ISRA `07 SEVILLA 11.9.2007

ON THE INFLUENCE OF THE CEILING AND also AUDIENCE PROFILE mainly only ON THE REVERBERATION TIME

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Presentation much extended compared with the written paper.
Figures available at post@umstephenson.de or on USB stick

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On the influence of the ceiling and audience profile on the reverberation time and other room acoustical parameters

Long-term goal: "inverse room acoustics":

given: wanted room acoustical parameters

to optimize: room shape and surface properties

Present first approach:

influence only of the ceiling and audience profile in 2D

Assumptions: local r.a. parameters as EDT, Deutlichkeit , Clarity… will depend mainly on the longitudinal section

Restrictions: mainly 2D investigation by 2D ray tracing
extension to 3D (with a peak in the roof)

Focus: effect on the Reverberation Time RT_{30} /RT_{Eyring}

Special occasion: draft of the “Elbphilharmonie”, Hamburg

(copies from the newspaper “Hamburger Abendblatt”, Easter 2007)

max. height: 30m!

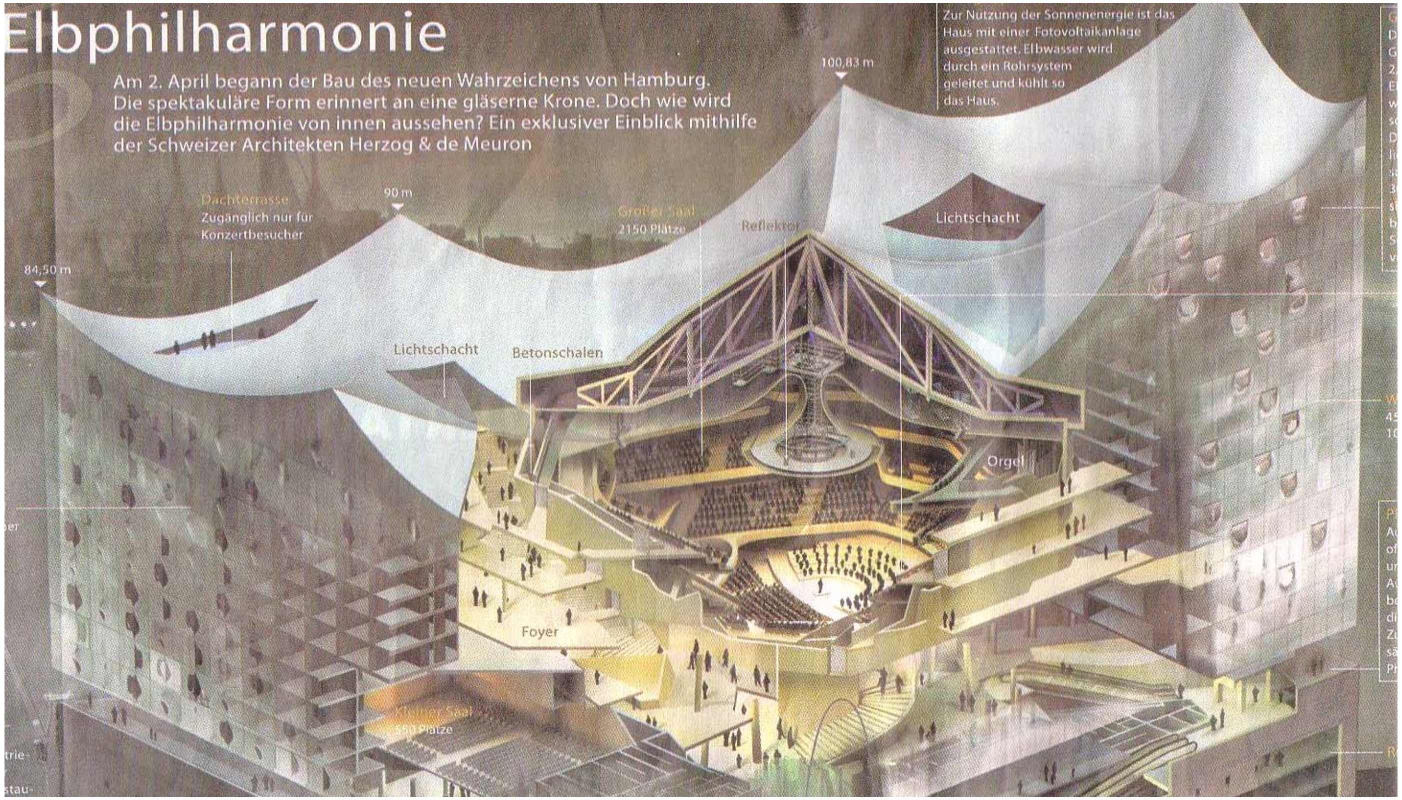
cross section:

30m

Max. length 60m

Max. width: 40m

Y. Toyota: “Higher volume /person necessary due to the more overall sound incidence in a centralistic tent-shaped room.”



With audience terraces rising up to 20m, ca. elliptical groundplan:

Volume: ca. 30000m³ !?, with N=2150 seats: **V/N=14m³/p!?**

Recommended for symphonie halls : V/N=8…10m³/p

average of 70 halls (Beranek) : 9m³/p

after Sabine with 2/3 m²/person with alpha=0.8 + 5 times this area with alpha 5%

$$T_{sab} = 0.161 \cdot \frac{V}{A} \approx 0.23 \cdot V / N \approx 3.2s$$

without extra ceiling absorption: **T_{30} must be < 0.7 T_{sab} !**

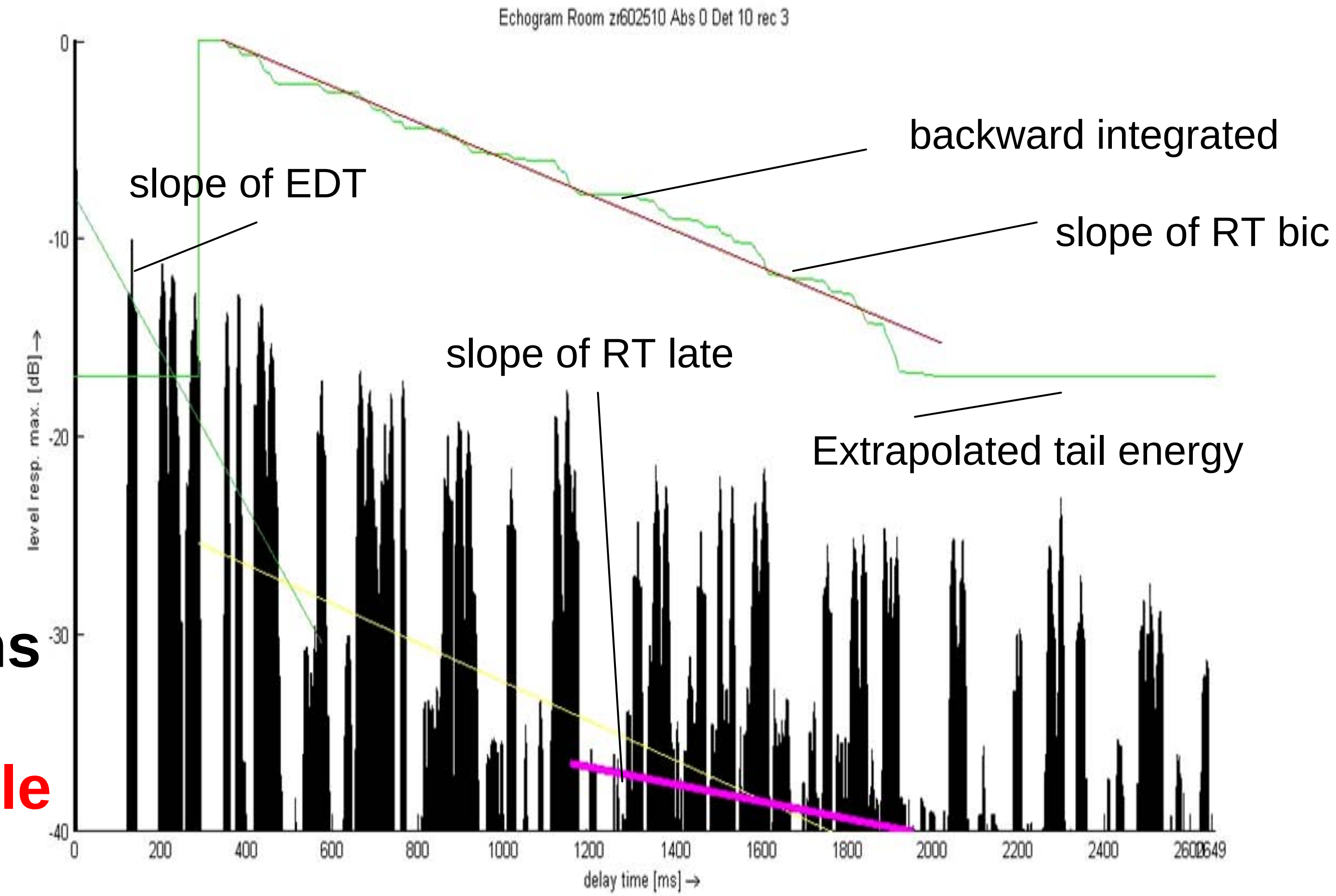
In this study, 2D- Particle tracing is used to compute:

- **Reverberation times** (from regression at echograms in the range -5…-35dB)
  RT late from regression at echogram in the range -20…-35dB
  RT bic from regression at the backwards integrated and corrected echogram
  corrected by extrapolation with RT late

- **EDT** from direct regression
  at the echogram in the range
  0..-10dB

- **Deutlichkeit**
  D= E (0..50ms) / E $_{total}$

- **Echograms**
- **Decay curves**
- **Irradiation distributions**



as function of ceiling angle and audience angle

Reference Reverb. times

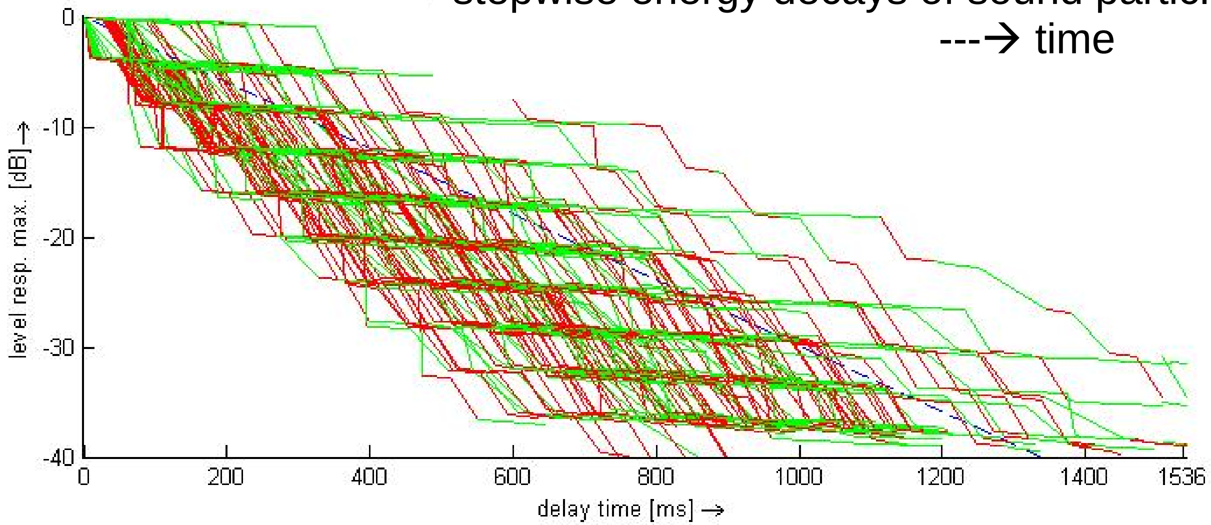
all with totally diffusely reflecting surfaces

idea:

$$RT \propto \frac{\text{mean(free path lengths)}}{-\ln(1-\text{mean(absorption degrees)})}$$

with V= Volume, S=Surface, U=circumference

stepwise energy decays of sound particles
---→ time



For the diffuse sound field:

$\alpha_m = \sum S_i / S \cdot \alpha_i$, $\alpha_m` = -\ln(1-\alpha_m)$ in 3D: $\Lambda = 4V/S$ in 2D: $\Lambda = \pi \cdot S / U$

