Microscopic Phenomenological Model
for the
Secondary Emission Process

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LBNL

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- Motivation
- Definition of the model
- Fits to Cu and St. St. data
- Applications
  - time dependence of the electron-cloud power deposition in an LHC arc dipole
  - time dependence of the electron cloud dissipation in the PSR following extraction of the beam
- Conclusions

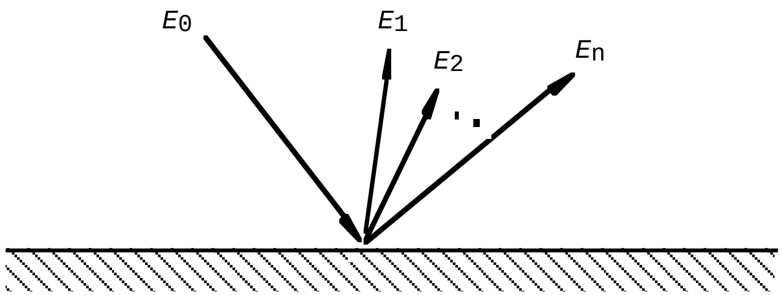
Our main focus:

• Understand in detail the effects of:
 – details of the secondary electron yield (SEY)
 – details of the secondary electron energy spectrum

• Simulations started in 1995 (with G. Lambertson):
 – PEP-II, LHC, APS, SPS, ...
 – main input: SEY (δ) and secondary energy spectrum ($d\delta/dE$)
 – obtained from lab measurements (R. Kirby, SLAC; N. Hilleret, CERN)
 – also books by Bruining, Redhead et al, and various articles in J. Appl. Phys. and other journals

• SEY model in the simulation originally developed in 1995
 – several refinements over past 1-1/2 years (M. Pivi)
 – some errors fixed (no major effect on results)

Details of the model:



- event-by-event simulation(*)
  - event=one electron-wall collision
  - instantaneous generation of n secondaries (or absorption)
  - include E_0 and θ_0 dependence

- constraints for any single event:
  - $E_k \leq E_0$, k=1,2,…,n
  - $\Sigma_k E_k \leq E_0$
- constraints for the average over many events:
  - $\Sigma\, nP_n = \delta(E_0,\theta_0)$=input data
  - $d\delta/\delta E$=input data

(*) In our ECE simulation code, *all* macroparticles have the same charge (and mass)

LBNL–49711, CBP Note–415

Microscopic Probabilistic Model for the Simulation of Secondary Electron Emission*

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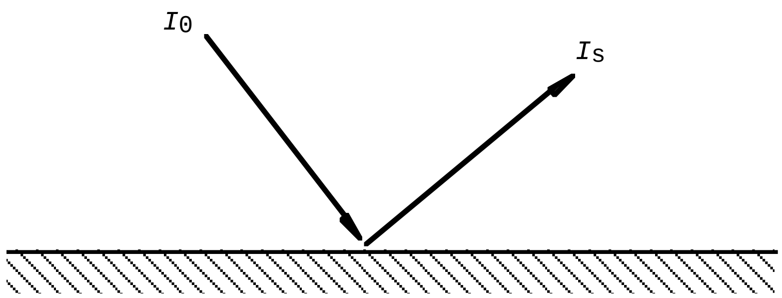
Abstract

We provide a detailed description of a model and its computational algorithm for the secondary electron emission process that has been used for some time now in the simulations of the electron cloud effect (ECE). We provide the numerical values for several parameters which have been obtained by fitting this model to laboratory measurements of the secondary yield and emitted energy spectrum.

Basic macroscopic phenomenology



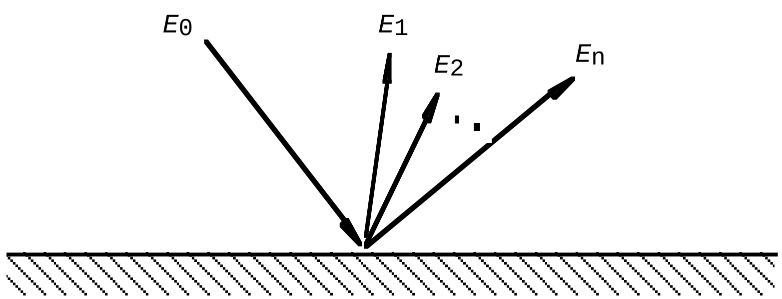
SEY: $\delta = \frac{I_s}{I_0}$ (steady-state currents)

Cumulative energy spectrum:
apply a retarding voltage E=eV

$$S(E_0, E) = \frac{[I_s]_{\text{energy} \geq eV}}{I_0}$$

Retarding-voltage spectrum:

$$\left(\frac{d\delta}{dE}\right)_{\text{RV}} = -\frac{\partial S(E_0, E)}{\partial E}$$



What we need for an event-by-event simulation is:

$$\mathcal{P}_n = \frac{dP_n}{dE_1 d\Omega_1 dE_2 d\Omega_2 \cdots dE_n d\Omega_n}, \qquad n = 1,\ 2,\ \cdots$$

From $\mathcal{P}_n$ obtain any macroscopic quantity:

$$P_n = \int (dE)_n (d\Omega)_n \mathcal{P}_n \,, \qquad n \geq 1$$

$$\delta = \langle n \rangle = \sum_{n=1}^{\infty} n P_n$$

$$\left(\frac{d\delta}{dE} \right)_{\mathrm{RV}} = \sum_{n=1}^{\infty} \int (dE)_n (d\Omega)_n \mathcal{P}_n \sum_{k=1}^{n} \delta(E_k - E)$$

We have constructed a phenomenological model for $\mathcal{P}_n$

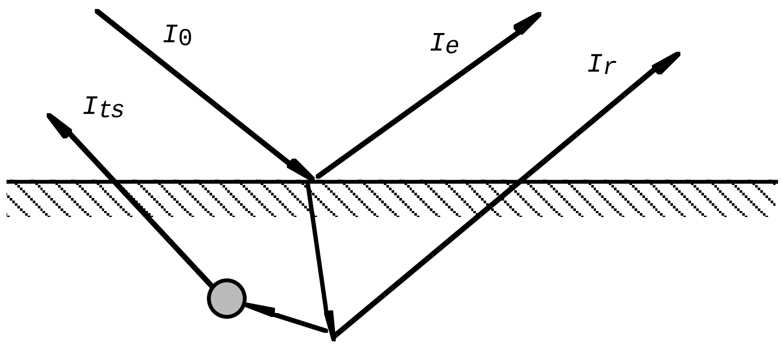
- based as much as possible on data for δ and dδ/dE
- not unique (use simplest assumptions whenever data is not available)
- many adjustable parameters, fixed by fitting δ and dδ/dE to data
- satisfies the single-event constraints
  - $E_k \leq E_0$, k=1,2,…,n
  - $\Sigma_k E_k \leq E_0$
- still evolving
- good agreement with data (by construction)
- some shortcomings

Ignore for now the emission-angle distribution (*ie*., integrate over angles)

$$\frac{dP_n}{(dE)_n} = \theta(E_0 - E_1 - \cdots - E_n) \prod_{k=1}^{n} f_n(E_k)\theta(E_k)\theta(E_0 - E_k)$$

$$\int (dE)_n \frac{dP_n}{(dE)_n} = P_n$$

Three components of emitted electrons:



backscattered: $\delta_e = \frac{I_e}{I_0}$,

rediffused: $\delta_r = \frac{I_r}{I_0}$,

true secondaries: $\delta_{ts} = \frac{I_{ts}}{I_0}$

$$f_{1,e} = \theta(E)\theta(E_0 - E)\,\delta_e(E_0,\theta_0)\,\frac{2e^{-(E-E_0)^2/2\sigma_e^2}}{\sqrt{2\pi}\sigma_e\,\mathrm{erf}(E_0/\sqrt{2}\sigma_e)}$$

$$f_{1,r} = \theta(E)\theta(E_0 - E)\delta_r(E_0,\theta_0)\,\frac{(q+1)E^q}{E_0^{q+1}}$$

$$f_{n,ts} = \theta(E)F_n E^{p_n - 1}\,e^{-E/\epsilon_n}$$

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

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

$$\delta_{ts}(E_0,\theta_0) = \hat{\delta}(\theta_0)D(E_0/\hat{E}(\theta_0)) \qquad D(x) = \frac{sx}{s-1+x^s}$$

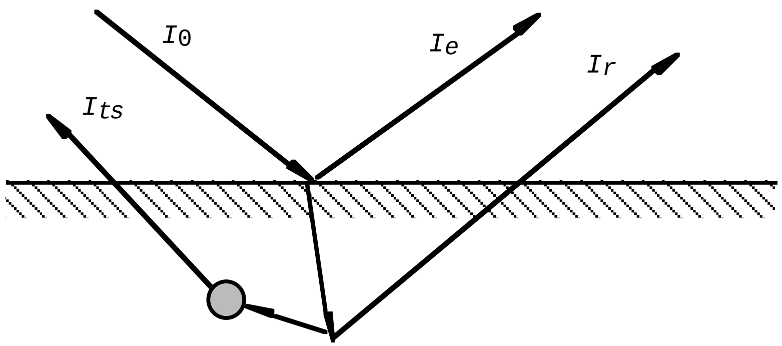
$$P'_{n,ts} = \binom{M}{n}p^n(1-p)^{M-n}, \quad 0 \le n \le M \qquad p = \langle n\rangle/M = \delta'_{ts}/M.$$

$$\delta'_{ts} = \frac{I_{ts}}{I_0 - I_e - I_r} = \frac{\delta_{ts}}{1-\delta_e-\delta_r}$$

$$P_0 = 1 - \sum_{n=1}^{\infty} P_n$$

Exclusion assumption:

• if n=1, electron can be either backscattered, rediffused or true secondary

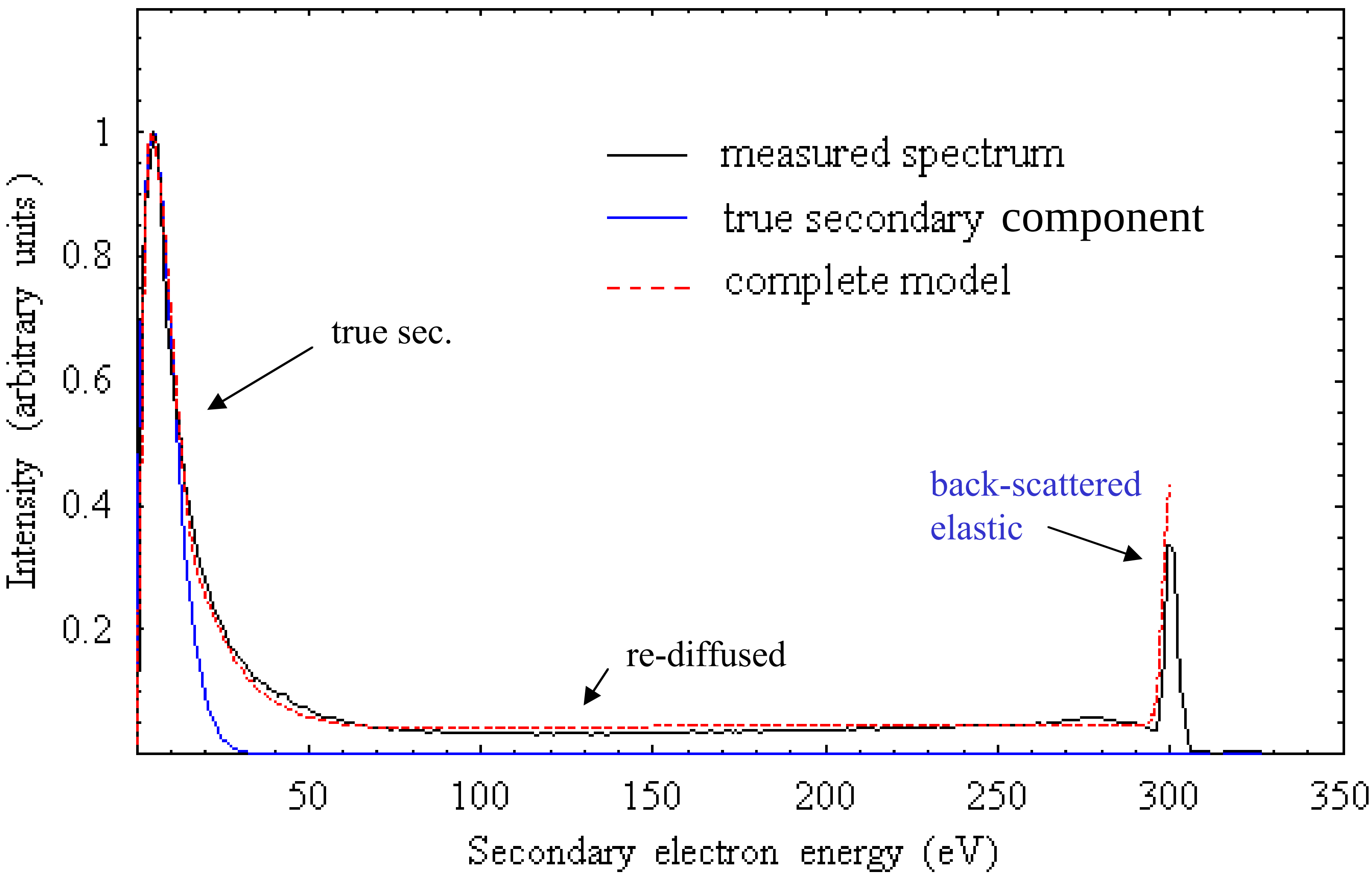


• if n≥2, electron can only be true secondary

This is a simplifying assumption:

- allows to easily extract the energy distribution functions $f_n(E)$ directly from the energy spectrum $d\delta/dE$
- no fundamental physical reason
- consistent with data on $d\delta/dE$ for E_0>50 eV or so, but not implied by it

Typical secondary emitted-electrons energy spectrum



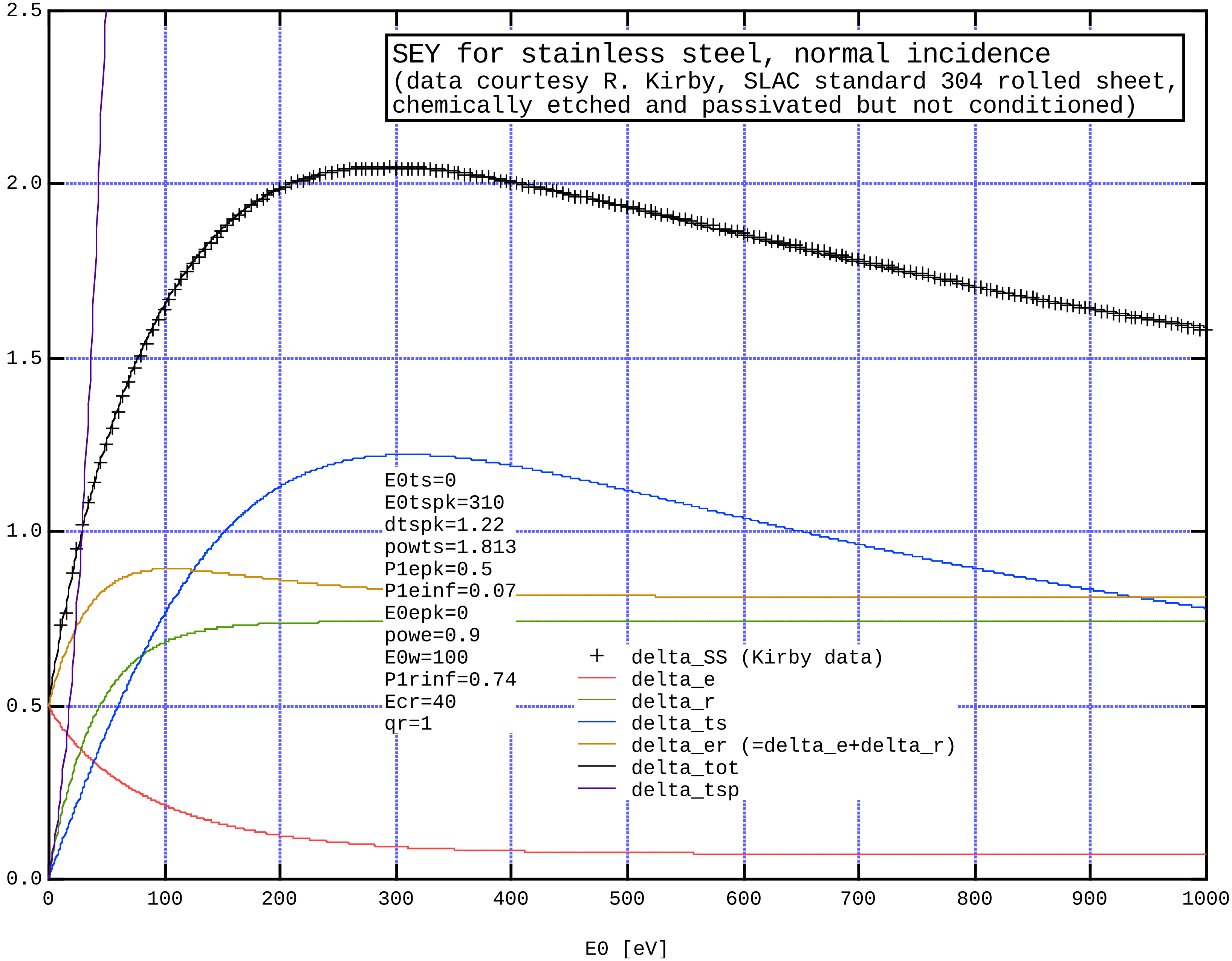
Algorithm:

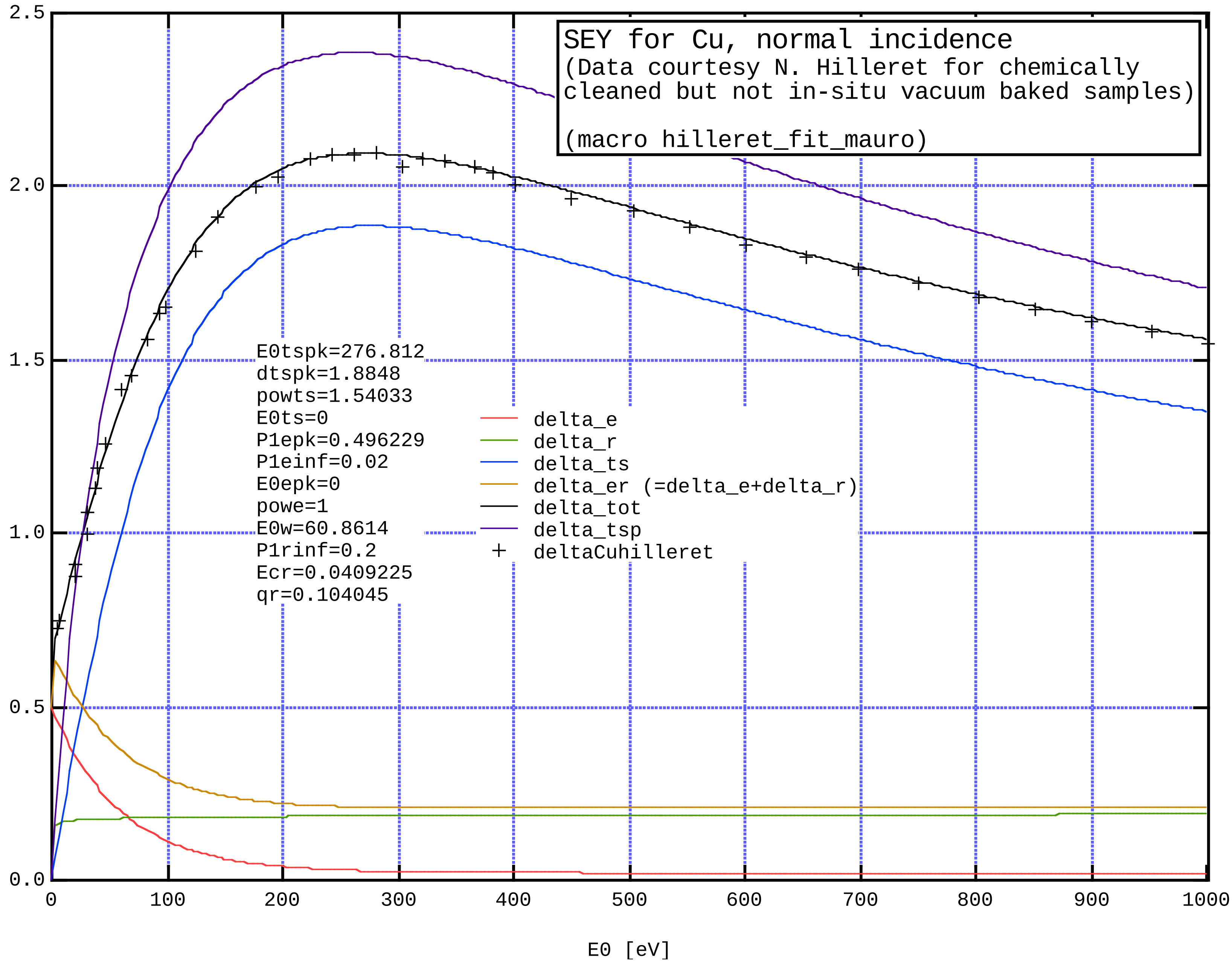
1. When an electron hits the wall, record E_0 and θ_0
2. Compute $\delta_e(E_0,\theta_0)$, $\delta_r(E_0,\theta_0)$ and $\delta_{ts}(E_0,\theta_0)$
3. Compute P_n, n=1,2,…,M (typically, M=10)
4. Generate a random integer $n \in [0,M]$ with probability distribution $\{P_n\}$
5. If n=0, electron got absorbed; continue with next incident electron
6. If n=1, generate its energy E with probability distribution $f_{1e}(E)+f_{1r}(E)+f_{1ts}(E)$ such that $E \le E_0$
7. If $n \ge 2$, generate their energies E_k with probability distribution $f_{nts}(E_k)$ such that $\sum_{k=1}^{n} E_k \le E_0$
8. Generate the emission angles (θ_k,ϕ_k) for k=1,2,…,n
9. Continue with next incident electron

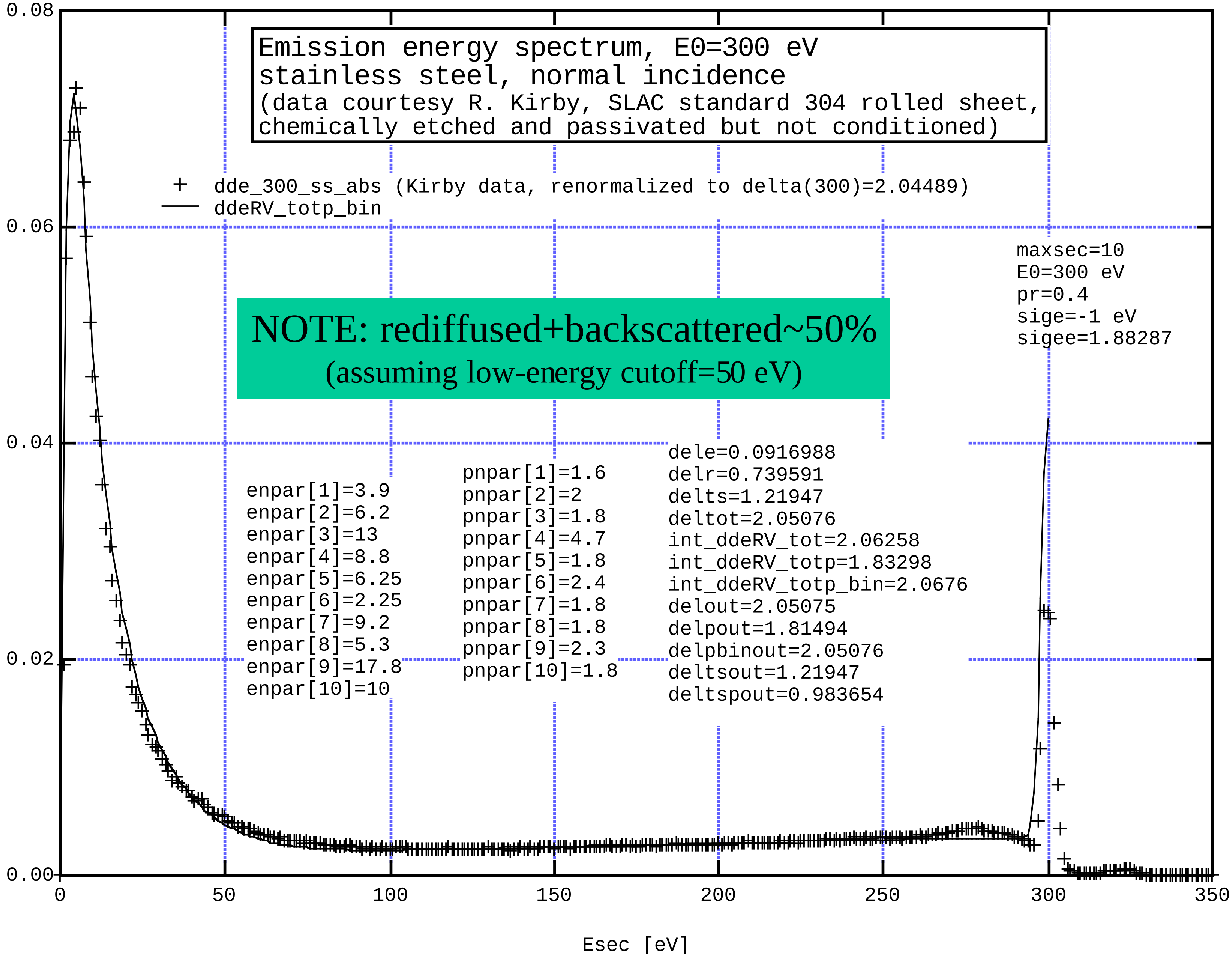
Fits to data:

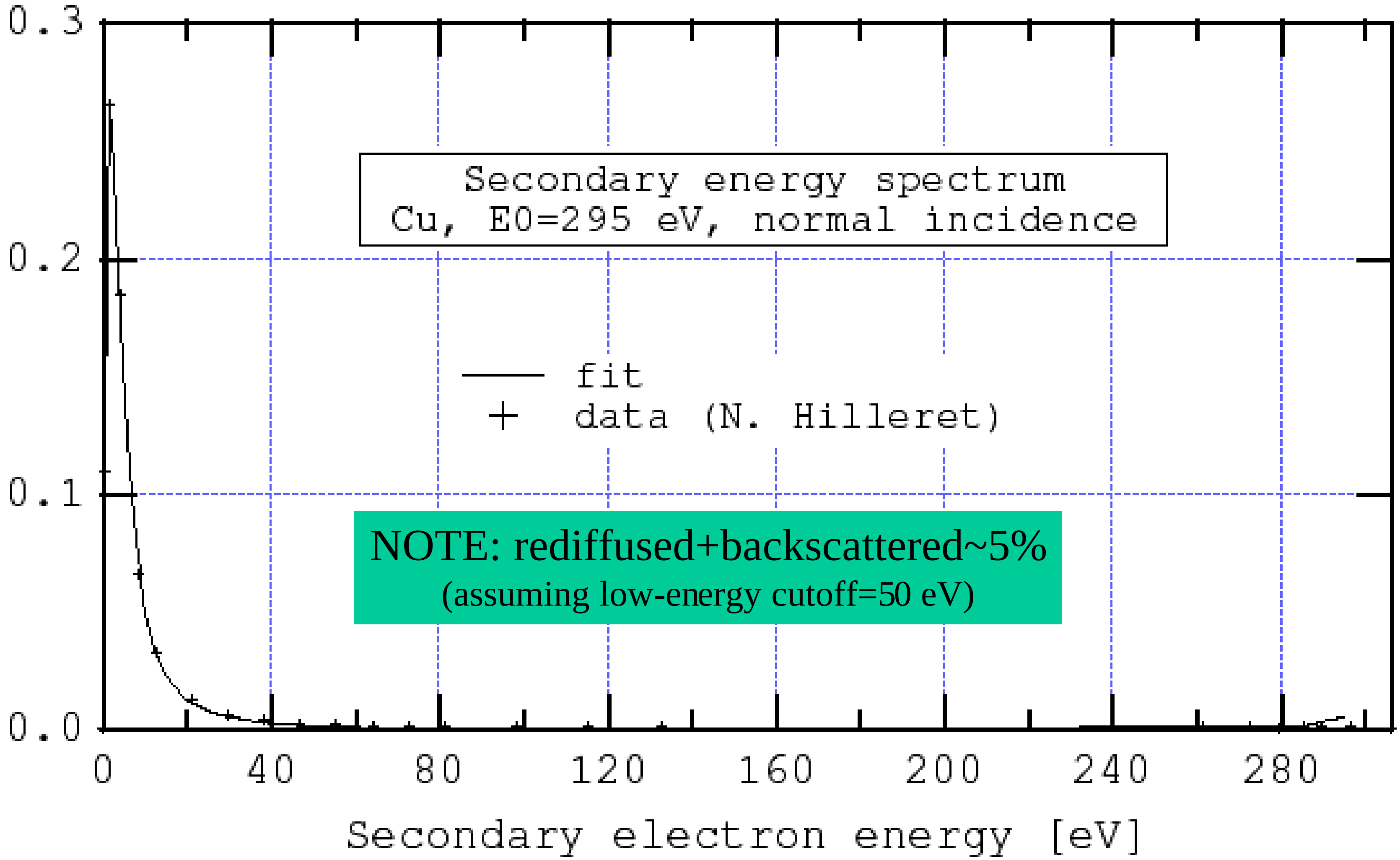
- Copper (data courtesy N. Hilleret, CERN)
  — sample: chemically cleaned but not vacuum-baked *in situ*

