Optimization of Renewable Energy Processes: Projects at the Synchrotron Radiation Facility PETRA III

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Outline

Introduction

Energy consumption
Sustainable energy resources
Energy storage
Advances to be achieved

Synchrotron radiation facilities

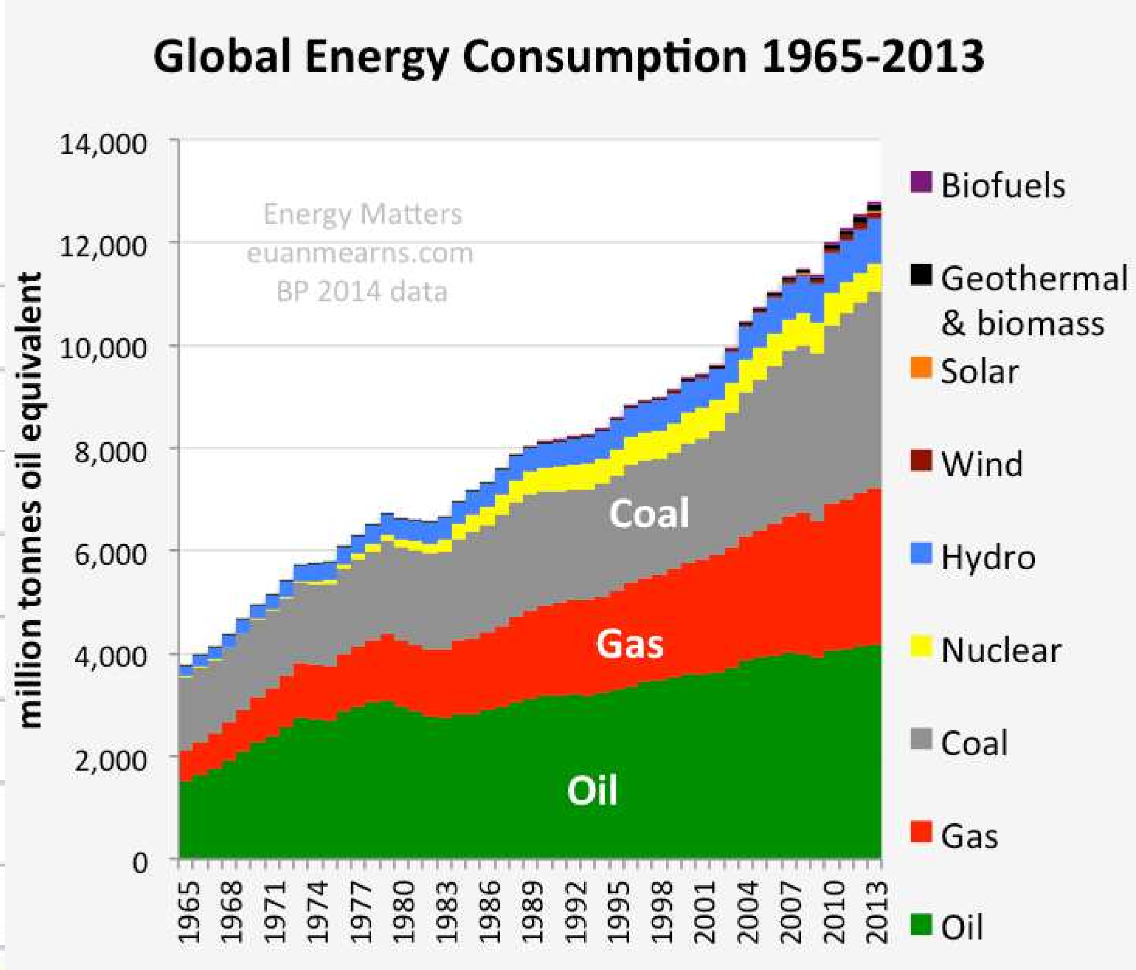
PETRA III

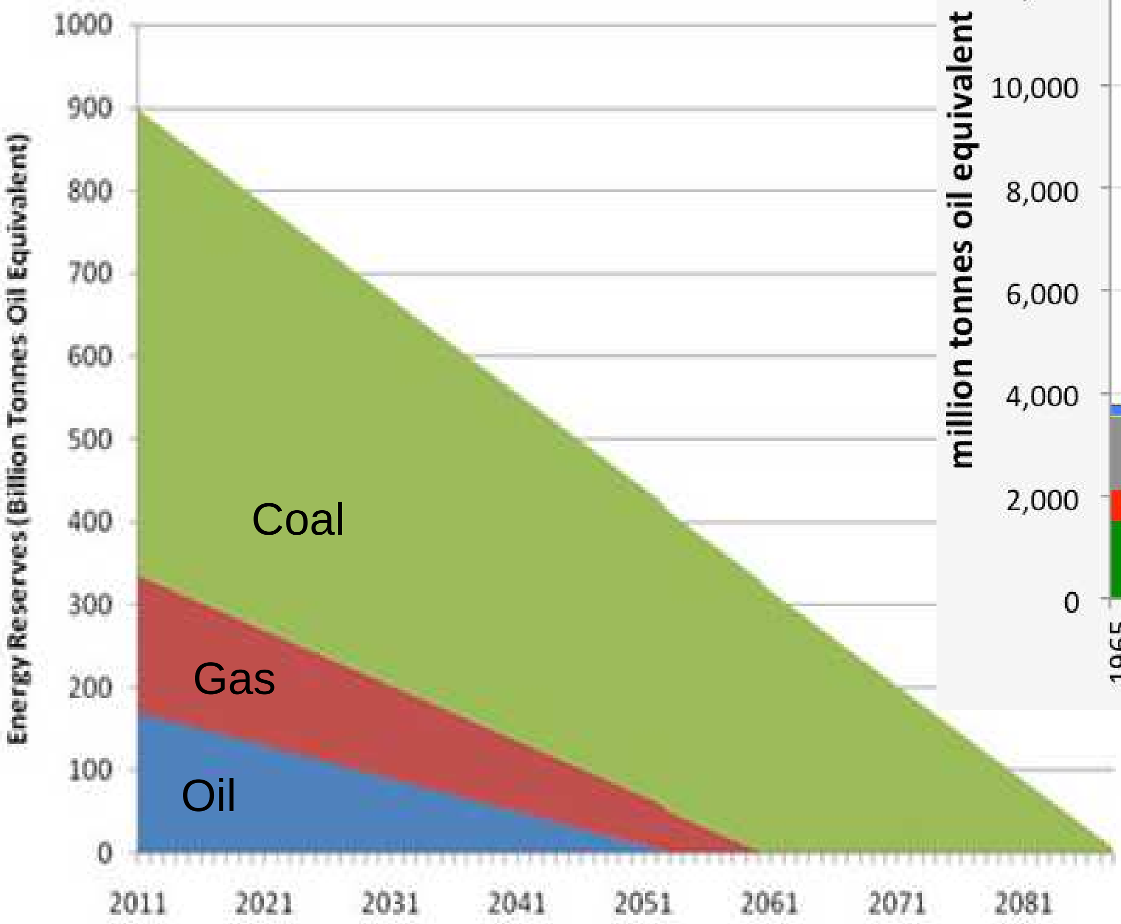
Examples (X-Ray Imaging)

Organic Solar Cells
Lithium Batteries

Worldwide Energy Consumption

Fossil fuels are more and more in use to produce energy





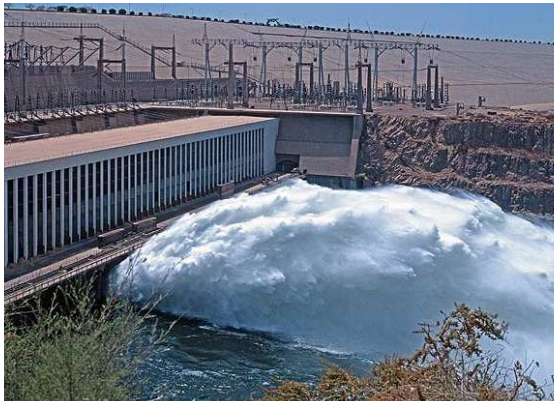
The resources of all fossil fuels are a limited

Fossil fuels create carbon dioxide gas CO_2 which is the origin of the global warming

Varieties of sustainable energy

Hydroelectric plants

Aswan Dam (Egypt)



- Needs a lot of land for the dam lake
- In one state already one plant can produce a significant share of electricity

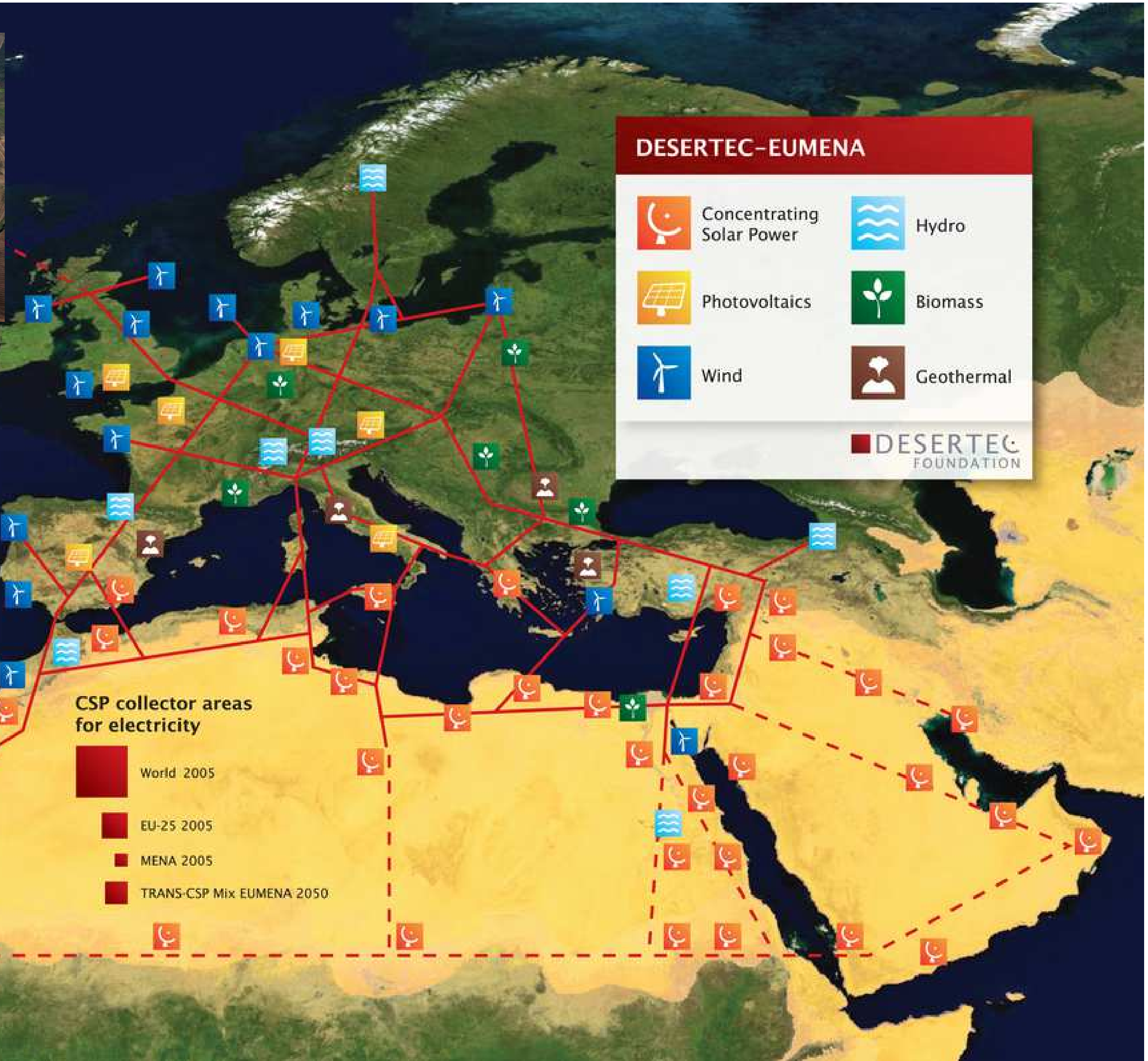
Tarfaya wind farm (Morocco)

Wind farms

- Can be raised delocalized or as farm
- Depend on the wind
- Needs backup power plants or energy storage (no wind)

Sun-based power plants
e.g. DESERTEC project (discontinued)

Gemasolar Concentrated Solar Power (CSP) plant in Seville, Spain.