Eyring: 'representative sound particle', **always mixing fates**!, constant mean free path length:

$$Tey = \frac{6 \cdot \ln(10)}{c} \cdot \frac{4 \cdot V}{-\ln(1-\overline{\alpha})} \approx 0.161 \frac{s}{m} \cdot \frac{V}{S \cdot \alpha_m'}$$

in 2D: $Tey \approx 0.128 \frac{s}{m} \cdot \frac{S}{U \cdot \alpha_m'}$

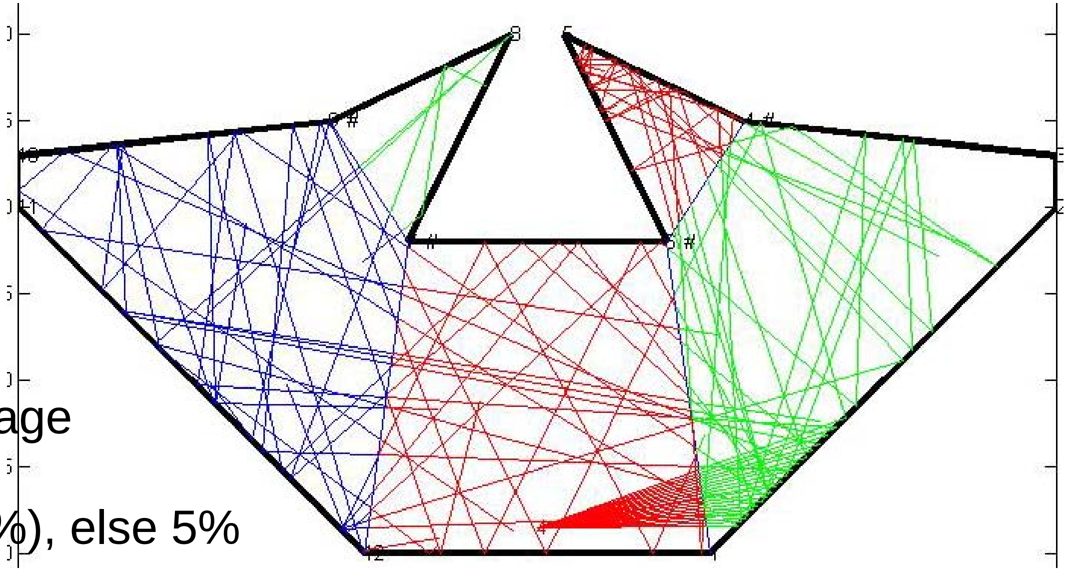
Sabine: simplification $\alpha_m` \approx \alpha_m$ or **with** by γ^2 **varying free path lengths:** $Tey \xrightarrow[\gamma^2 \to 1]{} Tsab$

for non-constant wall irradiations (weighting the variance of the absorption degrees)

Kuttruff: with $\alpha_m'' = \alpha_m' + \left(\sum (1-\alpha_i) \cdot (\alpha_m - \alpha_i) \cdot S_i^2\right) / \left((1-\alpha_m) \cdot S^2\right)$: $T_{sab} > T_{ey} > T_{kutt}$

(. if one surface with dominating absorption)

Method of Computation: 2D (later 3D) Sound Particle Simulation



20 rays emitted to the left in a 2D-room subdivided in convex parts

- omnidirectional sound source in room
  (1.5m over the middle of the stage)

- quadratic (2m*2m-) detectors in a grid
  from these **10 receivers** with computation
  of the r.a. parameters, symmetrical and
  equally distributed over the audience, 2 on the stage

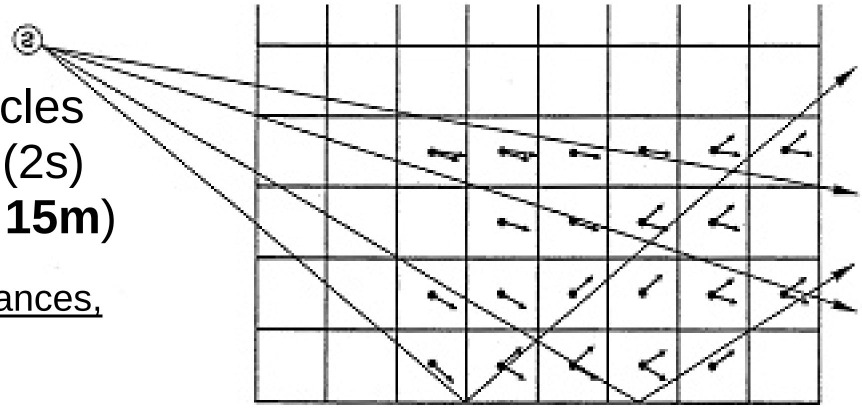
- absorption degrees AG: audience: 58% (70%*80%), else 5%

- diffusivity degrees DG 0 , 5, 10, 30 100 % **as parameter**
- or fixed 100% for the (wineyard-) audience, stage 10%

- ca. 2000…20000 emmitted and also about immitted particles
- followed up to expected **3/4 Eyring Reverberation time** (2s)
- i.e. typ. 540m or 36 reflections (**mean free path length 15m**)

$$I' = \frac{P}{S_d \cdot m_0} \cdot \sum_{n=1}^{n_0} w_n \cdot e_n$$

w_n inner crossing distances,
e_n = rel. energies.
I'= intensity in 2D,
P= fictive constant sound power,
S_d= detector area,
m_0= number of emitted SP



sound particle detection:
particle crossings
marked with arrows

Partially diffusely reflecting surfaces: the Diffusivity degree DG

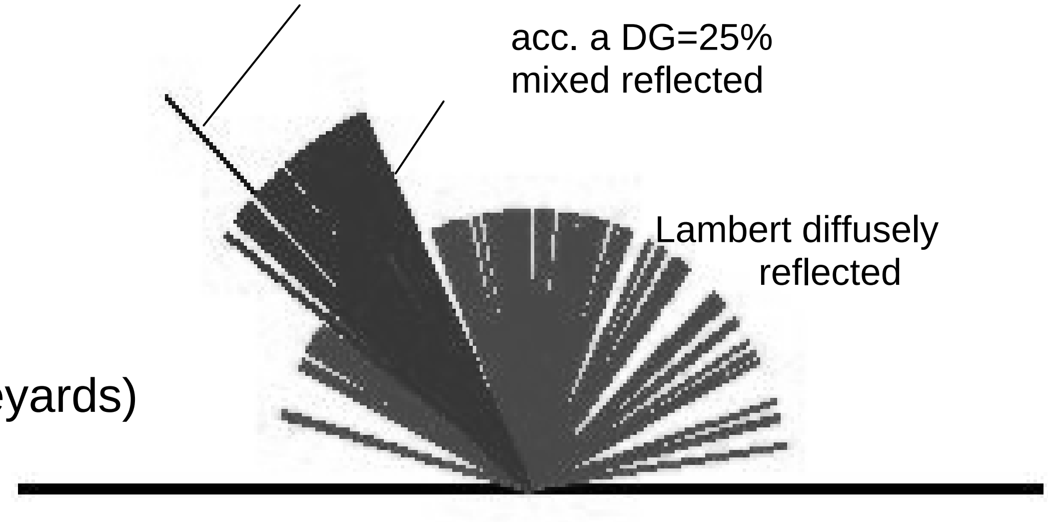
For perfectly 'diffuse walls' (DG=1):

Lambert`s cosine-law in 2D: probability-density = $\cos(\vartheta)/2$

δ computed by drawing a random number

reflected sound particle directional vector

$\mathbf{V_{refl} = DG^* \, V_{scatt} + (1\text{-}DG) \, ^* \, V_{geo}}$ (re- normalized)



Simplifications:

- audience with maximum diffusivity 100% (wineyards)
  or fixed 100% for the (wineyard-) audience,
- smooth surfaces with 5….10% diffusivity

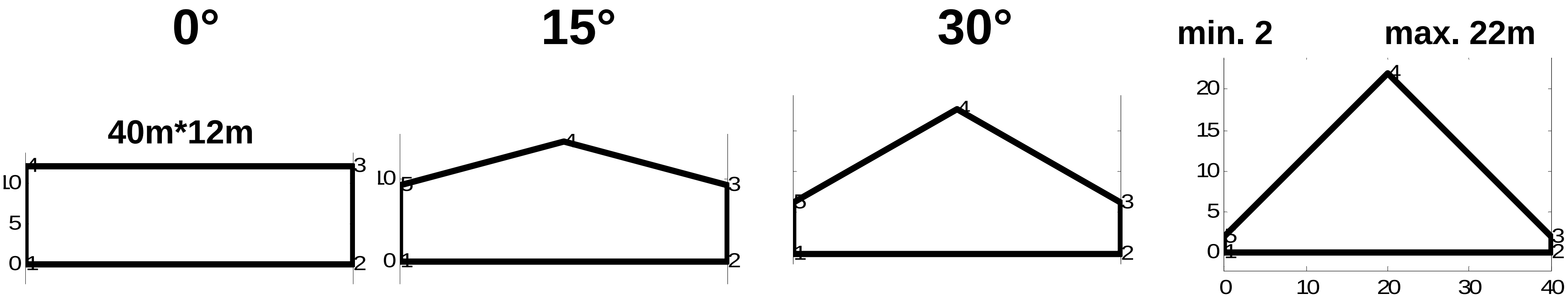
Neglects:

- **DGs increasing with distances (time)**
  (after 3-6 reflections, at mid frequencies, all reflections are diffuse)

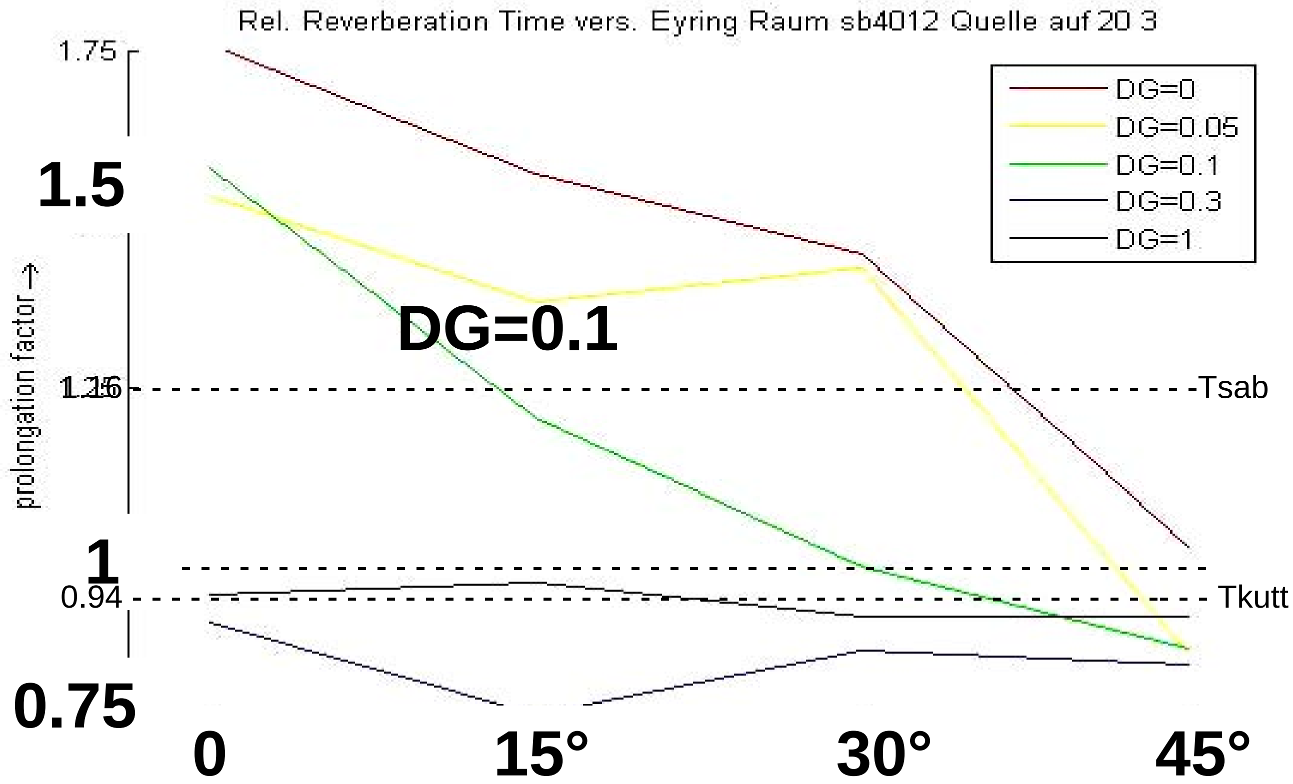
- **angle dependant absorption degrees (at grazing incidence in the audience)**

STUDY 1: RT_{30}/T_{eyr} as function of ceiling angle

with constant area and flat audience area, parameter DG:



