Simulation of electron cloud build-up in the ISIS proton synchrotron and related machines

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Outline

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the ISIS oddity

No history of electron-proton instability at ISIS in its > 20 years of bunched beam operations.
Dedicated experiment with a coasting beam ($4 \times 10^{13} p$ at 70 MeV and $\epsilon_{\perp,rms} = 50\pi\mu rm$) proved inconclusive [G.H.Rees,1999].
Program launched to understand lack of e-p related instabilities and predict behaviour of future machine upgrades (ISIS-1MW?)
Simulations carried out with ECLOUD code (thanks to F.Zimmermann and G.Rumolo)
Unfortunately no experimental results yet for benchmarking

hunting eclouds...

the idea: *Use simulations to understand e- cloud formation and dependence on (which?) critical parameters*
Compare simulations with electron detector measurements on electron wall flux, time structure, energy spectrum etc.
Study (absence of) instability

however... *Simulation not self-consistent (proton beam nondynamical) and currently limited by lack of realistic input parameters on e^-/ion-surface interactions*
Machine experimental program hasn't progressed significantly: need lab measurements to calibrate parameters of the code
Instability studies not started yet

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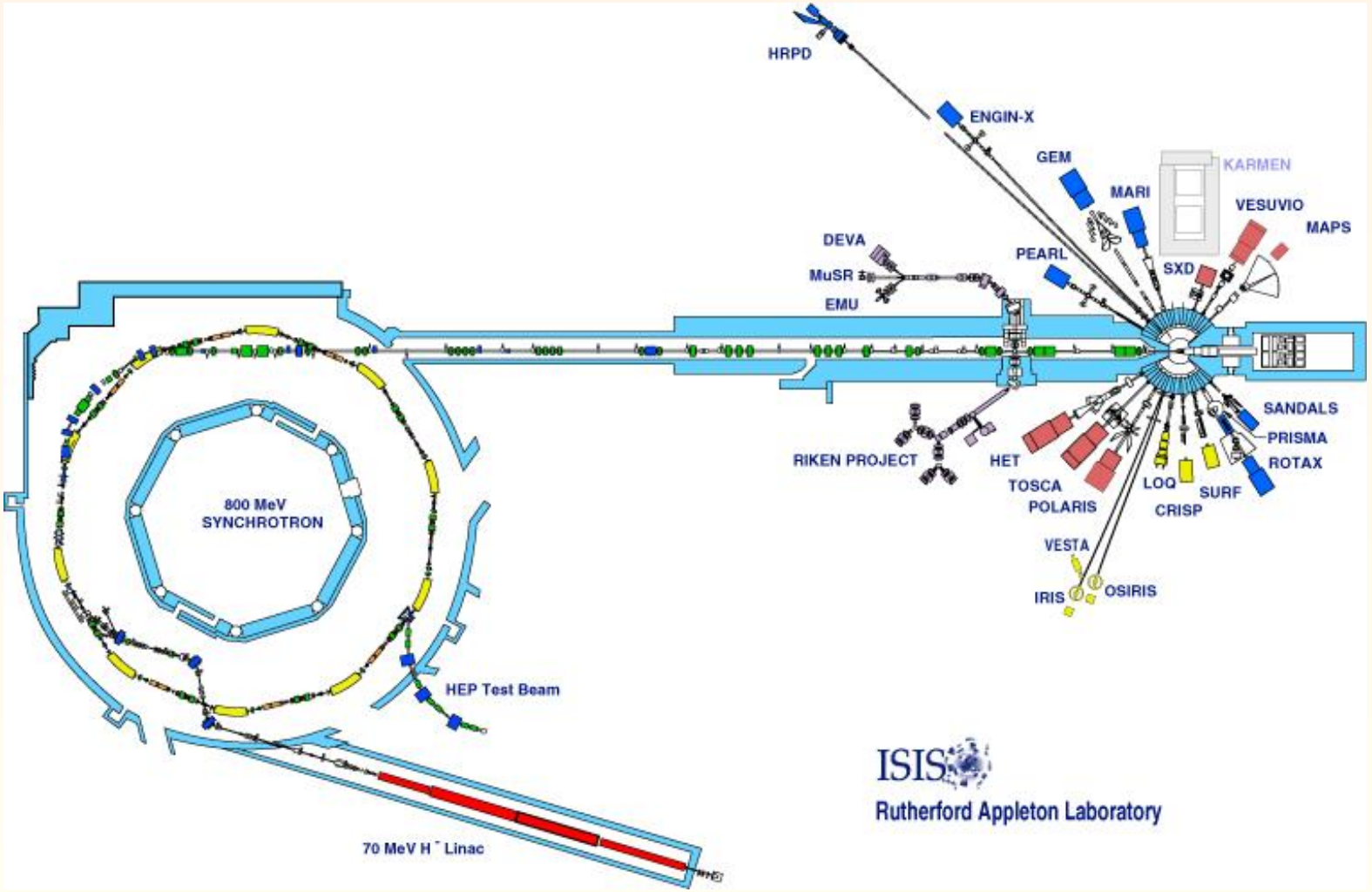
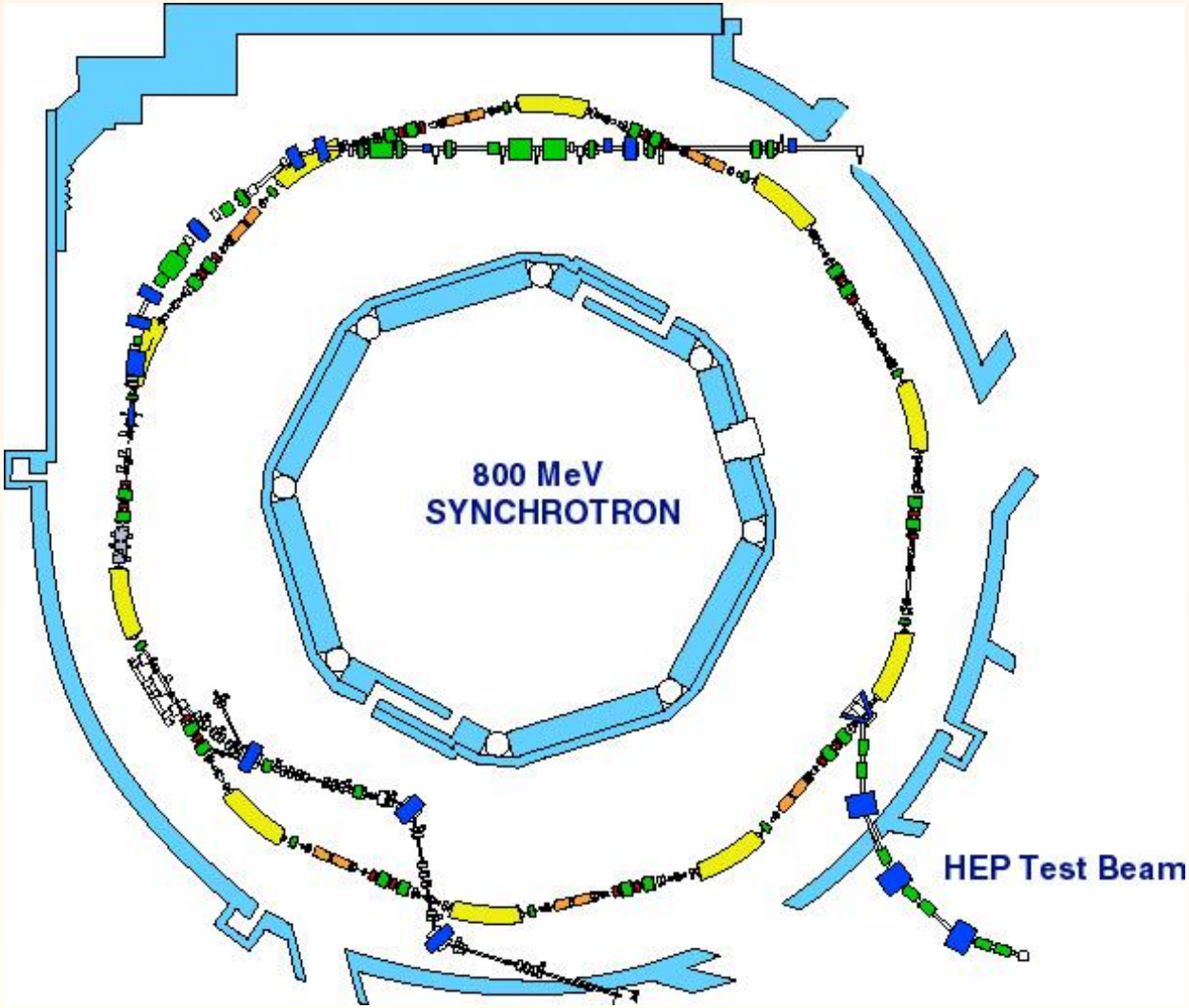
ISIS


HRPD
ENGIN-X
GEM
MARI
KARMEN
VESUVIO
MAPS
DEVA
MuSR
EMU
PEARL
SXD
SANDALS
PRISMA
ROTAX
RIKEN PROJECT
HET
TOSCA
POLARIS
LOQ
SURF
CRISP
VESTA
IRIS
OSIRIS
800 MeV
SYNCHROTRON
HEP Test Beam
70 MeV H ¯ Linac
ISIS
Rutherford Appleton Laboratory

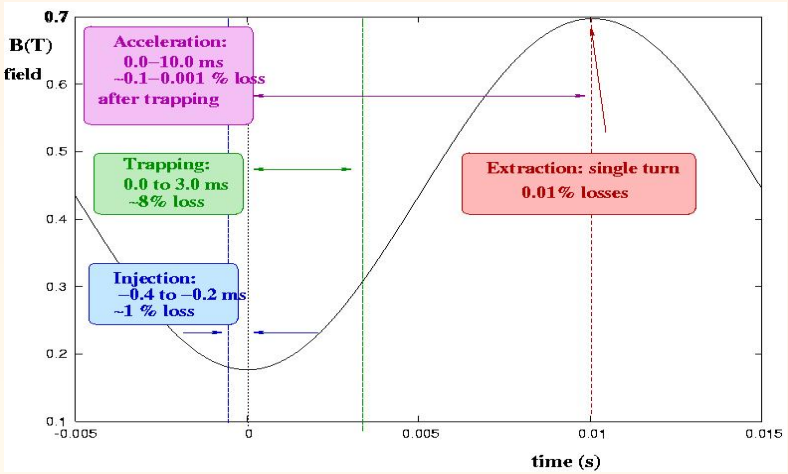
ISIS

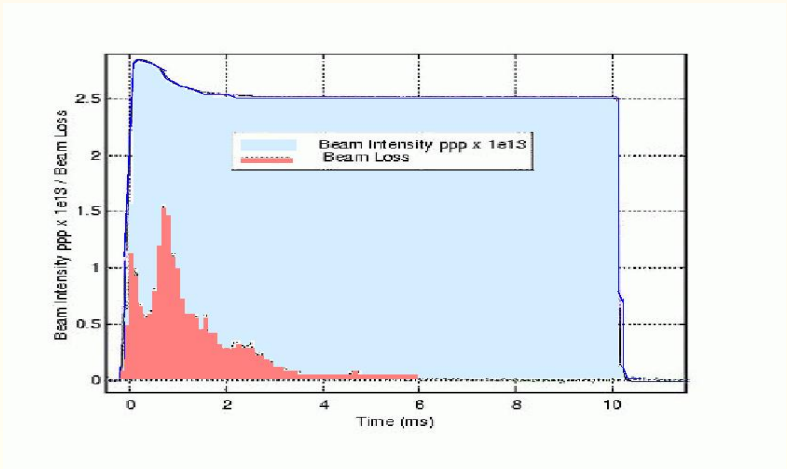


10
super-periods:
1 dipole
1 doublet
1 singlet
structure
(32% DF, 19% QF, 49% FF)

ISIS operation

1.25×10^{13} p per bunch, h=2
E = 70 to 800 MeV at 50 Hz rep rate
$200\mu A$ average current
130 turns charge exchange injection
$\epsilon = 25\pi$ mm mrad (@inj)
hor. acceptance $540\pi\mu mr$ with
$\Delta P/P = \pm 0.6\%$
vert acceptance 430 $\pi\mu mr$
f_{RF} sweep : 1.3-3.1 MHz
V_{RF} peak 140 KV/turn
B = 0.185-0.7 T





ISIS parameters, FF section

Parameter	description	ISIS
C(m)	circumference	163.4
E(GeV)	beam energy	1.014 (*inj*)
N_p	bunch population	1.25×10^{13}
h	harmonic number	2
$\tau_b(ns)$	bunch length	232
$\tau_g(ns)$	gap length	470
$(a, b)cm$	pipe semi-axes	(6.3,8)
$(\sigma_x, \sigma_y)cm$	$\perp$ rms bunch sizes	(2.3,3.4)

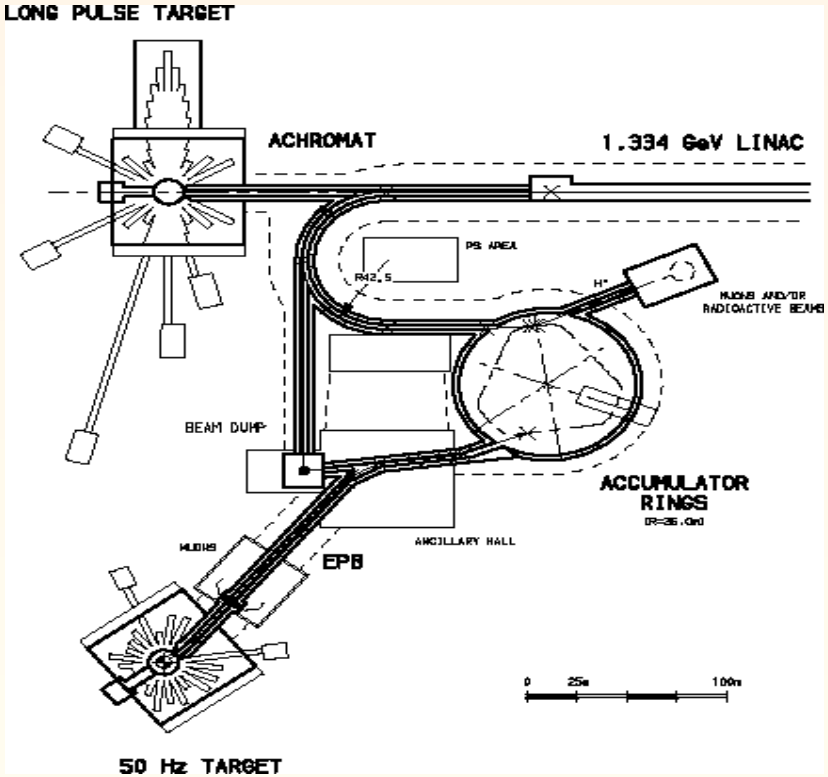
ISIS parameters, FF section

Parameter	description	ISIS	PSR
C(m)	circumference	163.4	90
E(GeV)	beam energy	1.014 (*inj*)	1.735
N_p	bunch population	1.25×10^{13}	5×10^{13}
h	harmonic number	2	1
$\tau_b(ns)$	bunch length	232	254
$\tau_g(ns)$	gap length	470	103
$(a, b)cm$	pipe semi-axes	(6.3,8)	(5,5)
$(\sigma_x, \sigma_y)cm$	$\perp$ rms bunch sizes	(2.3,3.4)	(1,1)

ISIS parameters, FF section

Parameter	description	ISIS	PSR	ESS
C(m)	circ.	163.4	90	220
E(GeV)	energy	1.014 (*inj*)	1.735	2.272
N_p	bunch pop. ($\times 10^{13}$)	1.25	5	23.4
h	harm. number	2	1	1
$\tau_b(ns)$	bunch length	232	254	560
$\tau_g(ns)$	gap length	470	103	246
$(a,b)cm$	pipe	(6.3,8)	(5,5)	(5.8,5.2)
$(\sigma_x,\sigma_y)cm$	$\perp$ rms bunch sizes	(2.3,3.4)	(1,1)	(1.45,1.3)

