New developments photons: High brightness sources
“Diffraction-limited Storage Rings”

C. Quitmann et many al.

MAX IV Laboratory, Lund, Sweden

MAX IV

“Diffraction-limited Storage Rings”

- Why?

Diffraction limit: $\varepsilon_r = \frac{\lambda}{4\pi}$ or $\frac{\lambda}{2\pi}$, Emittance: ε_0

$$B_{avg} = \frac{F(\lambda)}{(2\pi)^2} \cdot \frac{1}{\varepsilon_r(\lambda) \oplus \varepsilon_x(e^-)} \cdot \frac{1}{\varepsilon_r(\lambda) \oplus \varepsilon_y(e^-)}$$

$$\varepsilon_x = \frac{1}{1+k}\varepsilon_0(e^-) \qquad \varepsilon_y = \frac{k}{1+k}\varepsilon_0(e^-)$$

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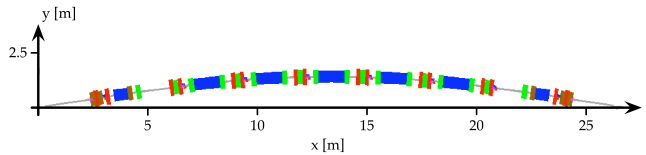
- How?



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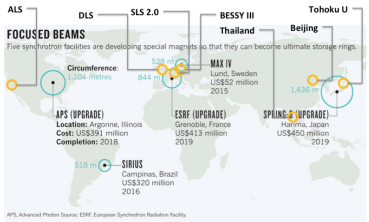
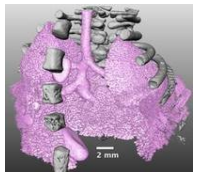


- Future science at DLSR’s



- MAX IV

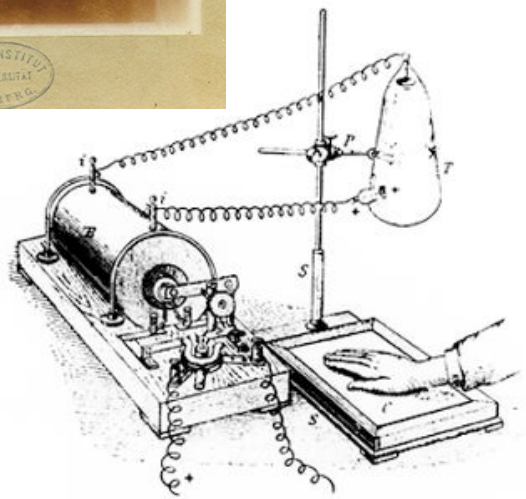
MAX IV Team

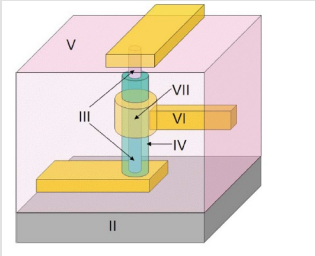
Literature:

Eds.: *J.F. van der Veen and M. Eriksson*

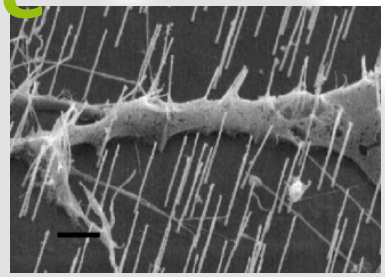
J. Synchrotron Rad. (2014). 21, Special volume: DLSR

X-Rays make the invisible visible

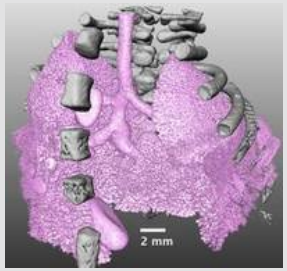




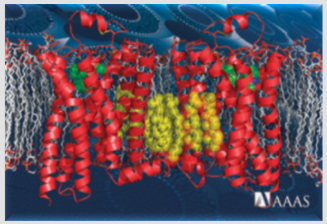
operando



Spectro-/Microscopy



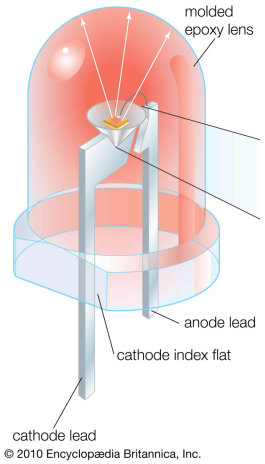
in-vivo & soft tissue

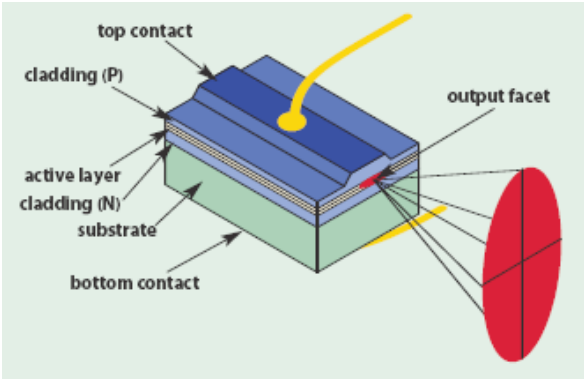


μ-crystals

Higher Brightness – What does that mean?

$$Brightness = \frac{Intensity}{Energy\ bandwidth * Area * \ Angle^2}$$





Area: mm^2
Angle^2: 4π
$\Delta E/E$: ≈ 1

Area: 10^{-3} mm^2
Angle^2: $\approx \pi$
Bandwidth: 25nm/500nm

Area: 10^{-6} mm^2
Angle^2: $\approx$
Bandwidth: 10^{-10}

Vacuum chamber of the 1947 GE synchrotron

Area: $< 10^{-3}$ mm^2
Angle: $\approx 10^{-7}$
Bandwidth: 10^{-2} - (10^{-8})

MAX IV

Higher Brightness – What does that mean?

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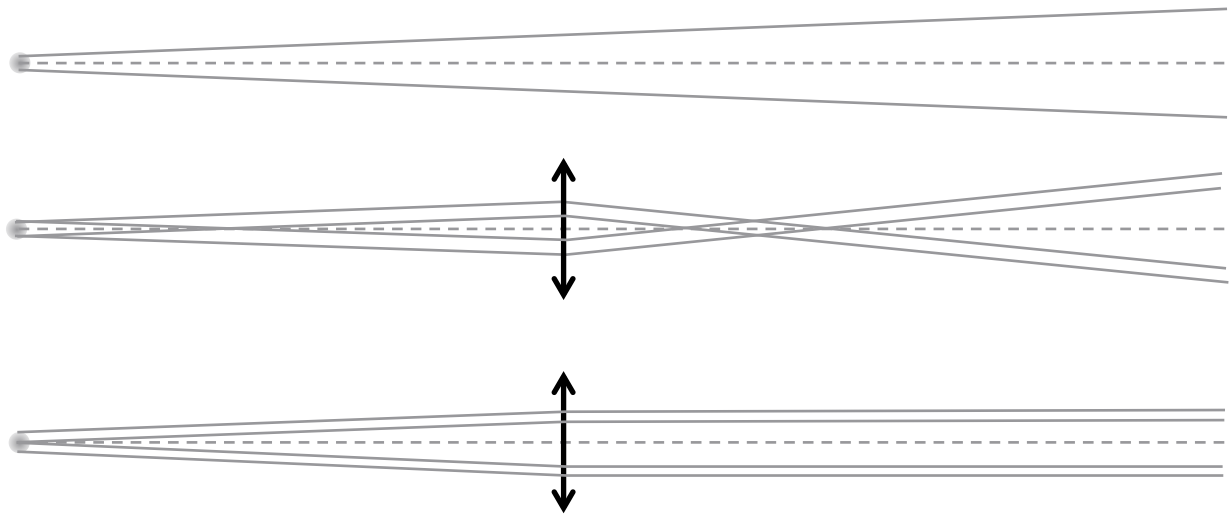
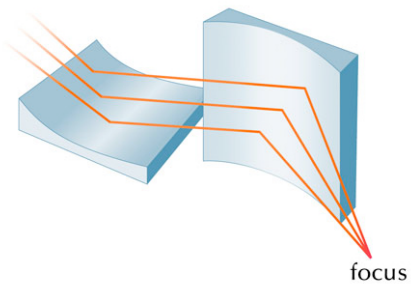
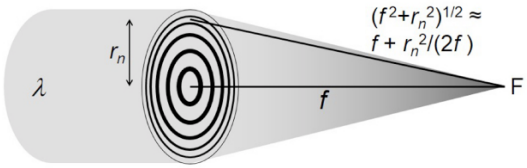
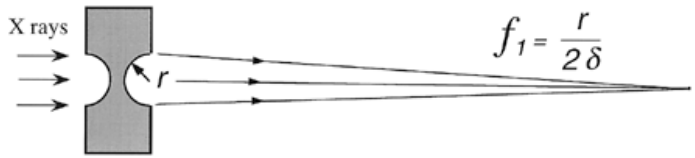


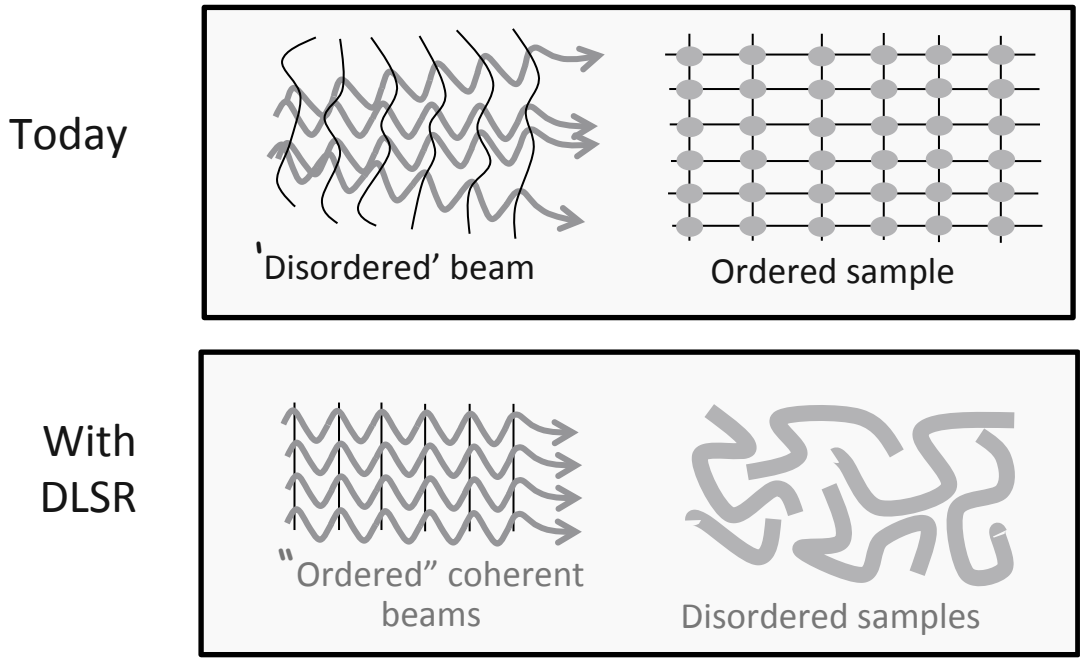


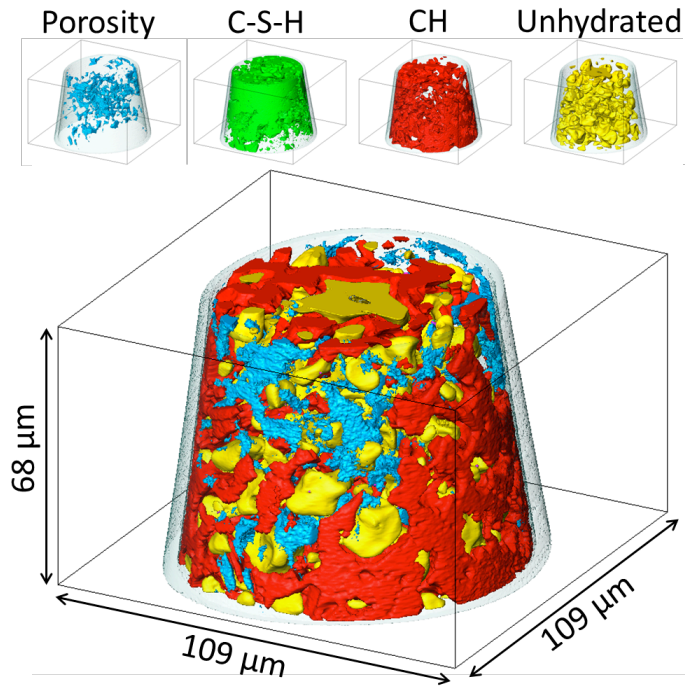




Crazy about Coherence?!

(MAX IV, SIRIUS, ESRF, APS, SPring8, ALS, …)





M. Holler et al., SLS/PSI

- **Disordered materials**
- Multi-scale/ meta-material
- Near phase-transitions

- **More information per radiation damage**
- Information below focus size

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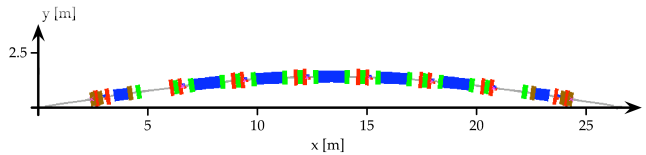

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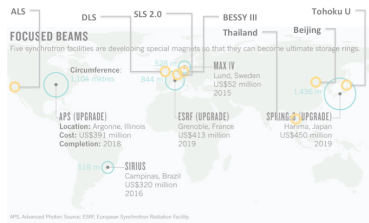
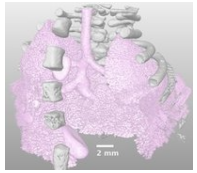


- Future science at DLSR’s



- MAX IV

Low emittance storage rings -> High Brightness & Coherence!

B. Hettel & M. Borland, J. Synchrotron Rad. (2014). 21

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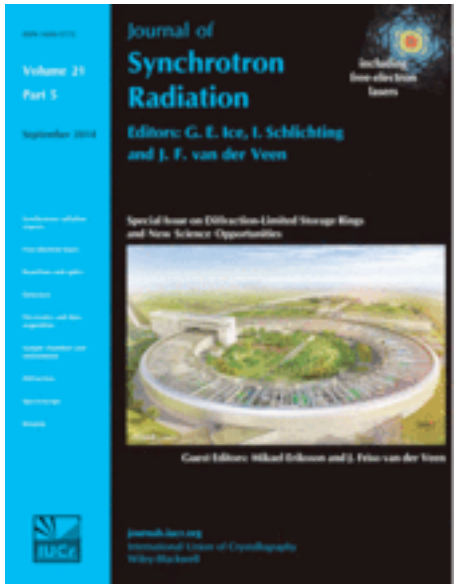
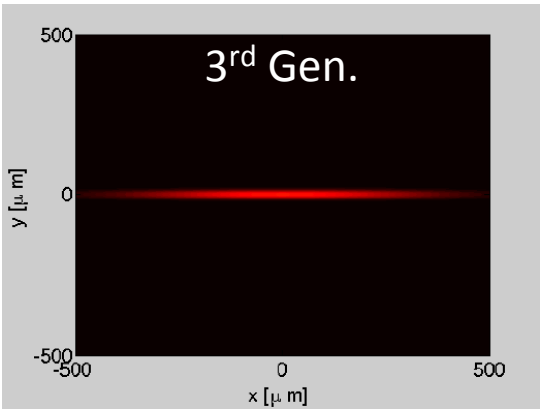
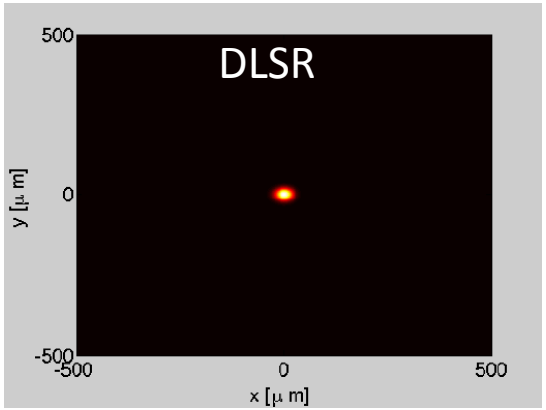


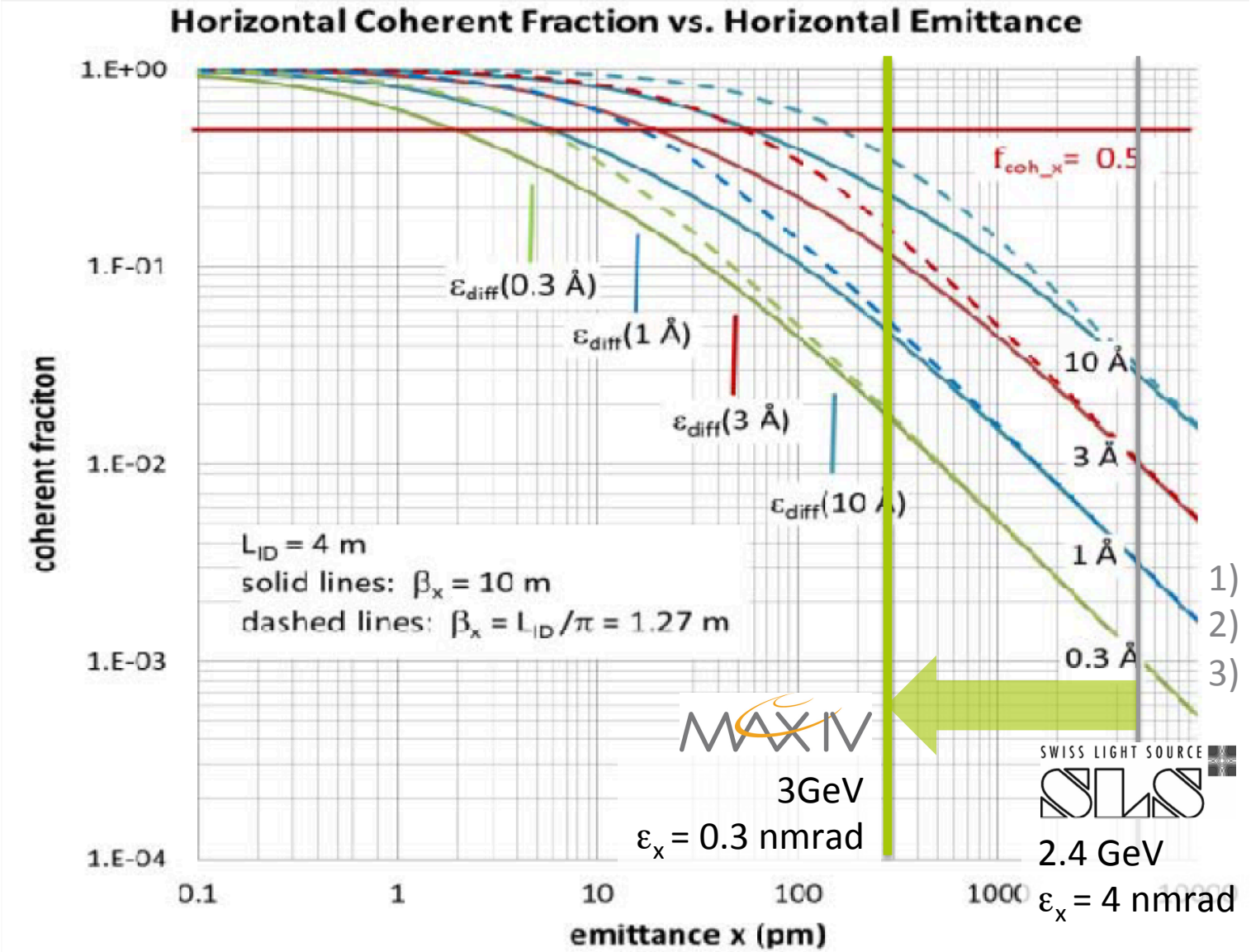


Courtesy:
C. Steier /ALS



Coherent fraction

B. Hettel, J. Synchrotron Rad. (2014). 21
Data: M. Borland



1) Reduce emittance!
2) Match β(s)
3) Play w/ coupling?

$$\sigma(s) = \sqrt{\epsilon \cdot \beta(s)}$$

MAX IV

Lowest emittance ⇒ Highest Brightness!

