

# Skenovací elektronová mikroskopie

(Úvod do historie spíše než použití)

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Oddělení materiálové analýzy FZÚ AV ČR

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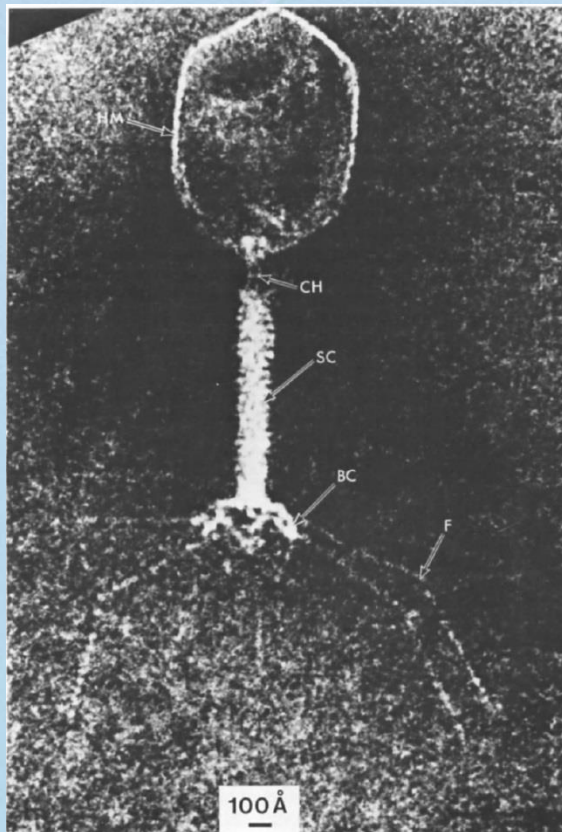
# Elektronová mikroskopie

## Proč byla vyvinuta?

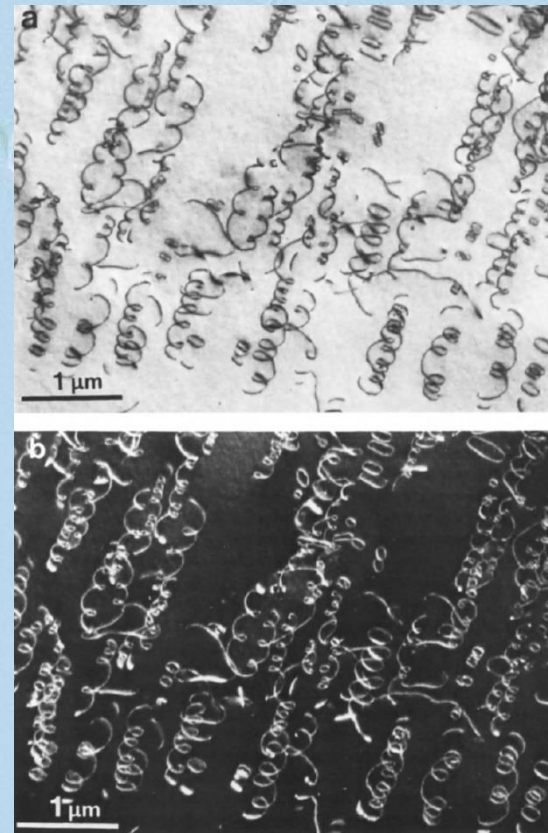
- Má větší rozlišení než optická mikroskopie
- Umožňuje sledovat:
  - Poruchy krystalové mříže
  - Buněčné struktury
- Pracuje s dobře zvládnutou elektrinou

# Typické cíle EM

Virus 1962



Dislokace v Al-Cu, 1969

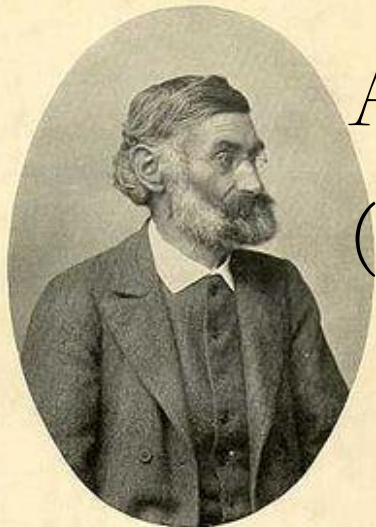


# Elektronová mikroskopie

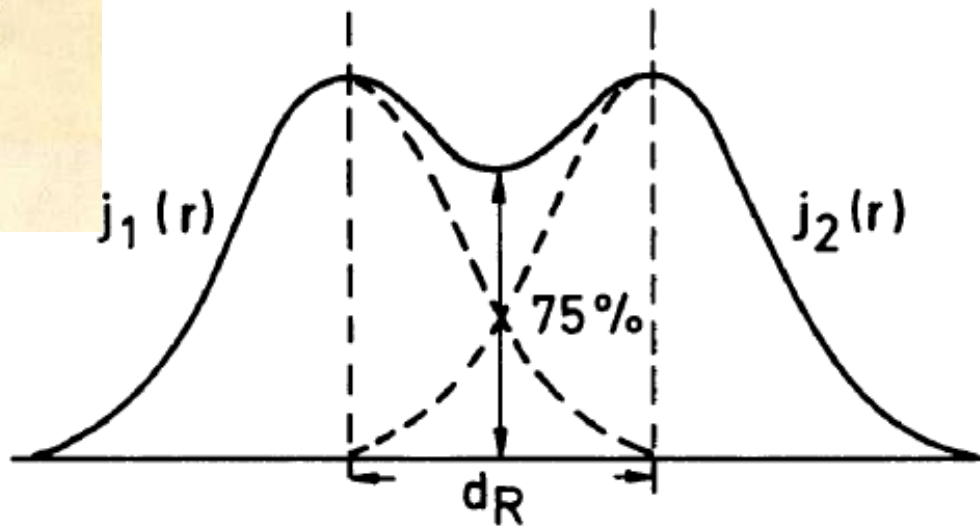
## Proč byla vyvinuta?

Abbeho kritérium pro rozlišení mikroskopu

(1873): 
$$d = \frac{\lambda}{2n \sin \alpha} \cong \frac{0.6\lambda}{\alpha} \sim 200 \text{ nm}$$



*Dr. E. Abbe*



# Elektronová mikroskopie

## Proč byla vyvinuta?

- Má větší rozlišení než optická mikroskopie.






S využitím de Broglieho hypotézy je vlnová délka elektronu ( $E_0 = 511 \text{ keV}$ ):

$$\lambda = \frac{1.226}{[U(1 + 0.9788 \times 10^{-6}U)]^{1/2}}$$

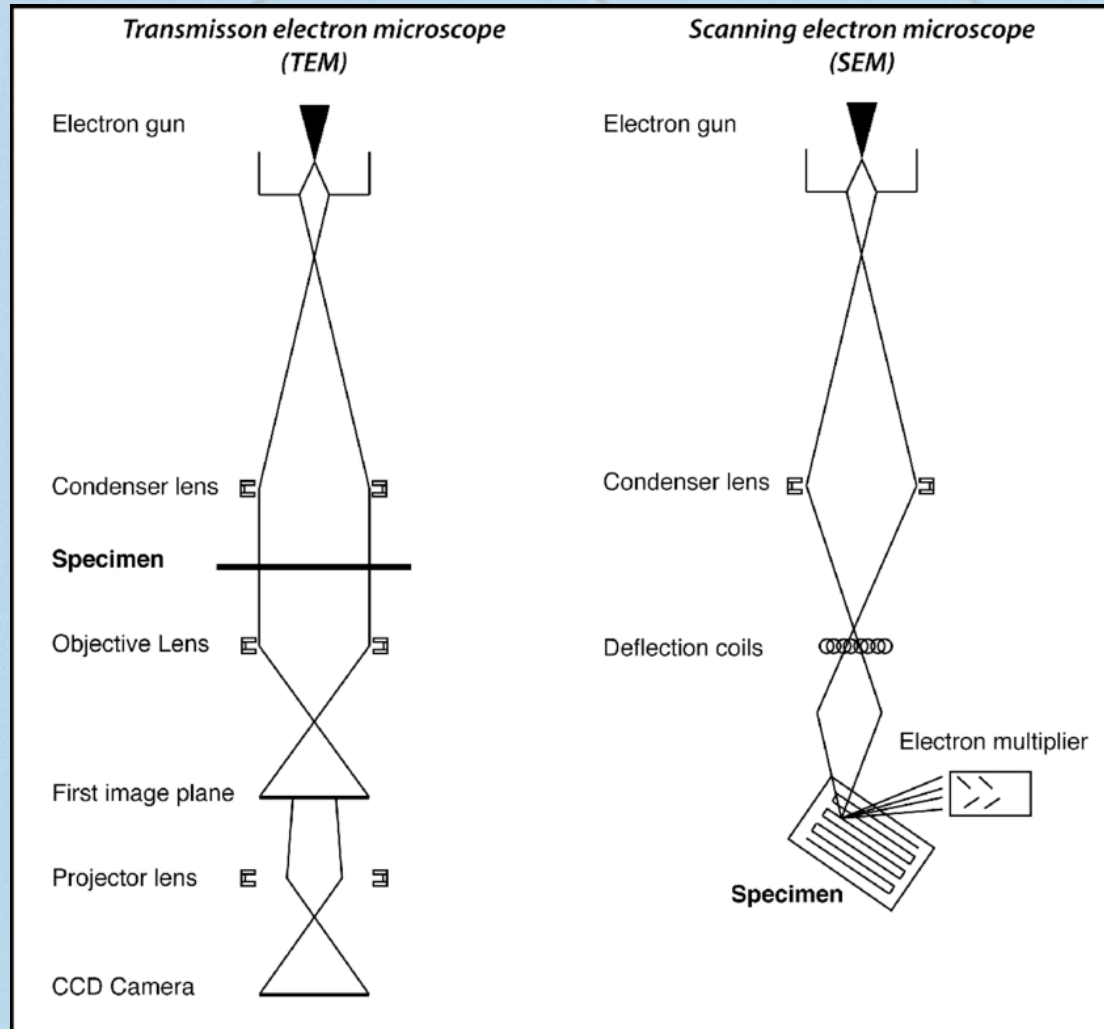
což je  $\lambda = 38.8 \text{ pm}$  pro  $E = 1 \text{ keV}$  a  $6.98 \text{ pm}$  pro  $30 \text{ keV}$ .

# Elektronová mikroskopie

## Proč byla vyvinuta?

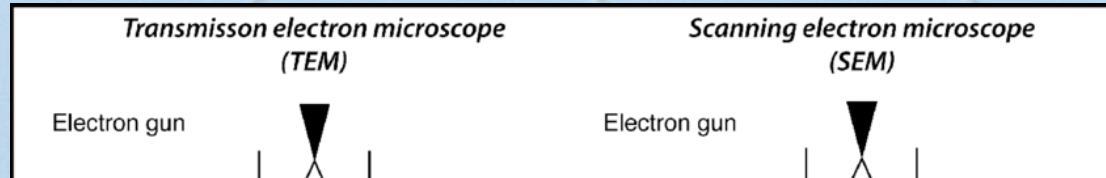
COLOPHON					
OPTICAL EQUIPMENT	Unaided eye	Hand lens	Light microscope	Scanning electron microscope	Transmission electron microscope
(Approximate) SIZE OF SUBJECT IN METERS	$10^{-3} - 10^{-1}$	$10^{-4} - 10^{-2}$	$10^{-6} - 10^{-4}$	$10^{-8} - 10^{-2}$	$10^{-9} - 10^{-5}$

# Elektronový mikroskop



Harald Hagendorfer, PhD thesis, EPMA, 2011

# Elektronový mikroskop



Harald Hagendorfer, PhD thesis, EPMA, 2011



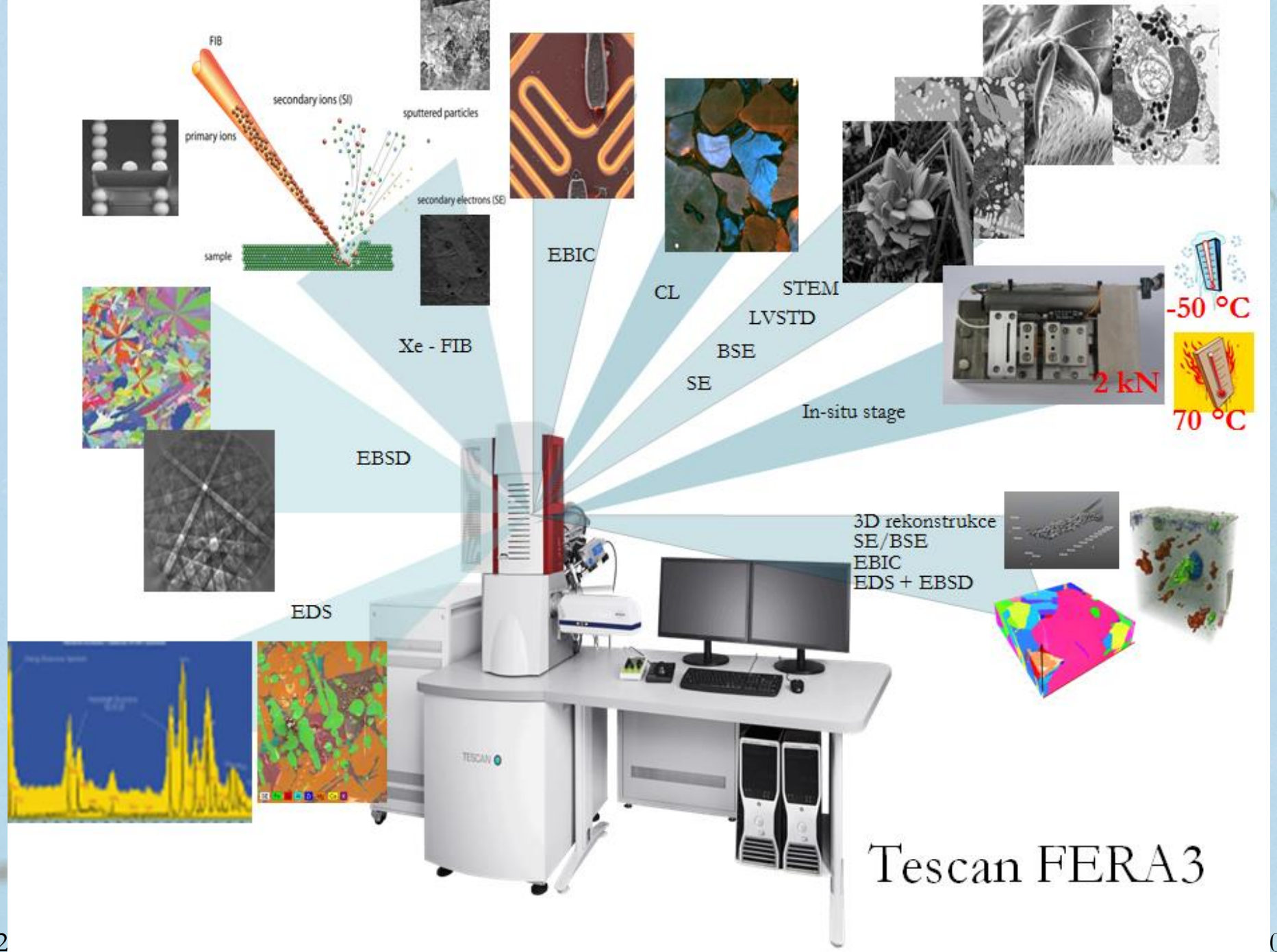
# Skenovací elektronový mikroskop

Tescan FERA 3



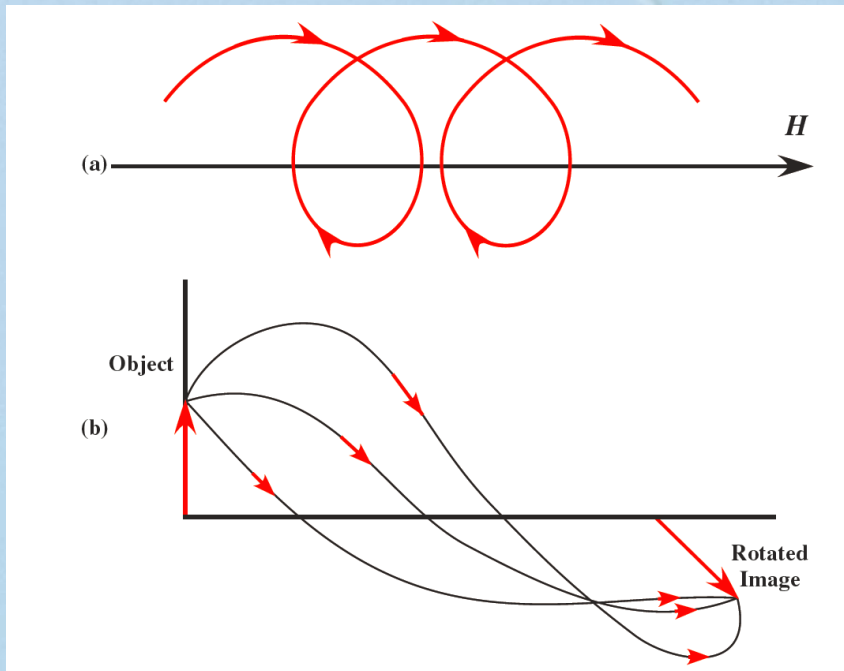
Jeol JXA-733





# Tescan FERA3

# Pohyb elektronu v elektromagnetickém poli



Síla magnetické čočky

$$k^2 = \frac{eB_0^2 a^2}{8mU}$$

Lorentzova síla:

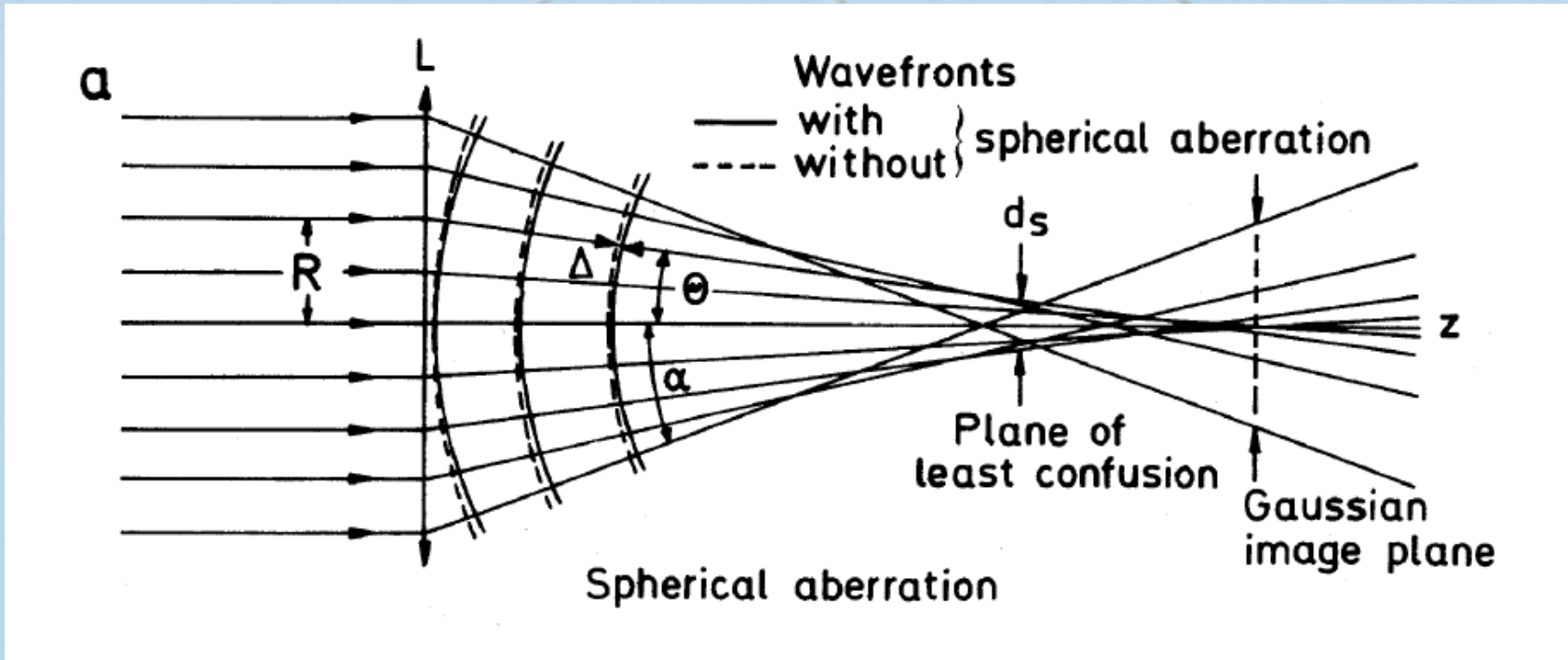
$$\vec{F} = -e(\vec{E} + \vec{v} \times \vec{B})$$

Díky ní se elektron  
pohybuje po Landauových  
hladinách a stáčí se o  $\varphi$ :

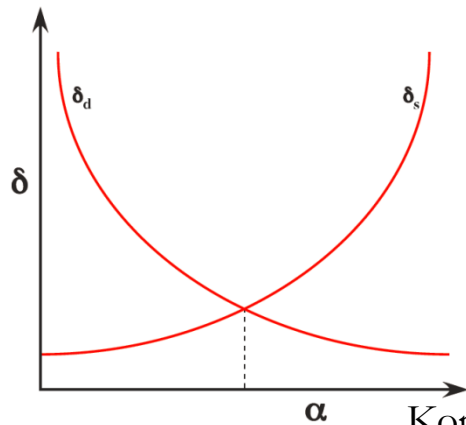
$$\varphi = \sqrt{\frac{e}{8m_0U}} \int_{-\infty}^{+\infty} B_z dz$$

Pro  $k^2 \ll 1$  je  $\varphi = \pi k$

# Kulová vada



$$\delta_S \sim C_S \alpha^3$$



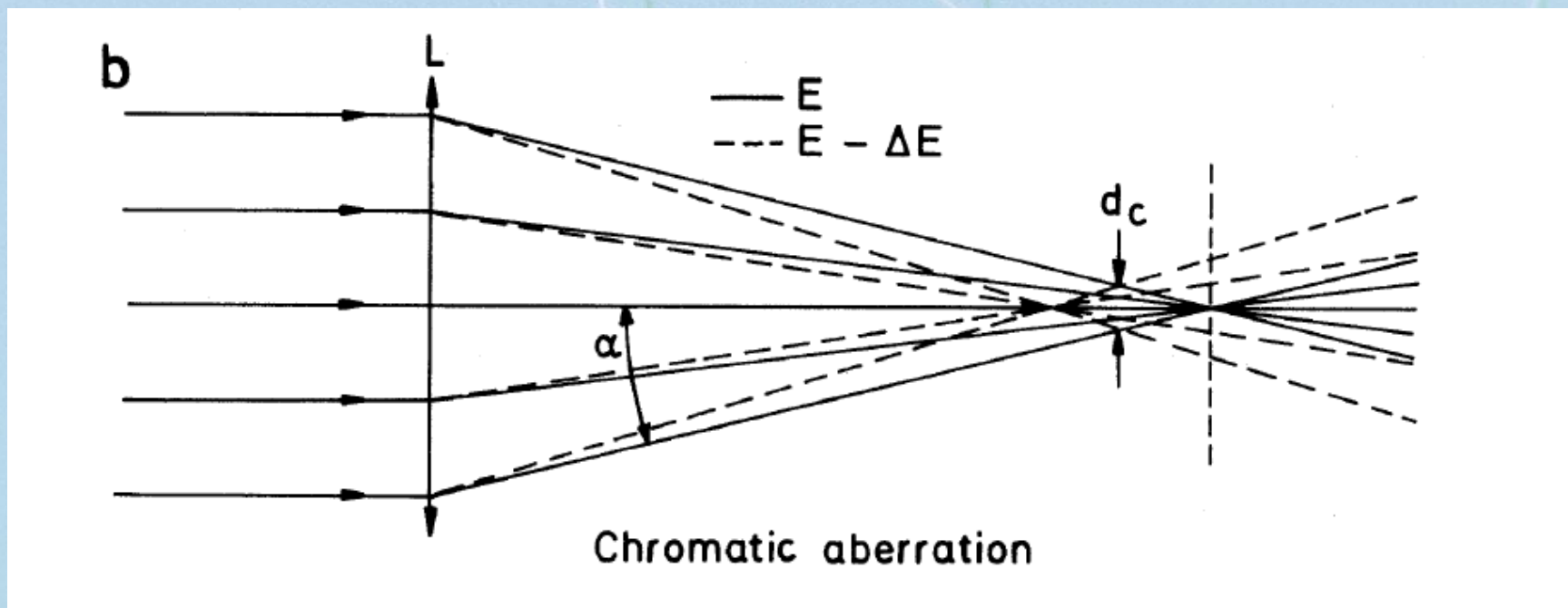
Rayleighho kritérium:

$$\delta_d \sim 0,61\lambda/\alpha$$

$$\sim 0,75/[\alpha\sqrt{V(1+10^{-6}V)}]$$

# Barevná vada

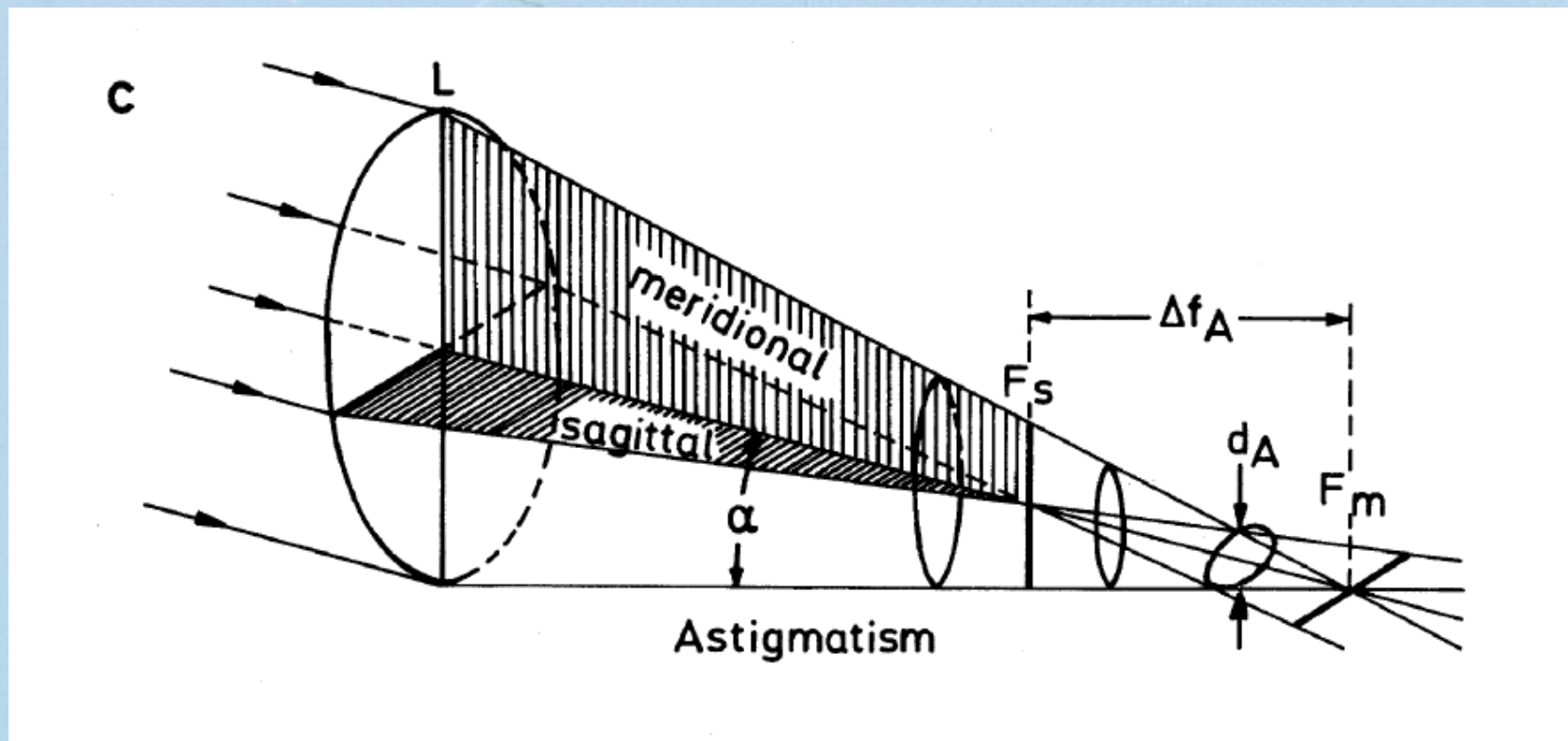
$$\delta_c = C_c \frac{\Delta E}{E_0} \alpha$$



