

Skenovací elektronová mikroskopie (Úvod do historie spíše než použití)

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Oddělení funkčních materiálů FZÚ AV ČR

kopeczek@fzu.cz

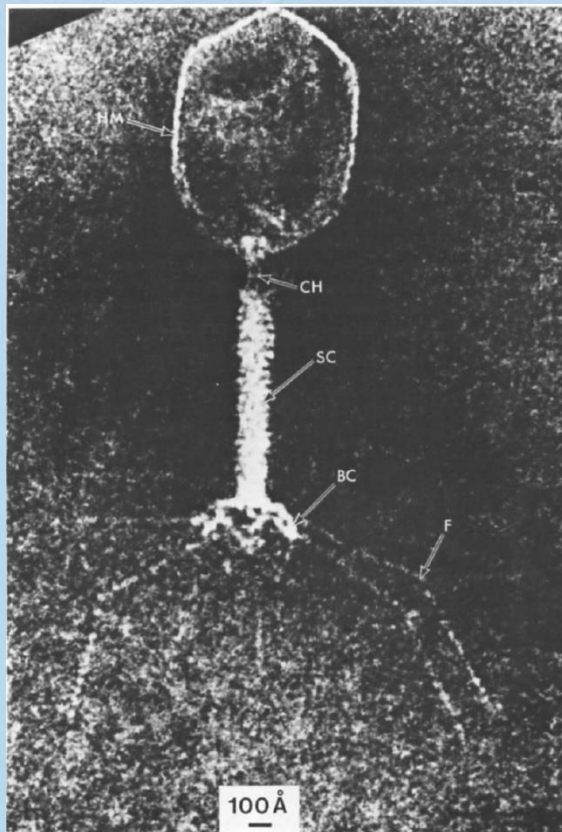
Elektronová mikroskopie

Proč byla vyvinuta?

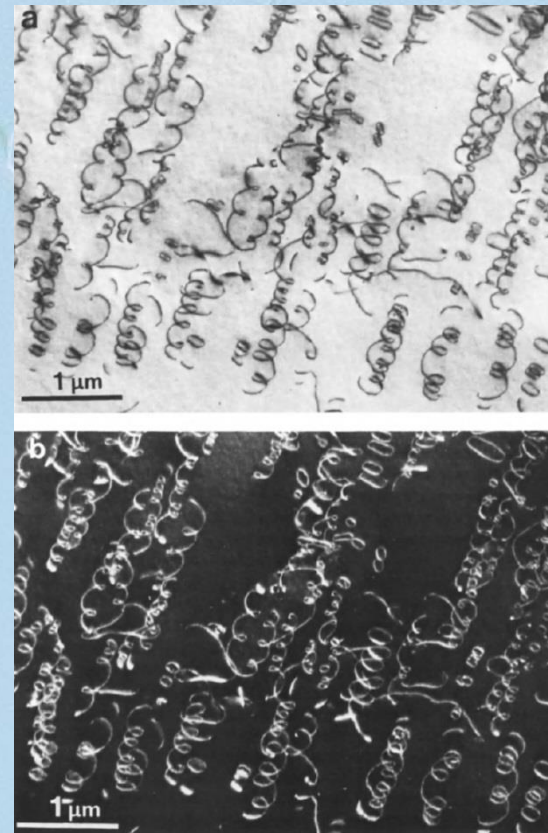
- Má větší rozlišení než optická mikroskopie
- Umožňuje sledovat:
 - Poruchy krystalové mříže
 - Buněčné struktury
- Pracuje s dobře zvládnutou elektrinou

Typické cíle EM

Virus 1962



Dislokace v Al-Cu, 1969

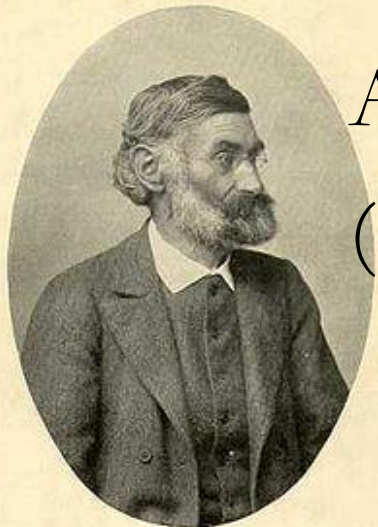


Elektronová mikroskopie

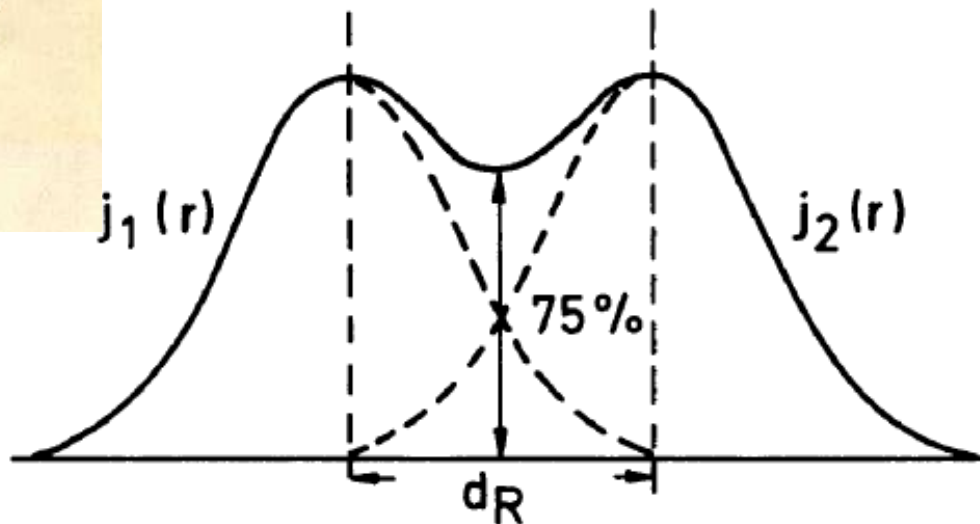
Proč byla vyvinuta?

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 ($E_0 = 511 \text{ keV}$):

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

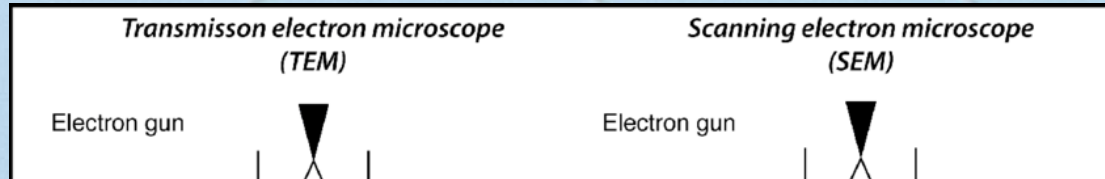
což je $\lambda = 38.8 \text{ pm}$ pro $E = 1 \text{ keV}$ a 6.98 pm pro 30 keV .

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

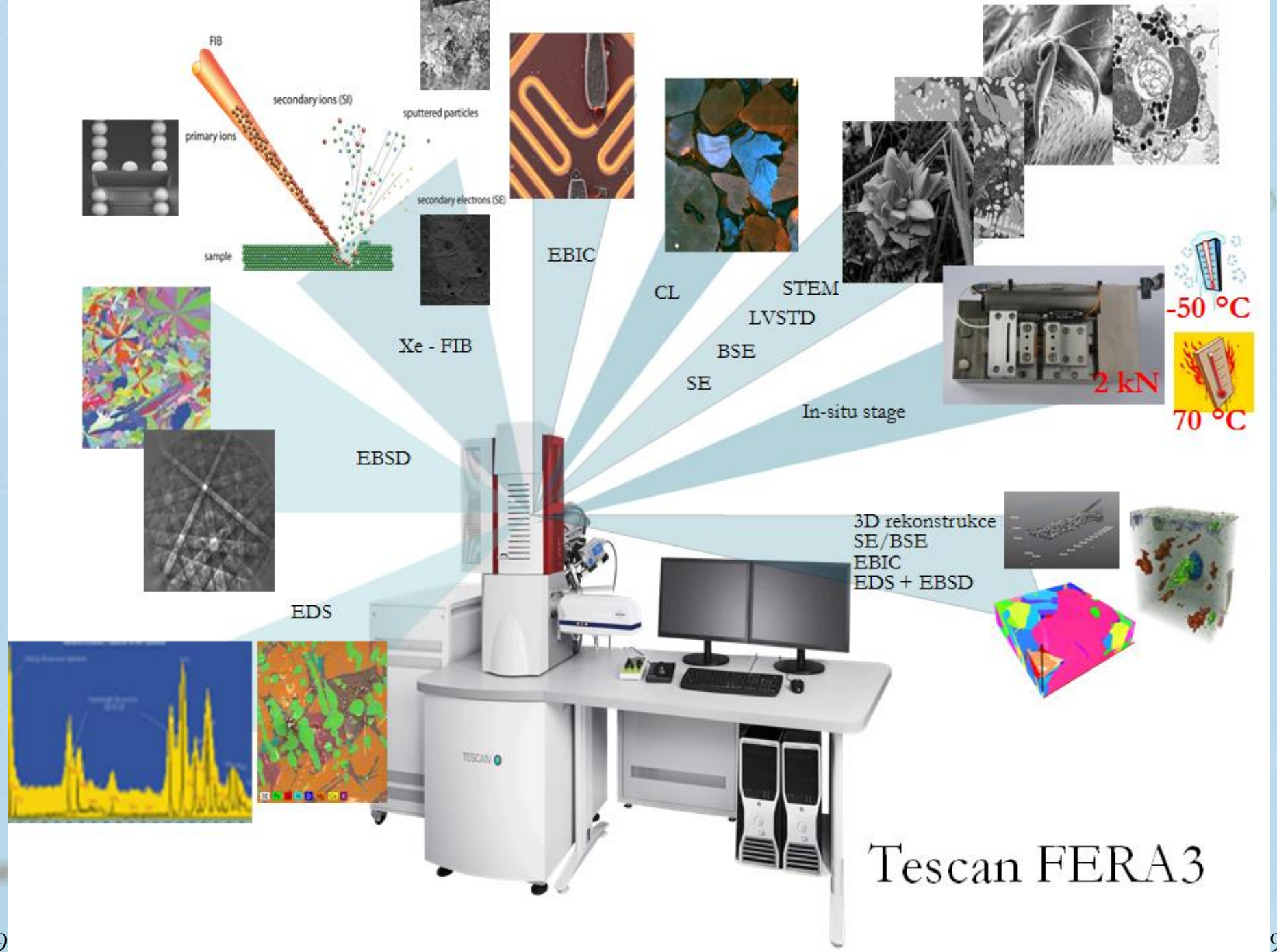
Skenovací elektronový mikroskop

Tescan FERA 3

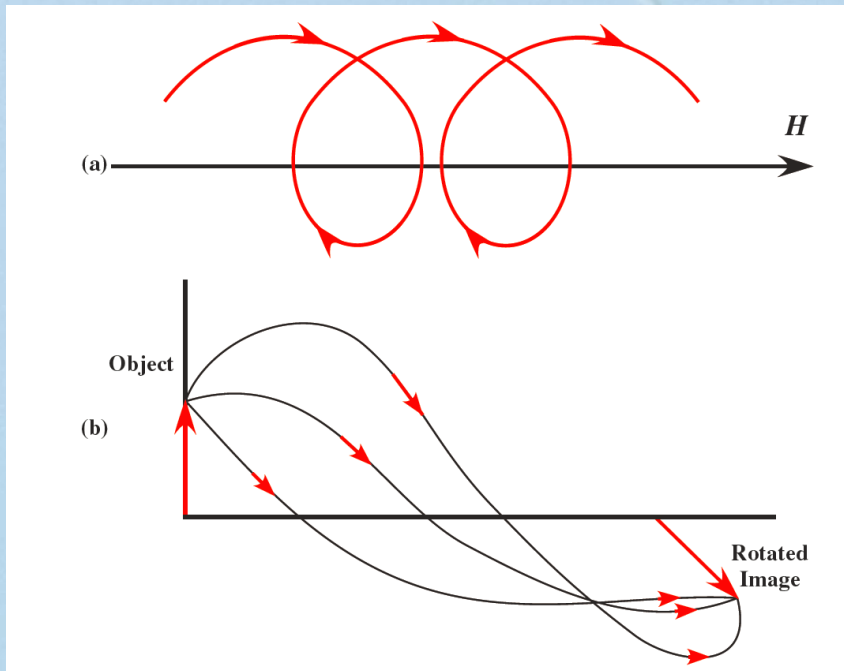


Jeol JXA-733





Pohyb elektronu v elektromagnetickém poli



Síla magnetické čočky

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

Lorentzova síla:

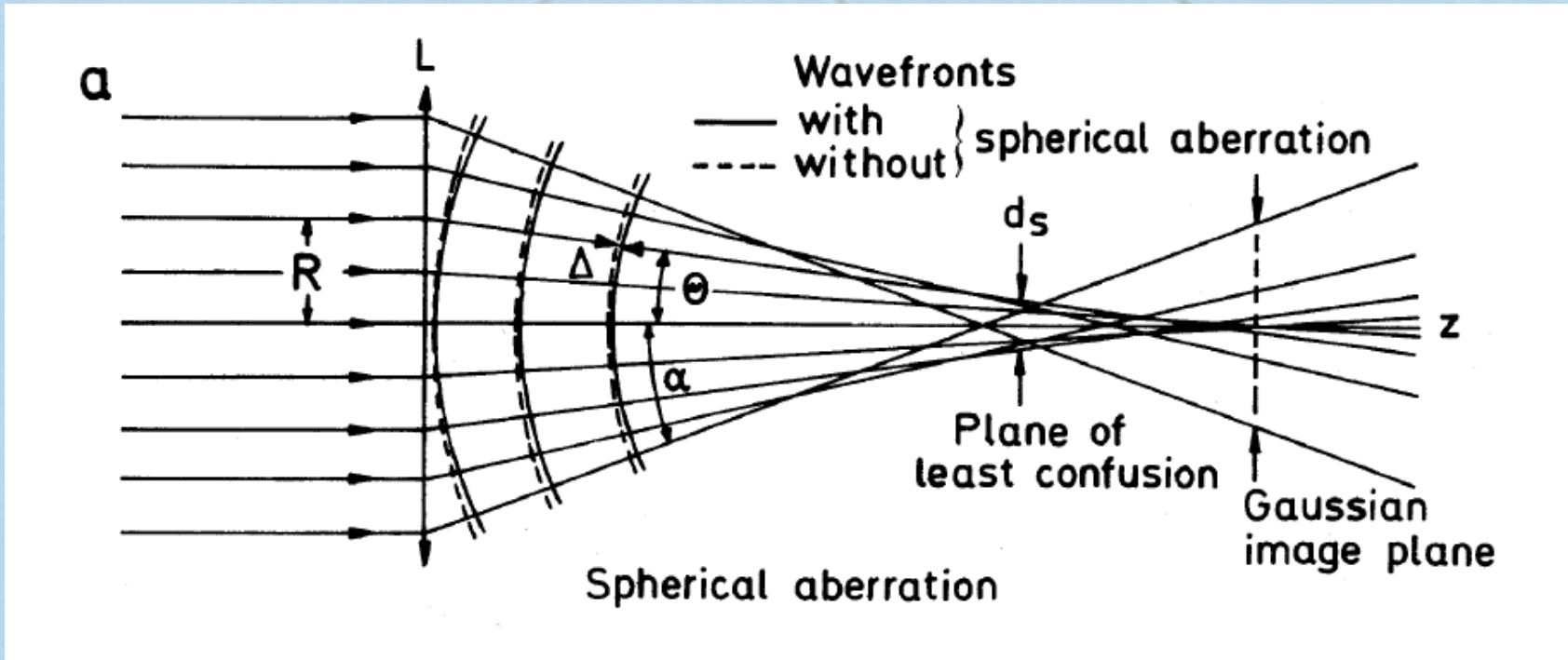
$$\vec{F} = -e(\vec{E} + \vec{v} \times \vec{B})$$

Díky ní se elektron
pohybuje po Landauových
hladinách a stáčí se o φ :

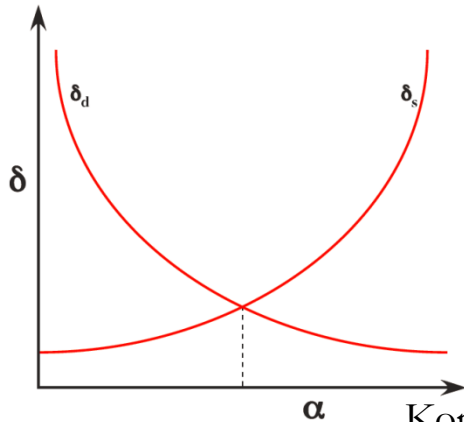
$$\varphi = \sqrt{\frac{e}{8m_0U}} \int_{-\infty}^{+\infty} B_z dz$$

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

Kulová vada



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



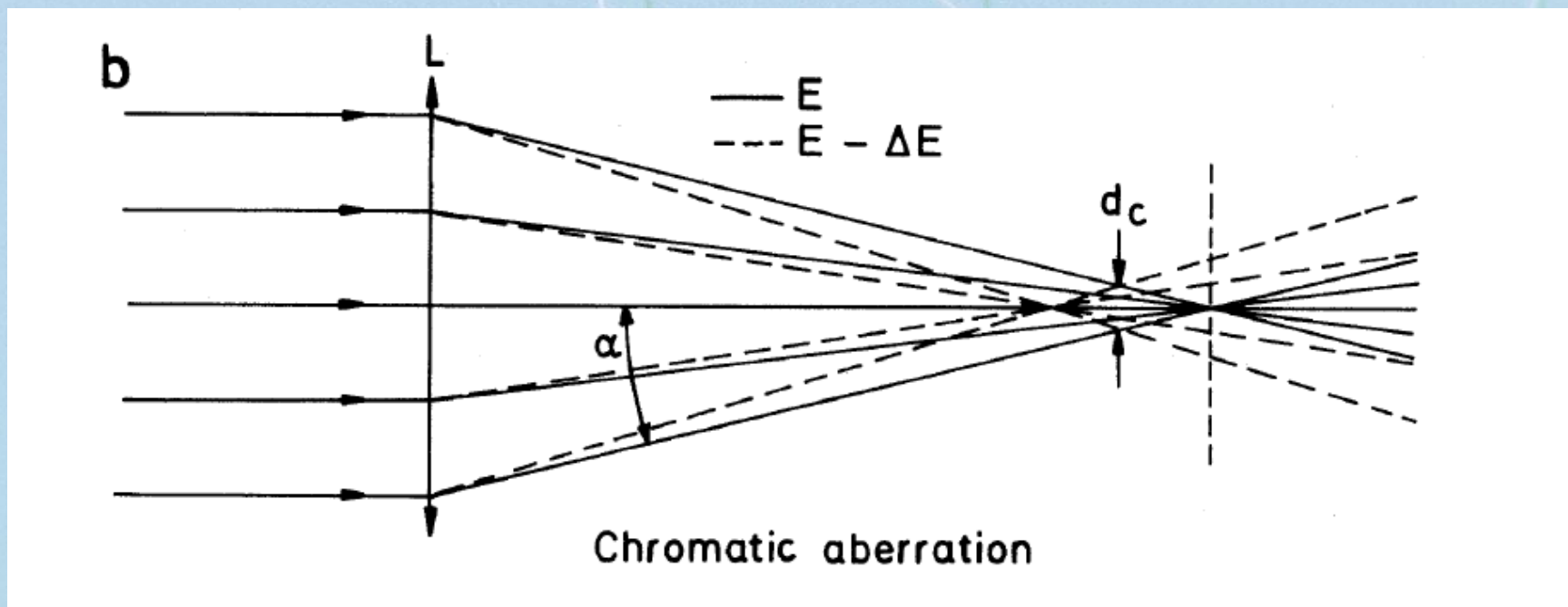
Rayleighho kritérium:

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

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

Barevná vada

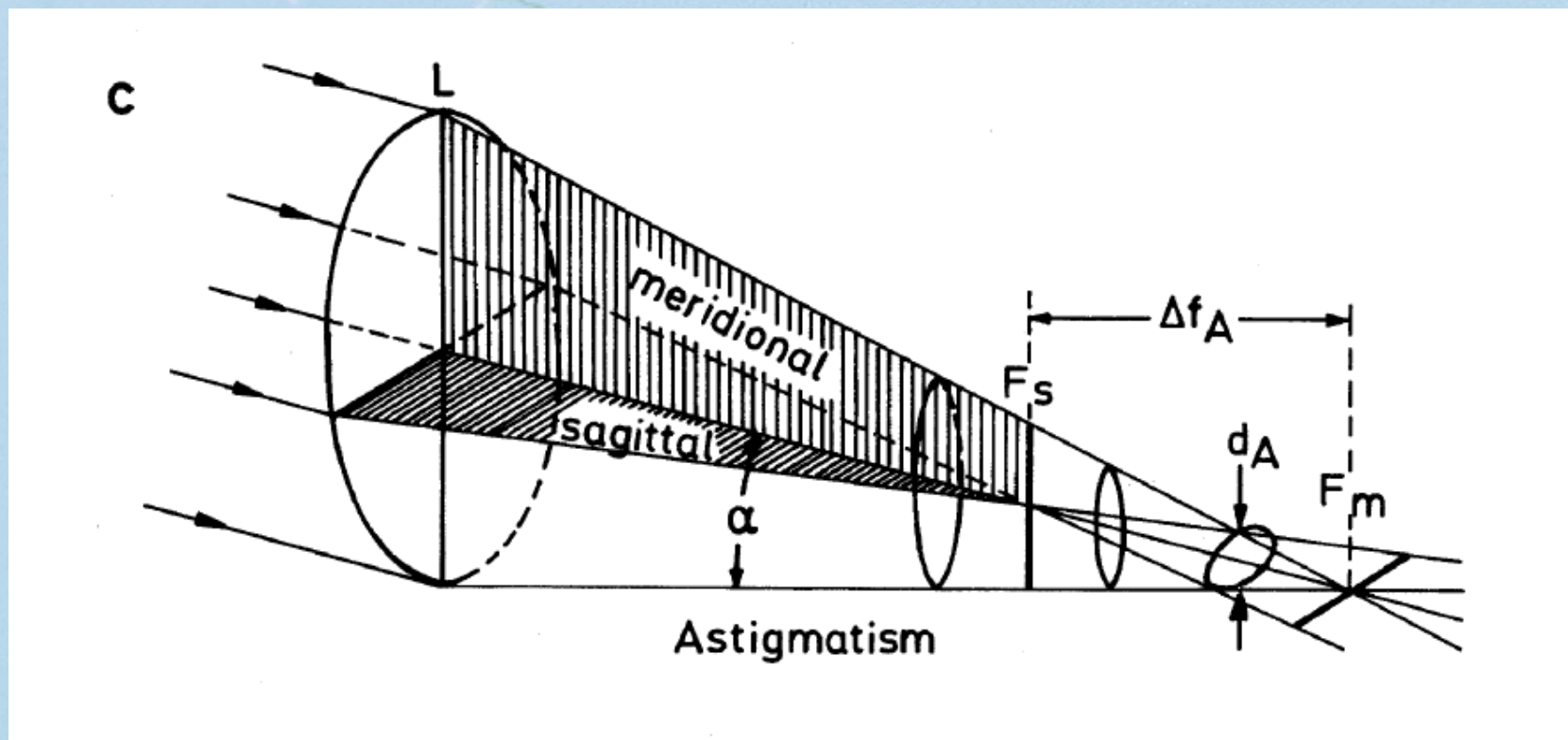
$$\delta_c = C_c \frac{\Delta E}{E_0} \alpha$$



