The 36th Inter. Space Development Conference, St. Louis, USA, May 25-26, 2017

On New Developments of Space Solar Power Station (SSPS) of China

Baoyan Duan

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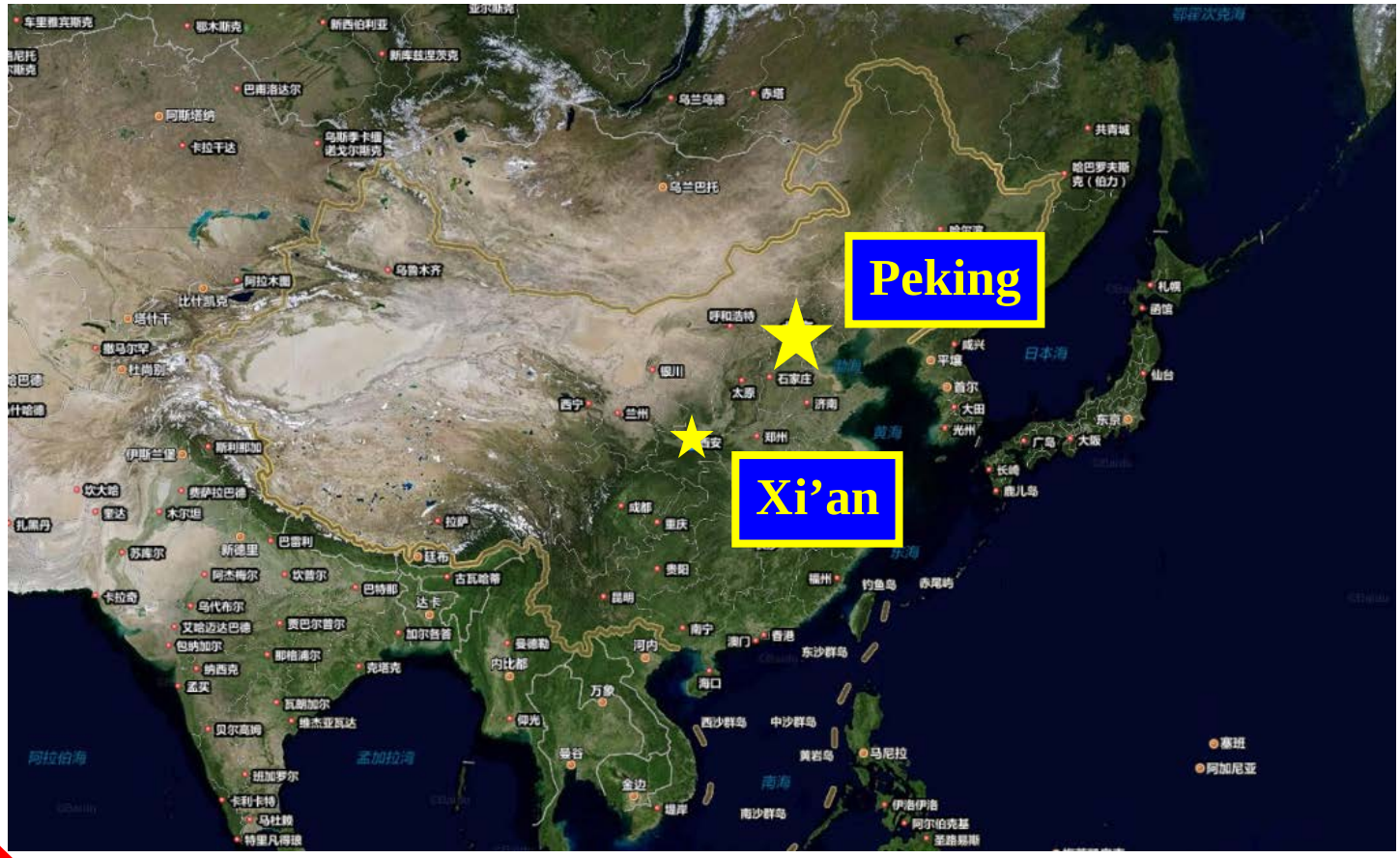
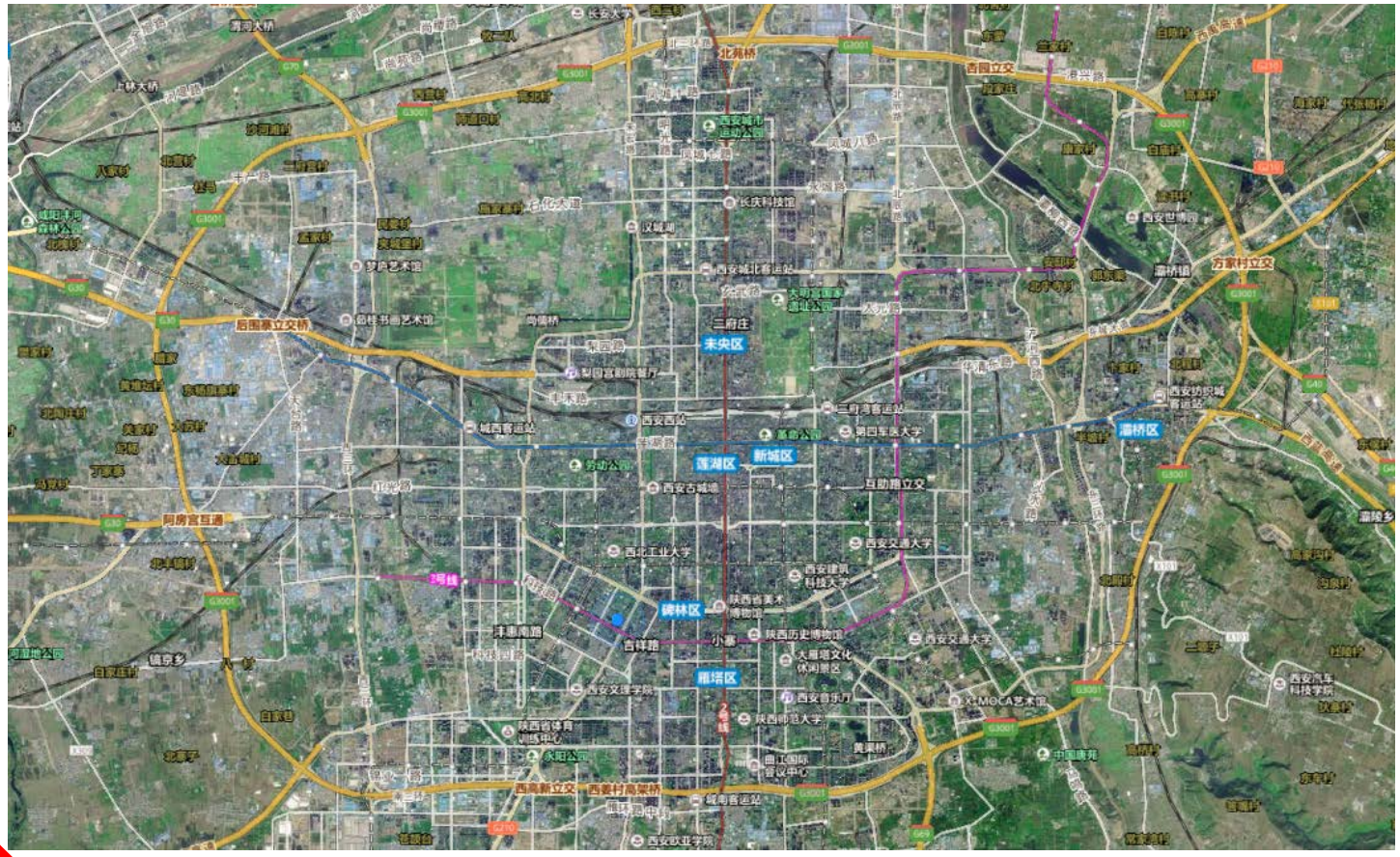
Research Institute on Mechatronics, Xidian University, Xi'an, China

China



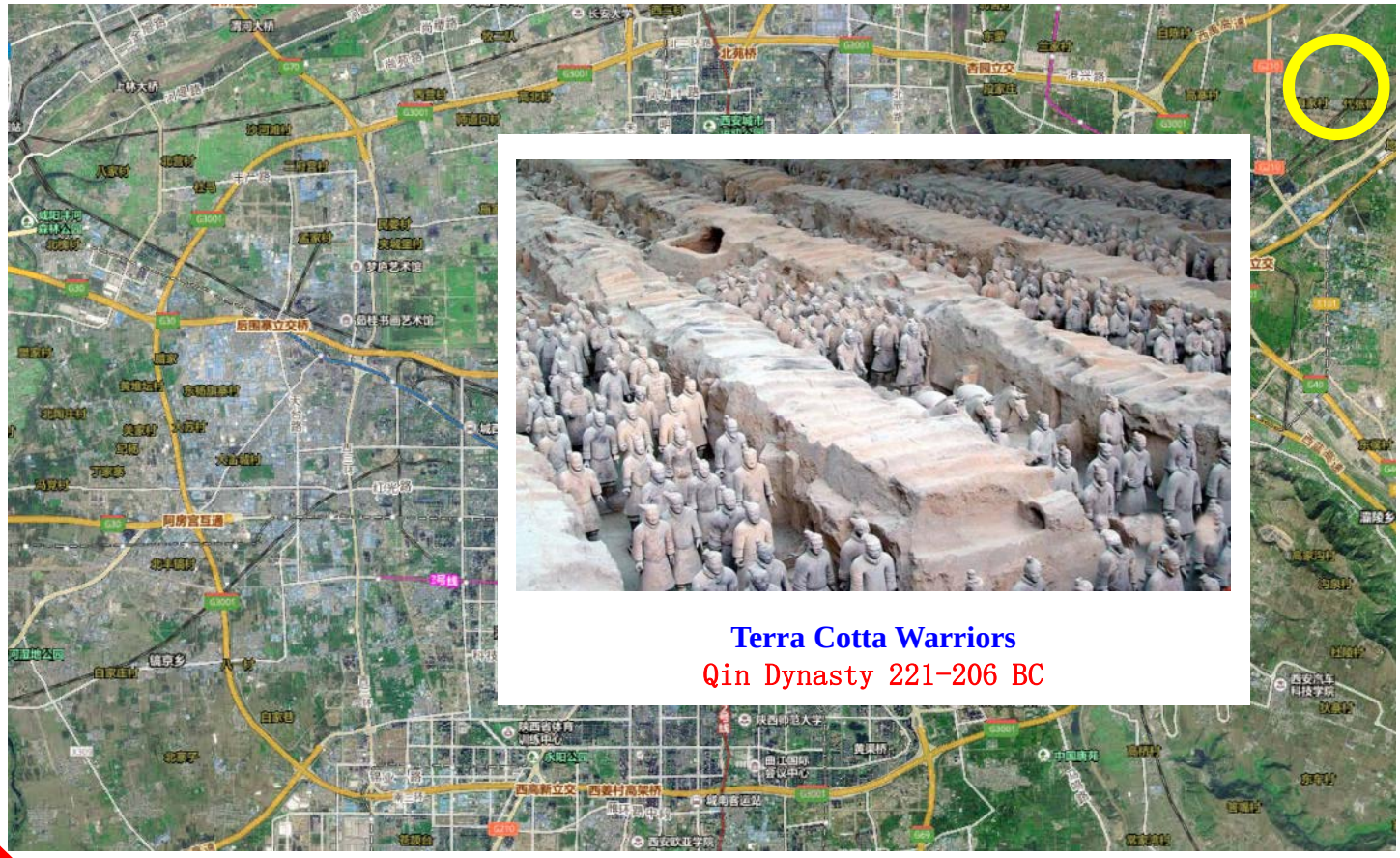
China

Xi’an


北苑桥
西安城市运动公园
长庆科技馆
汉城湖
西安世博园
西安城北客运站
大明宫国家遗址公园
方家村立交
后围寨立交桥
三府庄
未央区
梨园宫剧院餐厅
西安西站
城西客运站
二府湾客运站
灞桥区
莲湖区
新城区
劳动公园
西安古城墙
互助路立交
阿房宫互通
西北工业大学
西安交通大学
西安建筑科技大学
碑林区
陕西省美术博物馆
陕西历史博物馆
吉祥路
小寨
大雁塔文化休闲景区
雁塔区
西安音乐厅
陕西师范大学
大唐不夜城
陕西省体育训练中心
永阳公园
曲江国际会议中心
中国康复
西高新立交
西姜村高架桥
城南客运站
西安欧亚学院
西安汽车科技学院

China

Xi’an

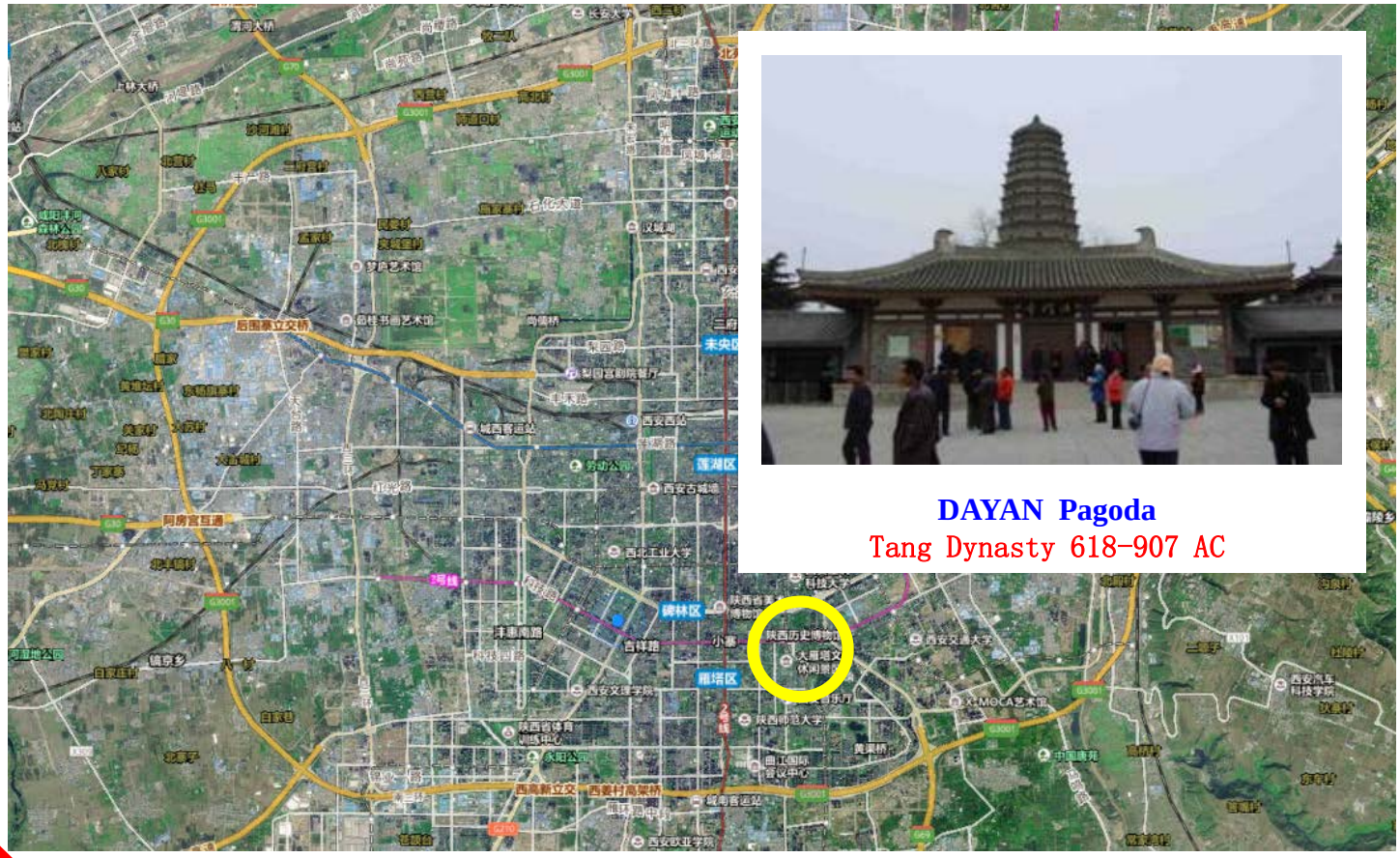


Terra Cotta Warriors

Qin Dynasty 221-206 BC

China

Xi’an



DAYAN Pagoda

Tang Dynasty 618-907 AC

China

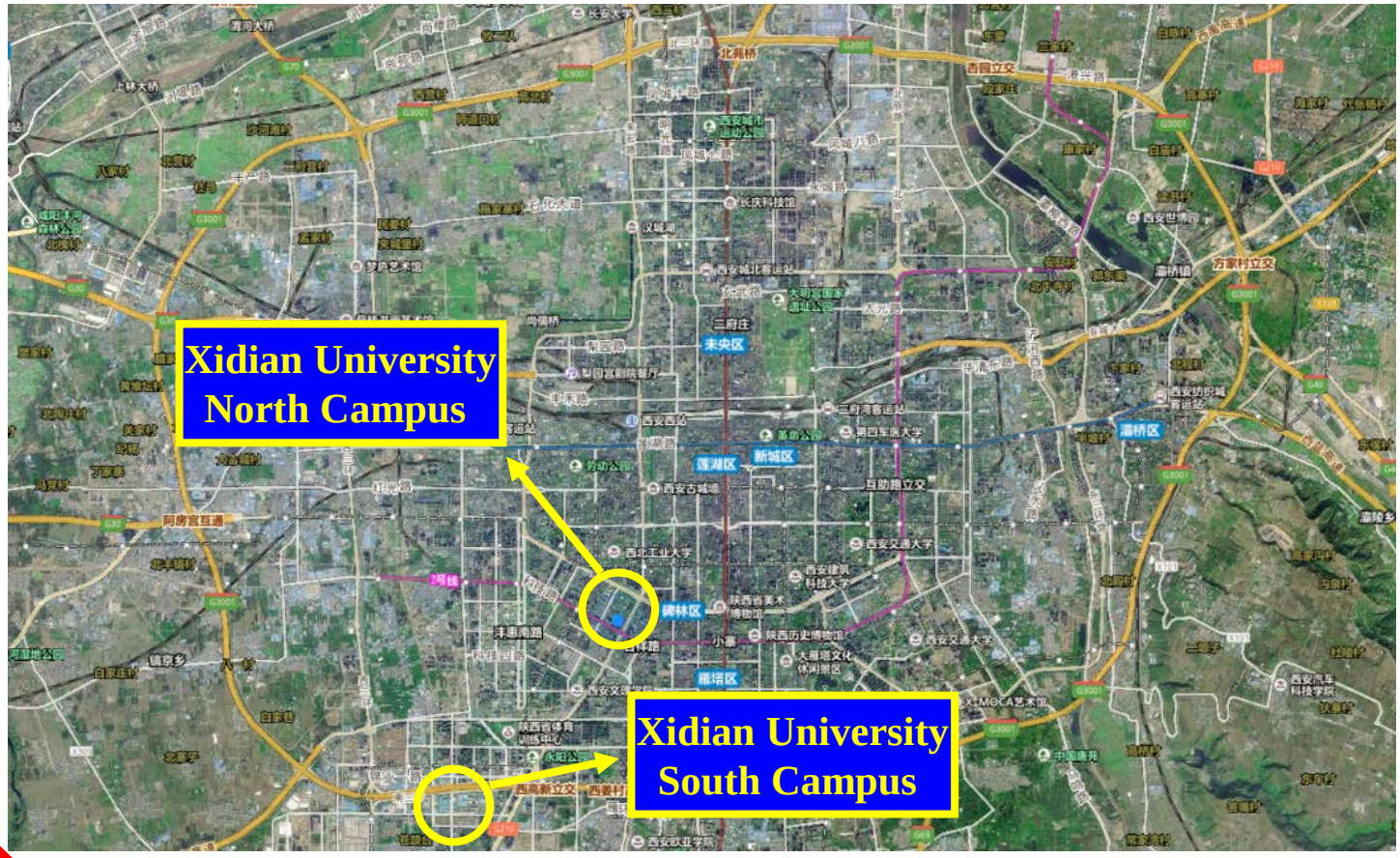
Xi’an

Ancient city wall

Ming Dynasty 1368-1644 AC

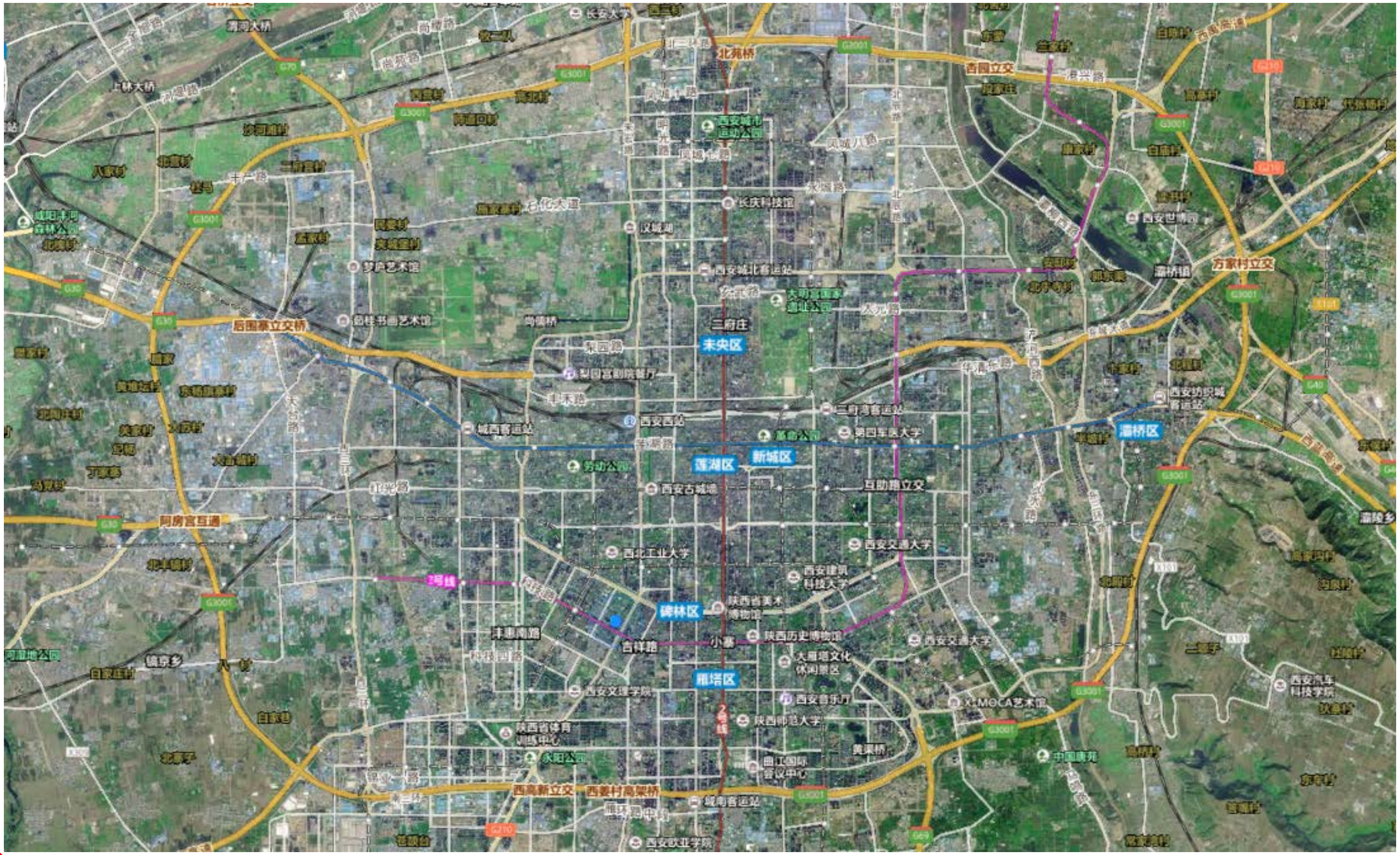
China

Xi’an


Xidian University
North Campus
Xidian University
South Campus

China

Xi’an

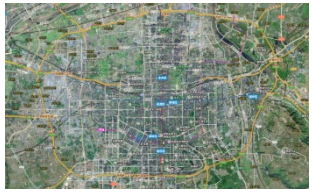


XIDIAN University, under the jurisdiction of the Ministry of Education, dedicates primarily to the electronics and information education and research, with an integration of a wide range of academic subjects covering engineering, science, management, economy, arts and social sciences.

