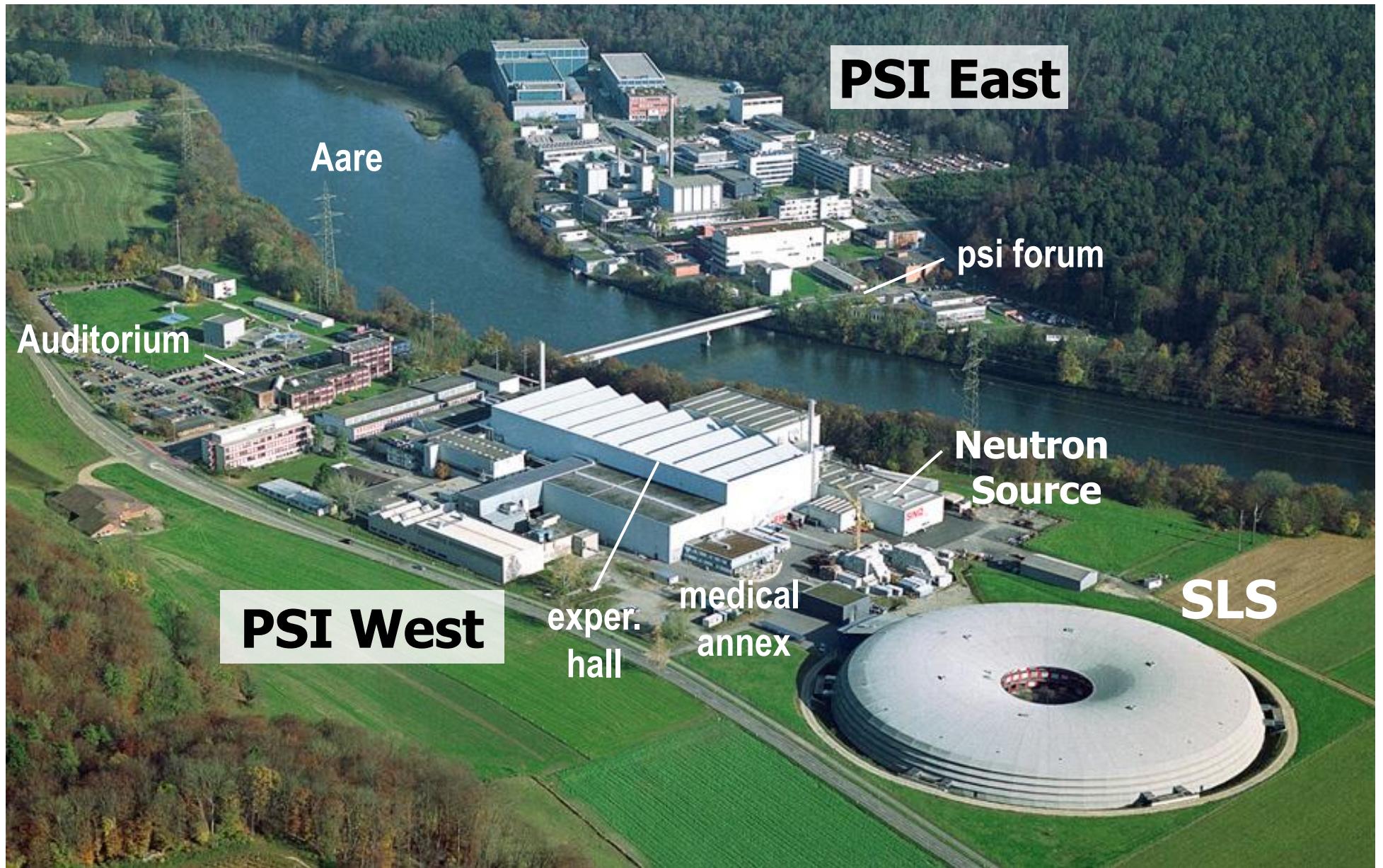


# SLS Swiss Light Source

Werner Joho

PSI

## Aerial View



## State of the Art Accelerator Facilities

Ringcyclotron 590 MeV protons

superconducting cyclotron

**1.4 MW average Beam Power**

high Intensity Muon Beams  
 $5 \cdot 10^8 \mu^+/s$ ,  $10^8 \mu^-/s$

Spallation Neutron Source  $10^{14} n/s$

Radiation Therapy with Spot Scanning and rotating Gantry

Swiss Light Source SLS  
2.4 GeV Electron Storage Ring

- extremely stable photon beams ( $< 0.5 \mu m$ )
- „top-up“ and „fast orbit feedback“ (FOFB)

Nobel Prize in Chemistry 2009 !

