68th ICFA Advanced Beam Dynamics Workshop on
High-Intensity and High-Brightness Hadron Beams (HB2023)

Measurement of Transverse Beam Emittance for a High-Intensity Proton Injector

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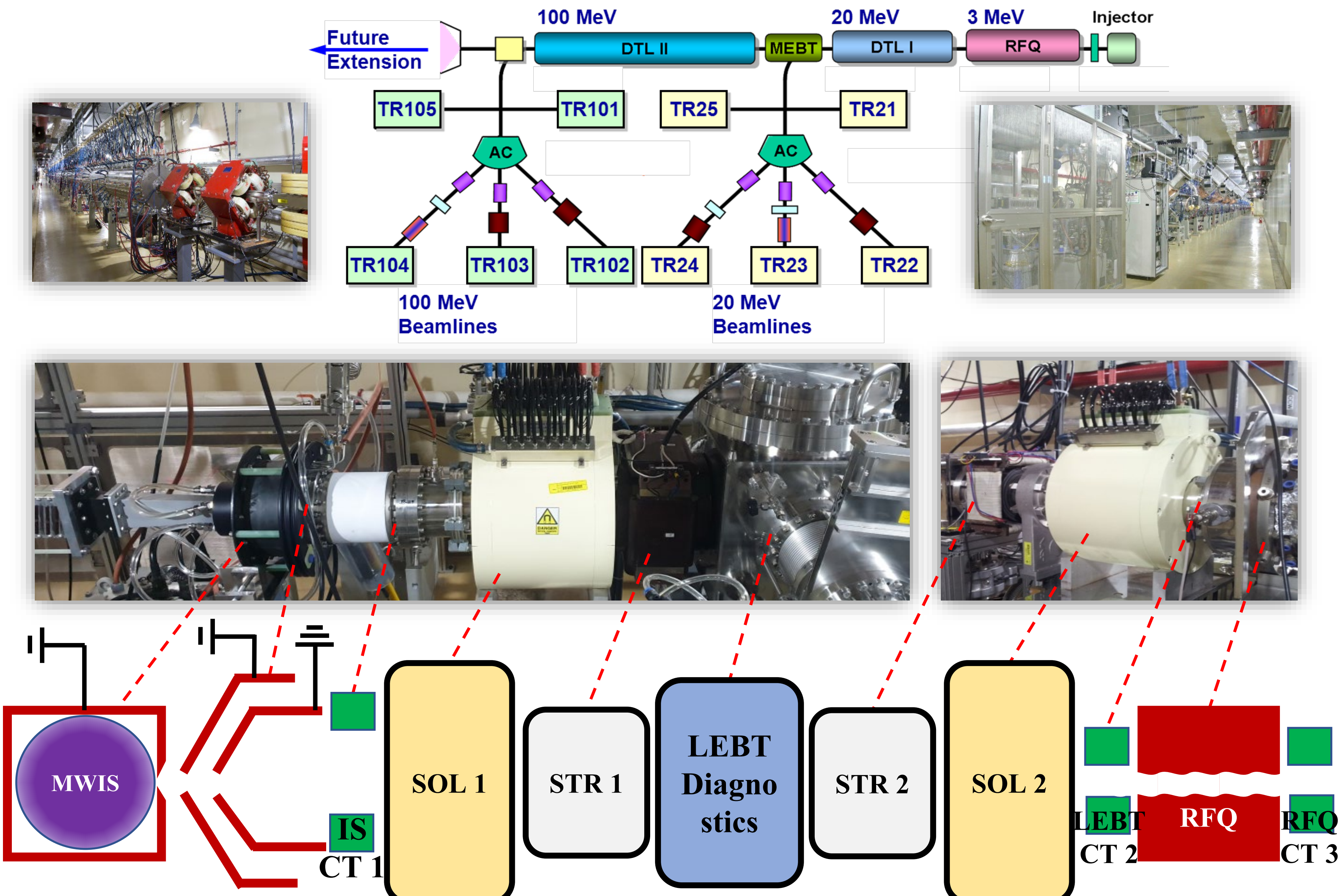
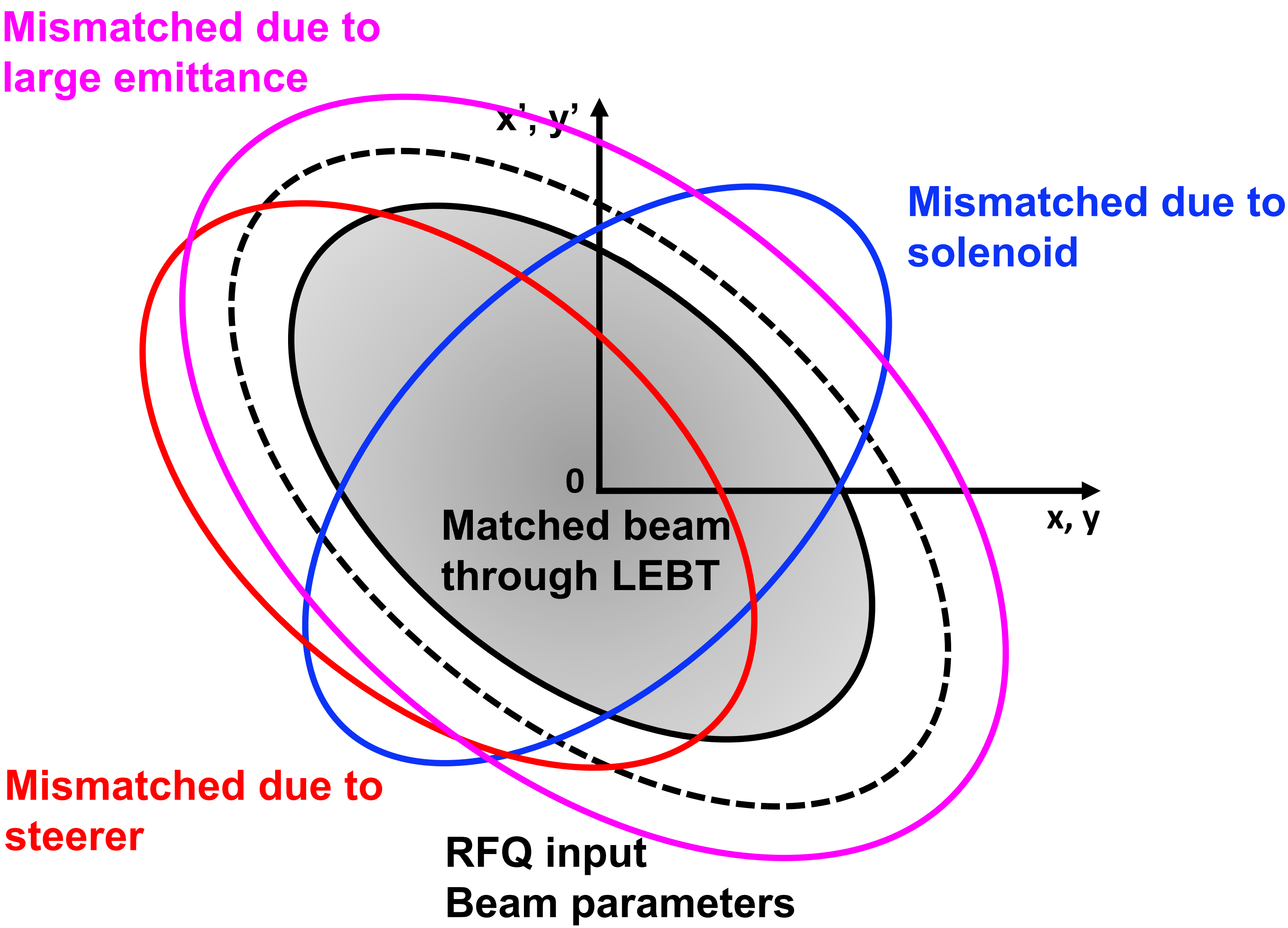
- KOMAC proton injector
- RFQ-based Beam Test Stand (RFQ-BTS)
- Low Energy Beam Diagnostics
- Solenoid Scan: Simulations and Experiments
- Summary