T_{eyr} =2.02 s = const



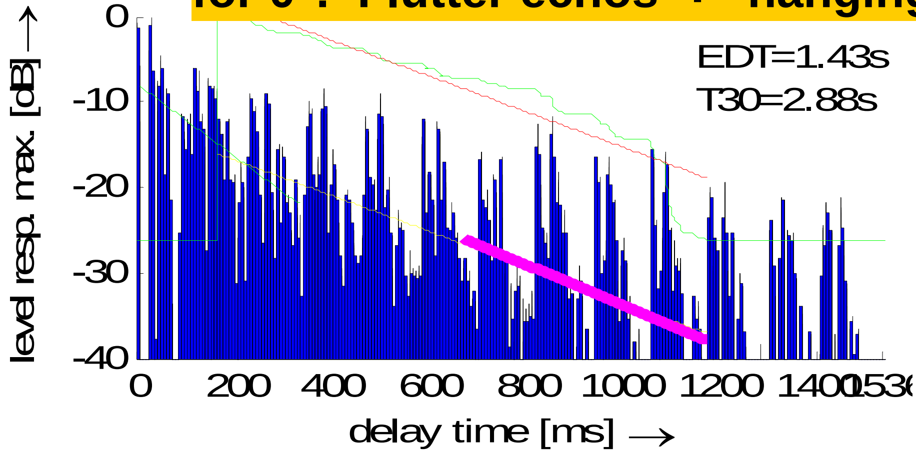
0.75 0 15° 30° 45°

EDT /T_{eyring} as function of the ceiling angle

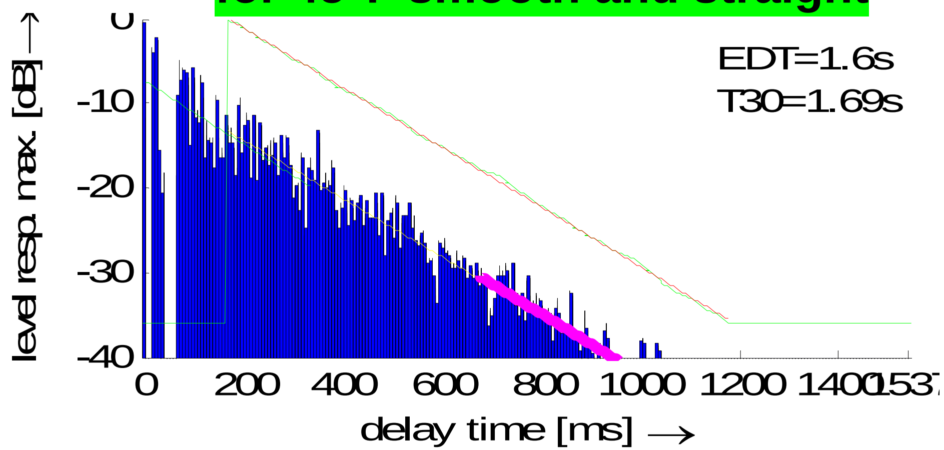
with flat audience area, DG as parameter:

Echograms for DG=0.1

for 0°: Flutter echos + 'hanging'

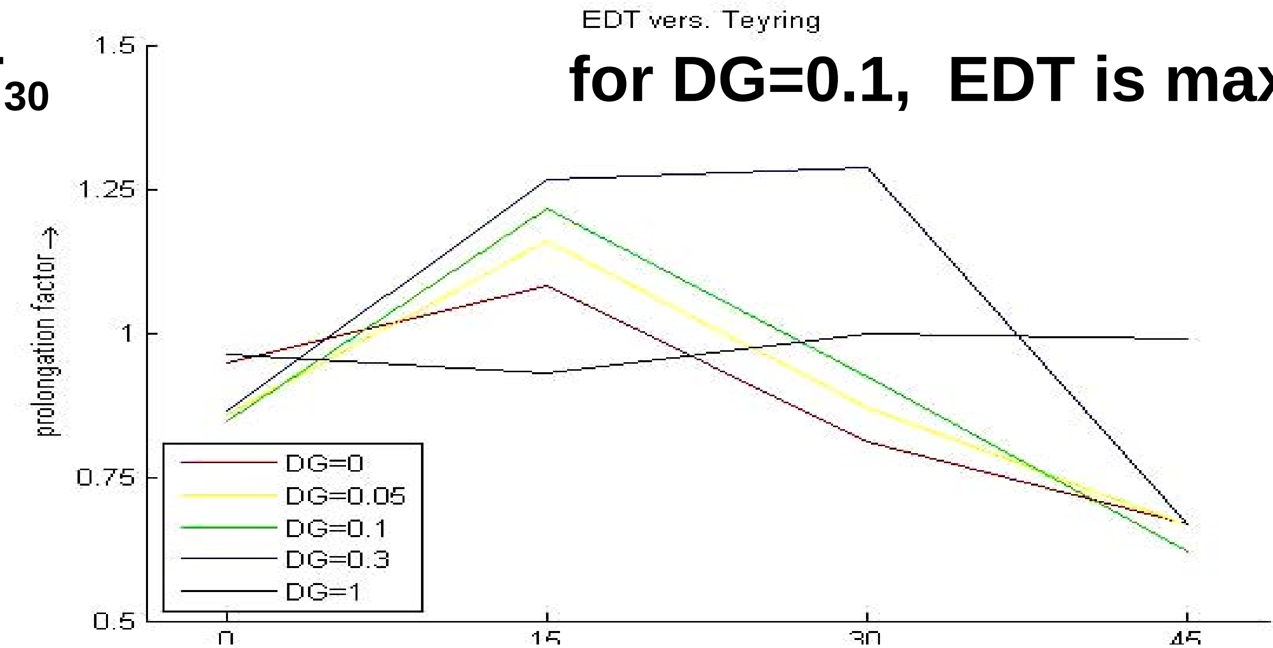


for 45°: smooth and straight



EDT < RT_{30}

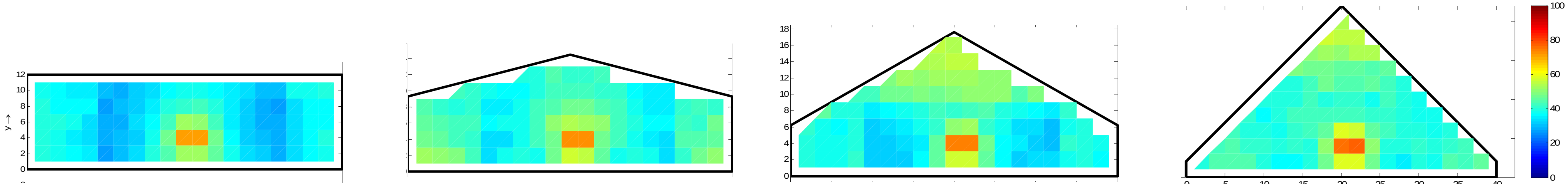
for DG=0.1, EDT is max. with 15°

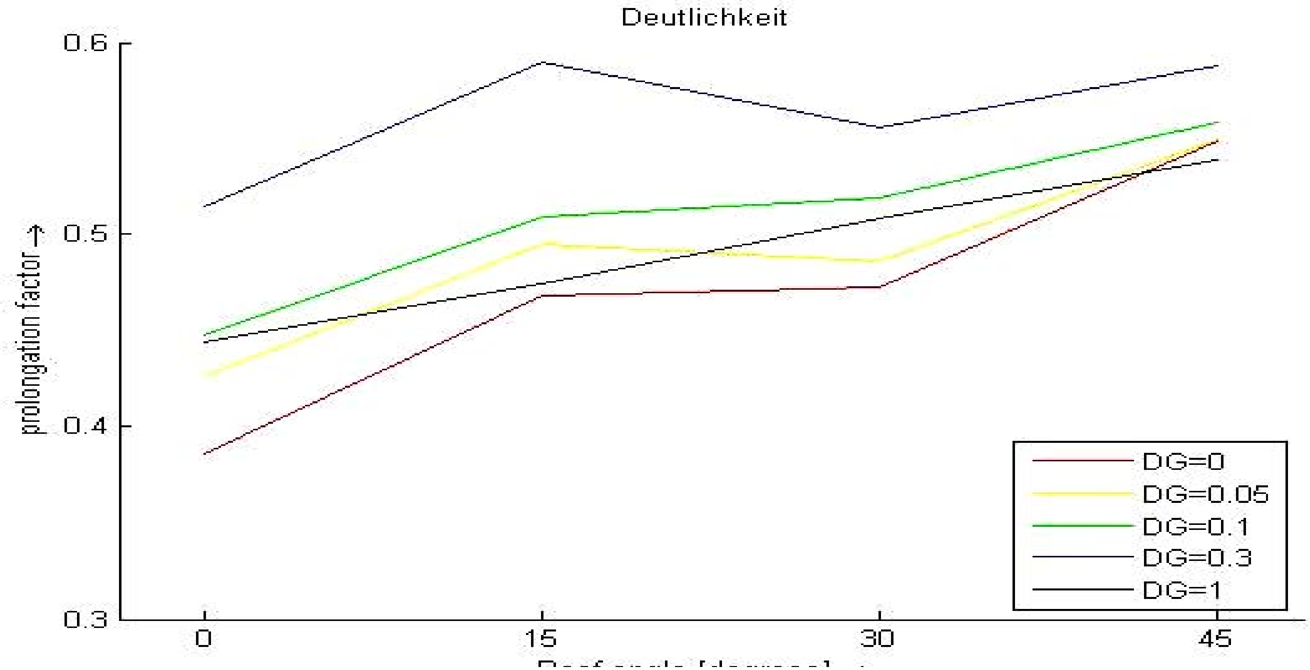


0 15° 30° 45°

Deutlichkeit D as function of the ceiling angle
with flat audience area, DG as parameter:

Deutlichkeit Distributions for DG=0.1 (yellow = 60%)





for DG=0.1
D=0.45 …0.55

(as if
T=1.5…0.8s)

(mean values
only for
receivers
on the ground)

0 15° 30° 45°

Why does the RT depend so much on the scattering and the roof angle?

It can be **not** explained by:

- different effective mean absorption degrees $\alpha_{stat} \approx \alpha_m = \sum S_i / S \cdot \alpha_i$

  the surface weighted and the statistically evaluated values are the same

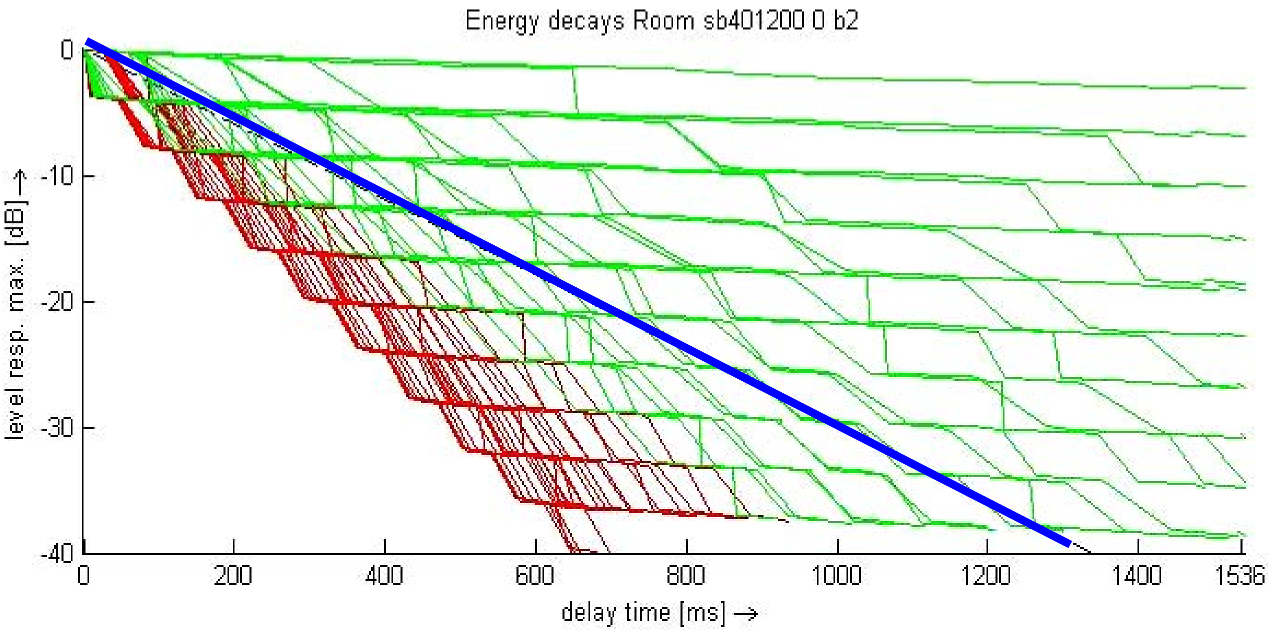
- varying mean free path length (of all particles) $\Lambda_{stat} > \Lambda_{expect} = \pi \cdot S / U$

  mfp **rises** for ex. from 14.5 m… 17m while the RT is **de**creasing

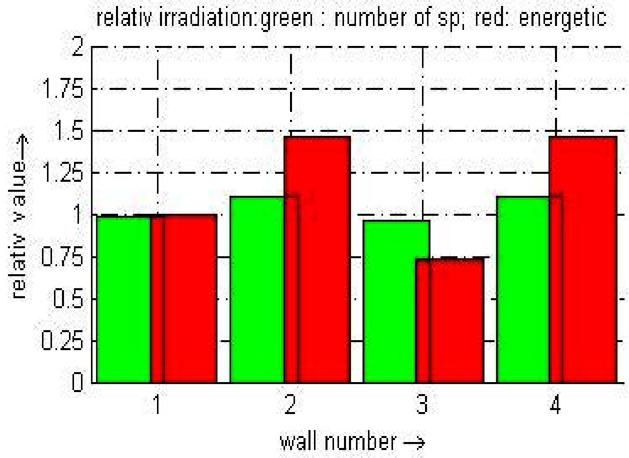
- unequal densities of particle hitting (Kuttruffs formula)

