Can electron multipacting explain the pressure rise in a cold bore superconducting undulator?

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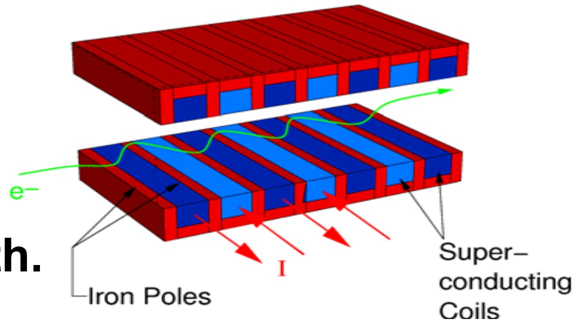
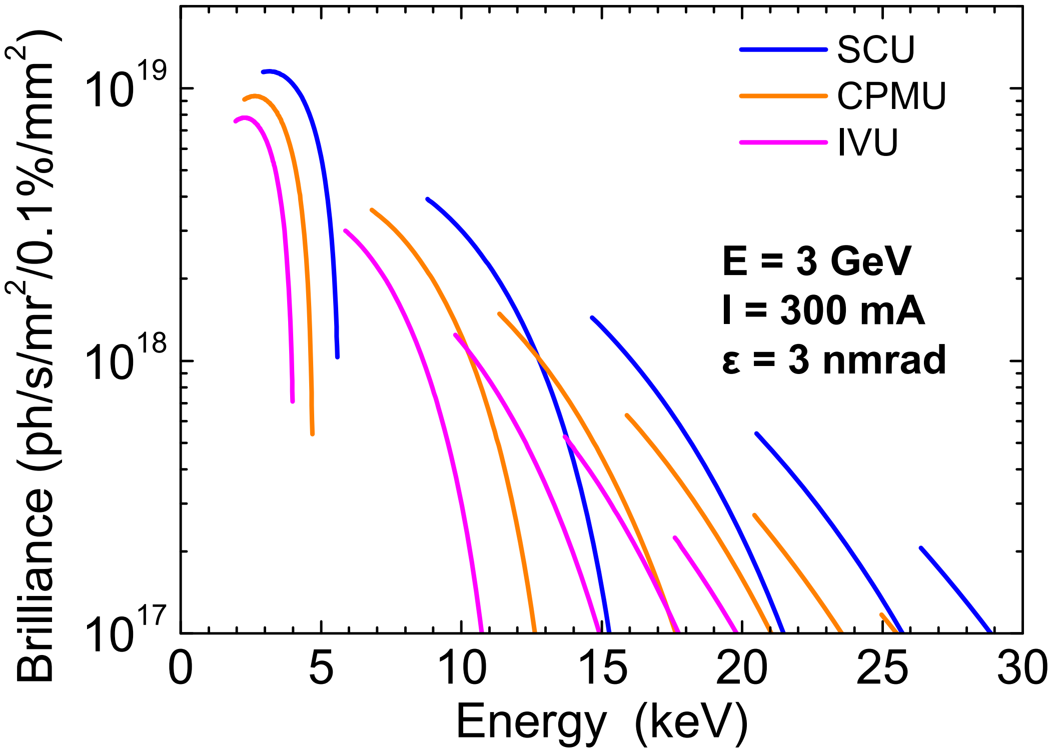
Outline

- Introduction
- Experimental setup
- Observations
- Model and input parameters
- Results: numerical solutions to the gas dynamic balance equations
- Conclusions and outlook

Introduction: Motivation and objective R&D of scIDs

Develop, manufacture, and test superconducting undulators to generate:
•Harder X-ray spectrum
•Higher brilliance X-ray beams
with respect to permanent magnet undulators.
Why?
Larger magnetic field strength for the same gap and period length.



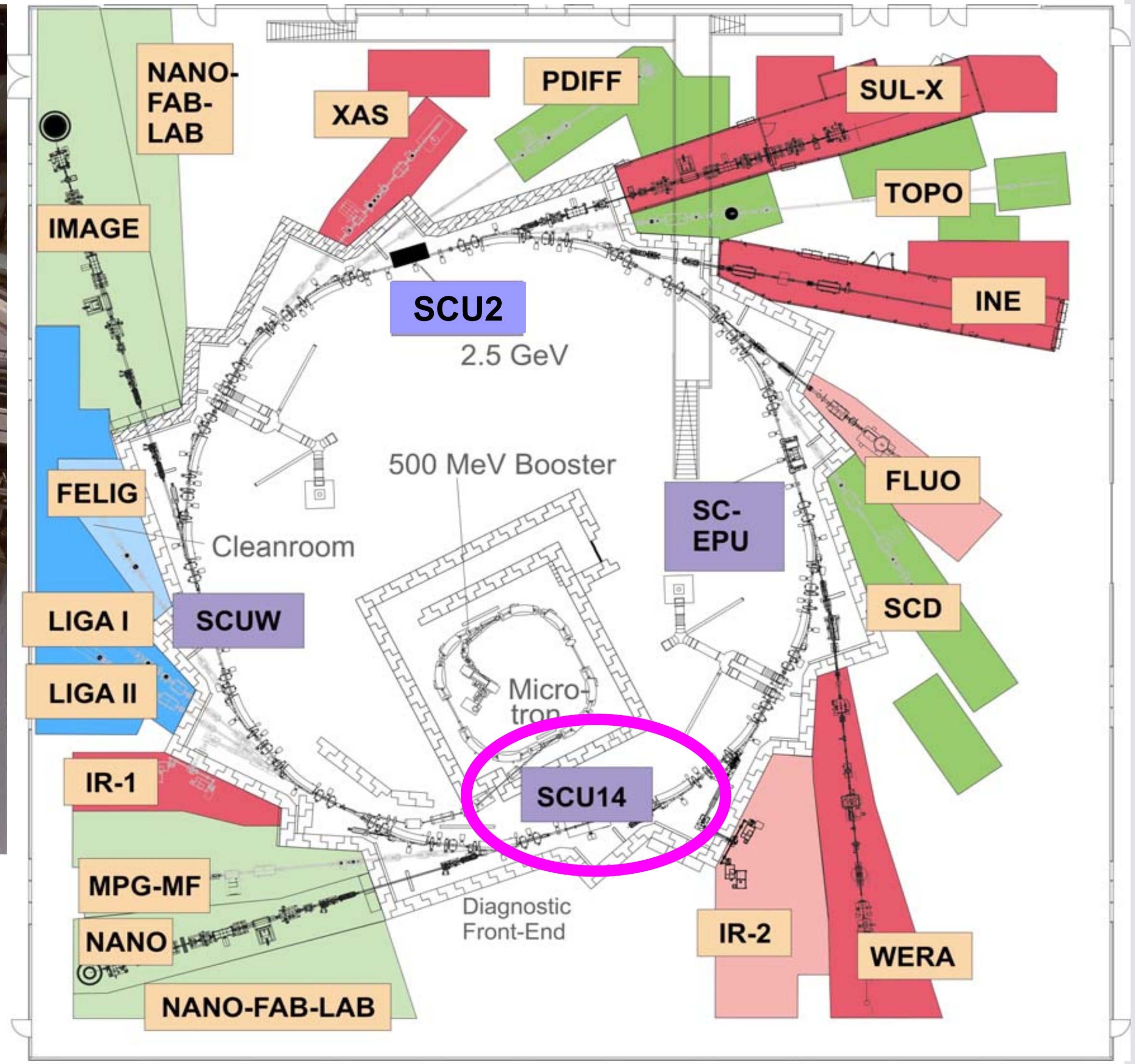


Same magnetic length=2 m and vacuum gap=6mm

	IVU	CPMU	SCU
λ_u (mm)	21	18	15
N	95	111	133
m. gap (mm)	6	6	7
B (T)	.75	.88	.98
K	1.47	1.48	1.37

A given photon energy can be reached by the SCU with lower order harmonic:
20 keV reached with the 5th harm. of SCU, with 7th harm. of CPMU and with the 9th harm. of IVU

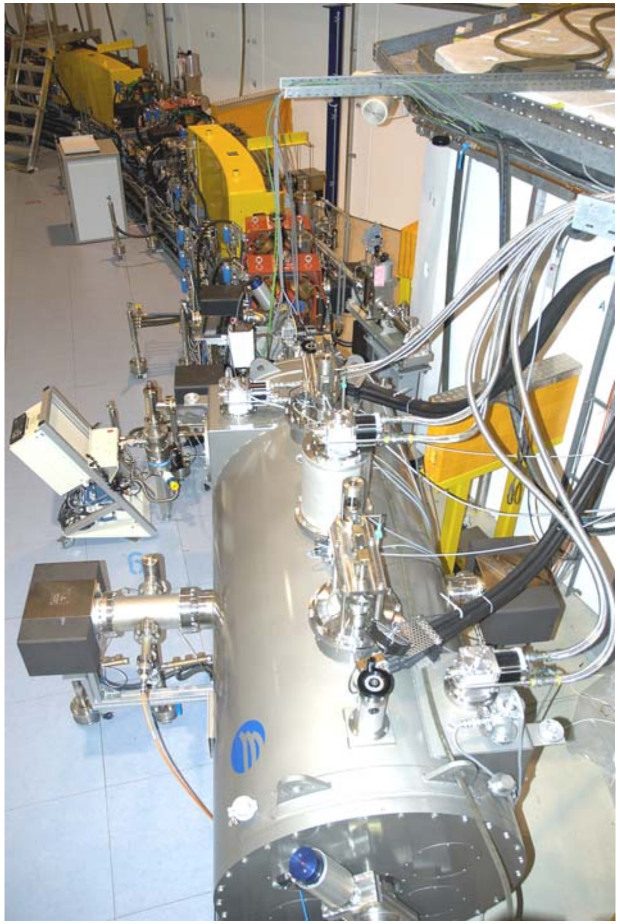
Introduction: ANKA



Energy:	**2.5 GeV**
Current:	**200 mA**
Circumference:	**110.4 m**

Introduction: Beam heat load studies

- **Cryogen free magnet**
- **Period length: 14 mm**
- **Length: 100 periods**
- **NbTi - coils**



0.4 W < Observed heat load (I_{beam}=100mA) < 1 W

Performance limited by too high beam heat load: beam heat load observed cannot be explained by synchrotron radiation from upstream bending and resistive wall heating.

