



中国科学院电工研究所

Institute of Electrical Engineering
Chinese Academy of Sciences

PV测试方法简介

中科院电工所

光伏组件的IEC标准

IEC60891:1987	晶体硅光伏器件的IV测试温度和辐照度校准过程
IEC60904-1:1987	光伏器件—部分1：光伏器件的电流电压测试
IEC60904-2:1989	光伏器件—部分2：参考电池的要求
IEC60904-3:1989	光伏器件—部分3：具有参考辐射光谱数据的地面光伏器件的测量原理
IEC60904-5:1993	光伏器件—部分4：通过开路电压法来确定光伏器件的等效温度
IEC60904-6:1994	光伏器件—部分5：太阳电池参考组件要求
IEC60904-7:1995	光伏器件—部分6：光伏组件测试中引入的光谱时配的计算
IEC60904-8:1995	光伏器件—部分8：光伏器件光谱响应的测试指导
IEC60904-9:1995	光伏器件—部分9：太阳模拟器要求
IEC60904-10:1995	光伏器件—部分10：线性测试方法

IEC60904-3: 太阳能电池测试标准条件

The performance data of PV modules is referred to the internationally agreed „Standard Test Conditions (STC)“:

Module temperature:

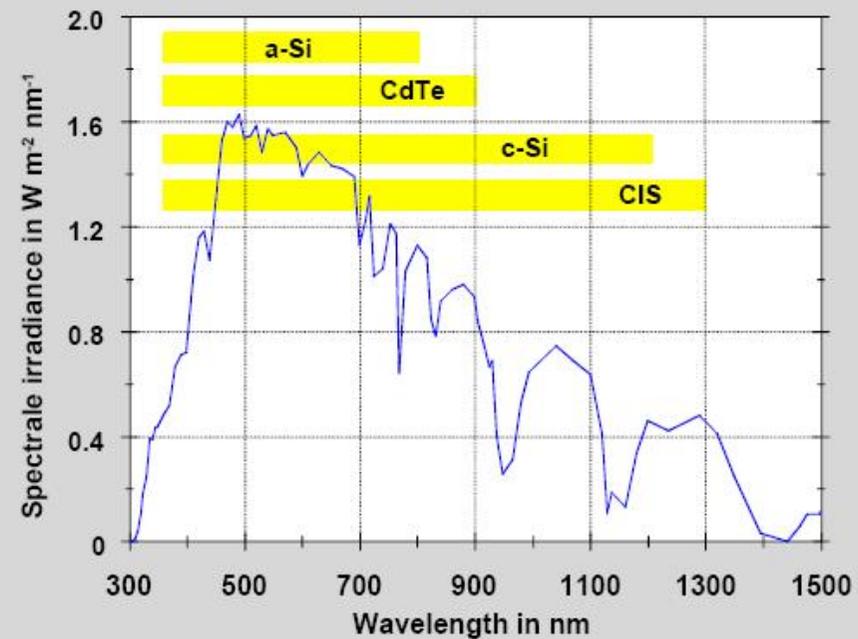
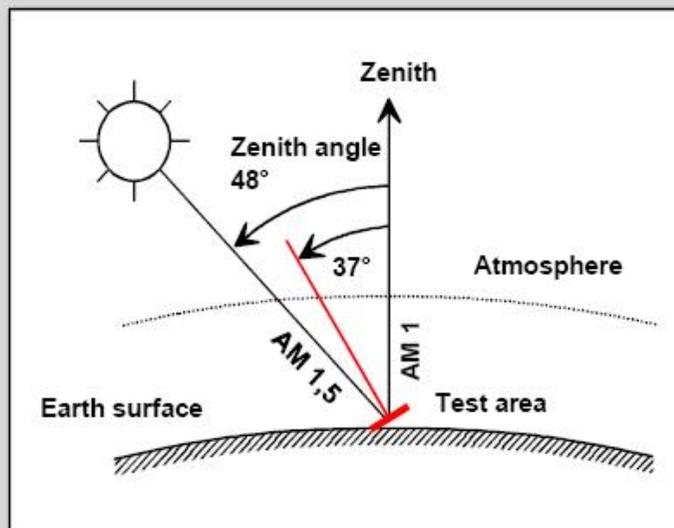
25°C

Total irradiance:

1000 W/m²

Spectral irradiance:

AM 1.5 reference spectral irradiance

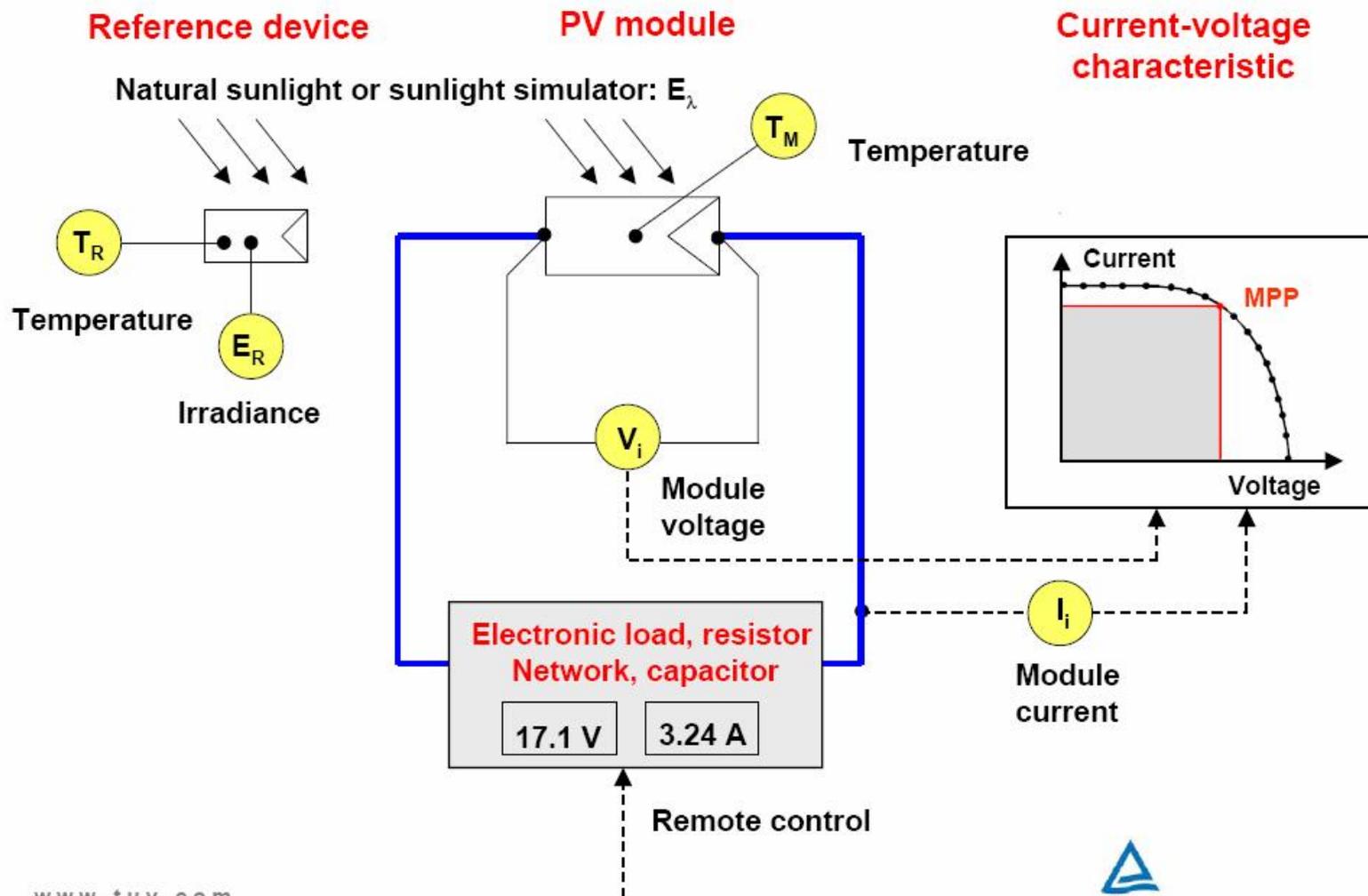


IEC60904—1: PV电流电压特性测试

对模拟光源的要求

	1987年第一版	2005年第二版
电流电压测试精度	$\pm 0.5 \%$	$\pm 0.2 \%$
温度测试精度	$\pm 1 \text{ C}^\circ$	$\pm 1 \text{ C}^\circ$
参考电池的测试样品的水平度	$\pm 5^\circ$	$\pm 2^\circ$
样品温度均匀性		$\pm 1 \text{ C}^\circ$
模拟太阳光		Class: BBB

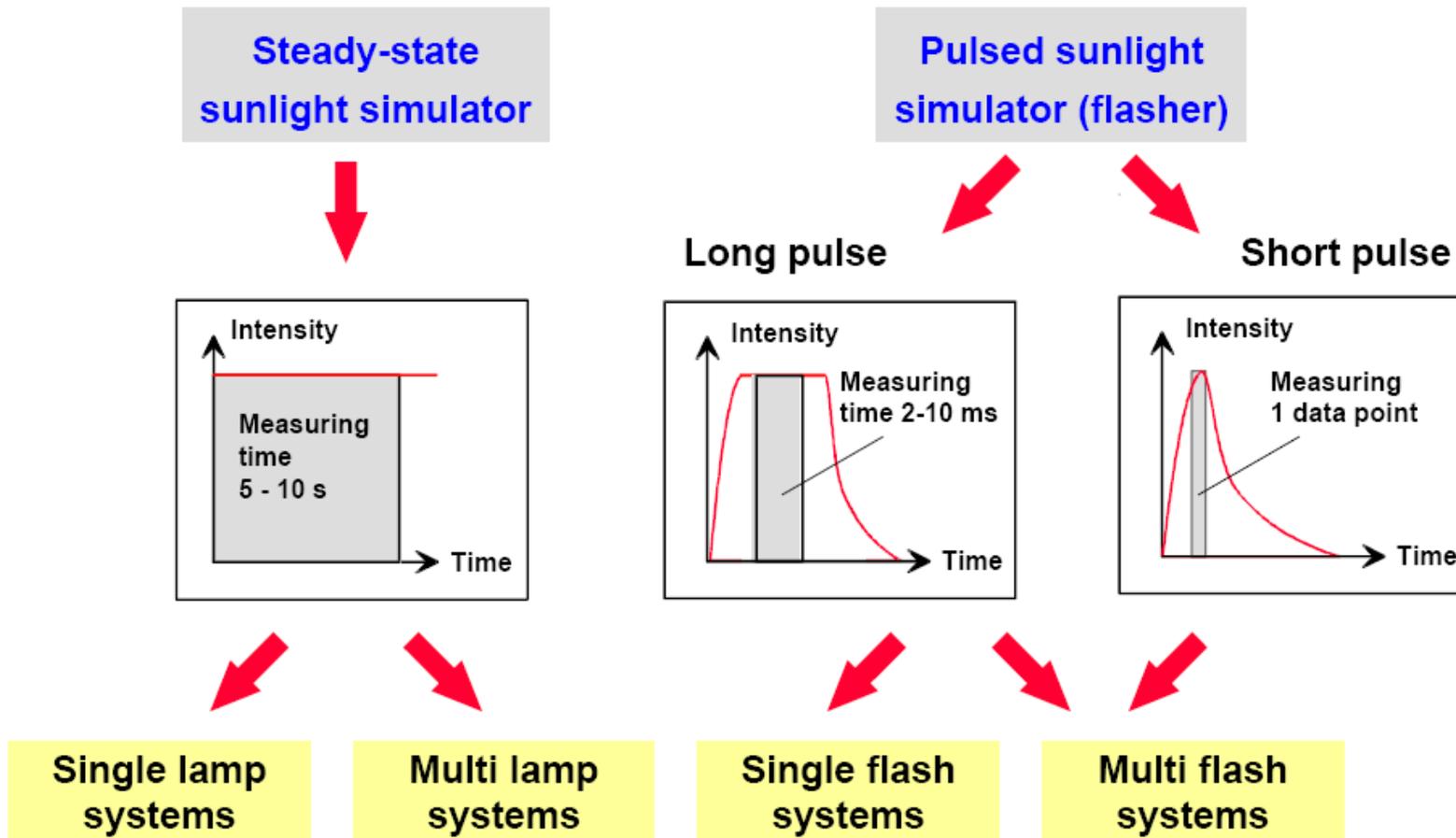
IEC60904—1: PV电流电压特性测试



IEC60904—1: PV电流电压特性测试

- £ **Isc**引入的外加影响：外电路电阻引入的电压降不得超过开压的**3%**
- £ **光谱失配修正**：在参考电池和待测样品间光谱响应不一致时应进行光谱时配修正
- £ **温度和辐照度的修正**精度应该定期测量。
- £ **仪器的校准**应在规定的范围内，并经过标定。
- £ 样品的温度均匀性应在空气中小于 **$\pm 1\text{ C}^\circ$**

