Space-Charge Effects in H^- Low-Energy Beam Transport of LANSCE

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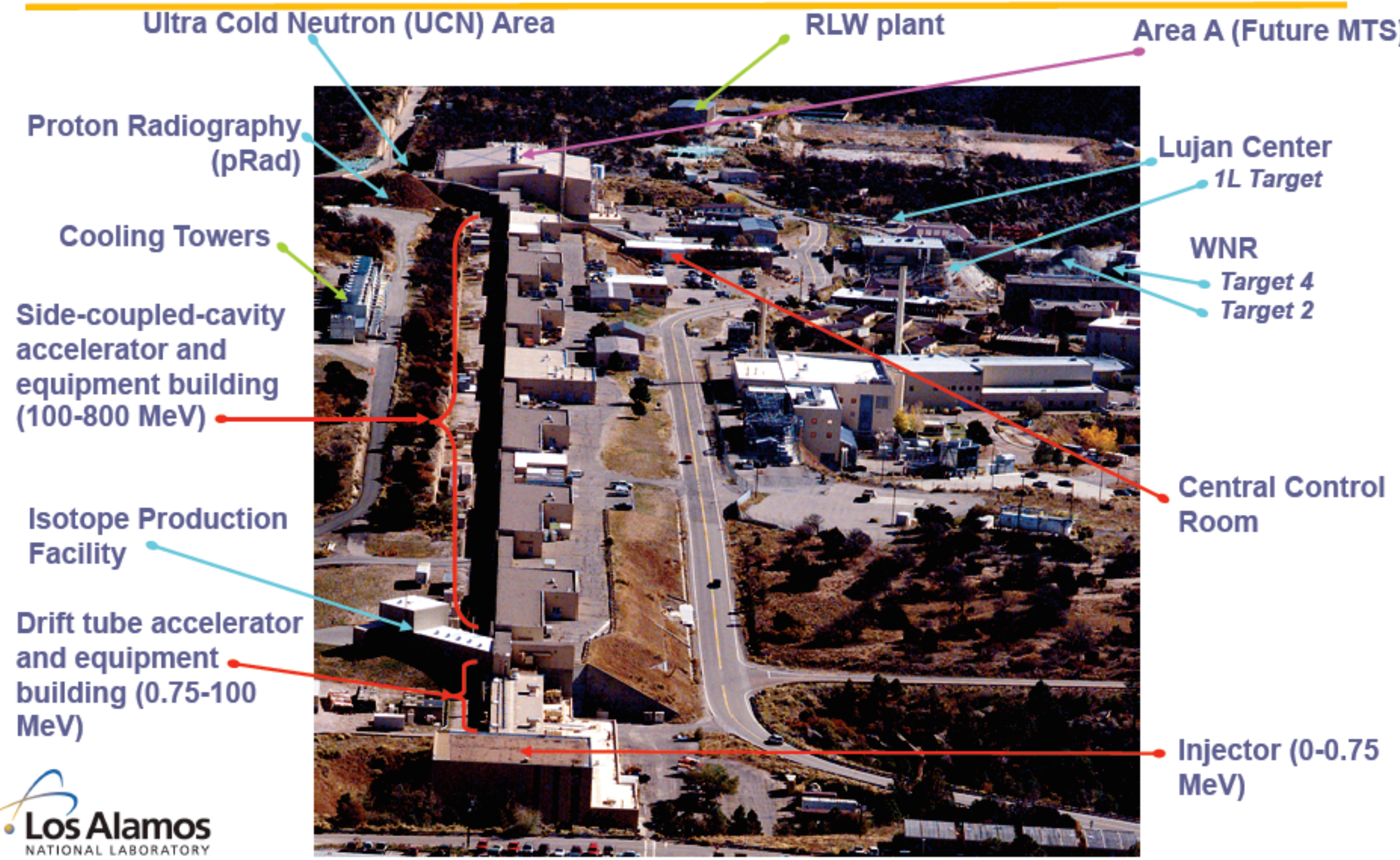
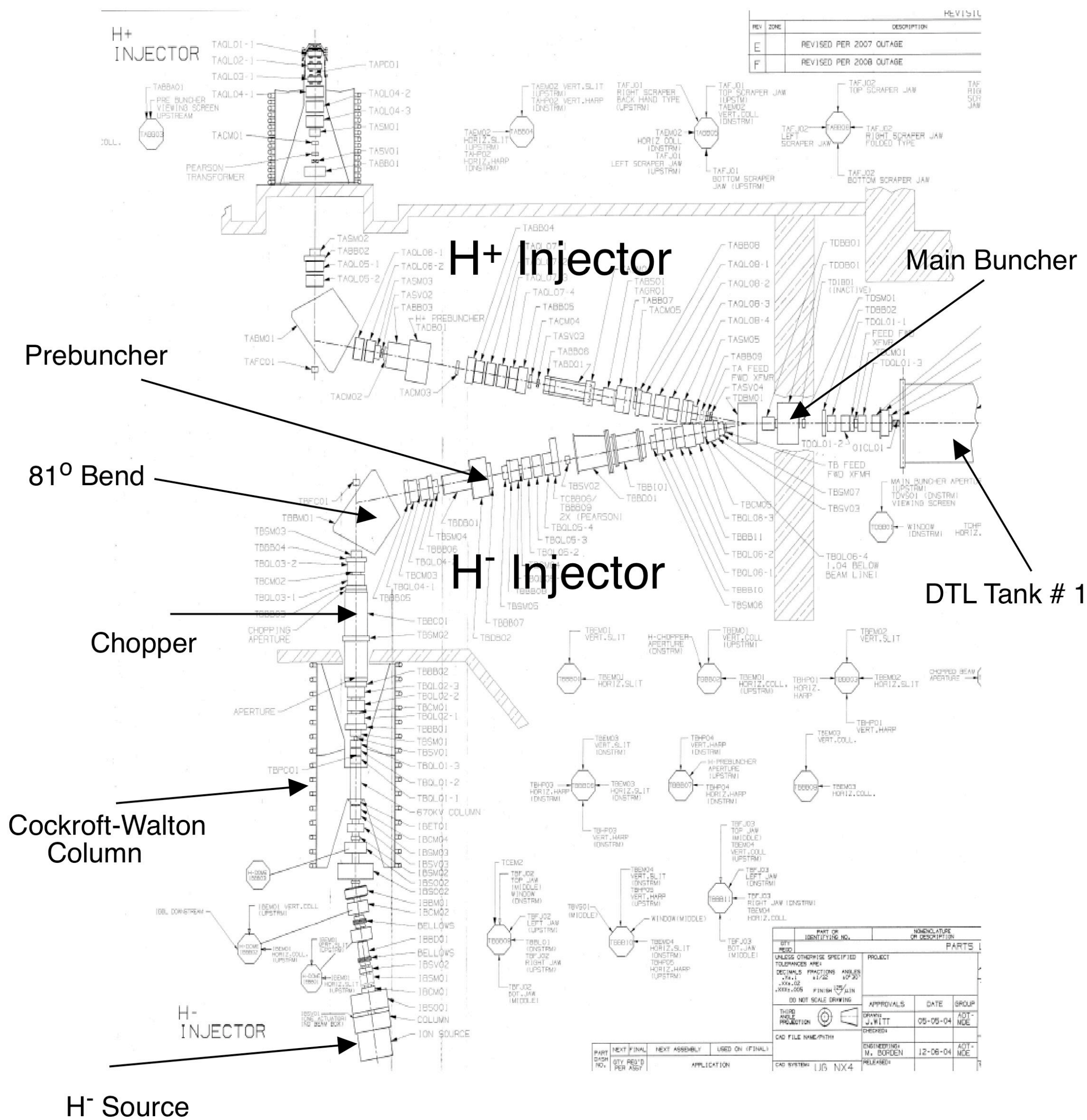
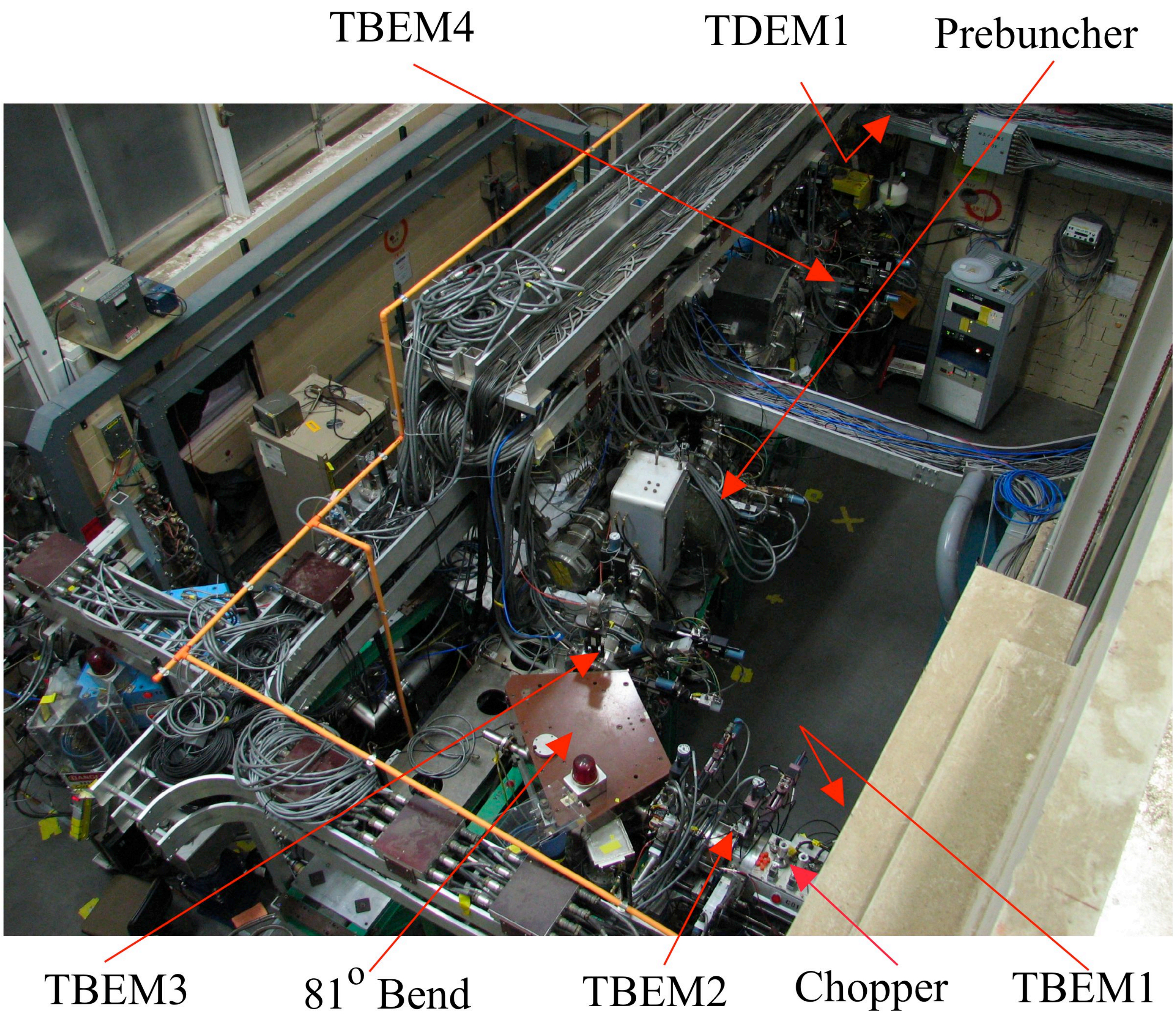
The LANSCE accelerator provides unique flexible time-structured beams from 100 to 800 MeV



