Vacuum System and Synchrotron Radiation in the Very Large Hadron Collider - VLHC

Mauro Pivi

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Very Large Hadron Collider

Vacuum System and Synchrotron Radiation in the VLHC

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    - electron-cloud
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VLHC parameters	symbol	LF	HF
energy at collision	E, *TeV*	50	
dipole field at 50 TeV	B, *T*	1.8	12.6
circumference	C, *km*	646	104
number of particles per bunch	N_b	0.94 X 10^{10}	0.5 X 10^{10}
total beam current	I, *mA*	90	48
beta function	β, *m*	255	
normalized emittance	ε_n, π *mm-mrad*	1	
vacuum chamber dimensions	r_w, *cm*	0.75 X 1.5	1.65
beam tube temperature	T_w, ^oK	~294	~15-20
pp collision IP lifetime	τ_{pp}, *hrs*	130	32

Synchrotron Radiation related parameters

Parameter	symbol	LF	HF
photon flux	Γ', *ph/m-sec*	0.34 X 10^{16}	1.26 X 10^{16}
critical energy	*Ec, keV*	0.48	3.4
power deposited per meter	$P/2\pi\rho$, *W/m*	0.082	2.12
total power	*P, kW*	47.5	176.6
energy loss per turn	ΔE, *MeV/turn*	0.53	3.7
radiation damping time	τ_D, *hrs*	114	2.6

Desorption mechanisms in particle accelerators

Three main desorption mechanisms (besides thermal desorption):

- photon stimulated desorption (PSD)
- electron (cloud) stimulated desorption (ESD)
- ion-induced desorption

Desorption mechanisms in particle accelerators (1/3):

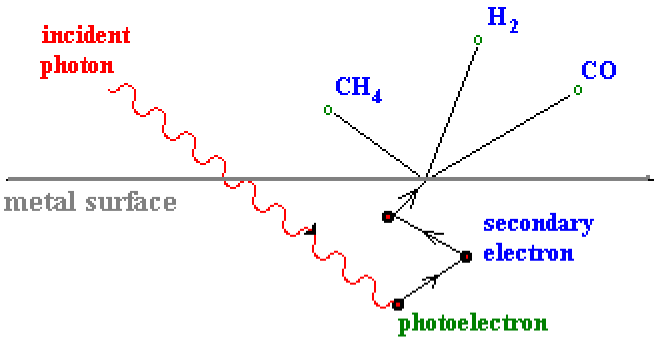
Photon Stimulated Desorption (PSD)

total desorption coefficient

$$\text{Molecules per photon} = (\eta_1 + \eta')\,\dot{\Gamma} = \eta\,\dot{\Gamma}$$

phisisorbed molecules per photon

molecules tightly-bound per photon



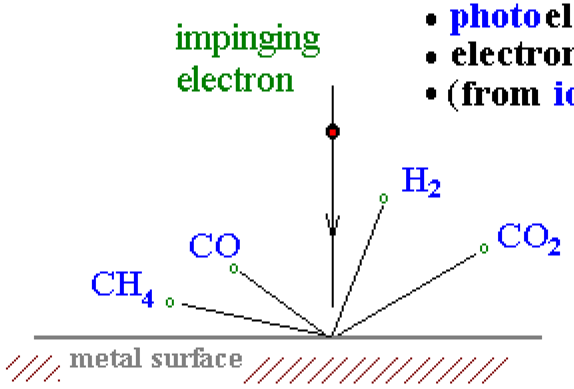
Photon stimulated desorption (PSD) has been attributed to a two-step process [Fisher, Mack, Bernardini, Malter]:

1) photons produce photoelectrons and secondary electrons

2) secondary electrons excite strongly-bound molecules, which may desorb spontaneously

Desorption mechanisms in particle accelerators (2/3):

Electron Stimulated Desorption (ESD)



- **photoelectrons**
- **electron cloud**
- **(from ion impact)**

Photoelectric yield

electron production from ion impact

electron cloud

$$\text{Molecules per electron} = (\eta_{e1} + \eta'_{e})[\dot{\Gamma} Y' + \frac{I\sigma_{pi}}{e} nY_i]\xi(I) = \eta_e[\dot{\Gamma} Y' + \frac{I\sigma_{pi}}{e} nY_i]\xi(I)$$

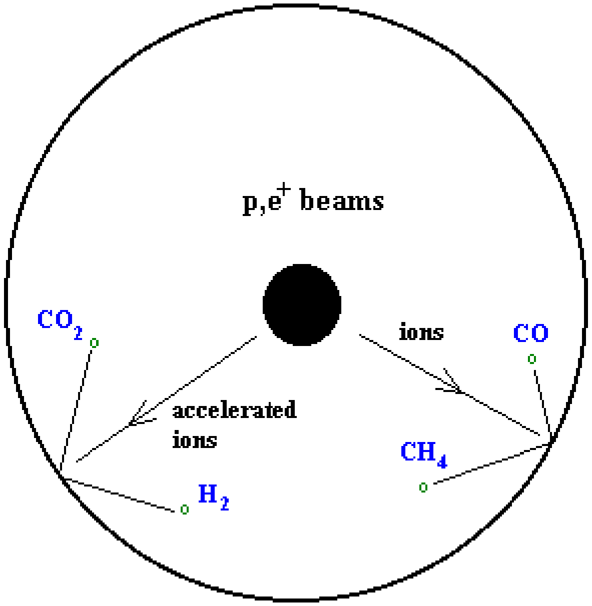
Electron desorption yield for tightly-bound molecules

