Development of Non-Destructive Beam Envelope Measurements

Using BPMs for Low-Beta Heavy Ion Beams in SRF Cavities

RIKEN Nishina Center Accelerator Advanced Group
Takahiro Nishi

Collaborators

T. Adachi, O. Kamigaito, N. Sakamoto,
T. Watanabe and K. Yamada

Outline

1. Introduction: SRILAC and B(E)PMs
2. Beam envelope estimation by BPM signals
3. Signal distortions caused by BPM shapes with short bunch beam
4. Improvement of sensitivity for beam emittance
5. Example of analysis with experimental data
6. Future Outlook and Summary

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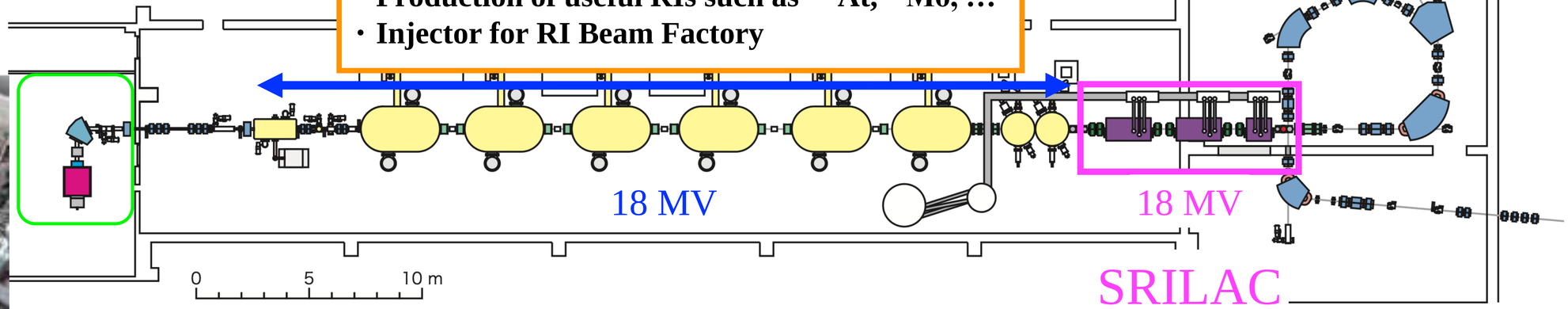
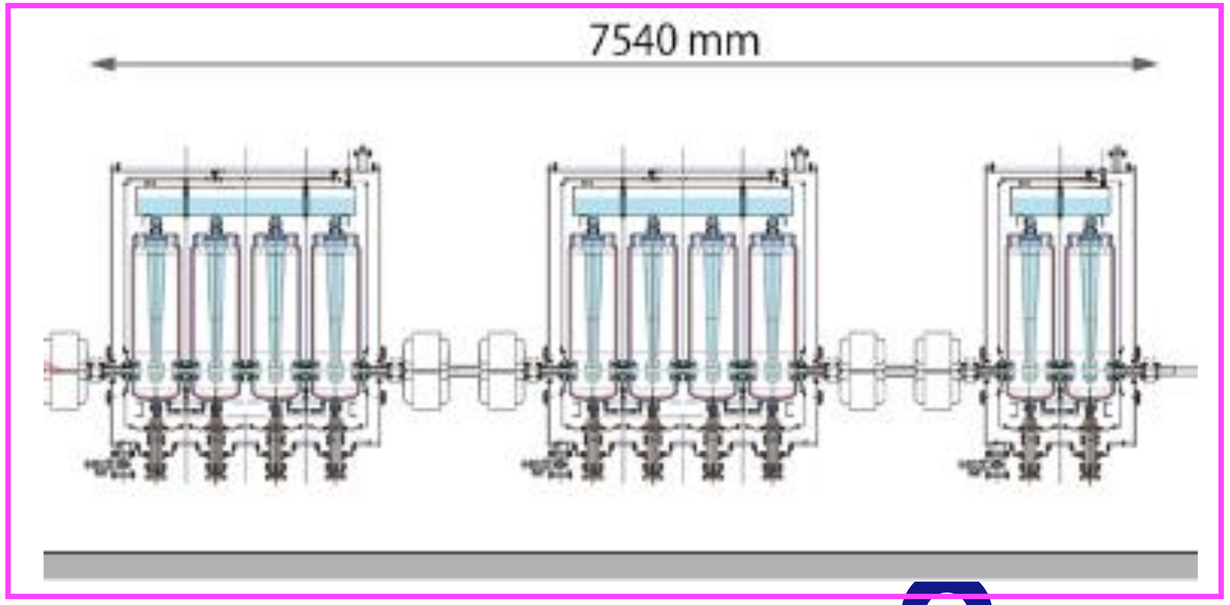
Superconducting RIKEN LINAC: SRILAC

28GHz SC-ECRIS

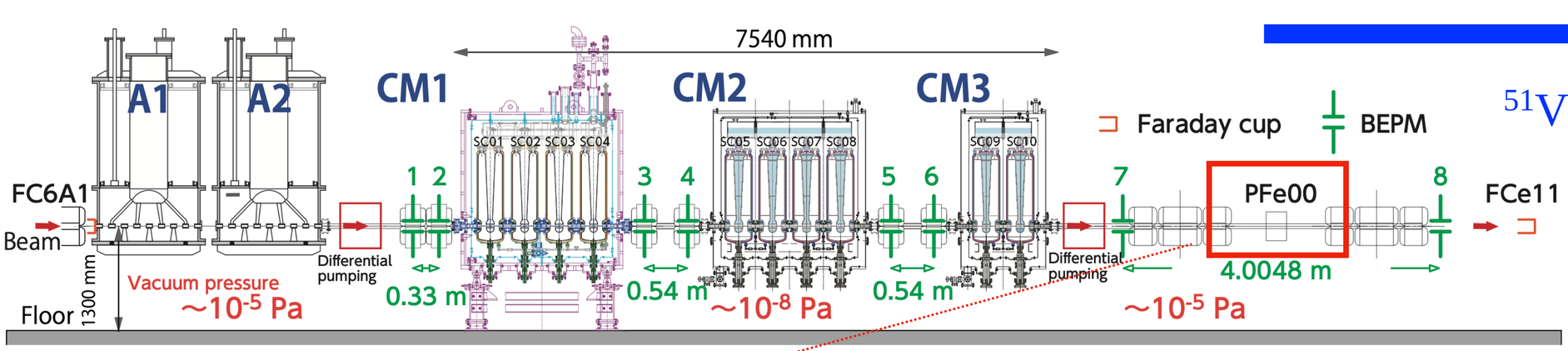
- **Super-heavy element synthesis: [119], [120], …**
- **Production of useful RIs such as ^{211}At, ^{99}Mo, …**
- **Injector for RI Beam Factory**



Num. of Cryomodules	3
Num. of Cavities	10 (SC-QWRs)
Frequency	73 MHz (CW)
Operating Temperature	4.5 K
E_{in}	3.6 MeV/u
E_{out} (design)	6.5 MeV/u for M/q = 6 (tunable)
Total voltage (design)	~ 18 MV



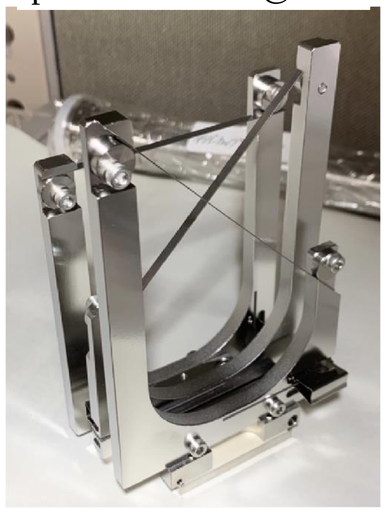
Beam control after SRILAC: Q-scan method



$^{51}V^{13+}$ a few tens eμA / ~ kW

Schematic view of Superconducting RIKEN LINAC (SRILAC)

profile monitor @ e00



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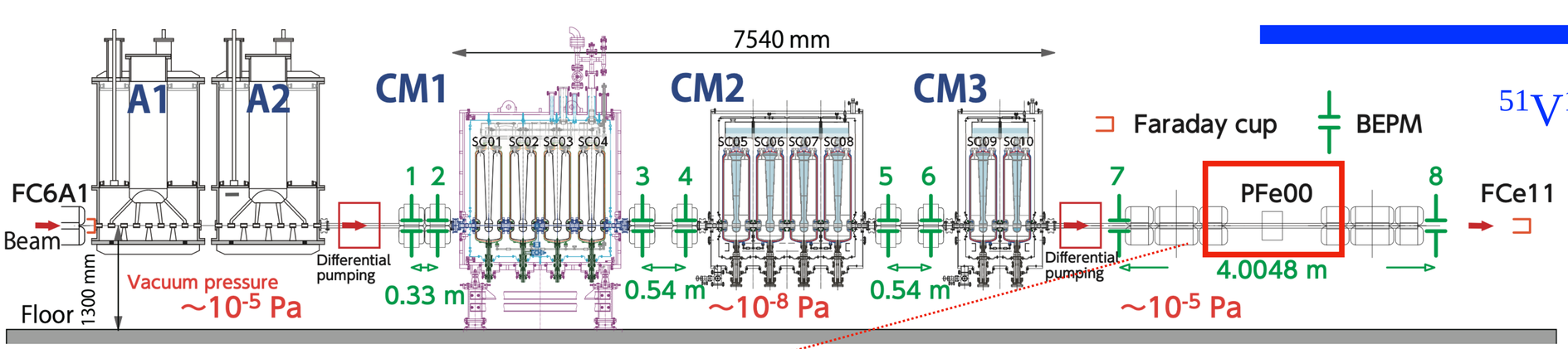
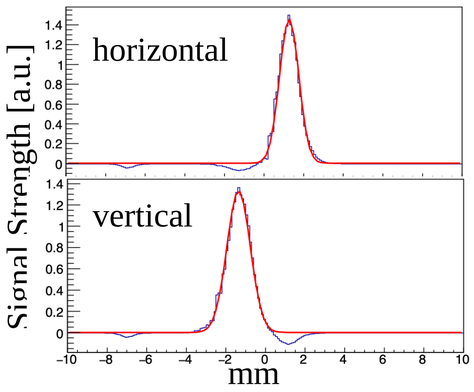
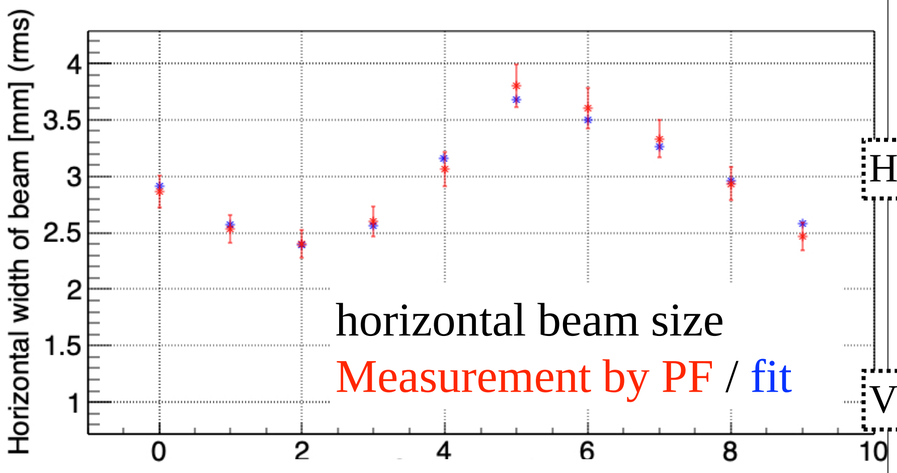


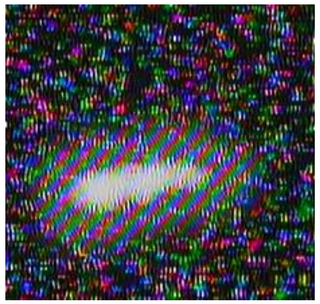
Schematic view of Superconducting RIKEN LINAC (SRILAC)

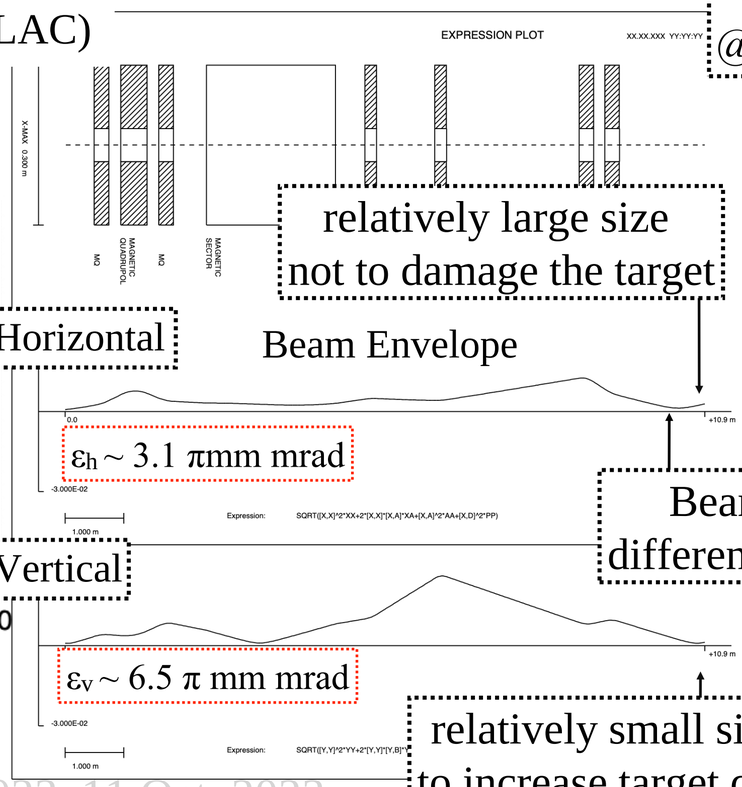
signal of profile monitor





Spot image
@ GARISIII target (Viewer)

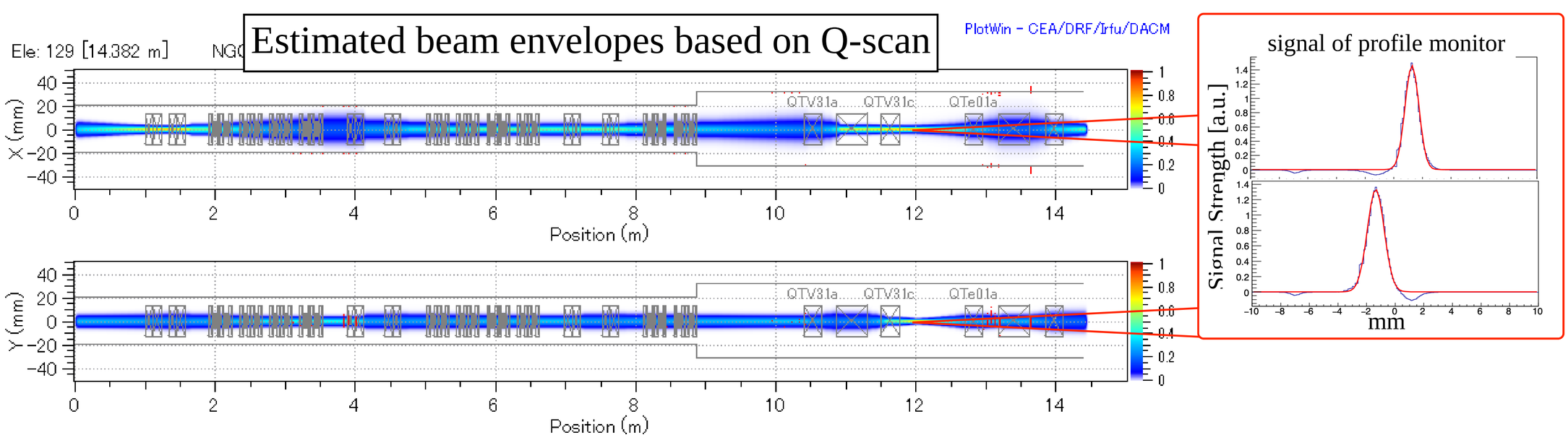


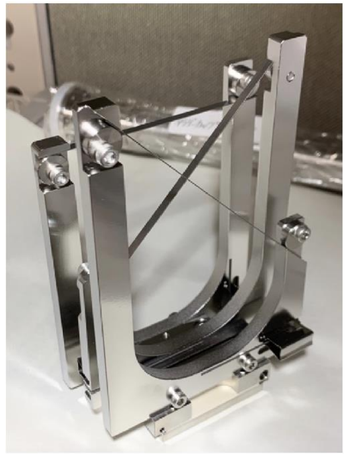


Beam loss < a few %
(measured by FC)

Motivation: Beam envelope / loss control

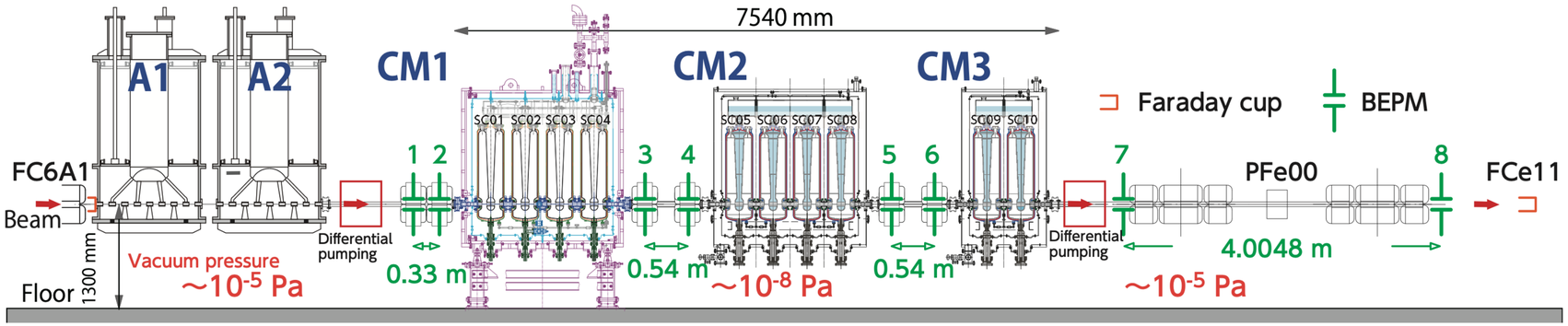
- Control beam envelope / loss is essential especially for SRF cavities….
- Destructive monitors (wire scanner called profile monitors etc…)
  → not installed between cavities to avoid dust creation
- Conventional Q-scan and simulation based on transfer matrix
  → works well / needs to reduce beam intensity (~100 enA) and to change optics to several modes
- For continuous monitor during beam supply, we needs **non-destructive method**





profile monitor @ e00

Candidate: Beam Energy Position Monitor (BEPM)



Schematic view of Superconducting RIKEN LINAC (SRILAC)

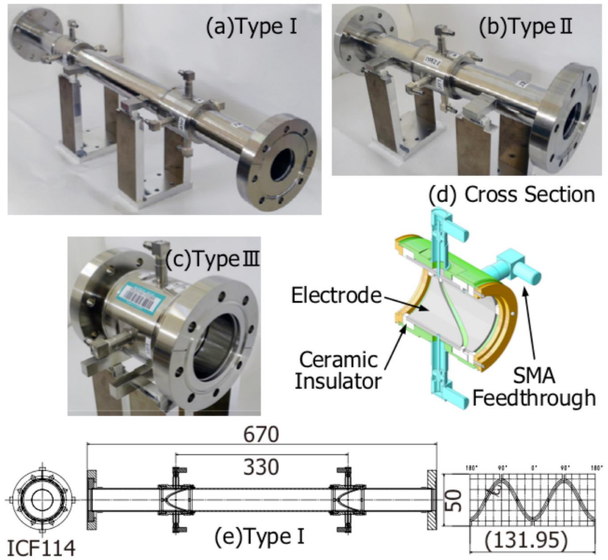
8 B(E)PMs are installed in beam line

・Position at each BEPMs

・Energy at each sections (2 BEPMs)

are continuously monitored.

