“The Emerald Forest”

An Integrated Approach for Sustainable Community Development and Bio-derived Energy Generation

Fouad Teymour

Department of Chemical & Biological Engineering

Illinois Institute of Technology

Chicago, IL

Collaborators

- **Dr. Omar Khalil**
- **Aly Eltayeb**
- **Nicole Craig**
- **Dr. Said Al-Hallaj (UIC)**

Outline

- The Emerald Forest Vision
- Research Challenges and Obstacles
- Optical System Design
- Conclusions

The Emerald Forest Concept

- **Biofuel production from *massive/vertical* farms growing marine *algae biomass* coupled with Desert reclamation.**
- **Integrates biomass production with a Living Community whose energy and water needs are fully Sustainable.**
- **Suitable for arid environments within reasonable distance (50-100 miles) from coastal waters.**
- **Addresses three Global Crises: Energy, Climate Change, and Overcrowding.**

Why Biomass?

- **Need for Elimination of Fossil Fuels**
- **Carbon Neutral/Reduced**
- **Dependence on liquid fuels**
- **Need for transition technology, but maybe long-term sustainable**

Why Algae?

- **No need for Agricultural Landmass**
- **Minimal need for fresh water**
- **High Yield and productivity**
- **Biodiversity**
- **Challenge: Large scale production**

Historical Context: *NREL Aquatic Species Program, mid 70s to mid 90s*

Why Massive / Vertical?

- Economy of scale
- Coupling with biofuel production technology
  - Demand/supply issues
  - Optimal plant size requires large amounts of biomass
- The need for process intensification
- Global needs are increasing
- Higher impact on fossil fuel displacement

Energy Crisis

- Continued dependence on fossil fuels non-sustainable
    - Diminishing supplies, volatile prices, and political leveraging.
- Fossil fuel conversion to materials brings a lot more value-added than Fossil fuel to energy.
- Sustainable routes to renewable fuels is needed

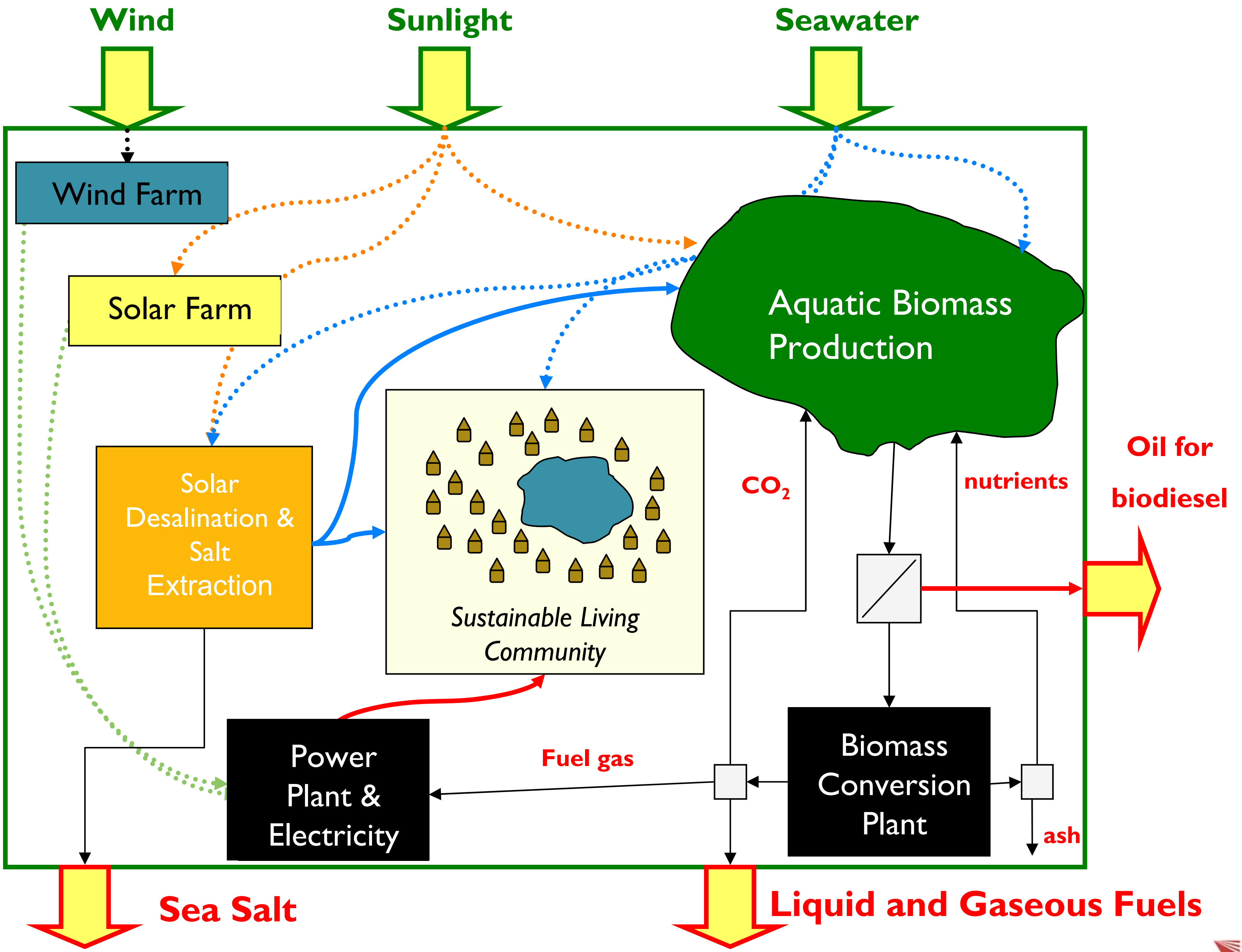
Climate Change Crisis

- Burning fossil fuels for energy to elevated levels of Carbon dioxide and GHG levels in the atmosphere
- Unprecedented levels of GHG predicted to lead to a catastrophic global warming phenomenon.
- Annual net loss of planetary green mass resulting from deforestation, desertification, and non-sustainable agricultural practices.
- Desertification destroys ecological biodiversity

Overcrowding and Prosperity Crisis

- Overpopulation and the need for decent quality, affordable housing is not a problem reserved for the developing world only.
- In the Developing World:
    - Severe overcrowding.
    - Inadequate housing developments.
    - Insufficient resources.
- In the Developed World:
    - The urban sprawl phenomenon is systematically depleting arable rural land that otherwise would be contributing to the betterment of quality of life.

The Emerald Forest Concept

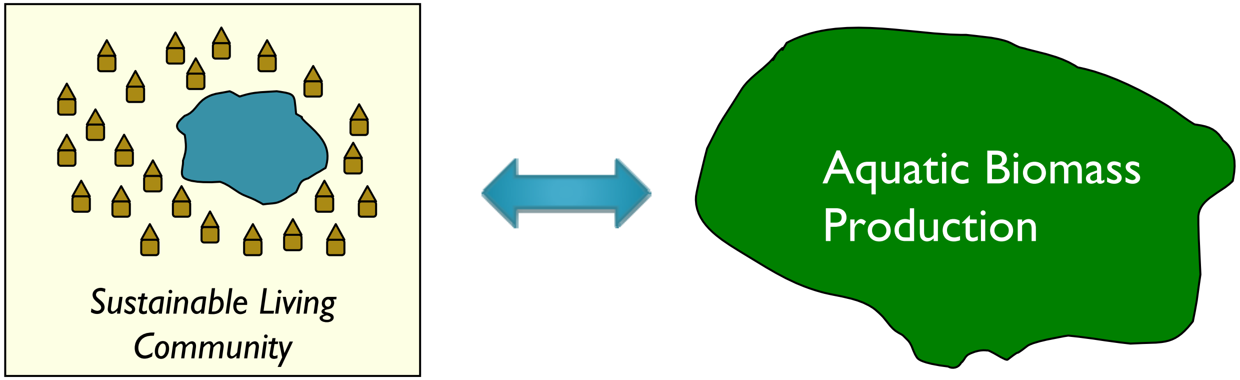


Challenges and Issues of Importance (I)

- *Optical assembly design and optimization*
- *Photovoltaic integration*
- *Reactor Design – Flow patterns and mixing*
- *CO_2 transient sequestration and nutrient delivery*
- *Organisms: pH compatibility, Fast growth, Robustness, Mixed cultures, diverse portfolio of products, Odor control*
- *Materials: Algae attachment - UV stability*

Challenges and Issues of Importance (II)

- *Sustainable Architecture*
- *Sustainable salt extraction methodology*
- *Biofuel / energy delivery technologies*
- *Scheduling and Control MADCABS (NSF ITR Grant, PI: Çinar, Teymour, Hood)*
- *Process Integration and Design problem of a new nature – coupling a societal system with a production system.*



Sustainable Living Community

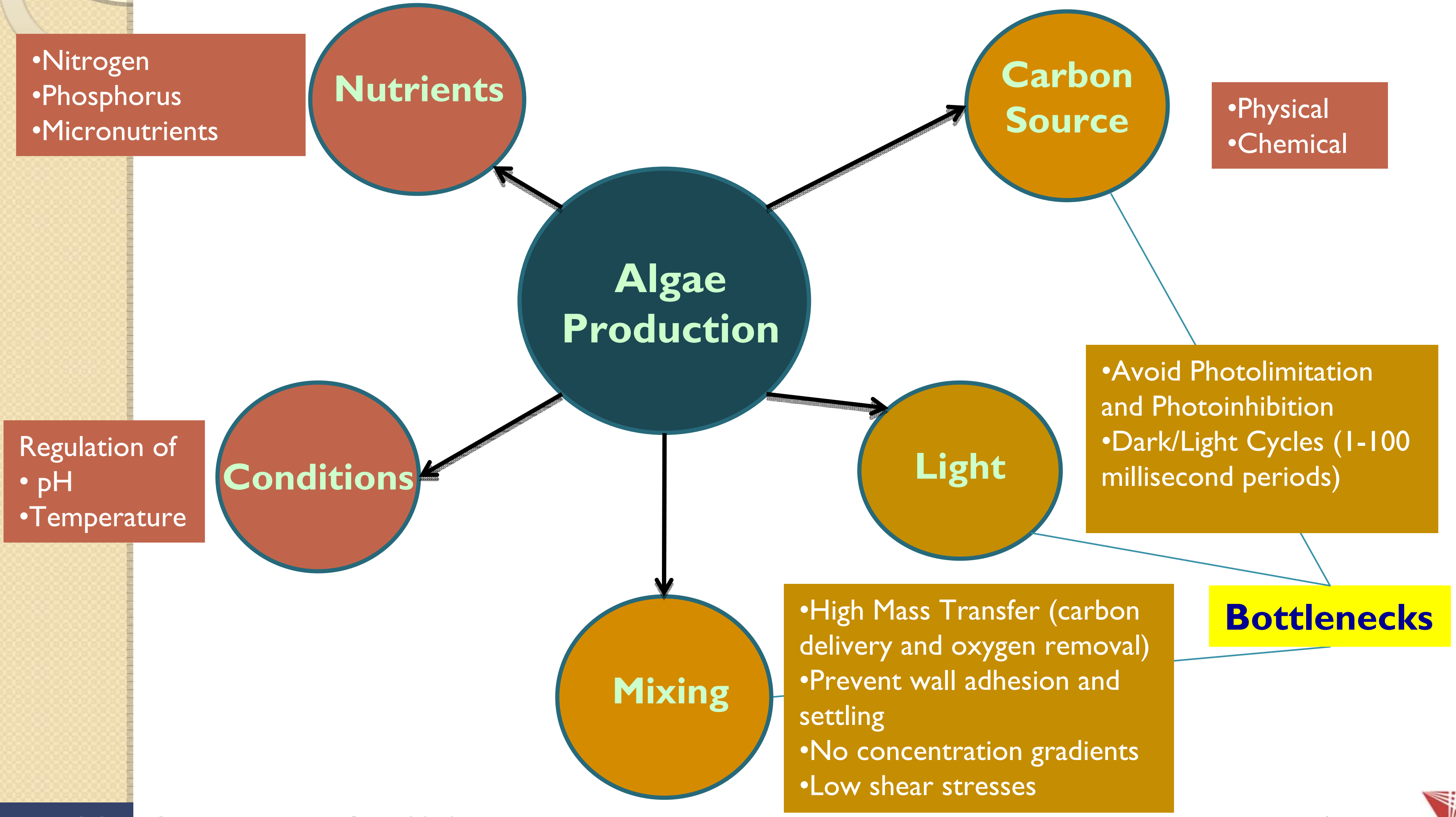
Aquatic Biomass Production

The Ecology of the Emerald Forest

- **A Modern-day desert oasis**
- *Living community*
- *Salinity-controlled ponds*
- *Fish and shrimp hatcheries*
- *Sustainable Agriculture*
- *Palm trees*
- *Switchgrass underfoot*
- *Bird Sanctuary*
- *Microclimate control/rainfall (???)*

Reactor Issues

Requirements for Algae Production



Algae Production

Nutrients

- Nitrogen
- Phosphorus
- Micronutrients

Carbon Source

- Physical
- Chemical

Conditions

Regulation of
- pH
- Temperature

Light

- Avoid Photolimitation and Photoinhibition
- Dark/Light Cycles (1-100 millisecond periods)

Mixing

- High Mass Transfer (carbon delivery and oxygen removal)
- Prevent wall adhesion and settling
- No concentration gradients
- Low shear stresses

Bottlenecks

Algae Production in Open Systems

Artificial

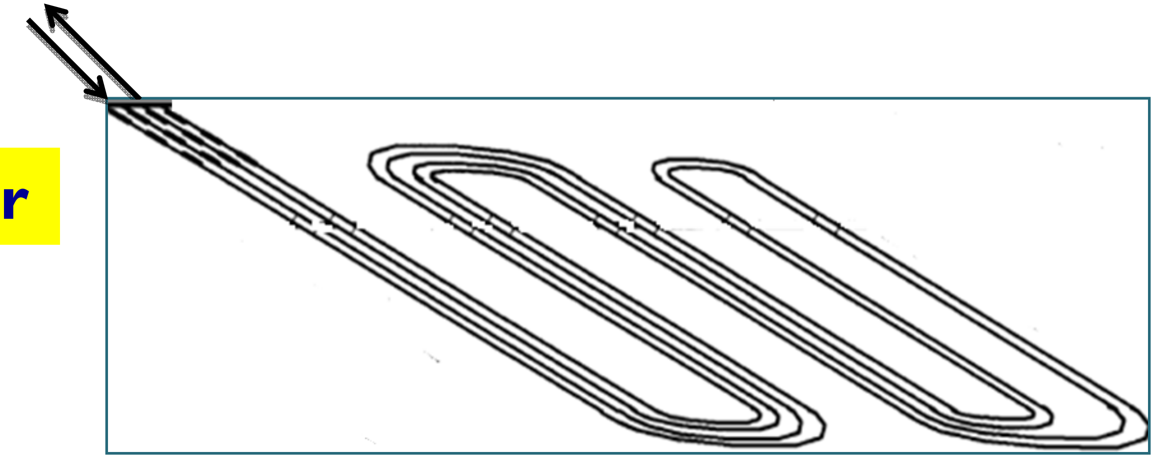
Natural

PROs:Simplicity
- smaller capital
- easier to build and operate

CONs:Low Productivity
- Lack of control on growth conditions
- Inefficient light utilization
- Low mass transfer due to stagnant nature
- Vulnerable to evaporative losses and contamination
- Reached their upper productivity limit

Algae Production in Closed Systems

Tubular Reactor

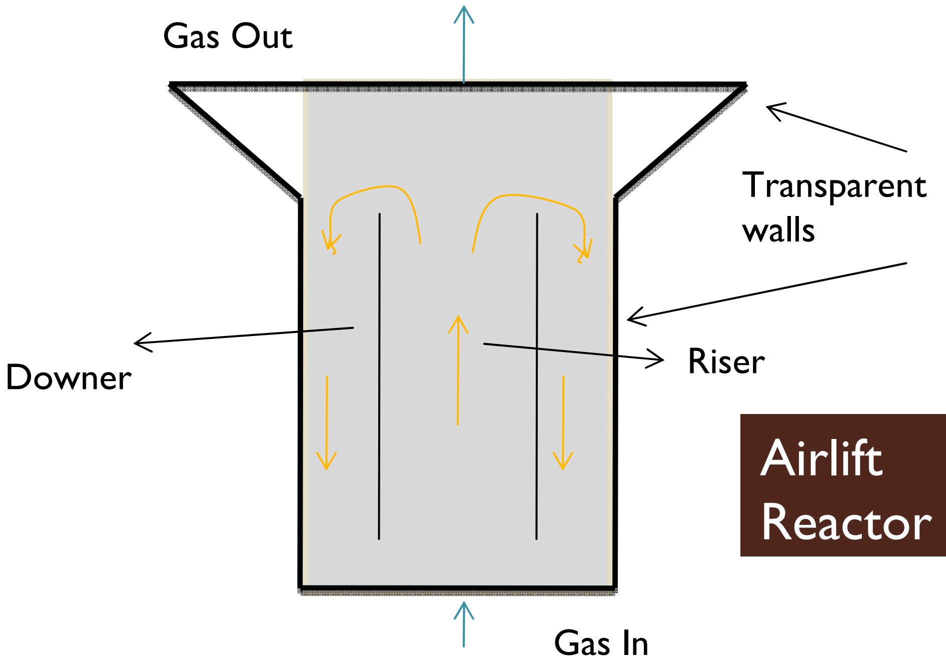


- No light limitation (Diameter around 8 cm)
- Lower mass transfer: fouling; nutrient, carbon gradients; high oxygen content
- Flow induced by power-intensive pumping
- Low productivity per unit area

Algae Production in Closed Systems

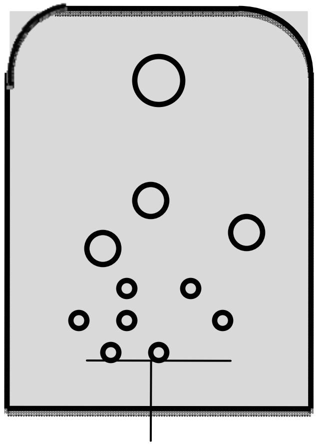
Examples of Gas-Mixed Reactors

- Growth concentrated in downer since light is not available in riser
- Dark/light cycle frequency controlled by gas flow rate
- Fluid circulation (controlled by gas bubbling and reactor geometry) to induce mixing
- Maximum thickness of downer around 5-10 cm due to light attenuation



Airlift Reactor

- Dark/light cycle frequency controlled by gas flow rate and size of bubbles
- Rising bubbles induce mixing
- Maximum thickness of downer around 5-10 cm due to light attenuation



Bubble Column Reactor

The Tree Design (one possibility)

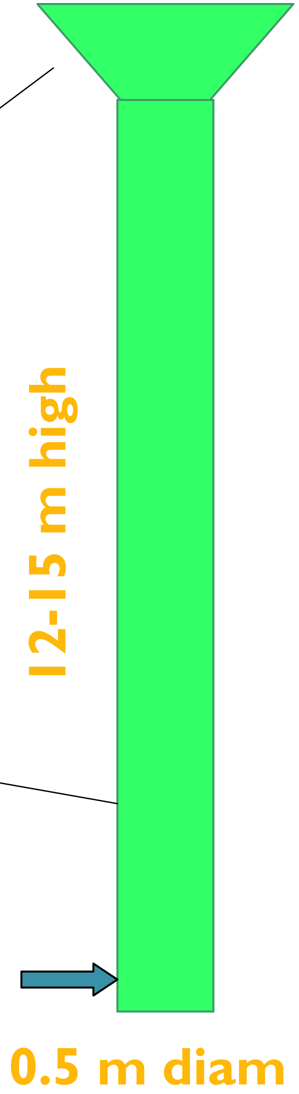
Optical Gathering Assembly

Large Volume (3 m^3)

