PXIE LEBT Commissioning Update

Lionel Prost

on behalf of, R. Andrews, B. Brooker, K. Carlson, J.-P. Carneiro, J. Czajkowski, R. D'Arcy, F.G. Garcia, B. Hanna, S. Hays, W. Johnson, M. Kucera, A. Saewert, G. Saewert, V. Scarpine, A. Shemyakin, D. Slimmer, D. Snee, J. Steimel, C. Wiesner, mechanical, electrical and other technical support

PIP-II Technical Meeting

March 24th, 2015

Fermilab

Content

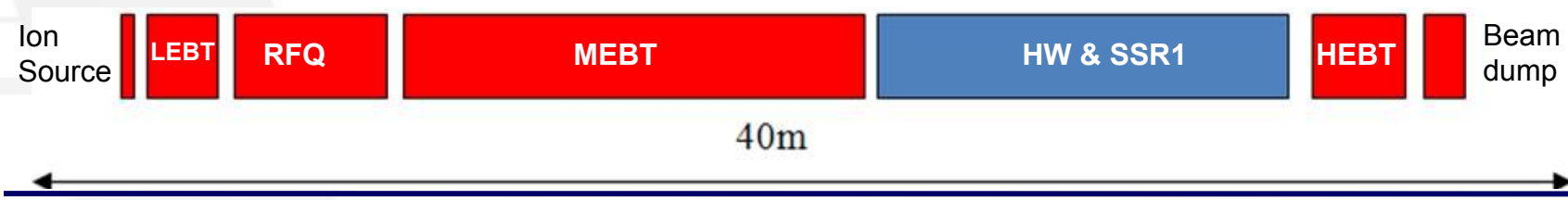
- Setup
- MEBT scrapers prototypes test
  - One slide digression
- LEBT transport
  - Previous status
  - Transport optimization
    - Phase space measurements
  - Some discussion of the results
    - Beam profile measurements
- Outlook

Role of LEBT in PXIE

- Prepare beam for RFQ (i.e. α, β) and machine protection
- DC operation
  - 5 mA, reliable and 'stable'
    - $\varepsilon_{n,rms} \leq 0.25$ mm mrad
  - Uncontrolled losses <10%
- Pulse operation
  - 1-16667 μs, 60 Hz

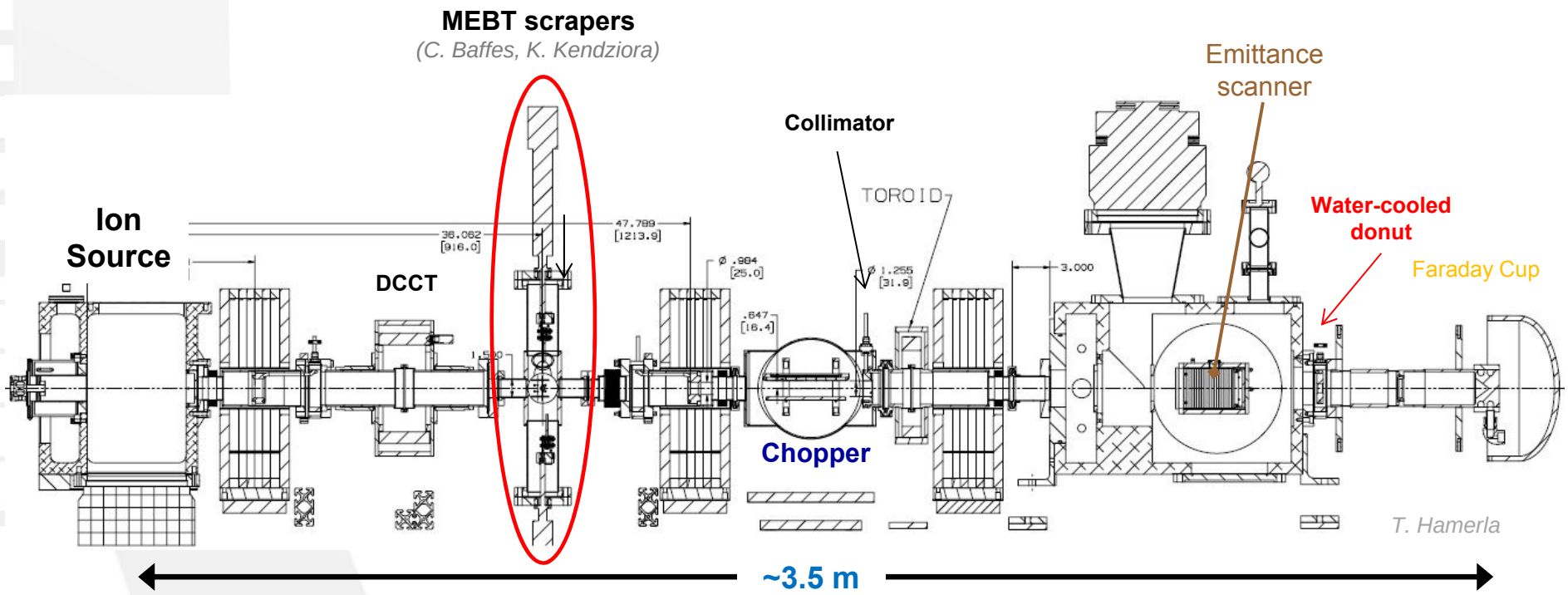
Demonstrated and reported on 01/06/15

  - 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*



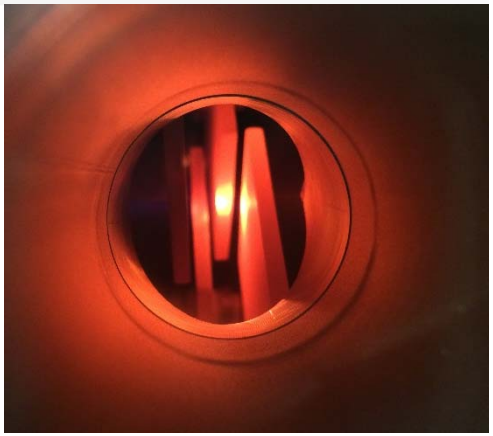
Current setup

- 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*



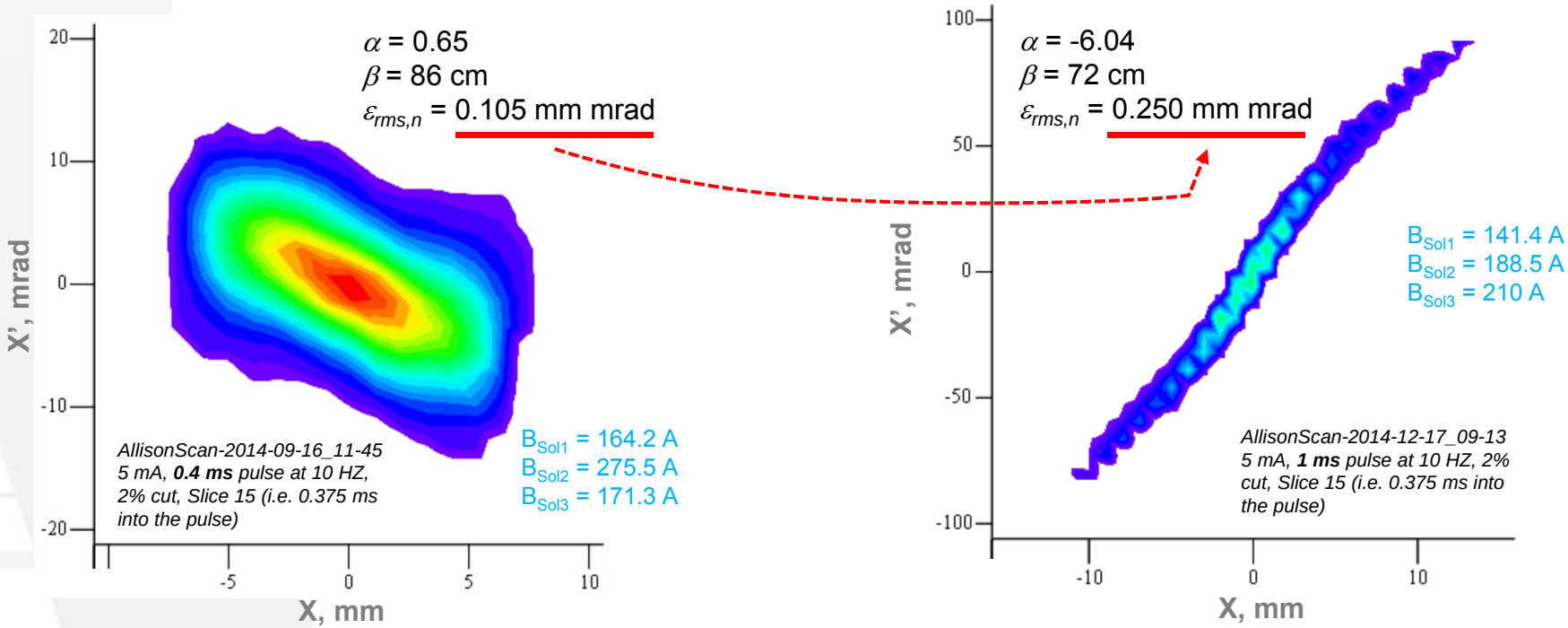
Picture of the scrapers with 68 W DC on each (*thru a 45° angle viewport*)

