# Simple estimations for a LEBT kicker

A. Shemyakin

Project X front end meeting

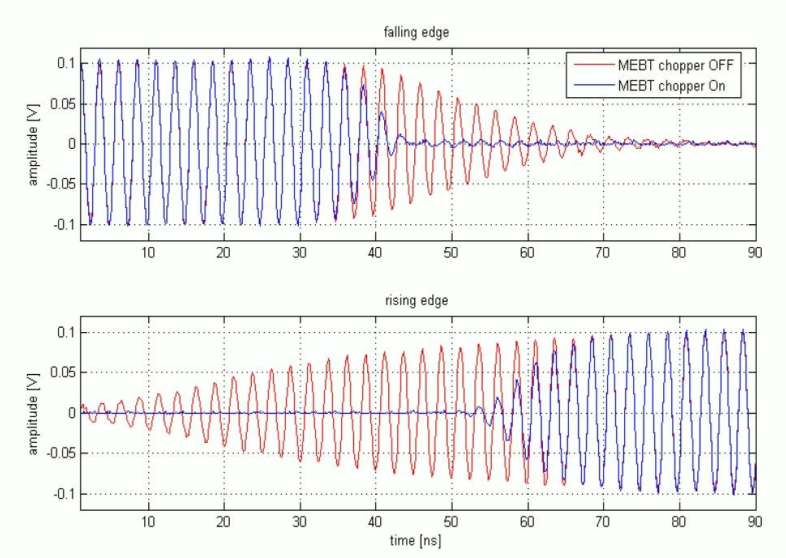
April 20, 2011

# Introduction

- The present scheme of the front end requires the LEBT kicker only for commissioning.
  - To form a microsec-long pulse or similar
- Because of uncertainties with the first experiment’s time structure requirements and with the progress with critical elements of MEBT (chopper and target) it may change for the initial phase.
  - For some cases, using an LEBT kicker could decrease the power on the internal MEBT target by pre-chopping.
  - Usefulness depends on the minimum duration of perturbation introduced by the kicker in the beam.
- The goal of this presentation is to make the simple estimations for an LEBT kicker
  - Estimations of typical possible times and required voltages
  - Made for my own education
    - Still may be helpful for somebody else as well

# Example: SNS LEBT chopper

- The rise/drop time between 90% and 10% intensity of bunches in the linac with only LEBT chopper is 25 / 50 ns.
- Hence, if one wants to remove completely at least a portion of the beam, the minimum duration of the perturbation in the beam is ~ 25+50 = 75 ns
- 60 Hz, 1 ms macropulse, 300ns gap in a 1 μs trains




Performance of SNS LEBT chopper (IPAC'2010). Red – bunches with LEBT chopper only, blue – with MEBT chopper.

- Can it be made shorter for the Project X?
  - Here, only simple estimations for
    - Space charge
    - Kicking time
    - Kicker angle and voltage

# Parameters to use in estimations

- LEBT energy, $eU_0$ – 25 keV
- Beam current, $I$ – 5 mA
- Beam emittance, $\varepsilon_n$ - 0.5 π µm (n, 4*rms)

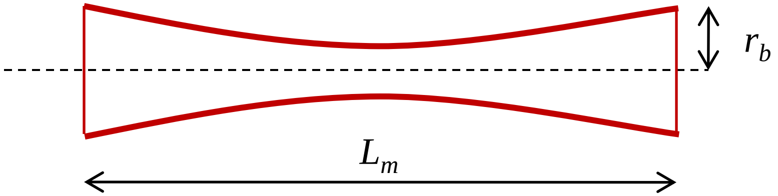
- Useful numbers
  - Ion velocity, $v_0$ - 2.2 mm/ns
  - Emittance, $\varepsilon$ - 0.07 π mm (un-normalized, 4*rms)
  - Perveance, $P$ - $P = I / U^{3/2} = 1.3 \cdot 10^{-9} A/V^{3/2}$

- Constants
  - Speed of light, $c$ - 300 mm/ns
  - Characteristic perveance for protons, $P_0$ - $P_0 \equiv \sqrt{\frac{2e}{M_p}} = 1.54 \cdot 10^{-6} A/V^{3/2}$