Astigmatismus

Axiální astigmatismus

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

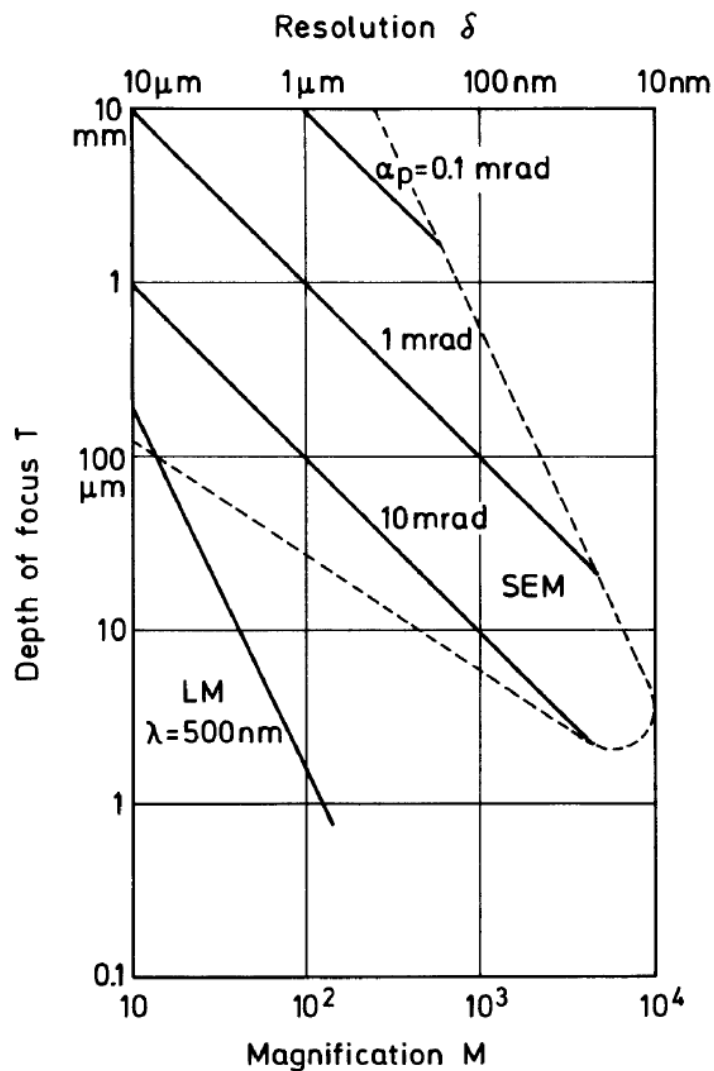


Celková chyba zobrazení

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

Δ – rozlišení

M – zvětšení

α_p – výstupní apertura
objektivu

LM – limity optické
mikroskopie

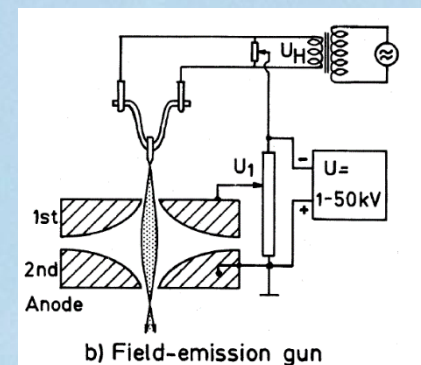
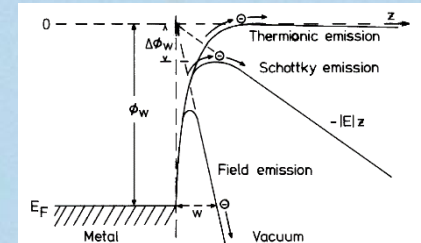
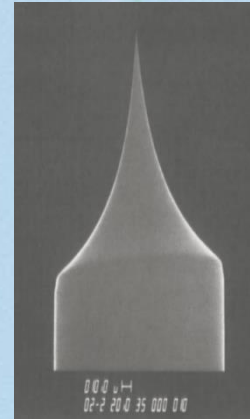
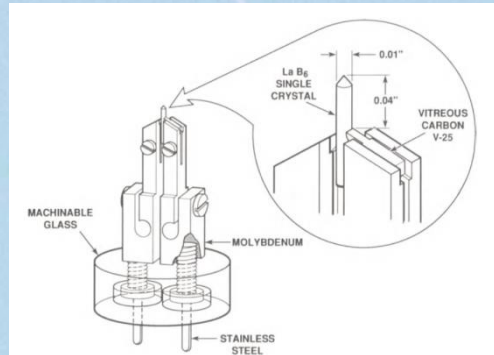
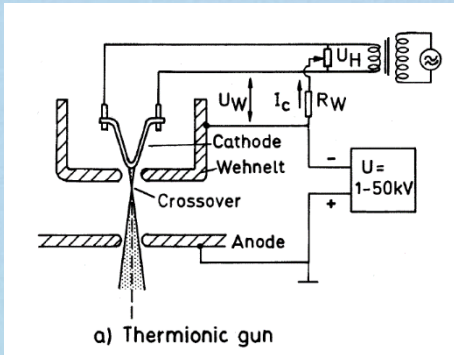
$$T = \delta \sqrt{\delta^2 / \lambda^2 - 1}$$

Složení SEM

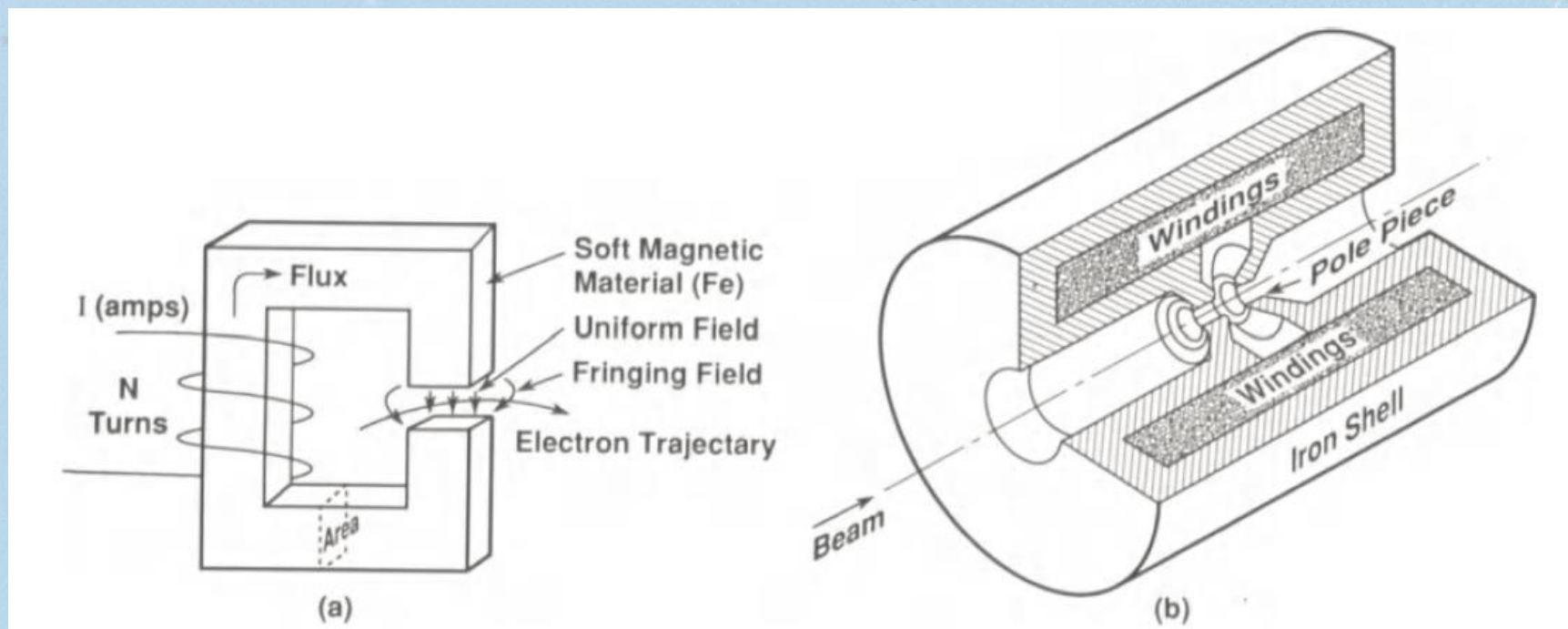
- Zdroj elektronů
- Zobrazovací soustava – čočky
- Interakce se vzorkem
- Detektory

Zdroje elektronů

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



Princip elektromagnetické čočky



Interakce elektronového svazku

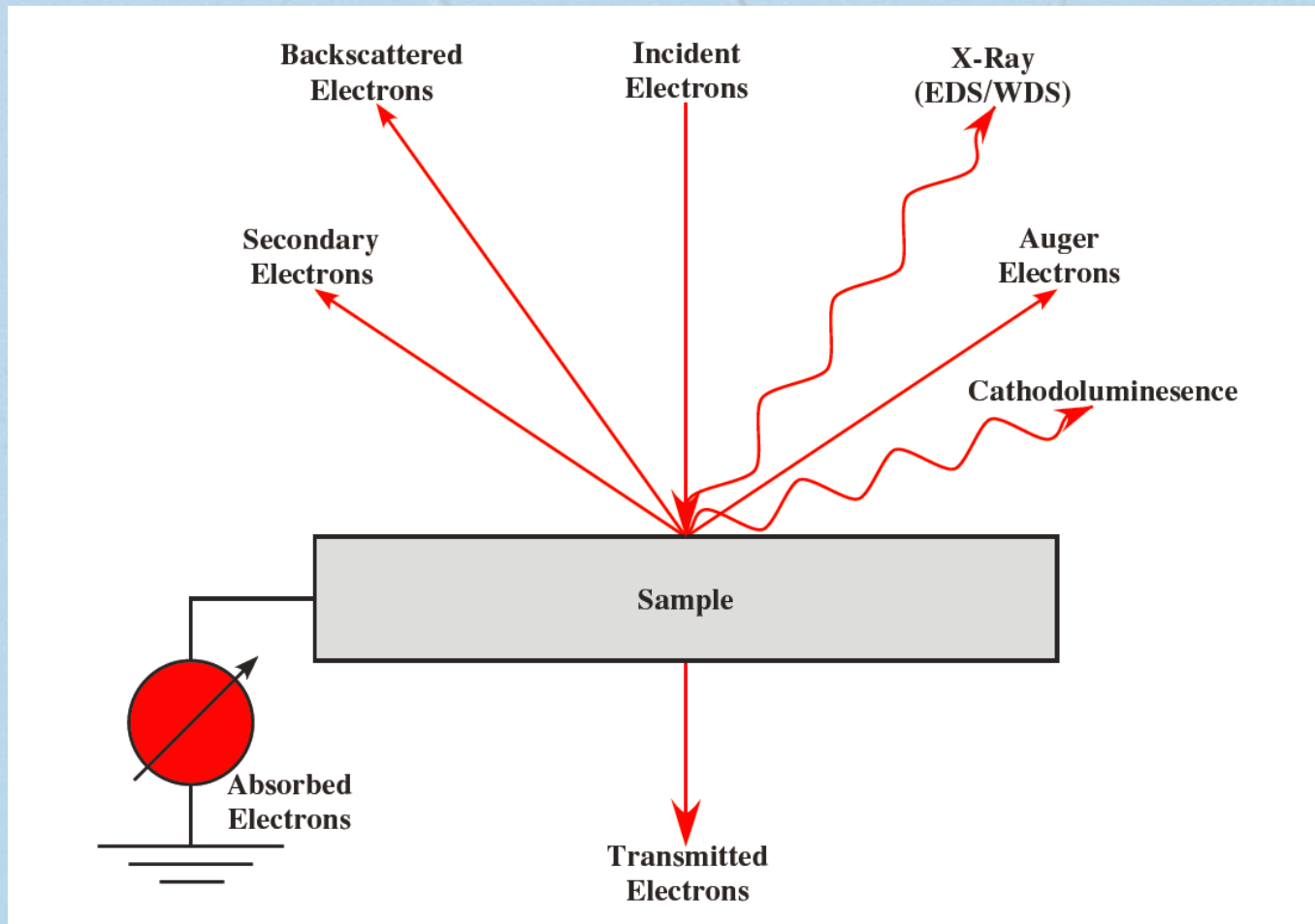
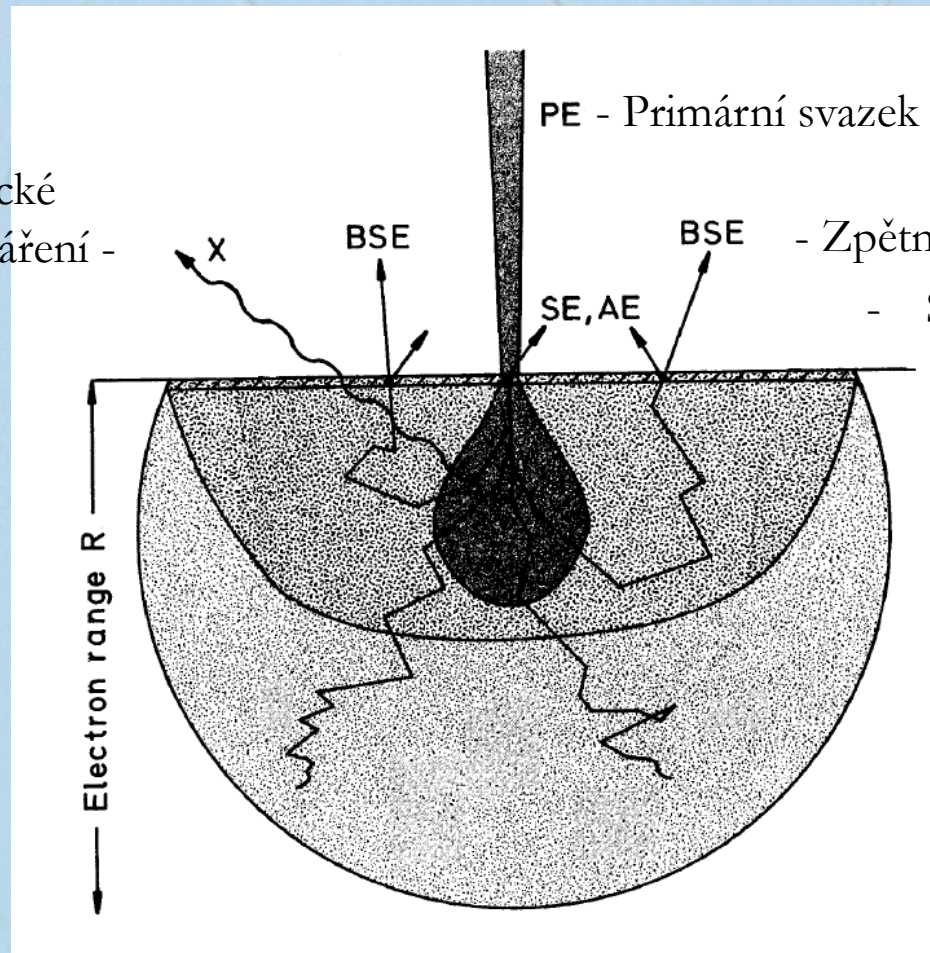


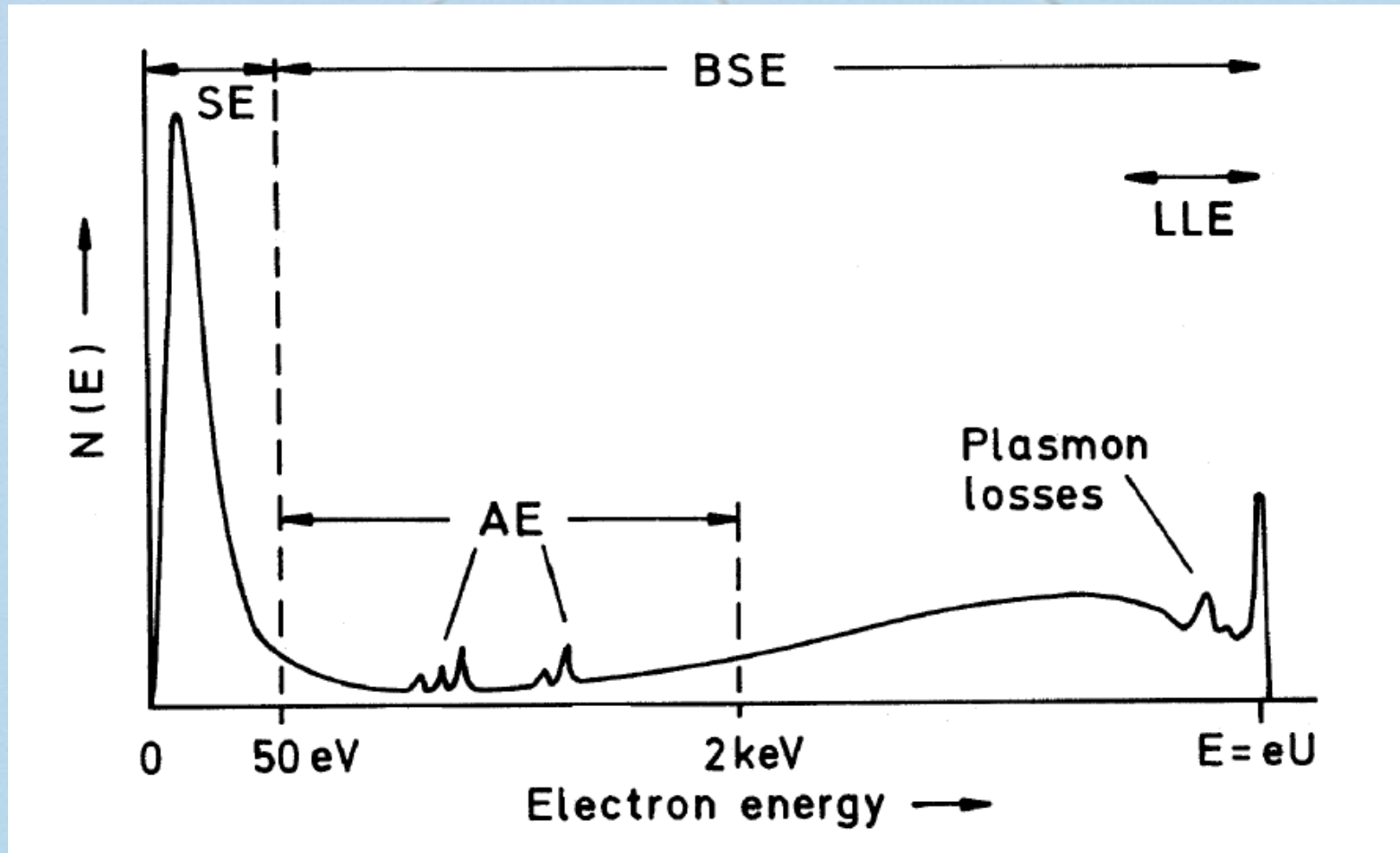
Schéma interakční oblasti

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

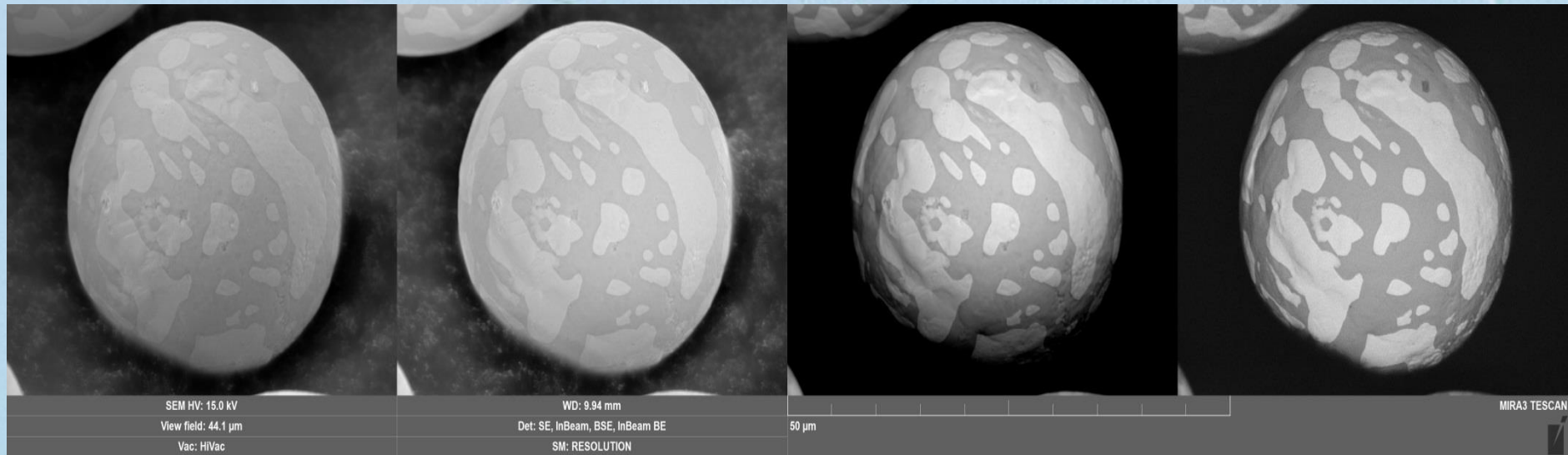
Srovnání zobrazovacích módů

SE E-T

In-Beam SE

R-BSE

In-Beam BSE

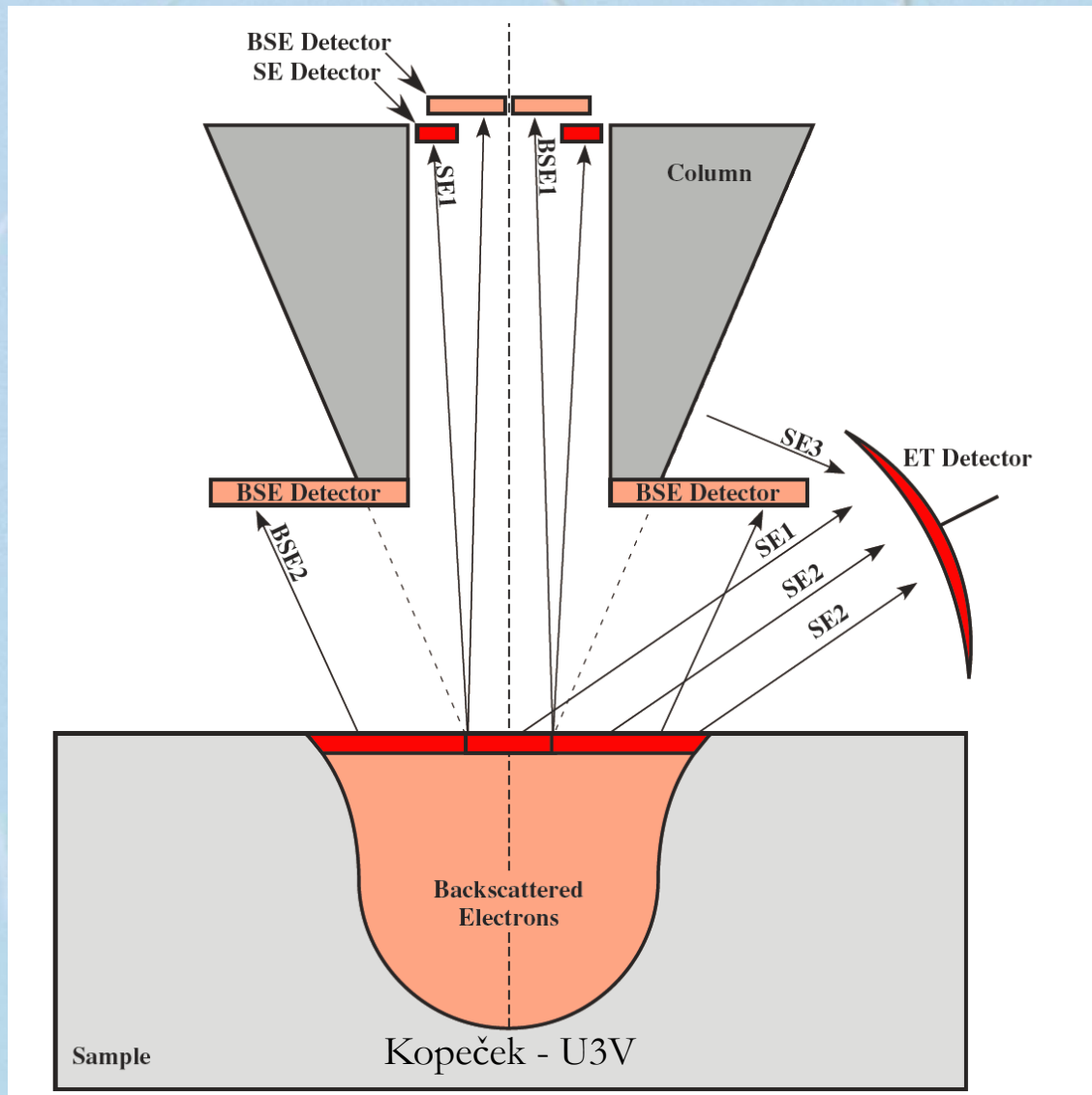


+ Higher surface
sensitivity
= better resolution

+ 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

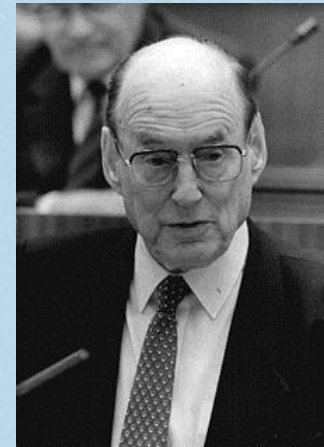


20 January 1907 – 26 May 1997

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

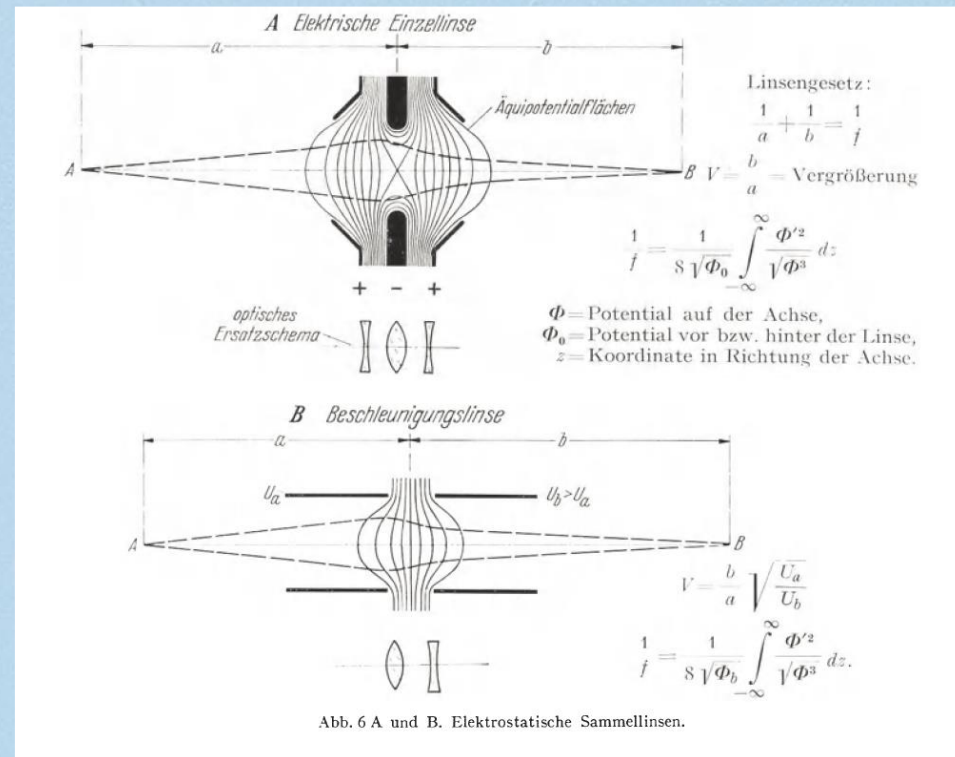
Von

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.