# Astigmatismus

Axiální astigmatismus

$$\delta_A = \Delta f_A \alpha$$

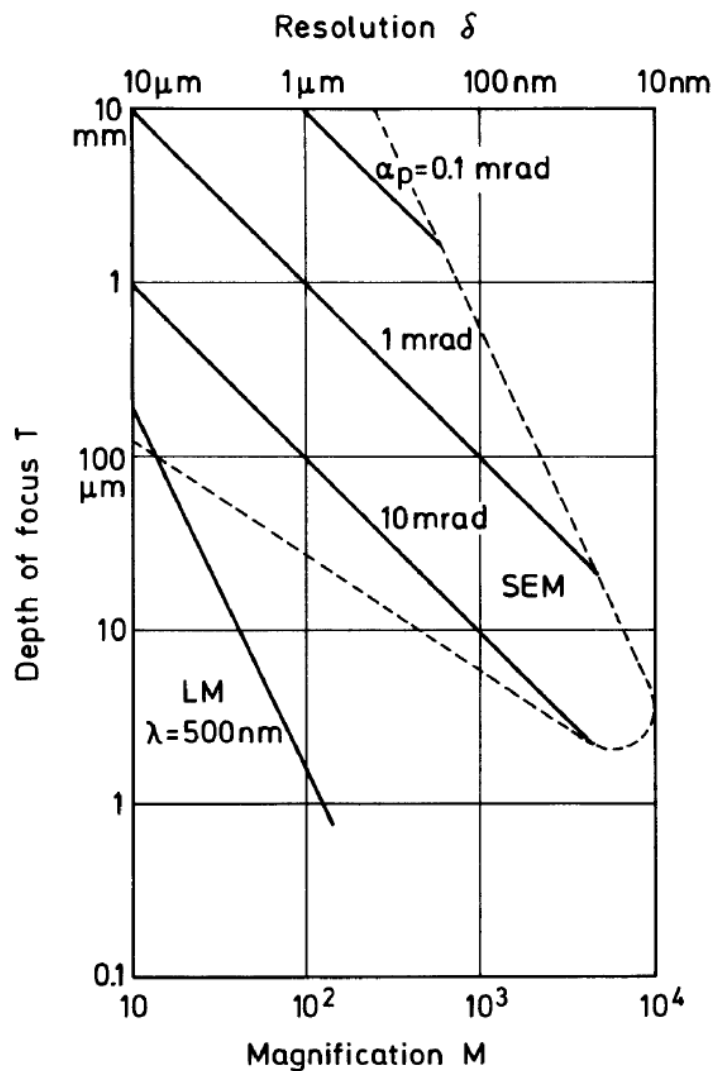


# Celková chyba zobrazení

Předpokládáme, že příspěvky rozmazání zobrazovaného bodu jsou Gaussovské, proto jejich příspěvky sloučit konvolucí:

$$\begin{aligned}d_p^2 &= d_0^2 + d_d^2 + d_s^2 + d_c^2 \\ &= [C_0^2 + (0.6\lambda)^2]\alpha_p^{-2} + \frac{1}{4}C_s^2\alpha_s^6 + \left(C_c \frac{\Delta E}{E}\right)^2 \alpha_p^2\end{aligned}$$

# Rozlišení, hloubka ostrosti a zvětšení



$T$  – hloubka ostrosti

$\Delta$  – rozlišení

$M$  – zvětšení

$\alpha_p$  – výstupní apertura  
objektivu

LM – limity optické  
mikroskopie

$$T = \delta \sqrt{\delta^2 / \lambda^2 - 1}$$

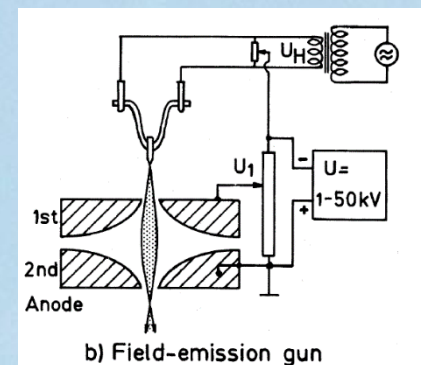
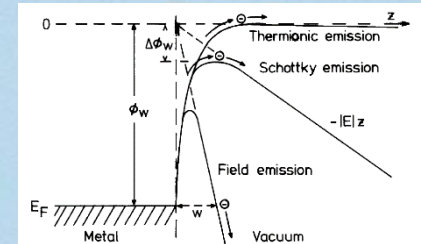
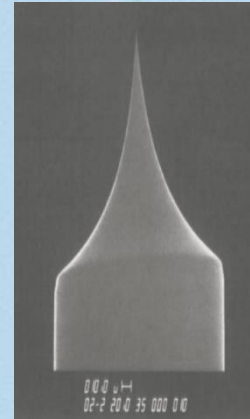
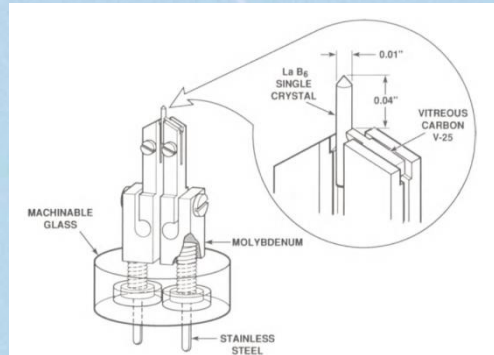
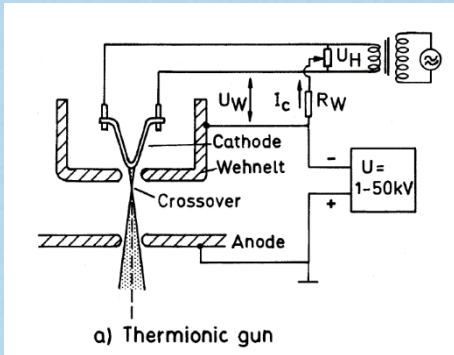


# Složení SEM

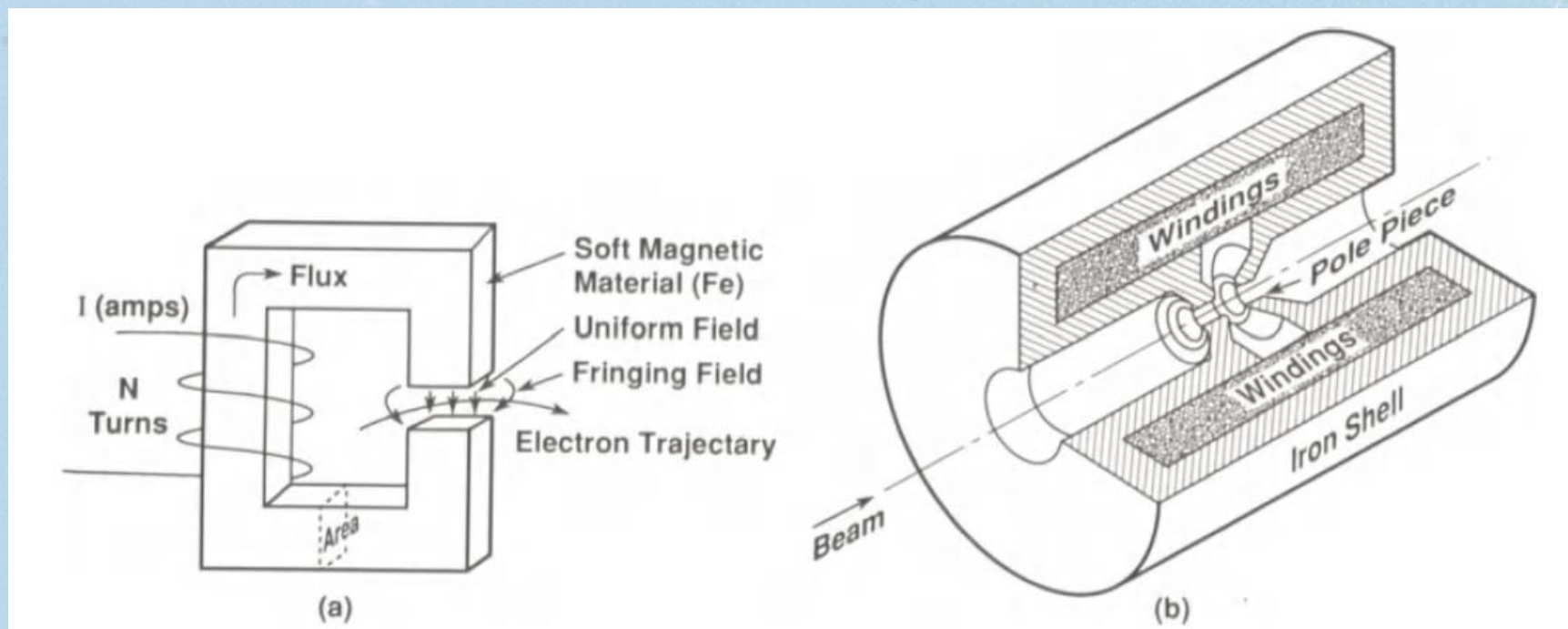
- Zdroj elektronů
- Zobrazovací soustava – čočky
- Interakce se vzorkem
- Detektory

# Zdroje elektronů

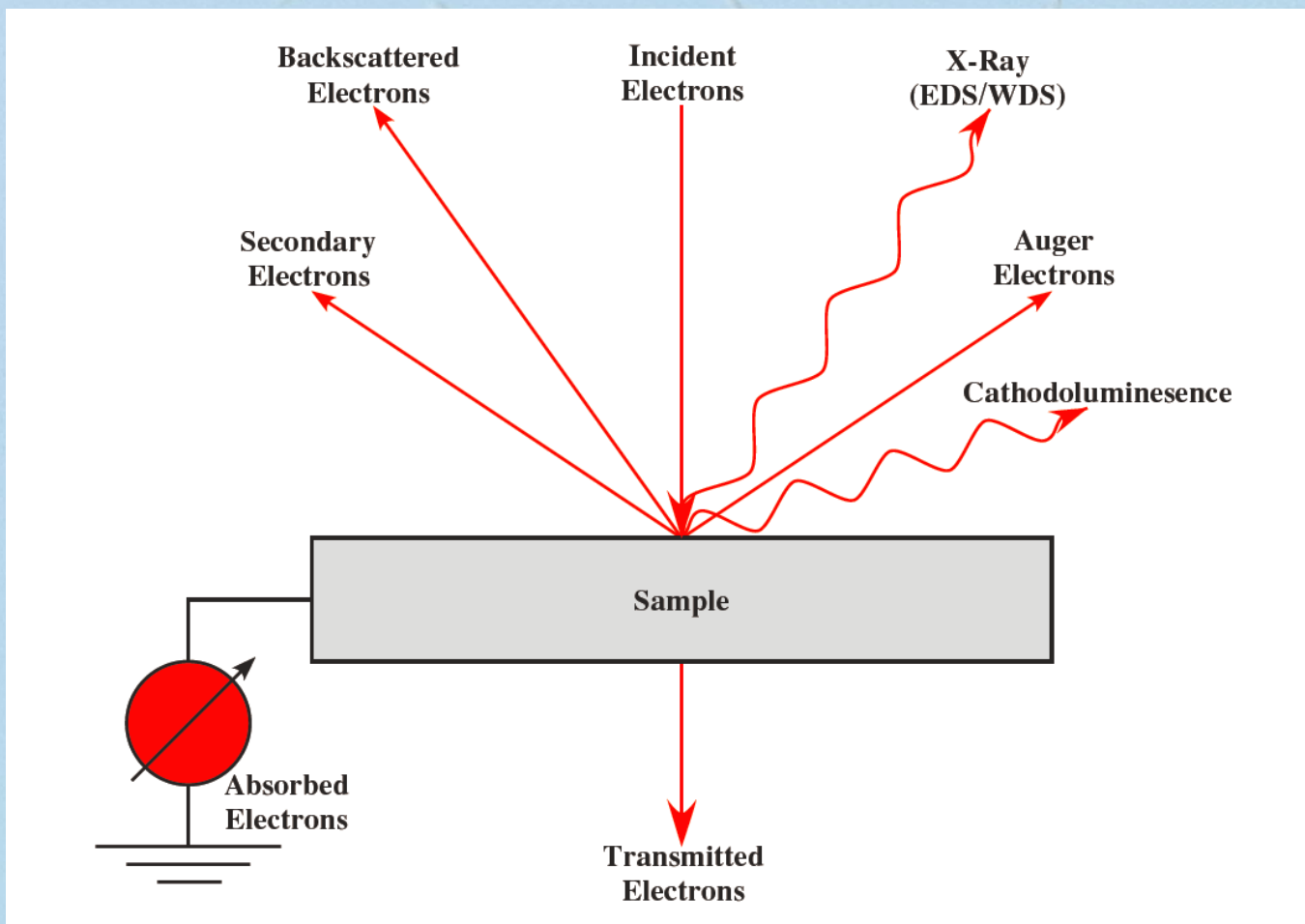
	Tlak	Jas	Velikost stopy (ze zdroje)	Energiový rozptyl
	[Pa]	[A/cm <sup>2</sup> sr]	r [μm]	ΔE [eV]
Termoemise	10 <sup>-3</sup>	2×10 <sup>4</sup>	10-50	1-3
LaB <sub>6</sub>	10 <sup>-4</sup>	10 <sup>5</sup>	10-50	0,5-2
Schottkyho	10 <sup>-6</sup>	10 <sup>8</sup>	1	0,4-0,6
Autoemise	10 <sup>-8</sup>	10 <sup>9</sup>	0,003	0,2-0,4



# Princip elektromagnetické čočky

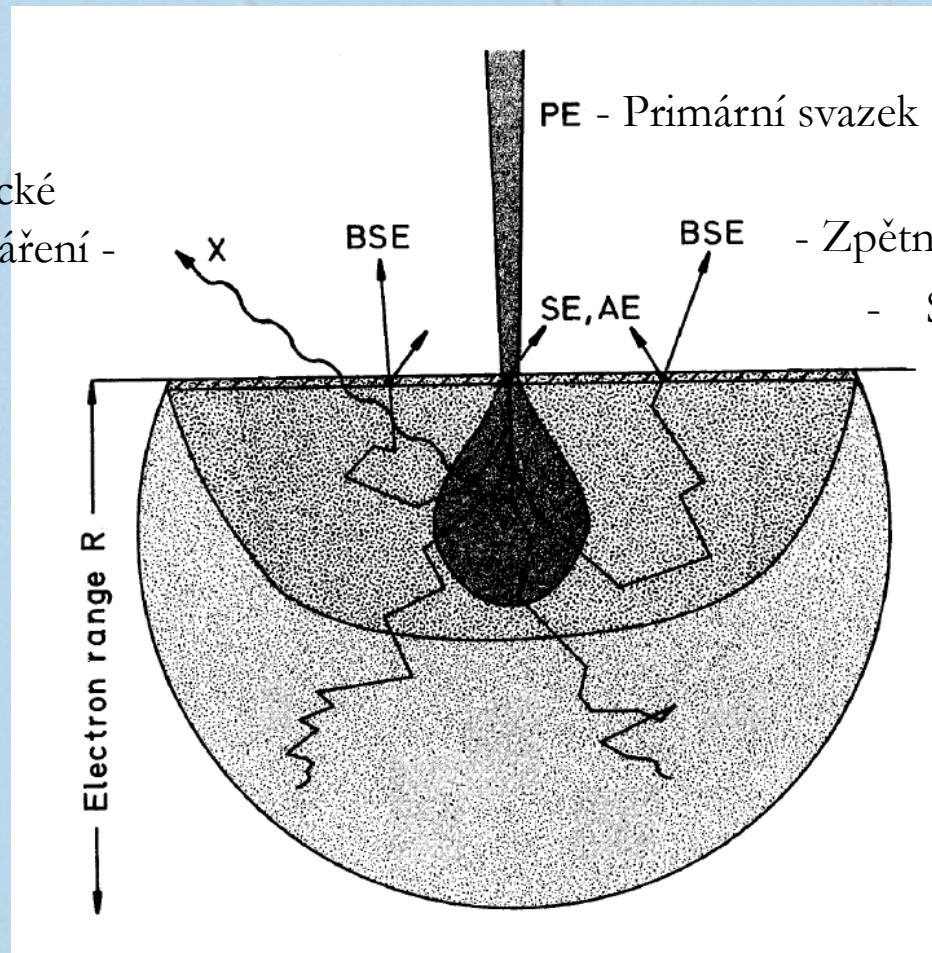


# Interakce elektronového svazku



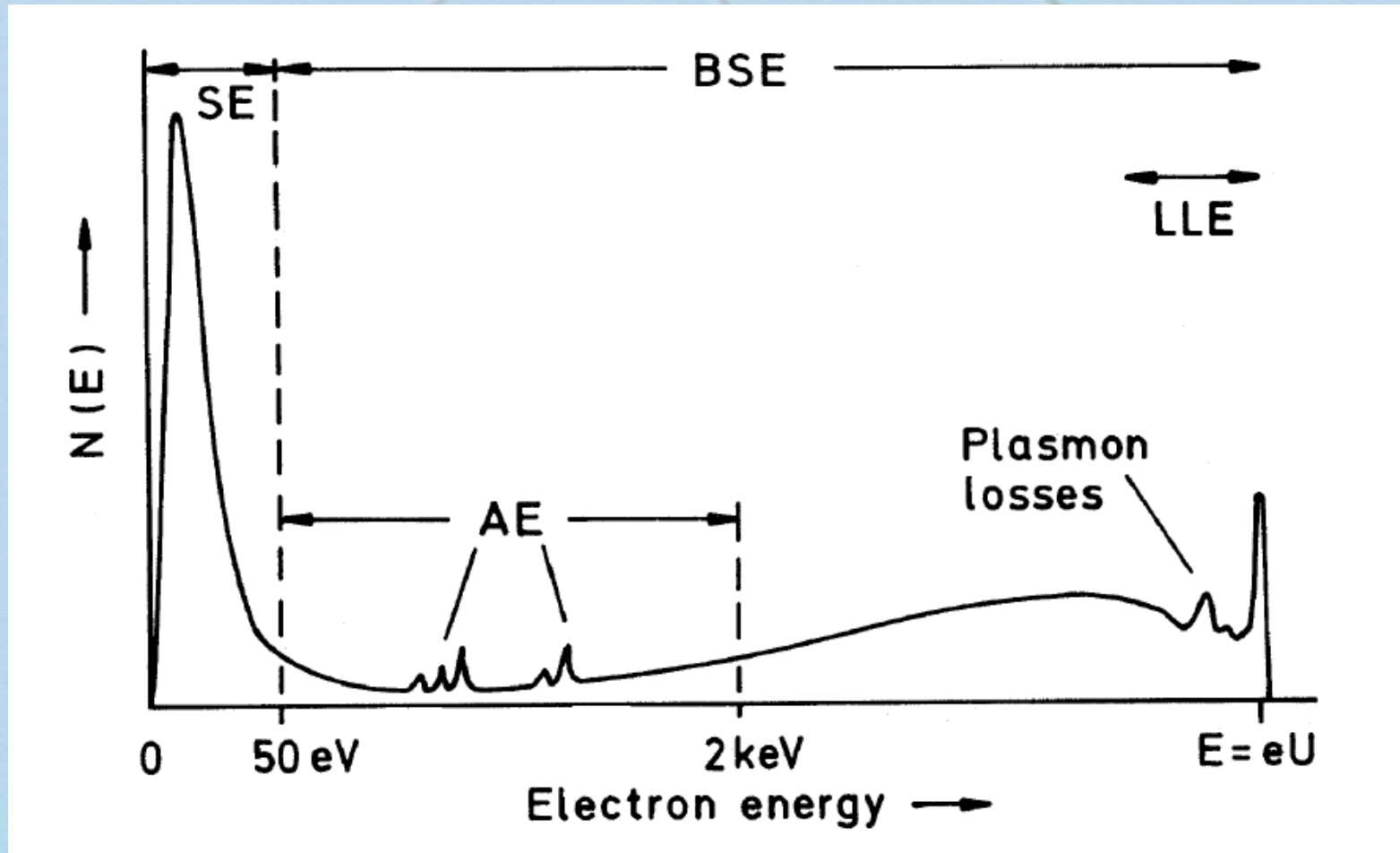
# Schéma interakční oblasti

Charakteristické  
rentgenové záření -



- Zpětně odražené elektrony  
- Sekundární elektrony,  
Augerovy elektrony

# Spektrum elektronů ze vzorku



Sekundární elektrony  $E_{SE} \leq 50$  eV, low-loss electrons (LLE) ztráta energie oproti primárnímu svazku je jen několik stovek eV, backscattered electrons (BSE) – zpětně

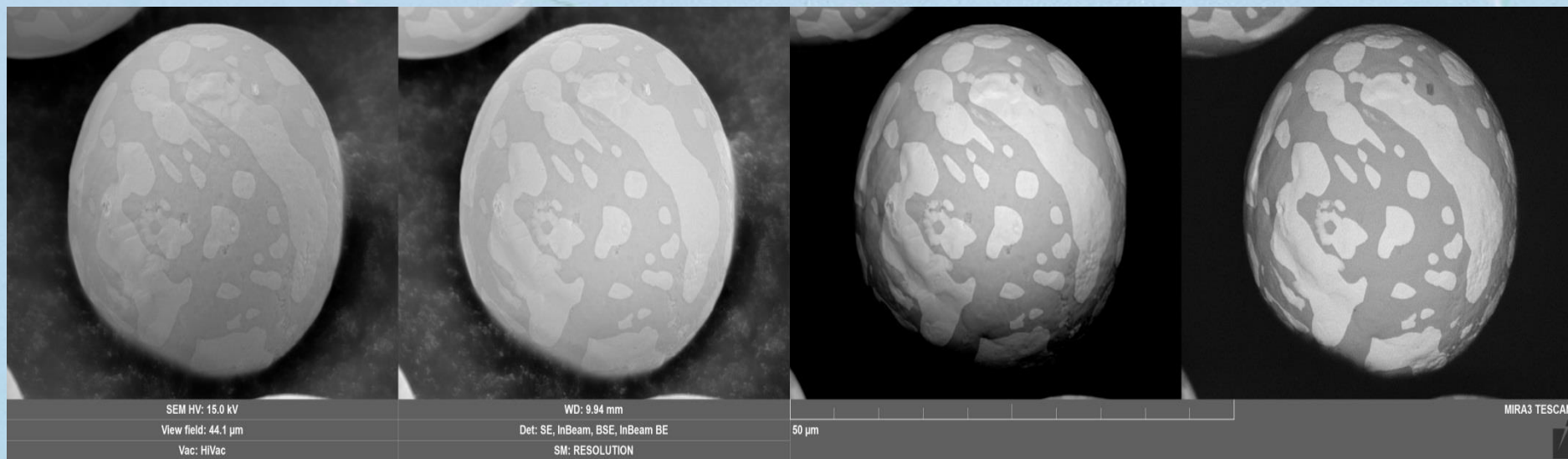
# Srovnání zobrazovacích módů

SE E-T

In-Beam SE

R-BSE

In-Beam BSE

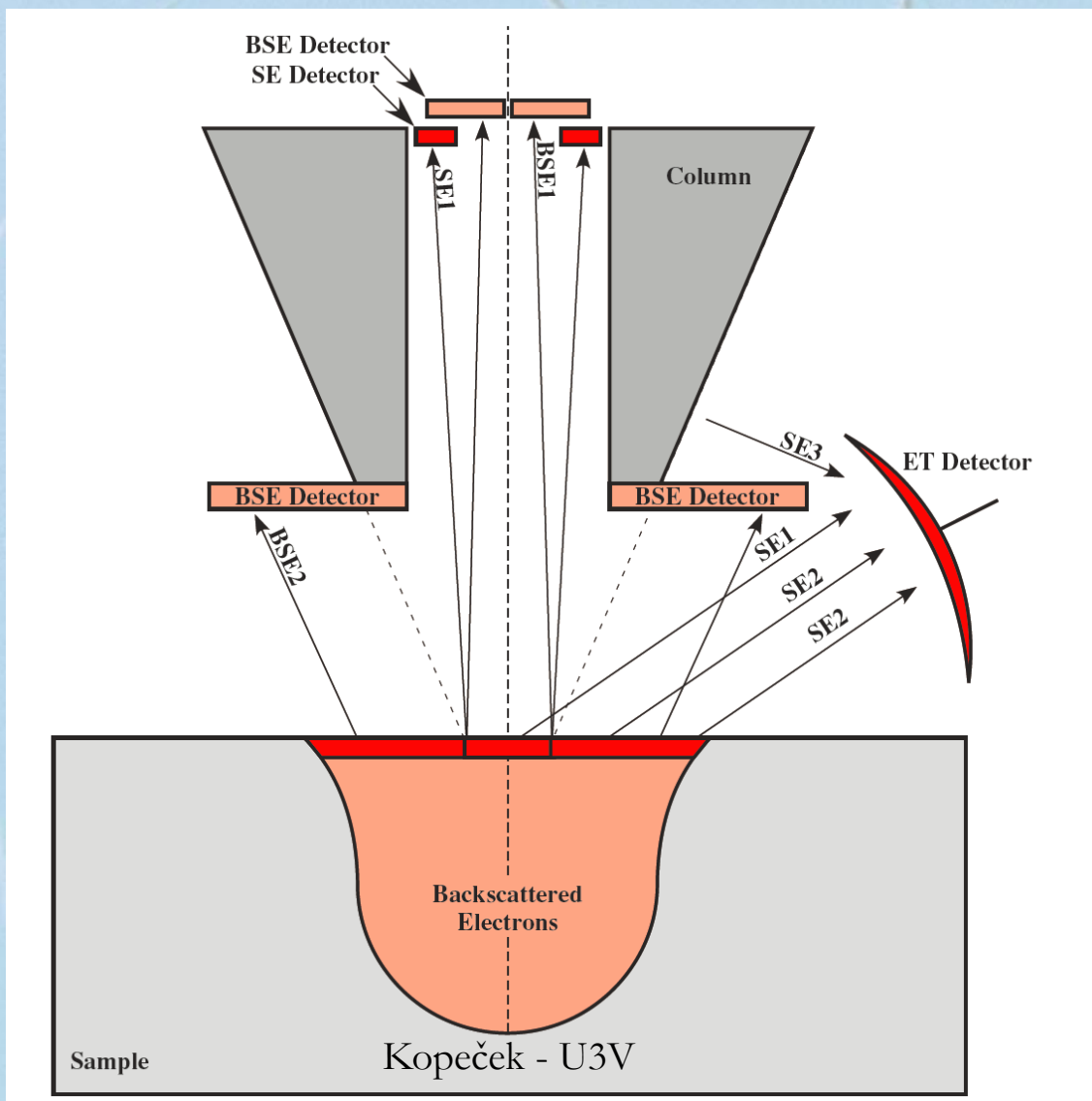


+ Higher surface  
sensitivity  
= better resolution

+ Large field of  
view

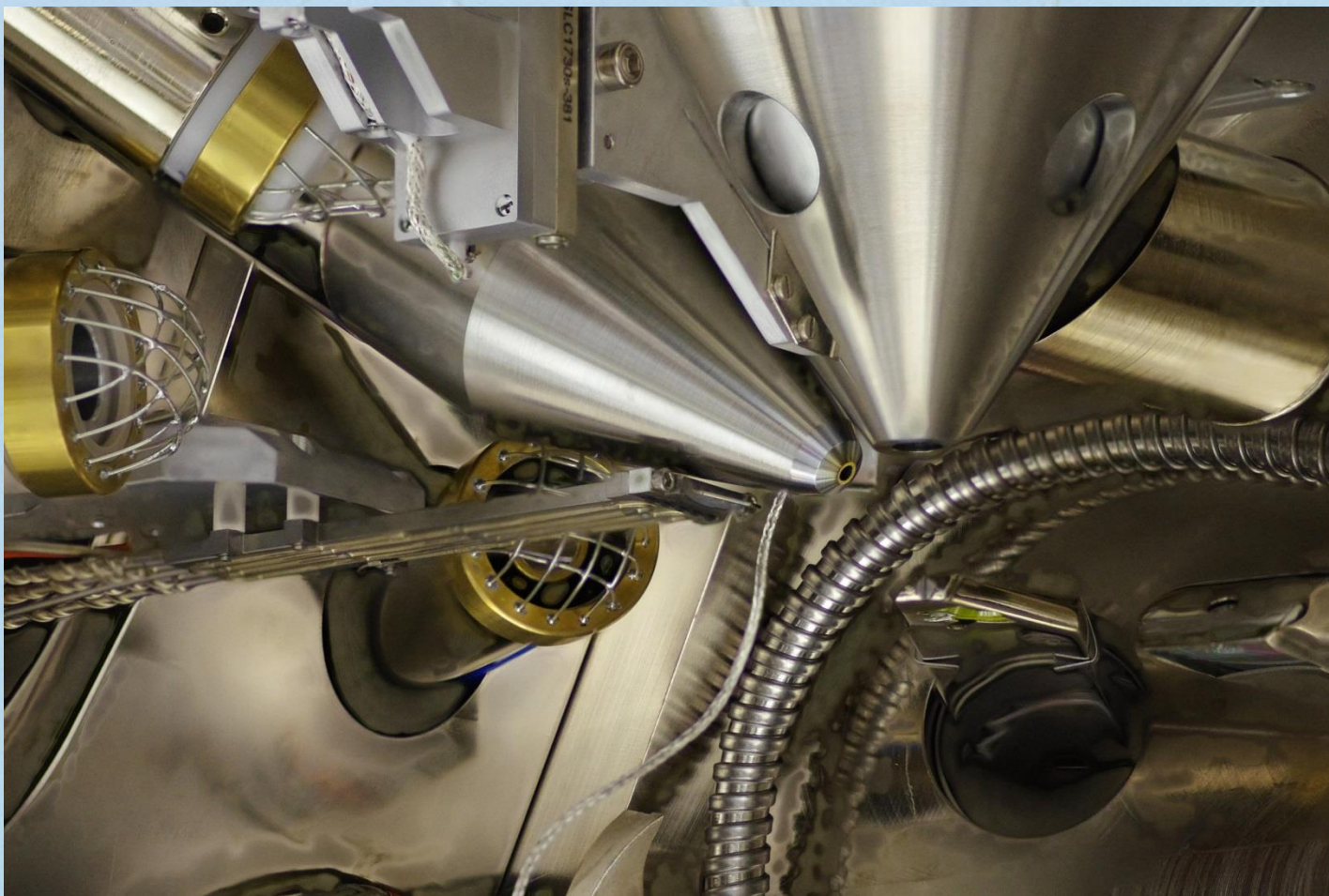
+ lower topography  
info

# Detekce elektronů





# Pohled do komory SEM



# Ernst August Friedrich Ruska



25. 12.1906 – 27. 5. 1988

1986 Nobelova cena za elektronovou optiku

1931 ukázal, že cívka funguje jako čočka pro elektrony

1933 sestavil z více čoček elektronový mikroskop

Od 1937 pracoval v Siemens-Reiniger-Werke AG a nechal zřídit „visiting scientist“ laboratoř,

