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ABSTRACT FINAL ID: SM2A.3

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TITLE: Free form Optics Applications in Photovoltaic Concentration

Abstract (35 Word Limit): Freeform surfaces are the key of the state-of-the-art nonimaging optics to solve the challenges in concentration photovoltaics. Different families (FK, XR, FRXI) will be presented, based on the SMS 3D design method and Köhler homogenization.

AUTHORS/INSTITUTIONS: J.C. Minano, , Universidad Politecnica de Madrid, Madrid, SPAIN;

KEYWORDS: General: 000.0000, General: 000.0000.

Freeform Optics Applications in Photovoltaic Concentration

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Universidad Politécnica de Madrid (UPM), Spain
LPI , Altadena, California, USA

SOLAR Optics for Solar Energy
11th-14th November 2012, Eindhoven

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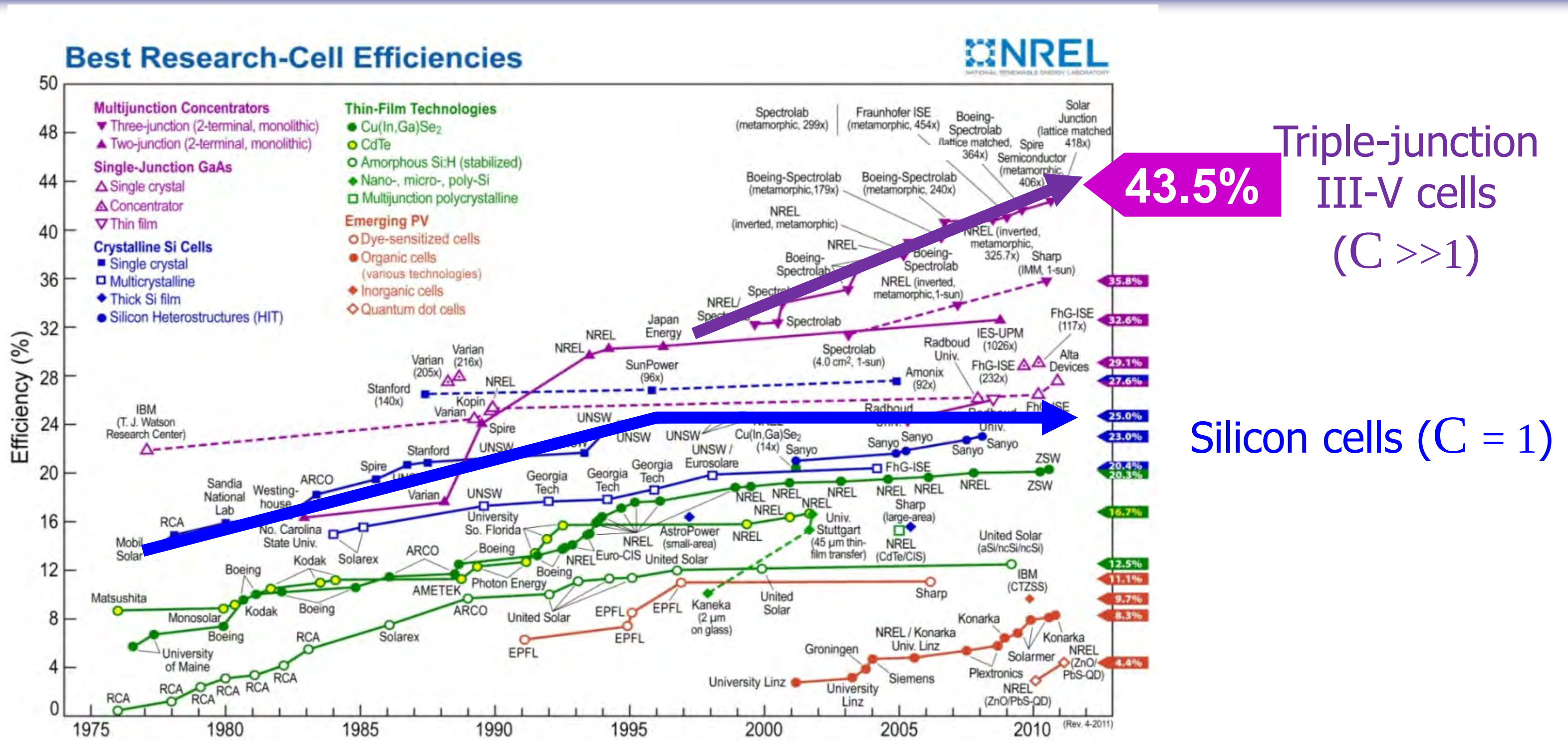
2. Free-forms in asymmetric systems
3. Freeform Köhler array concentrators
   - ✓ The VENTANA optical train
   - ✓ Daido Steel's DFK
4. Conclusions

PV technologies



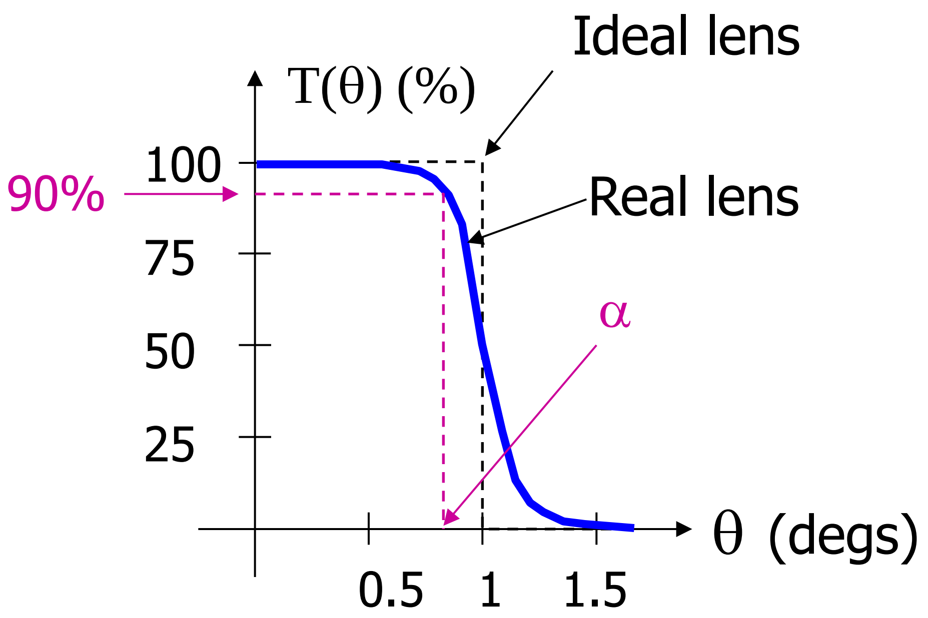
III-V cells are very expensive (~\$50,000/m²-\$150,000/m²)!!!!!

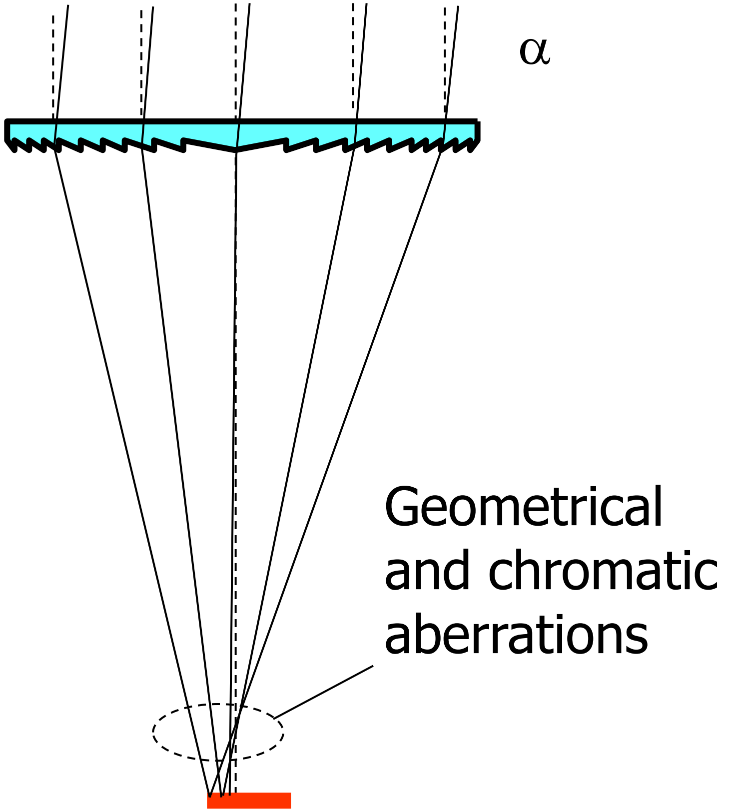
HCPV optical specs

1. Geometrical concentration: 500-1,500
2. Low cost of optics (<\$100/m^2)
3. High optical efficiency (~80-90%), spectrally balanced
4. Good irradiance uniformity, spectrally balanced
5. High acceptance angle (preferred > ±1deg)

Acceptance angle definition

Angle at which transmission drops to 90% of maximum





Tolerance budget

The acceptance angle is a common basis to measure the tolerance of a design

Tolerance budget has to be shared among:

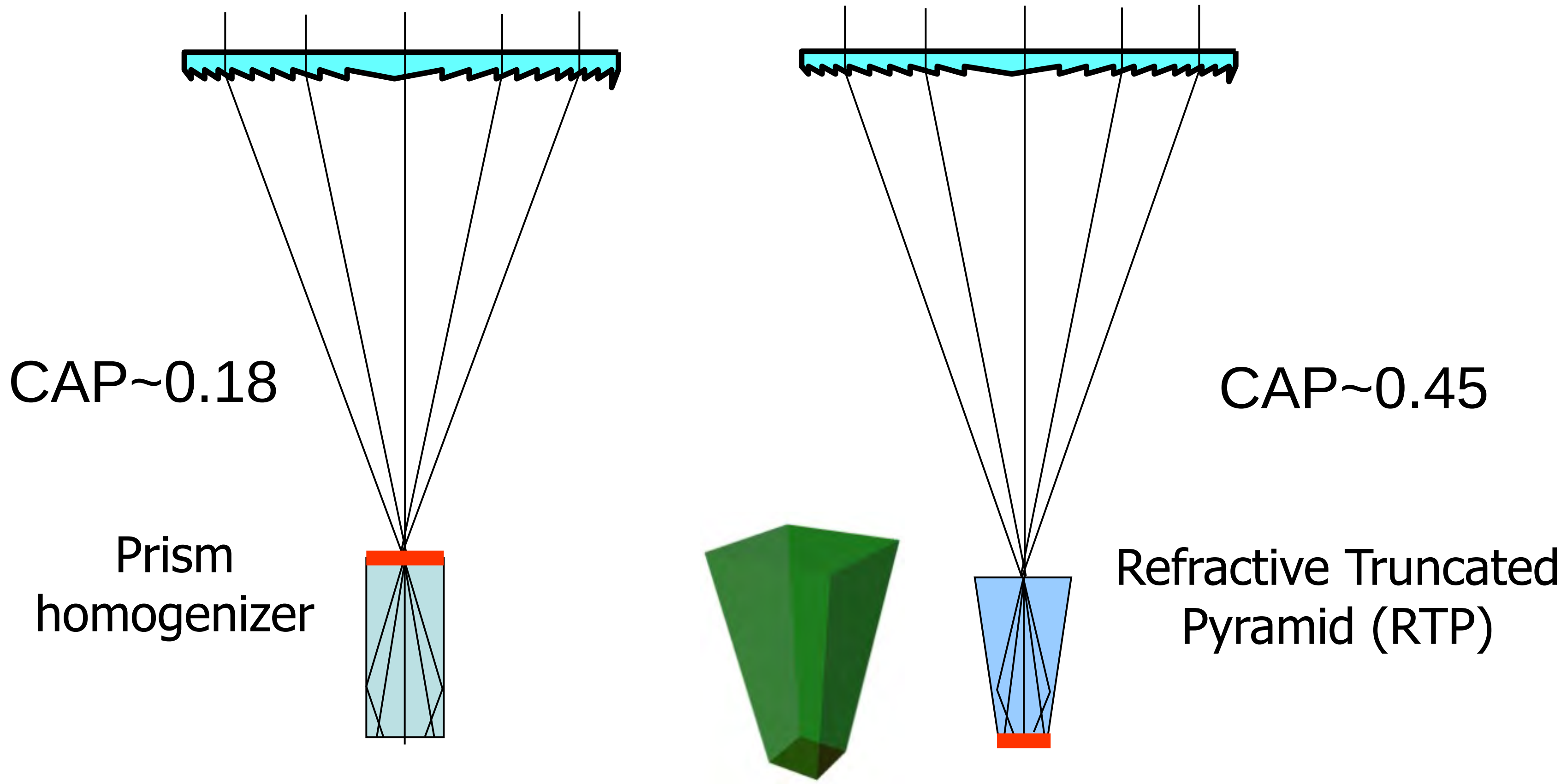
1. Sun's angular extension ±0.27°
2. Optical components manufacturing (shape and roughness)
3. Module assembling
4. Array assembling, series connection mismatch
5. Tracker structure stiffness
6. Tracking accuracy

