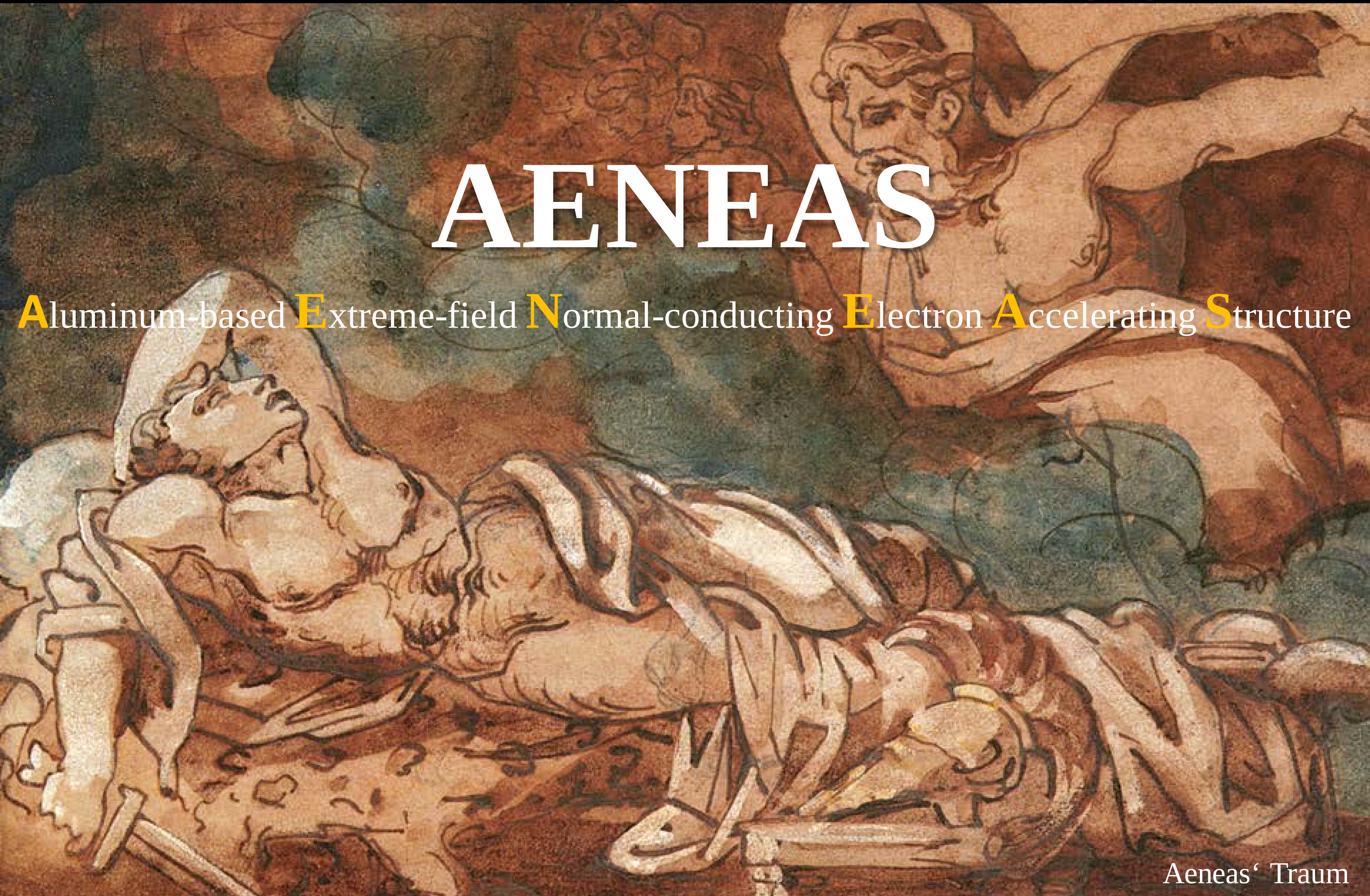
Contribution to the soap „wild and romantic physics“:

AENEAS

Aluminum-based **E**xtreme-field **N**ormal-conducting **E**lectron **A**ccelerating **S**tructure



Aeneas‘ Traum

Wolfgang Hillert

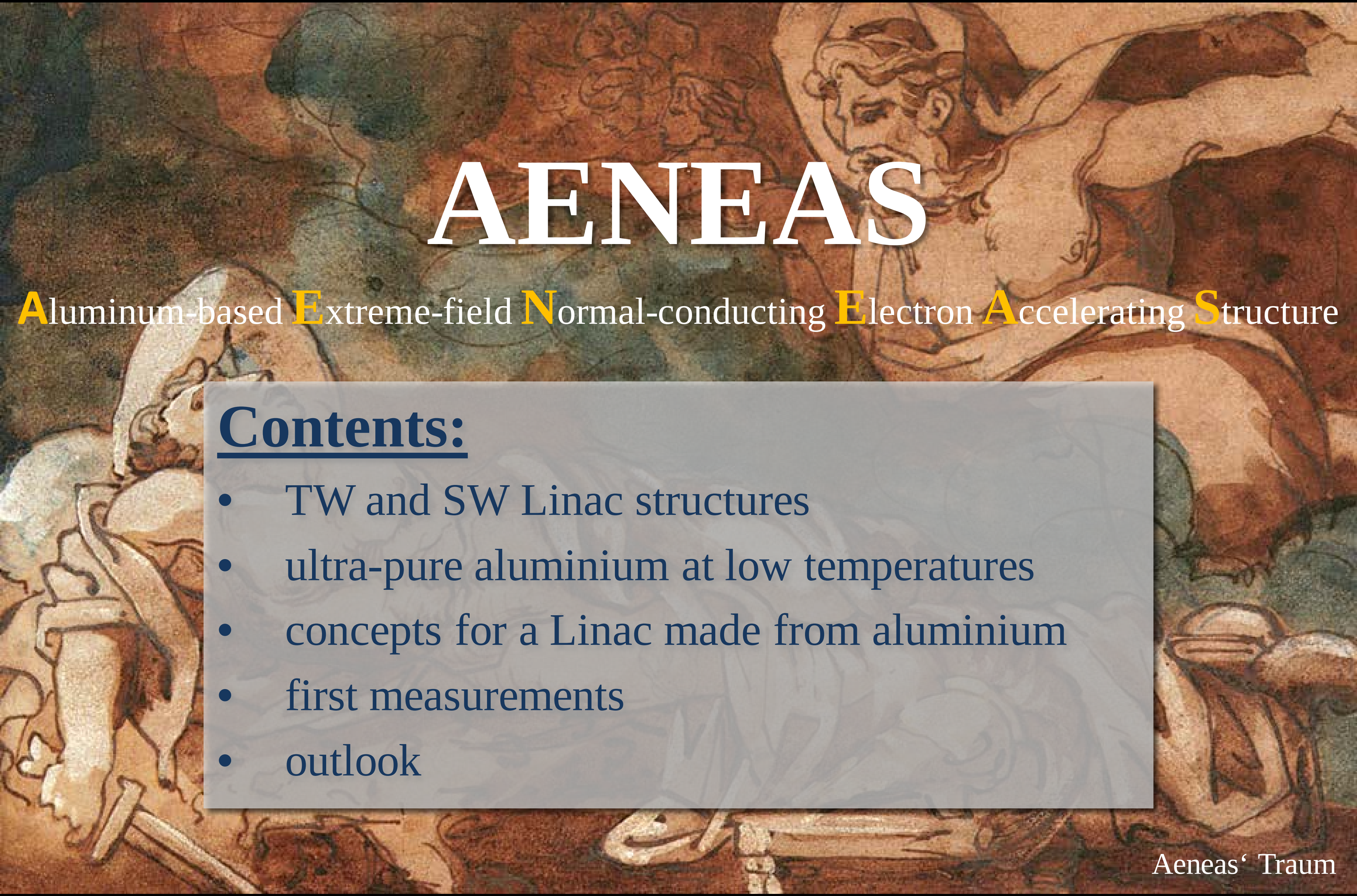
Contribution to the soap „wild and romantic physics “:

AENEAS

Aluminum-based **E**xtreme-field **N**ormal-conducting **E**lectron **A**ccelerating **S**tructure

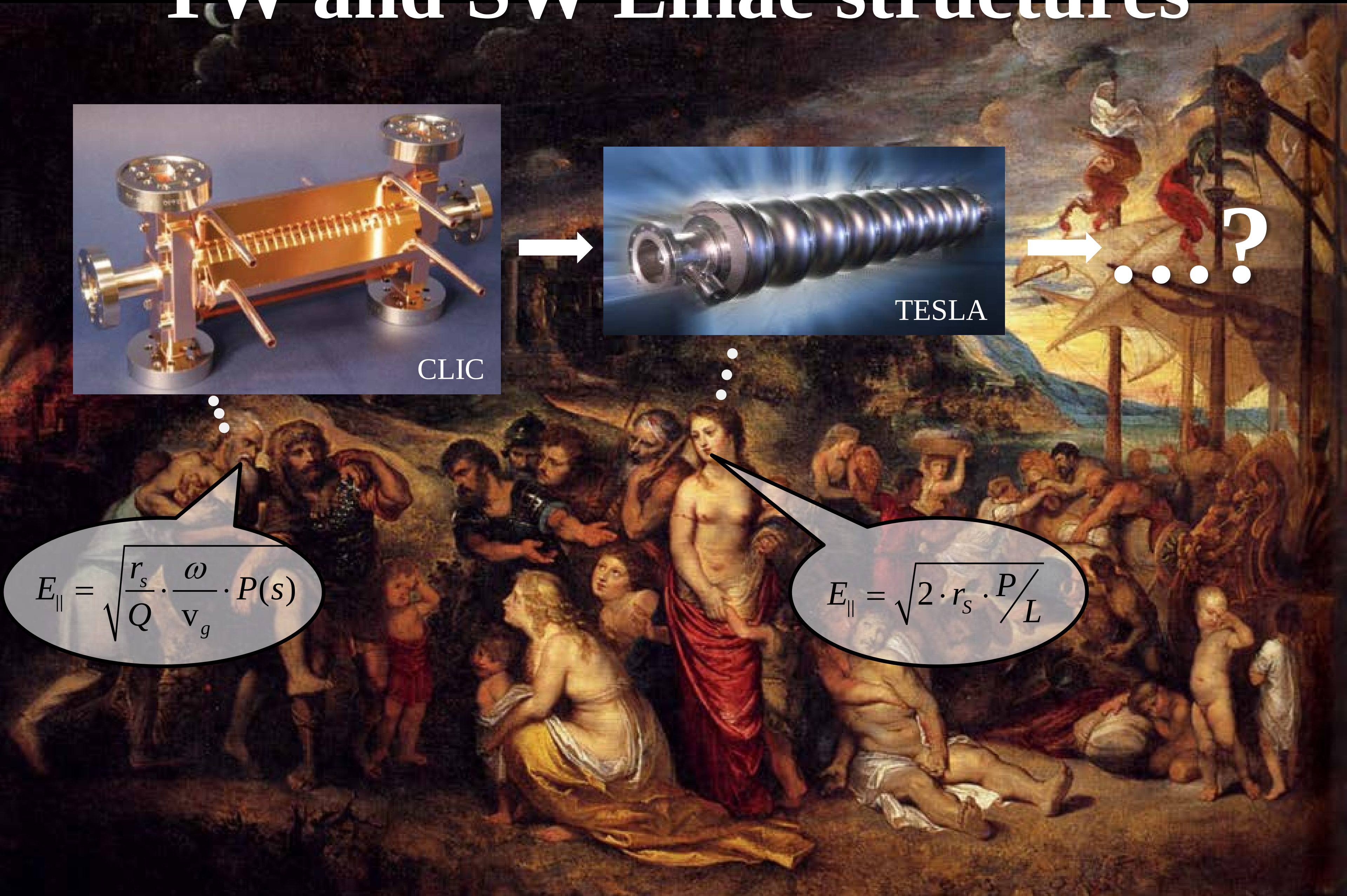
Contents:

- TW and SW Linac structures
- ultra-pure aluminium at low temperatures
- concepts for a Linac made from aluminium
- first measurements
- outlook



