Optics of electron beam in the Recycler: analysis of first results

A. Burov, G. Kazakevich, T. Kroc, V. Lebedev, S. Nagaitsev, L. Prost, S. Pruss, A. Shemyakin, M. Sutherland, M. Tiunov, A. Warner

Electron cooling beam line:

Acceleration section

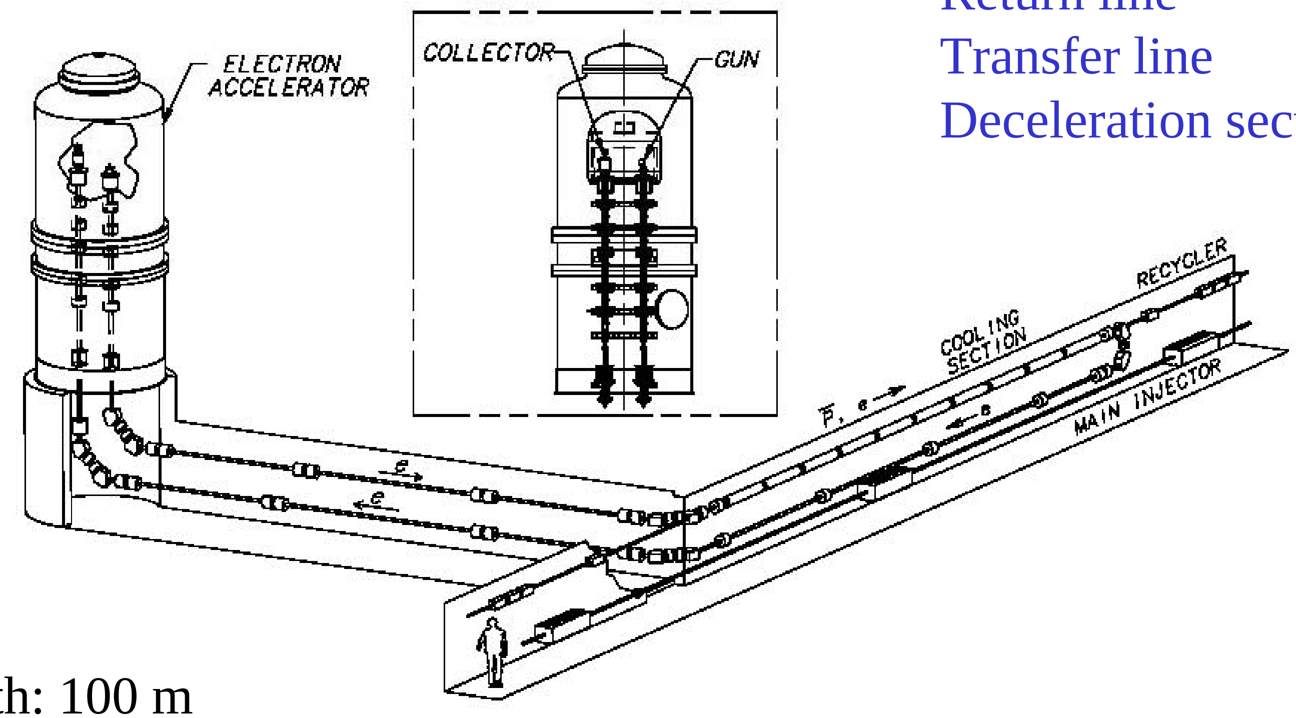
Supply line

Cooling Section

Return line

Transfer line

Deceleration section



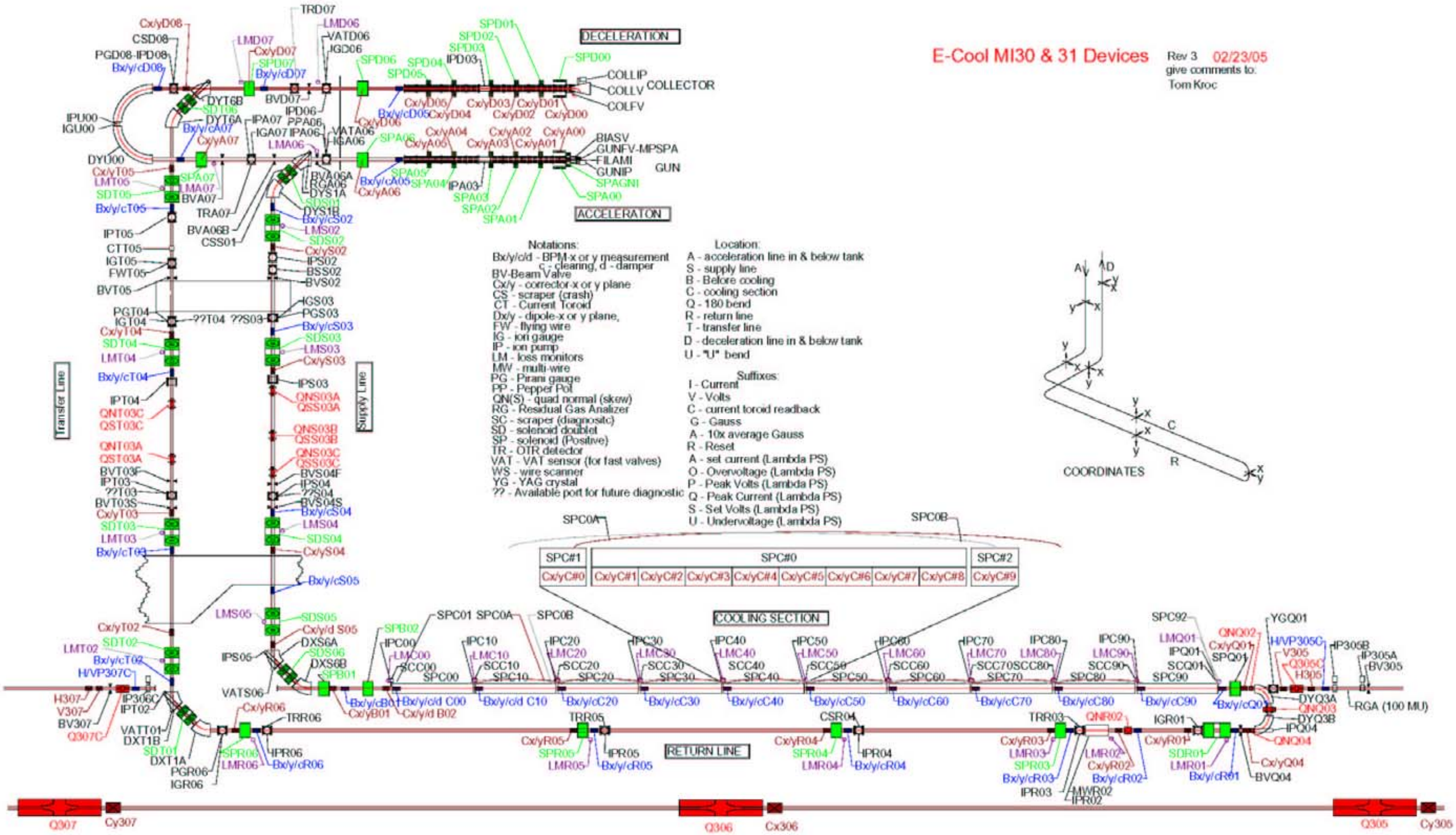
Total length: 100 m

Cooler length: 20 m

Kinetic energy: 4.35 MeV

Phase advance: ~30 rad

Electron beam line



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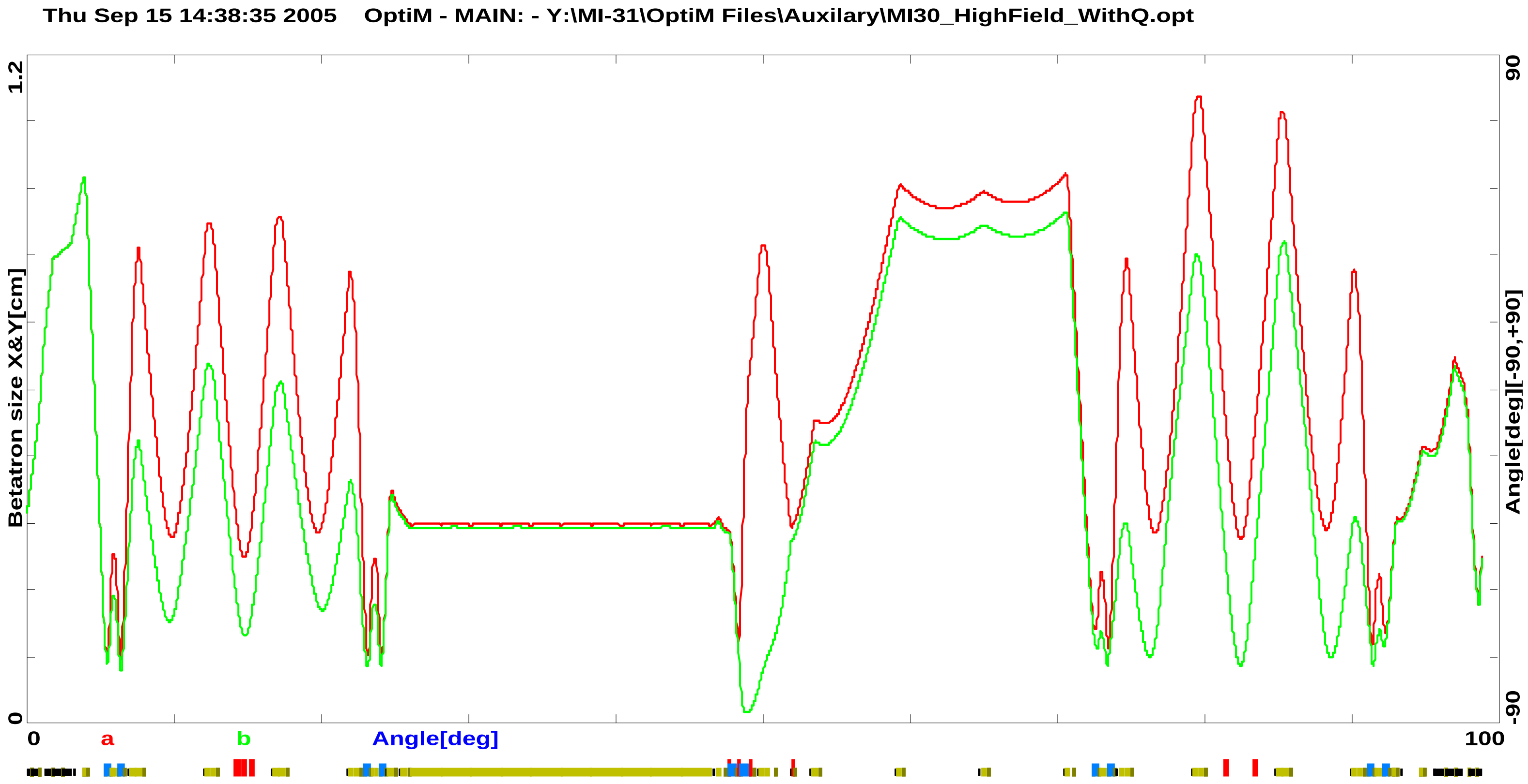
Design Envelope



Main Features of the Design Optics

- Magnetic Field in the cooler for focusing; ~ 100 G;
- Cylindrical envelope in the cooler requires magnetic flux at the cathode to be equal to the flux at the cooler,

$$B_{emit} a_{emit}^2 = B_{cool} a_{cool}^2$$

