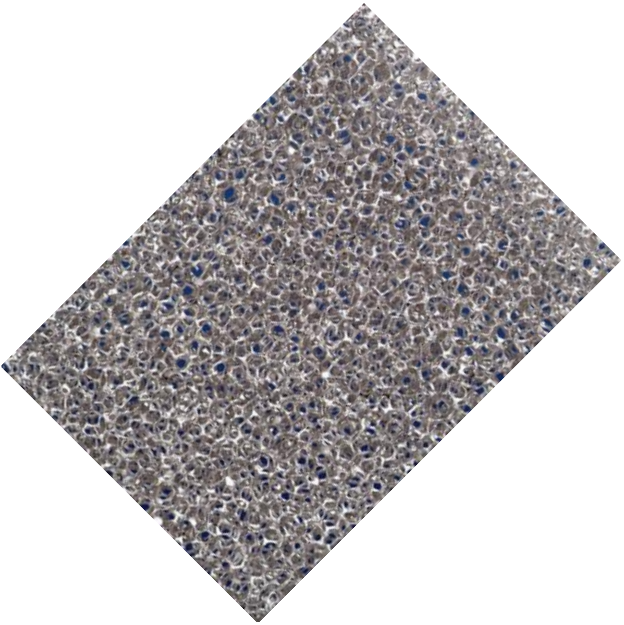
European Organization for Nuclear Research

"Frontier Capabilities for Hadron Colliders 2013"

Metallic Foam Option for the Vacuum System ?



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Outline

Synchrotron Radiation Issues : LHC and beyond

Open Cell Metal Foams (OCMF)

A mini-primer

OCMF for Beam Liners: Pros and Cons

Vacuum, Impedance, SEY

Conclusions

Synchrotron Radiation - LHC and Beyond

Synchrotron radiation induced molecular gas desorption from the beam-pipe wall should be properly taken into account in the design of high energy particle accelerators and storage rings. Nuclear scattering in the residual gas would limit the beam luminosity lifetime, and eventually cause thermal runaway .

Synchrotron radiation is also responsible of the e-cloud buildup phenomenon, which may also severely limit the achievable luminosity/energy goals [K.C. Harkay, "Observation and Modeling of Electron Cloud Instability ," Proc. EPAC '06, paper WEXFI02 (2006)].

This has been a *major (solved) challenge* for the Large Hadron Collider ["*The Large Hadron Collider Conceptual Design,*" CERN Rept. AC/95-05 (1995)].

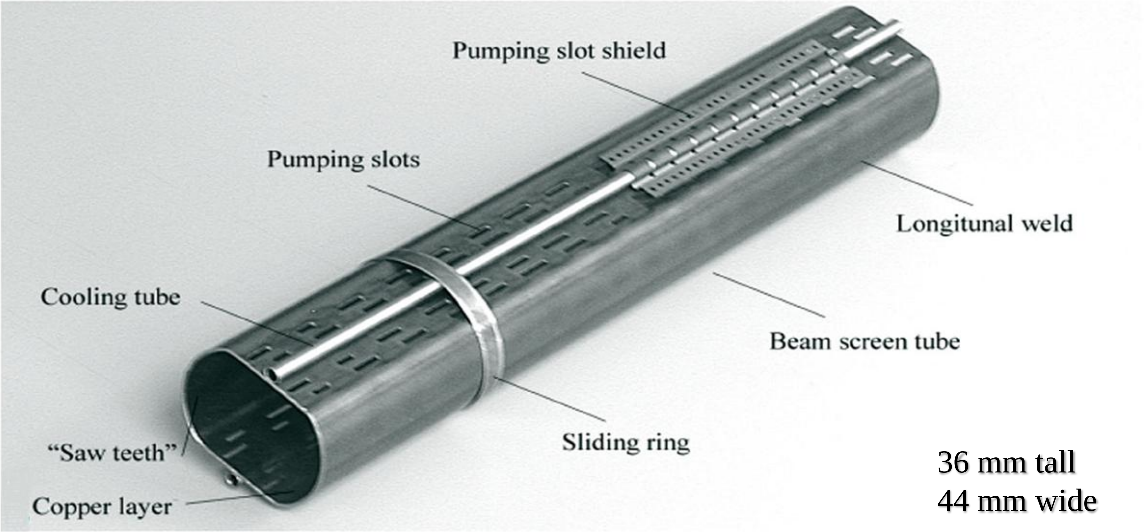
It will be even *more critical* for the HL-LHC, in view of its higher level of synchrotron radiation [A. Valishev, "Synchrotron Radiation Damping, Intrabeam Scattering and Beam-Beam Simulations for HE-LHC," arXiv:1108.1644v1 [physics.acc-ph] (2011)].

And will be *crucial* for the successful operation of the proposed electron-positron Higgs factories [A. Blondel et al., "LEP3: A High Luminosity e+e- Collider to Study the Higgs Boson," ArXiv: 1208 .0504v2 [physics.acc-ph] (2012)]

The LHC Beam Screen

- In the LHC a copper-coated stainless-steel beam pipe kept at ~20K by active He-cooling, handles the heat load represented by synchrotron radiation, photoelectrons, and image-charge losses.

- A *large* number (~ 10^2 m^{-1}) of tiny slots drilled in the liner wall keep the desorbed gas densities below a critical level (~ 10^{15} molecules m^{-3} for H_2). Desorbed gas is continuously cryopumped unto a co-axial stainless-steel tube (the magnets' cold-bore), kept at 1.9K by superfluid He.



36 mm tall
44 mm wide

- Geometry, number and placement of the slots *affect the beam dynamics and stability* through the beam coupling impedances. The slots pattern is designed to *prevent coherent buildup* of radiation leaking into the (TEM) waveguide limited by the beam pipe and the cold bore.

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OCMF Technology

Open cell metal foams (OCMF) can be produced nowadays by several technologies see, e.g.,

[J. Banhart and N.A. Fleck, "Cellular Metals and Metal Foaming Technology,“ MIT Press (2003)]

The typical foam is a highly connected trabecular structure of solid metal filaments, which encircle the pores. The structure is highly gas-permeable, and has remarkable mechanical, electrical and thermal properties. The solid metal is only a *small* fraction of the total volume (some 10%, typ.).

Key *morphological* parameters of OCMF :

