KEK, High Energy Accelerator Research Organization

ID:THOM09

コンパクトERLにおけるビームハローとビームロスのスタディ

29年8月3日(木)11:40 - 12:00
第14回日本加速器学会年会
北海道大学　クラーク会館・学術交流会館、小講堂(1F)

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高エネルギー加速器研究機構、KEK

内容

- はじめに
  - コンパクトERLの現状
  - ビームハロースタディの現況
- 縦方向バンチテール
- 入射器空洞におけるRFキックの影響
- ビーム軌道に対するステアリングコイルの影響
- ビームハローシミュレーション
  - 定性的な比較検討
  - 定量的な比較検討
- 結論

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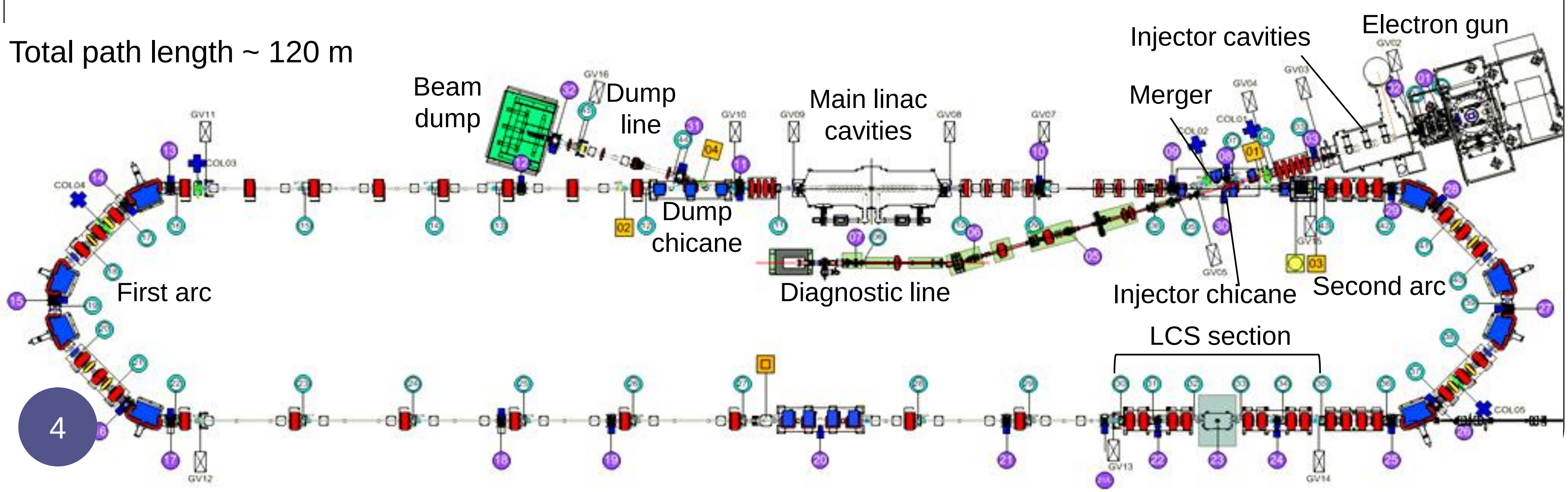
はじめに
コンパクトERLの現状

- cERL has been developed as a next-generation light source and constructed at KEK as a small demonstration machine
- We succeeded in energy recovery operation with energy of 20 MeV and average current of 1 mA in March 2016
- This spring the main purpose of the cERL machine study was a beam operation with higher bunch charge (up to 60 pC)

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 (usual) 0.1 ps (compressed)	1-3 ps (usual) 0.25 ps (compressed)
Repetition rate	1.3 GHz	1.3 GHz (usual) 162.5 MHz (for LCS)

Total path length ~ 120 m



はじめに
コンパクトERLの現状

1．FSP006

KEKコンパクトERLの現状

Present status of the compact ERL at KEK

○加藤 龍好（高エネ研）

○Ryukou Kato (KEK)

2．TUP033

光陰極電子銃により生成された高電荷ビームへのレーザーミラーの影響

Influence of laser mirror on high charge beam generated by photocathode electron gun

○布袋 貴大（総研大），宮島 司（高エネ研）

○Takahiro Hotei (SOKENDAI), Tsukasa Miyajima (KEK)

3．TUP092

cERLの入射超伝導空洞のHOMを使ったビームタイミング測定

Beam timing measurement using HOMs in injector superconducting cavity at cERL

○岡田 貴文（総研大），許斐 太郎，梅森 健成，加古 永治，阪井 寛志（高エネルギー加速器研究機構）

○Takafumi Okada (SOKENDAI), Taro Konomi, Kensei Umemori, Eiji Kako, Hiroshi Sakai (KEK)

4．WEP004

共振器型CDRによる広帯域THz光源

Broadband THz source by means of resonant CDR system

○本田 洋介，アリシェフ アレクサンダー，島田 美帆，加藤 龍好，宮島 司，高井 良太，帯名 崇，山本 尚人（高エ研）

○Yosuke Honda, Alexander Aryshev, Miho Shimada, Ryukou Kato, Tsukasa Miyajima, Ryota Takai, Takashi Obina, Naoto Yamamoto (KEK)

5．WEP041

cERL入射器クライオモジュールの大電力RFパルスコンディショニング

High power RF pulsed conditioning in cERL injector cryomodule

○今田 信一，浅野 峰行，柳町 太亮，山田 浩気（日本アドバンストテクノロジー），許斐 太郎，加古 永治（KEK）

○Shin-ichi Imada, Mineyuki Asano, Taisuke Yanagimachi, Hiroki Yamada (NAT), Taro Konomi, Eiji Kako (KEK)

6．WEP044

cERL入射器クライオモジュールにおける長期間ビーム運転経験

Long operational experience with beam in cERL injector cryomodule

○山田 浩気，浅野 峰行，今田 信一，柳町 太亮（日本アドバンストテクノロジー），許斐 太郎，加古 永治（KEK）

○Hiroki Yamada, Asano Asano, Shin-ichi Imada, Taisuke Yanagimachi (NAT), Taro Konomi, Eiji Kako (KEK)

