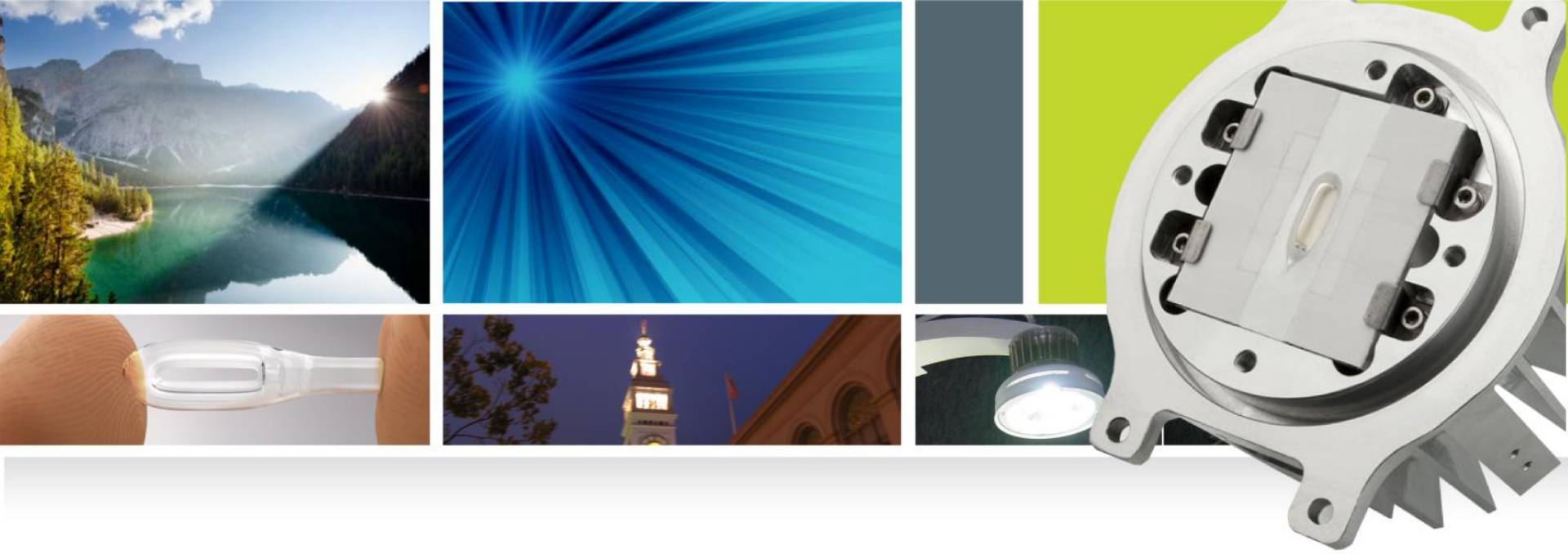

High Power RF Plasma Light Sources for Industrial Applications

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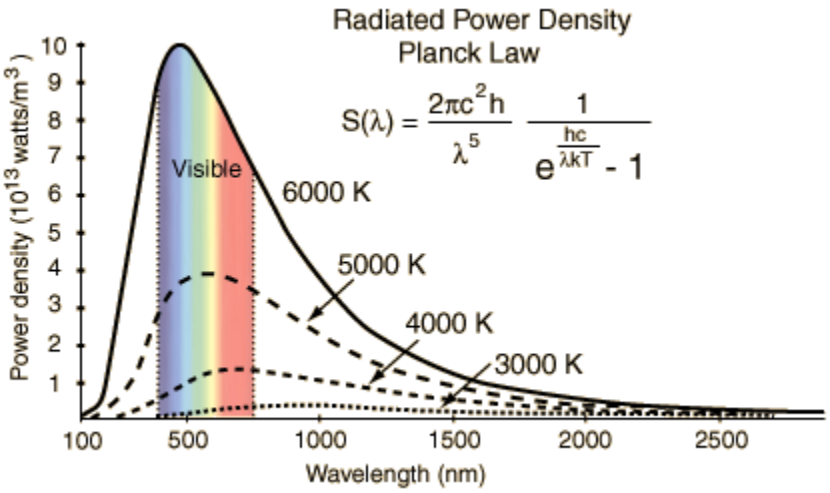
Thin Film Users Group, Display and Lighting. 7/15/14

LUXIM®

Conventional Light Sources

- Incandescent sources work by heating up a metal filament (tungsten typically) to the point where it begins to glow visibly
- Light emitted is due to blackbody radiation of the filament
- Addition of halogens help extend lifetimes, but efficacy hasn't improved much in the last 100 years
- Ironically still has many industrial uses today (mostly as IR heaters)
- Blackbody radiator has perfect color rendering (CRI ≡ 100)
- Efficacy inherently limited by melting point of tungsten (3400C).

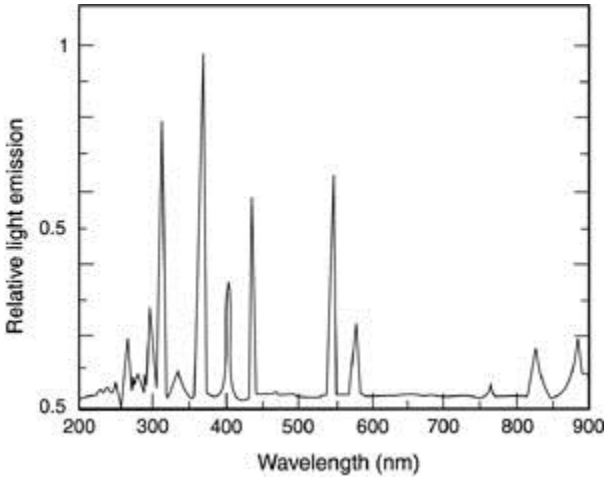
  At typical operating temperatures (~2500C), nearly 95% of energy is converted into IR radiation.



