FFC Measurements at PIP-II Injector Test and corresponding Tracewin simulations

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PIP-II Technical Meeting
05 June 2018
Outline

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• Part III: Transverse-Longitudinal correlation: Measurement
  – RMS bunch length at the FFC for different horizontal and vertical beam position (from -6 mm to +6 mm hor. and ver. in 1 mm steps).

• Part IV: Estimate of the RMS long. emittance at 5 mA (measured at 0.34 mm-mrad, which is within 10% of the specs).

• Part V: Transverse-Longitudinal correlation at the RFQ exit
Part I

Experimental layout
The FFC is inserted vertically into the beamline. The FFC is connected to a 6 Ghz Bandwidth scope remotely operated from the control room.

Once inserted into the beamline, the FFC samples a small part of the beam (few percent). If the beam is perfectly centered, the FFC samples the core of the beam. The beam is aligned using correctors and by optimizing the FFC signal.

When installed after the fifth triplet, the FFC data were taken as function of the field in Buncher 2 (Buncher 1 at 60 kV). At the end of the beamline, the FFC data were taken as function of the field in Buncher 3 (Buncher 1 at 60 kV and Buncher 2 at 50 kV).
Part II

Transverse-Longitudinal correlation: Tracewin prediction

**Question:** Is the part of the beam sampled by the FFC representative of the RMS bunch length of the full beam? *Not necessarily*
Is the part of the beam sampled by the FFC representative of the RMS bunch length of the full beam? 

**6D Gaussian**

- For a 6D ellipse filled with 6 Sigma Gaussian Distribution (which we usually use as input distribution at the MEBT entrance), sampling the beam with a 0.8 mm aperture does always report the same RMS bunch length which always equals the RMS beam length of the entire (100%) of the beam.

*6D Gaussian Distribution*

6 Sigma / 1E6 particles

Sampling different portion of the beam with an aperture at different vertical location reports the RMS bunch length of the full beam (7.2 deg or ~123 ps)
Is the part of the beam sampled by the FFC representative of the RMS bunch length of the full beam? *FFC Distribution*

- The 6D Gaussian / 1E6 macro-particle input distribution at the start of the MEBT is transported with Tracewin to the FFC located after the 5\textsuperscript{th} triplet. The transport can is done without space charge or at 5 mA.

- **At 0 mA**: Tracewin predicts that if the 6D Gaussian input distribution is transported to the FFC without space charge, then as observed with the distribution at the MEBT, sampling any part of the beam reports the same RMS bunch length as the full beam.

- **At 5 mA**: Tracewin predicts that if the 6D Gaussian input distribution is transported to the FFC with space charge at 5 mA, then sampling the core of the beam reports an RMS bunch length *higher* than the RMS bunch length of the entire beam. Also, Tracewin predicts that the *further away* from the beam core the sampling is *the lower* the reported RMS bunch length.
Is the part of the beam sampled by the FFC representative of the RMS bunch length of the full beam? **FFC Distribution**

- **0 mA at FFC / 1E6 Tracewin**
  - FFC axis: 11.4 deg
  - 11.4 deg
  - 11.4 deg

- **5 mA at FFC / 1E6 Tracewin**
  - FFC axis: 13.33 deg
  - 16.6 deg
  - 13.23 deg
Is the part of the beam sampled by the FFC representative of the RMS bunch length of the full beam? **FFC Distribution**

- The plot below reports RMS bunch lengths from Tracewin distributions at the FFC at different sampling positions. For a distribution transported to the FFC without space charge and with space charge.
- The RMS bunch length of the full beam at 5 mA is 14 deg, which is about 18% lower than reported when sampling the beam core with a 0.8 mm aperture.
Is the part of the beam sampled by the FFC representative of the RMS bunch length of the full beam? **Along Beamline**

- The plot below reports RMS bunch lengths from Tracewin distributions at different location along the beamline and at different sampling positions. For a distribution transported at 5mA, 1E6, lattice #1527.
Is the part of the beam sampled by the FFC representative of the RMS bunch length of the full beam? *Not everywhere*

- The plot below shows the ratio at different location along the MEBT of the RMS bunch length of a full beam divided by the RMS bunch length of a sample of the beam going through a 0.8 mm diameter aperture located in its core.