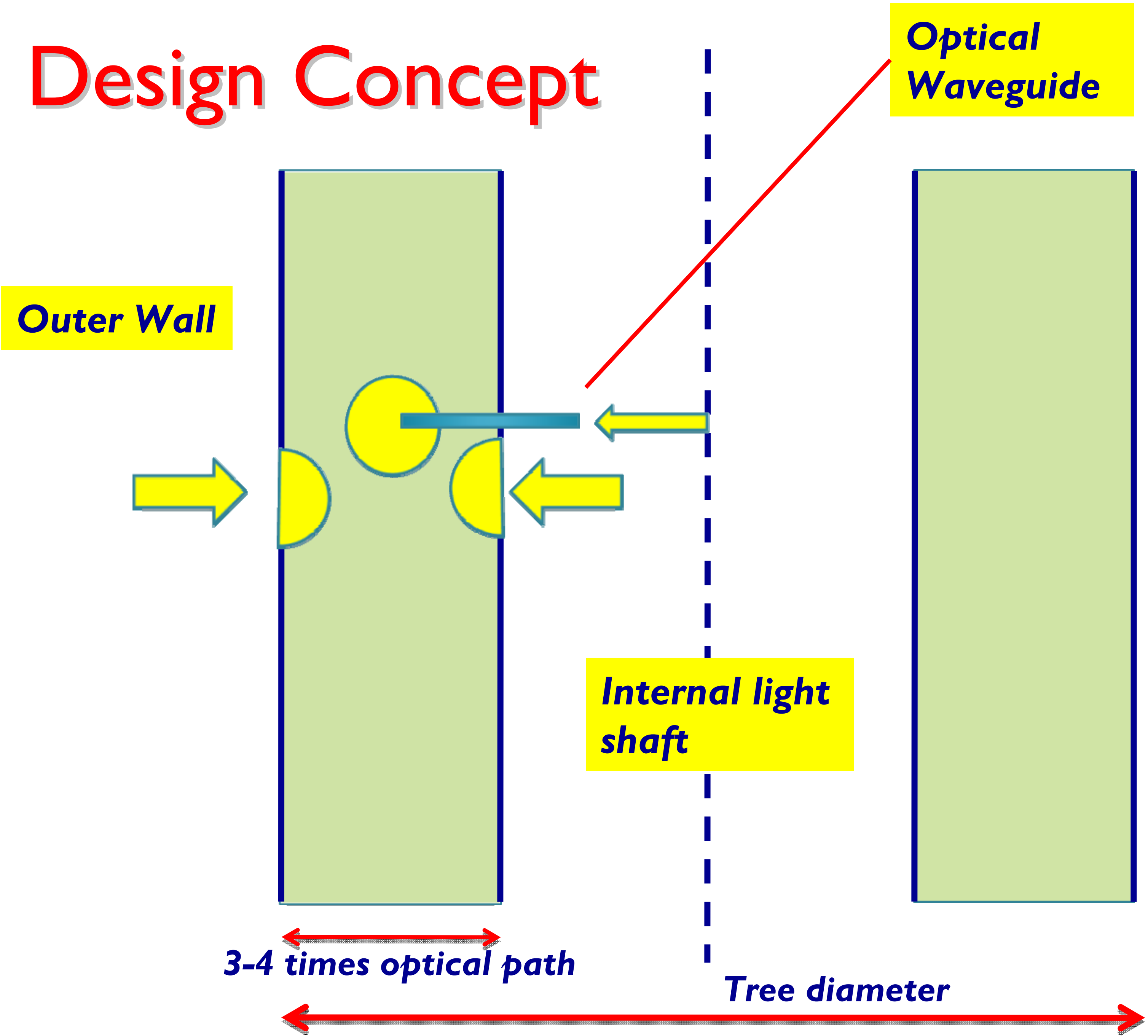
Internal Structure

Circulation

CO$_2$ addition



Design Concept


Optical Waveguide

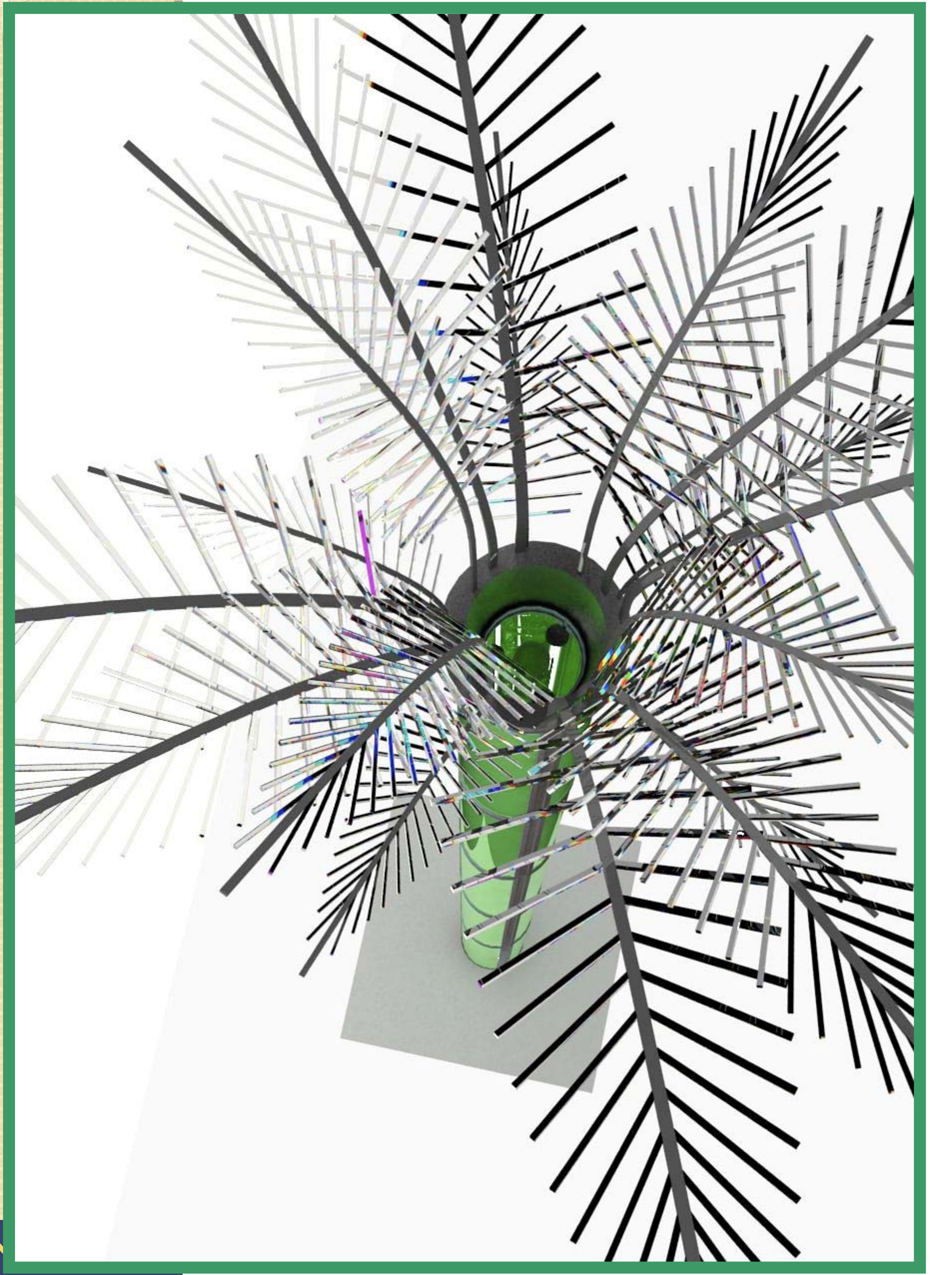
Outer Wall

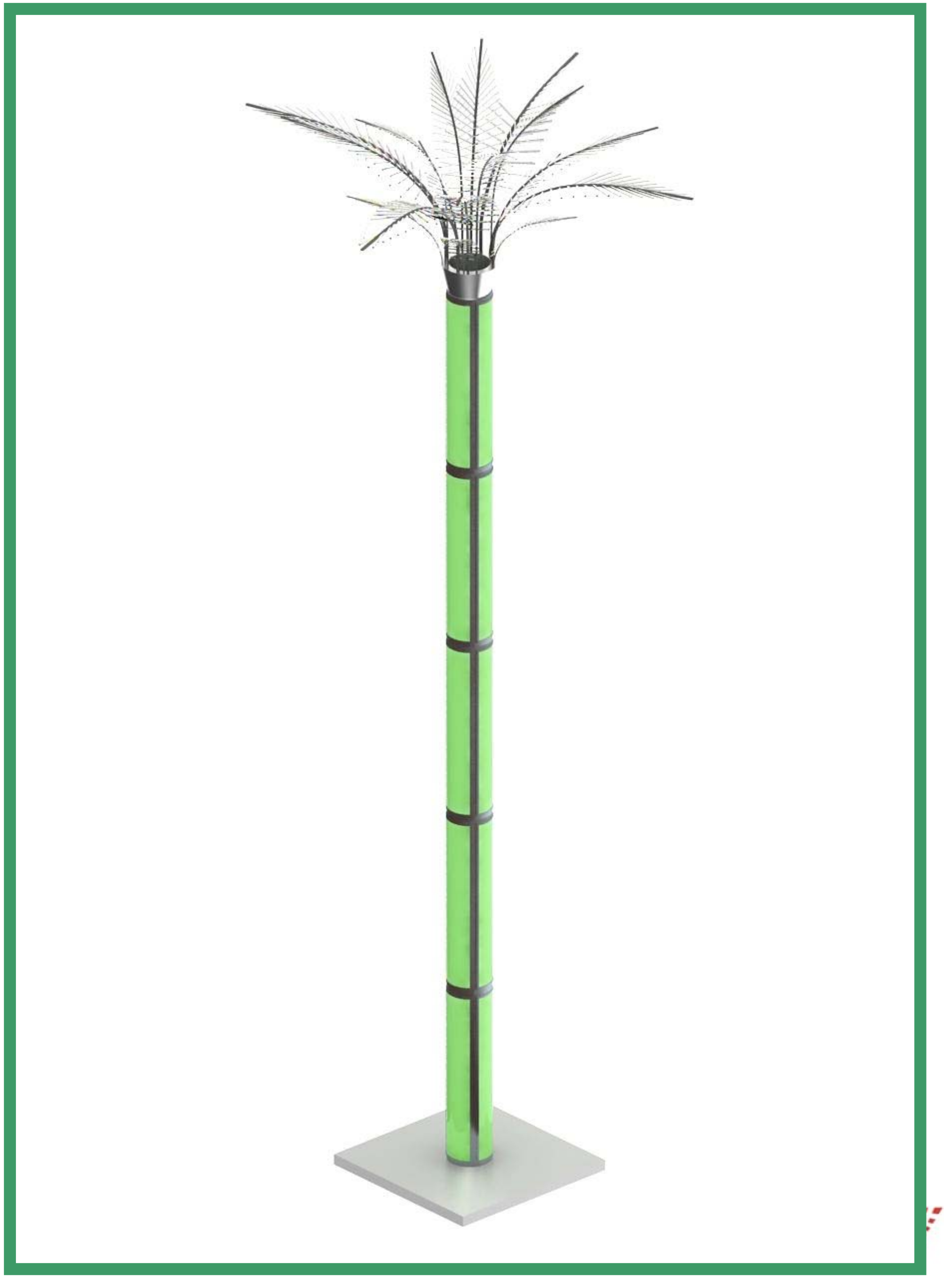
Internal light shaft

3-4 times optical path

Tree diameter

Tree-like PhotobioreactorDesign





Reactor Flow Patterns and Mixing

- Gas lift over tall span could be challenging
    - *Distributed CO_2 Injection along height*
- Prevent Settling of Algae
- Provide the needed light/dark short cycle
- Recirculation patterns will depend on internal structure design. Will be simulated by CFD (FLUENT).
- Hydrostatic pressure difference could lead to unique bubbling characteristics for physical CO_2.

Design Target for Biomass Productivity

Traditional Biomass 4-5 tons/acre/year

Energy Crops 10-15 tons/acre/year

Algae 100-200tons/acre/year *OR MORE*

400 Biotrees/ac

0.5 ton/tree/year → 1.4 kg/tree/day

3 m³/tree @ 0.01 solid content

At maturation contains 30 wet kg → 3 dry kg

Harvest 50% → means harvest once a day

Critical assumption
Depends on light penetration

200 tons/acre/year requires a doubling time on the order of 1 day, which falls in the range of reported kinetics for various species; especially with CO_2 assistance.

Carbon Dioxide Issues

CO_2 Sequestration

Underground in Geologic Formations

- Energy intensive, requires compression.
- Capacity is unlimited.
- Could be used for secondary oil production, if injected strategically.
- Long-term fate is unknown.
- Effect on stability of the formations is unknown.

Underwater

- Much easier, but still requires energy for compression.
- Has a marked impact on ocean acidity, especially in a specific region.
- Interference with marine life can lead to even more environmentally disastrous results.

CO_2 Sequestration

In Biomass Form

- Plant Biomass has been fixating Carbon for millions of years.
- Requires Carbon source and solar energy.
- Process is Carbon Neutral.
- The challenge is in transportation.
- Two avenues for solution:
    - *Locally integrated power production for a portion of the biomass with immediate recycling of* CO_2
    - *Development of technologies for transient sequestration of* CO_2 *in aqueous media.*

Transient CO_2 Capture and Delivery

- Aqueous medium in the form of
  - *Physical carbonation*
  - *Chemical fixation ($NaHCO_3$, $KHCO_3$)*
- Many species capable of utilizing both forms (*Botryococcus braunii, Tetraedron minimum, Chlamydomonas noctigama, …*)
- Challenges:
  - *Offshoot CO_2 usually hot, sometimes pressurized*
  - *Liquid medium requires intermediate process steps*
  - *High temperature sorbents (2-step process)*

Other Issues

Biofuel Technology

Sustainability requires TOTAL biomass utilization.

Produced biomass can be used along multiple routes:

- Biodiesel
- Fermentation to bio-ethanol, bio-butanol
- Biomass gasification
- Catalytic Hydro-reforming
- Nutrient supply for fish and shrimp hatcheries.

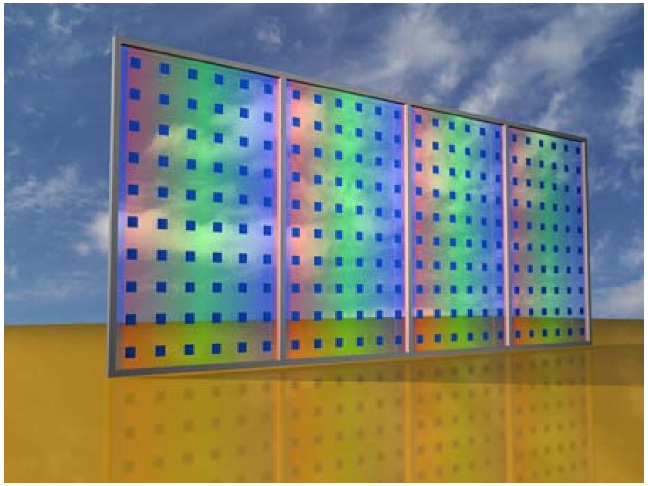
Sustainable Architecture

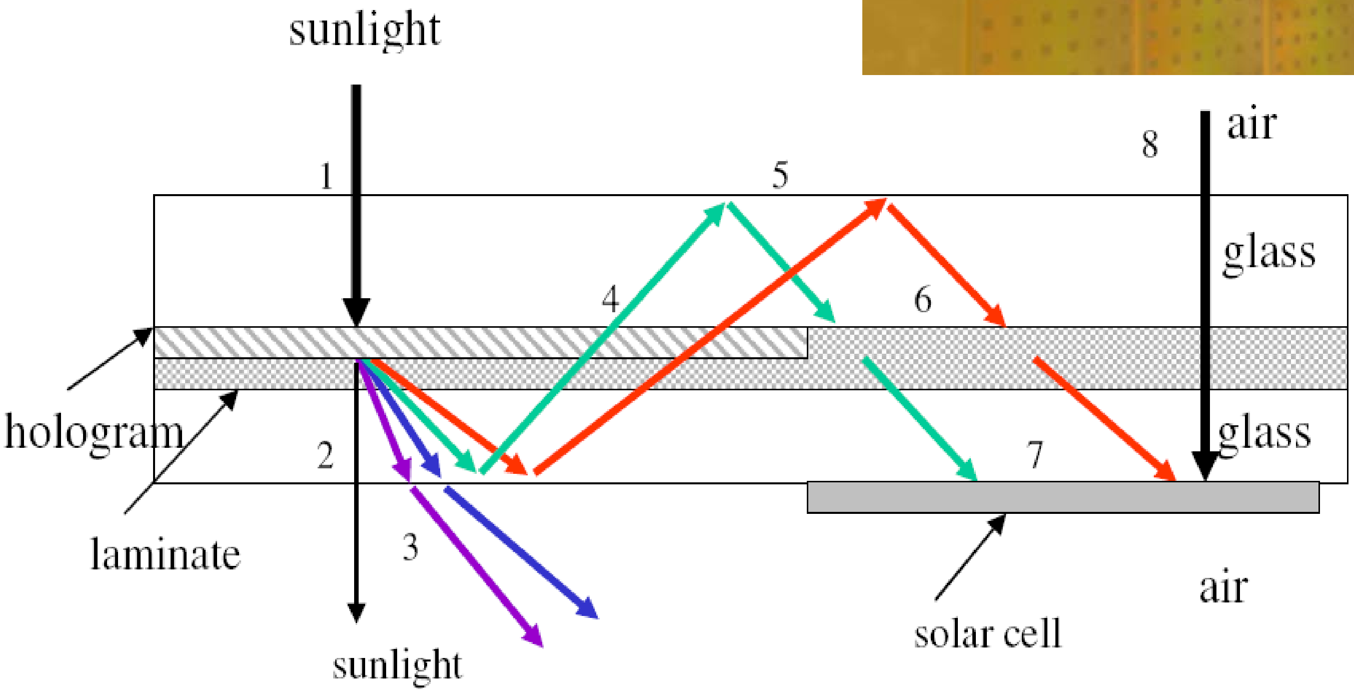
Example Technology BIPV

- *Building Integrated PhotoVoltaics*
- *Uses Windows, facades, building skin*
- *Can be enhanced with holographic elements*

BIPV with Holograms

- ***Redirects the light***
- ***More light reaches PV element***





Sustainable Architecture (Other)

- ***Wind-integrated buildings***
- ***Geothermal heat pump for heating/cooling***
- ***Green roofs***
- ***Storm water collection and reuse***
- ***Solar thermal collectors***
- ***Thermal storage management with phase change materials***
- ***Sustainable building materials***
- ***Recycled polymers for paints and coatings***
- ***Energy efficient windows***
- ***Advanced control systems***

Optical System Design

Objectives

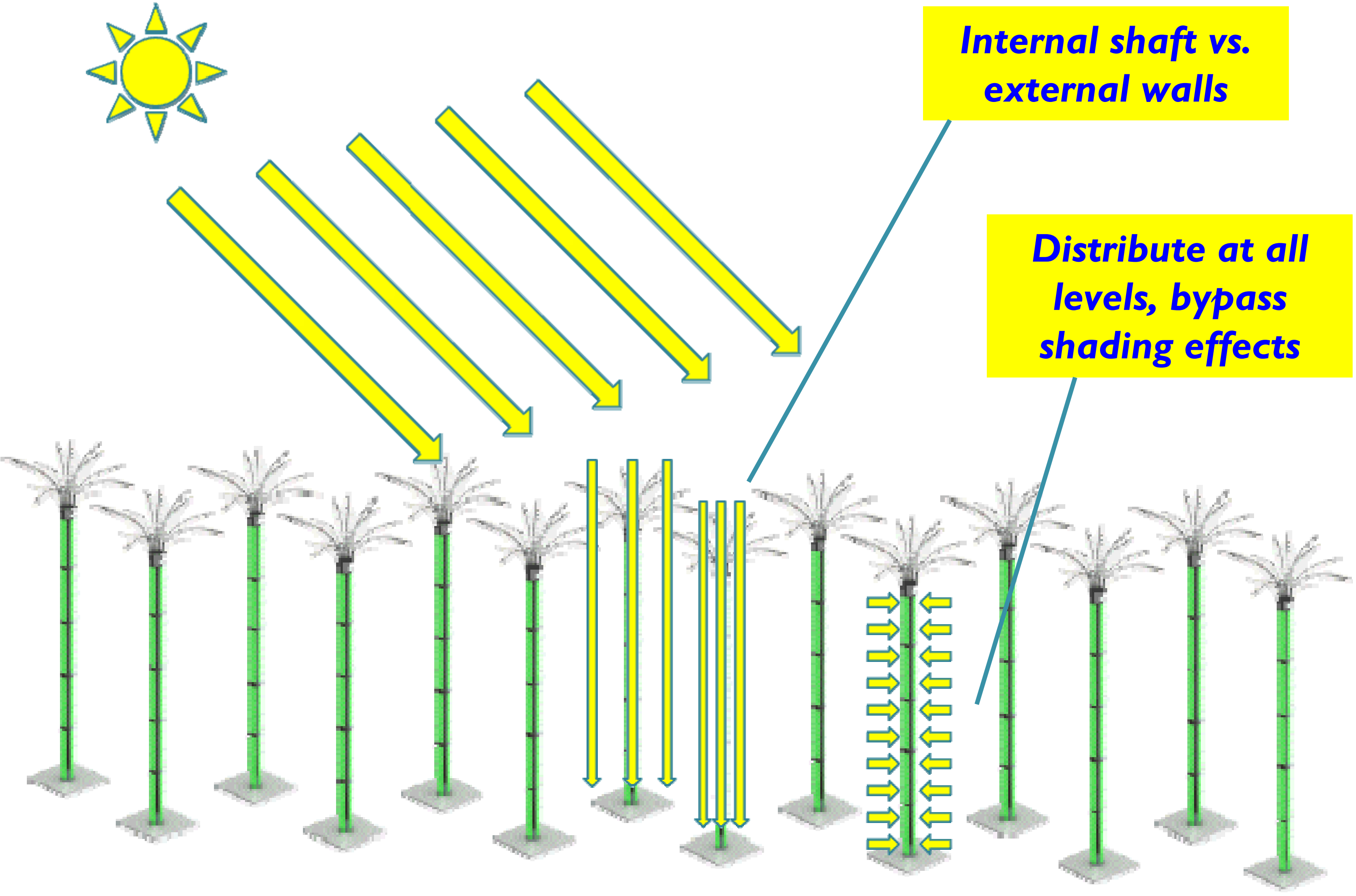
1. Design a collection system that maximizes light capture and utilization at all times of day.