China

- One of the universities funded by Project 985
  (Innovation Platform for Superiority Subject)
- One of the universities funded by Project 211
- One of the universities funded by 2011 Project
  (National Collaborative Innovation Plan)
- One of 55 universities with Graduate School

Xi'an

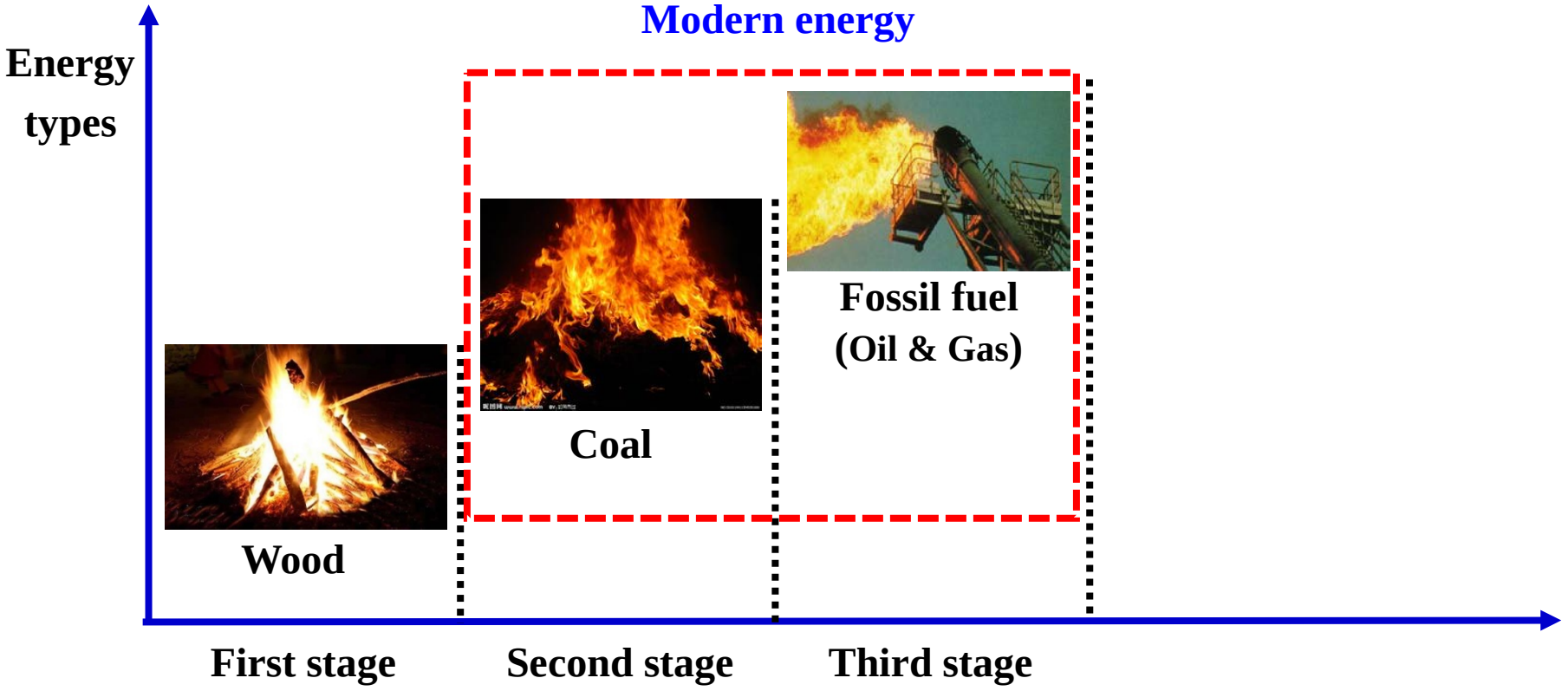


Xidian

Contents

Background

Energy: material basis for the survival and development of human society



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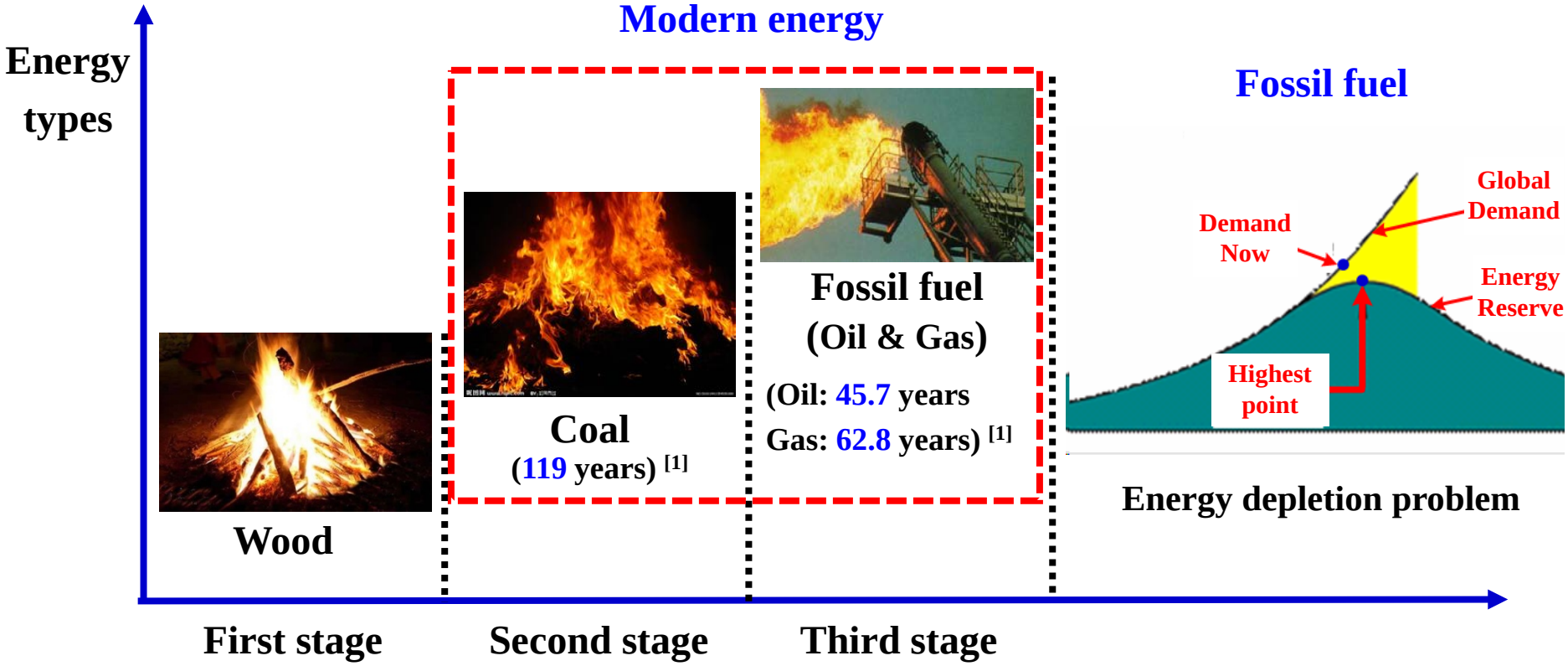
Energy: material basis for the **survival** and **development** of human society



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Global demand for energy： 15 TW·year（2007）

30 TW·year（2025） 50TW·year（2050） [3]

[1] Statistical Review of World Energy, British Petroleum, 2015

[2] World Population Prospects, United Nations., 2015

[3] R. Doombosch, For official use SG/SD/RT, 2006

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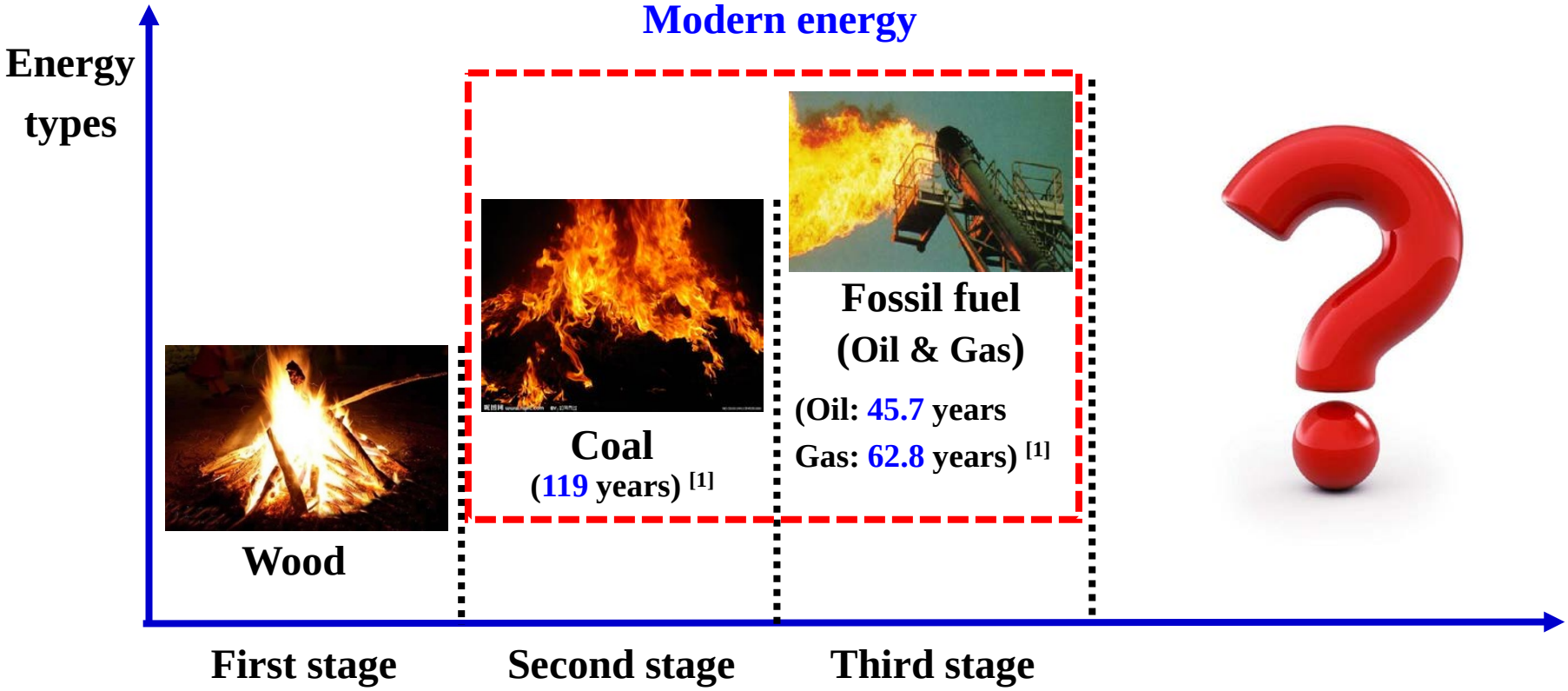

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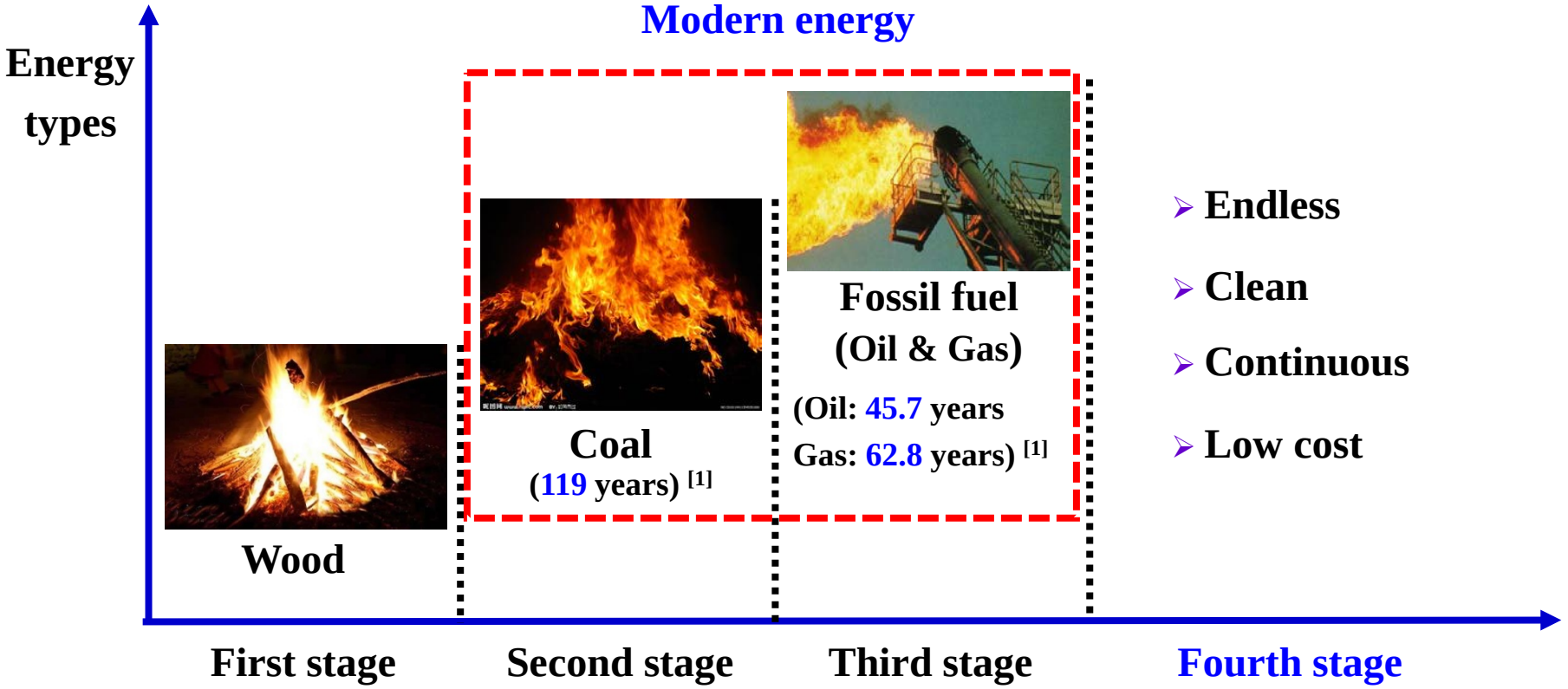

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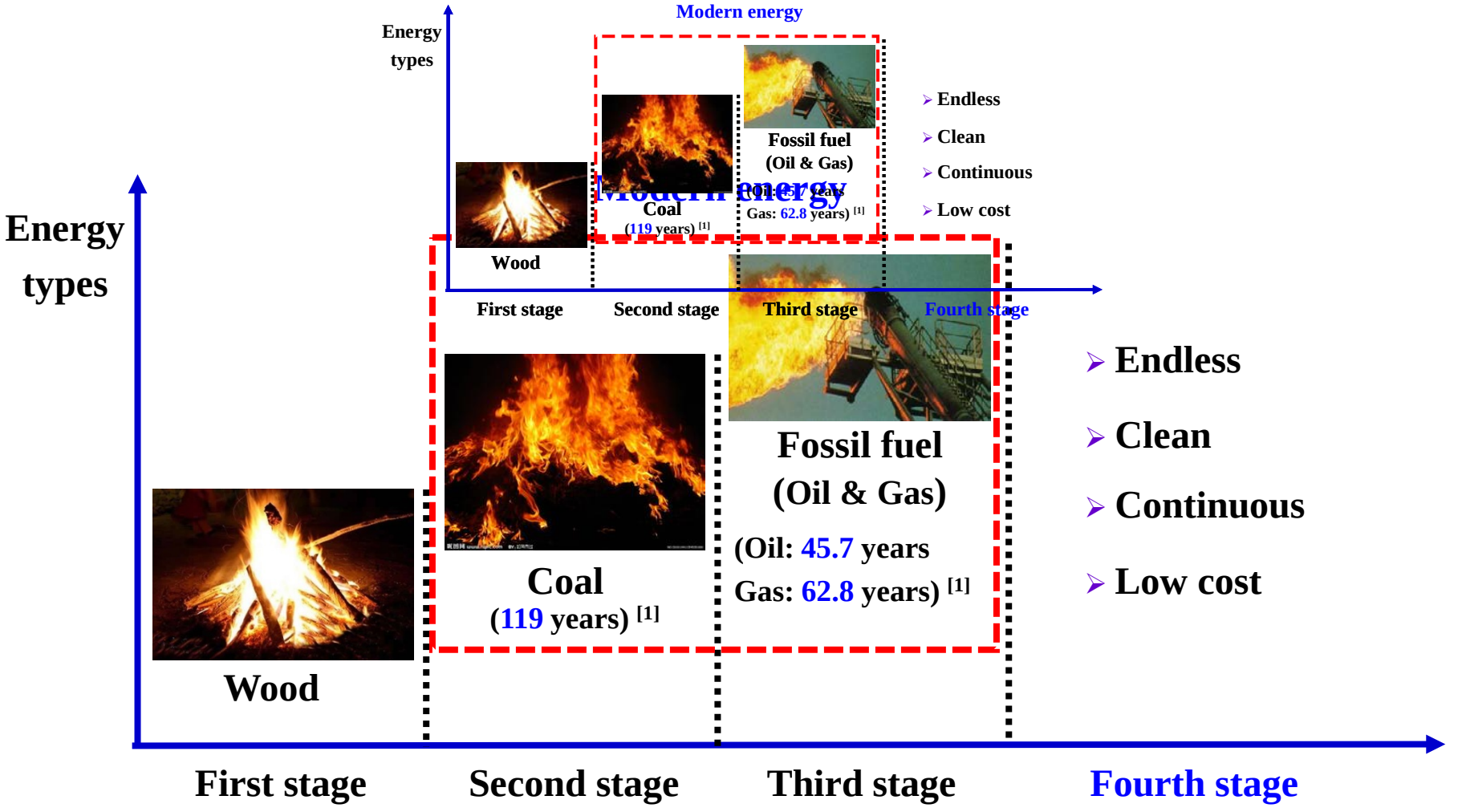
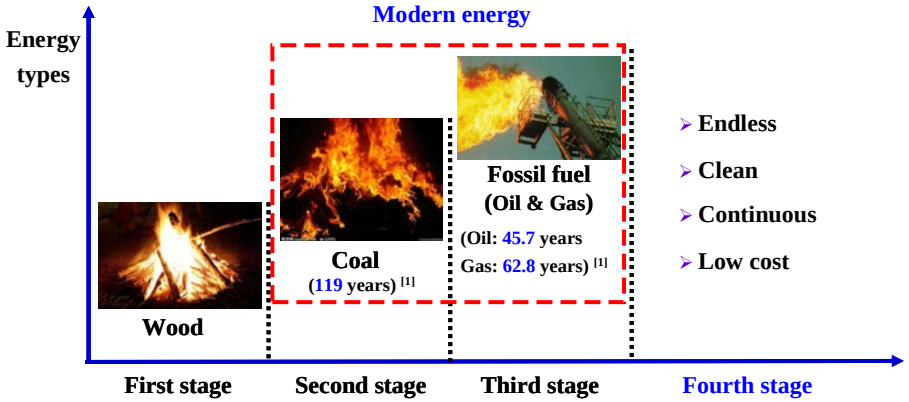

Energy types
Modern energy
Fossil fuel
(Oil & Gas)
(Oil: 45.7 years
Gas: 62.8 years) [1]
Coal
(119 years) [1]
Wood
Endless
Clean
Continuous
Low cost
First stage
Second stage
Third stage
Fourth stage

Background



Candidate energies for the fourth stage

Energy types	Clean	Safety	Reliability	Price / cent
Nuclear	Yes	?	?	13
Wind	Yes	Yes	Geographic restrictions	8
Ground solar	Yes	Yes		12
Hydropower	Yes	Yes		6
Space solar	Yes	Yes	Yes	6

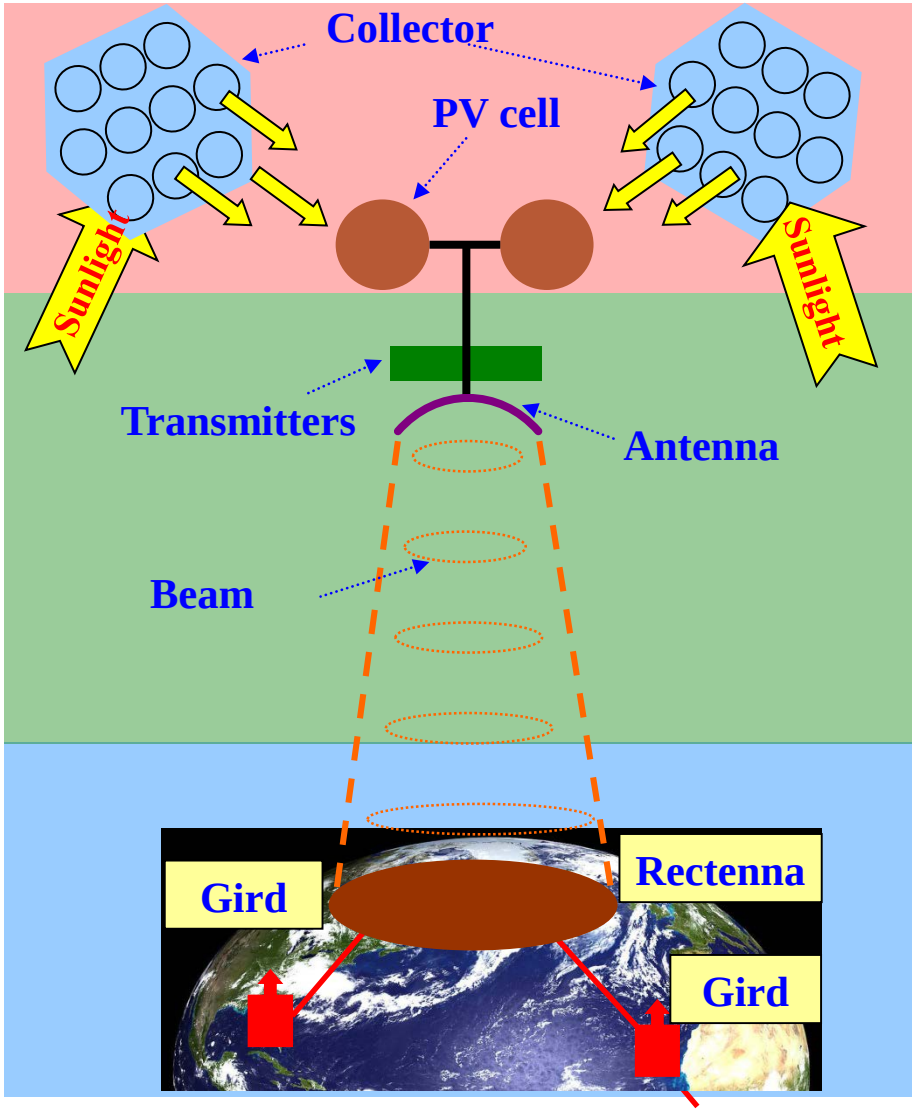
Space solar: satisfy energy demand for human society

SSPS : a good choice to solve the energy problem

Background

Main parts：

- **Solar power collection and photoelectric conversion**
- **Wireless power transmission**
- **Ground-receiving system**



