Central European Institute of Technology
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Transmission Electron Microscopy

Design

Fall 2023

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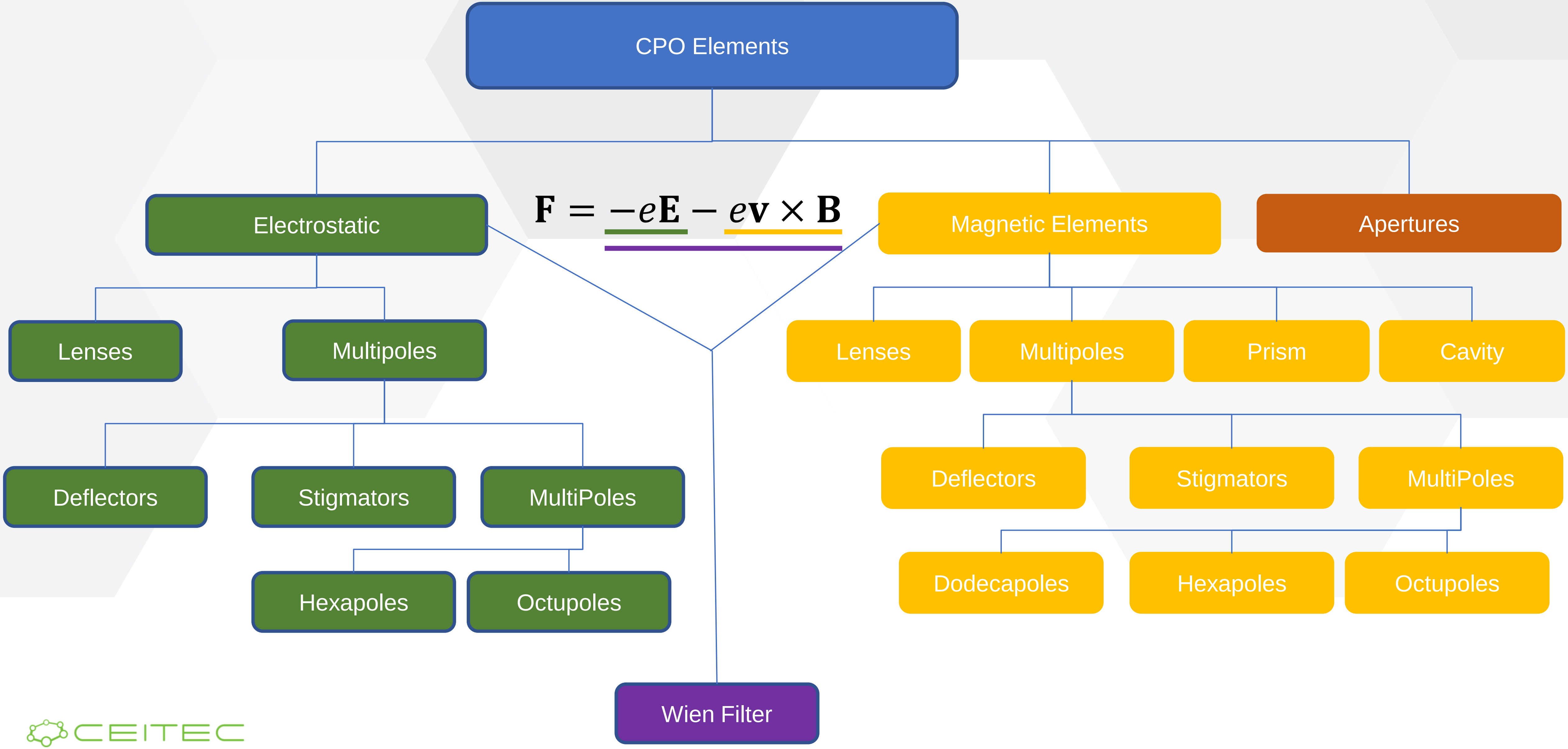
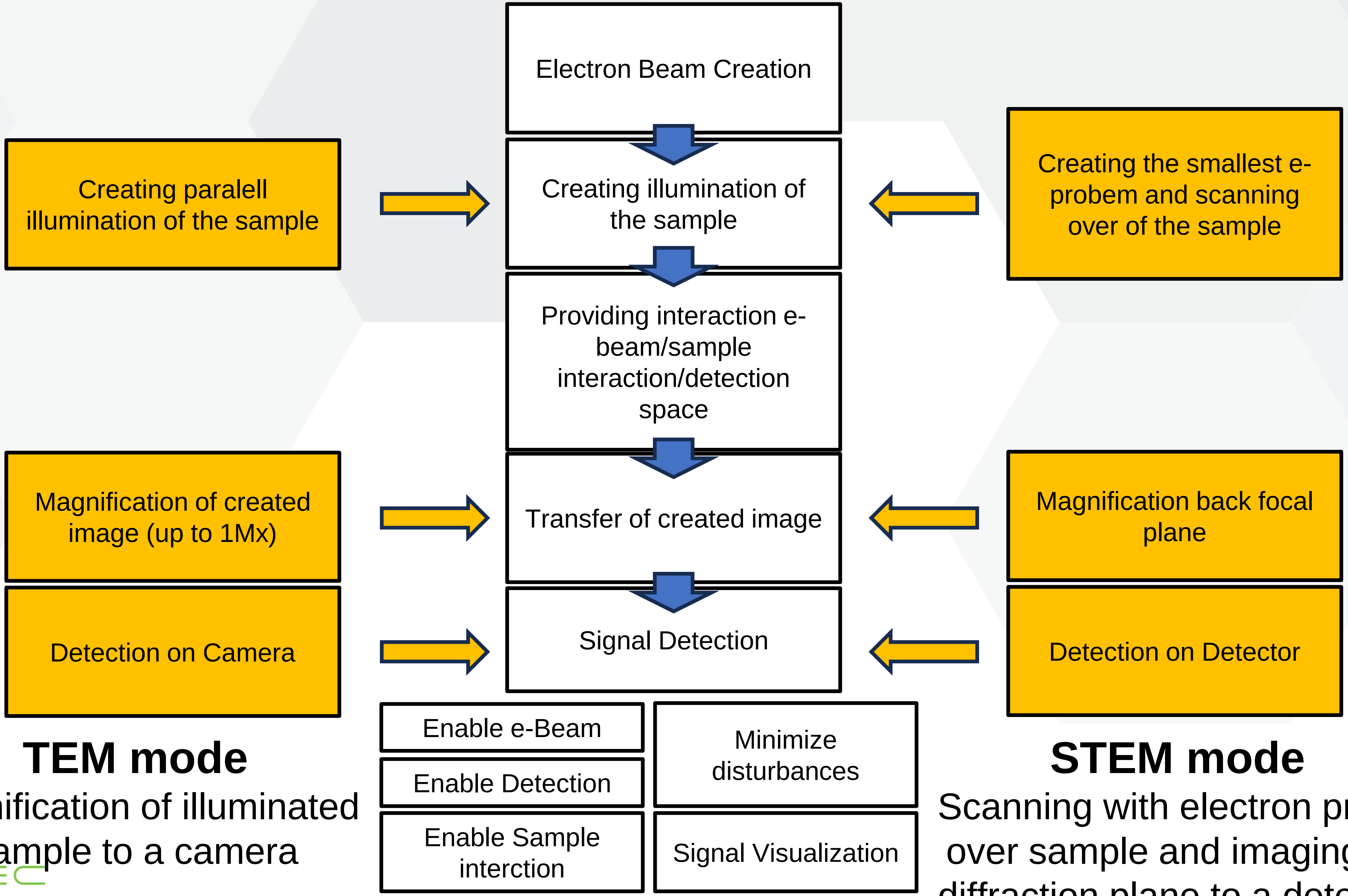
CPO elements overview



TEM Principle – Functional Decomposition



TEM mode

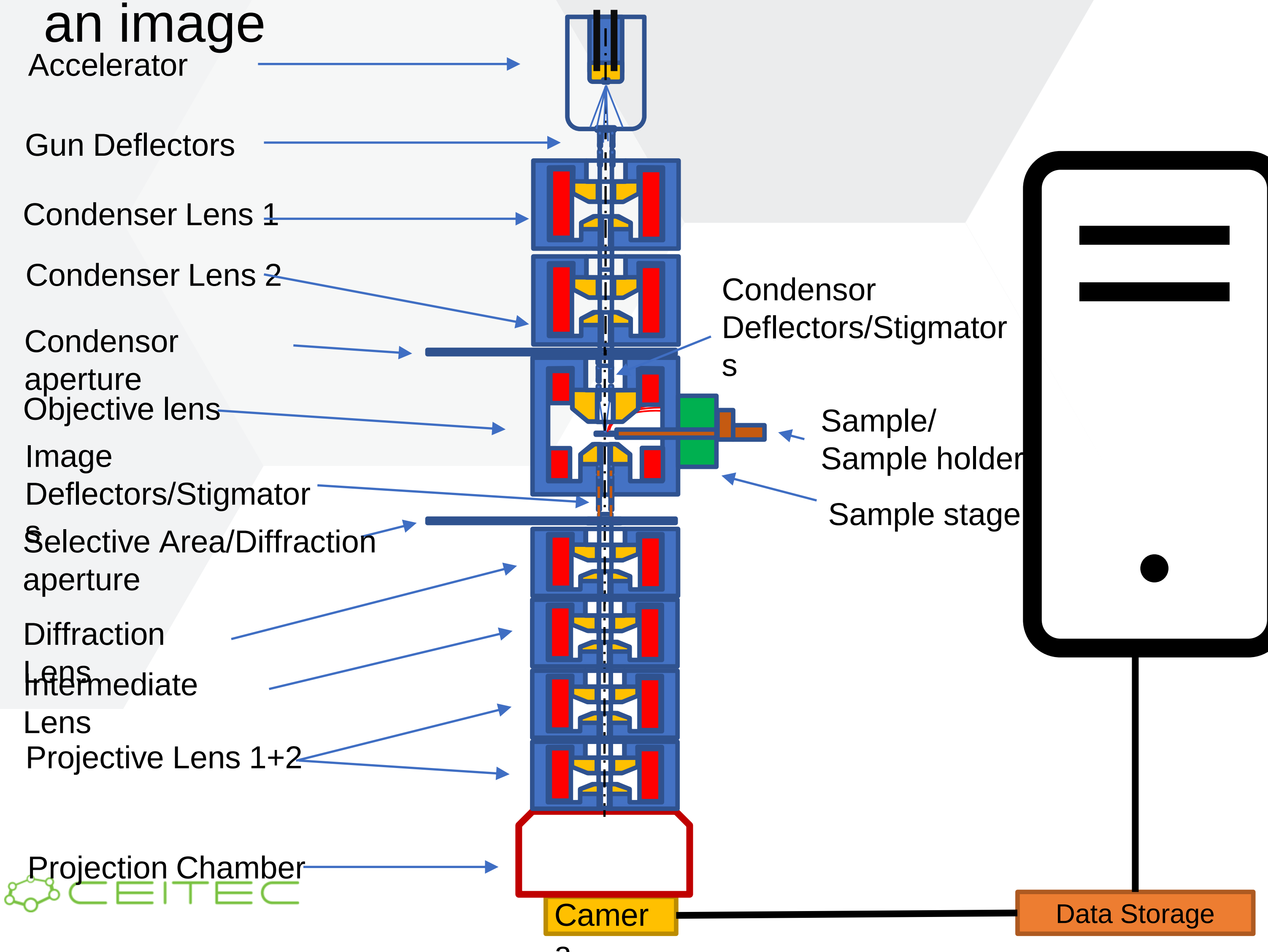
Magnification of illuminated sample to a camera

