Elias Métral (20 + 5 min, 30 slides)
Many thanks to Vincent Baglin, Sergio Calatroni, F. Caspers and N. Kos for helpful discussions!

BEAM SCREEN ISSUES
(with 20 T dipole magnets instead of 8.3 T)

- **Introduction and current LHC beam screen**
- **Magneto-Resistance (MR)**
  - **What was done in the past (approx. of the approx. Kohler's rule)**
  - **Exact and approximate Kohler's rules**
- **Anomalous Skin Effect (ASE)**
  - **Approximate formula used in the past**
  - **Exact formula from Reuter & Sondheimer**
- **Conclusions and outlook**
- **PS: Important issue of Synchrotron Radiation (SR) not discussed, even if the power would be increased by ~ 30 and the critical photon energy by ~ 13**

From ~ 3.8 kW for 1 beam to ~ 120 kW (scaling: E^4)

From ~ 43 eV to ~ 574 eV (scaling: $B E^2$)

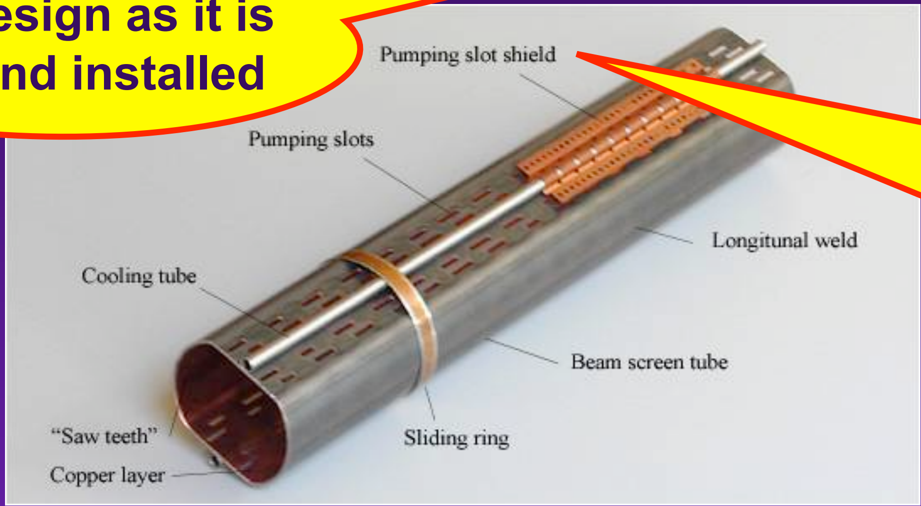
INTRODUCTION AND CURRENT LHC BEAM SCREEN (1/7)

- In the LHC:
  - ~ 90% (beam screen) between 5 and 20K
  - ~ 10% at room temperature (2 mm thick copper beam pipe)
- Main purpose of the beam screen: Shield the cold bore from SR => Made of SS to resist to mechanical stresses
- Cu coating to keep the resistance as low as possible
  - Transverse resistive-wall instability (low-frequency phenomenon, from a few kHz to a few MHz) => MR important
  - Power loss is a different issue due to the short bunch length + ASE + surface roughness (both important at high frequencies)
- Drawback from Cu coating: Eddy currents mainly in the Cu layer when quenches => The smaller the copper coating thickness the better for the quench force (which deforms the beam screen horizontally)
- Other impedance issues: pumping slots (for the vacuum) + weld

INTRODUCTION AND CURRENT LHC BEAM SCREEN (2/7)

Courtesy of N. Kos

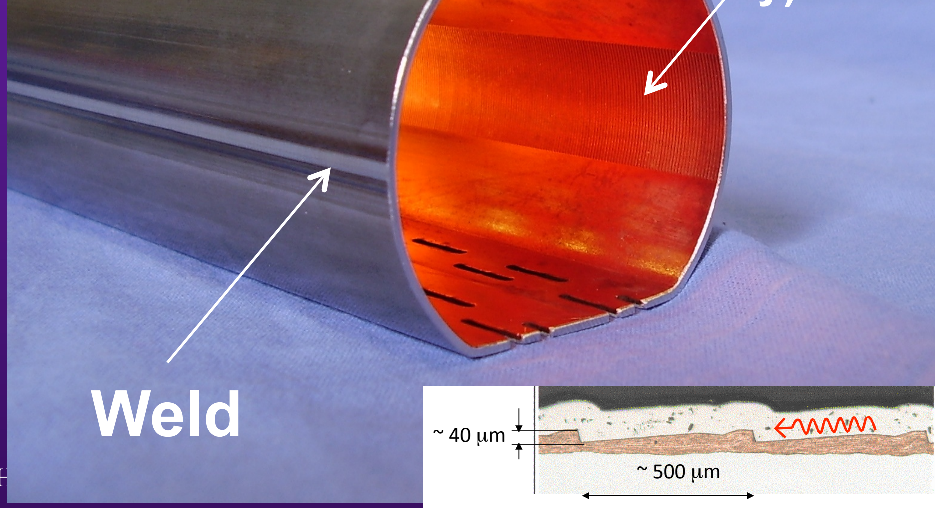
LHC design as it is built and installed



In dipoles, also called baffles, to avoid direct e$^-$ path along magnetic field lines to the cold bore (which would then add to the heat load)

Saw teeth in the arcs on Cu

(a series of ~ 30-40 µm high steps spaced by ~ 500 µm in the long. direction, to reduce the forward reflectivity)



INTRODUCTION AND CURRENT LHC BEAM SCREEN (3/7)

- **Power loss from the image currents in the beam screen (neglecting the holes) at 7 TeV => It was checked by N. Mounet that the same numerical result is obtained with our more precise multi-layer impedance formula**

$$P_{loss/m}^{G,RW,1\,\text{layer}} = \frac{1}{2\,\pi\,R}\,\Gamma\left(\frac{3}{4}\right)\frac{M}{b}\left(\frac{N_b\,e}{2\,\pi}\right)^2\sqrt{\frac{c\,\rho\,Z_0}{2}}\;\sigma_t^{-3/2} \approx 85\ \text{mW/m}$$

Euler gamma function

$$\Gamma\left(\frac{3}{4}\right) = 1.23$$

$$\rho_{Cu}^{20K} = 5.5 \times 10^{-10}\ \Omega\text{m}$$

$$\text{LHC circumference} = L = 2\,\pi\,R = 26658.883\ \text{m}$$

$$M = \text{number of bunches} = 2808$$

$$b = \text{beam screen half height} = 36.8\,/\,2 = 18.4\ \text{mm}$$

$$N_b = 1.15 \times 10^{11}\ \text{p/b}$$

$$\sigma_t = 0.25\ \text{ns}$$

$$Z_{//}^{RW0}(\omega) = (1 + j)\,\frac{L}{2\,\pi\,b}\sqrt{\frac{\omega\,\rho\,Z_0}{2\,c}}$$

INTRODUCTION AND CURRENT LHC BEAM SCREEN (4/7)

- **Power loss from the image currents due to the weld**

$$\rho_{Cu}^{20K} = 5.5 \times 10^{-10}\ \Omega\text{m}$$

$$\rho_{SS}^{20K} = 6 \times 10^{-7}\ \Omega\text{m}$$

$$\frac{\Delta_l^{Weld}}{2\,\pi\,b} = \frac{2}{2\,\pi \times 18.4} = \frac{1}{\pi \times 18.4} \approx \frac{1}{60}$$

=>

$$P_{loss/m}^{Weld} \approx P_{loss/m}^{G,RW,1\,\text{layer}} \times \sqrt{\frac{\rho_{SS}^{20K}}{\rho_{Cu}^{20K}}} \times \frac{\Delta_l^{Weld}}{2\,\pi\,b} \approx 48\ \text{mW/m}$$

$$\frac{P_{loss/m}^{Weld}}{P_{loss/m}^{G,RW,1\,\text{layer}}} \approx 57\ \%$$

Even though the weld corresponds to only ~ 1/60 of the surface, the power loss due to the weld is not negligible

INTRODUCTION AND CURRENT LHC BEAM SCREEN (5/7)

- Comparison between what I re-"estimated" and what is in the LHC Design Report, Vol. 1, Chap. 5 (https://edms.cern.ch/file/445833/5/Vol_1_Chapter_5.pdf) => For 1 single beam

~ 85 mW/m (with the same formula as F. Ruggiero in his paper CERN SL/95-09 (AP)), i.e. without ASE (which gives an increase of ~ 11%). Mostacci found ~ 80 mW/m (with simulations). The value quoted comes from meas.

