Chapter 2 Electron Optics/ Operation Modes

Electron gun

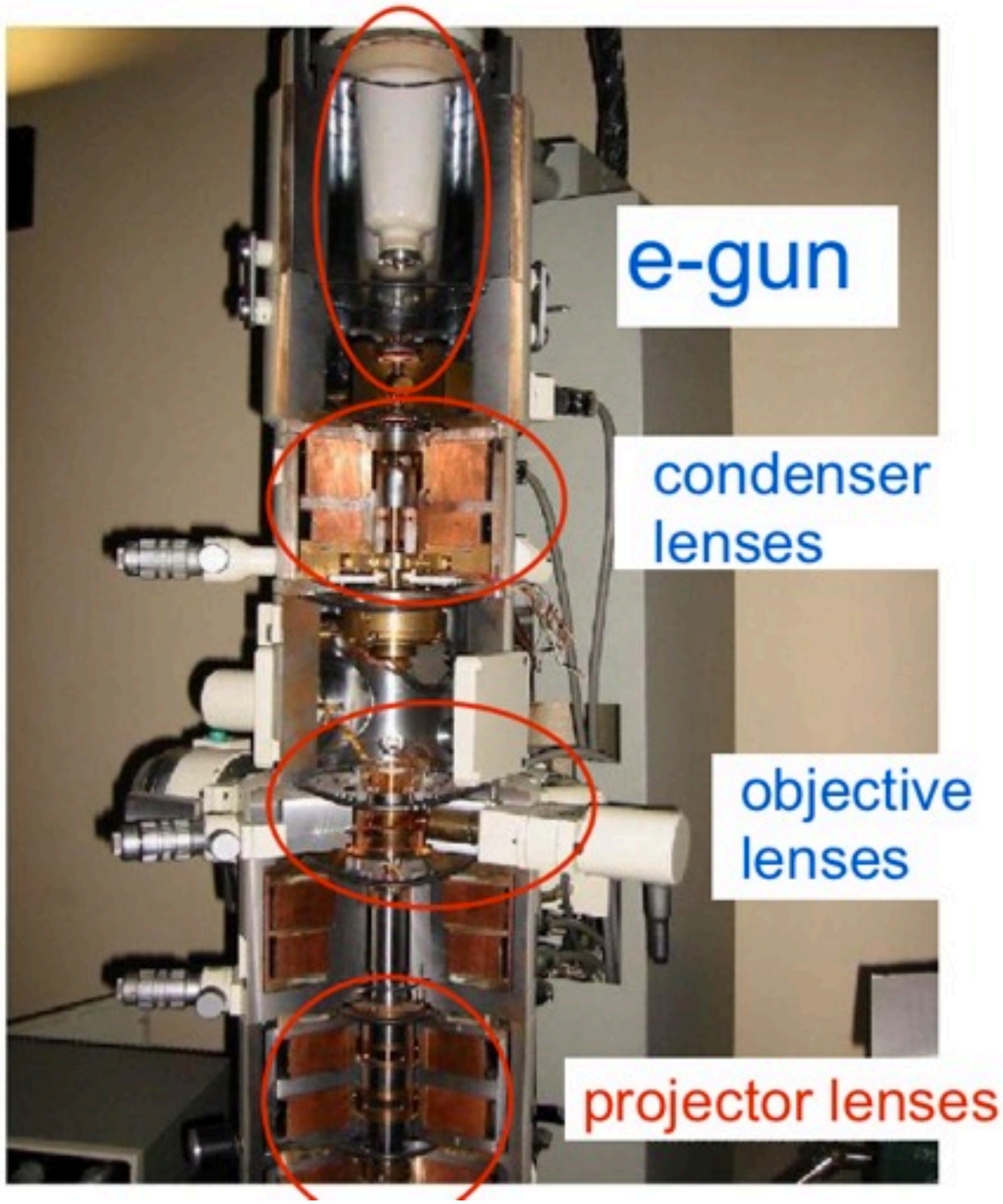
- thermionic source
- Field emission source
- Brightness of source
- Coherence of source

Magnetic lenes

- Spherical aberration
- Chromatic aberration
- Astigmatism

電子顯微鏡夠構造圖

- 我們必須使用透鏡(聚光鏡，物鏡，投影鏡）及光闌(聚光光闌，物鏡光闌，擇區光闌）的組合來控制成像(imaging)，繞射(diffraction)及成份分析的號。



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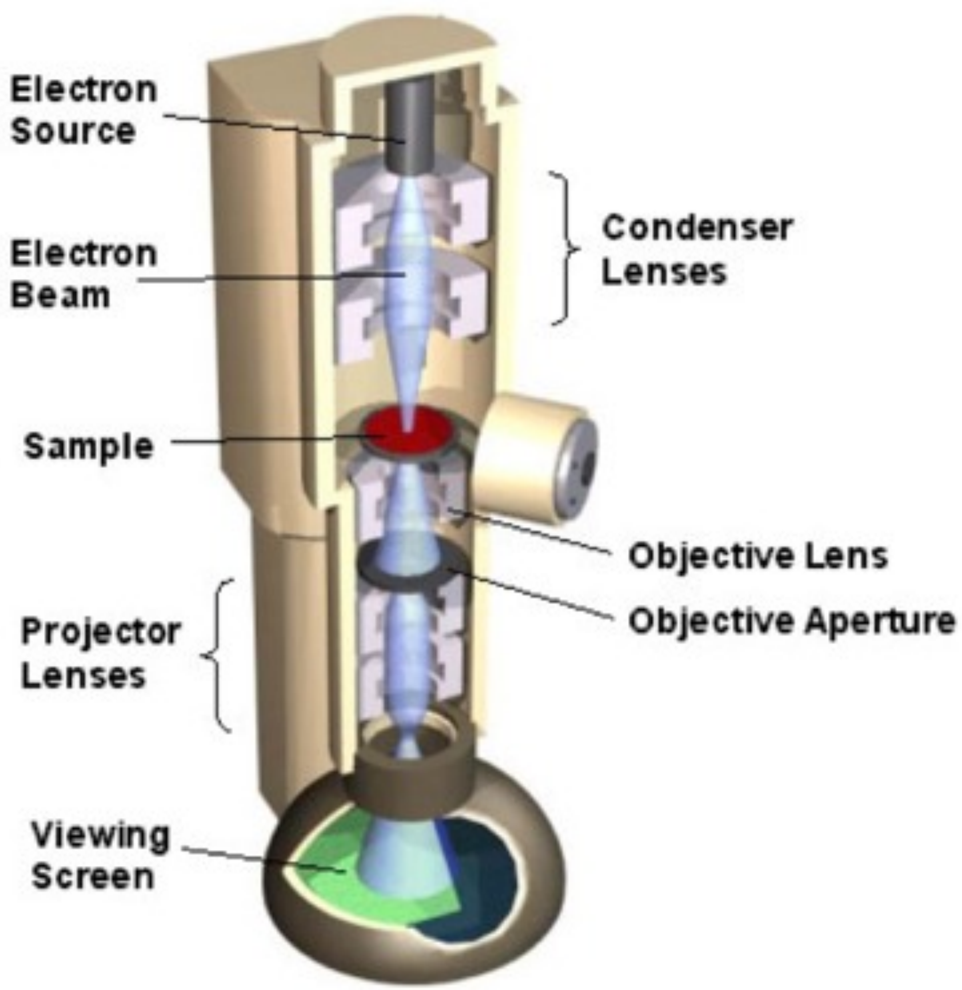

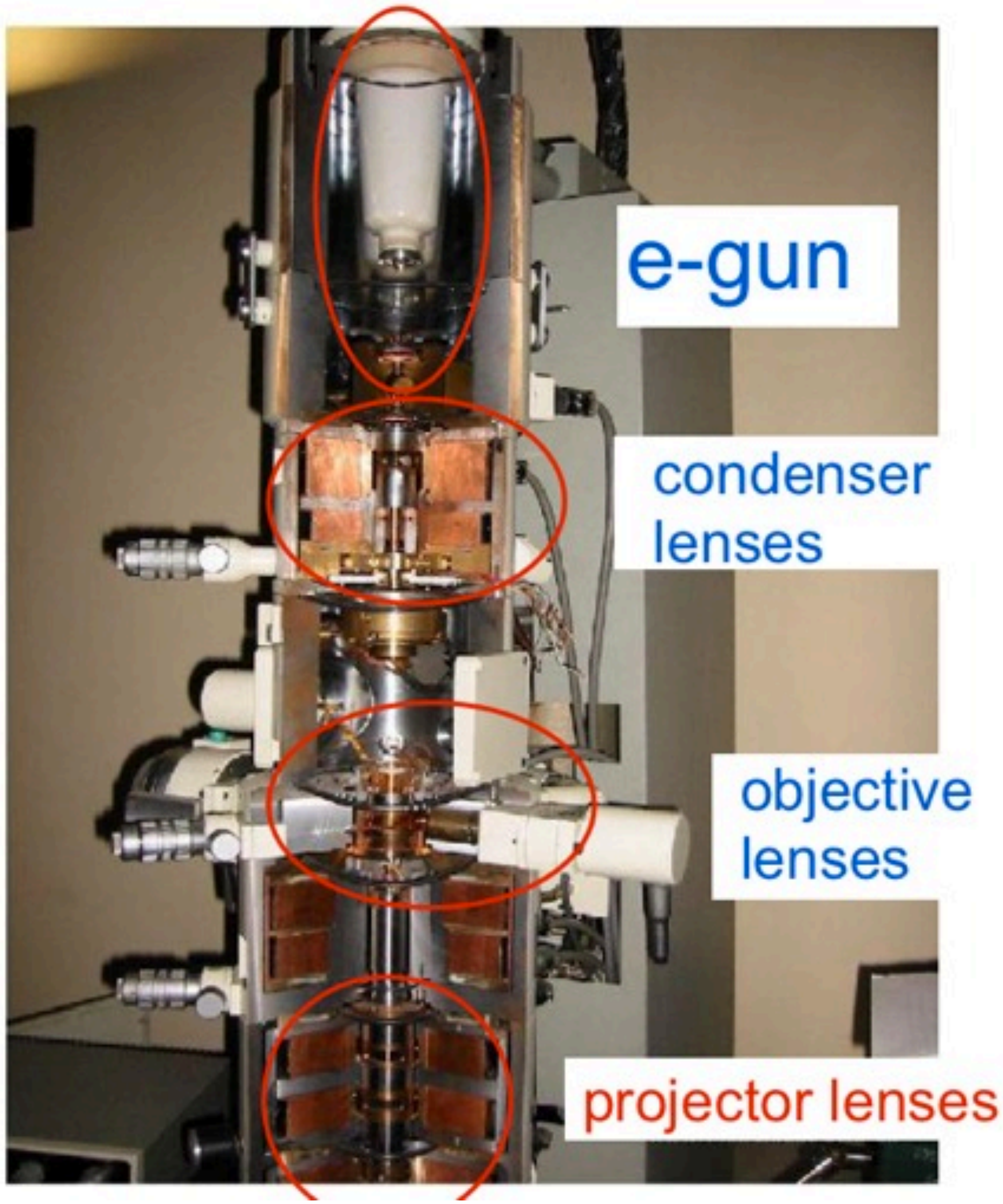

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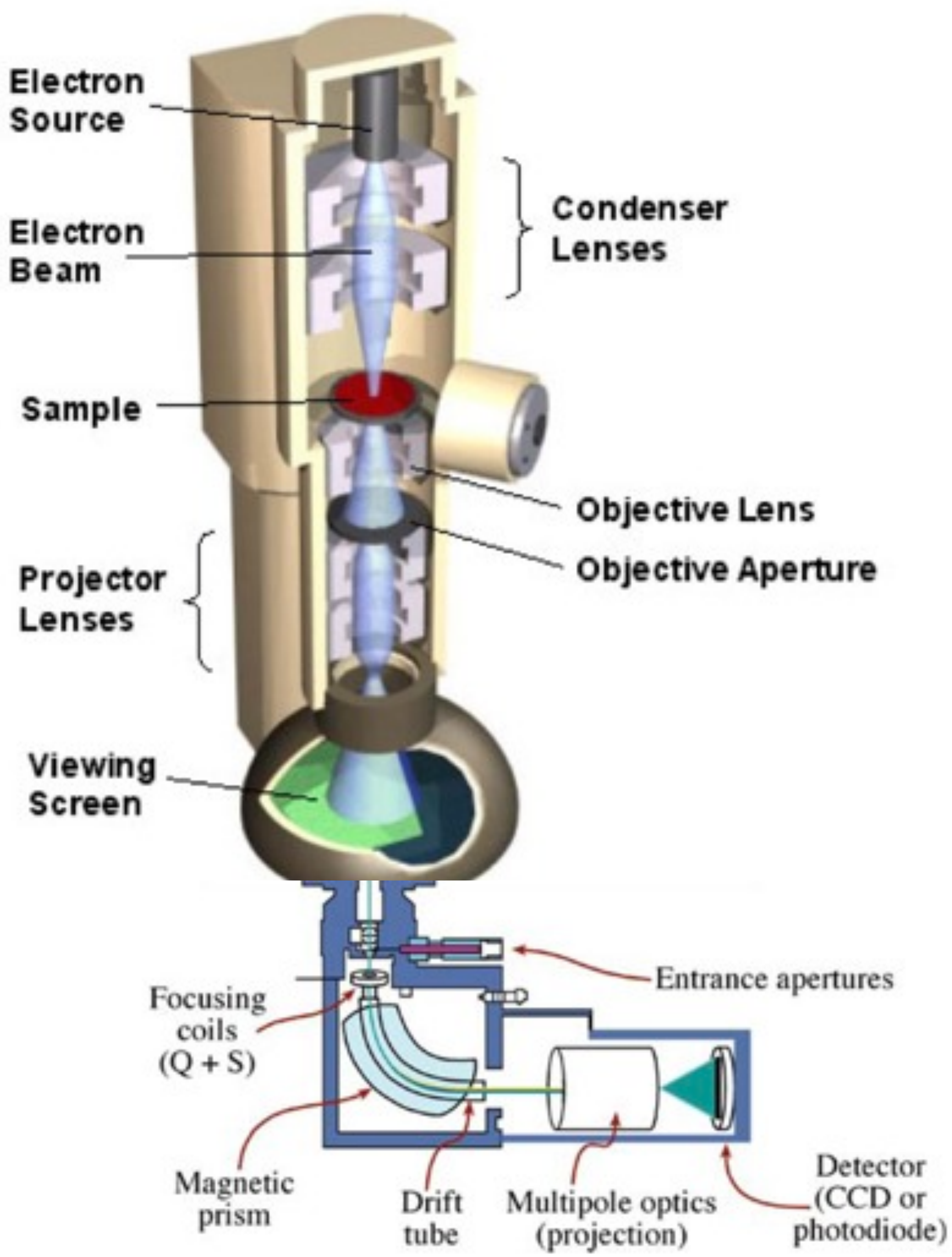
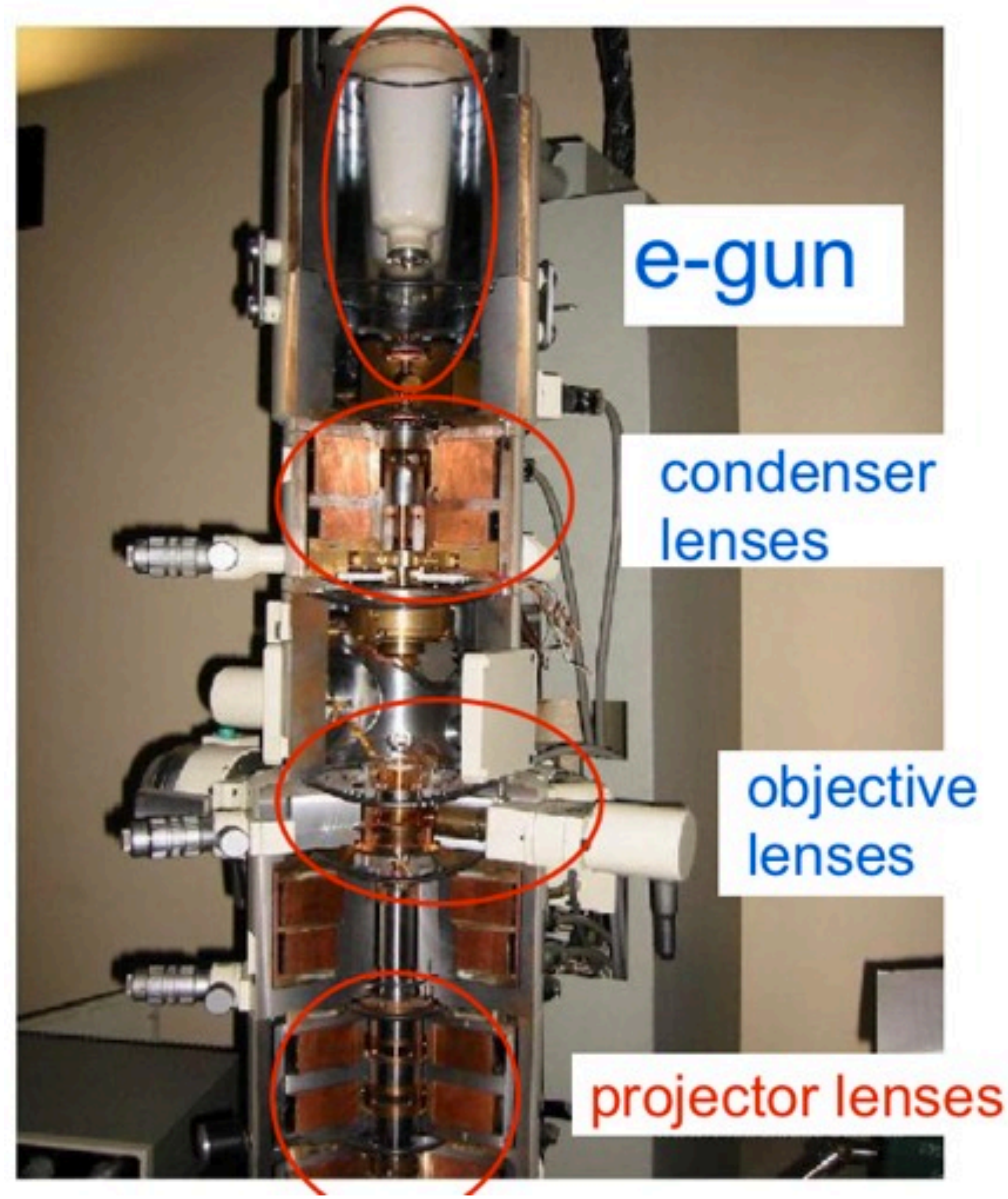
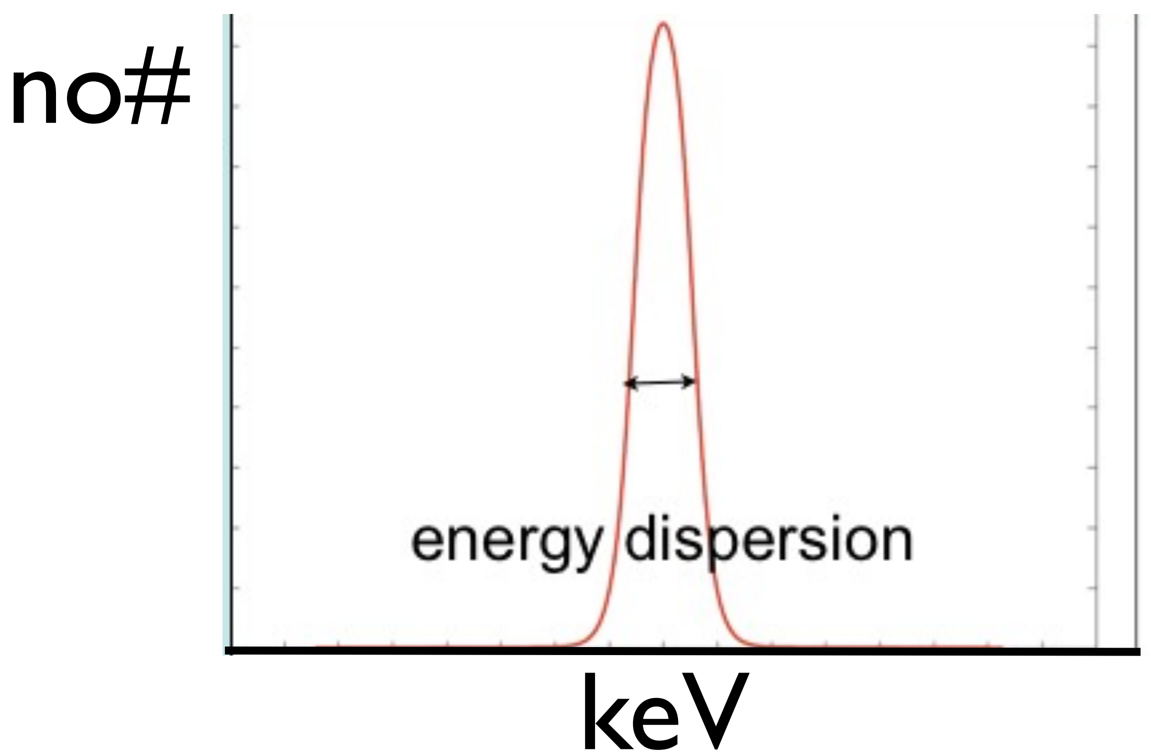
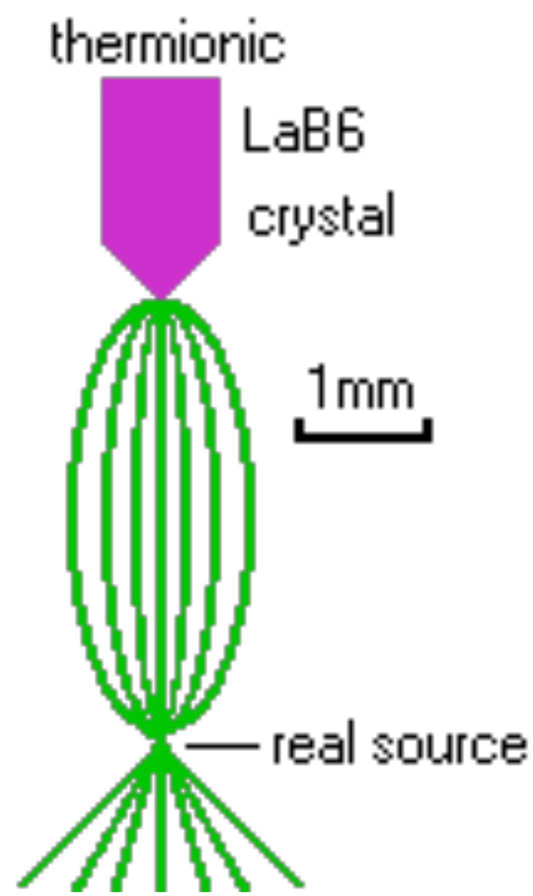




2.1Electron Source

- thermionic source
- field-emission source

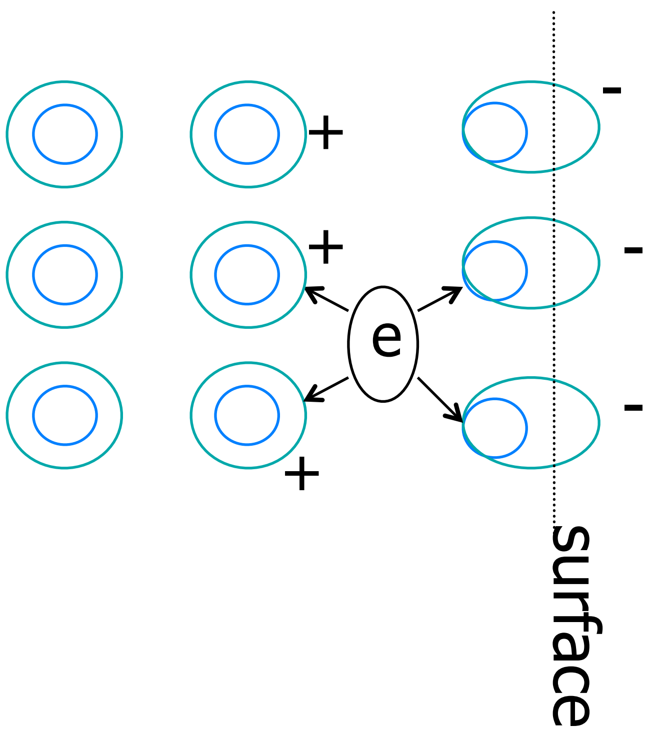


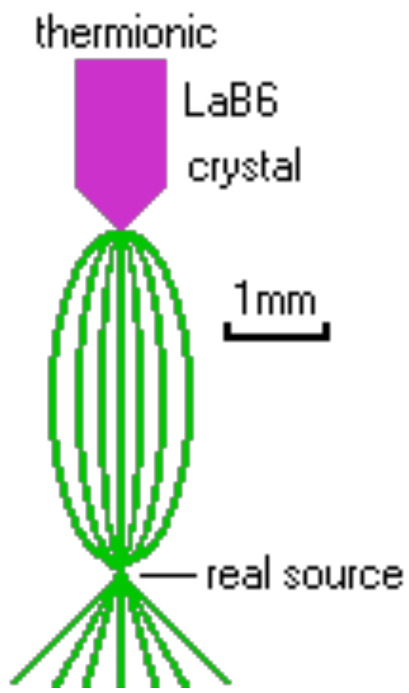


A. Thermionic Source

- Work function: energy barrier required for an electron to escape from the metal surface

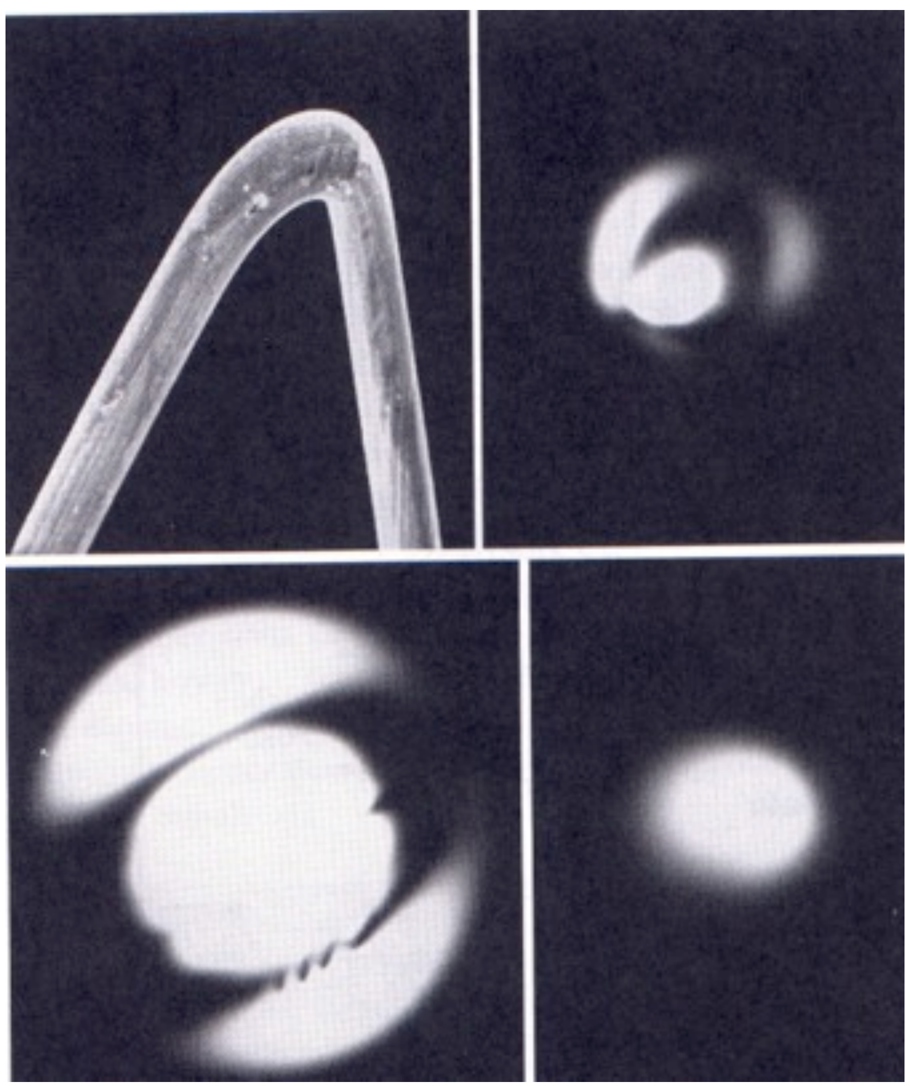
①Polarization effect
②Image effect)





To extract electrons from the “tip”, work is needed.