Electron desorption yield for phisisorbed molecules

total desorption coefficient

Desorption mechanisms in particle accelerators (3/3):

Ion Induced Desorption (ESD)



Molecular density in the chamber

$$\text{Molecules per ion} = (\eta_{i1} + \eta'_{i})\frac{I\sigma_{pi}}{e}n = \eta_{i}\frac{I\sigma_{pi}}{e}n$$

total desorption coefficient

molecules tightly-bound per ion

phisisorbed molecules per ion

Model equations for vacuum stability in a cryosorbing beam tube exposed to Synchrotron Radiation, Ion and e- bombardment

equation for
volume density

$$(1)\quad V\frac{\partial n}{\partial t}=(\eta_1+\eta')\dot{\Gamma}+(\eta_{e1}+\eta'_e)[\dot{\Gamma}Y'+\frac{I\sigma_{pi}}{e}nY_i]\xi(I)+(\eta_{i1}+\eta'_i)\frac{I\sigma_{pi}}{e}n+$$

$$+\frac{A_w s}{\tau_w^t}-\sigma_w S_w n-Sn+A_c D\frac{\partial^2 n}{\partial s^2}$$

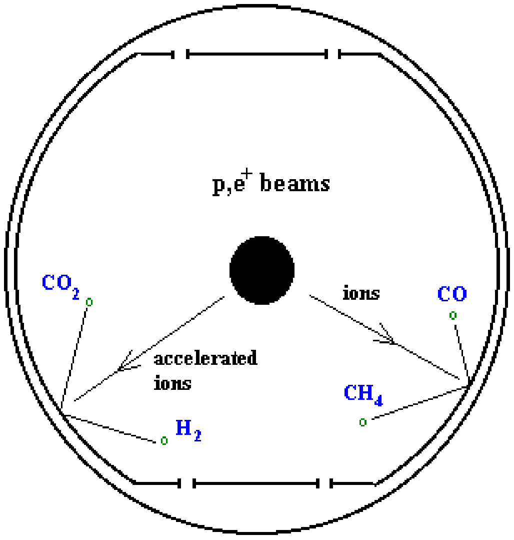
equation for
surface density

$$(2)\qquad A_w\frac{\partial s}{\partial t}=\eta_2\dot{\Gamma}+\sigma_w S_w n-\frac{A_w s}{\tau_w^t}-\eta'\dot{\Gamma}-\eta'_i\frac{I\sigma_{pi}}{e}n-\eta'_e\dot{\Gamma}_{el}$$

where V is the chamber volume, n is the molecular density, η_1 *the desorption coefficient for tightly bound molecules (the suffix "i" and "e" are for ion and electron),* $\eta_{2,}$ *prod. phisis. molec per photon,* η' *the desorption coefficient for phisisorbed molecules,* Γ *the photon flux,* ξ *the contribution given by the electron cloud, Y' the photoelectric yield,* Y_i *the yield for electron production from ion impact on the surface,* σ_{pi} *the cross section for ion production,* A_w *the desorbed area, s thesurface density (monolayer) ,* τ^t_w *the sojourn time,* σ_w *the sticking coefficient,* S_w *the ideal wall pumping speed (v*A_w*/4),* A_c *the cross section chamber area, D the Knudseen diffusion coefficient,* $\eta_{2,}$ *prod. phisis. molec per photon.*

Ion induced desorption instability

Ion desorption term in equation (1) is linearly dependent with the molecular density *n*, and since the process is regenerative this may lead to the so called ion-induced desorption instability (ion pressure bump instability).



ex. solving eq. (1) for a *long* 4.2 ^{o}K beam tube without a liner:

$$(\eta_{i1}+\eta'_i)I < \frac{e}{\sigma_{pi}}\sigma_w S_w$$

or with a liner:

beam intensity threshold

$$\eta_{i1} I < \frac{e}{\sigma_{pi}} S$$

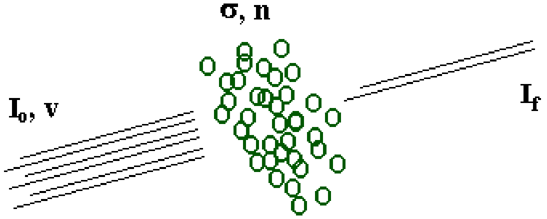
→ *for VLHC, HF I_{thresh}~12.4 Amp.*

(η_{i1}=3, S=42 l/m-s)

- Up to now, the ISR (CERN) has been the only machine where the ion-induced pressure instability has been observed