kterou řídil jeho bratr

Helmut, který

prosazoval aplikace

v medicíně



# Manfred von Ardenne

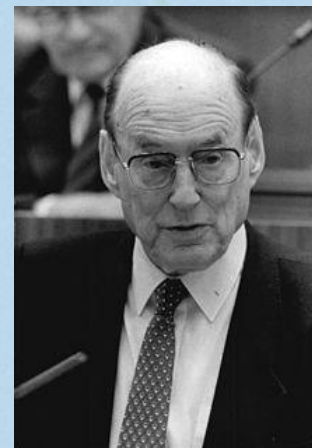


20 January 1907 – 26 May 1997

Asi 600 patentů

1928 – 1945 řídil svou vlastní  
Forschungslaboratorium für  
Elektronenphysik, pak v SSSR jaderné  
zbraně (získal Stalinovu cenu).

1931 poprvé předvedl princip televize –  
skenování obrazu.



# Manfred von Ardenne

## Elektronen- Übermikroskopie

Physik · Technik · Ergebnisse

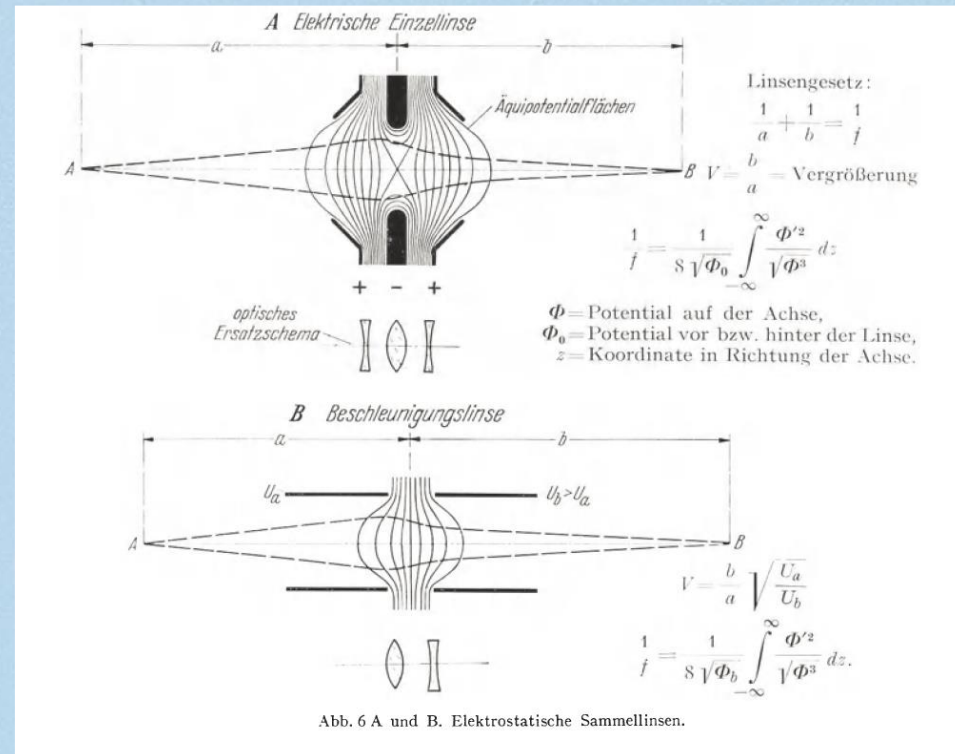
Von

Manfred von Ardenne

Mit einem Titelbild,  
einer photographischen Tafel  
und 404 Abbildungen



Berlin  
Verlag von Julius Springer  
1940



# Max Knoll



17 July 1897 – 6 November 1969

Elektroinženýr, šéf Rusky

Po konstrukci EM 1931 v dubnu 1932  
odešel do Telefunken, kde vyvíjel televizi.

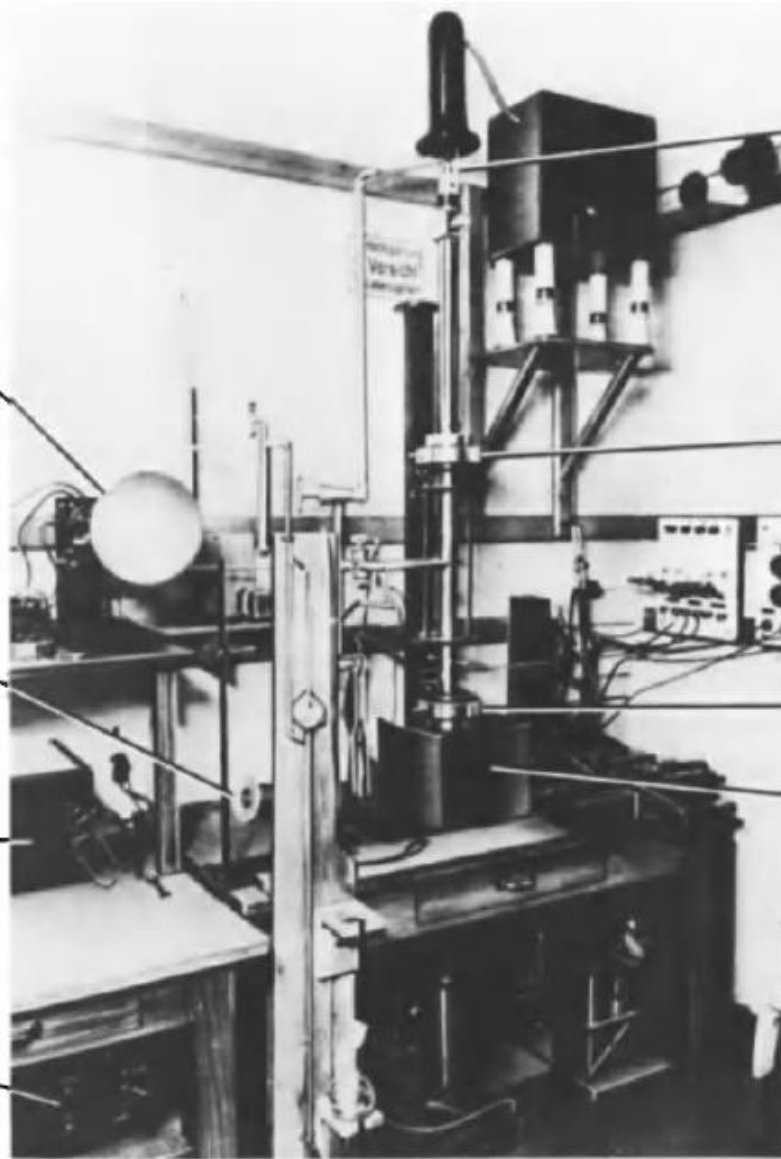


*image reproduction tube with a synchronous swept electron beam modulated by the signal of the secondary electrons (long-persistence screen)*

*a further version of an exchangeable collector unit for secondary electrons*

*wide-band amplifier for the signal of the secondary electrons*

*image raster deflection unit*



*electron directional radiator (20 to 50 keV)*

*1. reduction lens*

*deflection system (x-y direction)*

*2. reduction lens*

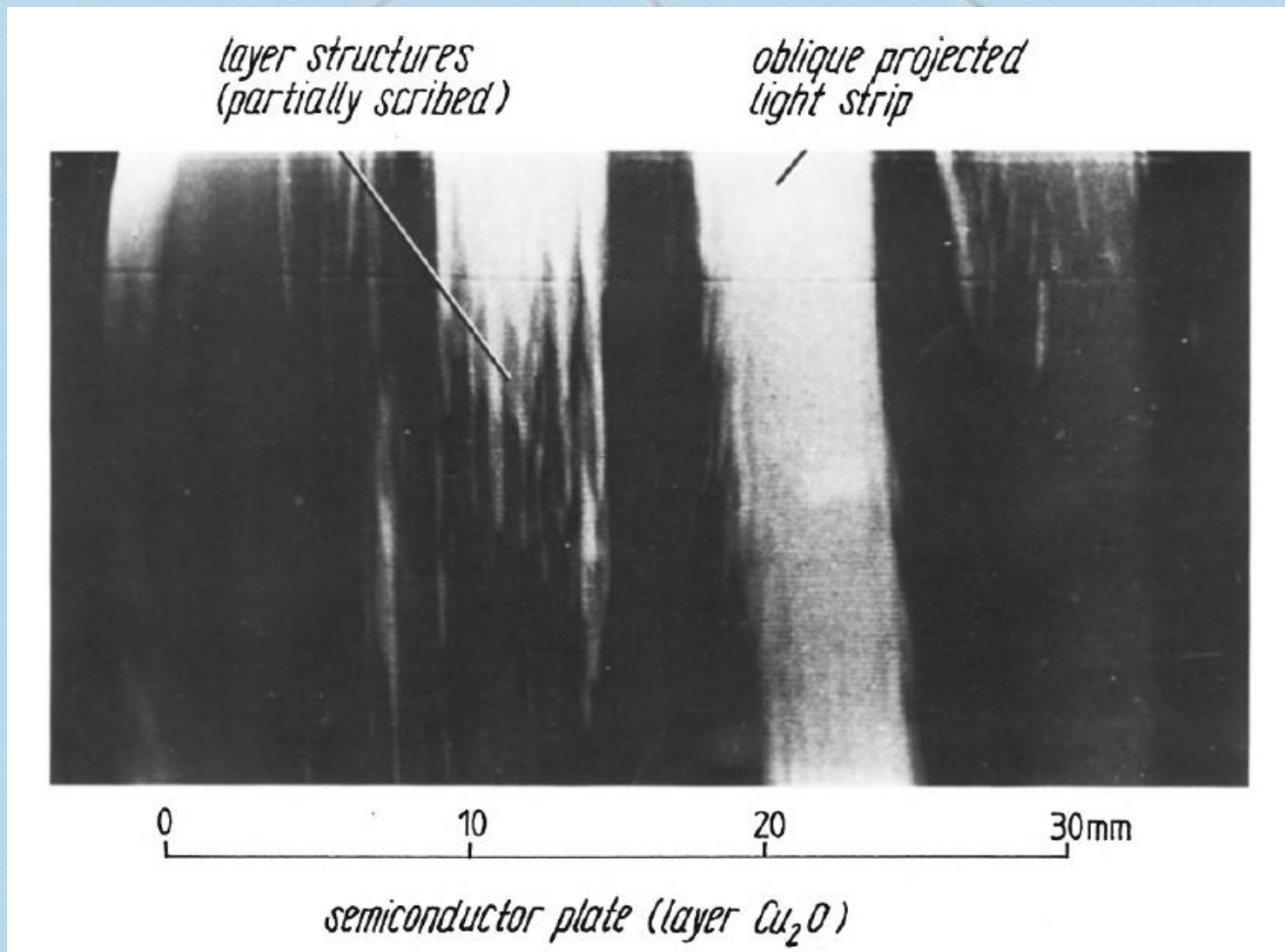
*collector unit for the secondary electrons*

První skenovací elektronový mikroskop pro zobrazování povrchů s rozlišením 100 nm. 1937,



Univerzální  
elektronový  
mikroskop pro energie  
200 až 300 keV, M.  
von Ardenne, 1941-43

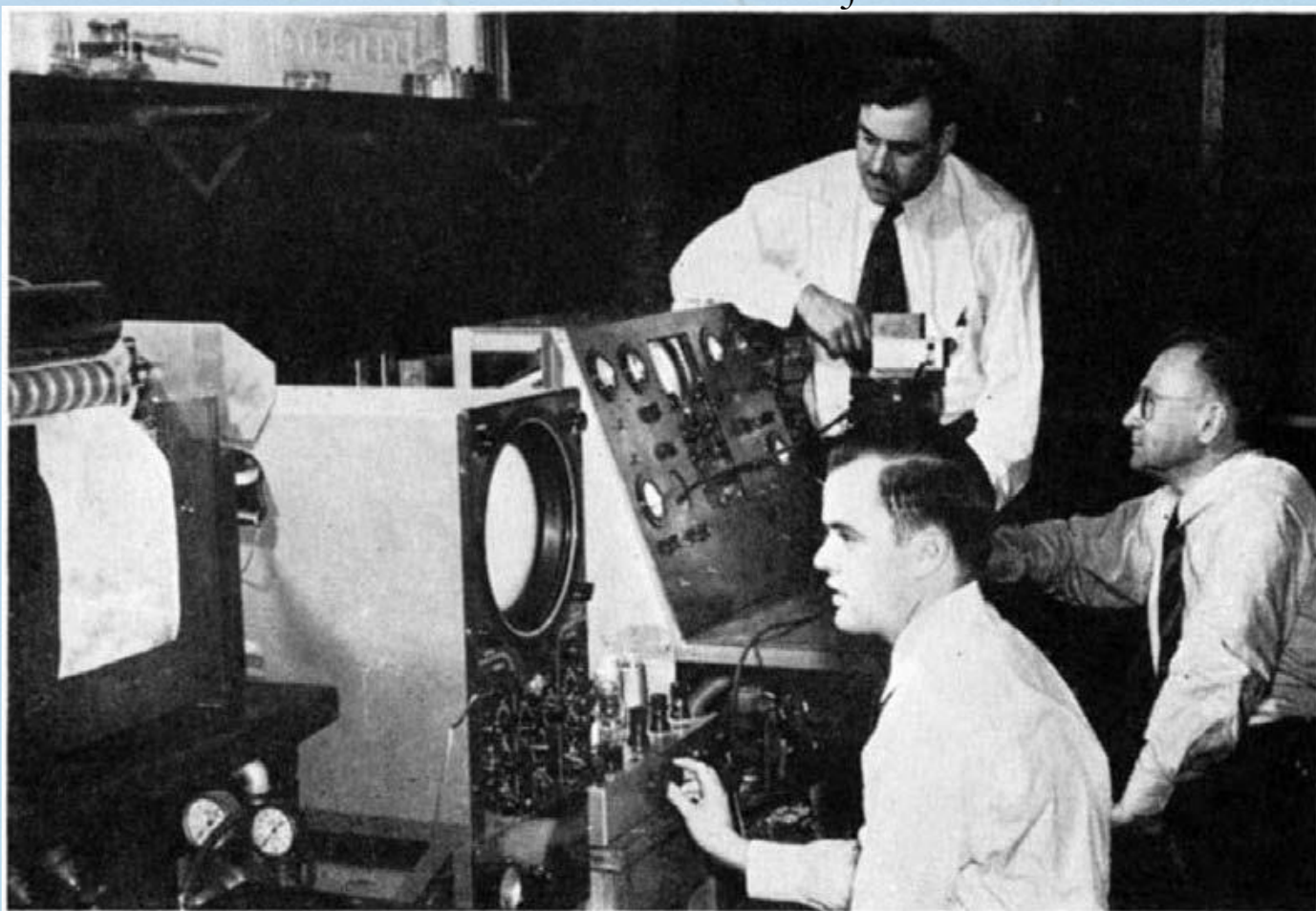
# První BSE skenovací obraz, von Ardenne





# USA - Vladimír Kosma Zworykin

James Hillier



V. K. Zworykin

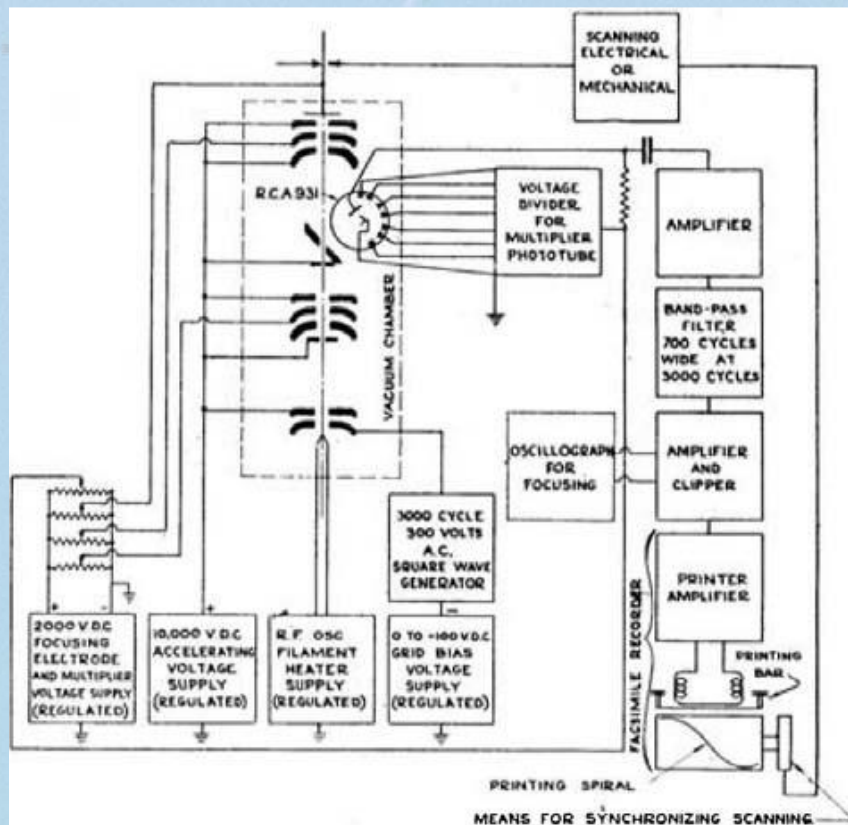
SciAm1942-111

Kopeček - U3V

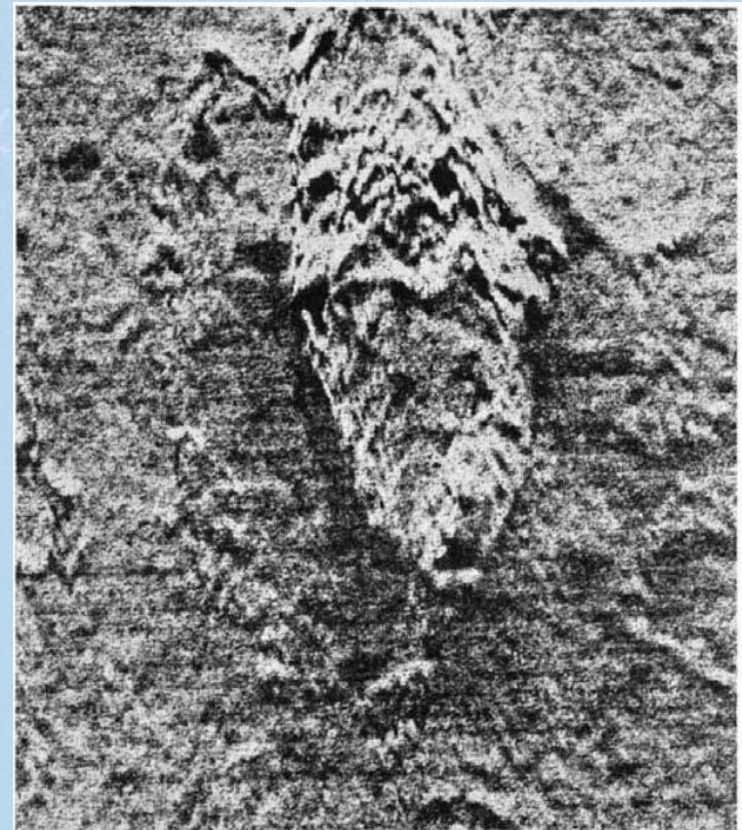
Richard L. Snyder

# USA - Vladimír Kosma Zworykin

Schéma SEM



Etched brass (leptaná mosaz)



# Washington state, USA: 1<sup>st</sup> EM outside of Germany

## Pioneers of Electron Microscopy at Washington State University and Their Work



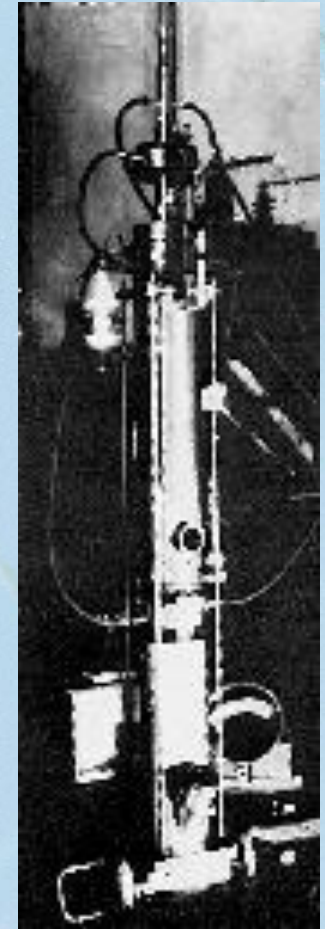
Zensaku YOSHII

*Department of Microbiology,  
Yamaguchi University School of Medicine  
Ube, Yamaguchi-ken  
Japan (755)  
(Received November 2, 1970)*

Bull. Yamaguchi Med. School, Vol. 17, Nos. 3~4, 1970

### SUMMARY

The first appearance of a transmission-type electron microscope in North America was reported to have occurred in Toronto, Canada in 1939. However, two physicists, Paul A. Anderson and Kenneth E. Fitzsimmons, had worked toward the development of electron microscopy at Washington State University in Pullman from 1931-38. Moreover, they built a prototype electron microscope before 1935 and performed many kinds of electron optical experiments. Unfortunately, their pioneering



U. of Washington did pioneering research in CFEG in 1938-45. Some of the students, e.g. Gertrude Fleming-Rempfer, later transferred to Oregon. FEI (=Field Emission Incorporated) can trace its origin directly to their efforts.