	Calculated heat load (W) for I_{beam}=100mA
Synchrotron radiation from upstream bending	**< 0.063**
Resistive wall heating	**< 0.022**

Simple model of electron bombardment appears to be consistent with the beam heat load and pressure rise observed in the cold bore of the SCU14 at ANKA.

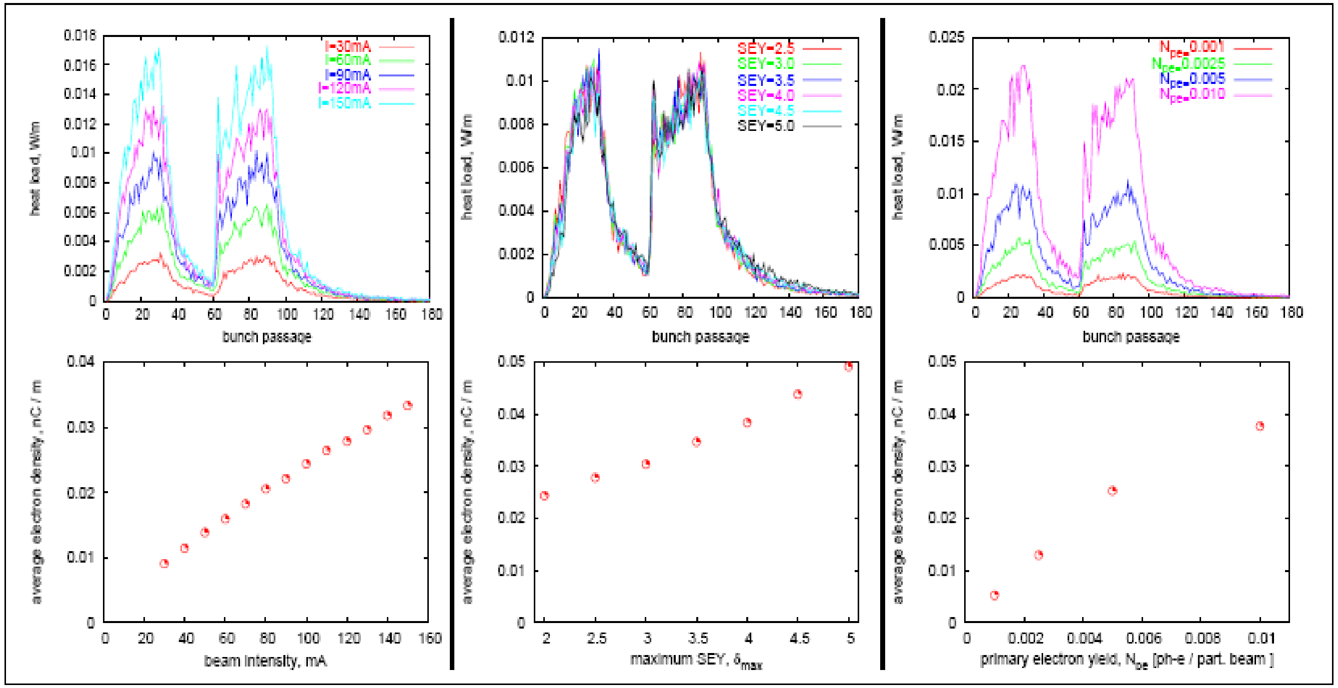
S. C. et al., PRSTAB2007

Introduction: Beam dynamics studies

Simulations with ECLOUD code for the SCU14 demonstrator at ANKA

Table 1: ECLOUD input parameters.

Parameter	ref. value	scan
beam intensity (mA)	100	30 - 150
bunches / train	32	...
# trains	2	...
bunch charge (e-)	3.5e9	(1 - 5.4)e9
bunch spacing (ns)	2	...
energy (GeV)	2.5	...
rev. period (ns)	360	...
hor beam size (mm)	0.840	...
ver beam size (mm)	0.063	...
long beam size (mm)	12	...
hor aperture (mm)	80	...
ver aperture (mm)	30	8 - 30
SEY at zero energy, δ_0	0.5	0.5 - 0.9
max SEY, δ_{max}	2.0	1.5 - 5
energy for δ_{max} (eV)	290	150 - 290
peak energy ph-e (eV)	7.0	...
energy ph-e, sigma (eV)	5.0	...
energy ph-e, sigma (eV)	1.8	...
primary e- yield, N_{pe} (ph-e/part. beam)	0.005	0.001- 0.01



The maximum heat load inferred from the ECLOUD simulations ~ 20mW.

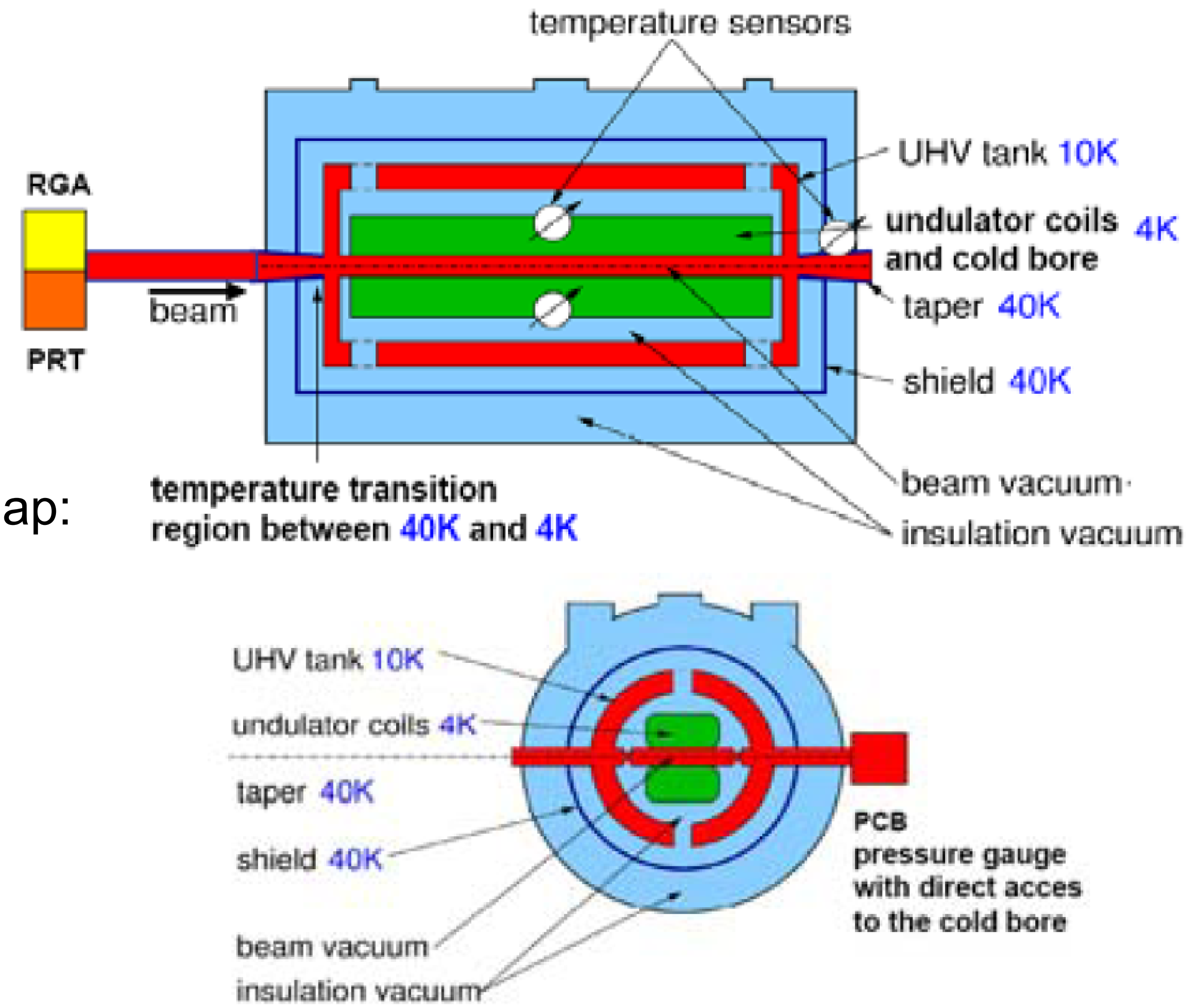
The calculated energy spectrum shows that there are barely no electrons above 40 eV.

U. Iriso et al., PAC09

Do the ecloud build up codes contain all the physics going on for e^- beams?

- APS change photoelectron model in POSINST (see talks of K. Harkay and L. Boon)
- ANKA include ion cloud potential in ECLOUD