Table 5.7: Summary of heat load on the arc beam screen for nominal LHC beam at 7 TeV. The three columns give the source, the latest relevant reference, and the peak heat load in mW/m.

source	Ref.	Peak power [mW/m] at 7 TeV
Synchrotron Radiation	[48]	220
Ohmic Losses	[52]	110
Pumping Slots	[53]	10
Welds	[2]	10

~ 1 mW/m for the most critical pumping holes in the arc beam screen (very close to Mostacci's result) => See Appendices

~ 47 mW/m. Mostacci found 27 mW/m

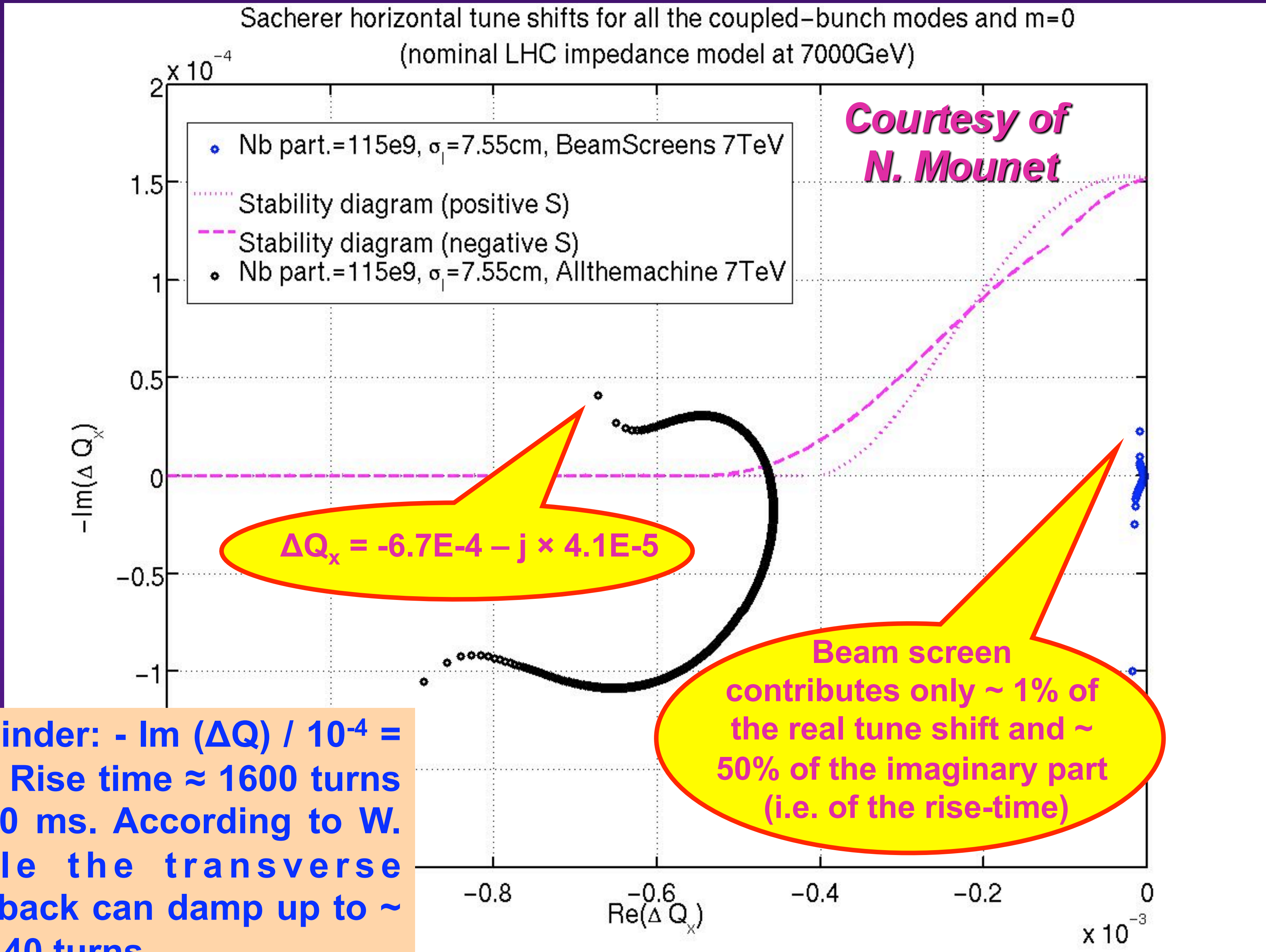
INTRODUCTION AND CURRENT LHC BEAM SCREEN (6/7)

- **Transverse resistive-wall impedance**

$$Z_{\perp}^{RW1}(\omega) = (1 + j)\,\frac{L\,Z_0}{\pi\,b^3}\sqrt{\frac{\rho}{2\,\mu_0\,\omega}}$$

  - **In the next slides, the transverse coupled-bunch instabilities were studied with the exact dimensions of all the beam screens and the correct transverse betatron functions**

INTRODUCTION AND CURRENT LHC BEAM SCREEN (7/7)



Reminder: - Im (ΔQ) / 10^{-4} = 1 => Rise time ≈ 1600 turns ≈ 140 ms. According to W. Hofle the transverse feedback can damp up to ~ 20 – 40 turns

MAGNETO-RESISTANCE (1/13)

- **How were the values of the Cu resistivity at low B and high B for the current beam screen obtained?**
- **In the paper "Surface Resistance Measurements and Estimate of the Beam-Induced Resistive Wall Heating of the LHC Dipole Beam Screen" (LHC Project Report 307, 1999) by F. Caspers et al., the following formula was used (referred to as "Kohler's law")**

$$\frac{\rho(B,T)-\rho_0(T)}{\rho_0(T)} = \frac{\Delta\rho}{\rho_0} = 10^{-2.69} \times (B \times RRR)^{1.055}$$

B = Magnetic induction in Tesla

T = Temperature in Kelvin

$\rho_0(T)$ = Resistivity at temperature T, without B

RRR **(Residual Resistivity Ratio) is a measure of purity**

$$RRR = \frac{R(273\ \mathrm{K})}{R(4\ \mathrm{K})}$$

Resistance

$$R = \rho \frac{l}{S} \Rightarrow \frac{\Delta R}{R_0} = \frac{\Delta\rho}{\rho_0}$$

MAGNETO-RESISTANCE (2/13)

- **As the resistivity decreases with temperature towards a minimum (determined by purity), the RRR is defined as the ratio of the DC resistivity at room temperature to its cold-DC lower limit**

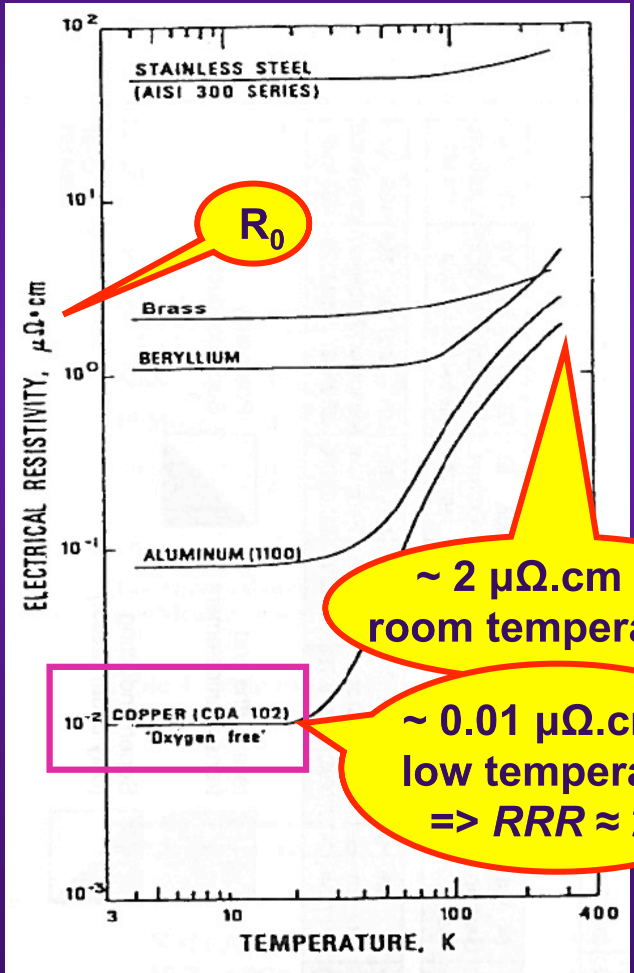


Figure 2: Resistivity of several metals vs T.

(See for instance the "Handbook of Accelerator Physics and Engineering", 2nd Printing, Edited by A.W. Chao and M. Tigner, p. 368)

- **Assuming** $\rho_0\left(20\ \mathrm{K}\right) = 1.55 \times 10^{-10}\ \Omega\mathrm{m}$, $RRR = 100$

=> $\rho\left(0.535\ \mathrm{T}, 20\ \mathrm{K}\right) \approx 1.8 \times 10^{-10}\ \Omega\mathrm{m}$