Solar cells

Droogfontein (South Africa)

- Can be raised delocalized or as farms
- Depends on the sun
- Needs backup power plants or energy storage (night)

Energy storage is eminently important

Direct conversion from sun light to electrical energy

90% of solar cells are made from silicon

Efficiency of 15% - 20%

Cells are quite costly

New development: Organic solar cells

- Efficiency 10%

- Very cheap
- Easy to make
- Flexible design
- Small life time

Batteries

Laurel Mountain wind farm’s storage facility
West Virginia (USA)

Batteries
can be used to store
Electrical energy

- Batteries are still quite expensive

- Have a limited life time

Advancements of solar cell technology and Battery technology are eminently important

On molecular level

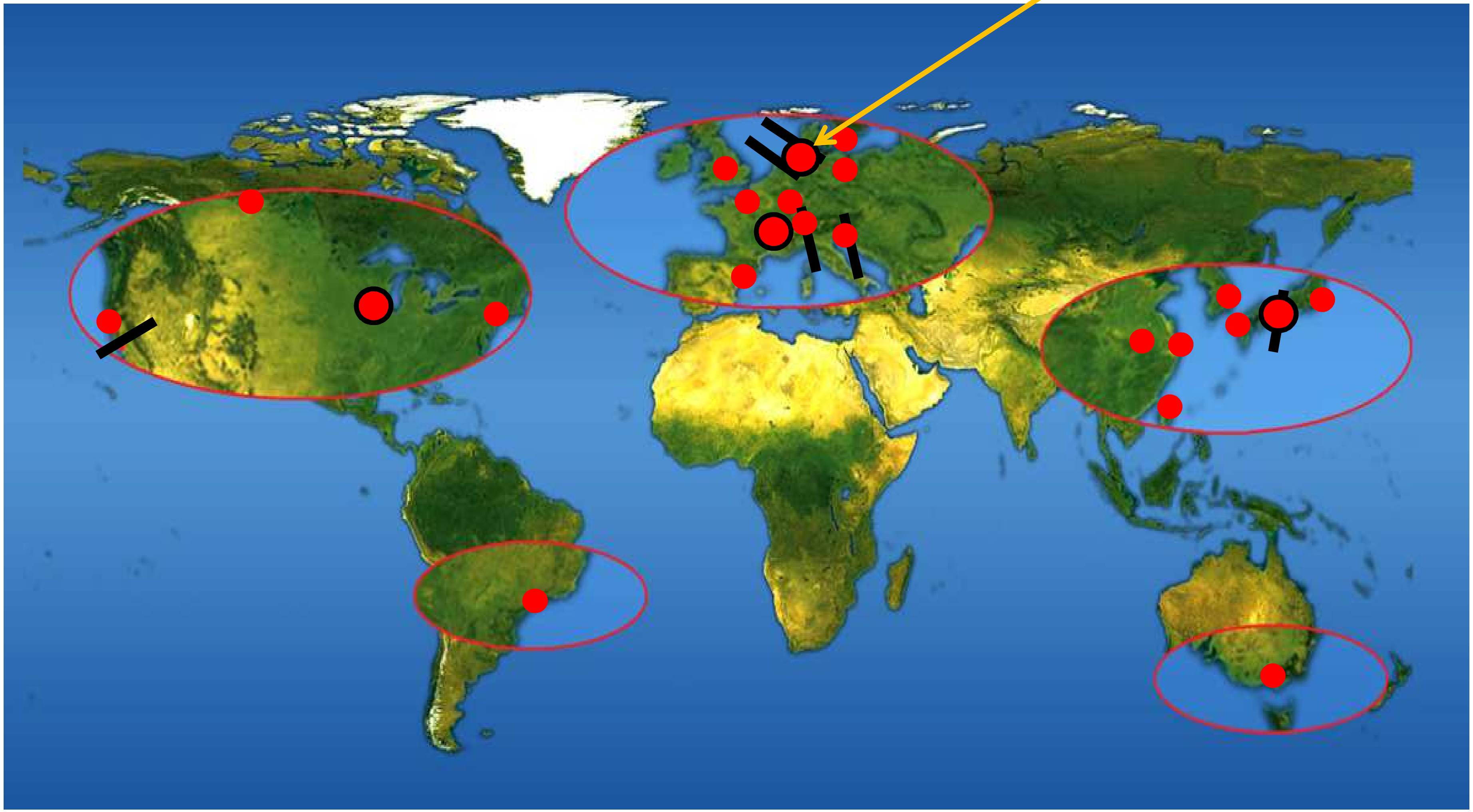
On grain size level

=> Synchrotron radiation sources

Synchrotron radiation sources

PETRA III
Flash (VUV FEL)
European XFEL (coming up)

Some X-ray sources sources



● low energy sources < 4GeV

● high energy 3rd generation sources > 4GeV

x-ray lasers

PETRA III: DESY's Brilliant Hard X-Ray Source

> **particle energy:**	6 GeV
> **stored current:**	100 mA (top-up)
> **emittance:**	1.2 nmrad
> **circumference:**	2304 m
> **# of undulators:**	25 (incl. canted)
> **# of experiments:**	50
> **X-ray wavelength:**	10 – 0.05 Å
> **annual operation:**	5000 h (for users)