V.Ramakrishnan won Nobel prize in chemistry

He is a user of a protein crystallography beam line at  
the SLS at PSI

**Investigation of Ribosomes with x-ray diffraction**

## 3 Probes for Material Research

only at PSI and Rutherford Lab

**Photons (SLS)**  **Electron Cloud**

**Neutrons (SINQ)**  **Atomic Nuclei**

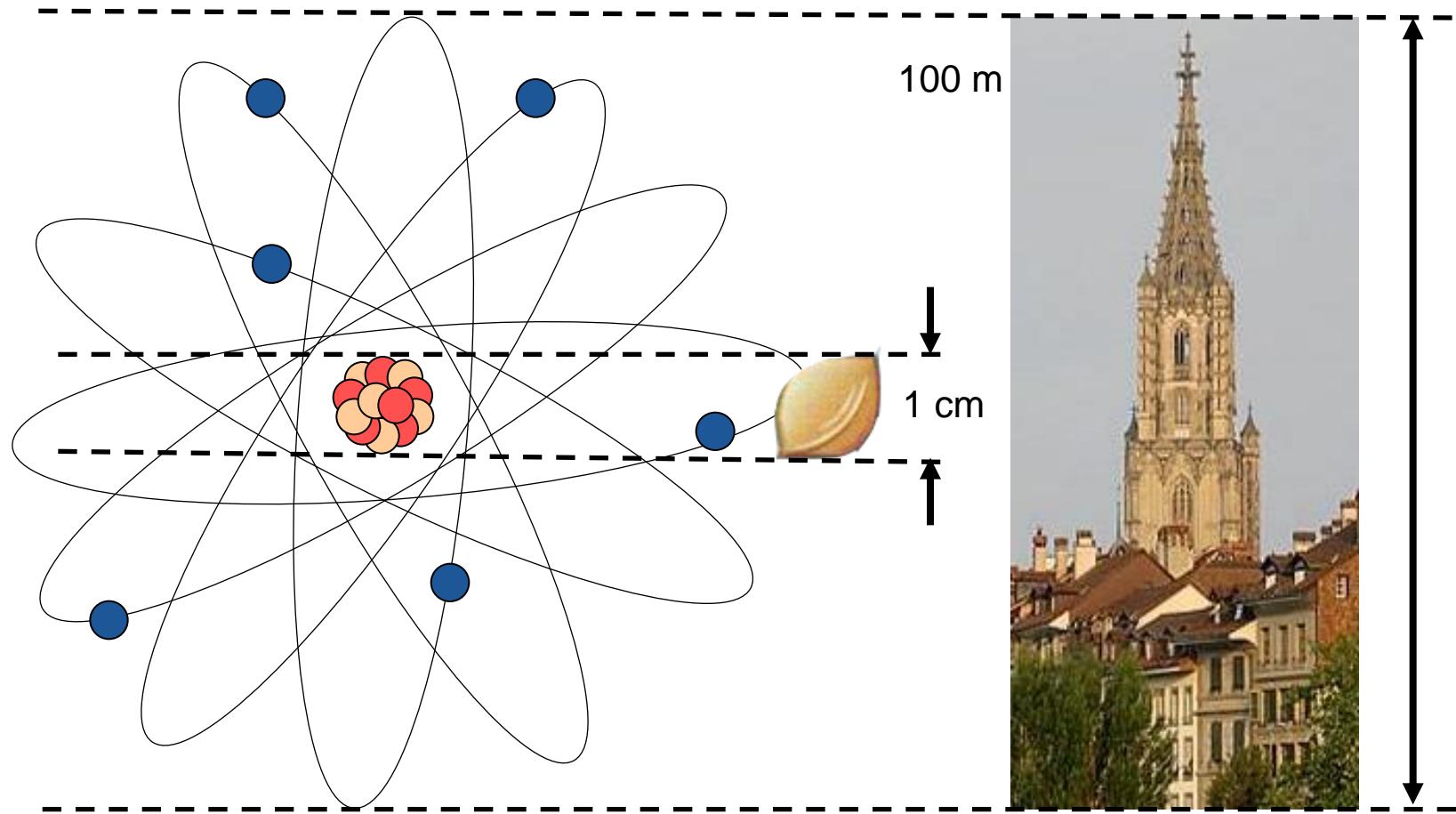
**Muons ( $\mu$ SR)**  **internal magnetic  
Fields in Crystals**

