Peculiarities of the emittance growth in LEBT

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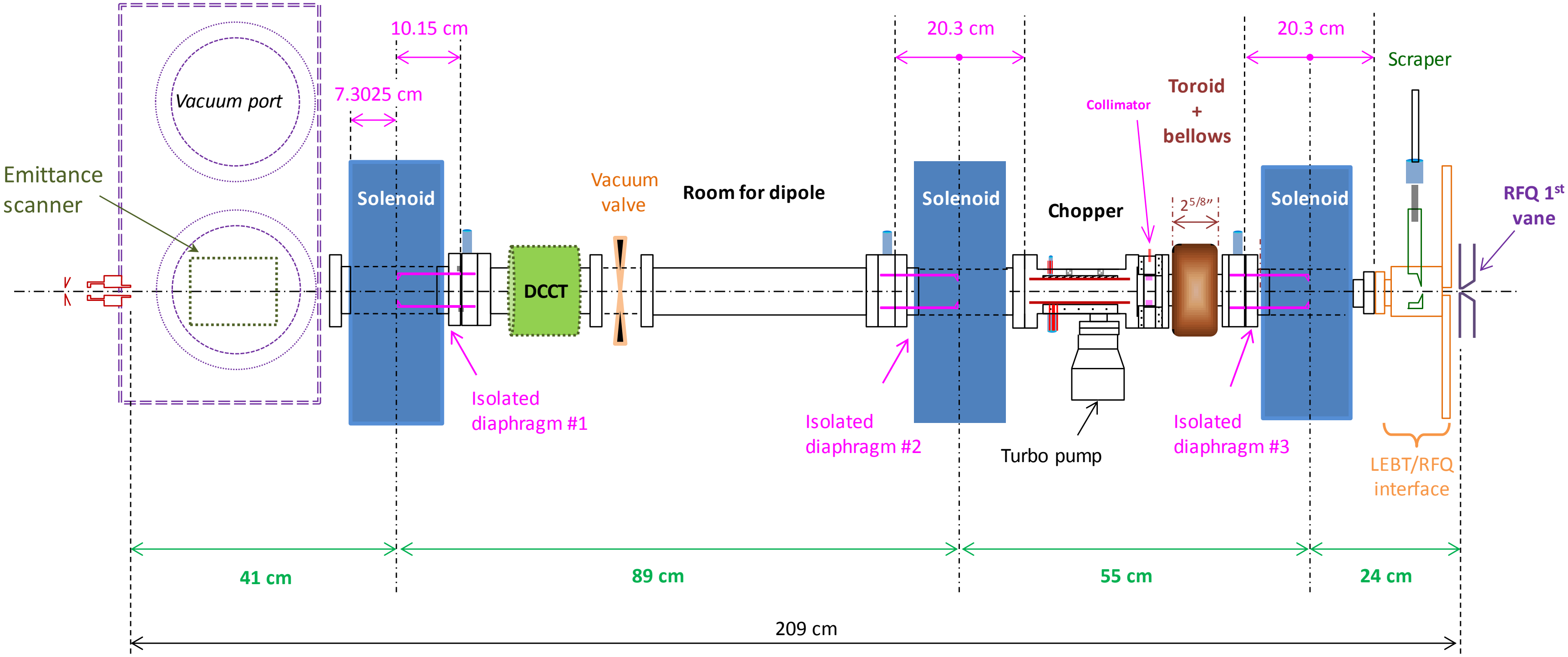
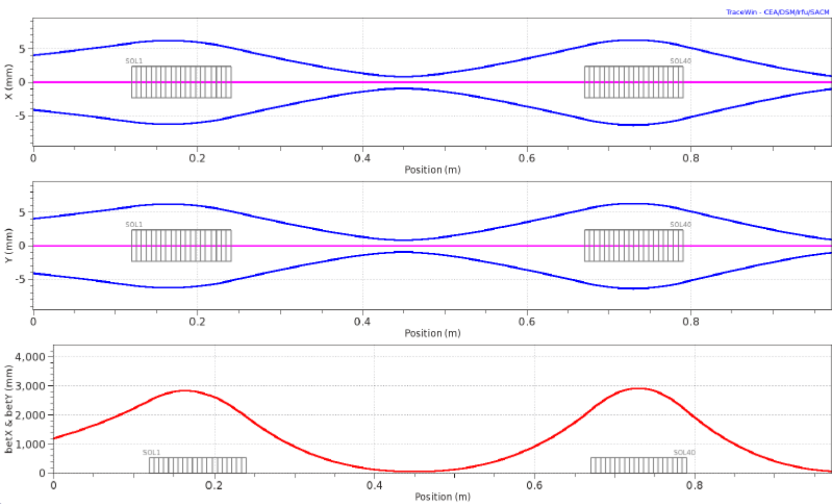
PXIE LEBT