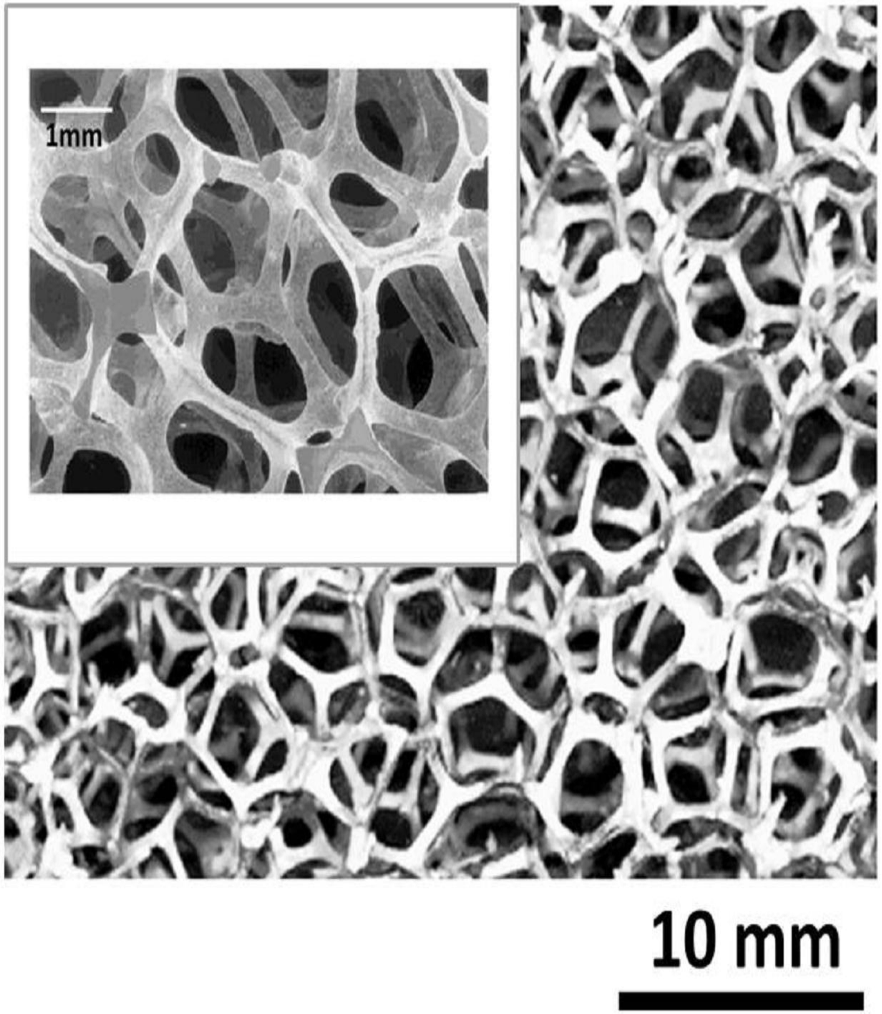
i) *pore size* ($\varnothing\ 10^{-3} – 10^{-4}$ mm, typ.)
ii) *porosity* (volume fraction of pores, 0.8-0.99, typ.)

Open-Cell Metal Foams

…highly connected web of thin metal ligaments encircling (connected) void pores…

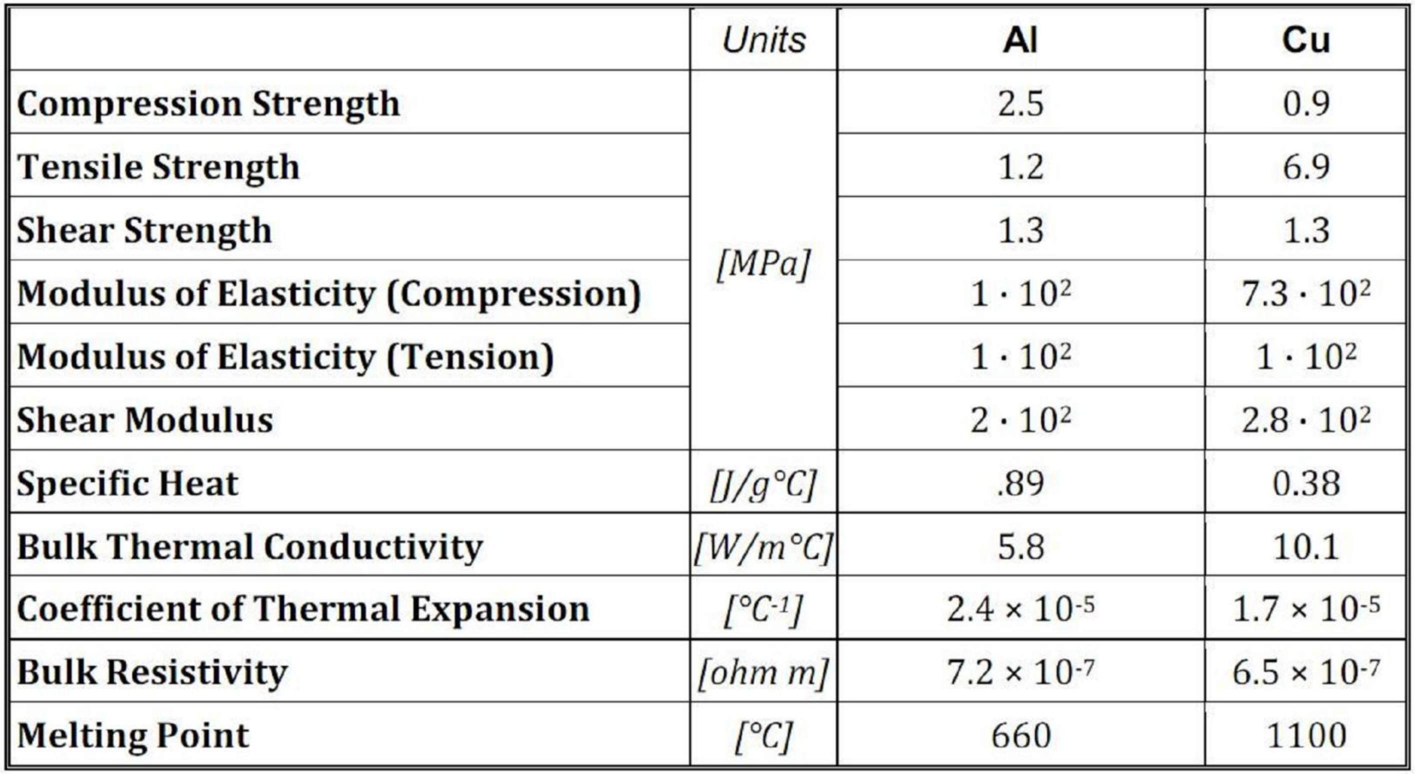
↓

Excellent mech. props.,
Large gas permeability,
Large heat exchange,
Good conductivity …



OCMF Typical Structural Properties

(20 ppi, 0.92 porosity)



	Units	Al	Cu
Compression Strength	*[MPa]*	2.5	0.9
Tensile Strength		1.2	6.9
Shear Strength		1.3	1.3
Modulus of Elasticity (Compression)		$1 \cdot 10^2$	$7.3 \cdot 10^2$
Modulus of Elasticity (Tension)		$1 \cdot 10^2$	$1 \cdot 10^2$
Shear Modulus		$2 \cdot 10^2$	$2.8 \cdot 10^2$
Specific Heat	*[J/g°C]*	.89	0.38
Bulk Thermal Conductivity	*[W/m°C]*	5.8	10.1
Coefficient of Thermal Expansion	*[°C^{-1}]*	2.4×10^{-5}	1.7×10^{-5}
Bulk Resistivity	*[ohm m]*	7.2×10^{-7}	6.5×10^{-7}
Melting Point	*[°C]*	660	1100

Solid metal

2.65×10^{-8} ,1.72×10^{-8}

[Courtesy ERG Aerospace]

OCMF Materials and Manufacturers

- *Al* and *Cu* OC-foams cheap and now available off-the-shelf;
- Foam *coating* (e.g., with *Ag*, *Ti* or *Pt*) possible;
- OC-foams using *Ag, Ni, Co, Rh, Ti* and *Be*, as well as various alloys (e.g., *Steel* or *Brass*) feasible;
- *Several* Manufacturers, worldwide, e.g., ERG/Aerospace, and Goodfellow (USA); Mitsubishi (JP); Lyrun (CHN); Universal Metaltech (IN), Dunlop (UK), M-Pore (DE), and more…

…motivated by growing demand in Aerospace and Automotive applications…

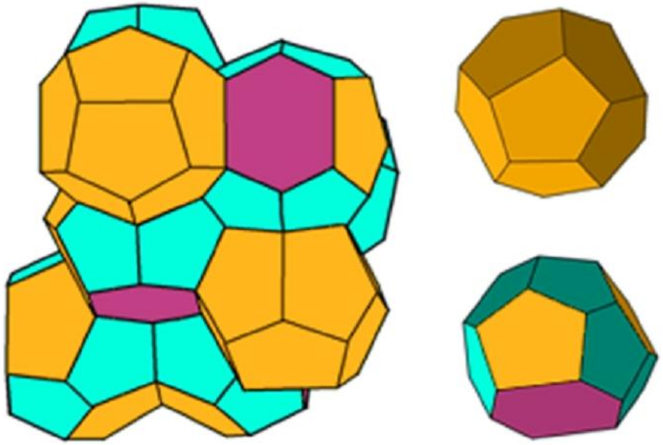
Structural Modeling of OCMF

- The Weaire-Phelan (WP) space-filling honeycombs are credited as the natural (i.e., Plateau's minimal-surface principle compliant) building blocks for modeling reticulated metal with equal-sized (and possibly un-equal-shaped) pores.