用于光伏系统的太阳模拟器技术



用于光伏系统的太阳模拟器技术

£ 稳态模拟器

- 与光伏组件在实际日光下的使用规程相吻合
- 光源质量测量可以进行：光谱辐照测量，待测表面的辐照均匀性测量

£ 脉冲模拟器

- 短脉冲测量：在I-V测量过程中可能造成光强变化（脉冲衰减部分）。必须进行数据点修正 ↔ 测量的稳定性
- 在测量具有高电容特性的光伏组件时会出现问题。在短的测量周期内不会发生充放电过程 ↔ IV曲线畸变
- 很难进行光源质量测量

用于光伏系统的太阳模拟器技术

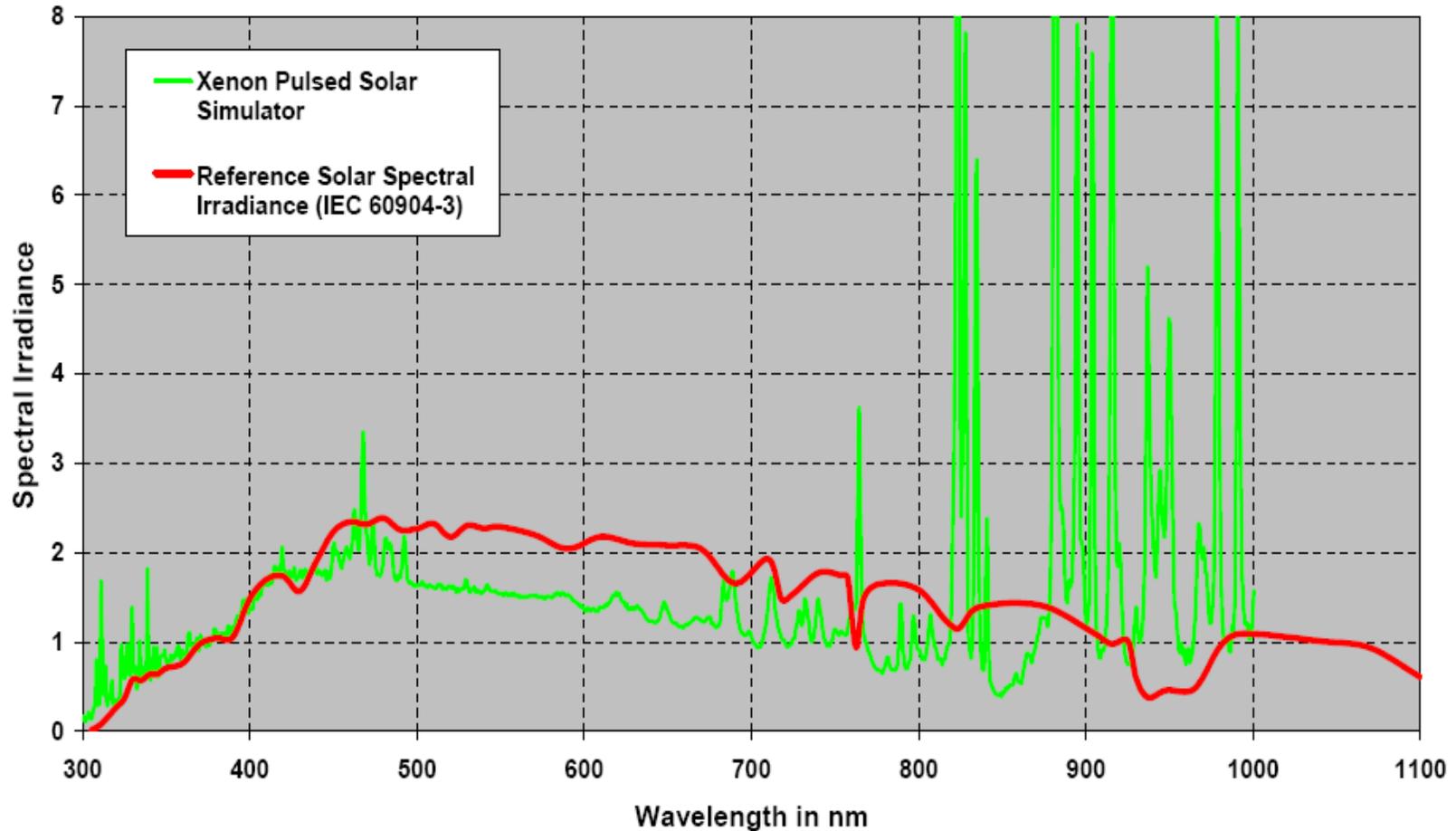
	Natural sunlight		Pulsed sunlight simulator	
	Steady-state sunlight simulator		One data point per flash	Full I-V record during one flash
Electronic load	X		X	
Bi-polar power supply	X			
Resistor network		X	X	X
Capacitor		X		X
I-V sampling rate	Low ¹	High	Low ²	High
Transient effects	No	Yes ³	No	Yes ³

- 1 – due to equipment response time
- 2 – dependant on stroboscope velocity
- 3 – due to cell response time

IEC60904—9太阳模拟器的要求

质量	方法	等级		
		A	B	C
辐照非均匀性	在测试面积内进行辐照度的检测，计算从小到大的差	<2%	<5%	<10%
与AM1.5光谱的失配	在6个波段内比较光强 (400-500-600-700-800-900-1100) 太阳模拟器/AM1.5数据	0.75~1.25	0.6~1.4	0.4~2.0
辐射光的稳定性	在待测面积内定点测量模拟器辐照度，在1分钟内计算最小点至最大点	<2%	<5%	<10%

IEC60904—9 氙灯与AM1.5的光谱失配



➔ Xenon lamp spectrum shows major differences to the AM 1.5 reference in the range 800 nm – 1100 nm

IV测试

模拟光源

TABLE 1

Classification of a solar simulator using the ASTM procedure [4]

	Class		
	A	B	C
Spatial nonuniformity	< ± 2%	< ± 5%	< ± 10%
Temporal instability	< ± 2%	< ± 5%	< ± 10%
Total irradiance within a 30° field of view	>95%	>85%	>70%

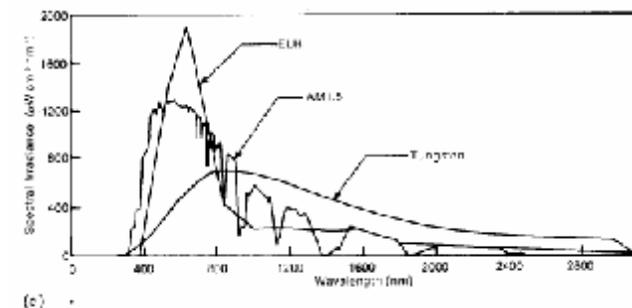
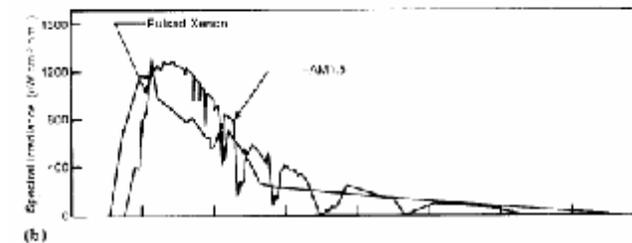
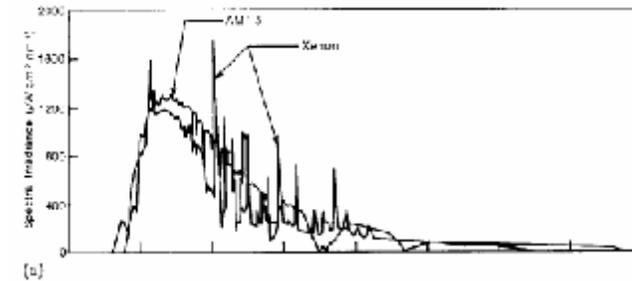
TABLE 2

Spectral classification of simulator

Class	Simulator spectrum in wavelength band (%)
	Reference spectrum in wavelength band (%)
A	0.75 - 1.25
B	0.6 - 1.4
C	0.2 - 2.0

Reference:

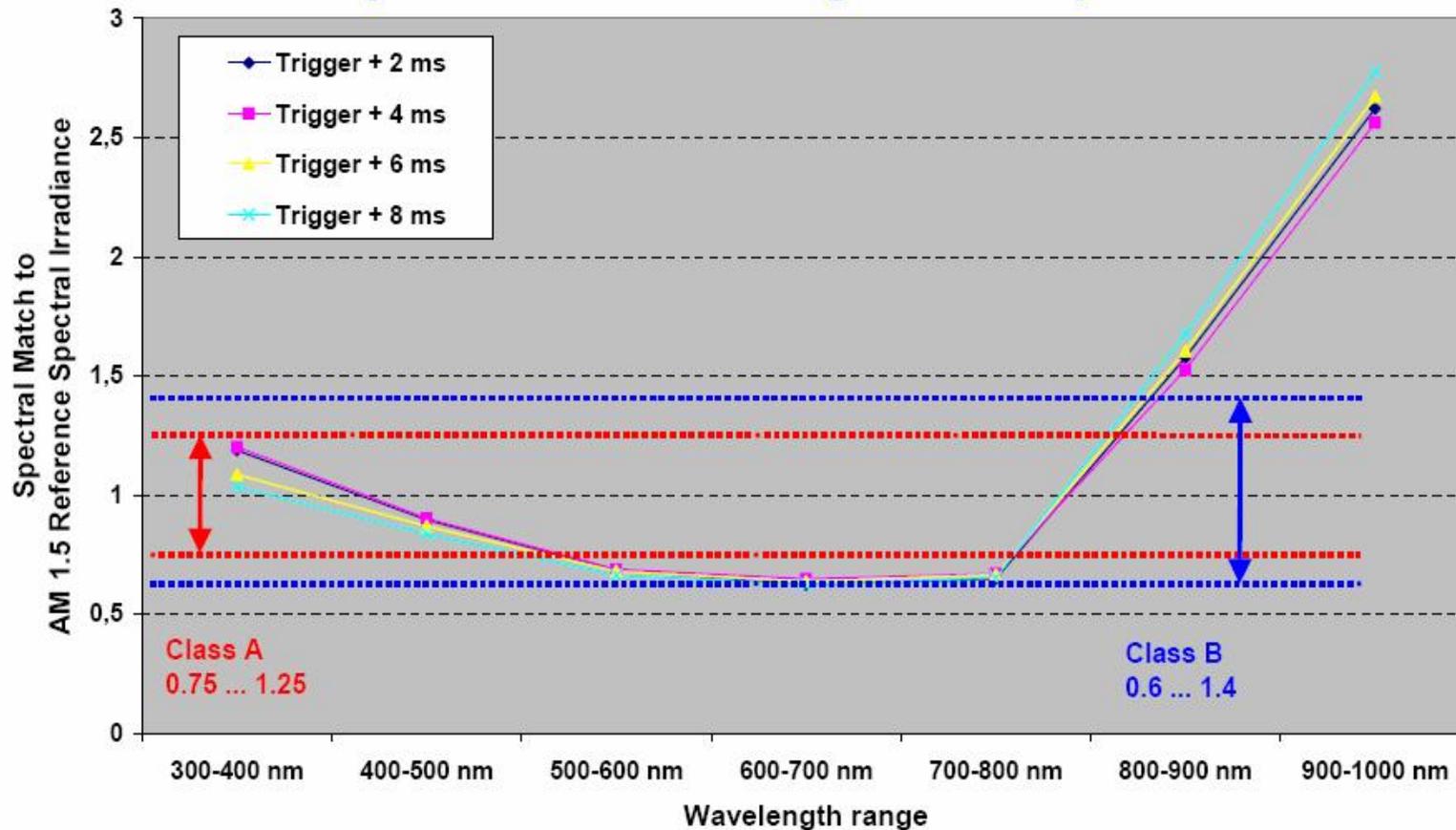
K.A. Emery, Solar cells 18 (1986) 251-260



