Electron-Cloud Simulations for the FCC-ee Collider Arcs and for the e+ Damping Ring

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Acknowledgments:
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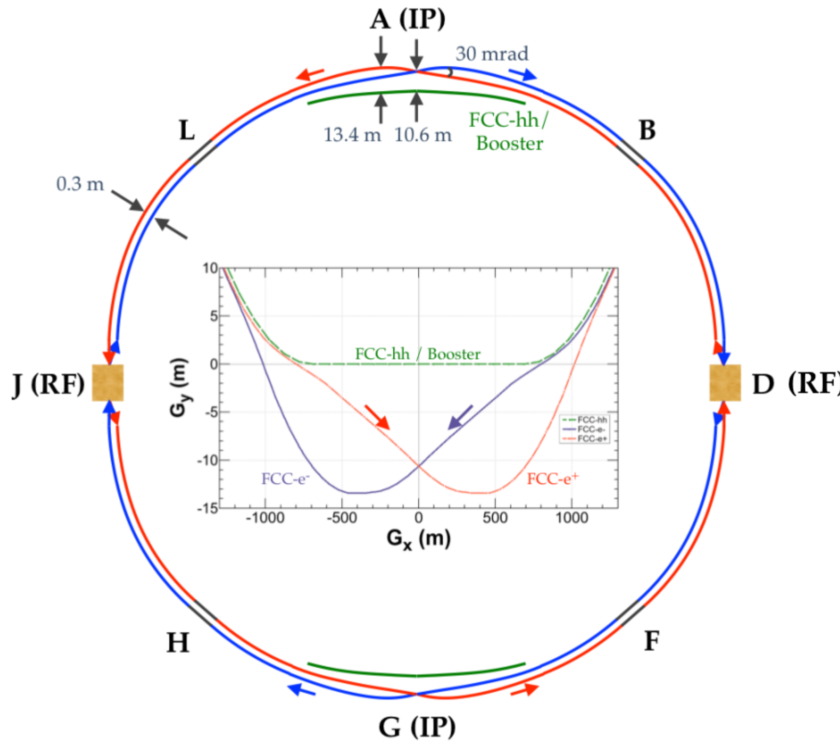
FCC-ee Collider and Beam Parameters

beam energy [GeV]	45.6
bunch spacing [ns]	10, 12.5, 15, 17.5, 20
bunches per train	150
trains per beam	1
circular beam pipe radius [mm]	35
r.m.s. bunch length (σ_z) [mm]	3.5
h. r.m.s. beam size (σ_x) [μm]	120
v. r.m.s. beam size (σ_y) [μm]	7
number of particles / bunch	1.7 x 10^{11}
bend field [T]	0.01415
secondary emission yield (SEY)	1.1, 1.2, 1.3, 1.4, 2.1
photoelectrons generation rate $n'_{e(\gamma)}$	1e-3, 1e-4

Frank Zimmermann, 'FCC-ee design overview'
FCC Week 2019 Brussels, June 2019
https://indico.cern.ch/event/727555/



$$n'_{e(\gamma)} = Y_\gamma \frac{dN_\gamma}{dz}$$

$$Y_\gamma \approx 0.1$$

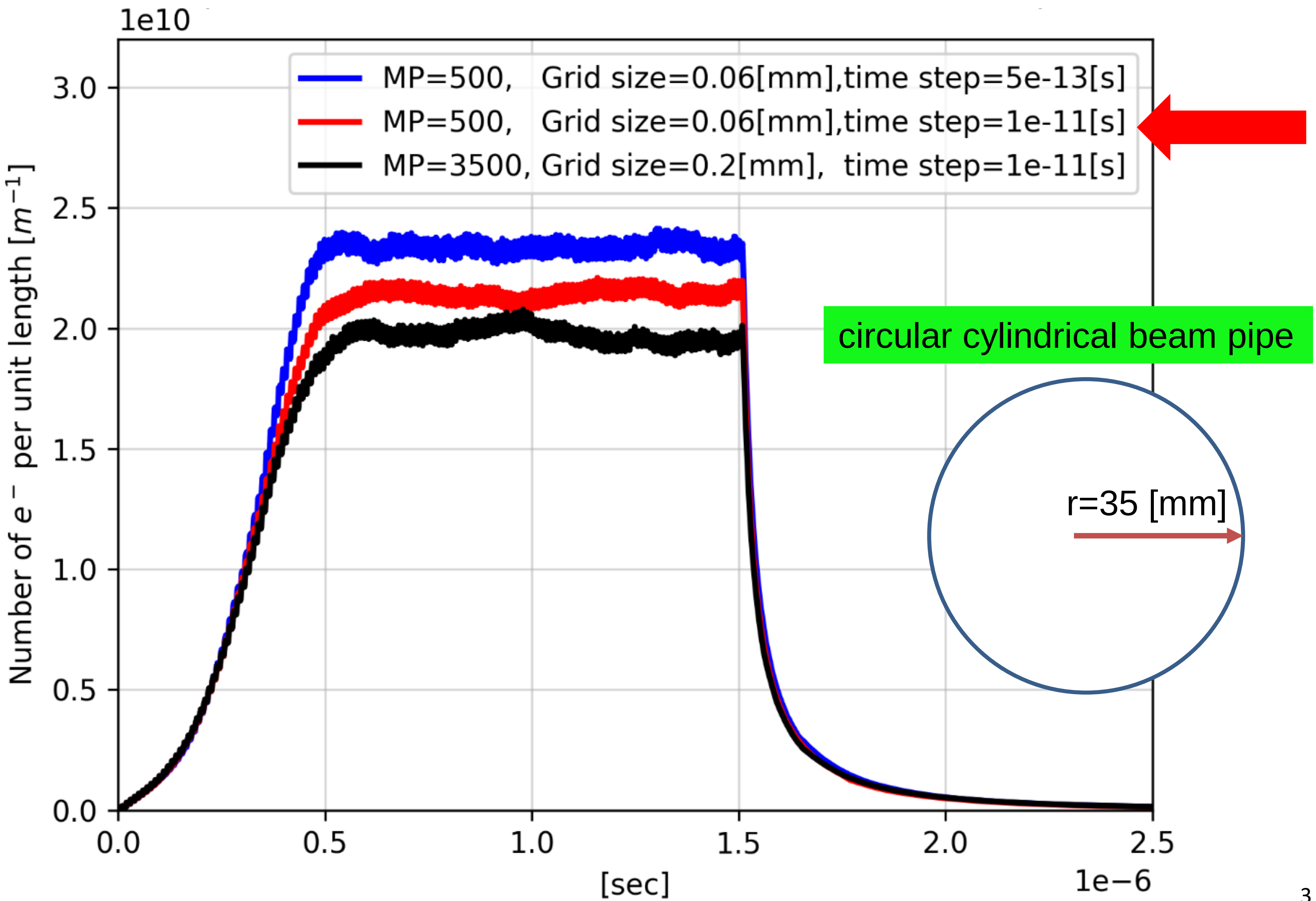
(photo-electron yield coefficient)

Number of photoelectrons emitted per length:

$$\frac{dN_\gamma}{dz} = \frac{5\alpha\,\gamma}{2\sqrt{3}\rho}$$

- $\alpha \approx 1/137$, fine structure constant
- $\gamma \approx 10^5$, the Lorentz factor
- $\rho \approx 11000$ [m] , radius of curvature of the particle path

Convergence for bunch spacing 10[ns]



Furman- Pivi Model for various SEY values

TABLE I: Main parameters of the model.

	Copper	Stainless Steel
Emitted angular spectrum (Sec. II C 1)		
α	1	1
Backscattered electrons (Sec. III B)		
$P_{1,e}(\infty)$	0.02	0.07
$\hat{P}_{1,e}$	0.496	0.5
$\hat{E}_e$ [eV]	0	0
W [eV]	60.86	100
p	1	1
σ_e [eV]	2	1.9
e_1	0.26	0.26
e_2	2	2
Rediffused electrons (Sec. III C)		
$P_{1,r}(\infty)$	0.2	0.74
E_r [eV]	0.041	40
r	0.104	1
q	0.5	0.4
r_1	0.26	0.26
r_2	2	2
True secondary electrons (Sec. III D)		
$\hat{\delta}_{ts}$	1.8848	1.22
$\hat{E}_{ts}$ [eV]	276.8	310
s	1.54	1.813
t_1	0.66	0.66
t_2	0.8	0.8
t_3	0.7	0.7
t_4	1	1
Total SEY[a]		
$\hat{E}_t$ [eV]	271	292
$\hat{\delta}_t$	2.1	2.05

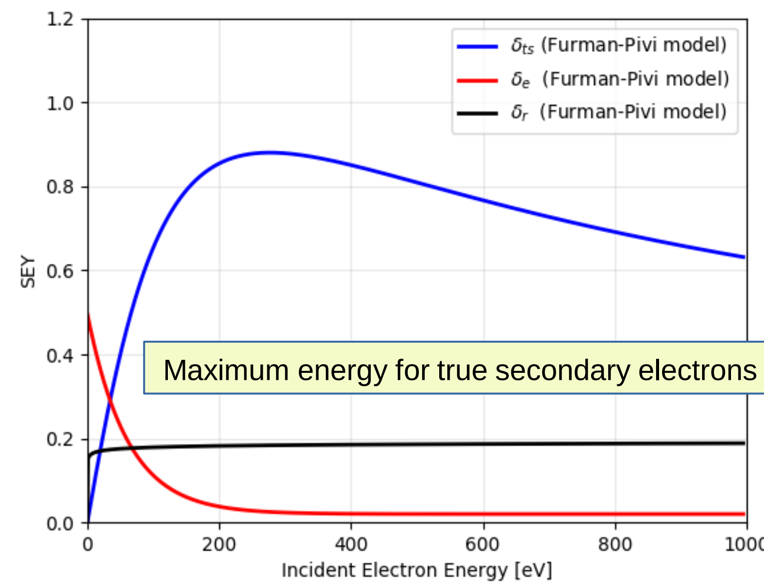
[a]Note that $\hat{E}_t \simeq \hat{E}_{ts}$ and $\hat{\delta}_t \simeq \hat{\delta}_{ts} + P_{1,e}(\infty) + P_{1,r}(\infty)$ provided that $\hat{E}_{ts} \gg \hat{E}_e, E_r$.

$$\delta_e(E_0,\theta_0) = \delta_e(E_0,\theta_0=0)[1+e_1(1-\cos^{e_2}\theta_0)]$$
$$\delta_r(E_0,\theta_0) = \delta_r(E_0,\theta_0=0)[1+r_1(1-\cos^{r_2}\theta_0)]$$
$$\delta_{ts}(E_0,\theta_0) = \hat{\delta}(\theta_0)D(E_0/\hat{E}(\theta_0)),$$

$$\delta(E_0,\theta_0) = \delta_e(E_0,\theta_0) + \delta_r(E_0,\theta_0) + \delta_{ts}(E_0,\theta_0)$$

[a]Note that $\hat{E}_t \simeq \hat{E}_{ts}$ and $\hat{\delta}_t \simeq \hat{\delta}_{ts} + P_{1,e}(\infty) + P_{1,r}(\infty)$ provided that $\hat{E}_{ts} \gg \hat{E}_e, E_r$.

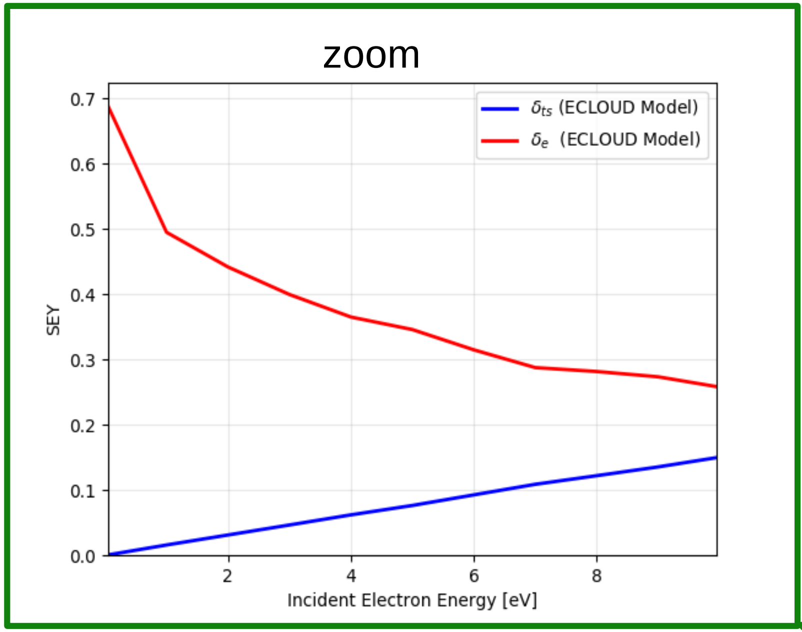
1.1 0.88 0.02 0.2

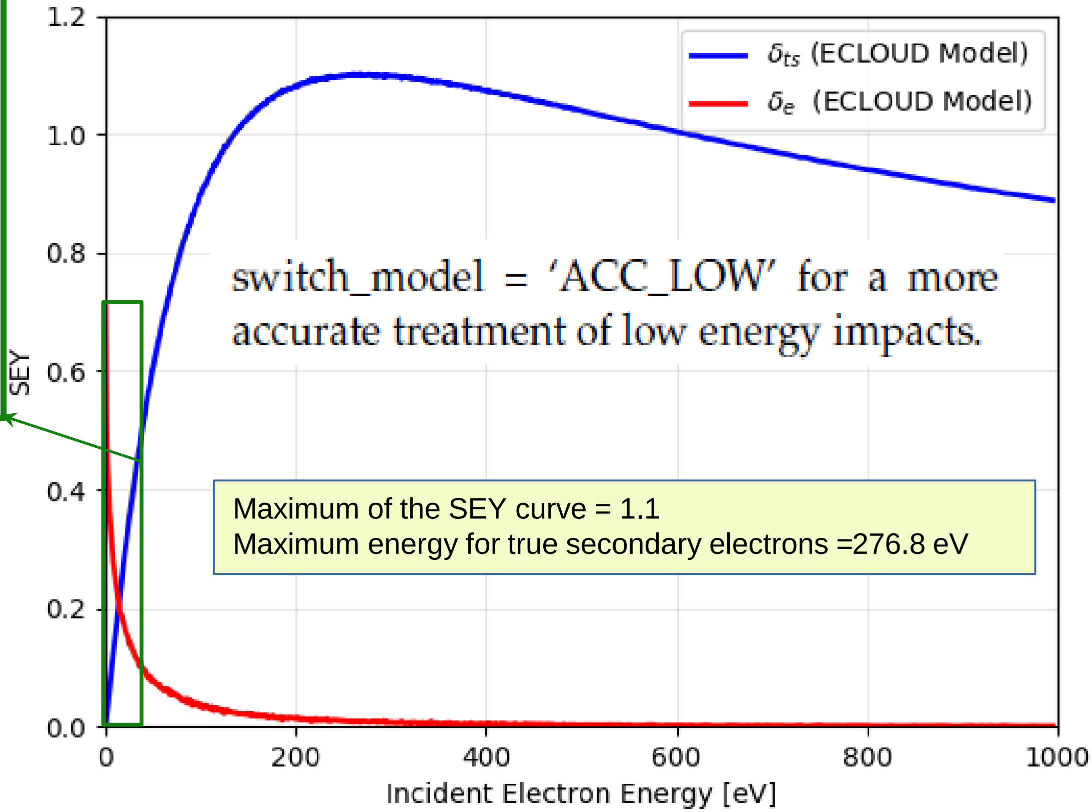


Maximum energy for true secondary electrons = 276.8 eV

M.A. Furman and M.T.F. Pivi, 'Probabilistic Model for the Simulation of Secondary Electron Emission', SLAC-PUB-9912, 2003

ECLOUD SEY Model

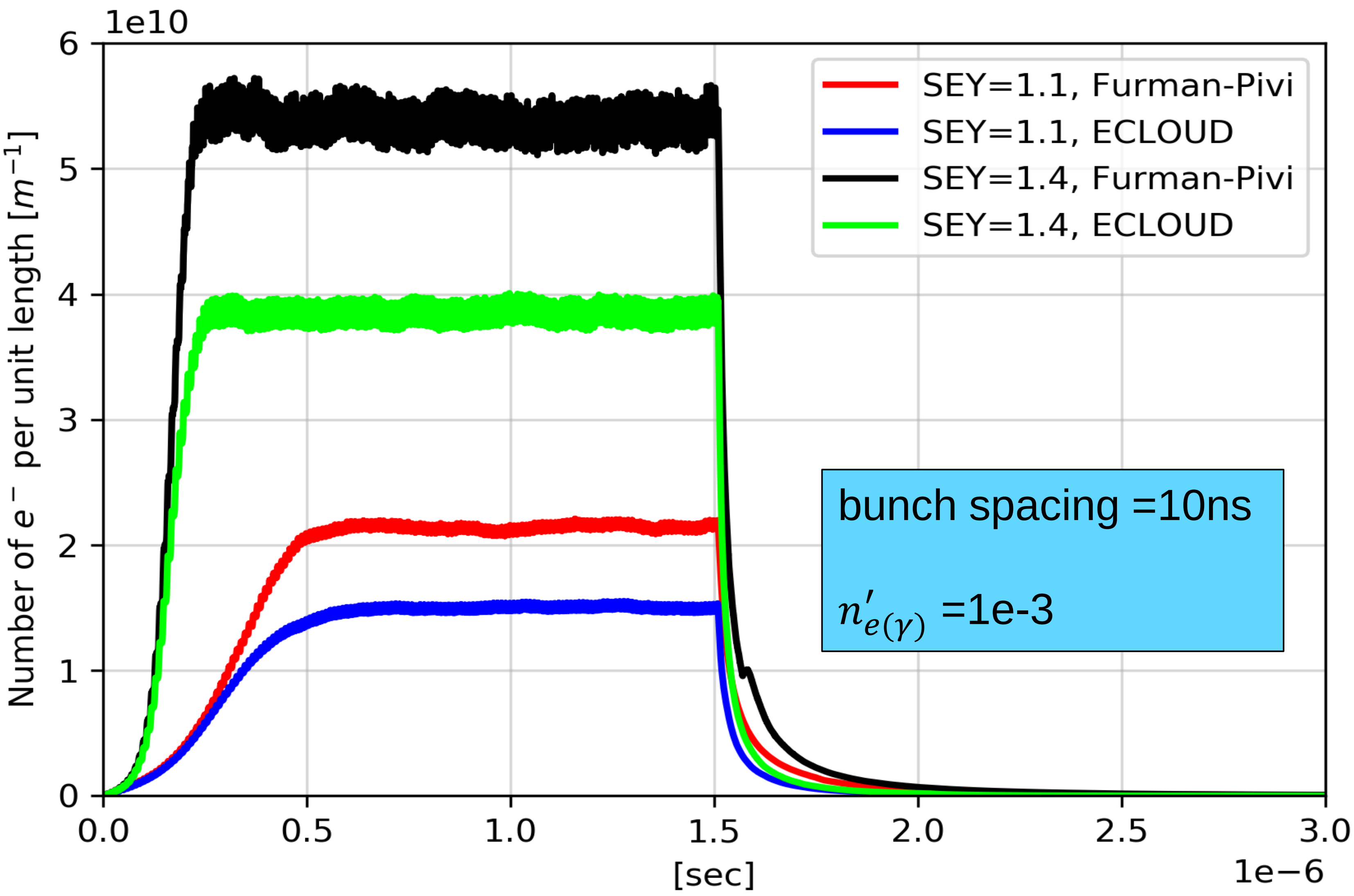




switch_model = 'ACC_LOW' for a more accurate treatment of low energy impacts.

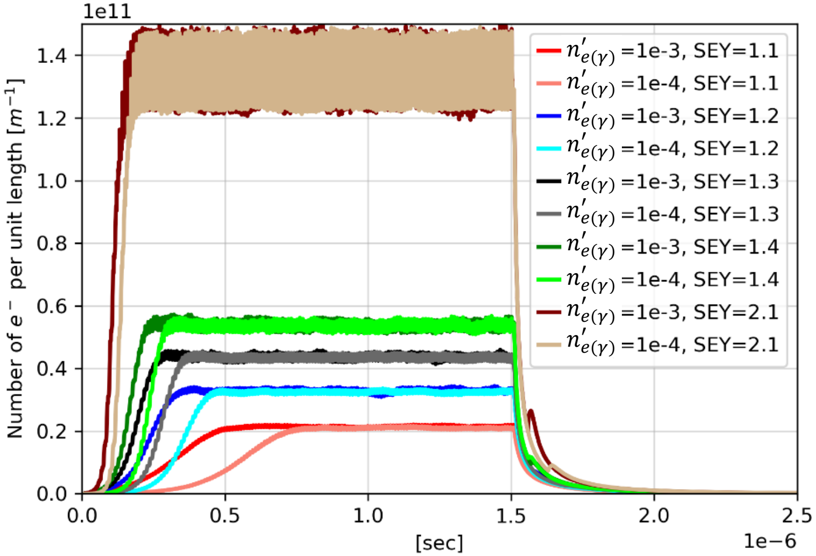
Maximum of the SEY curve = 1.1
Maximum energy for true secondary electrons =276.8 eV

SEY model comparison

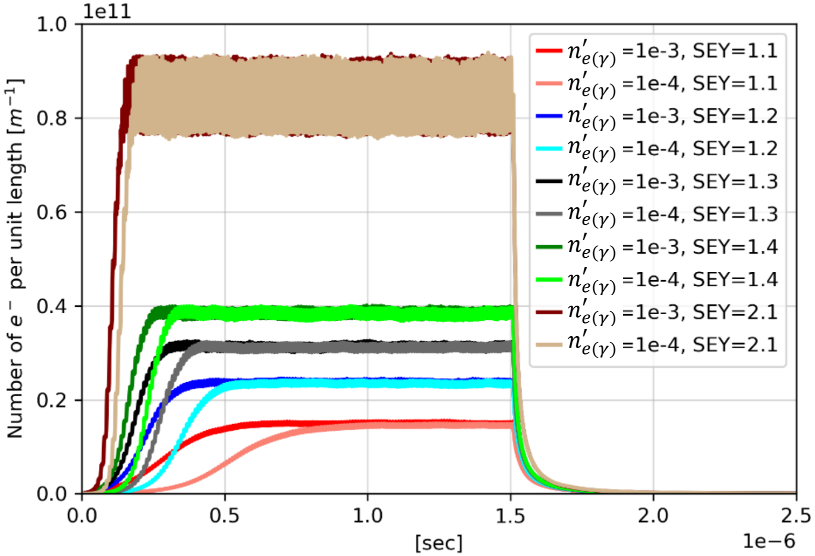


SEY model comparison for 10ns bunch spacing

Furman-Pivi Model

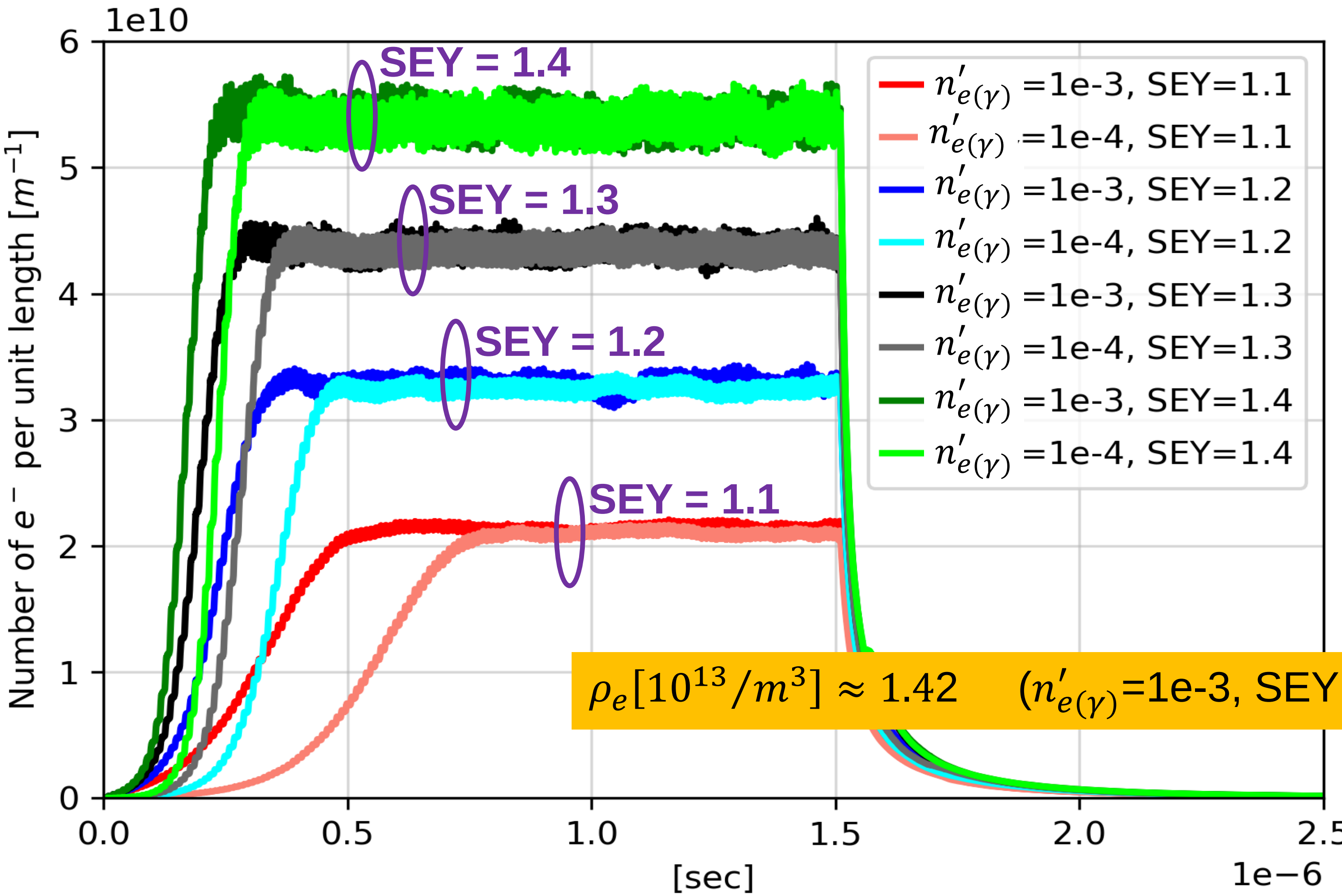


ECLOUD Model



Number electrons in the saturation region is higher for the Furman-Pivi SEY model.