→ utilize these BEPMs for beam envelope measurement



T. Watanabe *et al.*,

Proc. of IBIC2020, pp. 718–723, (2020)

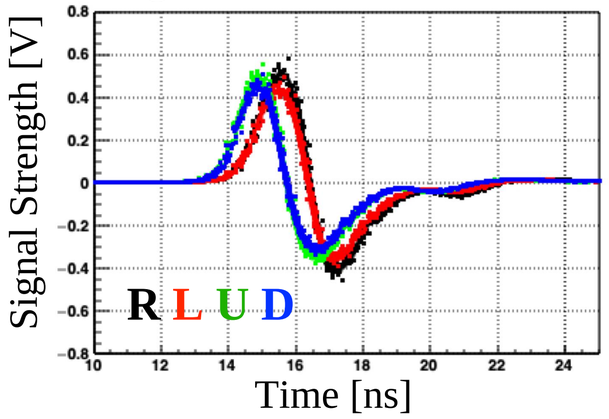
List of BEPMs in SRILAC beam line

Name in this talk	BEPM#	Length of electrode	Inner radius	Shape
Type A	**1 ~ 6**	50 mm	20 mm	**cos2θ**
Type B	**7, 8**	60 mm	30 mm	

※ TypeI, II: A TypeIII: B

higher sensitivity for position, timing and **quadrupole moments**

Signals from BEPM#3



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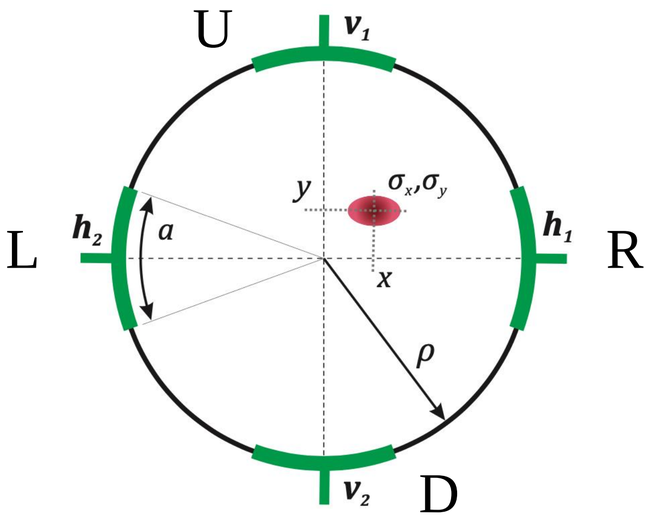
Quadrupole measurements by BPMs



schematic view of BPMs

Emittance measurements by BPMs are studied in decades…

- R. H. Miller *et al.*, Proc. HEACC'83, pp. 603-605 (1983)
- **A. Sounas *et al.*, Proc. HB2018, pp. 399–403 (2018)**

$$Q \equiv \sigma_x^2 - \sigma_y^2 = \langle x^2 \rangle - \langle y^2 \rangle - \langle x \rangle^2 + \langle y \rangle^2$$

second-order quadrupolar term

$$V_R = I_{beam}(c_0 + c_1 D_x + c_2 M_2 + c_3 M_{3,x} + \cdots)$$
$$V_L = I_{beam}(c_0 - c_1 D_x + c_2 M_2 - c_3 M_{3,x} + \cdots)$$
$$V_U = I_{beam}(c_0 + c_1 D_y - c_2 M_2 + c_3 M_{3,y} + \cdots)$$
$$V_D = I_{beam}(c_0 - c_1 D_y - c_2 M_2 - c_3 M_{3,y} + \cdots)$$

A. Sounas, M. Gasior, and T. Lefevre,
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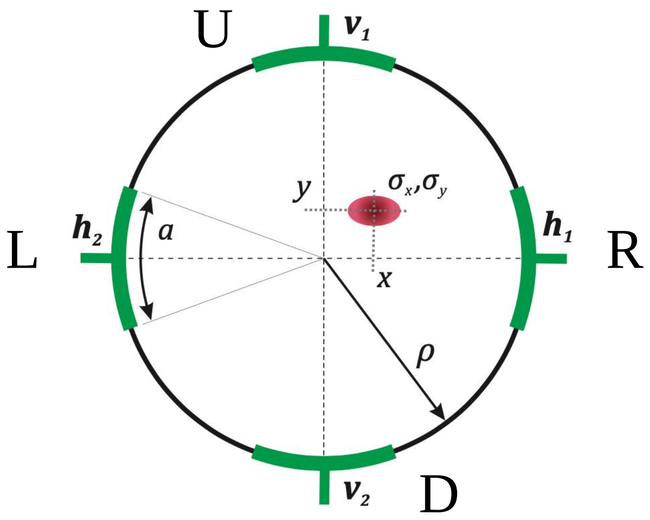

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higher order term

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$$= M_2 - D_x^2 + D_y^2 \quad \text{second-order quadrupolar term}$$
$$= k_q \frac{V_R + V_L - V_U - V_D}{V_R + V_L + V_U + V_D} - D_x^2 + D_y^2$$

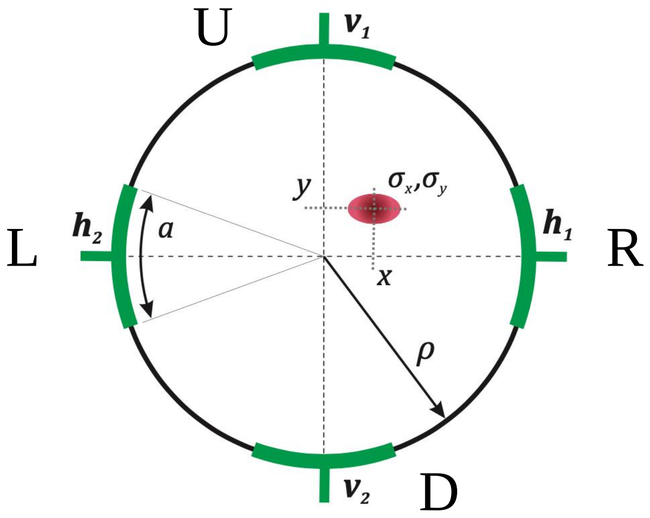
$$D_x = k_x \frac{V_R - V_L}{V_R + V_L + V_U + V_D},\ D_y = k_y \frac{V_U - V_D}{V_L + V_R + V_U + V_D}$$

(neglect higher order term / $k_q \equiv c_2/c_0$ / $k_{x,y} \equiv c_1/2c_0$)

"Their application has been proven to be limited …."

- low sensitivity for quadrupole momentum Q
  →
- parasitic position signal incorporated into the measured Q
  →

Quadrupole measurements by BPMs



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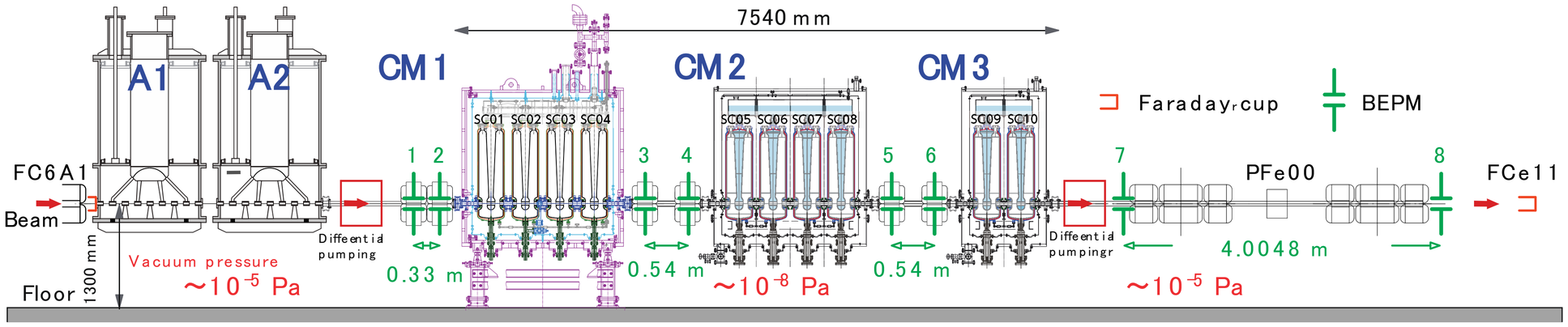
"Their application has been proven to be limited …."

- low sensitivity for quadrupole momentum Q
  → Relatively large beam size (~ a few πmm mrad)
- parasitic position signal incorporated into the measured Q
  → Small contribution from higher order term (by cos2θ shape)

Quadrupole moments and beam envelope

$$\begin{pmatrix} Q_1 \\ Q_2 \\ \vdots \\ Q_8 \end{pmatrix} = \begin{pmatrix} M_x(1\ 0)_{11}^2, -2M_x(1\ 0)_{11}M_x(1\ 0)_{12}, M_x(1\ 0)_{12}^2, -M_y(1\ 0)_{11}^2, \cdots \\ M_x(2\ 0)_{11}^2, -2M_x(2\ 0)_{11}M_x(2\ 0)_{12}, M_x(2\ 0)_{12}^2, -M_y(2\ 0)_{11}^2, \cdots \\ \vdots \\ M_x(8\ 0)_{11}^2, -2M_x(8\ 0)_{11}M_x(8\ 0)_{12}, M_x(8\ 0)_{12}^2, -M_y(8\ 0)_{11}^2, \cdots \end{pmatrix} \begin{pmatrix} \sigma_{xx}(0) \\ \sigma_{xx'}(0) \\ \sigma_{x'x'}(0) \\ \sigma_{yy}(0) \\ \sigma_{yy'}(0) \\ \sigma_{y'y'}(0) \end{pmatrix}$$



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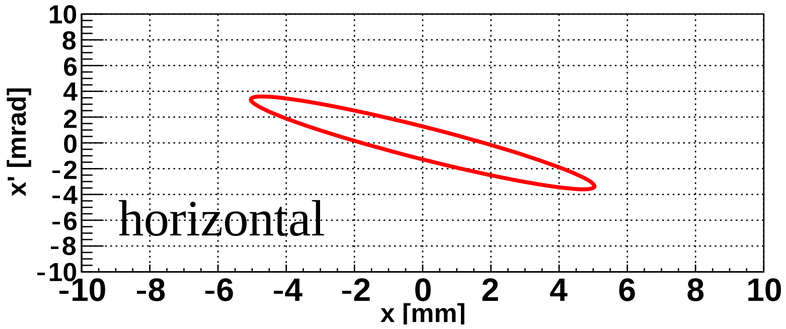
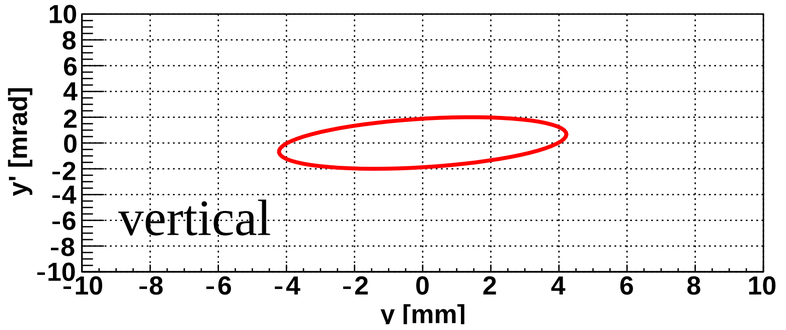
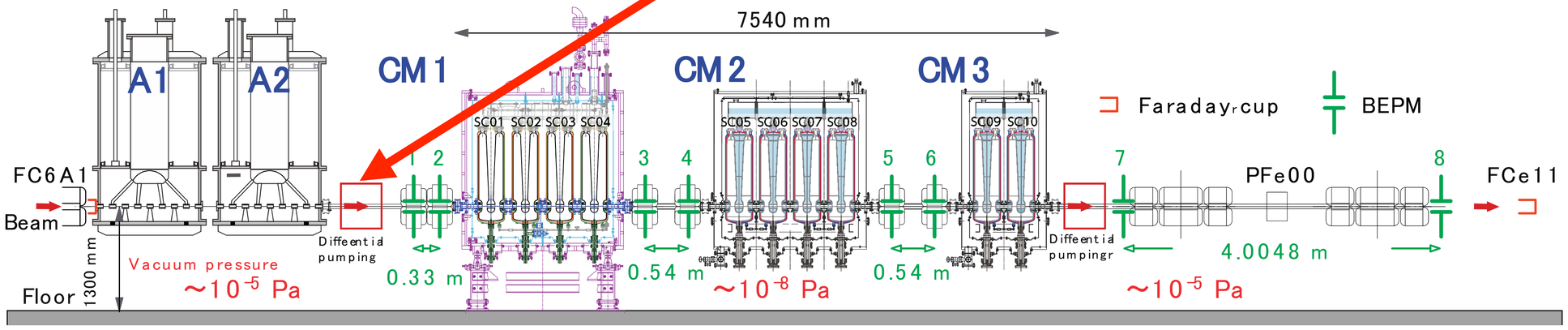
Phase Ellipse at input point







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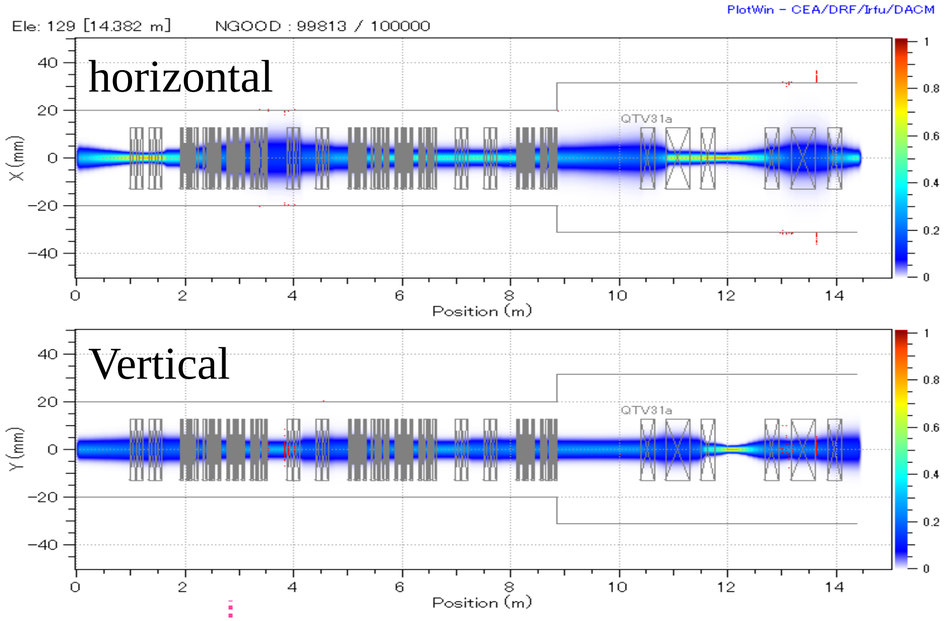
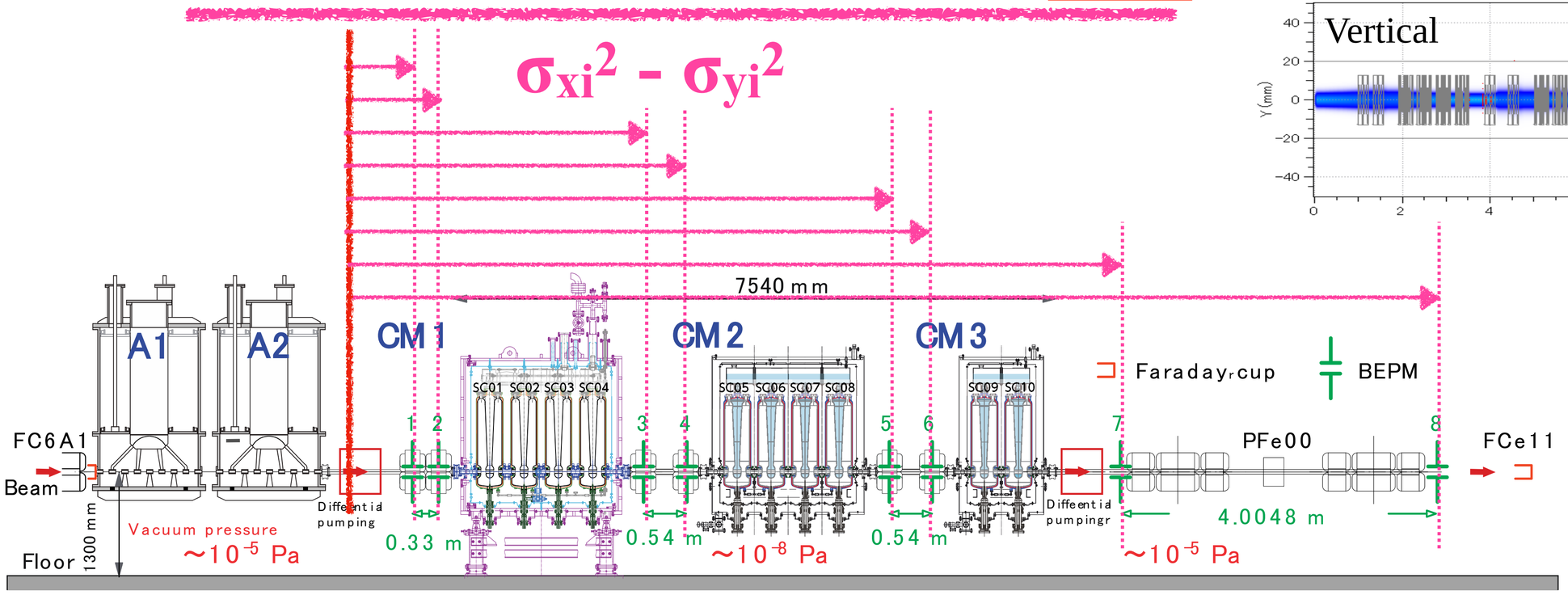
Beam Envelope (calc. by TraceWin)





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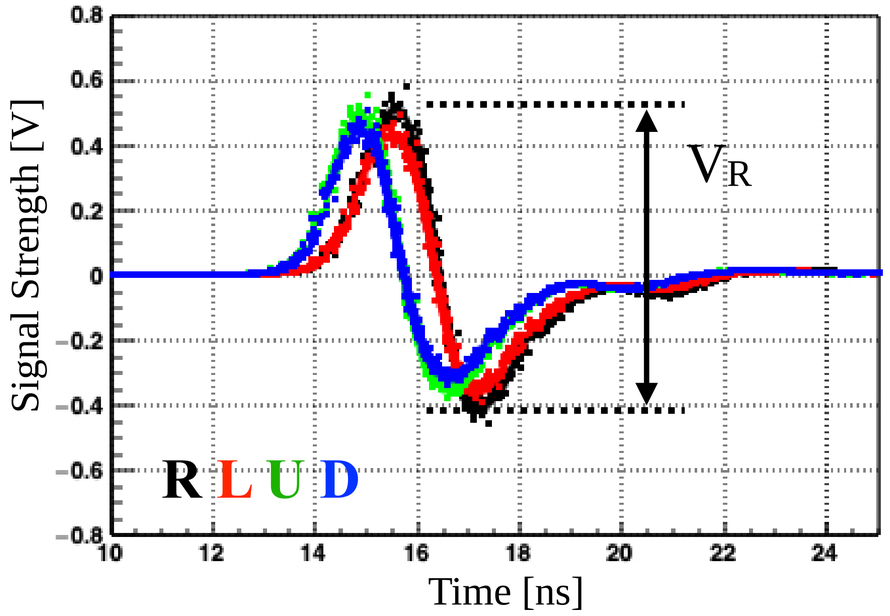
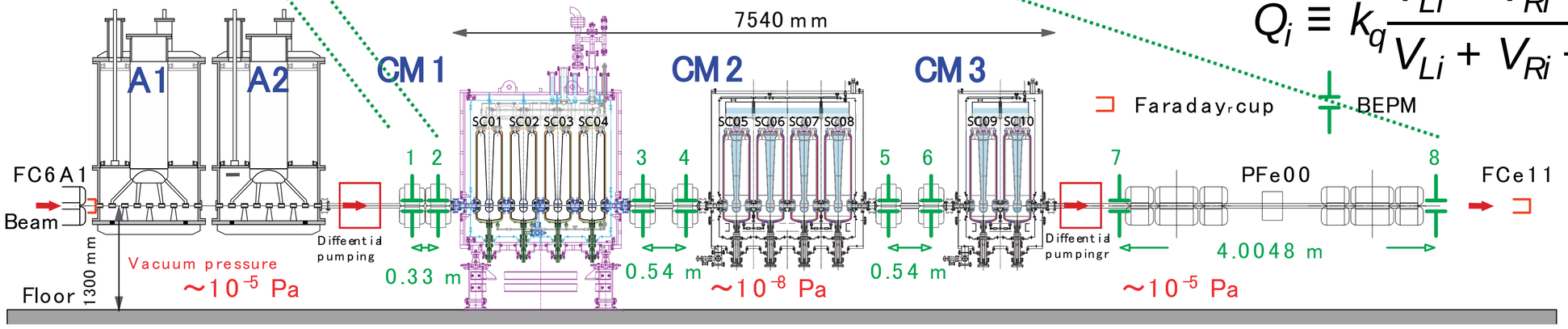
Signals from BEPM#3



$$Q_i \equiv k_q \frac{V_{Li} + V_{Ri} - V_{Ui} - V_{Di}}{V_{Li} + V_{Ri} + V_{Ui} + V_{Di}} - \langle x \rangle^2 + \langle y \rangle^2$$