Background

Process of energy conversion：

Sunlight

↓

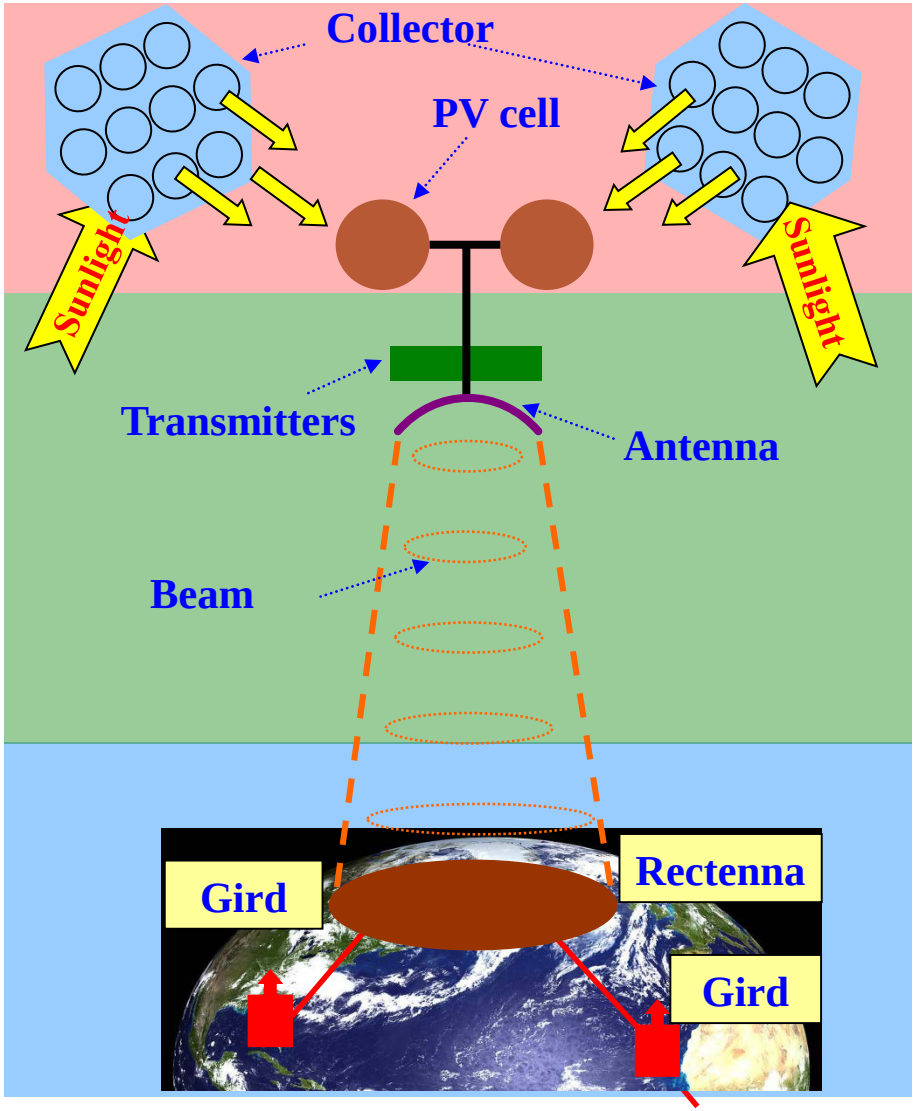
Direct current

↓

Microwave

↓

Direct current



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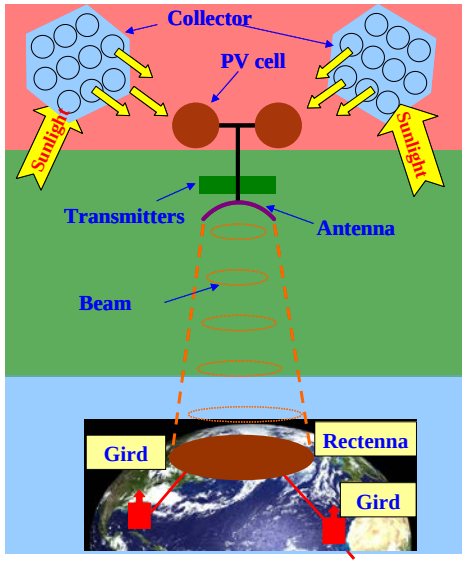
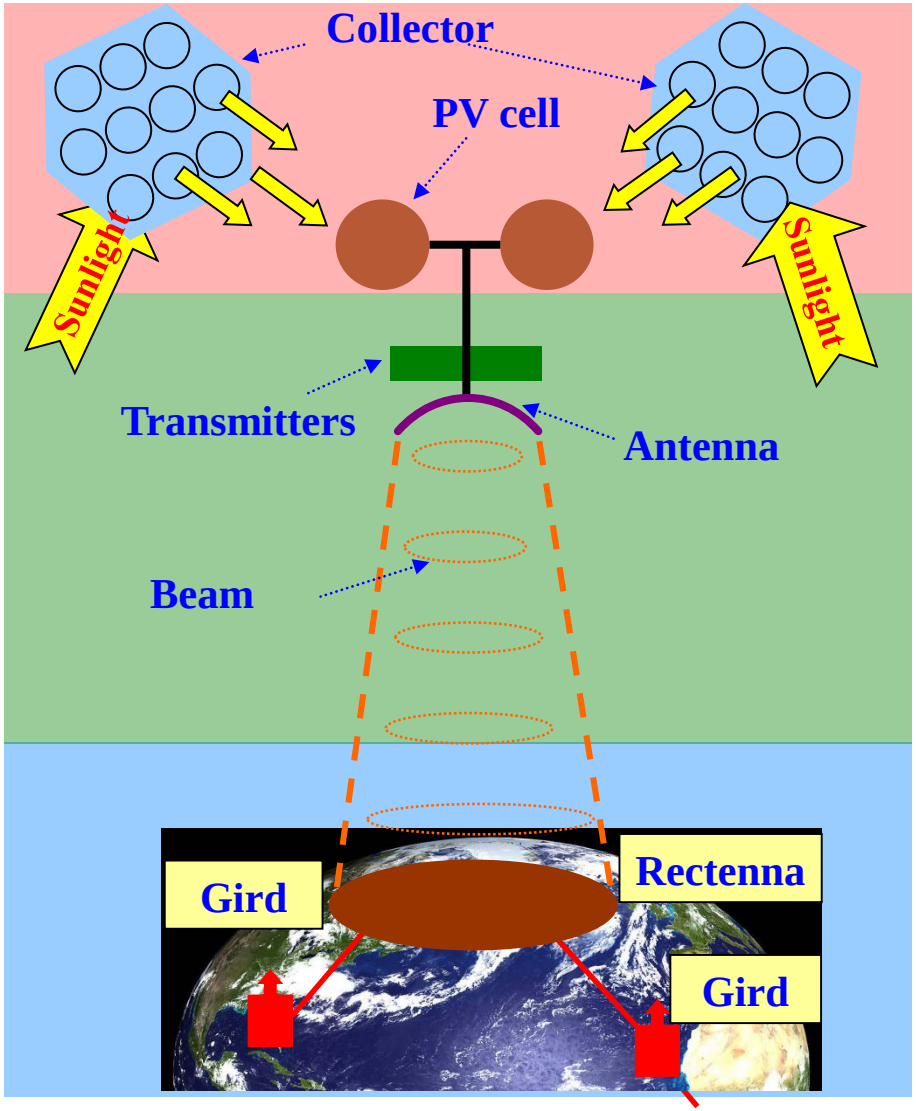

Collector
PV cell
Sunlight
Sunlight
Transmitters
Antenna
Beam
Gird
Rectenna
Gird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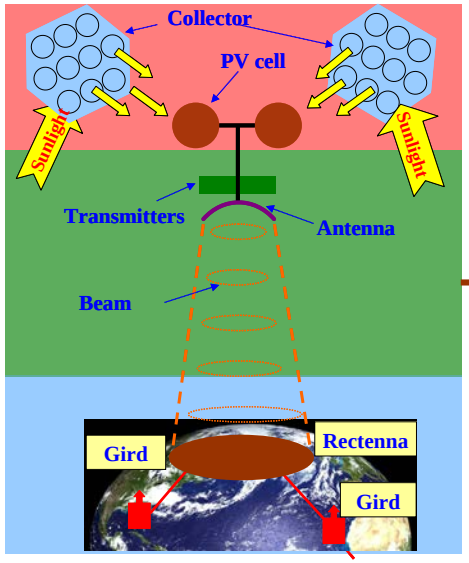
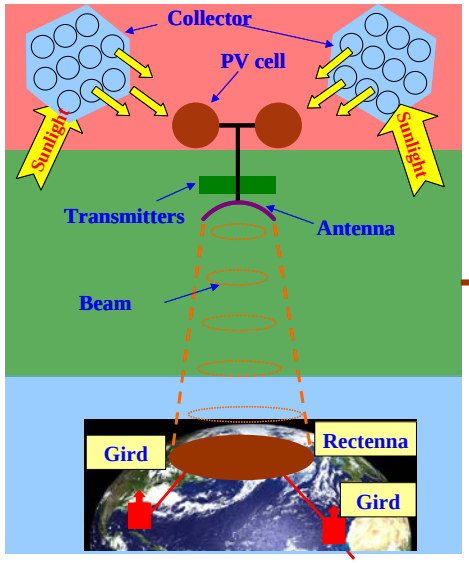
Background



- Non-condenser
- Condenser

Background



Non-condenser

Advantages: Easily Extensible

Simple construction

Disad.: Low ratio on power to mass

Low optical collection efficiency

Large inertia (difficult to control)

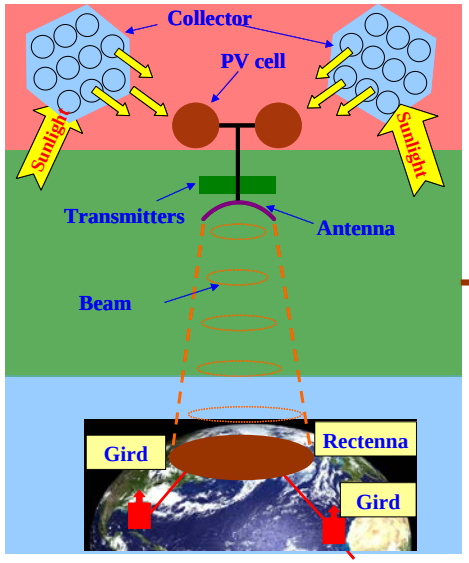
Condenser

PV cell toward the sunlight

Antenna toward the earth

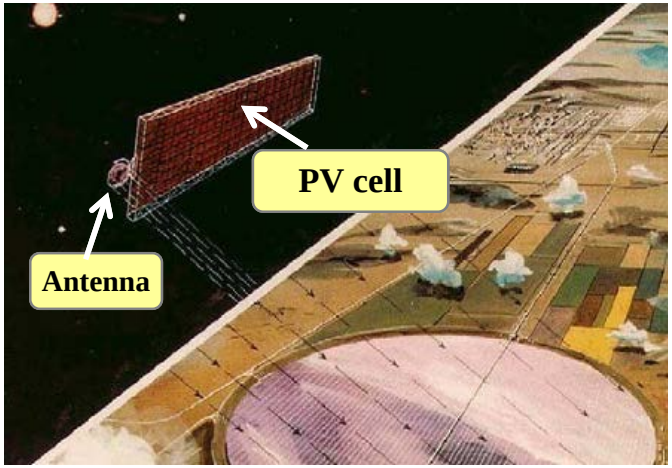
} relative rotation

Background



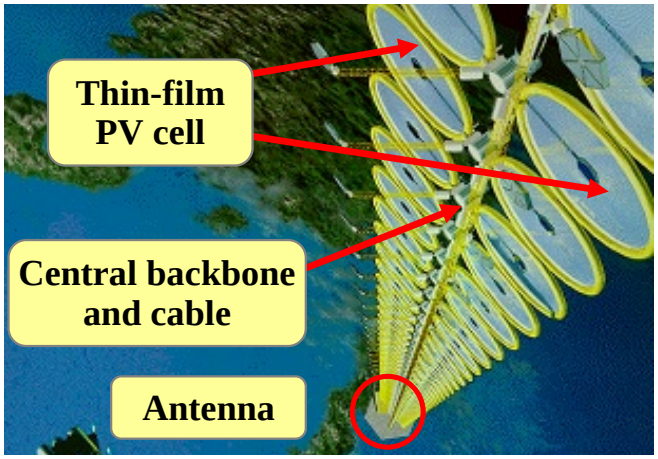
Non-condenser

Condenser



Reference Model

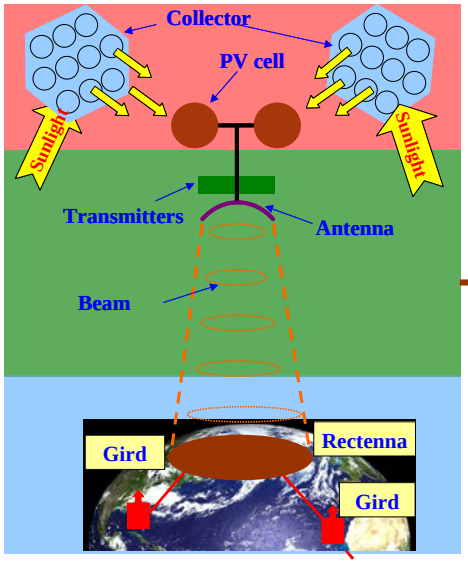
Power-mass ratio: 51 W / kg



Sun Tower

Power-mass ratio: 72 W / kg

Background



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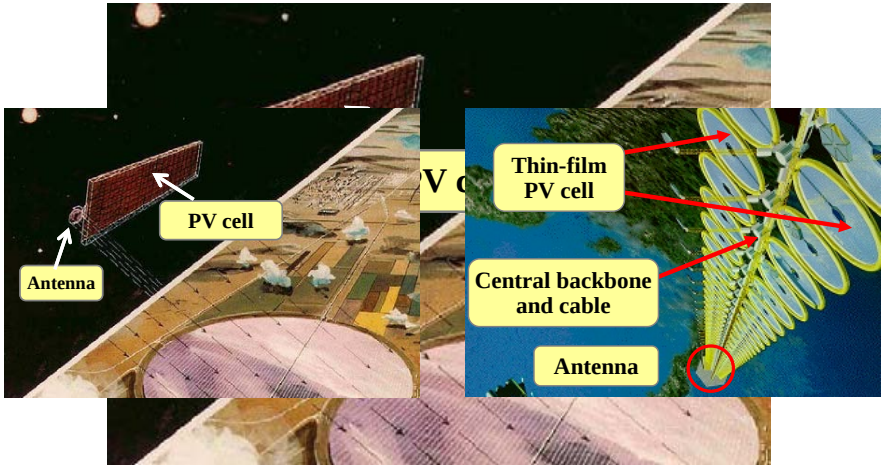

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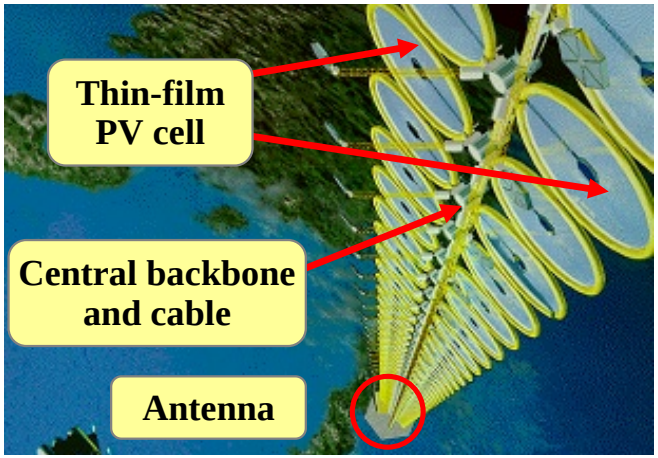

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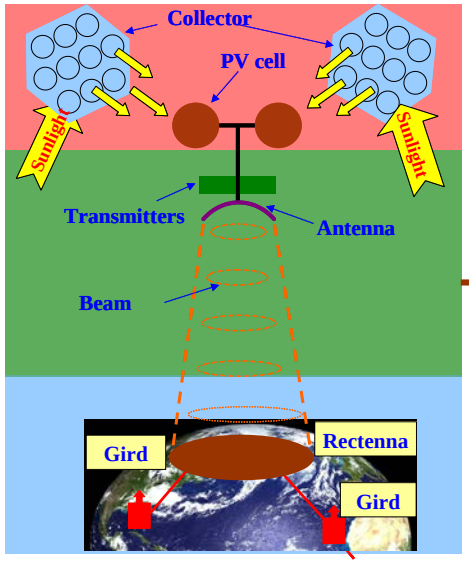

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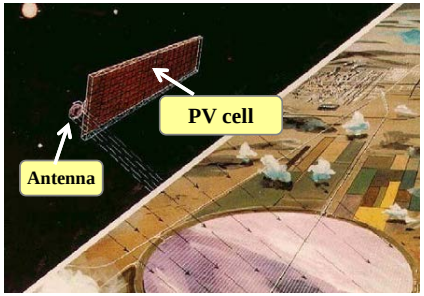
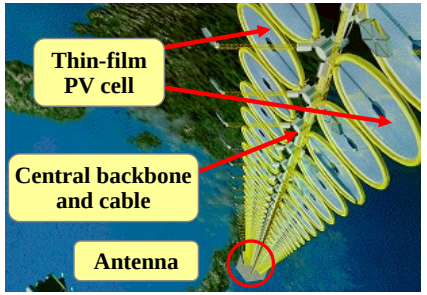


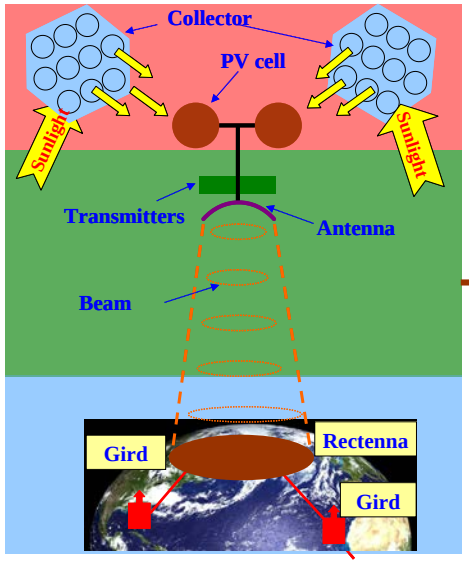


Rotary joints: GW level

bottleneck

Implementation: 75 kW

Background



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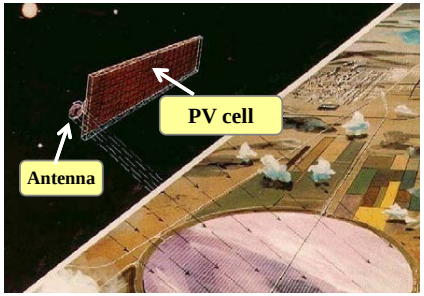
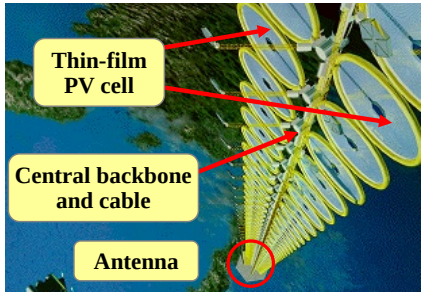
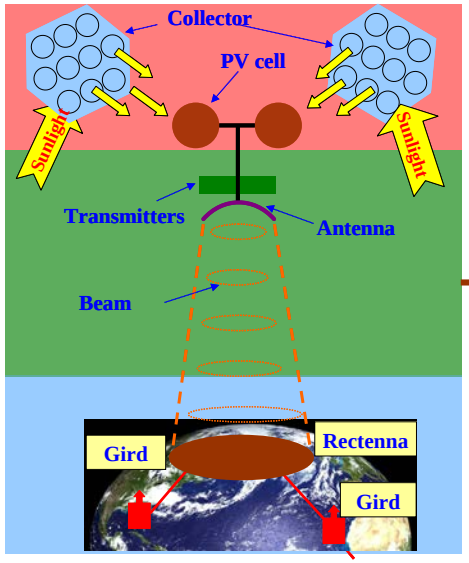




Multi-Rotary Joints Concept

China Academy of Space Technology, 2013

Background



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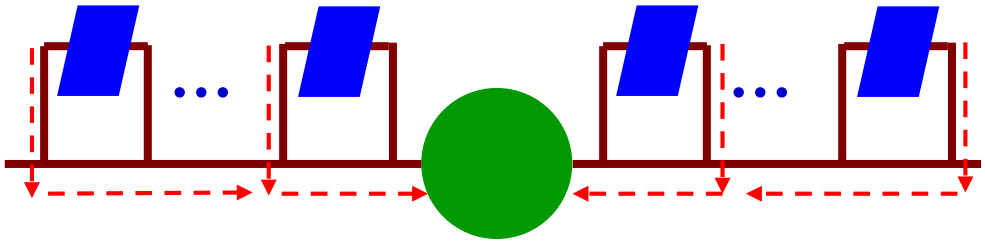

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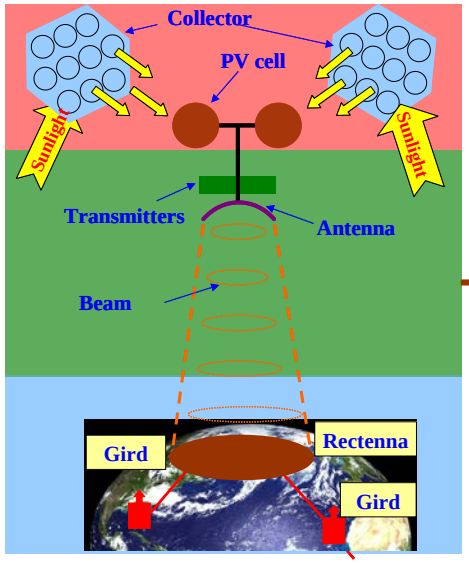

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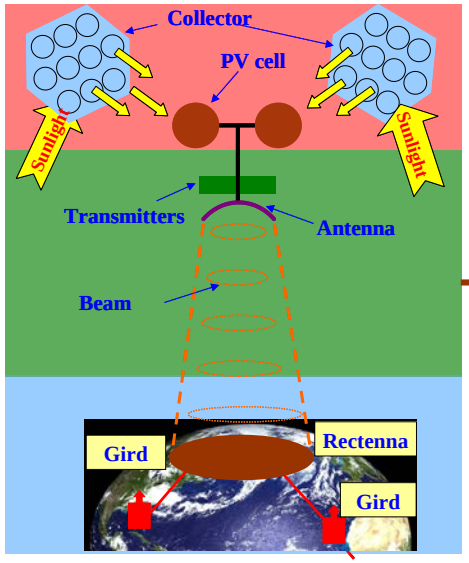

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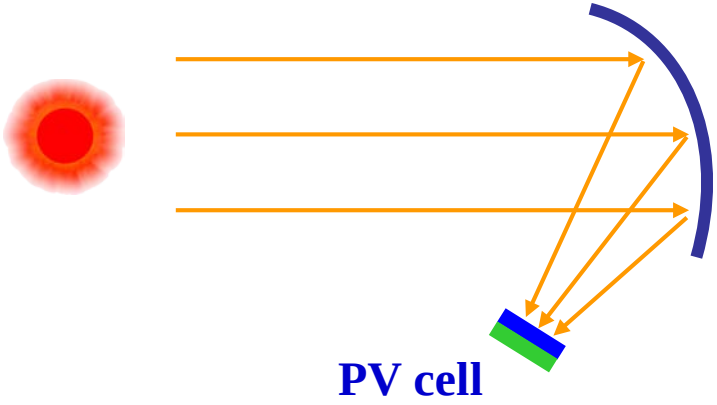