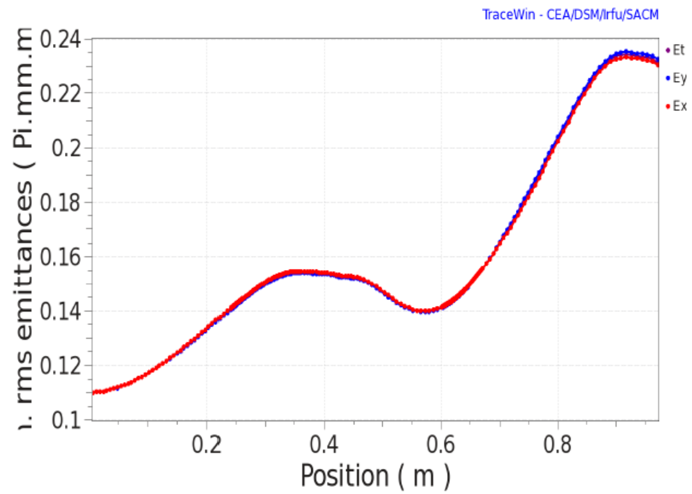


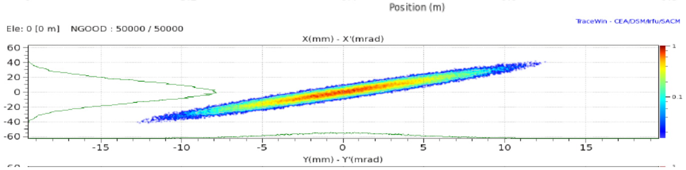
- H^-, 30 keV, up to 10 mA DC
- Capability to create 1µs – 16 ms pulses at 60 Hz with the chopper
- Isolated diaphragms for stopping the residual gas ions
- Possibility to test a concept of partially neutralized transport

Emittance growth in LEBT

- Simulations showed that even at modest currents of PXIE LEBT, the space charge can significantly increase the emittance







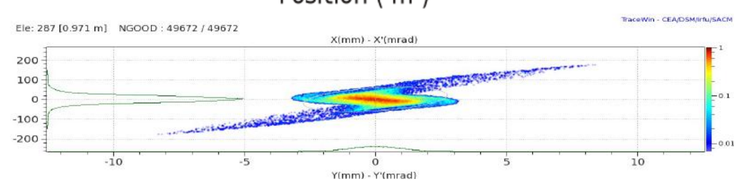
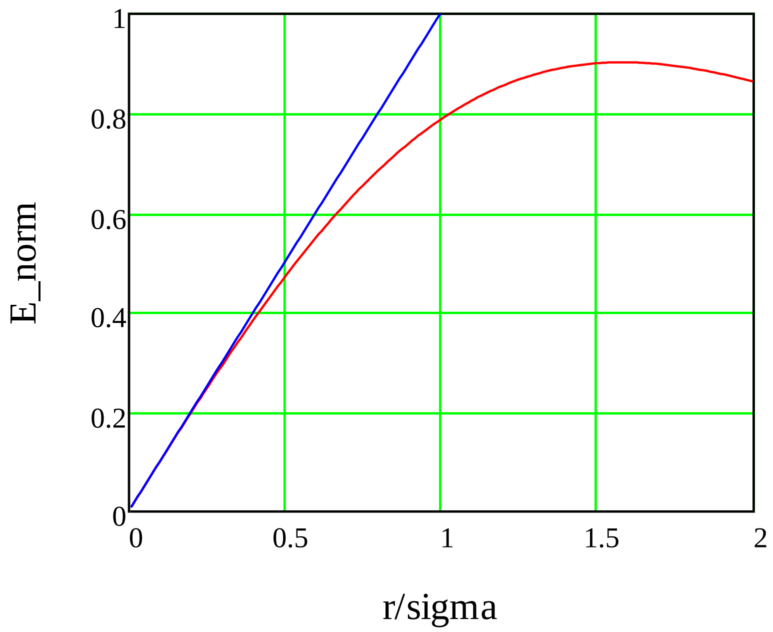


Illustration: 2 – solenoid LEBT, H-, 30 keV, 5 mA, initial beam is Gaussian in space and transverse momentum. No neutralization.
Simulation by TraceWin. J.-F Ostiguy & N. Solyak, Apr 2, 2012.

Source of the growth

- The dominant source of the emittance growth is non – linear forces from the beam space charge



Example:
Electric field of a beam with Gaussian density distribution of density (red). Blue – a straight line for comparison.

- How can one decrease this growth?

Neutralization

- Standard answer in LEBTs: space charge neutralization by ions of the residual gas
  - No space charge => no non-linear forces => no related emittance growth
  - However, having no neutralization at the LEBT chopper and downstream would be beneficial to avoid variations during transition from pulse regime to DC regime
    - Presently, all PXIE commissioning is assumed to be made with a pulsed beam of ~5 µs width.