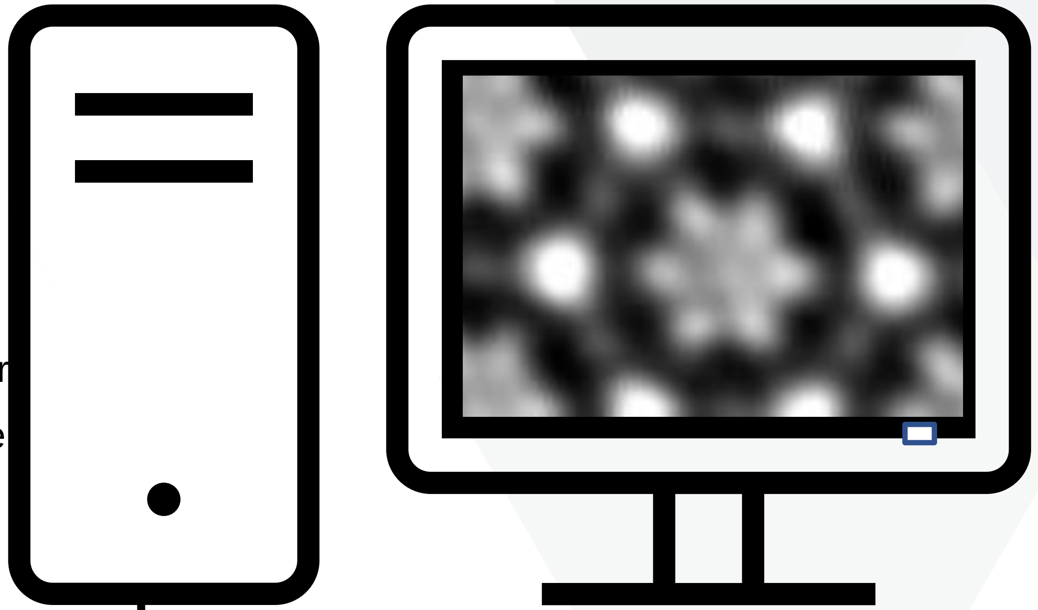
STEM mode

Scanning with electron probe over sample and imaging its diffraction plane to a detector

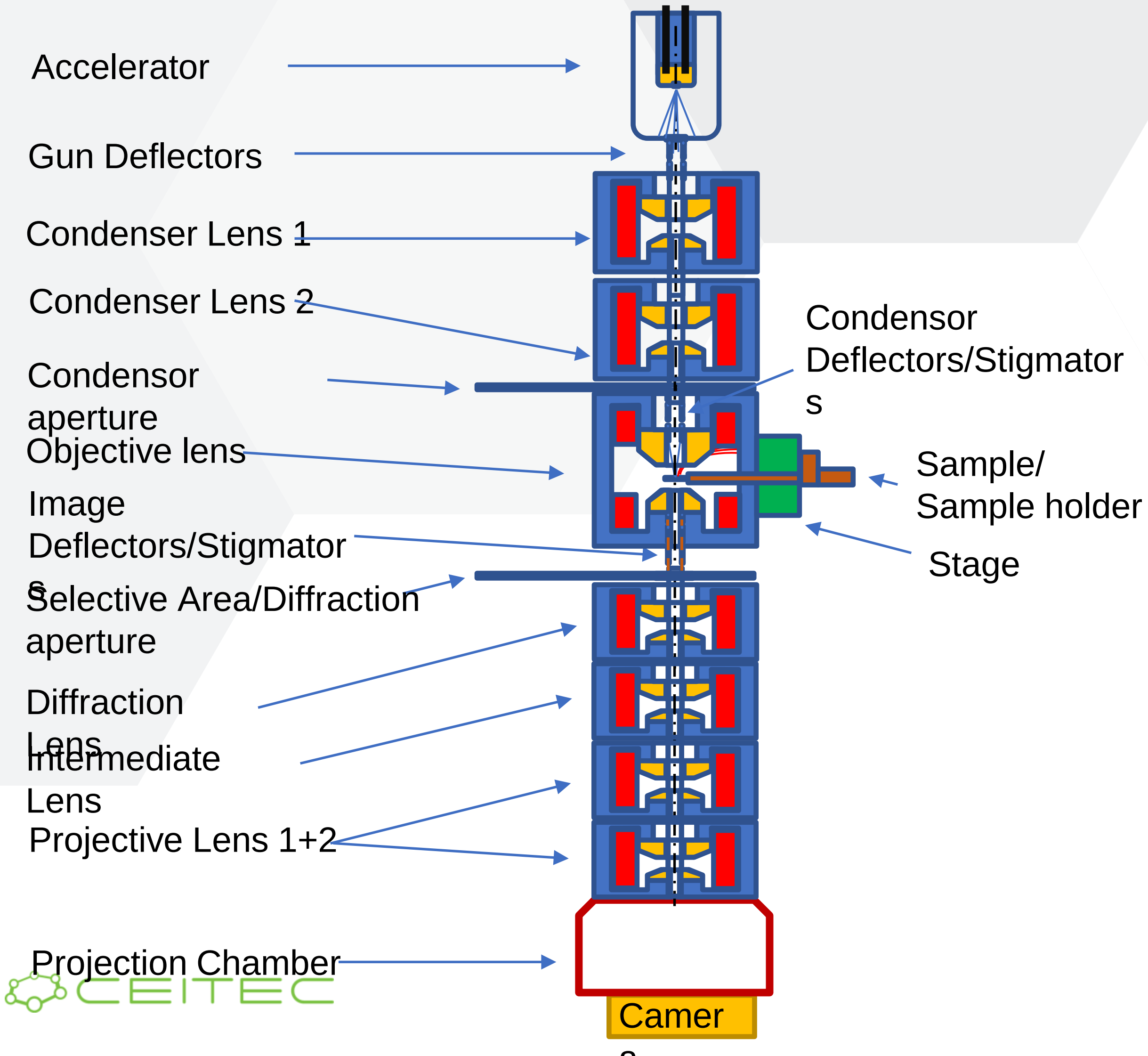
TEM Principle – Design Schematic

- TEM mode – Image of an illuminated sample is magnified onto a camera
- STEM Mode - Focused Beam scanning over the sample → processed signal creates an image



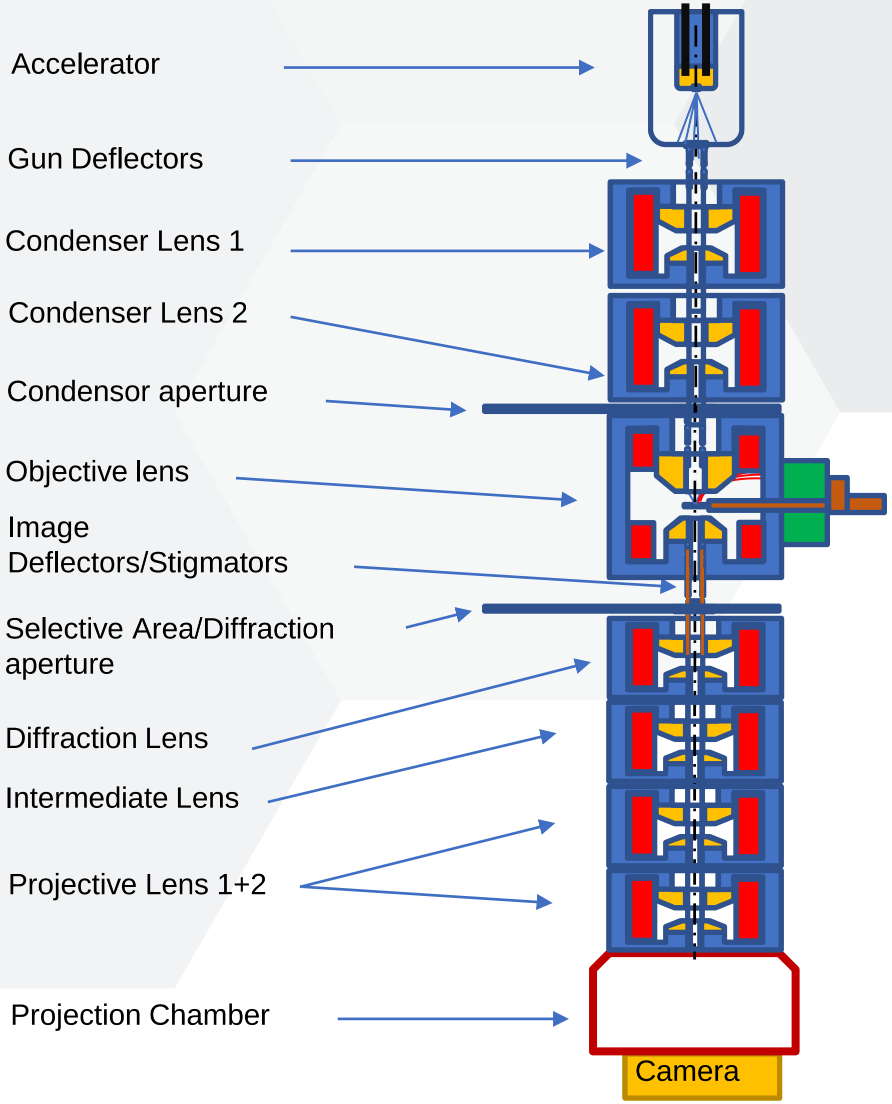


TEM Standard Parameters



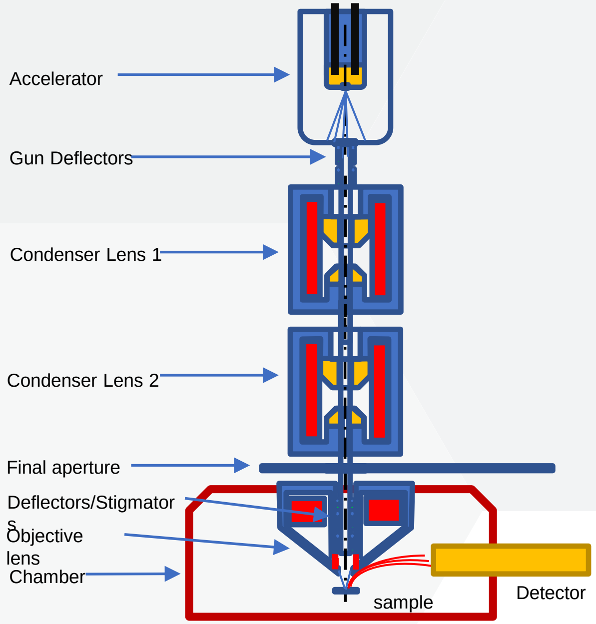
Parameter	Value
Accelerating voltage [kV]	30-300
Beam current [nA]	0.01-100
Chamber Vacuum	1e-5 – 1e-8
Resolution [nm] Cs corrected/uncorr	~0.05/~0.1
Sample size [mm3]	3.05^2 * 1E-5 - 1E-4

