Interaction between protons and electrons in the Recycler

MI departmental meeting

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Outline

- Motivation
- Electron beam configurations
- Idea: e-beam in a helix configuration as a scraper
- Experimental observations
- Estimations
- Summary

Motivation

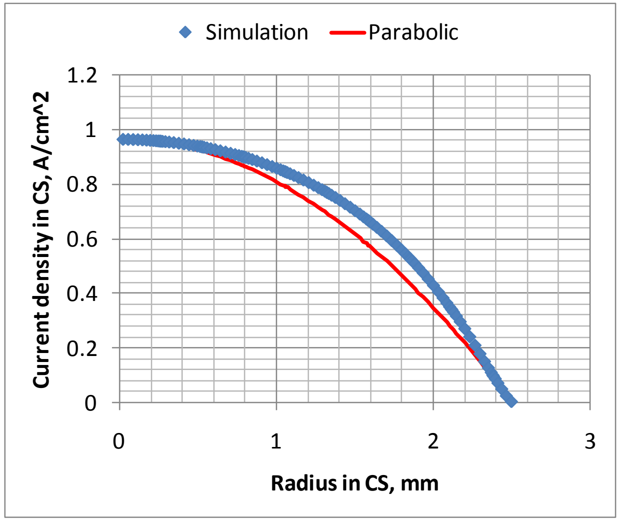
- V. Danilov’s proposal: using an electron beam in a proton machine as an non-linear focusing element
  - Can RR + Ecool be considered as a model?
    - Can the life time in the present configuration be reasonable?
- Curiosity: why the proton life time is so short when e-beam is on?
  - Can it be used for scaling the effect to pbars?
- Can the electron beam be used as a scraper?
  - V. Shiltsev proposal: use a hollow, axially symmetrical electron beam to clean a proton halo in LHC
    - Electromagnetic field inside is zero, and the core particles should not be disturbed
    - Outside, it is nonlinear and can be strong enough to kick out the halo particles
      - The beam can be modulated near tune frequency
  - In RR E-cooler, we can’t make a hollow beam. Can an electron beam travelling along a **helix** has a similar effect?
    - What are the limitations for such scheme?

E-beam configurations

- “On axis”
  - Protons and electron travel along the same axis (within 0.1 mm)
- “Parallel shift”
  - The electron beam moves in the cooling section parallel to protons with an offset up to 9 mm
    - Main mode in regular operation with pbars
- Can we increase the area of a relatively constant electron current density?
  - Proton beam size is much large than electron’s
    - Non-linear fields can be harmful
  - Adjusting of magnetic fields and focusing may be able to do so, but with no easily available tools for e-beam profiling has been proved to be difficult
    - May require adjusting of all 200 CS correctors as well
  - That is for s straightforward case of parallel electron trajectories. Do other option exist?

Effective electron density of e-beam

- If the electron trajectories deviate significantly from straight lines, a proton feels the integral of the electron density distribution over its trajectory inside the interaction section.
- The simplest model:
  - Beta-function in the interaction section is much larger than the section length
    - Integral can be taken over straight lines parallel to the axis
  - Electron trajectories are perfect helixes with a whole number of turns
  - Current distribution inside the electron beam is parabolic