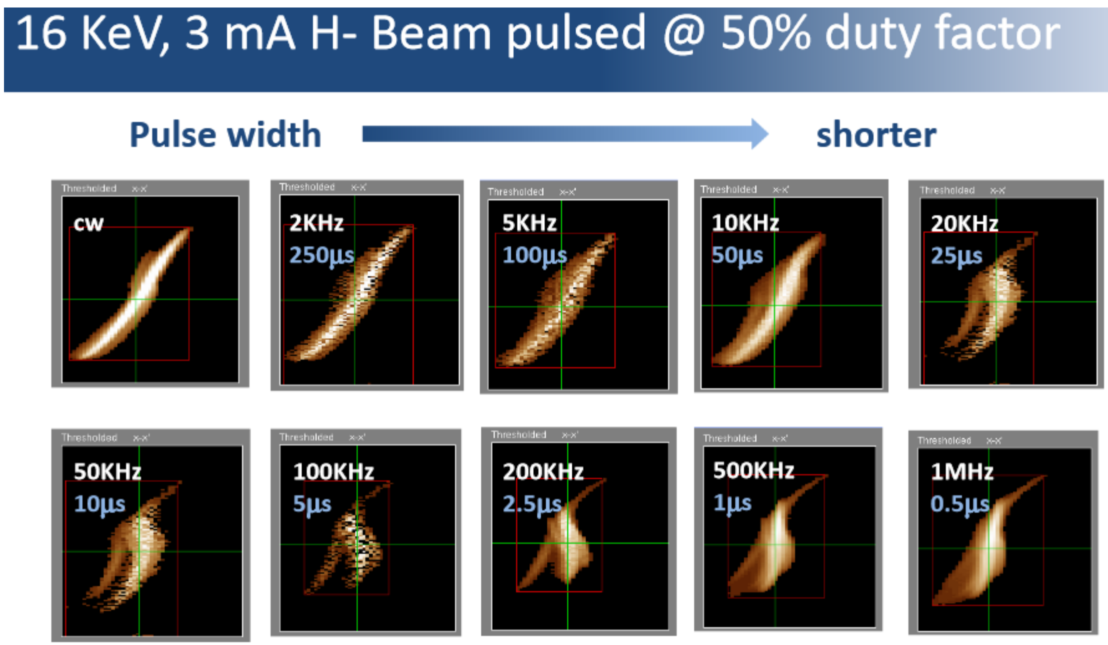


Illustration: phase portraits of an H^- beam at different pulse durations.
Qing Ji (LBNL), PXIE ion source.
PX meeting, November 27, 2012.

Linear force

- The emittance doesn't grow if the current density distribution is constant
  - The space charge force is linear with radius

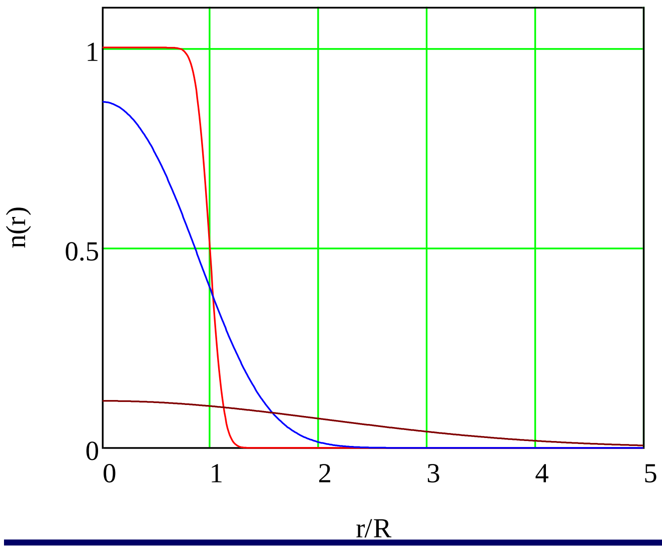
- The distribution may stay close to constant if the beam transport is space charge – dominated
  - Cannot be fulfilled everywhere in the LEBT
    - Requires strong focusing
    - Pressure is high near the ion source (>1.E-5 Torr), thus neutralization is unavoidable

Transition from constant distribution to Gaussian

- Let's consider a zero-current beam with initially constant current density but a Gaussian transverse velocity distribution

$$\frac{\partial^2 n}{\partial V_x \partial V_y} = \frac{1}{2\pi\sigma_V^{\ 2}} \exp\left(-\frac{V_x^{\ 2} + V_y^{\ 2}}{2\sigma_V^{\ 2}} \right) \cdot \begin{cases} 1, & r \le R \\ 0, & r > R \end{cases}$$

  - When the beam expands, a particle position is determined mainly by its initial transverse velocity rather than initial position, and the current density approaches a Gaussian shape



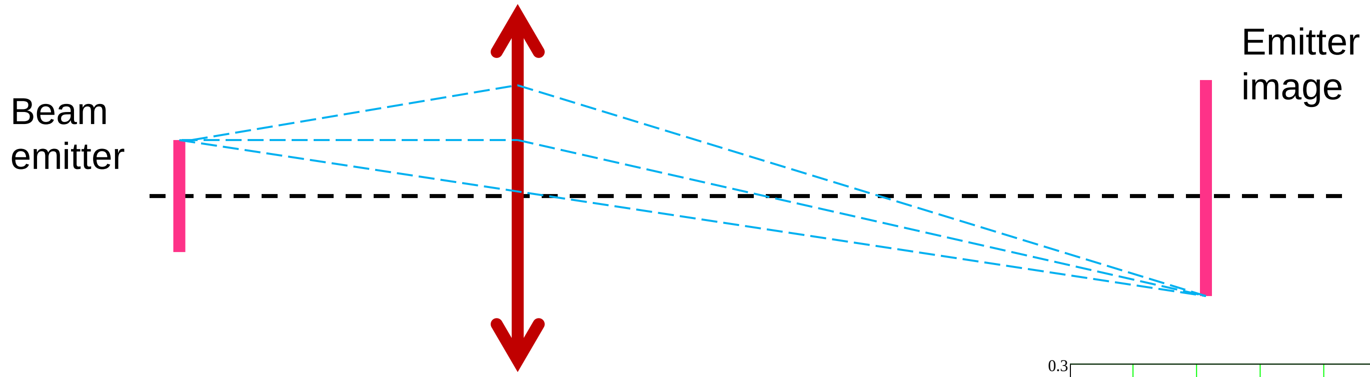
Evolution of the density profile of a beam with initially constant current density and a Gaussian distribution of transverse velocities after traveling a distance L with the longitudinal velocity Vz.