TEM and SEM comparison



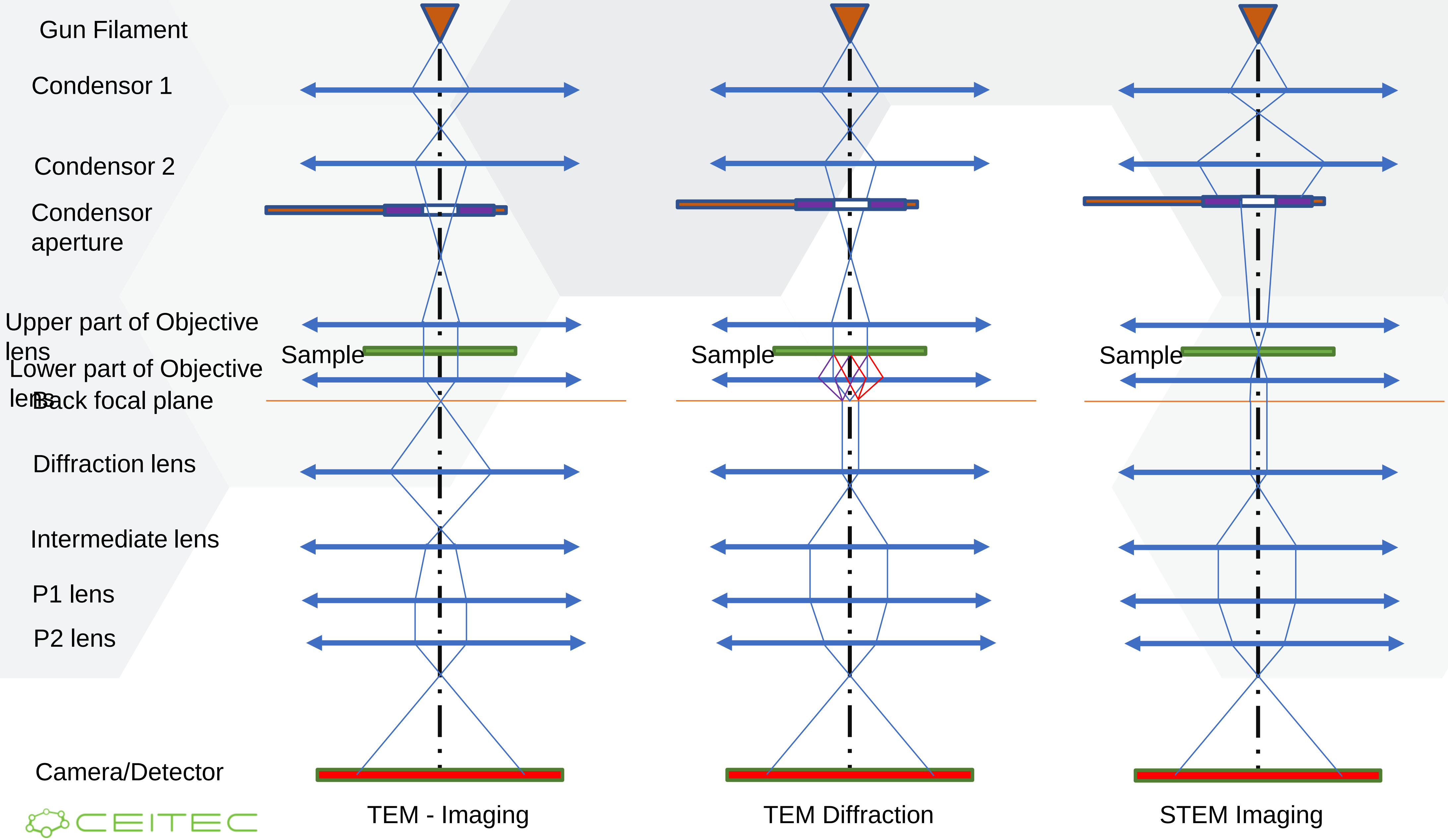
TEM Schematic

TEM Value	Parameter	SEM Value
30-300	Accelerating voltage [kV]	0.5-30
0.01-100	Beam current [nA]	0.01-100
1e-5 – 1e-8	Chamber Vacuum	1e-3 – 1e-6
~0.05/~0.1	Resolution [nm]	~0.5
3.05^2 * 1E-5 - 1E-4	Sample size [mm3]	90x90x20



SEM Schematic

TEM modes


Gun Filament
Condensor 1
Condensor 2
Condensor aperture
Upper part of Objective lens
Lower part of Objective lens
Back focal plane
Diffraction lens
Intermediate lens
P1 lens
P2 lens
Camera/Detector
Sample
Sample
Sample
TEM - Imaging
TEM Diffraction
STEM Imaging

TEM – Přenosová funkce kontrastu - intenzita

Incoming wave (assumed parallel wave): $\psi_0(\vec{r}) = 1$

Sample-electron interaction: $\psi_{out}(\vec{r}) = 1 + \epsilon(\vec{r}) + i\varphi(\vec{r})$

Image in back focal plane: $\psi_{bfp}(\vec{q}) = \delta(\vec{q}) + E(\vec{q}) + i\Phi(\vec{q})$

Optics Aberration impact:

→ $\chi(\vec{q},\theta) = \sum_n \sum_m \frac{1}{n+1} \cos(m\theta - \theta_{n,m})\, C_{n,m} \lambda^{n+1} \vec{q}^{\,n+1}$

→ $\chi(\vec{q}) = \frac{1}{2} C_{1,0} \lambda^2 \vec{q}^{\,2} + \frac{1}{4} C_{3,0} \lambda^4 \vec{q}^{\,4}$

$$W(\vec{q}) = \frac{2\pi}{\lambda} \chi(\vec{q})$$

$$\psi_{bfp,ab}(\vec{q}) = \delta(\vec{q}) + E(\vec{q}) e^{-iW(\vec{q})} + i\Phi(\vec{q}) e^{-iW(\vec{q})}$$

$$\psi_{det}(\vec{r}') = M \cdot \mathrm{IFT}\{\psi_{bfp,ab}(\vec{q}/M)\}$$

$$\mathrm{Intenzita}(\vec{q}') = \mathrm{FT}\{\mathrm{Intenzita}(\vec{r}')\} = \mathrm{FT}\{\psi_{det}(\vec{r}')\overline{\psi_{det}}(\vec{r}')\}$$

Contrast Transfer Function (CTF)

$$\mathrm{CTF}(\vec{q}') = E_t(q') E_s(\vec{q}') E_d(\vec{q}') E_u(\vec{q}') \cdot \mathrm{Intenzita}(\vec{q}') \in \langle -1; 1 \rangle$$

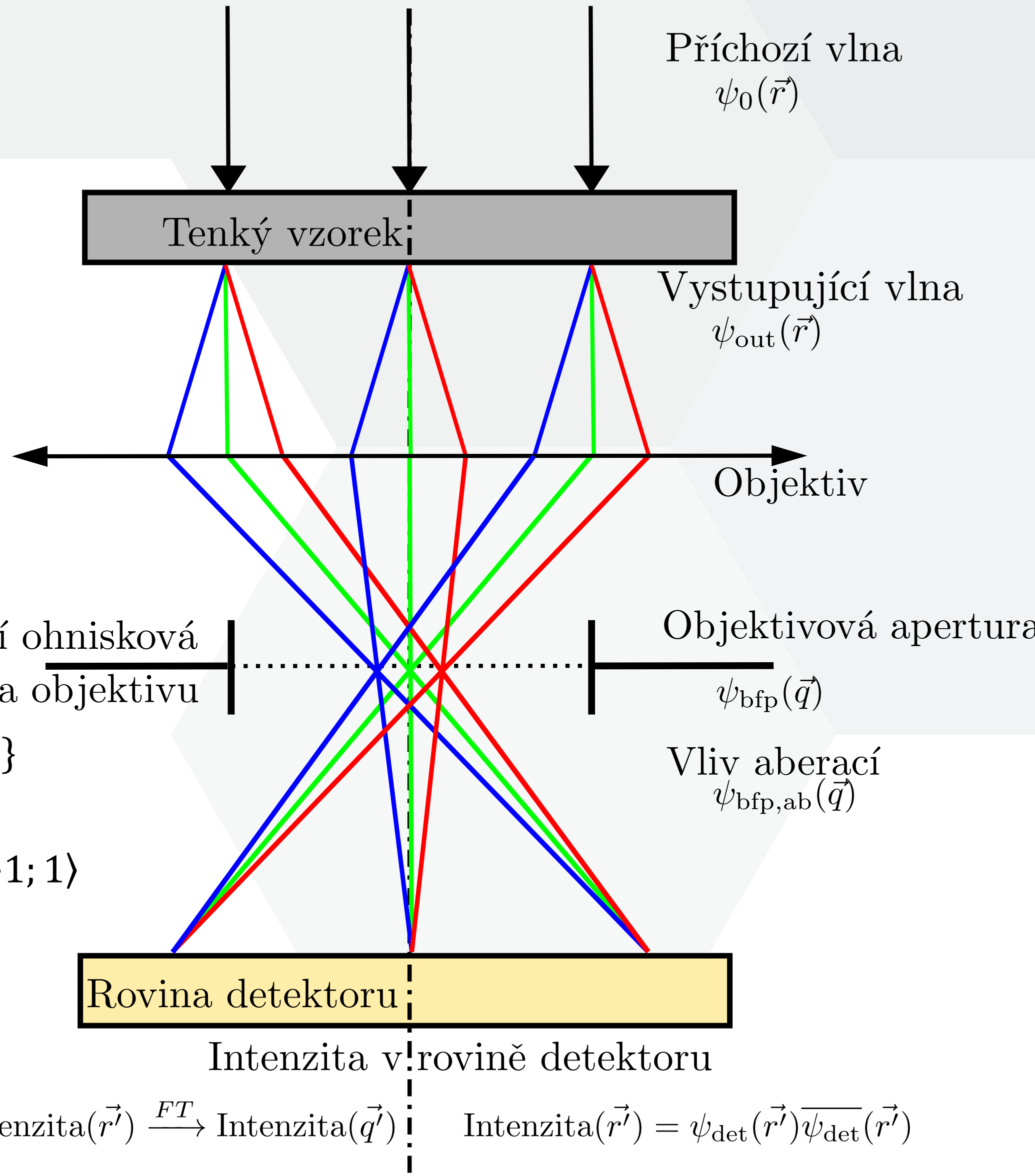
where

$E_t(q')$ - *temporal coherency,*

$E_s(\vec{q}')$ - *spatial coherency,*

$E_d(\vec{q}')$ - drift impact,

$E_u(\vec{q}')$ - *vibration dumping*



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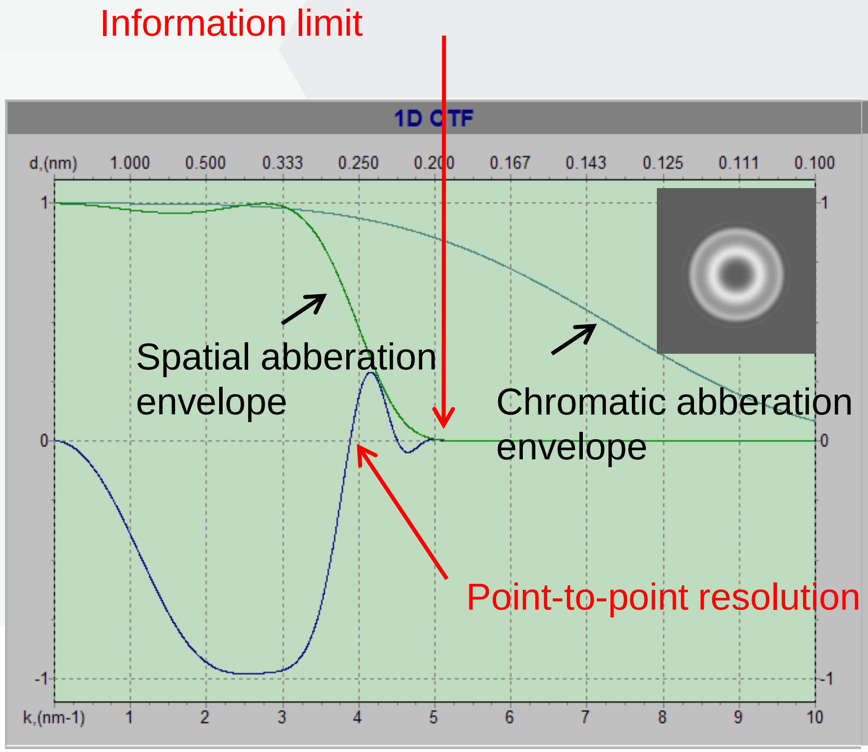
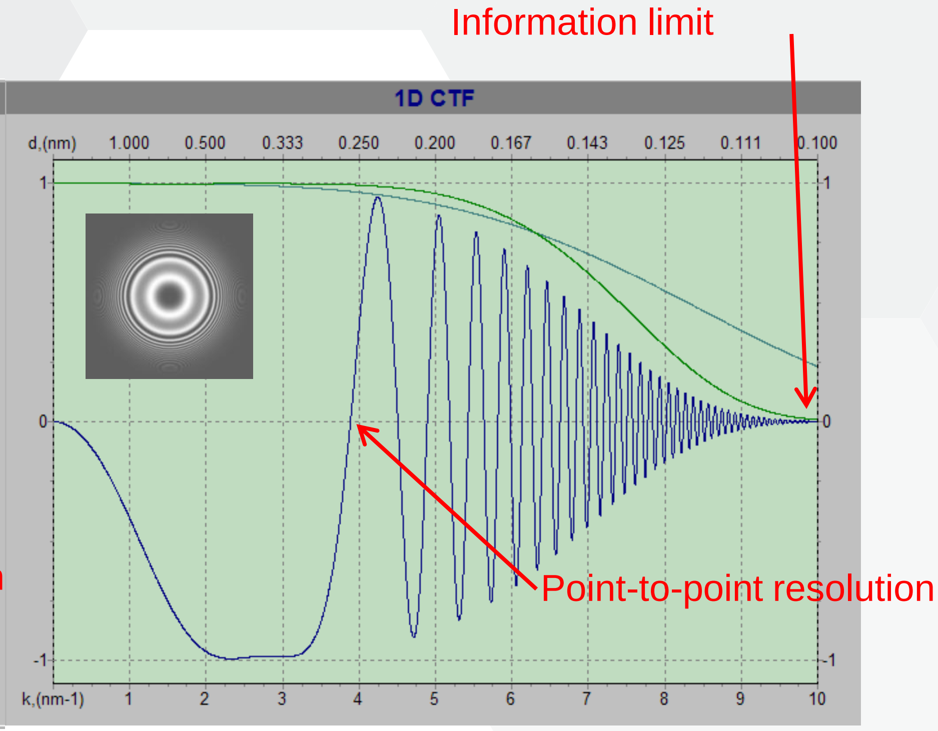
TEM imaging - CTF