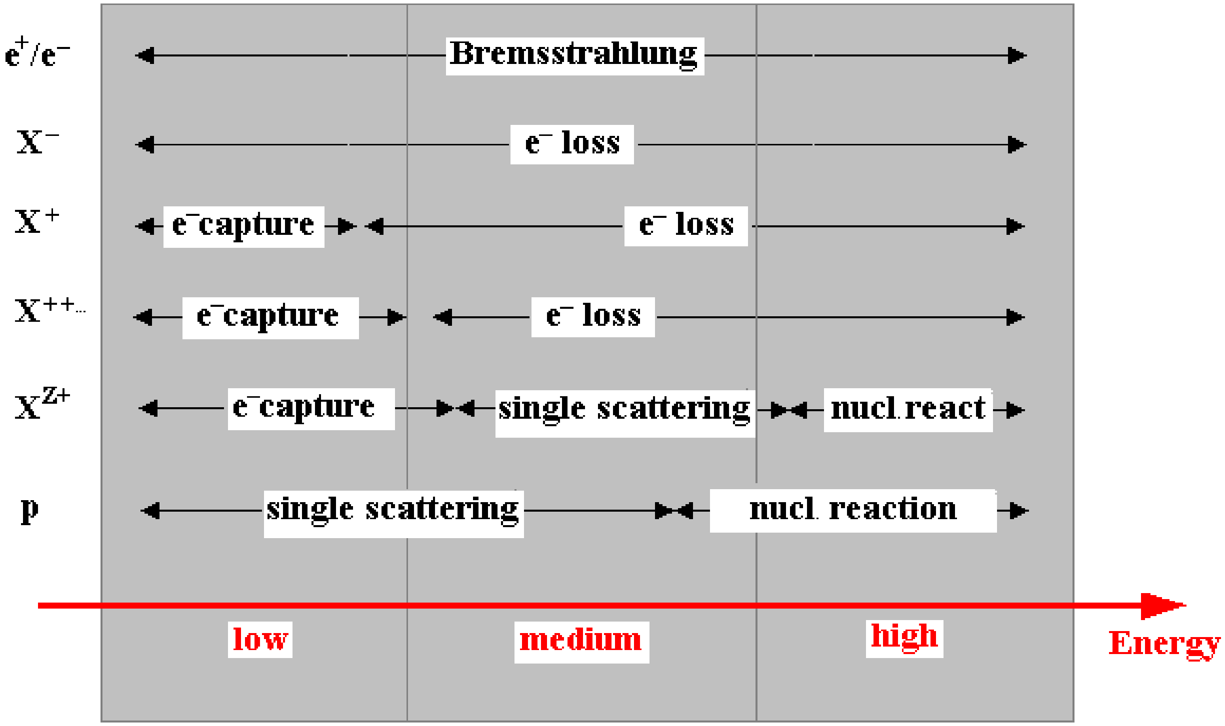
Beam-residual gas interaction

Lifetime and interaction cross section: $\tau = \frac{1}{v\sigma n}$



$$\sigma_{tot} = \sigma_1 + \sigma_2 + \ldots \sigma_k$$

$$\frac{1}{\tau_{tot}} = \frac{1}{\tau_1} + \frac{1}{\tau_2} + \ldots \frac{1}{\tau_k}$$



	low	medium	high
e^+/e^-		Bremsstrahlung	
X^-		e^- loss	
X^+	e^-capture	e^- loss	
$X^{++...}$	e^-capture	e^- loss	
X^{Z+}	e^-capture	single scattering	nucl react
p	single scattering		nucl. reaction

VLHC Vacuum System Requirements

Luminosity loss rate due to beam-gas scattering

collision with gas nuclei

emittance growth<- multipl. Coulomb scattering
(second term **only for VLHC - Low Field**)

Lifetime due to beam
gas scattering

$$\frac{1}{\tau_g} = \frac{2}{\tau_p} + \frac{1}{\tau_\varepsilon}$$

negligible if:

$$\tau_g >> \tau_L \left(= \frac{\tau_{pp}}{2}\right)$$

assuming

$$\tau_g = 5\tau_L$$

LF - τ_g ~ 330hrs

HF - τ_g ~ 80hrs

gas	σ_{pj} (Mb)	$\overline{P}_{oj}$(nTorr) [$\tau_g = 5\tau_L$]		P_j (nTorr) [0.1 W/m]	
		LF	HF	LF	HF
H2	0.12	2.8	14.6	56.1	105
CH4	0.65	0.43	2.7	10.3	19.4
H2O	0.69	0.36	2.5	9.7	18.3
CO	1.0	0.25	1.8	6.7	12.6
CO2	1.6	0.15	1.1	4.2	7.9

local pressure bump limits

Required Pumping Speed for VLHC

$$S \cdot P = Q \; = Q_{psd} + \ldots Q_{other}$$

Required pumping speed S **decreases** with time … :

$$Q_{psd} \propto \eta \dot{\Gamma}$$

$$\eta = \eta_o D^{-\alpha}$$

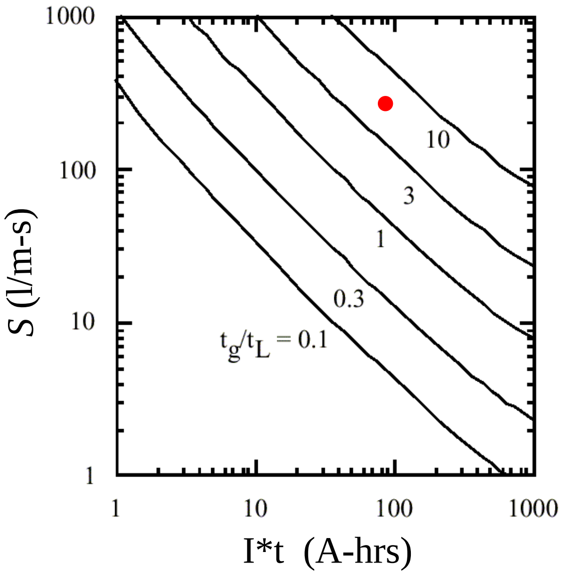
photon dose linear function of **I*t** (A-hrs)

Estimating the pumping speed S (for CO) required to achieve the desired pressure within a "short" conditioning time.

reasonably short --> few tenths of a year of operation at nominal beam intensity, 10^7 sec/year ~