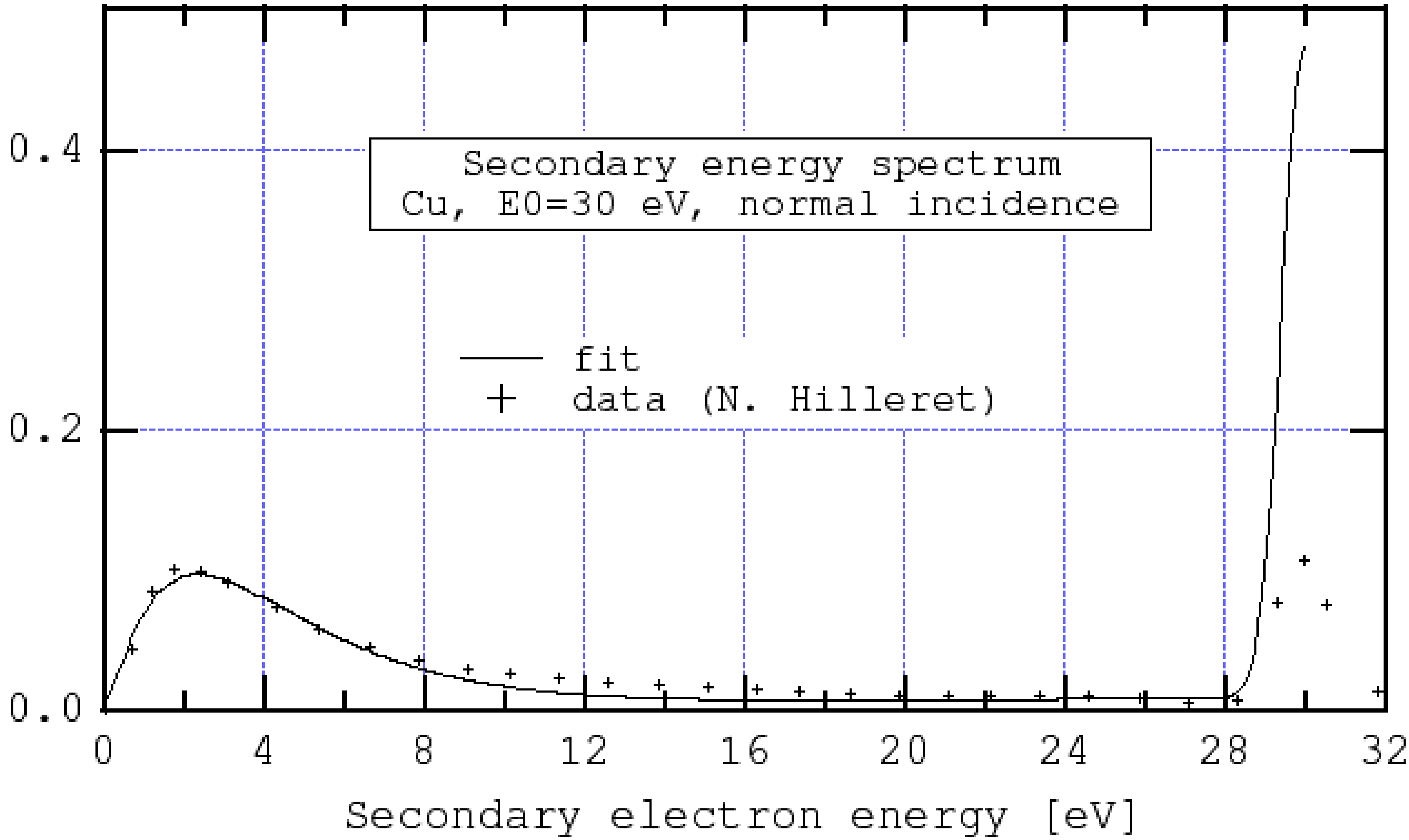
- Stainless steel (data courtesy R. Kirby, SLAC)
  — sample: SLAC standard 304 rolled sheet, chemically etched and passivated but not conditioned

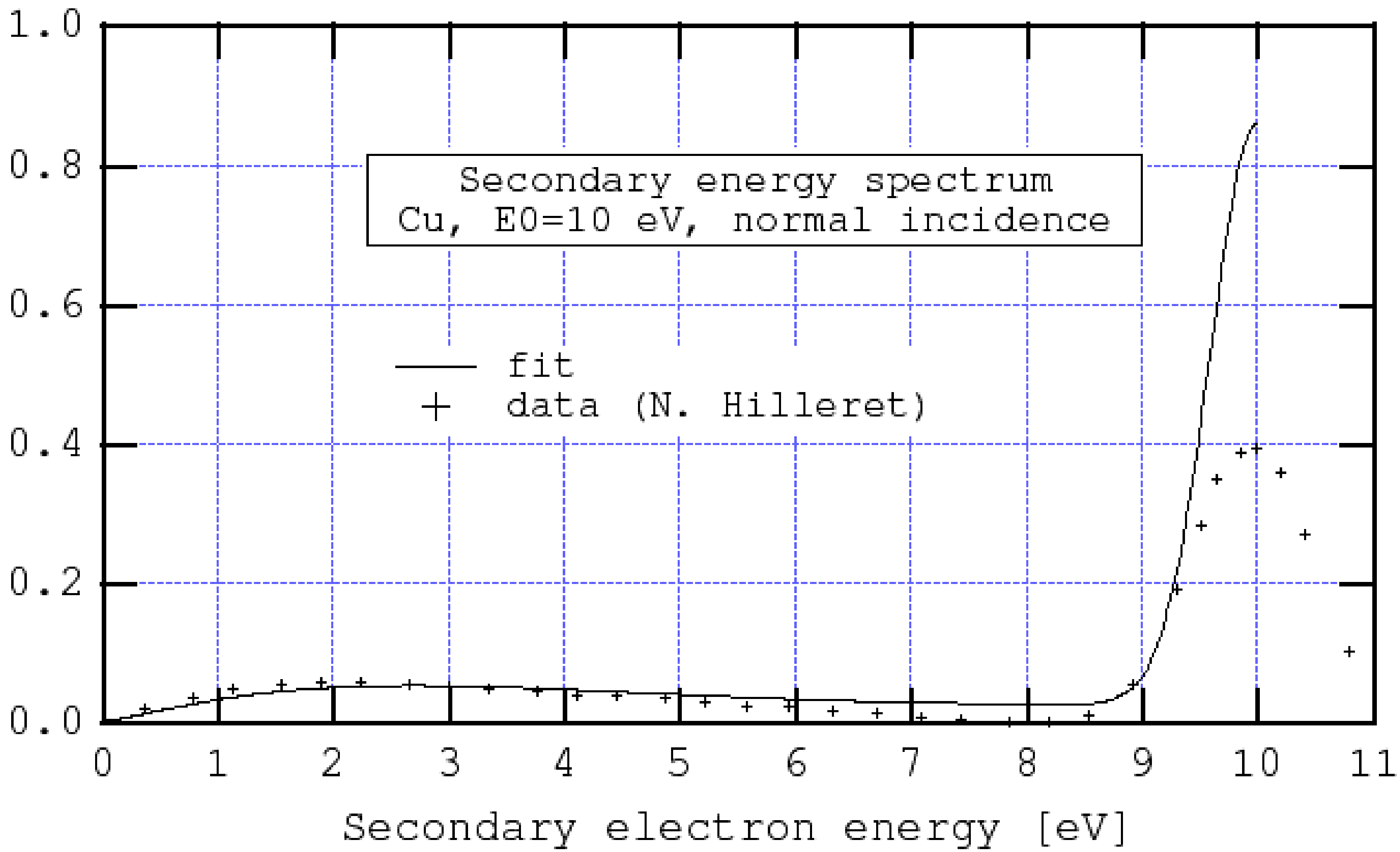

SEY for stainless steel, normal incidence
(data courtesy R. Kirby, SLAC standard 304 rolled sheet,
chemically etched and passivated but not conditioned)
E0ts=0
E0tspk=310
dtspk=1.22
powts=1.813
P1epk=0.5
P1einf=0.07
E0epk=0
powe=0.9
E0w=100
P1rinf=0.74
Ecr=40
qr=1
delta_SS (Kirby data)
delta_e
delta_r
delta_ts
delta_er (=delta_e+delta_r)
delta_tot
delta_tsp
E0 [eV]
0.0
0.5
1.0
1.5
2.0
2.5
0
100
200
300
400
500
600
700
800
900
1000


SEY for Cu, normal incidence
(Data courtesy N. Hilleret for chemically cleaned but not in-situ vacuum baked samples)
(macro hilleret_fit_mauro)
E0tspk=276.812
dtspk=1.8848
powts=1.54033
E0ts=0
P1epk=0.496229
P1einf=0.02
E0epk=0
powe=1
E0w=60.8614
P1rinf=0.2
Ecr=0.0409225
qr=0.104045
delta_e
delta_r
delta_ts
delta_er (=delta_e+delta_r)
delta_tot
delta_tsp
deltaCuhilleret
E0 [eV]
0.0
0.5
1.0
1.5
2.0
2.5
0
100
200
300
400
500
600
700
800
900
1000