KOMAC 100-MeV Linac and Proton Injector

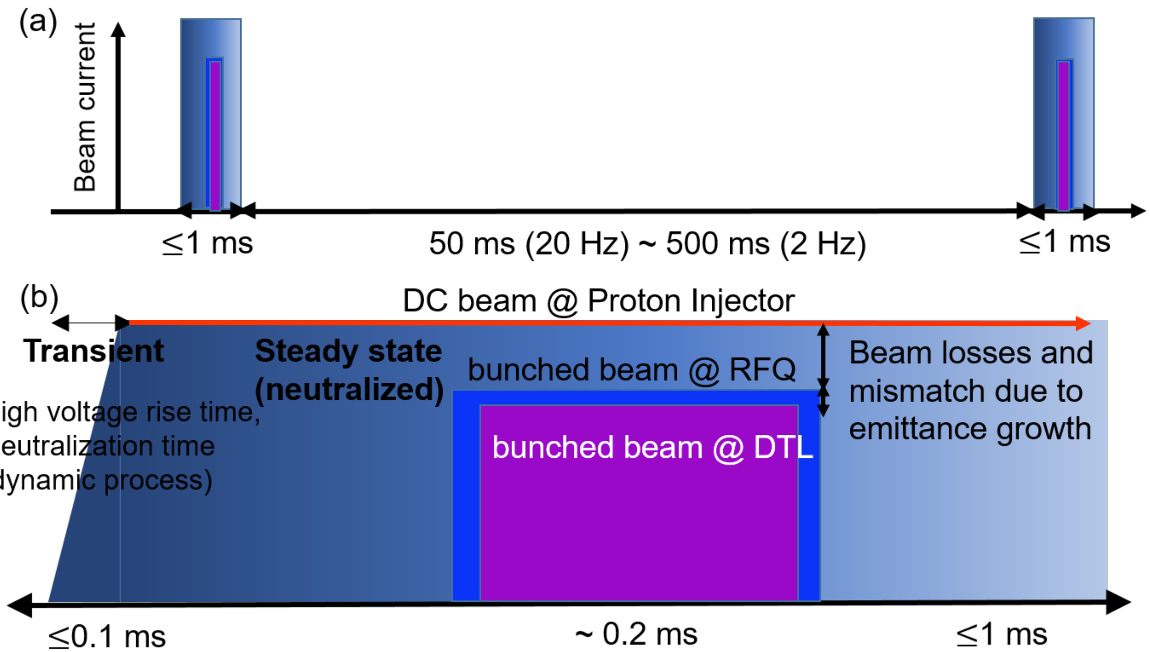


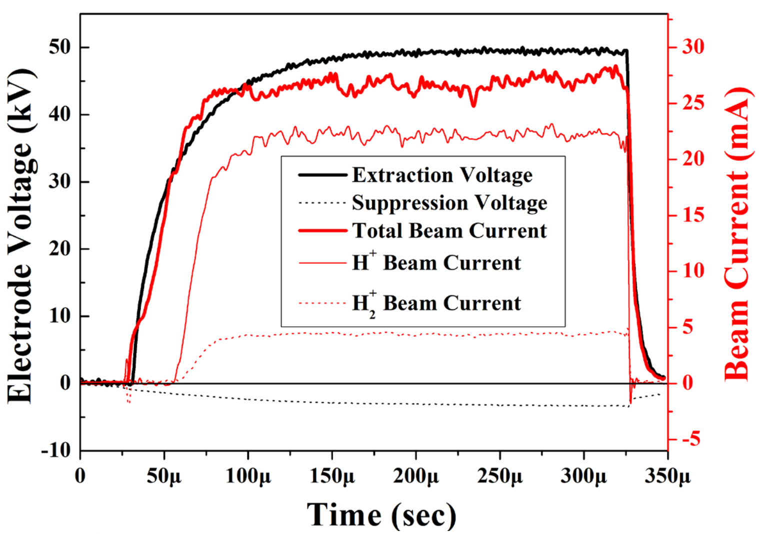
Proton, 50-keV, 30-mA, 1-msec

Beam matching in Transverse Phase Space

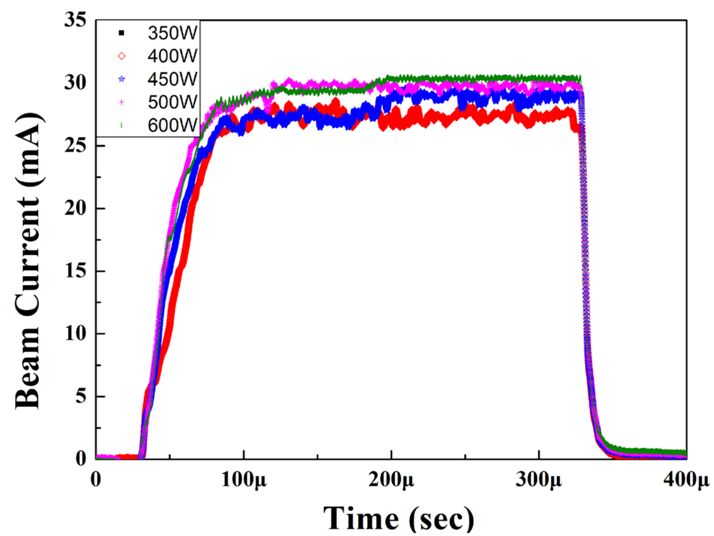


Time Structure of Pulsed Beam in KOMAC Linac



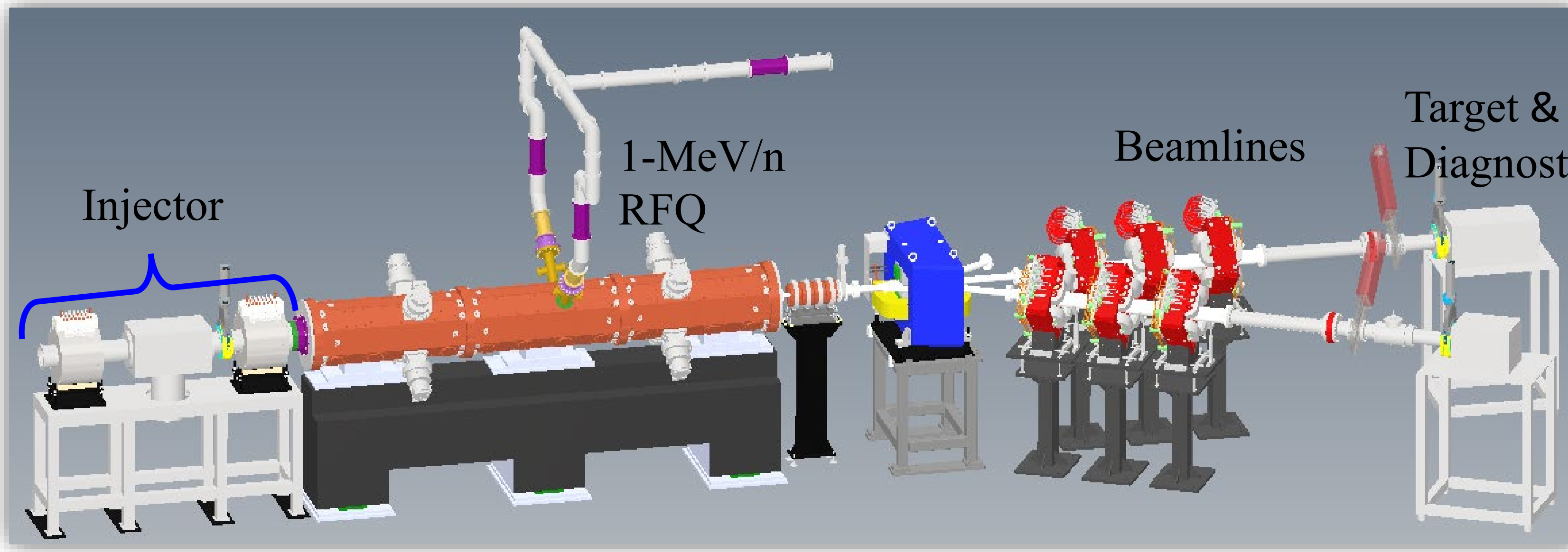


✓ Typical beam extraction data



✓ Microwave power vs. Beam current

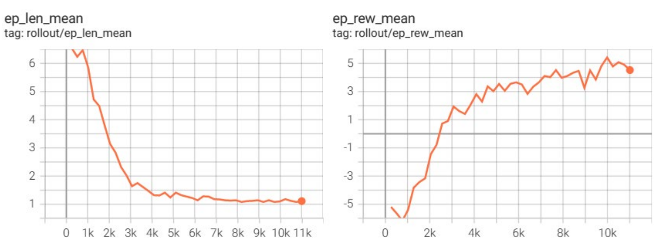
RFQ-based Beam Test Stand (RFQ-BTS)