Some Fresnel-based CPV systems

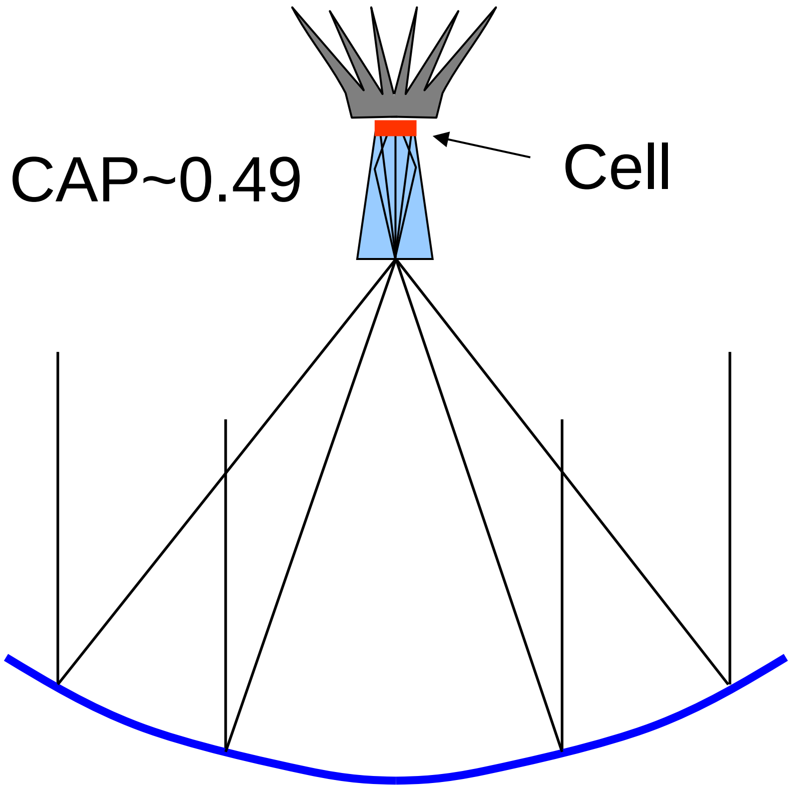
Concentration Acceptance Product

- $CAP = \sqrt{C} \times \sin\alpha$
- $CAP \approx$ constant for a given architecture
- CAP is an important merit function

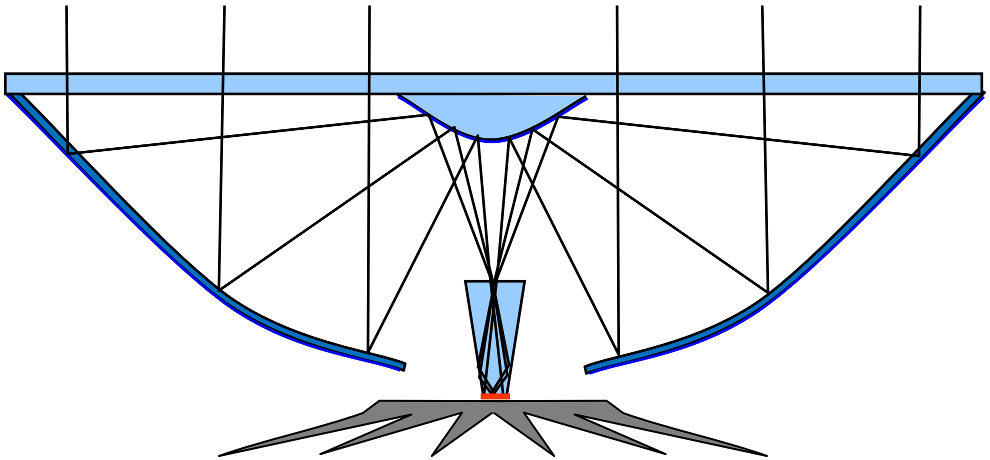
Classic homogenization scheme



Classical mirror based designs



Parabolic mirror



Cassegrian aplanat

Some mirror-based CPV systems

SolarSystems Parabolic mirror

Cassegrian aplanat SolFocus

Why freeforms in CPV?

- Freeforms provide more freedom to improve performance and functionality
- Nonimaging freeforms are not more expensive than symmetric surfaces
- Symmetric optics cannot solve satisfactorily some asymmetric CPV problems

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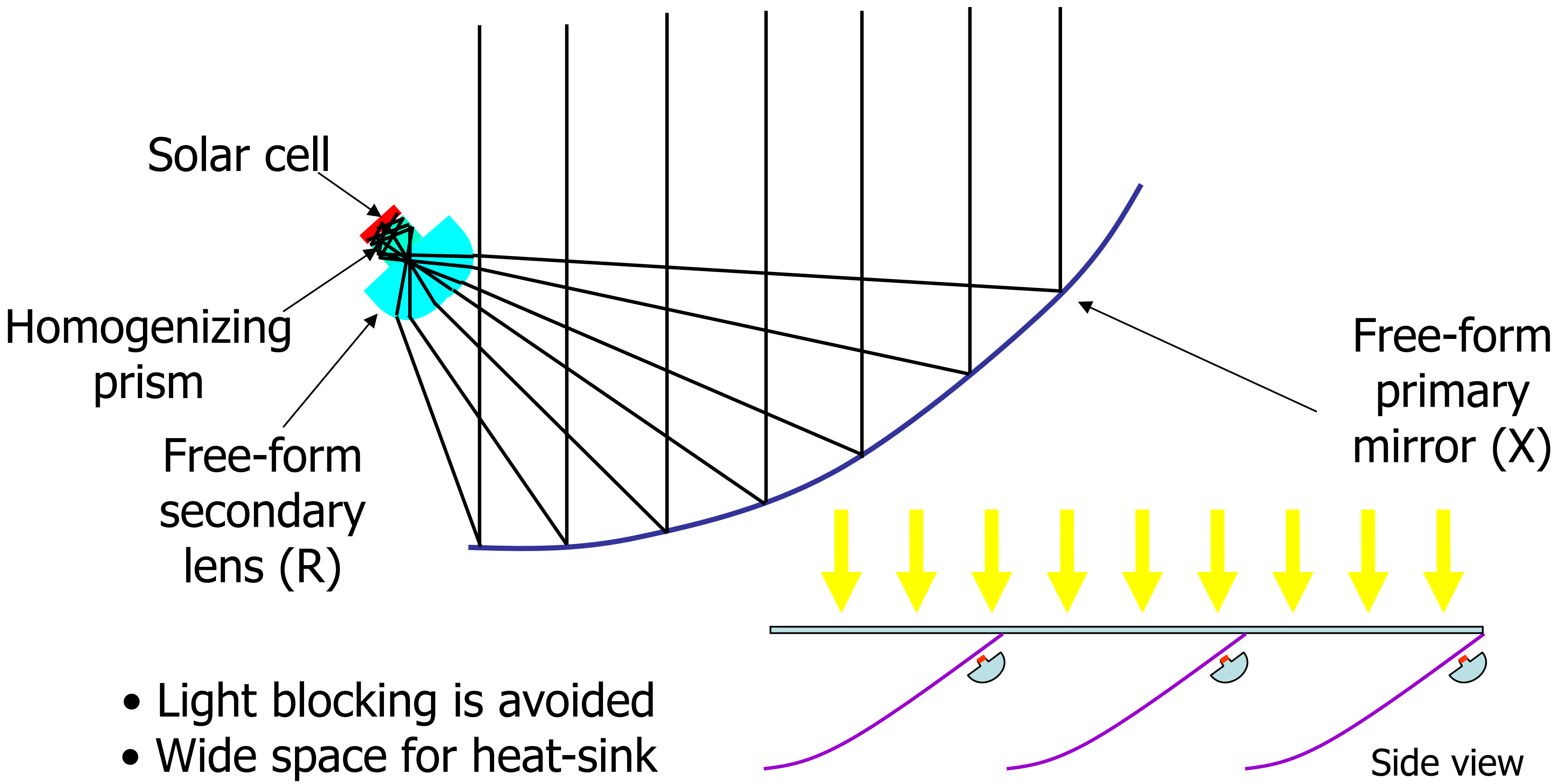
The freeform XR concentrator



- Light blocking is avoided
- Wide space for heat-sink

The SMS3D design method

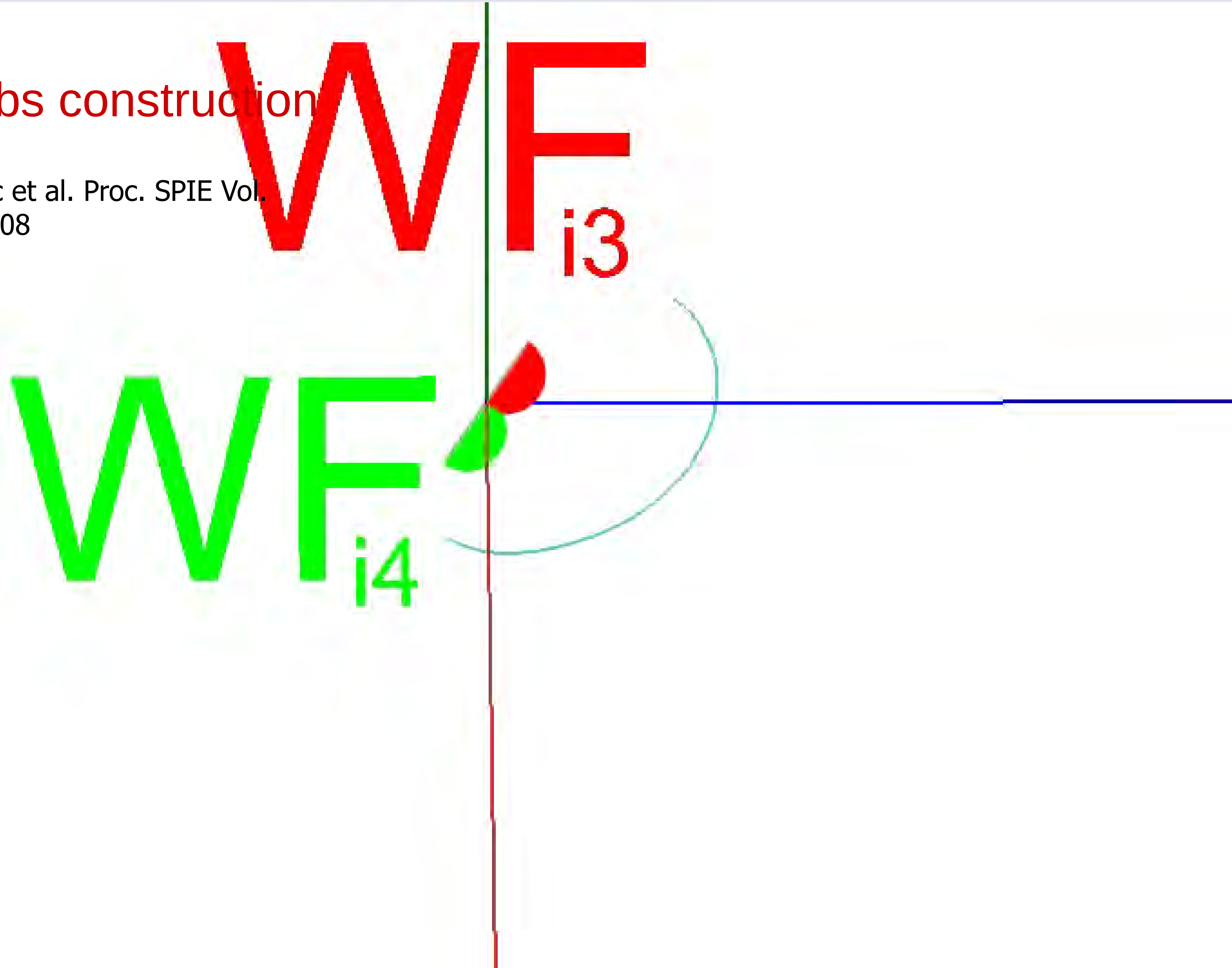
- SMS3D is an advanced optical design method
- SMS3D is capable to design two freeform surfaces without optimization
- SMS3D deals with extended sources and receivers

Benítez, P., Miñano, J. C., Blen, J., Mohedano, R., Chaves, J., Dross, O., Hernández, M., Falicoff, W, Opt. Eng. 43(7), 1489–1502, (2004)