Emission energy spectrum, E0=300 eV
stainless steel, normal incidence
(data courtesy R. Kirby, SLAC standard 304 rolled sheet,
chemically etched and passivated but not conditioned)
dde_300_ss_abs (Kirby data, renormalized to delta(300)=2.04489)
dddeRV_totp_bin
maxsec=10
E0=300 eV
pr=0.4
sige=-1 eV
sigee=1.88287
NOTE: rediffused+backscattered~50%
(assuming low-energy cutoff=50 eV)
enpar[1]=3.9
enpar[2]=6.2
enpar[3]=13
enpar[4]=8.8
enpar[5]=6.25
enpar[6]=2.25
enpar[7]=9.2
enpar[8]=5.3
enpar[9]=17.8
enpar[10]=10
pnpar[1]=1.6
pnpar[2]=2
pnpar[3]=1.8
pnpar[4]=4.7
pnpar[5]=1.8
pnpar[6]=2.4
pnpar[7]=1.8
pnpar[8]=1.8
pnpar[9]=2.3
pnpar[10]=1.8
dele=0.0916988
delr=0.739591
delts=1.21947
deltot=2.05076
int_ddeRV_tot=2.06258
int_ddeRV_totp=1.83298
int_ddeRV_totp_bin=2.0676
delout=2.05075
delpout=1.81494
delpbinout=2.05076
deltsout=1.21947
deltspout=0.983654
0.08
0.06
0.04
0.02
0.00
0
50
100
150
200
250
300
350
Esec [eV]


0.3
0.2
0.1
0.0
0
40
80
120
160
200
240
280
Secondary electron energy [eV]
Secondary energy spectrum
Cu, E0=295 eV, normal incidence
fit
data (N. Hilleret)
NOTE: rediffused+backscattered~5%
(assuming low-energy cutoff=50 eV)


Secondary energy spectrum
Cu, E0=30 eV, normal incidence
fit
data (N. Hilleret)
0.4
0.2
0.0
0
4
8
12
16
20
24
28
32
Secondary electron energy [eV]



1.0
0.8
0.6
0.4
0.2
0.0
Secondary energy spectrum
Cu, E0=10 eV, normal incidence
fit
data (N. Hilleret)
0
1
2
3
4
5
6
7
8
9
10
11
Secondary electron energy [eV]

Current parameter values from fits to data

Table 1: Model parameters.

	Cu	SS	POSINST name
Emission angular spectrum (Sec. 2.3.1)			
α	1	1	pangsec
Elastically backscattered electrons (Sec. 3.2)			
$P_{1,e}(\infty)$	0.02	0.07	P1einf
$\hat{P}_{1,e}$	0.496	0.5	P1epk
$\hat{E}_e$ [eV]	0	0	E0epk
W [eV]	60.86	100	E0w
p	1	0.9	powe
σ_e [eV]	2	1.9	sige
e_1	0.26	0.26	epar1
e_2	2	2	epar2
Rediffused electrons (Sec. 3.3)			
$P_{1,r}(\infty)$	0.2	0.74	P1rinf
E_r [eV]	0.041	40	Ecr
r	0.104	1	qr
q	0.5	0.4	pr
r_1	0.26	0.26	rpar1
r_2	2	2	rpar2
True secondary electrons (Sec. 3.4)			
$\hat{\delta}_{ts}$	1.8848	1.22	dtspk
$\hat{E}_{ts}$ [eV]	276.8	310	E0tspk
s_0	1.54	1.813	powts
t_1	0.66	0.66	tpar1
t_2	0.8	0.8	tpar2
t_3	0.7	0.7	tpar3
t_4	1	1	tpar4
t_5	0	0	tpar5
t_6	0	0	tpar6
Total SEY†			
$\hat{E}_t$ [eV]	271	292	
$\hat{\delta}_t$	2.1	2.05	dtotpk

† 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 $\hat{E}_{ts} \gg \hat{E}_e, E_r$.

Table 2: Further model parameters for the true secondary component.

	Cu	POSINST name
p_n	2.5, 3.3, 2.5, 2.5, 2.8, 1.3, 1.5, 1.5, 1.5, 1.5	pnpar(n)
ϵ_n [eV]	1.5, 1.75, 1, 3.75, 8.5, 11.5, 2.5, 3, 2.5, 3	enpar(n)
	SS	**POSINST name**
p_n	1.6, 2, 1.8, 4.7, 1.8, 2.4, 1.8, 1.8, 2.3, 1.8	pnpar(n)
ϵ_n [eV]	3.9, 6.2, 13, 8.8, 6.25, 2.25, 9.2, 5.3, 17.8, 10	enpar(n)

Q: is the electron emitted spectrum Maxwellian?
A: only approximately.

definition of Maxwellian spectrum:

$$\frac{dN}{d^3\mathbf{p}} \propto \exp(-E/kT), \qquad E = \frac{\mathbf{p}^2}{2m_e}$$

$$\Rightarrow \frac{dN}{dE} \propto E^{1/2}\exp(-E/kT) \equiv E^{p_n - 1}\exp(-E/\varepsilon_n)$$

$$\Rightarrow p_n = 3/2$$

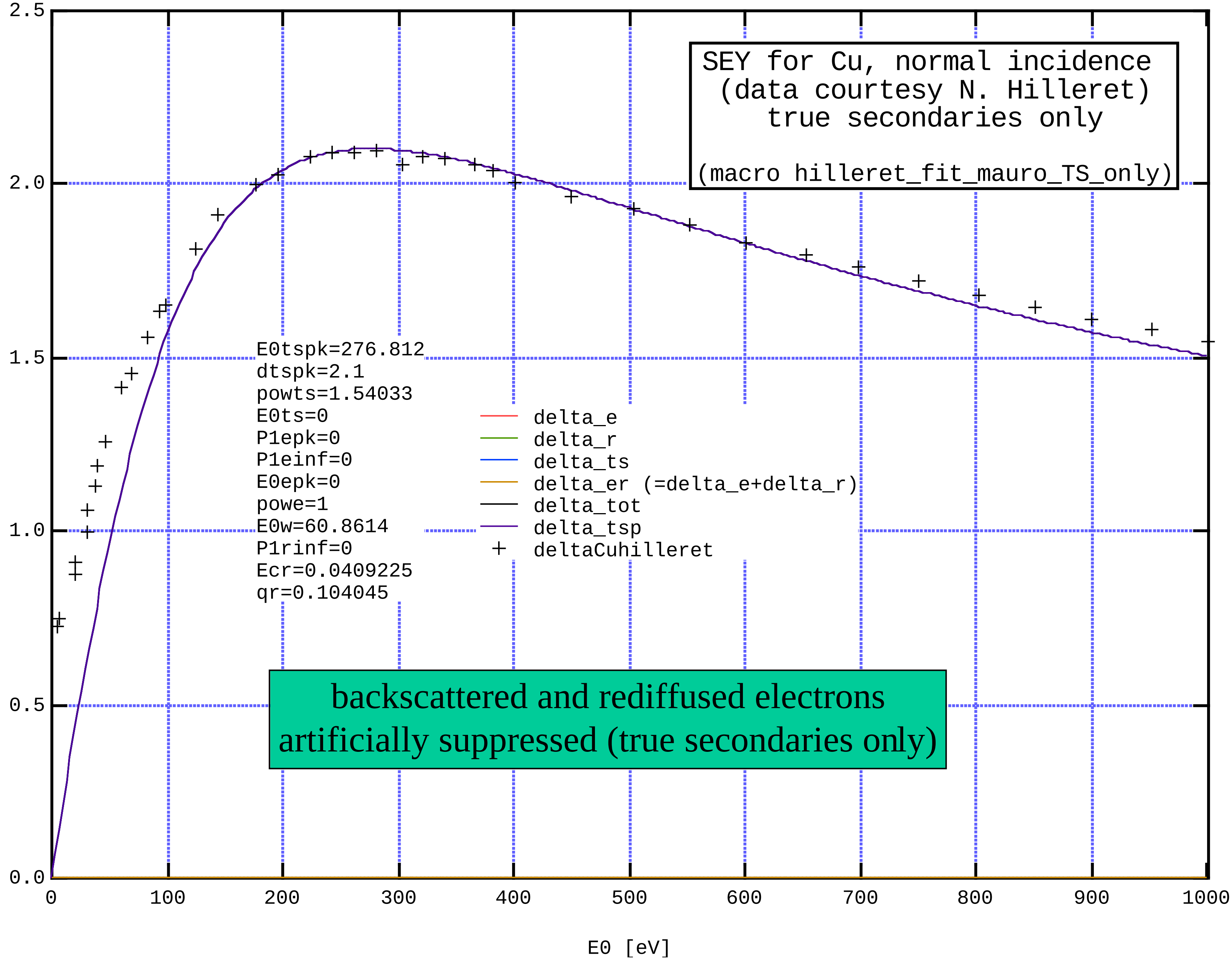
Fits to data, however, imply p_n~1.8–5, depending on n and material

Applications:

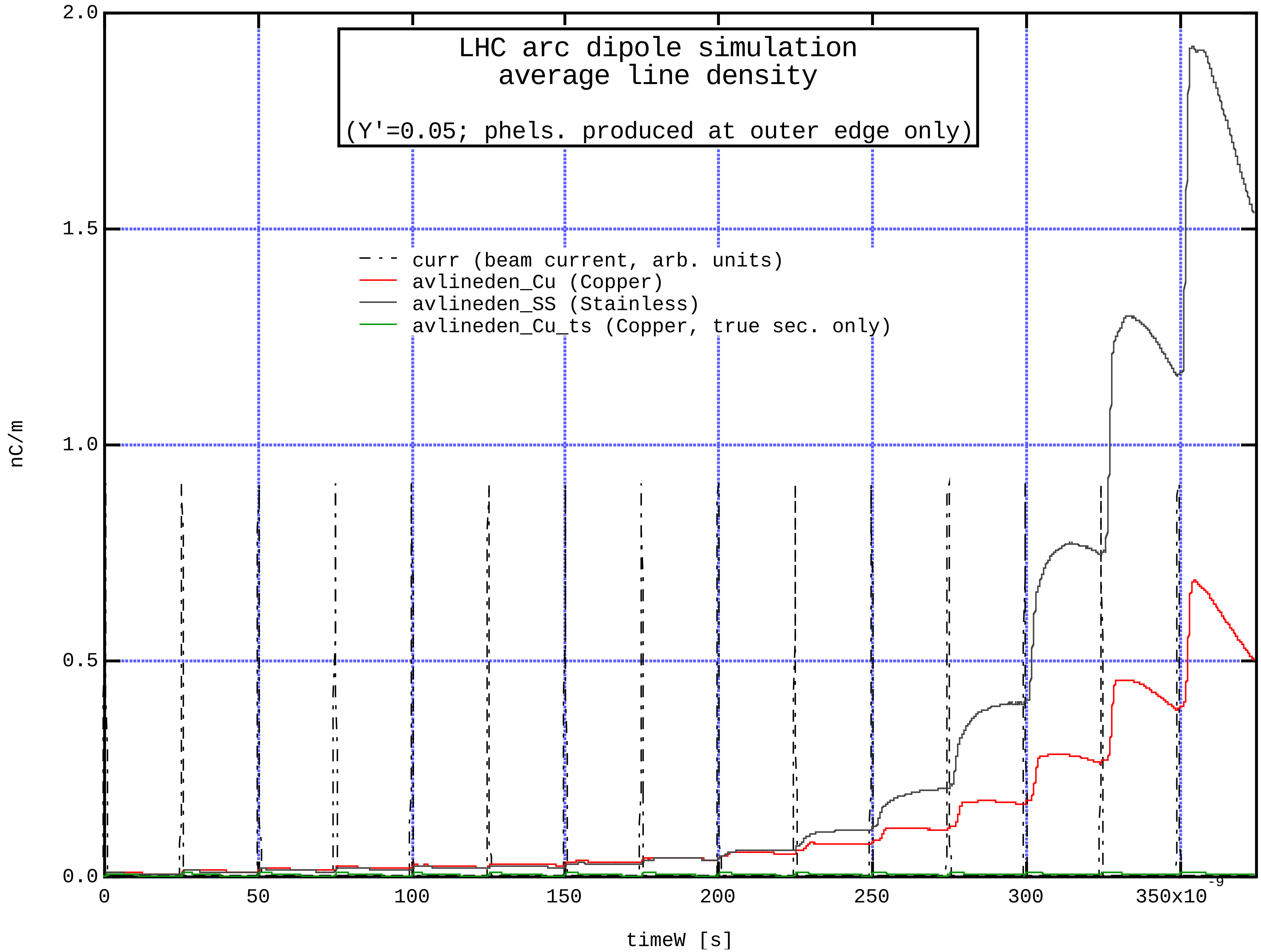
(1) time dependence of the electron-cloud power deposition in LHC arc dipole: simulate injection of a 15-bunch train into an empty chamber;

- sensitivity to relative ratio of backscattered, rediffused and true secondaries
- sensitivity to $\delta(0)$

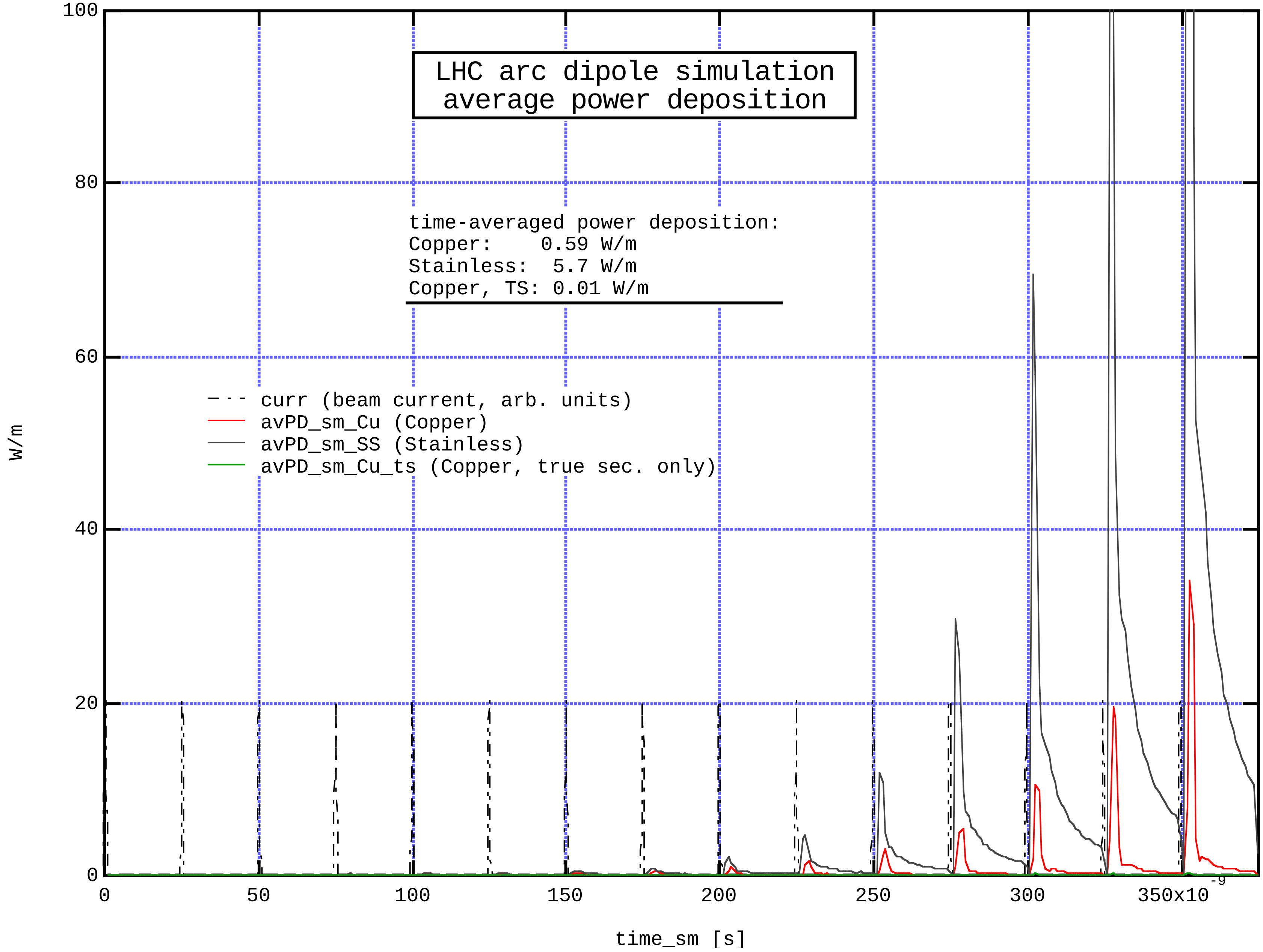
(2) time dependence of the electron cloud dissipation following extraction of the PSR beam