> **built in 1978**

> **rebuilt as a synchrotron radiation source starting in 2007**

> **user operation since 2010**

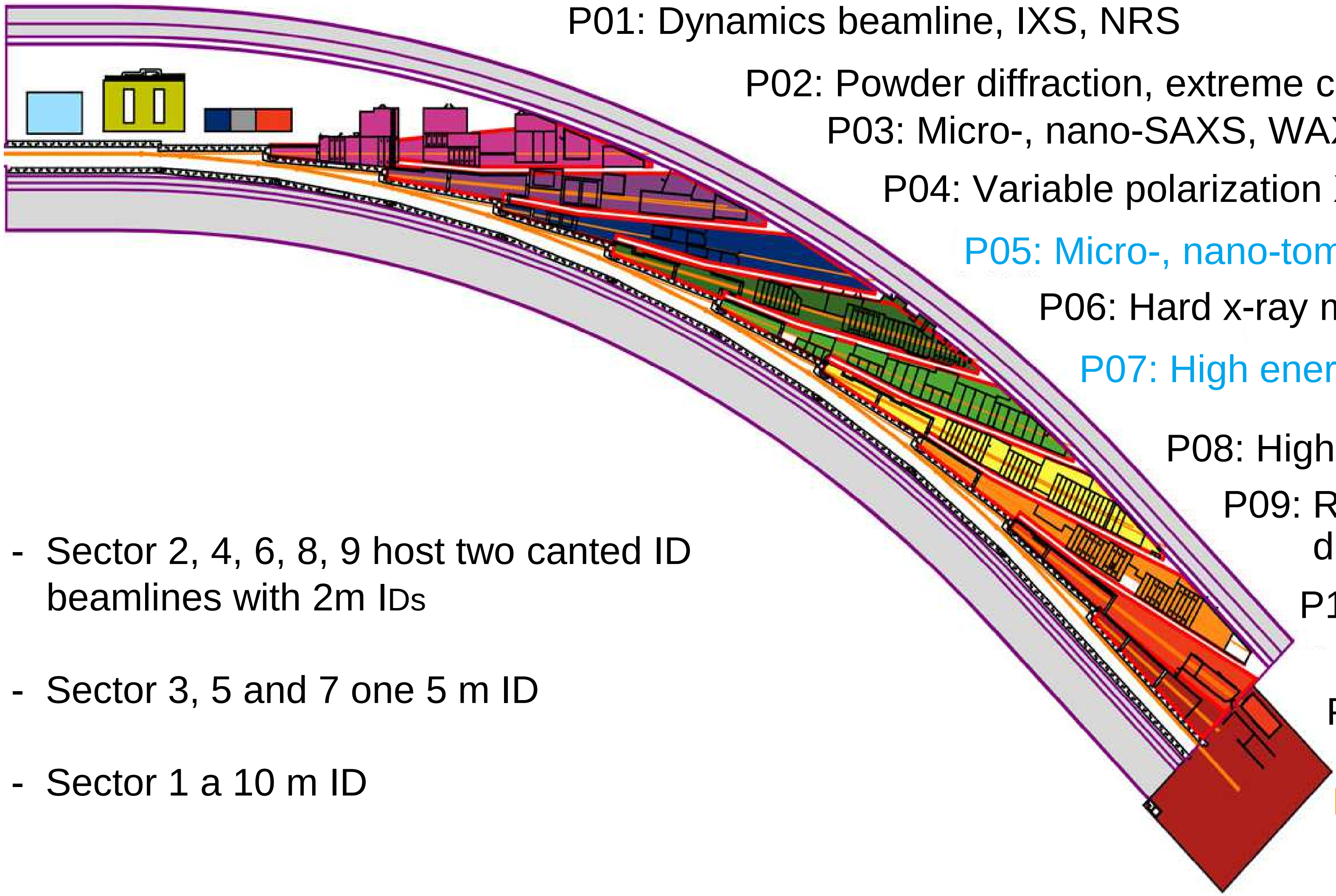
> **start of upgrade: March 2014**

> **restart of user operation: April 2015**

> **First beam in PETRA III extension : October 2015**

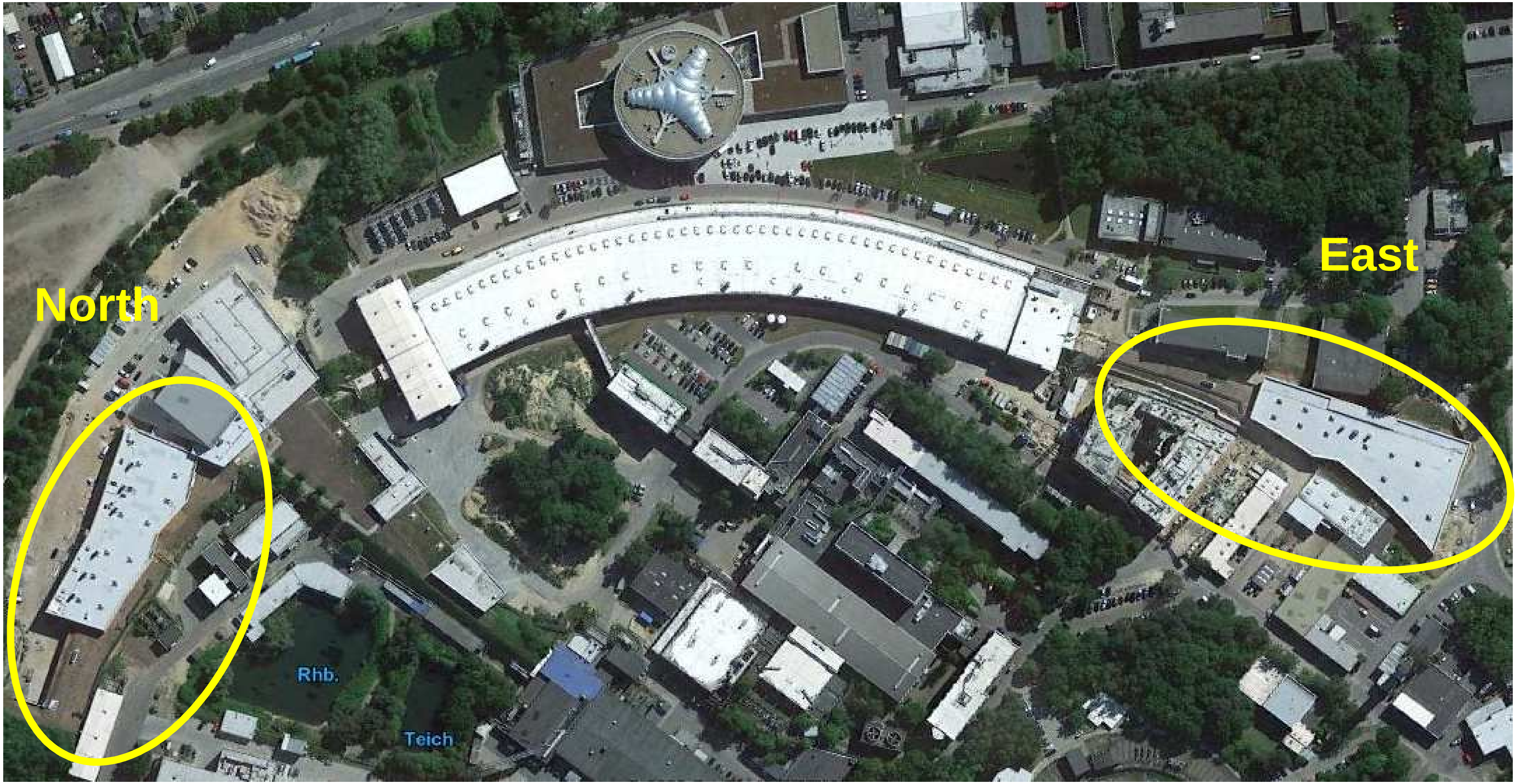
Max von Laue Hall: 9 Sectors – 14 Beamlines

Run by EMBL
Run by HZG



- Sector 2, 4, 6, 8, 9 host two canted ID beamlines with 2m IDs
- Sector 3, 5 and 7 one 5 m ID
- Sector 1 a 10 m ID

PETRA III Extension : Two further halls



PETRA III Extension : Hall North

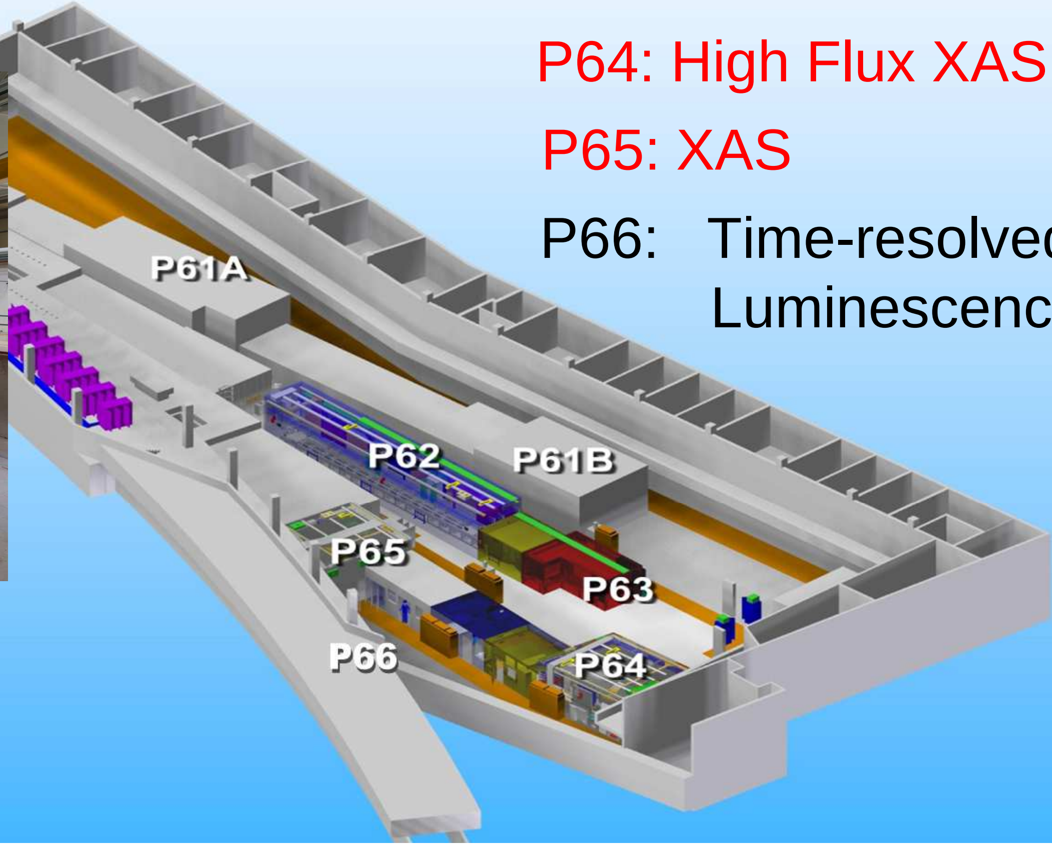
P61: High-Energy X-ray Engineering Materials Science (DESY&HZG)

P62 & P63: SAXS & Pink Beam (tentative)