Low-Energy Beam Transport



750 keV H^- Low Energy Beam Transport

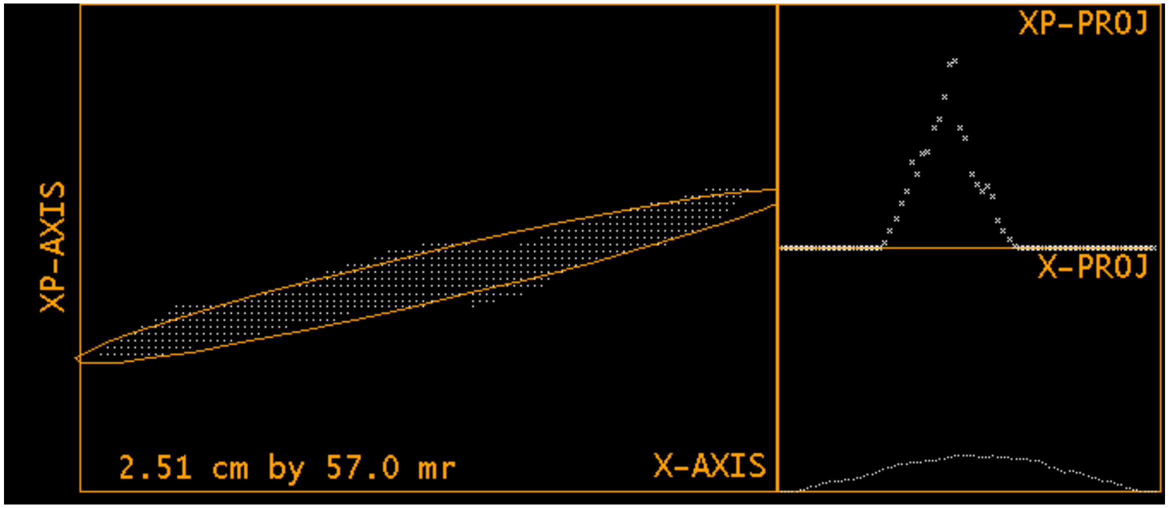


Typical parameters for LANSCE linac beams

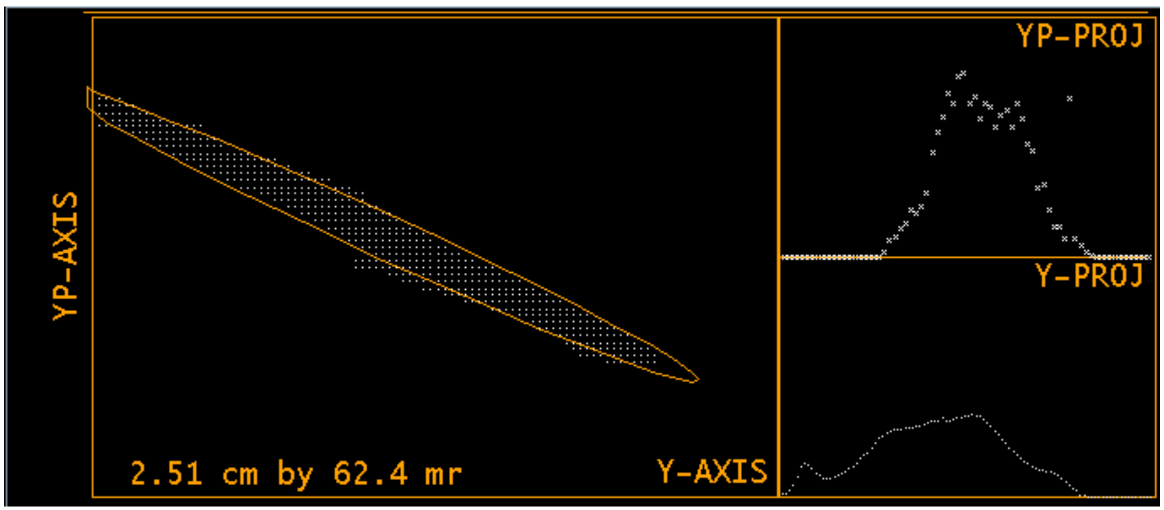
Area	Rep Rate [Hz]	Pulse Length [μs]	Chopping pattern	Iavg [μA]	Pavg [kw]
pRad	~1	625	60 ns bursts every ~1 μs	< 1	< 1
WNR (Tgt4)	40	625	1 μ–pulse every ~ 1.8 μs	≤2	~ 1.6
Lujan	20	625	290ns/358ns	100-125	80-100
UCN	20	625	Lujan-like to none	< 5	< 4
IPF	≤30 in pulsed mode	625	NA	250	25

Note: All beams are 800 MeV, H^- except for IPF which is 100 MeV, H^+.

Beam emittance scan at TBEM1

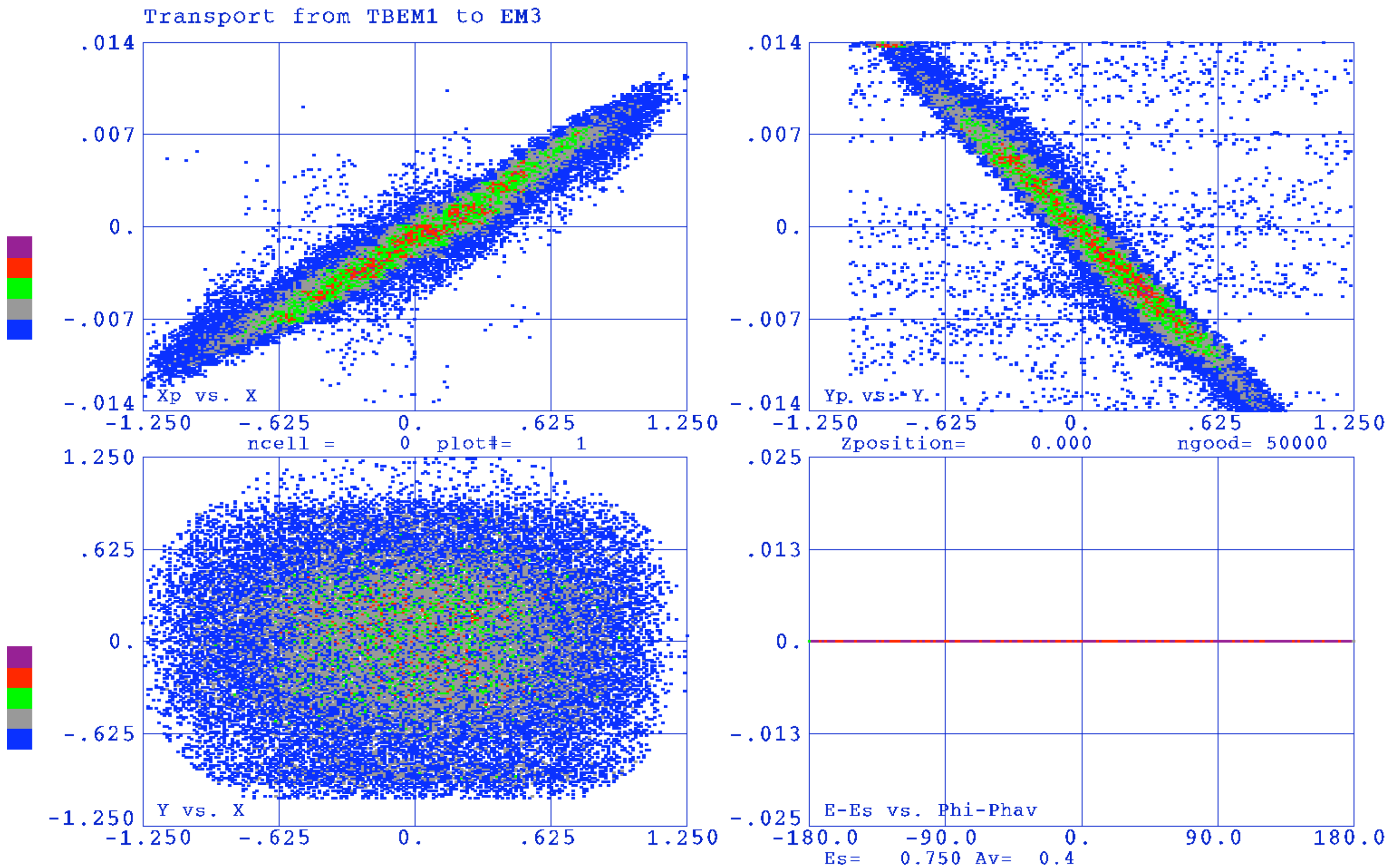



```
Run:22681   Stn: TBEM01-H
03:15:29      24-Aug-2010
Beam: H-        Meas,    Norm
E(total)=      4.058,   0.162 pi
E(edge) =      3.661 pi
E(rms)  =      0.591,   0.024 pi
Etot/rms=       6.86
 Alpha   =    -3.218
 Beta    =     0.422
4*E(rms)=      2.365 pi
      C   =    0.021 cm
     CP   =   -3.334 mr
X Sigma =    0.4995 cm
XP Sigma=    3.9883 mr
 Thold   =     2.0 %,     40 cnts
 Maximum Counts =         2045
Beam thru thresh=     404326
        Total Beam =     416559
Clctr Pos=      1228   1747
Jaw Pos   =       870   1089
```

