100	0.060	0.1400
ZV08	-0.58	1.73268E-04	-10.05E-05	5.654474	0.100	0.060	0.1400

Beam halo simulation

Beam line elements misalignment

- The non-linearity of the positions of the three injector cavities was evaluated by using the HOM coupler signals*
- Cell#2 has the 2.6 mm offset in x direction of the cavity transverse plane
- To reproduce the vertical halo as at measured profiles, a vertical misalignment of 2 mm of all 3 cells was also added into simulation



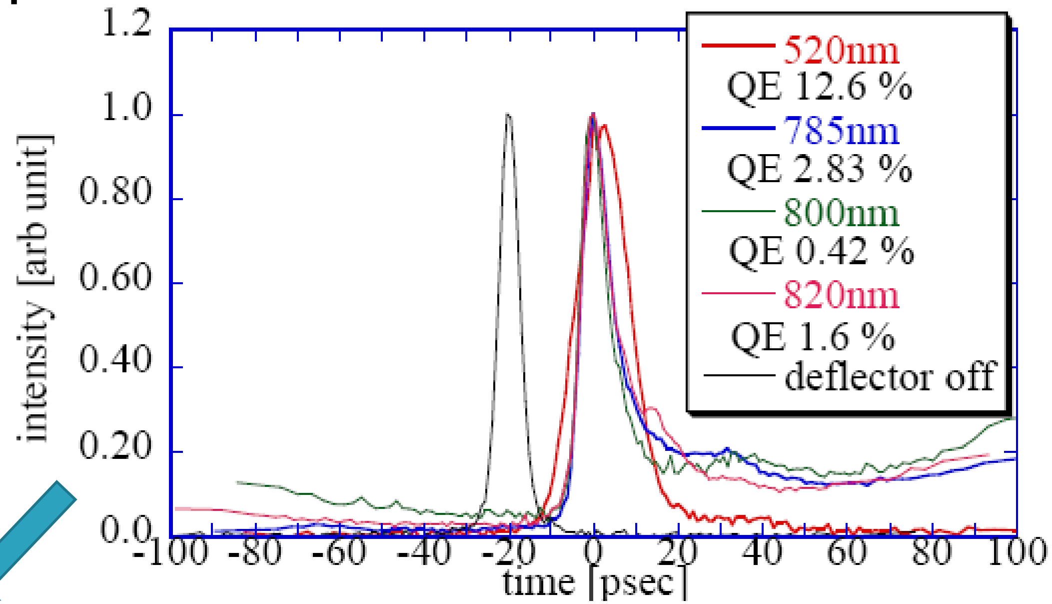


* Y. Honda, "Injector cavity HOM-BPM 3 cells nonlinearity", (in Japanese), unpublished.

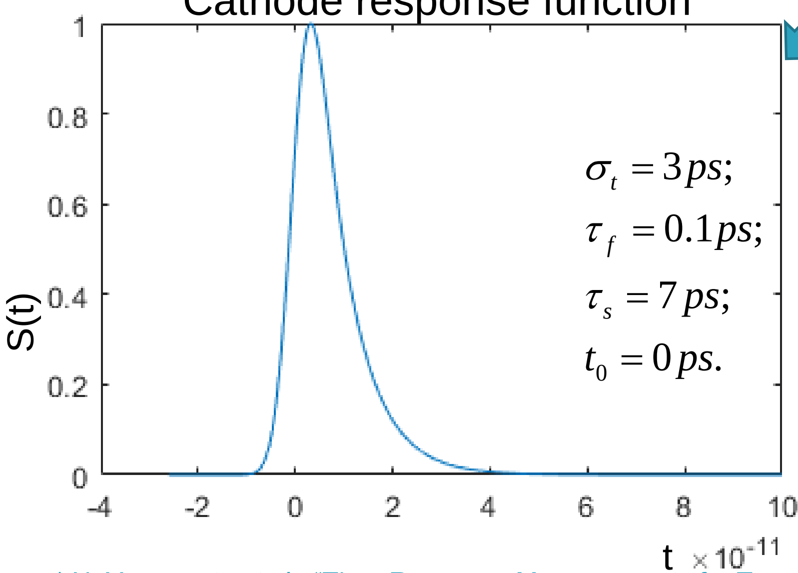
Beam halo simulation

Cathode temporal response

The initial distribution (uniform in transverse plane and Gaussian with tail in longitudinal) was generated and tracked through the injector lattice with GPT, creating the output distribution at the exit of the main cavity.



Cathode response function



$\sigma_t = 3ps;$

$\tau_f = 0.1ps;$

$\tau_s = 7ps;$

$t_0 = 0ps.$

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

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

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

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

* N. Yamamoto et al., "Time Response Measurements for Transmission-Type GaAs/GaAsP Superlattice Photocathodes", WEPMY039, IPAC'16, Busan, South Korea (2016)