LUXIM

Discharge sources

- First discharge lamp for general lighting invented in 1901
- Produced 3-4x the luminous efficacy compared to an incandescent lamp
- Color rendering was terrible due to the few number of resonance lines in the red region
- Had “side effect” of producing UV radiation
- By 1910 they were being used for water purification…



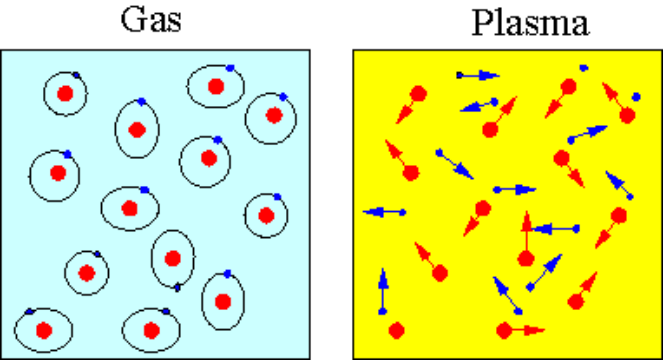
Electric discharge lamp invented by Hewitt in 1901

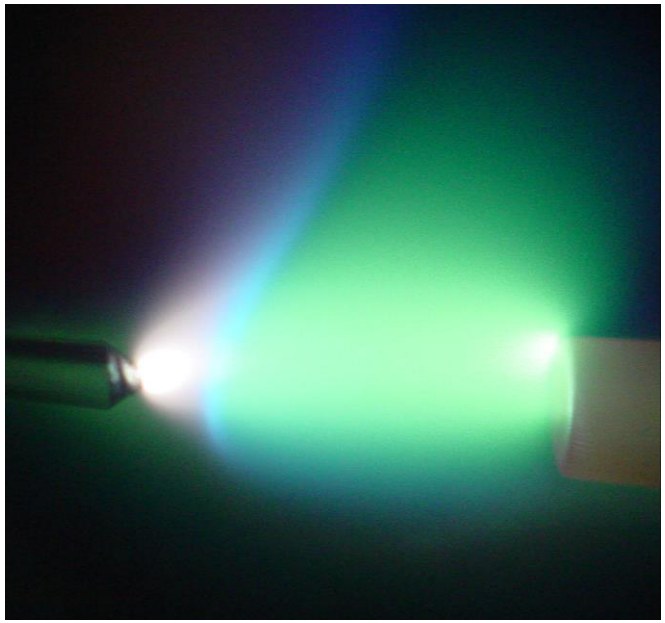
Modern UV germicidal lamp

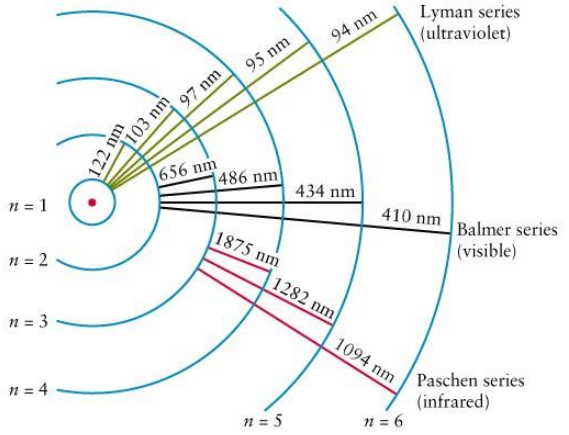
LUXIM

Discharge sources

- Work by ionizing a gas (plasma) in a sealed glass envelope between two electrodes (also typically tungsten)
- Electric field imparts energy to the plasma by accelerating free electrons which then collide with ions
- Collision either excites more electrons, or recombines with ion, releasing a photon
- Photon energy is characteristic of the element's allowed transition states, hence spectrum is unique to the elements in the plasma
- Spectrum is also a function of the pressure in the glass envelope
- Generally, lower pressures allow for longer electron free paths, producing higher energy collisions, and hence higher energy photons (blue shifted)
- Radiated spectrum is much more efficient compared to incandescent sources, since radiated spectrum isn't constrained by blackbody curve, but defined by transition states of the elements in the plasma

