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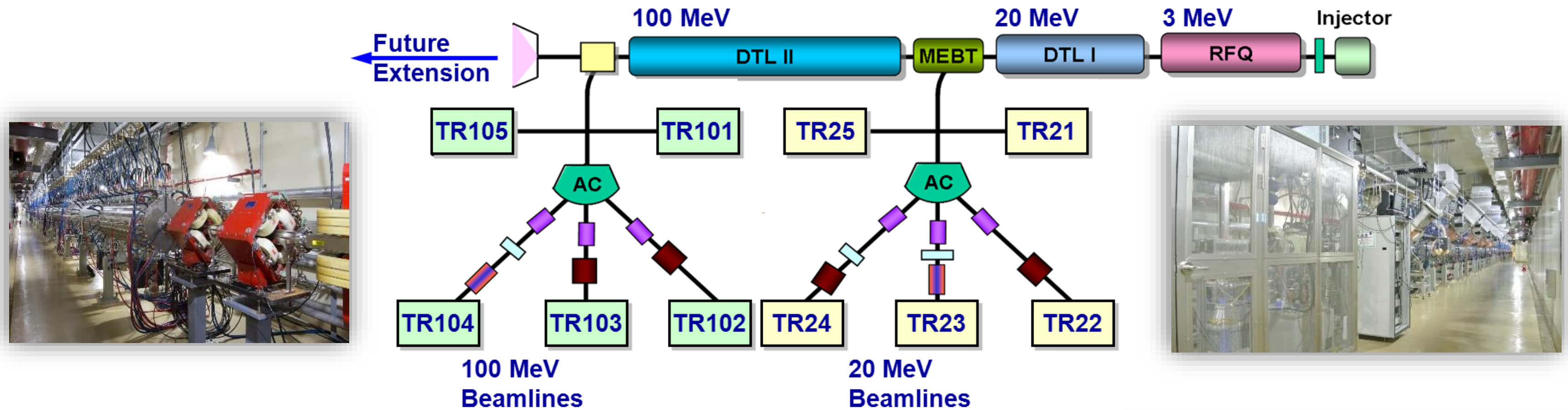
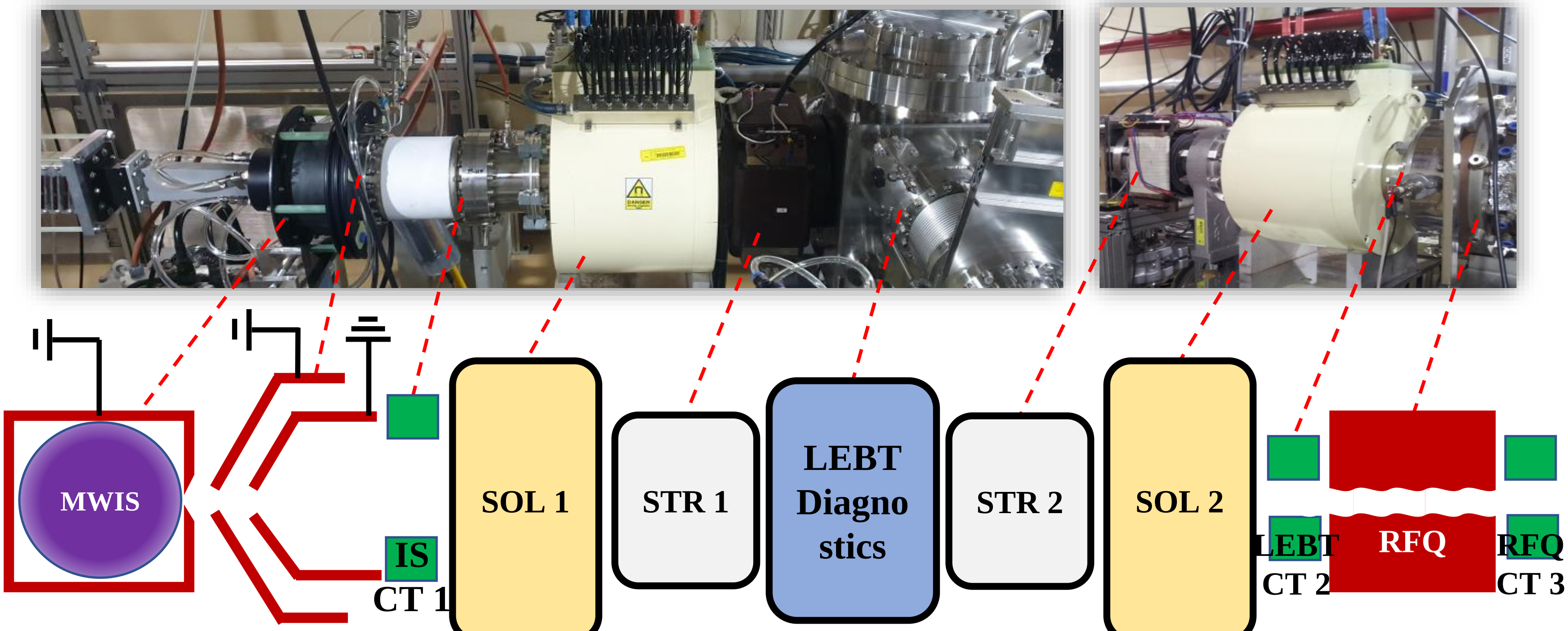
- KOMAC proton injector
- RFQ-based Beam Test Stand (RFQ-BTS)
- Low Energy Beam Diagnostics
- Solenoid Scan: Simulations and Experiments
- Summary