Tecnai T20 Thermionic



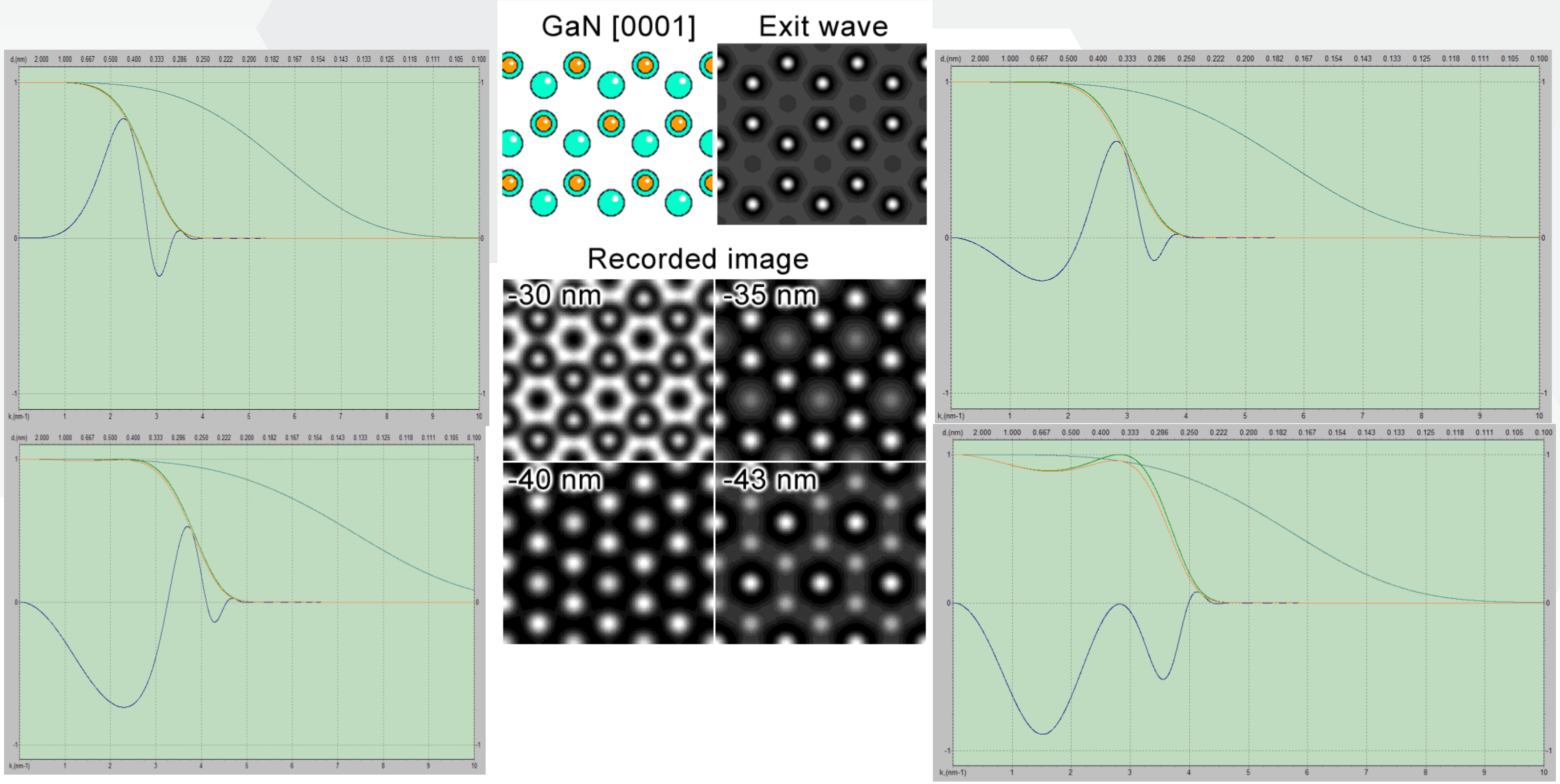
Tecnai T20 FEG

Scherzer defocus – optimal for point-to-point resolution:

$$\Delta f = -1.2\sqrt{C_s \lambda}$$

Where C_s is spherical aberrations, λ – electron wavelenght

TEM imaging – Defocus impact



STEM - Spot size calculation

- First order calculation

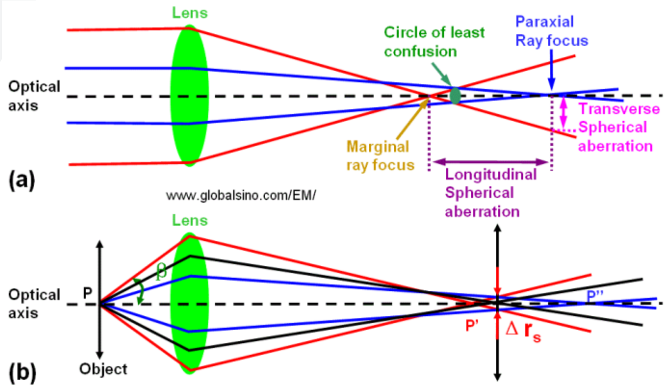
$$d_{50} = \sqrt{(0.43 C_s \alpha^3)^2 + (C_c \alpha H)^2 \; + \; (\frac{\sqrt{I}}{\pi\alpha\sqrt{BrU}})^2 + (\mathrm{M}\ d_0)^2 + (\frac{0.63\lambda}{\alpha})^2},$$

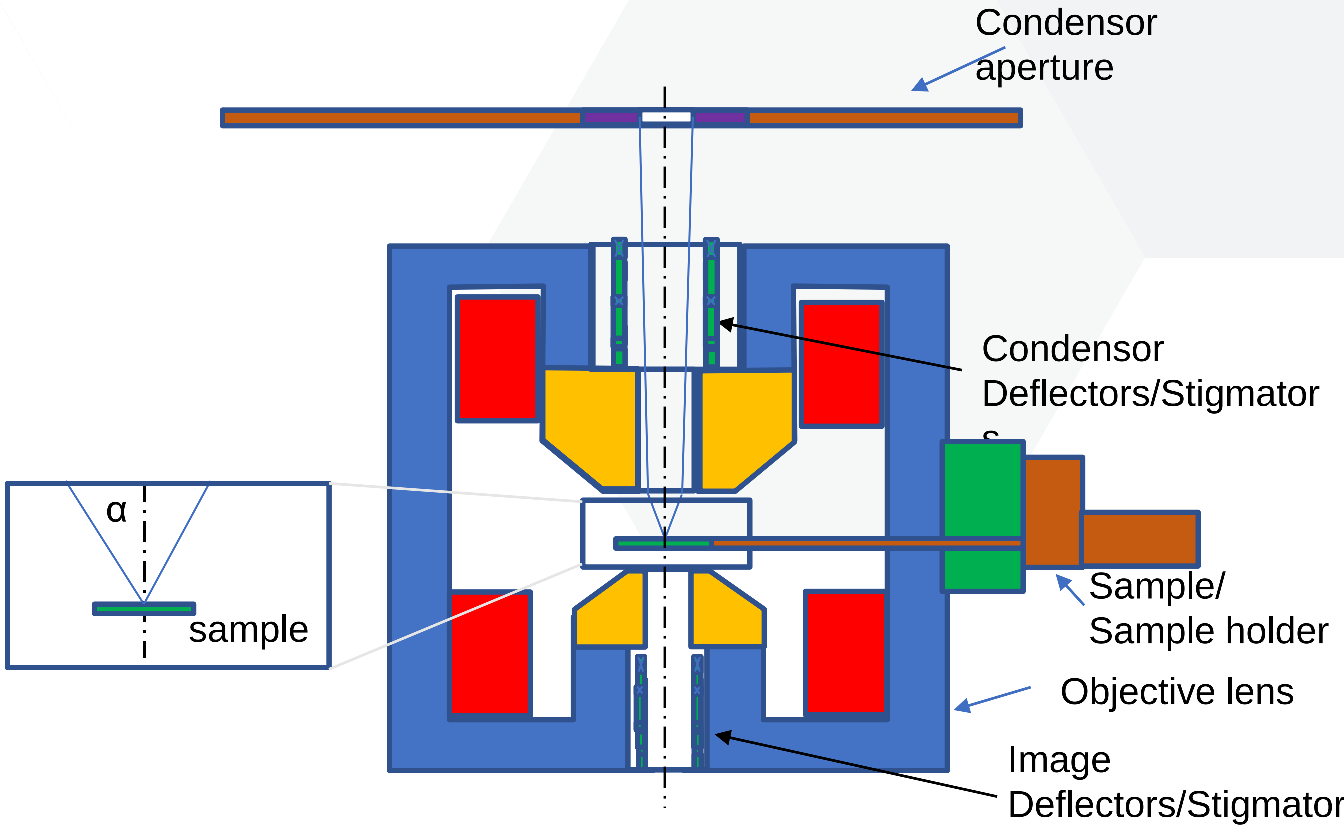
where α – is beam convergent semiangel, ***Cs*** – spherical aberration, ***Cc*** – chromatical aberration, ***H*** – stability factor, ***I*** - beam current, λ – electron wavelenght, ***Br*** – e-source brightness, U - acceleration voltage, ***M*** – demagnification of source, d_0 - original source size

$$H = \sqrt{4(\frac{\Delta I}{I})^2 + (\frac{\Delta E}{U})^2 + (\frac{\Delta U}{U})^2},$$