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

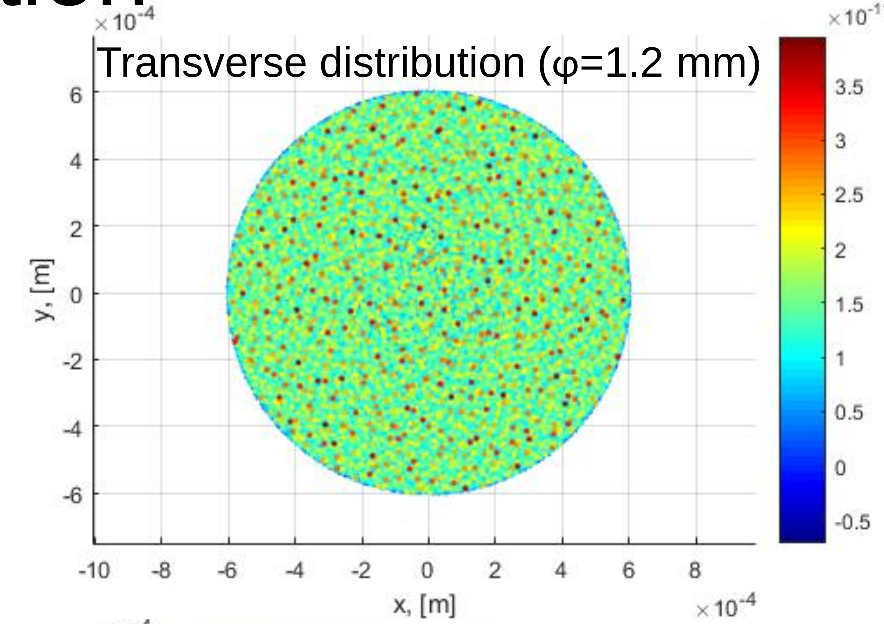
Beam halo simulation

Initial particle distribution

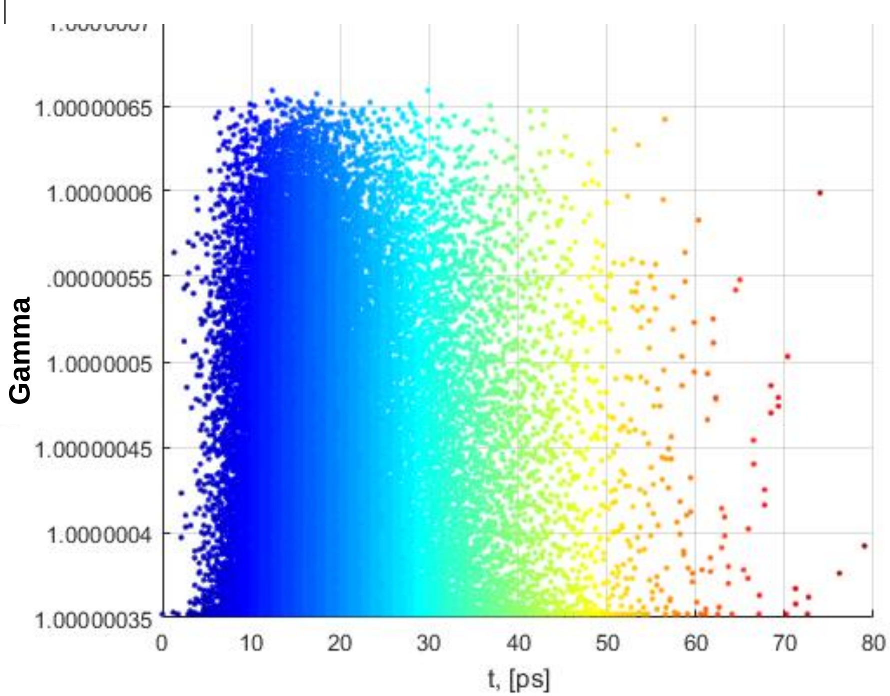
Simulation input parameters

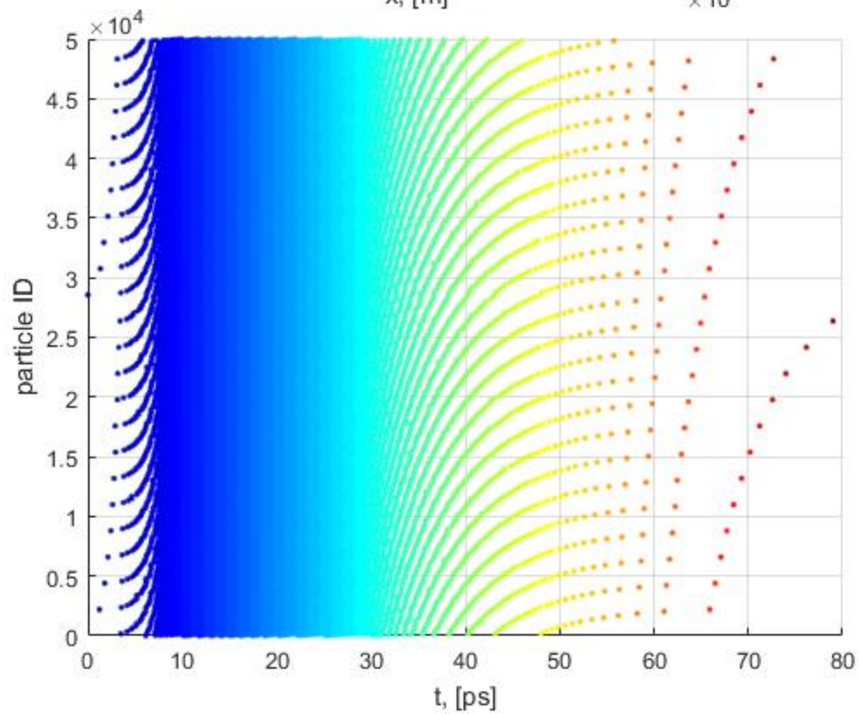
Number of particles	5E4
Beam energy	2.9 – 20 MeV
Total charge	0.5 pC / bunch
RF frequency	1.3 GHz
Laser spot diameter	1.2 mm
Bunch length	3 ps

Transverse distribution (φ=1.2 mm)

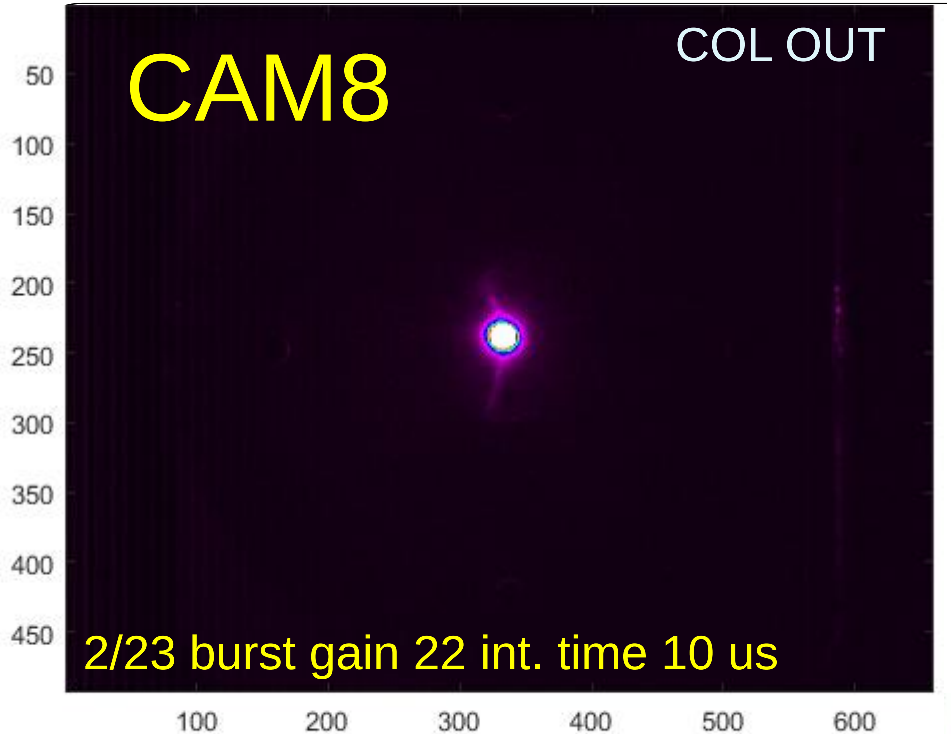


Longitudinal distribution (3 ps gaussian+tail)