LF - I*t ~ 75 A-hrs

HF- I*t ~ 40 A-hrs

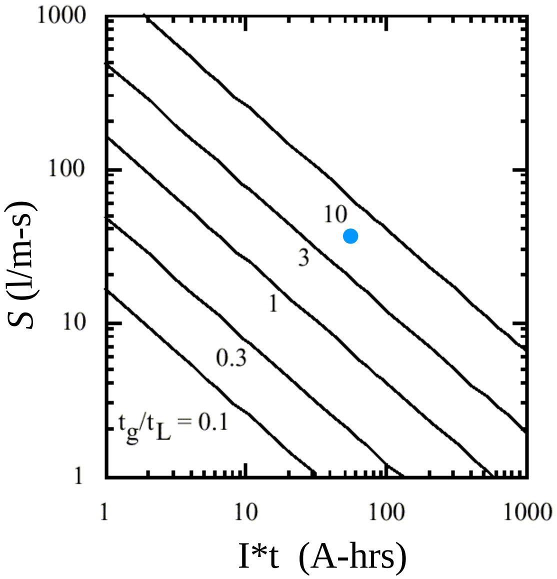


assuming:
$\tau_g / \tau_L = 5$

LF

● @

S_{CO}~270 l/m-s



HF

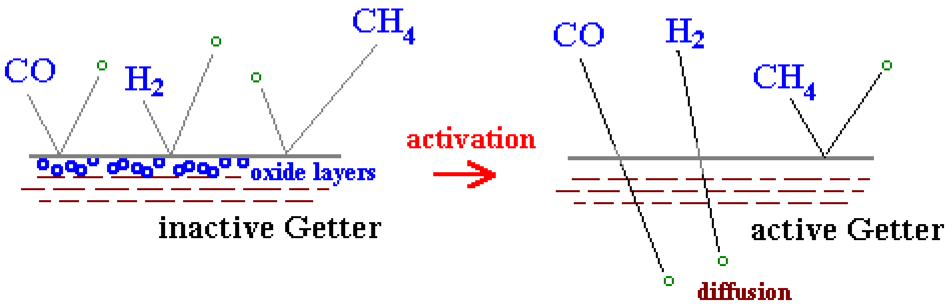
● @

S_{CO}~42 l/m-s

Pumping Options for VLHC

NEG pump or Cryopumping ?

Non Evaporable Getter



Commercial NEG:

St 101 activ. T~ 750ºC for 30’ (Zr 84%, Al 16%)
St 707 activ. T~ 400ºC for 1 h (Zr 70%, V 24.6%, Fe 5.4%)

NEG under development:

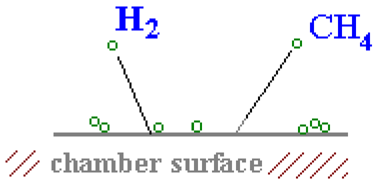
TiZrV (CERN) activ. T~ 200ºC

Cryopumping

Frenkel eq.