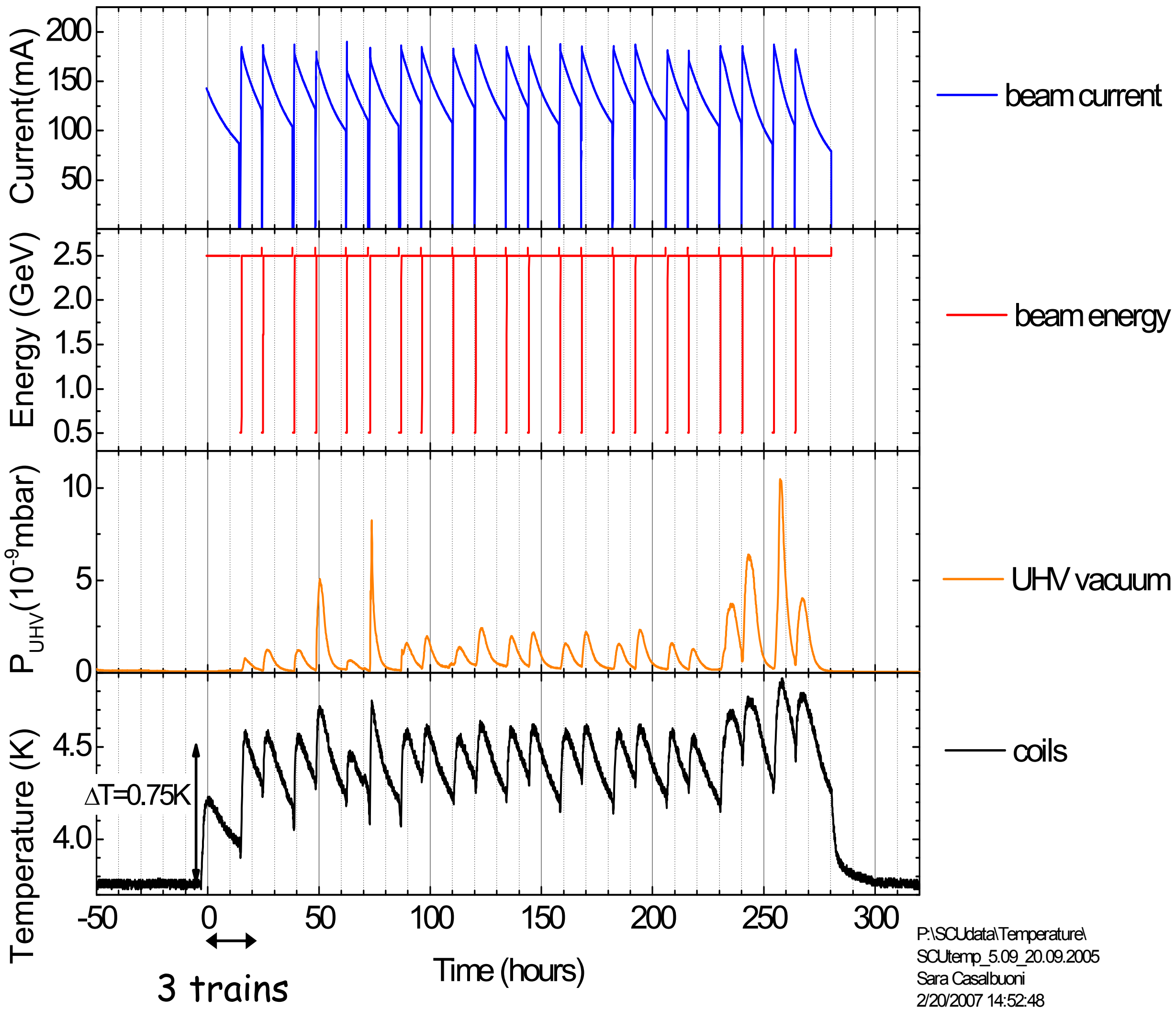
Experimental setup



Variable magnetic gap:
8mm,12mm, 16mm

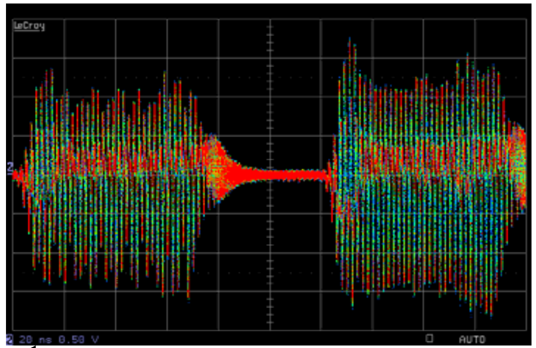
Beam stay clear:
29 mm

Observations:
Typical run for user operation



E_{beam} = 2.5 GeV; gap=29mm;
2 trains

1 train=32 bunches=64ns



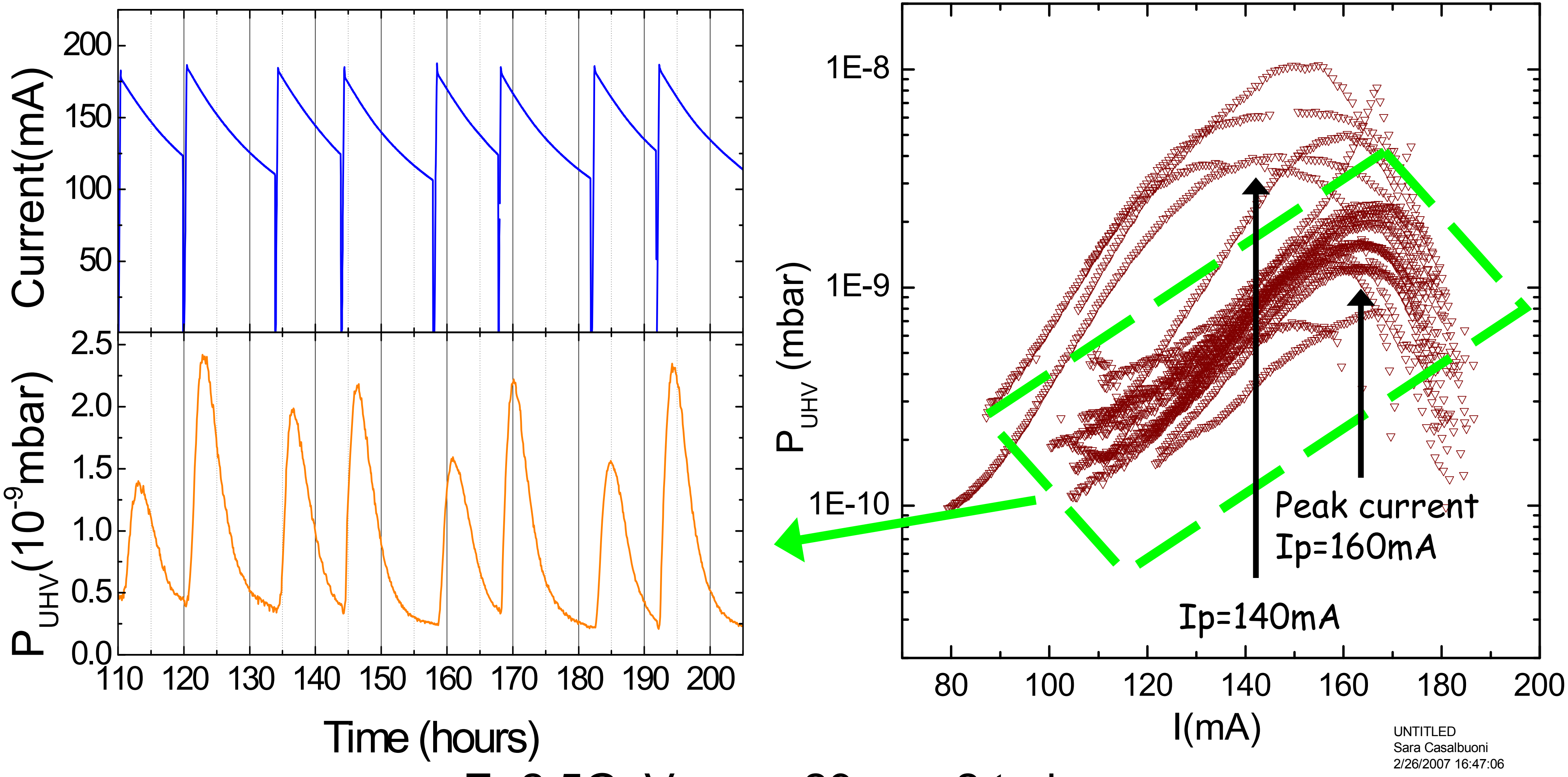
T_r=revolution time = 368ns

Pressure rise

Heat load coils

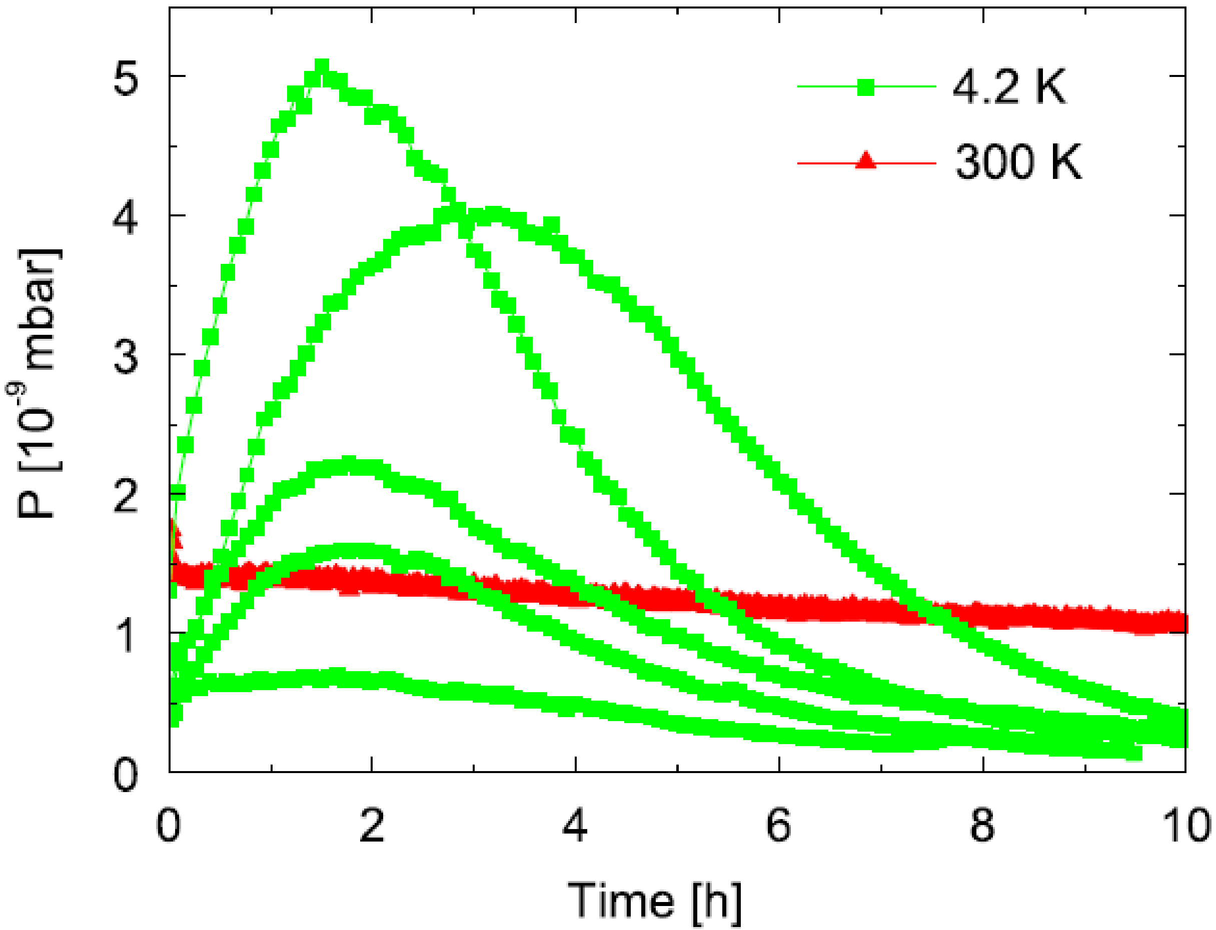