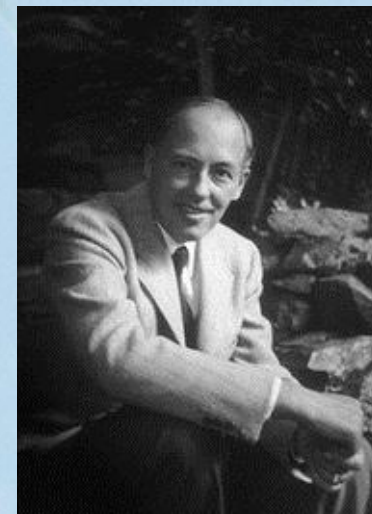
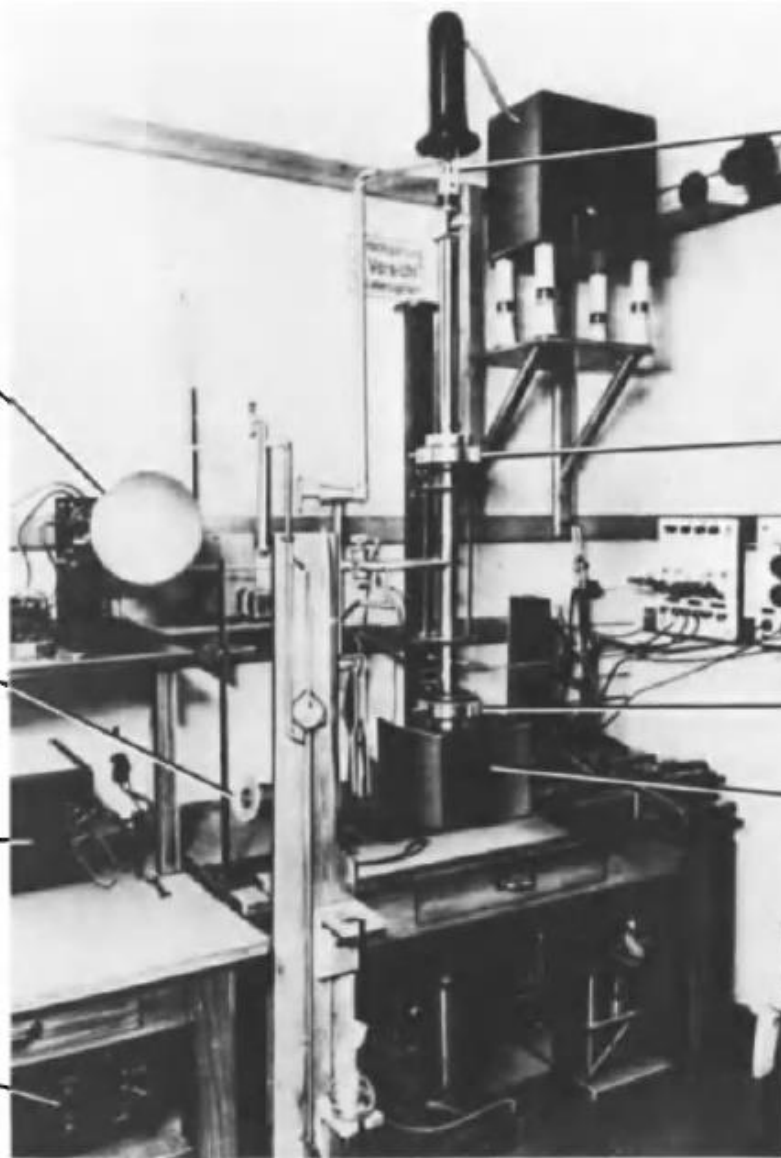


image reproduction tube with a synchronous swept electron beam modulated by the signal of the secondary electrons (long-persistence screen)

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

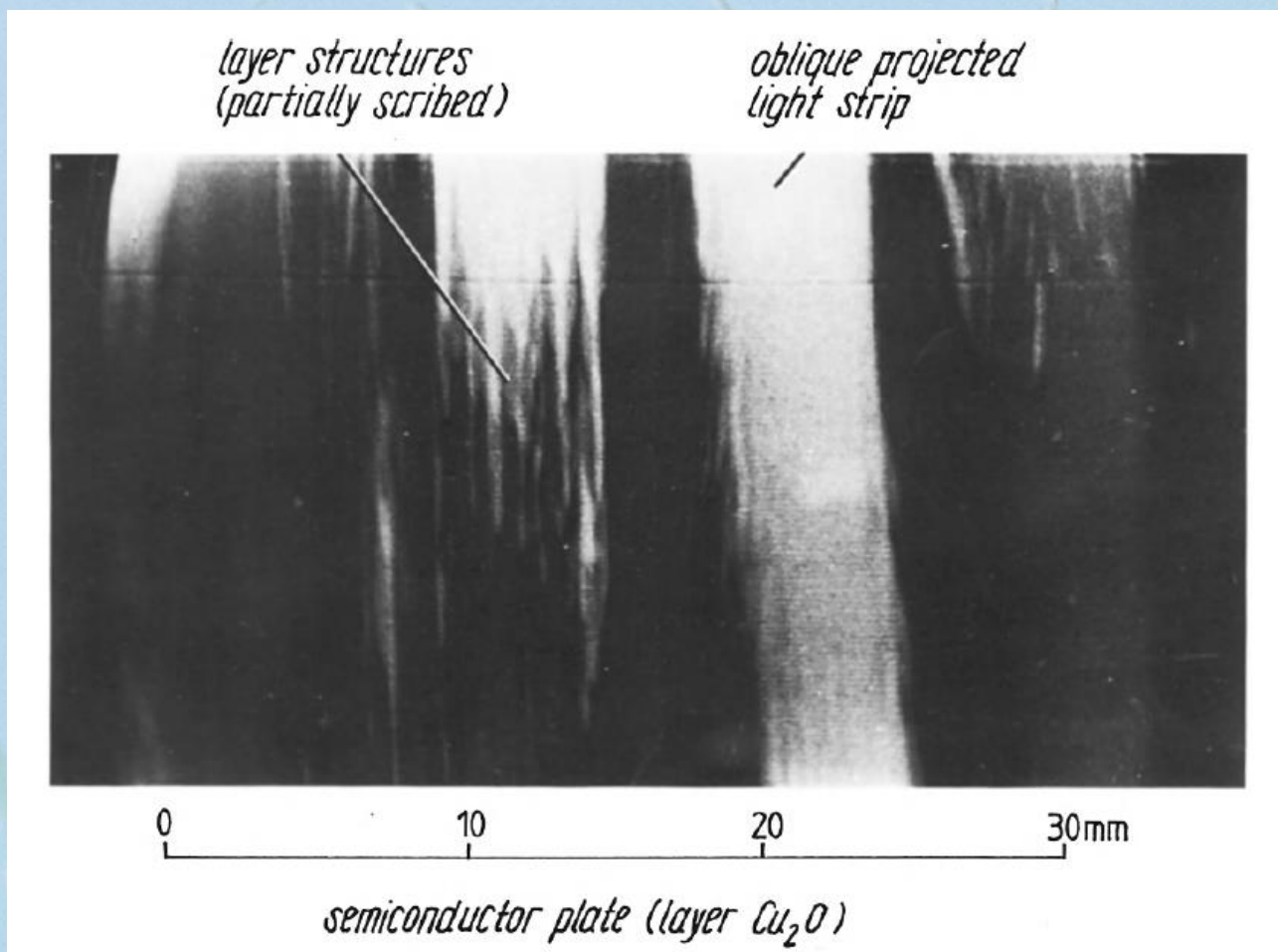
collector unit for the secondary electrons

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



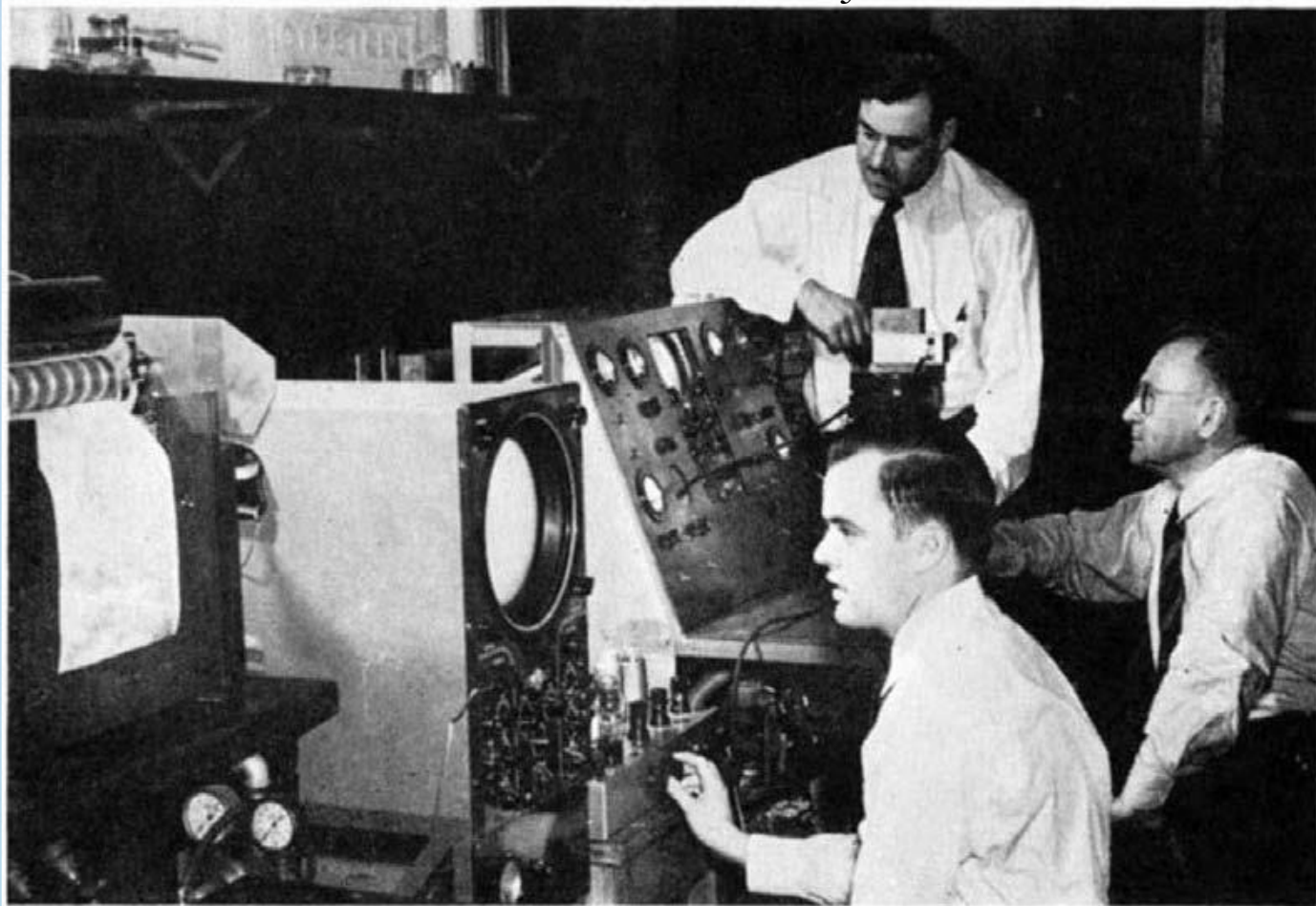
Univerzální
elektronový
mikroskop pro energie
200 až 300 keV, M.
von Ardenne, 1941-43

První BSE skenovací obraz, von Ardenne



USA - Vladimír Kosma Zworykin

James Hillier



V. K. Zworykin

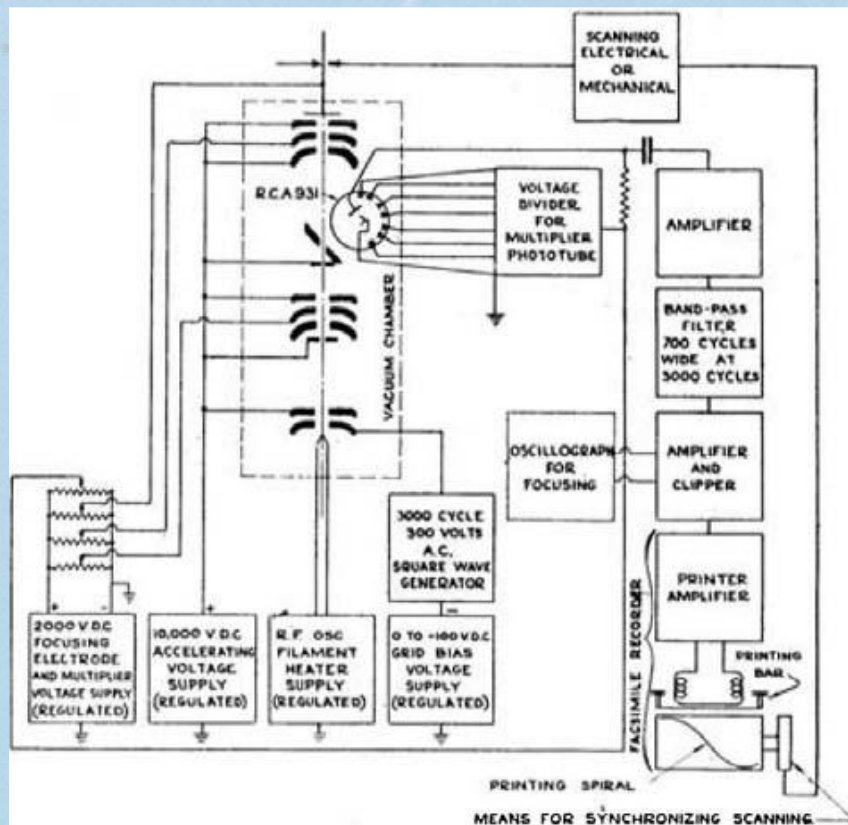
SciAm1942-111

Kopeček - U3V

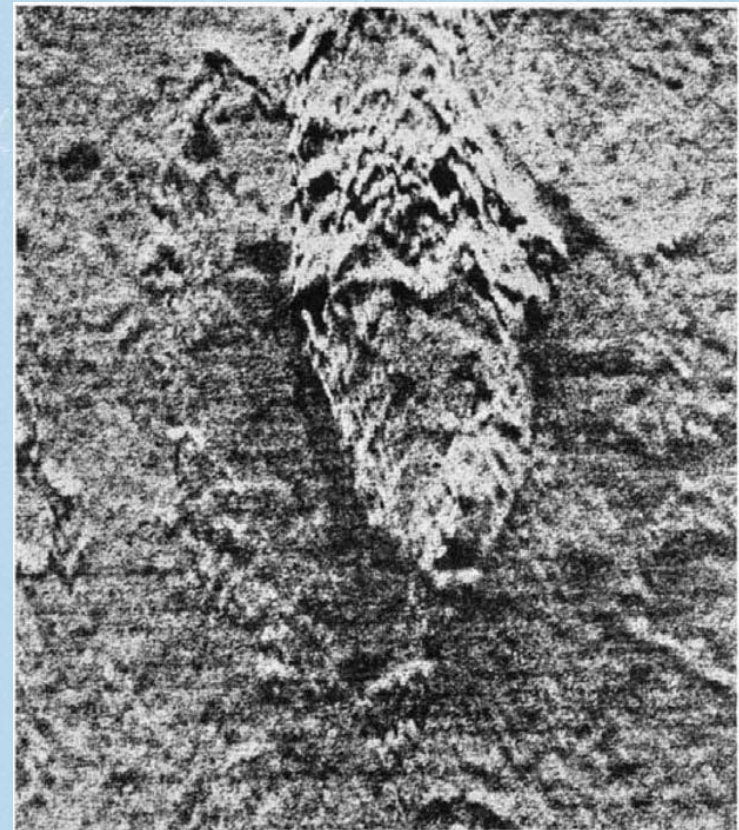
Richard L. Snyder

USA - Vladimír Kosma Zworykin

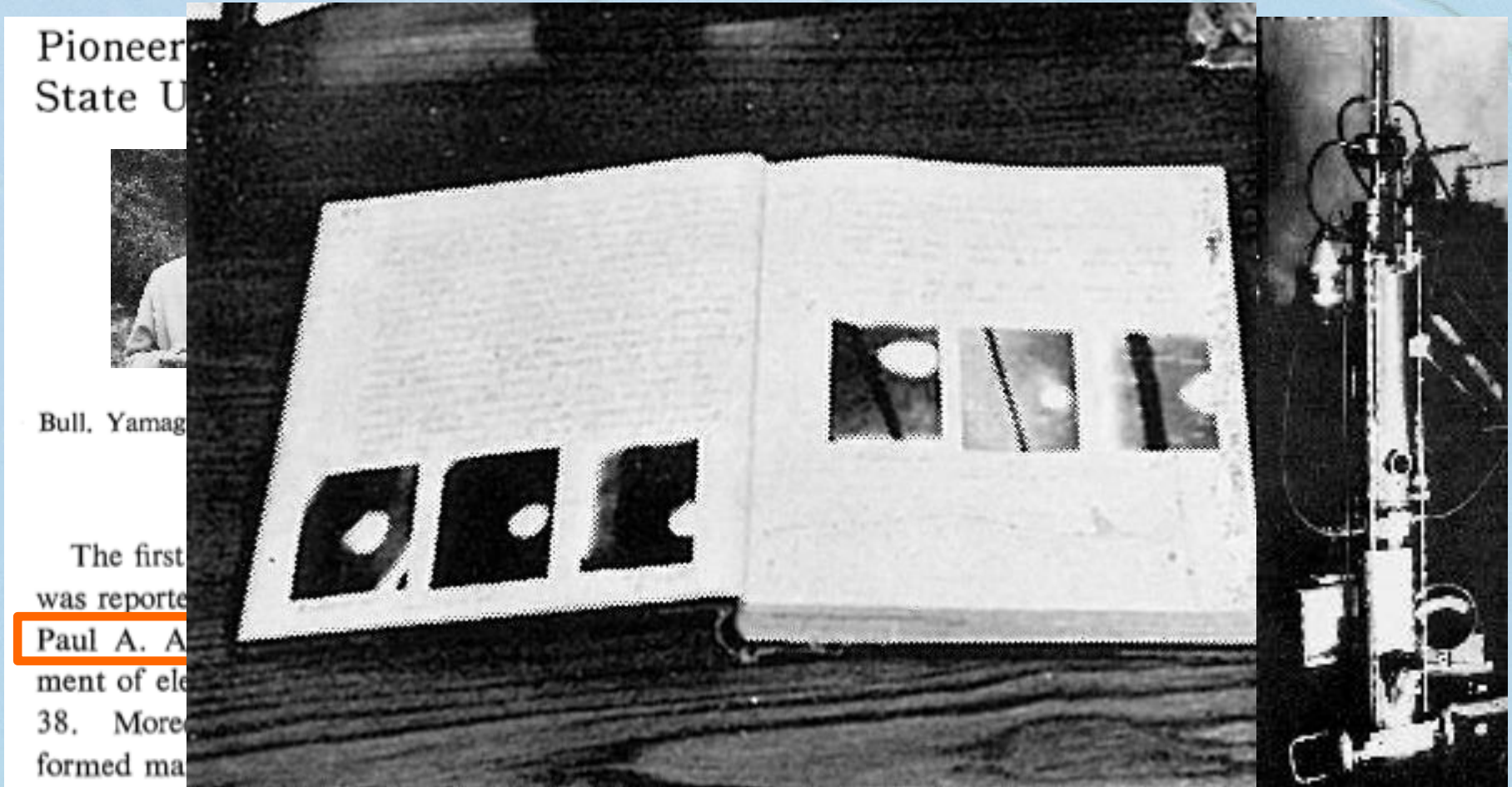
Schéma SEM



Etched brass (leptaná mosaz)



Washington state, USA: 1st EM outside of Germany



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*

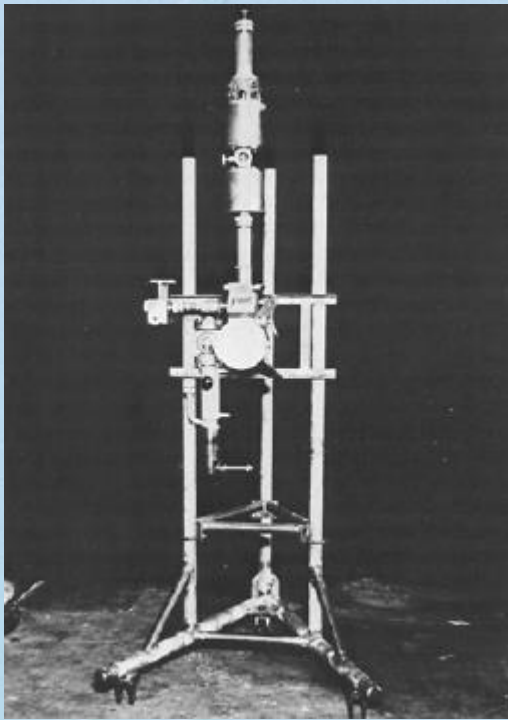
I. Introduction	63
II. Construction of the First Electron Microscope in Czechoslovakia.....	68
III. Desk Transmission Electron Microscope BS 242	69
IV. Production of Electron Microscopes in Czechoslovakia.....	74
V. Conclusion.....	76
Appendix A: Bibliography of Related Publications.....	76
Appendix B: Publications from the Institute of Scientific Instruments of the Czechoslovak Academy of Science in Brno (in Czech).....	77
References	79

I. INTRODUCTION

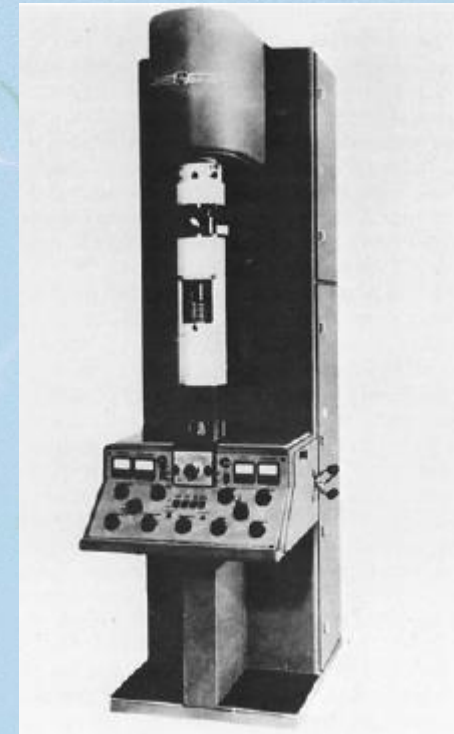
Czechoslovakia, with its 15 million inhabitants, ranges among the relatively small countries of Central Europe. On the average, there are some 0.36 ha. of soil, 0.32 ha. of woods, 0.15 automobiles, and not more than 0.000034 electron microscopes per citizen in the country. In other words, one electron 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