See also: TUP016, TUP040, WEP002

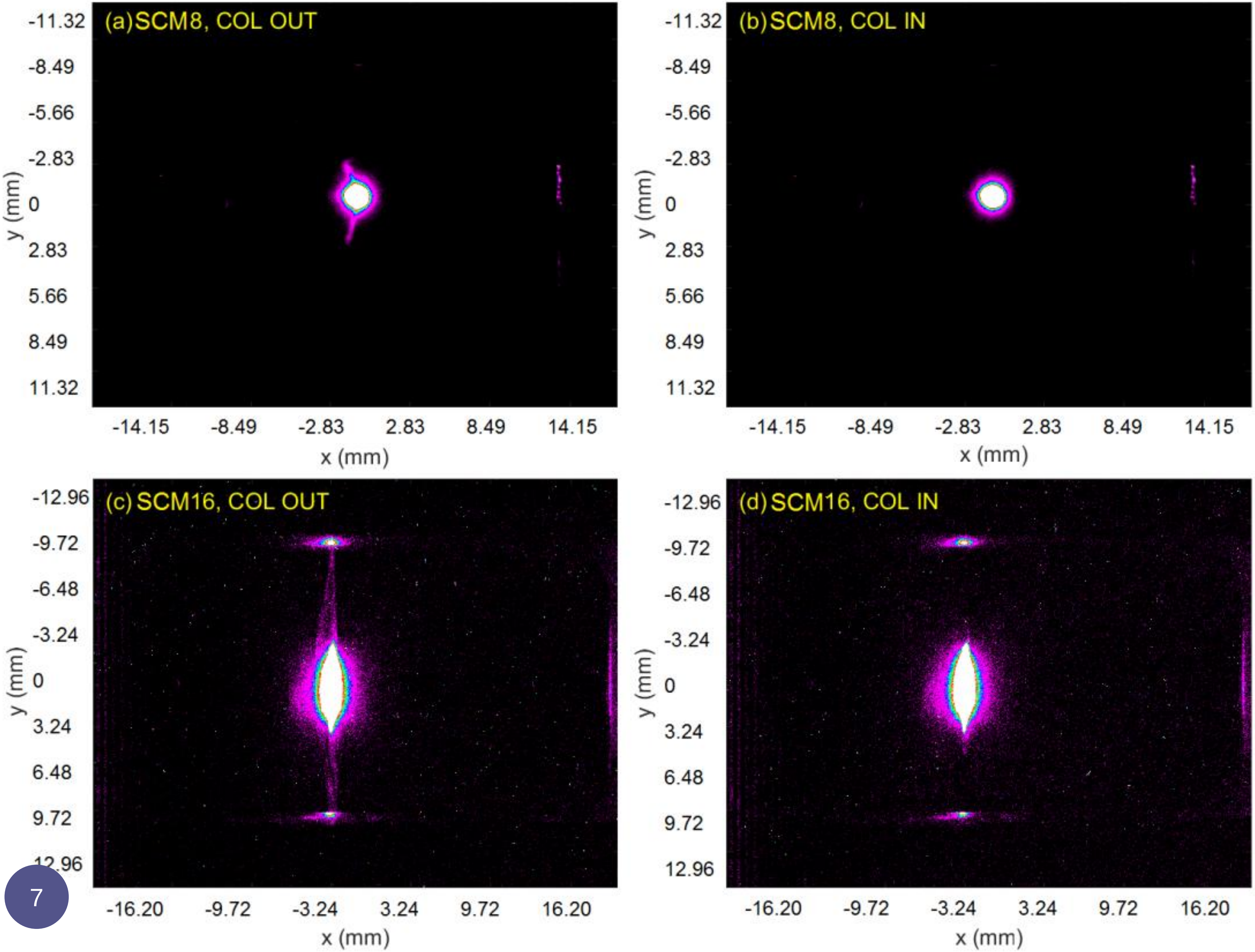
はじめに
ビームハロースタディの現況

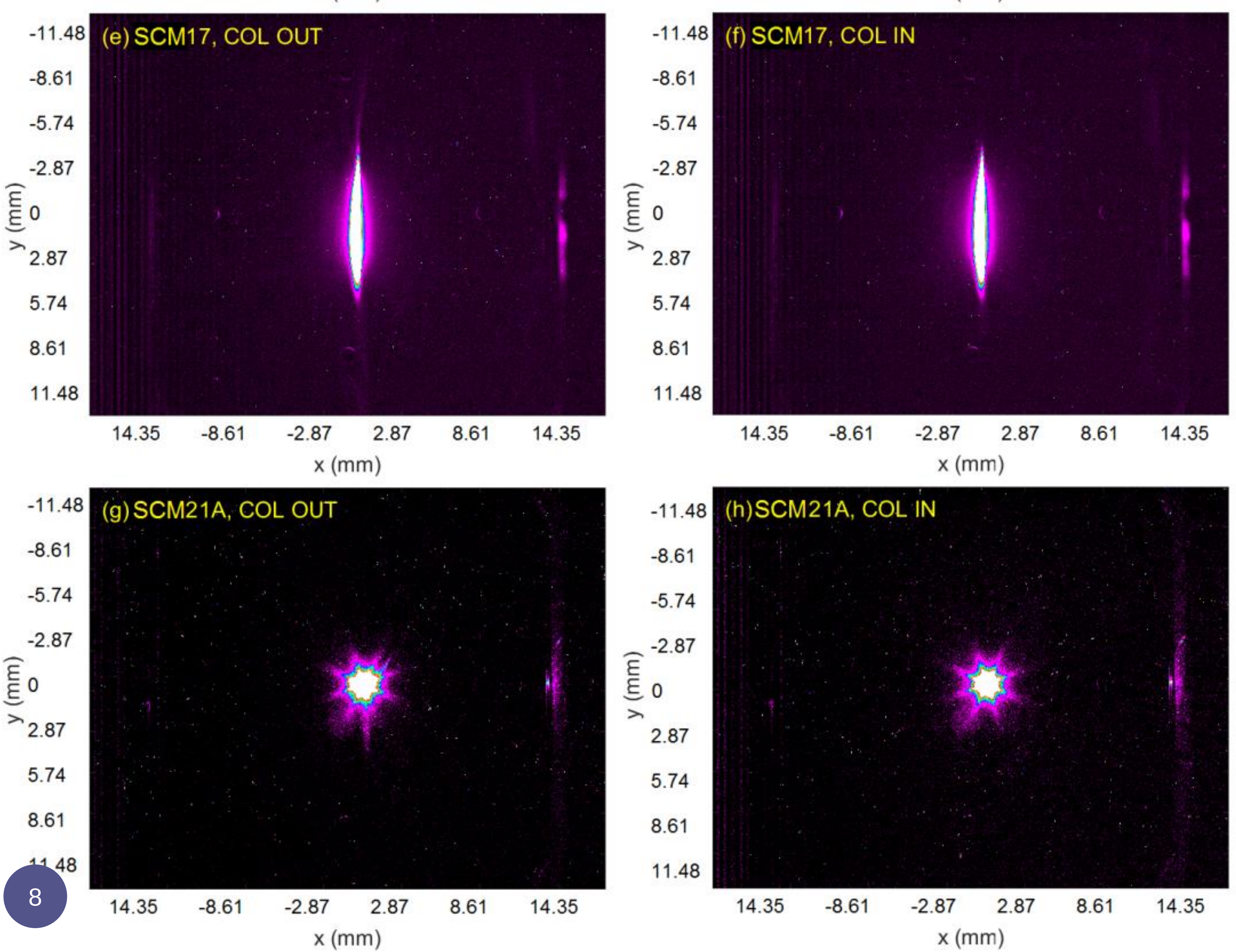
2016年の結果

- ☑ Beam loss observation, when the beam passes the recirculation loop without collimation
- ☑ Enhancement of the beam loss reduction when the beam enters the injector cavities with a slight angle to the central axis
- ☑ Experimental evidence of the transverse beam halo existence at different beamline locations
- ☑ Consideration of the longitudinal bunch tail originated at photocathode
- ☑ Inclusion of the steering coils effect on the beam trajectory
- ☑ Estimation of the beam core-halo ratio