- Due to space charge effects, Tracewin predicts that the RMS bunch length measured by the FFC is about 20% **higher** than the RMS bunch length of the full beam at the end of the MEBT.
Part III

Transverse-Longitudinal correlation: Measurement
• We performed a set of measurement with the actual location of the FFC at the end of the beamline. For a fixed position of the FFC we moved the beam horizontally and vertically at the FFC using the C7 and C8 upstream correctors.

• The value of the correctors were computed with Tracewin to move the beam at the FFC parallel or with an angle.

• On 04/11/2018 we connected the scope to the FFC and moved the beam horizontally and vertically at the FFC from -6 mm to +6 mm by 1 mm steps. We repeated this measurement for -2 mrad, 0 mrad and +2 mrad vertically and -4mrad, -2mrad, 0mrad and +2 mrad horizontally.
RMS Bunch Length Vs Vertical Beam Position at FFC. Data (as measured, no shifting of vertical axis) Vs Tracewin (red line)

- The plot below shows 3 set of measurement moving the beam vertically and for 3 different angles at the FFC. The red line corresponds to Tracewin simulation implementing a 0.8 mm diameter in Tracewin.
- The transverse-to-longitudinal correlation reported by Tracewin is also observed experimentally.
RMS Bunch Length Vs Horizontal Beam Position at FFC.
Data (as measured, no shifting of vertical axis) Vs Tracewin (red line)

- The plot below shows 4 set of measurement moving the beam horizontally and for 4 different angles at the FFC. The red line corresponds to Tracewin simulation implementing a 0.8 mm diameter in Tracewin.
- The transverse-to-longitudinal correlation reported by Tracewin is also observed experimentally.

\[ \sigma_z \text{ at FFC Vs horizontal beam position at 5mA / 04112018} \]
Part IV

Longitudinal emittance estimate at 5mA
Estimate of the long. emittance at 5 mA : about 0.34 mm-mrad

- The plot below shows a measurement of the bunch length at the FFC performed on 11/10/2017 with the FFC located downstream of the 5th triplet.
- Implementing a 0.8 mm diameter aperture in Tracewin at the location of the FFC allows to have a good agreement with the data taking an input long. Emittance in Tracewin of 0.34 mm-mrad.
- Without aperture a good agreement is achieved for 0.5 mm-mrad input long. emittance (as presented in the talk of Feb. 6th, 2018)
Part V

Distribution at the RFQ exit (Toutatis simulation)
Toutatis simulation of the PIP2IT RFQ with KV and Gaussian (6 Sigma) input matched distribution at the start of the RFQ. 1M / 5mA

- The plots below show 2 Toutatis RFQ output distribution with 1E6 particle with KV and Gaussian 4D input distribution. Correlation seems more pronounced with Gaussian than KV distribution.
- A “true” 6D input distribution would need some correlation between the degrees of freedom.
Summary

- A transverse-to-longitudinal correlation has been predicted by Tracewin and observed experimentally.

- The measurement of the RMS bunch length with the FFC is performed by sampling few percent of the beam at its core. From our studies, at the end of the beamline where most of the FFC measurement have been performed, the measured RMS bunch length with the FFC is overestimated by about 20%.

- Implementing an aperture in front of the FFC in Tracewin allows to reconstruct the long. emittance. The best fit at 5 mA reports a long. emittance at 0.34 mm–mrad, which is within the specs taking 10% of error uncertainty in our measurement. The 0.34 mm-mrad of long. emittance reported in this talk is significantly lower than the 0.5 mm-mrad reported in the talk of Feb. 6th during which no aperture was implemented in the code.

- Transverse-to-longitudinal correlation is also observed at the exit of the RFQ. Building an input distribution with such correlation is probably important in order to improve our model. Such a work is currently being done at SNS by Aleksandrov et al. (IPAC 2018 talk).