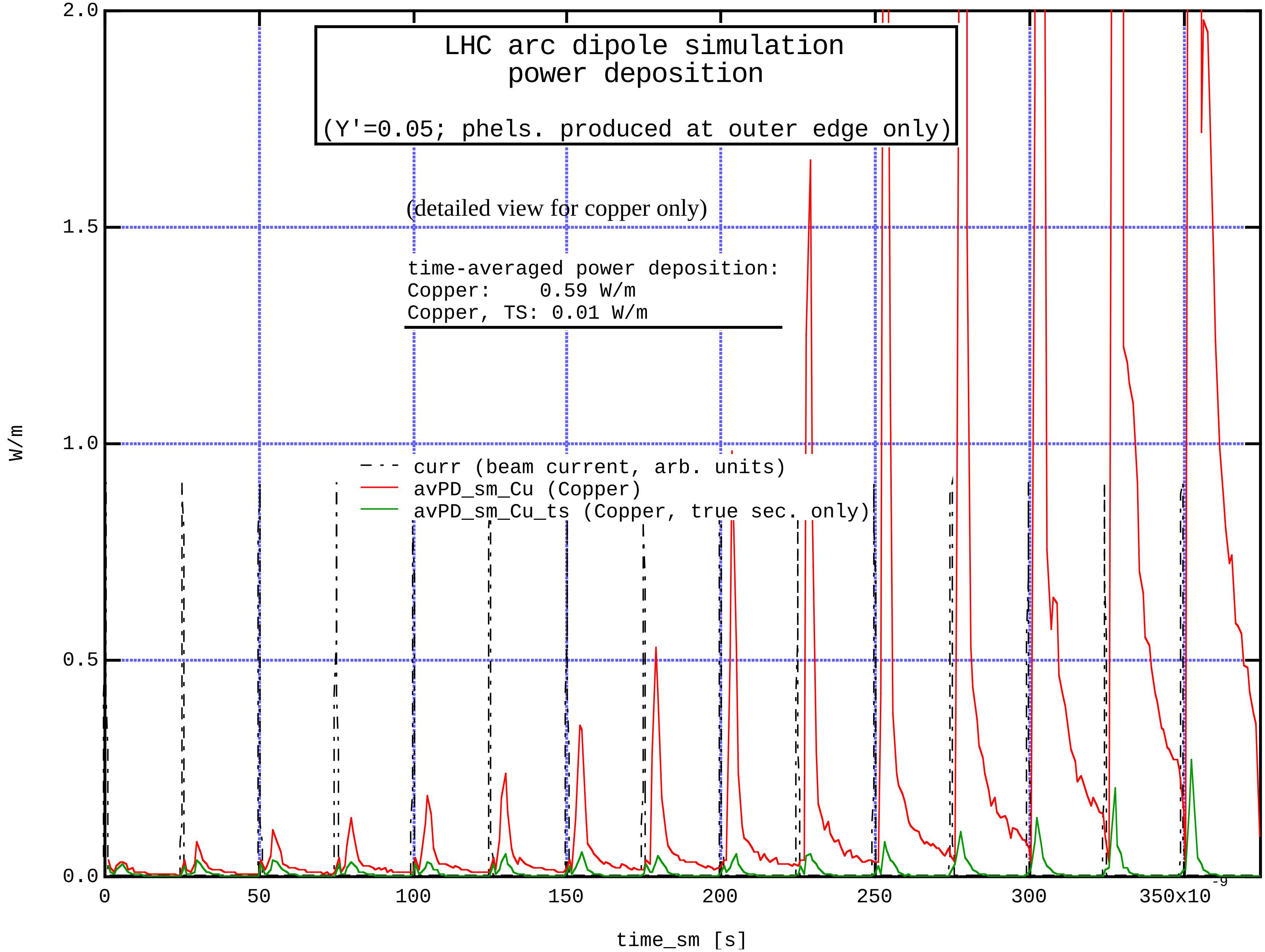


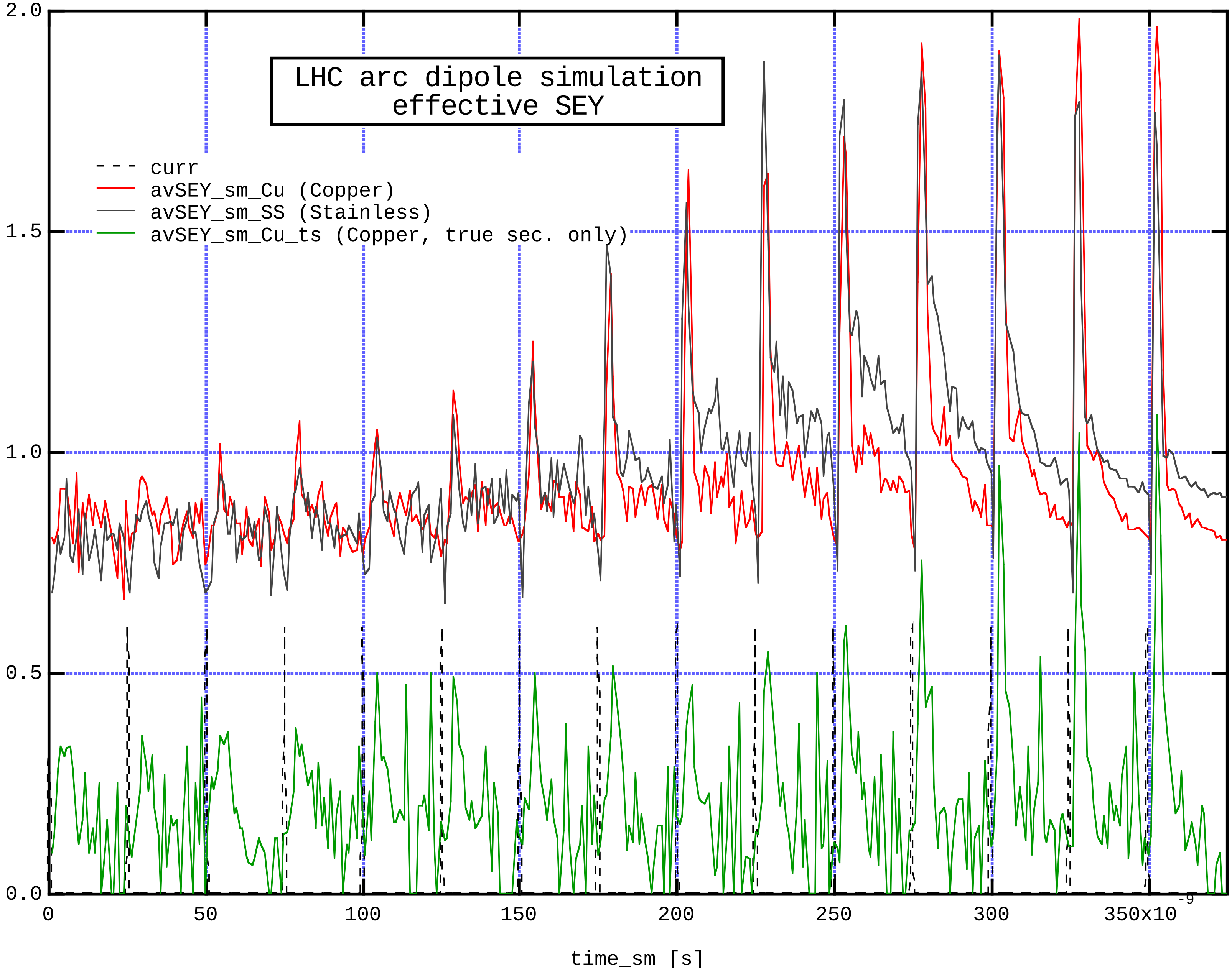
SEY for Cu, normal incidence
(data courtesy N. Hilleret)
true secondaries only
(macro hilleret_fit_mauro_TS_only)
E0tspk=276.812
dtspk=2.1
powts=1.54033
E0ts=0
P1epk=0
P1einf=0
E0epk=0
powe=1
E0w=60.8614
P1rinf=0
Ecr=0.0409225
qr=0.104045
delta_e
delta_r
delta_ts
delta_er (=delta_e+delta_r)
delta_tot
delta_tsp
deltaCuhilleret
backscattered and rediffused electrons artificially suppressed (true secondaries only)
2.5
2.0
1.5
1.0
0.5
0.0
0
100
200
300
400
500
600
700
800
900
1000
E0 [eV]



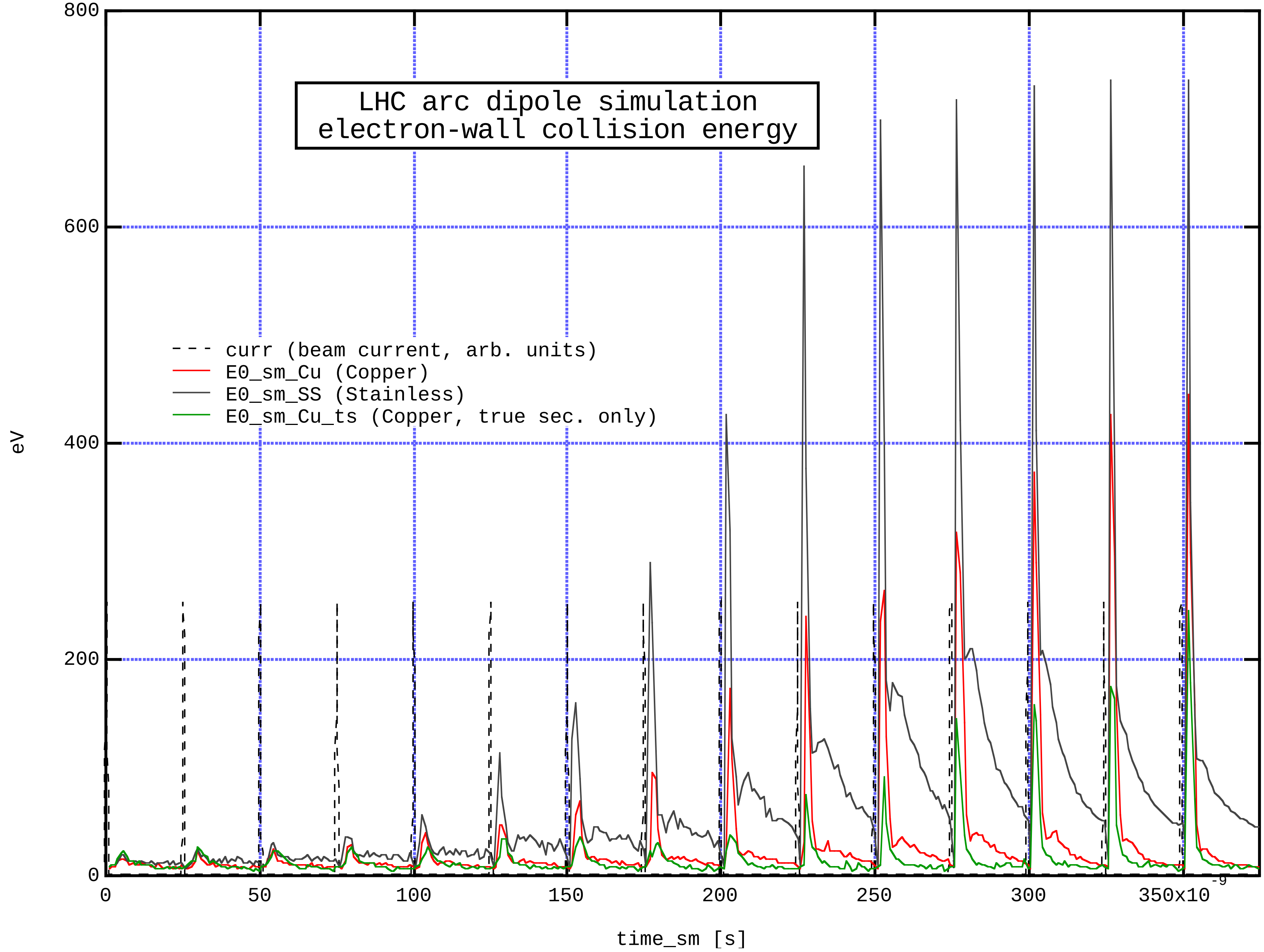
LHC arc dipole simulation
average line density
(Y'=0.05; phels. produced at outer edge only)
curr (beam current, arb. units)
avlineden_Cu (Copper)
avlineden_SS (Stainless)
avlineden_Cu_ts (Copper, true sec. only)
nC/m
2.0
1.5
1.0
0.5
0.0
0
50
100
150
200
250
300
350x10
-9
timeW [s]