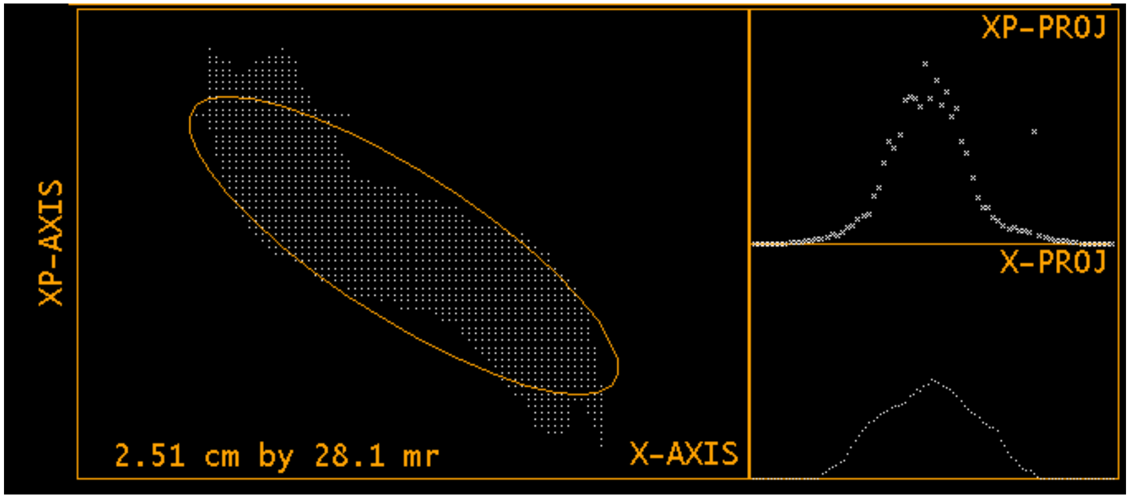



```
Run:22680   Stn: TBEM01-V
03:02:20      24-Aug-2010
Beam: H-        Meas,    Norm
E(total)=      3.832,   0.153 pi
E(edge) =      3.439 pi
E(rms)  =      0.532,   0.021 pi
Etot/rms=       7.20
 Alpha   =     6.062
 Beta    =     0.371
4*E(rms)=      2.128 pi
      C   =   -0.203 cm
     CP   =    3.179 mr
X Sigma =    0.4440 cm
XP Sigma=    7.3627 mr
 Thold   =     2.0 %,     34 cnts
 Maximum Counts =         1739
Beam thru thresh=     239457
        Total Beam =     264341
Clctr Pos=      1244   1851
Jaw Pos   =       867   1092
```

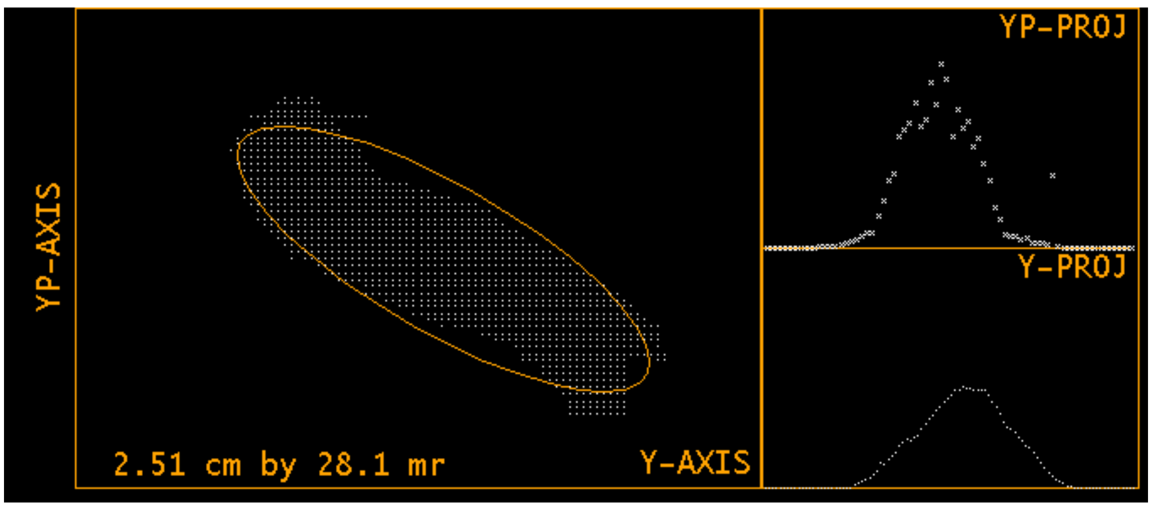
Particle distribution generated from TBEM1 emittance scan data



Measured beam distribution at TBEM3

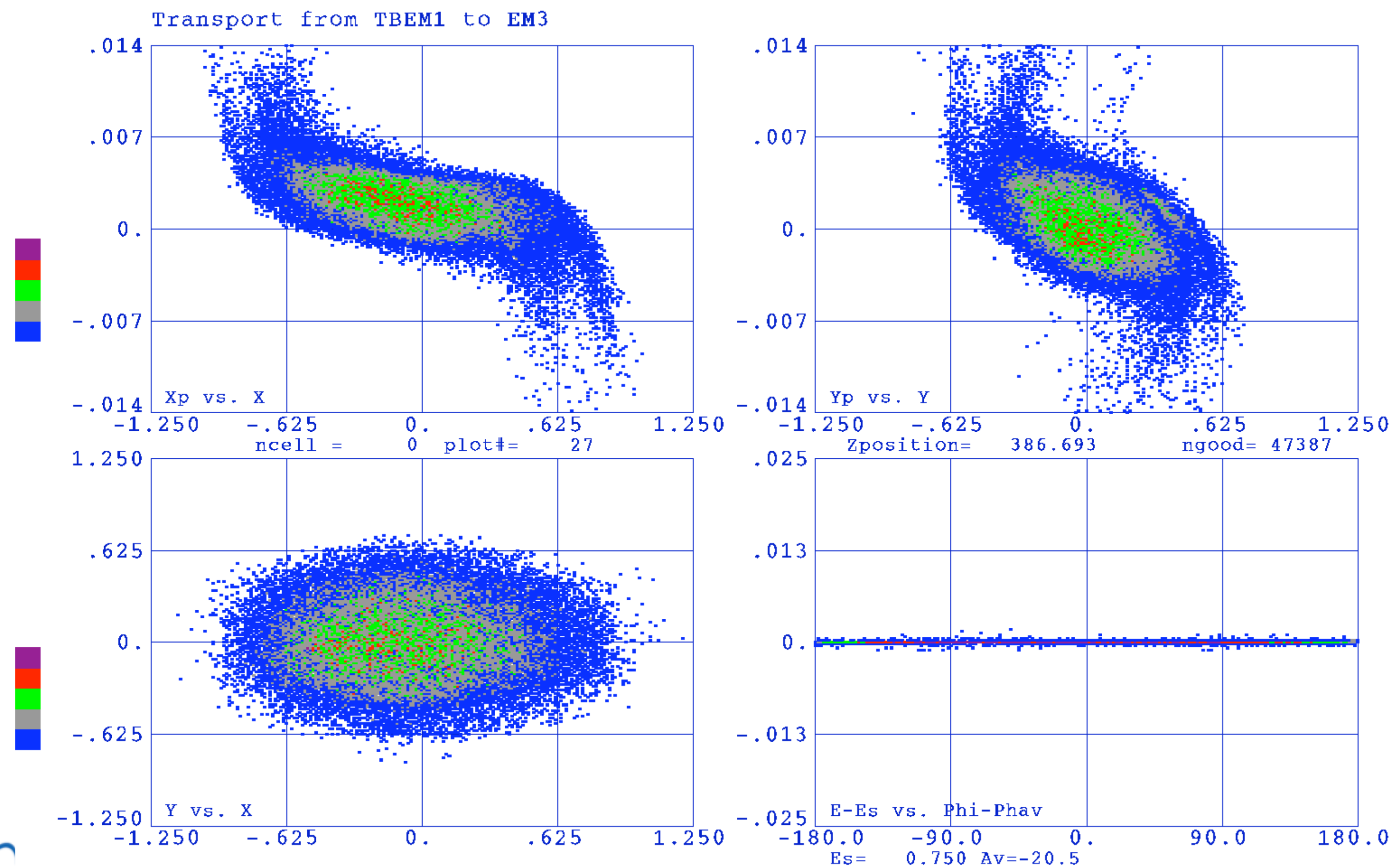



```
Run:22693    Stn: TBEM03-H
05:44:32       24-Aug-2010
Beam: H-        Meas,    Norm
E(total)=      4.285,   0.171 pi
E(edge) =      4.173 pi
E(rms)  =      0.633,   0.025 pi
Etot/rms=       6.77
 Alpha   =      1.447
 Beta    =      0.157
4*E(rms)=      2.533 pi
   C     =     -0.033 cm
   CP    =     -0.042 mr
X Sigma =     0.3154 cm
XP Sigma=     3.5315 mr
 Thold   =      2.0 %,    16 cnts
 Maximum Counts =         801
Beam thru thresh=      283815
     Total Beam =      287213
Clctr Pos=      1357    1947
Jaw Pos   =     1382    1971
```