# Facilities in Europe

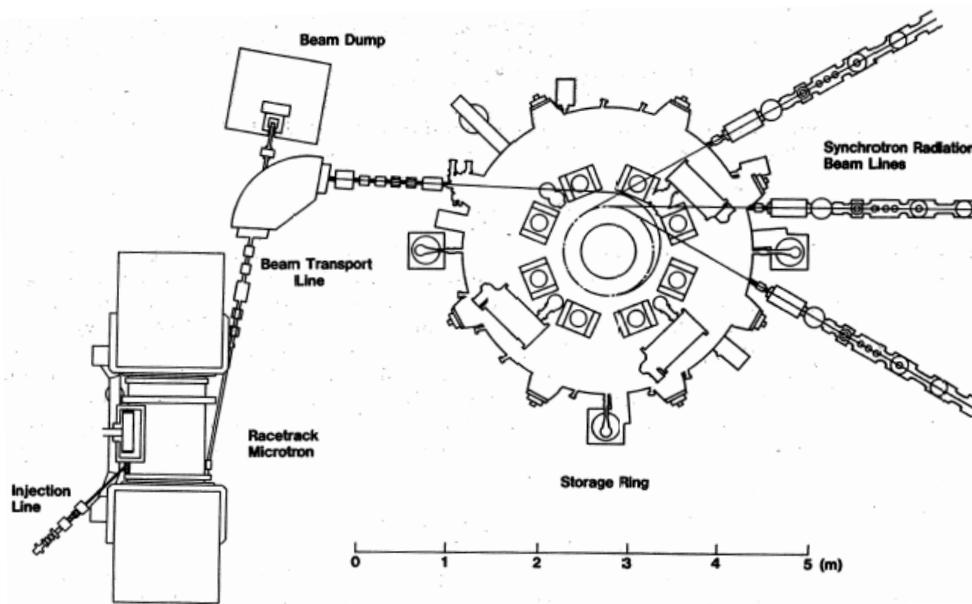


X-rays  
Neutrons  
Muons

# Size comparison Nucleus => Atom



# Aurora (Japan)

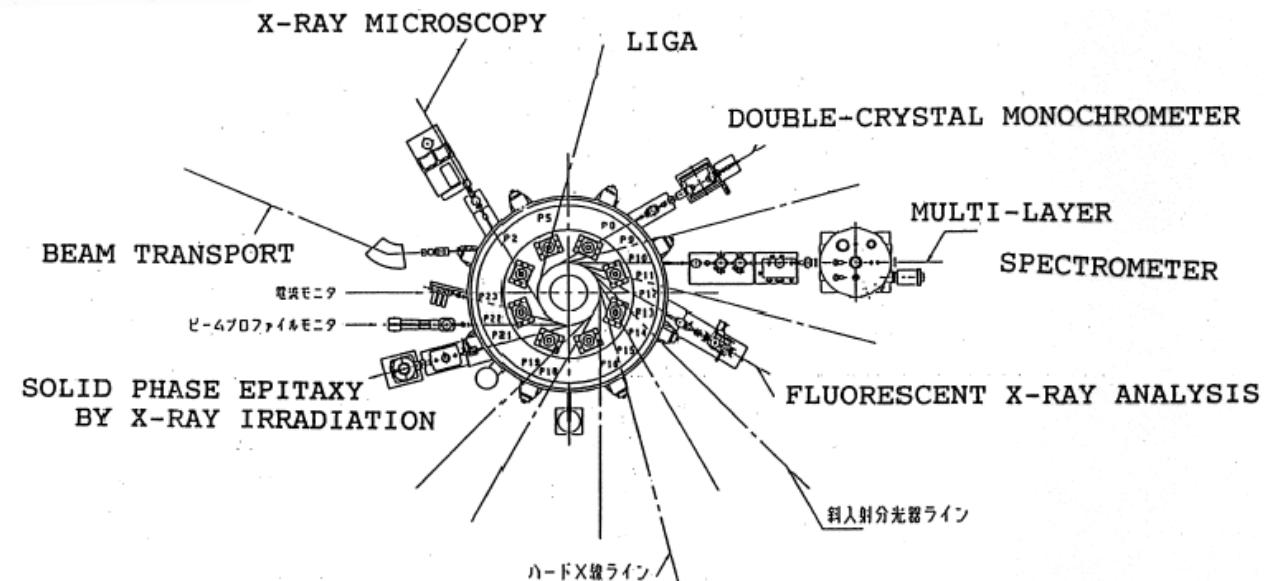


a very compact Storage Ring ,  
orbit radius = 0.5m

superconducting magnet,  $B = 4.3\text{ T}$

$E = 650\text{ MeV}$  (Injection at 150 MeV)