- Rotation-invariant matrix from the Pelletron to the cooler;
- Possibility for no-dispersion in the return line;
- Round beam in the return line;
- Rotation-invariant matrix from the Return line back to the Pelletron.

Angles

- Cooling efficiency strongly depends on the effective angle between the pbars and electrons, $\propto 1/\theta_{eff}^2$. To have maximal cooling, the electron rms angle should not exceed the proton angle, at least for the tail protons.

- Proton angles, rms: $\theta_p \cong \sqrt{\varepsilon_p/(6\gamma\beta_p)}$;for 95% norm. emittance $\varepsilon_p = 5\,\text{mm mrad}$ this gives $\theta_p = 60\ \mu\text{rad}$. For the tail pbars this number can be estimated as ~ 150 μrad.

- Electron angles are contributed by the following sources:
  - Electron thermal angles

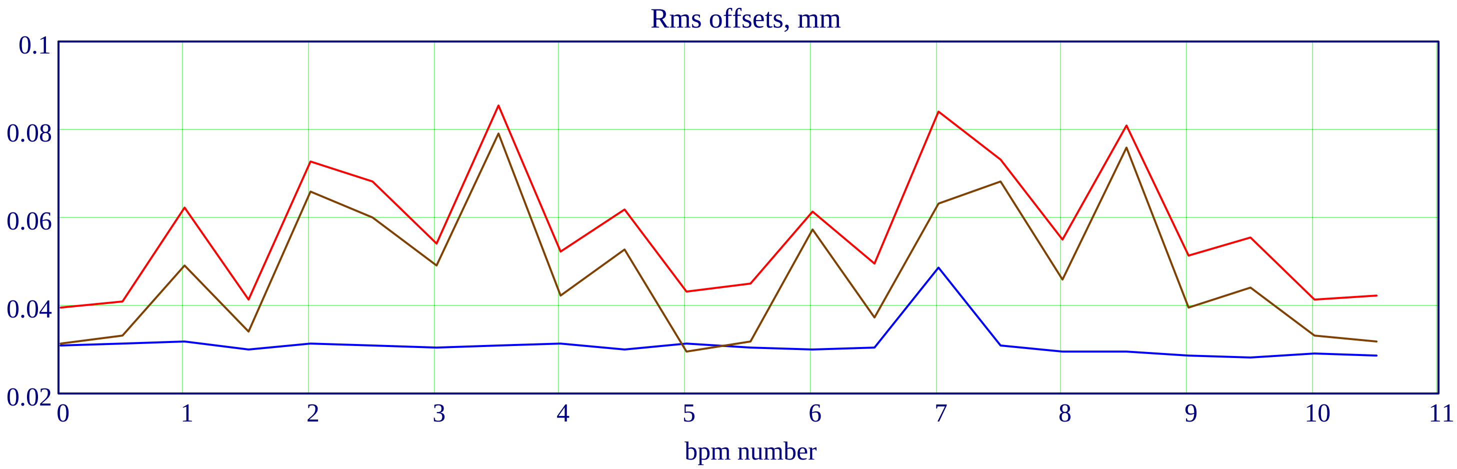
$$\theta_{eT} = \frac{a_{emit}}{a_{cool}\gamma}\sqrt{\frac{T_{emit}}{mc^2}} \approx 50\ \mu\text{rad}$$