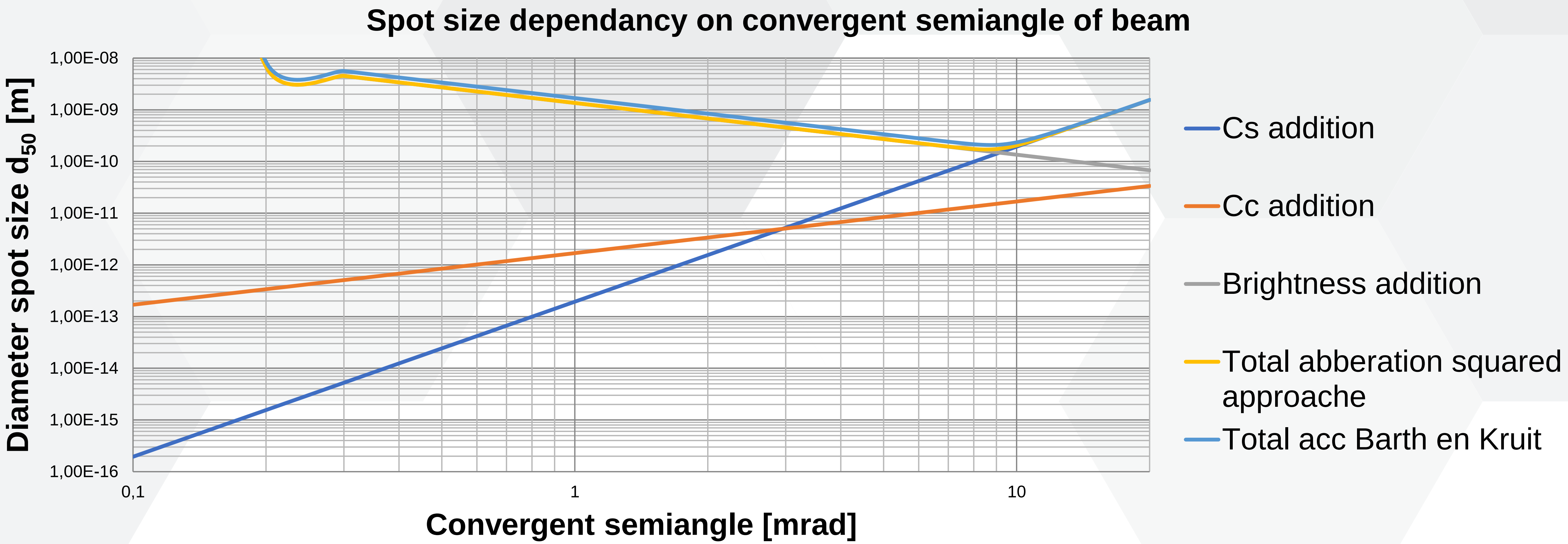
where ΔI - objective current instability, ΔE – energy source spread, ΔU – instability of accelerating voltage

- Better approaches : Barthel, Kruit, Optics 1999
- Absolute accuracy → Wave calculation





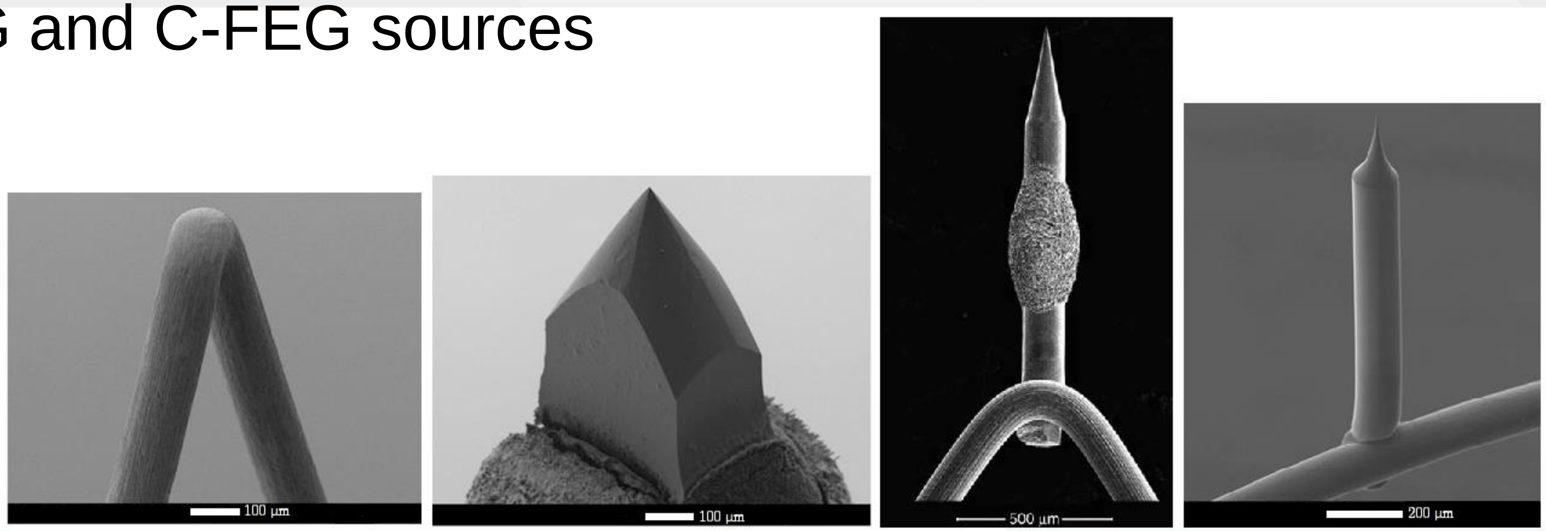
Spot size calculation



HT = 200kV, Cs=1.1mm,Cc=1.6mm, ΔE = 0.8eV, I = 20pA, H = 4e-6

Electron sources

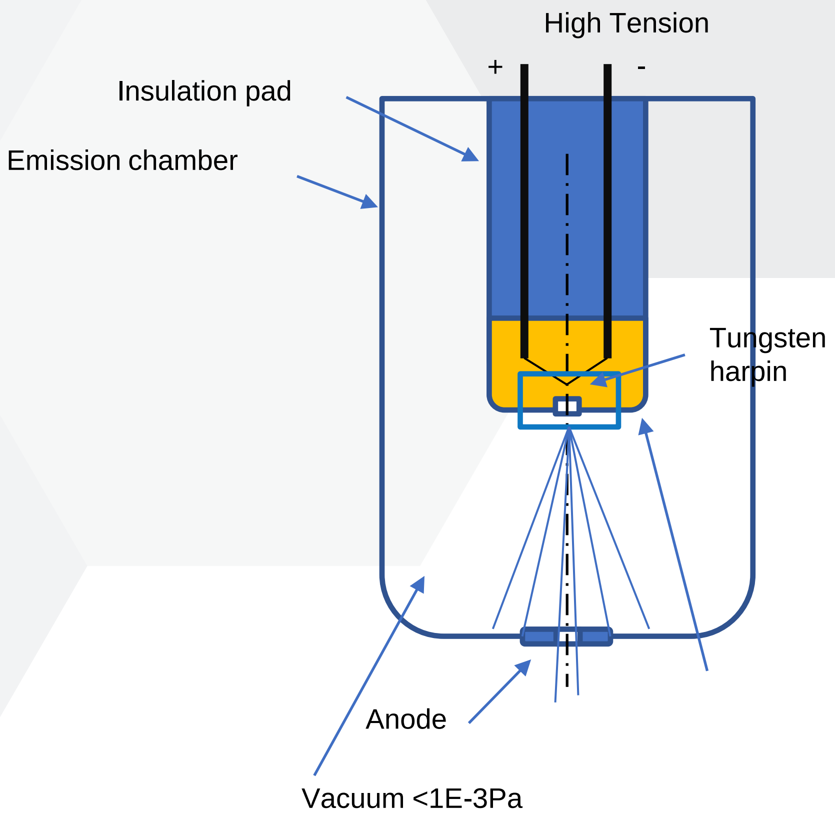
- Using Thermionic, FEG and C-FEG sources

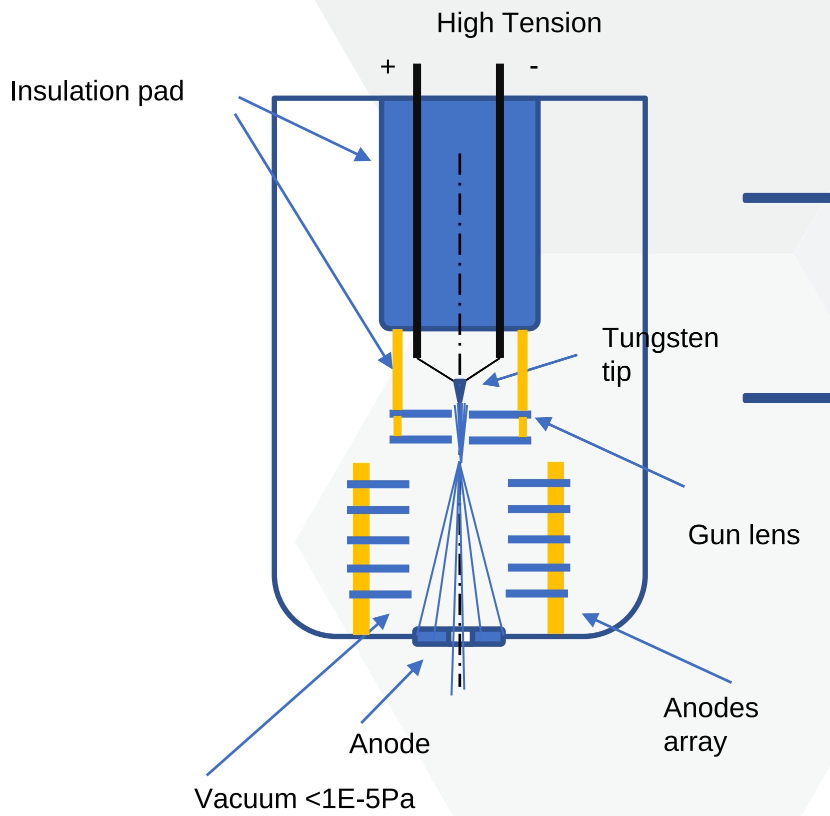


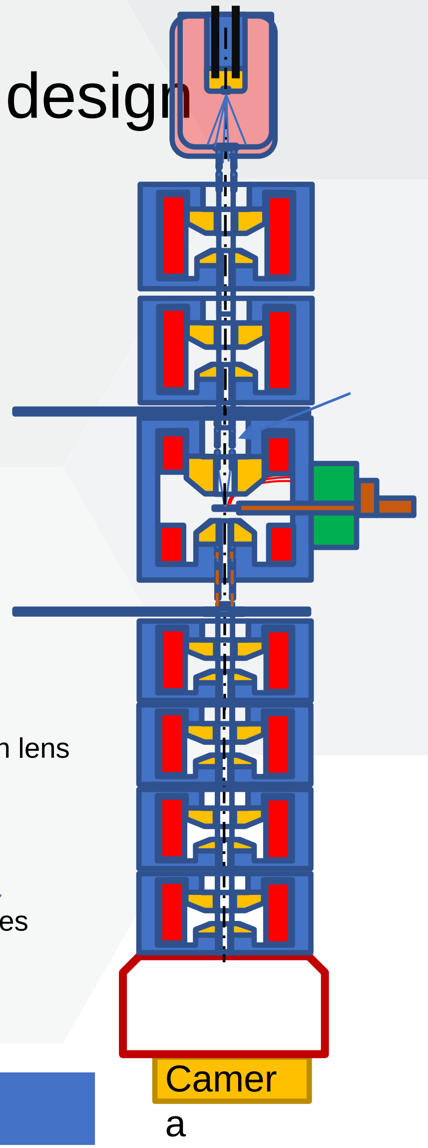
E-source	Thermoemission		Schottky FEG	C-FEG
Cathode	W	LaB6/CeB6	W/ZrO	Cold FEG
Work function[eV]	4.5	2.4	2.7	4.5
Operating Temp [K]	2700	1700	1750	300
Virtual source size[µm]	50	10	~ 0.015	~ 0.005
Energy spread [eV]	2-3	1.5	0.6-0.9	0.2-0.3
Operating vacuum [Pa]	10-3	10^{-4}-10^{-5}	10^{-6}-10^{-7}	10^{-8}-10^{-9}
Max beam current [µA]	1- 3	1-3	0.3	0.1
Lifetime [h]	40-100	500-1000	>2000	>2000
Red. brightness [A/m²sr·eV]	(1-3)*10^4	(3-10)*10^5	(0.2-2)*10^8	(0.5-5)*10^8