2. Design and optimize the light distribution system to achieve near-even distribution, avoid dark spots, and minimize shading effects.

Optical System Components

- *Transmitting leaves + photovoltaic leaves*
- *Total internal reflection elements*
- *Holographic elements*
- *Mirrors*
- *Internal illumination shaft*
- *Illumination at varying depths*

Optimization of Light Distribution



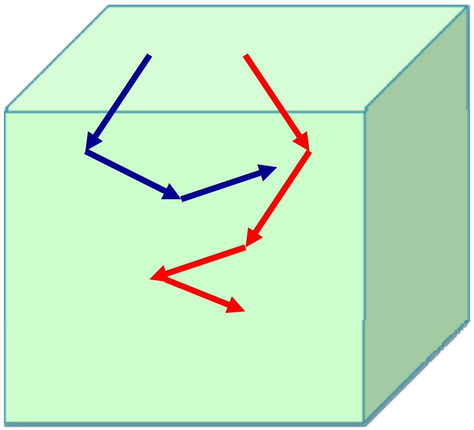
Internal shaft vs. external walls

Distribute at all levels, bypass shading effects

Modeling Light Propagation in Scattering/Absorbing media

Ray tracing (Monte Carlo)

- Fire a large ensemble of light rays
- Trace each ray through reflection, refraction, and scattering, until it is either absorbed or leaves the bounds of the system
- Calculate light intensity distribution for the ensemble
- Computationally intensive

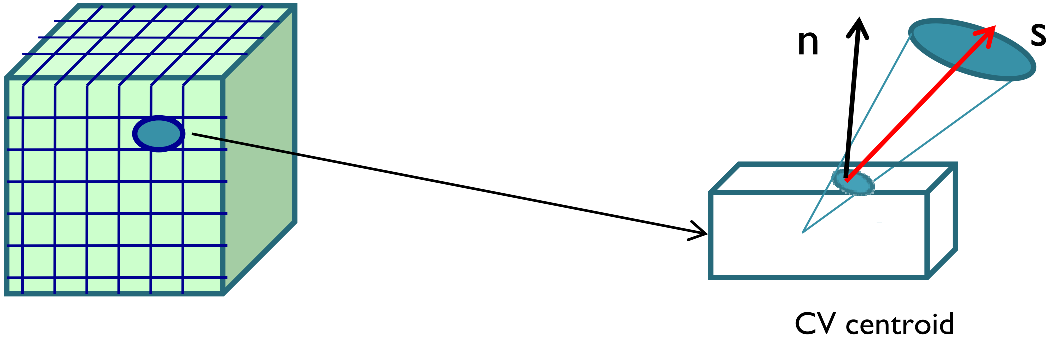


Scattering and absorbing phenomena are modeled probabilistically

Fermat's Principle:
"Light rays follow a path that is an extremum compared to other nearby paths"

Modeling Light Propagation in Scattering/Absorbing media

Finite Volume with Discrete Ordinates



- Solves the Radiative Transport Equation (RTE) derived by performing a photon balance on a fixed solid angle and volume
- In finite-volume scheme, problem is discretized spatially and angularly
- Scattering and absorption are directly modeled in each control solid angle and volume
- Accuracy of the results depends on the spatial and angular grid used
- Qualitative results can be obtained in relatively short computational times

The Radiative Transport Equation (RTE)

Transport Phenomena for Photons

Divergence of radiation Intensity reaching solid angle Ω in direction of propagation,

emission term, negligible for algae problems

$$\nabla \cdot I(\vec{r},\vec{s}) + (a+\sigma_s)\, I(\vec{r},\vec{s}) = a n^2 \frac{\sigma T^4}{\pi} + \underbrace{\frac{\sigma_s}{4\pi} \int_0^{4\pi} I(\vec{r},\vec{s})\, \Phi(\vec{s}\cdot\vec{s}')\, d\Omega'}$$

extinction by absorption and out-scattering

radiation entering control volume (defined by a solid angle) by scattering from other control volumes

The phase function Φ determines probability of in-scattering from all solid angles Ω' into volume defined by solid angle Ω

FVDO Model solution in FLUENT

Grid Geometry and Discretization

- Spatial Discretization: Tetrahedral elements
- Angular Discretization to represent directional dependence of radiation at each spatial node; each octant is divided into N_θ X N_ψ solid angles

Assumptions

- Wavelength independence; isotropic scattering
- Integration over each solid angle in each CV
- Outward fluxes approximated by upwind differencing

Solution Strategy

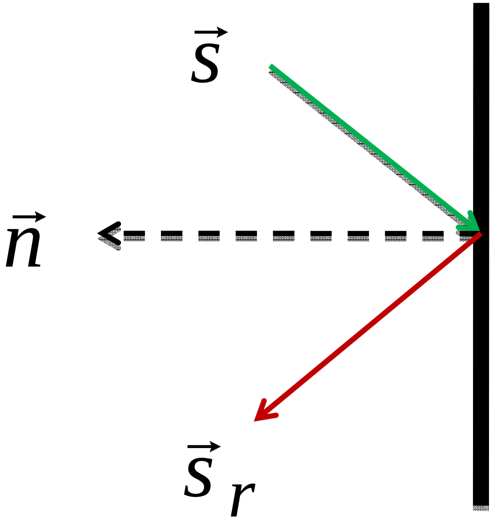
- Equations coupled by inscattering term (dependent on incoming radiation from other directions), and by fluxes crossing CV surfaces (which are approximated in terms of the intensities in neighboring cells)
- Iterative solution is used

Advantage of this approach: Light modeling and hydrodynamic CFD can be integrated in the same simulation environment, with the same grid discretization.

Wall Boundary Conditions in FVDO

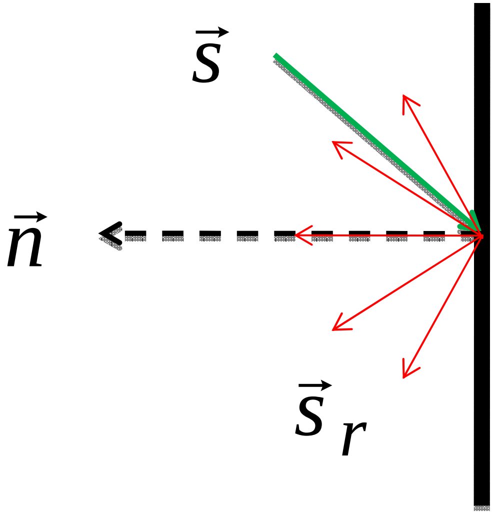
Opaque Walls

Specular reflection



$$\vec{s}_r = \vec{s} - 2(\vec{s}\cdot\vec{n})\vec{n}$$
$$I(\vec{s}_r) = (1 - f_d)I(\vec{s})$$

Diffuse reflection



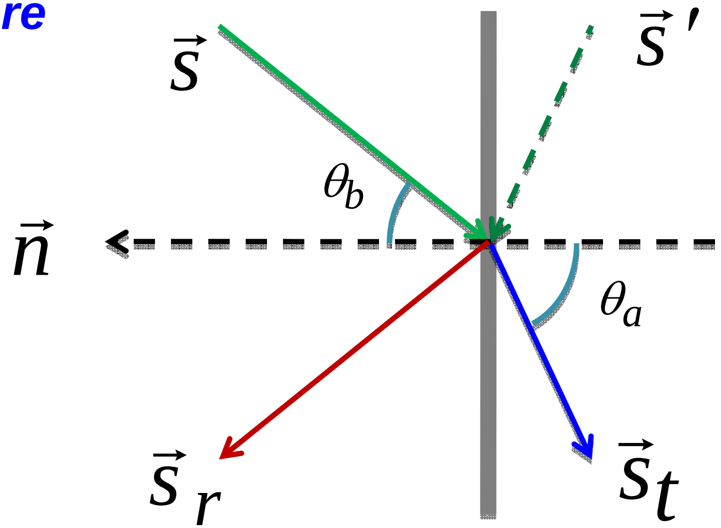
$$I_{\text{out}} = \frac{f_d}{\pi}\int_{\vec{s}\cdot\vec{n}<0} I_{\text{in}}\vec{s}\cdot\vec{n}\, d\Omega$$

- **Diffuse fraction is material dependent (*f*$_d$)**
- **NO absorption, NO emission**

Wall Boundary Conditions in FVDO

Semi-Transparent Walls

Wave guide culture $n_b > n_a$ ***Algae***



$$\sin\theta_a = \sin\theta_b \frac{n_b}{n_a}$$

Snell's law

$$I(\vec{s}_r) = r_b(\vec{s})I(\vec{s}) + \tau_a(\vec{s}\,')I(\vec{s}\,')$$

$$I(\vec{s}_t) = r_a(\vec{s}\,')I(\vec{s}\,') + \tau_b(\vec{s})I(\vec{s})$$

reflected portion

transmitted portion

$$r_b = \frac{1}{2}\left(\frac{n_b\cos\theta_a - n_a\cos\theta_b}{n_b\cos\theta_a - n_a\cos\theta_b}\right)^2 + \frac{1}{2}\left(\frac{n_b\cos\theta_b - n_a\cos\theta_a}{n_b\cos\theta_b - n_a\cos\theta_a}\right)^2$$

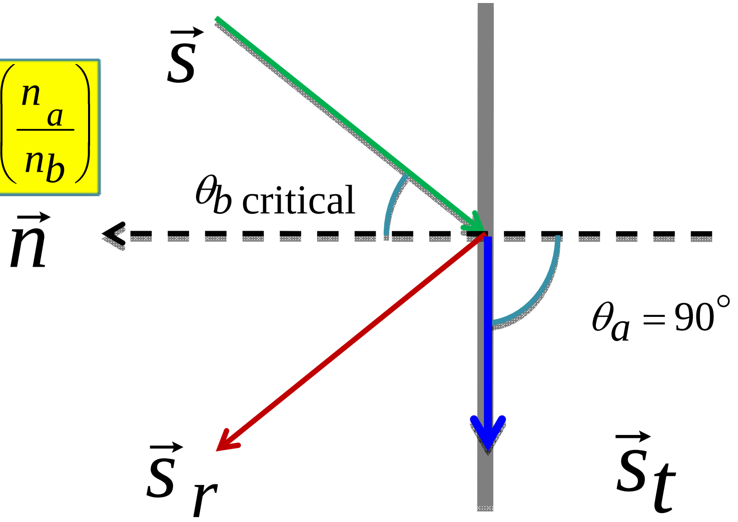
$$\tau_b = 1 - r_b$$

Total Internal Reflection (TIR)