P64: High Flux XAS

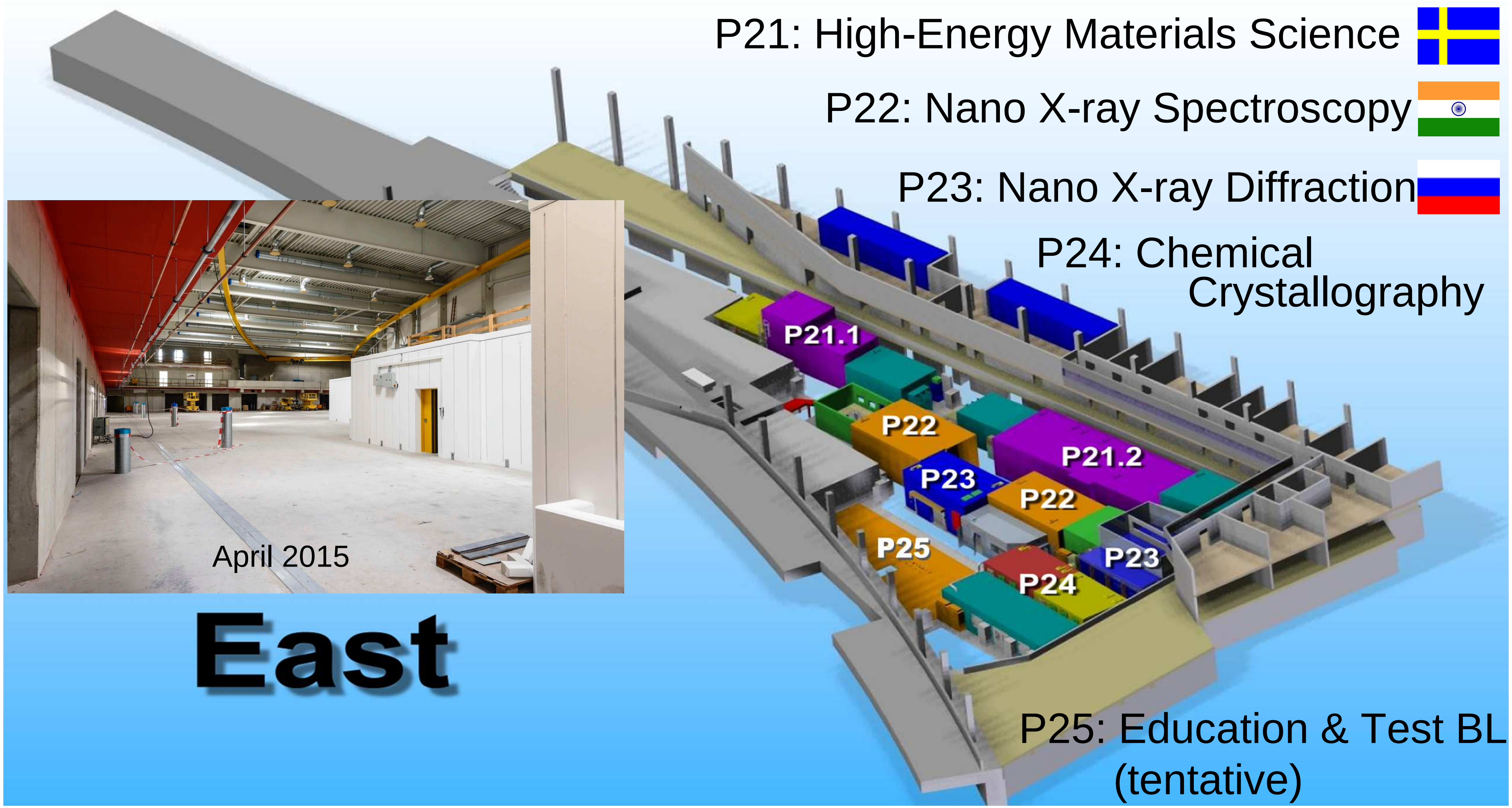
P65: XAS

P66: Time-resolved Luminescence



North

PETRA III Extension : Hall East

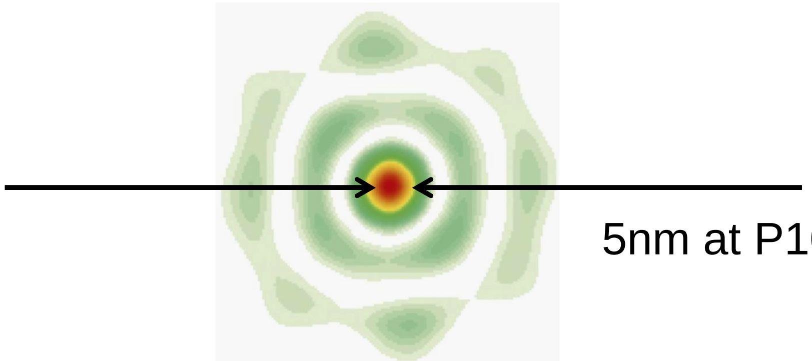


X-Ray beam parameters at PETRA III

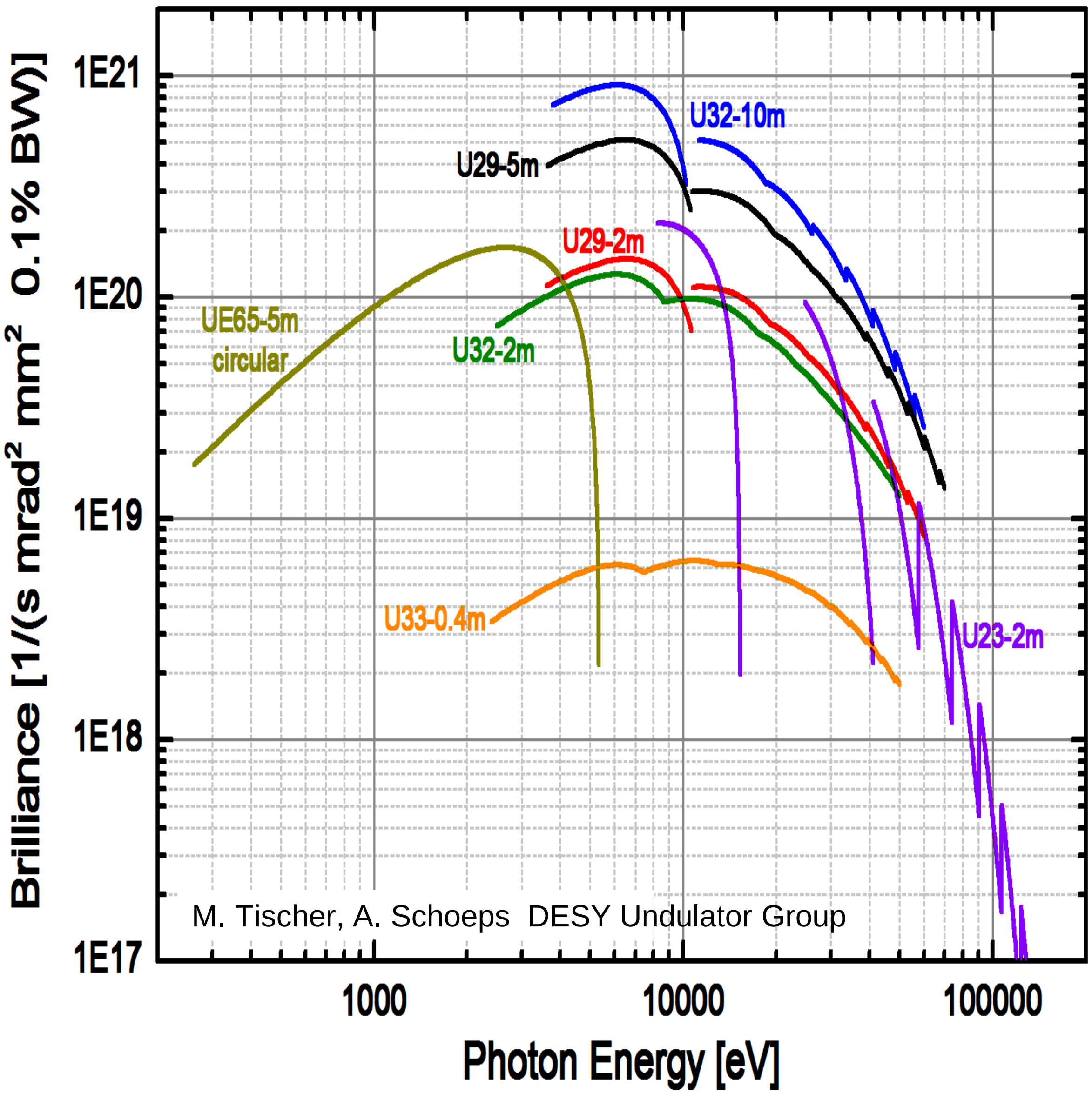
Low-β sector (hor. x ver. RMS):		
β function	approx.	1.3x3 m^2
Source size		35x6 μm^2
Source divergence		28x6 μrad^2
High-β sector:		
β function	approx.	18x3 m^2
Source size		140x6 μm^2
Source divergence		8x6 μrad^2
Photon flux at $\Delta E/E = 10^{-4}$		
Coherent flux		10^{11} ph/sec
Full beam		$3 \cdot 10^{13}$ ph/sec

Extraordinary beam parameters

$\Rightarrow$ X-ray beam focus can be as small as 5 nm

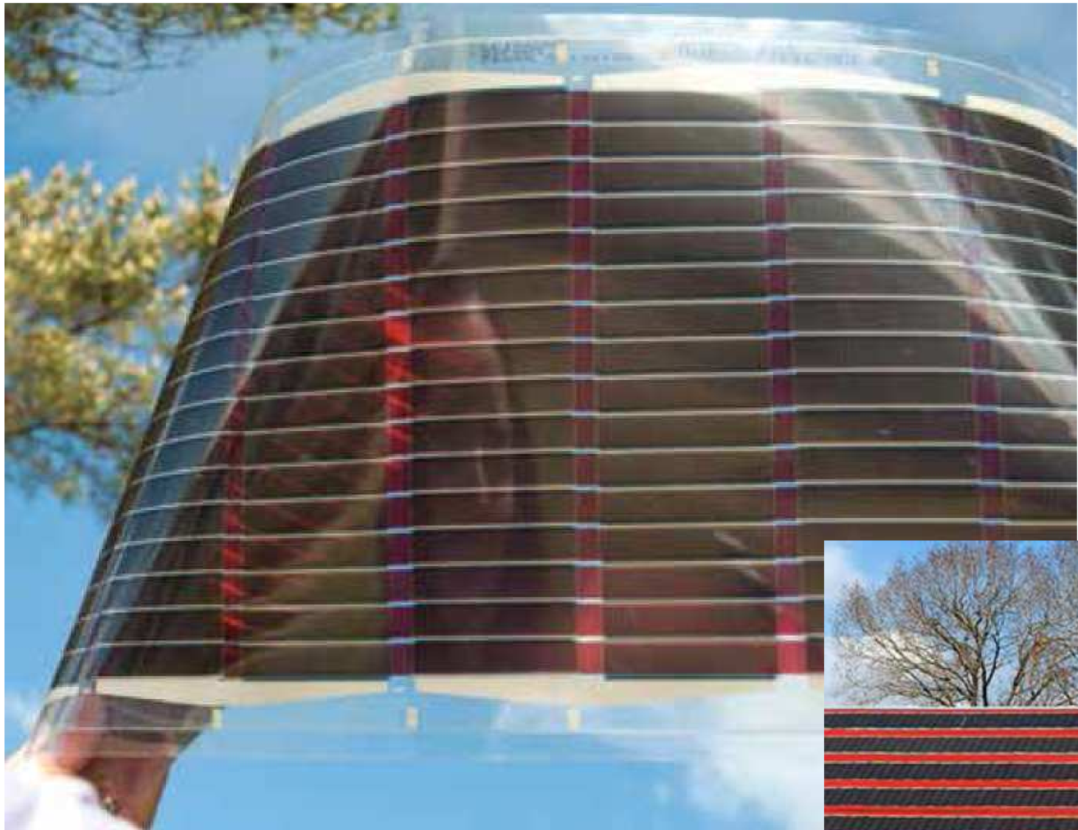


5nm at P10



Organic Solar cells @ PETRA III

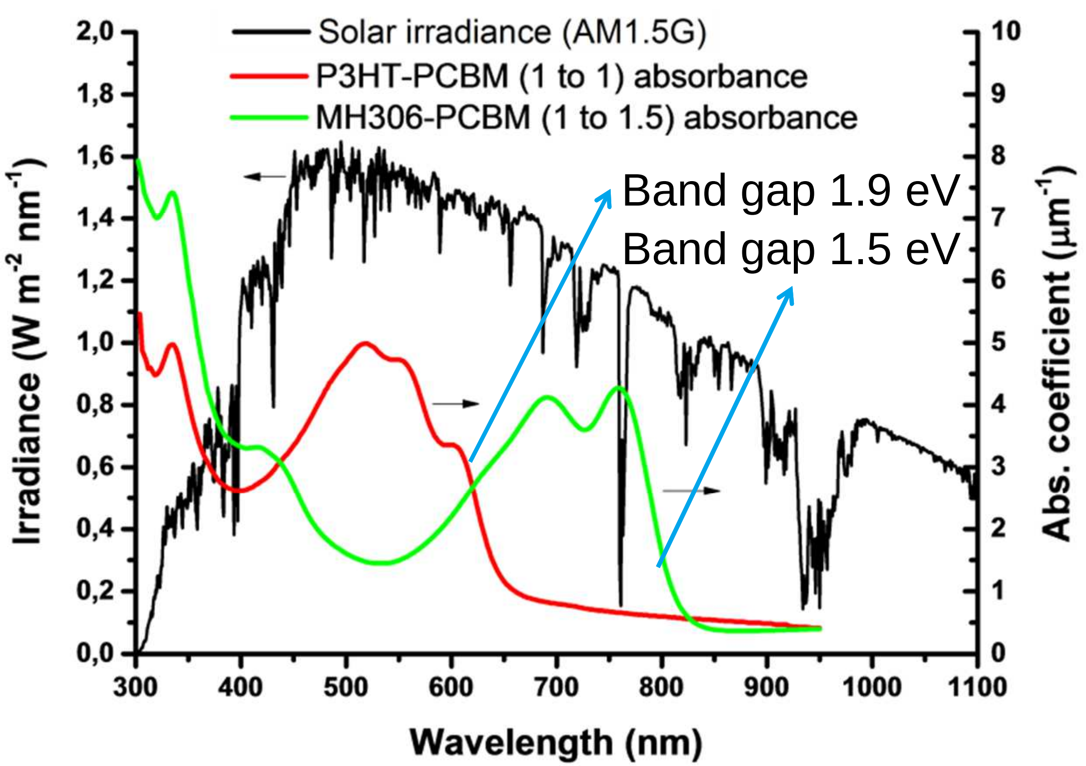
The Danish Technical University runs projects on organic solar cells