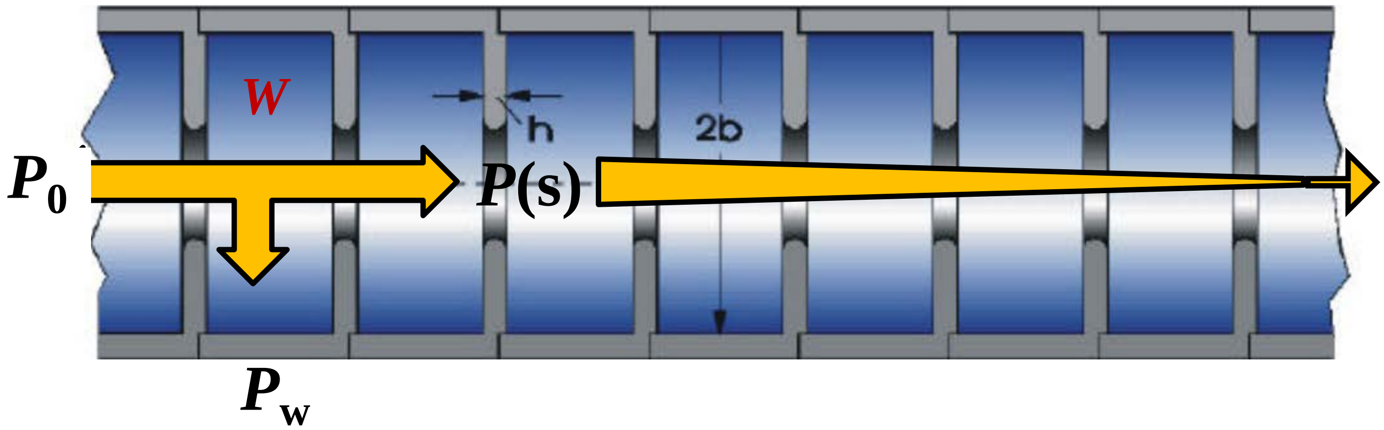
Aeneas‘ Traum

TW and SW Linac structures



Abreise von Aeneas und seiner Familie von Troja

Travelling Waves in an iris-loaded Waveguide (Runzelröhre)



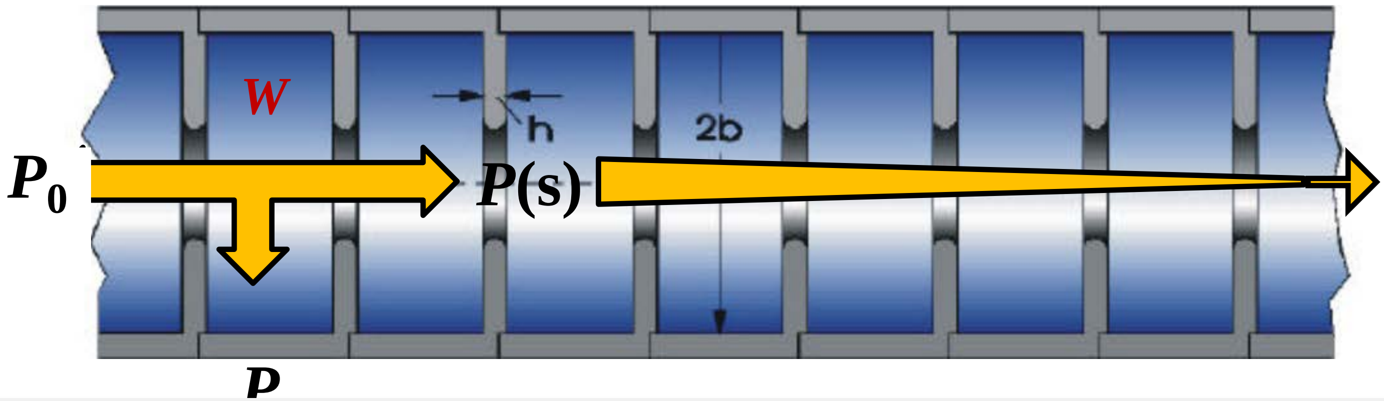
<u>Energy diffusion equation</u>:

$$\frac{\partial W}{\partial t} + \frac{\partial P}{\partial s} + P_w + I_b E_{\parallel} = 0$$

where:

where:	W	=	stored energy per unit length,
	P	=	energy flux along s,
	P_w	=	wall losses per unit length,
	$I_b E_{\parallel}$	=	energy transferred to the beam.

Travelling Waves in the Runzelröhre



Parameters and their link:

$$Q = \frac{\omega W}{P_W}, \qquad P_W = \frac{\hat{E}_{||}^{\,2}}{r_S}$$

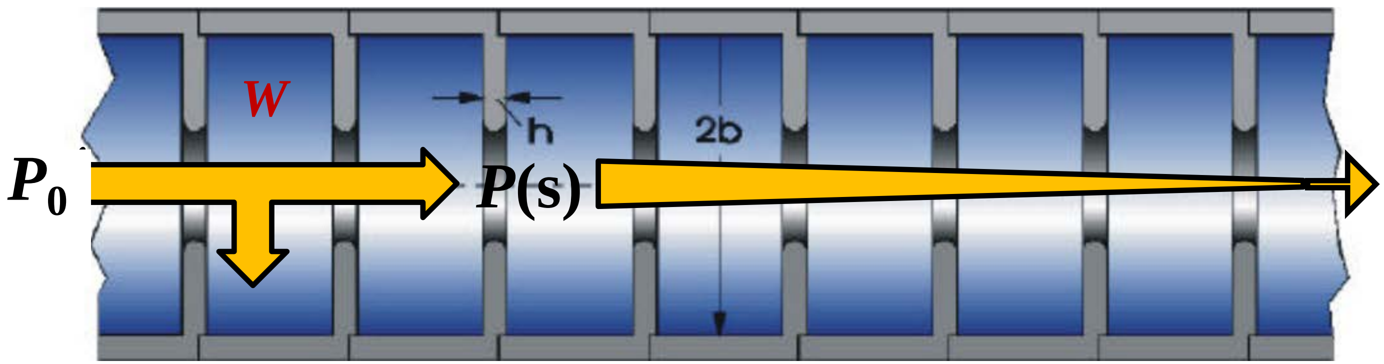
Energy flux along the structure, damping length:

$$P = \mathrm{v}_g \cdot W \qquad l_0 = \frac{2\,\mathrm{v}_g\,Q}{\omega}$$

Energy dissipation:

$$P_W = \frac{\omega}{\mathrm{v}_g Q} \cdot W \cdot \mathrm{v}_g = \frac{\omega}{\mathrm{v}_g Q} \cdot P = \frac{2}{l_0} \cdot P$$

Travelling Waves in the Runzelröhre



Example.: E=100MV/m, ω =2π·12GHz, P =68MW → $v_g \approx 0.015 \cdot c$!!!

Energy diffusion equation:

$$\frac{\partial W}{\partial t} + \frac{\partial P}{\partial s} + P_w + I_b E_{\parallel} = 0$$

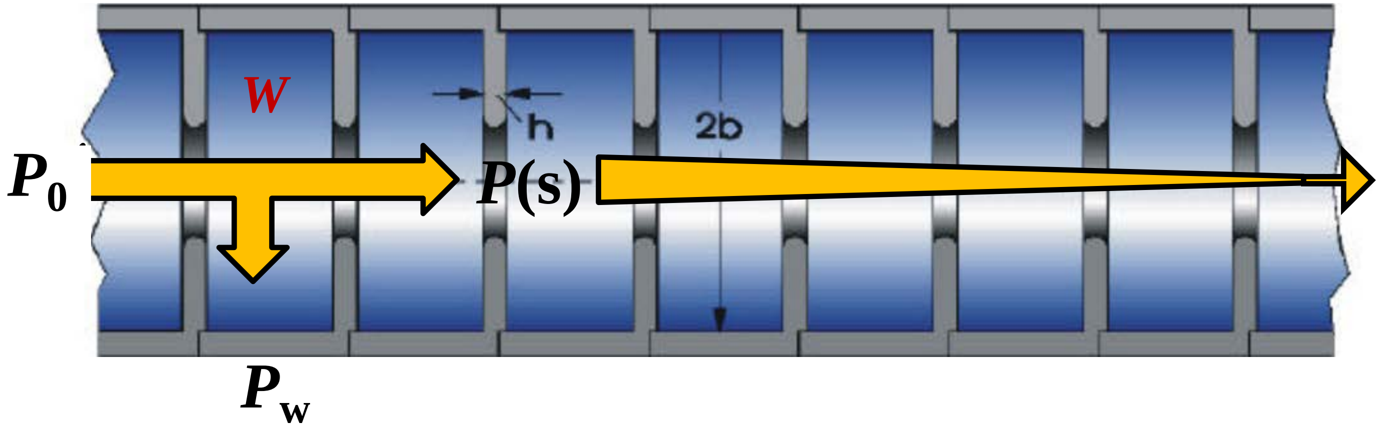
$$P_w = \frac{2}{l_0} \cdot P$$

$$l_0 = \frac{2 v_g Q}{\omega}$$

$$r_S = \frac{\hat{E}_{\parallel}^2}{P_W} = \frac{l_0 \hat{E}_{\parallel}^2}{2P} \quad \Rightarrow \quad E_{\parallel} = \hat{E}_{\parallel} \cdot \cos\psi = \sqrt{\frac{2 r_S}{l_0} P} = \sqrt{\frac{r_S}{Q} \cdot \frac{\omega}{v_g} \cdot P(s)}$$

Acc. field $E_{\parallel}$ does not depend on electrical properties of material!!!

Constant Gradient Structure:

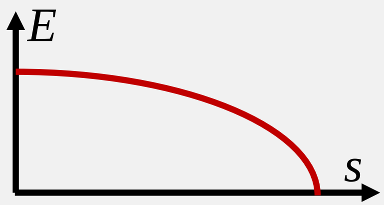


Energy diffusion equation with beam loading:

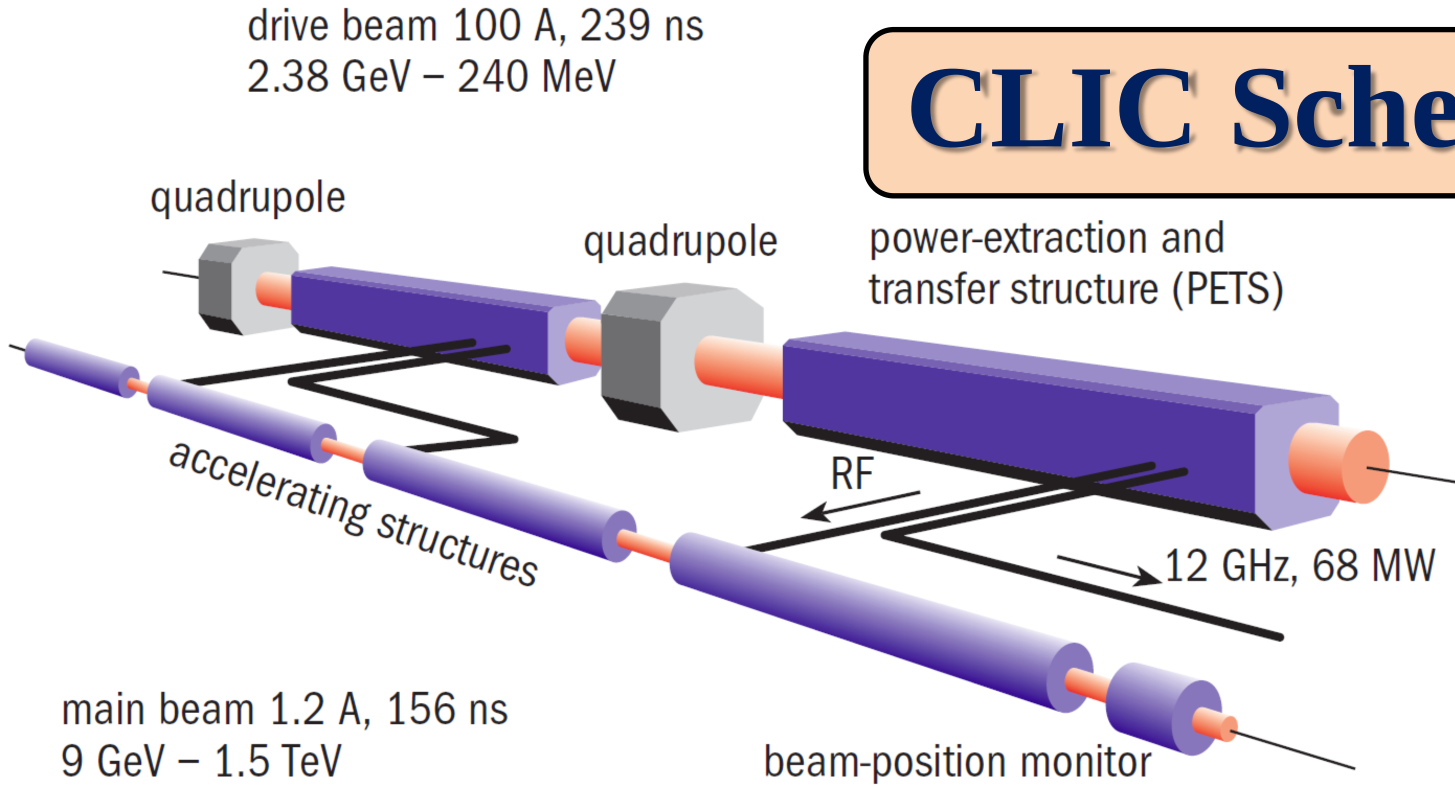
$$\cancel{\frac{\partial W}{\partial t}} + \frac{\partial P}{\partial s} + P_w + I_b E_{\parallel} = 0$$

After „lengthy“ calculations (c.f. script of lecture acc. physics):