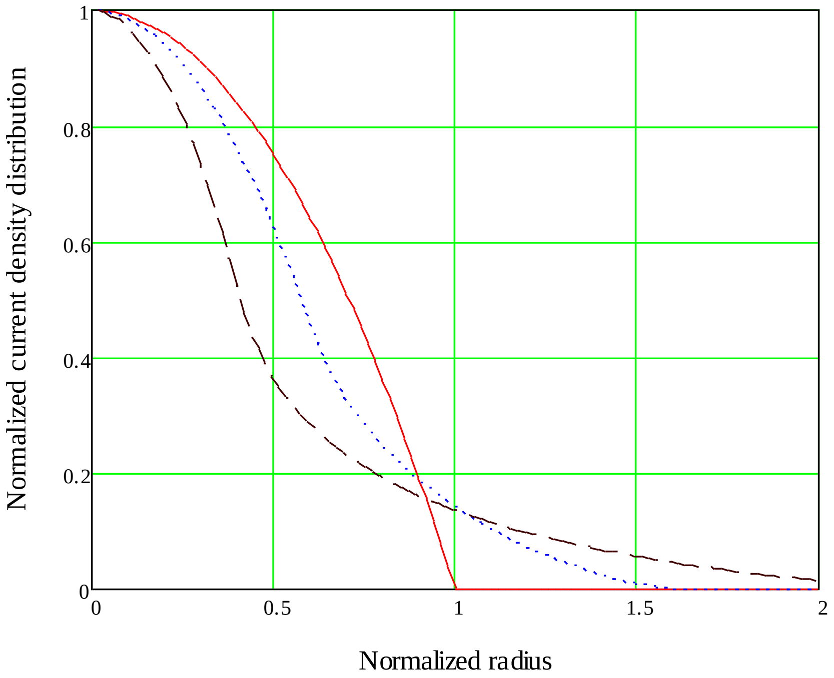


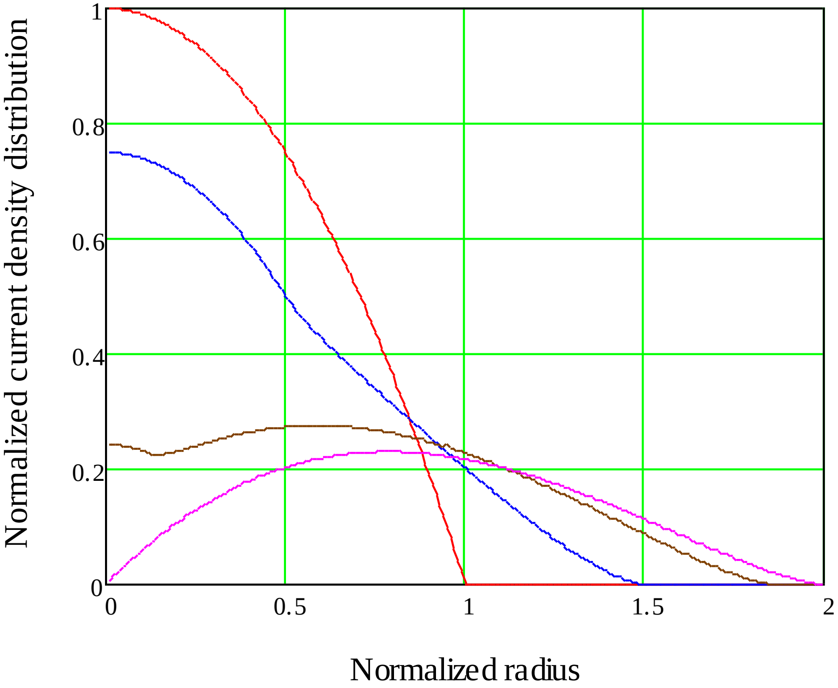
Current density in 0.1A electron beam.

Blue- current density simulated in the gun and re-calculated to the cooling section according to the ratio of magnetic flaxes.

Red – a parabola with the same height and zero point.

Effective density for focusing and dipole kicks





Radial focusing kick.

Red – original distribution (no kick, ρ =0),

Blue- ρ =0.5, Brown - ρ =1.

ρ is the radius of Larmor rotation of the boundary electron normalized by the beam radius.

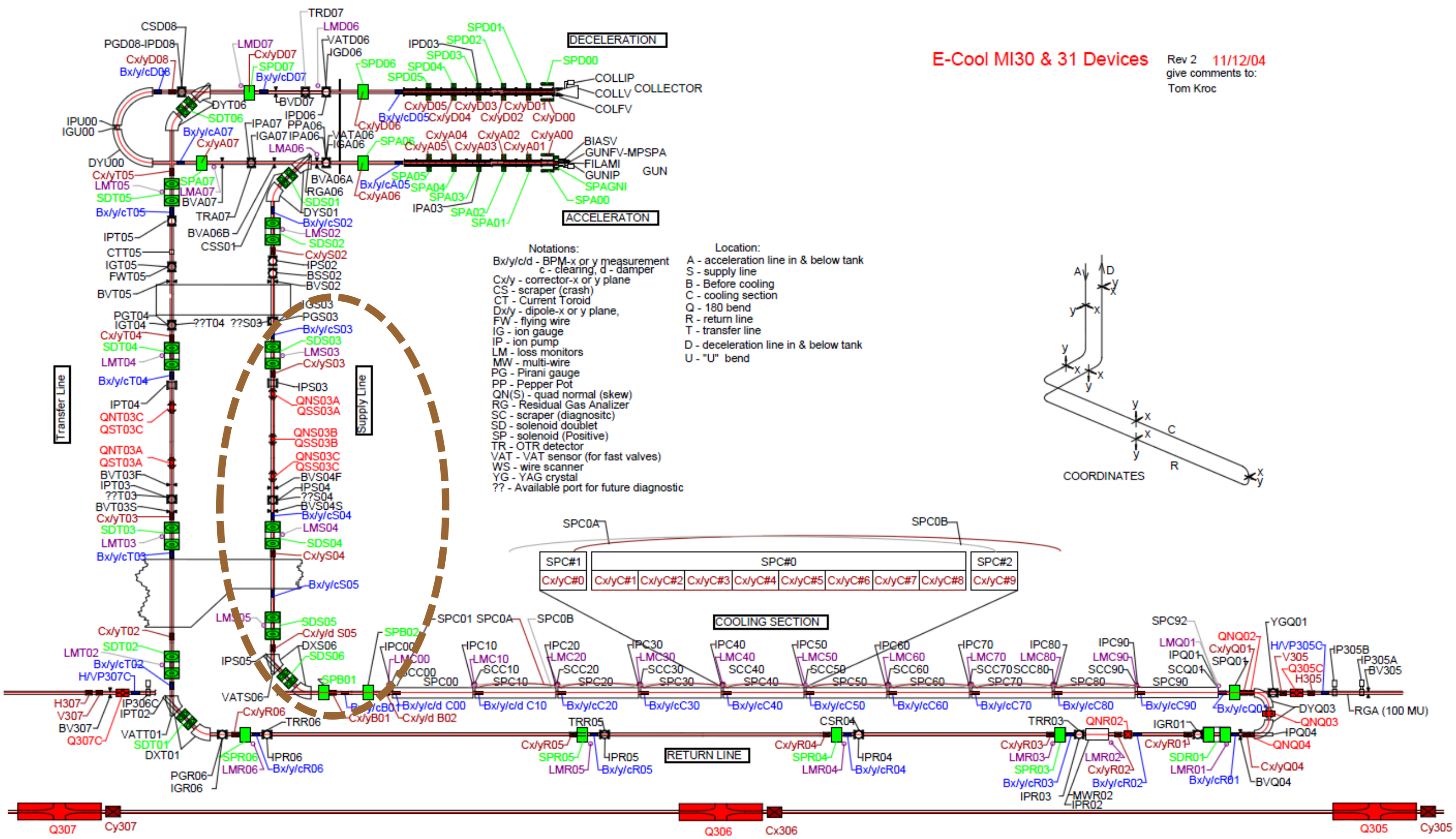
Dipole kick. The trajectory of the beam is a helix centered around axis.