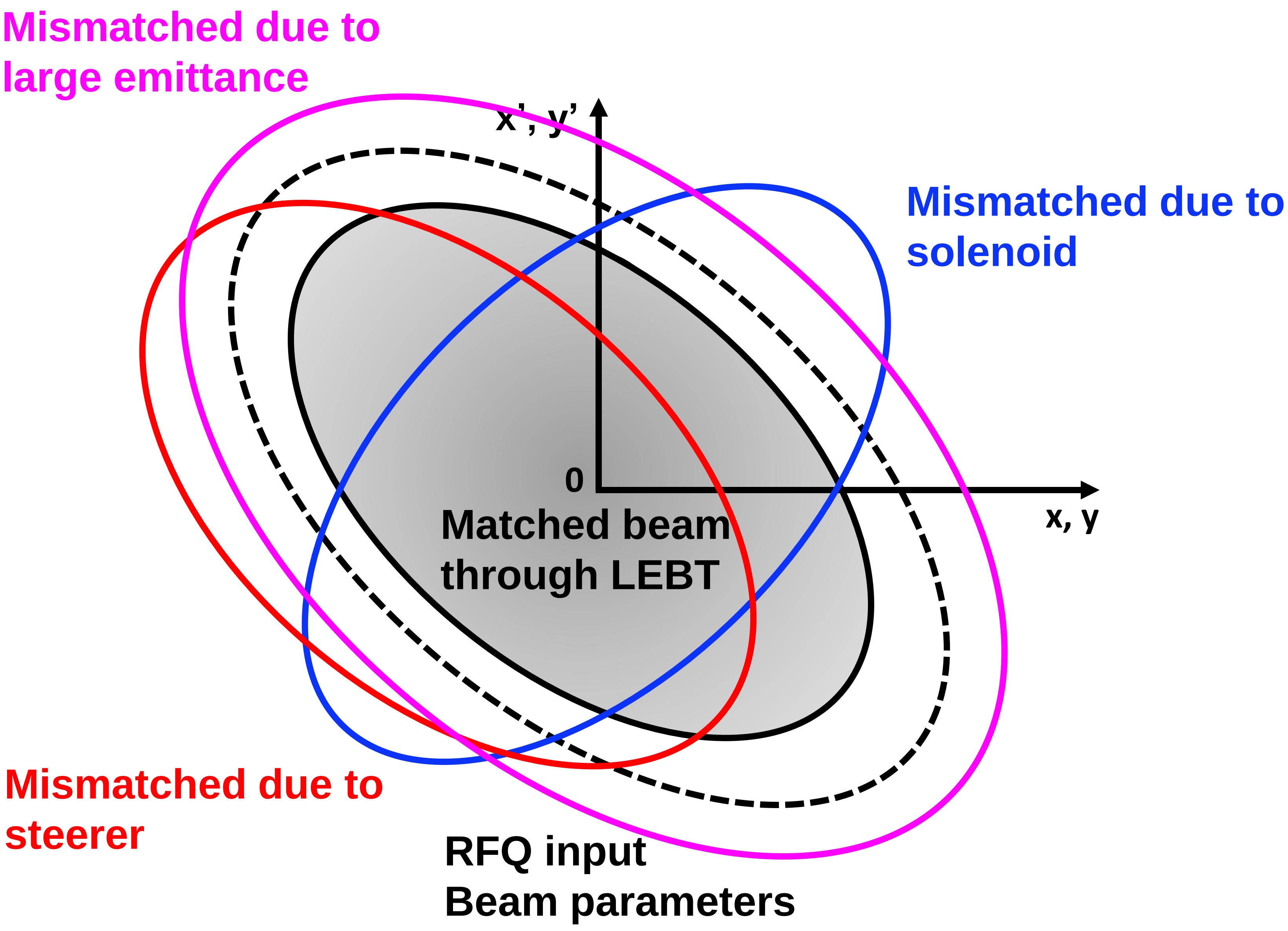
KOMAC 100-MeV Linac and Proton Injector



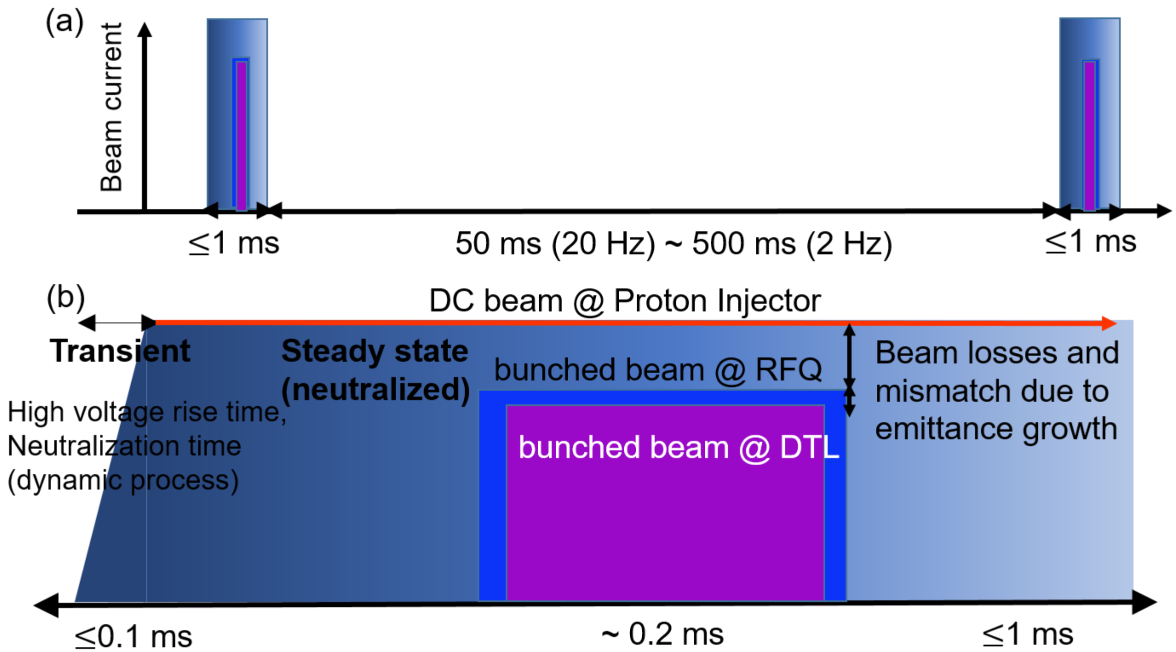


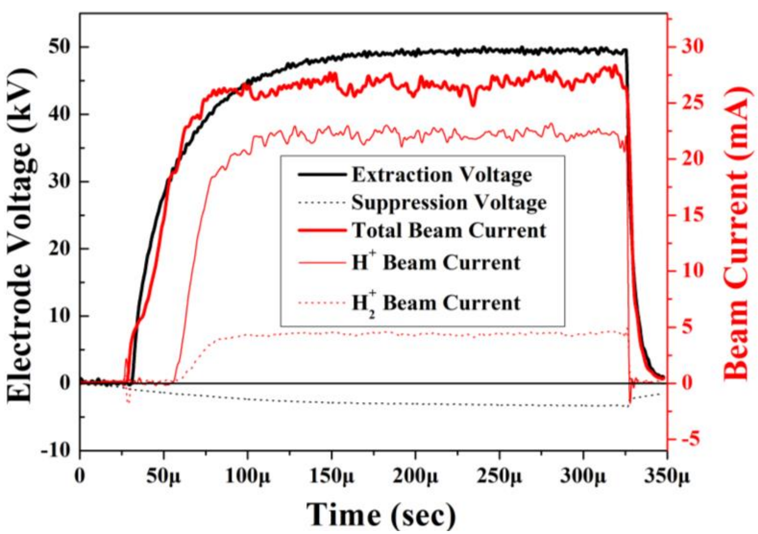
Proton, 50-keV, 30-mA, 1-msec

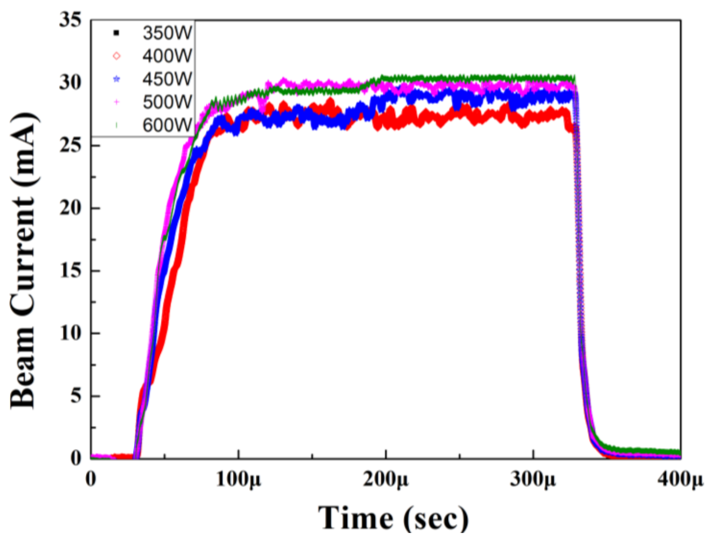
Beam matching in Transverse Phase Space



Time Structure of Pulsed Beam in KOMAC Linac

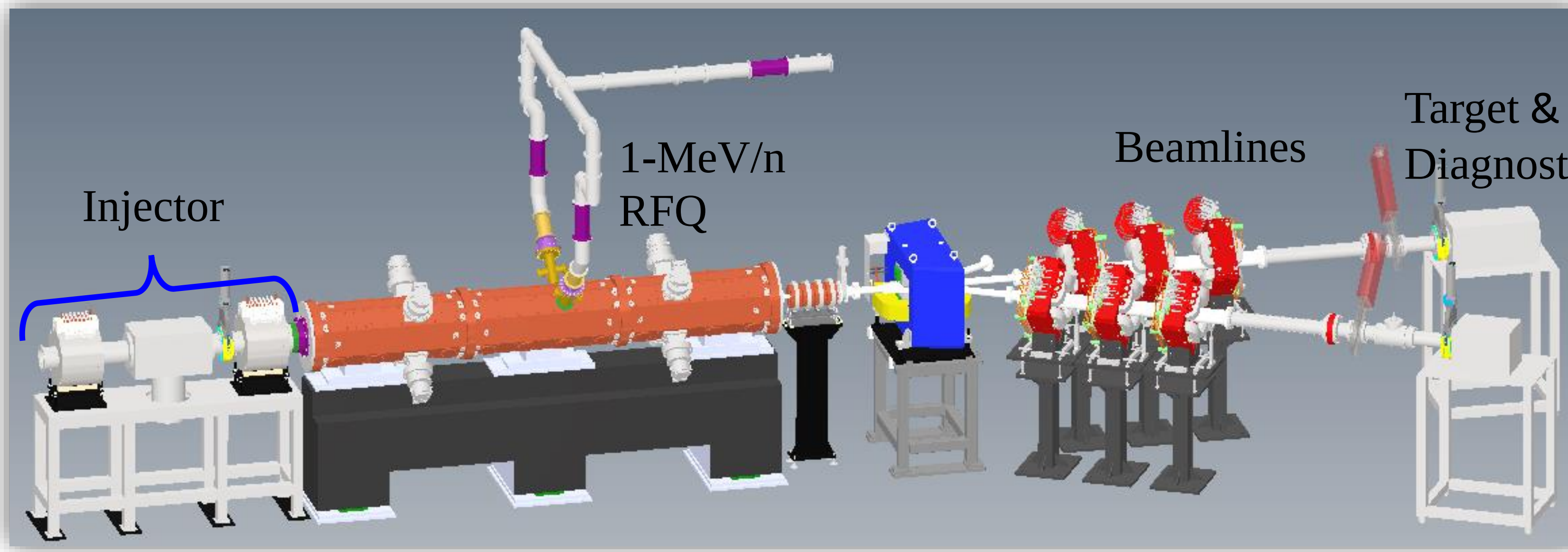






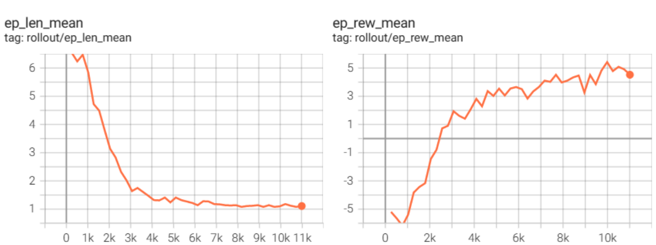
✓ Typical beam extraction data ✓ Microwave power vs. Beam current

RFQ-based Beam Test Stand (RFQ-BTS)