# Early History of Electron Microscopy in Czechoslovakia

ARMIN DELONG

*Institute of Scientific Instruments of the Czechoslovak Academy of Sciences  
Brno, Czechoslovakia*

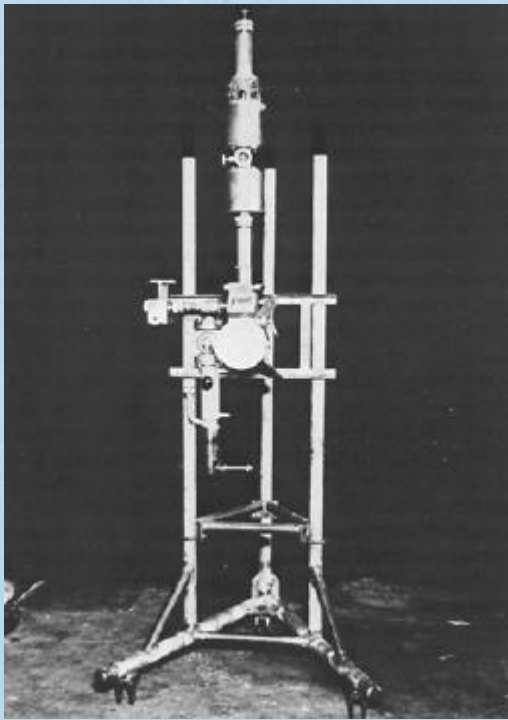
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## I. INTRODUCTION

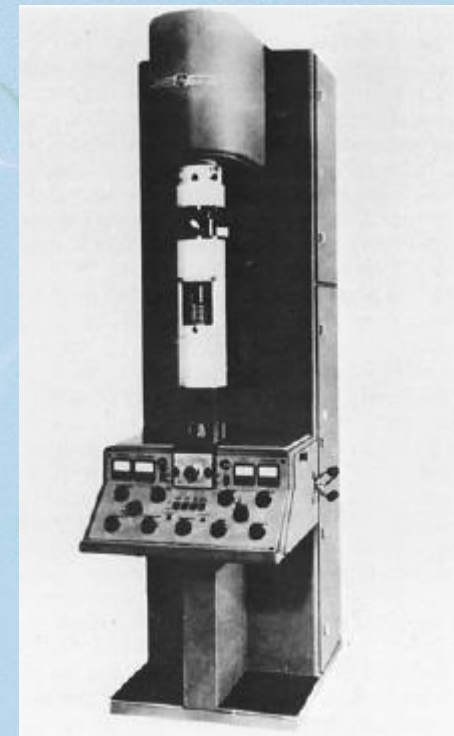
Czechoslovakia, with its 15 million inhabitants, ranges among the relatively small countries of Central Europe. On the average, there are some 0.36 ha. of soil, 0.32 ha. of woods, 0.15 automobiles, and not more than 0.000034 electron microscopes per citizen in the country. In other words, one electron microscope is shared by 30,000 people. Some 90% of available electron microscopes are of home production. This means that besides atomic power plants, locomotives, and automobiles, electron microscopes are also produced on a commercial scale in Czechoslovakia. In 30 years as many as 1800 electron microscopes of different types, from the two-stage

# Historie EM v Československu

Experimentální dvoučočkový  
elektronovo-optický mikroskop,  
1947



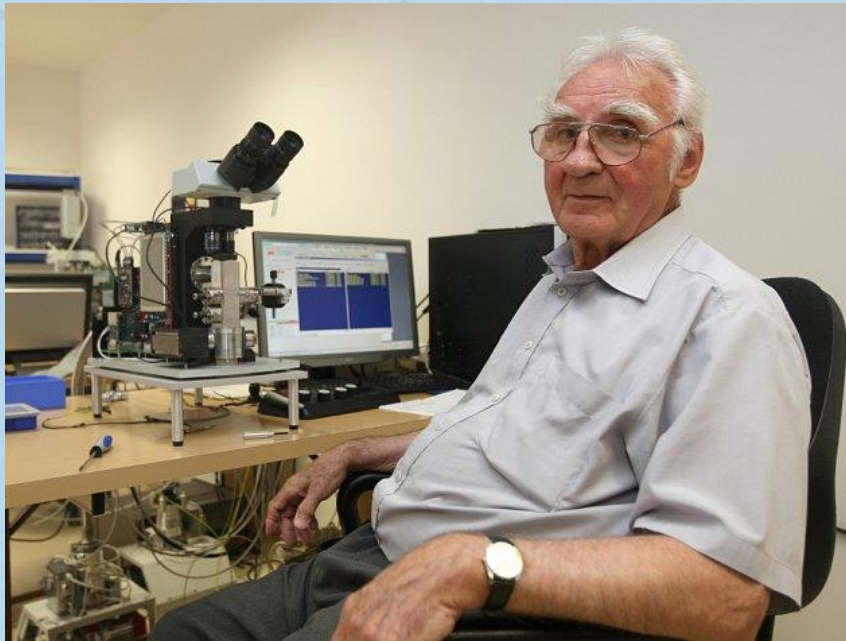
1. Elektronový mikroskop  
vyrobený v ČSR



A. Delong, V. Drahoš, L. Zobač, J. Speciální

# Armin Delong

29.1.1925 Bartovice (Ostrava) – 5. 10. 2017 Brno



<http://brnensky.denik.cz/serialy/jeden-z-nejlepsich-vedcu-sveta-bada20081013.html>

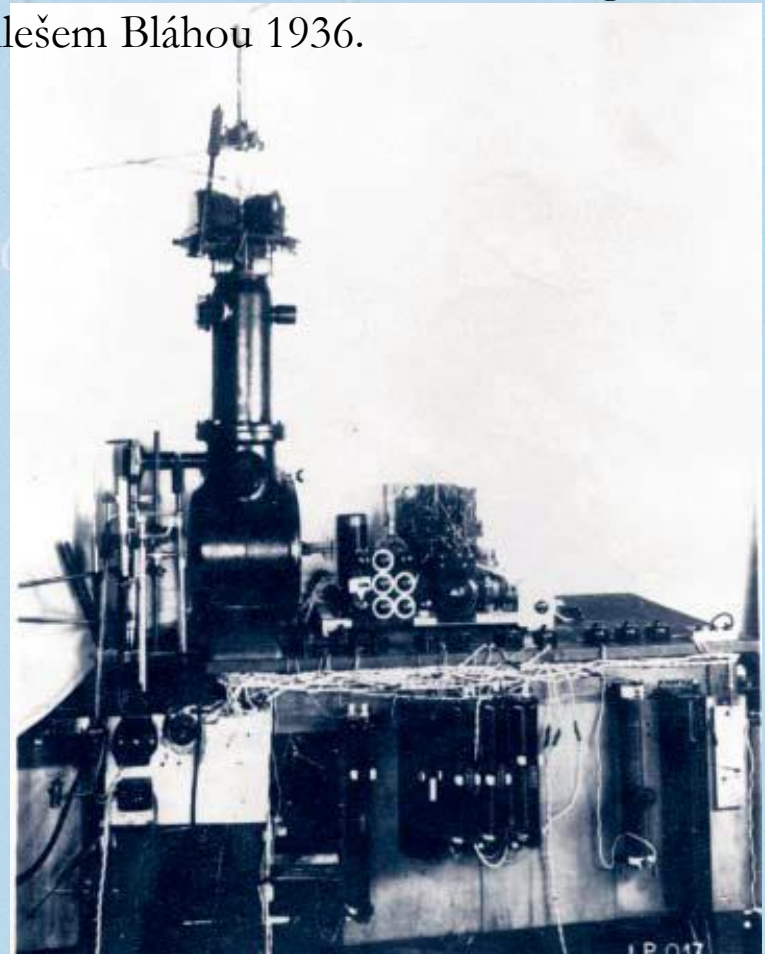
Delong Instruments: <http://www.delong.cz/>

# Delong Instruments



# Aleš Bláha (1906 – 1986)

První model elektronového oscilografu sestavený  
Alešem Bláhou 1936.



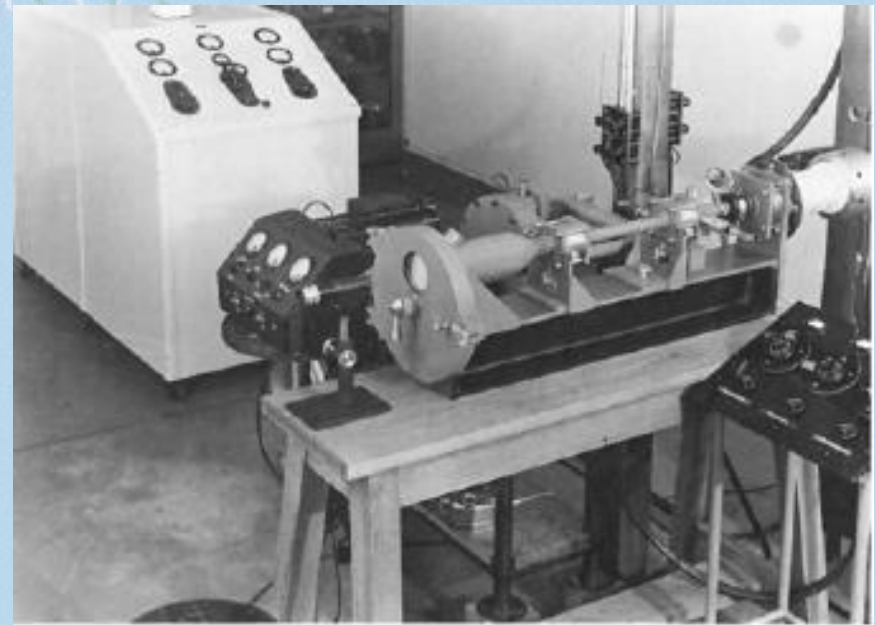


# Historie EM v Evropě

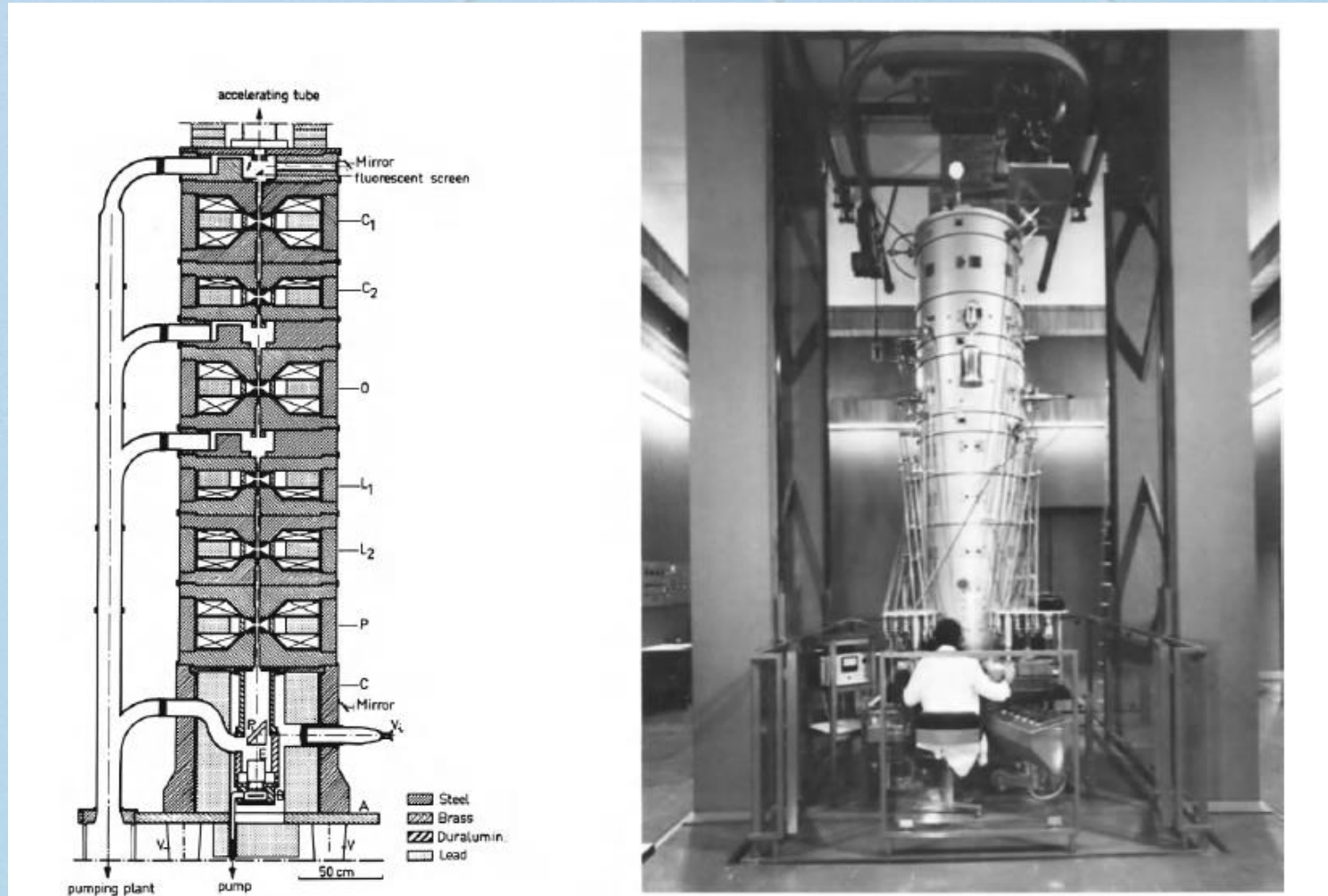
Toulouse, 1942



Siegbahn-Schönanderův  
electronový mikroskop,  
Stockholm, okolo 1943.



# Francie 3MeV SEM



G. Dupouy, F. Perrier: 12. 1960 1 MeV, 5. 1969 2 MeV

# TEM, MeV

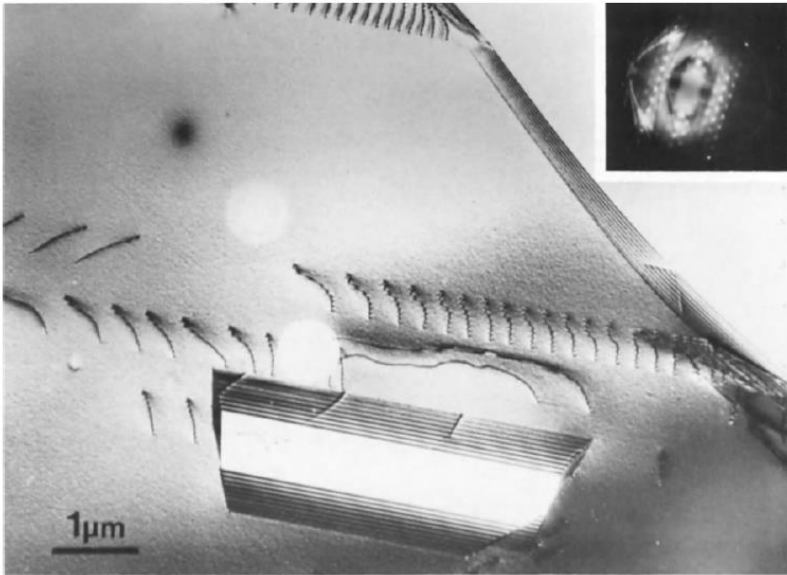


FIG. 15. Stainless steel: twin boundary dislocations; diffraction pattern from the overprinted selected area;  $V = 1$  MV.

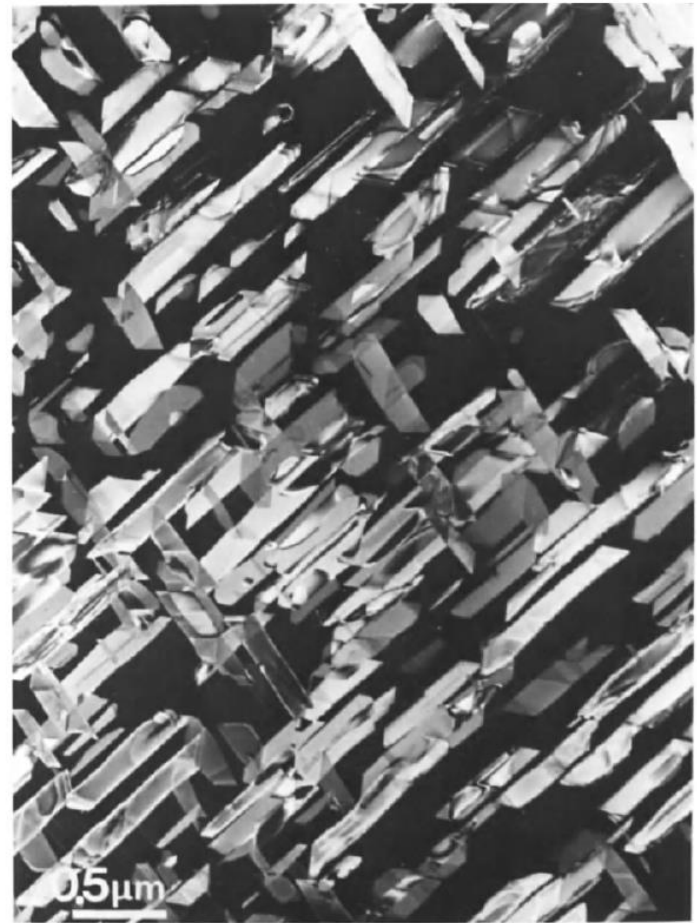


FIG. 21. First image obtained at 2 MV: precipitates in an Al-Cu alloy.

Výhoda velmi vysokého urychlovacího napětí – kontrast na magnetických doménách v Fe-Si

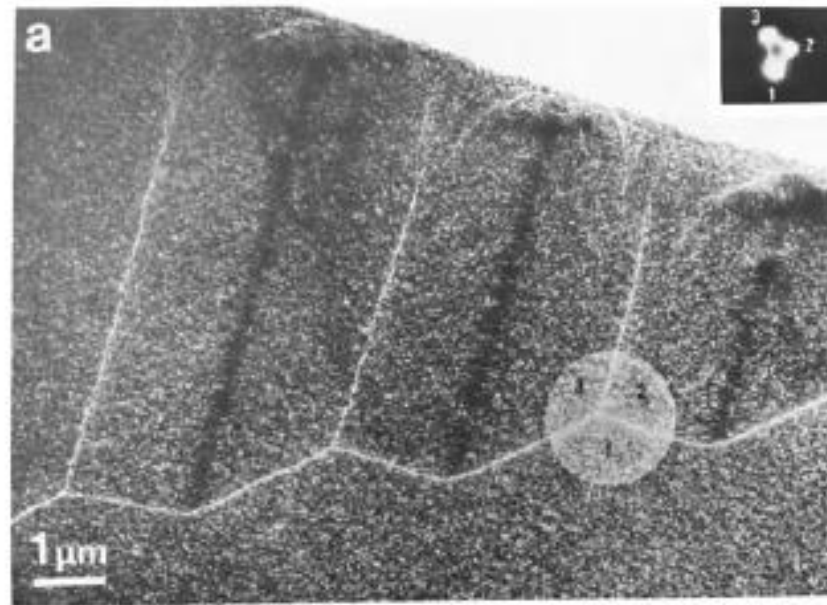


FIG. 27. (a) Defocused image of an Fe-Si alloy specimen showing three magnetic domains. (b) The domain corresponding to spot 3.

# EM v biologii

ARKIV FÖR ZOOLOGI.

BAND 40 A. N:o 6.

---

Ačkoliv to tak nevypadá, biologické aplikace stály též u zrodu SEM.

## **Examination of Brain Tumor Tissue with the Electron Microscope.**

By

**HUMBERTO FERNÁNDEZ-MORÁN.**

With 13 figures in the text.

Communicated June 4th 1947 by MANNE SIEGBAHN and HUGO THEORELL.

---

**Examination of Brain Tumor Tissue with the Electron  
Microscope.**

# Brusel, 1932, L.L. Marton (aka Ladislaus László)

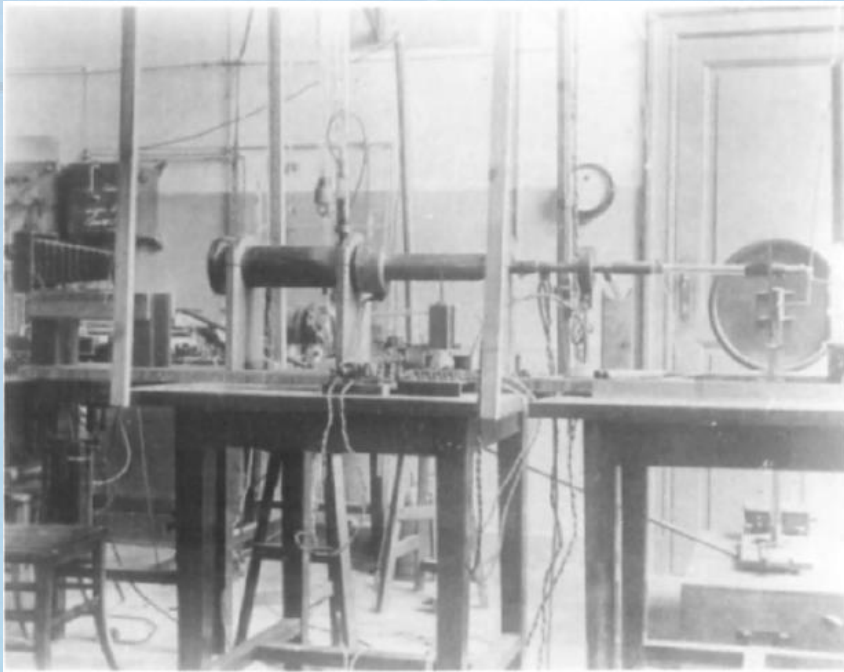


FIG. 2. Marton's No. 2 electron microscope (Brussels, 1934).

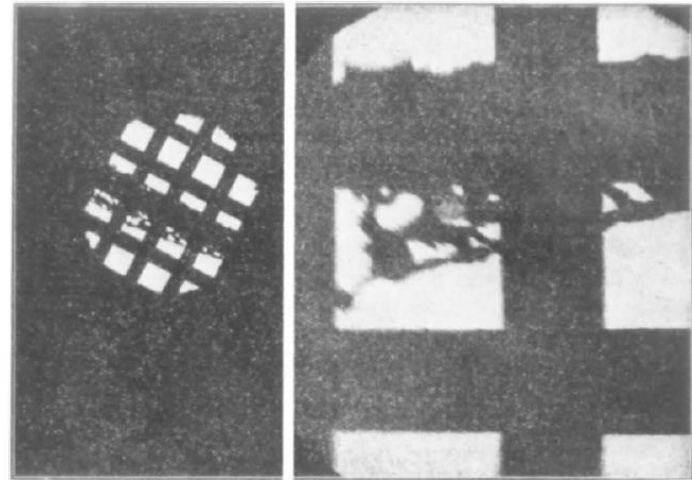
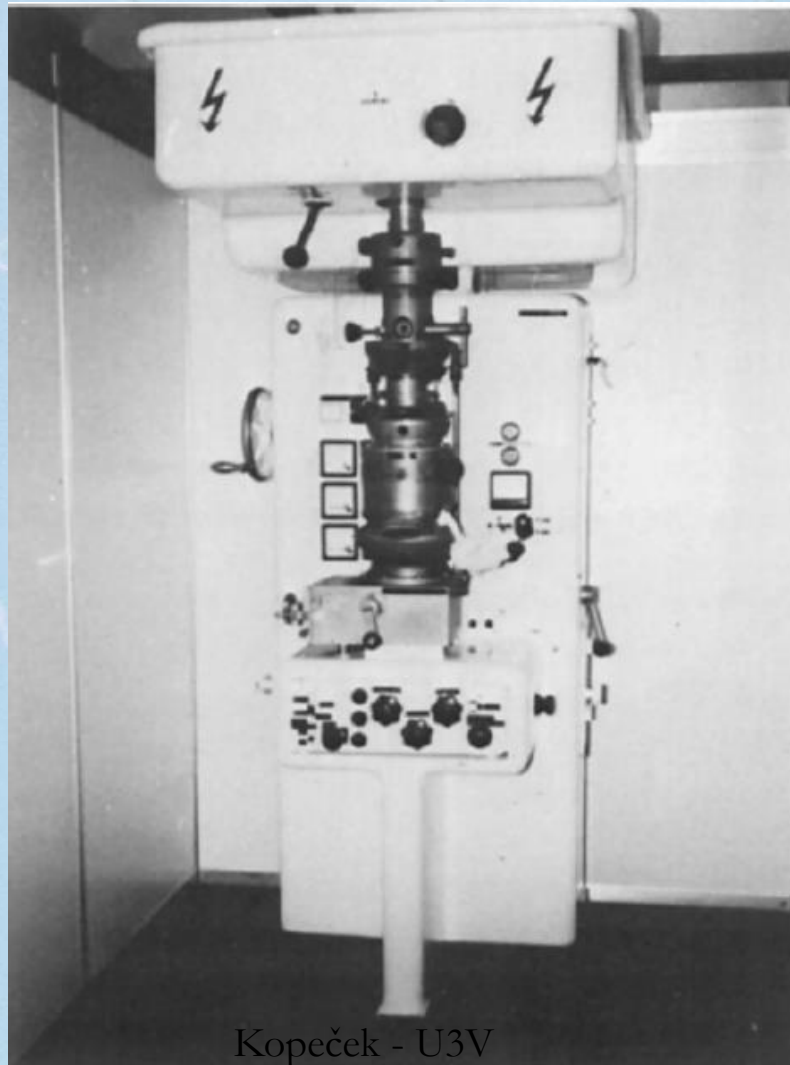
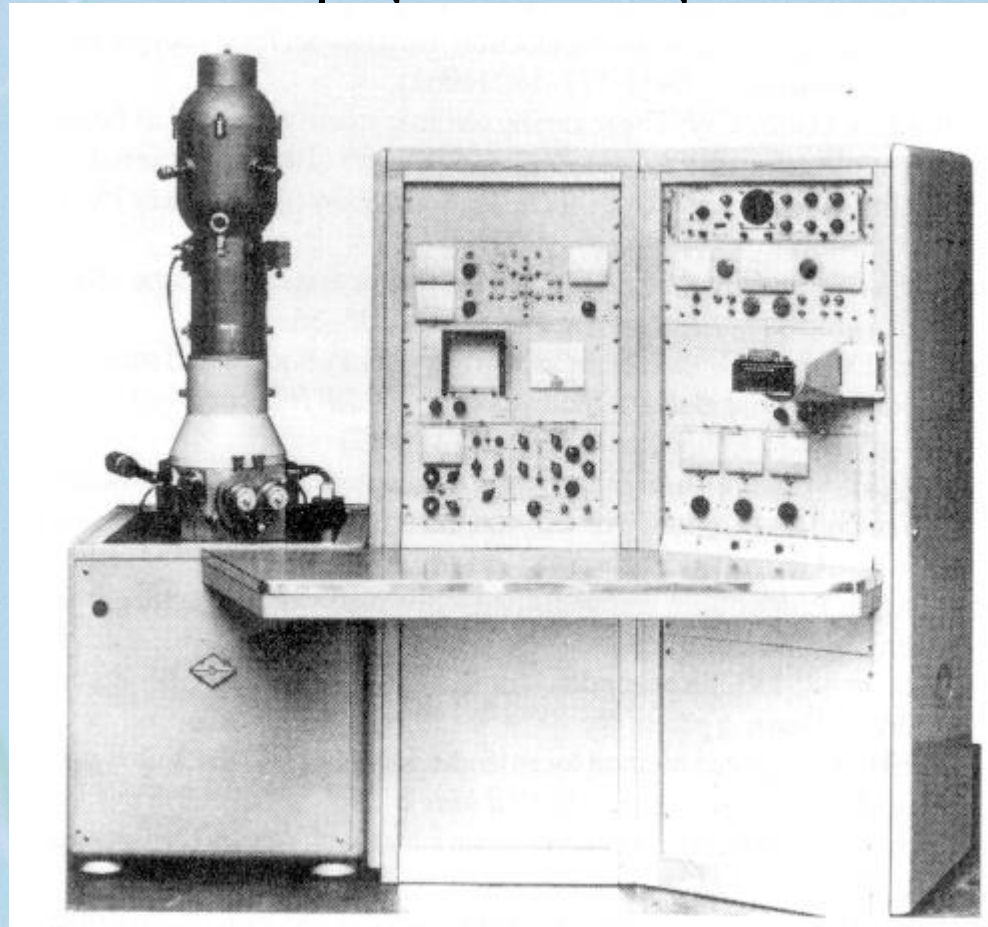


FIG. 3. First electron micrographs of biological sample (15- $\mu$ m-thick slice of *Drosera intermedia* leaf on copper net), April 4, 1934.