critical wavelength of  
synchrotron radiation = 1 nm

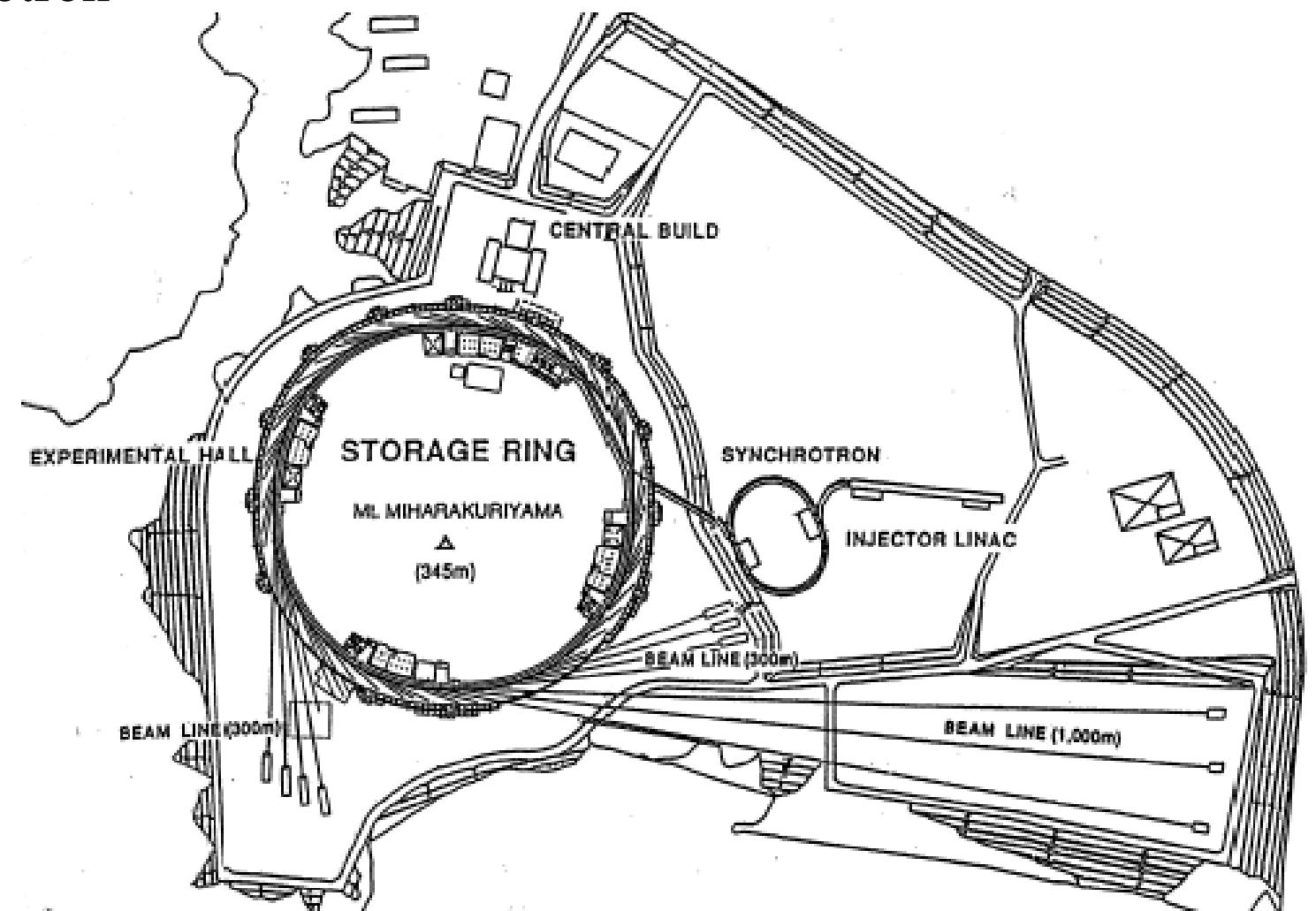


## Spring8 (Japan)

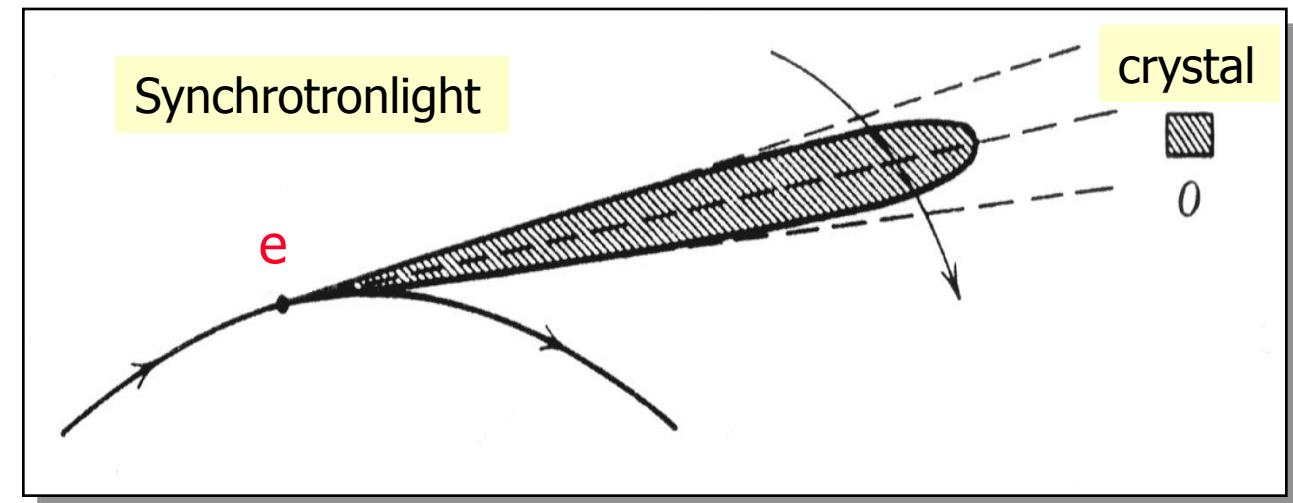
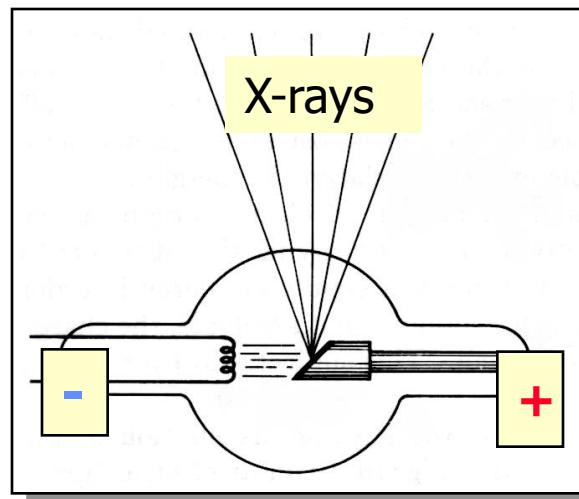
the largest Synchrotron  
Radiation Source

8 GeV electrons

circumference of  
storage ring: 1435 m  
(circling a 60m high  
mountain!)