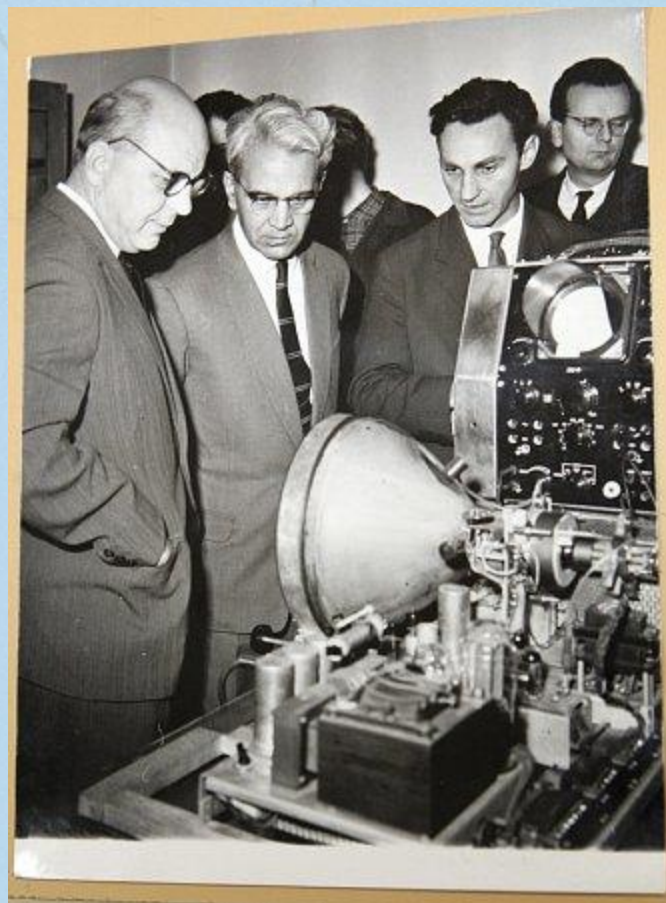
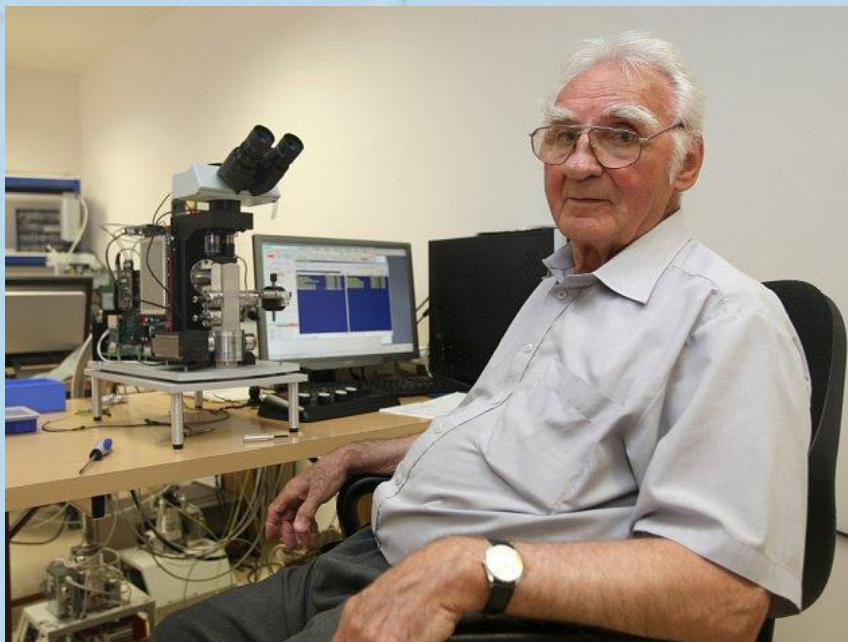
1. Elektronový mikroskop
vyrobený v ČSR



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>

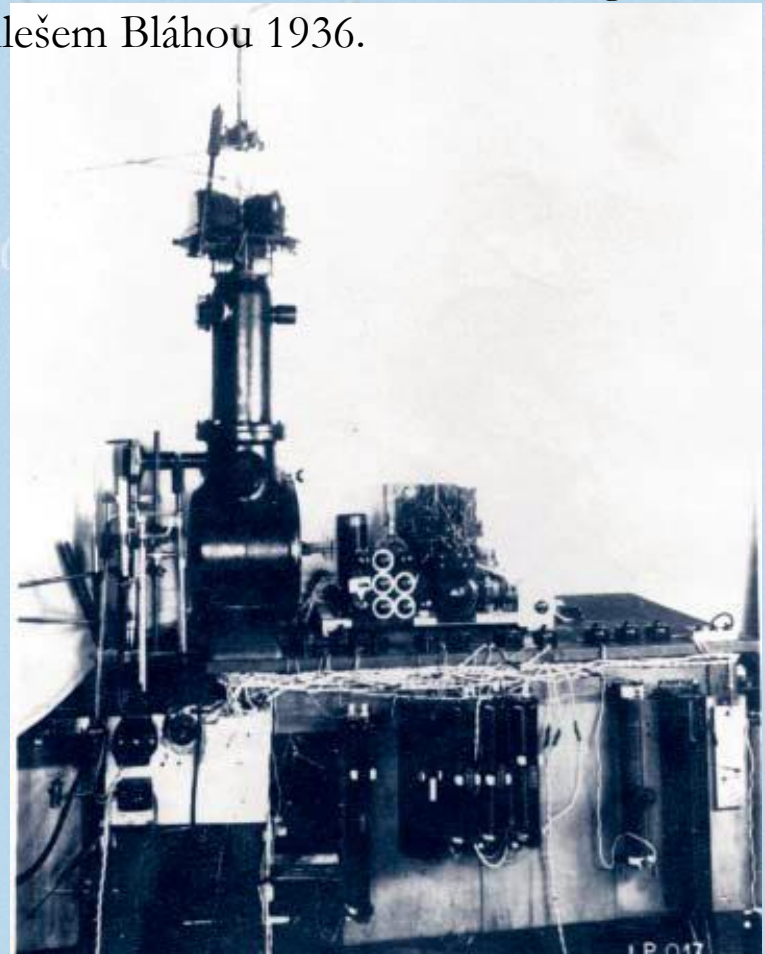
Delong Instruments: <http://www.delong.cz/>

Delong Instruments



Aleš Bláha (1906 – 1986)

První model elektronového oscilografu sestavený Alešem Bláhou 1936.

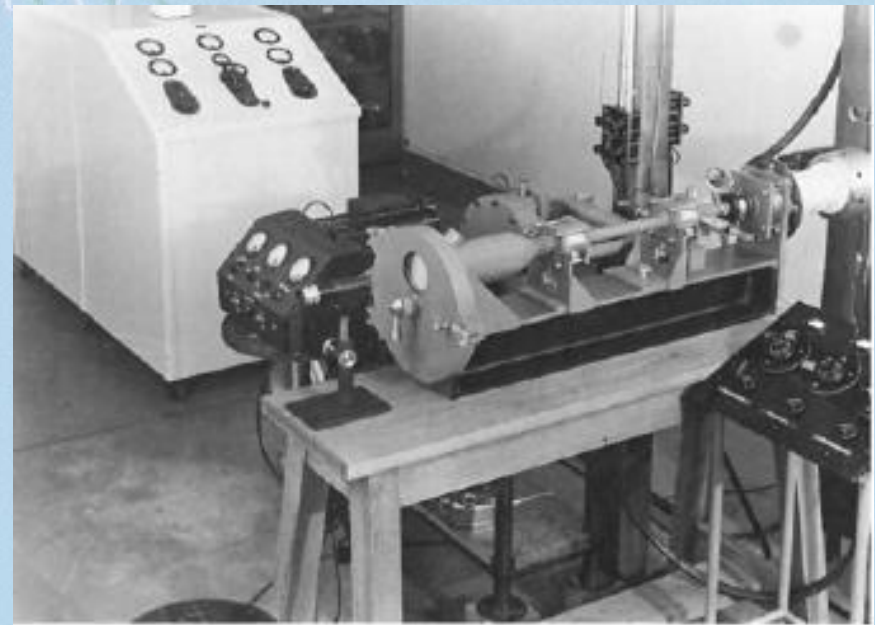


Historie EM v Evropě

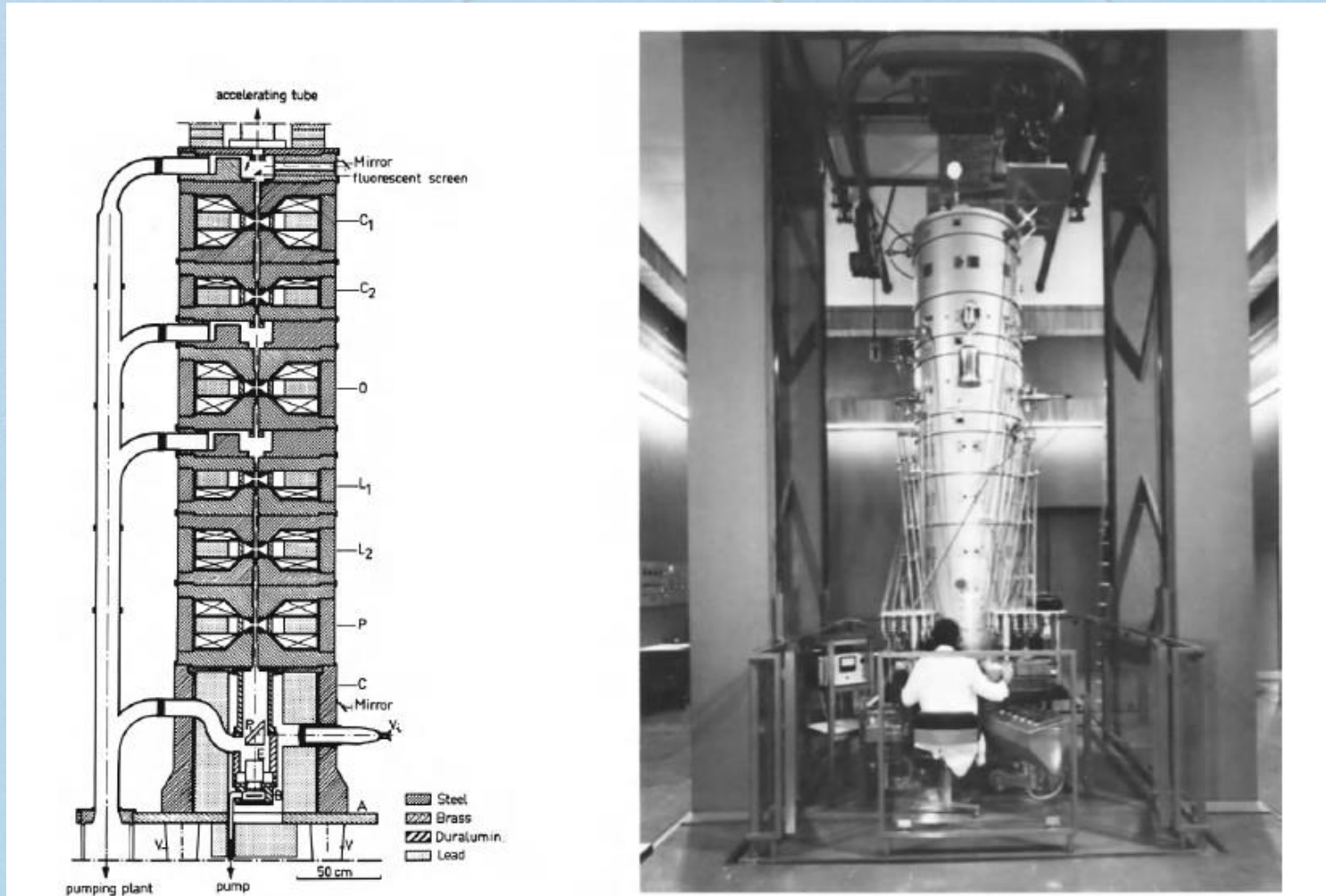
Toulouse, 1942



Siegbahn-Schönanderův
electronový mikroskop,
Stockholm, okolo 1943.



Francie 3MeV SEM



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

TEM, MeV

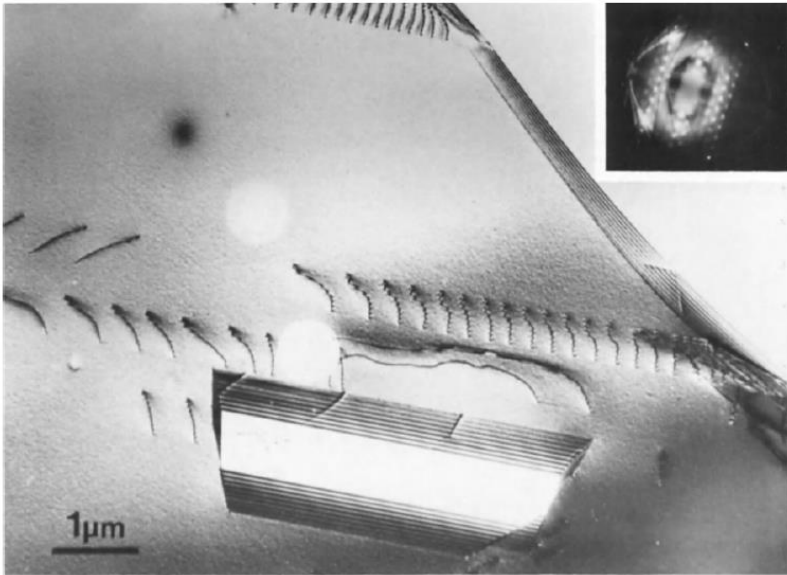


FIG. 15. Stainless steel: twin boundary dislocations; diffraction pattern from the overprinted selected area; $V = 1$ MV.

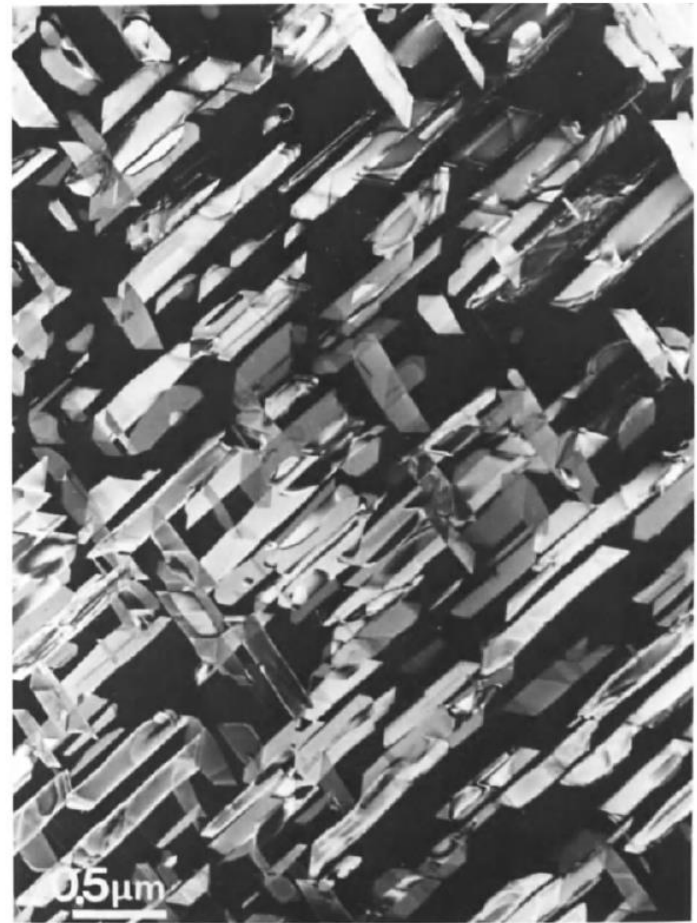


FIG. 21. First image obtained at 2 MV: precipitates in an Al-Cu alloy.

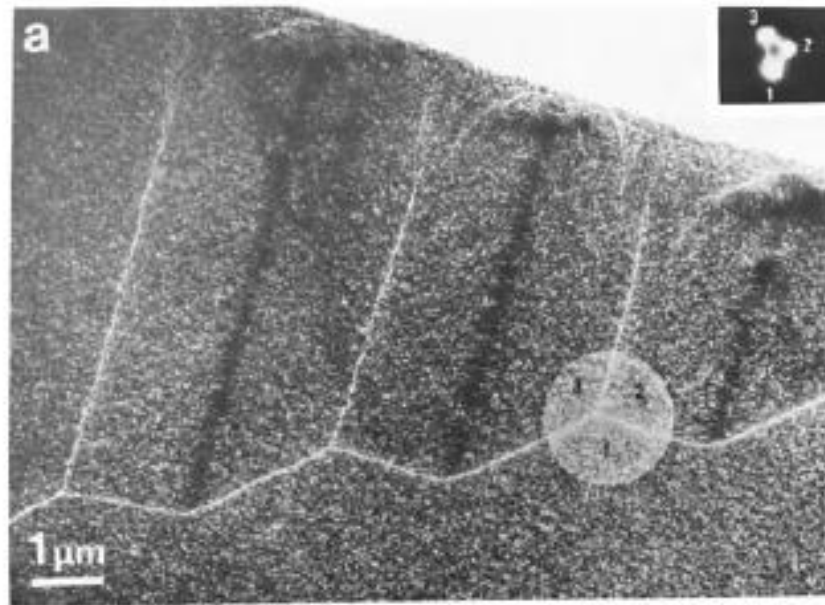


FIG. 27. (a) Defocused image of an Fe-Si alloy specimen showing three magnetic domains. (b) The domain corresponding to spot 3.

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

EM v biologii

ARKIV FÖR ZOOLOGI.

BAND 40 A. N:o 6.

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.**

Kopeček - U3V

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

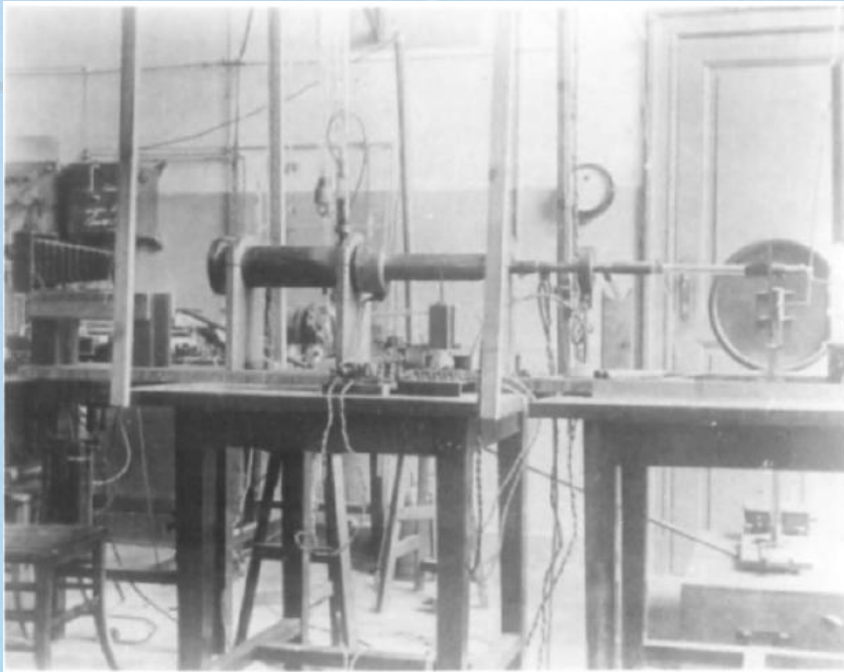


FIG. 2. Marton's No. 2 electron microscope (Brussels, 1934).

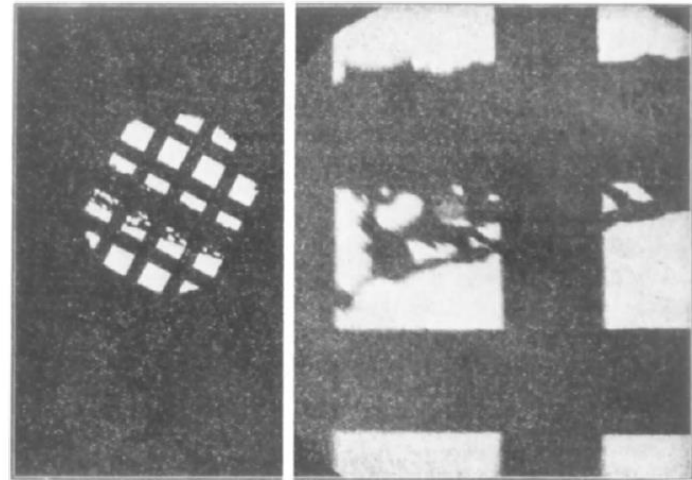
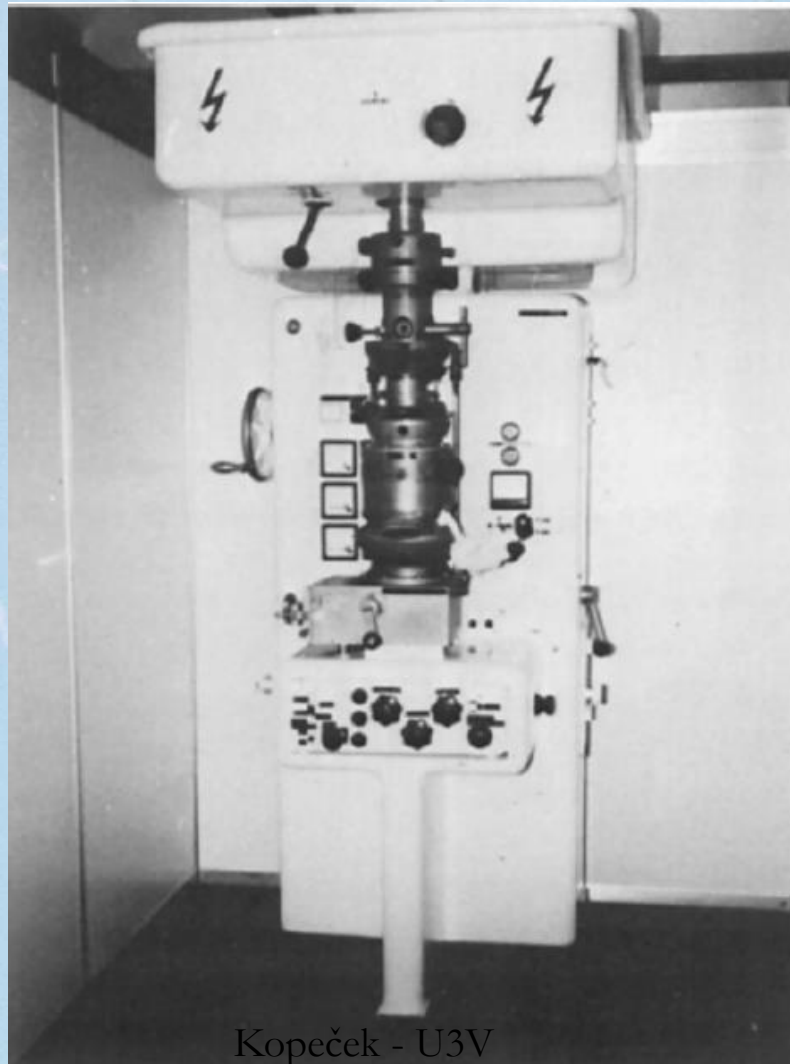


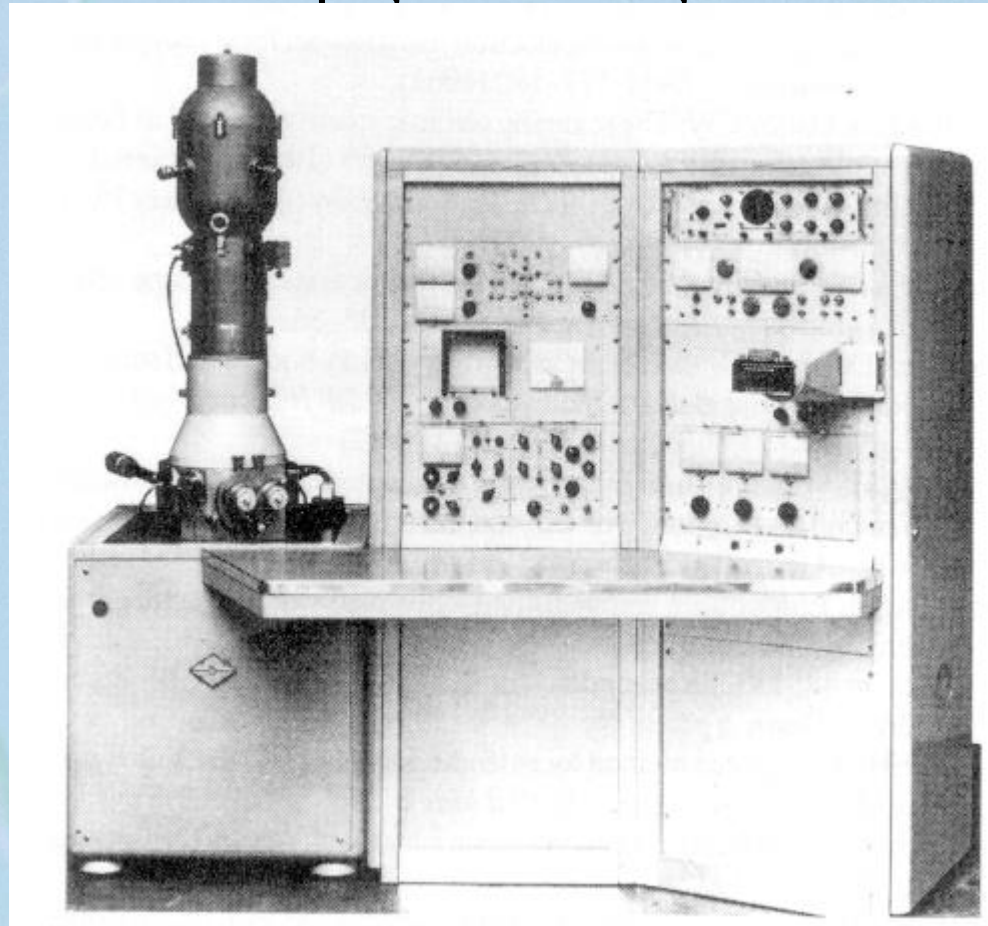
FIG. 3. First electron micrographs of biological sample (15- μ m-thick slice of *Drosera intermedia* leaf on copper net), April 4, 1934.