Red – original distribution (no kick, ρ =0),

Blue- ρ =0.5, Brown - ρ =0.85, Magenta - ρ =1.

- Focusing kick decreases the area with relatively constant effective density
- Helical trajectory creates a nearly flat central distribution at ρ =0.85.

Creating helix

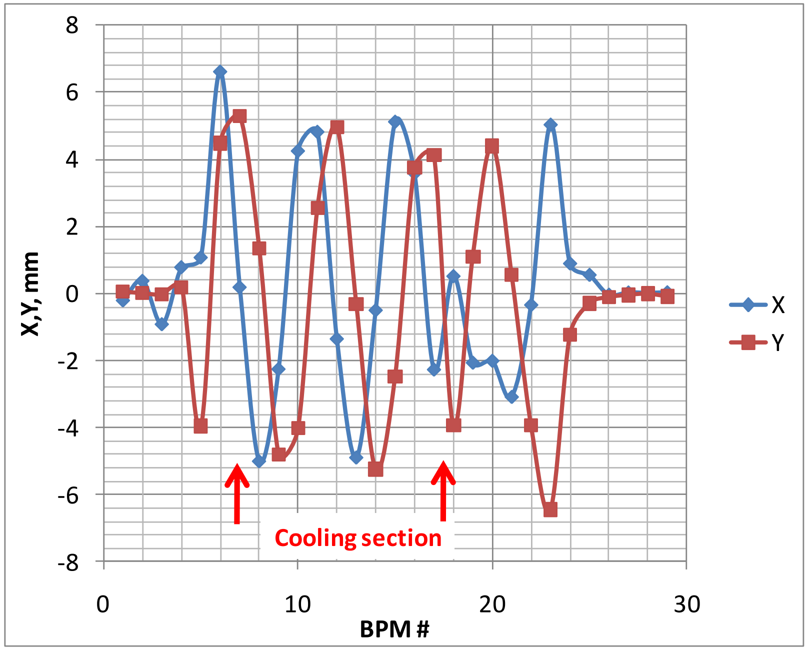


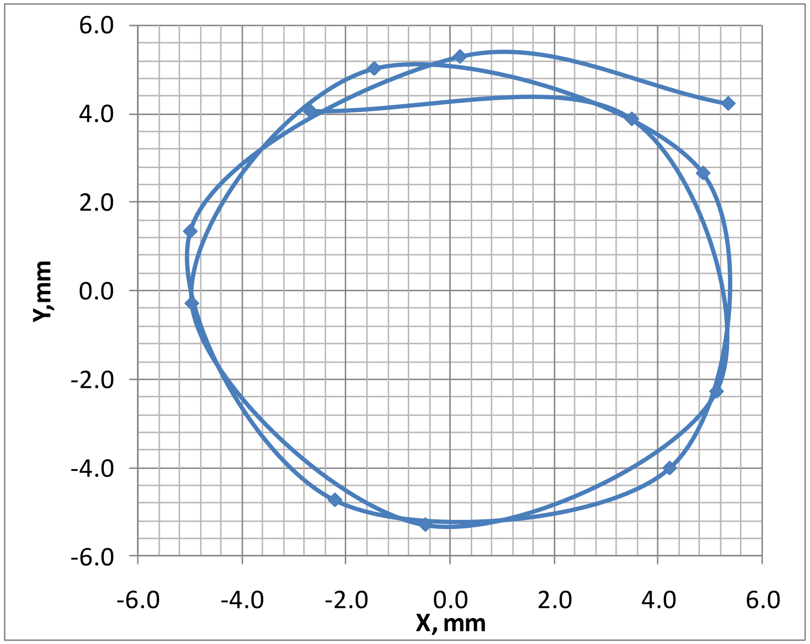
- Helical trajectory is created by kicking the beam with correctors upstraem of the cooling section

E-beam in a helix as a scraper

- If one can make a good helix, the total kick on protons with small betatron amplitudes (less than the helix radius) can be much smaller than for the tail particles
  - Scraping with no mechanical parts!
- Perfect helix:
  - an integer number of turns
  - the wavelength much shorter than the proton beta-function
  - Recycler cooling section is quite far from that, but can we observe an effect?

Helical trajectory (example of 5mm radius)





- In the interaction section, the e-beam makes two full turns + ~90°
  - Parts of the trajectory outside of boundary BPMs are not included
    - ~ 1m each
    - At the exit of the cooling section, the e-beam is likely crossing the axis
    - The length of the cooling section (immersed into 105G longitudinal magnetic field) is 20 m; the entire length where electrons and protons interact is ~23.5 m
    - Average beta-functions in the CS are ~30 m

