ERL Injector Operations

Bela Abolfathi

Advisors:
Florian Löhl
Bruce Dunham

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Main Goal

$$\text{Ultra low emittance} \quad \underbrace{\text{High average current}}_{\text{particle beam}} \longmapsto \text{High brightness} \quad \text{High coherence} \quad \underbrace{\text{High intensity}}_{\text{photon beam}}$$

Automation Procedures

Startup

- Secure L0 area
- Check vacuum status
- Open gate valves
- Check laser settings
- Turn on klystrons
- Turn on buncher IOT
- Turn on gun HV
- Turn on ICM cavties
- Turn on buncher cavity
- Turn on deflector cavity

Automation Procedures

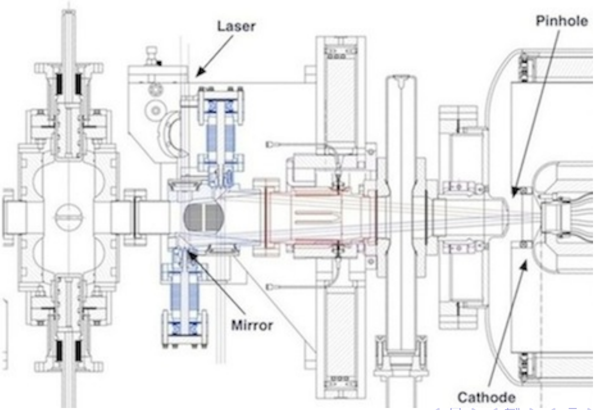
Shutdown

- Turn off gun HV
- Turn off all ICM cavities
- Turn off buncher cavity
- Turn off deflector cavity
- Turn off buncher IOT
- Close A1 gate valve
- Turn off klystron HV

Cathode Alignment

What's happening?

- Laser is reflected off mirror
- Photon beam hits cathode
- Electrons accelerate through a pinhole in the anode



Cathode Alignment

Why is it important?

- Obtain symmetric cylindrical beam
  - Focusing
  - Space charge induced emittance growth
  - Elliptical beam shape

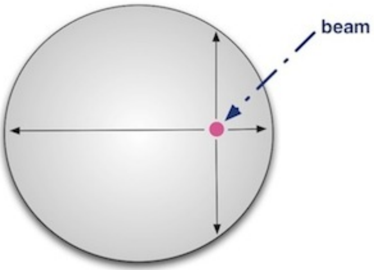


Figure: The cathode alignment process. The beam is shown as the pink dot. It is first moved horizontally in equal step sizes until it reaches the edge of the cathode (the circular disk), and then reverses direction until it reaches the opposite edge. Bunch charge values are taken at each step. The process is repeated in the vertical direction. The center of the cathode is determined by finding the center of the fitted flat-top curve (with Gaussian decay).

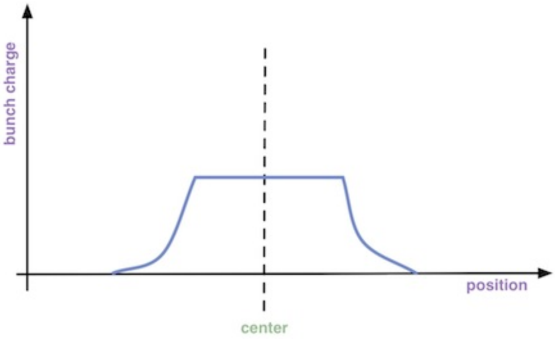
Cathode Alignment

Methods

- Obtain bunch charge values
  - Check if A1 screen is moved in
  - Enable horizontal motor
  - Move beam across cathode according to motor step size
  - Read bunch charge at each step
  - Reverse direction at edge of cathode
  - Plot bunch charge as a function of horizontal position
  - Apply flat-top fit with Gaussian decay
  - Repeat for vertical motor
- Find cathode center
- Move beam to this position