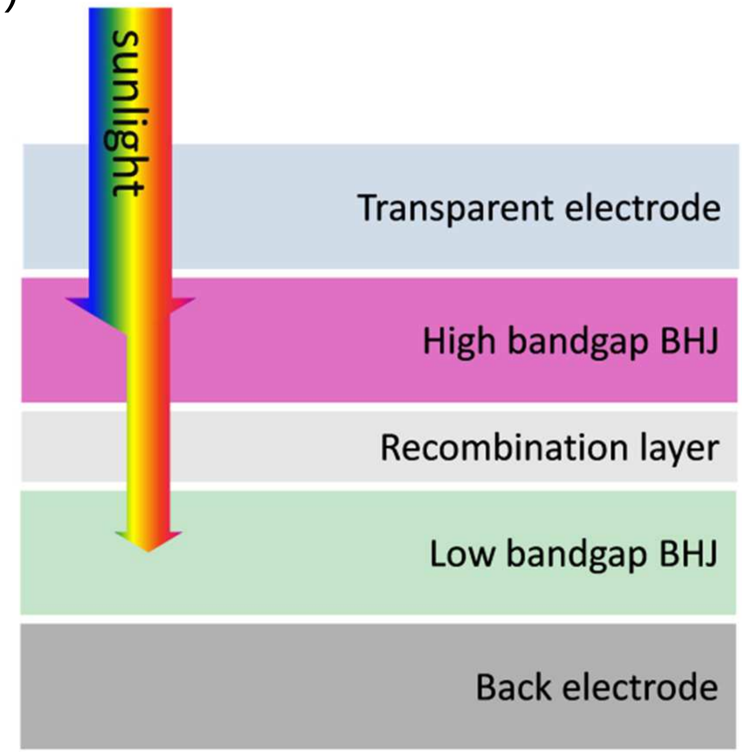


Jens Wenzel Andreasen (DTU)

Enabling Flexible Polymer Tandem Solar Cells

Figures: Jens Wenzel Andreasen (DTU)



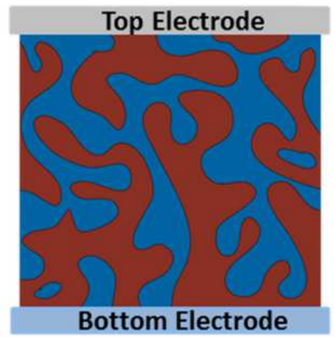


www.plasticphotovoltaics.org

Power Conversion Efficiency

- Single junction: PCE < 10% (module, ~ 3%)
- Conventional silicon: PCE ~ 20%

Multi junctions for better coverage of the solar spectrum

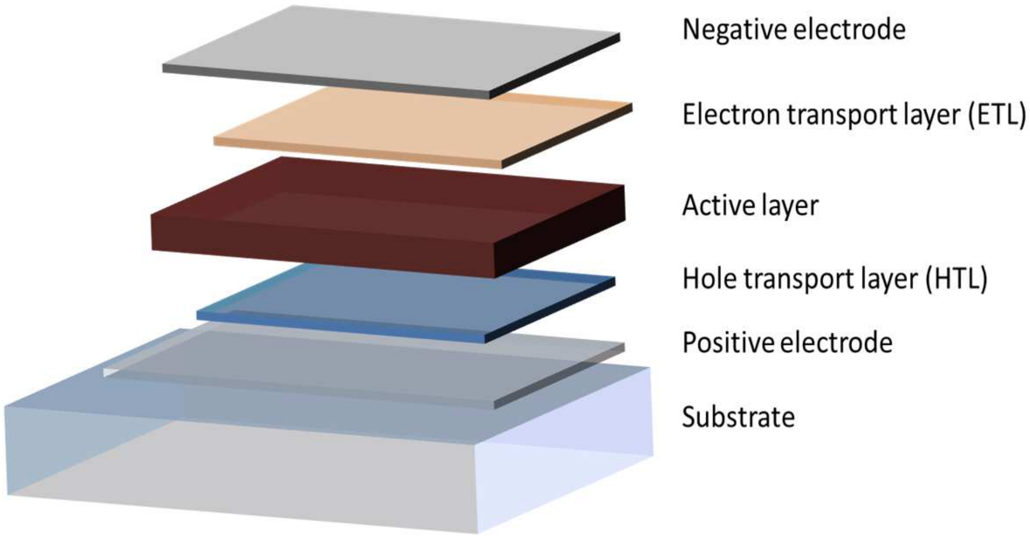


Bulk Heterojunction

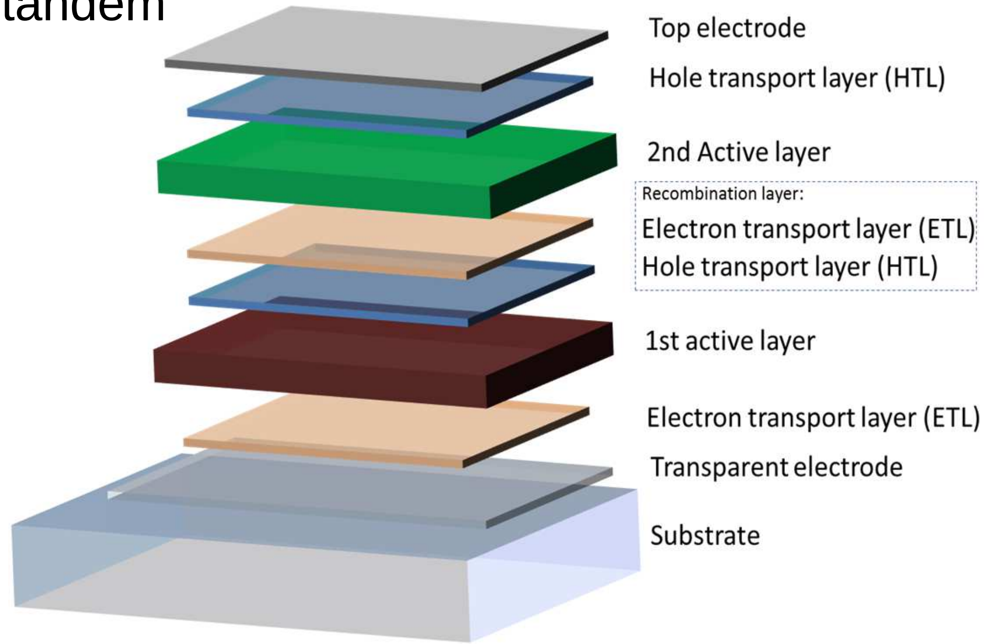
H. F. Dam, et al., Adv. Energy Mater. **5**, 1400736 (2015).

Enabling Flexible Polymer Tandem Solar Cells

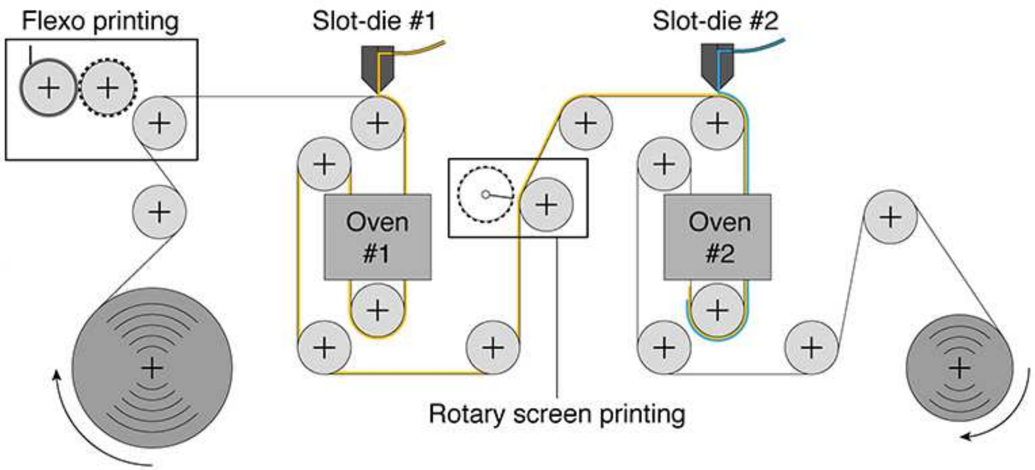
Single junction



tandem



Roll-to-roll processing:

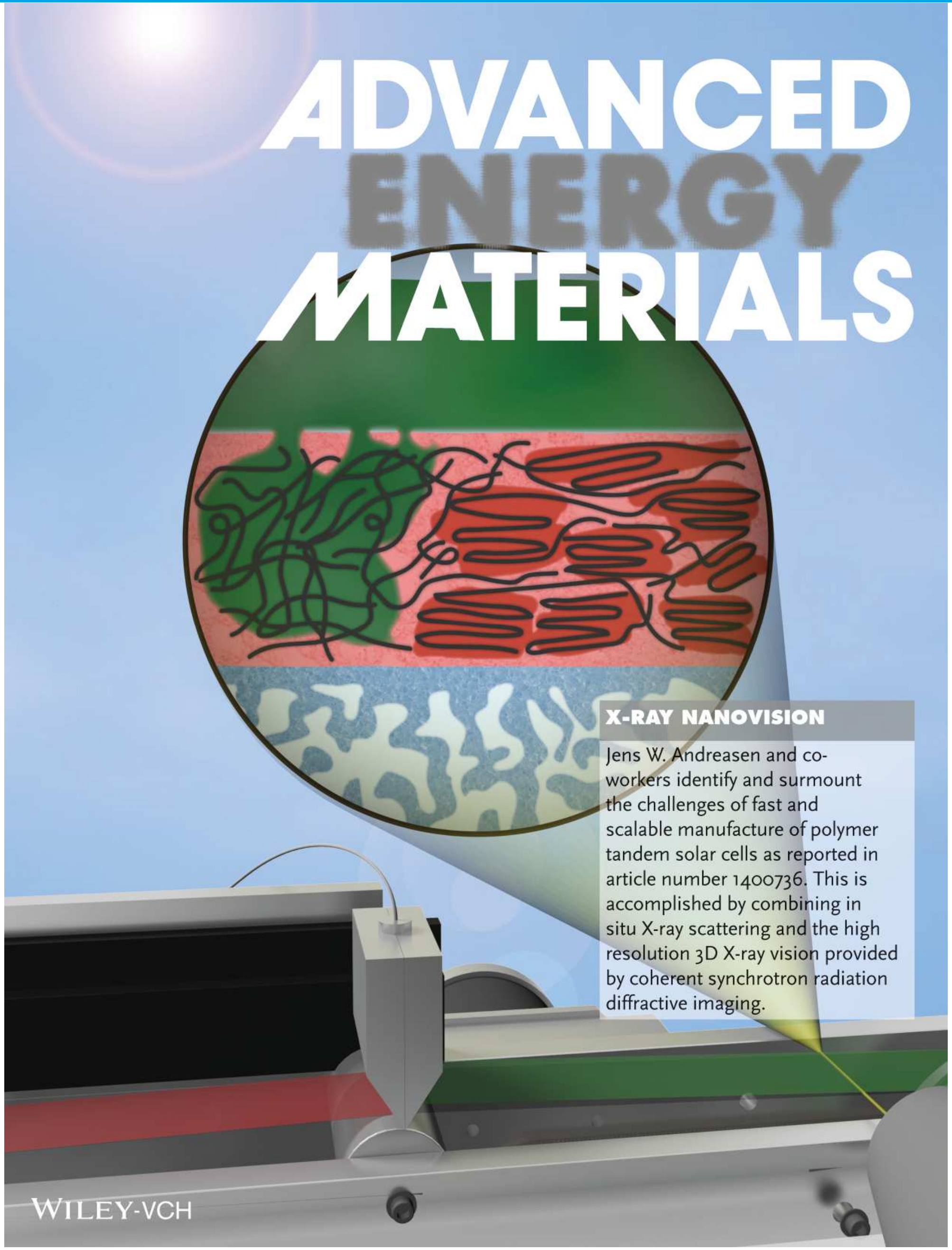


R2R processing

- cost-efficient
- large scale
- homogeneous mulitlayer (10-14 layers)
- difficulty: dissolving layers by subsequent coating
- separation layer: ZnO (40 nm thickness)