M. Borland, J. Synchrotron Rad. (2014). 21

$$Brightness \propto \frac{1}{\varepsilon^2} \qquad \varepsilon = C_q \frac{Energy^2}{(N_{Cells} N_d)^3}$$

1. Minimize C_q (Theoretical Minimum Emittance)
   ☹ Ring gets unstable.

2. Increase the number of magnets.
   ☹ Ring ≈ few 10^3m circumference (PETRA III, PEP-X) ⇒ cost!

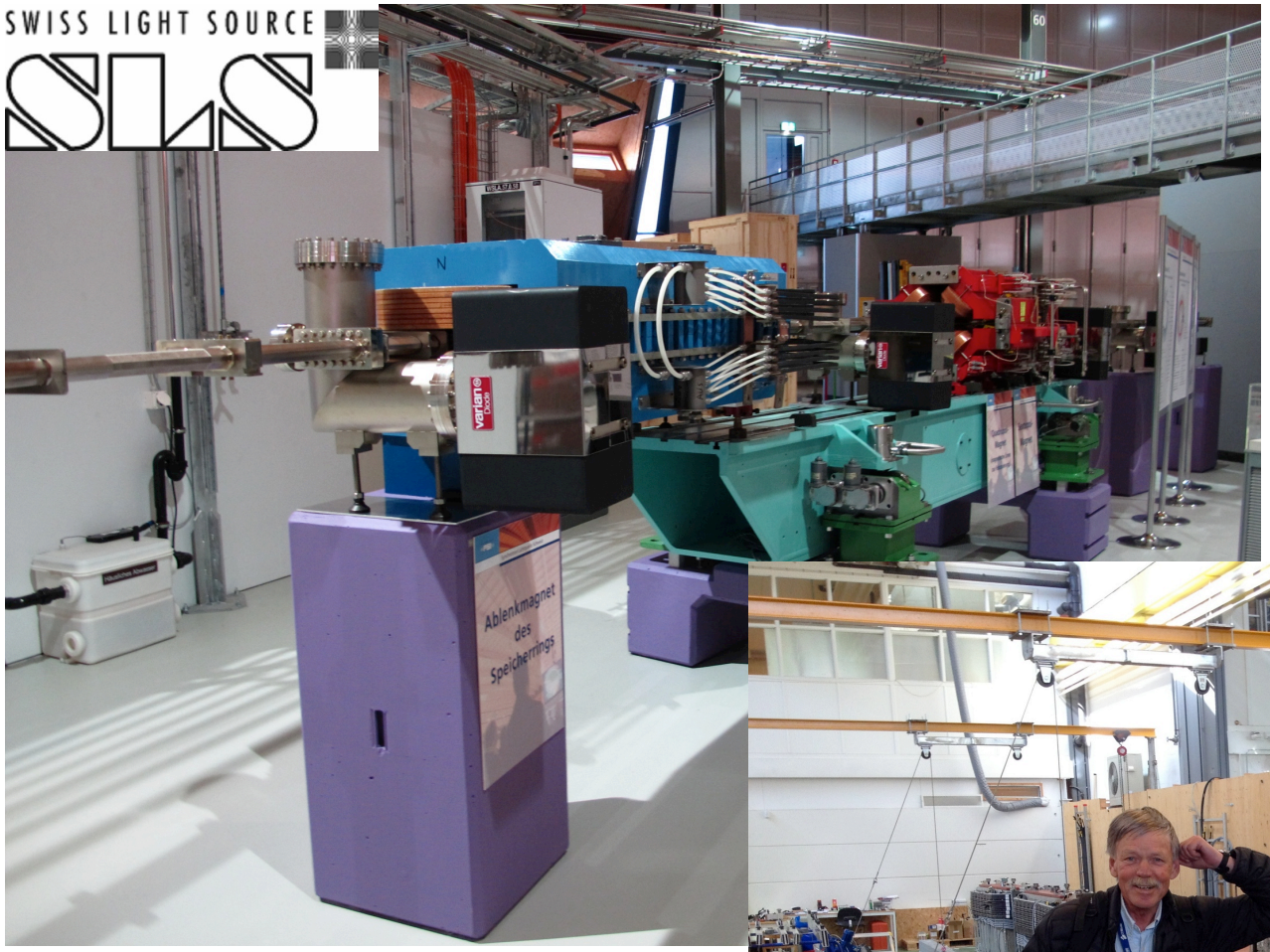
MAX IV "Multi-Bend Achromat" (N_{cells} = 20, N_d = 7):

- Many small gap dipole magnets: small, machined out of bulk!
- Strong focusing in each cell: quad-, sextu-, octopoles
  ⇒ complicated optics & dynamics & modeling
- Vacuum & magnets considered together

J. Synchrotron Rad. (2014). 21

D. Einfeld: Early history / P. Fernandes Tavares: MAX IV

MAX IV



SLS TBA Girder:

Dipole, quad-, sextupole-magnets

Girder ≈ 10 t, 2001

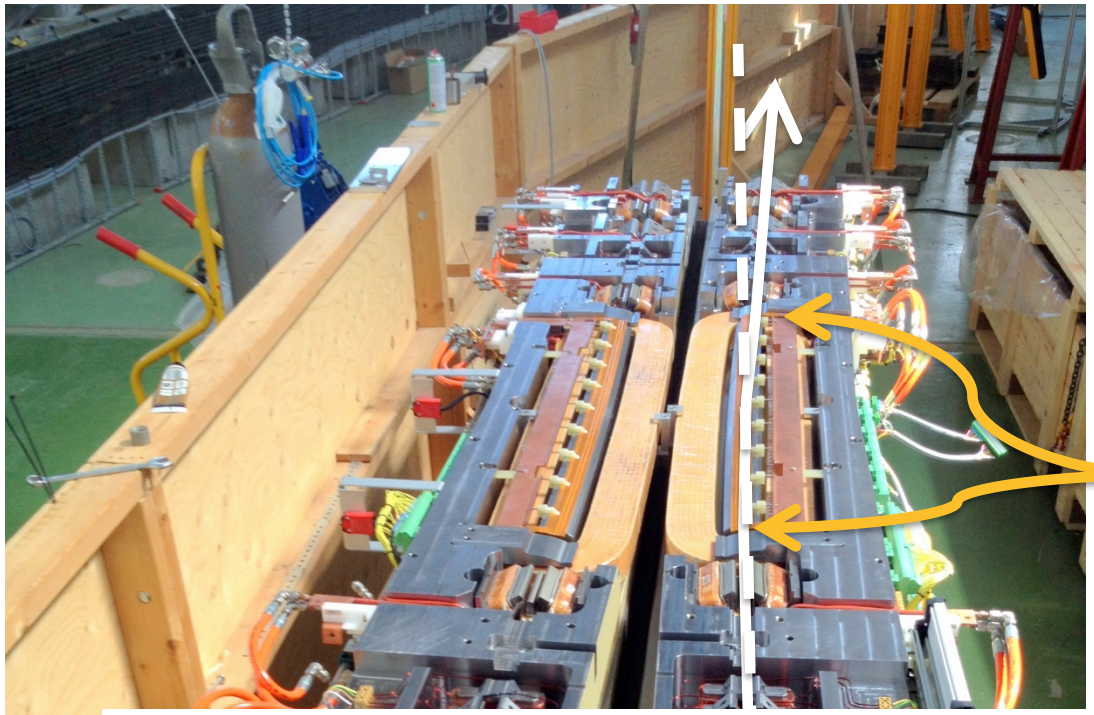
ε_0= 4 nm rad

MAX IV 7-BA magnet:

Dipole & multipol. magnets

Installation test: May 2014

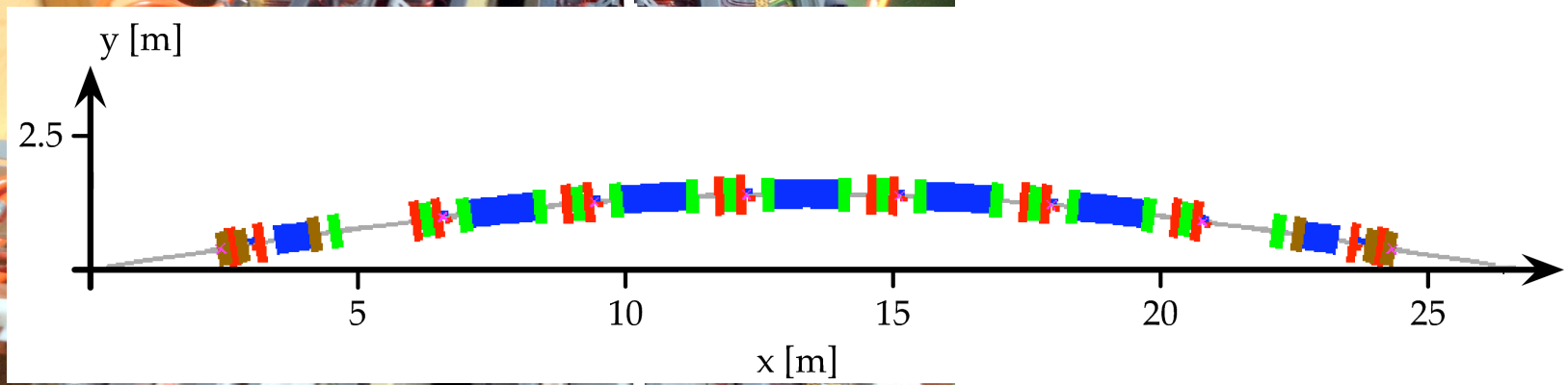
ε_0 < 0.3 nm rad

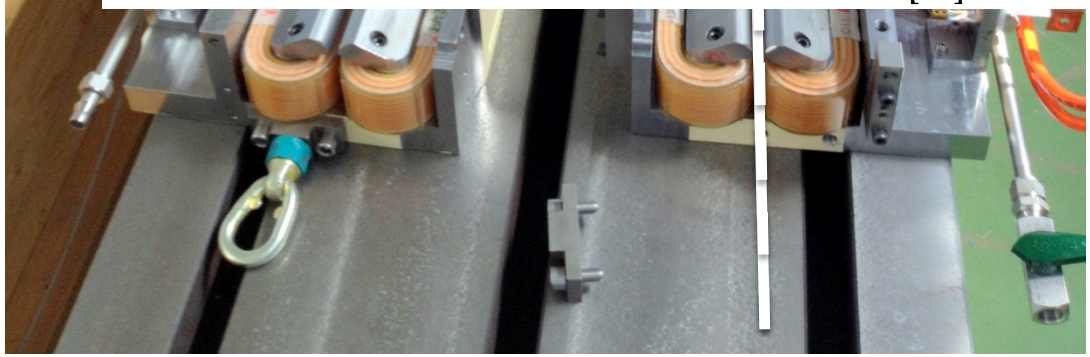


1 of the 7 magnet blocks for 3GeV achromat opened for inspection

N = 140 (20 x 7)
Precision ≈ 10μm
L = 2.3 / 3.3m

Dipole magnet: 0.57 T





MAX IV

Mikael Eriksson

Pedro Tavarez

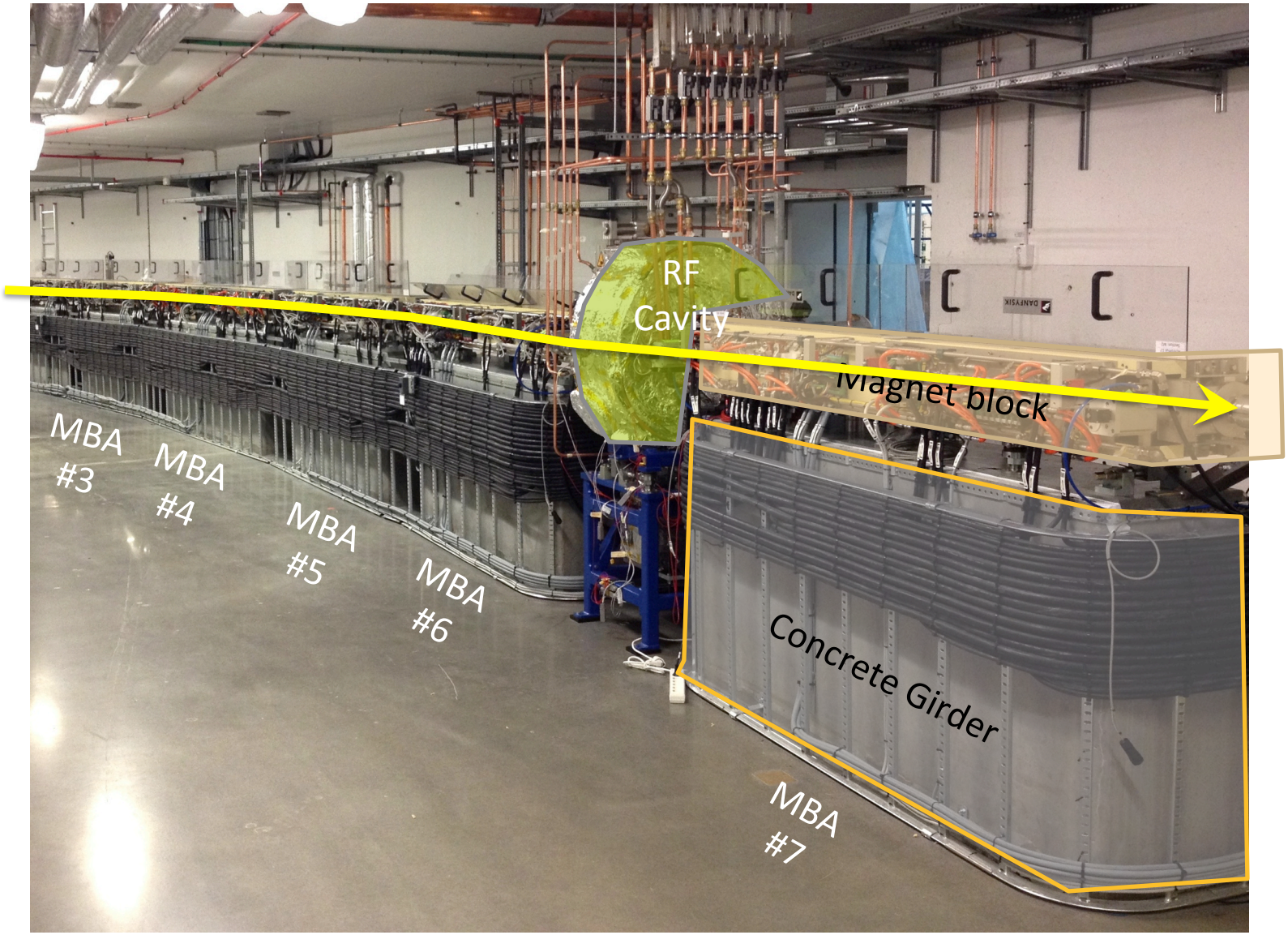
MAX IV

MAX IV

Vacuum chamber (20m x 0,022m) supported by “strong back” hanging over the magnets ready for installation

MAX IV

MAX IV 3 GeV Ring



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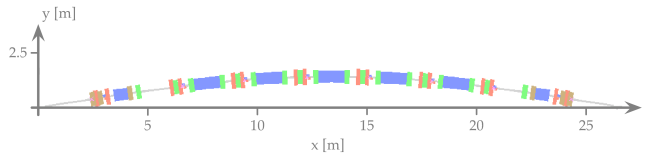

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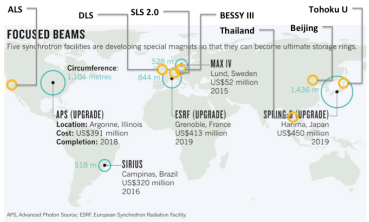
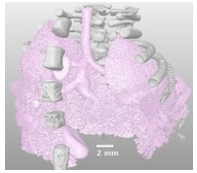
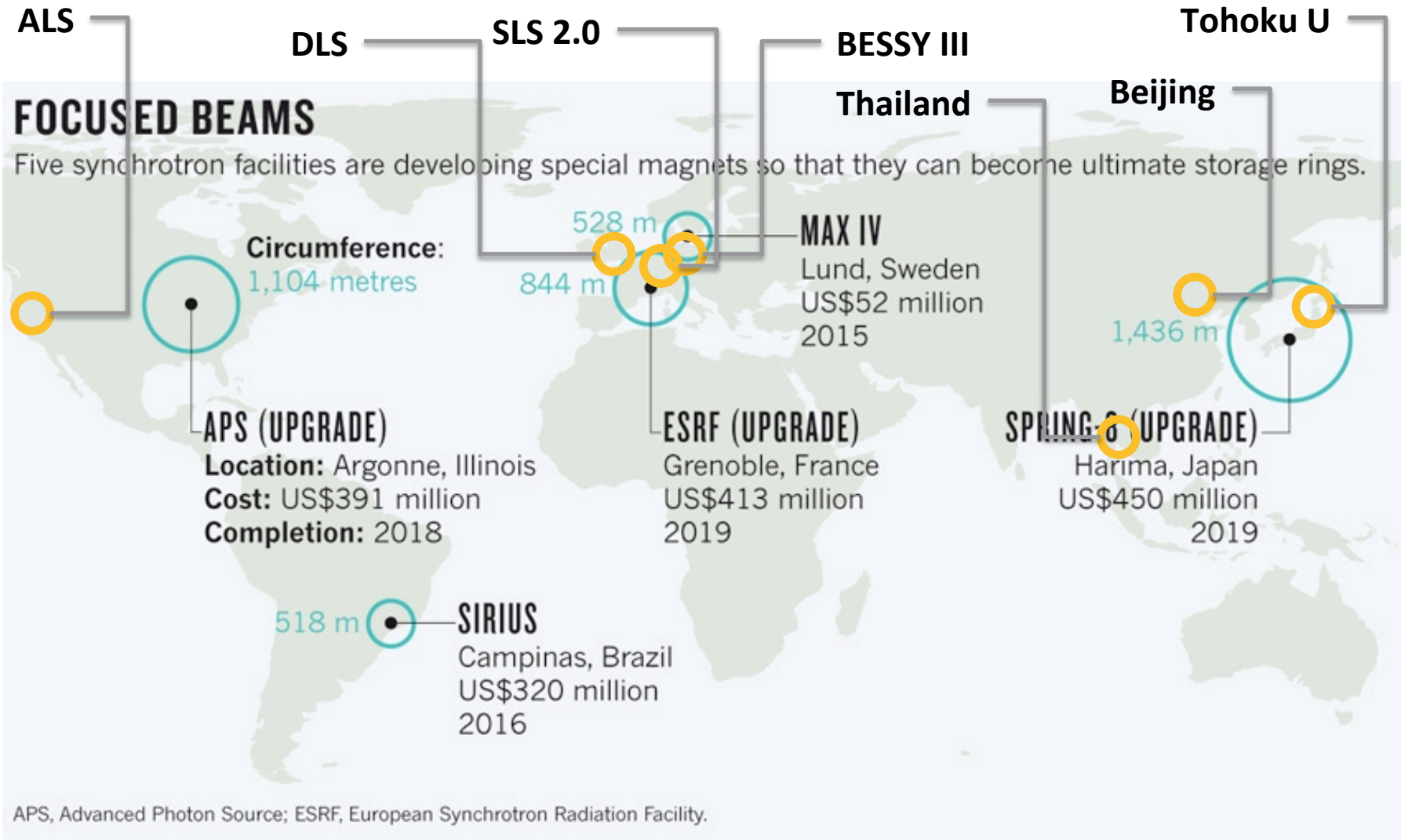


- Future science at DLSR’s



- MAX IV

International Scene: DLSR's all over the world



Nature 501, 148–149 (12 September 2013) doi:10.1038/501148a

PHYSICS

Ultimate upgrade for US synchrotron

Argonne lab banks on beam-bending magnets in bid for world's most focused X-ray light source.

BY EUGENIE SAMUEL REICH

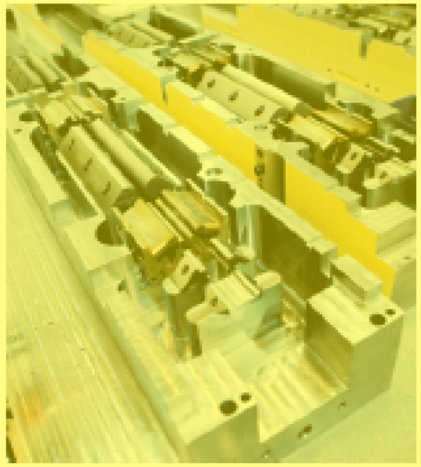
Every day, in dozens of synchrotrons around the globe, electrons are whipped around in circular storage rings to provoke them into emitting X-rays, useful for imaging materials, identifying chemical-reaction products and determining crystal structures.

But photon scientists do not want just any old storage ring. For more than a decade, they have dreamt of 'ultimate' storage rings — ones that use specialized magnets to produce X-ray beams that are as tightly focused as theory allows.

Now, researchers at the largest US synchrotron, the Advanced Photon Source (APS) at the Argonne National Laboratory in Illinois, are taking steps to develop this technology. In the process, they hope to leapfrog several international facilities that have a head start.

In Sweden, ultimate-storage-ring technology is being pioneered at MAX IV, a 528-metre-circumference synchrotron in Lund. Scientists there first sought to increase the intensity and brightness of the synchrotron's X-ray light in 2006 by focusing electron beams more tightly. The design relied on groups of seven magnets, known as multi-bend achromats, that could be used in as many as 20 places around the ring to nudge the paths of electrons back and forth until they lined up more-or-less perfectly. Machine director Mikael Eriksson recalls that when he toured US light sources to describe the project, "few believed it".

Eriksson now has believers. In a report posted online on 29 August, researchers at the Argonne lab describe how they are hoping to upgrade the 1.1-kilometre-circumference APS with multi-bend achromats (see go.nature.com/asxrqb). "There's a new technology that has come along and it's pretty revolutionary," says APS director Brian Stephenson. Current storage rings have at most double-bend achromats, which contain two magnets rather than seven. Physicists had thought that including more magnets would make the beam unstable by bending it too much and introducing too many fluctuations. But the work at MAX IV showed that very compact magnets enable bending paths that are short enough to stop fluctuations from building up.



DA HYTER

Magnets for the Swedish MAX IV synchrotron.

The US Department of Energy, which funds the APS, still needs to approve the plan. In July, one of the department's advisory committees suggested that US labs were being left behind while other countries push towards ultimate storage rings. The committee had also recommended pursuing a next-generation X-ray laser, useful for making 'molecular movies' of chemical reactions, among other things (see *Nature* 500, 13–14; 2013). But such a laser would have limitations: its strongly peaked light pulses would destroy delicate materials. Ultimate storage rings, by contrast, satisfy a need for more gradually peaked pulses of light.