Thermionic tip



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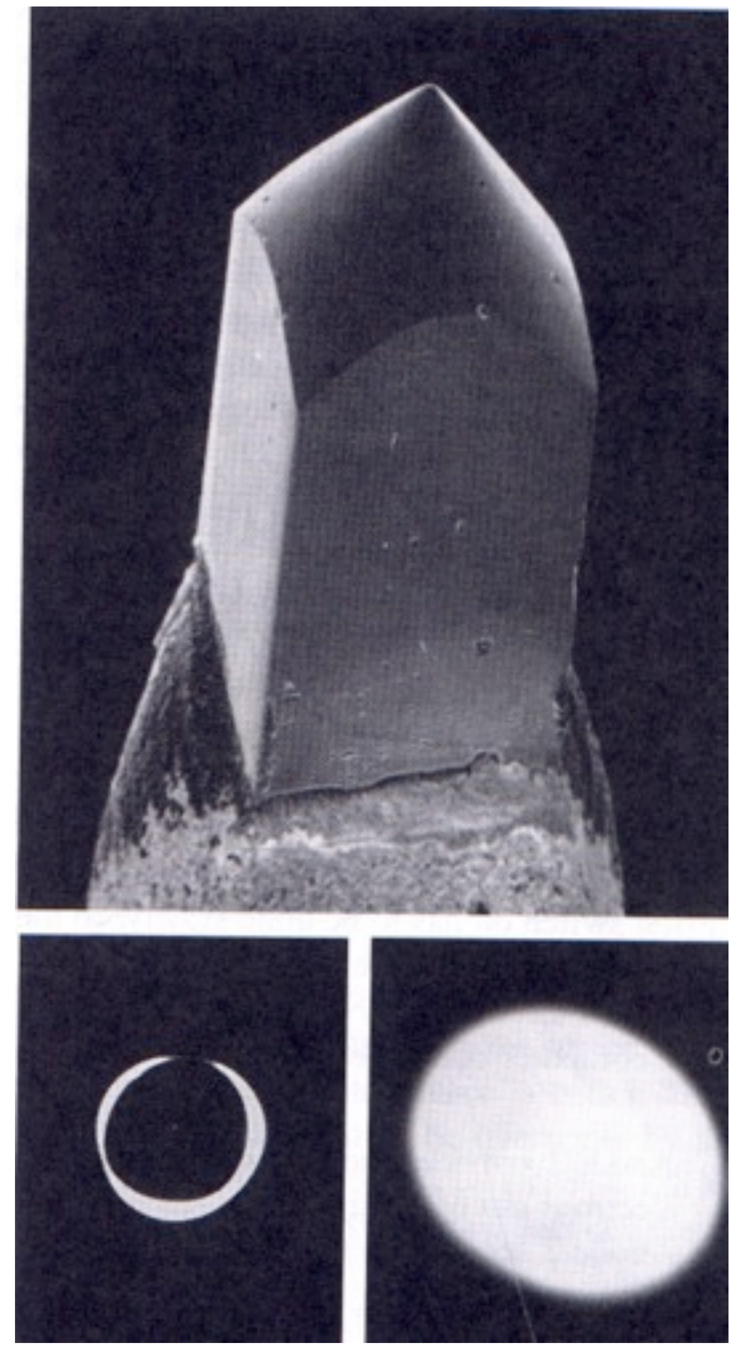
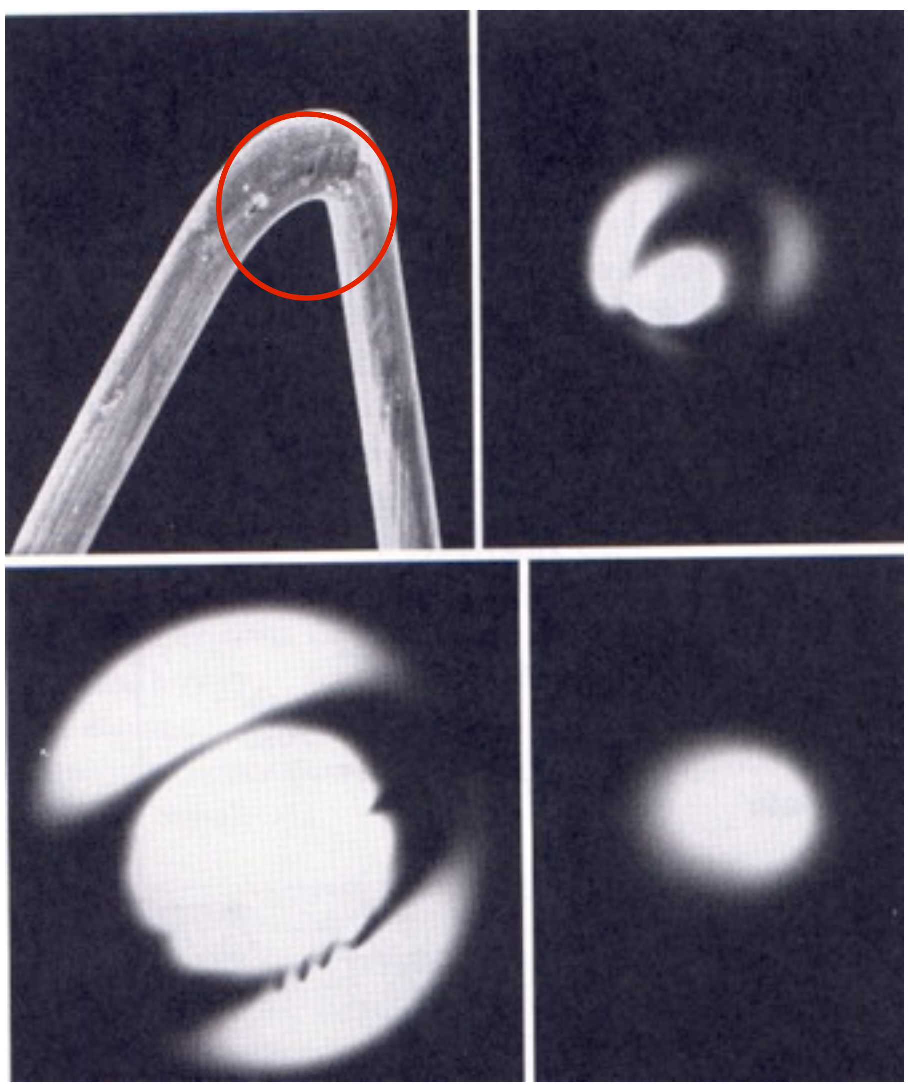


LaB_6

Thermionic tip

50μm



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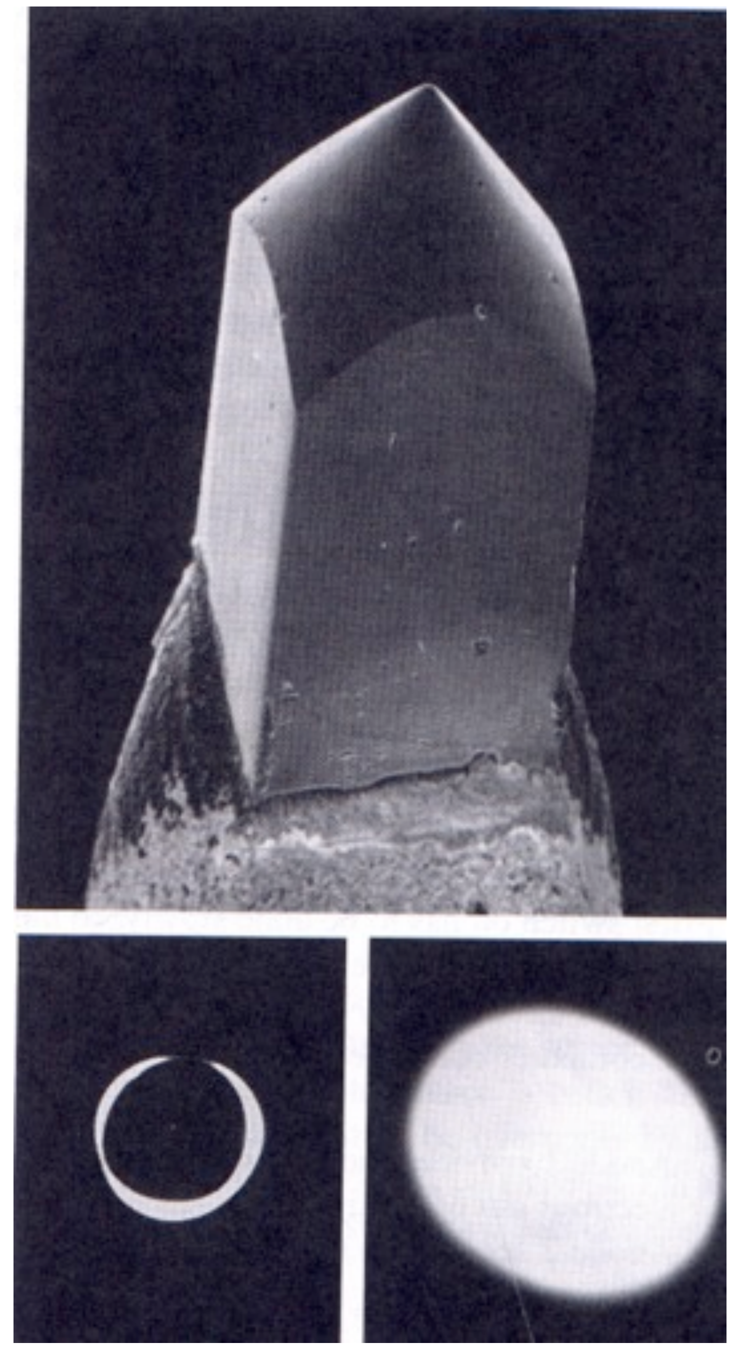
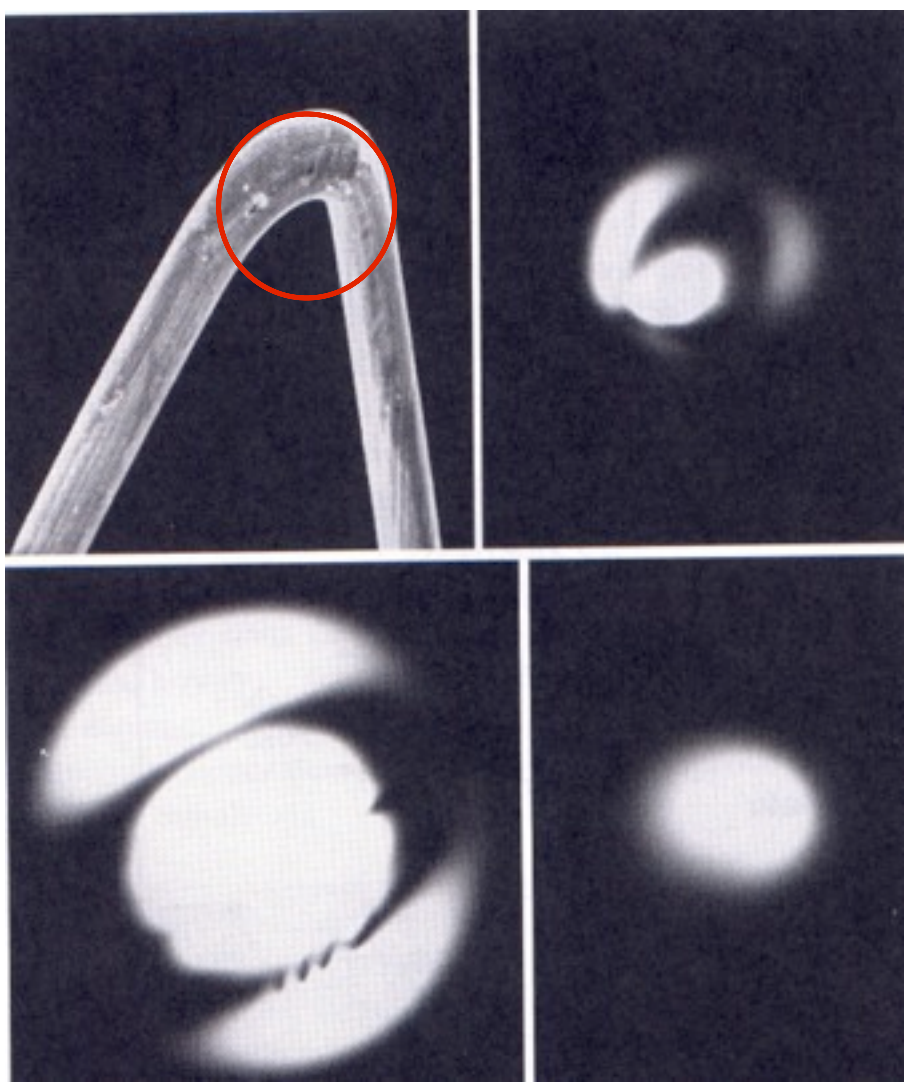


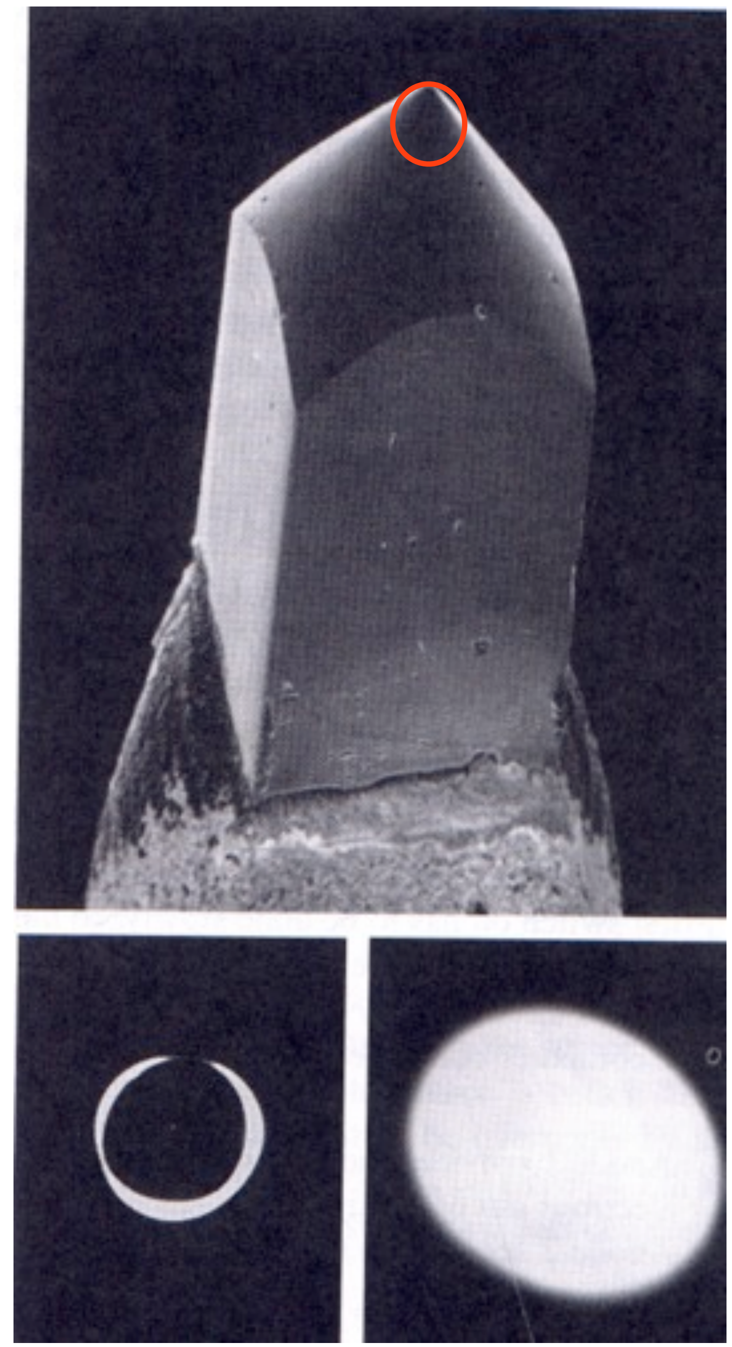
LaB_6

Thermionic tip

50μm



W



10μm

LaB_6

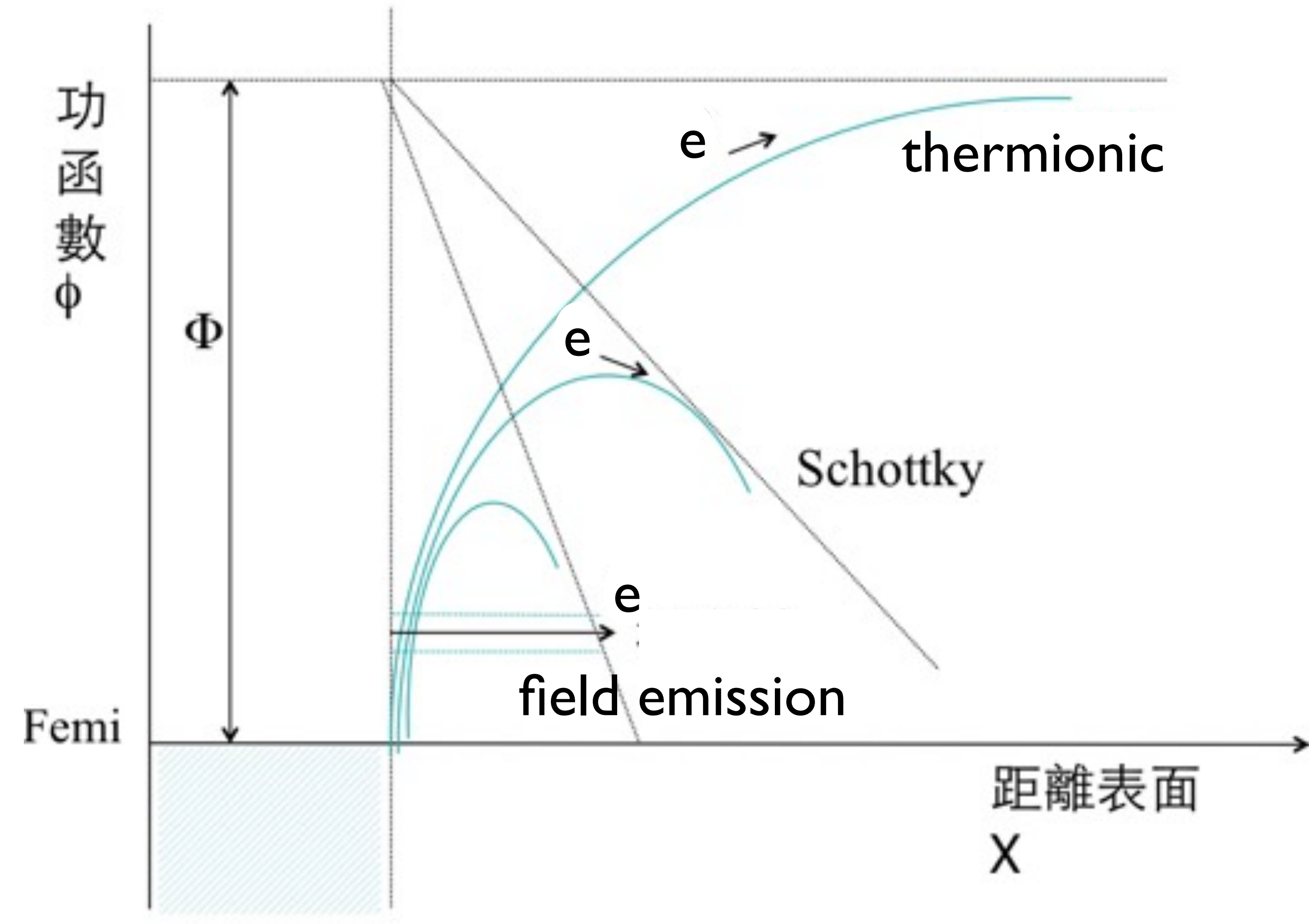
Richardson's Law

$$J = AT^2 e^{-\frac{\phi}{KT}}$$

- J：current density (Amp/cm^2)
- A：Richardson's constant (A/cm^2 * k^2)：
- T：operating temperature (°k)

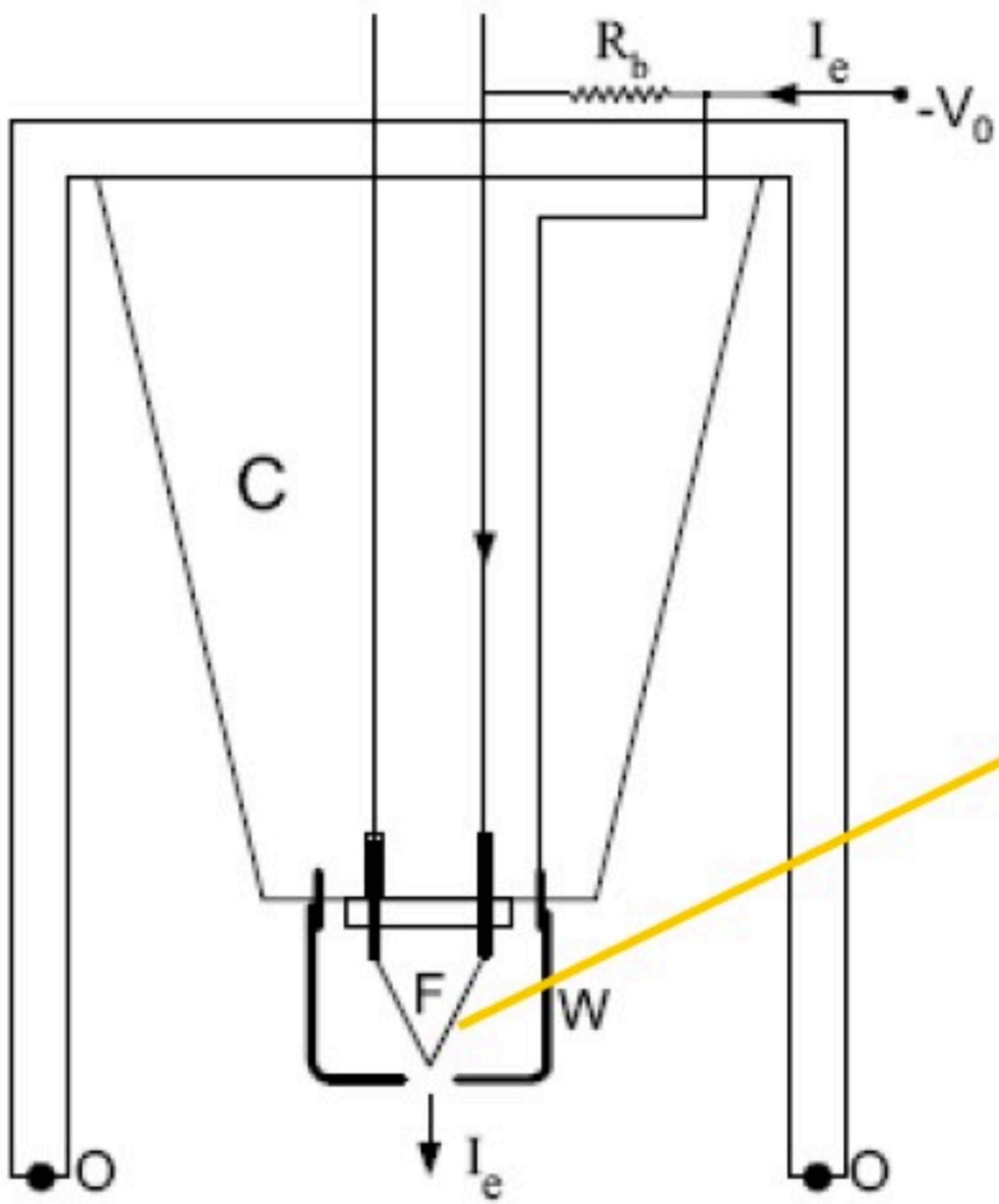
- Requirement for a filament

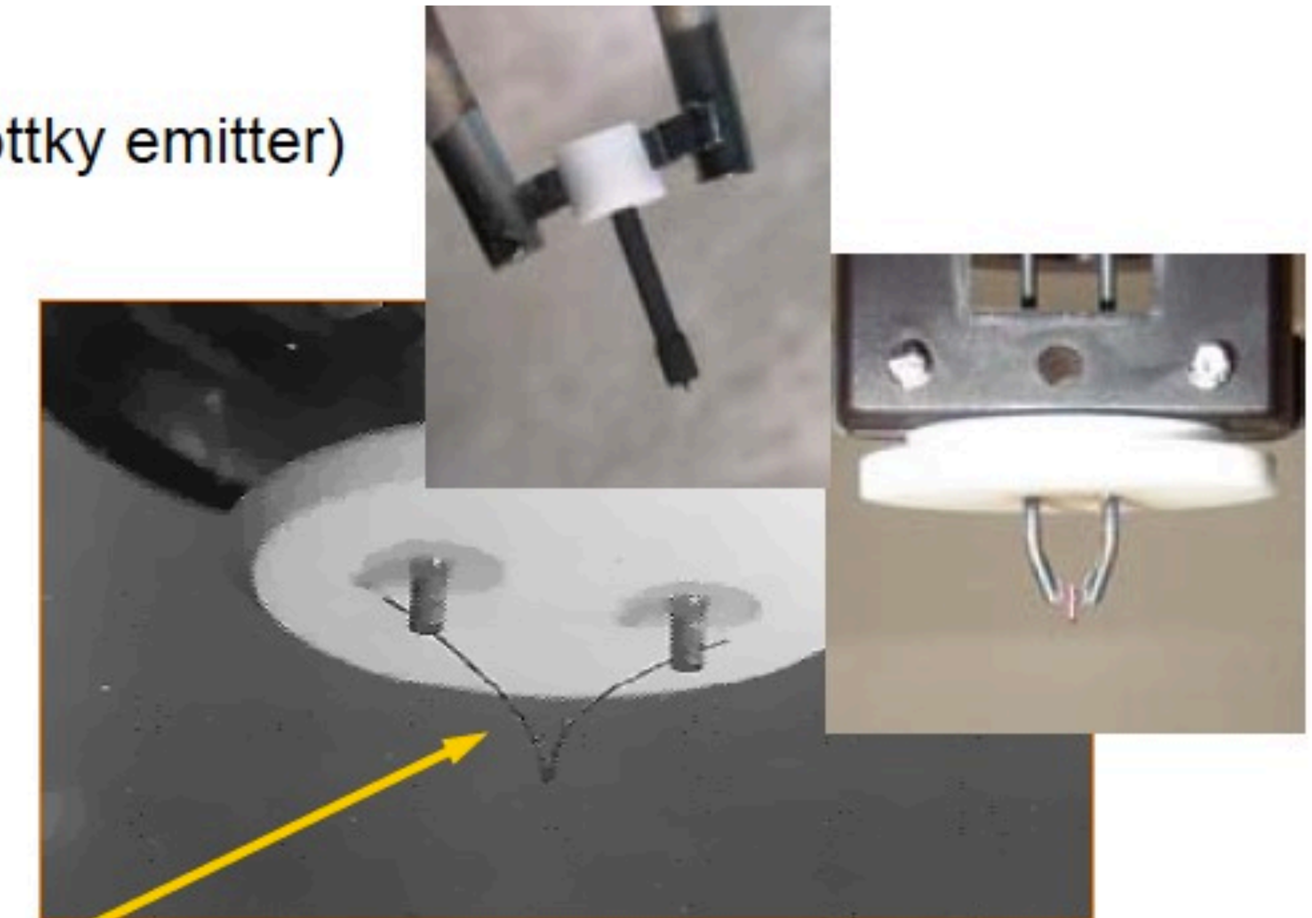
  1. low work function
  2. high melting temperature
  3. stable at high T



Electron Source

Thermionic emission (tungsten, LaB6, Schottky emitter)