Jens Wenzel Andreasen (DTU)

Enabling Flexible Polymer Tandem Solar Cells



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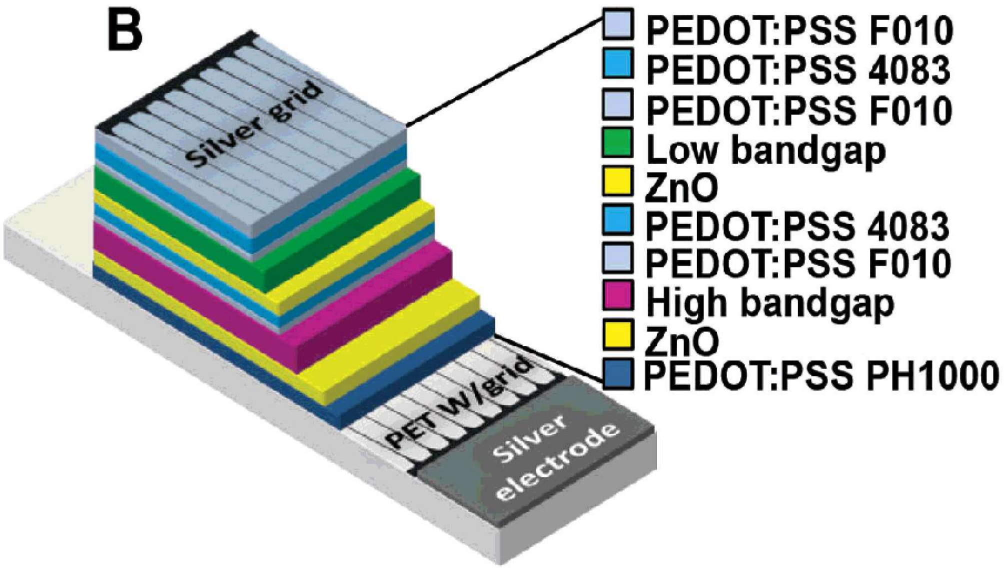
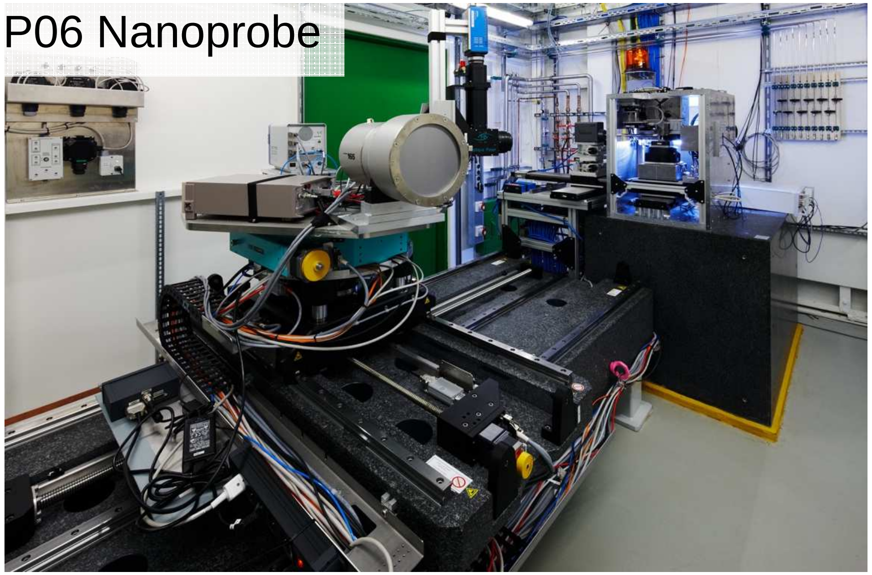
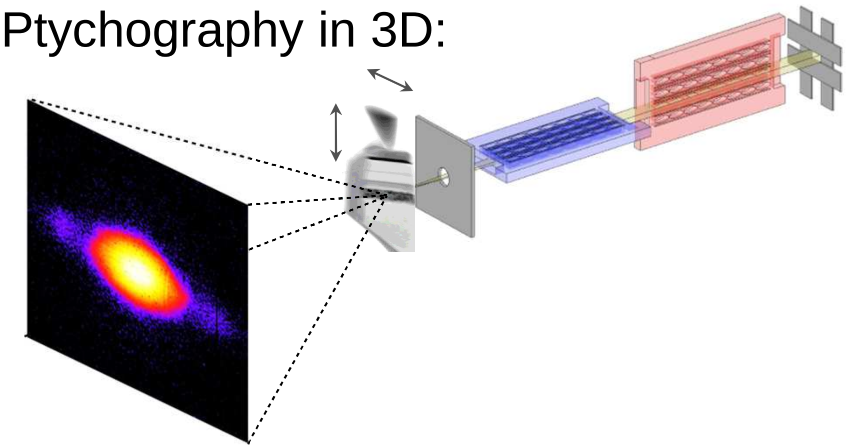


X-ray Imaging of the Tandem Solar Cell

P06 Nanoprobe



Ptychography in 3D:

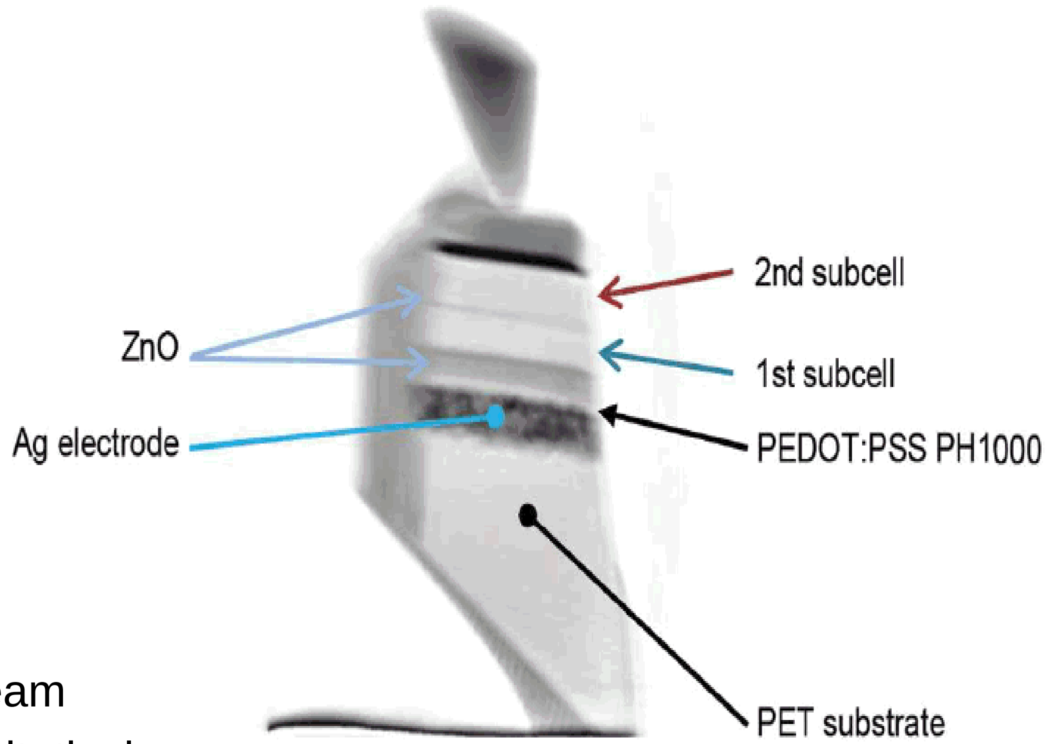


- Scan sample with nanofocused coherent beam
- Reconstruct absorption and refraction quantitatively

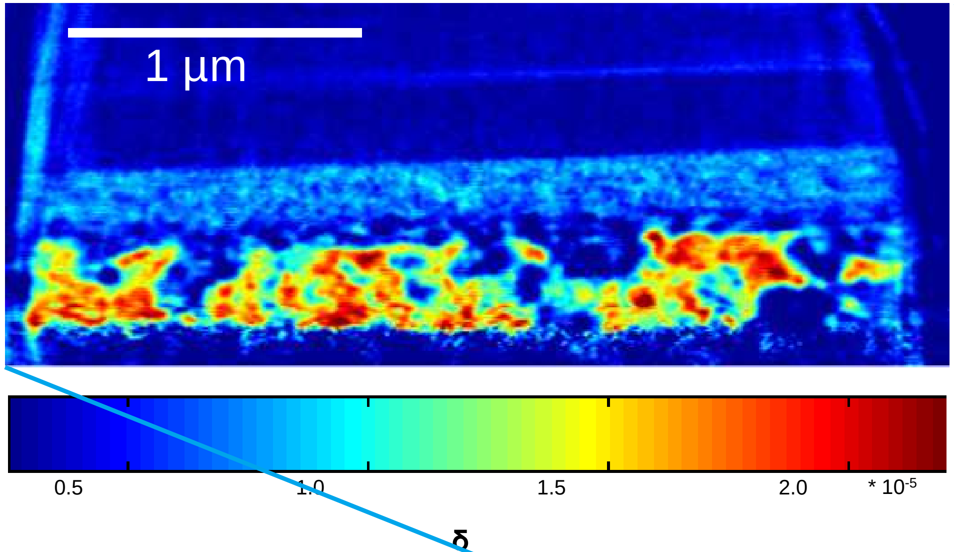
H. F. Dam, et al., Adv. Energy Mater. **5**, 1400736 (2015).