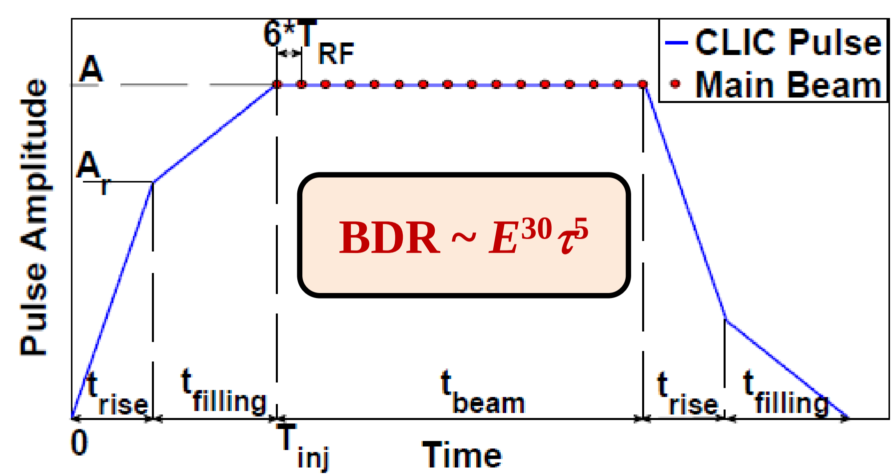
$$\boxed{E_{\parallel}(s) = E_0 + \frac{1}{2} r_S I_b \cdot \ln\left\{1 - \frac{s}{L}\left(1 - e^{-2\tau}\right)\right\}}$$



CLIC Scheme:



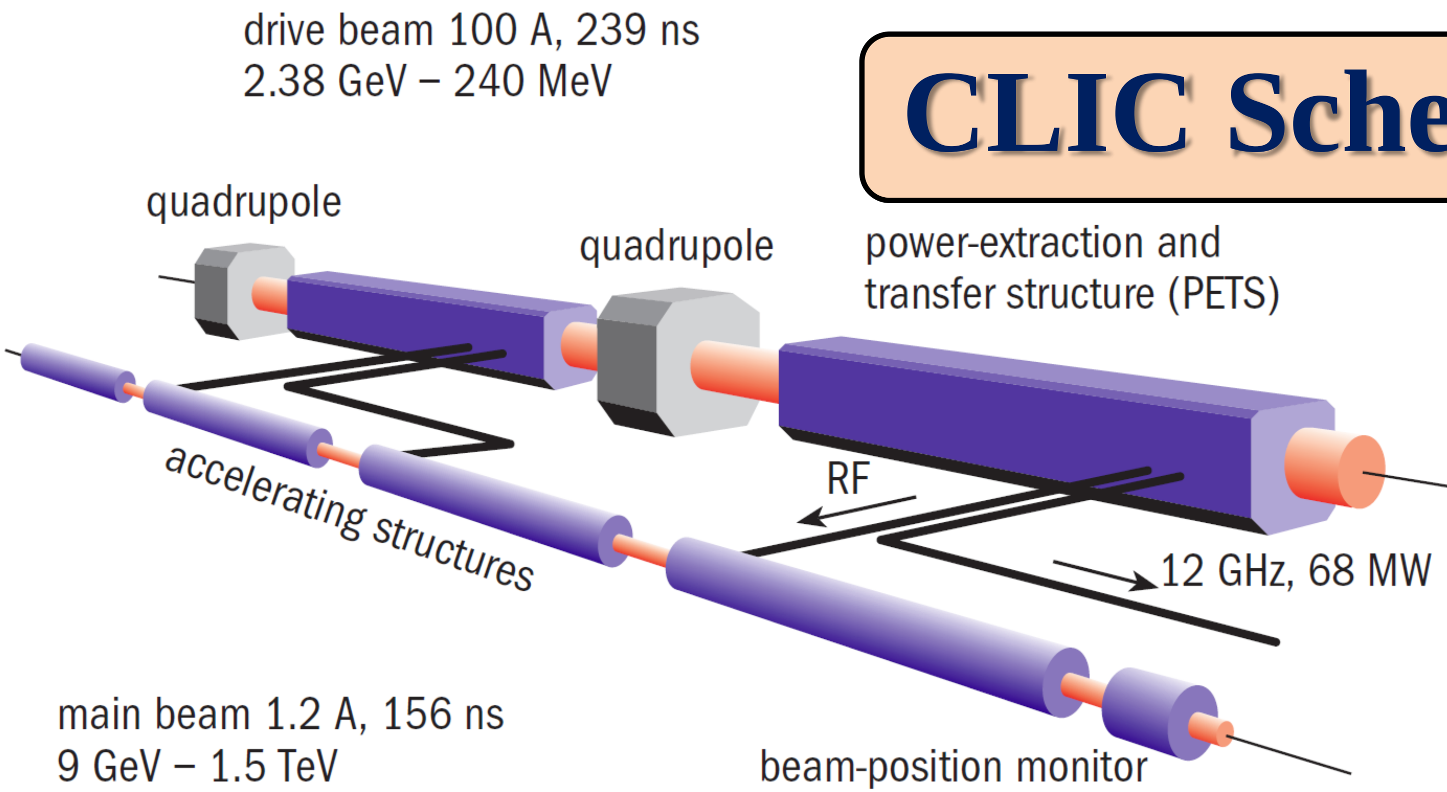
CLIC PULSE SHAPE OPTIMIZATION



<u>Compensation of beam loading:</u>

→ dedicated RF drive!

CLIC Scheme:

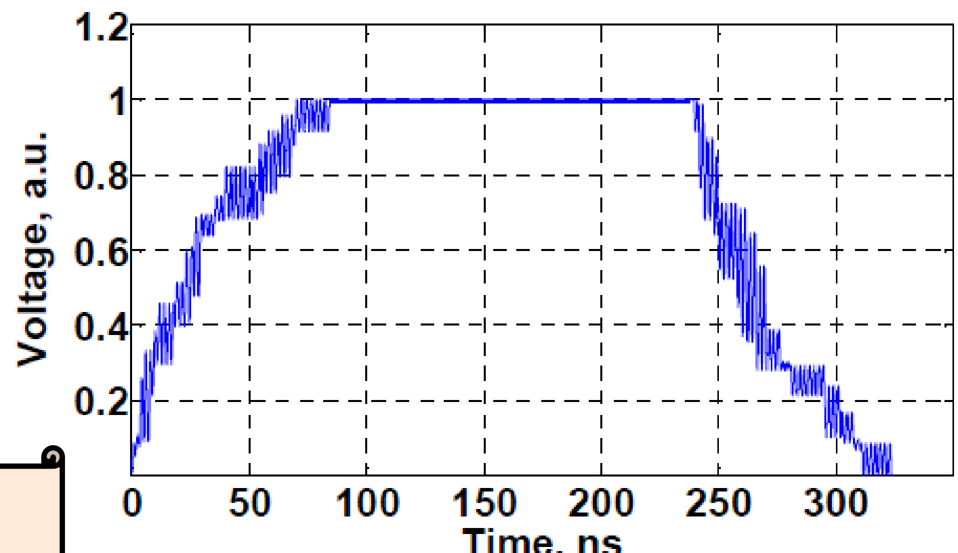


Compensation of beam loading:

→ dedicated RF drive!

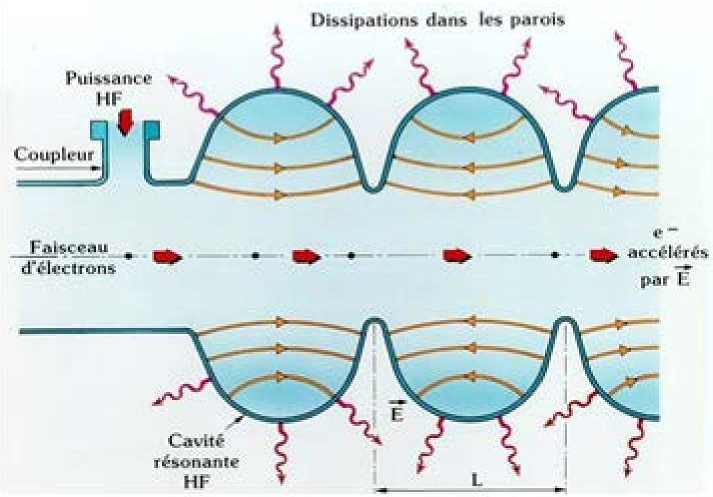
→ fill time ≈ 80ns ↔ structure length!!

design: *L* = 23cm (incl. coupler!)



No gain from higher *Q* values!!!

Standing Waves in the Fridge



Dynamics determined completely by beam loading:

Optimum coupling: $$\kappa_{opt} = 1 + \frac{P_{beam}}{P_{wall}}$$

„hopeless“ overcritical coupled!

The high κ approach:

- Typical quality factors $Q \approx 10^{10} \rightarrow$ resonance width ca. 0.1 Hz!!!
- R_S comes for free, therefore optimimization for low crit. fields
- Strong overcritical coupling causes many advantages:
  - broad resonance curve by ext. loading / Q_{ext} of typ. 10^5 - 10^6
  - no influence on dissipation, R_S remains unchanged
  - no reflection when operating with design beam current
  - reduction of structure filling time: $\tau = \frac{Q_l}{\omega_0} = \frac{Q_0}{(1+\kappa)\omega_0}$

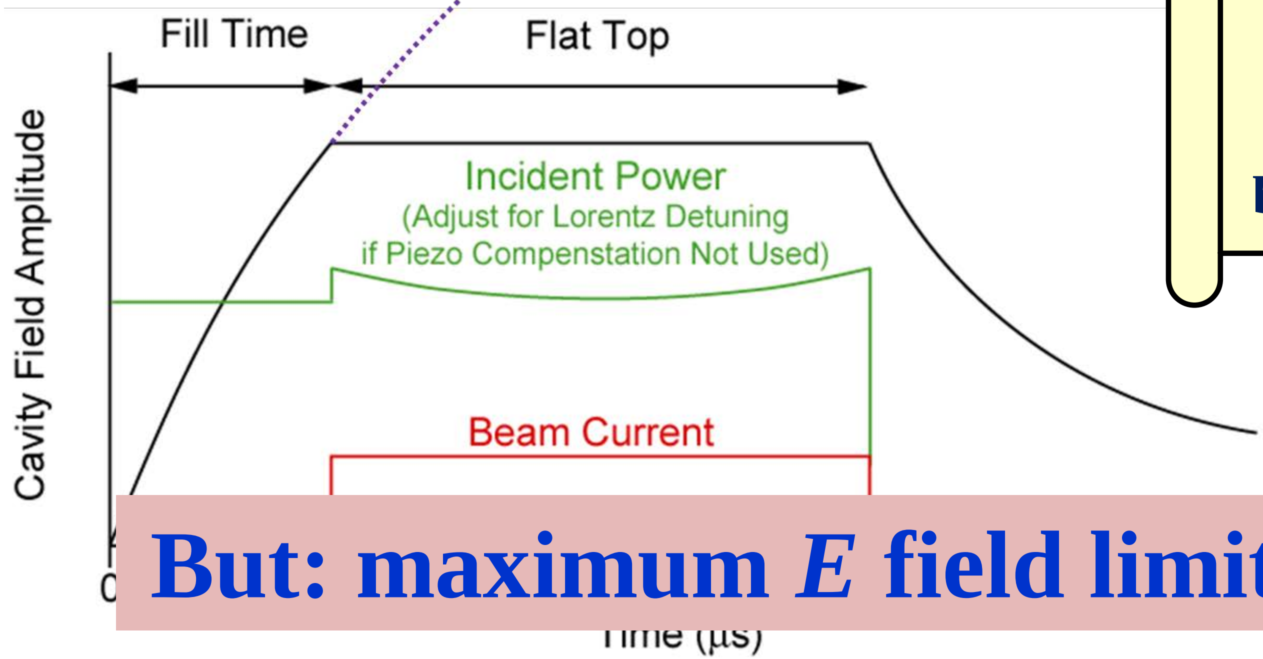
Fill Times ↔ Pulse Lengths

Generator power for field generation: $P_{Gen} = \frac{(1+\kappa)^2}{4\kappa} \cdot \frac{U^2}{2R_S} \approx \frac{\kappa}{4} \cdot \frac{U^2}{2R_S}$

Generator power for acceleration: $P_{Gen} \approx U \cdot I_{beam} = \frac{U \cdot I_{beam}}{P_{wall}} \cdot P_{wall} \approx \kappa \cdot \frac{U^2}{2R_S}$

$$E(t) = E_{\max} \cdot \left(1 - e^{-\frac{t}{2\tau}}\right), \quad \tau = \frac{Q}{\omega_0}$$

Generator power has to be increased by factor of 4 for beam acceleration!!