Researchers say that these storage rings could revolutionize X-ray imaging by making it possible to map evolving chemical processes. Current X-ray sources are not bright enough to track changes in materials with nanometre and nanosecond resolution, because there are not enough coordinated photons in the beams. Ultimate storage rings would change that. "A whole class of new problems opens up," says Paul Evans, a materials scientist at the University of Wisconsin–Madison. For example, he says that the rings could be used to investigate what happens chemically and electrically at the interface between materials inside a battery as it runs out.

The APS is seeking to tack the installation of ultimate-storage-ring technology on to a separate upgrade that had already been approved. Cost calculations are still ongoing, but Stephenson hopes that the multi-bend achromats can be included without raising the upgrade budget much above US$391 million. MAX IV is implementing the technology for only 340 million Swedish kronor ($52 million), but that ring is smaller and the price tag would not include the overhead costs that are charged at US energy-department labs.

After its upgrade, the APS could surpass MAX IV by approaching the theoretical limit for the most focused beam possible. The Swedish synchrotron will contain 20 multi-bend achromats, whereas the APS upgrade calls for around 40. In 2012, physicists at SLAC National Accelerator Laboratory in Menlo Park, California, showed that the number of multi-bend achromats around a larger ring could be pushed even higher without fundamentally destabilizing the electron beam. "The key is to make the bending gentle," says Yunhai Cai, head of beam physics at SLAC.

Alongside APS, the European Synchrotron Radiation Facility (ESRF) in Grenoble, France, has also opted for a multi-bend-achromat upgrade, after a working group concluded last October that the technology was affordable. ESRF director-general Francesco Sette says that accelerator physicists there showed that multi-bend achromats could work with the facility's existing injector, a part of the machine that supplies extra electrons to the main ring a few times each day. He had previously thought that a new injector would be needed. "We are today in full swing to launch as soon as possible," he says.

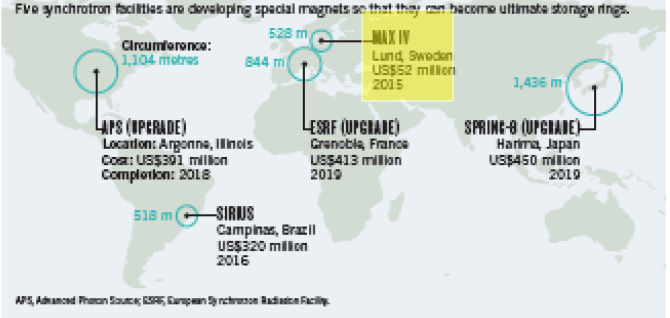
Storage rings in Brazil and Japan will also be upgraded with multi-bend achromats, giving MAX IV a window of only one year from its projected completion date of 2015 before it faces competition (see 'Focused beams').

Some have suggested that particle-physics tunnels, too, could eventually be turned into light sources with multi-bend achromats. SLAC has an idle 2.2-kilometre-circumference tunnel that originally housed a particle accelerator used to compare the decay rates of matter and antimatter. And a 6.3-kilometre tunnel used by the now-closed Tevatron particle accelerator at Fermilab near Batavia, Illinois, is another candidate for conversion. Eriksson says that building ultimate storage rings of that size would not be realistic for Sweden, given the relative size of its science budget.

He knows that Sweden's time in the vanguard will be short-lived, and has mixed feelings about seeing other countries adopting the technology that he and his colleagues pioneered so enthusiastically. "We are both happy and a little sorry," he says. ■

FOCUSED BEAMS

Five synchrotron facilities are developing special magnets so that they can become ultimate storage rings.



APS, Advanced Photon Source; ESRF, European Synchrotron Radiation Facility.

SOURCES: US DEPARTMENT OF ENERGY/ESRF; MAX IV

CORRECTION

The News story 'NASA ponders Kepler's future' (*Nature* 501, 16–17; 2013) inflated the size of asteroids that the probe could watch for — they would be several hundred metres in diameter rather than several hundred kilometres.

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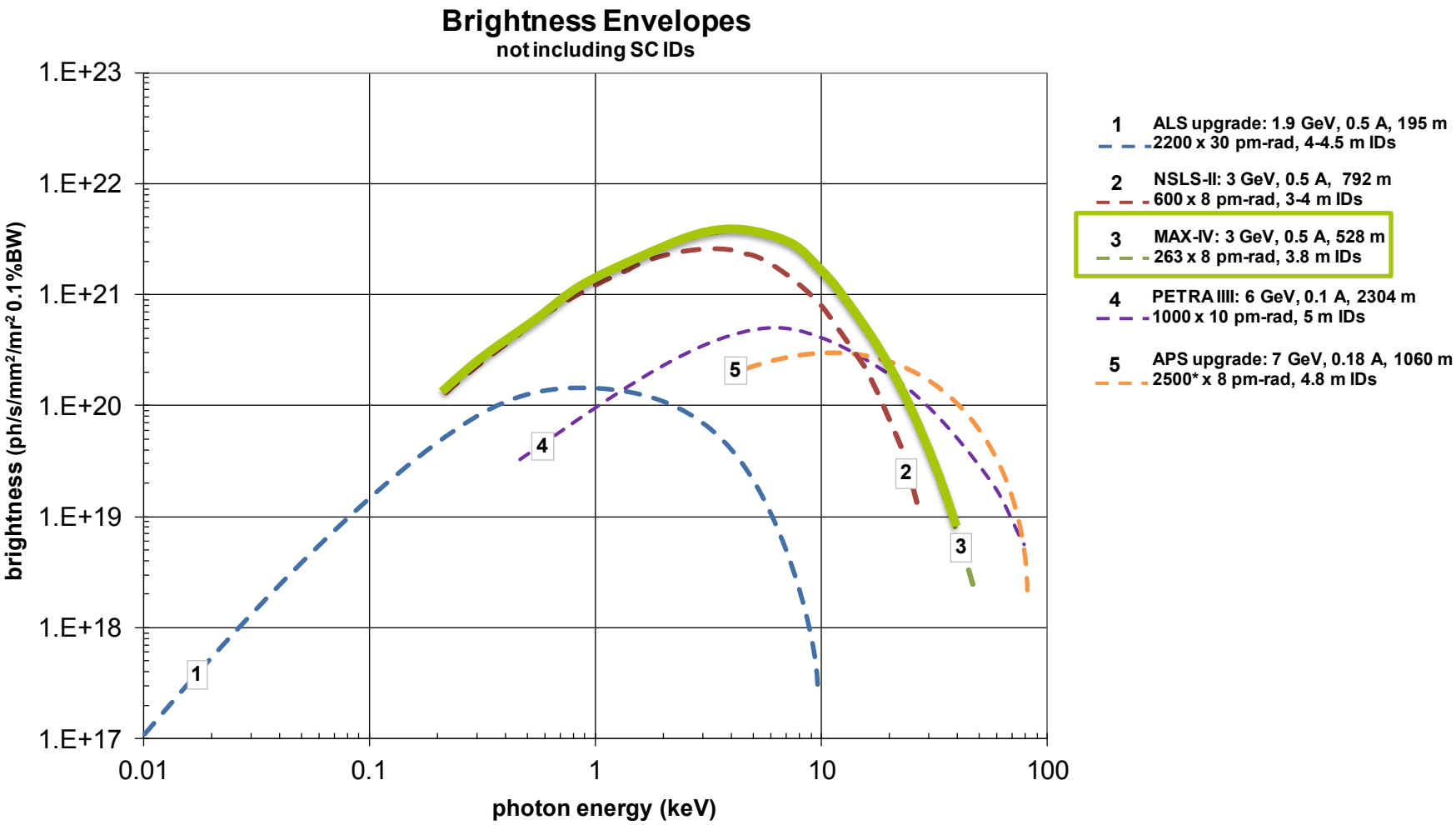
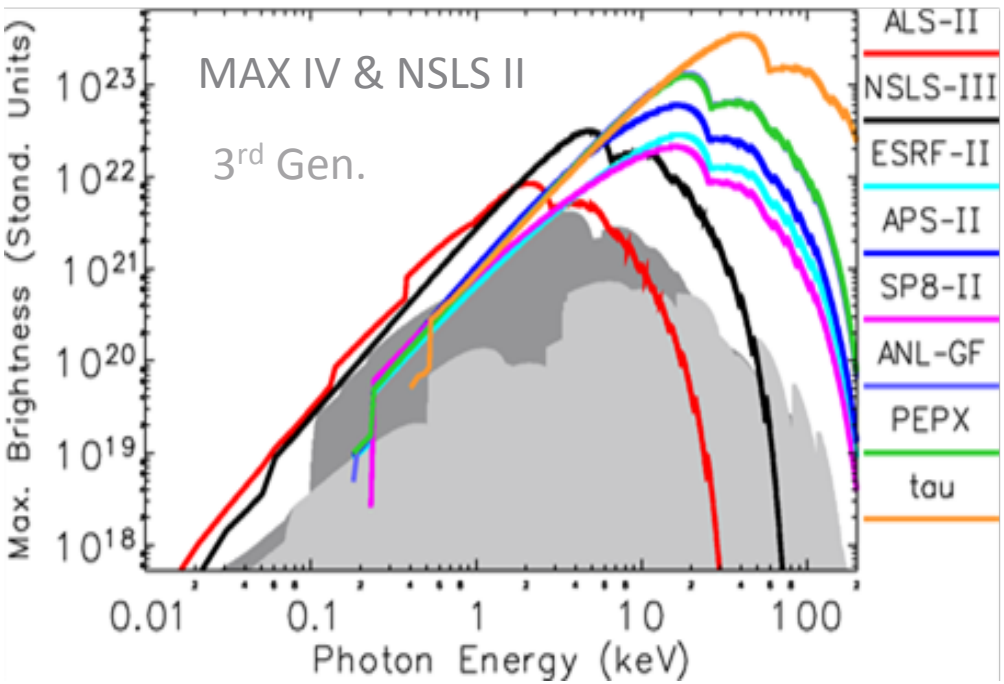
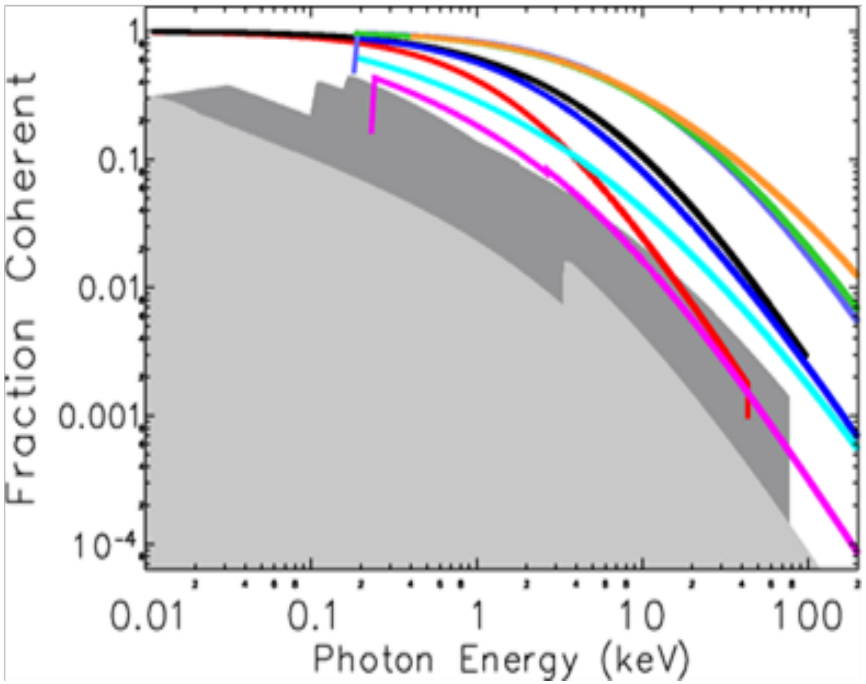
MAX IV & other DLSR's



More Brightness to come!

B. Hettel, J. Synchrotron Rad. (2014). 21





Facility	E(GeV) / I(A)	C (m)	ε_0 (pm-rad)	Features
NSLS-II	3 / 0.5	792	600	2BA, DW, operation 8.2014
MAX-IV	3 / 0.5	528	250	7BA, 100 MHz RF, in construction
Sirius	3 / 0.5	518	280	Hybrid 5BA, superbend insert, in construction
ESRF	6 / 0.2	844	150	Hybrid 7BA, dipole longit. grad., 3-pole wiggler insert, exploratory
APS-U	6 / 0.2	1104	60	ESRF style, swap-out inject, exploratory
SPring-8-II	6 / 0.1	1436	100	5BA, exploratory
ALS-U	1.9 / 0.5	200	100	9BA, superbend insert, swap-out, exploratory

“Diffraction-limited Storage Rings”

- Why?

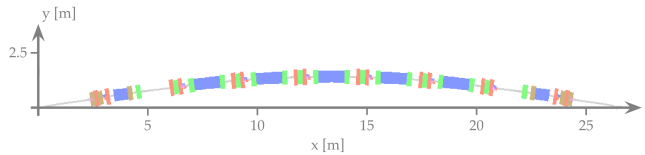
Diffraction limit: $\varepsilon_r = \frac{\lambda}{4\pi}$ or $\frac{\lambda}{2\pi}$, Emittance: ε_0

$$B_{avg} = \frac{F(\lambda)}{(2\pi)^2} \cdot \frac{1}{\varepsilon_r(\lambda) \oplus \varepsilon_x(e^-)} \cdot \frac{1}{\varepsilon_r(\lambda) \oplus \varepsilon_y(e^-)}$$

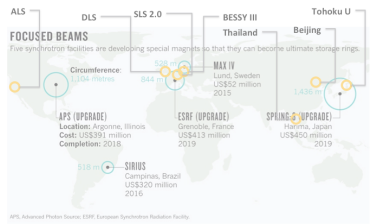
$$\varepsilon_x = \frac{1}{1+k}\varepsilon_0(e^-) \qquad \varepsilon_y = \frac{k}{1+k}\varepsilon_0(e^-)$$

$$f_{coh} = f_{coh_x} \cdot f_{coh_y} = \frac{\varepsilon_r(\lambda)}{\varepsilon_r(\lambda) \oplus \varepsilon_x(e^-)} \cdot \frac{\varepsilon_r(\lambda)}{\varepsilon_r(\lambda) \oplus \varepsilon_y(e^-)}$$

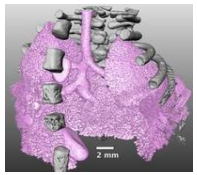
- How?



- Where?



- Future science at DLSR’s

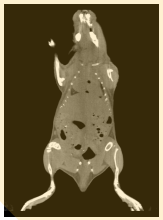


- MAX IV

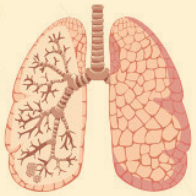
Biology from atomic to anatomic

MedMAX II | MedMAX I | NanoMAX SoftiMAX | coSAXS | BioMAX | MicroMAX | FemtoMAX Balder

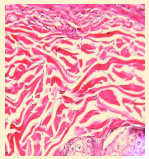
10^{-6} m | 10^{-9} m | 10^{-10} m



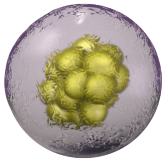
Animals



Organs

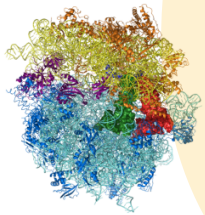


Tissues

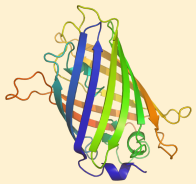


Cells

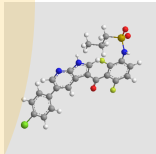
Micro-structures



Molecular complexes



Biomolecules

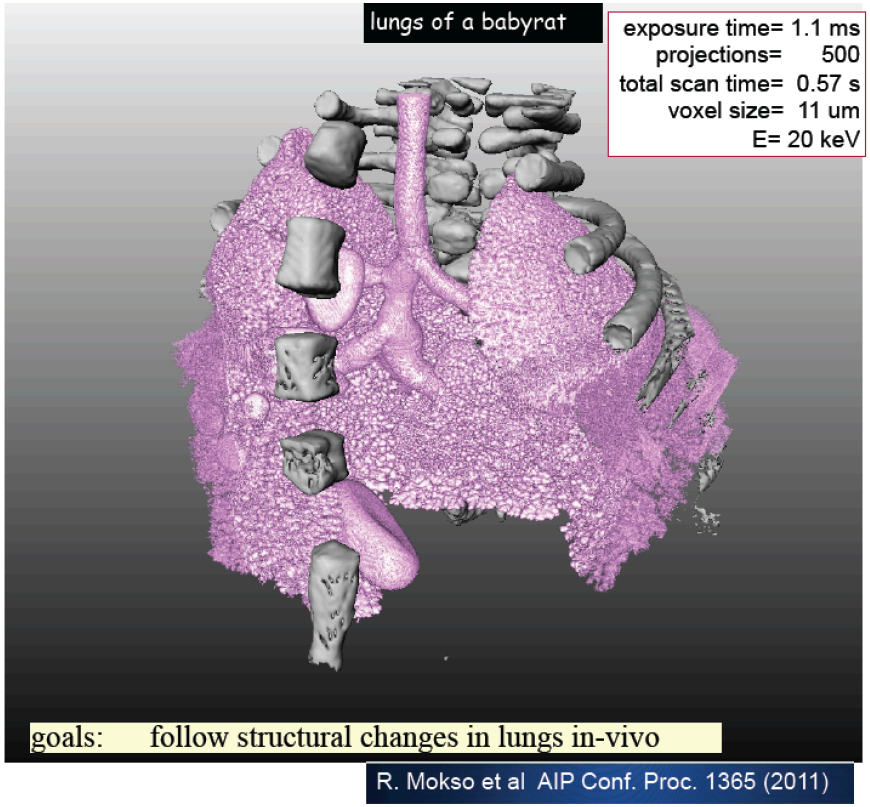


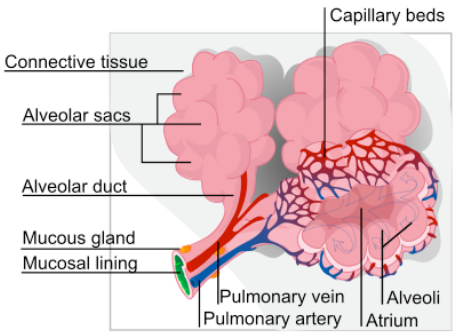
Atoms

Disease models | Histopathology | Cellbiology | Molecular Medicine/Chemical Biology

MAX IV

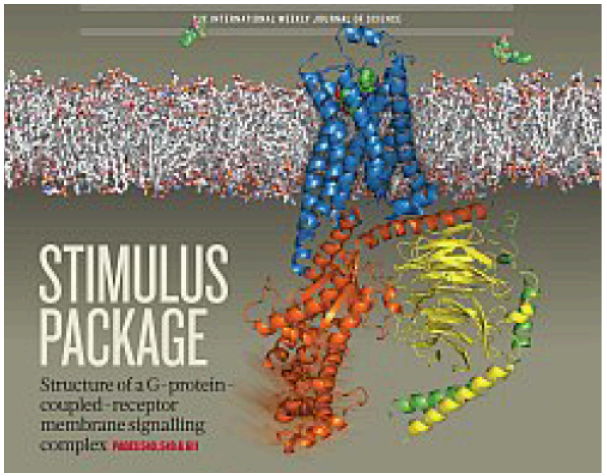
MedMAX (Martin Bech, Rajmund Mokso, ...)

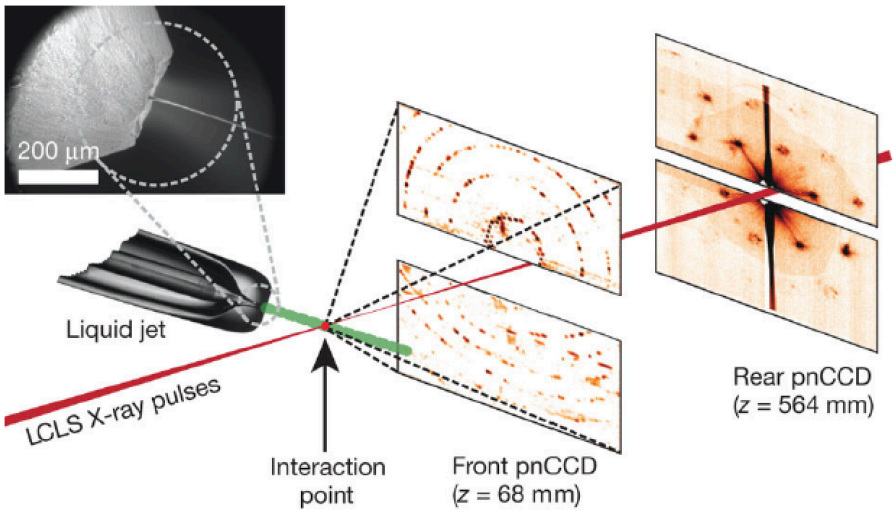




- **What?**
  Lung function & repair: breathing, development & repair, influence of medication
- **How?**
  Phase contrast tomography, in-vivo, real time
- **Why?**
  Low radiation damage, high resolution (time & space)

MicroMAX (R. Neutze, P. Nissen, ...)