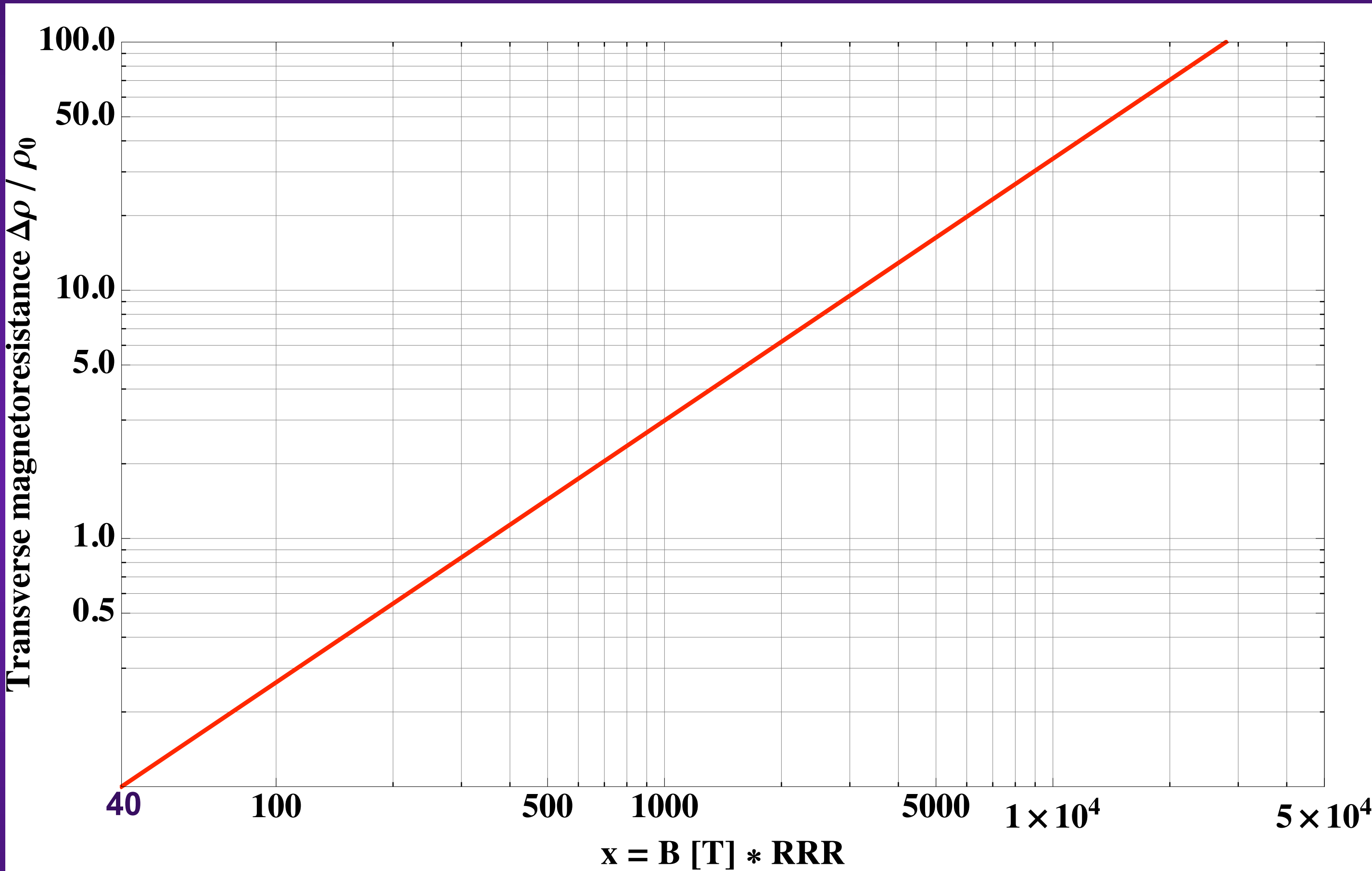
$\rho\left(8.33\ \mathrm{T}, 20\ \mathrm{K}\right) \approx 5.5 \times 10^{-10}\ \Omega\mathrm{m}$

- **Using the same formula, yields for 20 T:**

$$\rho\left(20\ \mathrm{T}, 20\ \mathrm{K}\right) \approx 11.2 \times 10^{-10}\ \Omega\mathrm{m}$$

MAGNETO-RESISTANCE (3/13)

- Plot of the approximate formula (of the approximate Kohler's rule)



- **0.535 T**

  $x = 53.5$

  $\Delta\rho / \rho_0 \approx 0.14$

- **8.33 T**

  $x = 833$

  $\Delta\rho / \rho_0 \approx 2.5$

- **20 T**

  $x = 2000$

  $\Delta\rho / \rho_0 \approx 6.2$

MAGNETO-RESISTANCE (4/13)

- Reminder on Kohler's rule (See "Kohler's rule and relaxation rates in high-Tc superconductors" by Nie Luo and G.H. Miley, Physica C 371 (2002) 259-269)
  - It is shown in this paper that care must be exercised when applying Kohler's rule to the magnetoresistance of some conductors (including high Tc-superconductors), where the density of charge carriers might change with temperature
  - Kohler's rule may take 2 forms:
    - One exact
    - One approximate
  - EXACT Kohler's rule

If there is only 1 relaxation rate in the transport process of a certain conductor => $\Delta\rho / \rho_0 = F\left(H\,\tau\right)$, which is generally a tensor

Function given only by the intrinsic electronic structure and external geometry of the conductor

Resistivity when H = 0

Magnetic field

Relaxation rate (or time)

MAGNETO-RESISTANCE (5/13)

- **APPROXIMATE Kohler's rule**
  - Reminder on the link between relaxation time and DC resistivity under 0 magnetic field => Use Ohm's law for a wire carrying the current density $\vec{J}$ to get the resistivity in terms of the relaxation time

    - Equation of motion for 1 e⁻

e⁻ charge

e⁻ mass

$$m \frac{d\vec{v}}{dt} = -e\,\vec{E} - \alpha\,\vec{v}$$

$$\alpha = \frac{m}{\tau}$$

Relaxation time

    - Permanent regime (DC)

$$\frac{d\vec{v}}{dt} = 0$$

$$\vec{J} = -N\,e\,\vec{v} = \sigma_{DC}\,\vec{E}$$

=>

$$\sigma_{DC} = \frac{N\,e^2}{\alpha}$$

Density of carriers

or

$$\rho_0 = \frac{1}{\sigma_{DC}} = \frac{m}{N\,e^2\,\tau}$$

MAGNETO-RESISTANCE (6/13)

- The exact Kohler's rule can then be re-written

$$\frac{\Delta\rho}{\rho_0} = F\left(\frac{H}{\rho_0} \times \frac{m}{N\,e^2}\right)$$

- IF the factor $\frac{m}{N\,e^2}$ does not change with temperature, then Kohler's rule can be simplified to

$$\frac{\Delta\rho}{\rho_0} = F\left(\frac{B}{\rho_0}\right)$$

$$B = \mu_0\,H$$

Most of the problem comes from N which could be very sensitive to T in various conductors…

Kohler's rule in its approximate but often used form

MAGNETO-RESISTANCE (7/13)

- $$RRR = \frac{R(273\,\mathrm{K})}{R(\mathrm{T})} = \frac{\rho_0(273\,\mathrm{K})}{\rho_0(\mathrm{T})}$$

= Cte for Copper

=> $$\rho_0 = \rho_0(T) \propto \frac{1}{RRR}$$

=> $$\frac{\Delta\rho}{\rho_0} = F(B \times RRR)$$

This is the form of Kohler's law used for instance in the "Handbook of Accelerator Physics and Engineering", 2nd Printing, Edited by A.W. Chao and M. Tigner, p. 368