Collider Parameters, bunch spacing =10 [ns]



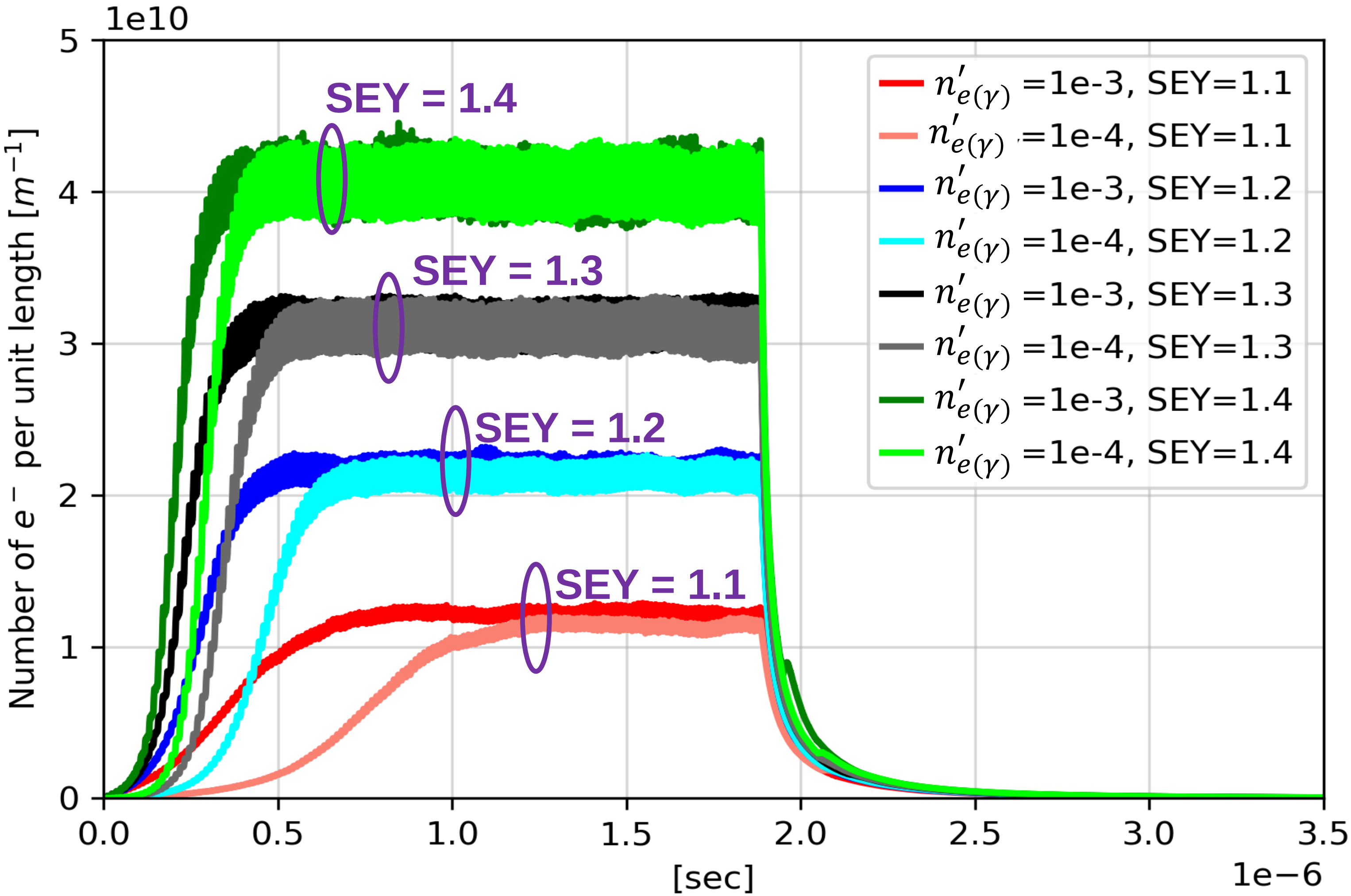
$\rho_e[10^{13}/m^3] \approx 1.42$ ($n'_{e(\gamma)}$=1e-3, SEY =1.4)

$$\rho_{neutr} = \frac{N_b}{L_{sep}\,\pi\,h_x\,h_y}$$

- L_{sep} , bunch spacing in m
- $h_x\ h_y$, beam pipe radius

$\rho_{neutr}[10^{13}/m^3] = 1.47$

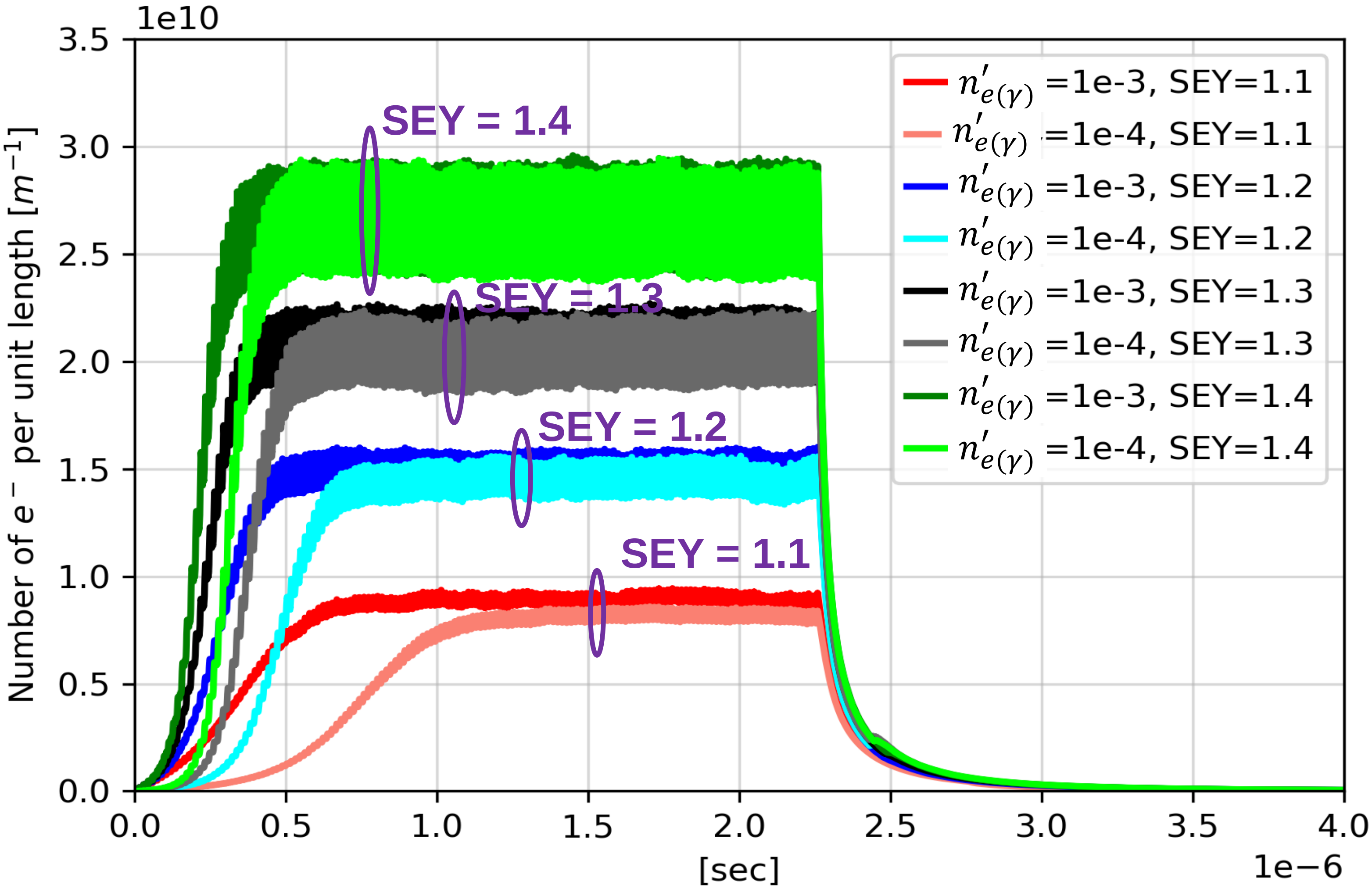
Collider Parameters, bunch spacing =12.5 [ns]



$\rho_e[10^{13}/m^3] \approx 1.03$ ($n'_{e(\gamma)}$=1e-3, SEY =1.4)

$\rho_{neutr}[10^{13}/m^3] = 1.17$

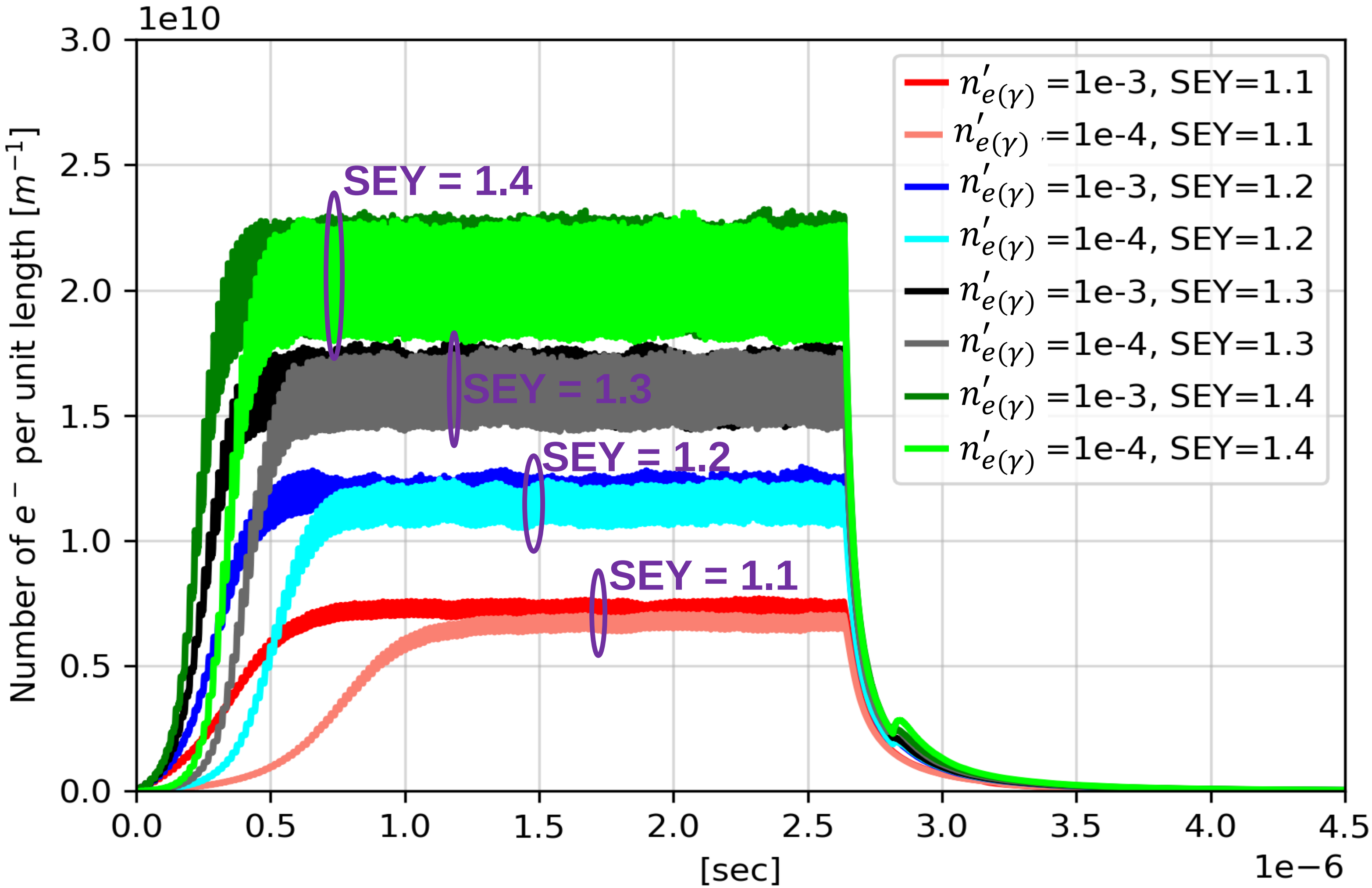
Collider Parameters, bunch spacing =15 [ns]



$\rho_e[10^{13}/m^3] \approx 0.71$ ($n'_{e(\gamma)}$=1e-3, SEY =1.4)

$\rho_{neutr}[10^{13}/m^3] = 0.98$

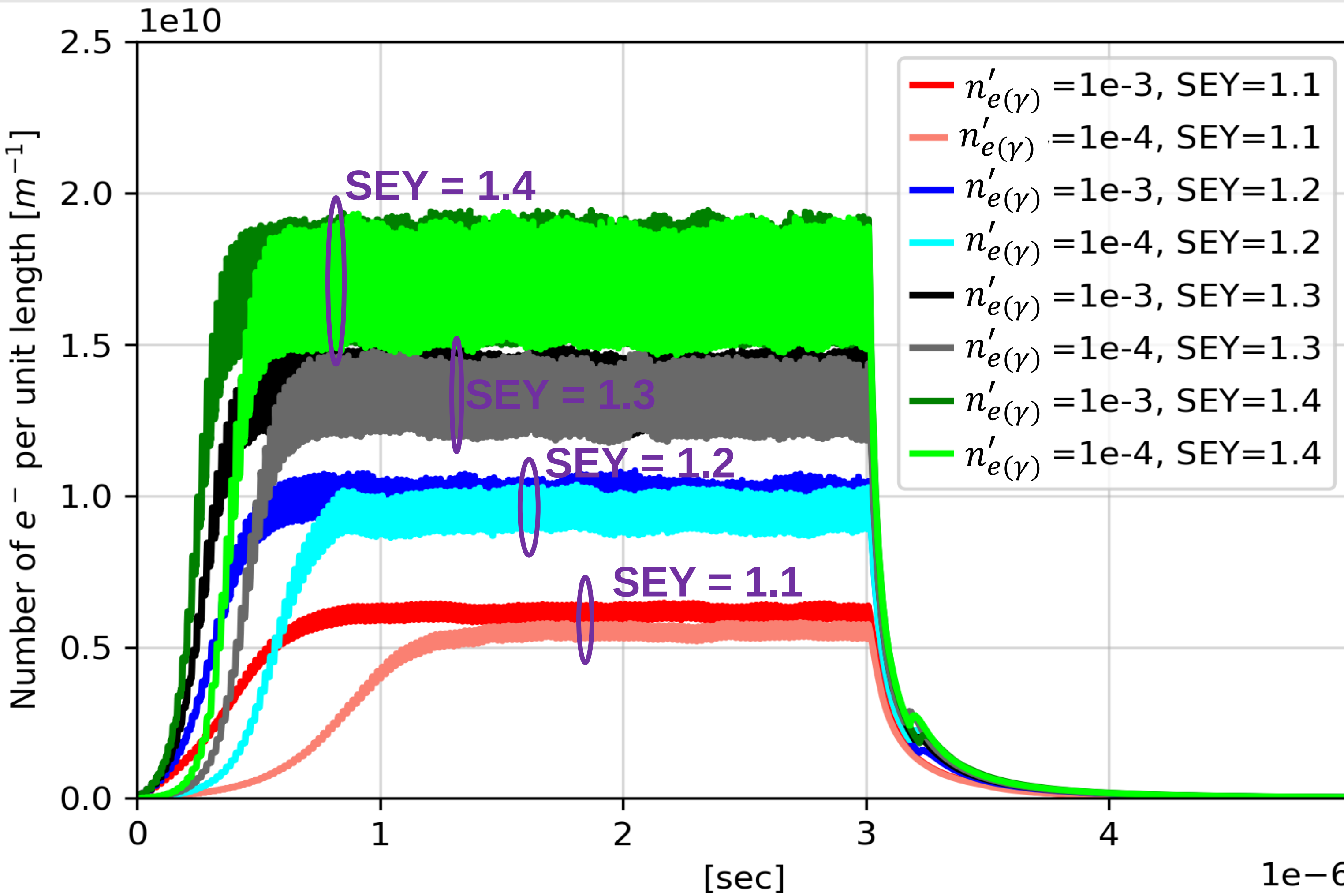
Collider Parameters, bunch spacing =17.5 [ns]



$\rho_e[10^{13}/m^3] \approx 0.51$ ($n'_{e(\gamma)}$=1e-3, SEY =1.4)

$\rho_{neutr}[10^{13}/m^3] = 0.84$

Collider Parameters, bunch spacing =20 [ns]

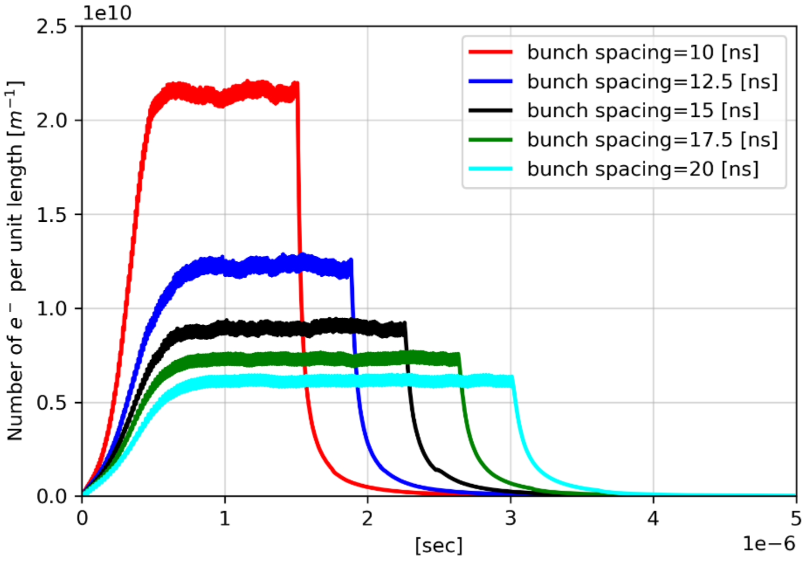


$\rho_e[10^{13}/m^3] \approx 0.45$ ($n'_{e(\gamma)}$=1e-3, SEY =1.4)

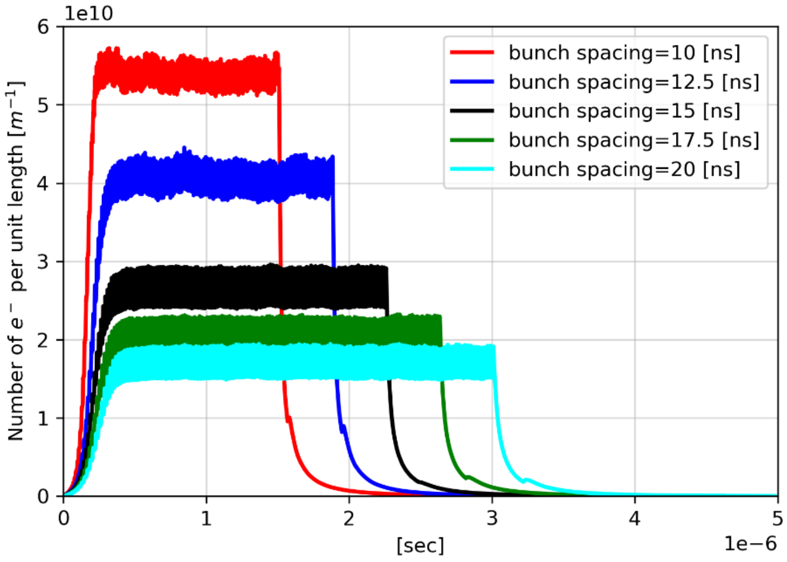
$\rho_{neutr}[10^{13}/m^3] = 0.73$

Collider Parameters for different bunch spacings

SEY=1.1

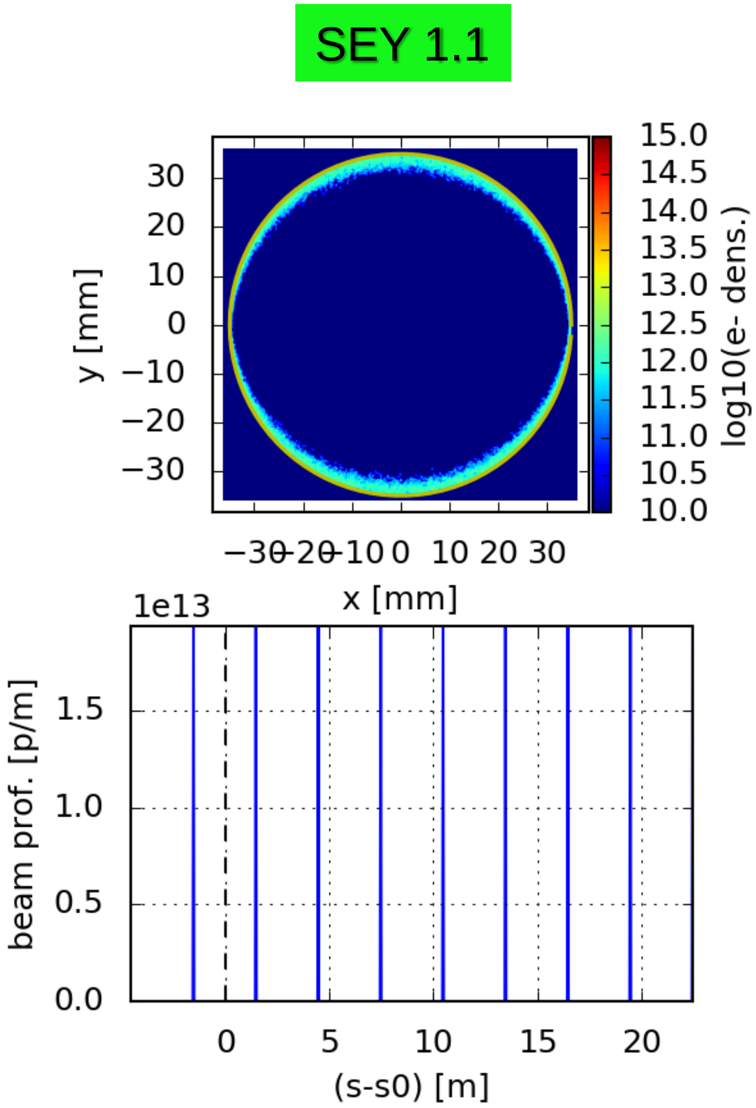


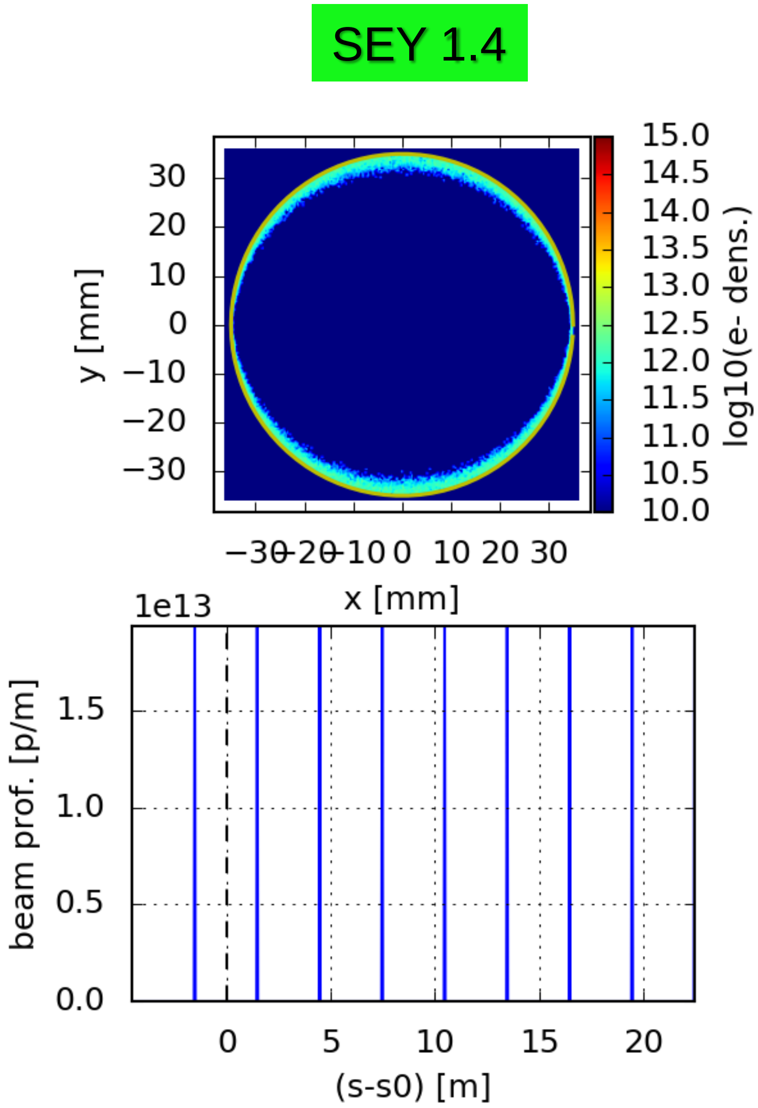
SEY=1.4



bunch space [ns]	neutralization value $[10^{13}/m^3]$	electron density $[10^{13}/m^3]$
10	1.47	1.42
12.5	1.17	1.03
15	0.98	0.71
17.5	0.84	0.51
20	0.73	0.45

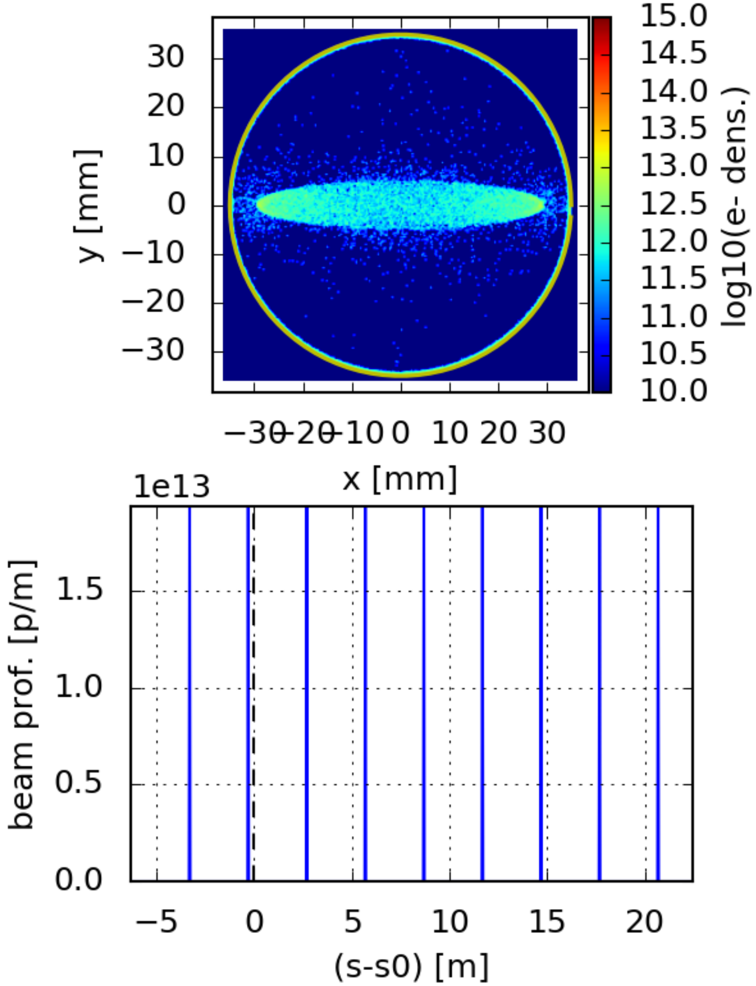
Collider Parameters, bunch spacing =10[ns]



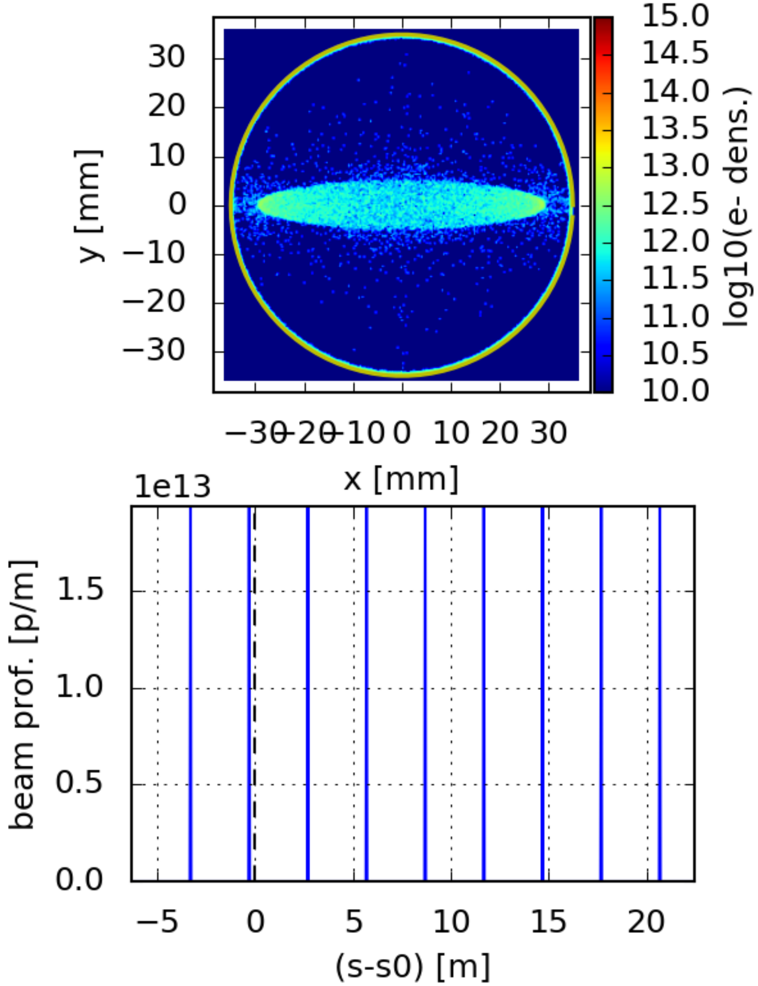


Collider Parameters, bunch spacing =10[ns]