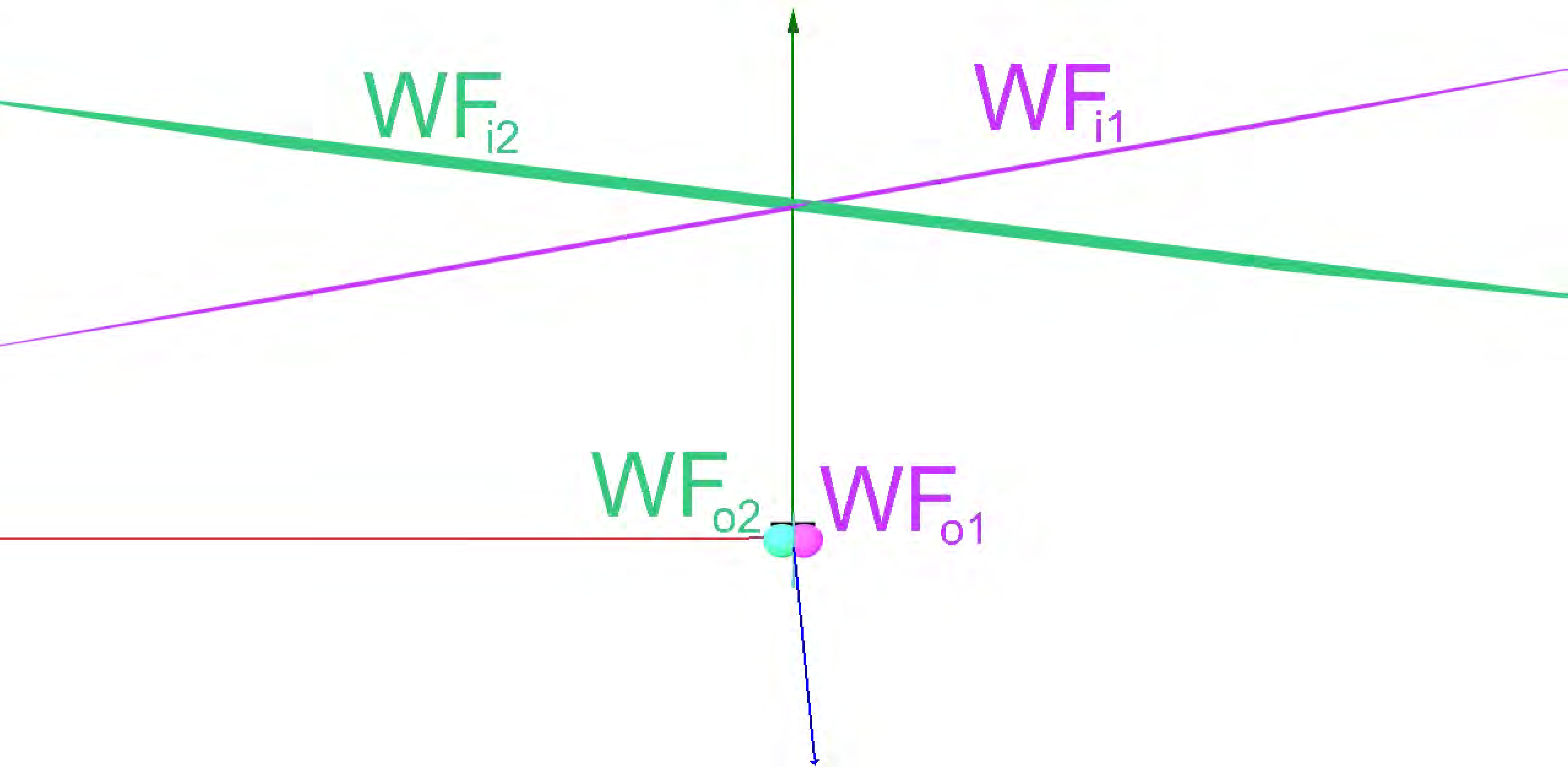
XR SMS 3D design

SMS ribs construction

A. Cvetkovic et al. Proc. SPIE Vol. 7043-12, 2008

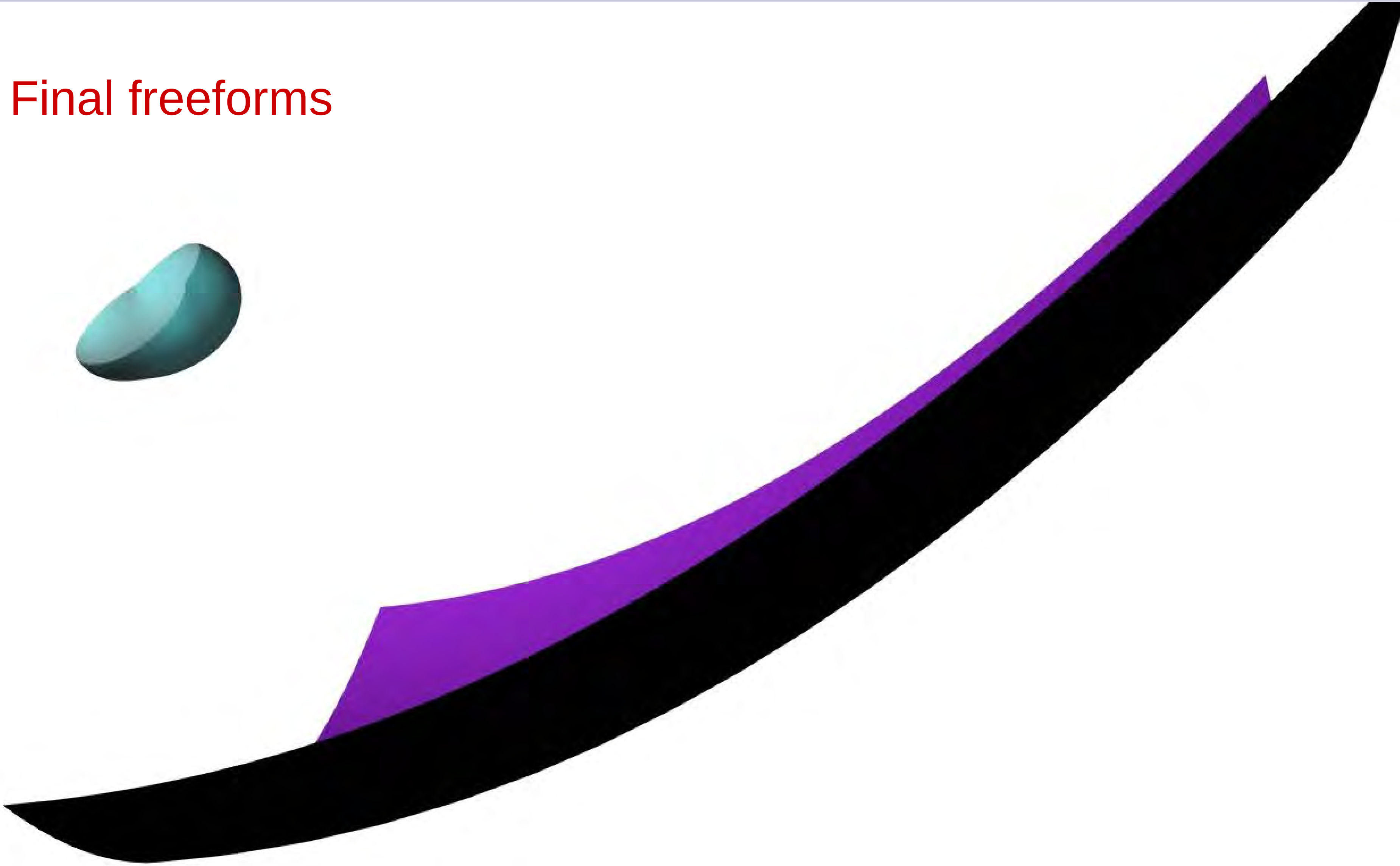


XR SMS 3D design

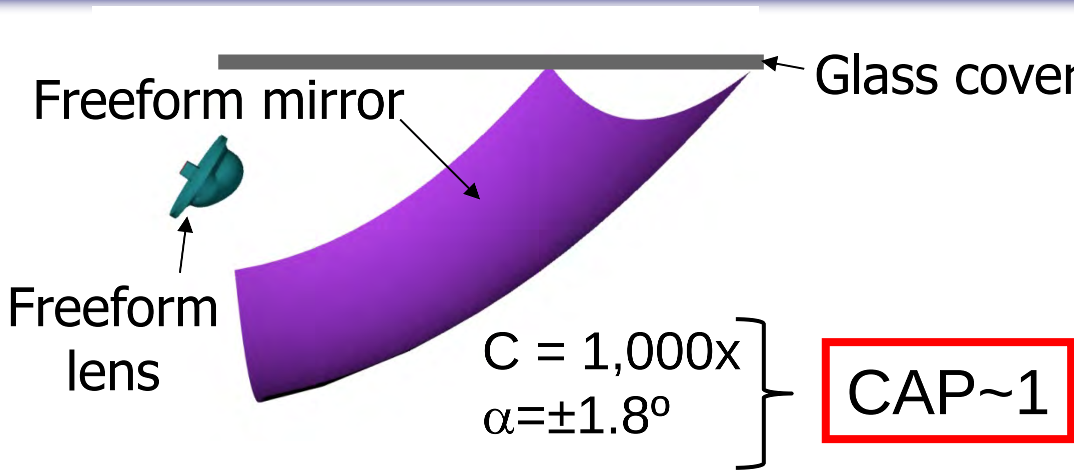


XR SMS 3D design procedure

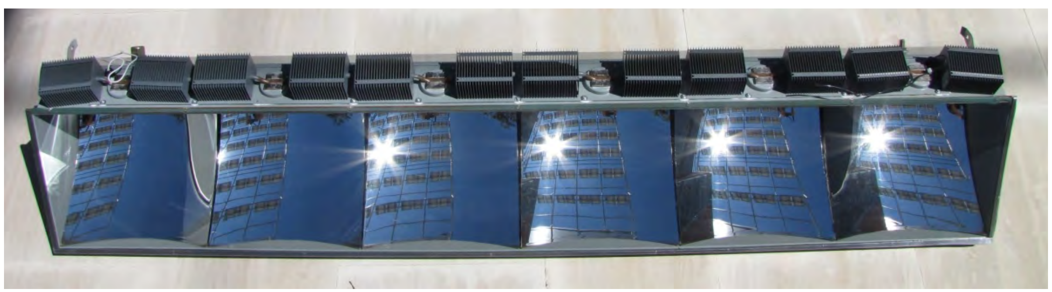
Final freeforms



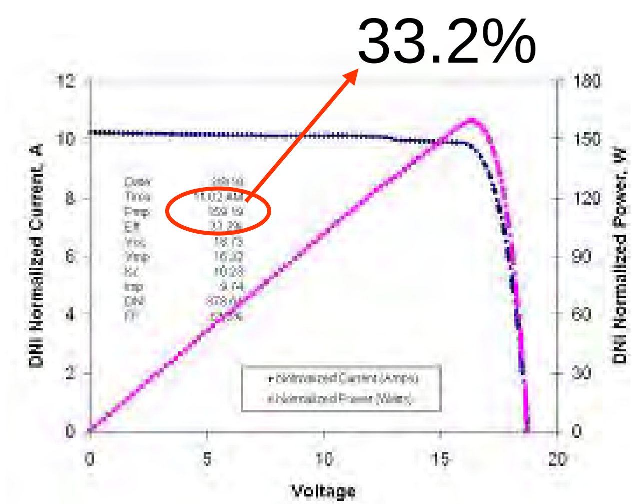
The freeform XR concentrator

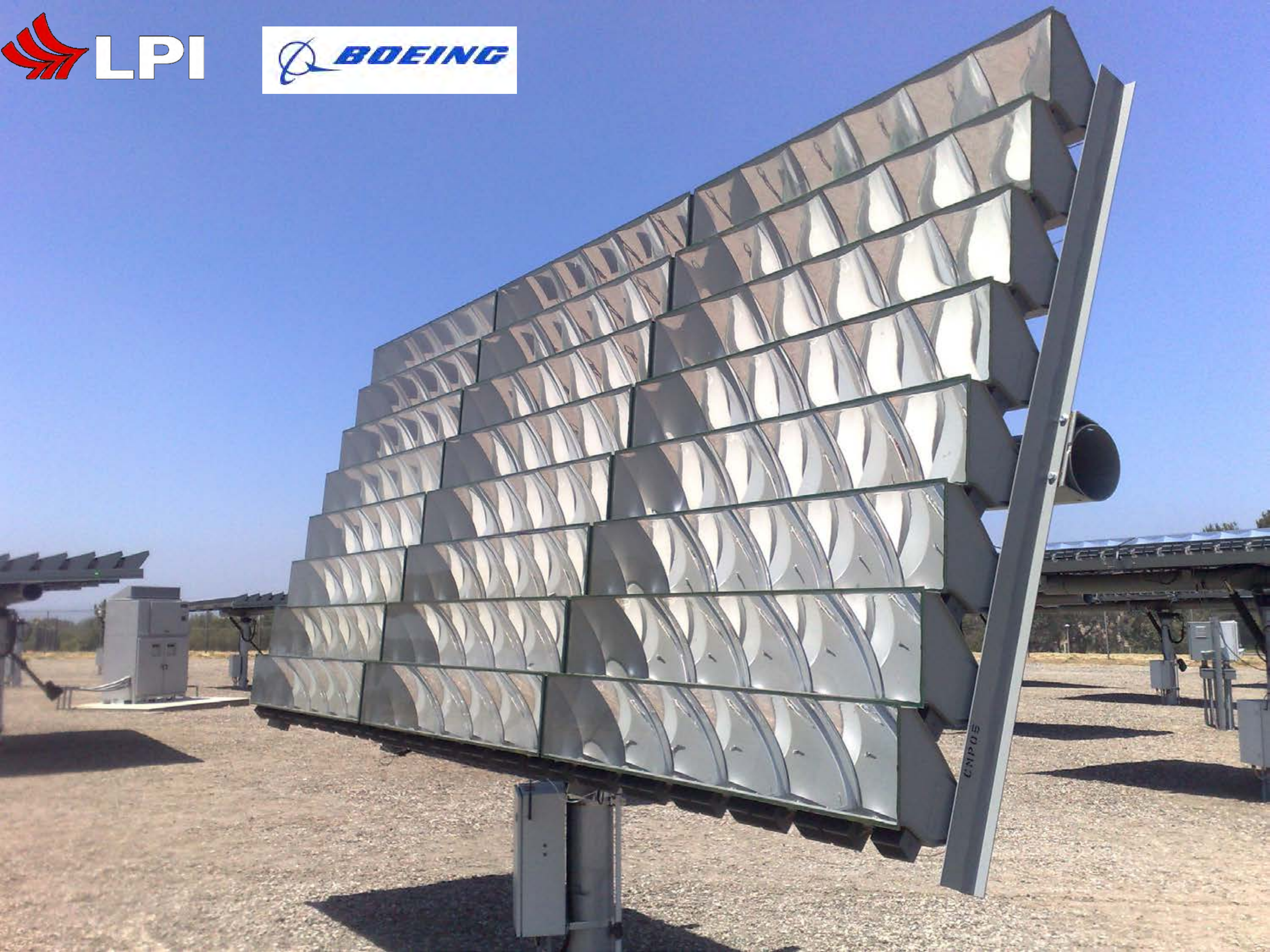


A. Cvetkovic, M. Hernández, P. Benítez, J. C. Miñano, J. Schwartz, A. Plesniak, R. Jones, D. Whelan, Proc. SPIE Vol. 7043-12, 2008



* The XR700 module developed by BOEING Co. and LPI (*A.Plesniak et all*. 34th IEEE PV Specialist Conference, 2010)




