5. Low Pressure Discharge Lamps

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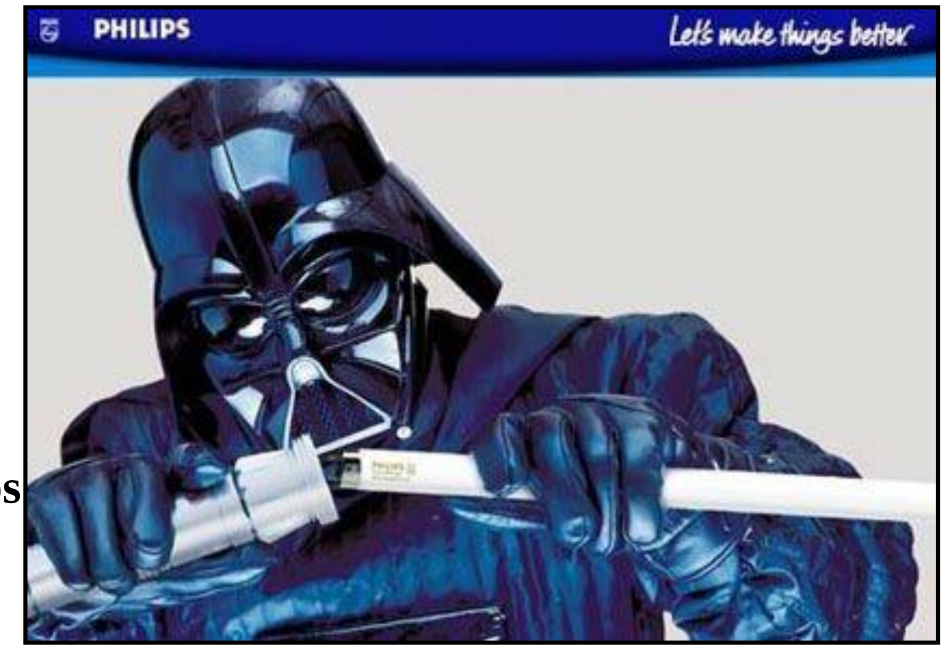
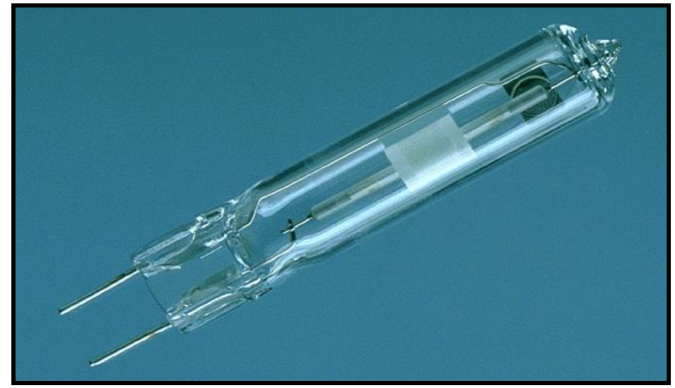


5.1 Classification of Gas Discharge Lamps

	Low-pressure gas discharge lamps	High-pressure gas discharge lamps
	 	
Pressure	**10 µbar to 10 mbar**	**> 1 bar**
Length	**approx. 1 m**	**approx. 1 cm**
Power	**4 – 58 W (200 W)**	**100 – 2000 W**

5.1 Classification of Gas Discharge Lamps

Mercury

Low pressure

p < 10 mbar

Hg/Ar Hg/Ne

185.0 nm
253.7 nm

Compact fluorescent lamps
or
Fluorescent lamps

High pressure
p > 1 bar

Hg/Ar

Broadband spectrum

Line emitters
NaX / TlX / InX, X = I, Br
Multi line emitters
NaX / TlX / LnX_3
(Ln = Dy, Ho, Tm, Sc)
SnX_2

Metal halide lamps

Sodium

Low pressure

Na/Ar/Ne

589 nm

High pressure

Na/Hg/Xe

Sodium vapour lamps

Noble gases

Low pressure

Ne

74 nm

Medium pressure

Xe/Ne
147 + 172 nm
Plasma displays

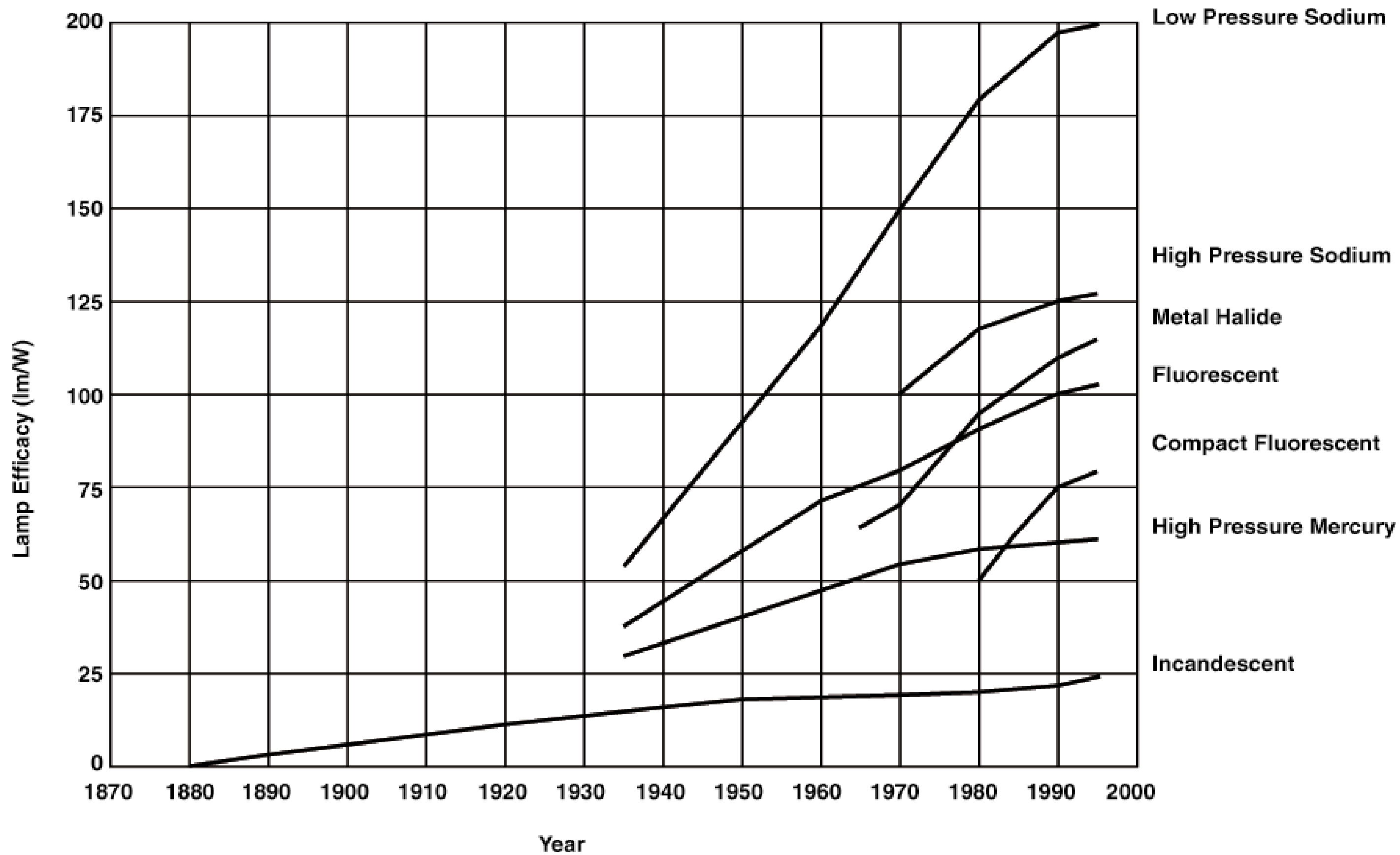
Sulphur

High pressure

S_2

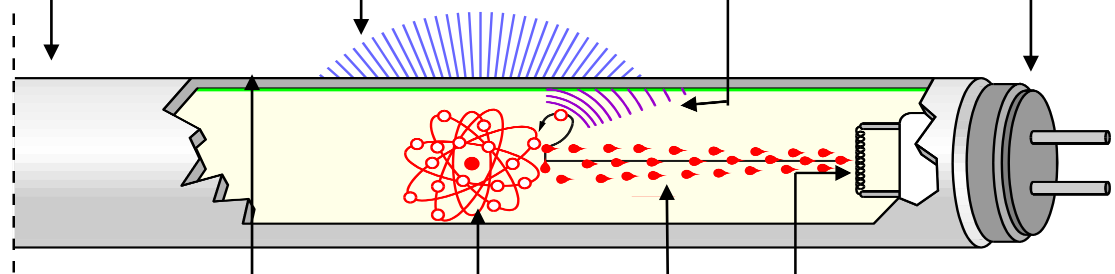
Broad band spectrum

5.2 Historical Development



1852	Stokes: Monitoring of the phenomenon “fluorescence”	
1938	General electric: First fluorescent lamp, phosphor = $(Zn,Be)_2SiO_4$:Mn	~ 40 lm/W
1942	Fluorescent lamps with halophosphate phosphor:	60 lm/W
1971	Fluorescent lamps with trichromatic phosphor blend:	100 lm/W

5.3 Principle of Fluorescent Lamps



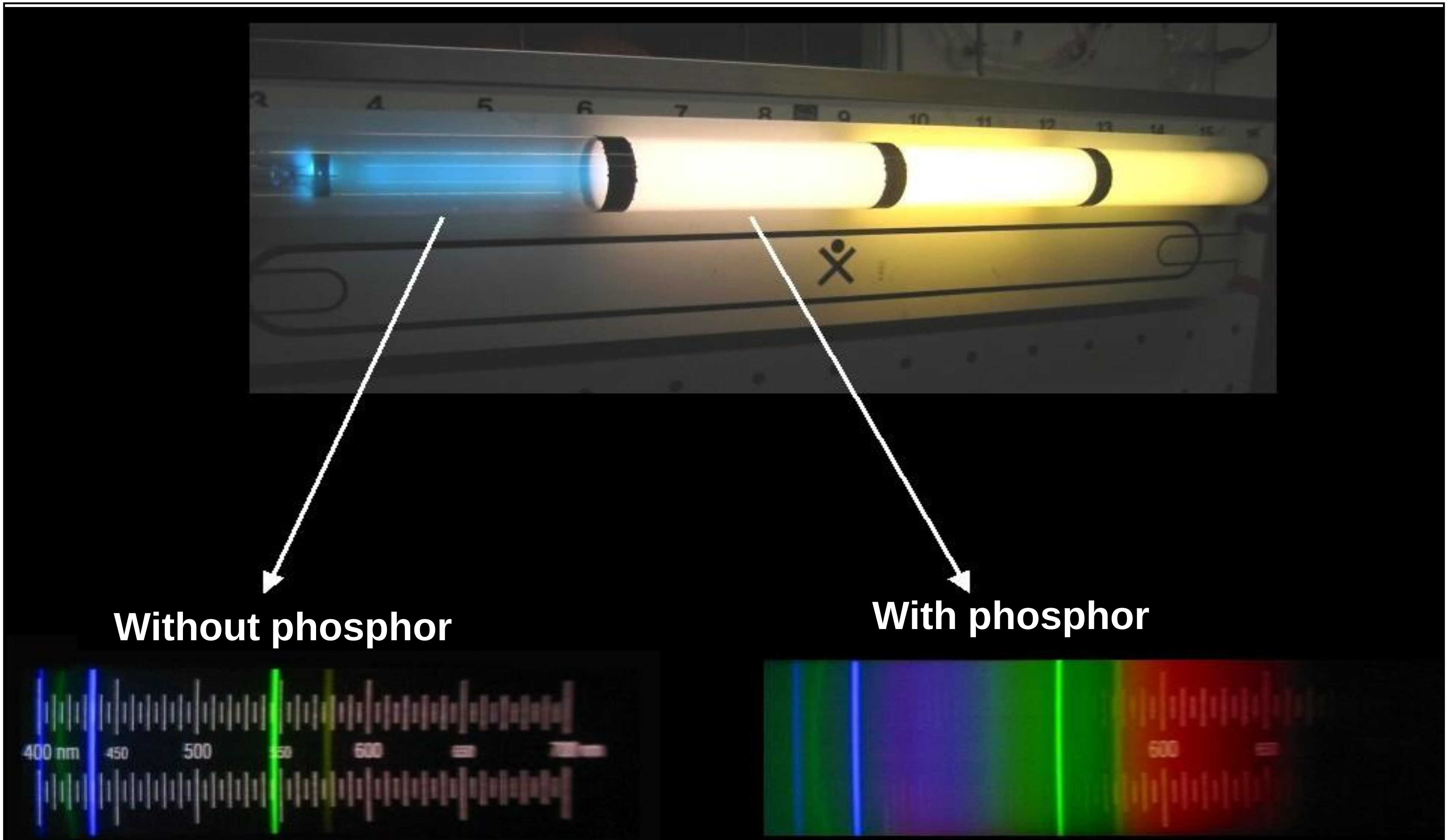
Gas discharge → UV radiation → (Phosphor screen) → Visible light