Sources of electron angles

- Imperfections of the magnetic field in the cooler (static); last measurements give < 100 μrad (V. Tupikov's poster);
- Perturbations from the Main Injector ramps; recent data give ~ 40 μrad (more details are below);
- Optics nonlinearities, ~50-100 μrad at the core edge, could be as high as ~500 μrad for the halo due to the gun non-linearity
- Envelope mismatch; so far, this is a major source of the angles, far above all other. At the e-beam boundary, this is estimated as ~ 0.4 mrad.

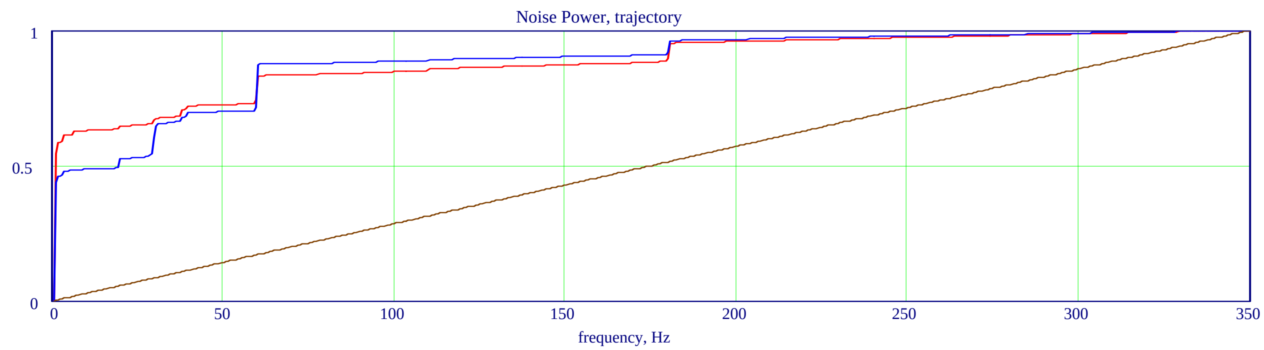
MI ramp contribution

- BPM data were taken with a sample frequency 700 Hz during 2 s of the MI ramp (P. Joireman).
- Electron helical trajectory was fitted to the AC signal every moment of time. The figure shows rms values along the cooler for the row signal (red), helical fit (brown) and the residual (blue).

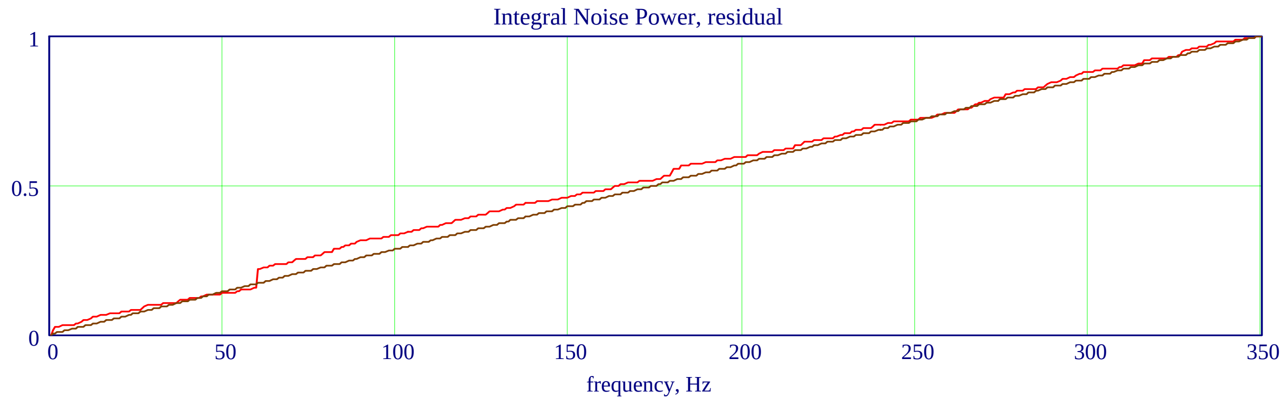


Larmor radius, rms = 54 μm,   angle, rms = 35 μrad.
The residual is relatively small, and of the constant power along the line.

Spectra of these BPM signals



Noise power distribution for the trajectory drift mode (red) and the Larmor mode (blue), compared with a pure white noise (brown). White noise contribution is clearly small.



The same for a typical residual signal: almost nothing but the white noise.

Envelope: Best Cooling Requirements

- A pbar with an rms offset a_p and an rms angle $\theta_p = a_p / \beta_p$ sees electrons which angle at this offset has to be smaller than its own:

$$\theta_e(a_p) < a_p / \beta_p$$

- Assuming the electron angles caused by the envelope mismatch grow linearly with the offset, this is the same as

$$\theta_e(a_e) < a_e / \beta_p \,, \quad \text{or} \quad \Delta a_e / a_e < \beta_e / \beta_p$$

  where Δa_e is an amplitude of the envelope oscillations, and $\beta_e = B\rho / B_{cool}$ is the Larmor beta-function.

- Note that the condition for the small envelope mismatch is independent of the pbar emittance.