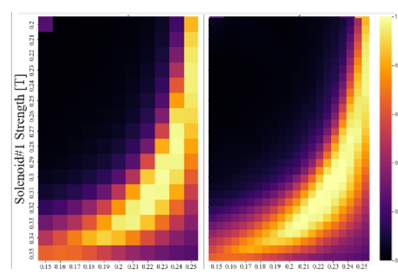


Machine Learning Applications

Reinforcement learning for Beam orbit correction

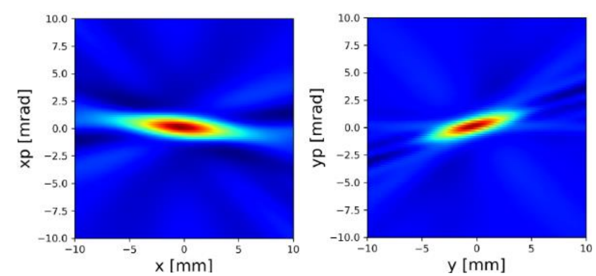


Deep neural networks for LEBT-RFQ beam matching



Beam Diagnostics

4D transverse phase space tomography



*S. Lee, THAFP07

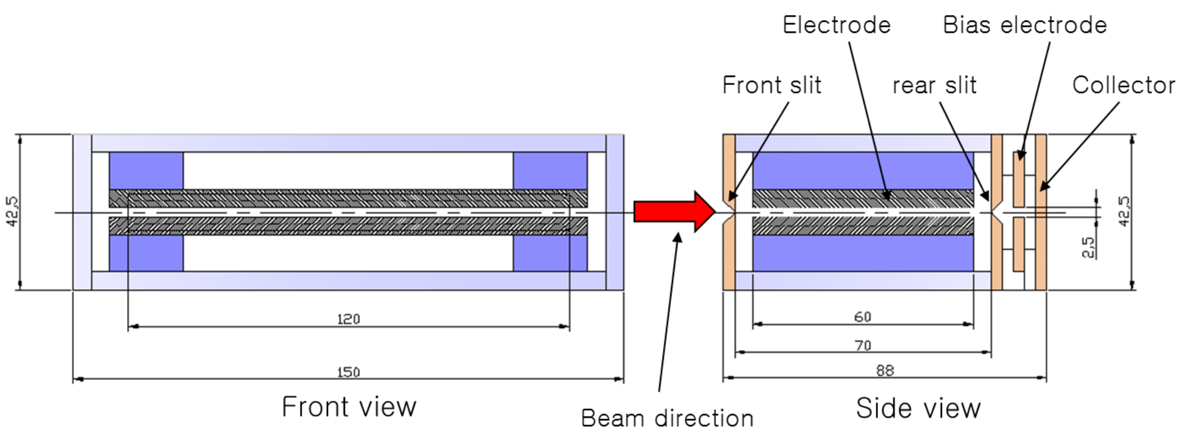
and …

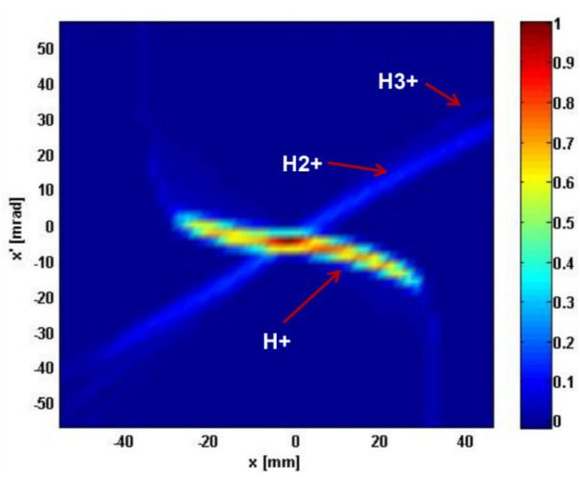
low energy beam dynamics and diagnostics

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

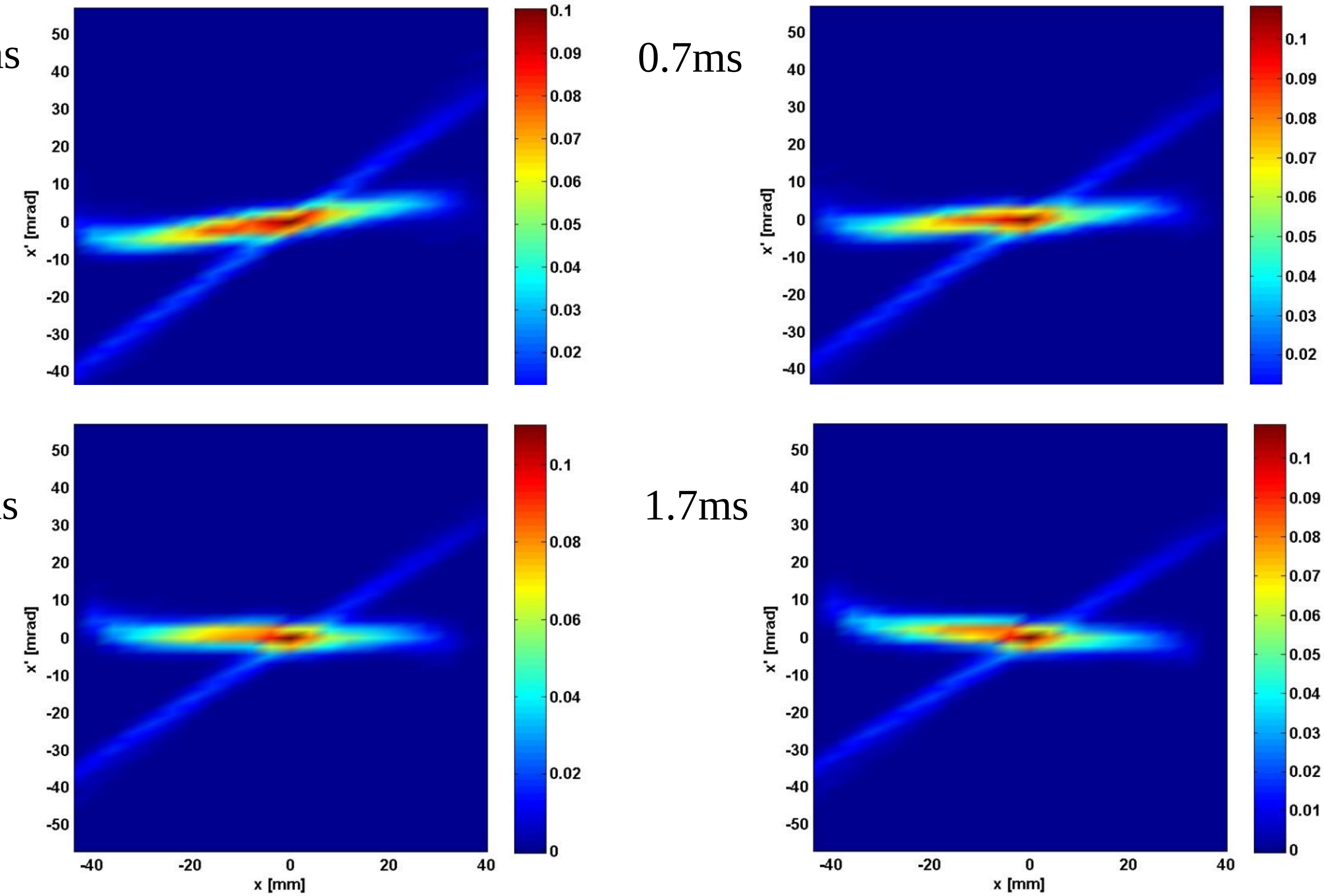
- Temporal evolution of 2D transverse phase space distribution for the hydrogen beam pulse (50-keV, 20-mA, 2-msec).

0.2ms

0.7ms

1.2ms

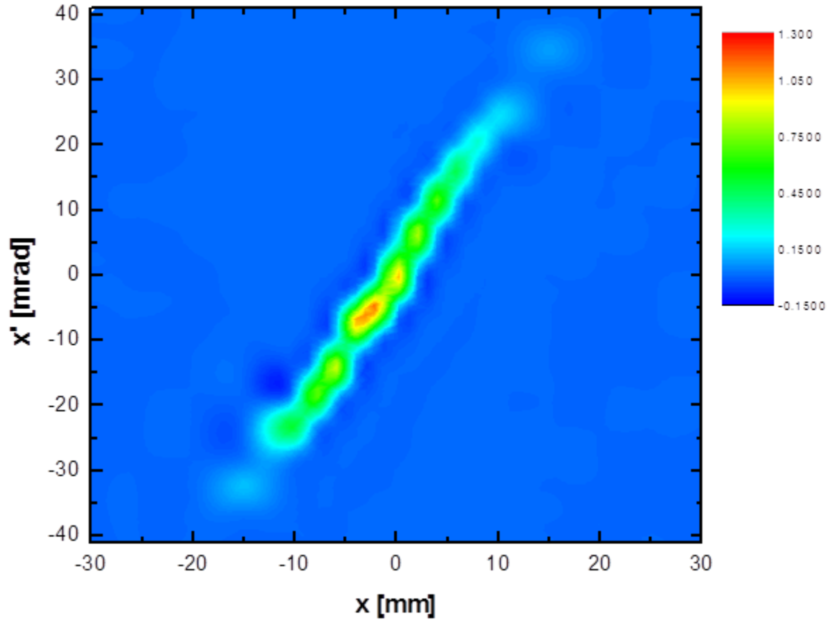
1.7ms



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

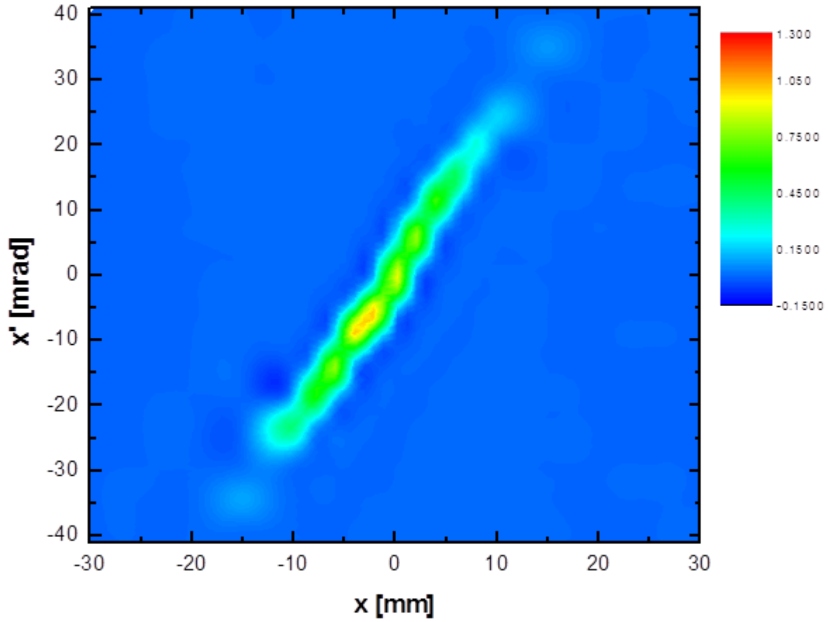
2D Phase Space Measurement by Allison-type Scanner