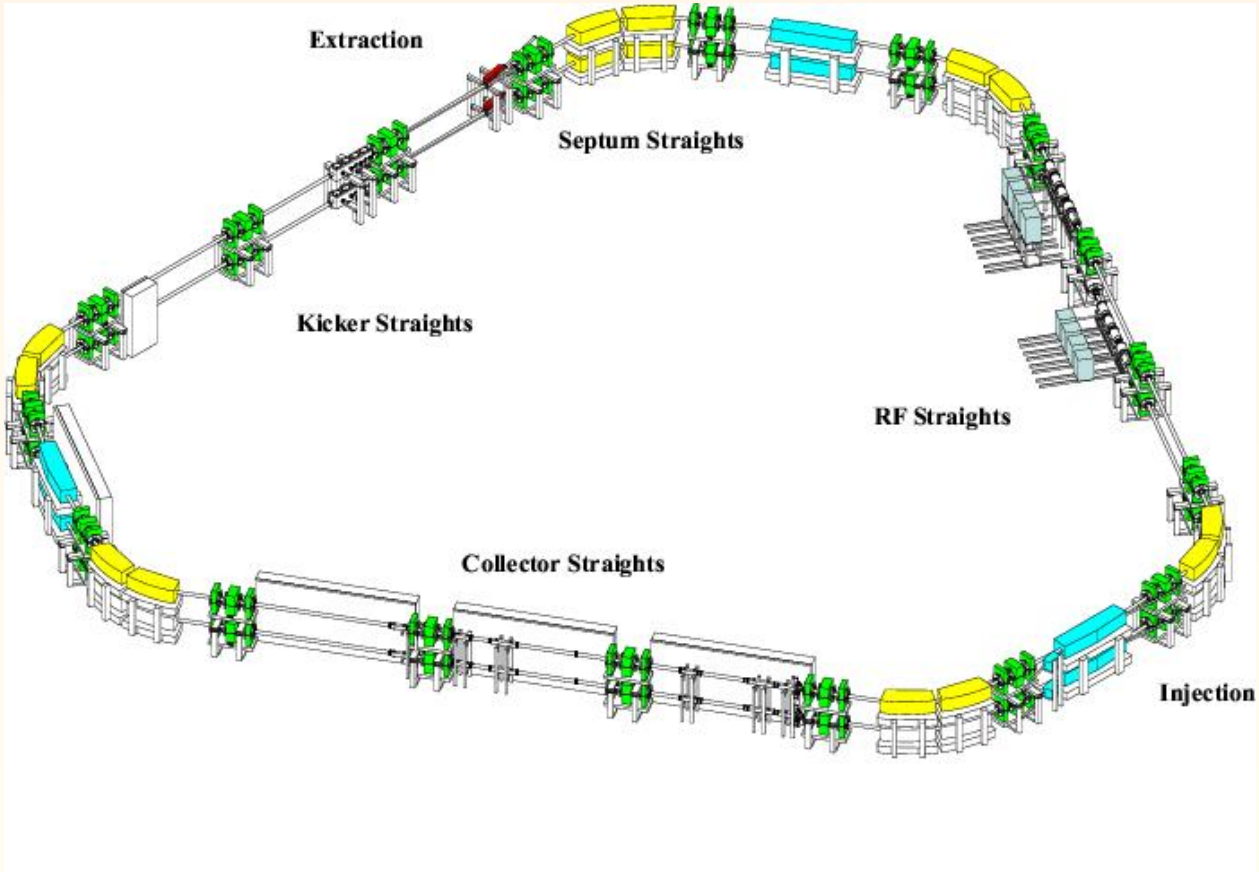
ESS layout



latest specs:

10MW proton beam at 1.334 GeV
50Hz rings at 1.242MHz
two target stations (long and short pulse)
2x0.6μs at 50Hz,
2.5ms at 16.667Hz

ESS layout



23.3% *DF*
$\sim$ 11% *QF*
65.6% *FF*

Outline

ECLOUD features

- e- production via residual gas ionization, photoelectric effect, multipacting
- field free/ dipole field
- 3D electron kinematics (Runge-Kutta integration)
- transverse electron space charge
- transverse beam-electron forces
- elliptical and circular geometry
- perfectly conducting walls

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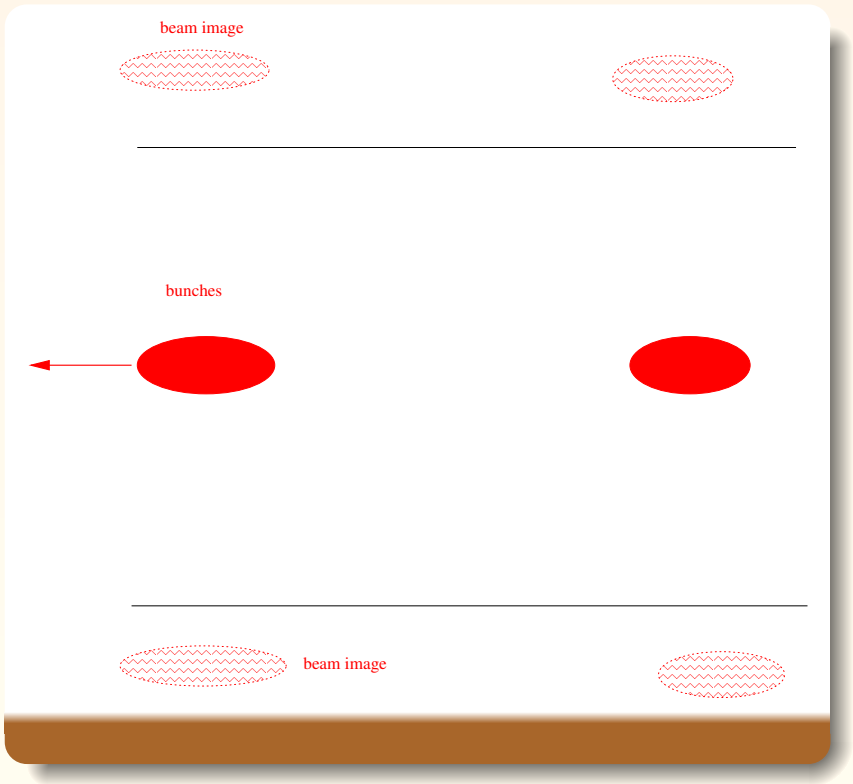
recently added:

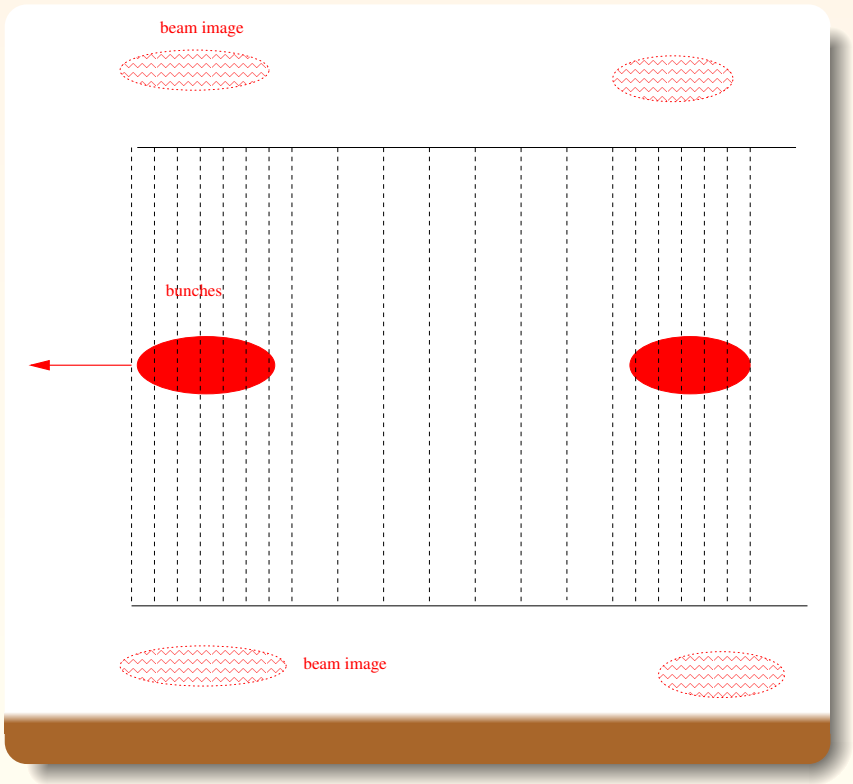
- e- production via proton losses
- rectangular geometry (image charges)
- adapted for treatment of superbunches
- StSt SEY fit and high reflectivity fit for Cu (Cimino-Collins)

Simulation recipe



- focus on beamline segment
- slice bunch and interbunch gaps
- represent e- by macroparticles; create and accelerate e- in beam, space charge and beam image fields
- if e- hits the wall, create secondary e- and change macrocharge

Simulation recipe



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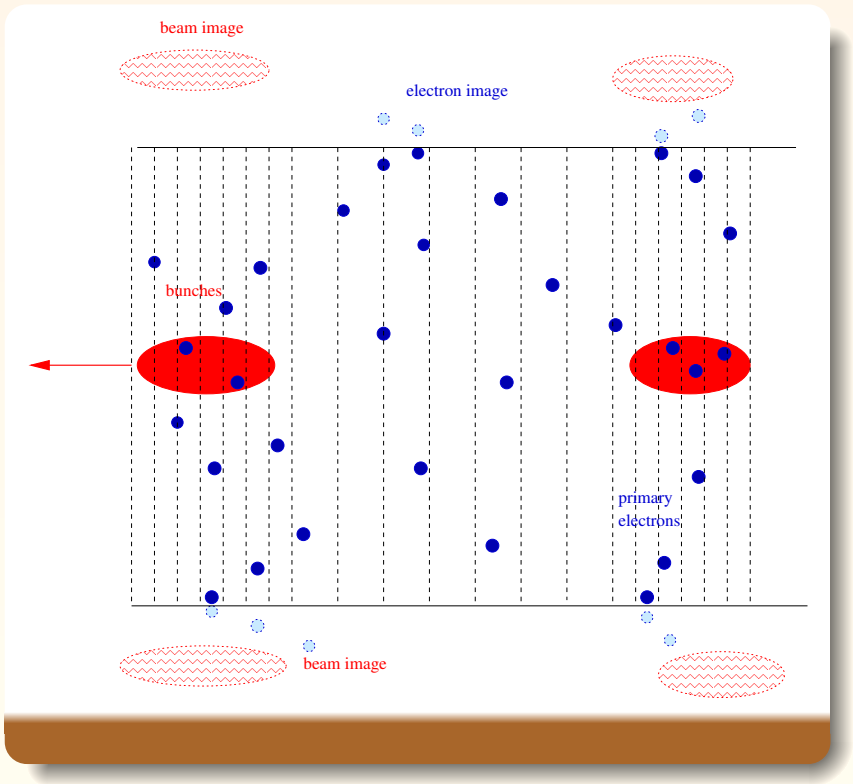

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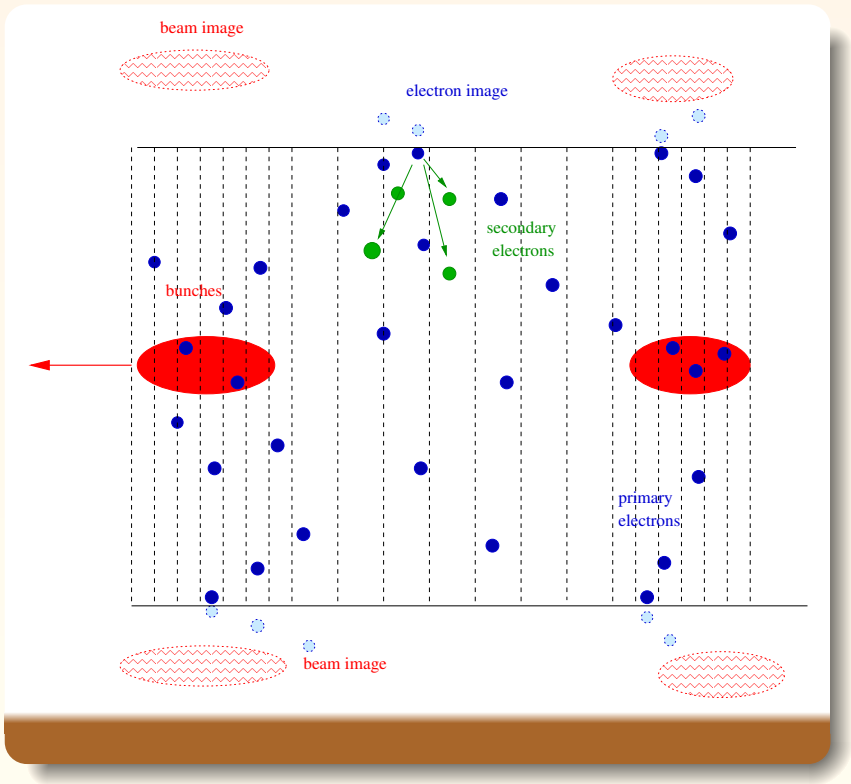

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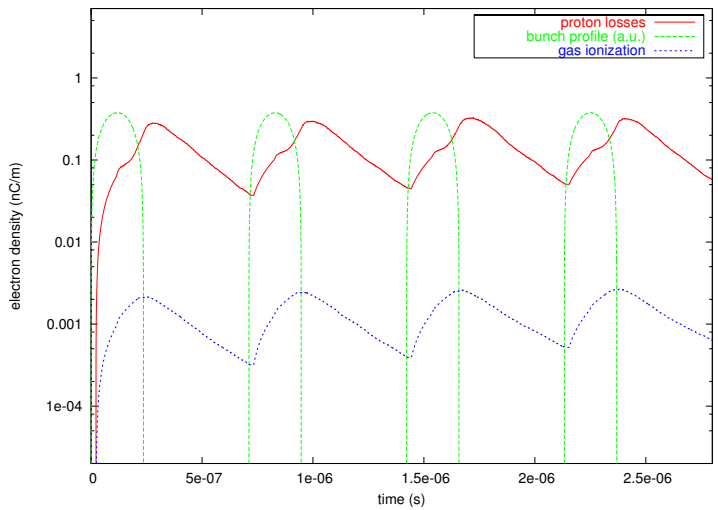
$(\sigma_x,\sigma_y)cm$	$\perp$ rms bunch sizes	(2.3,3.4)	(1,1)	(1.45,1.3)
$n'_{pl}(p/m)$	p loss rate ($\times 10^{-9}$)	763	44	1.8
η_{eff}	$p-e^-$ yield	100	100	100
δ_{max}	peak SEY	1.5	1.5	1.5
$E_{max}(eV)$	E peak SEY	300	300	300
$\delta(0)$	low E SEY	0.4	0.4	0.4

Outline

Free field simulation- buildup

ISIS *peak <0.3 nC/m*



assume

- *E=76 MeV (constant)*
- *StSt chamber w/ rectangular cross section, tapered*
- *transverse Gaussian beam*
- *parabolic longitudinal profile*
- 6.3% *losses b/w* 500^{th} *and* 1000^{th} *rev or*
- σ_{ion} *= 2 Mbarns and P=500 nTorr*

Free field simulation- buildup

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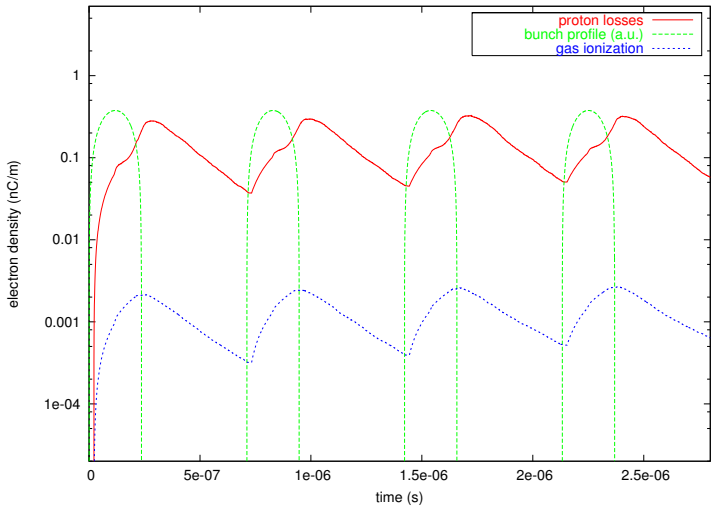
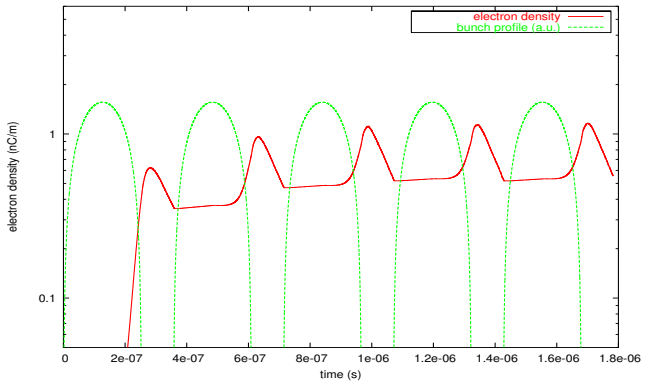
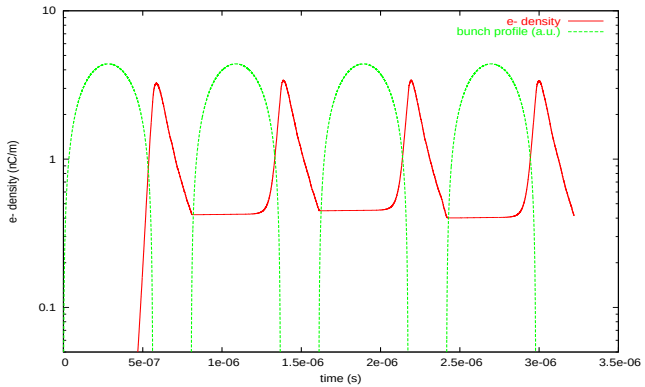




PSR

(peak 1nC/m)

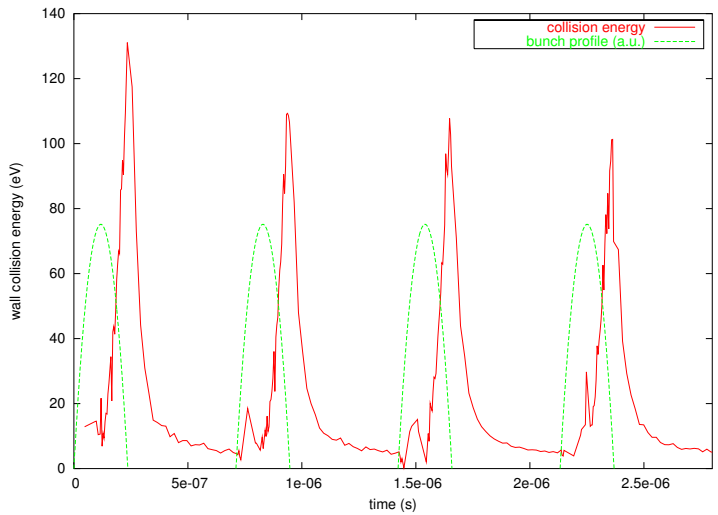


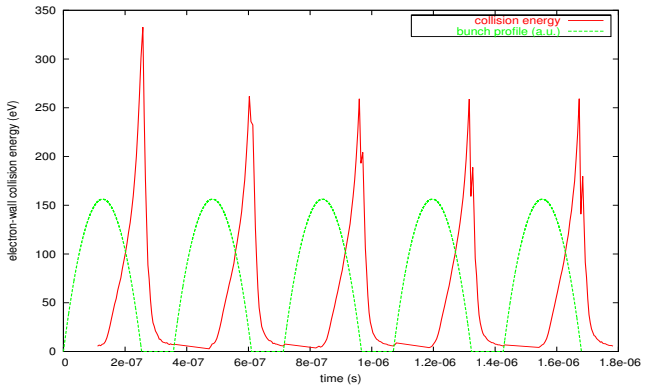
ESS

(peak 3nC/m)