  [D. Weaire and R. Phelan, Phil. Mag. Lett. 69 (1994) 107]

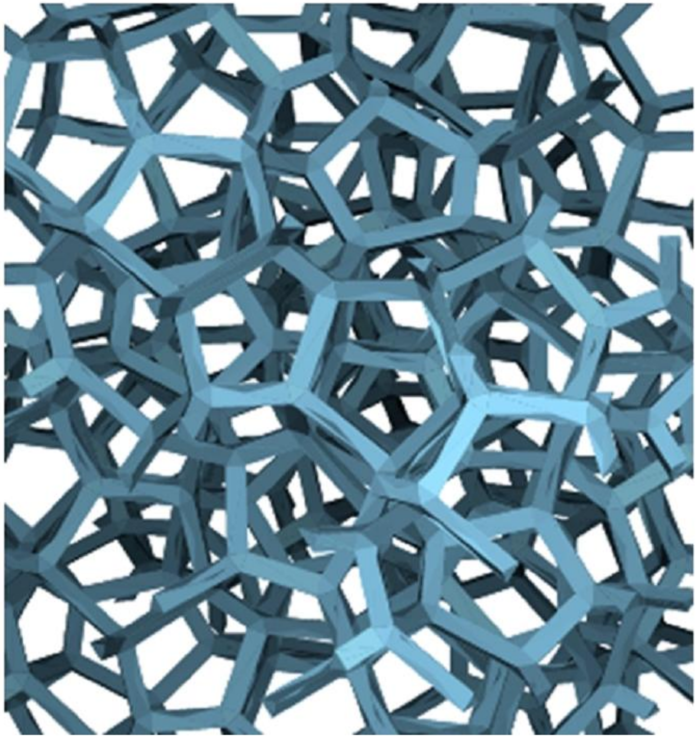
  The WP unit cell consists of a certain arrangement of (irregular) polyhedra, namely *two pentagonal - face dodecahedra* (with tetra-hedral symmetry *Th*) *, and six tetrakaidecahedra*, featuring two hexagonal and twelve pentagonal faces (with antiprysmatic symmetry D_{2d}) …

Structural Modeling of OCMF, contd.



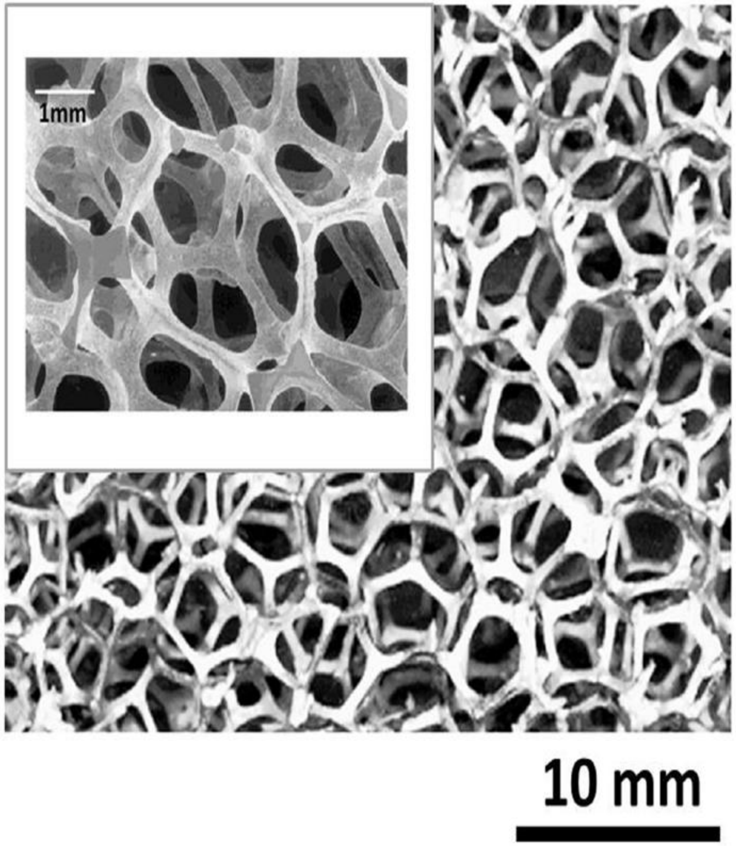
the Wearie-Phelan cell (left),
and its building blocks (right),

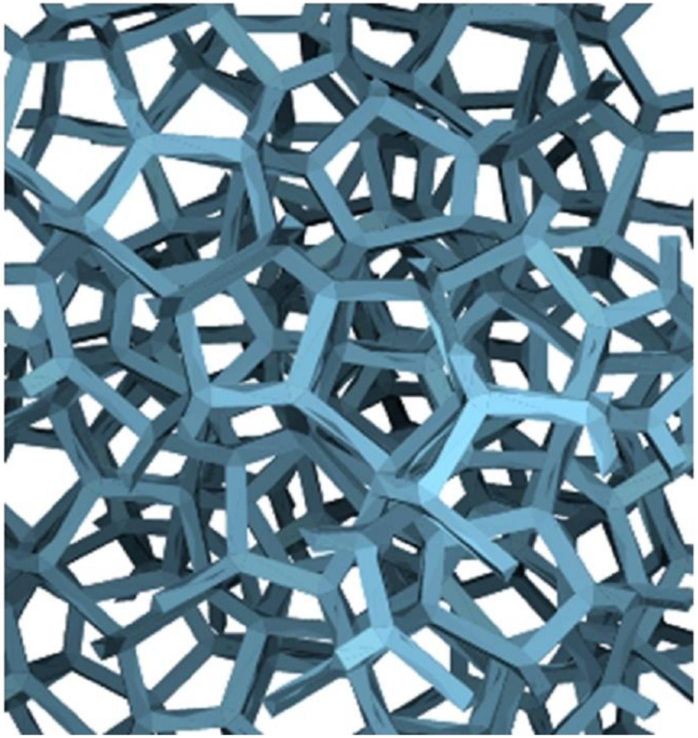
[D. Weaire and R. Phelan,
Phil. Mag. Lett. 69 (1994) 107]



numerically generated Wearie-Phelan
cell-edge network (compare with foam…)

Structural Modeling of OCMF, contd.





numerically generated Wearie-Phelan cell-edge network (compare with foam…)

Effective Medium Theory

In the limit where pores and metal struts are (much) smaller than the (smallest) wavelength of interest, the properties of a metal foam can be computed using *effective medium theory* (EMT), e.g. Brüggemann formula,

complex conductivity of host

complex conductivity of mixture

complex conductivity of inclusions

$$(1-\gamma_{incl})\frac{\eta_{host}-\eta_{eff}}{\eta_{host}+2\eta_{eff}}+\gamma_{incl}\frac{\eta_{incl}-\eta_{eff}}{\eta_{incl}+2\eta_{eff}}=0$$

vol. fraction of inclusions

[D.A. Brüggemann, Ann. Phys. s5, **24** (1935) 636]

… an idea tracing back to Rayleigh [Phil. Mag. **34** (1897) 28] and Clausius-Mossotti …

Effective Medium Theory, contd.