SEY 1.1

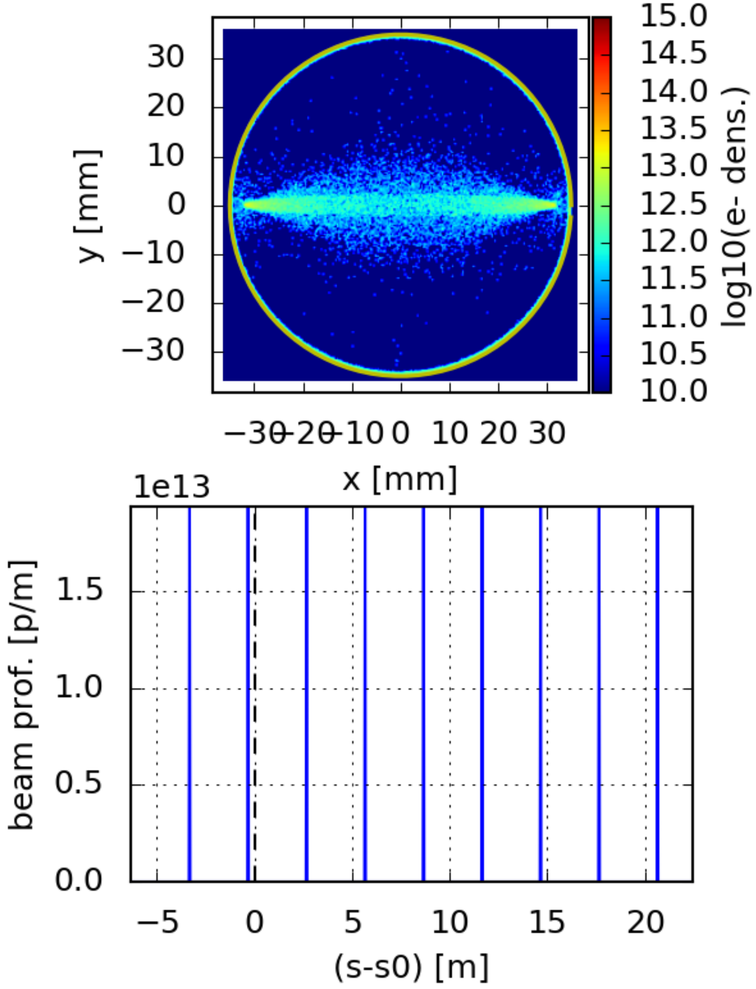


SEY 1.4

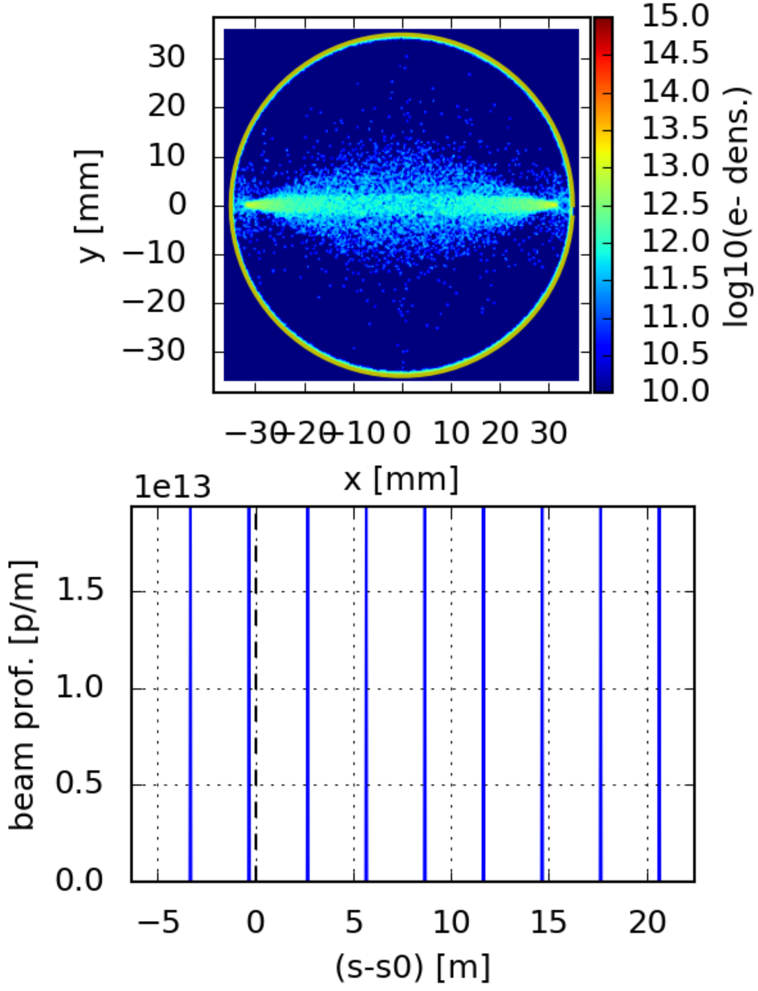


Collider Parameters, bunch spacing =10[ns]

SEY 1.1

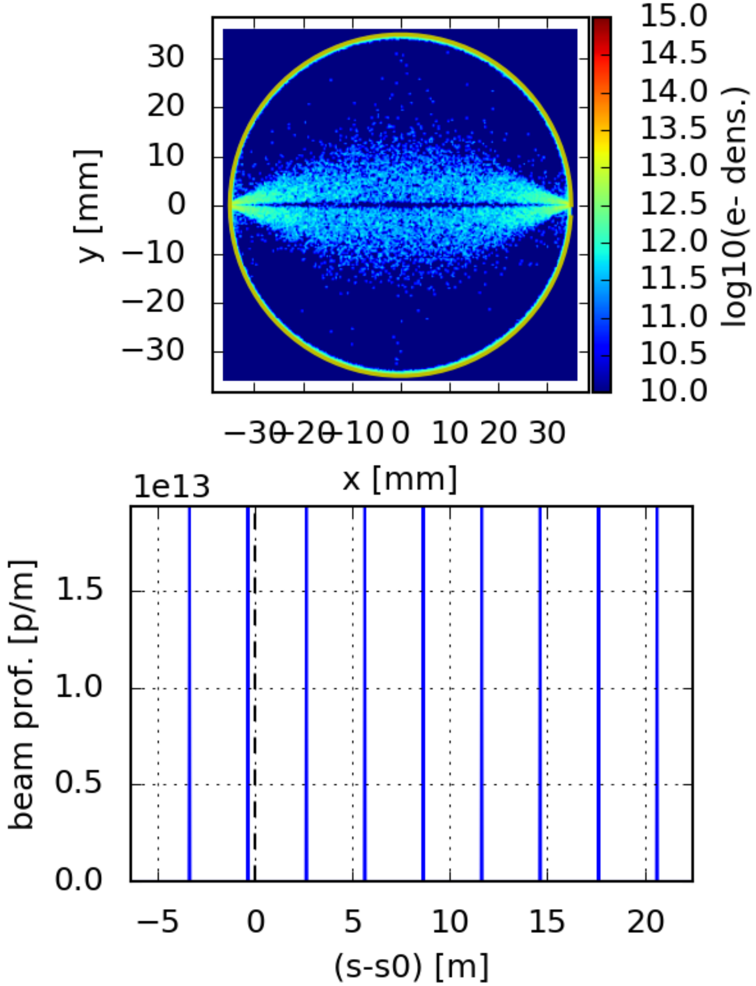


SEY 1.4

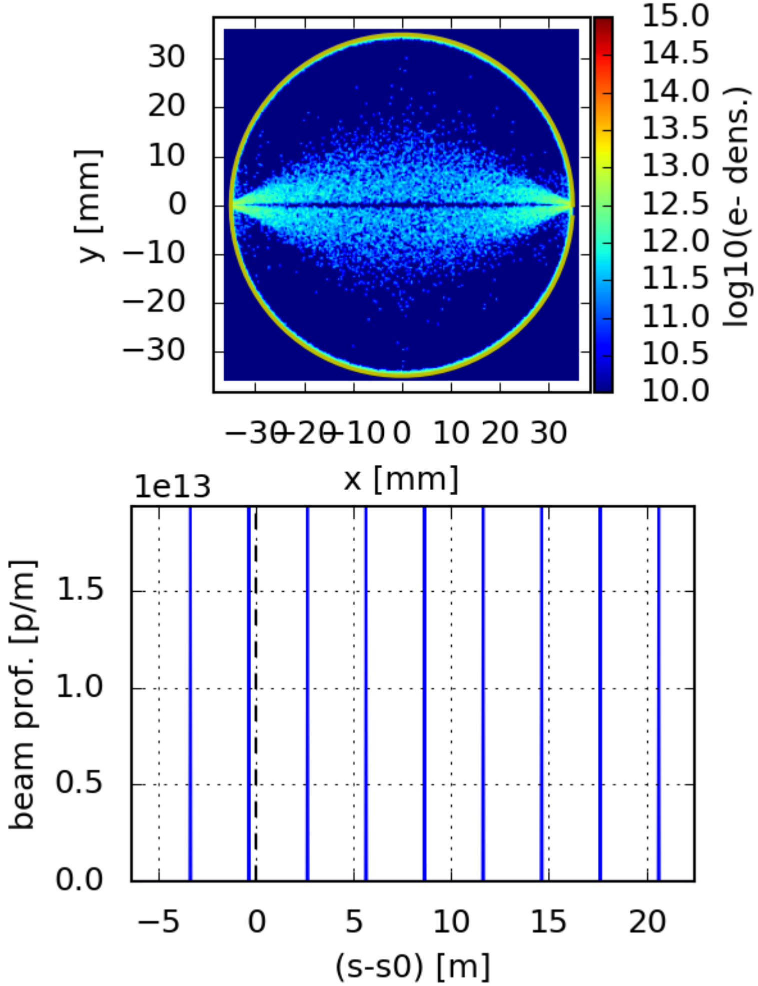


Collider Parameters, bunch spacing =10[ns]

SEY 1.1

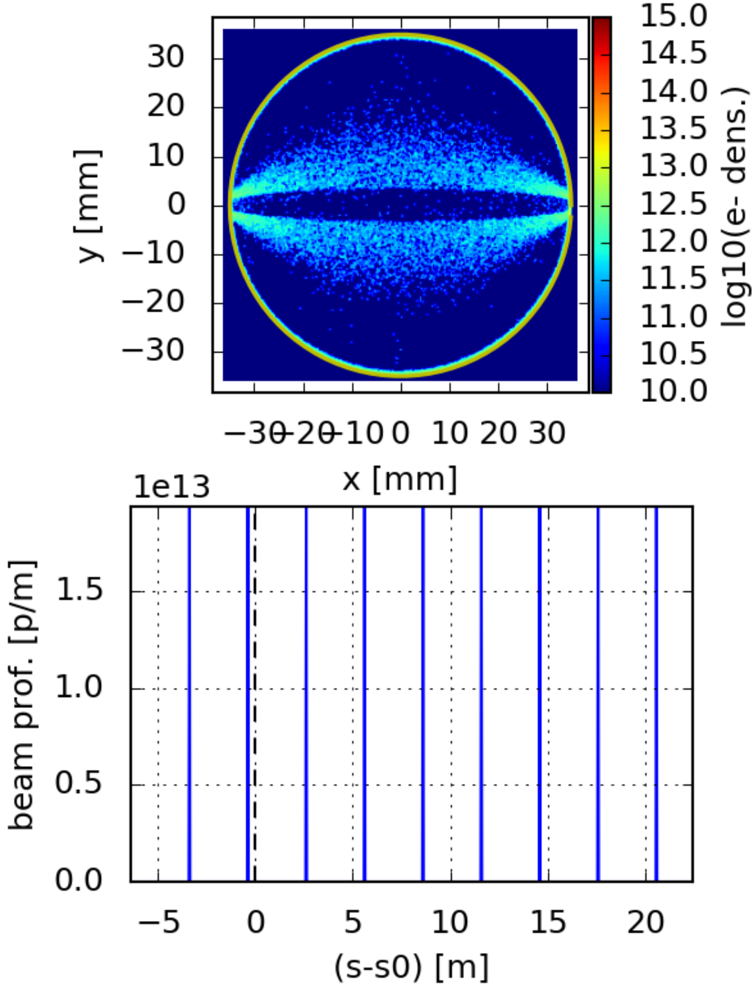


SEY 1.4

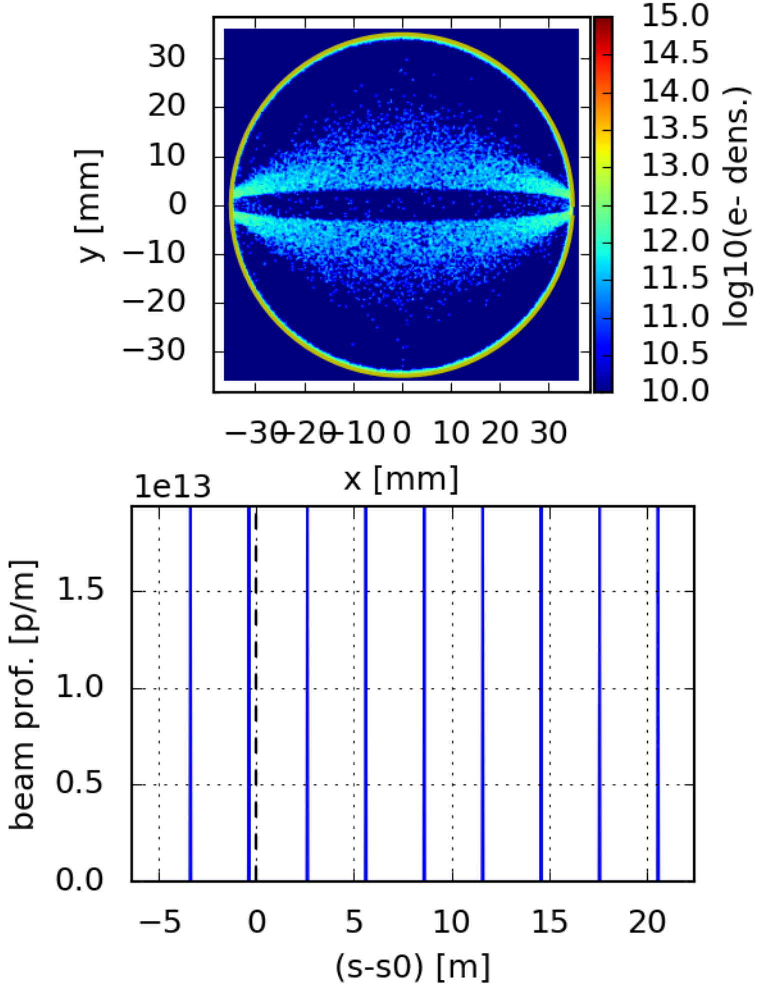


Collider Parameters, bunch spacing =10[ns]

SEY 1.1

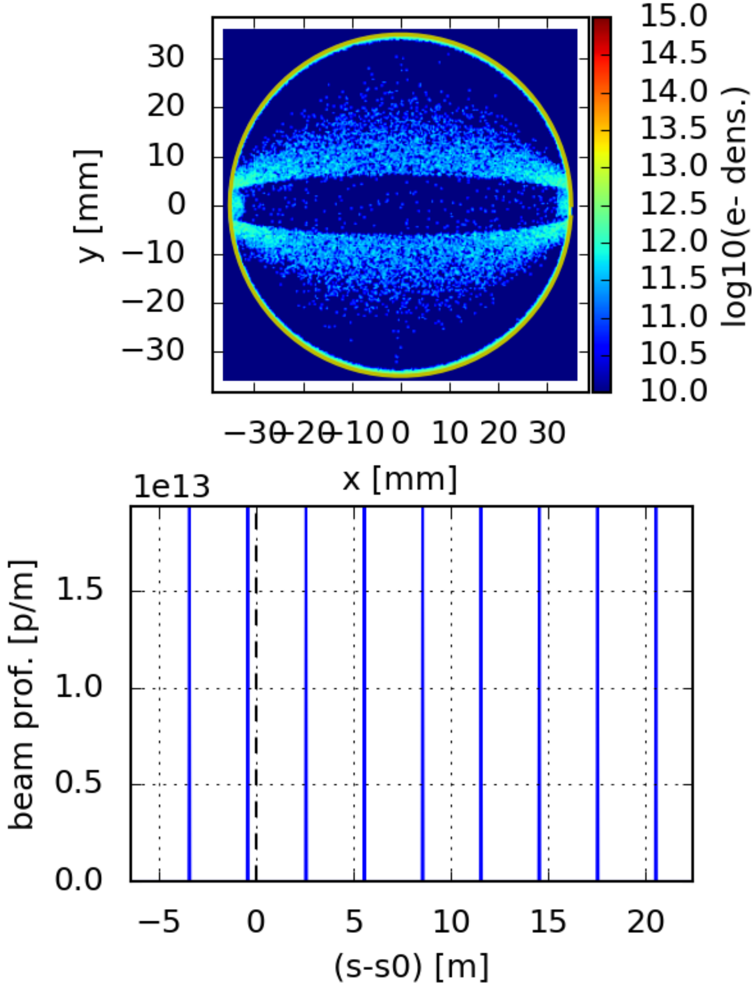


SEY 1.4

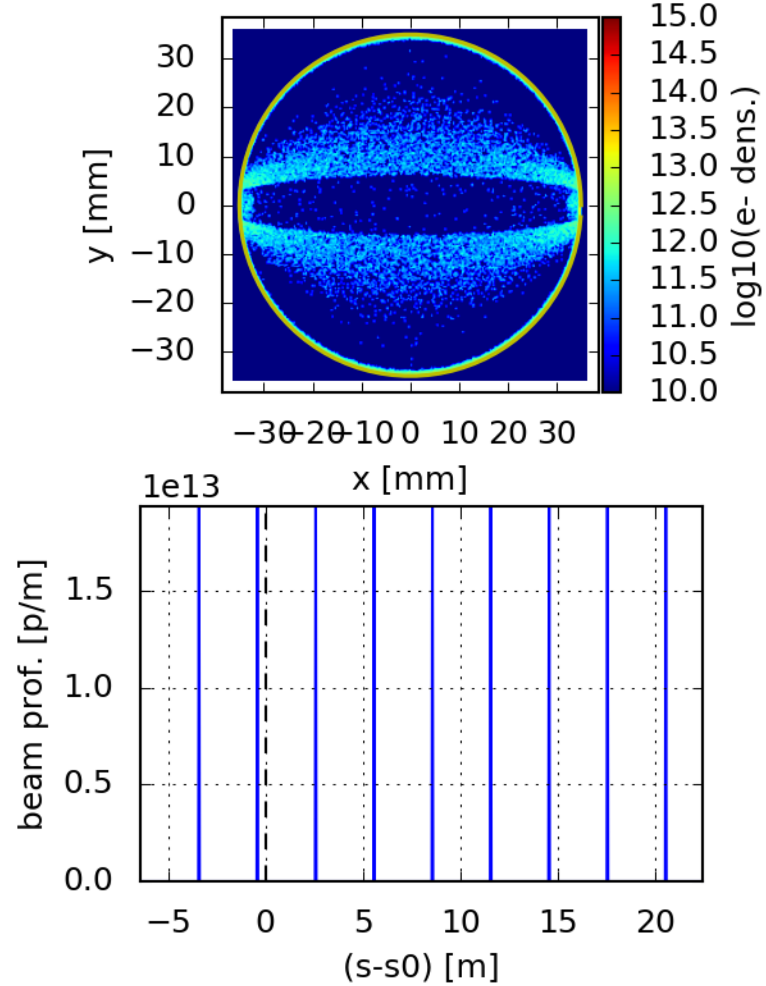


Collider Parameters, bunch spacing =10[ns]

SEY 1.1

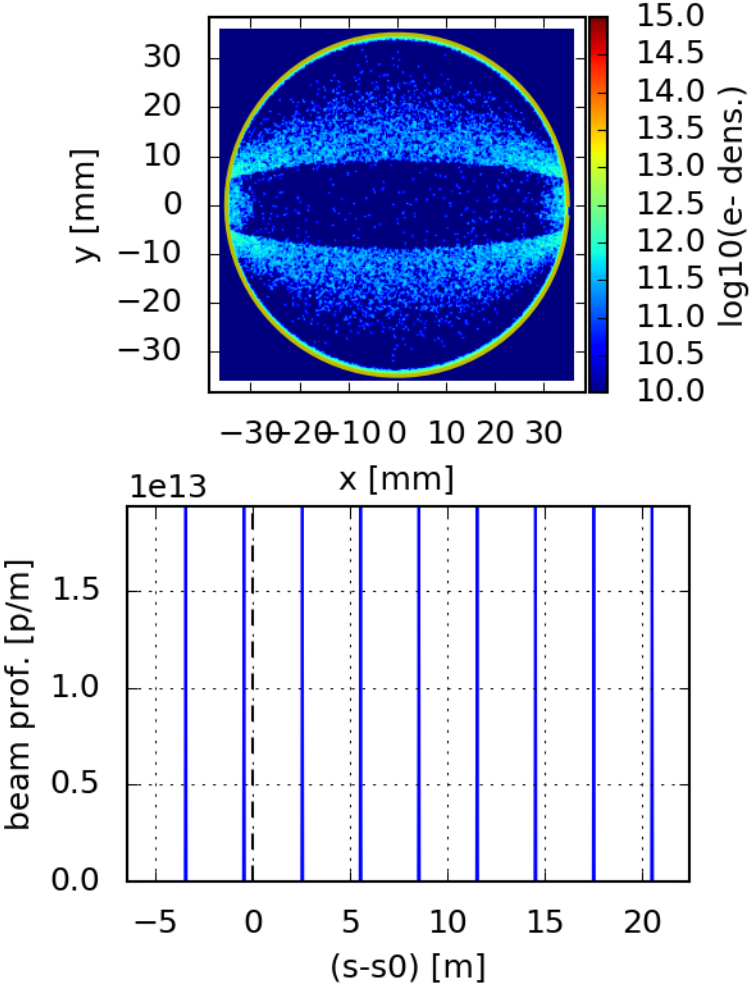


SEY 1.4



Collider Parameters, bunch spacing =10[ns]

SEY 1.1



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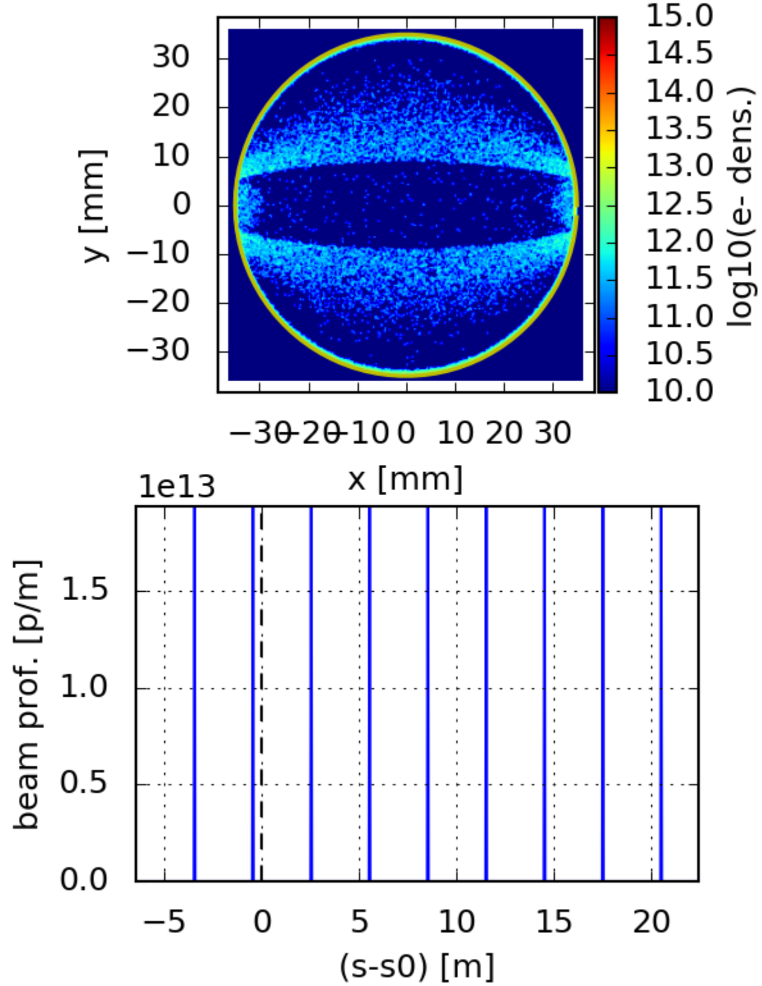
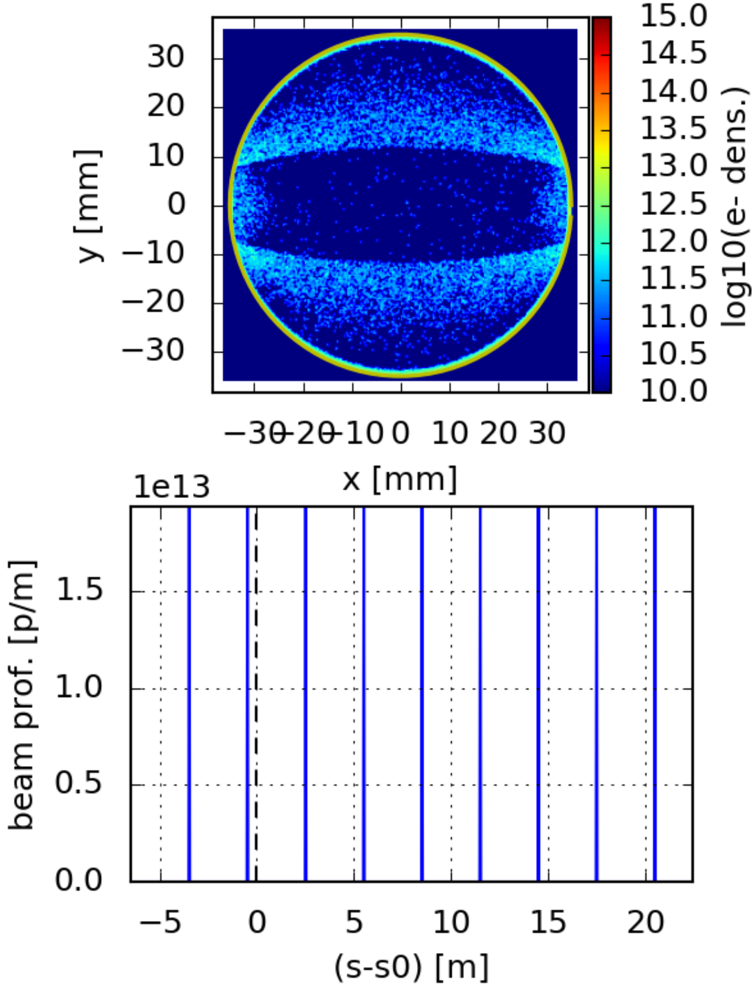


Collider Parameters, bunch spacing =10[ns]

SEY 1.1



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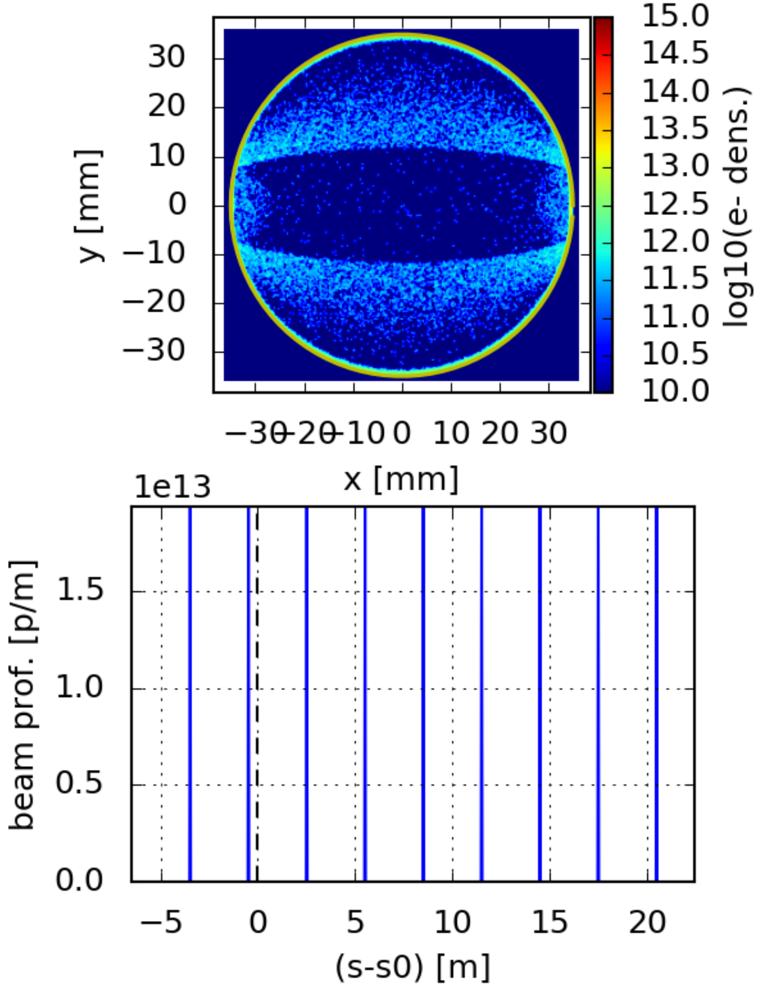