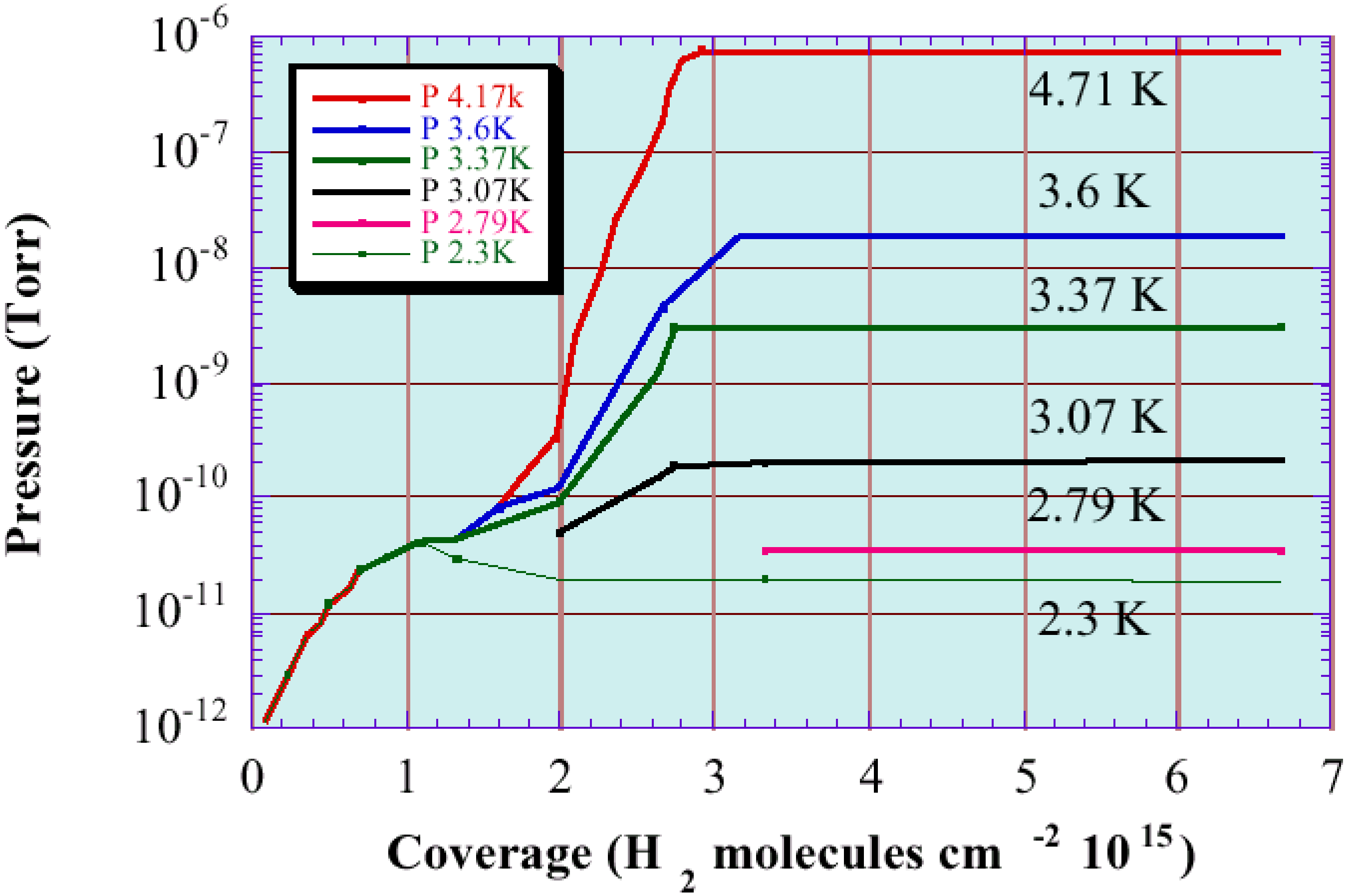
$$t = t_0 e^{\frac{E}{RT}}$$

E energy of vaporisation
(ex. 0.2 kcal/mole for H_2)
R 1.98 10^{-3} kcal $mole^{-1}$ K^{-1}
t_0~10^{-13} s