Cathode Alignment

steps to center = offset − current position



Cathode Alignment

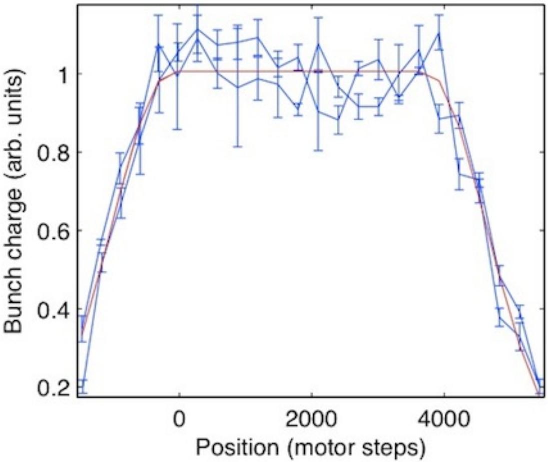


Figure: Bunch charge values as a function of horizontal position of the beam on the cathode taken on the first day.

Cathode Alignment

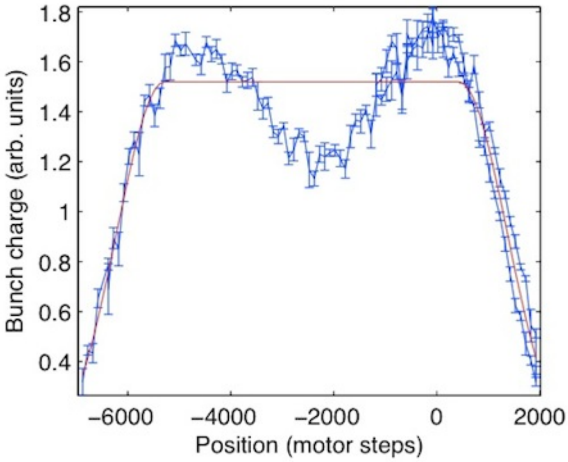


Figure: Bunch charge values as a function of horizontal position of the beam on the cathode taken on the second day. Calculated horizontal center was -2424 motor steps.

Cathode Alignment

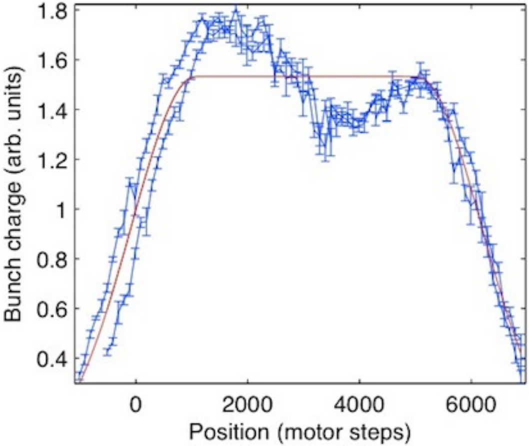


Figure: Bunch charge values as a function of vertical position of the beam on the cathode taken on the second day. Calculated vertical center was 3053 motor steps.

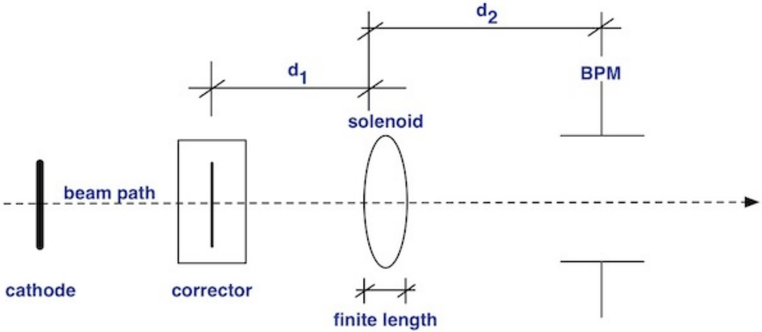
Cathode Alignment

Summary

- The program was successfully executed
- The integrated charge as a function of motor position was well approximated by the flat-top fit with Gaussian decay
- Slight dip in the bunch charge curve on the second day revealed the fact that the quantum efficiency of the cathode near the centered had decreased from high current runs from the previous day
- Motor reproducibility as source of error
- Possible solution: use position of beam on the screen as a measure of how much it moved