# Space charge

- A cold beam with a space charge can be transported within the radius $r_b$ at the maximum length $L_m$

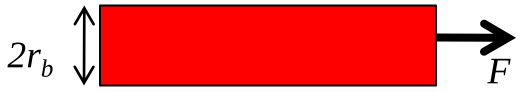
$$\frac{L_m}{r_b} = \sqrt{2.33\frac{P_0}{P}} = \sqrt{\frac{3.55}{\mu P}}$$




- For project X parameters, the ratio = 53 >> 1
  - Beam transport with lamped focusing doesn't require neutralization
    - Probably better to clean positive ions upstream of the chopper
  - A long LEBT is possible with focusing by solenoidal lenses
    - Preferable to have
      - (distance between lenses) ≥ 10* (lens inner diameter) and
      - (lens inner diameter) ≥ 3* (beam diameter) => $L_m / r_b \geq 60$
    - Further decrease of the energy or an increase of the beam current would make the optimum design different
  - This consideration might be one of the reasons for short designs of high-current LEBTs

# Limitations for chopping:  bunch elongation

- Space charge
  - For a sharp edge (semi-infinite cylinder), elongation over the length $L_t$ can be estimated as




$$F \approx \frac{2eI}{r_b \cdot v_0}; \quad \frac{\Delta v}{v_0} \approx \frac{eI}{M_p v_0^{\,3}} \frac{2L_t}{r_b}; \quad \frac{\Delta l_{sc}}{L_t} \approx \frac{L_t}{2r_b} \frac{P}{P_0};$$

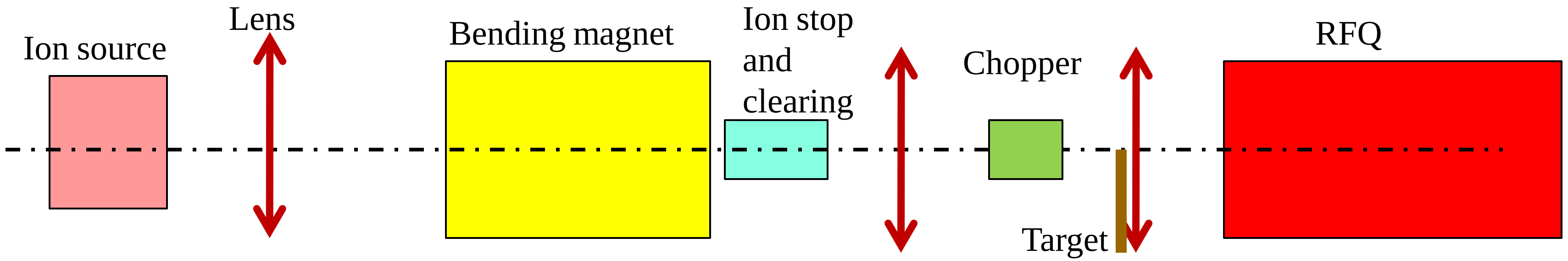
  - For $r_b$ =10 mm, $L_t$ = 500 mm, $\Delta l_{sc} \approx$ 10 mm or ≈ 5 ns
    - Smooth edge decreases the elongation
- Longitudinal velocity spread
  - I did not find a number for the energy spread. Let’s assume that it is roughly the same as a typical plasma potential,  T~5 eV

$$\frac{\Delta l_T}{L_t} \approx \frac{T}{2eU_0};$$

  - $\Delta l_T \approx$ 0.05 mm (negligible)
- Chopping significantly faster than at SNS LEBT is not forbidden

# A scheme to make estimations

- A long LEBT
  - 2 or 3 lenses to provide
    - Combination of two ion sources
    - Tuning of the beam parameters at the entrance of RFQ
    - Space for chopping
  - Chopper is in an optimum position
    - Optimizing the amplitude of the required kick and the minimum possible length (duration) of perturbation in the beam
    - No focusing between the kicker and the target (scraper)
  - Positive (residual gas) ions  are stopped upstream the chopper , and the ions downstream are cleared with a transverse E(M) field(s)
    - To avoid a possible transition times after long gaps in the beam
  - A good vacuum at the entrance of RFQ