- **What?**
  Structure of rare & difficult to crystalize proteins
- **How?**
  < 1 um focus @ low divergence!
  micro-crystals in loops
  nano-crystals on liquid jets

  pink beam, merging 10^1-10^4 crystals
- **Why?**
  Alleviate crystallization problems, most relevant proteins are most difficult,

“Diffraction-limited Storage Rings”

- Why?

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$$B_{avg} = \frac{F(\lambda)}{(2\pi)^2} \cdot \frac{1}{\varepsilon_r(\lambda) \oplus \varepsilon_x(e^-)} \cdot \frac{1}{\varepsilon_r(\lambda) \oplus \varepsilon_y(e^-)}$$

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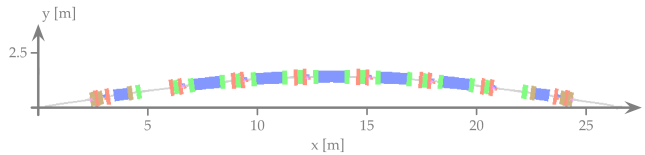
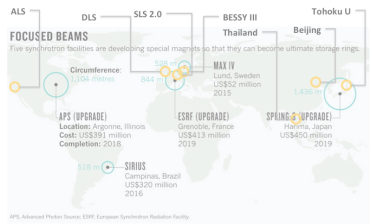
- How?



- Where?



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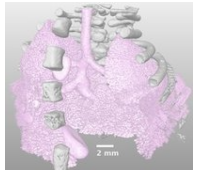
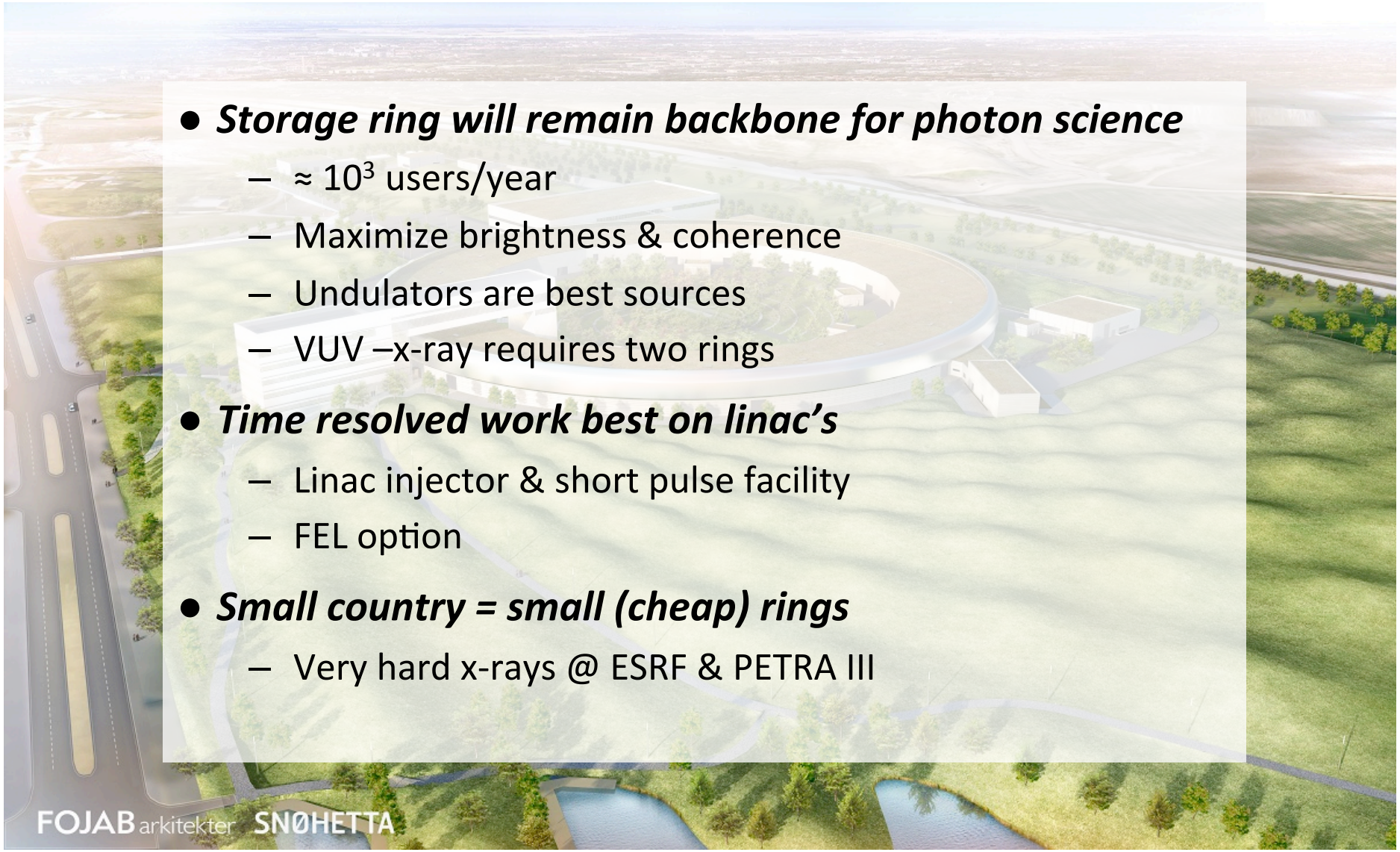


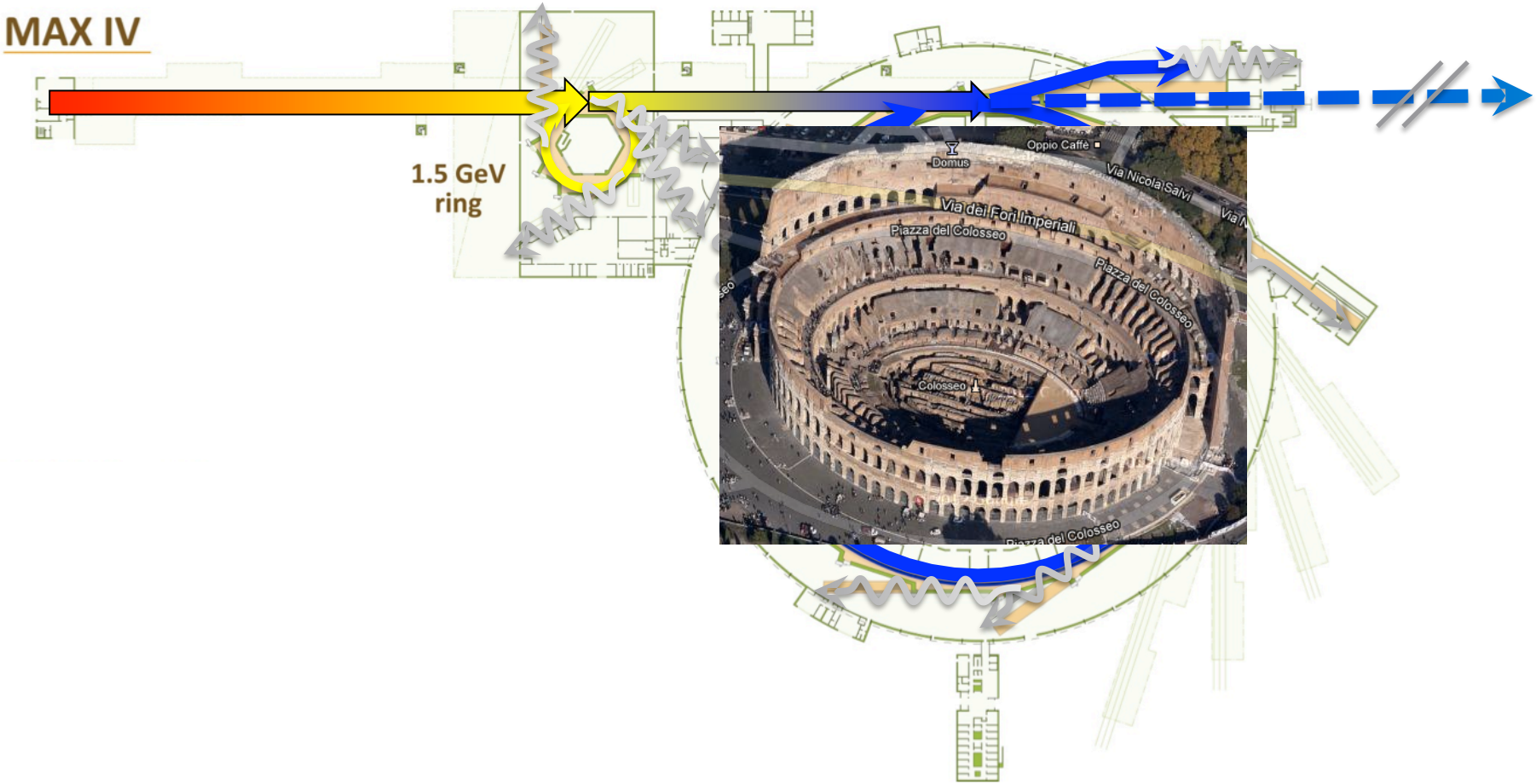
- MAX IV

MAX IV *Design credo*

- ***Storage ring will remain backbone for photon science***
  - ≈ 10^3 users/year
  - Maximize brightness & coherence
  - Undulators are best sources
  - VUV –x-ray requires two rings
- ***Time resolved work best on linac's***
  - Linac injector & short pulse facility
  - FEL option
- ***Small country = small (cheap) rings***
  - Very hard x-rays @ ESRF & PETRA III



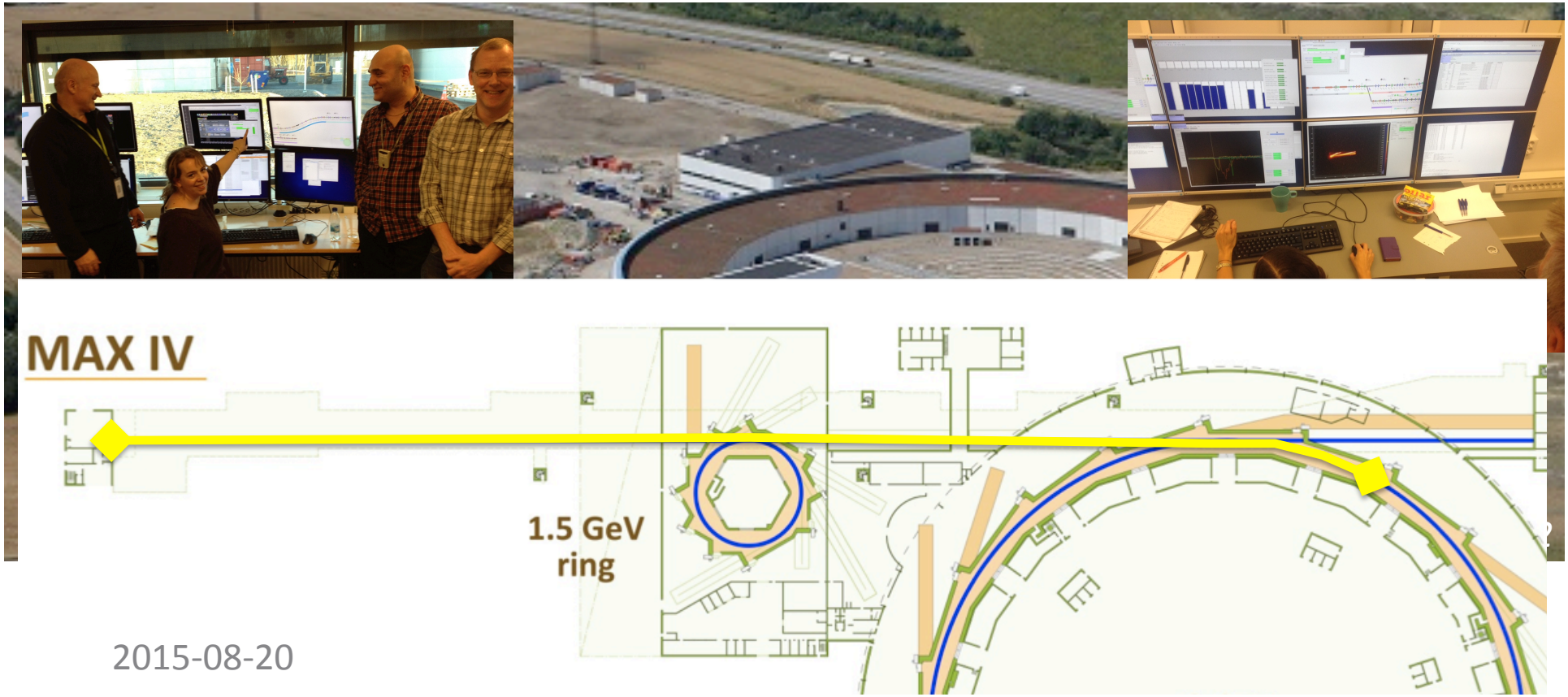
MAX IV – Phase I



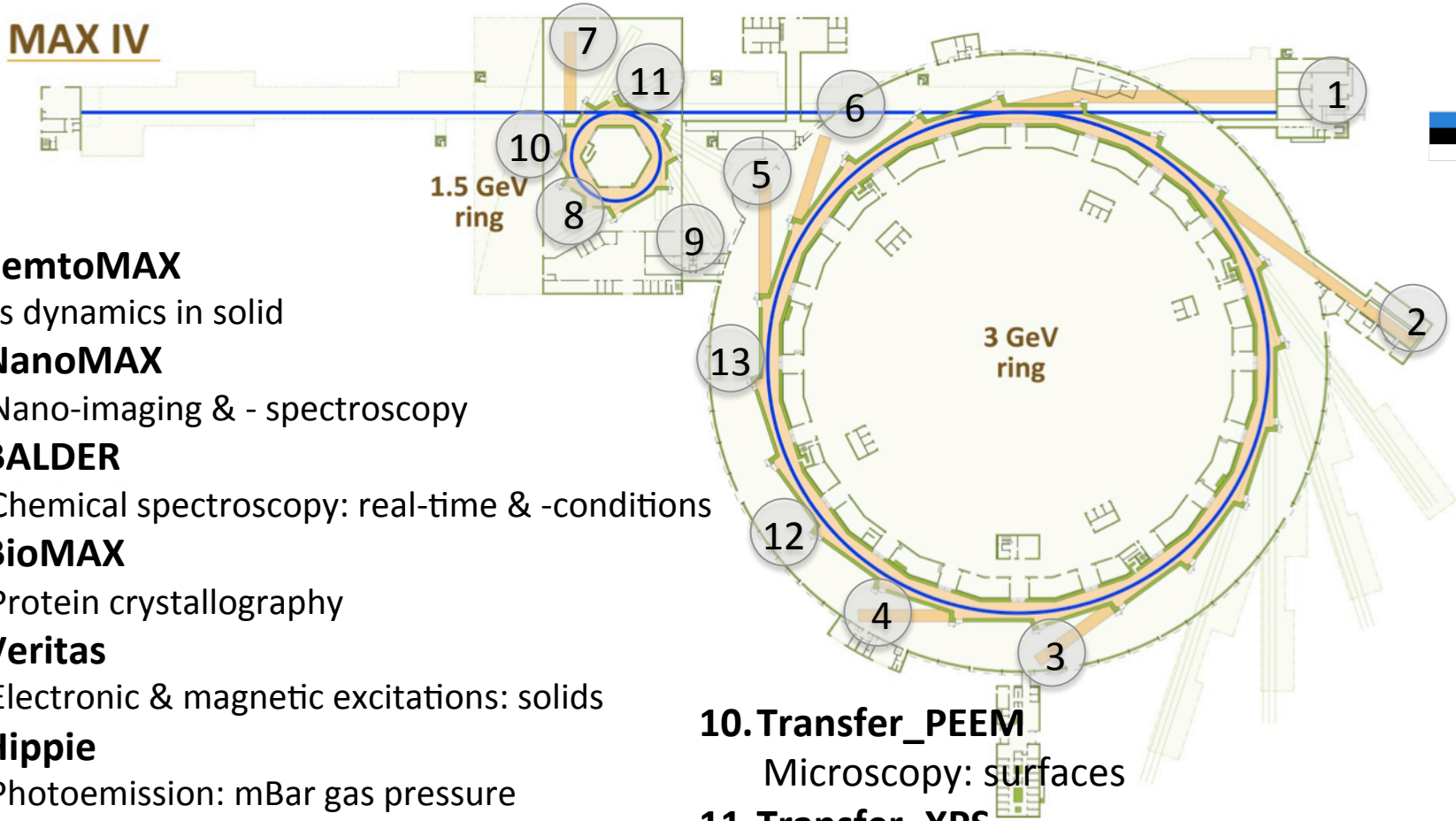
Linac	1.5 / 3 GeV
Length (m)	300
Bunch charge	100 pC @ 10 Hz
Pulse (FWHM)	30 fs – 5 ps
Full energy injector	1.5 / 3 GeV

Rings	3 GeV	1.5 GeV
Circumference (m)	528	96
Straight sections	20	12
Emittance (nm rad)	< 0.3	6
Beam (σ in µm) [H x V]	50 x 6	184 x 13

MAX IV – Aug 2015

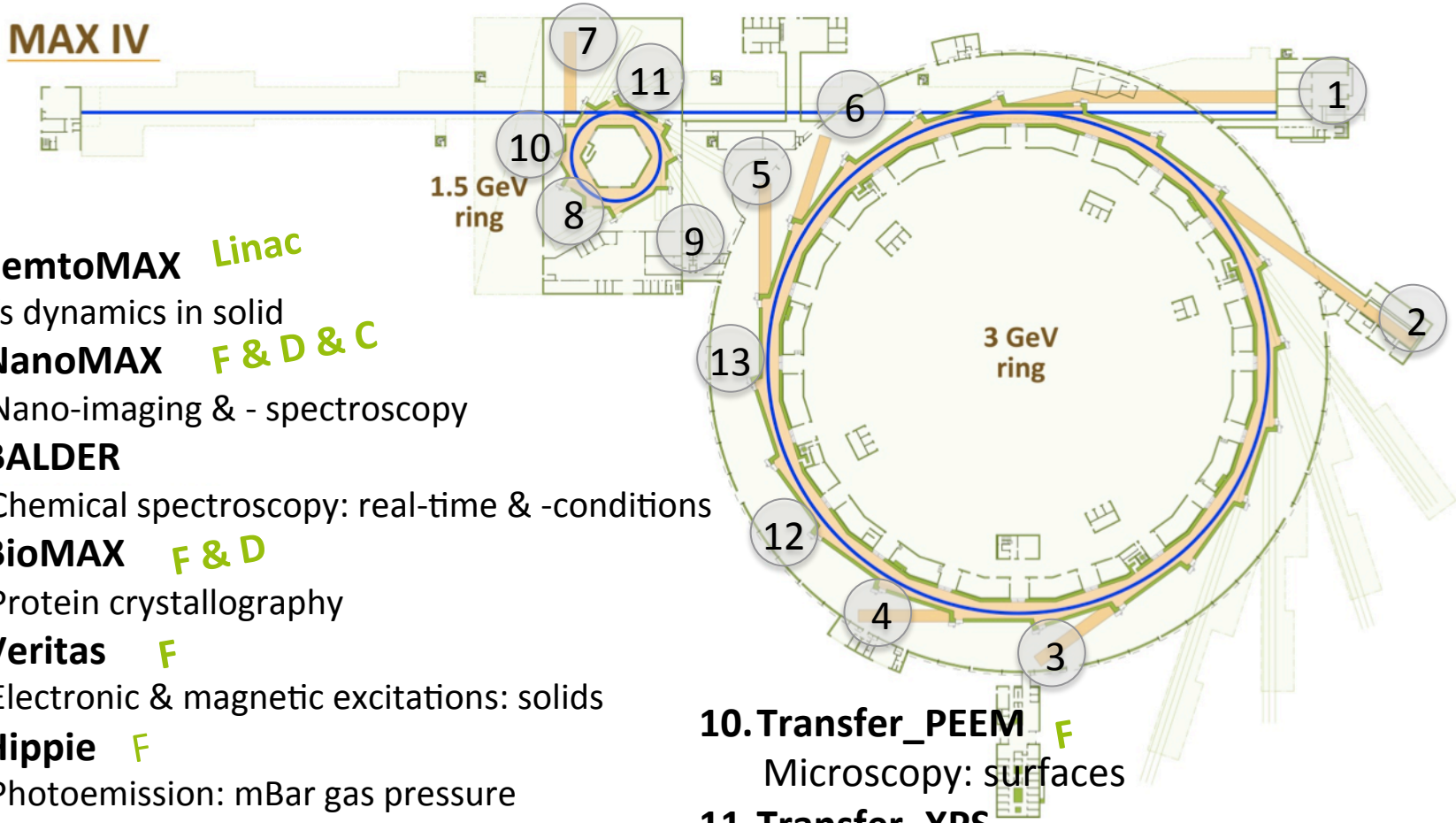


2015-08-20



1. **FemtoMAX**
   fs dynamics in solid
2. **NanoMAX**
   Nano-imaging & - spectroscopy
3. **BALDER**
   Chemical spectroscopy: real-time & -conditions
4. **BioMAX**
   Protein crystallography
5. **Veritas**
   Electronic & magnetic excitations: solids
6. **Hippie**
   Photoemission: mBar gas pressure
7. **ARPES**
   Electronic structure: solids
8. **FinEstBeaMS**
   Electronic structure: gases, aerosols
9. **SPECIES**
   Electronic & magnetic excitations: surfaces
10. **Transfer_PEEM**
    Microscopy: surfaces
11. **Transfer_XPS**
    Electronic structure: surfaces & gases
12. **CoSAXS**
    Geometric structure & correlation: (bio) liquids
13. **Soft*i*MAX**
    Microscopy & method development