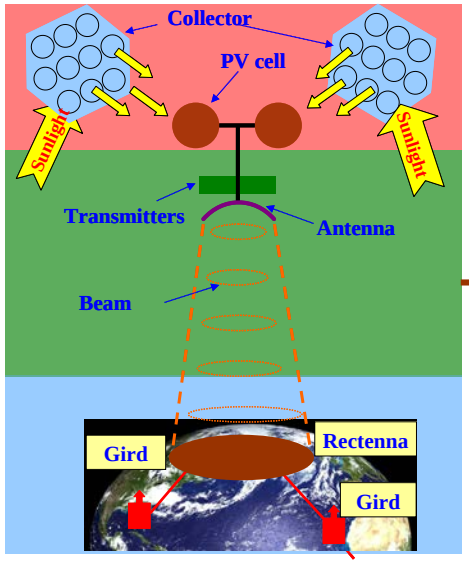
Advantages: Reduce the area of PV cell

High ratio on power to mass

Disadvantages: Complex control

Heat dissipation

Background



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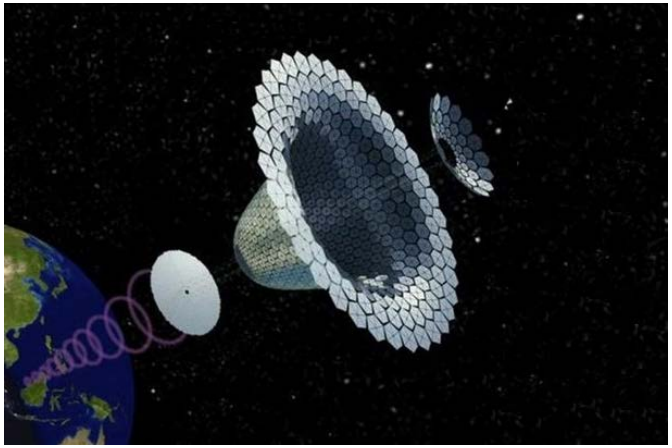
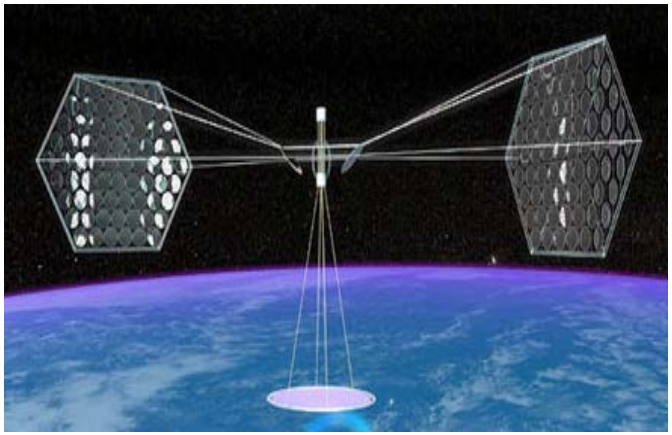


ALPHA Concept

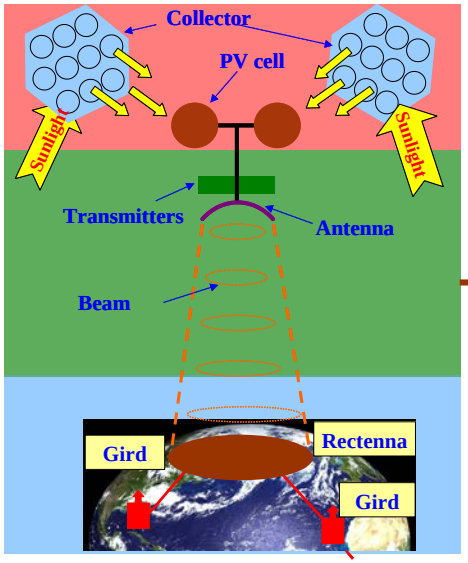
Power-mass ratio: 79 W / kg



Integrated Symmetrical Concentrator

Power-mass ratio: 63 W / kg

Background



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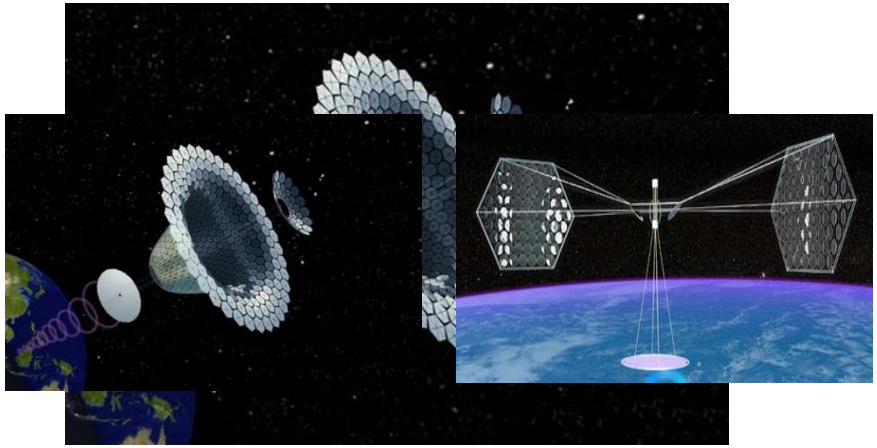

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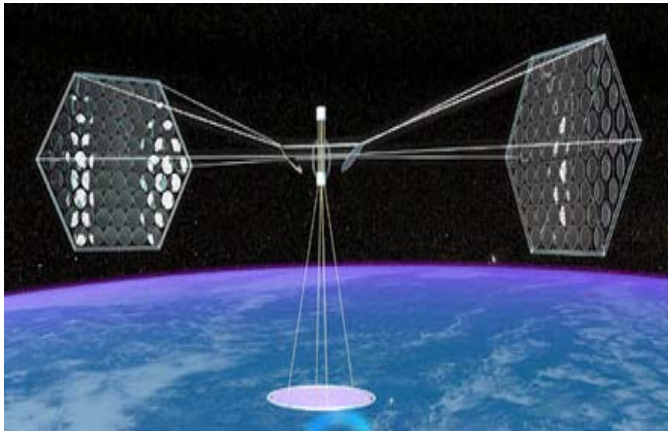

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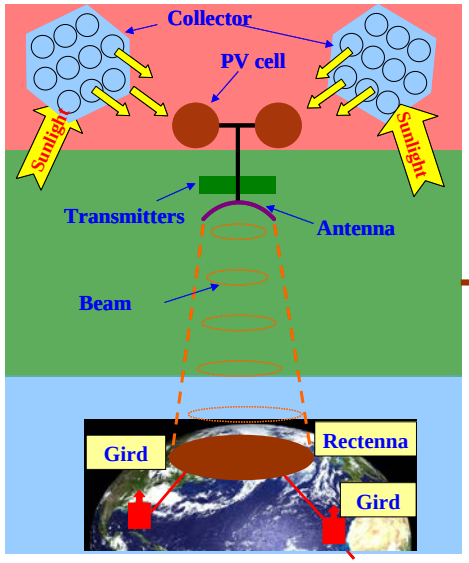

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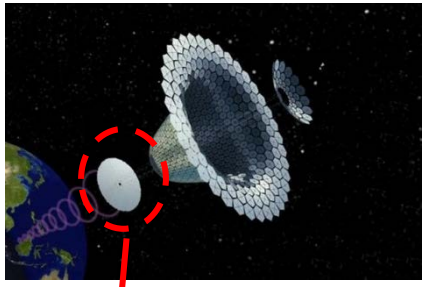
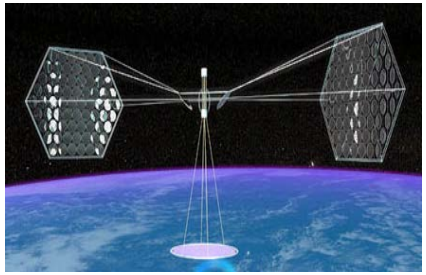
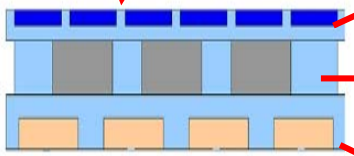






PV cell array

Microwave device

Antenna

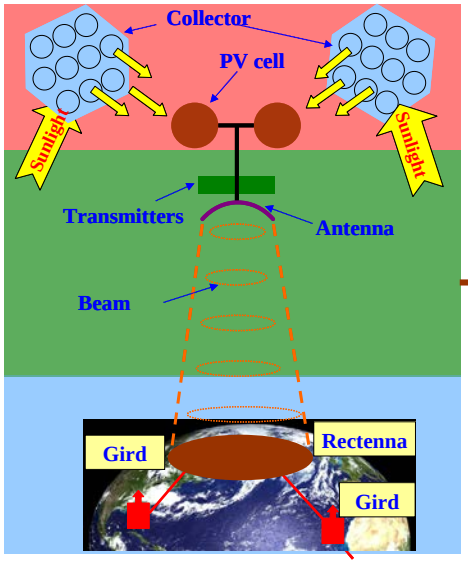
Advantages: **high modular** **scheme**

Disadvantages: **Complex control**

Light leakage

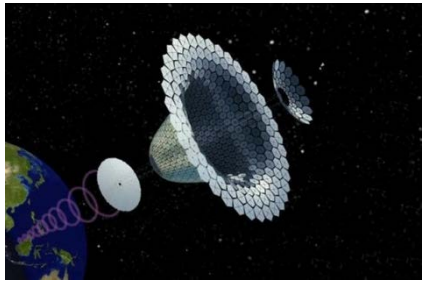
Heat dissipation

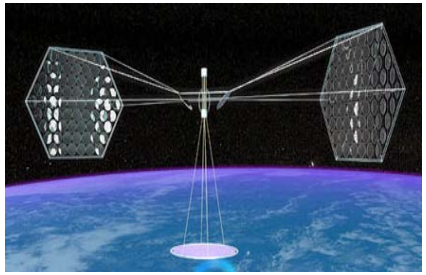
Background

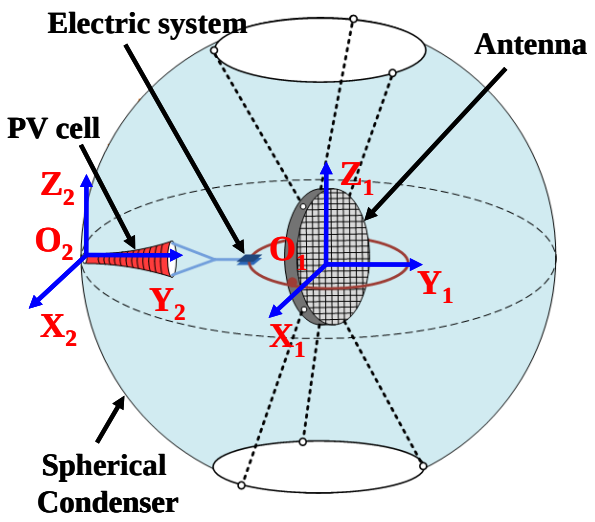


Non-condenser

Condenser



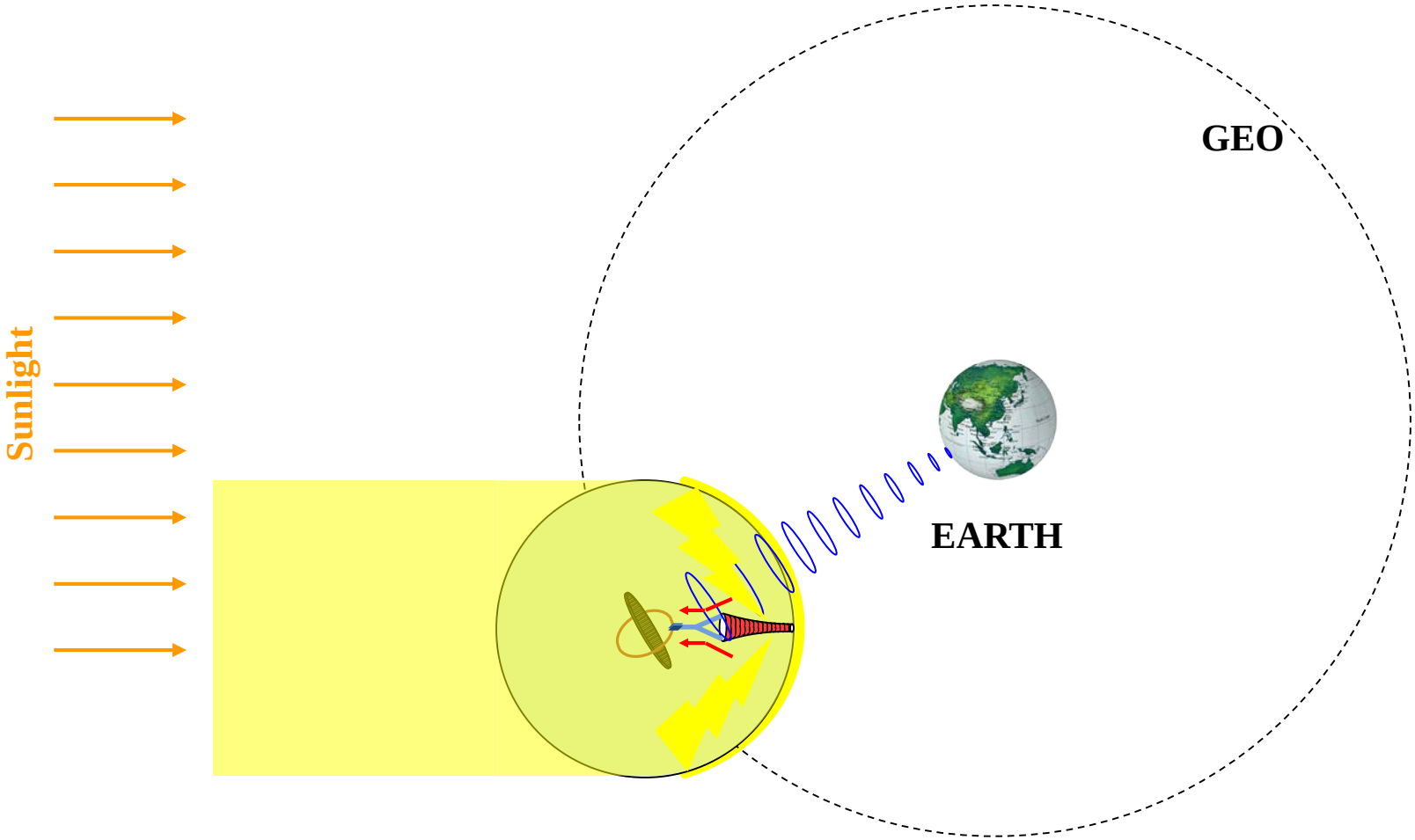




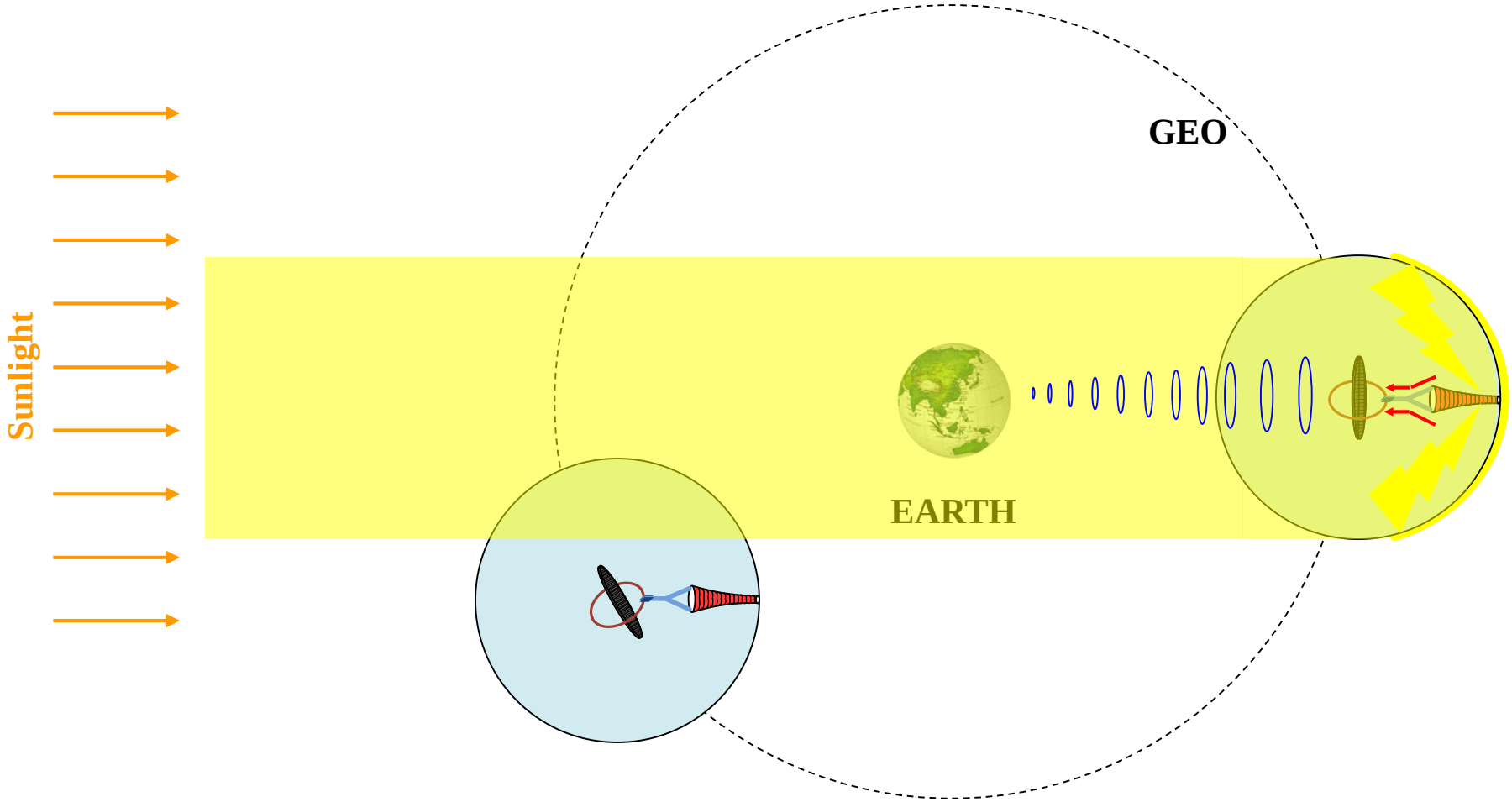
OMEGA Concept (Xidian University)

Power-mass ratio: 98 W / kg

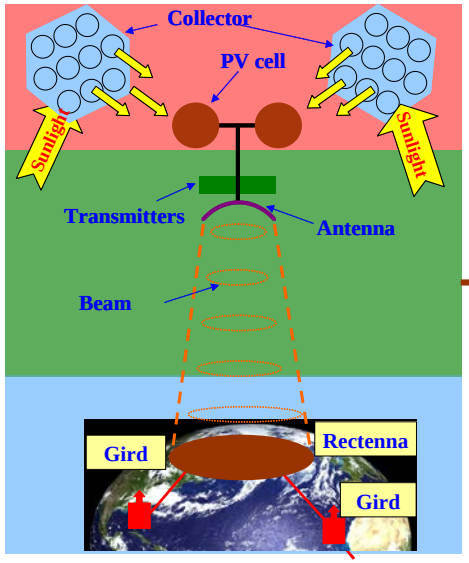
Fundamental problems



Fundamental problems



Background



Non-condenser

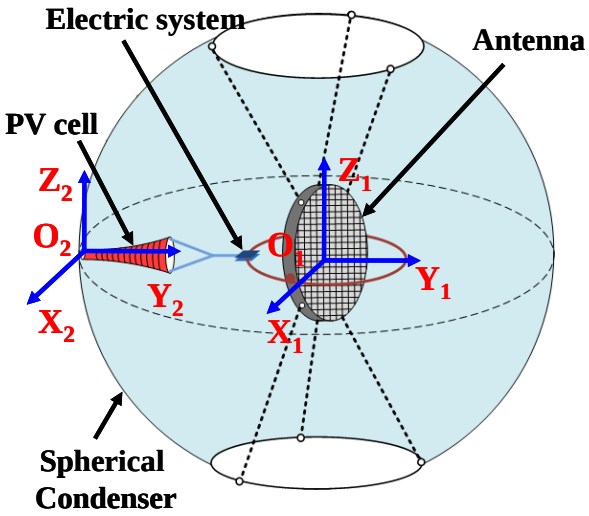
Condenser

Advantages:

- **Main reflector without adjustment**
- **Lower heat dissipation**

Assumption:

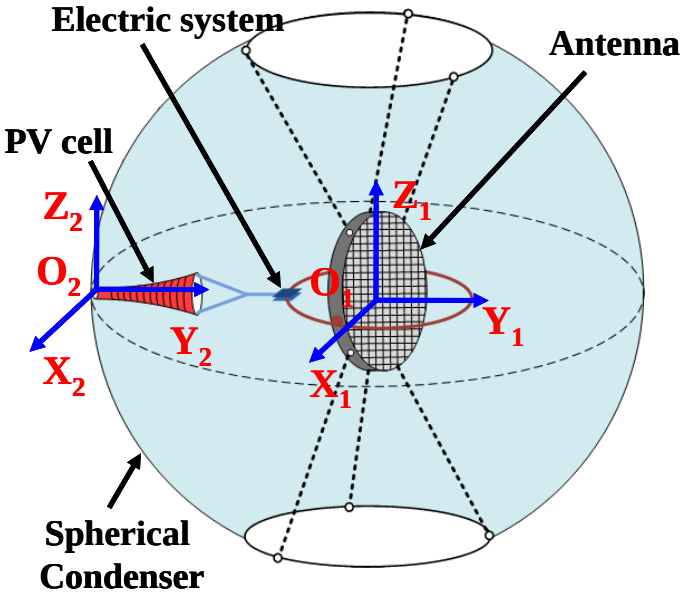
Thin film material: semi-transparent for sunlight

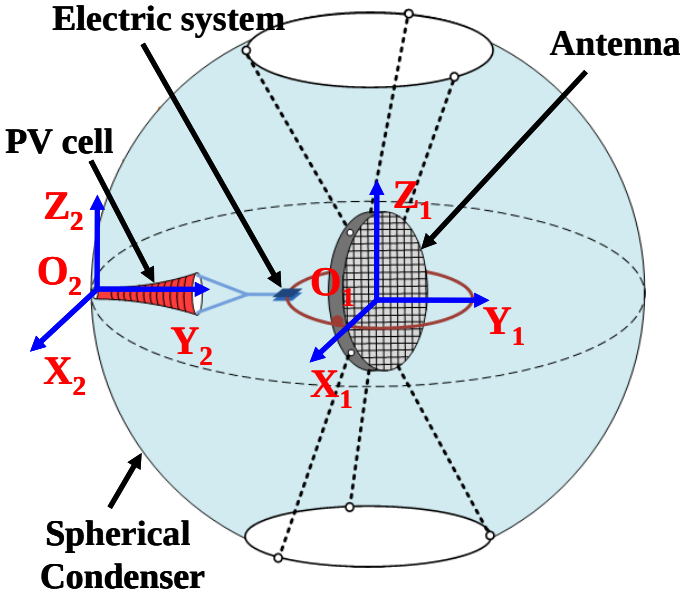


OMEGA Concept (Xidian University)

Power-mass ratio: 98 W / kg

Background


Electric system
Antenna
PV cell
Z2
O2
Y2
X2
O1
Z1
Y1
X1
Spherical
Condenser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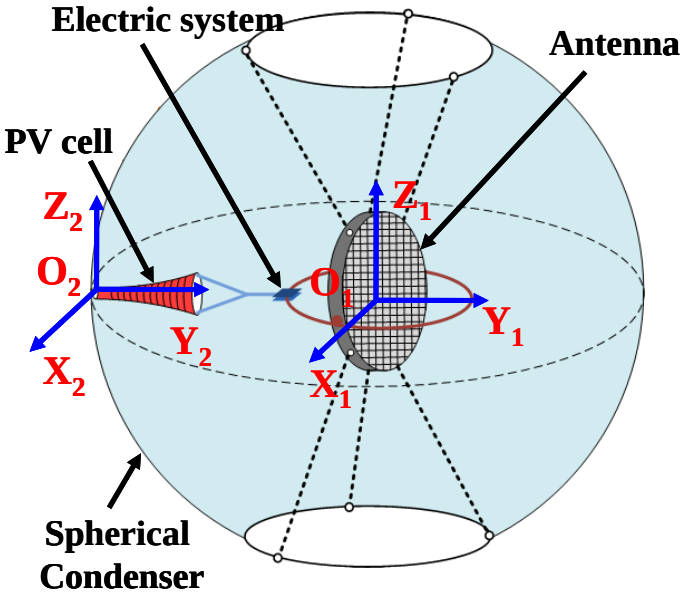
Background



- **Multi-domain Physical Systems**
  - Synthesization, Coordination, and Optimization
- **Wireless Power Transmission**
  - Transmitting antenna & Rectenna
  - Beam control (shape & direction)
- **In-orbit assembly**
  - Assembly sequence design
  - Vibration attenuation
- **Deployable array**
  - Large scale, Low areal weight, Small stowed package
  - Dynamic analysis and control
- **Heat dissipation**
- **Transport rocket**
- **Operation security**