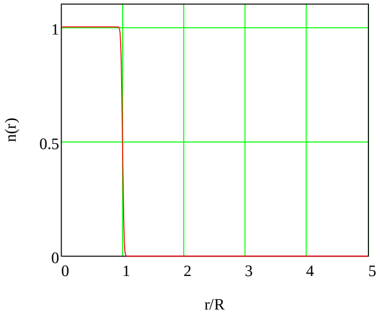
Parameter $\sigma = \frac{L}{R} \cdot \frac{\sigma_V}{V_z}$ characterizes the relative increase of the beam size.

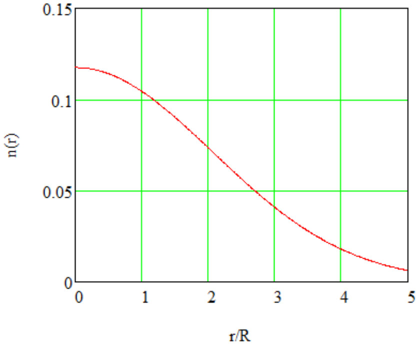
The value of σ is for the red curve 0.1, blue – 0.5, brown – 2.

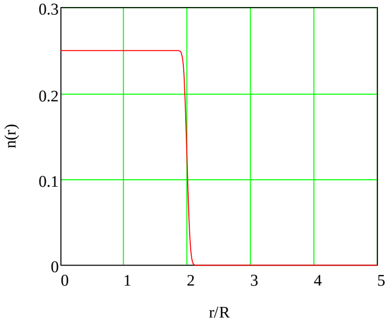
Transport through a lens (I)

- Focusing with an ideal lens reproduces the constant density distribution at the image plane