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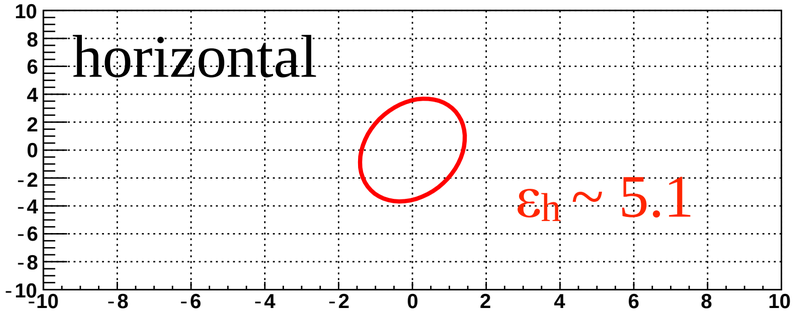
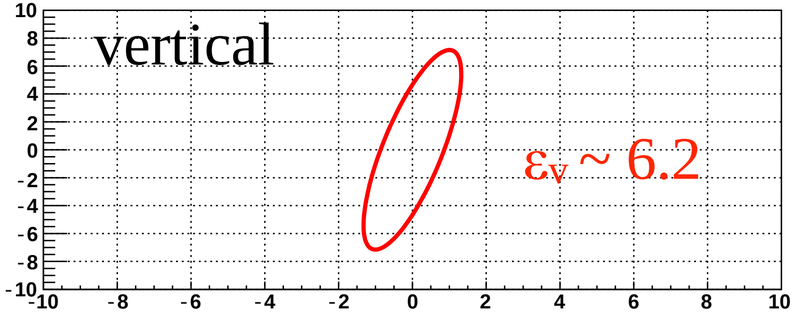
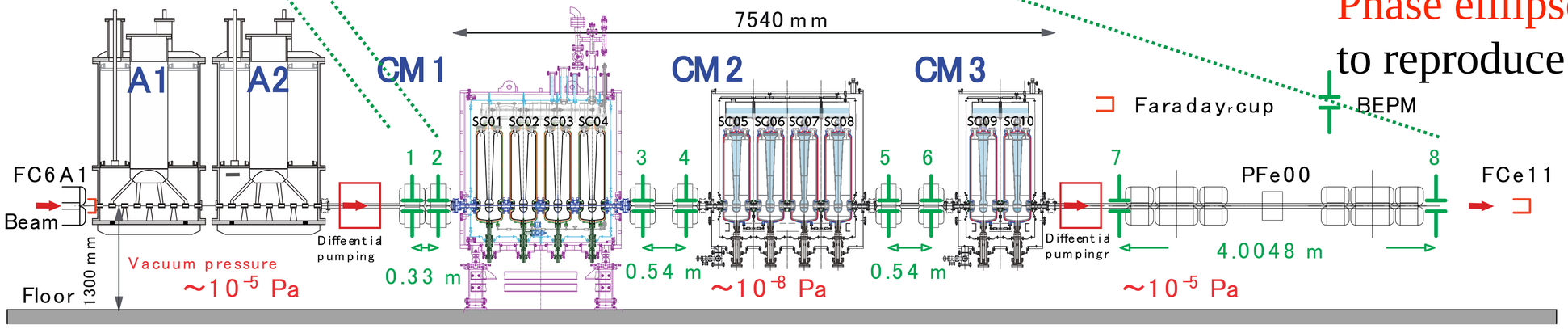




Phase elllipses are estimated to reproduce measured Qs.



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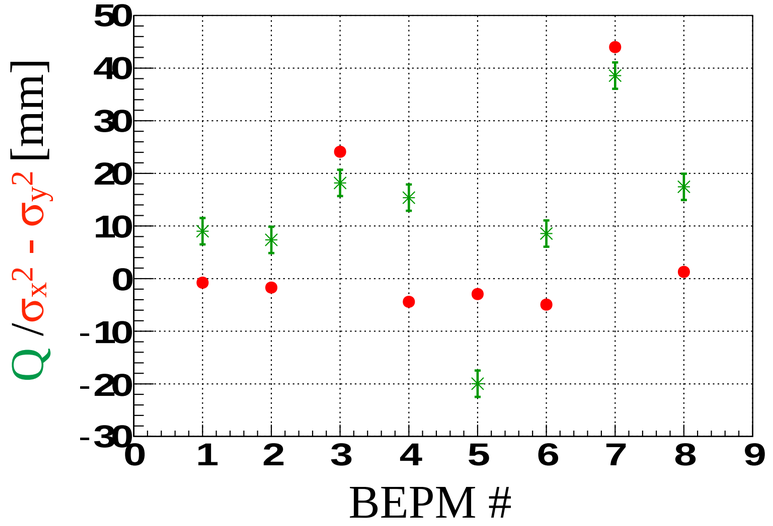
First trial to reproduce experimental data

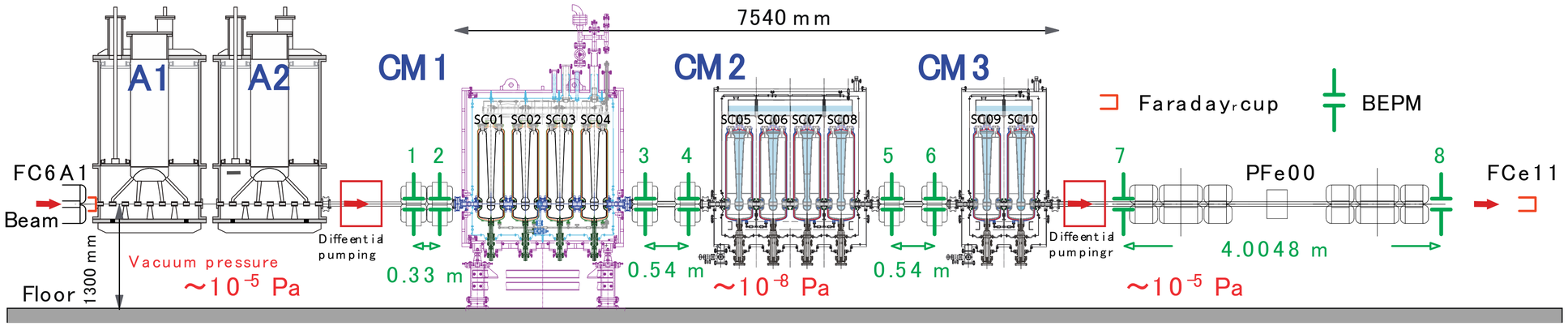


Measured

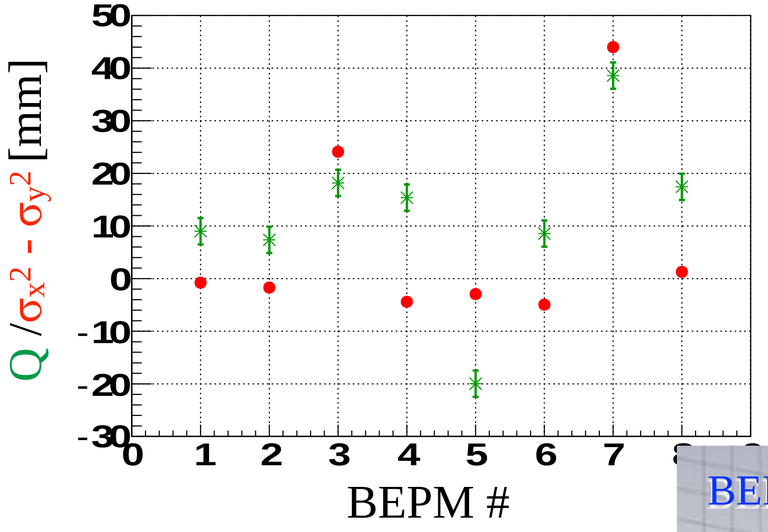
$$\begin{pmatrix} Q_1 \\ Q_2 \\ \vdots \\ Q_8 \end{pmatrix} = \begin{pmatrix} M_x(1\ 0)_{11}^2, -2M_x(1\ 0)_{11}M_x(1\ 0)_{12}, M_x(1\ 0)_{12}^2, -M_y(1\ 0)_{11}^2, \cdots \\ M_x(2\ 0)_{11}^2, -2M_x(2\ 0)_{11}M_x(2\ 0)_{12}, M_x(2\ 0)_{12}^2, -M_y(2\ 0)_{11}^2, \cdots \\ \vdots \\ M_x(8\ 0)_{11}^2, -2M_x(8\ 0)_{11}M_x(8\ 0)_{12}, M_x(8\ 0)_{12}^2, -M_y(8\ 0)_{11}^2, \cdots \end{pmatrix} \begin{pmatrix} \sigma_{xx}(0) \\ \sigma_{xx'}(0) \\ \sigma_{x'x'}(0) \\ \sigma_{yy}(0) \\ \sigma_{yy'}(0) \\ \sigma_{y'y'}(0) \end{pmatrix}$$

Fit

Could **NOT** reproduce exp. data…



First trial to reproduce experimental data



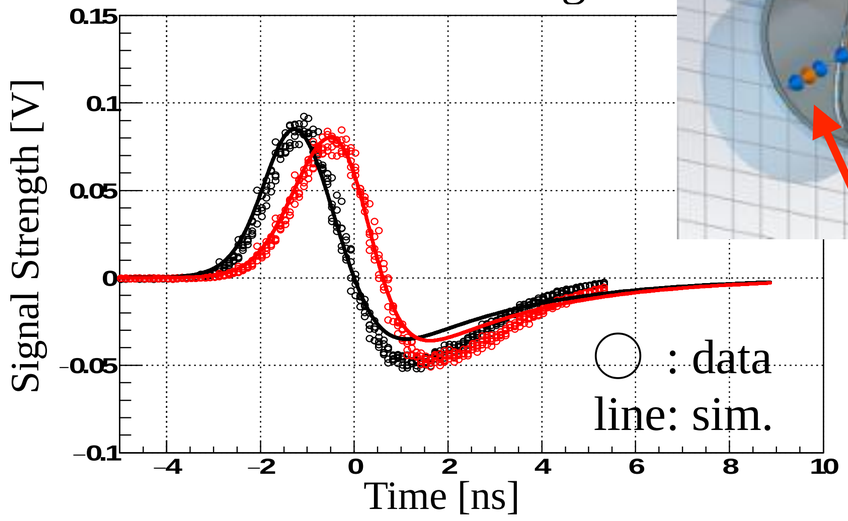
Measured

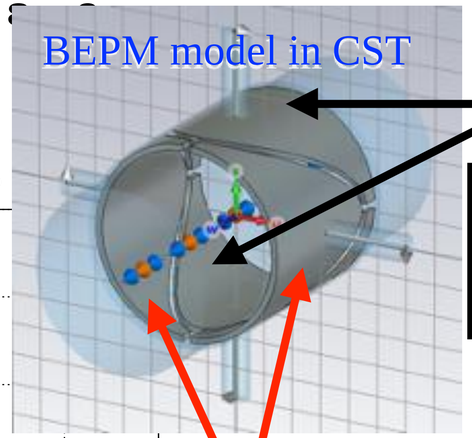
Fit

$$\begin{pmatrix} Q_1 \\ Q_2 \\ \vdots \\ Q_8 \end{pmatrix} = \begin{pmatrix} M_x(1\ 0)_{11}^2, -2M_x(1\ 0)_{11}M_x(1\ 0)_{12}, M_x(1\ 0)_{12}^2, -M_y(1\ 0)_{11}^2, \cdots \\ M_x(2\ 0)_{11}^2, -2M_x(2\ 0)_{11}M_x(2\ 0)_{12}, M_x(2\ 0)_{12}^2, -M_y(2\ 0)_{11}^2, \cdots \\ \vdots \\ M_x(8\ 0)_{11}^2, -2M_x(8\ 0)_{11}M_x(8\ 0)_{12}, M_x(8\ 0)_{12}^2, -M_y(8\ 0)_{11}^2, \cdots \end{pmatrix} \begin{pmatrix} \sigma_{xx}(0) \\ \sigma_{xx'}(0) \\ \sigma_{x'x'}(0) \\ \sigma_{yy}(0) \\ \sigma_{yy'}(0) \\ \sigma_{y'y'}(0) \end{pmatrix}$$

Could **NOT** reproduce exp. data…

BEPM waveform signals





$V_{downstream}$ tends to be **smaller** than $V_{upstream}$ in both experimental and simulation data.

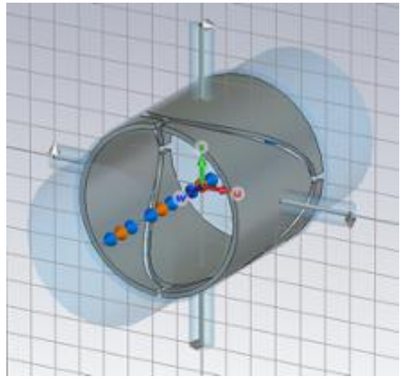
$$V_{upstream} = b \times V_{downstream}$$

b (bias factor) : 1.03 ~ 1.06

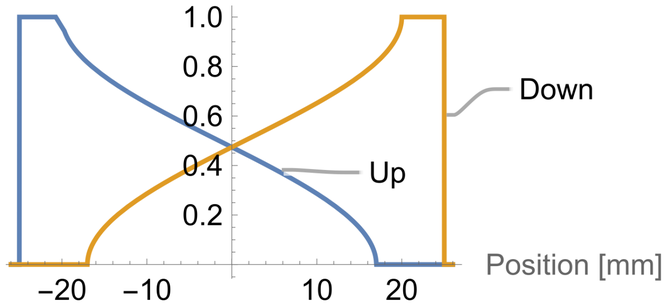
Origin of the bias: BEPM structure / short bunch length

Calculation of the output voltage with structure effect

T. Adachi *et al.*, Proc. of PASJ2023, THOA4 (2023)



Coverage of electrode $\phi(l)$



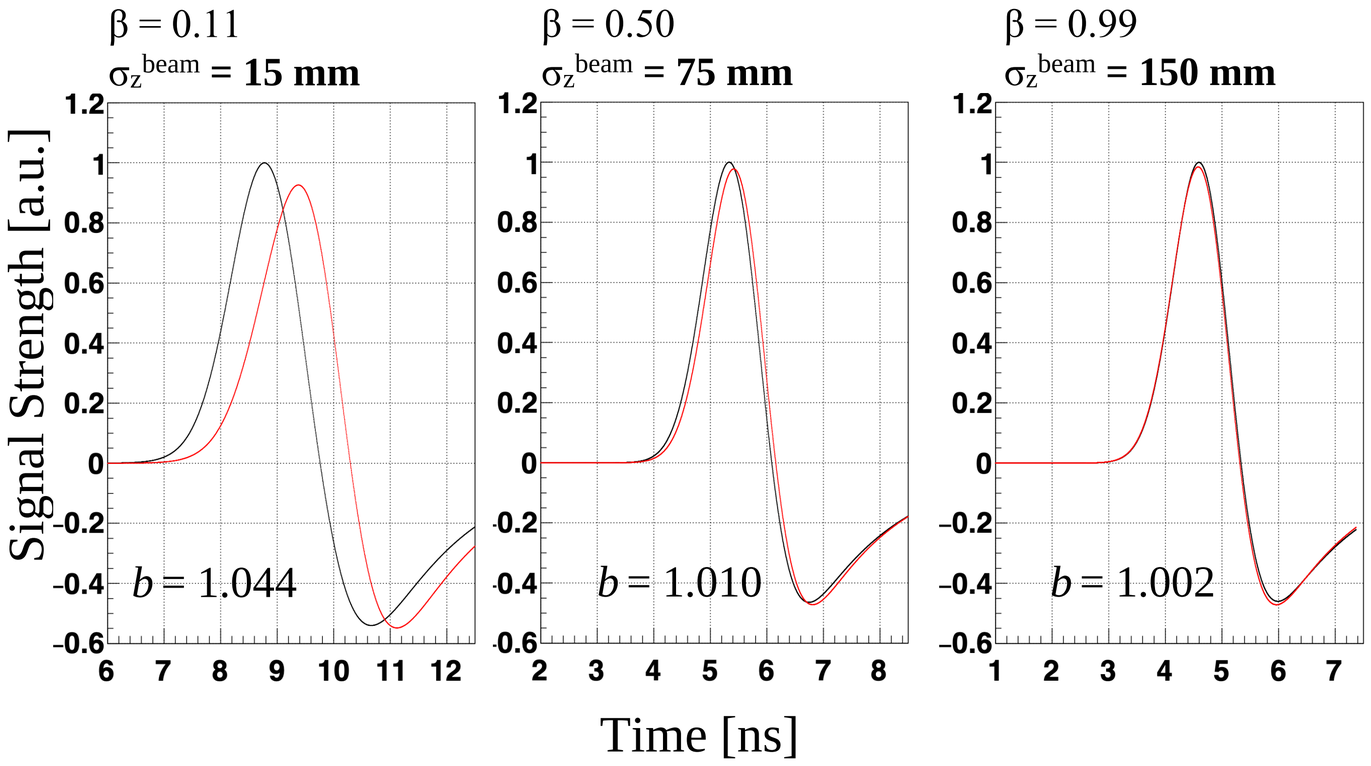
Shape functions of Up and Down electrode

$$V(t) = \frac{1}{L}\int_{-L/2}^{L/2}\left\{\frac{\phi(l)}{\overline{\phi}}V(t-1/\beta c)\right\}dl$$

parameter	explanation
t	time
V(t)	output voltage at time t w/o structure effect
L	electrode length
$\frac{l}{\phi}$	longitudinal position of an electrode
	averaged electrode coverage angle
φ(l)	electrode coverage angle at l
β, c	velocity of beam and light

CST simulation with TypeA BEPM

(L = 50 mm / σ_t^{beam} ~ 0.5 ns ⇔ 10° for RF)



