Proton Experiment at IOTA: Injection

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What we get from RFQ

Coasting beam

- Max SC tune shift

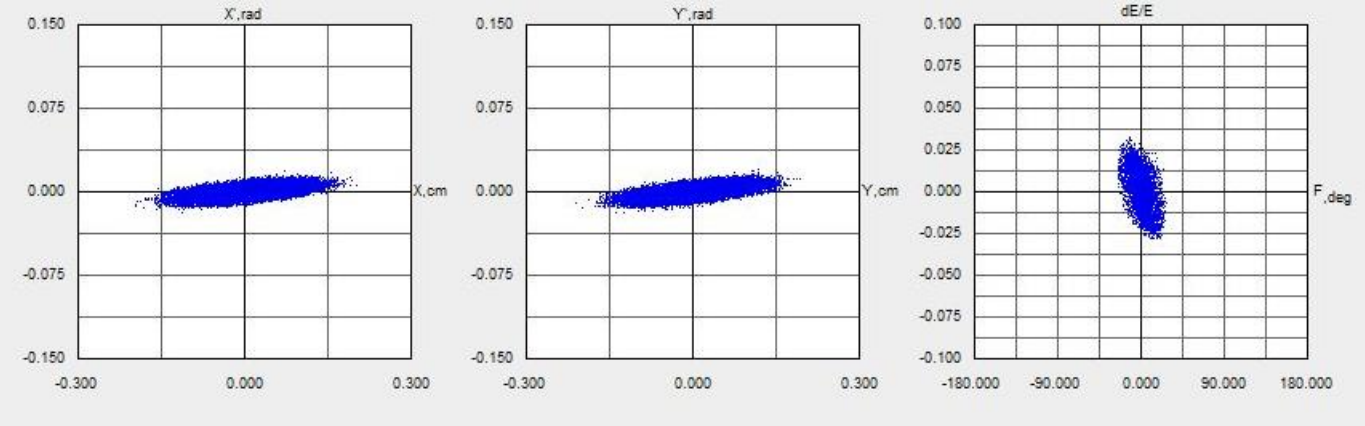
Limiting factors

- Residual gas scattering
- IBS

Bunched beam

Beamline

10 mA 2.5 MeV proton beam from RFQ



Frequency:	325 MHz
Distance between bunches:	6.7 cm
RMS size:	0.7 mm
RMS length:	1.3 mm
RMS momentum spread:	5.5*10^-3

RMS Normalized emittances

Transverse:	0.25 mm-mrad
Long:	1.5 keV-ns

Need a debunching cavity

Max δp is determined by dispersion and aperture limitation: $\delta p \cdot D = \frac{A}{2}$ $D_{max} := 2.5m$ $n_\sigma := 4$

$$\delta p_{max} := \frac{A_{phys}}{2D_{max} \cdot n_\sigma} = 2.4 \times 10^{-3}$$

Debunching Cavity

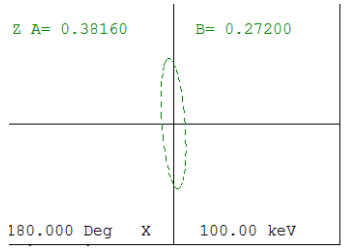
Frequency $f_{cav} := f_{RFQ}$ Wavelength $\lambda_{cav} := \lambda_{RFQ}$ Synch phase $\phi_s := 0$

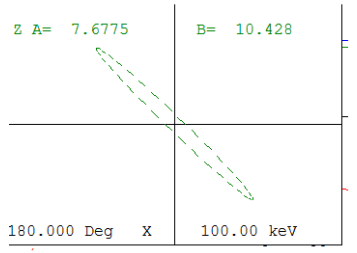
Cavity is placed such that the long. buch size is: $\sigma_{s\_cav} := 0.7cm$ $\frac{\sigma_{s\_cav}}{d_b} = 0.104$ $\Delta\phi_{cav} := \frac{\sigma_{s\_cav}}{d_b} \cdot 2\pi = 0.655$

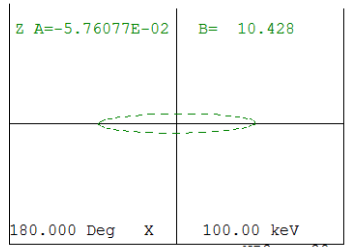
Distance from RFQ to the cavity: $S_{cav} := \frac{\sigma_{s\_cav}}{\sigma_p} = 127.273\,cm$ (In degrees: $\frac{\Delta\phi_{cav}}{1deg} = 37.513$)