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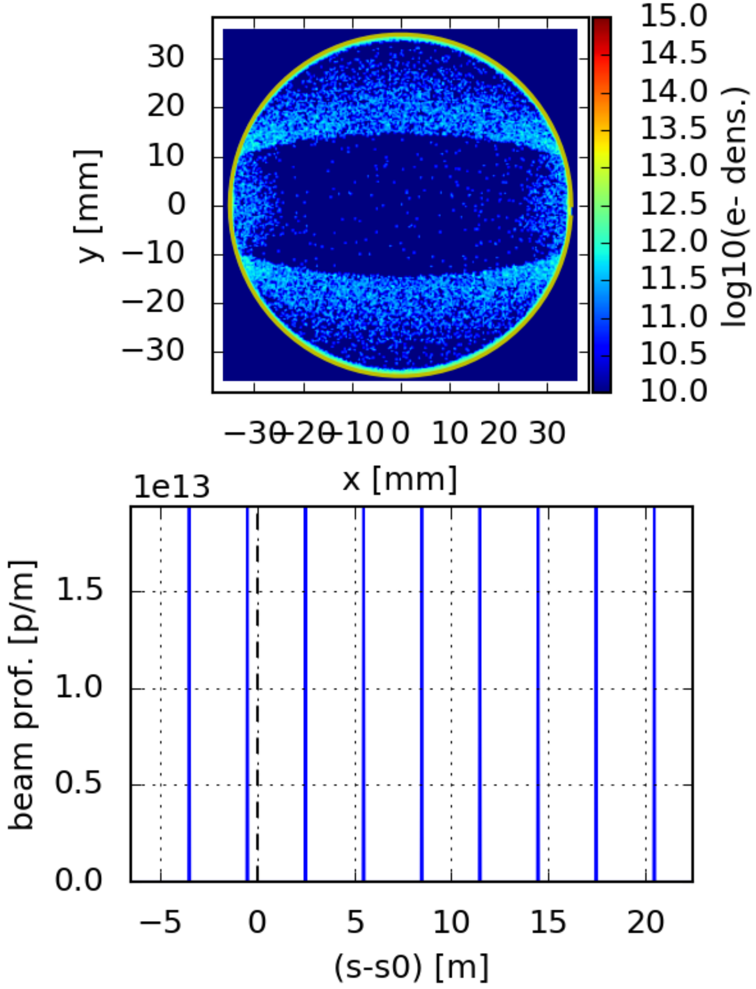

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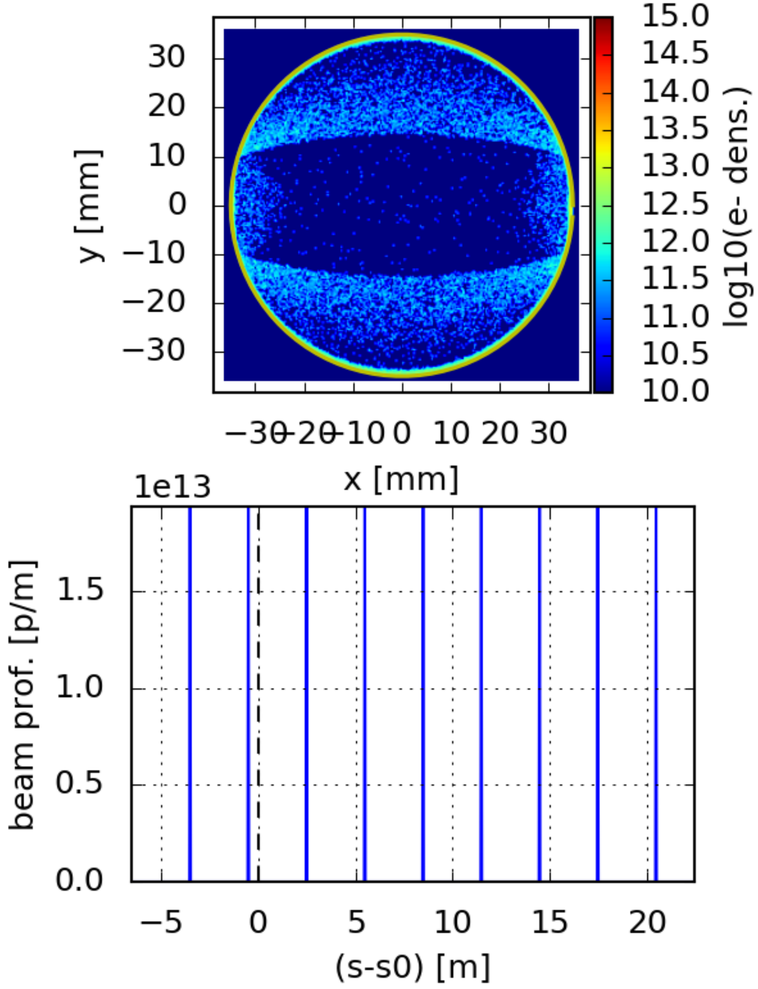

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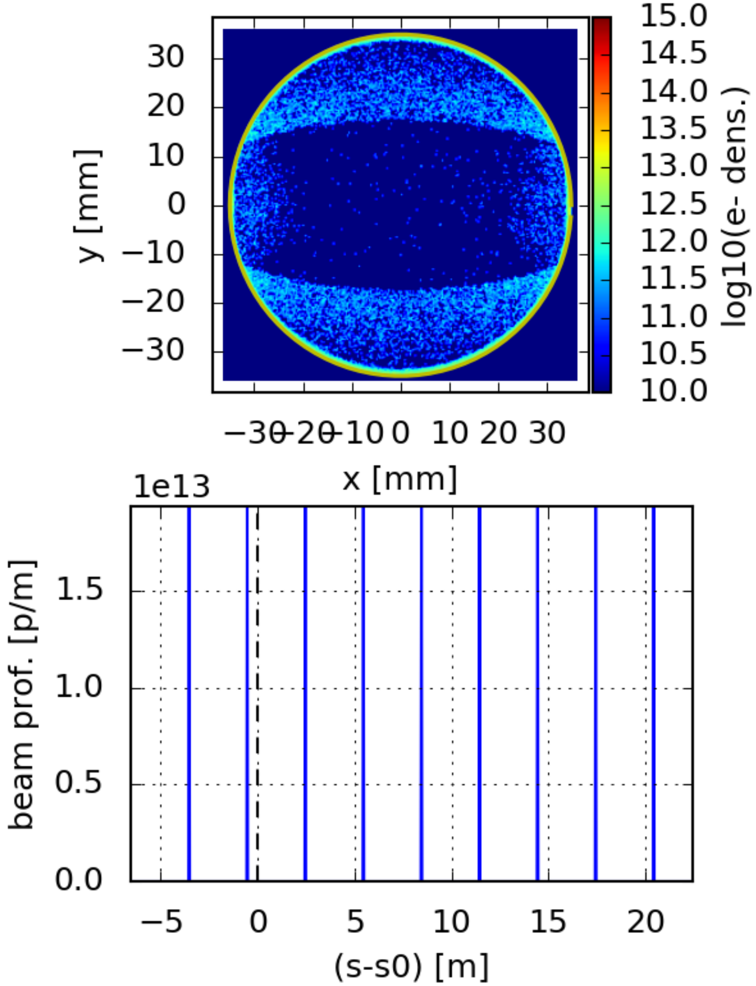
SEY 1.1



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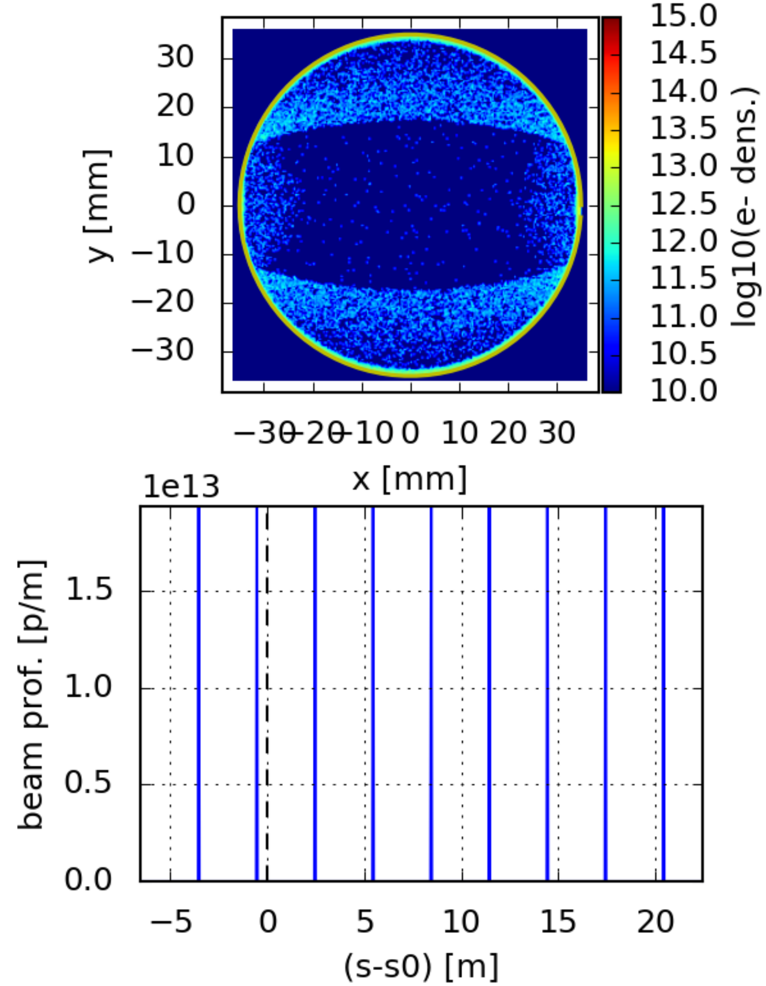

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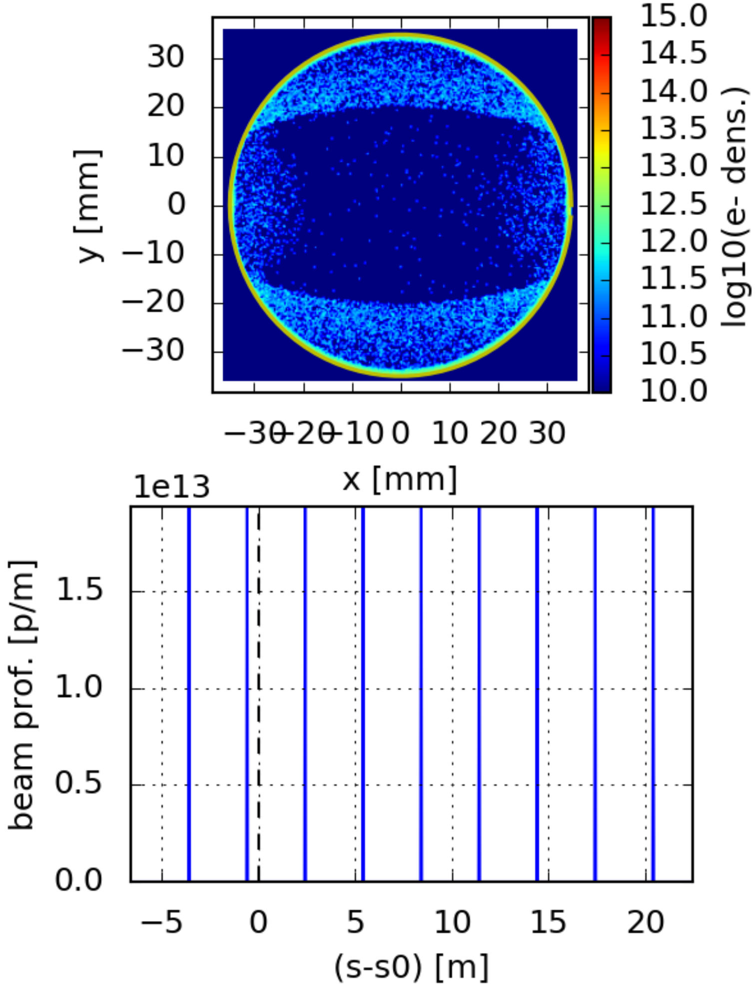

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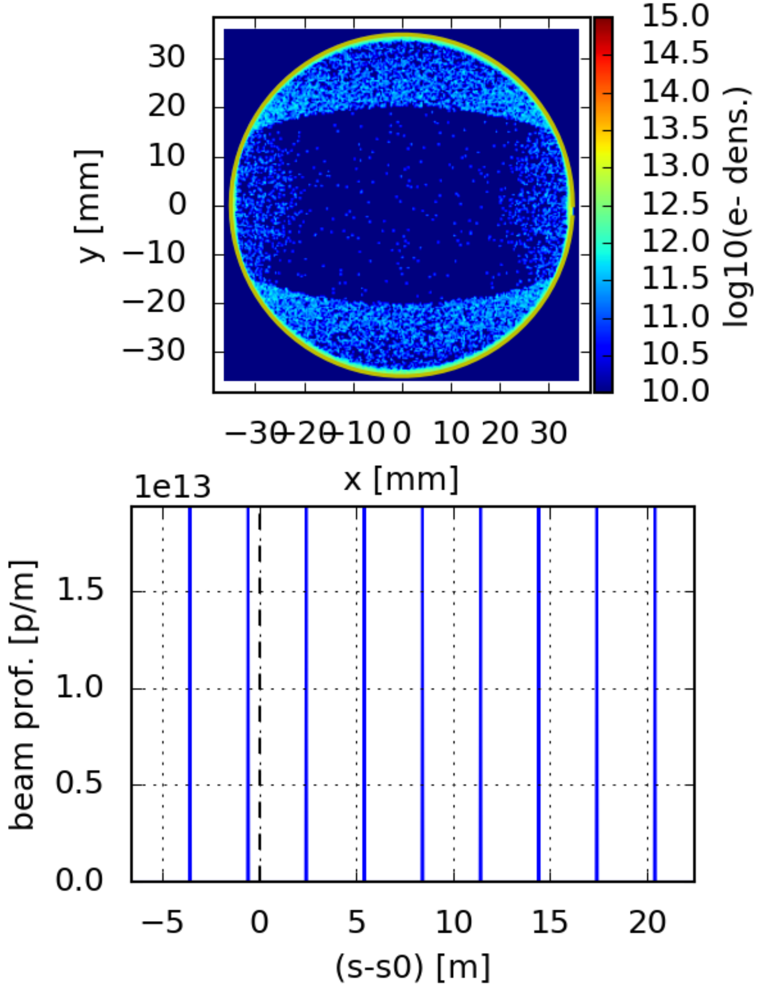

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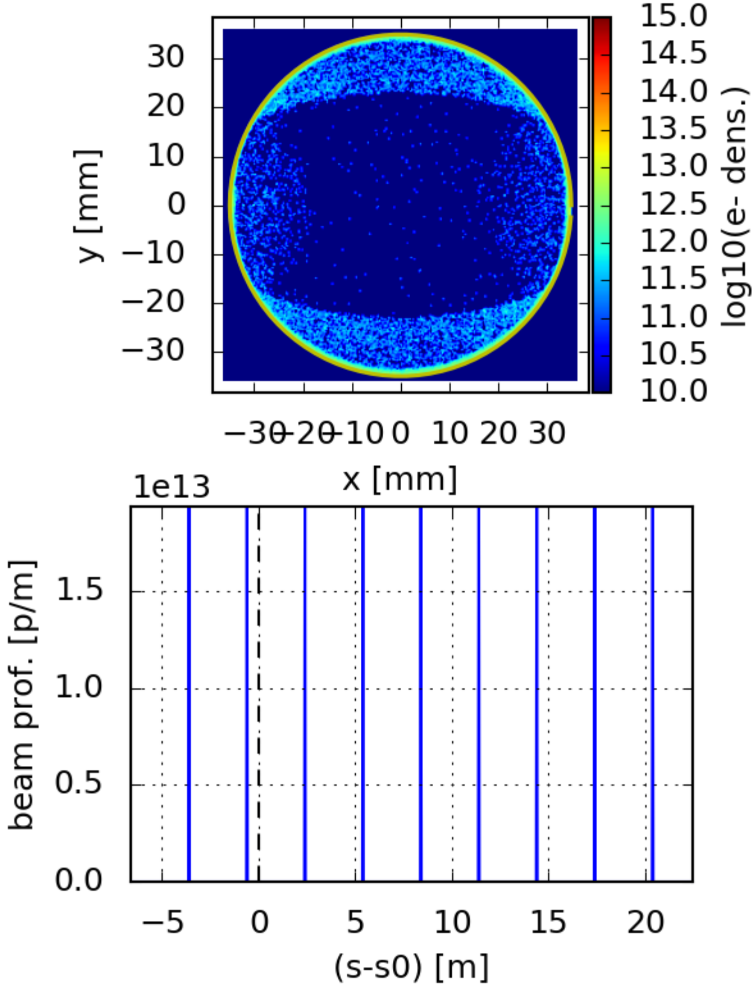
SEY 1.1



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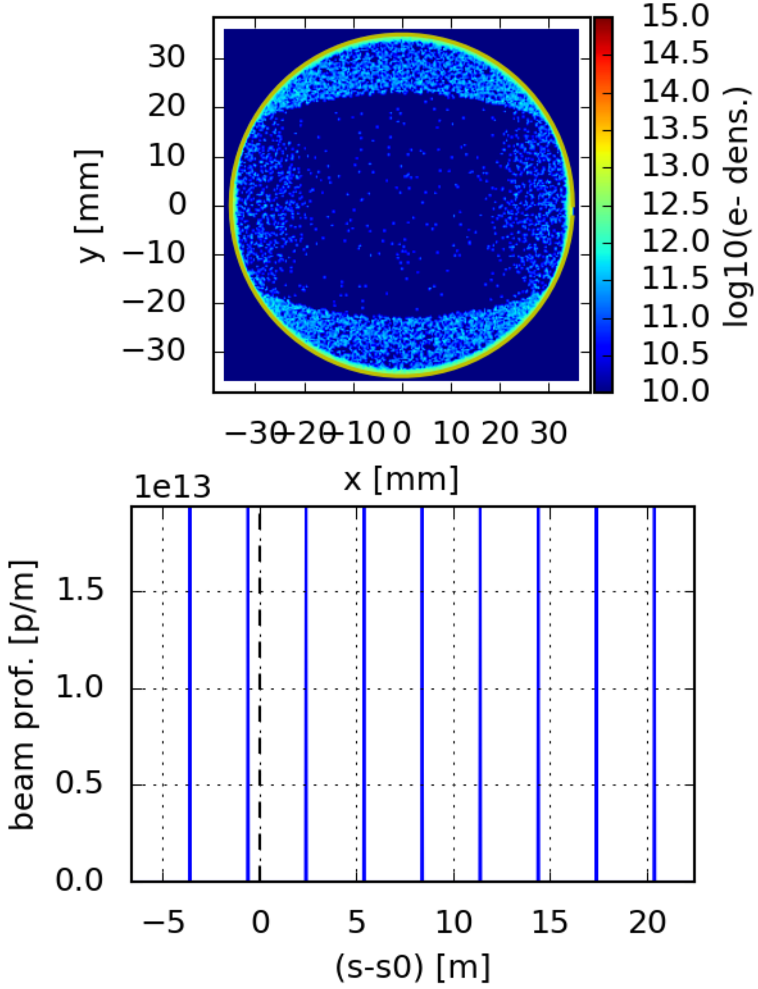

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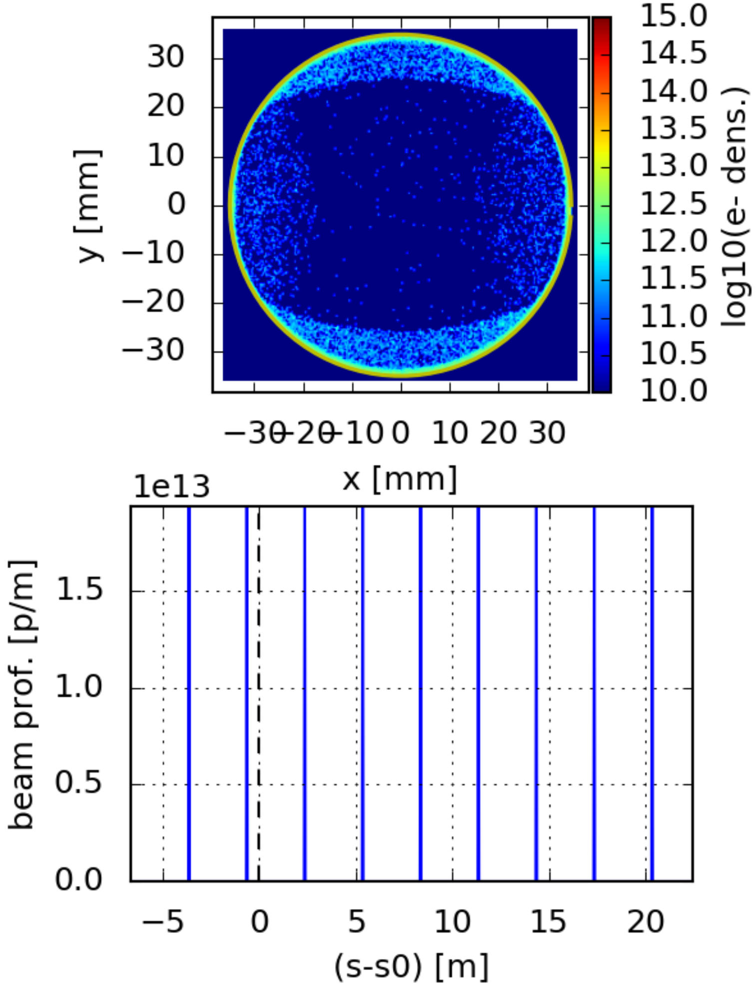

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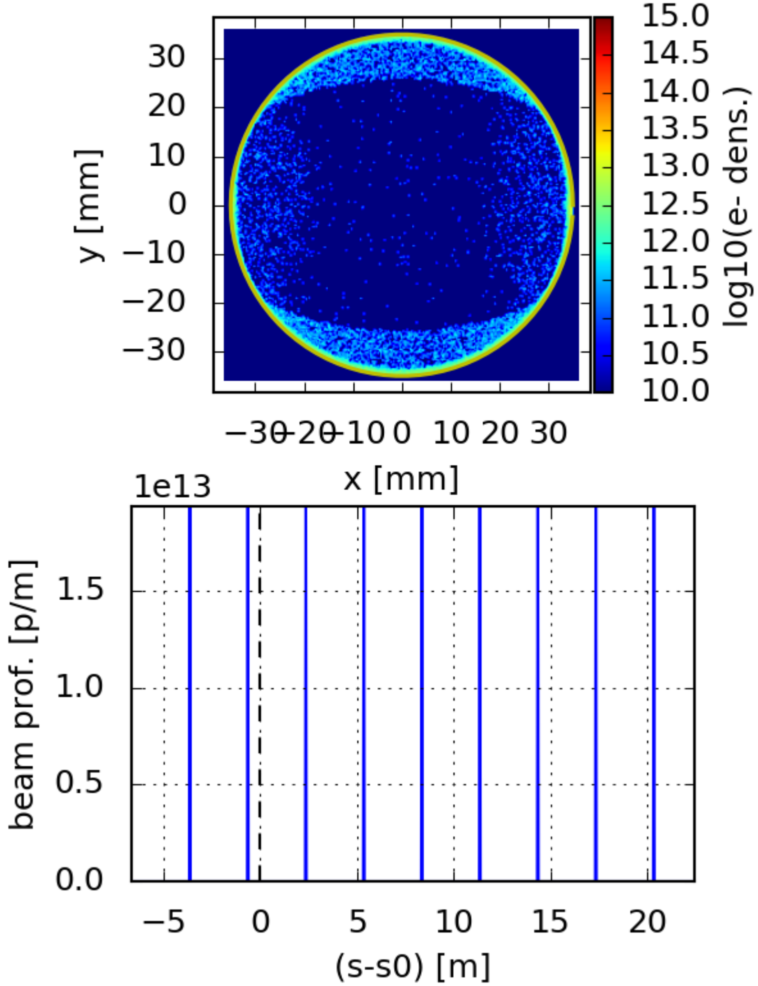

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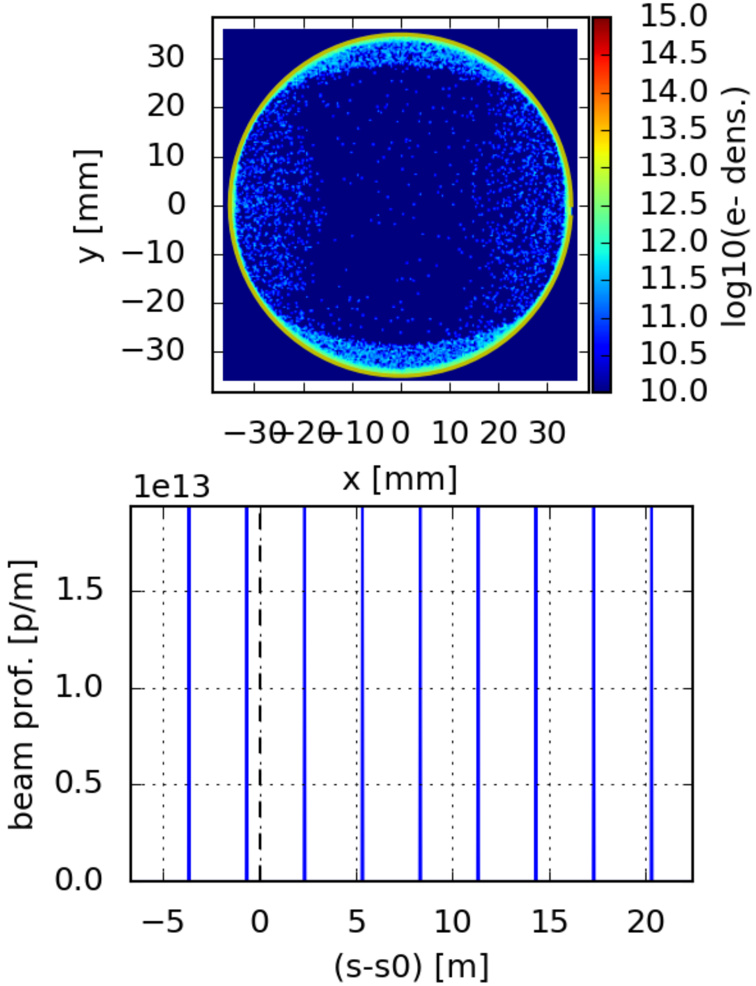

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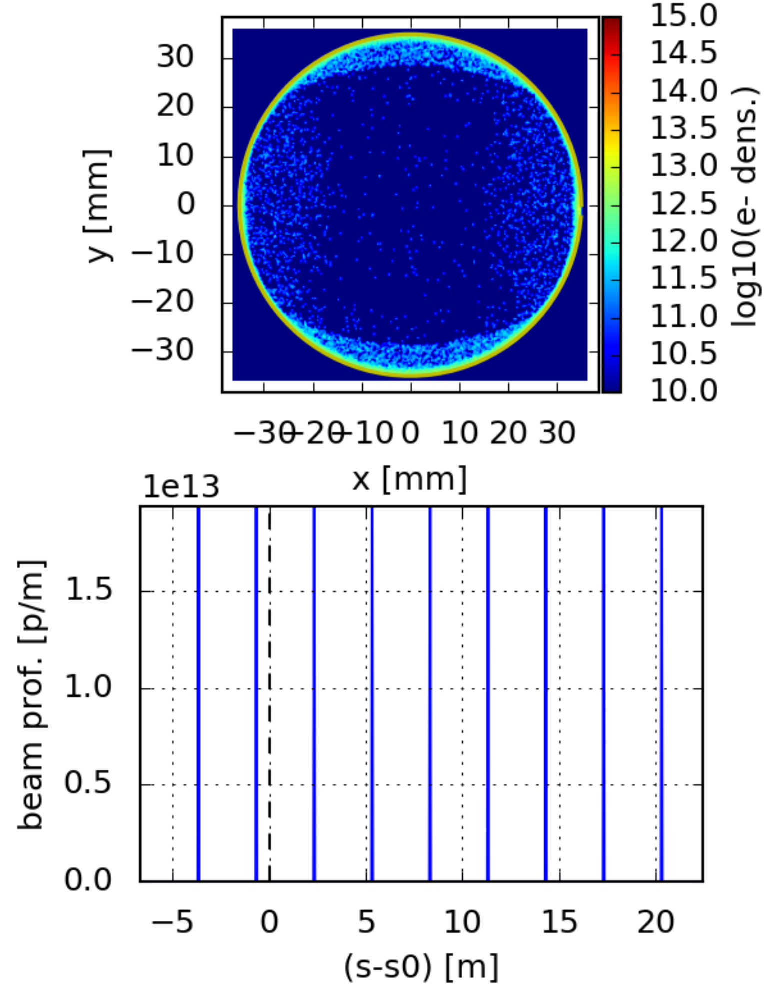