Hydrogen pumping ⟶ vapour pressure curve

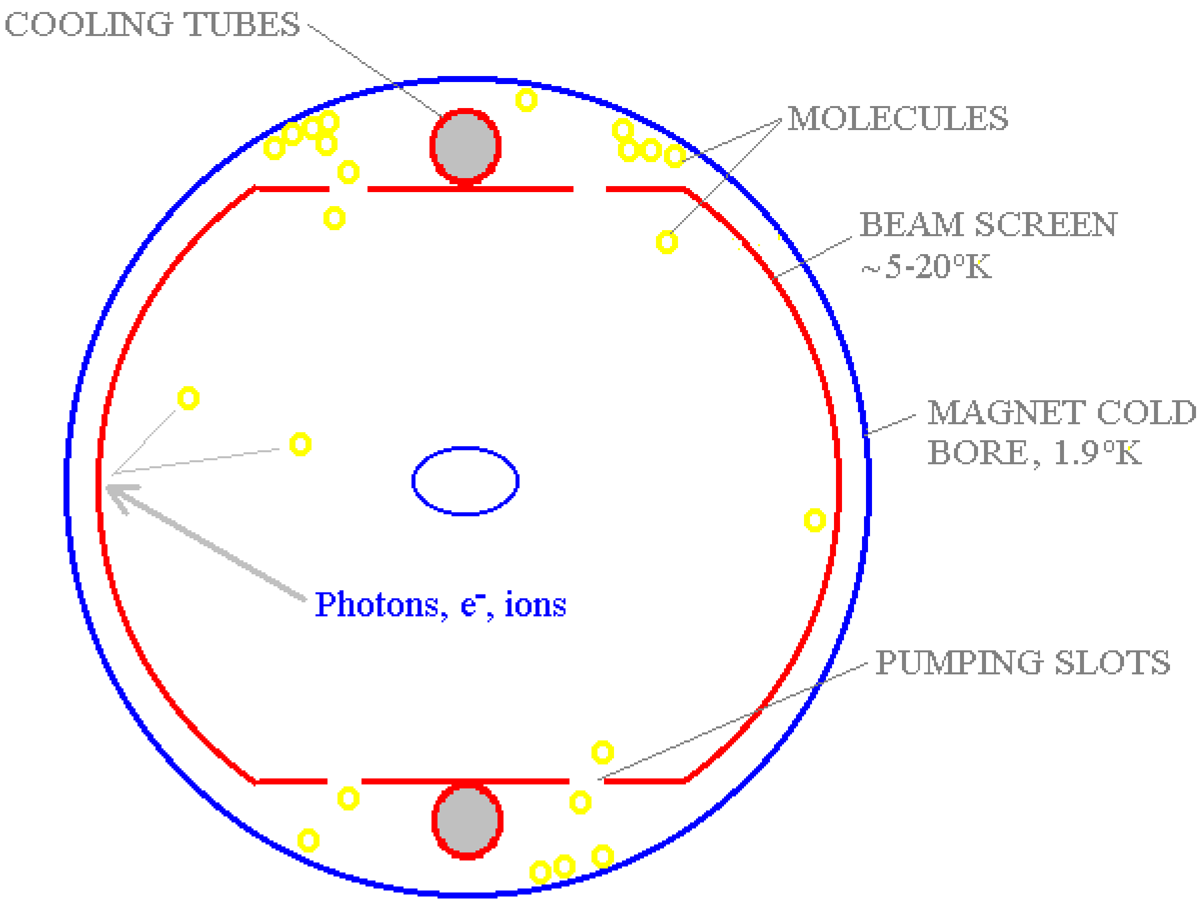
Hydrogen vapour pressure



Use of porous materials improve

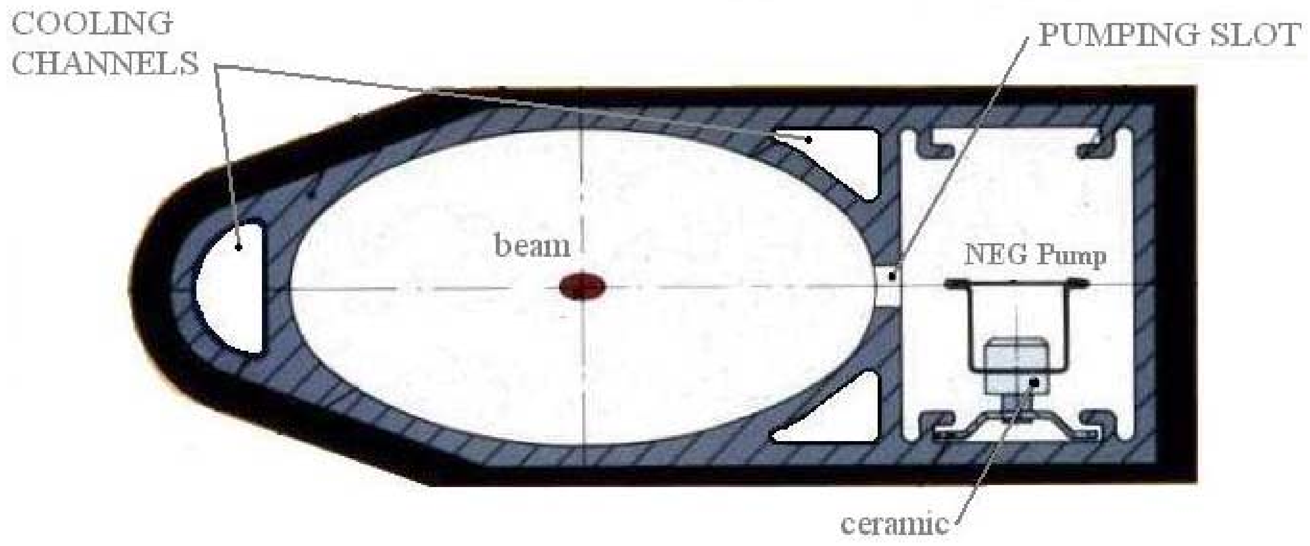
C. Benvenuti, R. Calder

LHC liner (beam screen) in a Cryo-magnet cold bore



actual LHC beam screen cross section

LEP vacuum chamber with NEG pumping system



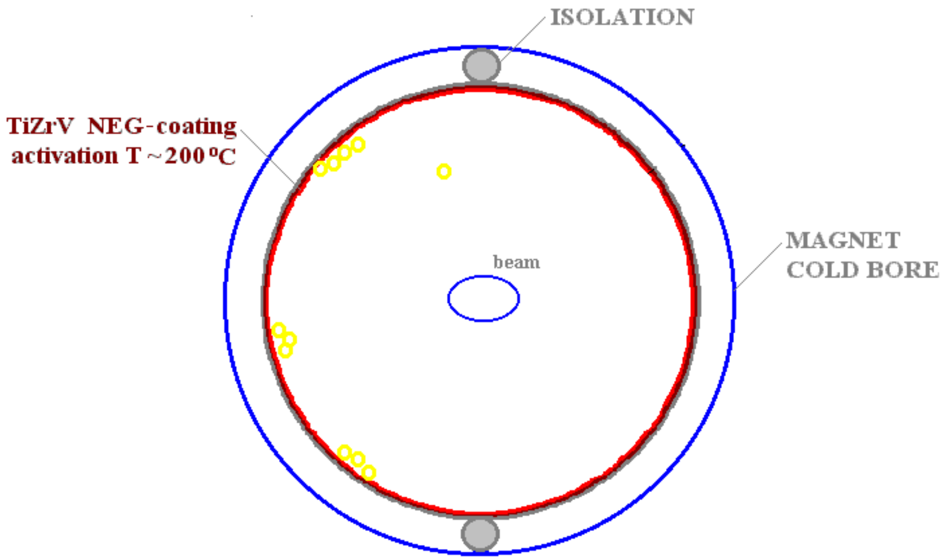
Non Evaporable Getter (NEG), St 101

Composition	Zr 84% Al 16%
Getter layer thickness	100 µm
Activation temperature	750 °C

CH_4 and inert gasses are not pumped by NEG, need to combine with ion pumps

An alternative option ...

Non evaporable getter-coating in a *SC* magnet cold bore



Adv:

- eliminates holes and cooling capillaries
- no He leak risk in the beam pipe
- low Secondary Electron Yield (very good to get rid of eventual electron-cloud)

Disadv:

- thermal excursions inside the chamber
- unknown technology (& costs)

... something to think about for the future

Pumping system Solutions for VLHC

Low Field

distributed NEGs + ion pumps (~20m) for CH_4

Neg strip 3cm wide
antechamber size 5x7cm
coupling pumping slots 7mm
LEP NEG St101 (500 *l/m-s*), St 707 or TiZrV (?!)
to get the required pumping speed *S=270 l/m-s*