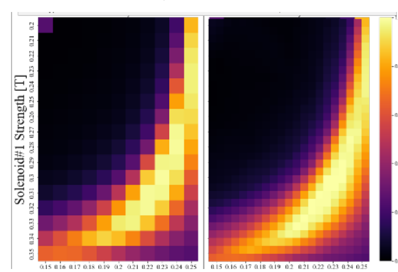
Machine Learning Applications

Beam Diagnostics

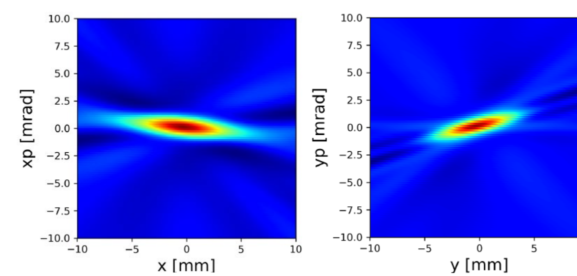
Reinforcement learning for Beam orbit correction



Deep neural networks for LEBT-RFQ beam matching



4D transverse phase space tomography



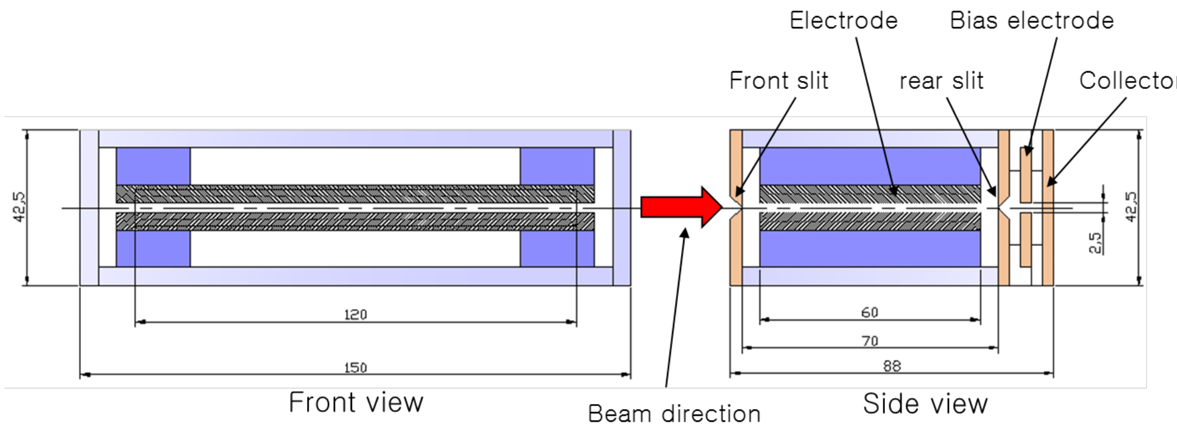
*S. Lee, THAFP07

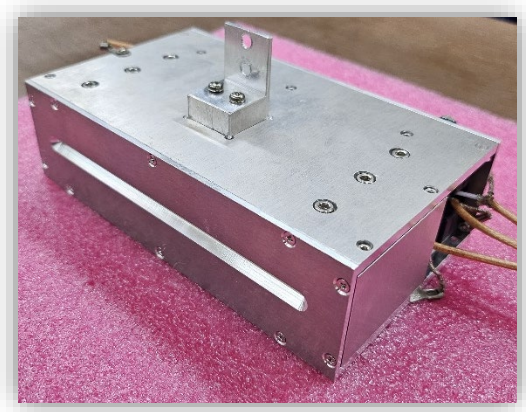
and …
low energy beam dynamics and diagnostics

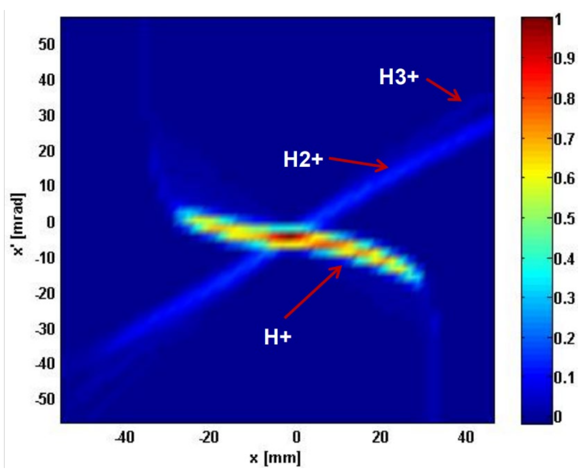
Options for Transverse Beam Emittance Diagnostics

- **Allison scanner**
  - Separated two 2D phase space distribution → transverse coupling issues from ECR ion source and compensation through solenoids or skew quadrupoles.
- **Pepper-pot**
  - Complete 4D phase space distribution → correlation coefficient between different phase plane.
  - Limited to low energy and large beam.
- **Tomography**
  - More than 4D phase space distribution.
  - Algorithm-dependent: image reconstruction, ML…
- **Magnet Scan**
  - Need to determine "good" scan range (near the beam waist) and consider space charge effect.
  - For hadron beams, quadrupoles are mainly used.