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



✓ No gas injection

ε (normalized, rms) = 0.32 π mm mrad

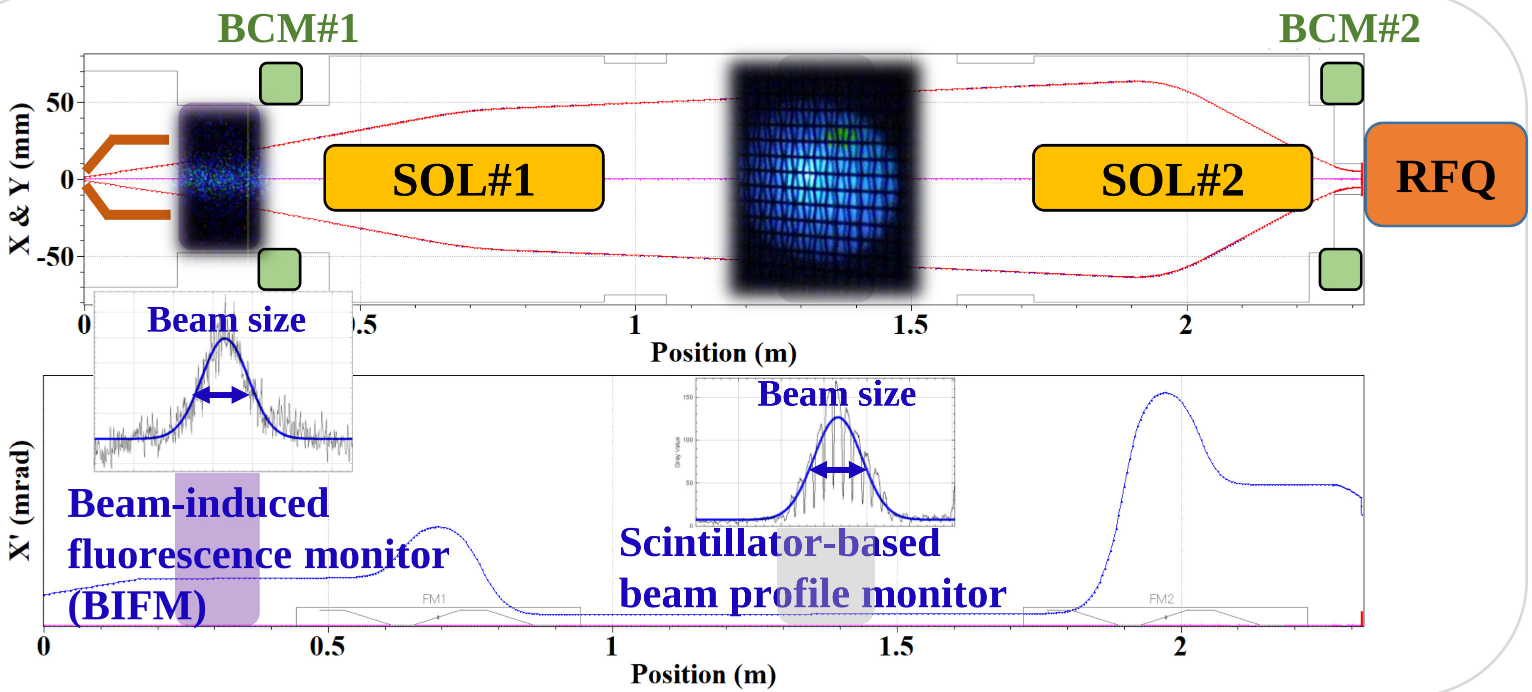


✓ Krypton gas injection (1sccm)