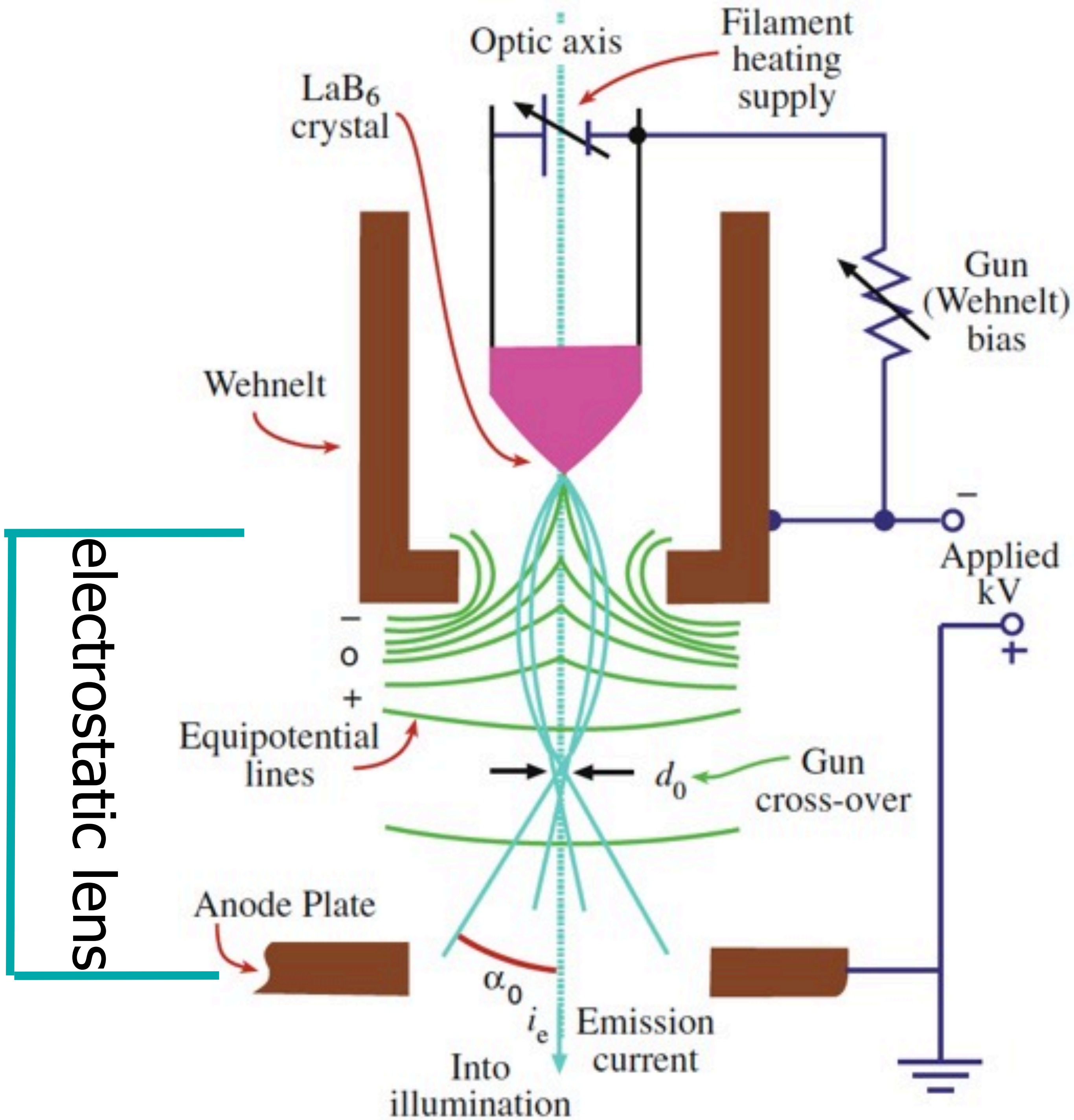


Filament is heated

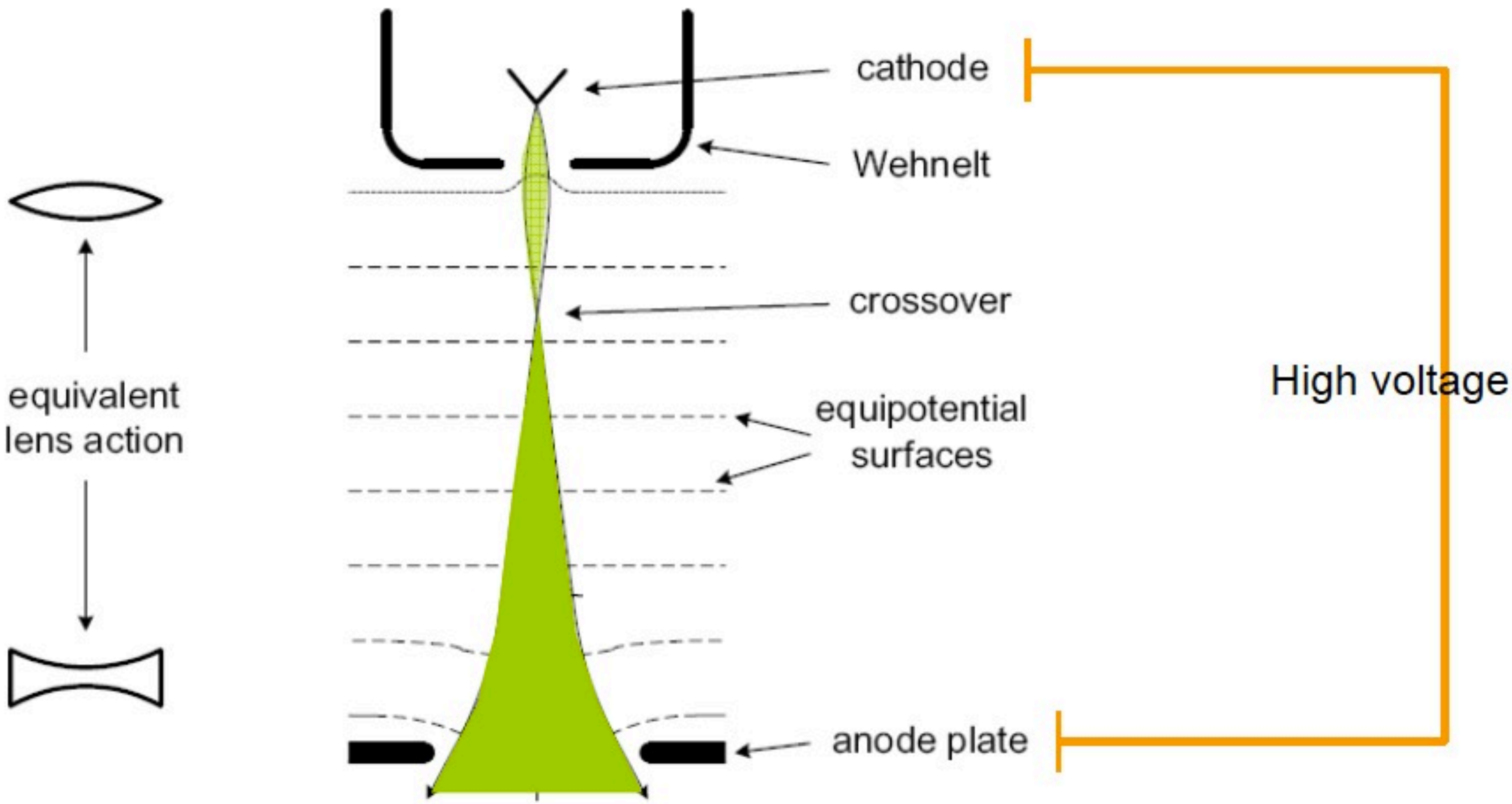
Electrons are emitted from the tip

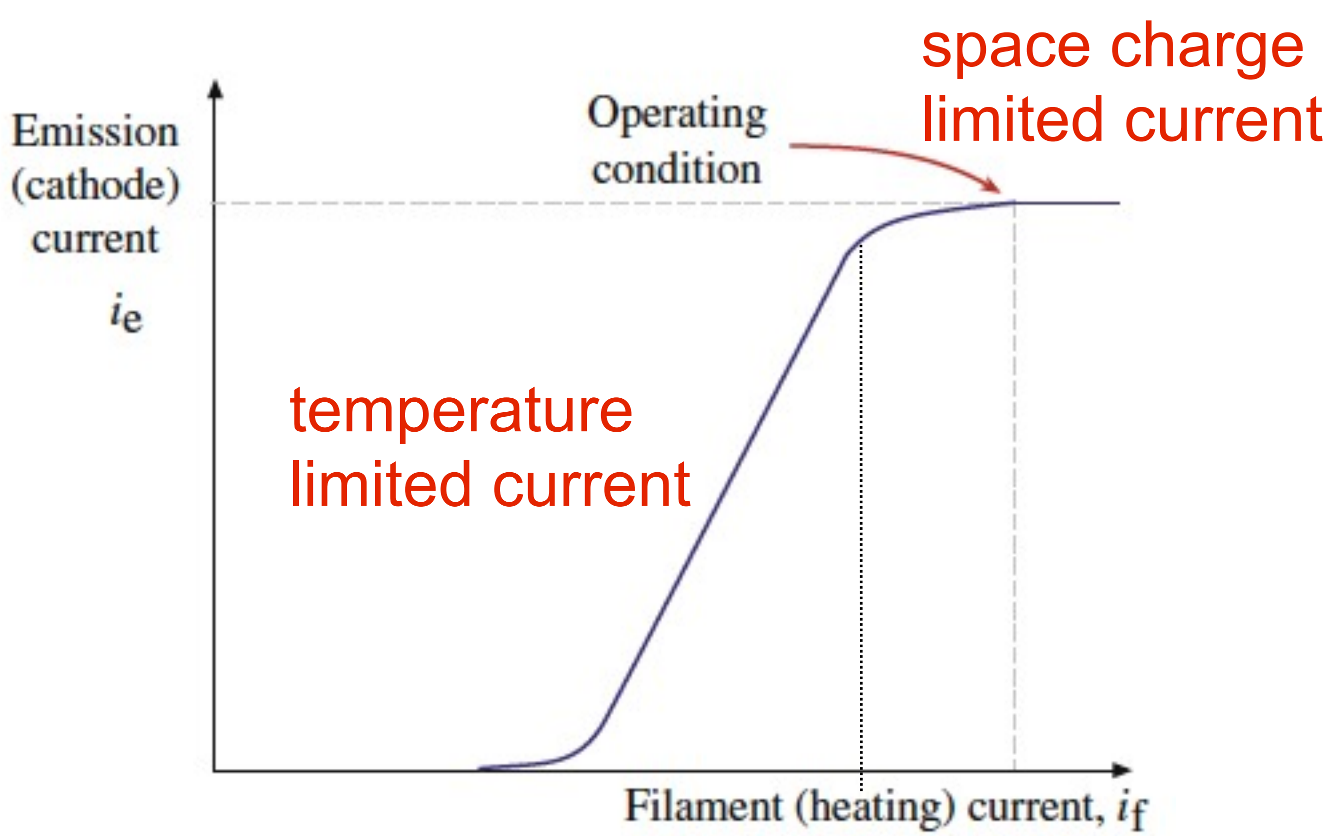
F…Filament
W…Wehnelt electrode
C…Ceramic high voltage insulator
Rb…Autobias resistor
Ie…Electron emission current

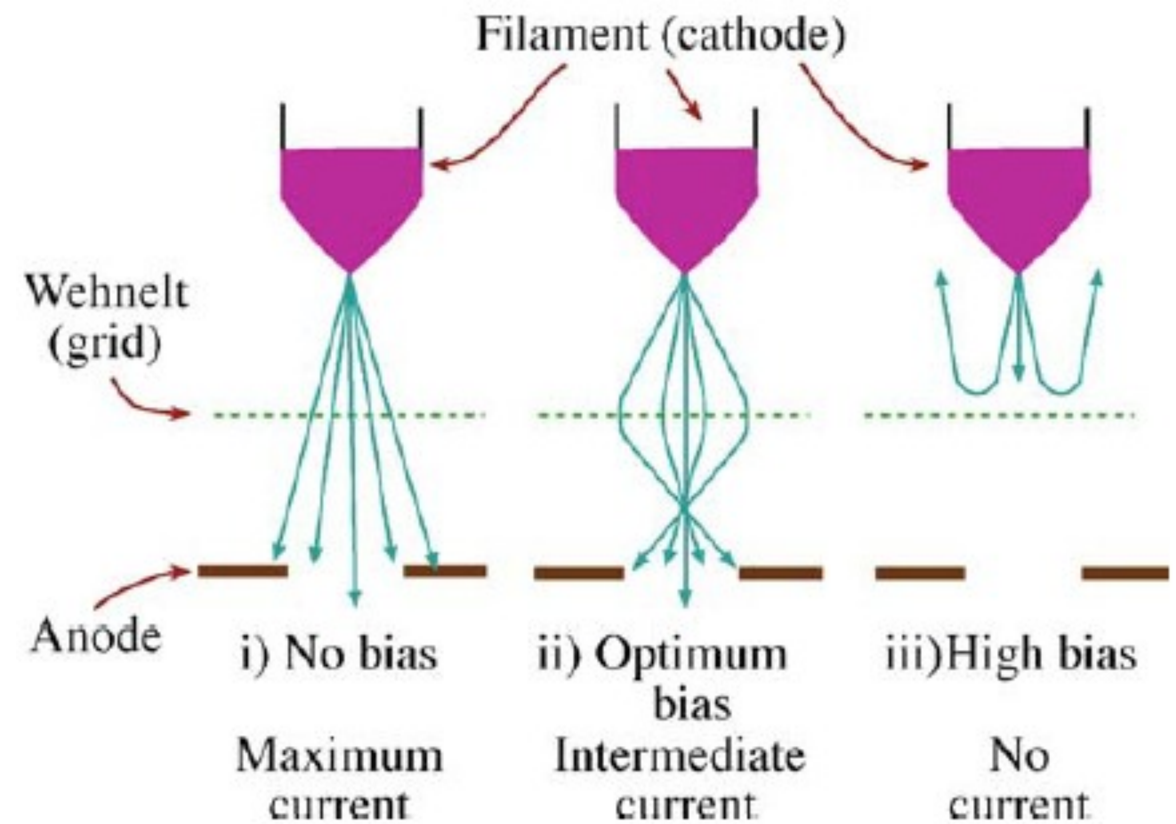
Thermionic gun

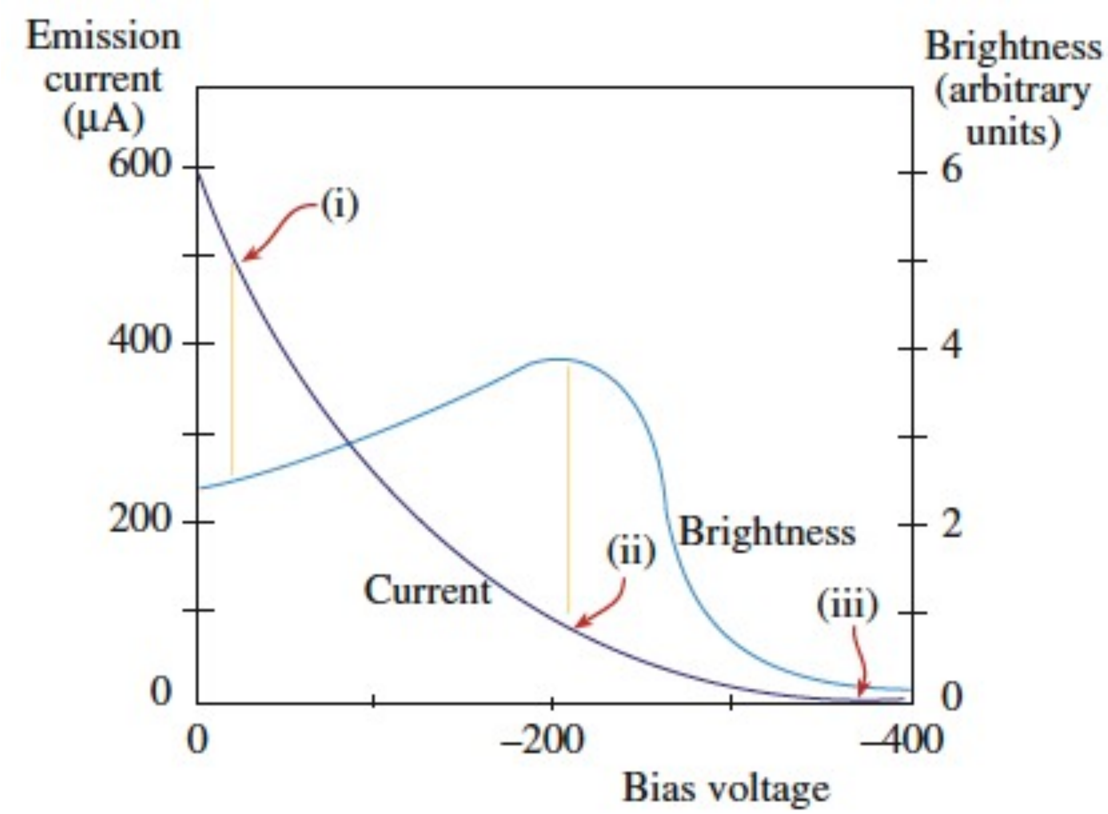


Electron source (Electron gun)

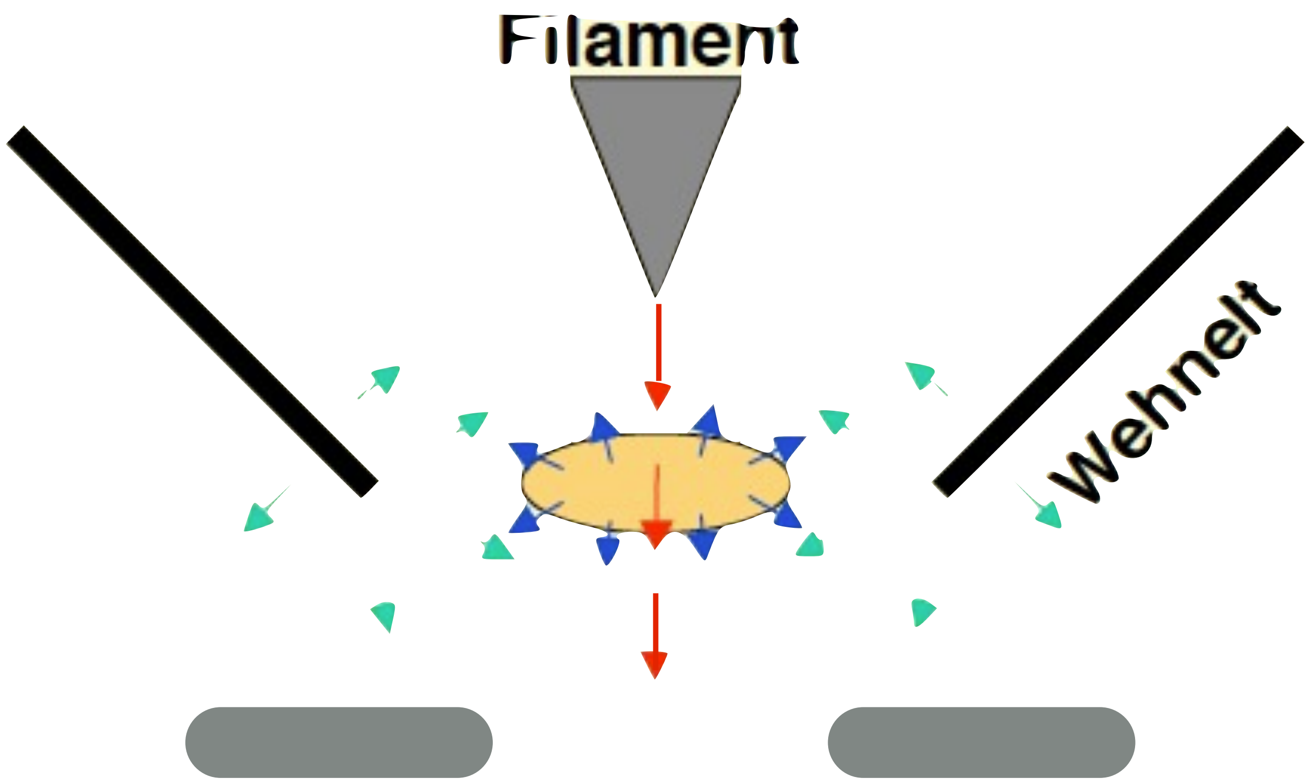



space charge
limited current
Operating
condition
Emission
(cathode)
current
i_e
temperature
limited current
Filament (heating) current, i_f

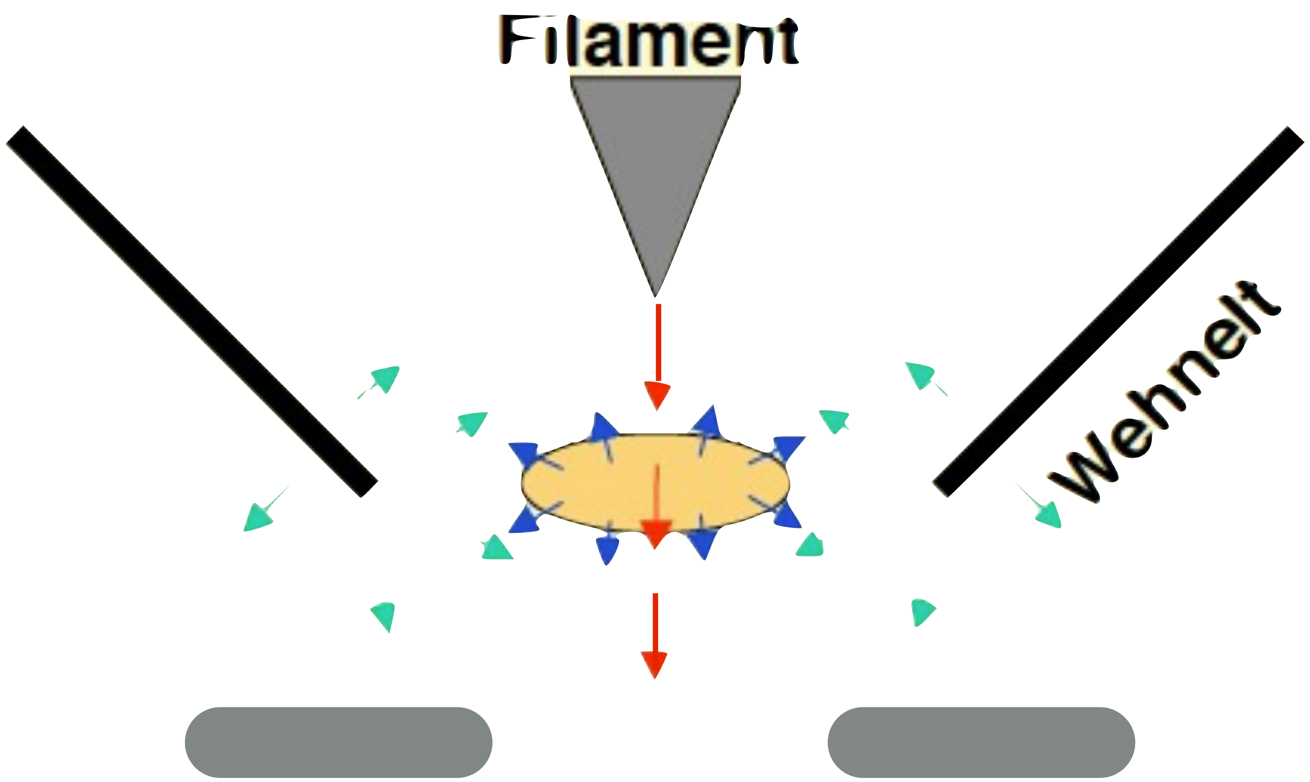

Filament (cathode)
Wehnelt
(grid)
Anode
i) No bias
Maximum
current
ii) Optimum
bias
Intermediate
current
iii)High bias
No
current

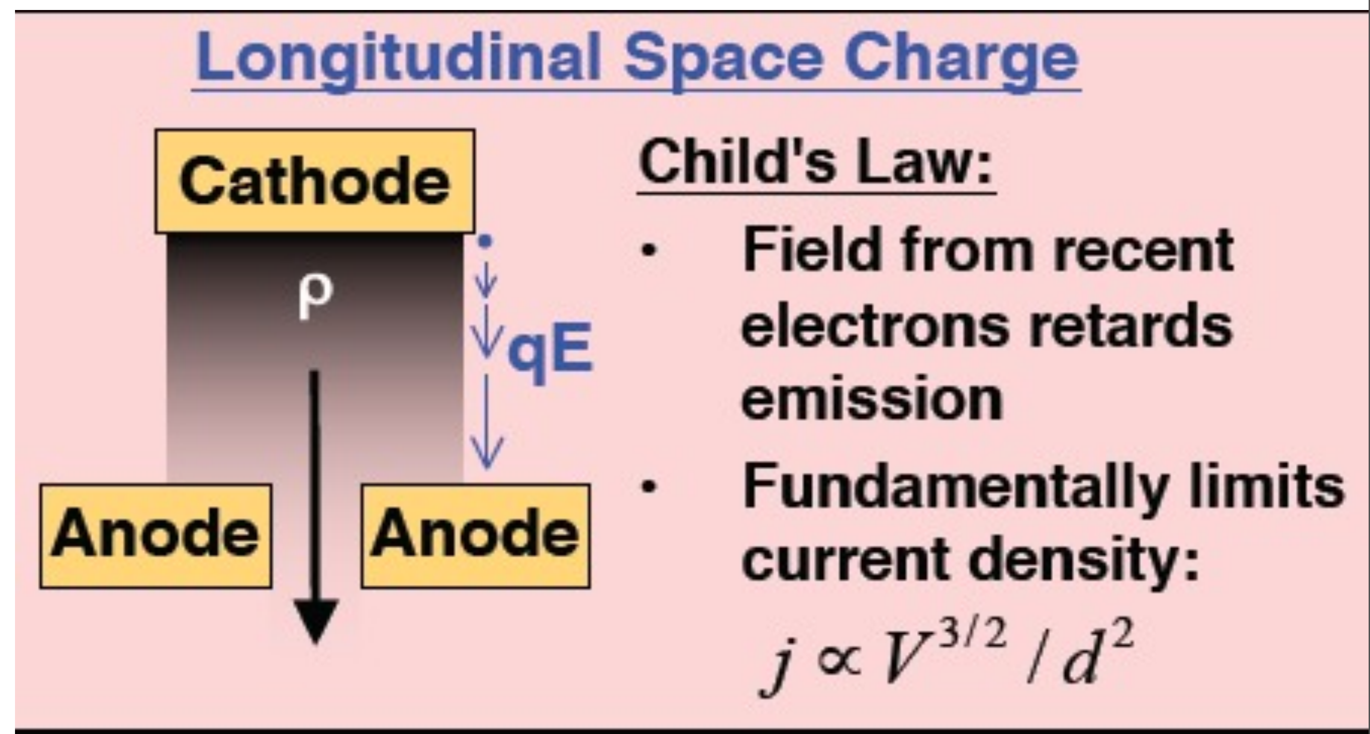

Emission
current
(μA)
600
400
200
0
Brightness
(arbitrary
units)
6
4
2
0
(i)
(ii)
(iii)
Current
Brightness
0
–200
–400
Bias voltage