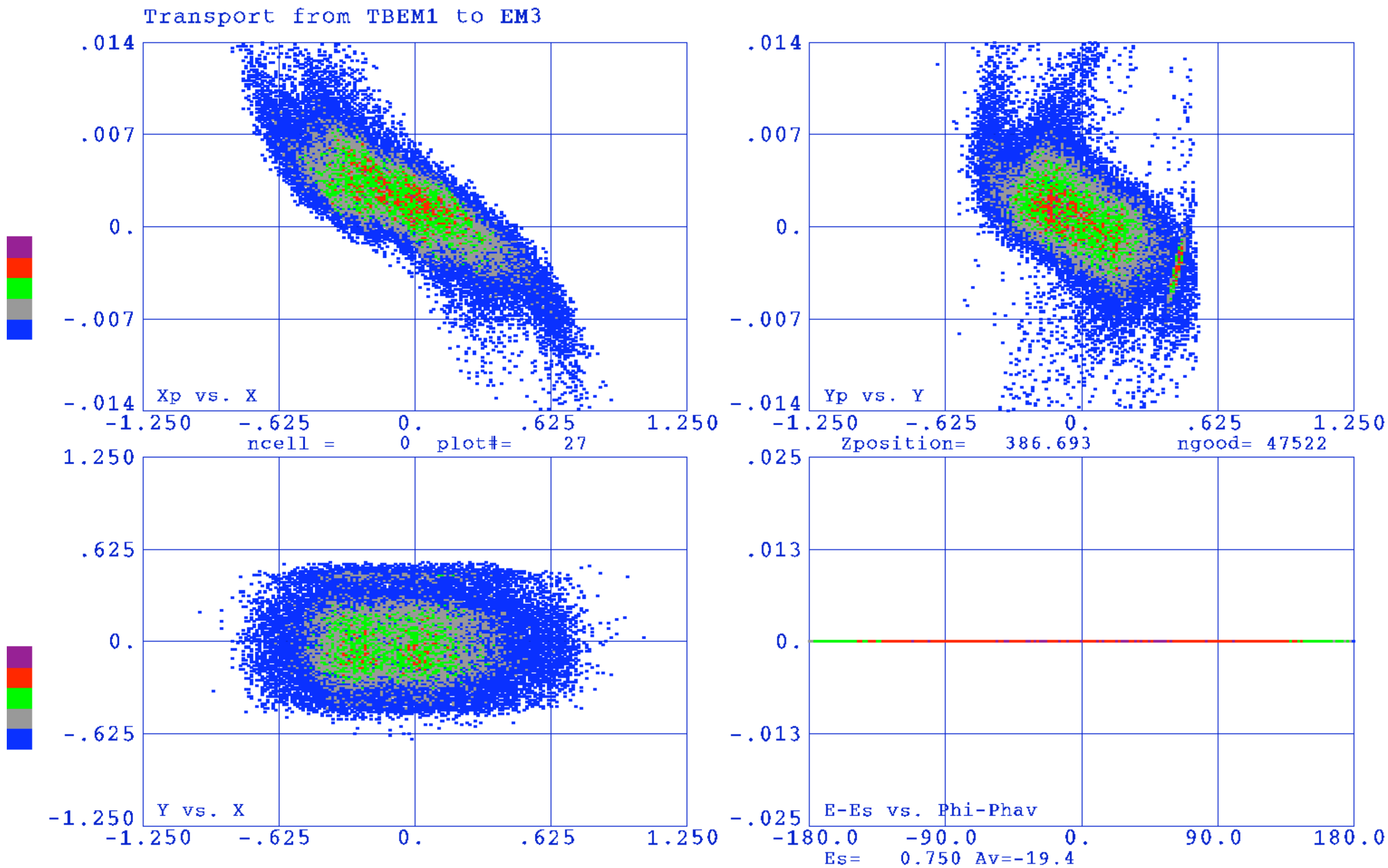



```
Run:22694    Stn: TBEM03-V
05:55:34       24-Aug-2010
Beam: H-        Meas,    Norm
E(total)=      3.853,   0.154 pi
E(edge) =      3.722 pi
E(rms)  =      0.560,   0.022 pi
Etot/rms=       6.88
 Alpha   =      1.250
 Beta    =      0.154
4*E(rms)=      2.240 pi
   C     =      0.098 cm
   CP    =     -0.603 mr
X Sigma =     0.2940 cm
XP Sigma=     3.0491 mr
 Thold   =      2.0 %,    17 cnts
 Maximum Counts =         852
Beam thru thresh=      283888
     Total Beam =      287316
Clctr Pos=      1352    1944
Jaw Pos   =     1376    1968
```

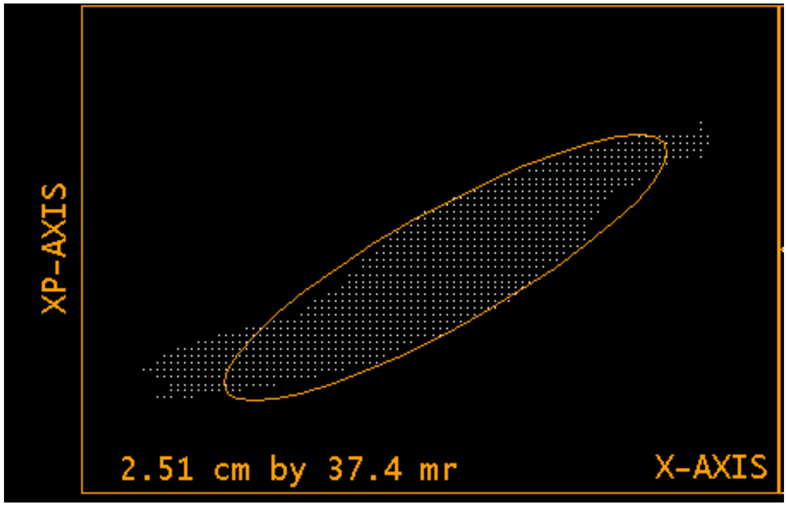
Results of PARMILA simulation from TBEM1 to TBEM3 with current of I = 15 mA