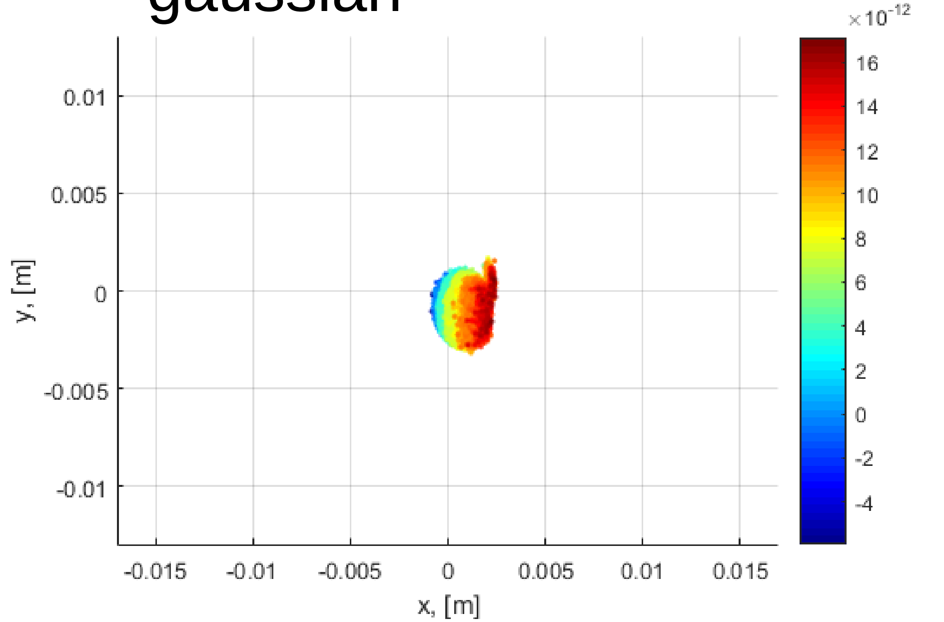




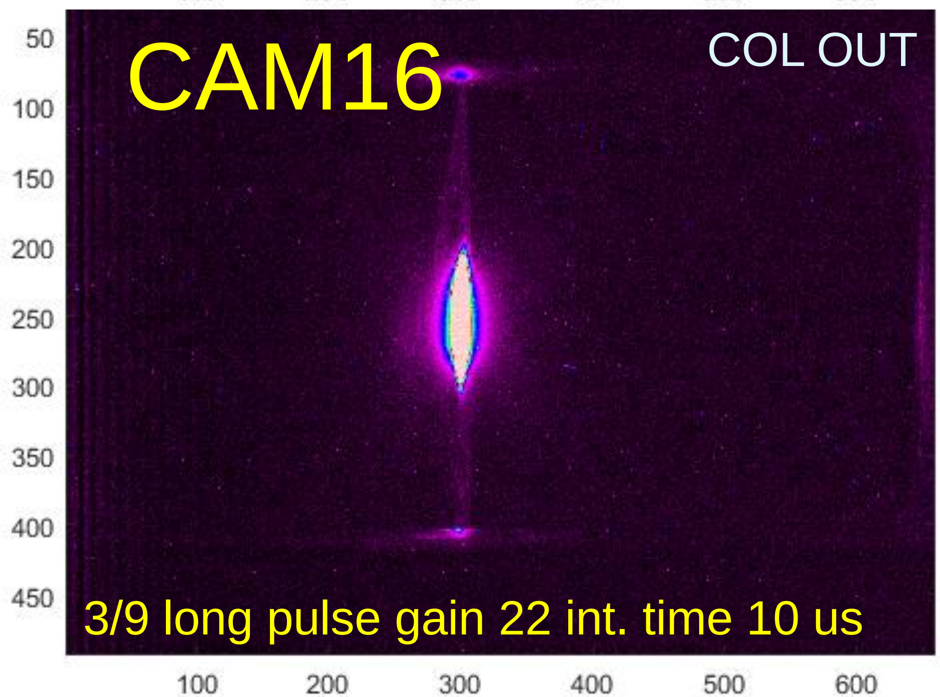
gaussian



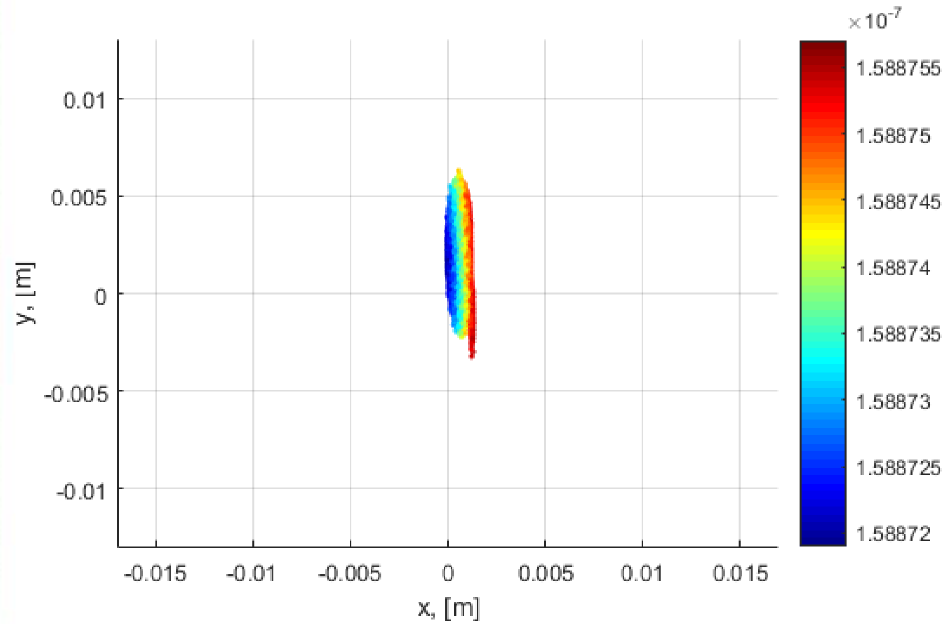
CAM8
COL OUT
2/23 burst gain 22 int. time 10 us



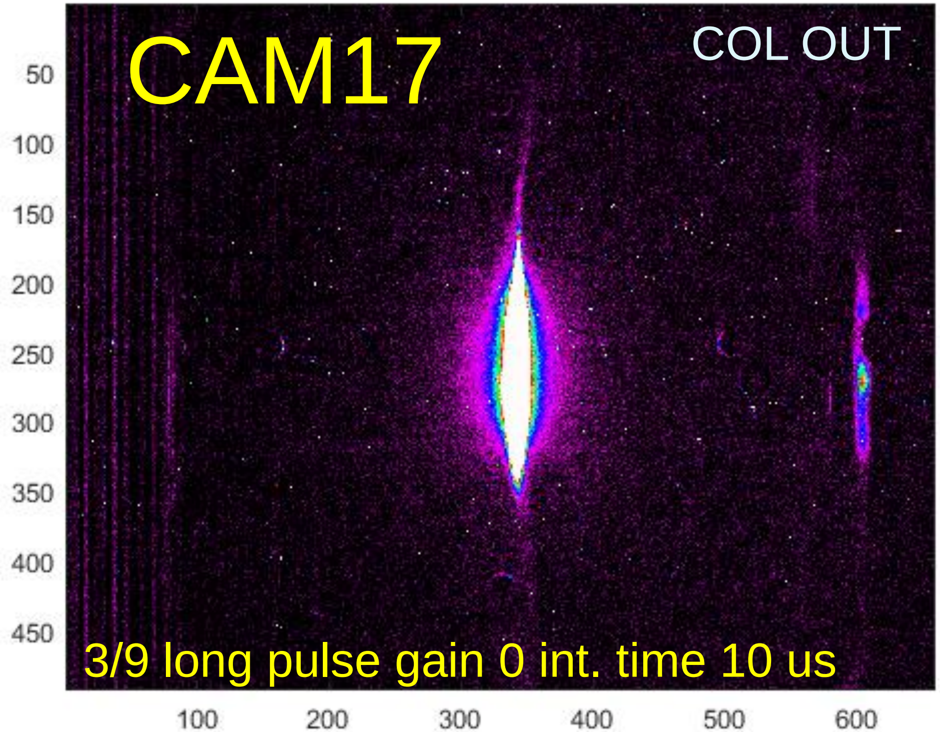
y, [m]
x, [m]
$\times 10^{-12}$



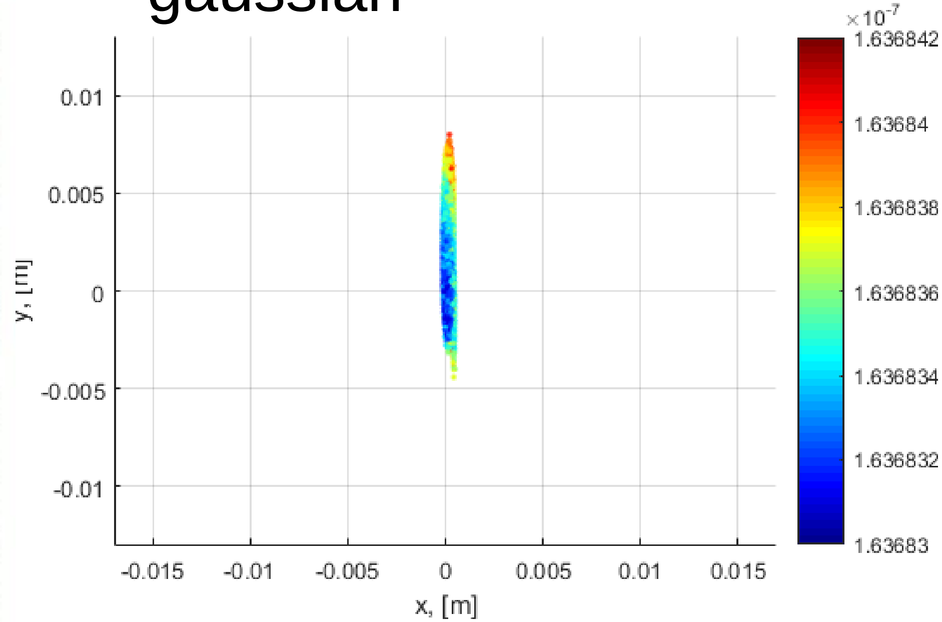
CAM16
COL OUT
3/9 long pulse gain 22 int. time 10 us