Space Charge/ Boersch Effect

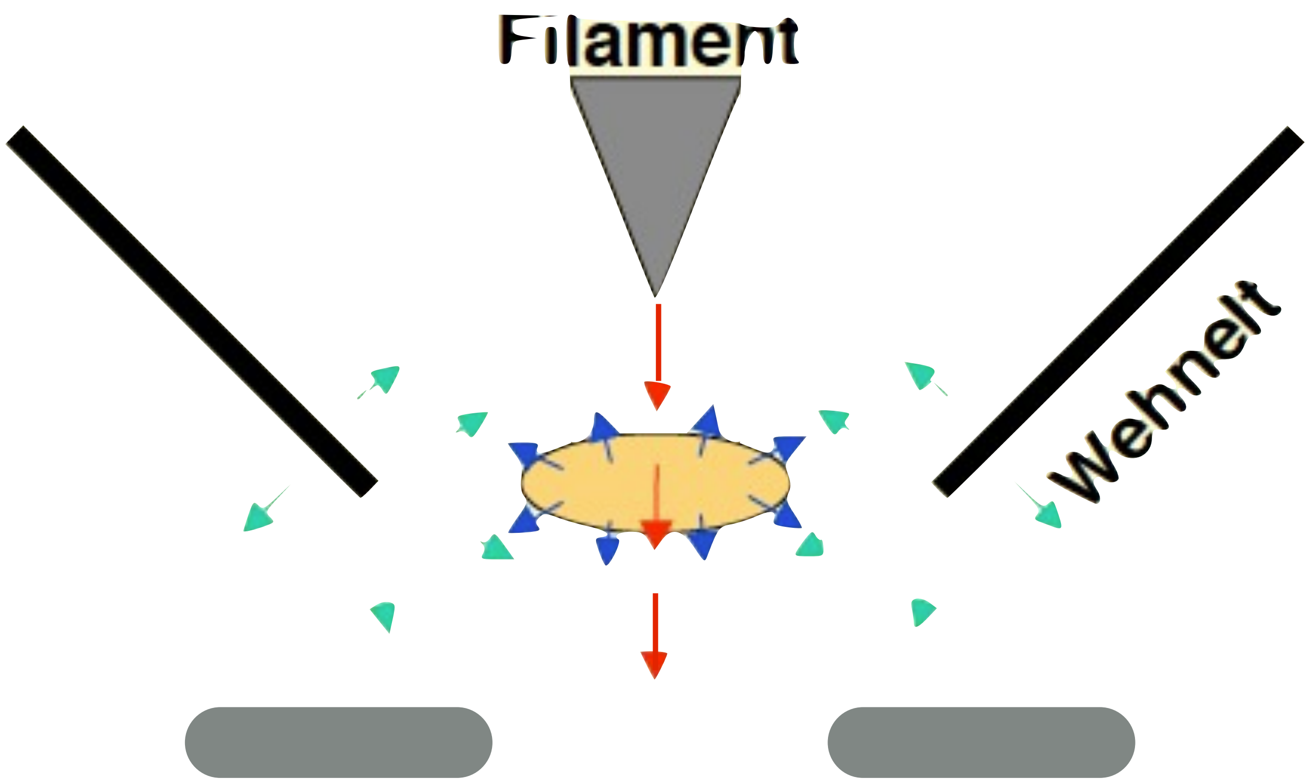


Space Charge/ Boersch Effect

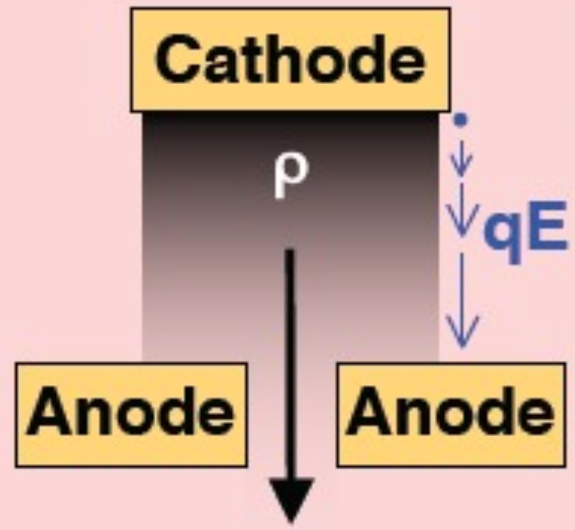




Space Charge/ Boersch Effect



Longitudinal Space Charge



Child's Law:

- Field from recent electrons retards emission
- Fundamentally limits current density:

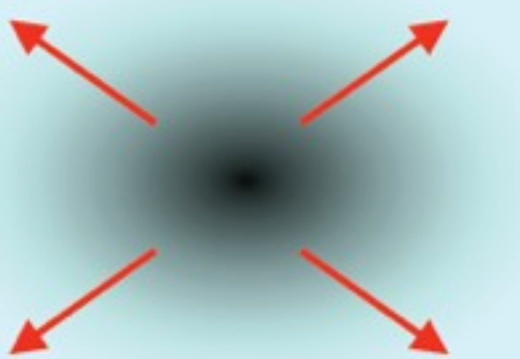
$$j \propto V^{3/2} / d^2$$

Homogeneous Effects

"Space charge"

Continuum model

ρ, $\vec{v}$, and $\vec{E}$ are continuous functions of space and time

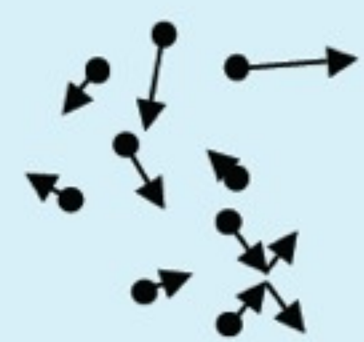


Inhomogeneous Effects

Includes Boersch effect

Discrete, stochastic model

Localized, random individual charges and statistical collisions




E-gun
pannel

BIAS
BEAM CURRENT(μA)
PROBE CONTROL
DEFLECTOR
EM STOP
COND STIG
OBJ STIG
DARK TILT
BRIT TILT
TEM
COARSE
FINE
FILAMENT
HT COND
EDS
PANEL LIGHT
NBD
SPOT SIZE
SHIFT X
CBD
ON
CRS
ACCEL VOLTAGE
α-SELECTOR
BRIGHTNESS
DEF X
UP
HT
ROOM LAMP
CRS
DOWN
OFF
元氣生活館
食物普林含量表


EM STOP
HT COND
PANEL LIGHT
ROOM LAMP
BIAS
BEAM CURRENT(μA)
COARSE
FINE
FILAMENT
ON
ACCEL VOLTAGE
UP
DOWN
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OFF
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BIAS
BEAM CURRENT(μA)
PROBE CONTROL
DEFLECTOR
EM STOP
COARSE
FINE
TEM
COND STIG
OBJ STIG
DARK TILT
BRIT TILT
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EM STOP
HT COND
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BEAM CURRENT(μA)
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BRIT TILT
SPOT SIZE
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CRS
SHIFT X
DEF X
CRS
元氣生活館
食物普林含量表

B. Field Emission Gun

$$E=V/r$$

r：radius of curvature of tip。

V: applied voltage

E: electric field

- Generally, r <0.1μm(1000Å), V=kv(1000ev)--->$E=10^6$ V/m

strong electric field makes electron tunneling

B. Field Emission Gun

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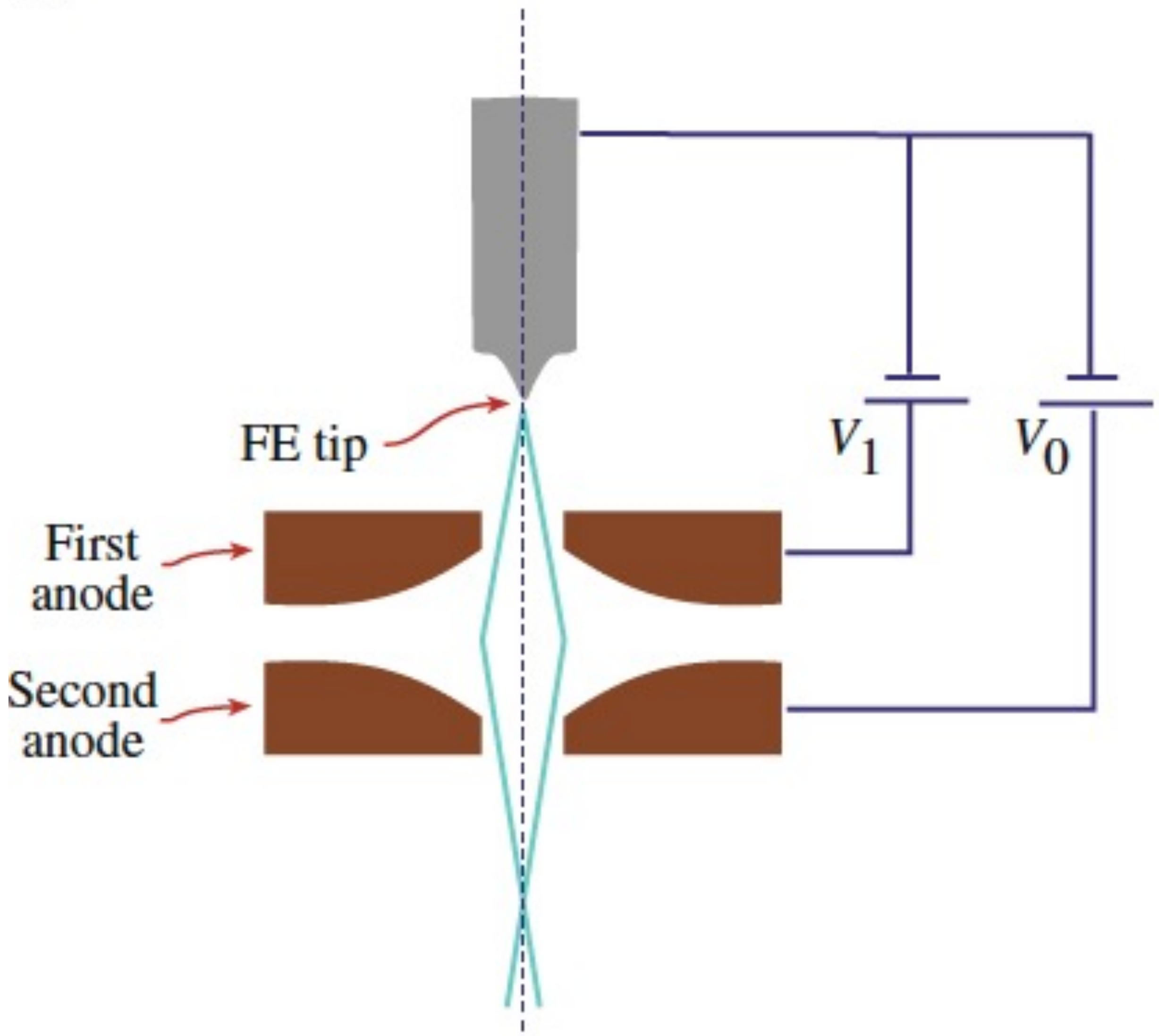
Field Emission Gun

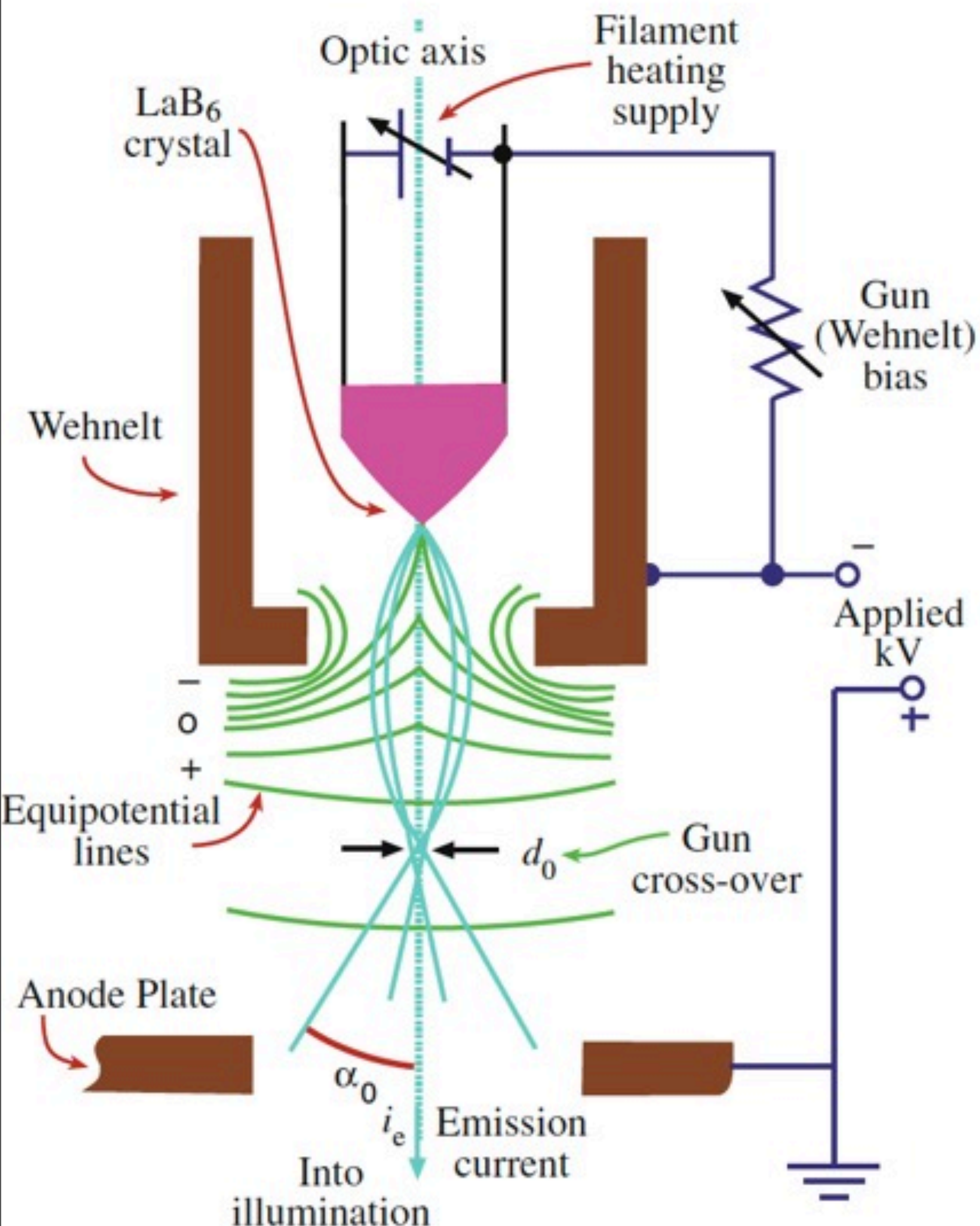


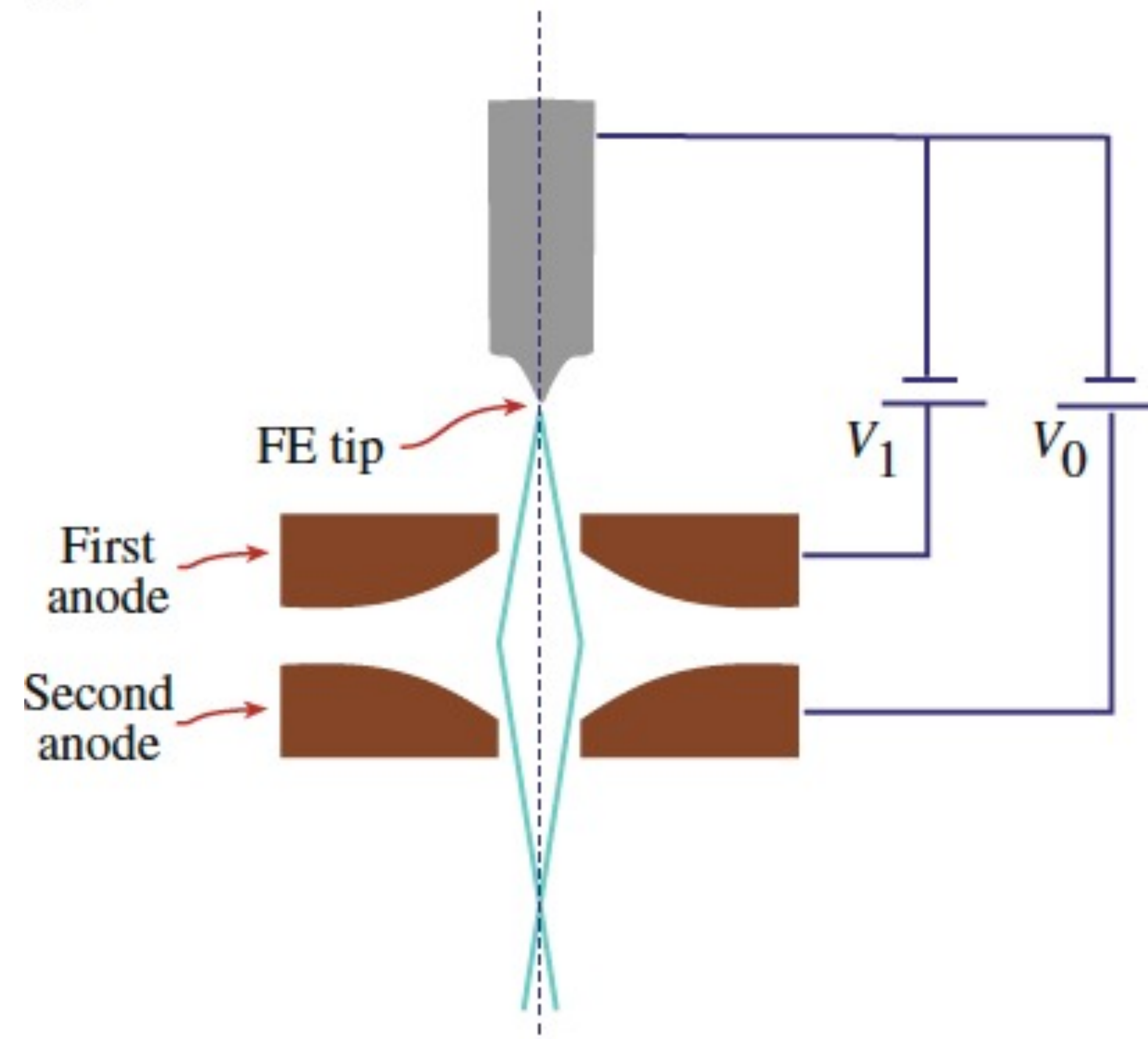
V_1=幾kV:extraction voltage萃取電壓

V_0=100kV or more:accelerating

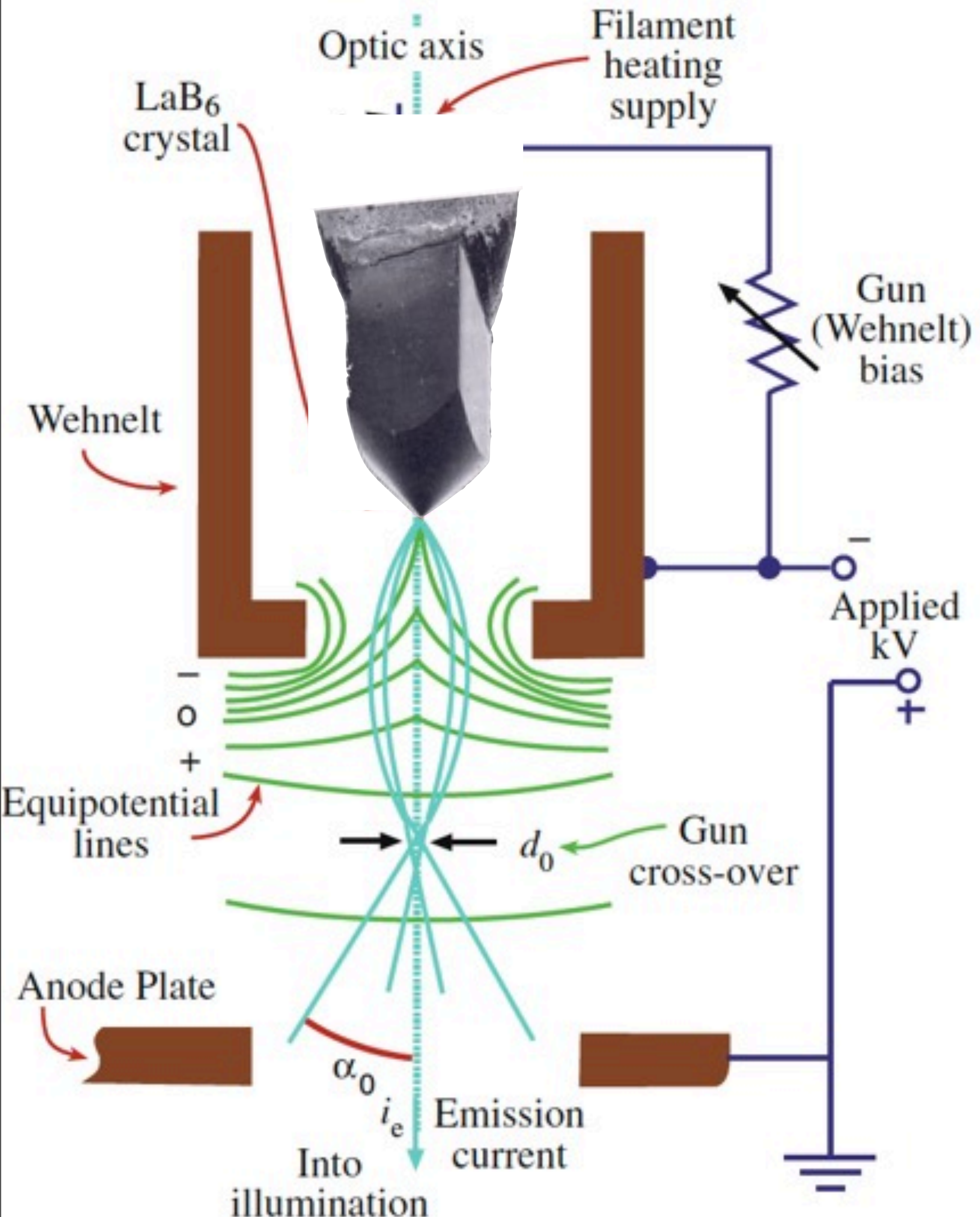
voltage(加速電壓)

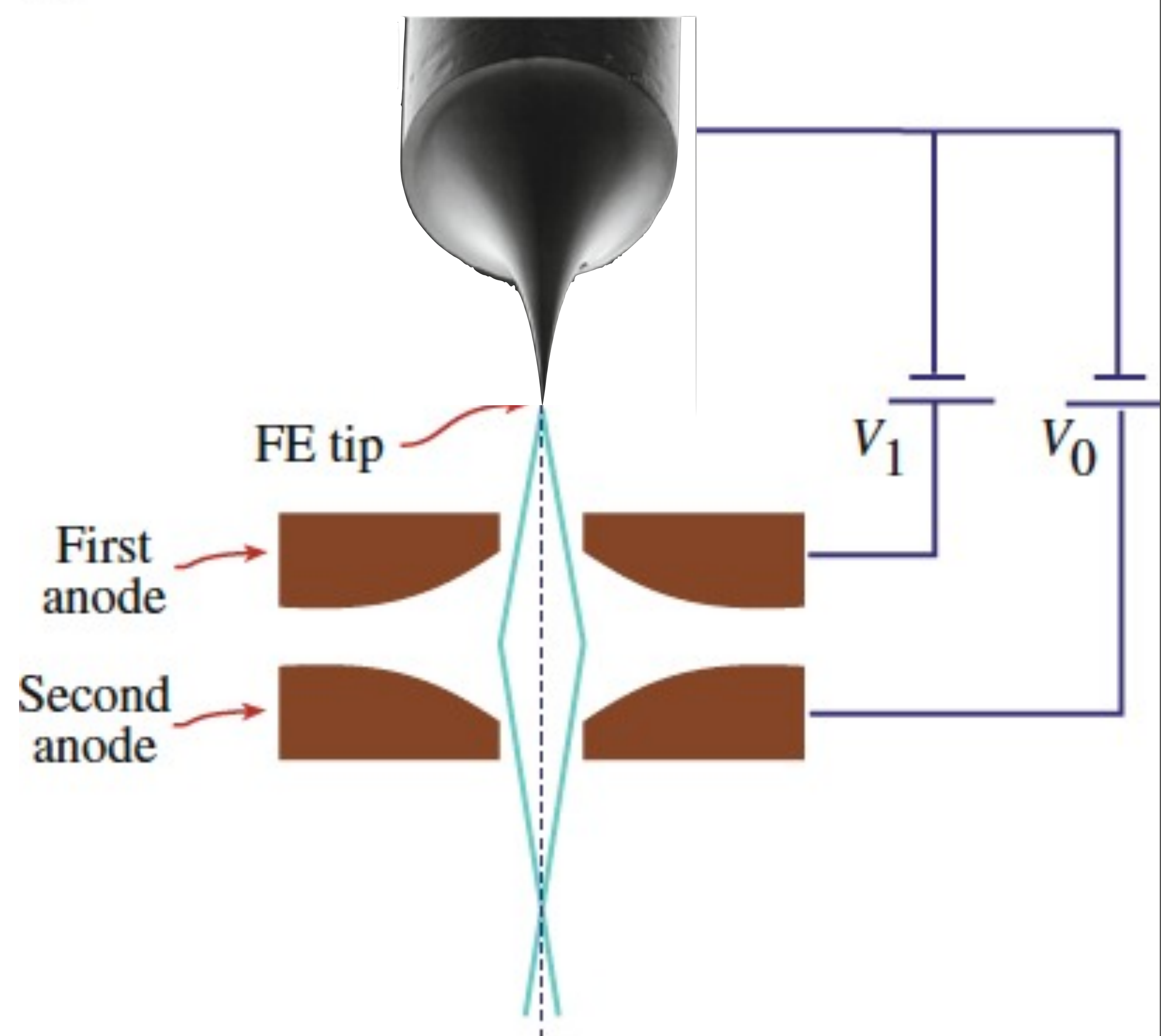
Thermionic Source vs. Field Emission Source



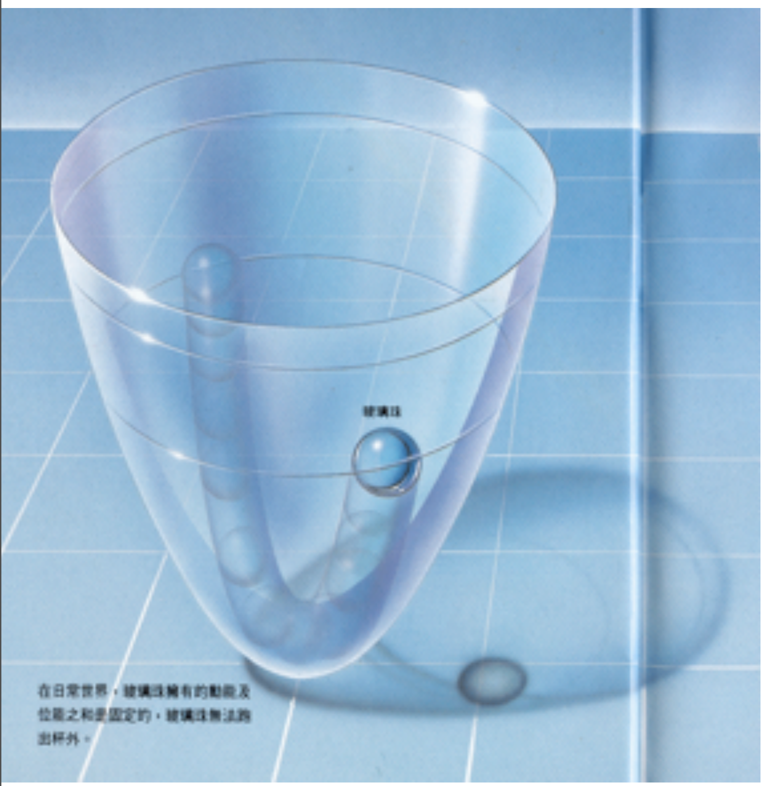


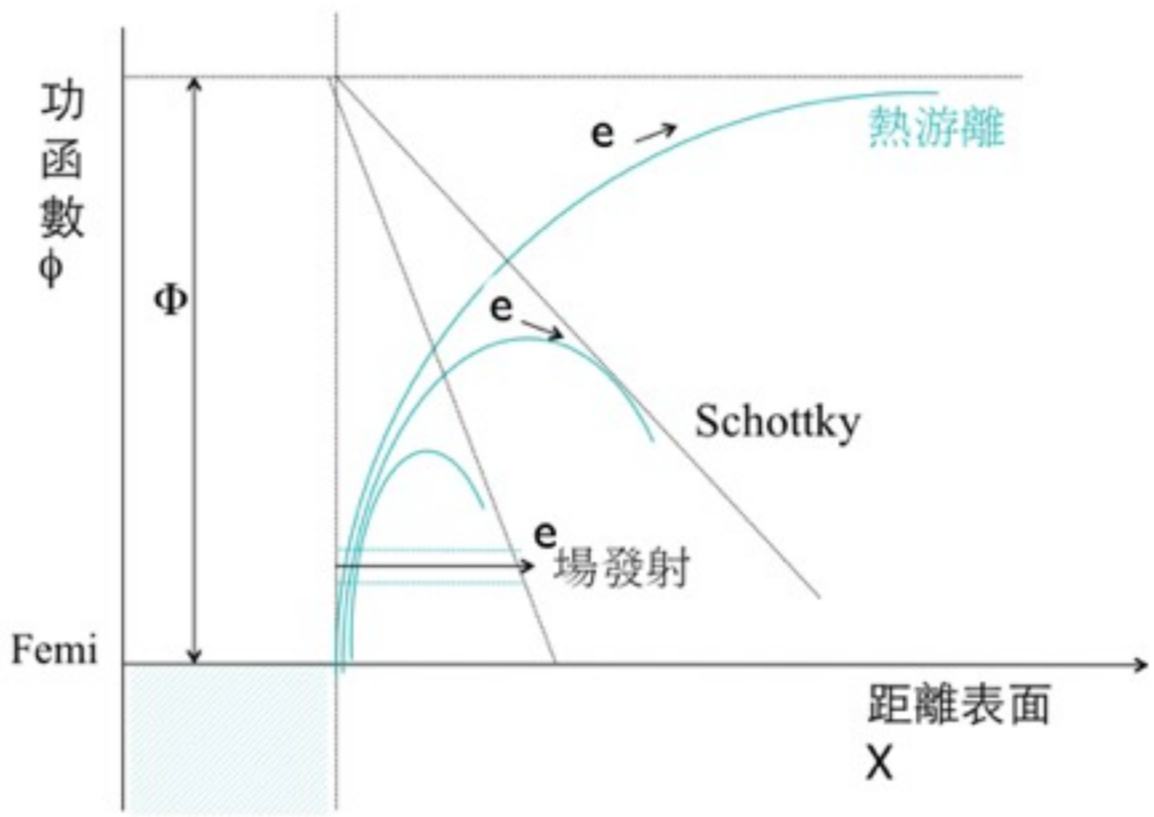
Thermionic Source vs. Field Emission Source

