Three dimensional determination of etch track parameters in plastic nuclear track detectors: findings on bulk etch rate and implications for dosimetry.

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Summary and Conclusion

- Bulk etch rate in plastic detectors varies significantly
    - during etch time (CR 39)
    - locally by 10% to 25% (CR 39 and cellulose nitrate)

- Precision of dose equivalent measured thereby limited to perhaps 20% or more

  (neglecting other sources of error)

Overview

Historical background – motivation

2D measurement technique

3D measurement technique – experimental

3D measurement technique – theoretical analysis

3D measurements – accuracy/precision

Local bulk layer data (cellulose nitrate, D1 mission)

Local bulk layer data (CR 39, ISS mission/HIMAC)

Global bulk layer data (CR 39, ISS/HIMAC, mechanical thickness)

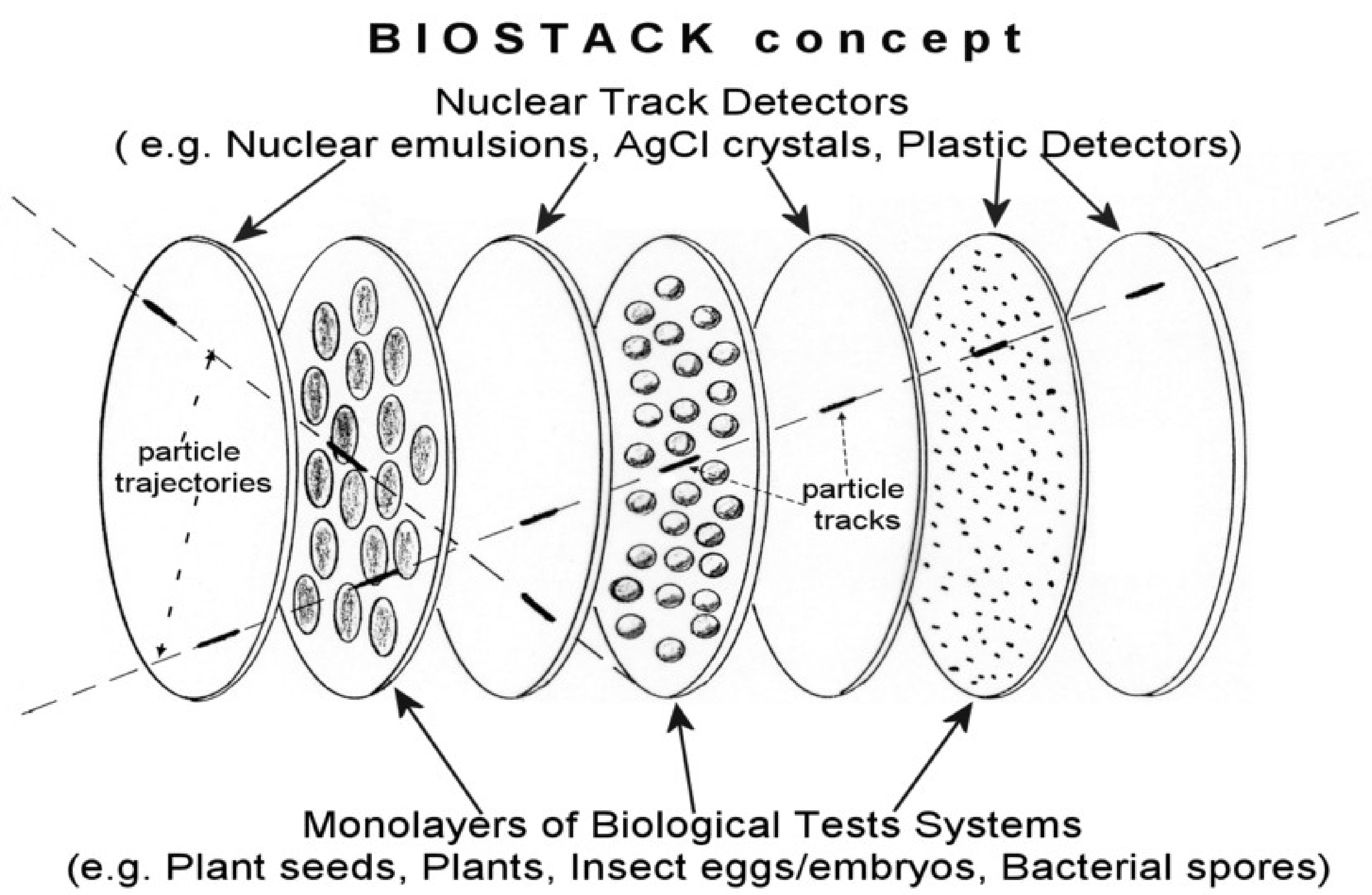
2D – 3D comparisons (CR 39)

Implications for dosimetry

Puzzles (a few, for me)

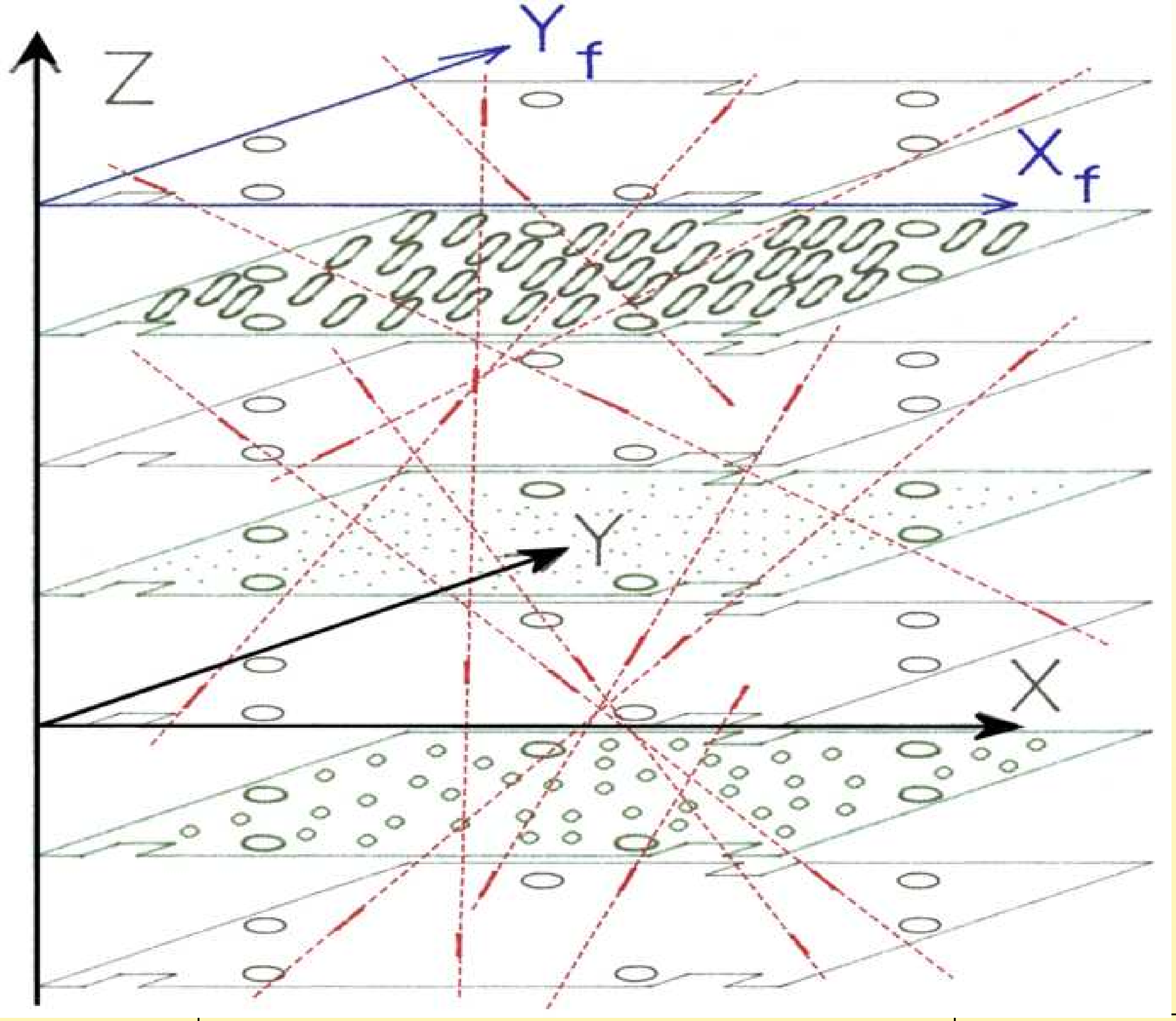
Historical background – motivation

Background



BIOSTACK concept
Nuclear Track Detectors
(e.g. Nuclear emulsions, AgCl crystals, Plastic Detectors)
particle trajectories
particle tracks
Monolayers of Biological Tests Systems
(e.g. Plant seeds, Plants, Insect eggs/embryos, Bacterial spores)

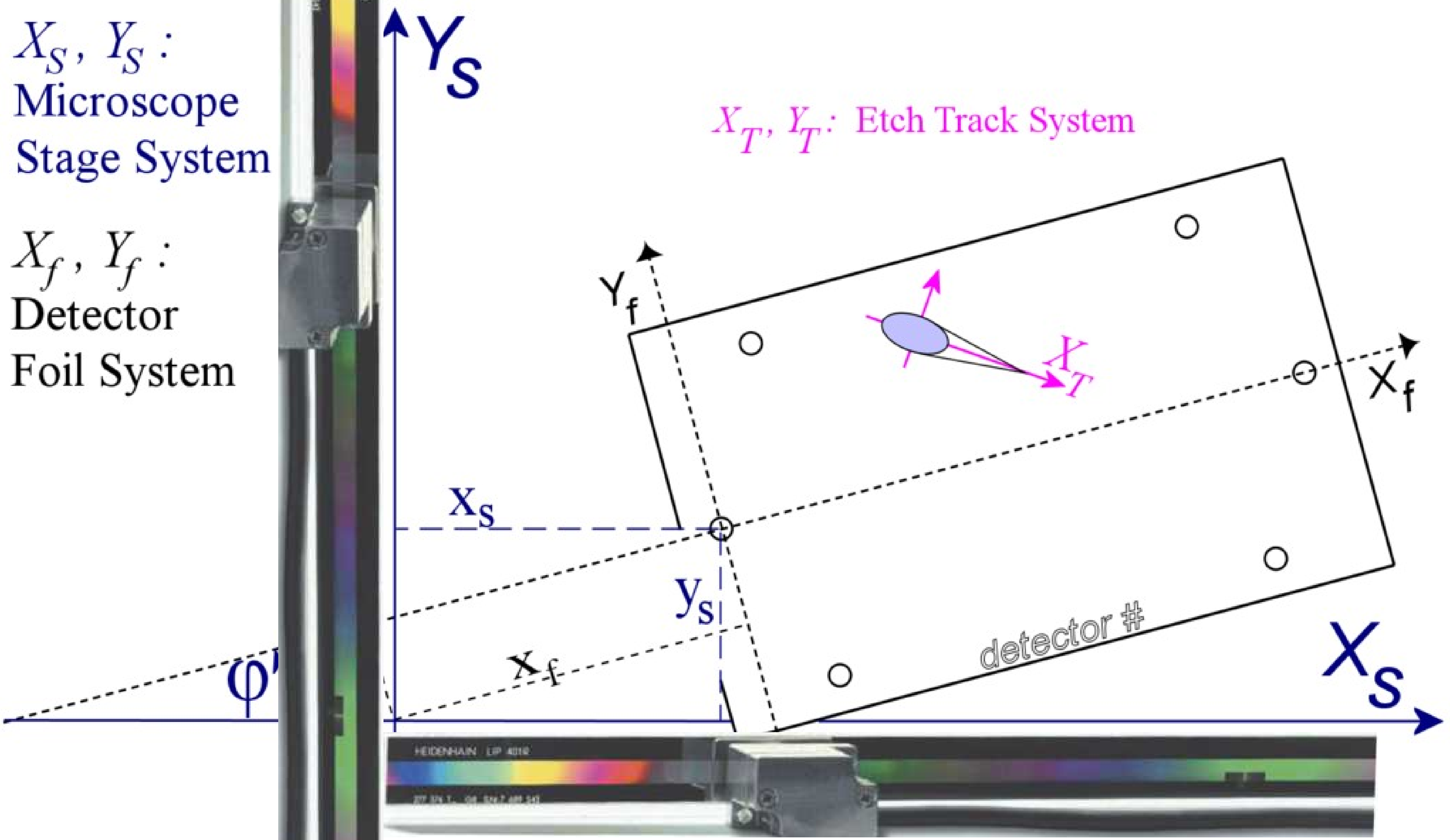
Localization of particle tracks in biological test organisms



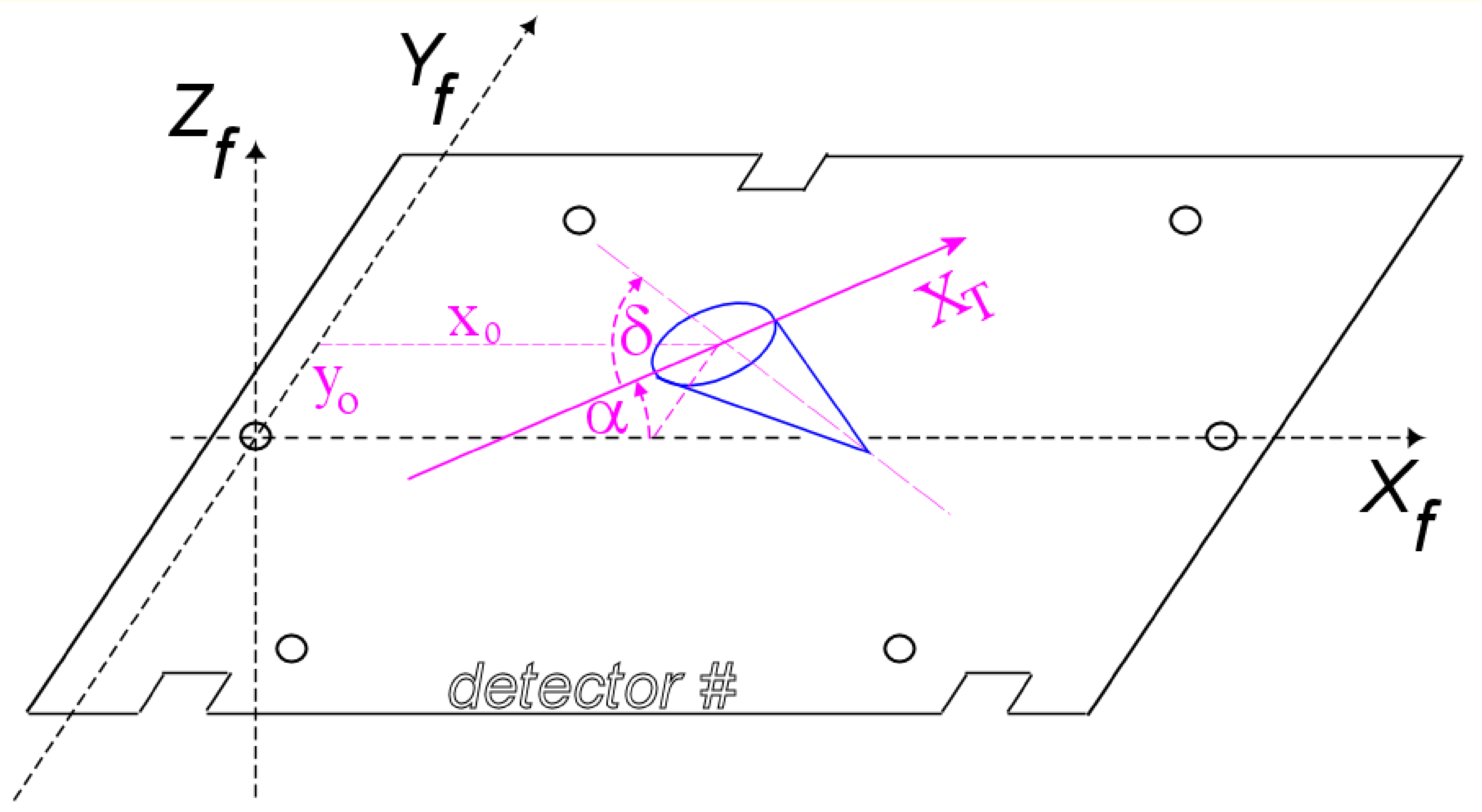
Co-ordinate systems involved in microscopic track measurements

X_S, Y_S : Microscope Stage System

X_f, Y_f : Detector Foil System

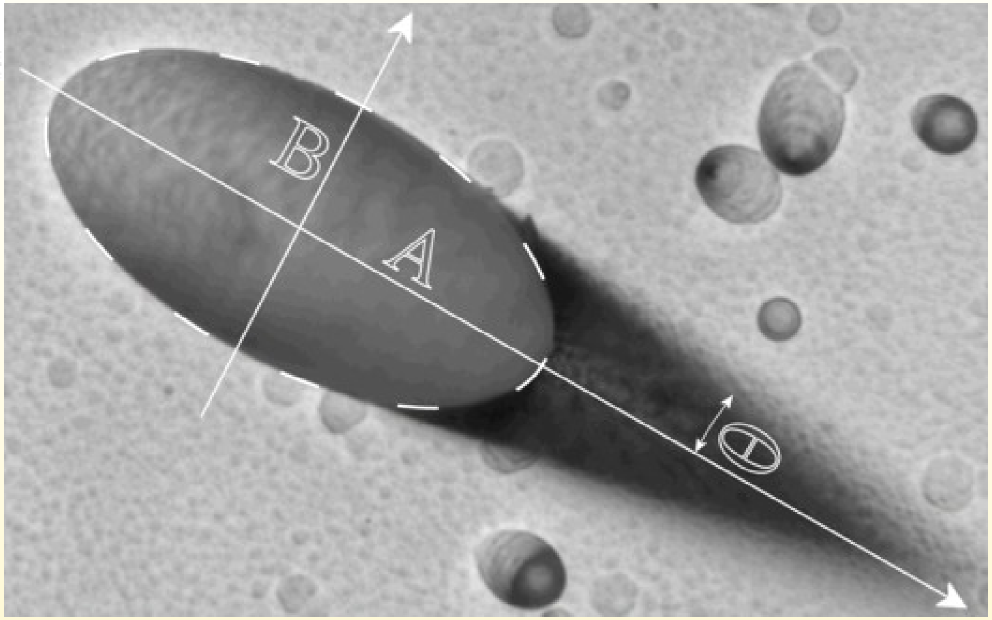


Position and orientation of etch tracks in the detector system



2D measurement technique

Principle



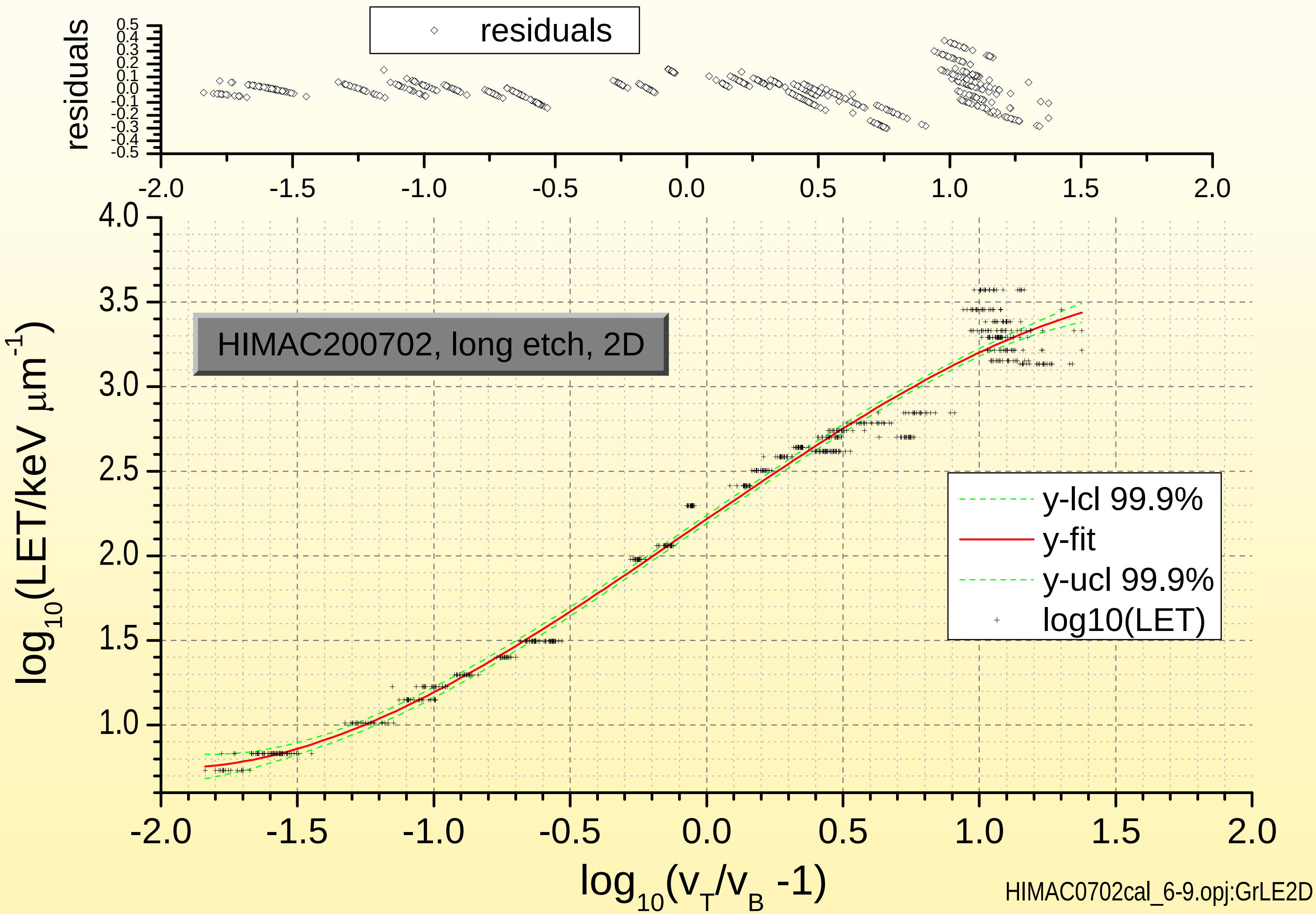
Relative etch rate $R = v_t / v_b = 1 / \sin\theta$

$$R = \sqrt{ (2A/H)^2 / [1-(B/H)^2]^2 + 1 }$$

A, B: semi- major, minor ellipse axis

H: bulk etch layer = const. **in space and time !**

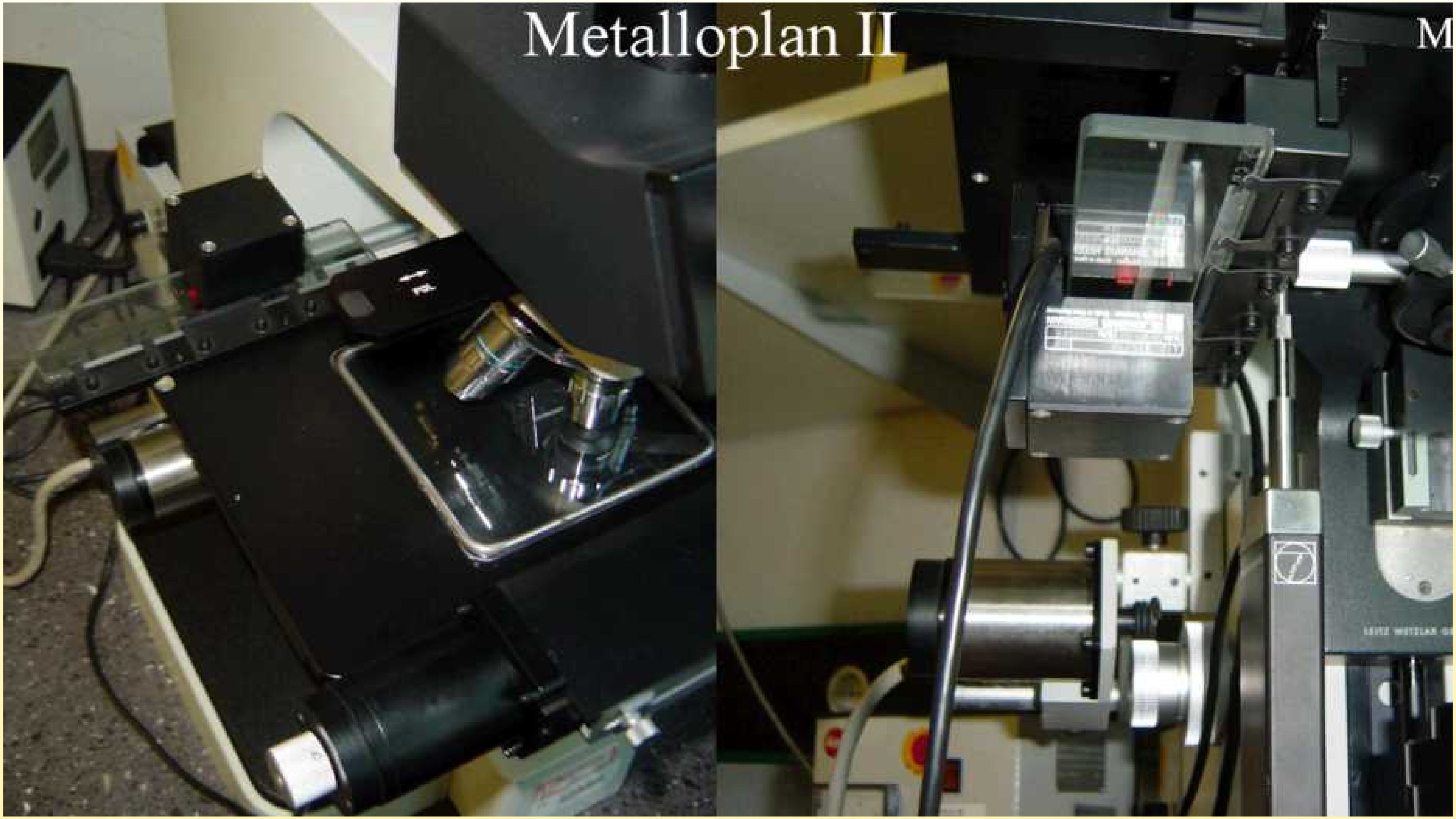
HIMAC-2007 calibration curve, **LET(R)**