- Functionality test
  - Beam profile measurements
    - Procedure, controls…
    - Some results in later slides

Also, useful for LEBT beam investigation

Back in January 2015…

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



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

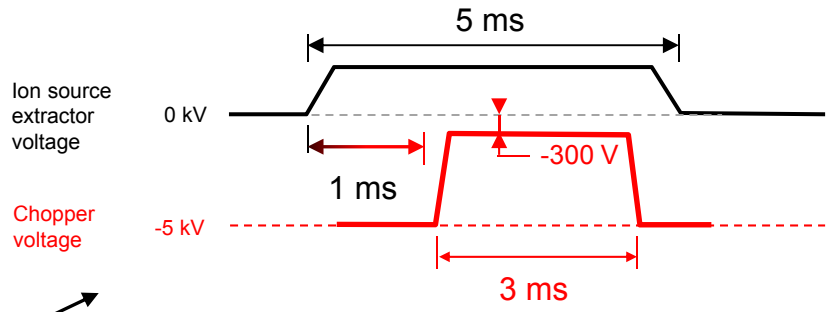
- May not have been running the source optimally or in a configuration that does not favor emittance preservation
  - High power, low gas flow
    - Arc: I = 20 A, 118 V; 10 sccm

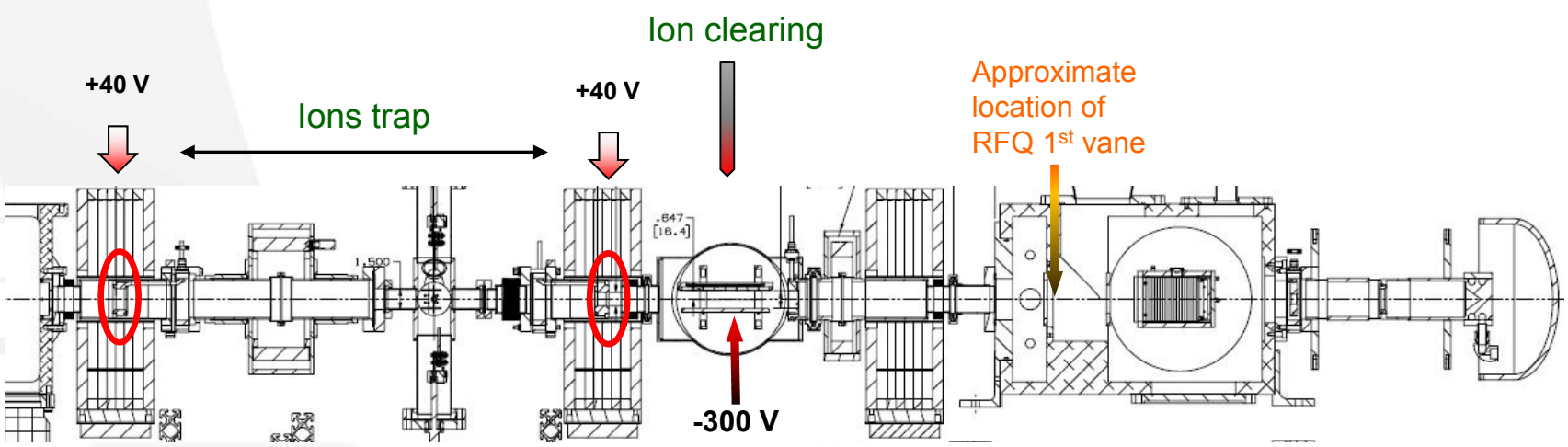
More on that later

- 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

Space-charge 'enhanced' configuration

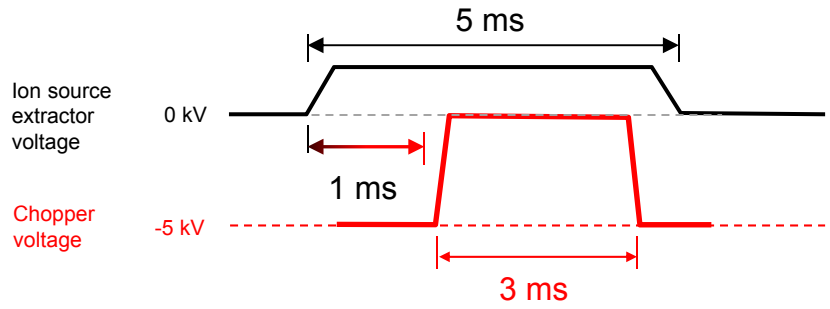
- Positive biasing of electrically isolated diaphragms to contain ions
- Clearing field at the chopper
- Vacuum downstream of solenoid #2: low 10^{-7} torr
- Chopped beam