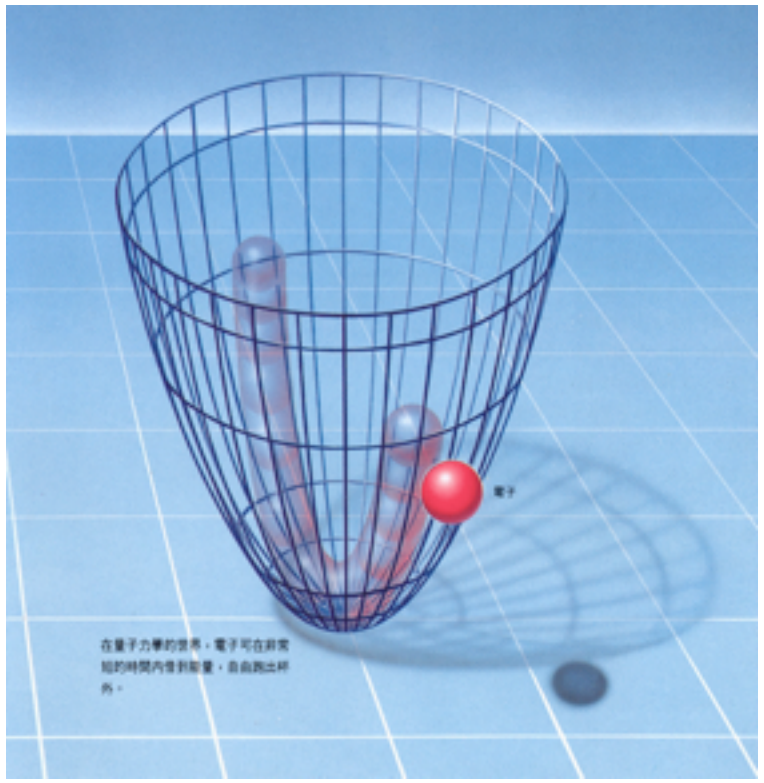




Thermionic Source vs. Field Emission Source







2.2. Brightness

A brightness vs intensity

●

Intensity: detector

(Amper/cm^2*sec) detector

Brightness ; Source

(Amper/cm^2*sr) source

Advantage of FEG

Brightness is 1000 times higher

Drawback of FEG

stability is poorer,

Flash is needed

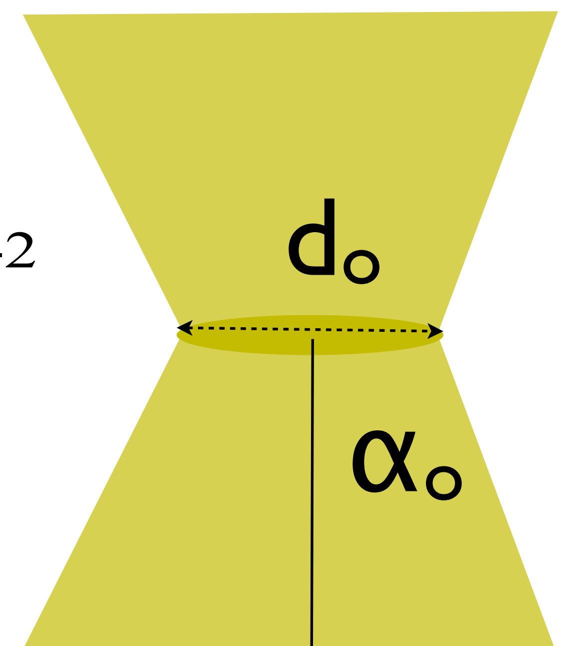
Brightness(β)

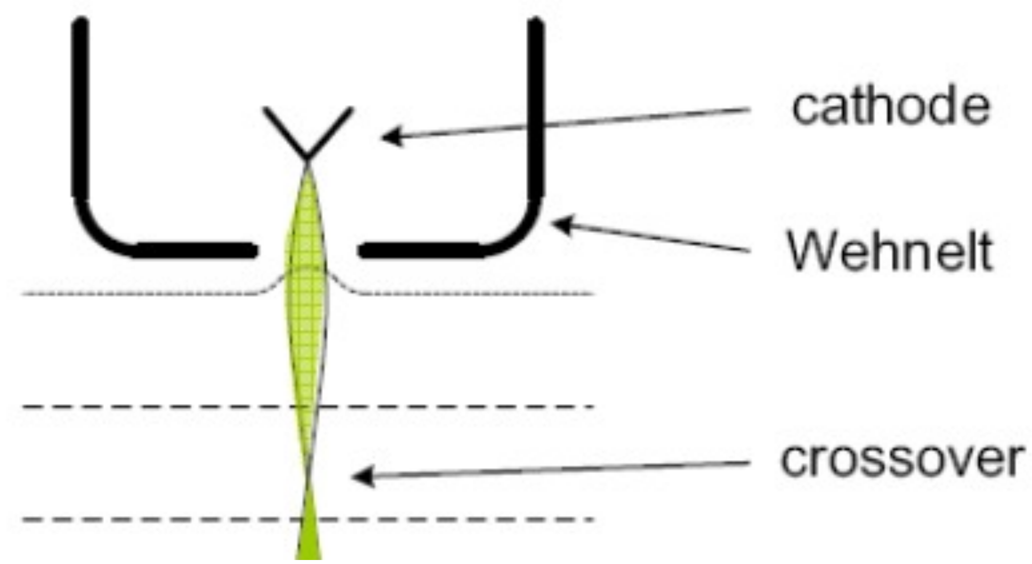
$$\beta = \frac{i_e}{\pi\left(\frac{d_o}{2}\right)^2 \pi(\alpha_o)^2} = \frac{4i_e}{(\pi d_o \alpha_o)^2}$$

- Cross-Over in electron gun
- current : i_e
- semi-angle : α_o

current density $\quad i_e \pi^{-1}\left(\frac{d_o}{2}\right)^{-2}$

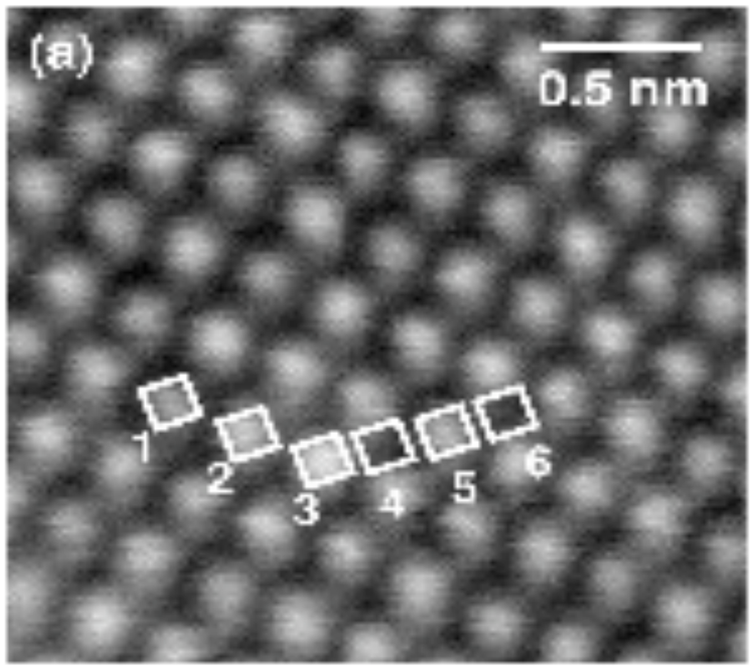
solid angle $\quad \pi\alpha_0$

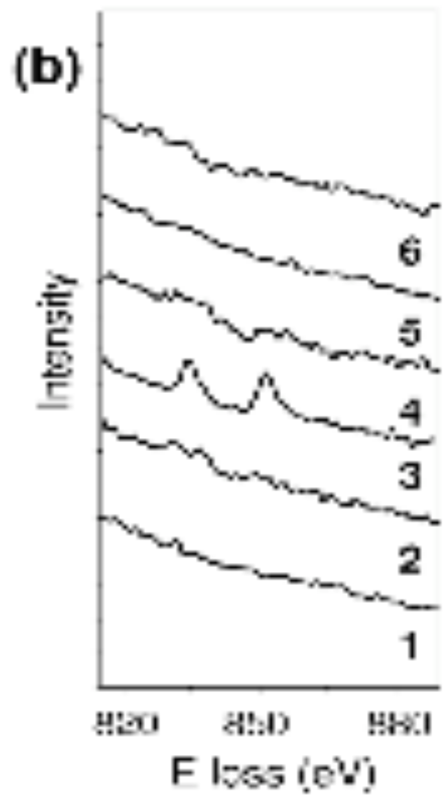


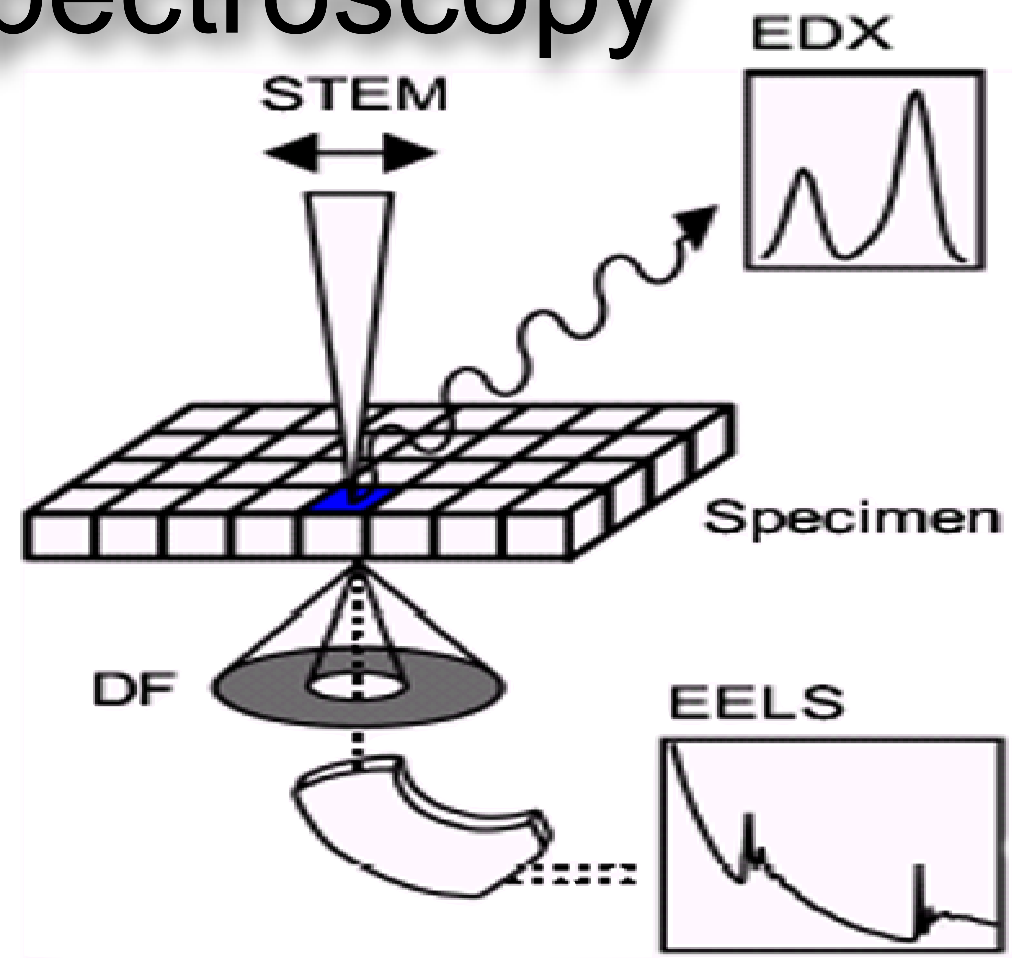


d_o	燈絲半徑(r_o)	交叉點半徑(d_o)
	W = 50μm	100 μm
	LaB_6 = 10 μm	10 μm
	FEG < 10 nm	10 nm

Importance of Brightness
Single atom spectroscopy

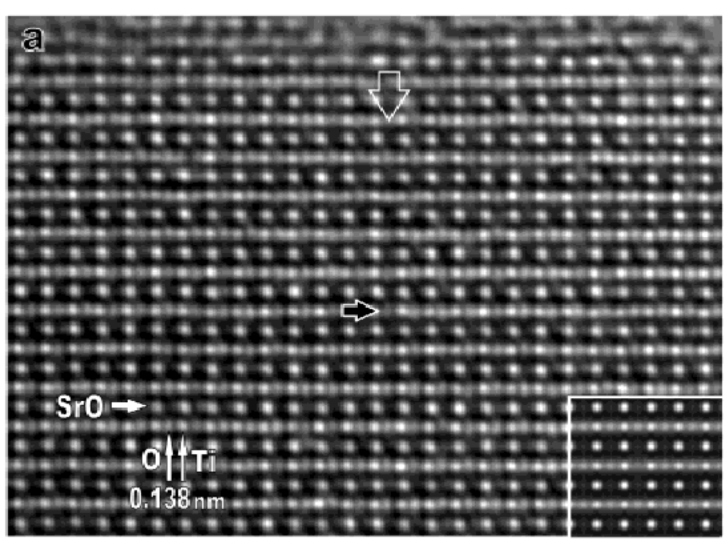


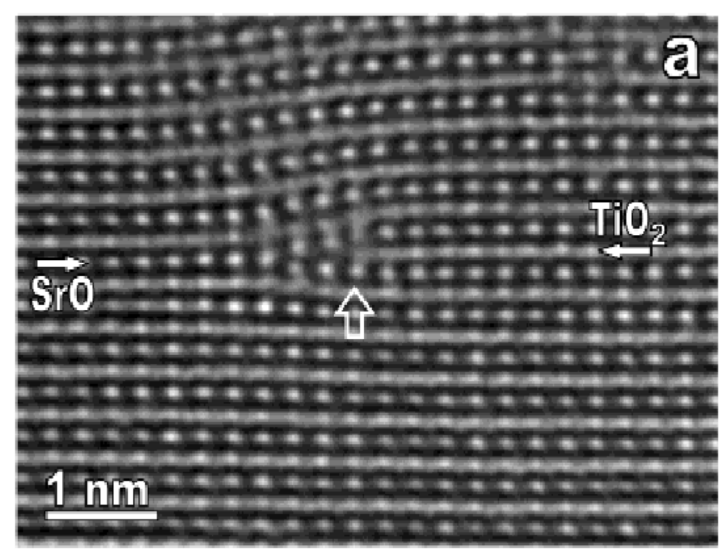




Energy band gap, phonon scattering, electronic structure

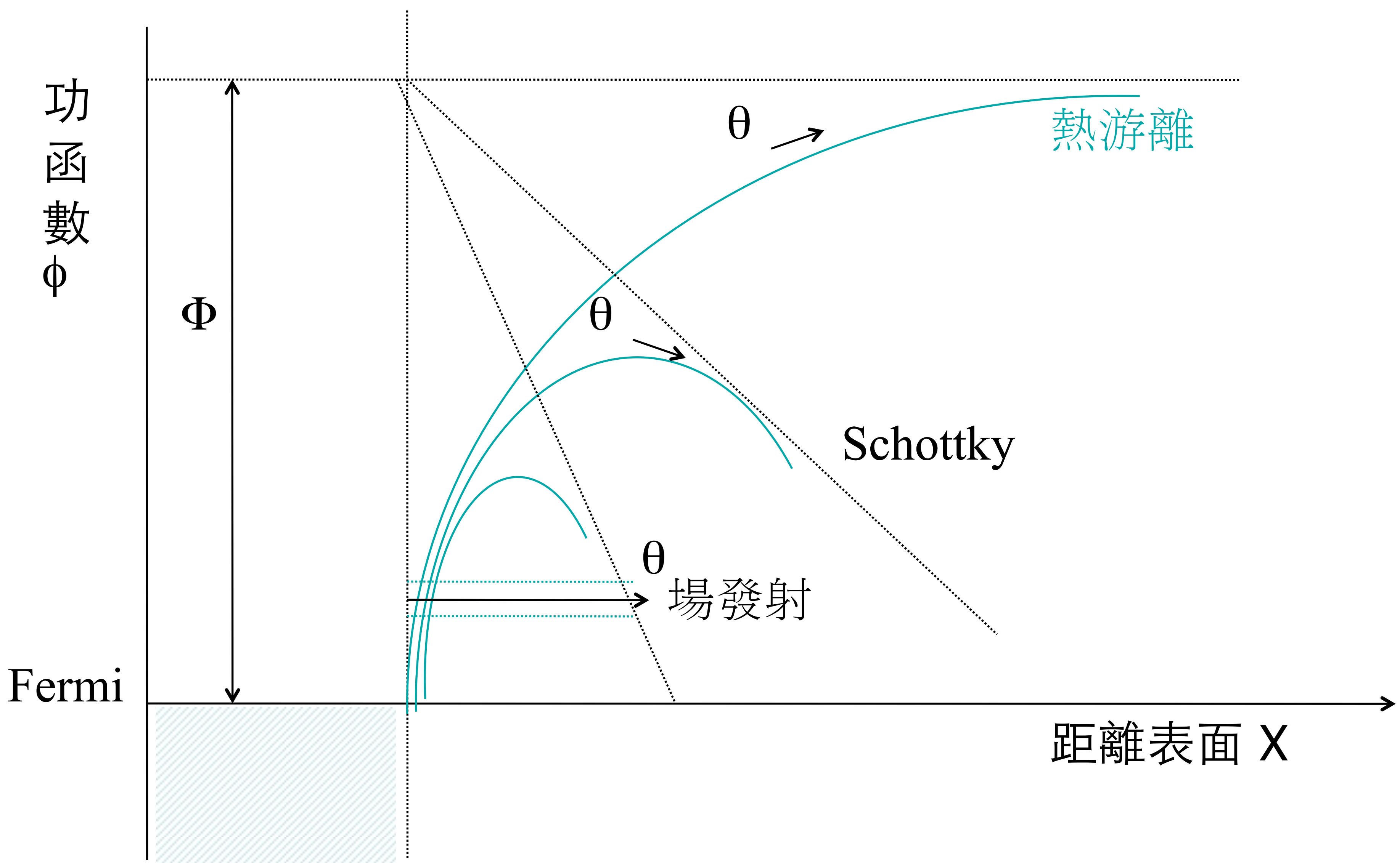
SrTiO$_3$





Schottky Gun

ZrO_2/W: Work function f ZrO2 is low. It takes advantage of both thermionic gun (stability) and FEG (high brightness)

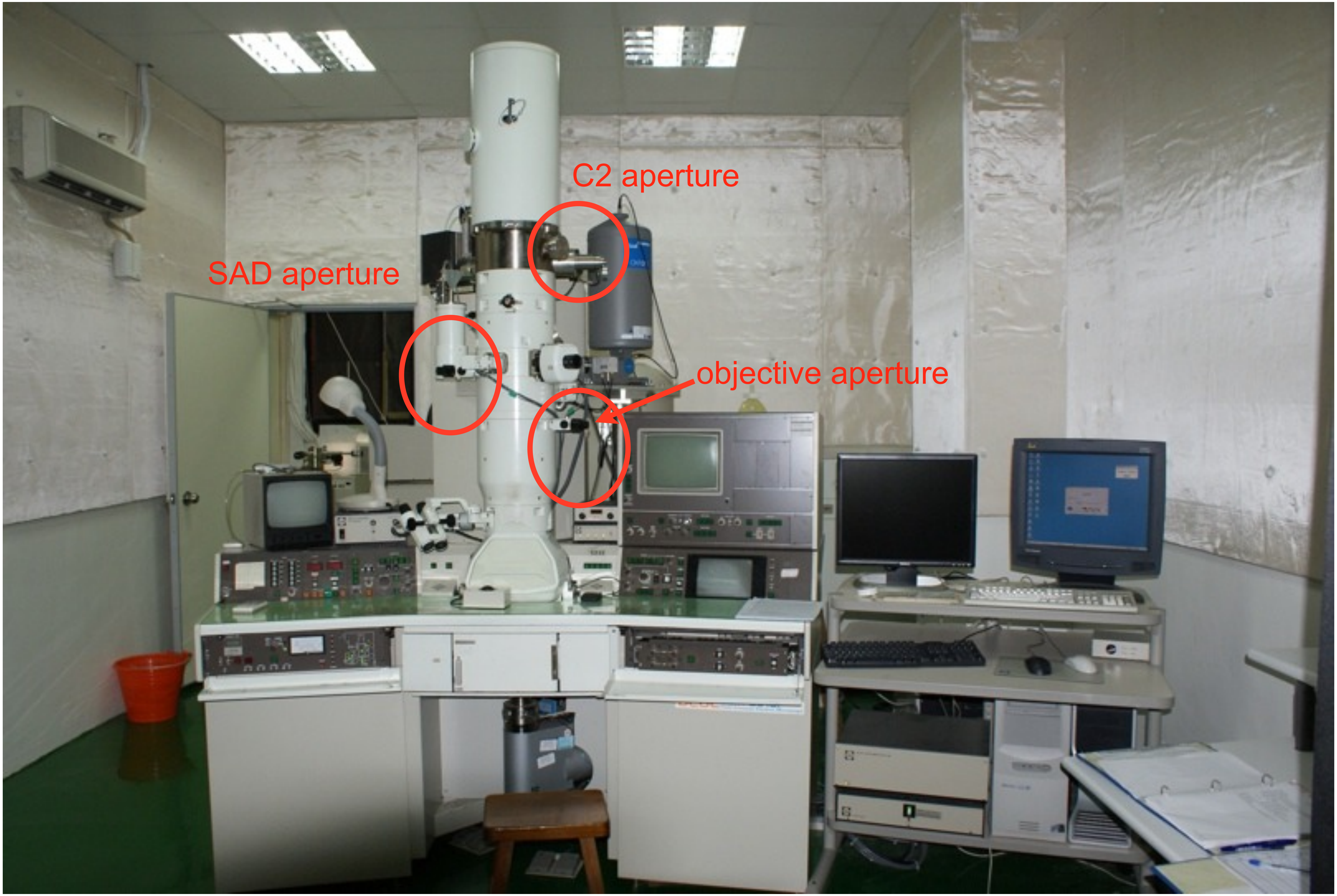


Characteristics of the Three Principal Sources

Operating at 100kV

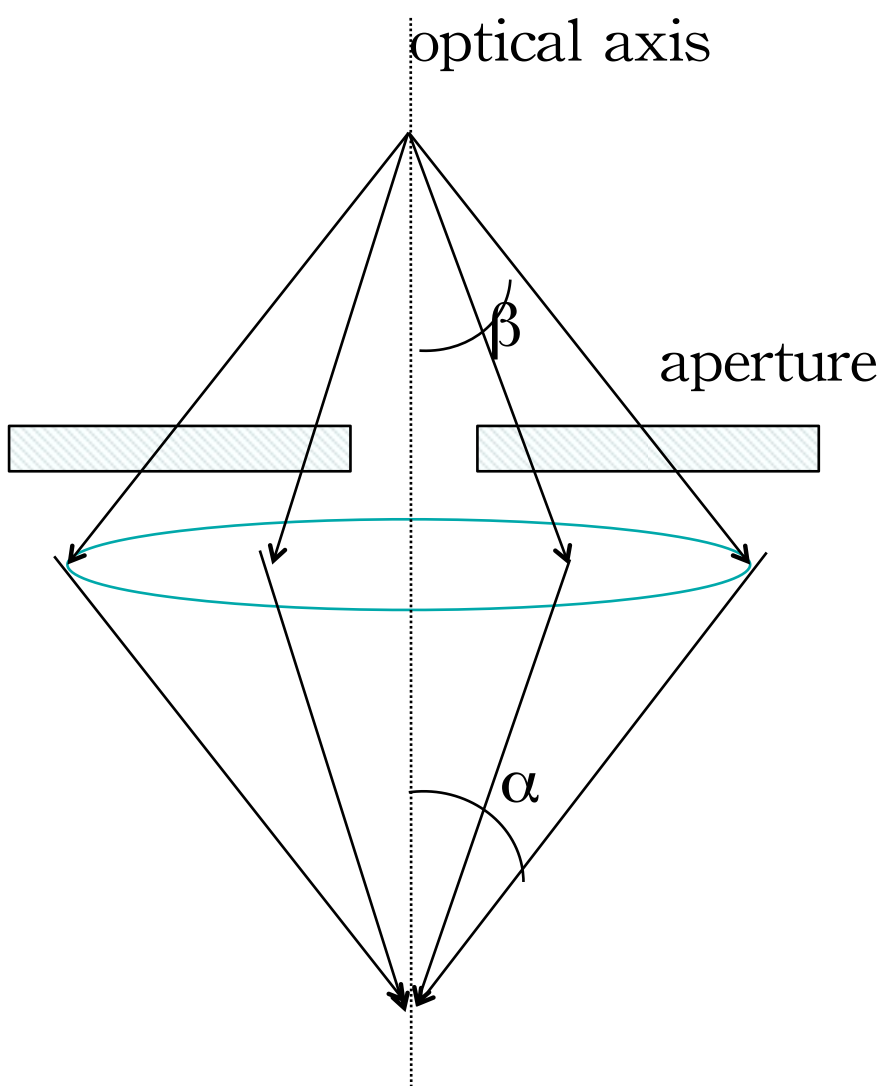
	Units	Tungsten	LaB_6	Field Emission
Work function, ϕ	eV	4.5	2.4	4.5
Richardson's constant	A/m^2K^2	6×10^5	4×10^5	
Operating temperature	K	2700	1700	300
Current density	A/m^2	5×10^4	10^6	10^{10}
Crossover size	μm	50	10	<0.01
Bringhtness	$A/m^2/sr$	10^9	5×10^{10}	10^{13}
Energy spread	EV	3	1.5	0.3
Emission current stability	%/hr	<1	<1	5
Vacuum	Pa	10^{-2}	10^{-4}	10^{-8}
Lifetime	hr	100	500	>1000

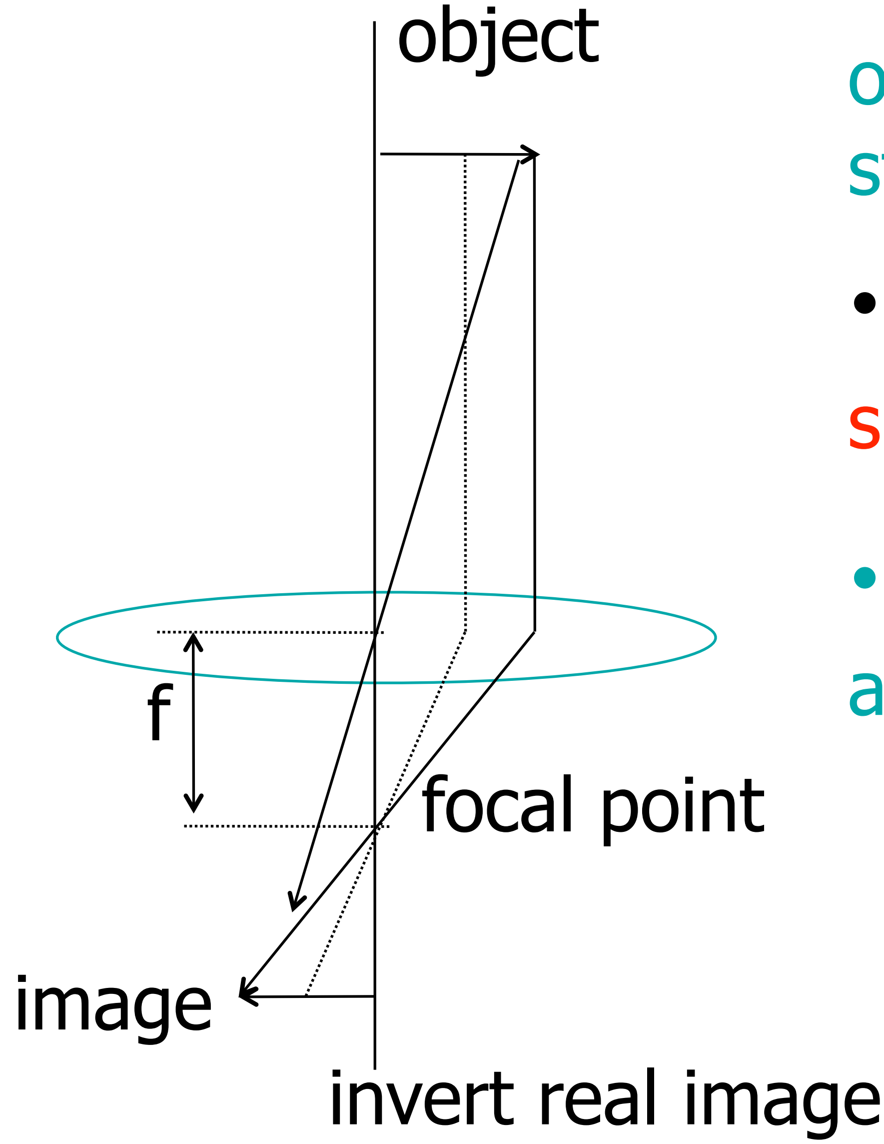
場發射光源具有點光源(好空間相干性)和小能量發散(好能量相干性)


C2 aperture
SAD aperture
objective aperture

2. 4. Magnetic lens

- The magnetic lens in an EM is like 凸 glass lens. It is always a convergent lens.