LPI
BOEING

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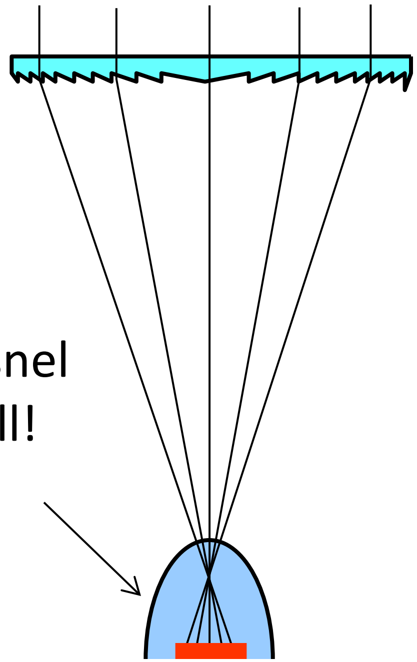
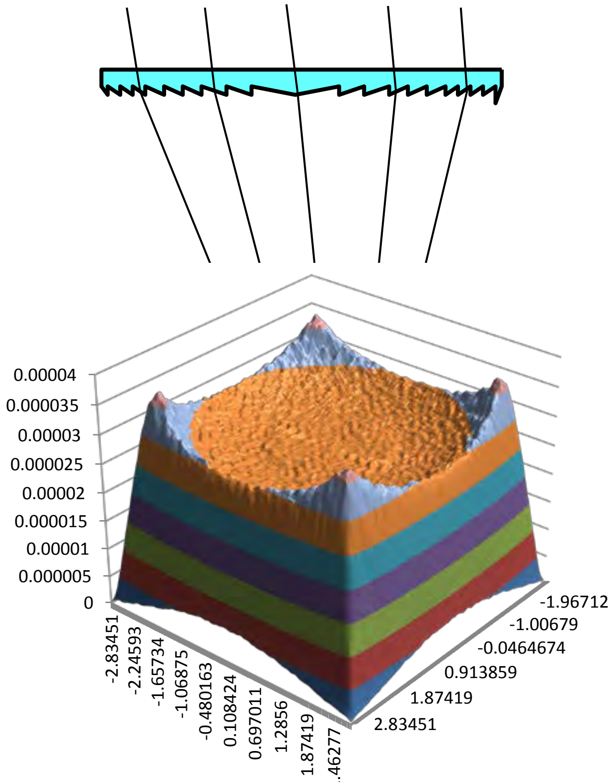
The simplest Köhler CPV design

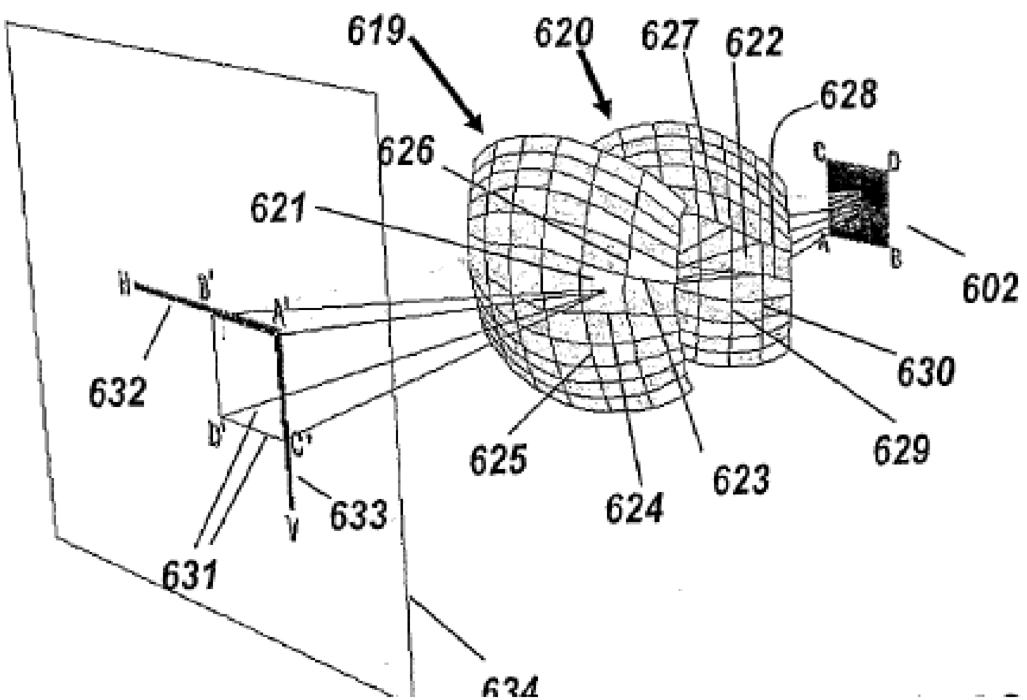
Images the Fresnel lens on the cell!





SILO (SIngle Lens secondary Optics)

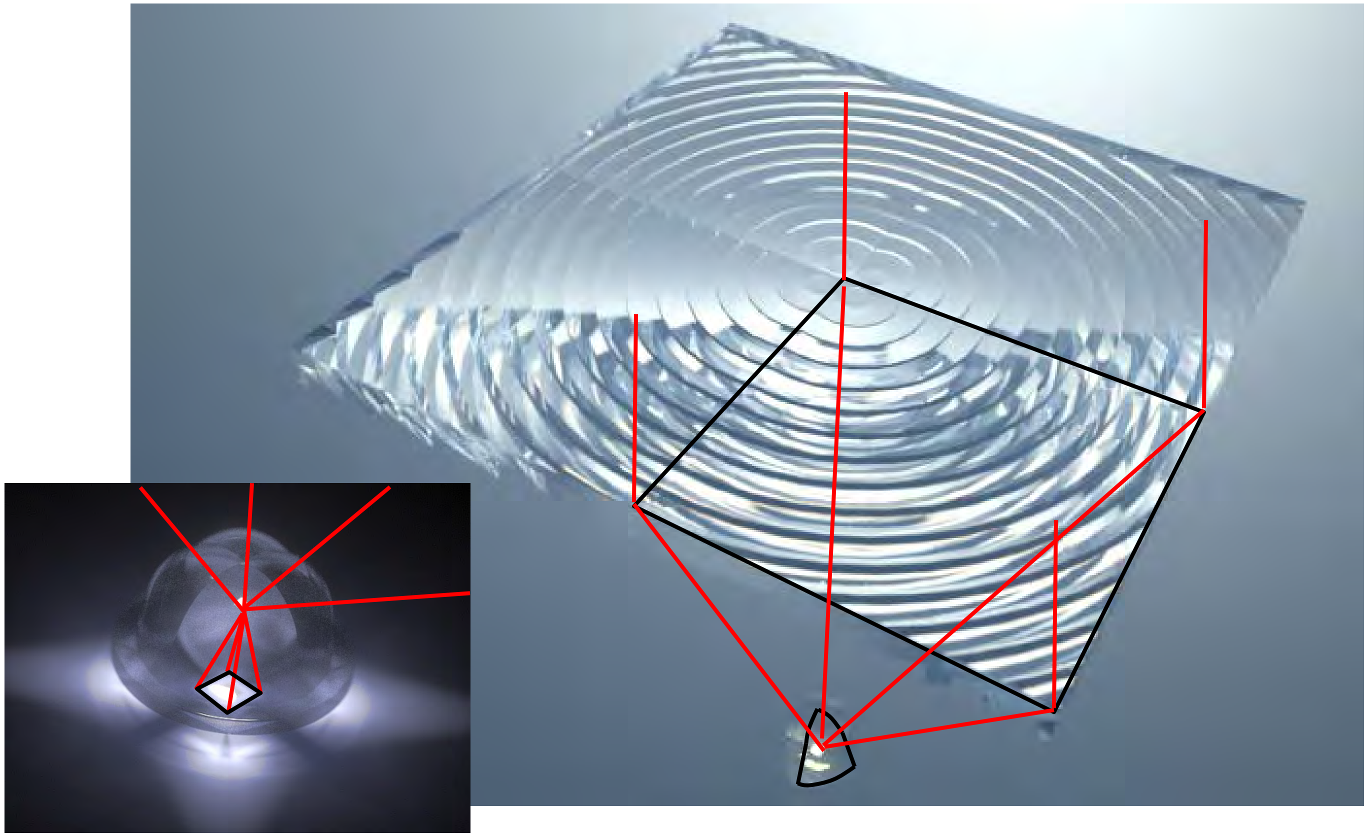
L. W. James, Contractor Report SAND89–7029, (1989) The optical process is done in parallel channels that homogenize and concentrate at the same time!



This can de done in 2D or 3D (free-form surfaces).

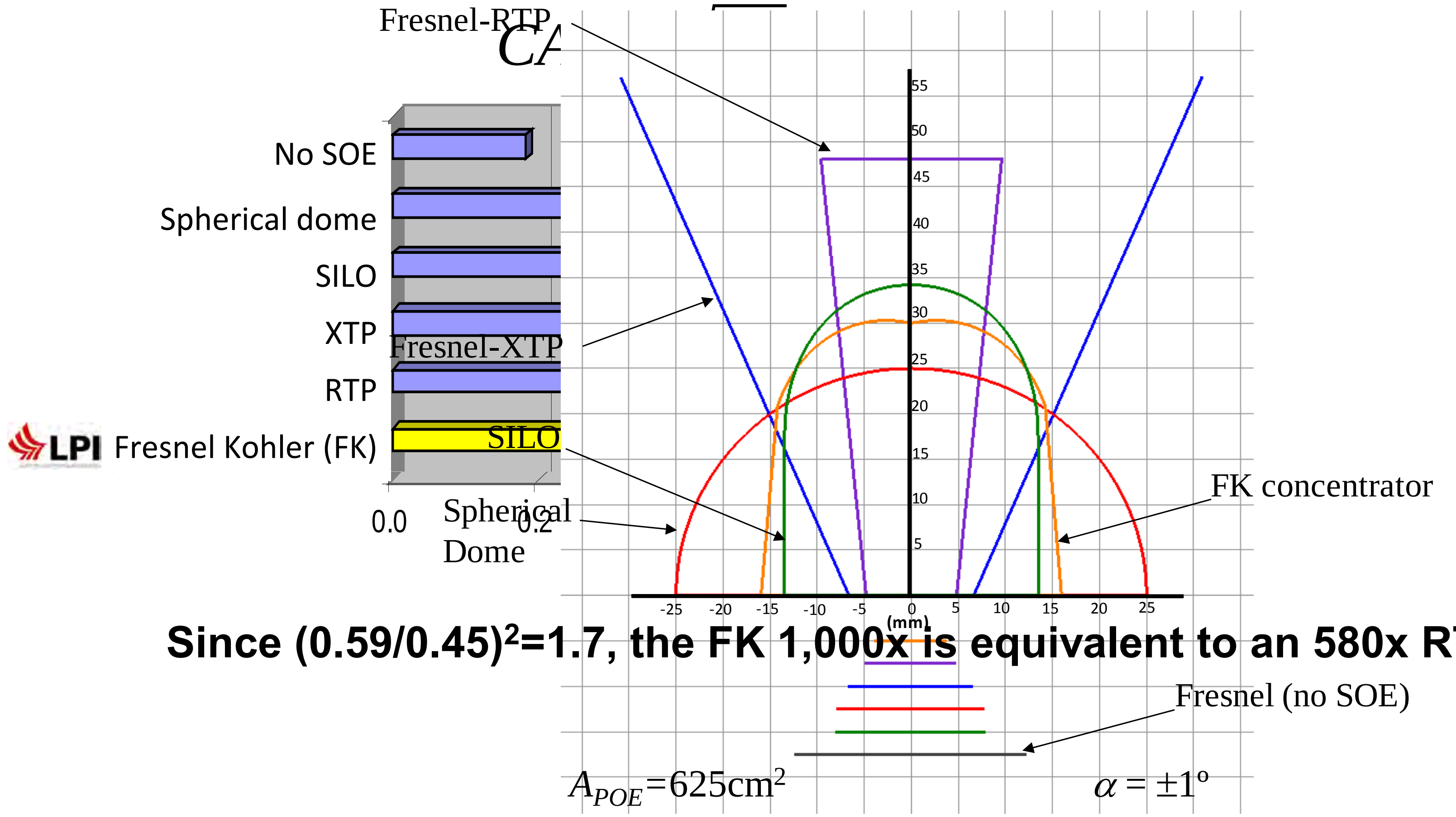
The Fresnel-Köhler (FK) concentrator

Free-form lens



P. Benítez, J.C. Miñano, P. Zamora, R. Mohedano, A. Cvetkovic, M. Buljan, J. Chaves, M. Hernández, Optics Express, Vol. 18, Issue S1 (Energy Express), April 2010