} Uninvolved here

Contents

Key technologies

Multi-systems	Effective WPT	In-orbit assembly	Deployable array

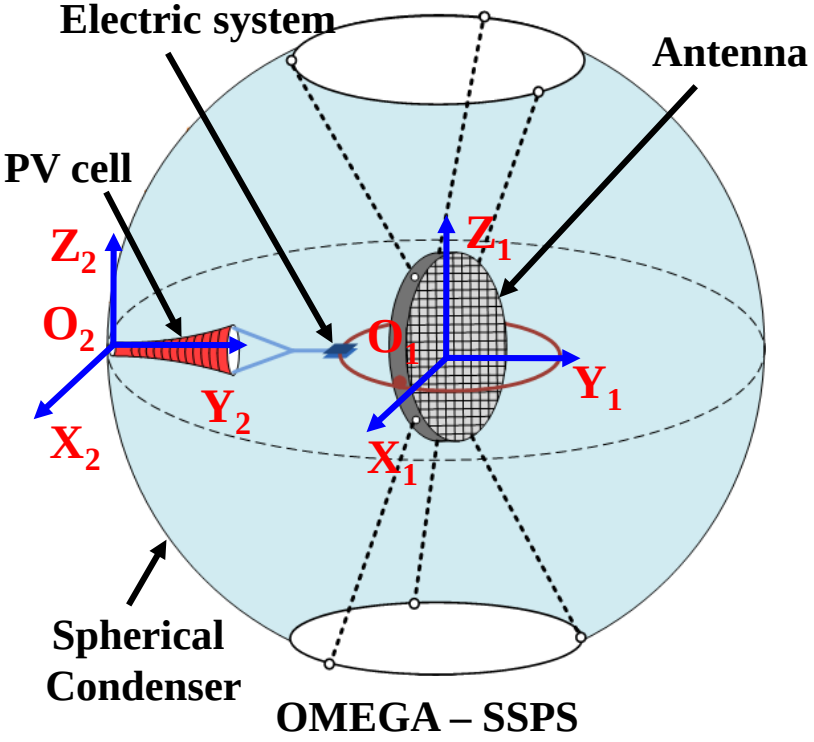
Key technologies

Multi-systems | **Effective WPT** | **In-orbit assembly** | **Deployable array**

Condenser Sub-system

Electric Sub-system

Antenna Sub-system



Key technologies

Multi-systems | **Effective WPT** | **In-orbit assembly** | **Deployable array**

Condenser Sub-system

Coordination

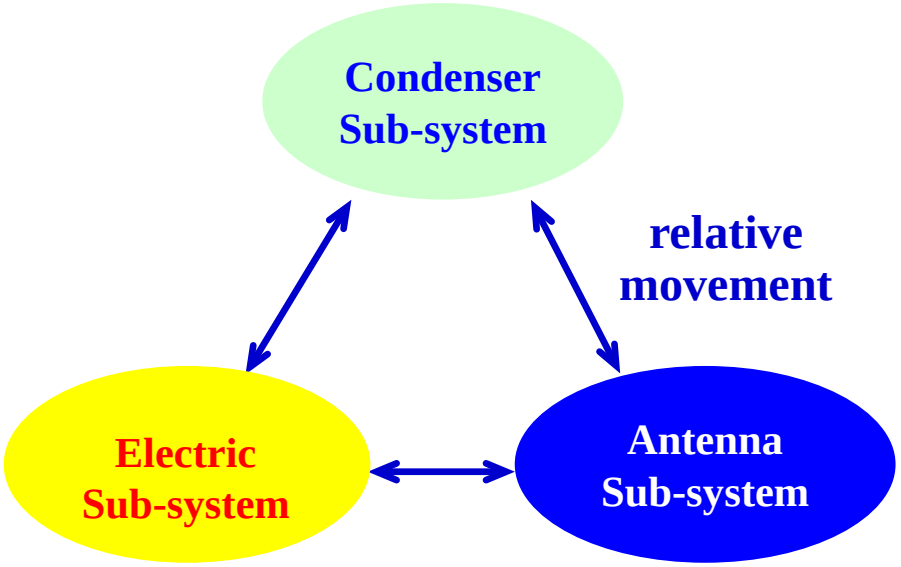
Synthesization

Electric Sub-system

Antenna Sub-system

Key technologies

Multi-systems | **Effective WPT** | **In-orbit assembly** | **Deployable array**



Coordination

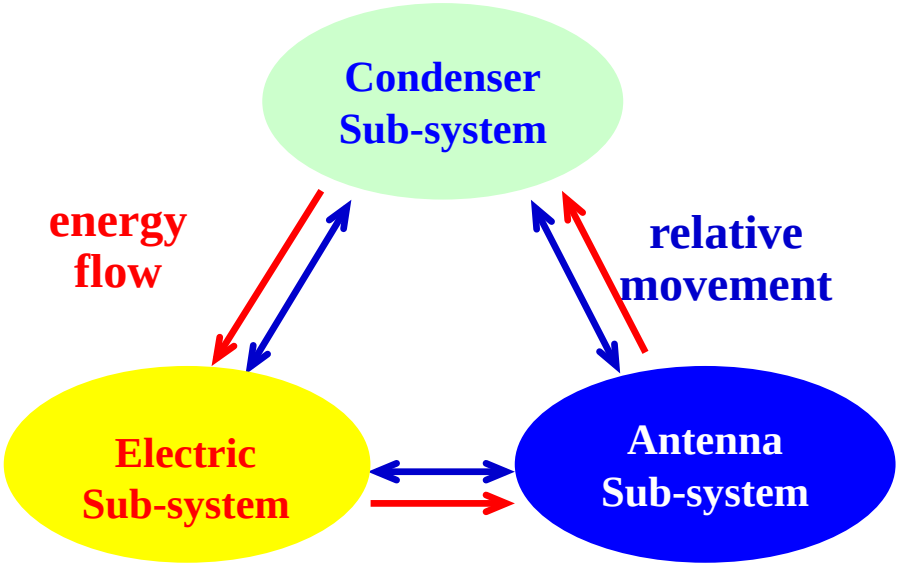
Synthesization

- stable operation
- functional coordination
- Low cost

Coordination equation

Key technologies

Multi-systems | **Effective WPT** | **In-orbit assembly** | **Deployable array**



Coordination

- stable operation
- functional coordination
- Low cost

Synthesization

- multidisciplinary
- Subsystems

(power-mass ratio)

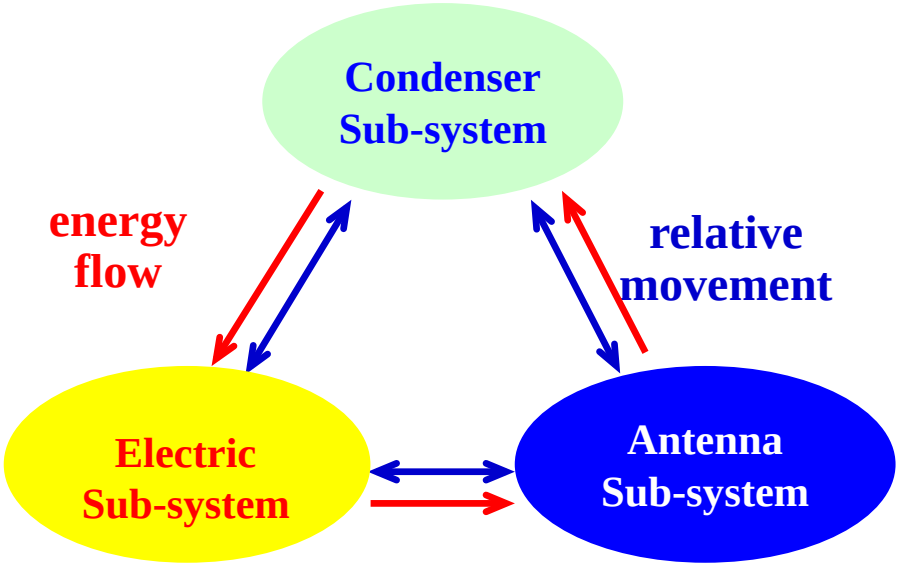
Coordination equation

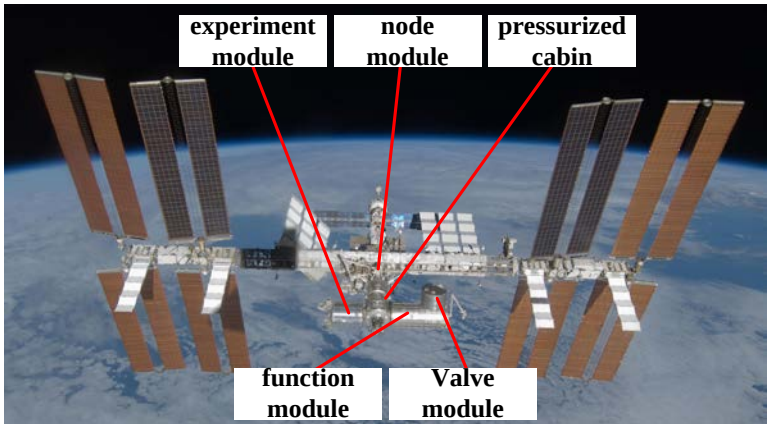
Coupling model

Systematic Optimization

Key technologies

Multi-systems | **Effective WPT** | **In-orbit assembly** | **Deployable array**





Space station

Coordination **Synthesization**

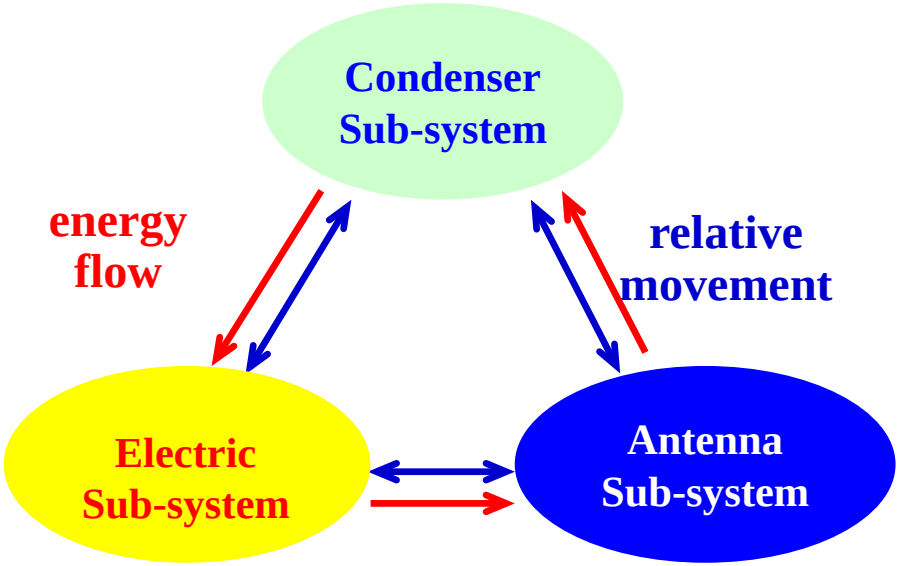
- **Rigid modules**
- **No relative movement among modules**

Limits:

- **lack of coordination equation among multi-sub-systems**
- **lack of coupling model among multidisciplinary in SSPS**

Key technologies

Multi-systems | **Effective WPT** | **In-orbit assembly** | **Deployable array**



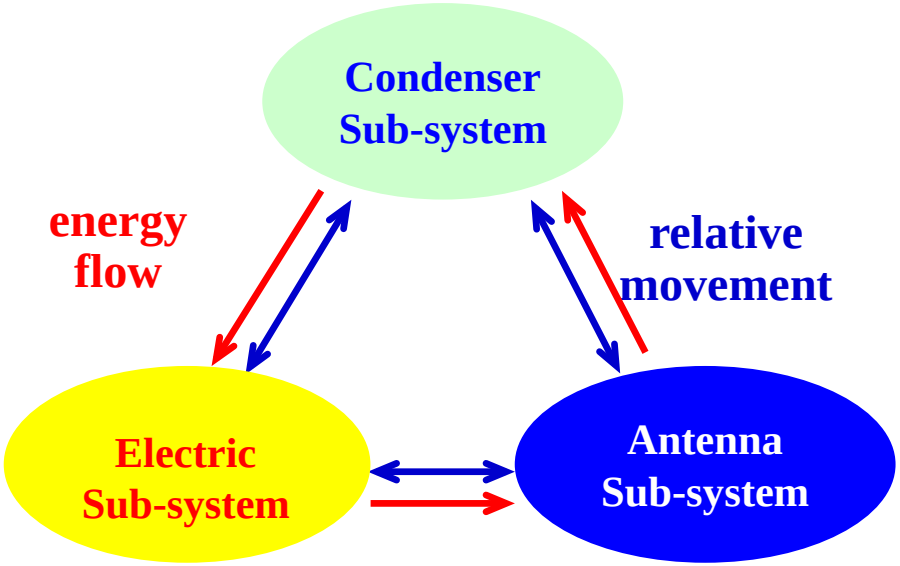
Coordination quation

$$F_1(m, V, J, x_1, \cdots, x_n) = 0$$

- **Attitude stabilization→distributed/centralization (x_n)**
- **Inertia (J) distribution of sub-systems**
- **Mass (m)、Volume (V) Coordination**

Key technologies

Multi-systems | **Effective WPT** | **In-orbit assembly** | **Deployable array**



Coordination quation

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Coupling model

$$F_2(\Gamma_1, \Gamma_2, \Gamma_3, \Pi_{12}, \Pi_{23}, \Pi_{13}) = 0$$

Coordination between the condenser and antenna

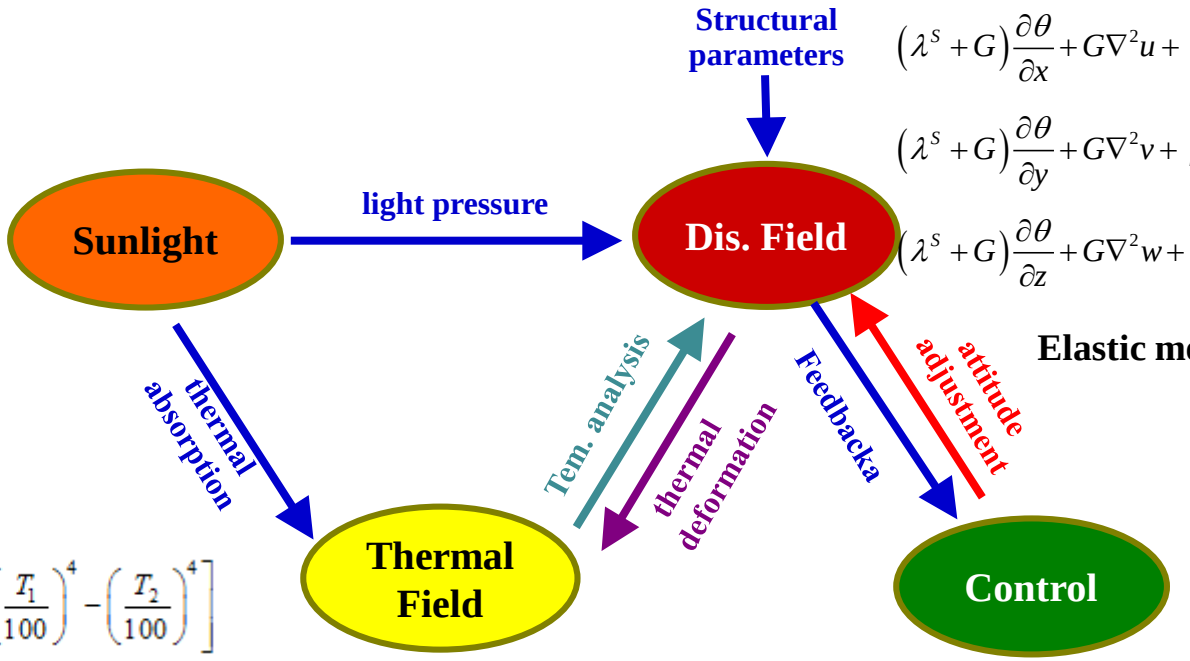
Coupling model of condenser

Condenser Sub-system

$$\begin{cases}\theta = \arcsin\sqrt{R_\theta \cdot \sin^2\theta_{\max}} \\ \varphi = 2\pi R_\varphi\end{cases}$$

$$\vec{l}_1 = \vec{l}_0 - 2(\vec{N}_r \cdot \vec{l}_0)\vec{N}_r$$

Cone angle of the light



$$\left(\lambda^S + G\right)\frac{\partial\theta}{\partial x} + G\nabla^2 u + f_x^S = 0\left(\rho^S \frac{\partial^2 u}{\partial t^2}\right)$$

$$\left(\lambda^S + G\right)\frac{\partial\theta}{\partial y} + G\nabla^2 v + f_y^S = 0\left(\rho^S \frac{\partial^2 v}{\partial t^2}\right)$$

$$\left(\lambda^S + G\right)\frac{\partial\theta}{\partial z} + G\nabla^2 w + f_z^S = 0\left(\rho^S \frac{\partial^2 w}{\partial t^2}\right)$$

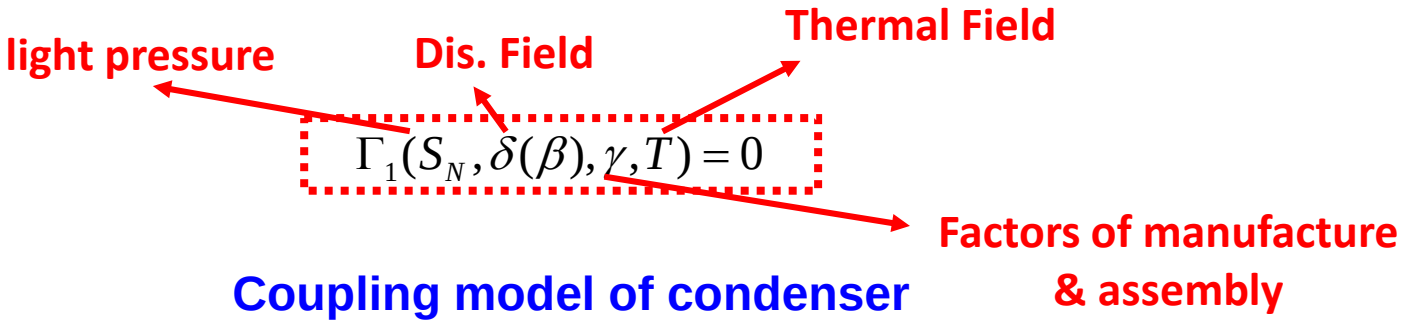
Elastic mechanics

Heat radiation $Q = \varepsilon_1 C_b A_1 I\left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right]$

Heat conduction $\rho c\frac{\partial t}{\partial \tau} = \frac{\partial}{\partial x}(\lambda\frac{\partial t}{\partial x}) + \frac{\partial}{\partial y}(\lambda\frac{\partial t}{\partial y}) + \frac{\partial}{\partial z}(\lambda\frac{\partial t}{\partial z}) + q_v$

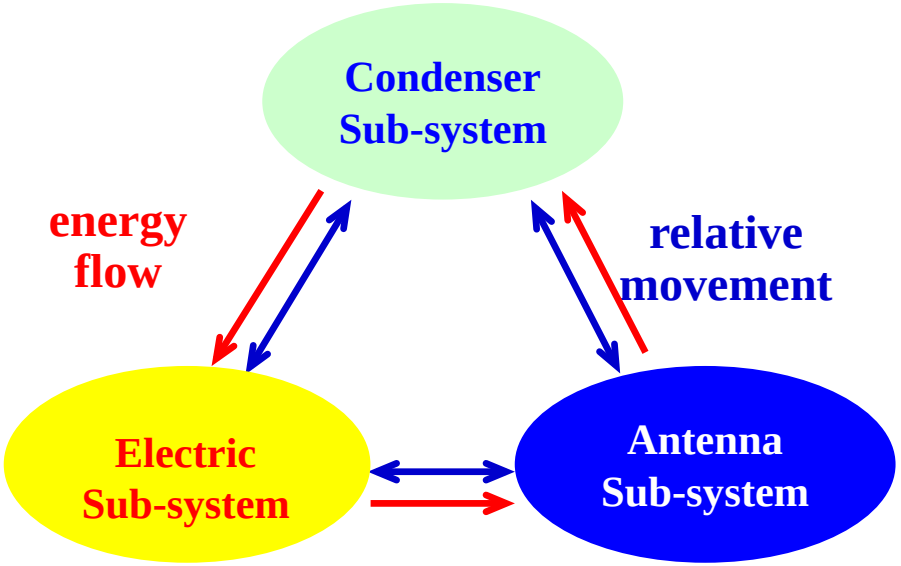
$$M\ddot{q} + C\dot{q} + kq = F$$

Control equations



Key technologies

Multi-systems | **Effective WPT** | **In-orbit assembly** | **Deployable array**



Coordination quation

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Coupling model

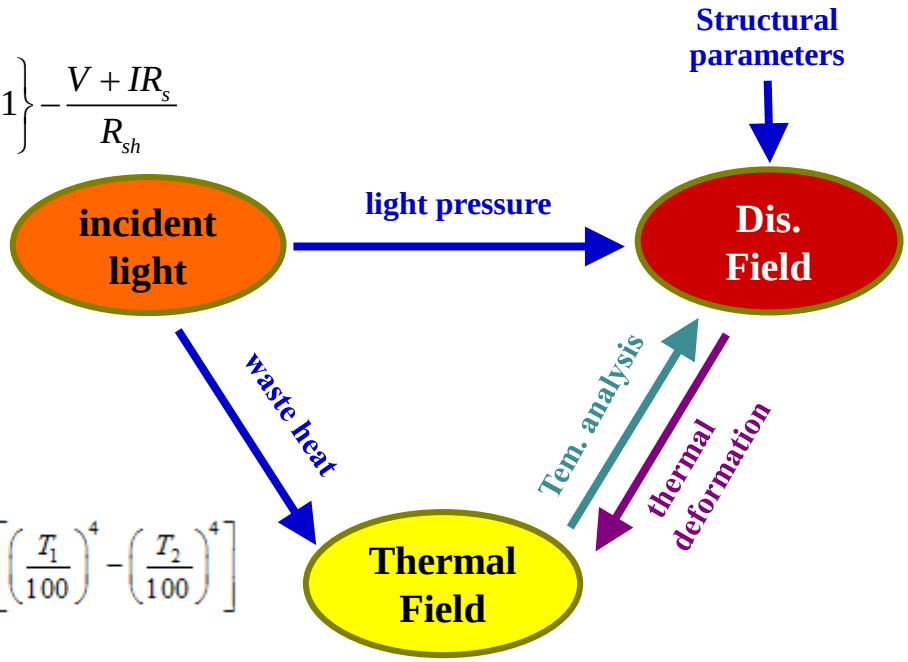
$$F_2(\Gamma_1, \Gamma_2, \Gamma_3, \Pi_{12}, \Pi_{23}, \Pi_{13}) = 0$$

$$\Gamma_1(S_N, \delta(\beta), \gamma, T) = 0$$

Electric Sub-system

$$I = m\phi - I_0\left\{\exp\left[\frac{q(V+IR_s)}{AkT}\right]-1\right\}-\frac{V+IR_s}{R_{sh}}$$