P_{beam} = 0.94±0.05 W

Observations: Pressure rise



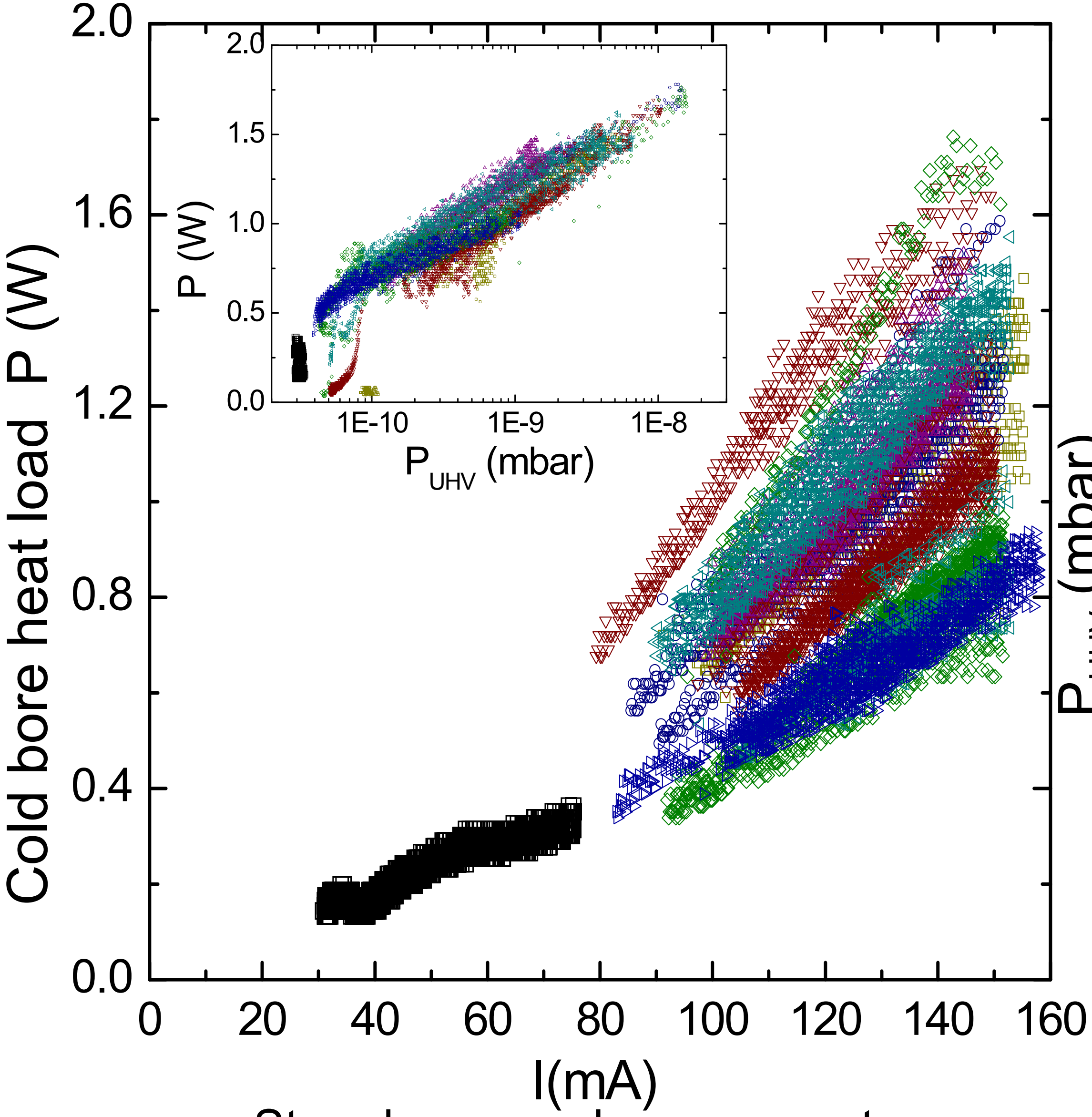
E=2.5GeV; gap=29mm; 2 trains

Observations: Pressure rise

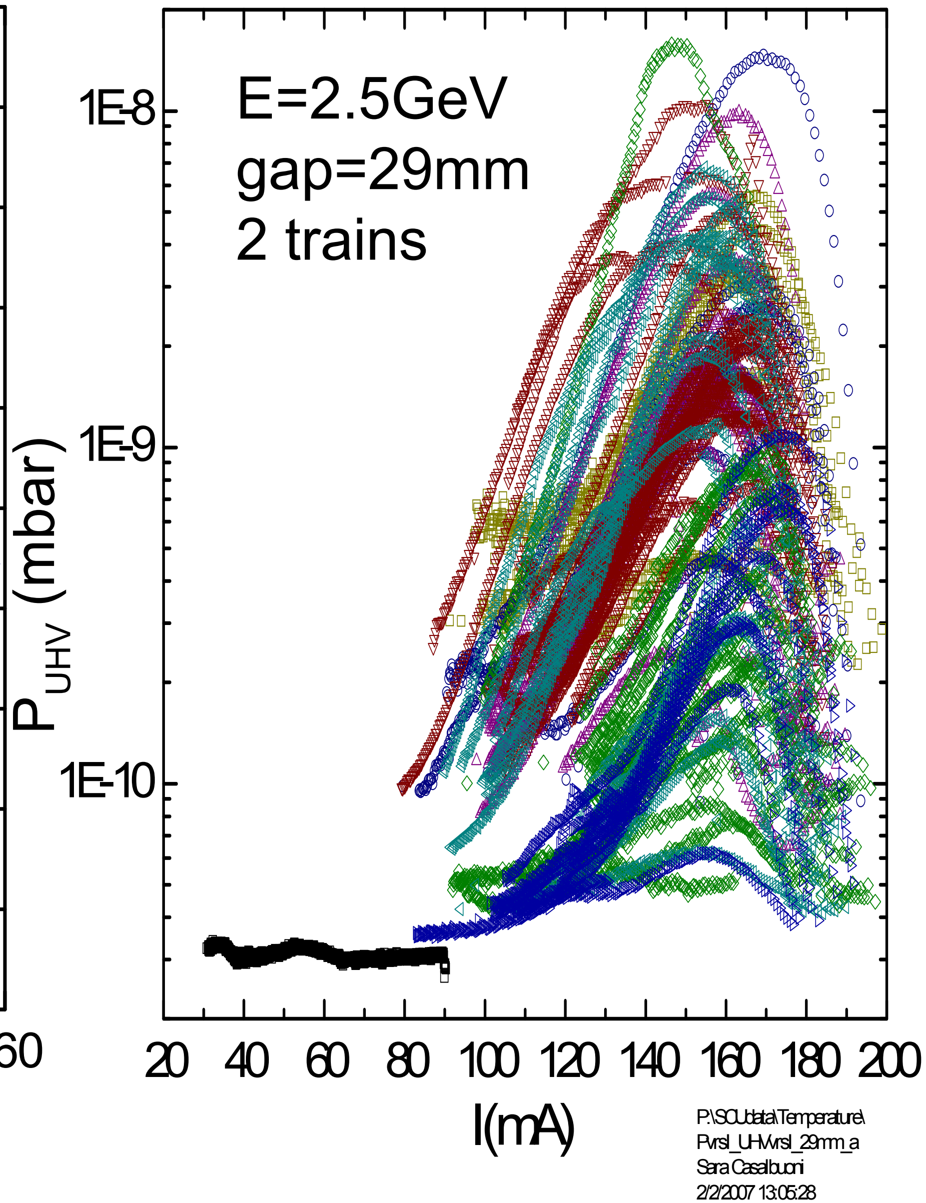


Comparison of the dynamic pressure in the cold bore with the one in the room temperature region. The static pressure in the cold bore (PCB) is about $2 \cdot 10^{-11}$ mbar and in the room temperature region (PRT) is about $2 \cdot 10^{-10}$ mbar.