FF: wall energy

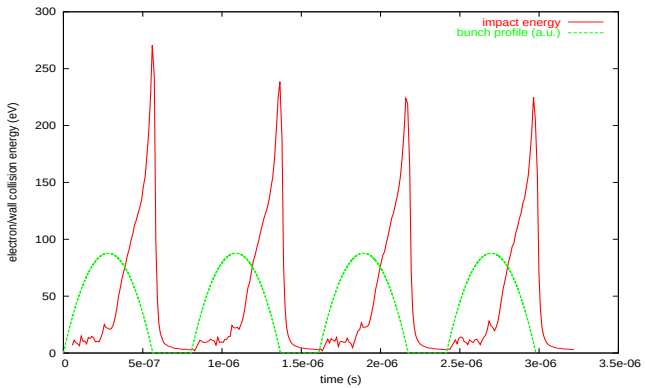
ISIS (max 110eV)





PSR

(max 250eV)

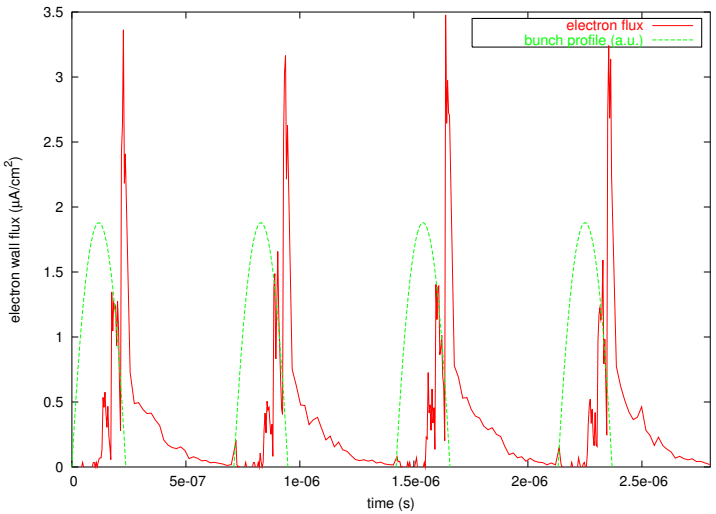


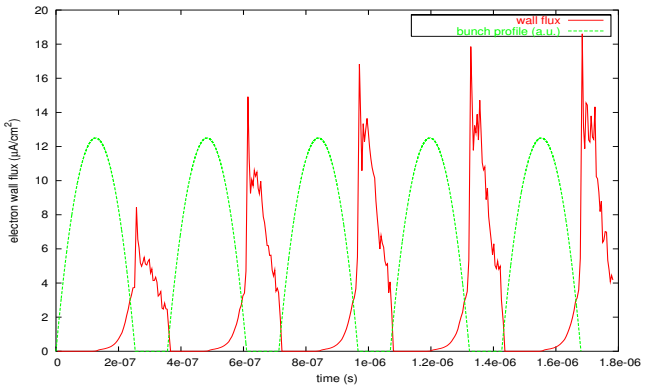
ESS

(max 225eV)

FF: wall flux

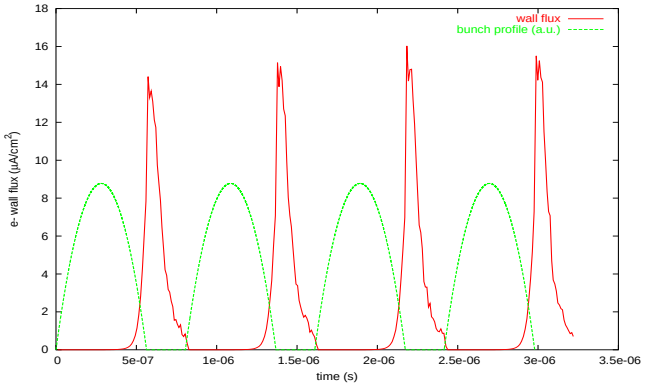
ISIS (max $\sim 3\ \mu A/cm^2$)





PSR

(max $15\mu A/cm^2$)

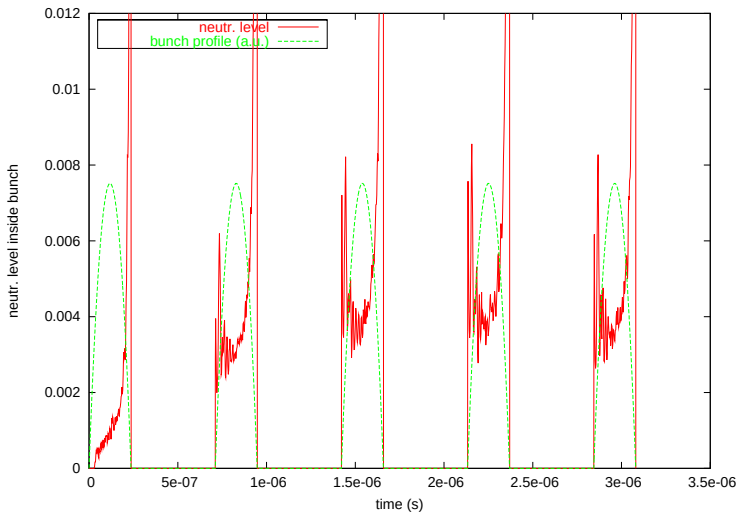


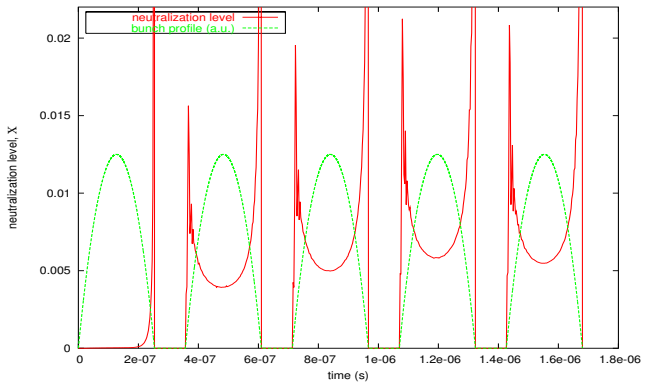
ESS

(max $15\mu A/cm^2$)

Neutralization level inside bunch

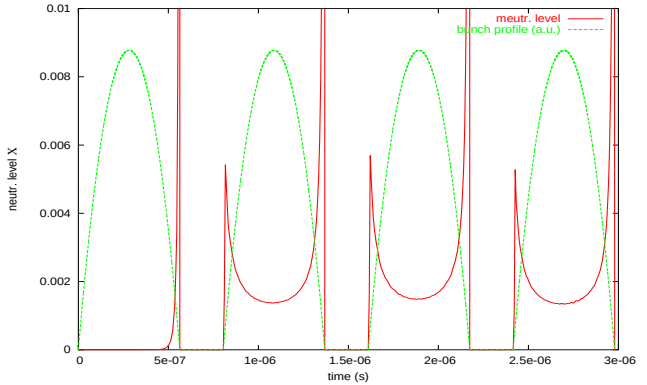
ISIS (~ 0.004)





PSR

(<0.01)



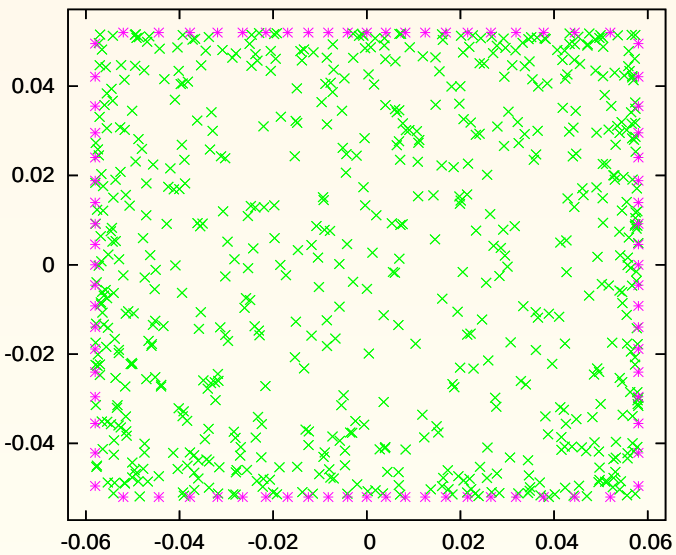
ESS

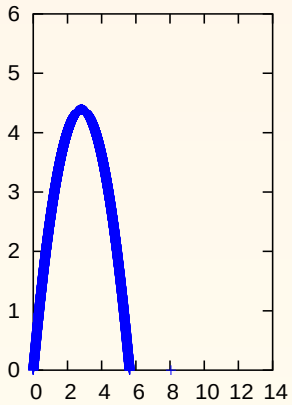
(<0.004)

Outline

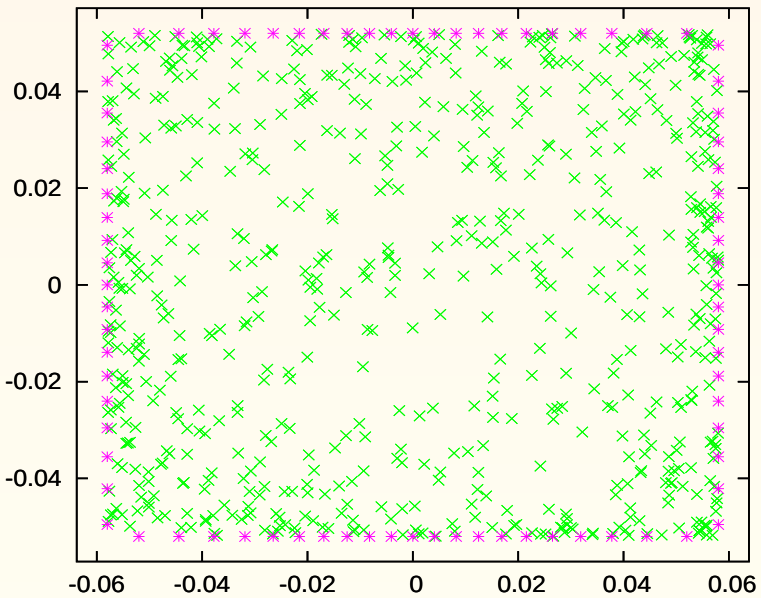
ESS multipacting

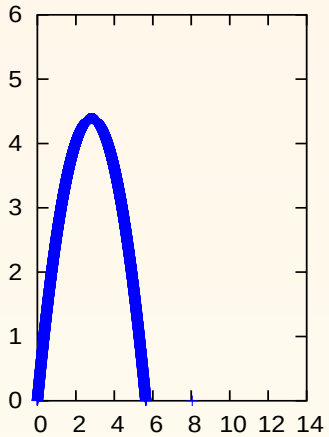
Skip animation





ESS multipacting





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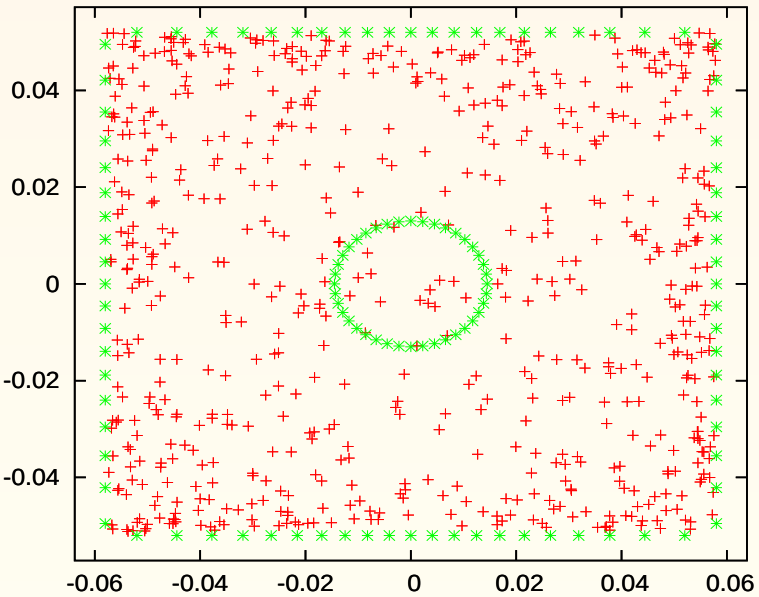

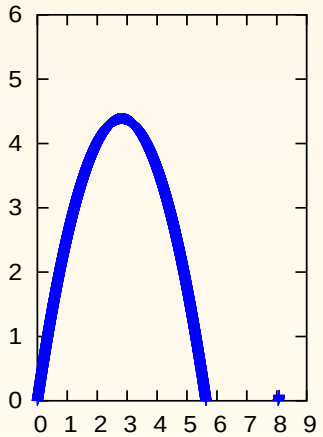

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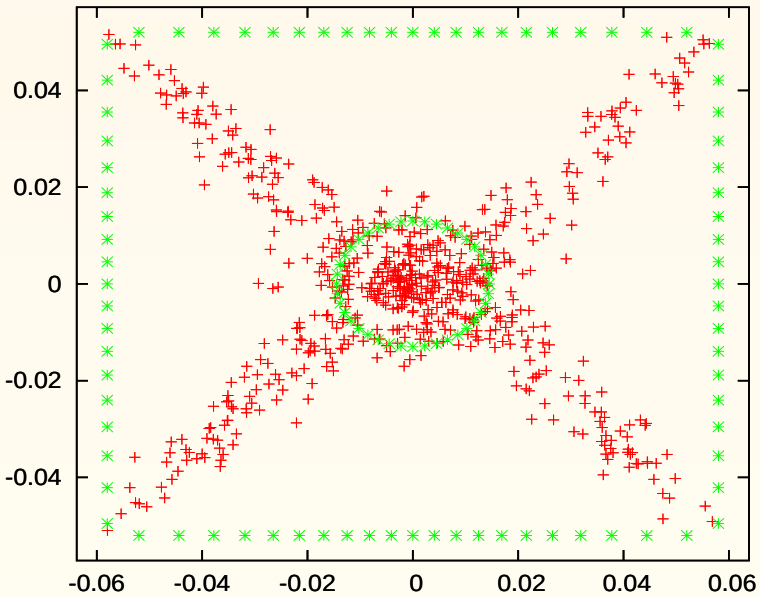

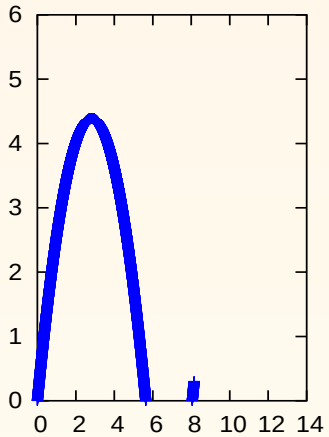

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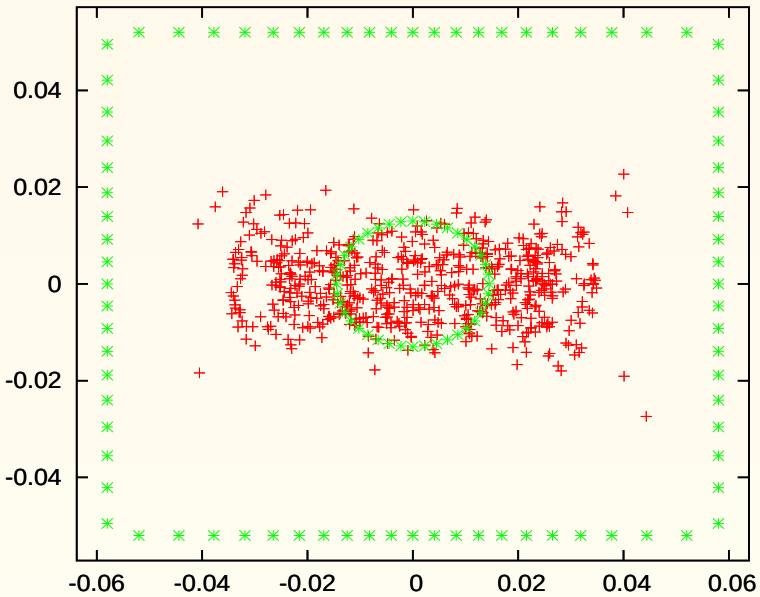