Allison-type Electric Sweep Scanners



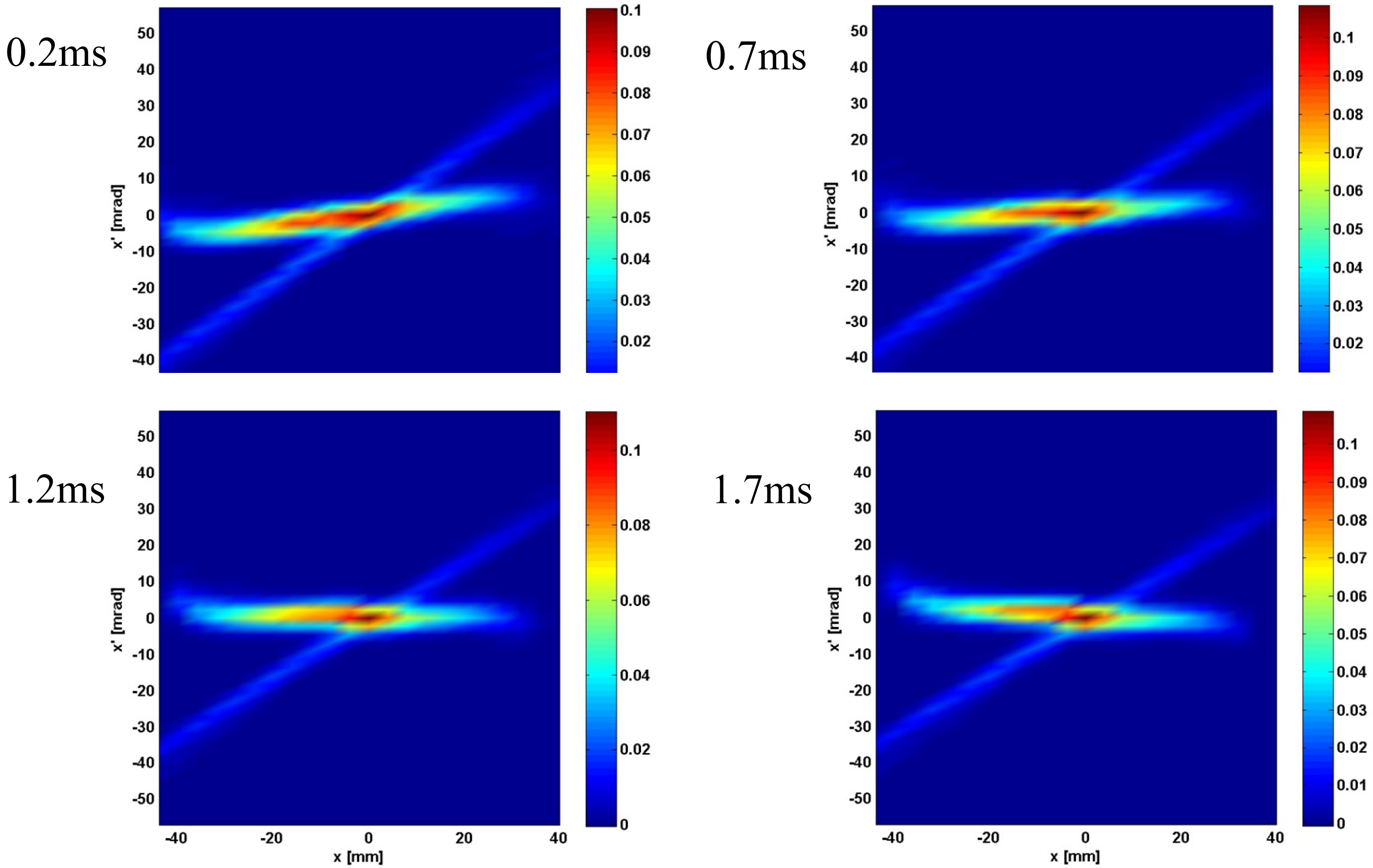




Proton Injector Beam	Typical values
Beam energy	$50\ keV$
Total beam current	$20 \sim 40\ mA$
Beam pulse width	$0.1 \sim 2\ msec$
Transverse emittance (RMS, normalized)	$0.2\ \pi \sim 0.4\ \pi\ mm.mrad$

2D Phase Space Measurement by Allison-type Scanner

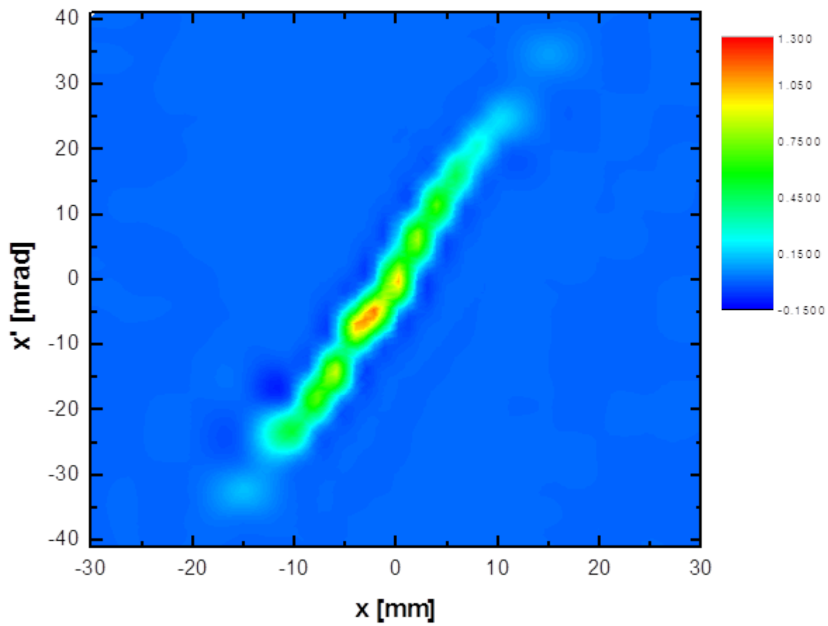
- Temporal evolution of 2D transverse phase space distribution for the hydrogen beam pulse (50-keV, 20-mA, 2-msec).



*H. S. Kim *et al.*, ECRIS2016

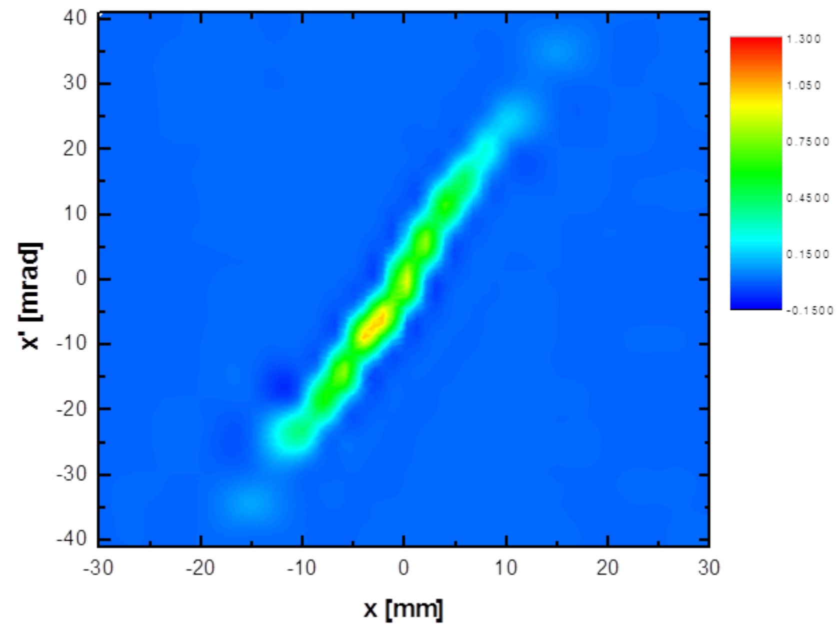
2D Phase Space Measurement by Allison-type Scanner

- Mitigation of beam emittance growth via inert gas injection into LEBT.



✓ No gas injection

ε (normalized, rms) = 0.32 π mm mrad

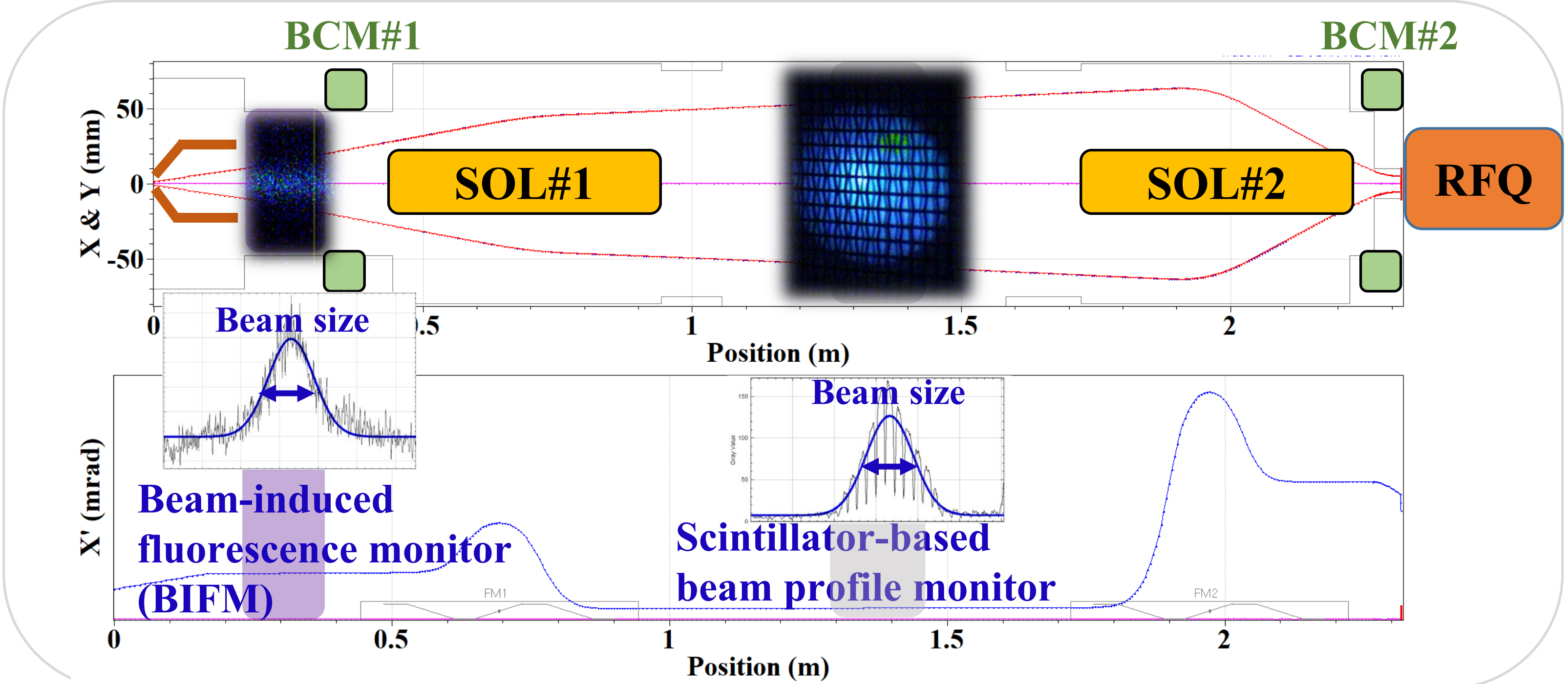


✓ Krypton gas injection (1sccm)