SHOE-BOX 40m*12m with DG=0 (all-specular)

Sound particle energy decays



Surface irradiation
(rel. diffuse exp. values)



floor r side ceiling l side

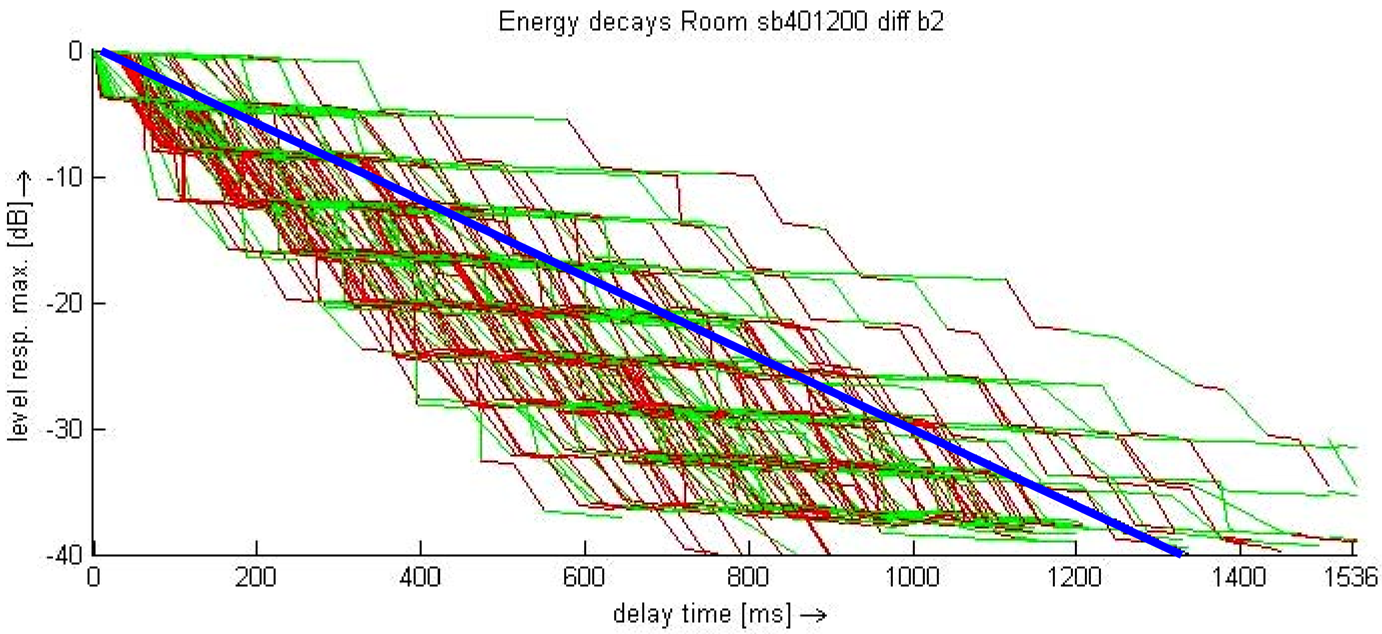
Green: more horizontal **red: more vertical running rays**

Green: number of SP
Red: energy of SP

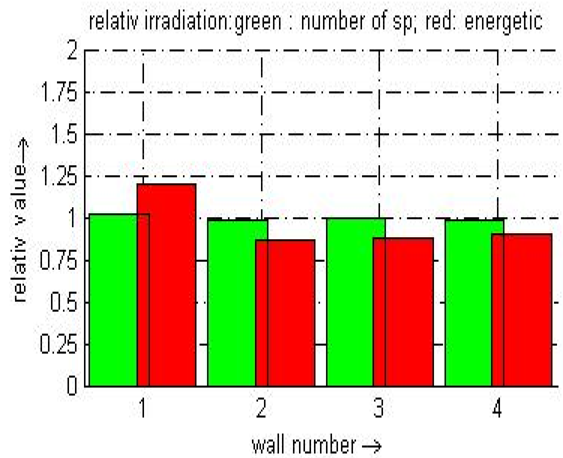
-> Many rays survive with high energy -> RT much longer than Tey

SHOE-BOX 40m*12m with DG=1 (all-diffuse)

Sound particle energy decays



Surface irradiation
(rel. diffuse exp. values)



floor r side ceiling l side

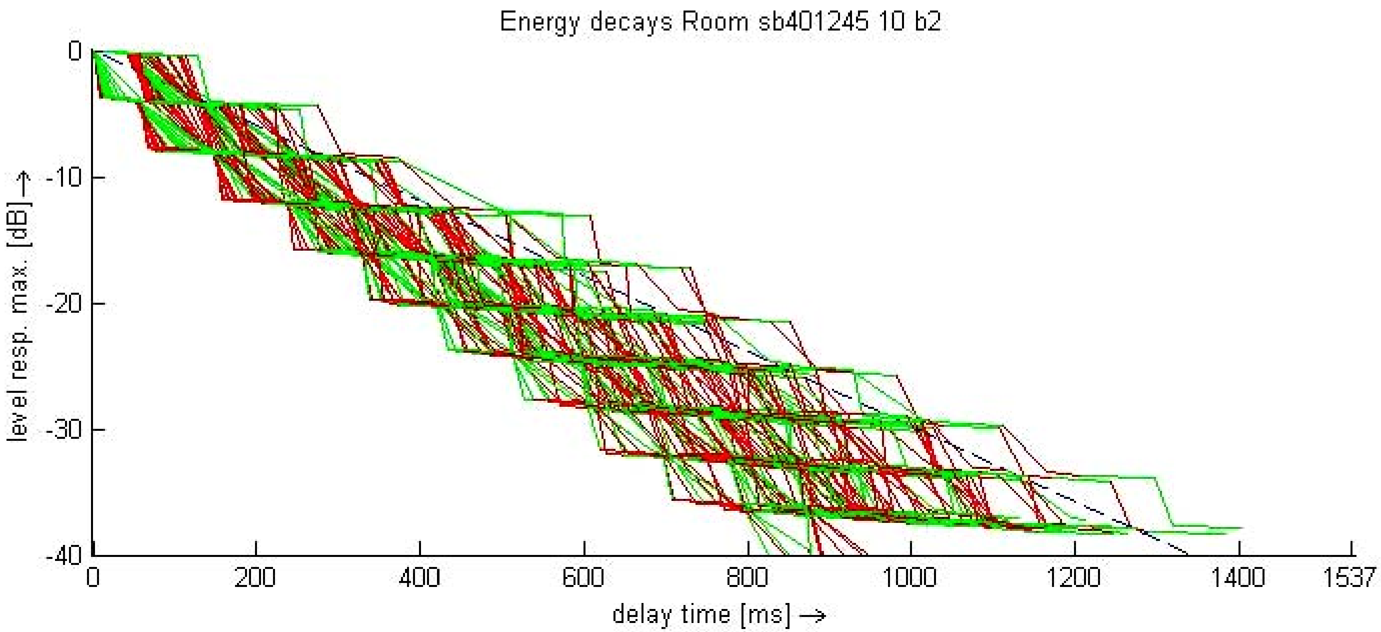
Green: more horizontal **red: more vertical running rays**

Green: number of SP
Red: energy of SP

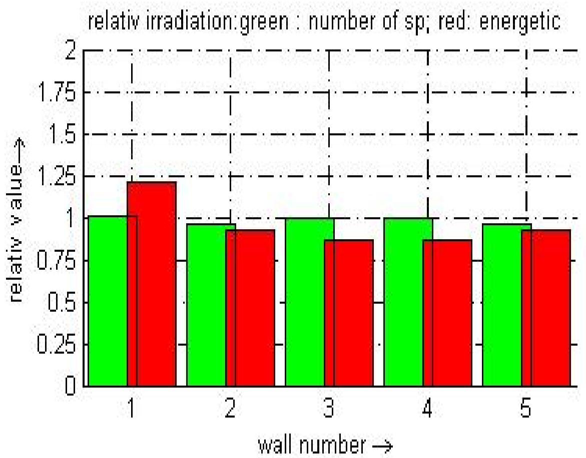
-> The absorbing floor is more illuminated than the other surfaces
-> The RT is lower than due to Eyring and close to Kuttruff

TENT, 45°” 40m*(2..22 m) with DG=0 (all-specular)

Sound particle energy decays



Surface irradiation
(rel. diffuse exp. values)



floor r side r +l ceiling l side

Green: more horizontal **red: more vertical running rays**

Green: number of SP
Red: energy of SP

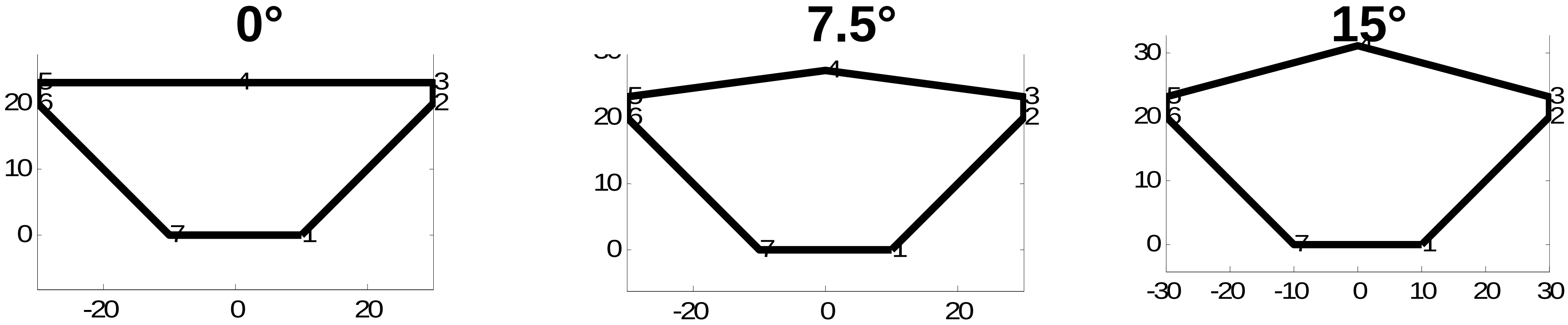
In the tent, particle fates are mixed as with totally diffuse walls!