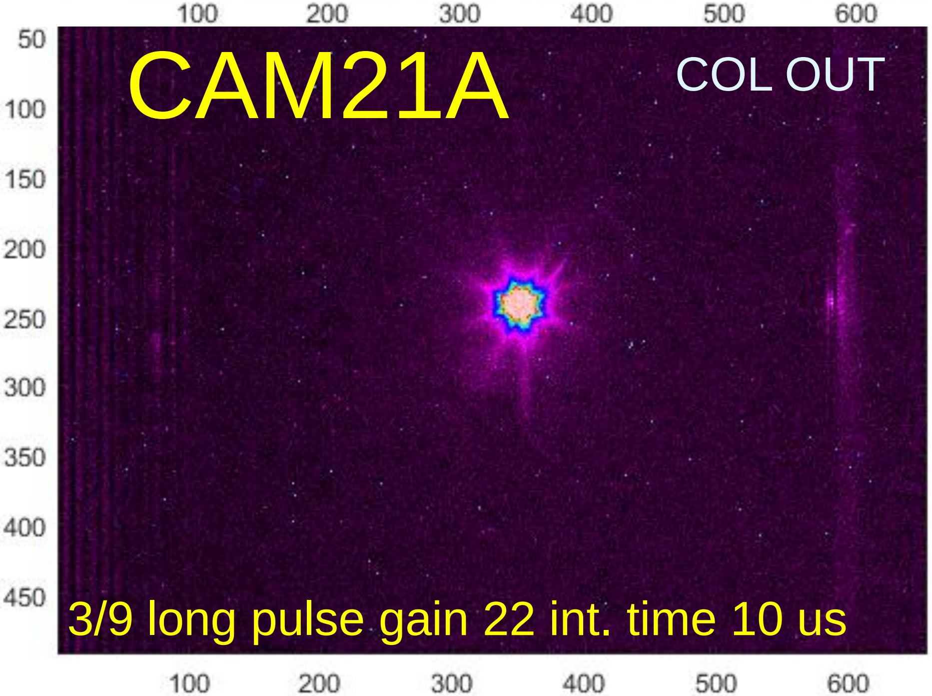


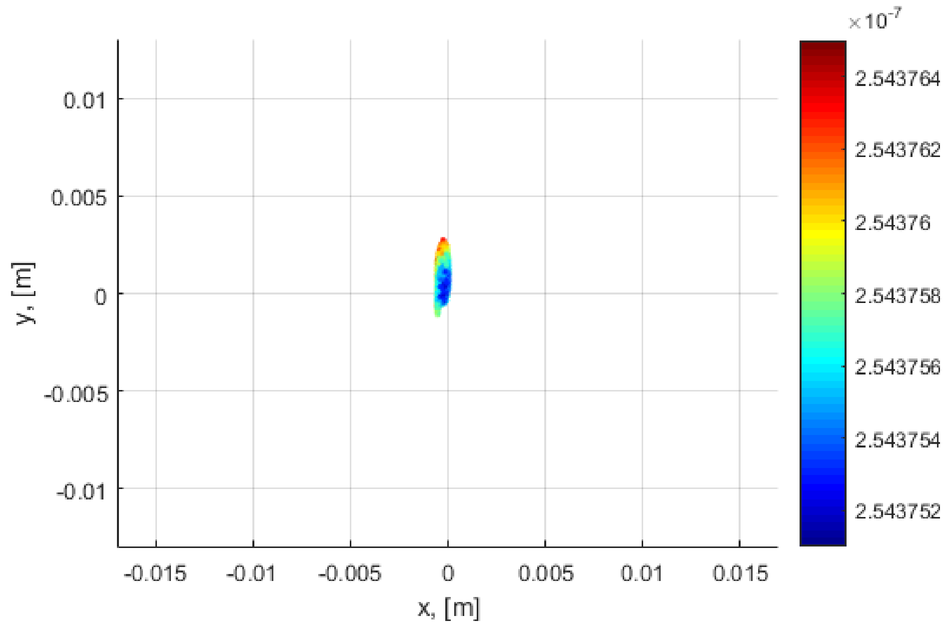
y, [m]
x, [m]
$\times 10^{-7}$


CAM17
COL OUT
3/9 long pulse gain 0 int. time 10 us

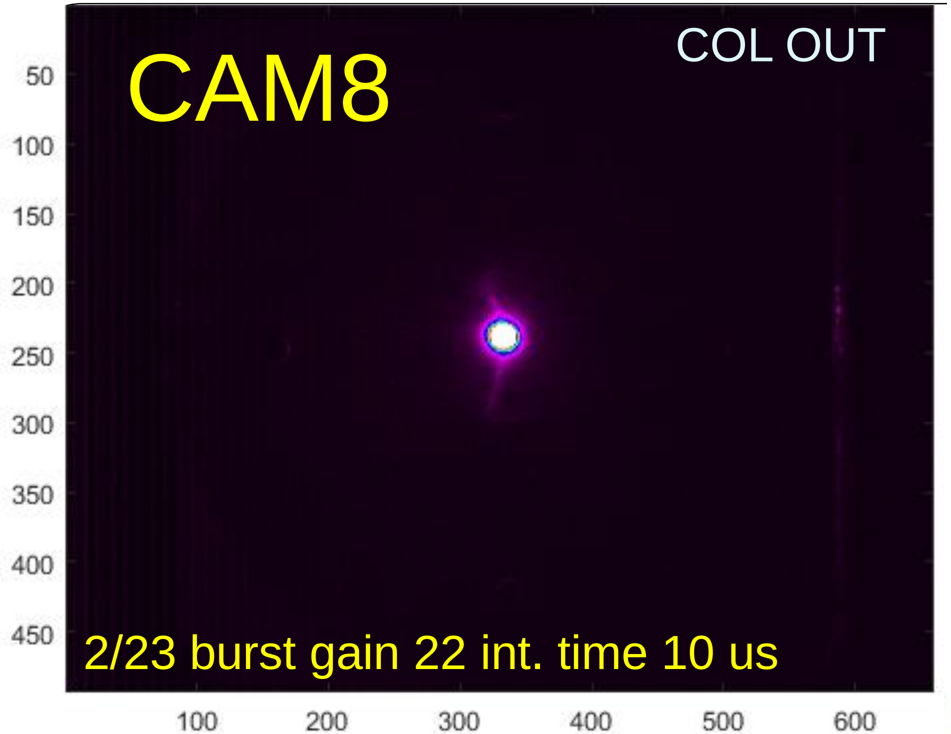
gaussian

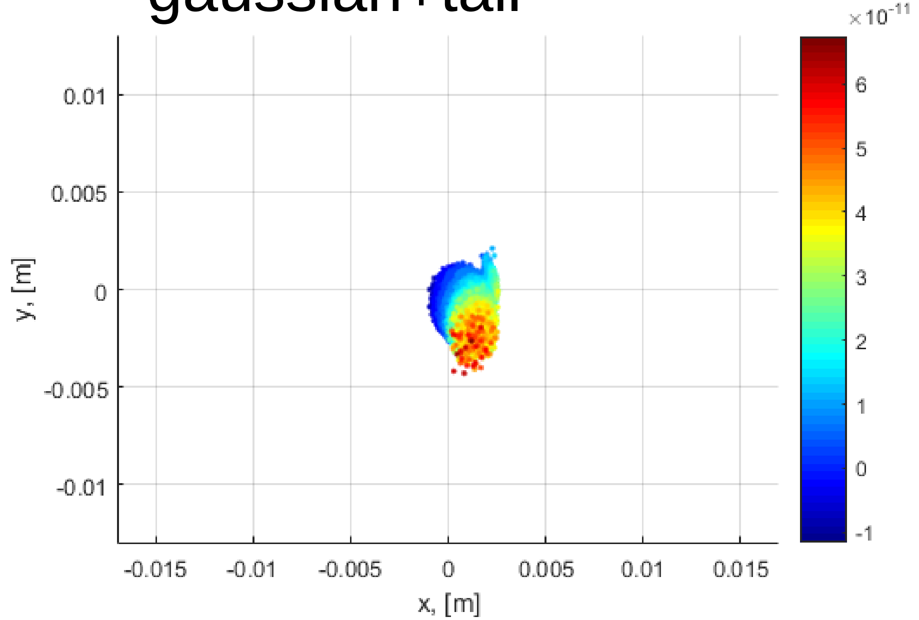

×10^-7
1.636842
1.63684
1.636838
1.636836
1.636834
1.636832
1.63683
y, [m]
x, [m]