Applied to solar cell:

- verify integrity of separation layer on small sample
- field of view: 4 x 6 µm^2
- 90 projections in 36 h



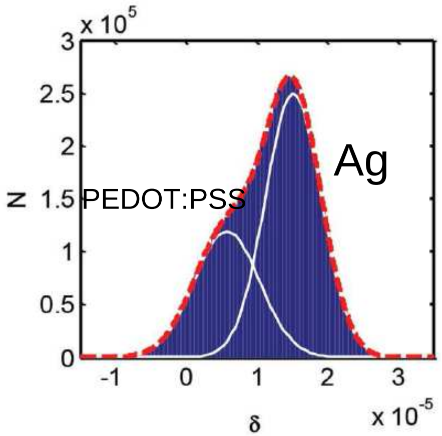
Enabling Flexible Polymer Tandem Solar Cells



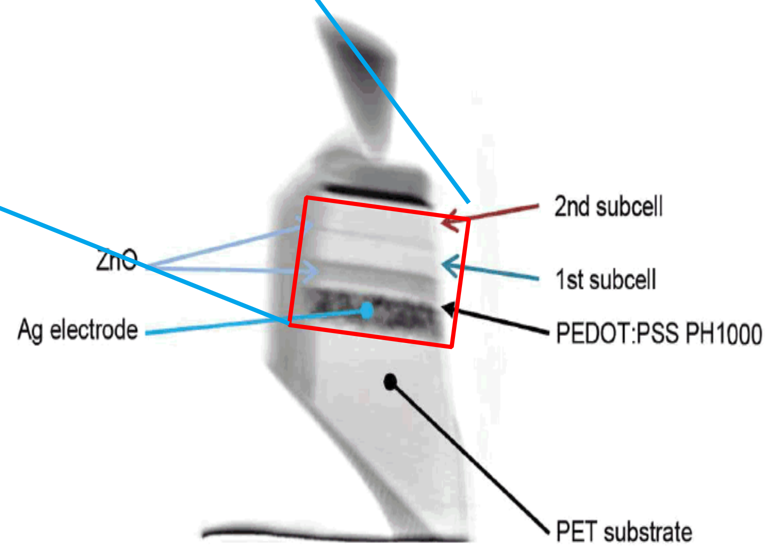
- verify integrity of ZnO layer:
- electron transport layer well defined and just 40 nm thick

- determine structure of silver electrode:

The rough and porous Ag electrode is efficiently infiltrated by conducting polymer forming a smooth surface for coating of the subsequent layers



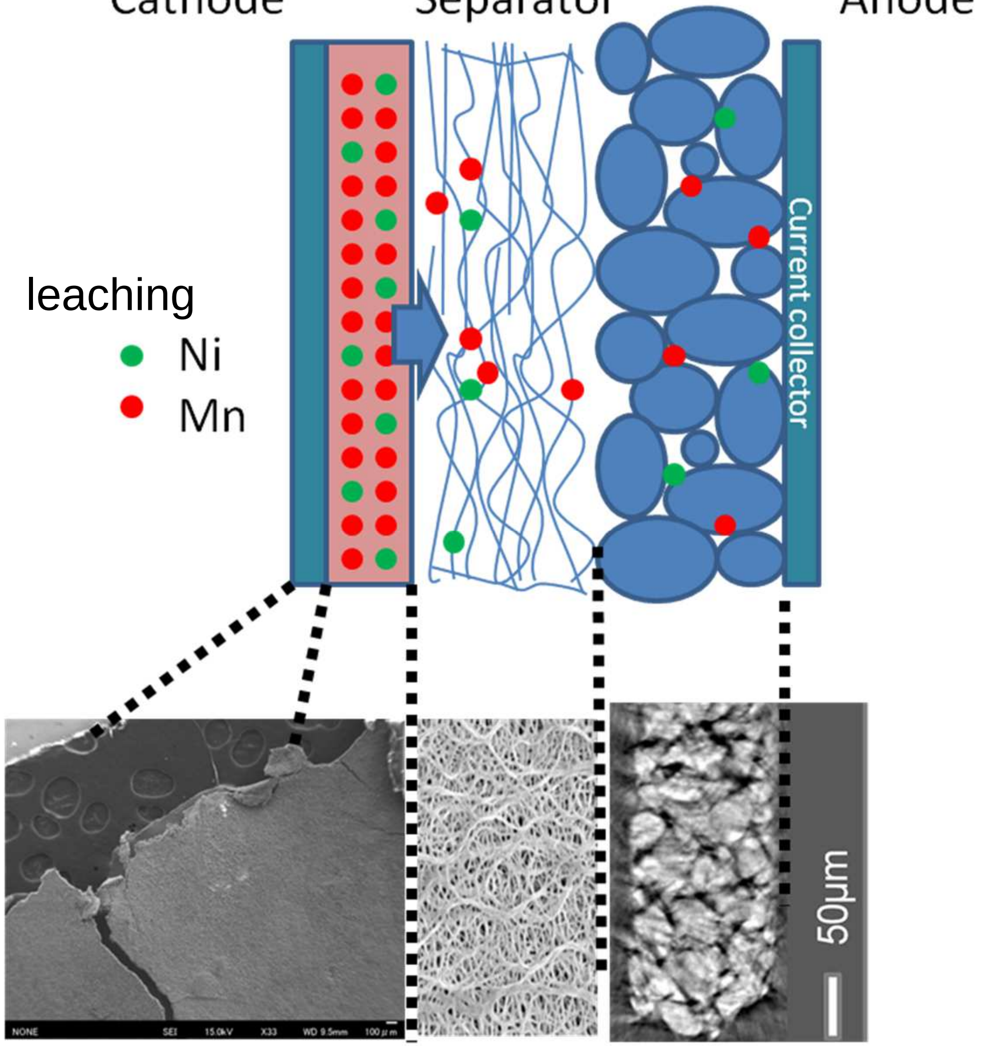
refractive index histogram for porous Ag electrode:



Verify roll-to-roll production process

H. F. Dam, et al., Adv. Energy Mater. **5**, 1400736 (2015).

Battery science @ PETRA III



Tsuji, Fittschen unpublished

Shearing et al. EC 2010

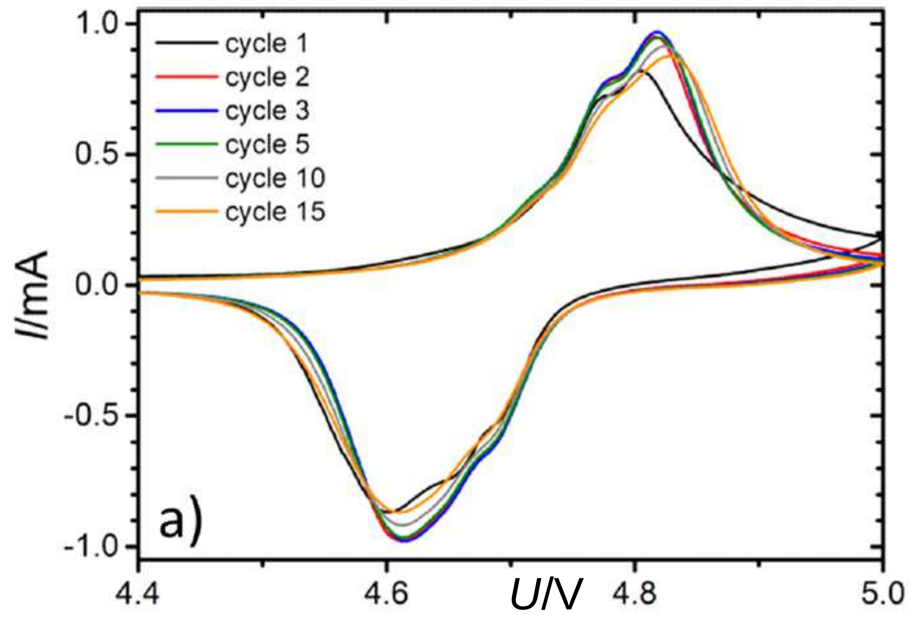
New type of high-voltage chargeable lithium battery:

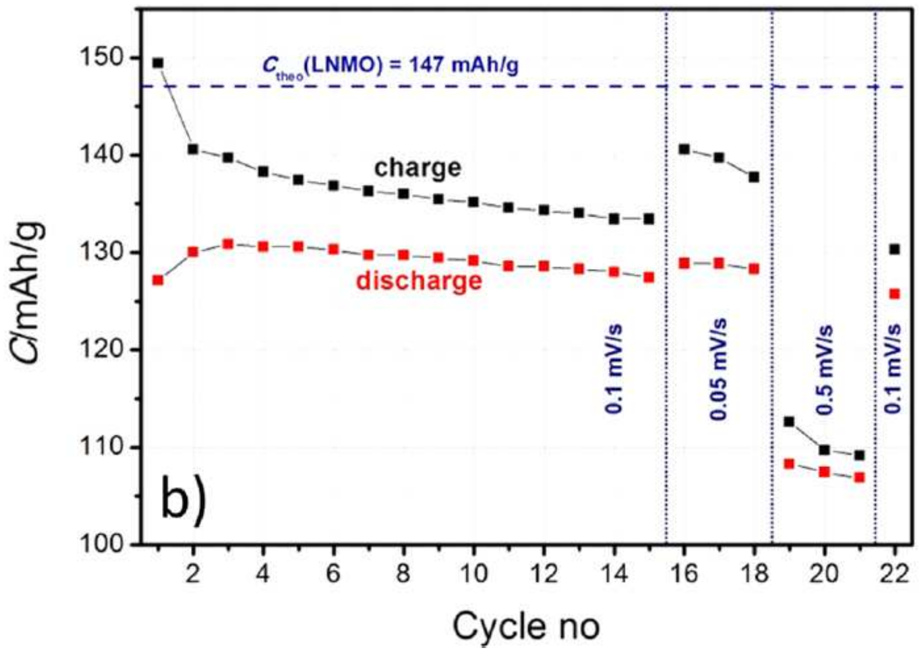
$LiNi_{0.5}Mn_{1.5}O_4$ (LNMO) Spinell
Operation potential : 4.7V

Standard Li batteries ($LiCoO_2$): 3.5 V

Disadvantage right now:
- Capacity fade
- Limited life time

Properties of LNMO cells





Cyclic voltammetry at
0.1 mV/s at room temperature

Charging : Ni2+/4+ oxidation at 4.8V

Discharging : Ni4+/2+ reduction at 4.6 V

Capacity fade for different
charge rates

- The capacity is generally fading out
- The capacity changes with charge rate

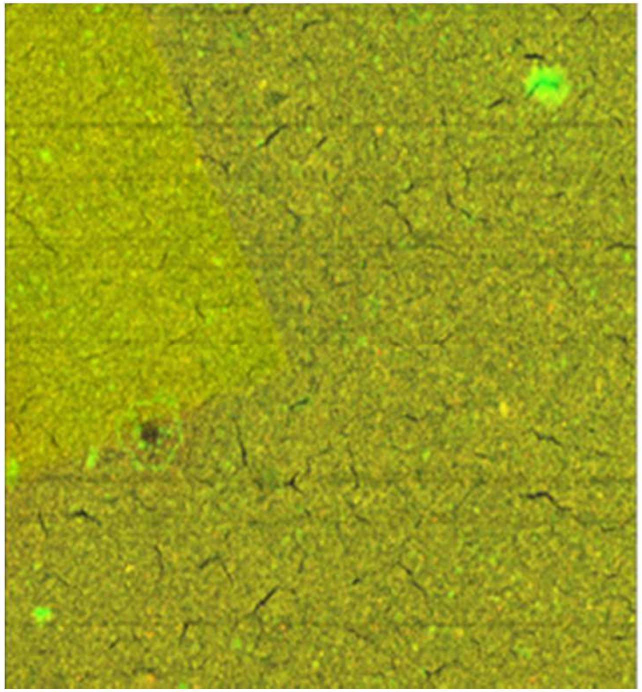
Mechanisms ?