- For $B_{cool} = 100\ \text{G} \;\Rightarrow\; \beta_e = 160\ \text{cm}$, and our $\beta_p = 25\,\text{m}$, this leads to $\Delta a_e / a_e < 0.06$, and with $a_e = 3.5\,\text{mm}$

$$\Delta a_e < 0.2\,\text{mm} \,, \quad \theta_e(a_e) < 140\ \mu\text{rad}$$

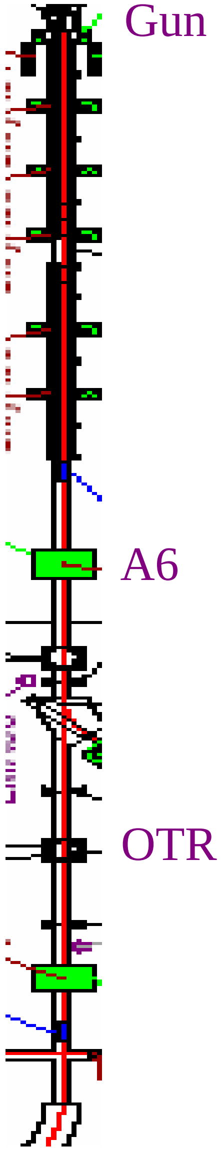
Envelope Smoothing

- If the electron angles are higher than that, the longitudinal cooling is suppressed. $\propto 1/\theta_e^2$

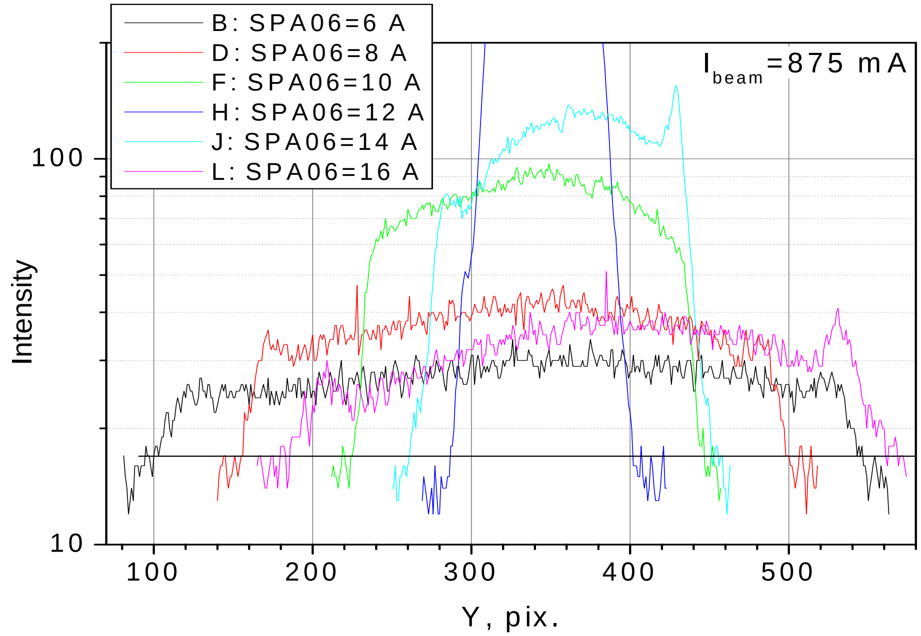
- The problem of unsmooth envelope grows from our current lack of knowledge about optical elements; the required accuracy is better than 1%.

- There are several ways to improve the envelope:
  - To use an improved version of the simulation code for the beam inside the Pelletron, M. Tiunov's UltraSam-Beam soft, and to improve Supply Line (SL) optical model implemented in the OptiM code of V. Lebedev.
  - To measure the envelope by the OTR located under the Pelletron, and to improve the Supply Line model.
  - To measure the envelope by scrapers in the CS, and to correct it using the SL model
  - To make sure that the SL optics is rotation-invariant, and to smooth the envelope, operationally maximizing cooling by 2 lenses just upstream CS.

OTR Tomography

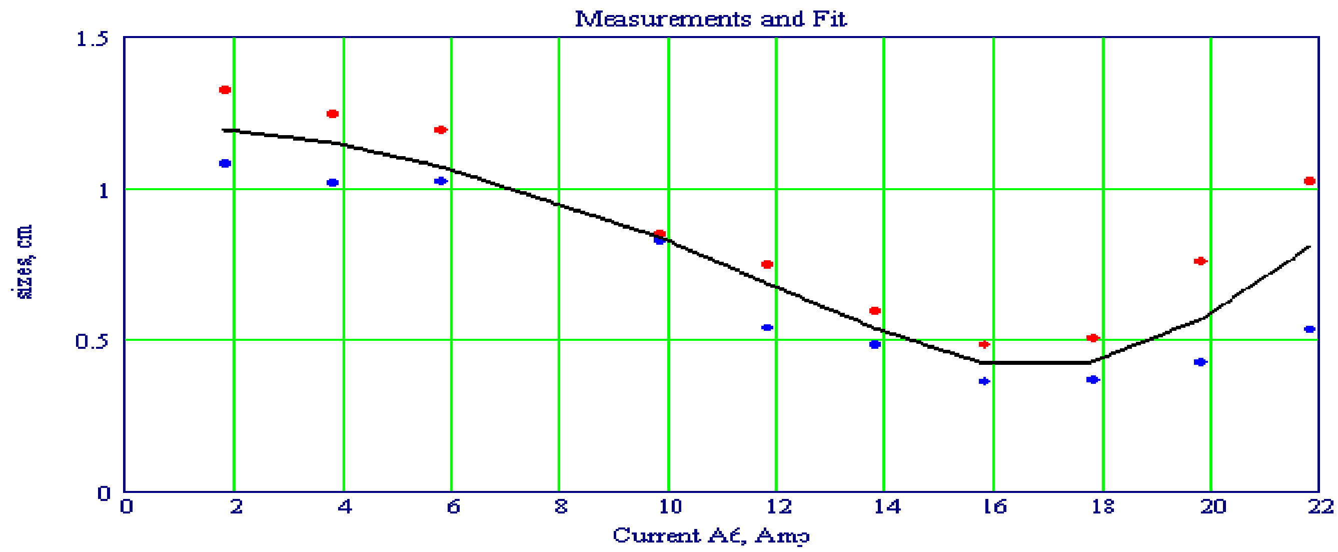


OTR images vs current in the nearest upstream lens A6 provide information about the beam density and angles distribution at the acceleration exit, or at 1 MeV, where the OptiM starts.



OTR Tomography

- OTR images vs current in the nearest upstream lens A6 provide information about the beam profile. In a simplest implementation, the analysis assumes a round and linear beam. Then, three parameters can be extracted for the beam state at the Acceleration exit: the beam radius, radial divergence, and the canonical emittance $\varepsilon_e = B_{cath} a_{cath}^2 / (B\rho)$