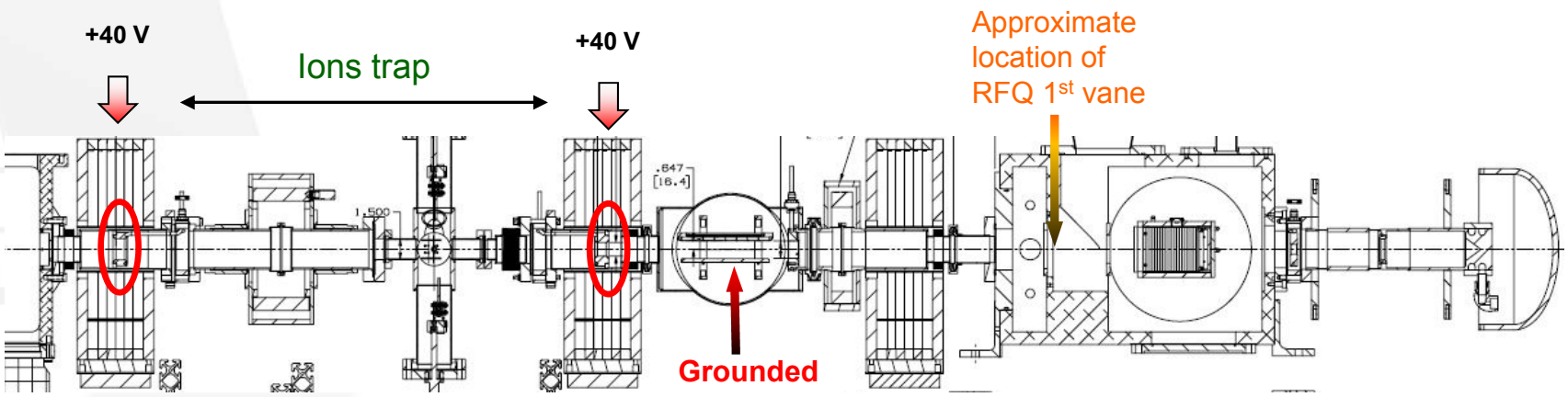




Configuration without ion clearing

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

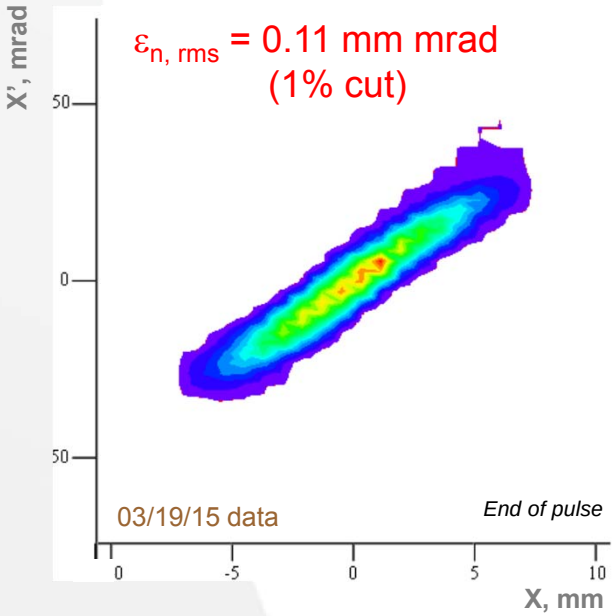




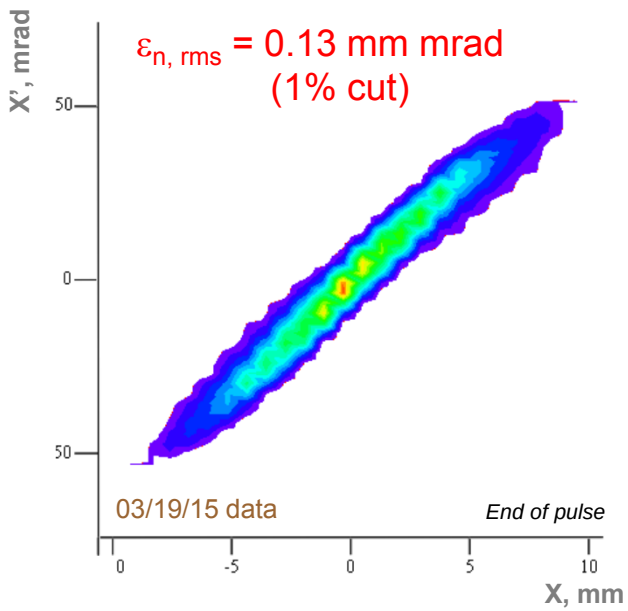
Phase space portraits

- 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

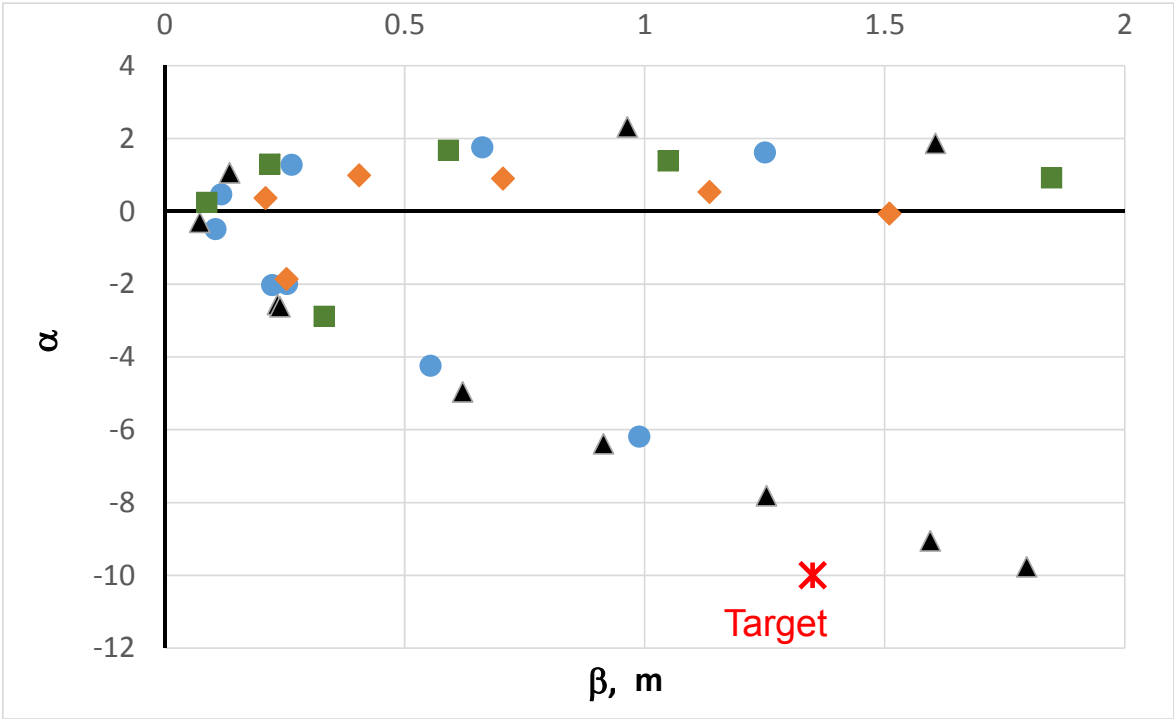


Space charge 'enhanced'



Twiss parameters at RFQ entrance (I)

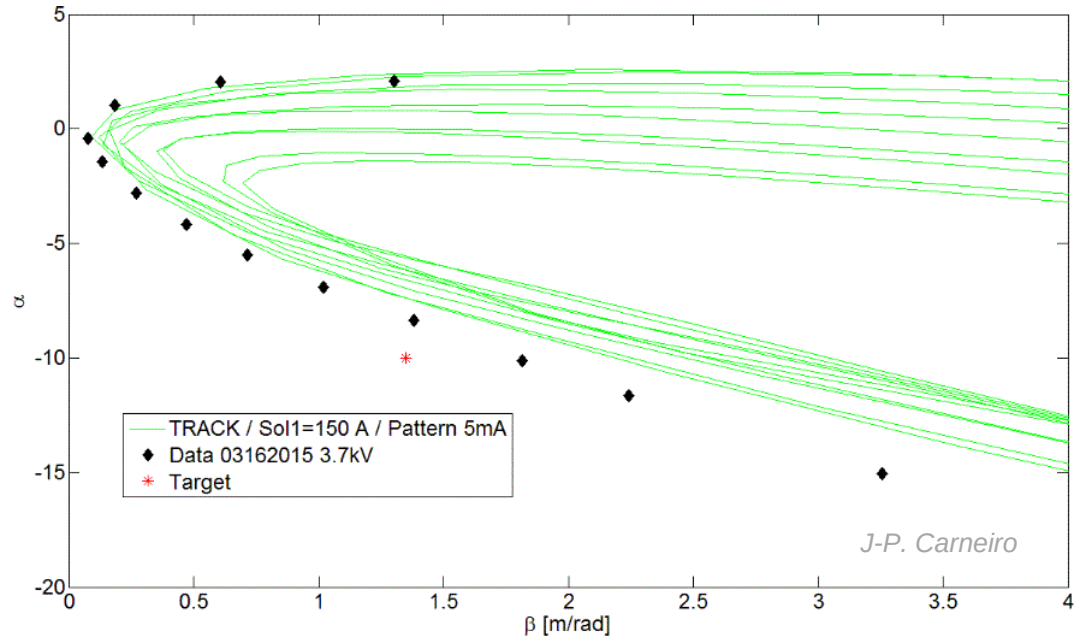
- Cannot get ideal Twiss parameters for RFQ
  - β = 1.35 m; α = -10 at the emittance scanner (⇔ 7 cm and 1.6, respectively, at the RFQ 1st vane)



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)

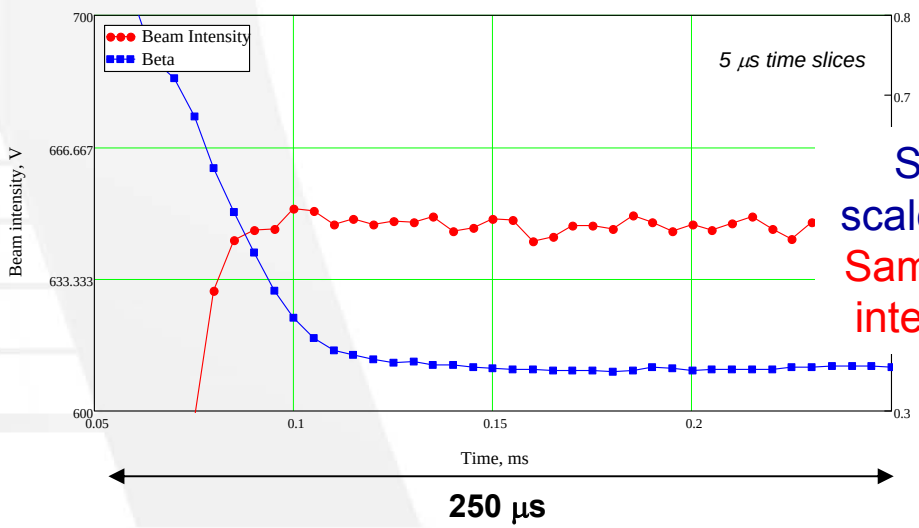


Ensemble of TRACK simulations where Solenoid #2 and Solenoid #3 are varied

Pulsed vs. chopped

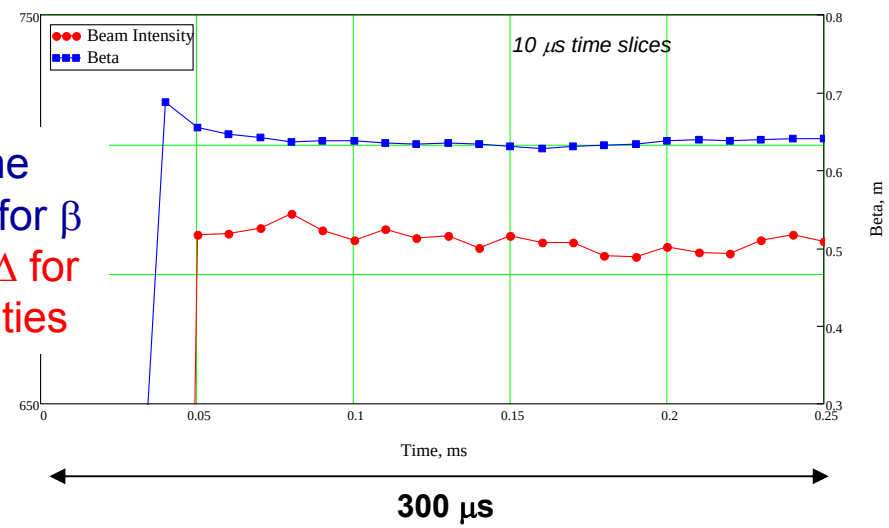
- No ion clearing in both cases
  - Additional positive bias in front of emittance scanner for IS pulse case (3/12/15)
  - Fast convergence to steady state parameters for the chopped beam