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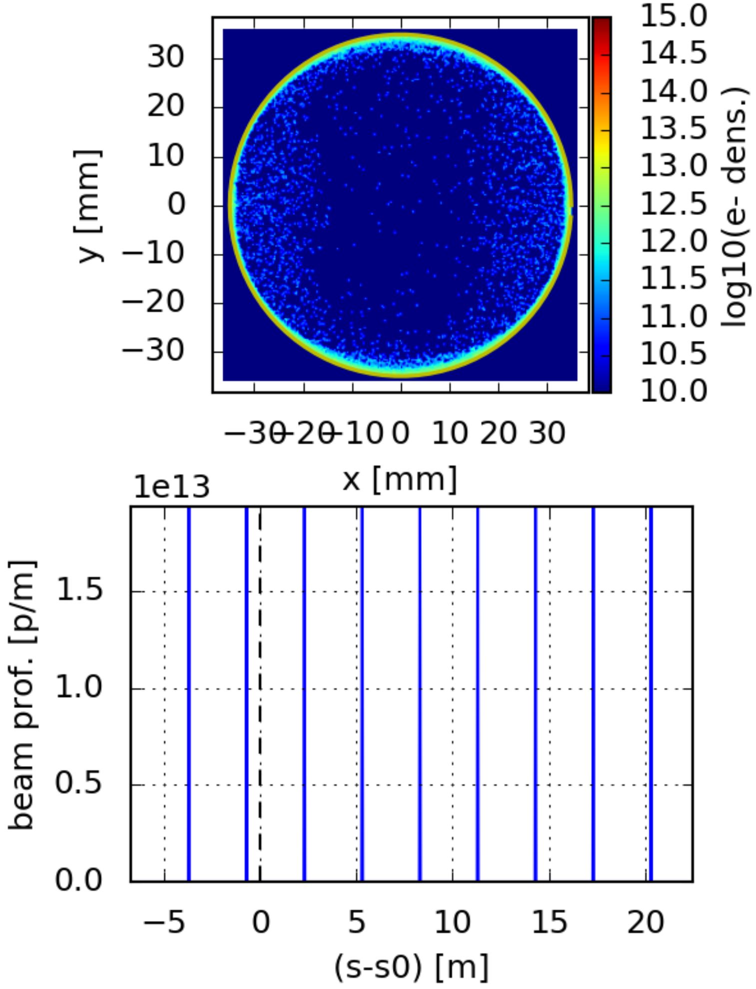
SEY 1.1



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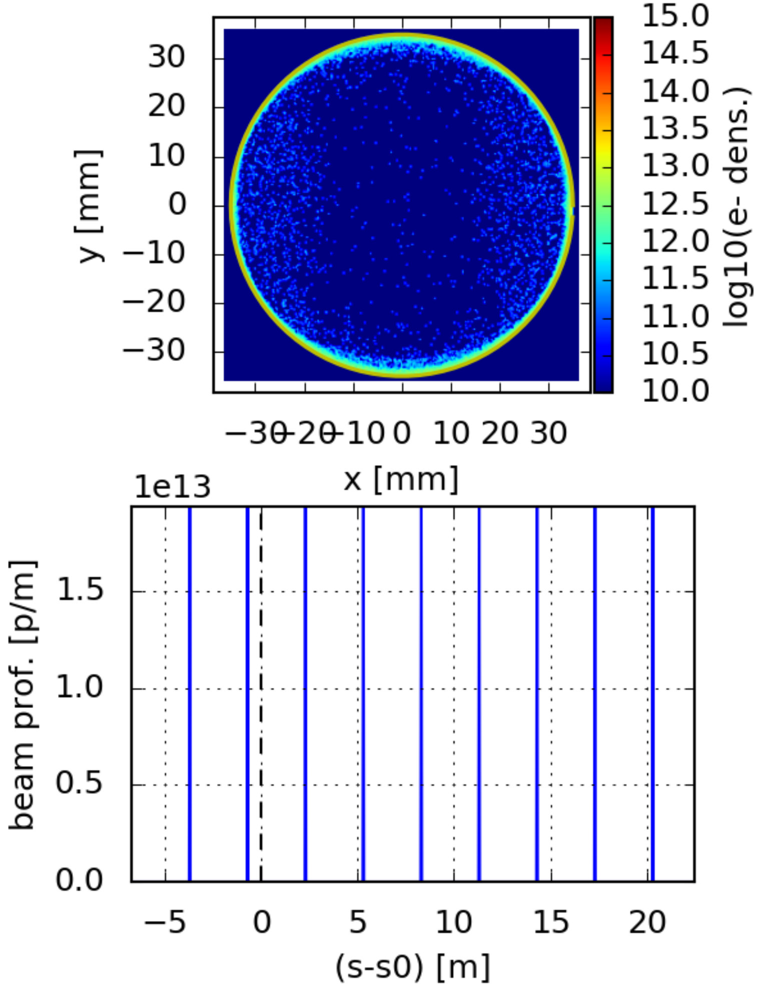
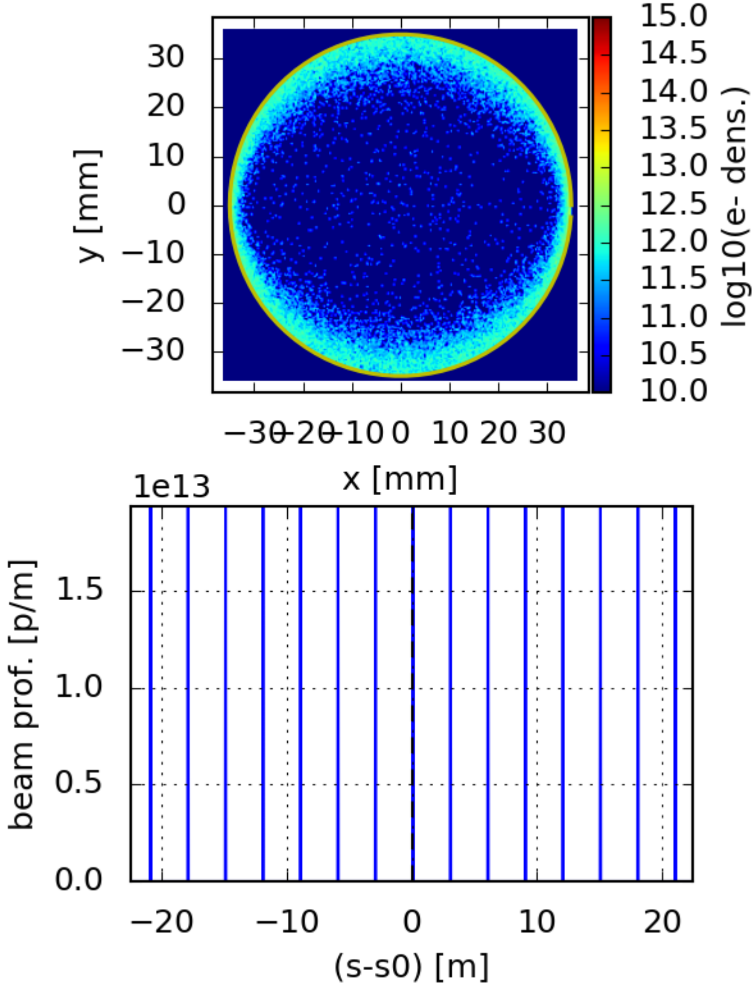


Collider Parameters, bunch spacing =10[ns]

SEY 1.1



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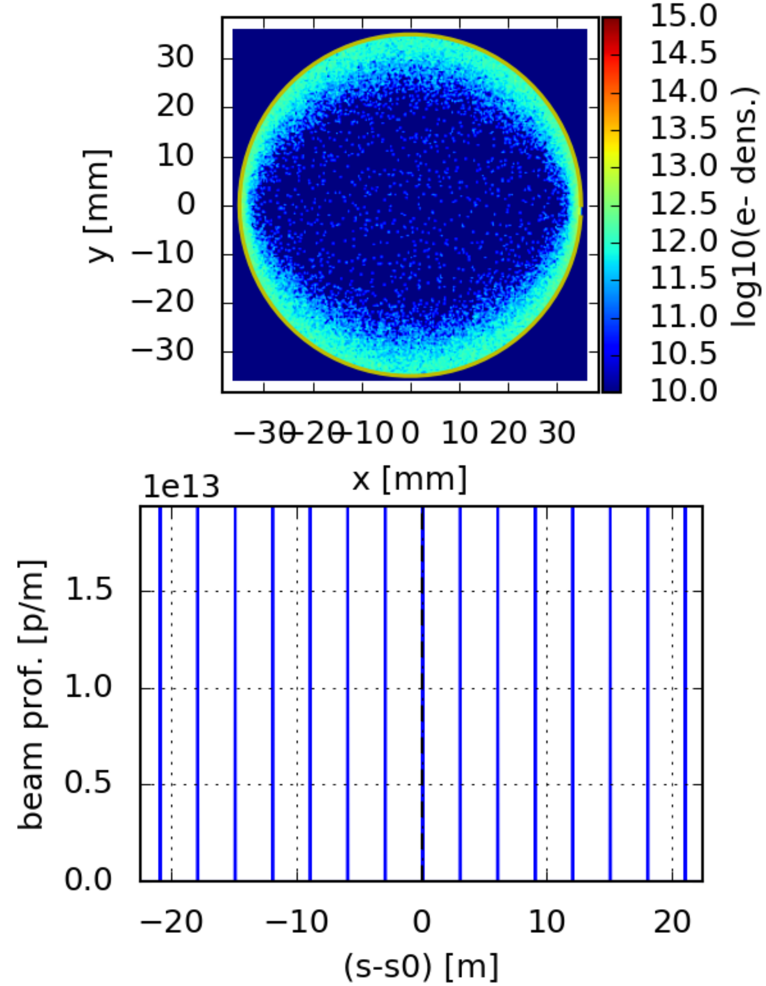
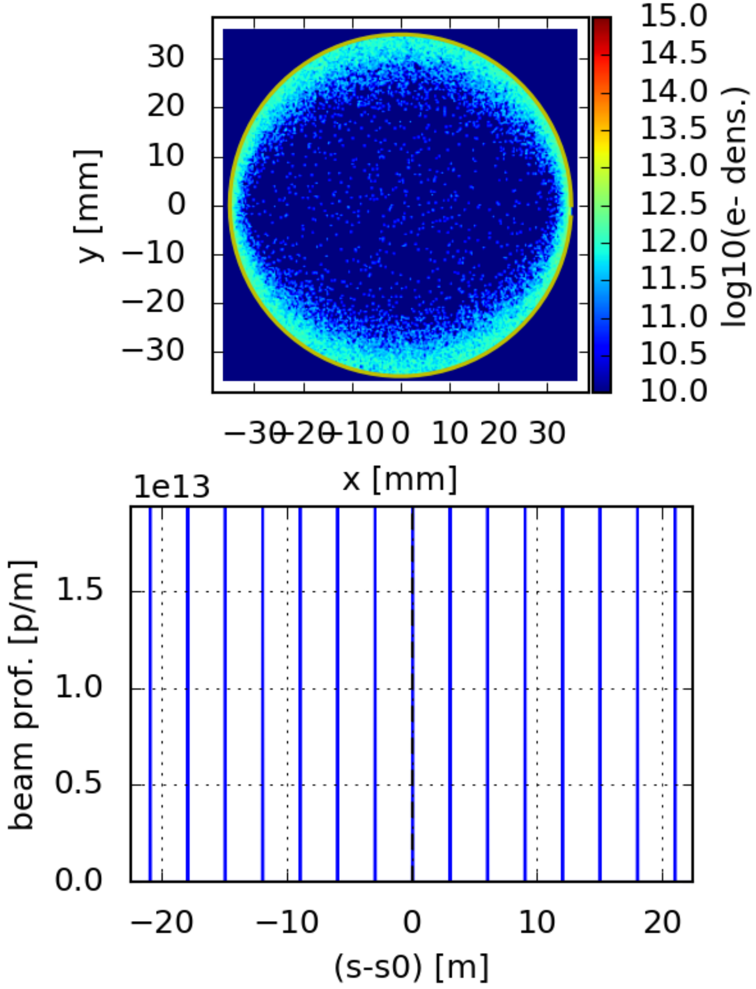


Collider Parameters, bunch spacing =10[ns]

SEY 1.1



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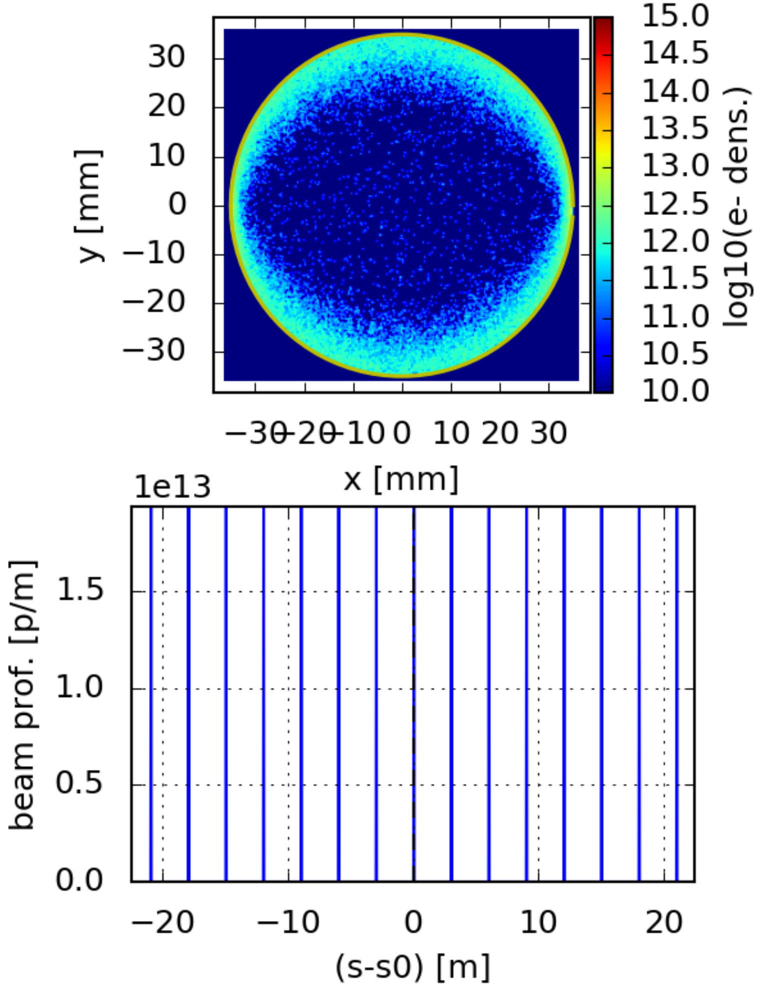

Collider Parameters, bunch spacing =10[ns]

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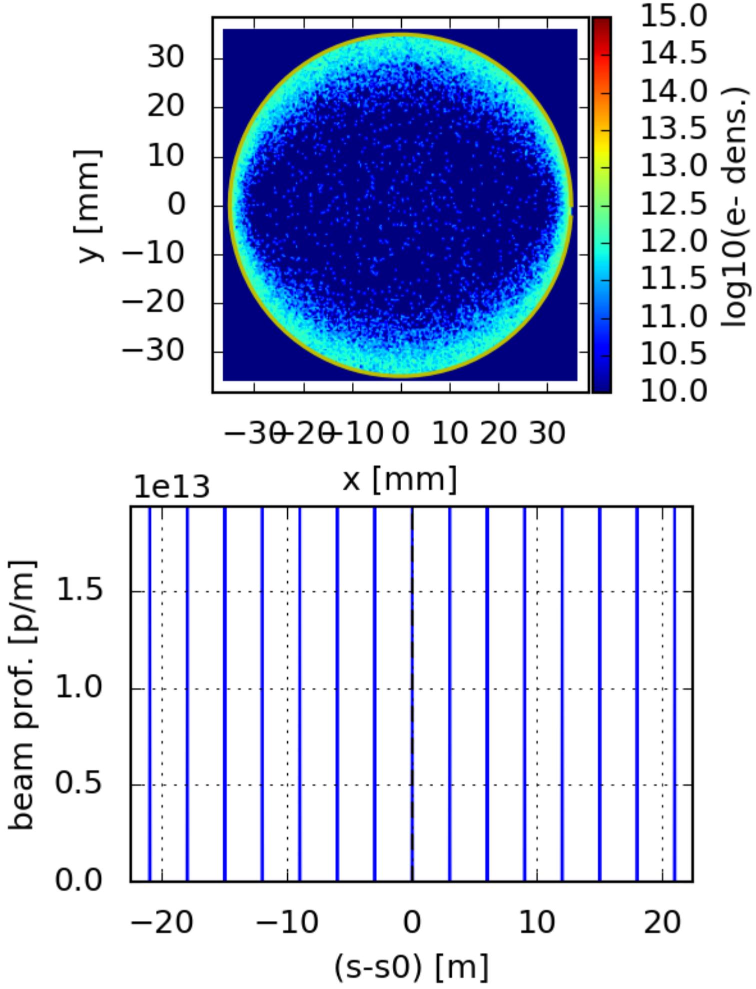
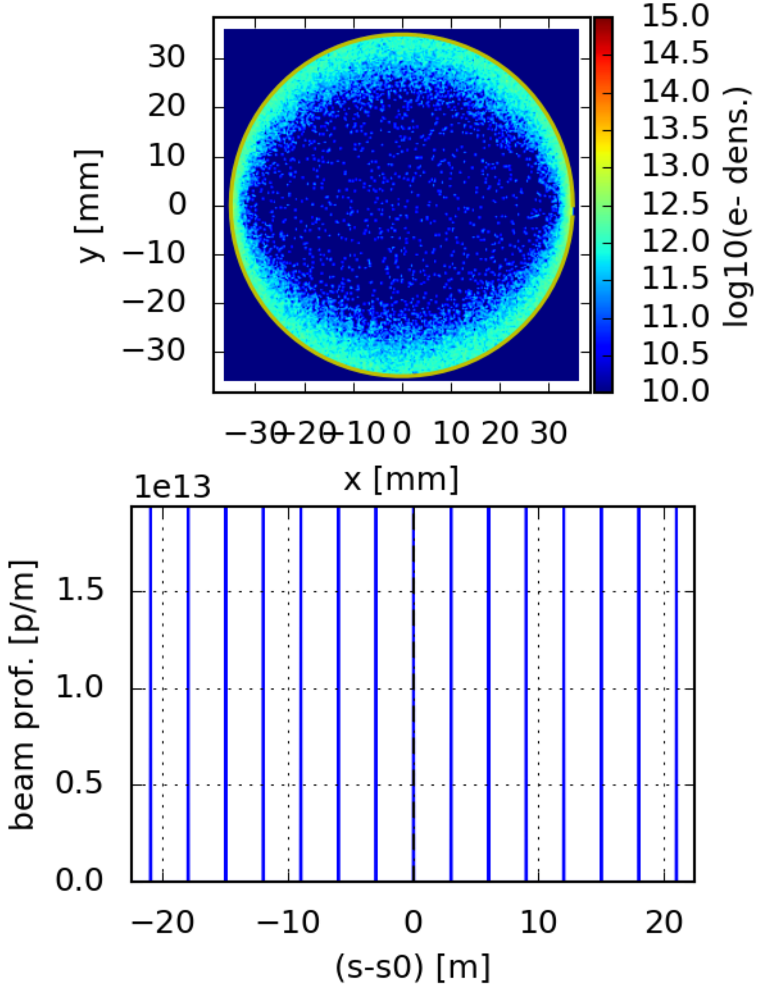
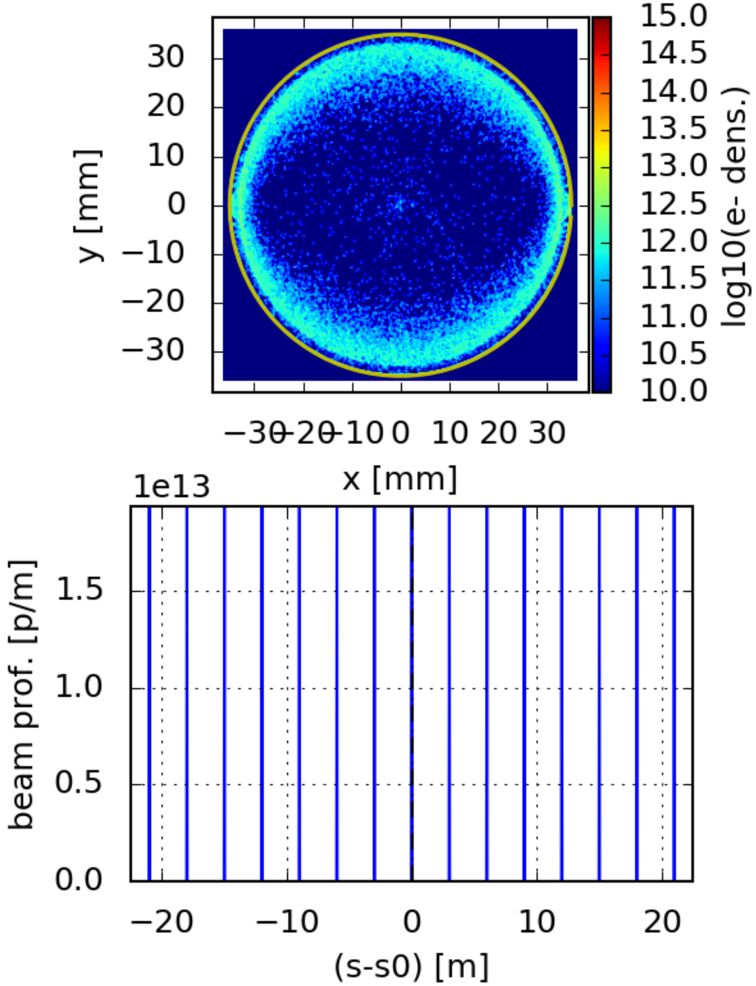


SEY 1.4



Collider Parameters, bunch spacing =10[ns]

SEY 1.1



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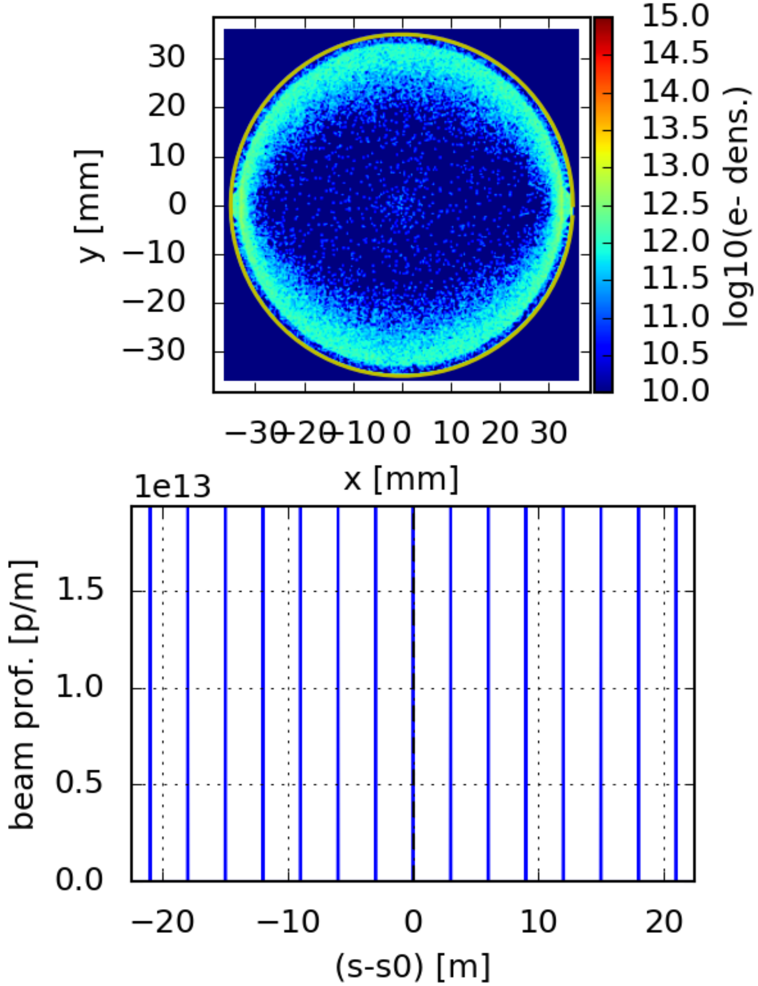

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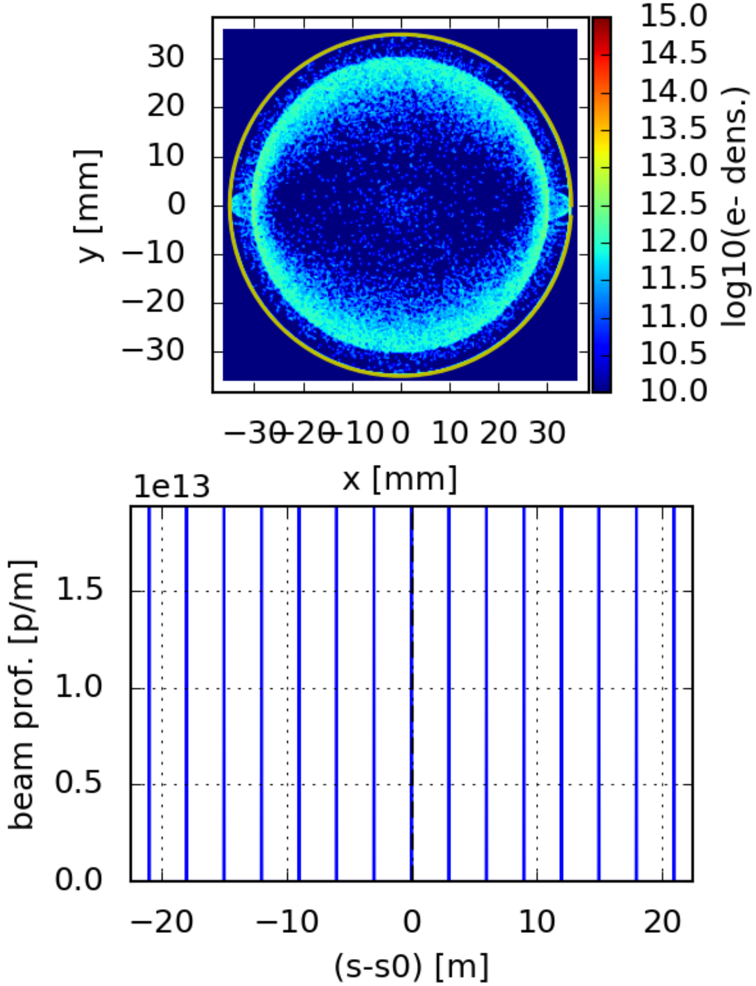
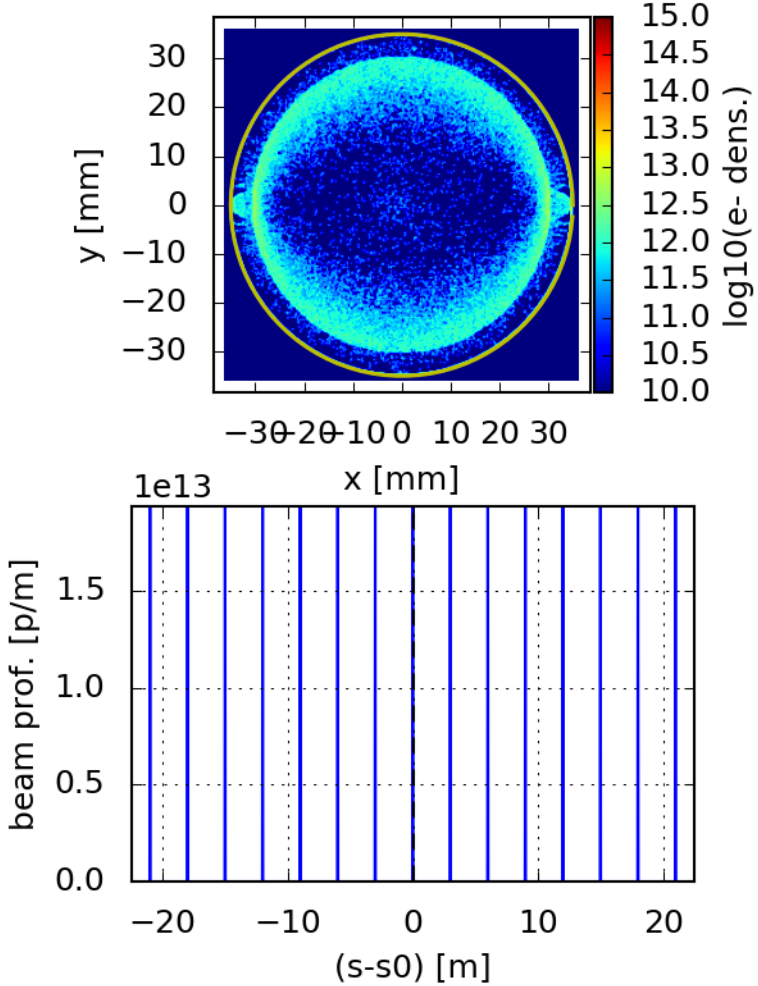