2017年の成果

- ☑ Upgrade of the longitudinal bunch tail model
- ☑ Study of the effect of injector cavities rf kicks on the particles of the beam moving inside the cavity with a transverse displacement from the central axis
- ☑ Search for all possible reasons of the beam trajectory displacement inside the cryomodule
- ☑ Forward tail treatment
- ☑ Overall simulation including all the effects described above
- ☑ Beam loss estimation


(a)SCM8, COL OUT
(b)SCM8, COL IN
(c) SCM16, COL OUT
(d) SCM16, COL IN
y (mm)
x (mm)
-11.32
-8.49
-5.66
-2.83
0
2.83
5.66
8.49
11.32
-14.15
14.15
-12.96
-9.72
-6.48
-3.24
3.24
6.48
9.72
12.96
-16.20
16.20



(e) SCM17, COL OUT
(f) SCM17, COL IN
(g) SCM21A, COL OUT
(h)SCM21A, COL IN
-11.48
-8.61
-5.74
-2.87
0
2.87
5.74
8.61
11.48
y (mm)
14.35
-8.61
-2.87
2.87
8.61
14.35
x (mm)

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縦方向バンチテール

GaAsフォトカソードの時間応答関数

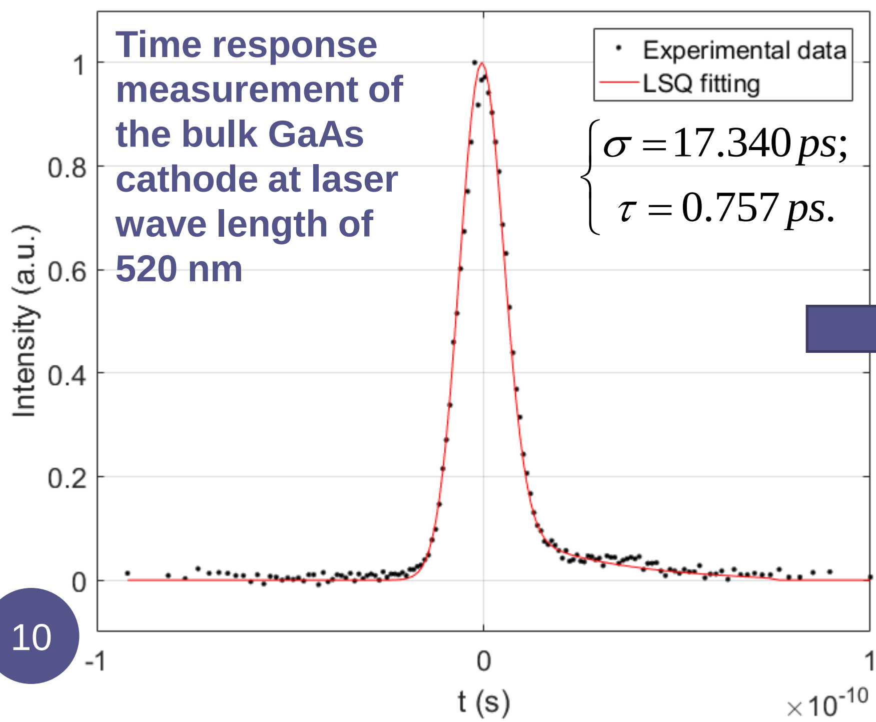
- A model function used in the fitting procedure is a convolution integral

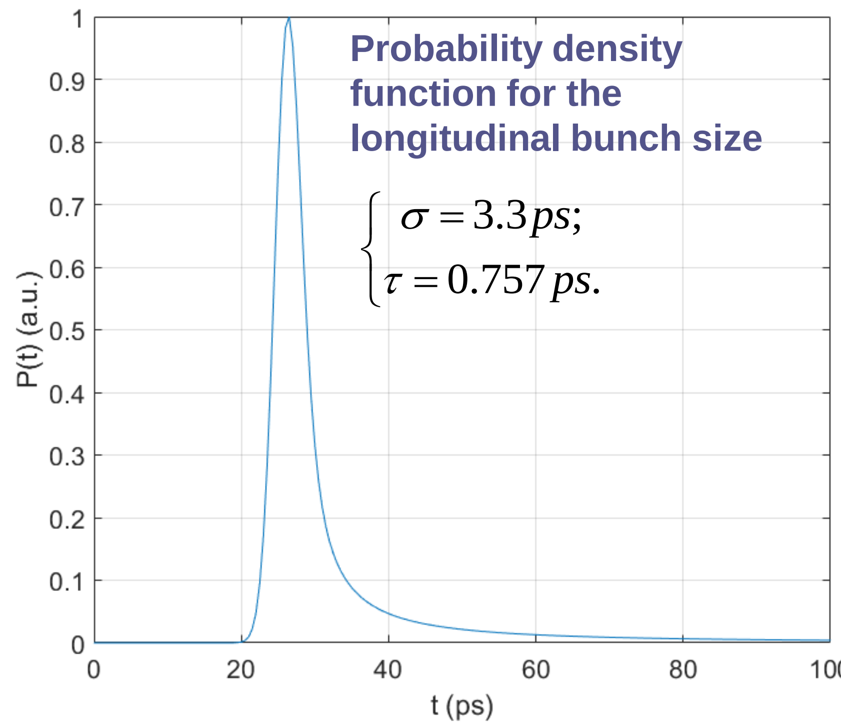
$$(f*g)(k)=\int_{-\infty}^{\infty} f(k)g(k-s)\,dk=\int_{-\infty}^{\infty} f(k-s)g(s)\,ds,$$