# První komerčně, sériově vyráběný EM, Siemens ÜM 100, 1939



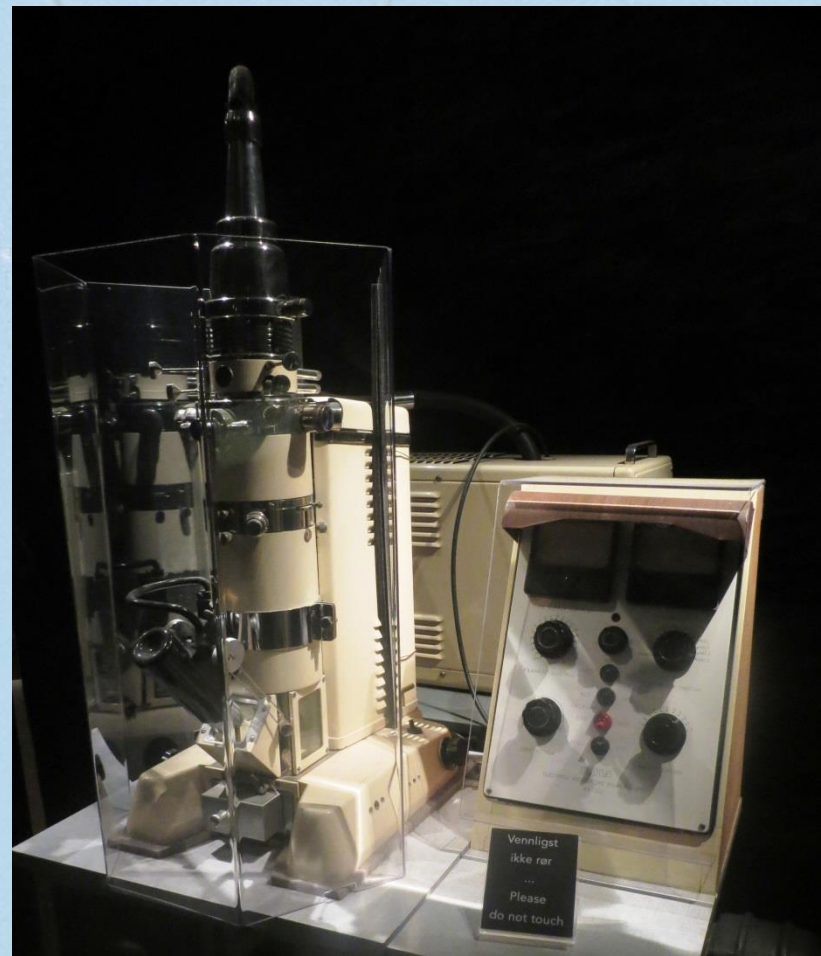
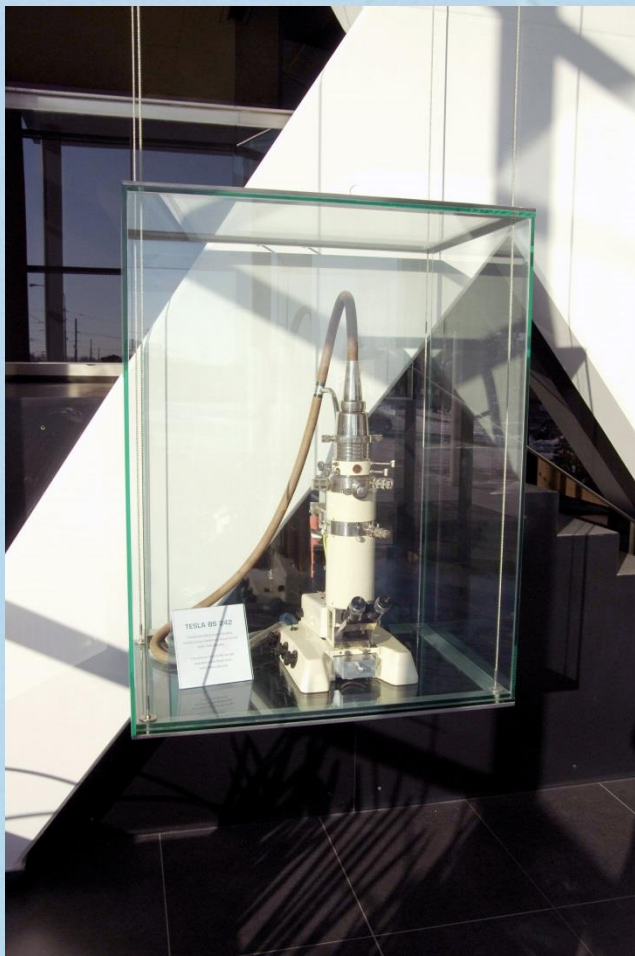
První komerčně dodaný SEM Stereoscan  
Cambridge Instrument Company do du Pont  
Comp., U.S.A., 1965



*1953  
rok  
výroby!*



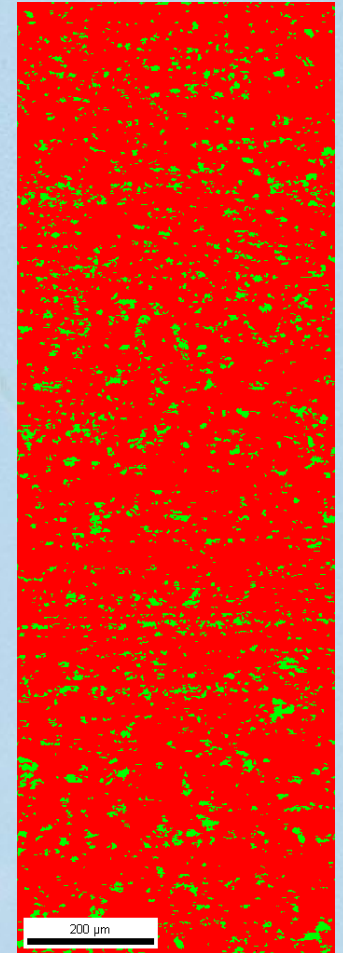
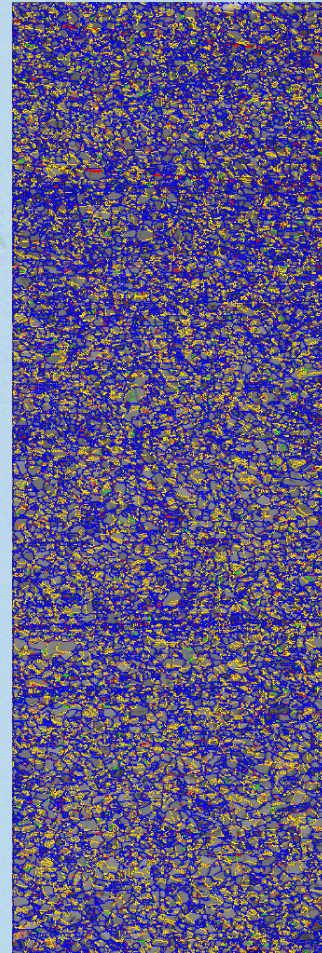
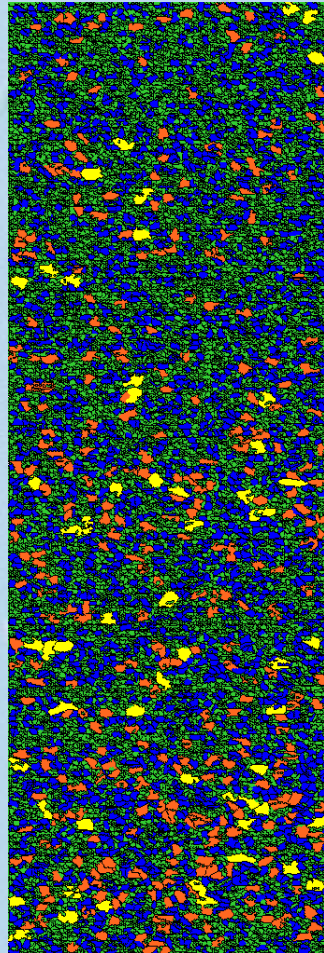
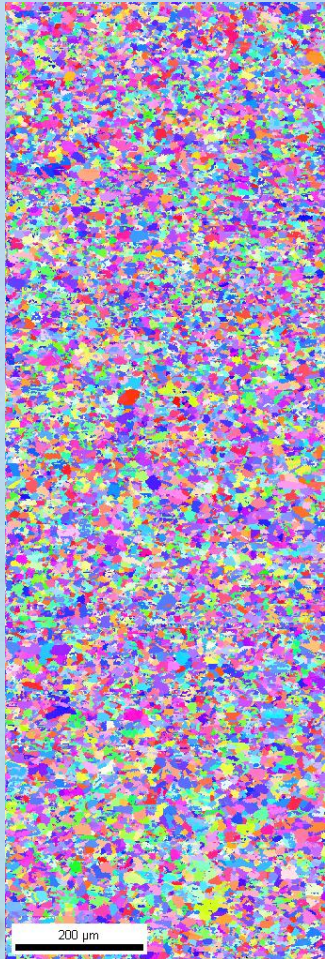
# Tesla BS 242 oceněný 1958 v Bruselu



# Další, „analytické“ metody doprovázející v instalacích SEM

- EBSD (orientace)
  - EDS (složení)
- CL (složení, typ vazby)
- EBIC (typ vodivosti)

# Ocel AISI304 2 min žíhání 1000 °C



# Jaké údaje nám EBSD dává?

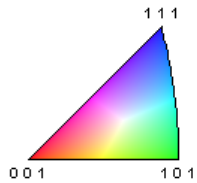
## Orientaci krystalové mříže



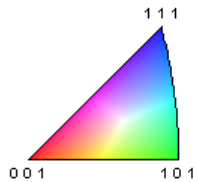
Gray Scale Map Type: <none>

Color Coded Map Type: Inverse Pole Figure [001]

Austenite



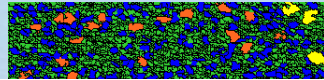
Ferrite



Boundaries: <none>



## Rozložení velikostí zrn



Gray Scale Map Type: <none>

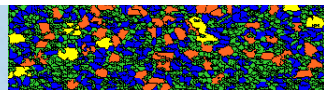
Color Coded Map Type: Grain Size

	Min	Max	Total Fraction	Partition Fraction
	0	20	0.561	0.561
	20	50	0.303	0.303
	50	100	0.105	0.105
	100	500	0.031	0.031
	500	1000	0.000	0.000
	1000	50000	0.000	0.000

Boundaries: Rotation Angle

	Min	Max	Fraction	Number	Length
	15°	180°	0.950	243496	28.12 cm

\*For statistics - any point pair with misorientation exceeding 2° is considered a boundary  
total number = 256201, total length = 29.58 cm)



## Vlastnosti hranic zrn

Gray Scale Map Type: Image Quality  
47.449...3909.13 (47.449...3909.13)

Color Coded Map Type: <none>

Boundaries: Rotation Angle

	Min	Max	Fraction	Number	Length
	2°	5°	0.020	5193	6.00 mm
	5°	10°	0.012	3060	3.53 mm
	15°	180°	0.950	243496	28.12 cm
	10°	15°	0.017	4452	5.14 mm

Boundaries: CSL

	Sigma	Tolerance	Fraction	Volume	MC
	3	8.66	0.239	0.0176	13
	9	5.00	0.025	0.0102	2.4
	5	6.71	0.006	0.0123	0.6
	7	5.67	0.006	0.0099	0.6
	11	4.52	0.006	0.0075	0.7
	13a	4.16	0.002	0.0029	0.6
	13b	4.16	0.003	0.0039	0.6
	15	3.87	0.005	0.0094	0.6
	17a	3.64	0.001	0.0020	0.4
	17b	3.64	0.003	0.0039	0.7
	19a	3.44	0.002	0.0033	0.6
	19b	3.44	0.002	0.0022	0.72
	21a	3.27	0.001	0.0019	0.66
	21b	3.27	0.003	0.0057	0.52
	23	3.13	0.002	0.0050	0.45
	summary	-	0.305	0.0976	3.13

\*For statistics - any point pair with misorientation exceeding 2° is considered a boundary  
total number = 256201, total length = 29.58 cm)

## Fázové složení

Gray Scale Map Type: <none>

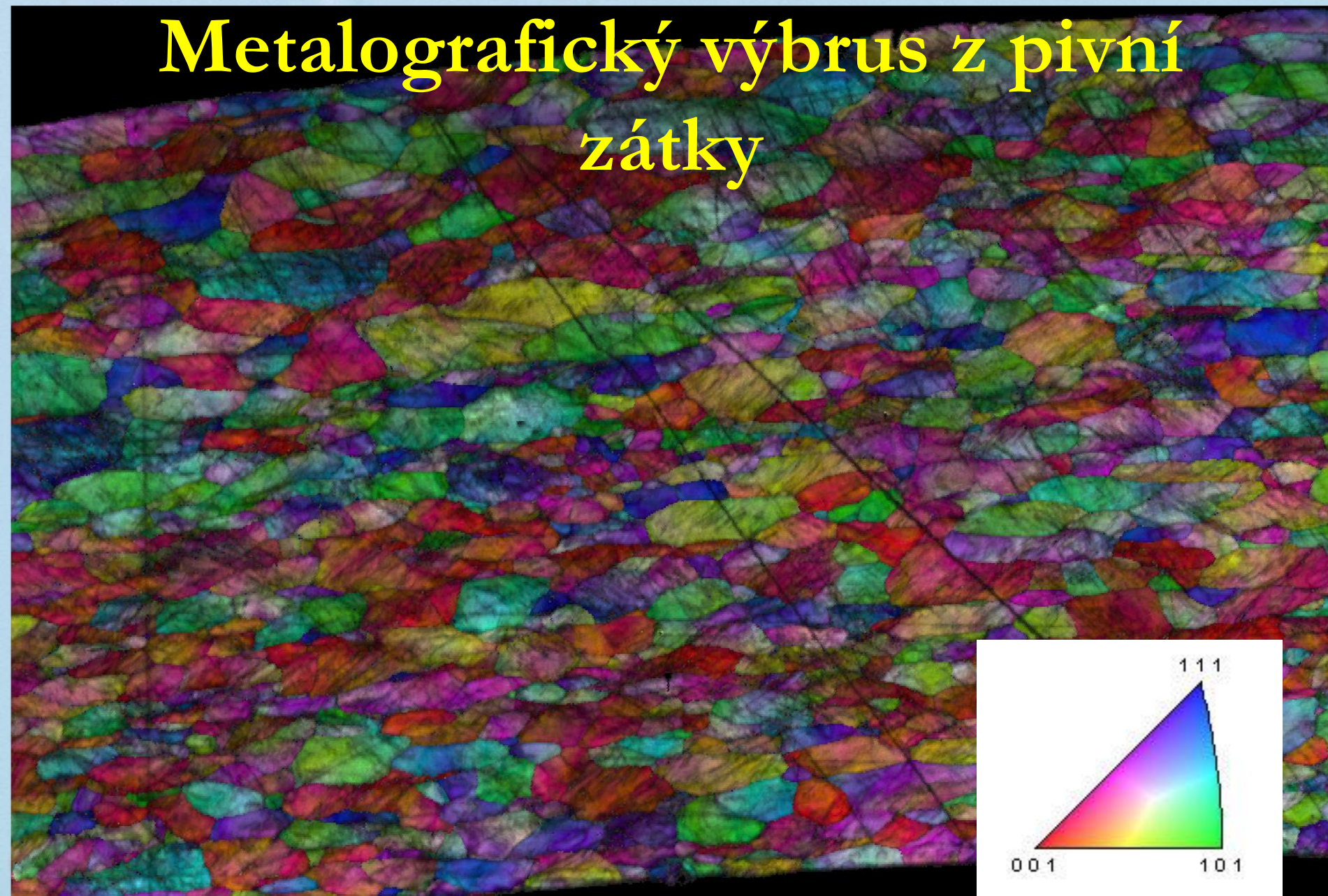
Color Coded Map Type: Phase

	Phase	Total Fraction	Partition Fraction
	Austenite	0.909	0.909
	Ferrite	0.091	0.091

Boundaries: <none>

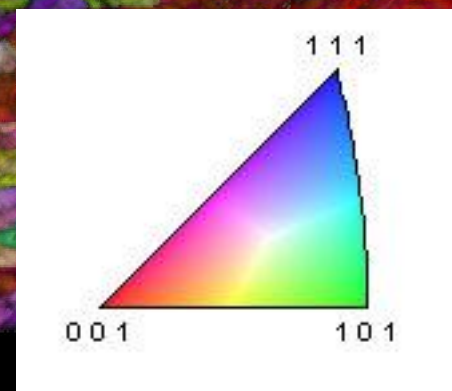
536	618.919 microns
405	467.654 microns
323	372.968 microns
755	871.799 microns
579	668.571 microns

# Metalografický výbrus z pivní zátky



100 um

Phase Map



# Metalografický výbrus z pivní zátky



Rekrystalizace – změna barvy (orientace) v zrně

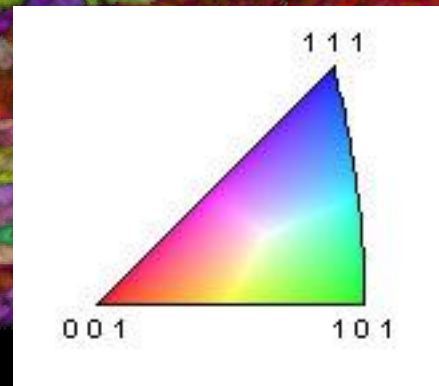


Směr válcování  
Prodloužená zrna

škrábance



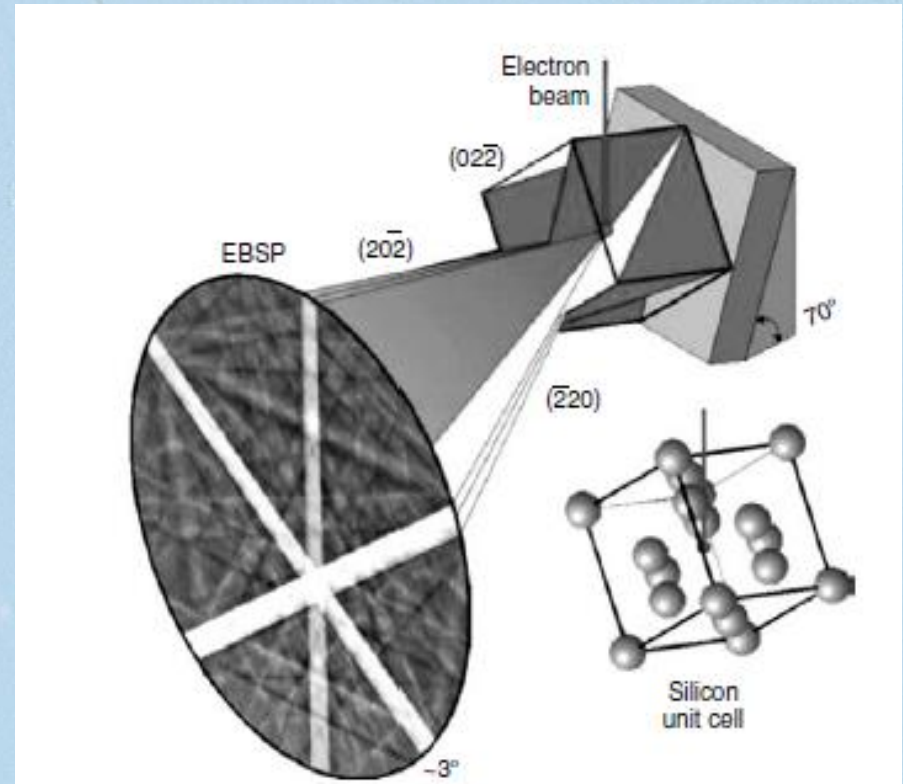
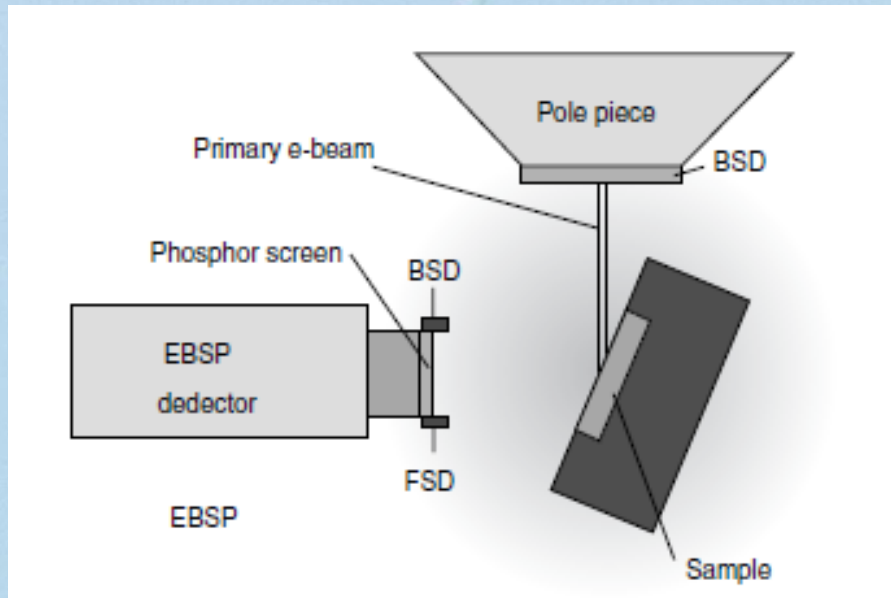
Skluzové pásy  
Lokalizovaná deformace



100 um

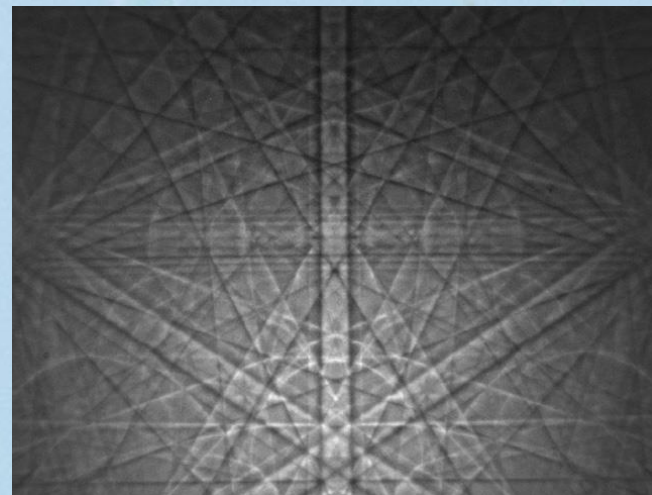
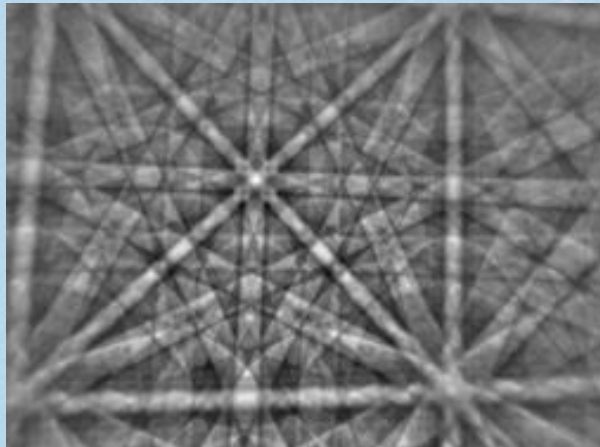
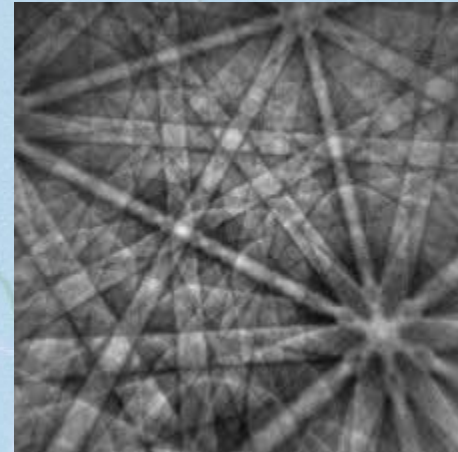
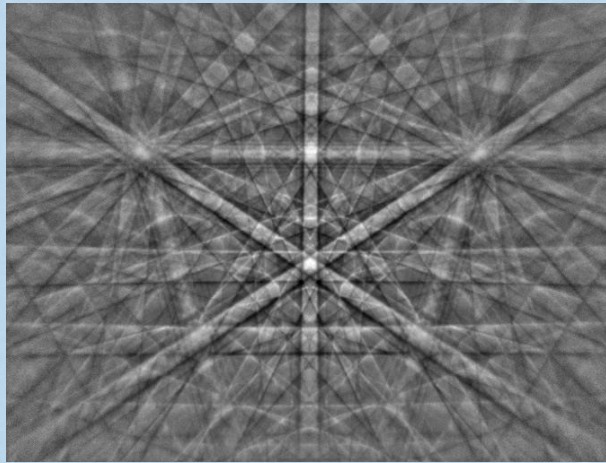
Phase Map

# EBSD – principy a pozice detektorů



Scanning Microscopy for Nanotechnology Techniques and Applications - Weilie Zhou, Zhong Lin Wang (Eds), Springer Science+Business Media, LLC, 2006

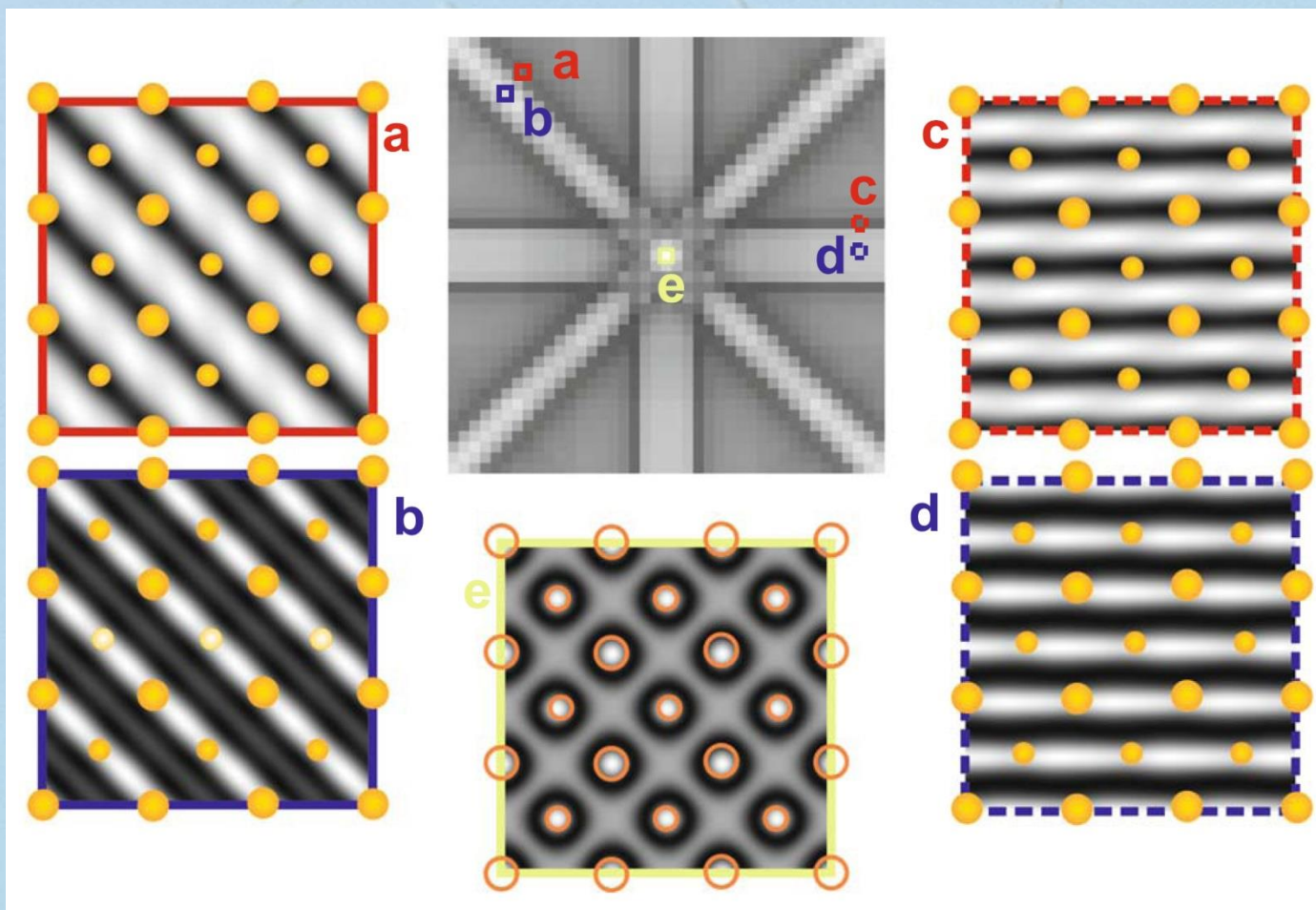
# Kikuchiho obrazce





# Modelování EBSP obrazců

9-i svazkový model

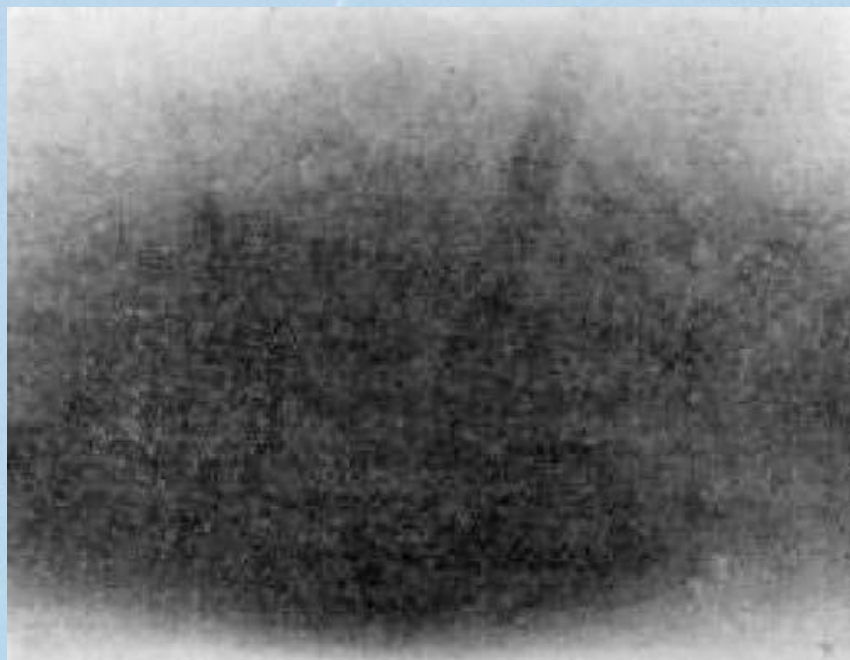


# Krátká historie EBSD

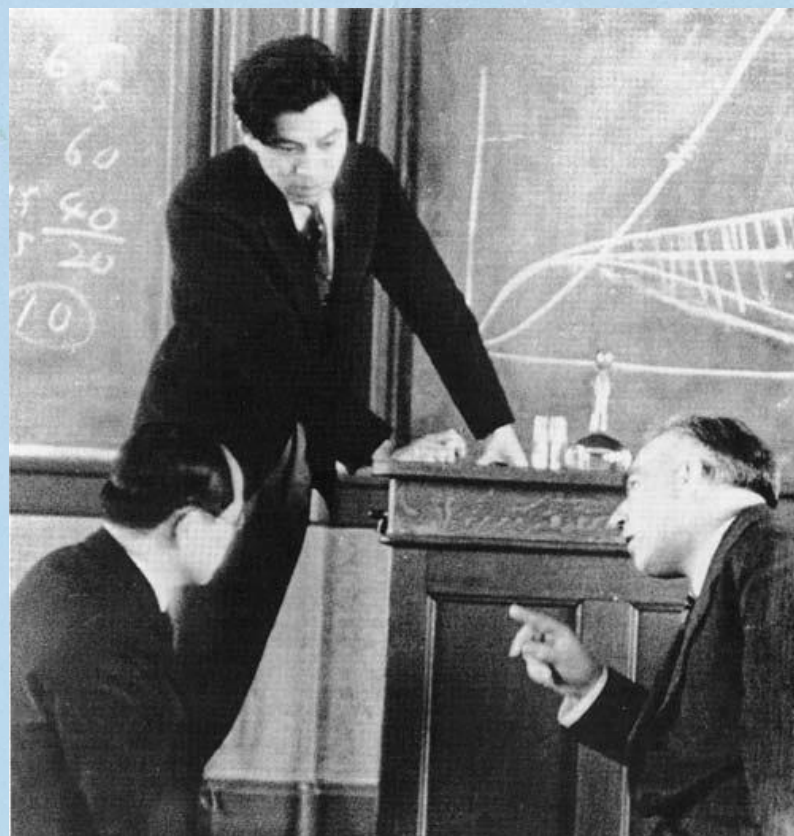
- 1928 Shoji Nishikawa, Seishi Kikuchi – kalcit, 50 KeV elektrony z plynového z výboje
- 1972-1979 John Venables
- 1979-1988 Bristol group – computerisation (D.J. Dingley)
- 1988-2006 OIM (Yale Univ, TSL, HKL)
- 1992 Použití Houghovy transformace pro vyhodnocení Kikuchiho obrazců
- 2006-2012 HR-EBSD (Oxford Univ., BLG, Saint Etienne Univ, Brigham Univ)

# Něco z historie metody EBSD

Vůbec první Kikuchiho linie pozorované Kikuchim 1927 v kalcitu.