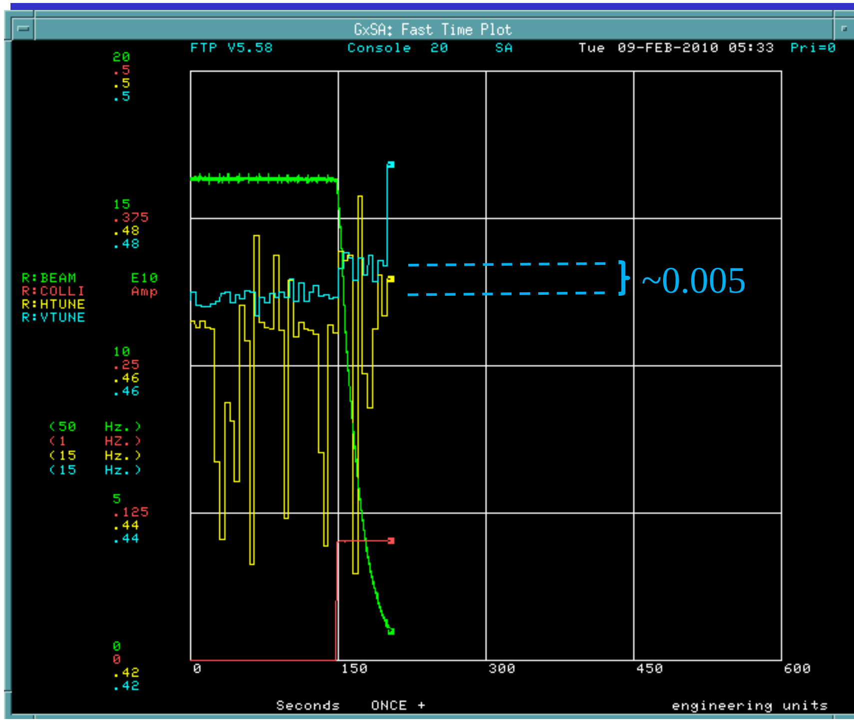
Study

- Two attempts to make measurements in the protons + e-beam configuration of RR
  - January 28-29, 2010 – 7 hrs
  - February 9, 2010 - 1hr
- Typical measurement:
  - Inject (5 – 15)E10 and keep them in four 2.5MHz buckets
    - Schottky emittance of the injected bunch ~13/18 π 95%n (H/V)
    - Rms momentum spread ~3 MeV/c ($dp/p = 3.5 \cdot 10^{-4}$)
  - Turn on e-beam in a specific configuration and measure the life time
    - Optional scraping

Tools

- No specially calibrated diagnostics was prepared
  - In part, Flying Wires were not tuned for protons
- Available tools:
  - Total number of particles from DCCT (R:BEAM)
    - Allows to measure the life time
    - Almost all information reported here is just the life time at various conditions
  - Schottky emittances (not calibrated recently)
    - 3 min interval between measurements was too long to use
  - “Fast” emittances
    - Power of the Schottky noise from the same 1.7 GHz Schottky detectors is integrated by an analog circuit and divided by the number of particles (DCCT R:BEAM)
      - Poor behavior at low intensities
  - Scrapers
    - Scrapes were impaired by jerky motion of scrapers and by beam motion due to MI ramps
    - Sometime, Loss monitors could be used

E-beam on axis



Degradation of proton time after turning e-beam. February 9, 2010.

Green – number of pbars, 5E10/box

Blue – vertical tune, 0.02/box

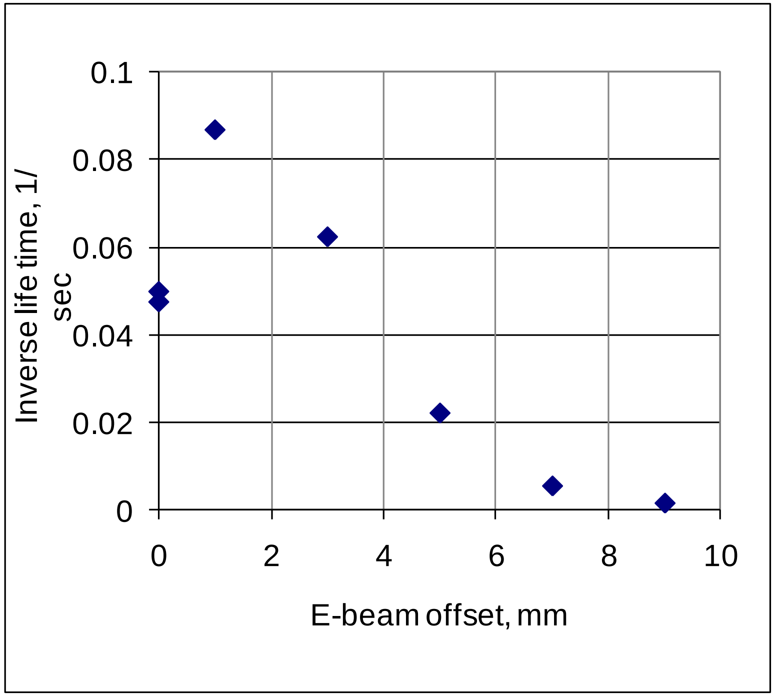
Yellow – horizontal tune/, 0.02box

Red – electron beam current, 0.125 A/box

- Turning on the e-beam decreases the life time from 20 hrs to ~20 sec
  - standard configuration:
    - on axis, 0.1A, 140 V modulation (23 mA ptp) at 32 kHz
      - Betatron frequency is ~42 kHz
- The vertical tune shifts up by ~0.005 (from 24.468)
  - Horizontal tune signal is too noisy
    - 5 sec averaging

Observations: Np; parallel shift

- The life time does not depend on the number of protons
  - The decay fits well with an exponent
    - With preliminary scraping, after first ~10% of the intensity drop
  - Reproducible at various intensities within 10%
- The life time improves if the electron beam is shifted parallel to axis
  - From 20 sec on axis to 600 sec at 9 mm offset