$k=t/\tau$ 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 $f(k)=\frac{1}{\sqrt{2\pi\sigma^2}}e^{-\frac{k^2}{2\sigma^2}},$

with the photoemission current function



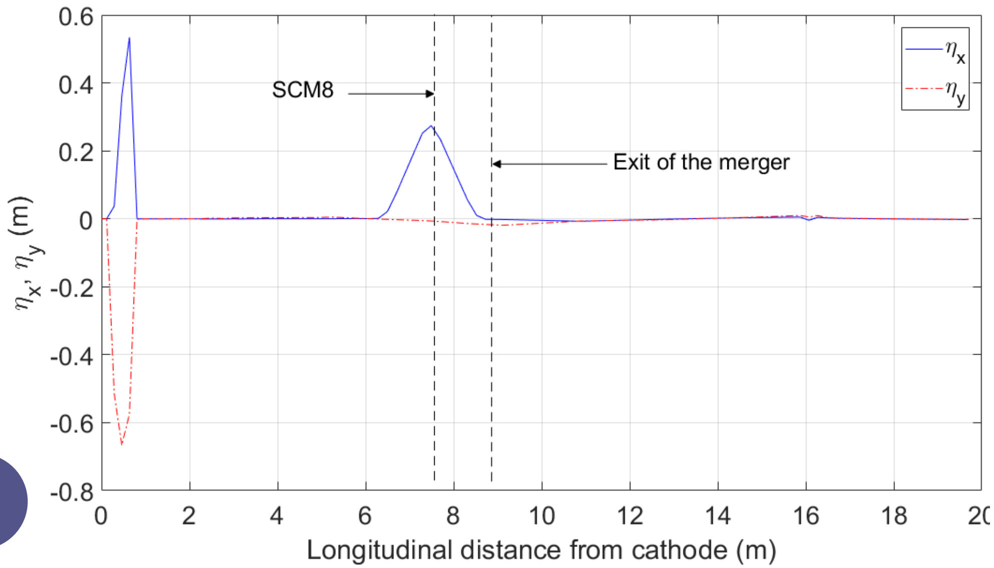


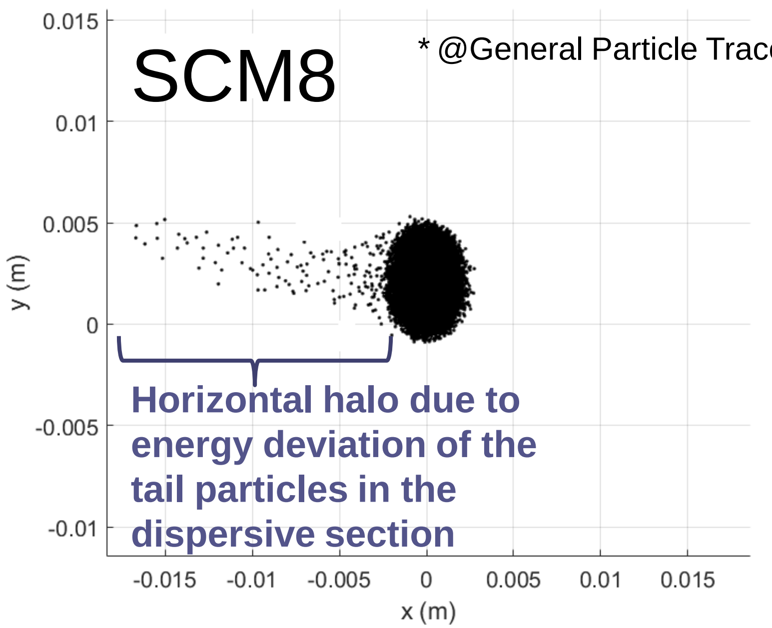
縦方向バンチテール

テールのトラッキング*

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





* @General Particle Tracer

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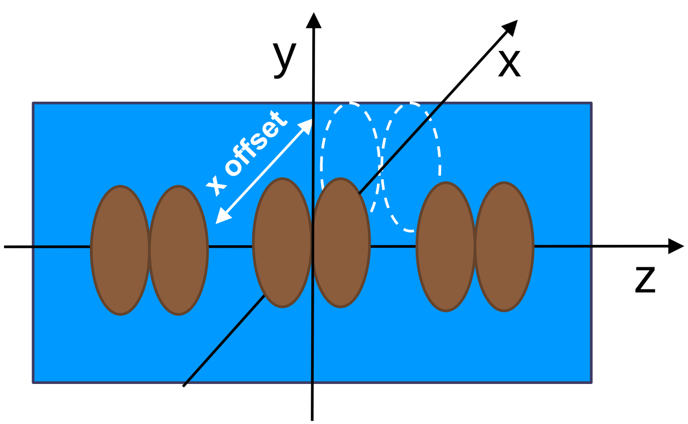
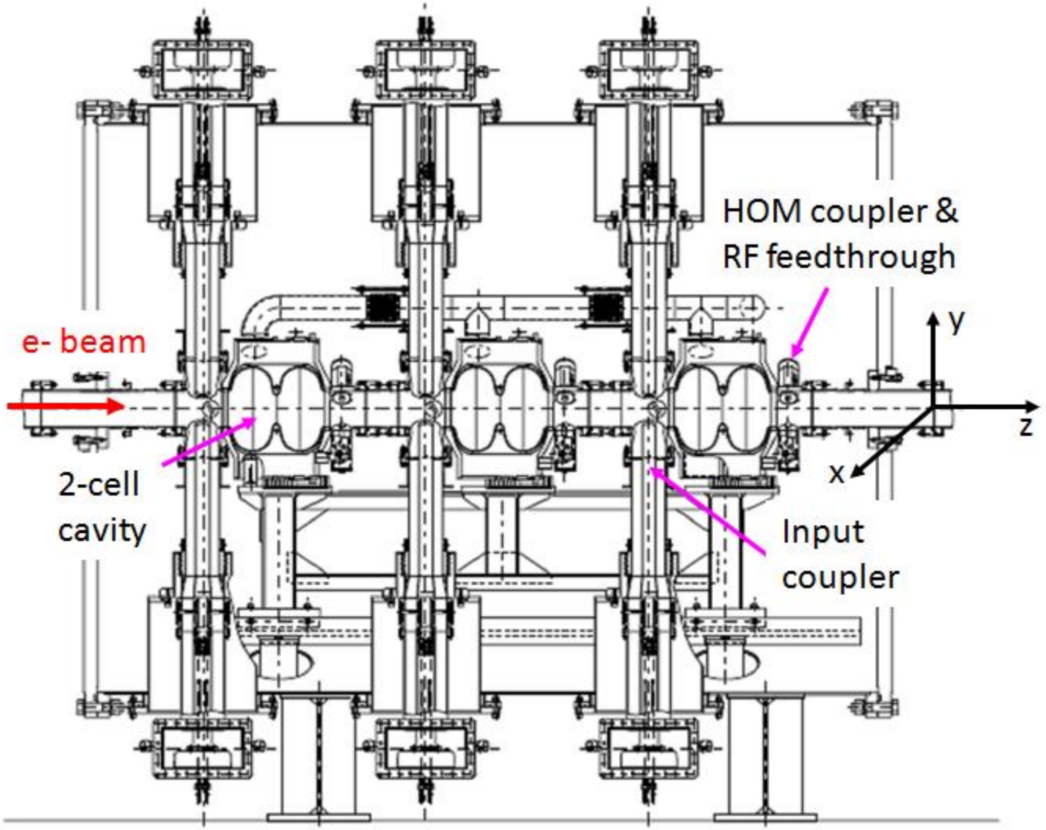
入射器空洞におけるRFキックの影響
コンパクトERL入射器クライオモジュール