各种模拟光源与AM1.5的比较

R.J. Matson, Solar cells 18 (1984) 105-145

IEC60904—9 脉冲氙灯光谱失配



➔ Change of spectral irradiance during a Xenon pulse is of minor importance and need not to be considered in the spectral mismatch

IEC60981 温度和辐照度修正

$$I_2 = I_1 + I_{SC1} \cdot (E_2 / E_1 - 1) + \alpha \cdot (T_2 - T_1)$$

$$V_2 = V_1 - R_S \cdot (I_2 - I_1) - K \cdot I_2 \cdot (T_2 - T_1) + \beta \cdot (T_2 - T_1)$$

Legend:

I_1, I_2 : Module current
 V_1, V_2 : Module voltage
 T_1, T_2 : Module temperature
 E_1, E_2 : Irradiance

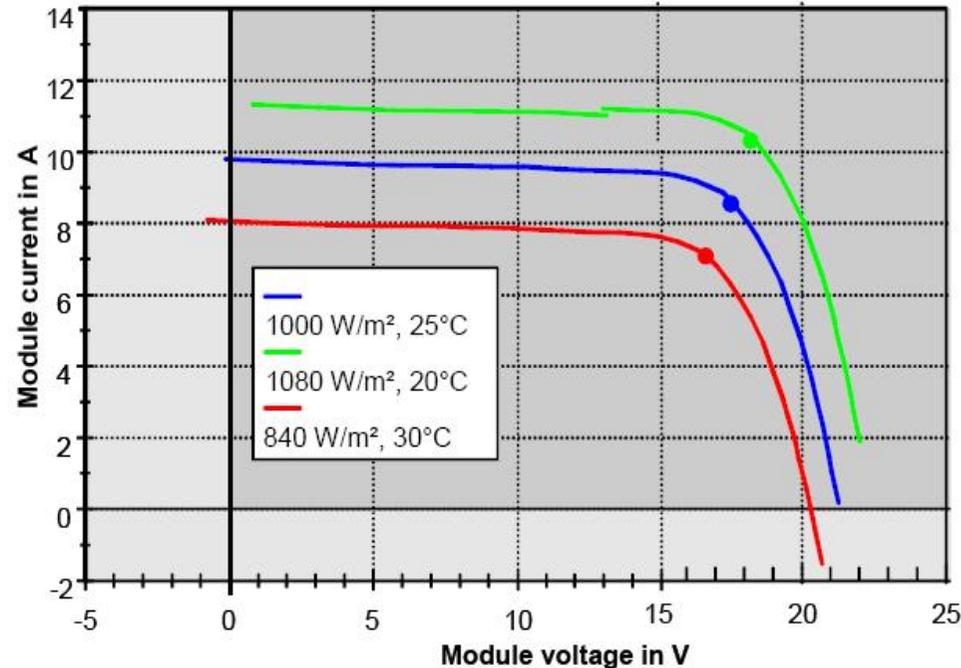
Index 1: Measurement conditions
Index 2: Corrected conditions

Module correction parameters:

α : Temperature coefficient I_{SC} [$A/^\circ C$]
 β : Temperature coefficient V_{OC} [$V/^\circ C$]
 R_S : Series resistance [Ω]
 K : Curve correction factor [$\Omega/^\circ C$]

- Requirements:**
- Irradiance $> 700 \text{ W/m}^2$
 - Procedure applicable over an irradiance range of $\pm 30\%$ of target irradiance level

IEC60981 温度和辐照度修正



- Disadvantages:**
- I_{SC} and V_{OC} of the corrected I-V curve must be extrapolated
 - V_{OC} is dependant on module series resistance
 - Procedure for calculating module parameters from cell parameters is not clear.

IEC60981 温度和辐照度修正

Based on the measured module correction parameters the **cell correction parameters** (Index “C”) can be extrapolated according the following equations:

$$\beta_c = \beta / N_s \text{ in } mV / cell$$

$$R_{s,c} = R_s \times N_p / N_s \text{ in } m\Omega / cell$$

$$\alpha_c = \alpha / (N_p \times A_c) \text{ in } \mu A / (K \cdot cm^2)$$

$$K_c = K \times N_p / N_s \text{ in } m\Omega / (K \cdot cell)$$

- ➔ These cell correction parameters can be used to calculate the module correction parameters of a new module circuitry which is characterised by (N_s , N_p).
- ➔ Care must be taken regarding the use of $R_{s,c}$ which may change for cell types of different power category.

新的温度和辐照度修正

$$I_2 = I_1 \cdot [1 + \alpha \cdot (T_2 - T_1)] \cdot E_2 / E_1$$

$$V_2 = V_1 + V_{OC1} \cdot [\beta \cdot (T_2 - T_1) + \chi \cdot \ln(E_2 / E_1)] - R_s \cdot (I_2 - I_1)$$

Legend:

I_1, I_2 : Module current
 V_1, V_2 : Module voltage
 T_1, T_2 : Module temperature
 E_1, E_2 : Irradiance

Index 1: Measurement conditions
Index 2: Corrected conditions

Module parameters:

α : Temperature coefficient I_{SC} [$1/^\circ\text{C}$]
 β : Temperature coefficient V_{OC} [$1/^\circ\text{C}$]
 R_s : Series resistance [Ω]
 χ : Irradiance correction factor

新的温度和辐照度修正

Advantage:

Procedure delivers already good results for crystalline silicon modules when default values for correction parameters are used:

$$\alpha = 0 \quad [1/^\circ\text{C}]$$

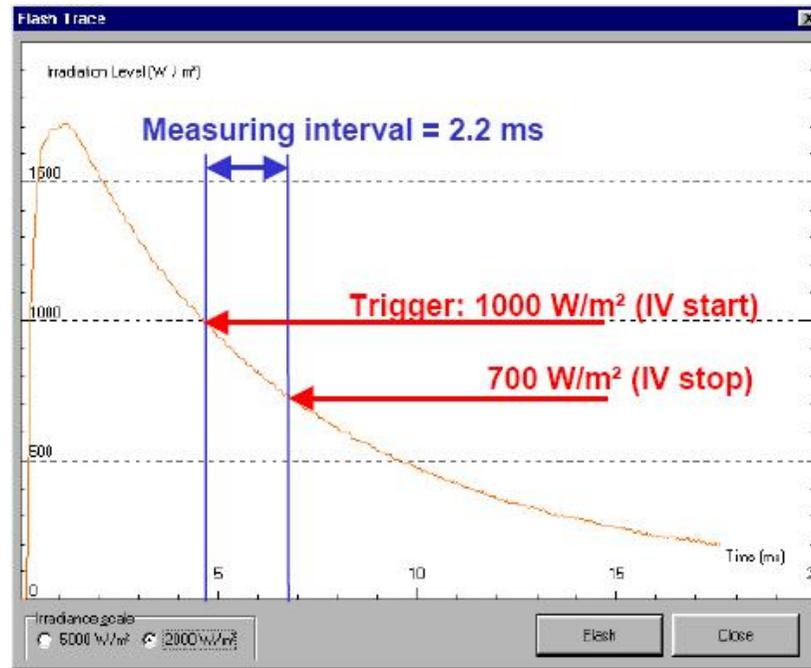
$$\beta = 0.004 \quad [1/^\circ\text{C}]$$

$$R_s = N_s \times 10 \text{ m}\Omega / N_p$$

$$\chi = 0.06$$

Note: The correction procedure is presently discussed for inclusion in a revised test standard IEC 60891

IEC60981 温度和辐照度修正的影响

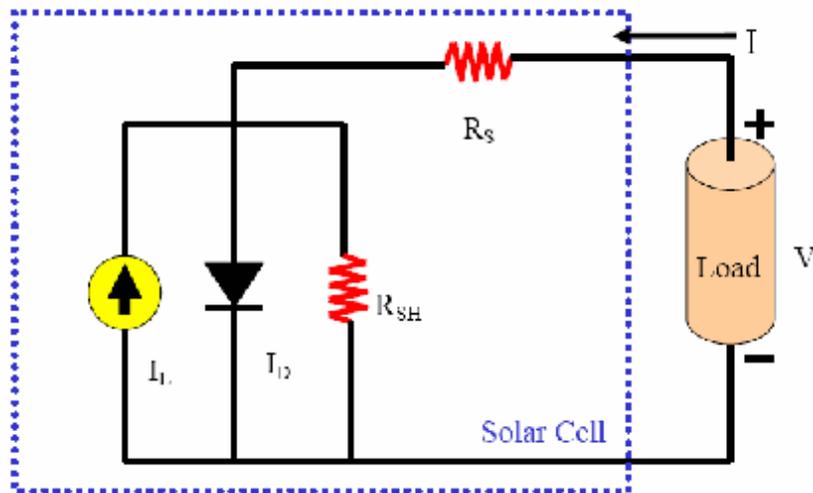


Measurement error caused by incorrect module series resistance:

$$\begin{aligned}\Delta V_{MP} &= \Delta R_S \times (I_{CORR} - I_{MEAS}) = \Delta R_S \times I_{CORR} \times (1 - I_{MEAS} / I_{CORR}) \\ &\approx \Delta R_S \times I_{MP} \times (1 - E_{MEAS} / 1000 \text{ W/m}^2)\end{aligned}$$

光伏器件等效电路图

太阳电池的电路特性:



I_L : 光生电流

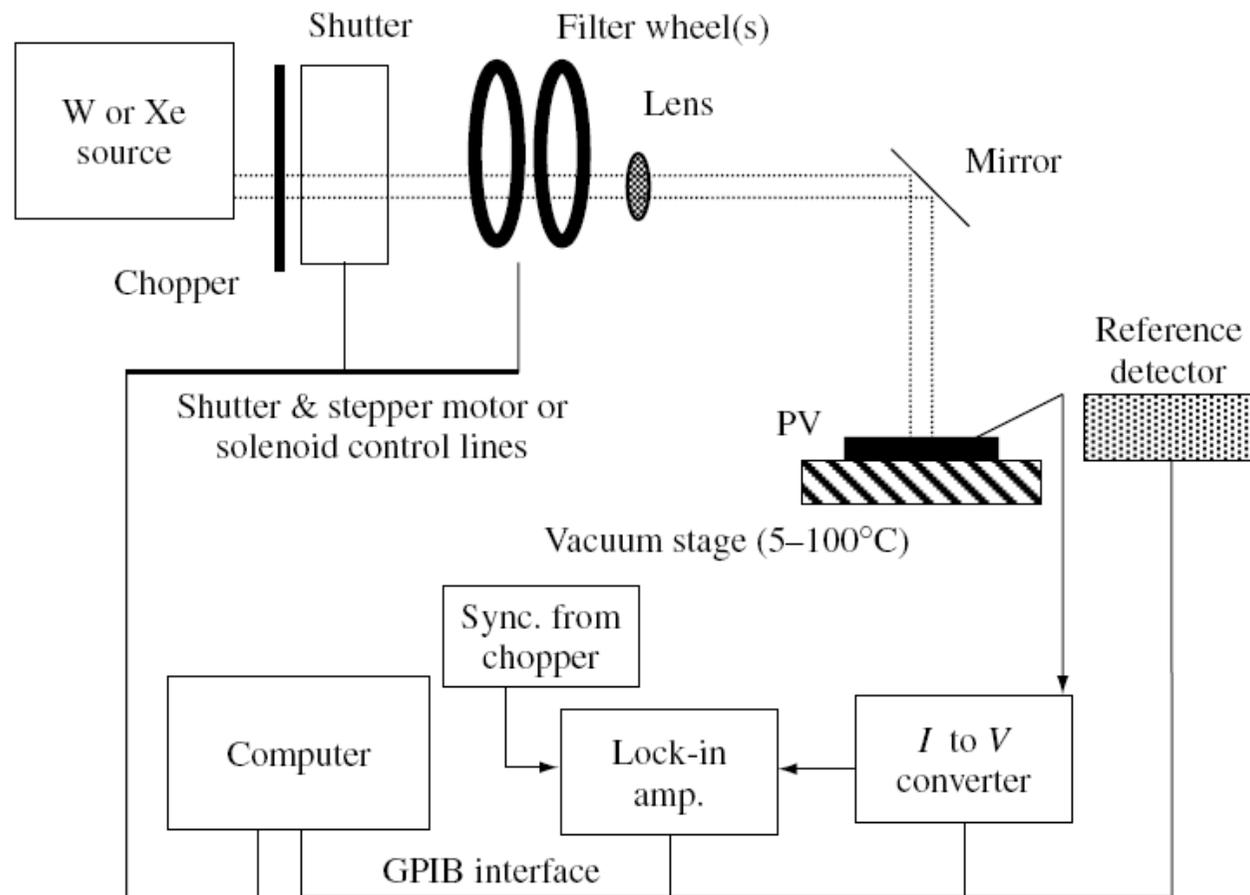
I_D : 二极管饱和暗电流

R_{sh} : 并联电阻

R_s : 串联电阻

图1 太阳电池的电路模型，蓝色虚线内表示太阳电池的等效电路

测试设备原理图



一、IV测试

暗IV特性：恒温，蔽光

电池在正向电压下工作，因此研究pn结的正向特性很重要。得出 I_0 和品质因子n。

二极管的暗电流密度 I_0 通过2-二极管模型描述为：

$$I_0(V) = I_{01} \left[\exp\left(\frac{V - R_s I_0(V)}{n_1 \mathcal{V}_{th}}\right) - 1 \right] + I_{02} \left[\exp\left(\frac{V - R_s I_0(V)}{n_2 \mathcal{V}_{th}}\right) - 1 \right] + \frac{V - R_s I_0(V)}{R_{sh}}$$

光照IV特性：直接反映电池的输出功率

标准条件：AM1.5，温度25°C，光源的标定（辐射计或者标准电池）

需要温度测试或者控温

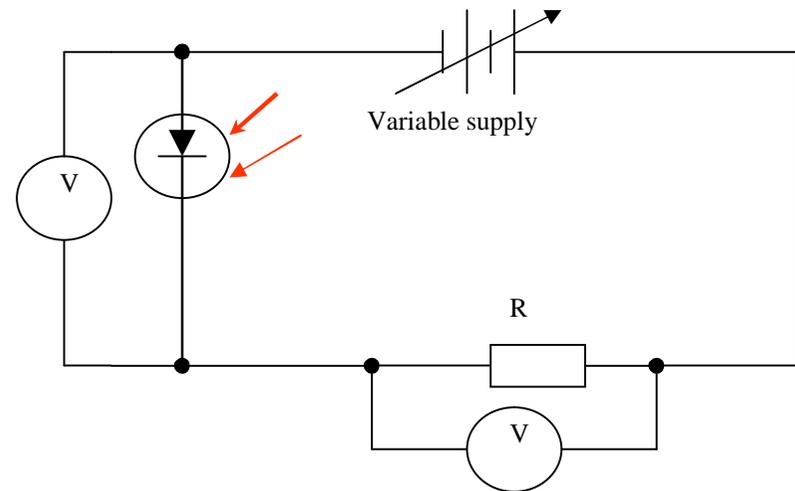
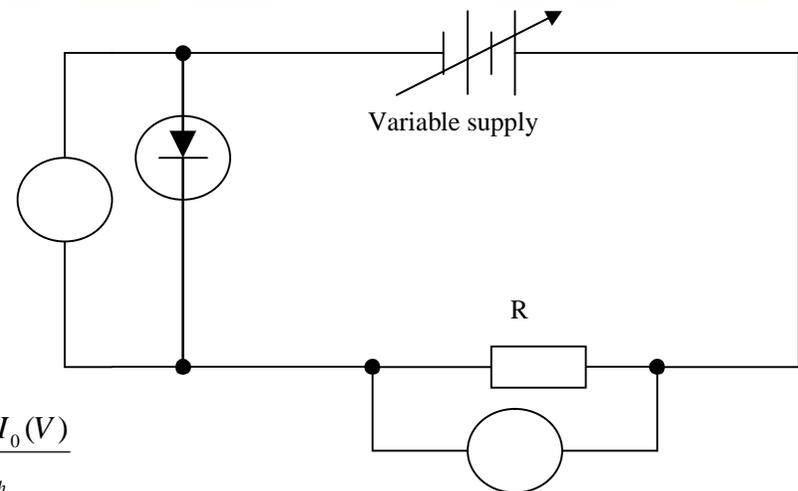
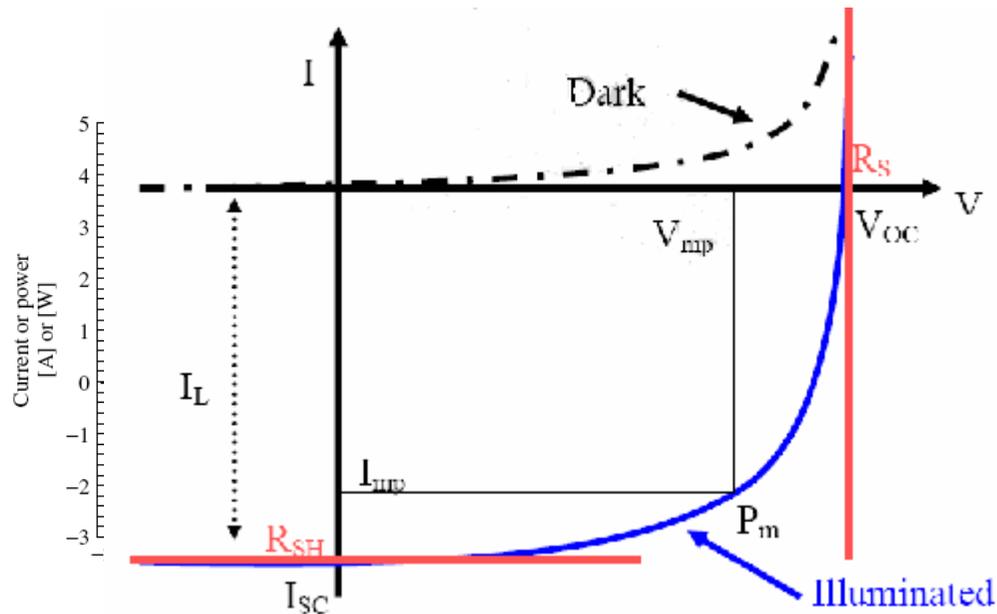


图6 典型的I-V测试结构图，上图为暗IV测试，下图为光照IV测试

一、IV测试

典型的测试结果:



$$J = J_{sc} - J_0$$

(superposition principle)

$$V_{oc} = \frac{kT}{q} \ln\left(\frac{I_{sc}}{I_0} + 1\right)$$

$$h = \frac{P_m}{P_{in}} = \frac{FFV_{oc}I_{sc}}{P_{in}}$$

$$FF = \frac{P_m}{I_{sc}V_{oc}} = \frac{V_{mp}I_{mp}}{I_{sc}V_{oc}}$$

文献: Antonio Luque, Steven Hegedus, Handbook of Photovoltaic Science and Engineering, Wiley Inc



串并联电阻的影响

串、并联电阻的影响：在不同光强下测试 I_{SC} 和 V_{OC} ，得出下图

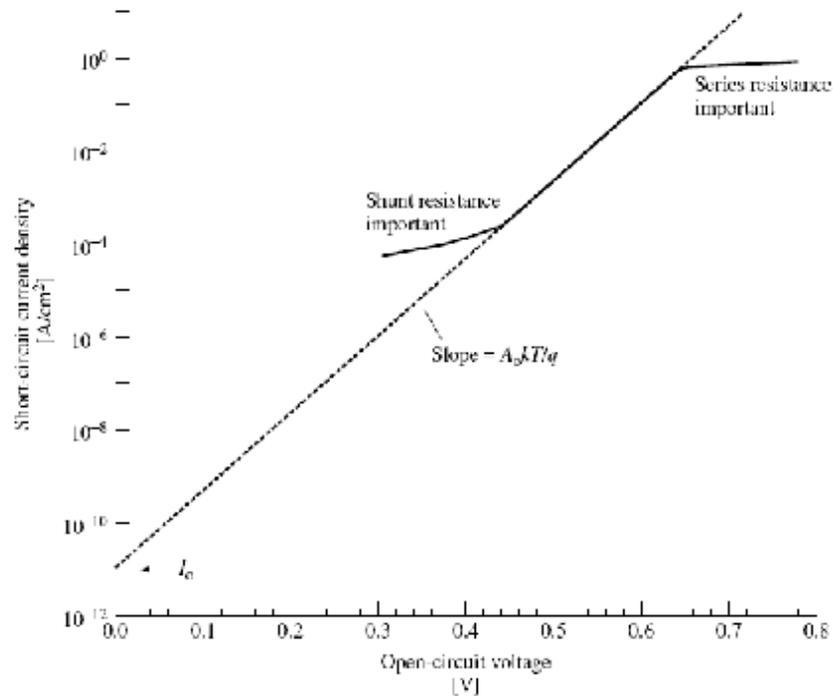


图5 I_{SC} 与 V_{OC} 关系曲线

结论：

- 1: 串连电阻减少了短路电流
- 2: 并连电阻减少了开路电压
- 3: 二极管的品质因子 A_0 ，值一般在1~2之间，二极管主要在准中性区域复合为1，在耗尽区域复合为2。
- 4: 饱和暗电流 I_0

文献：Antonio Luque, Steven Hegedus, Handbook of Photovoltaic Science and Engineering, Wiley Inc