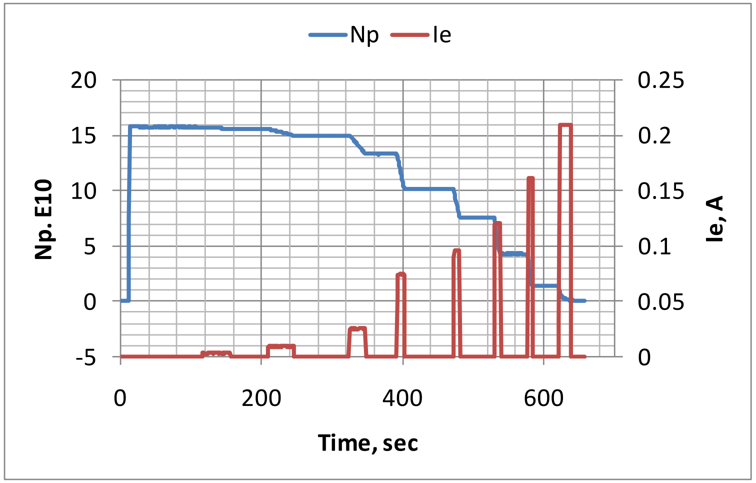


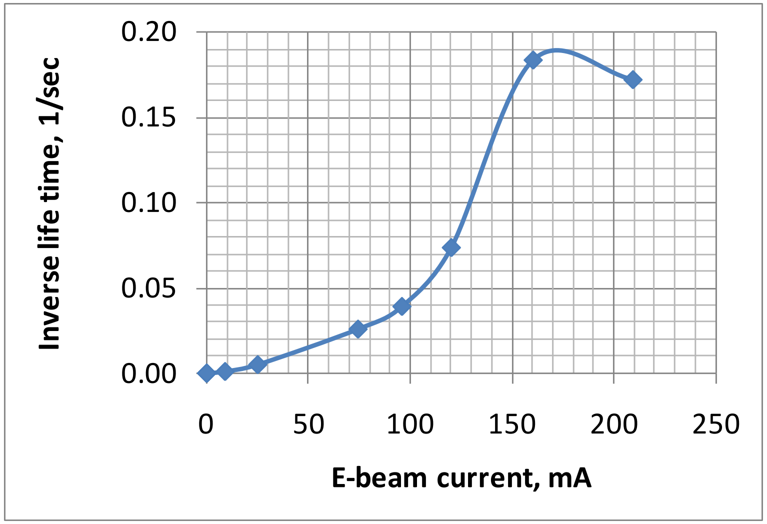
Inverse life time as a function of the parallel shift of e-beam.

January 28-29, 2010. Np ~ 5E10 after scraping ~15% with the vertical scraper. Standard mode of e-beam : 0.1A, modulation 32 kHz, 140V.

Observations: f(Ie)

Measurement of the proton life time at various e-beam currents. February 9, 2010. E-beam is on axis, modulation off.

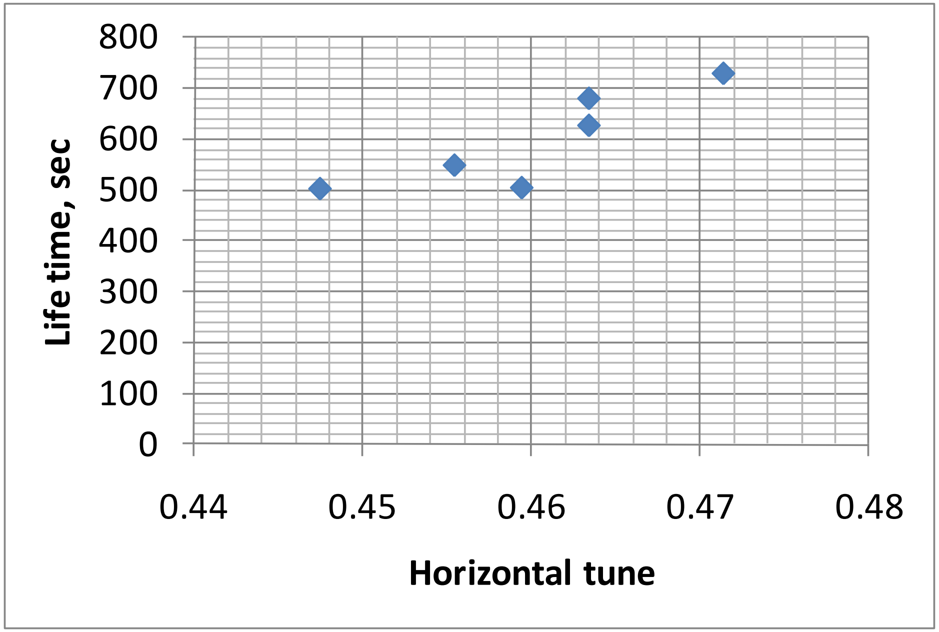




- The life time decreases starting with low e-beam currents
  - Ie = 9mA decreases the life time by ~10 times
  - The curve may be affected by the changing current density distribution in the e-beam
    - Which becomes flatter at Ie > 150mA
- Statistical error of the fits (with e-beam) is probably <10%
  - Based on fits to different parts of the same data set
- The life time stays constant within the scatter between the jumps of e-beam current (3 -8 hrs)

Inverse life time as a function of the e-beam current. The same data set.

Observations: effect of working point



Life time as a function of the Horizontal tune.