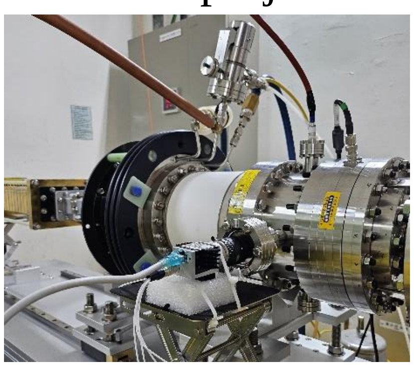
ε (normalized, rms) = 0.25 π mm mrad

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

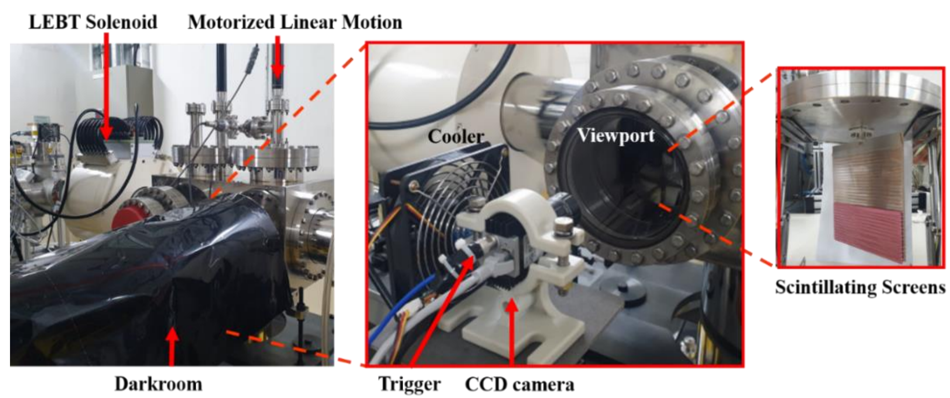
Layout of RFQ-BTS LEBT



Non-invasive &
vertical projection

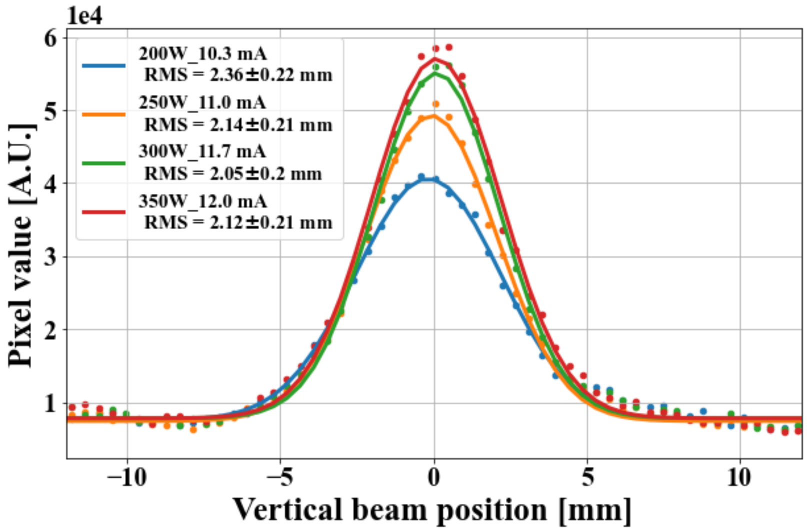


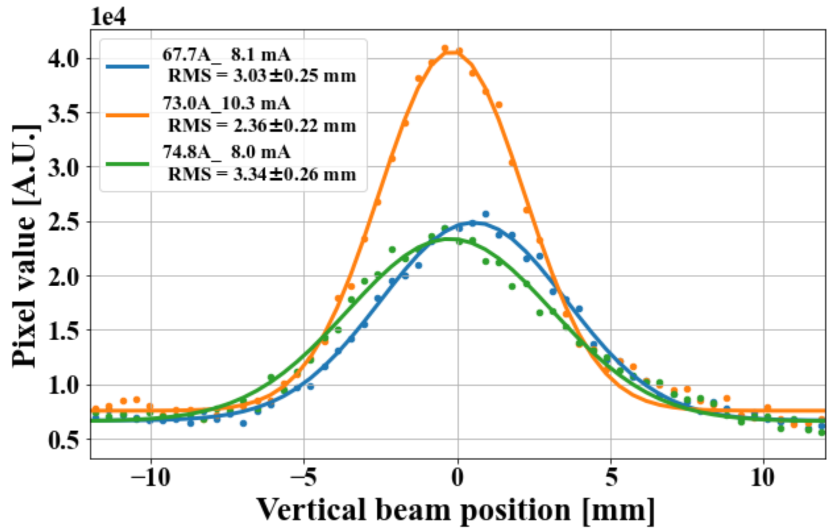
Invasive &
both directions



Beam Measurement and Simulation for RFQ-BTS

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

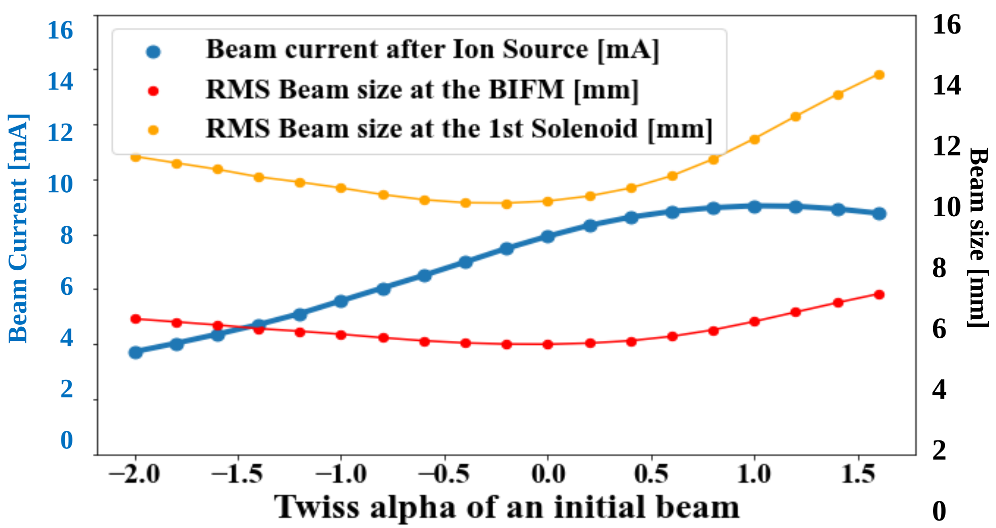




➢ Initial beam vs. Ion Source RF Power

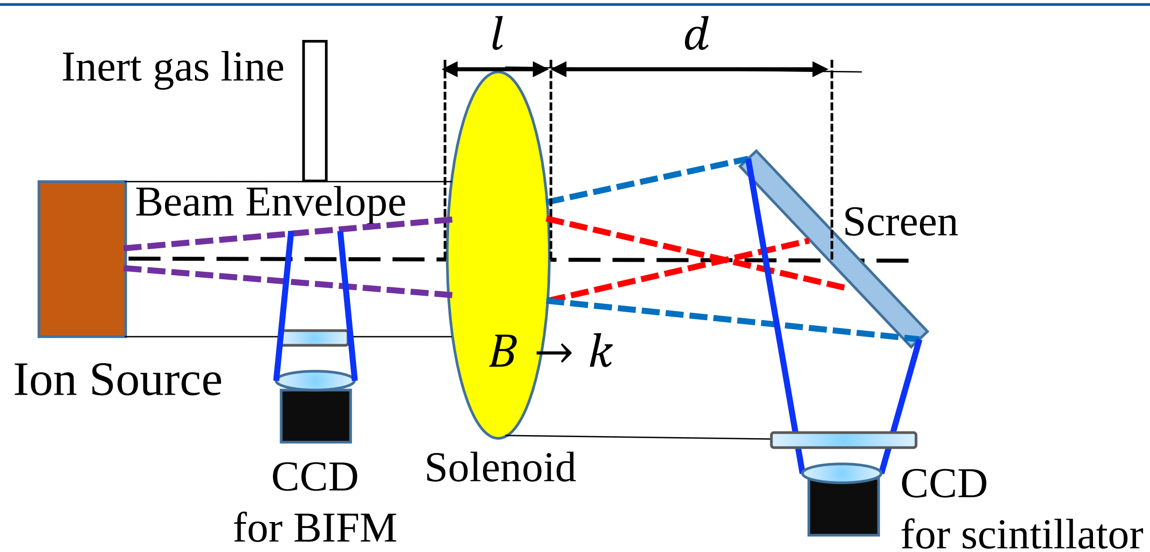
➢ Initial beam vs. Ion Source Solenoid

✓ **Simulation**



Solenoid Scan: Experiment and Simulation Setup

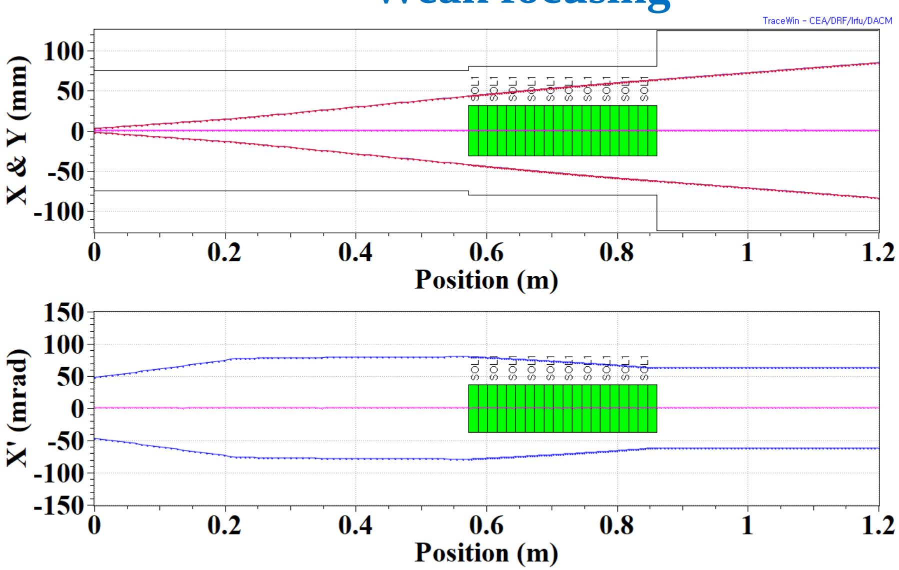
✓ **Measurement**

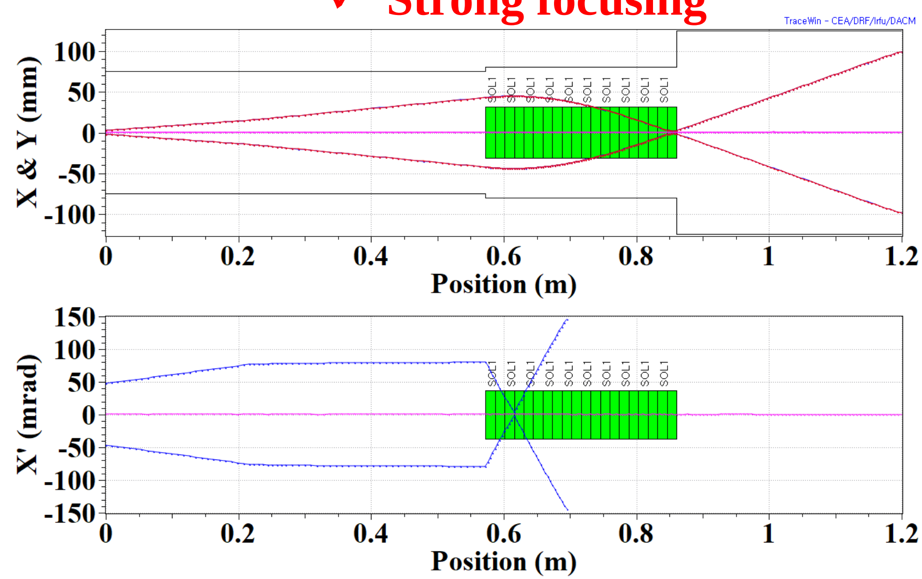


✓ **Simulation**

✓ **Weak focusing**

✓ **Strong focusing**





Thick-lens Approximation for Solenoid Scan

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

$$M = Drift \ast Solenoid$$

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

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,

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

$$x_{rms,meas}^2$$

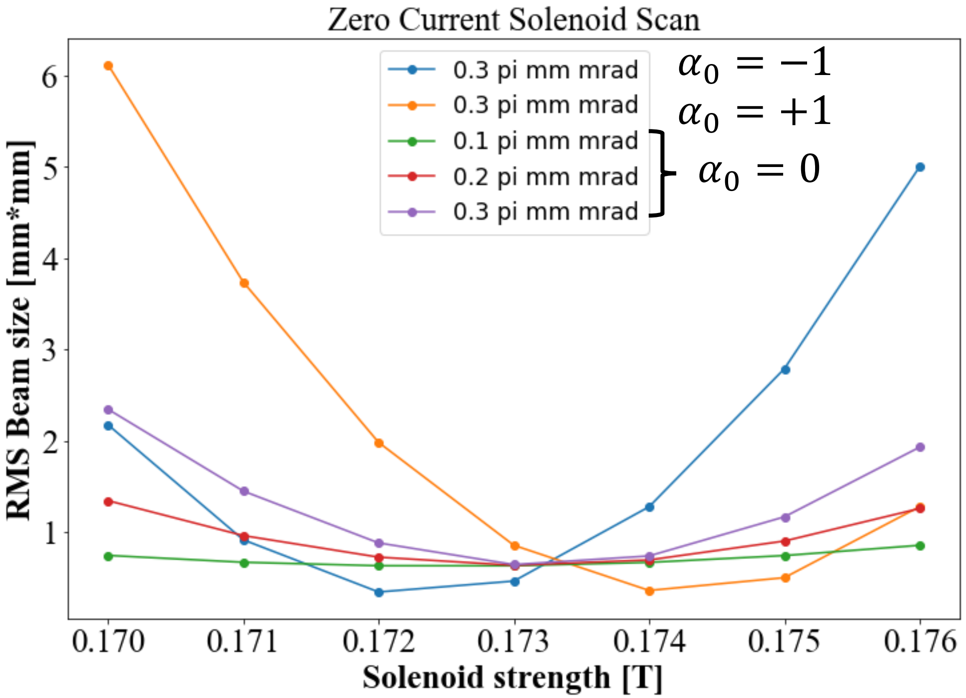
$$= (m_{11}^2 + m_{13}^2)\sigma_{0,xx} + (2m_{11}m_{12} + 2m_{13}m_{14})\sigma_{0,xx'} + (m_{12}^2 + m_{14}^2)\sigma_{0,x'x'}$$

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.

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

- 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

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

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

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

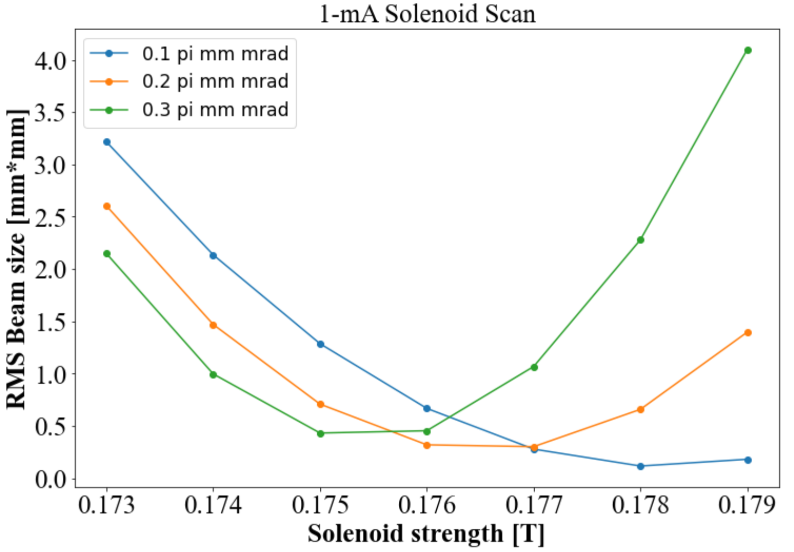
$$\begin{pmatrix} cos^2(kl/m) & \sin(2kl/m)/2k & -sin\,(2kl/m)/2 & -\sin^2(kl/m)/k \\ -ksin(2kl/m)/2 & \cos^2(kl/m) & ksin^2(kl/m) & -si\,n(2kl/m)/2 \\ sin\,(2kl/m)/2 & \sin^2(kl/m)/k & cos^2(kl/m) & \sin(2kl/m)/2k \\ -ksin^2(kl/m) & si\,n(2kl/m)/2 & -ksin(2kl/m)/2 & \cos^2(kl/m) \end{pmatrix}$$

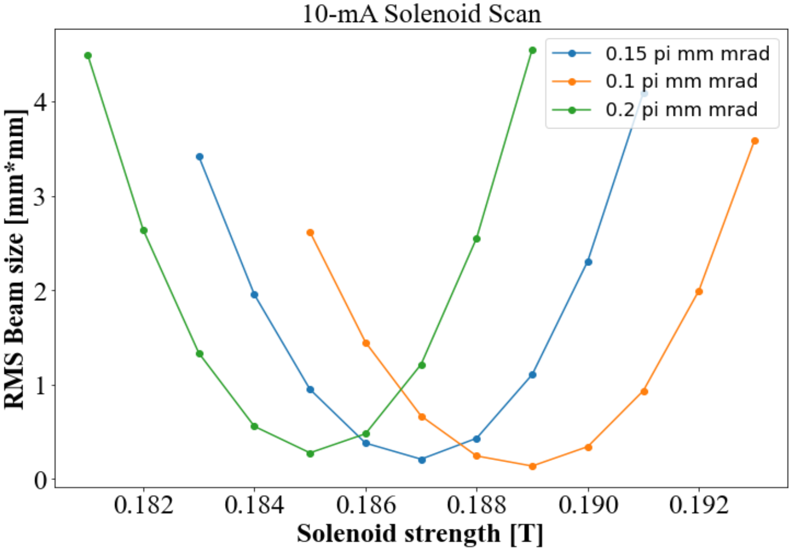
$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ F_b l/m & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & F_b l/m & 1 \end{pmatrix} \cdots$$