Technically, *several* EMT formulations exist, e.g.,

- infinite dilution approximation (non - interacting inclusions, subject to field which would exist in the *homogeneous* host) ;
- self-consistent approach (non interacting inclusions embedded in the *sought* effective medium) – e.g., D.A.G. Bruggemann, Ann. Phys. **24** (1935) 636;
- differential approach (inclusions added *incrementally*; infinite dilution approximation at each step) – e.g., R. Goodall et al., J. Appl. Phys., **100** (2006) 044912 ;
- effective field approach (interaction among the inclusions described in terms of an *effective field*) – e.g., Y. Qui and G.J. Weng, Int. J. Eng. Sci.28 (1990) 1121; S.K. Kanaun, Int. J. Eng. Sci. 41(2003) 1287 ;

… *all* have been applied for computing the OCMF DC conductivity…

OCMF DC Conductivity from EMTs

matrix (bulk) metal conductivity

Porosity (bubble volume fraction)

Morphology dep-endent factor ~ 1

1) $\sigma_{eff} = \sigma_0(1 - p\nu)$

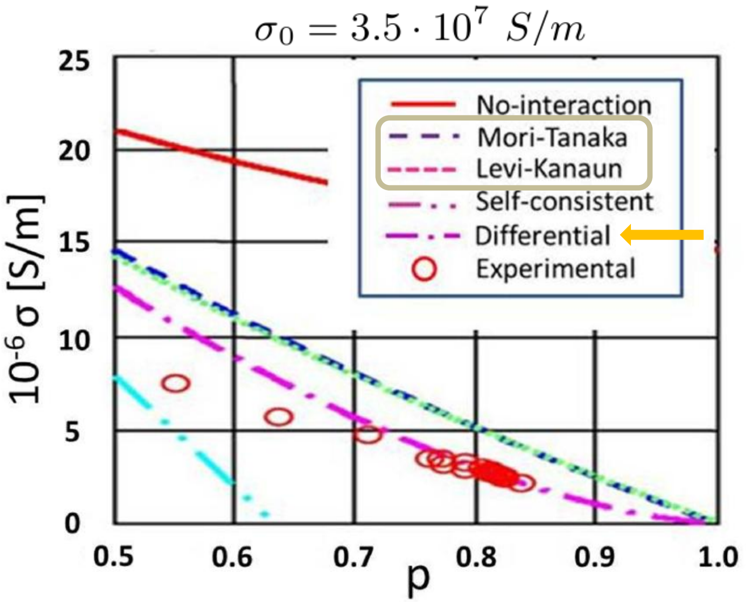
Infinite dilution & self-consistent appr.

2) $\boldsymbol{\sigma_{eff} = \sigma_0(1-p)^{\nu}}$

Differential approach, yields best agreement with experimental results

3) $\sigma_{eff} = \sigma_0 / \left(1 + \frac{\nu p}{1-p}\right)$

Effective field approach (MT & LK)



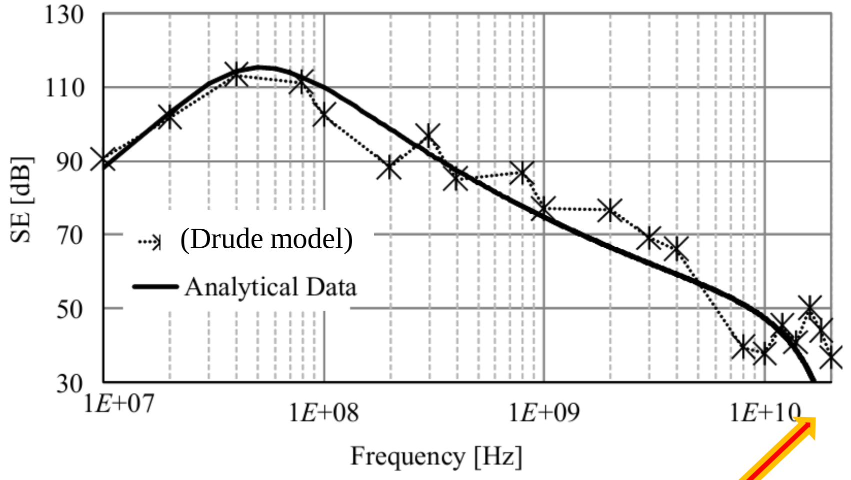
[I. Sevostianov et al., Material Sci. Eng. **A420** (2006) 87]

The differential approach agrees in form with a percolative one (but there's no threshold above which the conductive phase will disconnect, here …)

OCMF Microwave Conductivity – Drude Fits

OCMF transmission coefficient measurements in the microwave range are well fitted by a Drude model [L. Catarinucci et al., Progr. EM Research, **B45** (2012) 1]

Shielding efficiency (SE) of a OCMF sheet



electron plasma frequency, $\omega_p = (N_{eff}q^2/\epsilon_0 m)^{1/2}$

$$\sigma(\omega) = \frac{\omega^2{}_p\epsilon_0}{j\omega+\nu} \longrightarrow \sigma(0) = \frac{\omega^2{}_p\epsilon_0}{\nu}$$

electron collision frequency

… in OCMF ω_p was found to be much smaller (PHz → GHz) than in solid metal

… interpreted as due to the fact that [J.B. Pendry et al., Phys. Rev. Lett. **76** (1996) 4773]

i) the *effective density* of the electrons is *reduced* by a factor $\sim (1 - porosity)$;

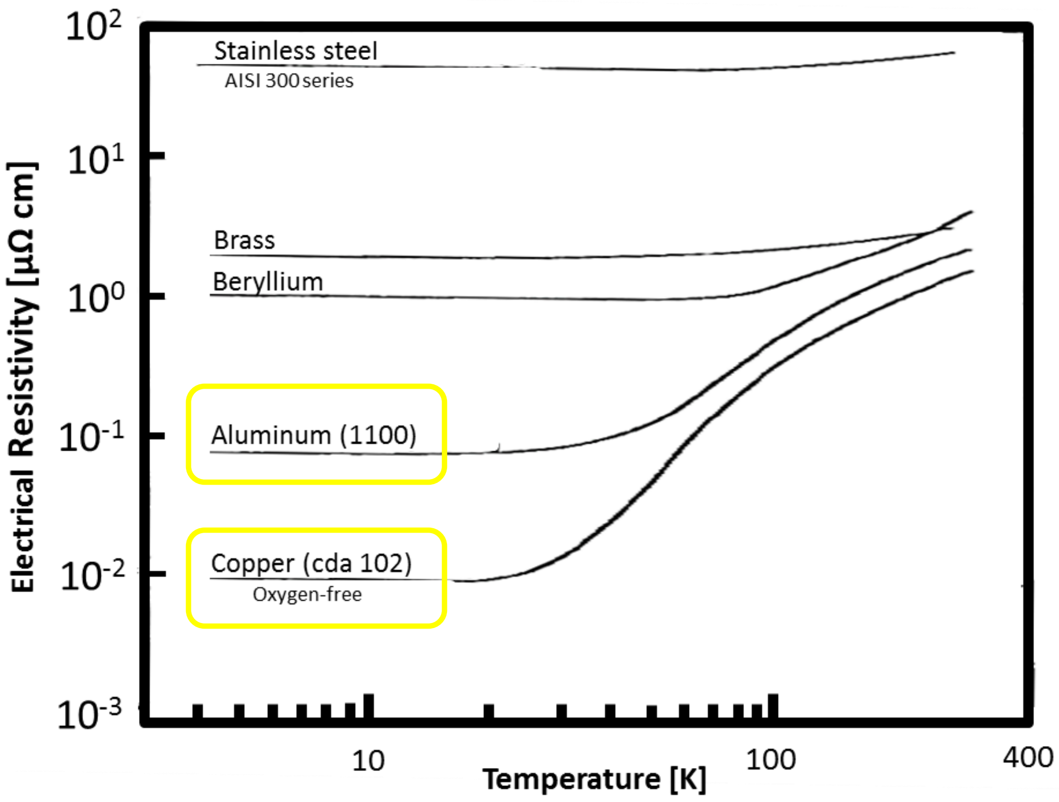
ii) the effective *momentum* of an electron in a *thin-wire* conducting web or lattice is *dominated* by the EM contribution ($\propto qA$), yielding a *very* large *effective* electron mass,

size of the metal "filaments"

$$m_{eff} \cong \frac{\mu_0 q^2 N_{eff}}{2} d^2 \log(d/D)$$

size of the "voids"