DC equation of PV



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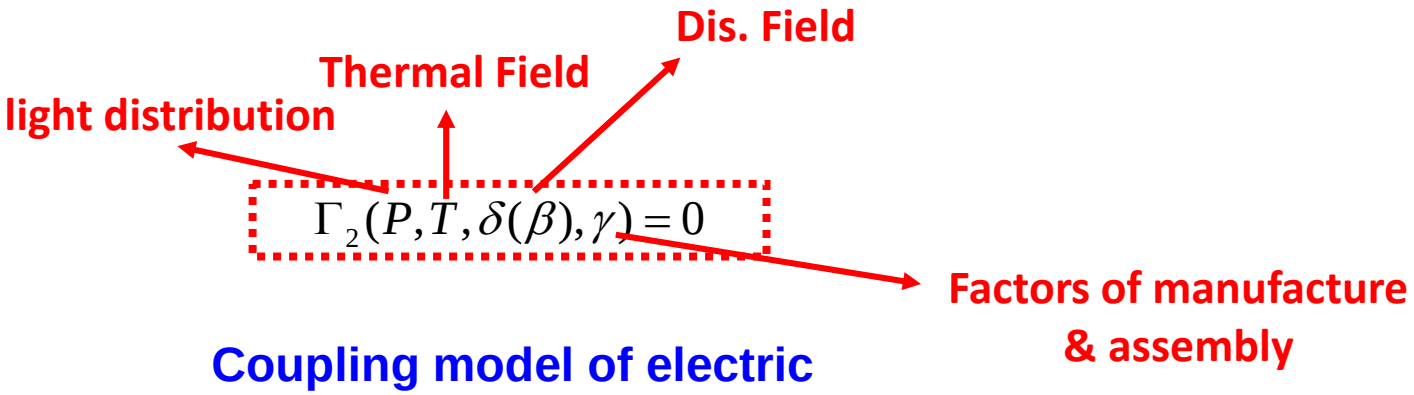
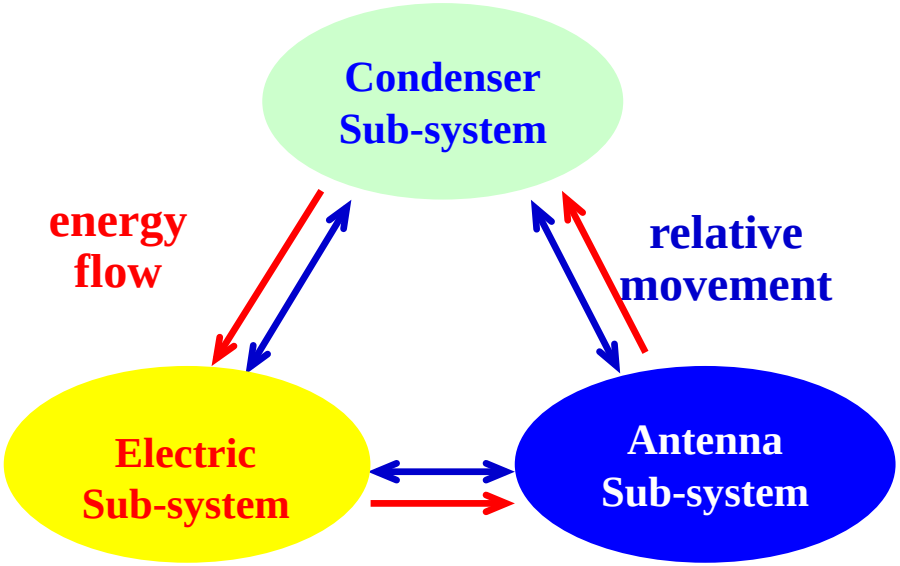


Coupling model of electric

Key technologies

Multi-systems | **Effective WPT** | **In-orbit assembly** | **Deployable array**



Coordination quation

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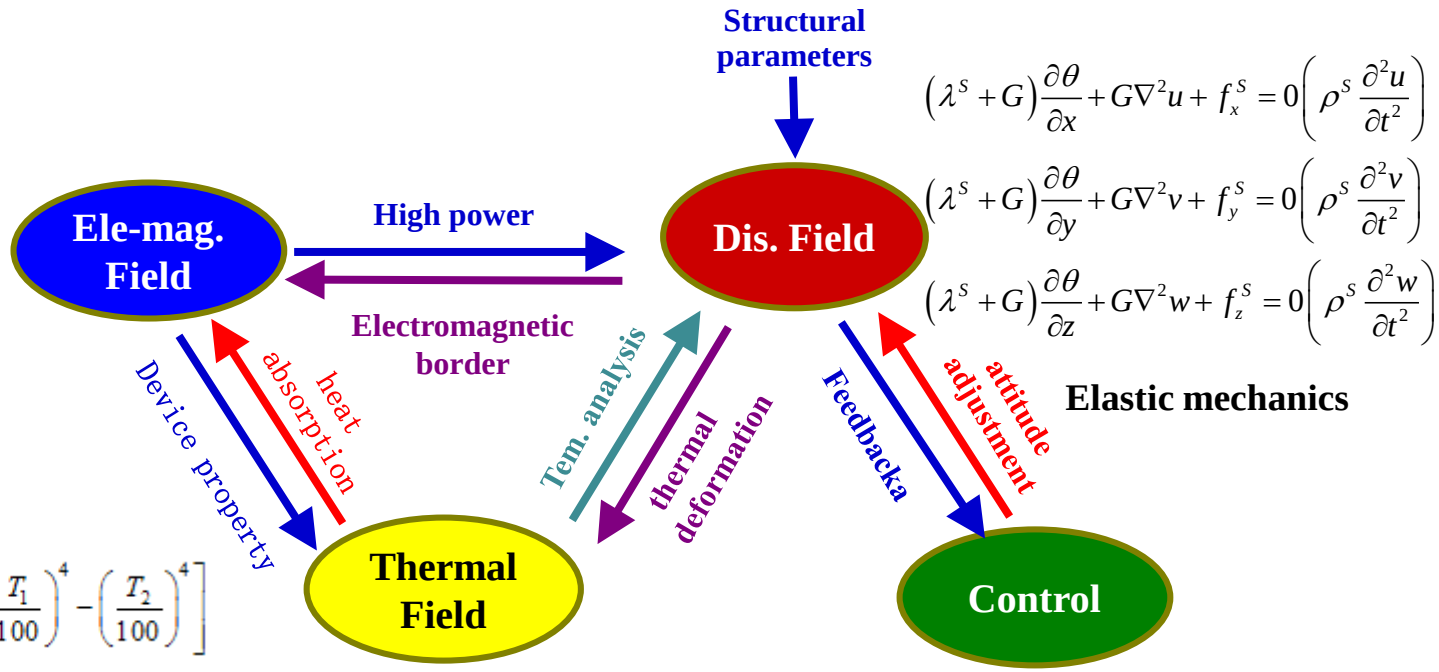
Coupling model

$$F_2(\Gamma_1, \Gamma_2, \Gamma_3, \Pi_{12}, \Pi_{23}, \Pi_{13}) = 0 \begin{cases} \Gamma_1(S_N, \delta(\beta), \gamma, T) = 0 \\ \Gamma_2(P, T, \delta(\beta), \gamma) = 0 \end{cases}$$

Antenna Sub-system



$$\nabla\times\vec{H}=\vec{J}+\frac{\partial\vec{D}}{\partial t}\qquad \nabla\cdot\vec{B}=0$$

$$\nabla\times\vec{E}=-\frac{\partial\vec{B}}{\partial t}\qquad \nabla\cdot\vec{D}=\rho$$

Maxwell

electromagnetic equation

$$\left(\lambda^S+G\right)\frac{\partial\theta}{\partial x}+G\nabla^2u+f_x^S=0\left(\rho^S\frac{\partial^2u}{\partial t^2}\right)$$

$$\left(\lambda^S+G\right)\frac{\partial\theta}{\partial y}+G\nabla^2v+f_y^S=0\left(\rho^S\frac{\partial^2v}{\partial t^2}\right)$$

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$$M\ddot{q}+C\dot{q}+kq=F$$

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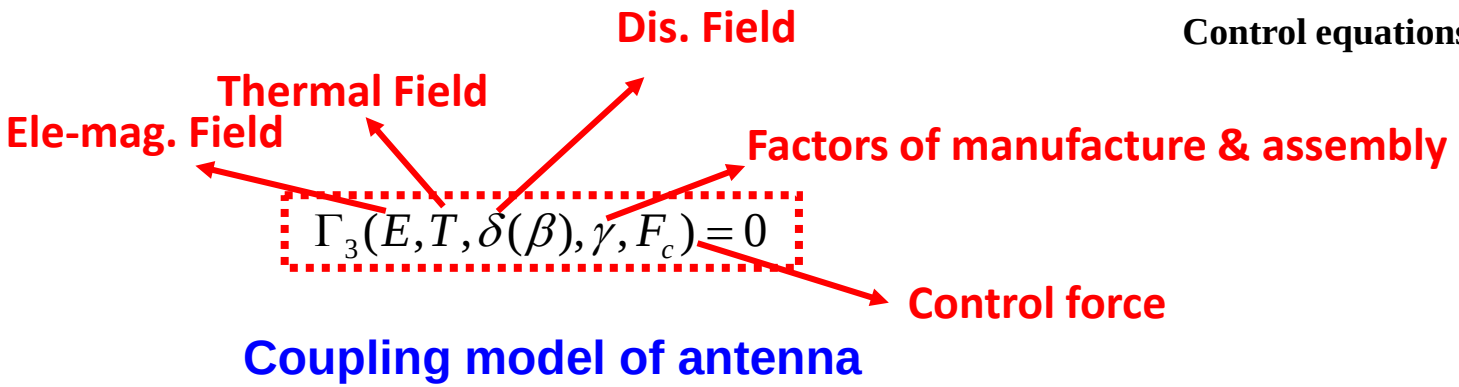
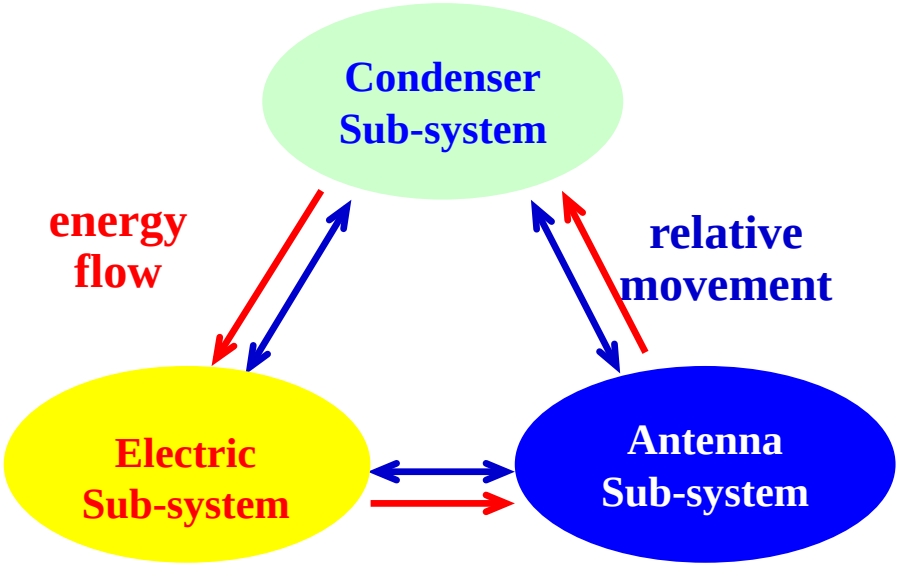


Coupling model of antenna

Key technologies

Multi-systems | **Effective WPT** | **In-orbit assembly** | **Deployable array**



Coordination quation

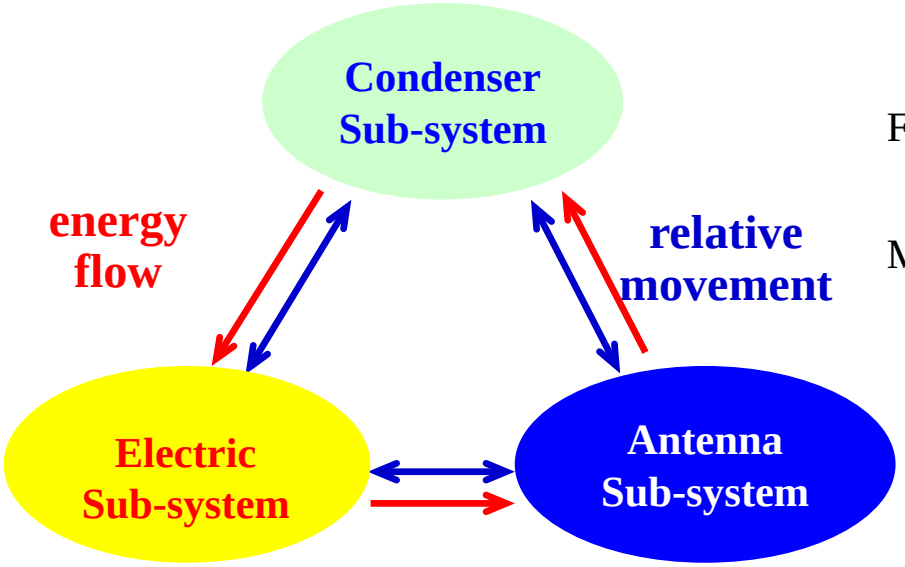
$$F_1(m, V, J, x_1, \cdots, x_n) = 0$$

Coupling model

$$F_2(\Gamma_1, \Gamma_2, \Gamma_3, \Pi_{12}, \Pi_{23}, \Pi_{13}) = 0 \begin{cases} \Gamma_1(S_N, \delta(\beta), \gamma, T) = 0 \\ \Gamma_2(P, T, \delta(\beta), \gamma) = 0 \\ \Gamma_3(E, T, \delta(\beta), \gamma, F_c) = 0 \end{cases}$$

Key technologies

Multi-systems | **Effective WPT** | **In-orbit assembly** | **Deployable array**



Coordination quation

$$F_1(m, V, J, x_1, \cdots, x_n) = 0$$

Coupling model

$$F_2(\Gamma_1, \Gamma_2, \Gamma_3, \Pi_{12}, \Pi_{23}, \Pi_{13}) = 0$$

Find $X = [x_1, x_2, \cdots, x_{nus}]^T$ — Parameters of Struc./Ther./Ele-mag. & control

Max $Z(X)$ — Synthetical evaluation to the power-mass ratio

S.T.

$$g_j^S(X) \le 0,\ j = 1, 2, \cdots, NUS$$
$$g_j^T(X) \le 0,\ j = 1, 2, \cdots, NUT$$
$$g_j^C(X) \le 0,\ j = 1, 2, \cdots, NUC$$
$$g_j^E(X) \le 0,\ j = 1, 2, \cdots, NUE$$

Behaviors

$$\Gamma_1(S_N, \delta(\beta), \gamma, T) = 0$$
$$\Gamma_2(P, T, \delta(\beta), \gamma) = 0$$
$$\Gamma_3(E, T, \delta(\beta), \gamma, F_c) = 0$$
$$F_1(m, V, J, x_1, \cdots, x_n) = 0$$
$$F_2(\Gamma_1, \Gamma_2, \Gamma_3, \Pi_{12}, \Pi_{23}, \Pi_{13}) = 0$$

Coupling & coordination

$$\underline{X} \le X \le \overline{X}$$

boundary conditions

Key technologies

Multi-systems | **Effective WPT** | In-orbit assembly | Deployable array

Type: Active phased array antenna **Operating frequency : 5.8GHz**

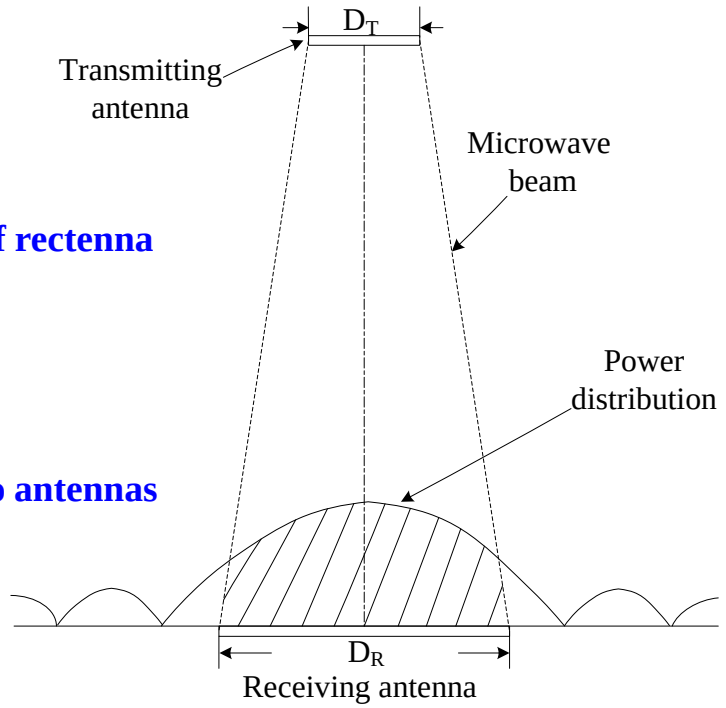
Friis Equation: $\eta = 1 - e^{-\tau^2}$

beam collection efficiency (BCE)

area of transmitting antenna **area of rectenna**

$$\tau = \frac{\sqrt{A_T A_R}}{\lambda L}$$

wavelength **distance between two antennas**



Efficiency requirement → BCE > 95%

$\tau \geq 2$ → $D_T D_R \geq 3.7 \times 10^6$ m^2

System cost

(Reduce the Trans. antenna size) → $D_R = 10$ km $D_T = 400$m; $D_R = 20$ km $D_T = 200$m

Key technologies

Multi-systems	Effective WPT	In-orbit assembly	Deployable array

- Subdivision
- Beam control
- RF-DC conversion

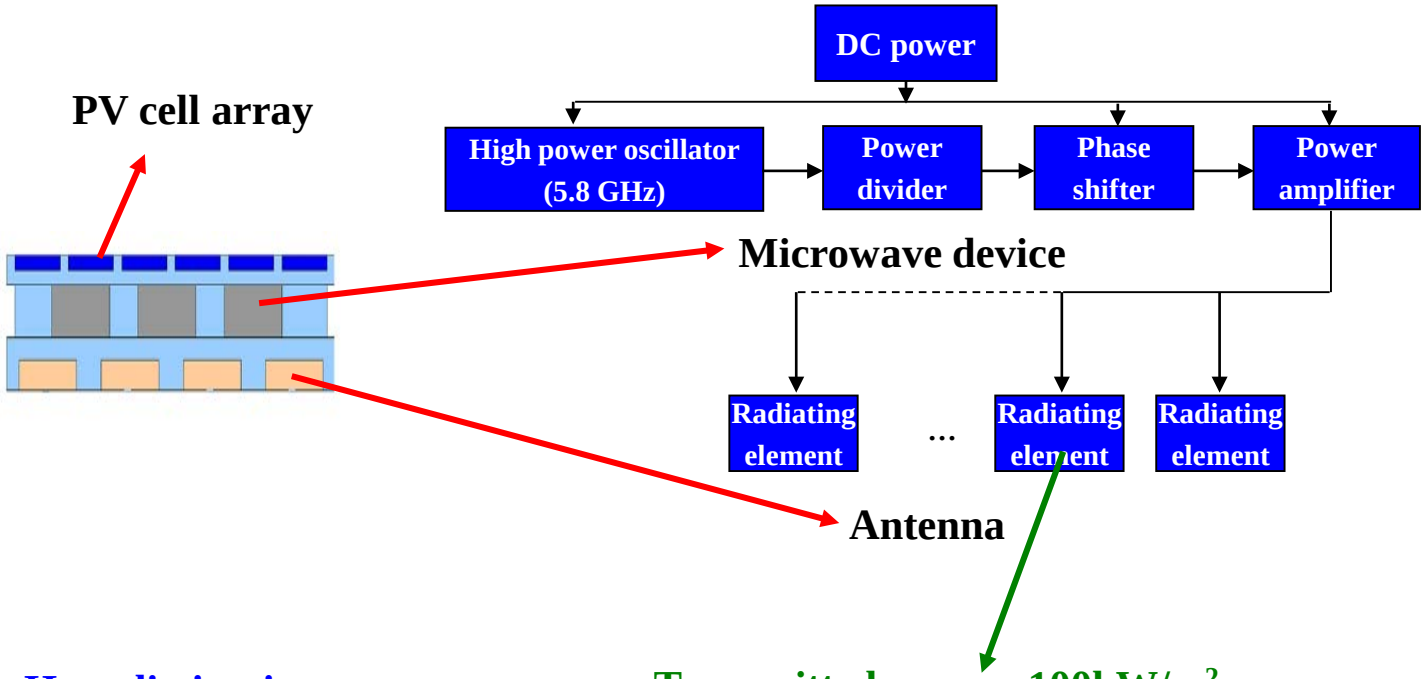
Key technologies

Multi-systems	Effective WPT	In-orbit assembly	Deployable array

Subdivision

Beam control

RF-DC conversion



- Heat dissipation

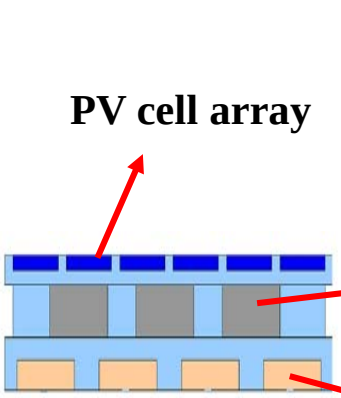
Key technologies

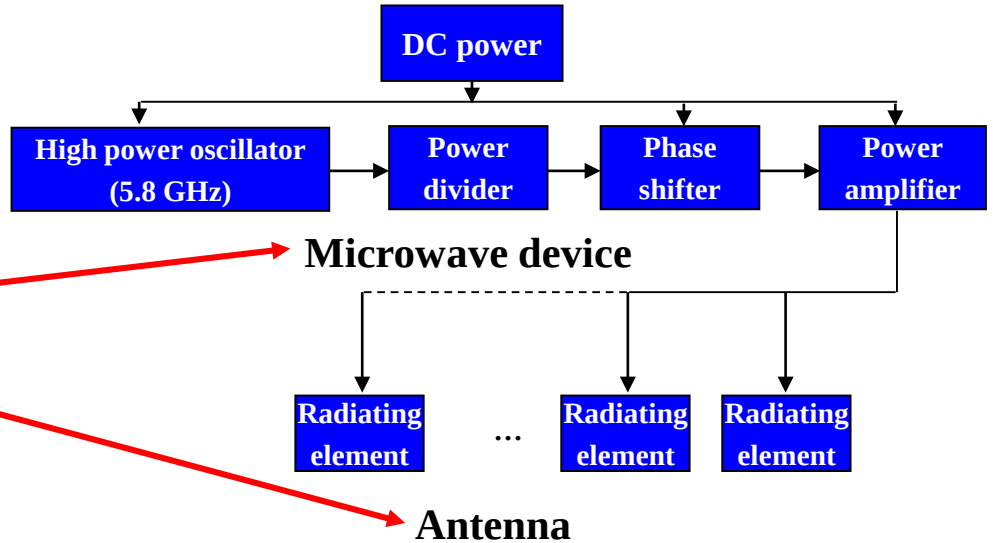
Multi-systems	Effective WPT	In-orbit assembly	Deployable array