Brightness: Focus * Divergence, Coherence



1. **FemtoMAX** Linac
   fs dynamics in solid
2. **NanoMAX** F & D & C
   Nano-imaging & - spectroscopy
3. **BALDER**
   Chemical spectroscopy: real-time & -conditions
4. **BioMAX** F & D
   Protein crystallography
5. **Veritas** F
   Electronic & magnetic excitations: solids
6. **Hippie** F
   Photoemission: mBar gas pressure
7. **ARPES**
   Electronic structure: solids
8. **FinEstBeaMS**
   Electronic structure: gases, aerosols
9. **SPECIES**
   Electronic & magnetic excitations: surfaces
10. **Transfer_PEEM** F
    Microscopy: surfaces
11. **Transfer_XPS**
    Electronic structure: surfaces & gases
12. **CoSAXS** F & D & C
    Geometric structure & correlation: (bio) liquids
13. **Soft*i*MAX** F & D & C
    Microscopy & method development

Twins but not identical

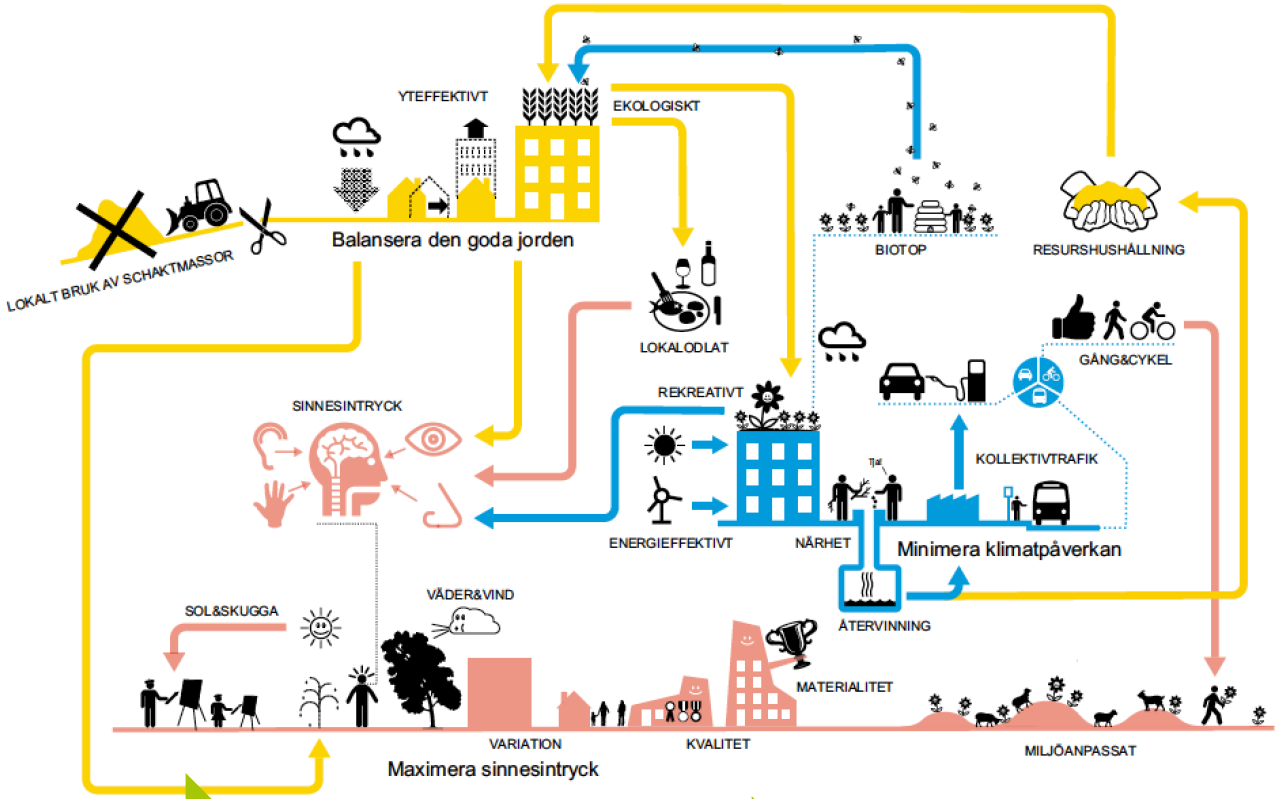
- **Light (X-rays)**
- Swedish
- MAX-lab since 1987
  MAX IV from 2016
- **…, microscopy, chemical bonds, …**

- **Neutrons**
  (from atomic nucleus)
- 17 member states
  (SWE, DK, NOR, …)
- Building started Sep 2nd 2014
  Science starts ≈2023
- **…, large & thick samples, H/D-substiution, …**

More for less!

BRUNNSHÖGSKONTRAKTET 2013

TEKNISKA FÖRSÖRJNINGSSYSTEM FÖR FRAMTIDENS LIVSMILJÖ I BRUNNSHÖG



1.) REDUCE ! → **2.) Reuse** → **3.) Recycle**

- Elec. Power [W/m] = 1/10 of MAX II ring!
- Soil:
  Vibration damping
  Radiation safety
- Local district heating

kraftringen

MAX IV

MAX IV Inauguration

Tuesday, June 21st 2016, noon (local time)

Vetenskapsrådet

LUNDS UNIVERSITET

VINNOVA

REGION SKÅNE

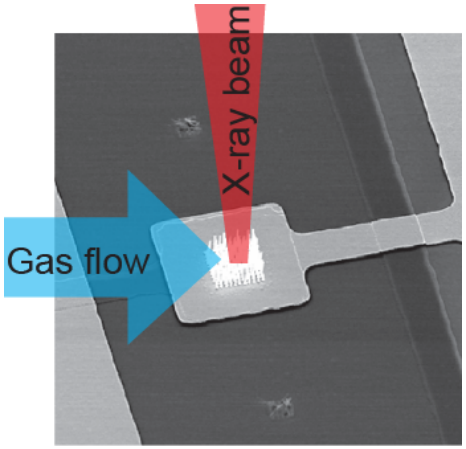
MAX IV

The End

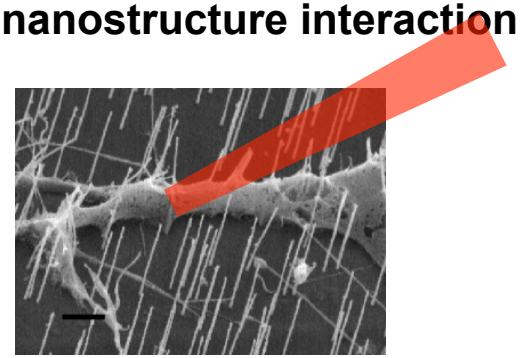
NanoMAX – Science case

Elemental & structural nano-analysis

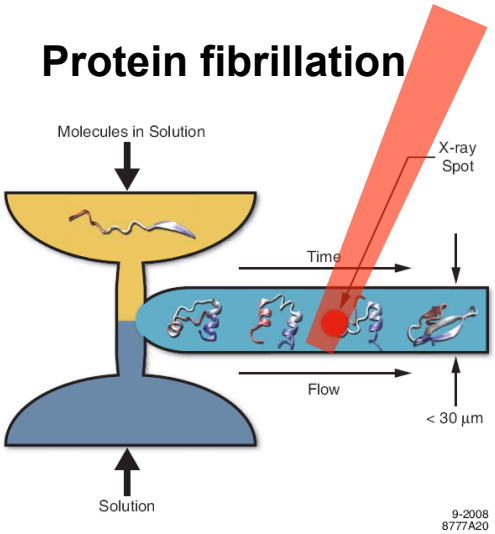
In-situ growth



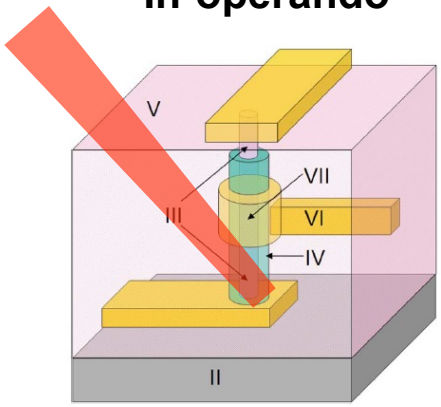
Cell - nanostructure interaction



Protein fibrillation

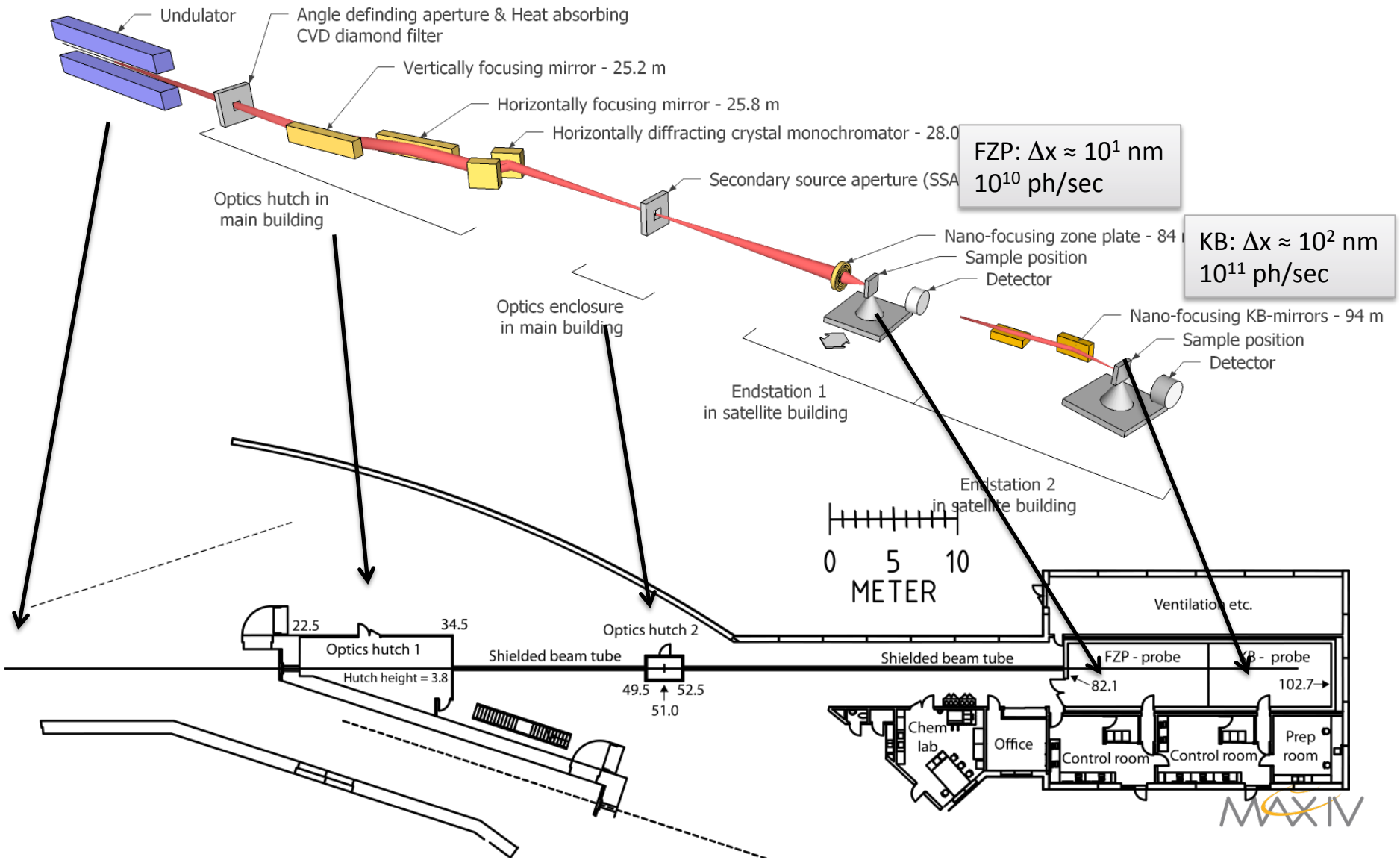


Device nanostructure In-operando



NanoMAX layout

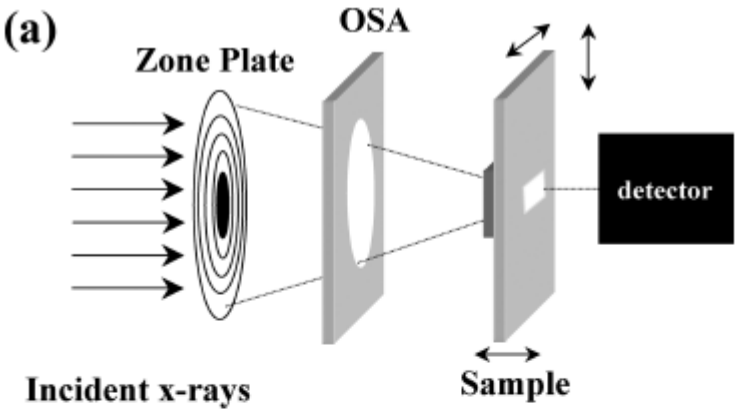
U. Johansson & G. Carbone (S1-107); U. Vogt (S2-16)

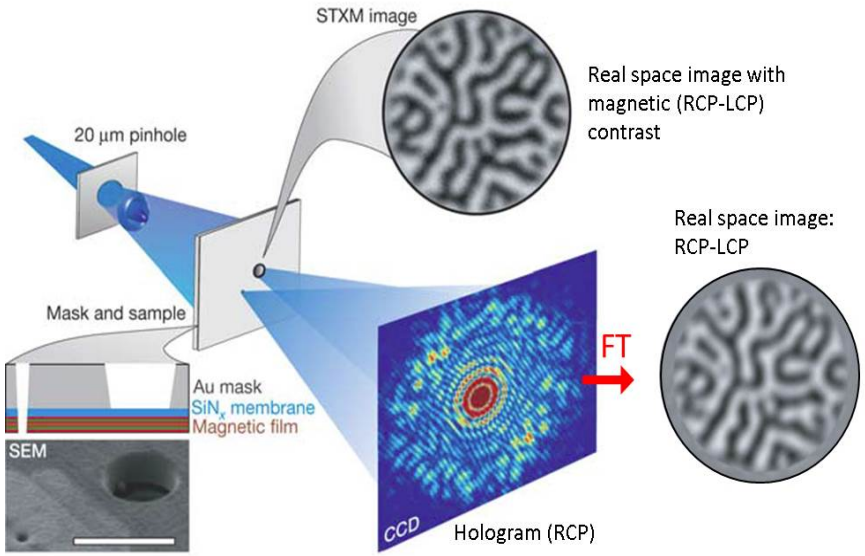


Soft*i*MAX – Science case

E≈ 250 – 2.5 keV, full polarization control

K. Schulte & S. Eisebitt





STXM as work horse

- Environmental science
- Bio-science
- …

Method Development CI

- Nano materials
- Magnetism
- Multi-ferroics
- …

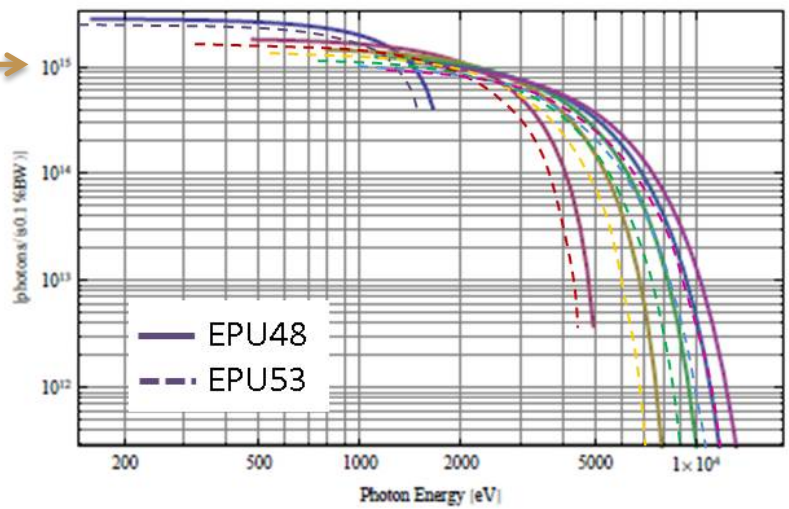
Synergies w/ Lund Laser Center

- Atto seconds
- HHG

Soft*i*MAX: Coherent Flux

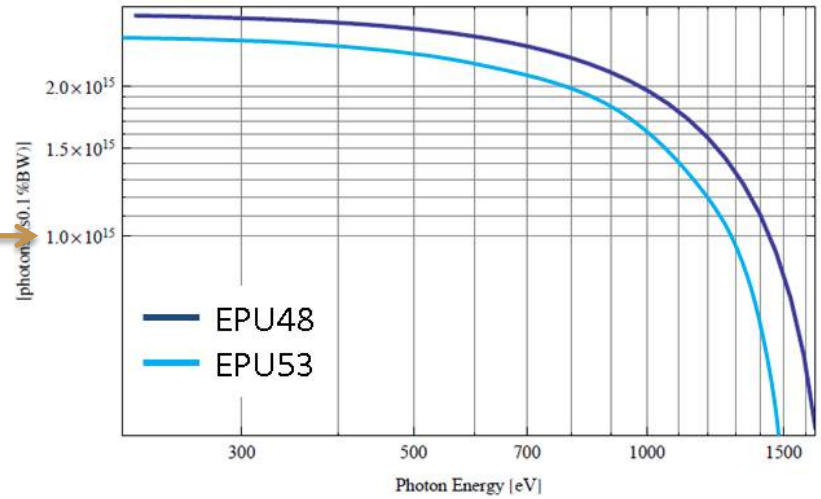
Flux in the harmonics in hor. planar mode, with a 0.1%BW monochr.

10^{15}



Flux in the 1st harmonic of the helical mode, with a 0.1%BW monochr.

10^{15}

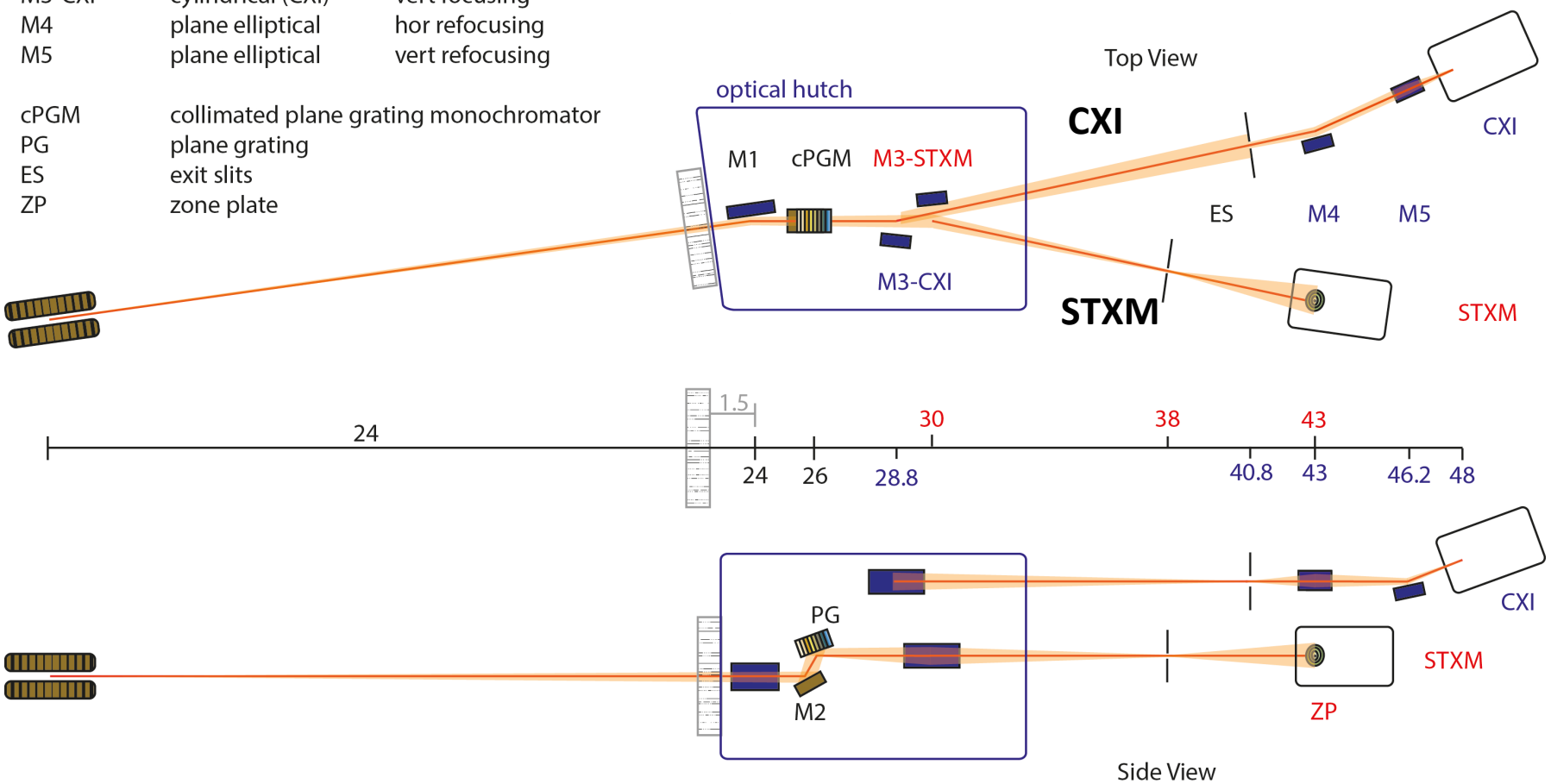


One BL - Two Coherence Experiments

270 eV – 2500 eV (2000 eV)
E/ΔE < 5000

M1	cylindrical	vertical collimation
M2	plane	deflecting
M3-STXM	toroidal (STXM)	hor and vert focusing
M3-CXI	cylindrical (CXI)	vert focusing
M4	plane elliptical	hor refocusing
M5	plane elliptical	vert refocusing

cPGM	collimated plane grating monochromator
PG	plane grating
ES	exit slits
ZP	zone plate