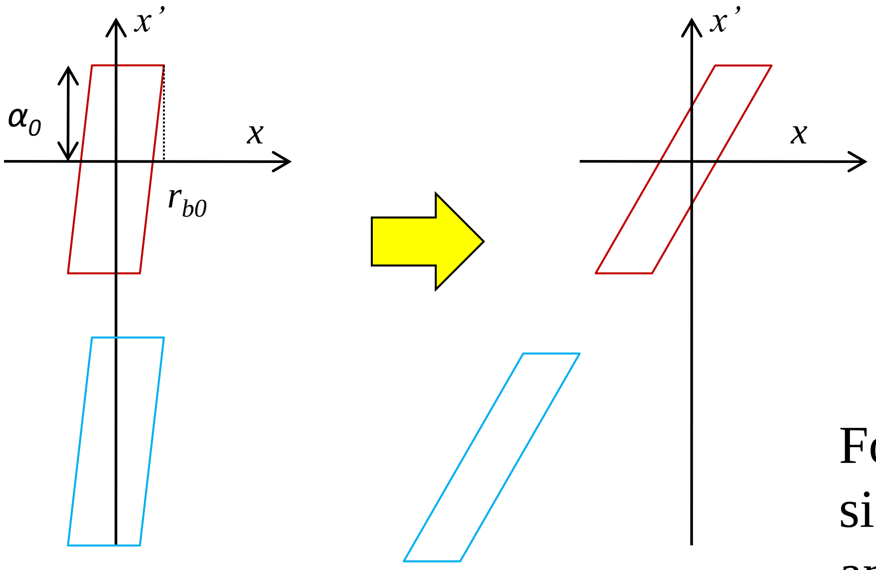
# Kicker positioning

- The simplest estimations are for a parallelogram – type phase portrait
- Te kick $\Delta\alpha$ should be large enough to separate the phase portraits at the target after the length $L_t$.

$$\Delta\alpha \geq 2\alpha_0 + \frac{2r_{b0}}{L_t} \geq 2\left(\alpha_0 + \frac{\varepsilon}{\alpha_0 L_t}\right)$$

- The optimum kick is at the **beam crossover** ($\varepsilon = r_b \cdot \alpha_0$) and and at the angle scatter of

$$\alpha_0 = \sqrt{\frac{\varepsilon}{L_t}}$$




The **optimum kick** is

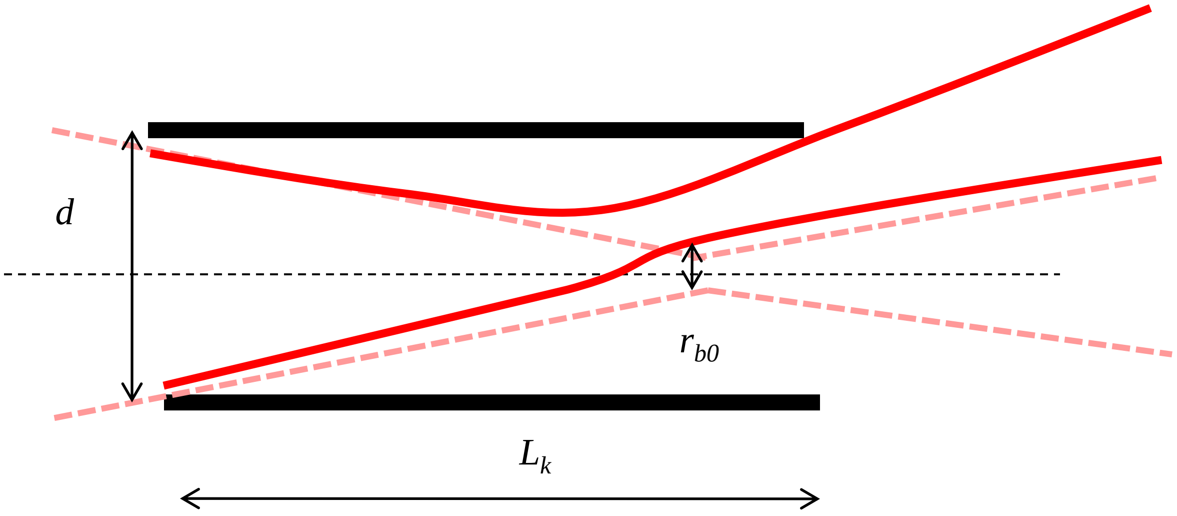
$$\Delta\alpha = 4\sqrt{\frac{\varepsilon}{L_t}}$$