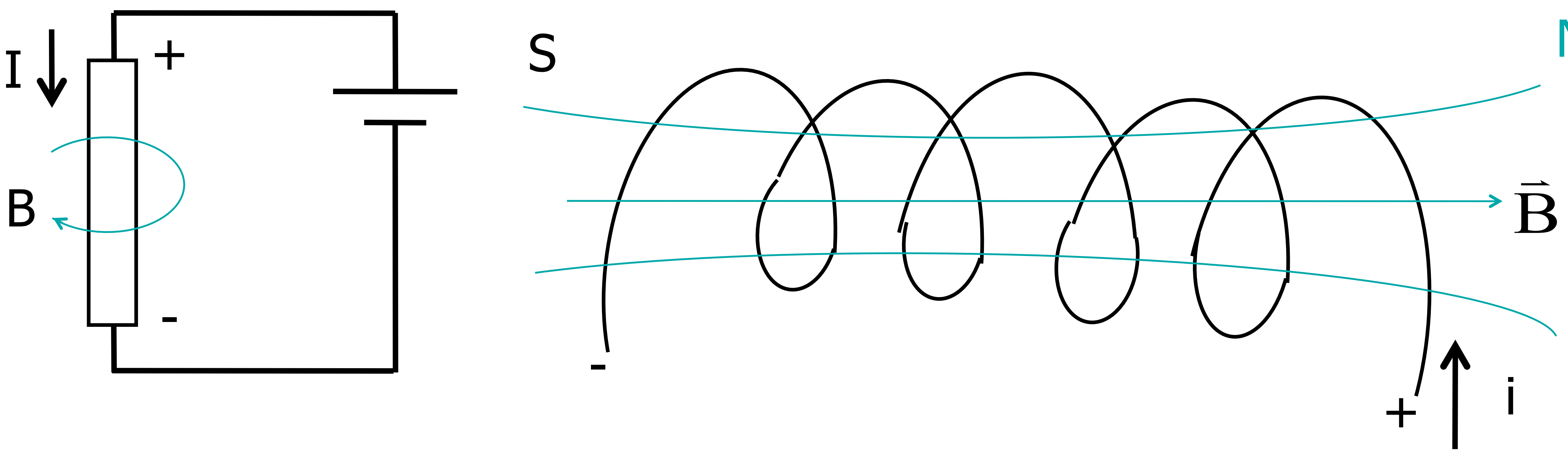


•in fact, the trajectory of electron is not straight line in lens

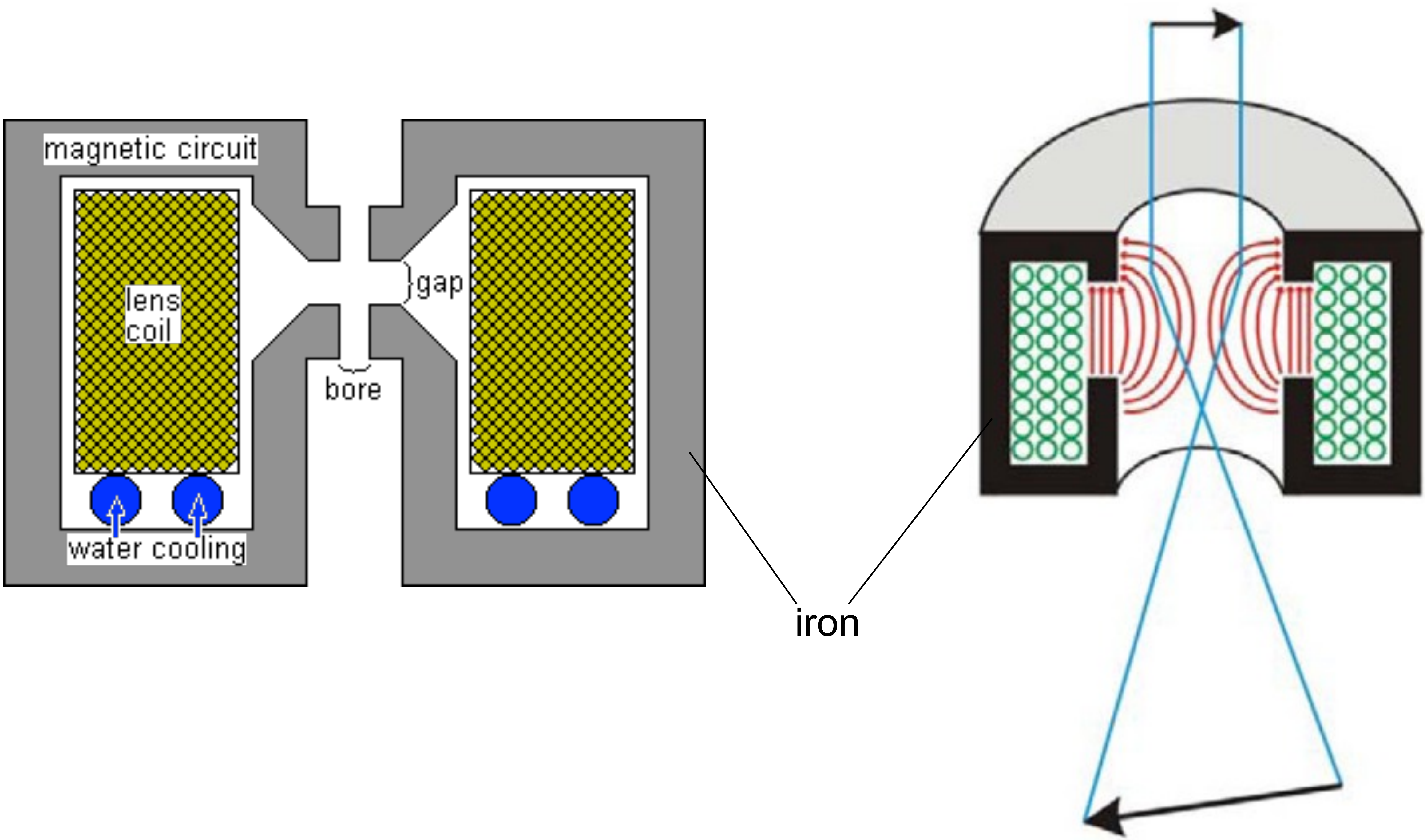
•stronger lens means smaller focal length。

•In typical EM，βis about 10 mrad ~ 0.57^{o}。

Induced Magnetic field



2.4.1 magnetic lens



2.4.2 trajectory of electron

- F (Lorentz force)

$$\vec{F} = -e(\vec{\upsilon}\ \mathbf{x}\ \vec{\mathbf{B}}),$$ $\vec{\upsilon}$ velocity of electrons

$$\vec{F} \perp (\vec{\upsilon}\ \mathbf{x}\ \vec{\mathbf{B}})$$

$$|\mathbf{F}| = \mathbf{e}\,\upsilon\,\mathbf{B}\,\mathbf{Sin}\theta$$

θ angle between optical axis and trajectory

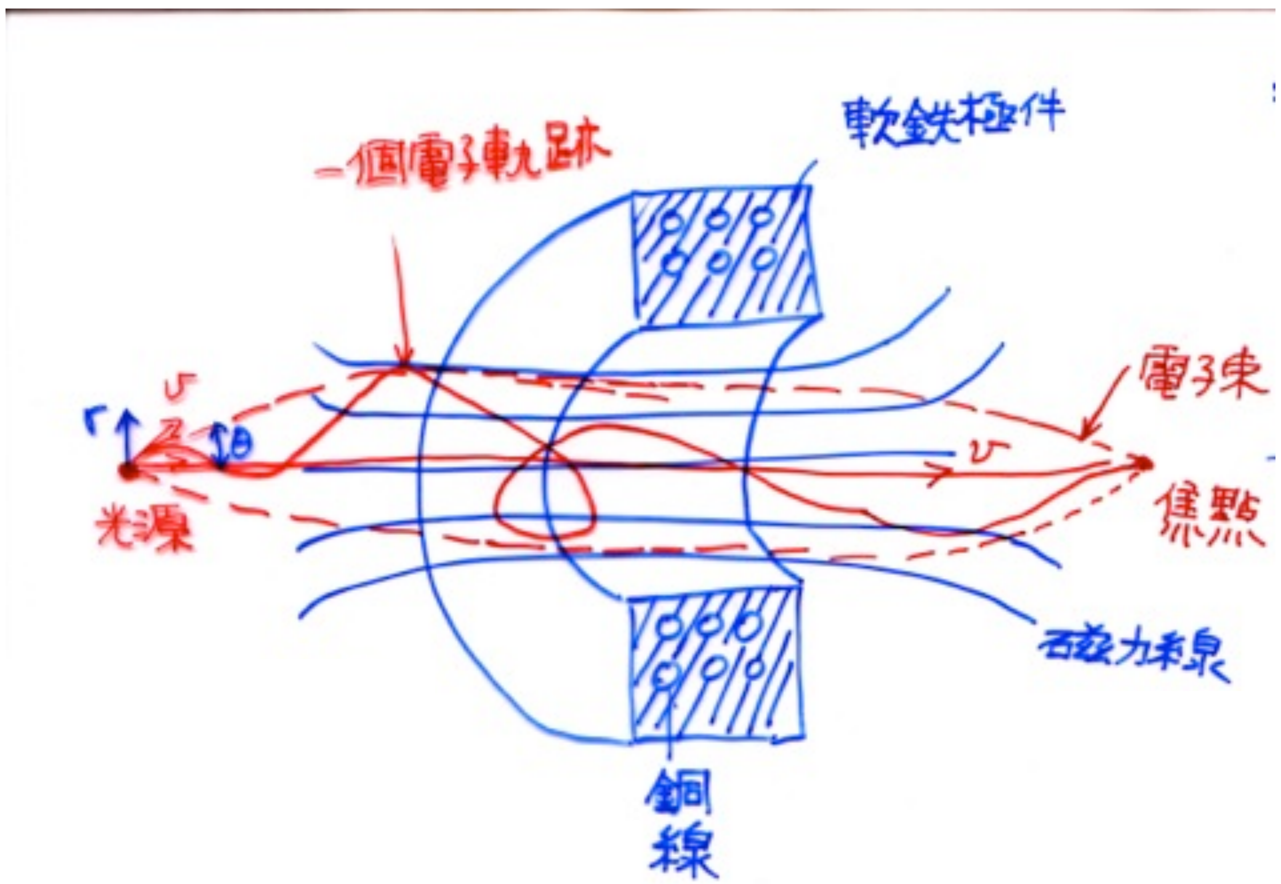
θ=0 , No force

θ=90 max. force

$$|F| = evB = \frac{m\upsilon^2}{\gamma},\ \gamma = \frac{\mathbf{m\upsilon}}{\mathbf{eB}}$$

$$\gamma = \frac{3.37x10^{-6}\left[V\left(1 + 0.9788x10^{-6}V\right)\right]^{1/2}}{B},\ \mathbf{V = 100Kv,\ \ B = 1\,Tesla,}\ \ \gamma \sim \mathbf{1mm}$$

- Higher magnetic field is needed for higher energy electron



$\vec{F} = -\mathbf{e}(\vec{\upsilon} \times \vec{\mathbf{B}})$

V : velocity of electrons

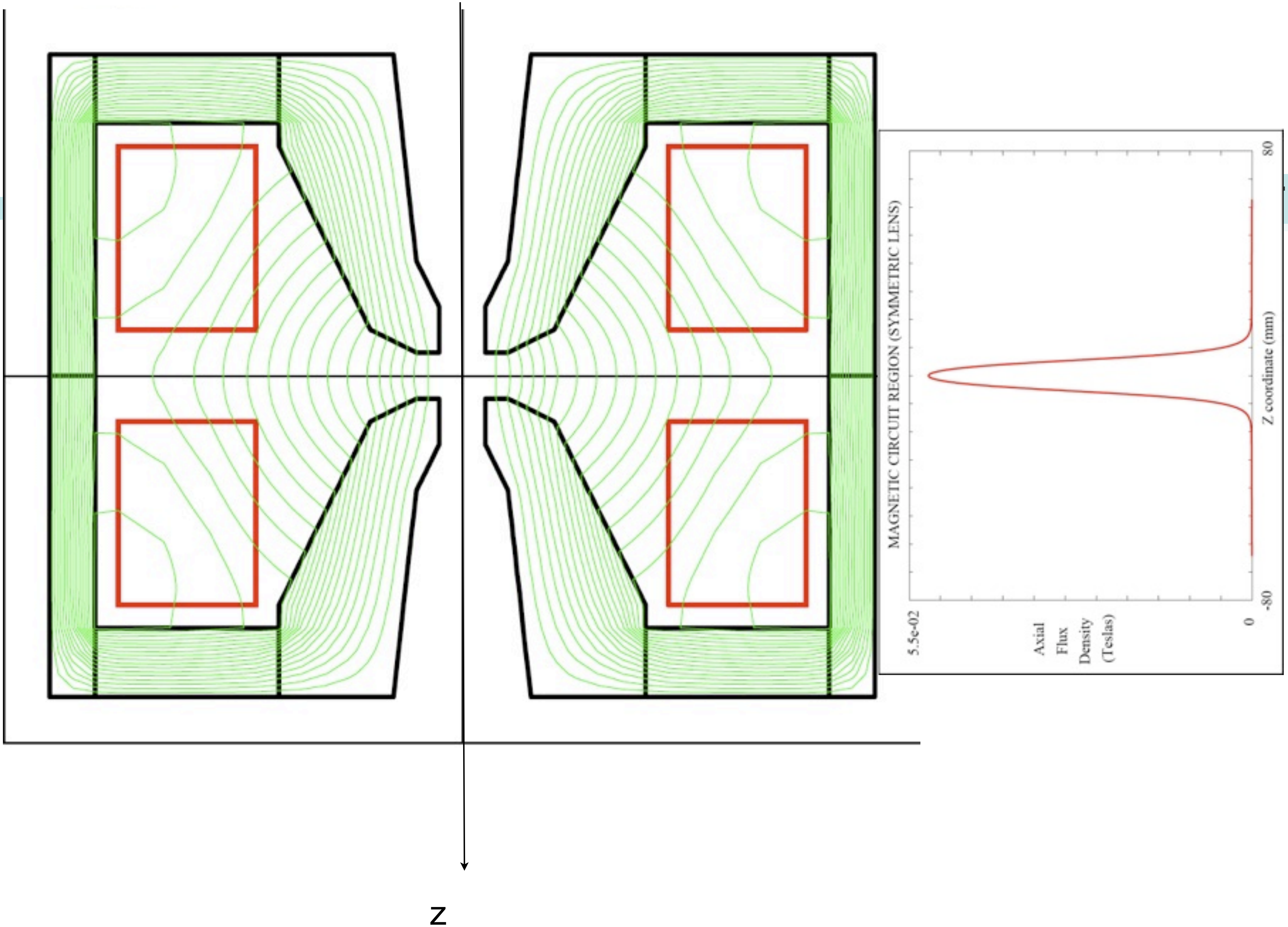
$\eta : e / (2m_oC^2)^{1/2}$

$$\frac{d^2r}{dz^2} + \frac{\eta^2 B^2 r^2}{2V^{1/2}} = 0$$

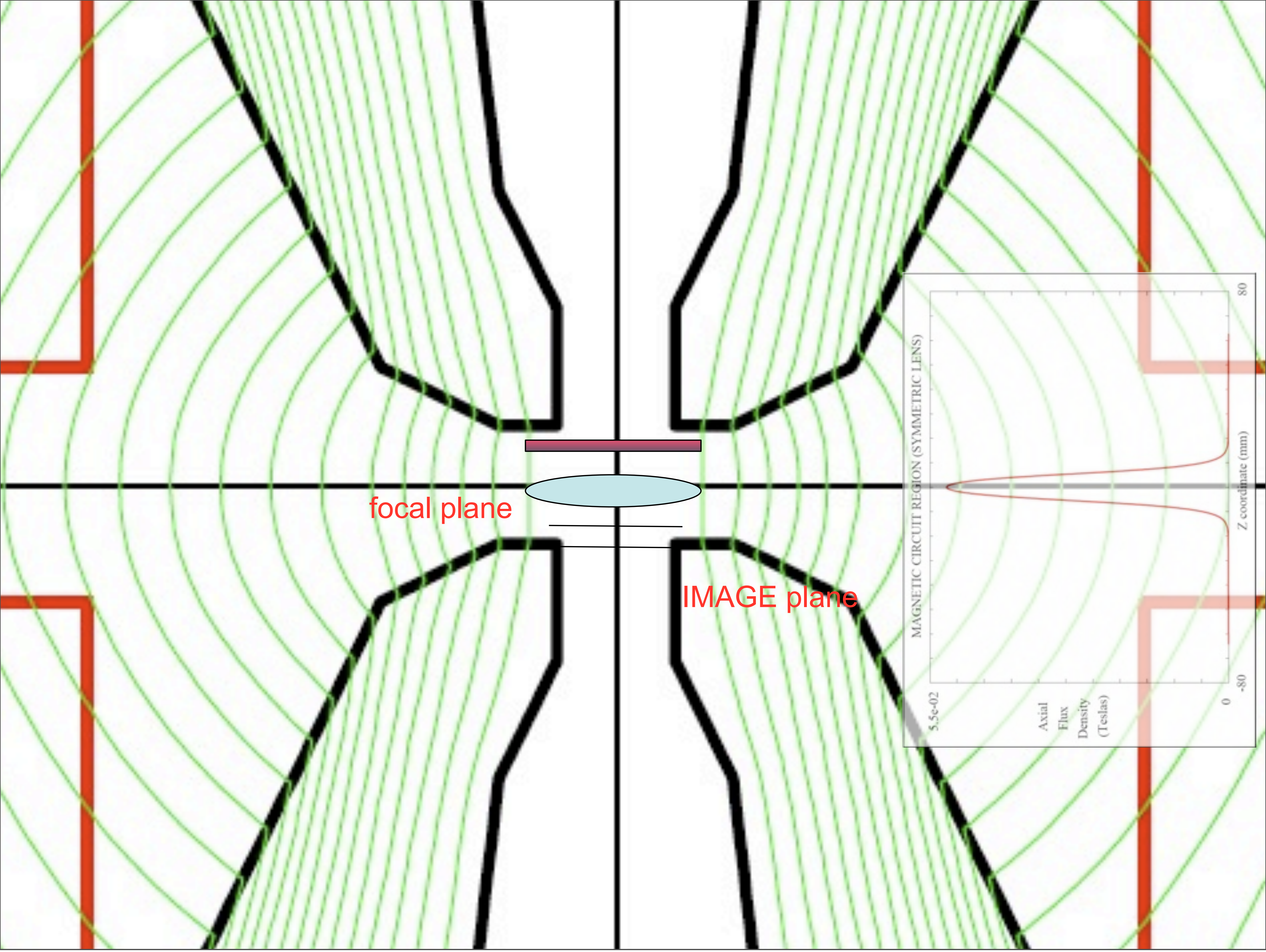
$$\frac{d\theta}{dZ} = \frac{\eta \mathbf{B}}{2V^{1/2}}$$

Paraxial **Egn.**

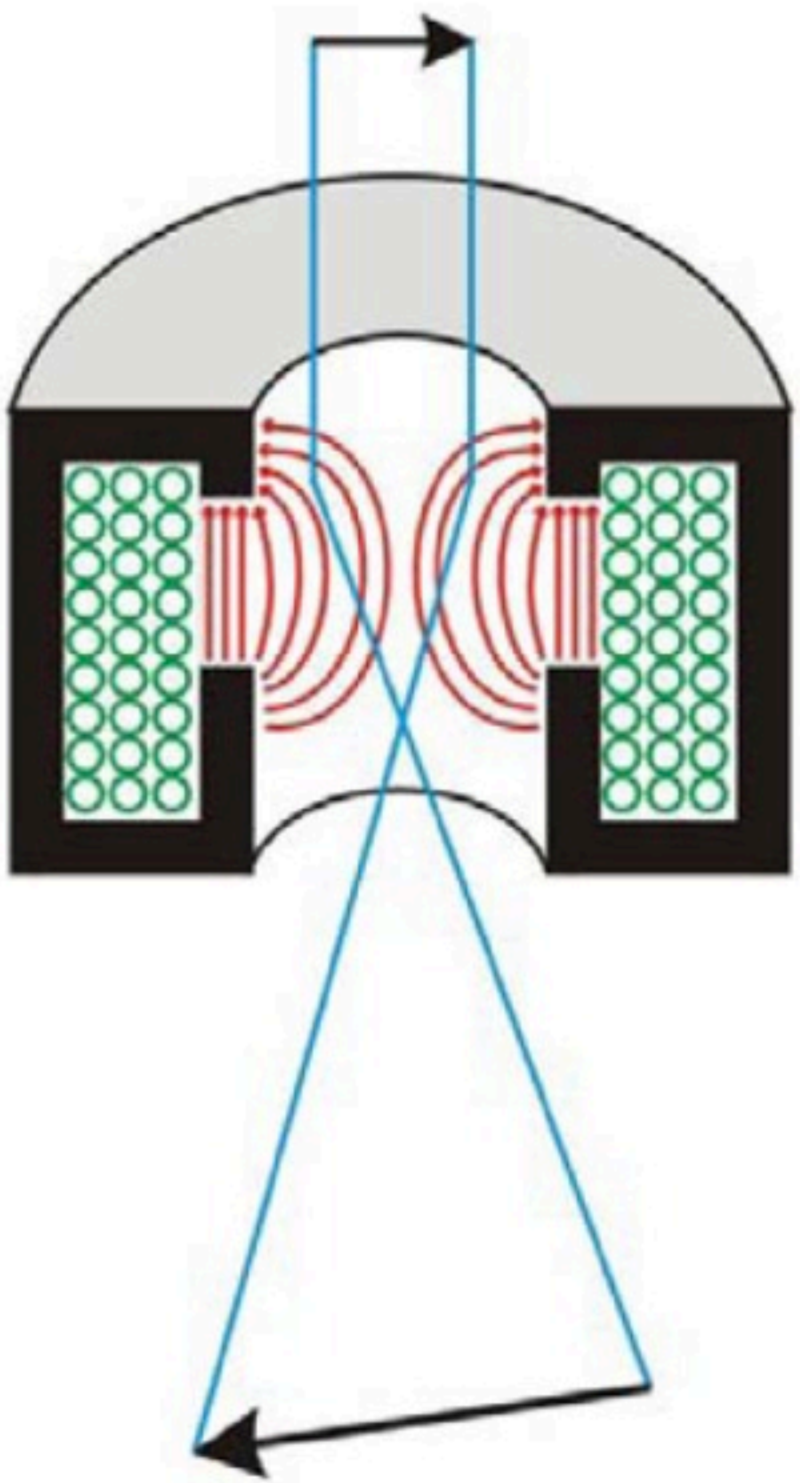
•electron trajectory is hellical .