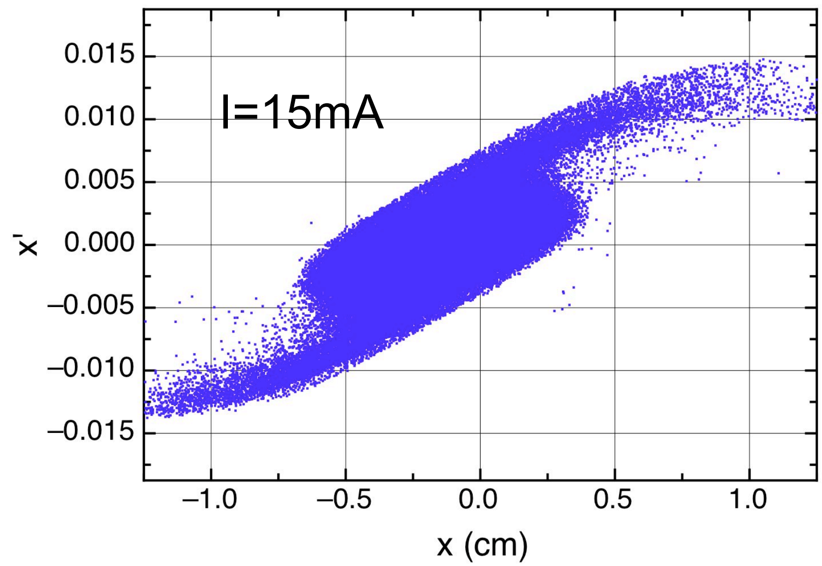


Results of PARMILA simulation from TBEM1 to TBEM3 with current of I = 0

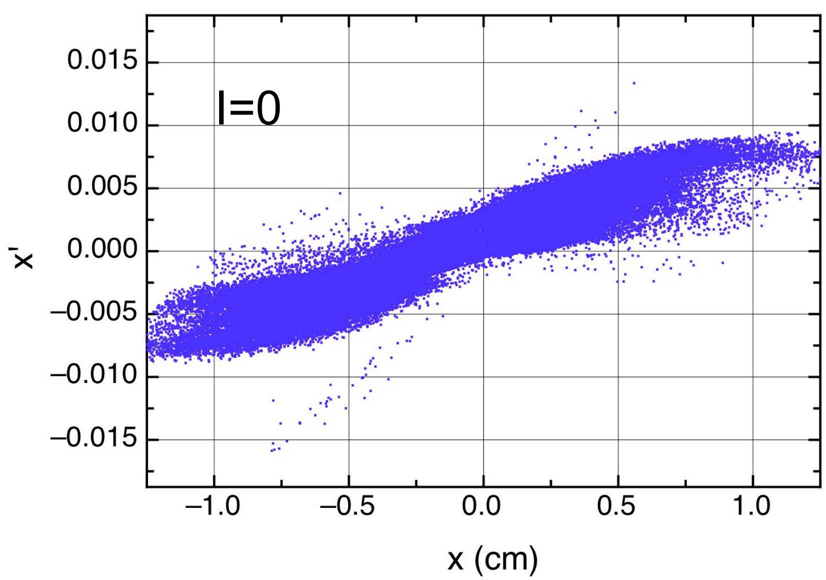


Comparison of BEAMPATH simulation with TDEM1 emittance scan





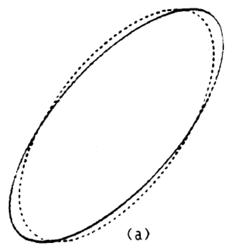

```
Run:22684  Stn: TDEM01-H
03:54:34     24-Aug-2010
Beam: H-      Meas,   Norm
E(total)=   4.219,  0.169 pi
E(edge) =   4.055 pi
E(rms)  =   0.505,  0.020 pi
Etot/rms=    8.35
 Alpha  =  -1.770
 Beta   =   0.158
4*E(rms)=   2.020 pi
     C  =   0.062 cm
    CP  =  -1.394 mr
X Sigma =   0.2824 cm
XP Sigma=   3.6365 mr
 Thold  =    2.0 %,     5 cnts
 Maximum Counts =      269
Beam thru thresh=    65369
     Total Beam =    68096
Clctr Pos=   1327  1853
Jaw Pos  =   1341  1930
```



Mismatch between emittance measurements and simulations

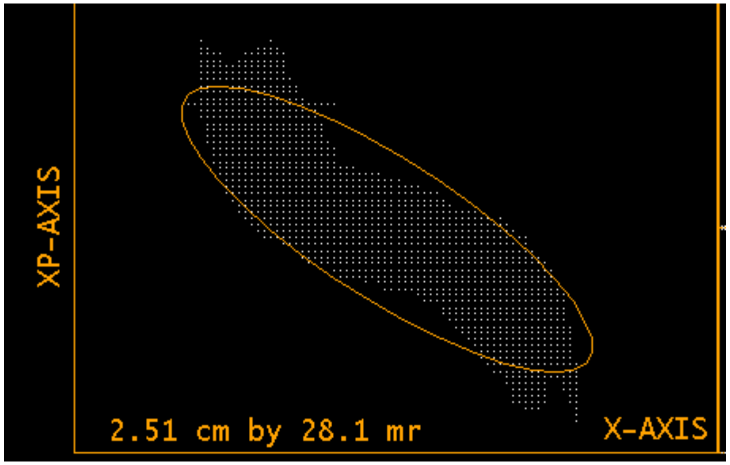
Mismatch factor $F=\sqrt{\frac{1}{2}(R+\sqrt{R^2-4})}-1$

$$R=\beta_{\exp}\gamma_s+\beta_s\gamma_{\exp}-2\alpha_{\exp}\alpha_s$$

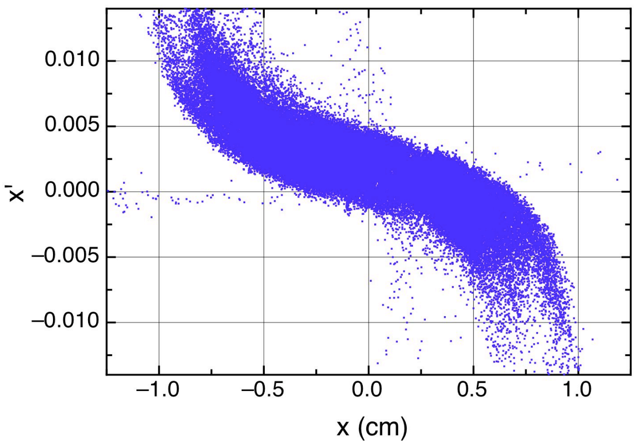


Station	I=0	I=15 mA
TBEM2-H	0.3003156	0.2039033
TBEM2-V	0.1455864	0.2105775
TBEM3-H	0.4146634	0.3143147
TBEM3-V	6.7809701E-02	3.7730098E-02
TBEM4-H	0.6731801	0.2845534
TBEM4-V	0.1216830	0.1859181
TDEM1-H	0.7964662	0.1929483
TDEM1-V	4.1545153E-02	0.1046102
	$\bar{F}=0.319$	$\bar{F}=0.191$

Effect of input distribution on beam emittance distortion



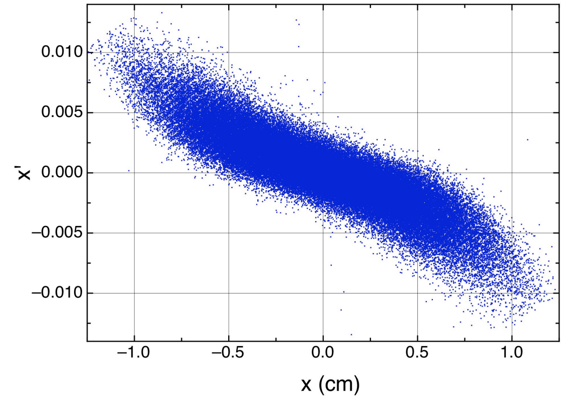
TBEM3 beam emittance scan



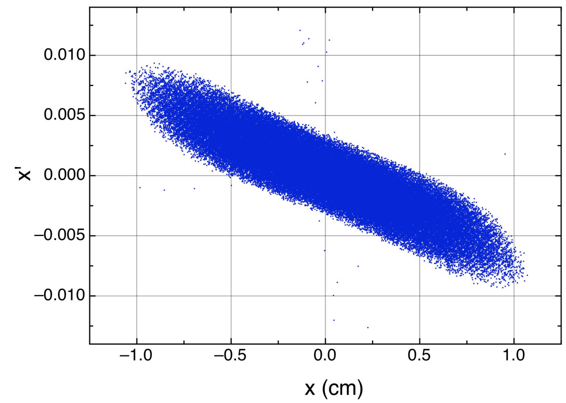
BEAMPATH simulation with measured input distribution

BEAMPATH simulation with elliptical input distributions

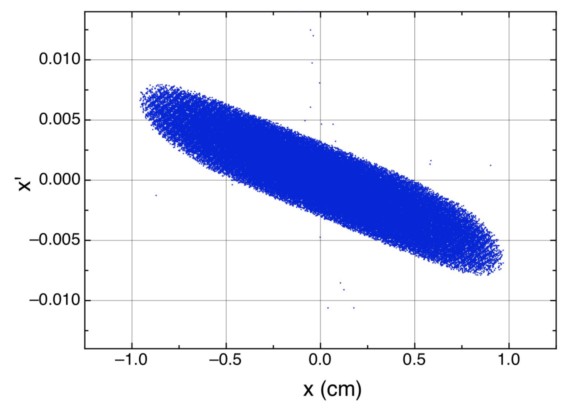
Gaussian



Parabolic

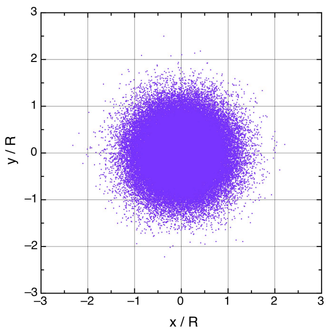


Water Bag



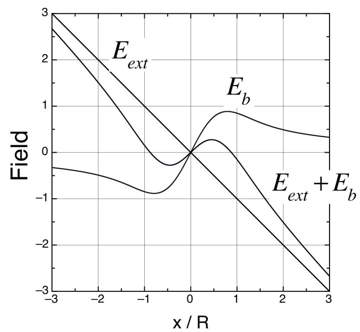
Effect of space charge aberration on beam emittance

Space charge density and space charge field of the beam with Gaussian distribution are given by



$$\rho(r_o) = \frac{2I}{\pi R_o^2 \beta c} \exp(-2\frac{r_o^2}{R_o^2})$$

$$E_b = \frac{I}{2\pi \varepsilon_o \beta c} \frac{1}{r_o} [1 - \exp(-2\frac{r_o^2}{R_o^2})]$$



Nonlinear function in space charge field is expanded as

$$f(r_o) = 1 - \exp(-2\frac{r_o^2}{R_o^2}) \approx 2\frac{r_o^2}{R_o^2} - 2\frac{r_o^4}{R_o^4} + \dots$$

At the initial stage of beam emittance growth we can assume, that particle radius is unchanged, while the slope of the trajectory is changed. It gives us the nonlinear transformation:

$$r = r_o$$

$$r' = r_o' + \frac{2zP^2}{R_o^2} r_o - \frac{2zP^2}{R_o^4} r_o^3$$

where $P^2 = \dfrac{2I}{I_c \beta^3 \gamma^3}$ is the generalized perveance, $I_c = 4\pi\varepsilon_o mc^3 / q$ is the characteristic beam current.