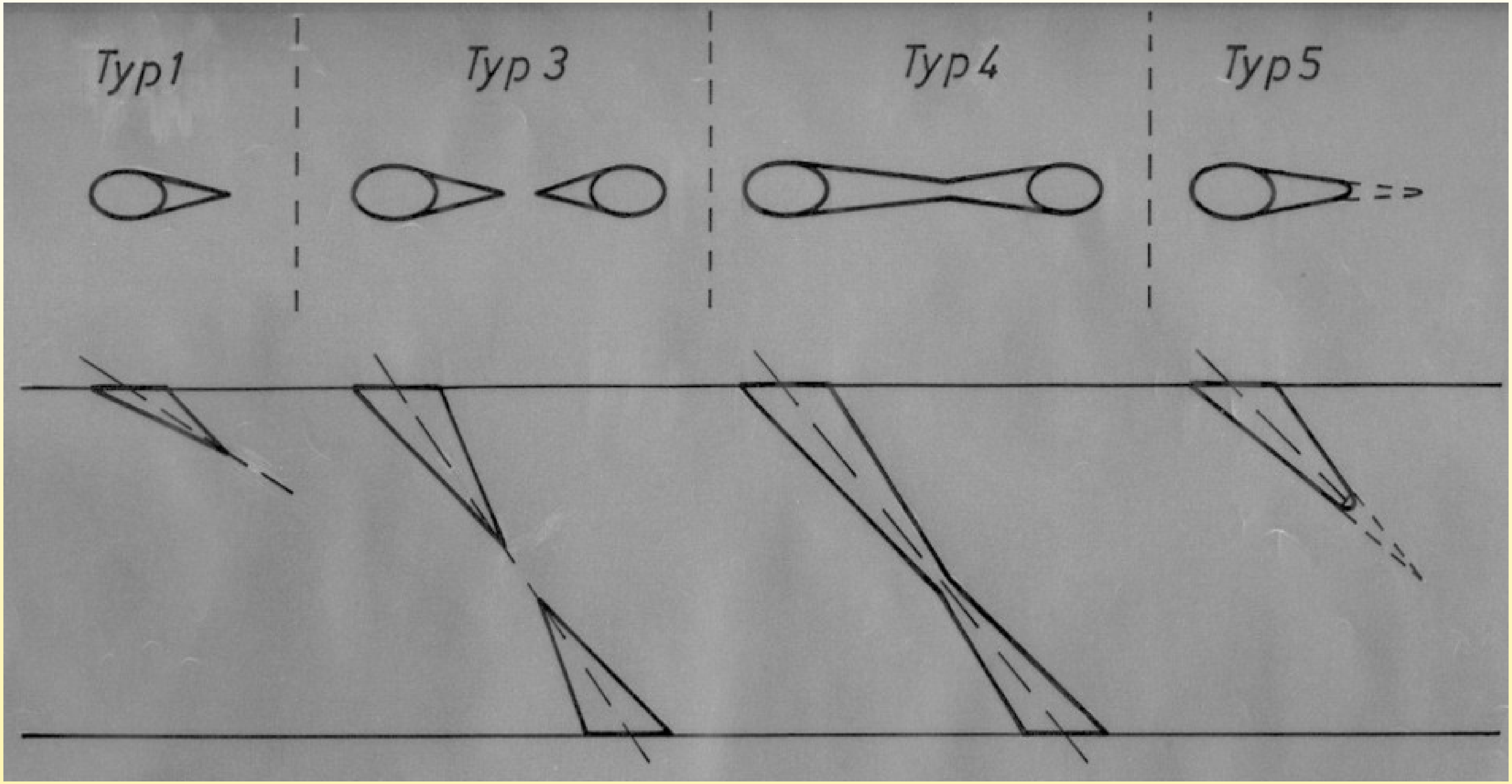
3D measurement technique

experimental

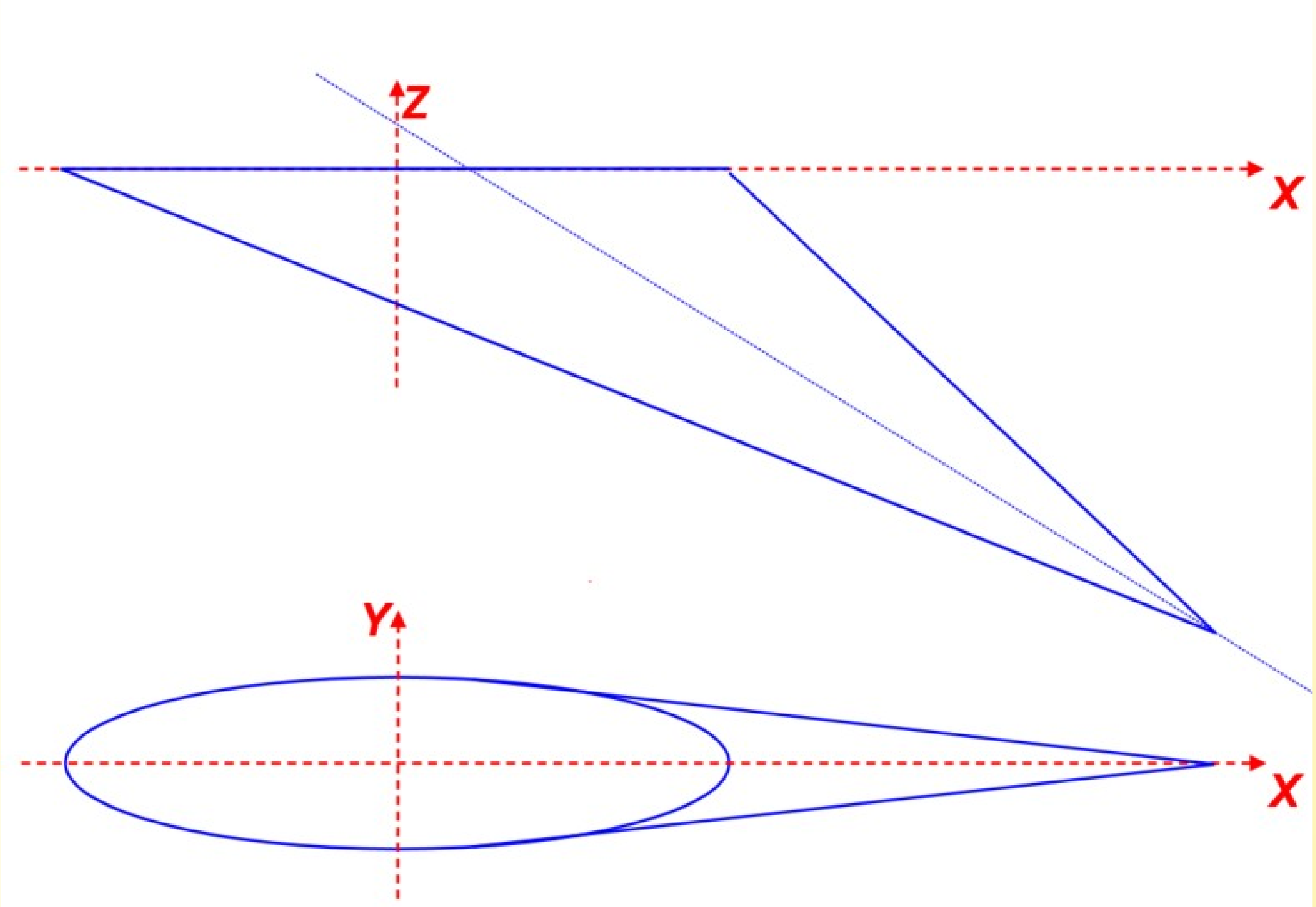
Microscope stage with linear position encoders on three axes (0.1 μm)



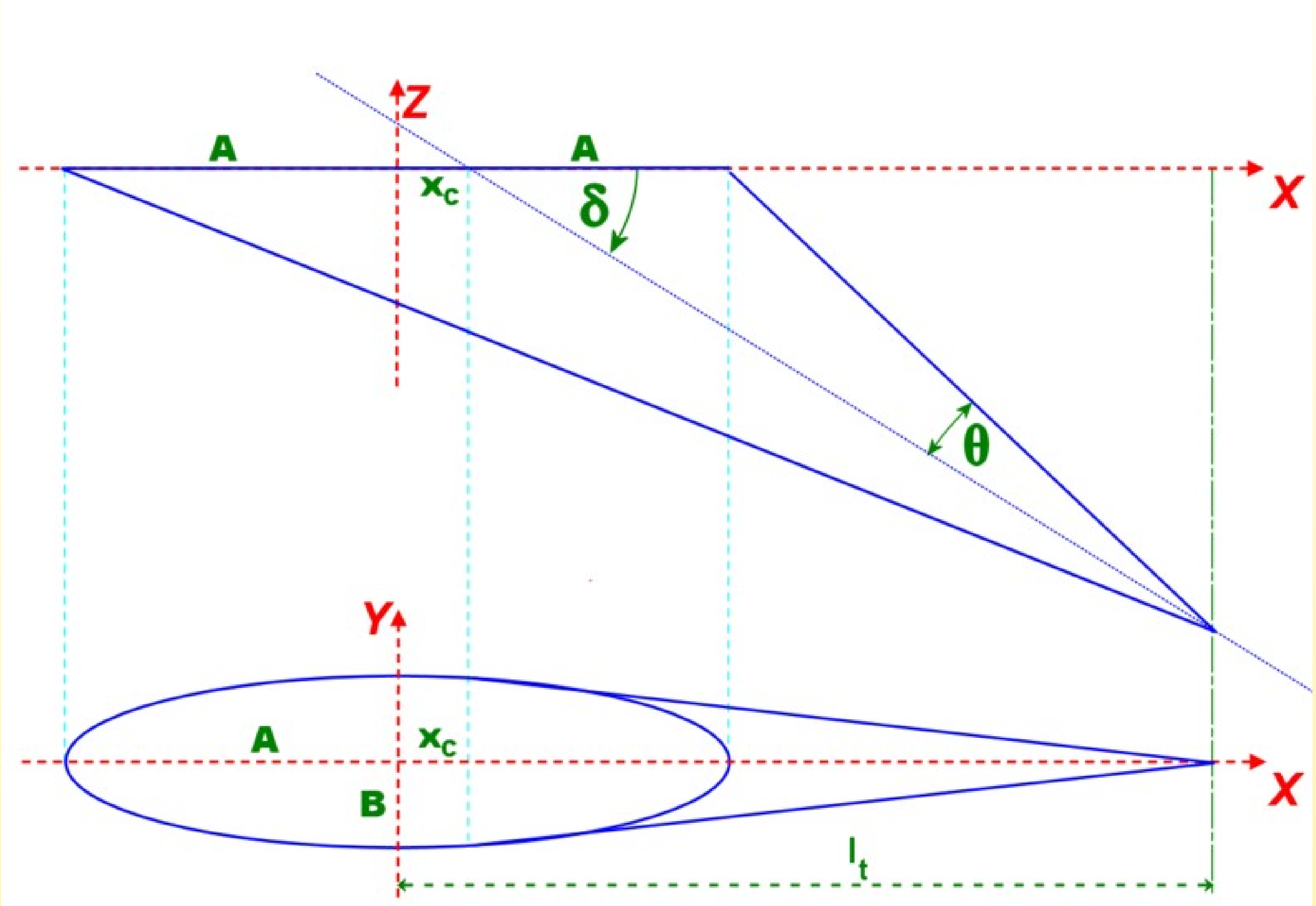
Geometry of etch track types assigned for measurement program



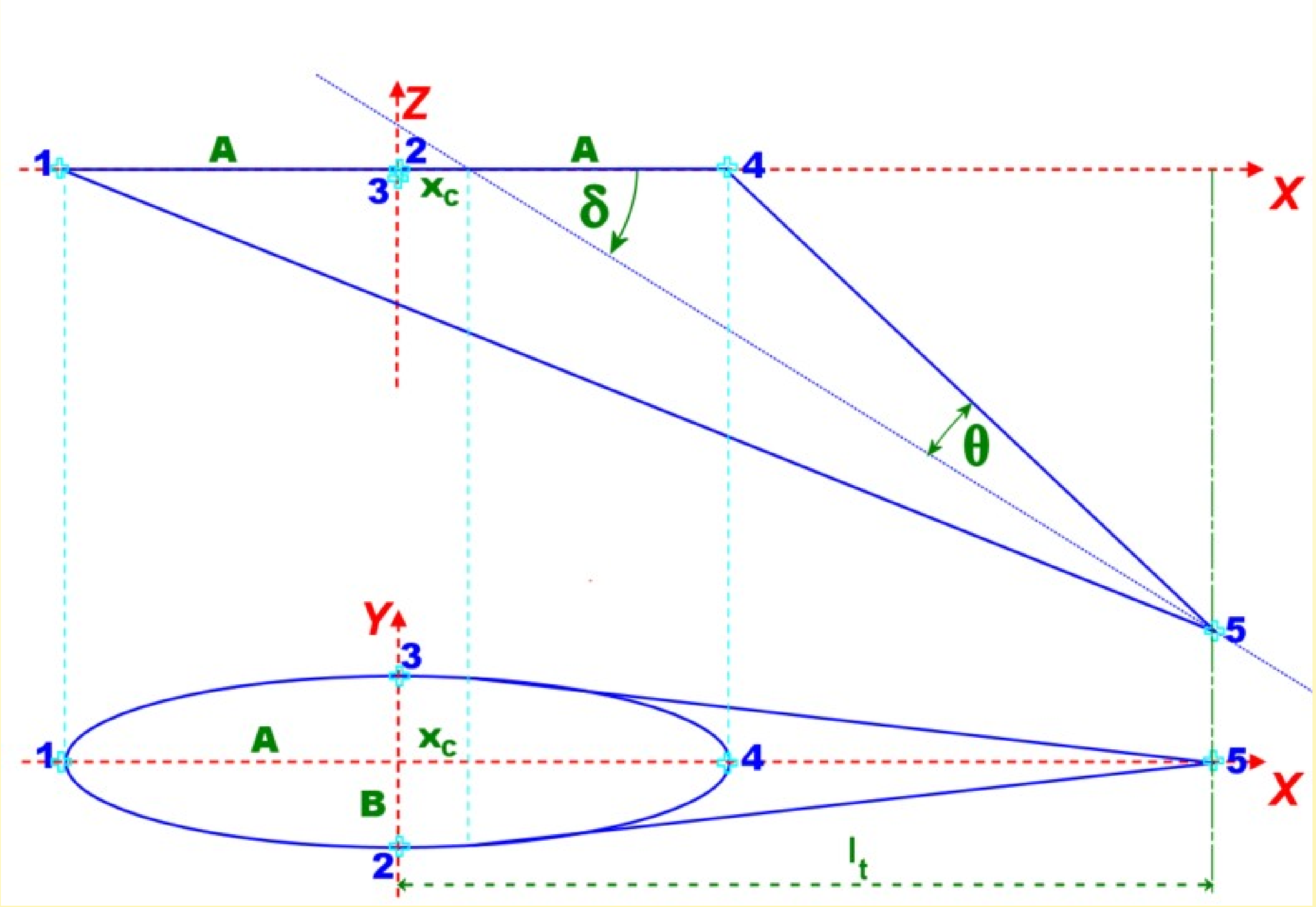
Geometry of etch track type 1 in the track system, T



Parameters defining the size of etch tracks type 1



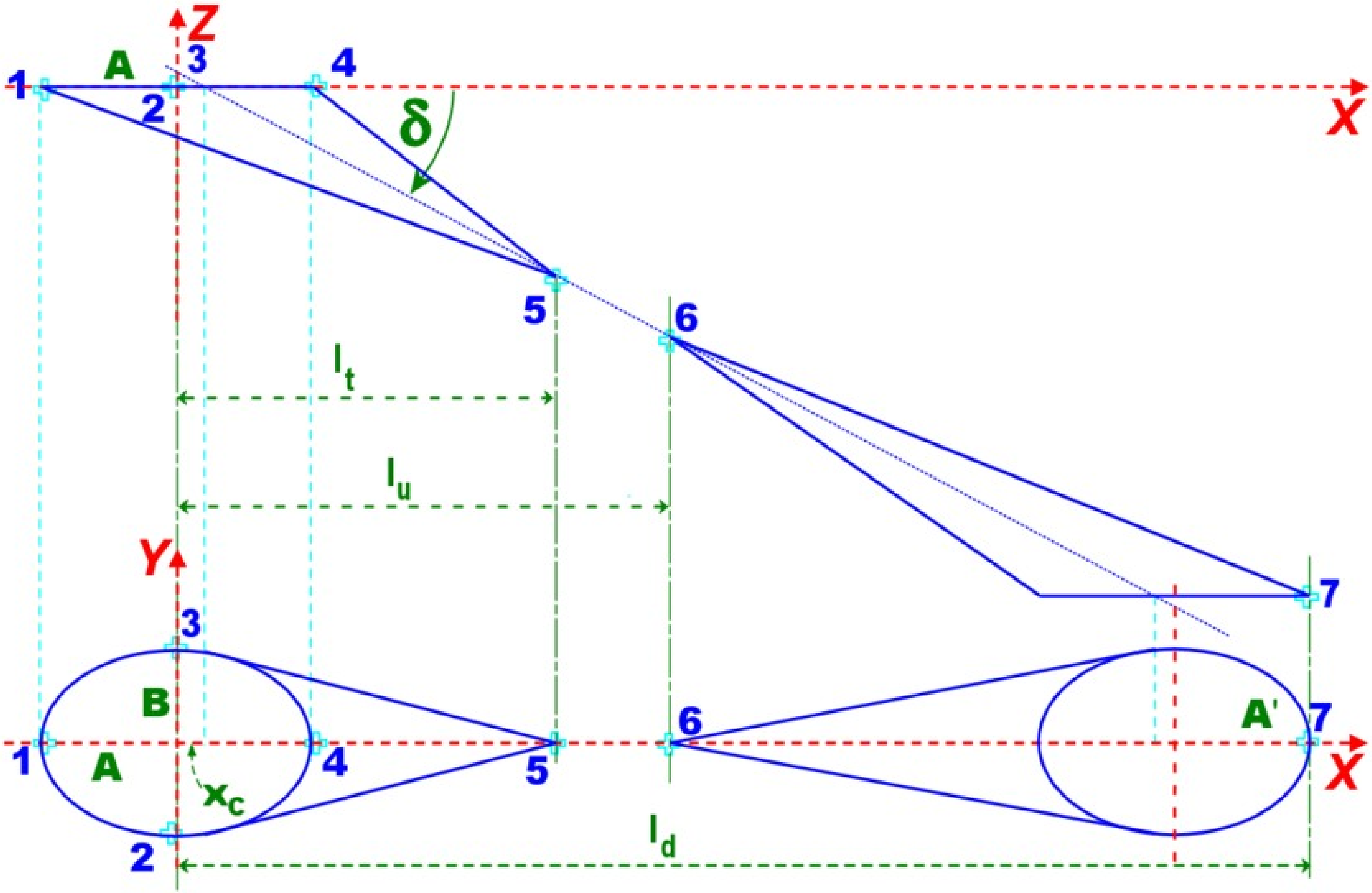
Measurement points for etch tracks type 1



Co-ordinates in the track system, T, of track measuring points for type 1 tracks

Point No.	$X_{T,i}$	$Y_{T,i}$	$Z_{T,i}$
1	$-A$	0	0
2	0	$-B$	0
3	0	$+B$	0
4	$+A$	0	0
5	l_t	0	$-(l_t - x_c) * tg(\delta)$