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



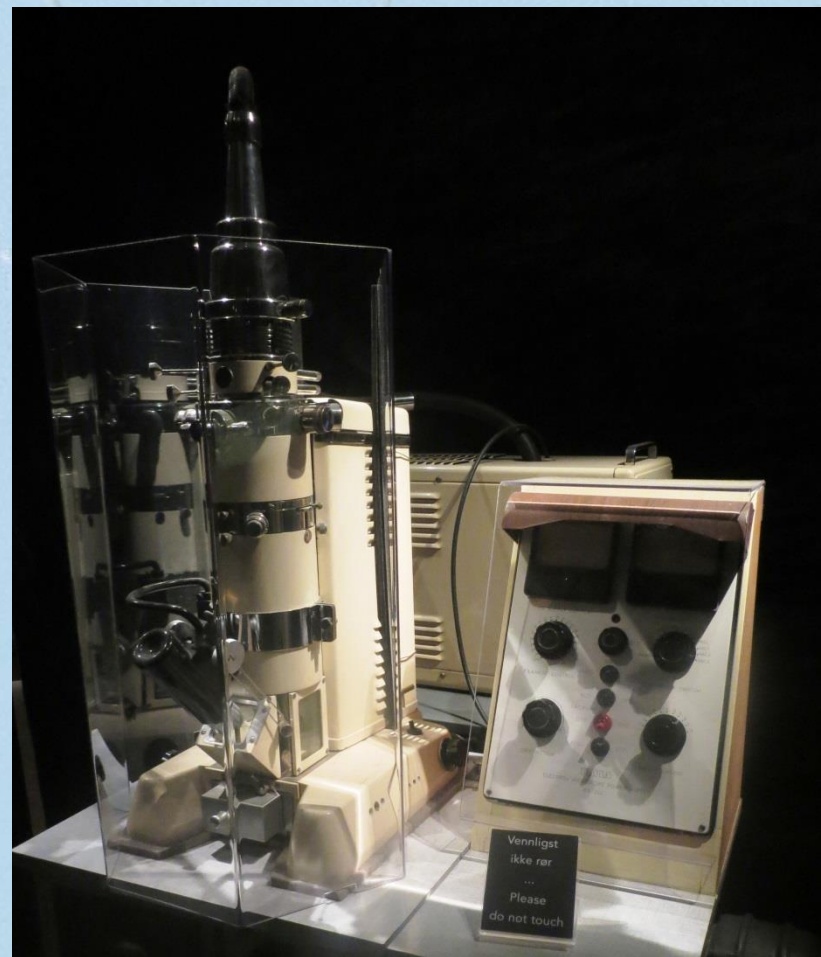
Kopeček - U3V

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



*1953
rok
výroby!*

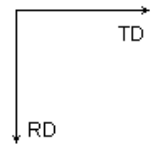
Tesla BS 242 oceněný 1958 v Bruselu



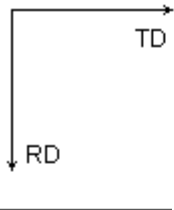
Další, „analytické“ metody doprovázející v instalacích SEM

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

Ocel A



0000 °C



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

Color Coded Map Type: <none>

Gray Scale Map

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

Color Coded Map

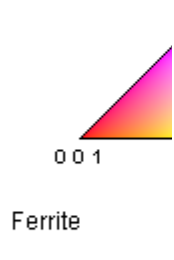
Gray Scale Map Type: <none>

Austenite

Color Coded Map Type: <none>

Boundaries: CSL

	Sigma	Tolerance	Fraction	Volume	MDF Value	Number	Length
	3	8.66	0.239	0.0176	13.61	61273	7.07519 cm
	9	5.00	0.025	0.0102	2.48	6447	7.44435 mm
	5	6.71	0.006	0.0123	0.50	1566	1.80826 mm
	7	5.67	0.006	0.0099	0.57	1448	1.67201 mm
	11	4.52	0.006	0.0075	0.76	1461	1.68702 mm
	13a	4.16	0.002	0.0029	0.56	418	482.665 microns
	13b	4.16	0.003	0.0039	0.68	676	780.577 microns
	15	3.87	0.005	0.0094	0.53	1287	1.4861 mm
	17a	3.64	0.001	0.0020	0.41	205	236.714 microns
	17b	3.64	0.003	0.0039	0.76	766	884.5 microns
	19a	3.44	0.002	0.0033	0.63	536	618.919 microns
	19b	3.44	0.002	0.0022	0.72	405	467.654 microns
	21a	3.27	0.001	0.0019	0.66	323	372.968 microns
	21b	3.27	0.003	0.0057	0.52	755	871.799 microns
	23	3.13	0.002	0.0050	0.45	579	668.571 microns
summary	-	-	0.305	0.0976	3.13	-	-



	Min	Max
	0	20
	20	50
	50	100
	100	500
	500	1000
	1000	50000

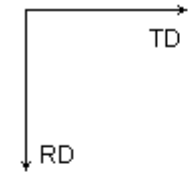
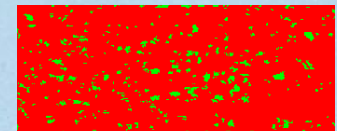
Boundaries: Rotation Angle

	Min	Max	Fra
	15°	180°	0.9

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

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

Boundaries: <none>

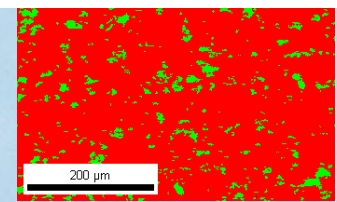


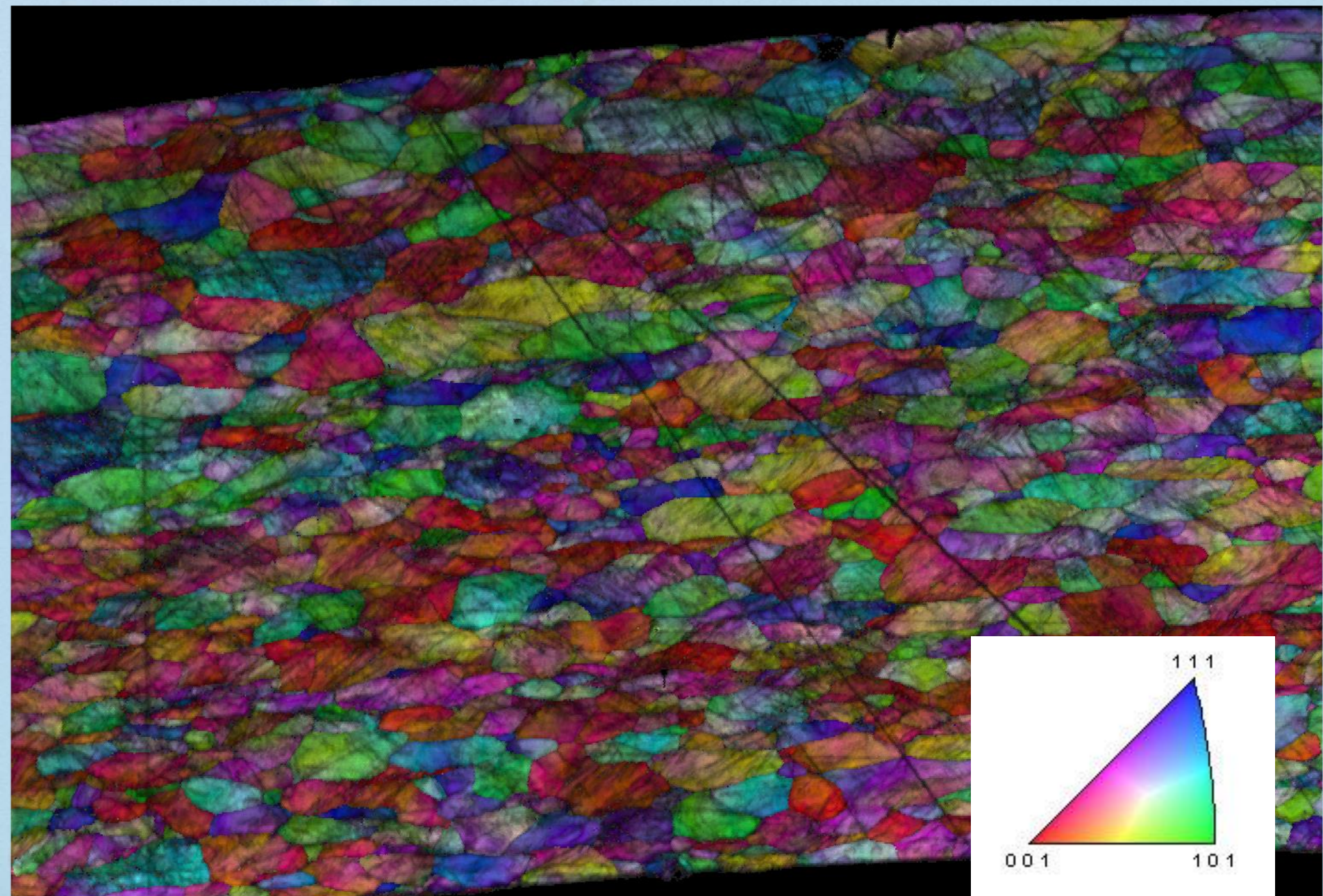
Gray Scale Map Type: <none>

Color Coded Map Type: Phase

	Phase	Total Fraction	Partition Fraction
	Austenite	0.909	0.909
	Ferrite	0.091	0.091

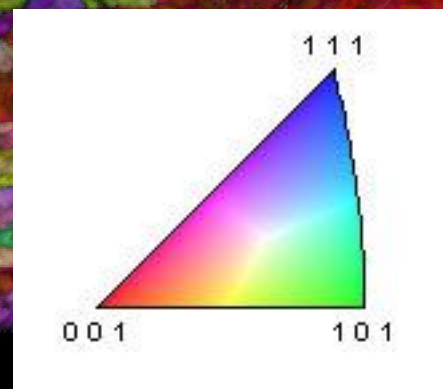
Boundaries: <none>



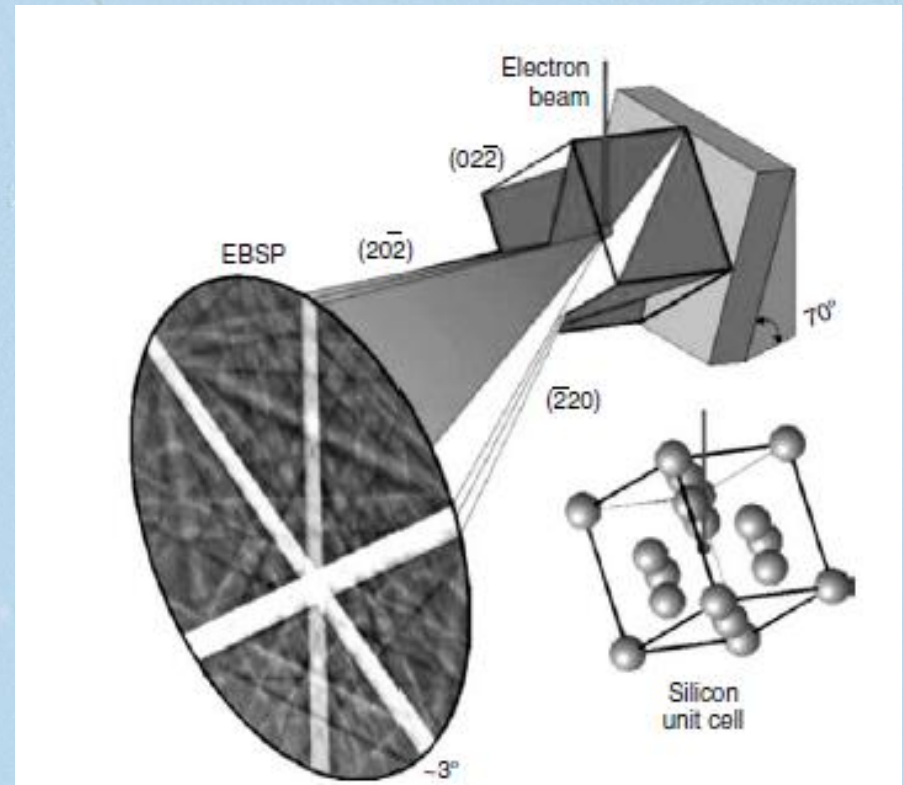
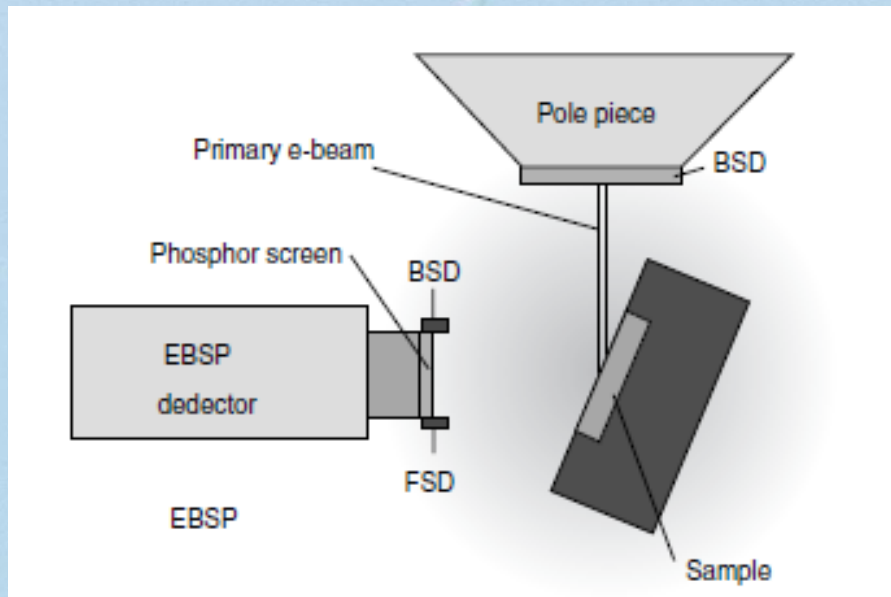


100 μm

Phase Map

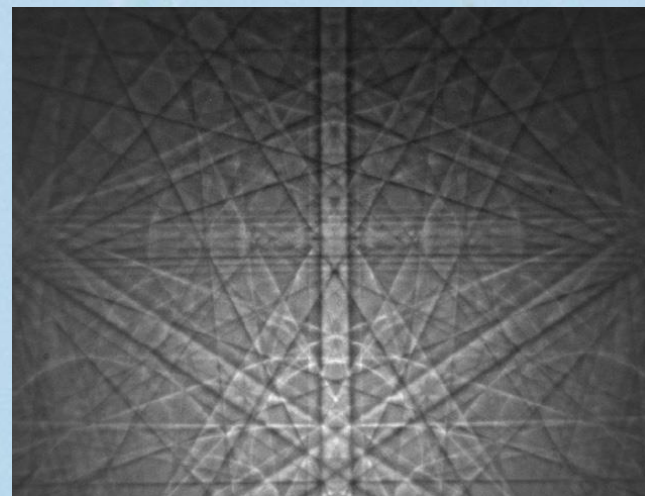
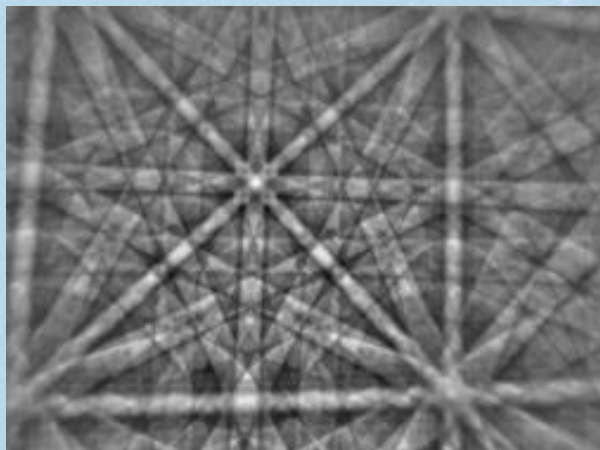
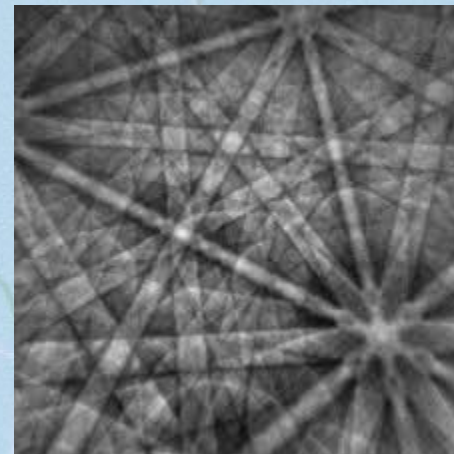
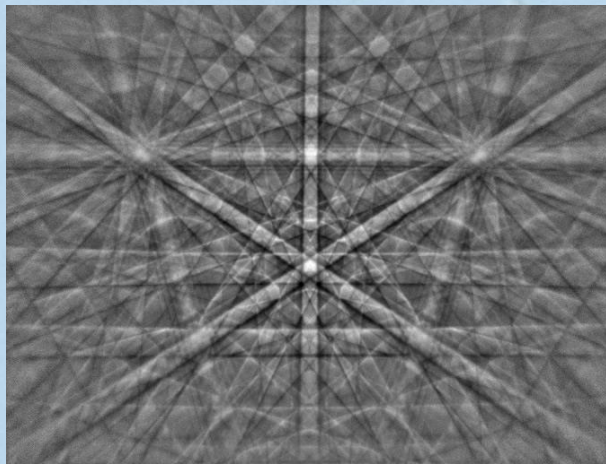


EBSD – principy a pozice detektorů



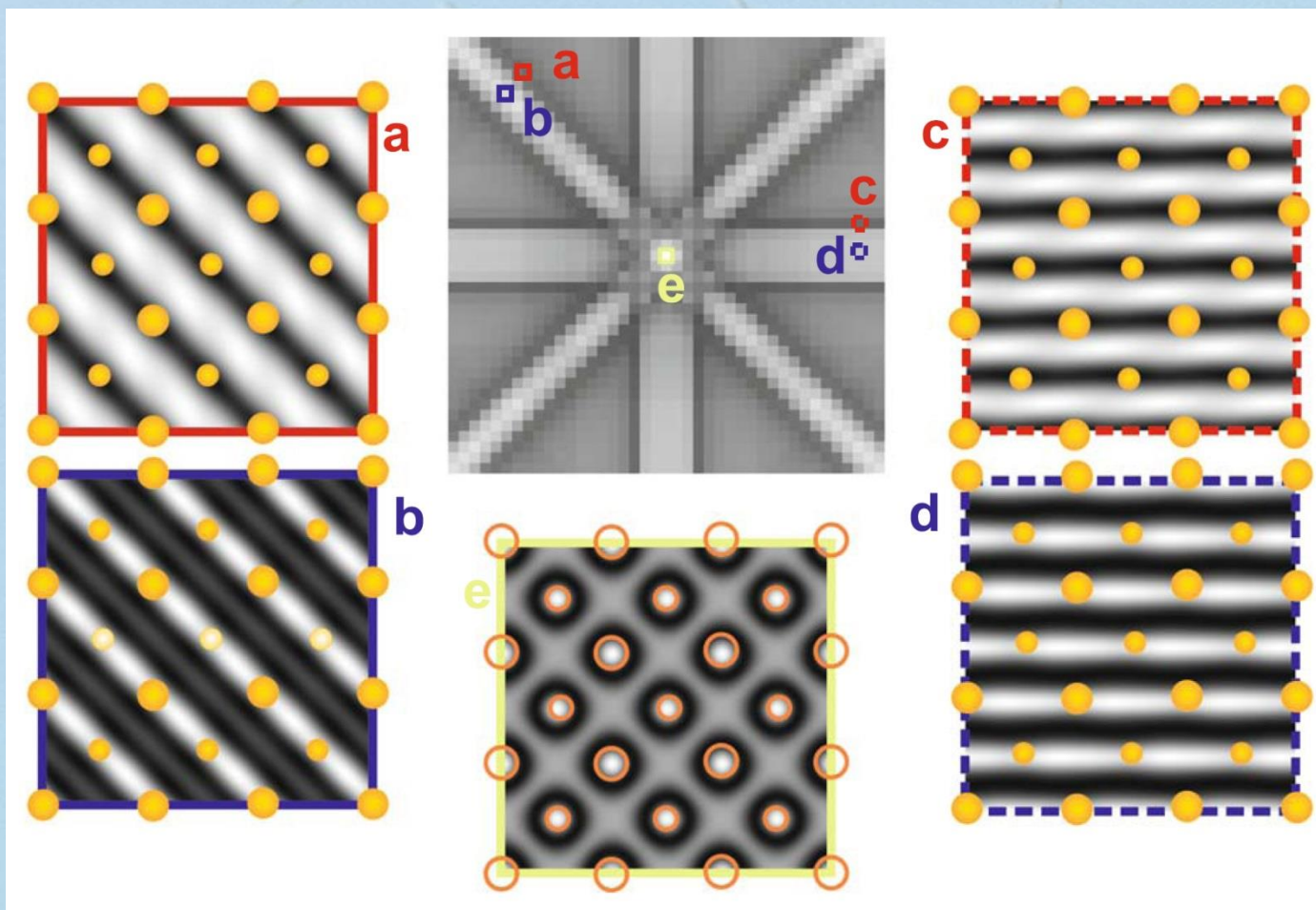
Scanning Microscopy for Nanotechnology Techniques and Applications - Weilie Zhou, Zhong Lin Wang (Eds), Springer Science+Business Media, LLC, 2006

Kikuchiho obrazce



Modelování EBSP obrazců

9-i svazkový model



Krátká historie EBSD

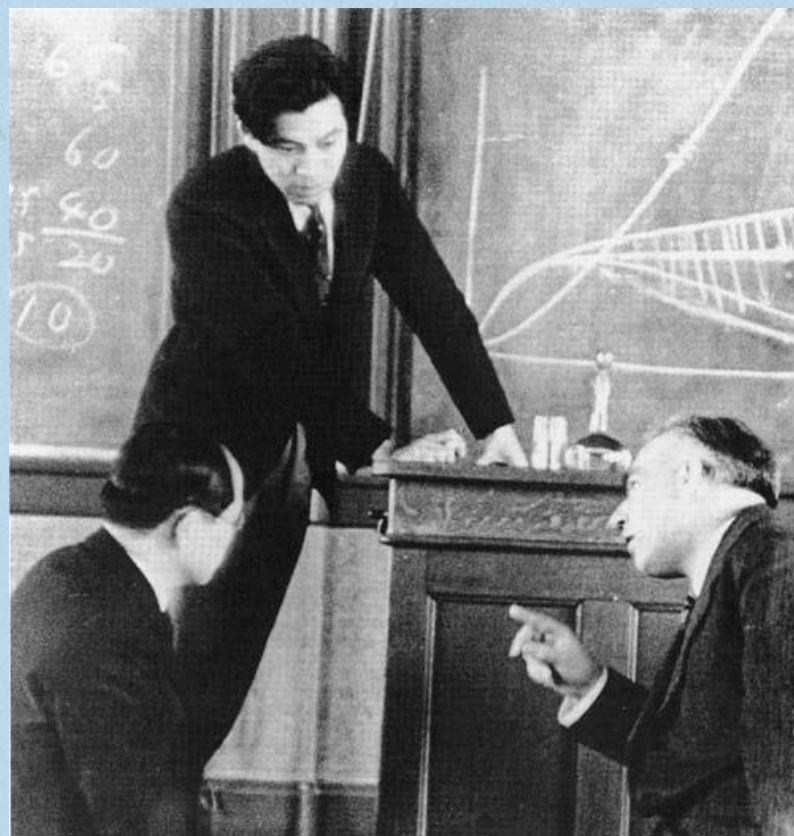
- 1928 Shoji Nishikawa, Seishi Kikuchi – kalcit, 50 KeV elektrony z plynového z výboje
- 1972-1979 John Venables
- 1979-1988 Bristol group – computerisation (D.J. Dingley)
- 1988-2006 OIM (Yale Univ, TSL, HKL)
- 1992 Použití Houghovy transformace pro vyhodnocení Kikuchiho obrazců
- 2006-2012 HR-EBSD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

Něco z historie metody EBSD

Vůbec první Kikuchiho linie pozorované Kikuchim 1927 v kalcitu.