Accelerators/Emission Chamber

- Using Signle- and Two-aperture Electrostatic lenses with Multi Anodes design







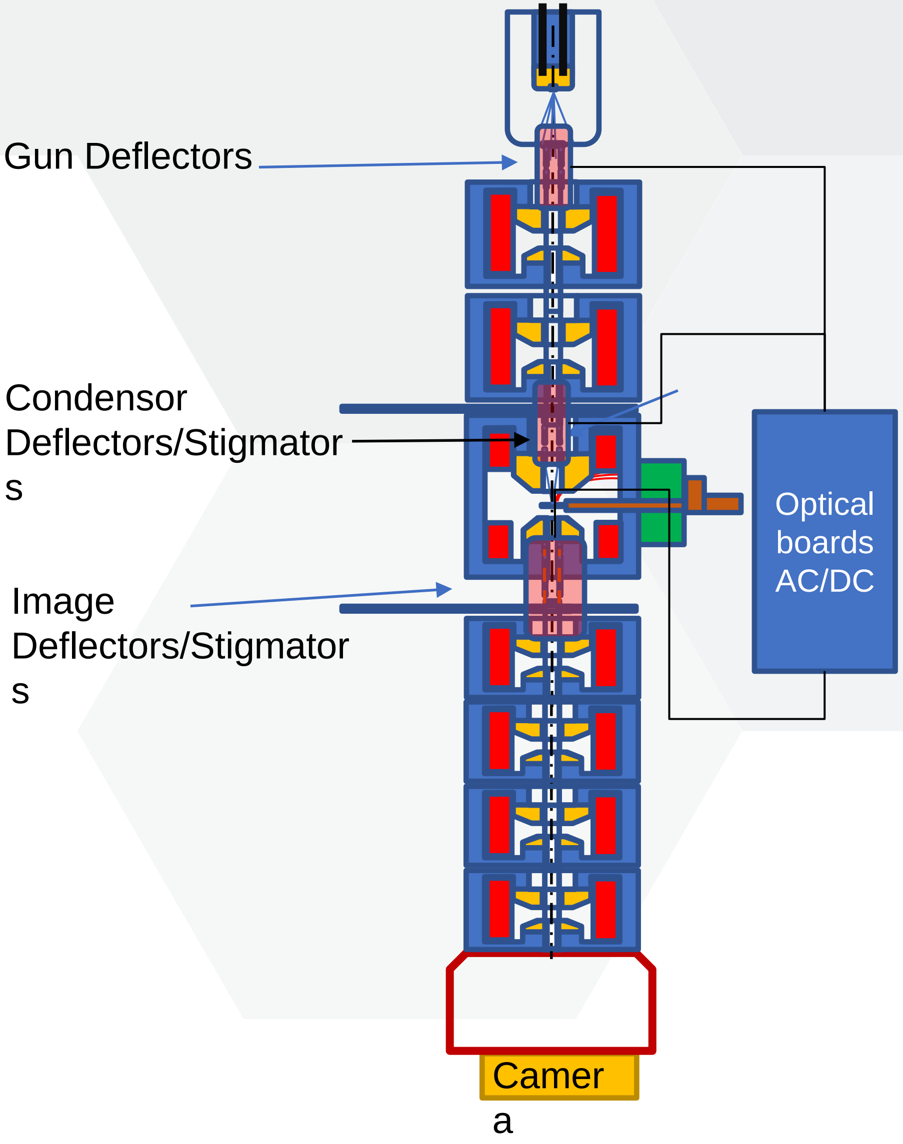
Type	Single-aperture (5 - 120kV)	Two-aperture + MultiCathodes
E-source	Thermionic	FEG, C-FEG
Pros	Cheap	Less aberrations, higher HT possible

Deflectors

- **Function**
  - Centering optical elements – Gun, Beam, Image
  - Image/Diffraction Shift, Tilt – Beam and Image
  - Gun optimization – Gun
  - Scanning/Descanning – Beam/Image

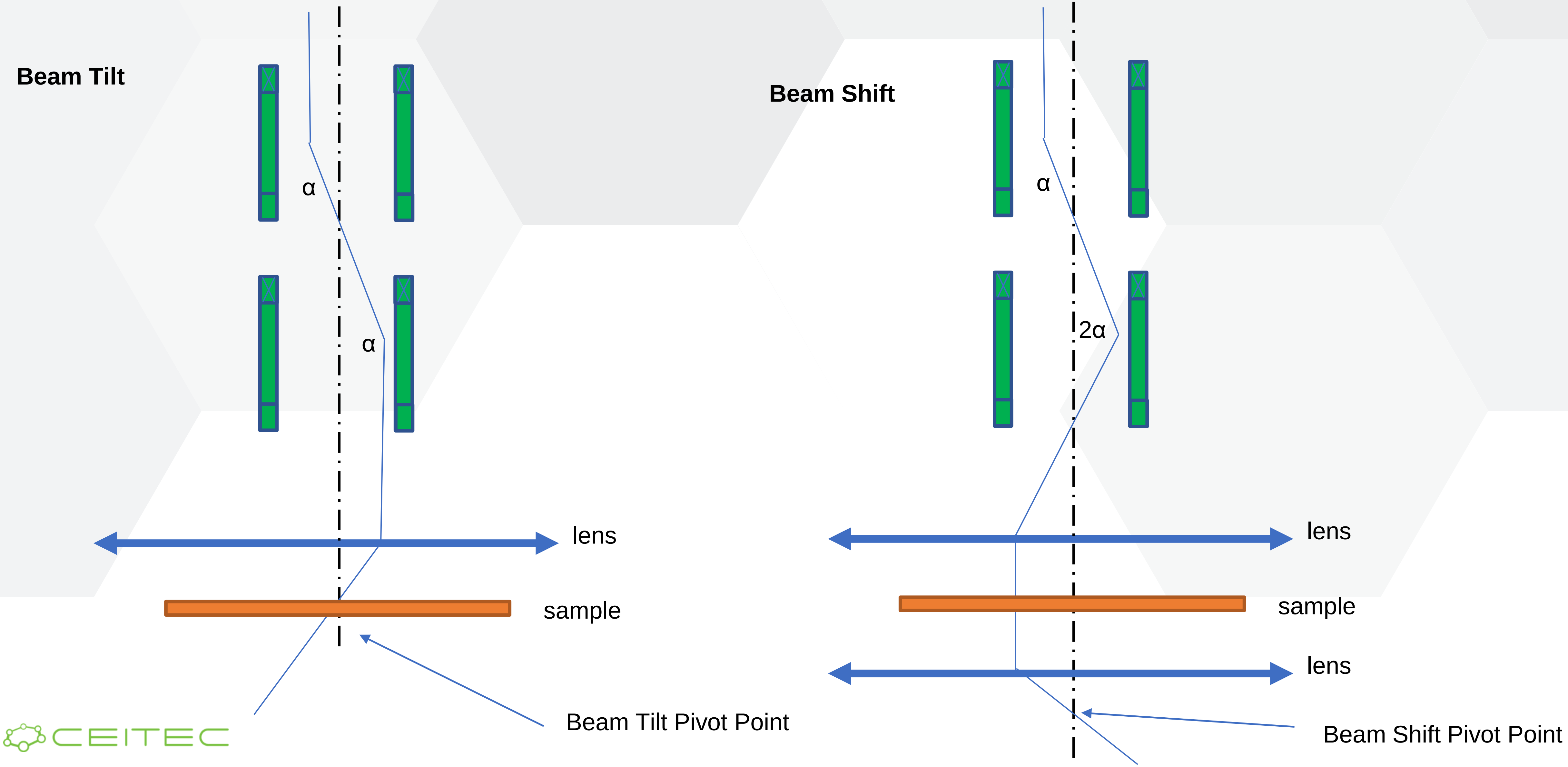
- **Magnetic**
  - Gun deflection coils – centering e-beam from Acc to Condensor lenses
  - Beam deflection coils
    - DC - centering e-beam from Condensor lenses to Objective lens
    - AC – Scanning over sample
  - Image deflection coils
    - DC - centering e-beam from Condensor lenses to Objective lens
    - AC – Scanning over sample

- Driven by Optical Boards
  - Signal to coils – AC (trending to DC directly)
  - Processing DC
  - Noise of Optical Boards translates to image instability or resolution lost (H)



Deflectors – Beam Tilt and Beam Shift – Pivot Points

- **Combinatin of two deflection coils pair to create independent beam Tilt and Shift**



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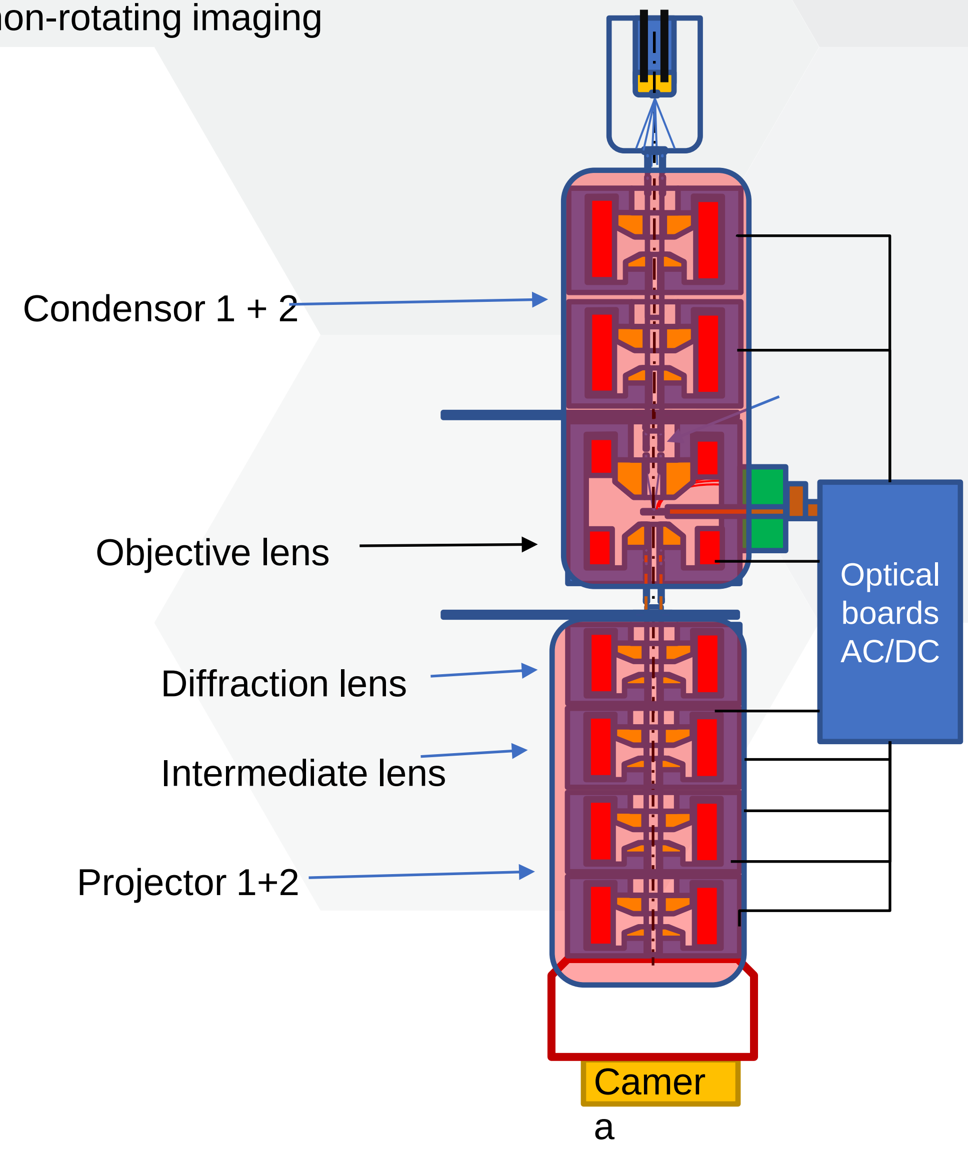
Lenses

- **Function**
  - **Condensor – 2 or 3 condenser system,** Make a sample illumination (TEM/STEM)
  - **Projector – 4 lenses system -** Magnify a sample image or diffraction, providing non-rotating imaging

- **Magnetic**
  - Condensor, Objective (immerse) and projector lenses
  - Water cooling