But: maximum *E* field limited by H_C

Ultra-pure Aluminium at low Temperatures

Die Leitfähigkeit eines freien Elektronengases in einem Phononenbad nach der statistischen Thermodynamik irreversibler Prozesse

Von RUDOLF KLEIN

Aus dem Institut für Theoretische Physik der Technischen Hochschule Braunschweig

(Z. Naturforschg. **18 a**, 1351—1359 [1963]; eingegangen am 3. Oktober 1963)

The formulation of the many-body problem by MARTIN and SCHWINGER is applied to a system of free electrons interacting with a phonon bath. Simplifying the general expression for the wave vector and frequency dependent complex conductivity to the case of a static dc situation the conductivity is expressed in terms of the LAPLACE transform of an appropriate GREEN's function. By means of a simple diagram method a transport equation for this function is derived. In the lowest approximation the solution of this equation gives the BLOCH–GRÜNEISEN law for the conductivity of metals at low temperatures.

In der bekannten Theorie der elektrischen Leitfähigkeit in Metallen benutzt man die BOLTZMANN-Gleichung. Die Herleitung dieser Gleichung enthält wichtige Annahmen [1], den „Stoßzahlansatz", bzw. in der quantenmechanischen Behandlung die „repeated random phase approximation", sowie die Voraussetzung der schwachen Kopplung zwischen Elektronen und Gitter.

Aus diesen Gründen hat man versucht, die elektrische Leitfähigkeit auf andere Weise zu behandeln, zum Teil, um zu sehen, in welcher Näherung einer allgemeinen Theorie die früher hergeleiteten Ergebnisse herauskommen, und zum anderen, um neue Ausdrücke für die Leitfähigkeit zu bekommen, die nicht auf den Fall schwacher Kopplung beschränkt sind. Diese enthalten die Kopplungskonstanten in höheren Potenzen. So leiteten KOHN und LUTTINGER [2] die BOLTZMANN-Gleichung aus der Bewegungsgleichung für die Dichtematrix her und zeigten im Fall elastischer Streuung an Verunreini-

[1] R. E. PEIERLS, The Quantum Theory of Solids, Clarendon Press, Oxford 1955.

[2] W. KOHN u. J. A. LUTTINGER, Phys. Rev. **108**, 590 [1957].

From R. Klein, last Pages:

Dazu tritt noch die Lösung der homogenen Gleichung. Man macht sich leicht klar, daß diese Lösung zur Leitfähigkeit nichts beiträgt, ganz analog zu der Situation bei der Behandlung dieses Problems mit Hilfe einer die BOLTZMANN-Gleichung erfüllenden Verteilungsfunktion.

Damit ist

$$\sigma = \frac{e^2 \beta}{6\, m^2} \sum_{p} p^2\, n_p\, n_{\bar{p}}\, \tau(p) + \text{k. k.} \qquad (61)$$

Diesen Ausdruck bringt man leicht auf die bekannte Form

$$\sigma = \frac{e^2\, n}{m}\, \tau(p_0)\ , \qquad (62)$$

wo p_0 der FERMI-Impuls und n die Anzahl der Elektronen pro cm^3 ist. Dabei macht man Gebrauch von

$$F(p_0) = -\int_0^\infty dp\, \frac{\partial n_p}{\partial p}\, F(p) = \frac{2\,\pi^2 \beta}{m} \sum_{p} n_p\, n_{\bar{p}}\, \frac{1}{p}\, F(p)\,, \qquad (63)$$

wobei $\partial n_p/\partial p$ in der ersten Gleichung als reine δ-Funktion angesehen wird und $F(p)$ eine stetige Funktion ist. Wir wollen $\tau(p_0)$ berechnen, um das so entstandenen Gleichung für $1/\tau(p_0)$ werden in Integrale verwandelt. Das Integral über $\boldsymbol{p}$ ist einfach, da die Faktoren $n_p\, n_{p+k}$ und $n_{p+k} n_p$ δ-funktionsartig sind. Das Integral über $\boldsymbol{k}$ ist unter der Berücksichtigung von $g^2(\boldsymbol{k}) \sim |\boldsymbol{k}|$ proportional dem auch bei SOMMERFELD und BETHE [14] auftretenden Integral

$$J_5\left(\frac{\Theta}{T}\right) = \int_0^{\Theta/T} \frac{\eta^5\, d\eta}{(e^{\eta}-1)\,(1-e^{-\eta})}\ .$$

Auf diese Weise ergibt sich schließlich

$$\tau(p_0) = \frac{9\, M\, N\, \pi\, p_0^3\, s^6}{m\, C^2 (k_B\, T)^5\, J_5(\Theta/T)}\ ,$$

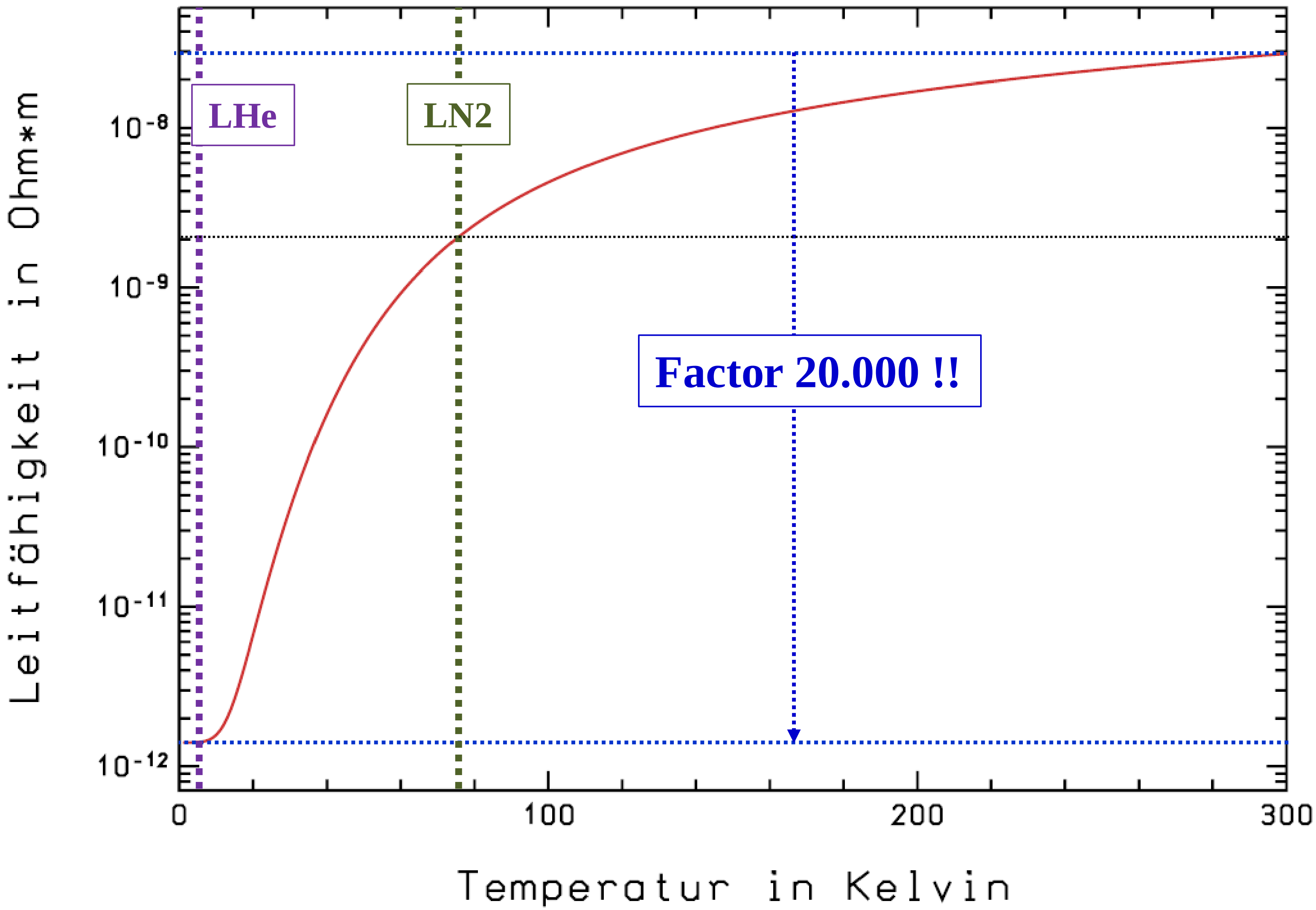
was mit Gl. (62)gerade das BLOCH–GRÜNEISEN-Gesetz darstellt.

Die hier hergeleitete Transportgleichung, die das bekannte Widerstandsverhalten liefert, ist prinzipiell einfach auszudehnen auf den Fall der frequenzabhängigen Leitfähigkeit und andererseits auch auf höhere Näherungen in der Kopplung, wo man also

[14] A. SOMMERFELD u. H. BETHE, Handbuch der Physik, Bd. 24, Teil II, Springer-Verlag, Berlin 1933.

Resistance from Grüneisen Law

$$\sigma(T) = \sigma(4K) + K_{GE} \cdot \left(\frac{T}{\Theta}\right)^5 \cdot \int_0^{\Theta/T} \frac{t^5 dt}{\left(e^t - 1\right)\left(1 - e^{-t}\right)} \quad mit \quad K_{GE} = \frac{\sigma(293K)}{\left(293K/\Theta\right)^5} \cdot \int_0^{\Theta/239K} \frac{t^5 dt}{\left(e^t - 1\right)\left(1 - e^{-t}\right)}$$



Desillusion 1st Part

Key Parameters for Accelerating Structures

Quick scan of textbook literature:

- Skin depth: $\delta = \sqrt{\dfrac{2}{\mu_0 \omega_0 \sigma}} \approx 7{,}5\,\text{nm} \;\; @ \;\; 6\,\text{GHz} \;\&\; 4\,\text{K}$
- Surface resistance: $R_{sf} = \dfrac{1}{\sigma\delta} = \sqrt{\dfrac{\mu_0 \omega_0}{2\sigma}}$ scales with the square root!!!
- Quality factor: $Q_0 = \dfrac{j_0 \cdot Z_0}{2R_{sf}\left(1 + {r}/{L}\right)}, \quad \text{with:} \quad Z_0 = \sqrt{\dfrac{\mu_0}{\varepsilon_0}}, \quad r = \text{radius}, \quad L = \text{length}$
- Shunt impedance: $R_S = 2\dfrac{\left(Z_0 \cdot L\right)^2}{\pi^3 \cdot r^2 \cdot R_{sf} \cdot J_1(j_0) \cdot \left(1 + {L}/{R}\right)}$

However: a factor > 100 remains! No H_C!!!

Useful Approaches

Venus zeigt Aeneas Waffen

IEEE Transactions on Nuclear Science, Vol.NS-24, No.3, June 1977

PARALLEL COUPLED CAVITY STRUCTURE*

R. M. Sundelin, J. L. Kirchgessner, and M. Tigner
Laboratory of Nuclear Studies, Cornell University
Ithaca, New York 14853

Summary

A parallel coupled RF cavity structure which provides favorable solutions to all of the requirements for use in an e^+e^- storage ring is described. Properties of this structure have been determined mathematically and through measurements on S-band models. An L-band prototype is being constructed and will be tested at high power.

Introduction

An RF cavity structure suitable for use in Cornell's proposed CESR e^+e^- storage ring must satisfy a number of requirements. These are summarized in Table I.

TABLE I STRUCTURE REQUIREMENTS
Operate at 500 MHz
Maximize shunt impedance in the available space (four spaces, 6 meters each)
Minimize number of separately powered modules
Avoid passband mode overlap
Minimize sensitivity of amplitude and phase to individual cell frequency errors
Obtain intrinsic thermal stability
Provide adequate cooling
Provide simple means for tuning the structure to compensate for loading by the beam
Provide sufficient loading of all important TM_0 and TM_1 modes to prevent cavity-induced instabilities

shows the equivalent circuit of the structure. All cells, shown as R, L, and C, are effectively in series with the coupling line at half-wavelength intervals. The coupling iris adds an effective inductance L' in series with each cell.

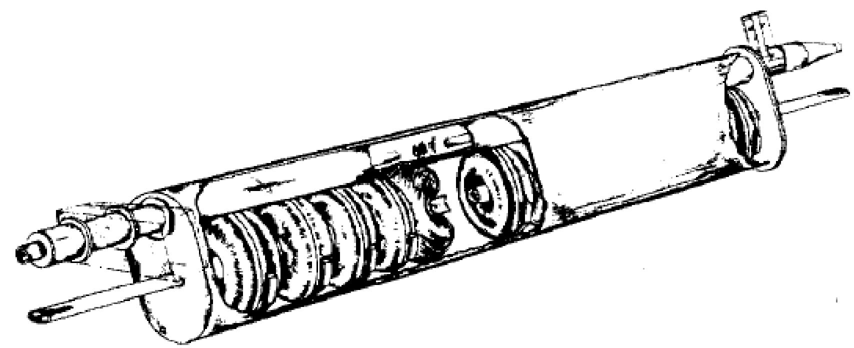
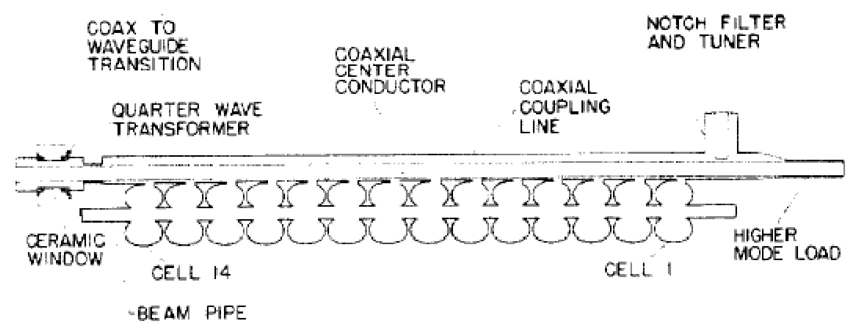


Fig. 1. Parallel coupled cavity structure, including water tank used for cooling.