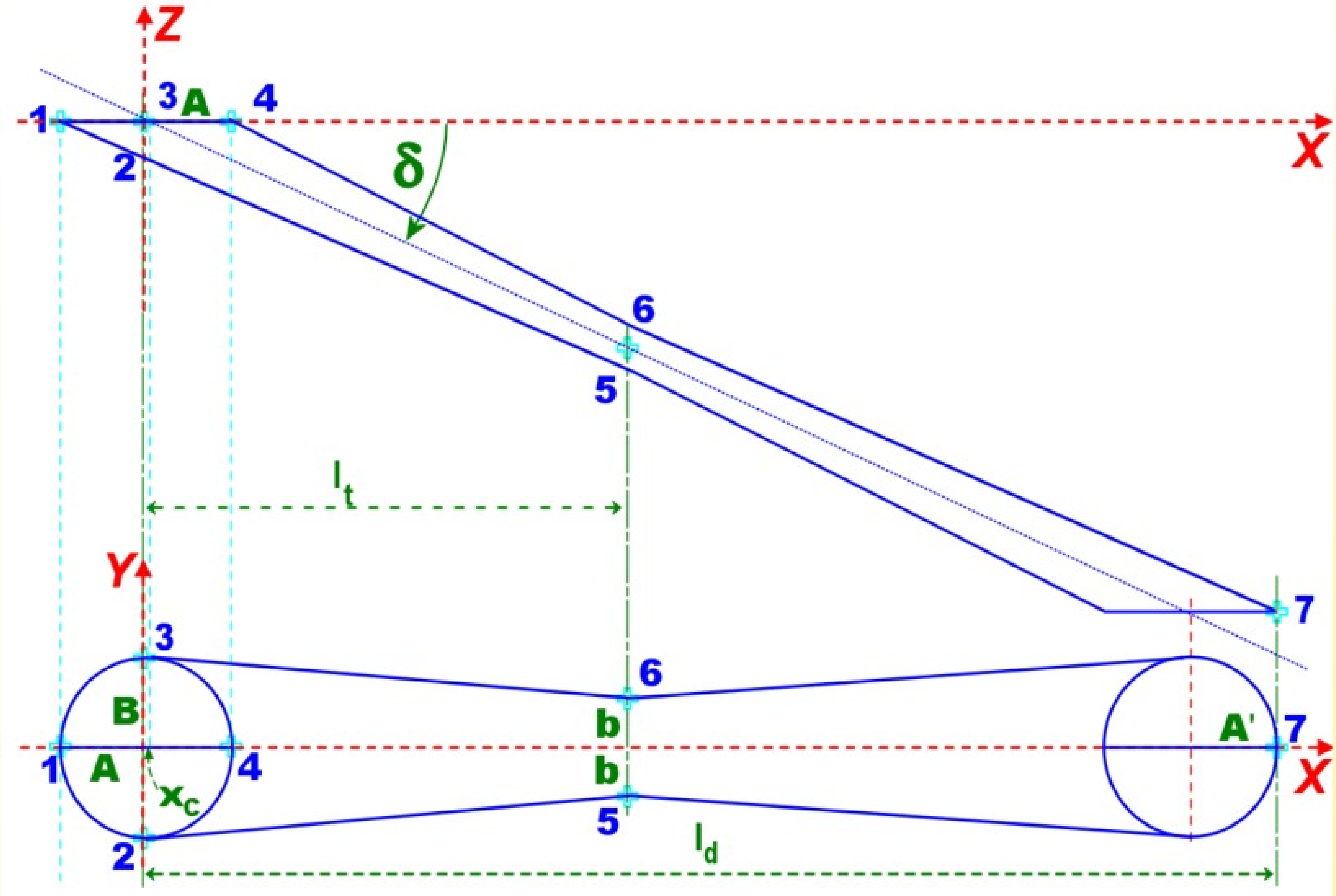
Measurement points for etch tracks type 3



Co-ordinates in the track system, T, of track measuring points for type 3 tracks

Point No.	$X_{T,i}$	$Y_{T,i}$	$Z_{T,i}$
1	$-A$	0	0
2	0	$-B$	0
3	0	$+B$	0
4	$+A$	0	0
5	l_t	0	$-(l_t-x_c)*tg(\delta)$
6	l_u	0	$-(l_u-x_c)*tg(\delta)$
7	l_d	0	$-(l_d-A'-2x_c)*tg(\delta)$

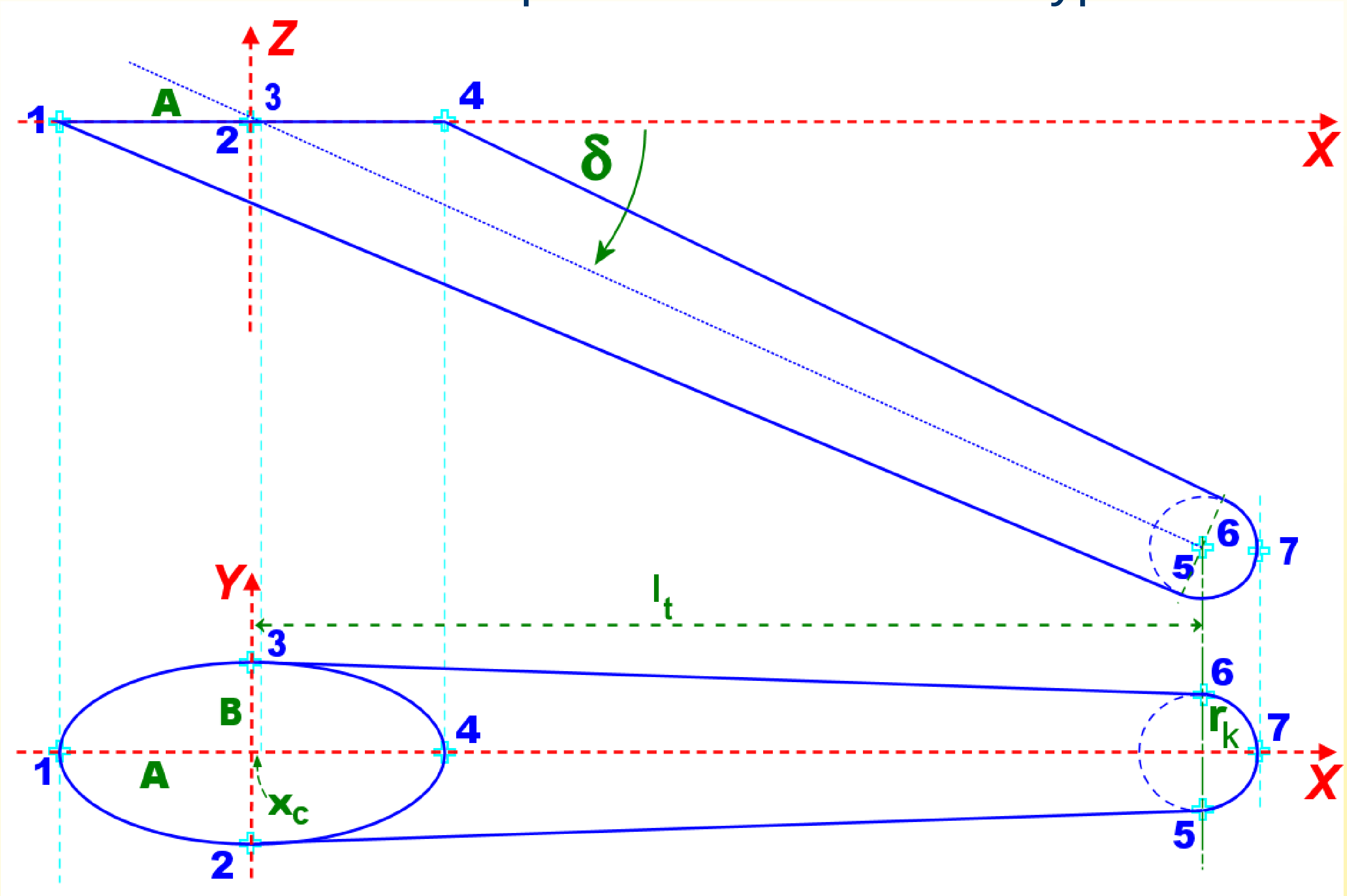
Measurement points for etch tracks type 4



Co-ordinates in the track system, T, of track measuring points for type 4 tracks

Point No.	$X_{T,i}$	$Y_{T,i}$	$Z_{T,i}$
1	–A	0	0
2	0	–B	0
3	0	+B	0
4	+A	0	0
5	l_t	–b	$-(l_t-x_c)*tg(\delta)$
6	l_t	+b	$-(l_t-x_c)*tg(\delta)$
7	l_d	0	$-(l_d-A'-2x_c)*tg(\delta)$

Measurement points for etch tracks type 5



Co-ordinates in the track system, T, of track measuring points for type 5 tracks

Point No.	$X_{T,i}$	$Y_{T,i}$	$Z_{T,i}$
1	$-A$	0	0
2	0	$-B$	0
3	0	$+B$	0
4	$+A$	0	0
5	l_t	$-r_k$	$-(l_t-x_c)*tg(\delta)$
6	l_t	$+r_k$	$-(l_t-x_c)*tg(\delta)$
7	l_t+r_k	0	$-(l_t-x_c)*tg(\delta)$

3D measurement technique

theoretical analysis

Transformation of co-ordinates from the track system, T, into the detector system, F.

$$X_{F,i} = X_{T,i} \cos(\alpha) - Y_{T,i} \sin(\alpha) + X_0$$
$$Y_{F,i} = X_{T,i} \sin(\alpha) + Y_{T,i} \cos(\alpha) + Y_0$$
$$Z_{F,i} = Z_{T,i} + Z_0$$

Co-ordinates in detector system, F, of track measuring points for type 1 tracks

Point No.	$X_{F,i}$	$Y_{F,i}$	$Z_{F,i}$
1	$x_0 - A*\cos(\alpha)$	$y_0 - A*\sin(\alpha)$	z_0
2	$x_0 + B*\sin(\alpha)$	$y_0 - B*\cos(\alpha)$	z_0
3	$x_0 - B*\sin(\alpha)$	$y_0 + B*\cos(\alpha)$	z_0
4	$x_0 + A*\cos(\alpha)$	$y_0 + A*\sin(\alpha)$	z_0
5	$x_0 + l_t*\cos(\alpha)$	$y_0 + l_t*\sin(\alpha)$	$z_0 - (l_t - x_c)*tg(\delta)$

Free parameters for track type 1:

$x_0, y_0, z_0, \alpha; A, B, \delta, x_c; l_t$

Co-ordinates in detector system, F, of track measuring points for type 3 tracks

Point No.	$X_{F,i}$	$Y_{F,i}$	$Z_{F,i}$
1	$x_0 - A*\cos(\alpha)$	$y_0 - A*\sin(\alpha)$	z_0
2	$x_0 + B*\sin(\alpha)$	$y_0 - B*\cos(\alpha)$	z_0
3	$x_0 - B*\sin(\alpha)$	$y_0 + B*\cos(\alpha)$	z_0
4	$x_0 + A*\cos(\alpha)$	$y_0 + A*\sin(\alpha)$	z_0
5	$x_0 + l_t*\cos(\alpha)$	$y_0 + l_t*\sin(\alpha)$	$z_0 - (l_t - x_c)*tg(\delta)$
6	$x_0 + l_u*\cos(\alpha)$	$y_0 + l_u*\sin(\alpha)$	$z_0 - (l_u - x_c)*tg(\delta)$
7	$x_0 + l_d*\cos(\alpha)$	$y_0 + l_d*\sin(\alpha)$	$z_0 - (l_d - A' - 2x_c)*tg(\delta)$

Free parameters for track type 3:

x_0, y_0, z_0 , α; A, B, δ, x_c; l_t , l_u, l_d, A'

Co-ordinates in detector system, F, of track measuring points for type 4 tracks

Point No.	$X_{F,i}$	$Y_{F,i}$	$Z_{F,i}$
1	$x_0-A*\cos(\alpha)$	$y_0-A*\sin(\alpha)$	z_0
2	$x_0+B*\sin(\alpha)$	$y_0-B*\cos(\alpha)$	z_0
3	$x_0-B*\sin(\alpha)$	$y_0+B*\cos(\alpha)$	z_0
4	$x_0+A*\cos(\alpha)$	$y_0+A*\sin(\alpha)$	z_0
5	$x_0+l_t*\cos(\alpha)+b*\sin(\alpha)$	$y_0+l_t*\sin(\alpha)-b*\cos(\alpha)$	$z_0-(l_t-x_c)*tg(\delta)$
6	$x_0+l_t*\cos(\alpha)-b*\sin(\alpha)$	$y_0+l_t*\sin(\alpha)+b*\cos(\alpha)$	$z_0-(l_t-x_c)*tg(\delta)$
7	$x_0+l_d*\cos(\alpha)$	$y_0+l_d*\sin(\alpha)$	$z_0-(l_d-A'-2x_c)*tg(\delta)$

Free parameters for track type 4:

x_0, y_0, z_0 , α; A, B, δ, x_c; l_t , b, l_d, A'

Co-ordinates in detector system, F, of track measuring points for type 5 tracks

Point No.	$X_{F,i}$	$Y_{F,i}$	$Z_{F,i}$
1	$x_0 - A*\cos(\alpha)$	$y_0 - A*\sin(\alpha)$	z_0
2	$x_0 + B*\sin(\alpha)$	$y_0 - B*\cos(\alpha)$	z_0
3	$x_0 - B*\sin(\alpha)$	$y_0 + B*\cos(\alpha)$	z_0
4	$x_0 + A*\cos(\alpha)$	$y_0 + A*\sin(\alpha)$	z_0
5	$x_0 + l_t*\cos(\alpha) + r_k*\sin(\alpha)$	$y_0 + l_t*\sin(\alpha) - r_k*\cos(\alpha)$	$z_0 - (l_t - x_c)*tg(\delta)$
6	$x_0 + l_t*\cos(\alpha) - r_k*\sin(\alpha)$	$y_0 + l_t*\sin(\alpha) + r_k*\cos(\alpha)$	$z_0 - (l_t - x_c)*tg(\delta)$
7	$x_0 + (l_t + r_k)*\cos(\alpha)$	$y_0 + (l_t + r_k)*\sin(\alpha)$	$z_0 - (l_t - x_c)*tg(\delta)$

Free parameters for track type 5:

x_0, y_0, z_0 , α; A, B, δ, x_c; l_t , r_k

Parameters are sought for the maximum of the likelihood function Λ, resp. its logarithm.

$$-2*\log \Lambda = \quad nm*\log 2\pi + nk*\log V_{xy} + n(m-k)*\log V_z + {}_{a=1}\sum^{k}(M_{aa}/V_{xy}) + {}_{a=k+1}\sum^{m}(M_{aa}/V_z)$$

$V_{xy} \cong (1/nk) * {}_{a=1}\sum^{k}(M_{aa})$; variance of x,y measurement

$V_z \cong (1/n(m-k)) * {}_{a=k+1}\sum^{m}(M_{aa})$; variance of z measurement

"Objective function" $\Psi(\mathbf{M})$ is minimized

$$\Psi(\mathbf{M}) = [\, nk*\log(\, {}_{a=1}\sum^{k}(M_{aa})\,) + n(m-k)*\log(\, {}_{a=k+1}\sum^{m}(M_{aa})\,)\,]/2$$

Matrix of moments **M**

$$\mathbf{M}(\Theta) = \varepsilon\, \varepsilon^T$$

vector of residuals/errors ε

$$\varepsilon^T = (X_1(\Theta)-x_1,\ldots,X_n(\Theta)-x_n,\ Y_1(\Theta)-y_1,\ldots,Y_n(\Theta)-y_n,\ Z_1(\Theta)-z_1,\ldots,Z_n(\Theta)-z_n)$$

$X_i(\Theta)$, $Y_i(\Theta)$, $Z_i(\Theta)$ = model coordinates

x_i, y_i, z_i = measured coordinates

$i=1\ldots n$

parameter vectors Θ

$\Theta = (x_0, y_0, z_0, \alpha; A, B, \delta, x_c; l_t);$ **type 1**

$\Theta = (x_0, y_0, z_0, \alpha; A, B, \delta, x_c; l_t, l_u, l_d, A');$ **type 3**

$\Theta = (x_0, y_0, z_0, \alpha; A, B, \delta, x_c; l_t, b, l_d, A');$ **type 4**

$\Theta = (x_0, y_0, z_0, \alpha; A, B, \delta, x_c; l_t, r_k);$ **type 5**

constraints for parameters

linear:

$A \geq B > 0; \quad x_c > 0; \qquad B > r_k \geq 0\ ; \quad B > b \geq 0$

nonlinear 'constraint'

$$\mathbf{A/B = \cos\theta \,/\, \sqrt{(\cos^2\theta - \cos^2\delta)}}$$

leads to the Langrange equation:

$$\mathbf{N_1(A, B, \delta, \theta) = (A^2 - B^2)(1 + tg^2\delta) - A^2(1 + tg^2\theta) = 0}$$

Determination of cone angle, θ, from track parameters

$$\mathrm{tg}(\theta) = \{\sqrt{[\, B^2(l_t - w)^2 - (A^2 - B^2)(B^2 - w^2)]} - w^2(l_t - w)\,\} \,/$$

$$/\ [(l_t - w)^2 - (A^2 - B^2)] * \sqrt{(1 - B^2/A^2)}$$

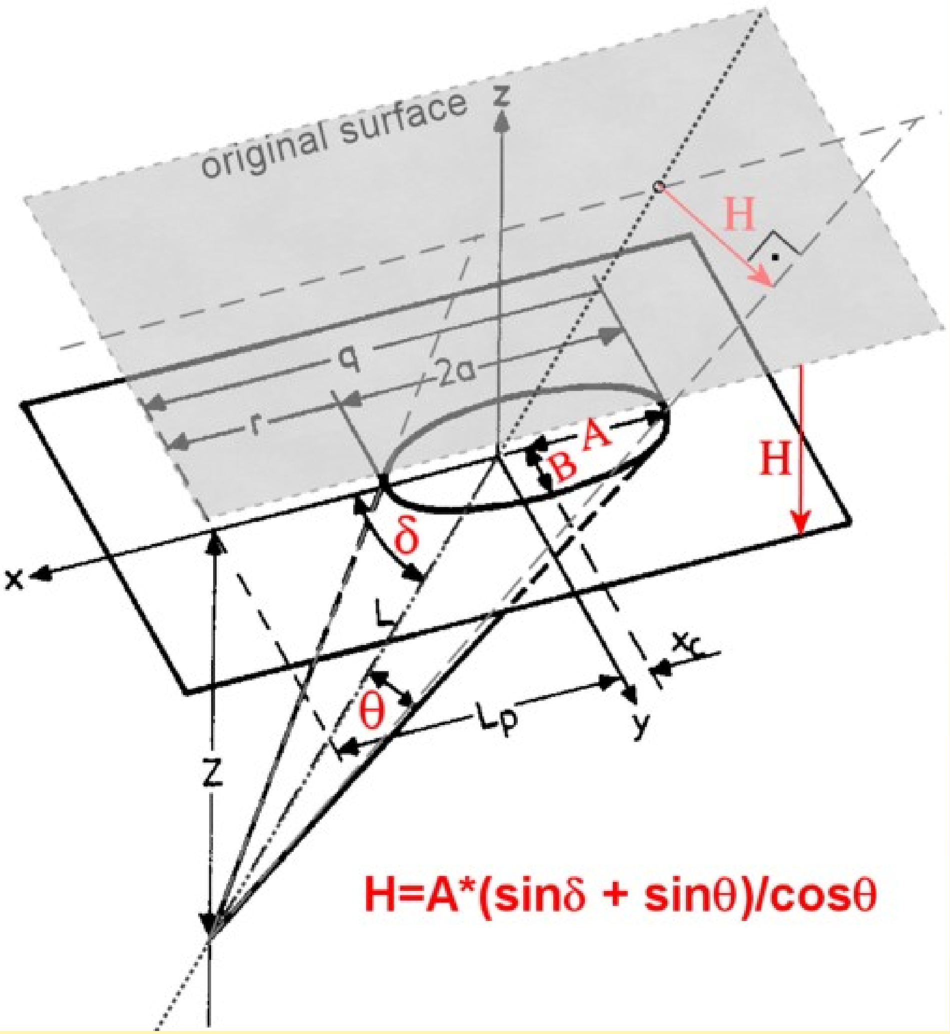
$\theta > 0$

$w = b$ for type 4; $w = r_k$ for type 5; $w=0$ otherwise

Determination of local bulk layer, H, from track parameters

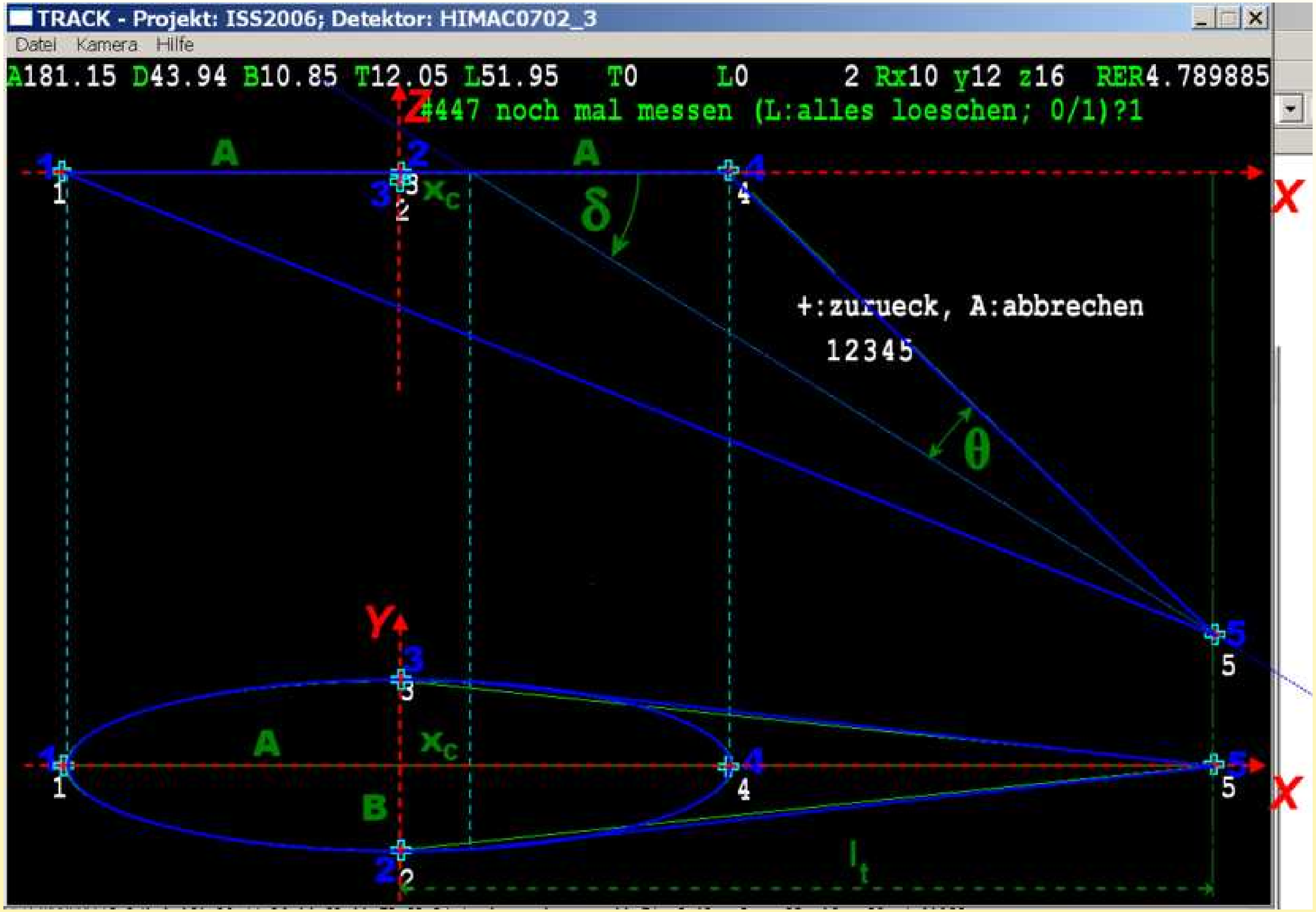
$$H = A * (\sin\delta + \sin\theta) / \cos\theta$$