-> The 45°- Tent serves as a diffusor -> the RT is close to Eyring

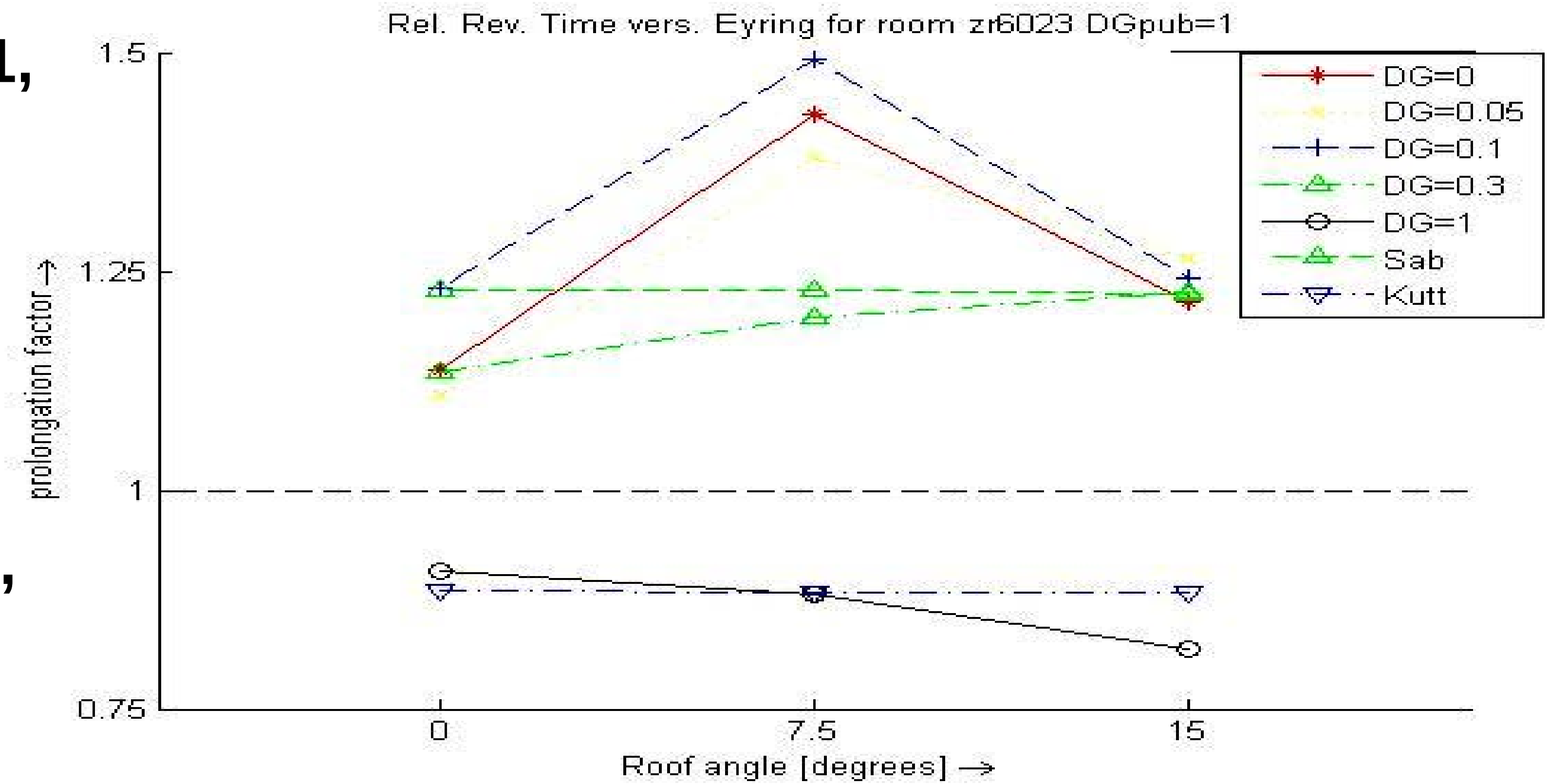
STUDY 2: RT_{30}/T_{ey} as function of ceiling angle (T_{ey}=2.05…2.5 s)

60m*23m room with 45° rising scattering audience (AG=0.8, DG=1) , stage: DG=.05

height: 23, 27,31m **parameter: DG only of the ceiling**



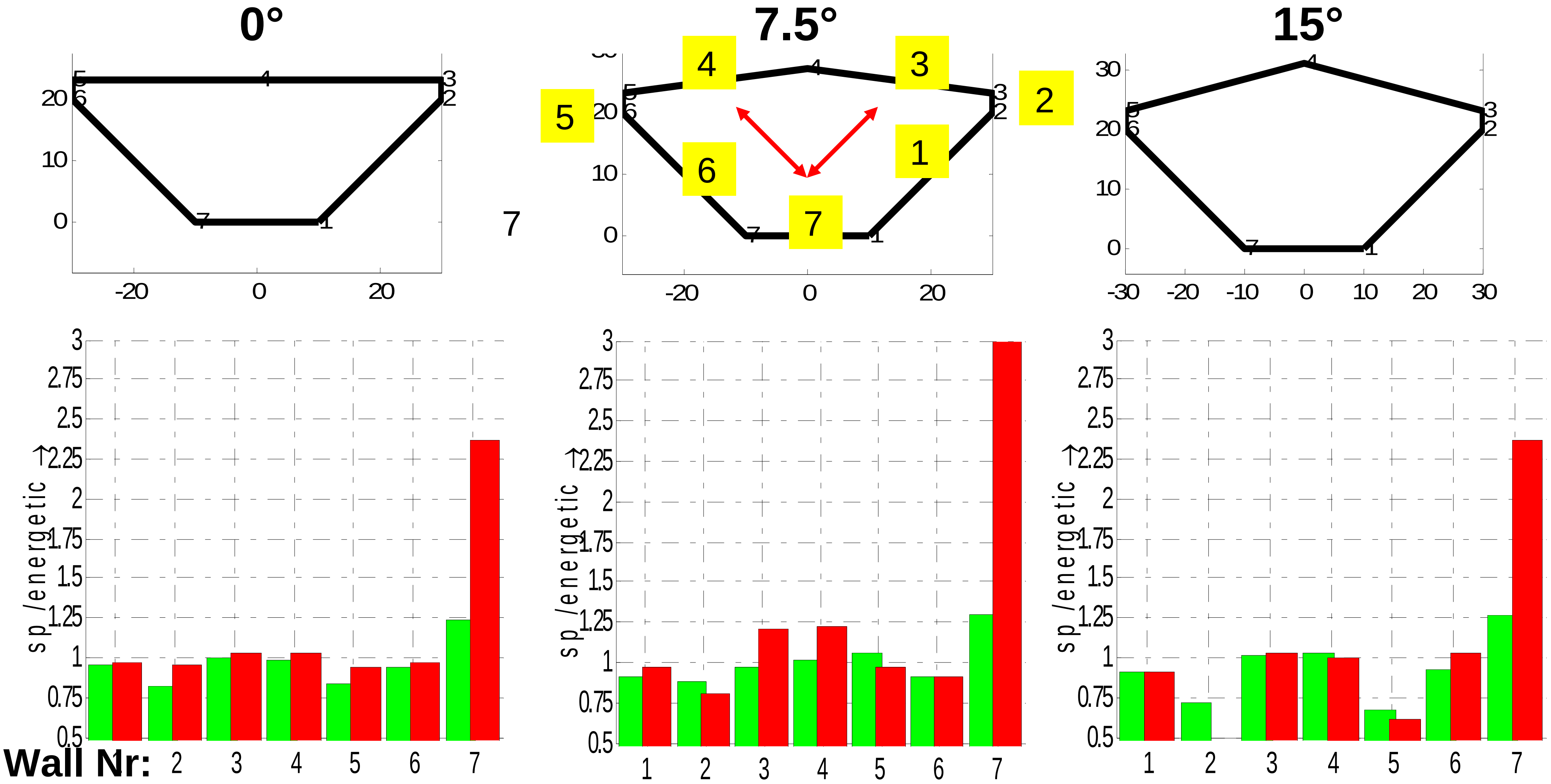
For DG=.1, RT is max for 7.5 °!



For DG=1, RT=T_{kutt}!

Surface irradiation (rel. diffuse field exp. values) **DG of the ceiling = 10%**

60m*23m room with 45° rising scattering audience (AG=0.8, DG=1) , stage: DG=.05



Wall Nr:

Rel. irr.: roof: 1.02 **1.22** **1.04**

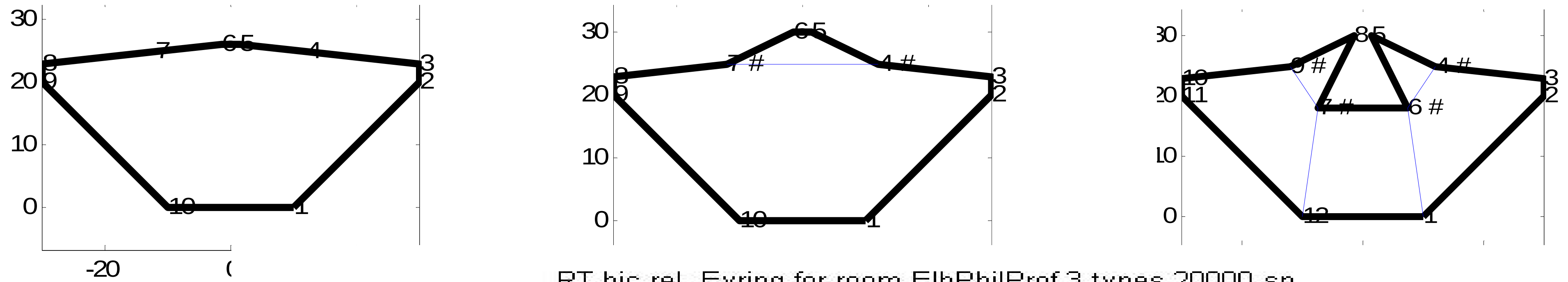
Rel. irr.: stage: 2.37 **3.02** **2.48**

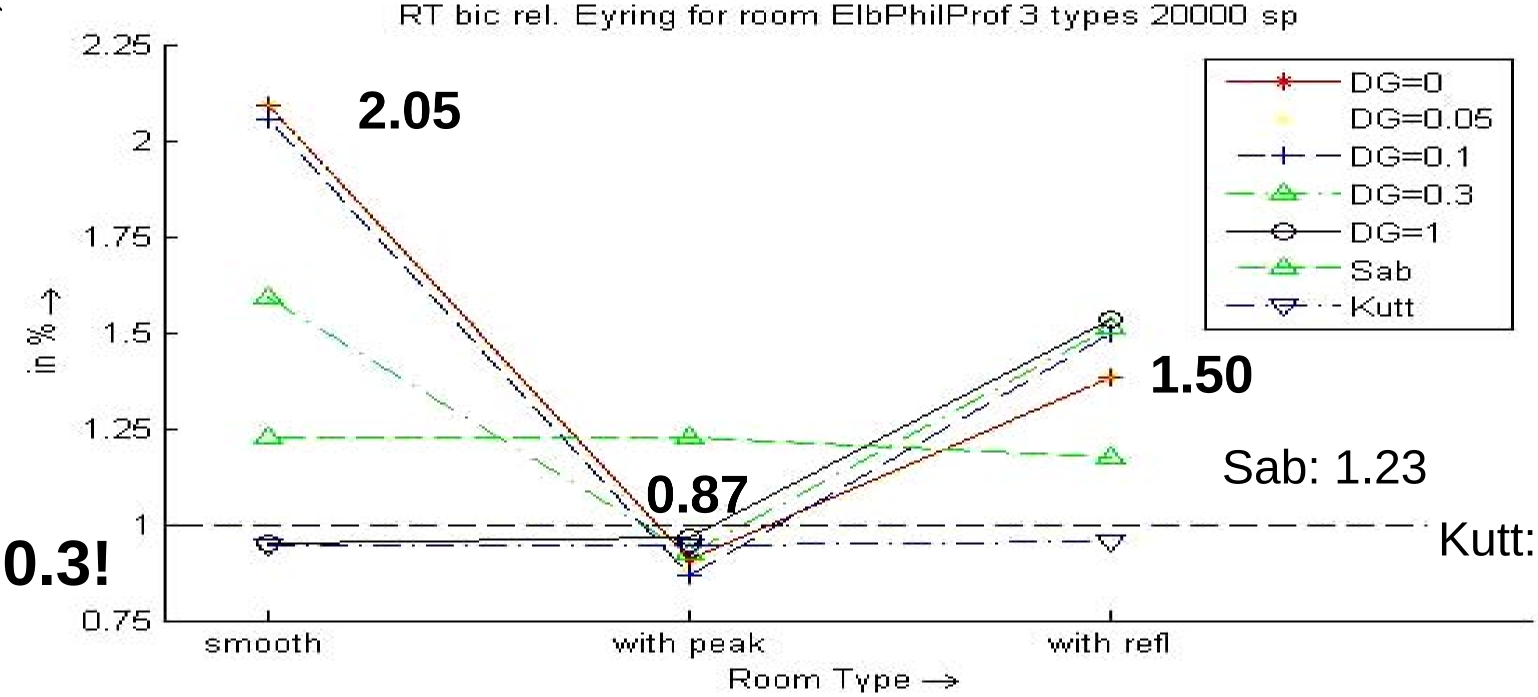
STUDY 3: RT_{30bic}/T_{eyring} without/with a peak in the roof

60m*23m with 45° (20m) rising scattering audience (AG=0.8, DG=1) , stage: DG=.1

$T_{ey} \approx$ **2.25s** height: 26….31m parameter: DG only of the ceiling

one ceiling 6° **with peak 24°** **with reflector**





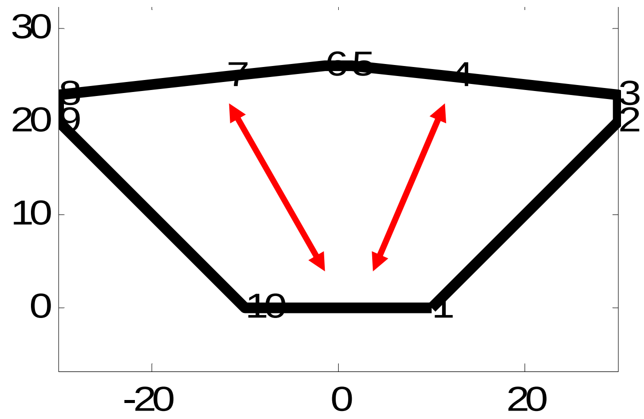
RT is minimum: half value with peak!