PARALLEL-COUPLED ACCELERATING STRUCTURES

O. N. Brezhnev, P. V. Logatchev, V. M. Pavlov, O. V. Pirogov, S. V. Shiyankov,
BINP, Novosibirsk, Russia
Ju. D. Chernousov, V. I. Ivannikov, I. V. Shebolaev,
Institute of Chemical Kinetic and Combustion, Novosibirsk, Russia

LINAC‘02

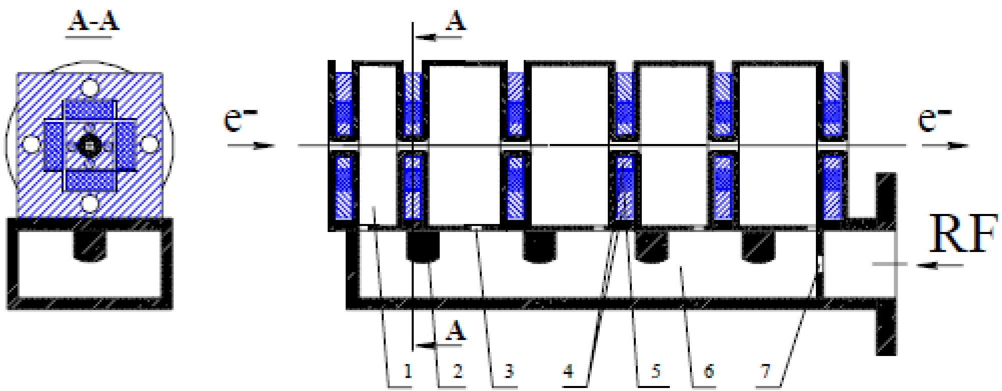
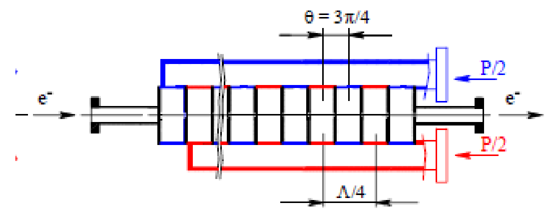


Figure 2. Scheme of the accelerating structure.
1 – accelerating cavity, 2 – capacity protuberance, 3 – coupling slot, 4 – symmetrized magnetic circuit, 5 – magnets, 6 – transmission-type cavity, 7 – input coupling hole.

The accelerating cavities (1) are excited from the transmission-type cavity (6) through coupling slots (3) in the common wall. Excitation of the whole system is carried out through a coupling hole (7). The transmission-type cavity (6) represents a cut of the rectangular wave-guide, operated on H_{104} -mode. The wave-guide is loaded

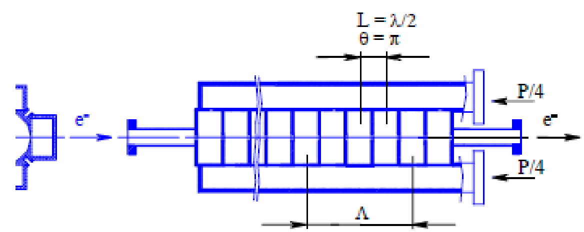
(b)

$\Lambda = 3\lambda$



(d)

$\Lambda = 2\lambda$



with rectangular feeding waveguides.

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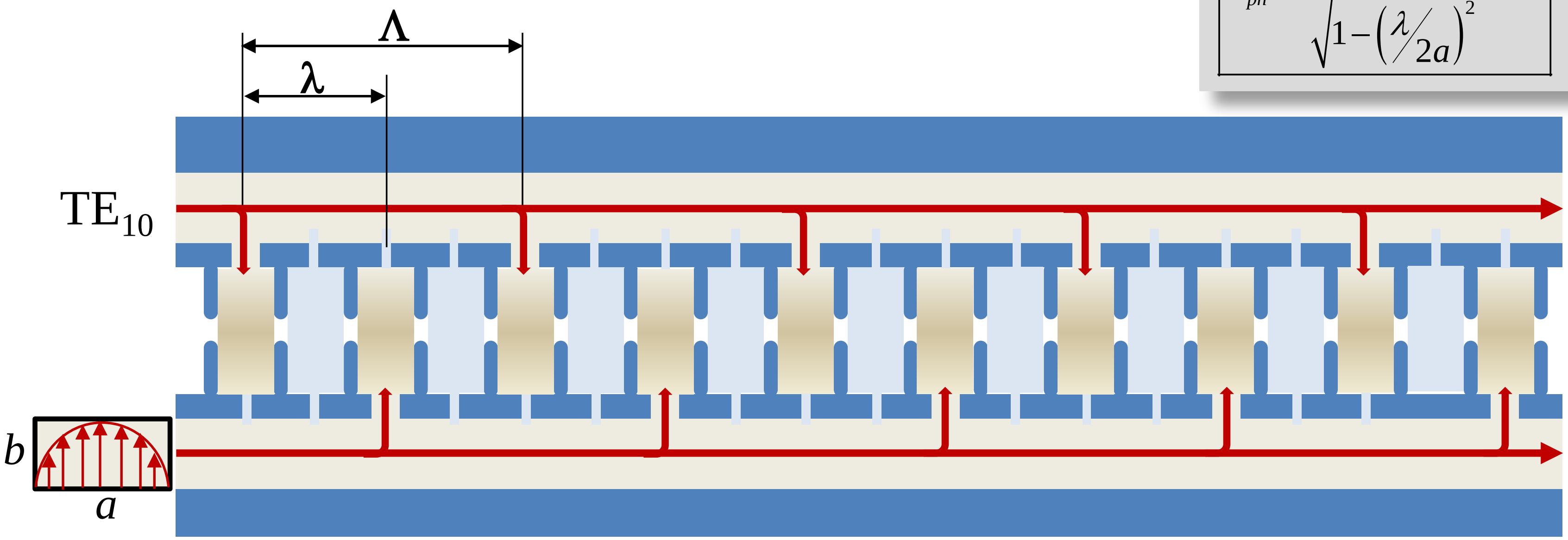
Aluminum-based **E**xtreme-field **N**ormal-conducting **E**lectron **A**ccelerating **S**tructure

$$\Lambda = \frac{\lambda}{\sqrt{1-\left(\lambda/2a\right)^2}} = 2\lambda$$

$$v_{ph} = \frac{c}{\sqrt{1-\left(\lambda/2a\right)^2}}$$

Side-Coupled LINAC-Structure:



$$\Lambda = 2\lambda \quad \Leftrightarrow \quad \lambda = \sqrt{3}\cdot a, \quad v_{ph} = 2c, \quad v_g = 0.5c, \quad Z = 2Z_{vac}$$

HOM Suppression?!

NLC design report 2001:

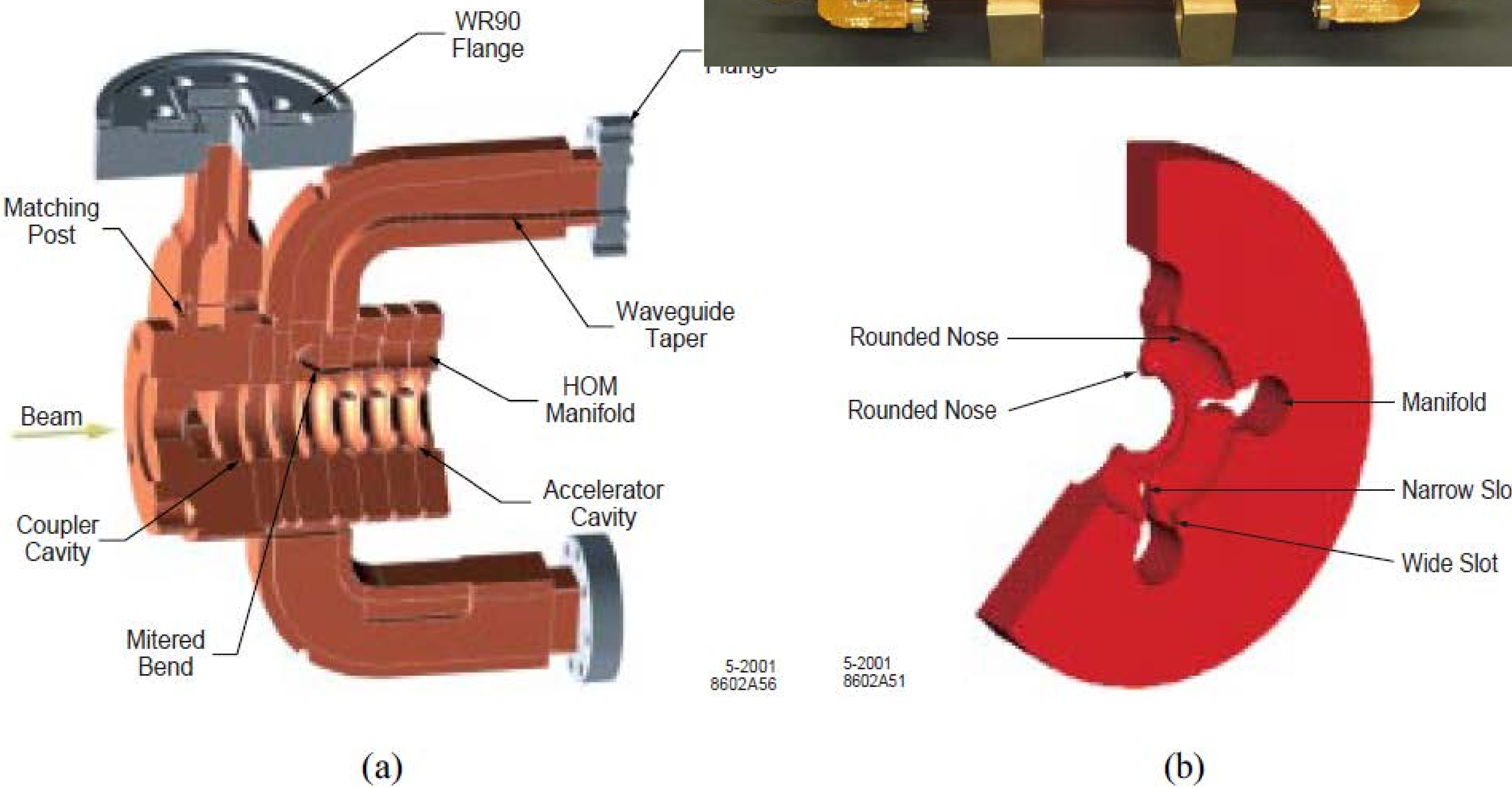


Figure 4.24: Cutaway view of (a) upstream end of RDDS1 and (b) RDDS1 cell.

HOM Forward Damping

Free choice of waveguide height *b* for TE_{10}!

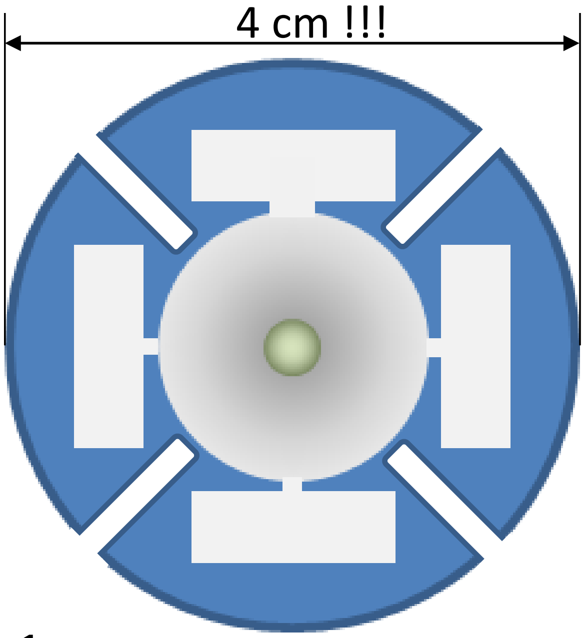
Idea: cancelling of dipole mode via coupling to TM_{11}!