Solenoid Alignment

Important process for focusing the beam



Solenoid Alignment

Process

- Reconstruct beam parameters ($x_\circ$, $x'_\circ$, $y_\circ$, $y'_\circ$) at the corrector (and obtain BPM offset values)
  - Calculate magnetic field using fieldmaps for solenoid
  - Determine length of solenoid and drift spaces
  - Use these values to calculate transfer matrices
  - Measure average x, y positions and standard deviation at BPM
  - Use weighted χ^2 method and pseudoinverse to obtain fit parameters
- Calculate statistical error

Solenoid Alignment

$$k = \frac{B_o}{2B\rho_o}$$

$$S = \sin(kL_s)$$

$$\underbrace{C = \cos(kL_s)}_{\text{for } 1^{st} \text{ order transfer matrix}}$$

$$S = \begin{pmatrix} C^2 & \frac{1}{k}SC & SC & \frac{1}{k}S^2 \\ -kSC & C^2 & -kS^2 & SC \\ -SC & -\frac{1}{k}S^2 & C^2 & \frac{1}{k}SC \\ kS^2 & -SC & -kSC & C^2 \end{pmatrix} \qquad D(d) = \begin{pmatrix} 1 & d & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Solenoid Alignment

$$M = D_2 \times S \times D_1 \qquad \begin{pmatrix} x_o \\ x'_o \\ y_o \\ y'_o \end{pmatrix} = M \times \begin{pmatrix} x \\ x' \\ y \\ y' \end{pmatrix}$$

$$M_F = \begin{pmatrix} M_{11}^{(1)} & M_{12}^{(1)} & M_{13}^{(1)} & M_{14}^{(1)} & 1 & 0 \\ M_{31}^{(1)} & M_{32}^{(1)} & M_{33}^{(1)} & M_{34}^{(1)} & 0 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ M_{11}^{(n)} & M_{12}^{(n)} & M_{13}^{(n)} & M_{14}^{(n)} & 1 & 0 \\ M_{31}^{(n)} & M_{32}^{(n)} & M_{33}^{(n)} & M_{34}^{(n)} & 0 & 1 \end{pmatrix} \qquad \begin{pmatrix} x_o \\ x'_o \\ y_o \\ y'_o \\ x_{offset} \\ y_{offset} \end{pmatrix} = M_F \times \begin{pmatrix} x \\ x' \\ y \\ y' \\ x_{offset} \\ y_{offset} \end{pmatrix}$$

Solenoid Alignment

$$b = Ba \quad \longmapsto \quad B^T b = (B^T B)\, a \quad \longmapsto \quad a = \underbrace{(B^T B)^{-1}}_{C} B^T b$$

$$B = \begin{pmatrix} \frac{M_{11}^{(1)}}{\sigma_{x_1}} & \frac{M_{12}^{(1)}}{\sigma_{x_1}} & \frac{M_{13}^{(1)}}{\sigma_{x_1}} & \frac{M_{14}^{(1)}}{\sigma_{x_1}} & \frac{M_{15}^{(1)}}{\sigma_{x_1}} & \frac{M_{16}^{(1)}}{\sigma_{x_1}} \\ \frac{M_{31}^{(1)}}{\sigma_{y_1}} & \frac{M_{32}^{(1)}}{\sigma_{y_1}} & \frac{M_{33}^{(1)}}{\sigma_{y_1}} & \frac{M_{34}^{(1)}}{\sigma_{y_1}} & \frac{M_{35}^{(1)}}{\sigma_{y_1}} & \frac{M_{36}^{(1)}}{\sigma_{y_1}} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \frac{M_{11}^{(n)}}{\sigma_{x_n}} & \frac{M_{12}^{(n)}}{\sigma_{x_n}} & \frac{M_{13}^{(n)}}{\sigma_{x_n}} & \frac{M_{14}^{(n)}}{\sigma_{x_n}} & \frac{M_{15}^{(n)}}{\sigma_{x_n}} & \frac{M_{16}^{(n)}}{\sigma_{x_n}} \\ \frac{M_{31}^{(n)}}{\sigma_{y_n}} & \frac{M_{32}^{(n)}}{\sigma_{y_n}} & \frac{M_{33}^{(n)}}{\sigma_{y_n}} & \frac{M_{34}^{(n)}}{\sigma_{y_n}} & \frac{M_{35}^{(n)}}{\sigma_{y_n}} & \frac{M_{36}^{(n)}}{\sigma_{y_n}} \end{pmatrix} \qquad a = \begin{pmatrix} x_o \\ x'_o \\ y_o \\ y'_o \\ x_{off} \\ y_{off} \end{pmatrix} \qquad b = \begin{pmatrix} \frac{x^{(1)}}{\sigma_{x_1}} \\ \frac{y^{(1)}}{\sigma_{y_1}} \\ \vdots \\ \frac{x^{(n)}}{\sigma_{x_n}} \\ \frac{y^{(n)}}{\sigma_{y_n}} \end{pmatrix}$$