## Production of X-rays



Production with X-ray Tube  
(60-90kV)

broad beam => big objects

Produktion of X-rays with fast Electrons  
in magnetic field

intensive, laser-like beam

=> Microstructures

## Electromagnetic Waves

- 1) RF-fields shake the electrons back and forth in an antenna  
=> **Radio/ TV/ Radar-waves**
- 2) in a X-Ray Tube electrons are accelerated to 50-90 keV and then stopped in an electrode  
=> **X-Rays**
- 3) Electrons are deflected in a magnetic Field B through the Lorentz Force  $e(v \times B)$   
=> **Synchrotron Radiation**  
  
increases dramatically with Energie  $E = \gamma mc^2$

## Synchrotron Radiation

- laser-like Beams (polarised),  
generated by high Energy **Electrons**
- very high Intensity (Brightness)
- free choice of Wavelength  
from infrared to hard X-Rays

what is needed?

⇒ a **Storage Ring** (with many Magnets), where  
Electrons can circulate for hours

# electromagnetic Spectrum

	Wavelength $\lambda$	Energy $\epsilon$
FM-Radio (100 MHz)	3 m	
Radar (3 GHz)	0.1 m	
infrared light	1-1000 $\mu\text{m}$	1-1000 meV
red light	700 nm	1.8 eV
violett light	400 nm	3 eV
vacuum ultra violet	4-200 nm	6-300 eV
soft X-Rays	0.4 nm	3 keV
hard X-Rays	0.04 nm	30 keV
Gamma-Rays		1-10 MeV

$$\lambda \cdot \epsilon = 1.24 \text{ nm} \cdot \text{keV}$$

Synchrotron Radiation: free choice of wavelength  $\lambda$

## SLS-Components

### Accelerators

- Electron gun                      90 keV
- LINAC                              100 MeV
- Booster, 3 Hz                    0.1-2.4 GeV
- Storage Ring, 288m            2.4 GeV

### Beamlines

- Protein Cristallography
- Material Sciences
- Surface Microscopy
- Surface Spectroscopy
- environment sciences

## SLS Strategy

Quality

- high brightness , small emittance,  
→ large circumference with many magnets

Flexibility

- large spectral range (VUV to hard x-rays)
- straights of 4 m, 7 m and 11 m => choice for undulators

Stability

- separation of building structure from floor
- stable temperature in tunnel and experimental hall
- positioning of the magnets on rigid girders
- fast orbit feedback (up to 100Hz)  
with high accuracy (< 0.5 µm)
- constant beam current with **top-up injection** (every 2 min)  
→ constant heatload on optical components