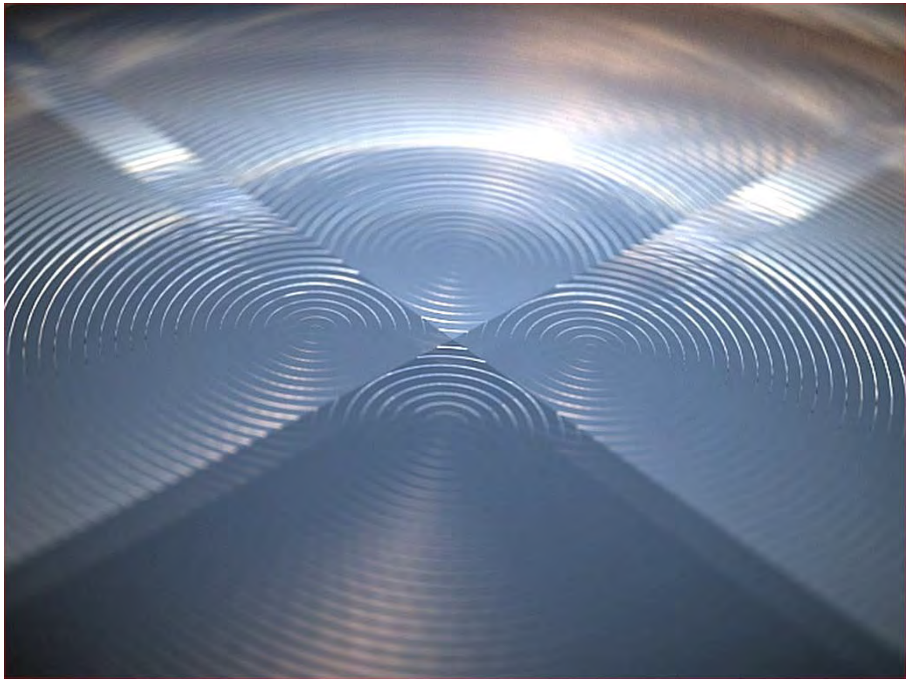
Comparison



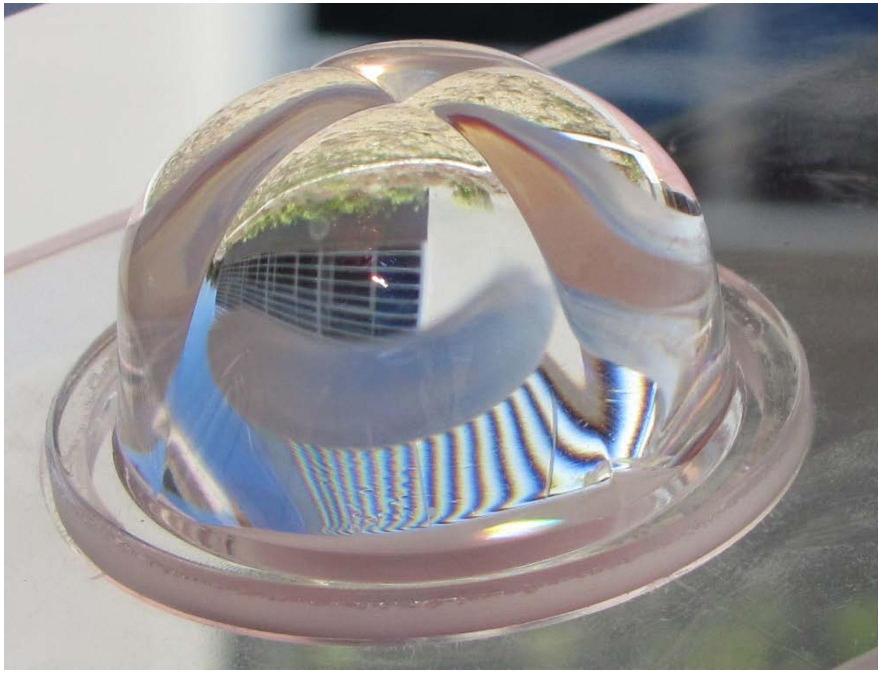
Since $(0.59/0.45)^2$=1.7, the FK 1,000x is equivalent to an 580x RTP!

The FK concentrator

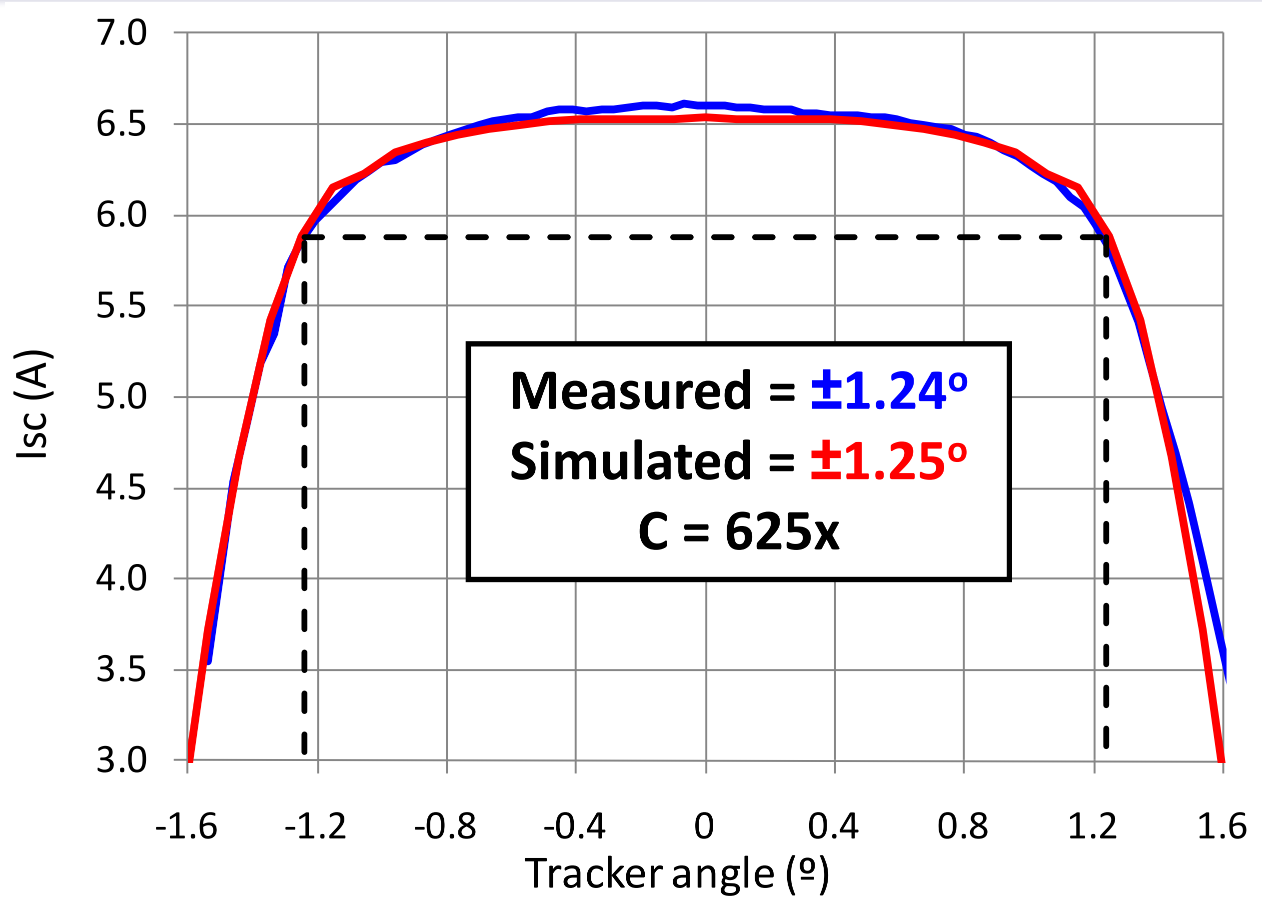
Fresnel lens



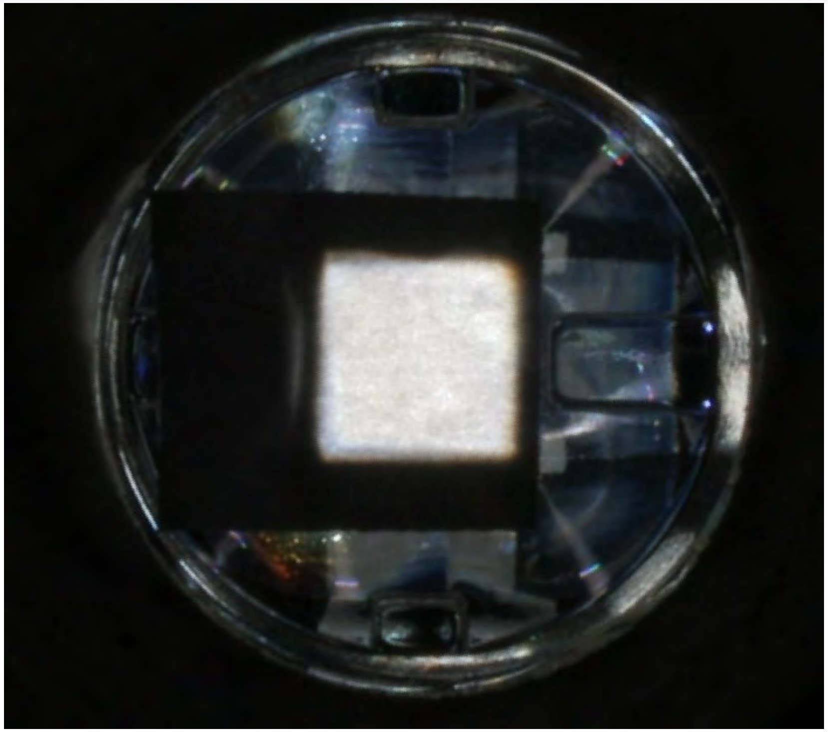
Freeform secondary lens



FK acceptance angle

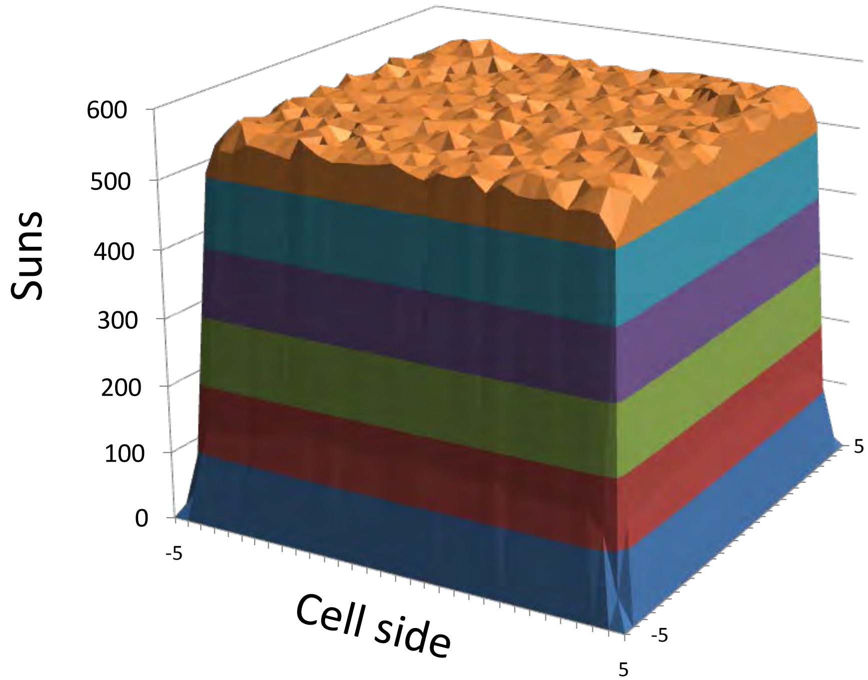


FK irradiance uniformity



Measured

Peak irradiance = 595 suns

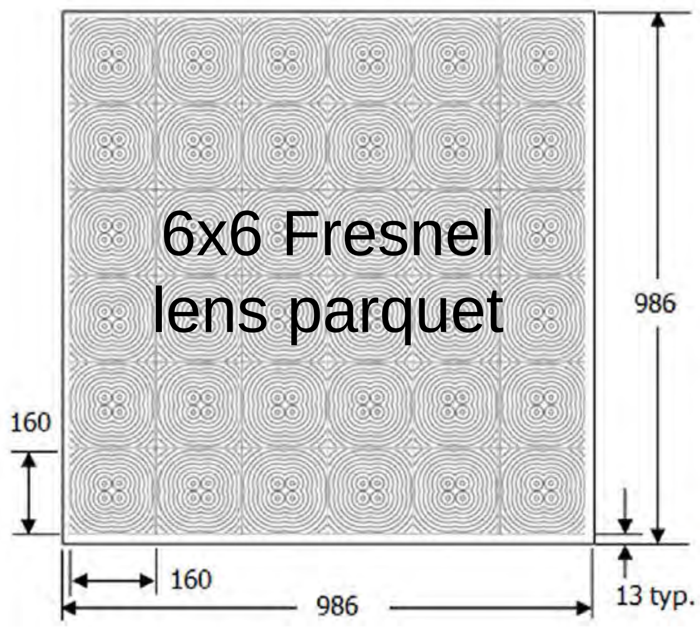


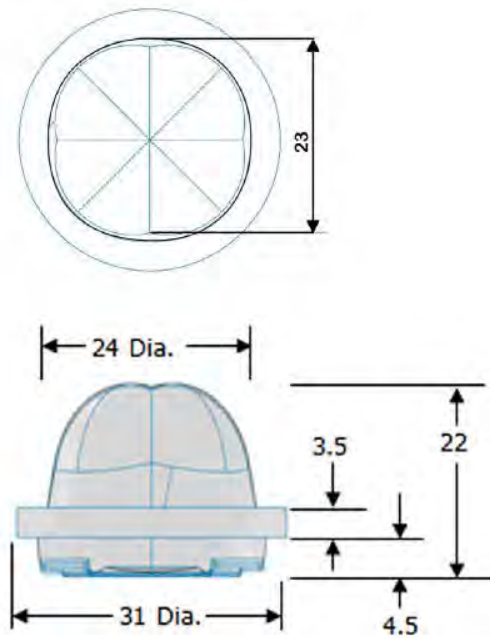
Simulated

Peak irradiance = 575 suns

The Ventana™ Optical Train

- A complete off-the-shelf optics solution by Evonik and LPI
- Based on the best-in-class design: The FK concentrator