Ideal etch cone relations

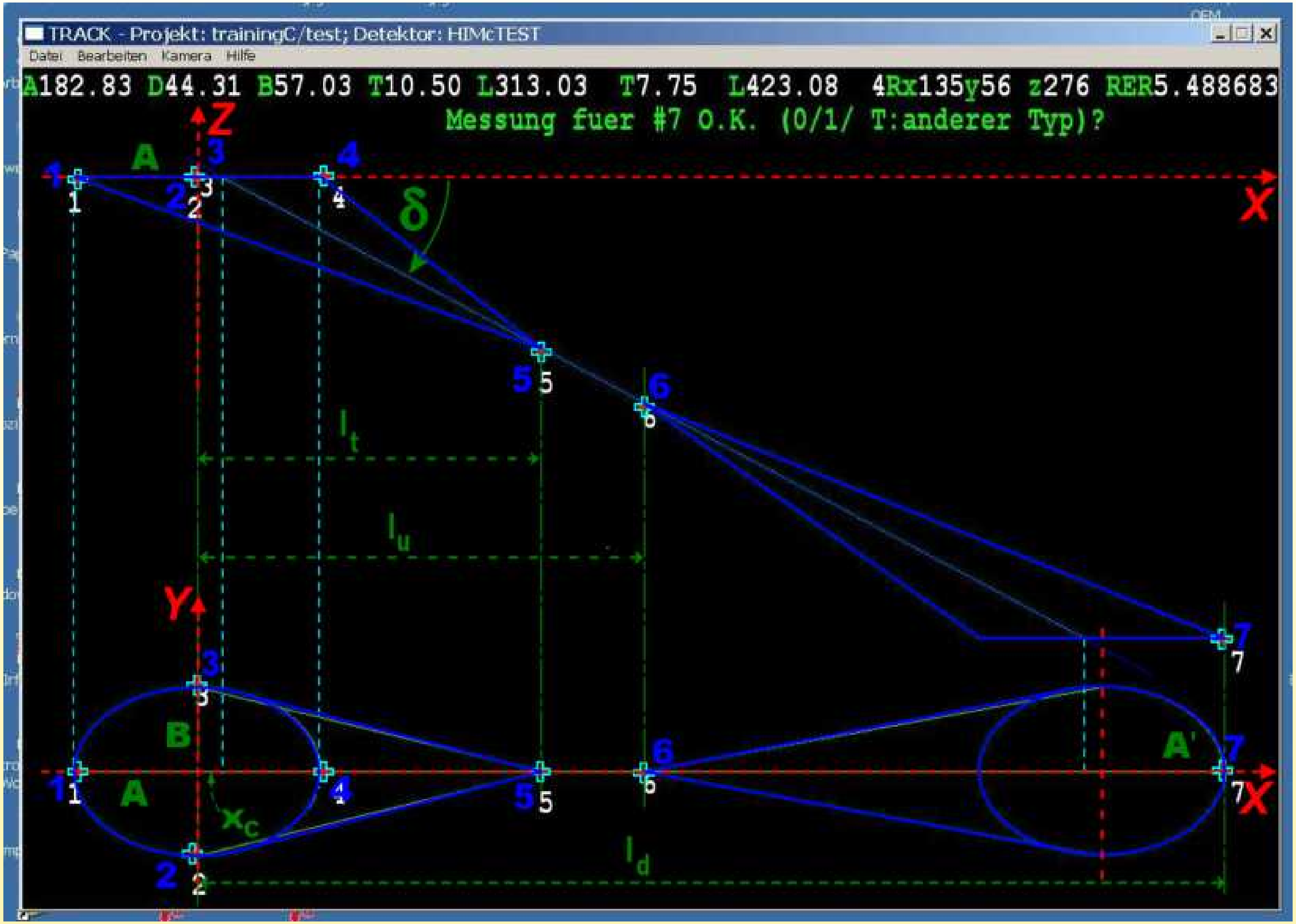


3D measurements – accuracy/precision

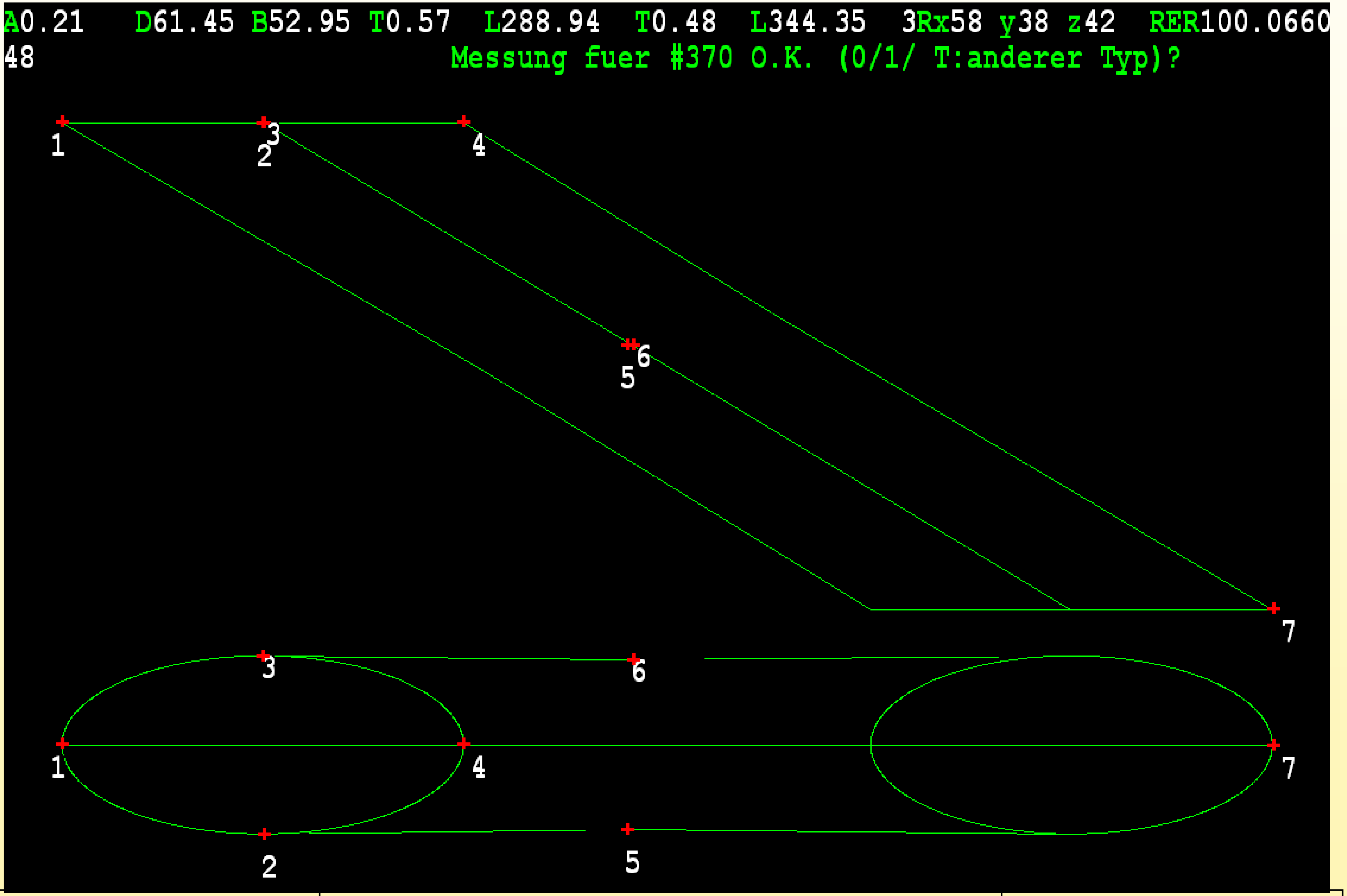
Screen shot of type 1 measurement with schematic



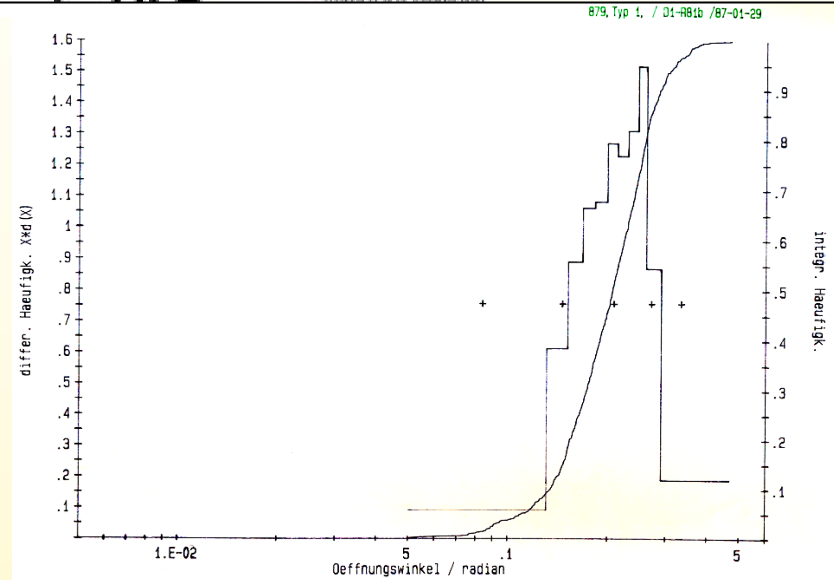
Screen shot of type 3 measurement with schematic

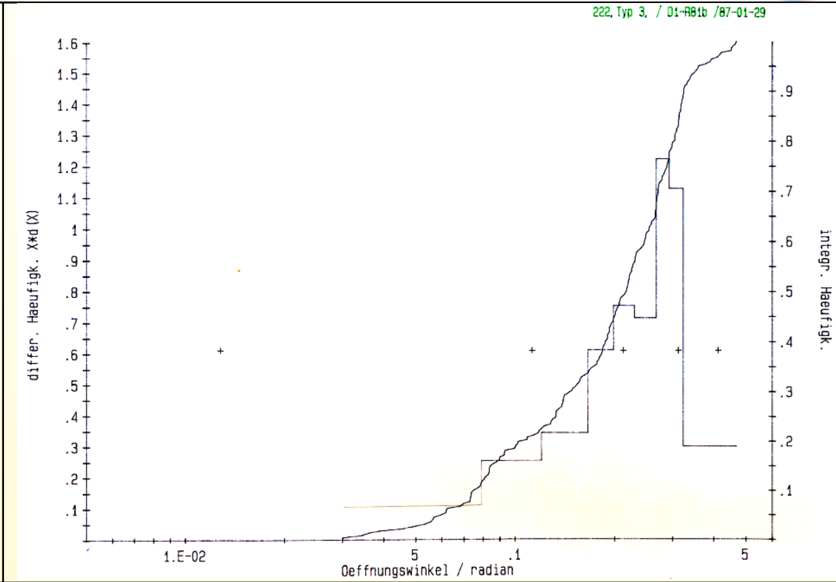


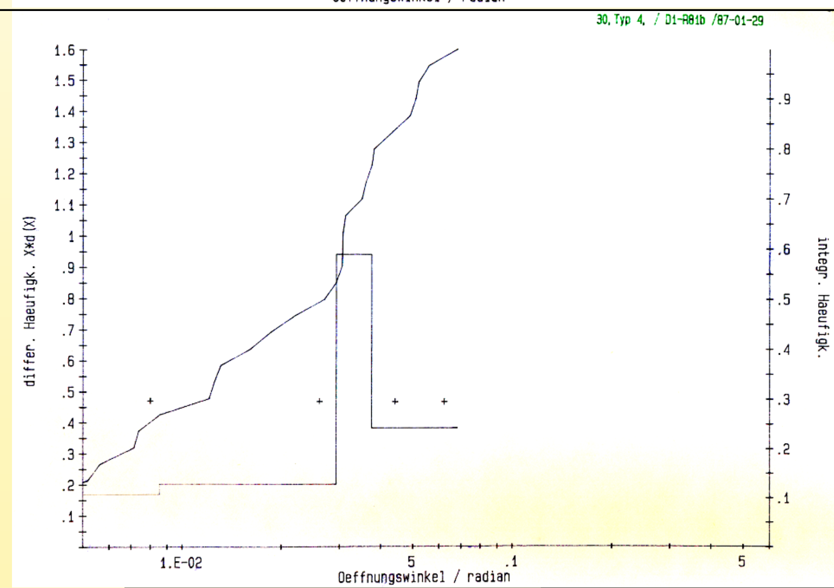
Screen shot of type 4 measurement

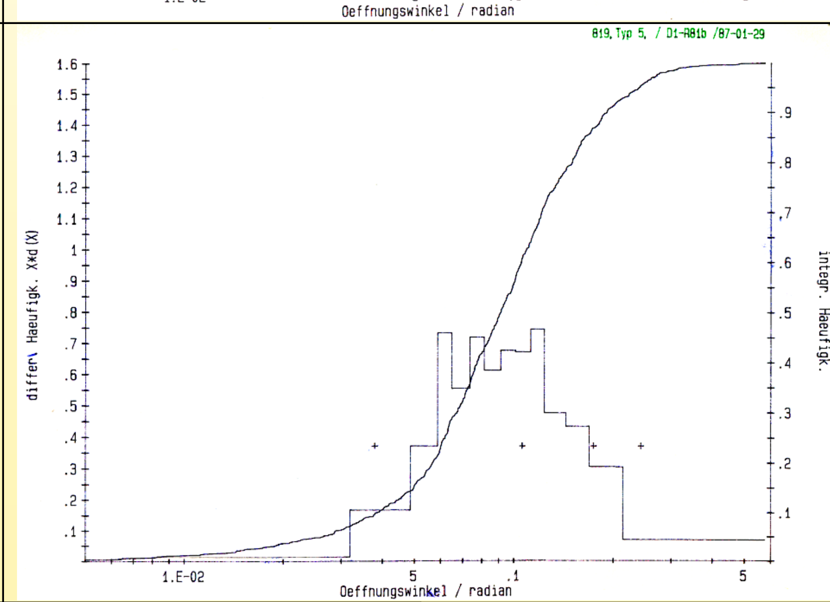


Distributions of cone angle measurements (cellulose nitrate)

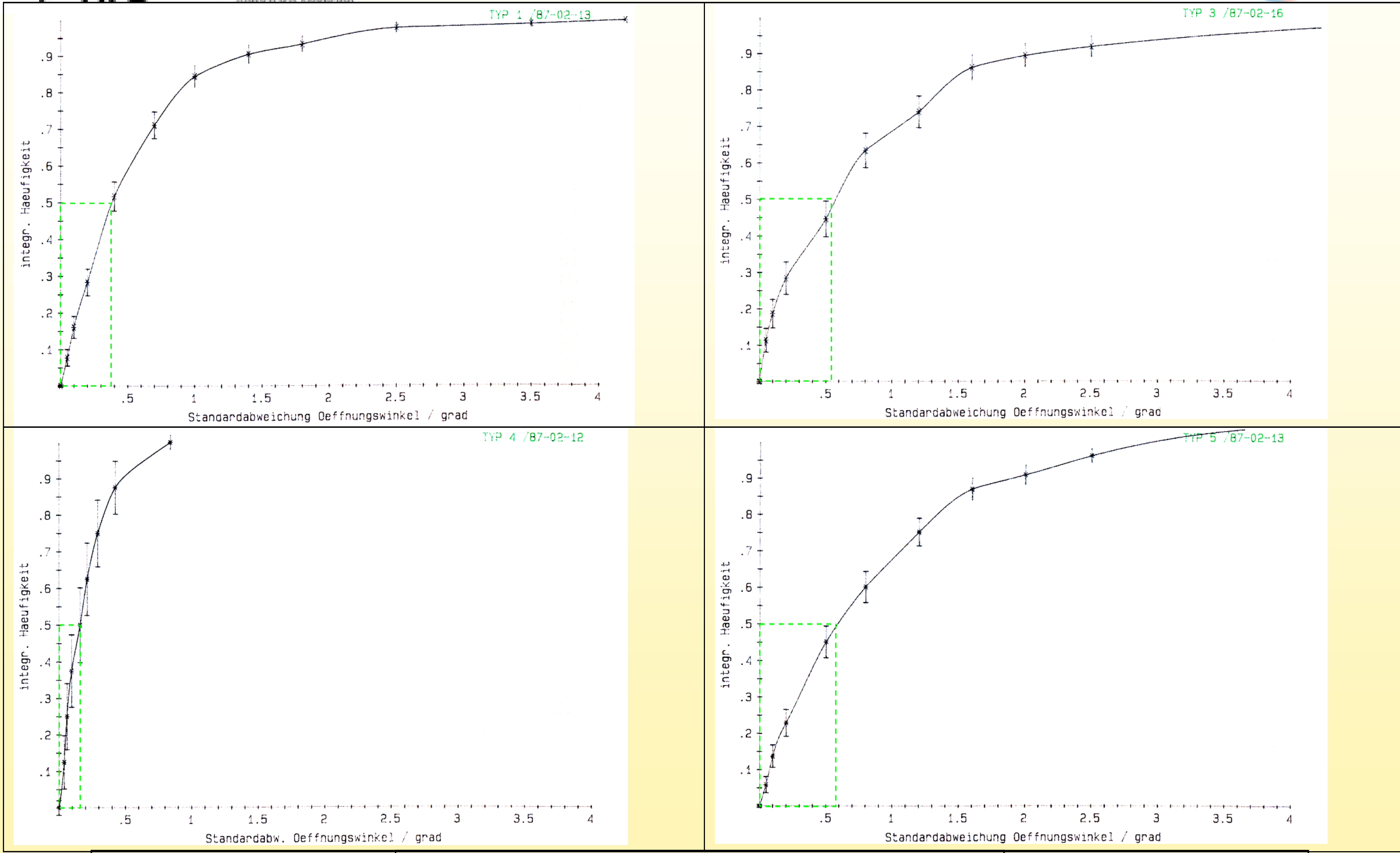






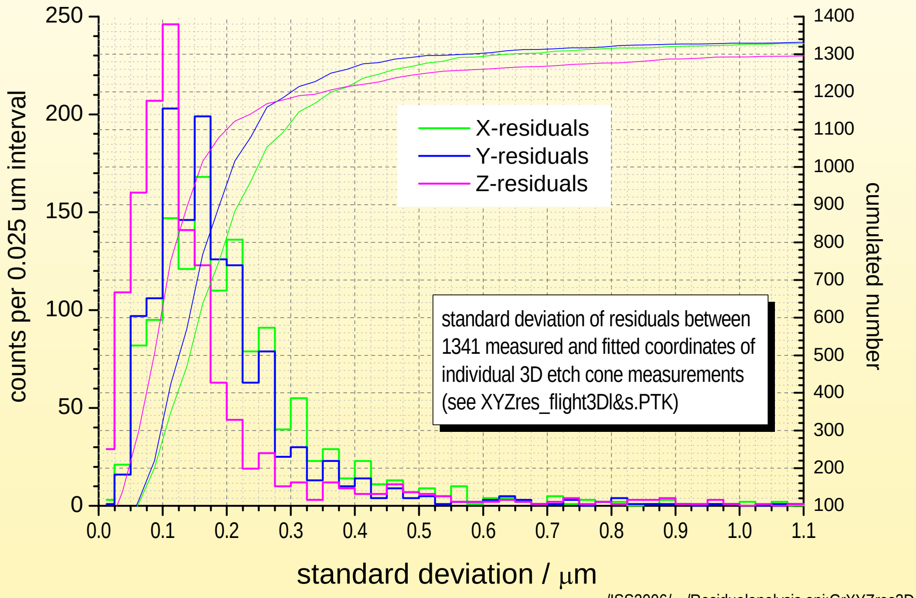


Distributions of cone angle measurement errors (CN)

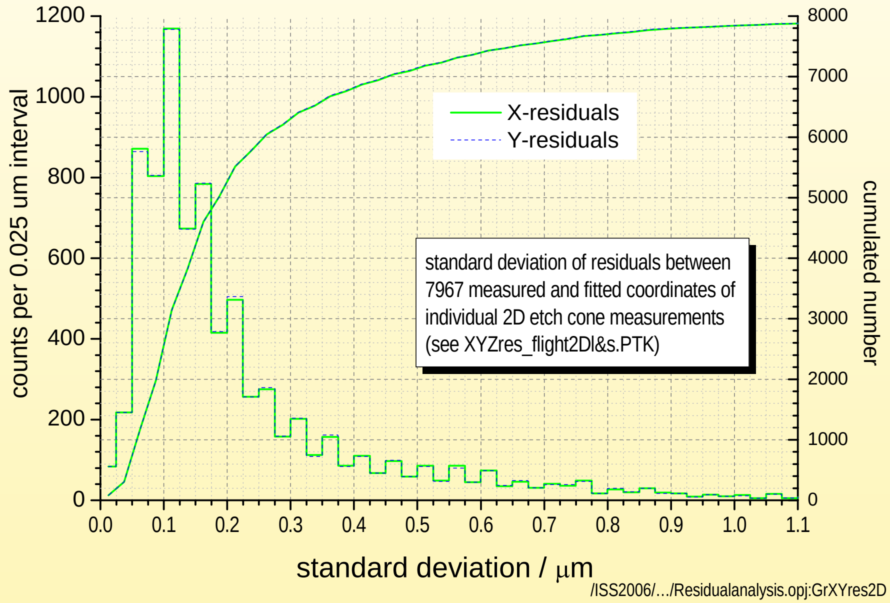


Precision of co-ordinate measurements; 3D vs. 2D (CR 39, standard deviation of residuals)