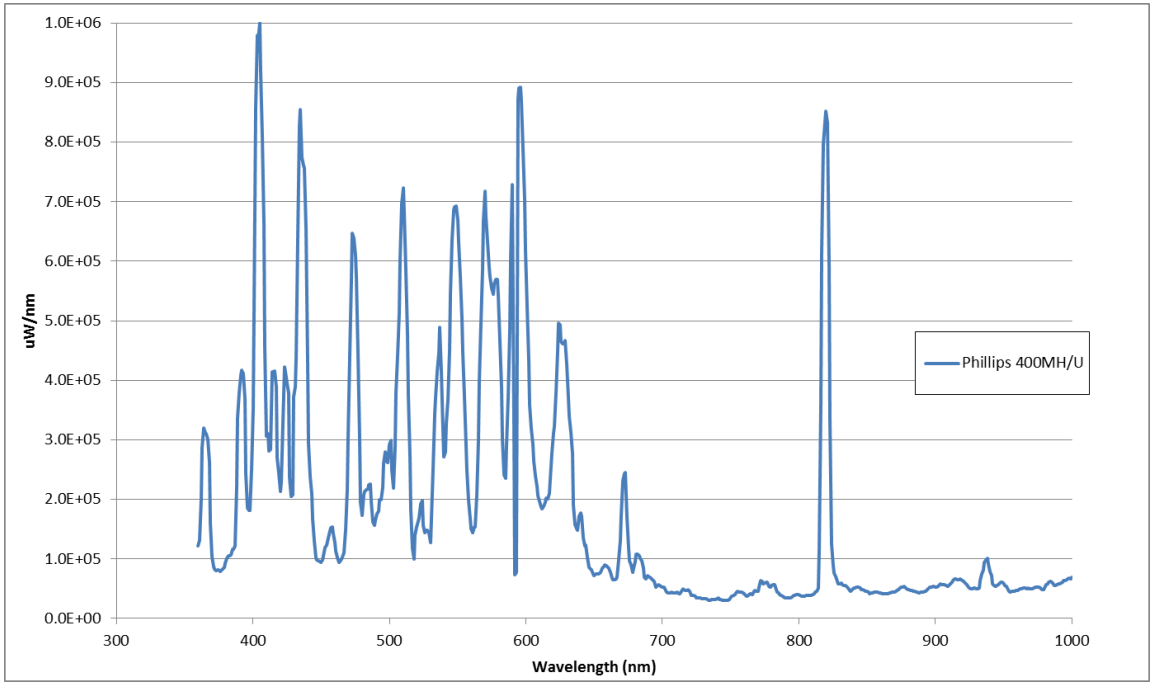


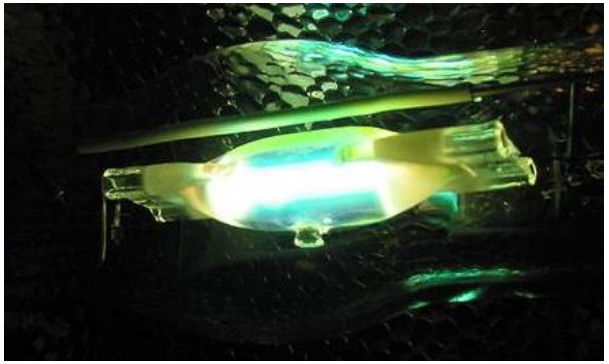




Metal Halide discharges

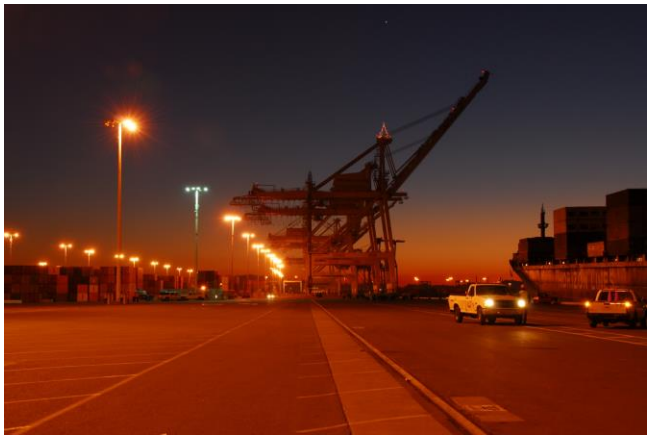
- To help increase efficacy and color rendering, metal halide salts were added
- Transition metals provide a large number of potential energy level transitions, and hence a large number of emission lines, able to fill in some of spectrum
- Spectrum can be customized for specific applications (general lighting, UV curing, high color rendering, hydroponics)

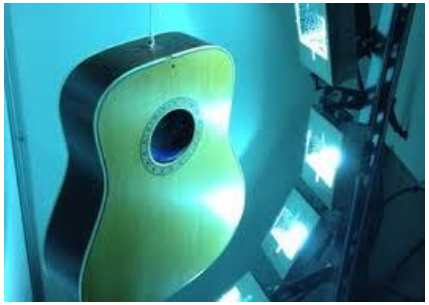




Metal Halide discharges

- Most high power industrial applications use these types of lamps



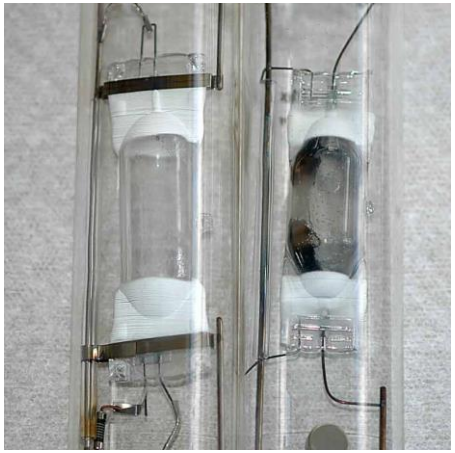


Metal Halide discharges

Major Technical Design Limitations:

- Choice of metal halide dose limited
- Preferred transition levels must be within desired photon energy range (~2-3eV for VIS)
- Certain metals react with the quartz vessel at high temperatures, causing devitrification of the silica.
- Other metals attack the tungsten electrodes, causing blackening of the walls
- High temperature at arc attachment points causes tungsten to slowly vaporize and redeposit on the walls.
- Metal/quartz hermetic seal inherently problematic due to CTE materials mismatch
- Principle root causes of failure is electrode related:
  - Metal/quartz seal failure
  - Reduced output due to wall blackening

Hermetic seal failure

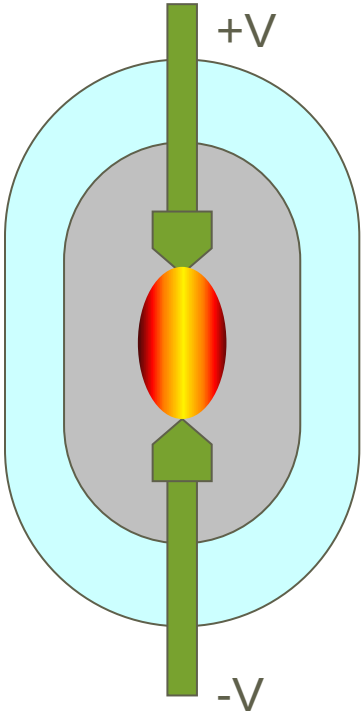


Wall blackening

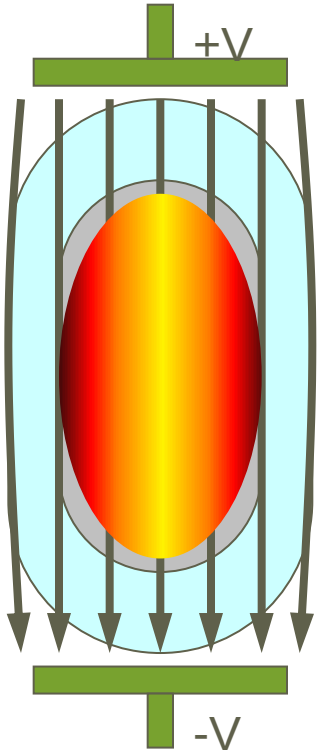
Electrodeless Solutions

Basic Principle:

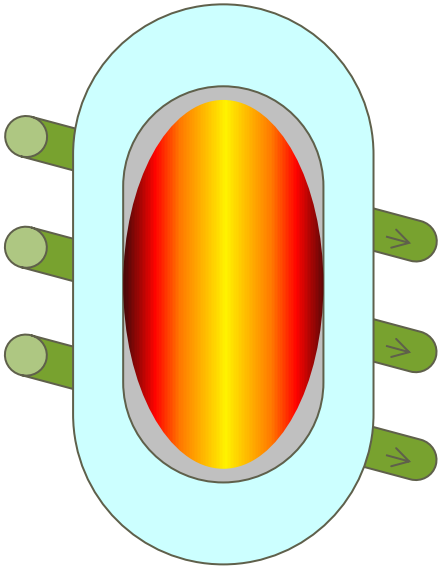
- Couple energy to plasma with high frequency E-field (or B-field)
- Quartz wall acts as a dielectric barrier
- Only limit to lifetime is quartz durability and drive electronics



HID



CCP



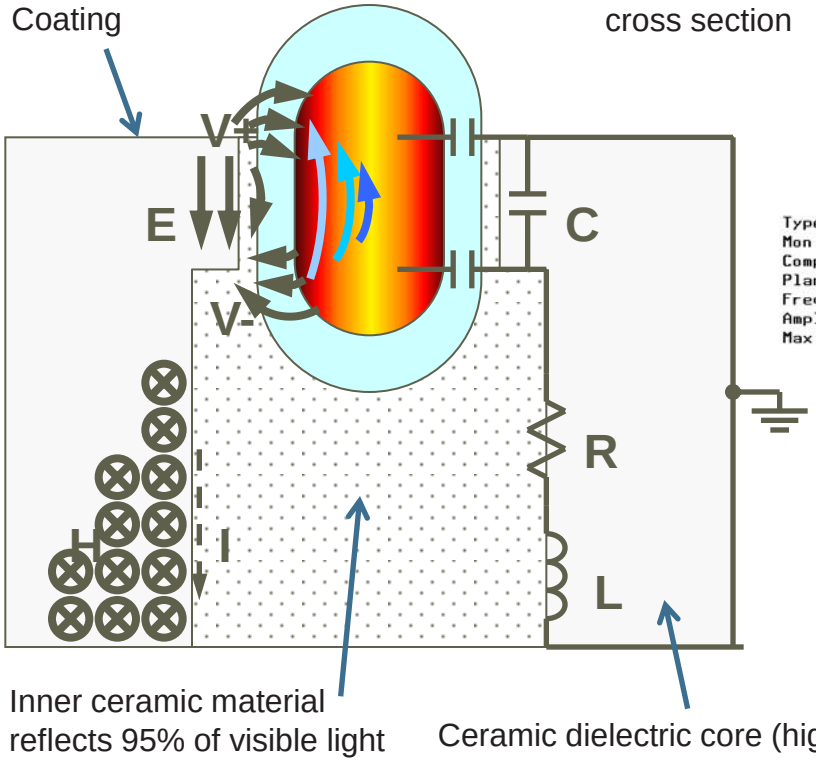
ICP

Electrodeless Solutions

- RF resonant cavity used to match impedance of plasma to 50Ω
- No “cathode fall” between electrode and plasma (no longer have to liberate electrons from metal each cycle), results in ~20% boost in efficiency
- No degradation in output due to tungsten deposition (wall blackening)

Conductive Coating

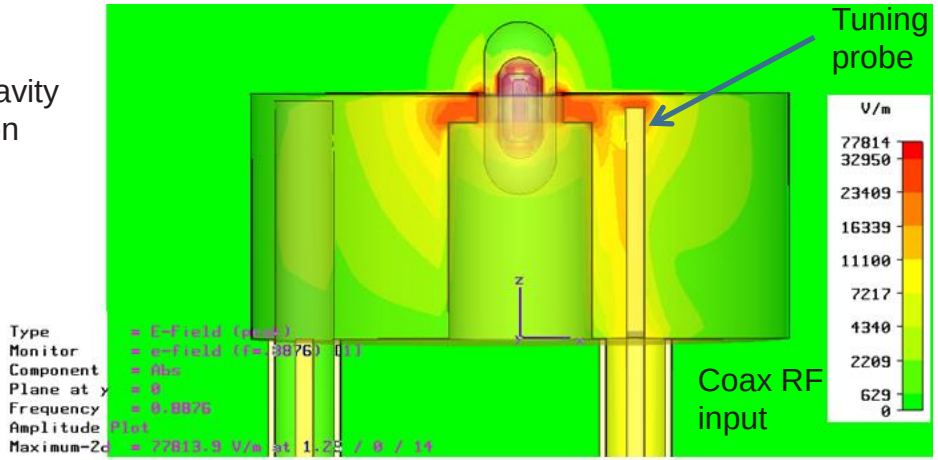
Resonant cavity cross section

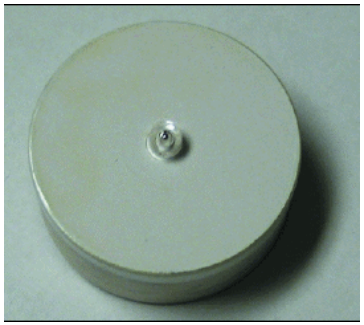


Inner ceramic material reflects 95% of visible light

Ceramic dielectric core (high Q)