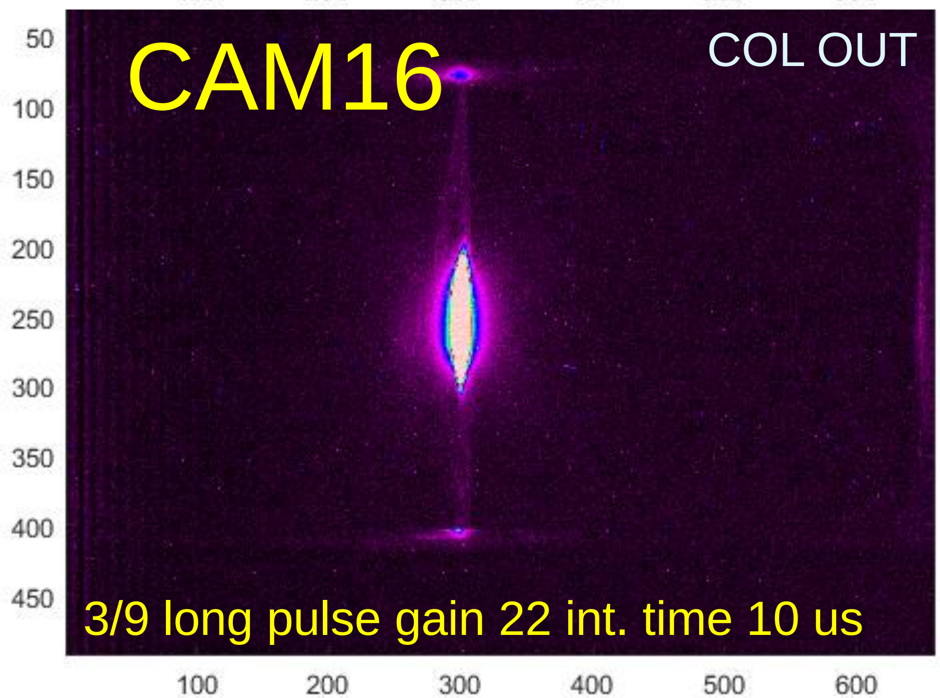

CAM21A
COL OUT
3/9 long pulse gain 22 int. time 10 us

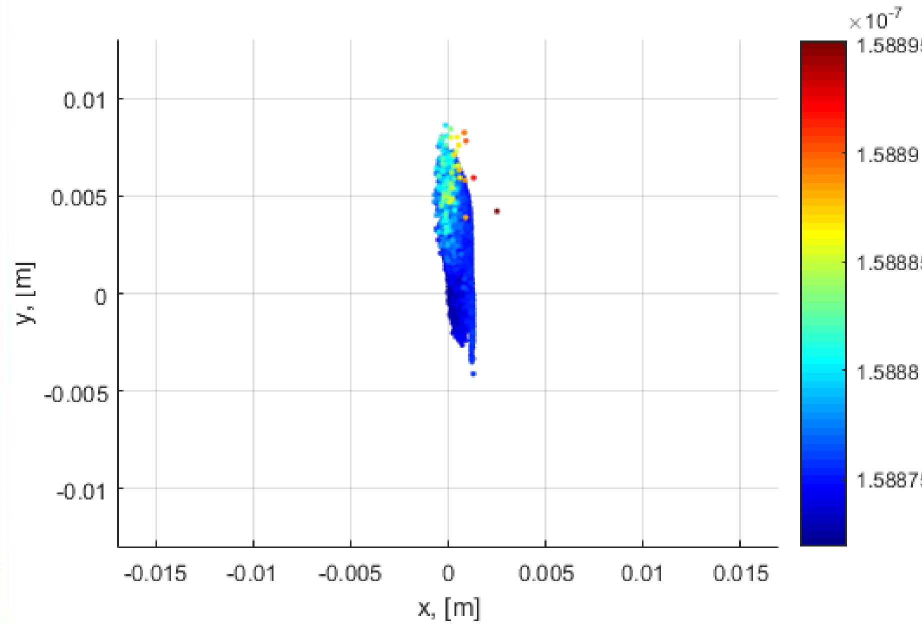

×10^-7
2.543764
2.543762
2.54376
2.543758
2.543756
2.543754
2.543752
y, [m]
x, [m]