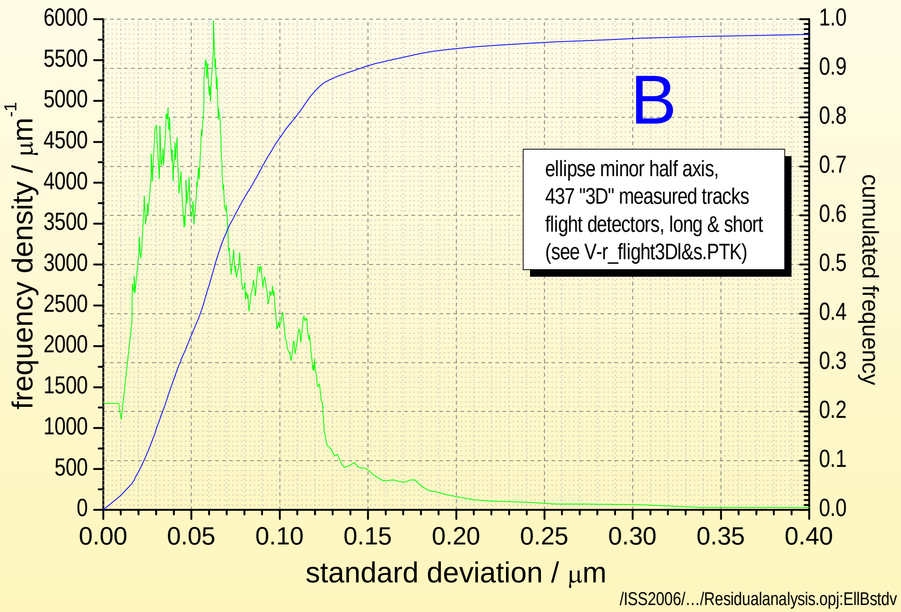
3D

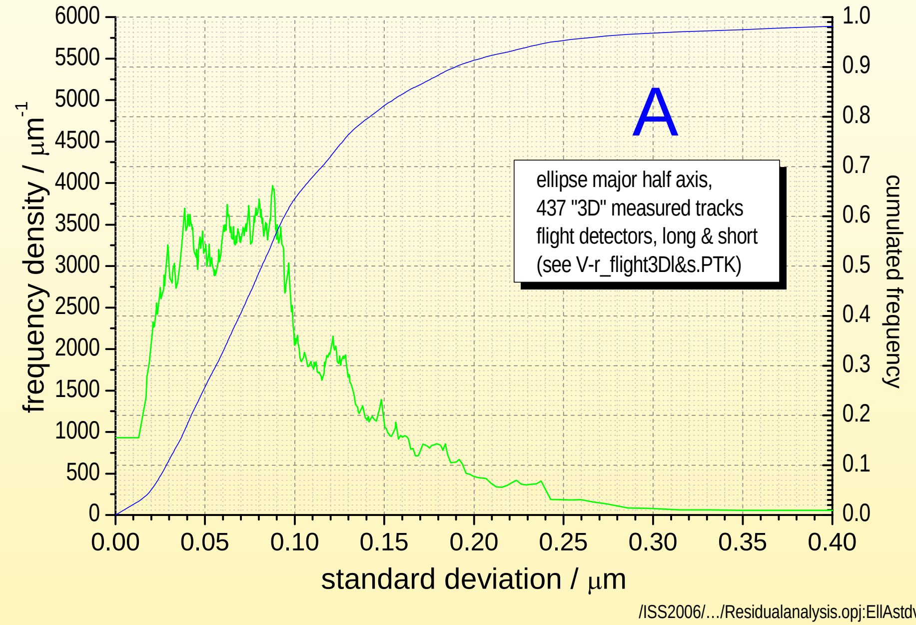


2D

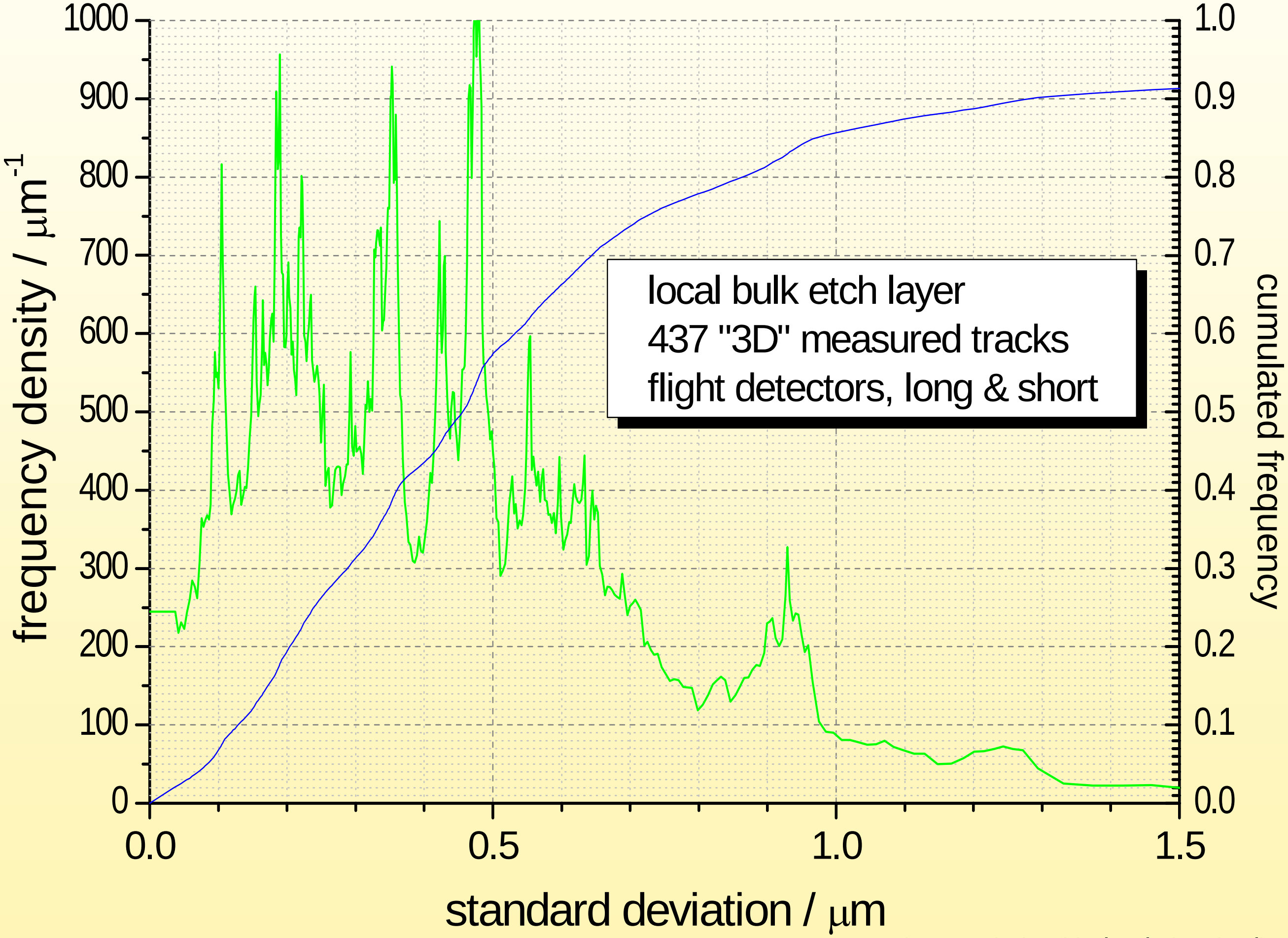


Precision of ellipse semi axes - 3D
(CR 39, standard deviation of repetitions)





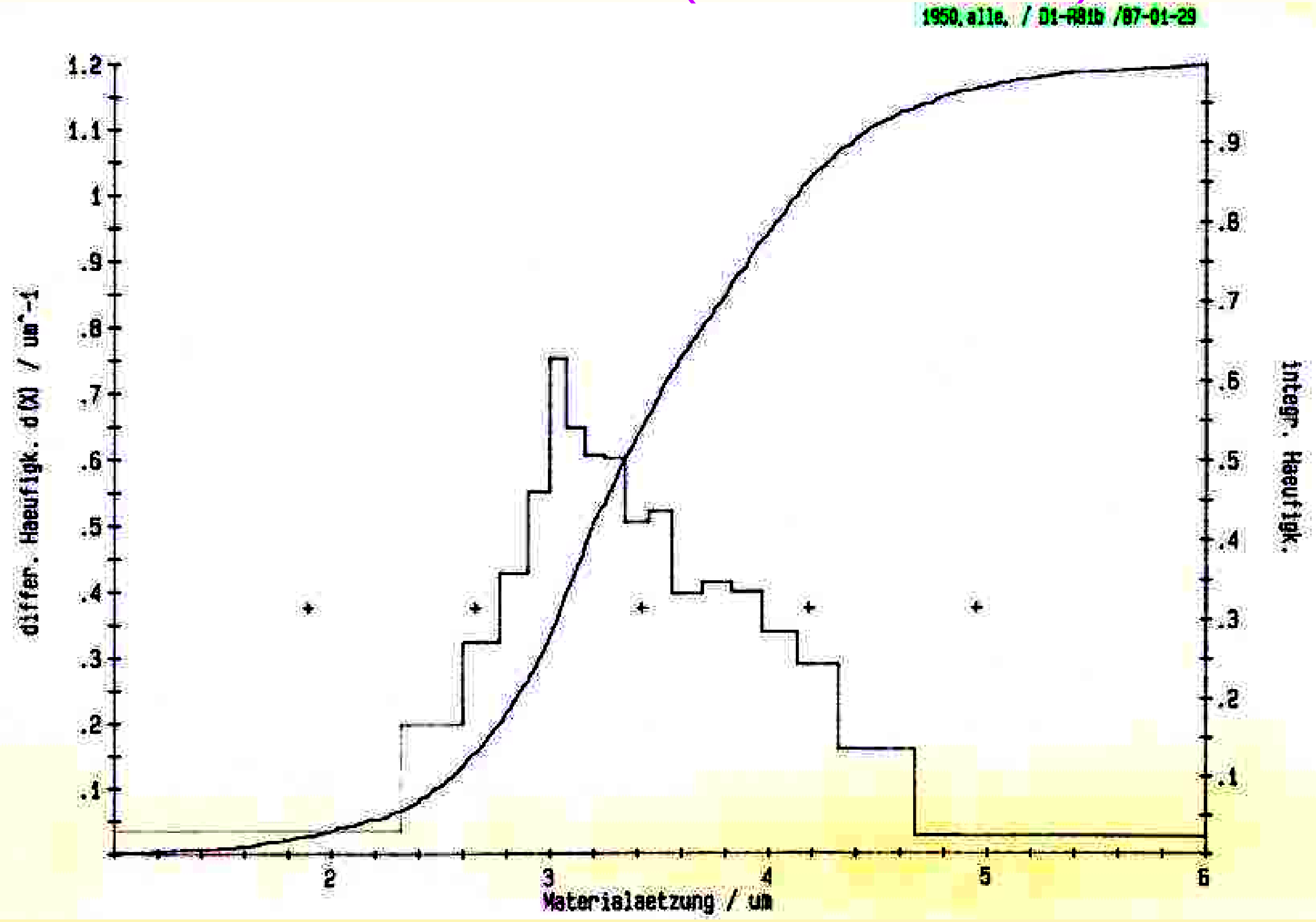
Precision of local bulk layer measurements - 3D
(CR 39, standard deviation of repetitions)



local bulk layer data

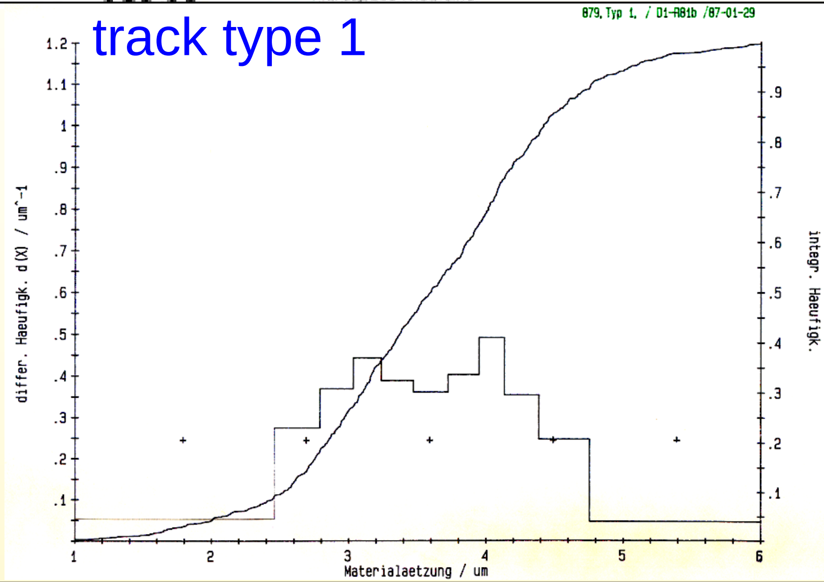
(cellulose nitrate, D1 mission)

Distribution of local bulk layer measurements (cellulose nitrate)

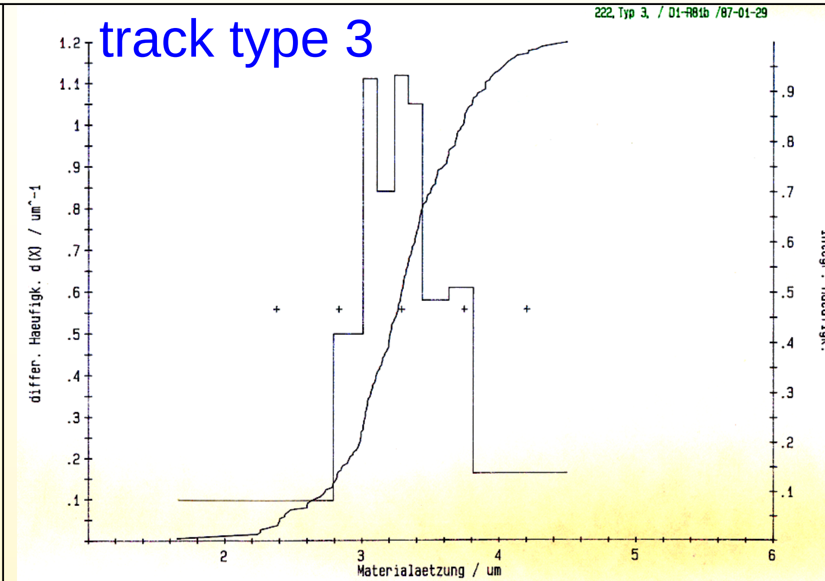


Distributions of local bulk layer measurements (CN)

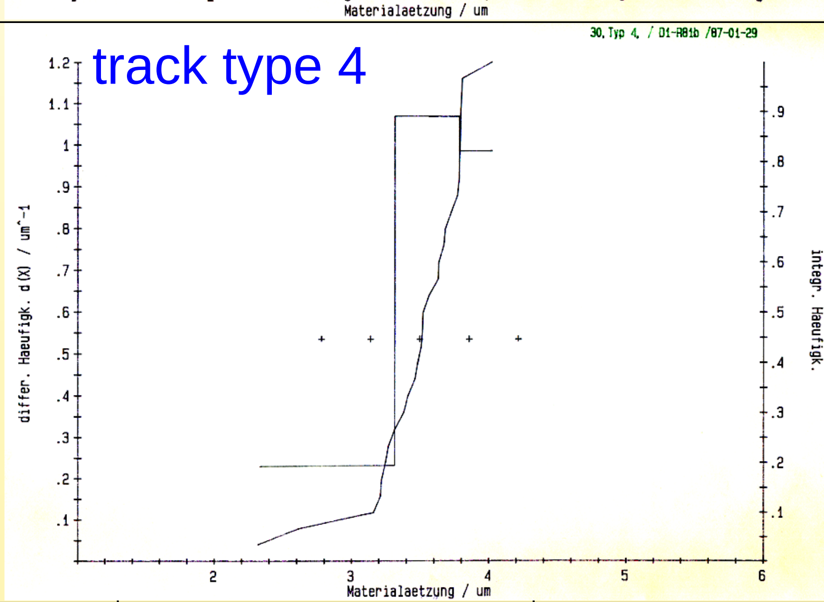
track type 1



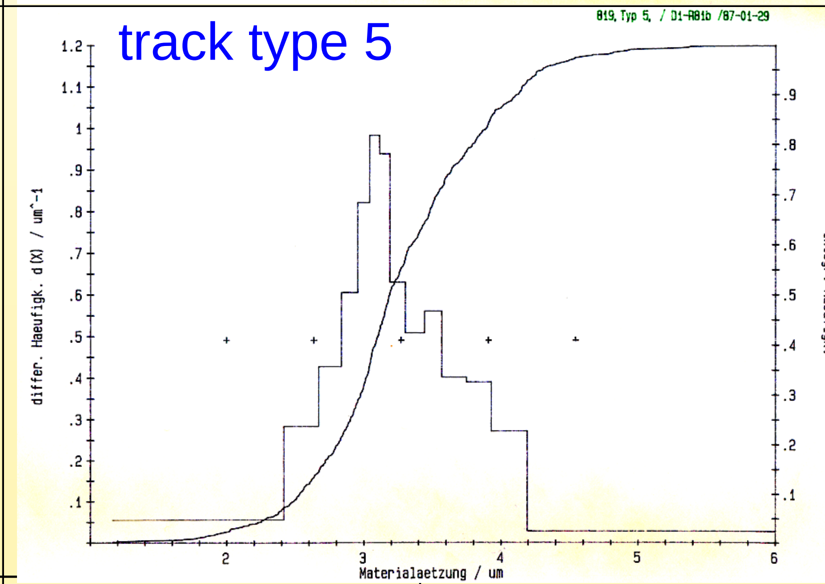
track type 3



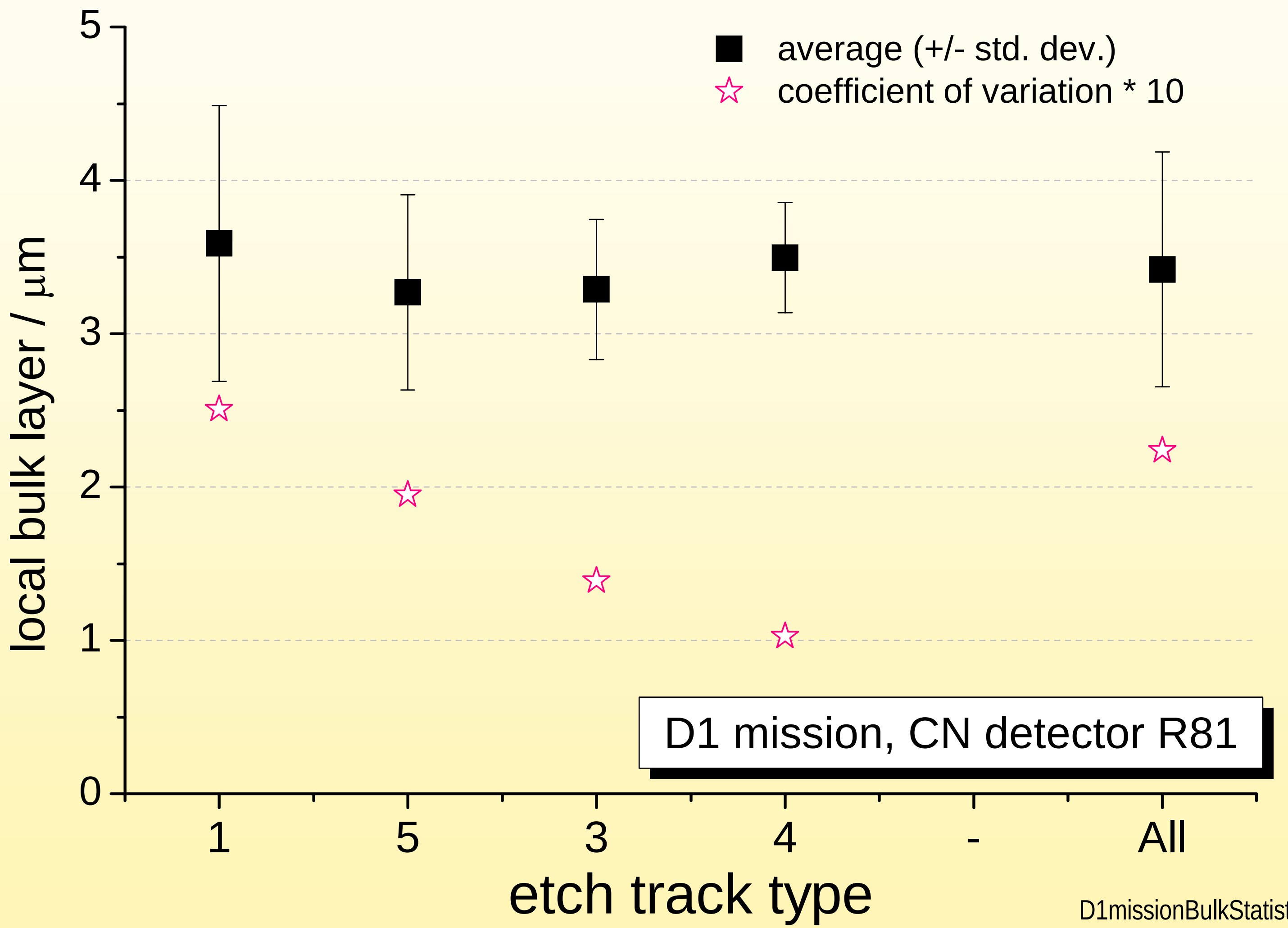
track type 4



track type 5



Summary of local bulk layer measurements **(CN)**

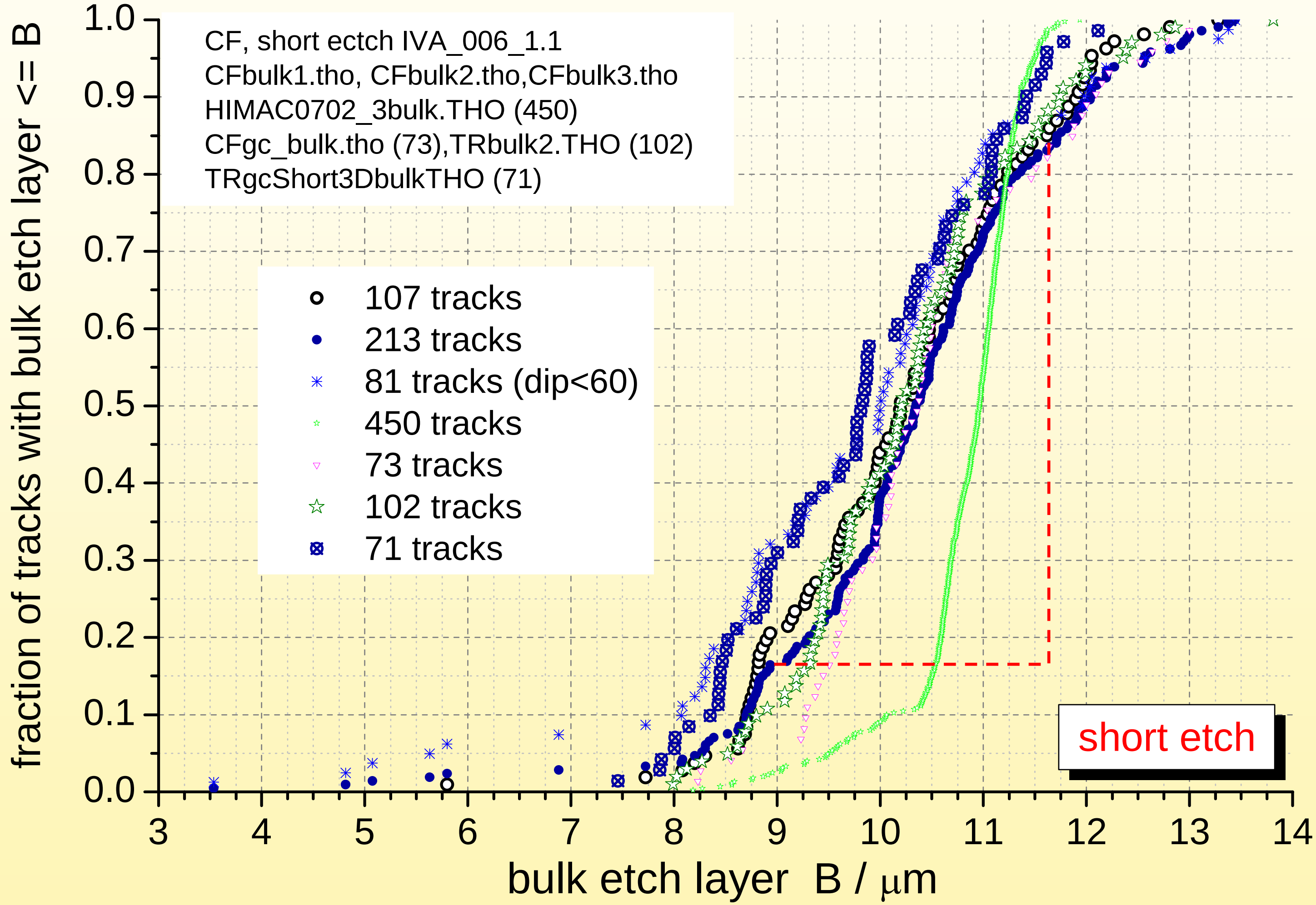


D1missionBulkStatistics.opj

local bulk layer data

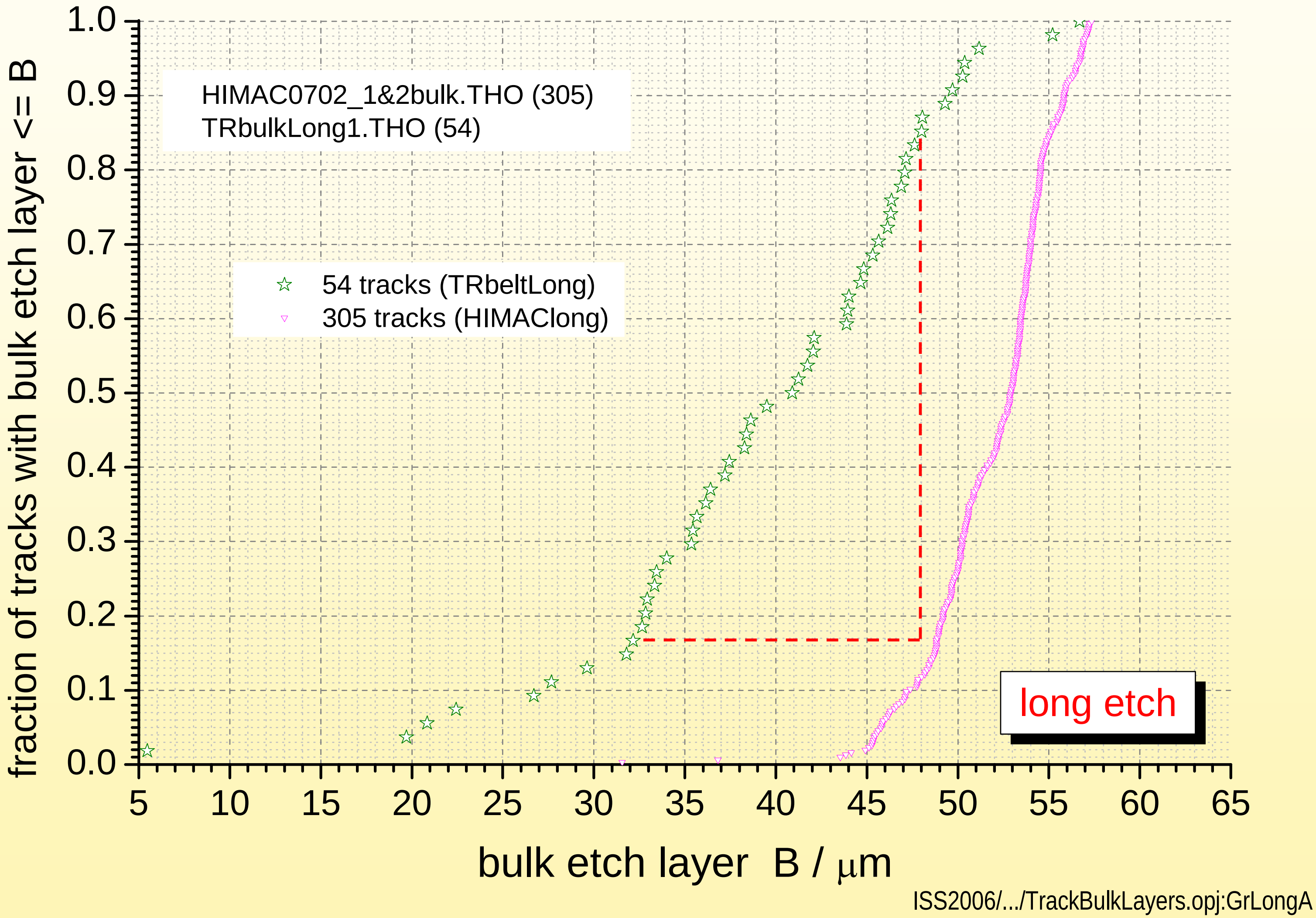
(CR 39, ISS mission/HIMAC)