Resonance frequencies: $f_1 = j_1/j_0 \cdot f_0$

- fundamental mode: $k_c r = j_0 = 2{,}405$
- dipole mode: $k_c r = j_1 = 3{,}83$

Cancelling after *n* resonators:

$$v_{ph,1} = \frac{c}{\sqrt{1-\left(\frac{j_o}{n \cdot j_1}\right)}}, \qquad \text{cut-off: } \frac{1}{\lambda_c} = \frac{1}{2}\sqrt{\frac{1}{a^2}+\frac{1}{b^2}}$$



After brave calculations:

$$\frac{b}{a} = \frac{3}{4}\cdot\left[\frac{2}{n}\cdot\frac{j_1}{j_0} - \frac{1}{n^2}\right]^{-1}$$

***n* = 1:**

$f_1 = 12$ GHz, $f_2 = 19.1$ GHz, $\lambda_0 = 25$ mm, $\lambda_1 = 15.7$ mm,
$r = 9.57$ mm, $a = 14.4$ mm, $b = 4.95$ mm

Machining Tolerances / Temperature

(why are side-coupled structures not used so far?)

Tolerances:

a) Standing wave structures:

$$\frac{\omega}{c} r = j_0, \quad \tan\varphi = Q_0 \cdot \left(\frac{\omega_0}{\omega} - \frac{\omega}{\omega_0} \right), \quad \frac{\omega}{\omega_0} = \frac{r_0}{r} \quad \Rightarrow \quad \boxed{\Delta\varphi = 2Q \cdot \frac{\Delta r}{r_0} \cdot \left\{ 1 + 4Q^2 \left(\frac{\Delta r}{r_0} \right)^2 \right\}^{-1}}$$

for $Q \approx 10^4$ we get:

$\Delta r/r$	10^{-6}	10^{-5}	10^{-4}
$\Delta\phi$ / deg	1,1°	11°	29°

12 GHz ($r \approx 10$ mm) $\rightarrow$ **Δr = 10 nm!!**

b) Travelling wave structures:

phase advance: $\varphi = 2\pi\, d/\lambda \quad \rightarrow \quad \Delta\varphi = d \cdot \Delta k$ und $\Delta k = dk/d\omega \cdot \Delta\omega = \Delta\omega / \mathrm{v}_g$

gives $$\boxed{\frac{d\varphi}{dr} = \frac{d\omega}{dr} \cdot \frac{d}{\mathrm{v}_g}}$$

12 GHz, $\mathrm{v_g} \approx 0{,}01 \quad d = \lambda/3$

$\Delta r/r \approx 10^{-4} \leftrightarrow \Delta\phi \approx 1°$

Δr = 1 µm

Machining Tolerances / Temperature

(why are side-coupled structures not used so far?)

Temperature:

Requirement for CLIC: $\Delta T < 0.1°C \leftrightarrow \Delta E/E < 0.05\%$

Temperatur change will detune all cavities in the same way!

General relationship:

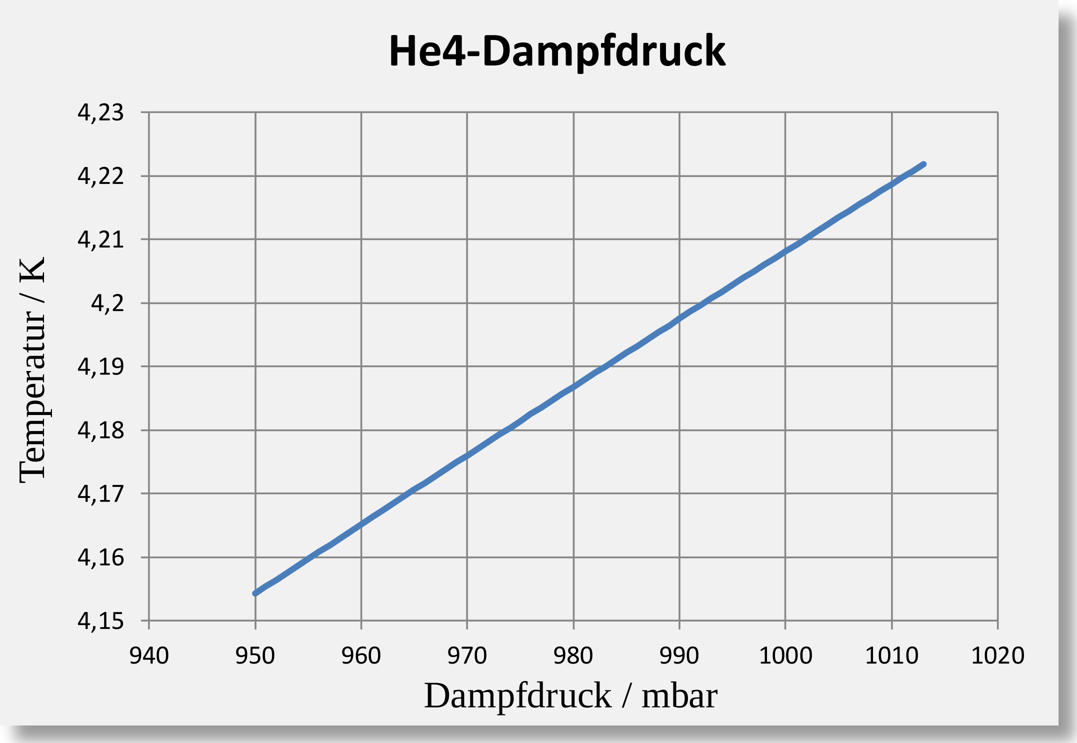
$$\frac{\Delta E}{E} = \tan\varphi \cdot \Delta\varphi + \frac{1}{2}\Delta\varphi^2$$

Gives for required $\Delta E/E$

$\Delta\phi = 1{,}3°$ @ $\cos(\phi = 0°)$
$\Delta\phi = 0{,}1°$ @ $\cos(\phi = 8°)$

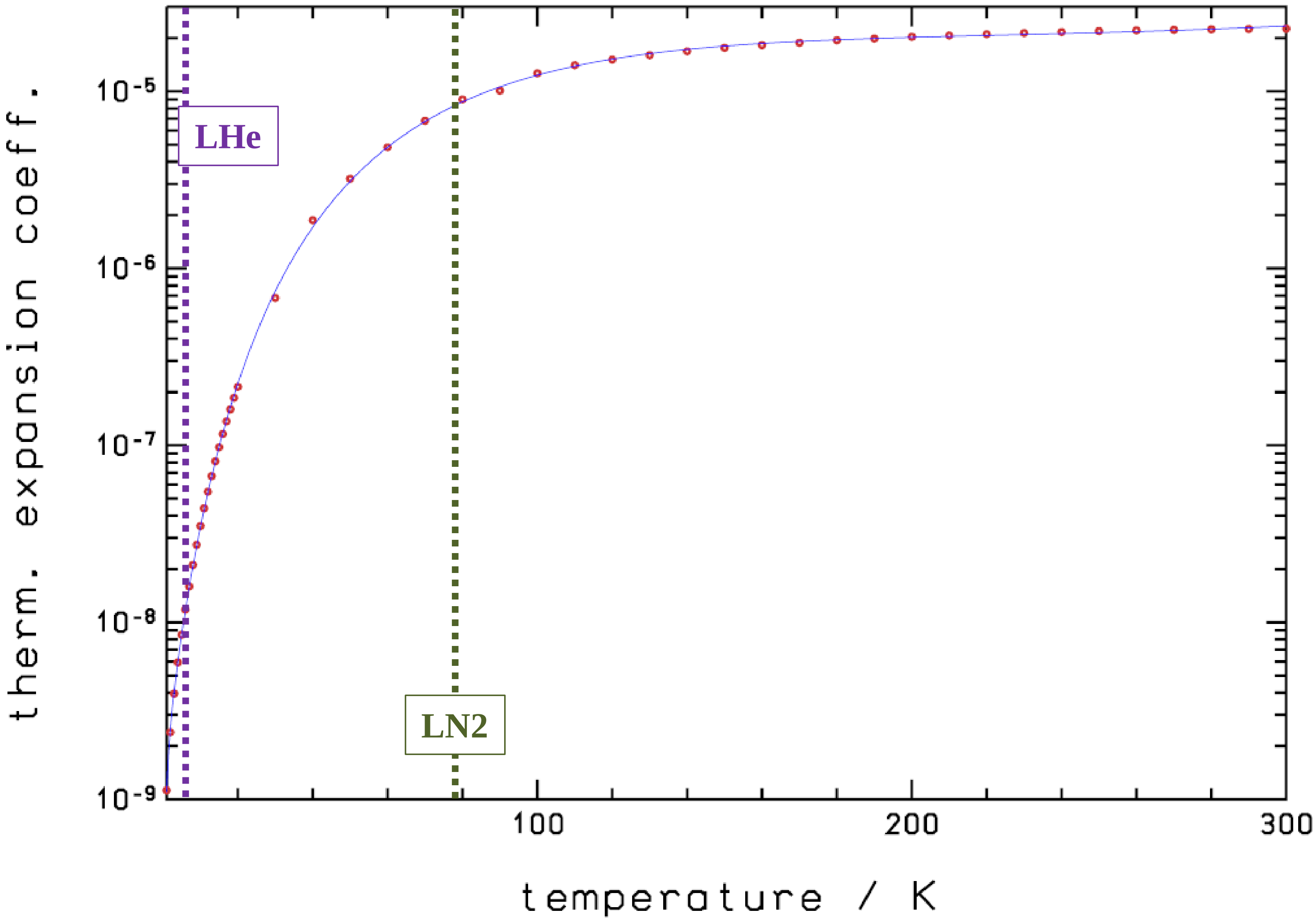
and for $\Delta r/r = 2.31 \cdot 10^{-5} \cdot \Delta T$