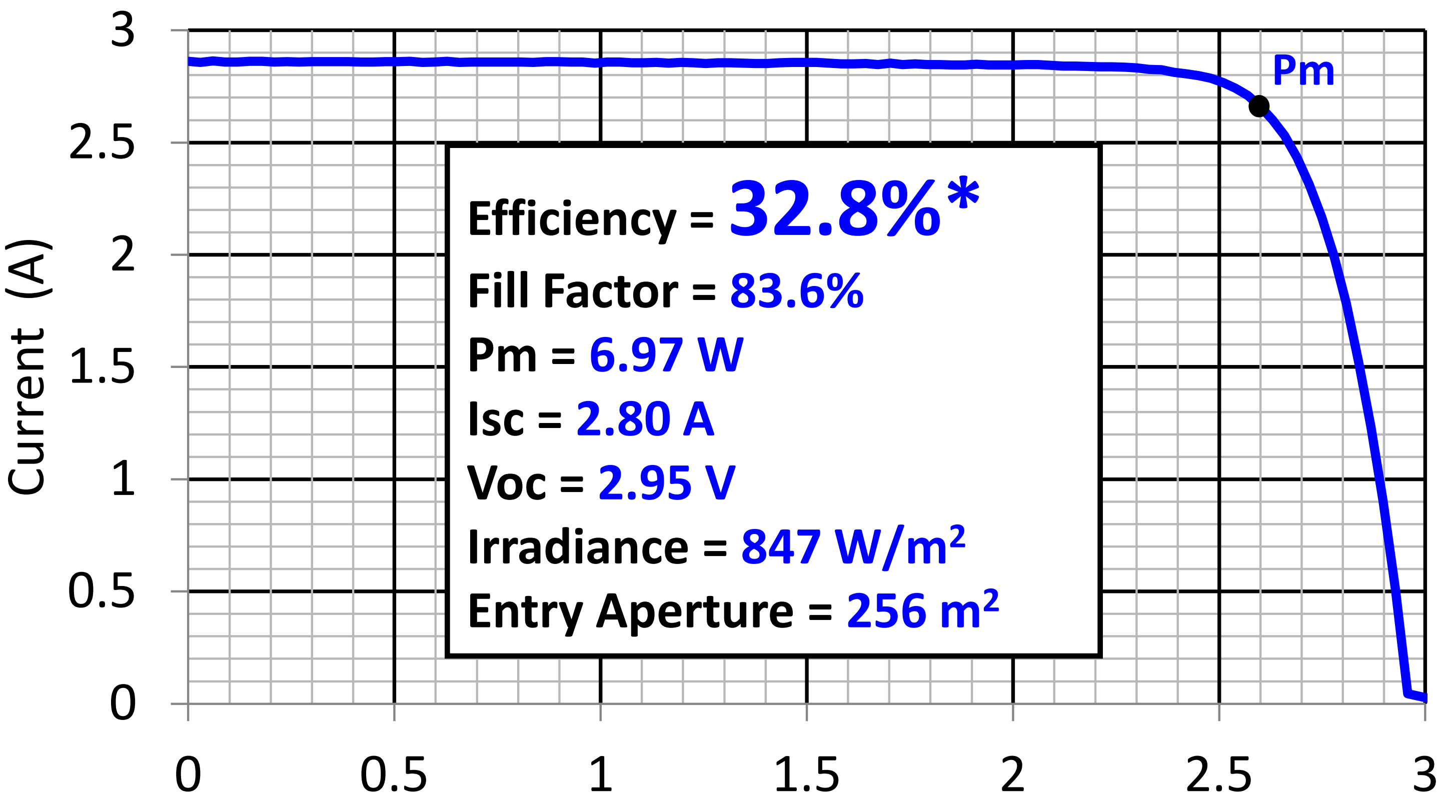




POE = primary optical element

SOE = secondary optical element

LPI-Evonik Ventana™ optical train



C = 1,024x
$\alpha > \pm 1^o$

*No AR coatings; @Tcell=25ºC
C3MJ Spectrolab cell bin 39%

DFK

- Daido Steel present CPV system:
  - $Cg^* = 950$
  - $\alpha = \pm 0.92^{o}$

  } CAP = 0.49

$CAP = \sqrt{Cg} \times \sin \alpha$

- Higher concentration without compromising acceptance angle is desired.
- LPI, in collaboration with UPM, has developed high-performance Köhler freeform concentrators.
- UPM and Daido Steel are developing a new Köhler technology, **DFK**, within the NGCPV project

New Generation CPV

*Over illuminated cell area

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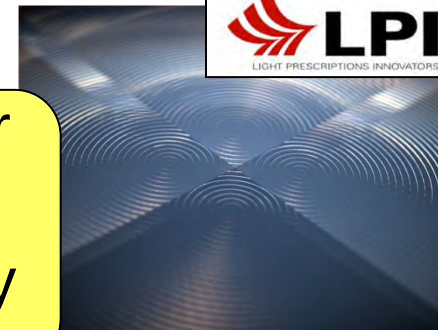
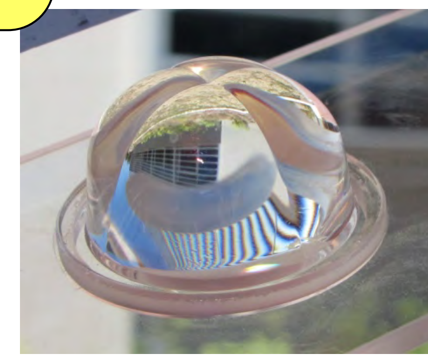
DAIDO STEEL

Daedo Steel module & system technology

LPI

LIGHT PRESCRIPTIONS INNOVATORS





LPI Köhler optical technology

DFK optics

- Cg = 1,234
- $\alpha > \pm 1.1^{o}$

} CAP > 0.67

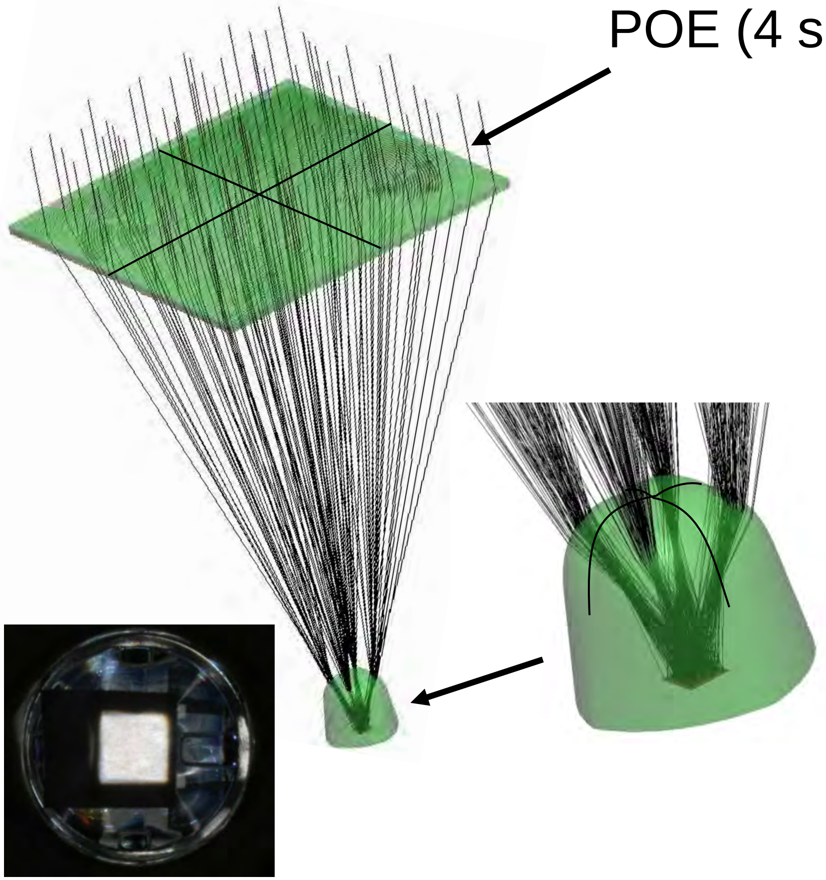
- Module efficiency > 35%

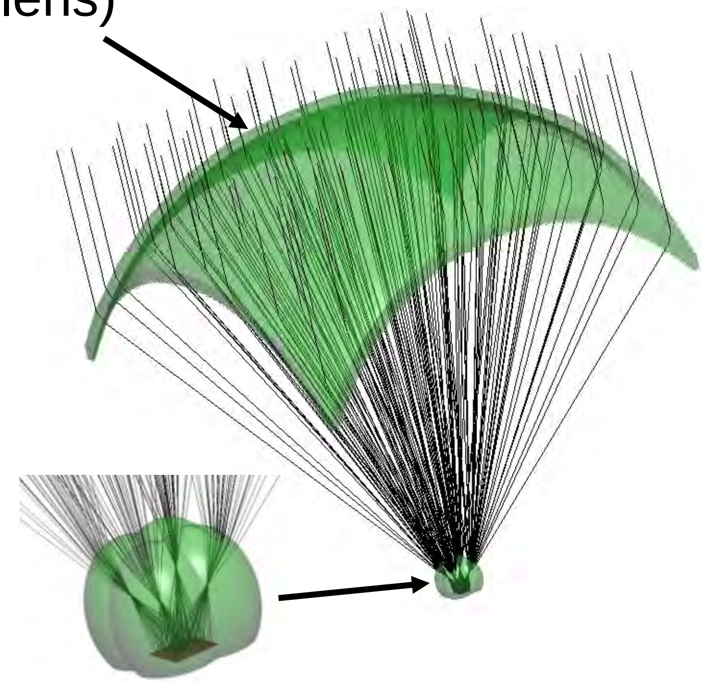
$$CAP = \sqrt{Cg} \times \sin \alpha$$

Flat FK (FK)

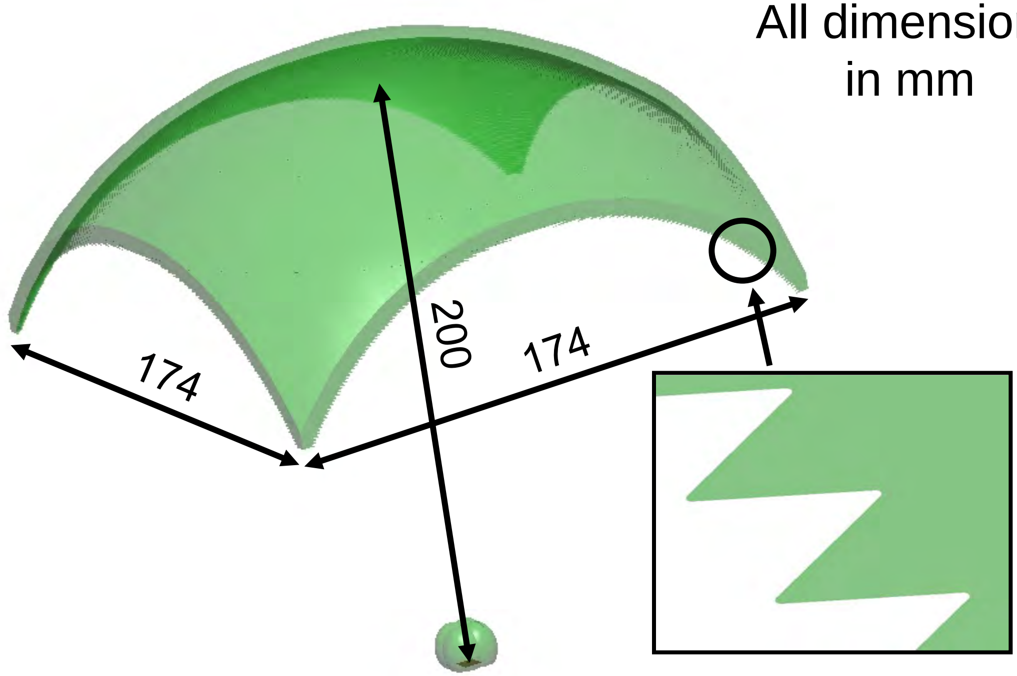
Dome-shaped FK (DFK)

POE (4 sectors Fresnel lens)