- 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





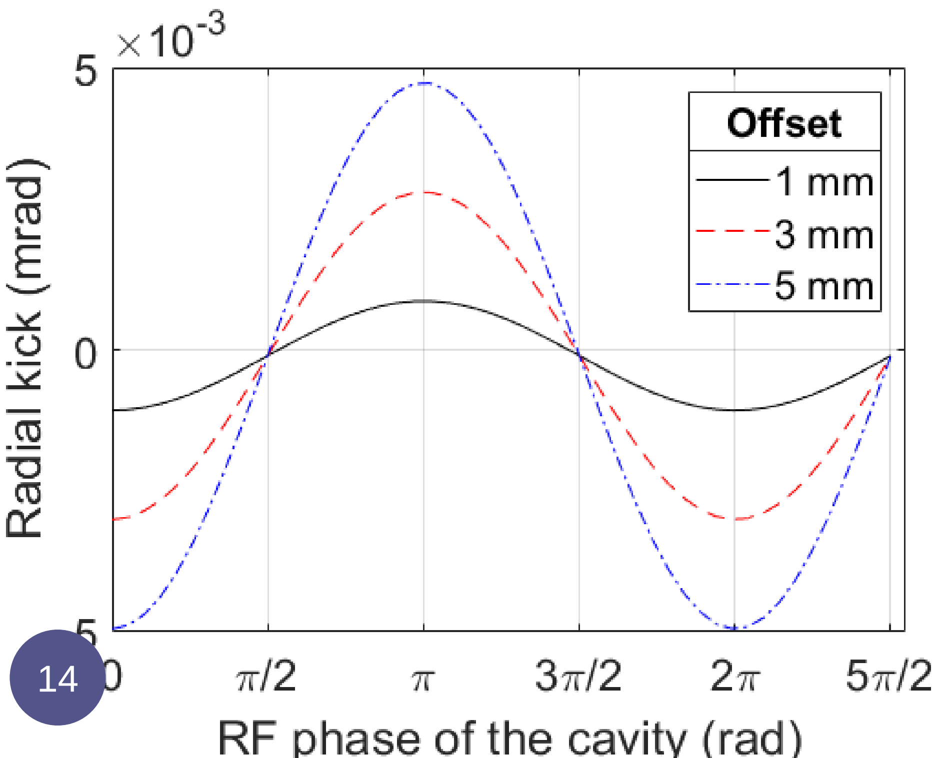
入射器空洞におけるRFキックの影響

横方向キックの値

- 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

入射器空洞におけるRFキックの影響
結論

- 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

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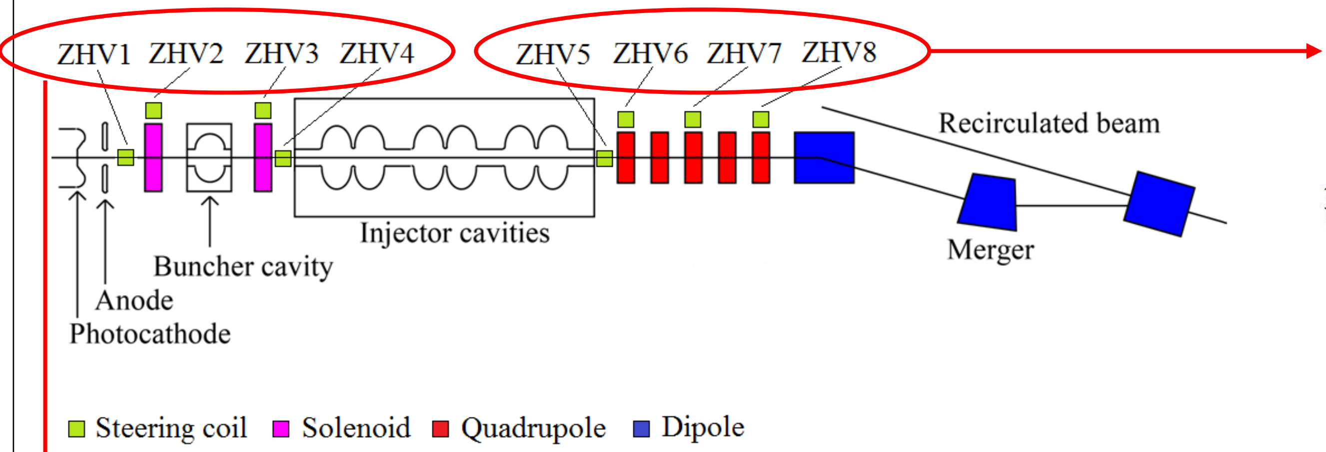
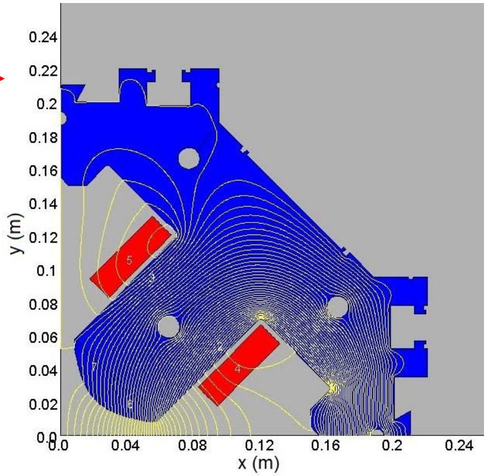
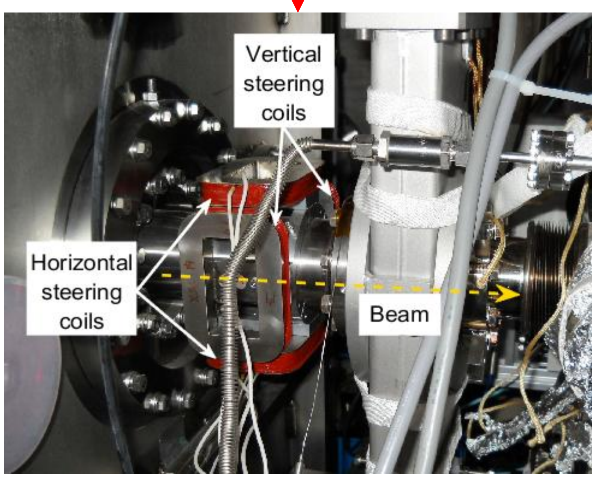
ビーム軌道に対するステアリングコイルの影響

