PXIE LEBT Commissioning Update

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• MEBT scrapers prototypes test
  ▪ One slide digression

• LEBT transport
  ▪ Previous status
  ▪ Transport optimization
    ❖ Phase space measurements
  ▪ Some discussion of the results
    ❖ Beam profile measurements

• Outlook
Role of LEBT in PXIE

- Prepare beam for RFQ (i.e. $\alpha$, $\beta$) and machine protection
- DC operation
  - 5 mA, reliable and ‘stable’
    - $\varepsilon_{n,\text{rms}} \leq 0.25 \text{ mm mrad}$
    - Uncontrolled losses $<10\%$
- Pulse operation
  - 1-16667 $\mu$s, 60 Hz
  - Twiss functions representative of DC beam operation
    - To transition from short pulse (commissioning) to DC (normal operation)
      - *If not the same, DC Twiss functions should be predictable from short pulse measurements*

Demonstrated and reported on 01/06/15

Ion Source | LEBT | RFQ | MEBT | HW & SSR1 | HEBT | Beam dump
---|---|---|---|---|---|---

40m
Current setup

- Only *temporary* addition since last report (Jan 6, 2015)

1. MEBT scraper prototypes (4 jaws – top, bottom, right, left)
MEBT scrapers prototypes tests

• Thermal test with H⁻
  ▣ ~75 W DC deposited concurrently on each paddle
    ❖ Water-cooled jacket around the housing
    ❖ Housing still a bit hot ⇒ Will be made larger
      (larger area to dissipate reflected energy)
      ❖ Also to accommodate a longer range
        of motion

• Functionality test
  ▣ Beam profile measurements
    ❖ Procedure, controls…
    ❖ Some results in later slides

Also, useful for LEBT beam investigation

Picture of the scrapers with
68 W DC on each
(thru a 45° angle viewport)
Back in January 2015...

- ‘Matched’ solution lead to emittance growth with respect to what had been achieved before

\[ \alpha = 0.65 \]
\[ \beta = 86 \text{ cm} \]
\[ \varepsilon_{\text{rms,n}} = 0.105 \text{ mm mrad} \]

\[ \alpha = -6.04 \]
\[ \beta = 72 \text{ cm} \]
\[ \varepsilon_{\text{rms,n}} = 0.250 \text{ mm mrad} \]

\[ B_{\text{Sol1}} = 141.4 \text{ A} \]
\[ B_{\text{Sol2}} = 188.5 \text{ A} \]
\[ B_{\text{Sol3}} = 210 \text{ A} \]
Transport optimization

- Beam line has been designed such that the neutralization pattern could be changed
  - Biasing apertures
  - DC voltage offset on the chopper kicking plate
- Beam envelope also influences neutralization
  - Beam potential varies and creates wells
    - E.g.: At the end of the LEBT where the beam is small for matching into the RFQ
      - However, this will not be true anymore when the RFQ is installed ⇒ some caveat to the interpretation of the measurements made with the emittance scanner
- Ion Source settings might have a significant role to play too
Ion source typical settings

• May not have been running the source optimally or in a configuration that does not favor emittance preservation
  - High power, low gas flow
    - Arc: I = 20 A, 118 V; 10 sccm

• Looked back at historical data (e.g.: acceptance tests at TRIUMF)
  - Adjusted Arc current and other electrode voltages
    - Arc: I = 13 A, 120 V; 15 sccm
    - Plasma voltage decreased from 4.5 V to 3.3 V

More on that later
Space-charge ‘enhanced’ configuration

- Positive biasing of electrically isolated diaphragms to contain ions
- Clearing field at the chopper
- Vacuum downstream of solenoid #2: low $10^{-7}$ torr
- Chopped beam

![Diagram of ion source and extraction system]
Configuration without ion clearing

- Positive biasing of electrically isolated diaphragms
- No DC offset at the kicker plate
- Chopped beam

Ion source extractor voltage:
- Ion source extractor voltage: 0 kV
- Chopper voltage: -5 kV

Approximate location of RFQ 1st vane

Grounded

Ions trap

+40 V

5 ms

1 ms

3 ms
In both cases, w/ or w/o ion clearing, achieved low emittance with small beam size at the location of the RFQ 1st vanes
- Same focusing and IS settings

No ion clearing

$\varepsilon_{n, \text{rms}} = 0.11 \text{ mm mrad}$
(1% cut)

Space charge ‘enhanced’

$\varepsilon_{n, \text{rms}} = 0.13 \text{ mm mrad}$
(1% cut)
Twiss parameters at RFQ entrance (I)