串并联电阻的影响

串、并联电阻的影响

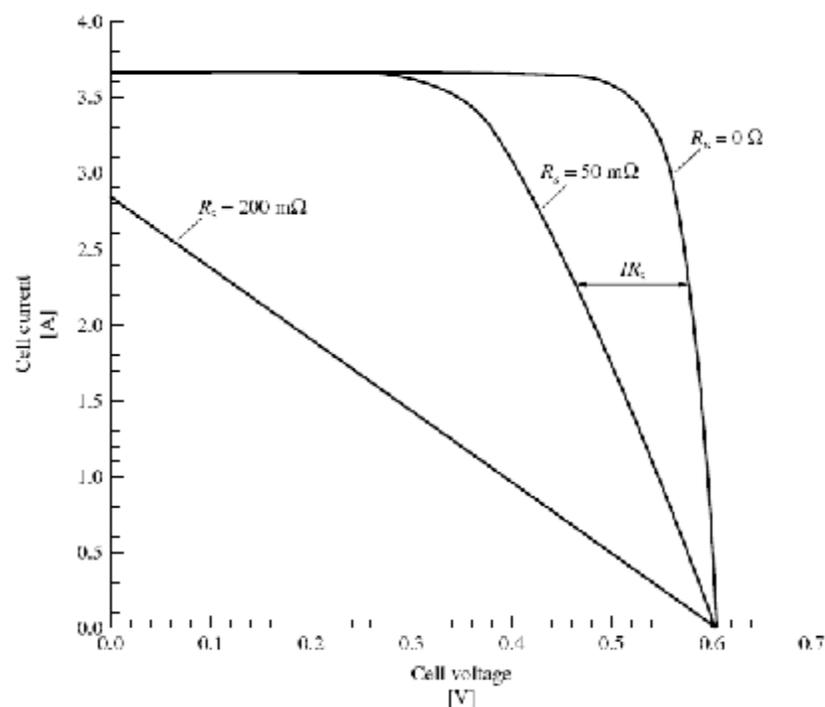


图3 不同串连电阻得出的IV测试结果

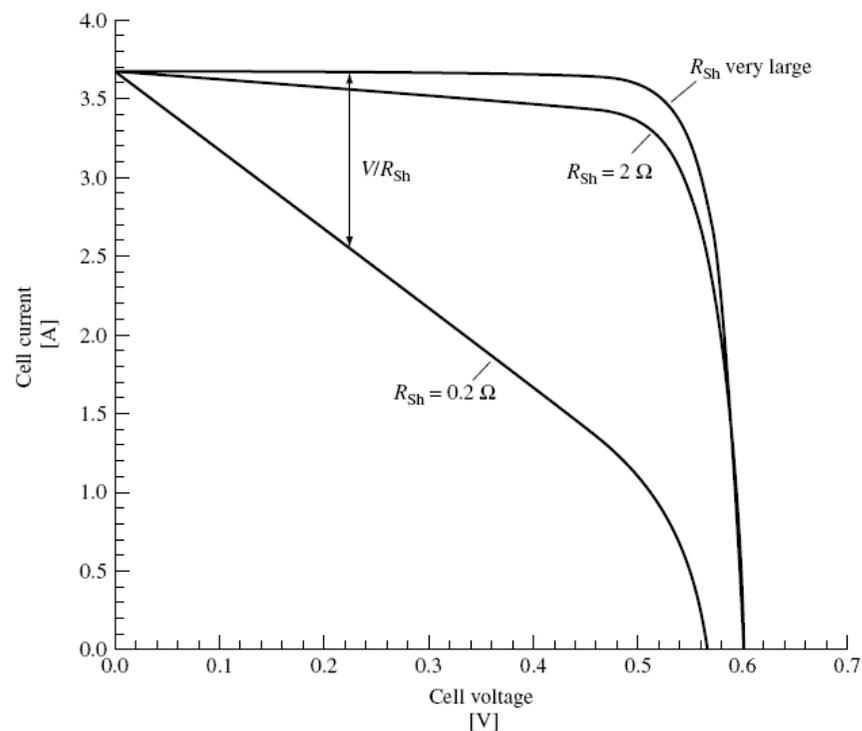
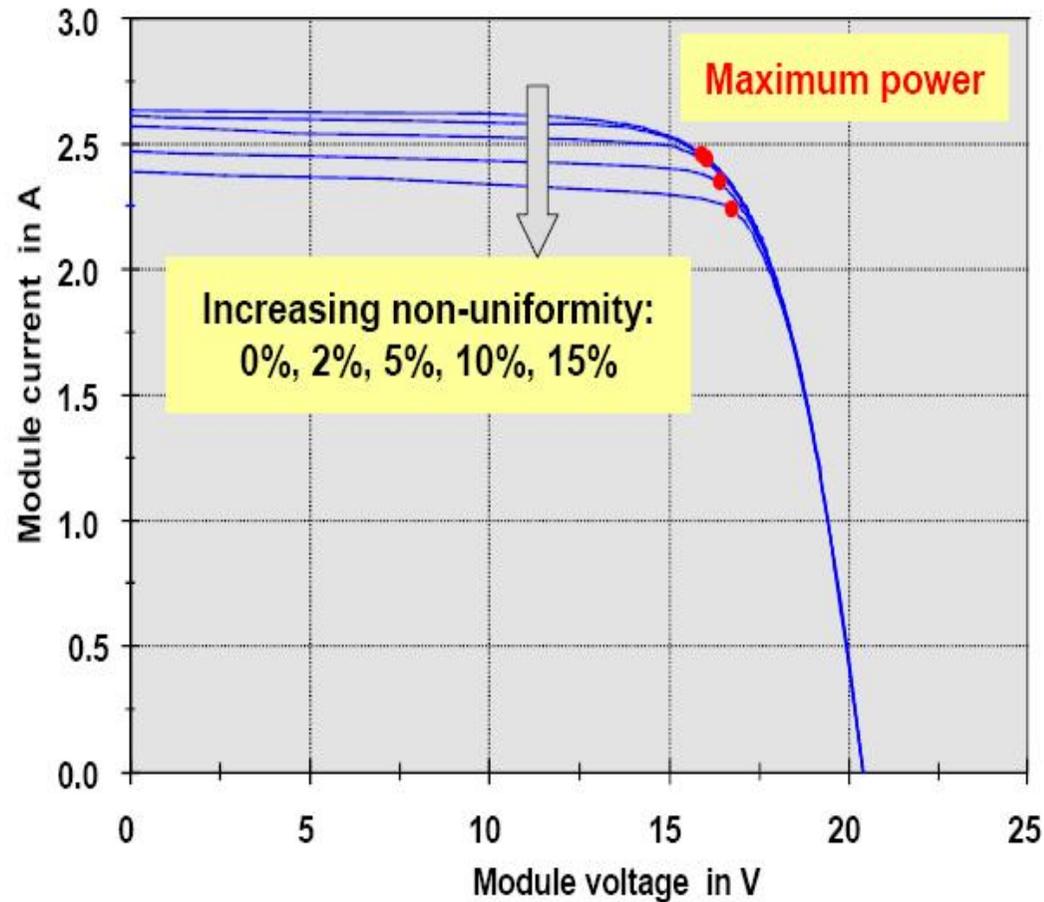


图4 不同并连电阻得出的IV测试结果

文献: Antonio Luque, Steven Hegedus, **Handbook of Photovoltaic Science and Engineering**, Wiley Inc

光伏器件辐照不均匀的影响



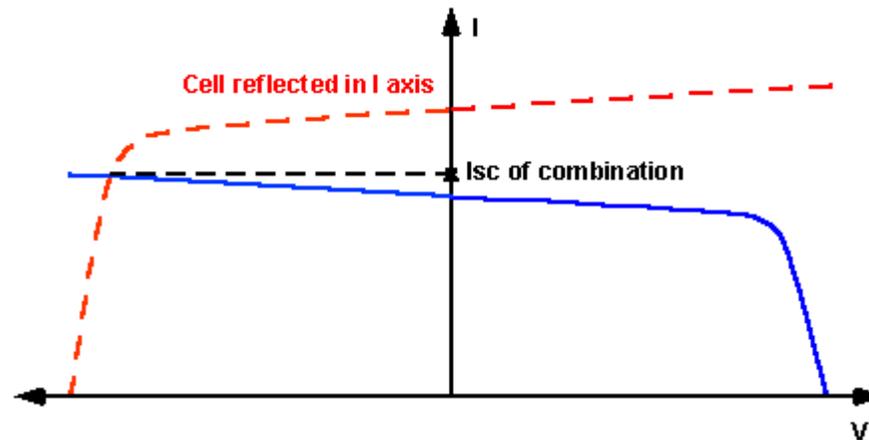
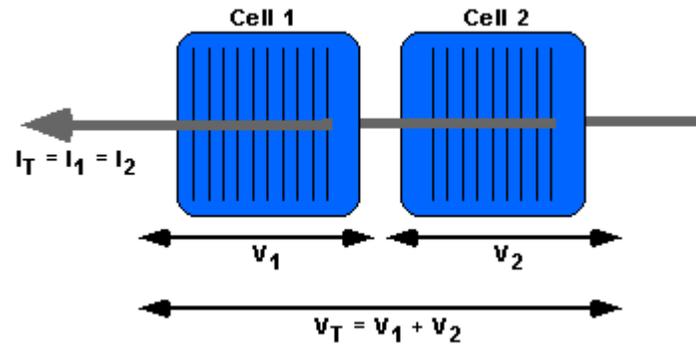
Non-uniformity:

$$\frac{E_{MAX} - E_{MIN}}{E_{MAX} + E_{MIN}} \times 100\%$$

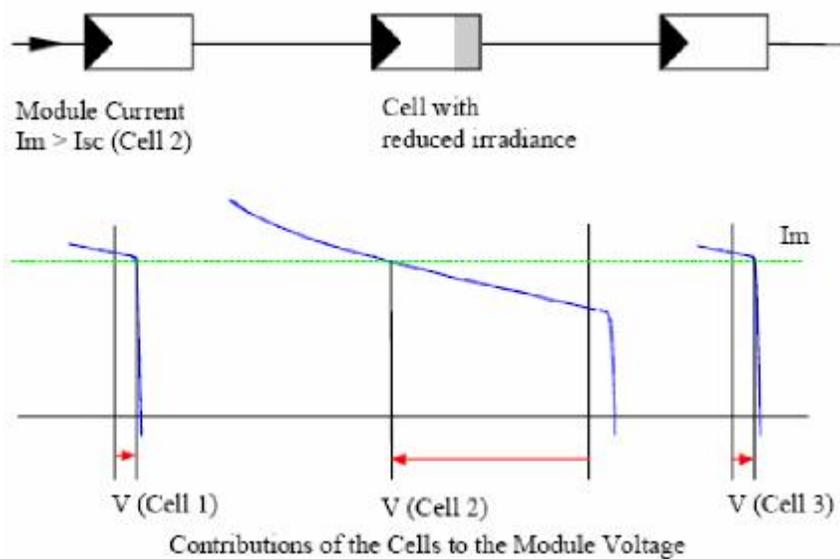
Calibration:

Effective irradiance in the module area = Average of irradiances measured at the positions of all cells in the module