IS pulse (3/12/15 – File #1555)



Same scales for β
Same Δ for intensities

Chopped beam (3/19/15 – File #1558)



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 → 10^{-5}-10^{-4} torr ⇨ μs-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

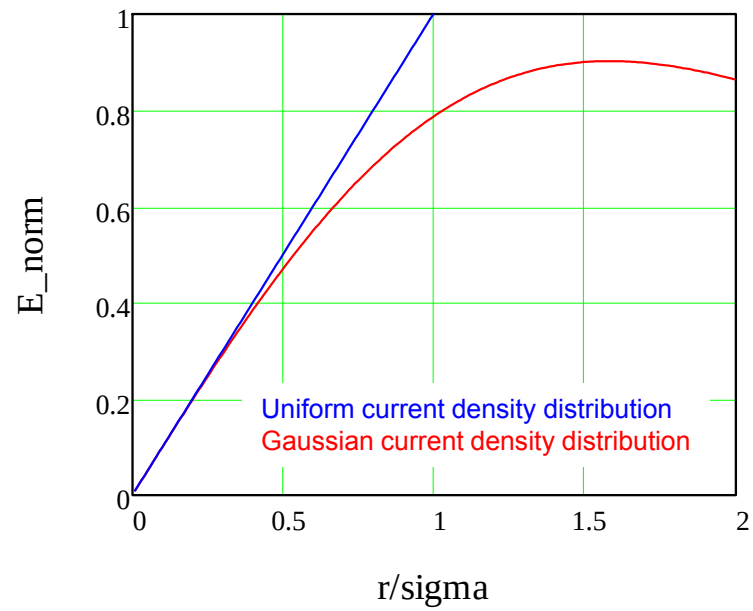
LEBT Transport scheme

- 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

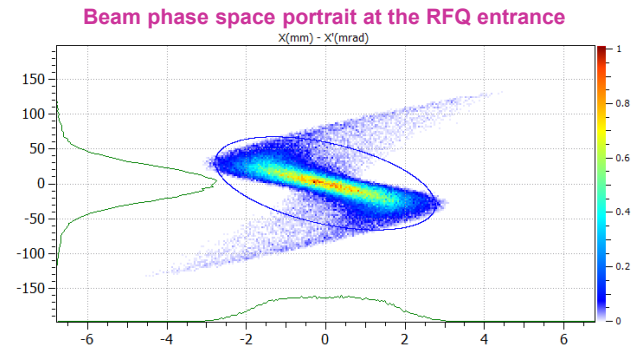
Normalized electric field of a beam with a Gaussian current density profile as a function of its normalized radius (red curve) compared with the field of a constant current density beam (blue curve) with the same density at the center

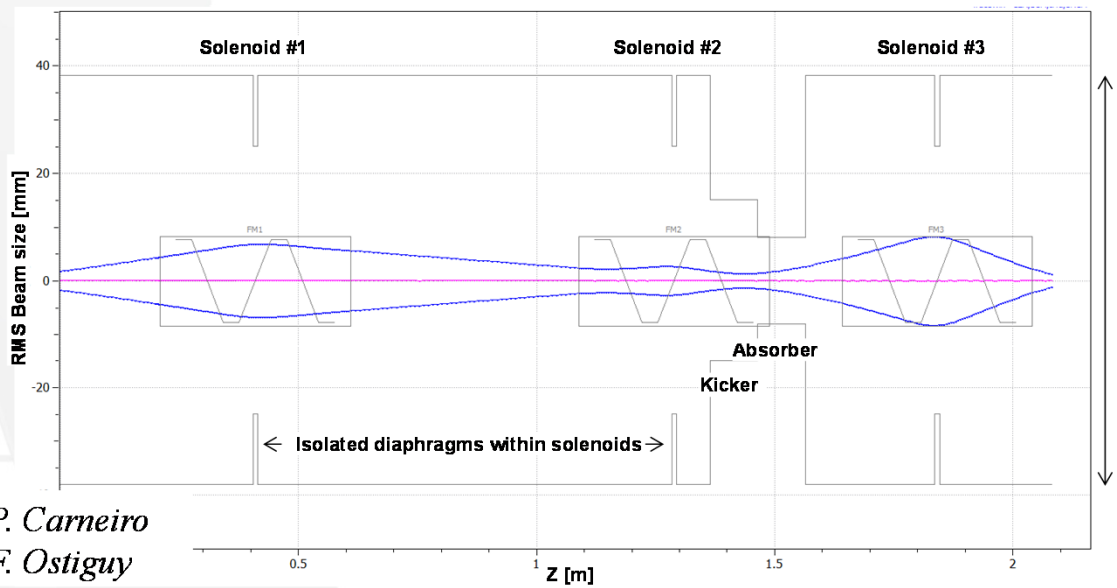


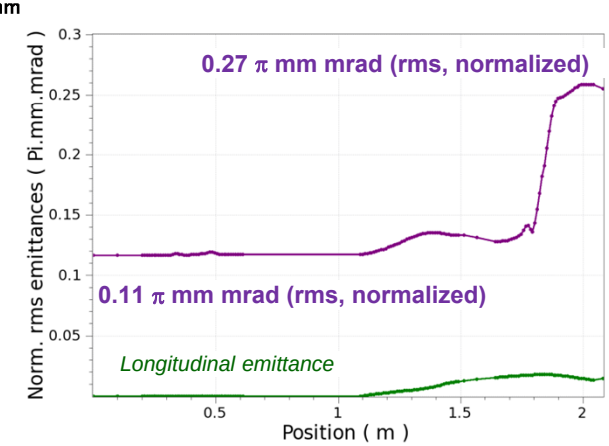
** Slides from 01/21/14 PIP-II Technical Meeting*
http://projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1250