$\Delta T < 0.005$ K $\leftrightarrow \Delta P < 5$ mbar



Thermal Expansion Coefficient

K. Anders: *Thermische Ausdehnung von Metallen bei tiefen Temperaturen*, Phys. kond. Mat. **2** (1964)

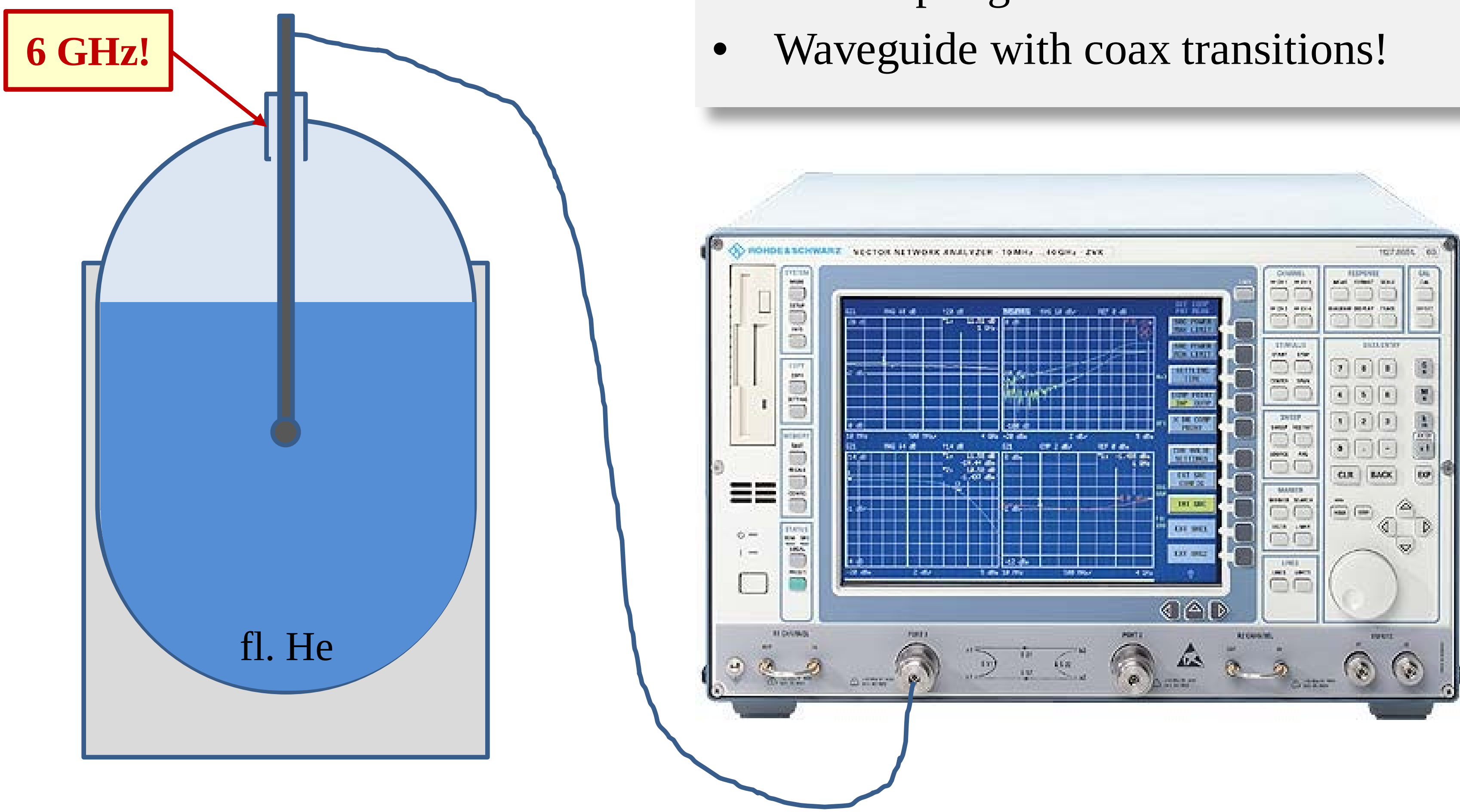


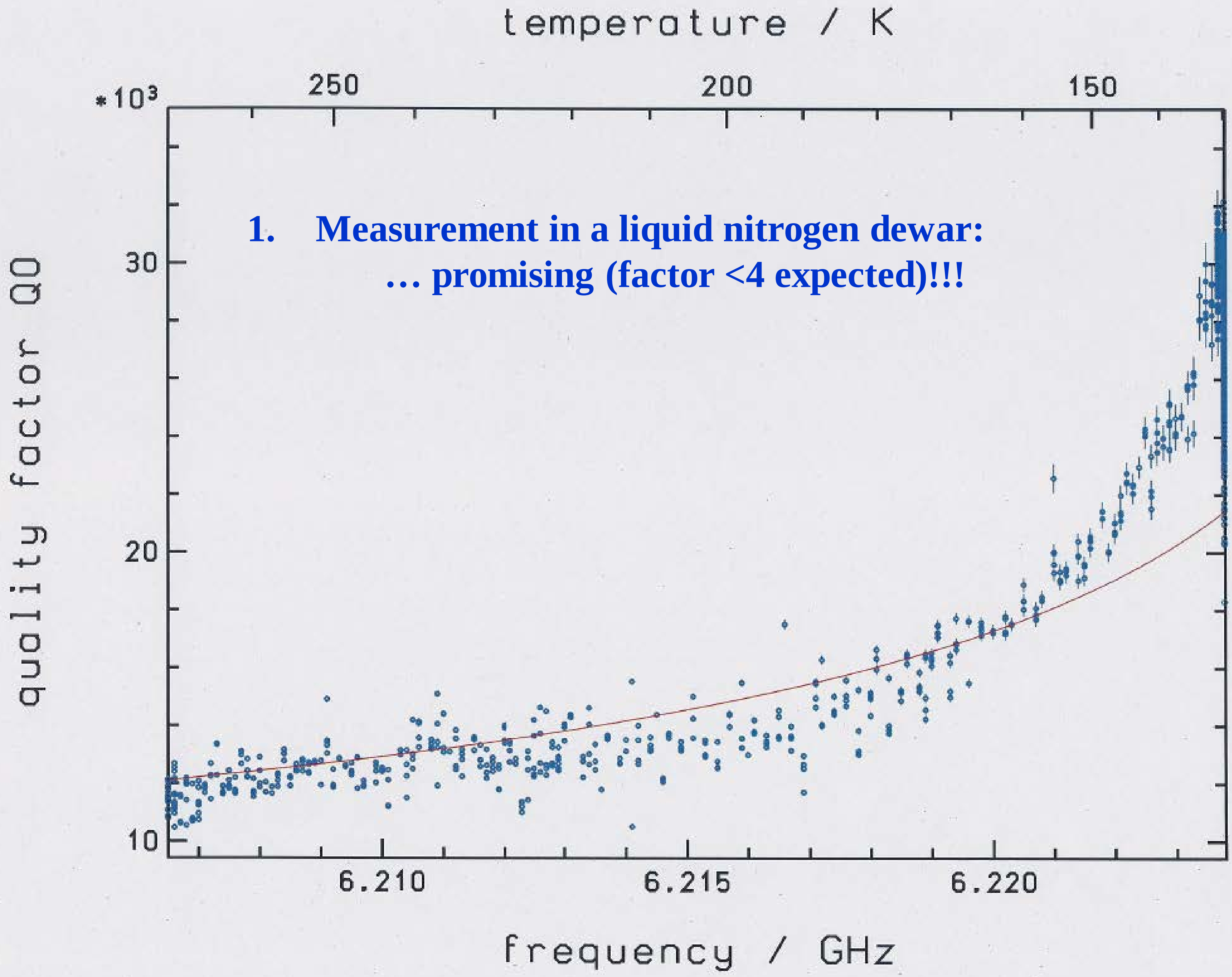
First Measurements

Venus erscheint Aeneas und Achates

Simple Set Up of a „He Cryostat“

- Slit coupling of resonator !
- Waveguide with coax transitions!

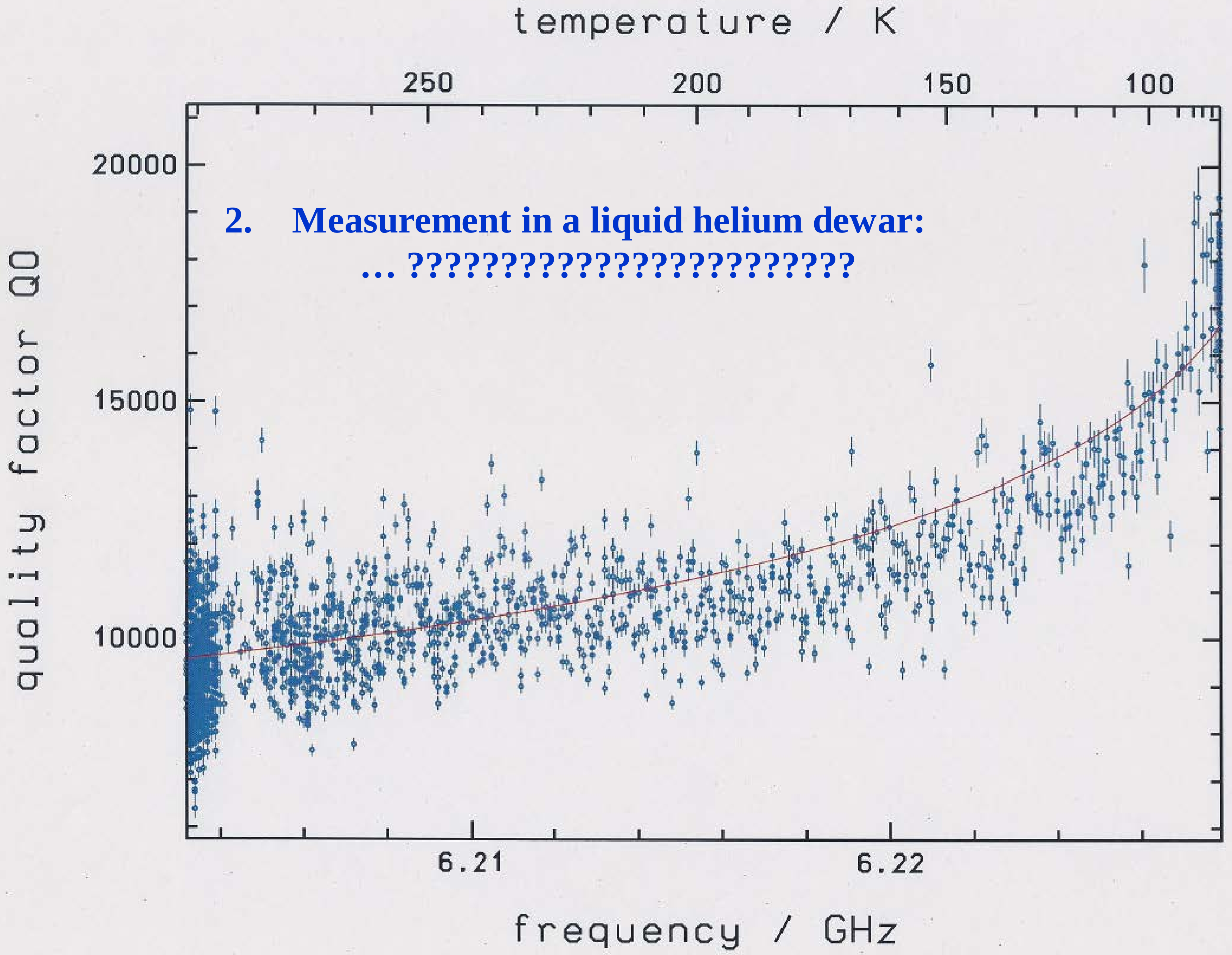




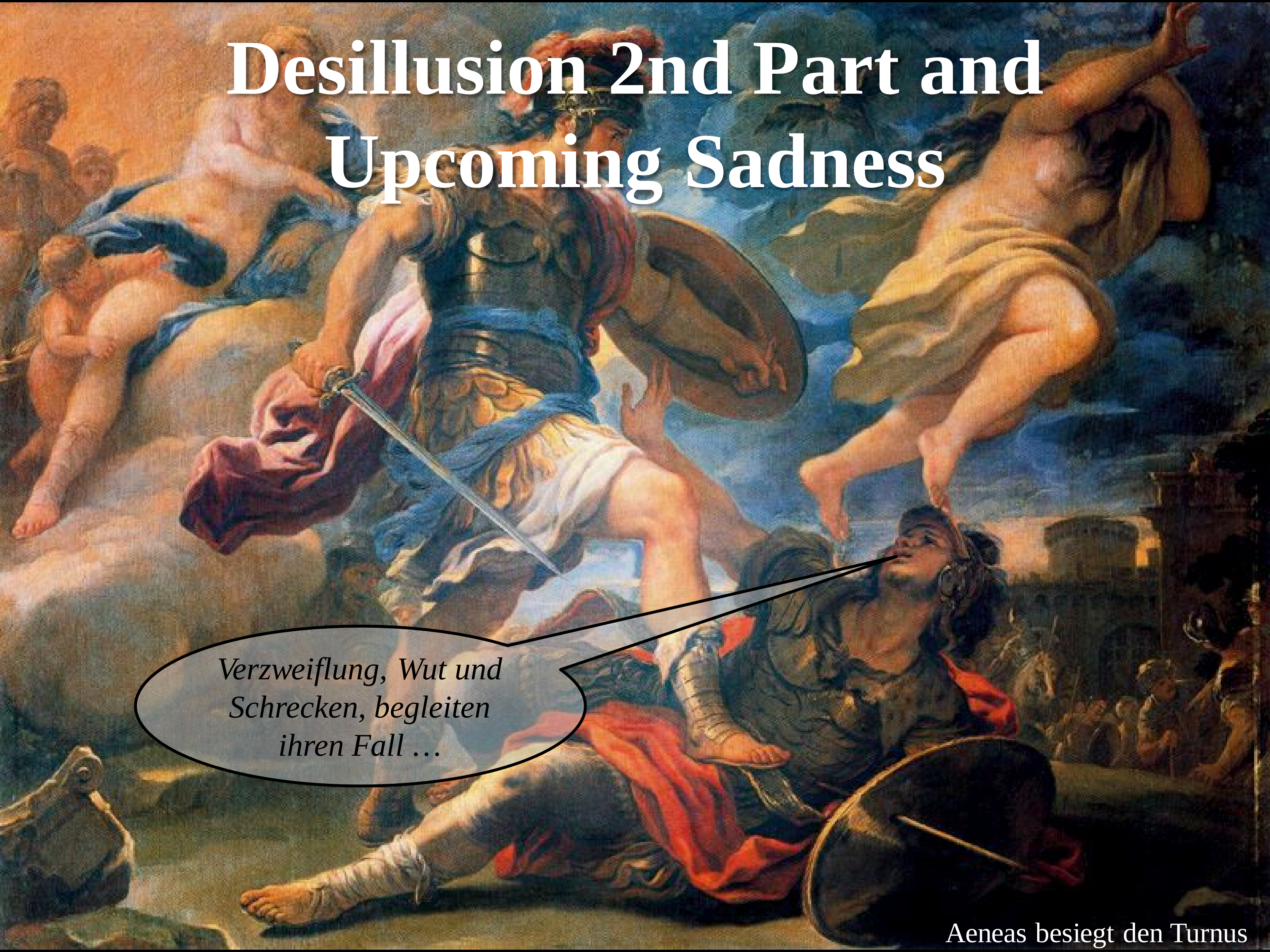
1. **Measurement in a liquid nitrogen dewar:**
   … promising (factor <4 expected)!!!

2. Measurement in a liquid helium dewar:

… ??????????????????????????