SEY 1.4



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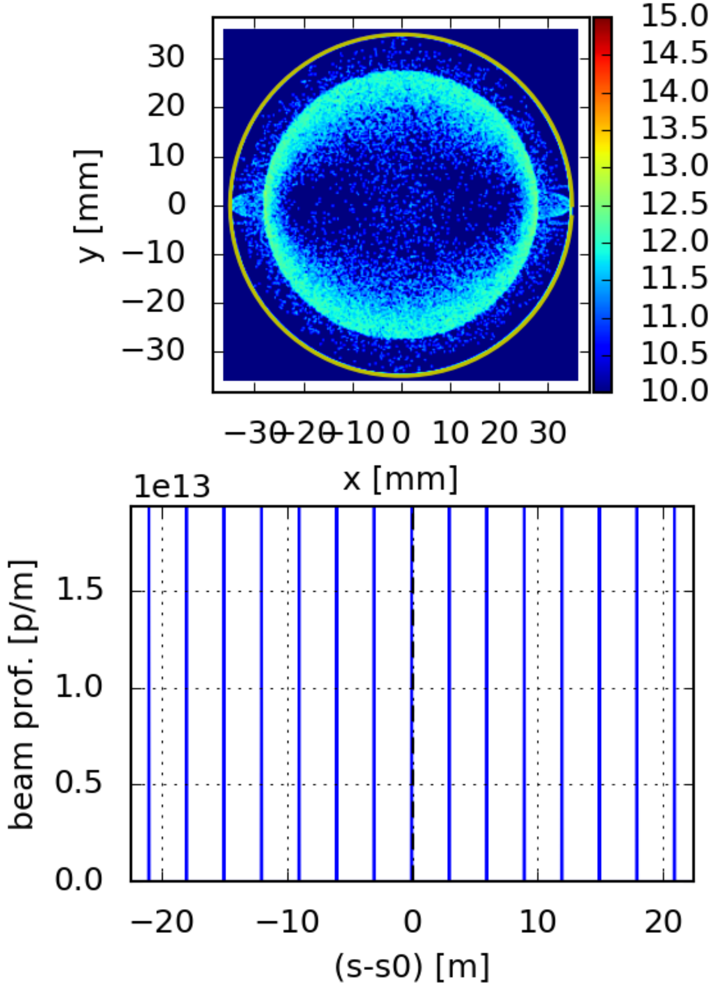

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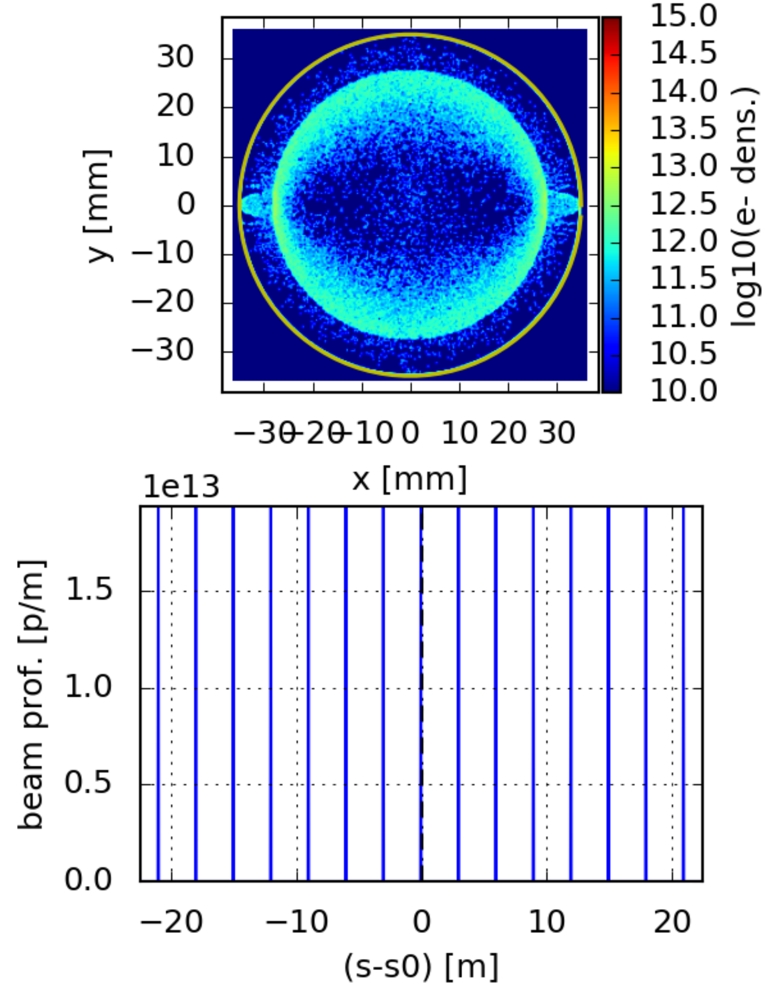

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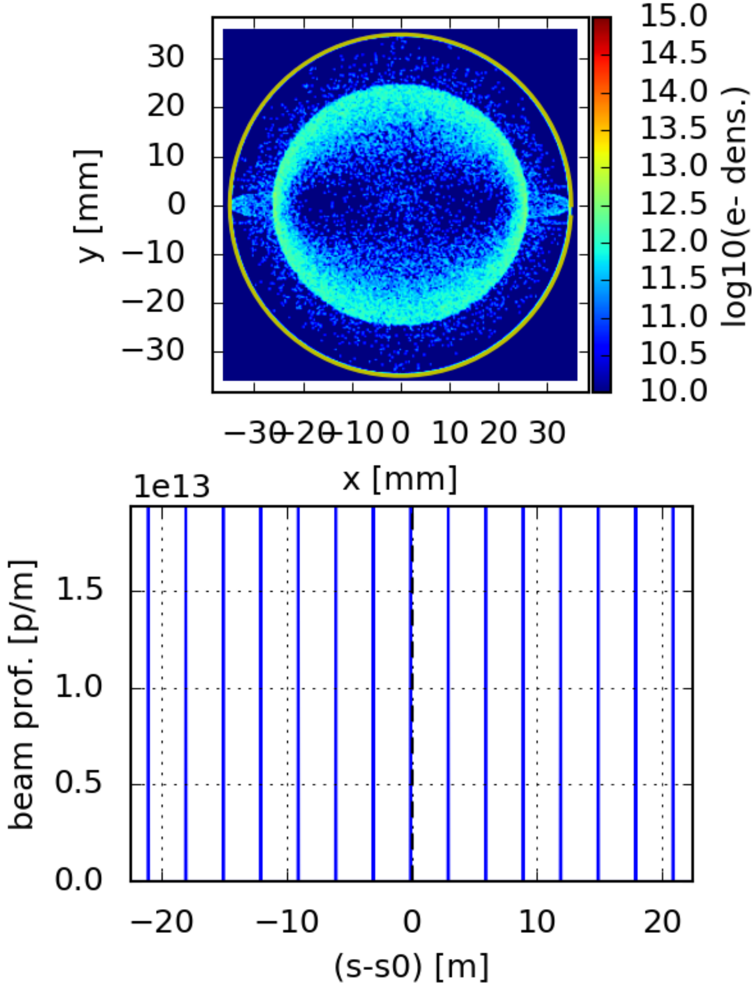

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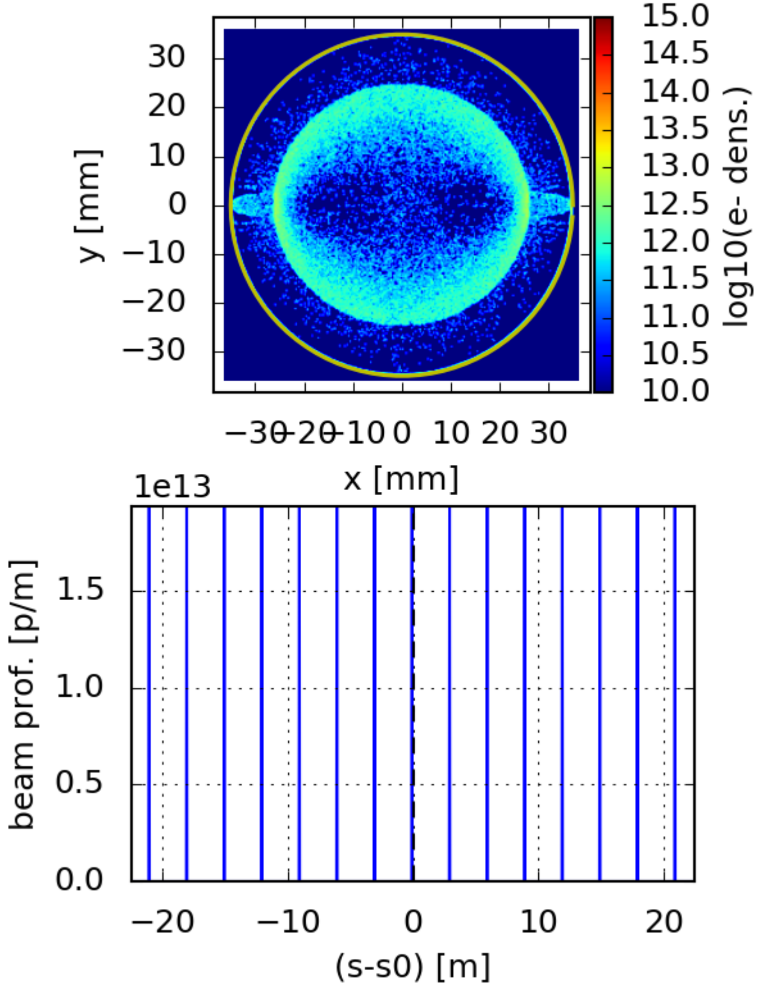

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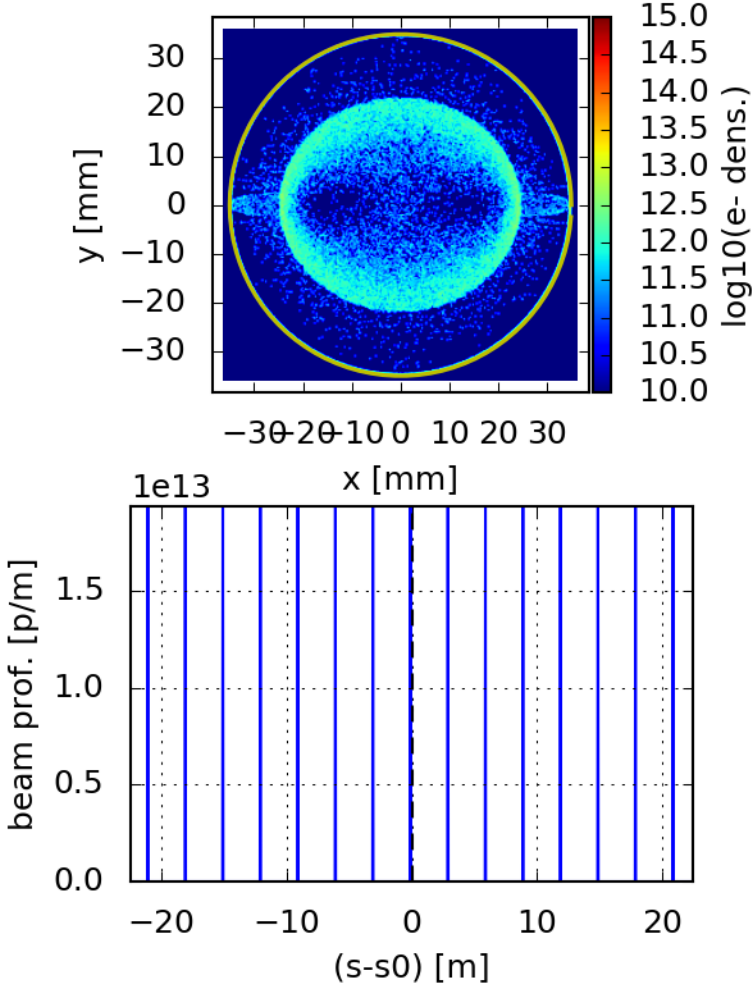

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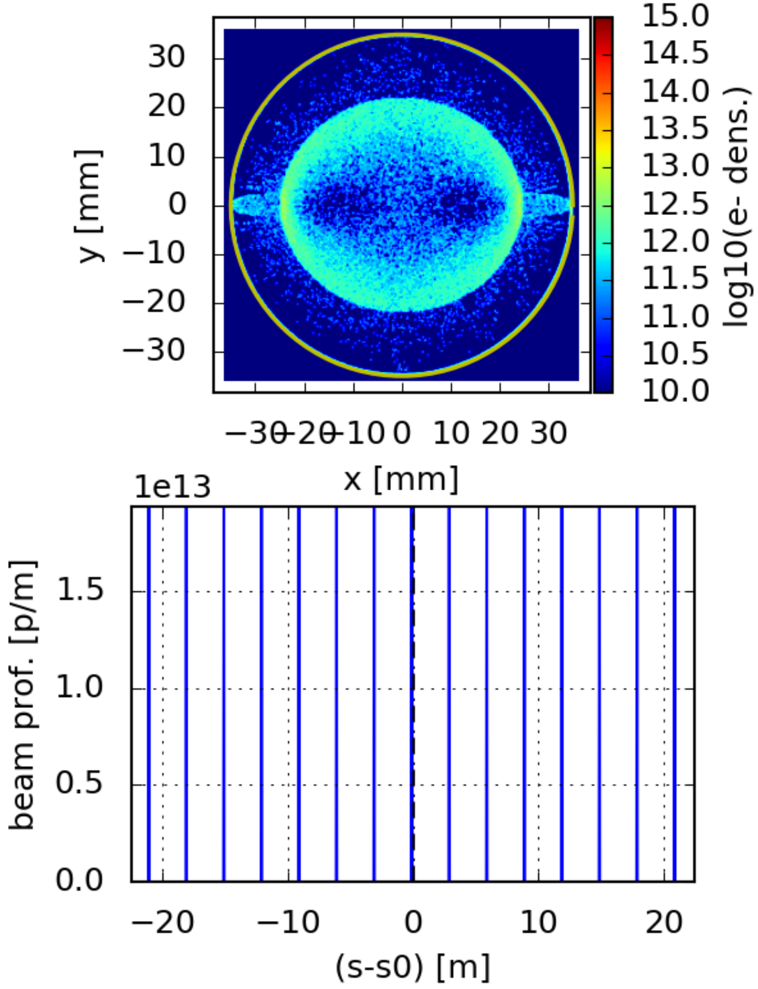

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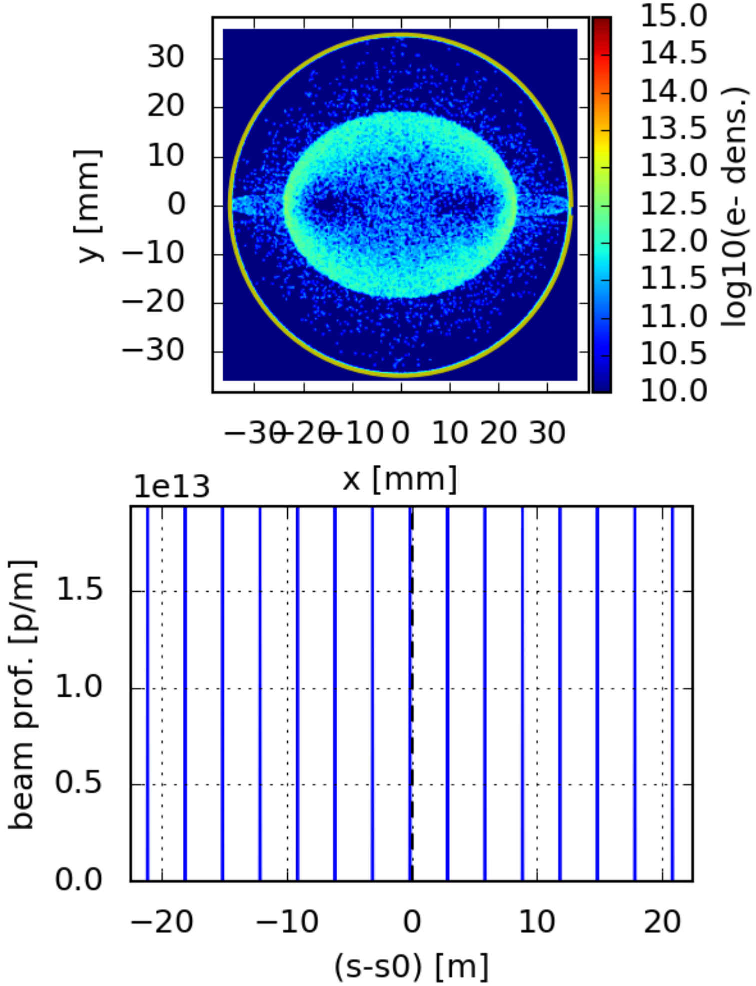

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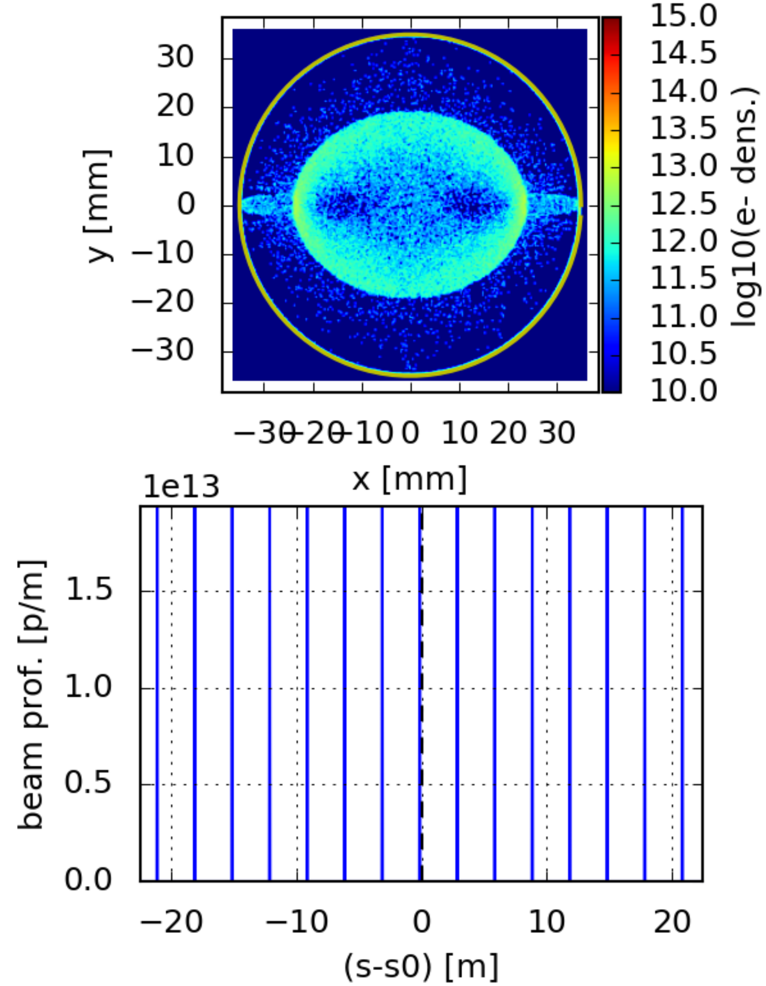

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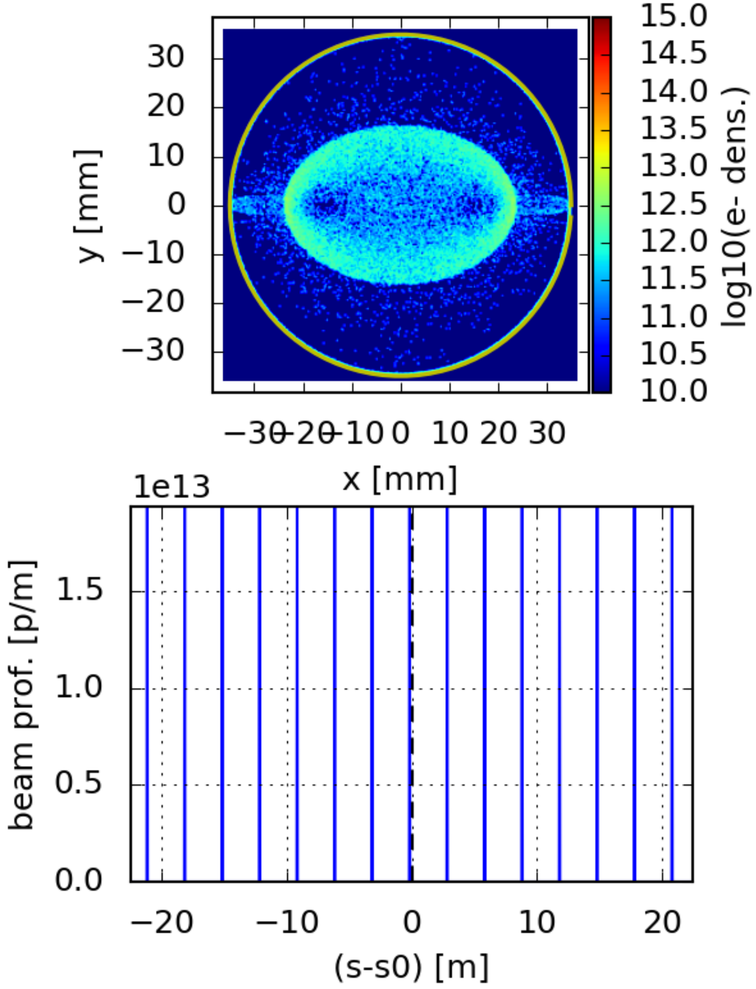

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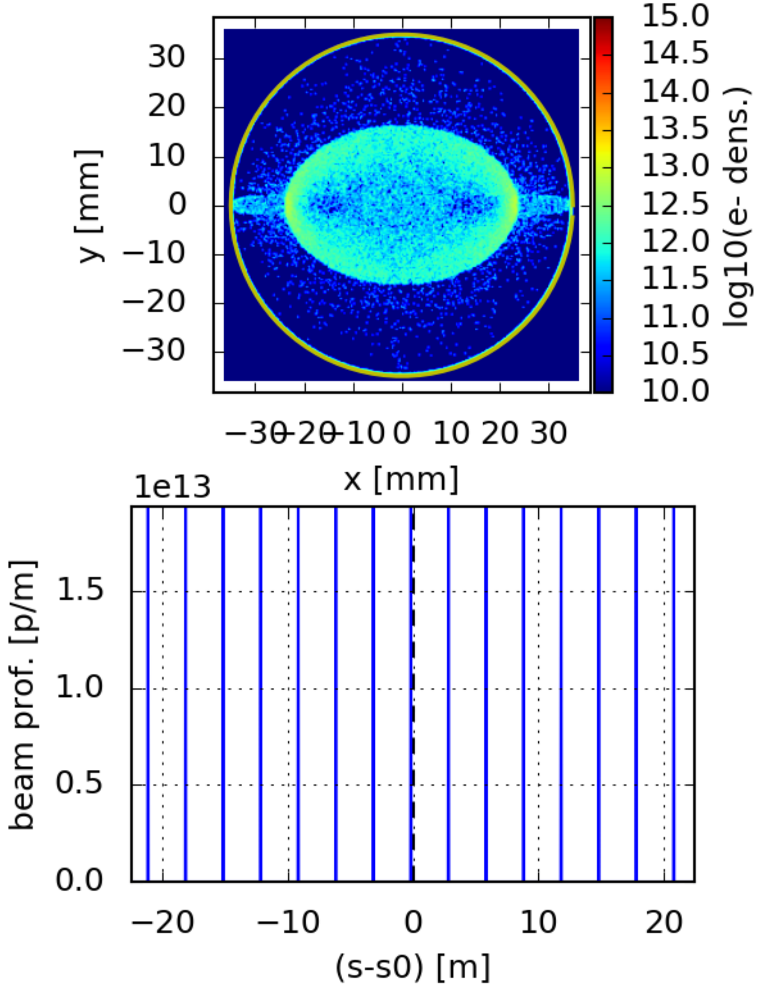

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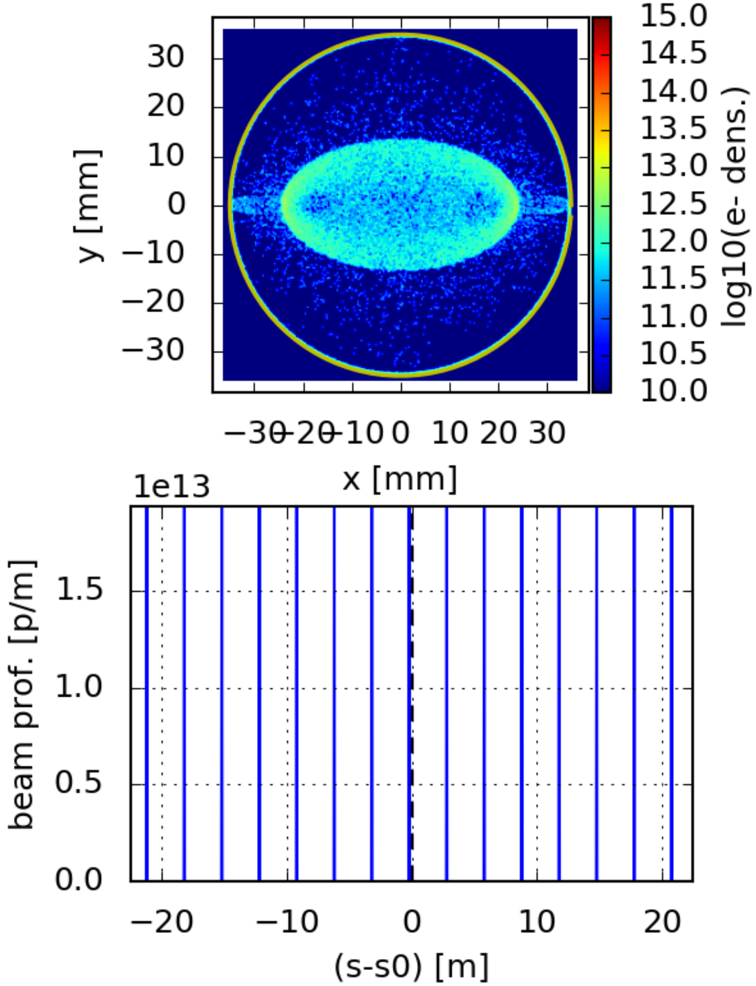

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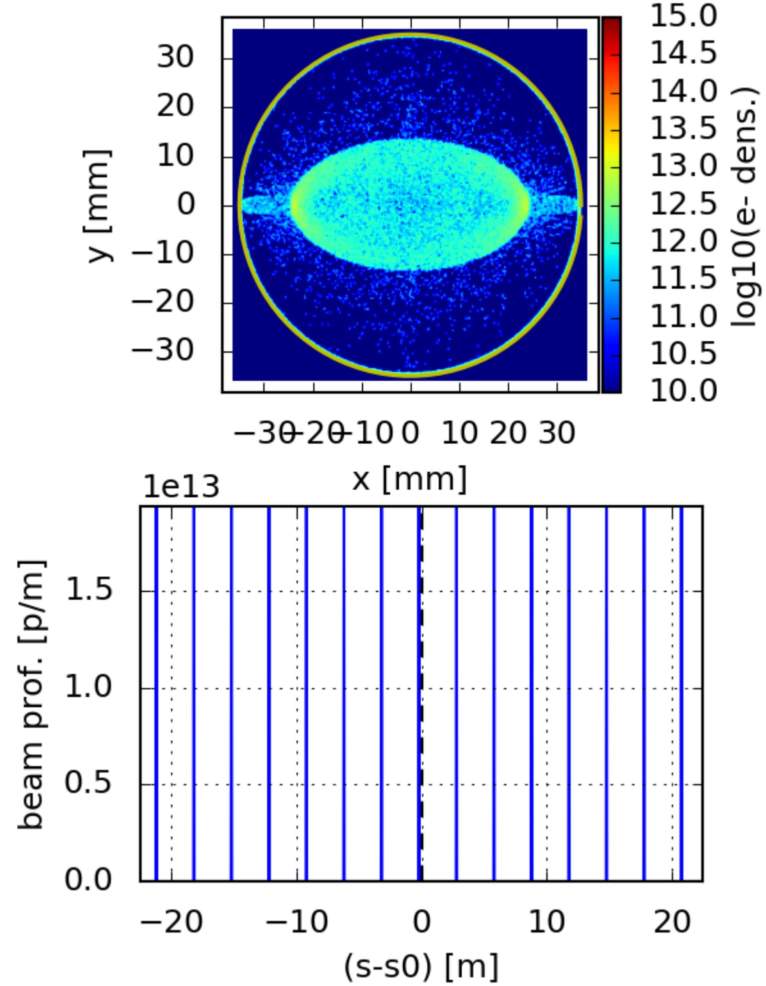