- Cannot get ideal Twiss parameters for RFQ
  - $\beta = 1.35 \text{ m}; \alpha = -10$ at the emittance scanner ($\Leftrightarrow 7 \text{ cm and } 1.6$, respectively, at the RFQ 1$^{\text{st}}$ vane)

Collection of data for 5 mA under various conditions (for illustration)
Twiss parameters at RFQ entrance (II)

- Collimator is an aperture limitation preventing the beam to get large enough in Solenoid #3
  - Work with simulations to understand consequences
    - E.g.: Use measured distribution to propagate through RFQ
- Data behavior can be reproduced analytically (no space charge) and in TRACK (w/ SC)

Ensemble of TRACK simulations where Solenoid #2 and Solenoid #3 are varied
Pulsed vs. chopped

- No ion clearing in both cases
  - Additional positive bias in front of emittance scanner for IS pulse case (3/12/15)
  - Fast convergence to steady state parameters for the chopped beam

**IS pulse (3/12/15 – File #1555)**

**Chopped beam (3/19/15 – File #1558)**

- Same scales for $\beta$
- Same $\Delta$ for intensities

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250 $\mu$s

300 $\mu$s
Tentative discussion about observed emittance preservation

- Recent measurements show that, for very different neutralization configurations, one can maintain a low emittance while transporting the beam through the LEBT
  - There are configurations for which the emittance gets much larger, for similar measured Twiss parameters

- Early simulations showed that large emittance growth would be likely if the beam was not fully neutralized (or close)
  - We argue that the Gaussian beam model is not always the best for the PXIE beam
Vacuum management approach

• Typical LEBT:
  ▪ Relatively ‘poor’ vacuum
    ◆ Complete beam space charge neutralization over its entire length
  ▪ Chopping as close of the RFQ as possible to limit distance of un-neutralized transport
    ◆ RFQ is also the ‘absorber’

• For PXIE, chose ‘good’ over ‘poor’ vacuum in the RFQ (hence near the end of the LEBT)
  ▪ ‘Poor’ vacuum $\rightarrow 10^{-5}$-$10^{-4}$ torr $\Rightarrow$ $\mu$s-range neutralization time
  ▪ PXIE RFQ design: $10^{-7}$-$10^{-6}$ torr
    ◆ Hope for better reliability and longer lifetime
      ◆ Also, no direct bombarding with beam
    ◆ Limit particles that could potentially reach the SRF section
LEBT Transport scheme

- **PXIE LEBT**: Un-neutralized transport over the last ~1m of the LEBT before RFQ
  - Consequence of vacuum design choice
  - Neutralized transport upstream of chopper
  - Possible if the beam perveance is *sufficiently* low
  - Note that another approach might have been to design the beam line with a vacuum transition similar to what will be done in the MEBT e.g.: differential pumping region just upstream of RFQ
Emittance growth*

- Unacceptable emittance growth may be the limitation to the proposed scheme
  - For a beam with Gaussian current density distribution, the space charge force is highly non-linear outside the beam core

Normalized electric field of a beam with a Gaussian current density profile as a function of its normalized radius (red curve) compared with the field of a constant current density beam (blue curve) with the same density at the center.

* Slides from 01/21/14 PIP-II Technical Meeting
http://projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1250
Preliminary simulations of the proposed scheme

- Tracewin simulations show the formation of a halo
  - Initial particles distribution is Gaussian
  - Space charge turned on within Solenoid #2

@ Project X Collaboration meeting 11/27/12
‘Real’ beam particle distribution*

- Gaussian distribution may not be the best model for the beam coming out of the ion source
  - Measurements from acceptance tests in TRIUMF indicate that the beam current density distribution is likely closer to being uniform than Gaussian

Red – projection of the measured distribution to X after back propagation in free space. Blue/Brown – X-projections for beam with a constant current density/ Gaussian profile and the same second moments and integrals

* Slides from 01/21/14 PIP-II Technical Meeting
http://projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1250
Further simulations with a different initial particles distribution*

- Dynamics of the beam with initial constant current density (and Gaussian velocities distribution) was simulated with Valery’s MathCad code (PIC-like)
  - Emittance growth is significantly lower than in a case of a double-Gaussian distribution: ~20% vs. ~75% (for similar envelope profiles)

* Slides from 01/21/14 PIP-II Technical Meeting
http://projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1250
Ion source tunes

- Electrodes near the extraction region determine not only the extraction current but also the current density distribution
  - With everything else constant, choose two extraction voltages that give the same beam current

Several currents vs. extraction voltage
- Faraday cup
- Isolated diaphragm #1
- Donut
- DCCT
Current density distributions measurements