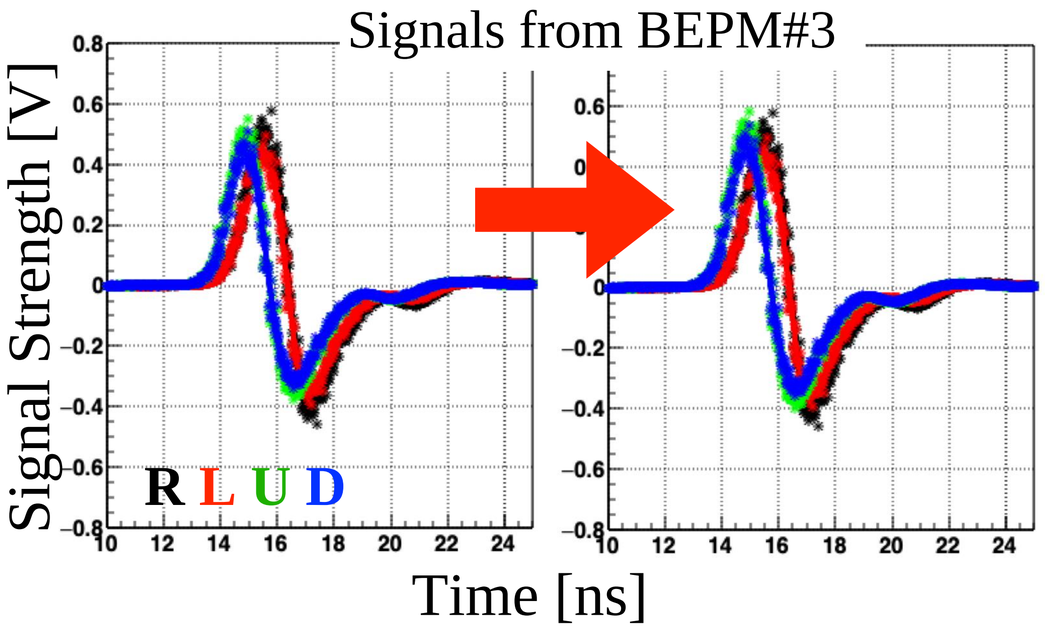
This effect become significant when bunch length $\sigma_z^{beam} \leqq L$

c.f. σ_z^{beam} in SRILAC ~ 10 mm

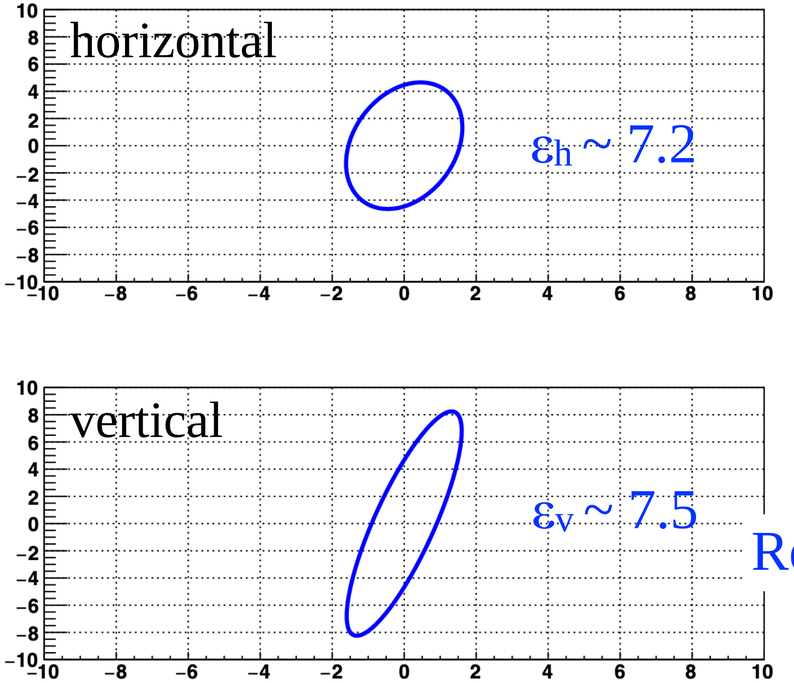
$L_{electrode}$ = 50 mm (typeA) / 60 mm (typeB)

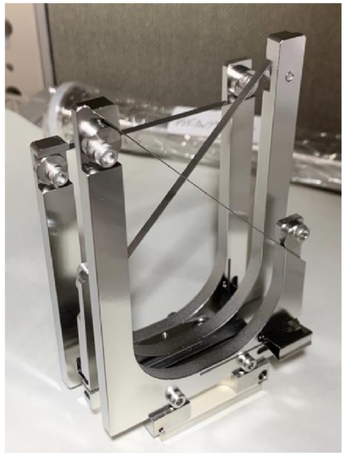
Solution A: bias factor correction

Bias factors can be estimated
to reproduce Q-scan results.



Phase Ellipse at profile monitor e00



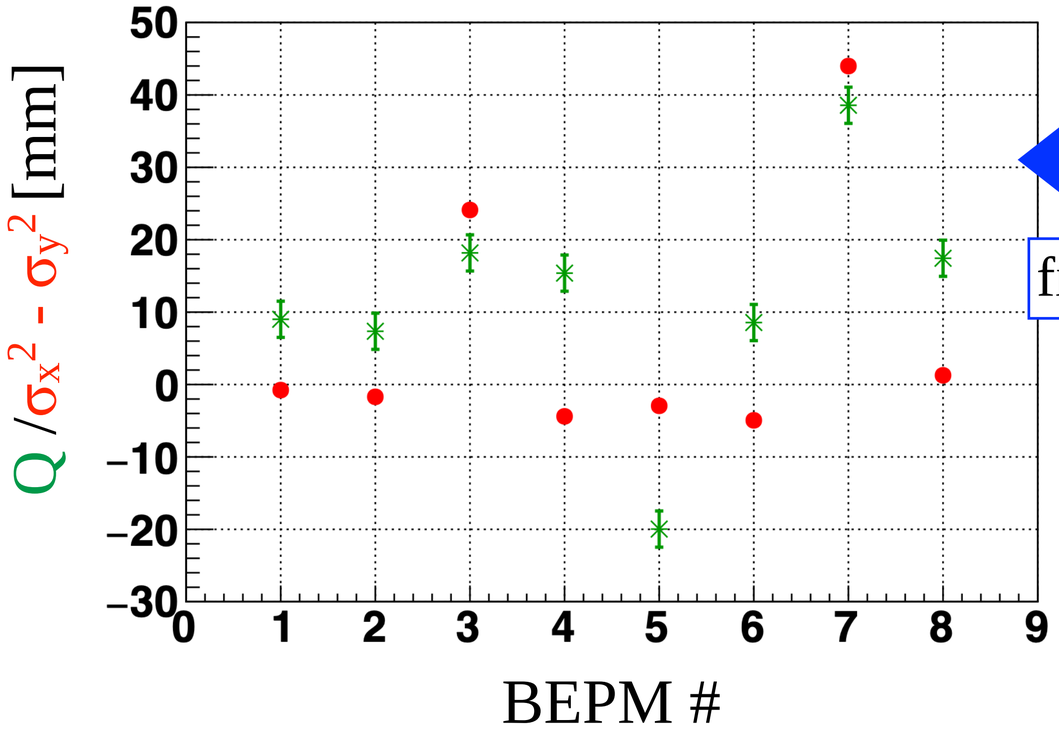


profile monitor @ e00

Result of Q-scan

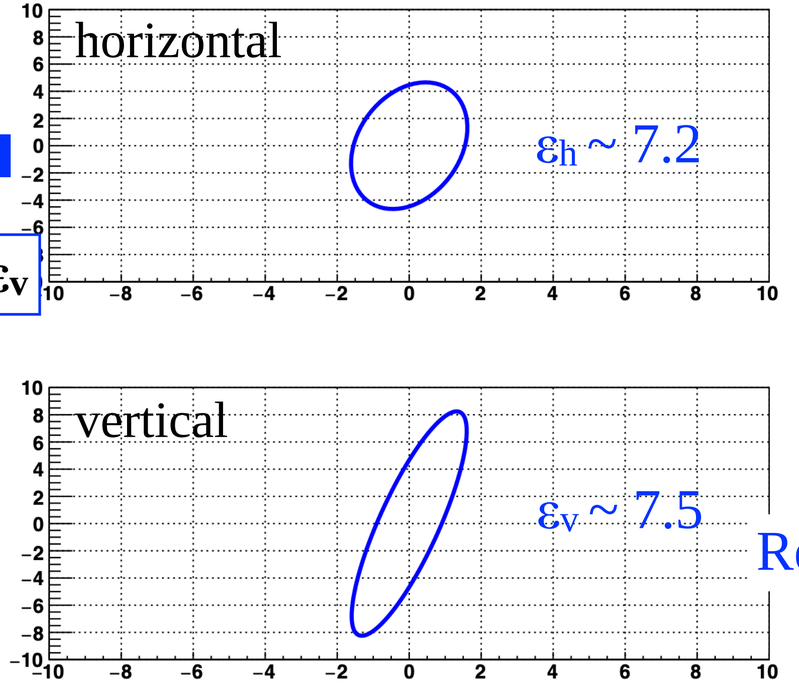
Solution A: bias factor correction

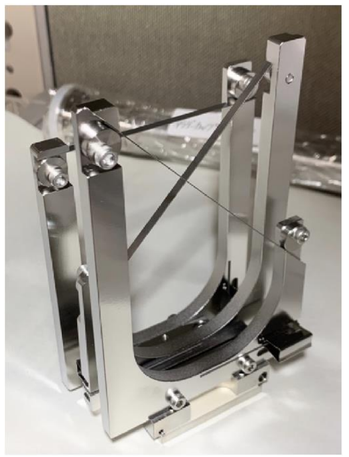
w/o bias correction



fix ε_h, ε_v

Phase Ellipse at profile monitor e00



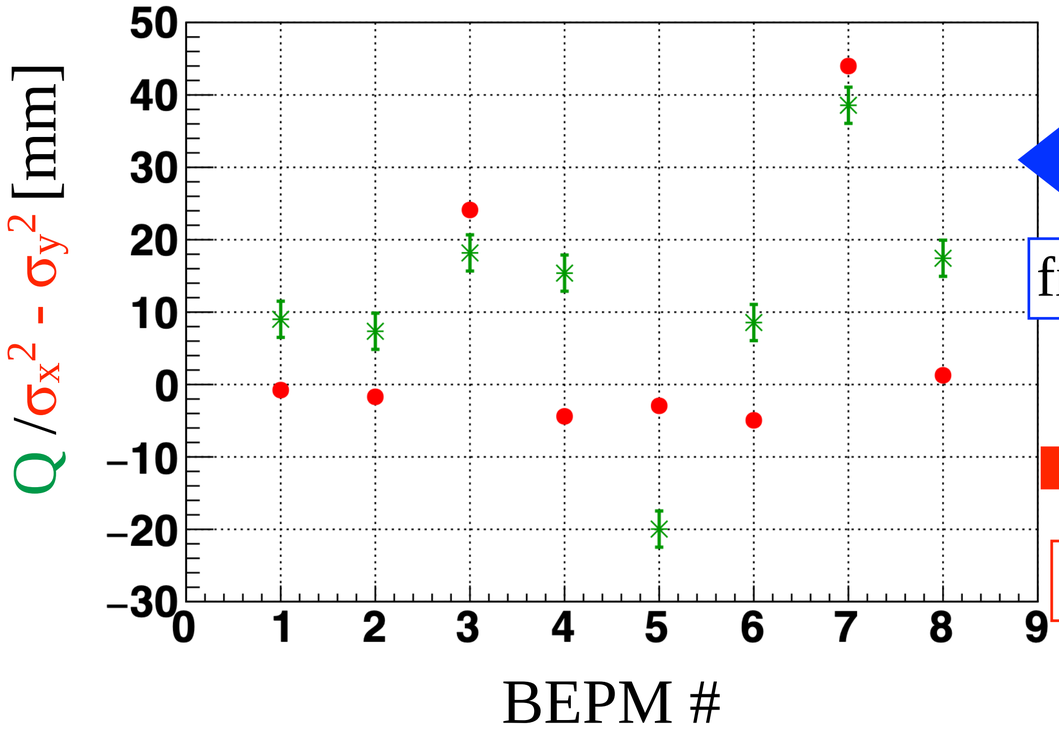


profile monitor @ e00

Result of Q-scan

Solution A: bias factor correction

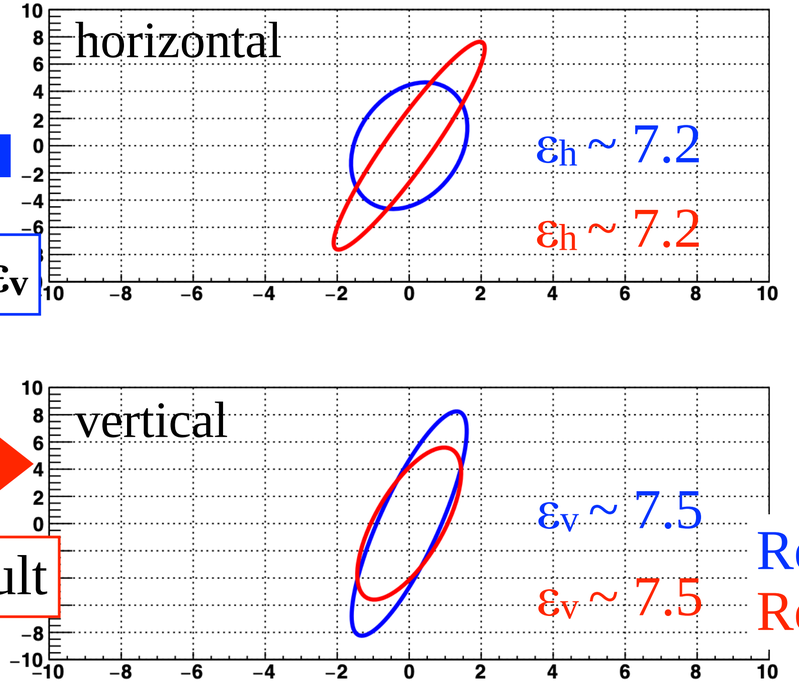
w/o bias correction

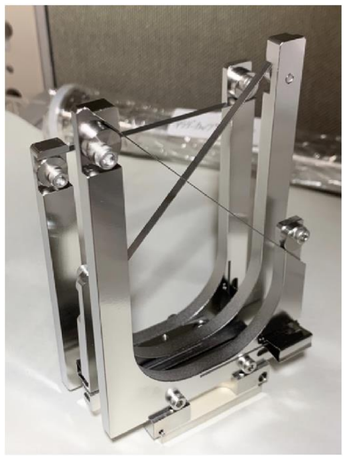


fix ε_h, ε_v

fit result

Phase Ellipse at profile monitor e00





profile monitor @ e00

Result of Q-scan

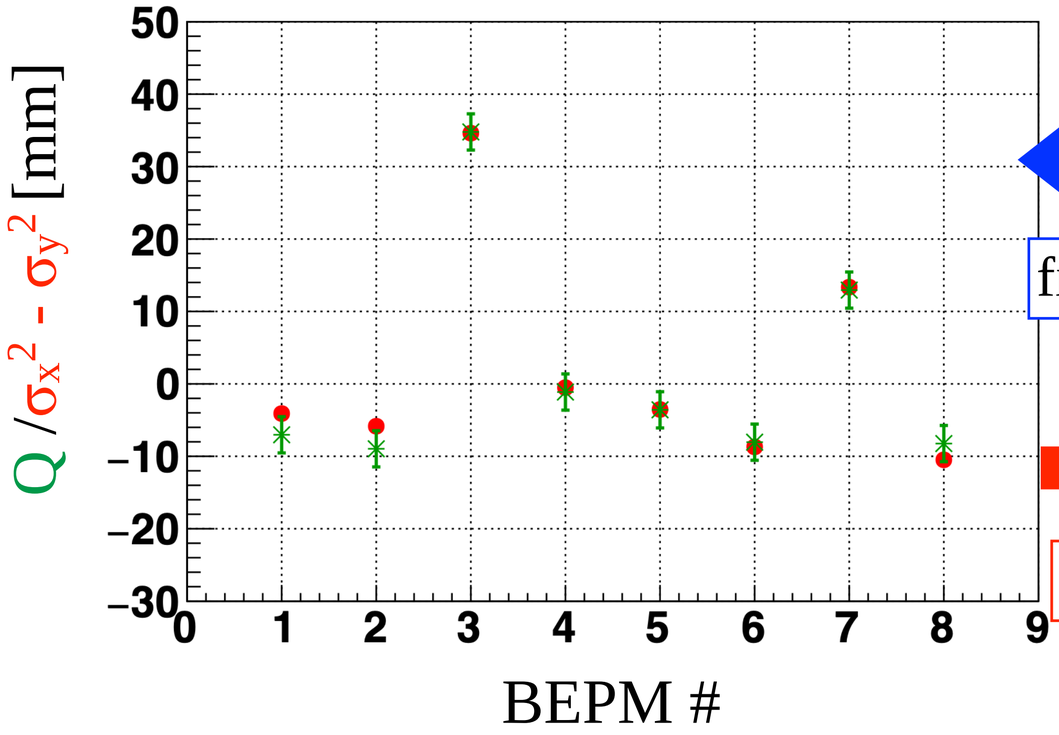
Result of BEPM analysis

Measured Qs are not reproduced by the fitting w/o bias correction…

Solution A: bias factor correction

w/ bias correction

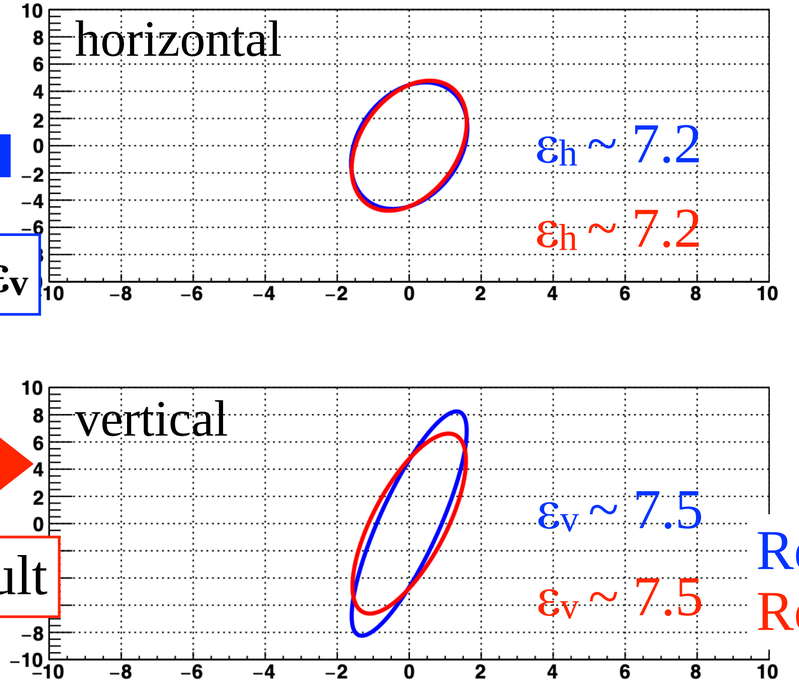
b = 1.060 / 1.044 (typeA/B)