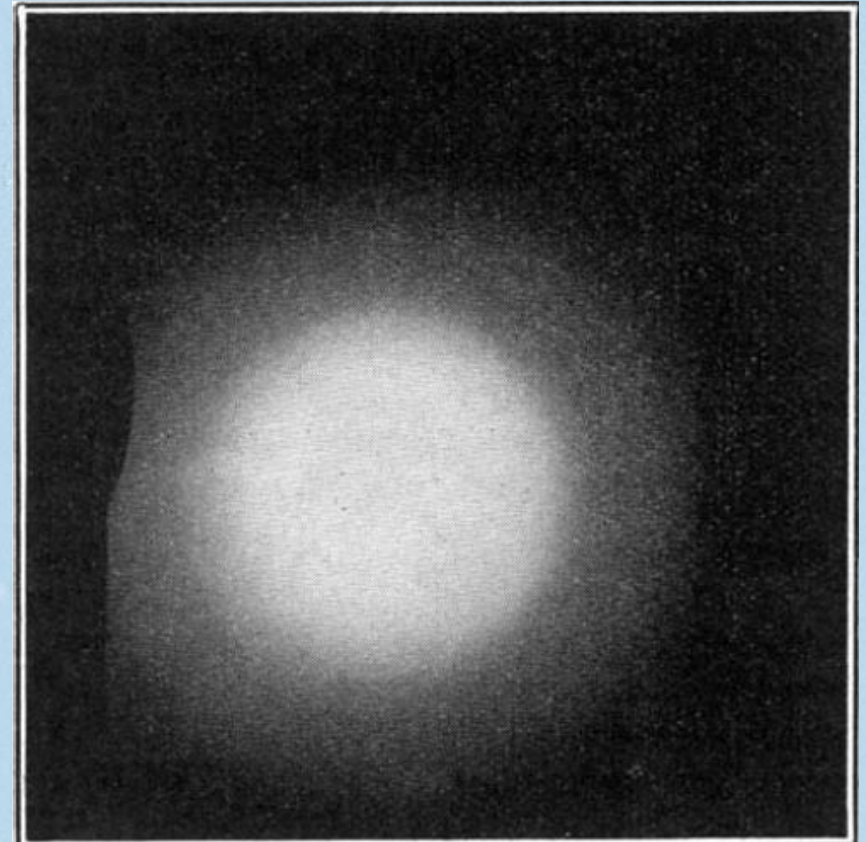
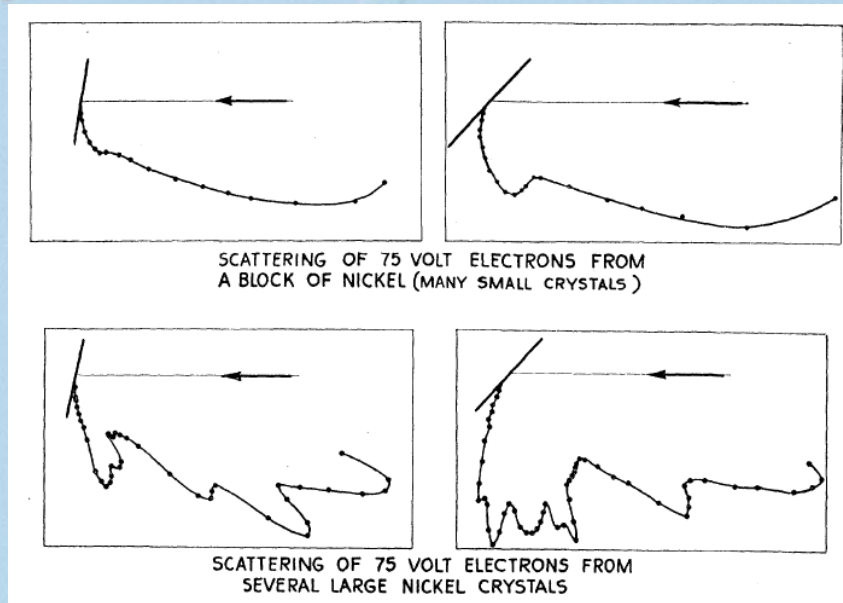
Seishi Kikuchi (*standing*).



Difrakce elektronů

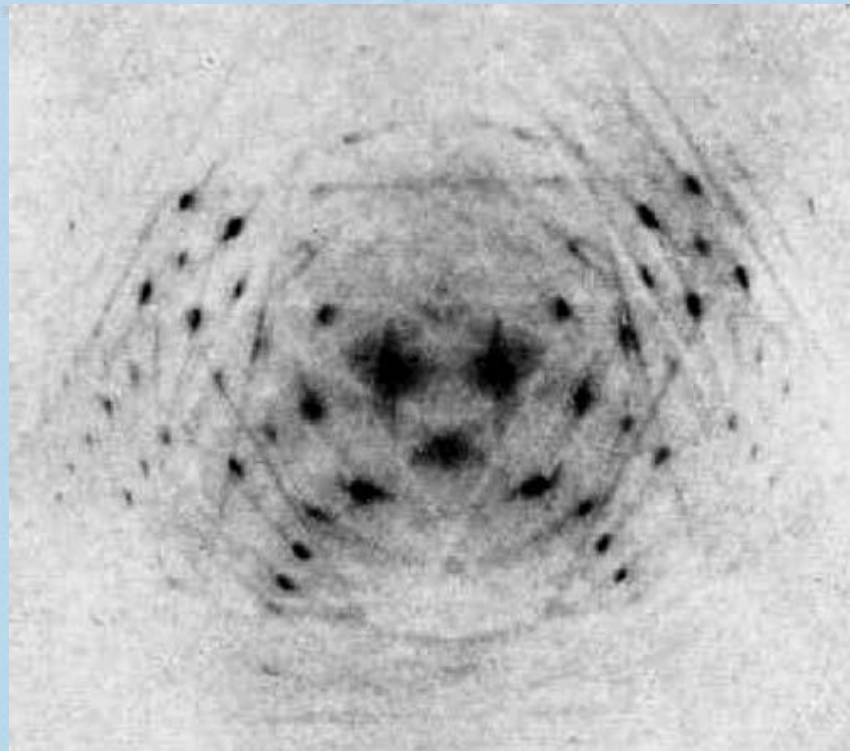
Nobelova cena 1937, za objevy v roce 1927

Clinton Joseph Davisson a George Paget Thomson

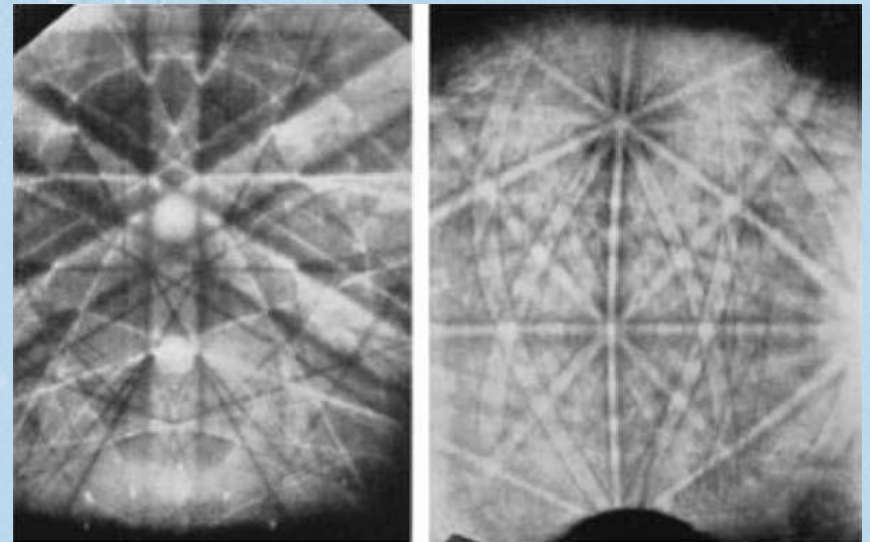


Něco z historie metody EBSD

Kikuchi P-pattern from mica.



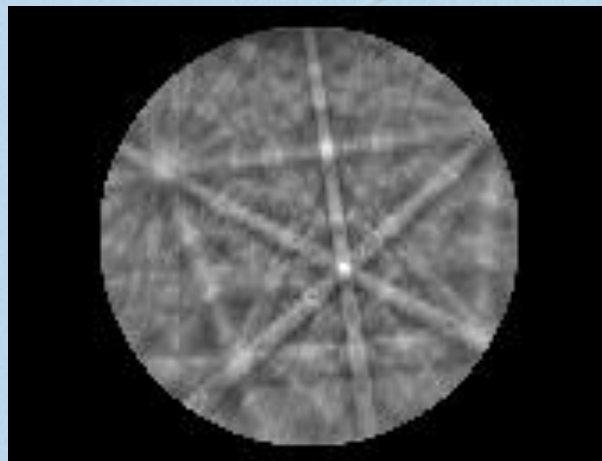
Boersch 1937 Iron Kikuchi patterns.



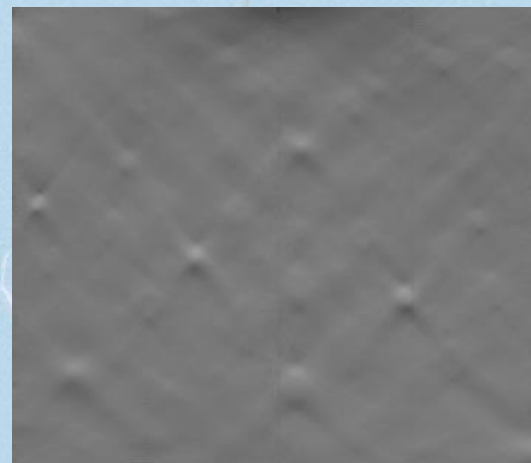
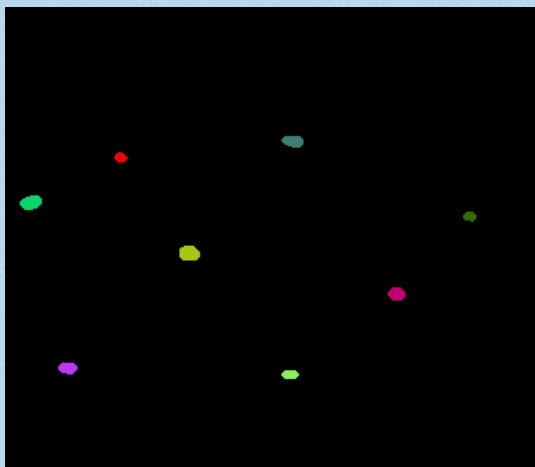
Jak se Kikuchiho linie vyhodnocují?

Body 1 - 2

Kikuchiho obrazec



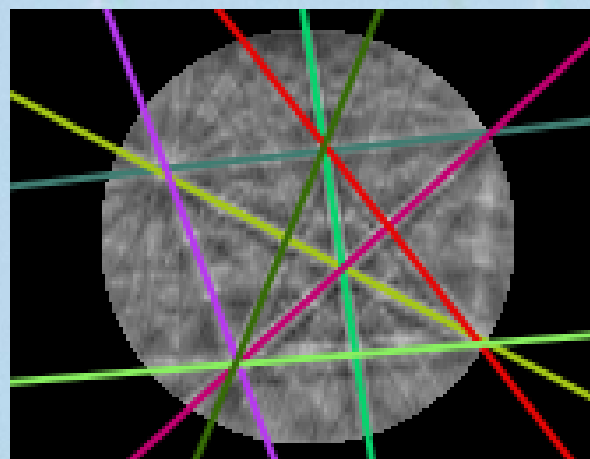
Nalezení píků a stanovení jejich intenzity



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.

Retrieved 16 December 2011.

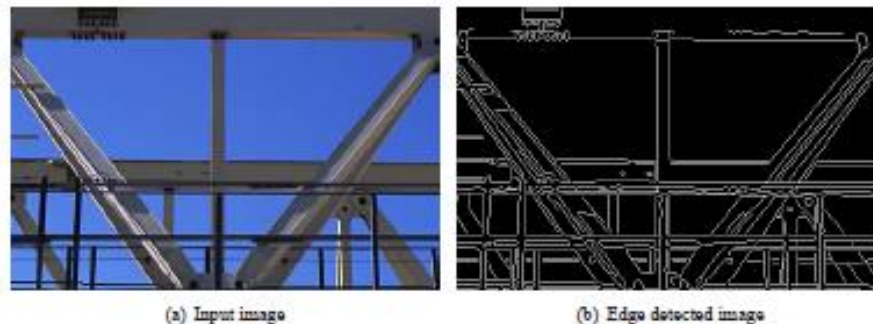


Figure 2: An example with an input image and the result of the edge detection, using the Canny edge detection.

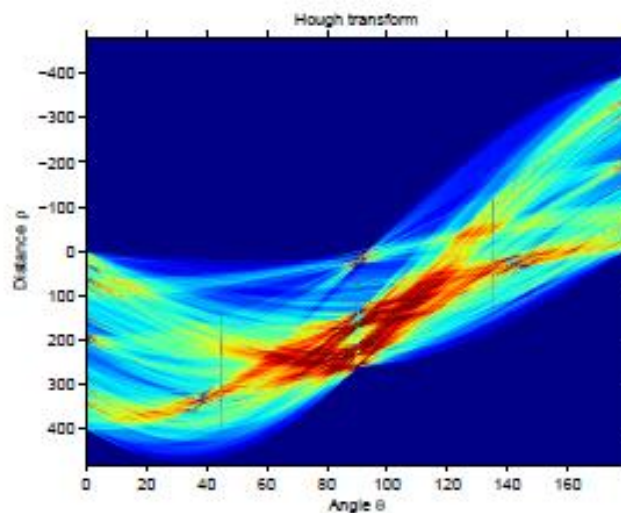
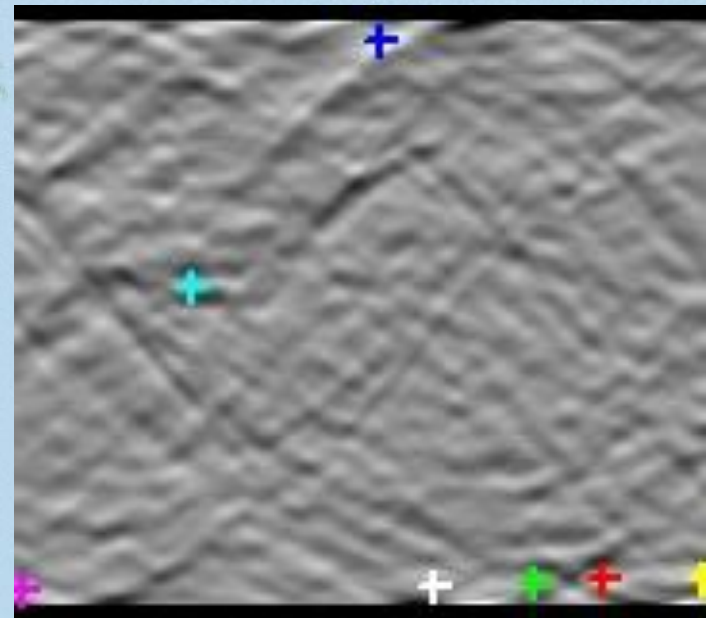


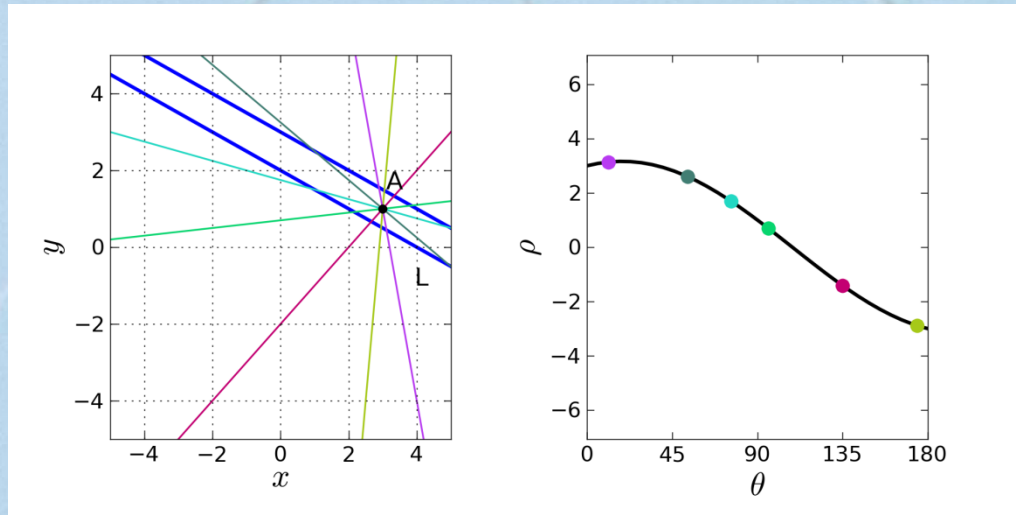
Figure 3: The Hough space of the input image in Figure 2. The dark red points are the points with the highest number of intersections. Many dark red points are around 90 degrees, i.e. that the image has many horizontal lines.

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.

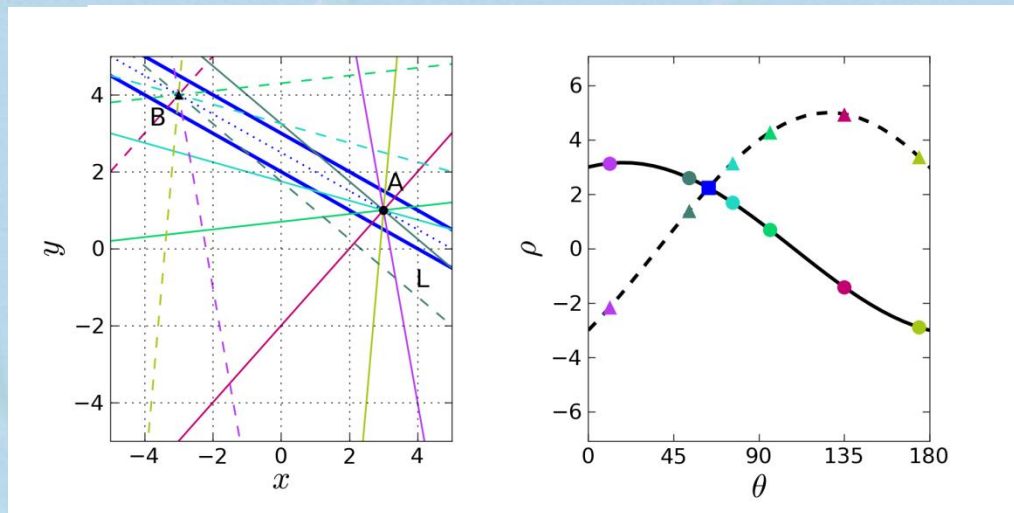
Kikuchiho linie – zpět ke kořenům



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“.

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

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

δ -funkce zajišťuje nenulovost na přímce.

Houghova transformace

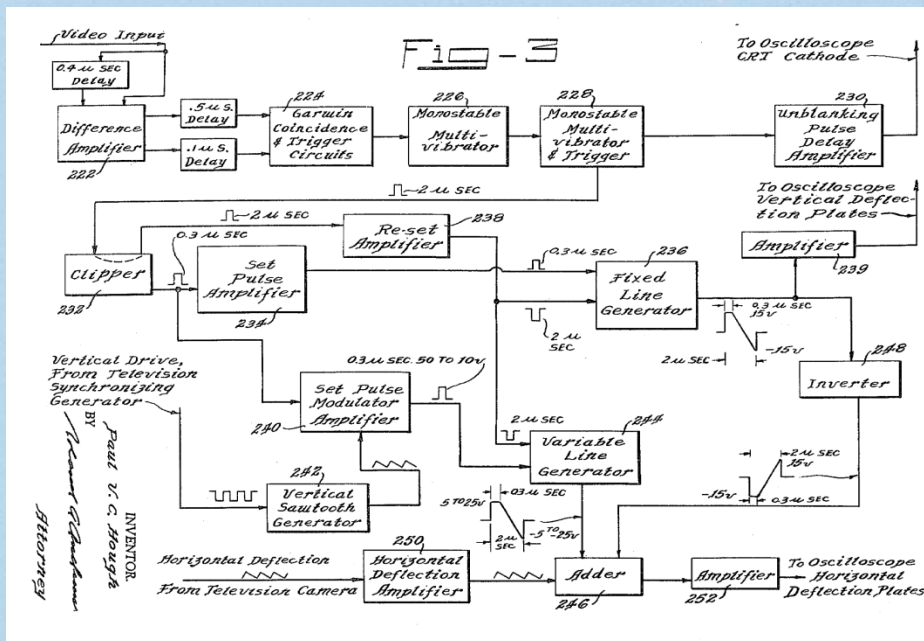
Paul V. C. Hough

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

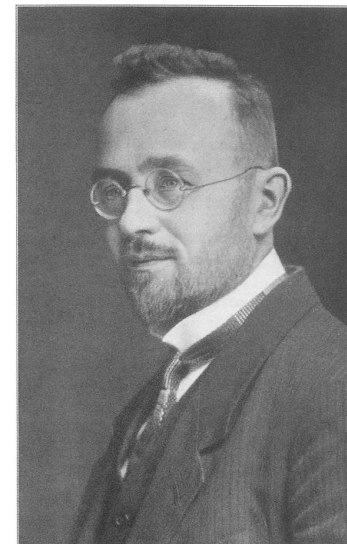
Je zobecněním Houghovy transformace a také je starší.