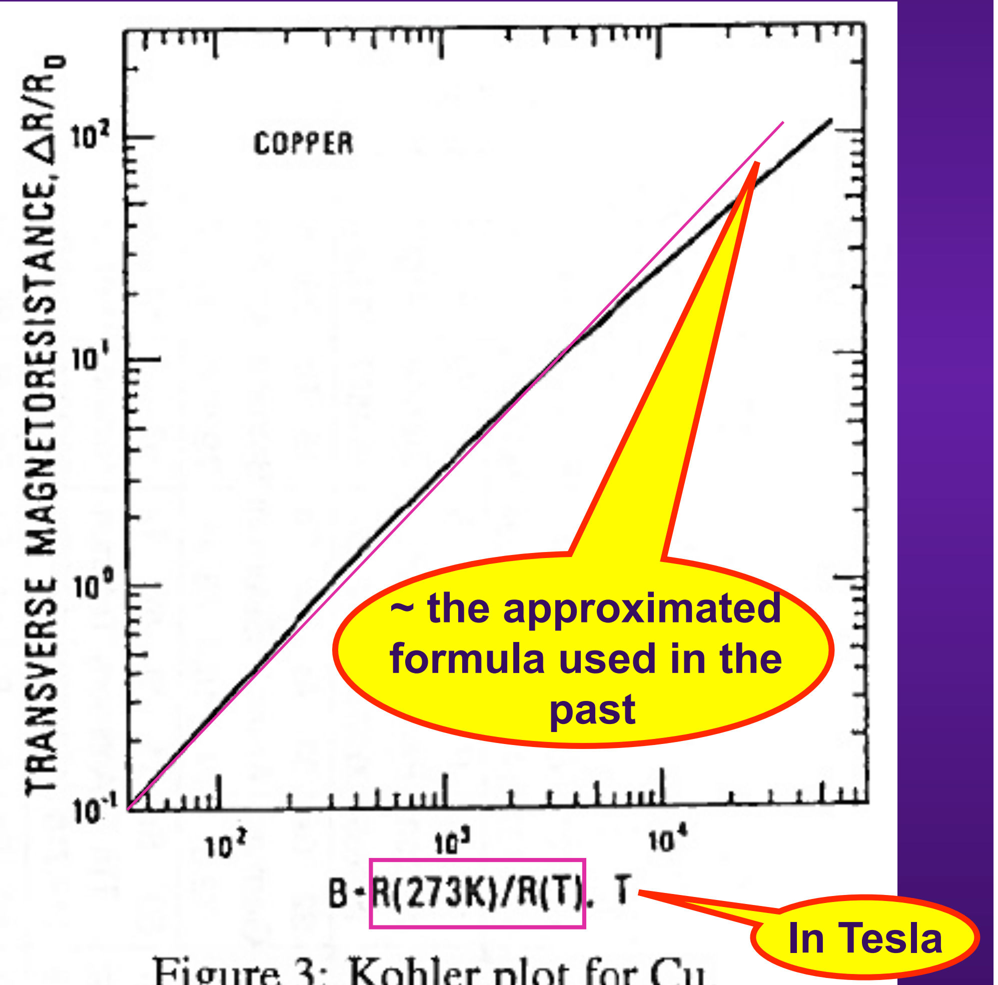
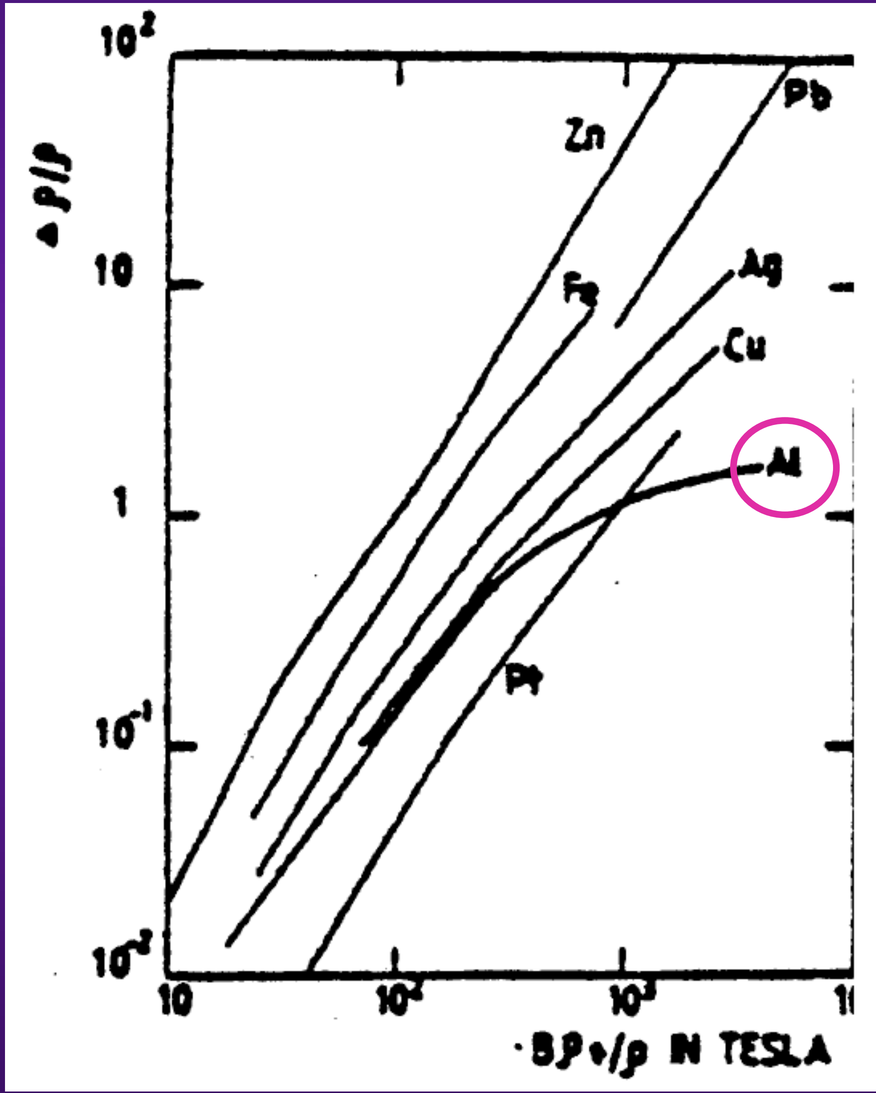


Figure 3: Kohler plot for Cu.

MAGNETO-RESISTANCE (8/13)

- **Al is one of the few materials which deviates from Kohler's rule (see "Beam Vacuum Chamber Effects in the CERN Large Hadron Collider" by L. Vos, 1985)**



MAGNETO-RESISTANCE (9/13)

- Experimental observations => Always an increase in resistance when increasing magnetic field:
  - For small B fields => $\rho \propto B^2$
  - For very high B fields => $\rho \propto B$

- Why an increase in resistance?

MAGNETO-RESISTANCE (10/13)

- **MEAN FREE PATH:**
  - The mean free path λ of a particle is the average distance covered by a particle (photon, atom or molecule) between successive impacts: $\lambda = v\,\tau$ ($v_{average}$). As $\rho_0 = \frac{m}{N\,e^2\,\tau}$, this leads to $\lambda = \frac{m\,v}{e^2\,N\,\rho_0}$

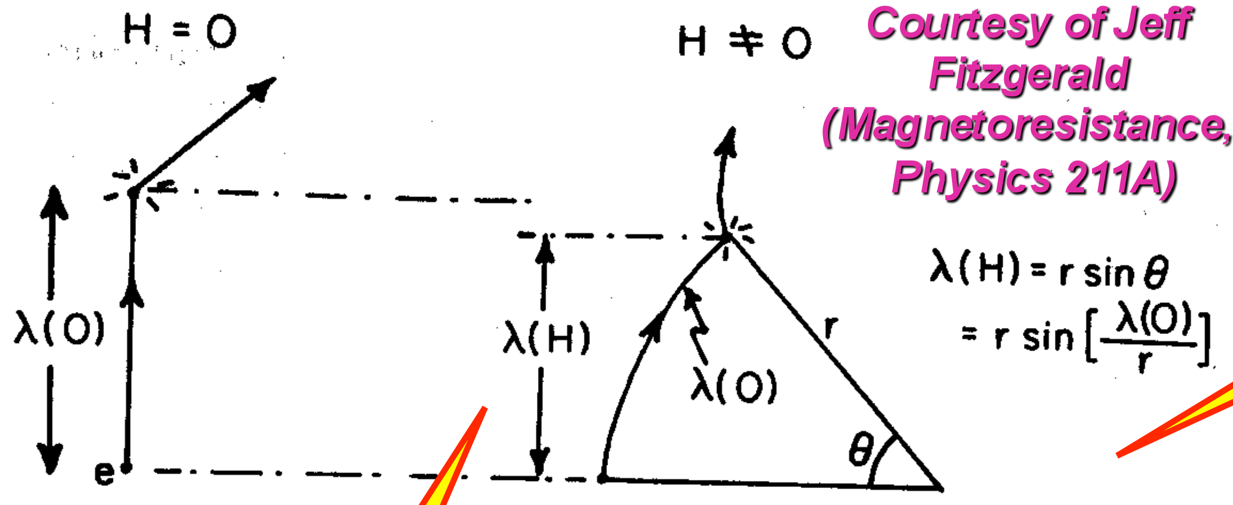
- **CYCLOTRON RADIUS and FREQUENCY:**
  - A particle, with a constant energy, describes a circle in equilibrium between the centripetal magnetic force and the centrifugal force

$$\frac{m\,v^2}{r} = e\,v\,B \quad \Rightarrow \quad r = \frac{m\,v}{e\,B} \quad \text{and} \quad \omega = \frac{v}{r} = \frac{e\,B}{m}$$

Cyclotron radius — Cyclotron frequency

$$\Rightarrow \quad \frac{B}{\rho_0} \propto \frac{\lambda}{r}$$

MAGNETO-RESISTANCE (11/13)



Courtesy of Jeff Fitzgerald (Magnetoresistance, Physics 211A)

For small B fields

$$\sin(x) \approx x - \frac{x^3}{3!}$$

=> $$\lambda(H) \approx \lambda(0) \times \left\{ 1 - \frac{1}{6} \times \left[\frac{\lambda(0)}{r} \right]^2 \right\}$$

A smaller λ means a larger ρ!