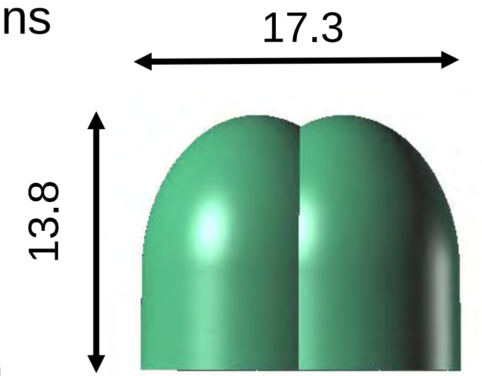


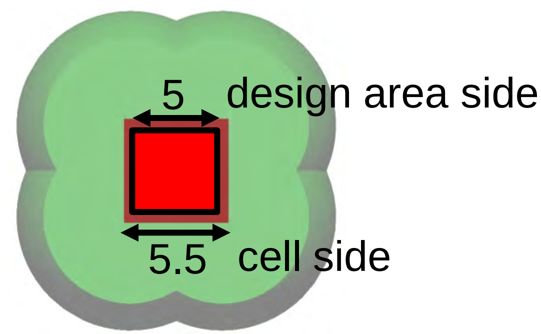


DFK design parameters



All dimensions in mm

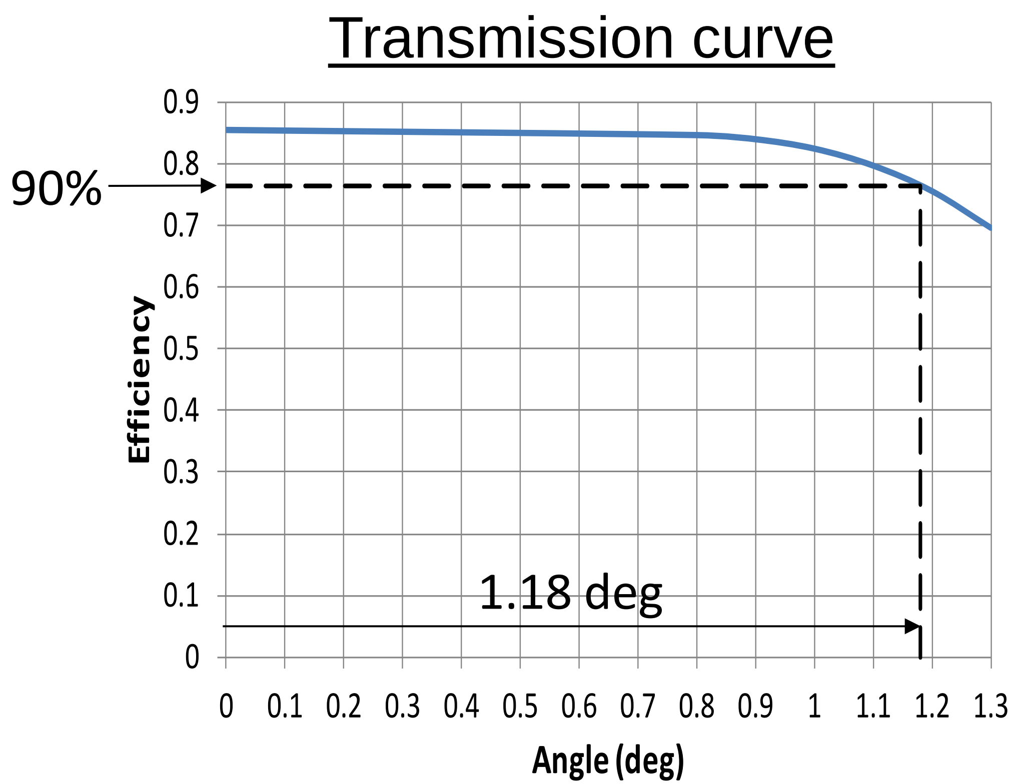


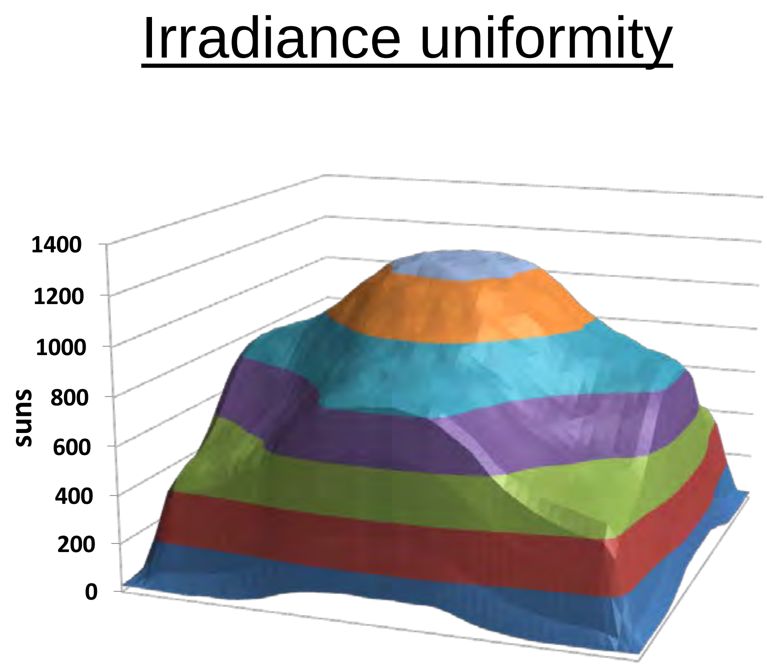


- C_g=1,234x
- f/ 0.81
- SOE material: B270-equiv. glass
- POE material: PMMA

0.25mm wide frame around the cell for assembly tolerances

DFK simulation results

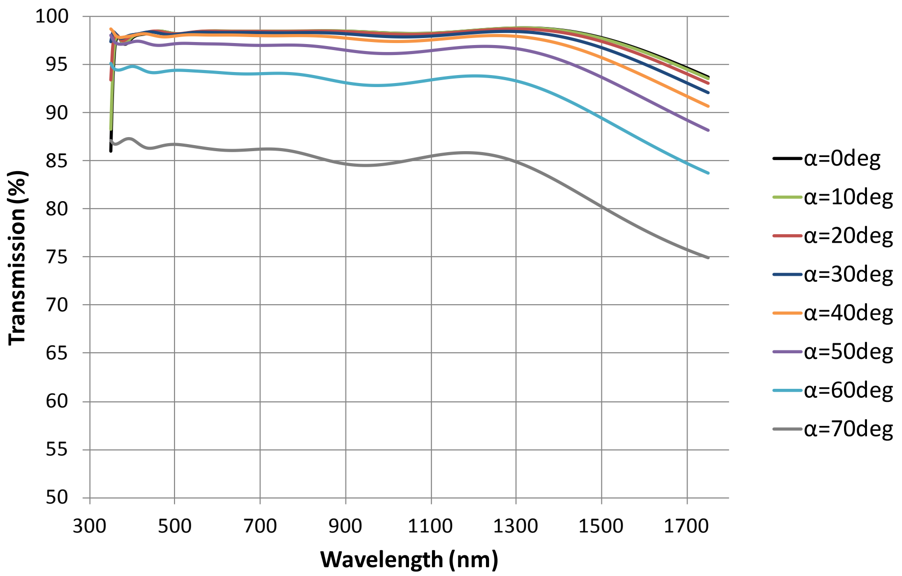


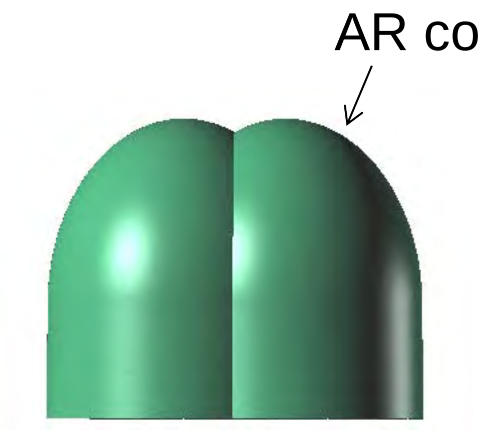


CAP=**0.72** > 0.67 (spec)

AM1.5D spectrum, finite sun, EQE's of 3J cell, Fresnel and absorption losses included in simulation

DFK: AR coating on SOE





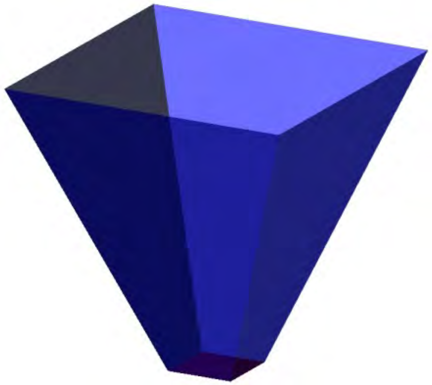
AR coating on SOE	Optical efficiency	Acceptance angle
NO	85.6%	±1.18º
YES	**87.5%**	±1.18º

Performance comparison

ISSUE	FLAT FK	DOME-SHAPED FK
Acc. angle (α) [1]	±1.03 deg	±1.18 deg
CAP	0.63	**0.72**
Optical efficiency[2]	86.5%	87.5%
Irr. uniformity	Excellent	Very good
F-number	1.07	**0.81**

[1] C_g = 1,234x for both concentrators
[2] With AR coating, no rounding of facet corners

Performance comparison



XTP

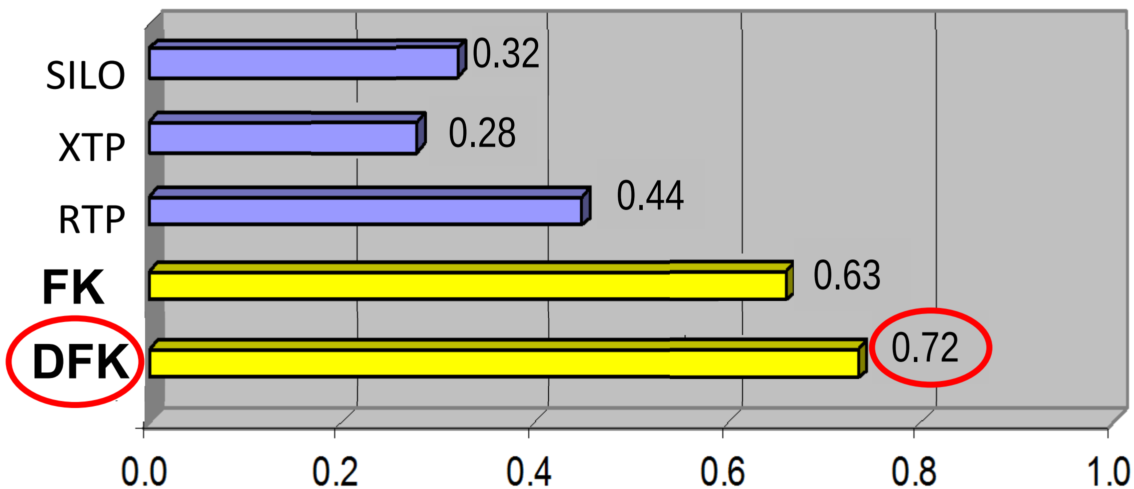
SILO

FK

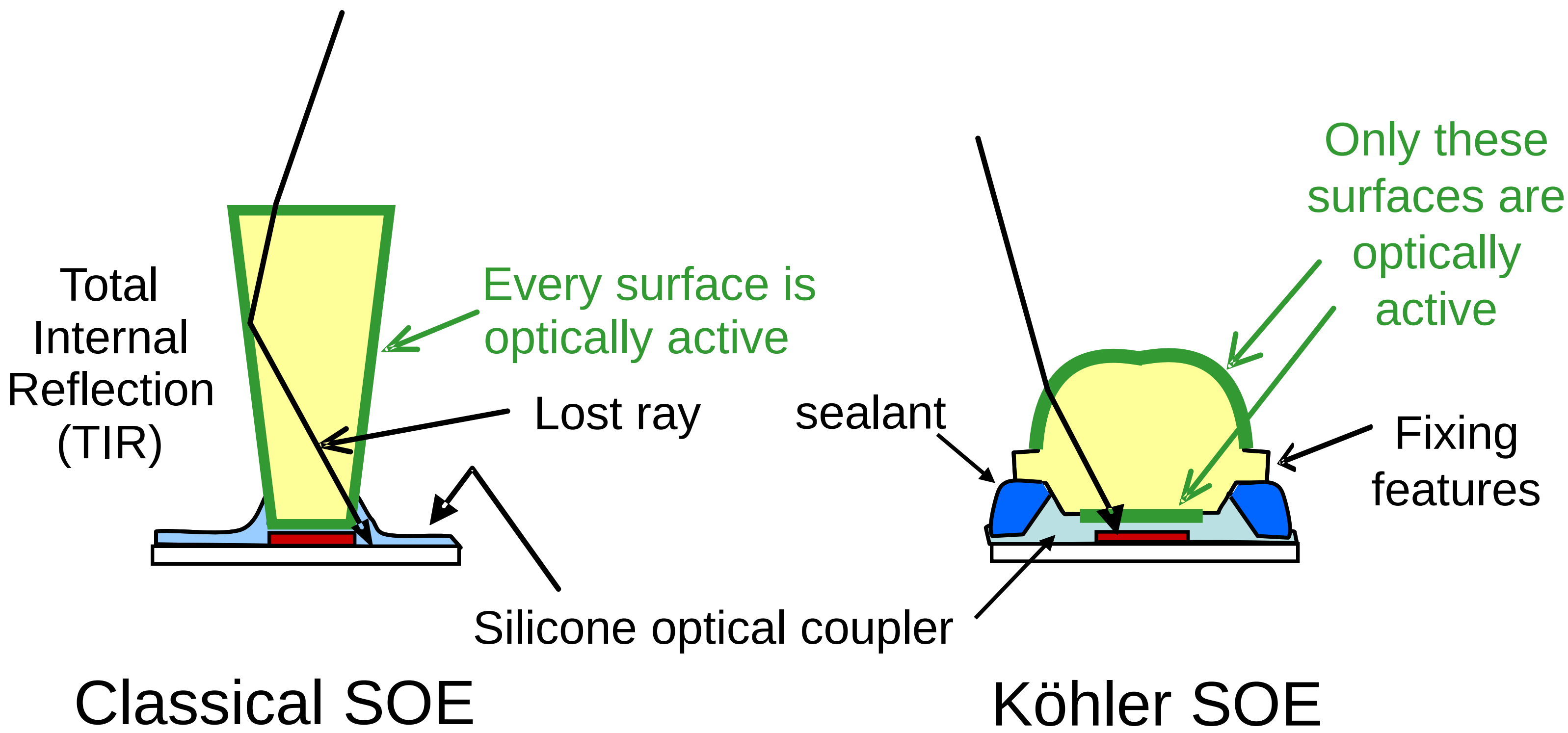
DFK

RTP

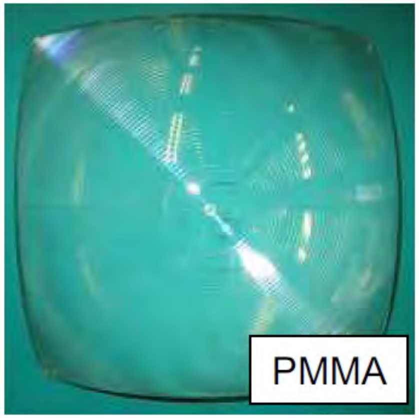
$$CAP = \sqrt{C_g} \times \sin\alpha$$

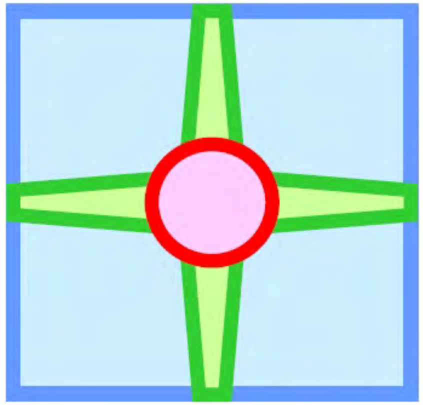


Practical problems with RTP secondaries

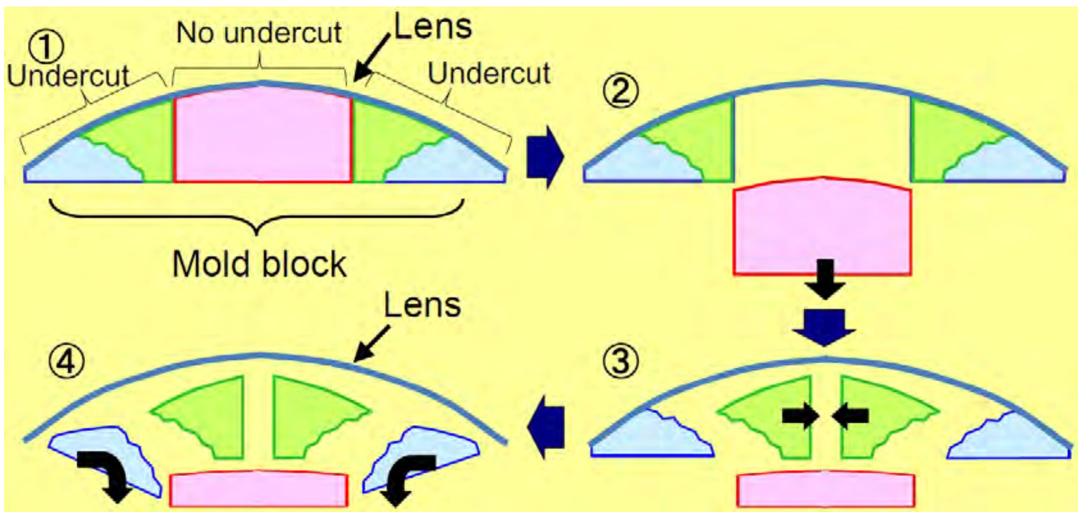


Daedo Steel advanced demolding technique





- POE mold has a **9-part molding die**
- 3 different demolding movements
- Only central part (red) needs positive draft angles