$x_{rms,meas}^2$

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

Thick-lens Approximation with Linear Space Charge

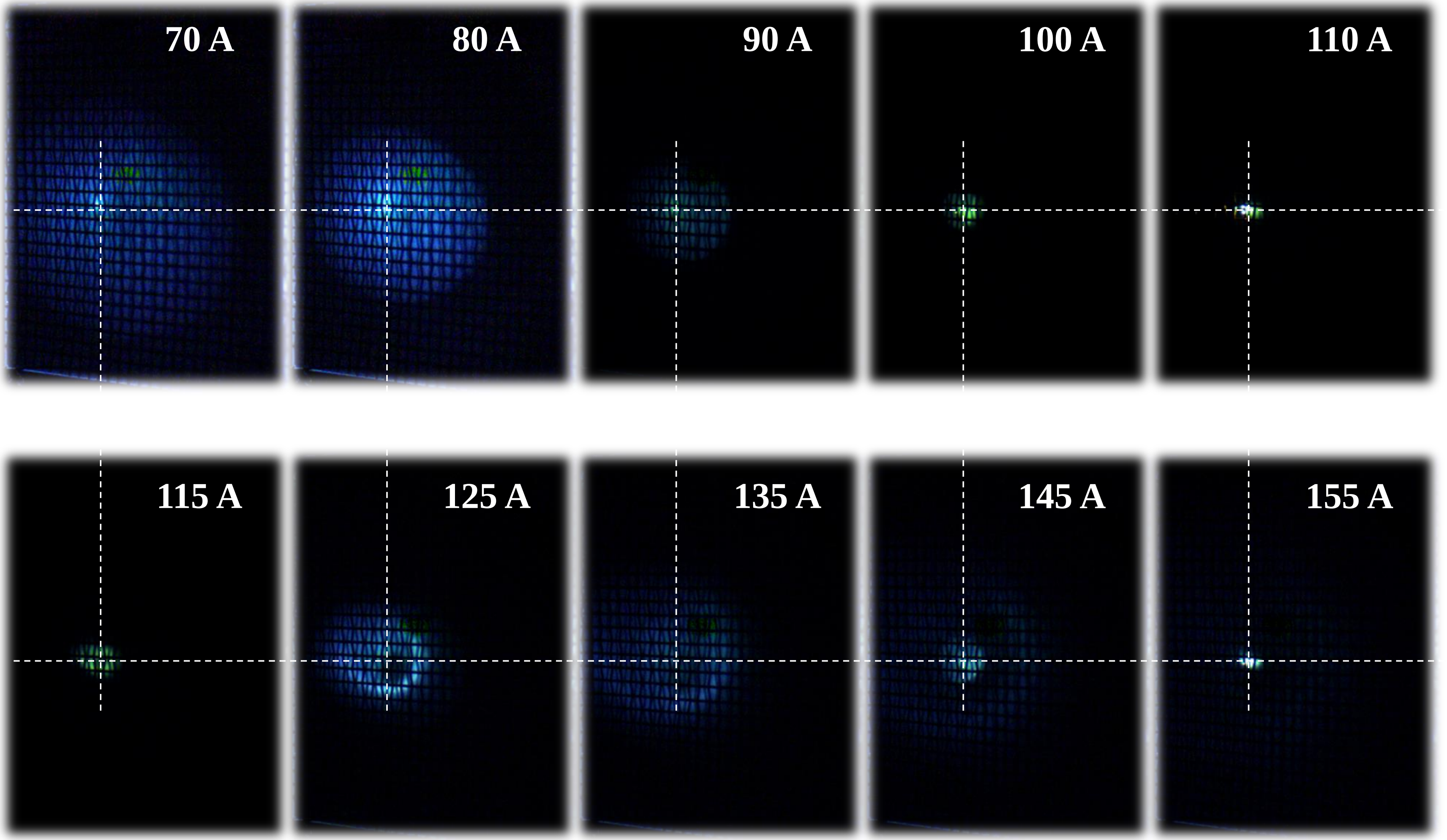




Transverse beam emittance (RMS, normalized) $[\pi.mm.mrad]$

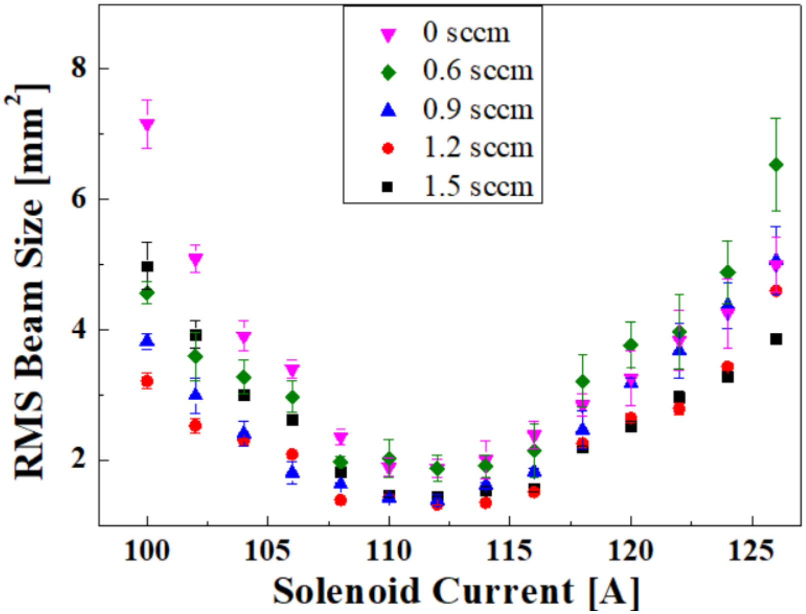
TraceWin input Initial beam emittance (with space charge)		TraceWin output RMS beam size + Solenoid scan w/o space charge M	TraceWin output RMS beam size + Solenoid scan with space charge M_{SC}	Error difference (w/o space charge – with space charge)
$I = 1\ mA$	$\epsilon_0 = 0.10$	0.104 (4%)	0.103 (3%)	-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

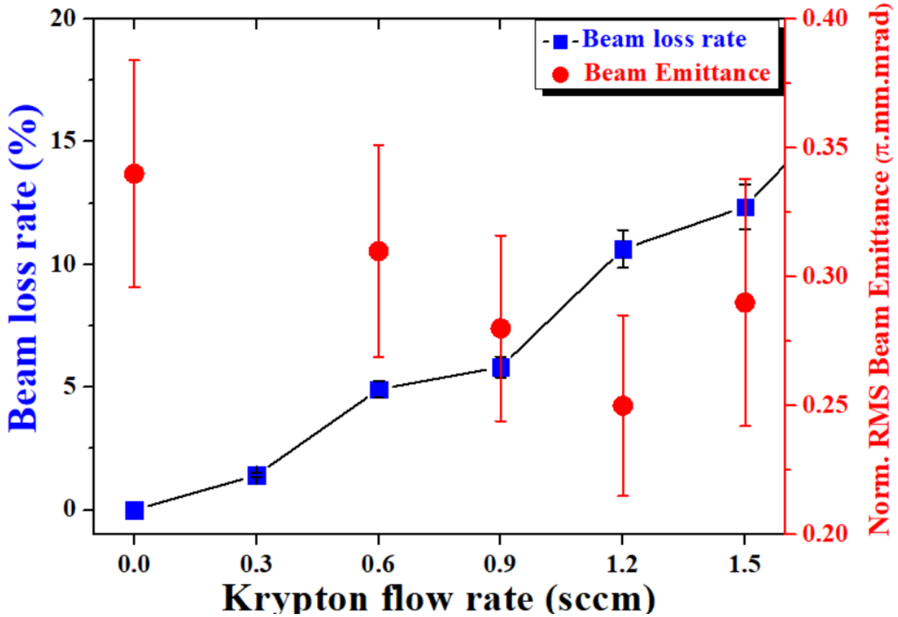


Transverse Beam Emittance Measurement during Inert Gas Injection

- **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!

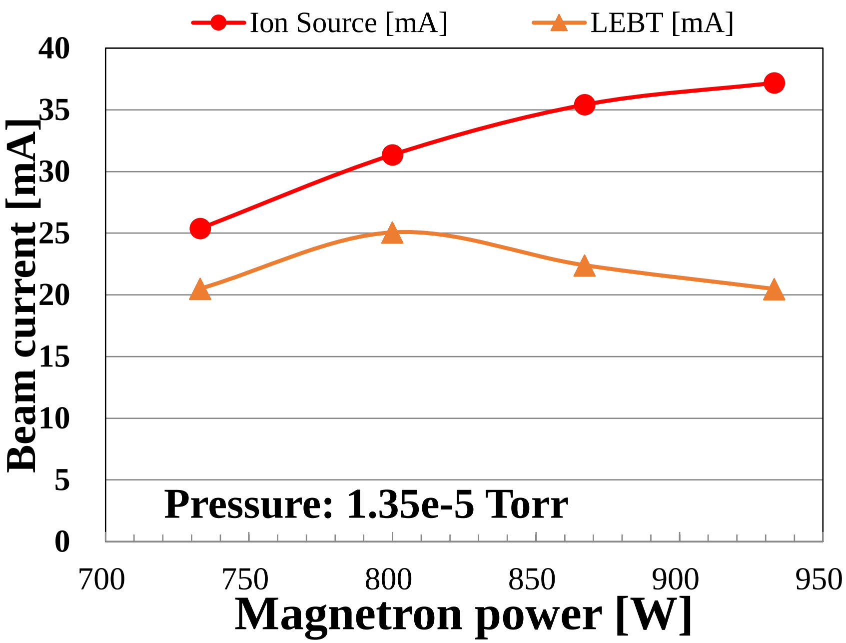
Question or Comment?