Local bulk layer distributions short etch (CR 39)

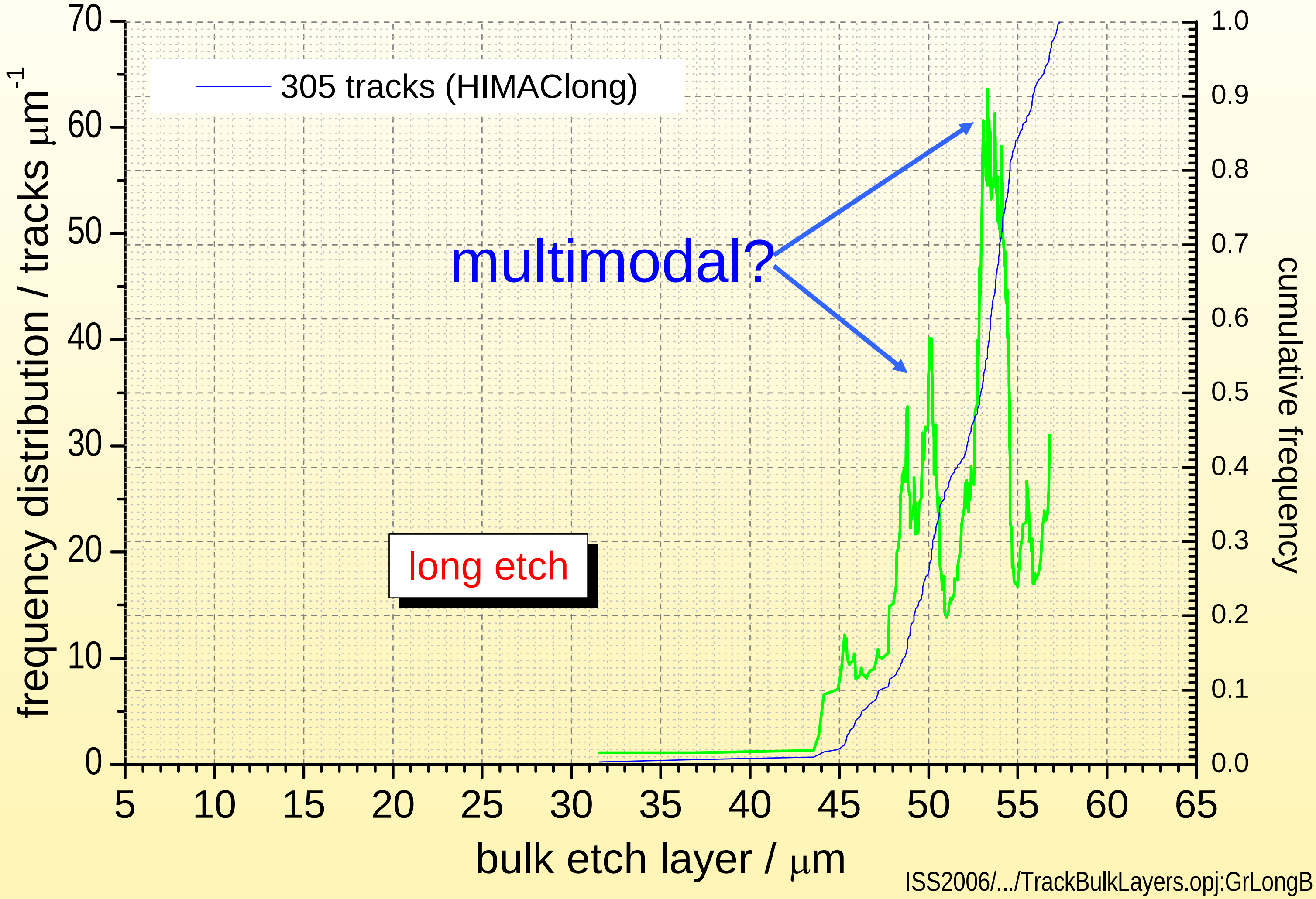


ISS2006/.../TrackBulkLayers.opj:GrShortA

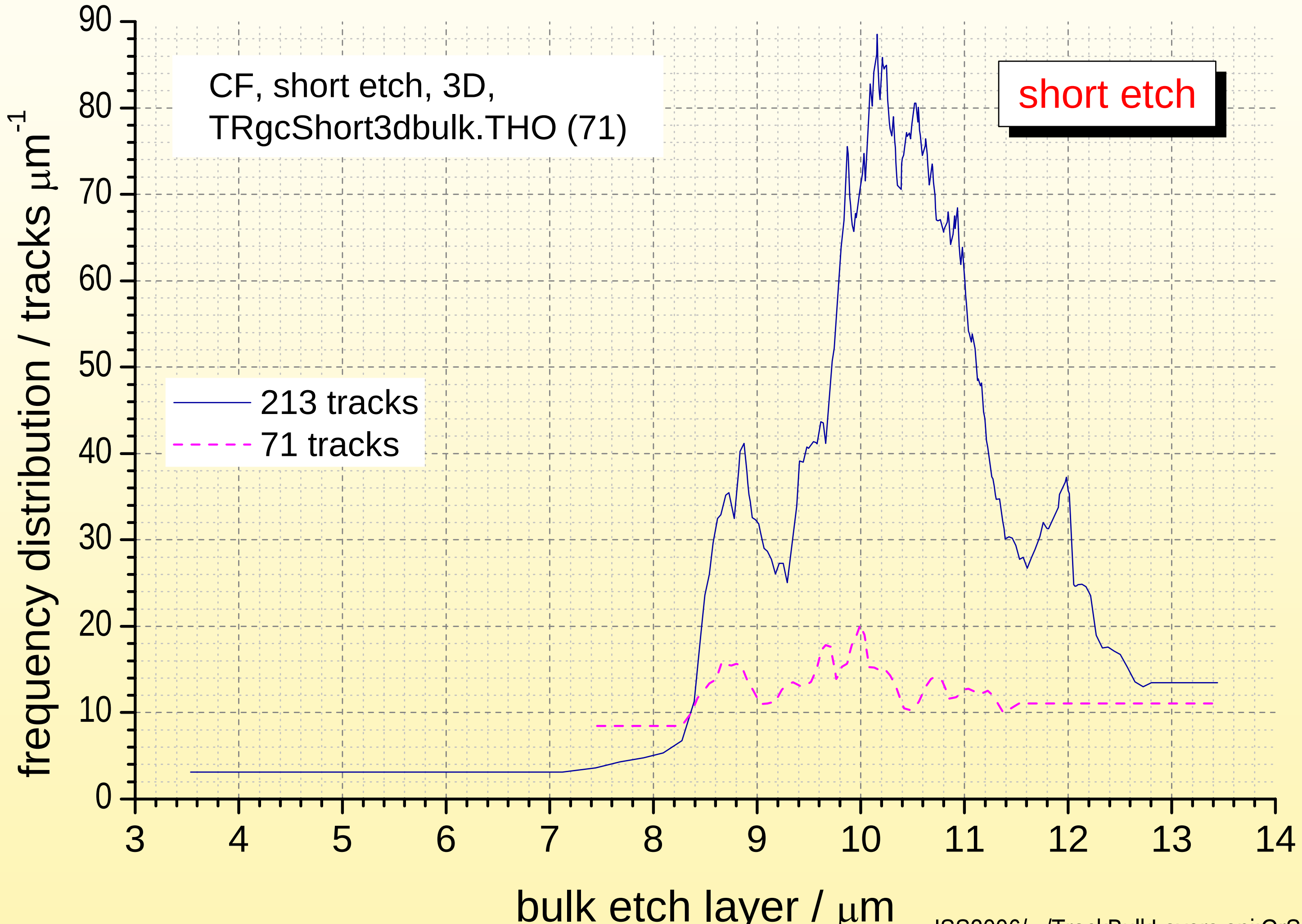
Local bulk layer distributions long etch (CR39)



Local bulk layer distributions long etch, accelerator only (CR 39)



Local bulk layer distributions short etch, ISS and ground control (CR39)

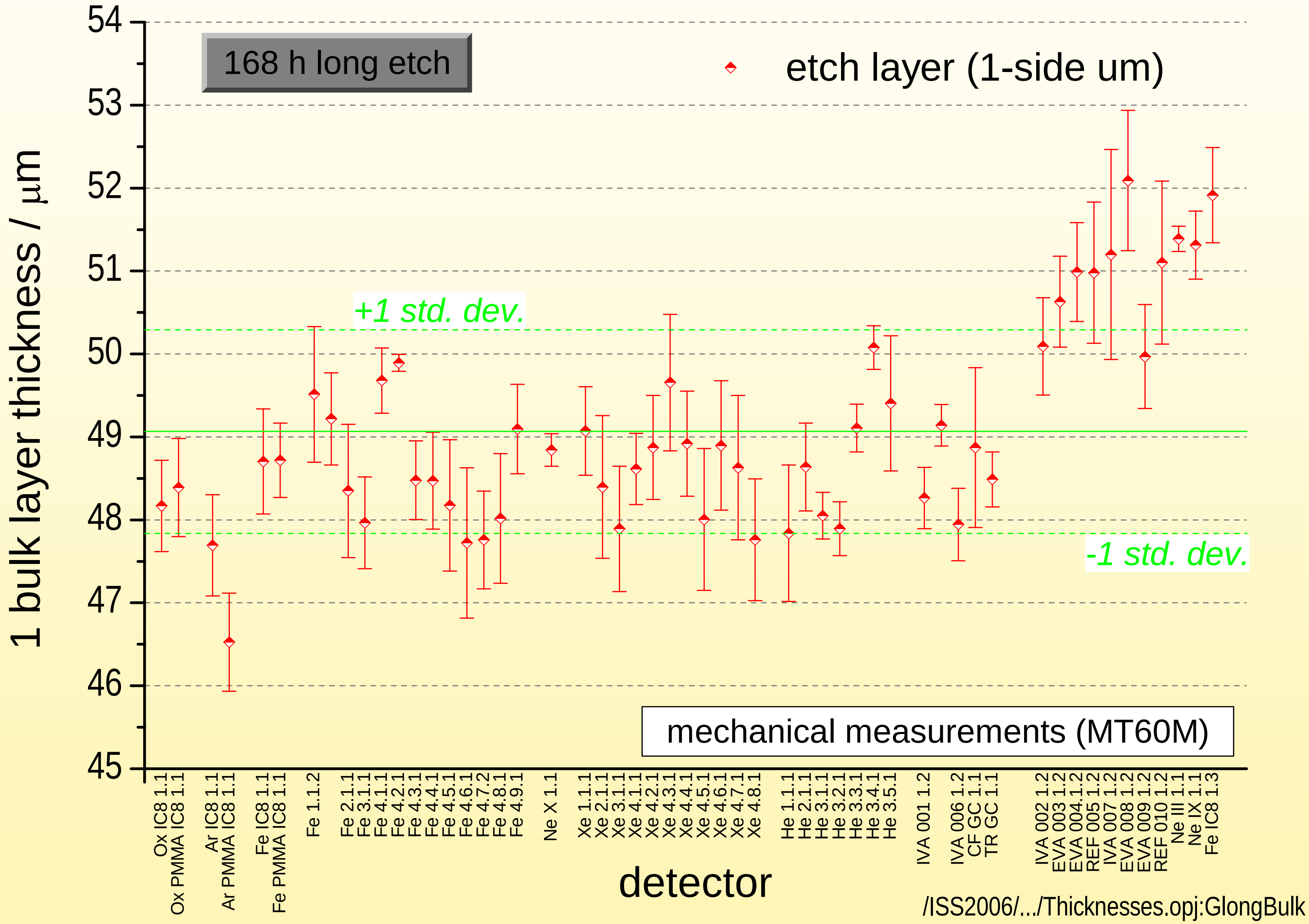


ISS2006/.../TrackBulkLayers.opj:GrShortB

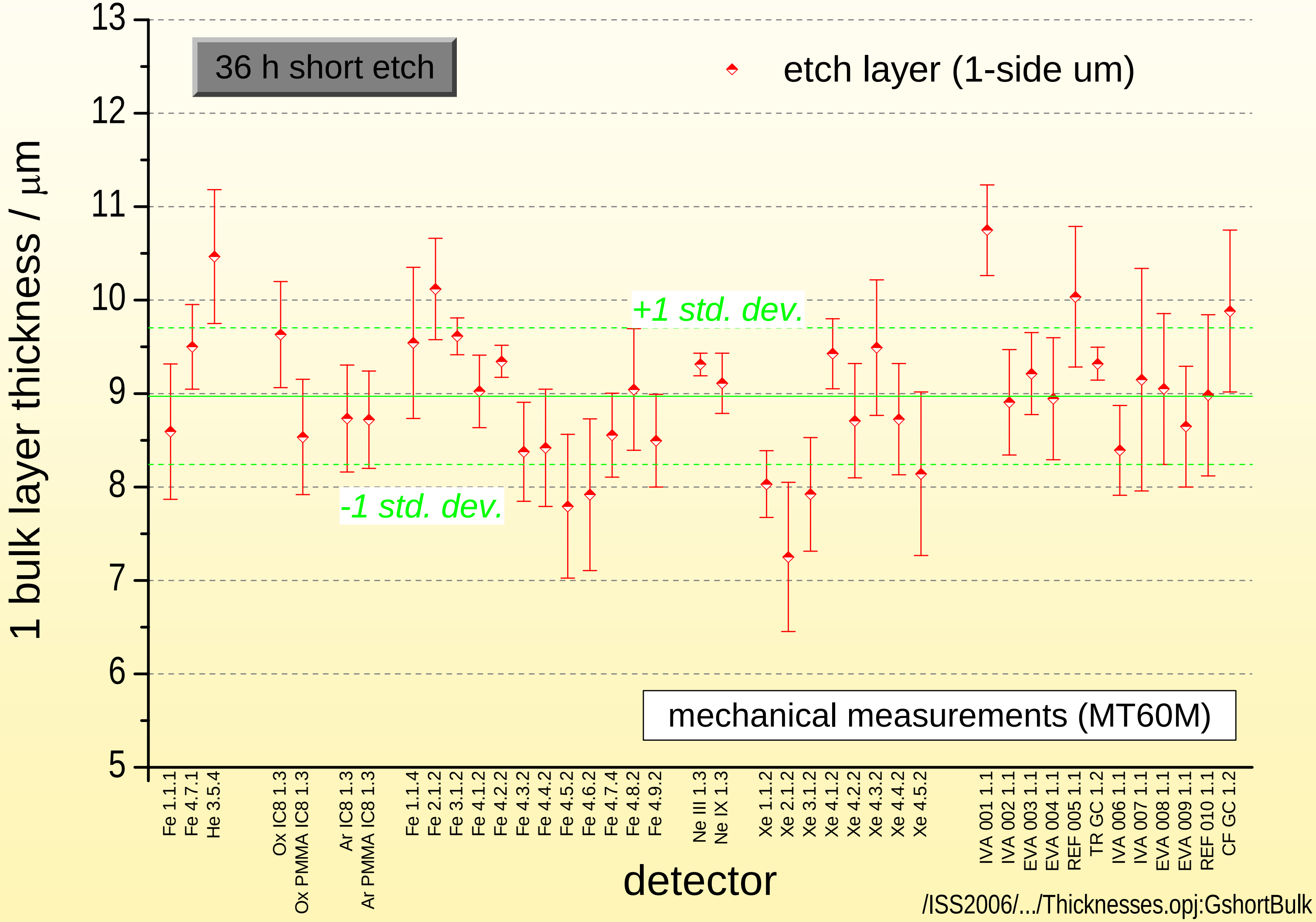
global bulk layer data

(CR 39, ISS mission/HIMAC mechanical measurement)

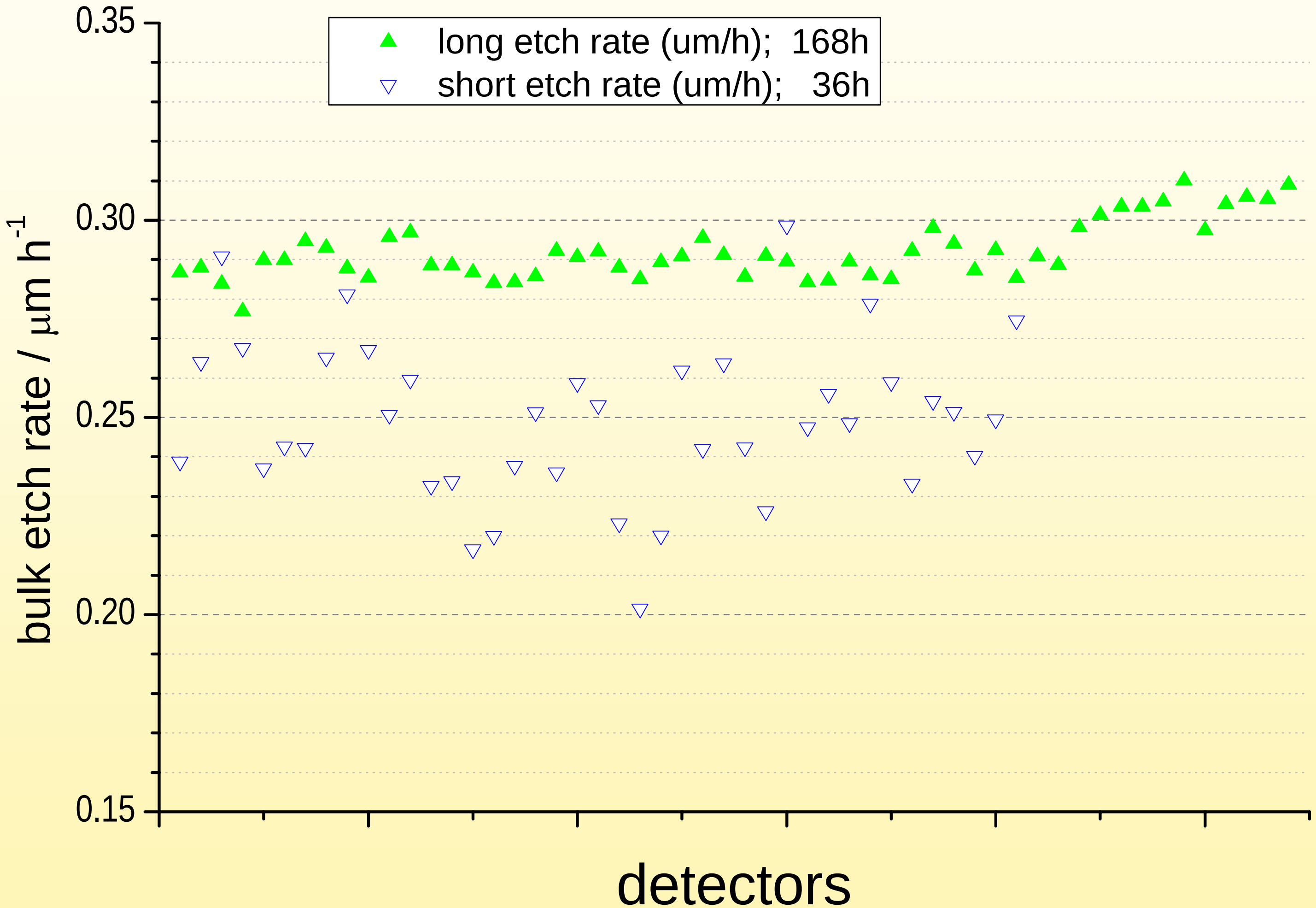
Global bulk layer variation long etch data (CR 39)



Global bulk layer variation short etch data (CR 39)



Global etch rate velocities - short etch versus long etch data (CR 39)



/ISS2006/.../Thicknesses.opj:GrEtchrates

2D – 3D comparisons

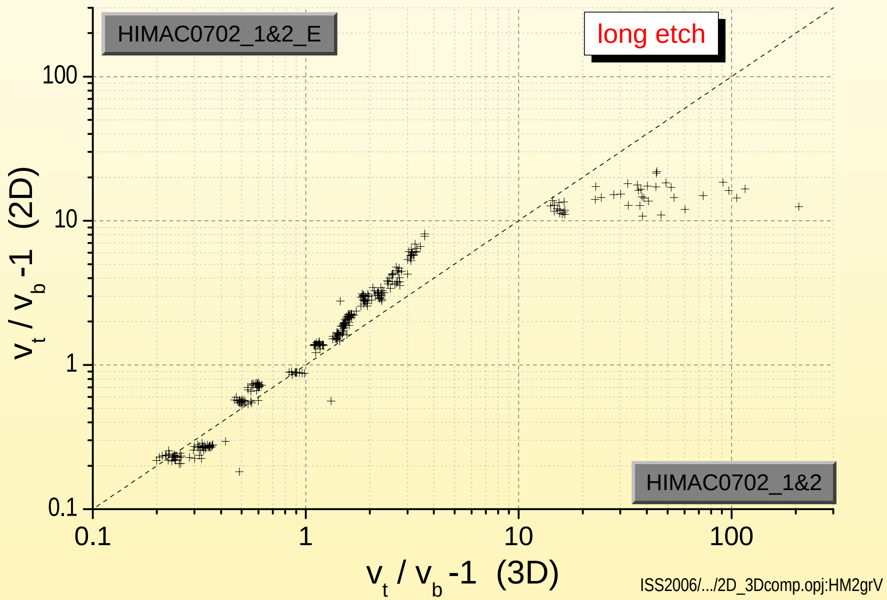
(CR 39)

Comparison excess etch rate and LET

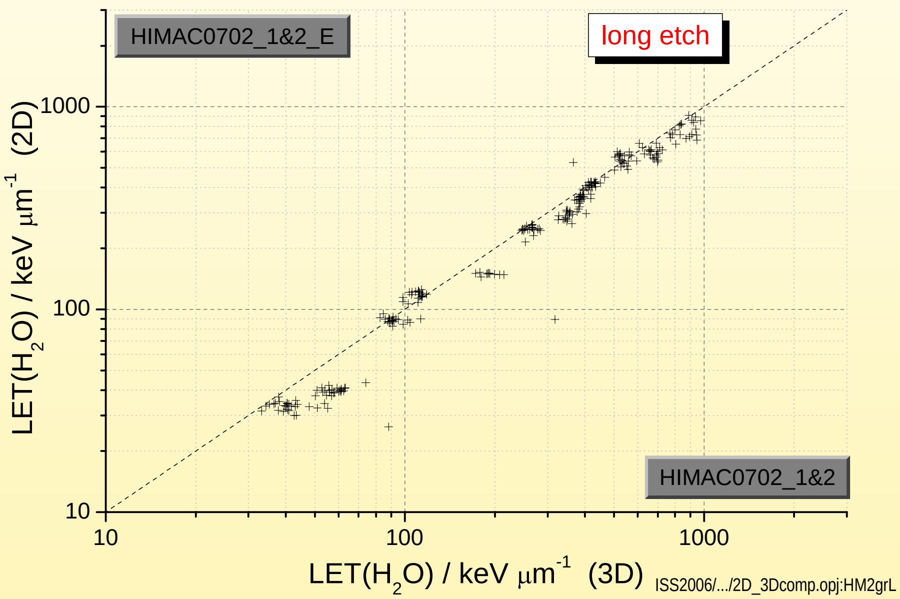
long etch (168h)