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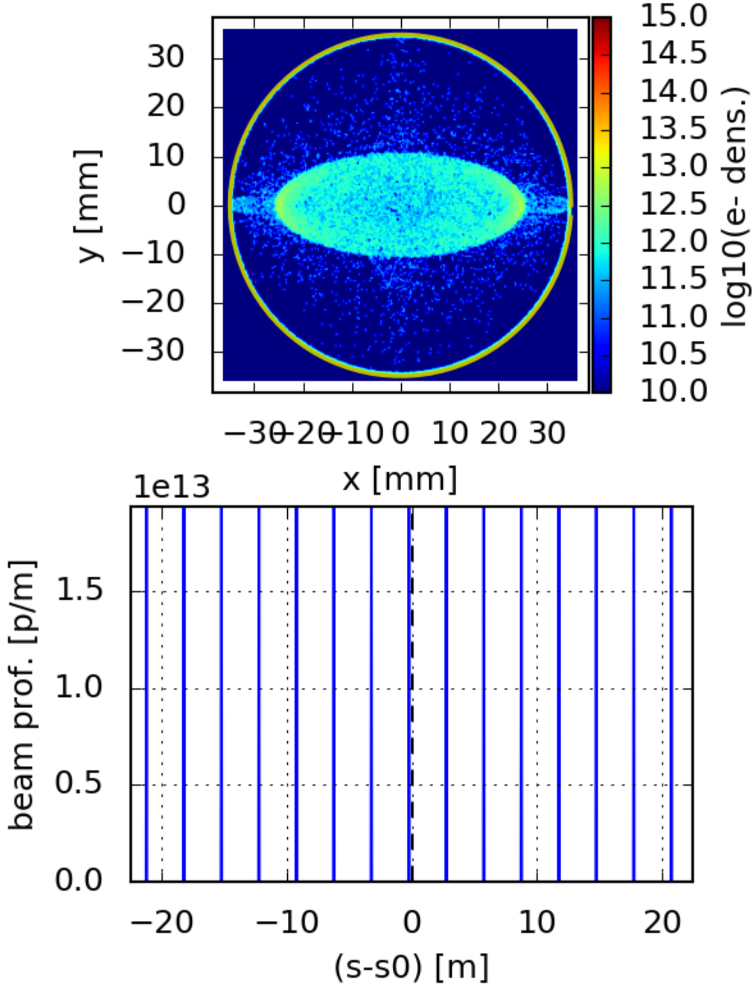

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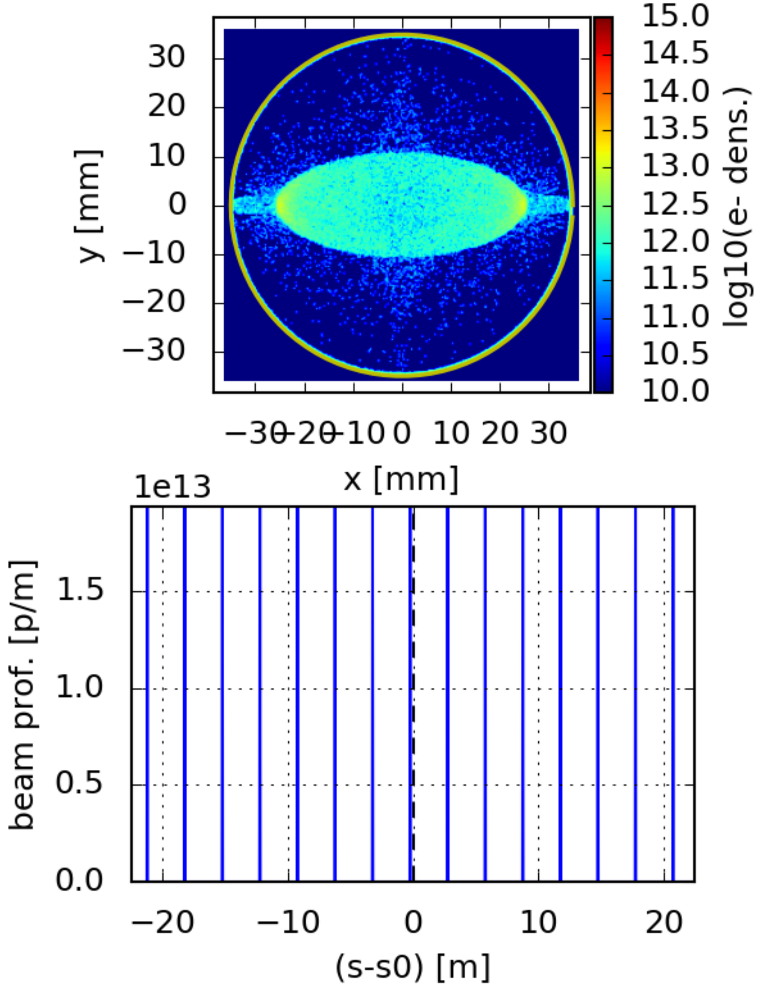
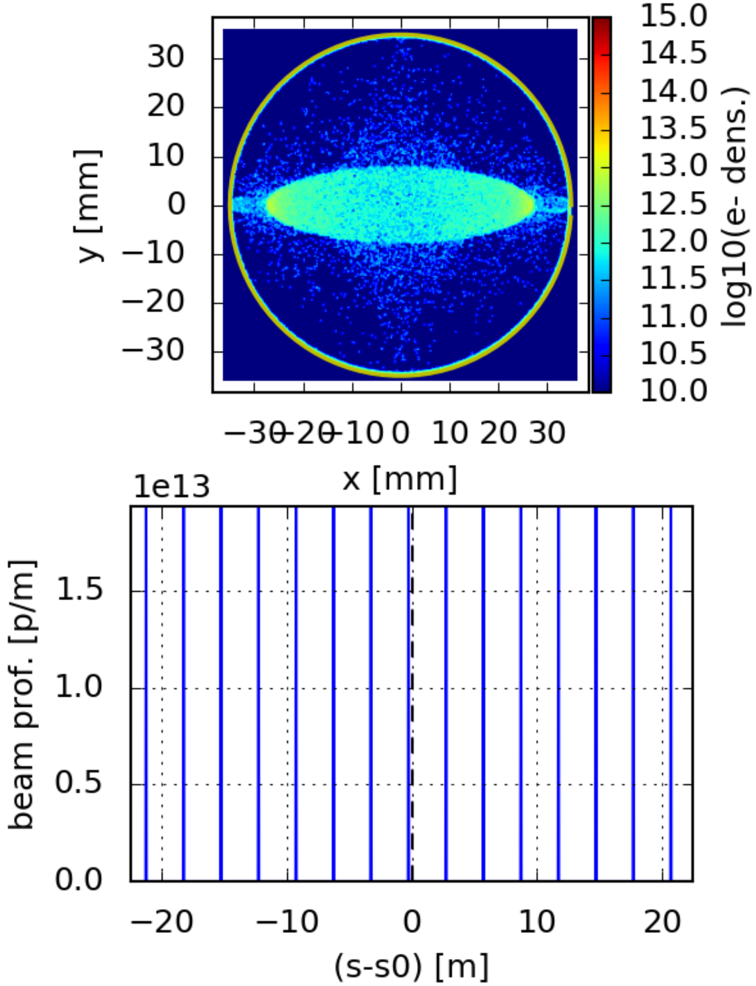


Collider Parameters, bunch spacing =10[ns]

SEY 1.1



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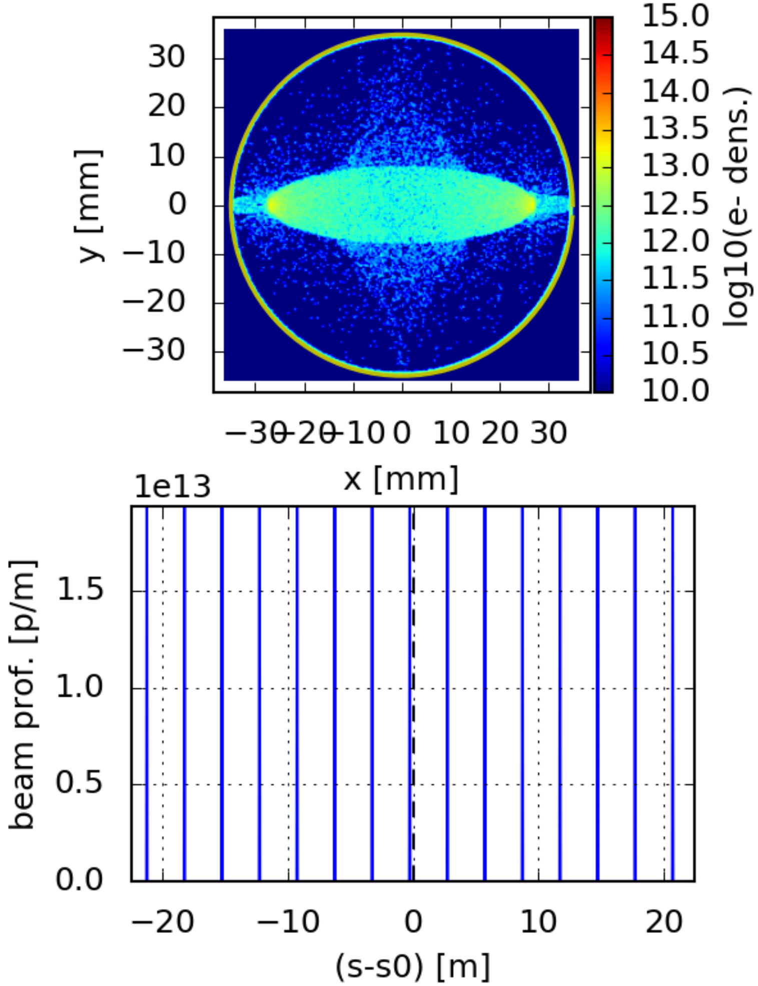
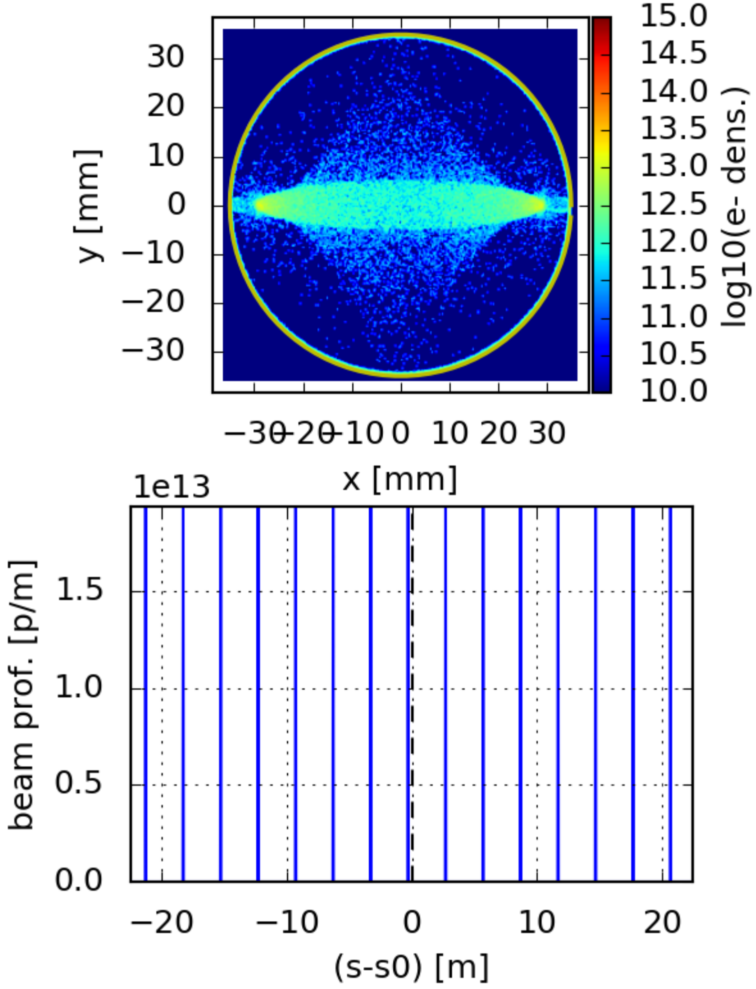


Collider Parameters, bunch spacing =10[ns]

SEY 1.1



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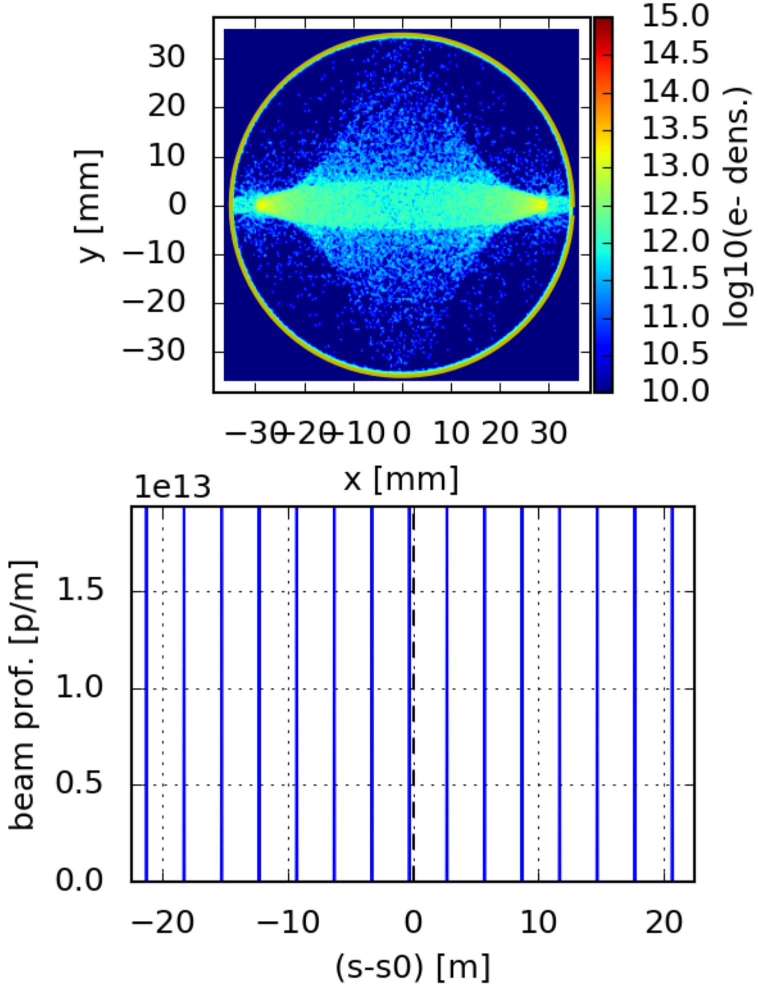

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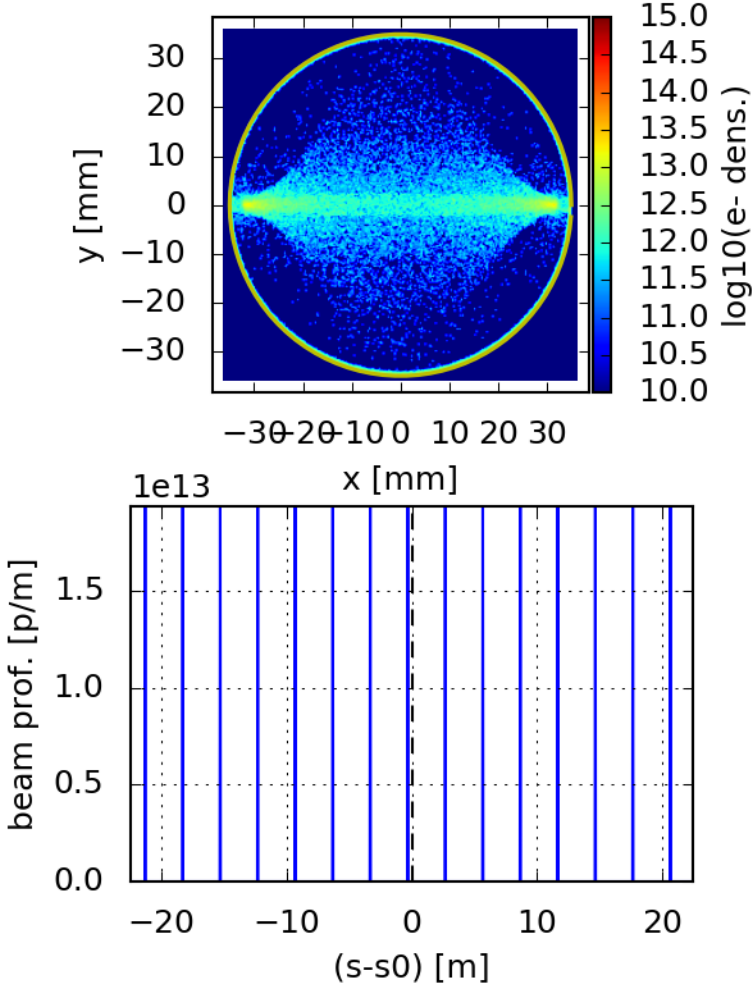

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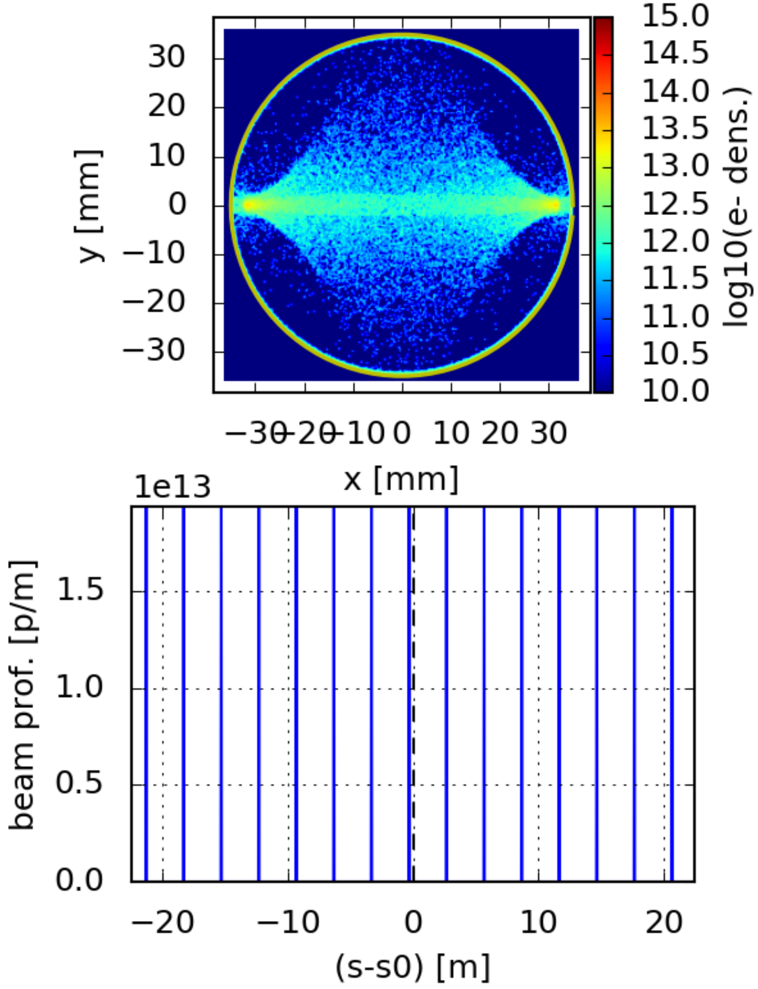

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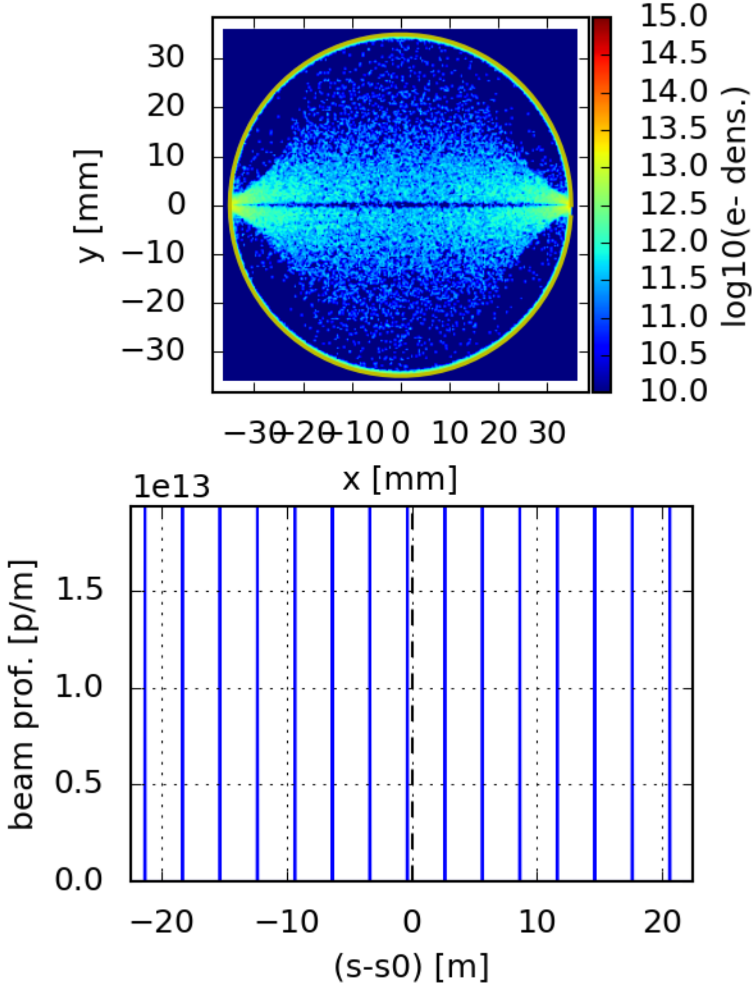

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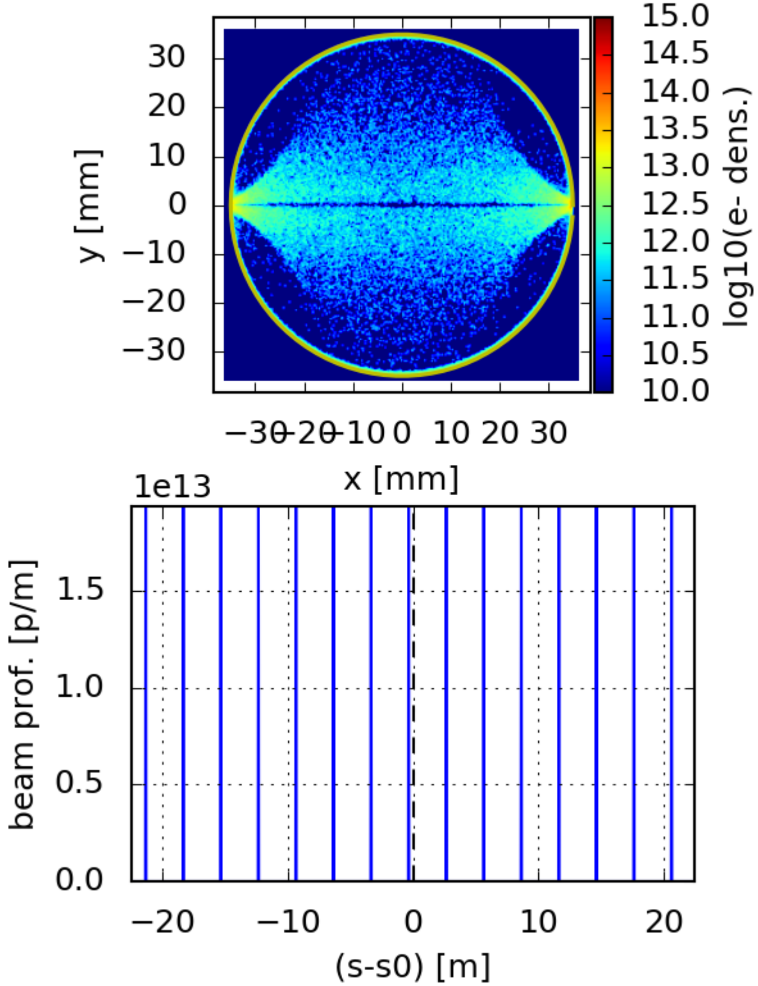

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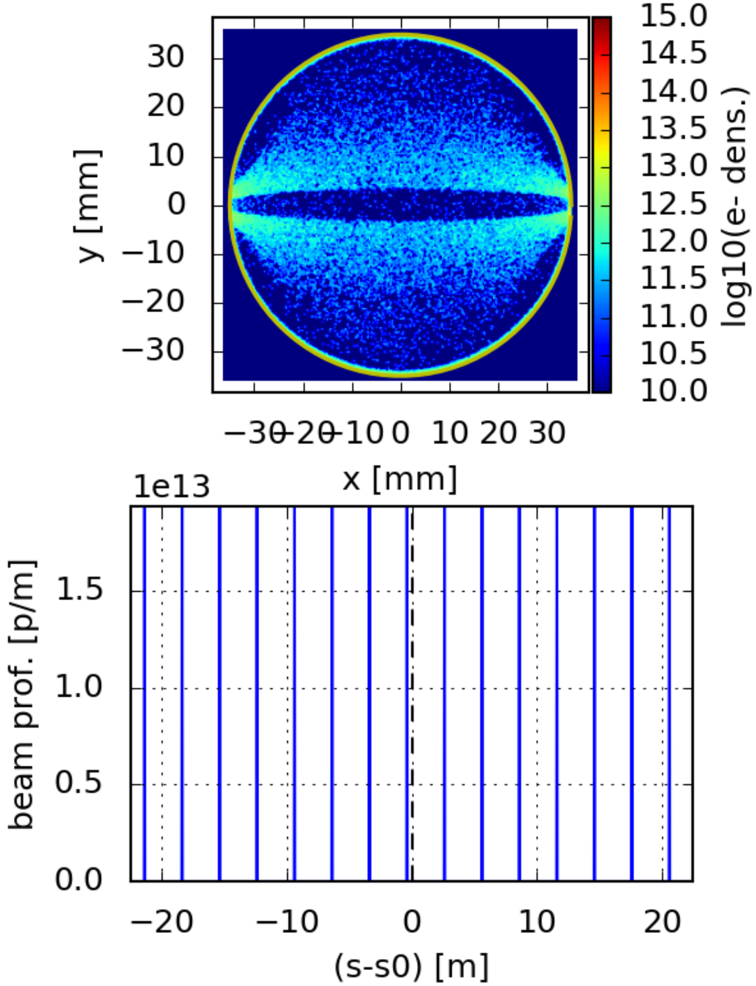