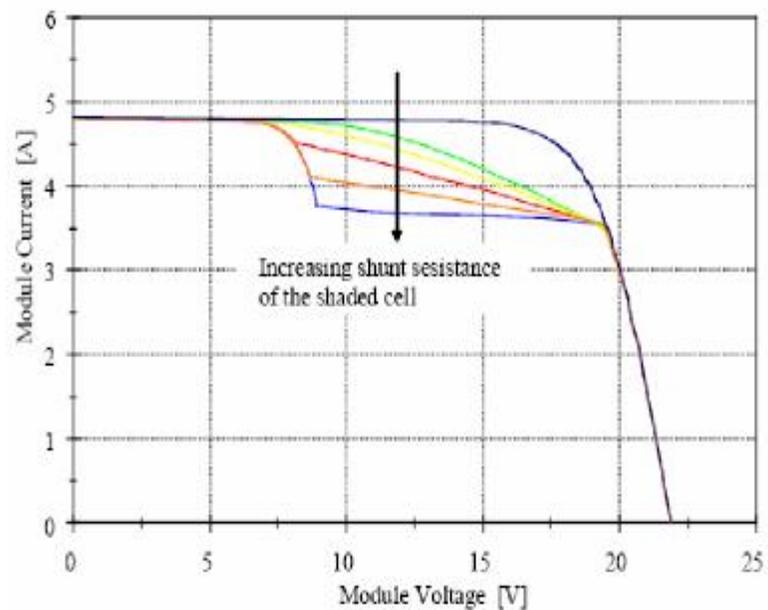
串联电池的电流计算



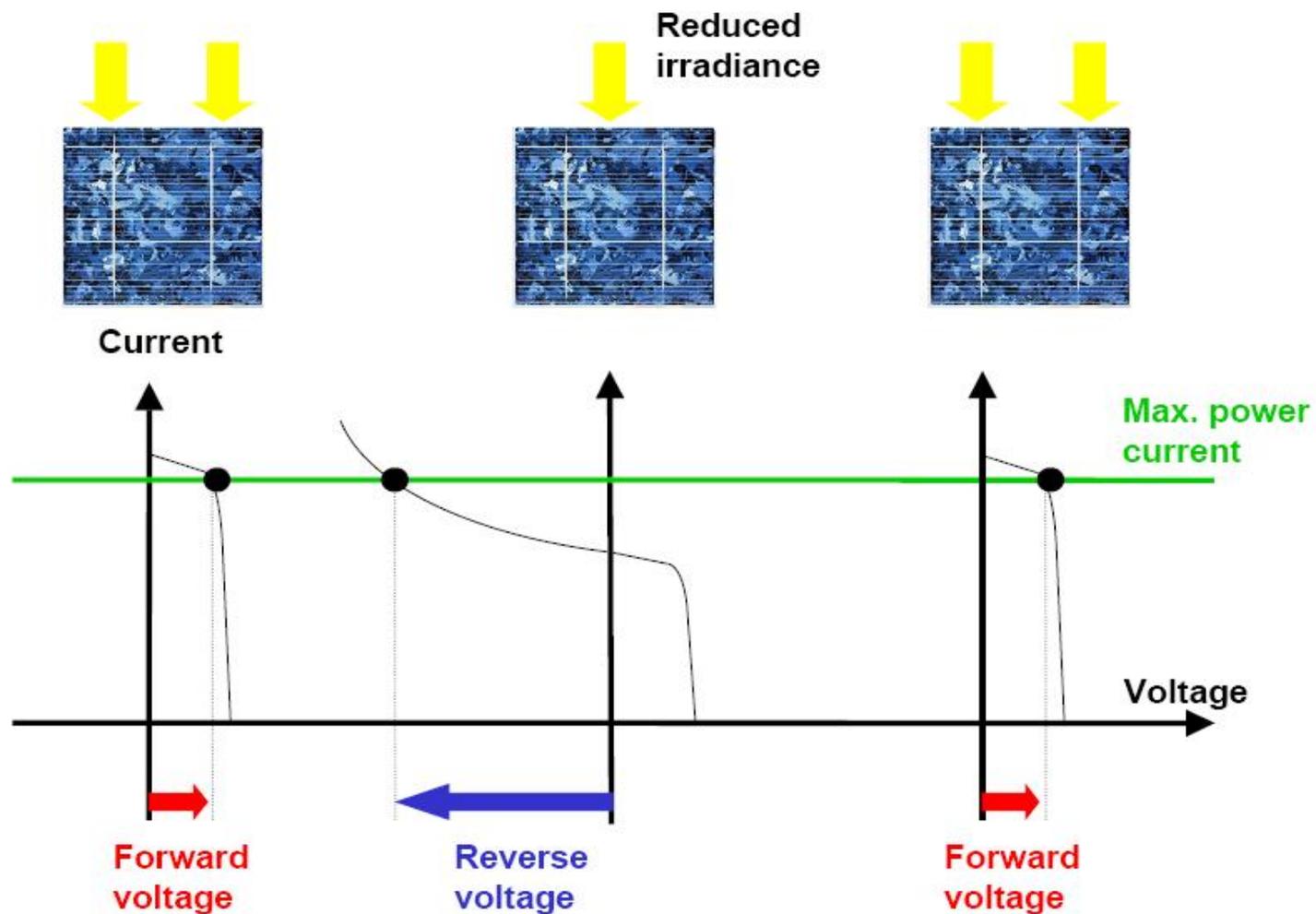
光伏组件不均匀辐照的影响



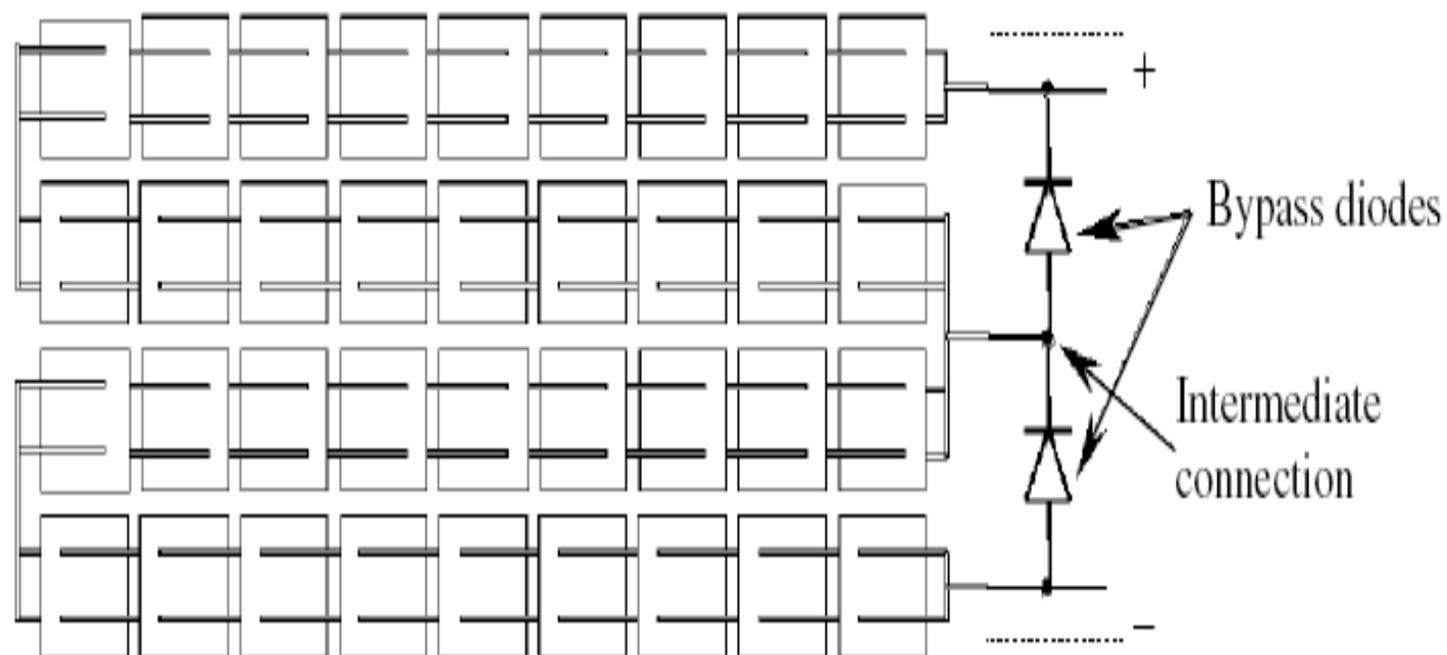
三个串联的电池中有一个被遮光（Cell 2）会造成总的工作电流大于被遮光电池的短路电流的情况