Cryogenic Operation



… “standard” *Al* or *Cu* based OCMF should have low resistivities at cryo – Temp. However, *neither Al nor Cu* would be superconducting at 20 K …

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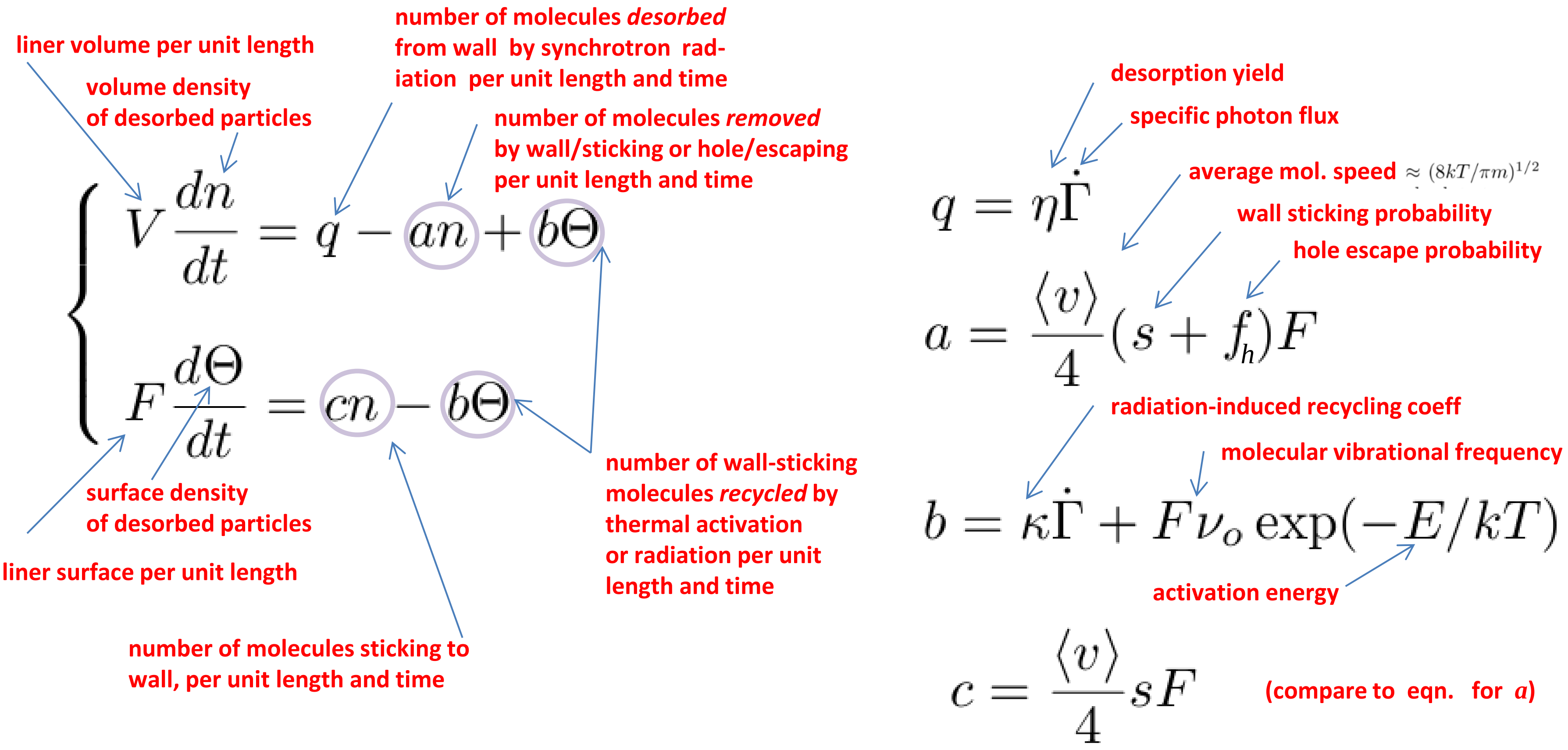
- Technology, Modeling Tools

OCMF for Beam Liners: Pros and Cons

- Vacuum, Impedance, SEY

Conclusions

Desorbed Gas Dynamics



$$\begin{cases} V\dfrac{dn}{dt} = q - an + b\Theta \\ F\dfrac{d\Theta}{dt} = cn - b\Theta \end{cases}$$

liner volume per unit length

volume density of desorbed particles

number of molecules *desorbed* from wall by synchrotron radiation per unit length and time

number of molecules *removed* by wall/sticking or hole/escaping per unit length and time

surface density of desorbed particles

liner surface per unit length

number of molecules sticking to wall, per unit length and time

number of wall-sticking molecules *recycled* by thermal activation or radiation per unit length and time

$$q = \eta\dot{\Gamma}$$

desorption yield

specific photon flux

$$a = \frac{\langle v\rangle}{4}(s + f_h)F$$

average mol. speed $\approx (8kT/\pi m)^{1/2}$

wall sticking probability

hole escape probability

$$b = \kappa\dot{\Gamma} + F\nu_o\exp(-E/kT)$$

radiation-induced recycling coeff

molecular vibrational frequency

activation energy

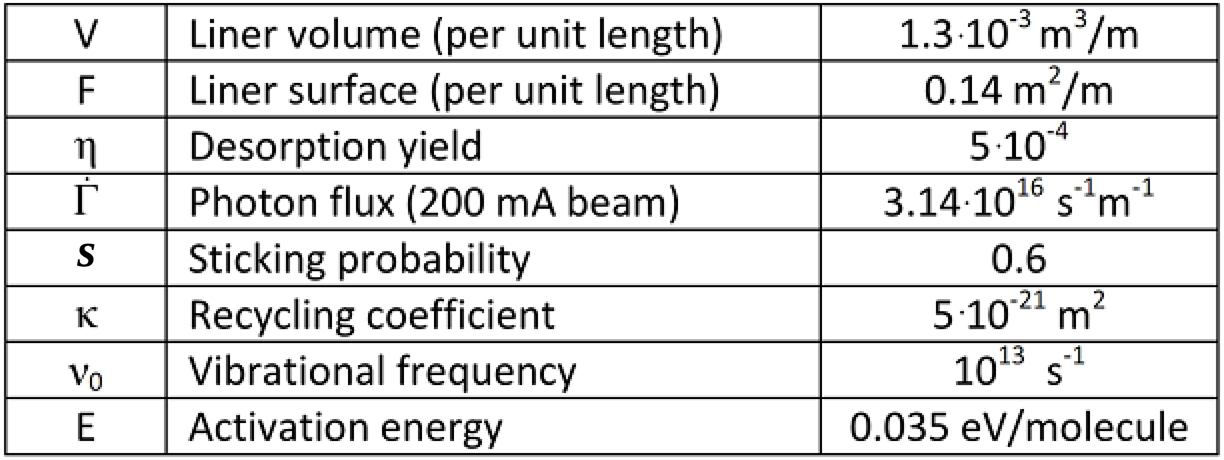
$$c = \frac{\langle v\rangle}{4}sF$$

(compare to eqn. for *a*)