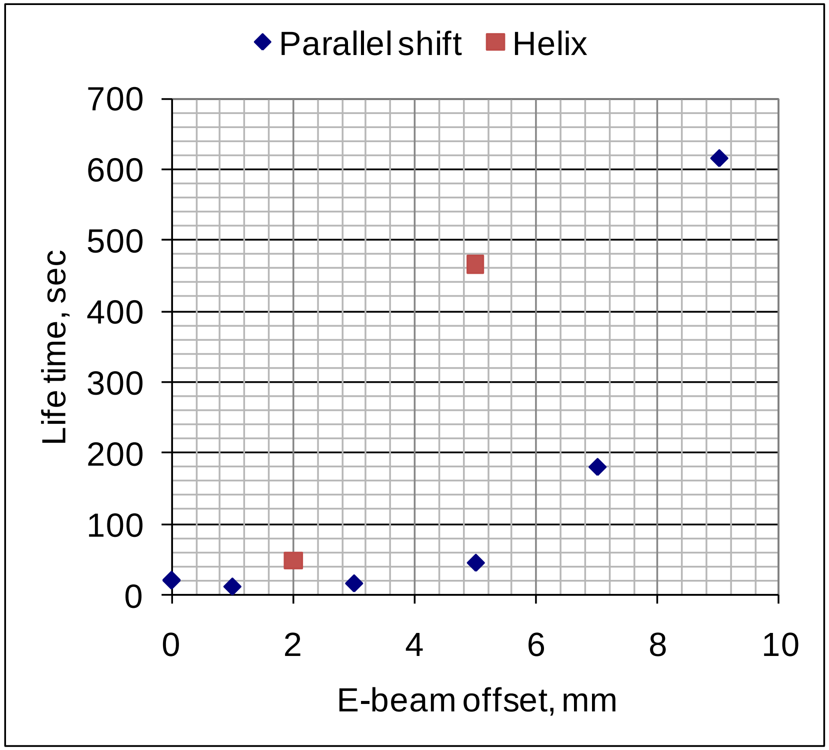
January 28-29, 2010. Np ~ (1.5 - 6)E10. E-beam is shifted parallel to axis by 9mm. Standard mode of e-beam: 0.1A, modulation 32 kHz, 140V. The horizontal axis shows the set values of the tune.

- The horizontal tune scan was done with e-beam shifted parallel to 9 mm. No reliable effect on the life time was found in the range of $\delta \nu_x$=0.024.
  - May be not representative for the case with e-beam on axis

Observations: e-beam modulation

- Life time with 5 mm helix (0.1A e-beam)
  - Standard modulation (23 mA ptp, 32 kHz) – 470 sec
  - Modulation close to the betatron frequency- 60 sec
    - 42 kHz , 23 mA ptp
  - Modulation is off – 700 sec
- The spectrum of the current modulation has never been measured
  - A component at betatron frequency may exist

Helix vs parallel shift



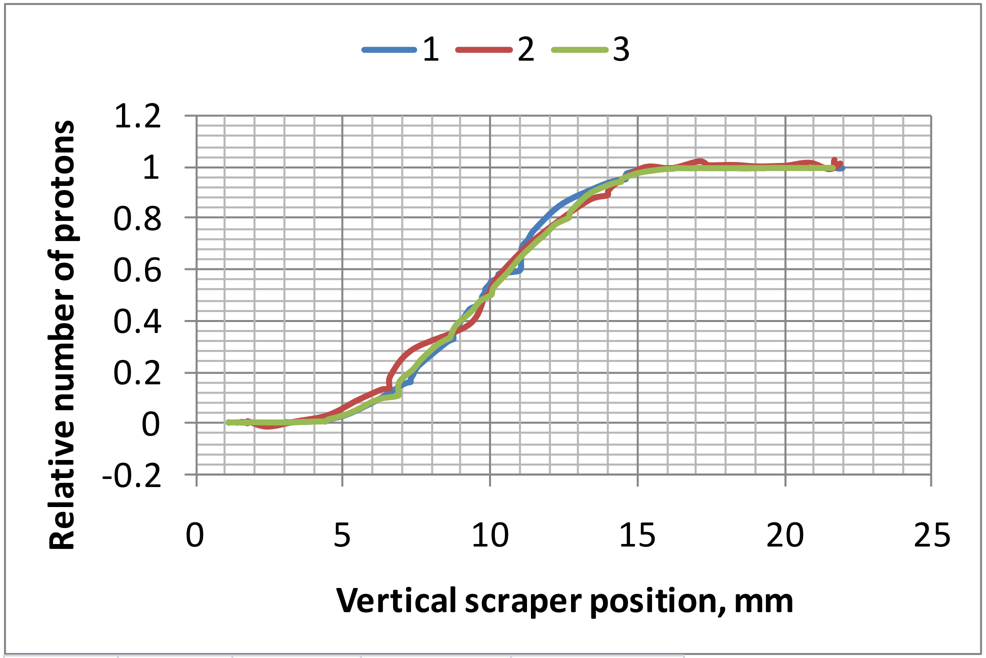
Life time as a function of the parallel shift of e-beam or helix.

January 28-29, 2010. Np ~ 5E10 after scraping ~15% with the vertical scraper. Standard mode of e-beam : 0.1A, modulation 32 kHz, 140V. For helix, the horizontal axis indicates the helix radius.

2 mm – radius helix corresponds to "flat effective current density distribution"

- Life time for interaction with a helix is significantly higher than for a e-beam shifted parallel by the amount equal to the helix radius
  - For 5 mm, the ratio is 10 times
  - The life time might be determined by an effect of parts of the interaction section outside of helix's 4π

Scraping after working with helix



Set #	E-beam config.	Np befor scraping E10	Time with e-beam sec	Time from e-beam to scraping sec
1	off	17	N/A	N/A
2	helix	2.4	10	84
3	helix	13.8	56	40

Relative number of protons as a function of the vertical scraper position. February 9, 2010.