At the critical angle

Wave guide $n_b > n_a$ ***Air***

$$\theta_{b\ \mathrm{critical}} = \sin^{-1}\left(\frac{n_a}{n_b}\right)$$



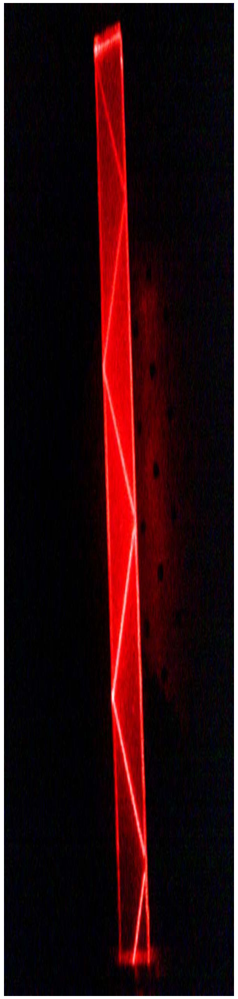
Above the critical angle

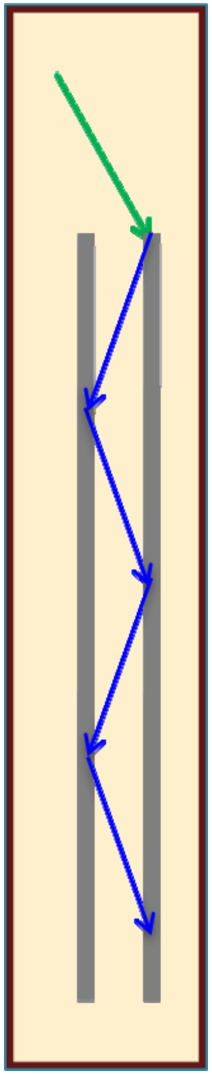
reflected portion

$$r_b = 1$$

transmitted portion

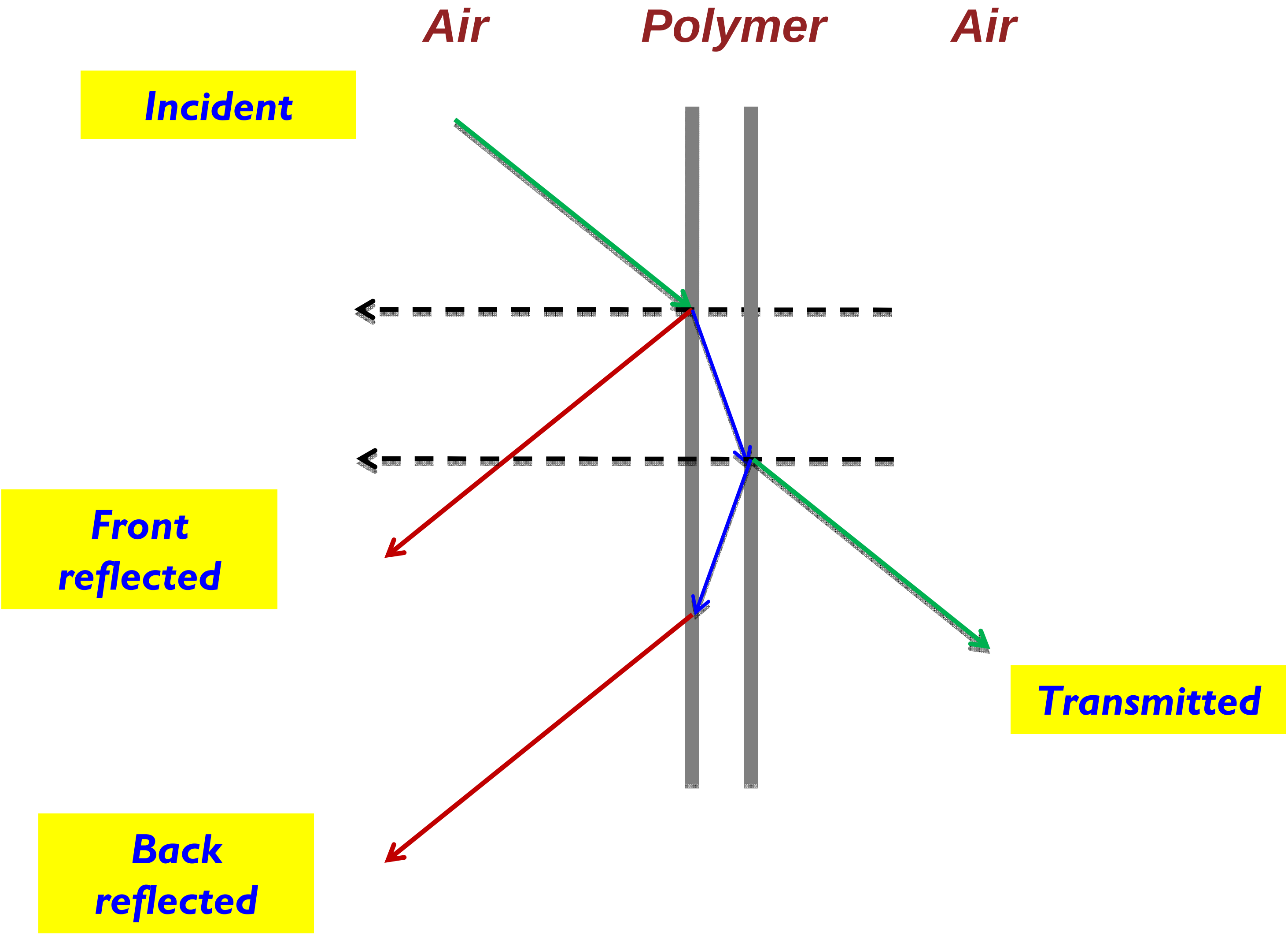
$$\tau_b = 0$$





fiber optics,
wave guides,
gratings, …

Reflection in Semi-Transparent Media



Air **Polymer** **Air**

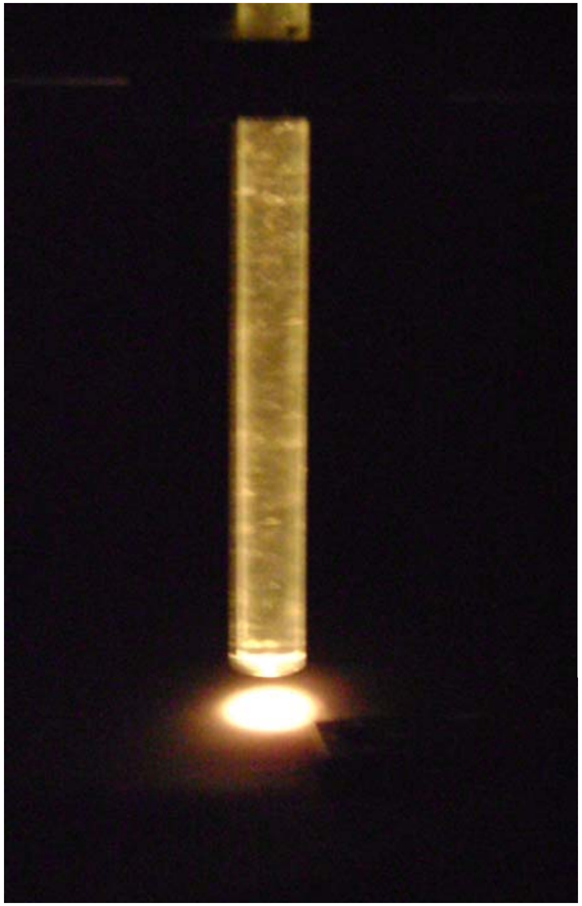
Incident

Front reflected

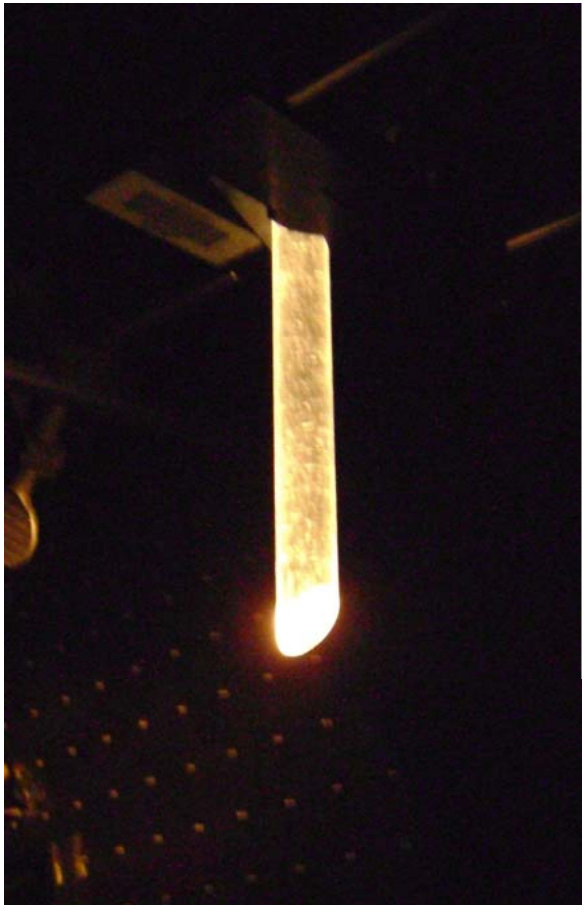
Transmitted

Back reflected

Simple Waveguides: Modeling & Testing



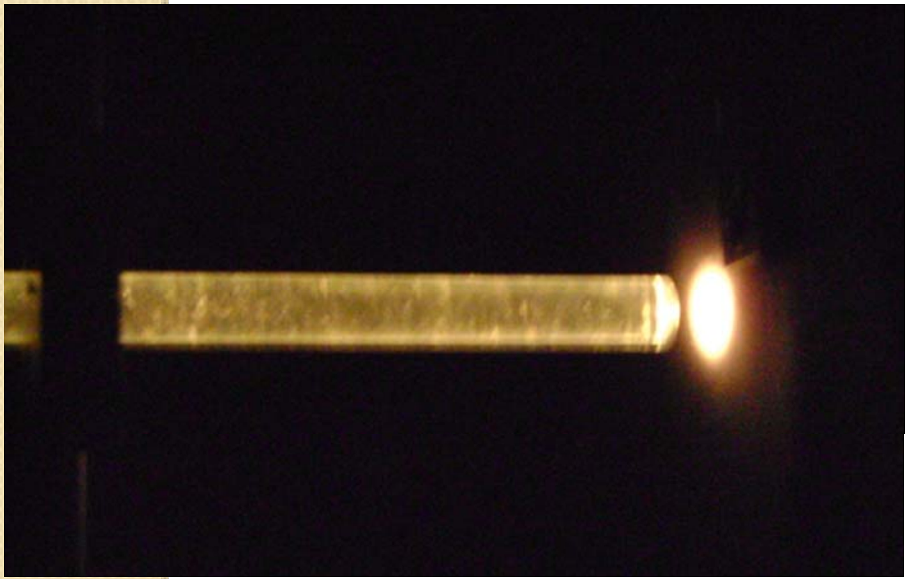
Straight cut



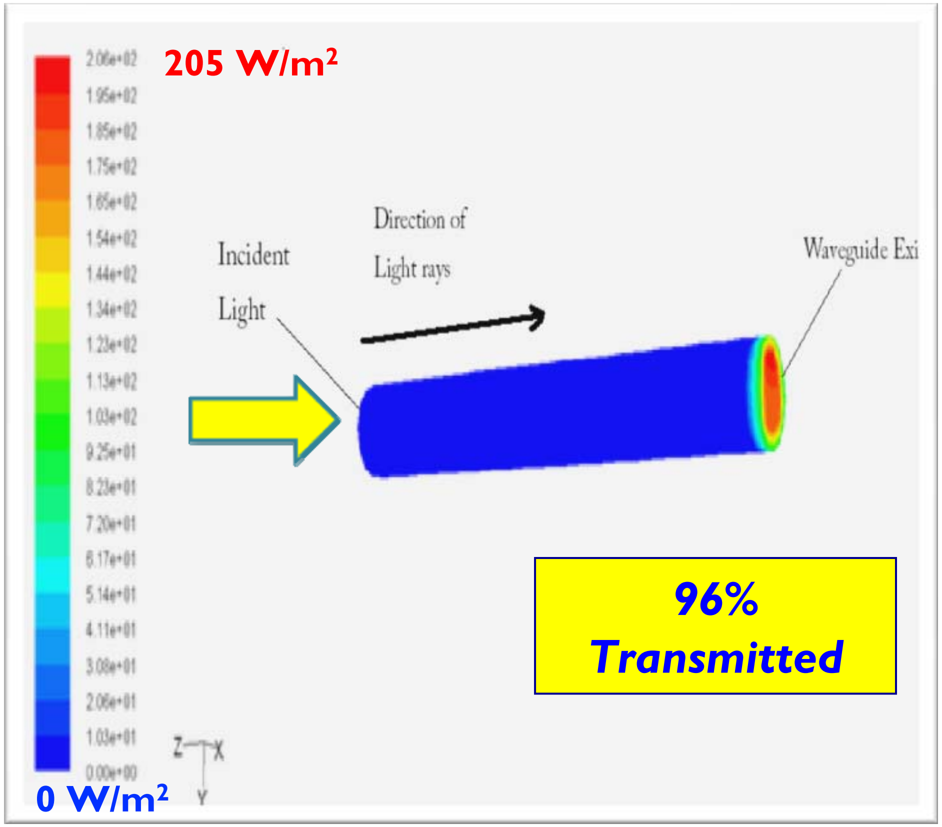
Bevel cut

Results: Simple Waveguide

Normal Incident Light rays, 200 W/m²



Notice scattering resulting from imperfections



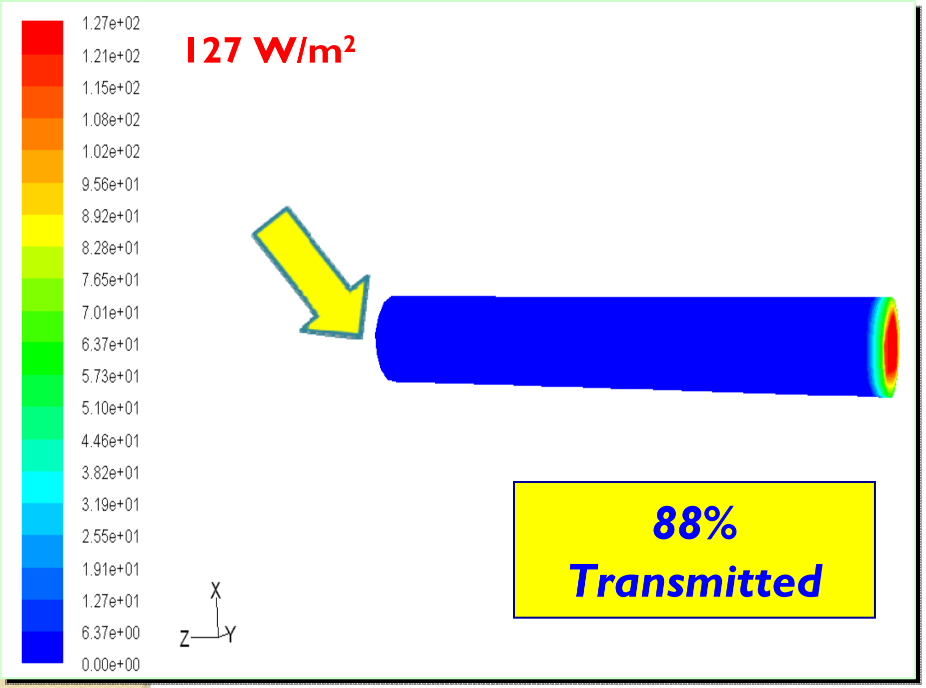
205 W/m²

0 W/m²

96% Transmitted

Results: Simple Waveguide

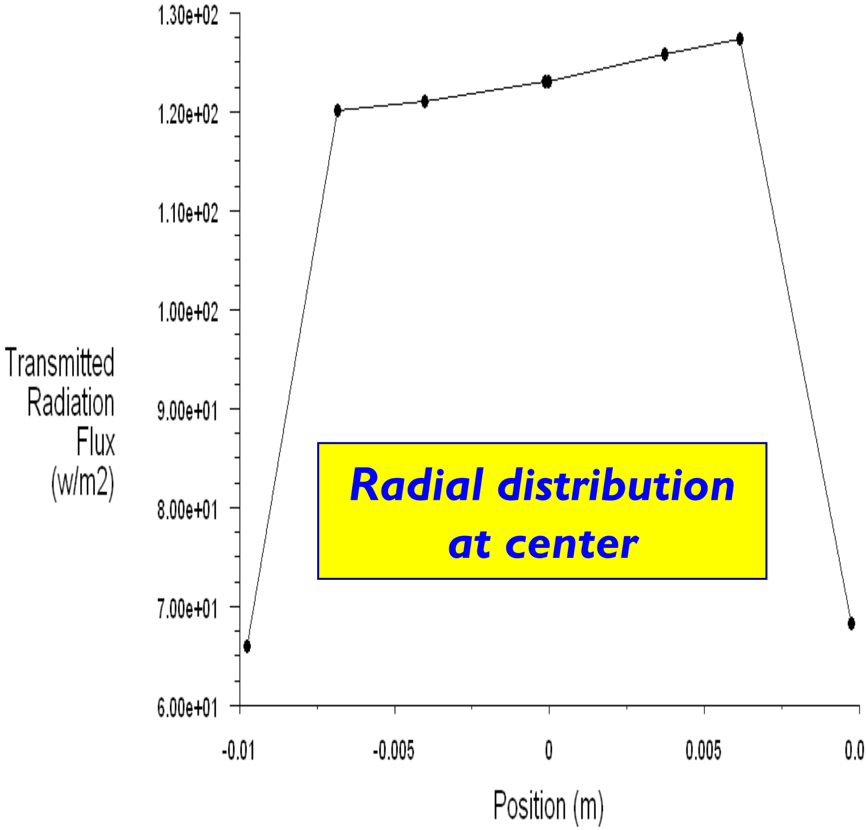
45° Incident Light rays, 200 W/m²



127 W/m²

88% Transmitted

0 W/m²

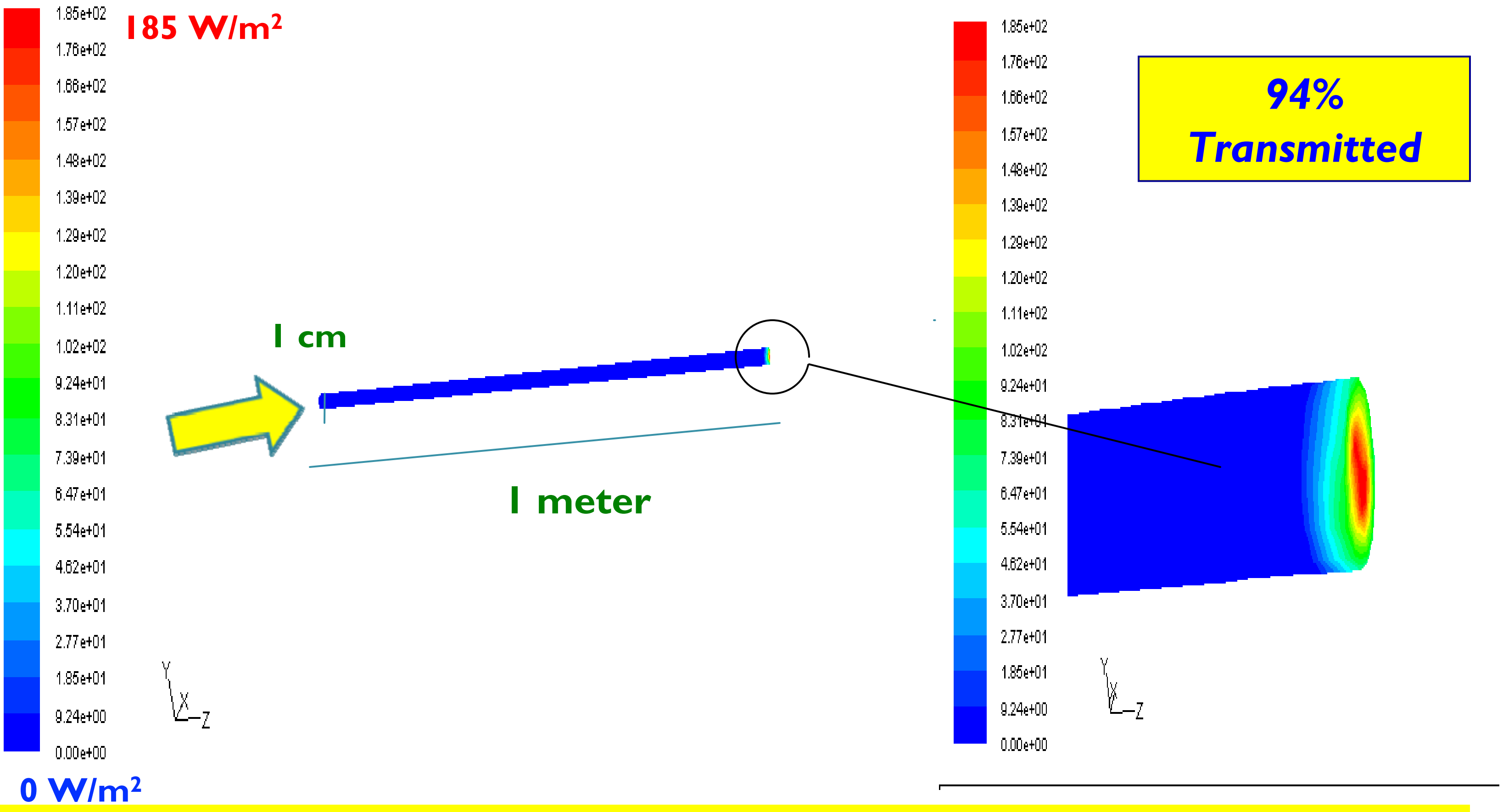


Radial distribution at center

Losses 6% front reflection, 6% back reflection

Results: Scalability

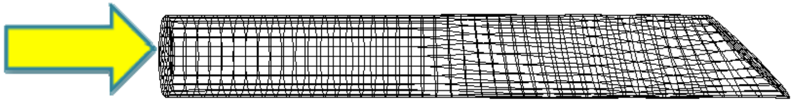
Normal Incident Light rays, 200 W/m²



94% Transmitted

- *guide length has no considerable effect on the efficiency of light transfer*
- *It is possible to model shorter versions and expect results to be similar for a longer waveguide*