For $L_t$= 250 mm, optimum beam size in crossover is $r_{b0}$~ 4 mm and the kick angle $\Delta\alpha$ ~ 70 mrad

# Length –gap relation

- The kicker gap $d$ depends on its length $L_k$. The crossover is determined by the emittance, so that the envelope is close to straight lines. For the optimum case,

$$d = 2r_{b0} \cdot \left(1 + \frac{3L_k}{2L_t}\right) = 2\sqrt{L_t \varepsilon} \cdot \left(1 + \frac{3L_k}{2L_t}\right)$$



# Length of perturbation in the beam

- If the length where the kicker produces a large enough perturbation is $L_k$ and the pulse duration is $T_p$, the beam is perturbed at the length of $$v_0 \cdot T_p + L_k$$
    - If one would like to use the full strength of the kicker, the pulse length needs to be longer than the flight time

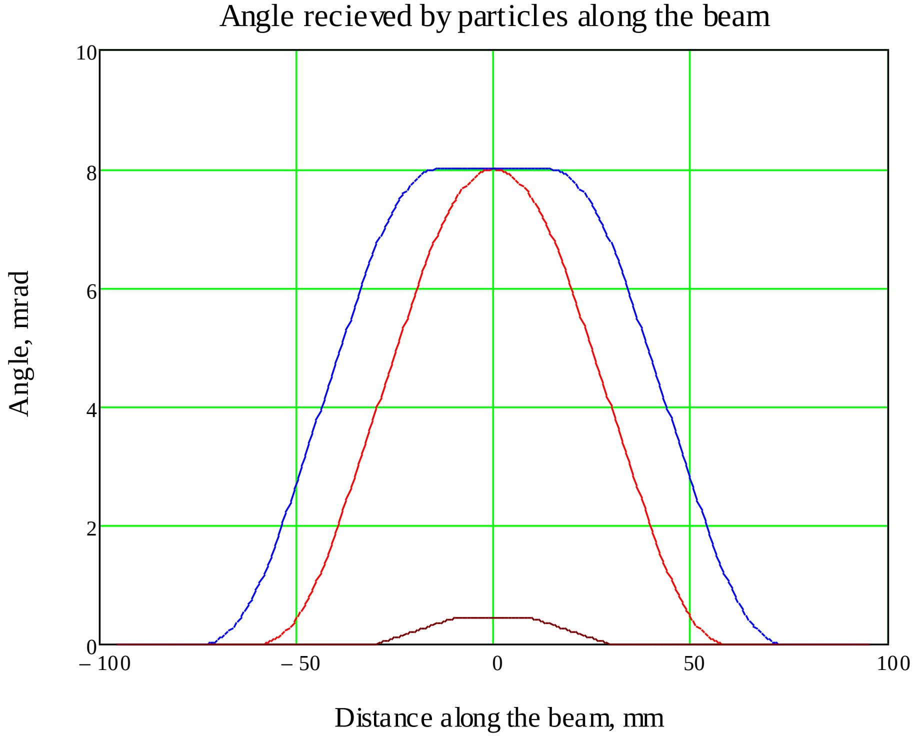
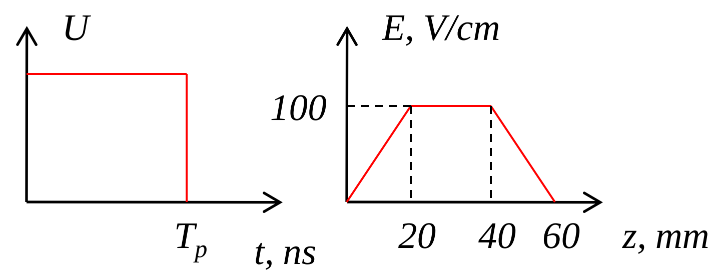
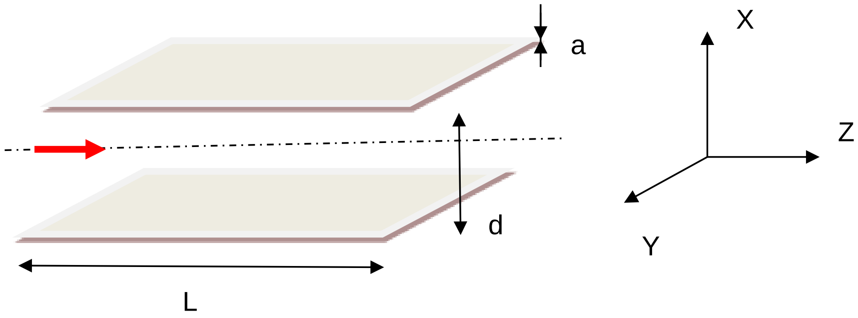