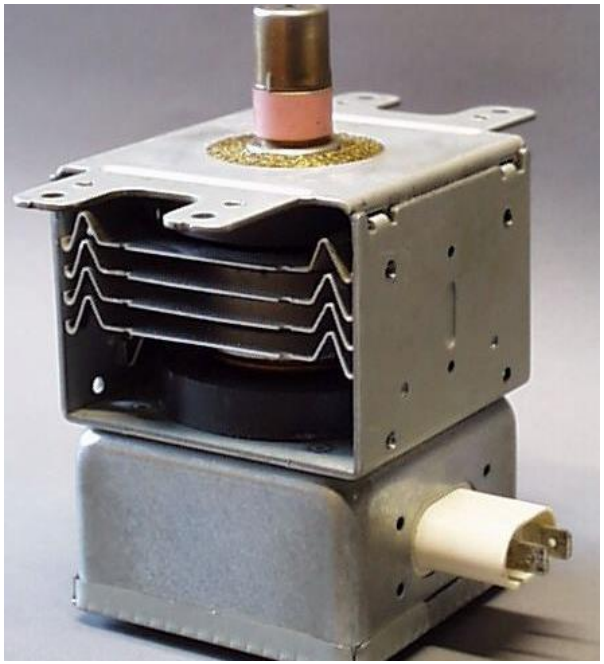
E-field simulation





Drive Electronics

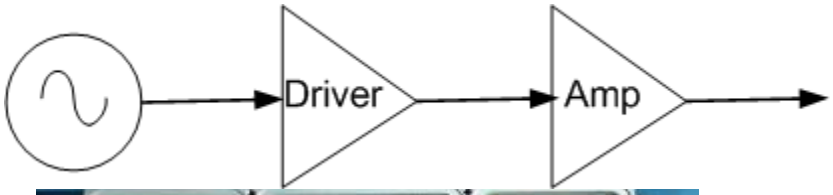
Magnetron



Magnetrons commonly used to drive RF plasma sources have a few issues:

- Frequency not tunable
- Inefficient
- Require forced cooling
- Rigid waveguide needed
- Short lifetime
- Large and bulky

Solid State RF driver with integrated controls



Integrated Solid State driver with on-board microcontroller

- Controller automatically detects emitter's resonant frequency and tunes output to match
- Variable Output
- Connects to emitter with flexible coax cable
- Long lifetimes

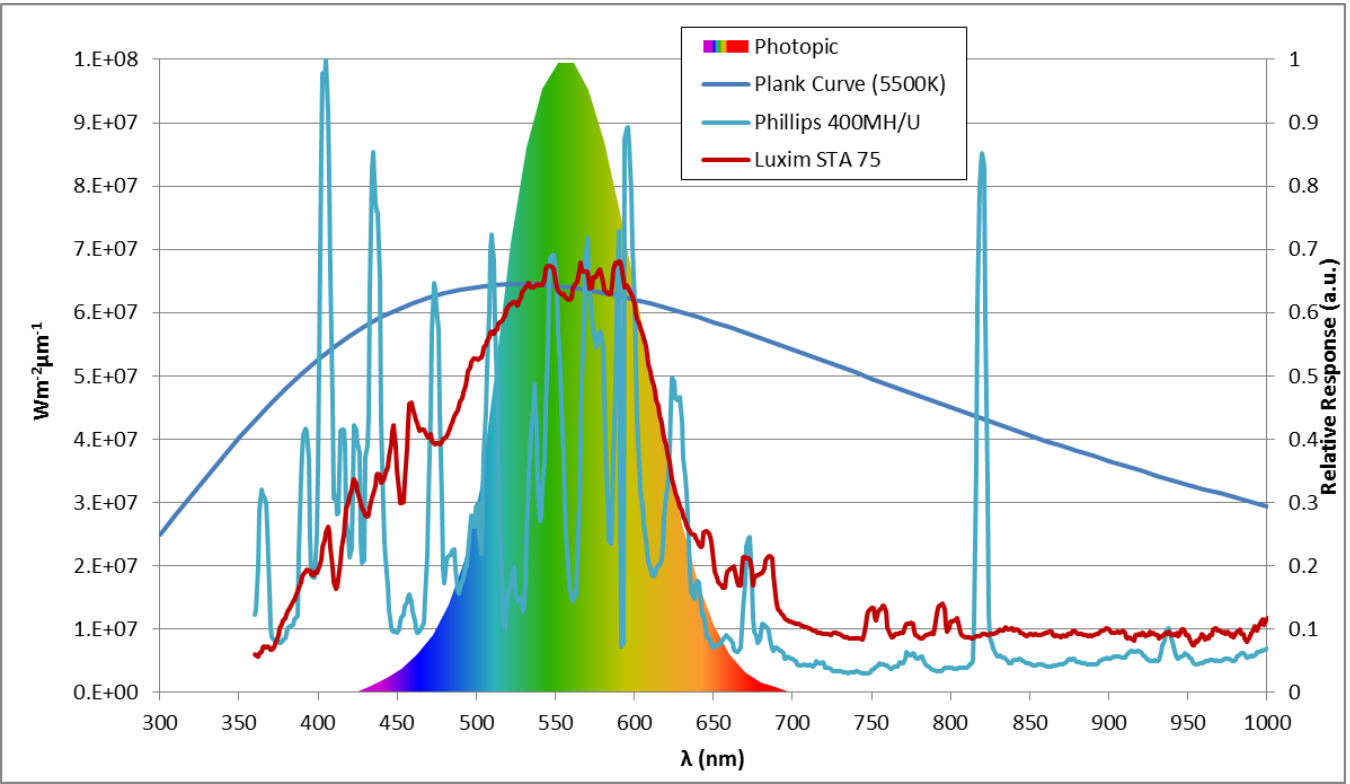
Spectral Comparison

General Lighting Comparison:

- Higher lumen efficiency than standard metal halide lamps of same wattage
- Better color rendering
- Spectrum closely matched to photopic curve (human eye response)

Spectrum is nearly continuous!