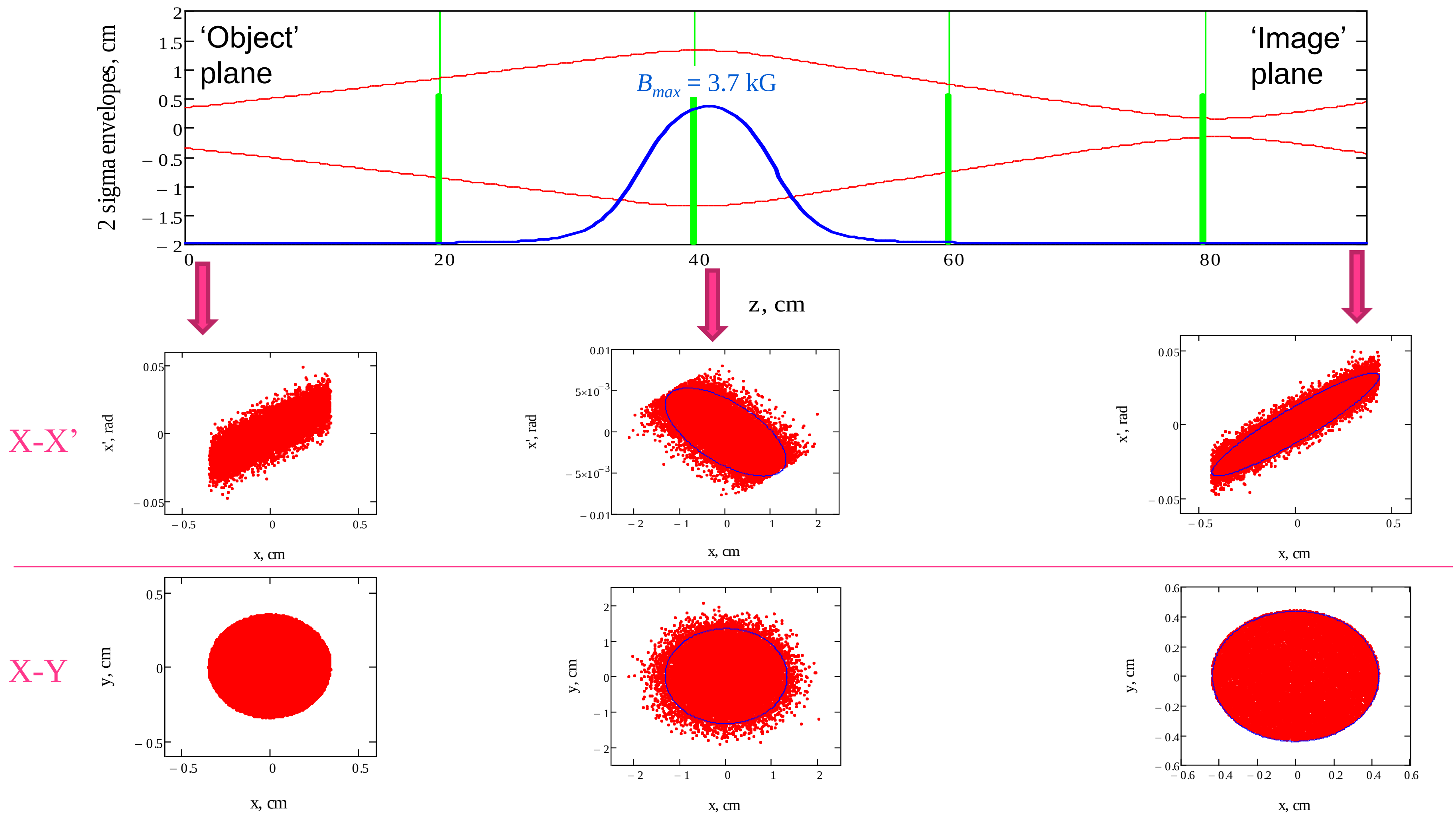








Transport through a lens (II)



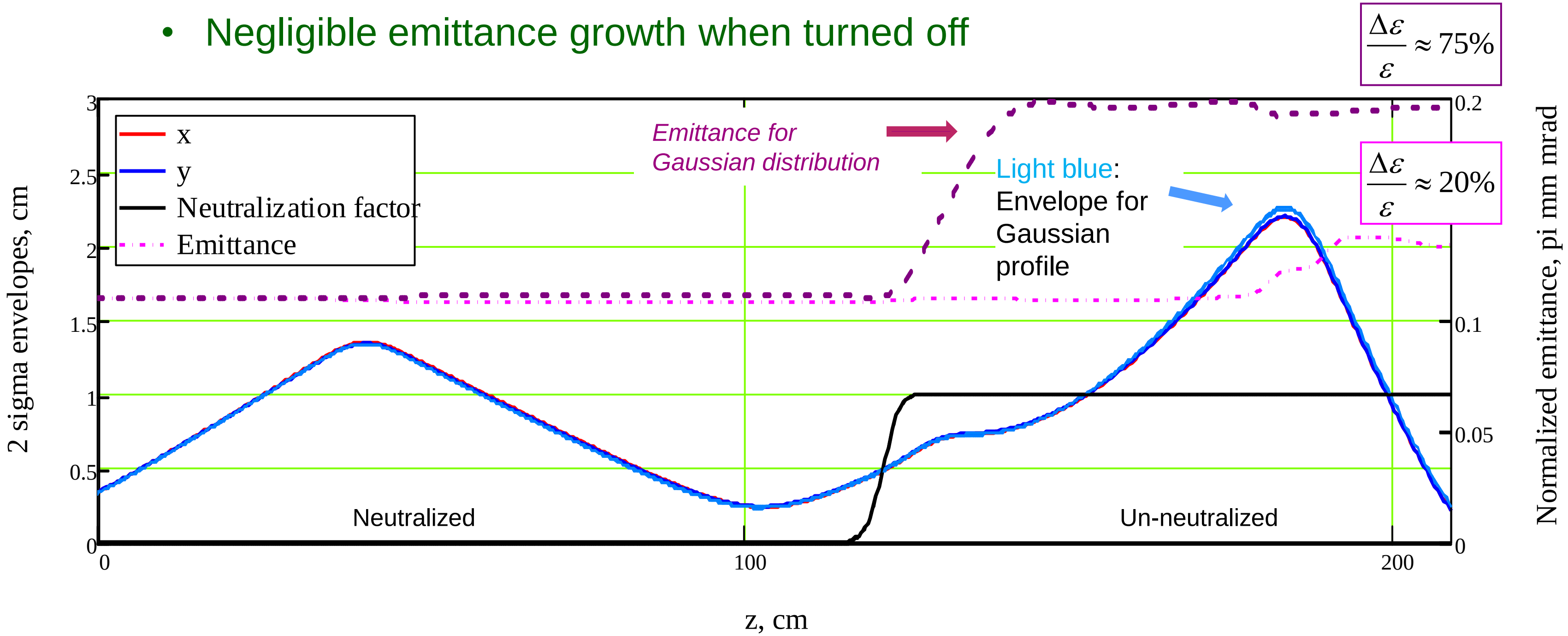
A possible recipe

- Recipe to combine a small emittance growth, neutralization near the ion source, and un–neutralized transport through a downstream portion of the LEBT
  - Create in the ion source a beam with a constant density distribution
  - Let it expand in the neutralized area
    - Emittance doesn't grow because the space charge is turned off
  - Focus with a low-aberration lens to get an image spot with the size preferably larger than the emitter's
  - Interrupt neutralization
  - Make the un-neutralized section as short as possible
    - Emittance growth is low because the distribution is close to constant

Project X

Simulations (I)