CR 39, accelerator calibration data

R-1



LET

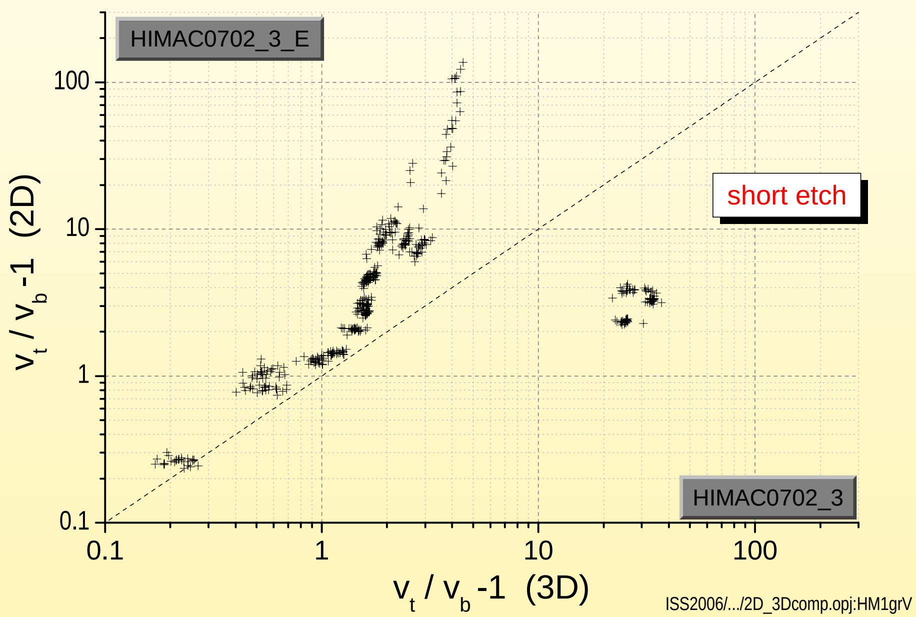


Comparison excess etch rate and LET

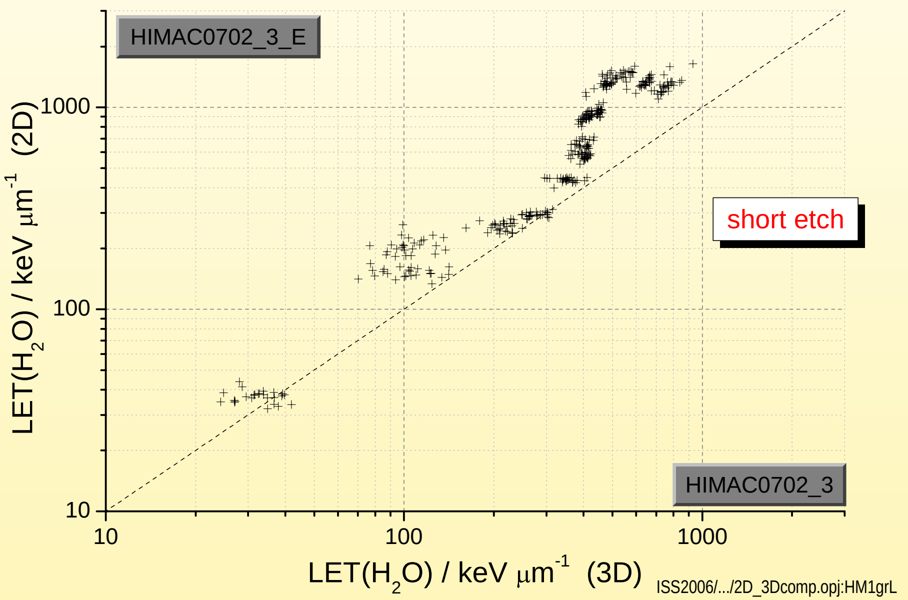
short etch (36h)

CR 39, accelerator calibration data

R-1



LET

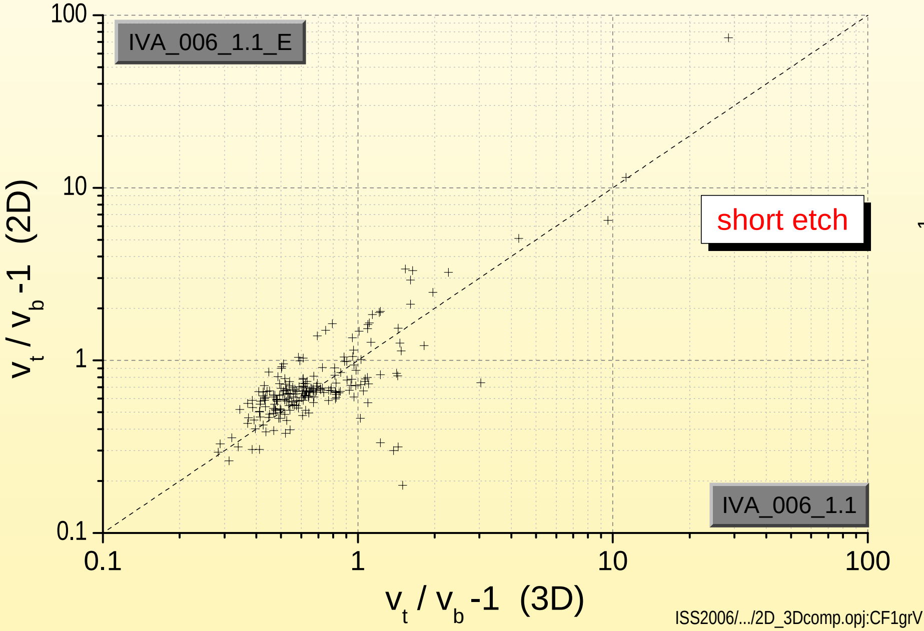


Comparison excess etch rate and LET

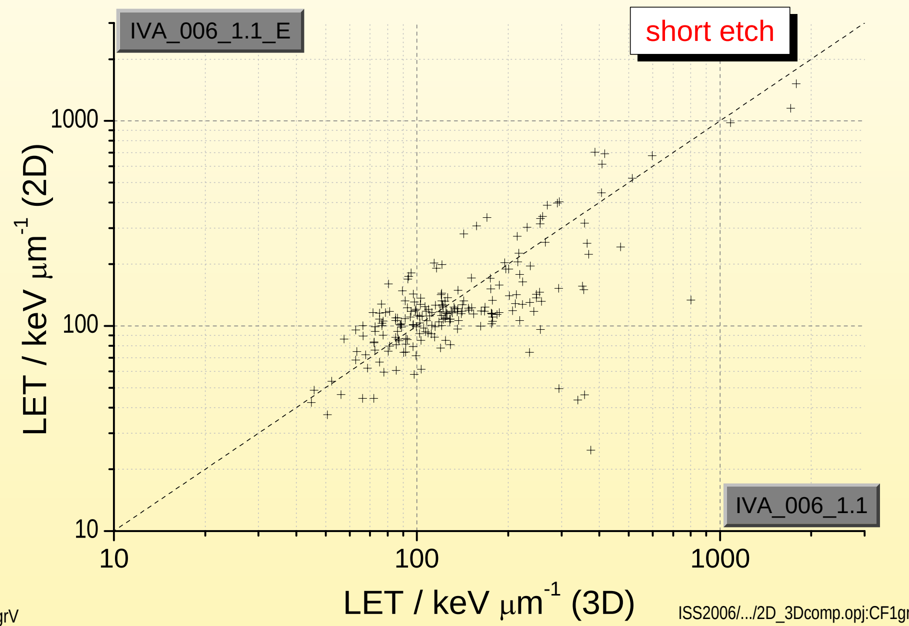
short etch (36h)

CR 39, ISS exposure data

R-1

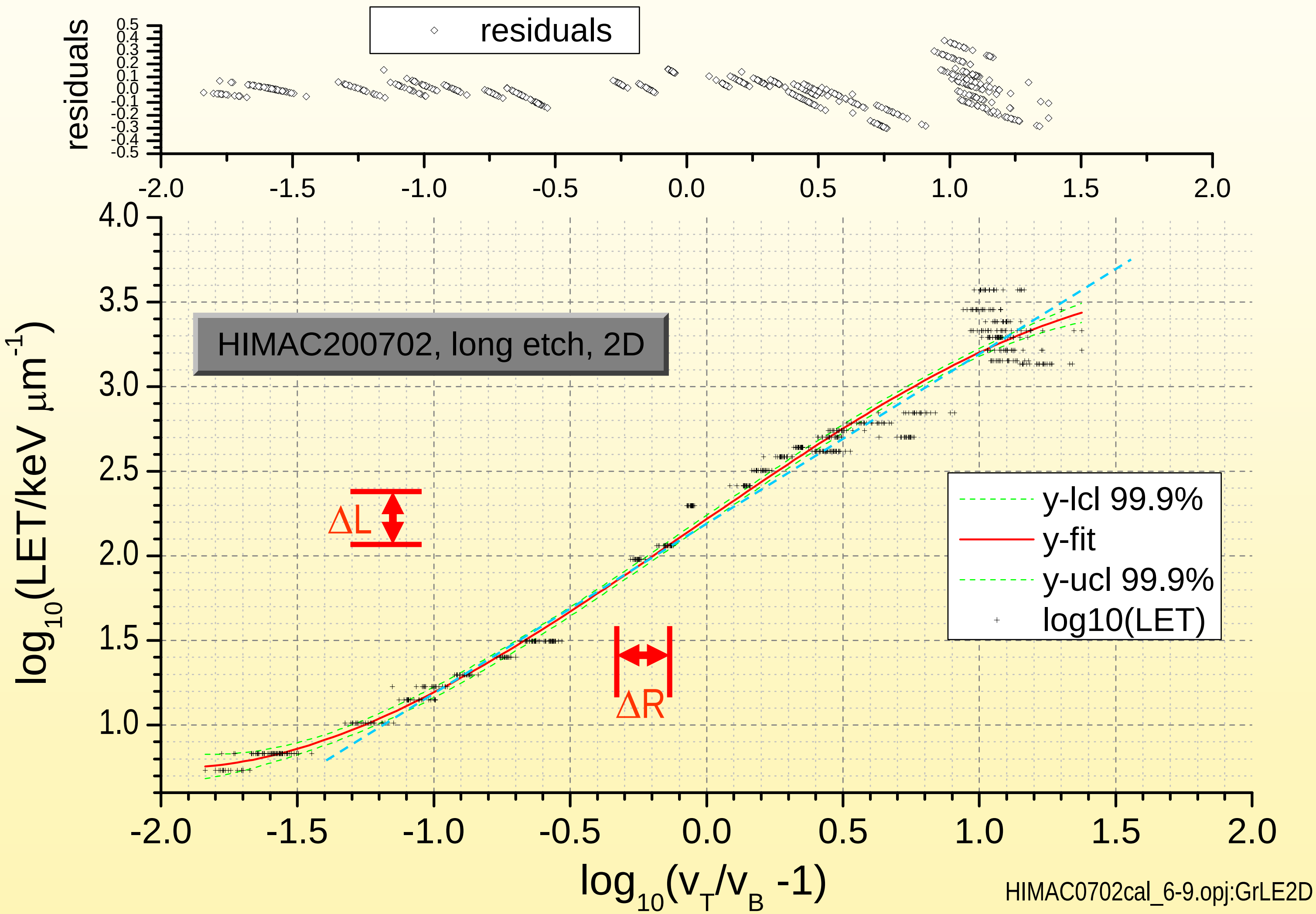


LET

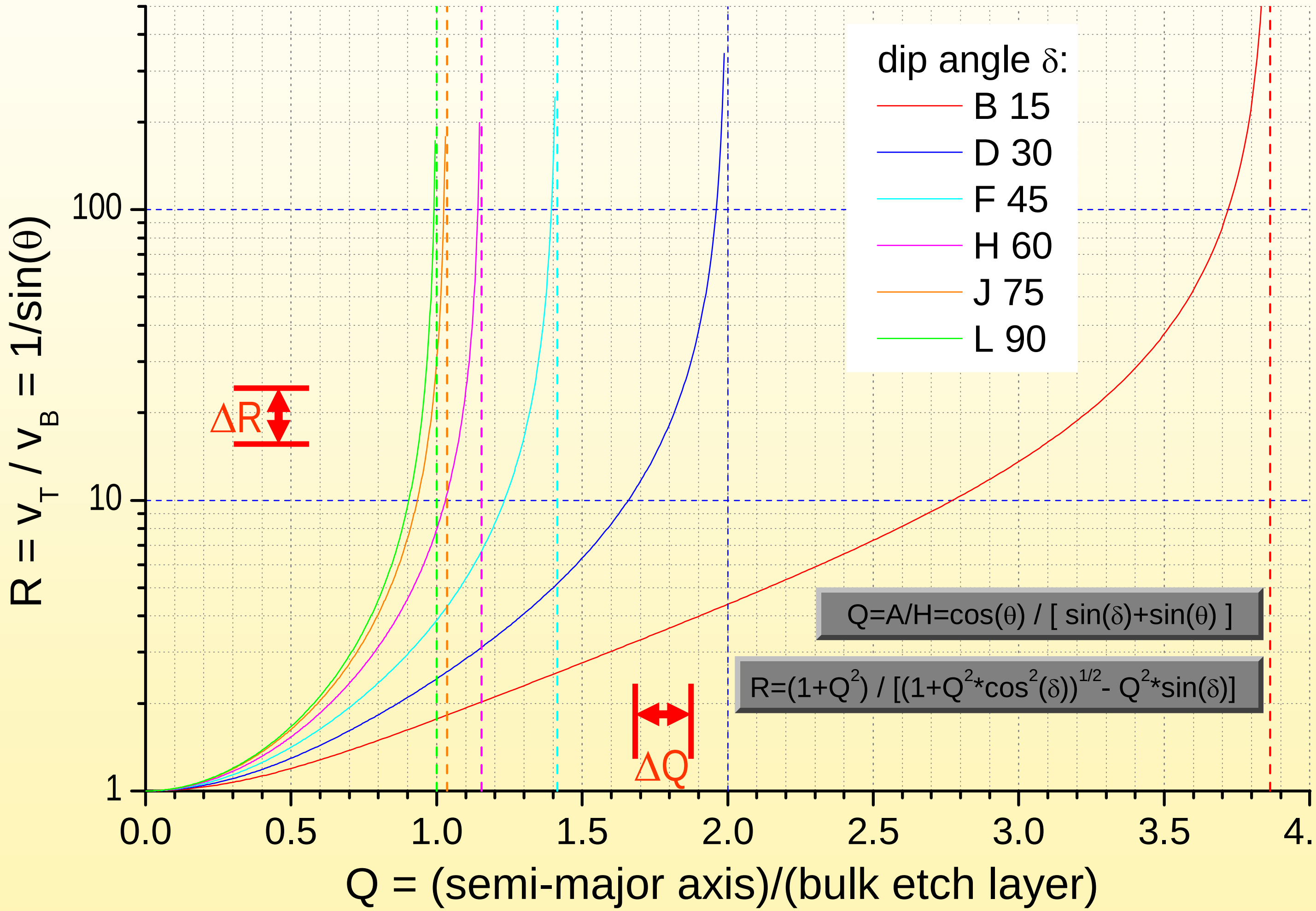


Implications for dosimetry

Calibration function LET(R)



Sensitivity analysis ΔR on ΔQ

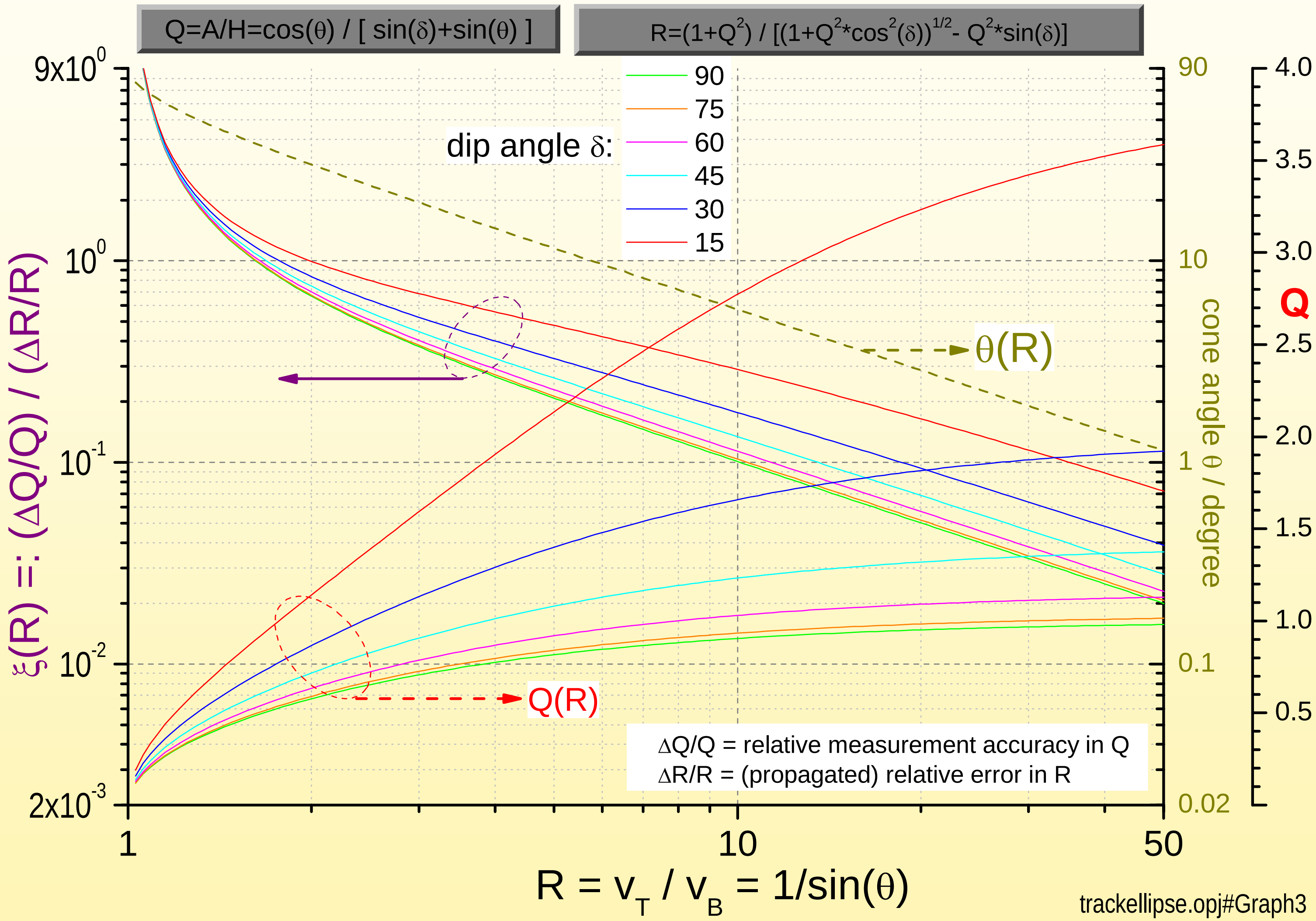


trackellipse.opj#Graph1

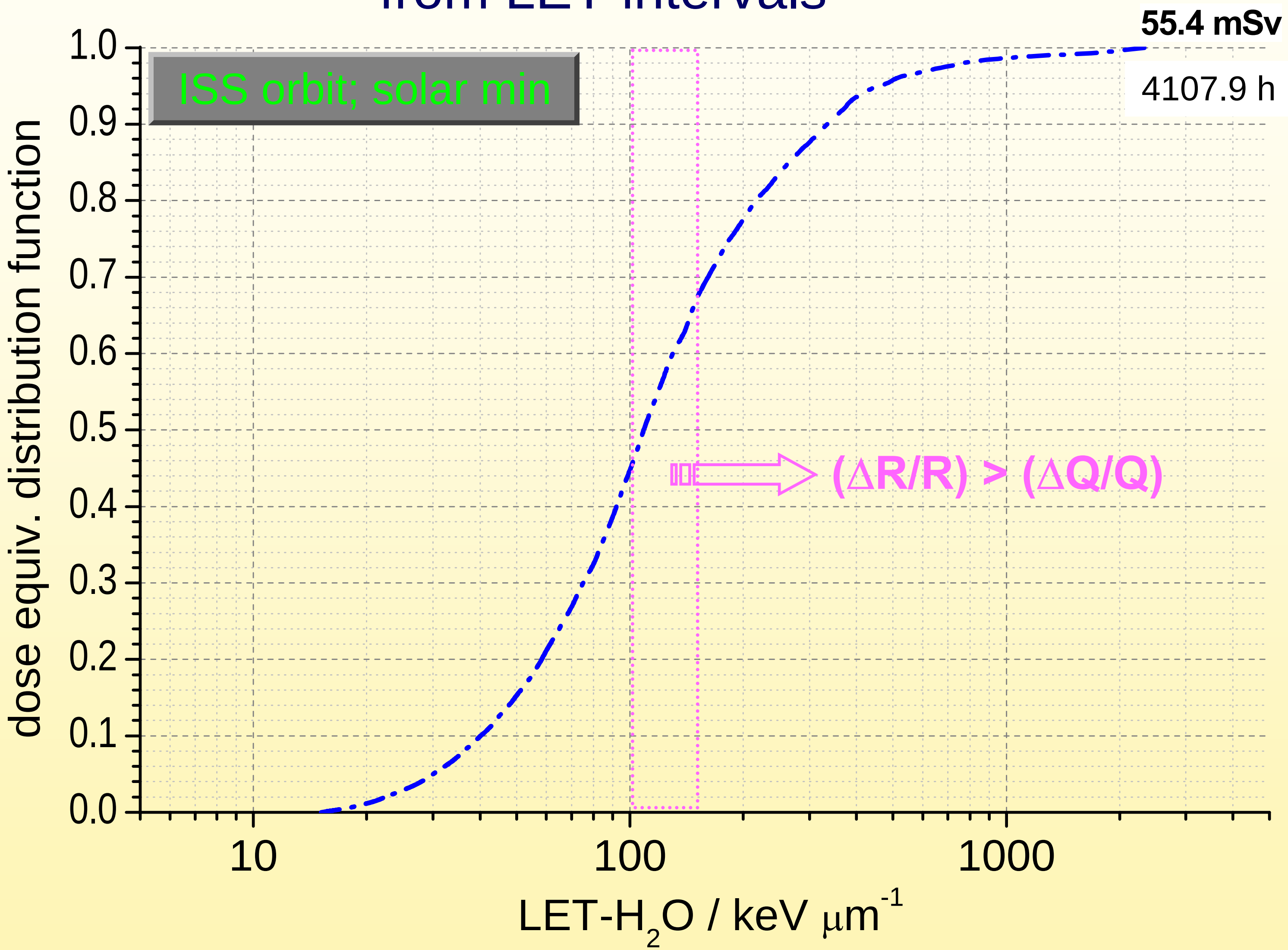
Case 1:

$\Delta Q/Q$ given, e.g. 20% =0.20

resulting $\Delta R/R = (\Delta Q/Q) / \xi = 0.20/ \xi$



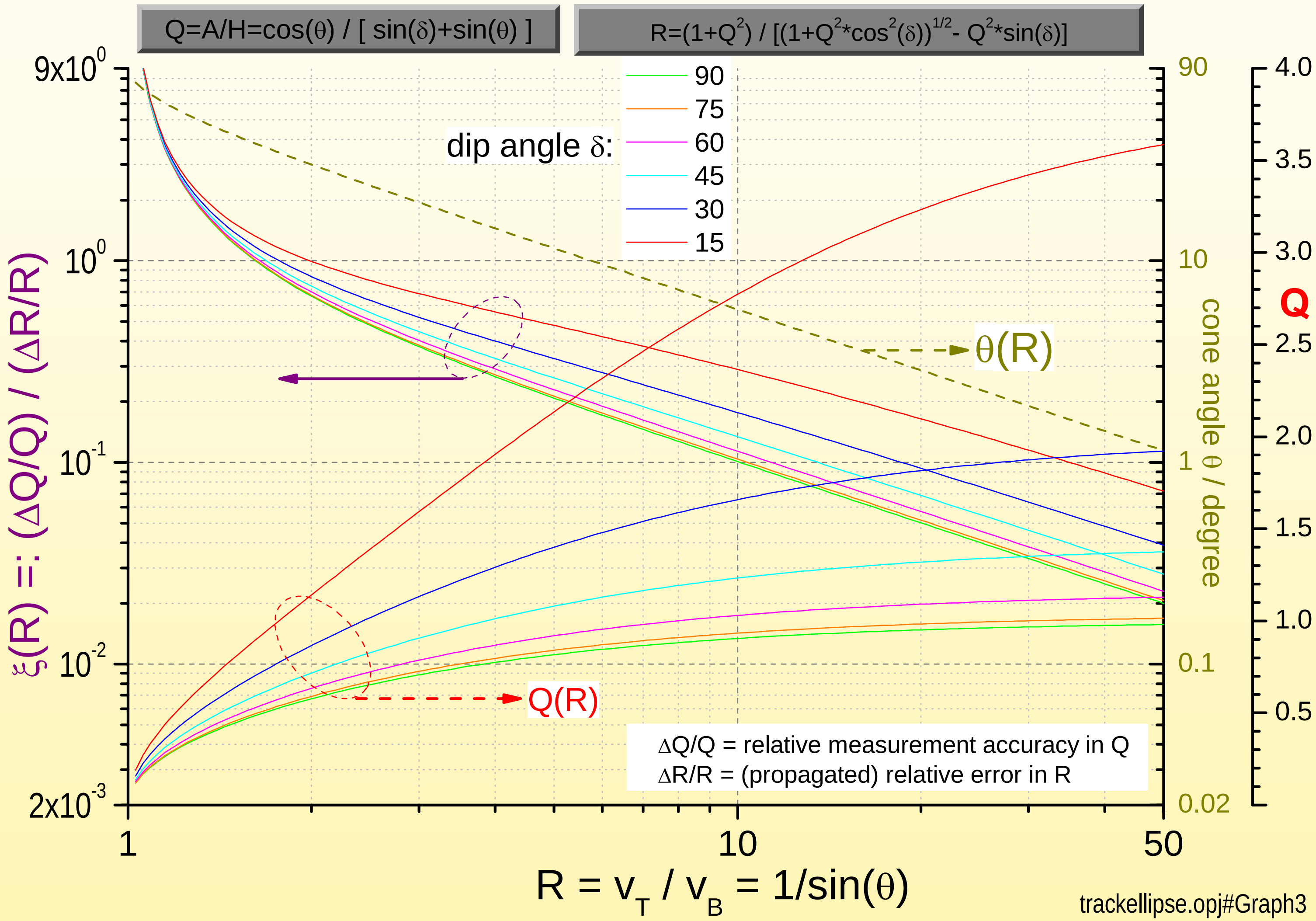
contributions to dose equivalent from LET intervals



Case 2:

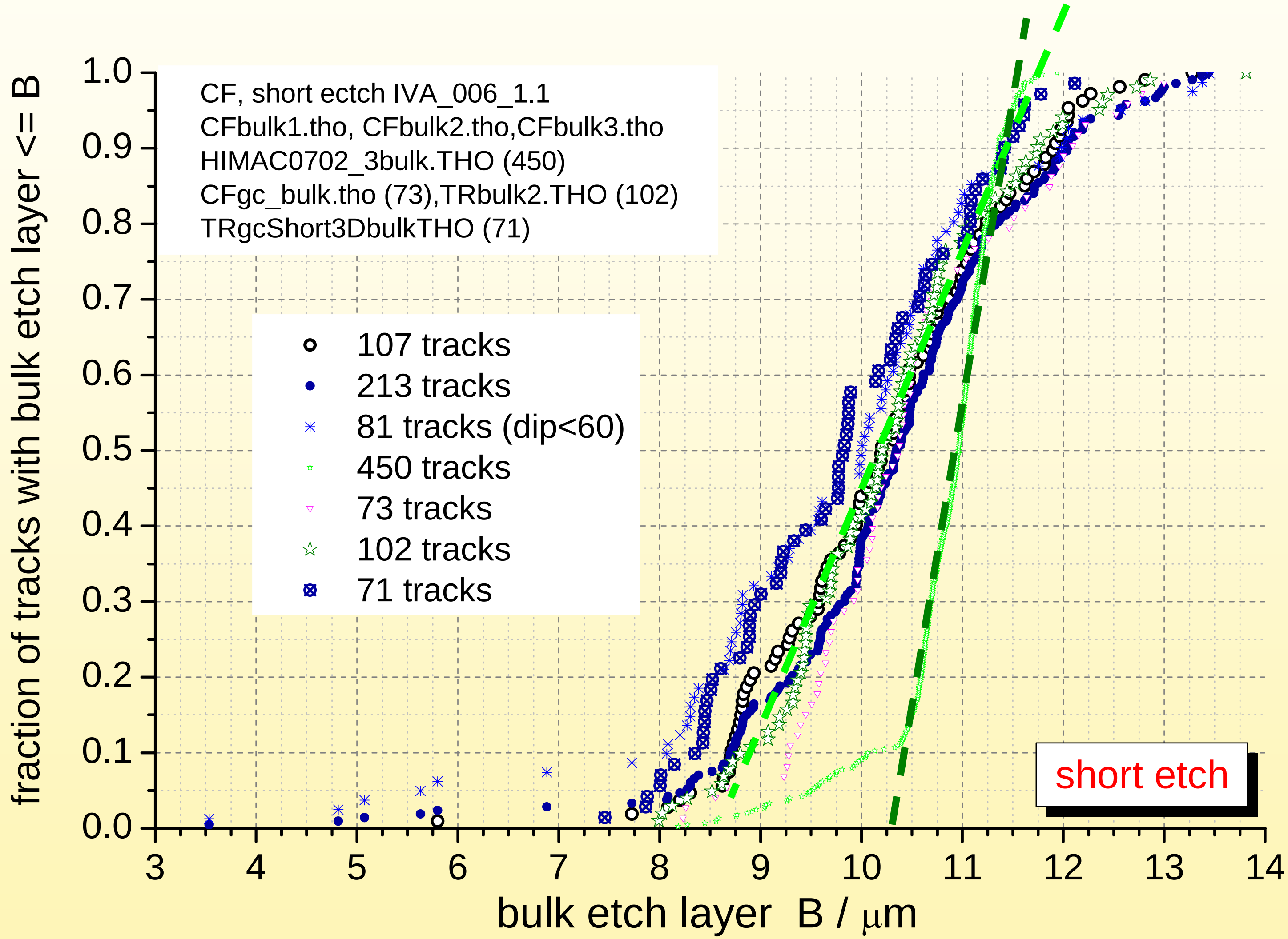
$\Delta R/R$ prescribed, **e.g. 20% =0.20**

required $\Delta Q/Q = (\Delta R/R) * \xi = 0.20 * \xi$

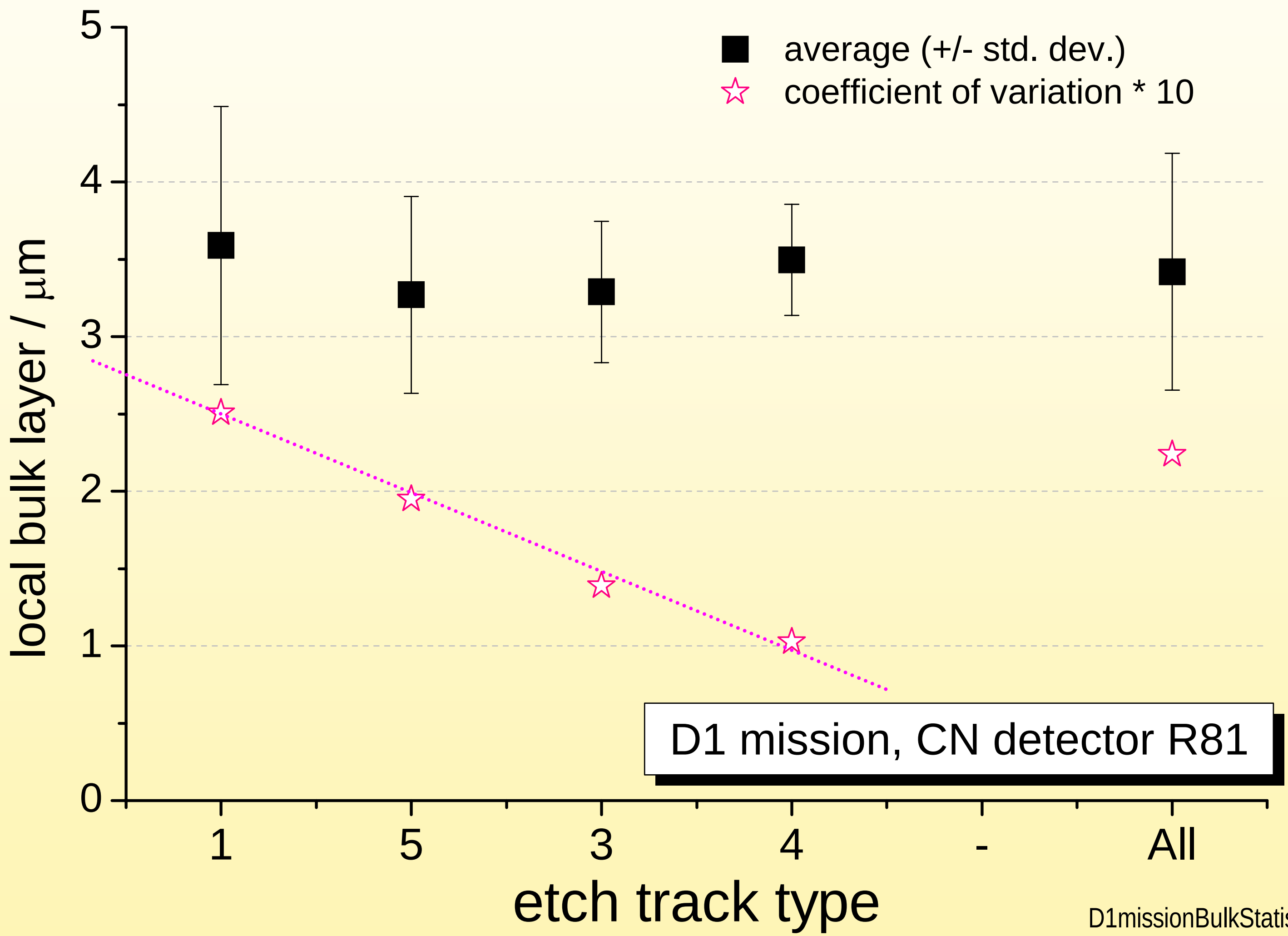


Puzzles

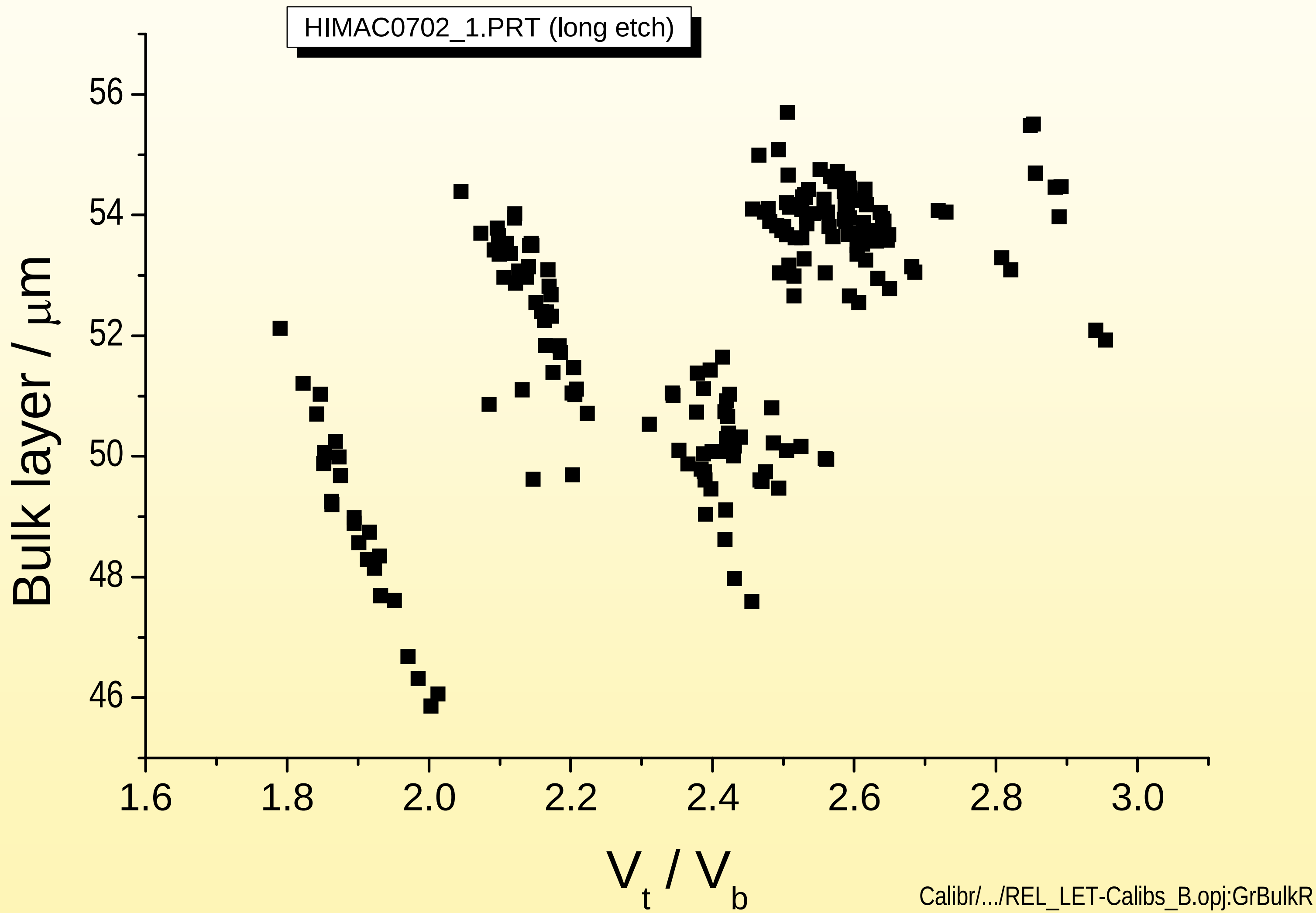
(a few, and for me)

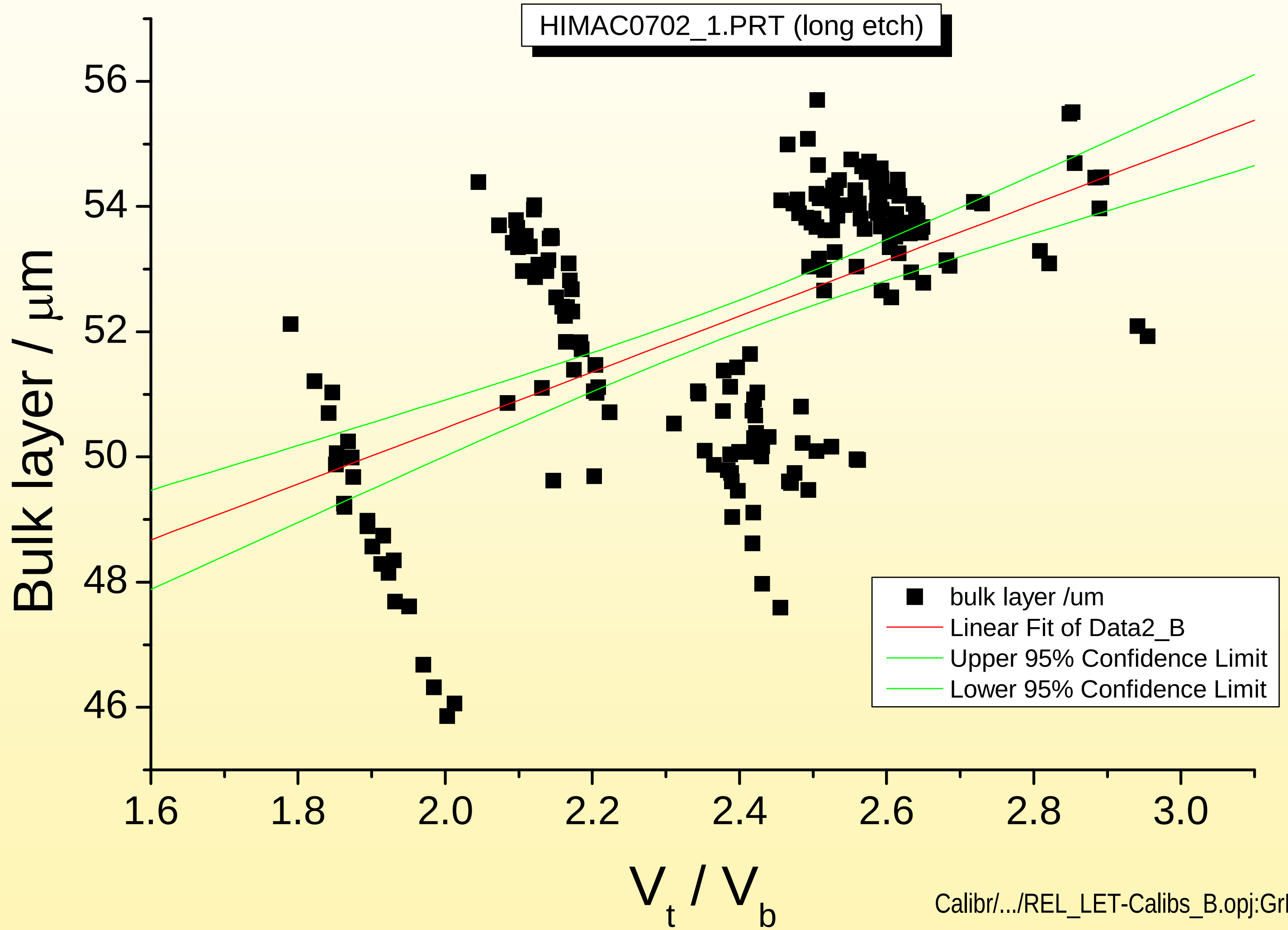


ISS2006/.../TrackBulkLayers.opj:GrShortA

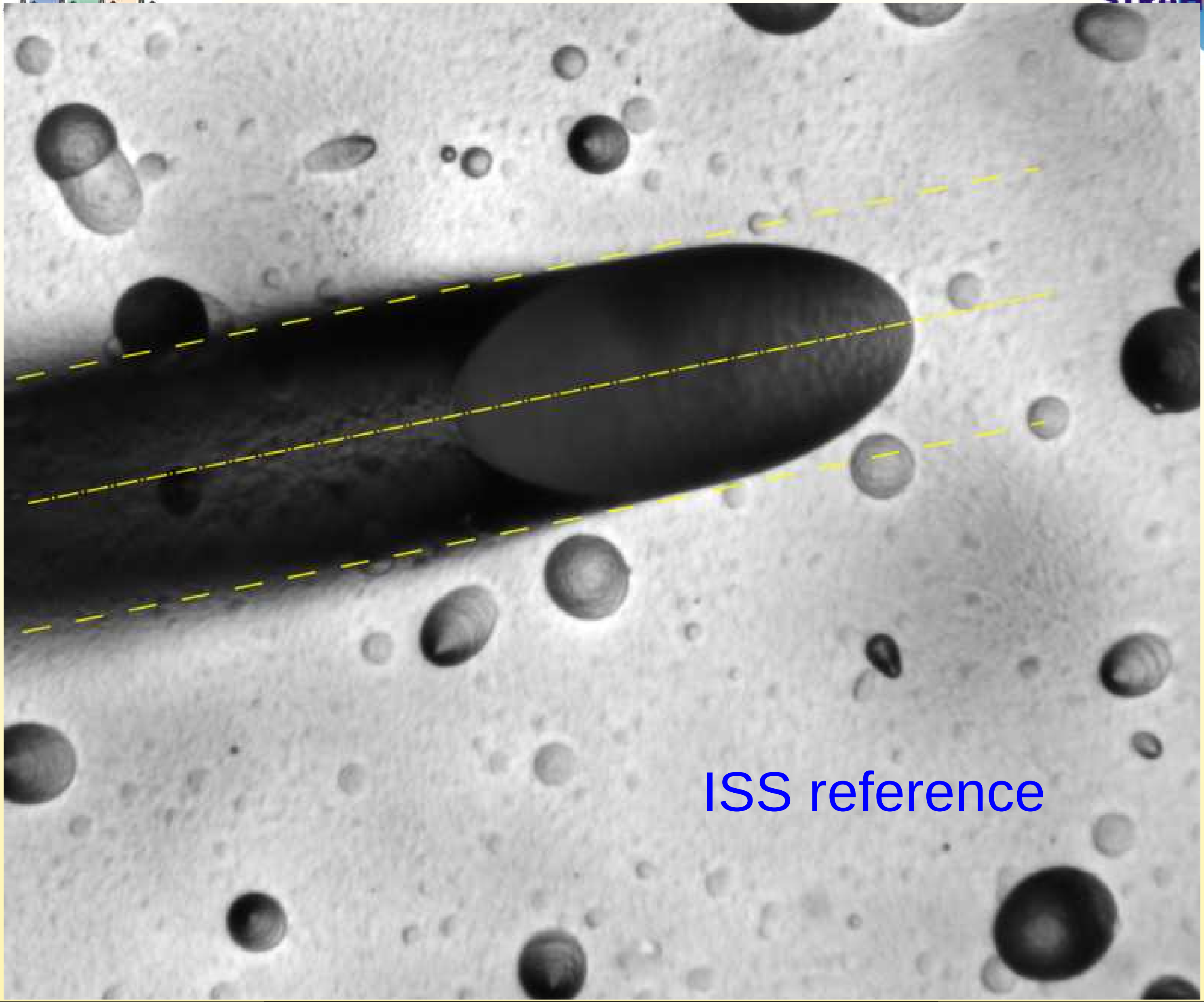


D1missionBulkStatistics.opj


HIMAC0702_1.PRT (long etch)
Bulk layer / μm
56
54
52
50
48
46
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
V t / V b
Calibr/.../REL_LET-Calibs_B.opj:GrBulkR



Calibr/.../REL_LET-Calibs_B.opj:GrBulkRfit


ISS reference

Summary and Conclusion

- Bulk etch rate in plastic detectors varies significantly
  - during etch time (CR 39)
  - locally by 10% to 25% (CR 39 and cellulose nitrate)

- Precision of dose equivalent measured thereby limited to perhaps 20% or more

  (neglecting other sources of error)

Overview

- Historical background – motivation
- 2D measure
- 3D measure
- 3D measure ysis
- 3D measure
- Local bulk la
- Local bulk la
- Global bulk l cal thickness)
- 2D – 3D co
- Implications for dosimetry
- Puzzles (a few, for me)