=> $$\frac{\Delta\rho}{\rho_0} = -\frac{\Delta\lambda}{\lambda_0} \propto \left[\frac{\lambda(0)}{r} \right]^2 \propto \left[\frac{B}{\rho_0} \right]^2$$

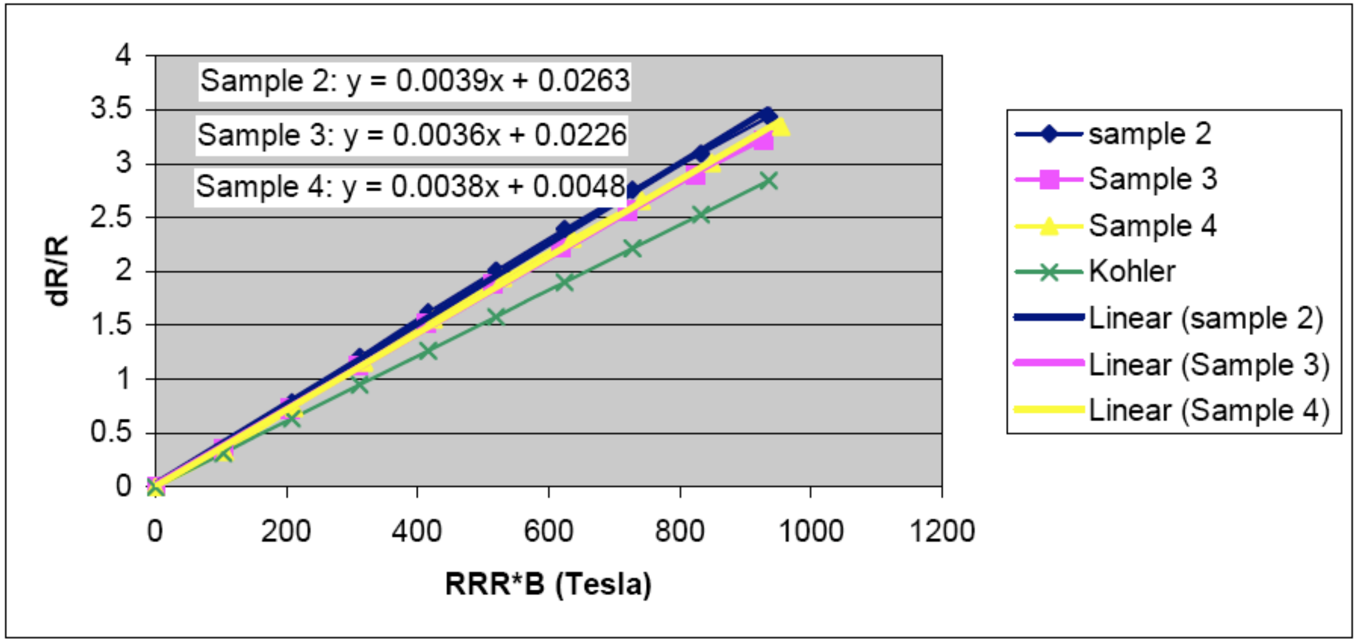
MAGNETO-RESISTANCE (12/13)

- **Electrical measurements of beam screen wall samples in magnetic fields were performed in the past (see for instance EDMS # 329882 by C. Rathjen):**
  - **Meas. showed that the trend line slopes of the voltage for all samples are always higher (around 20%) than the theoretical curves**

Graph: dR/R vs. RRR*B for samples 2, 3 and 4:

Courtesy of C. Rathjen

In this graph appears the theoretical curve of dR/R vs. RRR*B for OFE copper, found in Outokumpu copper literature (Kohler).



MAGNETO-RESISTANCE (13/13)

- Meas. confirmed the assumption of a heterogeneous RRR in the co-laminated copper layer => Cu close to the steel gets contaminated during the fabrication process such that the surface impedance is increased. The increase of the resistance has been compensated by increasing the thickness of the copper layer from 50 to 75 microm

ANOMALOUS SKIN EFFET (1/8)

- **The ASE theory attributes the anomalous increase of surface resistance of metals at low temperatures and high frequencies to the long mean free path λ of the conduction e^- => When the skin depth δ becomes much smaller than the mean free path λ, only a fraction of the conduction e^- moving almost parallel to the metal surface is effective in carrying current and the classical theory breaks down**

- **Some measurements were performed (see "Surface Resistance Measurements of LHC Dipole Beam Screen Samples, F. Caspers et al., EPAC2000), which were in relatively good agreement with predictions**

ANOMALOUS SKIN EFFET (2/8)

- **Reminder on the Normal Skin Effect (NSE): skin depth and surface resistance**

$$\delta = \sqrt{\frac{2\,\rho}{\omega\,\mu_0}}$$

$$R_s^{\mathrm{NSE}} = \frac{\rho}{\delta} = \sqrt{\frac{\omega\,\mu_0\,\rho}{2}}$$

- **Approximate formula for the surface resistance with ASE used in the past (See "Anomalous Skin Effect and Resistive Wall Heating", W. Chou and F. Ruggiero, LHC Project Note 2 (SL/AP), when** $\alpha \geq 3$

$$\alpha = \frac{3}{2}\left(\frac{\lambda}{\delta}\right)^2 = \frac{3\,\omega\,\mu_0}{4\,\rho^3}\left(\rho\,\lambda\right)^2$$

$$R_s^{\mathrm{ASE}} = R_\infty\left(1 + 1.157\,\alpha^{-0.276}\right)$$

$$\rho\,\lambda = \frac{m\,v}{e^2\,N} = \text{characteristic of the metal}$$

$$= 6.6 \times 10^{-16}\ \Omega\mathrm{m}^2 \text{ for copper}$$

Independent of T and impurity

$$R_\infty = \left[\frac{\sqrt{3}}{16\,\pi} \times \rho\,\lambda \times \left(\omega\,\mu_0\right)^2\right]^{1/3} = 1.123 \times 10^{-3}\ \Omega \times \left(\frac{f}{\mathrm{GHz}}\right)^{2/3}$$

ANOMALOUS SKIN EFFET (3/8)

- **Relative increase of the heating power**

$$\frac{P_{ASE}}{P_{NSE}} = \frac{\int_{\omega=0}^{\omega=+\infty} d\omega \, R_s^{ASE}(\omega) \, e^{-\left(\frac{\omega \sigma_z}{c}\right)^2}}{\int_{\omega=0}^{\omega=+\infty} d\omega \, R_s^{NSE}(\omega) \, e^{-\left(\frac{\omega \sigma_z}{c}\right)^2}}$$

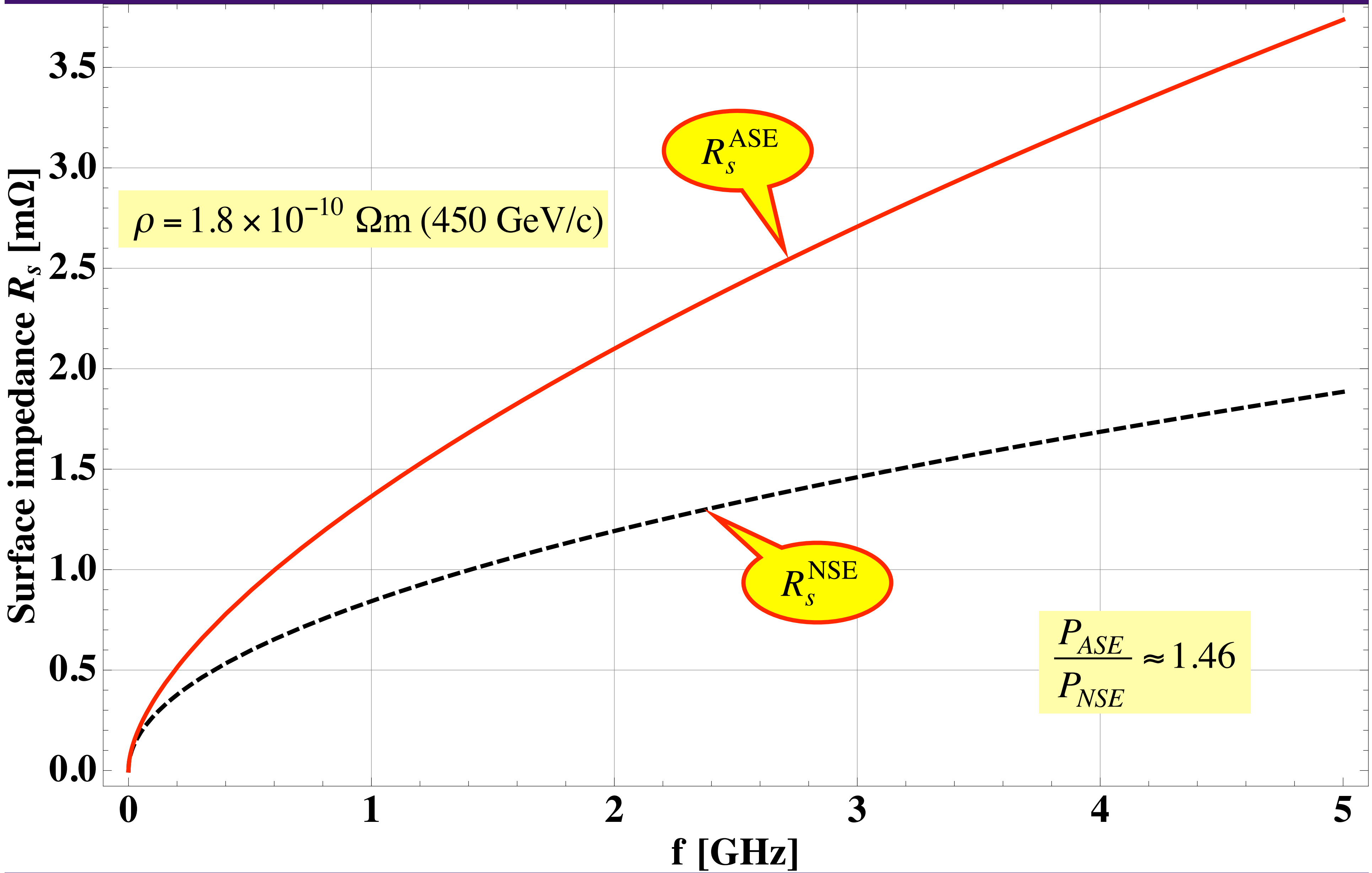
$\sigma_z = 7.5$ cm

$\rho = 1.8 \times 10^{-10}$ Ωm (450 GeV/c) => $\frac{P_{ASE}}{P_{NSE}} \approx 1.46$, i.e. increase of ~ 46%