UV radiation → Cleaning

UV radiation → Disinfection

Visible light → Lighting

5.3 Principle of Fluorescent Lamps

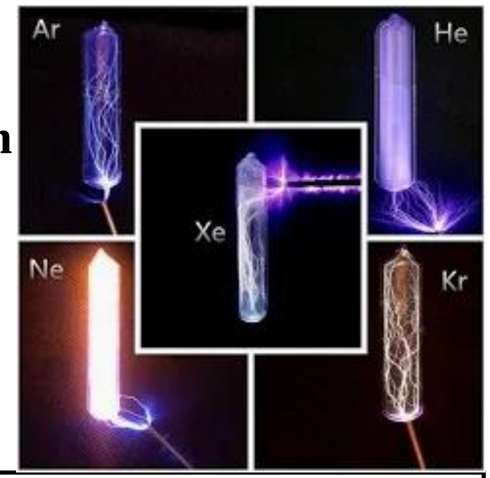


5.4 Low-Pressure Mercury Discharge

In gas discharge lamps, light is generated primarily by an electrically excited plasma

Definition of a plasma

Mixture of electrons, ions and neutral particles in different excited states and with strong interaction with each other

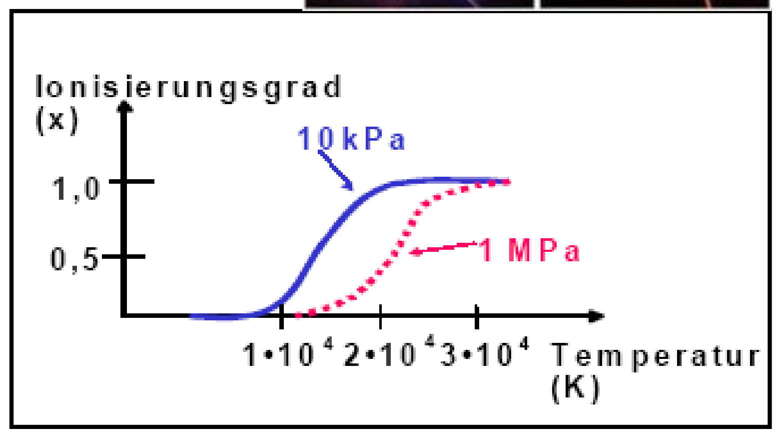


a) **Isothermal plasma: All particles are in thermodynamic equilibrium (high temperature plasmas: stars)**

b) **Non-isothermal plasma: Only electrons are in thermodynamic equilibrium (electrically generated plasmas: gas discharge lamps)**

In gas discharge lamps the gas atoms are indeed hardly ionized!

A significant ionization just occur at temperatures beyond 4000 K



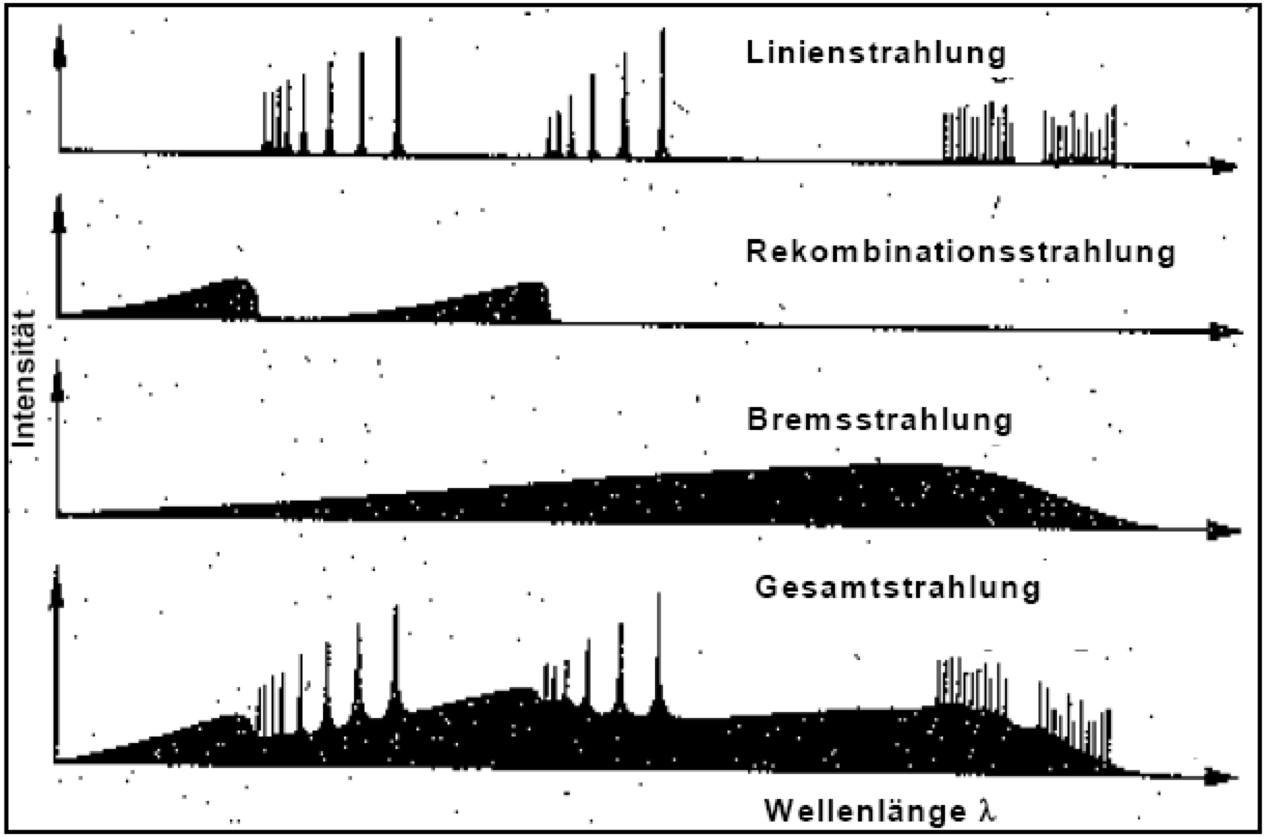
5.4 Low-Pressure Mercury Discharge

Spectrum of a gas discharge is caused by several physical processes

1. **Line emission (fluorescence)**
   $Hg^* \rightarrow Hg + h\nu$
   $Ar^* \rightarrow Ar + h\nu$
   $Na^* \rightarrow Na + h\nu$

2. **Recombination radiation**
   $Hg^+ + e^- \rightarrow Hg + h\nu$

3. **"Bremsstrahlung"**
   Thermalization of electrons

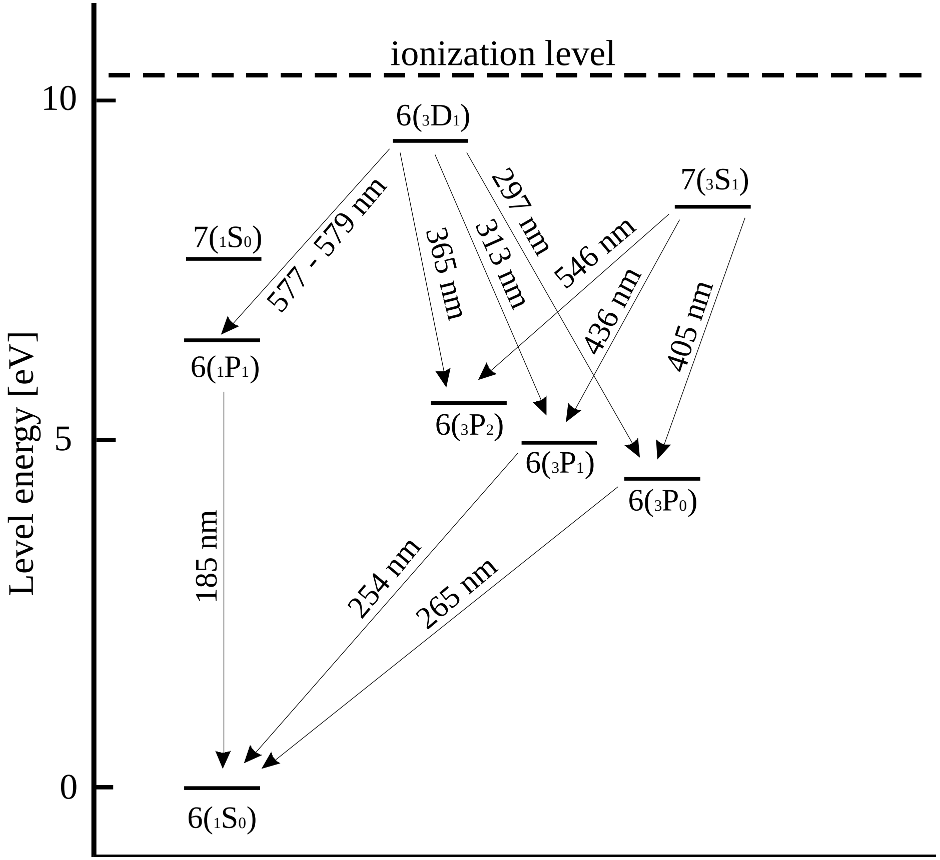


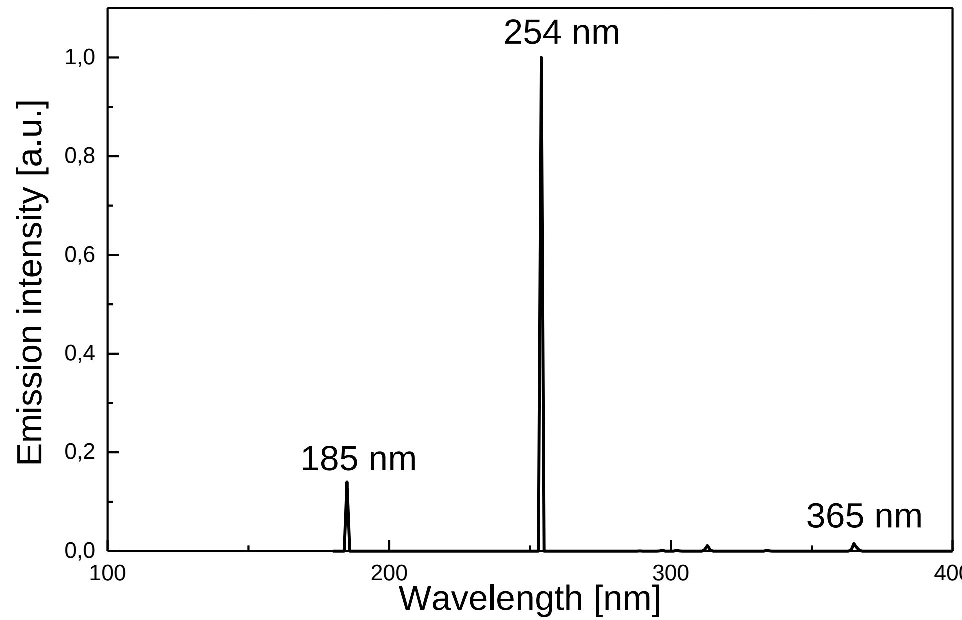
Additional contributions

- **Excimer radiation**
- **Phosphor emission**
- **Emission of LnX_3-filling (X = Cl, Br, I)**

5.4 Low-Pressure Mercury Discharge

Energy level diagram of Hg-atom and emission spectrum of a low pressure mercury gas discharge





[Xe]4f^{14}5d^{10}6s^{2} → [Xe]4f^{14}5d^{10}6s^{1}6p^{1}

Ground state term: $^{1}S_{0}$ (all shells filled)

Other lines are in the visible range at 405, 436, 546, and 579 nm

⇒ Hg discharge appears bluish-white

5.4 Low-Pressure Mercury Discharge

Processes in the gas discharge

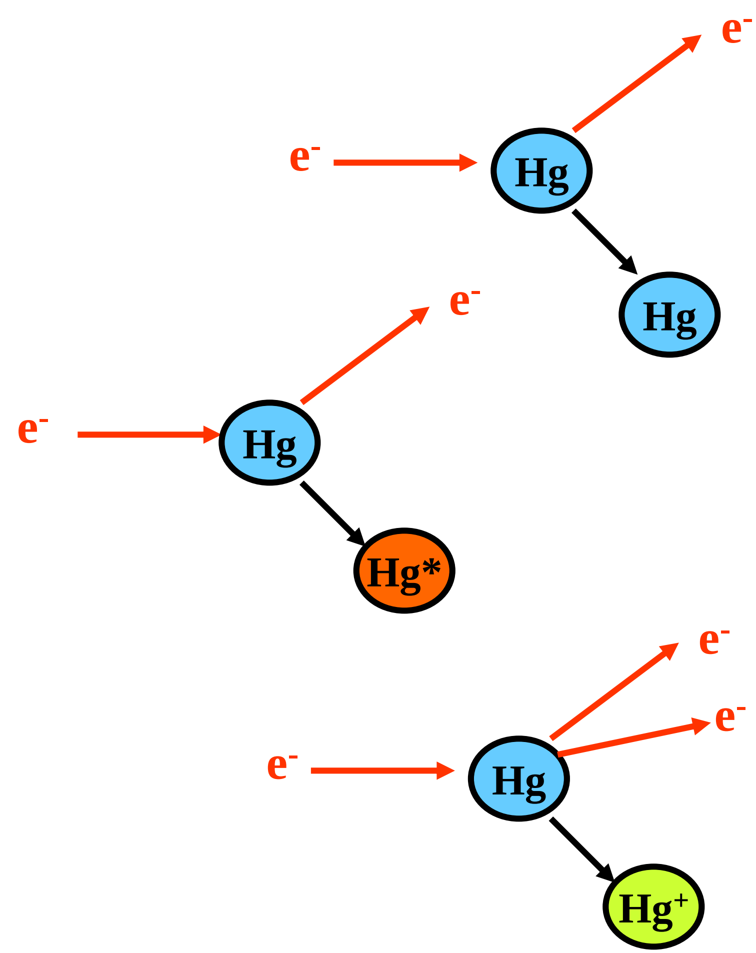
1. **Thermal emission of electrons**
   Cathode $\rightarrow$ e^-