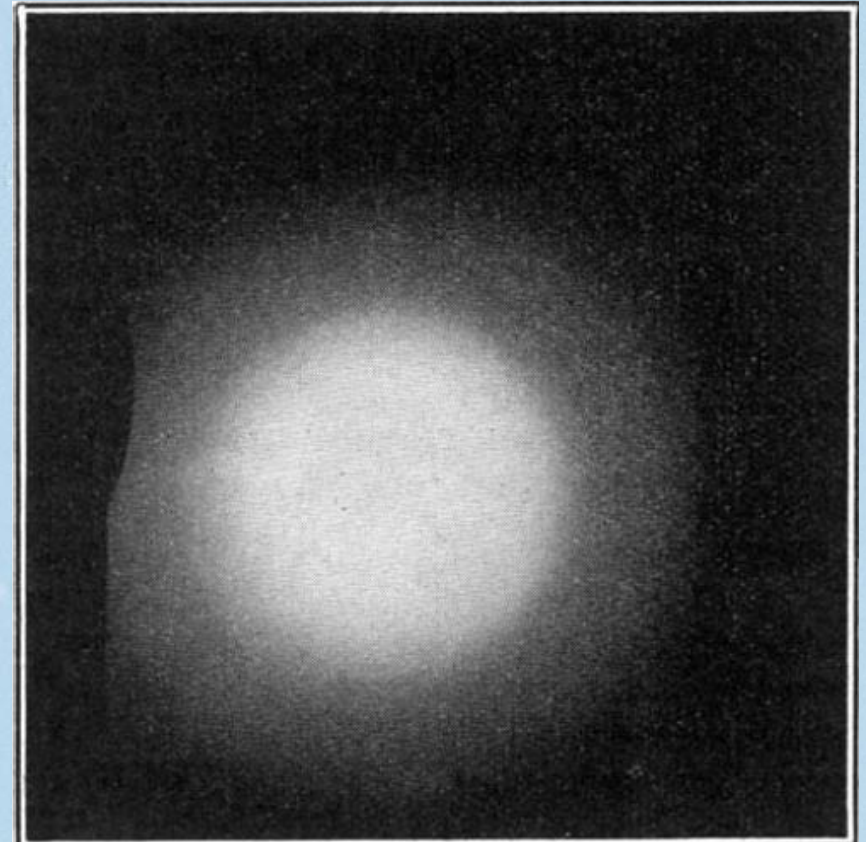
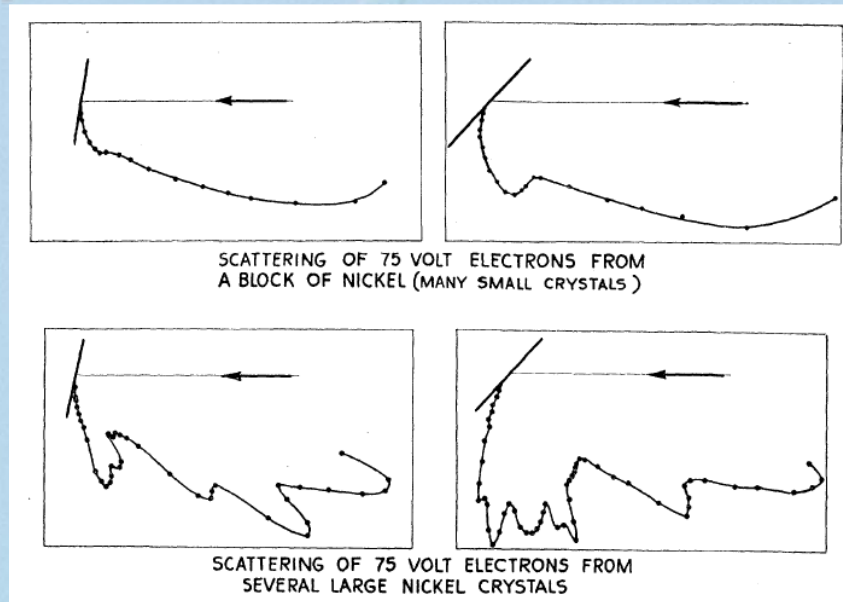
Seishi Kikuchi (*standing*).



# Difrakce elektronů

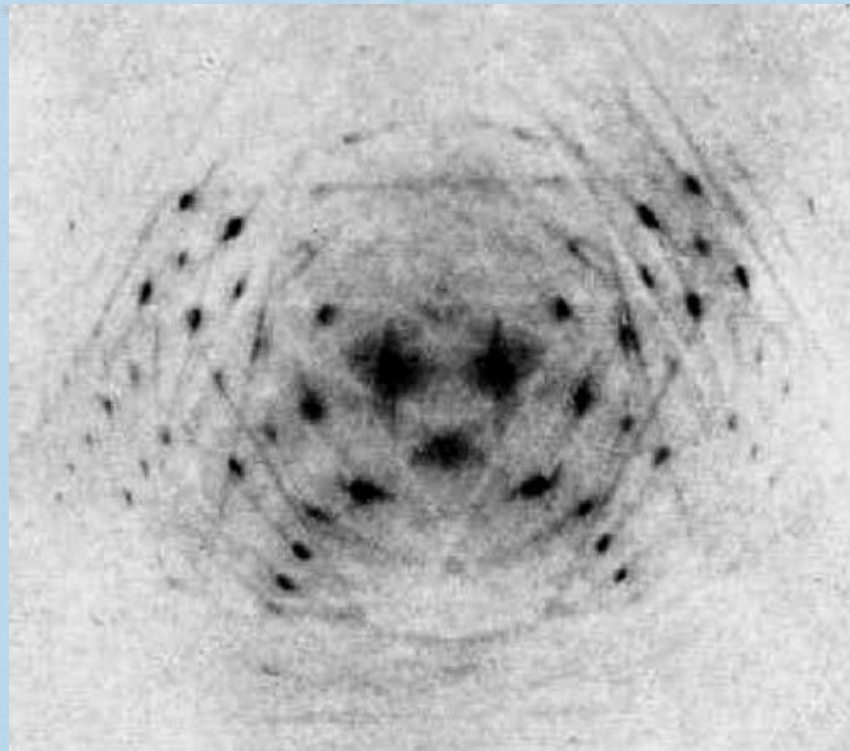
Nobelova cena 1937, za objevy v roce 1927

Clinton Joseph Davisson a George Paget Thomson

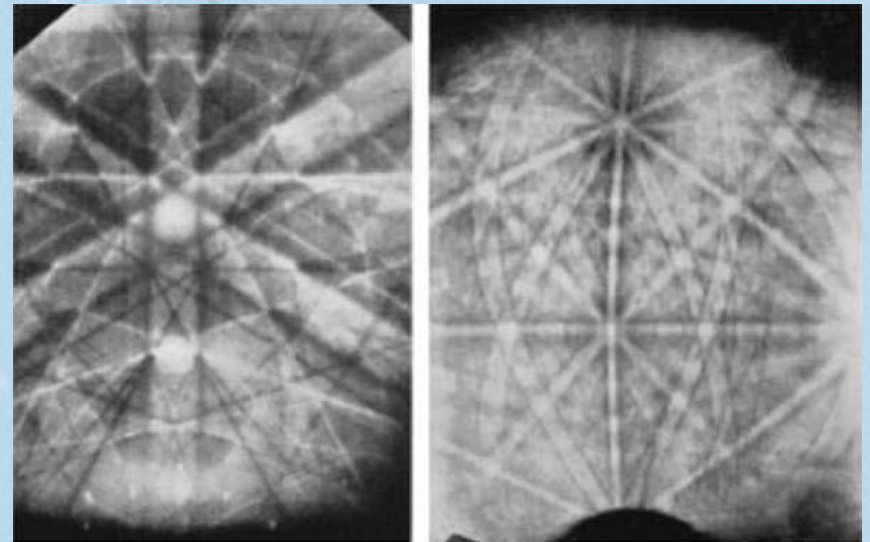


# Něco z historie metody EBSD

Kikuchi P-pattern from mica.



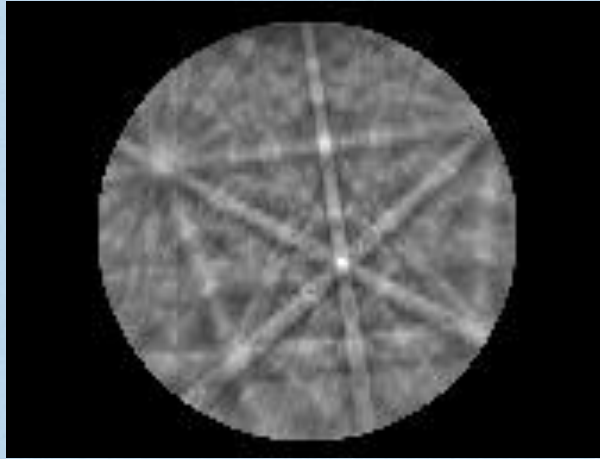
Boersch 1937 Iron Kikuchi patterns.



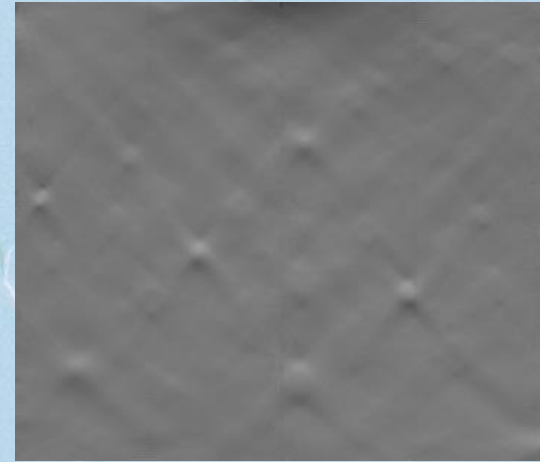
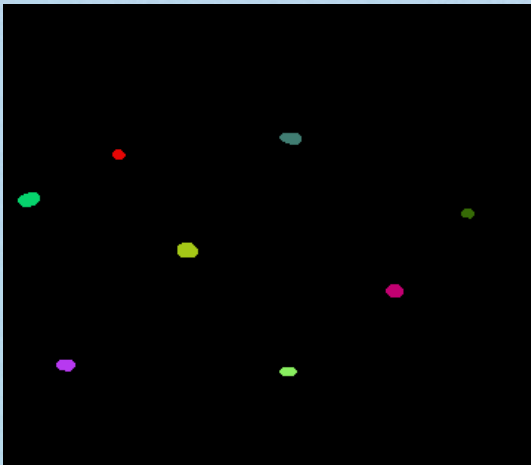
# Jak se Kikuchiho linie vyhodnocují?

Body 1 - 2

Kikuchiho obrazec



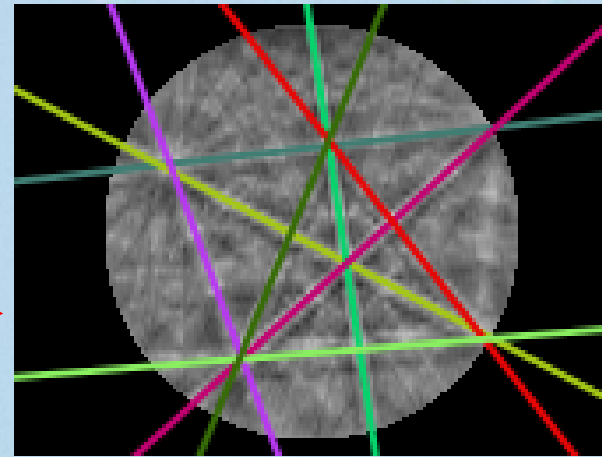
Nalezení píků a stanovení jejich intenzity



Houghova transformace



Nalezení Kikuchiho pásů



# Houghova transformace – od 1992

Jensen, Jeppe. "Hough Transform for Straight Lines". *Mini-project in Image Processing, 7th semester 2007*.  
[http://www.cvmt.dk/education/teaching/e07/MED3/IP/hough\\_lin.es.pdf](http://www.cvmt.dk/education/teaching/e07/MED3/IP/hough_lin.es.pdf).

Retrieved 16 December 2011.

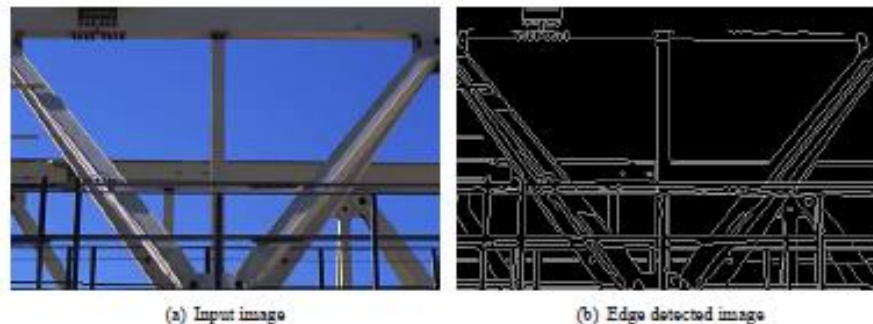


Figure 2: An example with an input image and the result of the edge detection, using the Canny edge detection.

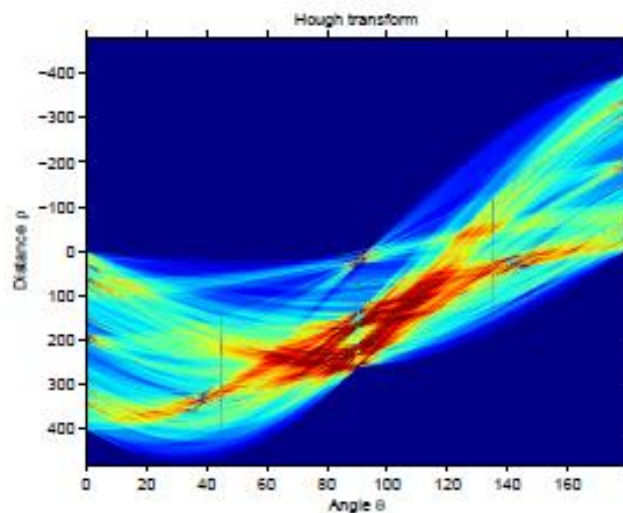
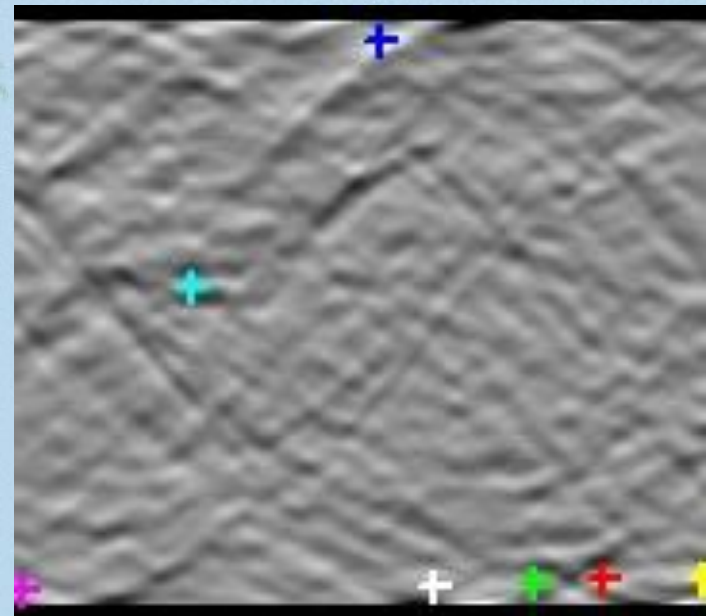


Figure 3: The Hough space of the input image in Figure 2. The dark red points are the points with the highest number of intersections. Many dark red points are around 90 degrees, i.e. that the image has many horizontal lines.

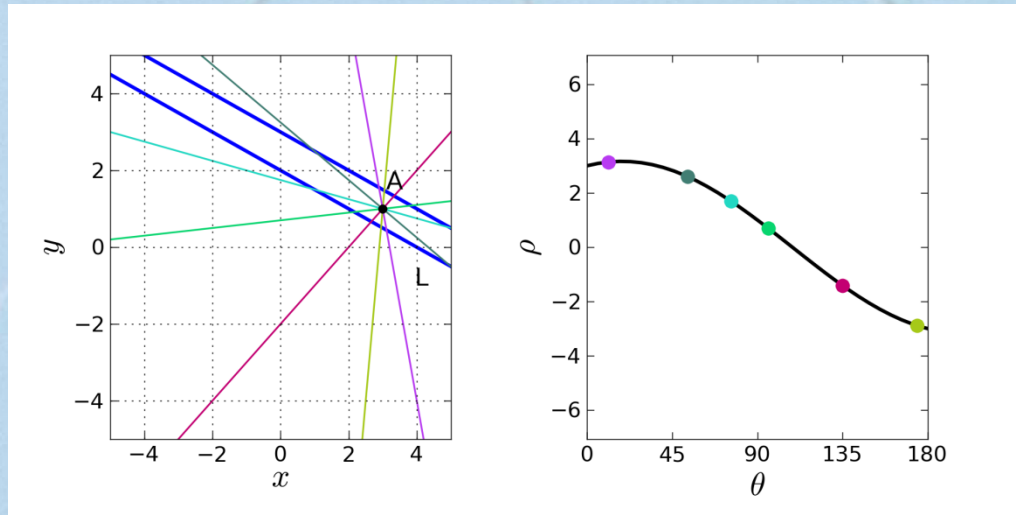
Převádí kartézské souřadnice na polární a tak Kikuchiho pásy na píky, jejichž detekce je snadná. Je speciálním případem Radonovy transformace (tomograf). Dříve probíhalo vyhodnocení každého bodu ručně prokládáním čar.

# Kikuchiho linie – zpět ke kořenům

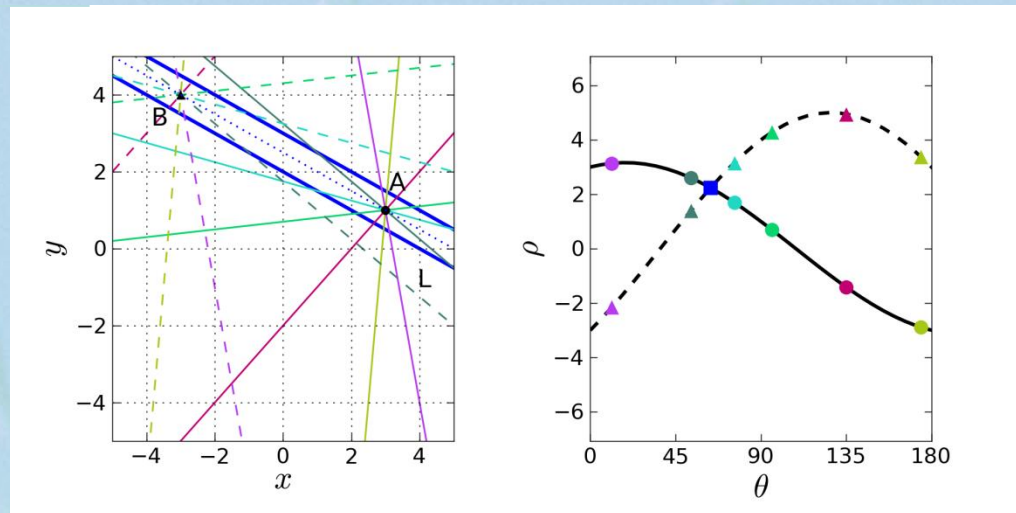




# Houghova transformace



Houghova transformace – převádí čáry (Kikuchiho linie) na sinusoidy



# Houghova transformace

Slouží k transformaci Kikuchiho pásů na píky. Pás – přímku si parametrizujeme v polárních souřadnicích, načež sečteme intenzitu „po přímce“.

$$r = x \cdot \cos \theta + y \cdot \sin \theta$$

$$R(\rho, \theta) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y) \cdot \delta(\rho - x \cdot \cos \theta - y \cdot \sin \theta) dx dy$$

$\delta$ -funkce zajišťuje nenulovost na přímce.

# Houghova transformace

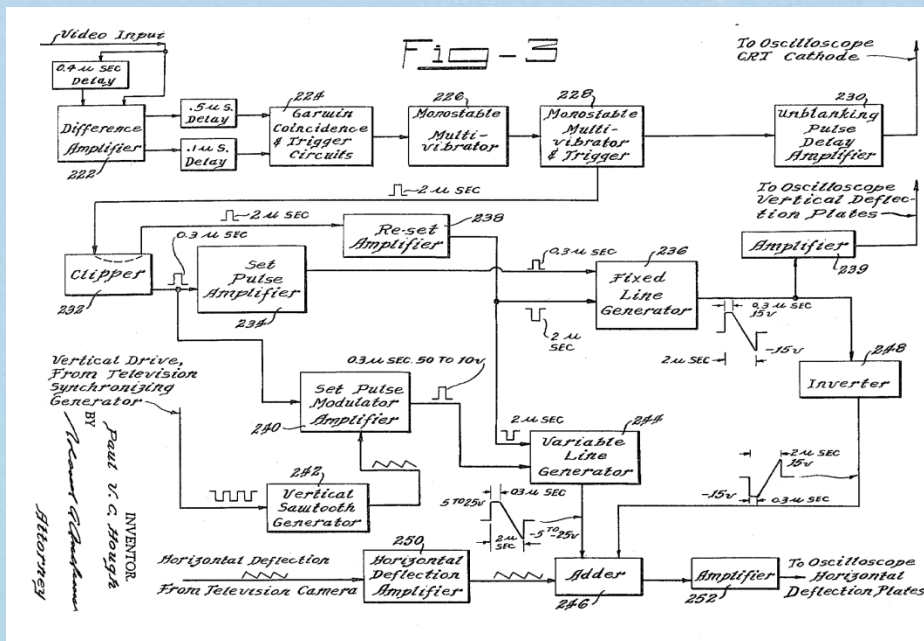
Paul V. C. Hough

Patent US 3069654 A; 18. prosinec 1962

<http://www.google.com/patents/US3069654>

Patentoval až do roku 2004 (metody snímání v AFM – 3 patenty)

John Simon Guggenheim fellow 1959 a 1973



Stanley R. Deans, *Hough Transform from the Radon Transform*, IEEE trans. PAMI3-2-185

# Radonova transformace

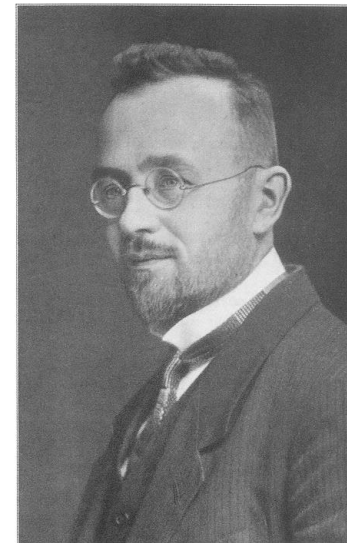
Je zobecněním Houghovy transformace a také je starší.