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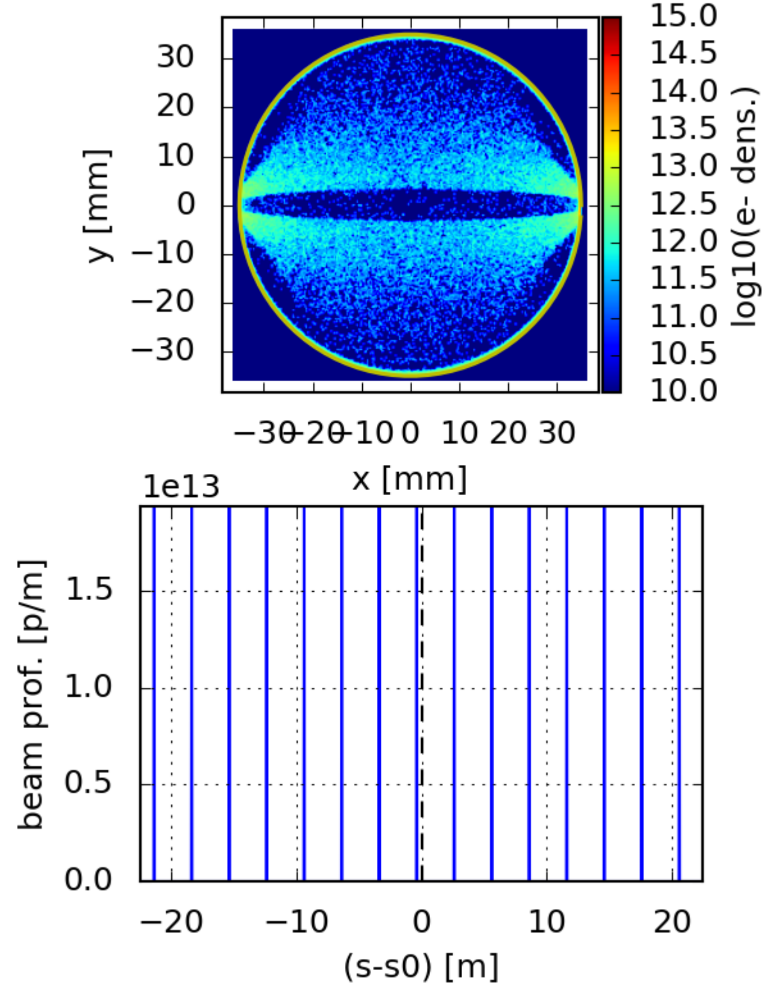
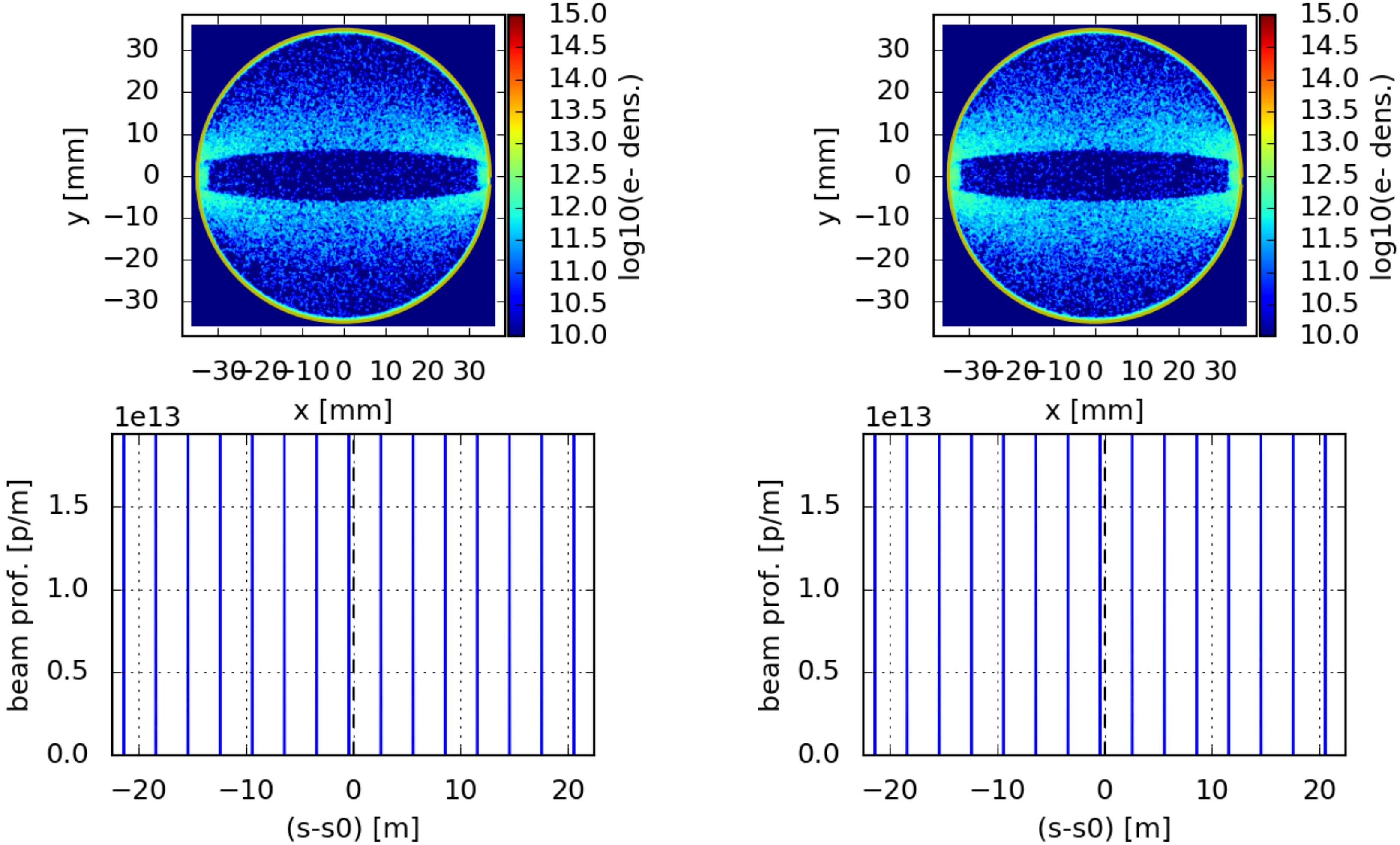


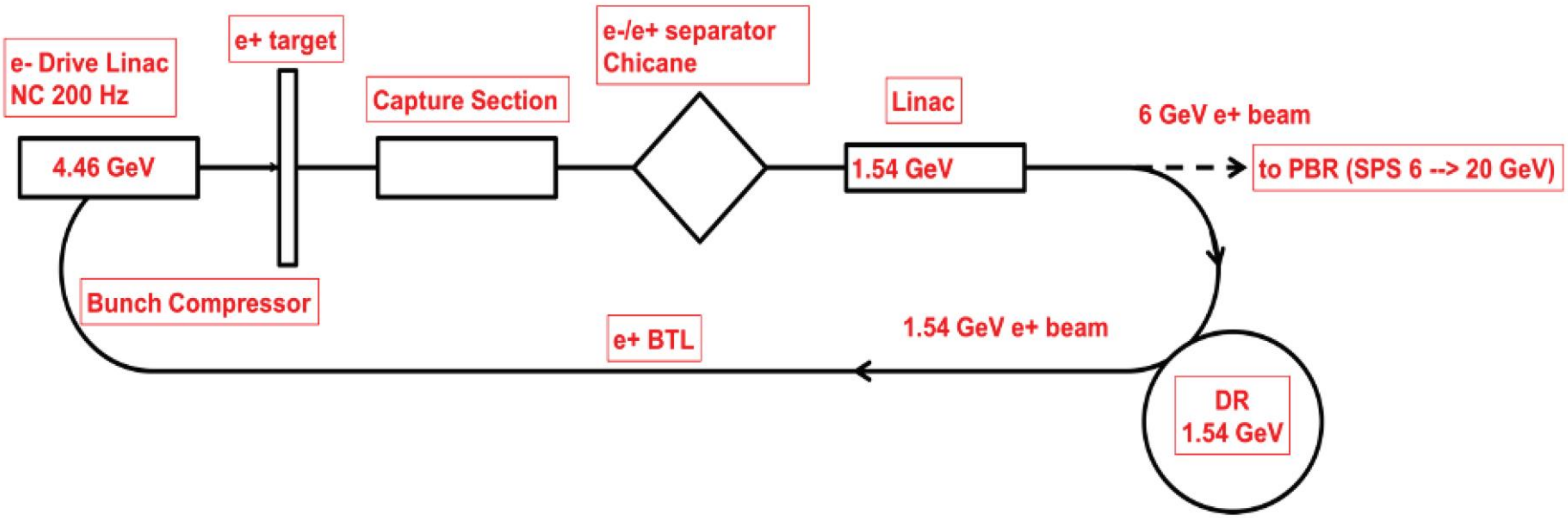
Collider Parameters, bunch spacing =10[ns]

SEY 1.1

SEY 1.4



Machine and Beam Parameters for FCC-ee DR

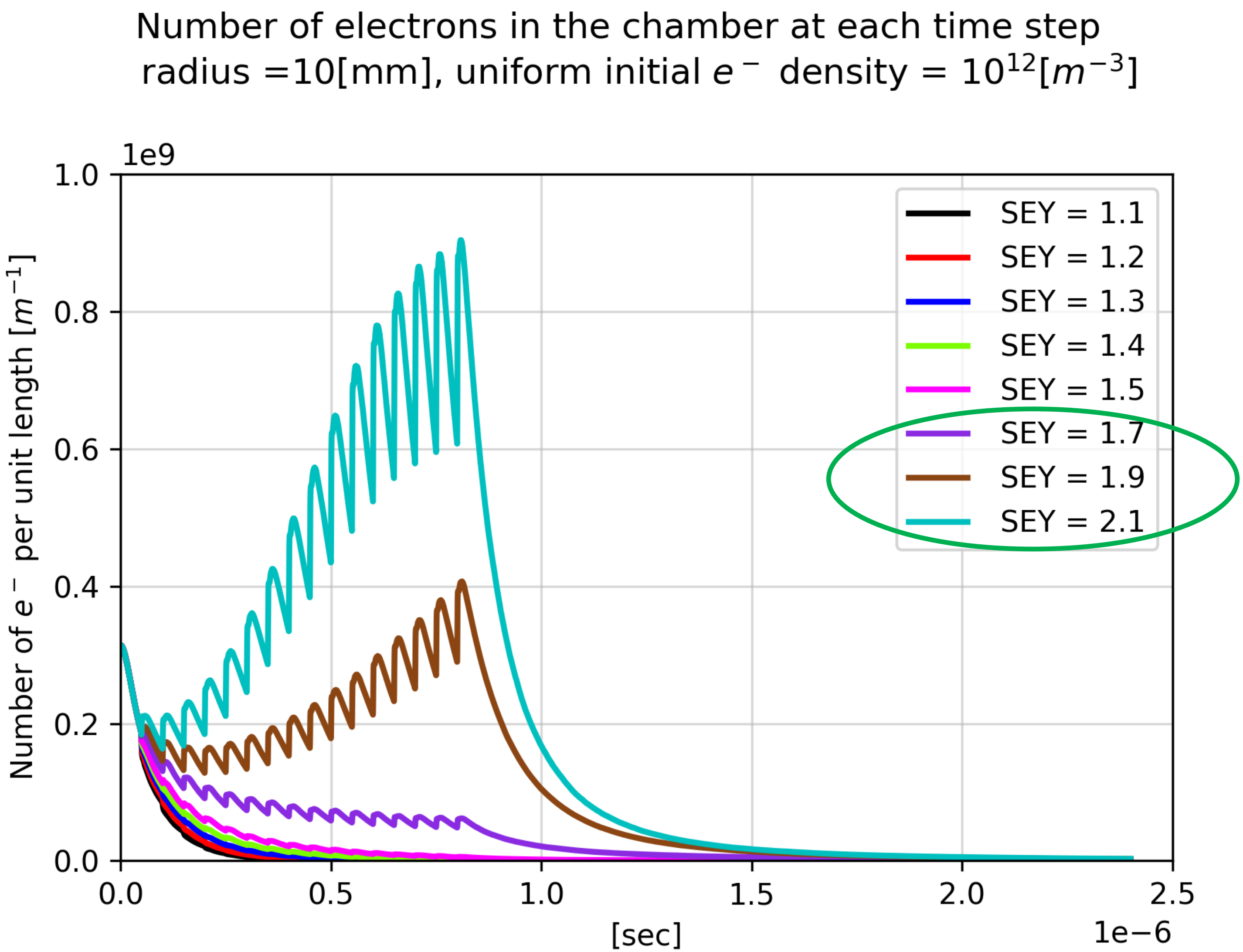


Energy	1.54 [GeV]
bunch spacing	50 [ns]
bunches per train	2
trains per beam	8
bunch length	3.4[mm]
bunch population	2.2×10^{10}

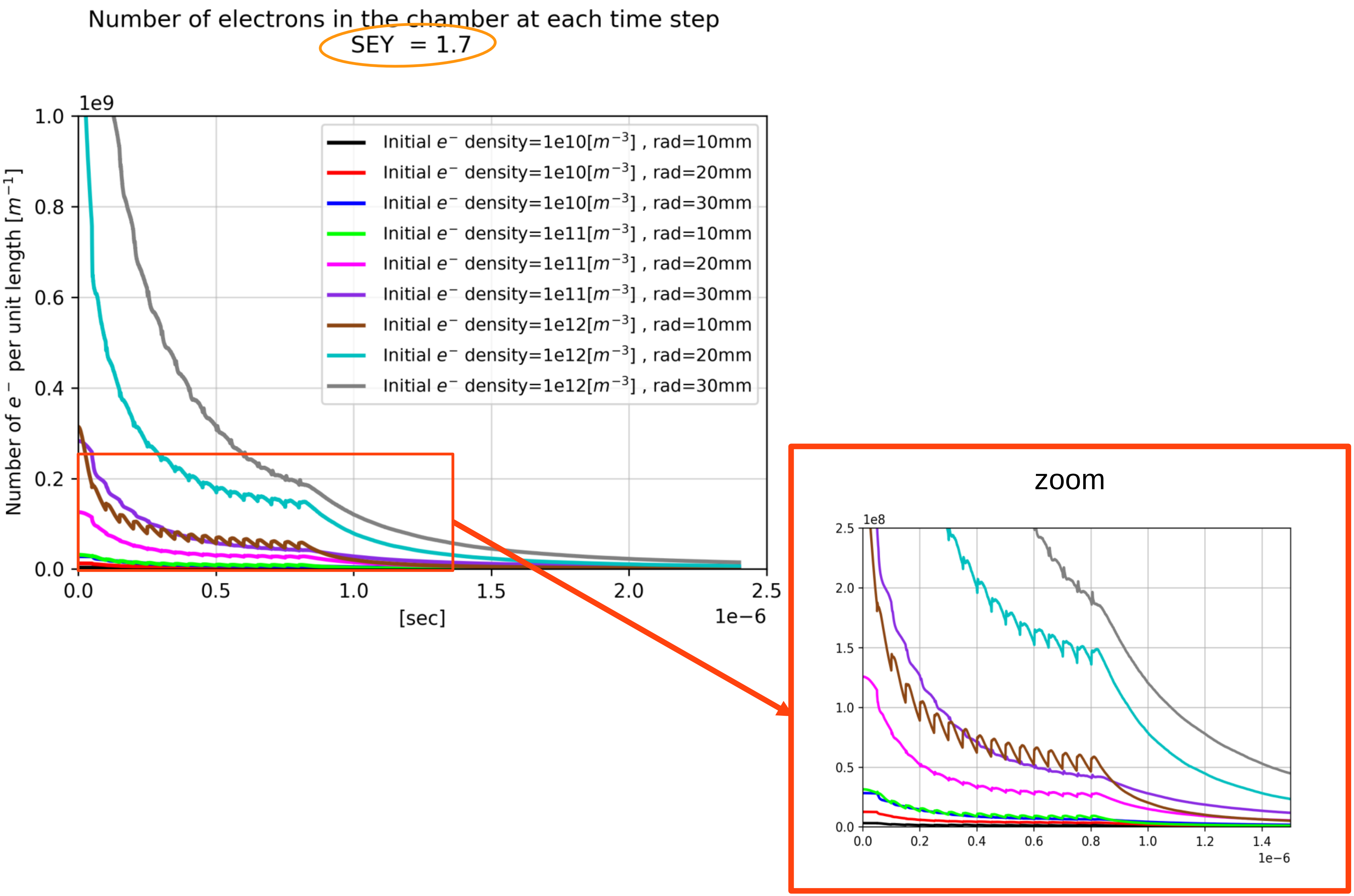
beam radius (H)	2.2 [mm]
beam radius (V)	2.8 [mm]
emittance (x,y)	1.29, 1.22 [μm]
external magnetic field	1.8 [T]
circular beam pipe radius	10 [mm]

Ogur et. al ‘Linac and Damping Ring Designs for the FCC-ee’, IPAC 2019

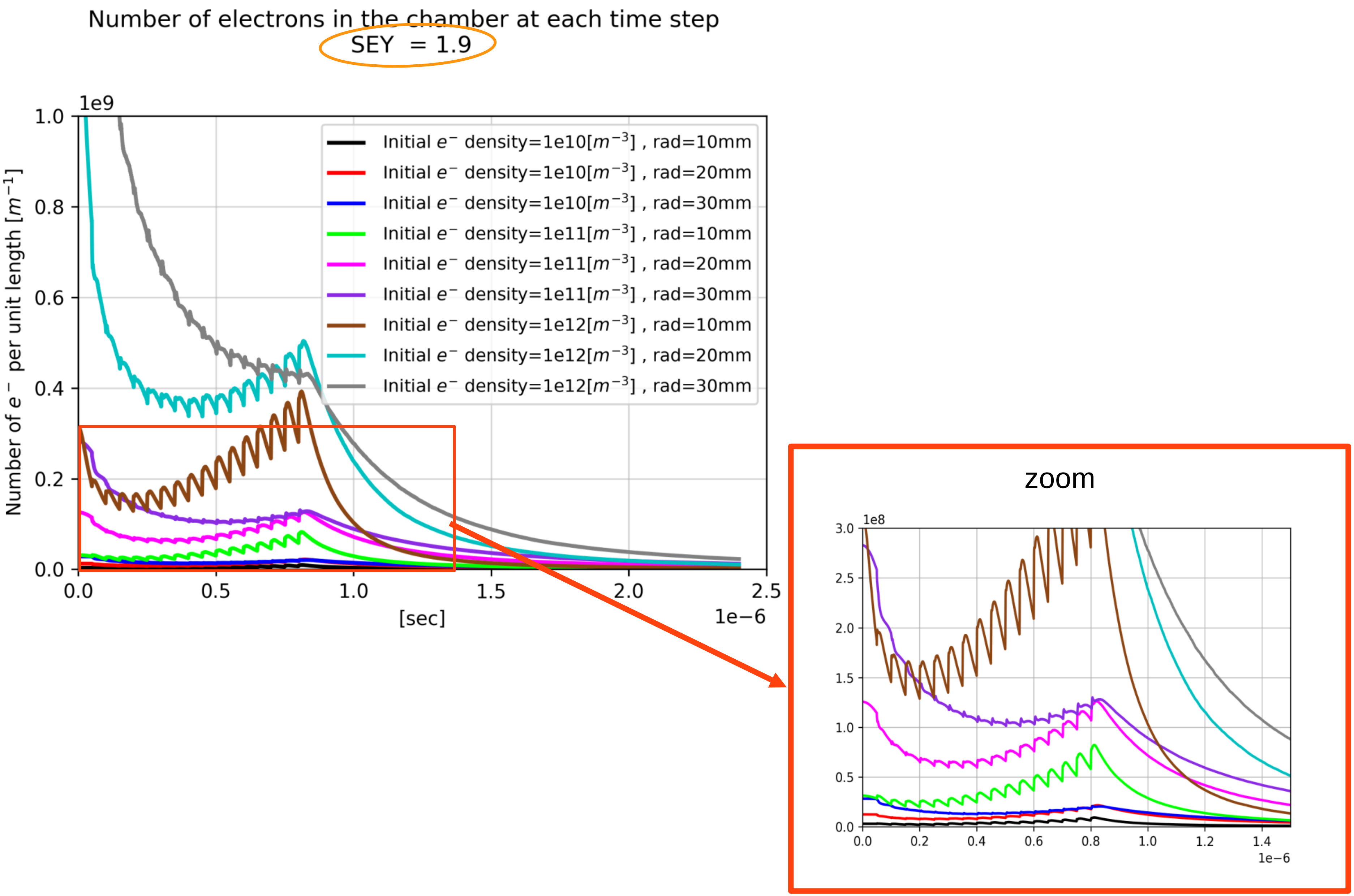
FCC-ee DR for different SEY



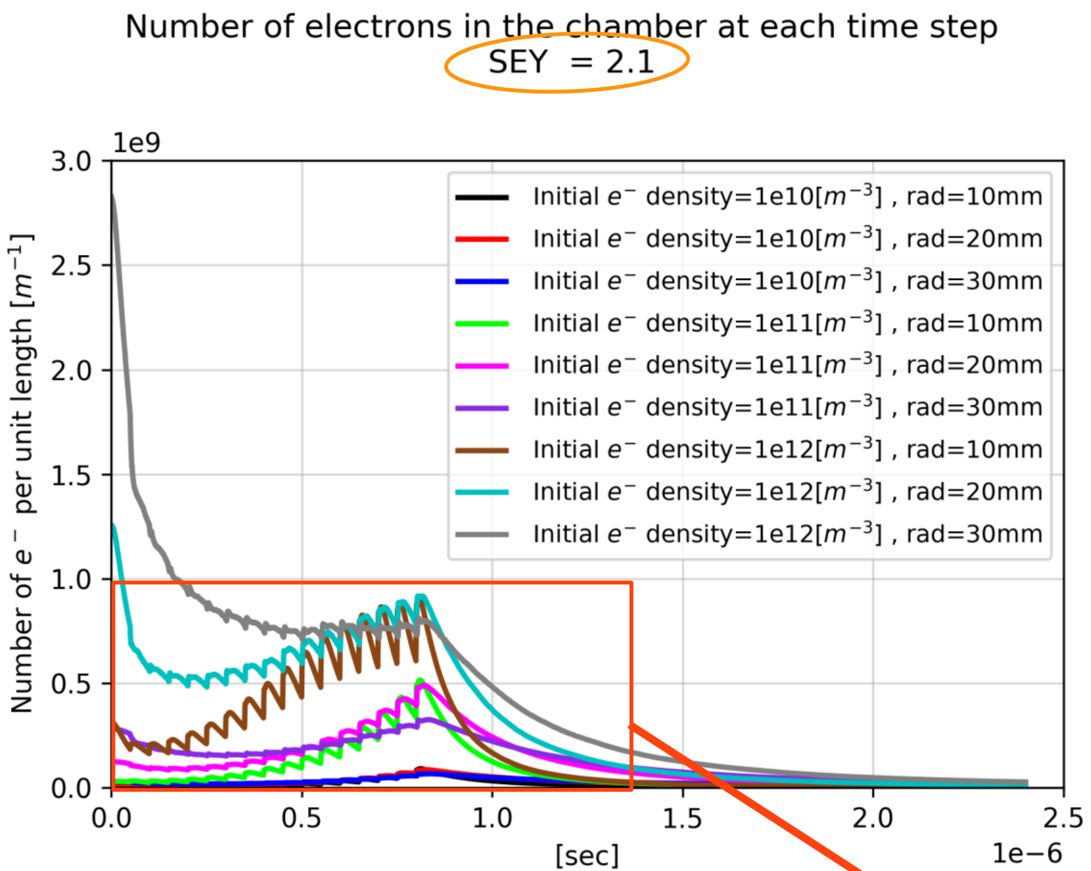
FCC-ee DR parameters for various radii and initial electron densities

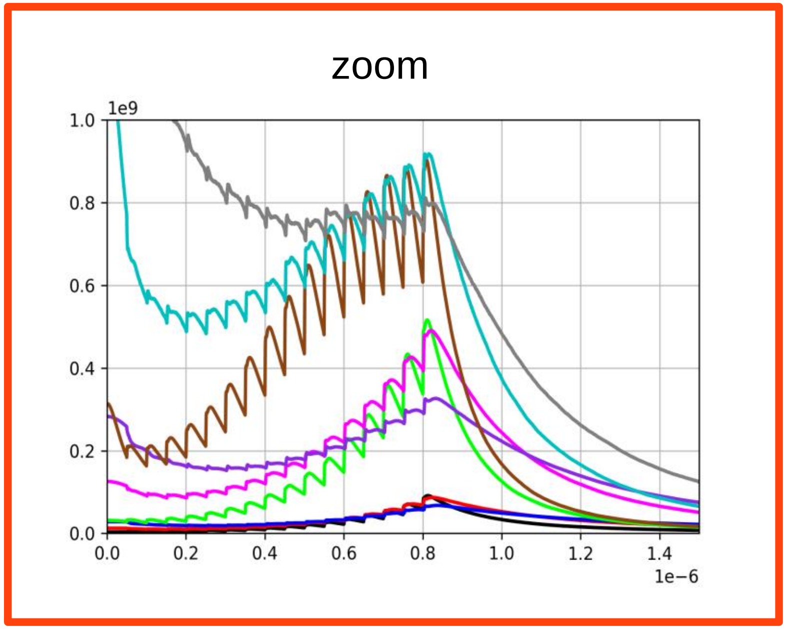


FCC-ee DR parameters for various radii and initial electron densities



FCC-ee DR parameters for various radii and initial electron densities





Thank you..

Furman-Pivi SEY model

$$\delta_e(E_0,\theta_0) = \underline{\delta_e(E_0,\theta_0=0)}[1+e_1(1-\cos^{e_2}\theta_0)]$$
$$\delta_r(E_0,\theta_0) = \underline{\delta_r(E_0,\theta_0=0)}[1+r_1(1-\cos^{r_2}\theta_0)]$$
$$\delta_{ts}(E_0,\theta_0) = \underline{\hat{\delta}(\theta_0)}D(E_0/\hat{E}(\theta_0)),$$

$$\delta_e(E_0,\theta=0) = P_{1,e}(\infty) + [\hat{P}_{1,e} - P_{1,e}(\infty)]e^{-(|E_0-\hat{E}_e|/W)^p/p},$$
$$\delta_r(E_0,\theta=0) = P_{1,r}(\infty)[1-e^{-(E_0/E_r)^r}],$$
$$\hat{\delta}(\theta_0) = \hat{\delta}_{ts}[1+t_1(1-\cos^{t_2}\theta_0)],$$
$$\hat{E}(\theta_0) = \hat{E}_{ts}[1+t_3(1-\cos^{t_4}\theta_0)],$$

$$D(x) = \frac{sx}{s-1+x^s}$$

Furman-Pivi SEY model Parameters

$$\delta_e(E_0, \theta = 0) = P_{1,e}(\infty) + [\hat{P}_{1,e} - P_{1,e}(\infty)]e^{-(|E_0 - \hat{E}_e|/W)^p/p},$$

$$\delta_r(E_0, \theta = 0) = P_{1,r}(\infty)[1 - e^{-(E_0/E_r)^r}],$$

$$\hat{\delta}(\theta_0) = \hat{\delta}_{ts}[1 + t_1(1 - \cos^{t_2}\theta_0)],$$

$$\hat{E}(\theta_0) = \hat{E}_{ts}[1 + t_3(1 - \cos^{t_4}\theta_0)],$$

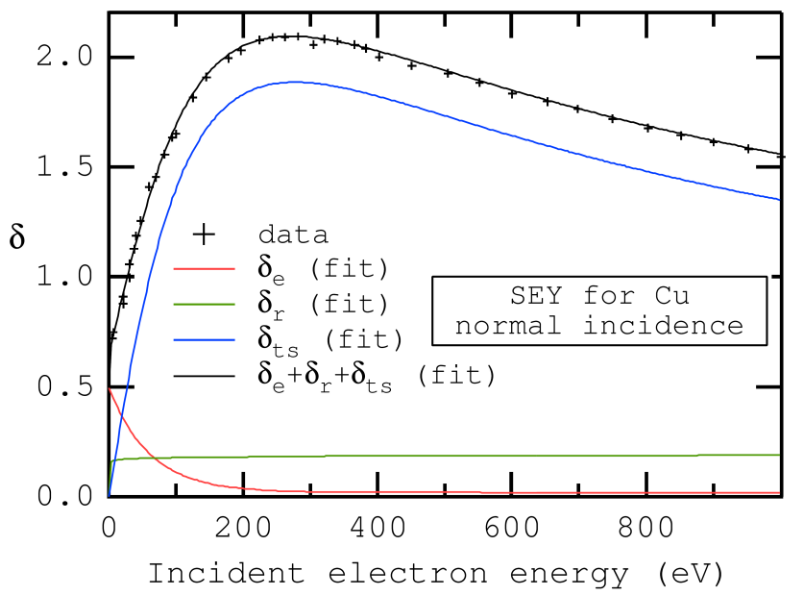


TABLE II: Additional model parameters for the true secondary component.

	Copper	Stainless Steel
p_n	2.5, 3.3, 2.5, 2.5, 2.8, 1.3, 1.5, 1.5, 1.5, 1.5	1.6, 2, 1.8, 4.7, 1.8, 2.4, 1.8, 1.8, 2.3, 1.8
ϵ_n [eV]	1.5, 1.75, 1, 3.75, 8.5, 11.5, 2.5, 3, 2.5, 3	3.9, 6.2, 13, 8.8, 6.25, 2.25, 9.2, 5.3, 17.8, 10

TABLE I: Main parameters of the model.

	Copper	Stainless Steel
Emitted angular spectrum (Sec. II C 1)		
α	1	1
Backscattered electrons (Sec. III B)		
$P_{1,e}(\infty)$	0.02	0.07
$\hat{P}_{1,e}$	0.496	0.5
$\hat{E}_e$ [eV]	0	0
W [eV]	60.86	100
p	1	0.9
σ_e [eV]	2	1.9
e_1	0.26	0.26
e_2	2	2
Rediffused electrons (Sec. III C)		
$P_{1,r}(\infty)$	0.2	0.74
E_r [eV]	0.041	40
r	0.104	1
q	0.5	0.4
r_1	0.26	0.26
r_2	2	2
True secondary electrons (Sec. III D)		
$\hat{\delta}_{ts}$	1.8848	1.22
$\hat{E}_{ts}$ [eV]	276.8	310
s	1.54	1.813
t_1	0.66	0.66
t_2	0.8	0.8
t_3	0.7	0.7
t_4	1	1
Total SEY[a]		
$\hat{E}_t$ [eV]	271	292
$\hat{\delta}_t$	2.1	2.05

[a]Note that $\hat{E}_t \simeq \hat{E}_{ts}$ and $\hat{\delta}_t \simeq \hat{\delta}_{ts} + P_{1,e}(\infty) + P_{1,r}(\infty)$ provided that $\hat{E}_{ts} \gg \hat{E}_e, E_r$.

M.A. Furman and M.T.F. Pivi, ‘Probabilistic Model for the Simulation of Secondary Electron Emission’, SLAC-PUB-9912, 2003