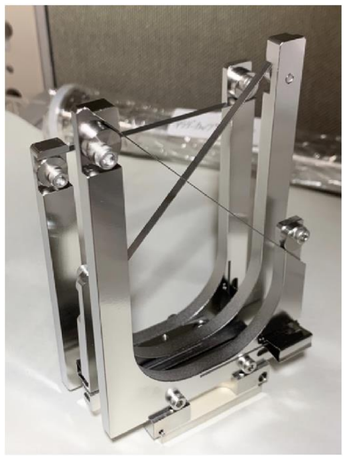


fix ε_h, ε_v

fit result

Phase Ellipse at profile monitor e00





profile monitor @ e00

Result of Q-scan

Result of BEPM analysis

Measured Qs are well reproduced by the fitting **with fixed emittance!**

※ Analysis w/o fixed emittance will be discussed latter…

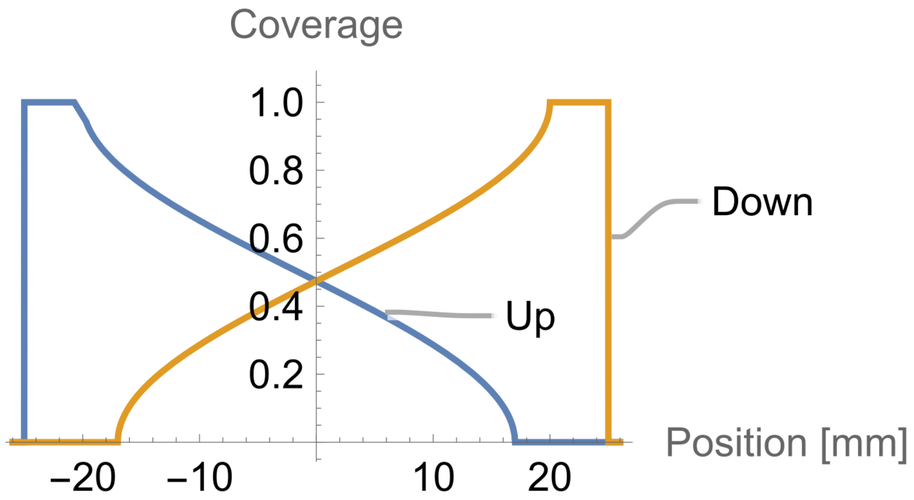
Solution B: Integral wave form signals

Solution B: Use double integrated signals

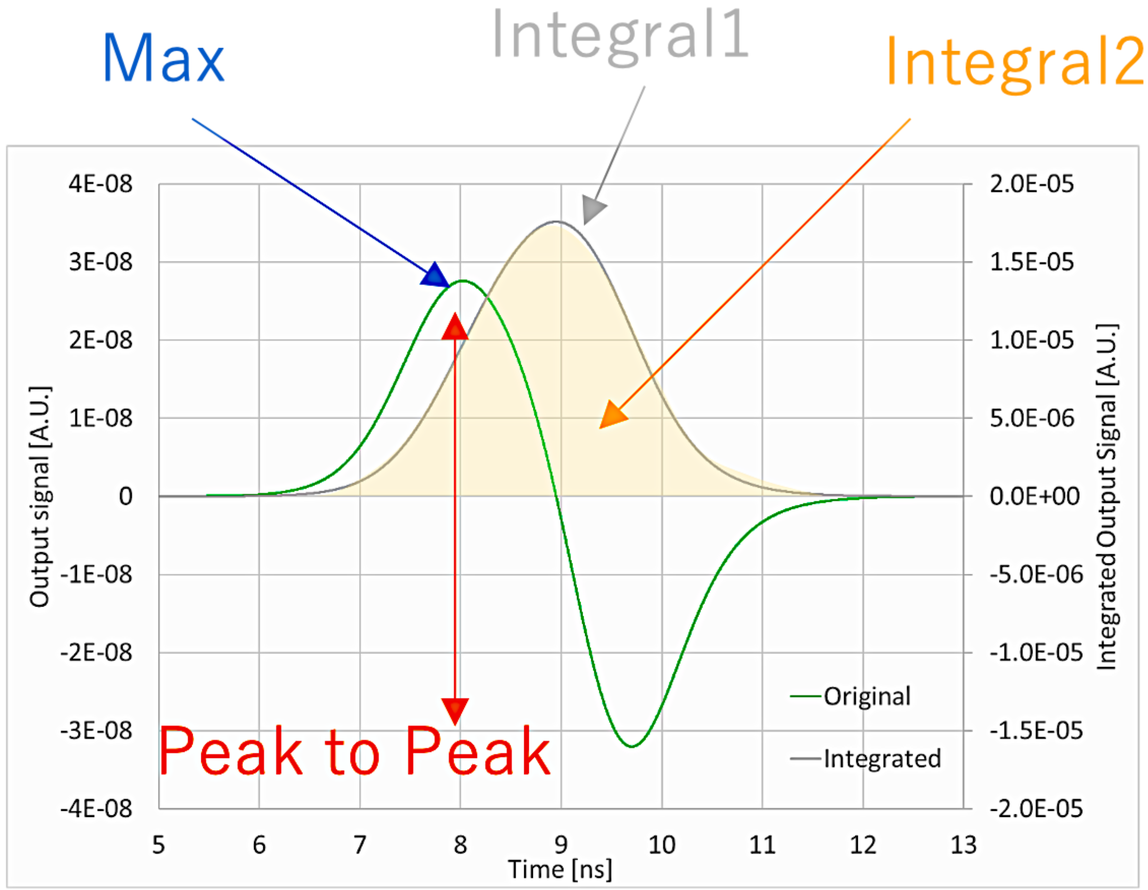
The effect caused by

time difference from different part of electrode

→ The effect disappear for the integrated signals.



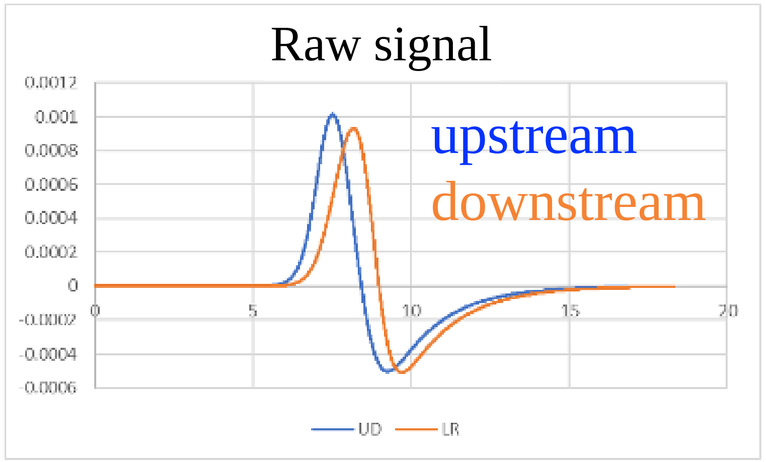
Shape functions of Up and Down electrode



Solution B: Integral wave form signals

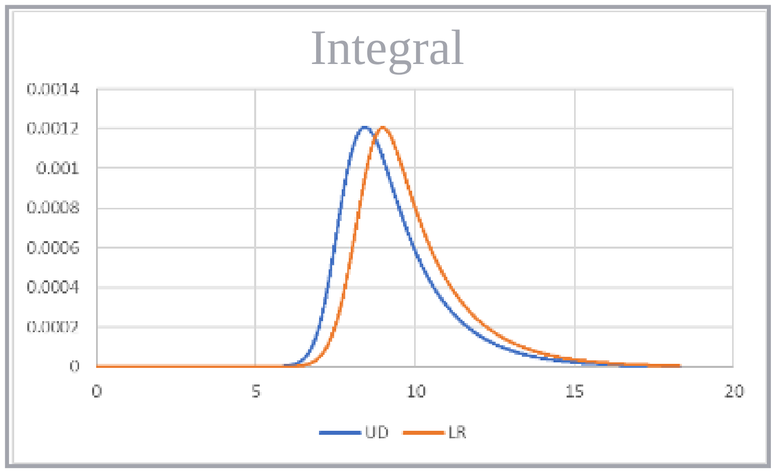
CST Simulation

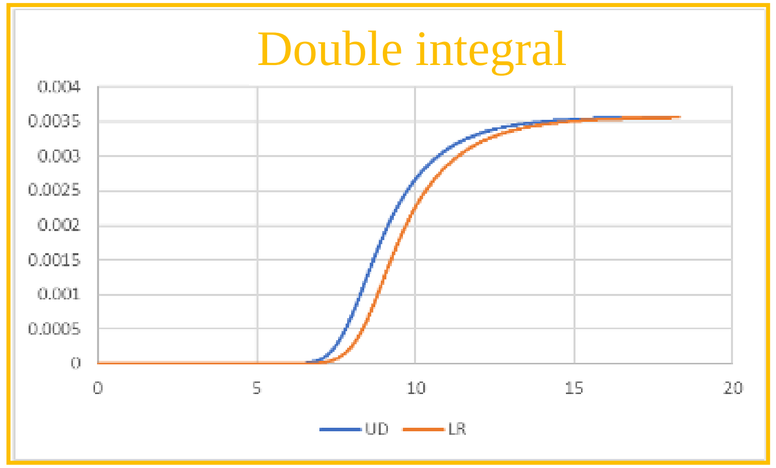
T. Adachi *et al.*, Proc. of PASJ2023, THOA4 (2023)
Patent application number 2023-128268 (JP)

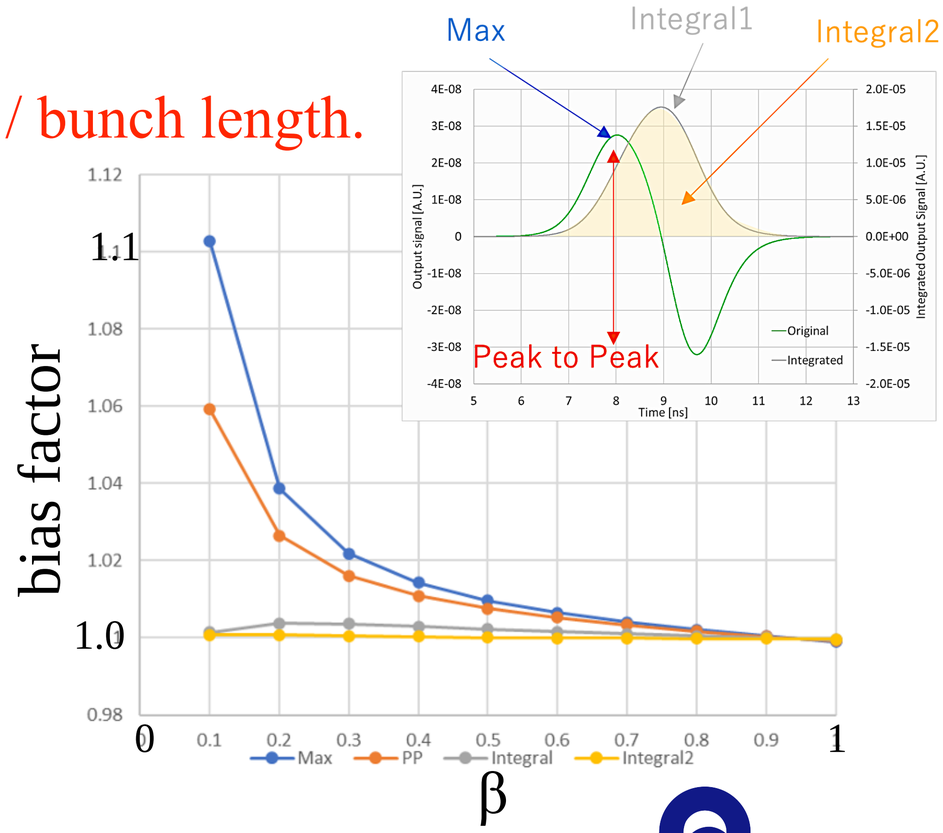


Double integration of the signal seems promising for eliminating the bias effect.

CST simulation shows no bias for double integration in any β / bunch length.

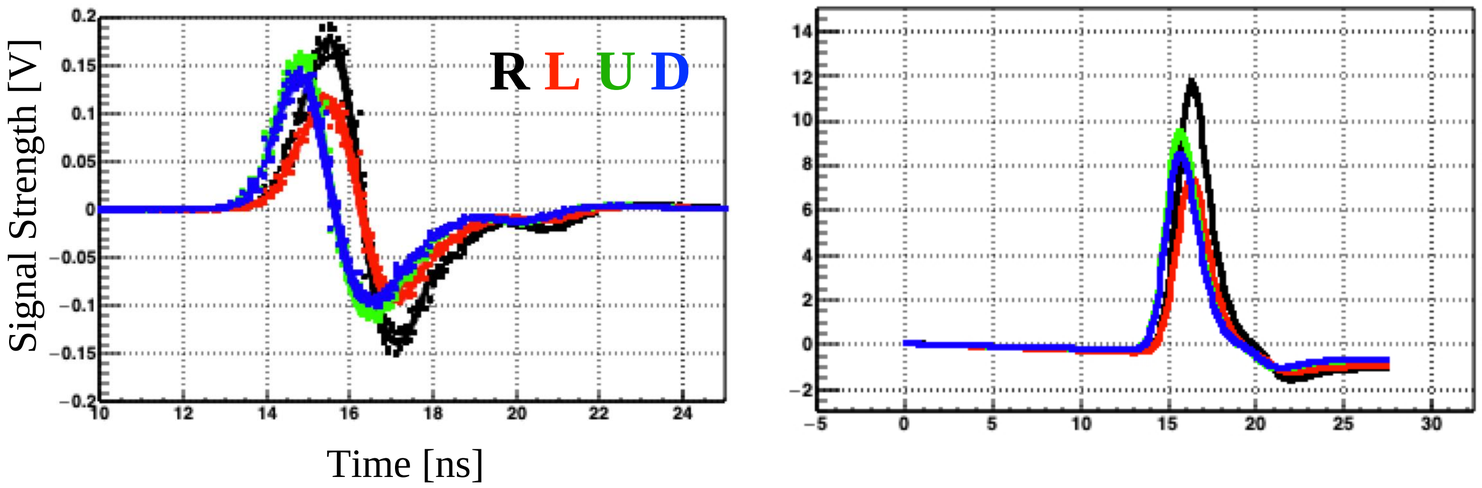






Solution B: Integral wave form signals

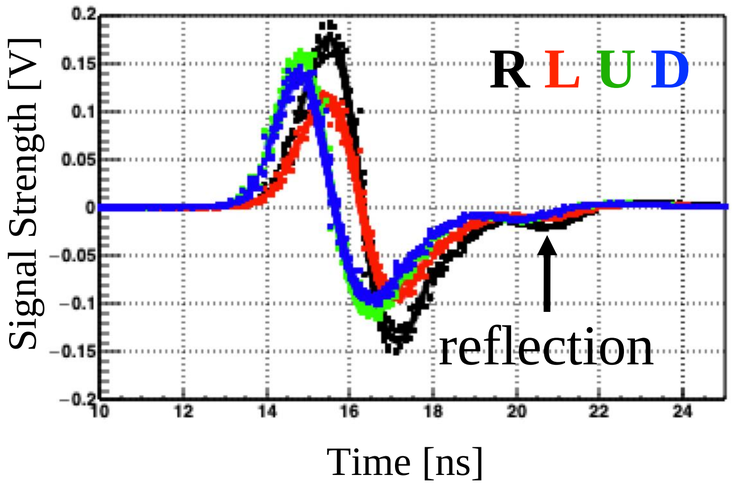
Measured data

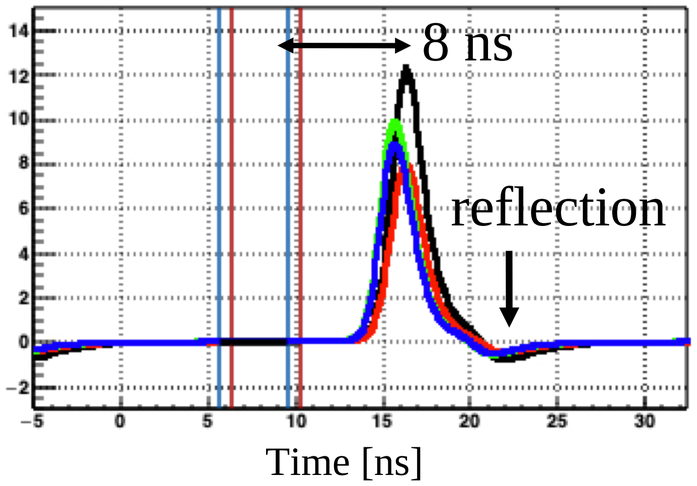


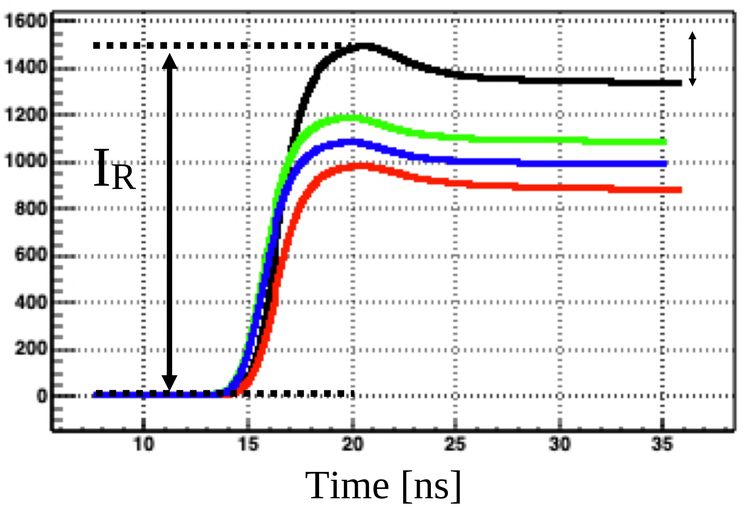
Simple integration is not robust for offset of the signal.

Solution B: Integral wave form signals

Measured data







Simple integration is not robust for offset of the signal.

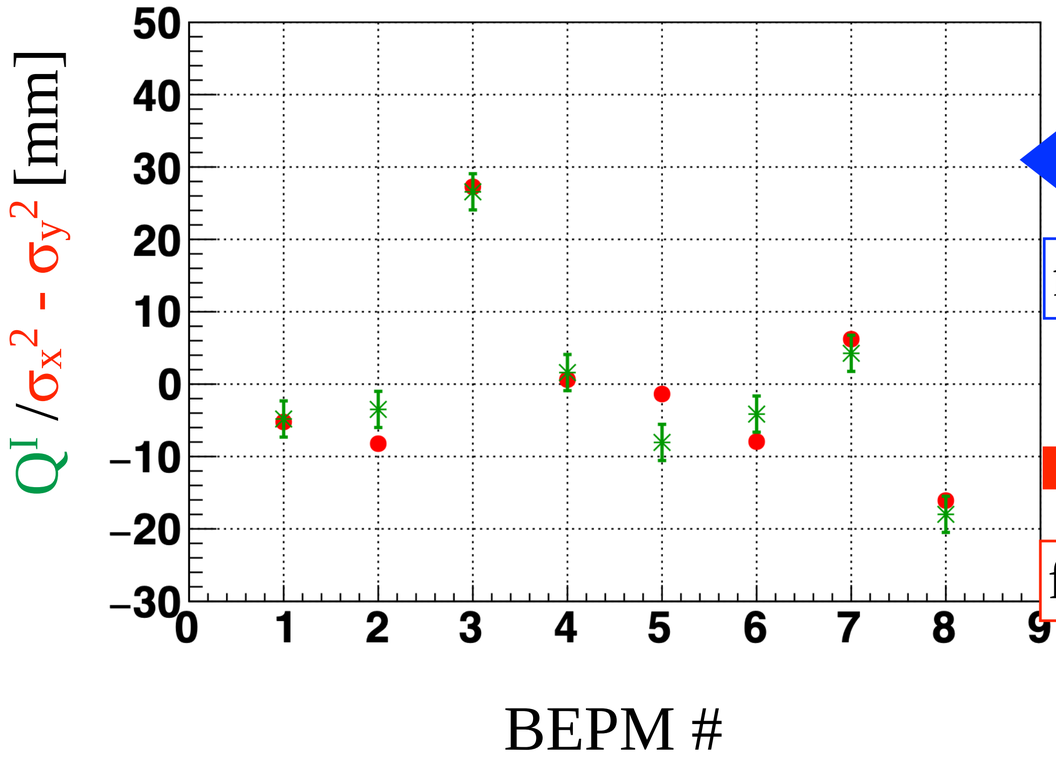
→ After the correction of the slope (cyclic boundary condition) and offset in integration, double integration and corresponding Qs are calculated.

$$Q_i^I = k_q \frac{I_{Li} + I_{Ri} - I_{Ui} - I_{Di}}{I_{Li} + I_{Ri} + I_{Ui} + I_{Di}} - \langle x^I \rangle^2 + \langle y^I \rangle^2$$

※ k_q is the same as for the peak to peak values. / 〈x〉 , 〈y〉 should be also re-calculated with integrations.