ステアリングコイルのレイアウト







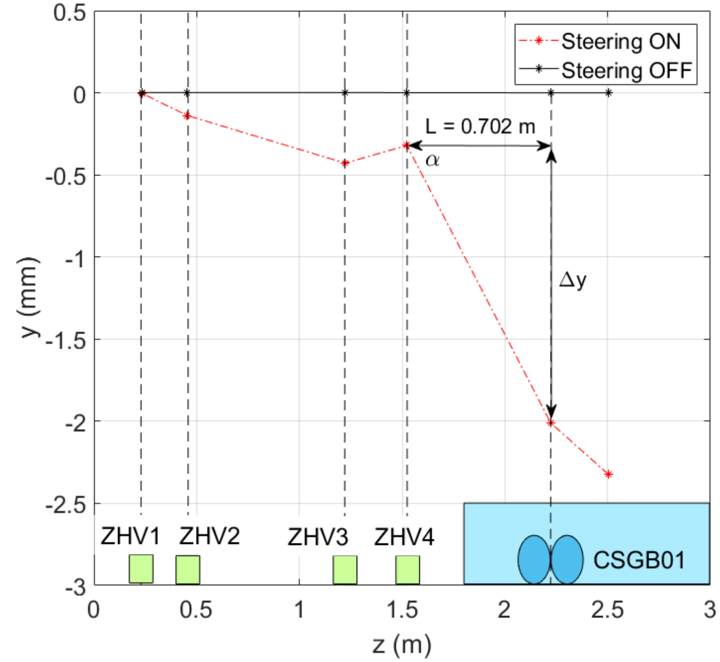
Steering name	Current (A)	ItoBL (T m/A)	Lenth (mm)	Gap (mm)	Width (mm)	Turns / coil
ZH1	-0.30	3.42 10^{-5}	59	133	95.5	90
ZV1	-0.90	3.23 10^{-5}				
ZH2	0.06	5.93 10^{-5}	63	132	66	122
ZV2	-0.18	6.07 10^{-5}				
ZH3	0.00	5.93 10^{-5}	63	132	66	122
ZV3	0.00	6.07 10^{-5}				
ZH4	0.71	3.21 10^{-5}	59	133	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}				

ビーム軌道に対するステアリングコイルの影響
垂直オフセットの推定

- 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.



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ビームハローシミュレーション
3つの影響のスタディから学んだこと

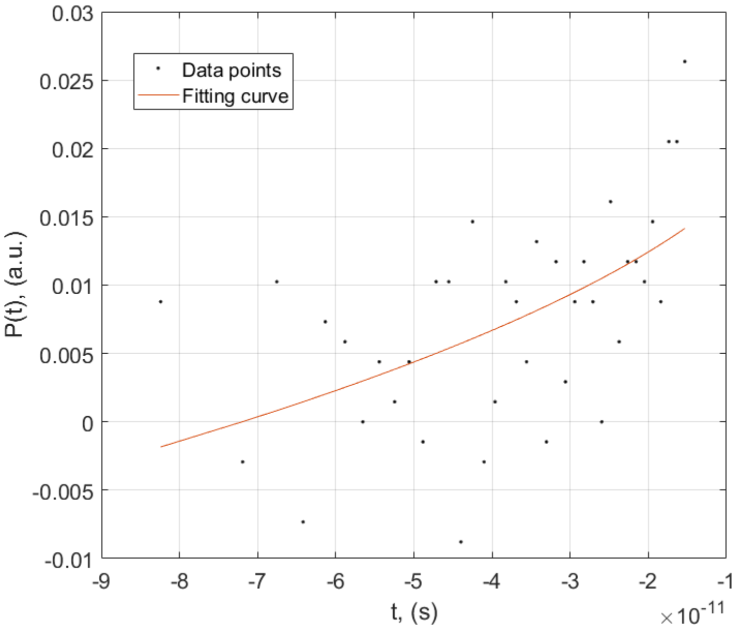
- Parameters of some devices that create transverse beam offsets in the injector cavities are already known
- The currents values of the steering coils ZHV1 – 8 are known from the operation log
- The relative horizontal offset of the injector cavity #2 is measured to be 2.6 mm
- As other possible effects 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:

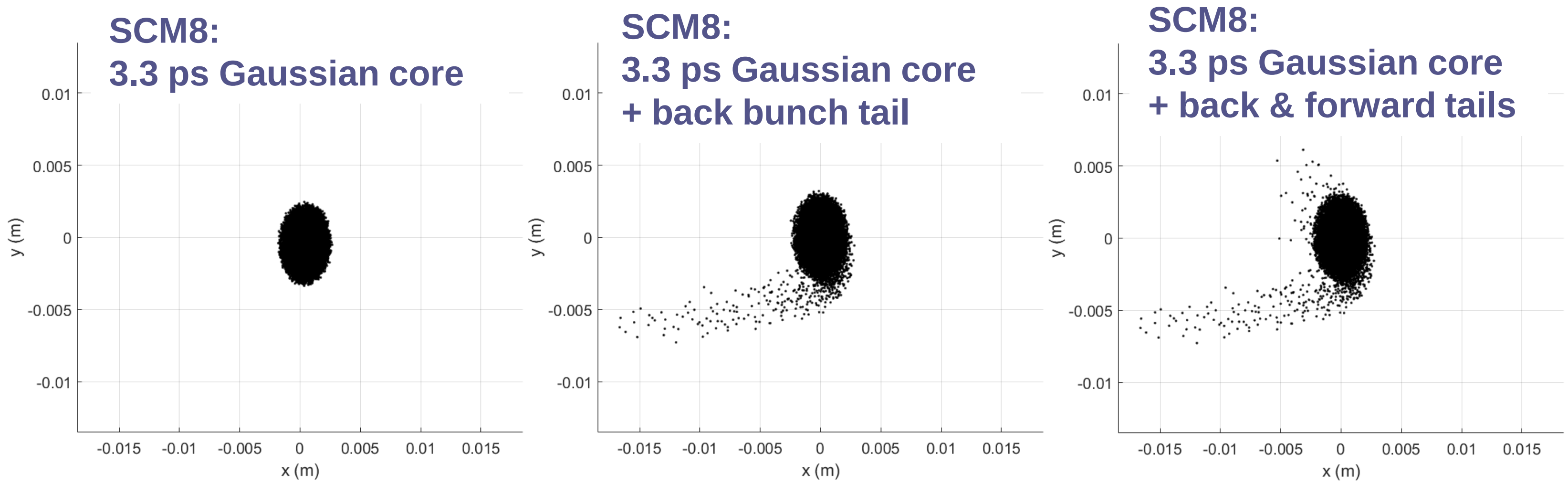
1. Longitudinal bunch tail
2. Effects of injector cavity RF kicks
3. Steering coils effects (and other possible effects) on the beam trajectory