2. **Elastic scattering of Hg and Ar (buffer gas)**
   $e^- + Hg \rightarrow e^- + Hg$
   $e^- + Ar \rightarrow e^- + Ar$

3. **Excitation of Hg atoms**
   $e^- + Hg \rightarrow e^- + Hg^* ({}^3P_1)$
   $e^- + Hg \rightarrow e^- + Hg^* ({}^1P_1)$

4. **Ionization of Hg atoms**
   $e^- + Hg \rightarrow 2\ e^- + Hg^+$

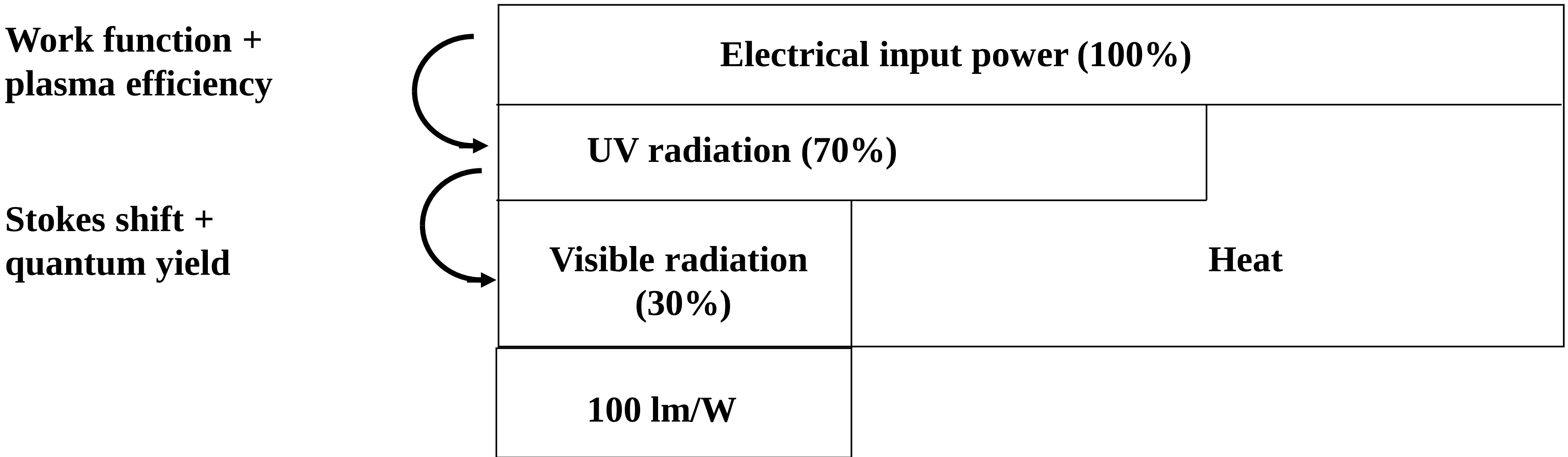
5. **Relaxation of excited Hg atoms**
   $Hg^*({}^3P_1, {}^1P_1, \ldots.) \rightarrow Hg + h\nu_{UV}$



In a low pressure mercury gas discharge about 70% of electrical input power is converted into UV radiation

5.5 Energy Balance

Loss processes in fluorescent lamps



ε_{dis} = Plasma efficiency

$$\varepsilon = \varepsilon_{dis} * QD*QY$$

Quantum deficit (Stokes-Shift) = $[\lambda_{Plasma}/\lambda_{Phosphor}] = 0.46$

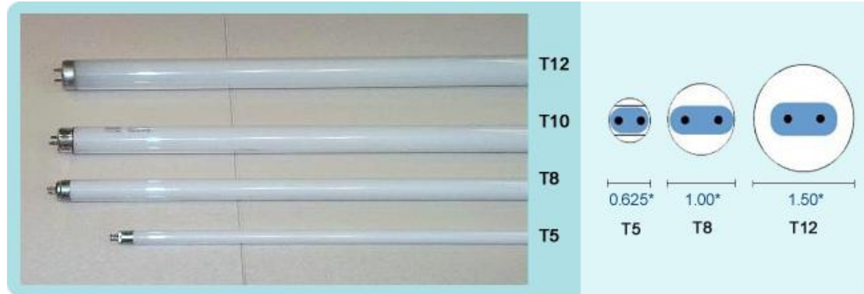
Quantum yield = $N_{emitted\ photons}/N_{absorbed\ photons} \sim 0.9$

Linear Fluorescent Lamps (TL) $\varepsilon_{dis} = 70\% \Rightarrow \varepsilon = 30\%$ (100 lm/W)

Compact Fluorescent Lamps (CFL) $\varepsilon_{dis} = 40\% \Rightarrow \varepsilon = 18\%$ (60 lm/W)

5.6 Typical Dimensions

Fluorescent tubes



Output	Length	Diameter	Type
18 W 36 W 58 W	0.6 m 1.2 m 1.5 m	T8 T8 T8	T8 = 8/8 inch = 2.54 cm
4 W 6 W 8 W 13 W	0.14 m 0.21 m 0.30 m 0.50 m	T5 T5 T5 T5	T5 = 5/8 inch = 1.59 cm

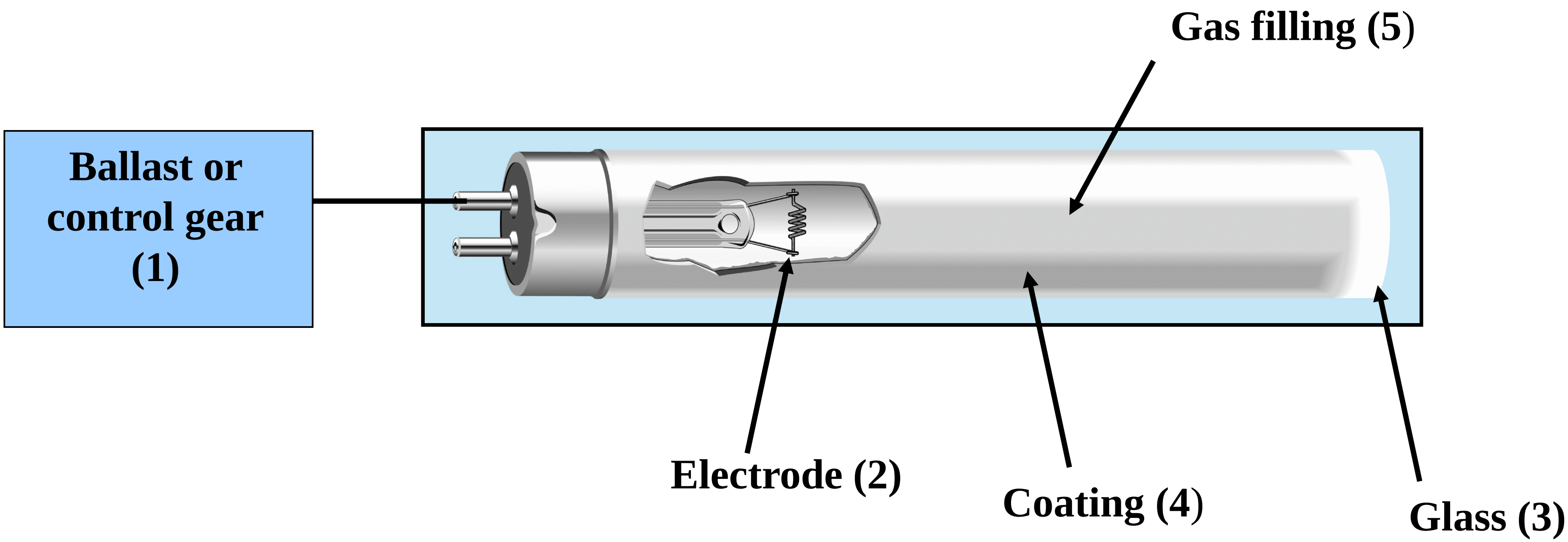
T12 → T8 → T5 → T4 → T3 → T1 (0.32 cm): Increasing wall load

Today: LED Retrofit lamps

5.7 Components of Fluorescent Lamps

Functional parts

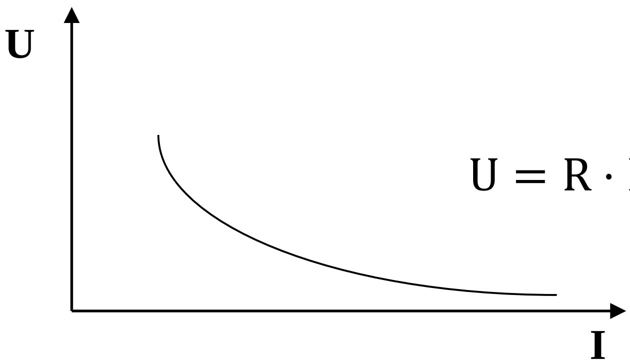
1. Ballast or control gear and starter
2. Electrodes and emitter
3. Glass
4. Coating = pre-coating + phosphor
5. Gas filling



5.8 Ballast

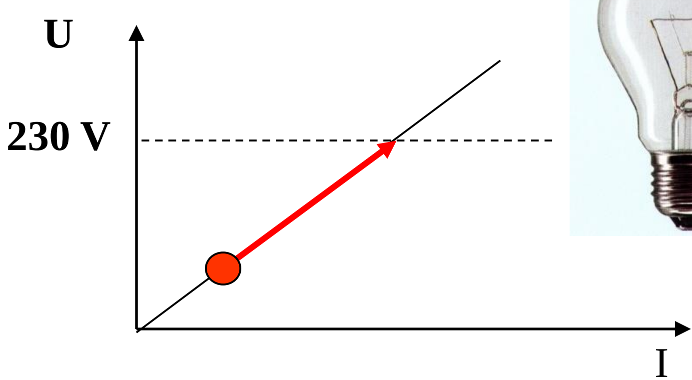
Why is a ballast required?

Discharge lamps have a negative current-voltage characteristic (S = 1/R = conductivity)

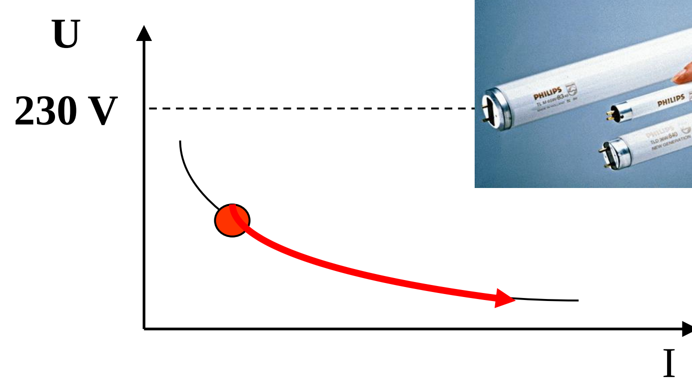


$$U = R \cdot I \quad \Rightarrow \quad U = \frac{I}{S} \qquad \frac{\sim n_e}{\sim \text{increases more than linearly with } n_e}$$

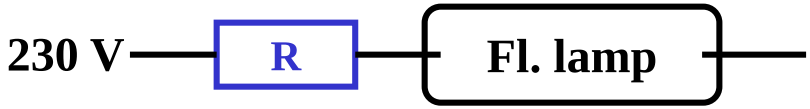
Incandescent lamps



Discharge lamps

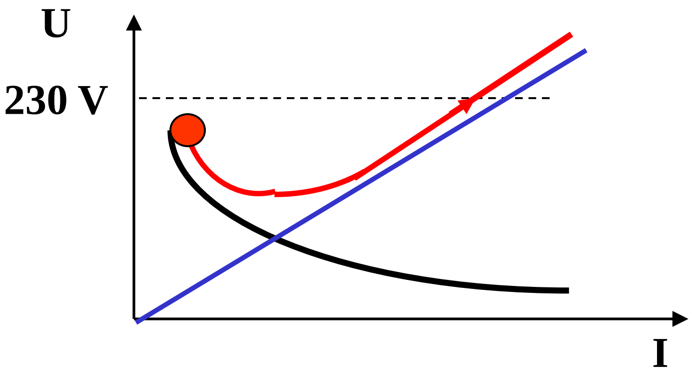


5.8 Ballast



36 W FL: U = 100 V, I = 0.36 A

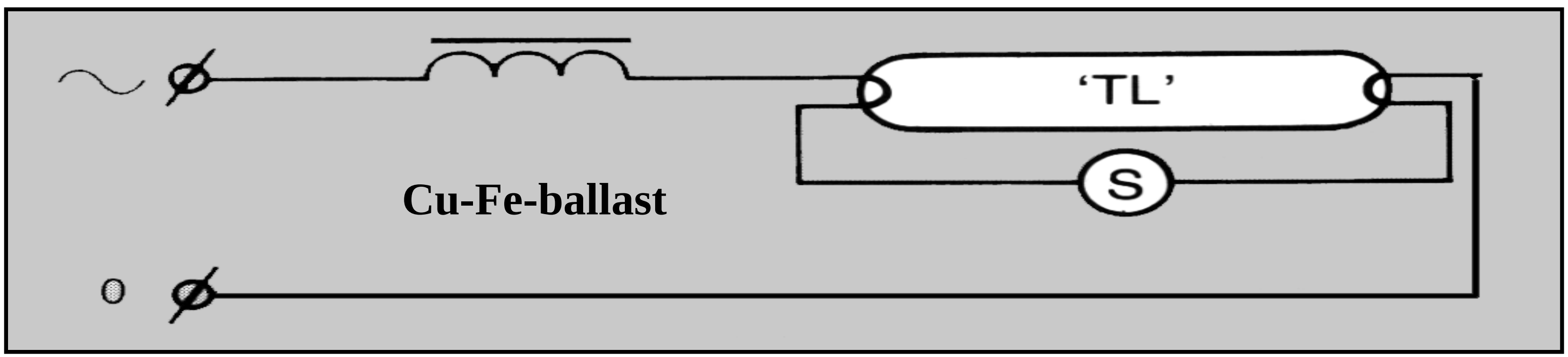
R: U_R = 130 V, I_R = 0.36 A ⇒ R = 360 Ω