Illustration of kicking the beam with a kicker. The electric field is a trapezoidal in space and rectangular in time.
a – very short pulse ($T_p$ = 1ns);
b- the pulse duration is equal to the flight time ($T_p$ = 27 ns);
c- long pulse ($T_p$ = 40 ns).



# Kick and capacitance

- The simplest model:
  - two parallel plates infinite in one direction (Y)
  - Small angles
  - Constant energy




- The angle is proportional to the capacitance between plates

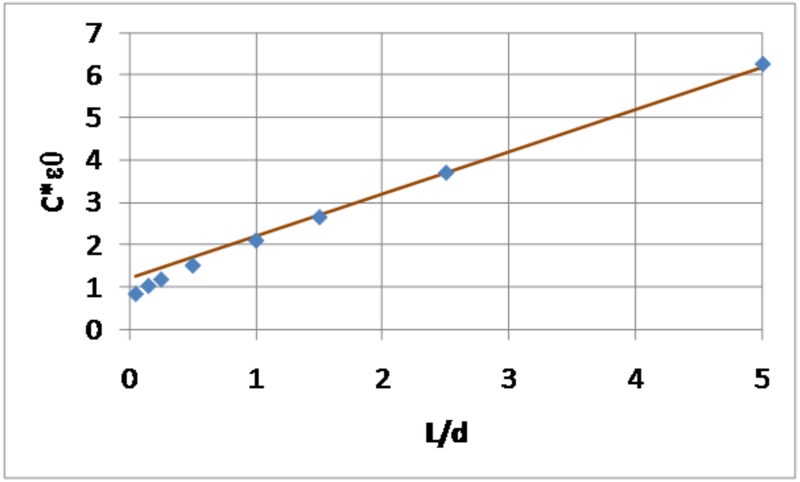
$$p_x = \frac{e}{v_z}\int_{-\infty}^{\infty} E_x(z)dz = \frac{e}{v_z}\varepsilon_0\rho = \frac{e}{v_z}\varepsilon_0 \cdot C \cdot U$$

- In this approximation, all particles are kicked identically by the angle

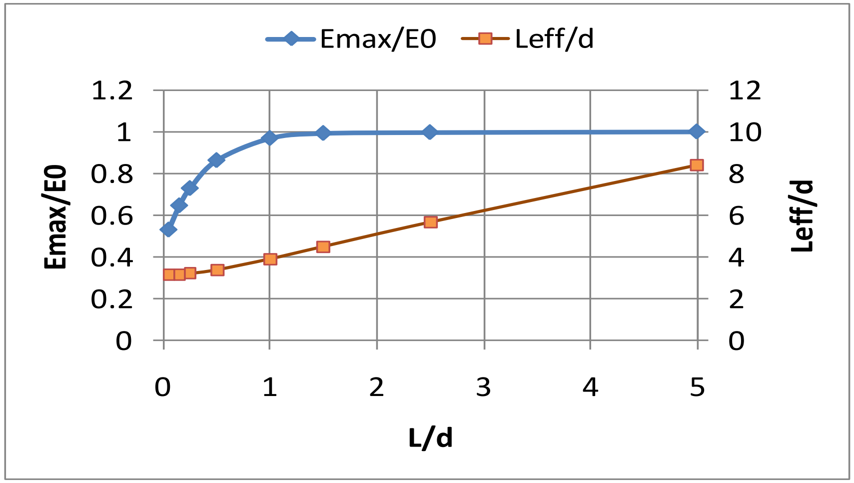
$$\Delta\alpha = \frac{eU}{2W}\varepsilon_0 \cdot C$$

- The conclusion doesn't depend on the shape of the electrodes

# Parallel – plate capacitor




Simulated capacitance (L.Prost) and the approximation by) $C = \varepsilon_0 \left( \frac{L}{d} + 1.2 \right)$




Maximum electric field and the length of area with the electric field above 10% of its maximum.