Observations:
Variation of the beam heat load over half a year

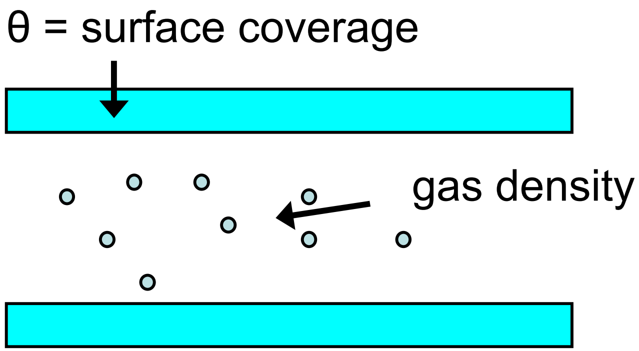


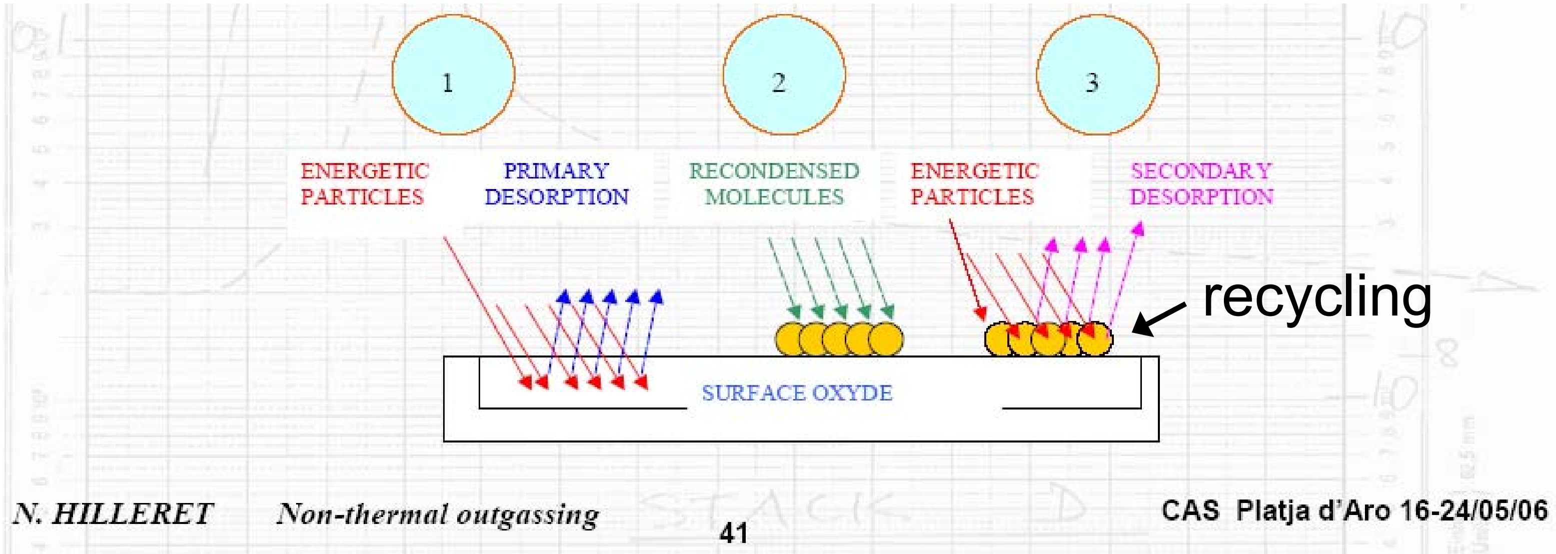
Stored average beam current



Orbit in all cases identical

Model and input parameters
Cryosorbed gas layer





Model and input parameters
Equations of gas dynamic balance

Molecules desorbed by impinging photons and electrons on the surface oxide and on the physisorbed gas layer

Molecules physisosorbed (pumped) by the cold surface

n = volume gas density

s = surface density of physisorbed gas

$$V\frac{dn}{dt} = \eta\dot{\Gamma} + \phi\dot{\Theta} + \eta'(s)\dot{\Gamma} + \phi'(s)\dot{\Theta} - \alpha\, S\left(n - n_e(s,T)\right)$$

$$A\frac{ds}{dt} = \alpha\, S\left(n - n_e(s,T)\right) - \eta'(s)\dot{\Gamma} - \phi'(s)\dot{\Theta}$$

W. C. Turner, PAC 1993;
I. R. Collins and O. B. Malyshev, LHC Project Report 274, 2001.

Molecules desorbed by impinging photons and electrons on the physisorbed gas layer

V = vacuum chamber volume

A = vacuum chamber wall area

ϕ, η = photon, e⁻ primary desorption yield, $\dot{\Theta}, \dot{\Gamma}$ = photon, e⁻ flux

ϕ', η' = photon, e⁻ secondary desorption yield (desorption of physisorbed molecules)

α = sticking coefficient

$S = \frac{1}{4}\bar{v}A$ = ideal wall pumping speed, $\bar{v}$ = average molecular velocity,

n_e = thermal equilibrium gas density

Model and input parameters: Assumptions

- Gas composition only H_2
- Neglected axial diffusion
- Neglected thermal outgassing
- $\phi' = \phi_0'(s/s_n)$ $s_n = 10^{18}$ molecules/m^2. **V.V. Anashin et al., J. Vac. Sci. Technol. 12, 2917 (1994).**
- $\eta' = \eta_0'(s/s_n)$ **H. Tratnik, Ph.D. thesis, Wien, 2005.**
- Photon flux $\dot{\Theta} = \dot{\Theta}_0 \exp(-t/\tau)$
- Electron flux $\dot{\Gamma} = \dot{\Gamma}_0 \exp(-t/\tau_{el})$

$$\dot{\Theta}_0 = 5 \cdot 10^{15} \text{ photons/s for gap} = 29 \text{ mm and } I = 150 \text{ mA}$$

$$\tau = \text{beam lifetime} = 22 \text{ hours}$$

$$\dot{\Gamma}_0 = 6 \cdot 10^{17} \text{ electrons/s for } P = 1\text{W and } \Delta W = 10\text{eV}$$

Model and input parameters: Obs. literature

The measurements of input parameters such as the photon and electron primary and secondary desorption yields, as well as the sticking coefficient, are quite challenging.

Several experiments have been performed to measure those parameters for a H_2 layer cryosorbed on a copper substrate at low temperatures and a wide range of values can be found in the literature.

The photon and electron primary and secondary desorption yields, as well as the sticking coefficient depend on the temperature, on the surface coverage, on the geometry (closed or open), on the photon, and on the electron energy distribution and dose.

The different experiments reported in the literature have been performed under a variety of conditions, and it is therefore difficult to compare them with each other and to extract the values needed for a consistent comparison with our experimental situation.

Model and input parameters: Obs. literature

$$2\cdot 10^{-4} \le \phi \le 5\cdot 10^{-2}$$

$$5\cdot 10^{-2} \le \frac{\phi'}{\alpha} \le 8 \qquad \phi' \propto s$$

For a copper electroplated stainless steel liner at 4.2 K in a quasiclosed geometry.
V.V. Anashin et al., J. Vac. Sci. Technol. 12, 2917 (1994).

$$0.25 \le \alpha \le 0.6 \qquad \text{for } s_m = 3\cdot 10^{19}\,\text{molecules}/\text{m}^2$$

H. Tratnik, Ph.D. thesis, Wien, 2005.

$$50 \le \eta + \eta' \le 2000$$

$$\eta + \eta' \propto s$$

For 300 eV electrons has been measured as a function of H_2 coverage at about 2 K on the LHC beam screen.

$$10^{-4} \le \frac{\eta + \eta'}{\alpha} \le 4$$

For 10eV electrons and an electron dose > $2\cdot 10^{24}$ electrons/m^2 on the cold bore SCU14 ANKA. S.C. et al., PRSTAB2007

$$10^{-2} \le \frac{\eta + \eta'}{\alpha} \le 30$$

For 100eV electrons and an electron dose from $2\cdot 10^{23}$ to 10^{21} electrons/m^2 at 12 K on the COLDDEX LHC beam screen.
V. Baglin and B. Jenninger, LHC Project Report No. 721, 2004.

$$s_0 < 1.5\cdot 10^{19}\,\text{molecules}/\text{m}^2$$

By the measured adsorption isotherms on copper plated stainless steel at 4.2 K. E. Wallèn, J. Vac. Sci. Technol. 14, 2916 (1996).

Results without electron desorption

At t_{max} $\frac{dn}{dt} = 0$ $G = \frac{1}{k_B\sqrt{TT_{RT}}}$

$$\exp(-t_{max}/\tau) = \frac{\alpha G S \Delta P}{(\phi + \phi')\dot{\Theta}_0}$$

Not satisfied
Because:

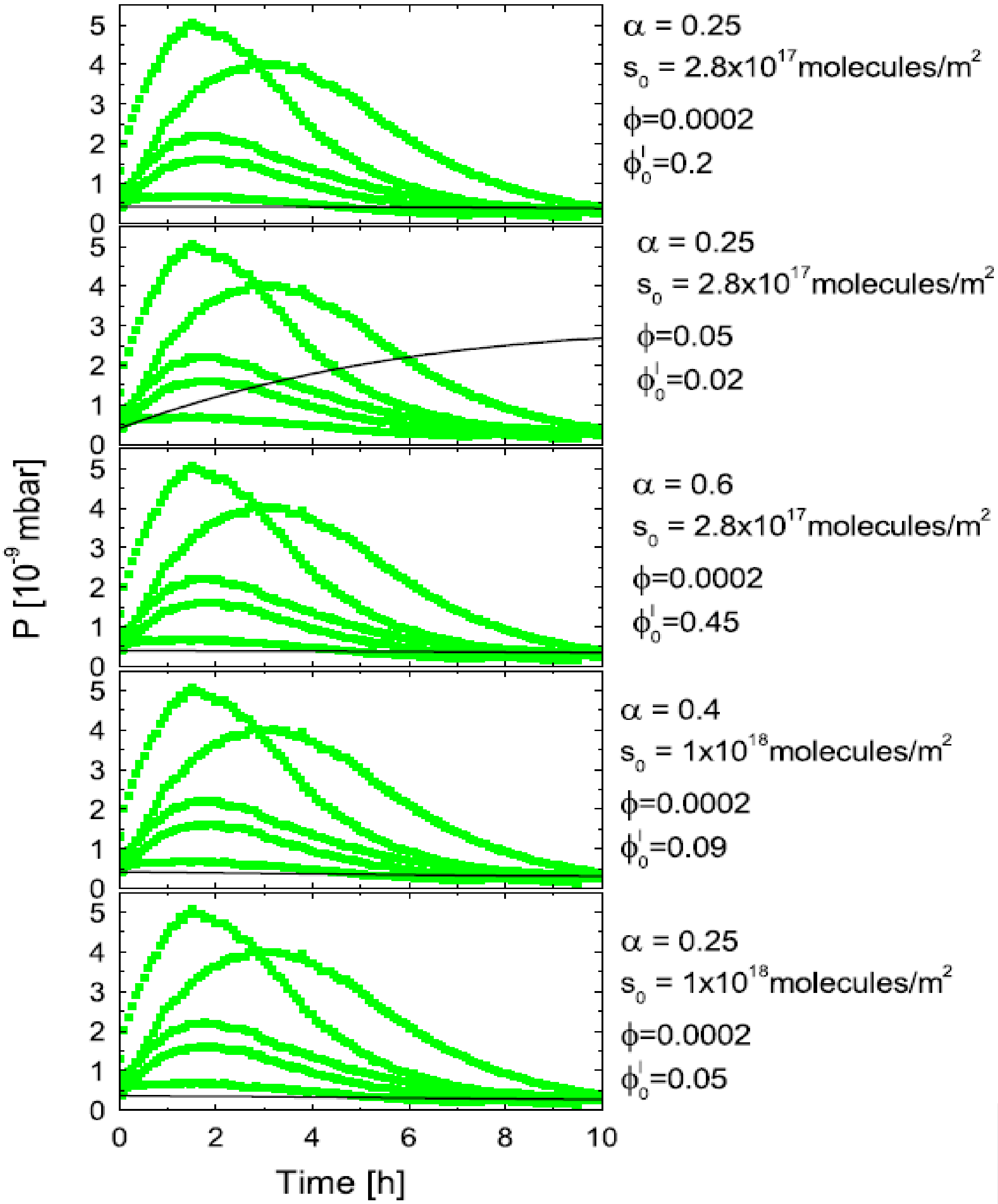
From obs. $\Delta P \approx 5 \cdot 10^{-9}$ mbar