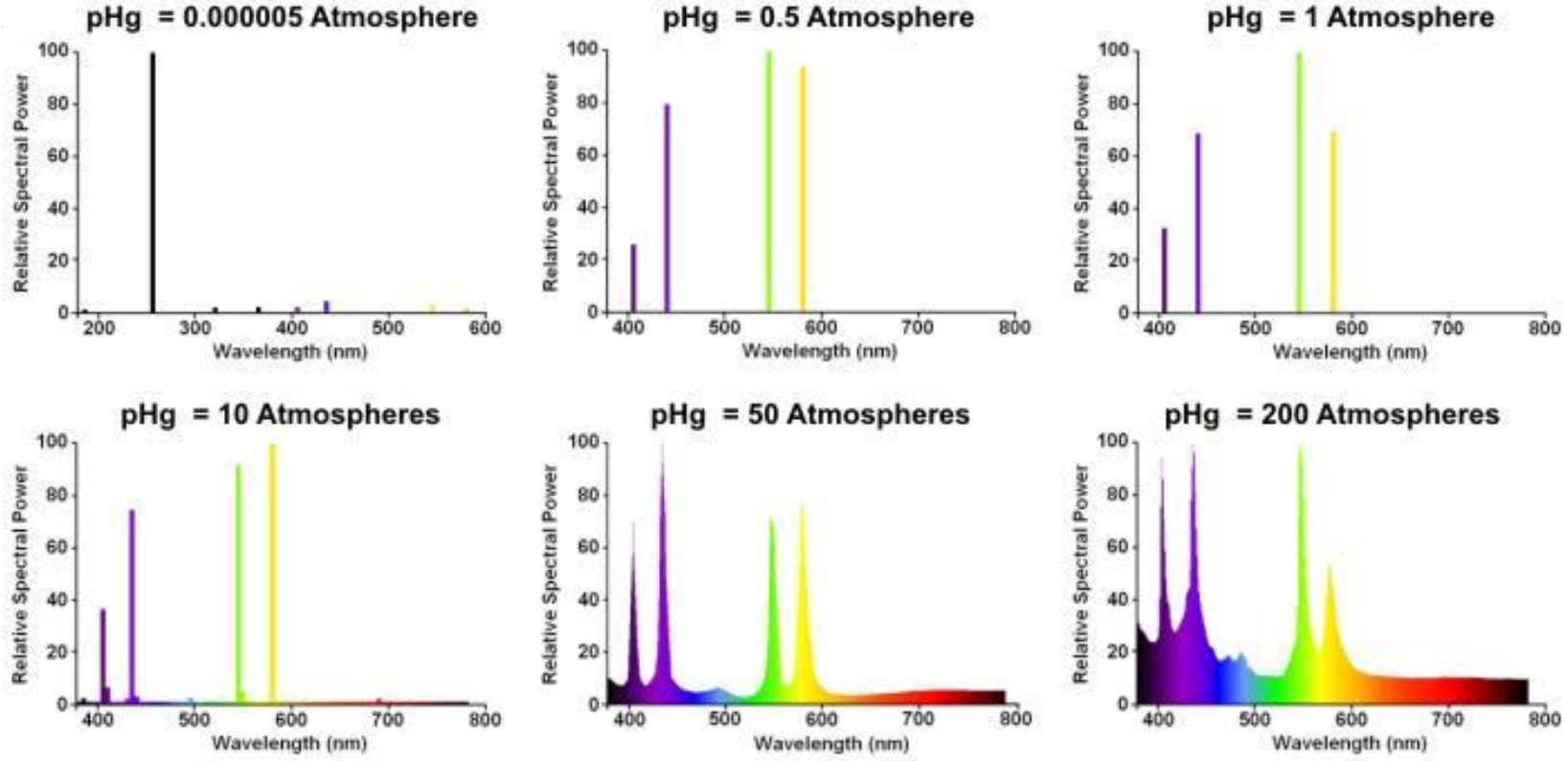
- Standard metal halide spectrum composed of closely spaced line radiators
- RF plasma appears to generate higher background radiation than can simply be explained by line broadening
- Spectrum begins to approach blackbody curve



Spectral Continuum Explained

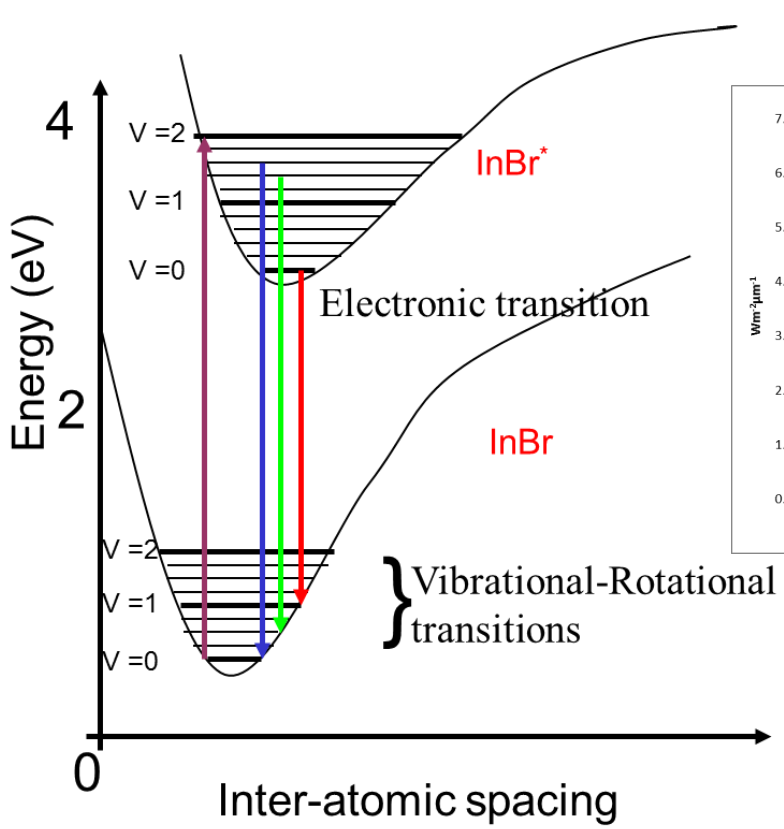
- While electrodeless lamps allow the use of metal halide additives that could never be used in the presence of tungsten electrodes at high temperature, allowing for unique spectral combinations

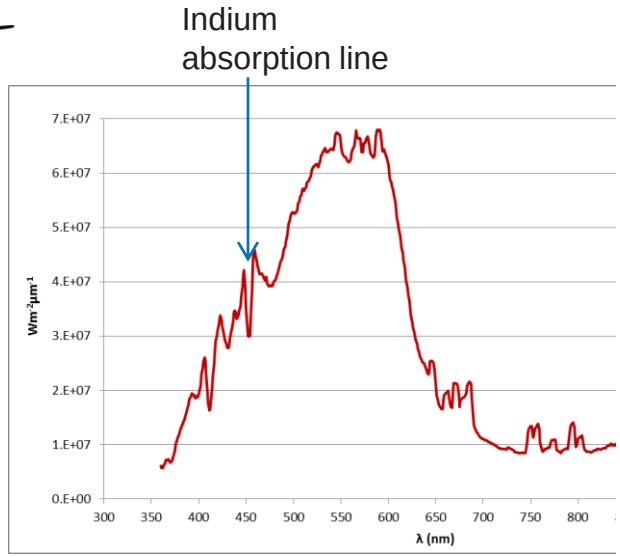
- In most metal halide lamps, line broadening due to doppler shift and background Bremstrahlung radiation
- As pressure increases, ΔE increases with increasing particle interactions