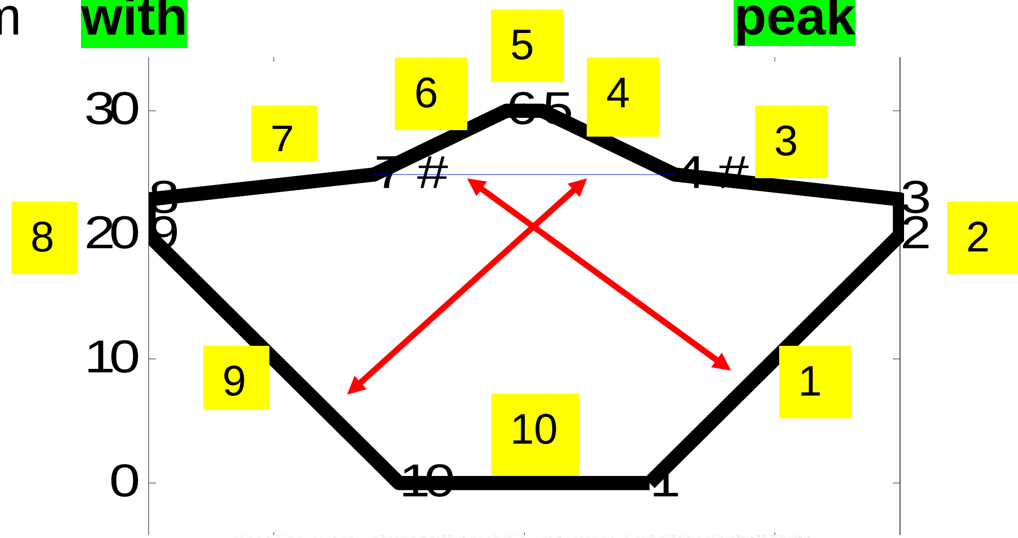
For all DG<0.3!

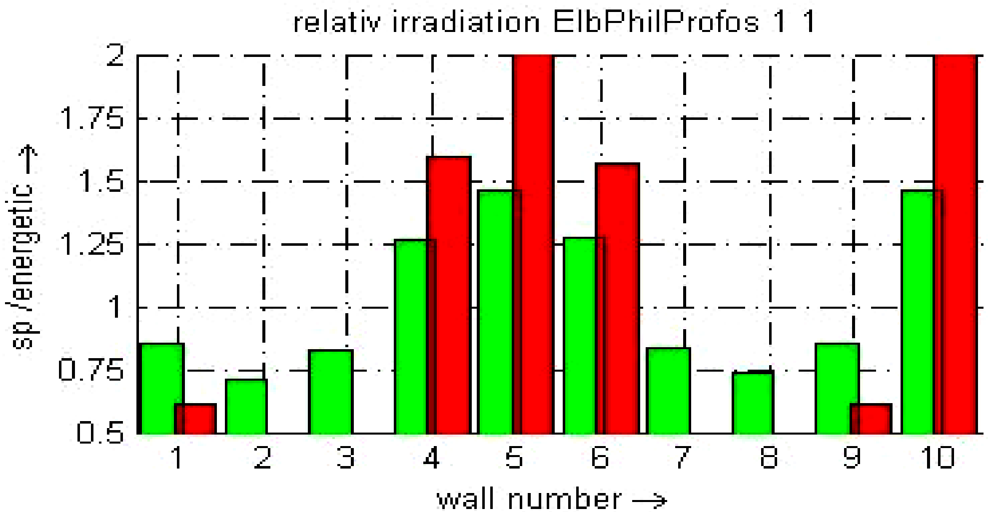
Surface Irradiation TENT $\alpha_{ceiling}$=6°, $AG_{ceiling}$=.05, $DG_{ceiling}$= 10%

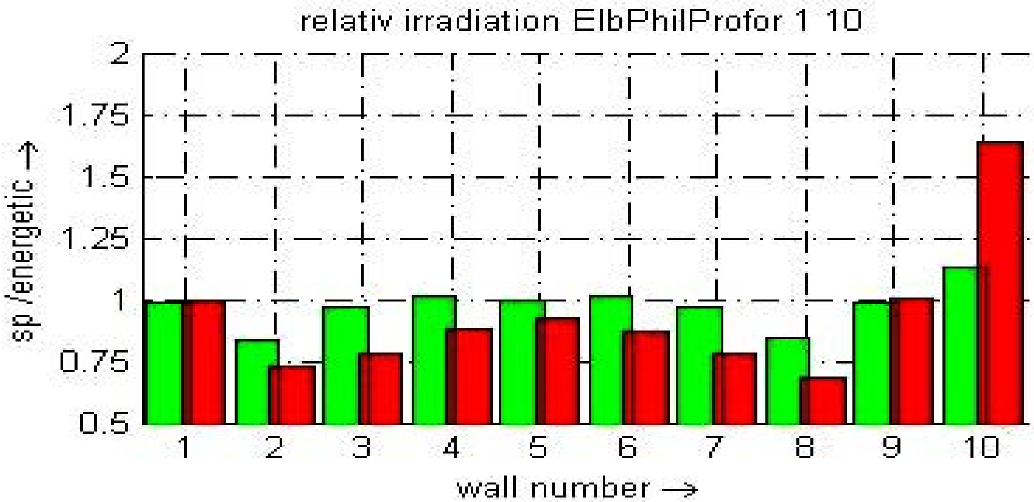
60m*(23..26m) room with 45° rising scattering audience (AG=0.8, DG=1), stage: DG=.05

without peak over Δx ± 12m, Δy=4m **with peak**







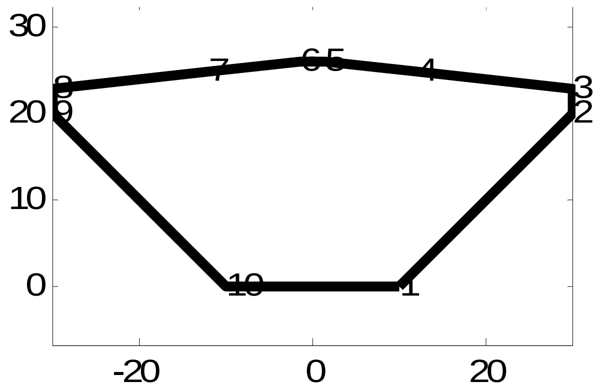


	aud.	roof	aud.	stage	aud.	roof	aud.	stage
irr.:	0.6	1.8	0.6	2.4	1	0.9	1	1.6

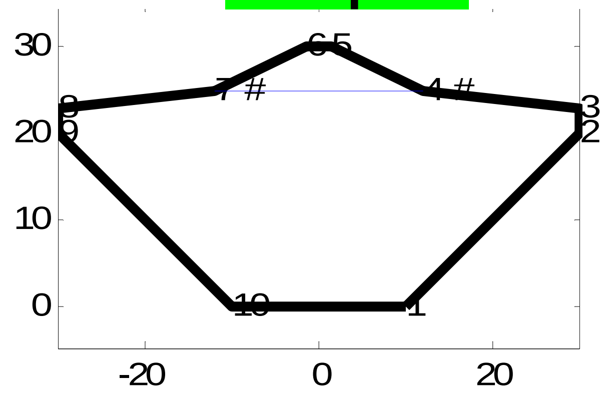
Energy Decays TENT $\alpha_{ceiling}$=6°, $AG_{ceiling}$=.05, $DG_{ceiling}$= 10%

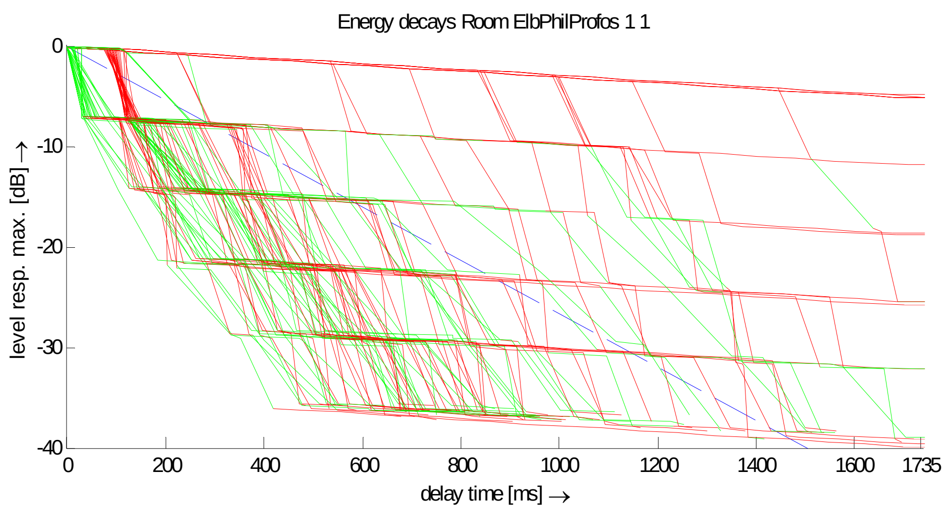
60m*(23..26m) room with 45° rising scattering audience (AG=0.8, DG=1), stage: DG=.05

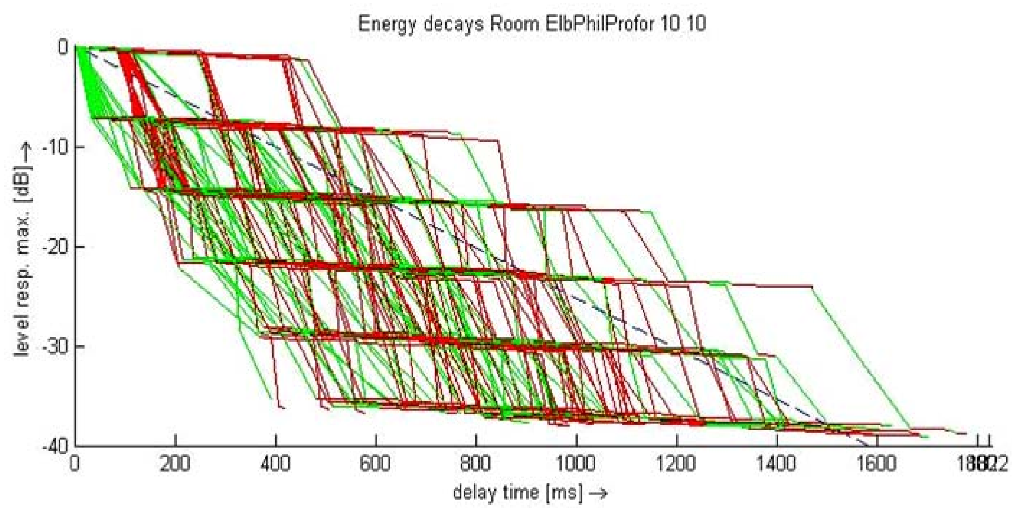
without peak



with peak







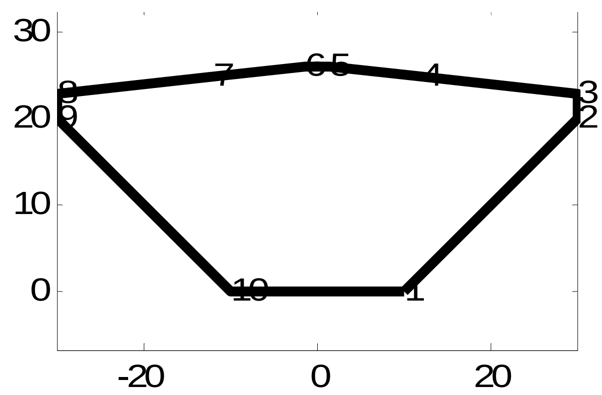
RT = 2.05* Tey

RT = 0.87* Tey

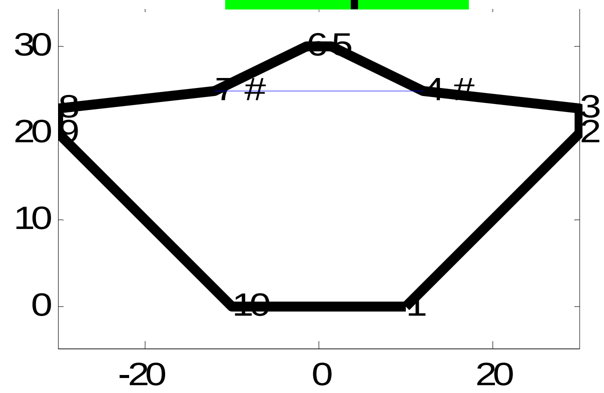
Echograms TENT $\alpha_{ceiling}$=6°, $AG_{ceiling}$=.05, $DG_{ceiling}$= 10%