- The perturbed length doesn't change significantly below *L/d*~1, while the kick is decreasing => *L/d*~1 is about the optimum
- Other geometries may be possible
  - Two tubes (wires) with *d/a*= 5 have the same capacitance as a flat capacitor with *L/d*=1
    - Doesn't take into account shielding by ground

$$C_w = \frac{\pi \varepsilon_0}{\ln\left( \frac{d}{2a} + \sqrt{\left(\frac{d}{2a}\right)^2 - 1} \right)}$$

# Summary of reasoning

- Space charge shrinks the gap in the beam by ~ 10 ns
- The optimum kick needs to be applied to the beam at the crossover

$$\Delta\alpha = 4\sqrt{\frac{\varepsilon}{L_t}}$$

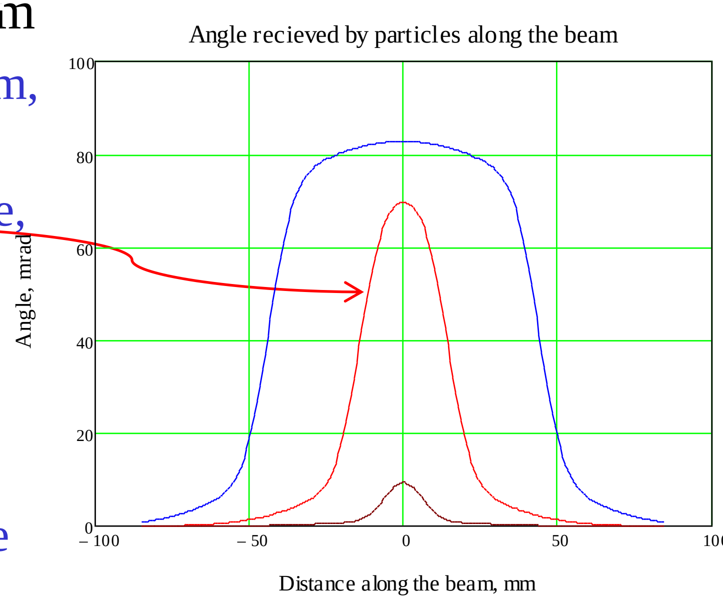
- Voltage between the kicker electrodes

$$U = 2\cdot\frac{W}{e}\cdot\frac{1}{\varepsilon_0\cdot C}\Delta\alpha = 8\cdot\frac{W}{e\sqrt{\beta}}\cdot\frac{1}{\varepsilon_0\cdot C}\sqrt{\frac{\varepsilon_n}{L_t}}$$

- Gap between plates

$$d = 2\sqrt{L_t\varepsilon}\cdot\ 1+3L_k/2L_t$$

- Numerical estimations for one pair of plates and the kicker-to-target distance $L_t$ = 250 mm
  - $d = L_k$, $\varepsilon_0\cdot C = 2$, $\Delta\alpha$ ~ 70 mrad, $d = L_k$ ~ 9 mm, $U$=2kV
  - If the pulse length is ~equal to the flight time, duration of the perturbed (~ 7 mrad) beam ~ ~2*4*$L_k/v_0$~ 25 ns
- For a travelling-wave design, 5 plates *($L_k$ =10mm +5mm gaps), the voltage $U$~ 400 V
  - Length of the perturbation could be the same



# Conclusion

- In the single plate case, the minimum duration that an LEBT kicker may put into the beam is 30 – 40 ns at 2 kV at the kicker plates
  - 10% of the maximum kick; the beam is moved by a diameter in the middle of the pulse
  - At higher kicker voltages, the gap edges will be sharper
    - Also, one can have grounded shields around the kicker plates to decrease the effective field length (with a simultaneous decrease of the kicker efficiency)

- The LEBT kicker can't help any significantly with reduction of power on the MEBT target if the frequency of "good" bunches is above ~20 MHz