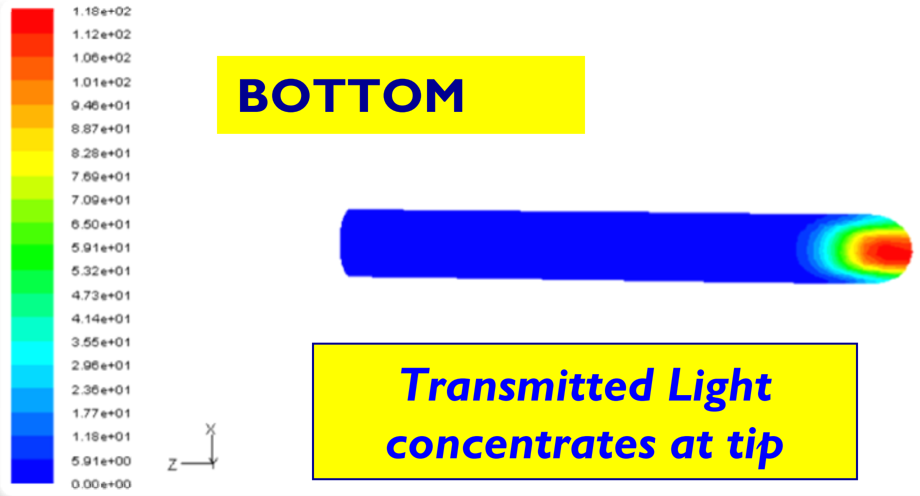
Results: Beveled (45°) waveguide



Normal Incident Light, 200 W/m²

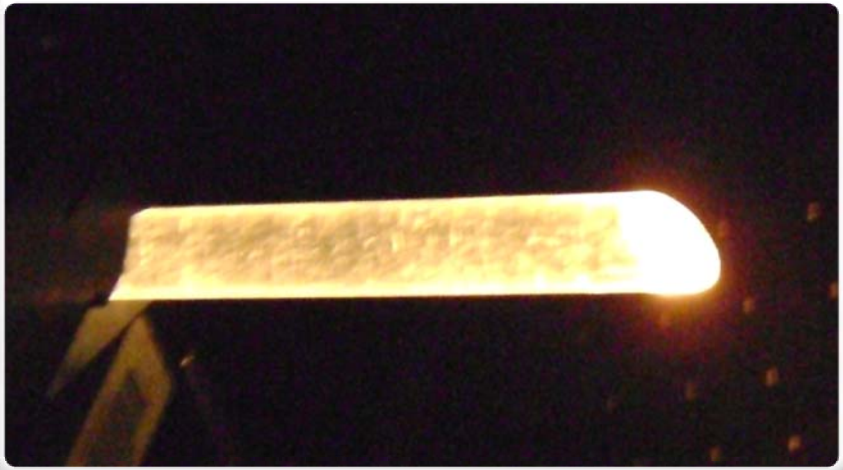
118 W/m²

TOP



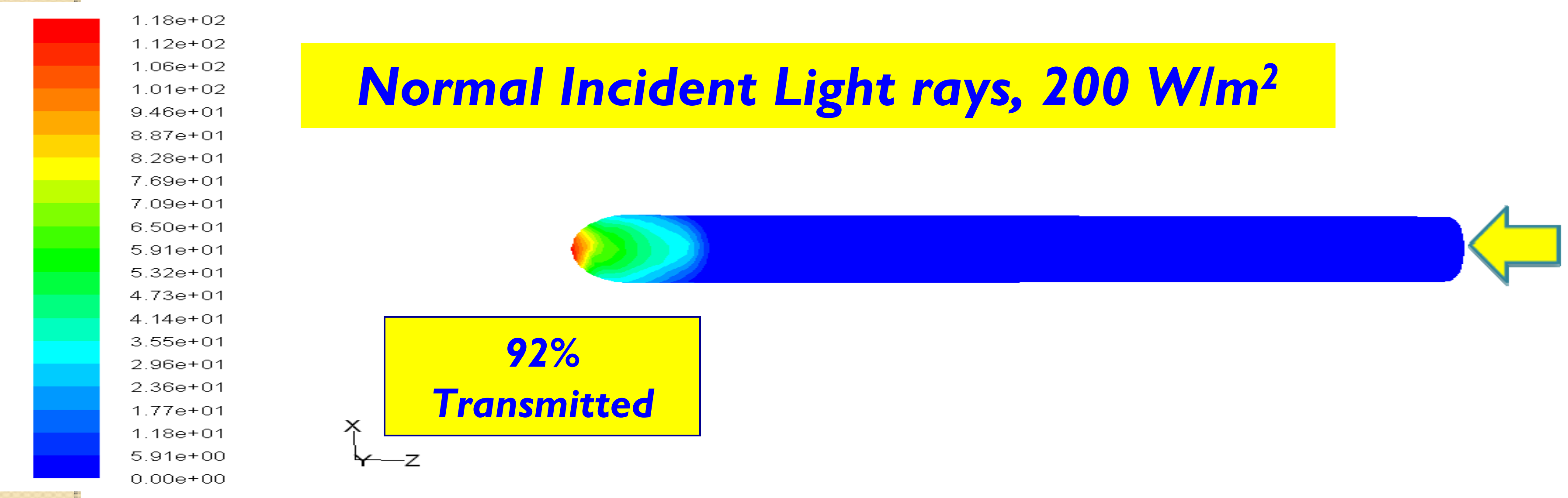
BOTTOM

Transmitted Light concentrates at tip

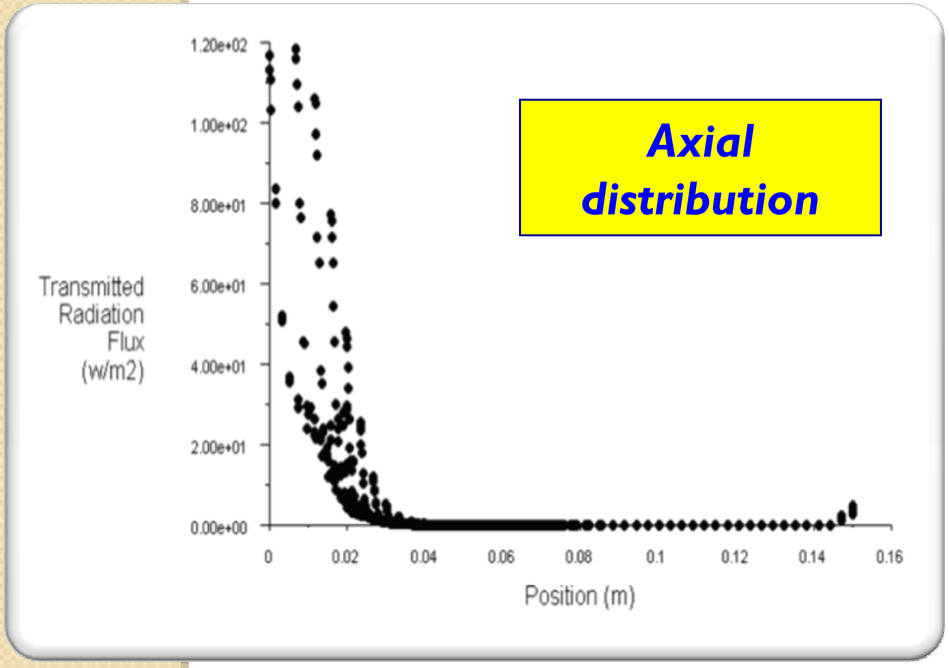


Axial and Radial Distributions

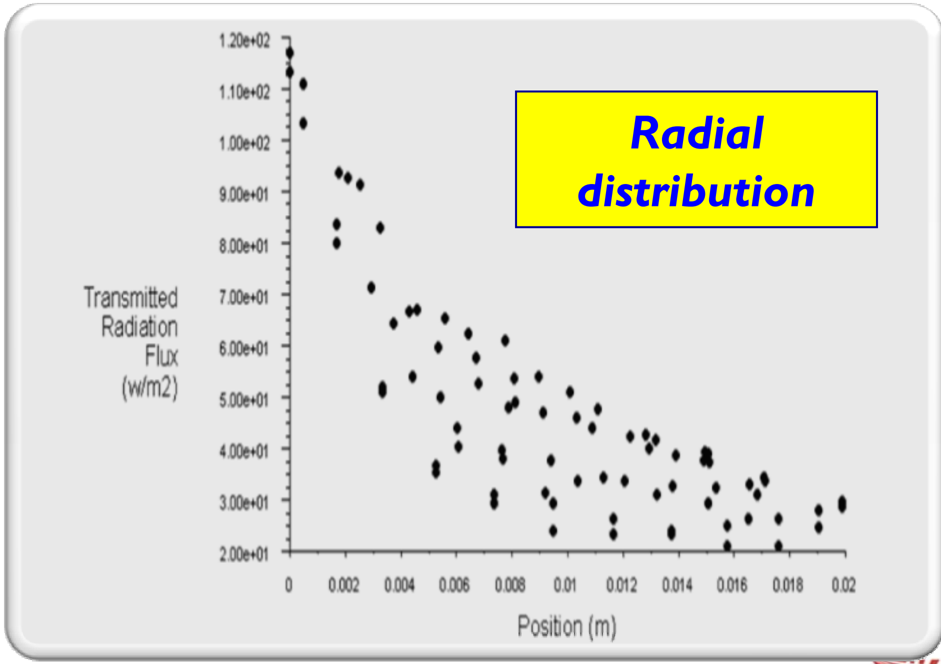
Normal Incident Light rays, 200 W/m²



_92%_
Transmitted

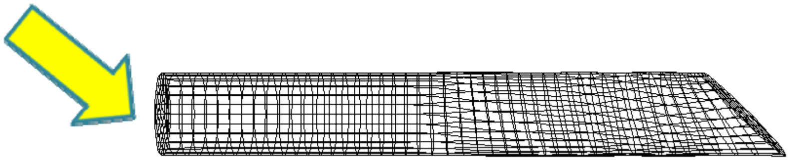


Axial distribution



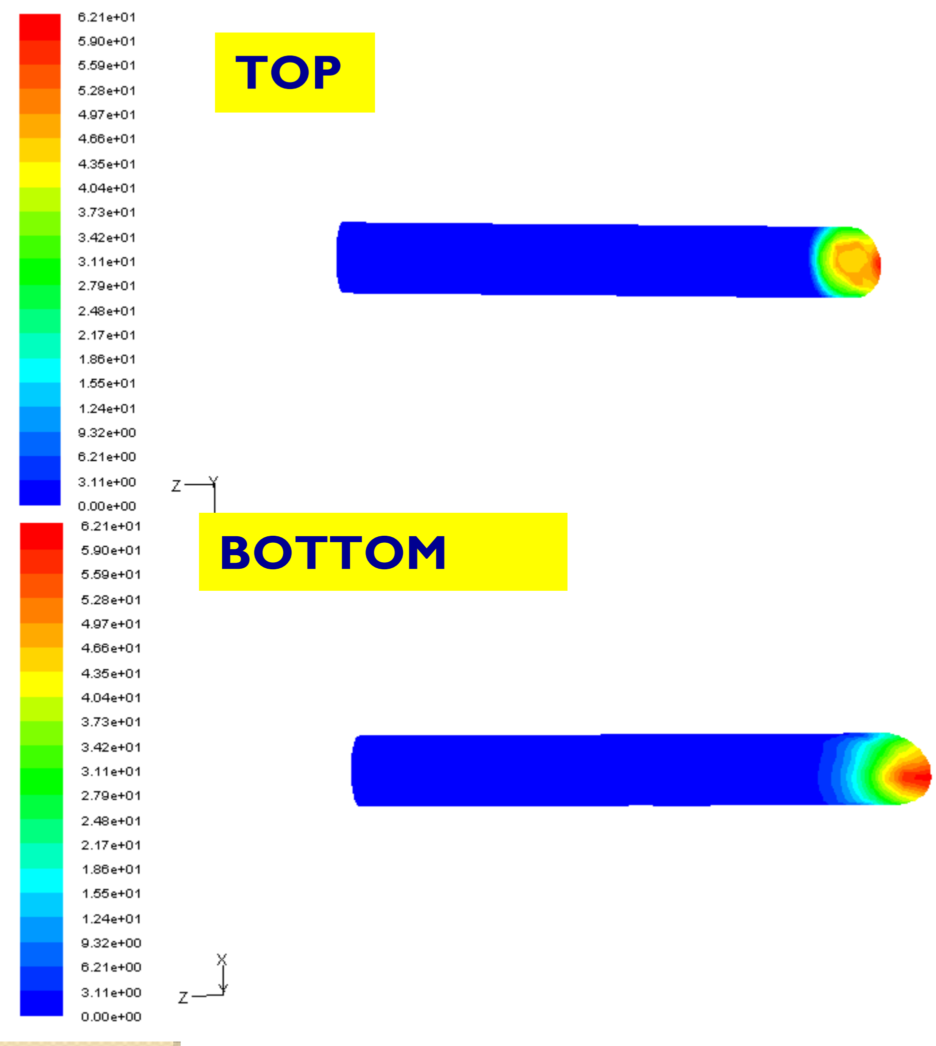
Radial distribution

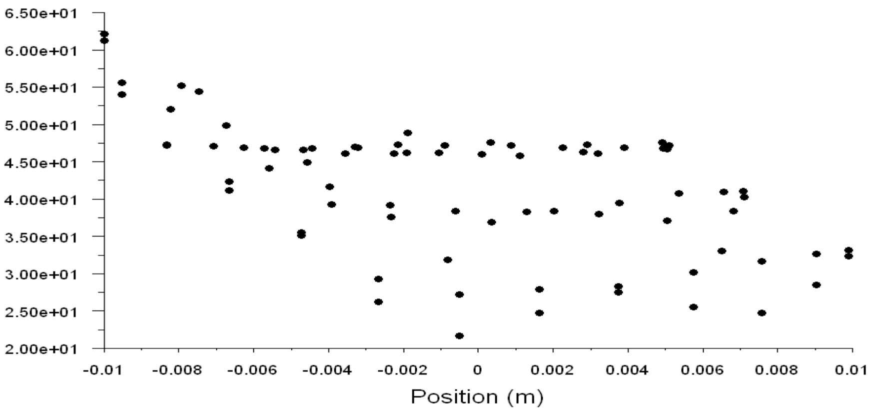
Results: Beveled (45°) waveguide



45° Incident Light, 200 W/m²

64 W/m²



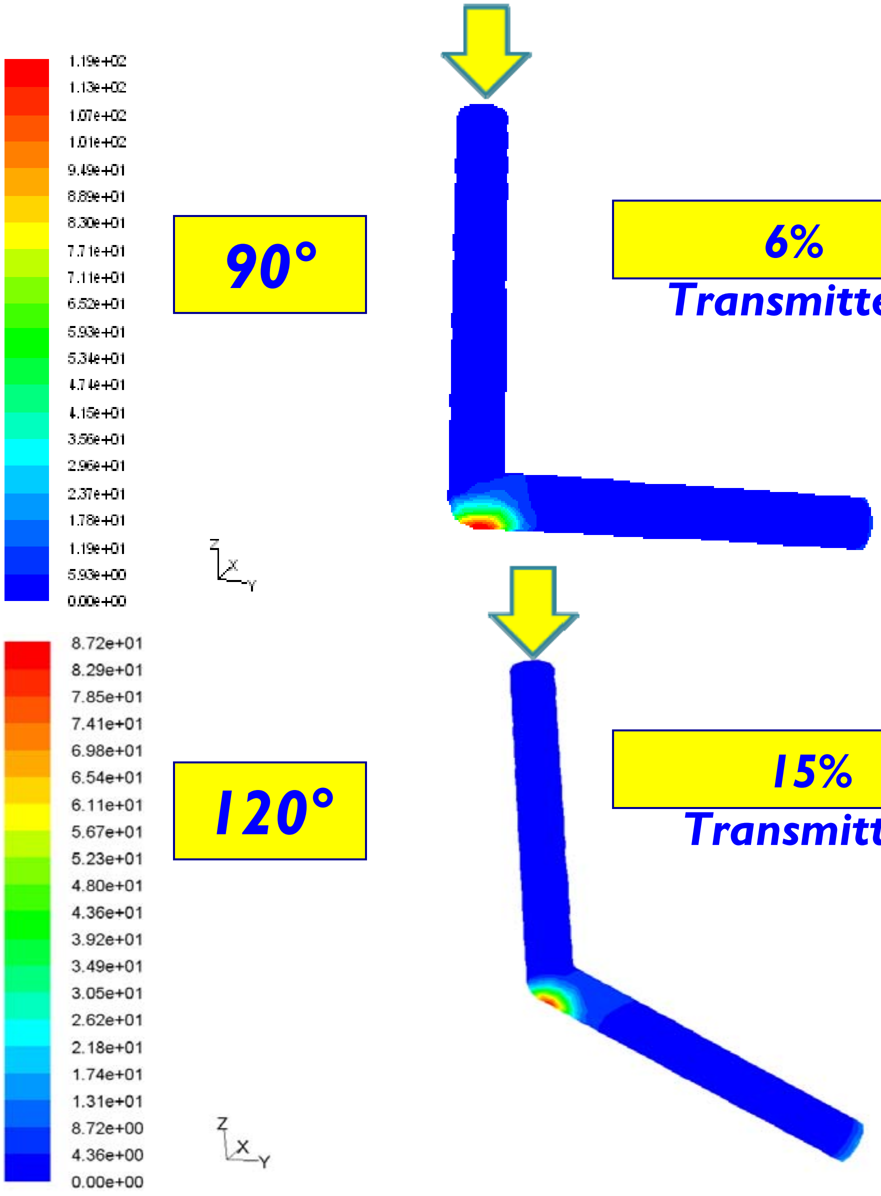


More uniform radial distribution

Results: Bent Waveguides (redirection)

Normal Incident Light rays, 200 W/m²

- ***Large losses***
- ***Most transmission is at junction***
- ***Need for optical insulation***



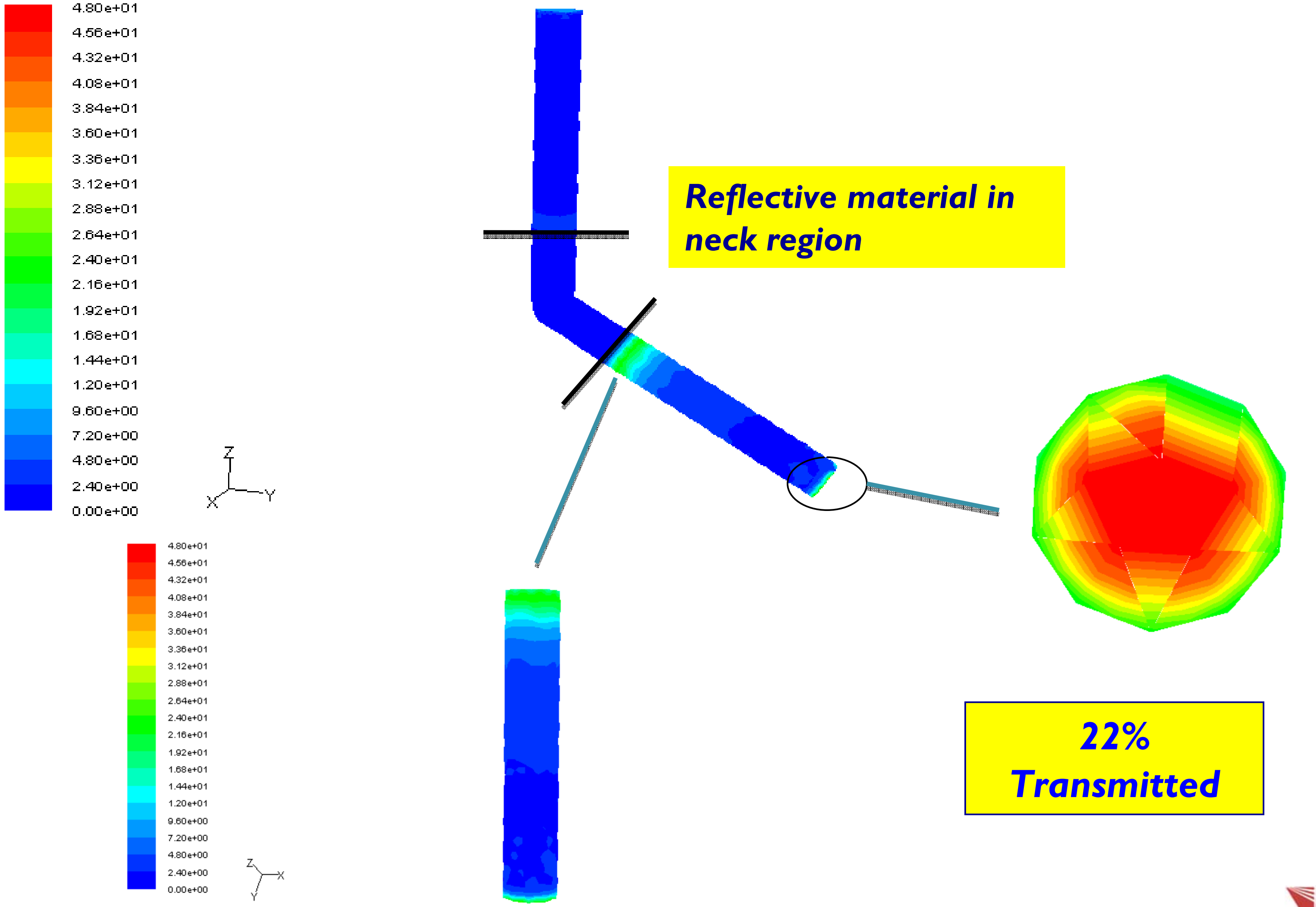
90°

6% Transmitted

120°

15% Transmitted

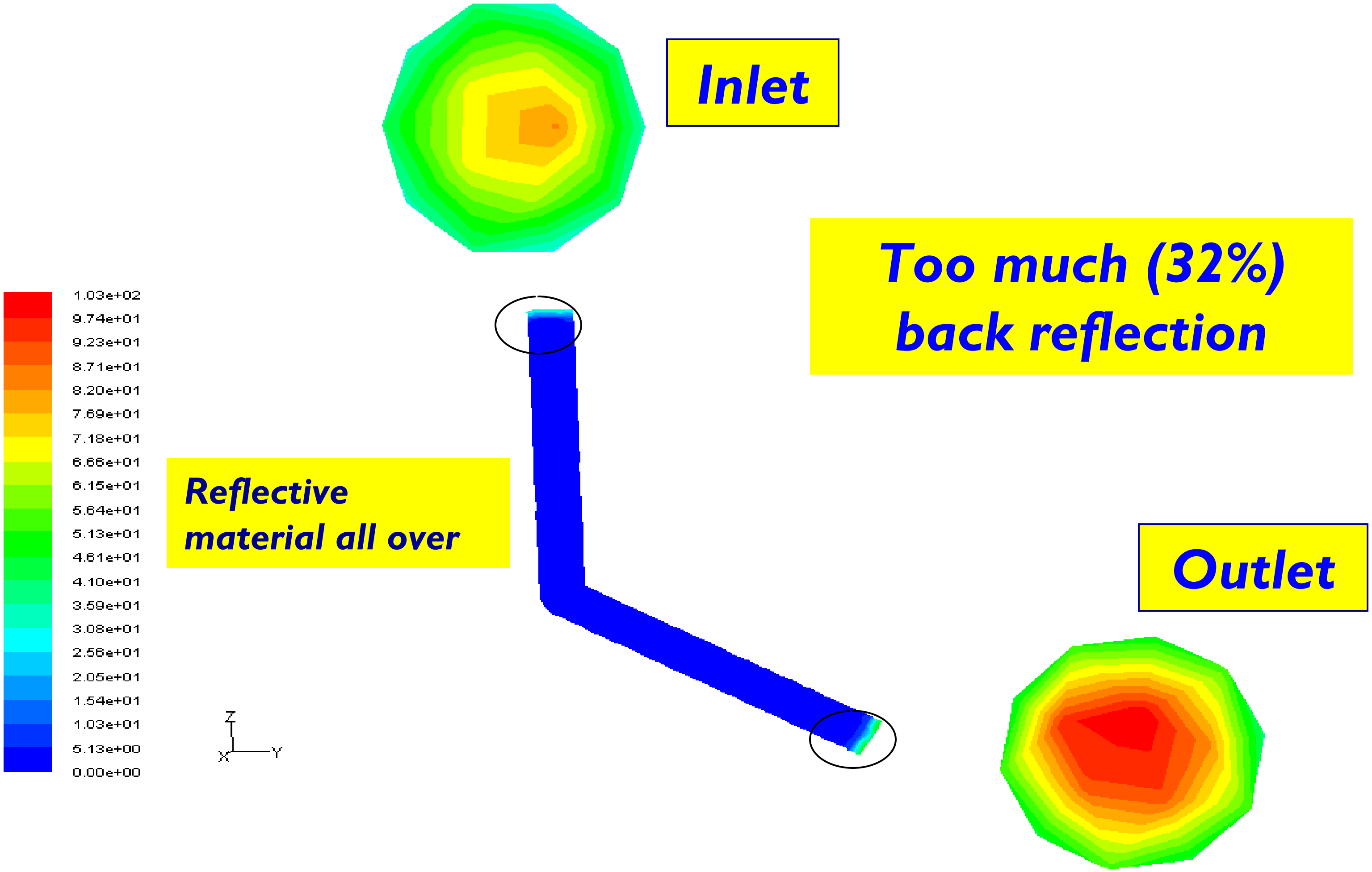
Effect of Insulation with reflective coating