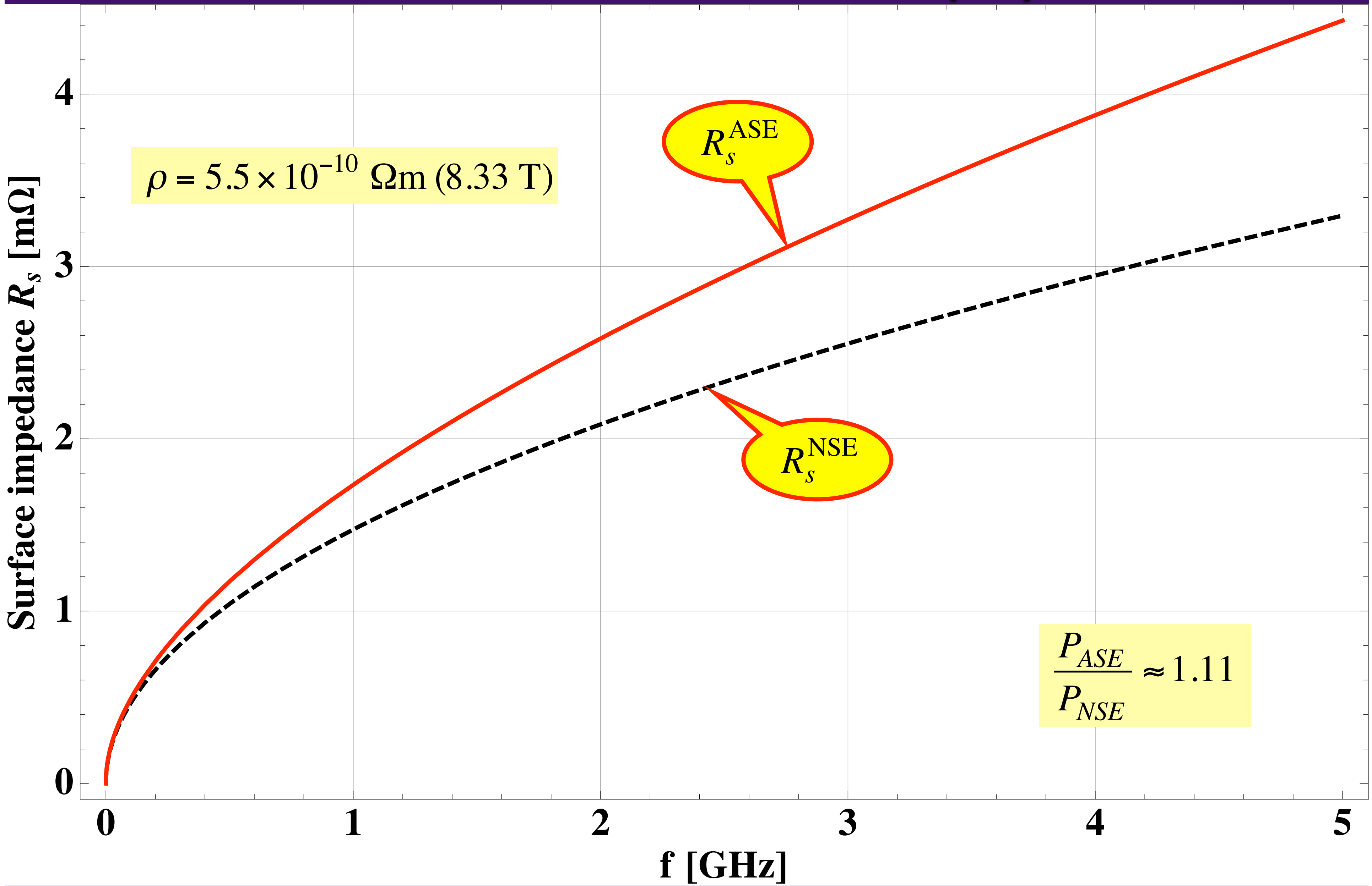
$\rho = 5.5 \times 10^{-10}$ Ωm (8.33 T) => $\frac{P_{ASE}}{P_{NSE}} \approx 1.11$, i.e. increase of ~ 11%

$\rho = 11.2 \times 10^{-10}$ Ωm (20 T) => $\frac{P_{ASE}}{P_{NSE}} \approx 1.04$, i.e. increase of ~ 4%

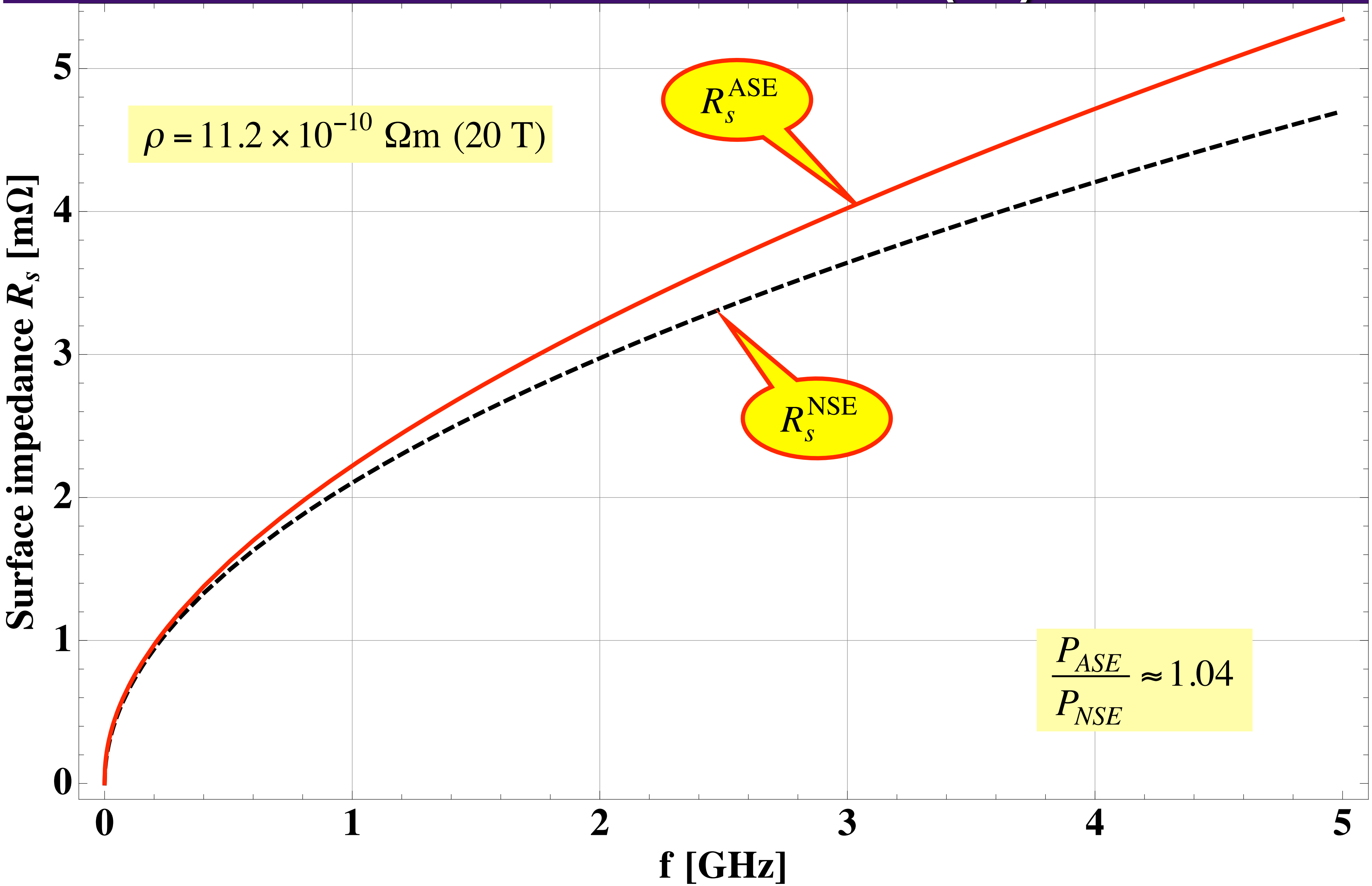
ANOMALOUS SKIN EFFET (4/8)



ANOMALOUS SKIN EFFET (5/8)