[O. Grobner, Vacuum **60** (2001) 25]

Typical Numbers

Typical values (solid portion of liner wall, LHC, Hydrogen)



V	Liner volume (per unit length)	$1.3 \cdot 10^{-3}$ m^3/m
F	Liner surface (per unit length)	0.14 m^2/m
η	Desorption yield	$5 \cdot 10^{-4}$
$\dot{\Gamma}$	Photon flux (200 mA beam)	$3.14 \cdot 10^{16}$ s^{-1}m^{-1}
s	Sticking probability	0.6
κ	Recycling coefficient	$5 \cdot 10^{-21}$ m^2
ν_0	Vibrational frequency	10^{13} s^{-1}
E	Activation energy	0.035 eV/molecule

[O. Grobner, Vacuum **60** (2001) 25]

Equilibrium Solutions

desorption yield

specific photon flux

Equilibrium volume density of desorbed particles

liner surface per unit length

At equilibrium ($\dot{n} = \dot{\Theta} = 0$)

$$\begin{cases} n_{eq} = \dfrac{4\eta\dot{\Gamma}}{\langle v\rangle f_h F} \\[2ex] \Theta_{eq} = \dfrac{s}{f_h}\,\dfrac{\eta\dot{\Gamma}}{\kappa\dot{\Gamma} + F\nu_o \exp(-E/kT)} \end{cases}$$

average mol. speed $\approx (8kT/\pi m)^{1/2}$

wall sticking probability

Equilibrium surface density of desorbed particles

hole escape probability

activation energy

molecular vibrational frequency

radiation-induced recycling coeff

n_{eq} , Θ_{eq} *must* be kept *below* some *critical* values…

Overall, we may expect from OCMF a (much) smaller "exposed" metal surface, and hence (much) *smaller* s and η and *larger* f_h

Perforated vs OCMF Wall

Perforated, solid wall

$$f_h^{(0)} = \frac{\text{surf. covered by holes}}{\text{total wall surface}}$$

Escape probability:

Thin wall: $f_h = f_h^{(0)}$

Thick wall: $f_h = \chi f_h^{(0)}, \quad \chi = 1 - 0.5(w/R_h)$

Clausing factor [R.P. Iczkowski et al. J. Phys. Chem. **67** (1963) 229]

wall thickness

hole radius

In LHC $f_h^{(0)} \cong 0.04$ and $\chi \cong 0.5$

$$\Longrightarrow \quad f_h \cong 0.02$$

OCMF wall

Porosity (pores vol. fraction)

$$f_h^{(0)} \cong 0.81\, \rho_h^{2/3}$$

pore volume density

avg pore radius

obtained by combining

surface density of pores $\approx N_h^{2/3}$

avg. exposed area of pores $\approx (2/3)\,\pi R_h^2$

porosity $\rho_h = (4/3)\,\pi R_h^3 N_h$

- *Solid* fraction of OCFM exposed surface is *small*

$$1 - f_h^{(0)} \cong 0.3 \quad (\text{for } \rho_h = 0.8)$$

Escape probability:

a Lambert – Beers reduction factor may account for the “maze” structure of foam (and should agree w. Clausing for $w \to 0$)

$$f_h = f_h^{(0)} exp(-w/2R_h) \cong 0.062 \quad (\text{for } \rho_h = 0.8,\; w \cong 5R_h)$$

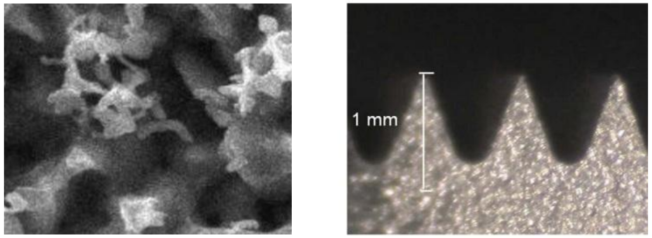
OCMF ⇨ ***the quantities ηf_h and $s\eta f_h$ are reduced by factors 0.1 and 0.03, resp.***
need to cover with OCMF only a (small) fraction of the liner surface

SEY : Rough(ened) vs OCMF Metal Wall

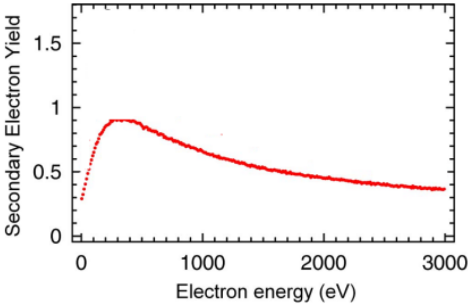
In general SEY gets reduced by making the wall *rough*, e.g., by "scrubbing" the pipe using high energy particle bombardment, or powder "blasting" its surface . Roughness with higher *depth-to-spacing* ratios yields *smaller* SEY.

[I. Montero et al., Proc. CERN AEC '09, paper #29 (2009), M. Pivi et al., SLAC Pub. 13020 (2007)]

"Rough(ened)" solid metal wall

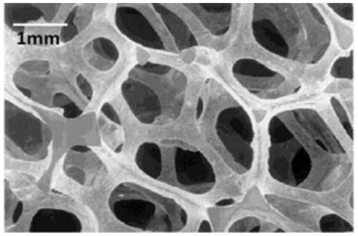


morphologies



SEY vs energy (typ)

OCMF wall



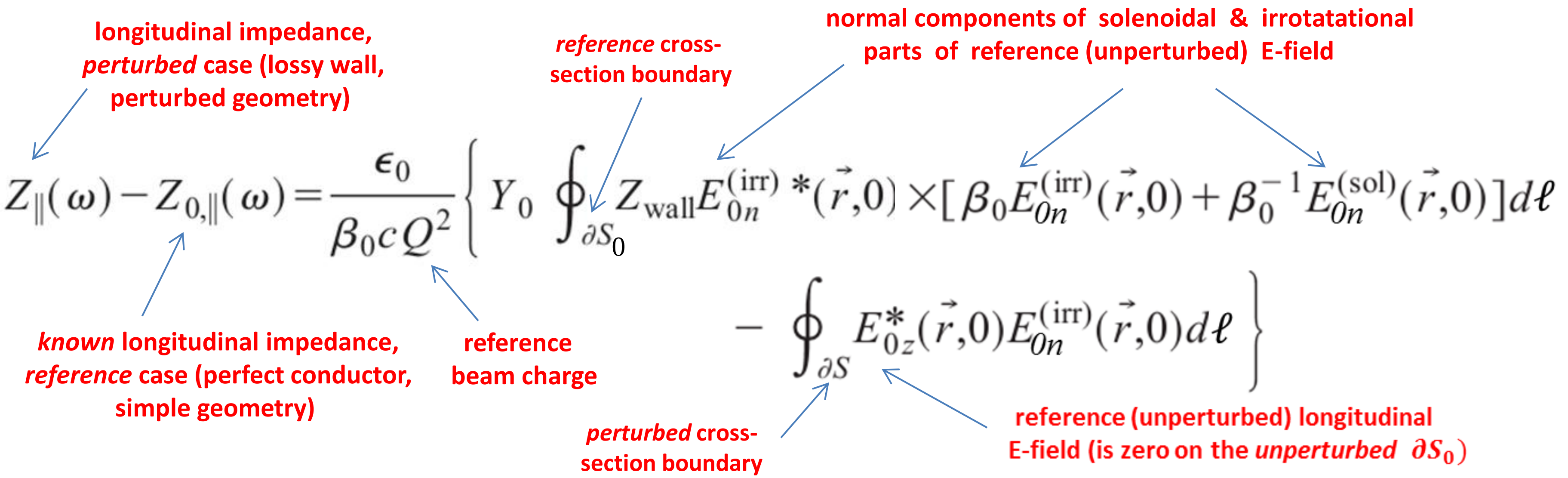
morphology

- *Small* exposed surface → small SEY expected
- SEY energy-dependence ?