Solenoid Alignment

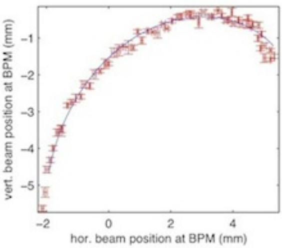
$$C = \begin{pmatrix} \sigma_{a_1}^2 & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \sigma_{a_2}^2 & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \sigma_{a_3}^2 & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \sigma_{a_4}^2 & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \sigma_{a_5}^2 & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \sigma_{a_6}^2 \end{pmatrix}$$

Solenoid Alignment

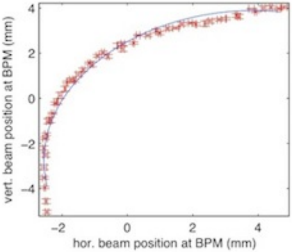
How did we check that this actually works?

- We changed the initial conditions at the corrector by adjusting the corrector current
- Depending which corrector was used, the beam experienced either a horizontal or a vertical 'kick'
- The only beam parameters that should be affected are x' or y'
- x' should change by -4.8 mrad (from horizontal kick)
- y' should change by $+4.8$ mrad (from vertical kick)

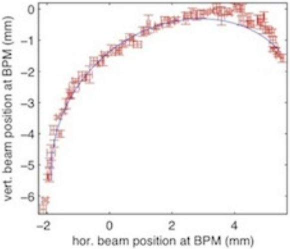
Solenoid Alignment



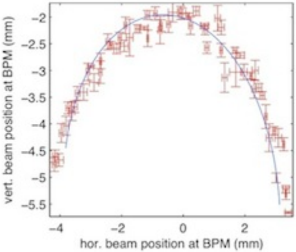
Trial 1



Trial 2



Trial 3



Trial 4

Solenoid Alignment

Results

	Trial 1	Trial 2	Trial 3	Trial 4
	original position	vertical kick	original position	horizontal kick
x (mm)	0.588 $\pm$ 0.009	0.524 $\pm$ 0.022	0.388 $\pm$ 0.013	-0.059 $\pm$ 0.015
x' (mrad)	1.238 $\pm$ 0.046	0.693 $\pm$ 0.080	1.718 $\pm$ 0.036	-2.500 $\pm$ 0.054
y (mm)	-1.006 $\pm$ 0.013	-1.175 $\pm$ 0.024	-0.997 $\pm$ 0.009	-0.420 $\pm$ 0.017
y' (mrad)	4.754 $\pm$ 0.022	9.358 $\pm$ 0.100	4.147 $\pm$ 0.052	6.648 $\pm$ 0.043
x_{off} (mm)	2.815 $\pm$ 0.041	3.447 $\pm$ 0.078	2.784 $\pm$ 0.031	0.630 $\pm$ 0.047
y_{off} (mm)	-4.538 $\pm$ 0.020	-4.399 $\pm$ 0.078	-4.046 $\pm$ 0.045	-8.468 $\pm$ 0.039

Table: Initial beam values with statistical error.

Solenoid Alignment

Possible sources of error:

- Hysterysis
  - Ferromagnetic materials
  - Nonlinear effect
- Dynamic range of BPM/BPM calibration
  - Beam may be too close to one side of the BPM
  - Larger offset
  - Nonlinearity in BPM positions
- Stray fields
  - May not have pure drift space
- Field integral of solenoid

What I Learned

- MATLAB
- EPICS
- DOOCS
- How to operate injector
- Theory behind ERL

Acknowledgements

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