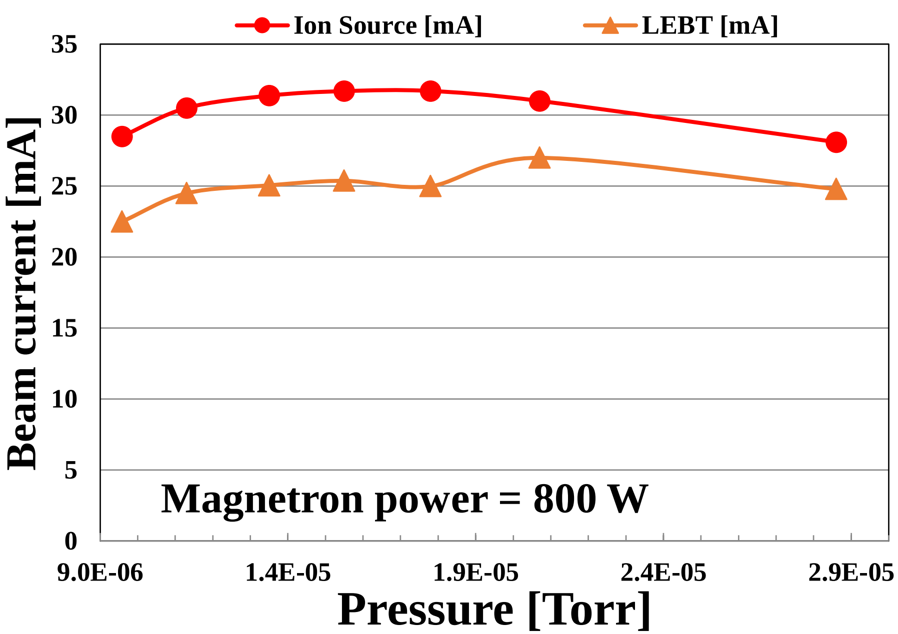
Backups

Plasma operating conditions and measured beam current

- **GOAL: Maximizing beam current** (ion source → LEBT → RFQ →…)
  - Scanning various plasma operation conditions and measuring beam current.
- Magnetron power increases plasma density and extracted beam current, but a diverging beam optics may decreases beam transmission in the LEBT accordingly.

→ Transverse beam emittance and **Twiss parameters**



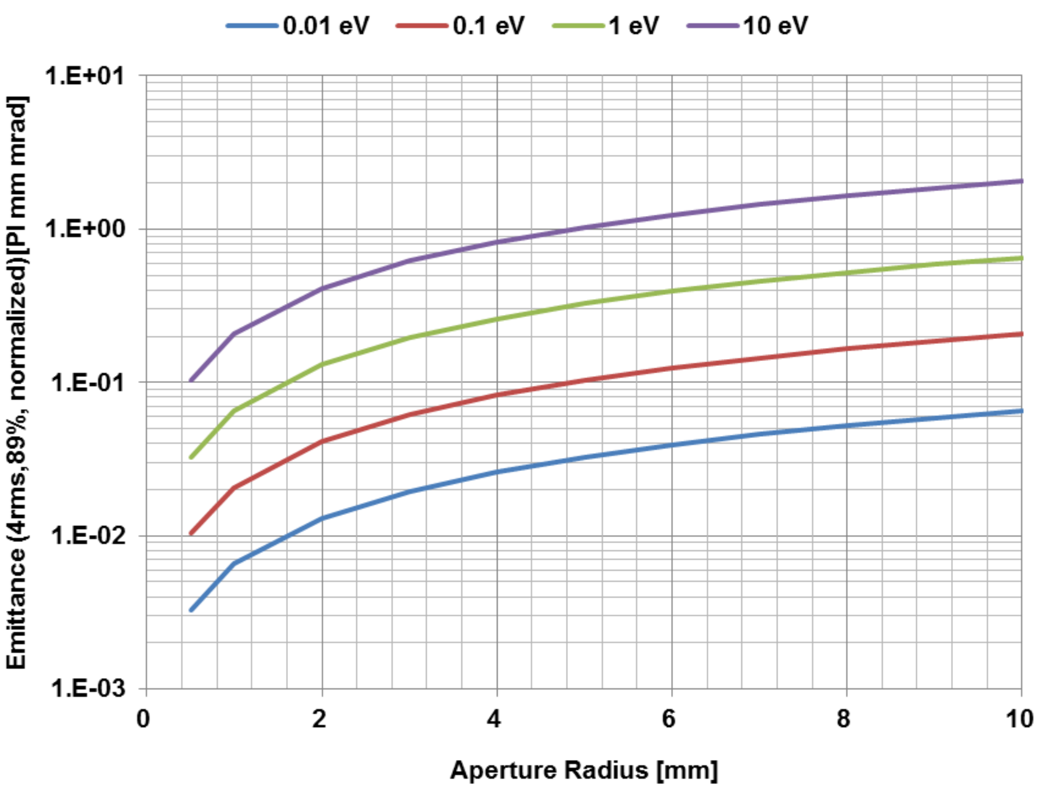


Initial Beam Emittance from Ion Sources

Assumptions

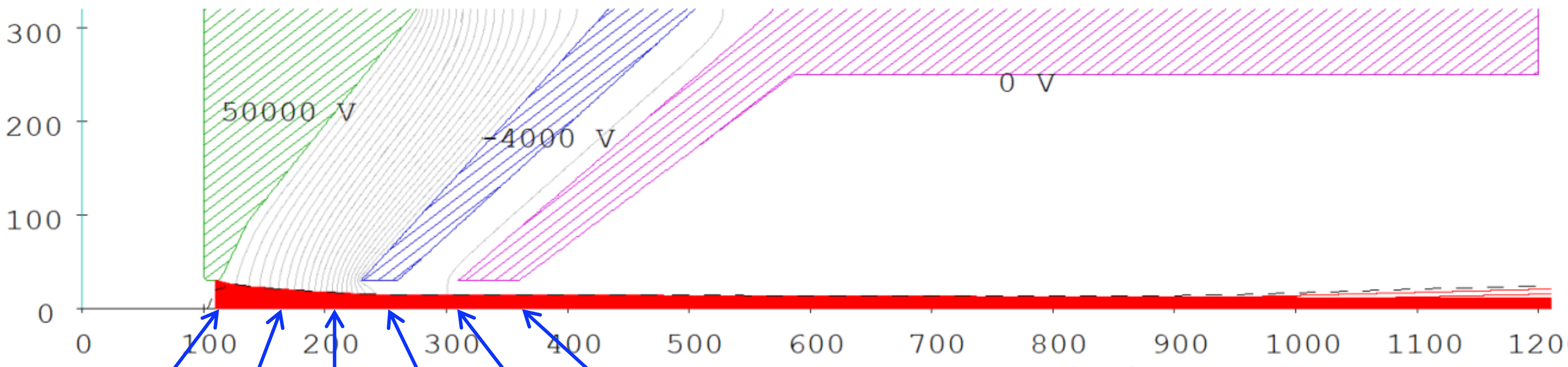
- Ion energy distribution: Gaussian (kT_i)
- Phase space distribution : Kapchinskij-Vladimirskij (KV)
- Transversal beam shape: circular beam of radius r

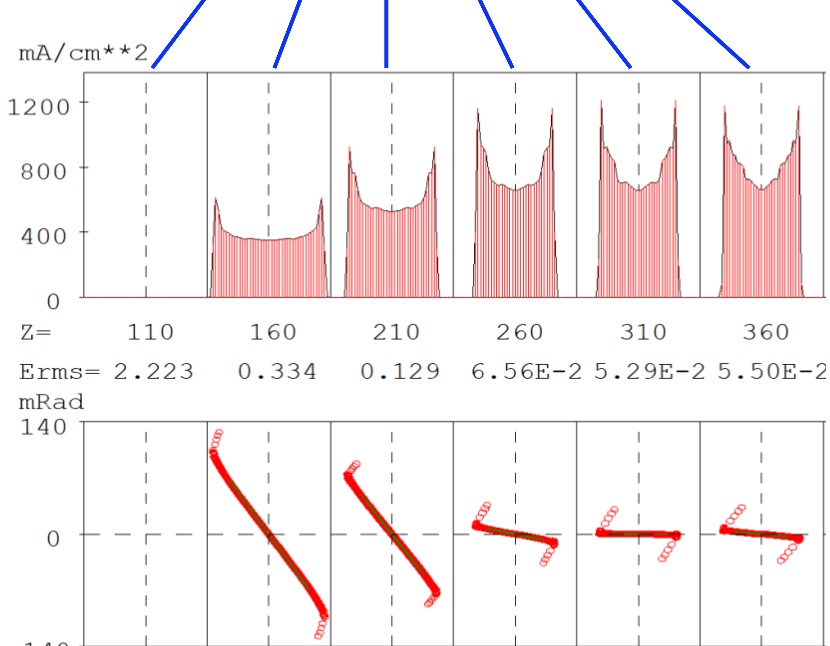
$$\epsilon_{un} \propto x \times v_x \propto r \times \sqrt{kT_i / m_i} \qquad \varepsilon_{norm,4rms,89\%} = 0.653 r \sqrt{\frac{kT_i}{A}}$$