# stable Beams with small Emittance

big Storage Ring with many Magnets

mechanical  
Stability

Temperature  
Stability

Orbit  
Stability

Hall

Magnet  
Girder

Hall  
 $\pm 0.2^0$

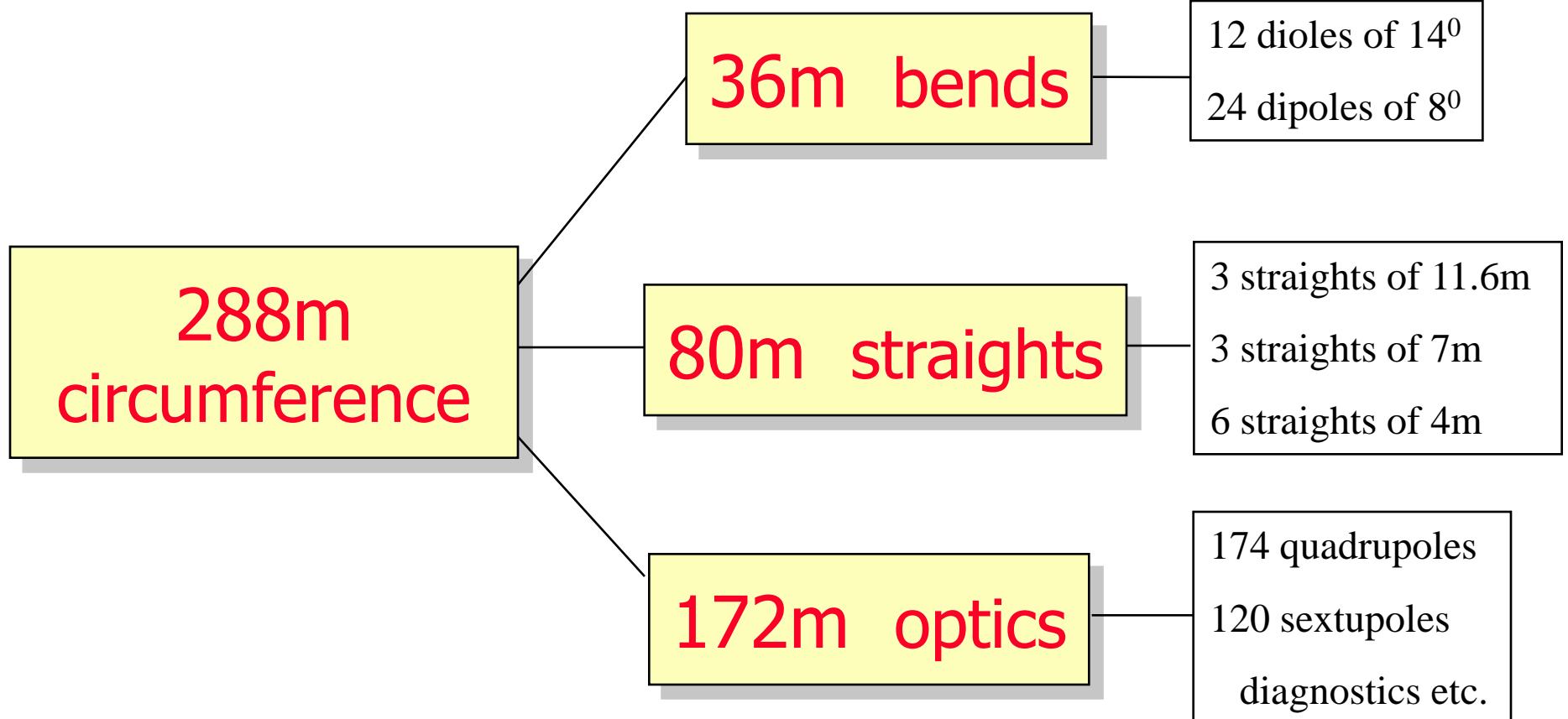
Tunnel  
 $\pm 0.03^0$

Optics  
Comp.

Top-up

„Fast Orbit  
Feed-Back“

## Allocation of space for Storage Ring



# what is special at SLS ?

## 1. very good beam quality , high brightness

(requires large circumference, many magnets)

- microscopy ( ca. 30 nm) , spectroscopy
- small probes (microcrystals)
- beamstability  $< 0.5 \mu\text{m}$  (with fast orbit feed back)

## 2. large spectral range :

infrared to hard X-rays (6 decades !)

## what is special at SLS ?

### 3. Short, Medium and Long Straights

(6 à 4 m, 3 à 7 m, 3 à 11.5 m)

- flexibel undulator schemes  
(e.g. variation of the polarization in the kHz-region)

### 4. Top-up Injection :

- constant beam intensity over days (beam lifetime is irrelevant !)  
=> constant heat load on optical components

## Research with Synchrotron Radiation

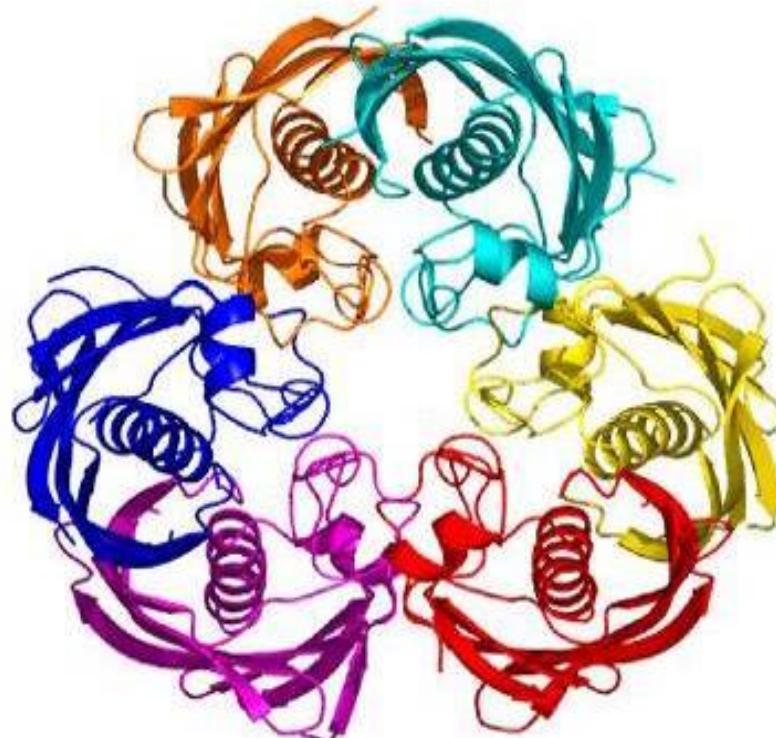
### X-Ray Analysis

- Structure of Bio-Molecules (Proteins)  
=> new drugs
- new Materials, Nano-Structures
- Micro-Tomography  
(3-dim. Reconstruction  
e.g. biological probes)
- high Temperature Superconductors

### X-Ray Microscopy

- compact magnetic Structures  
=> Data Storage
- Solar Cells
- special Surfaces  
(Catalysts, minimal Friction etc.)
- Detection of Trace Elements on  
Surfaces => Analysis of Impurities