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







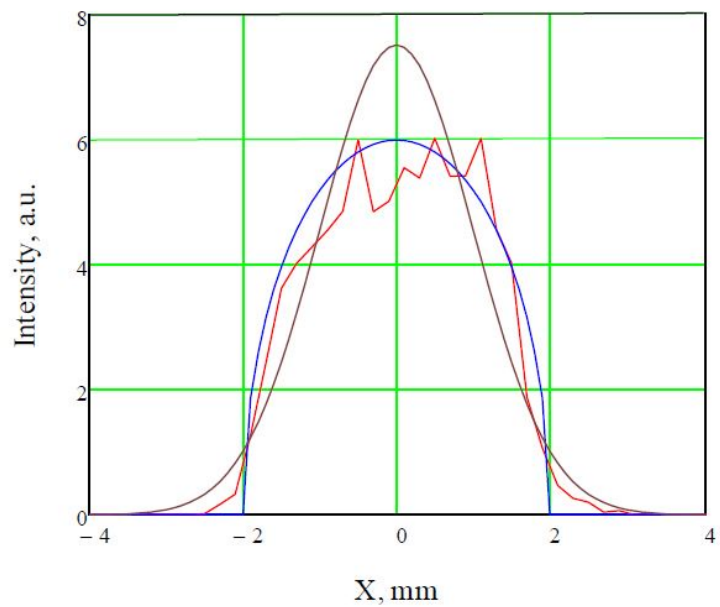
J-P. Carneiro
J-F. Ostiguy

@ 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



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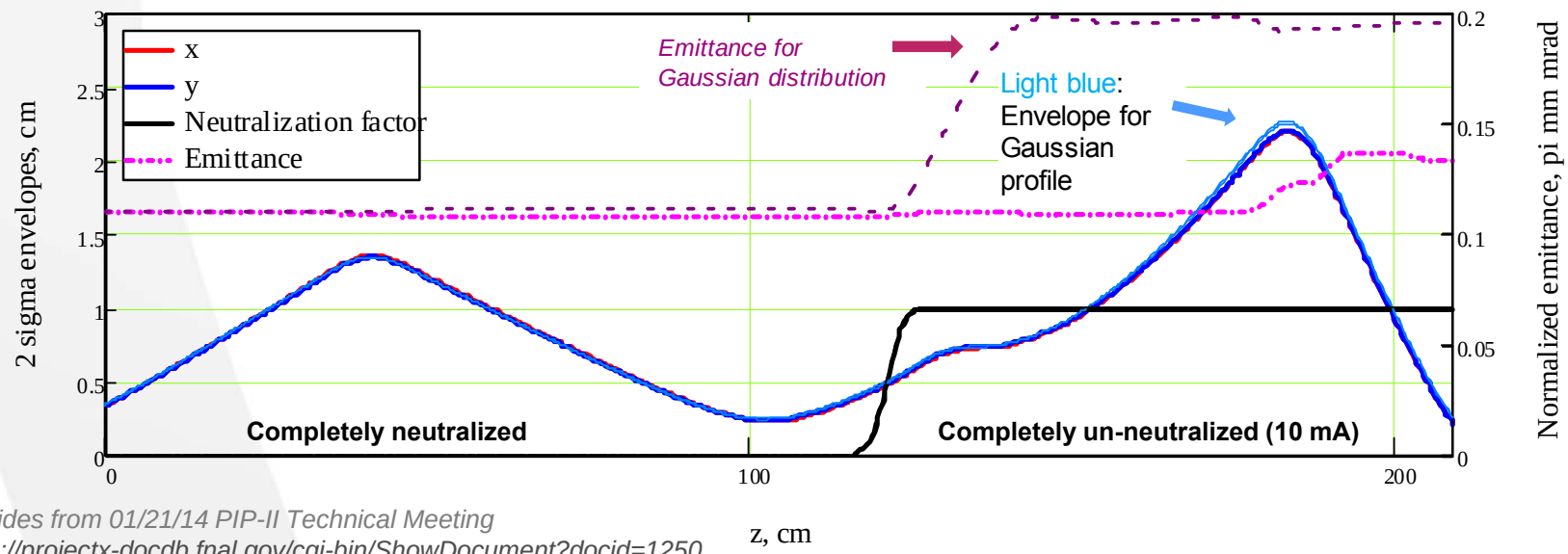
Further simulations with a different initial particles distribution*

- 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*
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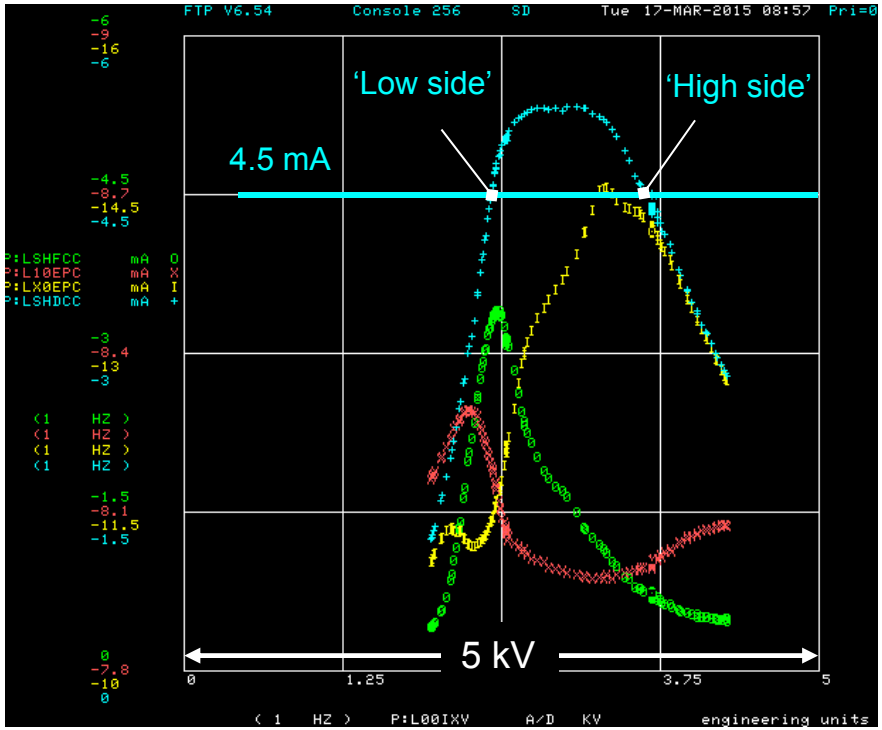
Ion source tunes

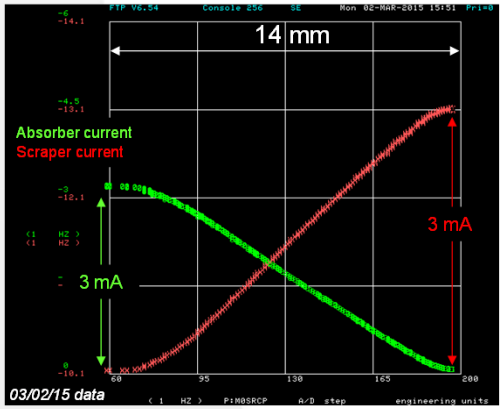
- Electrodes near the extraction region determine not only the extraction current but also the current density distribution
  - With everything else constant, choose two extraction voltages that give the same beam current

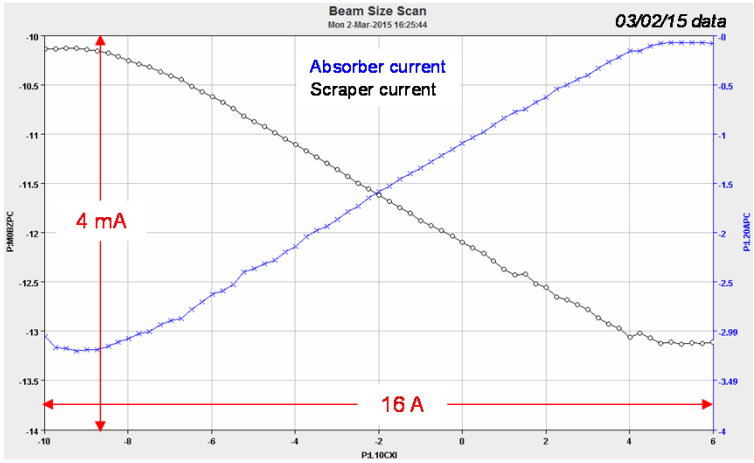


Several currents vs. extraction voltage
Faraday cup
Isolated diaphragm #1
Donut
DCCT

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: σ_x (Gaussian), r_x (Uniform) and mean (μ_x or m_x) along the direction which is measured
  - Raw data integrals are what is fitted
    - Minimize (sum of differences)^2

I_{beam} ≡ beam current – Not a fitting parameter

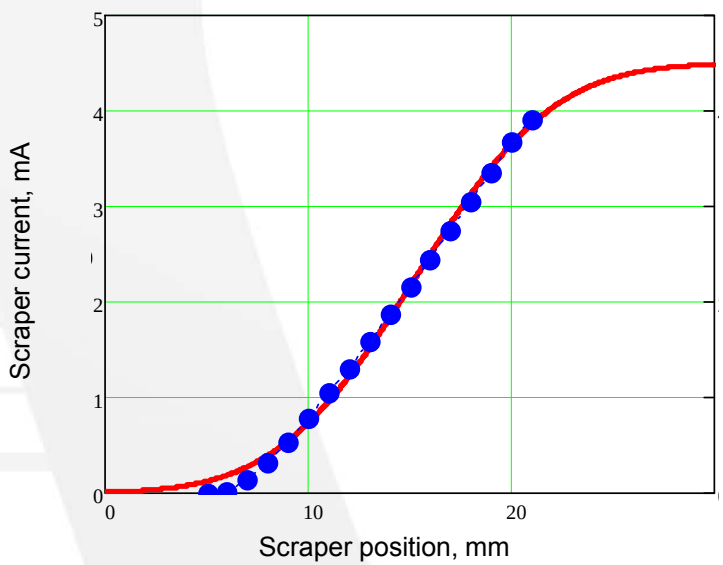
$$\mathrm{Gaussian}(x, \sigma_x, \mu_x, y, \sigma_y) := \frac{I_{beam}}{2 \cdot \pi \cdot \sigma_x \cdot \sigma_y} \cdot e^{\frac{-(x-\mu_x)^2}{2\sigma_x^2}} \cdot e^{\frac{-y^2}{2\sigma_y^2}}$$

$$\mathrm{Unif}(x, r_x, m_x, y, r_y) := \begin{cases} \dfrac{I_{beam}}{\pi \cdot r_x \cdot r_y} & \text{if } \left(\dfrac{x - m_x}{r_x}\right)^2 + \left(\dfrac{y}{r_y}\right)^2 \le 1 \\ 0 & \text{otherwise} \end{cases}$$