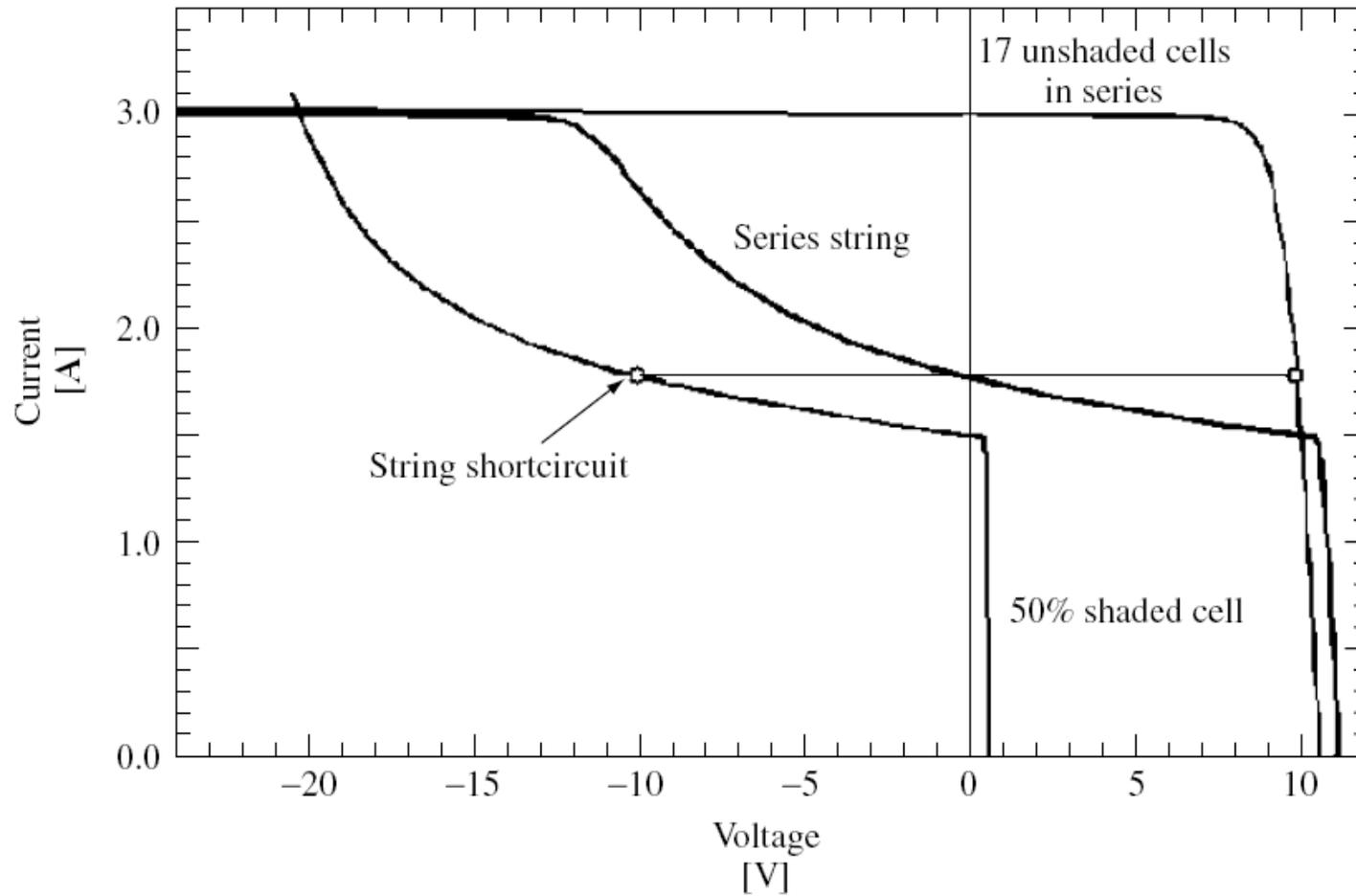
光伏组件不均匀辐照的影响



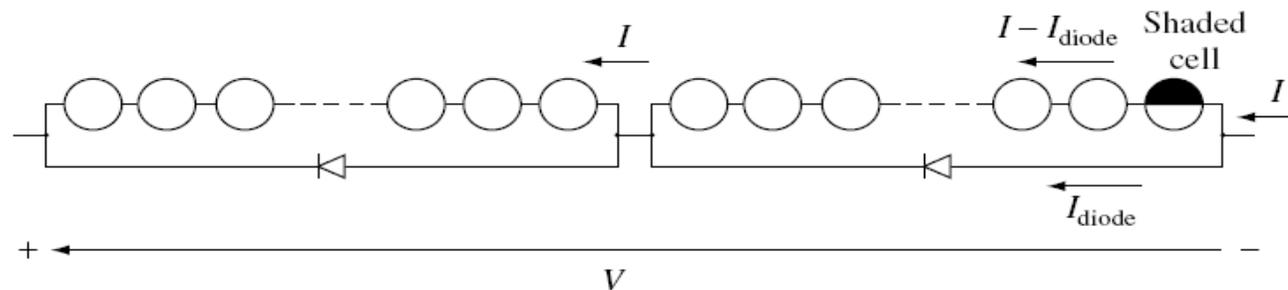
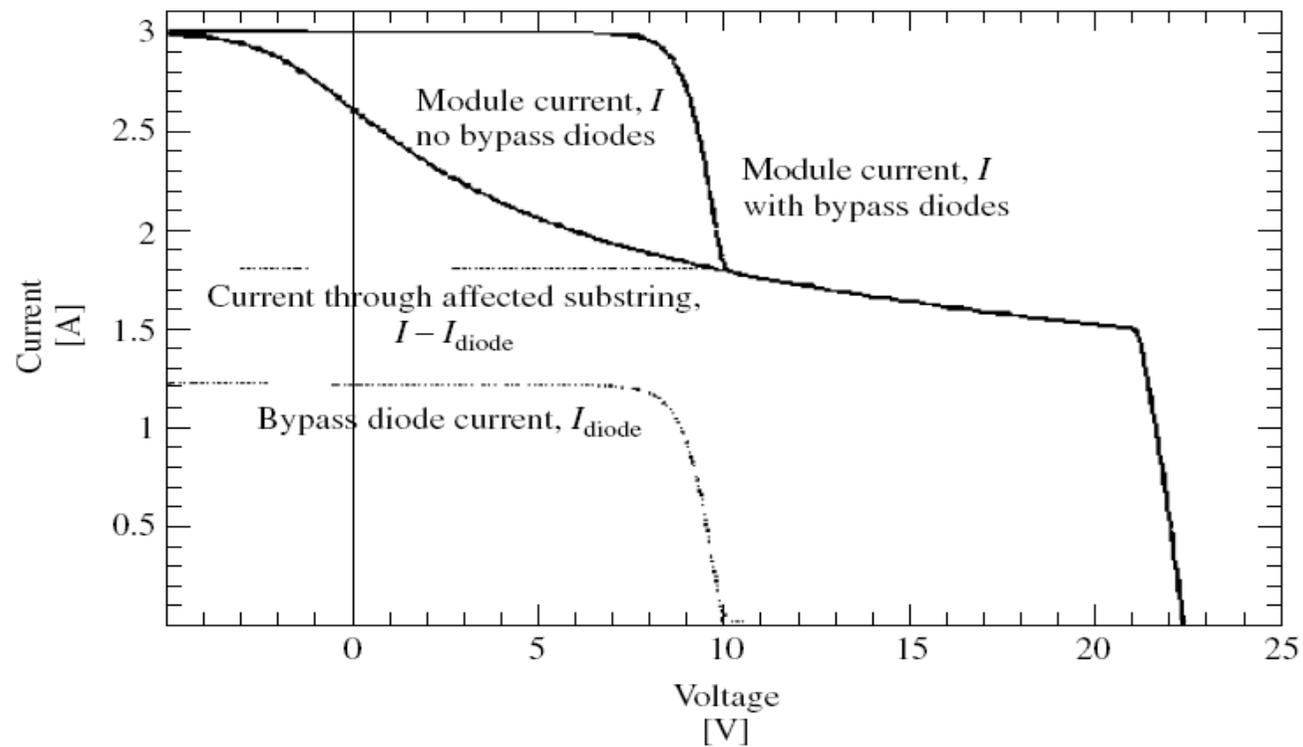
具有二极管的串联电池组件



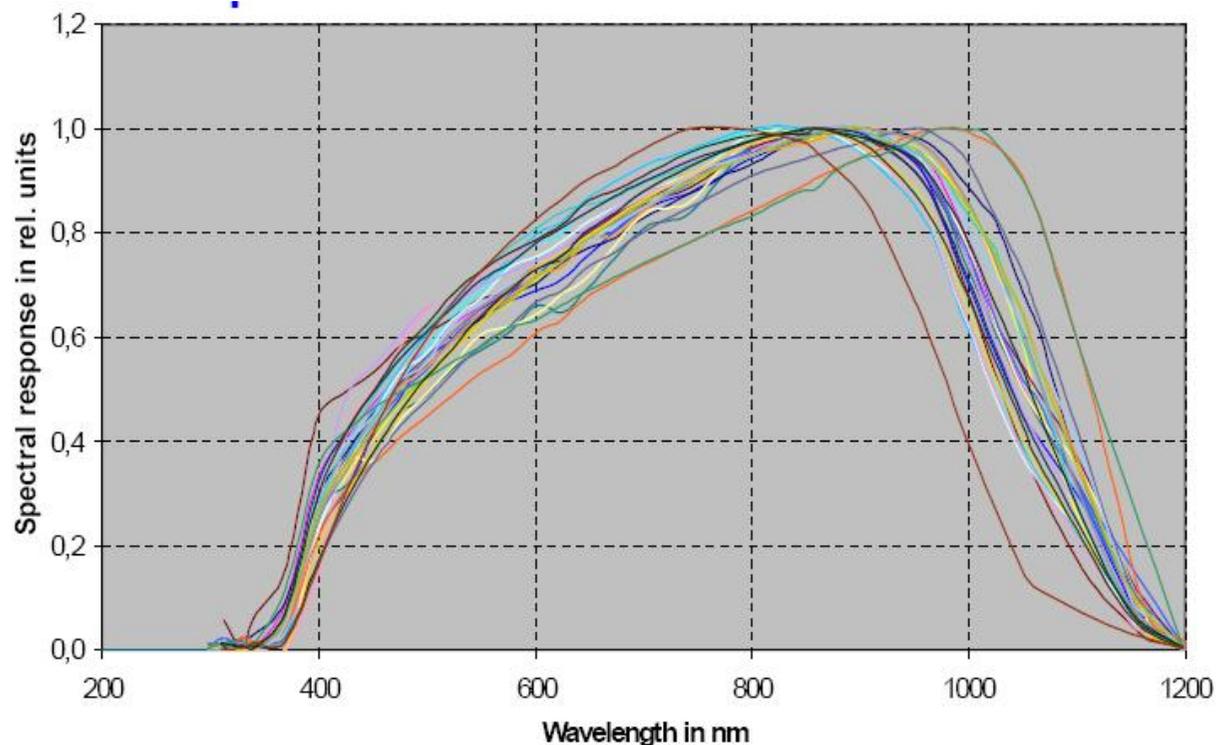
电池组件的辐照不均匀的影响



电池组件的辐照不均匀的影响



光谱失配的影响—1

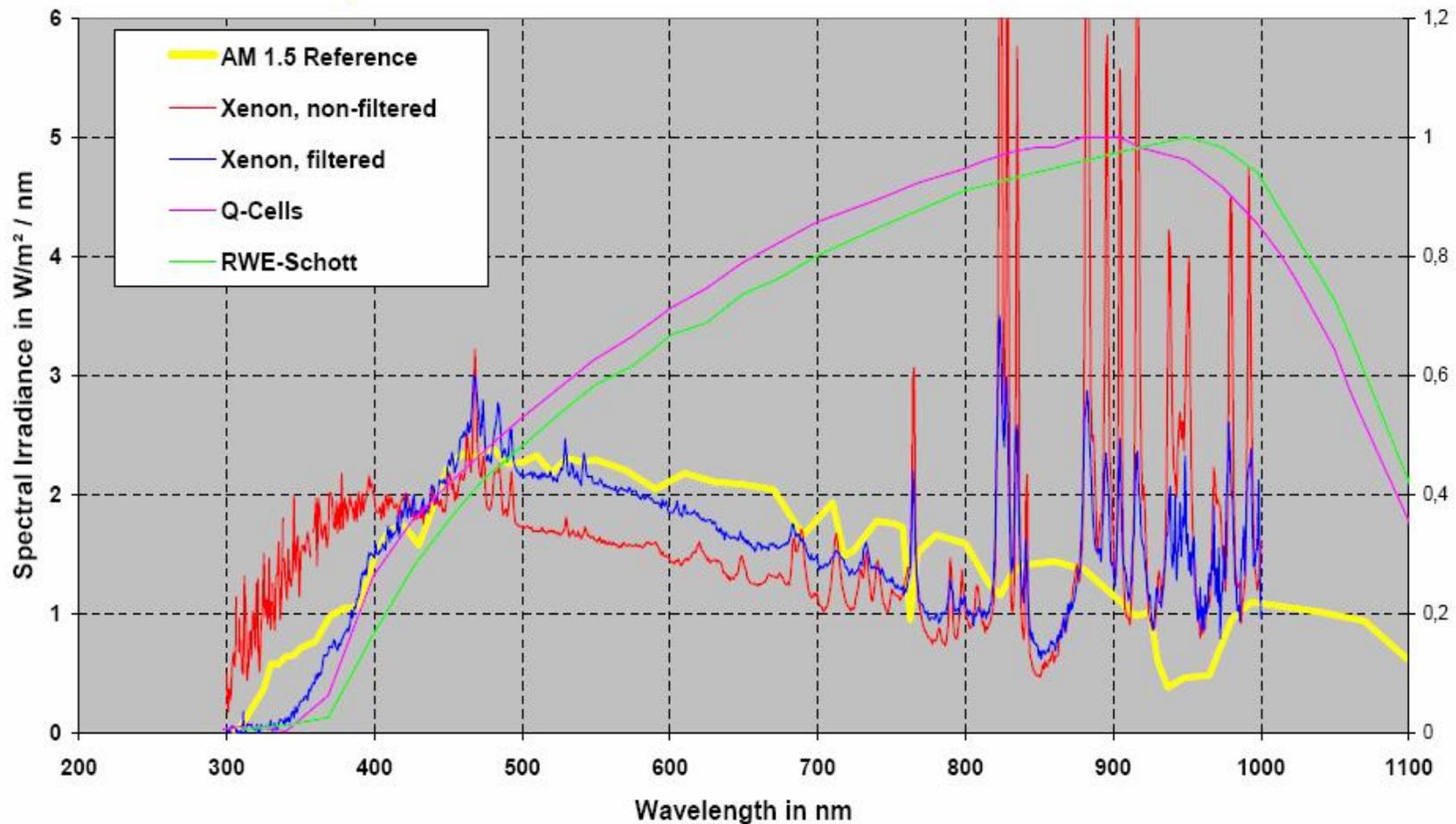


- ➔ Spectral response of encapsulated c-Si cells can differ considerably
- ➔ If necessary, spectral mismatch must be evaluated for different material combinations