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

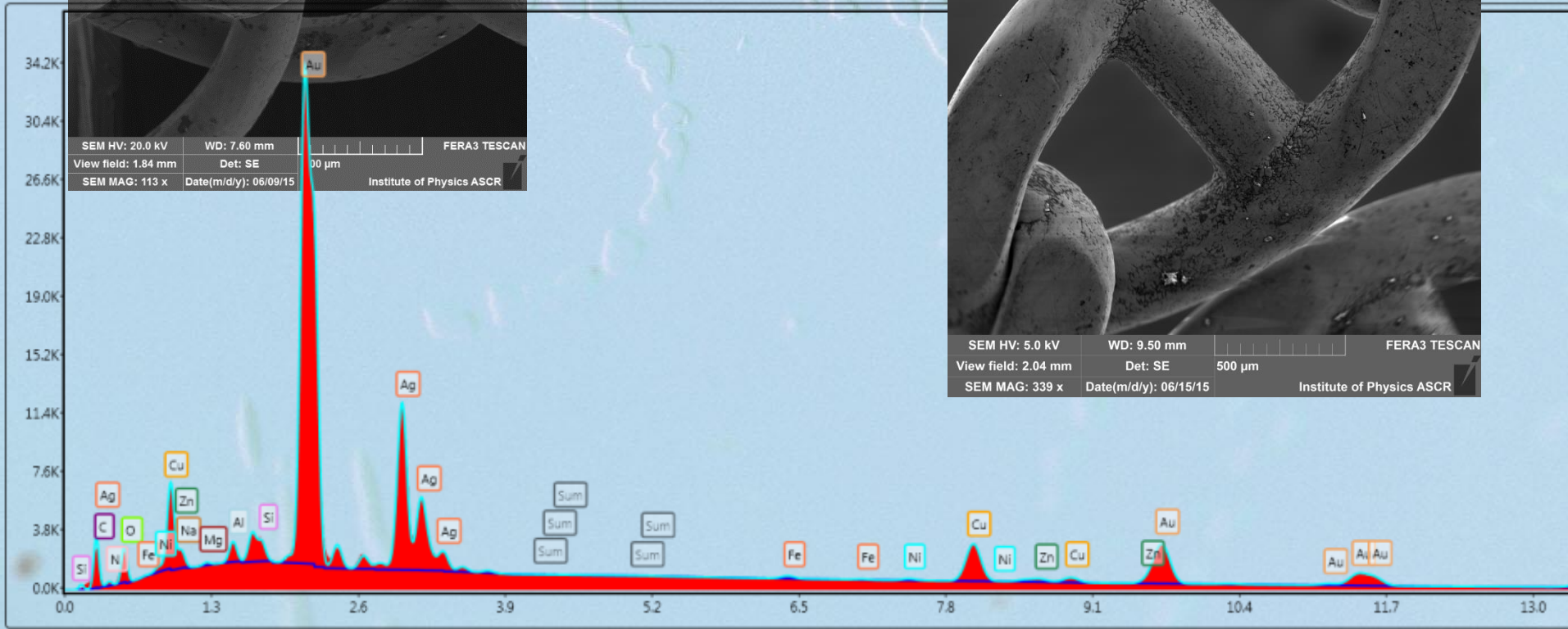
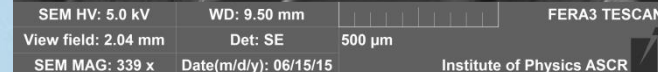
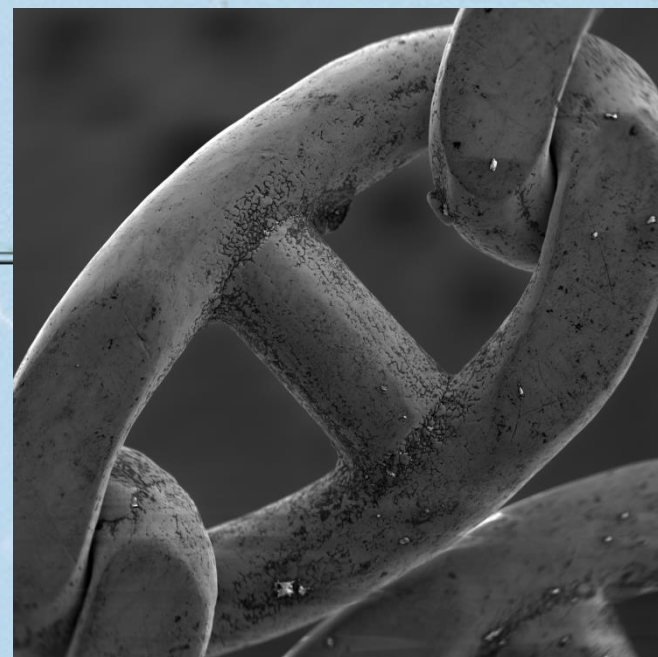
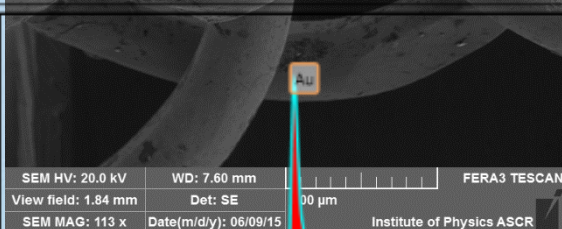
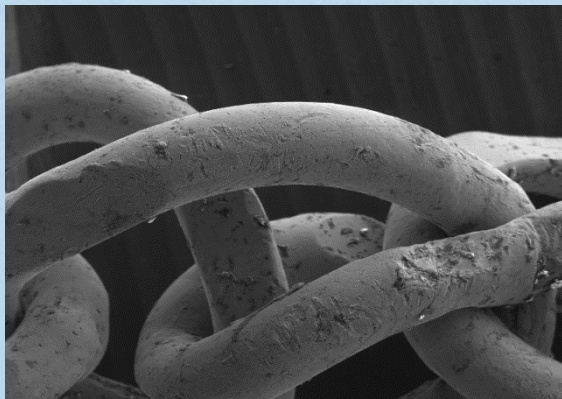
Dva přístupy

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

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

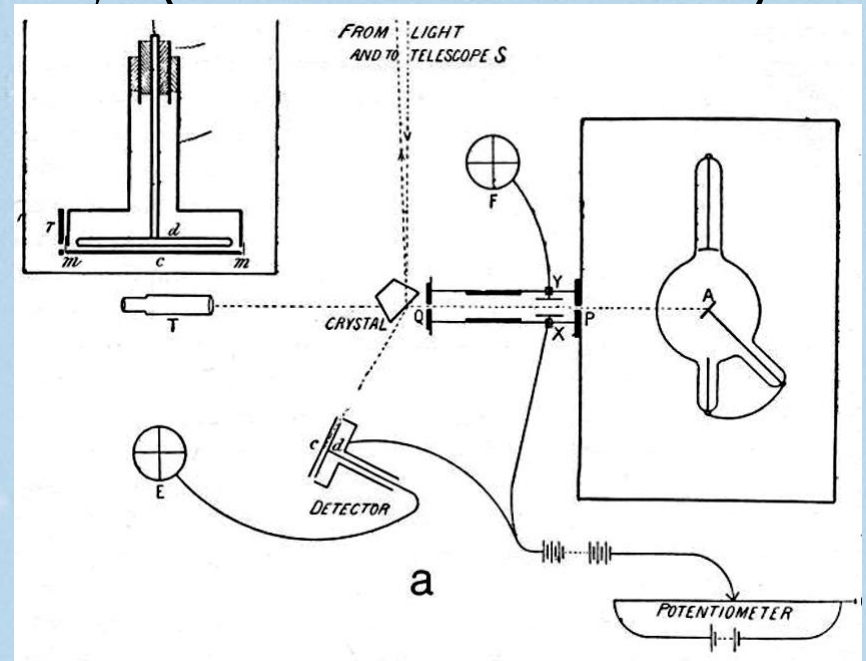
Výsledkem pak, že jsme nespokojeni buďto s rozlišením prostorovým nebo energiovým.

Analýza složení



Prvkové složení zkoumaných materiálů - EDS

Henry G. J. Moseley (1887 – 1915)



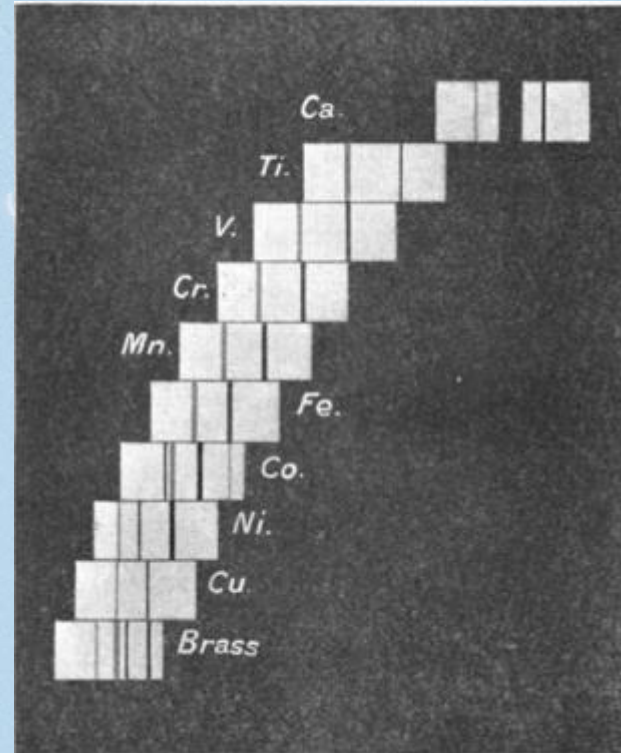
Objev – Moseley 1913

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

[Plate XXIII.]

IN 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.

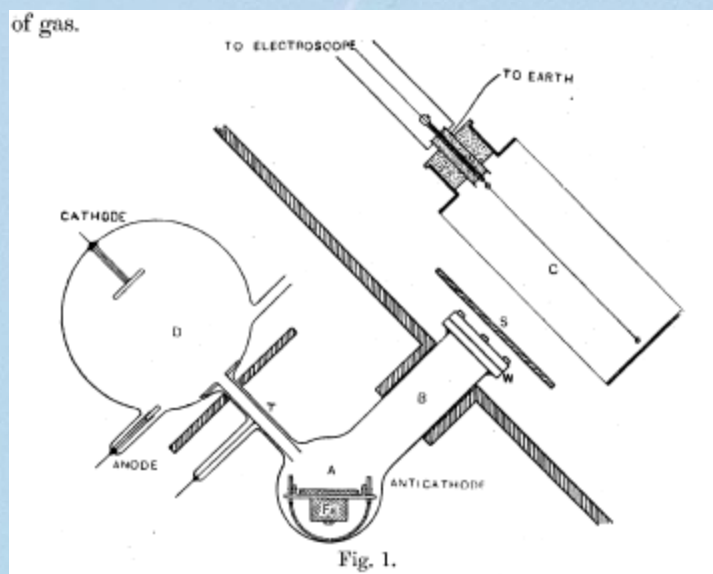
PhilMagSerie6-26-156-1024



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



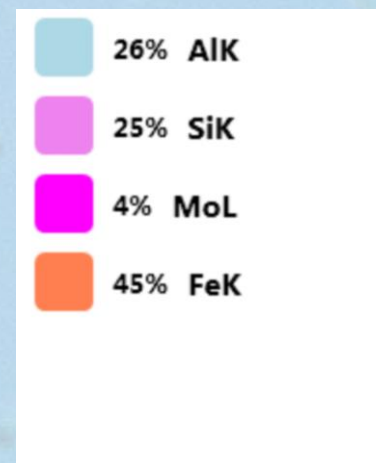
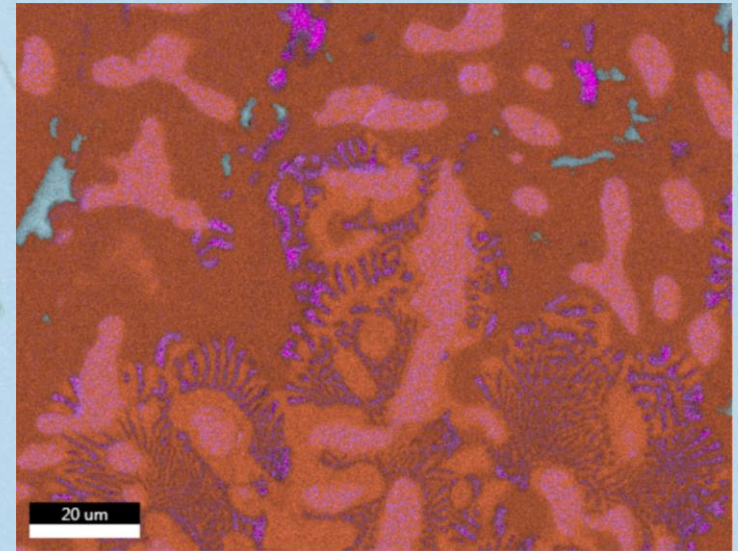
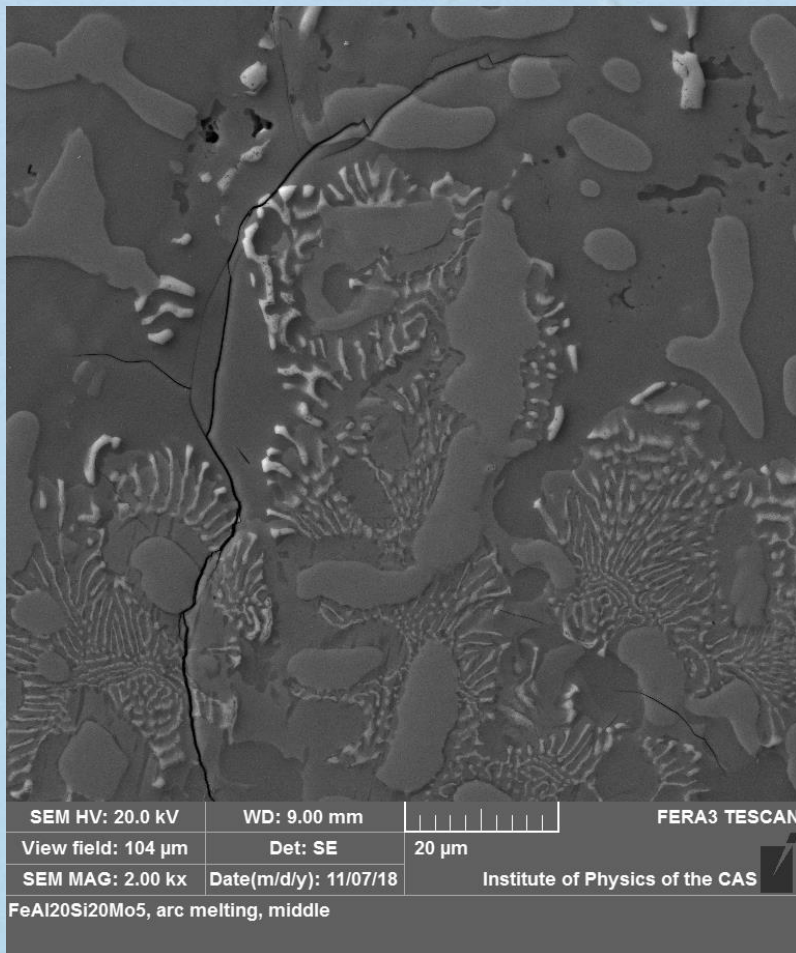
VI. *The Emission and Transmission of Röntgen Rays.*

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.

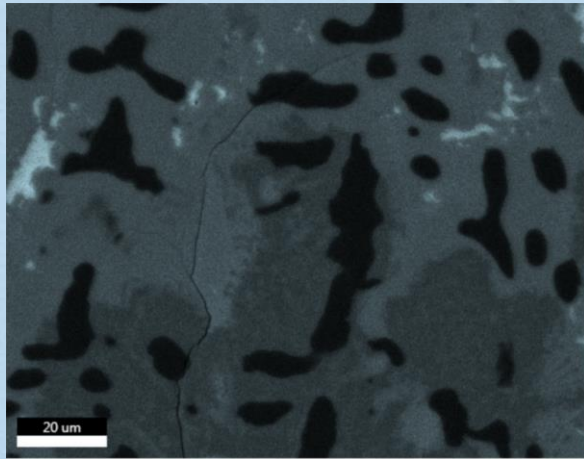
Received June 17,—Read June 25, 1908.

Fénix povstal z molybdenu

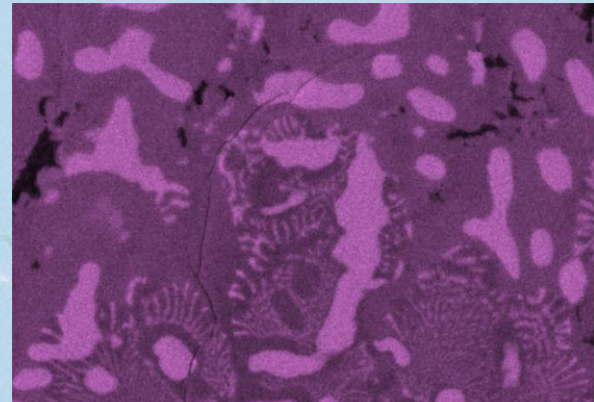


Fénix povstal z molybdenu

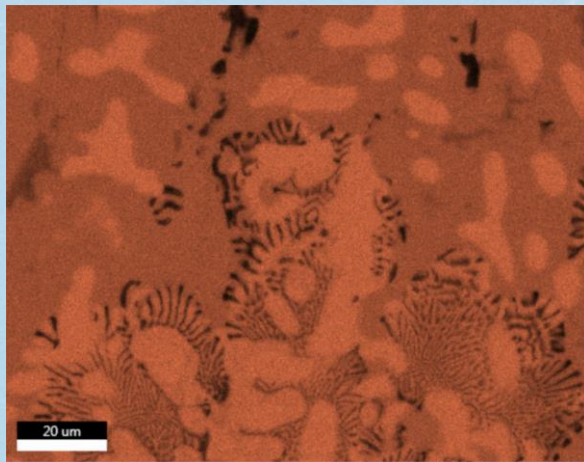
Hliník



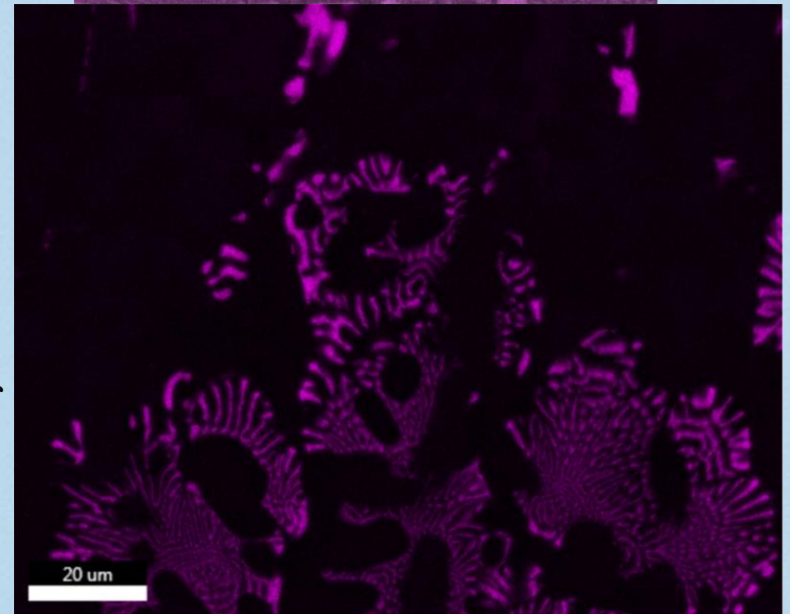
Křemík



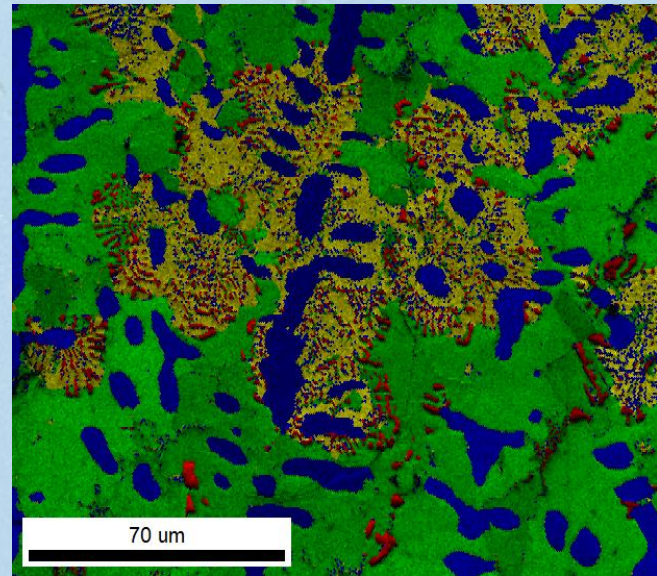
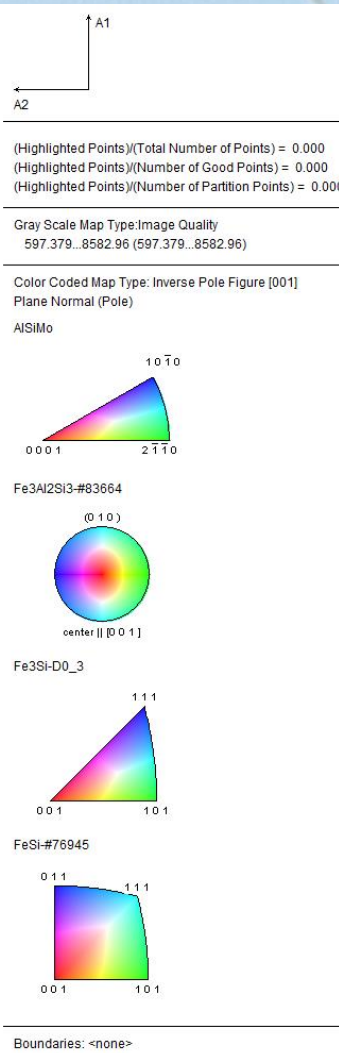
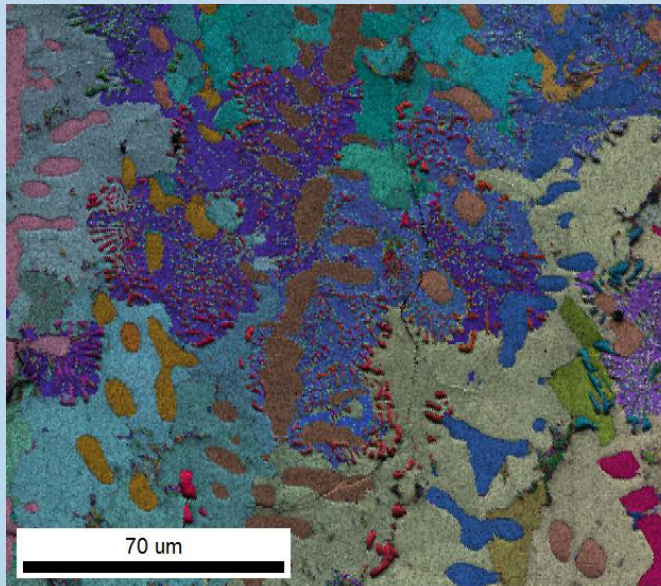
Železo



Molybden



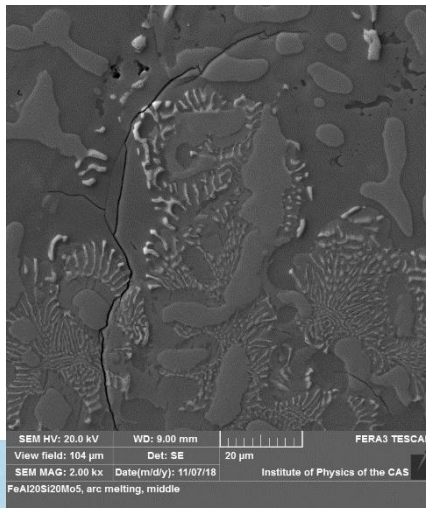
Fénix přistál



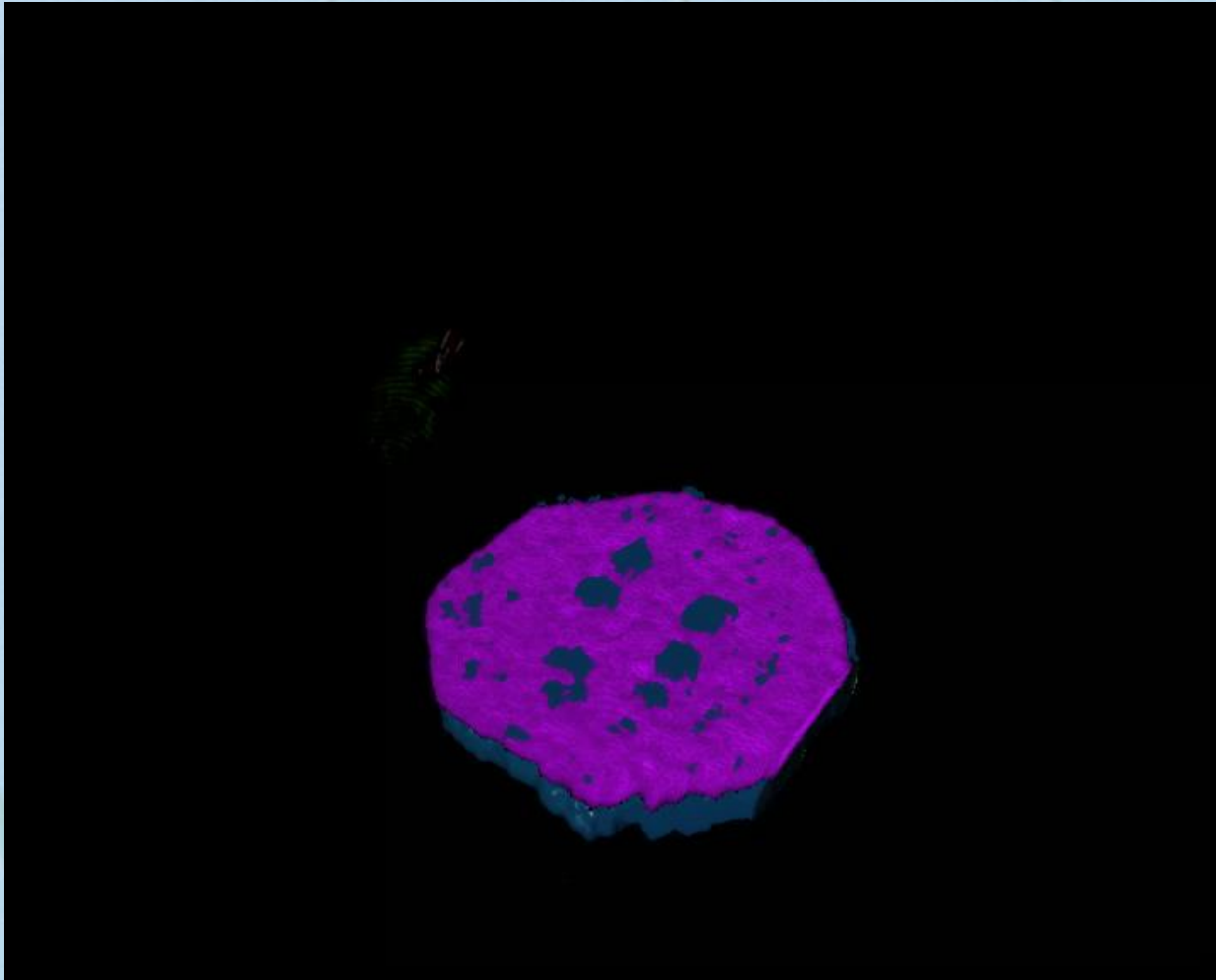
Color Coded Map Type: Phase

Phase	Total Fraction	Partition Fraction
AlSiMo	0.055	0.055
Fe ₃ Al ₂ Si ₃ -#83664	0.532	0.532
Fe ₃ 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