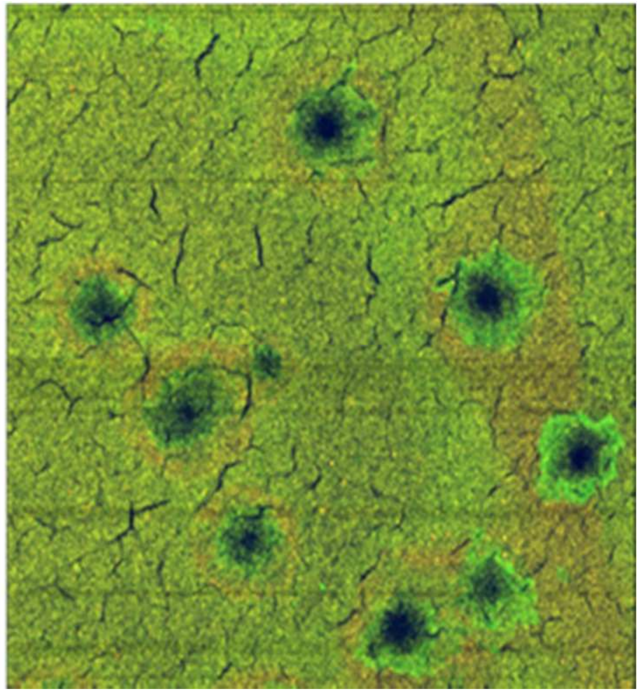
2-dim X-ray Fluorescence Imaging (0.5µm x 0.5µm resolution)

slow	medium	fast
0.005mV/s	0.05mV/s	0.5mV/s

RGB maps

Red	Mn
Green	Ni
Blue	transmission

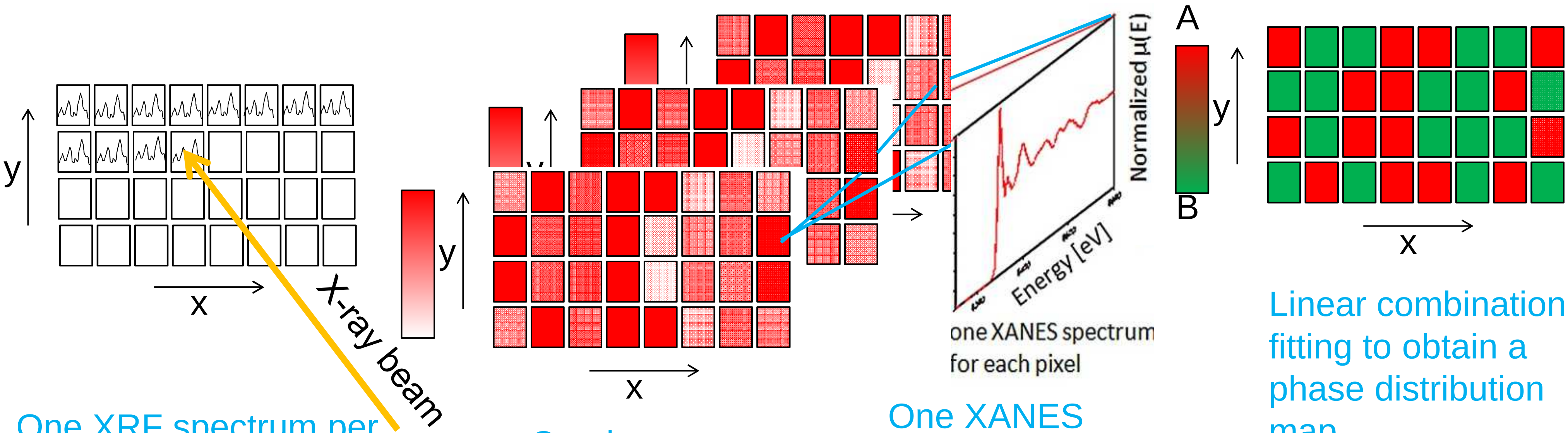




2mm

- After cycling pronounced “hot-spots” on the electrodes
- Higher cycling rates favor formation of “hot-spots”, cracks and holes.
- Holes are surrounded by nickel

2-dim XANES Imaging

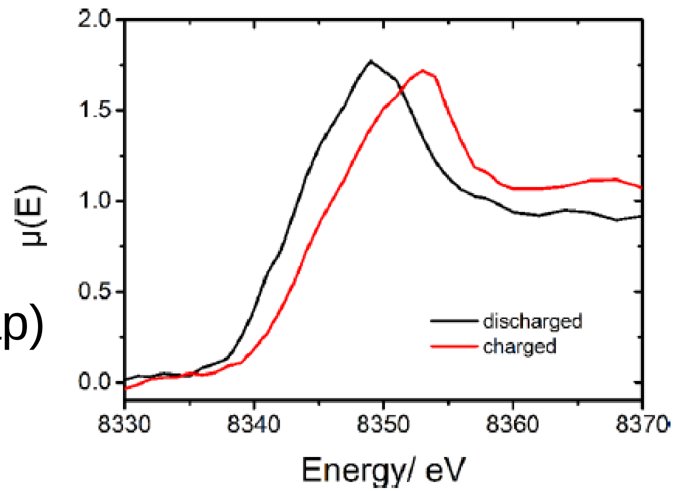


One XRF spectrum per pixel

One image per energy

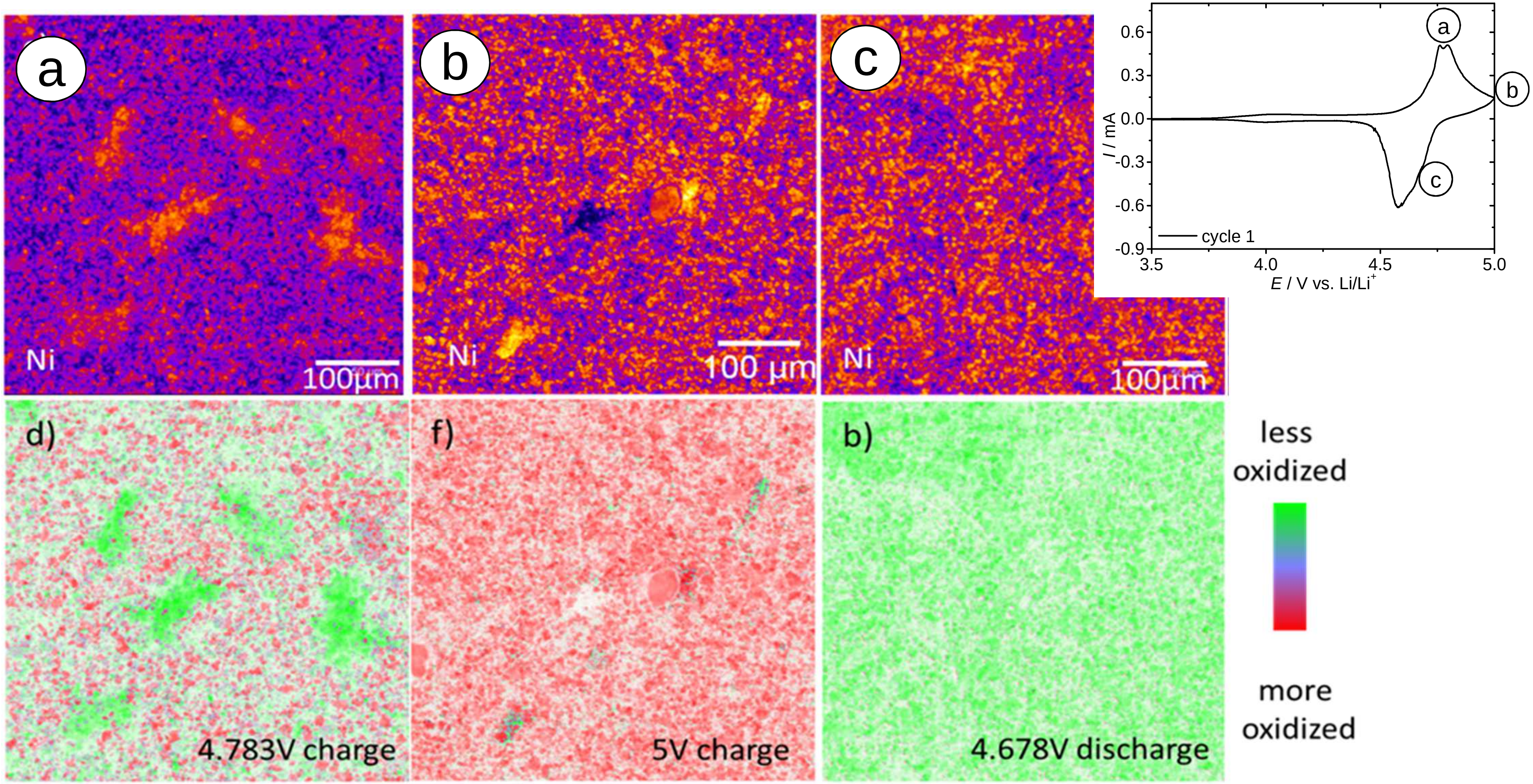
One XANES spectrum for each pixel

Linear combination fitting to obtain a phase distribution map



- Measurements at 53 energies in the vicinity of the Ni-K edge
- An area of 2x2mm covered with 500nm resolution (15min/map)
- Extracting the Ni map for each energy
- Create a XANES spectrum for each pixel
- Linear combination fitting using standards collected from pristine and cycled electrode.

2-dim XANES Imaging at the Ni-K edge



Ni „hot-spots“ show hampered kinetics,
=> do not participate in the redox reaction at 4.8V
=> At higher voltage looks fully oxidized

Summary

X-ray imaging techniques are powerful tools

- 20 Nanometer resolution for ptychography
- 500 Nanometer resolution for Fluorescence and XANES imaging

X-ray imaging techniques help

- To understand the process parameters of creating organic solar cells
- To view the processes of redox reactions in batteries

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Solar Cells

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