Curve 1- scrape of freshly injected beam,

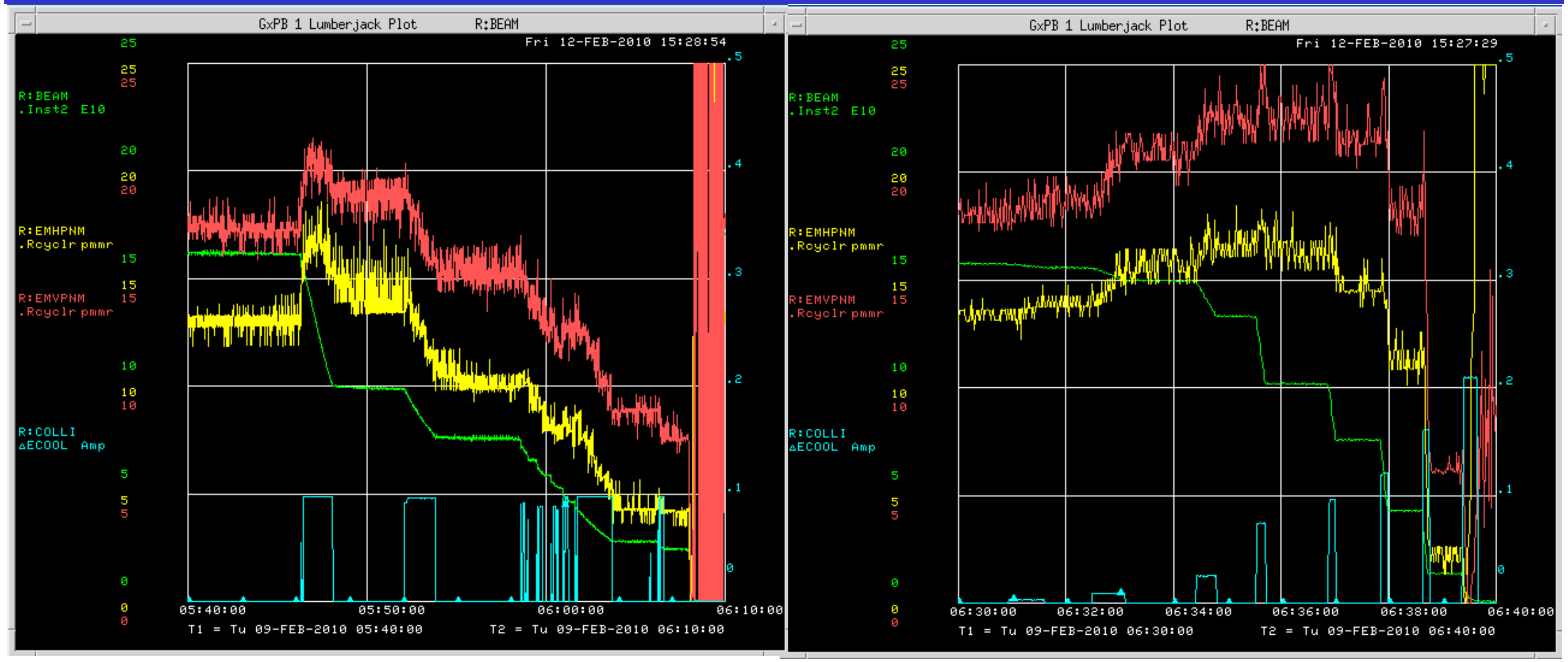
2 – after some work with e-beam with the last stage of the beam in a 5 mm helix,

3- freshly injected protons are exposed to a 5-mm helix and then scraped. Mode of e-beam : 0.1A, modulation 32 kHz, 140V.

Vertical beta-function in the scraper location is 55 m.

- Vertical scrapes do not show any “scraping” effect from staying with the helix
  - Scrapes were made many seconds after turning the e-beam off
    - The relaxation time seems to be much faster

Possible indication of “scraping”



Comparison of “fast” emittances dynamics while interacting with electron beam in the 5-mm helix configuration (left) and on axis (right).

February 9, 2010. Green – number of pbars, 5E10/box; Blue – electron beam current, 0.1A/box

Yellow – “fast” horizontal emittance 5 pi/box; Red – “fast” horizontal emittance 5 pi/box. Emittances are 95% normalized. Total time for the plot sis 30 min (left) and 10 min (right).

- E-beam in a helix configuration seems to be kicking out the high-amplitude particles faster than the core ones

Estimation: single kick

- Angle that a proton flying at the edge of an electron beam receives after passing the interaction section is

$$\delta\alpha = \frac{eE}{p_p}(1+\beta_e\beta_p)\frac{L_{cs}}{\beta c} = \frac{I_e}{I_0}\cdot\frac{m_e}{M_p}\cdot\frac{L_{CS}}{a_e}\cdot\frac{2\cdot(1+\beta_e\beta_p)}{\gamma_p\beta_p{}^2\beta_e}$$

  - For parameters
    - E-beam current I_e = 0.1A
    - $I_0 = m_e c^3/e$ = 17 kA
    - M_p/m_e = 1836 – proton-to-electron mass ratio
    - Length of interaction section L_{cs} = 23 m
    - E-beam radius a_e = 2.5 mm
    - Electron and proton relativistic factors $\beta_e = \beta_p \approx 1,\ \gamma_p = 9.5$
  - The angle is 12 μrad
- Admittance recalculated to the proton angle in the cooling section is ~150 μrad