Voltage $V_{cav} := \frac{W \cdot \delta W}{q_e \cdot \sin(\phi_s + \Delta\phi_{cav})} = 45.124\,kV$ Resulting momentum spread $\sigma_{p\_cav} := \sigma_p \cdot \frac{\sigma_s}{\sigma_{s\_cav}} = 1.004 \times 10^{-3}$

Trace3D







Coasting beam

Current 10 mA

Beam sizes at Lambertson, RMS
D not matched

$$\sigma_{ring\_x} := \sqrt{\varepsilon_x \cdot \beta_{inj\_x}} = 0.175\,cm$$

$$\sigma_{ring\_y} := \sqrt{\varepsilon_y \cdot \beta_{inj\_y}} = 0.182\,cm$$

Physical Aperture of Lambertson is only 15 mm !

We have 4σ for 10 mA current:

$$A_{lamb} := 15mm$$

$$\frac{A_{lamb}}{2\sigma_{ring\_x}} = 4.281$$

Can inject up to 500 bunches from RFQ, total 10^{11} particles

$$\delta Q_{SC}\left(N_b, L, \beta_{avg}, \sigma_s, \sigma_x, \sigma_y\right) := \frac{r_p \cdot N_b \cdot L}{(2\cdot\pi)^{1.5} \cdot v^2 \cdot \gamma^3 \cdot \sigma_s} \cdot \left\lceil \frac{\beta_x}{\left(\sigma_x + \sigma_y\right)\cdot\sigma_x} \right\rceil$$

For a 10 mA coasting beam, max SC tune shift is 0.7

Limitation: Residual Gas Scattering

Cross-section scales as 1/v

Lifetime due to single scattering, P = 10^-8 torr:

Lifetime $\tau_{gas} := \left[\frac{2 \cdot \pi \cdot n_{eff} \cdot c \cdot r_p^{\,2}}{\gamma^2 \cdot v^3} \cdot \left(\frac{\beta_{ring\_x}}{\varepsilon_{max\_x}} + \frac{\beta_{ring\_y}}{\varepsilon_{max\_y}} \right) \right]^{-1}$ ~ 30 sec

Emittance growth due to multi-particle scattering:

$$\frac{2\pi\, c \cdot r_p^{\,2}}{\gamma^2 \cdot v^3} \cdot \beta_{avg} \cdot \left[\sum_{gases} \left(n_{eff} \cdot L_c \right) \right]$$

$$\frac{\varepsilon_{max\_x}}{d\varepsilon x dt_{gas}} = 7.68\,s$$

Need to increase vacuum to 10^-9 – 10^-10 torr

10^{-9} torr: lifetimes ~ 5min single-particle scattering,
1 min multi-particle

10^{-10} torr: ~ 1 hour single-particle,
~ 10 min multi-particle

IBS limits max current

Beam sizes grow due to IBS

10 mA, coasting beam

For 45 mA rates of emittance growth due to IBS ~ 0.5 s

$$\begin{pmatrix} d\varepsilon x\_dt \\ d\varepsilon y\_dt \\ d\sigma p2\_dt \end{pmatrix} := \sum_{j=0}^{N_r-2} \left(r_{ibs_j} \cdot \frac{S_{j+1} - S_j}{C} \right) = \begin{pmatrix} 1.38 \times 10^{-4} \\ -4.08 \times 10^{-6} \\ 4.7 \times 10^{-7} \end{pmatrix} \frac{cm}{s}$$

For 10 mA ~ 2 s

$$\tau_x := \frac{\varepsilon_x}{d\varepsilon x\_dt} = 2.482\,s \qquad \tau_y := \frac{\varepsilon_y}{d\varepsilon y\_dt} = -83.915\,s \qquad \tau_s := \frac{1cm\,\sigma_p^{\,2}}{d\sigma p2\_dt} = 2.149\,s$$

Rate decrease as emittances come to a thermal equilibrium

Overall, ~ 1 min lifetime

Lower SC tune shift

Option: bunched beam

RFQ current 3 mA $N_b = 3.428 \times 10^{10}$

Thermalized emittances (IBS)