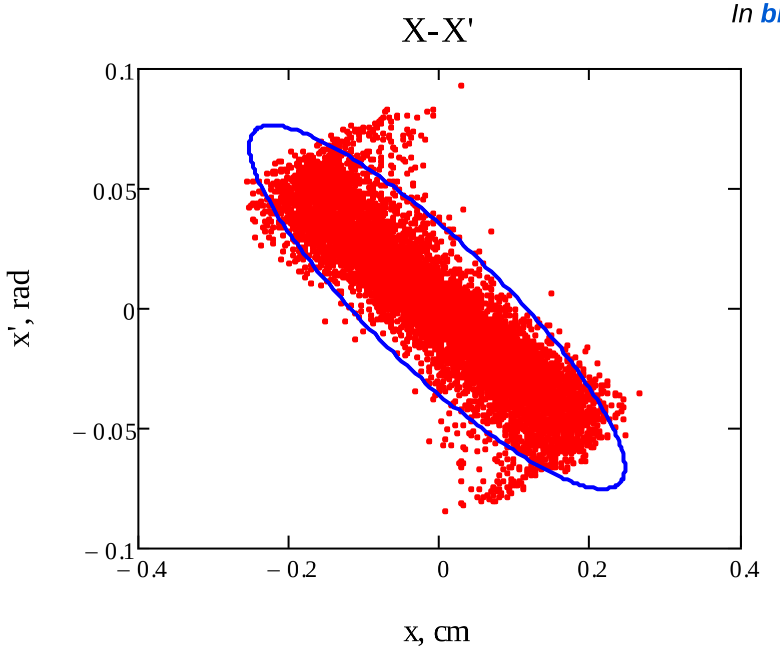
- Dynamics of the beam with initial constant current density in the PXIE LEBT was simulated with Valery's MathCad code
  - Emittance growth is significantly lower than in a case of a double-Gaussian distribution: ~20% vs. ~75% (*for similar envelope profiles*)
  - Source of emittance growth: <u>solenoid aberrations</u>
    - Negligible emittance growth when turned off



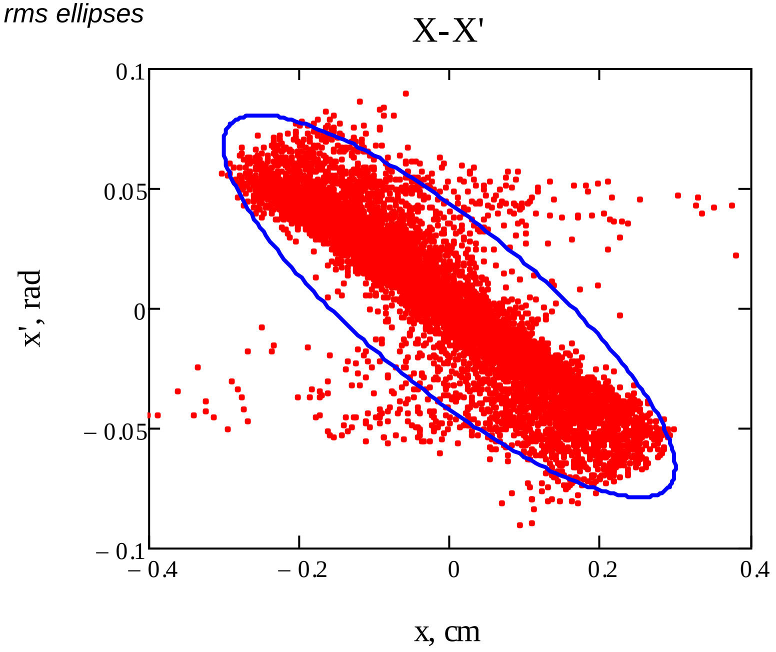
Simulations (II)

- Phase space portraits at the exit of the LEBT corresponding to the beam envelopes shown on the previous slide
  - 7500 macro-particles

*In **blue**: 4 rms ellipses*



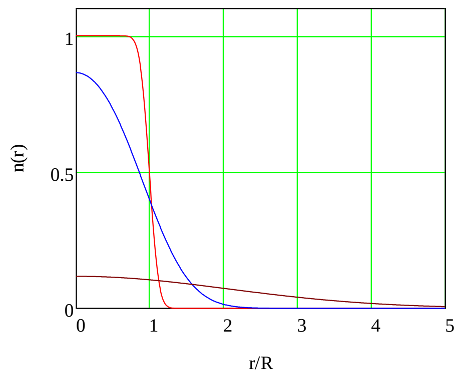
Uniform current density distribution
(*Gaussian distribution for velocities*)