Solution B: Integral wave form signals

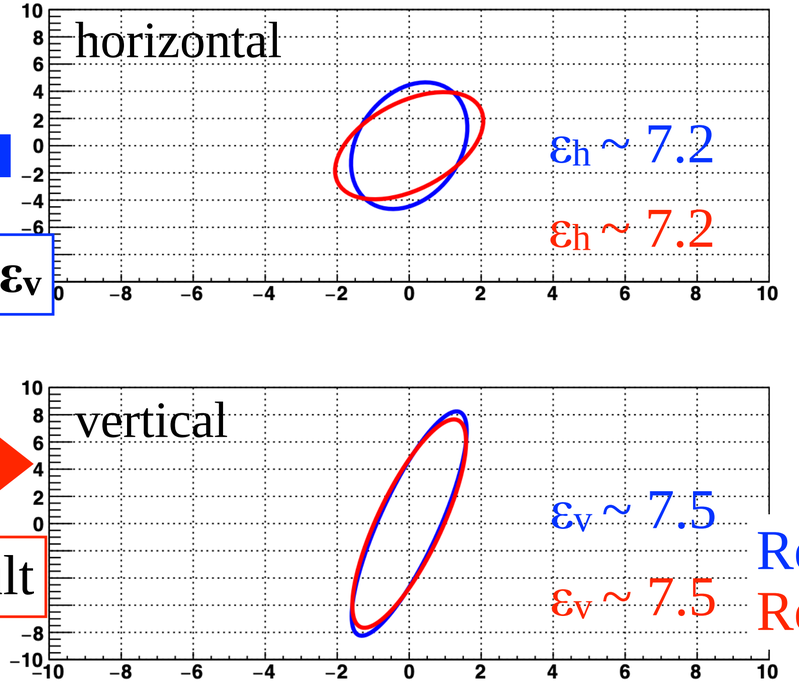
Fit with Q^I
calculated by double integration



fix ε_h, ε_v

fit result

Phase Ellipse at profile monitor e00

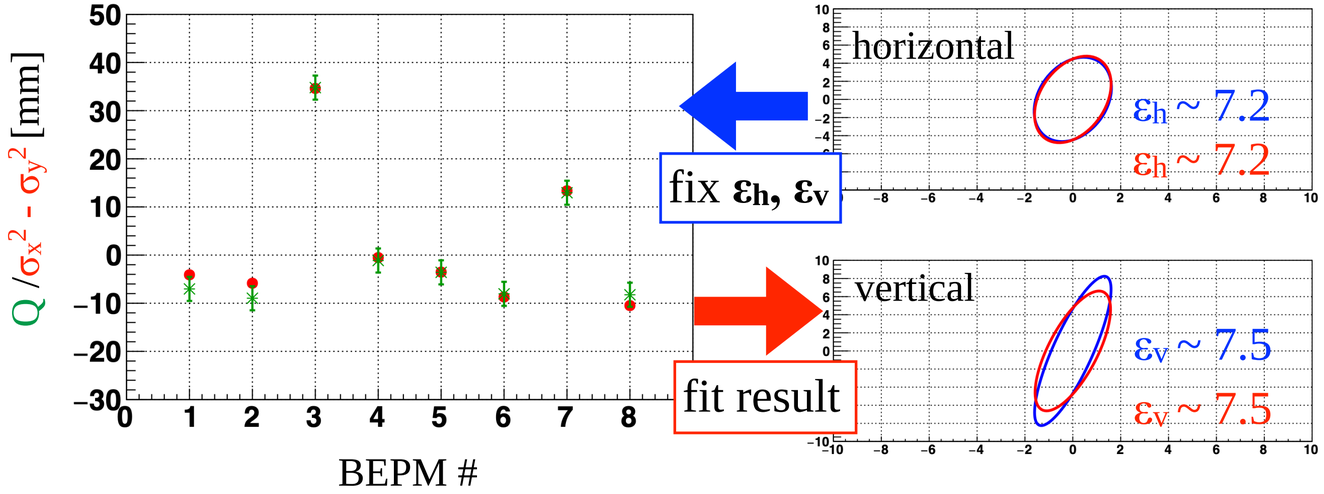


Result of Q-scan
Result of BEPM analysis

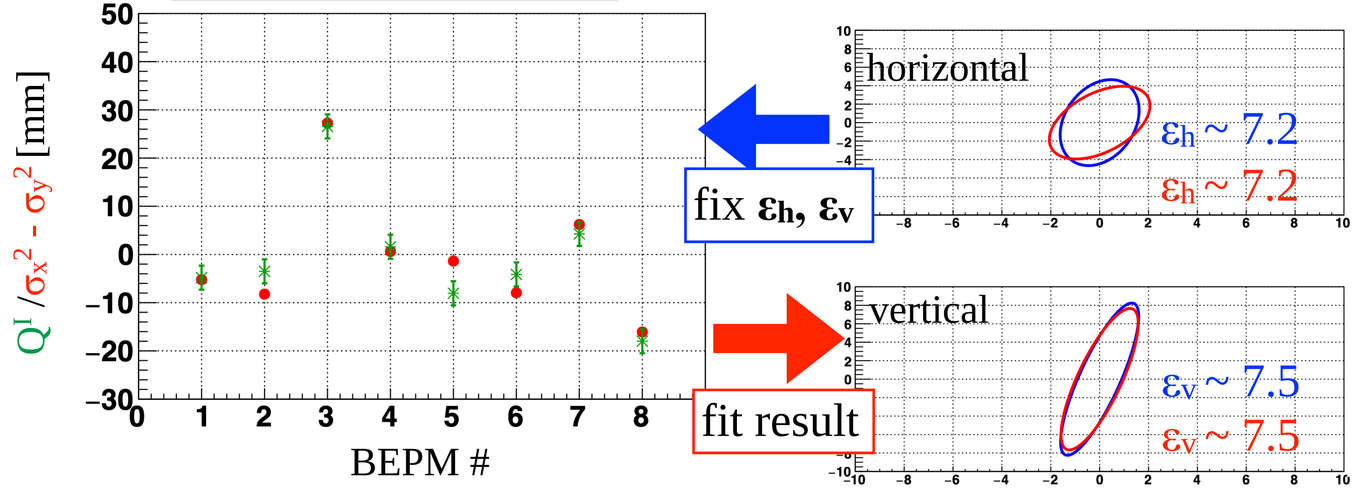
Measured Qs are again well reproduced as with calculated Q with bias corrections.
※ ε_h, ε_v are still fixed!

Comparison between solution A/B

Bias correction



Double integration



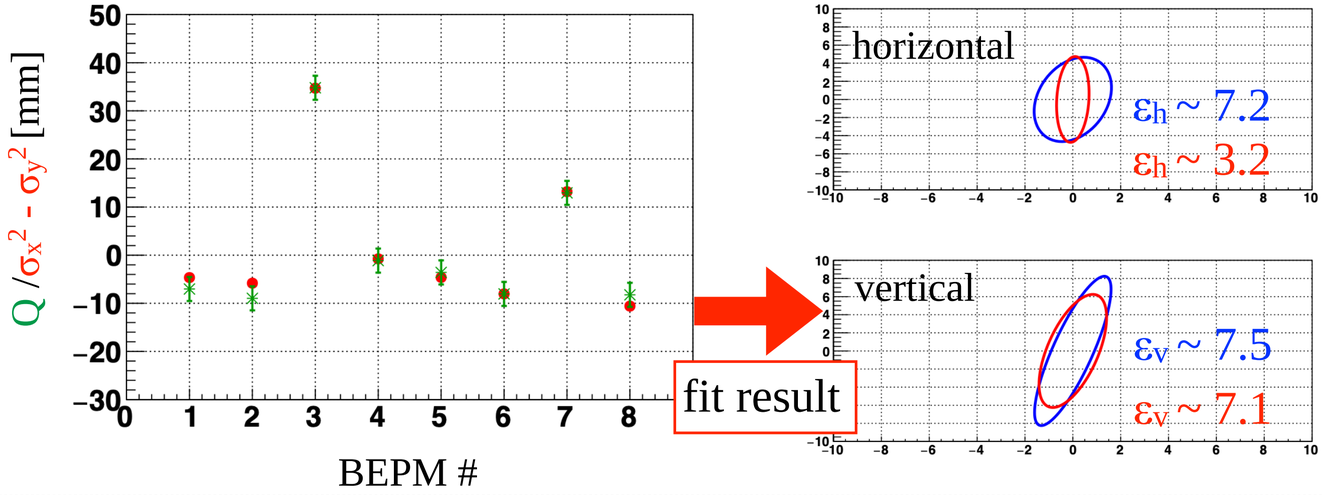
- Both method works well
- Double integration method is more comprehensive / robust for beam conditions.
- So far, only peak to peak values are archived in data base.
  (wave form signals are not archived)

→ We are preparing program upgrade to archive double integration for coming beam series.

Result of Q-scan
Result of BEPM analysis

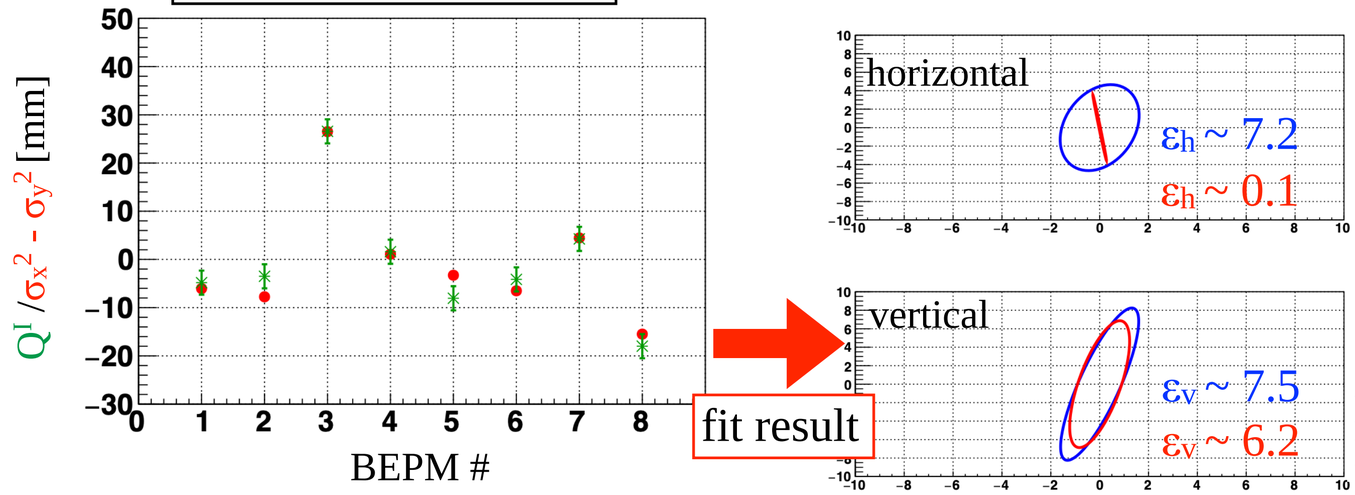
Comparison between solution A/B

Bias correction



Phase Ellipse
at profile monitor e00

Double integration



- Both method works well
- Double integration method is more comprehensive / robust for beam conditions.
- So far, only peak to peak values are archived in data base.
  (wave form signals are not archived)

→ We are preparing program upgrade to archive double integration for coming beam series.

In both methods,
sensitivities for ε_h, ε_v are poor…

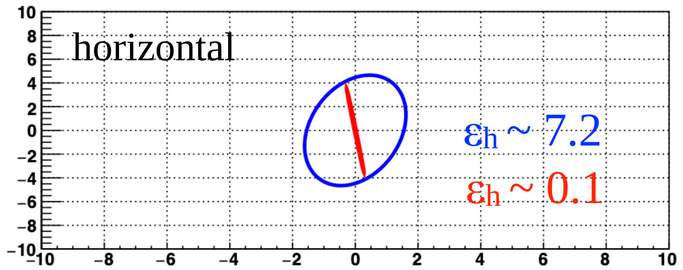
Result of Q-scan
Result of BEPM analysis

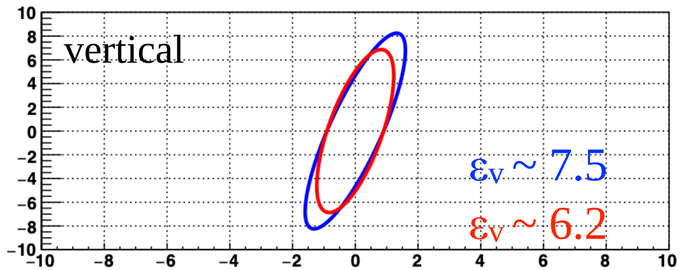
Outline

1. Introduction: SRILAC and B(E)PMs
2. Beam envelope estimation by BPM signals
3. Signal distortions caused by BPM shapes with short bunch beam
4. Improvement of sensitivity for beam emittance
5. Example of analysis with experimental data
6. Future Outlook and Summary

Improvement of sensitivity for beam emittance

Phase Ellipse at profile monitor e00
with double integral method





Result of Q-scan
Result of BEPM analysis

(1) Limitation of balance between ε_h / ε_v

ratio between ε_h and ε_v → expected to be robust in some range

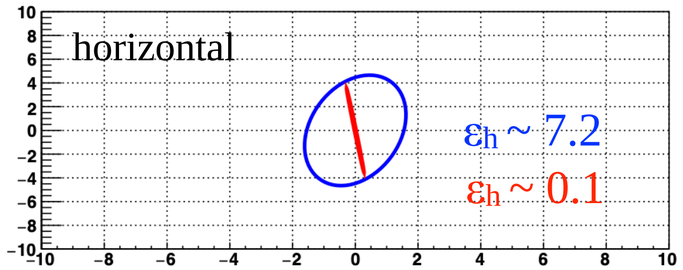
Fit is performed under the following condition,

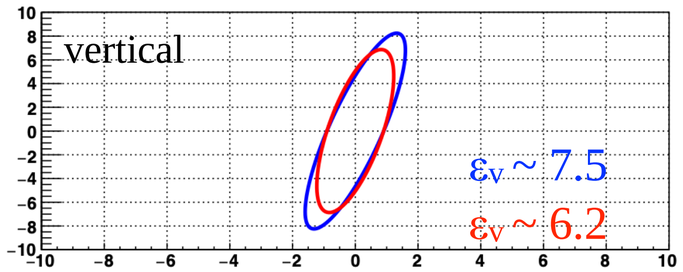
$$|\epsilon_{\mathrm{asym}}| \equiv \left|\frac{\epsilon_h - \epsilon_v}{\epsilon_h + \epsilon_v}\right| \leq 0.1.$$

※ $\Delta\varepsilon \sim 20\%$ in maximum

Improvement of sensitivity for beam emittance

Phase Ellipse at profile monitor e00
with double integral method





Result of Q-scan
Result of BEPM analysis

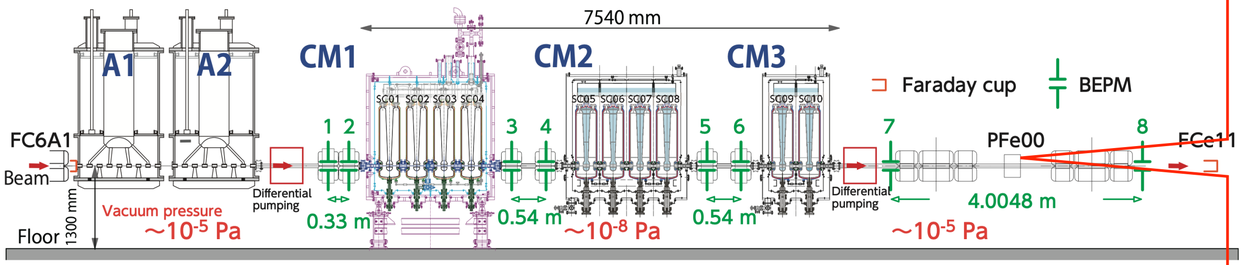
(1) Limitation of balance between ε_h / ε_v

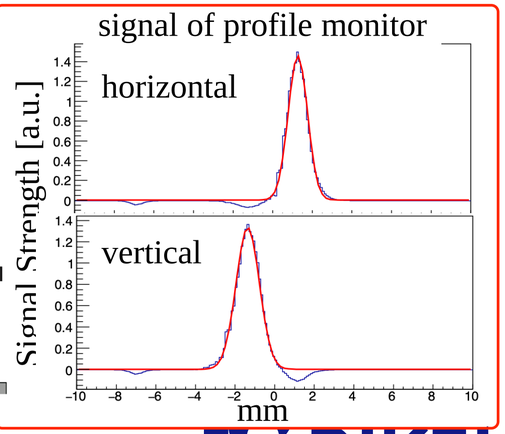
ratio between ε_h and ε_v → expected to be robust in some range
Fit is performed under the following condition,

$$|\epsilon_{asym}| \equiv \left|\frac{\epsilon_h - \epsilon_v}{\epsilon_h + \epsilon_v}\right| \leq 0.1.$$ ※ $\Delta\varepsilon \sim 20\%$ in maximum

(2) Utilize profile monitor data in the fitting

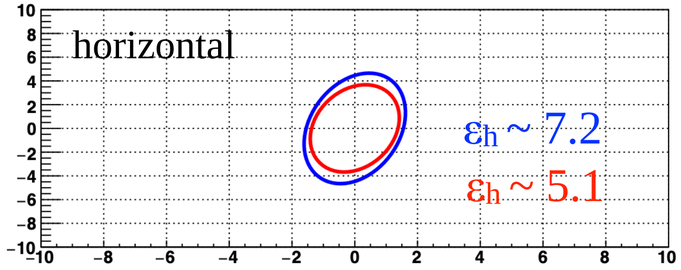
Quadrupole momentums $\sigma_x^2 - \sigma_y^2$ have less sensitivity
for absolute beam size.
→ Additional beam size in one point will improve the fitting result.

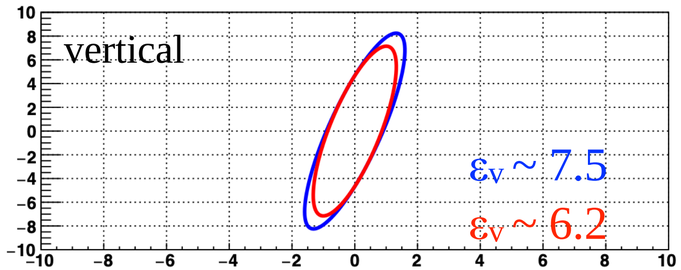




Improvement of sensitivity for beam emittance

Phase Ellipse at profile monitor e00
with double integral method
+ (1), (2)





Result of Q-scan
Result of BEPM + PF analysis

Improved so much!!

(1) Limitation of balance between ε_h / ε_v

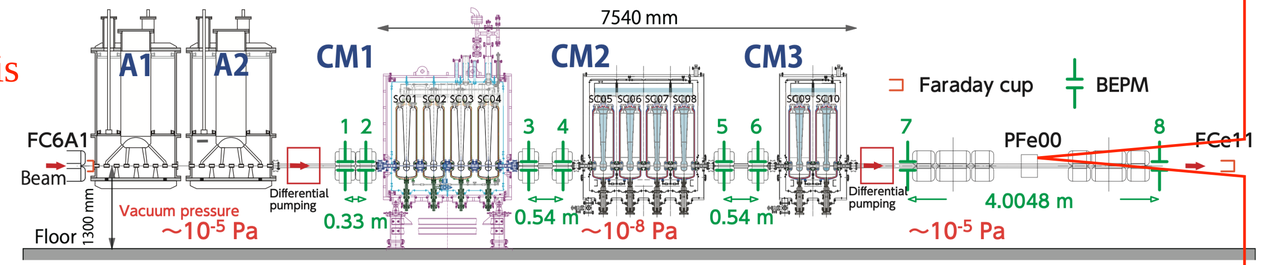
ratio between ε_h and ε_v → expected to be robust in some range
Fit is performed under the following condition,

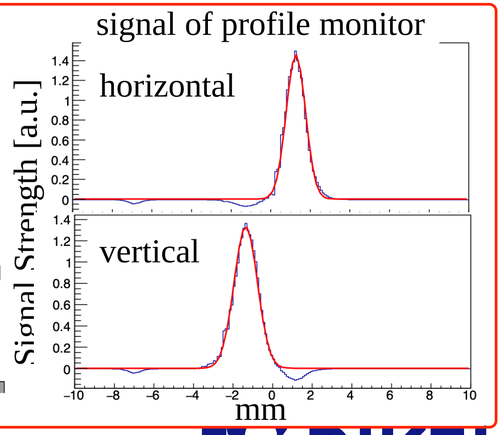
$$|\epsilon_{asym}| \equiv \left|\frac{\epsilon_h - \epsilon_v}{\epsilon_h + \epsilon_v}\right| \leq 0.1.$$

※ $\Delta\varepsilon \sim 20\%$ in maximum

(2) Utilize profile monitor data in the fitting

Quadrupole momentums $\sigma_x^2 - \sigma_y^2$ have less sensitivity
for absolute beam size.
→ Additional beam size in one point will improve the fitting result.