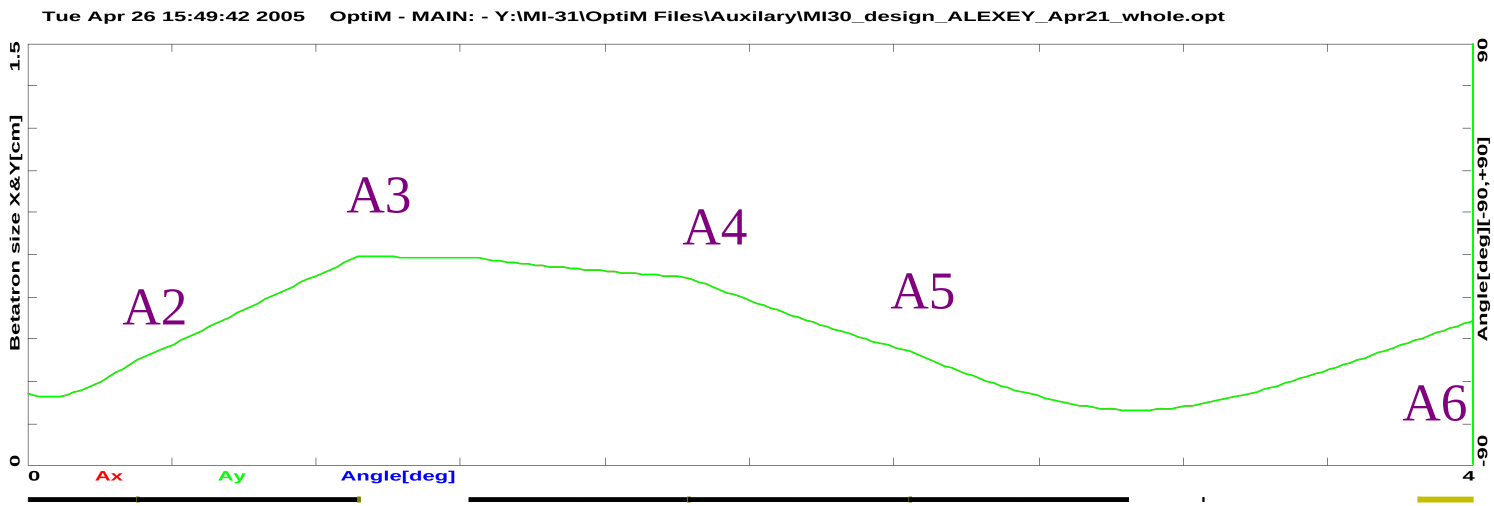
Apr 7 /2005 data

$r_0 = 2.26 \pm 0.06$ mm $\qquad r_0' = 0.2 \pm 0.2$ mrad $\qquad \varepsilon / \varepsilon_0 = 0.76 \pm 0.1$

A problem: the image is elliptical, althougth it should be round. So far, the reason is unknown.

Check of this method

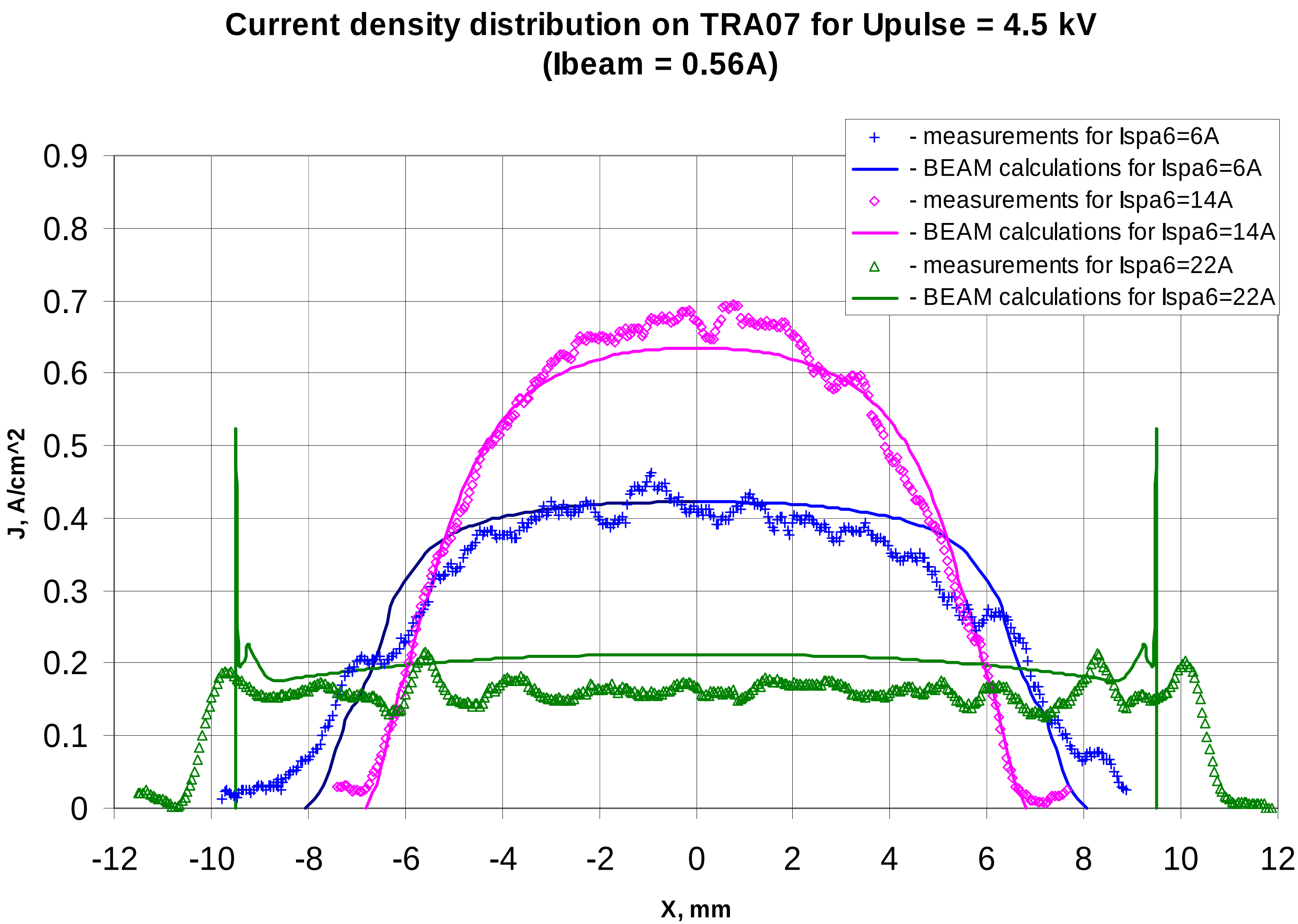
- If to calculate the initial conditions at 1 MeV from the data of Apr 22 (3,5,2,0) A, and put these initial conditions for the Apr 7 settings (3,5,5,5) A, I get the following envelope (vertical scale = 1.5 cm)



For the different settings at A4 and A5, I get the same initial conditions at 1 MeV (upstream A2):

$$r_0 = 2.2 \text{ mm} \ , \ r_0' \approx 0$$

OTR profiles: Measurements & UltraSam-Beam Simulations (Sep 14)