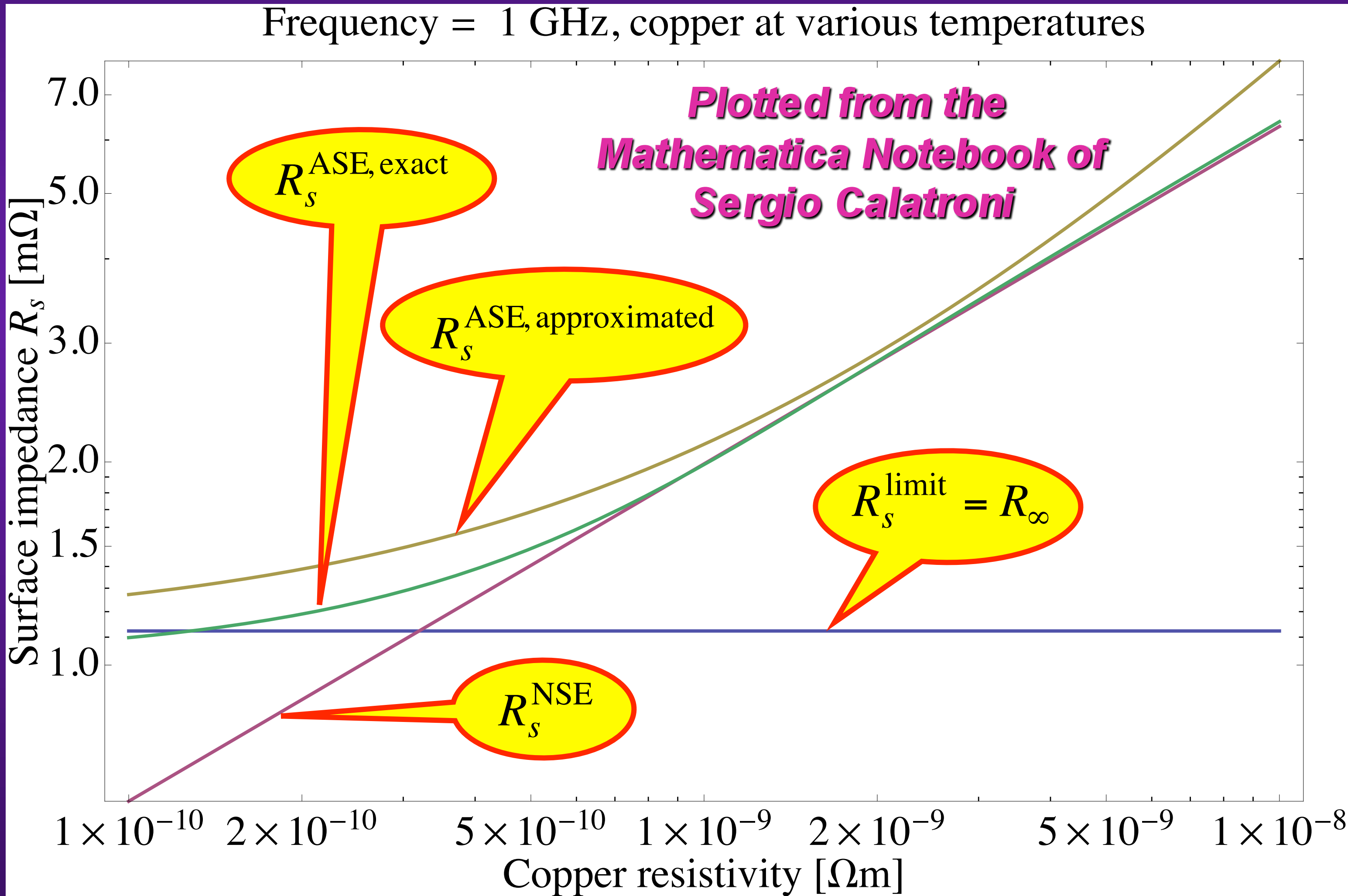


ANOMALOUS SKIN EFFET (6/8)

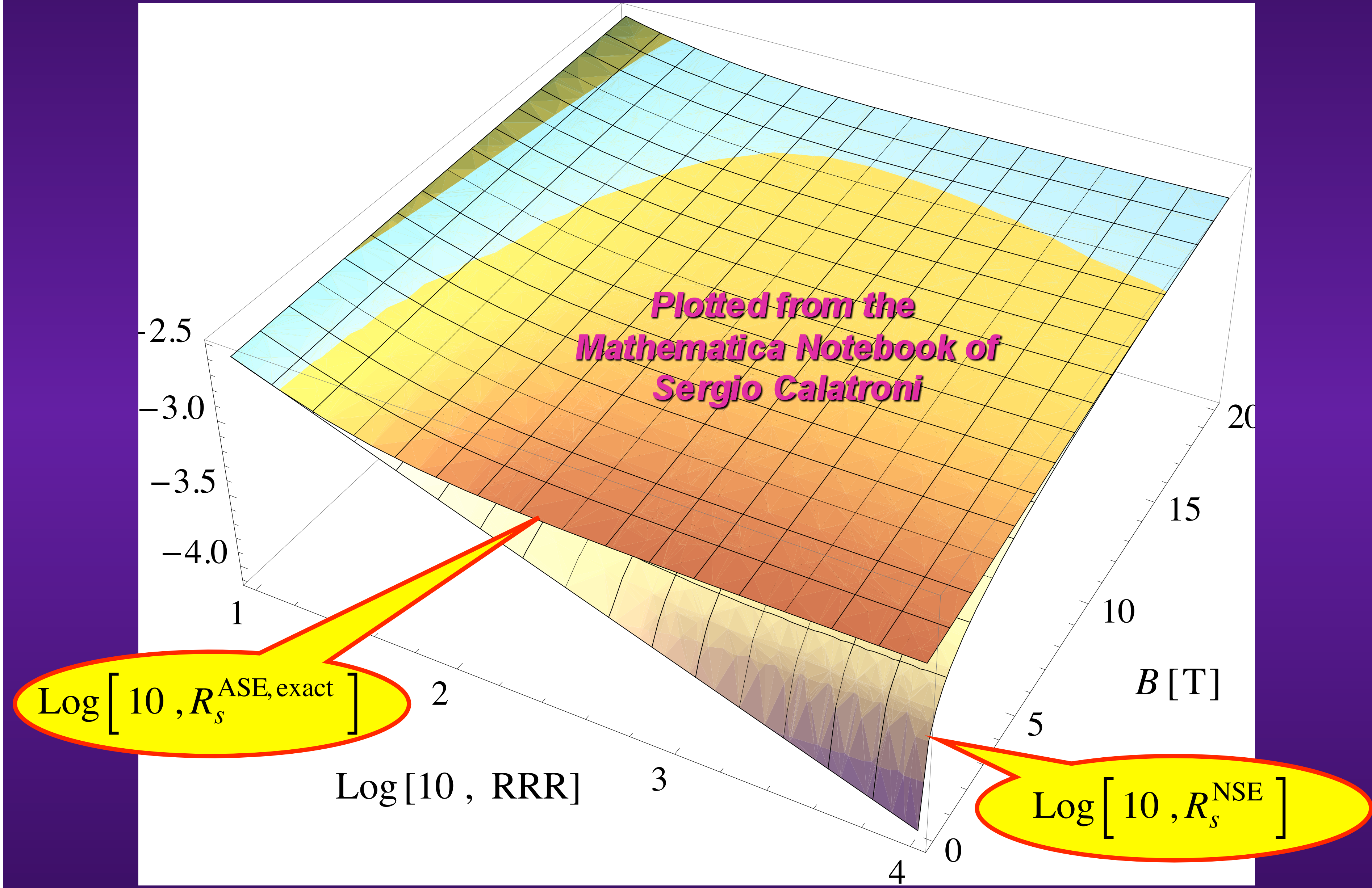


ANOMALOUS SKIN EFFET (7/8)

- Sergio Calatroni implemented the exact (full) formula from "The theory of the anomalous skin effect in metals" by G.E.H. Reuter and E.H. Sondheimer, Proc. Royal Society (London), A195, 336 (1948) => For the specular reflection of the e^-



ANOMALOUS SKIN EFFET (8/8)



CONCLUSIONS AND OUTLOOK

- In the LHC at 20 T, we are dominated by the magnetic field and we can neglect the rest! => The resisivity at top energy will increase from ~ 5.5E-10 Ωm (at 7 TeV) to ~ 11.2E-10 Ωm (at 16.5 TeV), i.e. by a factor ~2

- The longitudinal and transverse impedances are $\propto \sqrt{\rho}$
=> They are $\sqrt{2} \approx 1.4$ times larger

- The total (ohmic losses + pumping slots + welds) present power loss is ~ 150 mW/m for 1 beam at 7 TeV/c => At 16.5 TeV/c, it would be ~ 175 mW/m

- Other impedance issues: Collimators, whose gaps will be smaller and the TMCI might be critical! Reminder: At 7 TeV/c, the TMCI intensity threshold is estimated at (only) ~ 2 times the ultimate intensity…

APPENDICES

CURRENT LHC BEAM SCREEN (1/6)

Arc beam screens:

Inner dimension between flats:	36.8 mm
Inner dimension between radii:	46.4 mm
SS thickness:	1.0 mm
Cu thickness:	0.075 mm

LSS beam screens:

Inner dimension between flats:	varying from 37.6 until 61.0 mm
Inner dimension between radii:	varying from 47.2 until 70.7 mm
SS thickness:	0.6 mm
Cu thickness:	0.075 mm

Courtesy of N. Kos

CURRENT LHC BEAM SCREEN (2/6)

Resistance SS at room temp:	7E-7 ohm.m
RRR SS:	1.2
Low temp resistance SS:	7E-7/1.2 = 6E-7 ohm.m
Resistance copper at room temp:	2E-8 ohm.m
RRR Cu (co-laminated surface):	100
Low temp Cu resistance:	2E-8/100 = 2E-10 ohm.m

In contrast to pure metals, the resistivity of alloys does not decrease much at low temperature

Without magnetic field. In the past, we used 1.8E-10 Ωm at low B and 5.5E-10 Ωm at high B (due to magneto-resitance effect)

Courtesy of N. Kos

- Bunch charge (for nominal) $Q = e \times 1.15 \times 10^{11} = 18.4\ \text{nC}$
- Rms bunch length $\sigma_z = 7.5\ \text{cm}$
- Bunch spacing $S_b = 7.5\ \text{m}$
- Cold bore inner radius $d = 2.5\ \text{cm}$
- Covered surface from the holes
  - In the arcs: f = 4.0%
  - In the LSS: f = from 1.8% to 2.6% (depends on screen *Φ*)

CURRENT LHC BEAM SCREEN (3/6)

- The power loss goes with the square of the bunch charge => It is ~ 2 times more for the ultimate bunch (1.7E11 p/b) compared to the nominal one (1.15E11 p/b)

- Power loss

F. Ruggiero, CERN SL/95-09 (AP) (http://cdsweb.cern.ch/record/279204/files/sl-95-009.pdf)

Table 10: Summary of parasitic losses for LHC at 7 TeV.