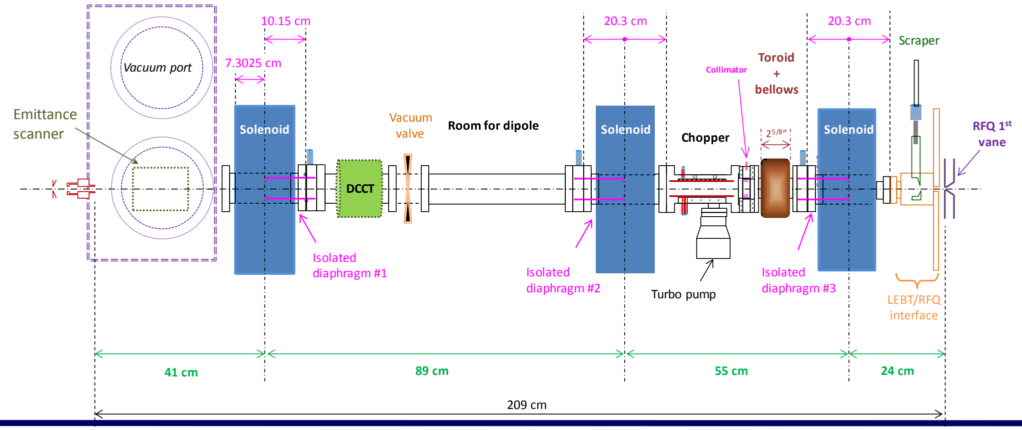
Gaussian current density distribution
(*Gaussian distribution for velocities*)

Limitations: kicker

- The length of the un-neutralized section with low disturbance grows with the beam radius at the transition
  - Parameter σ determines the distribution shape
  - For a fixed σ, $$L = \frac{R}{\sigma} \cdot \frac{V_z}{\sigma_V} = \frac{1}{\sigma} \cdot \frac{1}{\varepsilon} \cdot R^2$$

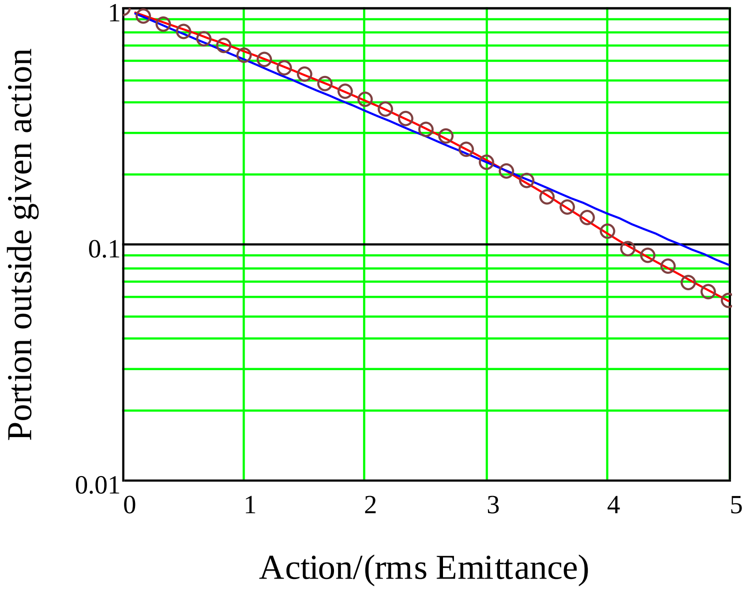


- The maximum diameter of the beam waist is determined by parameters of the chopping system: available space and the kicking voltage



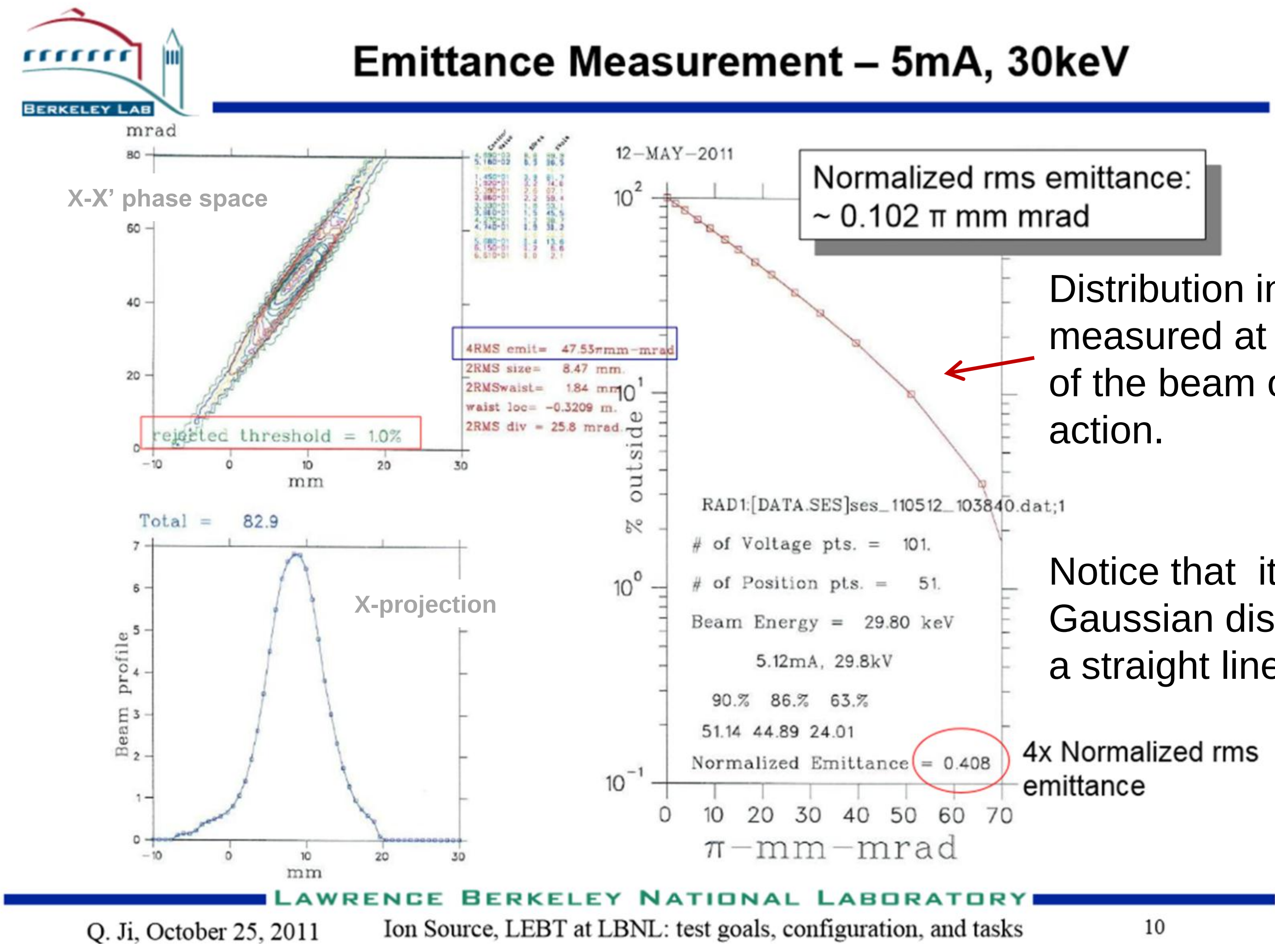
Limitations: distribution at the ion source