⇒130/230 = 56% of power output is consumed in R

⇒ η = 100 lm/W * 44% = 44 lm/W

Solution: "ballasted" with a coil (inductance) or a capacitor (capacitance)
⇒ in L and C are the current and voltage phase shifted by 90°
⇒ no power output is consumed

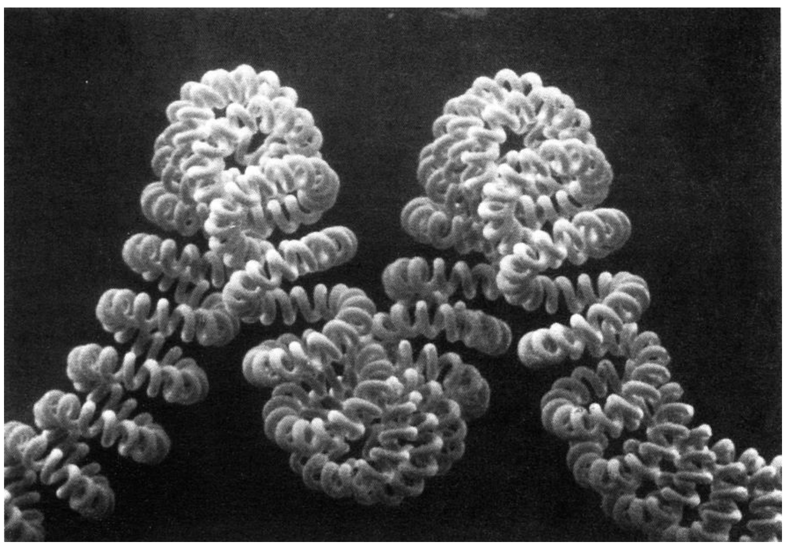


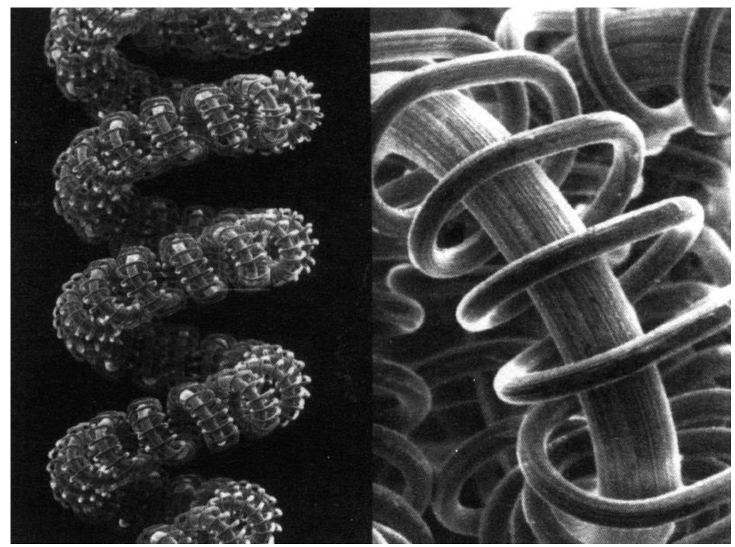
5.9 Electrodes and Emitters

Electrodes release electrons into the gas phase by thermal emission

Material: Tungsten (emission of electrons from about 2000 °C)

Typical design: Double-coiled wire

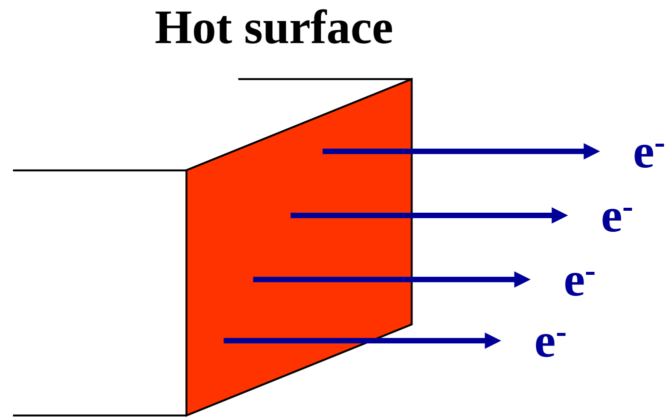




5.9 Electrodes and Emitters

Thermal thermionic emission of electrodes is described by the Richardson law

$$I = \text{Area} \cdot A \cdot T^2 \cdot e^{-\frac{W_A}{kT}}$$



A = Richardson constant = 60 A/cm²K²

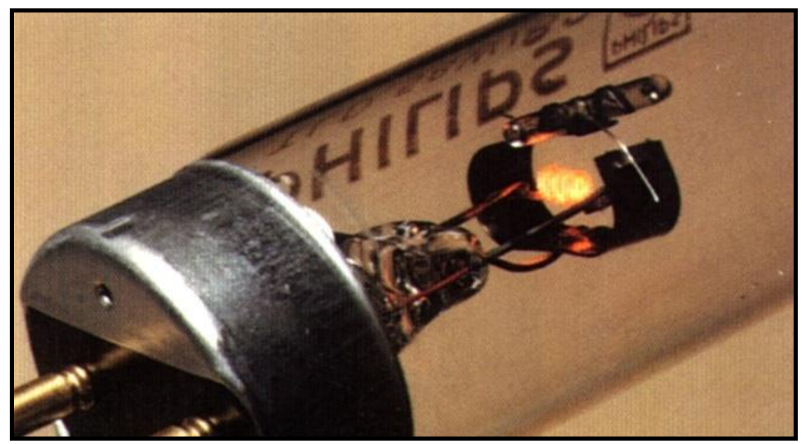
W_A = Work function (4.54 eV for tungsten)

kT = Thermal energy [J]

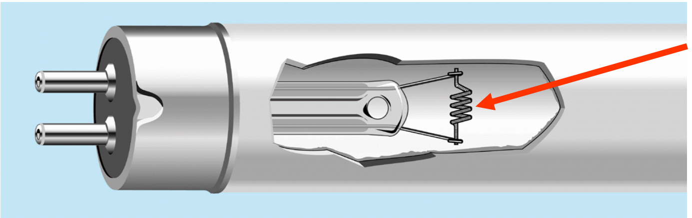
k = Boltzmann's constant = $1.38 \cdot 10^{-23}$ J/K

Probability that an electron leaves the surface is

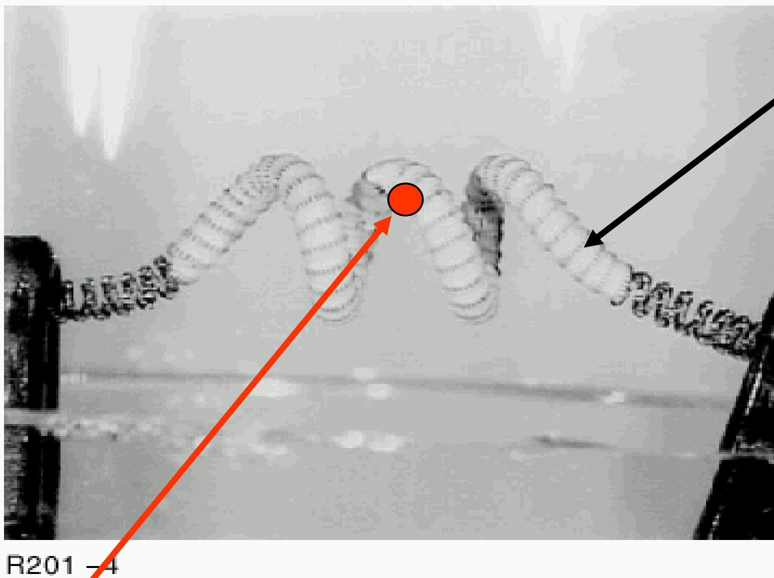
$$\sim e^{-\frac{W_A}{kT}}$$



5.9 Electrodes and Emitters



Electrodes made out of tungsten ⇒ Richardson: I = 0.5 A
⇒ T_W = 3100 K
⇒ Energy costs
⇒ Efficiency decreases

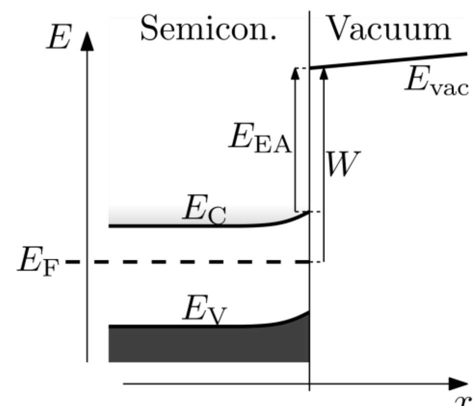


Arc operates at about 1 mm^2 area

Solution
Electrode is coated with an emitter
Emitter = Material with low work function

Material	Work function W_A [eV]
W	4.3 – 5.2
Ba	2.5
Sr	2.6
Ca	2.9
BaO	1.0 – 1.7
SrO	1.3 – 1.6
CaO	1.6 – 1.9
Y_2O_3	2.0 – 3.9

Ba → I = 0.5 A even at T_{Ba} = 1350 K



5.9 Electrodes and Emitters

Used emitter materials

Y_2O_3	High pressure sodium lamps
BaO/SrO/CaO	Na/Hg-low pressure lamps

Application as stable carbonates "triple mix"

1. Dip coating of the electrode with a suspension of the "triple mix"

2. Activation in the lamp: $MeCO_3 \rightarrow MeO + CO_2\uparrow$ (Me = Ca, Sr, Ba)

3. Operation of the lamp: $W + 6\ BaO \rightarrow Ba_3WO_6 + 3\ Ba$ (emitter)

5.10 Lamp Glass

General requirements

- Low cost (< 1 ct/lamp)
- High transparency
- Radiation stability (lower solarisation)
- Thermal stability

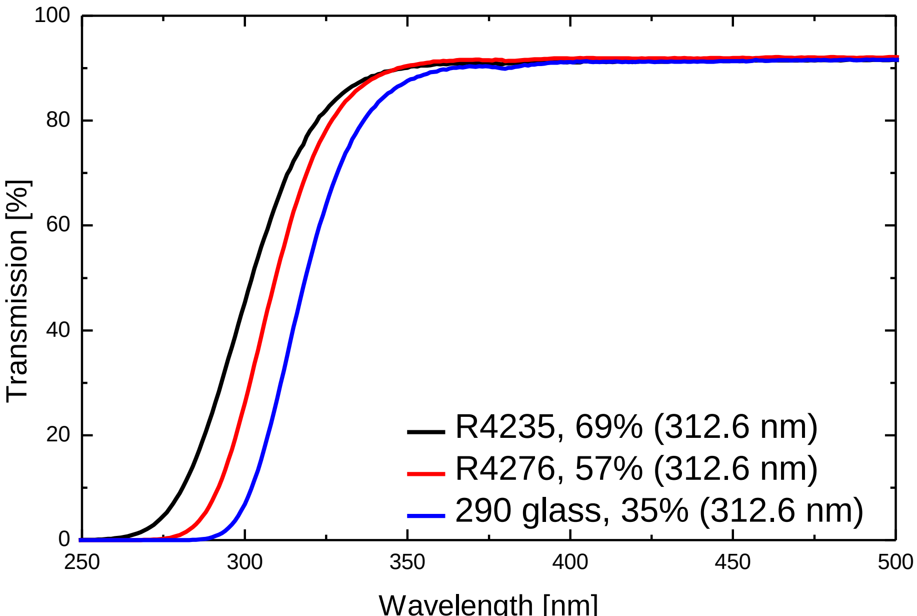
Composition of typical glasses for lamps