gaussian+tail

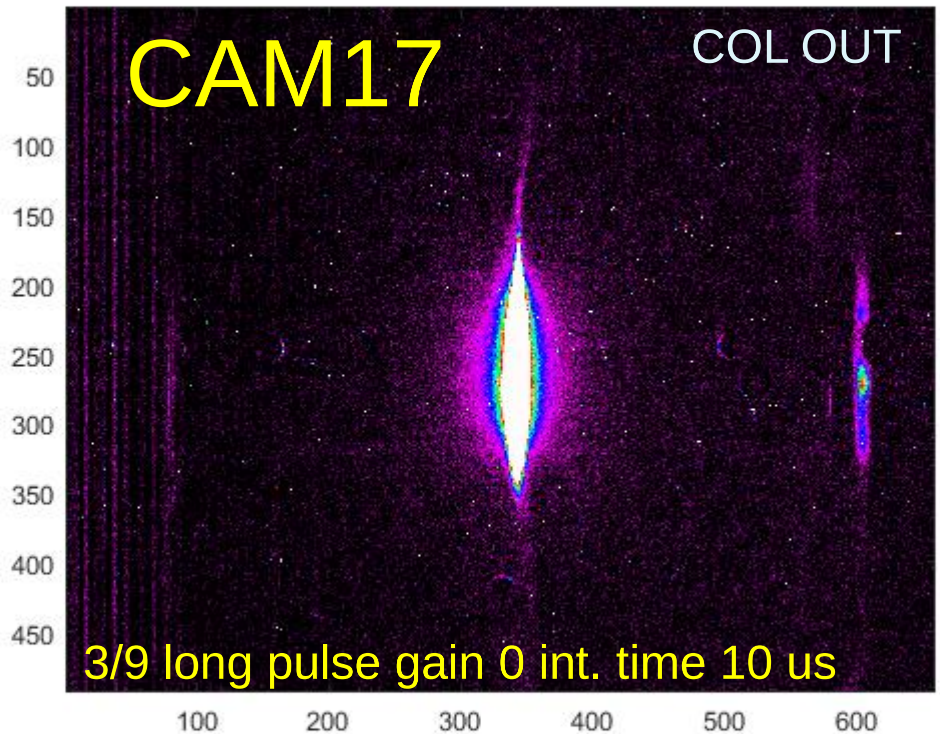


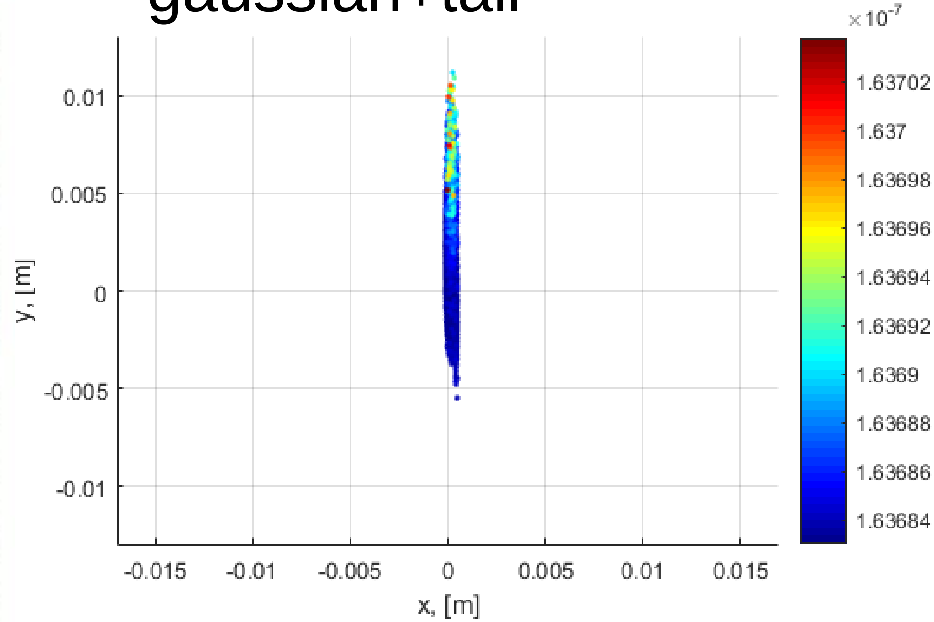


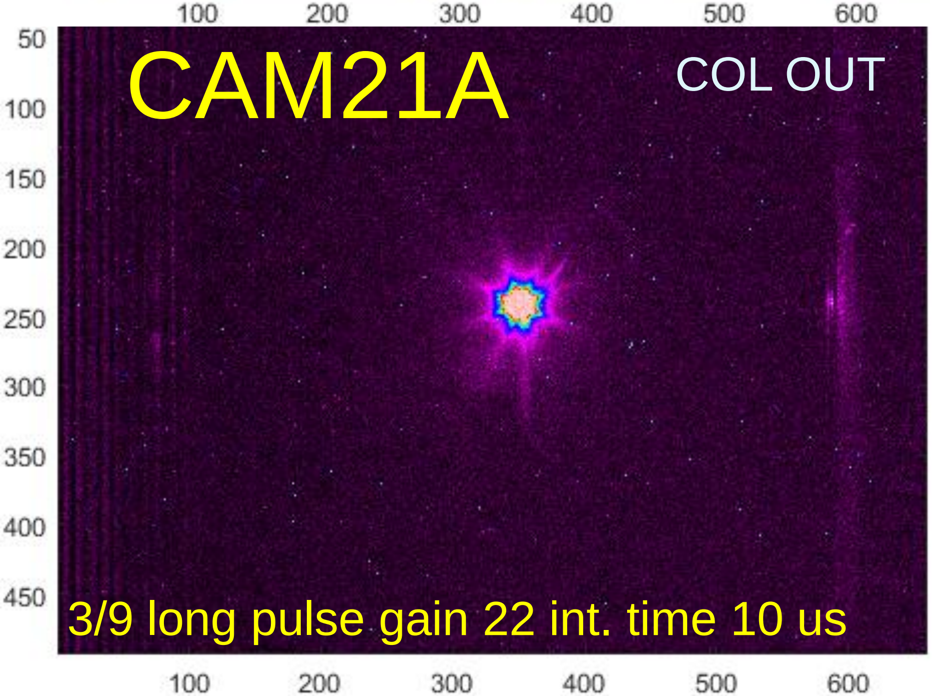


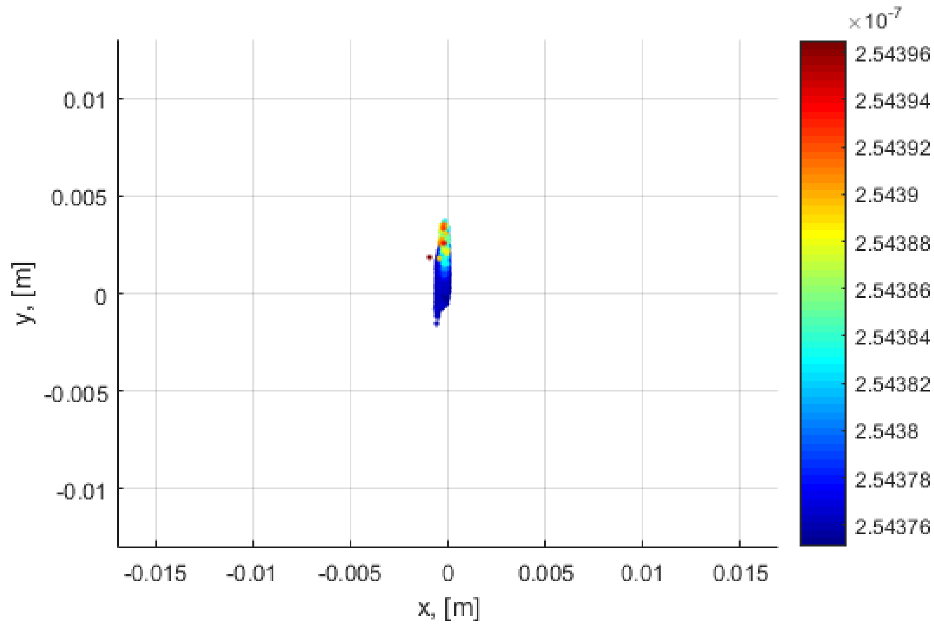


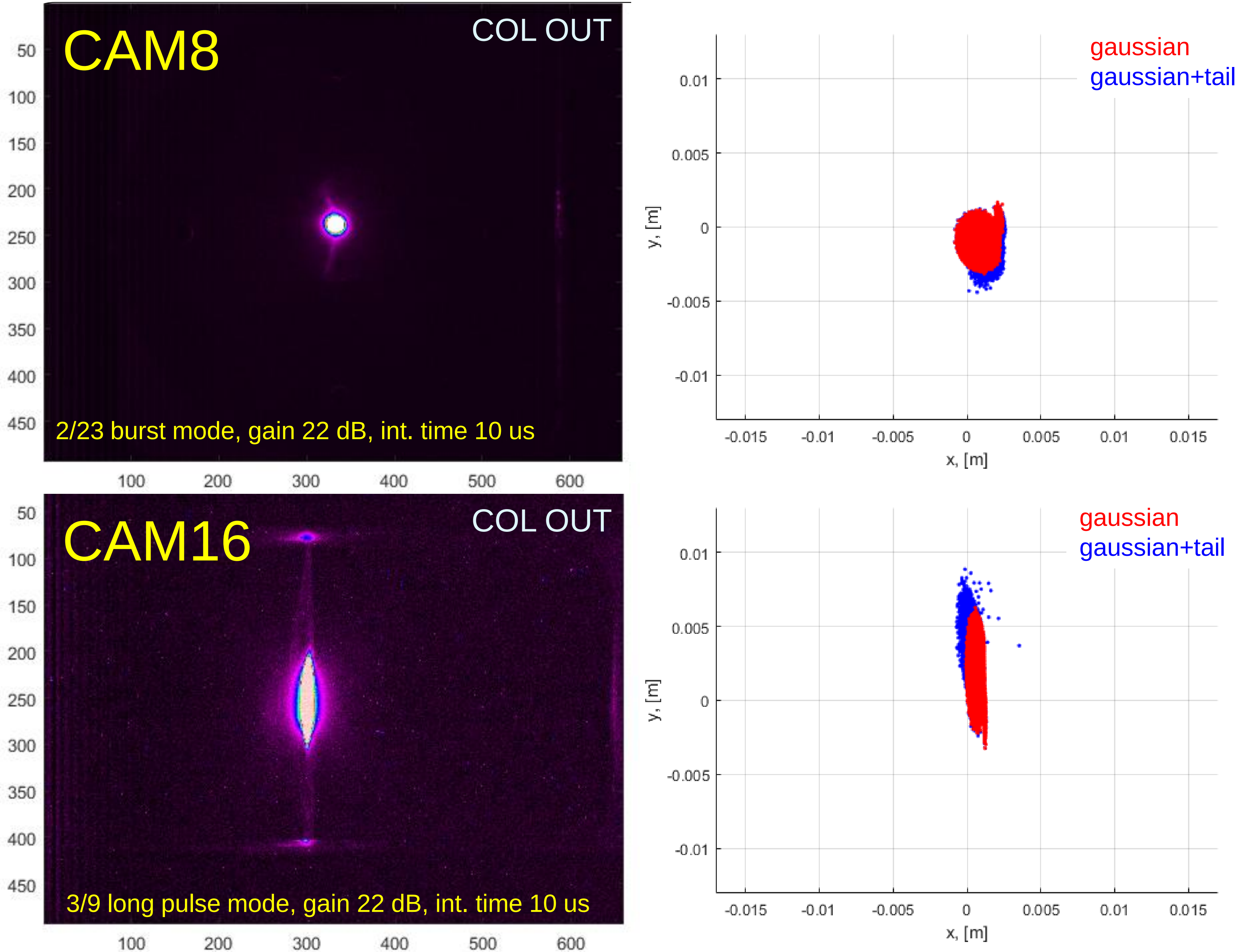
gaussian+tail



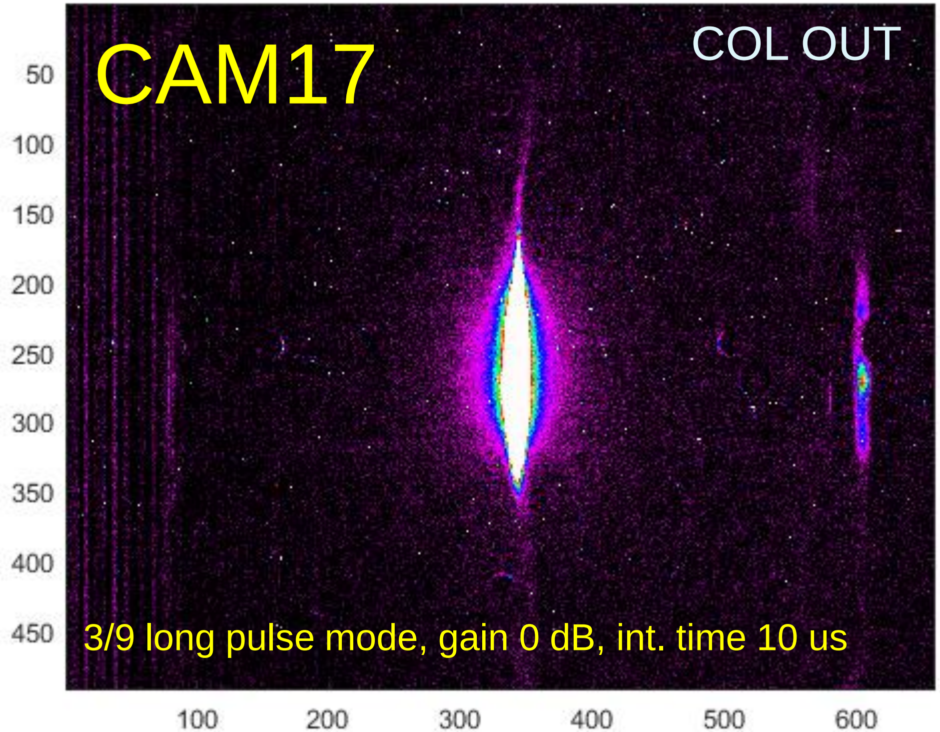


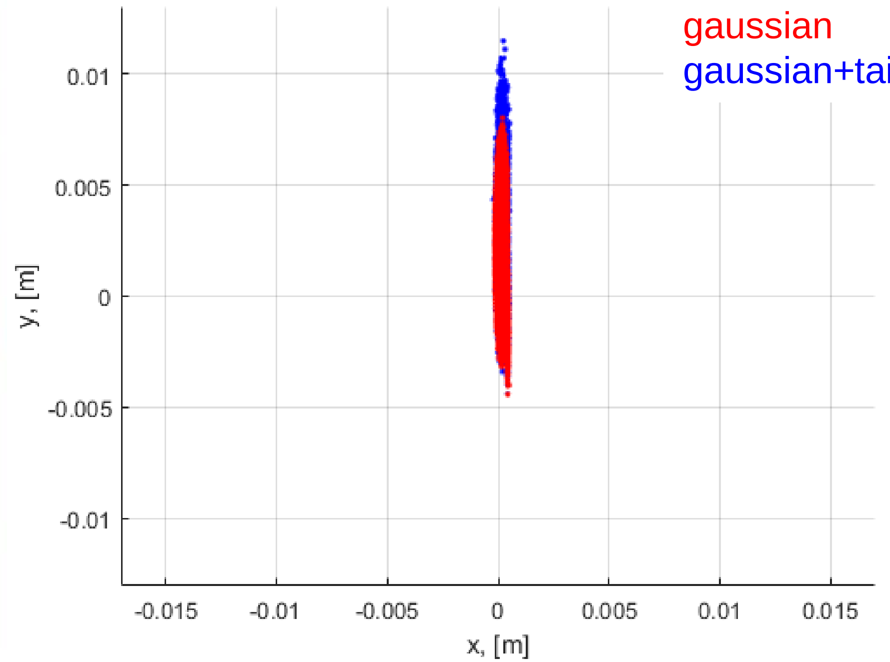


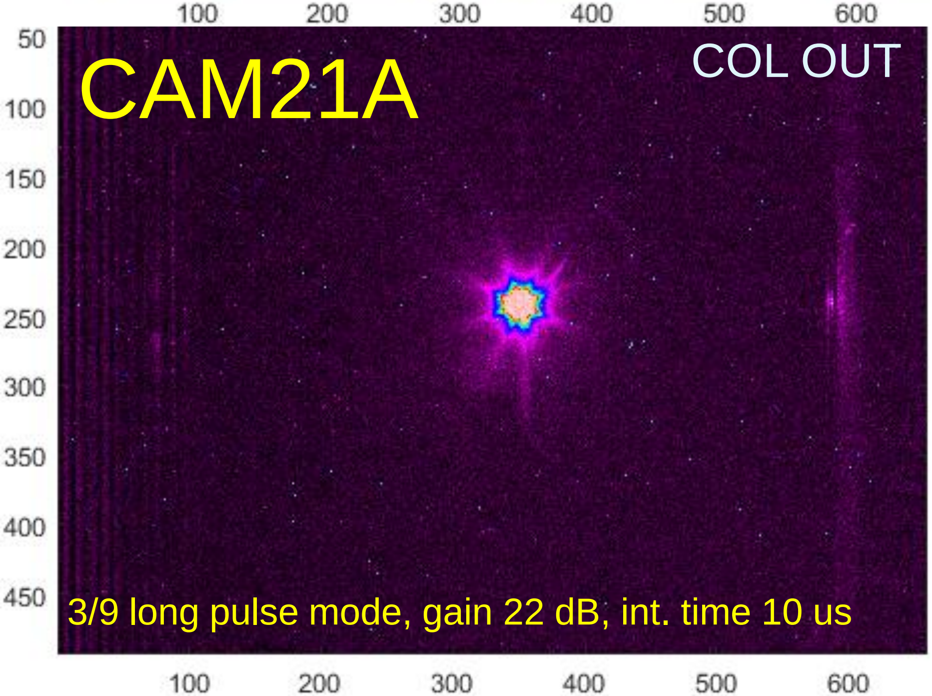


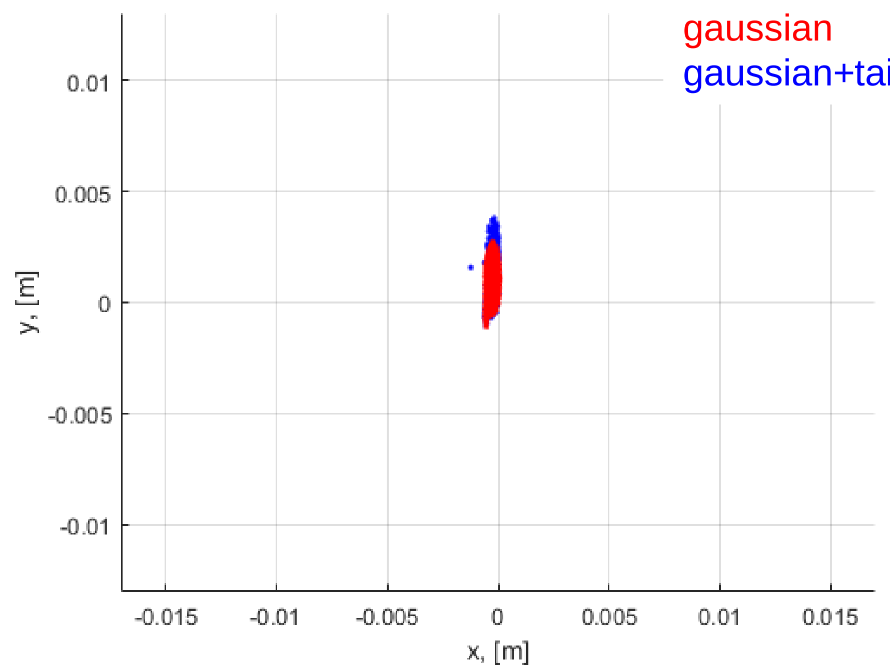


CAM8
COL OUT
2/23 burst mode, gain 22 dB, int. time 10 us
gaussian
gaussian+tail
y, [m]
x, [m]
CAM16
COL OUT
3/9 long pulse mode, gain 22 dB, int. time 10 us