✓ Emittance vs. Ion temperature and Aperture radius

Ion Beam Optics Calculations





- Optimal conditions on the potential structure (50 kV, -4 kV) are

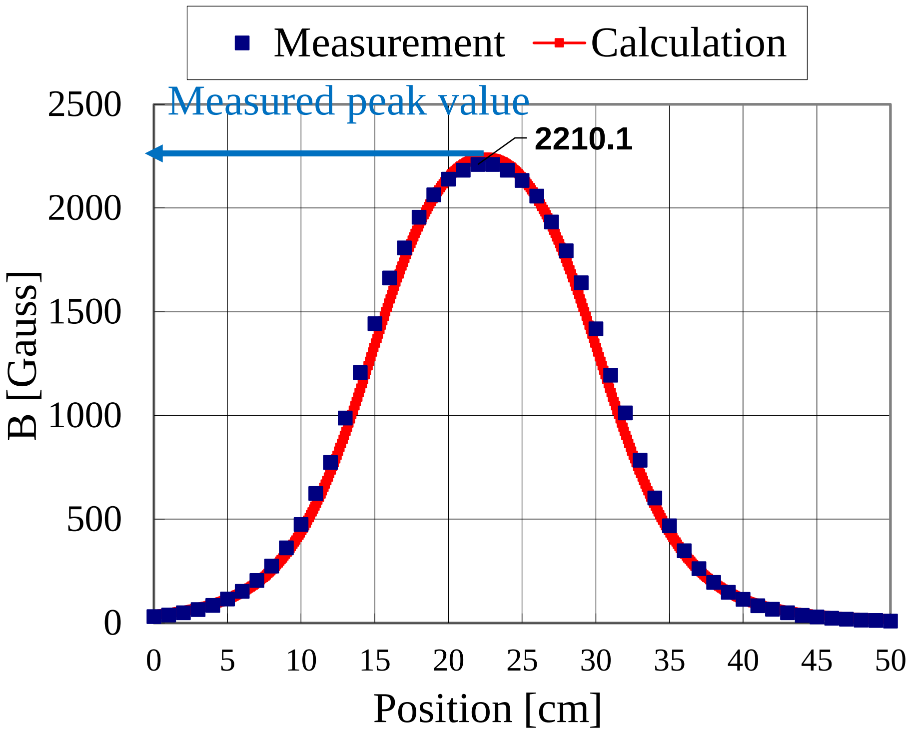
$$I_{ext} = 60\ mA$$

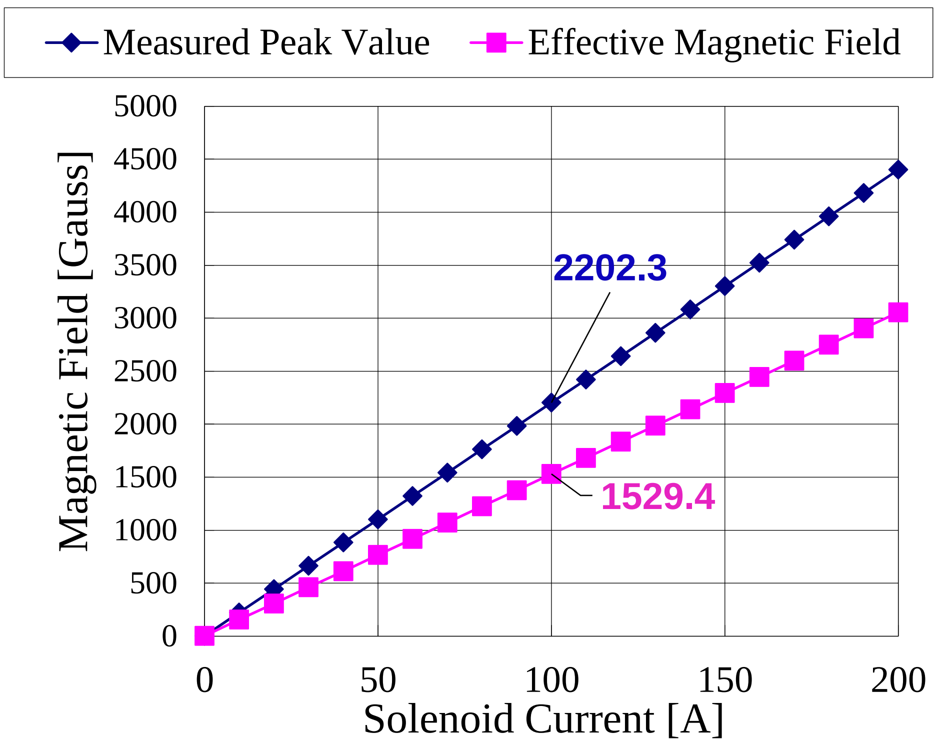
$$n_e = 3.5 \times 10^{17} m^{-3}$$

$$\epsilon_{N,rms} \sim 0.15\ \pi\ mm.mrad$$

- Other matched optics conditions should be further investigated; stable and low beam current, unstable and high current regime.

LEBT solenoid (field distribution and excitation curve)

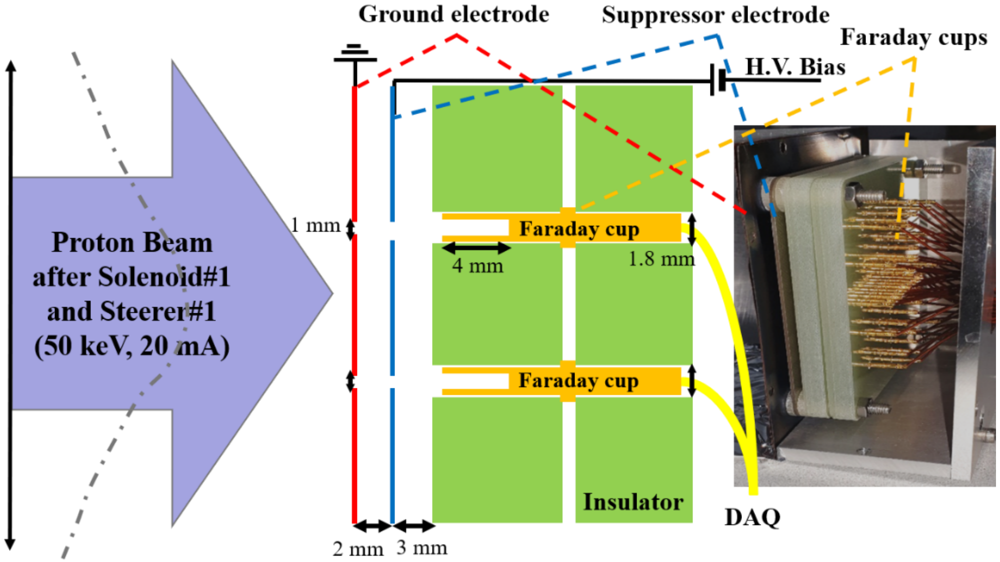


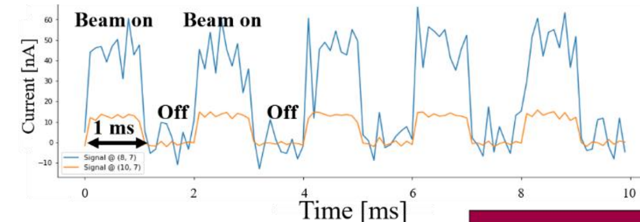


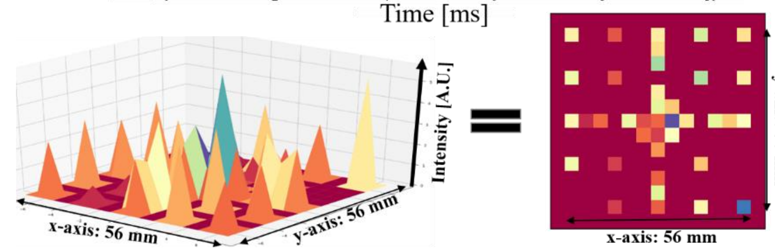
- Magnetic field distribution in solenoid @ 100 A
- Magnetic field: Peak & Effective value

- Magnetic field was calculated by *POISSON* and measured by magnetic probe.
  - The discrepancy btw calculation and measurement is less than 1%
  - Calculated 2-D magnetic field is used as the field map in Tracewin code
- Peak magnetic field at the center of the solenoid magnet = 2210 G @ 100 A
- Effective magnetic field values were derived from the measured peak values.

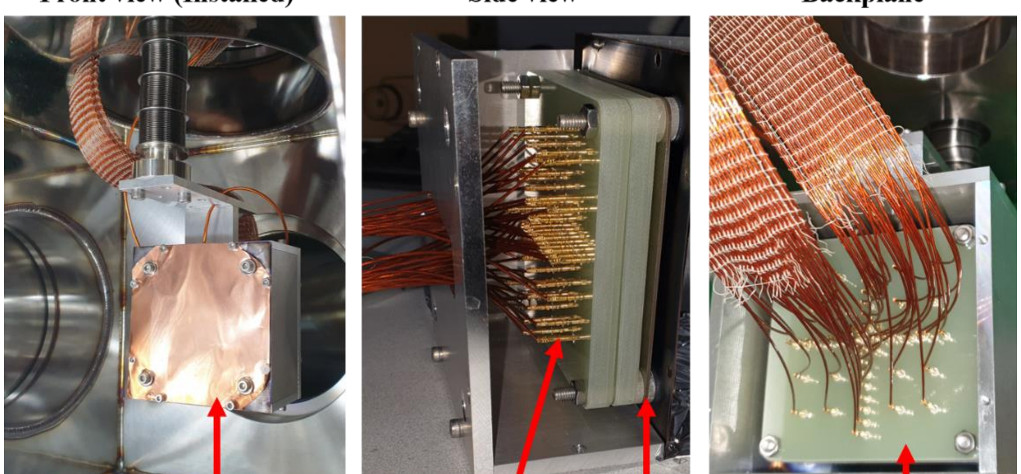
Scintillation Screen and Multi-Faraday Cups



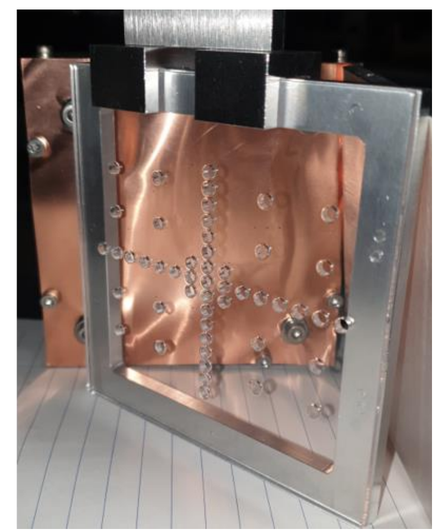




Front view (Installed) | Side view | Backplane



Ground Plate | Collector Pins | Suppressor Plate | Insulator



Beam envelop along beam current in LEBT