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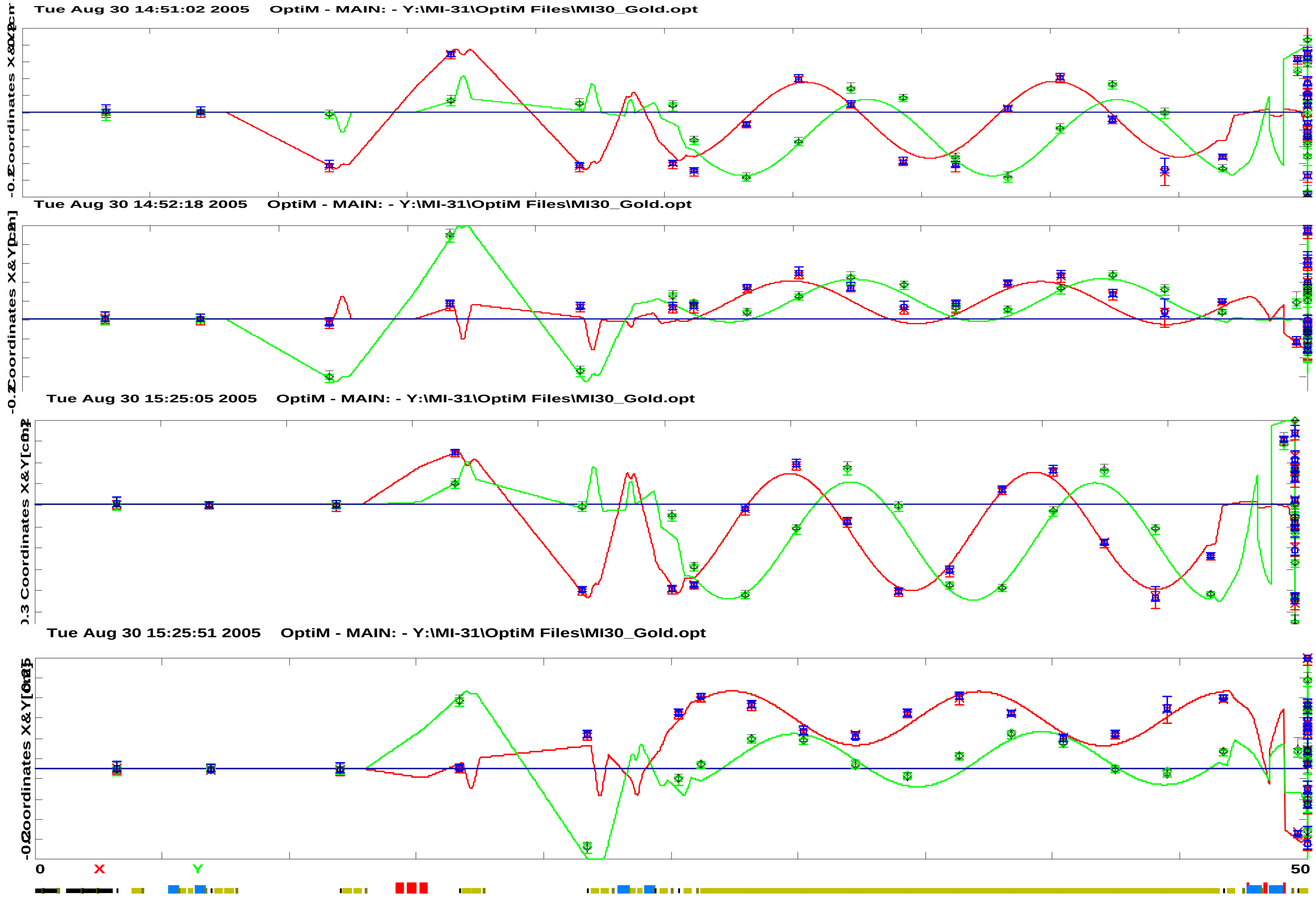
Differential orbits (Beam Response)

- Properties of the optical elements are extracted from a fit of the differential orbits, or trajectory responses on the correctors.
- Normally, 5 correctors (4 + energy offset) are used, and the measurement data are fit in the simulations (V. Lebedev's OptiM) with variation of the calibration coeficients.
- Problems:
  - The line is only recently settled (hopefully);
  - Reproducibility check just started;
  - The fit takes time.

Differential Orbits, Aug. 12 (quad QNS3C on)