Johann Radon se narodil 16. prosince 1887 v Děčíně a v letech 1897-1905 navštěvoval gymnázium v Litoměřicích. Od r. 1946 působil Radon jako profesor na vídeňské univerzitě, kde vykonával krátce funkci děkana a později v r. 1954 rektora. Zemřel 25. května 1956. (PokrokyMFA33-5-5)

Allan MacLeod Cormack (fyzik), Godfrey Hounsfield (elektroinženýr) – Nobelova cena za medicínu 1979 za CT tomograf

(PokrokyMFA29-4-196, A.M. Cormack, JAP34-9-2722)

$$I = I_0 \exp \left[ - \int_L g(s) ds \right],$$



*J. Radon*

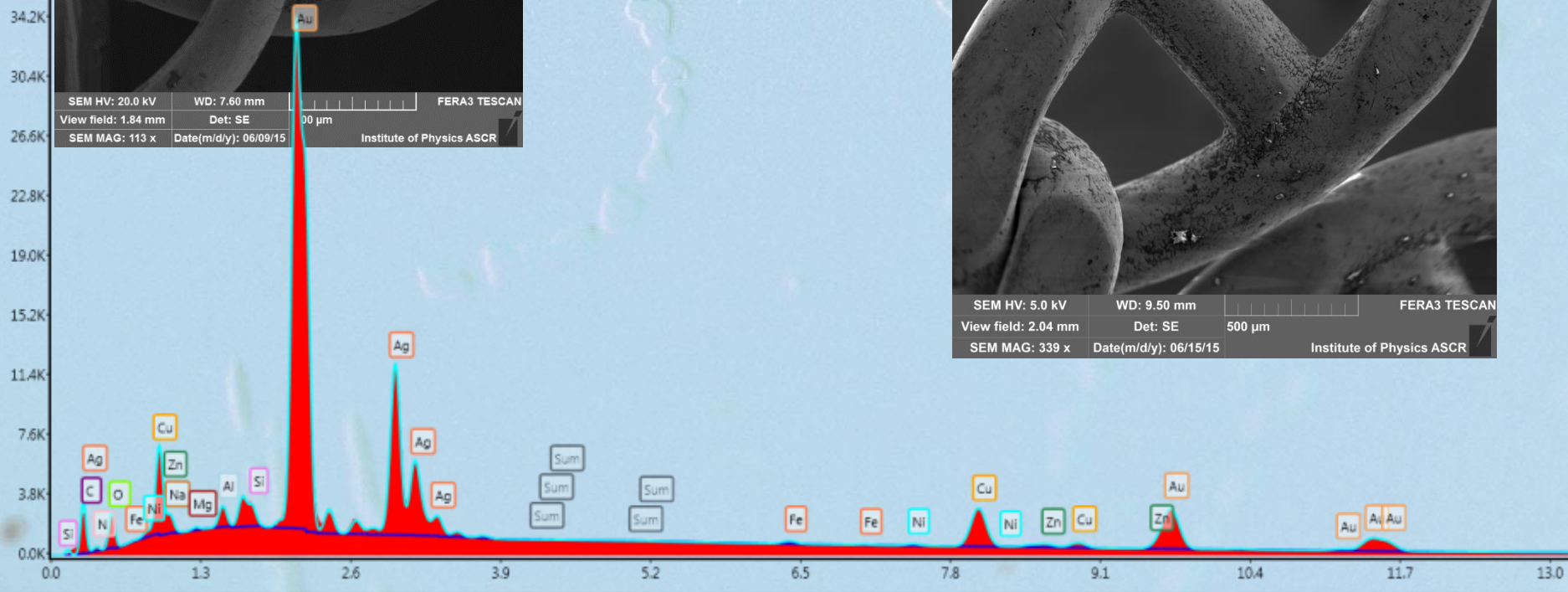
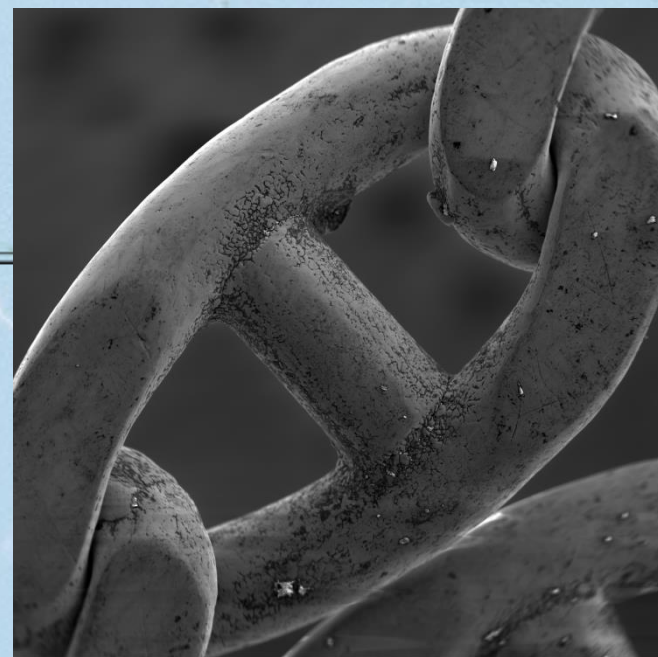
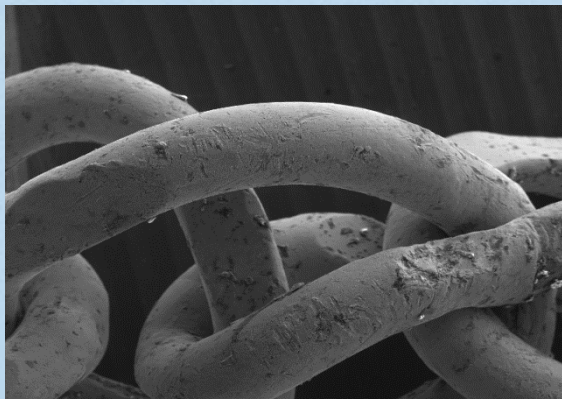
# Dva přístupy

Mikroskopický – cílem je co nejostřejší svazek, který co nejméně poškozuje vzorek

Spektroskopický – cílem je co nejintenzivnější, stabilní svazek, který co nejméně poškozuje vzorek

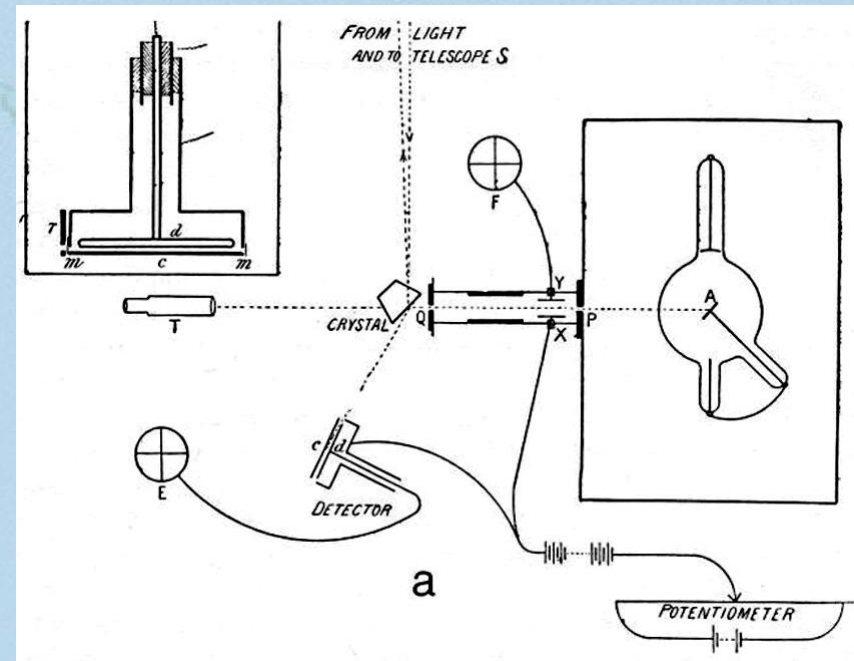
Výsledkem pak, že jsme nespokojeni buďto s rozlišením prostorovým nebo energiovým.

# Analýza složení



# Prvkové složení zkoumaných materiálů - EDS

Henry G. J. Moseley (1887 – 1915)



Objevitel charakteristického záření atomů

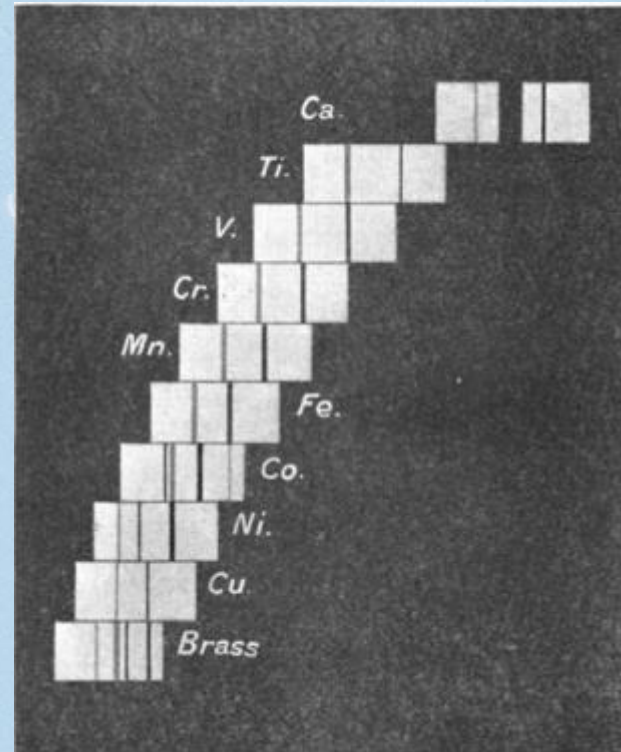
# Objev – Moseley 1913

XCIII. *The High-Frequency Spectra of the Elements.*  
By H. G. J. MOSELEY, M.A.\*

[Plate XXIII.]

**I**N the absence of any available method of spectrum analysis, the characteristic types of X radiation, which an atom emits when suitably excited, have hitherto been described in terms of their absorption in aluminium †. The interference phenomena exhibited by X rays when scattered by a crystal have now, however, made possible the accurate determination of the frequencies of the various types of radiation. This was shown by W. H. and W. L. Bragg ‡, who by this method analysed the line spectrum emitted by the platinum target of an X-ray tube. C. G. Darwin and the author § extended this analysis and also examined the continuous spectrum, which in this case constitutes the greater part of the radiation. Recently Prof. Bragg || has also determined the wave-lengths of the strongest lines in the spectra of nickel, tungsten, and rhodium. The electrical methods which have hitherto been employed are, however, only successful where a constant source of radiation is available. The present paper contains a description of a method of photographing these spectra, which makes the analysis of the X rays as simple as any other branch of spectroscopy.

PhilMagSerie6-26-156-1024

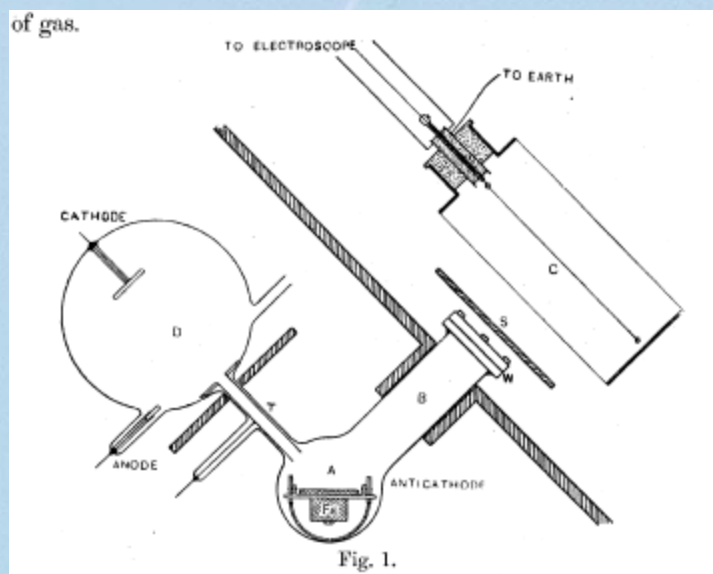


Kaye † has shown that an element excited by a stream of sufficiently fast cathode rays emits its characteristic X radiation. He used as targets a number of substances mounted



# Objev – G.W.C. Kaye

ptRSLA209-123



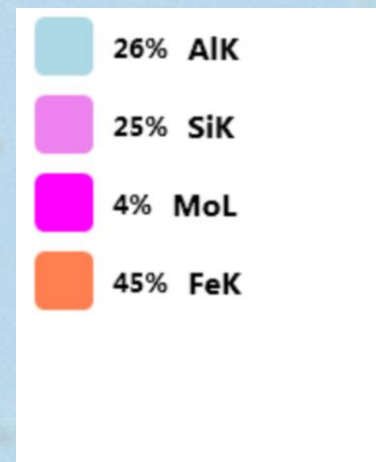
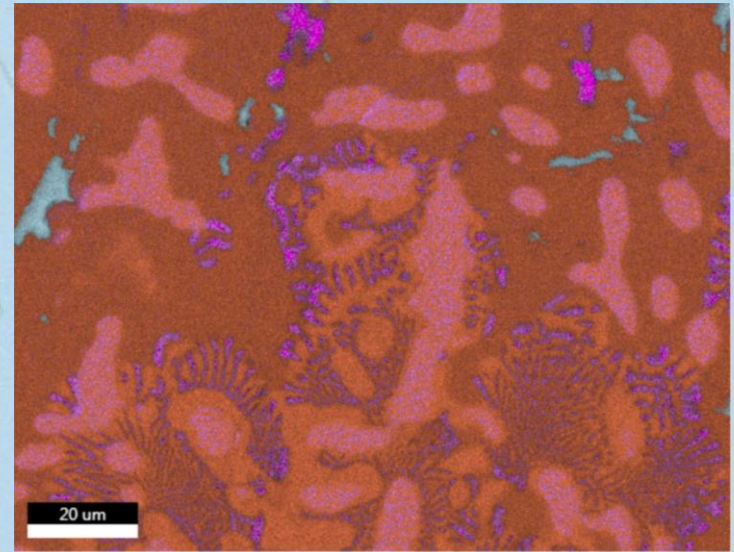
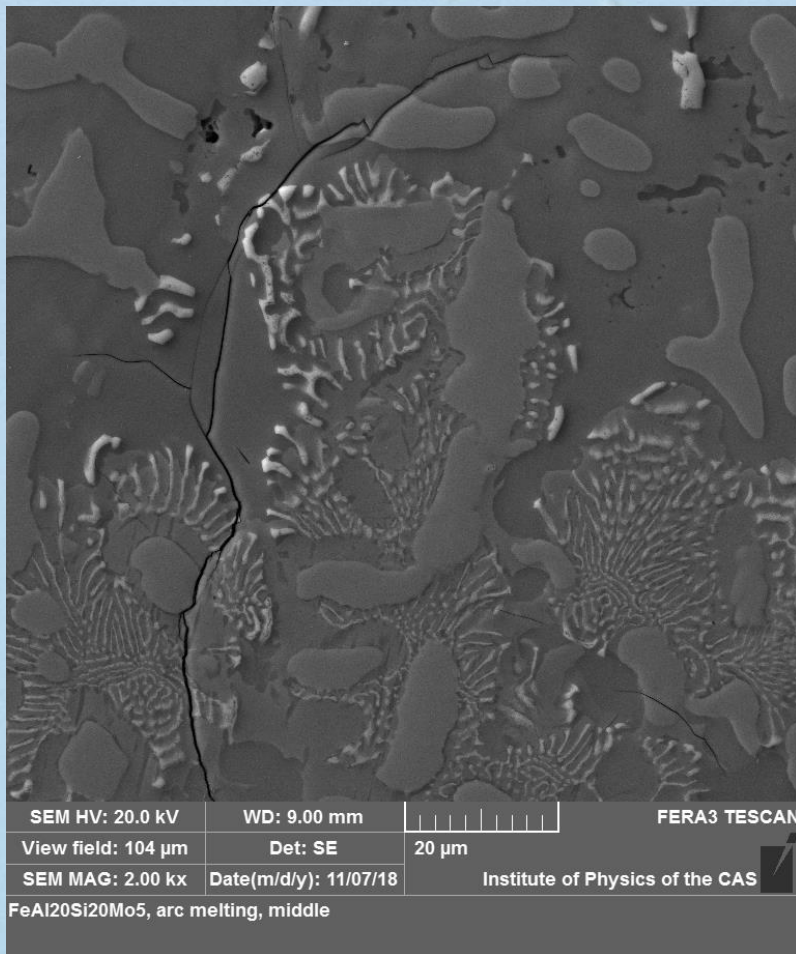
## VI. *The Emission and Transmission of Röntgen Rays.*

By G. W. C. KAYE, B.A. (Cantab.), B.Sc. (Lond.), A.R.C.Sc., Associate-Member  
of the Institution of Electrical Engineers, Trinity College, Cambridge.

Communicated by Prof. J. J. THOMSON, F.R.S.

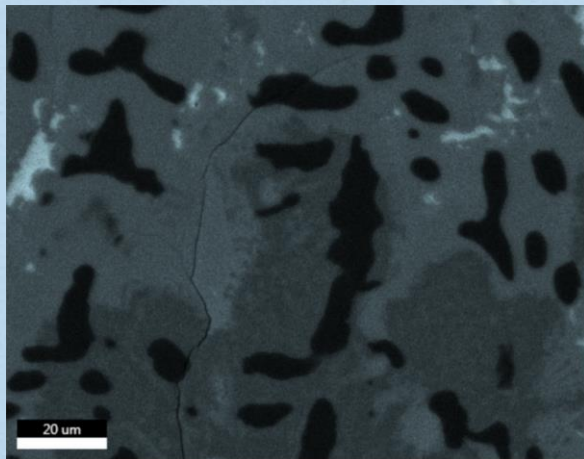
Received June 17,—Read June 25, 1908.

# Fénix povstal z molybdenu

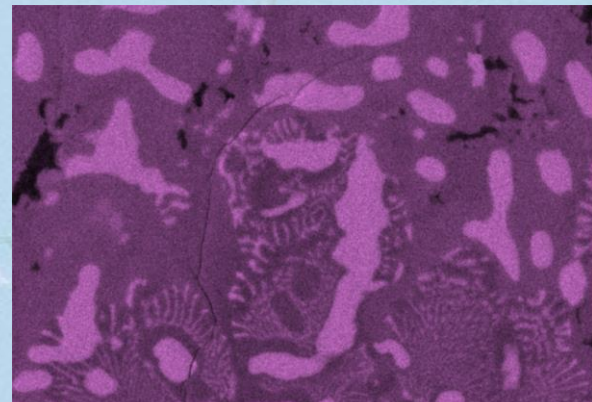


# Fénix povstal z molybdenu

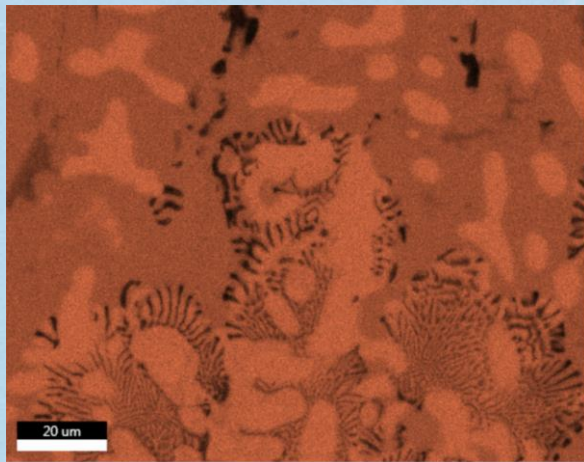
Hliník



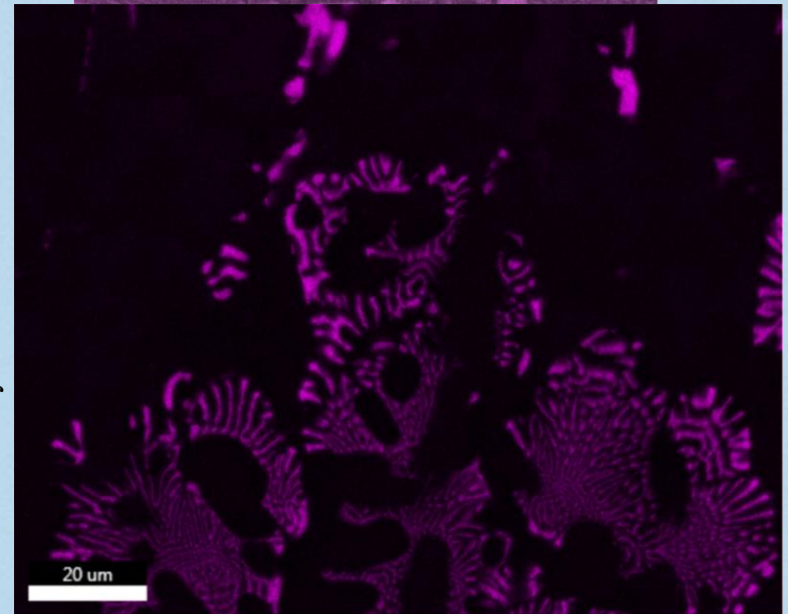
Křemík



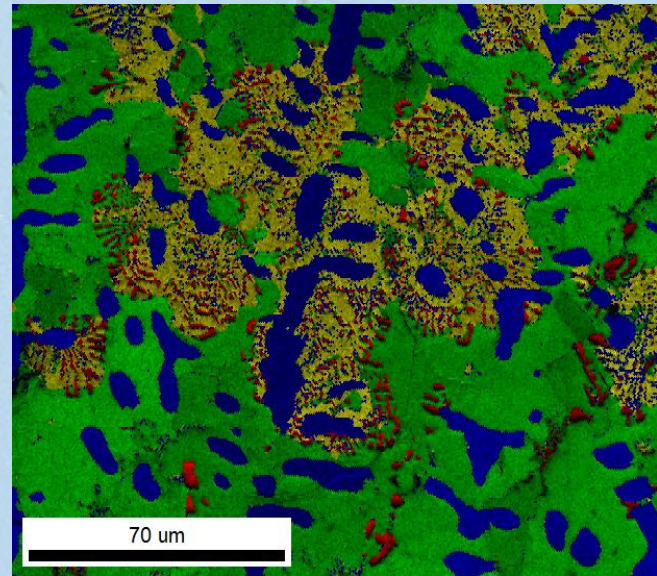
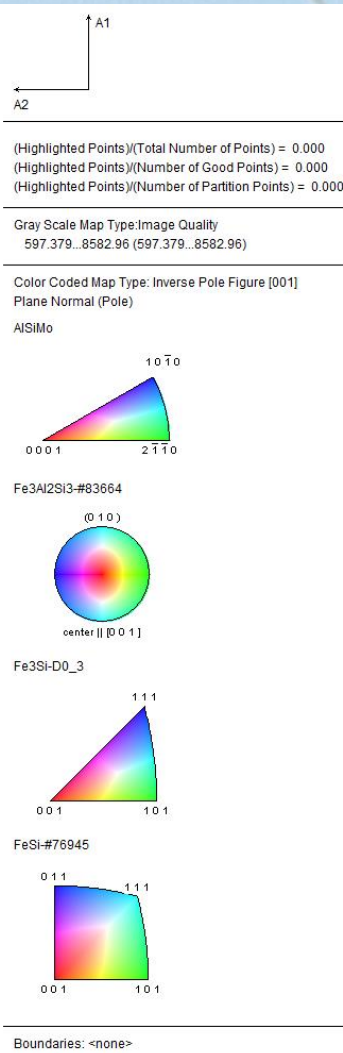
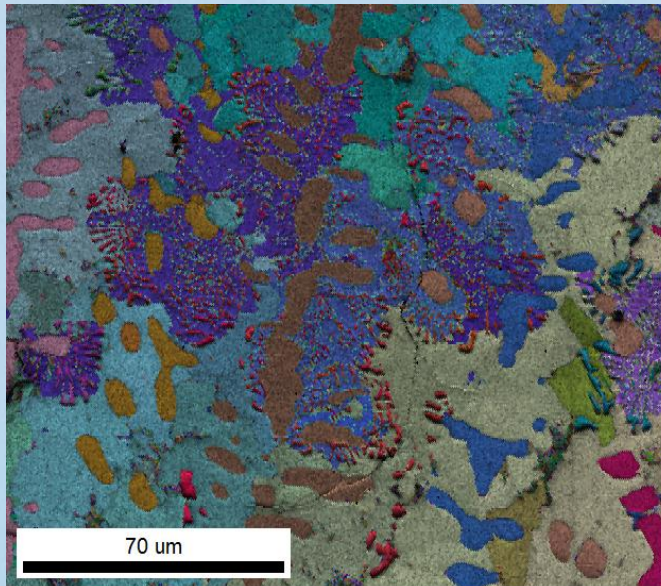
Železo



Molybden



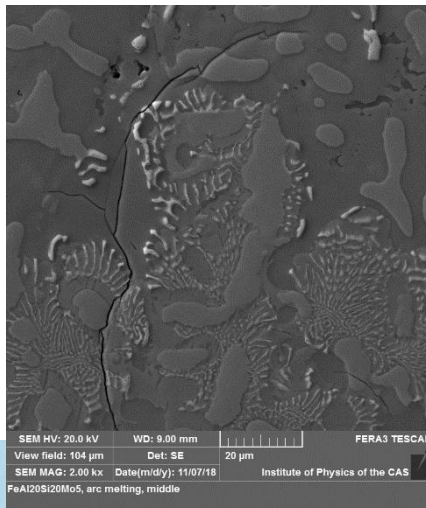
# Fénix přistál



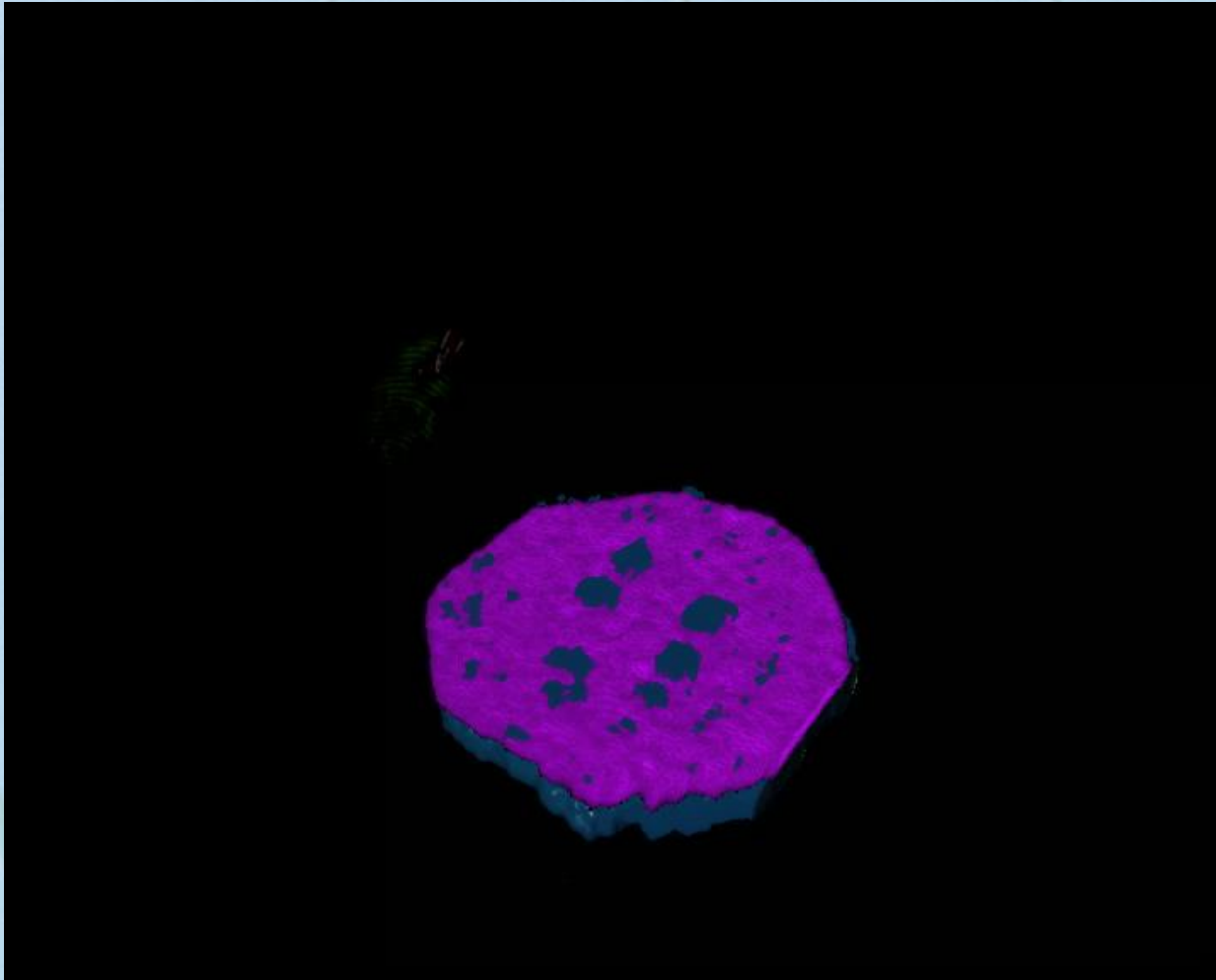
Color Coded Map Type: Phase

Phase	Total Fraction	Partition Fraction
AlSiMo	0.055	0.055
Fe <sub>3</sub> Al <sub>2</sub> Si <sub>3</sub> -#83664	0.532	0.532
Fe <sub>3</sub> Si-D0_3	0.185	0.184
FeSi-#76945	0.229	0.229