- Typical assumption in simulations: Gaussian distribution both in space and velocity ("double-Gaussian")
- How close is this assumption to reality?
  - Can look at the measurements of the PXIE ion source made during the acceptance tests
  - Need to look at deviations from the double-Gaussian



Portion of particles outside of a given action. Blue – double-Gaussian (a straight line in semi-logarithmic scale). Red – constant current density. Circles- experimental data (see the next slide).

The measurement

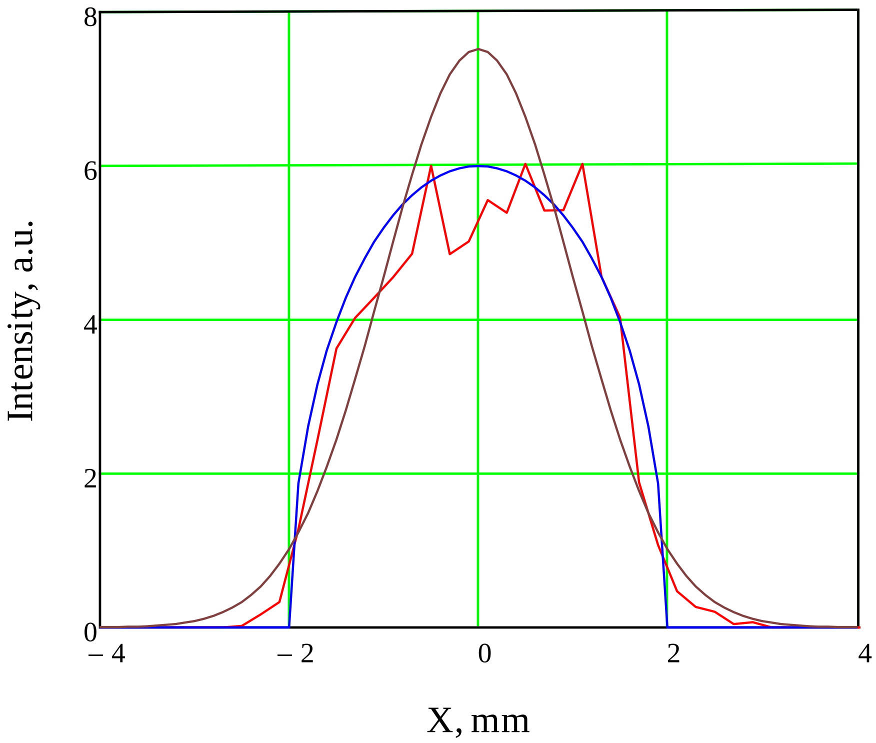


Distribution in PXIE source as measured at TRIUMF: portion of the beam outside of a given action.

Notice that it is not exactly Gaussian distribution (i.e. not a straight line).

Distribution

- One can propagate the measured distribution back to the minimum size (vertical phase-space trace ellipse) and look at the X–projection
  - The thus-obtained distribution is closer to the one resulting from a constant-density distribution than to a Gaussian



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

Summary

- Phase space distribution in PXIE ion source is likely closer to (constant in space)*(Gaussian in velocities) than to double-Gaussian

- A scheme with expanding the beam size in a neutralized space and interrupting the neutralization where the beam spatial distribution is nearly constant allows suppressing the space charge-related emittance growth

- Measurements in FY14 at the PXIE LEBT can be used to test such a scheme