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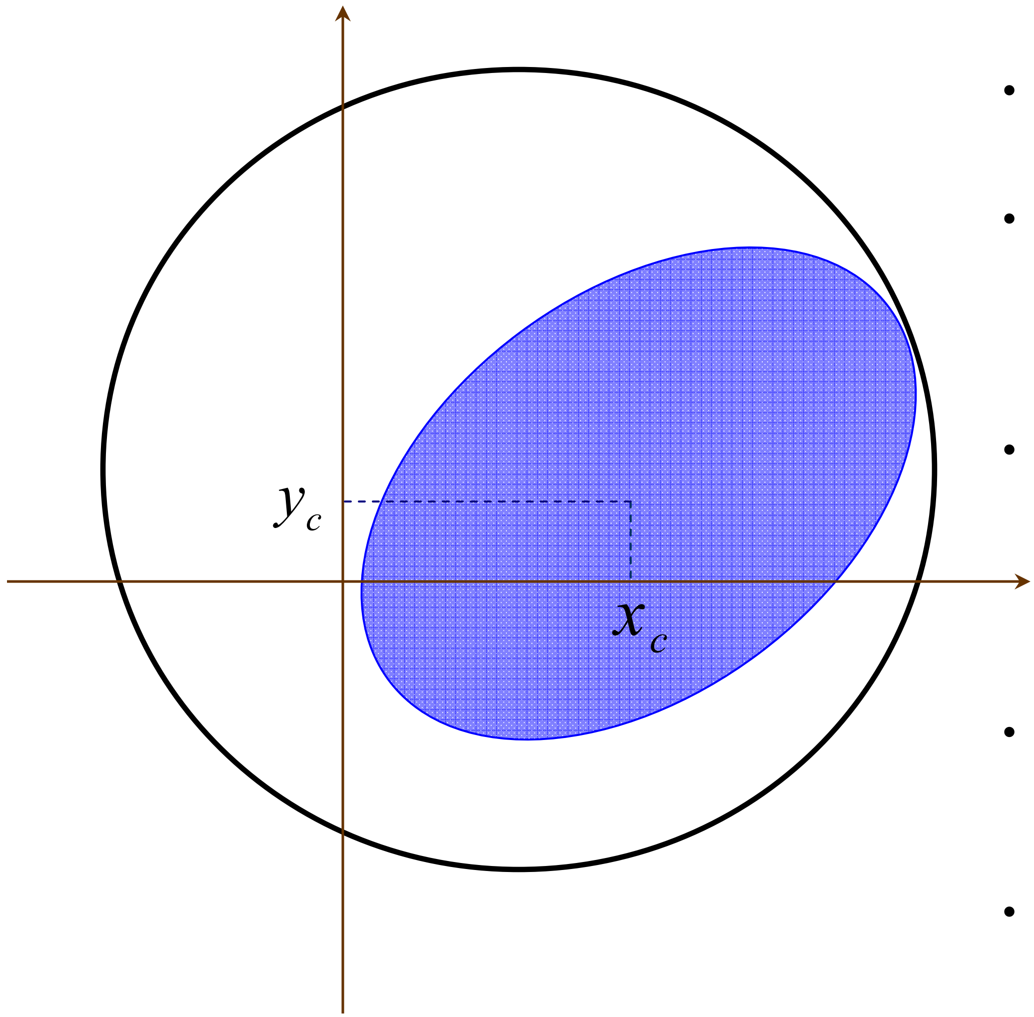
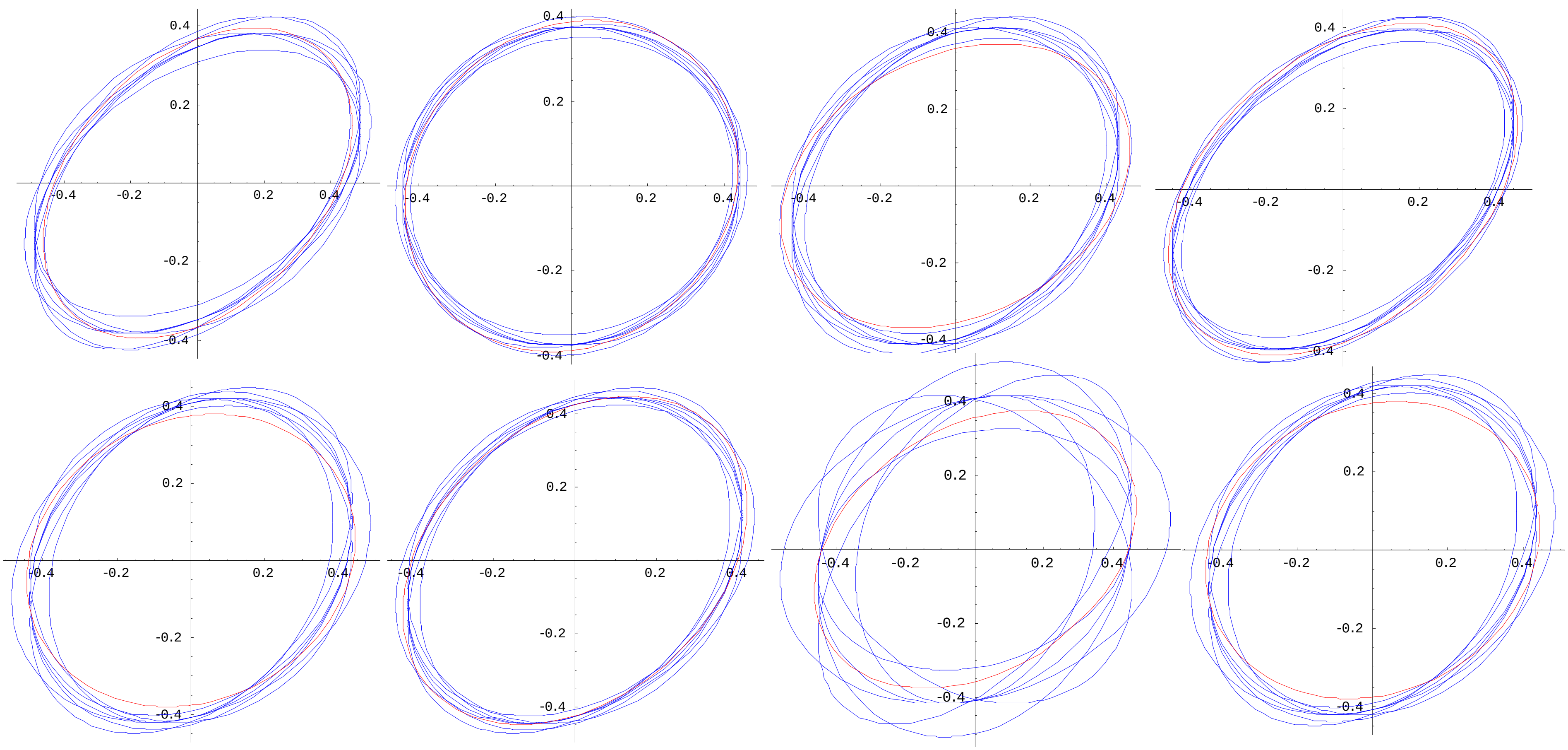
Envelope Measurements with Scrapers



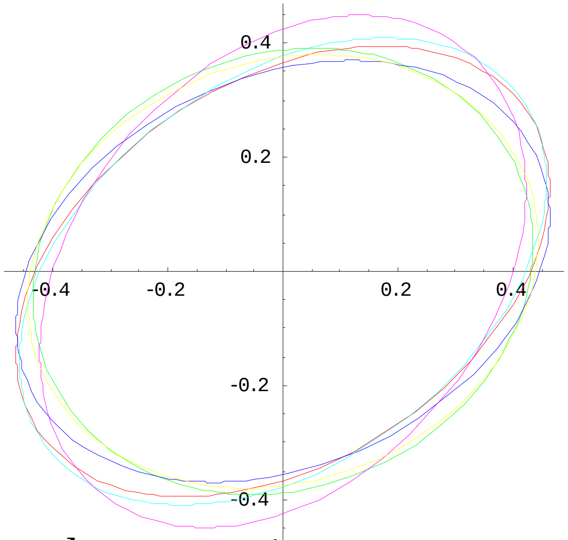
- The scrapers are diaphragms of 15 mm diameter, located every 2 m.
- While only one of them is in place, the beam is shifted in some direction until it touches the scraper. The bpm data for the beam center (x_c, y_c) is taken at this point.
- The beam is shifted in other direction, and the center coordinates at touch are detected again; usually 8 directions are used. Then, the entire procedure is repeated for other scrapers.
- From these data, the beam ellipse and the scraper offsets are found for every scraper involved.
- Initial conditions for the beam envelope are fitted for these ellipses.

Scraper Data Analysis (Sep 1, settings #888)

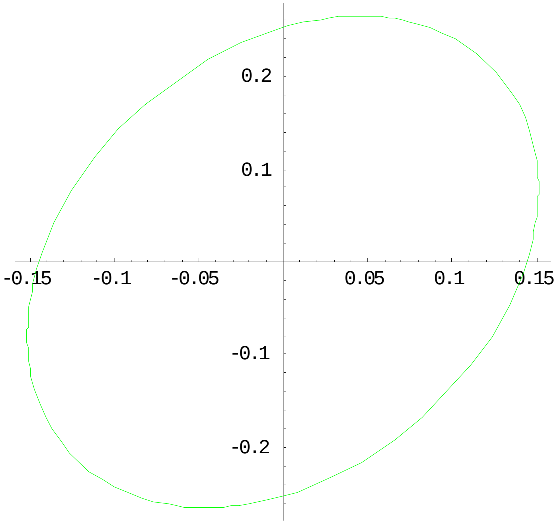
- The scraper measurements were repeated Sep 1 for the same focusing settings and with a standard (programmed by T. Bolshakov) procedure. The results are presented (SCC00, SCC30-SCC60, SCC80, SCC90, SCQ01).



Scraper Data Analysis Sep 1 (Cont)



Envelope at various scrapers.
the average beam radius is 0.43 cm.