- Use MEBT scrapers after solenoid #1 to measure the beam profile
  - Two methods:
    - Insert scraper and move beam across with solenoid correctors
    - Move scraper
  - Record Corrector current/scraper position vs. scraper current
    - Scraper is biased to +50 V
Profile data analysis

- Assume either a Gaussian or a Uniform current density distribution
  - Fitting parameters: $\sigma_x$ (Gaussian), $r_x$ (Uniform) and mean ($\mu_x$ or $m_x$) along the direction which is measured
  - Raw data integrals are what is fitted
    - Minimize $(\text{sum of differences})^2$

\[
\text{Gaussian}(x, \sigma_x, \mu_x, y, \sigma_y) := \frac{I_{\text{beam}}}{2\pi \sigma_x \sigma_y} \cdot e^{-\frac{(x-\mu_x)^2}{2\sigma_x^2}} \cdot e^{-\frac{y^2}{2\sigma_y^2}}
\]

\[
\text{Unif}(x, r_x, m_x, y, r_y) := \begin{cases} 
  \frac{I_{\text{beam}}}{\pi r_x r_y} & \text{if } \left(\frac{x - m_x}{r_x}\right)^2 + \left(\frac{y}{r_y}\right)^2 \leq 1 \\
  0 & \text{otherwise}
\end{cases}
\]

$I_{\text{beam}} \equiv \text{beam current} – \text{Not a fitting parameter}$
‘Low side’ data fit to Gaussian and Uniform distributions

- Data obtained by the ‘moving the scraper’ method
  - Somewhat coarse
- Better fit when using Uniform distribution
‘Low side’ profile vs. ‘High side’ profile

- Plot derivative of the measurement and of the fitted functions
  - ‘High side’: more Gaussian ; ‘Low side’: more Uniform
Phase space portraits comparison

- For nearly identical Twiss functions at the exit of the LEBT, emittance for the ‘High side’ is twice the emittance for the ‘Low side’

- **‘High side’**
  - $\varepsilon_{n, \text{rms}} = 0.22 \text{ mm mrad}$ (1% cut)
  - $\alpha = -8.06$
  - $\beta = 1.37 \text{ m}$

- **‘Low side’**
  - $\varepsilon_{n, \text{rms}} = 0.11 \text{ mm mrad}$ (1% cut)
  - $\alpha = -8.35$
  - $\beta = 1.38 \text{ m}$
Corresponding 1D projections i.e. profiles

- Like upstream, the beam profiles differ significantly, with the ‘Low side’ profile indicating a more uniform distribution than for the ‘High side’ data.

Red: data
Dotted blue: Gaussian distribution with same $\sigma$
Conclusions/Comments

- Hypothesis of having a non-Gaussian current density distribution at the exit of the ion source appears to be valid for some tunes
  - A beam with such a distribution helps preserve the emittance throughout the LEBT
    - In accordance with simulations

- While various neutralization patterns along the beam line definitely affects the beam dynamics, details are not understood yet
  - In particular, time dependence
Outlook

• Scraper and beam stop
  ▪ Scraper has been built
    ❖ Testing off-line is on-going
    ❖ Installation within the next 2 weeks
  ▪ Beam stop (for personnel protection)
    ❖ Looking into using one we already have
      ❇ In the process of determining its appropriateness with Safety

• On-track to be ready for RFQ arrival in June
  ▪ Delays give us the chance to study the beam line properties in more depth
Additional slides
Phase space measurements (neutralized)

- Somewhat matched Twiss parameters
  - Essentially no emittance growth w.r.t. ion source acceptance test measurements

\[ \varepsilon_{n, \text{rms}} = 0.11 \text{ mm mrad} \]

(1% cut)

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**Beam Intensity**

- Red dots represent beam intensity over time.

**Beta**

- Blue line represents beta over time.

Time, ms

Beam intensity, V

X, mm

X', mrad

End of pulse

03/19/15 data (10:50)

10 µs time slices
RFQ matching

- **Without matching constraints:**
  - Achieved 5 mA DC with $\varepsilon_{n,rms} < 0.15$ mm mrad

- **Matched parameters (design):**
  - $\beta = 7$ cm and $\alpha = 1.6$ at RFQ 1st vane tip
Operational notes

• Replaced filament after failure on 01/20/15
  ▪ Failure was expected
  ▪ Run time: 460 hours

• One power supply used with the emittance scanner failed
  ▪ Did not have any spare
    - ~1 week without instrument availability
  ▪ Procured 2 PSs
    - 1 replacement (refurbished) and 1 spare (new)
LEBT ‘scraper’

- Movable isolated electrode with holes
  - Beam measurements and RFQ protection
LEBT scraper pictures