Reflective material in neck region

22% Transmitted

Effect of Insulation with reflective coating



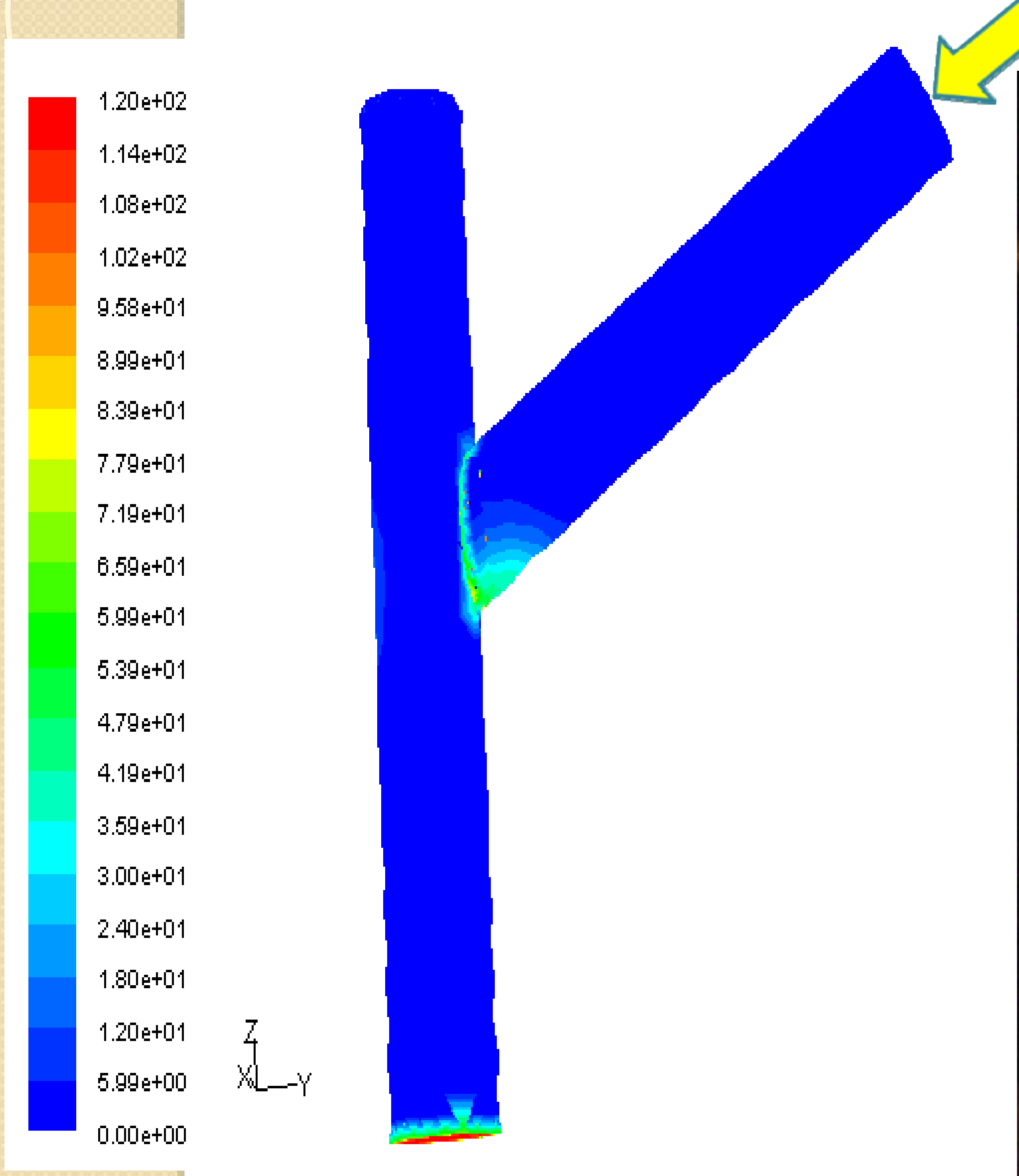
Inlet

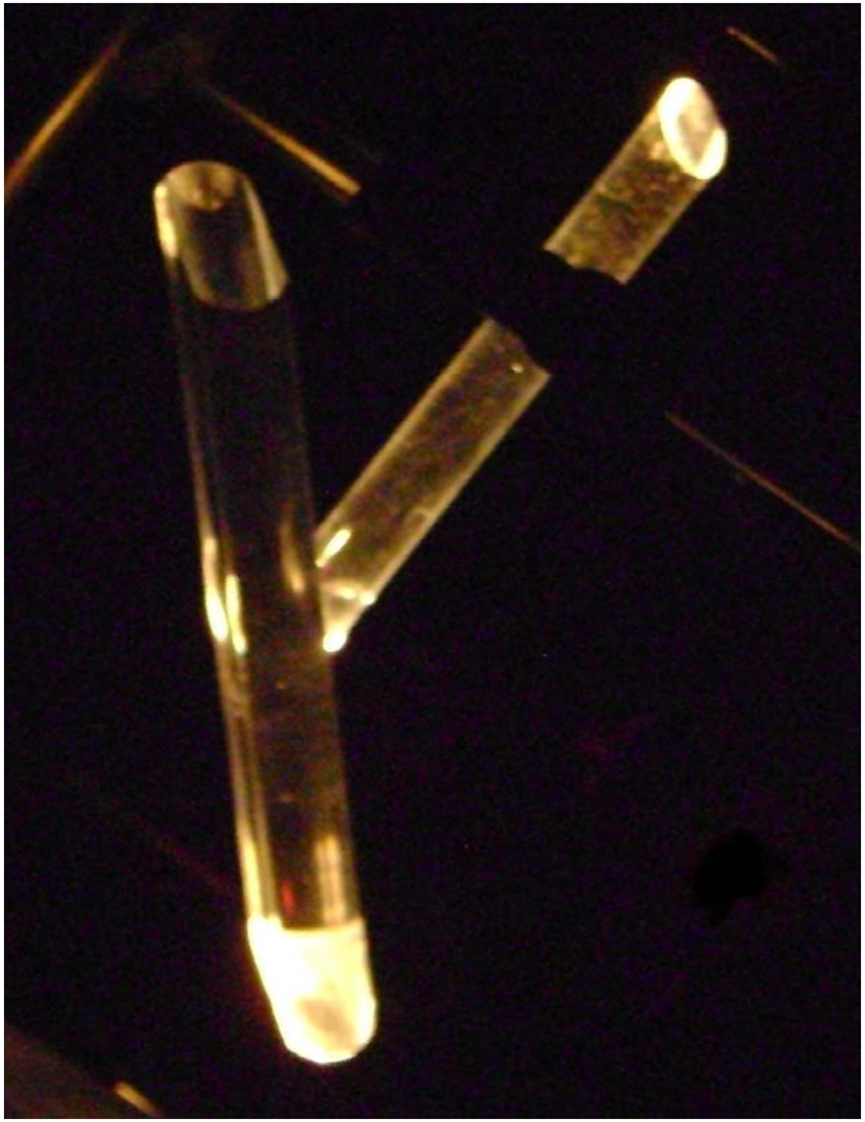
Too much (32%) back reflection

Reflective material all over

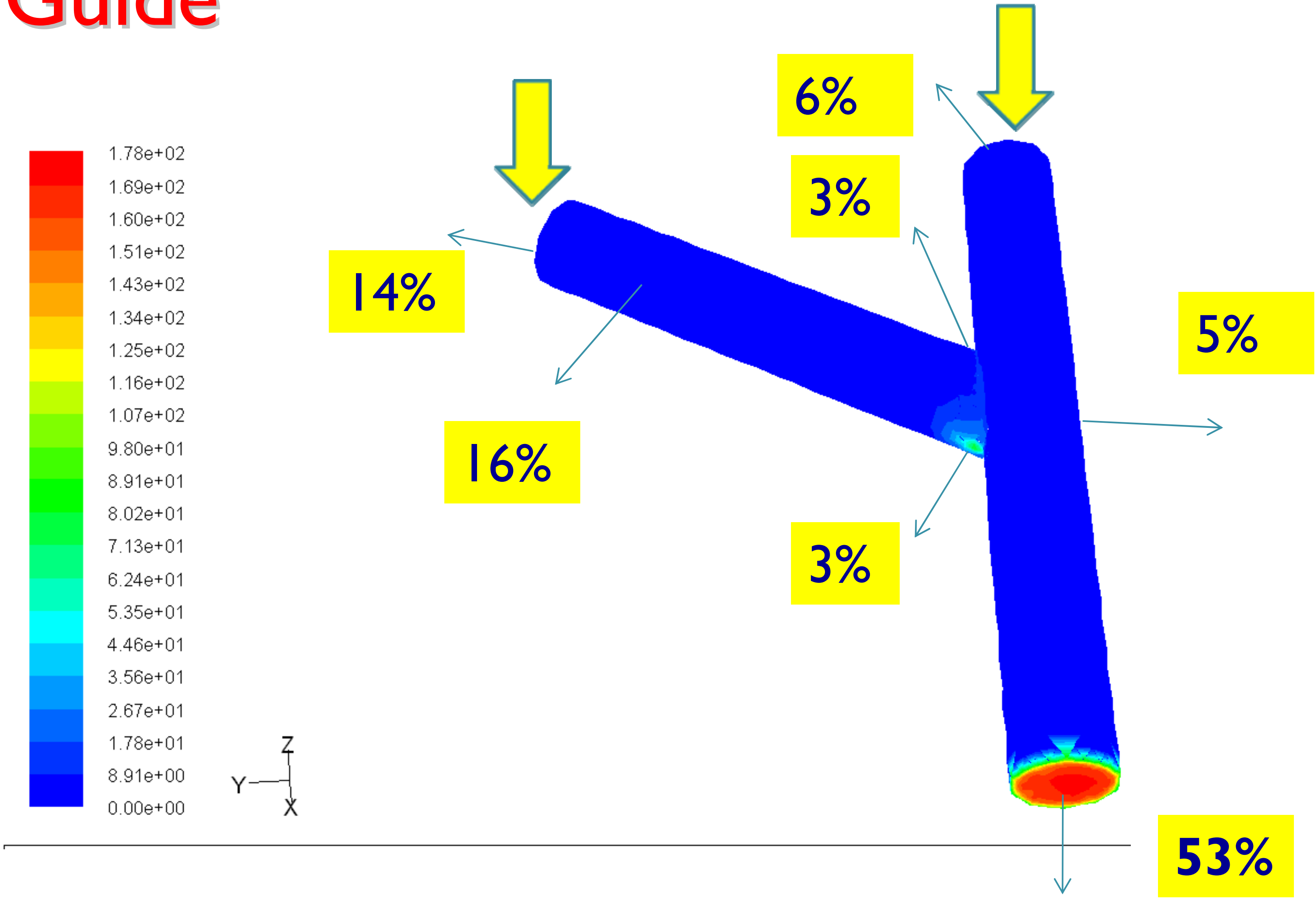
Outlet

Results: Compound Y-shaped Waveguide

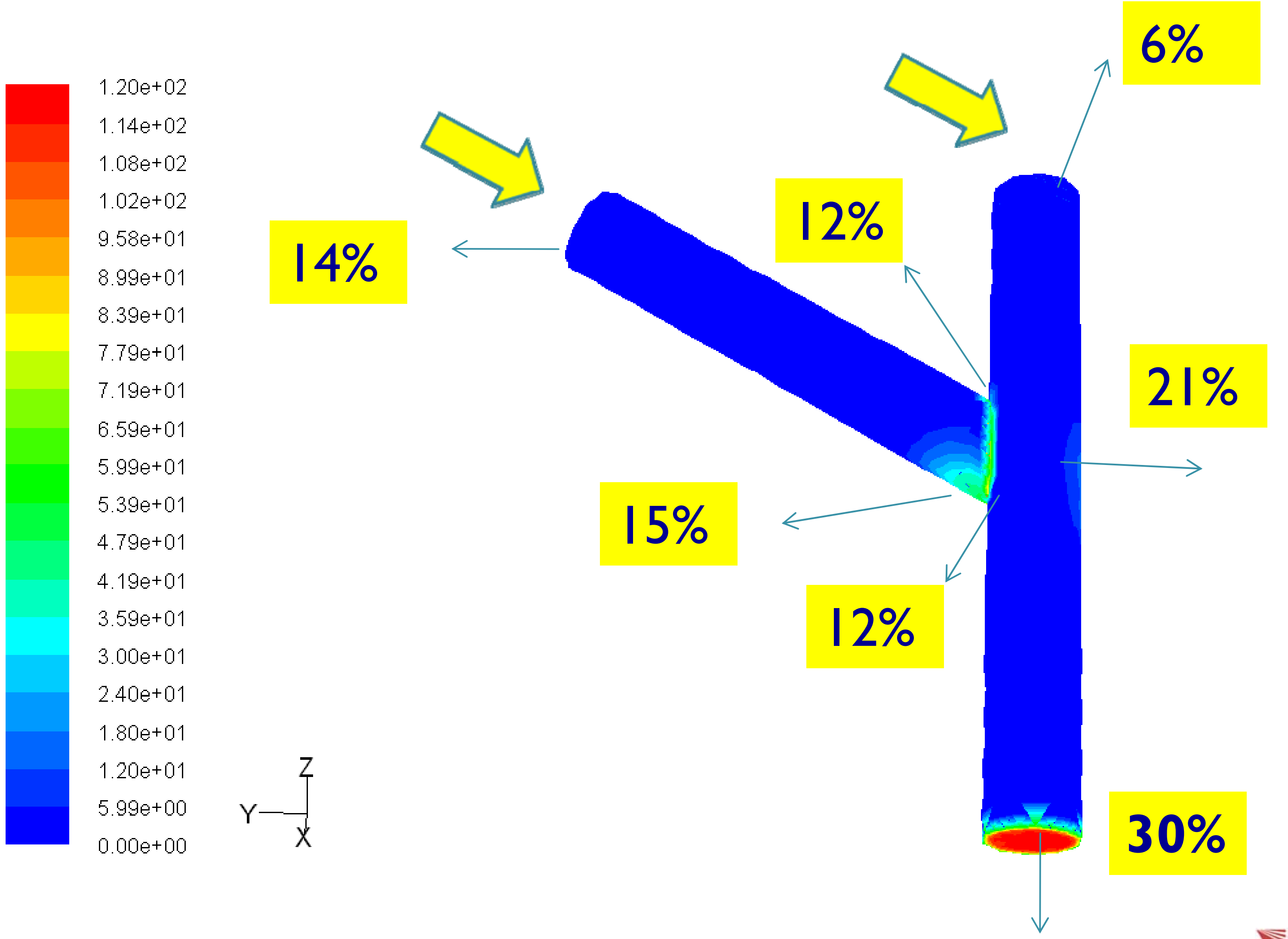




Results: Compound Y-Shaped Guide

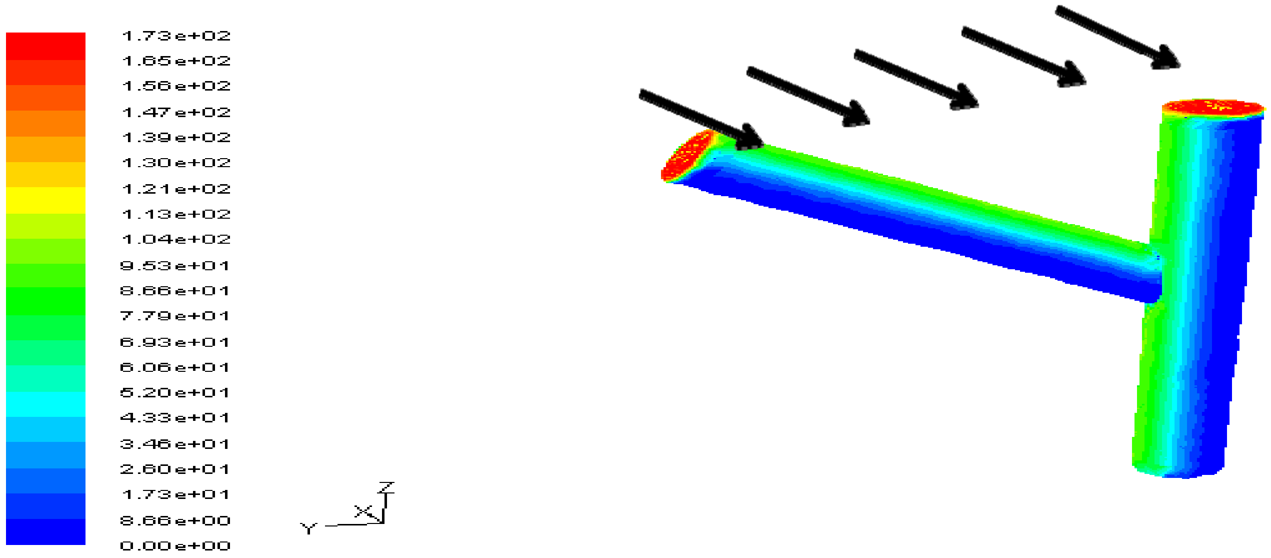


Results: Compound Y-Shaped Guide



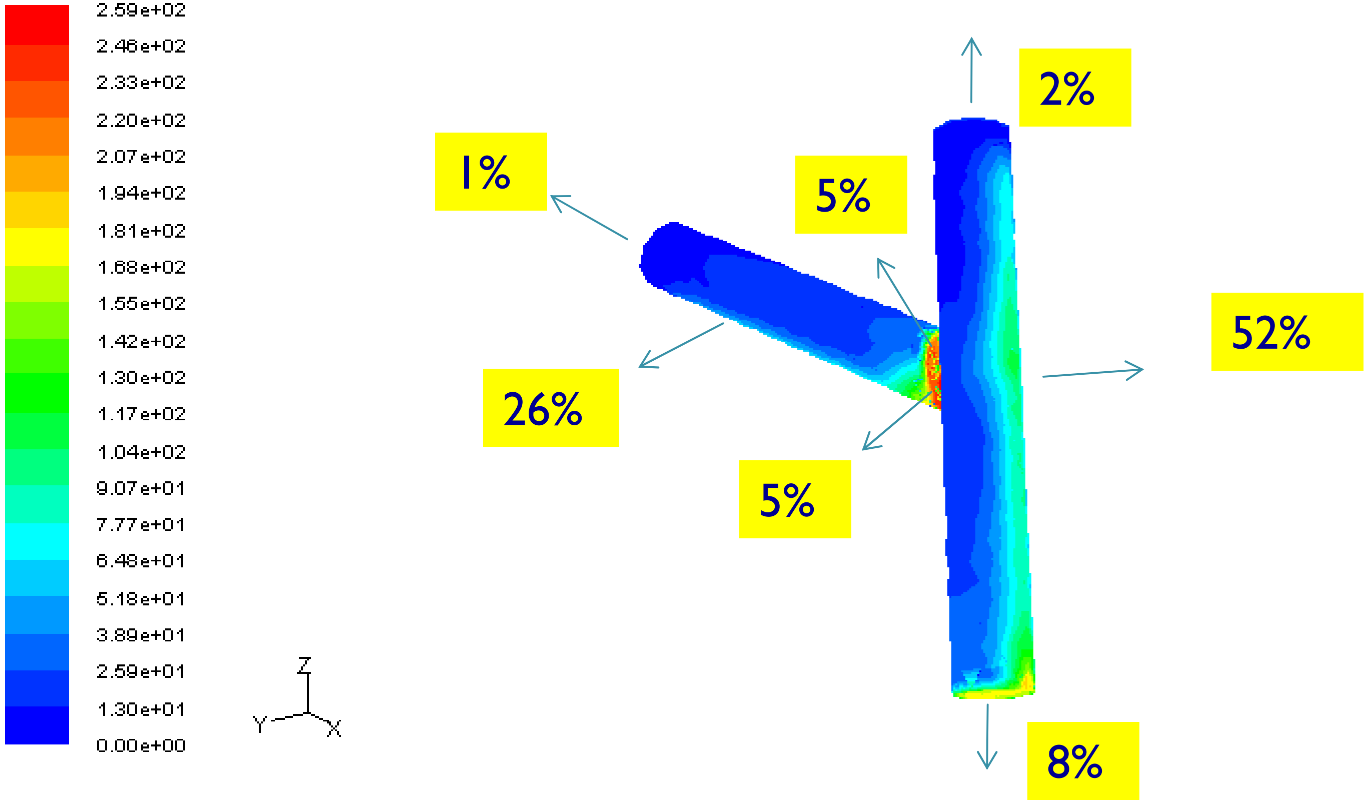
Results: Compound Y-Shaped Guide

All walls Irradiated by incident 45° light



Light distribution on outer surface of guide

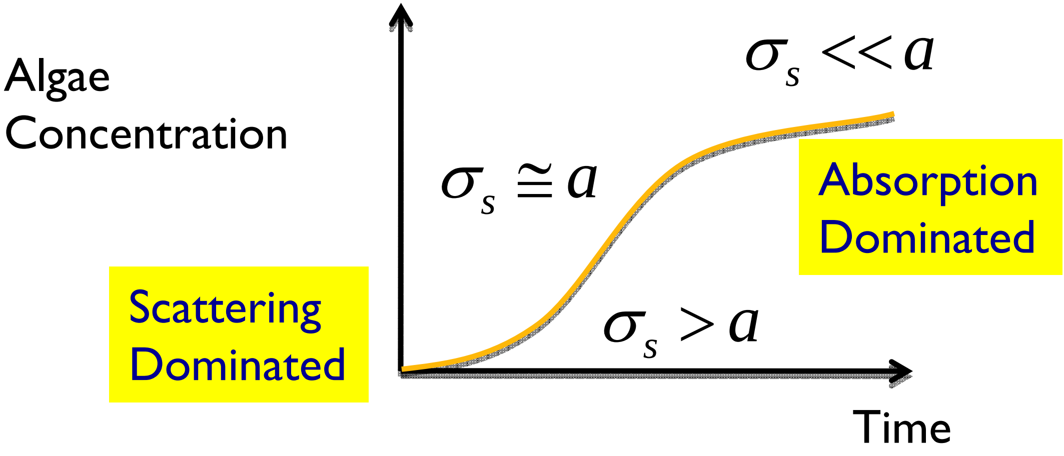
Results: Y-shaped guide, 45° incident light