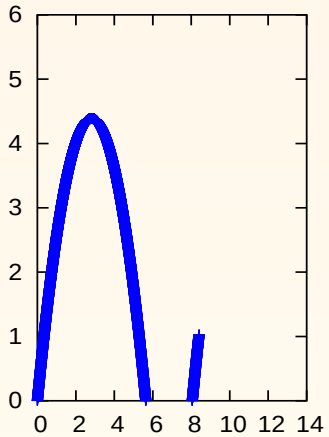

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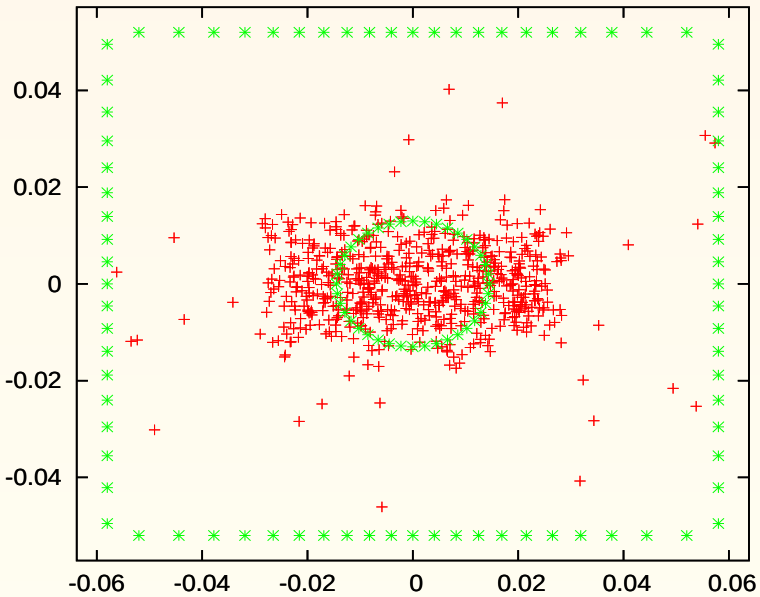

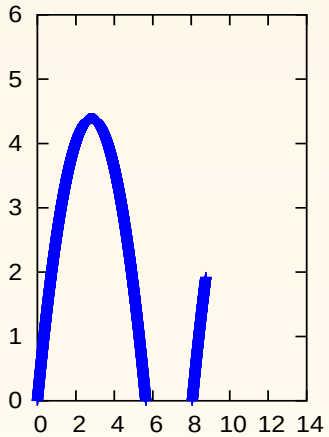

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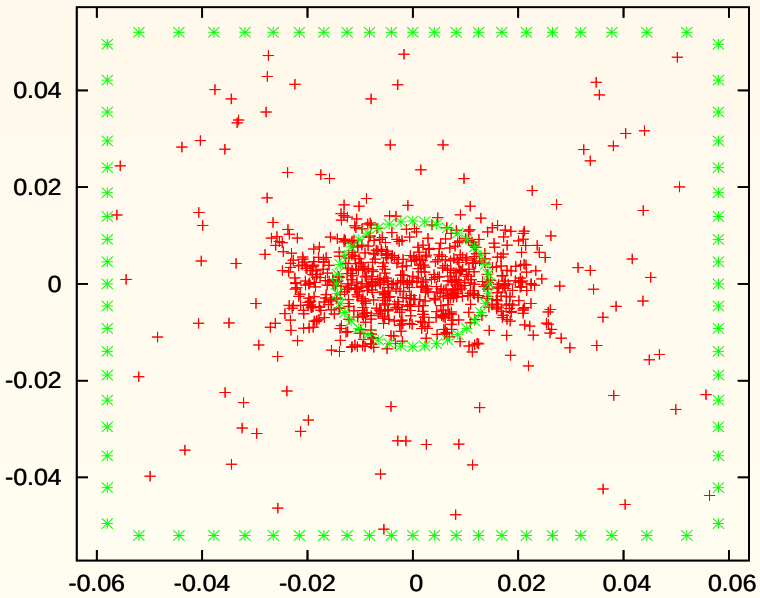

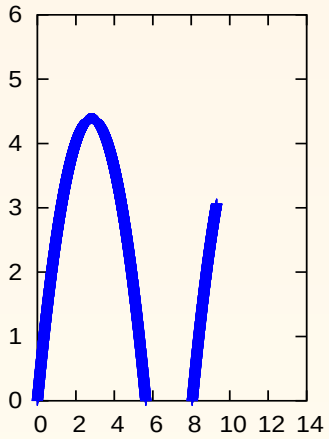

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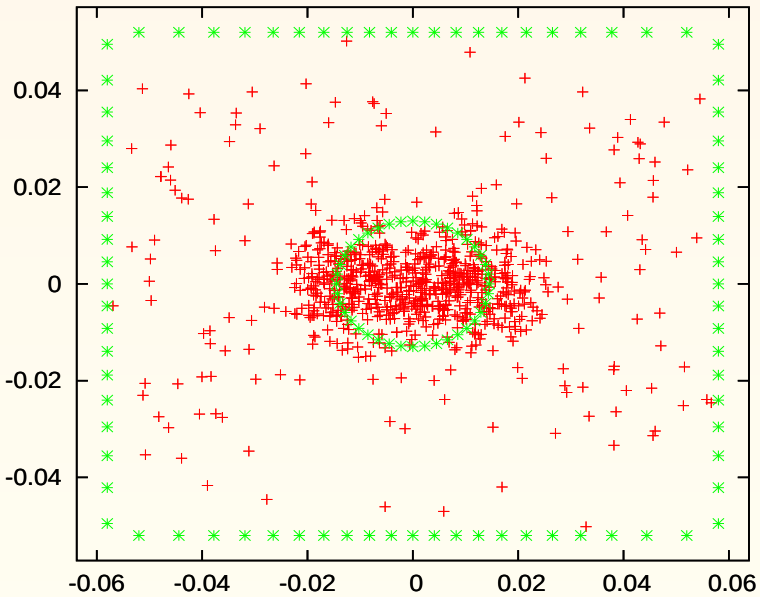
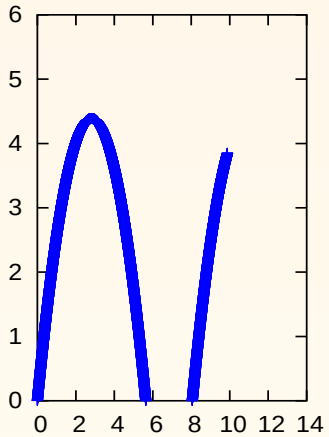
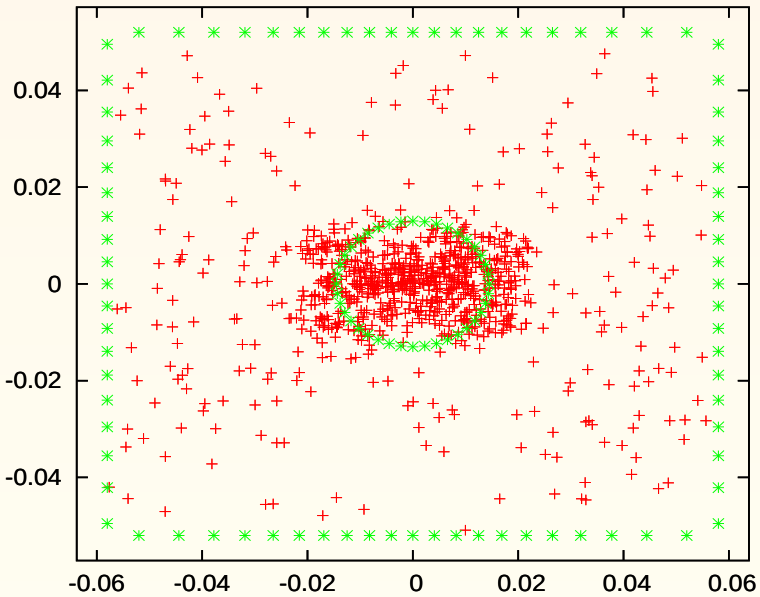
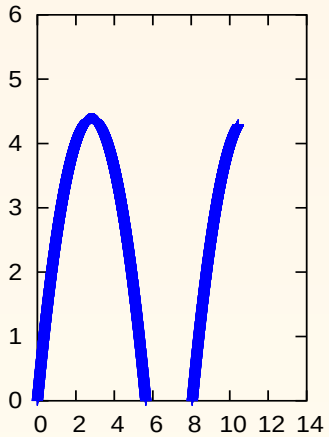




ESS multipacting





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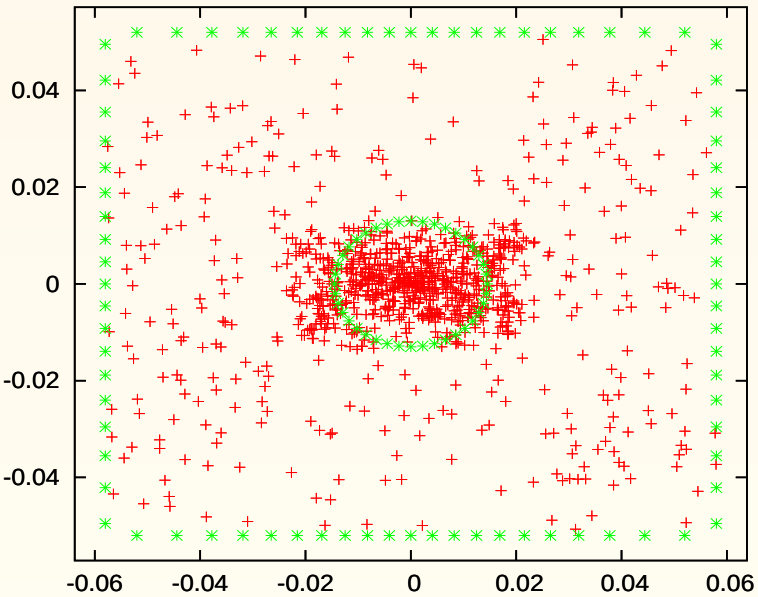

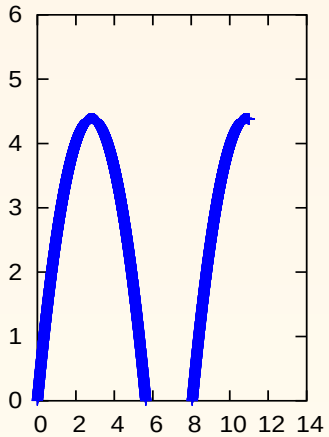

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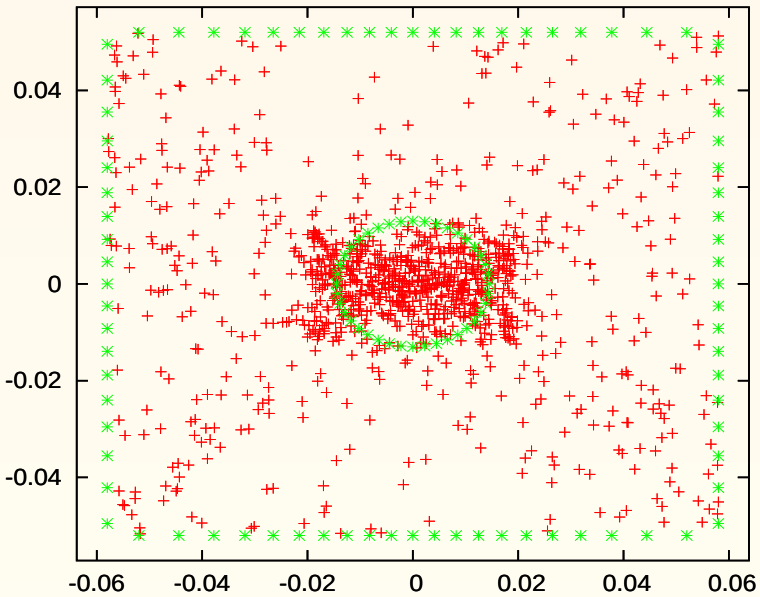

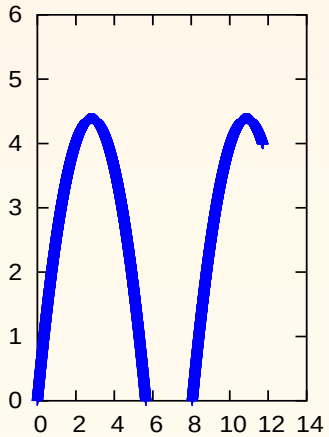

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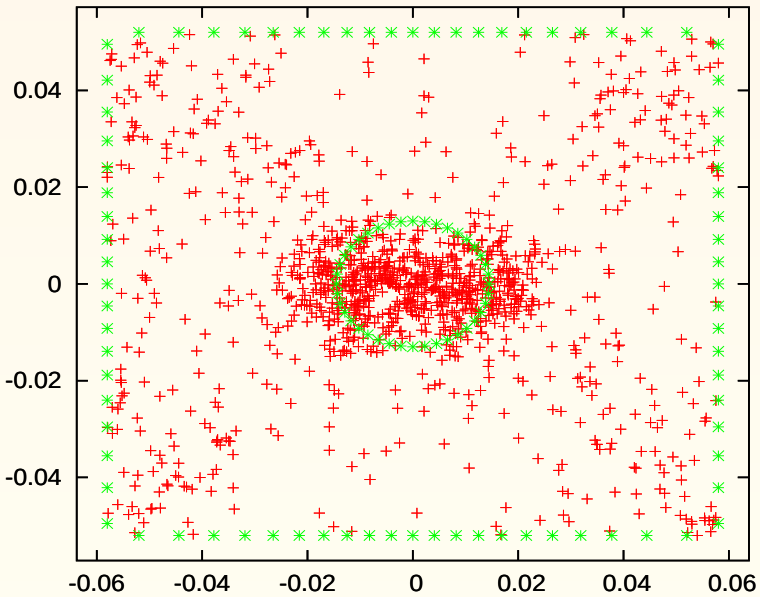

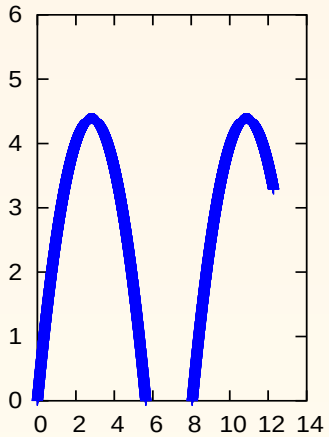

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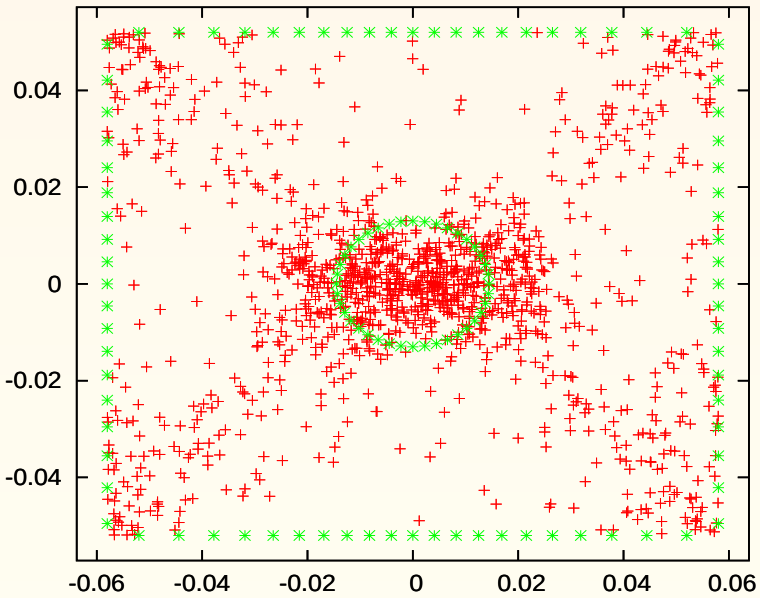

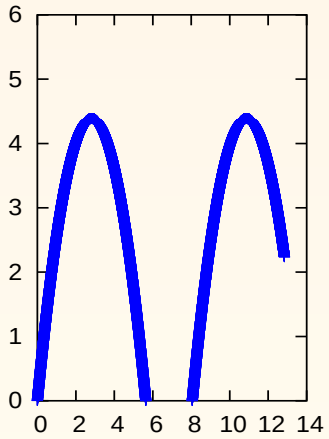

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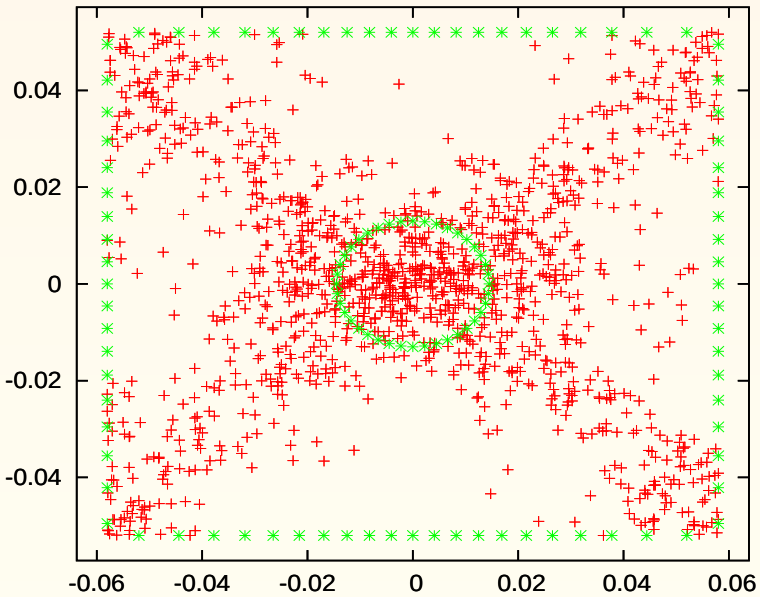