MAGNETIC CIRCUIT REGION (SYMMETRIC LENS)
Z coordinate (mm)
80
-80
5.5e-02
0
Axial Flux Density (Teslas)
Z


focal plane
IMAGE plane

Magnetic Lens



Object plane

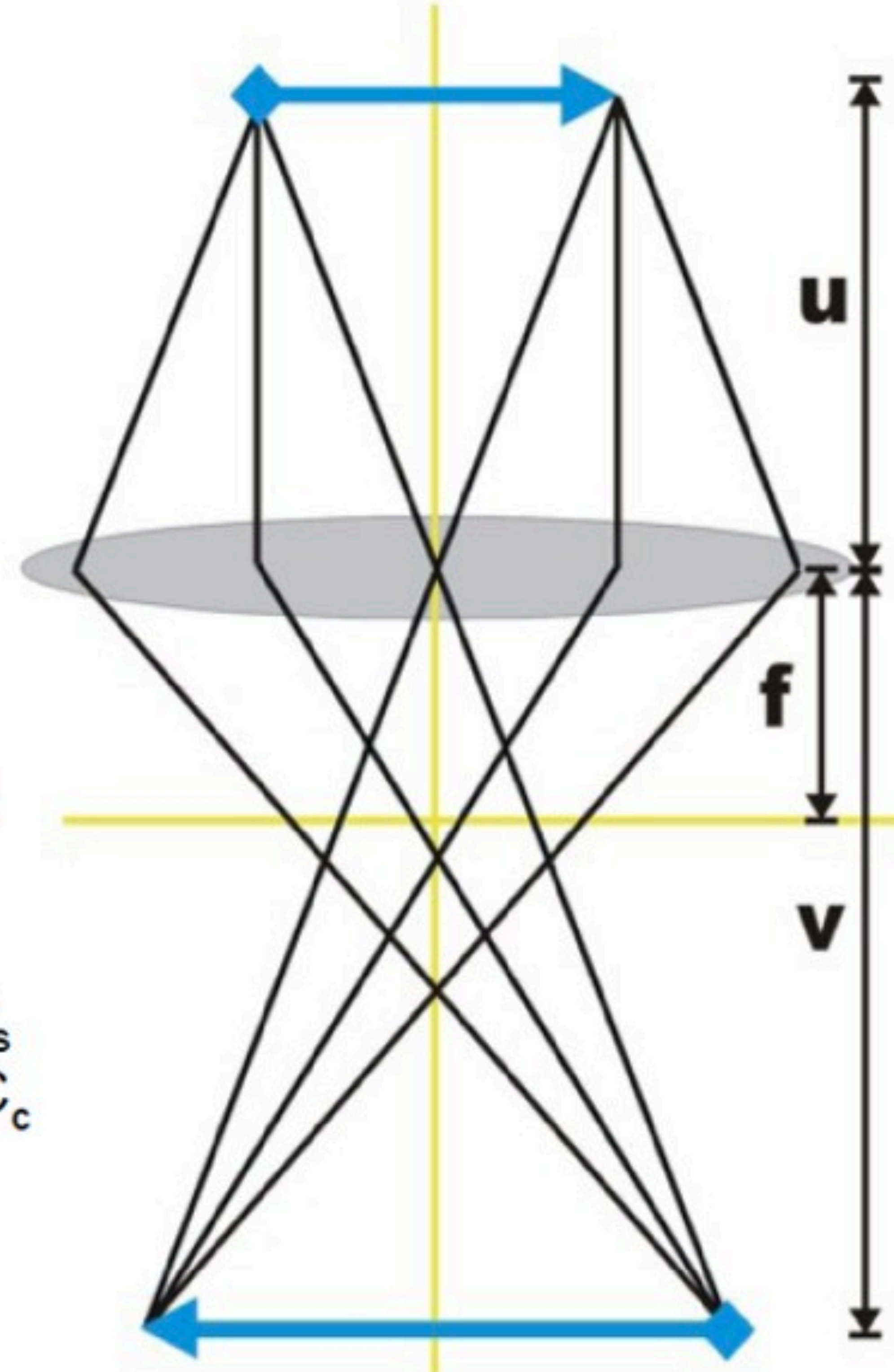
Lens

Back focal plane

Lens problems:
spherical aberation C_s
chromatic aberation C_c
astigmatism

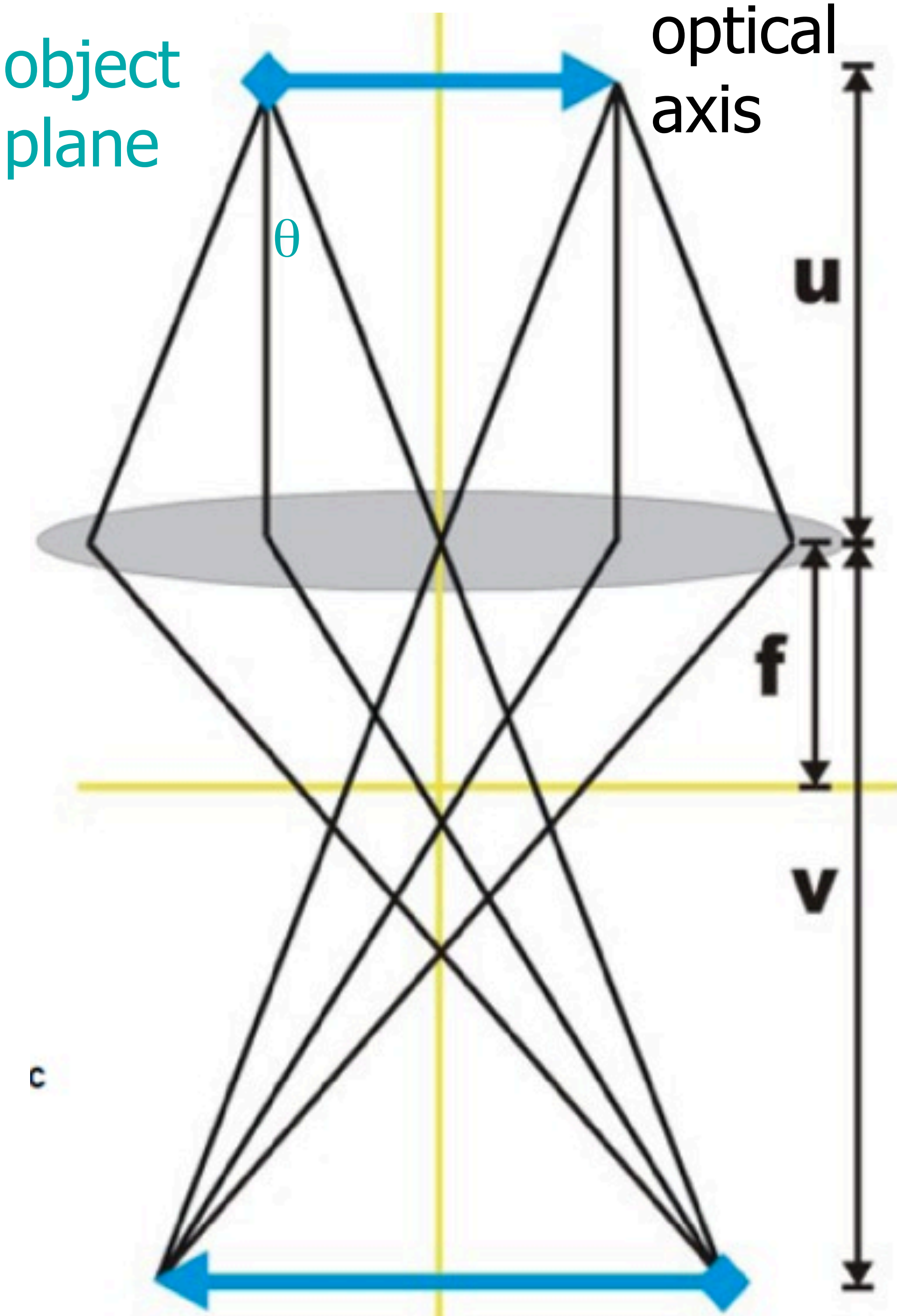
Image plane

Light optical analogue



Lens equation: $1/u + 1/v = 1/f$
Magnification $M = v/u$

Geometric Optics



(Back focal plane BFP)

(Gaussian image plane)

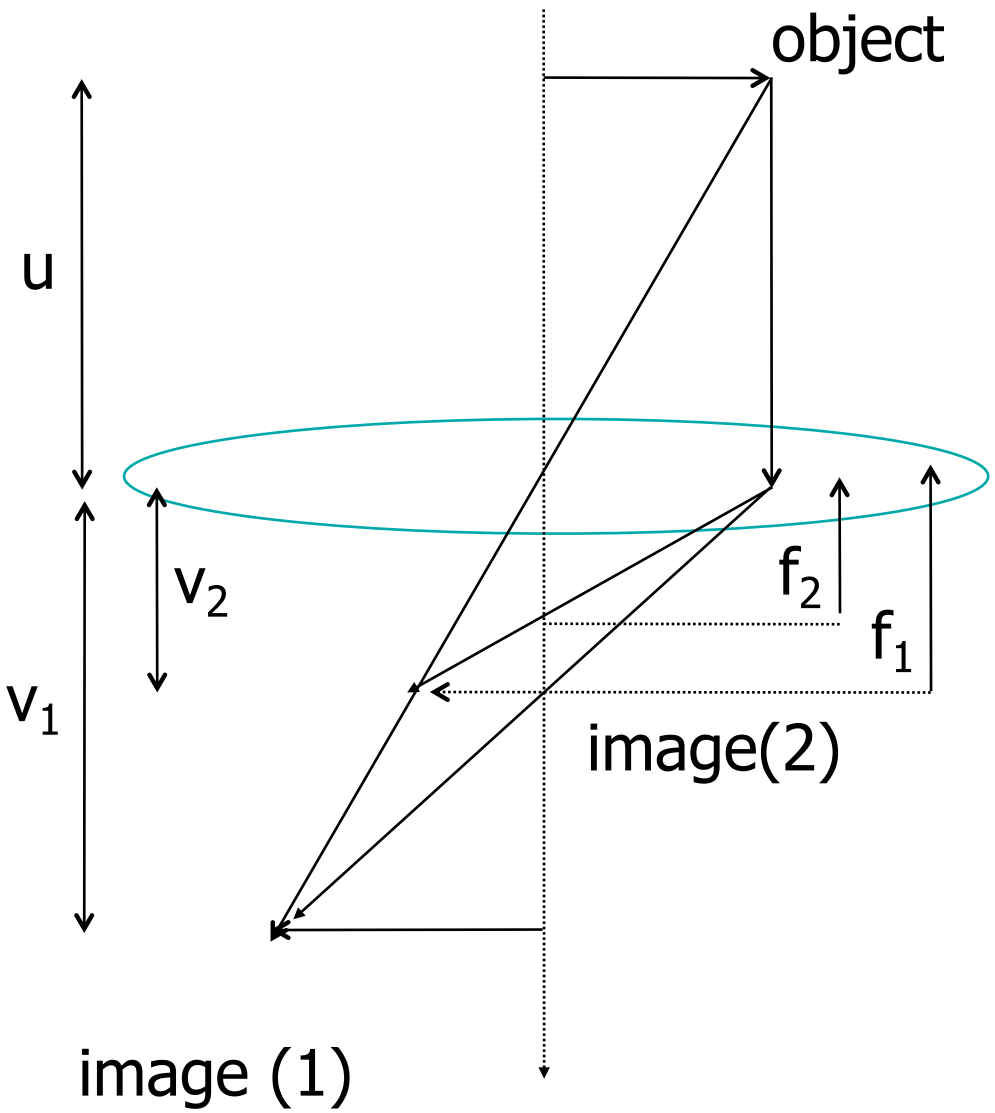
- Principal Optical Elements

--- object plane
--- back focal plane
--- image plane

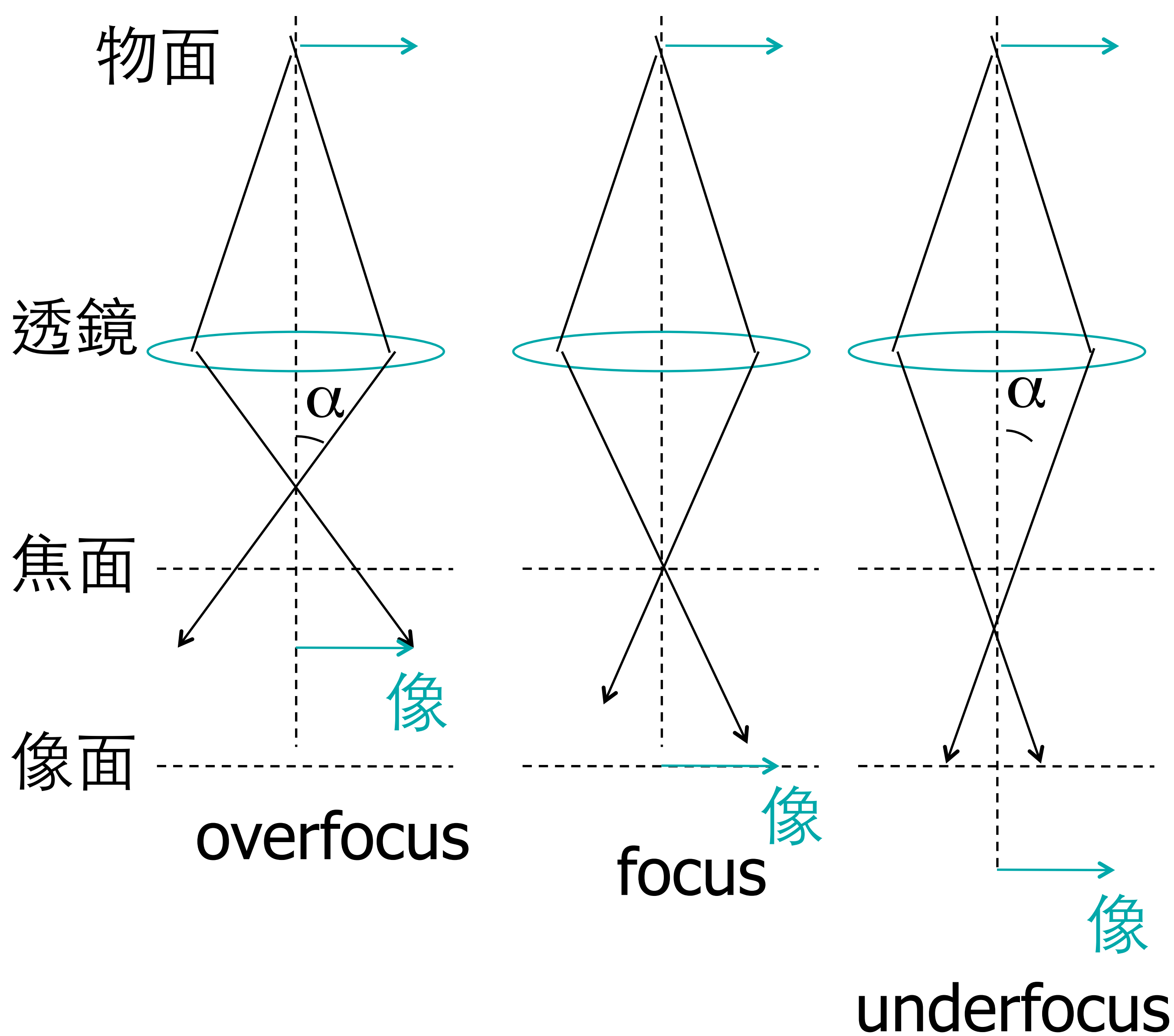
- image-object (conjugate planes)

- u object position
  υ image position
  f focal length
  M magnification

$$\frac{1}{u}+\frac{1}{v}=\frac{1}{f}(\text{牛頓透鏡公式}, M=\frac{v}{u})$$



$$\frac{1}{u} + \frac{1}{v \downarrow} = \frac{1}{f \downarrow} \;, \; \mathbf{M}^{\downarrow} = \frac{v \downarrow}{u}$$



- 若透鏡變弱，焦距變長使得聚焦及成像在特定的焦面及像面底下，我們稱為欠焦（underfocus）。

- 若透鏡變強，焦距變短使得聚焦及成像在特定的焦面及像面底下，我們稱為過焦（overfocus）。


FUNCTION
DIFF FOCUS
SCREEN
MAG 1
MAG 2
LOW MAG
SAM ROCK
DIFF
SHIFT
Y
OBJ FOCUS
FINE
COARSE
STEP
SELECTOR
FILM ADVANCE
EXP TIME
DEF
Y
WOBBLER
IMAGE X
IMAGE Y
H T
EXP
PHOTO
SHUTTER
AUTO

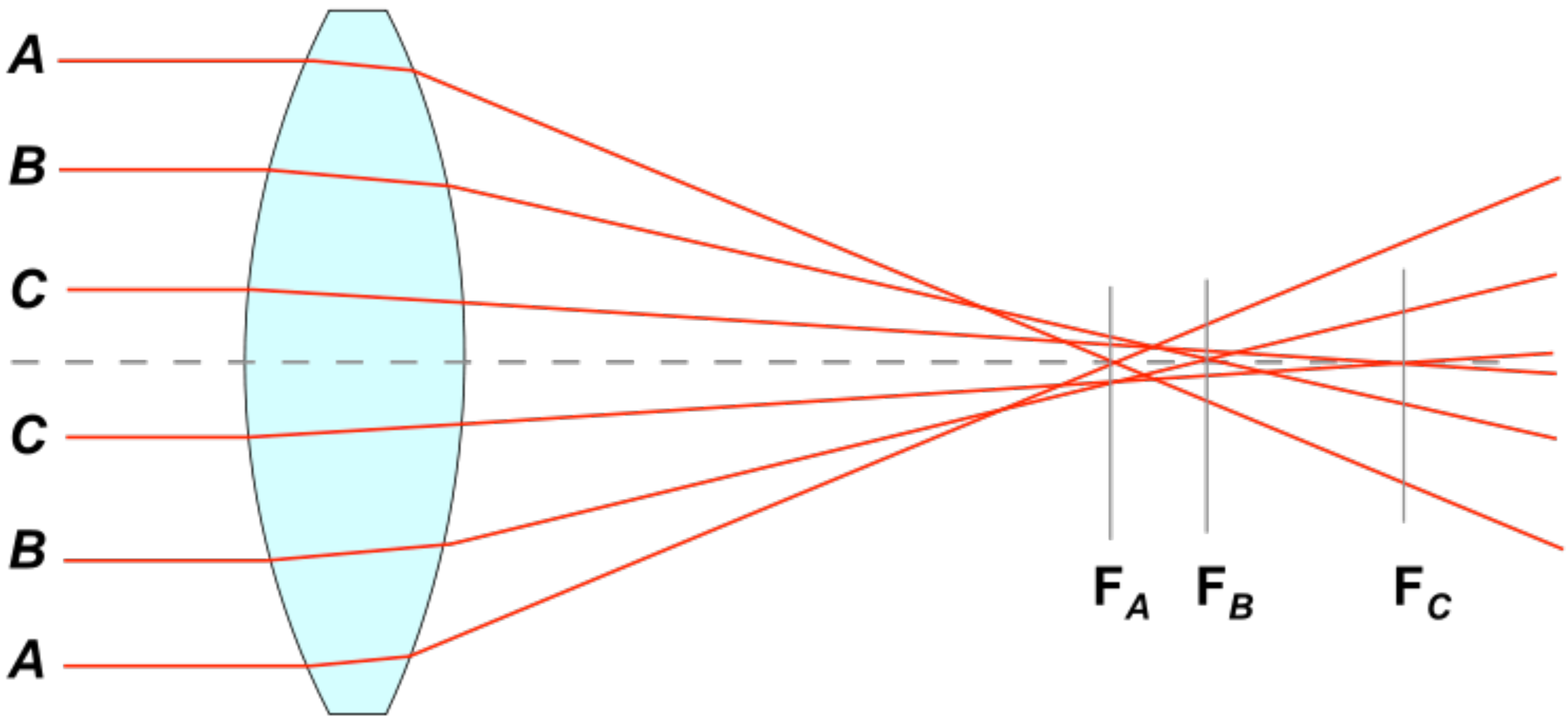
2.4.3. Lens aberration

NTHU

◆幾種重要的透鏡像差

- A.球面像差(Spherical aberration)
  --透鏡對不同角度的光束聚焦能力不同，
  而形成一模糊區。
- B.色像差(Chromatical aberration)
  --透鏡對不同頻率的光束聚焦能力不同，
  而形成一模糊區。
- C.散光（Astigmatism)
  --透鏡對水平及垂直方向的聚焦能力不同，
  而形成一模糊區。

- A.球面像差(Spherical aberration)



--透鏡對不同角度的光束聚焦能力不同，
而形成一模糊區

•影響聚光鏡的光斑大小
物鏡的分辨率

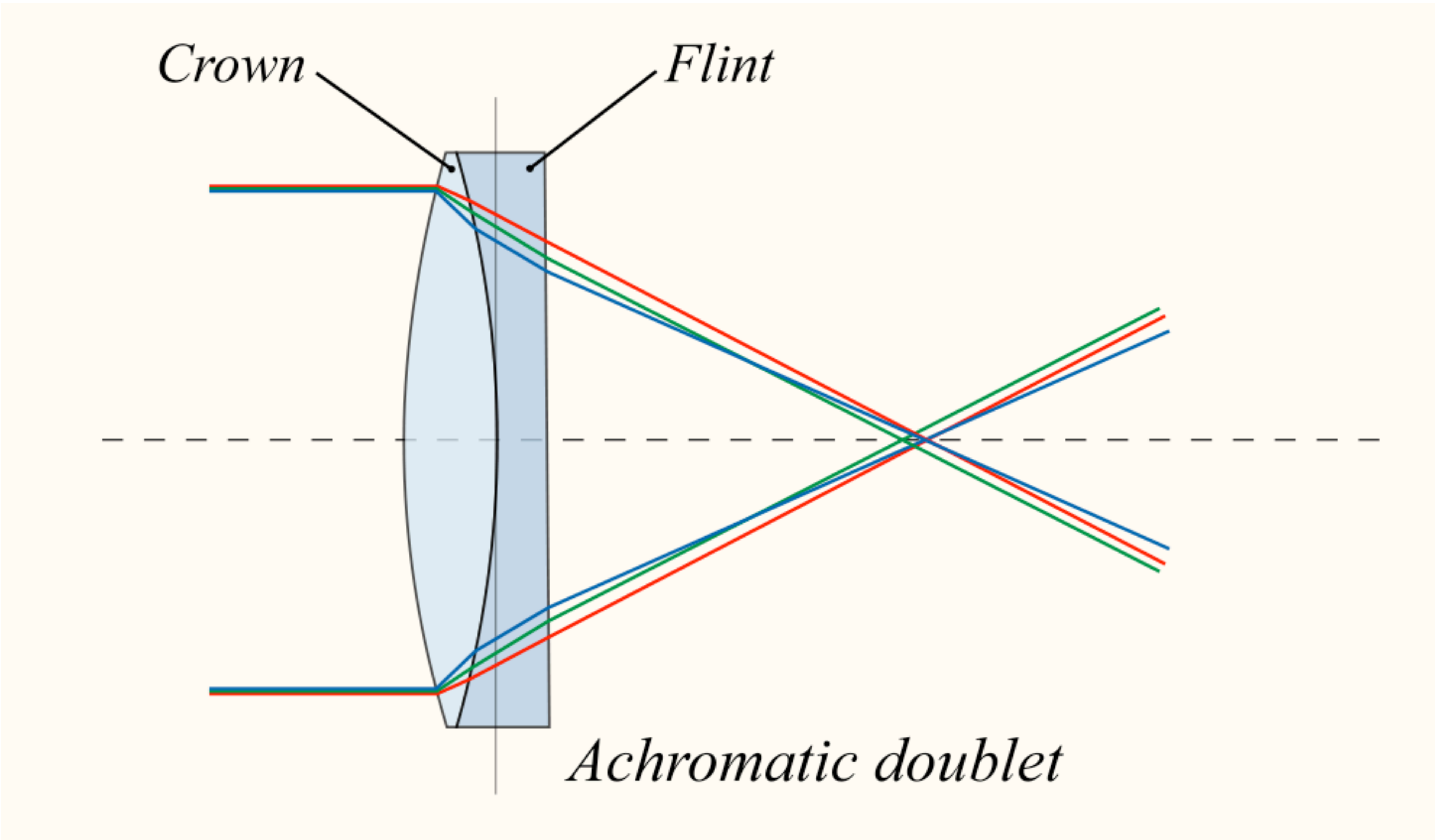
透鏡的聚光能力在外緣比中間要強，

也就是入射角度愈大的光束
被透鏡偏折得較利害。

•C_s : 球面像差係數

~ 1mm ~ 3mm比電子波長大太多

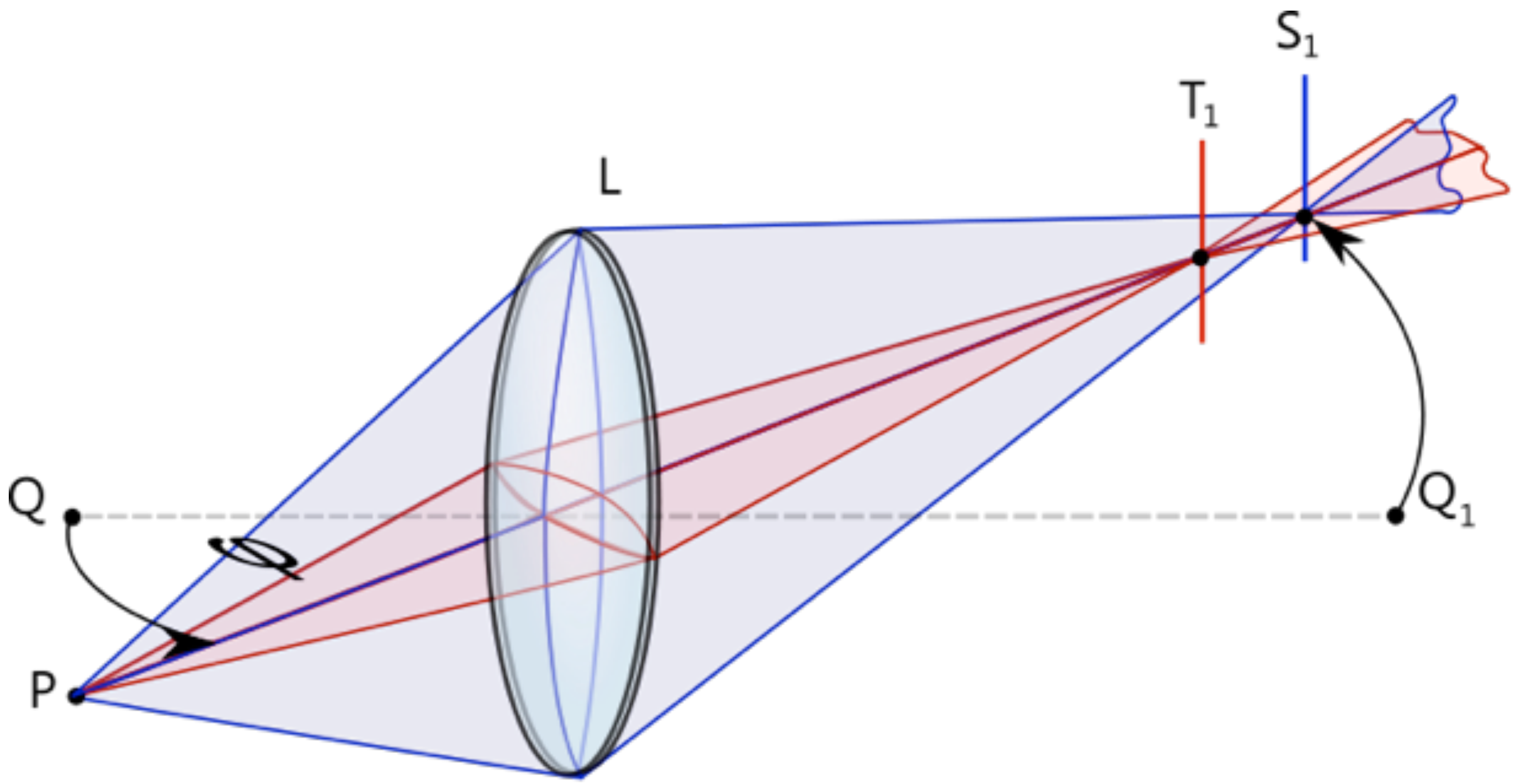
Chromatic Aberration Corrector



Hubble Telescope

aberration corrected

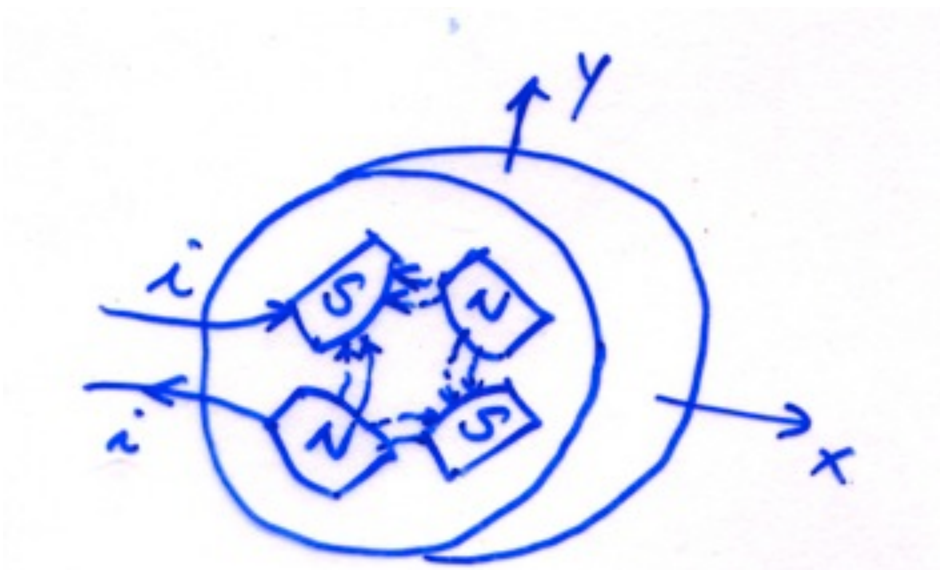
C. 散光(Astigmatism)