‘Low side’ data fit to Gaussian and Uniform distributions

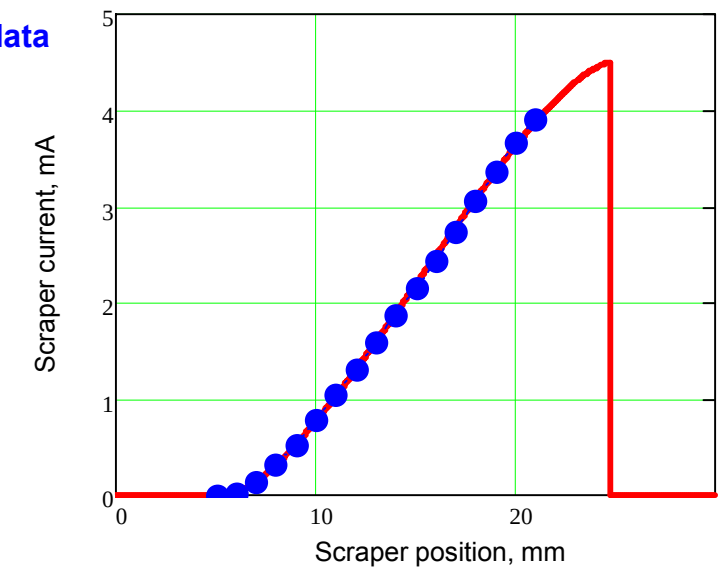
- Data obtained by the ‘moving the scraper’ method
  - Somewhat coarse
- Better fit when using Uniform distribution

Fit with Gaussian distribution



Blue circles ≡ data
Red line ≡ fit

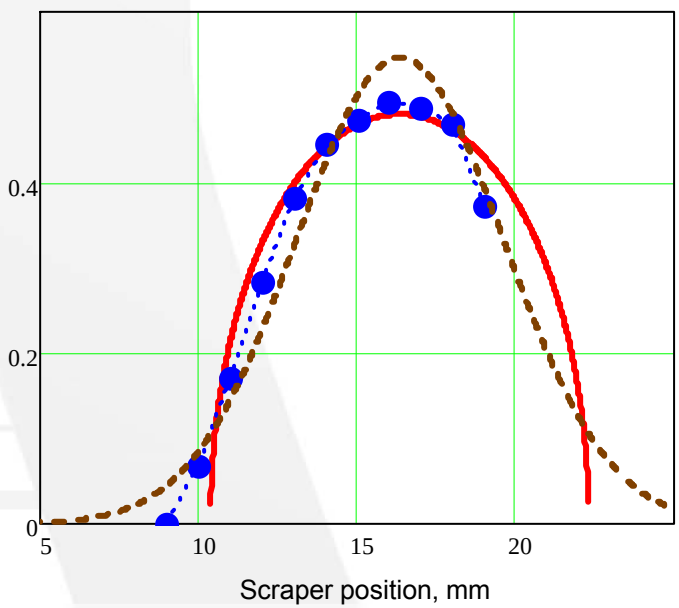
Fit with Uniform distribution



‘Low side’ profile vs. ‘High side’ profile

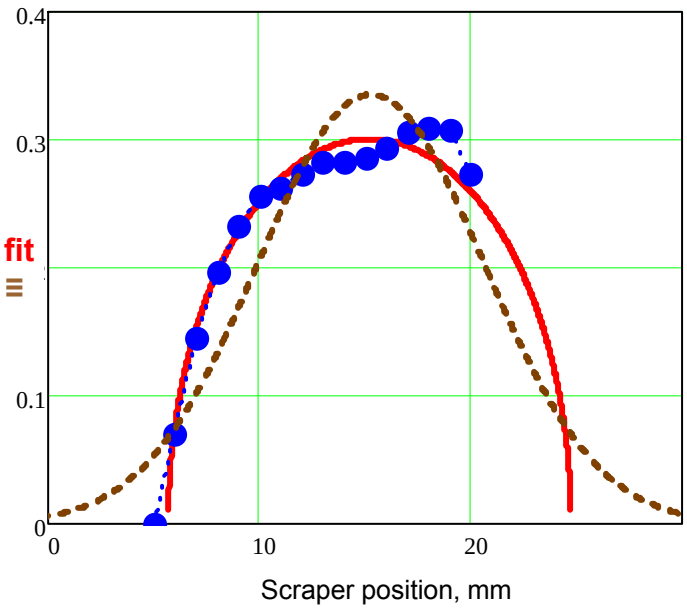
- Plot derivative of the measurement and of the fitted functions
  - ‘High side’: *more* Gaussian ; ‘Low side’: *more* Uniform

‘High side’ profile



Blue circles ≡ data
Red line ≡ Uniform fit
Brown dashed line ≡ Gaussian fit

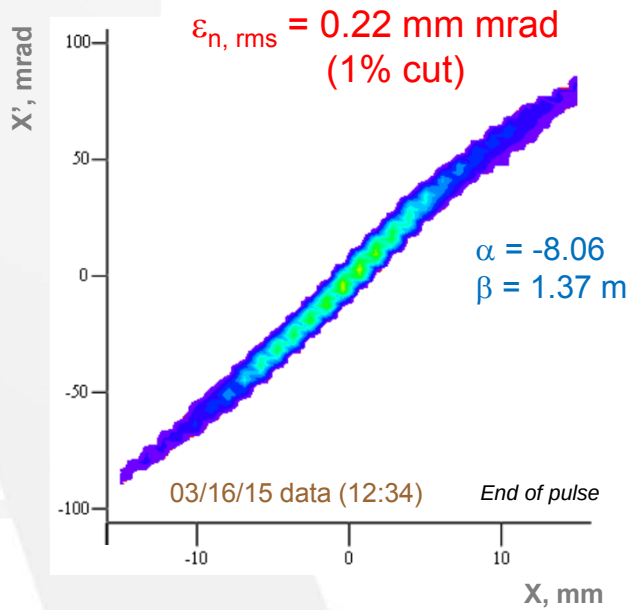
‘Low side’ profile



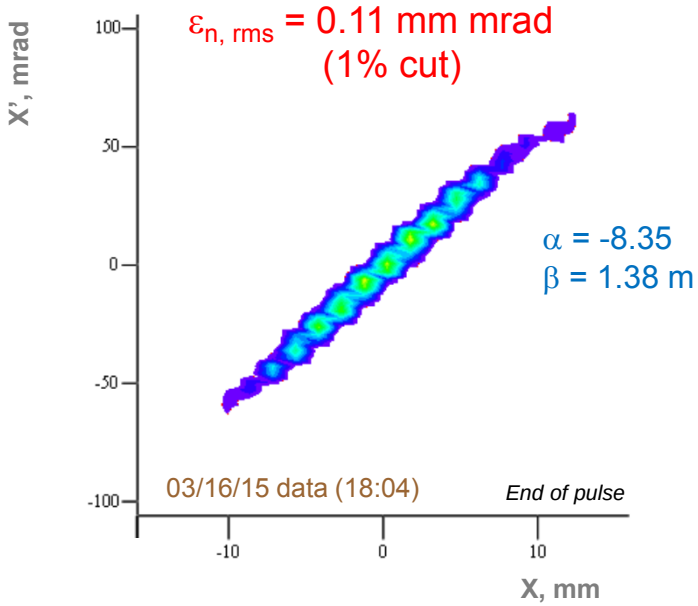
Phase space portraits comparison

- 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'



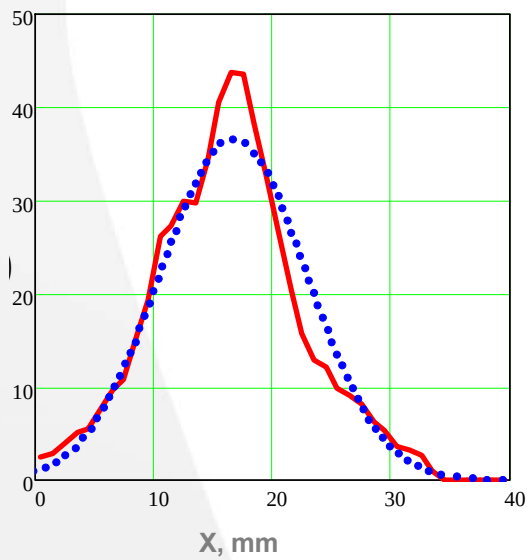
'Low side'



Corresponding 1D projections i.e. profiles

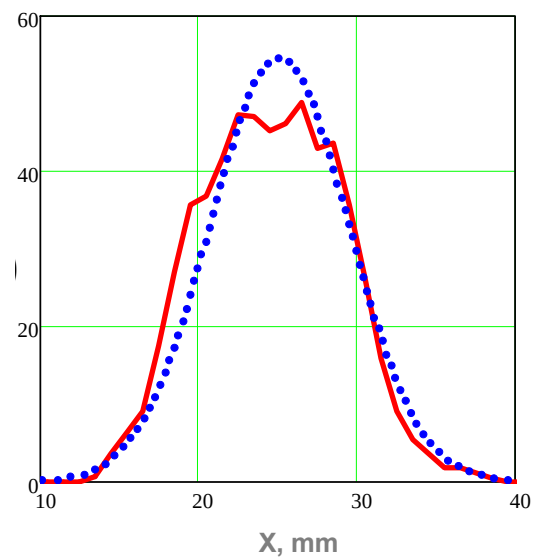
- Like upstream, the beam profiles differ significantly, with the ‘Low side’ profile indicating a more uniform distribution than for the ‘High side’ data

‘High side’



Red: data
Dotted blue: Gaussian distribution with same σ

‘Low side’