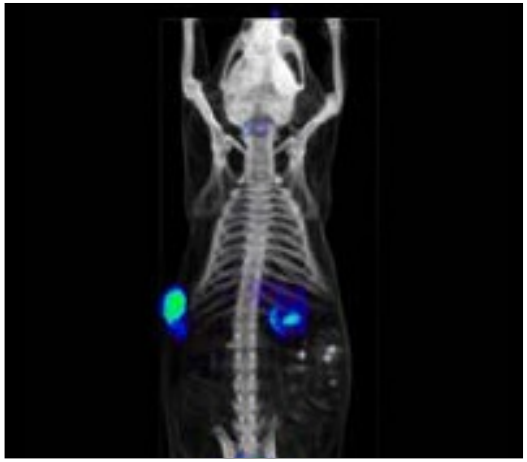


MedMAX: Bio- & Medical-Imaging

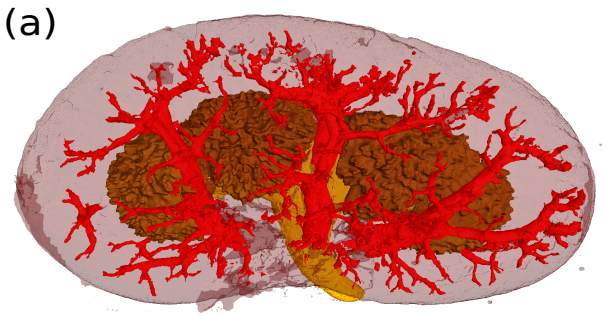
M. Bech (S1-70)

Lund Bio-imaging Center

Micro-PET/CT, micro-MRI



MedMAX



Fibrotic murine kidney
Velroyen, Bech et al, PlosOne 2014

BioMAX

Macromolecular crystallography

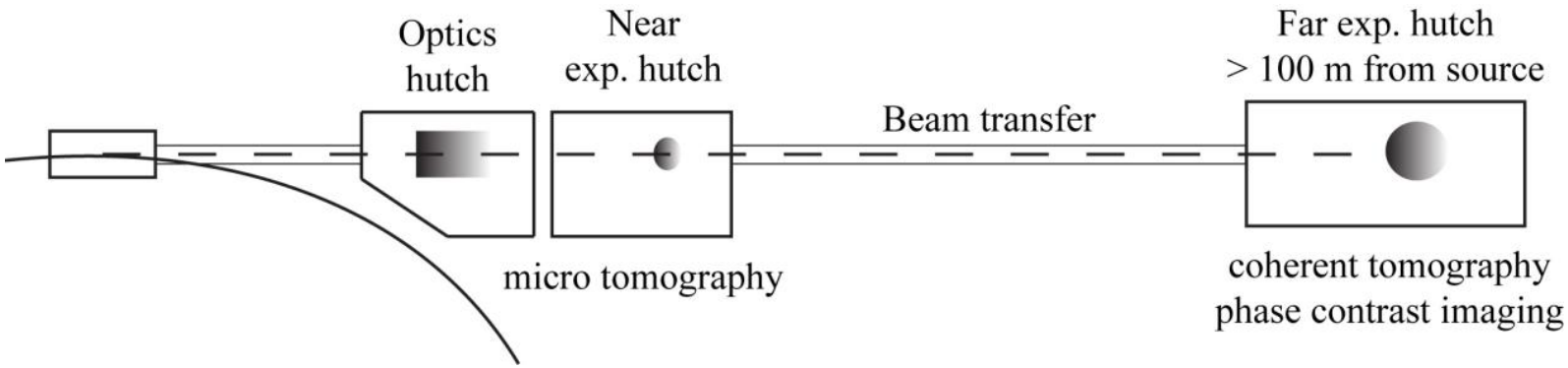
- Atomic ⇔ anatomic
- Research & diagnostics

MEDICON VILLAGE

REGION SKANE

MAX IV

MedMAX: Bio- & Medical-Imaging

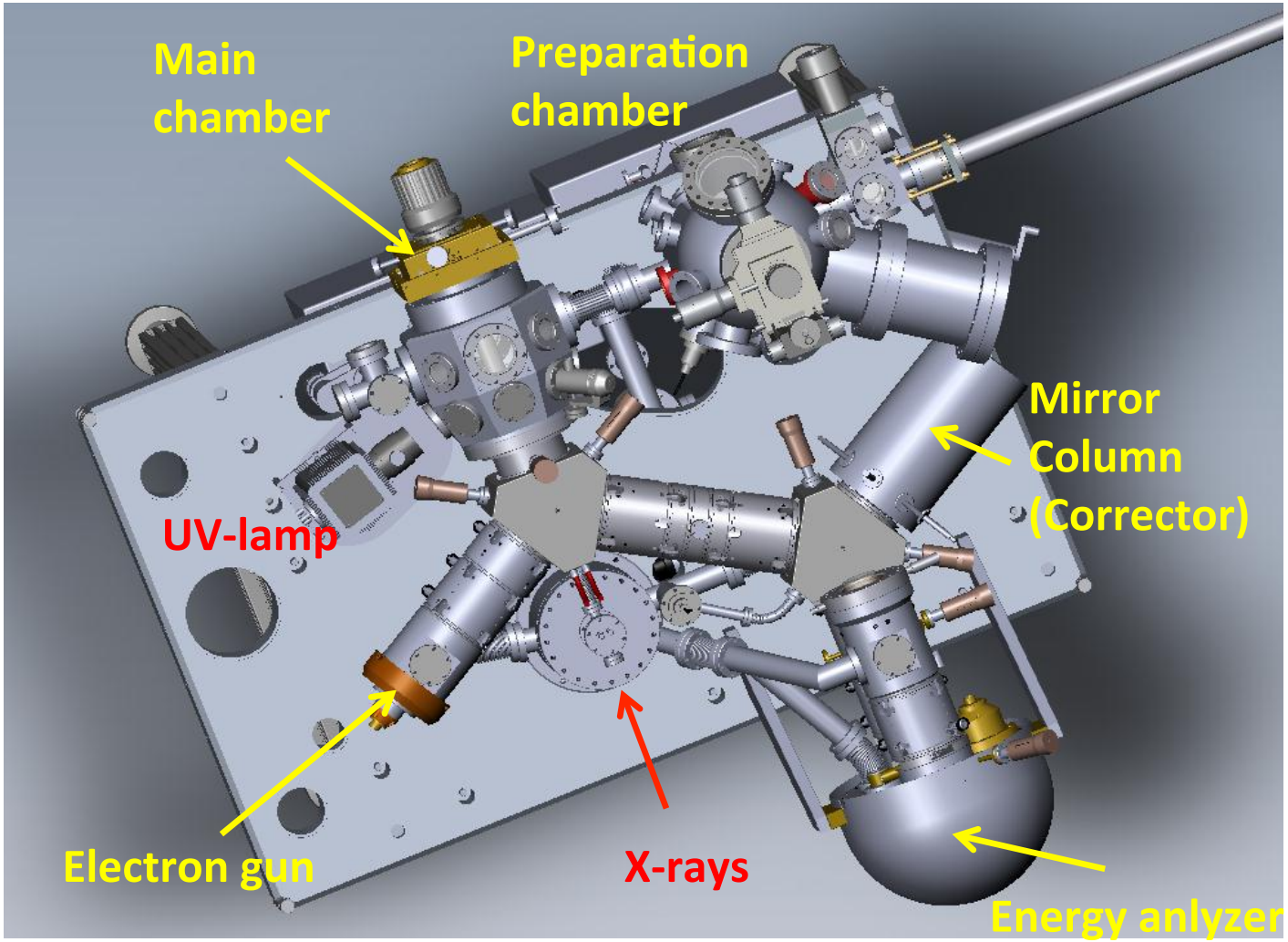


- Seed funding secured
- Full funding ≈ 2016?

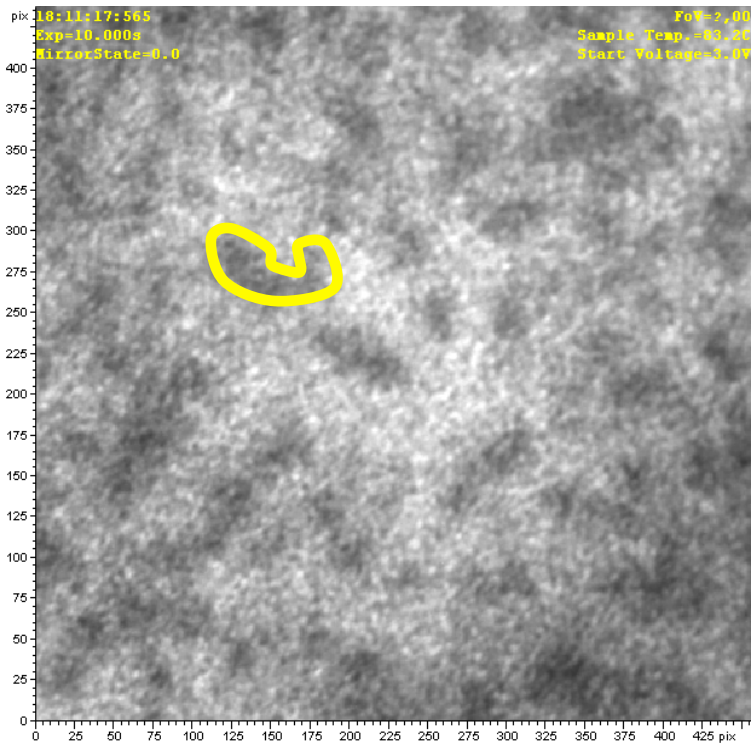
For a better world

PEEM @ MAX II

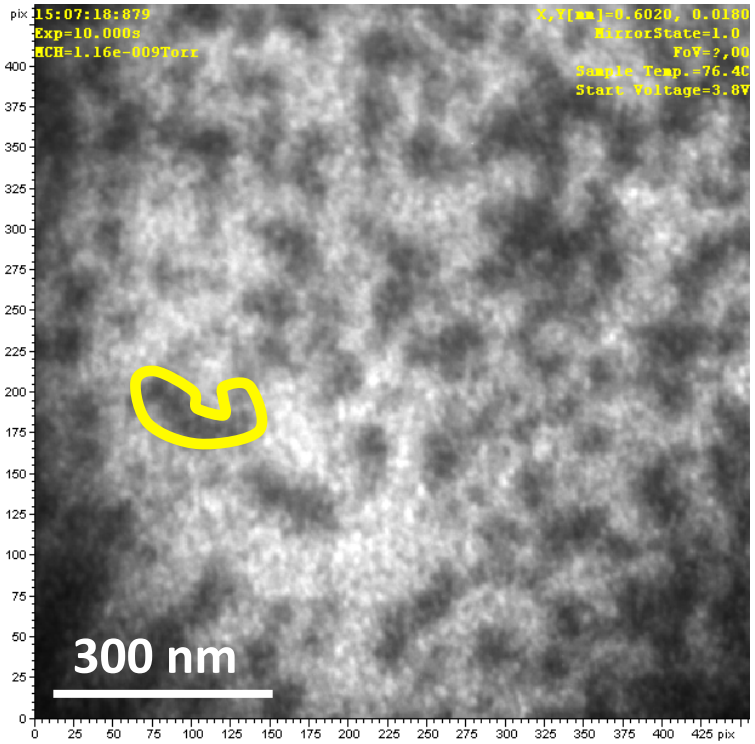
Surface Science



XPEEM hν=130eV SV=3eV SAA 30μm, FoV=1μm



Mirror OFF

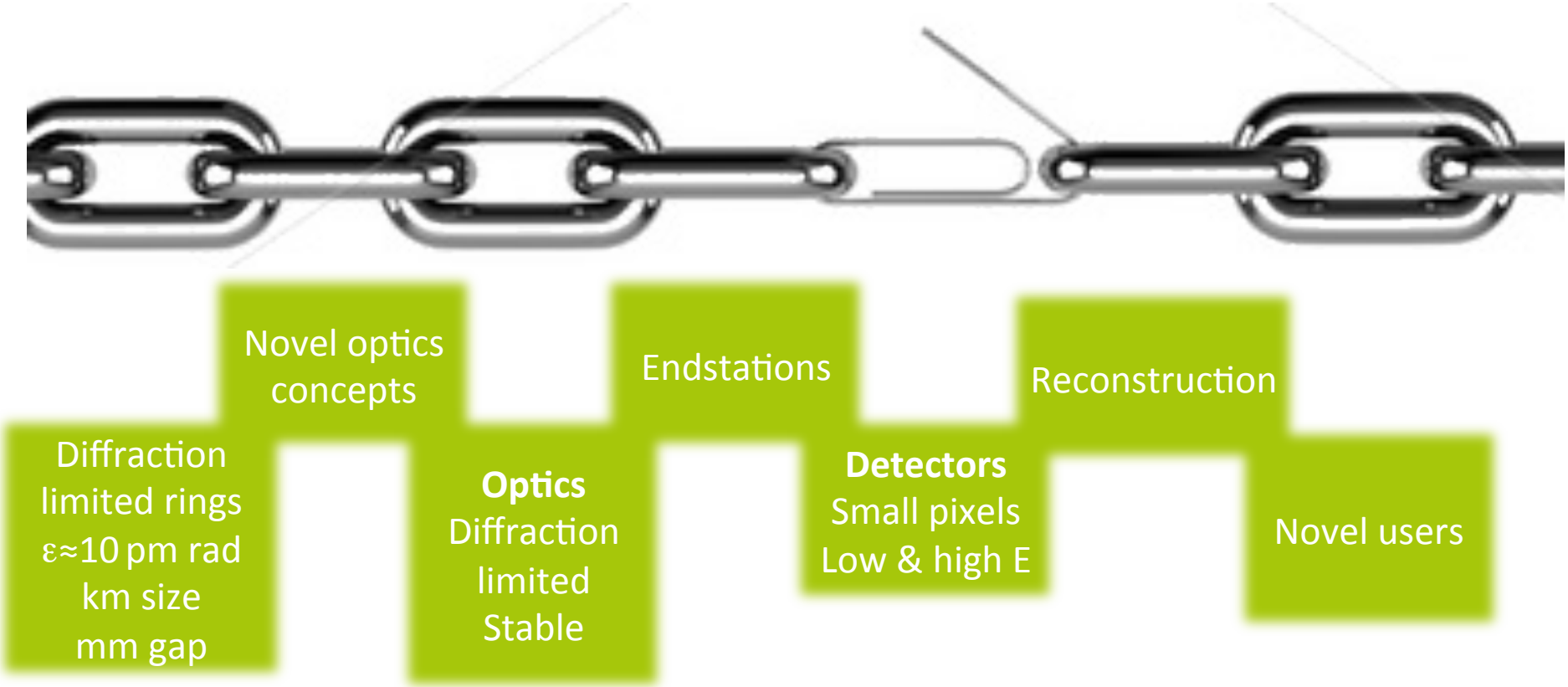


Mirror ON

Suppress space charge effect (insering SAA)!
Aberration corrected column improves spatial resolution & transmission!
Sample: Graphene /Ge/SiC(0001); contrast = $\Delta\Phi$

15nm resolution has been achieved in XPEEM
Higher resolution -> space charge suppression!

Better Microscopy?



- More good photons
- The right sample environment
- Every photon counts

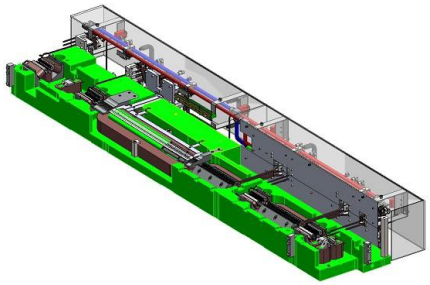
- Understand the imaging
- Show the image
- **Tools for dummies!**

M. Eriksson, J.F. van der Veen, C. Quitmann, J. Synchrotron Rad. (2014). 21

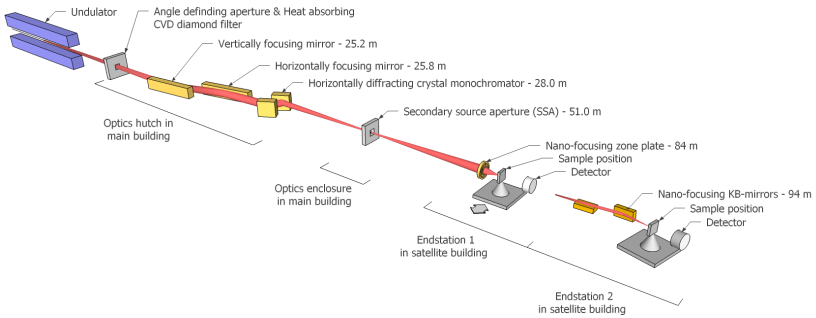
MAX IV: More Coherence!

- MAX-lab -> MAX IV Laboratory
- MAX IV Goals & Design credo

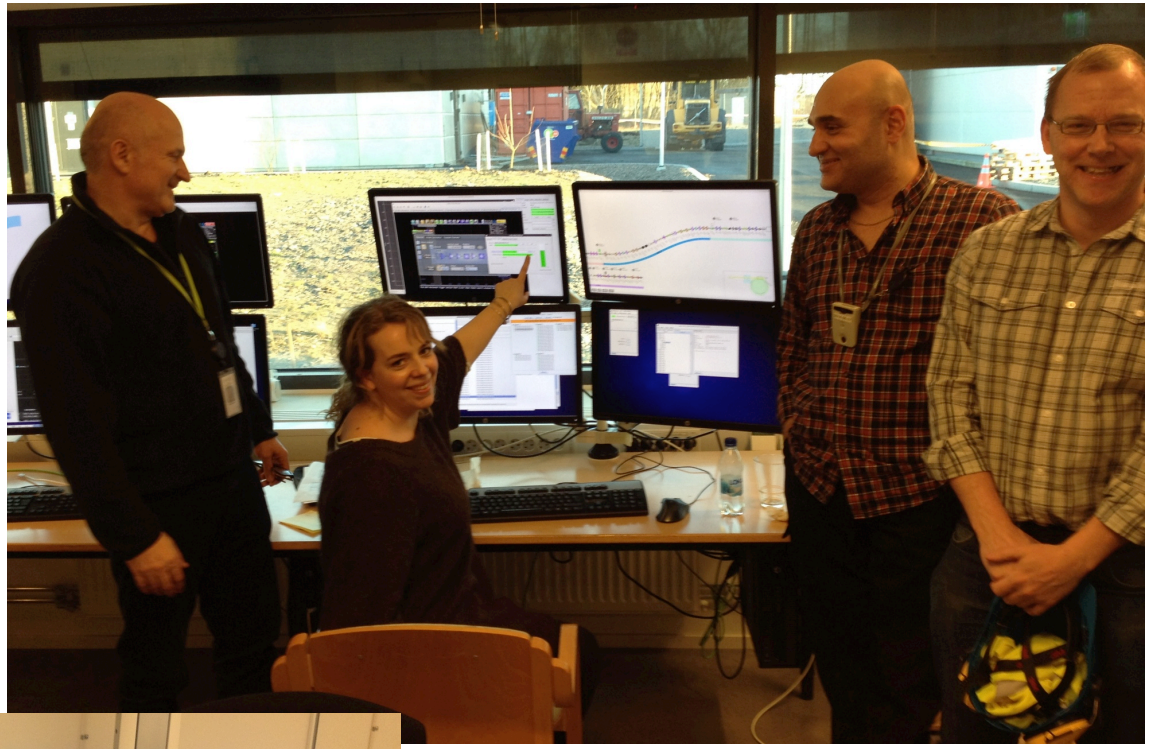
- MBA Concept
- Rings & Linac (& FEL)