Power loss [kW]	FOR A SINGLE BEAM	Power loss per unit length [mW/m]
3.67	Incoherent synchrotron radiation	216
$\ll$ 0.54	Coherent synchrotron radiation	$\ll$ 32
1.97	Resistive wall (20° K)	74
0.27	Welds	10
0.26	Pumping slots	10
< 0.80	Shielded bellows	< 30
$\ll$ 1.03	Leaks in bellows gaps	$\ll$ 38
8.54	TOTAL	410

Theoretical computation with a previous design

Meas. of LHC dipole beam screen samples without magnetic field + extrapolation

Table 5.7: Summary of heat load on the arc beam screen for nominal LHC beam at 7 TeV. The three columns give the source, the latest relevant reference, and the peak heat load in mW/m.

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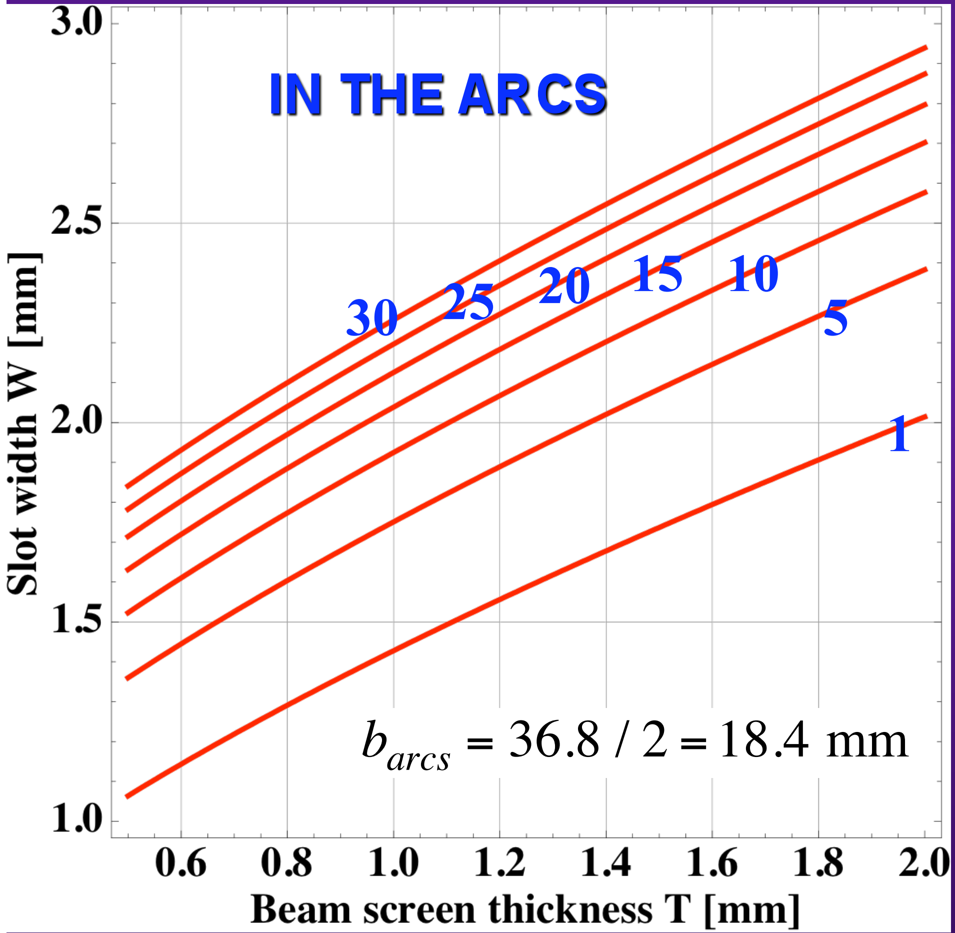
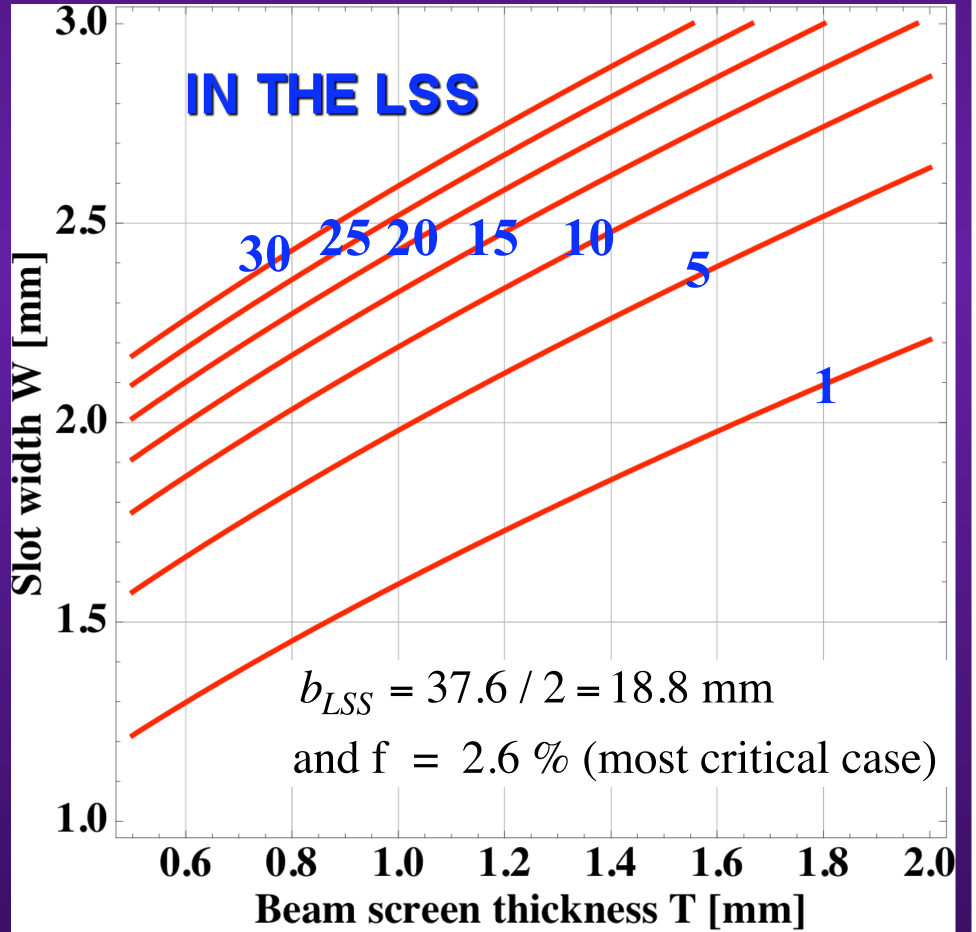
LHC Design Report, Vol. 1, Chap. 5 (https://edms.cern.ch/file/445833/5/Vol_1_Chapter_5.pdf)

CURRENT LHC BEAM SCREEN (4/6)

- Using A. Mostacci's Mathematica Notebook (*wwwslap.cern.ch/collective/mostacci/slots/note/slots.nb*), and updating the numerical values (only small changes), these curves were produced (curves of constant power in mW/m vs. the beam screen thickness T and the width of the slots W)





CURRENT LHC BEAM SCREEN (5/6)

- The current parameters of the beam screen are
  - Length of the slots: L = 6,7,8,9 and 10 mm => Laverage = 8 mm
  - Width of the slots:
    - In the arcs: W = 1.5 mm
    - In the LSS: W = 1.0 mm
  - Beam screen thickness:
    - In the arcs: T = 1 mm SS + 0.075 mm Cu = 1.075 mm
    - In the LSS: T = 0.6 mm SS + 0.075 mm Cu = 0.675 mm

=> Power loss from the holes in the arcs: $P_{arcs} \approx 1.1$ mW/m

Power loss from the holes in the LSS: $P_{LSS} \approx 0.1$ mW/m

In the most critical case

CURRENT LHC BEAM SCREEN (6/6)