$$0.05 \le \frac{\phi + \phi'}{\alpha} \le 8.2$$

$t_{max} \approx 2$hours $\tau \approx 2$hours

$$\frac{\alpha S G \Delta P}{(\phi + \phi')\dot{\Theta}_0} \le 0.02$$

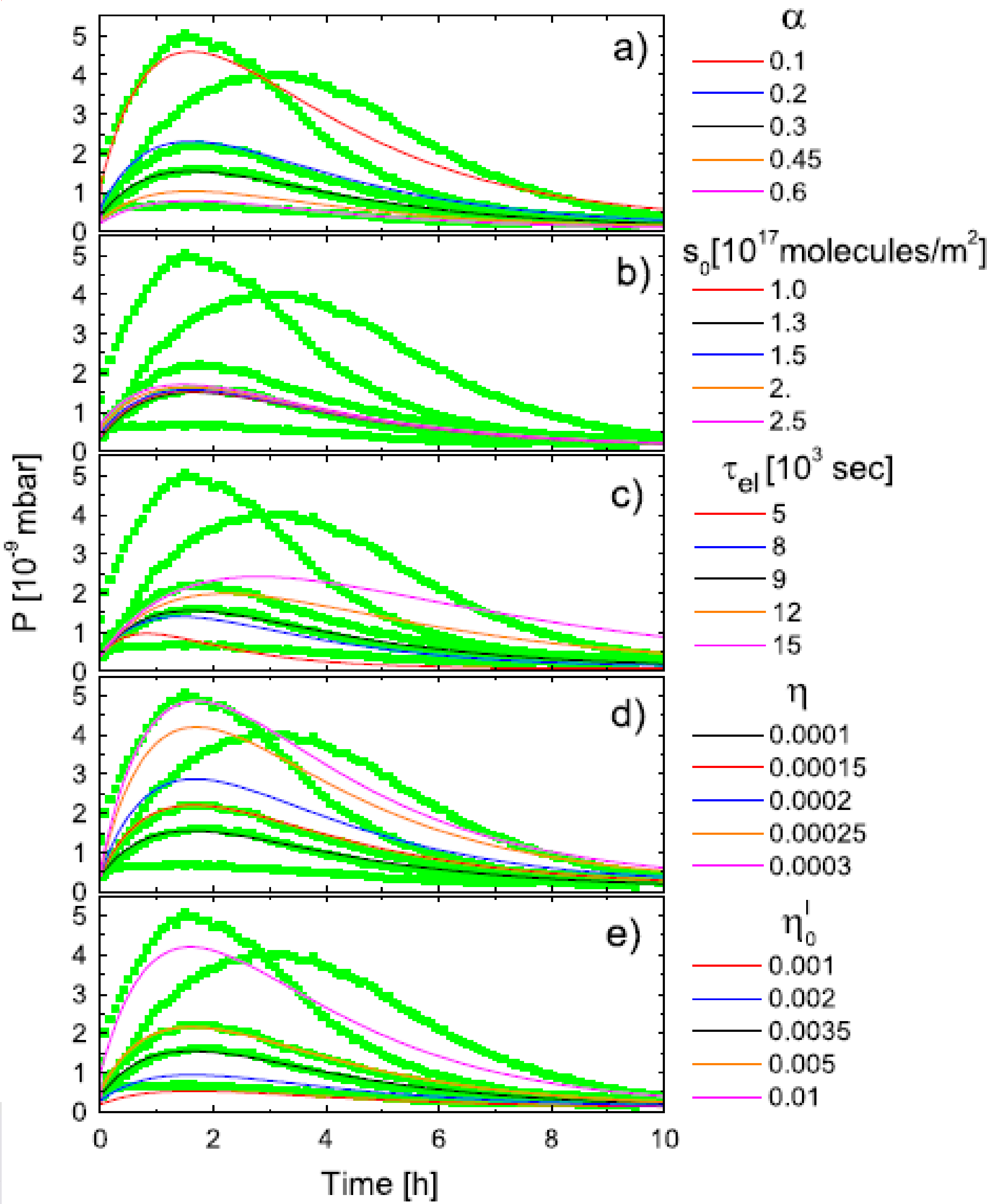
$$\exp(-t_{max}/\tau) \approx 1$$



Results: Values used as input parameters

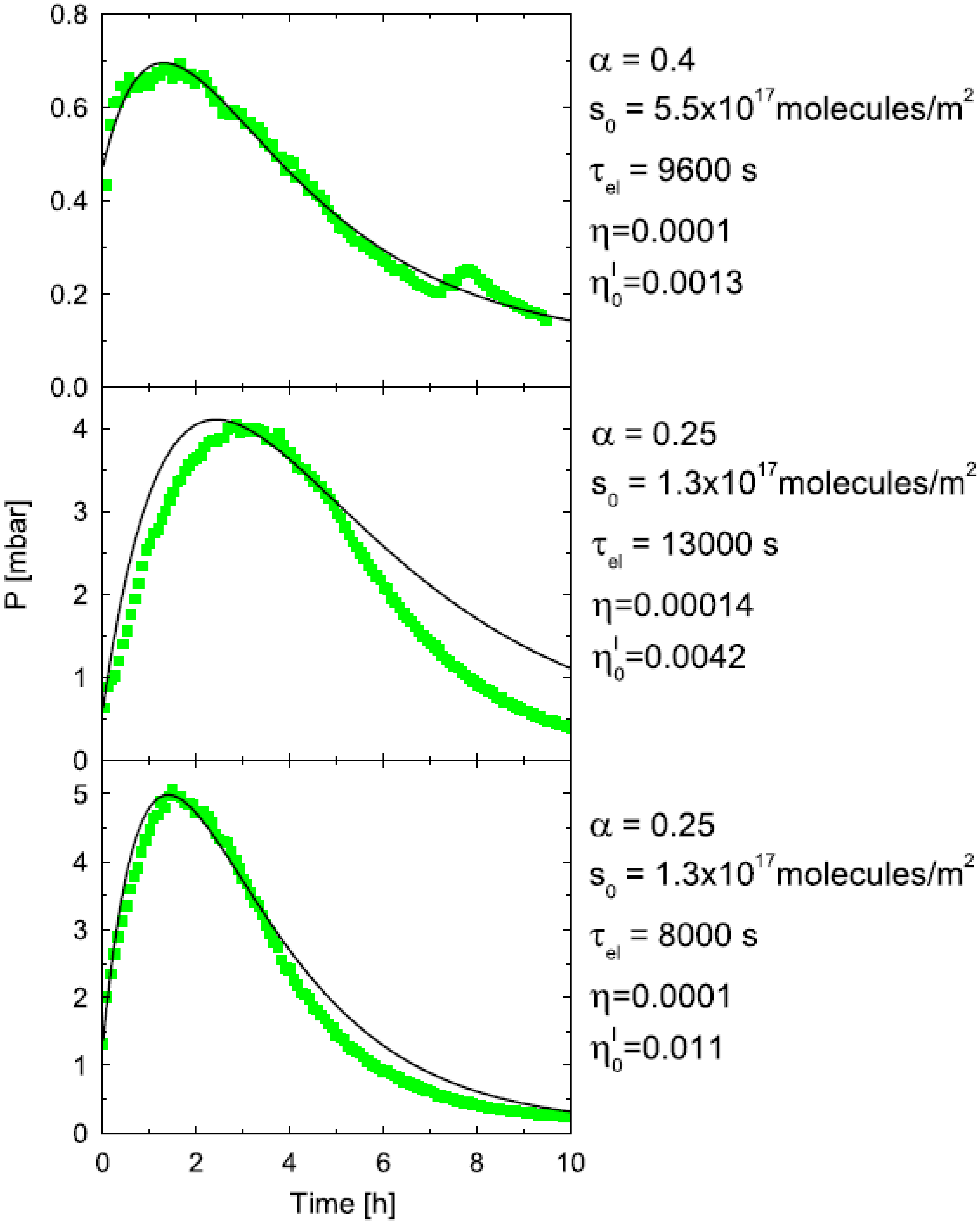
	min	max	Fixed
s_0 (10^{17} molecules/m^2)	1	2.5	1.3
α	0.1	0.6	0.3
ϕ			0.0002
ϕ'_0			0.01
η	0.0001	0.0003	0.0001
η'_0	0.001	0.01	0.0035
$\dot{\Theta}_0$ (10^{15} photons/s)			5
$\dot{\Gamma}_0$ (10^{17} electrons/s)			6
τ (s)			80 000
τ_{el} (s)	5000	15 000	9000

Results



P [10^-9 mbar]
Time [h]
a)
b)
c)
d)
e)
α
0.1
0.2
0.3
0.45
0.6
s0[10^17 molecules/m^2]
1.0
1.3
1.5
2.
2.5
τel [10^3 sec]
5
8
9
12
15
η
0.0001
0.00015
0.0002
0.00025
0.0003
η'0
0.001
0.002
0.0035
0.005
0.01

Results
with electron desorption



Conclusion:
Taking into account the contribution of molecules desorbed by electrons, it is possible to reproduce the observed behavior of the pressure by varying the input parameters in the range of values found in the literature.