NEGs are compatible with the
warm
LF configuration of the VLHC

High Field

Liner (beam screen) LHC type

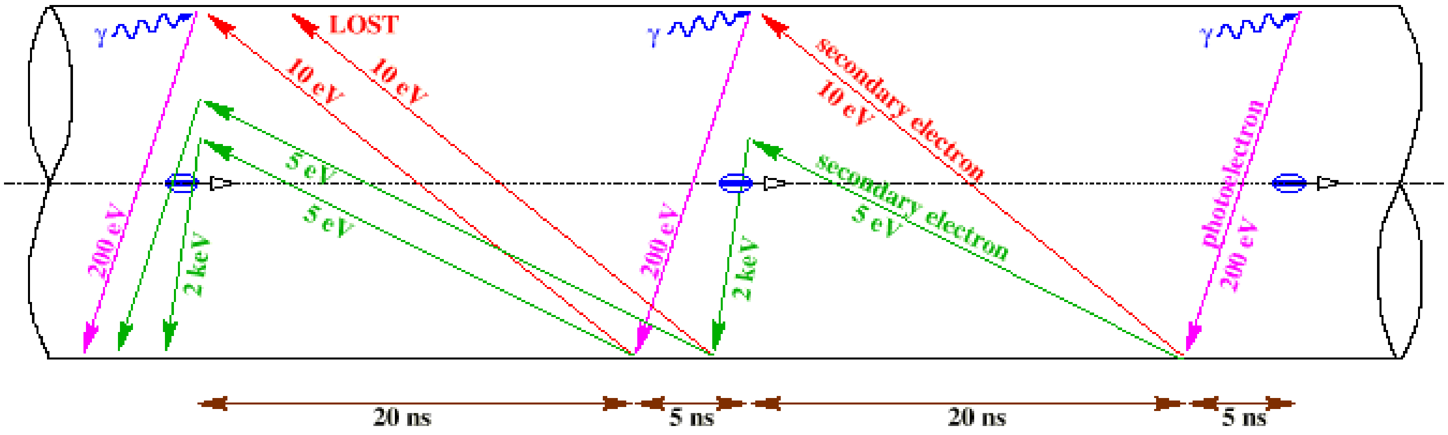
area holes *22.6 cm²/m* to get the estimated pumping speed *S=42 l/m-s* → *2.2%* surface covered with pumping slots

Cryopump system is compatible with the
superconducting
HF configuration of the VLHC

Electron-cloud instability (ISR['70], LANL-PSR, PEPII, KEKb, SPS+LHC...)

LHC: photoemission from Synchrotron Radiation

$$N_{ã} = \frac{5}{2\sqrt{3}}\, áã \;\; \frac{photons}{radian} \longrightarrow 3.5\;10^{9}\;\frac{photoelectrons}{magnet\;\;bunch} \qquad E_{crit} = \frac{3\hbar c}{2ñ}\, ã^{3} \approx 45eV$$



Schematic of electron-cloud build up in the LHC beam pipe

multipacting condition:
(on beam intensity)

$$\boxed{I_b = \frac{4\pi\varepsilon_0 mc}{e}\left(\frac{r_{pipe}}{T}\right)^2}$$

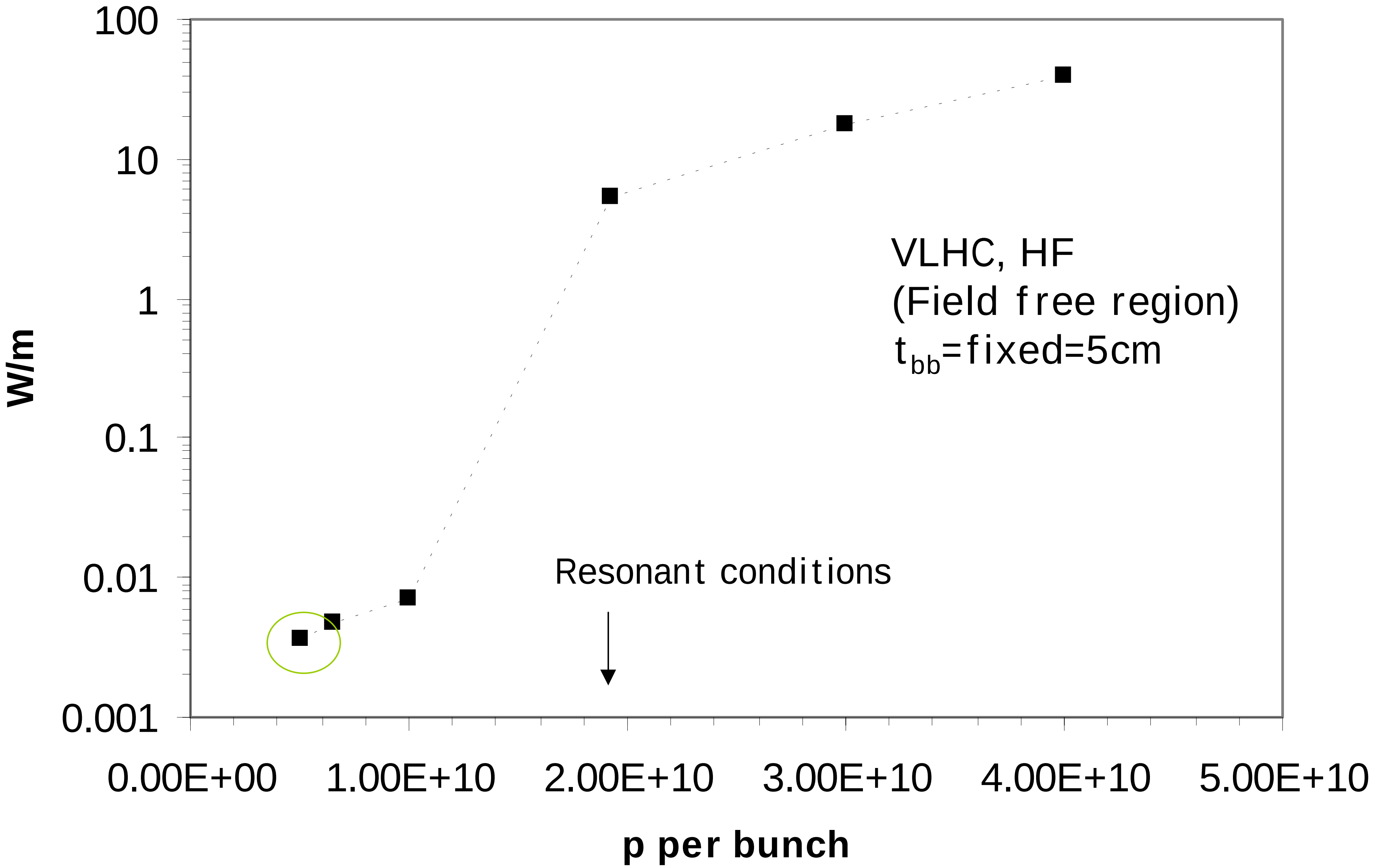
W.Turner (Luc Vos's formulas, LHC-Note-150 (7/98), field free regions)