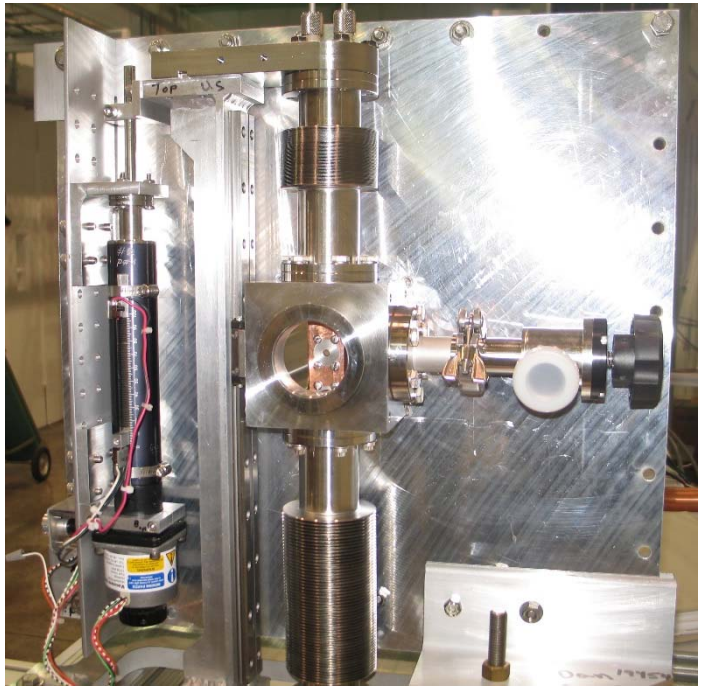
Conclusions/Comments

- 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*

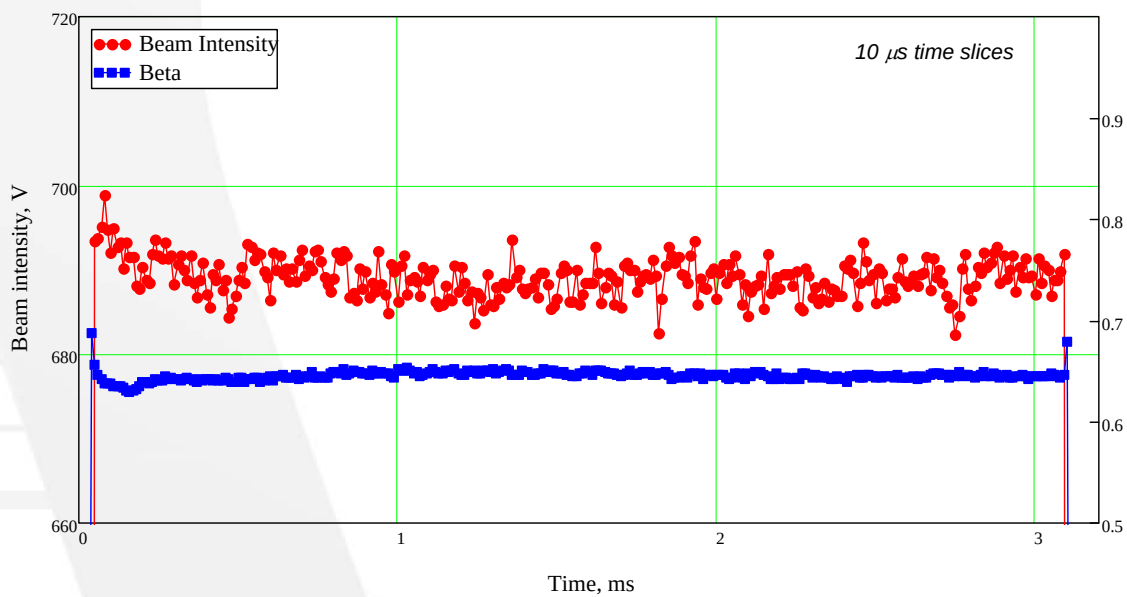


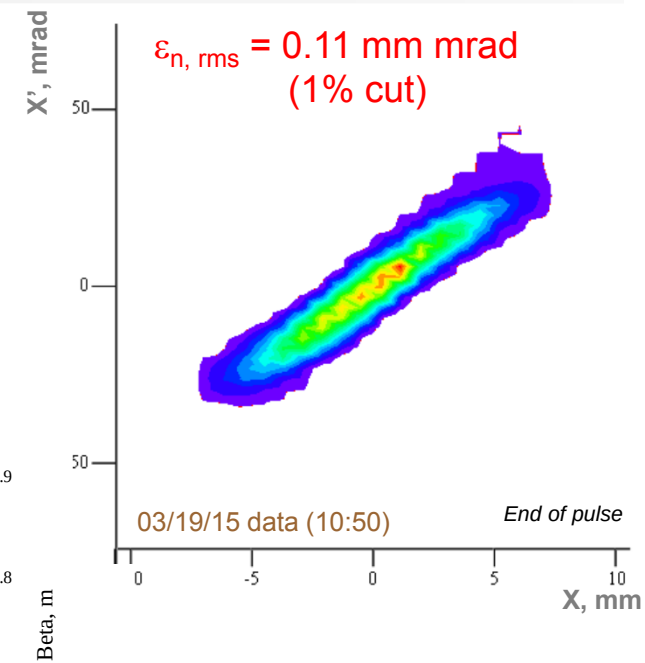
- On-track to be ready for RFQ arrival in June
  - Delays give us the chance to study the beam line properties in more depth

Additional slides

Phase space measurements (neutralized)

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

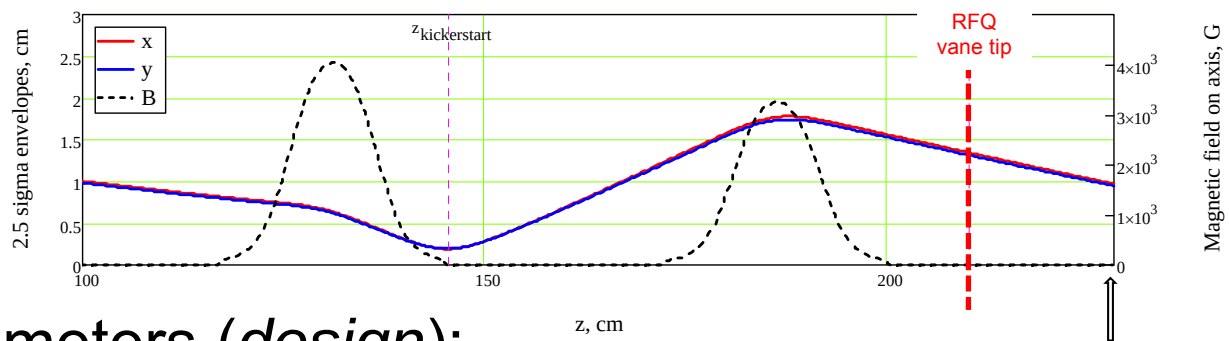




RFQ matching

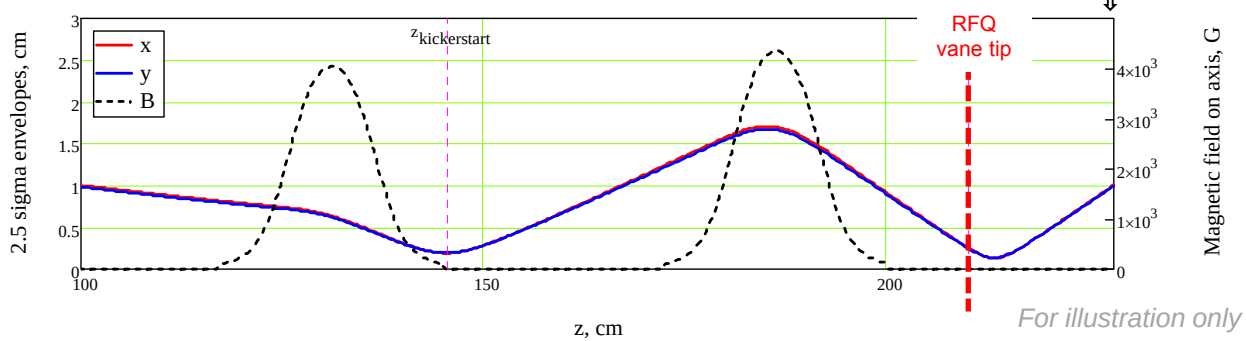
- Without matching constraints:
  - Achieved 5 mA DC with $\varepsilon_{n,rms}$ < 0.15 mm mrad