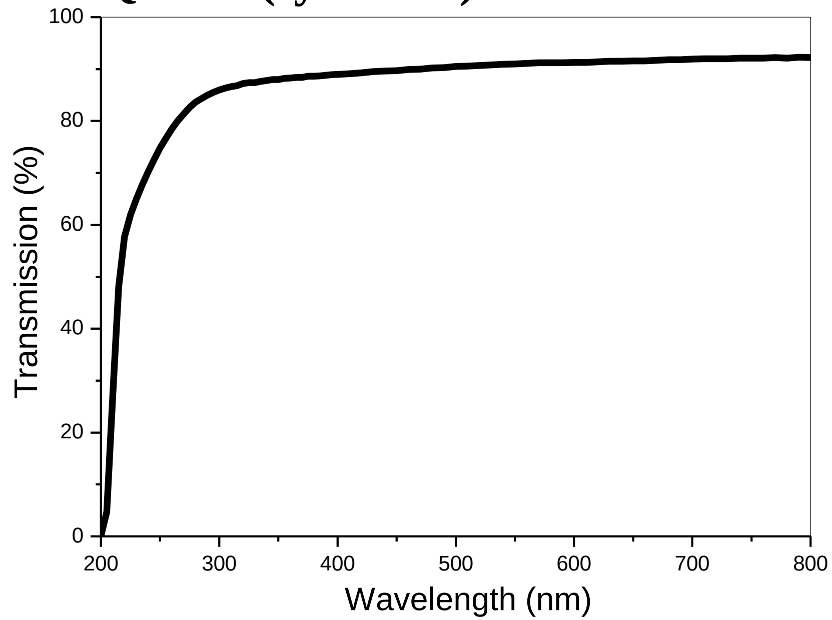
Komposition [%]	Natriumsilikat	Bleisilikat	Borsilikat	Aluminosilikat	Aluminoborat	Quarz
SiO_2	73	64	75	63	8	100
Na_2O	16	8	4		14	
K_2O	1	6	2			
CaO	5			9	6	
MgO	4					
Al_2O_3	1	2	1	16	24	
PbO		20				
B_2O_3			18		48	
Anwendung in	Glühlampen Fluor-eszenzlampen	Glühlampen Fluor-eszenzlampen	Hg-Hoch-drucklampen	Halogenlampen	Na-Nieder-drucklampen	UV-C Lampen

5.10 Lamp Glass

Transmission of lamp glasses

Lamp application	Absorption edge [nm]	Type of glass
Lighting	320	Sodium silicate glass
Tanning beds	300	Modified sodium silicate glass
Disinfection	220	Modified sodium silicate glass
Purification	170	Quartz (synthetic)

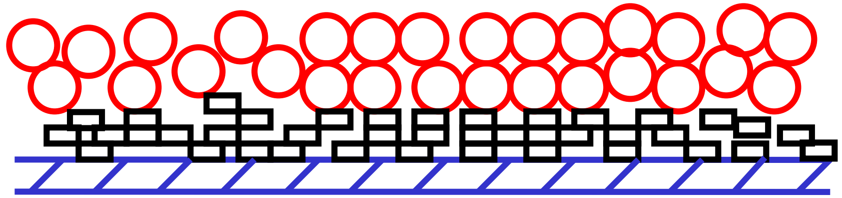




5.11 Coating

Basic structure

Schematic layer build-up



• Phosphor coating (phosphor + filling)

• Pre-coating (Al_2O_3, Y_2O_3, MgO, ...)

Dispersion medium	Butylacetat	Demineralised water
Binder	Nitrocellulose	Polyethylene oxide
Phosphor (blend)	Halophosphate	Halophosphates
	Color 80 phosphors Color 90 phosphors	Color 80 phosphors Color 90 phosphors
	UV-phosphors	
Adhesive agent	Alon-c (Al_2O_3)	$Ca_2P_2O_7$ or $Sr_2P_2O_7$
Dispersion agent	2-Methoxy-1-propanol	Polyacrylic acid

5.11 Coating

With fluorescent halophosphate (apatite)

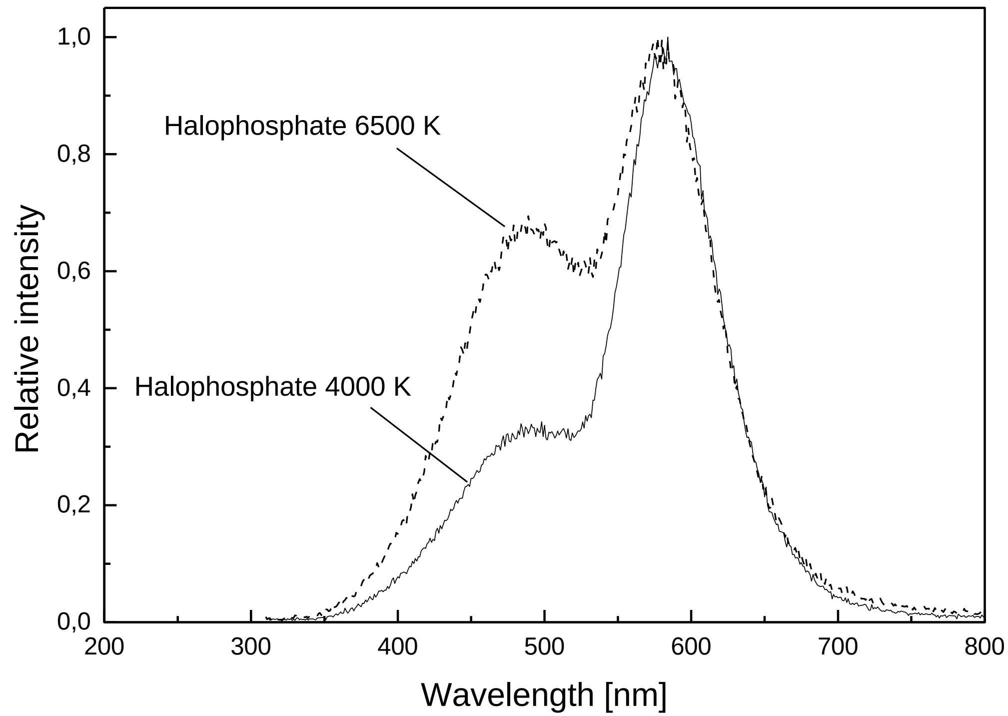
$Ca_5(PO_4)_3(F,Cl):Sb^{3+},Mn^{2+}$

$(Sb^{3+}) + h\nu_{254} \rightarrow (Sb^{3+})^*$

$(Sb^{3+})^* \rightarrow (Sb^{3+}) + h\nu_{480}$

$(Sb^{3+})^* + (Mn^{2+}) \rightarrow (Sb^{3+}) + (Mn^{2+})^*$

$(Mn^{2+})^* \rightarrow (Mn^{2+}) + h\nu_{580}$



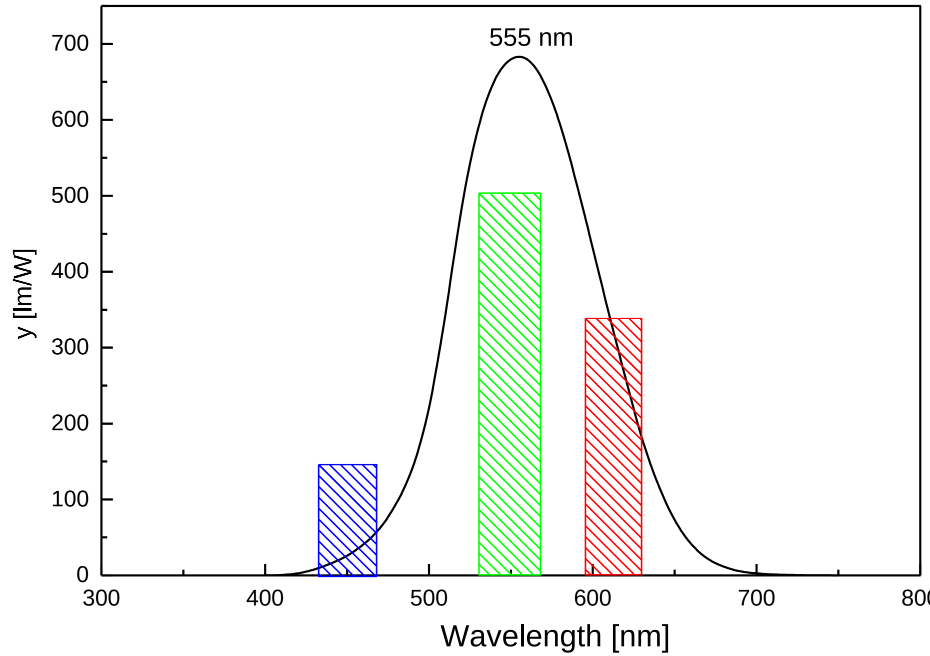
- **Sb/Mn mass ratio determines color temperature**
- **Light yield = 75 - 80 lm/W_{el}**
- **Colour rendering index CRI = 60**

5.11 Coating

With a trichromatic blend of phosphors (red-green-blue RGB)

Required positions of the emission bands

Blue	**440 - 460 nm**	**Eu^{2+}**
Green	**540 - 560 nm**	**Tb^{3+}**
Red	**590 - 630 nm**	**Eu^{3+}**

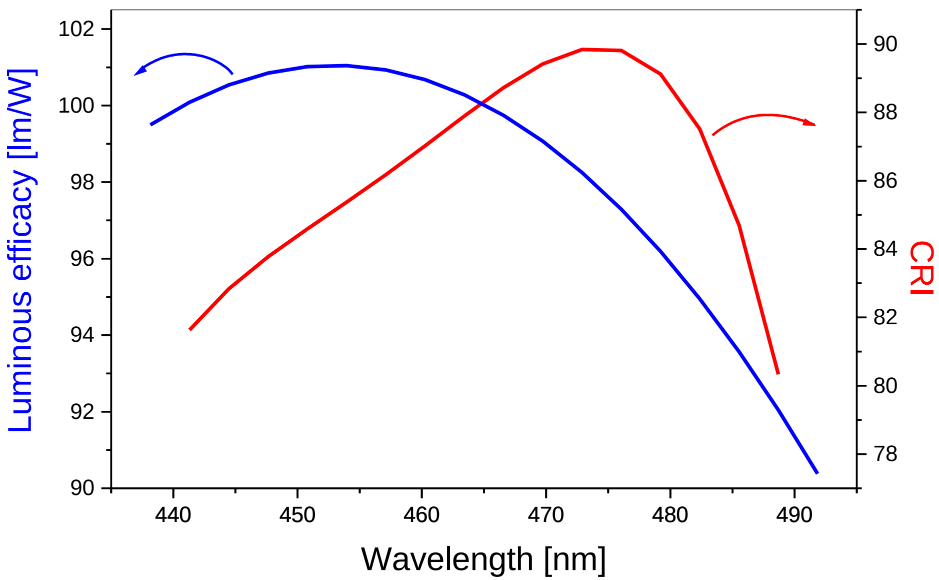


- **Light yield = 100 lm/W_{el}**
- **Color rendering index CRI = 80 – 85**
- **Lifetime L70 > 10,000 h → no fluorides, silicates, titanates, or zirconates**