光谱失配的影响—1

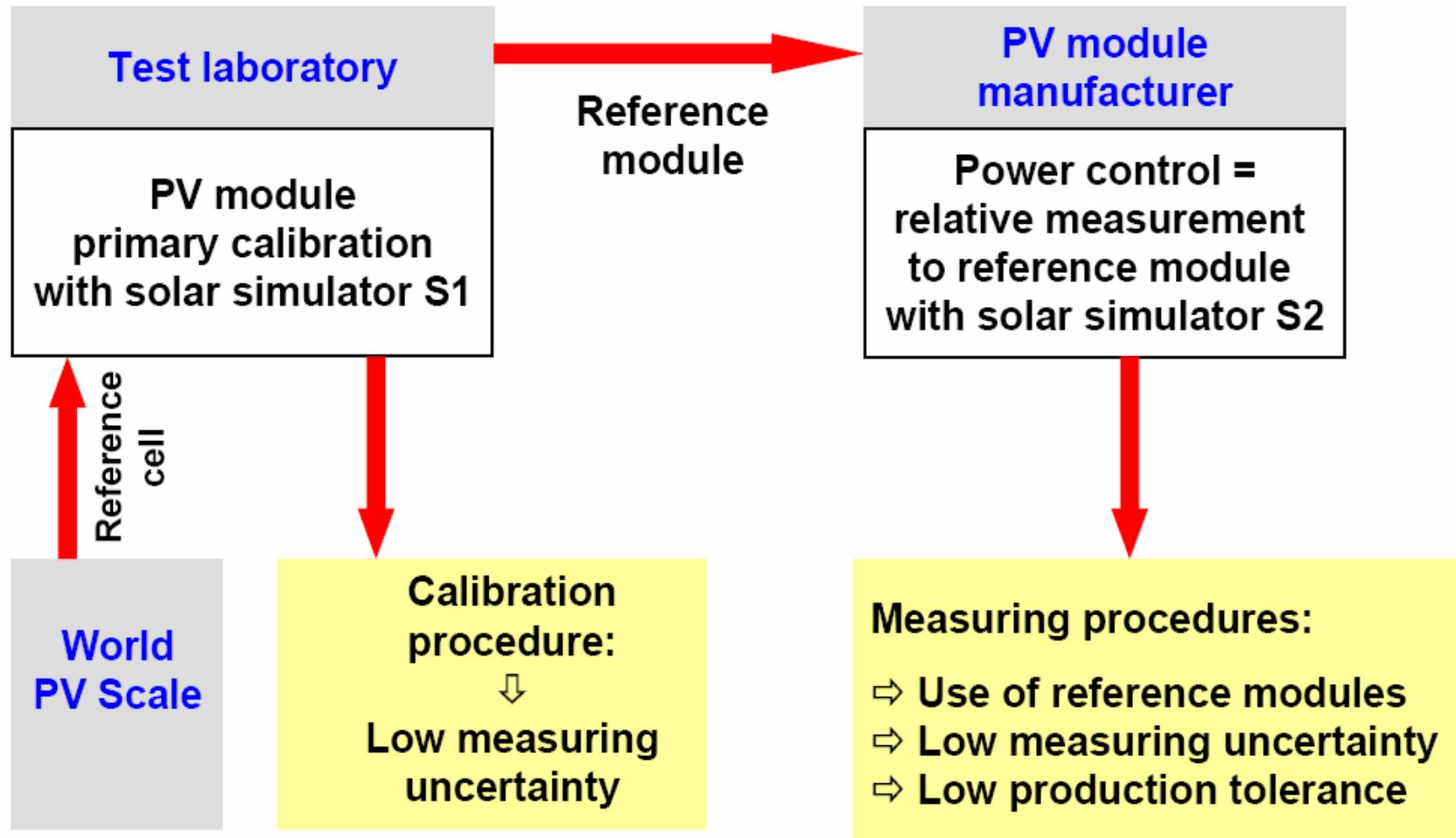
- £ 在以下情况下需要考虑光谱失配因子，以便修正结果
 - 当参考电池与待测电池有不同的光谱响应的时候
 - 所用的模拟光源与**AM1.5**具有不同的光谱的时候
- Ø 当参考组件与生产组件具有不同的光谱匹配时，模拟器的辐照光谱才是重要的。
- Ø 脉冲光源和光强的变化可能改变辐照光谱

光谱失配的影响—2



- ➔ Max. spectral mismatch for Xenon light: 2%
- ➔ No improvement for filtered Xenon light

电池标准的传递

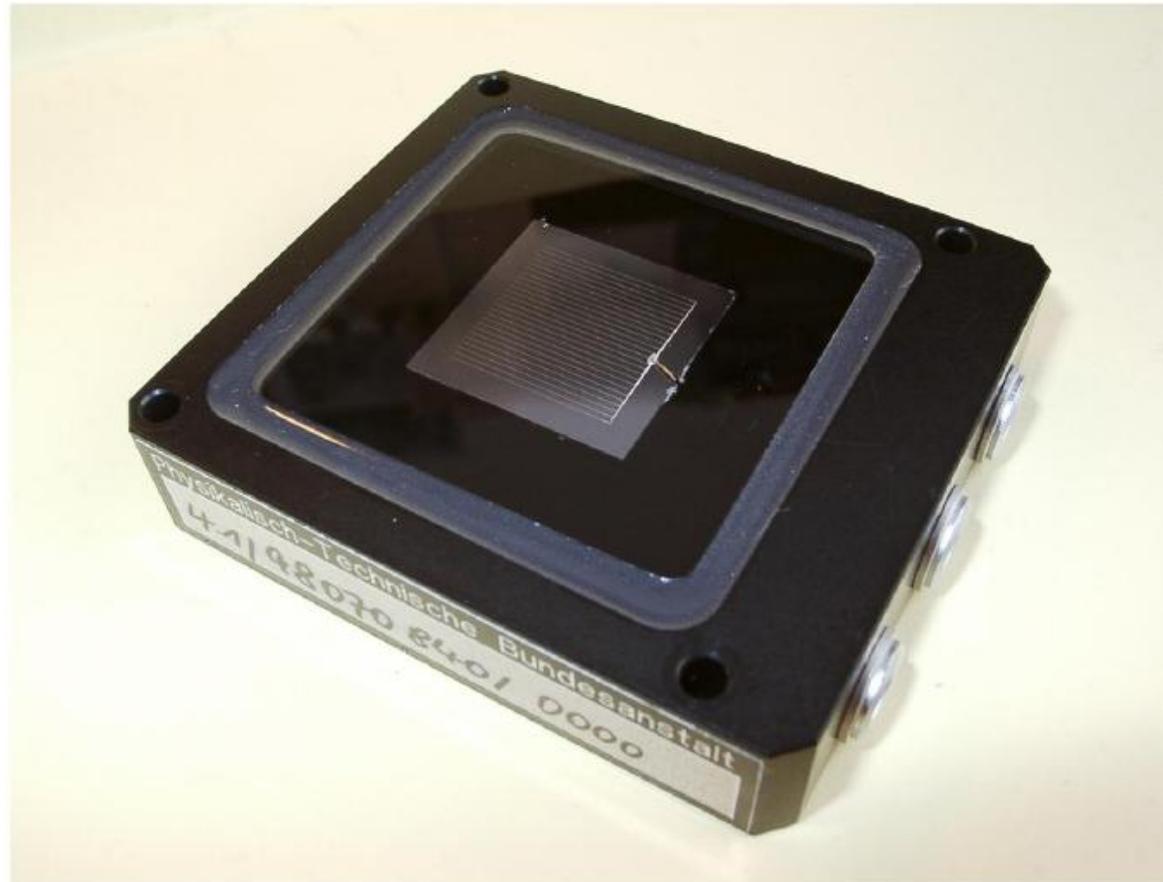


国际电池认证机构

- PTB, Germany
- NREL, USA
- AIST, Japan
- TIPS, China

- 每一个固定的时间周期，四个研究所要进行比对，比对20个原初电池
- 每一个原初电池对于每一个检测机构都是至关重要的
- 原初电池的不确定性应小于 $\pm 1\%$

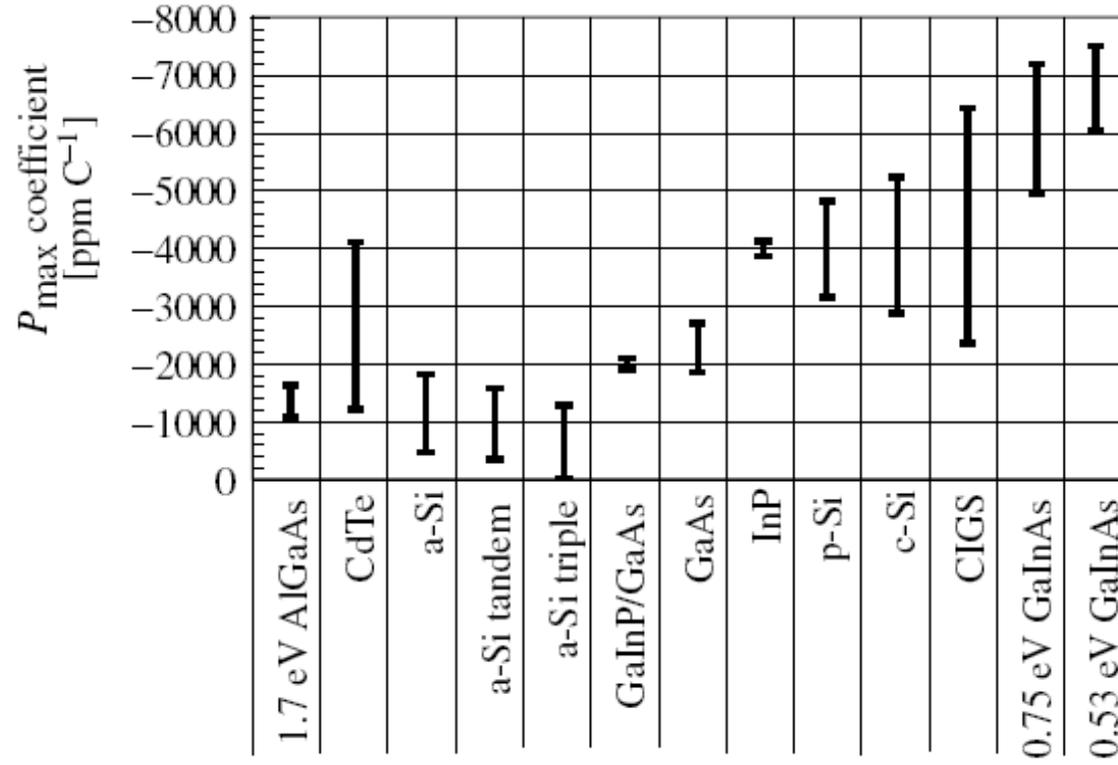
标准电池



标准电池的要求

- £ 电池尺寸和技术
- £ 组件中总的电池数目
- £ 电池互联线路（每个旁路二极管旁路掉的串联电池数、每个串联连接的电池组的并联数）
 - 需要一组参考电池，以匹配不同尺寸的电池
 - 对于不同类型的电池，必须进行光谱失配评估，标定电池的光谱响应有电池生产

各种太阳电池的温度系数



各种太阳电池的温度系数

晶体硅太阳能电池的温度系数

Table 16.5 Typical Si solar cell temperature coefficients [57]

Type	$-V_{oc}$ [ppm/°C]	I_{sc} [ppm/°C]	$-FF$ [ppm/°C]	$-P_{max}$ [ppm/°C]
Si cells & modules	2400–4500	400–980	940–1700	2600–5500

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谢谢