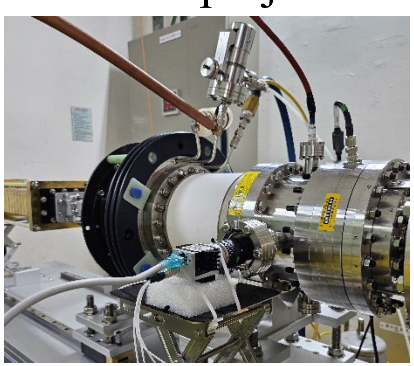
ε (normalized, rms) = 0.25 π mm mrad

*H. J. Kwon ***et al.***, ECRIS2016

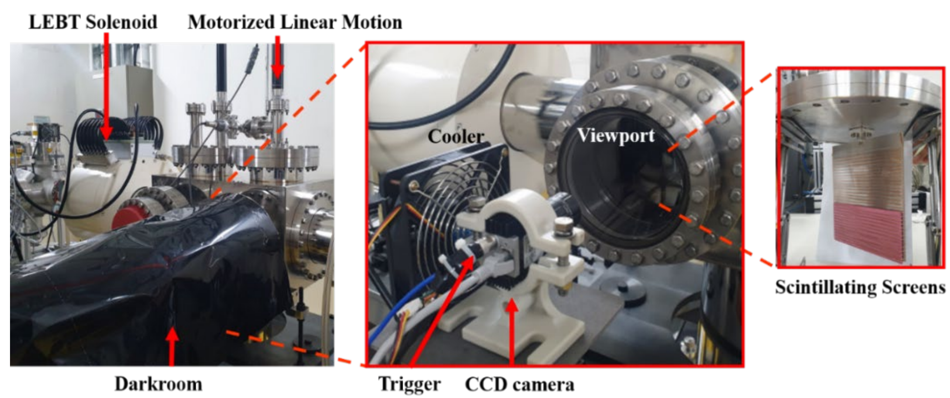
Layout of RFQ-BTS LEBT



Non-invasive & vertical projection

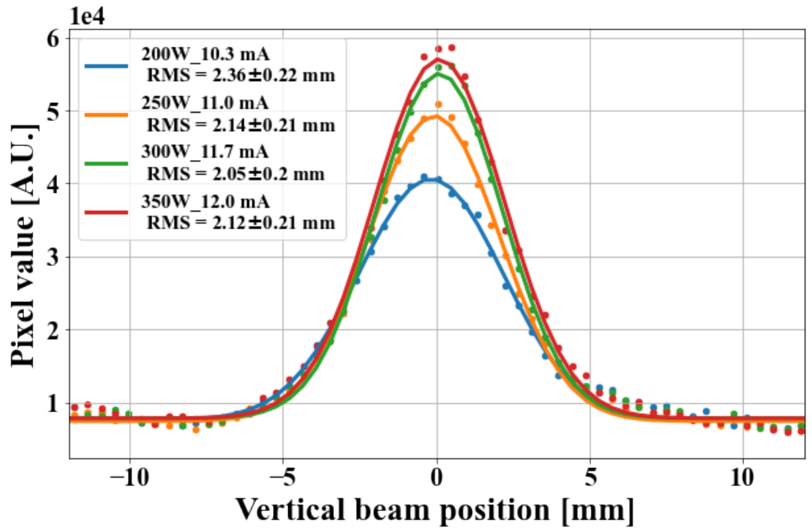


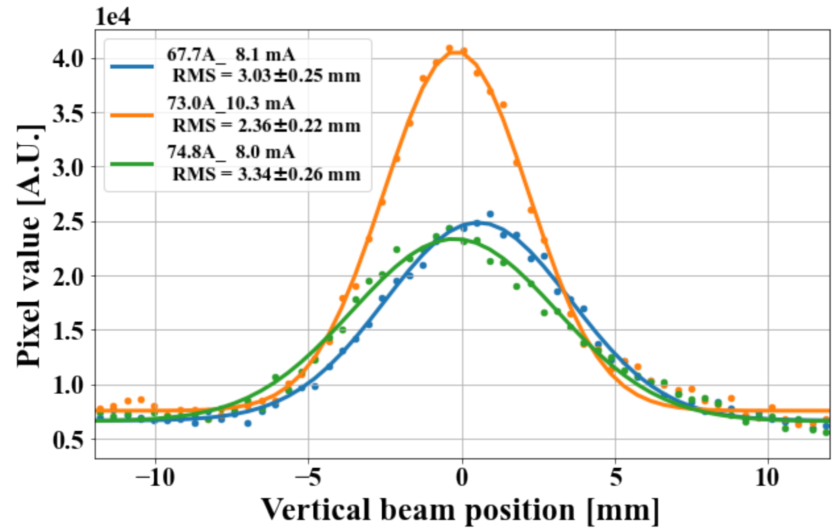
Invasive & both directions



Beam Measurement and Simulation for RFQ-BTS

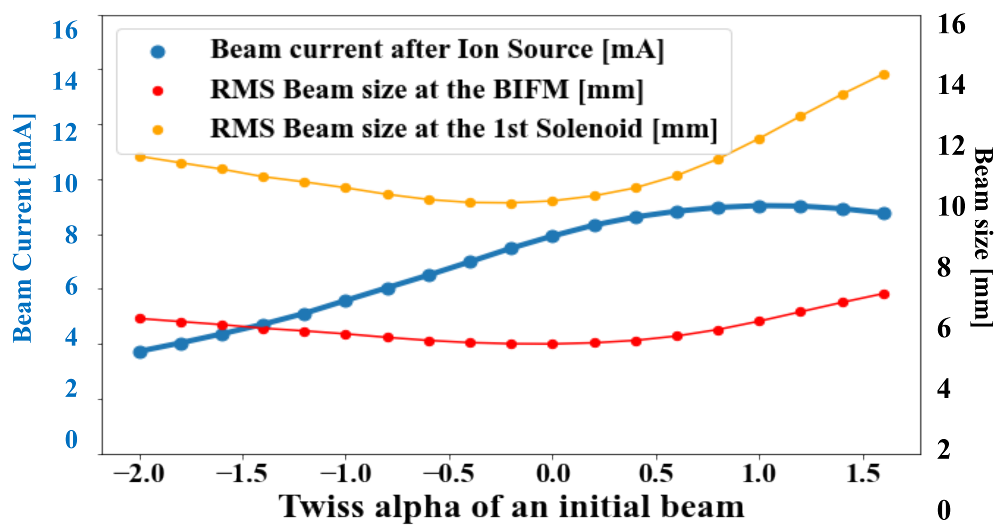
- ✓ **Measurement:** Beam induced fluorescemce monitor (BIFM)