Measurements ongoing

[collab. with R. Cimmino, INFN-LNF]

Beam Coupling Impedance



longitudinal impedance, *perturbed* case (lossy wall, perturbed geometry)

reference cross-section boundary

normal components of solenoidal & irrotatational parts of reference (unperturbed) E-field

$$Z_{\|}(\omega)-Z_{0,\|}(\omega)=\frac{\epsilon_0}{\beta_0 c Q^2}\left\{ Y_0 \oint_{\partial S_0} Z_{\mathrm{wall}} E_{0n}^{(\mathrm{irr})\,*}(\vec{r},0)\times\left[\beta_0 E_{0n}^{(\mathrm{irr})}(\vec{r},0)+\beta_0^{-1} E_{0n}^{(\mathrm{sol})}(\vec{r},0)\right]d\ell \right.$$
$$\left. -\oint_{\partial S} E_{0z}^{*}(\vec{r},0)E_{0n}^{(\mathrm{irr})}(\vec{r},0)\,d\ell \right\}$$

known longitudinal impedance, *reference* case (perfect conductor, simple geometry)

reference beam charge

perturbed cross-section boundary

reference (unperturbed) longitudinal E-field (is zero on the *unperturbed* ∂S_0)

- A similar formula exists also for $Z_\perp$ [S. Petracca, Part. Acc. **50** (1995) 211].
- Simplest case: circular pipe of radius b , on-axis beam : $Z_{\|}=\dfrac{Z_{\mathrm{wall}}}{2\pi b}$
- May be used to compute the parasitic loss : $\Delta\mathcal{E}=\dfrac{1}{2\pi}\displaystyle\int_{-\infty}^{+\infty}|I(\omega)|^2\,\Re e\ Z_{\|}(\omega)\,d\omega$

Beam Coupling Impedance

longitudinal impedance per unit length, *perturbed* case (lossy wall, perturbed geometry)

reference cross-section boundary

normal components of solenoidal & irrotatational parts of reference (unperturbed) E-field

$$Z_{\|}(\omega)-Z_{0,\|}(\omega)=\frac{\epsilon_0}{\beta_0 c Q^2}\left\{ Y_0 \oint_{\partial S_0} Z_{\text{wall}} E_{0n}^{(\text{irr})} {}^{*}(\vec{r},0)\times[\beta_0 E_{0n}^{(\text{irr})}(\vec{r},0)+\beta_0^{-1}E_{0n}^{(\text{sol})}(\vec{r},0)]d\ell \right.$$

$$\left. - \oint_{\partial S} E_{0z}^{*}(\vec{r},0)E_{0n}^{(\text{irr})}(\vec{r},0)d\ell \right\}$$

known longitudinal impedance per unit length, *reference* case (perfect conductor, simple geometry)

reference beam charge

reference (unperturbed) longitudinal E-field (is zero on the *unperturbed* ∂S)

First term in curly brackets accounts for "constitutive" perturbations of the beam pipe (wall impedance);

Effect of Z_{wall} can be minimized by "placing" the impedance at locations where the (unperturbed) field is *minimal* ...

- A similar formula exists also for $Z_{\perp}$ [S. Petracca, Part. Acc. **50** (1995) 211].
- Simplest case: circular pipe of radius b, on axis placing: $Z_{\|}=\frac{Z_{\text{wall}}}{2\pi b}$
- May be used to compute the parasitic loss : $\Delta\mathcal{E}=\frac{1}{2\pi}\int_{-\infty}^{+\infty}|I(\omega)|^2\Re e\ Z_{\|}(\omega)d\omega$

Beam Coupling Impedance

longitudinal impedance, *perturbed* case (lossy wall, perturbed geometry)

normal components of solenoidal & irrotatational parts of reference (unperturbed) E-field

$$Z_{\parallel}(\omega)-Z_{0,\parallel}(\omega)=\frac{\epsilon_0}{\beta_0 c Q^2}\left\{Y_0\oint_{\partial S_0} Z_{\mathrm{wall}}E_{0n}^{(\mathrm{irr})\,*}(\vec r,0)\times\left[\beta_0 E_{0n}^{(\mathrm{irr})}(\vec r,0)+\beta_0^{-1}E_{0n}^{(\mathrm{sol})}(\vec r,0)\right]d\ell \right.$$

$$\left. -\oint_{\partial S} E_{0z}^{*}(\vec r,0)E_{0n}^{(\mathrm{irr})}(\vec r,0)\,d\ell\right\}$$

***known* longitudinal impedance, *reference* case (perfect conductor, simple geometry)**

reference beam charge

reference (unperturbed) longitudinal E-field (is zero on the *unperturbed* ∂S)

Second term in curly brackets accounts for "geometric" perturbations of the beam pipe (e.g., wall roughness);

Roughness can be equivalently described in terms of an extra wall impedance
[K.L. Bane and G.V. Stupakov, SLAC-Pub 8023 (1998)]

$$Z_{wall}^{(rough)}\sim jZ_0\left(\frac{\omega}{c}\right)\frac{h^2}{\Delta_c}$$

h "vertical"
Δ_c "lateral"
scale of roughness

- A similar formula exists also for $Z_\perp$ [S. Petracca, Part. Acc. **50** (1995) 211].
- Simplest case: circular pipe of radius b, on-axis beam: $Z_\parallel = \frac{Z_{\mathrm{wall}}}{2\pi b}$
- May be used to compute the parasitic loss $\frac{1}{2\pi}\int_{-\infty}^{+\infty}|I(\omega)|^2 \mathrm{Re}\, Z_\parallel(\omega)\,d\omega$

Perforated vs OCMF Wall

Z_{wall} , perforated solid metal

Solid metal contribution : $Z_{wall} = \left(\frac{j\omega\mu_0}{\sigma_{wall}}\right)^{1/2}$

Pumping holes contribution (thin wall) :

vacuum impedance

surface density of holes

$$\begin{cases} Im[Z_{wall}] = Z_0\left(\frac{\omega}{c}\right)(\alpha_e+\alpha_m)n_\sigma \\ Re[Z_{wall}] = \frac{Z_0}{6\pi}\left(\frac{\omega}{c}\right)^4({\alpha_e}^2+{\alpha_m}^2)n_\sigma \end{cases}$$

electric (e) /magnetic (m) hole polarizabilities $\propto {R_h}^3$

[S.S. Kurrenoy, Part. Accel. 39 (1992) 1; thick wall corrections : R.L. Gluckstern, Phys. Rev. A46 (1992) 1106; effect of coaxial TEM region : S. Petracca, Phys. Rev. E60 (1999) 6030]

Z_{wall} , OCMF wall

Porous metal contribution : $Z_{wall} = \left(\frac{j\omega\mu_0}{\sigma_{eff}}\right)^{1/2}$

effective **(complex) OCMF conductivity including the effect of pores**

The related parasitic loss includes *both* ohmic (bulk) *and* ratiation (holes) losses. These can be easily separated, e.g.