Results:

Electron flux as a function of the average beam current

The measurements are well reproduced for $8000\ \mathrm{s} \le \tau_{el} \le 13000\ \mathrm{s}$

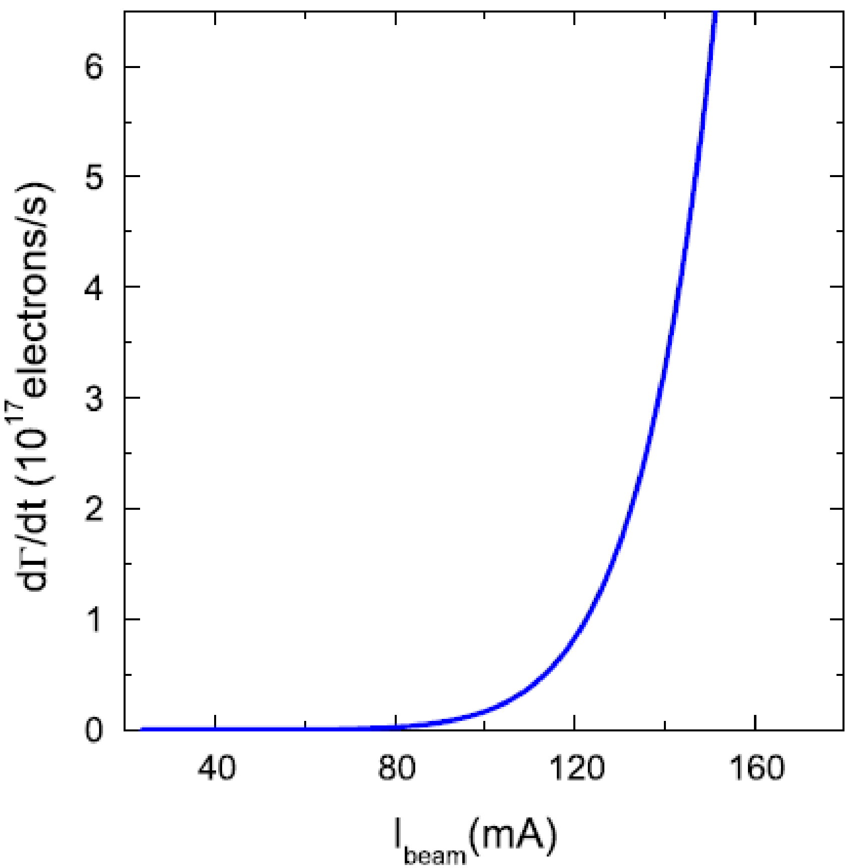
$\tau \approx 80000\ \mathrm{s}$

$$I_b = I_{b0} \exp(-t/\tau), \qquad \dot{\Gamma} = \dot{\Gamma}_0 \exp(-t/\tau_{\mathrm{el}}),$$

where I_{b0} is I_b at $t = 0$, it follows that

$$\dot{\Gamma} = \dot{\Gamma}_0 \exp[\tau/\tau_{\mathrm{el}} \ln(I_b/I_{b0})] = \dot{\Gamma}_0 \left(\frac{I_b}{I_{b0}}\right)^{\tau/\tau_{\mathrm{el}}}.$$

The behavior of the electron flux as a function of the beam current displays a growth much faster than linear showing an avalanche effect, which has often been described in the literature as multipacting



Conclusions I

•We have shown that in order to reproduce the pressure measurements it is necessary to include electron stimulated desorption with $\tau_{el} < \tau$. => This implies a very fast avalanche like growth of the electron flux as a function of beam current suggesting electron multipacting.

•Considering the simplified assumptions, for example, the gas made by H_2 only and the large measurement uncertainties, the agreement between simulations and measurements is satisfying.

Outllok I

•COLDDIAG…see talk of S. Gerstl

Conclusions II

- **Simple model of electron bombardment appears to be consistent with the beam heat load and pressure rise observed in the cold bore of the SCU14 at ANKA.**

- **A common cause of electron bombardment is the buildup of an electron cloud, which strongly depends on the chamber surface properties that are only partly been measured for a cryosorbed gas layer.**

- **Heat load from simulations with ECLOUD code is about only order of magnitude lower than the measurements.**

Outlook II

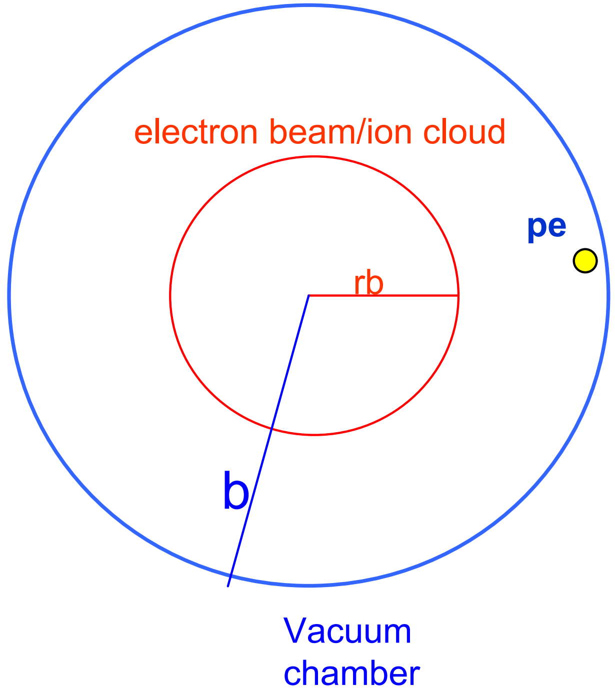
- **Beam dynamics studies including ion cloud effect in the ECLOUD code ongoing.**

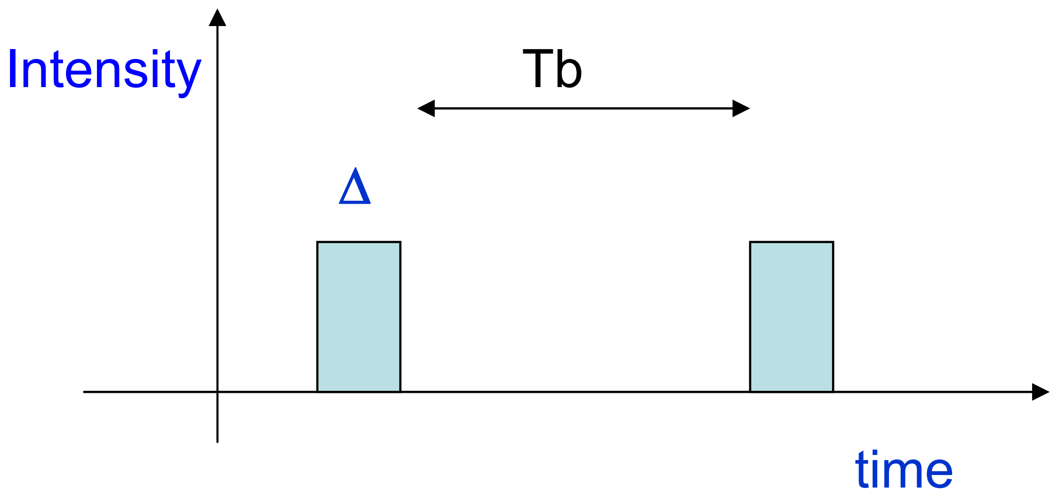
Outlook II
Beam dynamics studies

We have recently analyzed the question: **Can the presence of a *smooth ion background* (i.e. a partially neutralized electron beam) change the photo-electron dynamics so that the photo electrons can receive a significant amount of kinetic energy from the ion cloud + electron beam system ?**