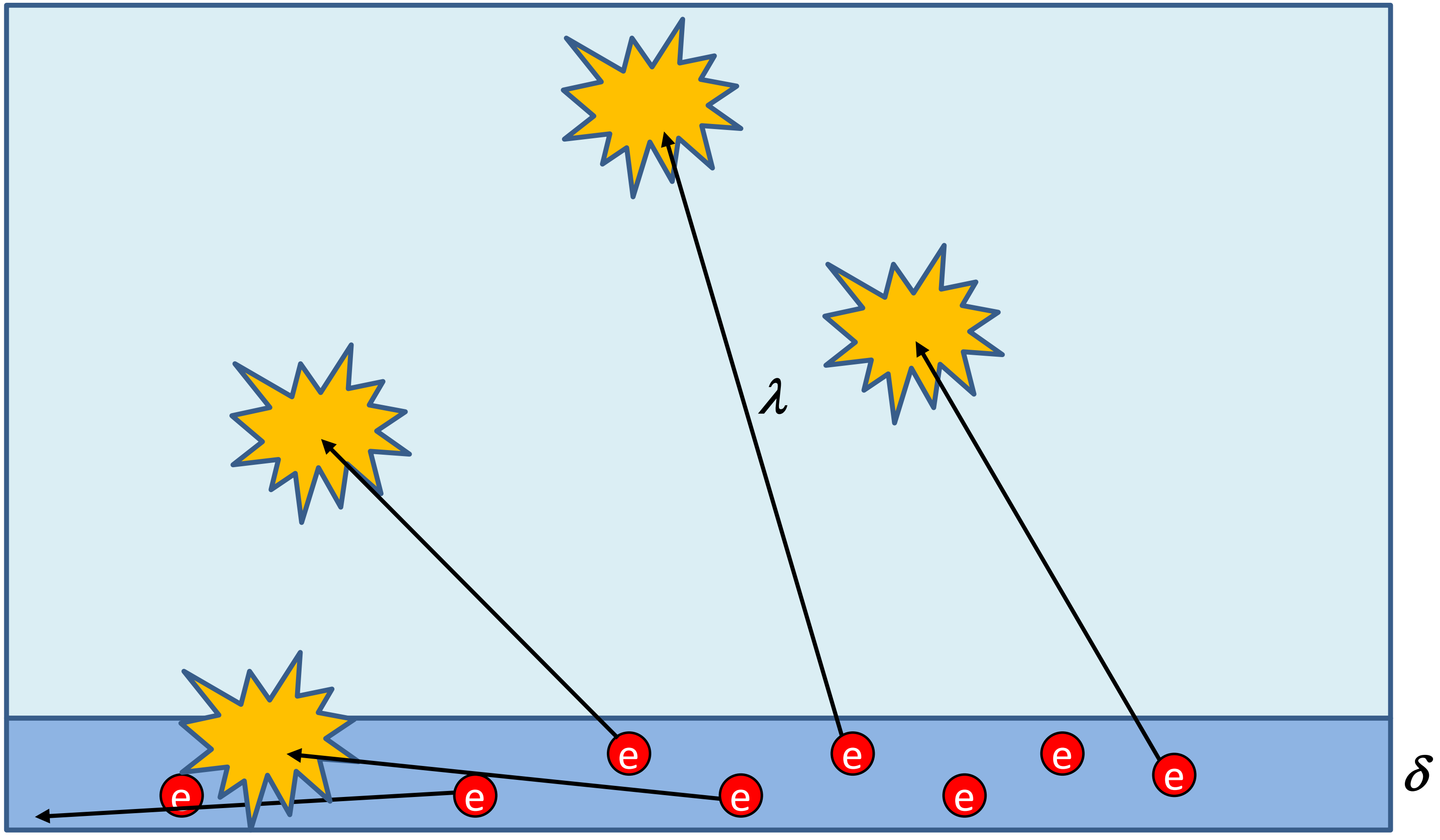


Desillusion 2nd Part and Upcoming Sadness



Aeneas besiegt den Turnus

Anomalous Skin Effect



Implications

W. Chou, F. Ruggiero: *Anomalous Skin Effect and Resistive Wall Heating*, LHC Project Note 2 (SL/AP), Geneva 9/8/1995

Increase of surface resistance according to:

$$R_{sf} = \frac{1}{\sigma \cdot \delta} \quad \rightarrow \quad R_{sf} = R_{\infty} \cdot \left(1 + 1.157\alpha^{-0.276}\right) \quad \text{für} \quad \alpha \geq 3$$

where:

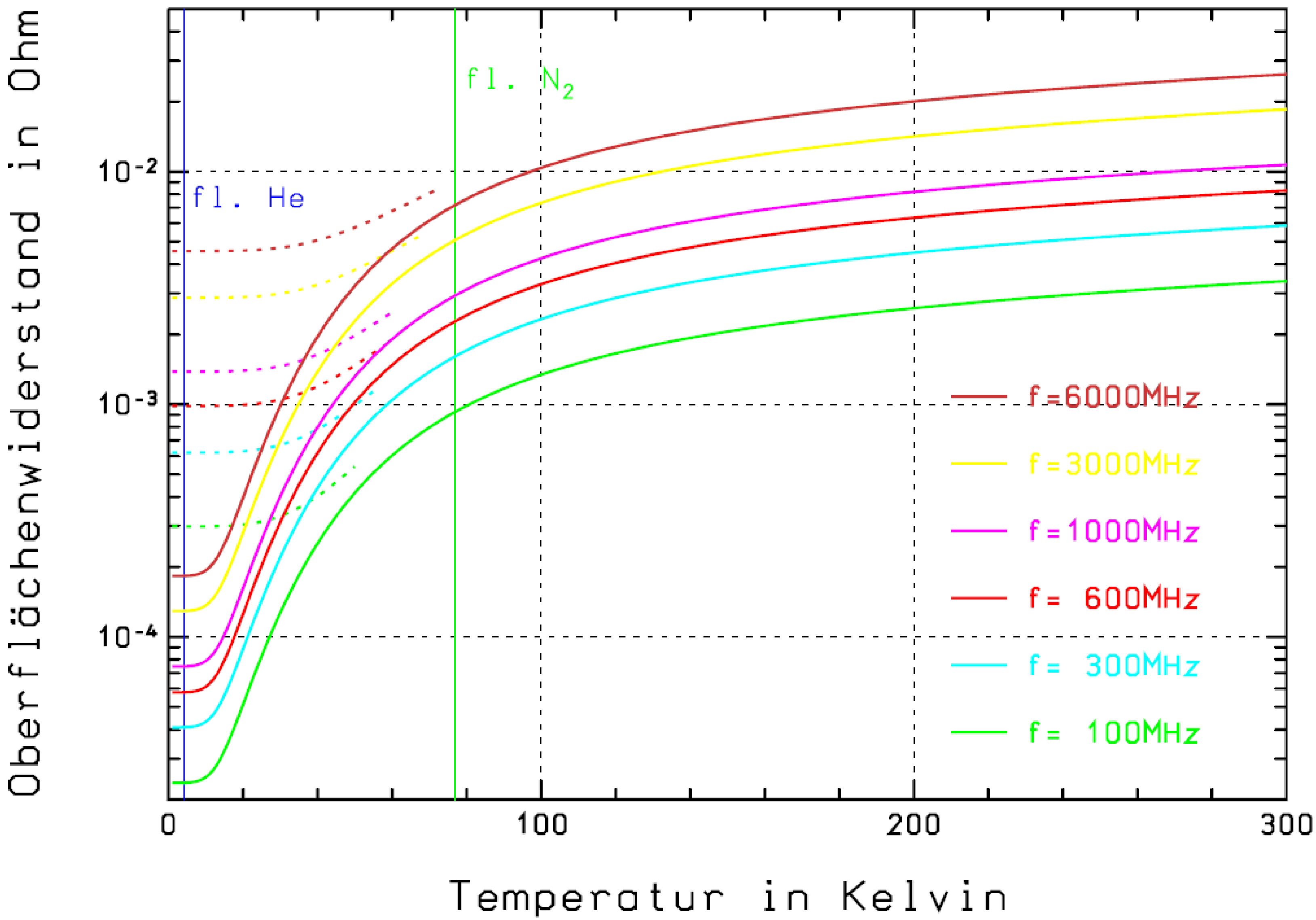
$$\alpha = \frac{3}{2}\left(\frac{\lambda}{\delta}\right)^2 = \frac{3}{4}\omega\mu_0\left(\lambda\sigma\right)^2 \quad und \quad R_{\infty} = \sqrt[3]{\frac{\sqrt{3}}{16\pi} \cdot \frac{\lambda}{\sigma} \cdot \left(\omega\mu_0\right)^2} = \frac{1}{\sigma \cdot \delta} \cdot \sqrt[3]{\frac{\sqrt{3}}{4\pi} \cdot \frac{\lambda}{\delta}}$$

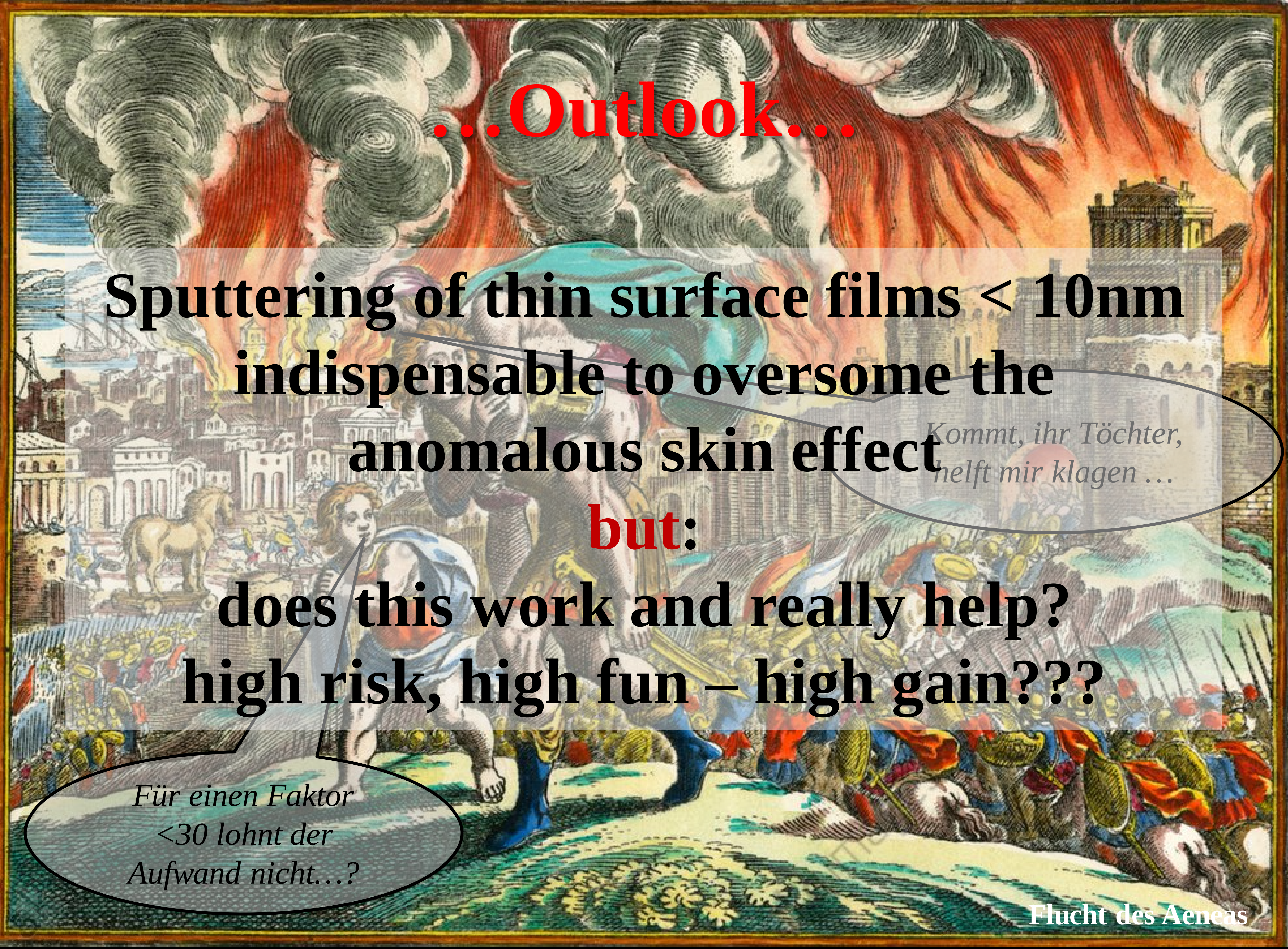
Unknown „material parameter“ λ/σ with $(\lambda/\sigma)_{Cu} = 6.6 \cdot 10^{-16}\ \Omega m^2$ taken from

- A.F. Mayadas: *Intrinsic Resistivity and Electron Mean Free Path in Aluminium Films*, J. Appl. Phys. **39**,9 (1965)
- J.C. Ashley et al.: *Electron inelastic mean free paths and energy losses in solids*, Surf. Sci. **81** (1979)

Conservative guess: $(\lambda/\sigma)_{Al} = 7 \cdot 10^{-16}\ \Omega m^2$!

Normal und Anomalous Skin Effect




…Outlook…
Sputtering of thin surface films < 10nm
indispensable to oversome the
anomalous skin effect
but:
does this work and really help?
high risk, high fun – high gain???
Kommt, ihr Töchter,
helft mir klagen …
Für einen Faktor
<30 lohnt der
Aufwand nicht…?
Flucht des Aeneas