Initial beam distribution:

$$\frac{x_o^2}{R^2}\varepsilon + \frac{x_o^{'2}}{\varepsilon}R^2 = \varepsilon$$

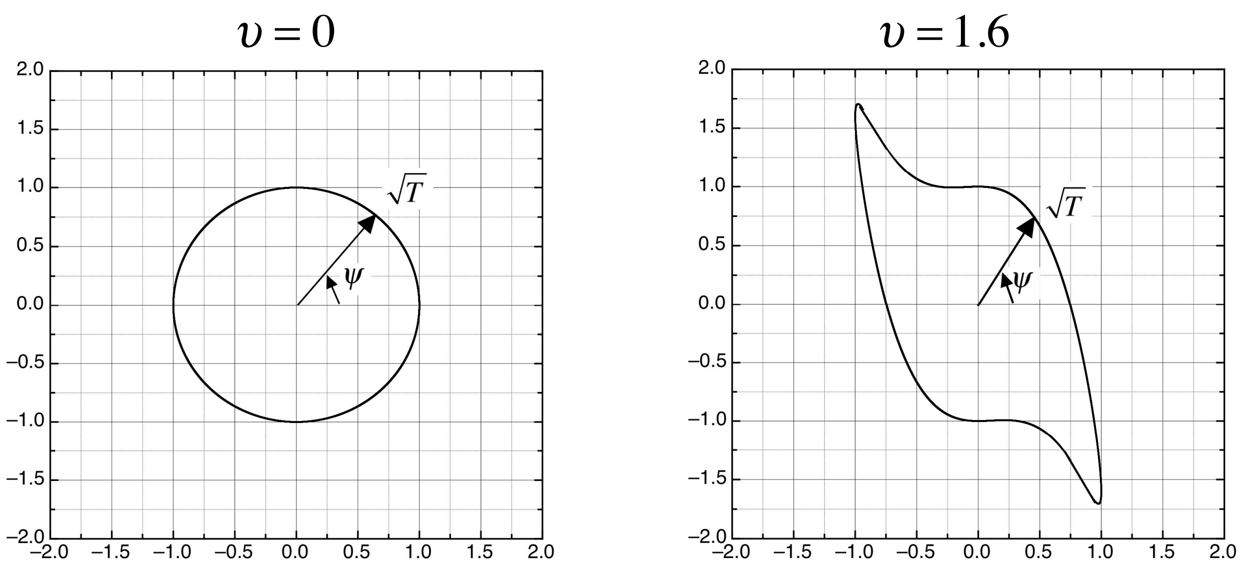
Change variables $(x, x^{'})$ to action-angle variables (J, ψ)

Beam ellipse distortion:

$$T + T^2 2\upsilon \sin\psi \cos^3\psi + T^3\upsilon^2 \cos^6\psi = 1$$

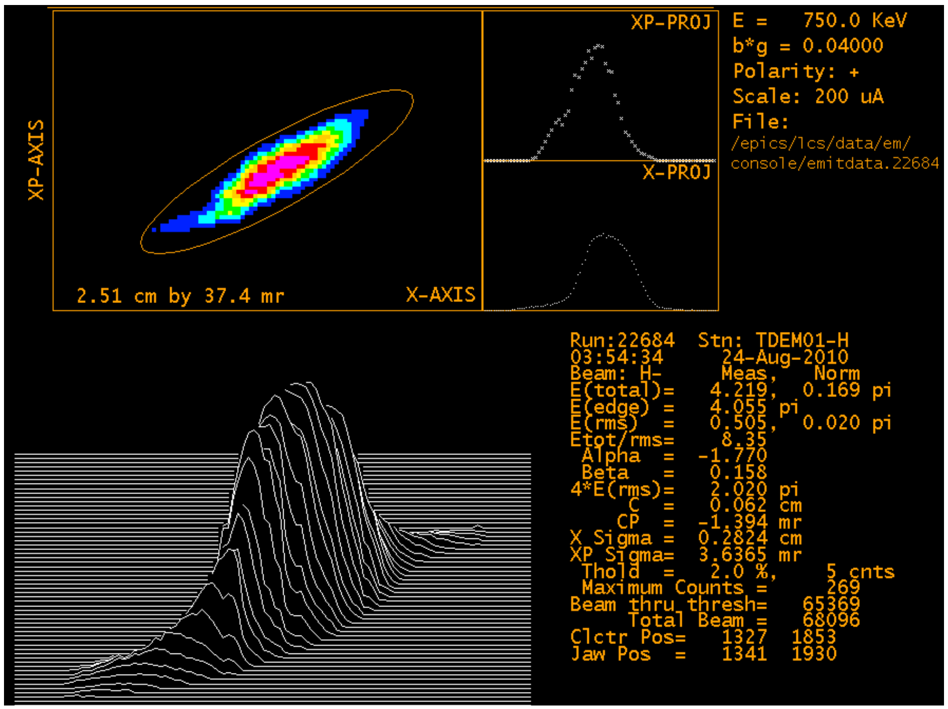
where

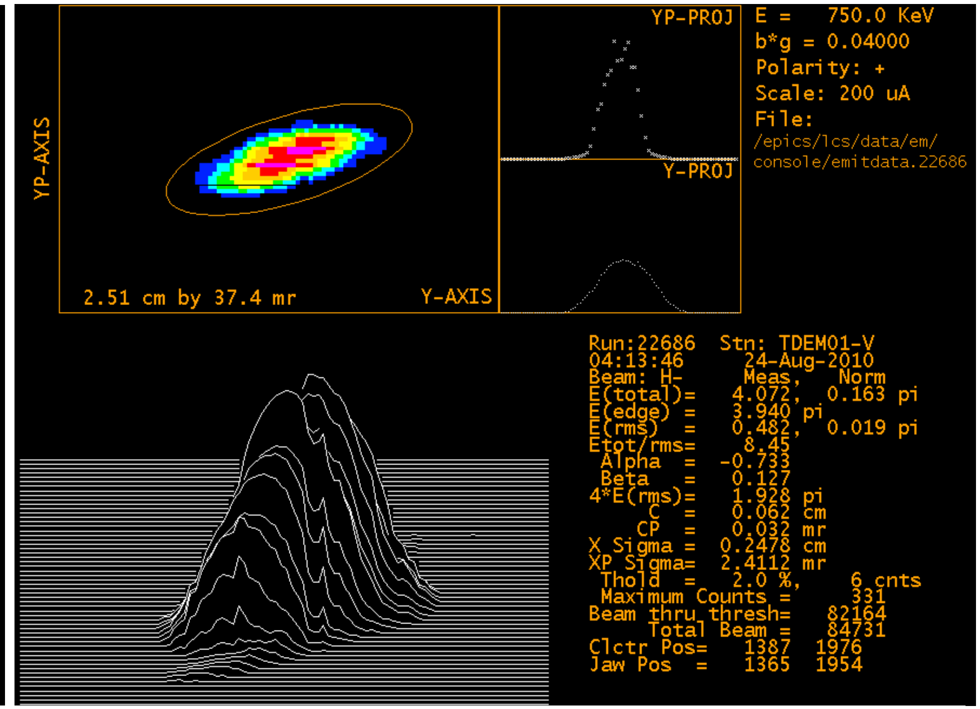
$$T = \frac{2J}{\varepsilon} \qquad \upsilon = \frac{2zP^2}{\varepsilon}$$

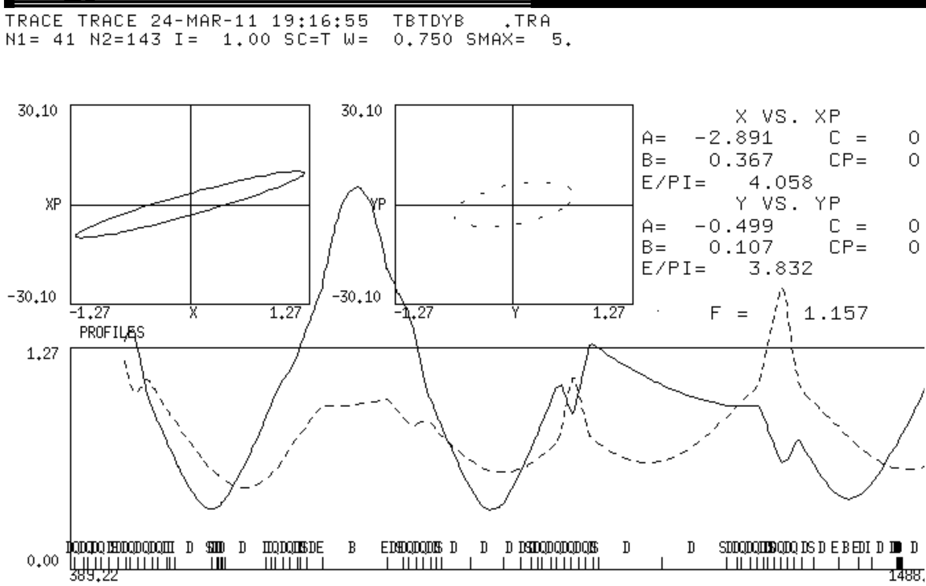


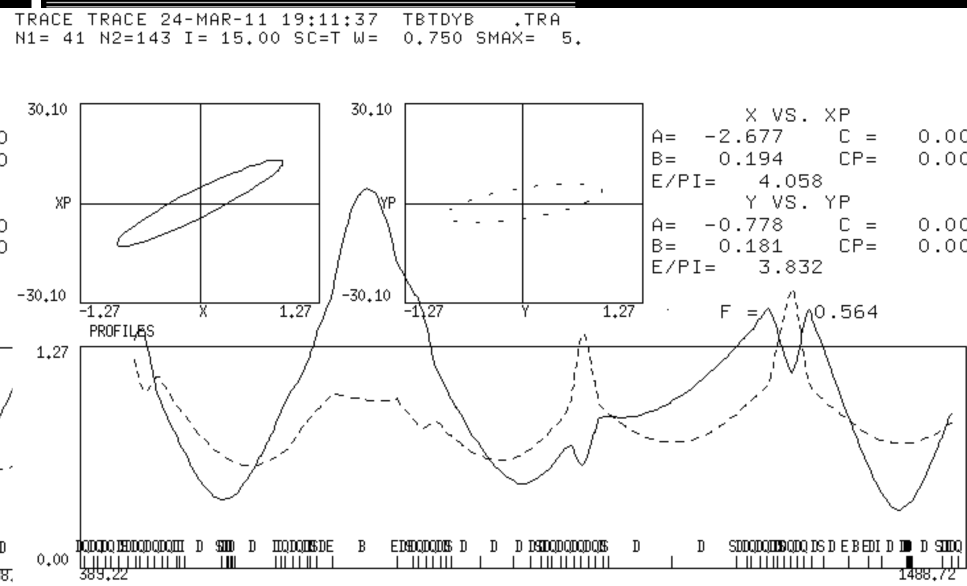
Distortion of beam emittance due to space charge aberration