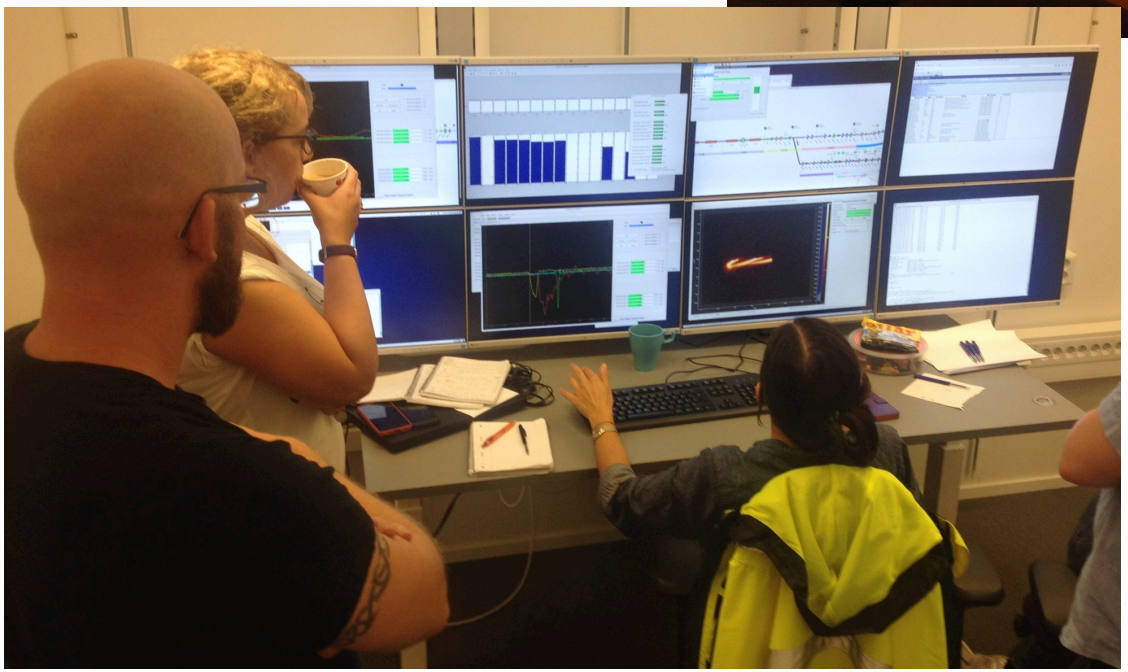


- Microscopy beamlines
  - Nanoprobe
  - Soft x-rays
  - *Bio-medical imaging*
  - PEEM



1st Electrons in LINAC
March 2015

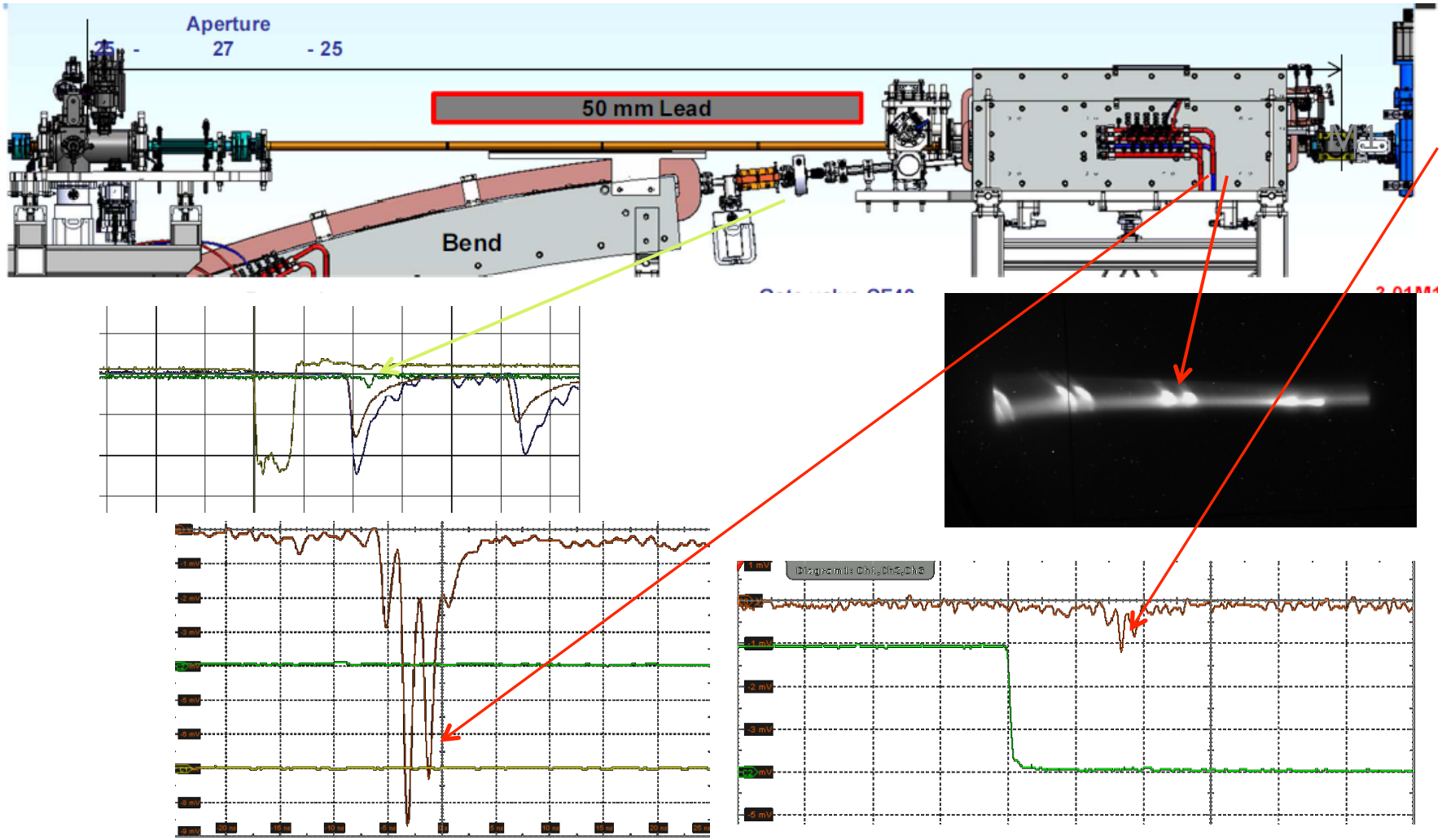




1st Electrons in 3 GeV Ring
Aug 2015

MAX IV

MAX IV Commissioning: Status Aug 14th

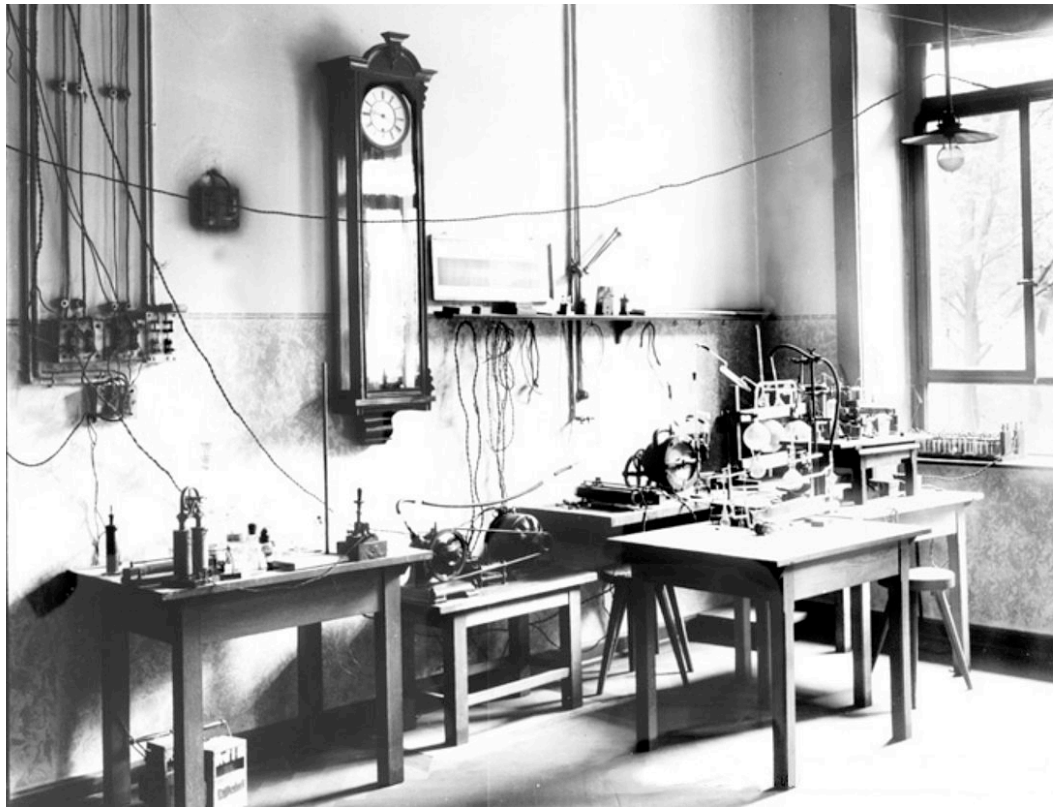


- Beam @ end of TR3 & in 3GeV ring !

MAX IV – A magic X-Ray Lamp

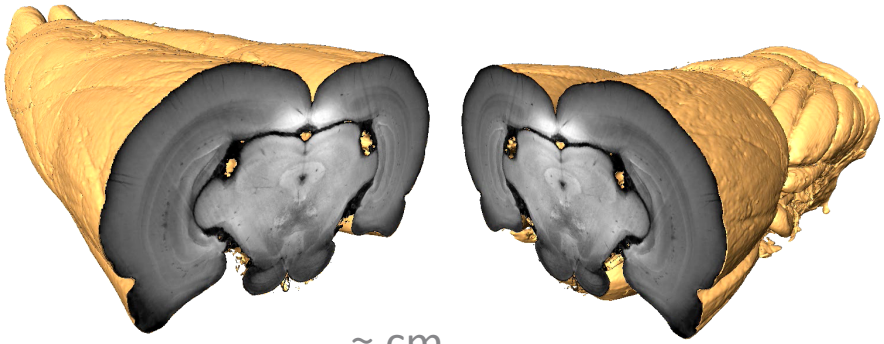
W.C. Röntgen
1845-1923

A.B. Röntgen
1845-1923



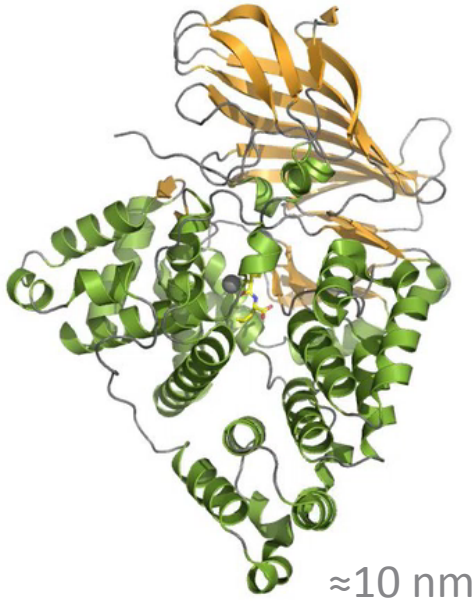
Röntgen's lab 1895, Univ. Würzburg

MAX IV – A magic X-Ray Lamp



≈ cm

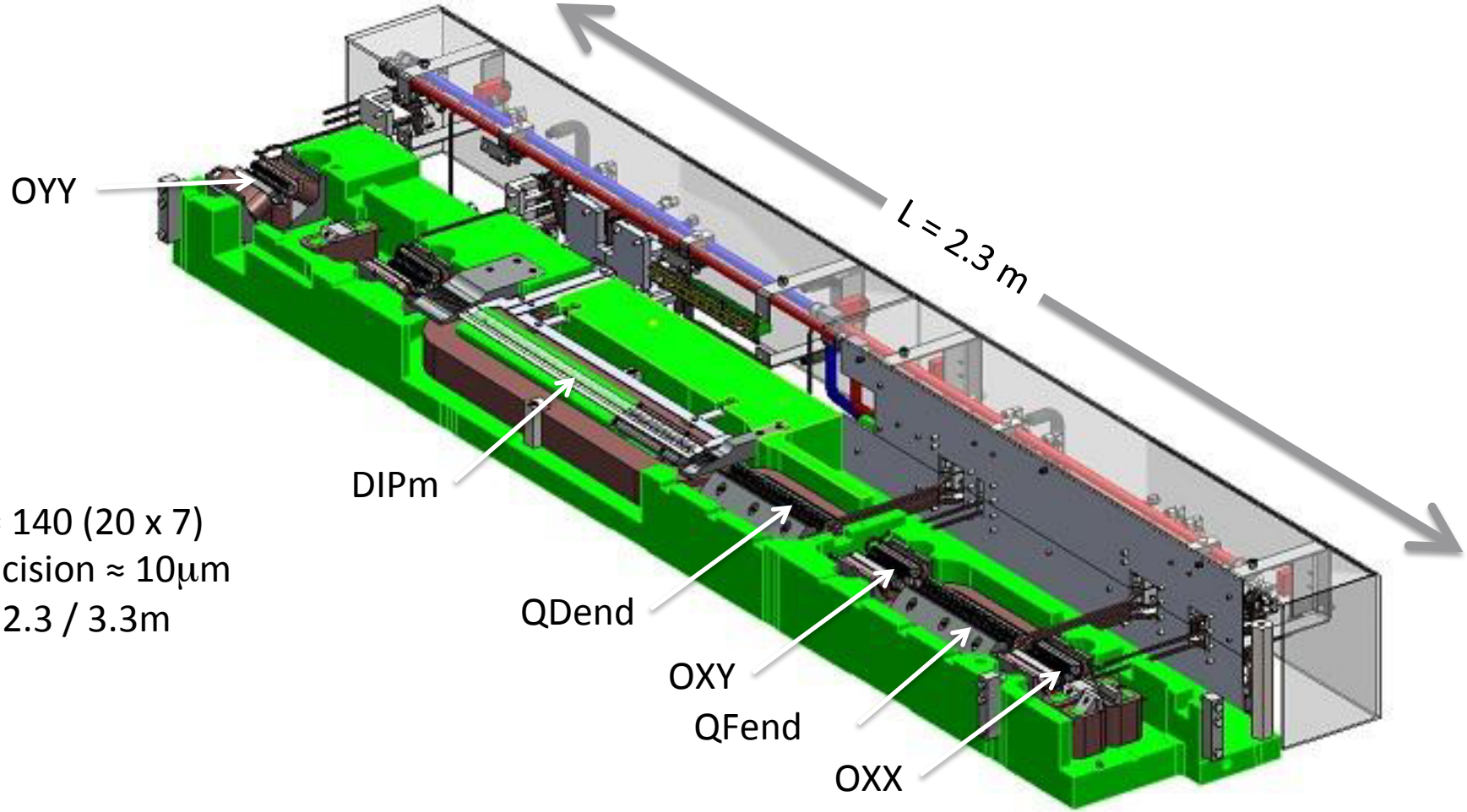
M. Stampanoni,



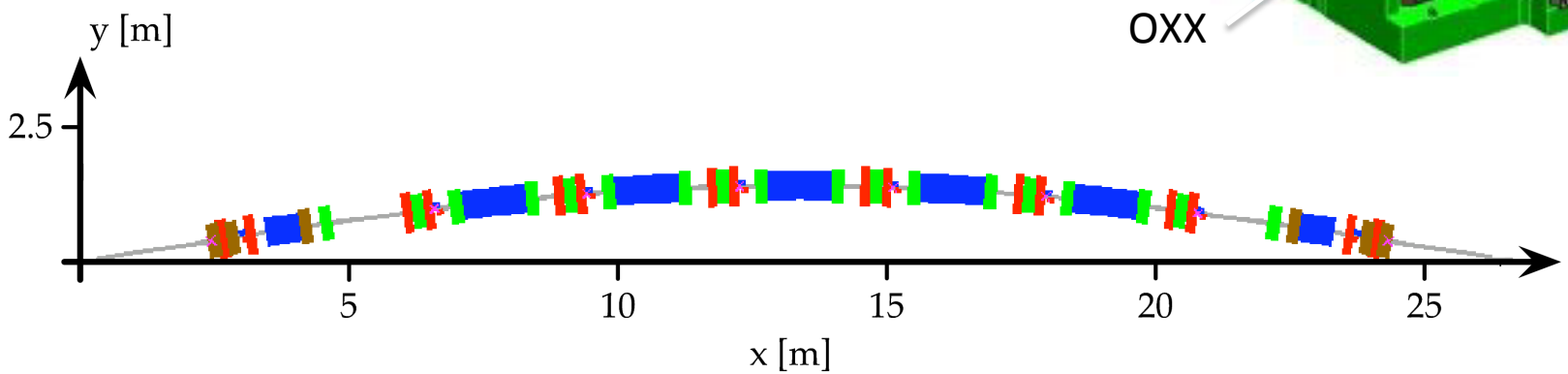
≈10 nm

M. Thunnissen,

MBA – Magnet



N = 140 (20 x 7)
Precision ≈ 10µm
L = 2.3 / 3.3m

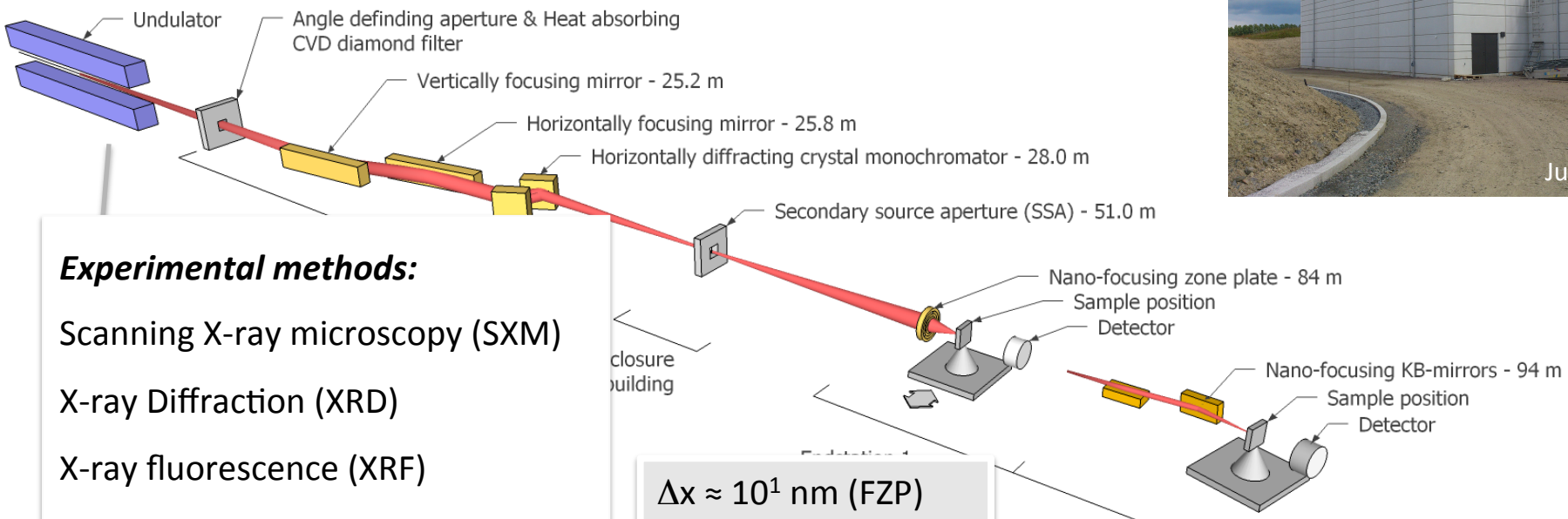


Goal

- Maximum information:
  - Spacial
  - Density
  - Chemical
- Minimum time
  - Radiation damage
  - 4D (x, y, z; t)
- Maximum coherent flux:
  - Flux in focus
  - Contrast to Noise Ratio
- Maximize detector efficiency
  - Every photon counts
- Optimize reconstruction
  - General understanding of x-ray phase- & spectroscopic-contrast
  - Special algorithms for different user communities

MAX IV

NanoMAX beamline @ MAX IV



Experimental methods:

Scanning X-ray microscopy (SXM)

X-ray Diffraction (XRD)

X-ray fluorescence (XRF)

Ptychography and CDI

$\Delta x \approx 10^1$ nm (FZP)
$\approx 3\ 10^{10}$ photons/sec

$\Delta x \approx 10^1$ nm (KB)
$\approx 3\ 10^{11}$ photons/sec

FZP station(s):

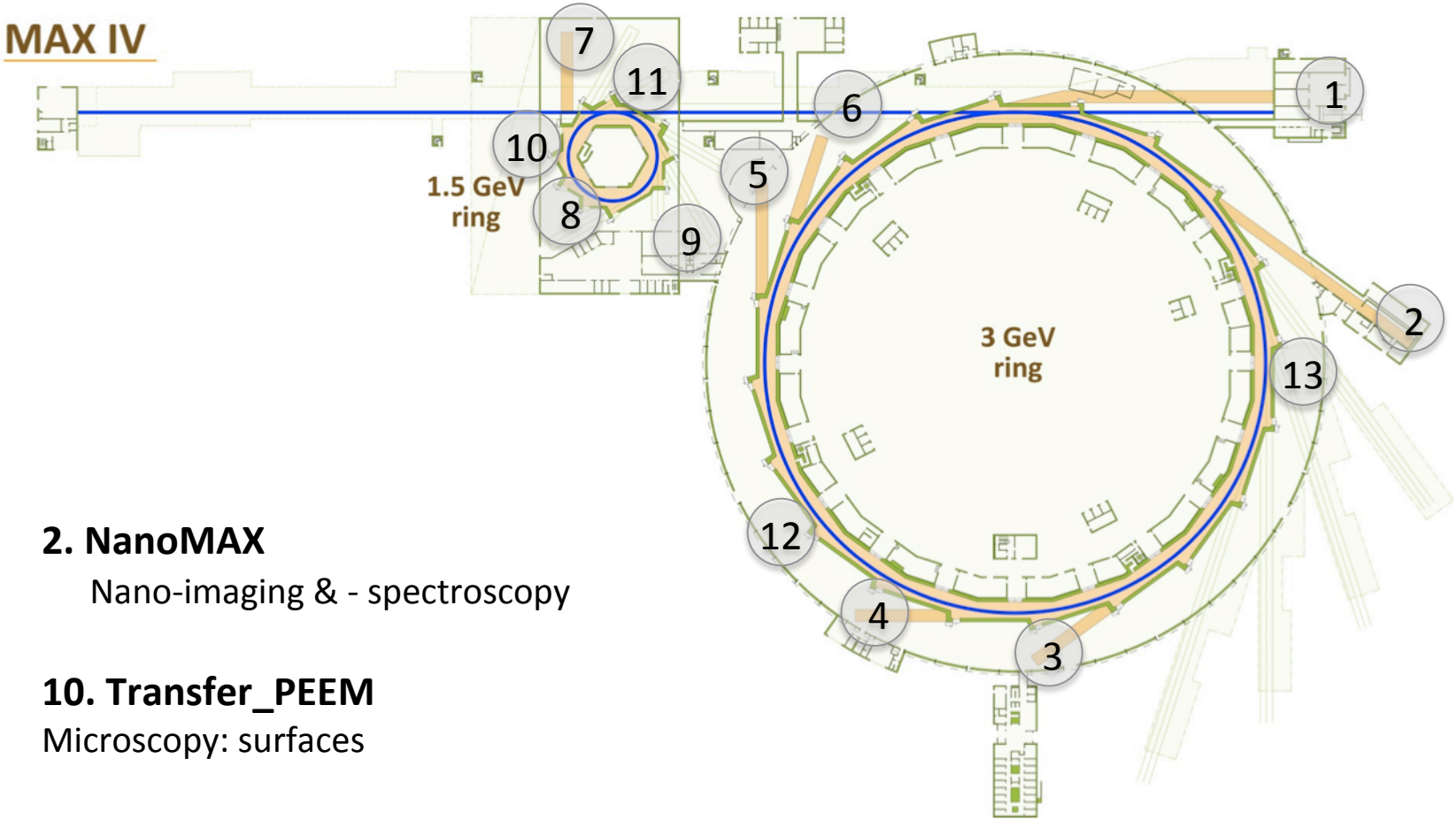
Scanning tomography – CDI and XRF

- "Single-purpose" instrument (sic)
- Cryo-cooling
- Little flexibility, high stability
- ad-hoc sample environment

KB station:

Scanning XRD (CDI) and XRF

- Multipurpose diffractometer
- Flexible sample environment
- Combined analysis (in-situ):
heating, cooling, external electric / magnetic fields, controlled pressure / gas environment, ...