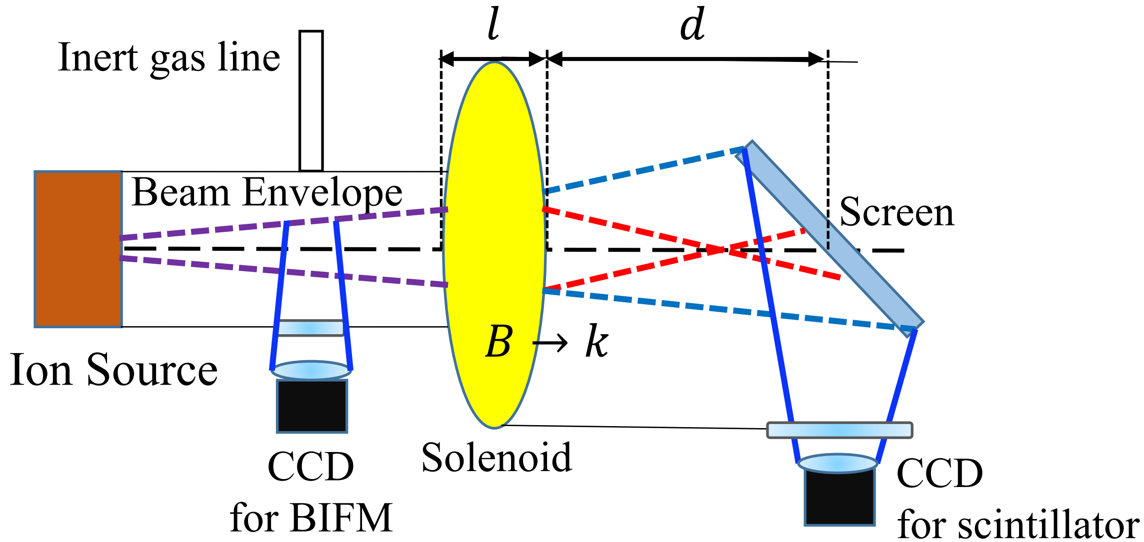
- ➢ Initial beam vs. Ion Source RF Power
- ➢ Initial beam vs. Ion Source Solenoid

- ✓ **Simulation**



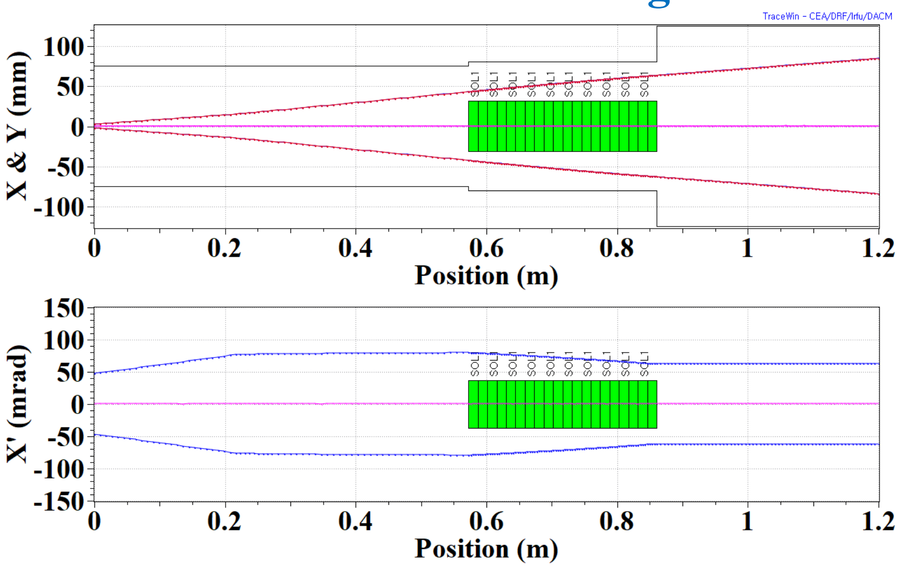
Solenoid Scan: Experiment and Simulation Setup

✓ **Measurement**

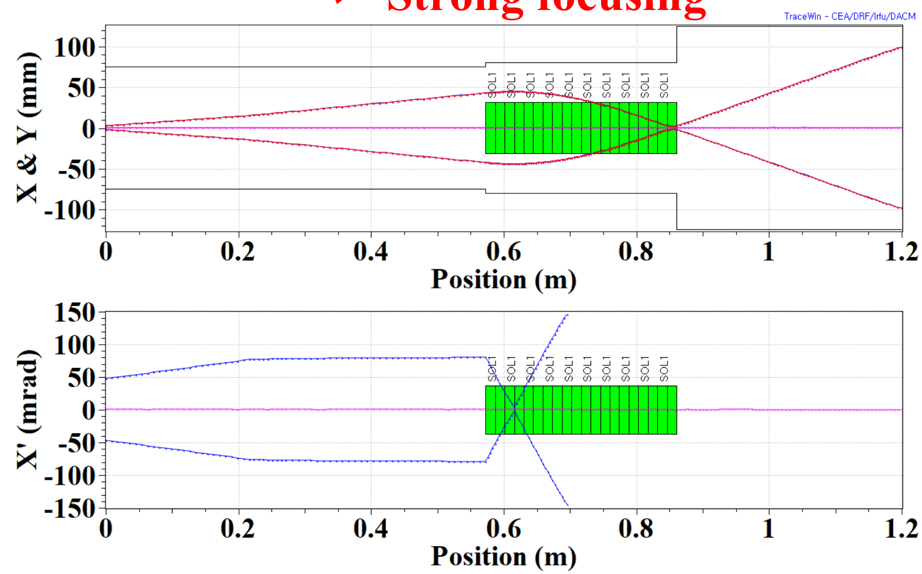


✓ **Simulation**

✓ **Weak focusing**



✓ **Strong focusing**



Thick-lens Approximation for Solenoid Scan

$$\sigma_{1,X} = M\sigma_{0,X}M^T$$

$M = Drift * Solenoid$

$$= \begin{pmatrix} 1 & d & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} cos^2(kl) & \sin(2kl)/2k & -sin(2kl)/2 & -\sin^2(kl)/k \\ -ksin(2kl)/2 & \cos^2(kl) & ksin^2(kl) & -sin(2kl)/2 \\ sin(2kl)/2 & \sin^2(kl)/k & cos^2(kl) & \sin(2kl)/2k \\ -ksin^2(kl) & sin(2kl)/2 & -ksin(2kl)/2 & \cos^2(kl) \end{pmatrix}$$

Vertical plane and horizontal plane is decorrelated in our case.

$$\sigma_{0,xy} = \sigma_{0,xy'} = \sigma_{0,x'y} = \sigma_{0,x'y'} = 0$$

$\sigma_{1,xx}^2 = x_{rms,meas}^2$

$= m_{11}^2\sigma_{0,xx} + 2m_{11}m_{12}\sigma_{0,xx'} + m_{12}^2\sigma_{0,x'x'} + m_{13}^2\sigma_{0,yy} + 2m_{13}m_{14}\sigma_{0,yy'} + m_{14}^2\sigma_{0,y'y'}$

Axisymmetric round beam,

$$\sigma_{0,xx} = \sigma_{0,yy}, \qquad \sigma_{0,x'x'} = \sigma_{0,yy'} \qquad \sigma_{0,x'x'} = \sigma_{0,y'y'}$$

$x_{rms,meas}^2$

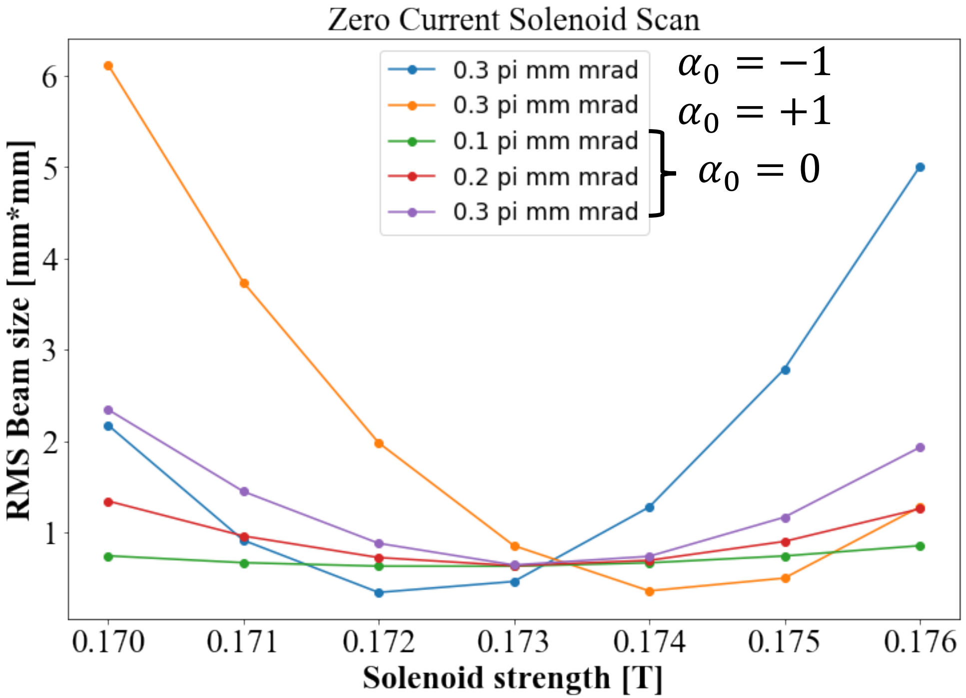
$= (m_{11}^2 + m_{13}^2)\sigma_{0,xx} + (2m_{11}m_{12} + 2m_{13}m_{14})\sigma_{0,xx'} + (m_{12}^2 + m_{14}^2)\sigma_{0,x'x'}$