Angles over the envelope at SCC00, mrad
The envelope-averaged angle is 0.22 mrad.

$$\beta_x = 190\ cm,\ \alpha_x = -0.16,\ \beta_y = 140\ cm,\ \alpha_y = 0.11,\ \nu = 68^\circ,\ u = 0.46$$

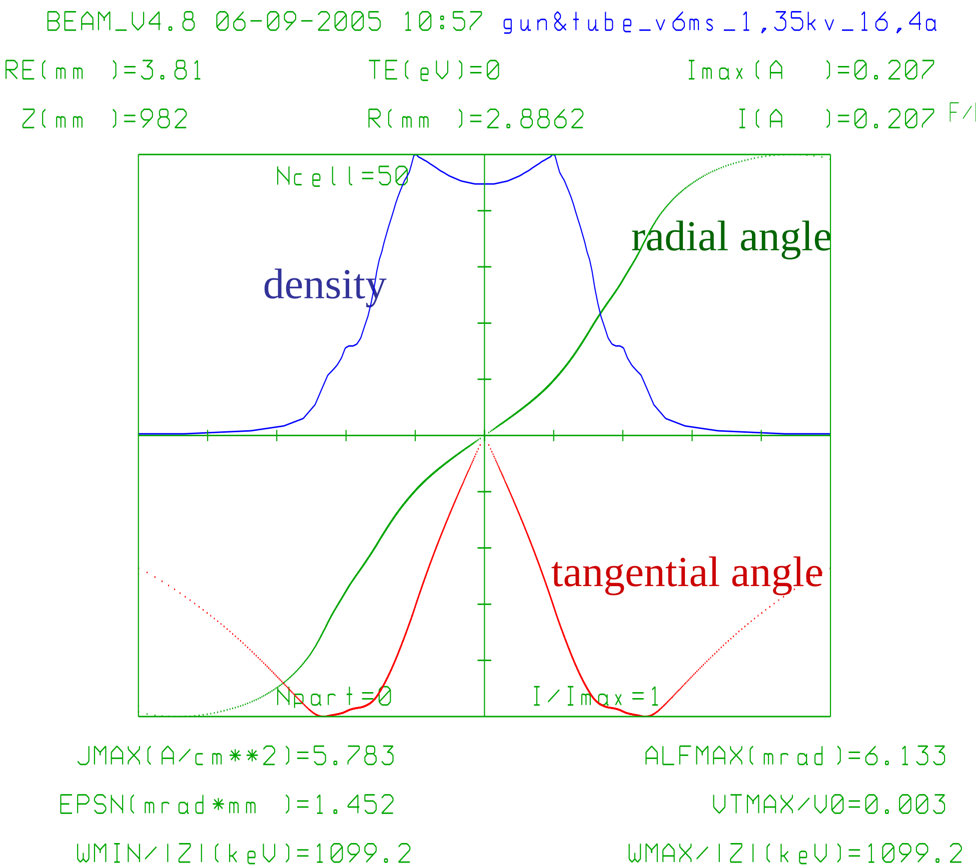
Electron Angles from the Drag Force

- Drag Force, measured at 200 mA and ~1.3 mm mrad pbar emittance:
  - ~20 MeV/hr at the beam center;
  - ~10 MeV/hr at 1 mm offset;
  - ~5 MeV/hr at 2 mm offset;
- Calculations for a round beam with a random dipole rms angle 140 μrad and the envelope angle 400 μrad:
  - 18 MeV/hr at the beam center;
  - 12 MeV/hr at 1 mm offset;
  - 5 MeV/hr at 2 mm offset;
- Discrepancy 400 vs 200 μrad from the scraper measurements could be easily due to the beam non-linearity.

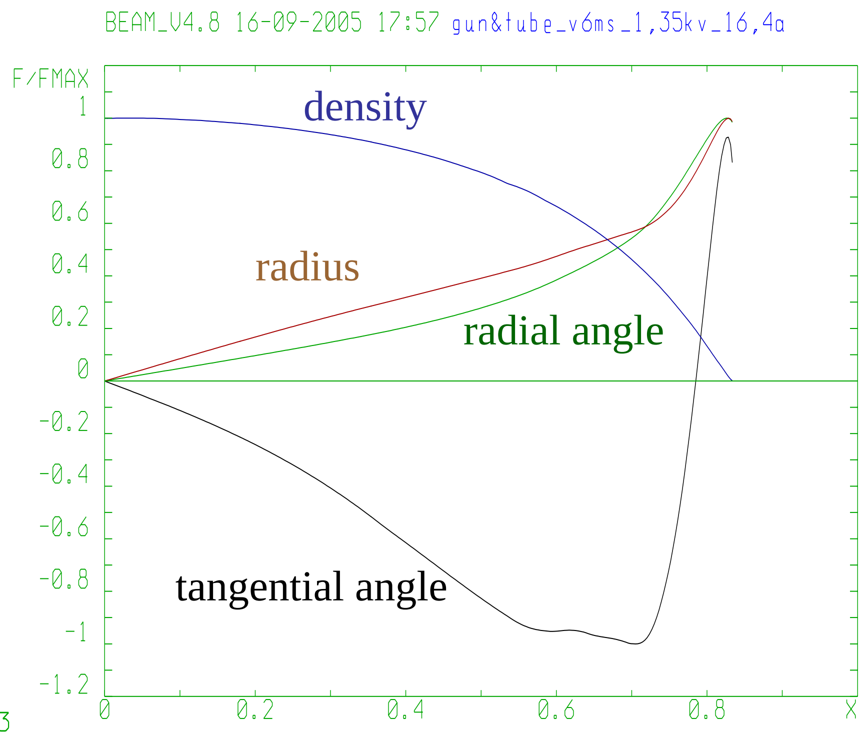
Beam Non-Linearity

- Beam profile for 200 mA, (Gun Sol = 0.6 A, A0 =3A, A1 = 4A) at 1 MeV, calculated with UltraSam-Beam. This non-linearity leads to ~ 400 μrad of the core envelope angle for a perfectly cylindrical halo.

Profile vs radius



Profile vs radius at cathode



Conclusions

- Although the pbars are routinely e-cooled, the electron optics is far from being optimal. The drag rate significantly drops with an offset, that shows the envelope mismatch is high.
- Envelope smoothing, hopefully, can be achieved by means of
  - Improving the optical model and implementing rotation-invariant optics with required accuracy;
  - Working as close to the Pierce regime as possible;
  - Until the beam core and the halo are far from being similar, use the UltraSam simulations and OTR measurements (hopefully cleaned from the ellipticity) for the envelope initial conditions. The CS scraper measurements are misleading at this stage.
- Smoothing the envelope, with the same dipole angles, would allow to have the drag force of 50 MeV/hr for 5 π mm mrad pbar beam with 0.5 A of the electron beam.

References

1. S. Nagaitsev et al., COOL05
2. A. Burov, S. Nagaitsev, A. Shemyakin, Ya. Derbenev, “Optical principles of beam transport for relativistic electron cooling”, Phys. Rev. ST-Accel. Beams **3**, 094002 (2000).
3. V. Lebedev, A. Bogacz, “Betatron motion with coupling”, JLAB-ACC-99-19 (1999).