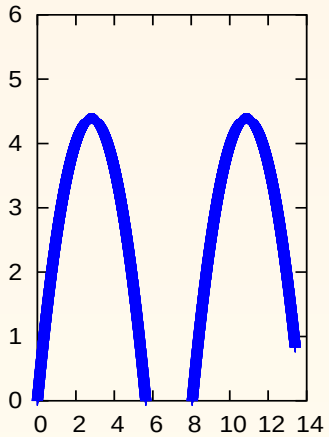

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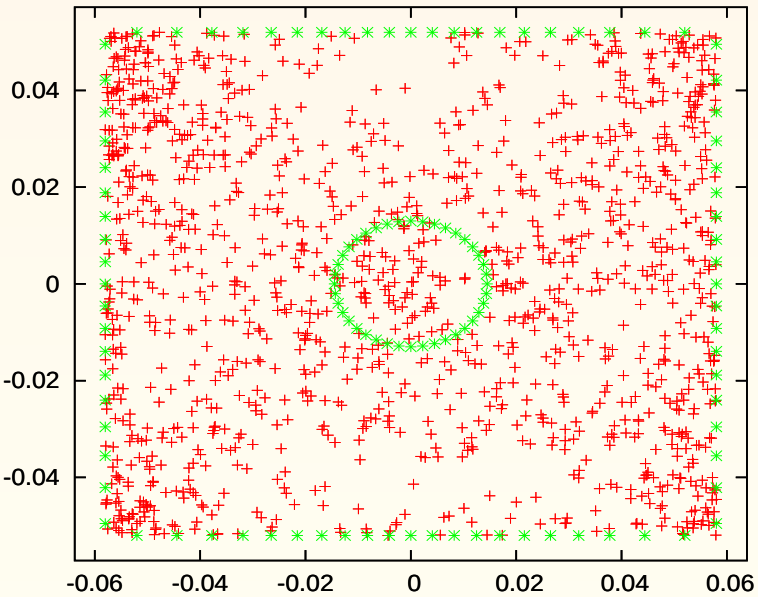

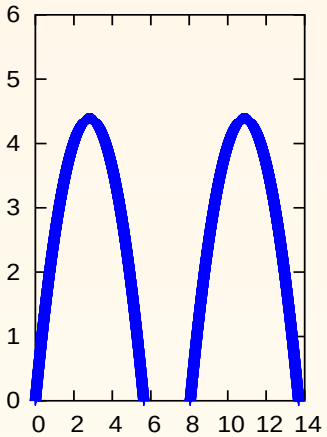

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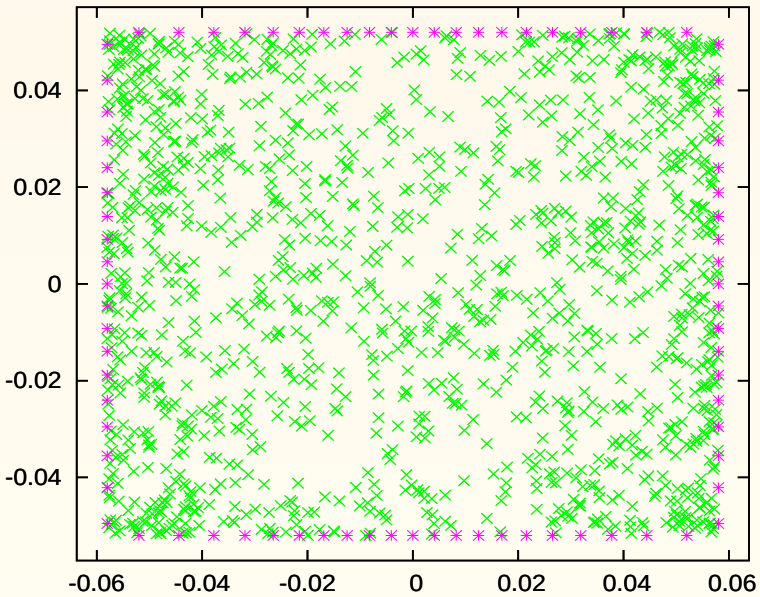

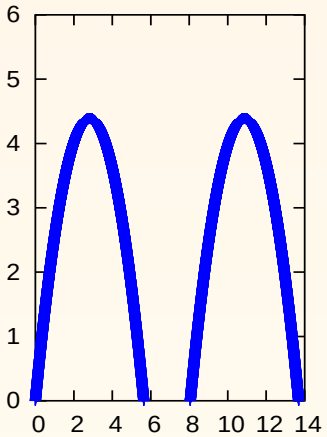

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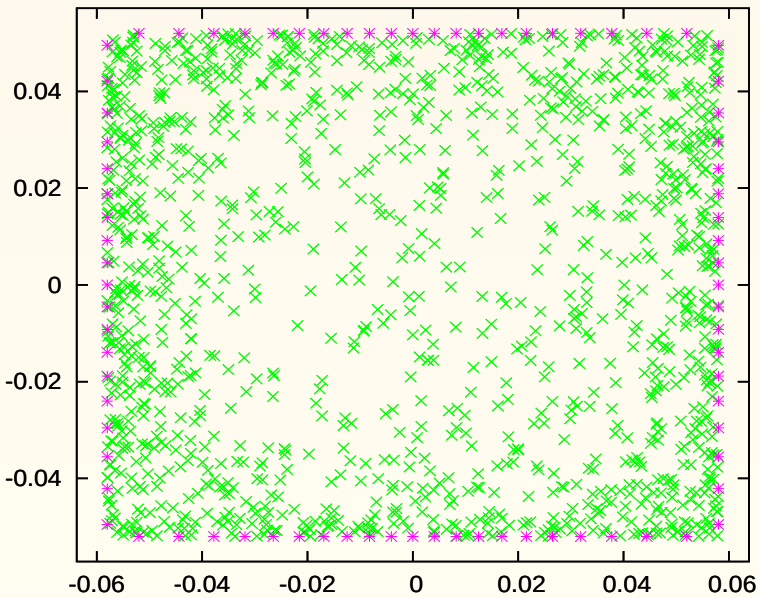

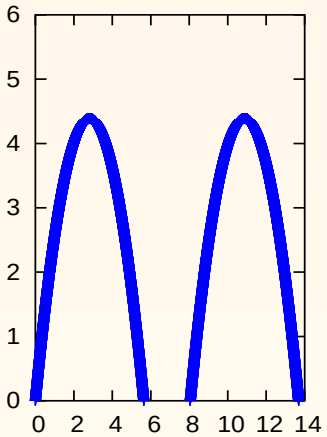

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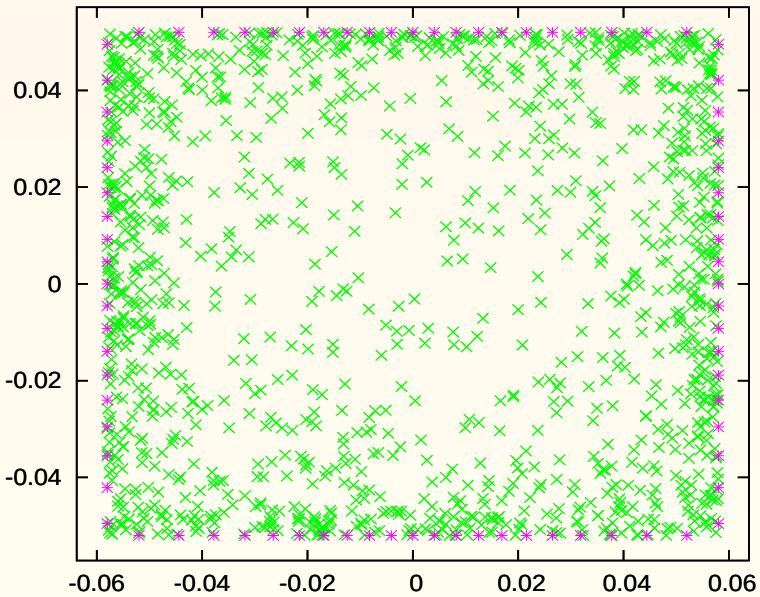
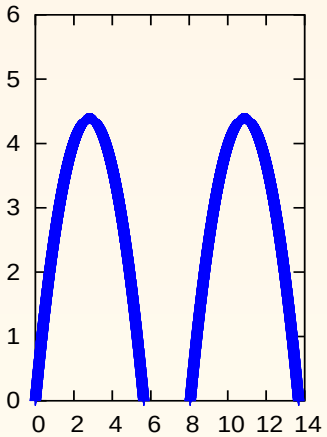
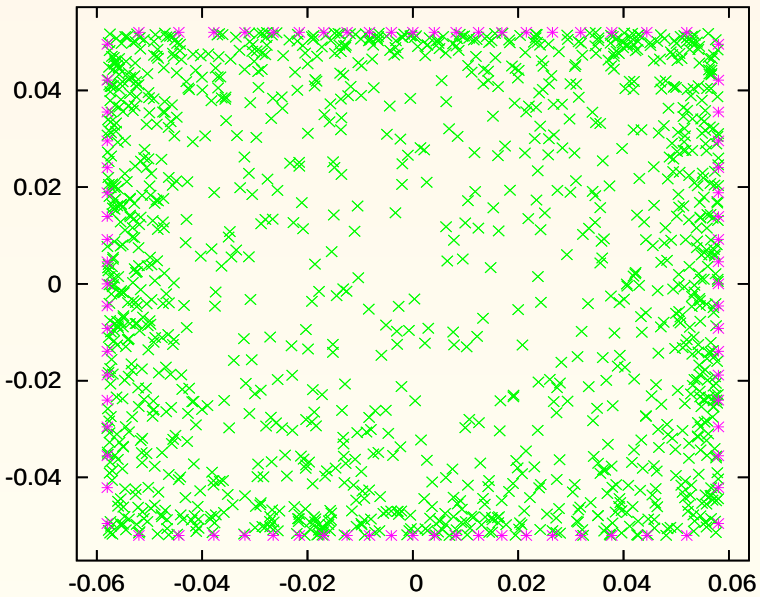
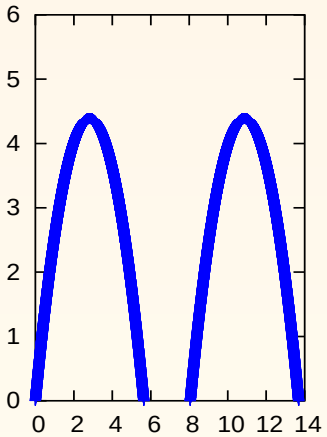