# Protein Crystallography



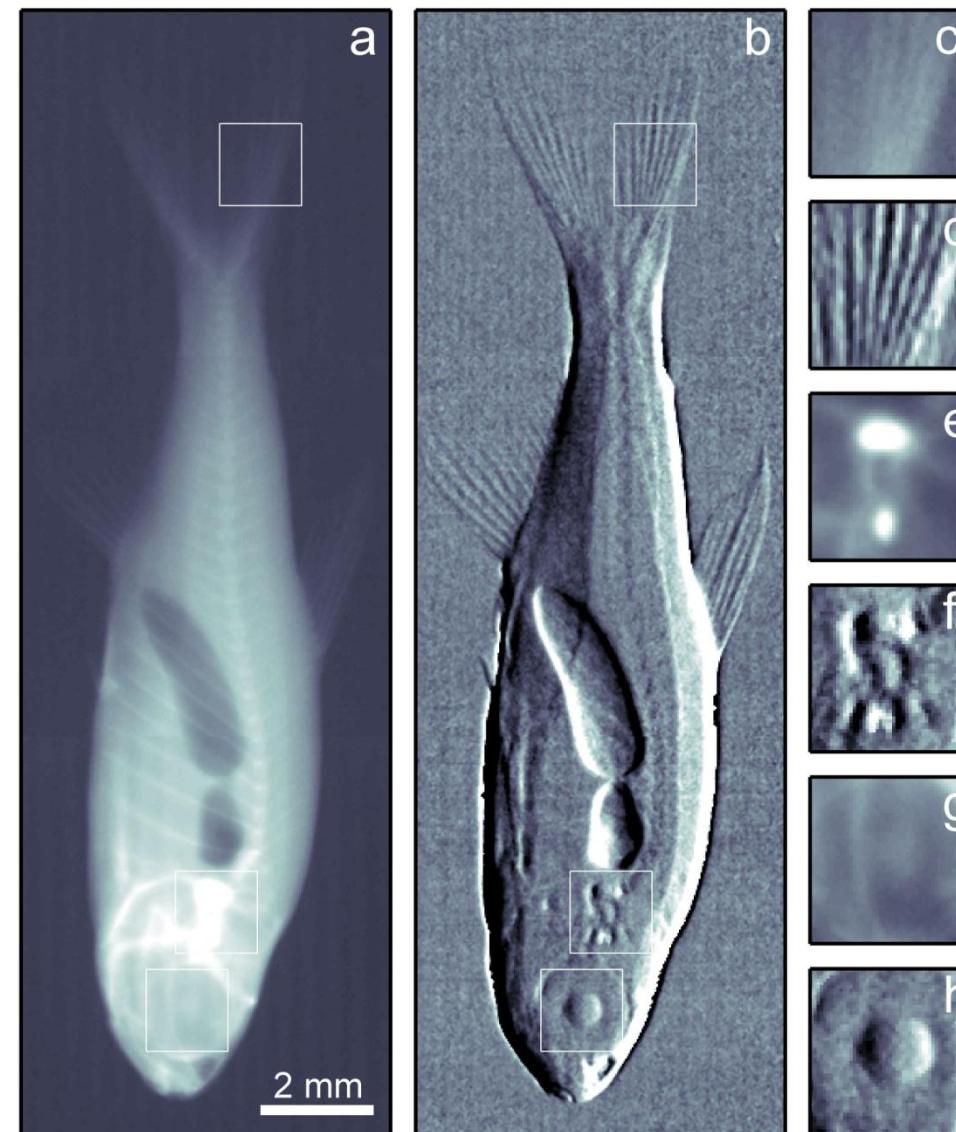
Structures of two important Enzymes of the Generator of Malaria

Growth of Bio Molecules to Crystals (size 5-50  $\mu\text{m}$ )

=> Reconstruction with X-rays

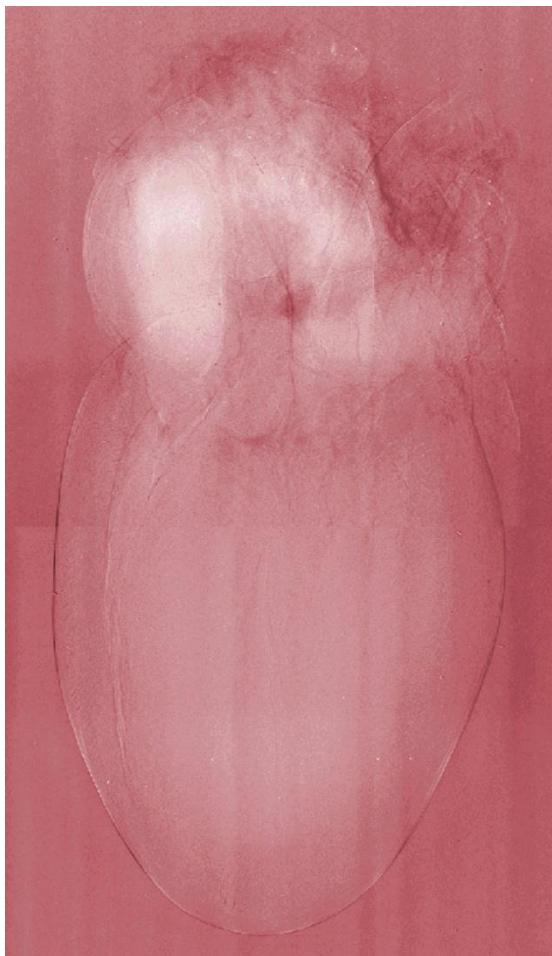
## X-ray Radiography of a fish

conventional  
Absorption a  
(+ details c , e, g)