gaussian
gaussian+tail
y, [m]
x, [m]


CAM17
COL OUT
3/9 long pulse mode, gain 0 dB, int. time 10 us
50
100
150
200
250
300
350
400
450
100
200
300
400
500
600


gaussian
gaussian+tail
y, [m]
x, [m]
0.01
0.005
0
-0.005
-0.01
-0.015
-0.01
-0.005
0
0.005
0.01
0.015

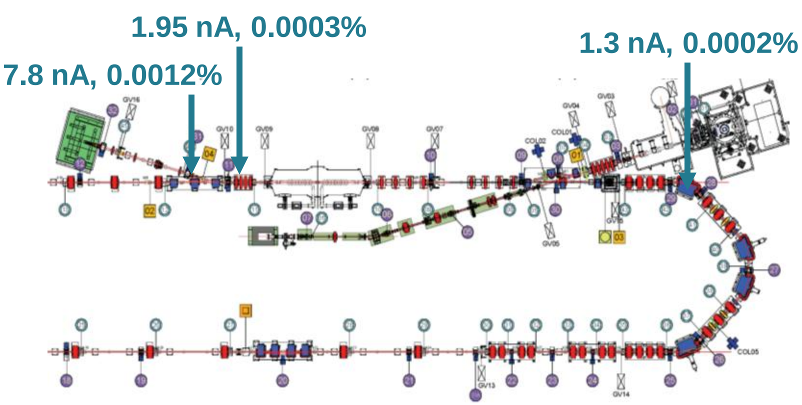

CAM21A
COL OUT
3/9 long pulse mode, gain 22 dB, int. time 10 us
50
100
150
200
250
300
350
400
450
100
200
300
400
500
600


gaussian
gaussian+tail
y, [m]
x, [m]
0.01
0.005
0
-0.005
-0.01
-0.015
-0.01
-0.005
0
0.005
0.01
0.015