Molecular Transitions

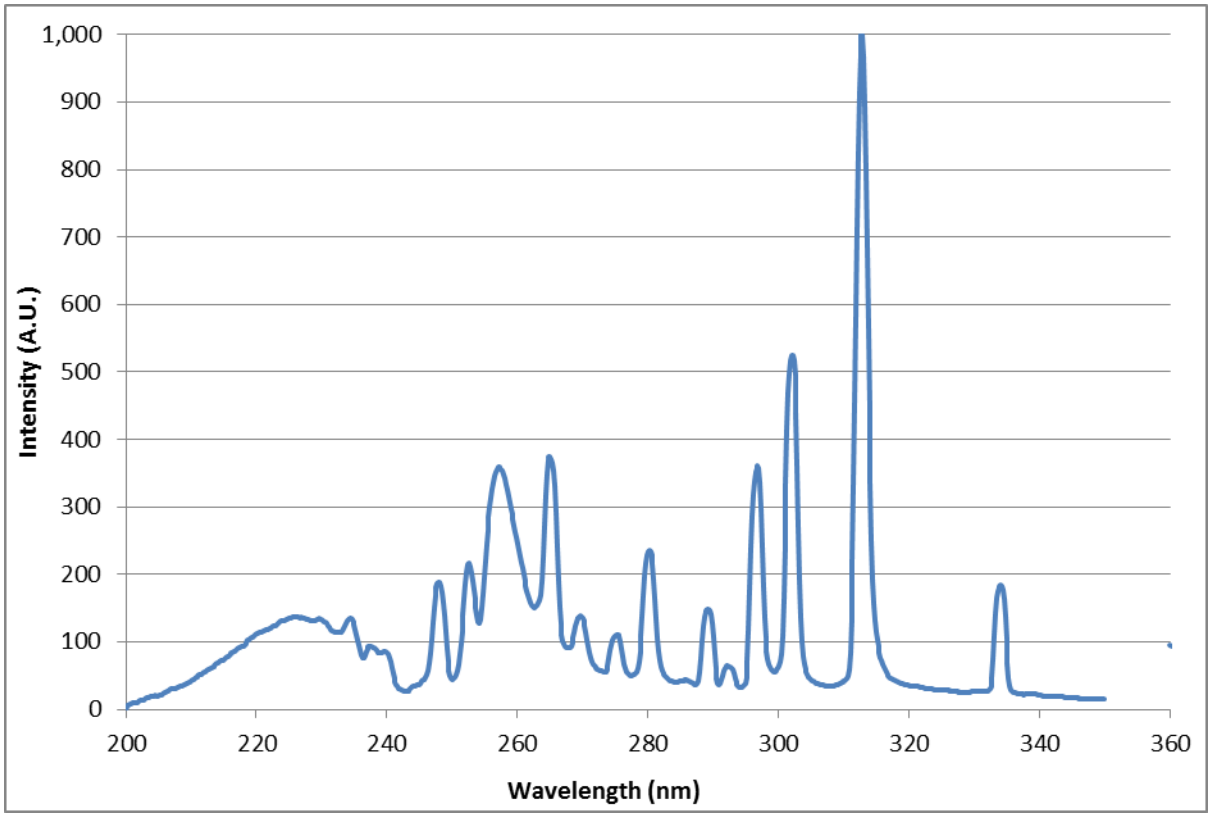
- Plasma column contains mostly ionized species, but some excited molecular states exist
- Franck-Condon Principle says that we can see some vibrational-electronic transitions
- Not observed in electroded metal halide lamps