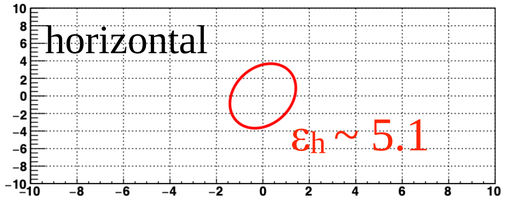


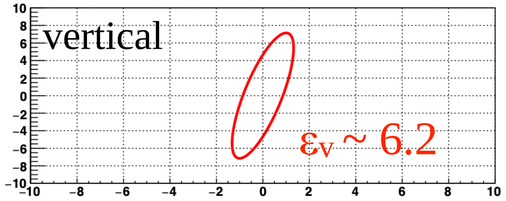
Operation procedure of the improved method (plan)

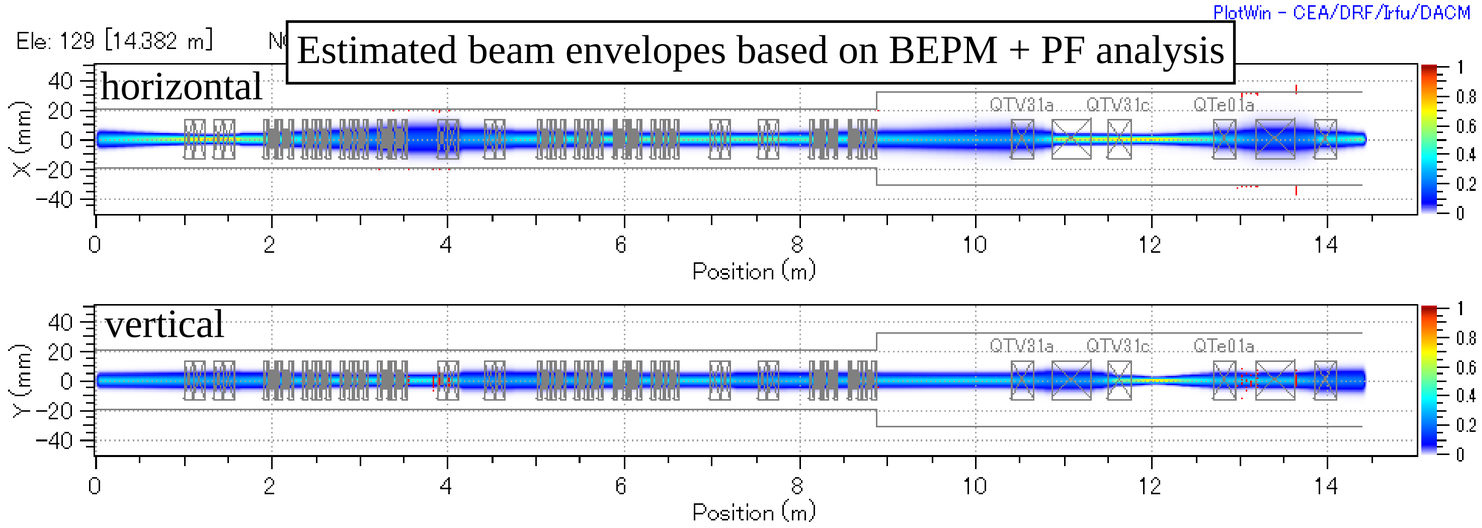
(1) Beginning of the beam supply
- Measure the beam emittance by Q-scan and check balance between ε_h / ε_v

(2) During the beam supply
- Check the beam size by profile monitors once a day
- Calculate transfer matrix in the beam line from the setting values
- Continuous display of the beam envelope during beam supply

→ “semi” non-destructive beam envelope monitor







Outline

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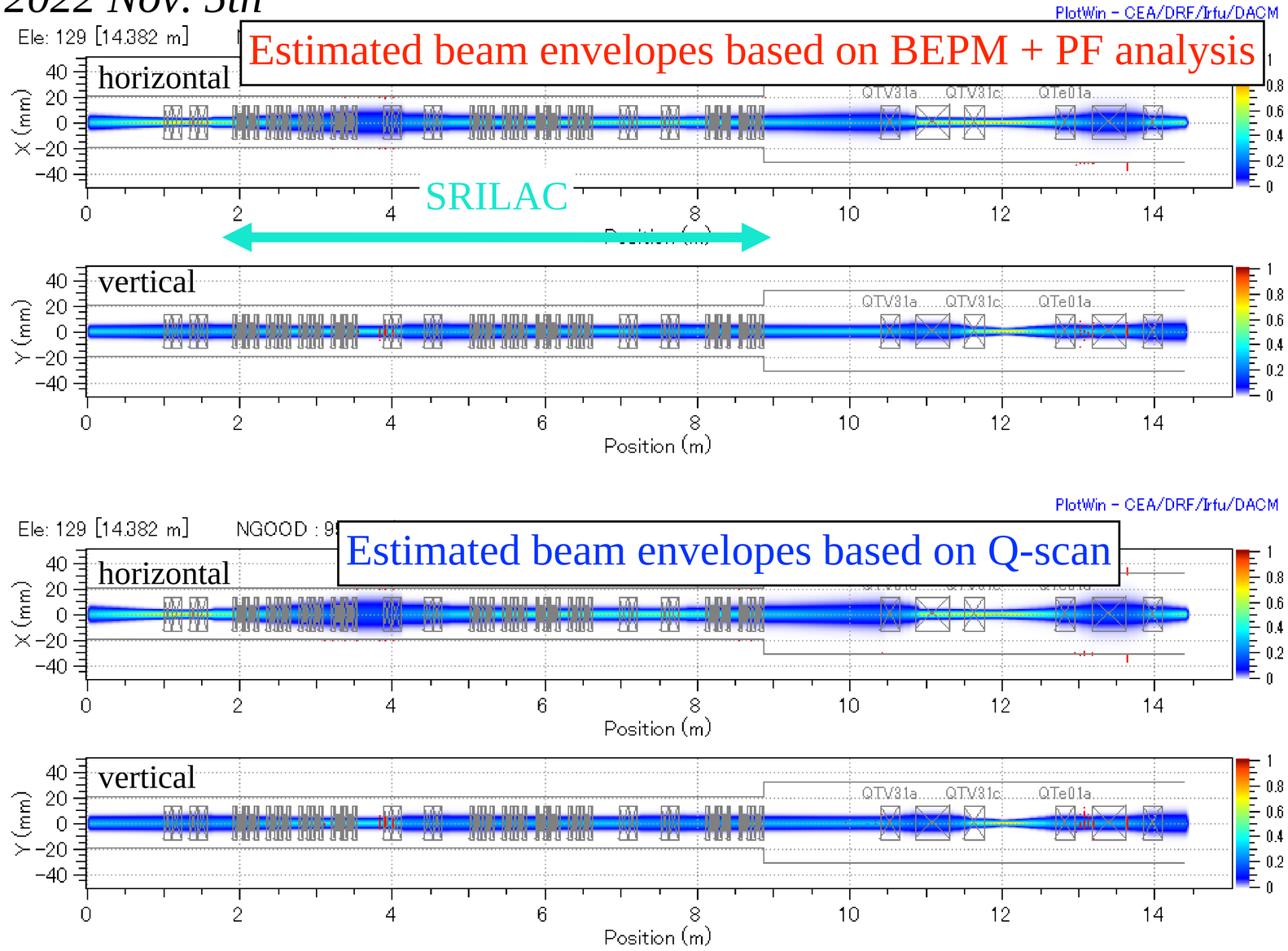
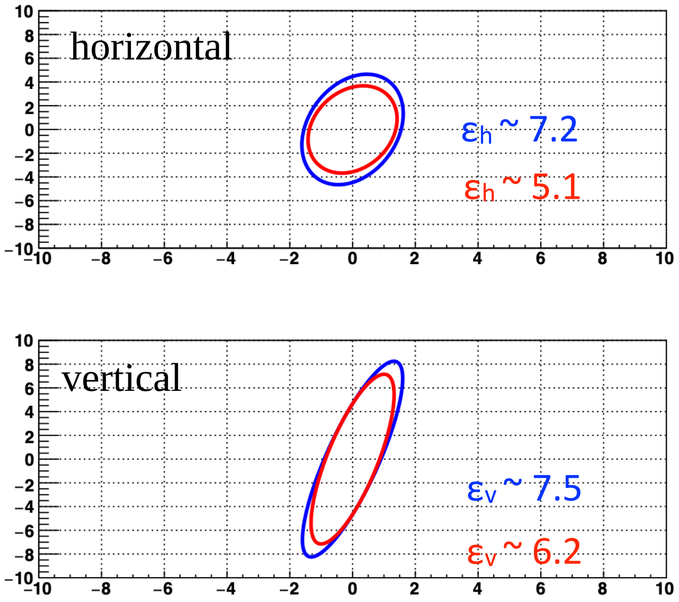
2. Beam envelope estimation by BPM signals
3. Signal distortions caused by BPM shapes with short bunch beam
4. Improvement of sensitivity for beam emittance
5. Example of analysis with experimental data
6. Future Outlook and Summary

Examples of estimated beam envelopes

2022 Nov. 5th



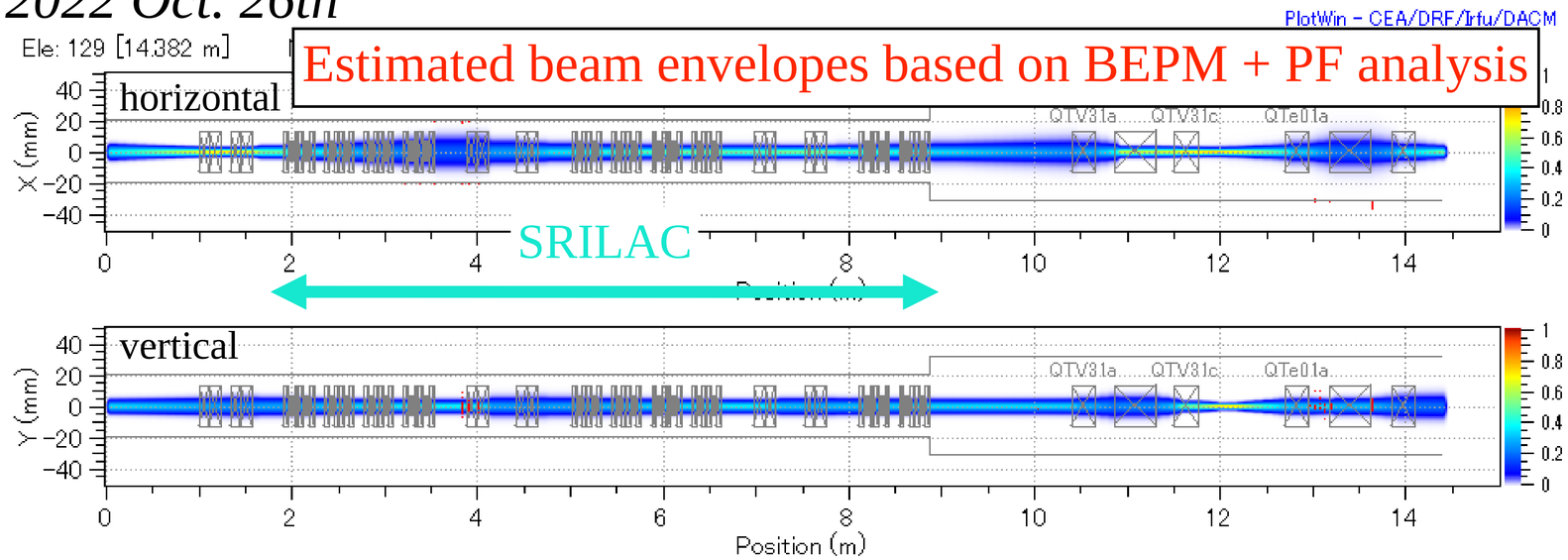


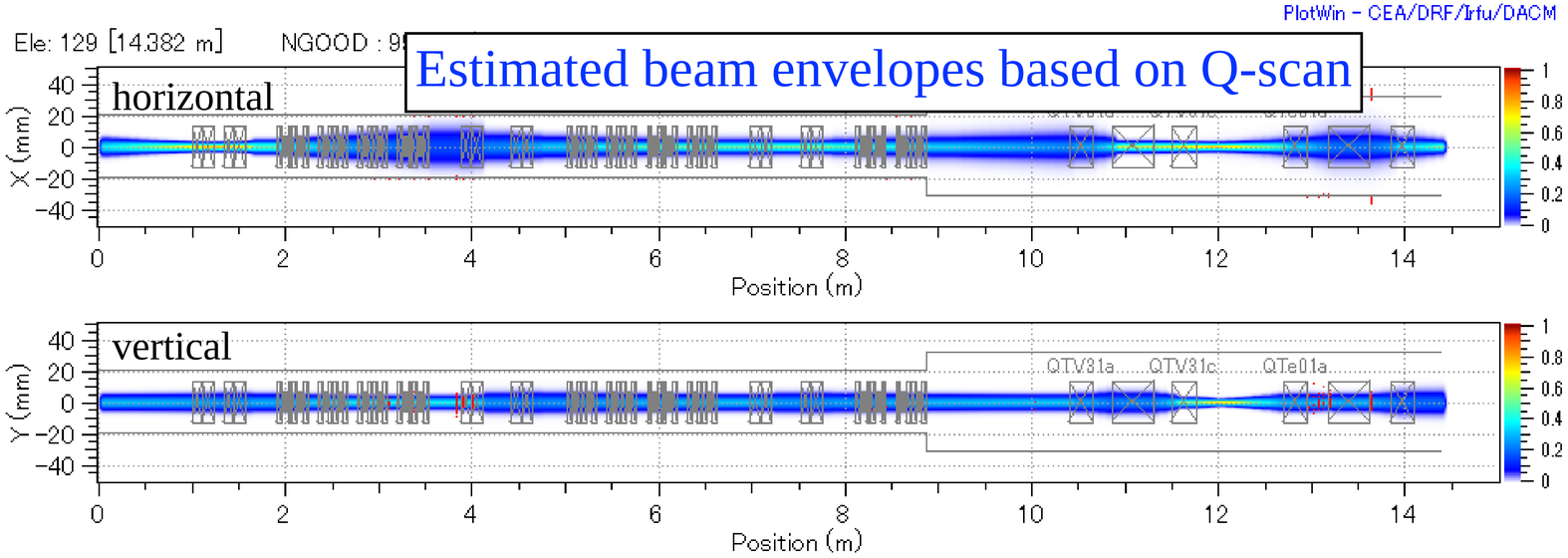
Result of Q-scan
Result of BEPM + PF analysis

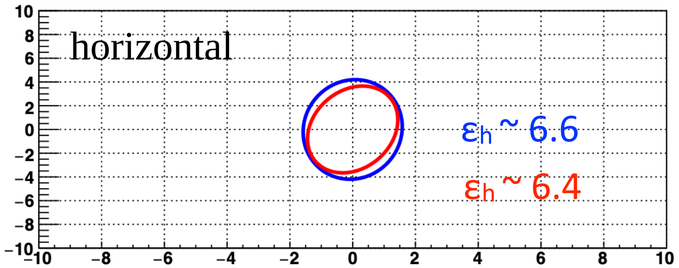
While the absolute ε tends to be small, beam envelope shape is well reproduced.

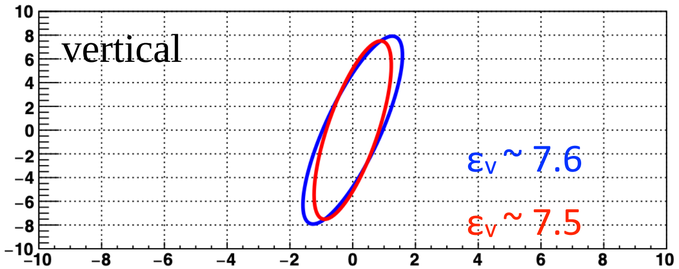
Examples of estimated beam envelopes

2022 Oct. 26th









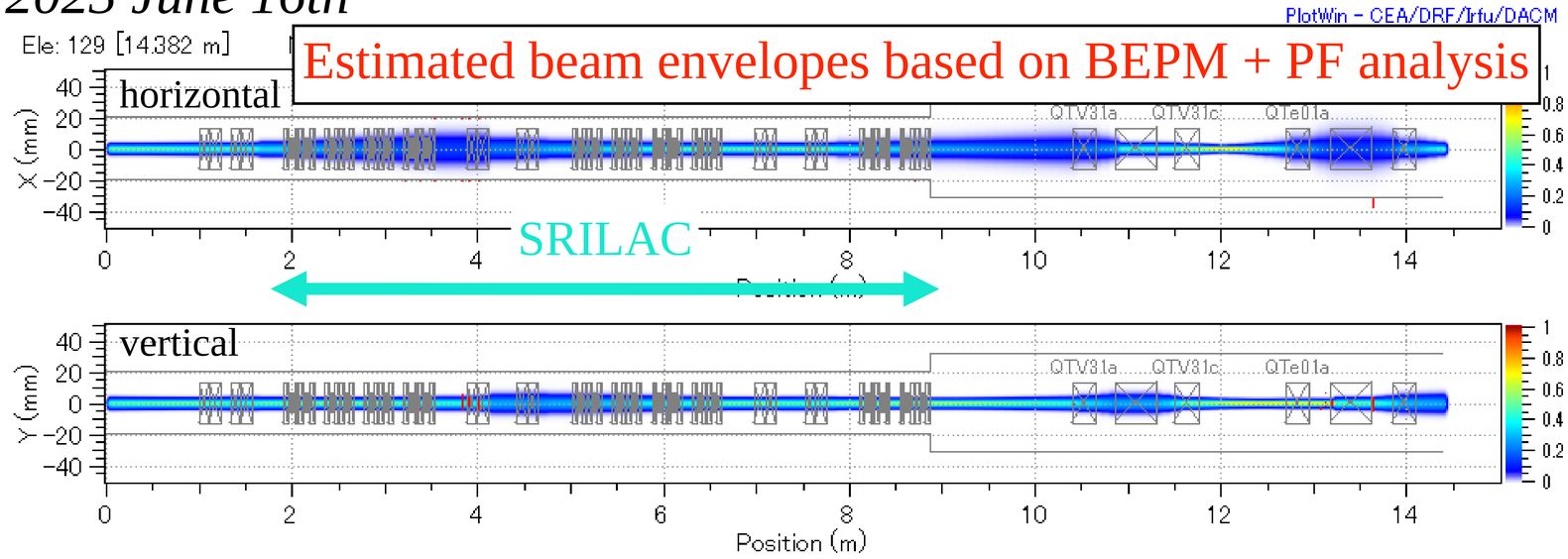
Result of Q-scan
Result of BEPM + PF analysis

In this case, emittances are also well reproduced by BEPM + PF data.