- **Electrostatic**
  - Accelerator only

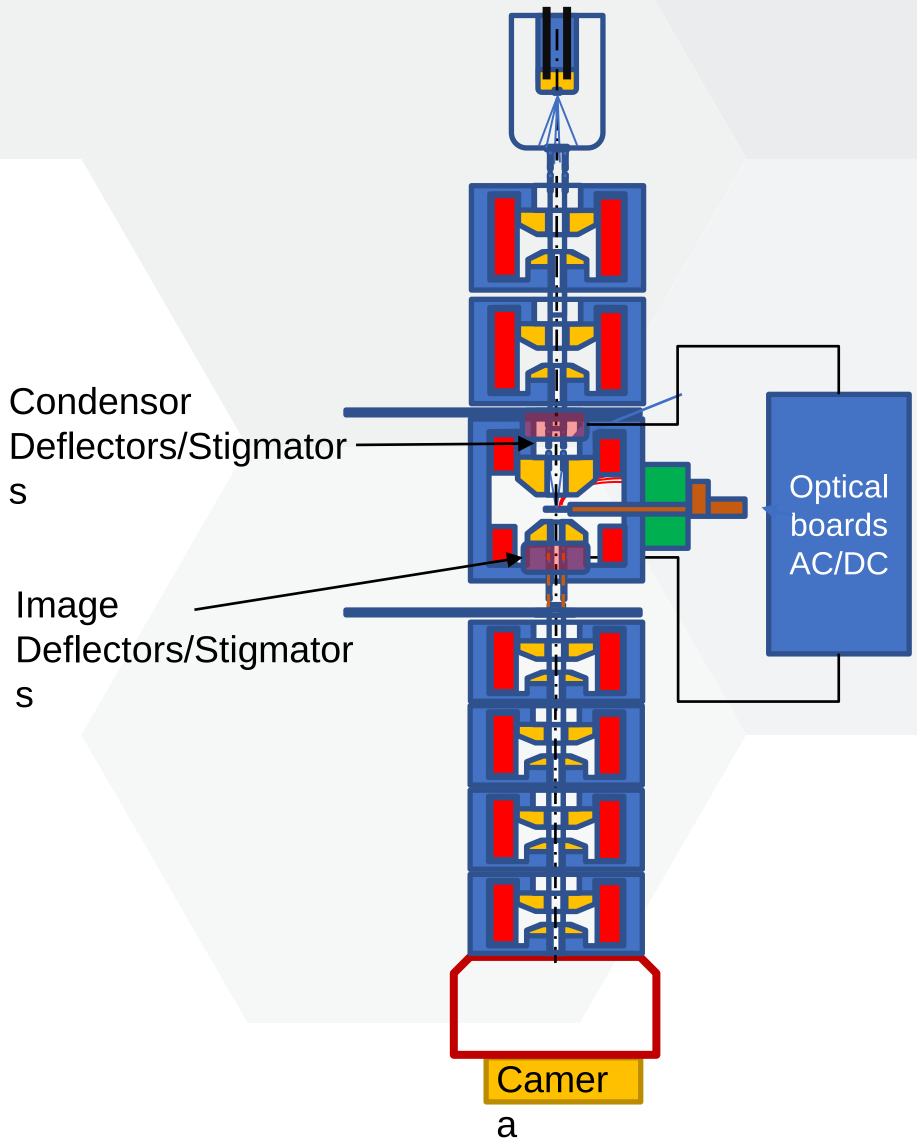
- Driven by Optical Boards
  - Signal to coils DC
  - Feedback loops for coils stability
  - Noise of Optical Boards translates to image instability or resolution lost (H)



Stigmators

- **Magnetic**
  - Objective or Gun stigmators
  - Correcting 2-fold and 3-fold astigmatism

- Driven by Optical Boards
  - Signal to coils – AC (trending to DC directly)
  - Processing DC
  - Noise of Optical Boards translates to image instability or resolution lost (H)



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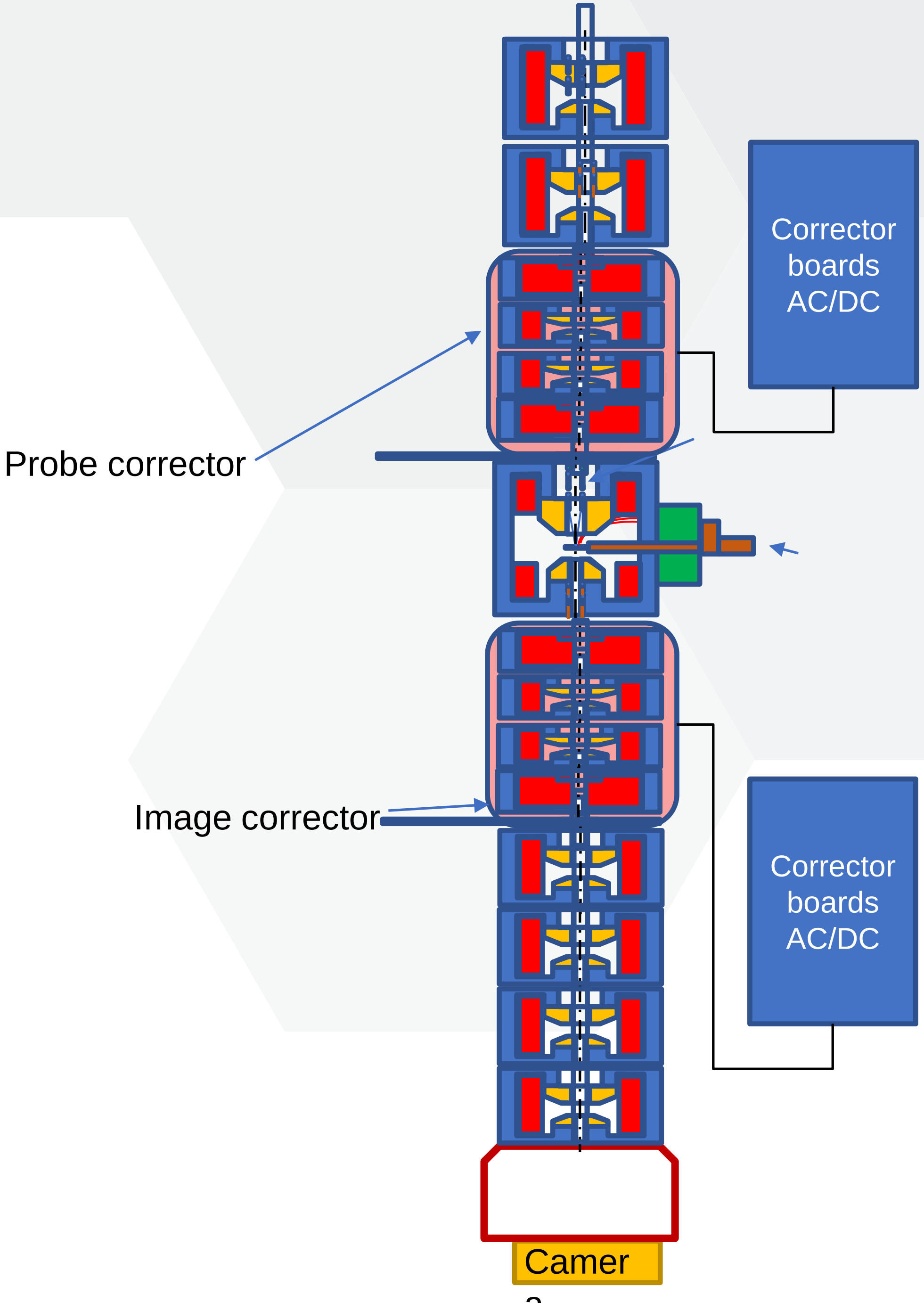
Correctors

- **Spherical Correctors – Image or Probe**
  - Hexapole based – CEOS supplier → Thermo Fisher Scientific, Jeol, Hitachi
  - Octupole based - Nion
- **Chromatic – Only Image**
  - Octupole based – CEOS – Thermo Fisher Scientific, Jeol

- Driven by Optical Boards
  - Most stable boards (<0.1 ppm)
  - AC drivers
  - Processing DC
  - Noise of Optical Boards translates to image instability or resolution lost (H)



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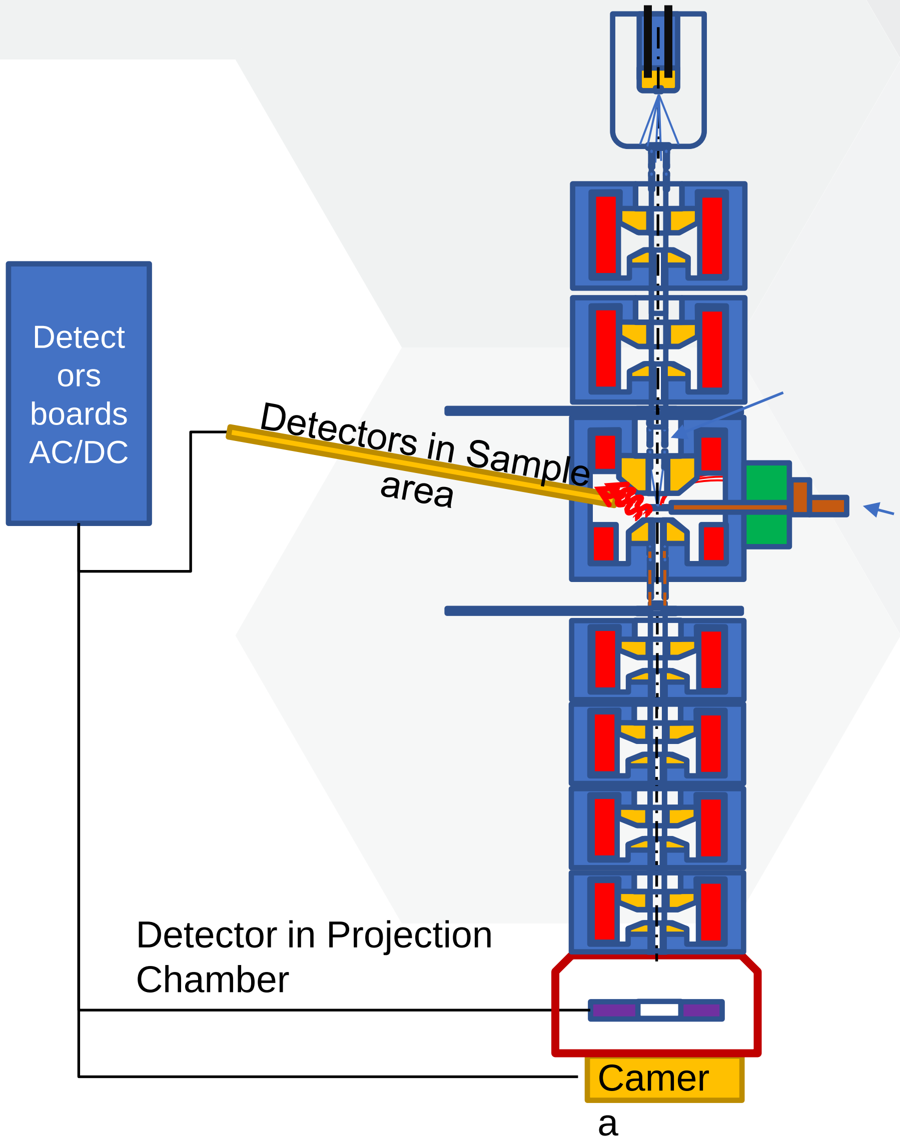
Detectors

- **Projection chamber area**
  - TEM – Cameras – CMOS, Hybrid, CCD
  - STEM – HAADF, BF, DF, Pixelized

- **Sample area**
  - EDS
  - CL
  - SE – SDD based
  - BSE - SDD based

- Driven by Optical Boards
  - Signals – AC/DC (trending to DC directly)
  - Processing DC
  - Noise of Optical Boards translates to image instability
  - Sync with Scanning Deflection coils