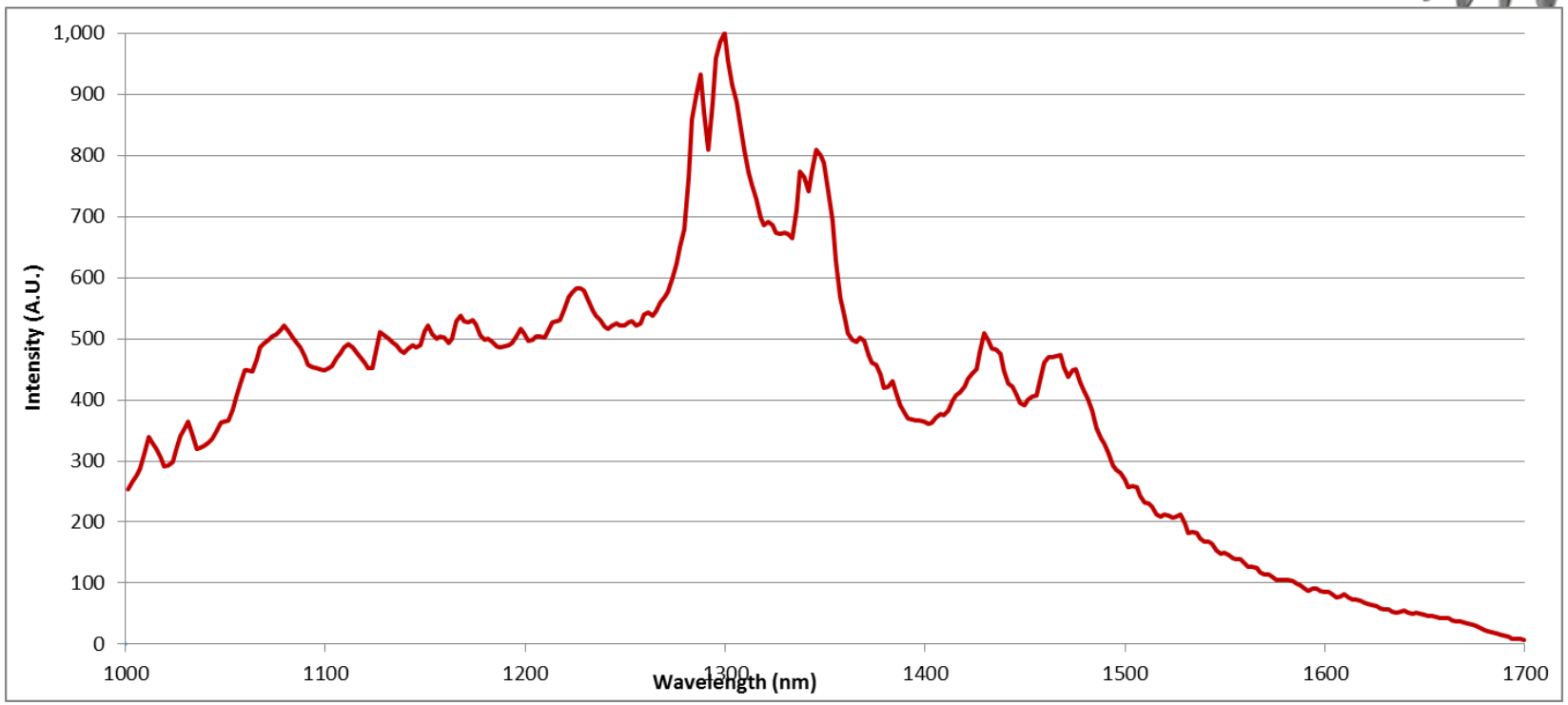
Molecular Transitions

- Molecular emission also seen with single-species discharges
- Low pressure, DUV regions show continuum radiation



Molecular Transitions

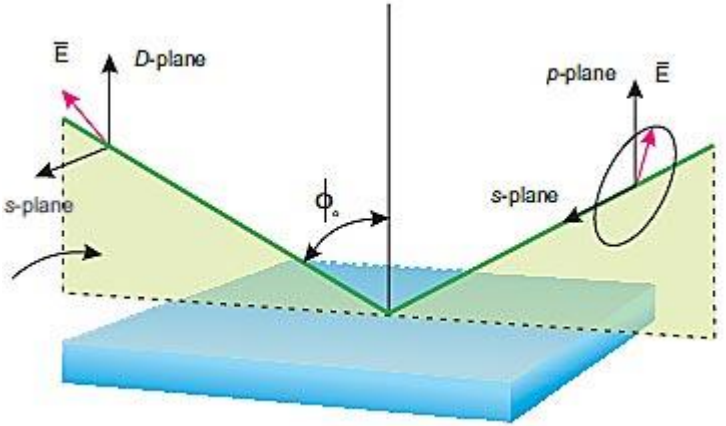
- Lamps with fills customized for IR, also show a high degree of background continuum radiation



Applications

Ellipsometry

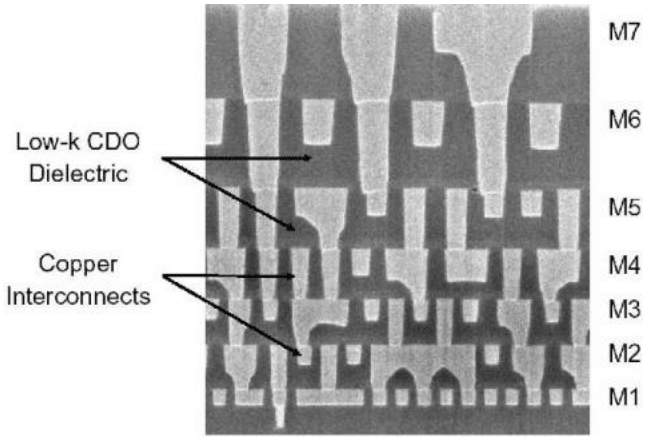
- Requires high degree of stability and very low noise for accurate measurements



Applications

Low-K dielectric UV curing

- Post-curing low-K dielectrics enhance mechanical strength and prevent delamination failures
- Unlike e-beams, no charging of surface
- Studies have shown that broad-spectrum UV radiation >200nm is ideally suited for SiOC enhancement



Applications

Plant Growth

- Case studies show broad-spectrum plasma light sources produce healthier hydroponic crops

High Pressure Sodium
@250uMol/m²

Light Emitting Plasma
@250uMol/m²

Applications

Coral Growth

Study conducted by major aquaculture facility

	Metal Halide (460 W)				LEP GRO 4102 (280 W)			
	Day 1 Weight (g)	Day 30 Weight (g)	Growth	Growth/ kWatt	Day 1 Weight (g)	Day 30 Weight (g)	Growth	Growth/ kWatt
Sample 1	9.2	9.6	4.35%	9.45%	10.0	12.3	23.00%	82.14%
Sample 2	14.3	15.9	11.19%	24.32%	8.3	10.4	25.30%	90.36%
Sample 3	34.4	40.4	17.44%	37.92%	31.0	40.8	31.61%	112.90%
Sample 4	37.6	45.2	20.21%	43.94%	13.5	17.7	31.11%	111.11%
Sample5	43.1	49.7	15.31%	33.29%	12.4	16.1	29.84%	106.57%
AVERAGE			13.70%	29.78%			28.17%	100.62%

Plasma lighting produced 3x more growth per watt

Applications

Industrial Lighting - Port Case Study

Data from Port trial, in collaboration with Emerging Technology Coordinating Council and PG&E

1000W HPS
20,000 hour life
High Glare, 20 CRI

500W LEP
50,000 hour life
Zero Glare, 80 CRI

Energy Savings
3,200 KW-Hr/Fixture/Year
$414/Fixture/Year
$414,000/Year for the port
Maintenance Savings
$69/Fixture/Year
$69,000/Year for the port

TOTAL SAVINGS: $483,000/year
ROI: 2.6 years

Questions

References

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Plant growth study courtesy of North Dakota State University

Port of Oakland Case Study:

http://www.etcc-ca.com/sites/default/files/reports/ET12PGE3172%20Light%20Emitting%20Plasma%20Assessment_0.pdf

Images courtesy of Luxim Corp or Wikipedia