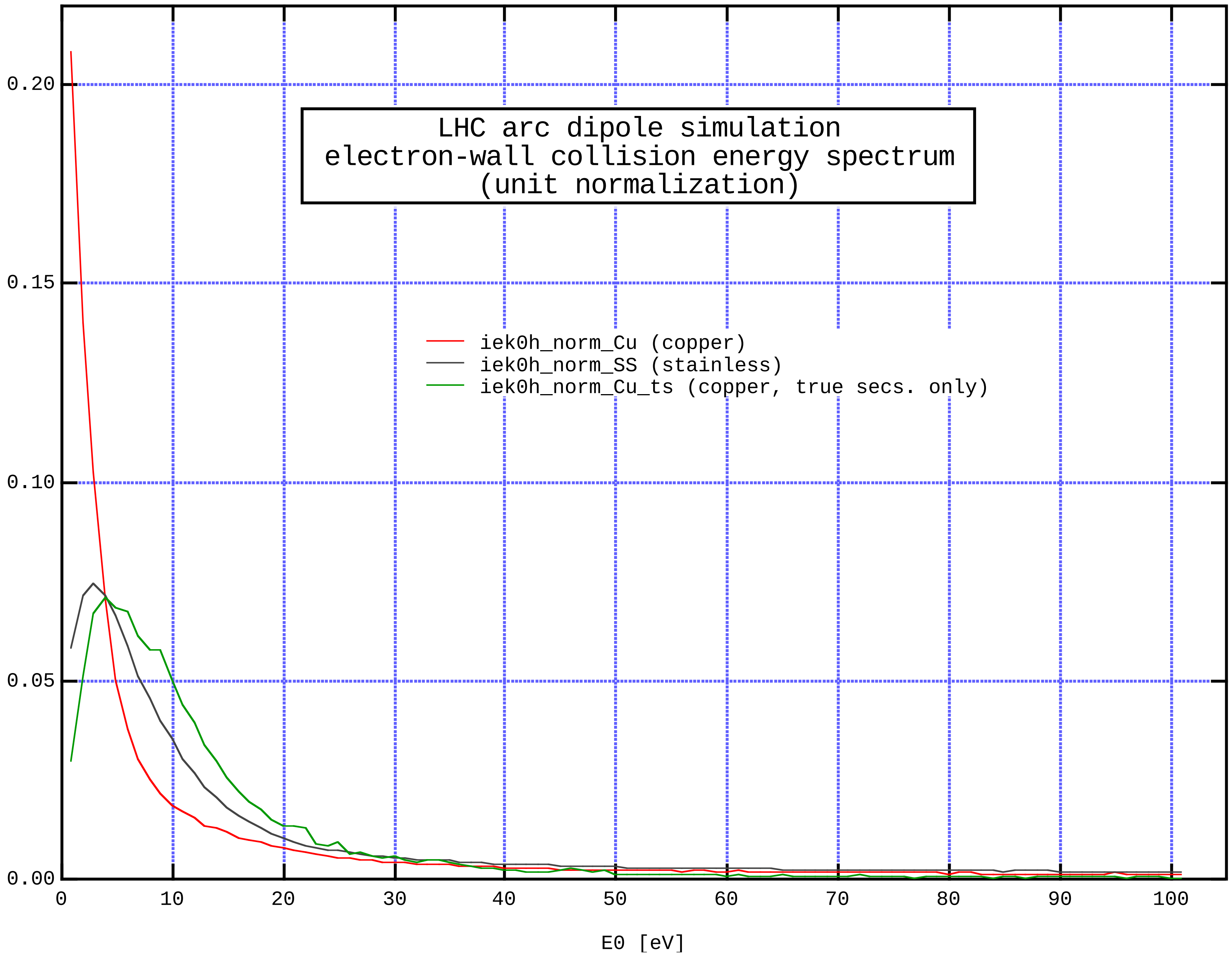

LHC arc dipole simulation
average power deposition
time-averaged power deposition:
Copper: 0.59 W/m
Stainless: 5.7 W/m
Copper, TS: 0.01 W/m
curr (beam current, arb. units)
avPD_sm_Cu (Copper)
avPD_sm_SS (Stainless)
avPD_sm_Cu_ts (Copper, true sec. only)
W/m
100
80
60
40
20
0
0
50
100
150
200
250
300
350x10
-9
time_sm [s]


LHC arc dipole simulation
power deposition
(Y'=0.05; phels. produced at outer edge only)
(detailed view for copper only)
time-averaged power deposition:
Copper: 0.59 W/m
Copper, TS: 0.01 W/m
curr (beam current, arb. units)
avPD_sm_Cu (Copper)
avPD_sm_Cu_ts (Copper, true sec. only)
W/m
2.0
1.5
1.0
0.5
0.0
0
50
100
150
200
250
300
350x10^-9
time_sm [s]

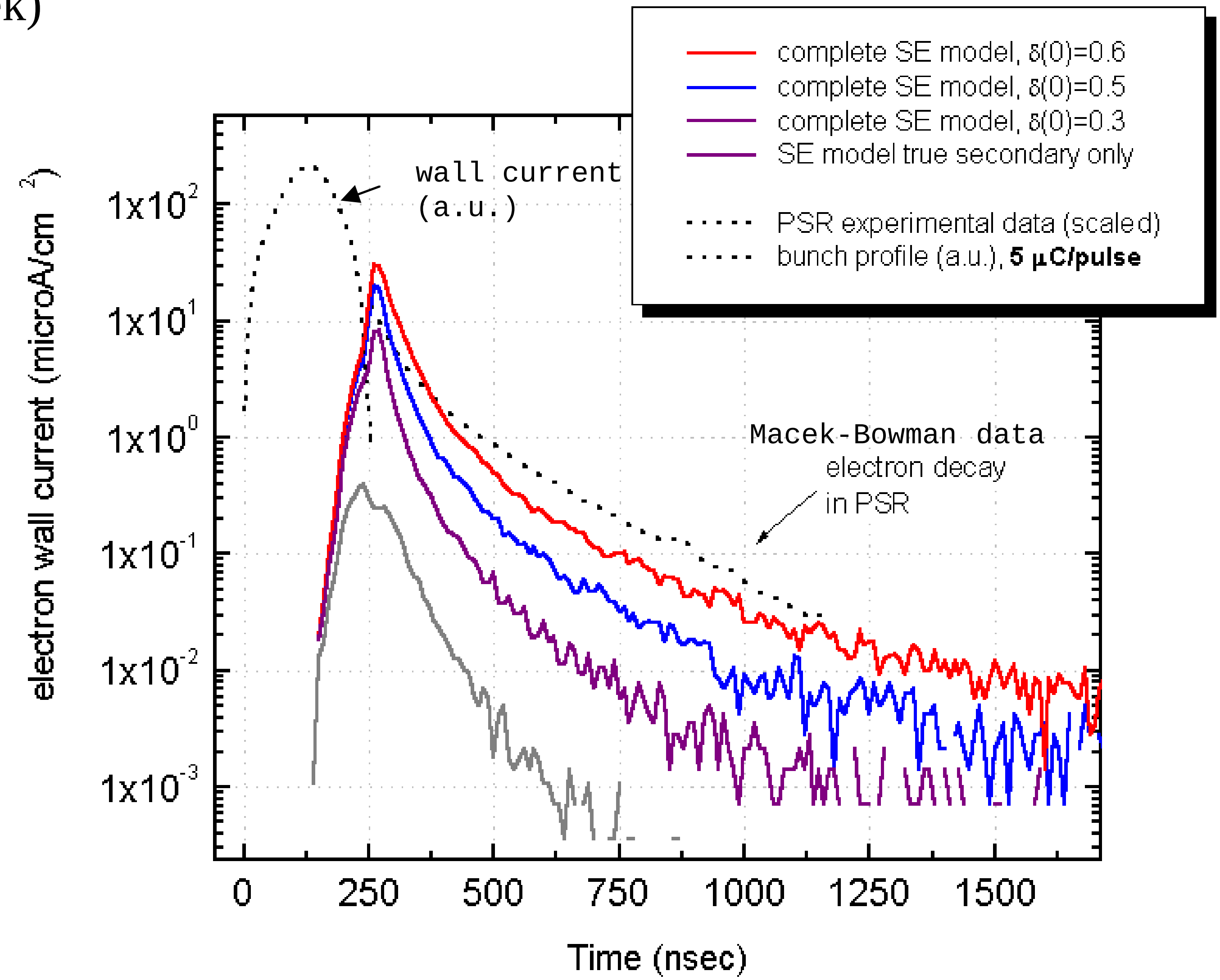


LHC arc dipole simulation
effective SEY
--- curr
avSEY_sm_Cu (Copper)
avSEY_sm_SS (Stainless)
avSEY_sm_Cu_ts (Copper, true sec. only)
2.0
1.5
1.0
0.5
0.0
0
50
100
150
200
250
300
350x10
-9
time_sm [s]


LHC arc dipole simulation
electron-wall collision energy
curr (beam current, arb. units)
E0_sm_Cu (Copper)
E0_sm_SS (Stainless)
E0_sm_Cu_ts (Copper, true sec. only)
eV
800
600
400
200
0
0
50
100
150
200
250
300
350x10-9
time_sm [s]


LHC arc dipole simulation
electron-wall collision energy spectrum
(unit normalization)
iek0h_norm_Cu (copper)
iek0h_norm_SS (stainless)
iek0h_norm_Cu_ts (copper, true secs. only)
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
50
60
70
80
90
100
E0 [eV]

Dissipation of the electron cloud upon extraction of the PSR beam (data courtesy R. Macek)



Conclusions:

- constructed phenomenological model for secondary emission process
- consistent with data on $\delta(E_0)$ and $d\delta/dE$ (by construction)
- probabilities P_n calculated self-consistently (ie., $\delta(E_0)$ and $d\delta/dE$ are reproduced from the P_n's)
- still evolving; not enough detailed data to pin down all parameters

- Applications:
  - power deposition in LHC dipoles exhibits a sensitivity to details of the secondary emission spectrum (relative ratio of backscattered, rediffused and true secondaries)
    - – however, this sensitivity may be less pronounced when in steady state
  - also sensitivity to $\delta(0)$ (not new)
  - for PSR, infer $\delta_{eff}(0)$=0.5-0.6 from measured data on dissipation of the electron cloud following extraction

Sample comparison of simulation vs. measurements at the APS