Effective **parasitic loss (ohmic loss + radiation)**

$$\Delta\mathcal{E}^{(rad)} \cong \Delta\mathcal{E}\exp(-2d/\delta_s)$$

Effective **skin depth** $\delta_s = (2/\omega\mu_0\sigma_{eff})^{1/2}$

Roughness (geometric) contribution :

$$Z_{wall}{}^{(rough)} \sim j\, Z_0\left(\frac{\omega}{c}\right)\frac{h^2}{\Delta_c}$$

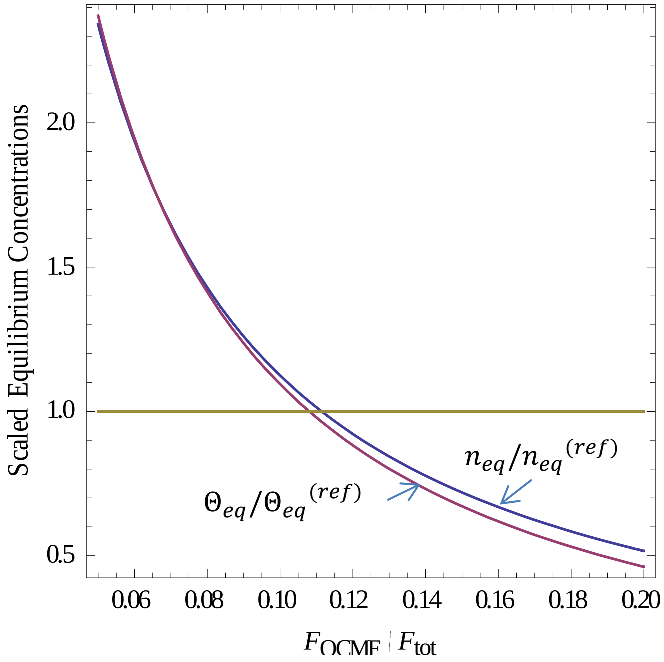
h "vertical" } scale of roughness
Δ_c "lateral"

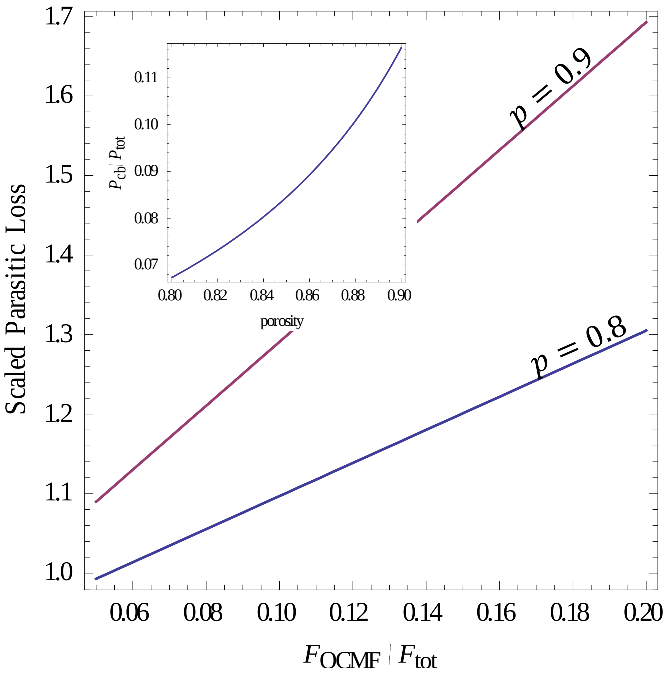
OCMF needs to cover a fraction of liner surface for adequate vacuum;
Z_{wall} of OCMF can be larger by a factor ~ 6 compared to solid metal;
⟹ need to place OCMF in *low field* regions to minimize effect on $Z_\parallel$

Perforated vs OCMF Wall

Reference: LHC w. 5% perforated surface

(copper coated liner, stainless steel cold bore)





Superconducting Foams ?

No experimental results on foamed *metallic* superconductors yet available in the Technical Literature, to the best of our knowledge.

Foamed *ceramic HTC superconductors* (especially YBCOs, $YBa_2Cu_3O_y$) have been manufactured, and investigated [E.S. Reddy and G.J. Schmitz, Supercond. Sci. Tech., 15 (2002) L21; D.A. Balaev et al., Phys. Solid St. 48 (2006) 207] in the Literature.

***Conceptually* interesting**: "new" SC materials, where a SC (multiply connected) cluster (with a percolating *electric current*) co-exists with an open-pore cluster (with a percolating *magnetic flux*); vortex pinning and transport *not yet* fully understood [E. Bartolome' et al., Phys. Rev. B70 (2004) 144514].

***Technologically* interesting**: *large* specific surface (high *effective heat exchange* coefficient); *large* critical currents (10^4 A/cm^2) observed in experiments [J. G. Noudem et al., Physica C390 (2003) 286].

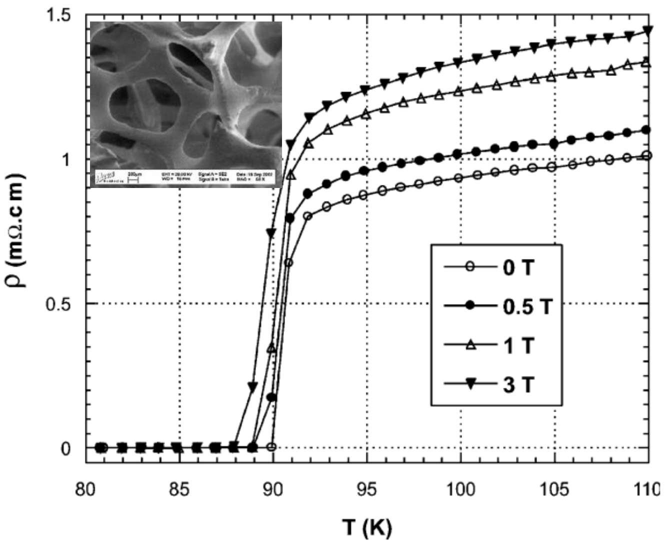
Superconducting Foams ? contd.

… we would be mainly interested in the *RF* (Leontòvich) *impedance* of the foams in the superconducting state ...

Plenty of theoretical and experimental results on the RF properties of type II superconducting *films* (e.g., YBCO) [e.g., M. J. Lancaster, *Passive Microwave Device Applications of HTS,* Cambridge Univ. Press (2006)];

No experimental or theoretical results in the Literature about the ***RF*** behaviour of *foamed* ceramic superconductors, as yet, to the best of our knowledge;

But *measurements should be straightforward*, using a std. VNA setup, as described e.g. in [J. Booth et al., SPIE Proc., **2559** (1995) 38].



Electrical resistivity versus temperature for *YBCO foam* (shown in inset) [J.G. Noudem et al. , Physica **C390** (2003) 286]

Outline

Synchrotron Radiation Issues : LHC and beyond

Open Cell Metal Foams

A Mini-Primer

OCMF for Beam Liners: Pros and Cons

Vacuum, Impedance, SEY

Conclusions

Conclusions

Could open cell (metal) foams be a vacuum option for next generation, high synchrotron - radiation rings ?

They may offer better performance compared to perforated solid metal in terms of vacuum control and SEY.

They are worse in terms of parasitic losses. This can be mitigated in part by proper placement, and perhaps resolved switching to superconducting (ceramic) foams.

A number of modeling tools and results are available; yet, there's ample room for further investigation, namely as regards SEY and superconducting foams.

Quite a bit of (interesting) work to do !

Thanks for your attention