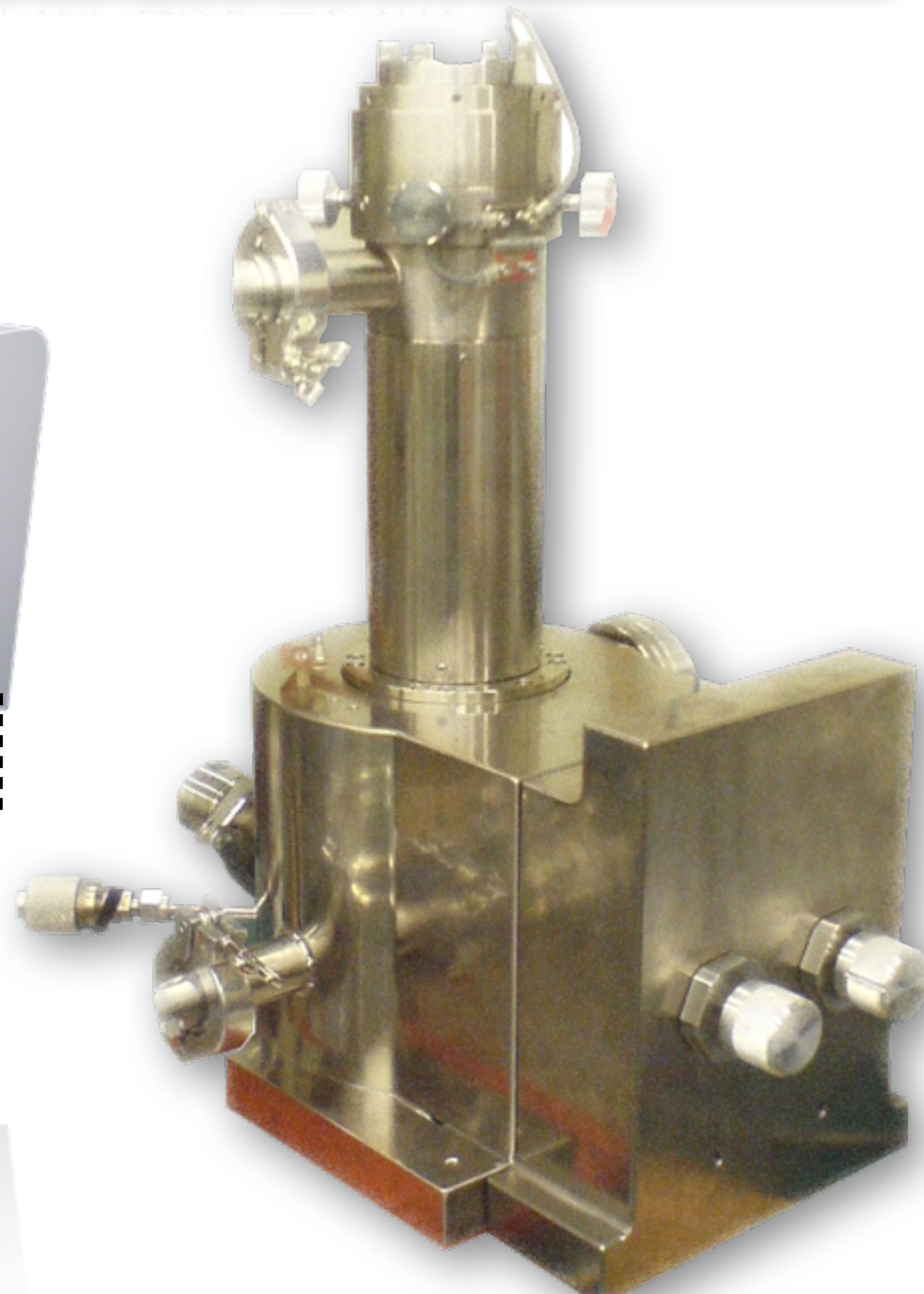
- 散光最主要的原因是磁場的不均勻性。 當電子感到這不均勻性會被聚焦在光軸的不同位置(因為軟鐵不易加工的完美對稱) 。

- Δf是因散光而引起的焦距發散。
- 散光可很容易由散光器來補償

  (最主要用於補償聚光鏡及物鏡)
- 散光器(Stigmator)是一個四極透鏡。



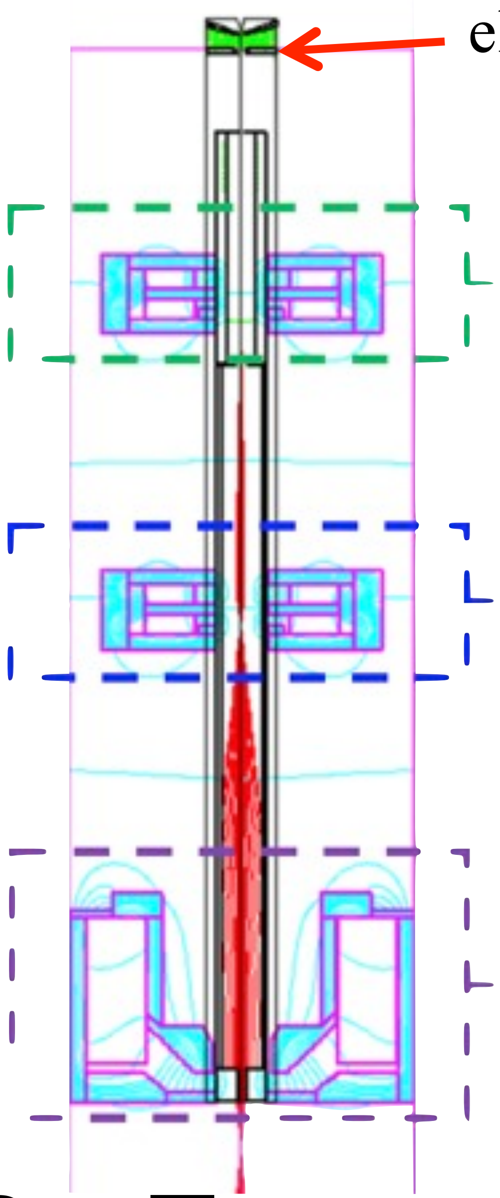
桌上型分析式掃描電鏡之技術



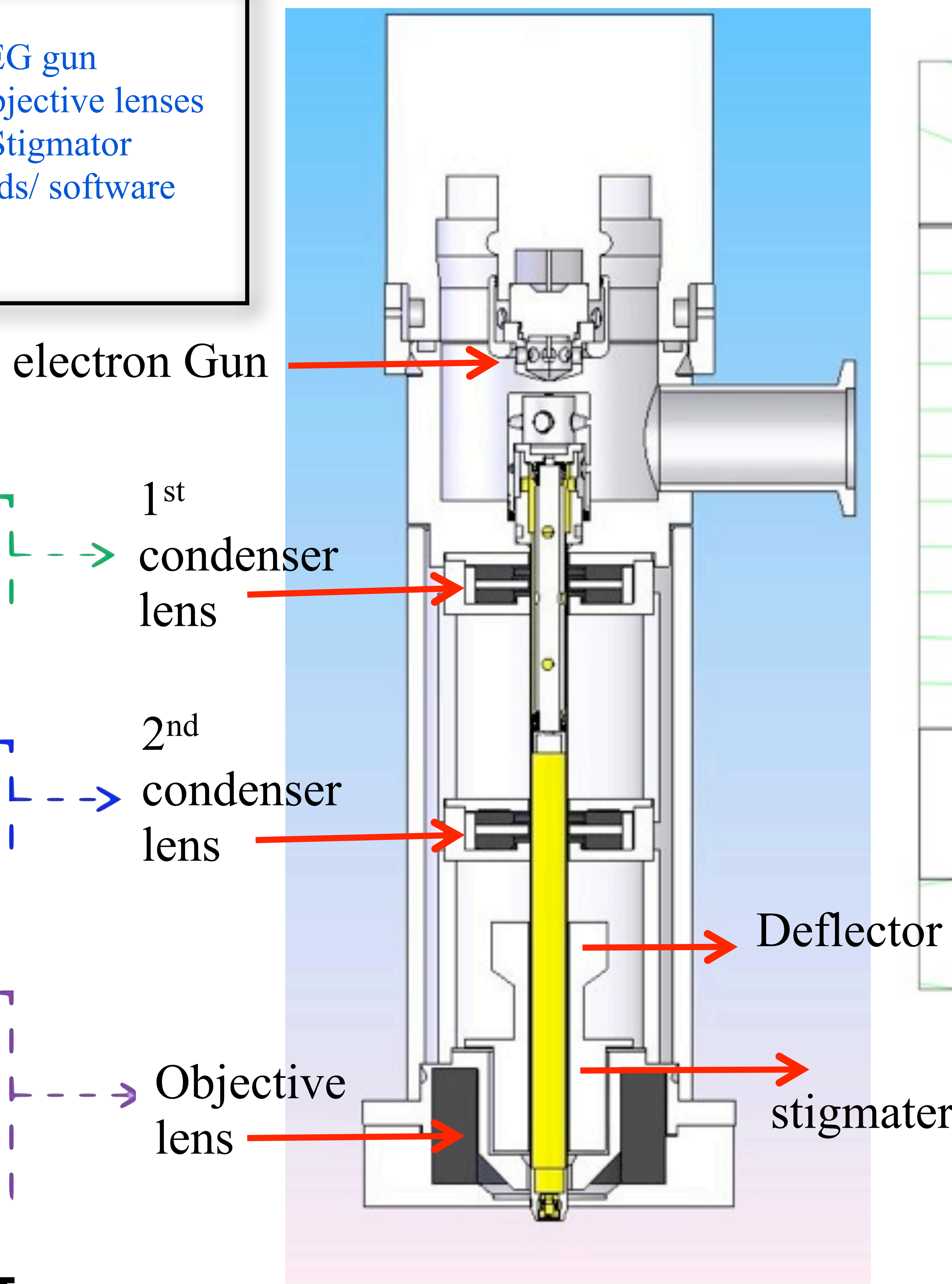
Established Technologies

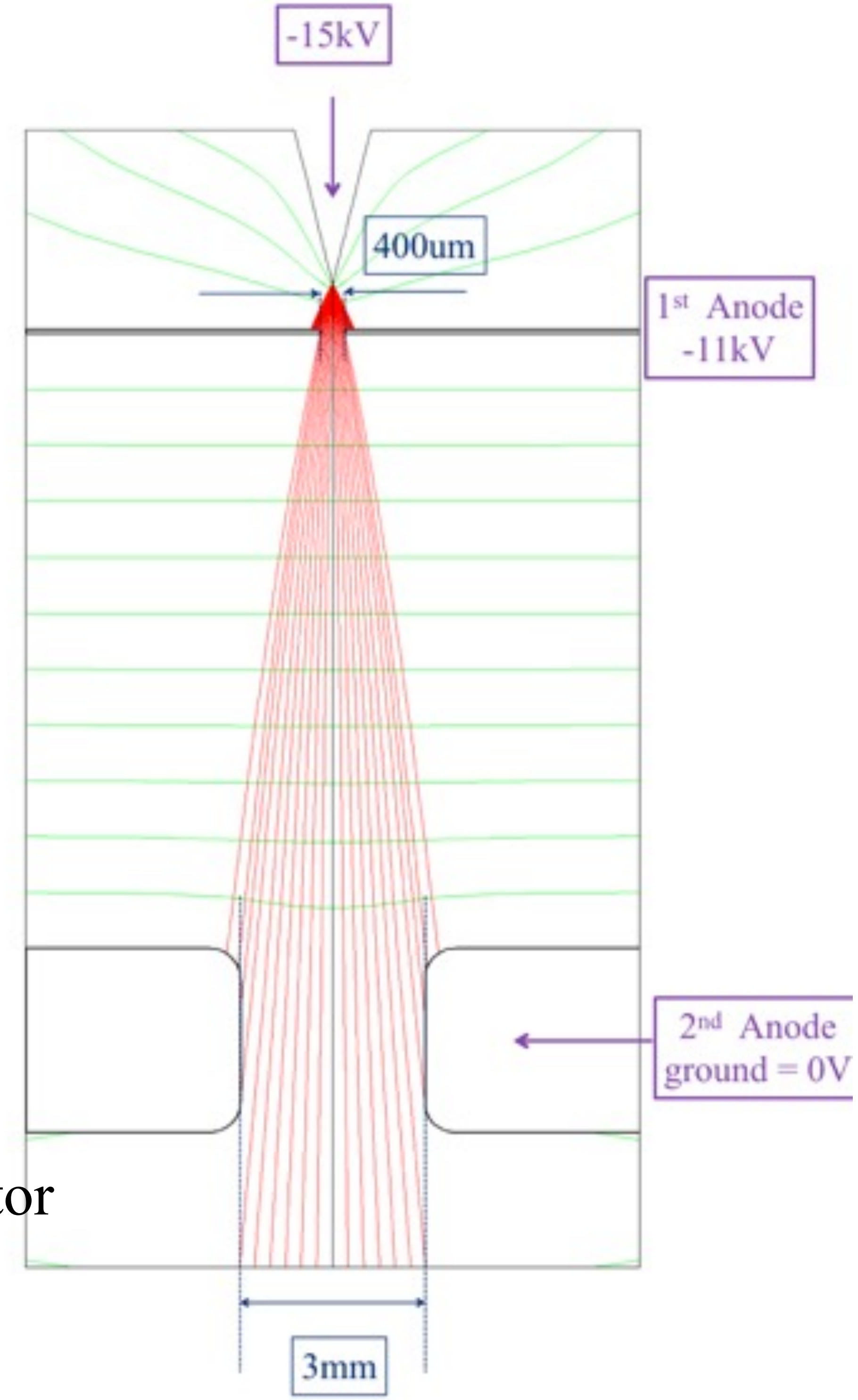
Table Top SEM

- Electron Optics design
- E-gun: Thermionic/ FEG gun
- Lenses: Condenser/ Objective lenses
- Multipole: Deflector/ Stigmator
- control electronic boards/ software
- image acquizition
- BSED Detectors



Ray Tracing





FEG gun

Established Technologies

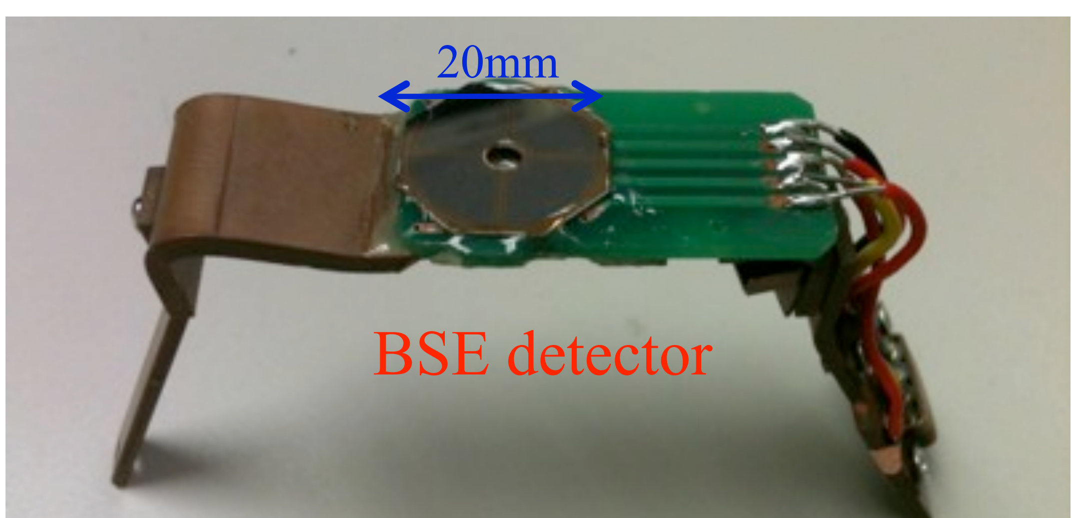
Control Electronics Boards

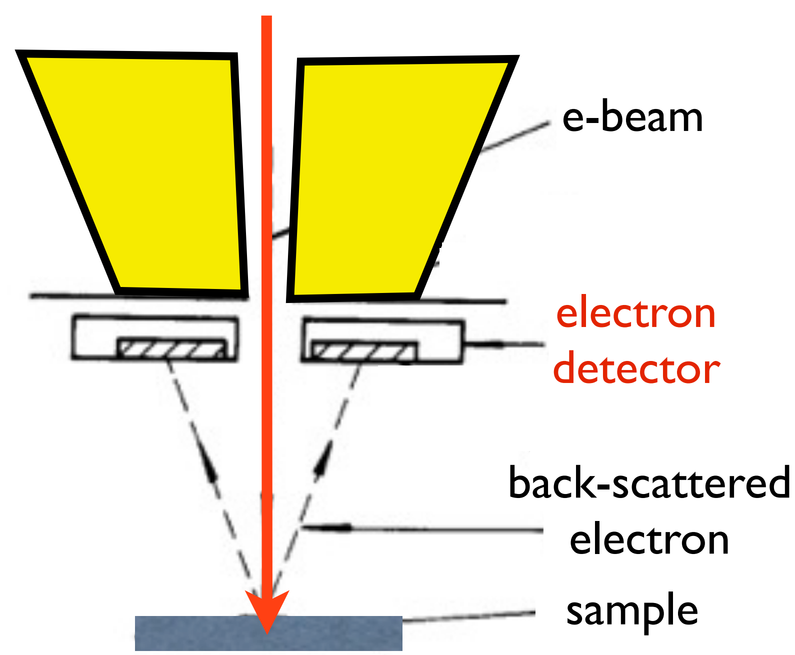
(a) (b) (c)

Voltage (gun)
vacuum (pump)
condenser lenses (spot size, resolution)
objective lenses (focus, magnification)
scanning (deflectors, magnifiaction)

stigmatism (stigmators)
image acquizition (processing)
Auto-tuning and alignment (future)
. etc

Home Made Electron Detector





Control Software Panel

Voltage: 7, 15, 30keV

magnification: 30x-10,000x

resolution: 20nm

image size: 1280x960

scan time: 2.5sec

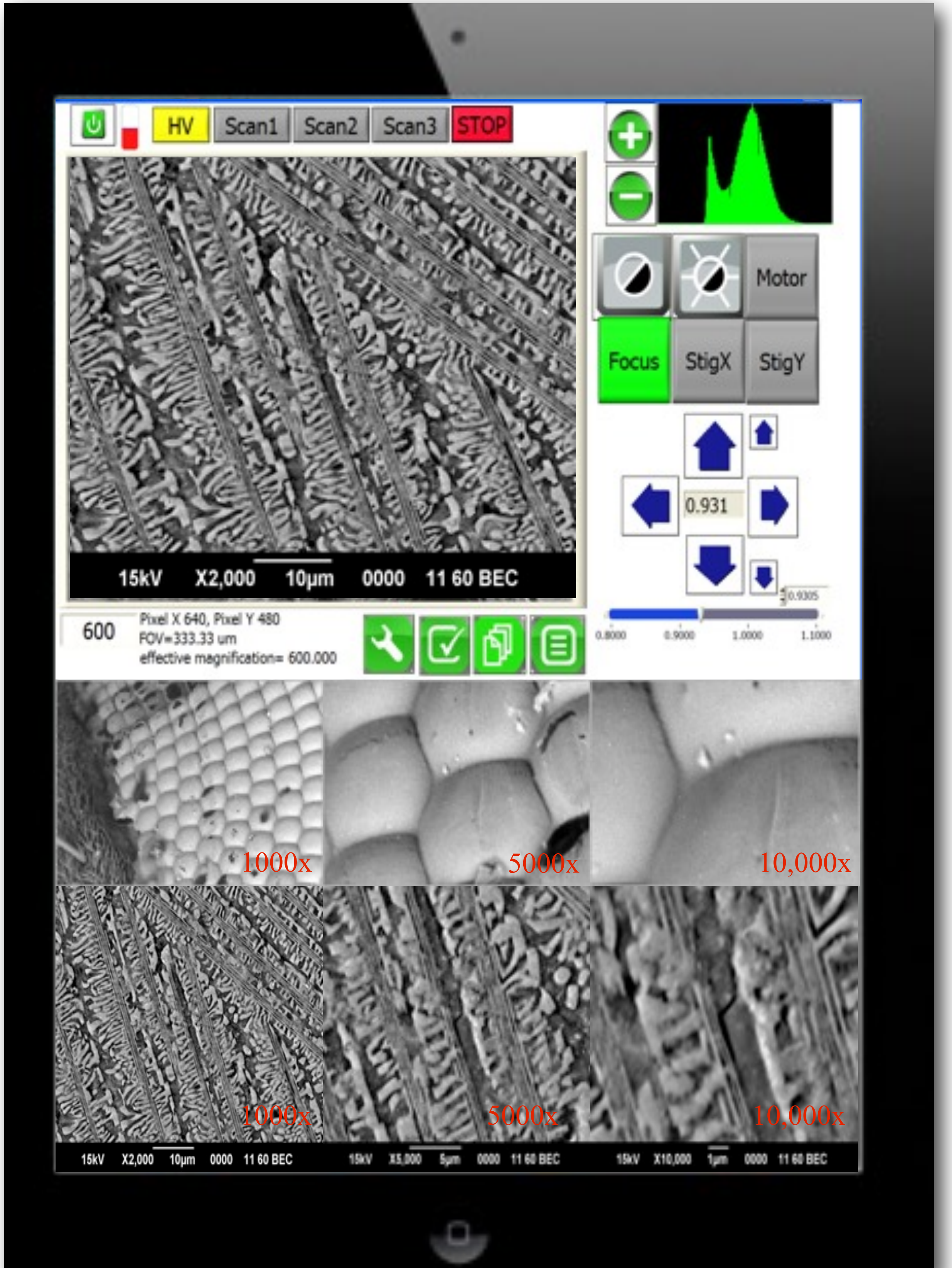
- 3 minutes from Air to Ready
- Fully automatic control

fly

Al-Ag

Cr_2O_3 NW

Control Software Panel



Voltage: 7, 15, 30keV
magnification: 30x-10,000x
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Al-Ag

Cr_2O_3 NW

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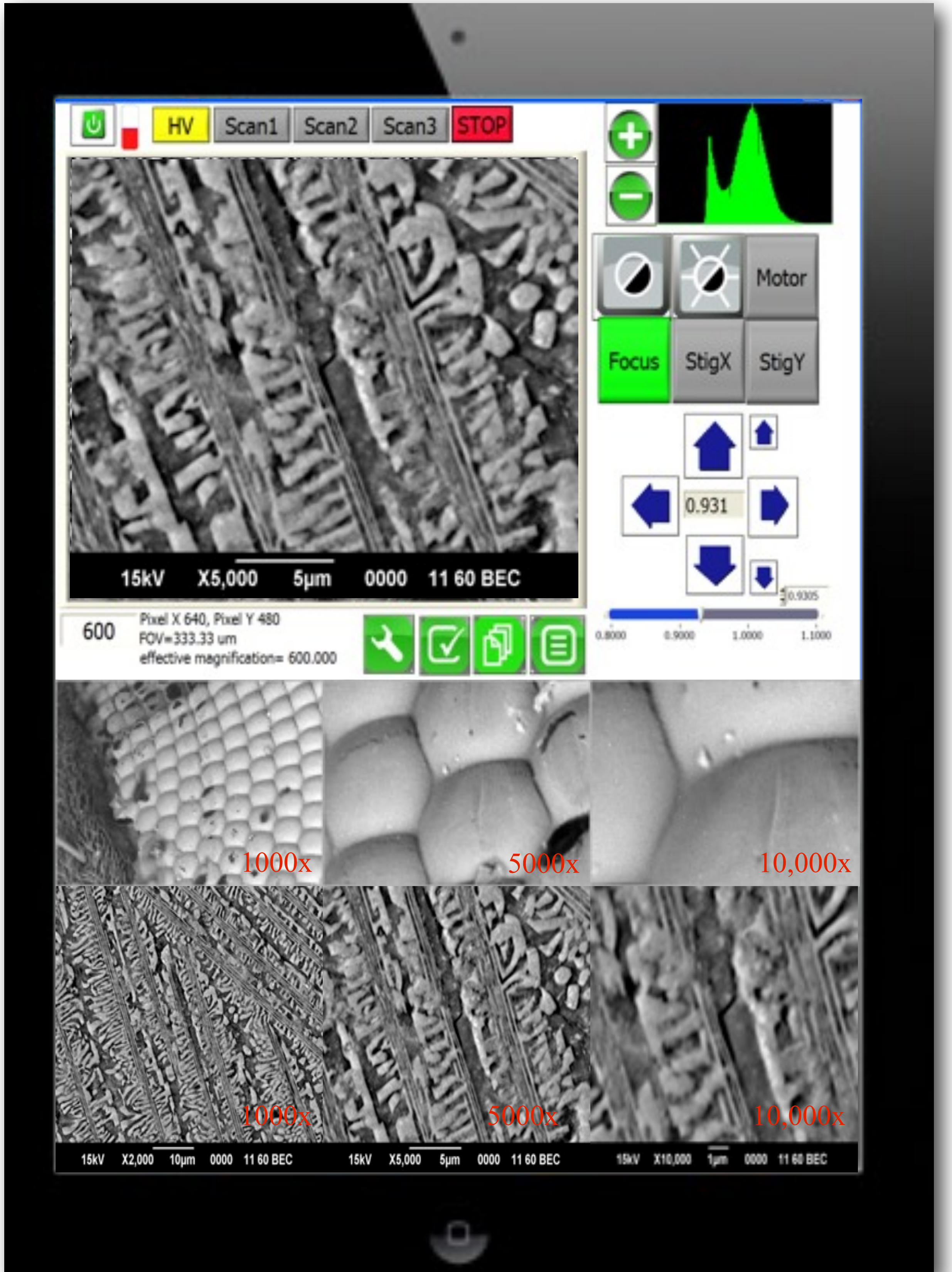

fly

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Cr_2O_3 NW

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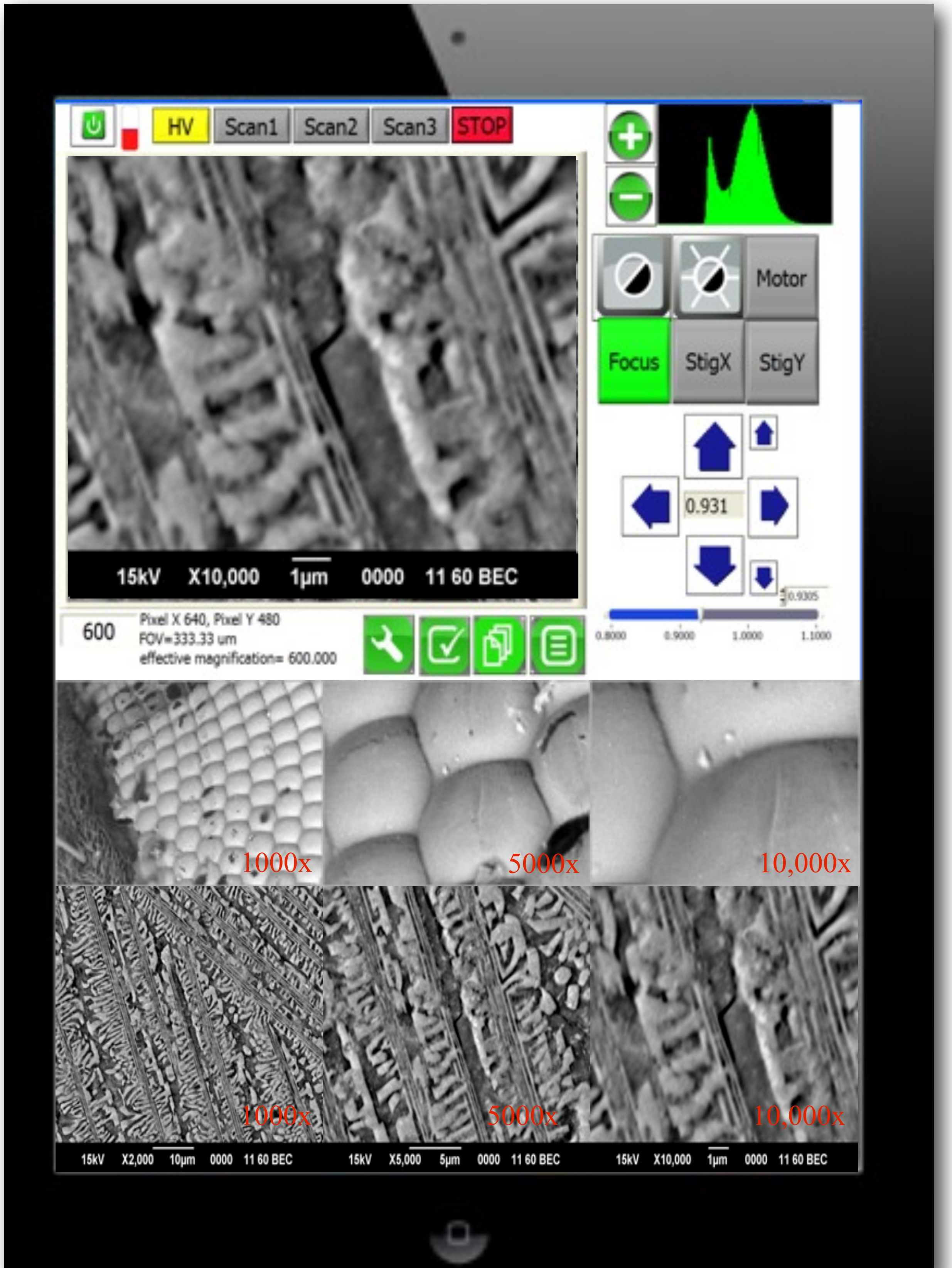

fly

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Cr_2O_3 NW