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Conclusions

- Freeform optics is a proven technology for higher performance CPV designs
- Highly asymmetric CPV problems can optimally solved with freeforms, as the SMS3D XR design
- Köhler array concentrators, as the FK, solve practical issues and outperform classical designs
- Further advanced freeform concepts in progress

LEGAL NOTICE

Devices shown in this presentation are protected by the following US and International Patents and Patents Pending:

Patents Issued

HIGH EFFICIENY NON-IMAGING **US 6,639,733 October 28, 2003**
COMPACT FOLDED-OPTICS ILLUMINATION LENS **US 6,896,381 May 24, 2005**
COMPACT FOLDED-OPTICS ILLUMINATION LENS **US 7,152,985 December 26, 2006**
COMPACT FOLDED-OPTICS ILLUMINATION LENS **US 7,181,378 February 20, 2007**
DEVICE FOR CONCENTRATING OR COLLIMATING RADIANT ENERGY US **7,160,522 January 9, 2007**
DISPOSITIVO CON LENTE DISCONTINUA DE REFLEXIÓN TOTAL INTERNA Y DIÓPTRICO ESFÉRICO PARA CONCENTRACIÓN O COLIMACIÓN DE ENERGÍA RADIANTE Spain **ES P9902661 December 2, 1999**
OPTICAL MANIFOLD FOR LIGHT-EMITTING DIODES **US 7,380,962**
OPTICAL MANIFOLD FOR LIGHT-EMITTING DIODES **US 7,286,296**
THREE-DIMENSIONAL SIMULTANEOUS MULTIPLE-SURFACE METHOD AND FREE-FORM ILLUMINATION-OPTICS DESIGNED THEREFROM **US 7,460,985 December 2, 2008**

Partial List of Patents Pending

DEVICE FOR CONCENTRATING OR COLLIMATING RADIANT ENERGY - a continuation of **US 7,160,522**
FREE-FORM LENTICULAR OPTICAL ELEMENTS AND THEIR APPLICATION TO CONDENSERS AND HEADLAMPS PCT/US2006/029464 **July 28, 2006**
MULTI-JUNCTION SOLAR CELLS WITH A HOMOGENIZER SYSTEM AND COUPLED NON-IMAGING LIGHT CONCENTRATOR PCT/US07/63522 **March 7, 2007**
OPTICAL CONCENTRATOR, ESPECIALLY FOR SOLAR PHOTOVOLTAICS PCT/US08/03439 **Mar 14, 2008**

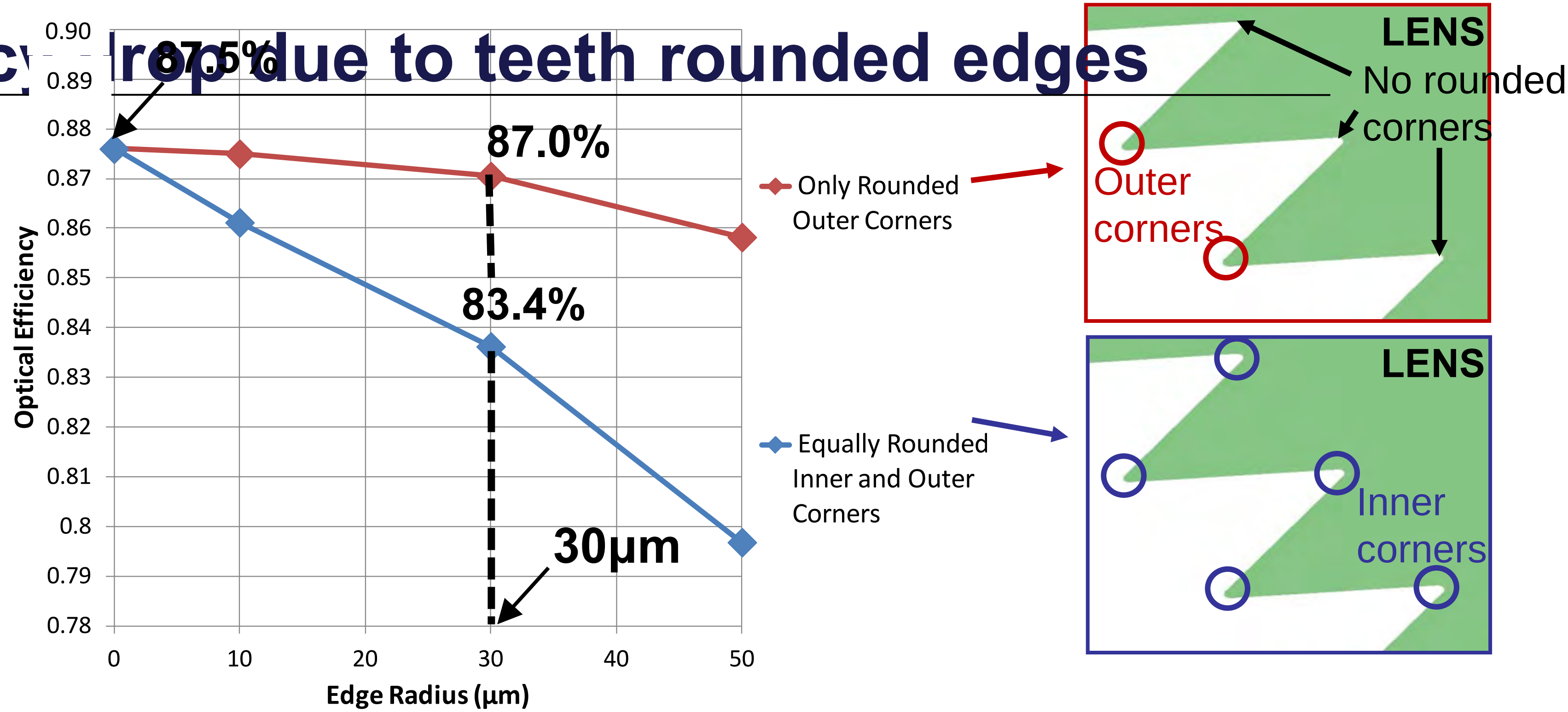
- This work is under the NGCPV EU-Japan project, funded by EU Commission (ENERGY,2011,2,1-1 Grant agreement no. 283798) and Japanese NEDO.

- Devices shown in this presentation are protected under US patent 8,000,018 & International patent applications 0905286.3, 200980154626.5, 762MUMNP2011

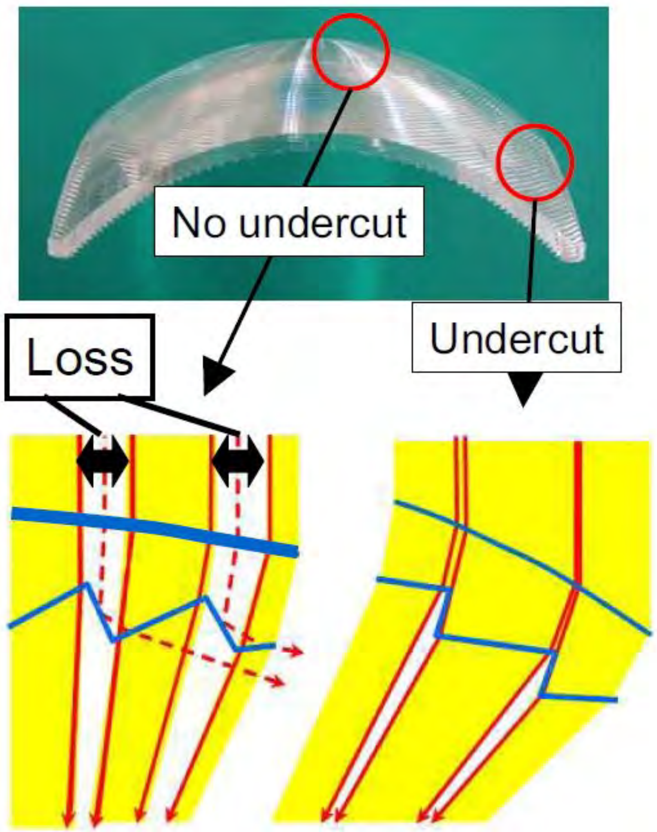
Thank you!

DFK round corners losses

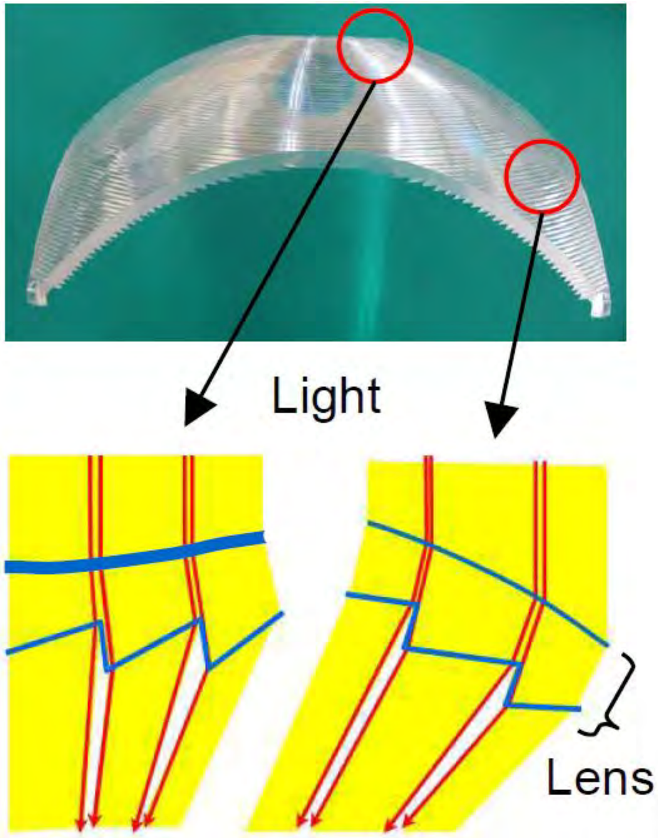
ciency drop due to teeth rounded edges



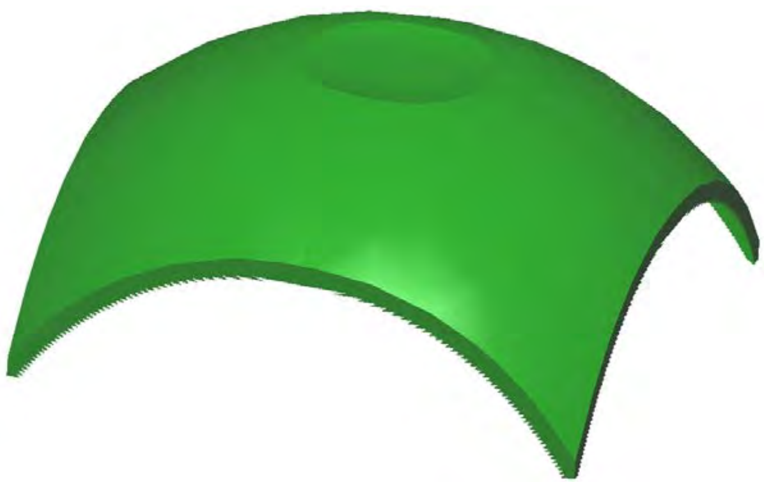
DFK without dimple



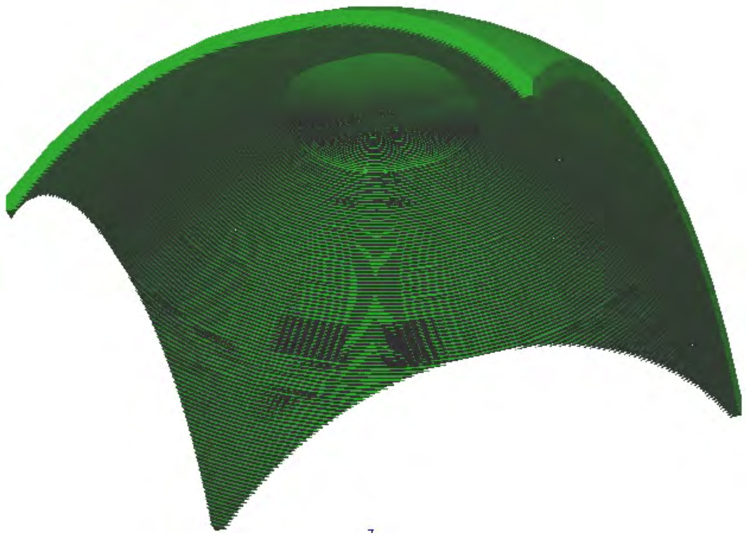
DFK with dimple



Central dimple enhanced POE design



Top view



Bottom view

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2. Free-forms in asymmetric systems
3. Freeform Köhler array concentrators
   - ✓ The VENTANA optical train
   - ✓ Daido Steel's DFK
4. Conclusions