Subdivision

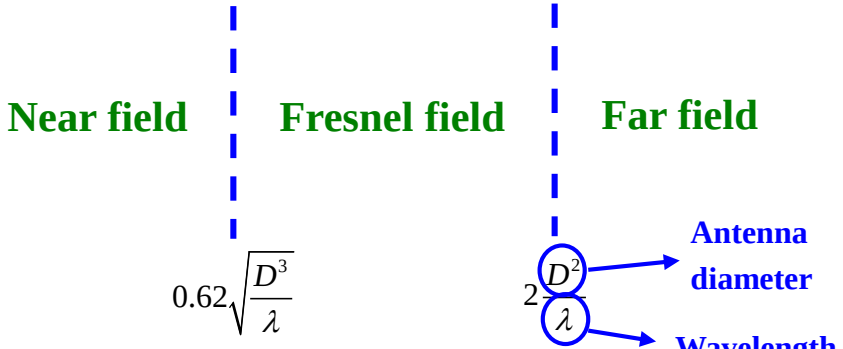
Beam control

RF-DC conversion





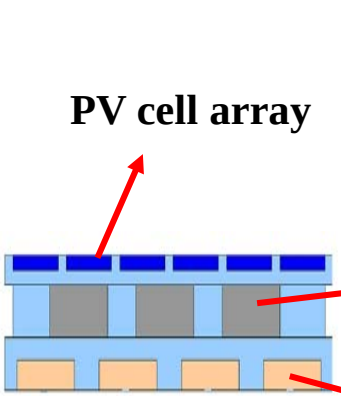
- Heat dissipation
- Radiating region

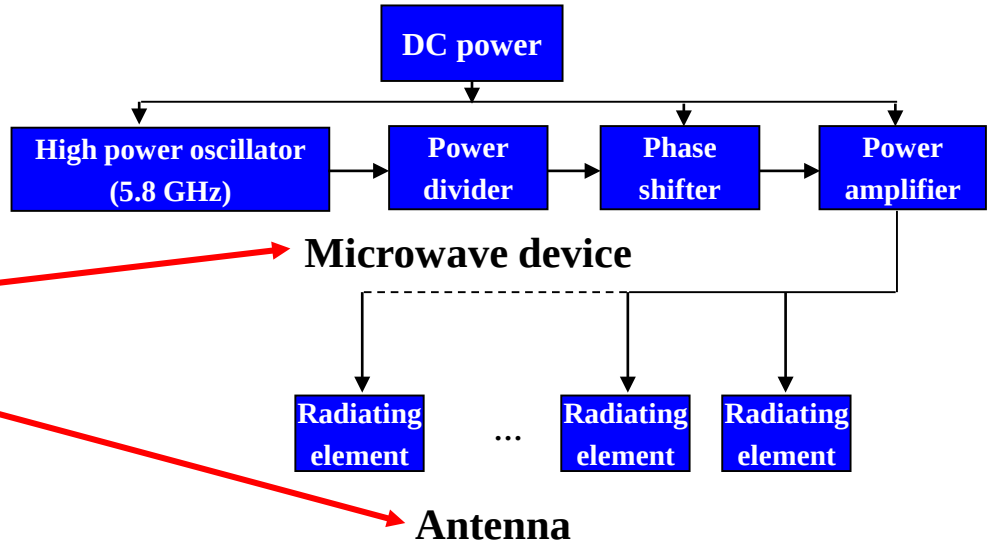


Key technologies

Multi-systems	**Effective WPT**	In-orbit assembly	Deployable array

Subdivision

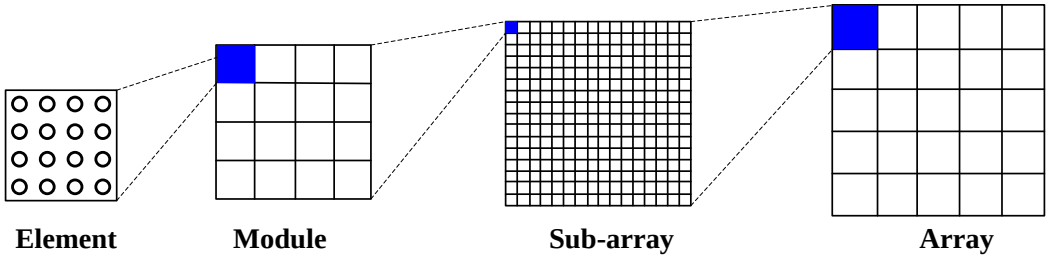




Beam control

RF-DC conversion

- Heat dissipation
- Radiating region
- Structural design



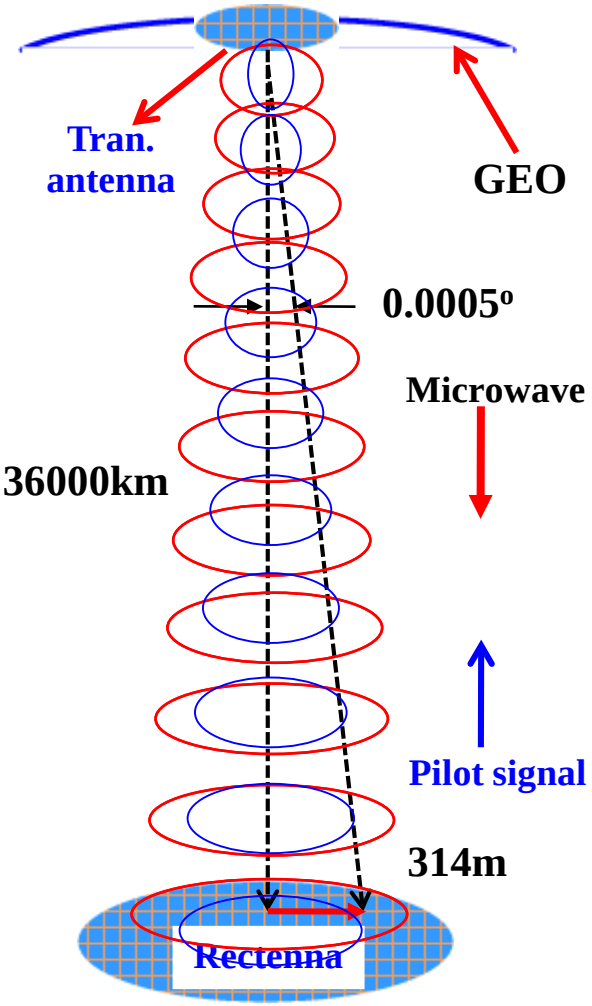
Key technologies

Multi-systems	Effective WPT	In-orbit assembly	Deployable array

Subdivision

Beam control

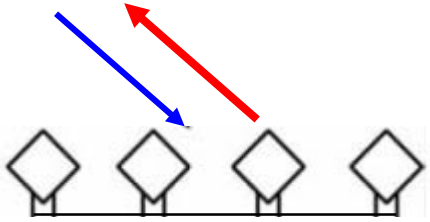
RF-DC conversion



Disturbance

1、Accurate and high efficiency microwave power density measurement

2、Retrodirective antenna array technique



Retrodirective array

Key technologies

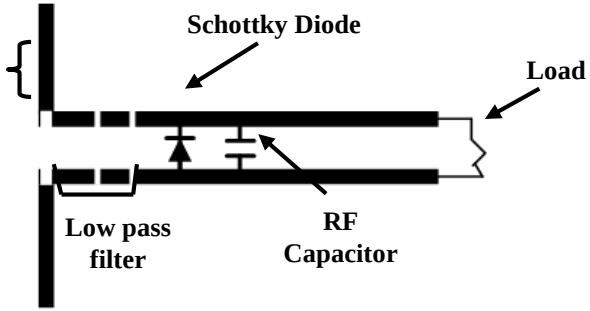
Multi-systems | **Effective WPT** | **In-orbit assembly** | **Deployable array**

Stepped taper

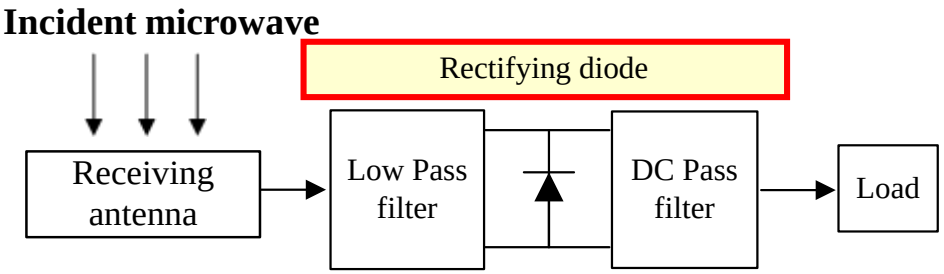
Beam control

RF-DC conversion

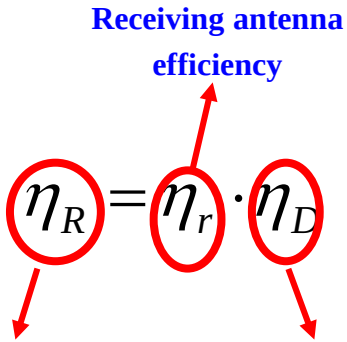
Rectenna array



Rectenna element



Rectifying circuit



Key technologies

Multi-systems | **Effective WPT** | In-orbit assembly | Deployable array

Outside test – Sichuan University

2016, Power: 1 kW, Distance: 1.6km
Efficiency: 8%

Magnetron: 2.45GHz, 500W, Eff.=75%

Advantages: High efficiency

Disadavantages: Difficulty of phase lock
Lifespan problem

Inside test – CAST & Xidian University

2015, Power: 50 W, Distance: 11 m
Efficiency: 16%

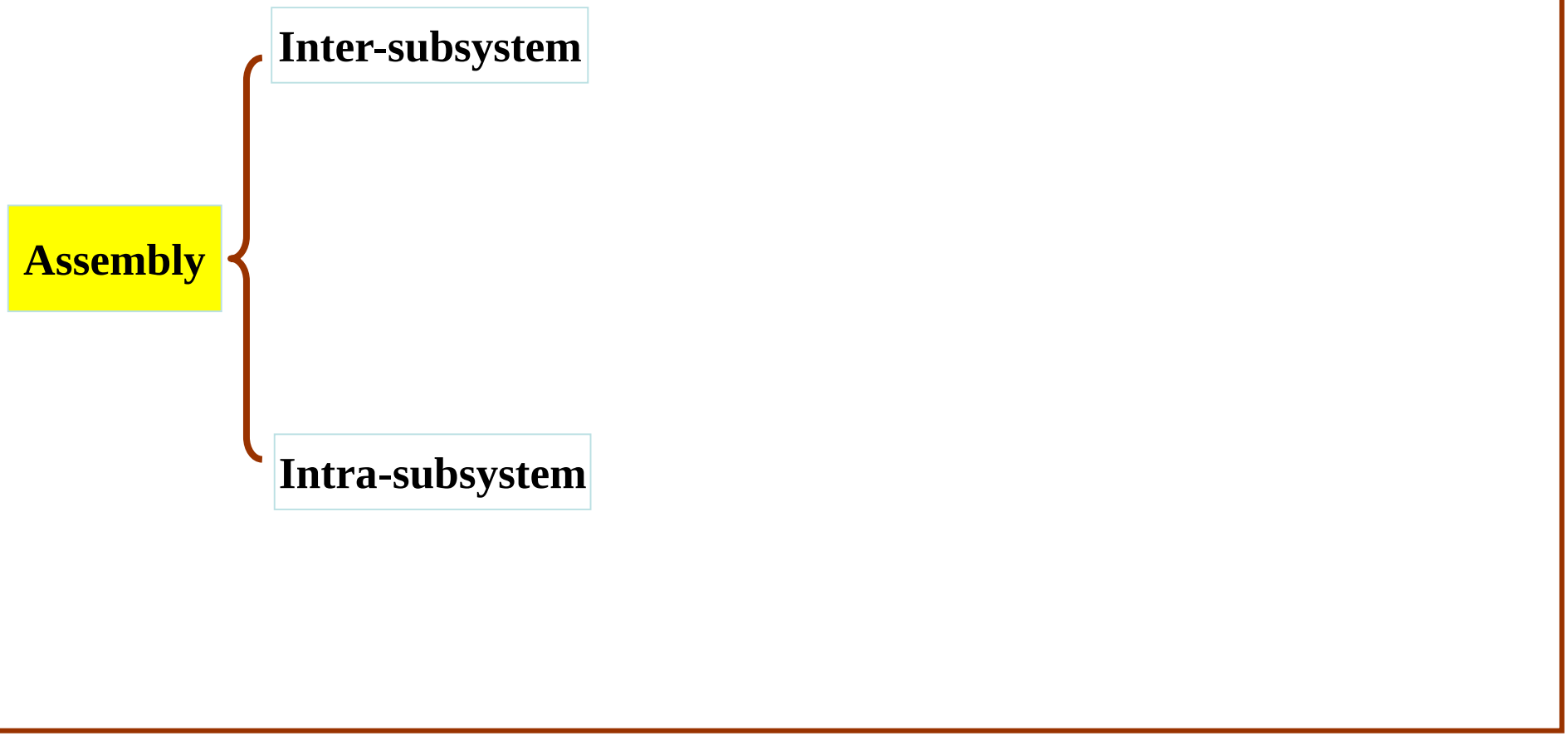
GaN solid-state amplifier: 5.8GHz
50W, Eff.=63

Advantages: High frequency stability

Disadvantages: Lower Efficiency

Key technologies

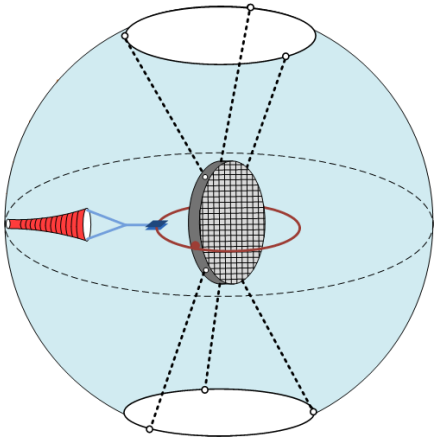
Multi-systems	Effective WPT	In-orbit assembly	Deployable array



Key technologies

Multi-systems	Effective WPT	In-orbit assembly	Deployable array

- Assembly
  - Inter-subsystem
    - Condenser
    - Electric
    - Antenna
  - Intra-subsystem

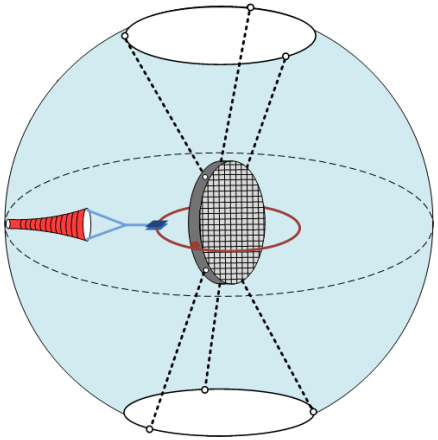


Key technologies

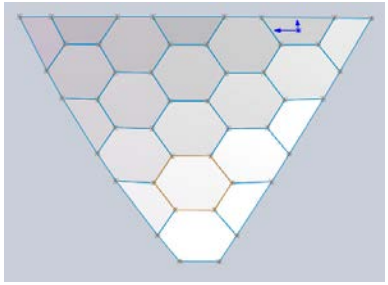
Multi-systems	Effective WPT	In-orbit assembly	Deployable array

Assembly

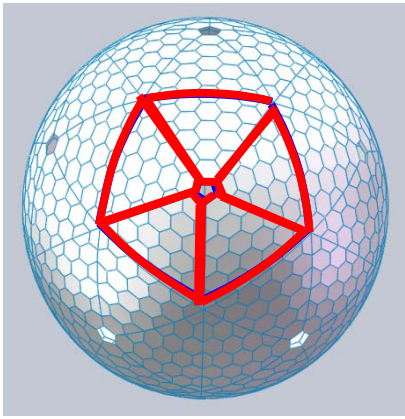
- **Inter-subsystem**
  - Condenser
  - Electric
  - Antenna



- **Intra-subsystem**
  - Subarray
  - ↕
  - Subarray

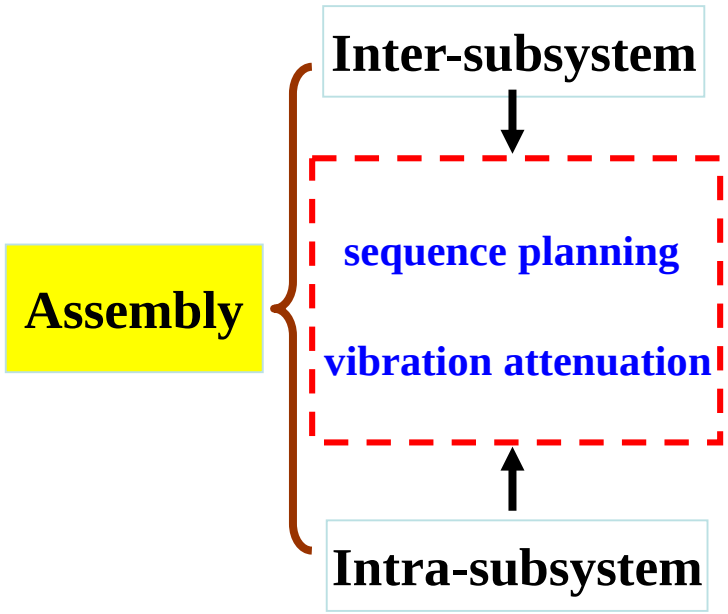


Subarray



Key technologies

Multi-systems	Effective WPT	In-orbit assembly	Deployable array

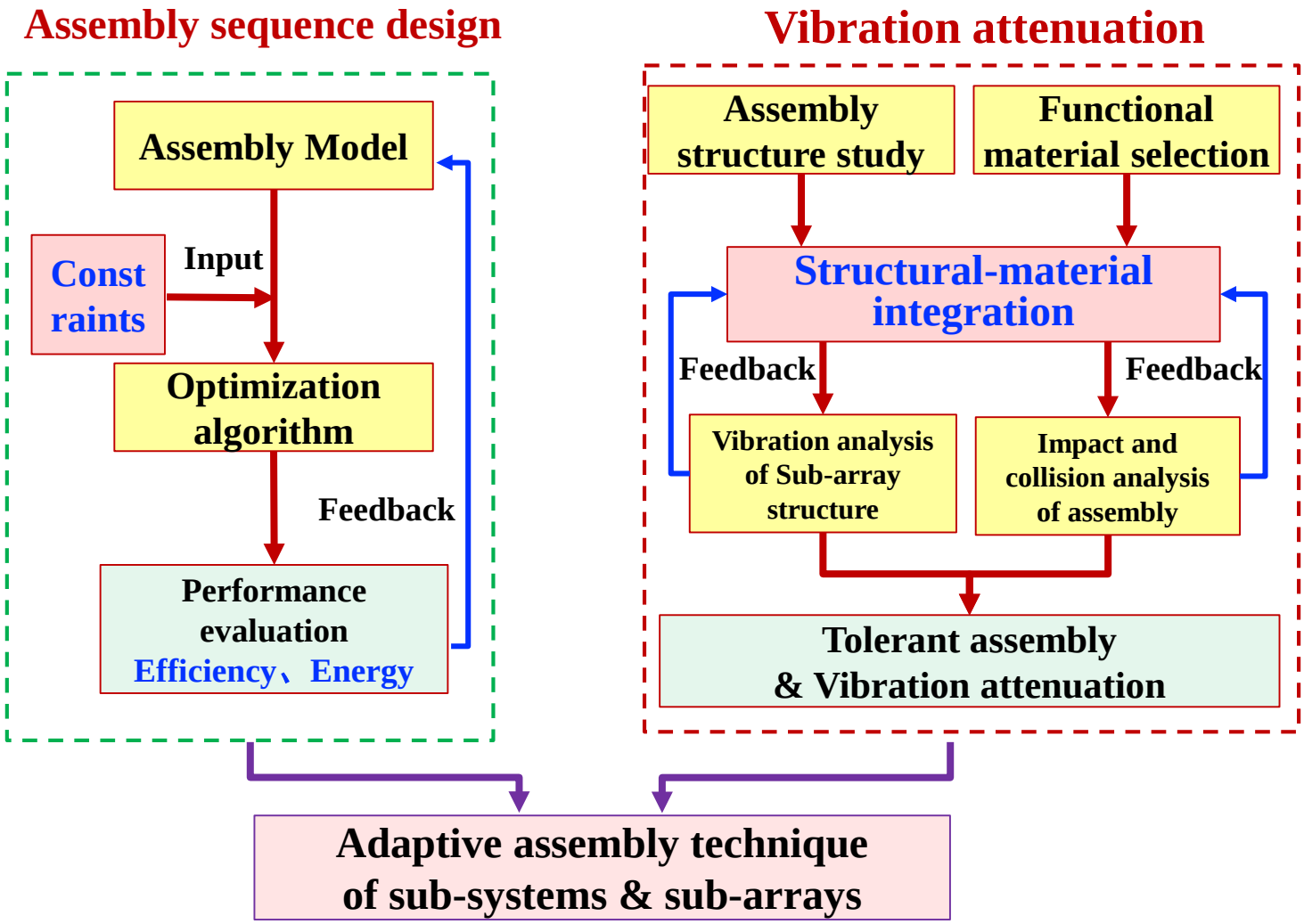


- ◆ Sybsystem→System:Rigid
- ◆ Subarray→Array: Lack

Large-scale、flexible objects
In-orbit assembly

Key technologies

Multi-systems	Effective WPT	In-orbit assembly	Deployable array



Key technologies

Multi-systems	Effective WPT	In-orbit assembly	Deployable array

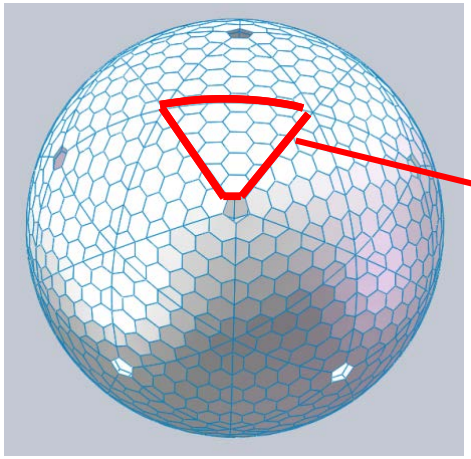
Subdivision

Deployable

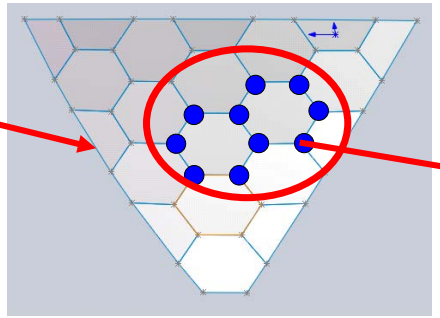
Key technologies

Fuller theorem

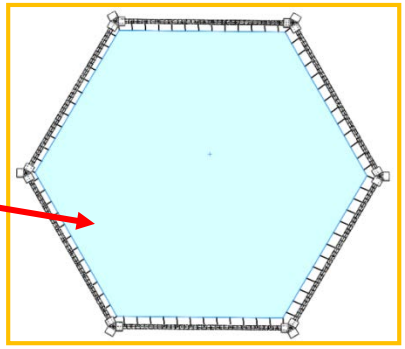
Subdivision



Sub-system



Sub-array



Module

Deployable

	Regular Pentagon	Regular Hexagon	Non-regular Hexagon
Number	12 (1)	20 (1)	3210 (21 kinds)
Size	0.0446R	0.0410 R	0.0446 R -0.0410R

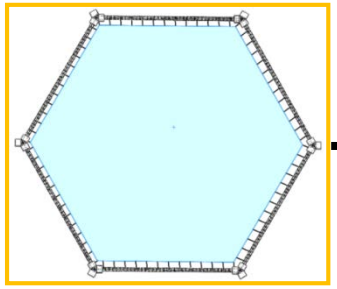
Condenser radius R=1km, side length: { Pen.: 44.6m ; Hex.: 41m – 44.6m }