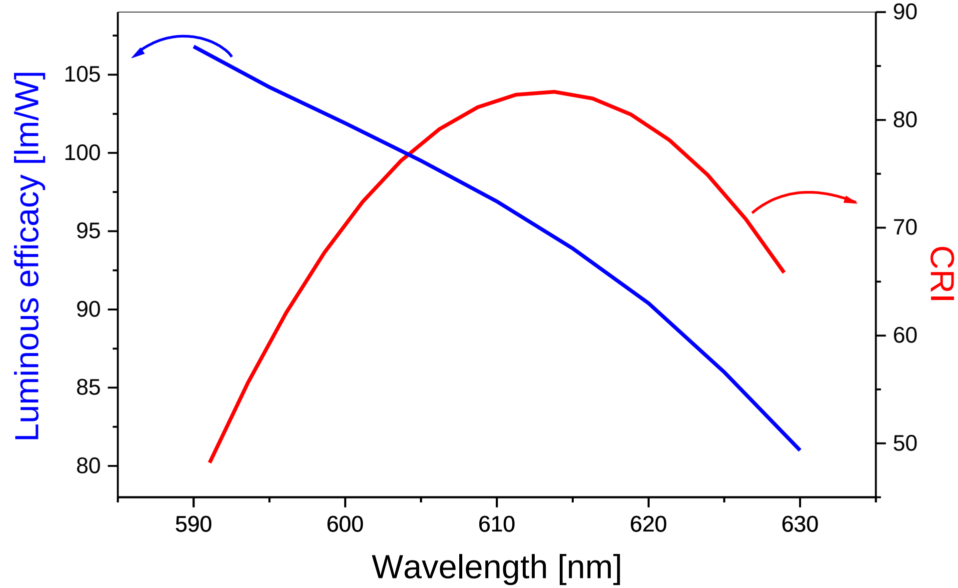
5.11 Coating

Lumen output of a trichromatic lamp

Blue + 545 nm + 610 nm



450 nm + 545 nm + Red

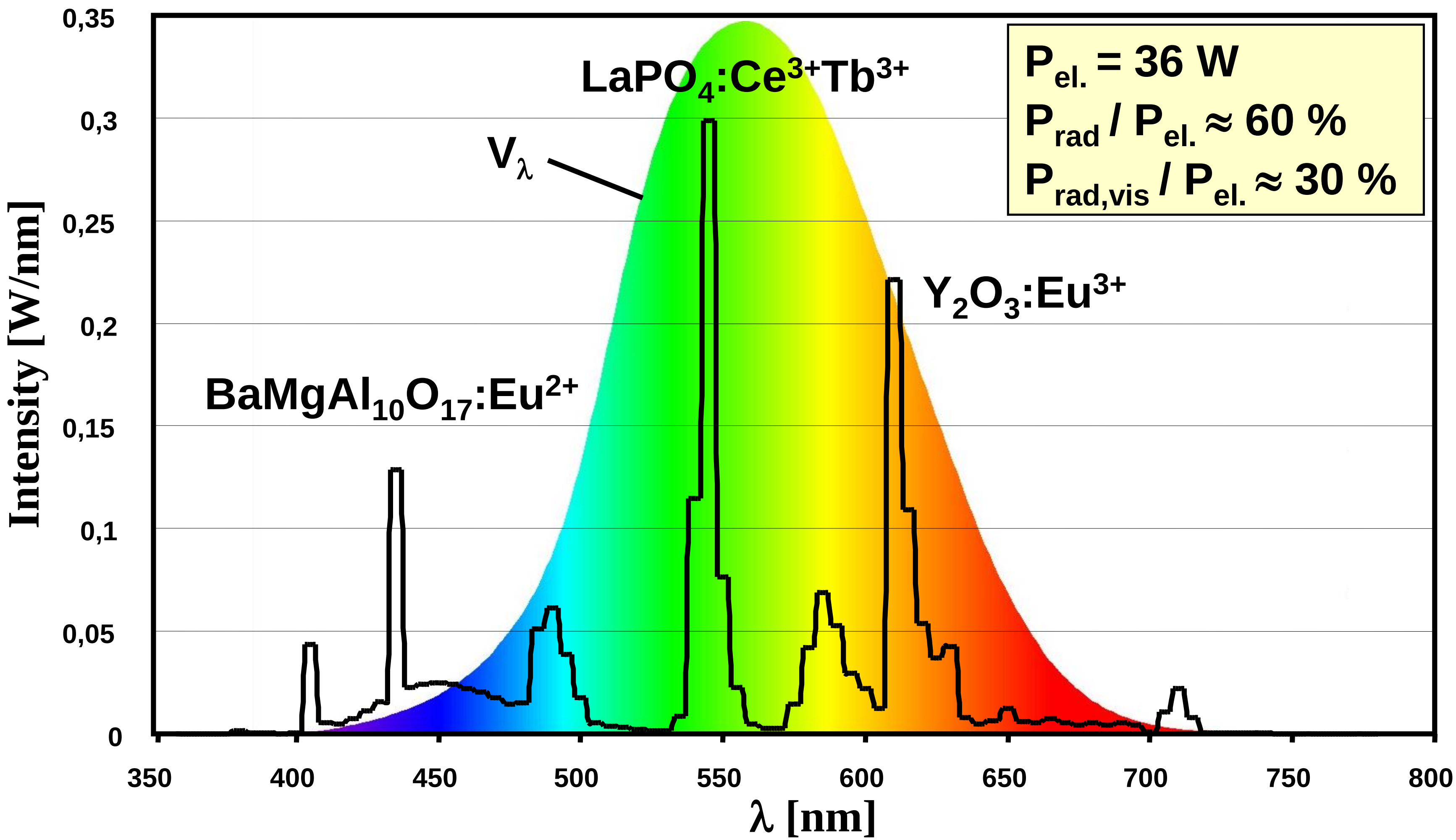


Optimum at about

- **Light yield 100 lm/W_{el}**
- **CRI = 80 - 85 (⇒ color 80 lamps)**

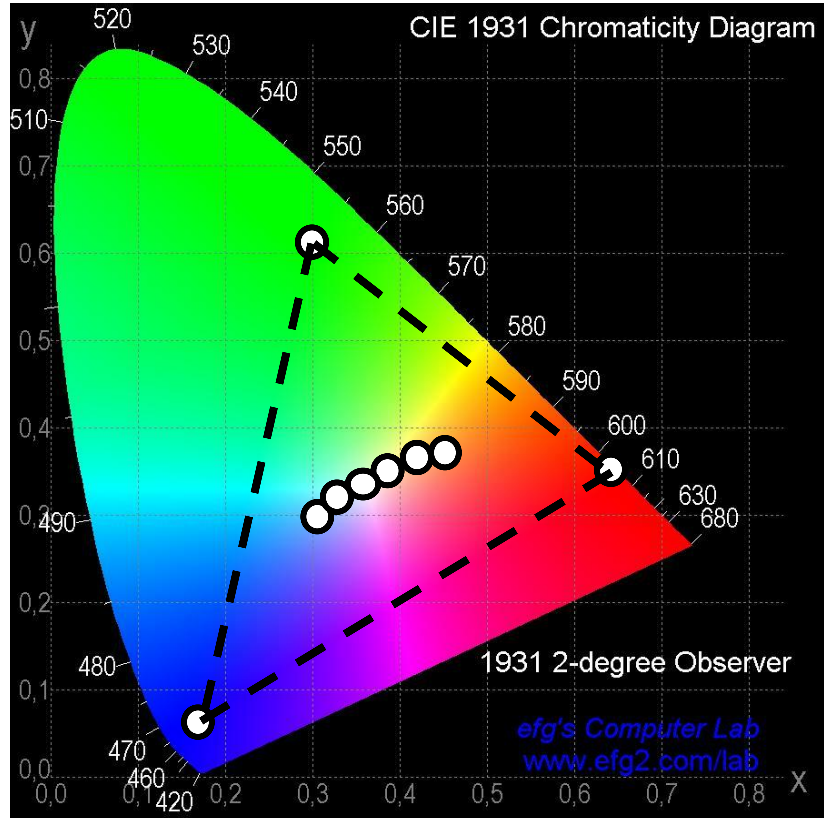
5.11 Coating

Emission spectrum of a trichromatic lamp



5.11 Coating

Color points of trichromatic lamps



Color temperature
2700 - 6500 K

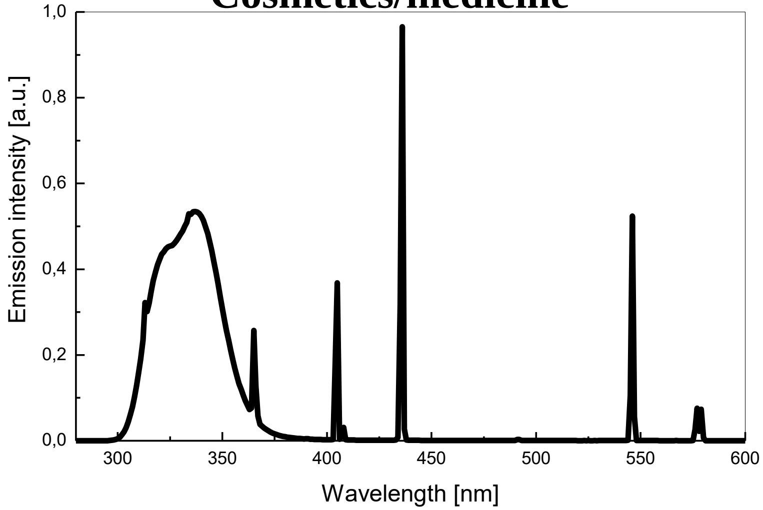
Only green and red phosphor
2700 K

RGB phosphor mixture
2700 - 6500 K depending on the mixing ratio

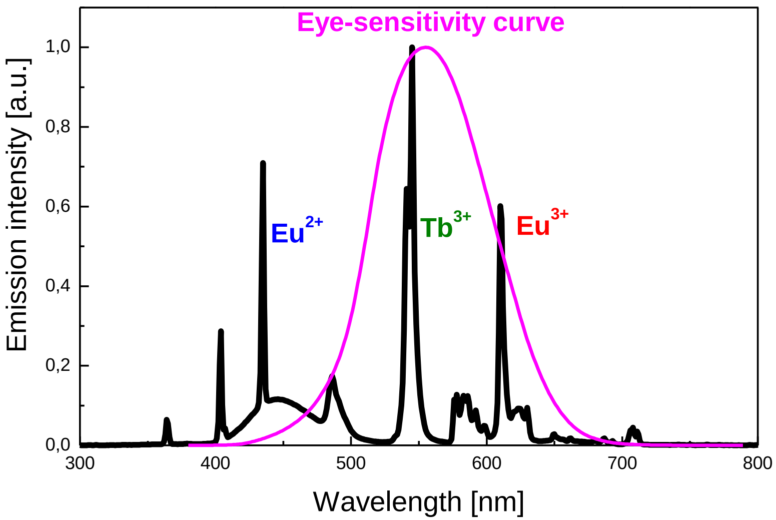
Color point
Is adjusted so that it lies close to the black body-line

5.11 Coating

Cosmetics/medicine



Lighting

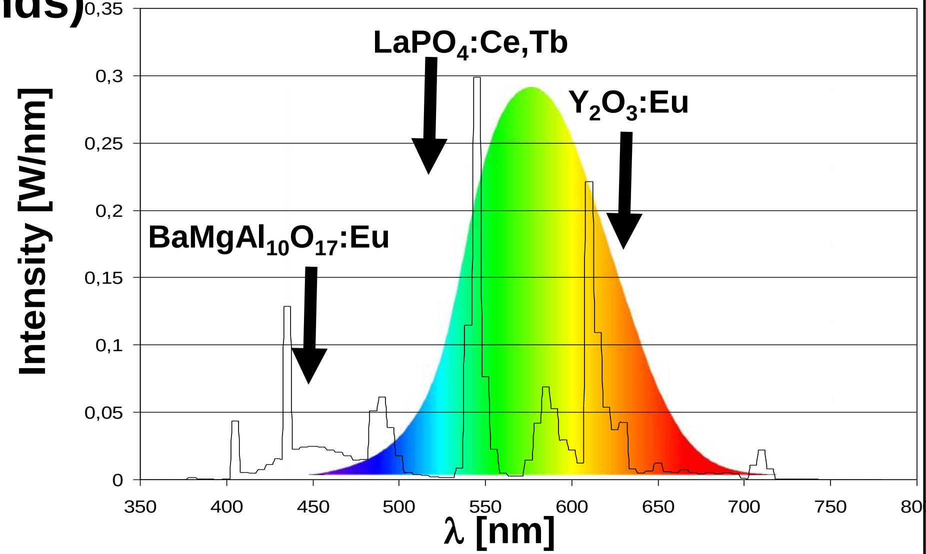


Lanthanide ions	s^2-/transition metal ions
Ce^{3+}	Pb^{2+}
$LaPO_4$:Ce	$Sr_2MgSi_2O_7$:Pb
YPO_4:Ce	$BaSi_2O_5$:Pb
Eu^{2+}	Sb^{3+}
$Sr_5(PO_4)_3$(F,Cl):Eu	$Ca_5(PO_4)_3$(F,Cl):Sb
$BaMgAl_{10}O_{17}$:Eu	
Tb^{3+}	Mn^{2+}
$LaPO_4$:Ce,Tb	$BaMgAl_{10}O_{17}$:Eu,Mn
$CeMgAl_{11}O_{19}$:Tb	Zn_2SiO_4:Mn
$LaMgB_5O_{10}$:Ce,Tb	$Ca_5(PO_4)_3$(F,Cl):Sb,Mn
	$LaMgB_5O_{10}$:Ce,Tb,Mn
Eu^{3+}	Mn^{4+}
Y_2O_3:Eu	$Mg_4GeO_{5.5}$F:Mn
(Y,Gd)(V,P)O_4:Eu	

5.11 Coating

Color rendering (trichromatic phosphor blends)

- Fairly good color rendering → $R_a = 80 – 85$
- Lack of radiation in the
  - cyan 500 – 535 nm
  - yellow 560 – 580 nm
  - deep red > 610 nm

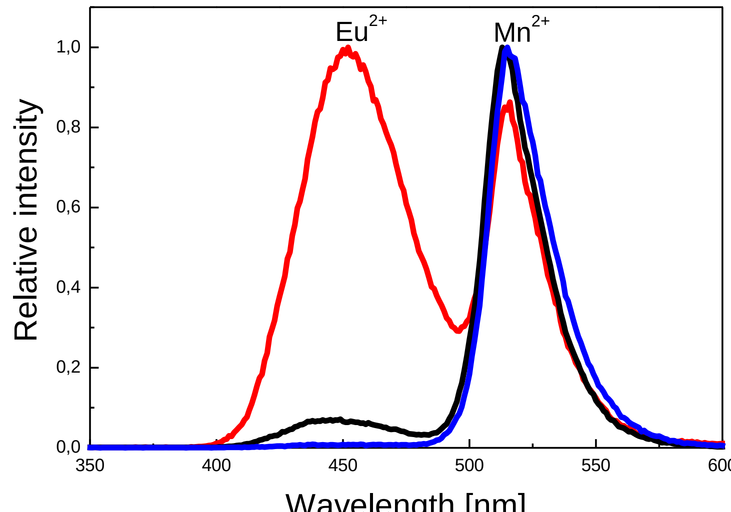


Consequences

- Additional broad band phosphors
  - $Sr_4Al_{14}O_{25}$:Eu
  - $Ca_5(PO_4)_3(F,Cl)$:Sb,Mn
- Modification of applied trichromatic phosphors
  - $BaMgAl_{10}O_{17}$:Eu → $BaMgAl_{10}O_{17}$:Eu,Mn
  - $GdMgB_5O_{10}$:Ce,Tb → $GdMgB_5O_{10}$:Ce,Tb,Mn