Thick-lens Approximation without Space Charge

Measuring n data points to fit 3 free parameters by using least square method and obtaining the transverse beam emittance before the solenoid magnet.

$$\epsilon_{0,x} = \sqrt{\sigma_{0,xx}\sigma_{0,x'x'} - \sigma_{0,xx'}^2}$$

- First verification study on solenoid scan analysis by using TraceWin beam dynamics data without space charge.



Transverse emittance (RMS, normalized) $[\pi.mm.mrad]$

TraceWin input Initial beam emittance (w/o space charge)	TraceWin output RMS beam size + Solenoid scan
$\epsilon_0 = 0.3$, $\alpha_0 = -1$	0.300
$\epsilon_0 = 0.3$, $\alpha_0 = +1$	0.300
$\epsilon_0 = 0.3$, $\alpha_0 = +0$	0.300
$\epsilon_0 = 0.2$, $\alpha_0 = +0$	0.200
$\epsilon_0 = 0.1$, $\alpha_0 = +0$	0.100

Thick-lens Approximation with Linear Space Charge

$$\sigma_{1,X} = M_{SC}\sigma_{0,X}M_{SC}^{T}$$

$$\boldsymbol{M_{SC}} = \prod_{\boldsymbol{a=1}}^{\boldsymbol{n}} \boldsymbol{Drift_{d/n}} * \boldsymbol{SCK_{d/n}} \prod_{\boldsymbol{b=1}}^{\boldsymbol{m}} \boldsymbol{Solenoid_{l/m}} * \boldsymbol{SCK_{l/m}}$$

$$= \begin{pmatrix} 1 & d/n & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d/n \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ F_a d/n & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & F_a d/n & 1 \end{pmatrix} \cdots$$

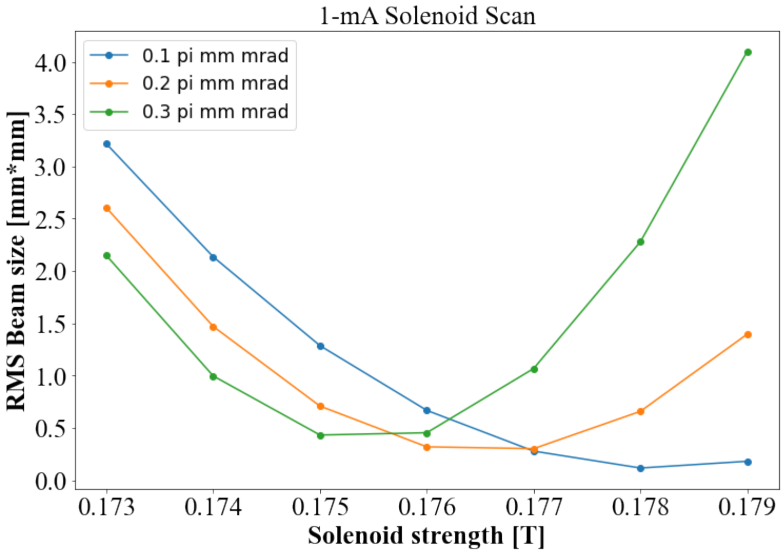
$$\begin{pmatrix} cos^2(kl/m) & \sin(2kl/m)/2k & -sin\,(2kl/m)/2 & -\sin^2(kl/m)/k \\ -ksin(2kl/m)/2 & \cos^2(kl/m) & ksin^2(kl/m) & -si\,n(2kl/m)/2 \\ sin\,(2kl/m)/2 & \sin^2(kl/m)/k & cos^2(kl/m) & \sin(2kl/m)/2k \\ -ksin^2(kl/m) & si\,n(2kl/m)/2 & -ksin(2kl/m)/2 & \cos^2(kl/m) \end{pmatrix}$$

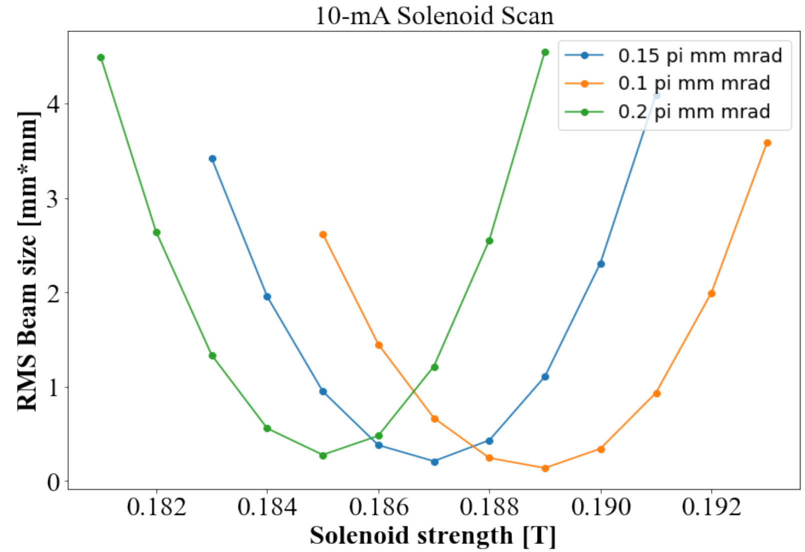
$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ F_b l/m & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & F_b l/m & 1 \end{pmatrix} \cdots$$

$x^2_{rms,meas}$

$$= (m^2_{\boldsymbol{SC},11} + m^2_{\boldsymbol{SC},13})\sigma_{0,xx} + (2m_{\boldsymbol{SC},11}m_{\boldsymbol{SC},12} + 2m_{\boldsymbol{SC},13}m_{\boldsymbol{SC},14})\sigma_{0,xx'} + (m^2_{\boldsymbol{SC},12} + m^2_{\boldsymbol{SC},14})\sigma_{0,x'x'}$$