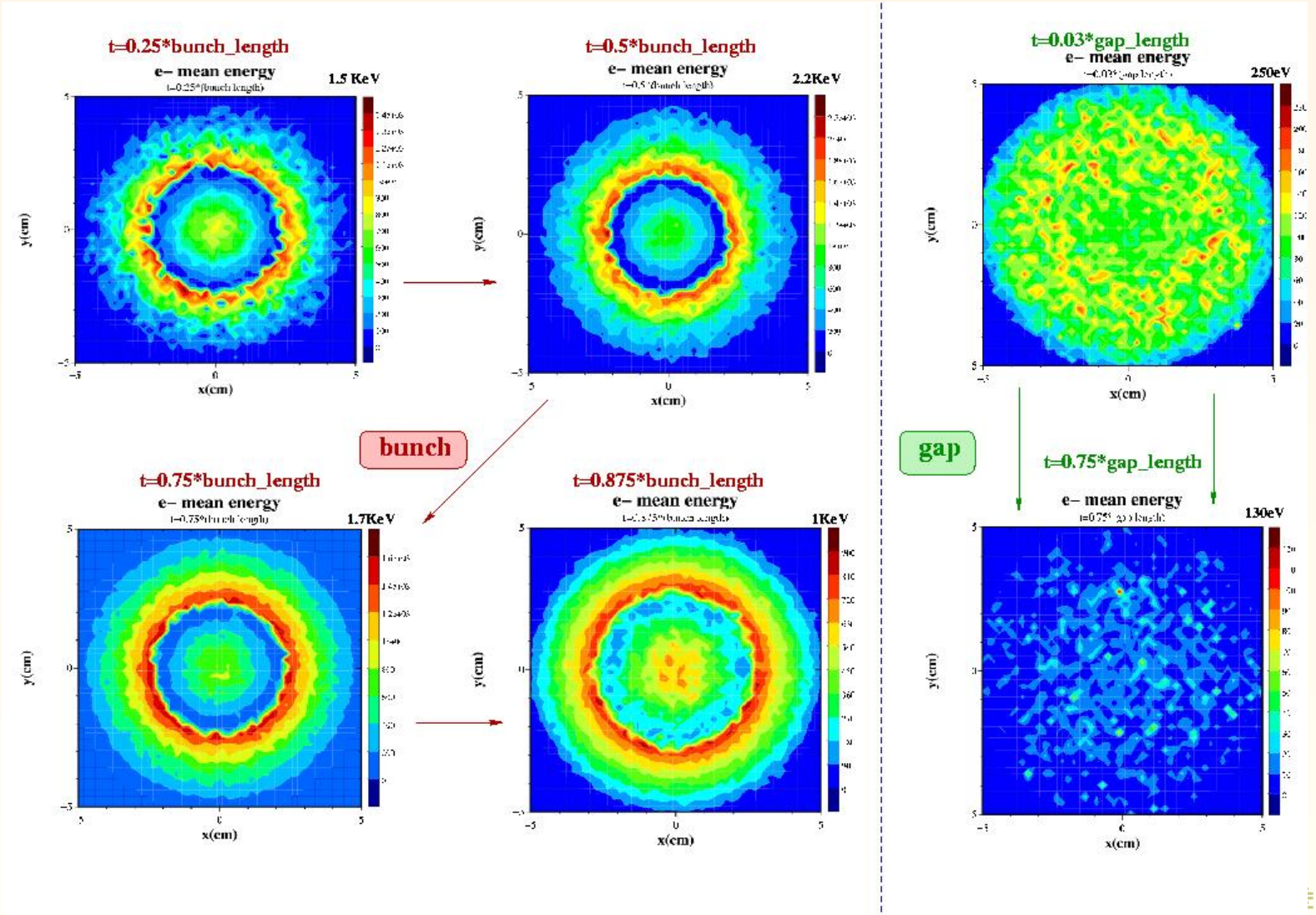


ESS multipacting

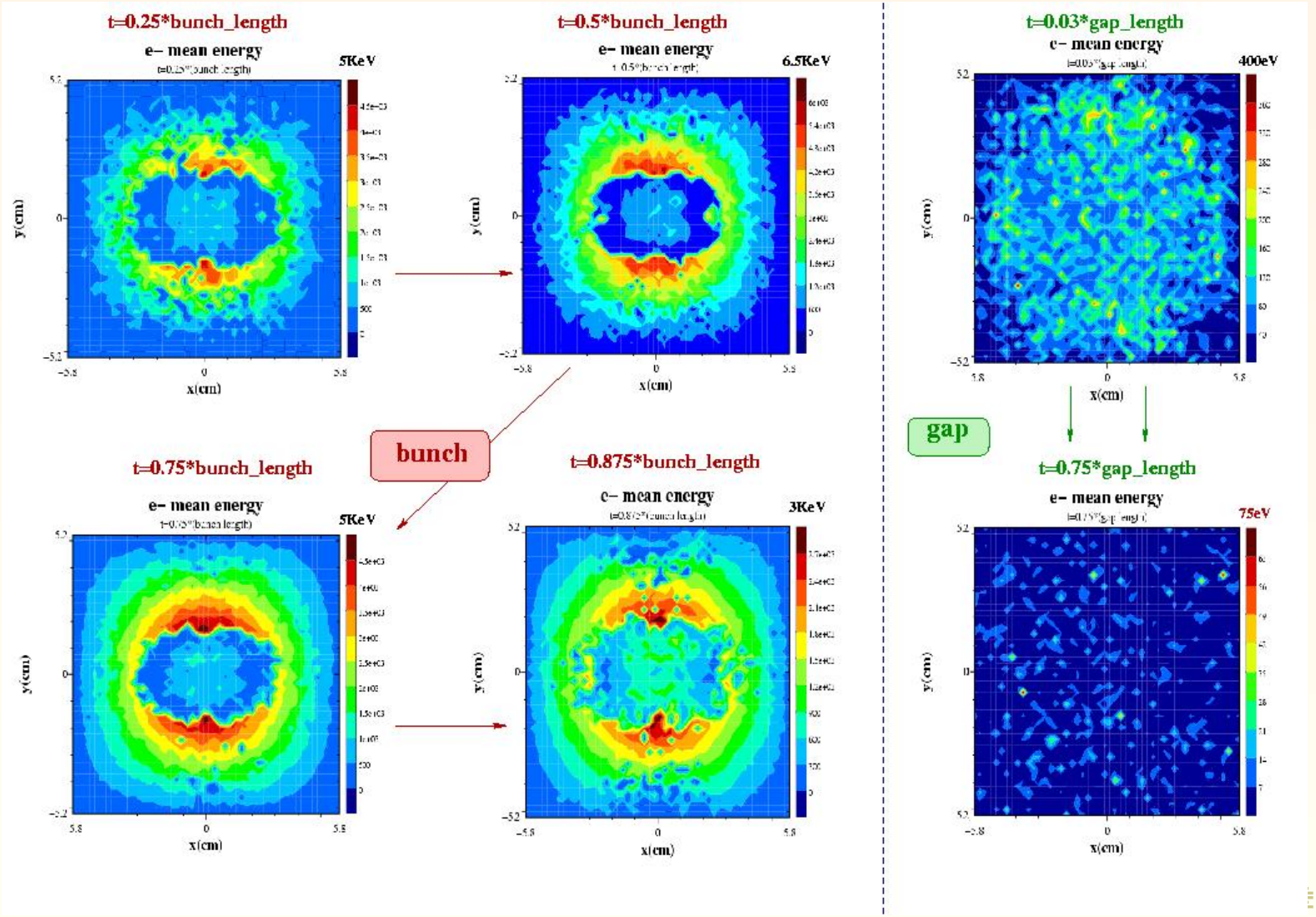




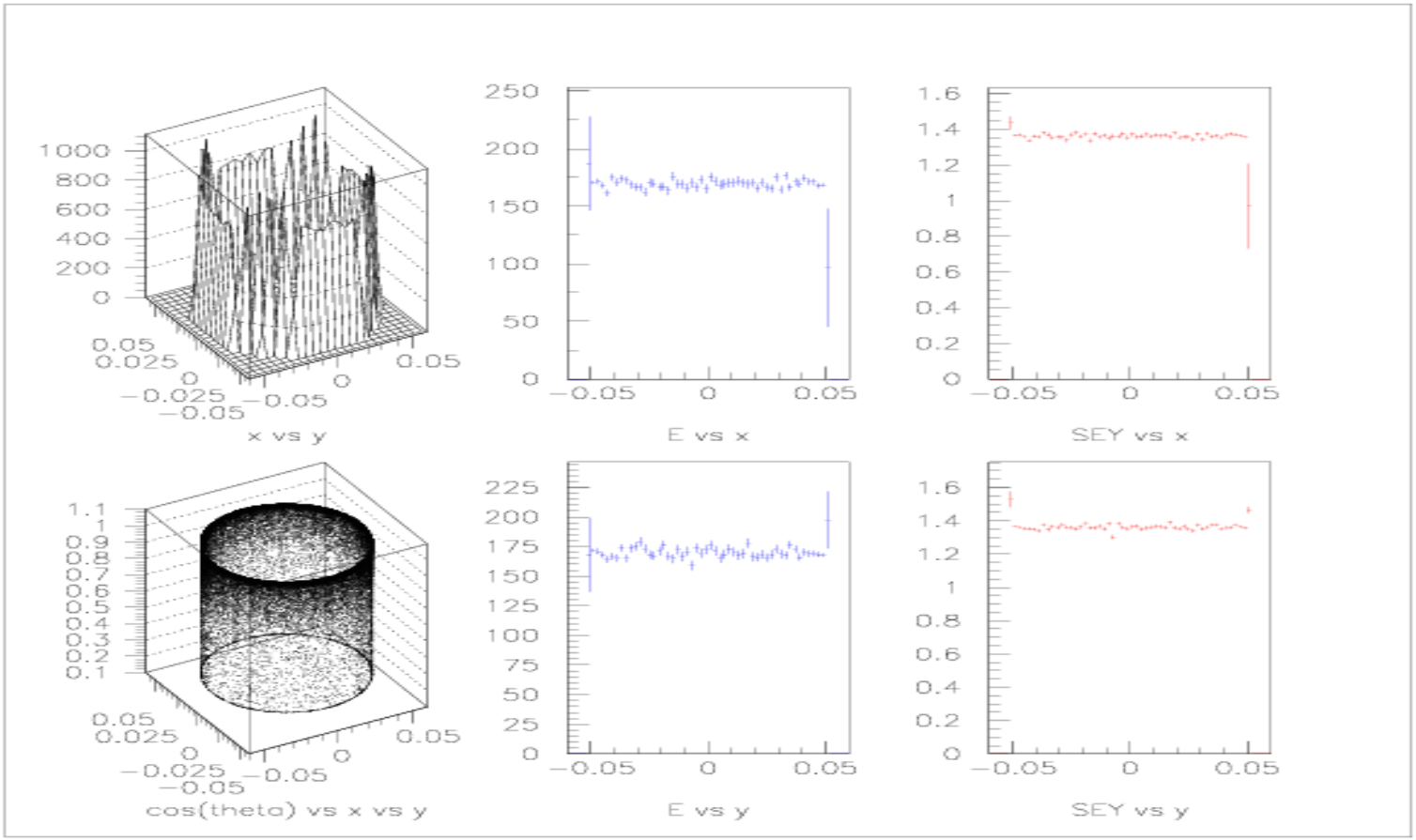
Energy contour plots: PSR



Energy contour plots: ESS

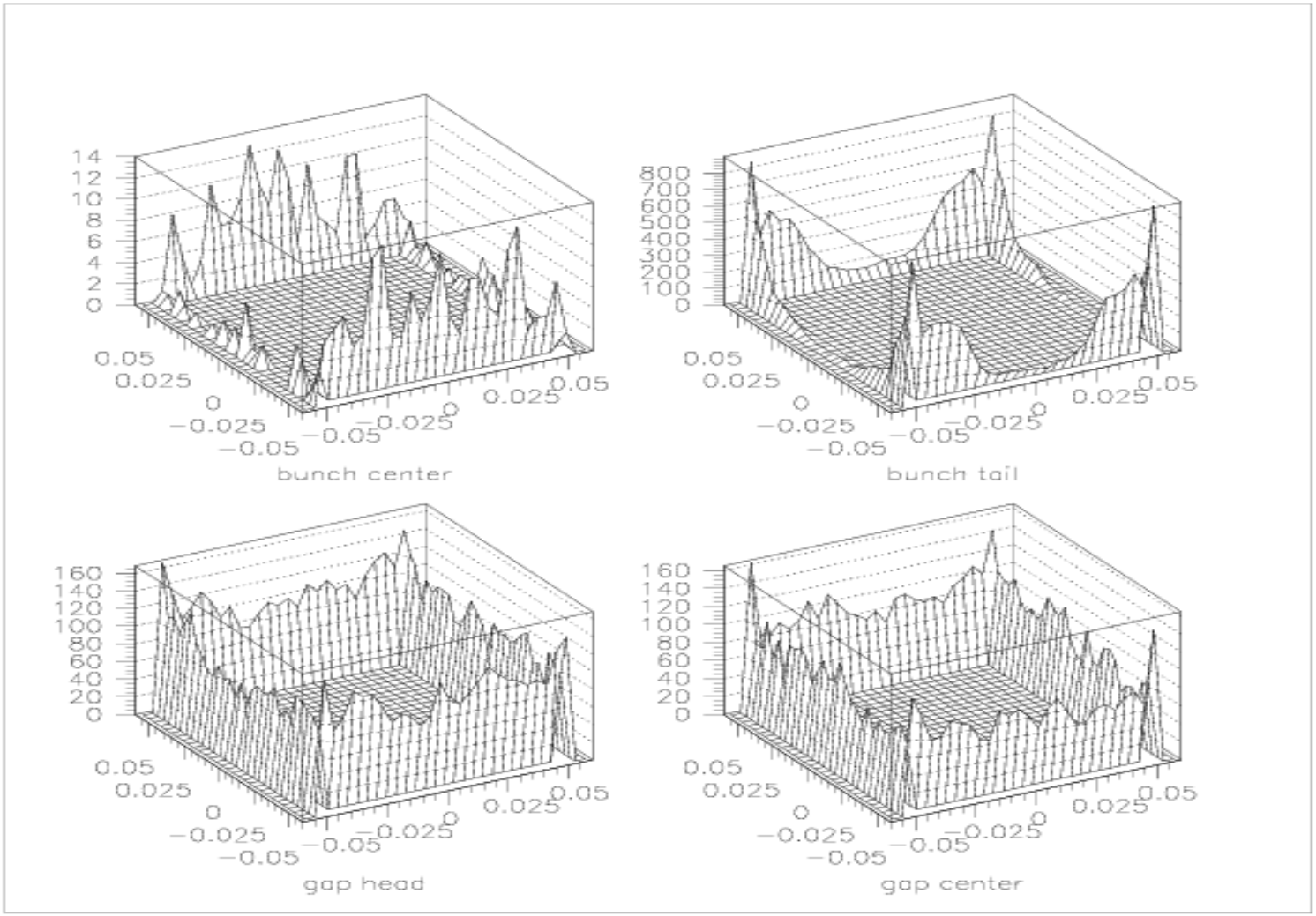


PSR multipacting (circular geometry)



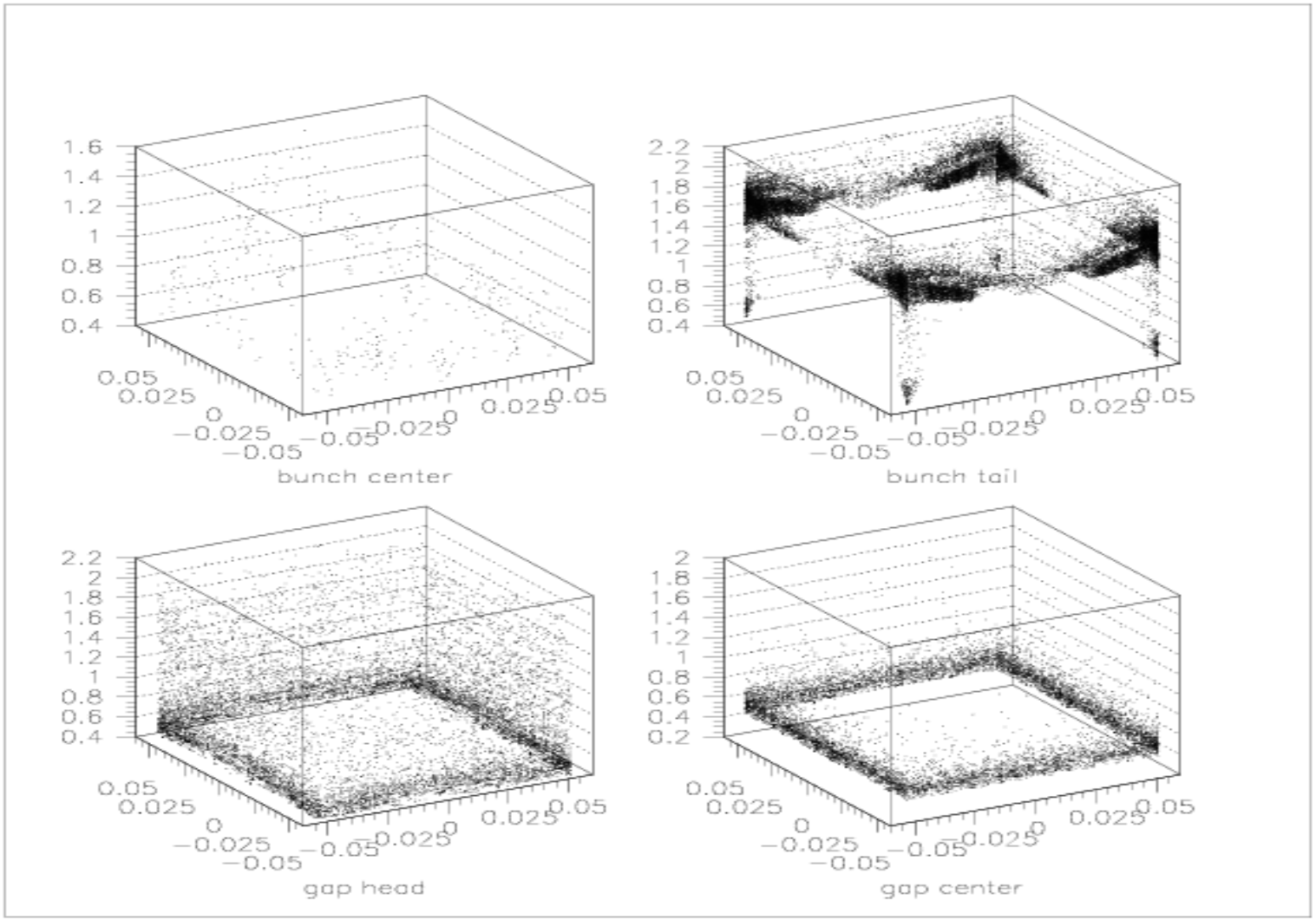
ESS multipacting (rectangular geometry)

x *vs* y



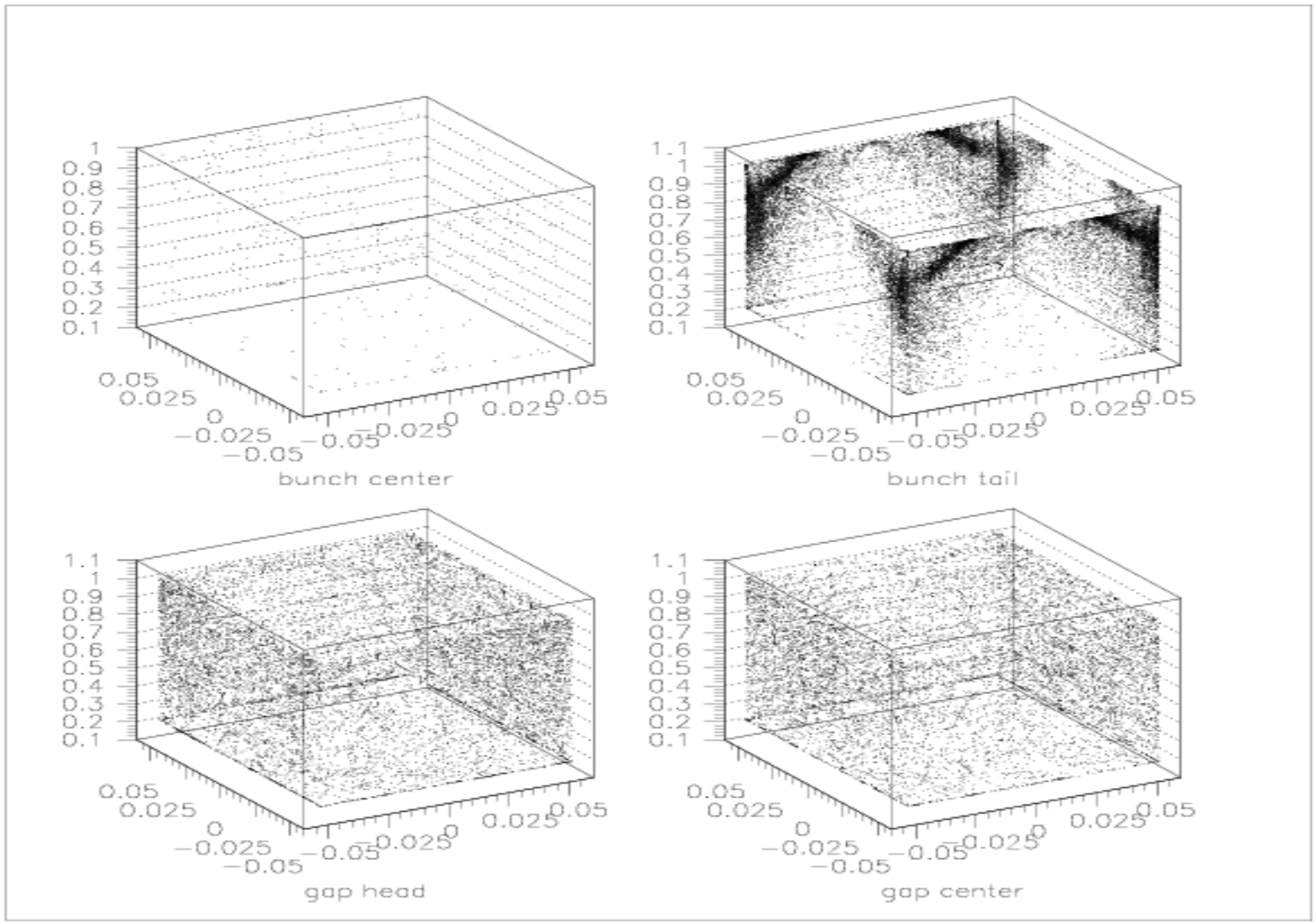
ESS multipacting (rectangular geometry)