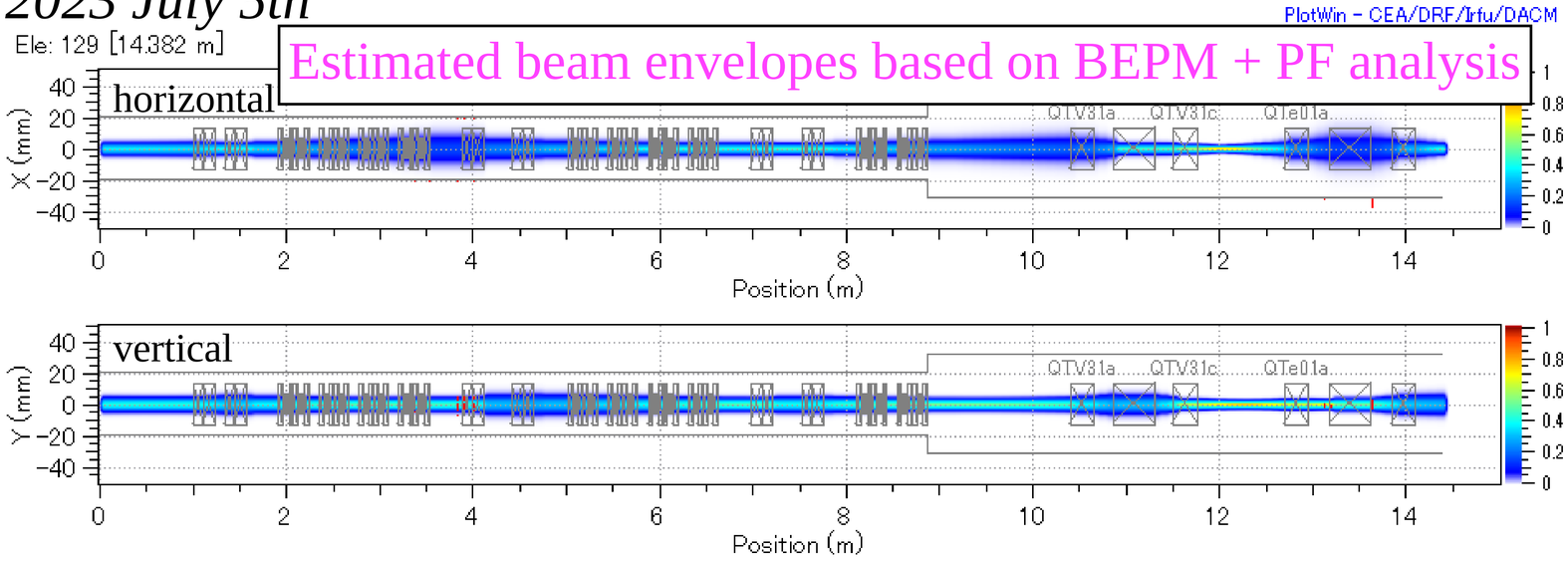
Examples of estimated beam envelopes

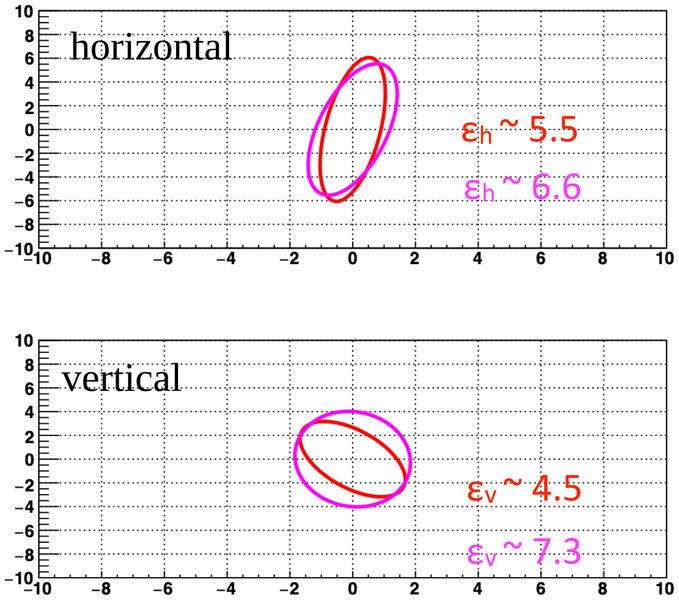
※ These analysis based on bias factor correction method

2023 June 16th



2023 July 5th





Result of BEPM + PF analysis in June 16th
Result of BEPM + PF analysis in July 5th

Estimated beam envelope has slightly changed in a few weeks during beam supply.
→ We need to check this change is real or not…

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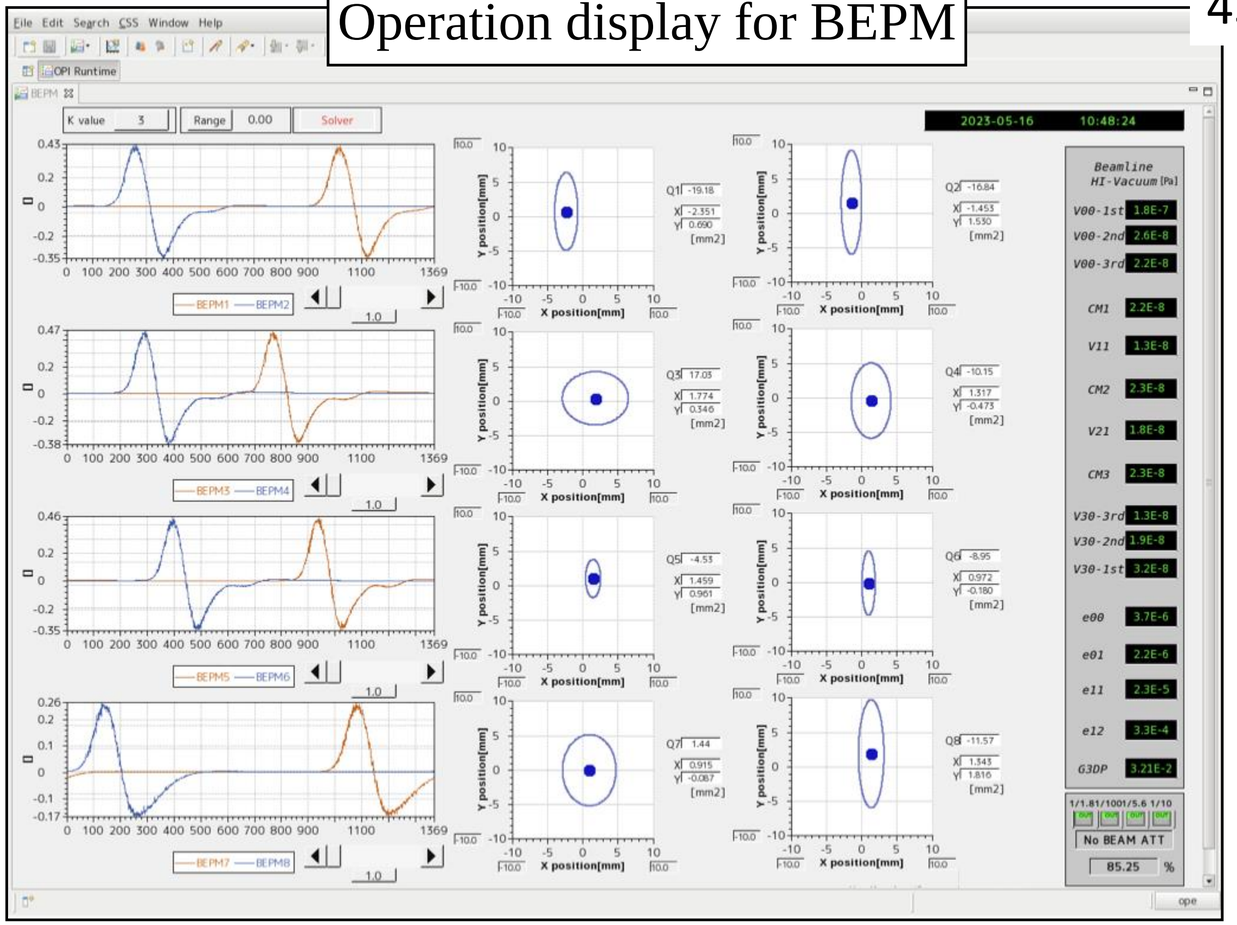
6. Future outlook and Summary

- We developed **“semi” non-destructive beam envelope measurement** using BPMs.
- With double integration of the signals, we obtained consistent result with Q-scan method.
- So far information from some destructive monitors are essential to estimate accurately.
- An improved program for the measurement will be introduced in the coming beam supply series.

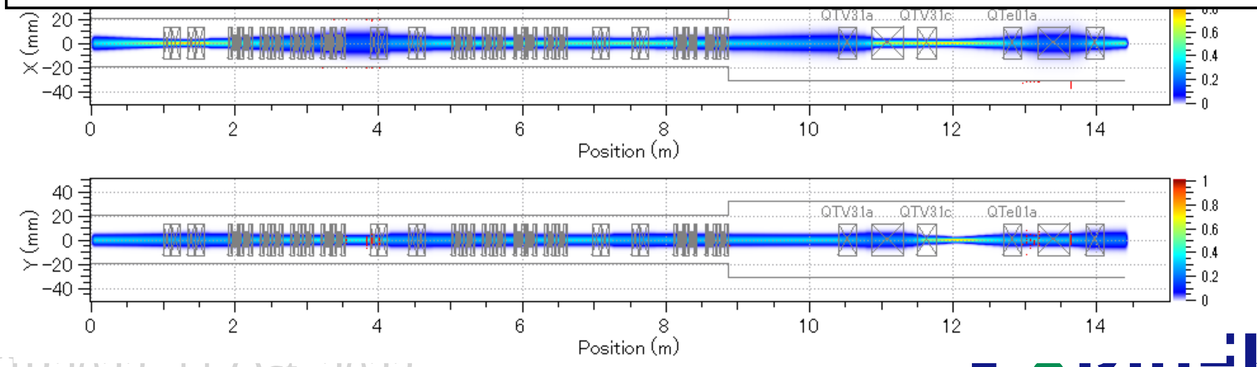
Remained Issue:

- Estimation uncertainty of the analysis
- Introduction of this system to other beam line
- Further development w/o wire scanner info. (Location of BEPM considering optics etc….)

Operation display for BEPM

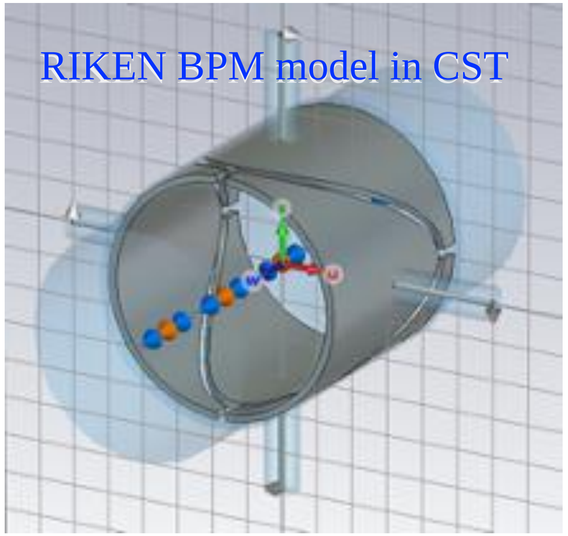


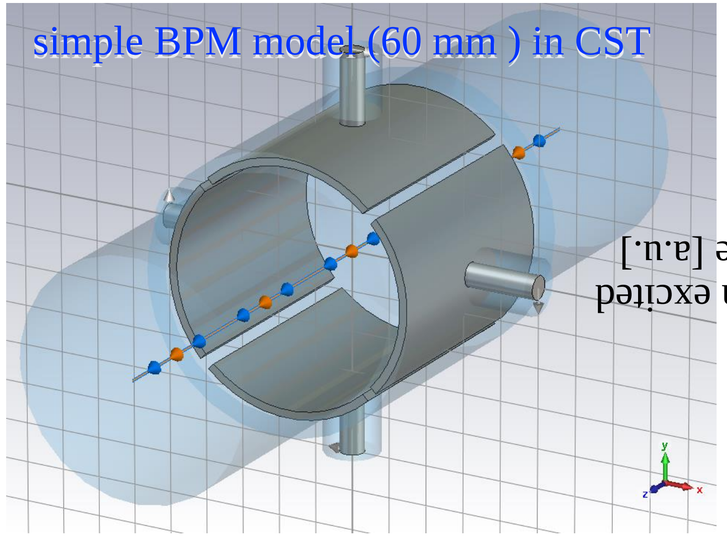
Beam envelope will be displayed simultaneously in future

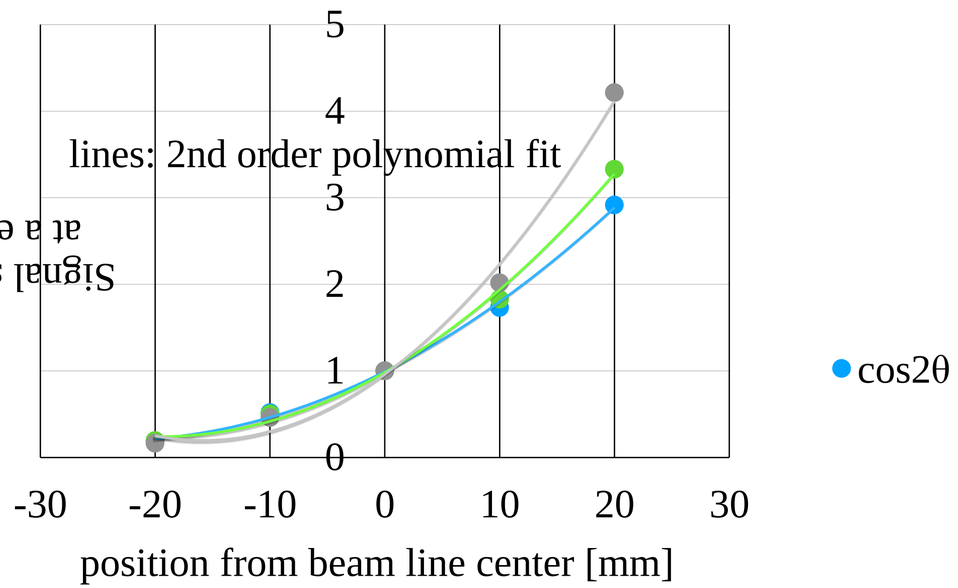


Backup

Quadrupole moment and cos2θ shape BPMs







Cos2θ shape realize ideal 2nd order dependence of signal※.

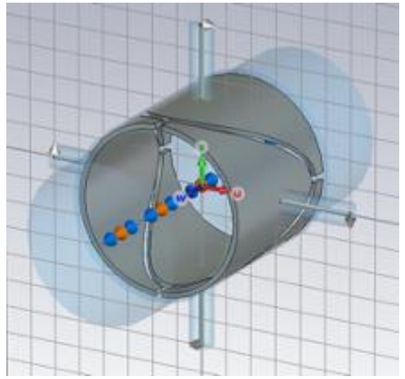
- Remove higher order effect
- Separate Dipole / Quadrupole moment clearly
- Improve the precision of Q (=σ_x^2 - σ_y^2)measurement

※ G.Nassibian, CERN-SI-NOTE-EL- 70-13, 1970.

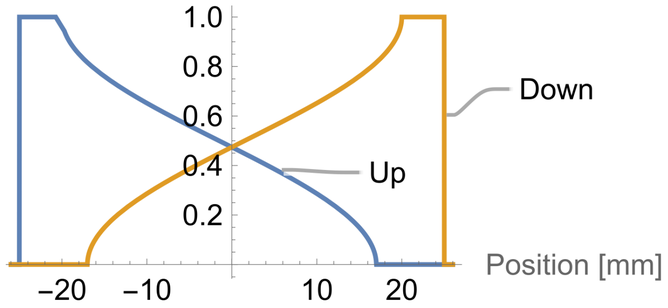
Origin of the bias: BEPM structure / short bunch length

Calculation of the output voltage with structure effect

T. Adachi *et al.*, Proc. of PASJ2023, THOA4 (2023)



Coverage of electrode $\phi(l)$



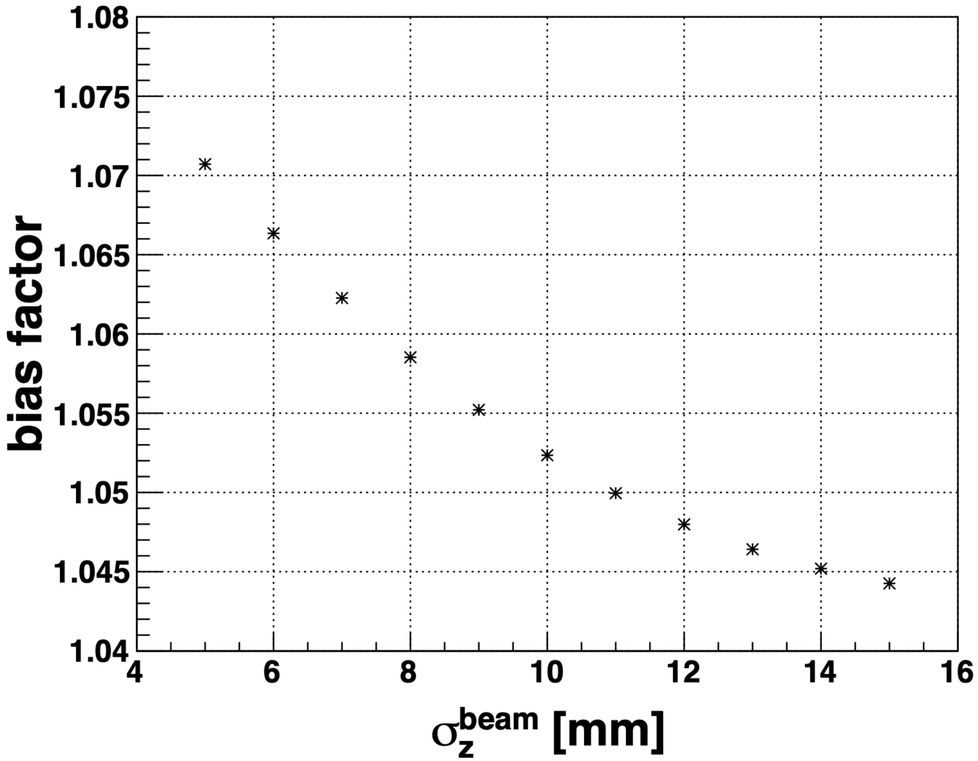
Shape functions of Up and Down electrode

$$V(t) = \frac{1}{L}\int_{-L/2}^{L/2}\left\{\frac{\phi(l)}{\overline{\phi}}V(t-1/\beta c)\right\}dl$$

parameter	explanation
t	time
V(t)	output voltage at time t w/o structure effect
L	electrode length
$\frac{l}{\phi}$	longitudinal position of an electrode
$\overline{\phi}$	averaged electrode coverage angle
φ(l)	electrode coverage angle at l
β, c	velocity of beam and light

CST simulation with TypeA BEPM

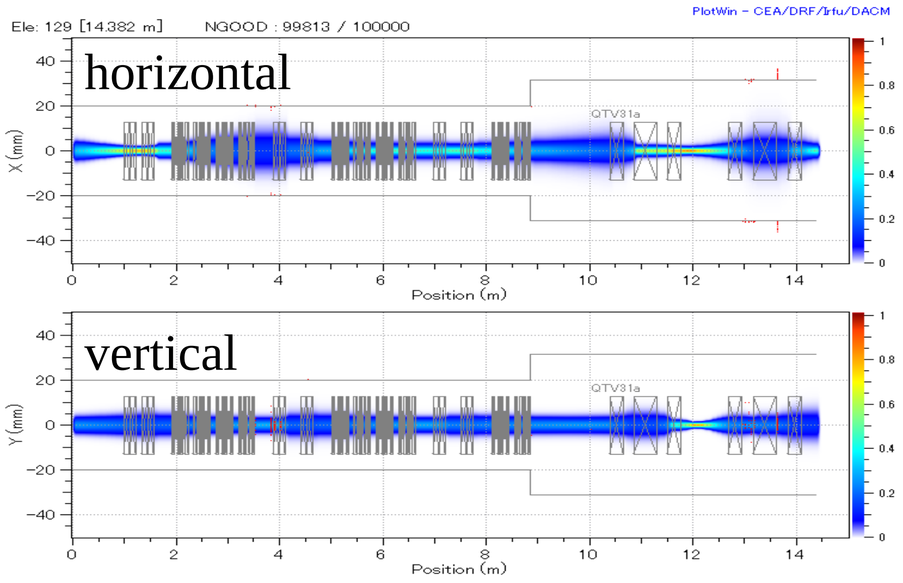
(L = 50 mm / σ_t^{beam} ~ 0.5 ns ⇔ 10° for RF)

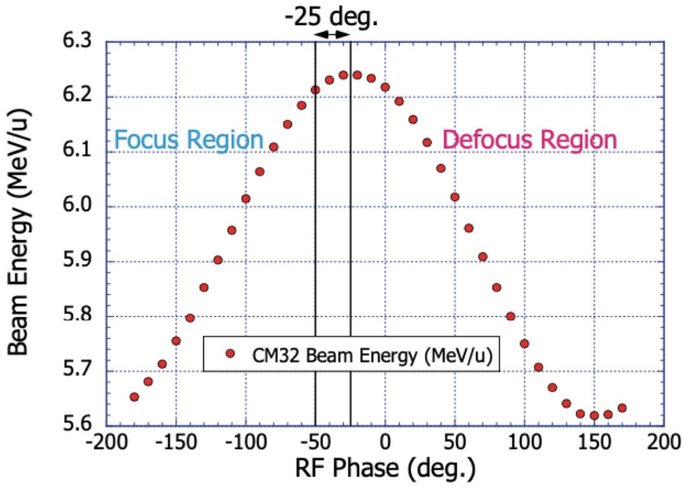


bias factor strongly depends on bunch length σ_z^{beam}

Transfer matrix: calculated by TraceWin

Beam Envelope (calc. by TraceWin)





TraceWin Feature from manual

TraceWin is used for linear and non linear calculations for 2D or 3D ions or electrons beams. It permits fast beam envelop computations or/and can be used as a GUI for Toutatis and Partran (macroparticle transport in linacs).

Transfer matrix elements are calculated by TraceWin

- **NOT** consider non-linear effect
  (beam intensity ~ a few pμA→ space charge: still small)
- Phases / HV of superconducting RF cavities
  → Calibrated by energy measurement with BEPM
- Simulated beam energy after acceleration
  → Reproduced exp. values well even after Phase / HV tuning
  ($\Delta E < 0.2\%$)