Model calculations of electron cloud parameters						
21-Sep-00						
Parameter	PEP II-LER	LHC	SSC	RHIC	VLHC-HF	VLHC-LF
E, GeV	3.1	7.00E+03	2.00E+04	1.00E+02	5.00E+04	5.00E+04
γ	6.07E+03	7.46E+03	2.13E+04	1.07E+02	5.33E+04	5.33E+04
C, km	2.2	26.66	87.12	3.83	104.00	646.00
ρ, m	13.75	2.78E+03	1.02E+04	238	13214.28571	9.25E+04
n_b	**5.90E+10**	**1.05E+11**	**7.50E+09**	**7.90E+10**	**5.00E+09**	**9.40E+09**
N_B	1658	2835	17333	60	20690	128594
σ_Z, cm	1	7.7	7	10	1.42	1.42
t_{bb}, nsec	**4.2**	**24.95**	**16.67**	**228.4**	**16.67**	**16.67**
I, A	2.13E+00	5.36E-01	7.16E-02	5.94E-02	4.77E-02	8.98E-02
I_{BT}, A	2.247619048	6.73E-01	7.20E-02	5.53E-02	4.80E-02	9.02E-02
$I_{BT,RES}$, A	6.71	9.85E-02	1.74E-01	4.45E-03	1.85E-01	6.81E-02
b, cm	2.5	1.8	1.6	3.5	1.65	1
photons/m-sec	2.56E+16	7.79E+16	7.28E+15	-	1.02E+16	3.08E+15
E_c, eV	4.82E+03	4.43E+01	2.81E+02	1.53E-03	3.40E+03	4.85E+02
$\langle E \rangle_\nu$, eV	1.48E+01	1.36E+01	8.65E+01	-	1.05E+03	1.49E+02
$P'_{\nu,bt}$ W/m	6.08E-02	1.70E-01	1.01E-01	-	1.70E+00	7.36E-02
g	2.16E+00	5.22E-01	1.77E+00	1.20E+00	2.80E+00	1.99E+00
$\langle \Delta E \rangle$, eV	1.95E+02	2.88E+02	6.31E+00	9.89E+01	4.17E+00	2.84E+01
ΔE (b), eV	4.51E+01	2.76E+02	1.78E+00	4.13E+01	7.44E-01	7.16E+00
t_{bb}/t_{tr}	**3.36E-01**	**6.85E+00**	**4.14E-01**	**1.25E+01**	**2.59E-01**	**1.33E+00**
$f_{EB}(2t_{BB})$	5.78E-01	2.61E+00	6.42E-01	3.52E+00	5.08E-01	1.15E+00
Matl	Al(TiN)	Cu(cond.)	Cu	SS	Cu	Al(warm)
α	1	0.66	1	0.1 ?	1	0.9 ?
κ	0	0	0	0	0	0
δ_ν	0.2	0.2	0.2	0.2	0.2	0.2
δ_{SE}	1.1	1.1	2.1	2.7	2.1	3.5
kT_{SE}(eV)	3.5	3.5	3.5	3.5	3.5	3.5
N'_{EC}, e/m	4.10E+07	1.03E+09	7.94E+07	-	1.40E+08	-
$N'_{EC,SC}$, e/m	3.65E+09	3.65E+09	3.65E+09	3.65E+09	3.65E+09	3.65E+09
P'_{EC}, W/m	4.74E-03	1.9	2.57E-03	-	3.59E-03	-
$P'_{EC,SC}$, W/m	-	6.7	-	2.53E-01	-	9.96E-01

$\propto \left(\frac{r_{pipe}}{T}\right)^2$

S.R. power

important


100
10
1
0.1
0.01
0.001
W/m
0.00E+00
1.00E+10
2.00E+10
3.00E+10
4.00E+10
5.00E+10
p per bunch
VLHC, HF
(Field free region)
t_{bb}=fixed=5cm
Resonant conditions

Conclusions:

- Electron-cloud

LF $P'_{ec,sc} \sim 1$ W/m, $P'_{\nu,bt} \approx 7 \cdot 10^{-2}$ W/m

red flag: close to EC threshold, vacuum issue: pressure instability, beam instability

HF 4 mW/m, $P'_{\nu,bt} \approx 1.7$ W/m

if $n_b \geq 2 \cdot 10^{10}$ → ~ 10 W/m ⟶ Need simulations

- Ion-induced desorption not a problem, because of low current

- Vacuum system for VLHC does not require new technology (need details design), we can use experiences acquired with existing systems
  - **LF**: LEP-style vacuum system, conventional NEG or low temperature NEG
  - **HF**: LHC-style vacuum system, liner (beam screen) abs. necessary (S.R.)

- Alternative solution for HF, low temperature NEG (unknown)

"Mauro Pivi" <mpivi@lbl.gov>, "William Turner" <wcturner@lbl.gov>