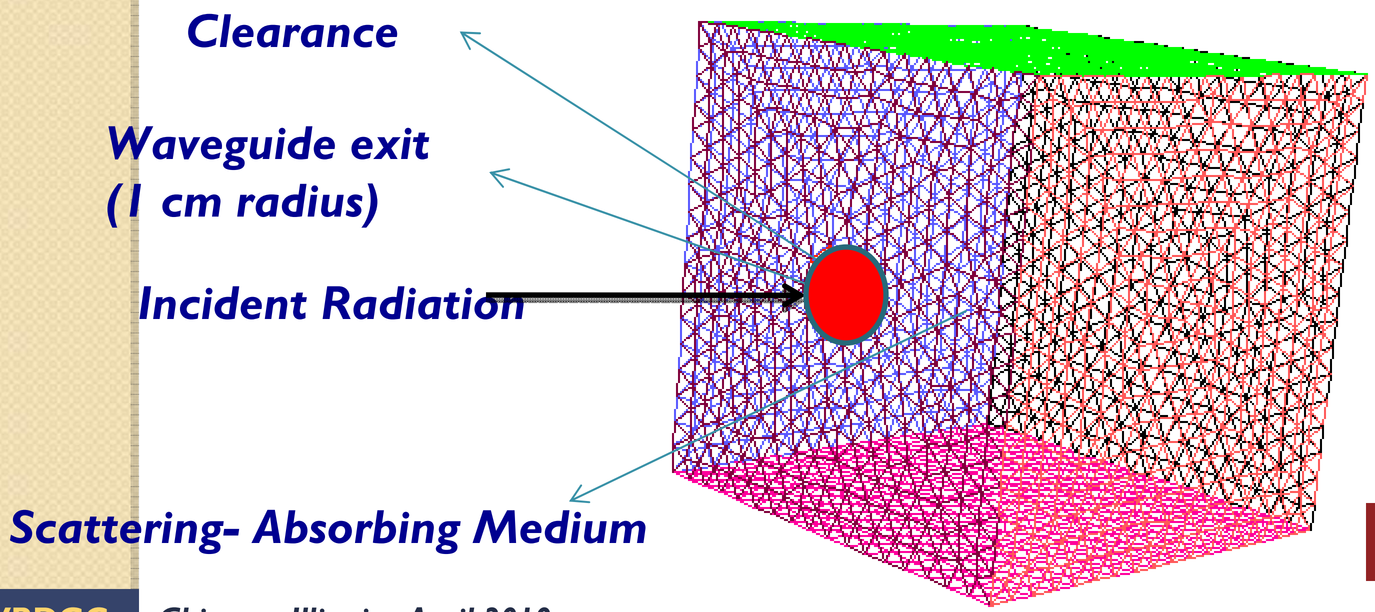
Outer surface collects a lot of light, but delivers at junction below critical angle

Results: Photobioreactor with Algae Suspension

PBR Optical Regimes

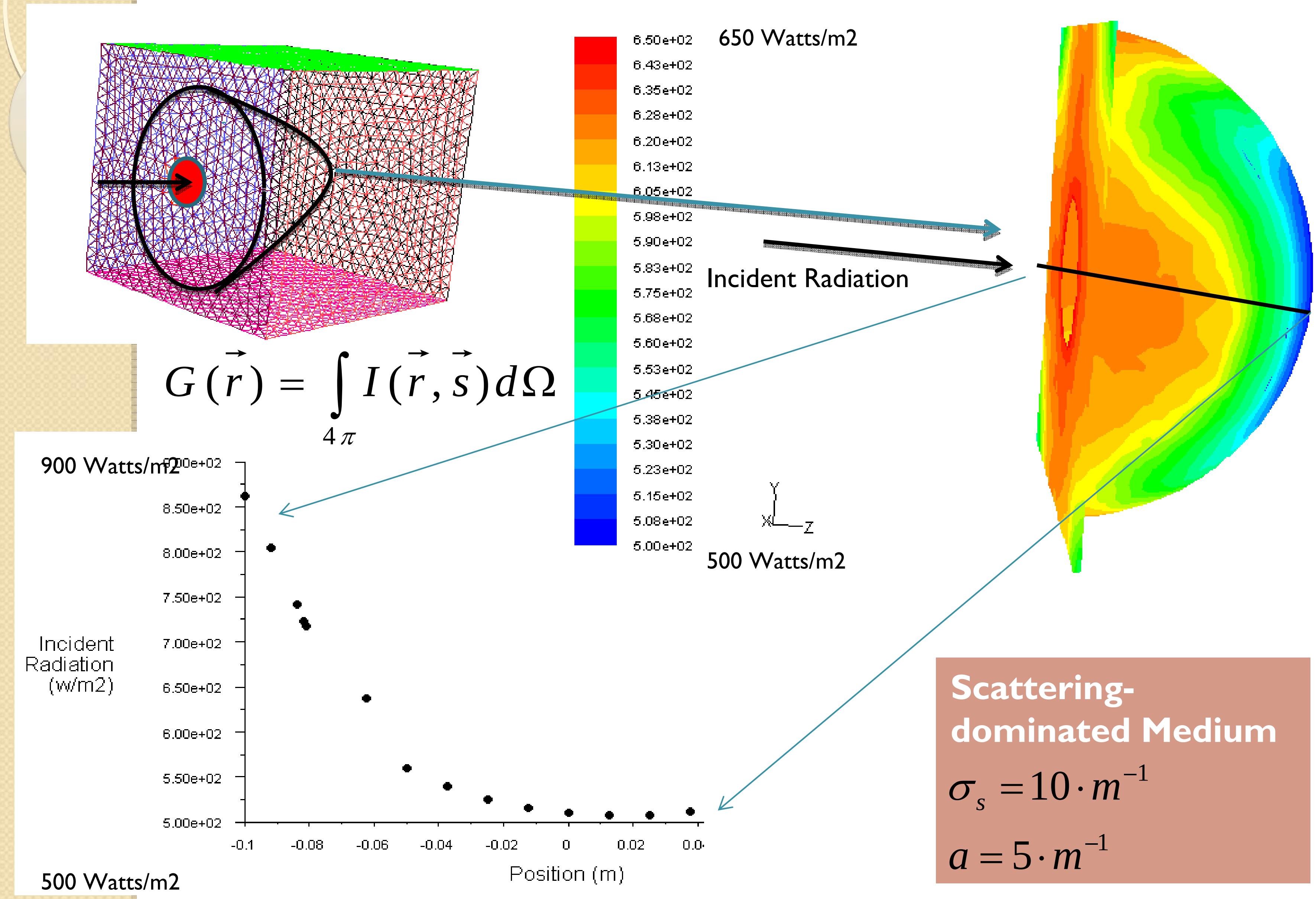


Reactor Segment Geometry



10X10X10 cm

Results: PBR with Algae Suspension



$$G(\vec{r}) = \int_{4\pi} I(\vec{r},\vec{s})\,d\Omega$$

Scattering-dominated Medium

$$\sigma_s = 10 \cdot m^{-1}$$

$$a = 5 \cdot m^{-1}$$

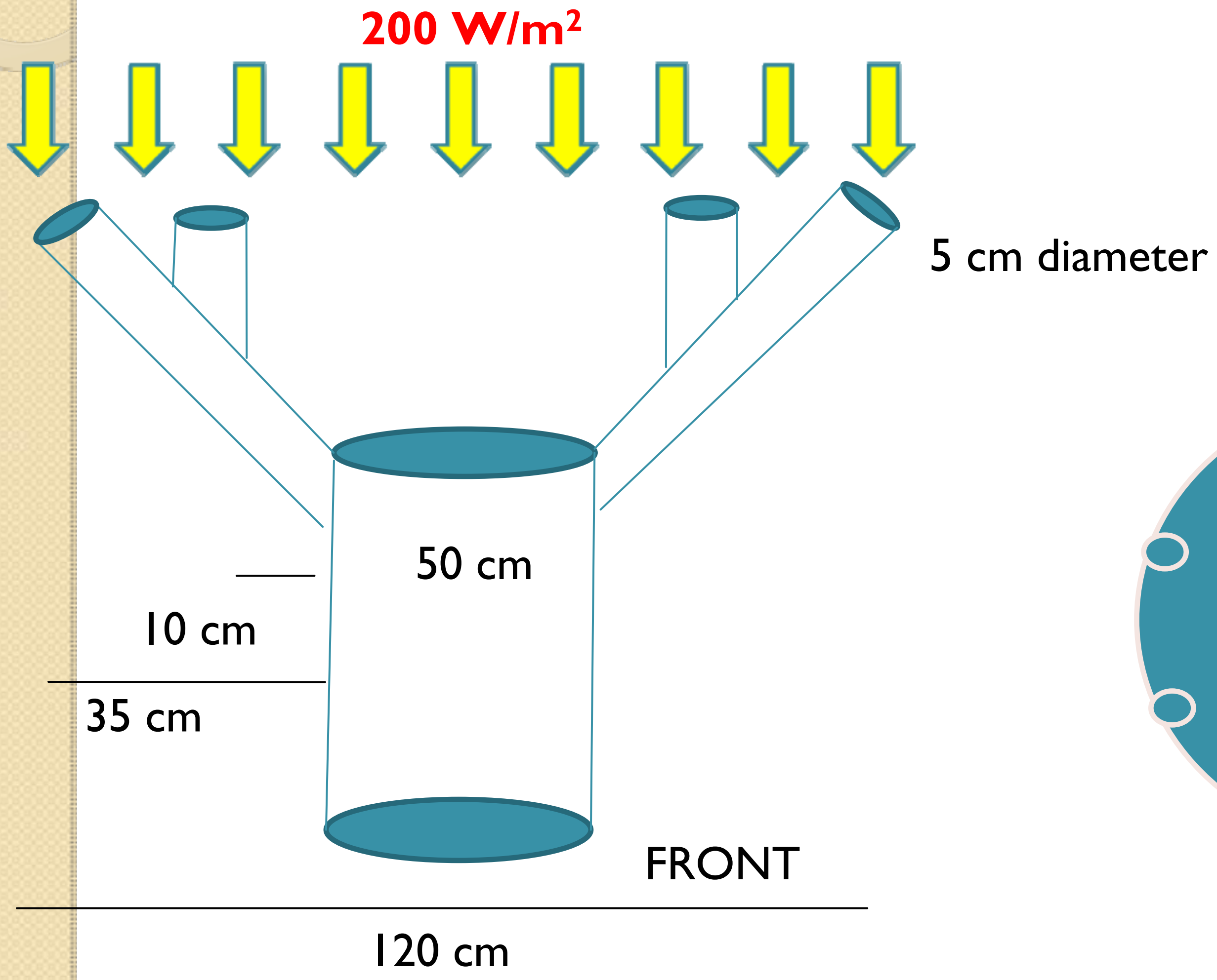
Light Collection System Schematic

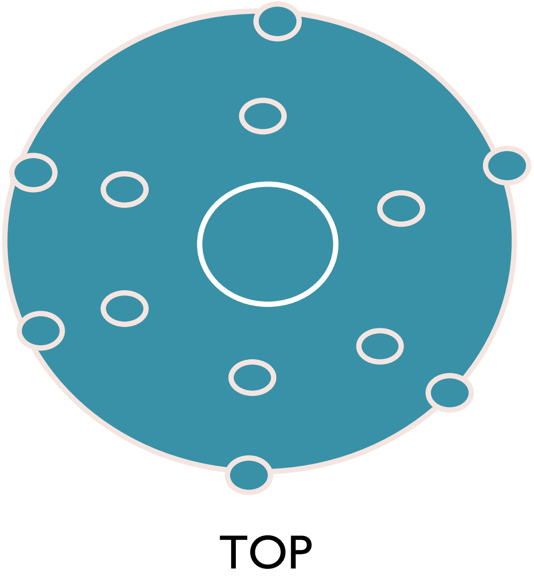
17% Efficiency

$$Incident = 200 \cdot \frac{\pi(1.2^2)}{4} = 226.19 \cdot Watts$$

$$Collected = 0.12*6 + 0.96*\frac{\pi}{4}(0.5)^2*200 = 38.42 \cdot Watts$$

12 PM





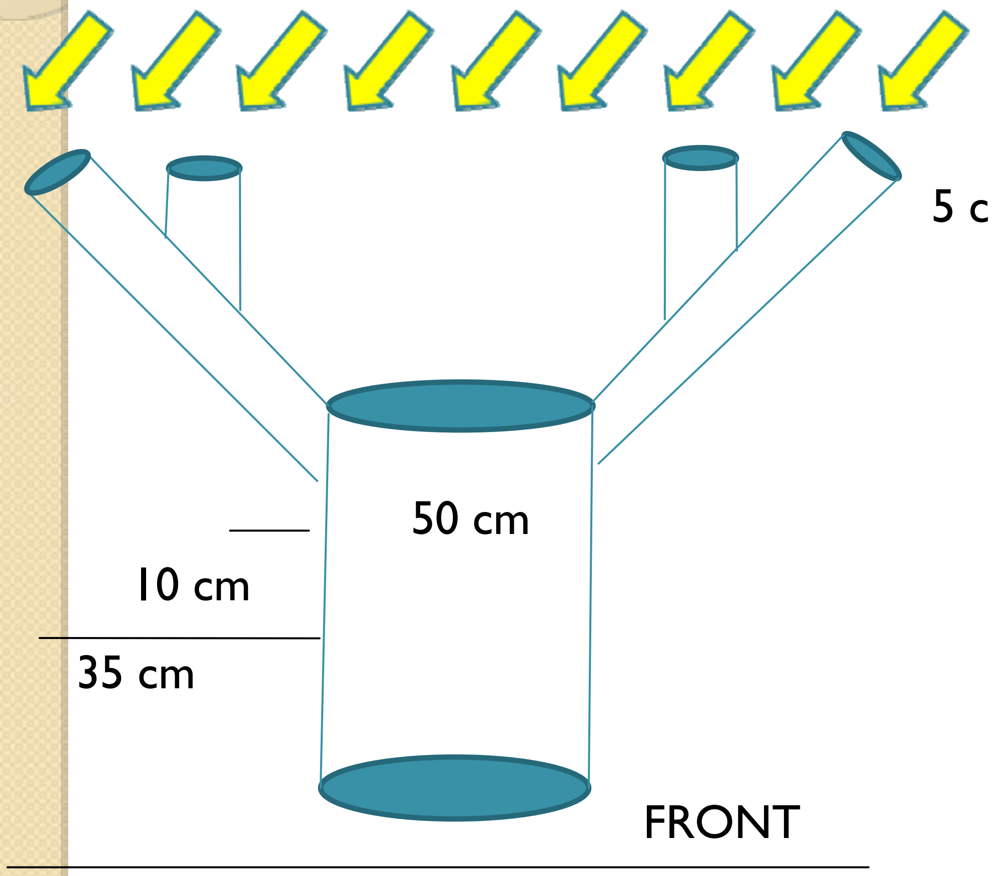
Light Collection System Schematic

15% Efficiency

$$Incident = 200 \cdot \sin 45 \cdot \frac{\pi (1.2^2)}{4} = 159.94 \cdot Watts$$

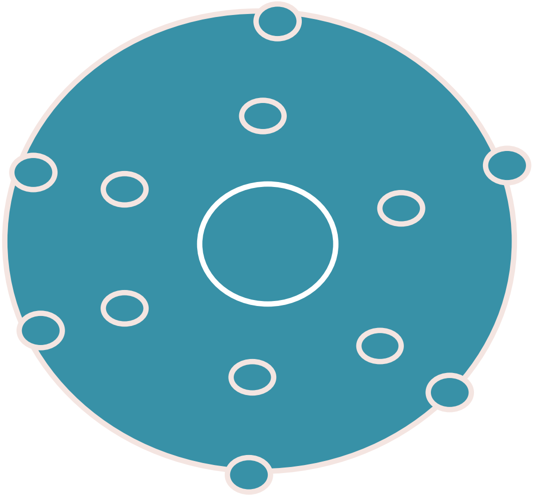
$$Collected = 0.11 * 6 + 0.86 * \frac{\pi}{4} (0.5)^2 * 200 \cdot \sin 45 = 24.54 \cdot Watts$$