$\varepsilon_x = 1.369 \times 10^{-3}$ cm

$\varepsilon_y = 7.149 \times 10^{-4}$ cm

$\sigma_p \equiv 2.034 \cdot 10^{-3}$

RF parameters

$q := 1$

$V_0 := 500$ V/turn

Emittance growth rate due to IBS

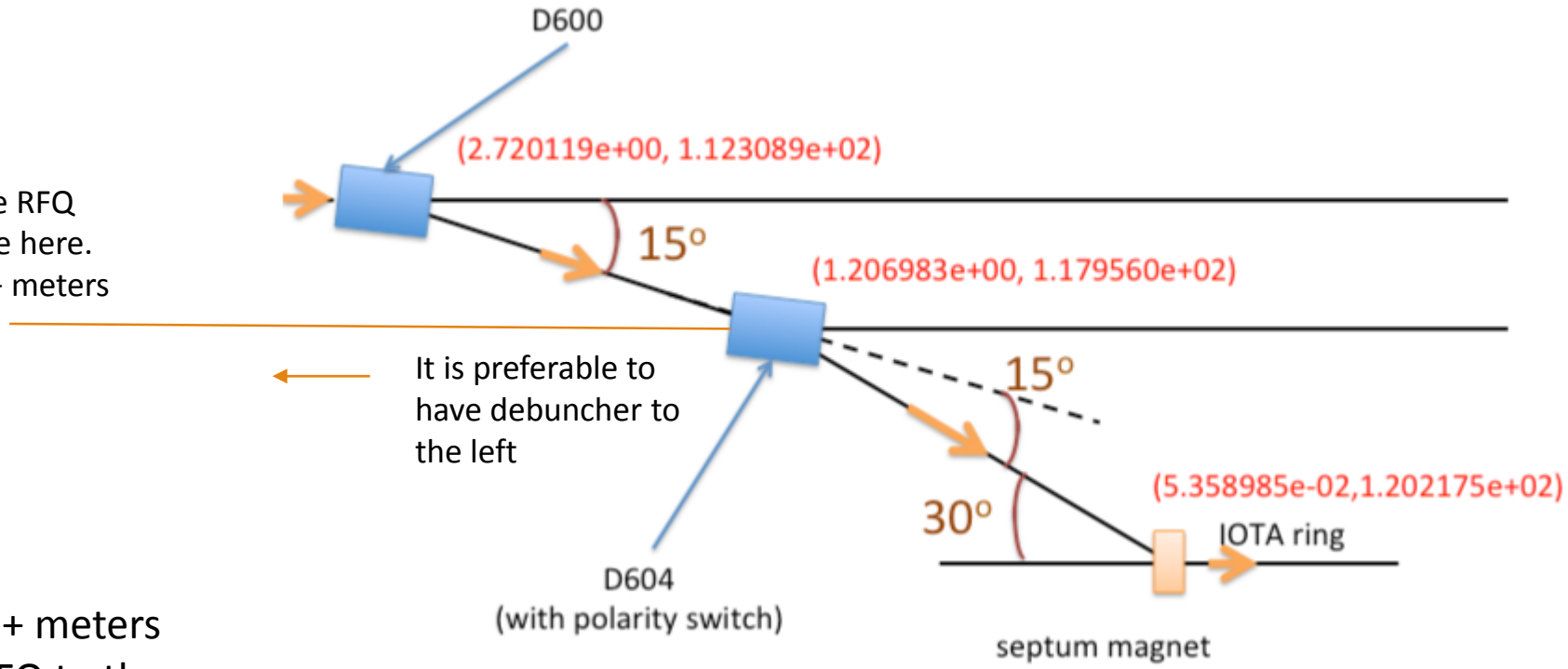
$\frac{\varepsilon_x}{d\varepsilon dt_x} = 35.177$ s $\frac{\varepsilon_y}{d\varepsilon dt_y} = 35.096$ s $\frac{\sigma_p^2}{d\sigma 2dt_p} = 35.079$ s