2. NanoMAX

Nano-imaging & - spectroscopy

10. Transfer_PEEM

Microscopy: surfaces

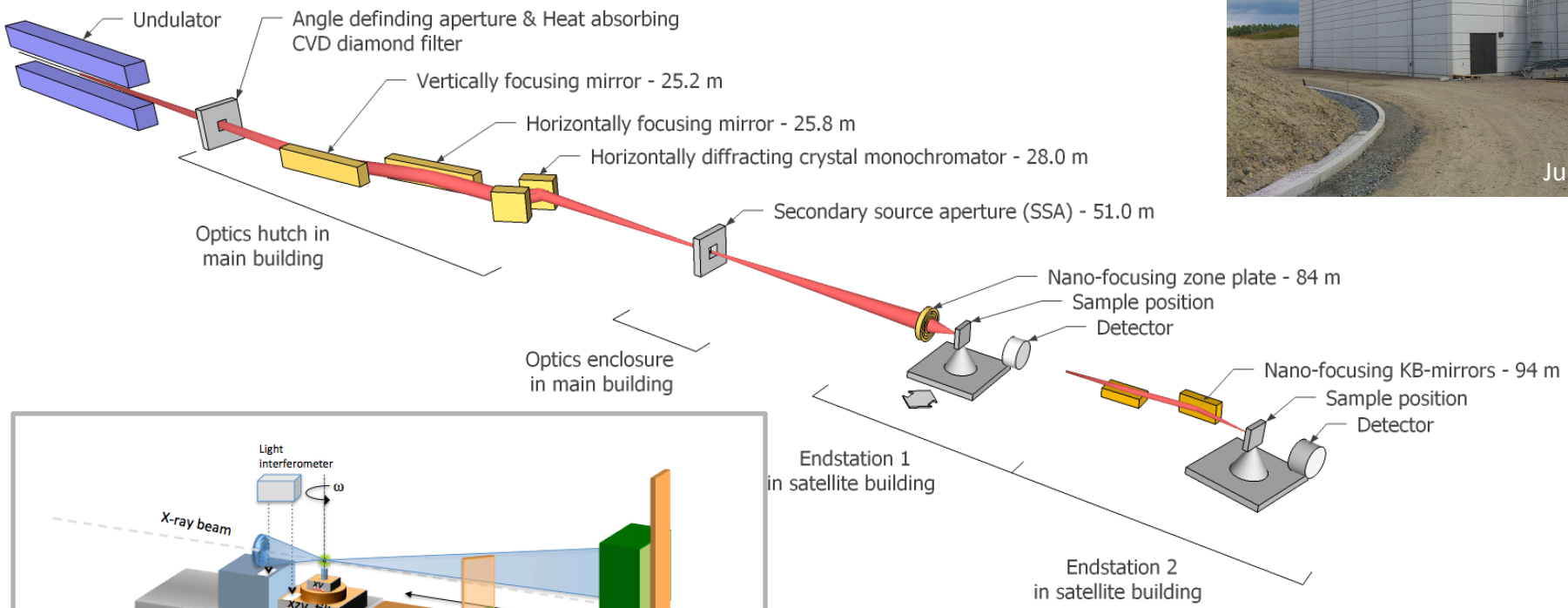
13. Soft*i*MAX

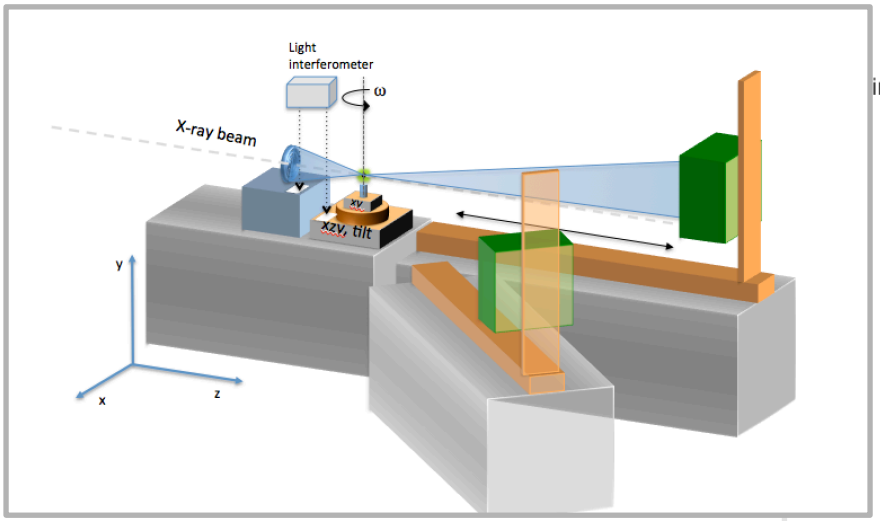
Microscopy & method development

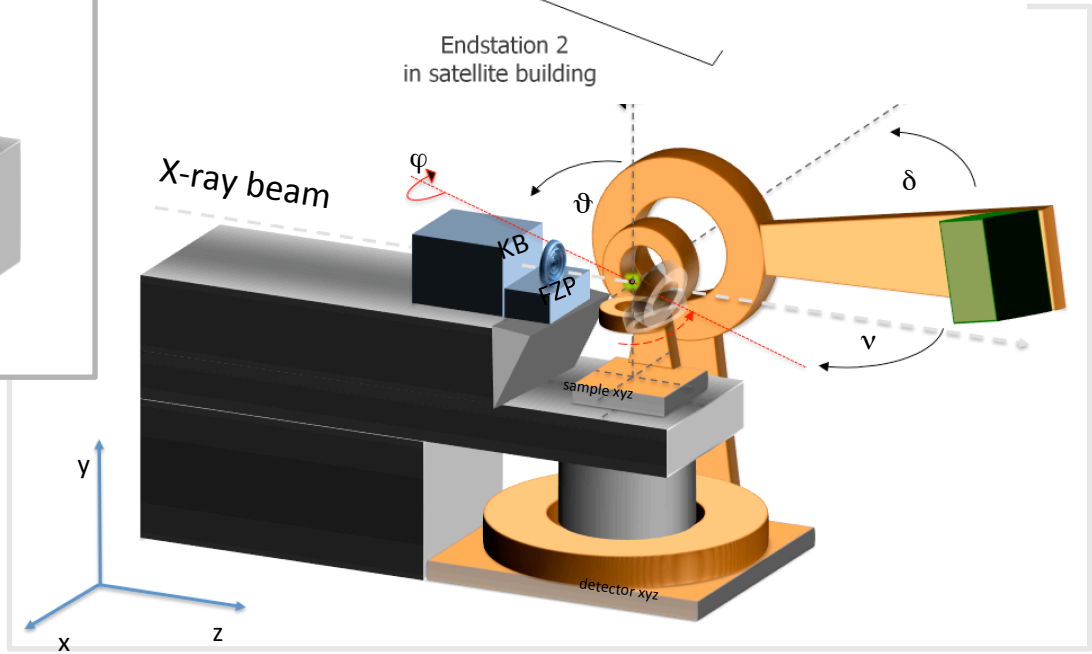
NN. MedMAX

Biomedical imaging

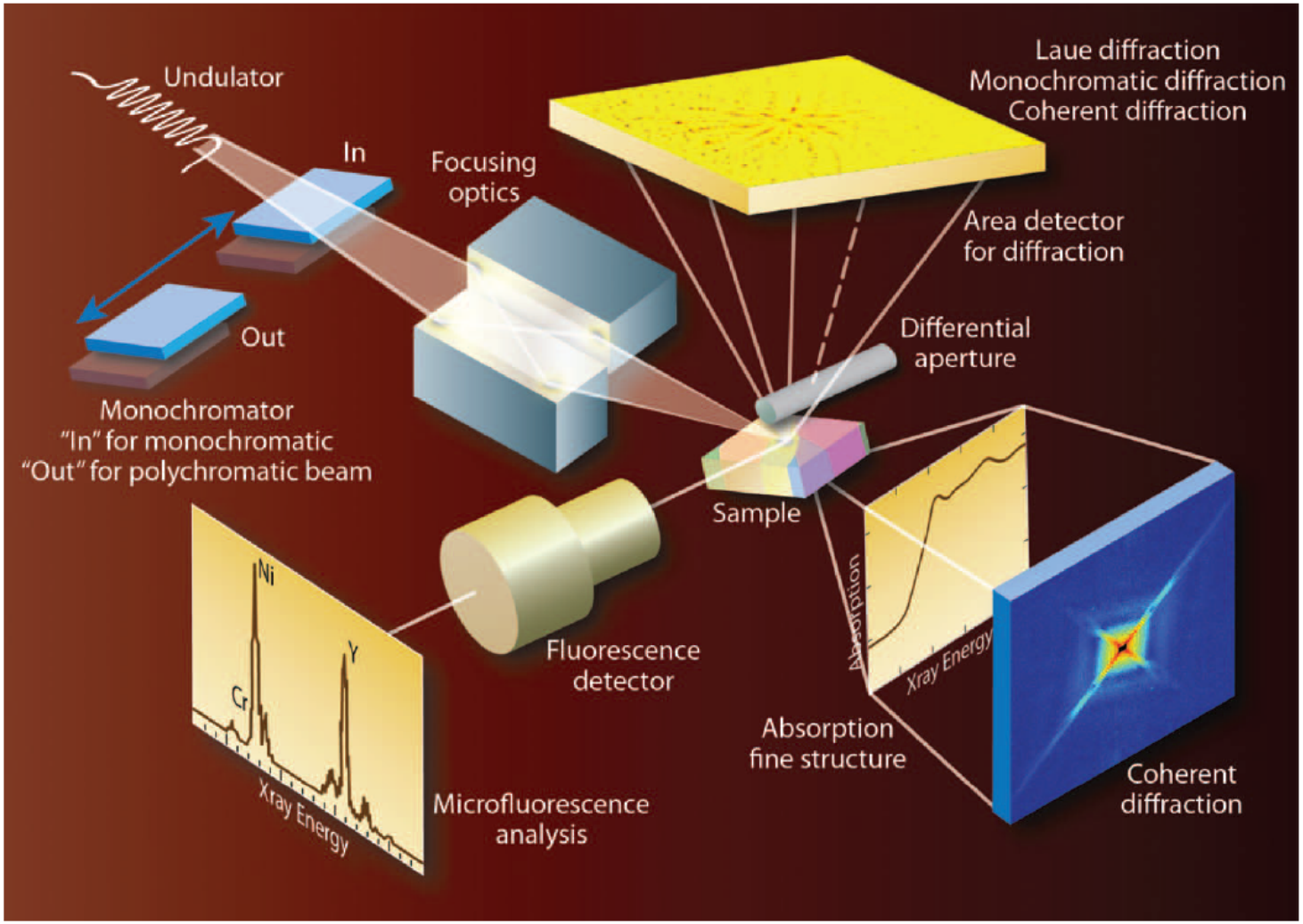
NanoMAX beamline @ MAX IV







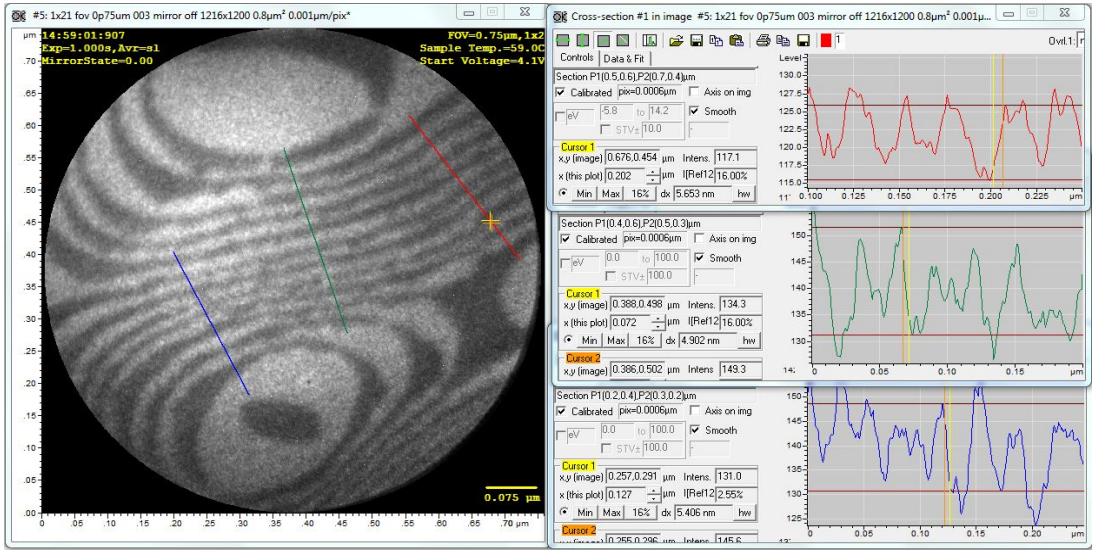
NanoMAX: Hard x-ray nanoprobe



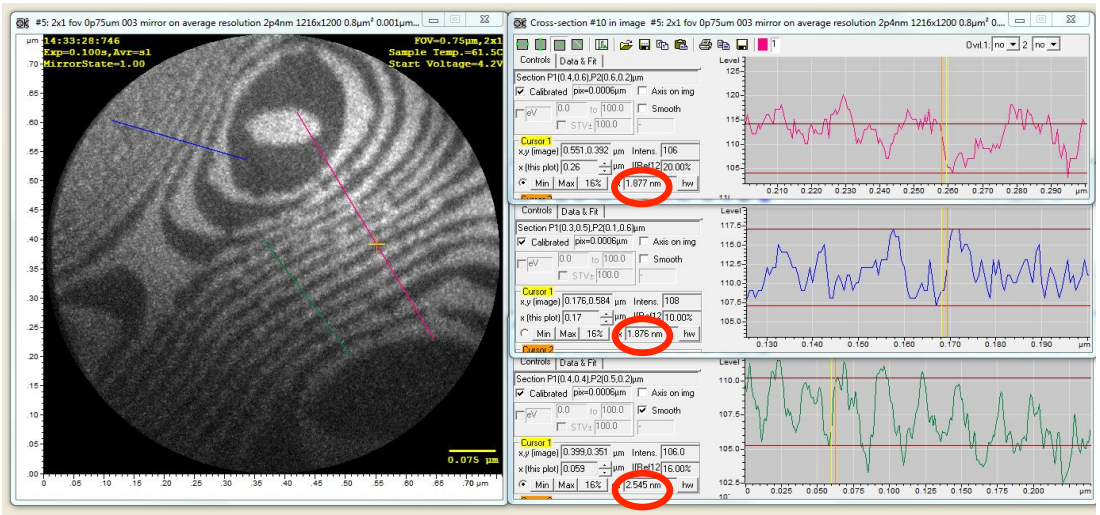
2D & 3D: Diffraction, SAXS, fluorescence, CI, ptychography, ….
Sequential implementation

LEEM Si(100) 1x2, 2x1 DF, FoV=750nm SV=4eV

Mirror OFF



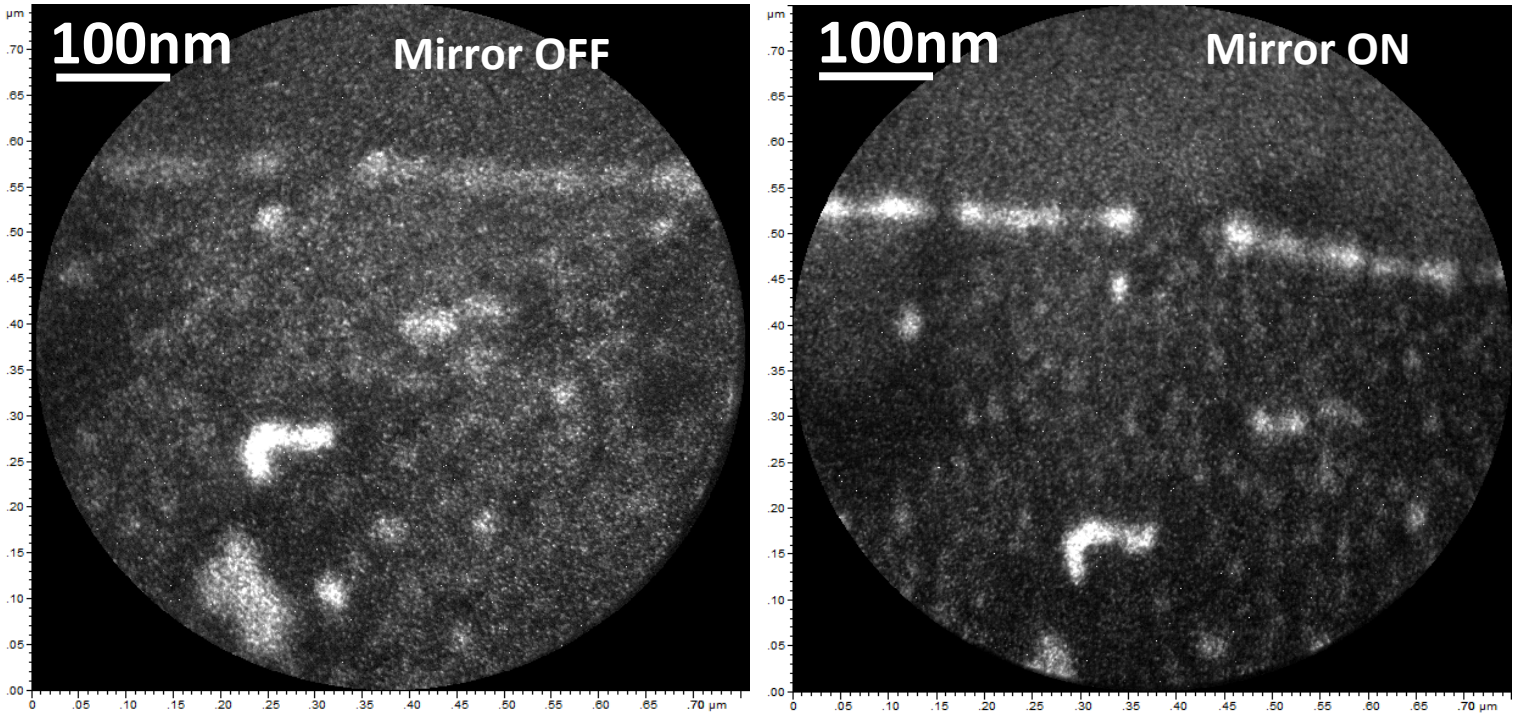
Mirror ON



2nm spatial resolution in the LEEM mode has been achieved with the mirror

MAX IV

UV PEEM G/Au/SiC(0001), FoV=750nm



Sample – Au intercalated graphene/SiC(0001) n-type and p-type areas with different amount of Au underneath graphene. Contrast is due to the work function difference.

It is possible to attain 4nm spatial resolution (diffraction limit!) in the UVPEEM mode with the corrector

MAX IV