ビームハローシミュレーション

前方テール



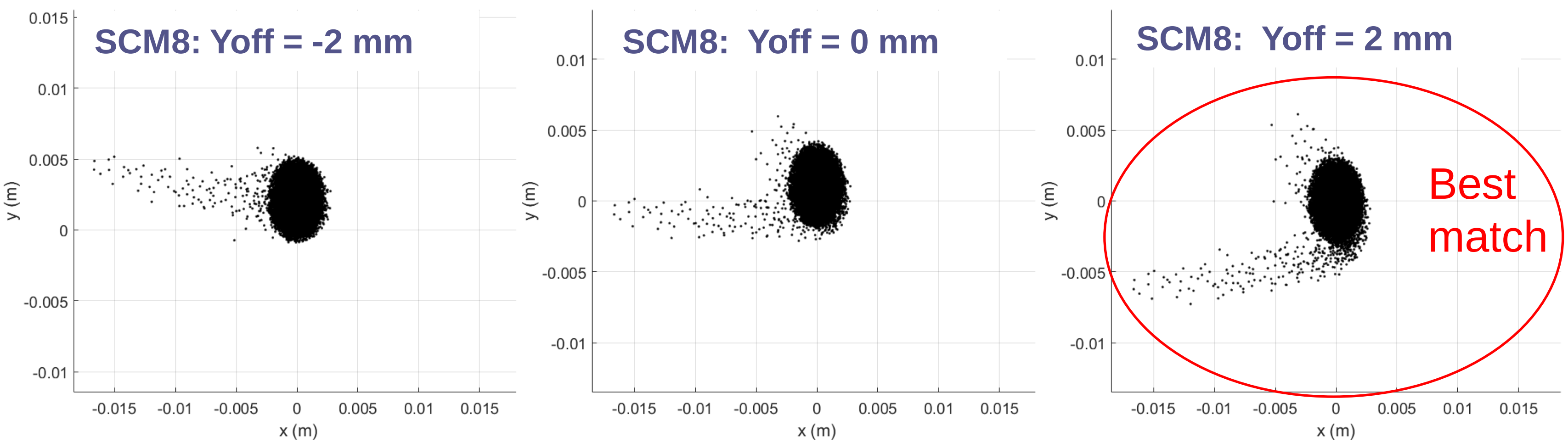
- The first step is to find a right combination of the halo formation factors, which reproduces well the measured profiles of vertical halo
- If one considers the longitudinal bunch tail alone, only one part of halo distribution (upper or lower, it depends on the observation point location) can be reproduced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