Thick-lens Approximation with Linear Space Charge

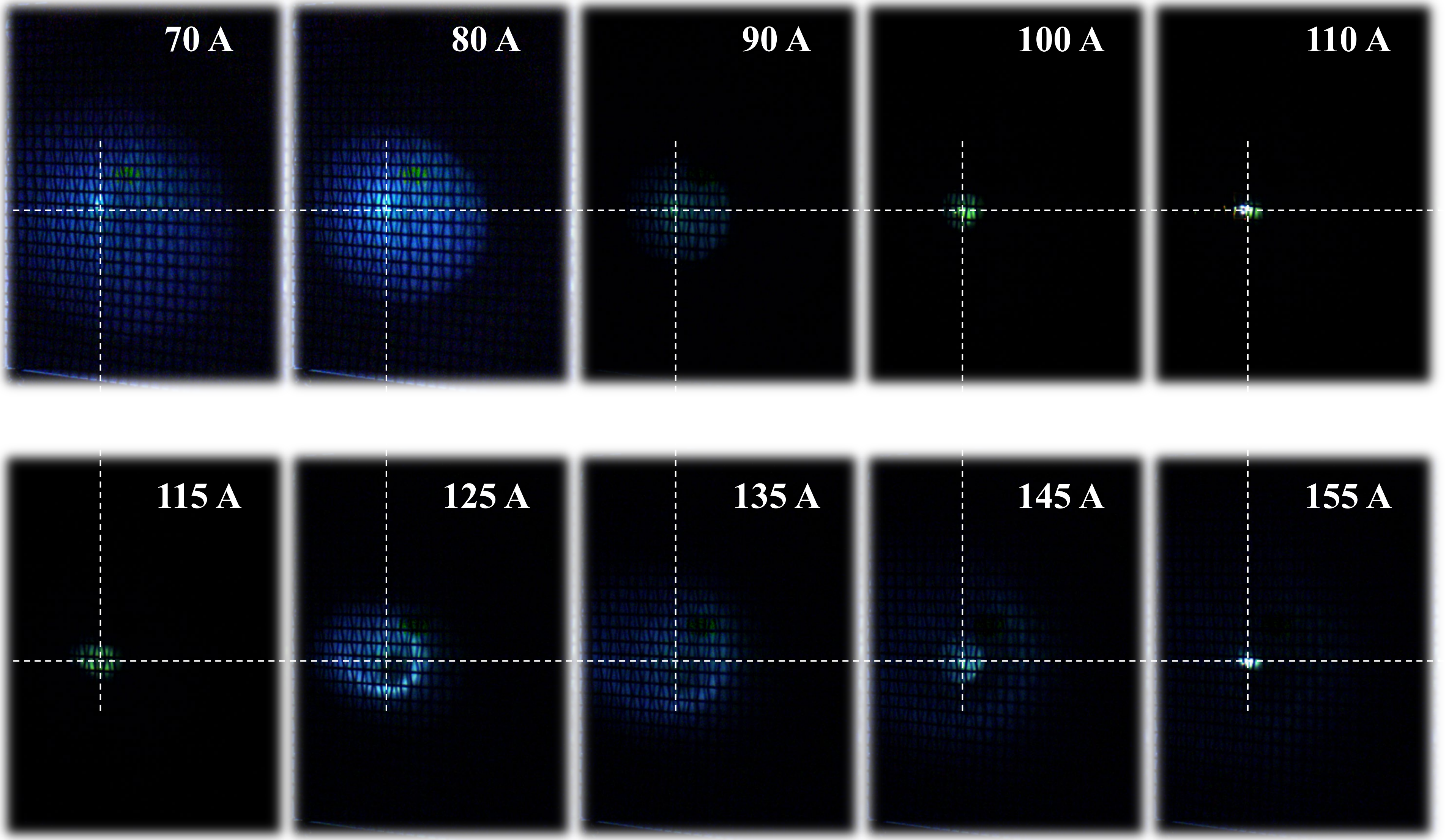




Transverse beam emittance (RMS, normalized) $[\pi. mm. mrad]$

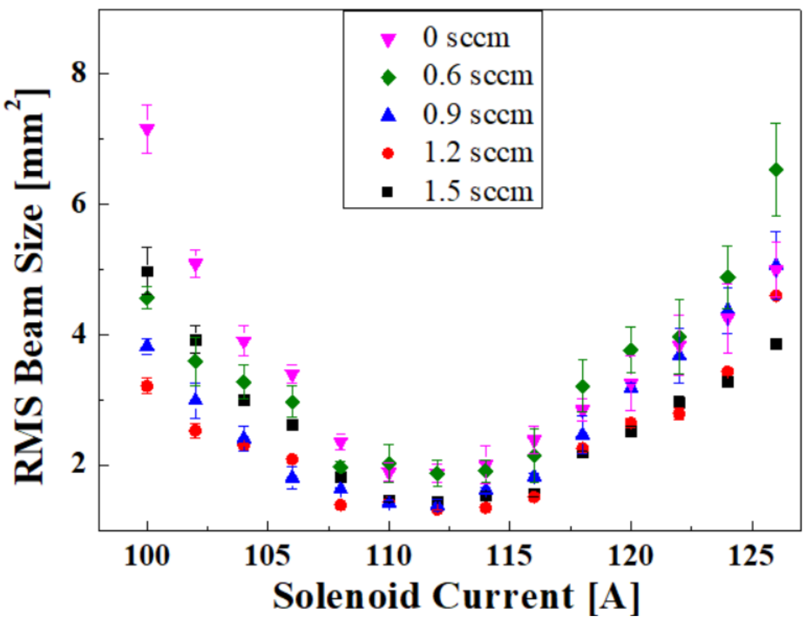
TraceWin input Initial beam emittance (with space charge)		TraceWin output RMS beam size + Solenoid scan w/o space charge M	TraceWin output RMS beam size + Solenoid scan with space charge M_{SC}	Error difference (w/o space charge – with space charge)
$I = 1\ mA$	$\epsilon_0 = 0.10$	0.104 (4%)	0.103 (3%)	-1%
$I = 1\ mA$	$\epsilon_0 = 0.20$	0.204 (2%)	0.203 (1.5%)	-0.5%
$I = 1\ mA$	$\epsilon_0 = 0.30$	0.304 (1.3%)	0.303 (1%)	-0.3%
$I = 10\ mA$	$\epsilon_0 = 0.10$	0.107 (7%)	0.108 (8%)	+1%
$I = 10\ mA$	$\epsilon_0 = 0.15$	0.173 (15%)	0.164 (9%)	**-6%**
$I = 10\ mA$	$\epsilon_0 = 0.20$	0.229 (15%)	0.210 (5%)	**-10%**

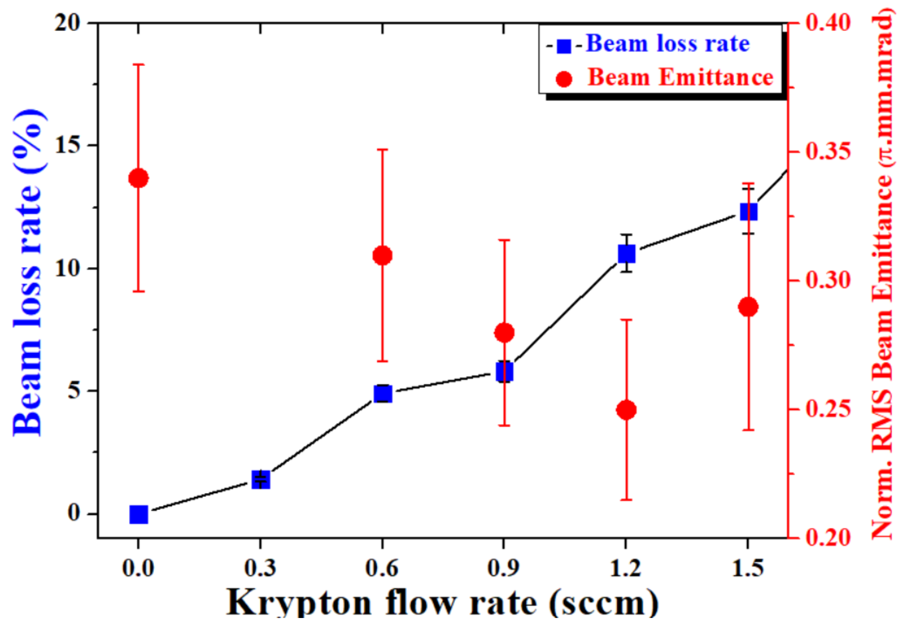
Transverse Beam Profile during Solenoid Scan



Transverse Beam Emittance Measurement during Inert Gas Injection

- **Solenoid scan** measurement and thick lens approximation with space charge.
  - Beam size at the 1st solenoid can be evaluated through the **BIFM**.
  - **Space charge** is approximately mapped through numerical iterations.
- **Mitigation of beam emittance growth** via inert gas injection into LEBT.
  - There is moderate **gas flow rate** at the expense of beam loss.





➢ Solenoid scan data with Krypton gas injection

➢ Measured transverse beam emittance and beam loss rate with Krypton gas.

Summary

- Beam characterization has been studied at **RFQ-based Beam Test Stand (RFQ-BTS)** to apply and to expand the obtained knowledge through higher-energy section.
- **Solenoid** may give simple and fast evaluation of low energy beam emittance even for the high-intensity proton beam by using thick-lens approximation with linear space charge terms.
- We will further integrate experiments and full simulation model from the low energy section through RF cavities to targets at several beamlines.

Thank you for your attention!

Question or Comment?