Key technologies

Multi-systems	Effective WPT	In-orbit assembly	Deployable array

Subdivision

Deployable



Mesh antenna

Max size： 22m

Surface density： 0.4kg/m^2

Surface accuracy： 0.1 mm level

Size restriction

Inflatable antenna

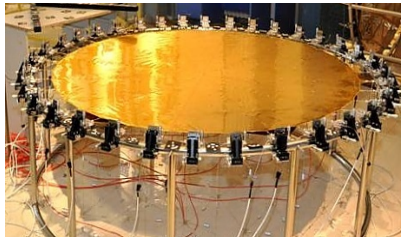
Max size： 14m

Surface density ： charger mass

Surface accuracy： mm level

Reliability restriction

Film antenna



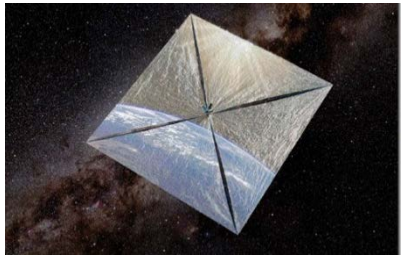
Max size： 5m

Surface density： 1kg/m^2

Surface accuracy： 0.1 mm level

Laboratory stage

solar sail



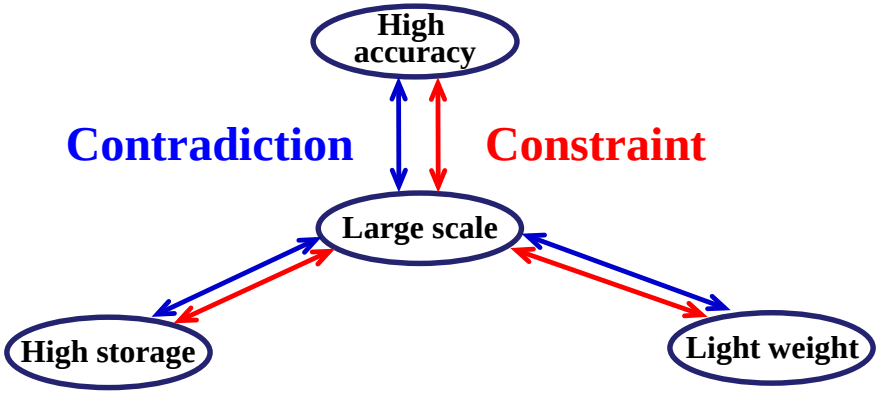
Max size： 1200m^2

Surface density： ultralight

Surface accuracy： low

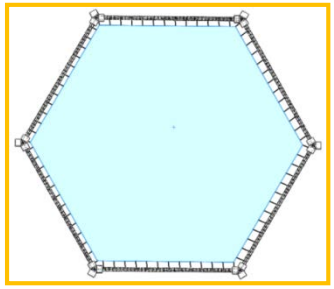
Key technologies

Multi-systems	Effective WPT	In-orbit assembly	Deployable array



Subdivision

Deployable

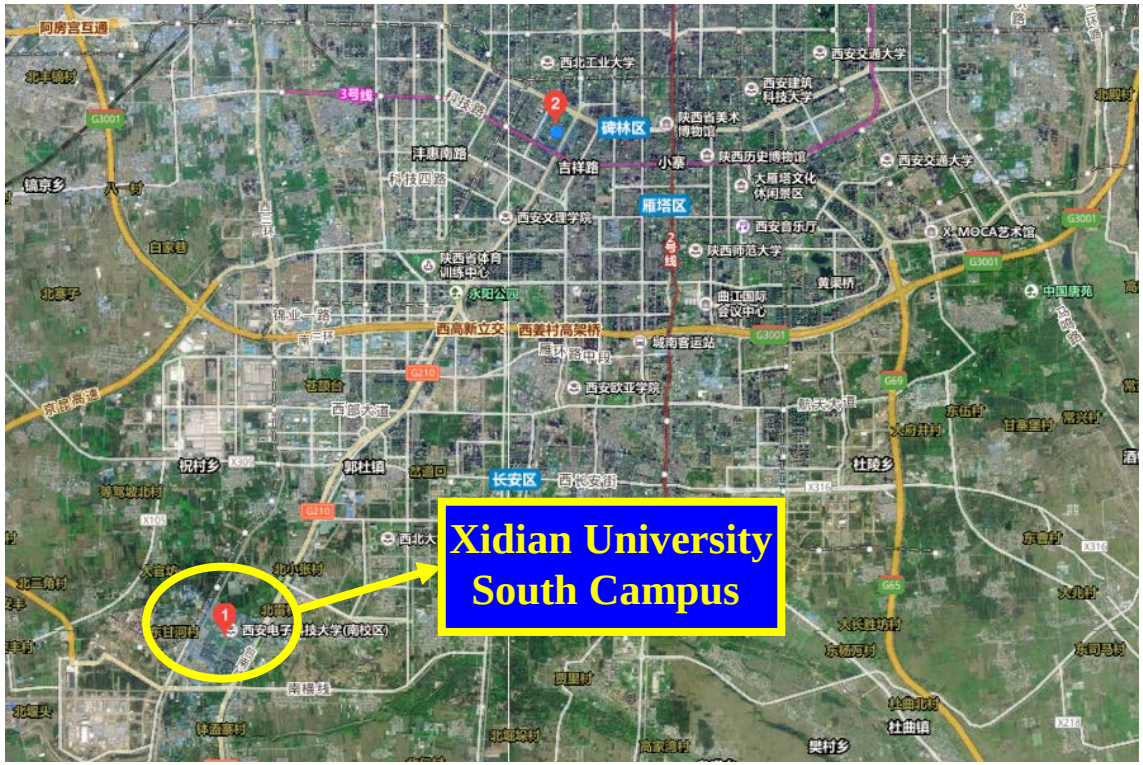


Innovation deployable structures for SSPS

- Integrated stowed/deployed states optimization
- Dynamic analysis and control
- Inter-modules connection scheme
- Truss-membrane structural design technique

Contents

Prototype of SSPS



Location ?

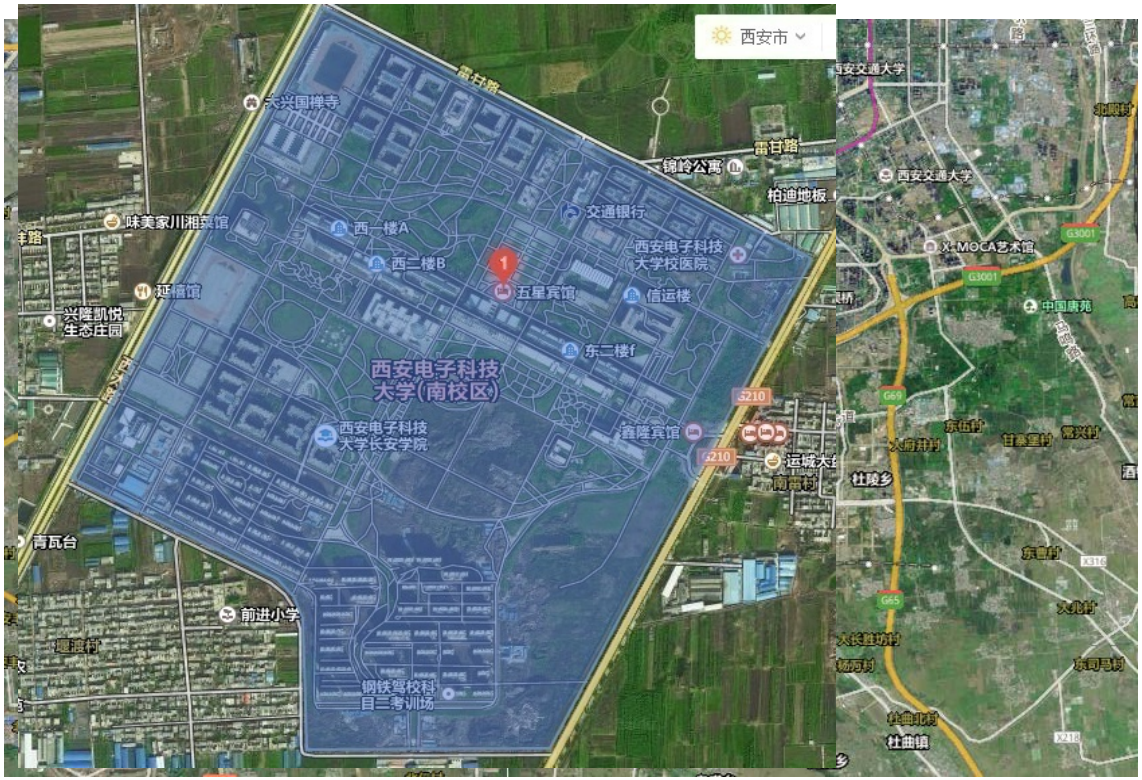
↓

Xi’an City

↓

South campus of the Xidian University

Prototype of SSPS



Location ?

Xi’an City

South campus of the Xidian University

Prototype of SSPS

FAST 50 experiment model

Location ?

↓

Xi'an City

↓

South campus of

the Xidian University

↓

FAST 50m experimental site

Prototype of SSPS

FAST 50 experiment model

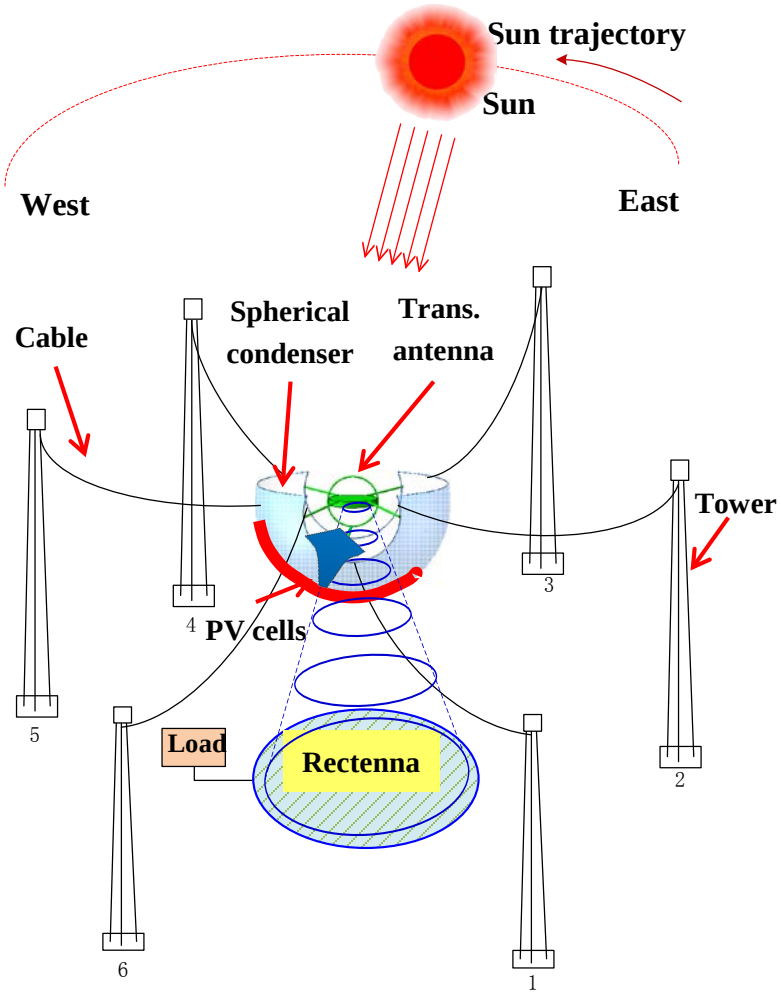
Pingtang county, Guizhou province

(Accomplished at 25/09/2016)

Major scientific event of 2016

Prototype of SSPS

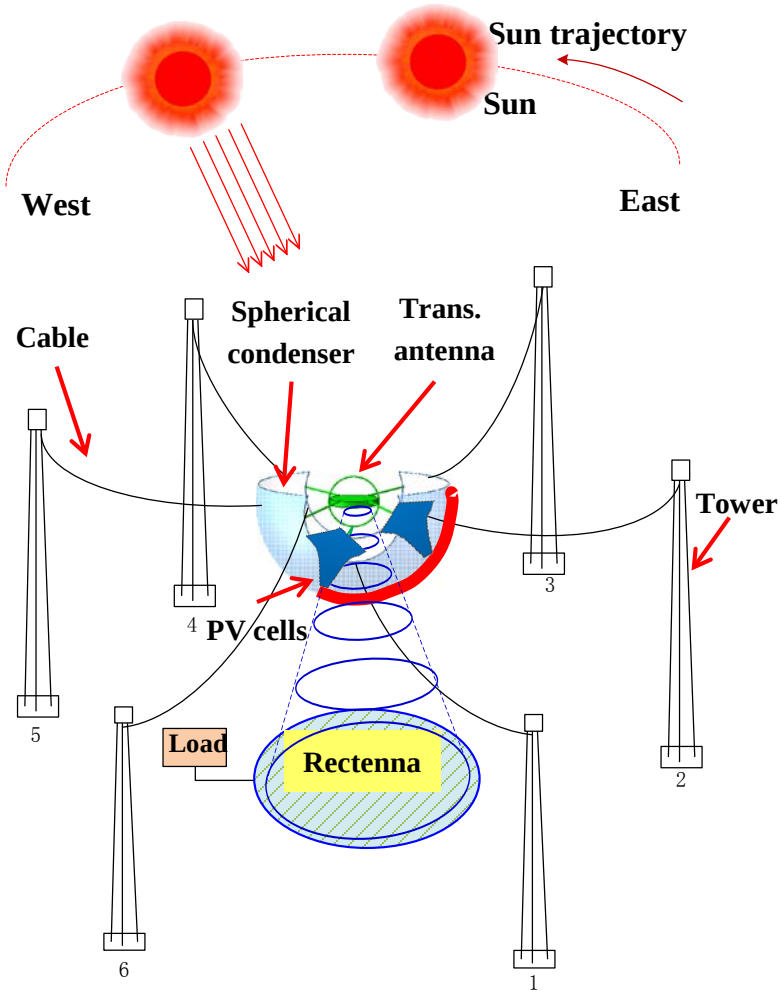
FAST 50 experiment model



Schematic diagram of the OMEGA – SSPS model
(Mode 1: Vertical transmission)

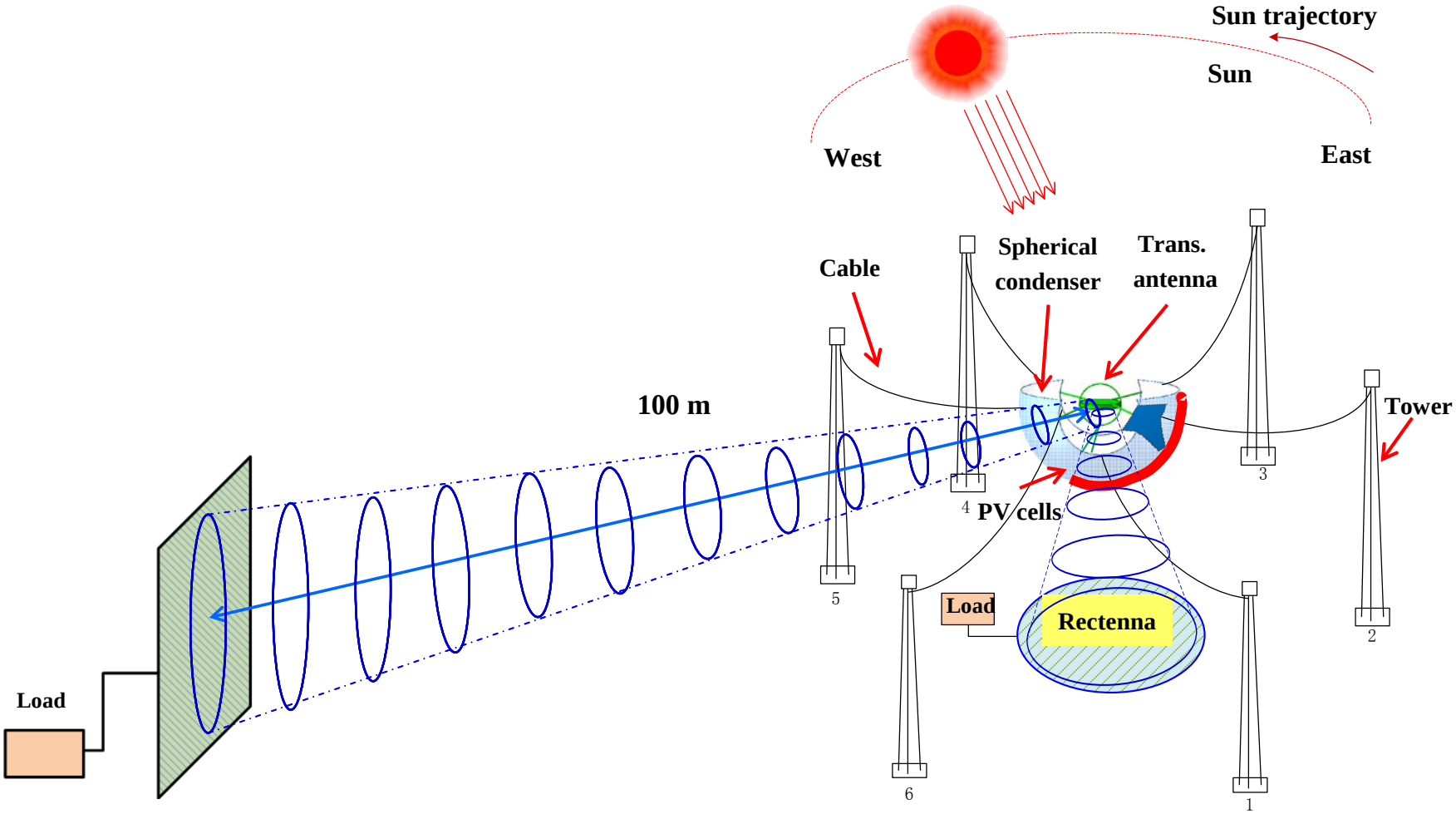
Prototype of SSPS

FAST 50 experiment model



Schematic diagram of the OMEGA – SSPS model
(Mode 1: Vertical transmission)

Prototype of SSPS



Schematic diagram of the OMEGA – SSPS model
(Mode 2 Horizontall transmission)

Prototype of SSPS

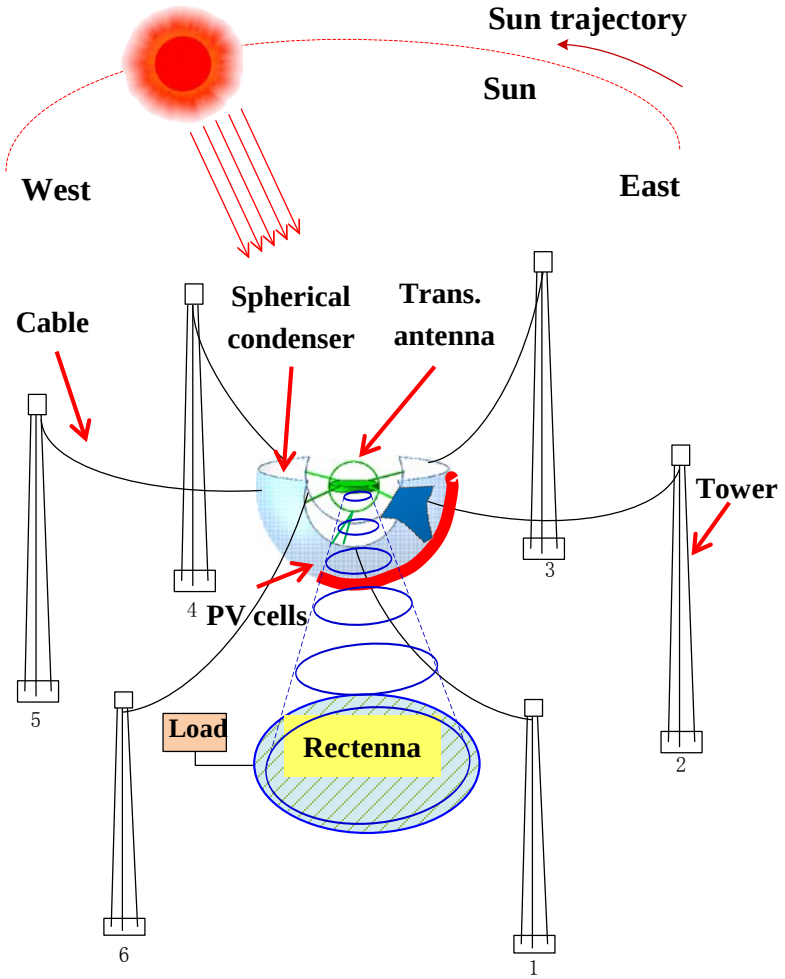
Expected system efficiency

- Photoelectric conversion: 30%
- DC- RF : 45 %
- Microwave Transmitting: 80%
- Beam collection: 90%
- RF- DC: 50%

Overall efficiency: 4.32%

DC-DC efficiency: 16.2% **(14.7% Japan)**

BCE is enhanced **(Stepped amplitude (90 %) v.s. Uniform amplitude (81.7 %))**



Schematic diagram of the OMEGA – SSPS model

Contents

Prospects

Technologies	Developments

Prospects

Technologies	Developments
Innovative structure	New SSPS concept; New antenna structural form
PV cells	High efficiency thin-film PV cells
Heat dissipation	Creative heat-dissipation structure design
MW generator	High efficiency amplifiers, phase shifters, power dividers
New Material	Light weight and high strength material

Prospects

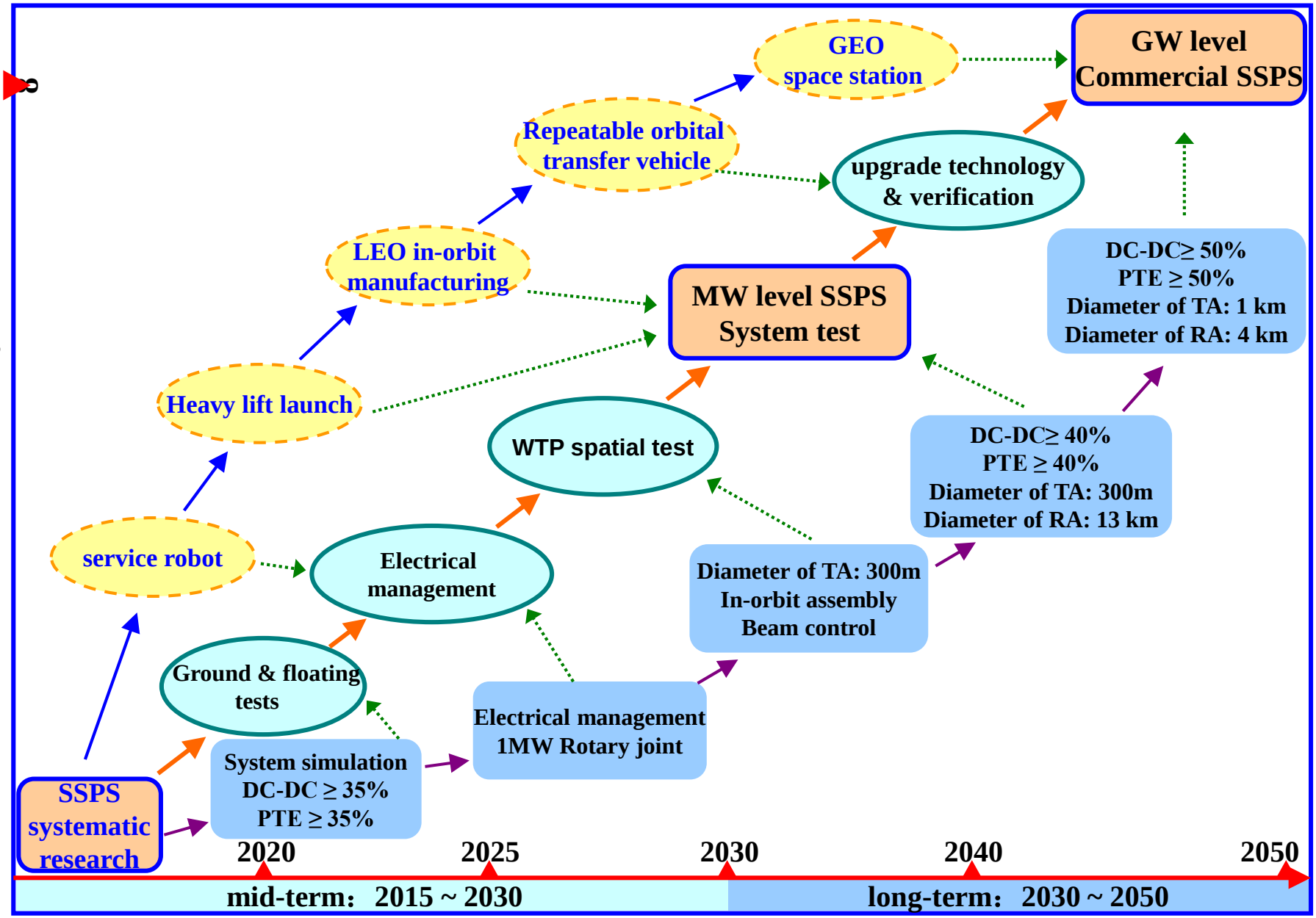
Technologies

Developments

senior consultant(6 academicians)
Xiji Wang, Guirong Min,
Lehao Long, Shizhong Yang,
Baoyan Duan, Changchun Ge

participating experts:
16 ministries
49 organizations
130experts

Road Map


TRL7~8
Technical maturity
SSPS systematic research
service robot
Heavy lift launch
LEO in-orbit manufacturing
Repeatable orbital transfer vehicle
GEO space station
GW level Commercial SSPS
System simulation
DC-DC ≥ 35%
PTE ≥ 35%
Ground & floating tests
Electrical management
WTP spatial test
MW level SSPS System test
upgrade technology & verification
DC-DC≥ 50%
PTE ≥ 50%
Diameter of TA: 1 km
Diameter of RA: 4 km
Electrical management
1MW Rotary joint
Diameter of TA: 300m
In-orbit assembly
Beam control
DC-DC≥ 40%
PTE ≥ 40%
Diameter of TA: 300m
Diameter of RA: 13 km
2020
2025
2030
2040
2050
mid-term：2015 ~ 2030
long-term：2030 ~ 2050

Thanks for your attention !