→ R_a ~ 88 – 90, but luminous efficiency ~ 60 – 80 lm/W

Emission spectra of $BaMgAl_{10}O_{17}$:Eu,Mn



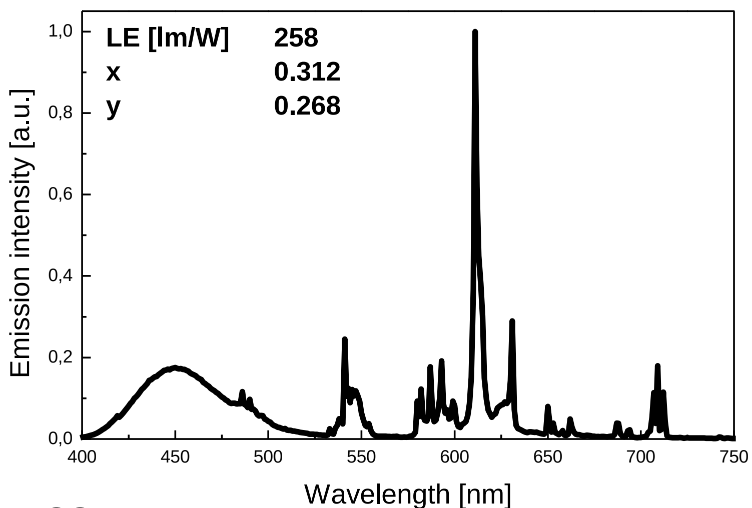
Typical blend *(Osram Patent EP1306885)*	
$Sr_4Al_{14}O_{25}$:Eu	28.5 wt-%
$(Ce,Gd)(Zn,Mg)B_5O_{10}$:Mn	28.5 wt-%
$Ca_5(PO_4)_3(F,Cl)$:Sb,Mn	26.9 wt-%
$BaMgAl_{10}O_{17}$:Eu	6.1 wt-%
$CeMgAl_{11}O_{19}$:Tb	10.0 wt-%

5.11 Coating

Fluorescent lamps with high color rendering

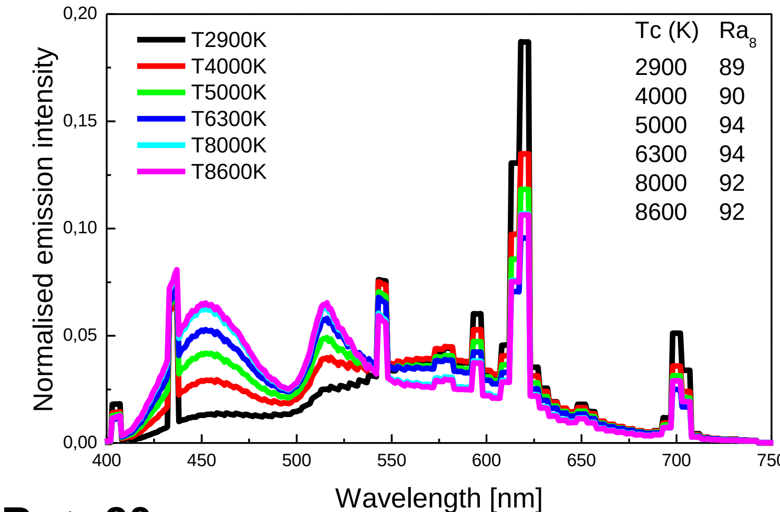
Application of $BaMgAl_{10}O_{17}$:Eu,Mn

Emission spectrum of a mixture of $BaMgAl_{10}O_{17}$:Eu,Mn + $LaPO_4$:Ce,Tb + Y_2O_3:Eu at 254 nm excitation



Ra ~ 88

Measured emission spectra of fluorescent lamps with a mixture of $BaMgAl_{10}O_{17}$:Eu,Mn + $Y_3Al_5O_{12}$:Ce + YVO_4:Eu (Al_2O_3 coated)



Ra > 90

5.12 Hg-Take up

The low-pressure mercury discharge requires for optimum operation 50 µg Hg

Standard filling: 10 - 20 mg / lamp

Origin: Hg consumption by lamp components → Hg take-up

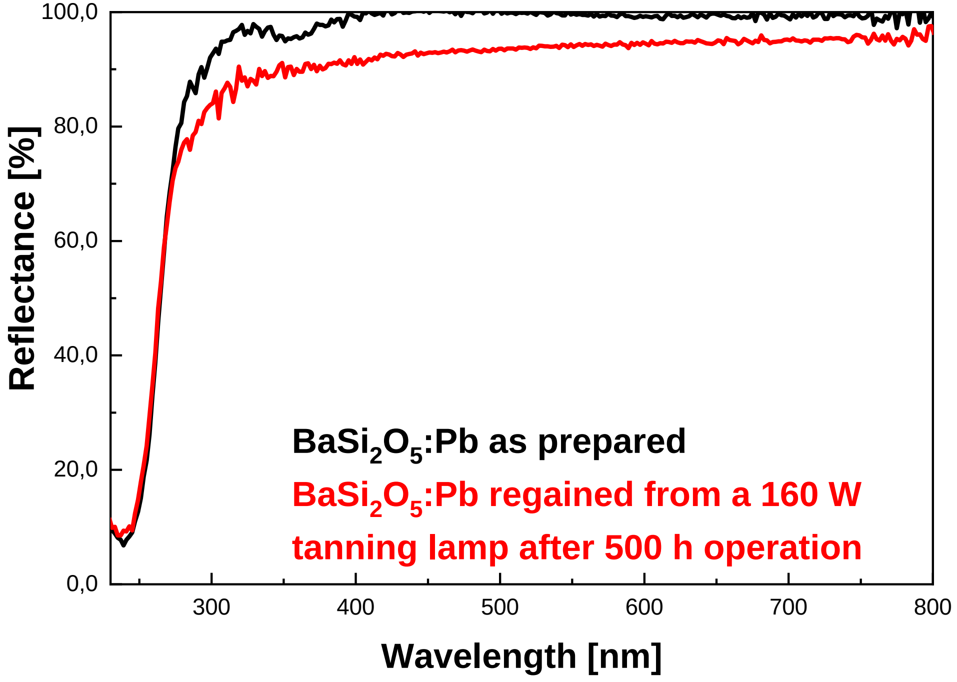
Lamp component	Hg consumption in 10000 h (4 ft TL Lamp)
• Glass	5 mg
• Phosphor	0.1 - 2.0 mg
• Electrodes	0.1 - 1.0 mg

⇒ Hg higher doses to compensate Hg consumption during the specified life time

5.12 Hg-Take up

Hg adsorption by glass and phosphor leads to the graying of the phosphor and to reduction of the discharge efficiency

Reflection spectrum of $BaSi_2O_5$:Pb



Material	IEP [pH]
WO_3	2.0
SiO_2/Glass	3.0
$BaSi_2O_5$	3.0
TiO_2	5.6
ZrO_2	6.0
$LaPO_4$	7.8
Al_2O_3	9.0
Y_2O_3	9.0
ZnO	9.4
Yb_2O_3	9.7
La_2O_3	10.4
MgO	11.0

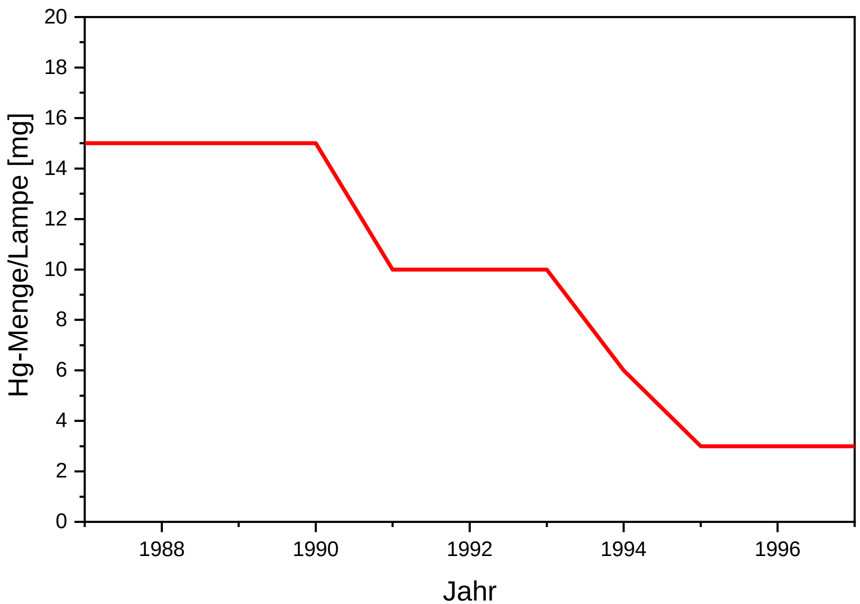
Hg/Hg^+- take up decreases with increasing electron density of the anions (alkalinity), i.e. with the increase in reactivity toward electrophilic agents, such as CO_2, H^+, Hg^+

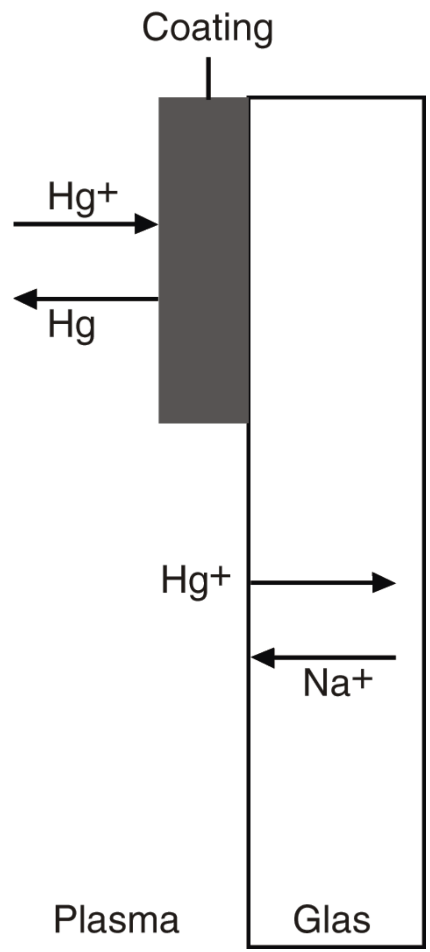
5.12 Hg-Take up

Measures to reduce Hg-consumption

- **Particle Coating**
- **Glass Coating**

With Y_2O_3 or Al_2O_3 (low Hg-take up)





3 mg Hg/lamp with Y_2O_3-glass coating

5.13 Compact Fluorescent Lamps

Compact fluorescent Lamps, also called energy saving lamps, are fluorescent tubes consisting of several (bent) tubes with an integrated ballast

Trends

- **Miniaturization**
- **Incandescent lamp form (outer envelope with a scattering layer)**

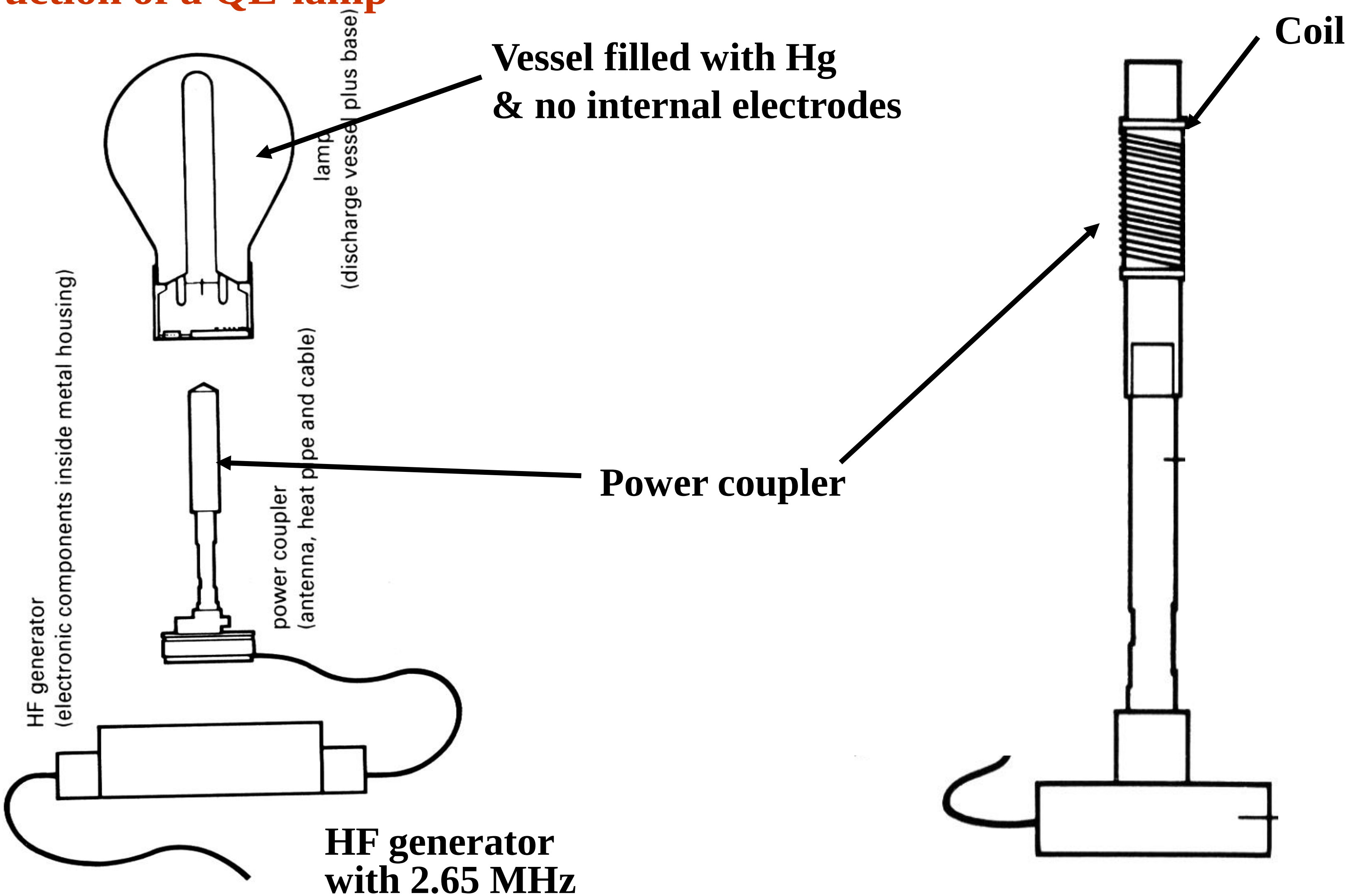
„incandescent look-a-like“

5.14 Inductively Driven Lamps

QL (Philips), Endura (Osram) lamps have an extremely long service life due to the lack of internal electrodes (light production as well as in conventional fluorescent lamps)