200 W/m²



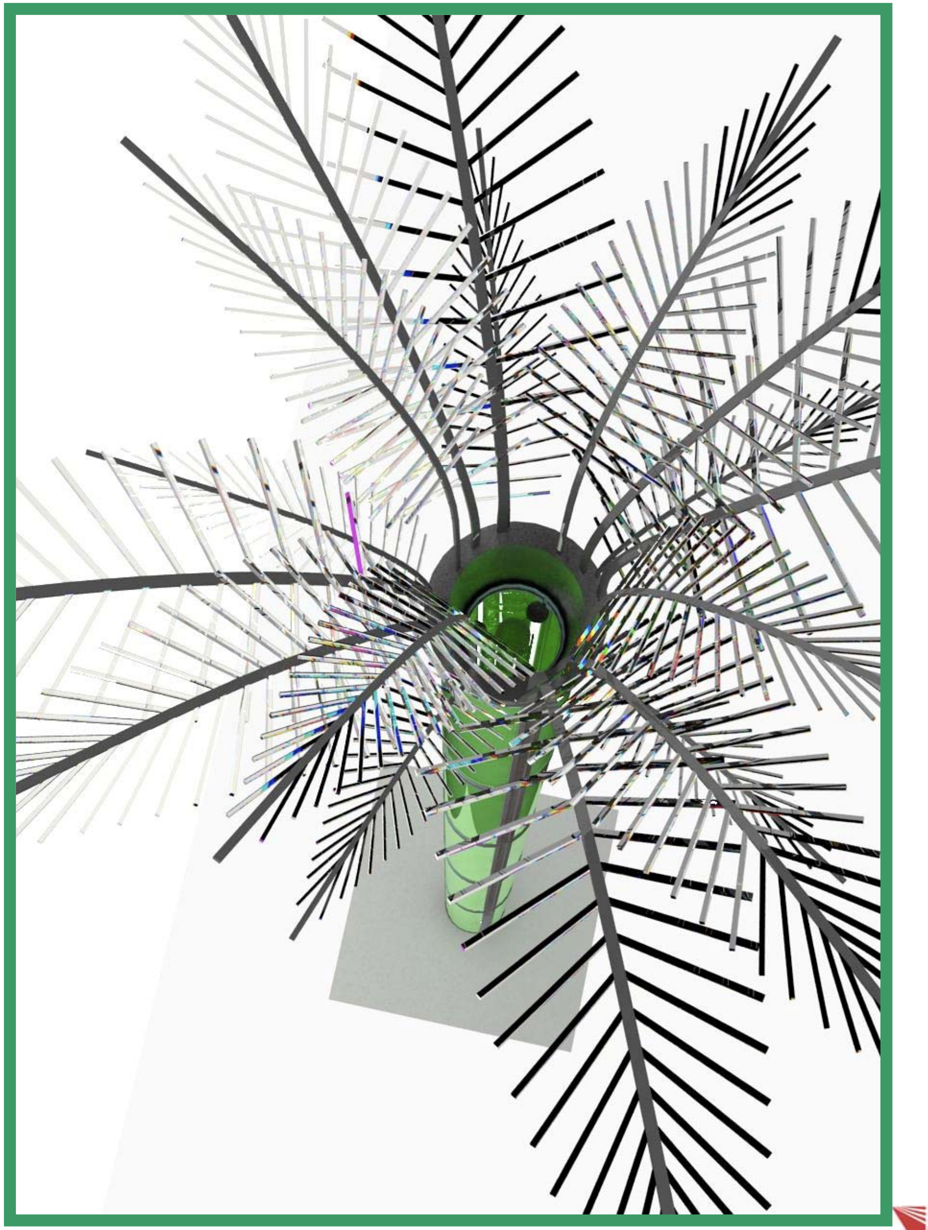
120 cm

3 PM



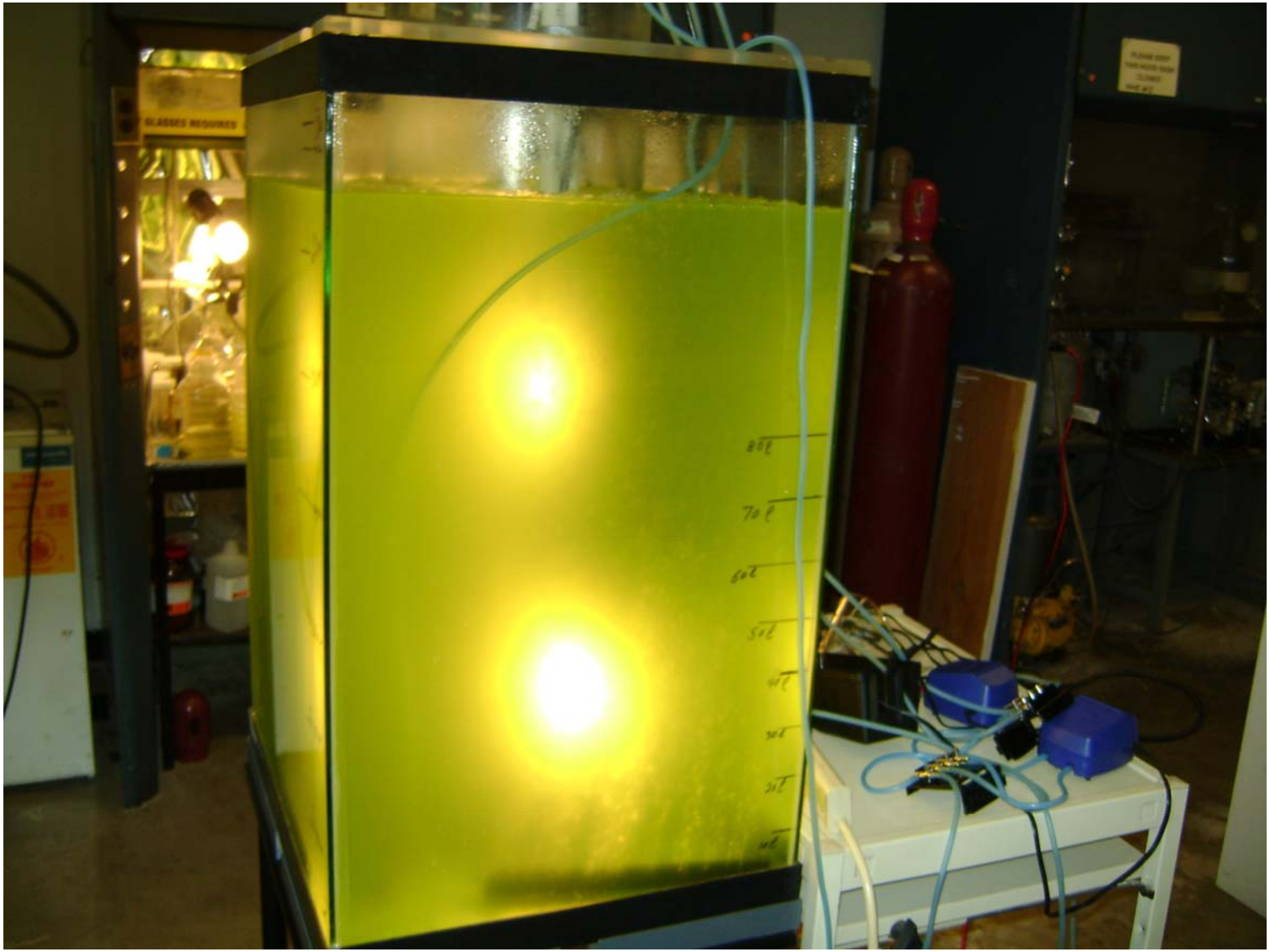
Light Collection System - Target

- ***Modular design approach***
- ***Need optimized Junctions and compound guides***
- ***Genetic algorithm for optimization by addition and mutation of elements***

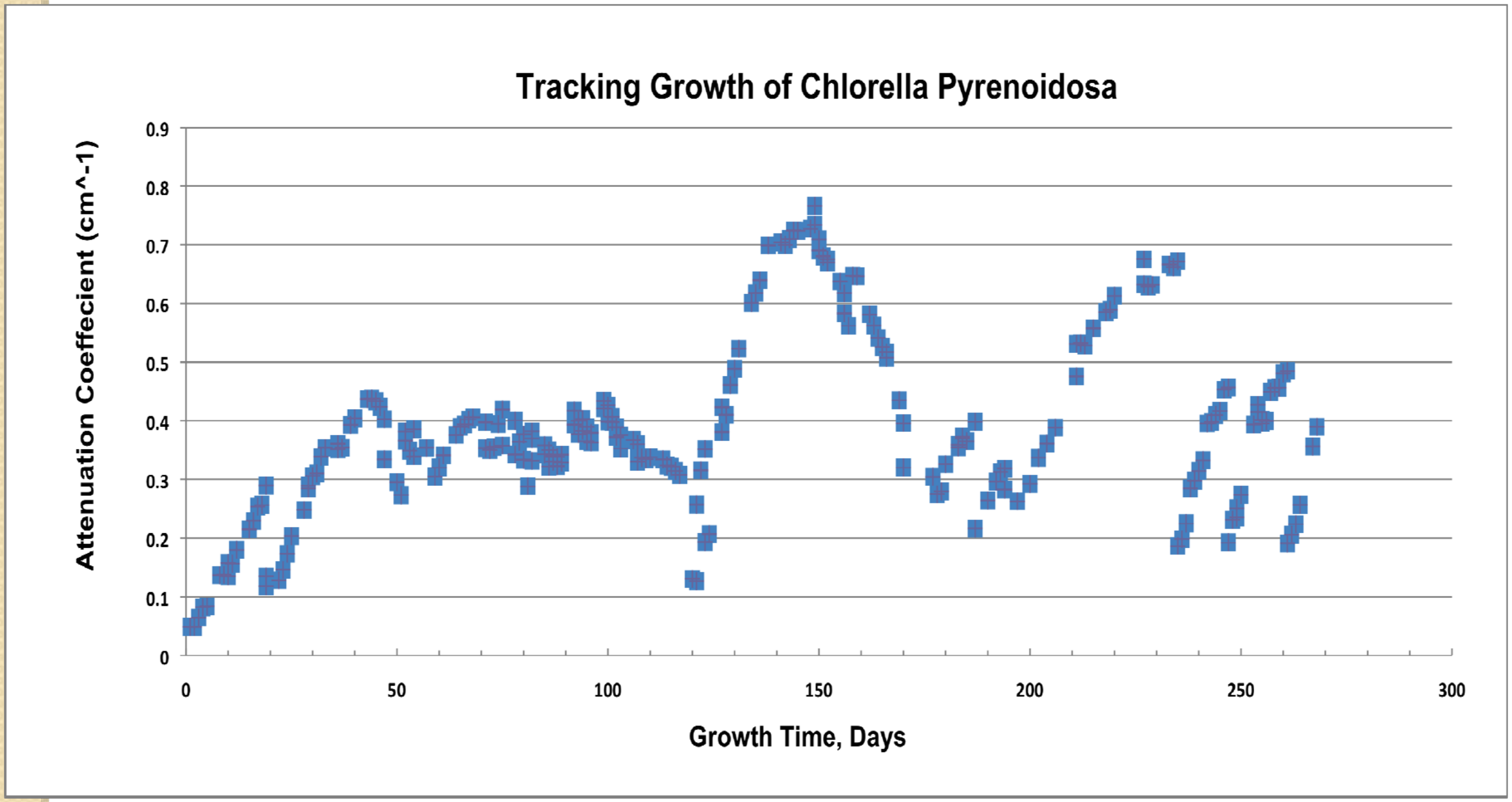


Tree in a Lab
Photo-Bioreactor

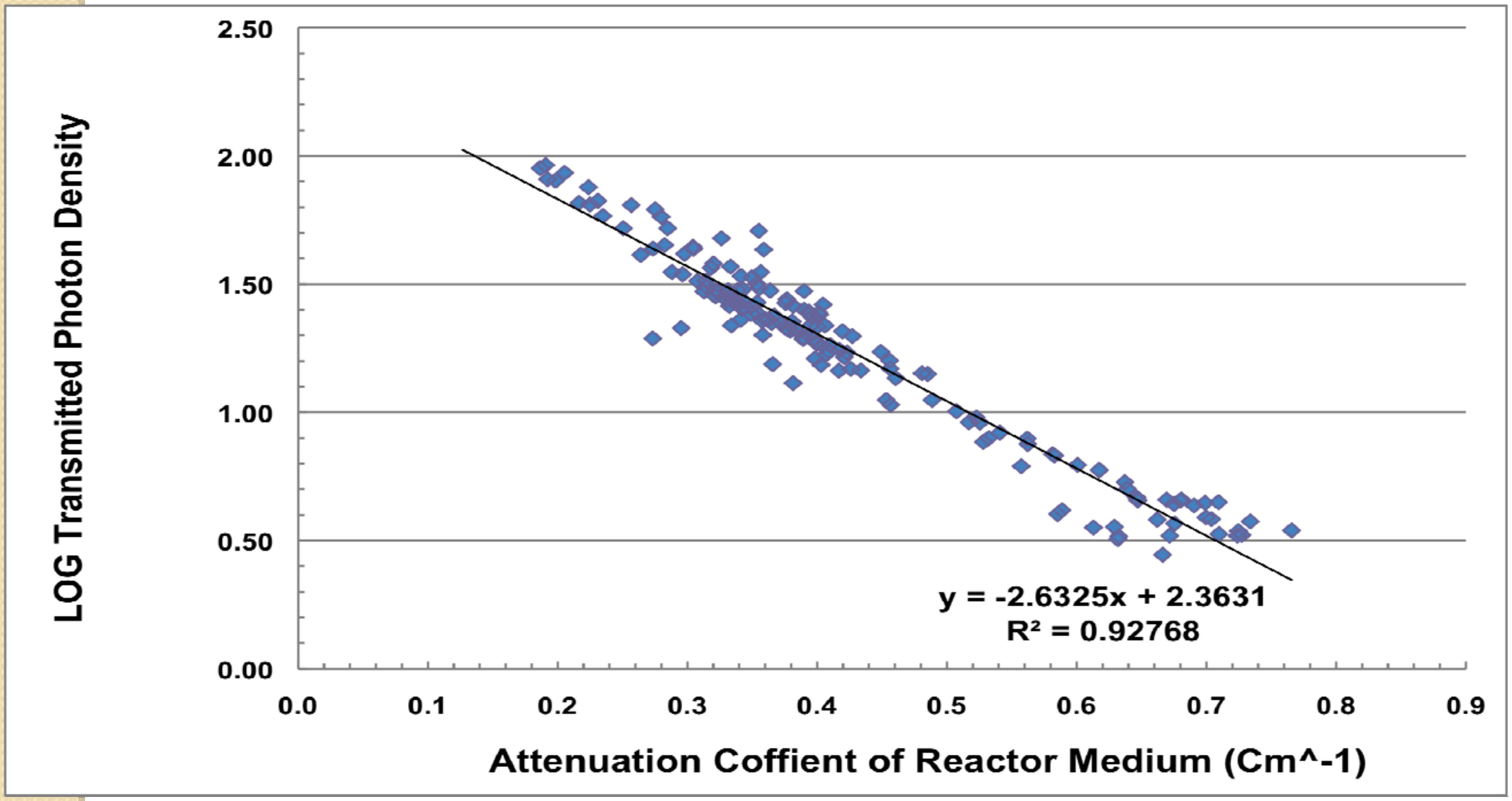
Reactor Setup



Tracking Growth of Chlorella Pyrenoidosa in PBR-1



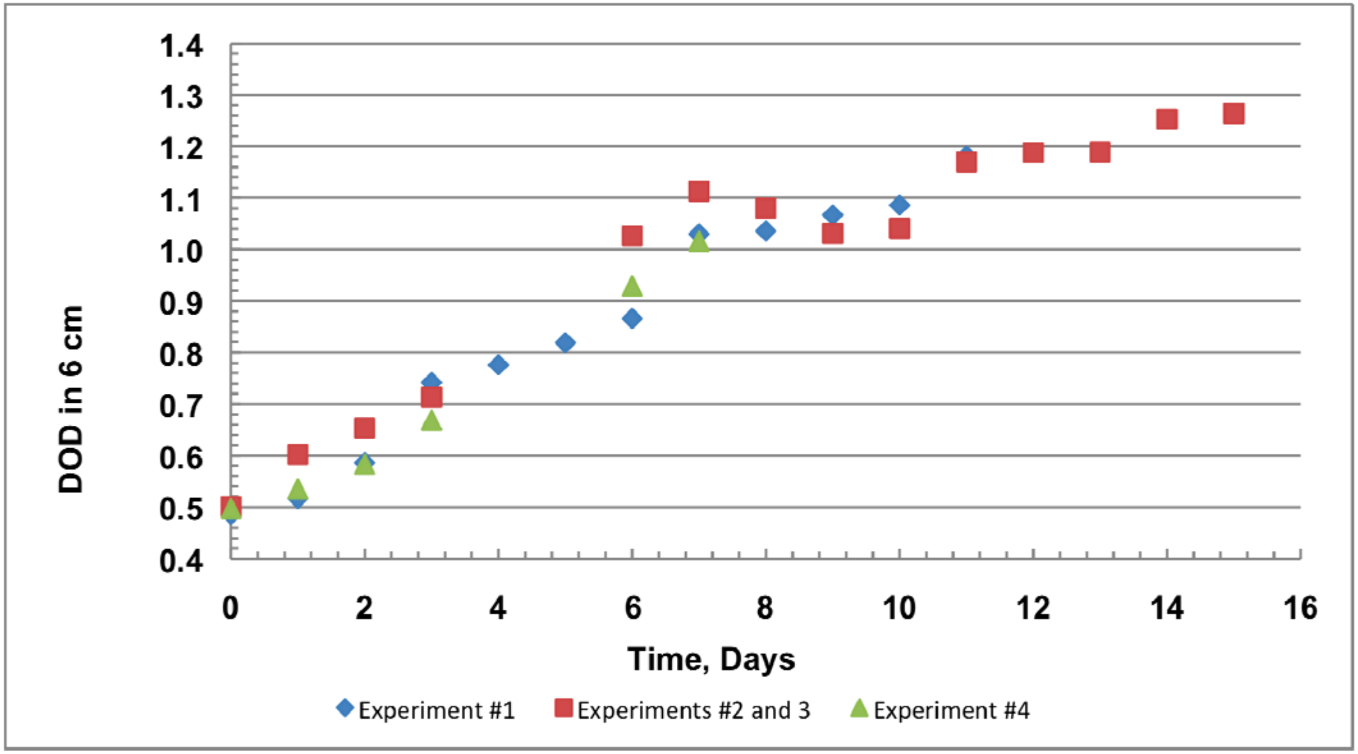
Direct Monitoring in Reactor



Monitoring Transmitted Illumination intensity at the surface of the reactor is indicative

Of algal growth

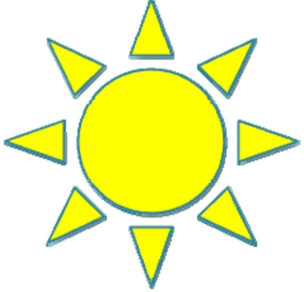
Growth of CP at a constant Low Salinity (400 mg/l) and various pH values



Medium pH increases and then leveled off.
An inflection point around DOD of 1.
Within an alkaline pH range 7.47 to 9.75

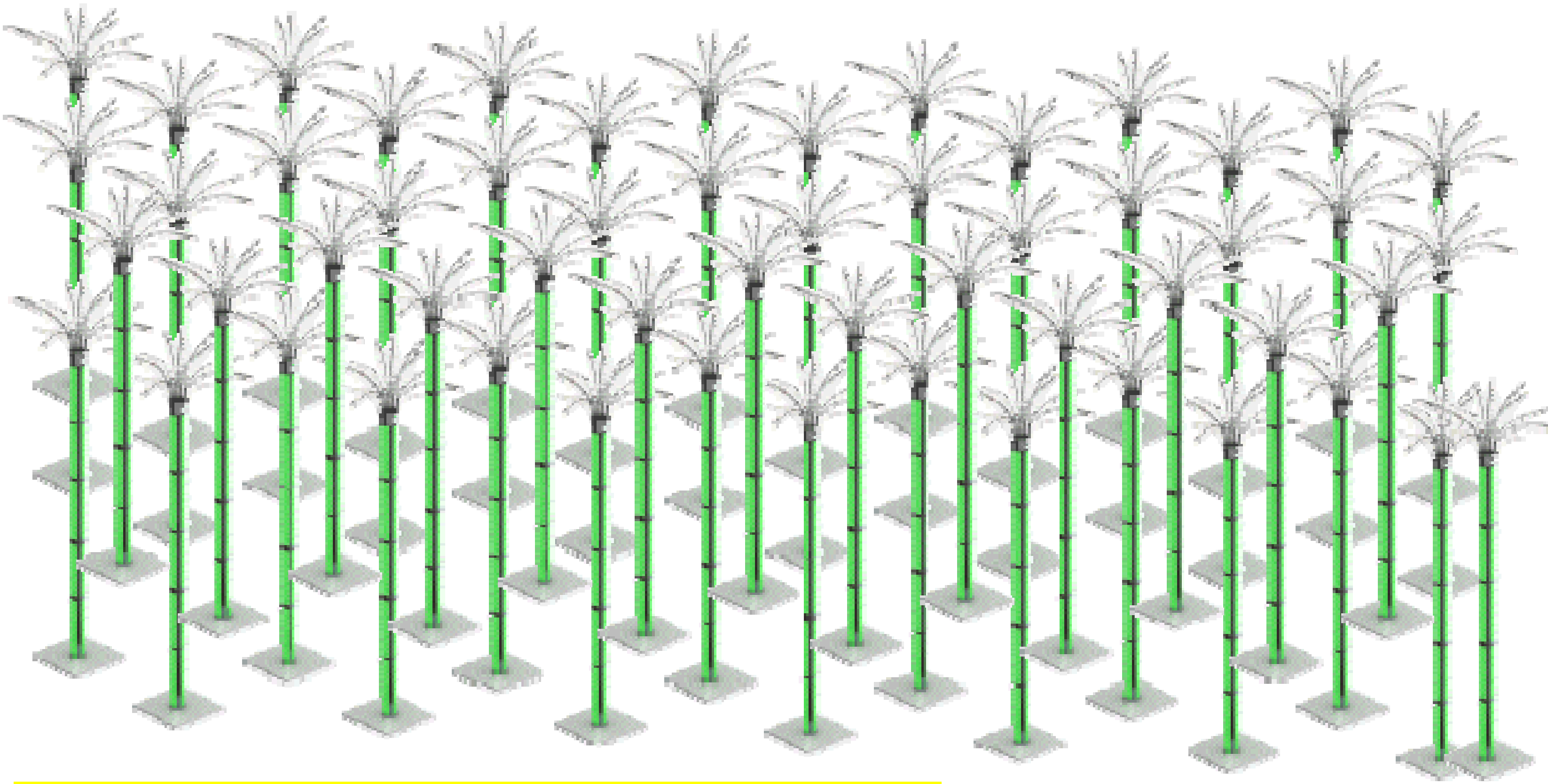
Summary and Conclusions

- **The Emerald Forest Concept has a high potential for alleviating the energy and climate changes crises, and for desert reclamation into sustainable living communities.**
- **Many challenges exist that require broad-spanning parallel research efforts.**
- **FVDO modeling was demonstrated for light propagation**
- **Can lead to efficient genetic optimization algorithms using a modular permutation approach**



Thank You!

WISER
WANGER INSTITUTE FOR SUSTAINABLE ENERGY RESEARCH



We gratefully acknowledge financial support from EPI Inc., Chicago and WISER at IIT