Boundaries: <none>



# 3D EDS – kapka Pb-Sn pájky



Jiří Dluhoš  
Tescan – Orsay  
Holdinng

# Soft X-ray Emission Spectrometer SXES fy Jeol



Vyvinuto firmou Jeol, prezentováno 2014

Hideyuki Takahashi

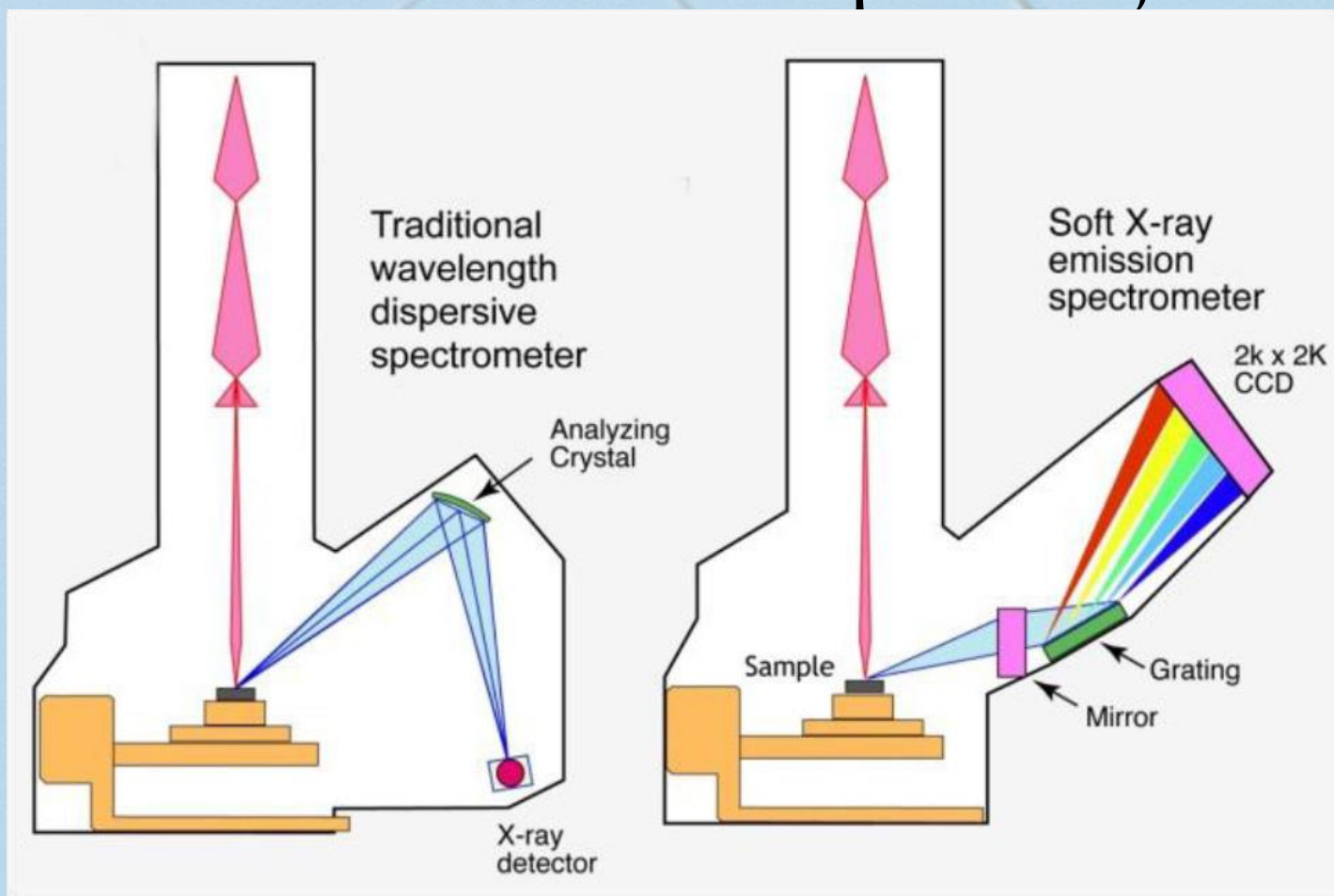
Spektrální rozlišení 0,3 eV

JS50XL 50 – 170 eV

JS200N 70 – 210 eV

Spektrum je snímáno CCD detektorem

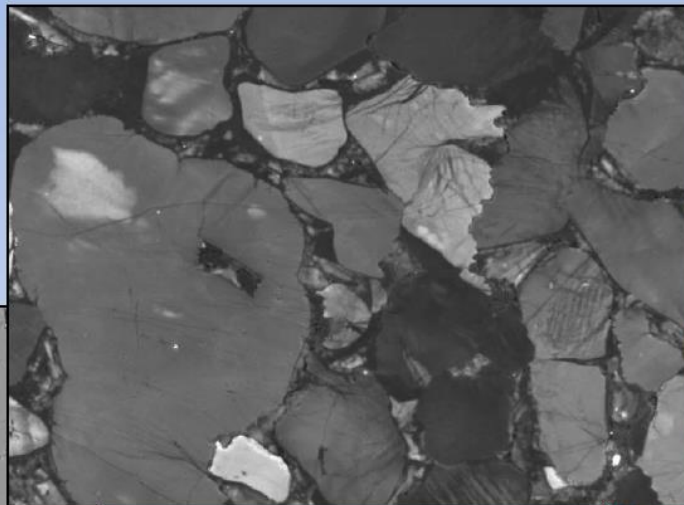
# SXES – schéma přístroje



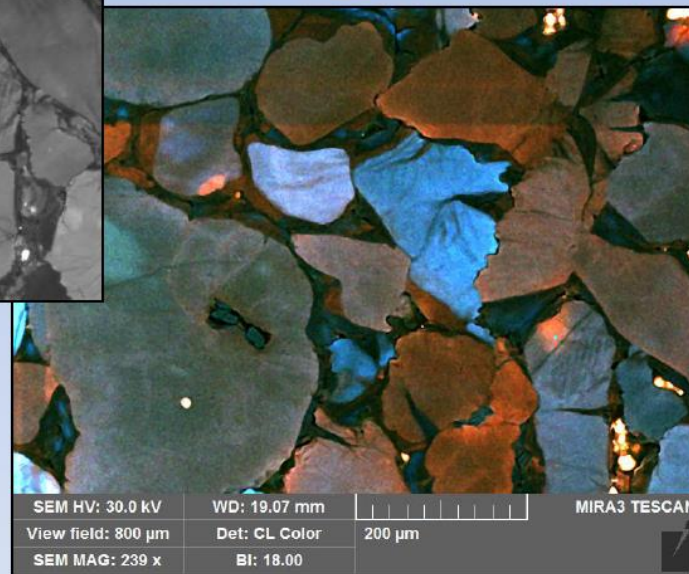
Hideyuki Takahashi, *Microsc. Microanal. Suppl.*, Dec. 2014, S4-S8

# Katodoluminiscence v pískovci

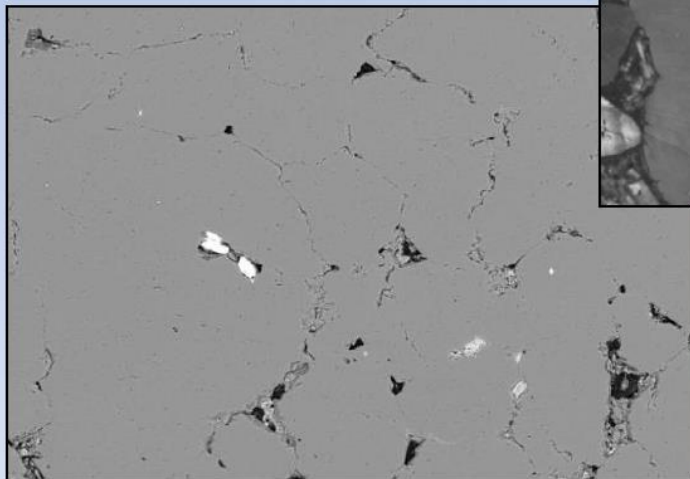
Sandstone



Panchromatic CL (20 kV)



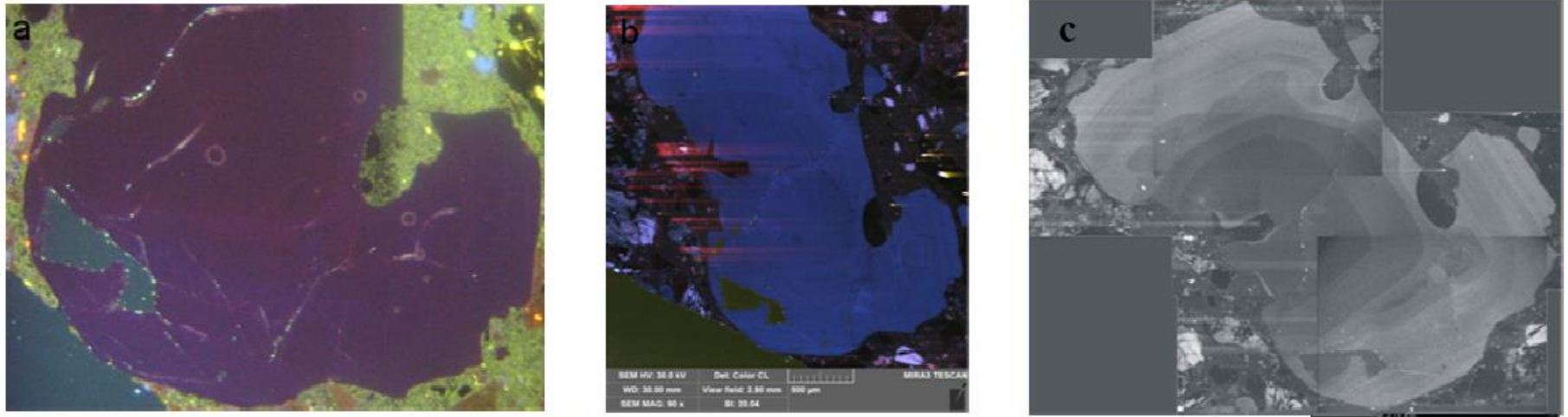
Color CL (30 kV, 5 nA)



BSE image (20 kV, 1 nA)



# CL v různých přístrojích



**Obr. 1** Totéž zrno křemene z teplického ryolitu v různém zobrazení:

a) CL s horkou katodou (ÚGV, PŘF MU Brno)

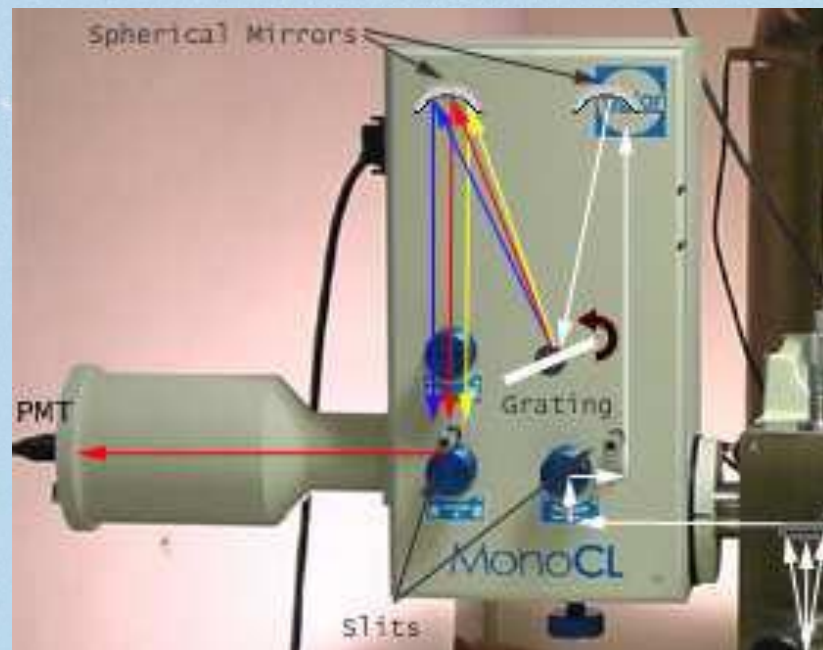
b) barevné rastrovací CL (Tescan, Brno, foto J. Kološová,)

c) panchromatické skenovací CL (obraz složen z dílčích částí; ÚGV, PŘF MU Brno, foto R. Škoda).

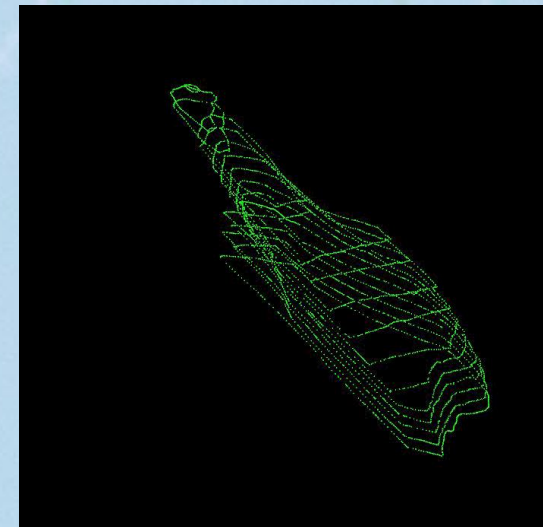
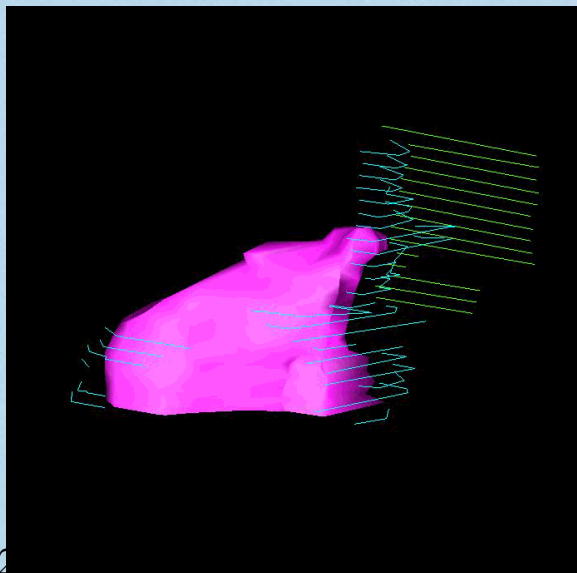
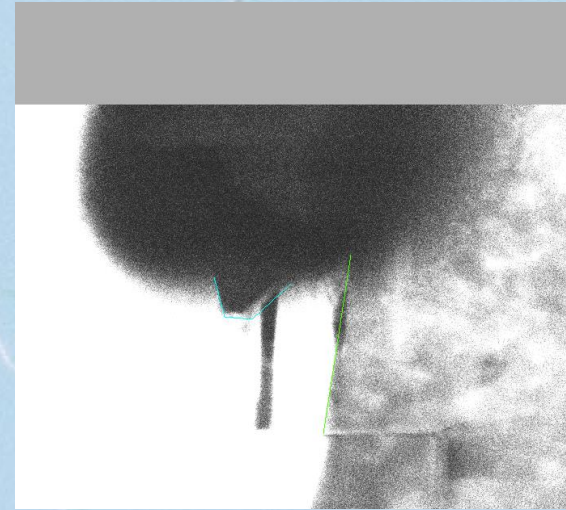
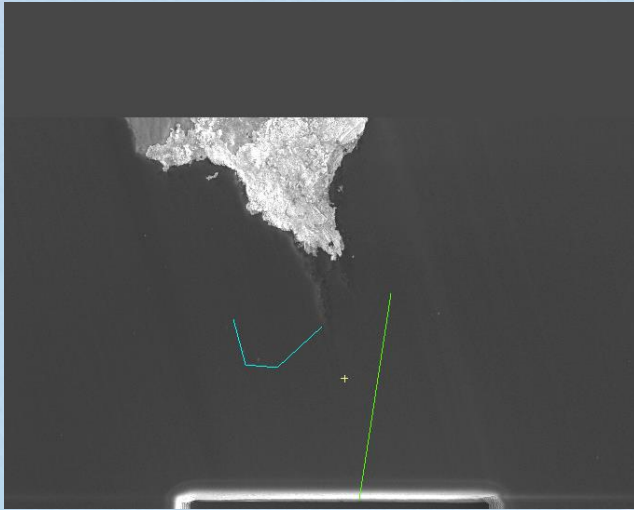
Kateřina Švecová in Využití katodové luminescence a LA-ICP MS

při studiu vnitřní stavby minerálů, 14. listopadu 2012, v budově děkanátu PŘF MU, Brno, pp. 6-7

# CL detektor fy Gatan

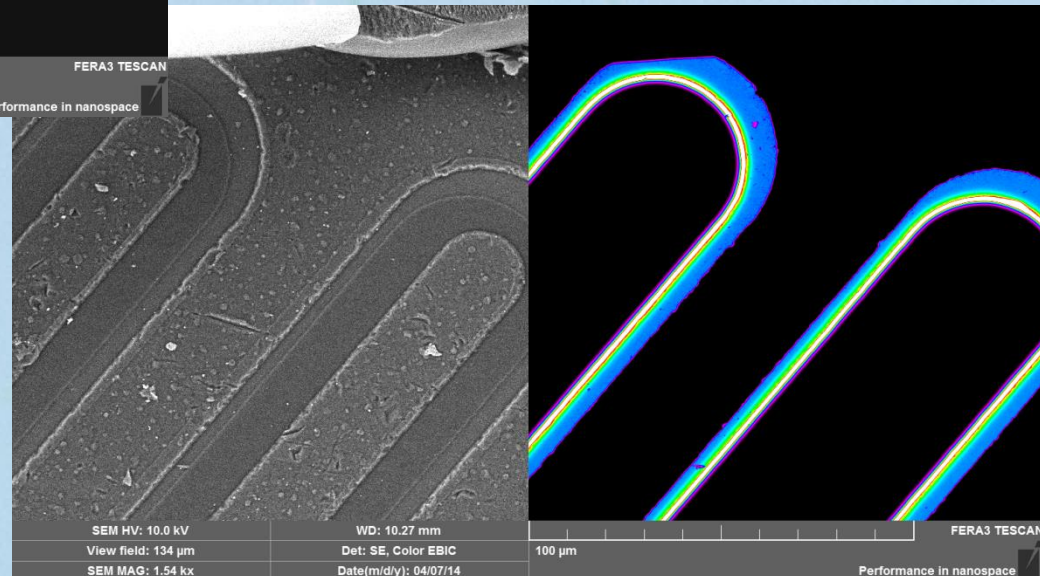
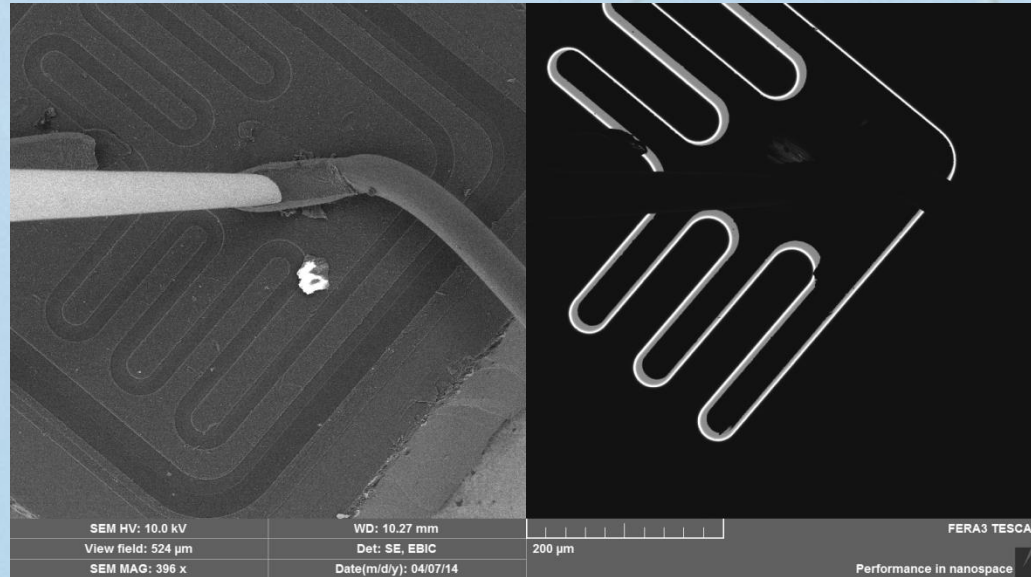


# 3D katodoluminiscence



# Electron Beam induced Current

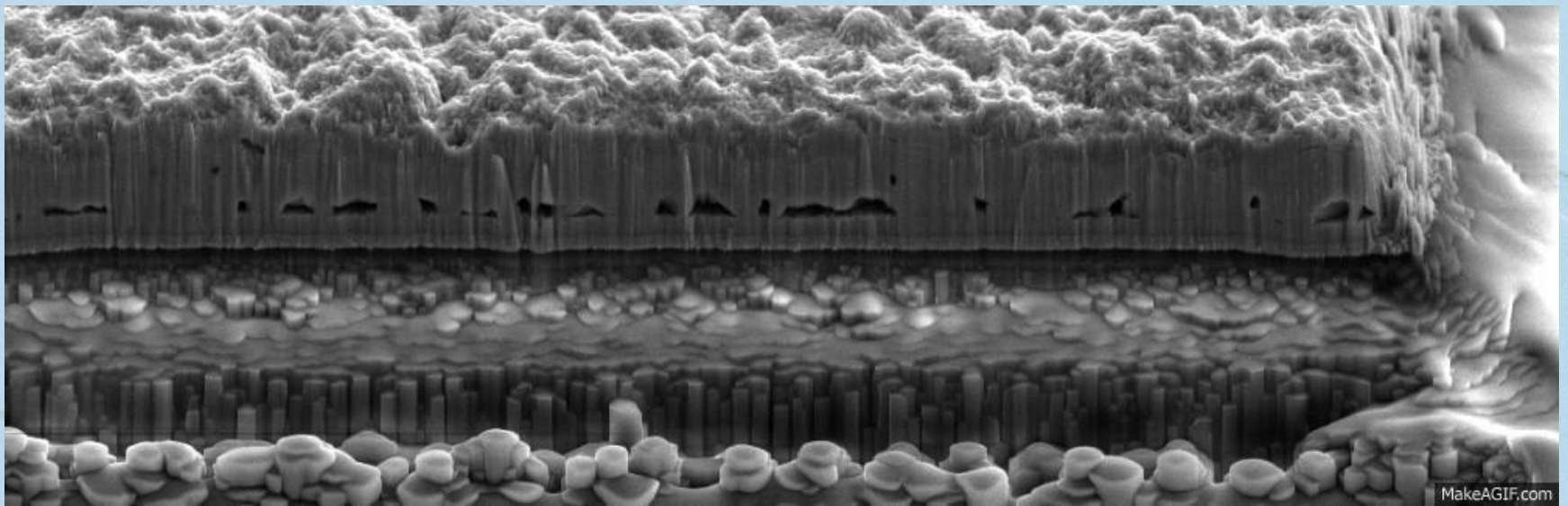
Modul fy Tescan  
Předpětí v intervalu -5 až 5 V  
16-bitový AD převodník



Ge tranzistor

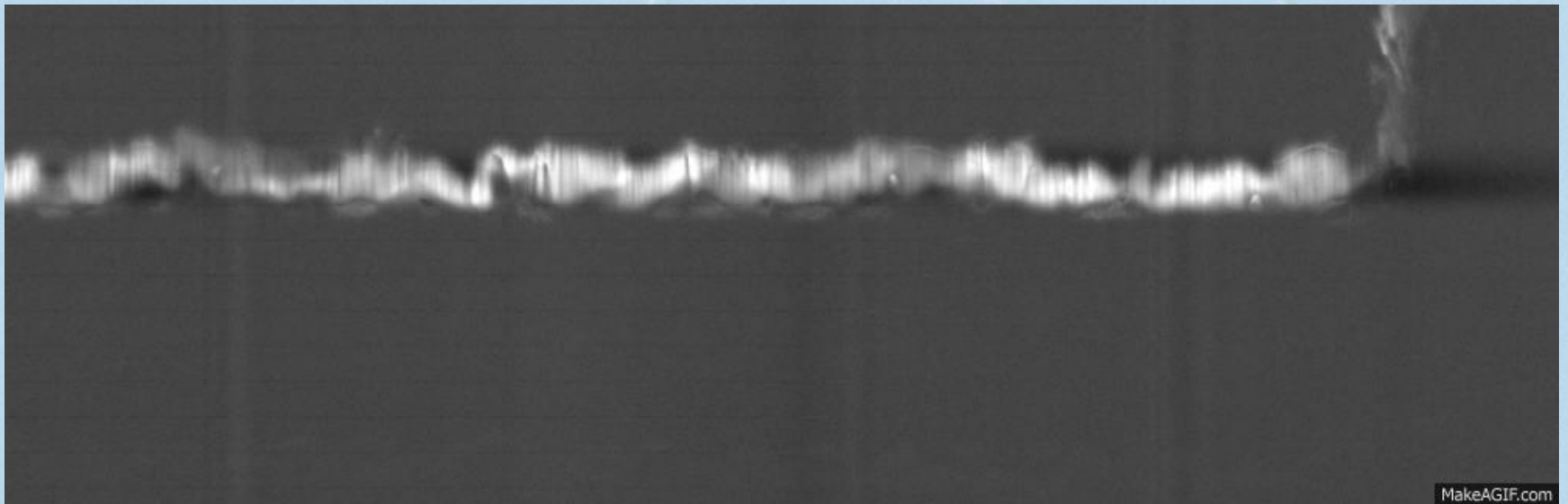
EBIC signál je možno zobrazit  
černobíle nebo softwareově přiřadit  
barevnou škálu.

Nalevo obraz v SE elektronech,  
napravo EBIC signál.



Up: SE signal FIB of CIGS

Down: EBIC signal FIB of CIGS



# Literatura

- *Scanning Electron Microscopy Physics of Image Formation and Microanalysis*, Ludwig Reimer, ISBN: 978-3-642-08372-3 Springer-Verlag Berlin Heidelberg 1985, 1998
- Doporučená literatura:
- *Scanning Electron Microscopy and X-Ray Microanalysis*, J. I. Goldstein, D. E. Newbury, P. Echlin, D. C. Joy, A. D. Romig Jr., Ch. E. Lifshin, ISBN-13: 978-0306472923, Plenum Press, New York, 1992, 1981
- *Handbook of Sample Preparation for Scanning Electron Microscopy and X-Ray Microanalysis* , Patrick Echlin, ISBN: 0387857303, Springer Science+Business Media, LLC 2009
- *Electron Backscatter Diffraction in Materials Science*, Adam J. Schwartz, Mukul Kumar, Brent L. Adams, David P. Field, 2nd Edition, ISBN 978-0-387-88135-5, Springer Science+Business Media, LLC 2009
- *Introduction to Focused Ion Beams Instrumentation, Theory, Techniques and Practice*, Lucille A. Giannuzzi , Fred A. Stevie, ISBN: 0-387-23116-1, Springer Science + Business Media, Inc., 2005
- *Zkoumání látek elektronovým paprskem*, V. Hulínský, K. Jurek, SNTL, Praha 1982
- *Úvod do transmisní elektronové mikroskopie*, Miroslav Karlík, ISBN: 978-80-0104-729-3, ČVUT, Praha, 2011

Děkuji za pozornost!