SC tune shifts: dQx = 0.35, dQy = 0.45

Ratio of phys aperture to RMS beam size is only 3

Beamline: constraints

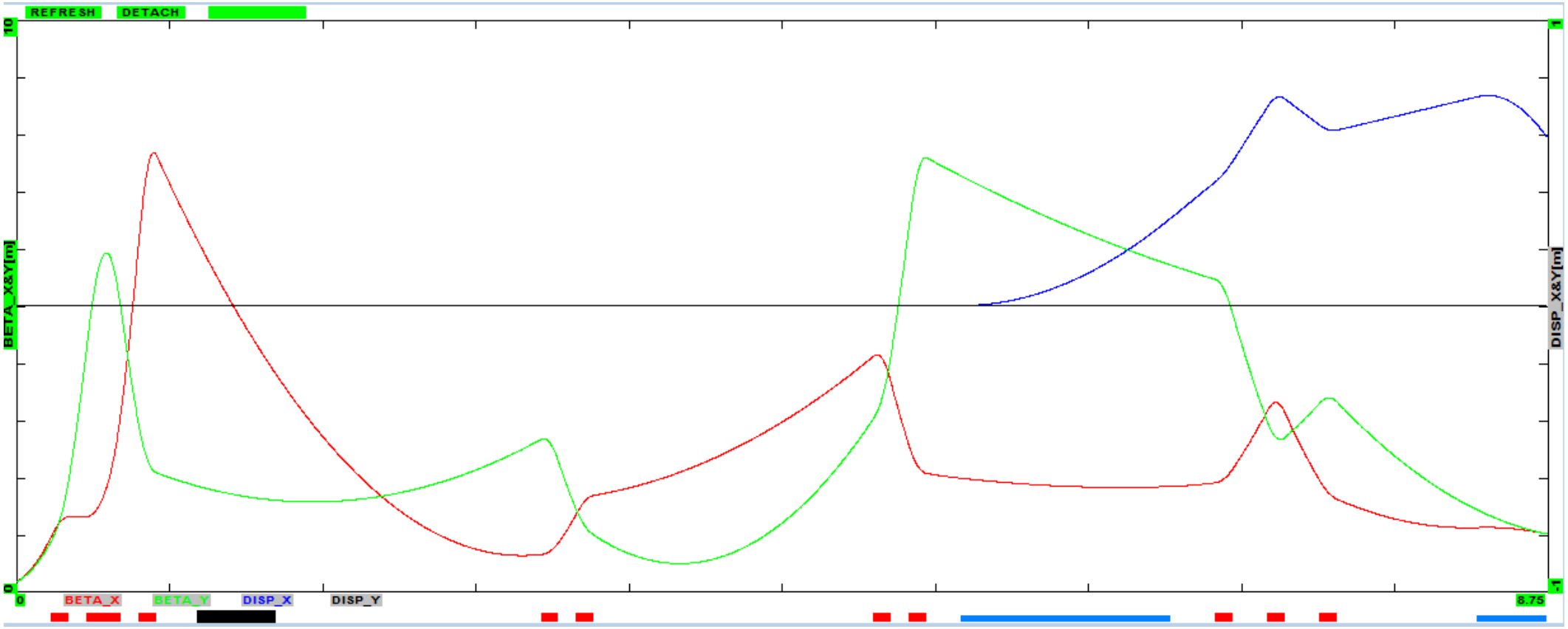
Can place RFQ anywhere here. Have 10+ meters