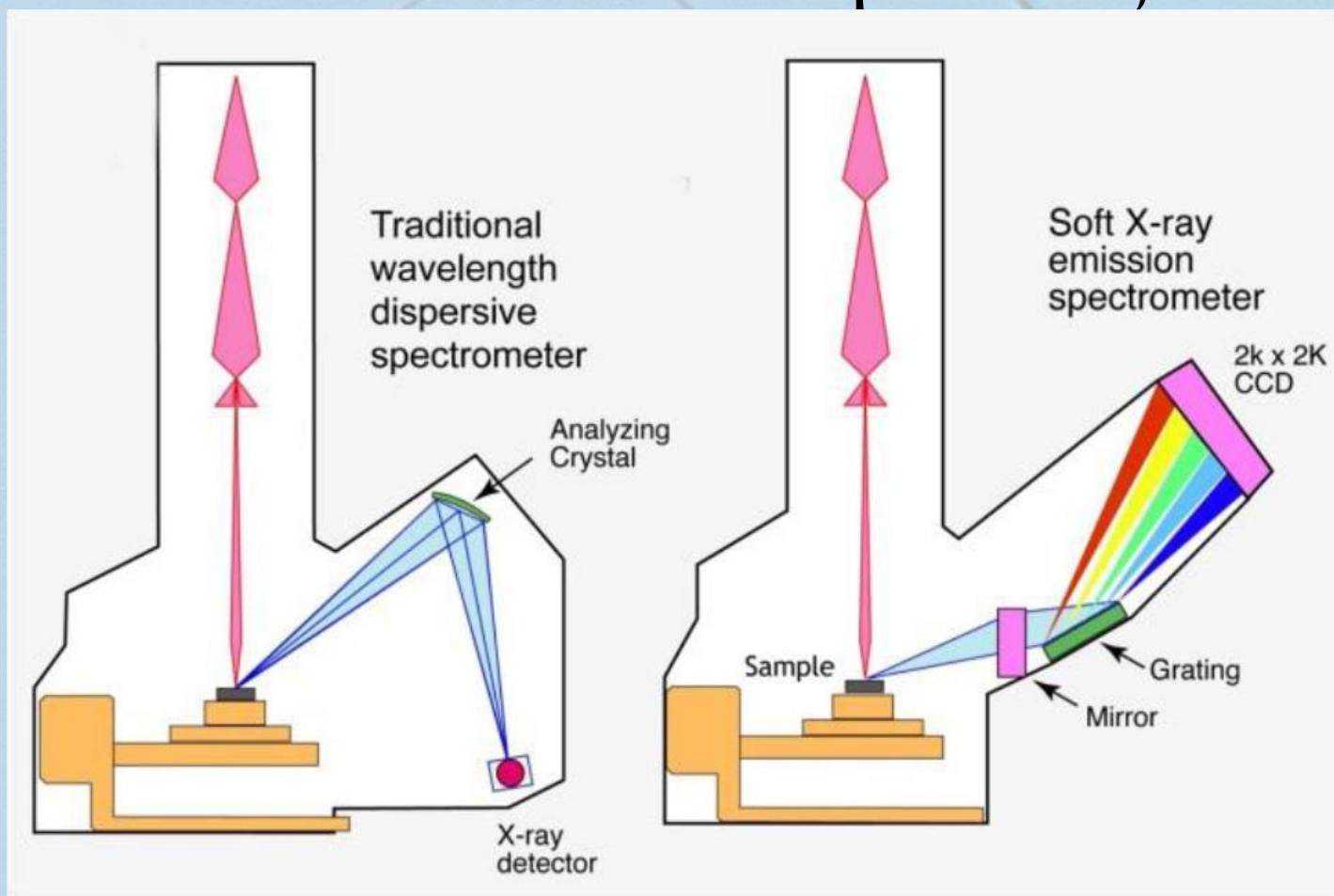
Spektrální rozlišení 0,3 eV

JS50XL 50 – 170 eV

JS200N 70 – 210 eV

Spektrum je snímáno CCD detektorem

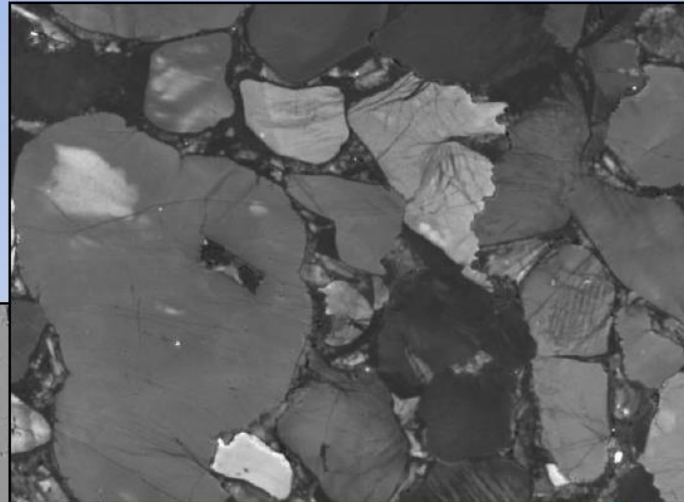
SXES – schéma přístroje



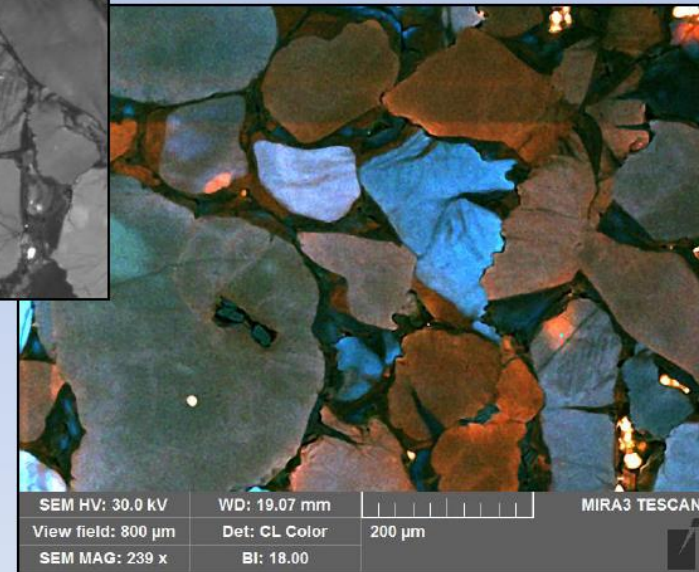
Hideyuki Takahashi, Microsc. Microanal. Suppl., Dec. 2014, S4-S8

Katodoluminiscence v pískovci

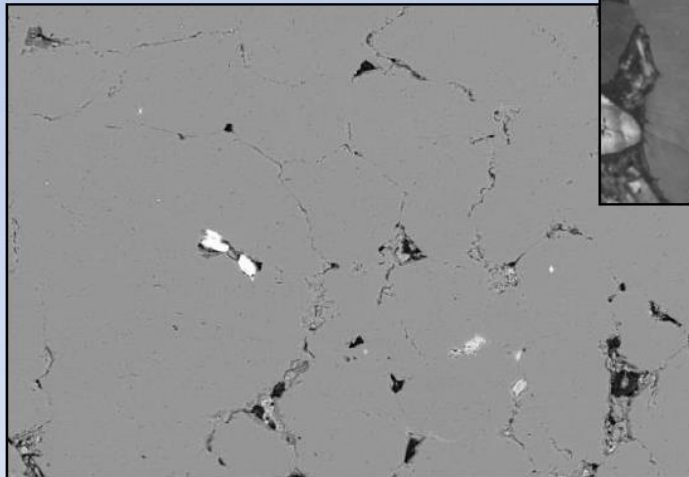
Sandstone



Panchromatic CL (20 kV)

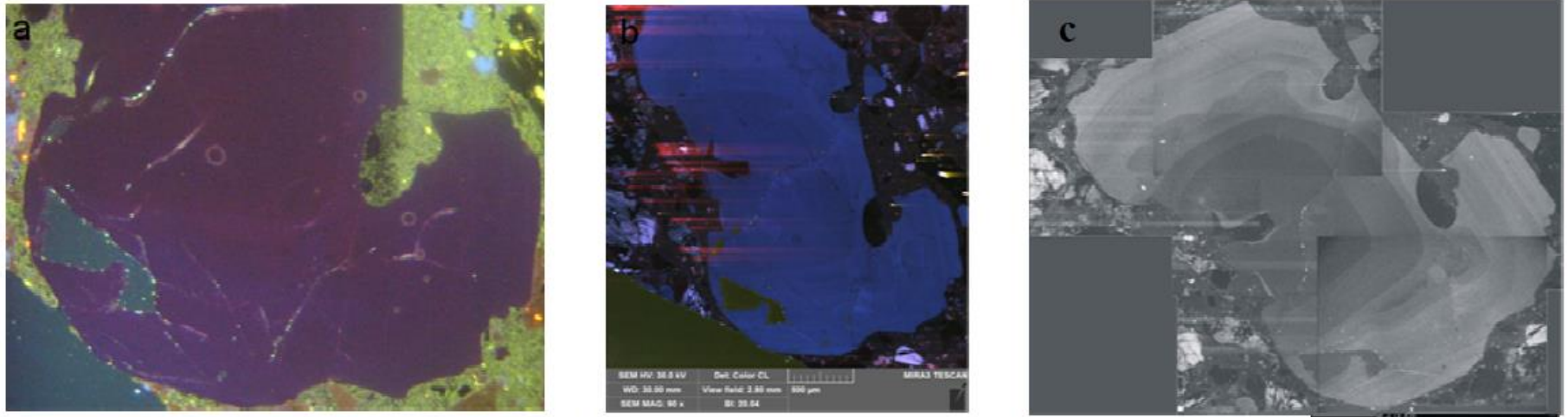


Color CL (30 kV, 5 nA)



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)

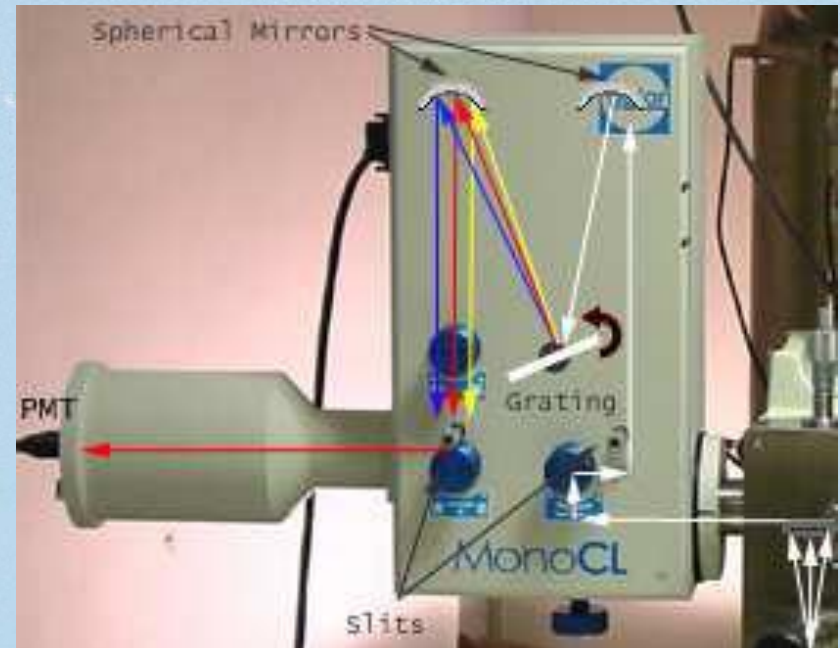
b) barevné rastrovací CL (Tescan, Brno, foto J. Kološová,)

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

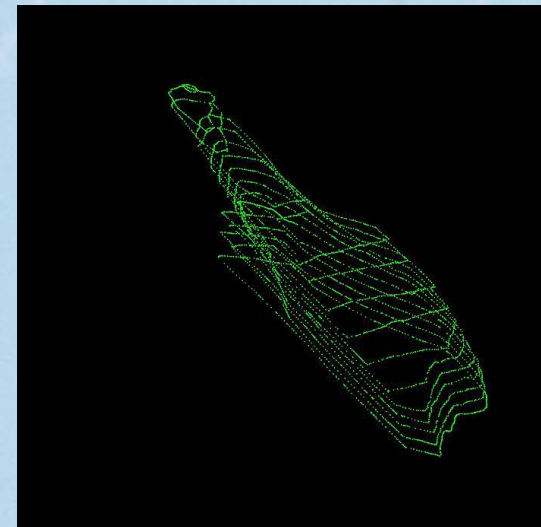
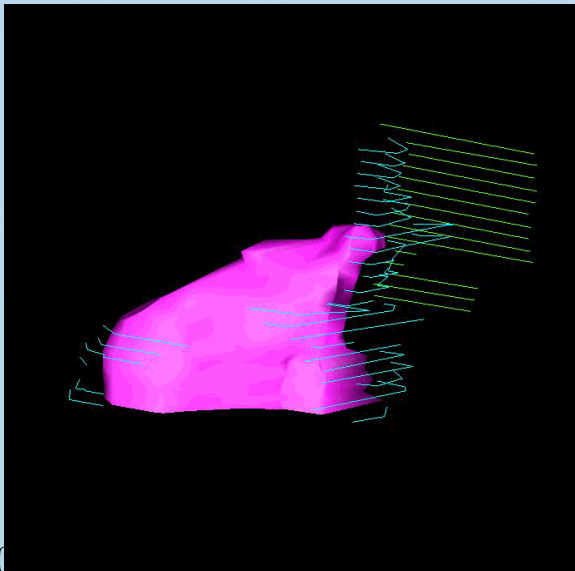
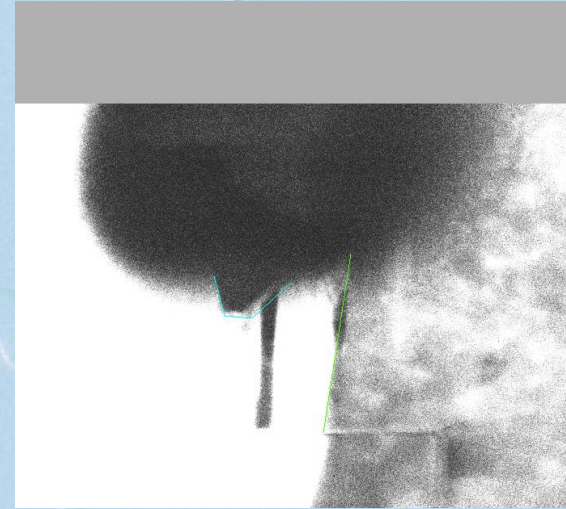
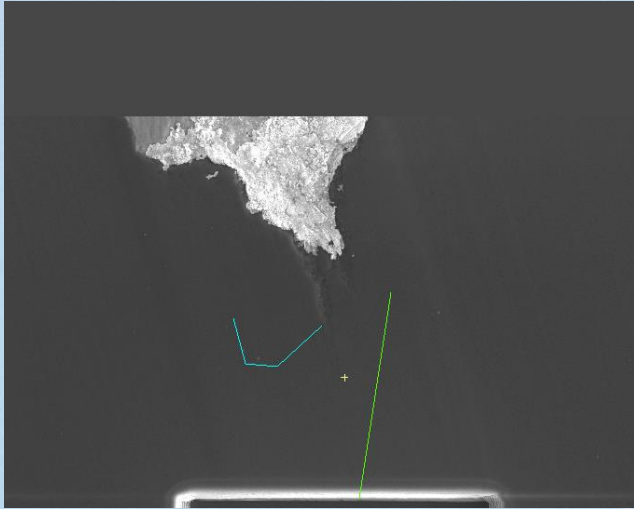
Kateřina Švecová in Využití katodové luminescence a LA-ICP MS

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

CL detektor fy Gatan

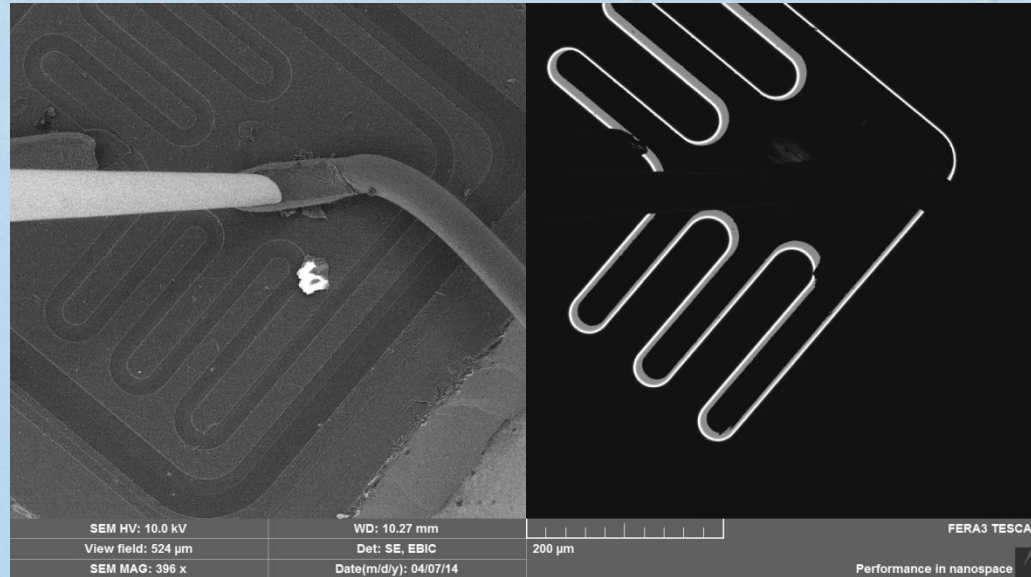


3D katodoluminiscence



Electron Beam induced Current

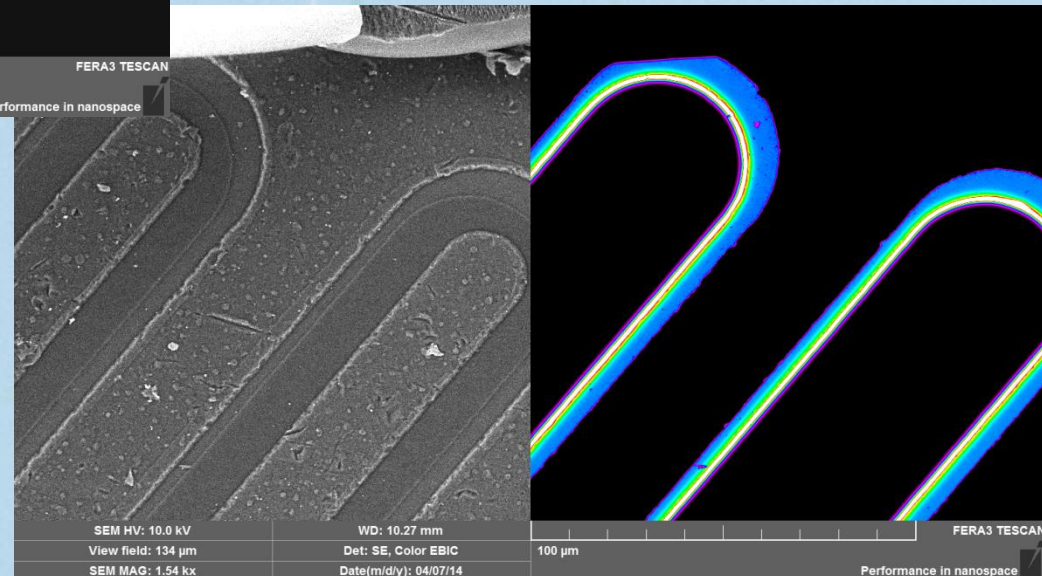
Modul fy Tescan
Předpětí v intervalu -5 až 5 V
16-bitový AD převodník

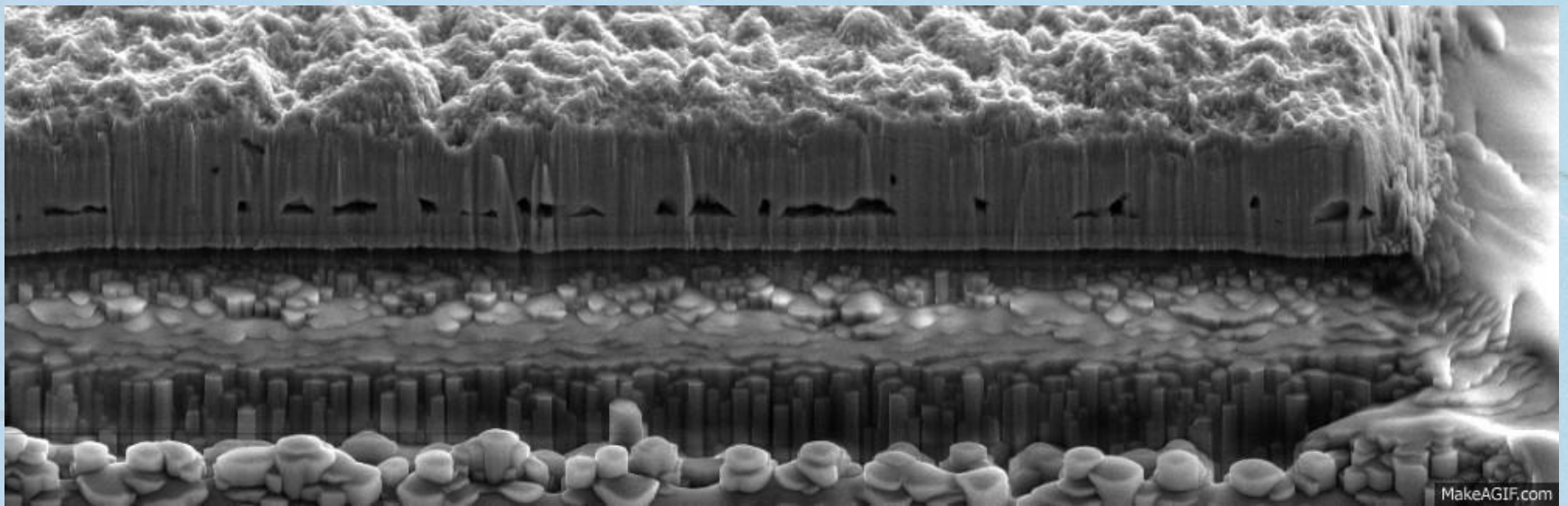


Ge tranzistor

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

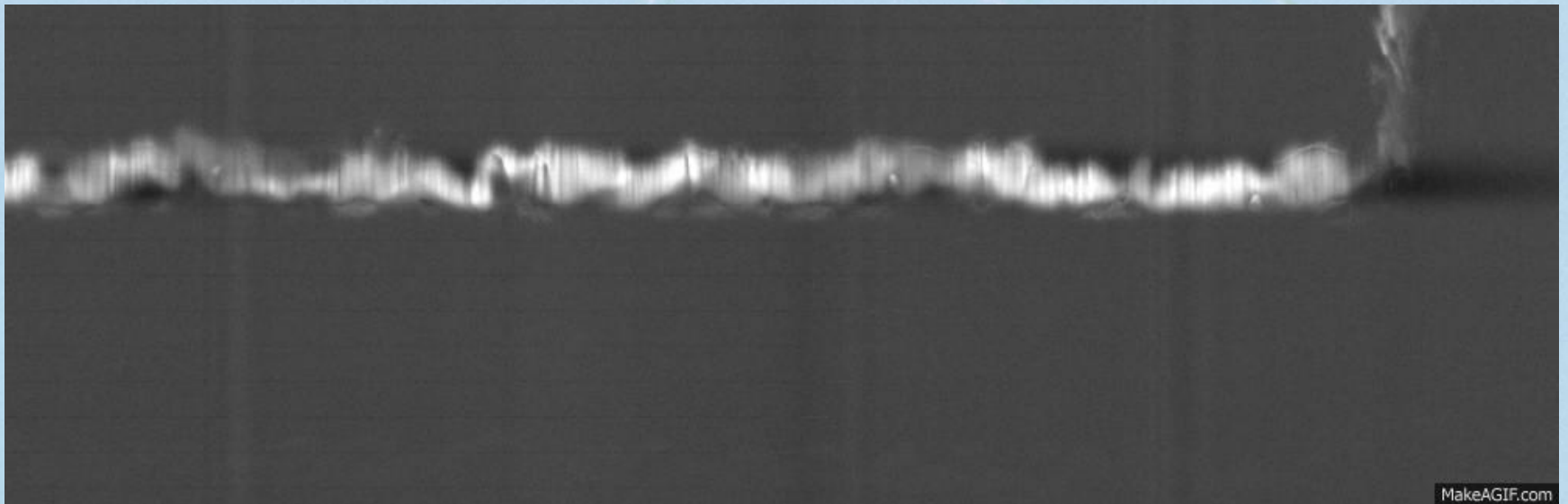
Nalevo obraz v SE elektronech, napravo EBIC signál.





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!