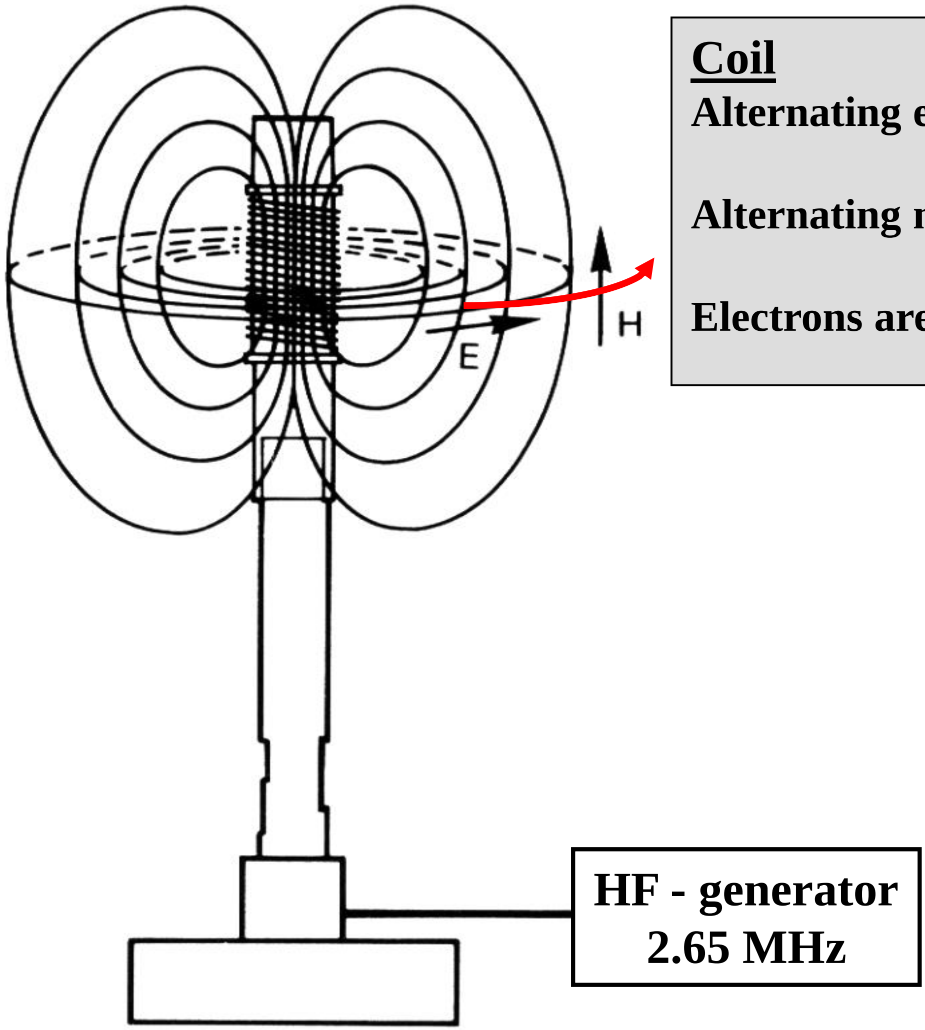
5.14 Inductively Driven Lamps

Construction of a QL-lamp



5.14 Inductively Driven Lamps

Energy in-coupling in a QL-lamp

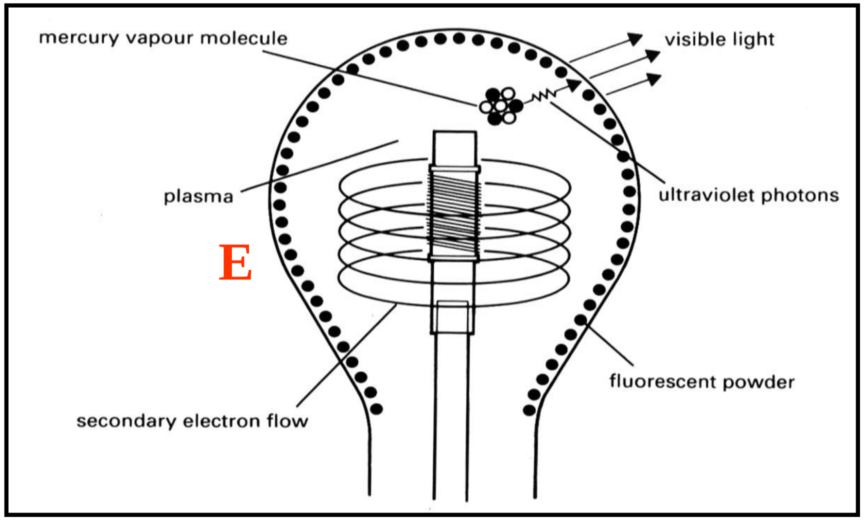


Coil

Alternating electric field ⇒ alternating magnetic field (H)

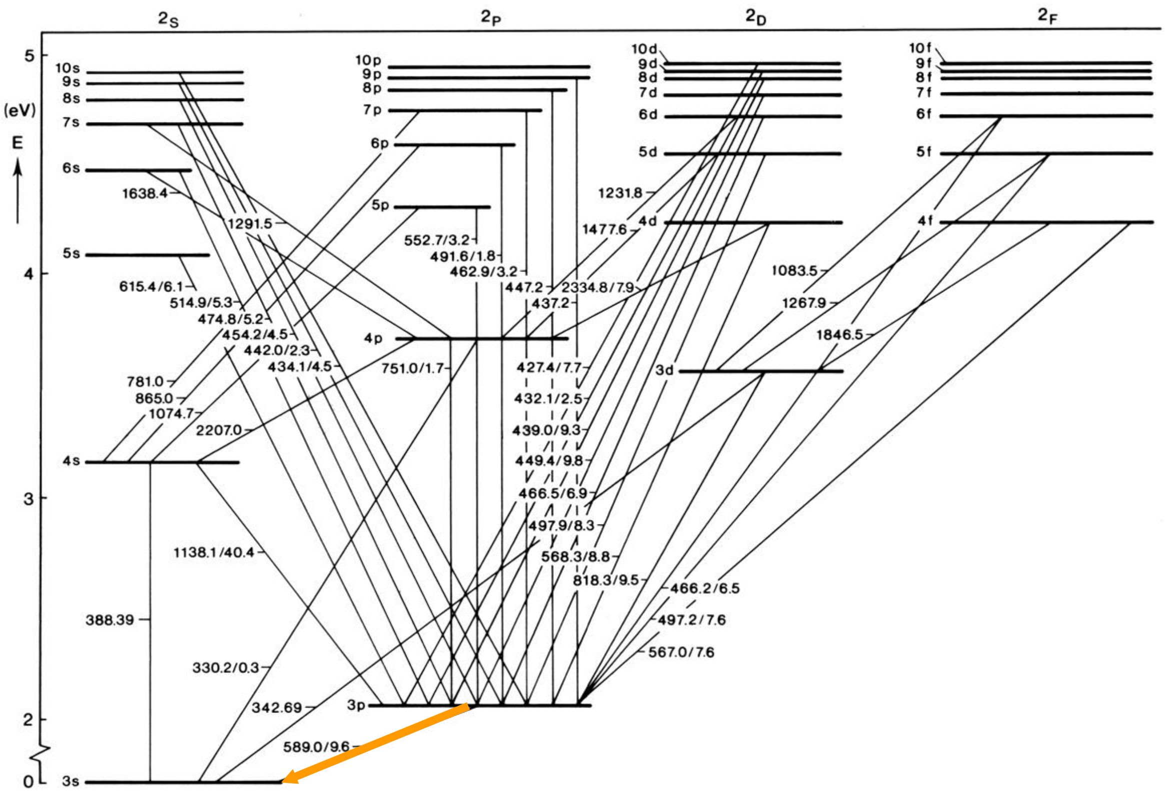
Alternating magnetic field (H) ⇒ alternating electric field (E)

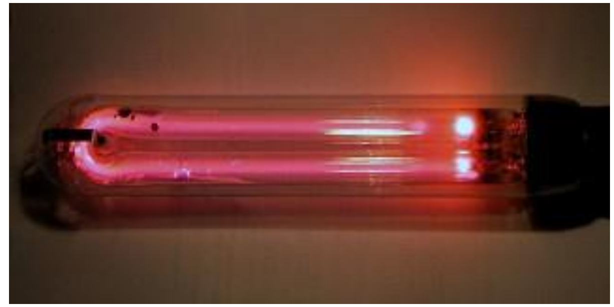
Electrons are accelerated in this field E



5.15 Low Pressure Sodium Gas Discharge Lamps

Energy level diagram of the Na atom





Time after ignition (sublimation of Na)

„Yellow Na-D lines“ (Fraunhofer line)

[Ne]3p¹ ($^2P_{1/2, 3/2}$) – [Ne]3s¹ ($^2S_{1/2}$)

Interconfiguration transitions

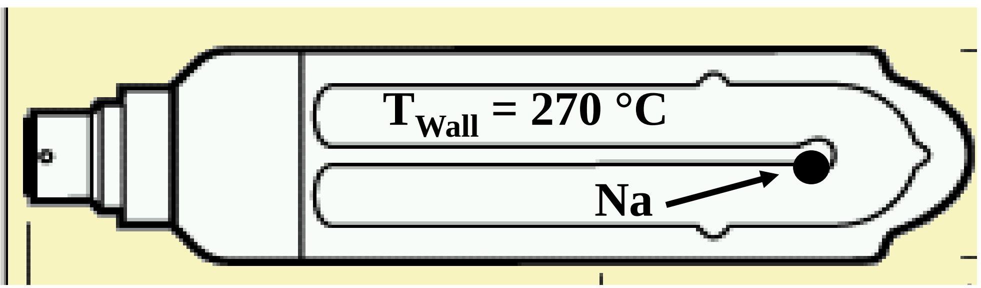
Na low pressure discharge: Main emission lines at 589.0 nm, 589.6 nm, 781.0 nm, and 818.3 nm

5.15 Low Pressure Sodium Gas Discharge Lamps

General construction

- Filling element Na with operating pressure of 1 Pa
- Buffer gas: Argon or Krypton
- No phosphor
- Inner and outer glass envelope (bulb)

High luminous efficacy ~ 200 lm/W
but poor color rendering R_a = - 50



Outer bulb with heat-reflective coating (→ SnO_2)

*Plate 8 Relative spectral energy distribution of a low pressure sodium lamp, with human eye sensitivity curve V(λ).
The two yellow resonance lines of the low pressure sodium discharge at 589 and 589.6 nm lie close to the eye sensitivity maximum at 555 nm, the cause of the high efficacy of this lamp type.*

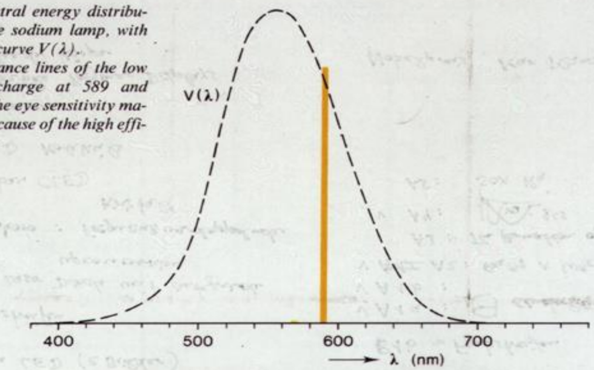


Plate 9 Motorway lighting with low pressure sodium lamps.

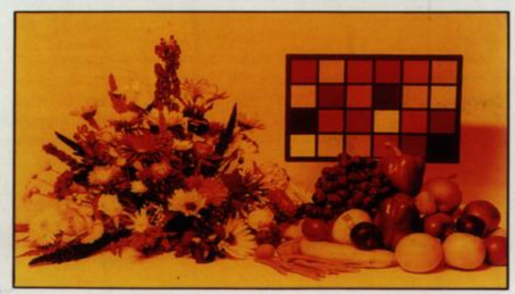


Plate 10 Colour photograph of illumination with a low pressure sodium lamp. Differences in colour are visible only as contrasts in grey.