60m*(23..26m) room with 45° rising scattering audience (AG=0.8, DG=1), stage: DG=.05

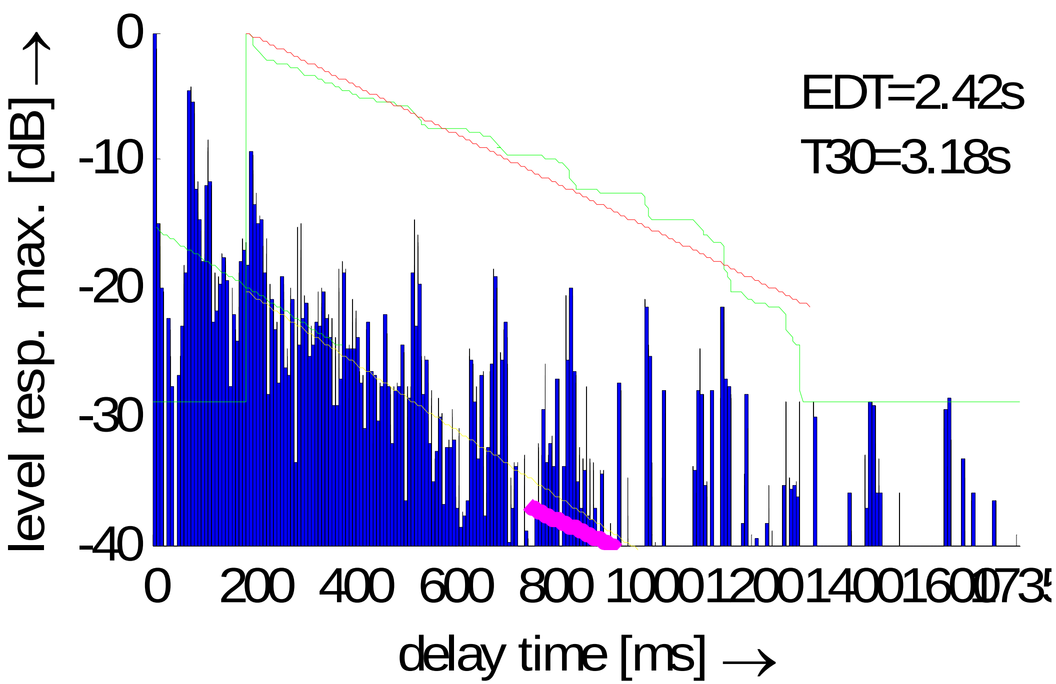
without peak

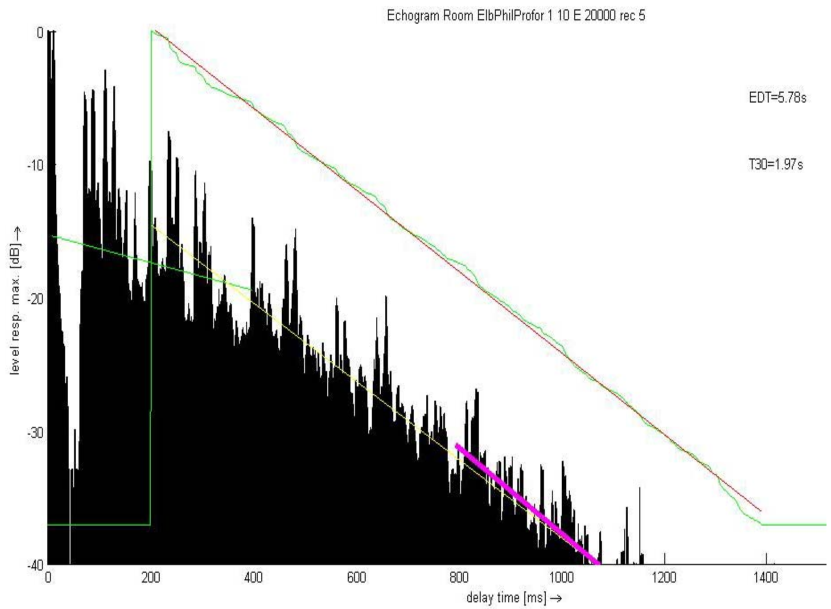


with peak



Echograms at a place middle in the right audience (x=17, y=9)



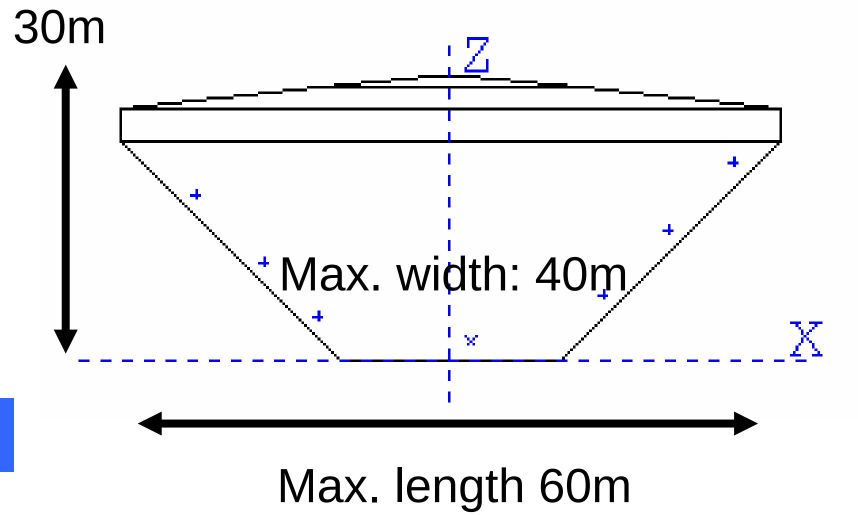


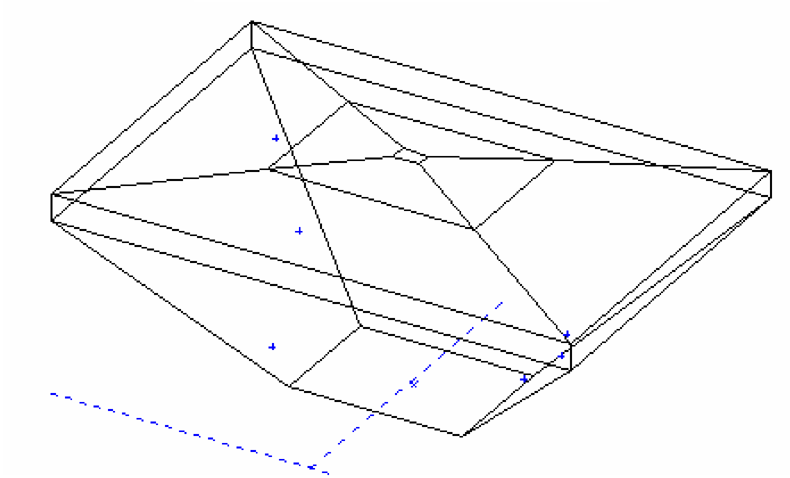
Study 4: 3D –Room Model V=33800….34600m³ (15.7…16.1m³/seat)

(max. 60m*40m* 23…26m, total surface 6700..6900m² (with 2150 seats on 1433m²)
with 4 45°or 20m rising audience areas, 3440m²

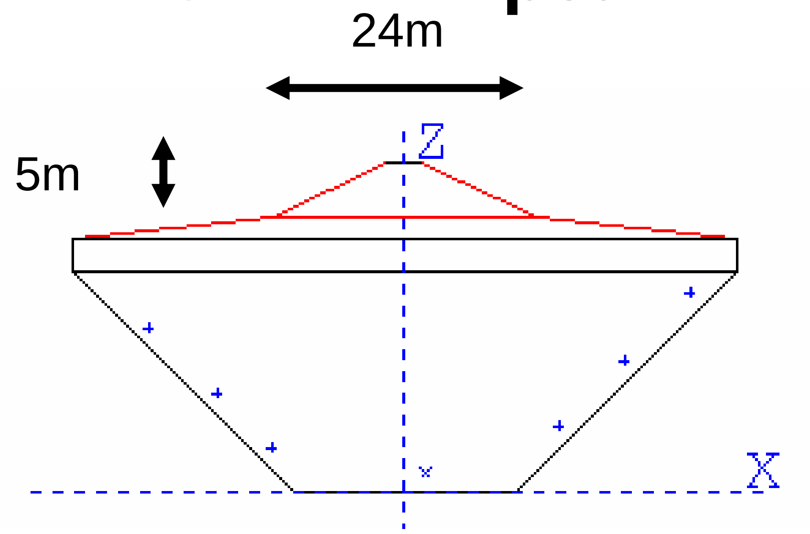
without peak

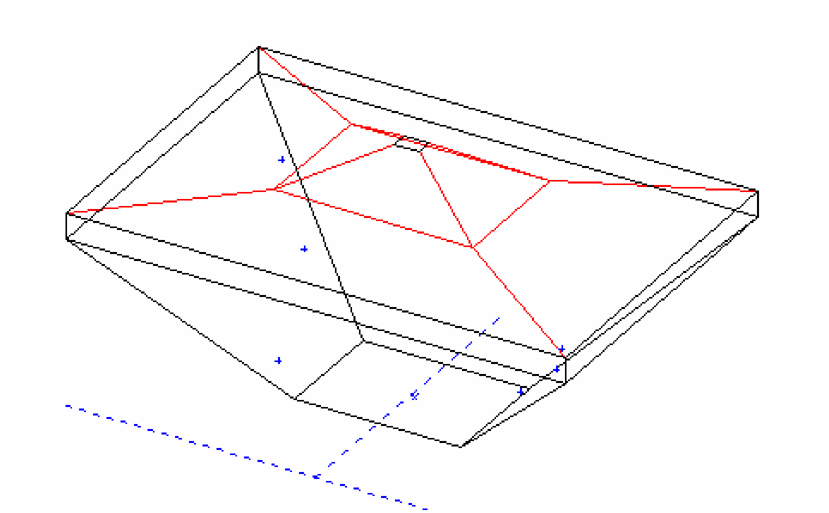
cross section:





with peak





RT_{30}/T_{ey} for the 3D –Room Model with / without peak

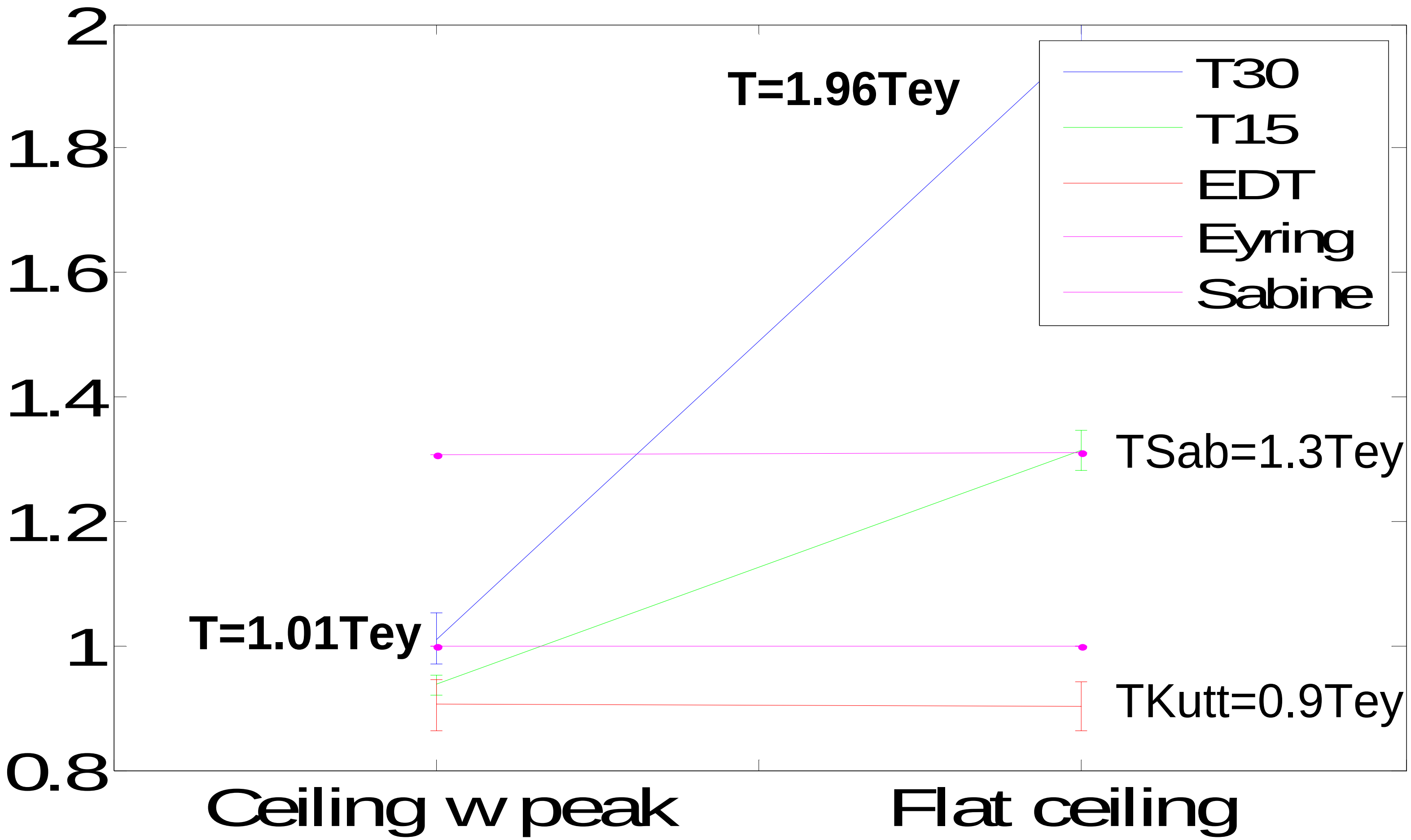
scattering audience: AG=0.8, DG=1, all other walls: AG= 5%, DG=10%

4 large audience areas, mean absorption degree = 42%; T_{ey}=1.41…1.43s

(with N =2150 seats expected: T_{sab}=3.6s; with 3440m², AG=80%: T_{sab}=1.87…1.91s)

computed with CATT (200000 rays, 6 receivers, 6 oct. bands, 8 repetitions)

Half value with a small peak in the roof!



Conclusions

For realistic diffusivity degrees of DG=0.1:

Reverberation times in an auditorium depend considerably on the of ceiling shape

Reason is the higher or lower irradiation of absorbing walls or of reflecting walls opposite

The RT vary by a factor of up to 1.5…2

a) with flat floor, decreasing with steeper roofs (0...45°)

b) with rising audience, maximum at certain angles (for ex. 6-7°)

c) steeper audience itself (with flat roof) has a weak effect

with 100% diffusely scattering walls the effect vanishes: RT -----→T_Eyring or T_Kuttruff

reverberation times are hardly ever lower than 20% under T_Eyring or under T_Kuttruff

The EDT is often lower than the RT, the ‘Deutlichkeit’ is increasing with increasing roofs

with an even small **peak in the roof** (2D or 3D) RT may be pushed down by a factor 2!

All these measures make the echograms much smoother.

THE PEAK IS LIKE A MAGIC DIFFUSOR !

A ‘tent’-shape is favourable. But the RT does not fall under about 70% of Tsab.

-> The volume of the draft of the Elbphilharmonie in Hamburg is probably too high!

OUTLOOK

Many questions remain open:

What is the correlation between ceiling profile, Deutlichkeit and level with distance?

What is the optimum shape of the ceiling for a wanted parameter distribution?
Is an elliptical, parabolic or similar shape best?

What is an ‘optimal parameter distribution’ and an optimal mix of parameters?

Can a self-optimizing procedure for the room ceiling shape be found?

the solution of this typical inverse problem remains a long-term goal.

Statistical error of the reverberation times computed by linear regression at the decay curves (repetition error)

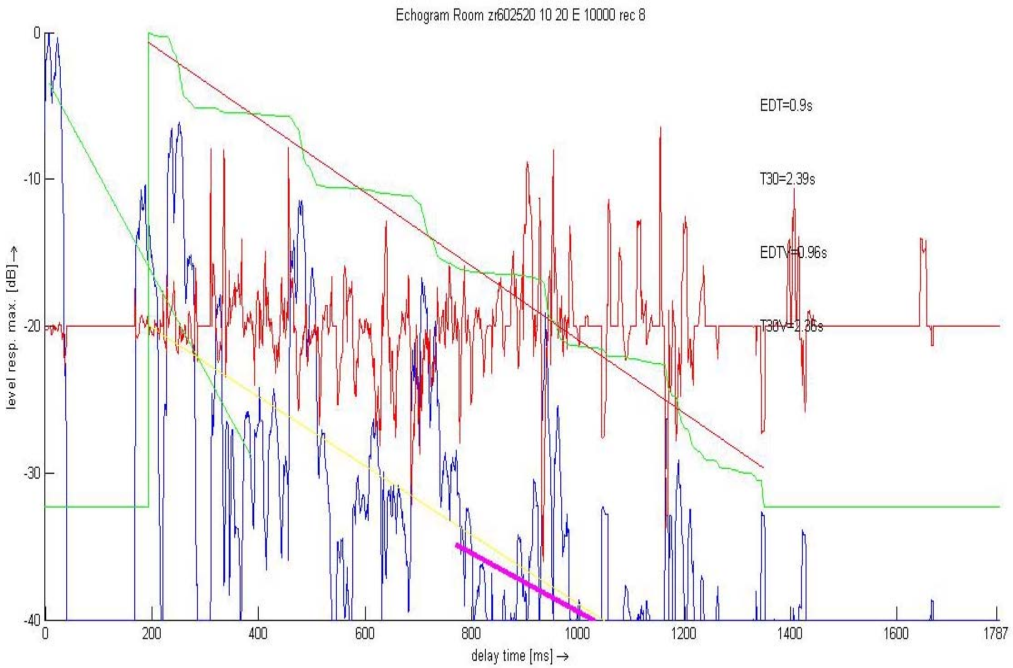
example of a result table (2400sp) for 9 receiver places:

special values of all receivers with echograms:

no.	Pos x	y	EDT	T60direkt	T20-35	T60ric
1	1.000	1.000	2.82	2.75	2.88	**3.02**
2	5.000	1.000	3.10	2.41	2.19	**2.23**
3	-5.000	1.000	5.65	2.85	2.68	**3.09**
4	11.000	3.000	4.36	2.43	2.27	**2.69**
5	-11.000	3.000	4.40	2.53	4.41	**3.80**
6	19.000	11.000	2.75	2.34	2.86	**2.78**
7	-19.000	11.000	3.36	2.12	1.76	**2.21**
8	29.000	21.000	2.05	2.18	2.82	**2.28**
9	-29.000	21.000	2.77	2.19	1.57	**2.10**
mean values			3.47	2.42	2.60	**2.69s**
standard deviations			**1.12**	**0.25**	**0.83**	**0.56s**

expected stand. dev. of the mean value : 0.18s

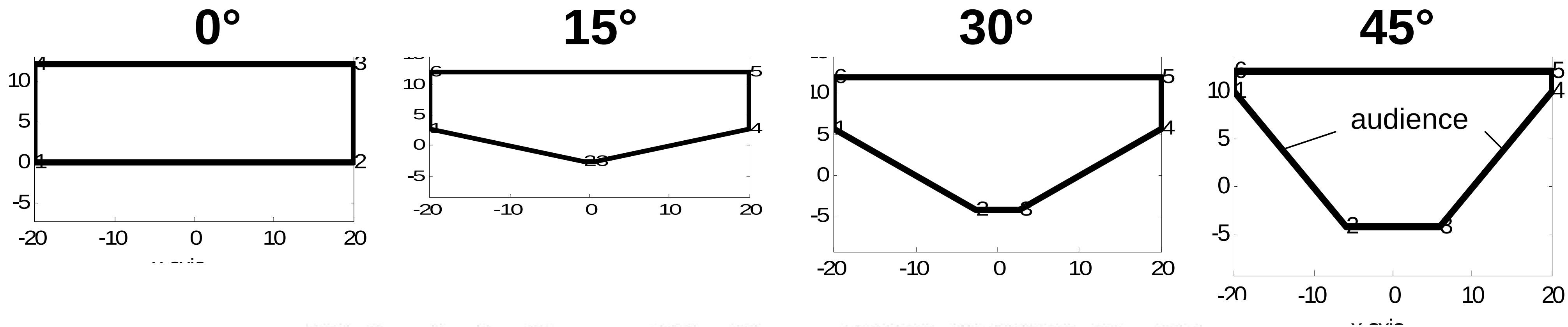
example of an echogram with 10000 immitted sound particles:



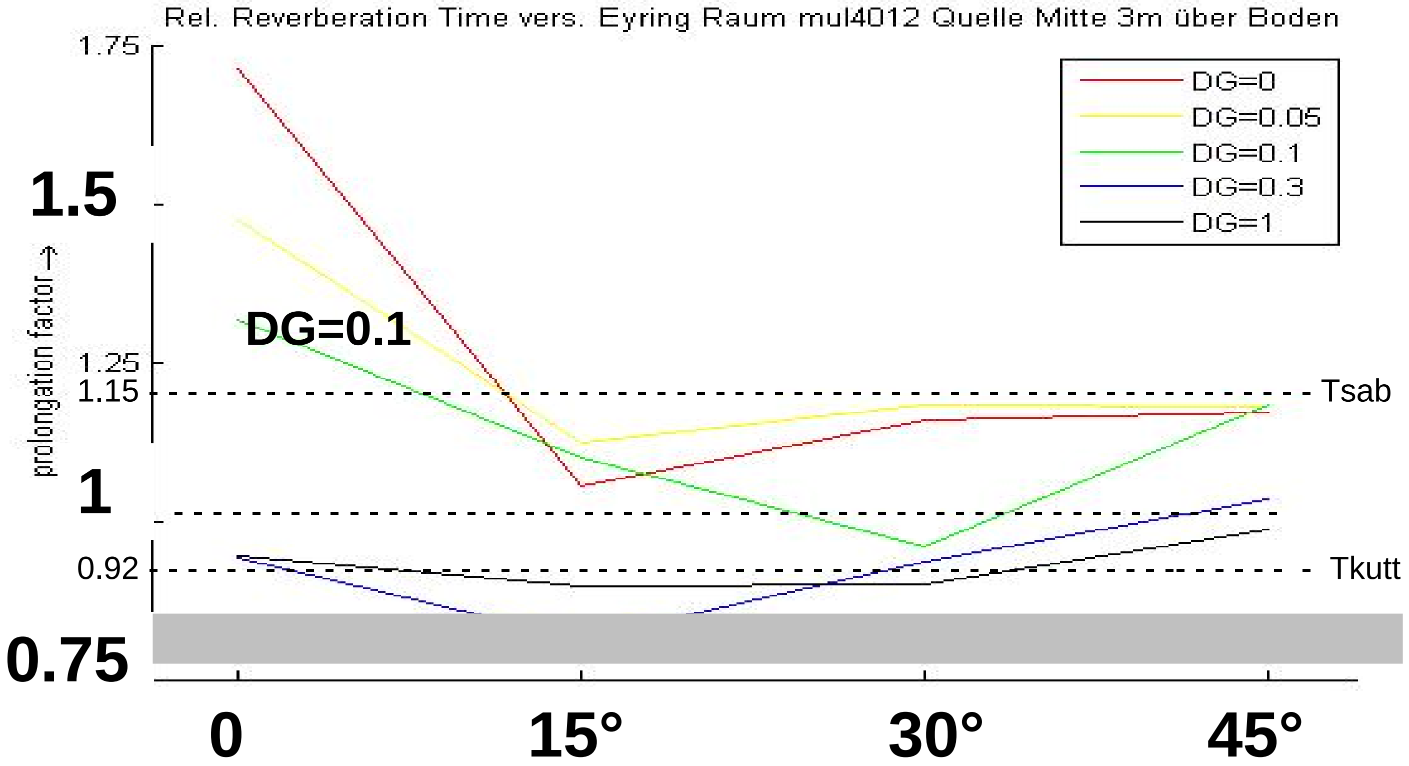
-> computed RT inaccurate due to statistics and regression analysis -> average over many places

$RT_{30\ bic} / T_{eyring}$ as function of the audience angle (T_{ey}=2.02s)

40m*12m room with constant absorption area and flat ceiling, parameter: DG



Only in the shoe-box RT is Enhanced



else T_{ey}<RT <T_{sab}

RT higher than in the "Tent"!

EDT