Comparison with TRACE simulations





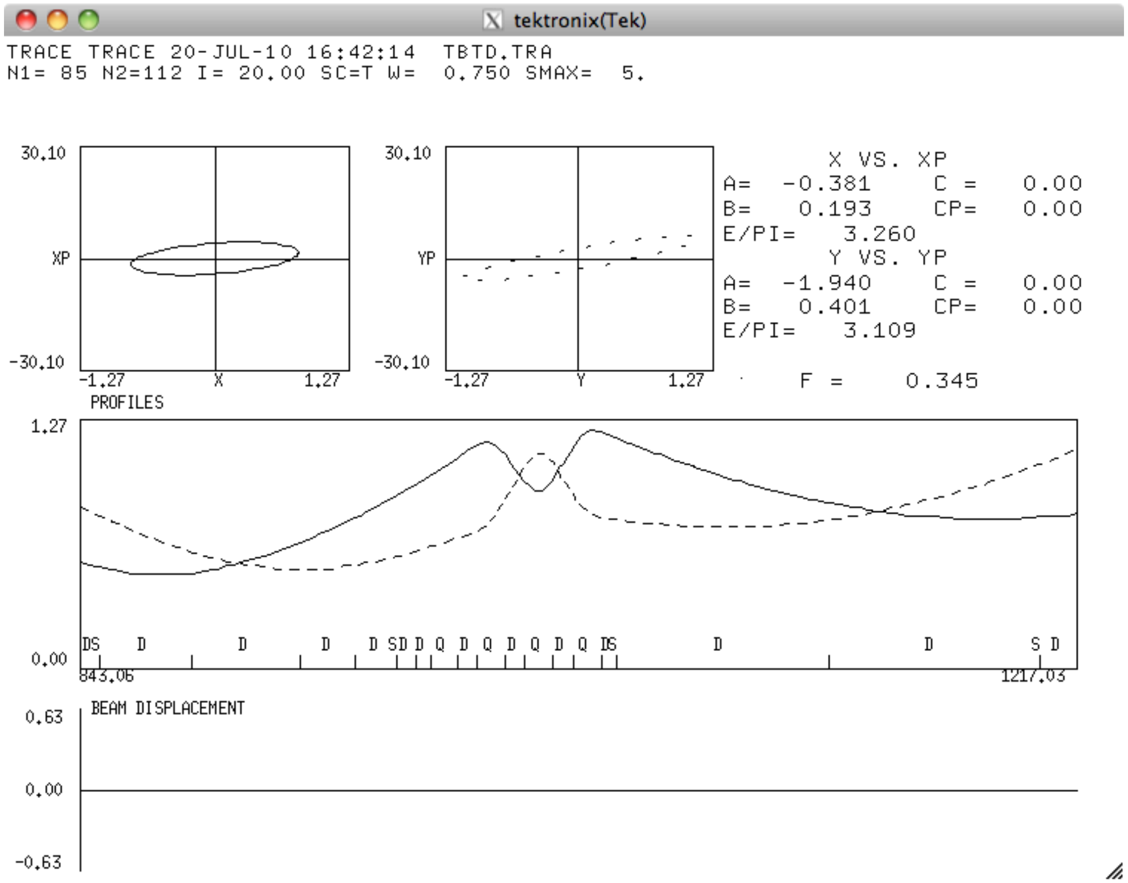


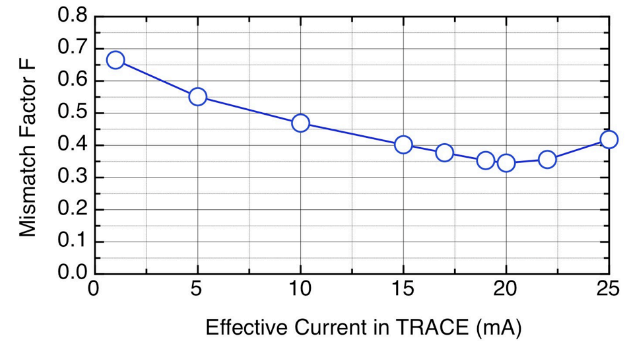


Mismatch factor F between emittance measurements and TRACE simulations

	$I = 0$		$I = 15\text{mA}$	
Station	$4\varepsilon_{rms}$	Total emittance	$4\varepsilon_{rms}$	Total emittance
TBEM1	0	0	0	0
TBEM2	0.607	0.626	0.456	0.359
TBEM3	0.627	0.648	0.732	0.513
TBEM4	0.879	0.935	0.922	0.428
TDEM1	1.093	1.161	0.686	0.565
	$\bar{F} = 0.801$	$\bar{F} = 0.843$	$\bar{F} = 0.699$	$\bar{F} = \mathbf{0.466}$

TRACE beam tracking in drift space from TBEM3 to TBEM4

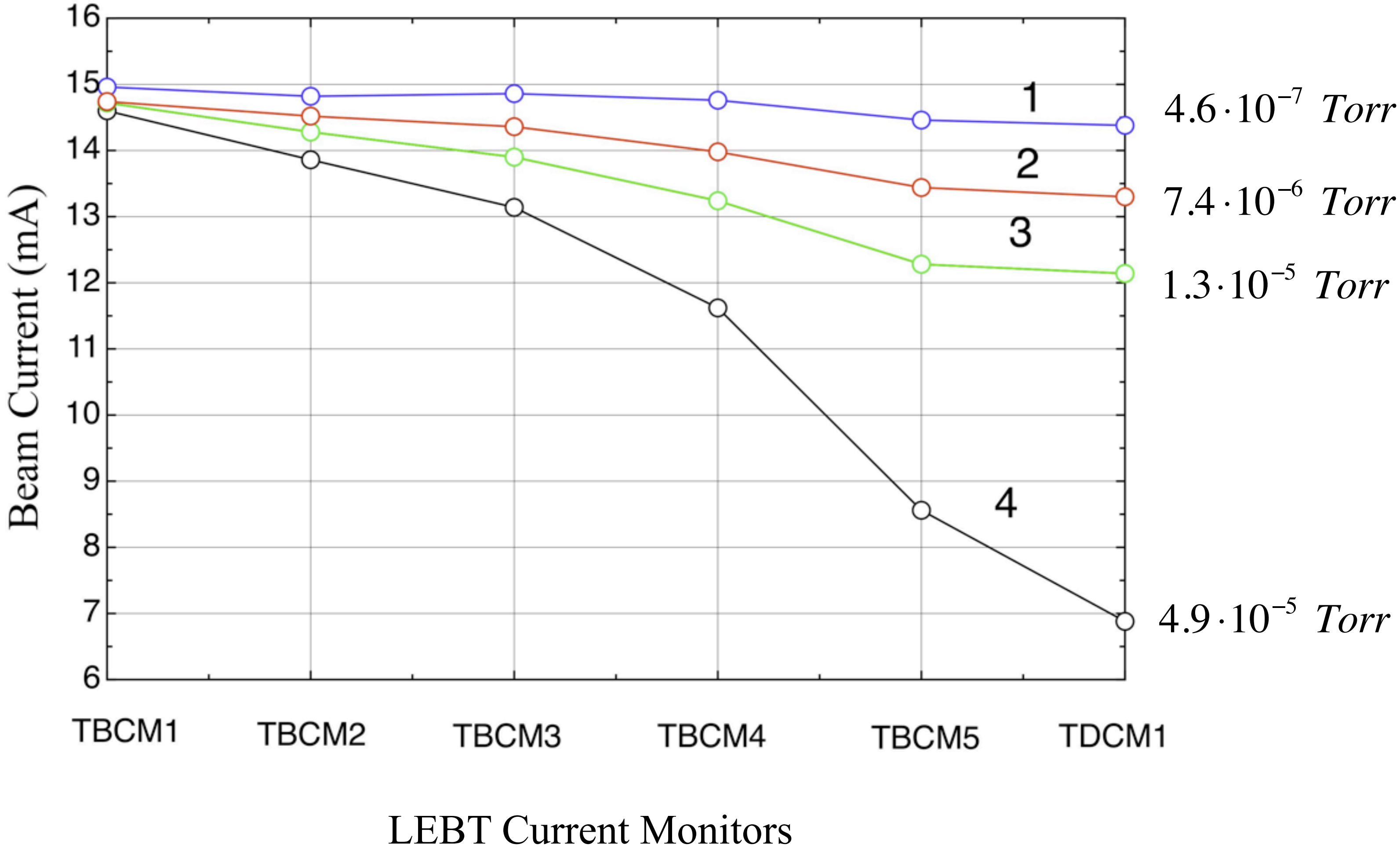




TRACE mismatch factor F as a function of beam current in beam drift between TBEM3 and TBEM4.