SEY



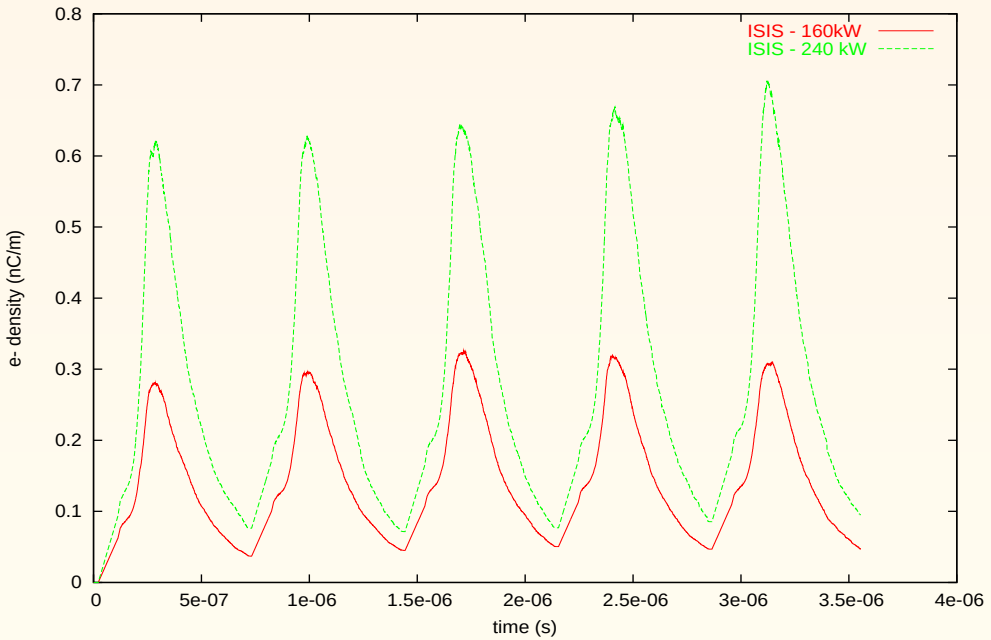
ESS multipacting (rectangular geometry)

impact
$\cos\theta$



Outline

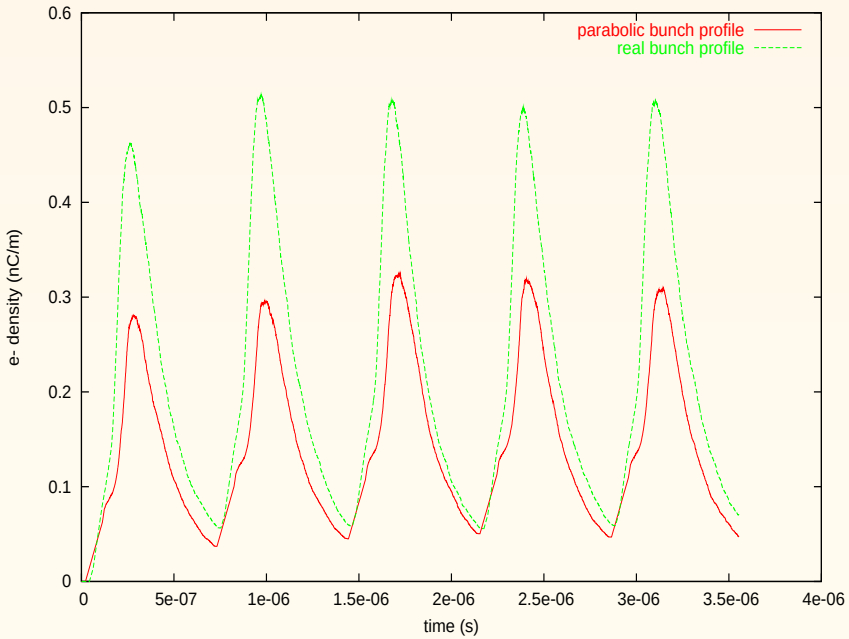
1. bunch intensity

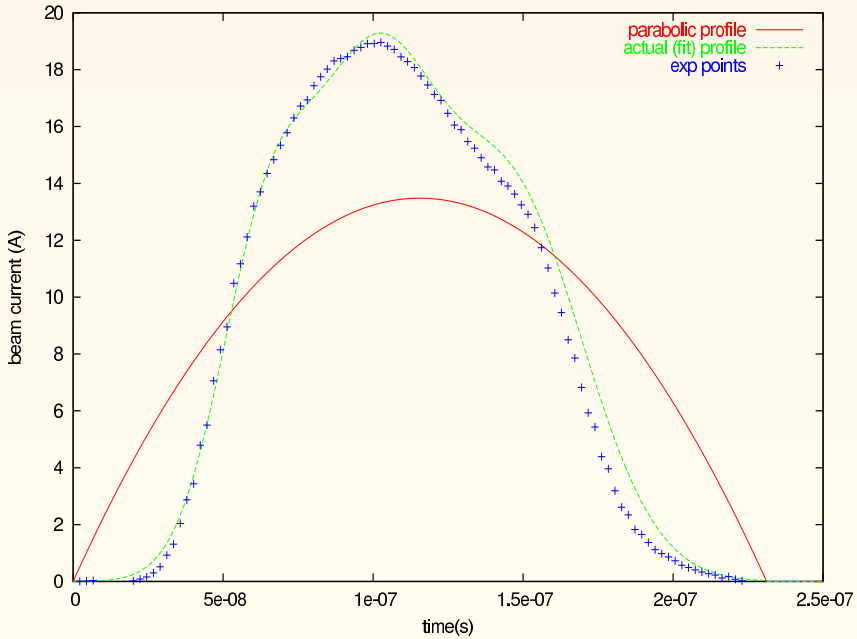


ISIS current upgrade to 240kW :

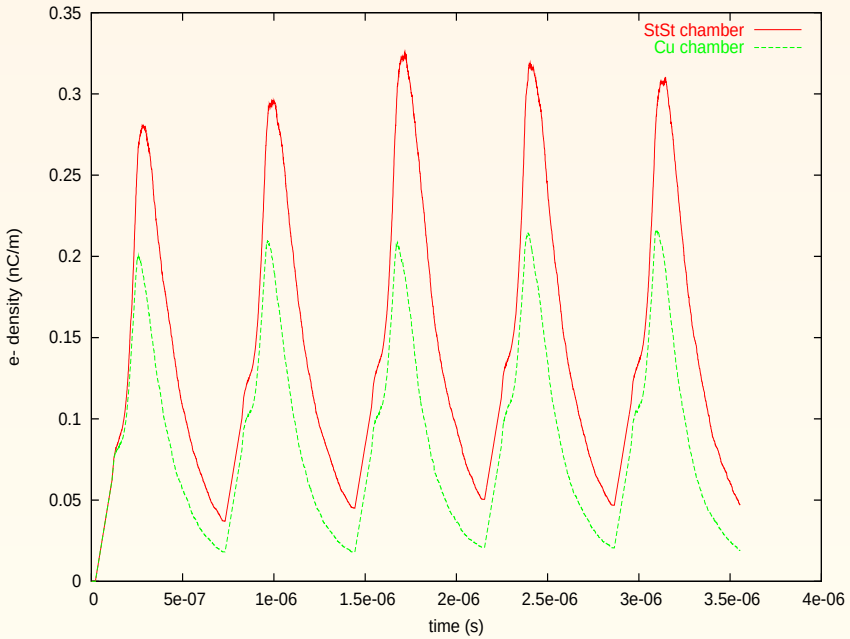
3.8×10^{13} *ppb* , *300* μA, *4 DHRF h=4*
(increase long. accept.)
f_{RF} *=2.6-6.2MHz*
V_{RF} *peak 80kV per turn*
(assuming same loss pattern)*

2. bunch shape

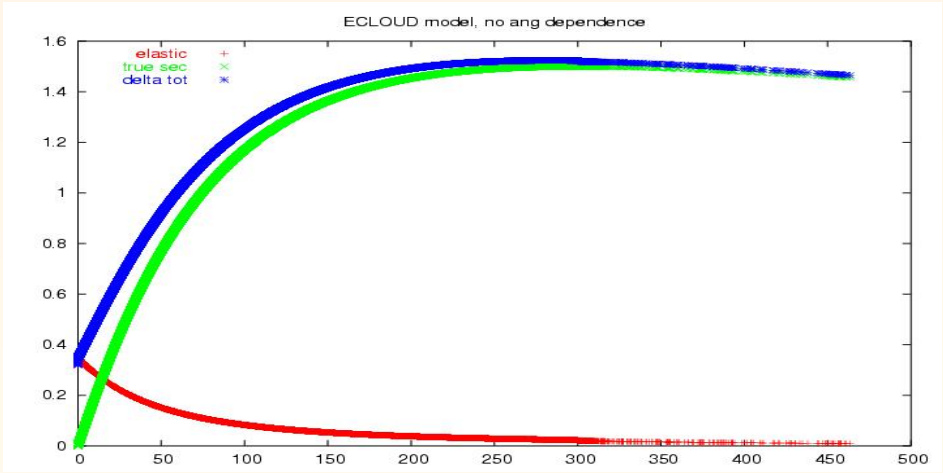




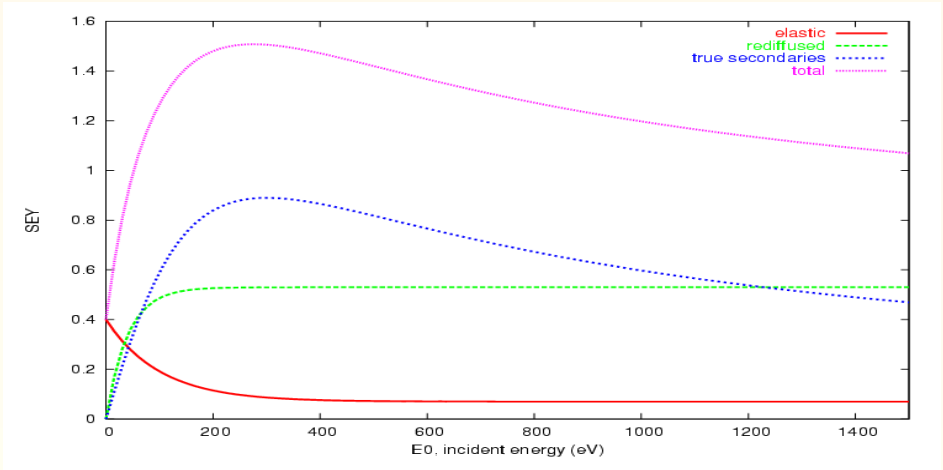
3. SEY model:



Cu $\delta_e \sim 0$ @ E_{max}

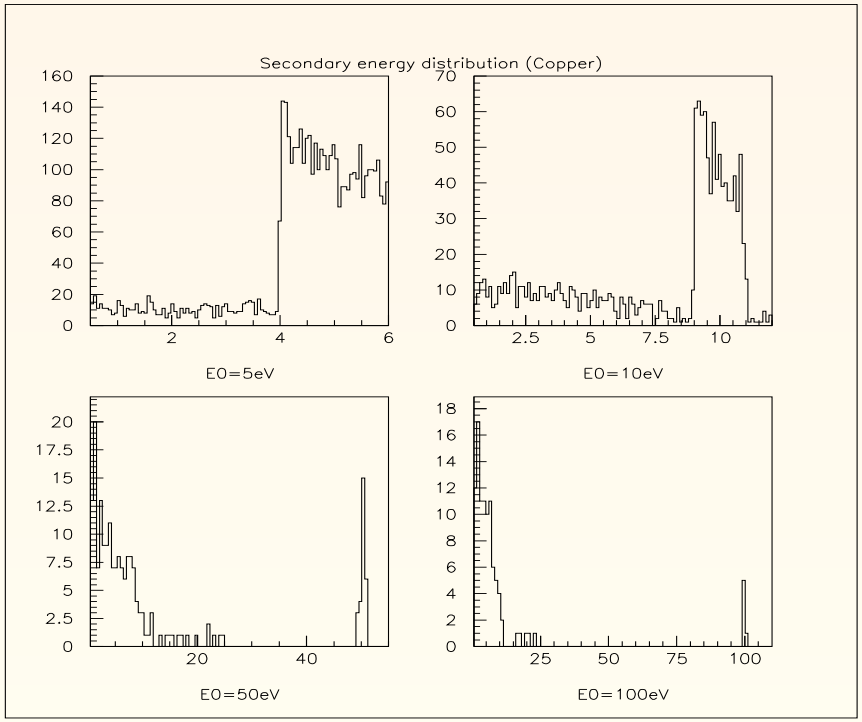


StSt $\delta_e + \delta_r \sim 0.6$ @ E_{max}

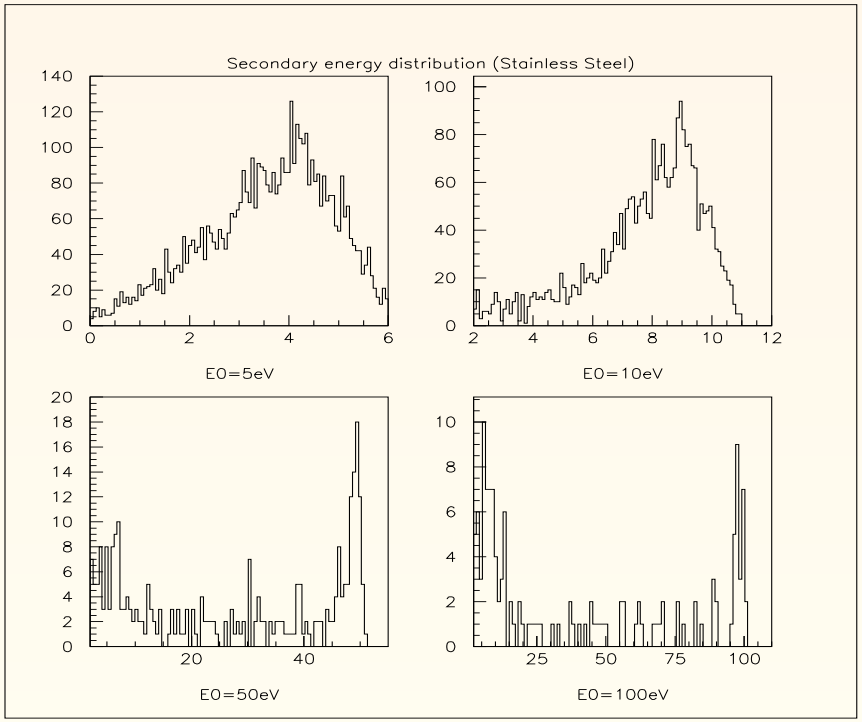


3. SEY model: secondary energy spectrum

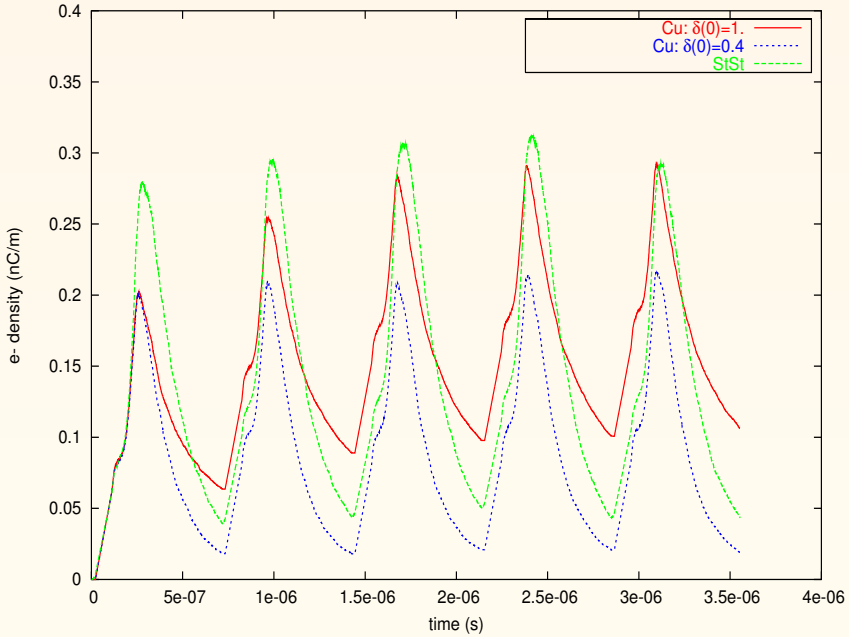
Copper

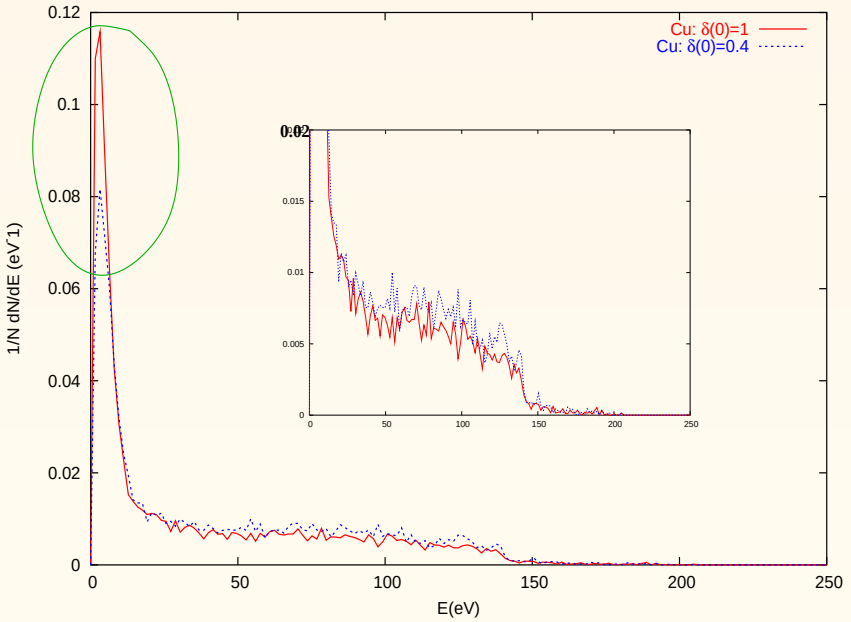


Stainless Steel



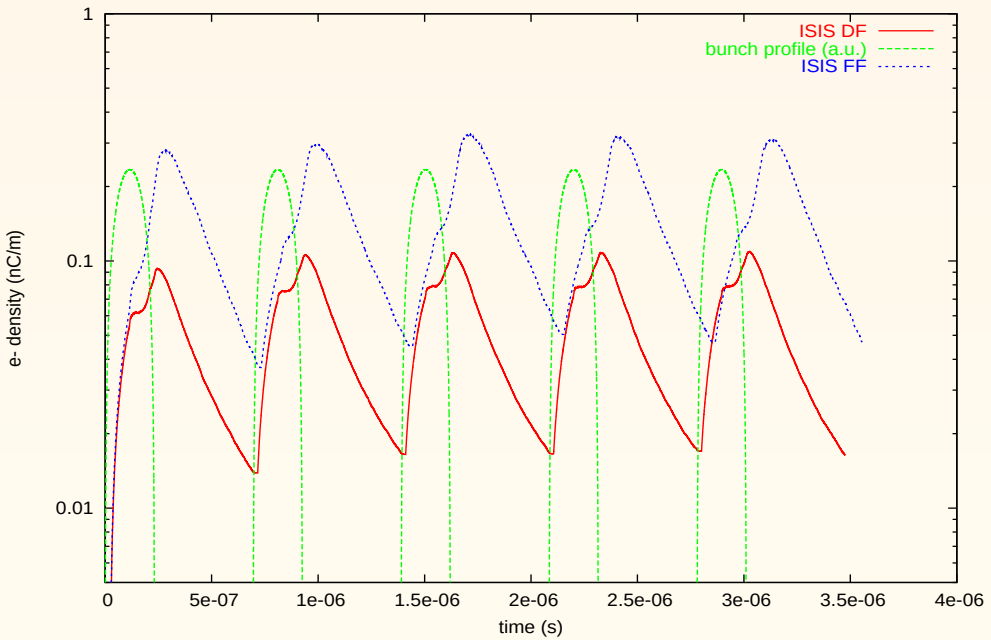
3. SEY model: low energy electrons





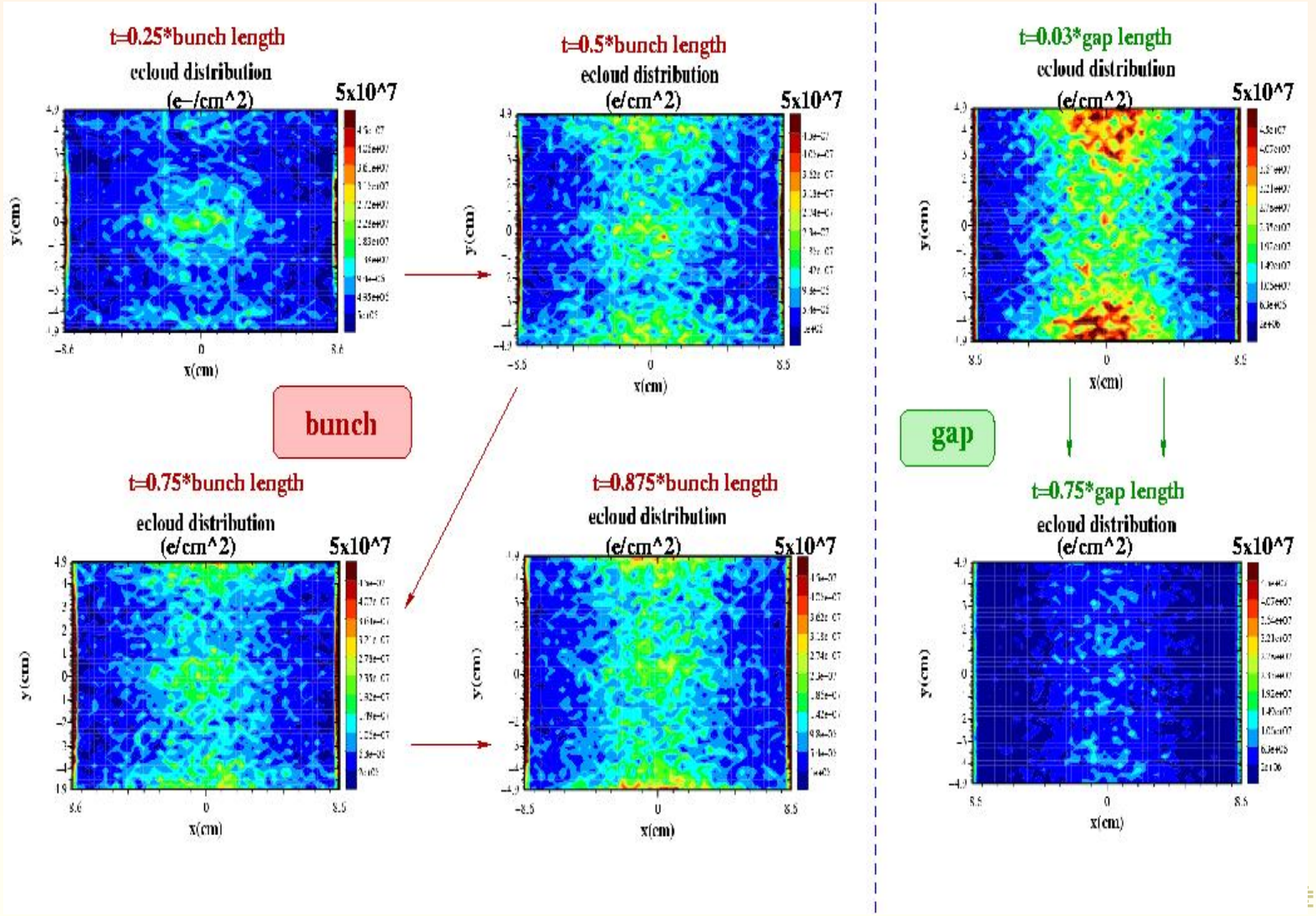
Outline

and the chamber was pure StSt....



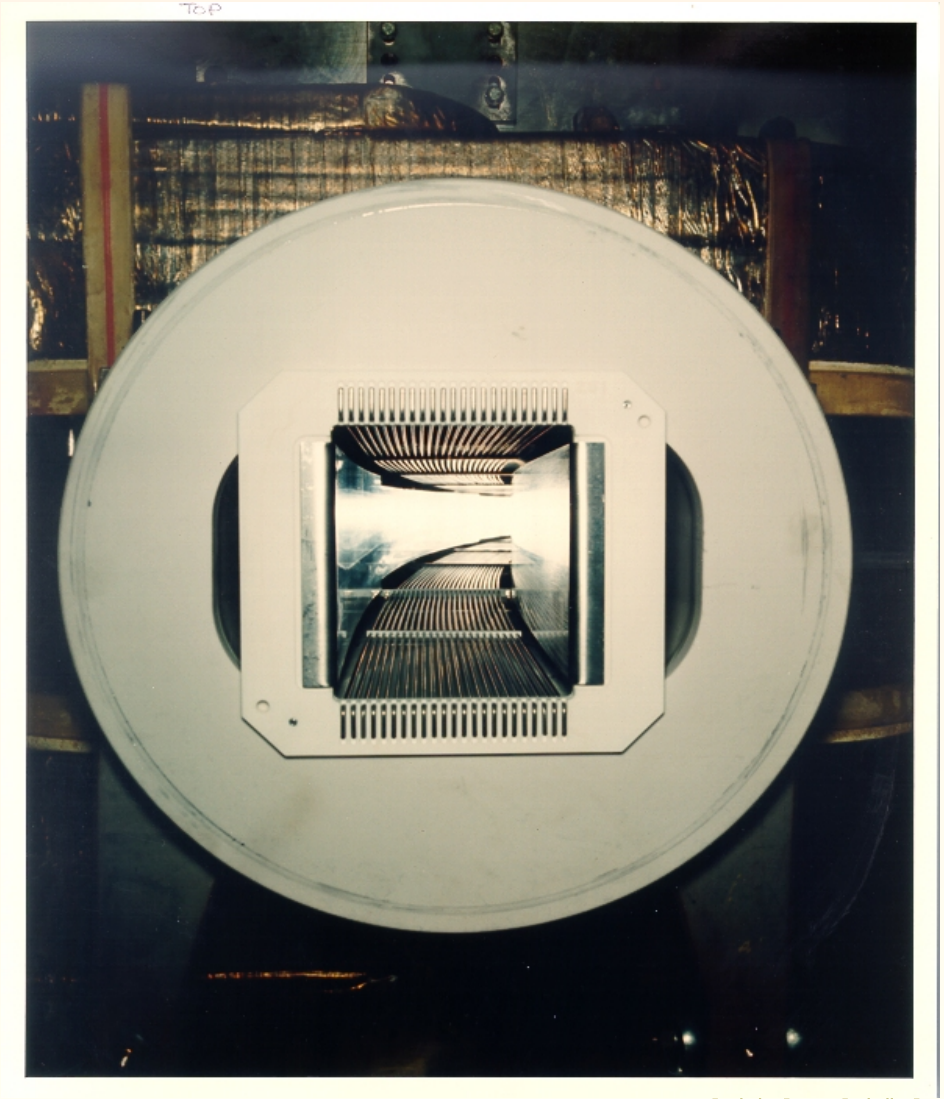
$(a, b) = (8.6,4.9)\text{cm}$
$(\sigma_x, \sigma_y) = (2.9,1.3)\text{cm}$
$\text{B} = 0.185\ \text{T}$
$SEY_{max} = 1.5$
$E_{max}(eV) = 300$
$\delta(0) = 0.4$
$\times 10$ *slices to resolve*
e^- *cyclotron motion*

ISIS DF: *density distribution*



Outline

ISIS real chamber: RF shields



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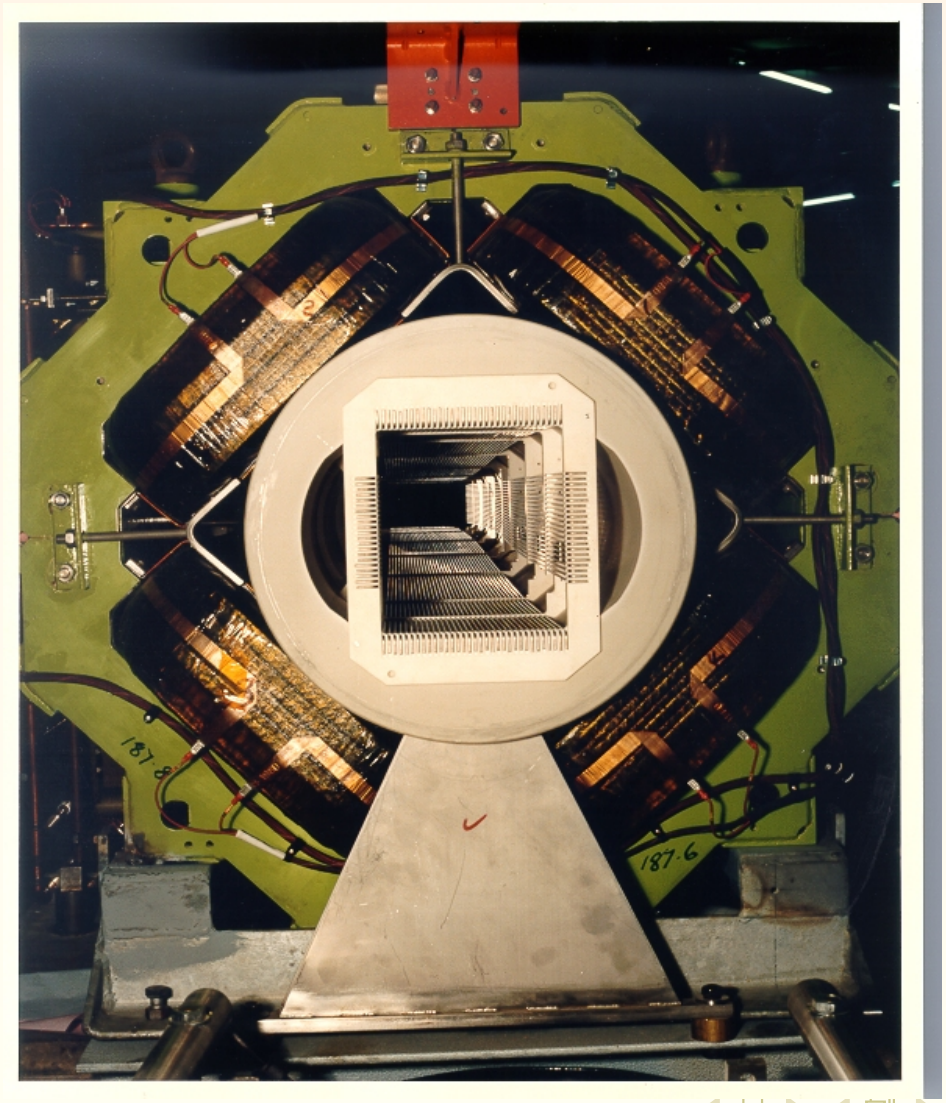

ISIS real chamber: RF shields

not just a geometrical nightmare!

RF shields wires are StSt:

x22 per grid
∼2mm diameter
∼3mm gap

underneath is MACOR:

46% SiO_2
16% Al_2O_3
17% MgO
10% K_2O
7% B_2O_3
4% F

Problem

what's the behaviour of ceramics under electron/ion bombardment?

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SEY from insulating targets

only a few experimental data sets available (..and uncertain theoretical descriptions)

- *energy dependence of total yield is similar to that for metal targets*
- *total yields are higher than for metals (up to a factor 5-10)*
- *time dependent surface charging asymptotically leads to equilibrium ($\delta \sim 1$).*
- *any data for MACOR in particular??*

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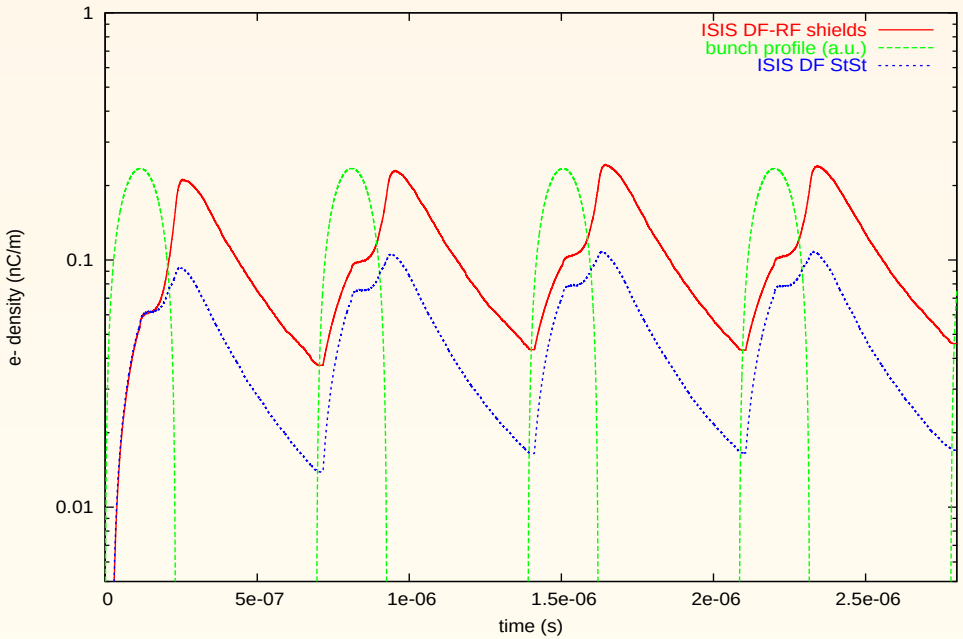
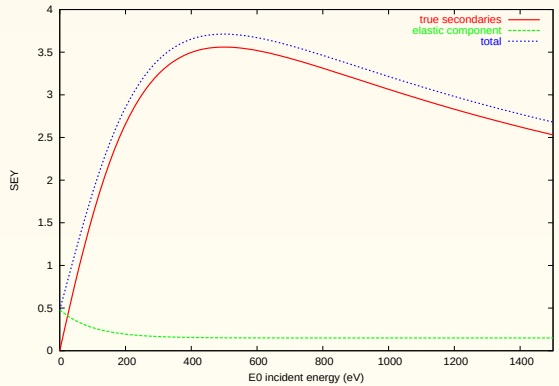
purely for exercise....



introduced (simple) grid in chamber geometry and assumed a time independent ceramic SEY curve ($SEY_{max} \lesssim 4$):



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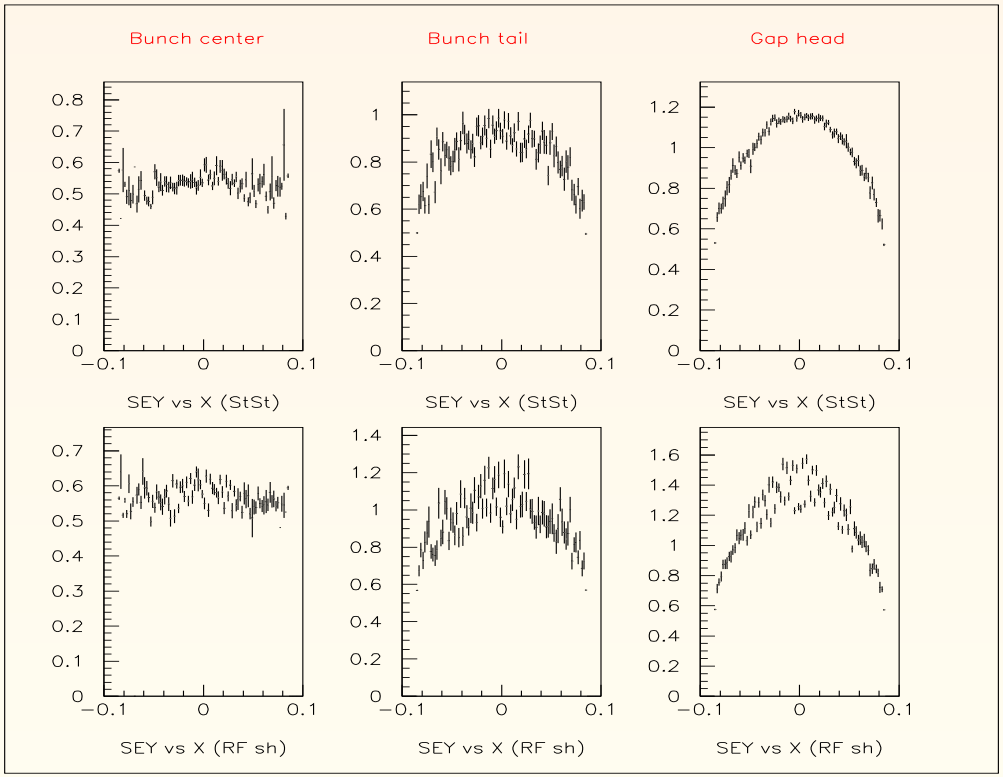
Stainless Steel ⟶

RF shields ⟶



Summary

- ECLOUD adapted for long bunch machines
- fairly good agreement of comparative study (FF) with results of POSINST simulations (Furman-Pivi, LBNL-52872)
- results very sensitive to longitudinal profile, intensity, transverse chamber size and geometry, low-energy electrons (different SEY curves)
- weakness of EC signal in ISIS FF due to large separation b/w bunches
- DF results currently limited by lack of realistic modelling of e-/wall interactions for RF shields geometry and lack of experimental inputs

Conclusions and outlook

- more realistic model of losses at injection (try integration with some 3D tracking code?)
- need experimental input for SEY modelling in presence of ceramic surfaces
- better understanding of chamber geometry (RF shields) and its influence on EC buildup
- study of instability
- pursue experimental program on ISIS (to restart October 2004 after DHRF upgrade)

RF shield closeup