For illustration only



- Matched parameters (*design*):
  - β = 7 cm and α = 1.6 at RFQ 1st vane tip

Emittance scanner front slit



For illustration only

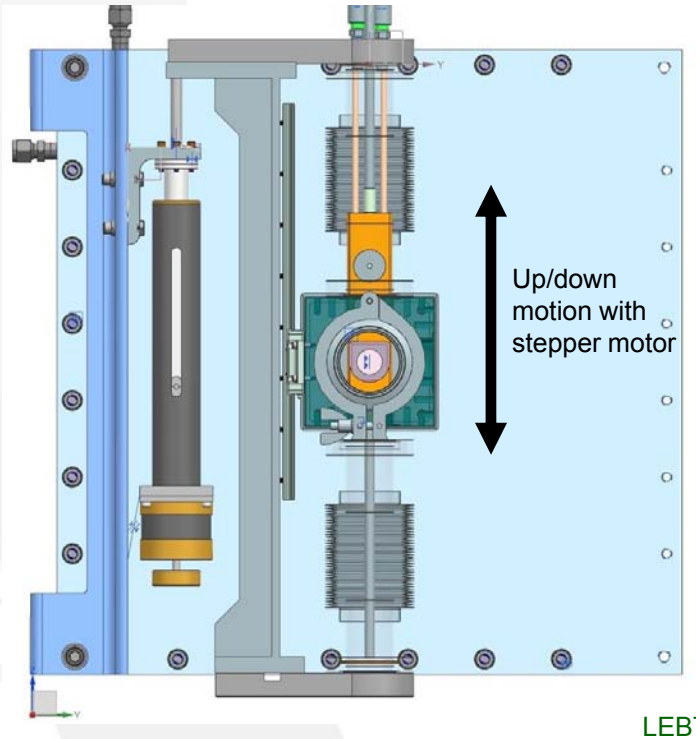
Operational notes

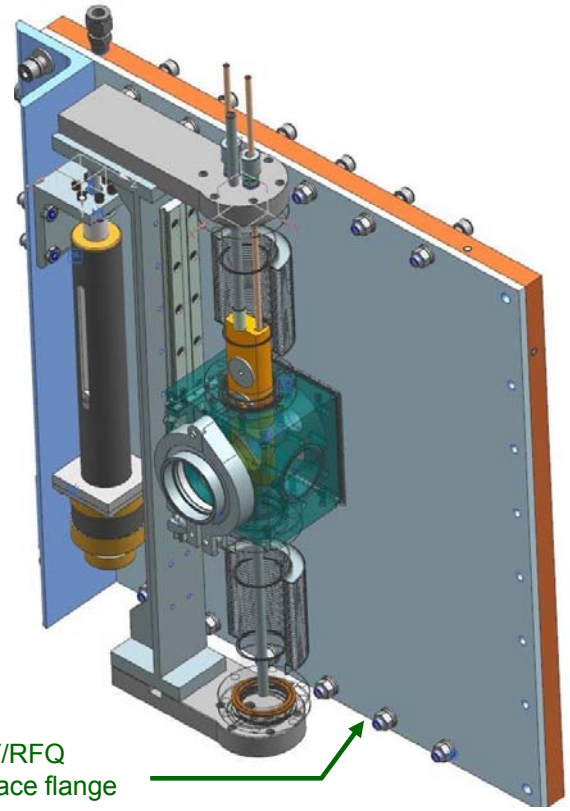
- Replaced filament after failure on 01/20/15
  - Failure was expected
  - Run time: 460 hours

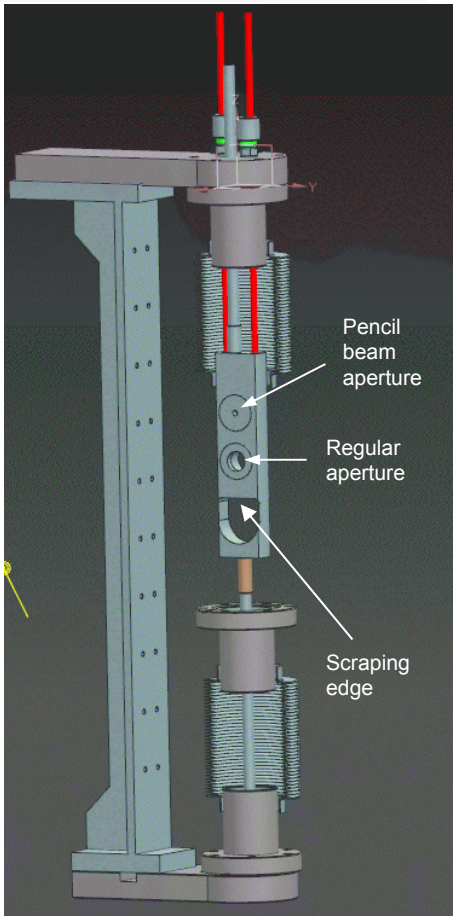
- One power supply used with the emittance scanner failed
  - Did not have any spare
    - ~1 week without instrument availability
  - Procured 2 PSs
    - 1 replacement (refurbished) and 1 spare (new)

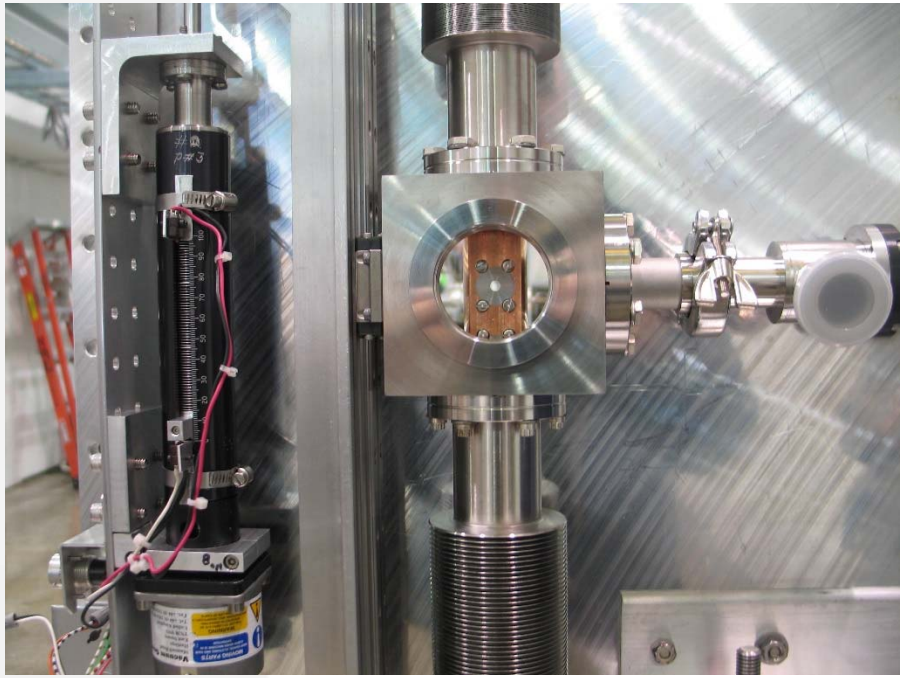
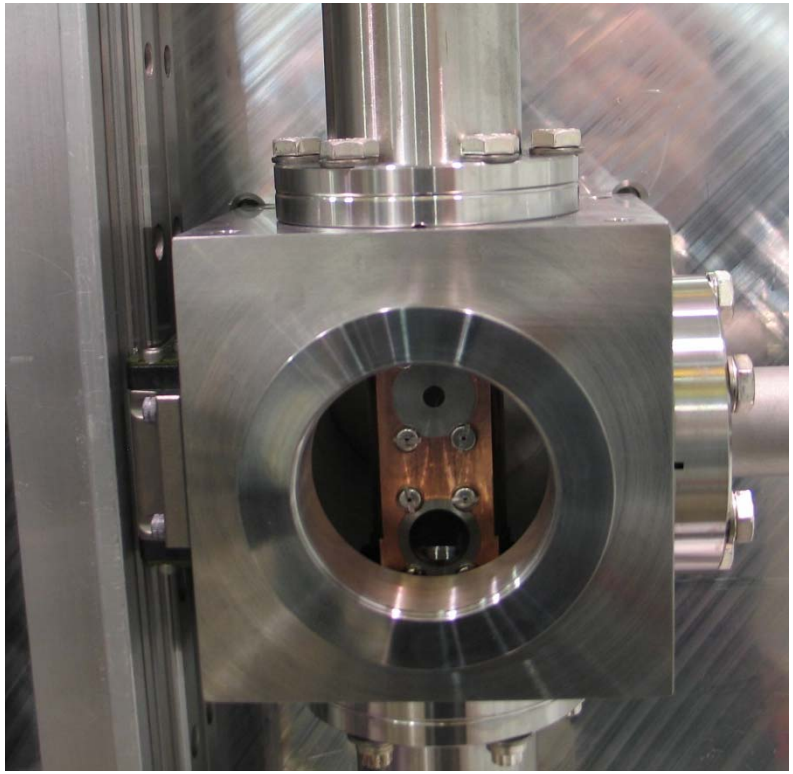
LEBT 'scraper'

- Movable isolated electrode with holes
  - Beam measurements and RFQ protection







T. Hamerla

LEBT scraper pictures