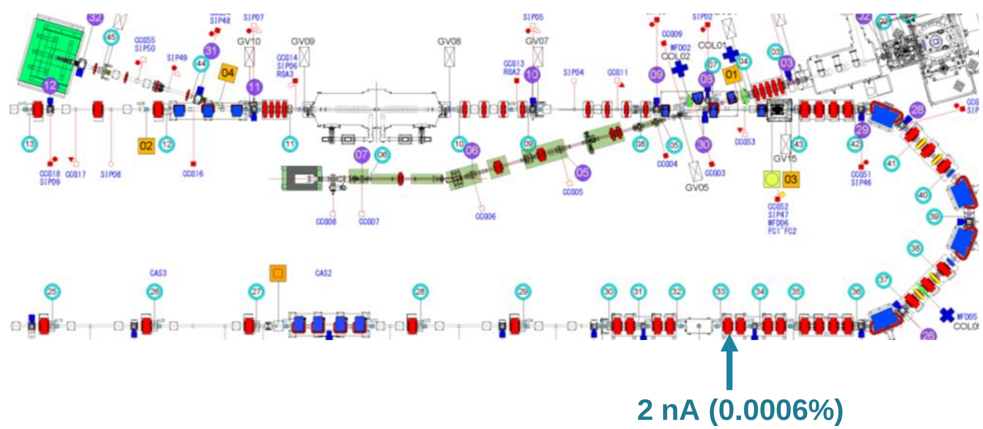
Beam loss estimation

Place	Simulated, COL out [nA, %]	Simulated, COL in [nA, %]	Calculated*, COL out [nA, %]
QMLC05	0, 0	0, 0	2, 0.0006
BMIR04	1.3, 0.0002	0, 0	0, 0
QMAD01-04	1.95, 0.0003	0.65, 0.0001	0, 0
BMAD01-03	7.8, 0.0012	1.95, 0.0003	0, 0

Simulation result for 1E6 macroparticles and total current 650 uA*



Calculated for total beam current 300 μA**



* O. Tanaka et al., “Simulation study of the beam halo formation for beam loss estimation and mitigation at KEK compact ERL”, TUPOW039, IPAC’16, Busan, South Korea (2016)

** H. Matsumura, “Beam loss estimated from the ceiling dose”, (in Japanese), BDWG meeting, February (2016).

Conclusion

- The probable reasons of the vertical halos observed could be:
  - Longitudinal bunch tail
  - Kicks from the steering coils
  - Injector cavity misalignment
- Upward halo at CAM8; downward at CAM16; downward and upward at CAM17, CAM21A come from the far part of the beam core
- Upward halo at CAM8; downward at CAM16, CAM17, CAM21A come from the longitudinal bunch tail
- Simulated beam loss rates are in a satisfactory agreement with the beam loss measurement
- Collimators insertion, in accordance with the measurement setup, decreases the simulated loss rates essentially
- The beam loss distribution along the beam line essentially differs from the measured one. This is a point to be improved
- Also there are some unaccounted factors. It could be kicks from input / HOM couplers
- The following simulation study should properly take such factors into account

謝辞

御清聴をどうもありがとうございます

小林教授から常に暖かいサポートと助言を頂いております。

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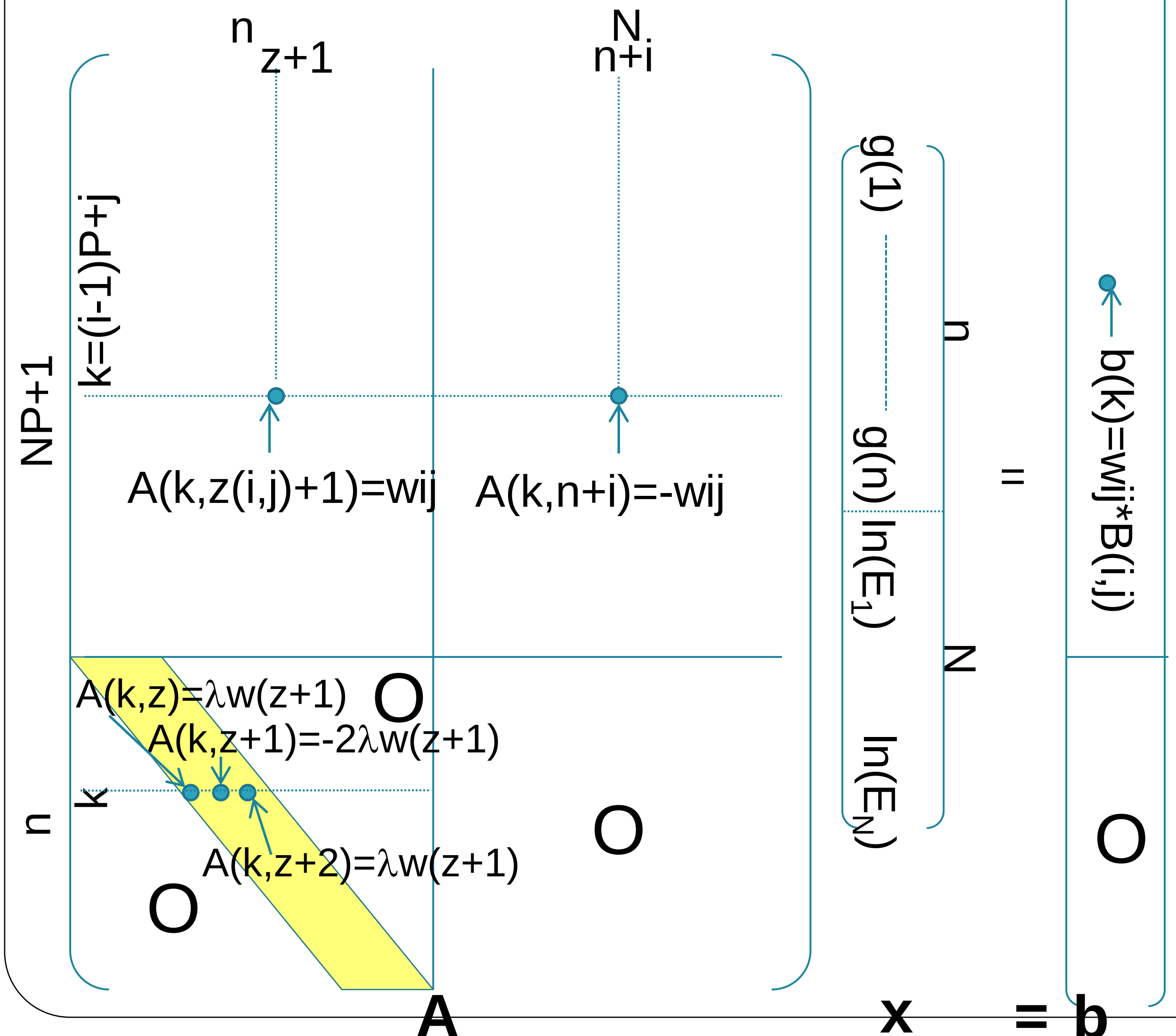
皆様へ感謝申し上げます。

Backup slides

Matrix structure

z=0,…,255 (digitized amplitudes)
i=0,…,N-1 (no. of pixels)
j=0,…,P-1 (no. of pictures)



- $B(i,j)=\ln(t_j)$

The matrix equation in the Matlab code : Ax = b

At Row k

$w_{ij}g(z_{ij})-w_{ij}\ln(E_i)=w_{ij}\ln(t_j)$

$\lambda w(z)g''(z)=0$

⇔The solution to minimize Equation below (4)

- Minimizing $|Ax-b|^2$

⇔Solve $x=A^{-1}b$

(A^{-1} :pseudo inverse matrix)

This equation can be solved by SVD method

(x=A\b in MatLab)

Matlab code*

```
function [g,lE]=gsolve(Z,B,l,w)

n = 256;
A = zeros(size(Z,1)*size(Z,2)+n+1,n+size(Z,1));
b = zeros(size(A,1),1);

k = 1;                  %% Include the data-fitting equations
for i=1:size(Z,1)
  for j=1:size(Z,2)
    wij = w(Z(i,j)+1);
    A(k,Z(i,j)+1) = wij; A(k,n+i) = -wij; b(k,1) = wij * B(i,j);
    k=k+1;
  end
end

A(k,129) = 1;           %% Fix the curve by setting its middle value to 0
k=k+1;

for i=1:n-2             %% Include the smoothness equations
  A(k,i)=l*w(i+1); A(k,i+1)=-2*l*w(i+1); A(k,i+2)=l*w(i+1);
  k=k+1;
end

x = A\b;                %% Solve the system using SVD

g = x(1:n);
lE = x(n+1:size(x,1));
```

* P. E. Debevec and J. Malik, “Recovering high dynamic range radiance maps from photographs ”. In SIGGRAPH, pages 369-378, (1997).