Estimation: tune shift

- Estimation of the tune shift for a proton near the center of the electron beam

$$\delta\nu = \frac{\beta_f}{4\pi}\cdot\delta\alpha' = \frac{\beta_f}{4\pi}\cdot\frac{\delta\alpha}{a_e} = 0.022$$

  - β_f= 30 m – beta function in the cooling section
  - a_e = 1.8 mm is calculated by the peak current density, 0.96 A/cm^2

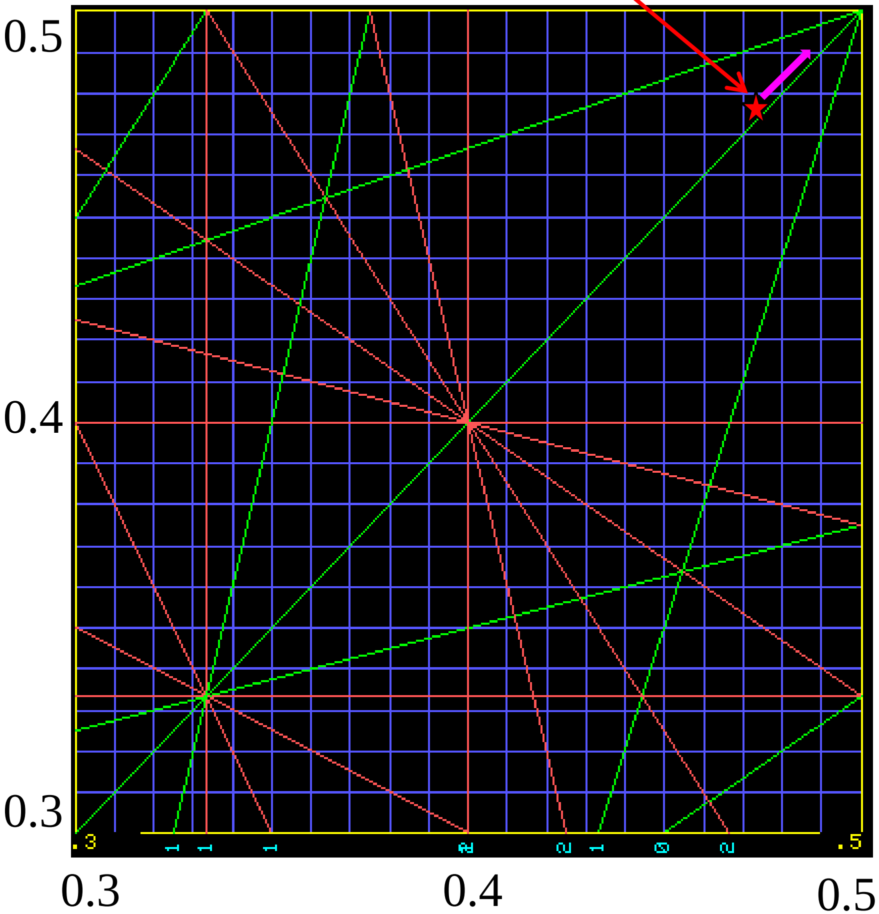
  - This shift means that for central protons the tune is (25.486, 24.490)
    - Quite close to half-integer
  - The measurement of the coherent tune shift gave ~0.005
    - No explanation for desrepancy

- Tune scatter due to chromaticity ξ = 6:
  - $\Delta\nu$=0.002 (rms)

Why the proton life time becomes so short?

- Incoherent tune shift moves central particles close to half-integer resonance
  - … but the scan of the horizontal tune did not show any strong dependence
    - … but it was done with a large e-beam offset
  - Note that for pbars the shift is in opposite direction (negative)
    - …and much smaller

Nominal working point and its calculated shift with e-beam on axis



Tune diagram with resonance lines up to 5th order.

Why the proton life time becomes so short? (cont.)

- Single pass kick is large
  - If there is a noise in the e-beam current, it can drive protons out
    - Turning the modulation off increases the life time significantly
      - Life time does depend on the modulation frequency
    - There are no measurements of the noise with modulation off
  - Dependence of the life time on the parallel beam shift and e-beam current doesn't contradict to this explanation
  - …but this effect should be scalable to pbars as the amplitude of the kick
    - The ratio is $2\gamma^2 = 180$
    - Proton life time of 20 sec should translate into ~1 hr for pbars
      - Had down to 30 hrs running without stochastic cooling
- Excitation of resonances by the non-linear fields outside the e-beam?
  - Life time for aligned beams is slightly higher than at 1 mm parallel offset
- Collective instabilities?
  - Life time doesn't seem to be dependent on the number of protons
    - More likely, a single-particle effect

Summary

- Life time of protons in presence of an electron beam is short
  - No cohesive explanation was found
  - Likely is a combination of effects
    - Kicking protons out related to e-beam current modulation or noise is one
  - In this configuration, e-beam doesn’t look promising to be used as a focusing element
- Life time improves considerably if the e-beam moves along a helical trajectory (in comparison with a parallel shift equal to the helix radius)
  - “Fast emittance” data indicate that this configuration kicks out high-amplitude protons faster than the core ones
    - “scraping”
      - Supports feasibility of axially symmetrical “hollow e-beam scraper”
  - Part of the life time degradation may be coming from the parts of the interaction sections where the beams are merged
    - Also, the total helix angle differed from $2 \cdot \pi \cdot$(integer)
      - If such configuration were for operation, one could look at 32 kHz component in a dipole motion of protons 90° from the interaction section and minimize it by adjusting the e-beam trajectory