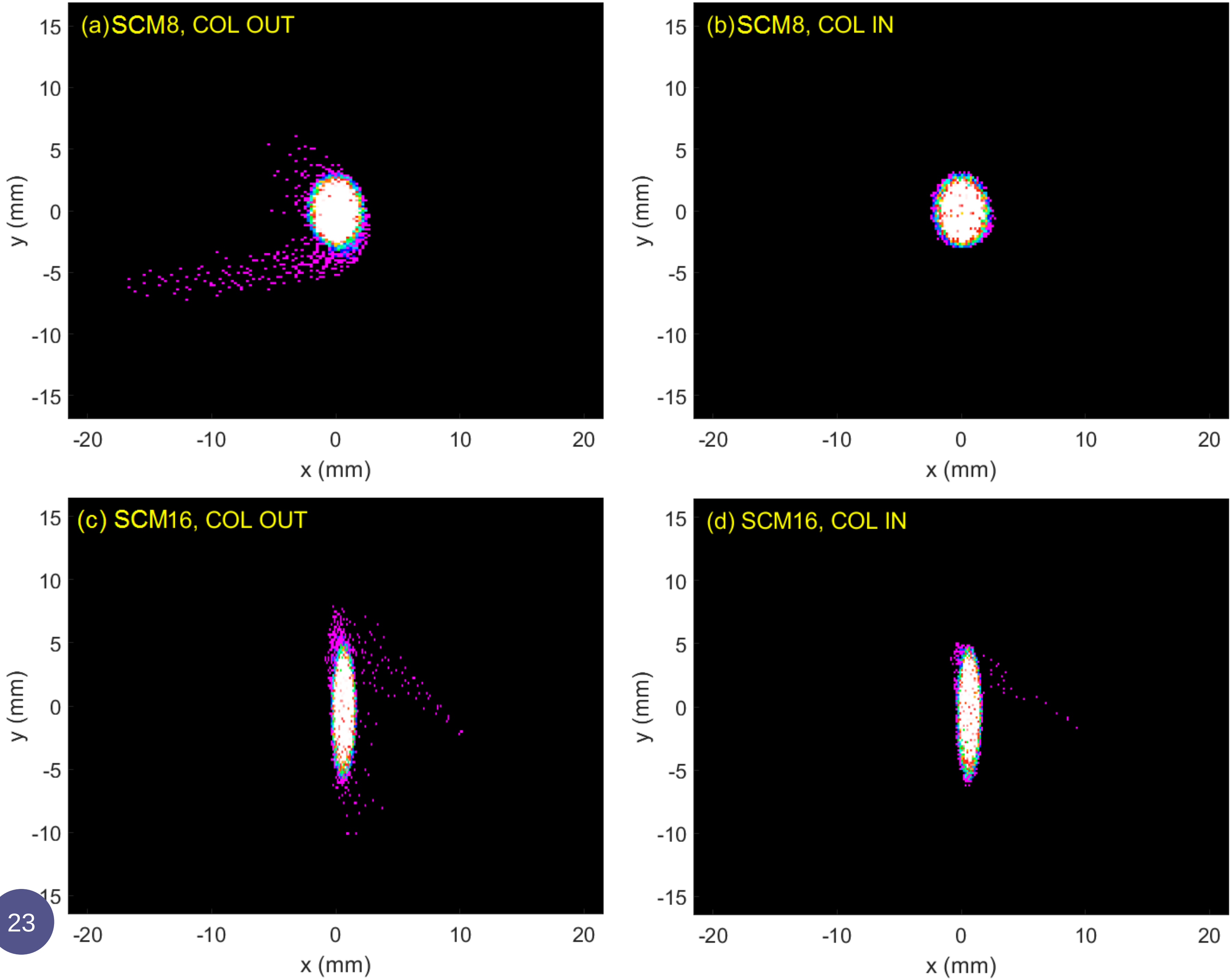


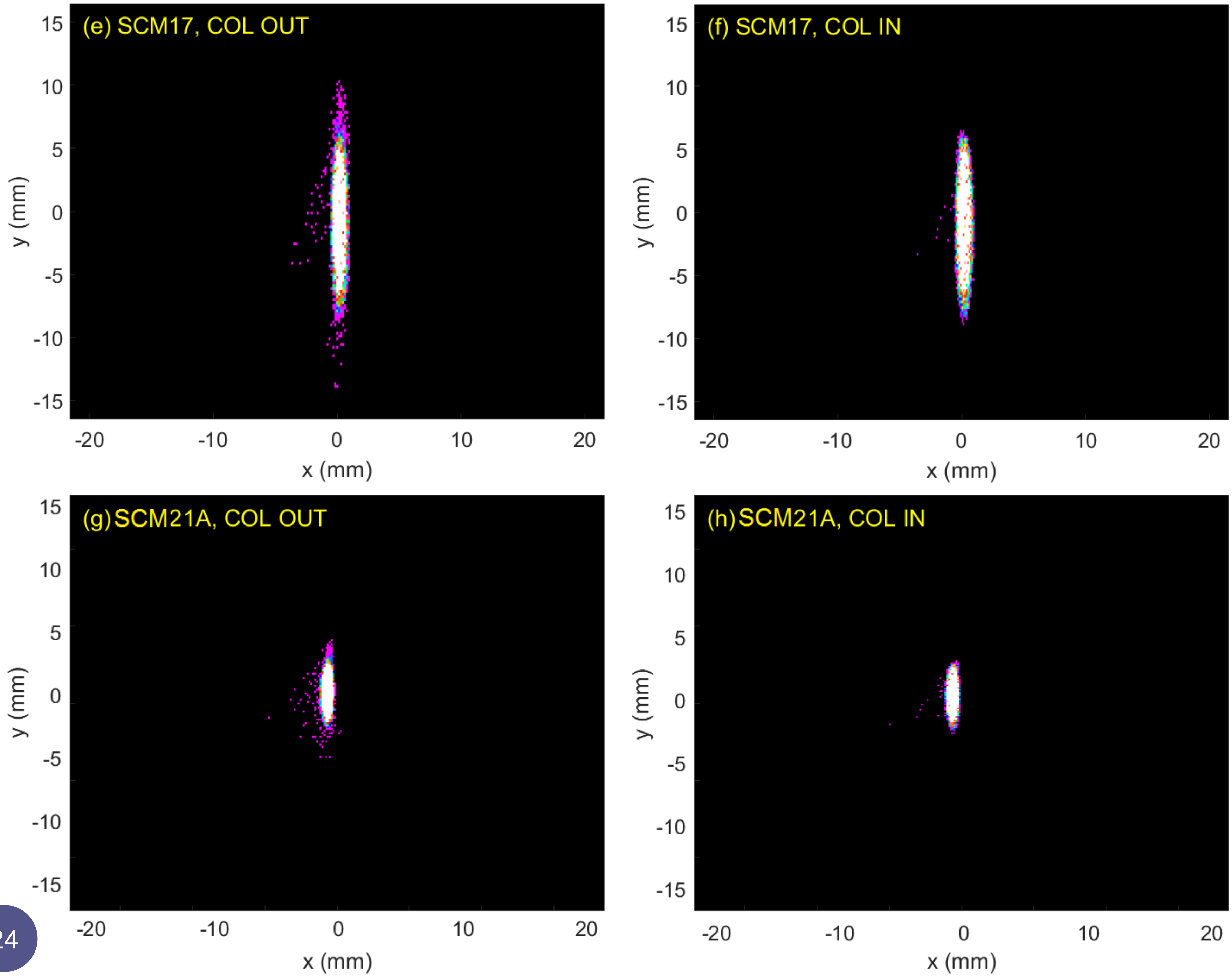
ビームハローシミュレーション

様々な影響によるビーム軌道のずれ

- 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

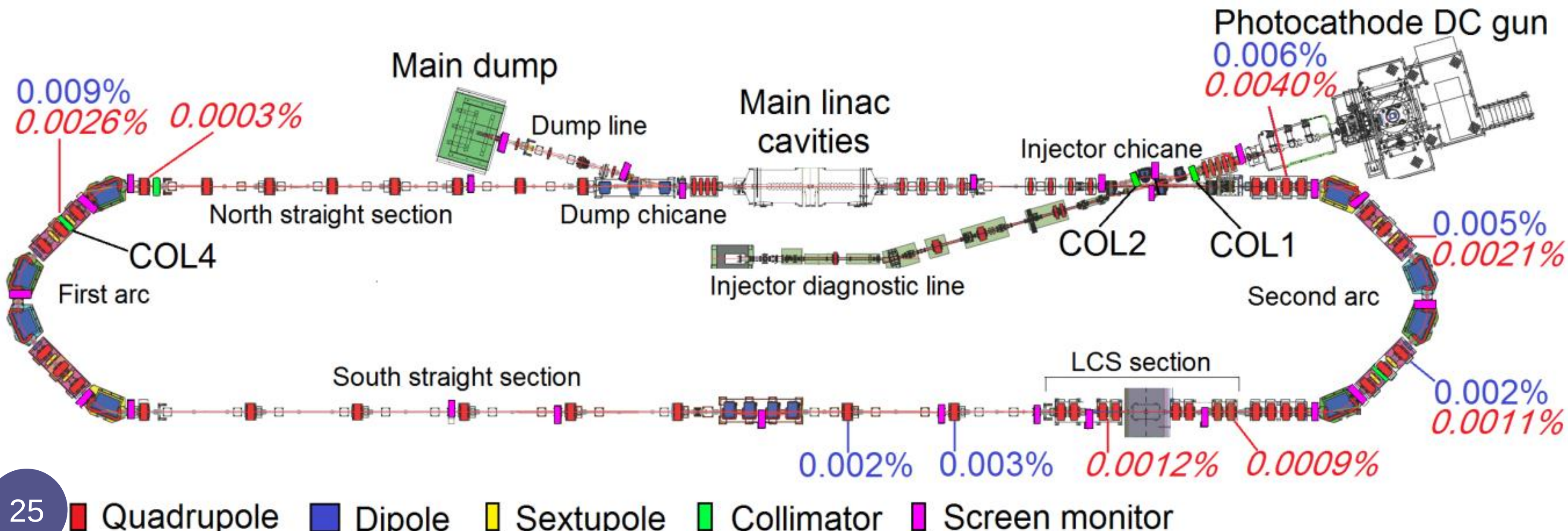



(a)SCM8, COL OUT
(b)SCM8, COL IN
(c) SCM16, COL OUT
(d) SCM16, COL IN
y (mm)
x (mm)
15
10
5
0
-5
-10
-15
-20
-10
0
10
20


(e) SCM17, COL OUT
(f) SCM17, COL IN
(g) SCM21A, COL OUT
(h) SCM21A, COL IN
y (mm)
x (mm)
15
10
5
0
-5
-10
-15
-20
20

ビームハローシミュレーション
ビームロス率の比較

- 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



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結論

- Non-negligible transverse halos have been experimentally observed at cERL
- We suppose 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
- It may be the first time to prove that the transverse halo can be formed from the longitudinal bunch tail
- 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.

ご清聴ありがとうございました