Results of TRACE beam tracking from TBEM3 to TBEM4 using measured data at TBEM3. Adjustment of beam current was done to get close to measured TBEM4 beam data.

Beam transmission through LEBT as a function of vacuum conditions



Estimation of H^- stripping cross section from measurements

Beam losses

$$\frac{\Delta I}{I} = n\sigma l$$

Cross section

$$\sigma = \left(\frac{\Delta I}{I}\right)\frac{1}{nl}$$

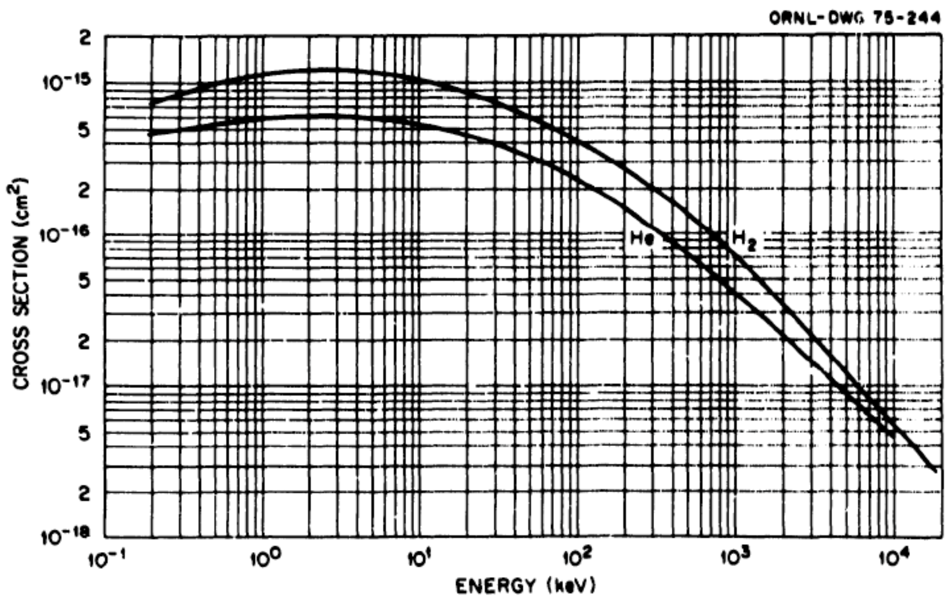
Residual gas density

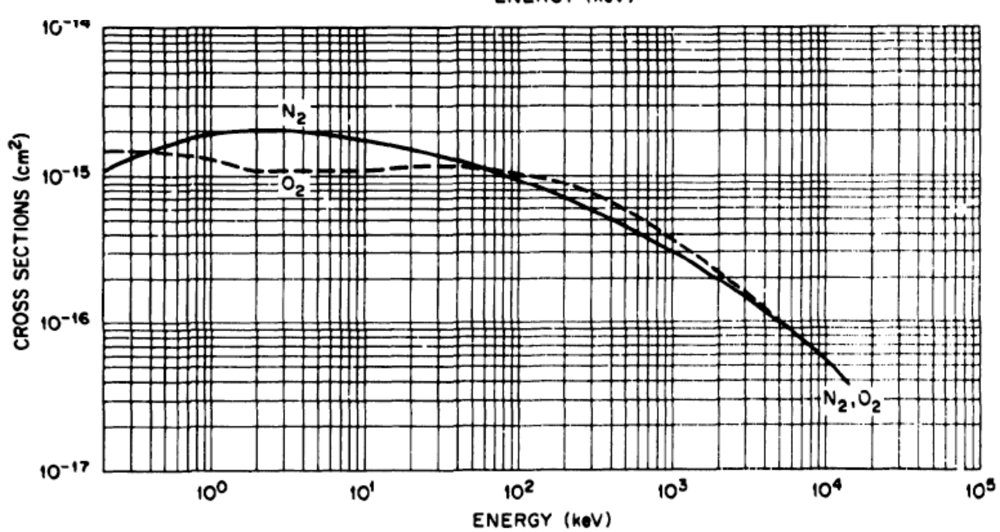
$$n = \frac{N_A P}{RT}$$

#	Pressure, Torr	Relative beam losses	Cross section, m^2
1	7e-07	0.0387	7.19e-20
2	7e-06	0.0977	1.8e-20
3	1.3e-05	0.175	1.75e-20
4	5e-05	0.528	1.5e-20
5	6e-07	0.0192	4e-20
6	7e-06	0.1049	3.9e-20
7	2.6e-05	0.305	1.52e-20

Average value of stripping cross section $\sigma = 3.08 \cdot 10^{-16}\, cm^2$

Cross Section for stripping H^- in different gases (Atomic Data for Controlled Fusion Research, ORNL-5206)

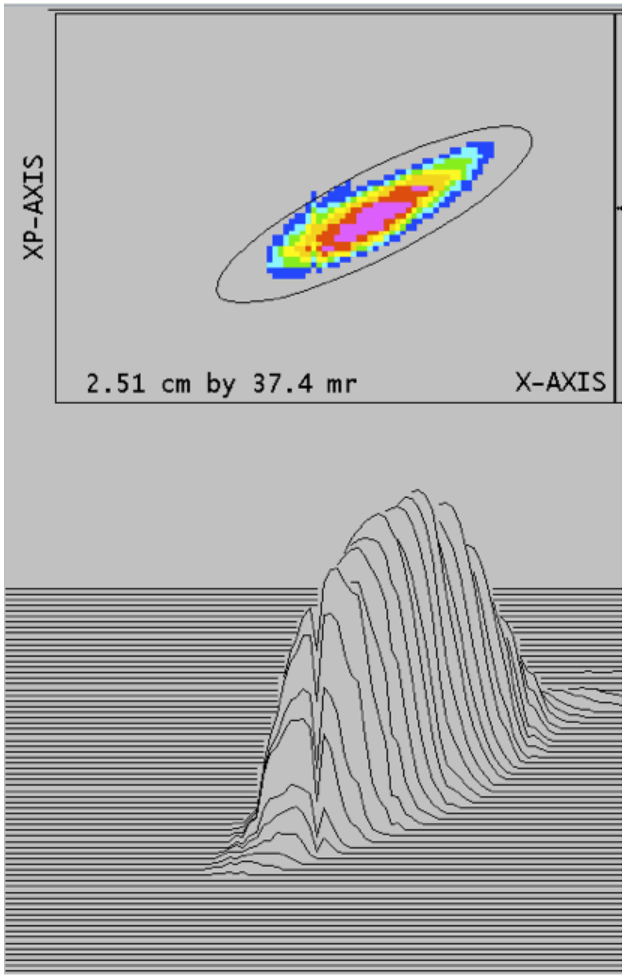




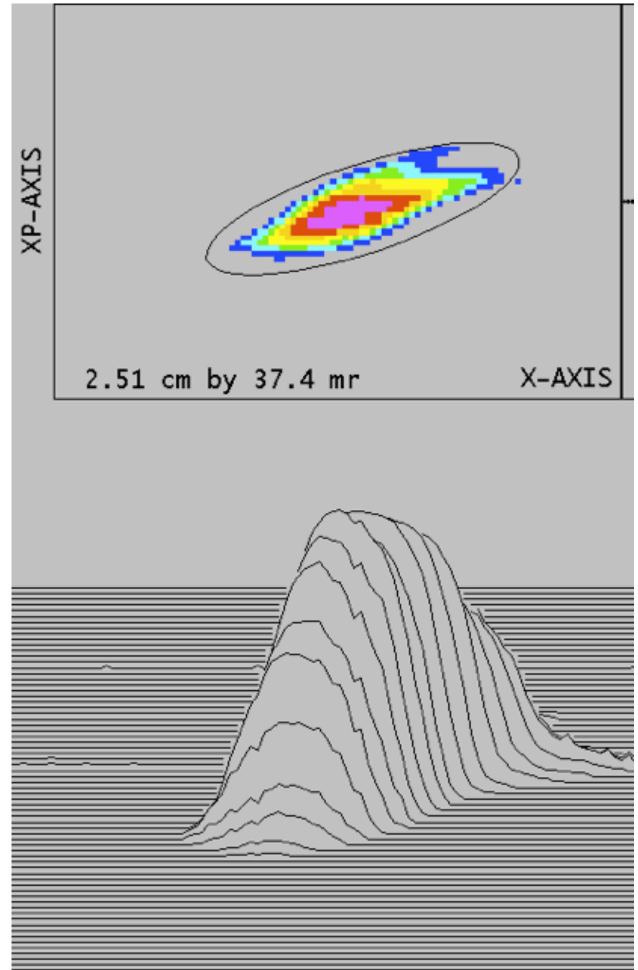
Single stripping cross-section σ_{-10} of 750 keV H^- in different gases

Gas	Cross section, cm^2
H_2	$7 \cdot 10^{-17}$
He	$5 \cdot 10^{-17}$
N_2	$3 \cdot 10^{-16}$
O_2	$4 \cdot 10^{-16}$

TDEM1 emittance scans under nominal and poor LEBT vacuum conditions



$7 \cdot 10^{-7}\ Torr$



$3 \cdot 10^{-5}\ Torr$

Summary

1. LANSCE H^- 750 keV beam transport is space charge uncompensated.
2. The beam develops S-shaped distortion in phase space typical for nonlinear space charge forces.
3. Macroparticle models give the best agreement to experimentally observed results when the input distribution is taken directly from measurements.
4. Elliptical models are insufficient to reproduce dynamics of H^- beam.