Photo-electron dynamics: A simple Model

I0 = average beam current

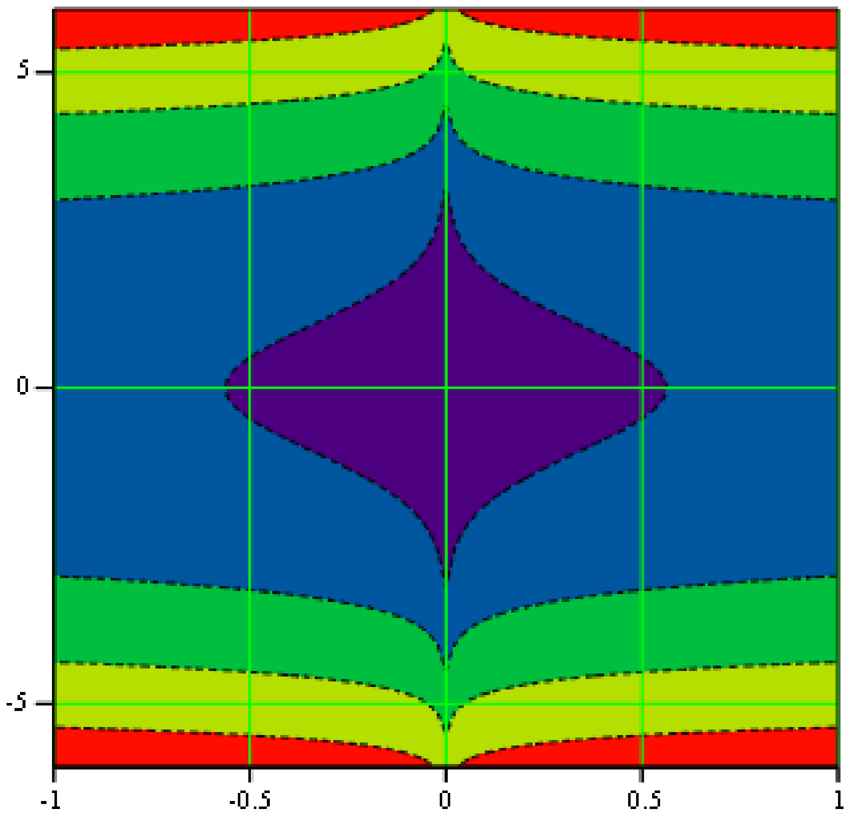




Courtesy P. Tavares

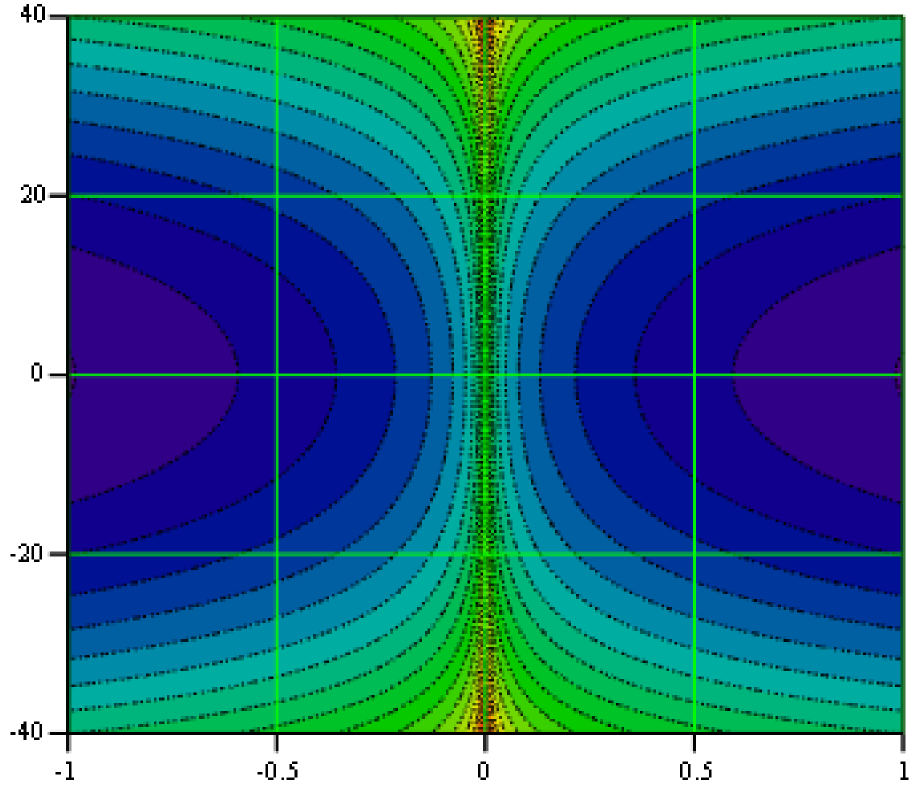
Outlook II

Dynamics of Photo-electrons
General Properties of the Solutions



H_{IC}

ION CLOUD



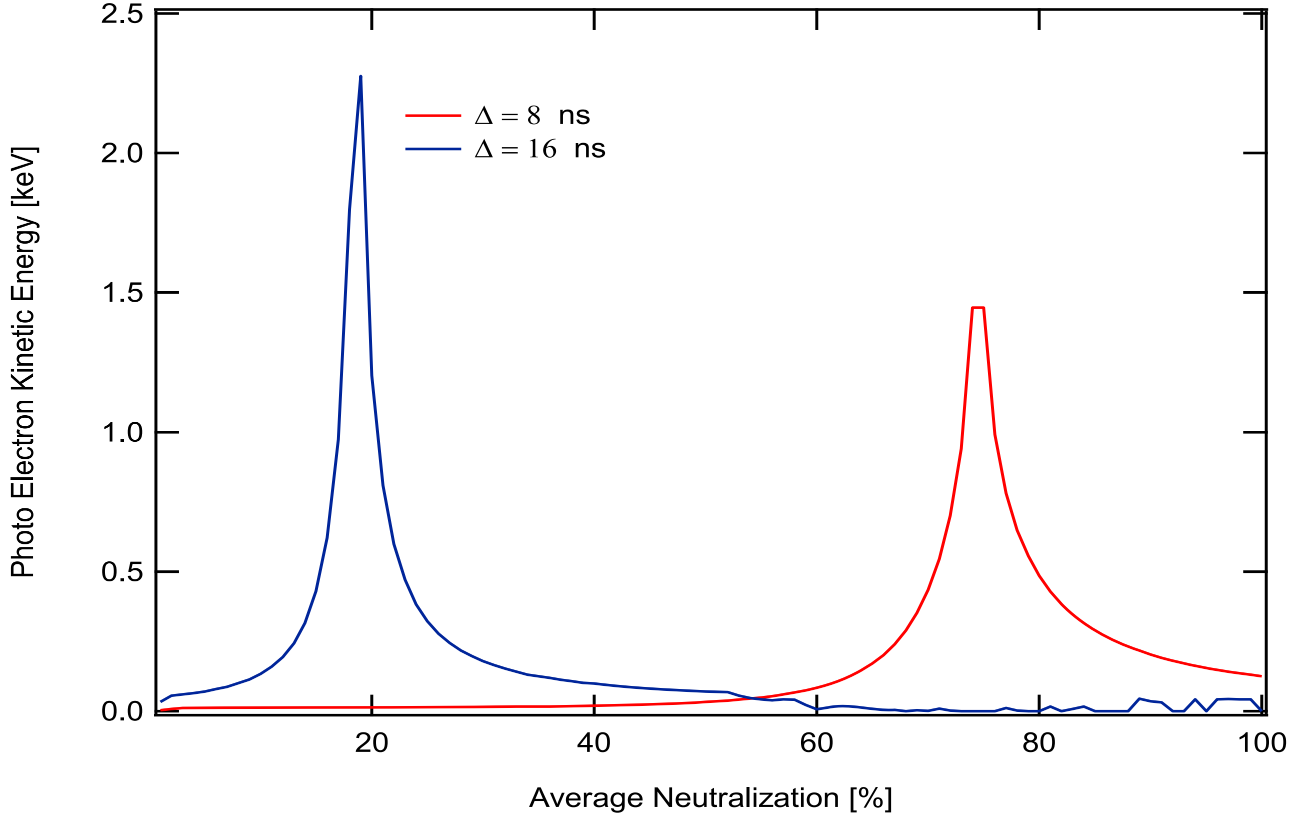
H_{BP}

ELECTRON BUNCH

Courtesy P. Tavares

Outlook II

Significant Energy gain may be possible !



More Detailed Calculations under way…..
Next step:
Inclusion of ion cloud potential in ECLOUD code (S. Gerstl)

Courtesy P. Tavares

Thanks to

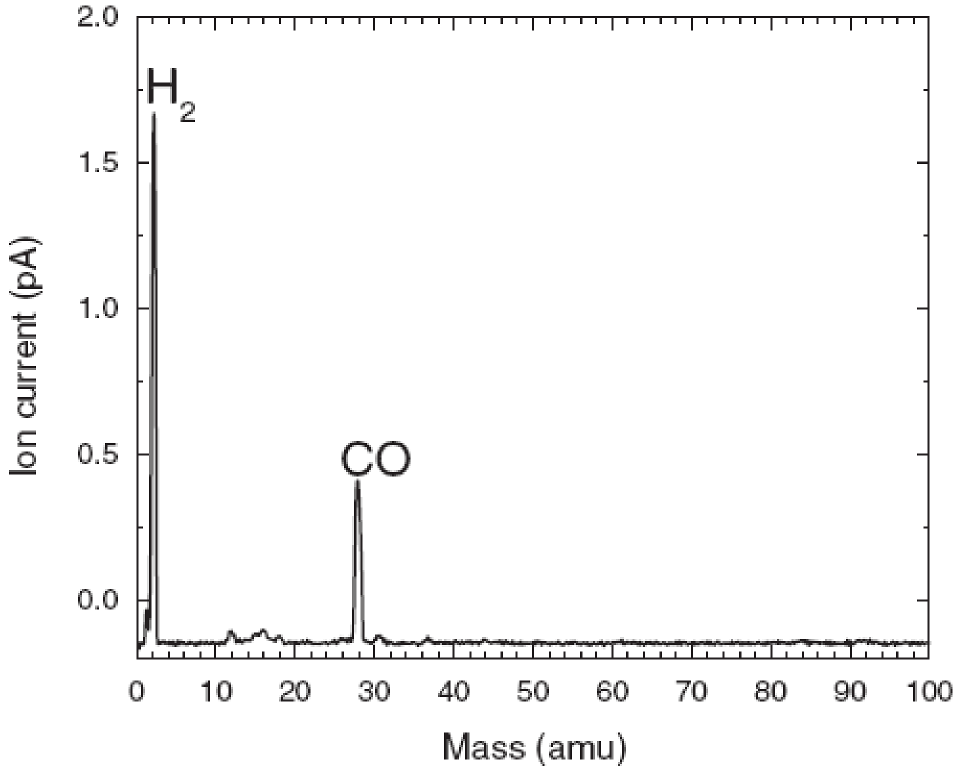
Frank Zimmermann for useful discussions in the initial phase of this project.

And to you all for your attention!

Backup slides

Model and input parameters: Assumptions

- Gas composition only H_2



Measured with RGA at RT when undulator cold.

Warming up the undulator to RT, RGA shows: H_2, CO, CO_2, and H_{2O}, indicating that the cryosorbed gas layer might have a more complex gas composition than simply H_2. However, H_2 is the only gas among the ones mentioned above that has a non-negligible vapor pressure at 4–20 K and we see that this is the main gas component measured when the undulator is cold.

Model and input parameters: Assumptions

- Neglected axial diffusion $$u\frac{d^2n}{dz^2} << \alpha\, S(n - n_e(s,T))$$

$$\text{vacuum conductance per unit length} = u = A_c D$$

Axial diffusion can be neglected when

$$A_c D / L^2 << S\alpha \quad => \frac{8}{3}\frac{A_c^2}{AL^2} << \alpha$$

W. C. Turner, Proceedings of PAC 1993,Washington, D.C. 2 (IEEE, Piscataway, NJ, 1993)

$$S = \text{ideal wall pumping speed} = A\,\bar{\upsilon}/4$$

$$D = 2A_c\,\bar{\upsilon}/3$$

$$\bar{\upsilon} = \text{mean molecular speed}$$

$$A_c = \text{area cross section vacuum chamber} = 0.266\,m^2$$

$$A = \text{area undulator vacuum chamber} = 0.266\,m^2$$

$$L = \text{length undulator vacuum chamber} = 1.4m$$

$$\alpha = \text{sticking coefficient} < 0.02$$

S. Andersson et al., Phys. Rev. B **40**, 8146 (1989)
V.V. Anashin *et al.*, J. Vac. Sci. Technol. **12**, 1663 (1994)