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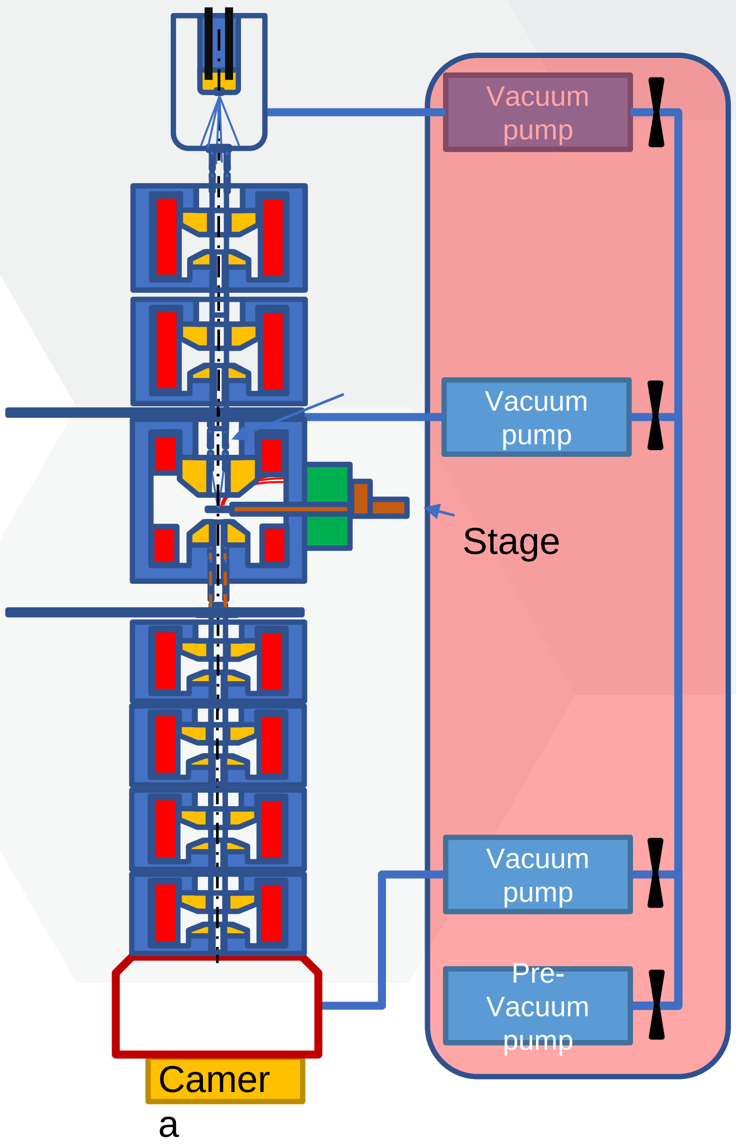
Infrastructure I

- **Vacuum**
  - Levels
    - Chamber 1e-4Pa
    - Accelerator 1e-4 Thermionic, 1e-9 CFEG
  - Pumps
    - TMP, IGP, NEG, Scroll, Diffusion, Rotary
  - Valve
    - Using to create separate vacuum volumes
  - Linening Tubes
    - Using to keep vacuum for electron trajectory
    - Non-magnetic materials (glass, stainless steel)
- **Stage**
  - 4 Axis stage, 5th axis done via holders
  - Resolution 1-10nm
  - Drift 0.5-1 nm/min
  - Ultrasonic, Piezo design



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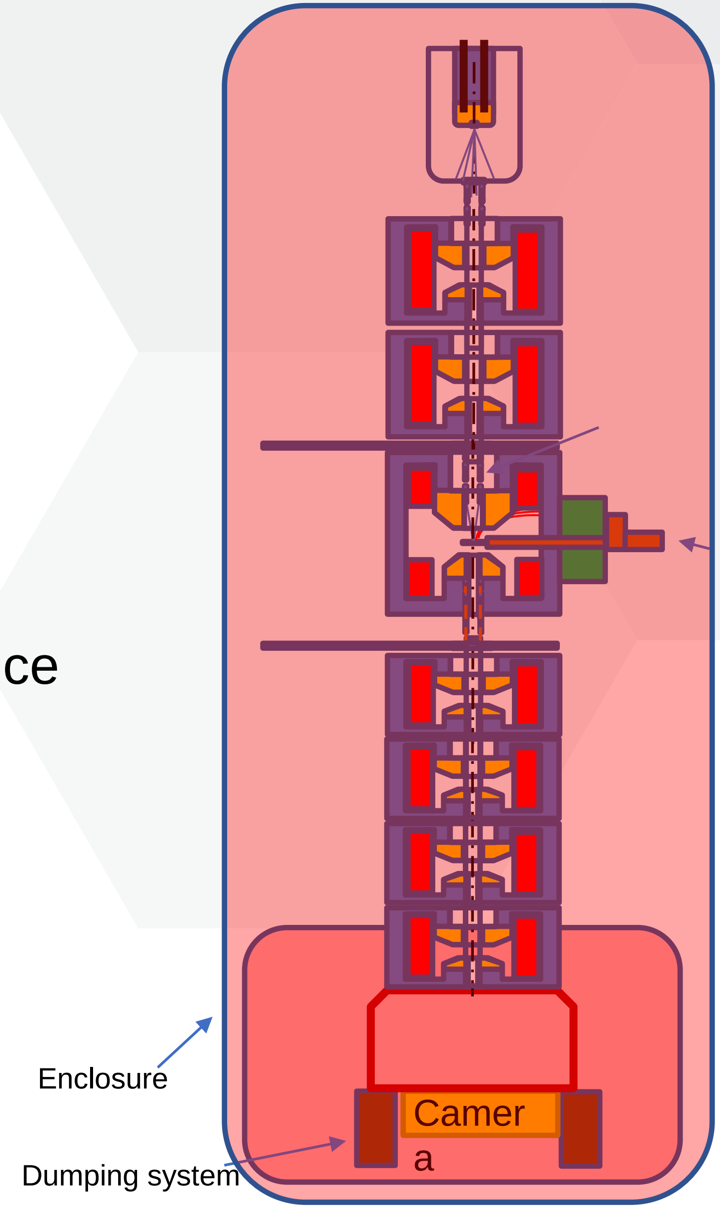
Infrastructure II

- **Chamber**
  - Vacuum level 1e-3 – 1e-6
  - Support column, stage, detectors
  - Shielding of sample area from any disturbance (EMI)

- **Frame, Dumping, Enclosure**
  - Supporting Chamber and the whole infrastructure
  - Dumping (typically 1/10 of required resolution)
    - Rubber pods
    - Air dumpers
    - Active dumping
  - Sound and EMI enclosure – suppressing EMI and sound influence



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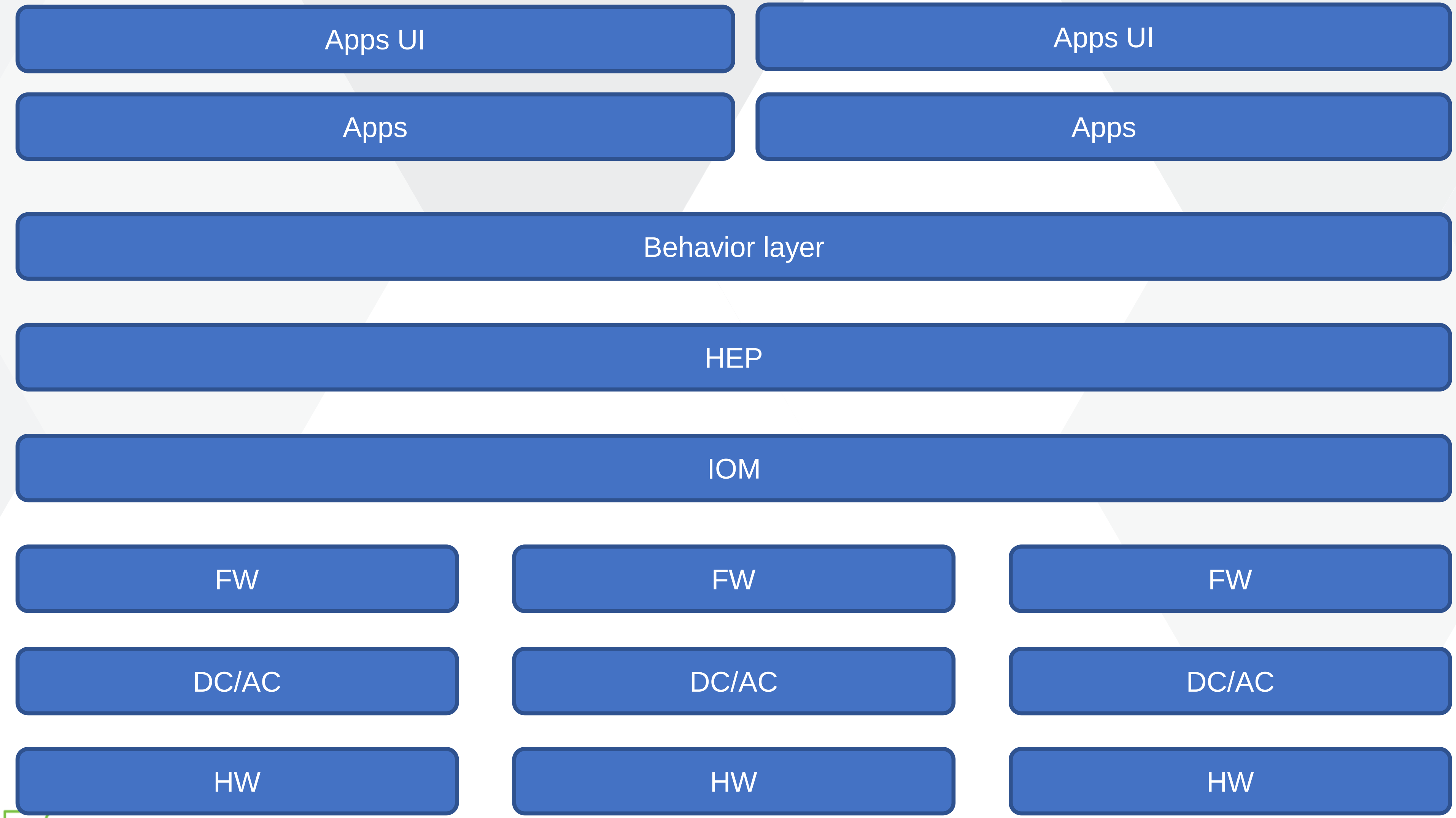
Electronics - Boards

- **Optical Boards**
  - Signals – AC/DC (trending to DC directly)
  - Processing DC
  - Noise of Optical Boards translates to image instability
  - **Lens**
    - Typical currents 1-12A or 10-1000V
    - Stability 0.5-10 ppm
  - **Deflectors/Stigmators**
    - Typical currents 10-100mA or 1-10V
    - Stability 1-10 ppm
  - **Correctors**
    - Typical currents 10-1000mA or 1-100V
    - Stability <0.1 ppm
- **Detectors Boards**
  - Signals – AC/DC (trending to DC directly)
  - Processing DC
  - Depending on specific Detectors needs
- **Infrastructure Boards**
  - Vacuum pump, vavles

SW


Apps UI
Apps UI
Apps
Apps
Behavior layer
HEP
IOM
FW
FW
FW
DC/AC
DC/AC
DC/AC
HW
HW
HW

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TEM examples

Name/Brand	**LVEM25E/ Delong**	**UltraSTEM 200/Nion**	**CryoArm 300 II /Jeol**	**Tensor/Tescan**	**HF5000/Hitachi**	**Krios/TFS**
Resolution [nm/kV]	<1	<0.08/200	<?/300	0.28/100	<0.078/200	<0.12/300
Operating Voltage [kV]	15-25	20?-200	300	100	30-200	300
Lens type	Magnetic/Coils+Magnets	Magnetic	Magnetic	Magnetic	Magnetic	Magnetic
Electron source	CFEG	CFEG	CFEG	SFEG	CFEG	XFEG/CFEG

To be continued…

Imaging theory…