Need 5+ meters from RFQ to the first dipole

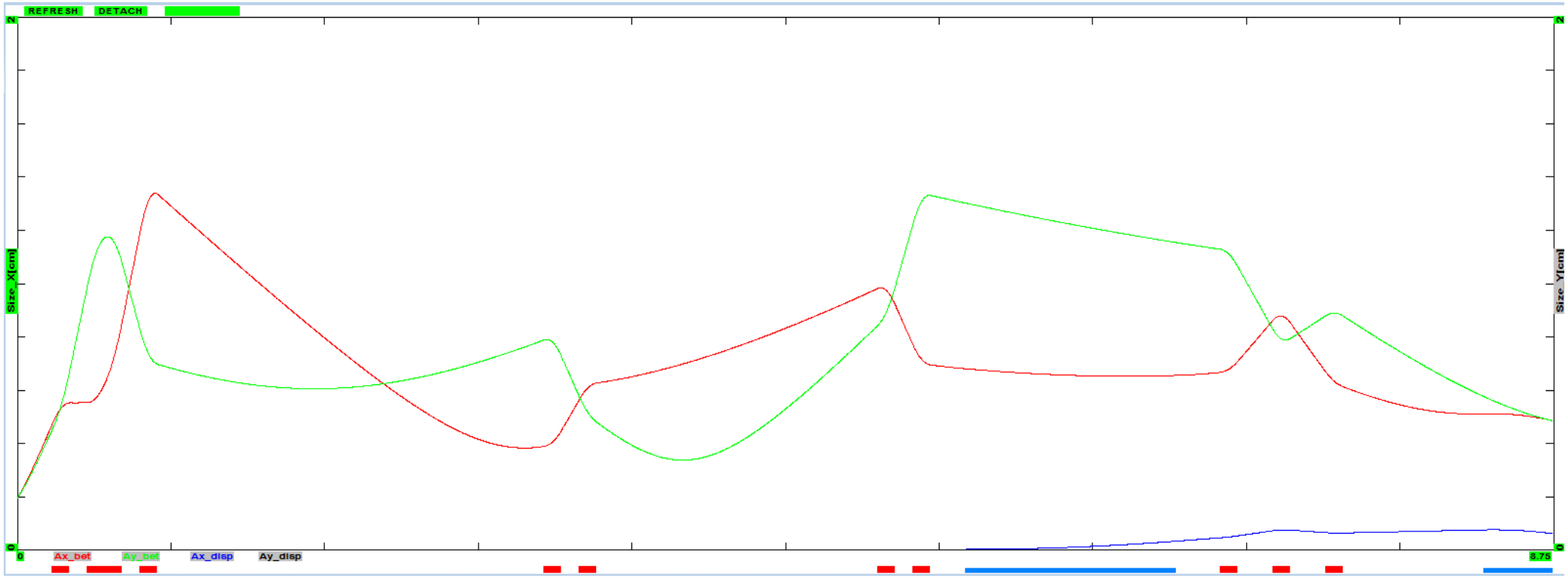
Matching of Twiss parameters

Use 10-cm-long quadrupoles, G not exceed 1 kG/cm



Beam sizes, 99.5 % - less than 2 cm

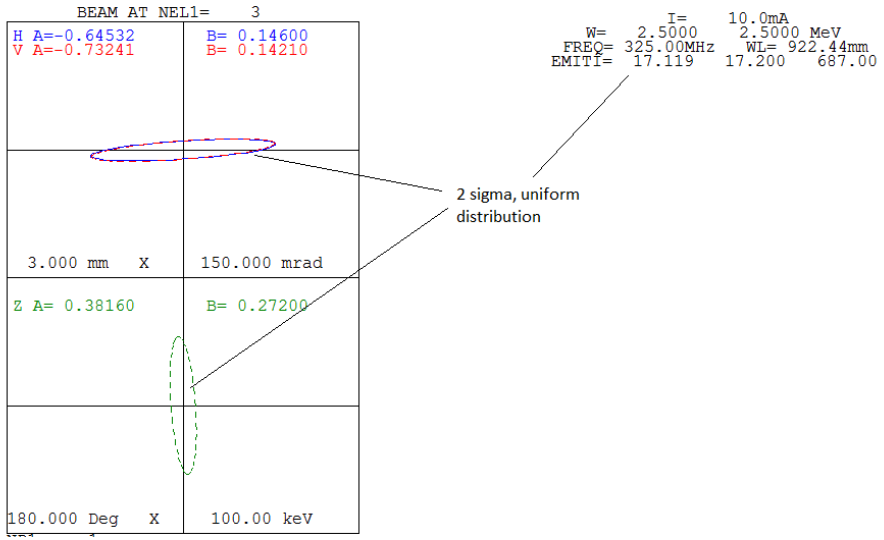
(For negligible current)



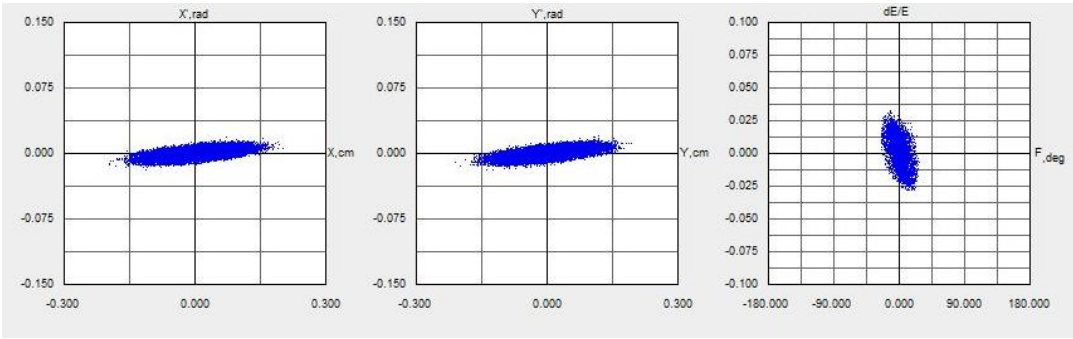
3D Simulation including space charge

Using Trace3D code

Initial data:



Beam footprints for 10 mA current
From Jean-Paul, TraceWin:



3D Simulation including space charge

Trace3D 10 mA