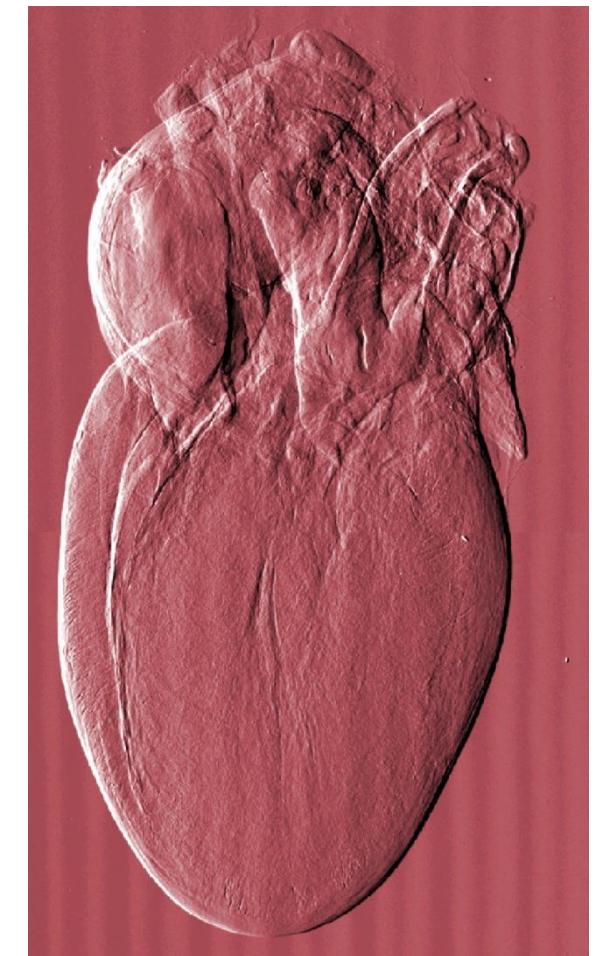
Phase contrast  
Microscopy b  
(+ details d, f, h)  
(F.Pfeiffer)

conventional  
Absorption



## X-ray Radiography on the heart of a rat

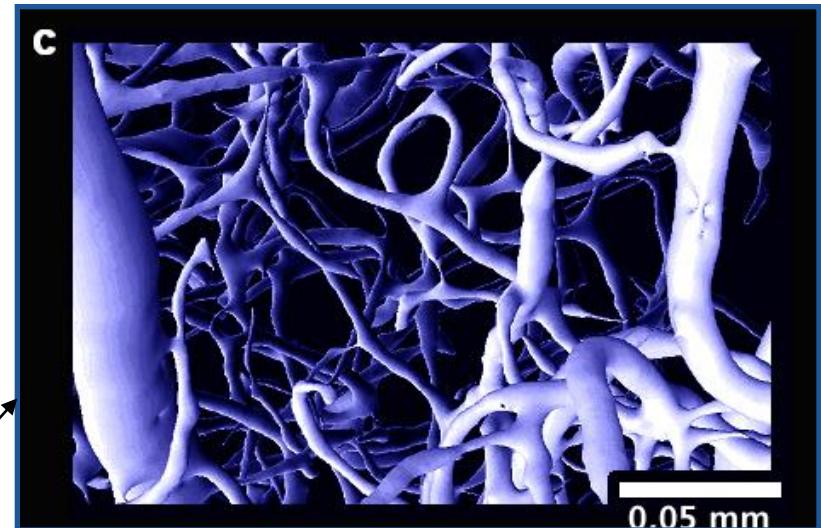
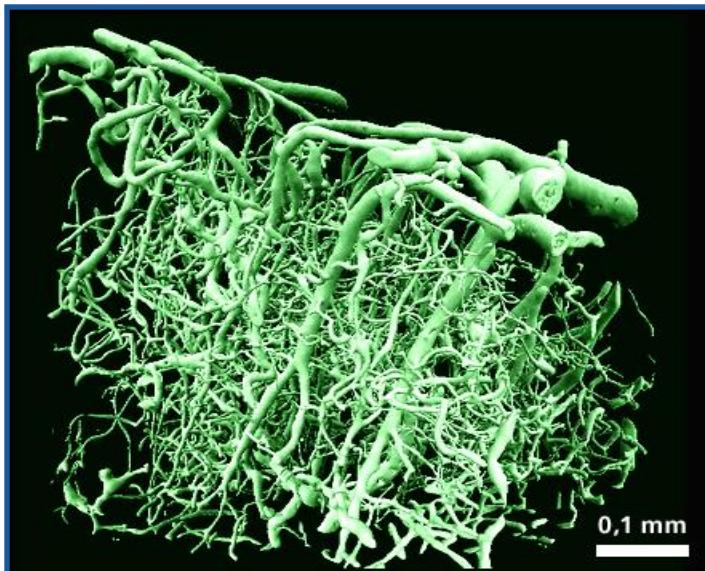
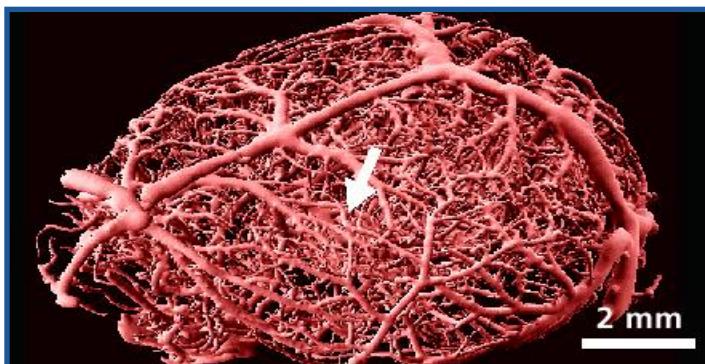
Phase contrast  
Microscopy  
(C.David, F.Pfeiffer)



# Microtomography

Blood Vessels in the Brain of a Mouse  
 (infected by Alzheimer)

full size



Details

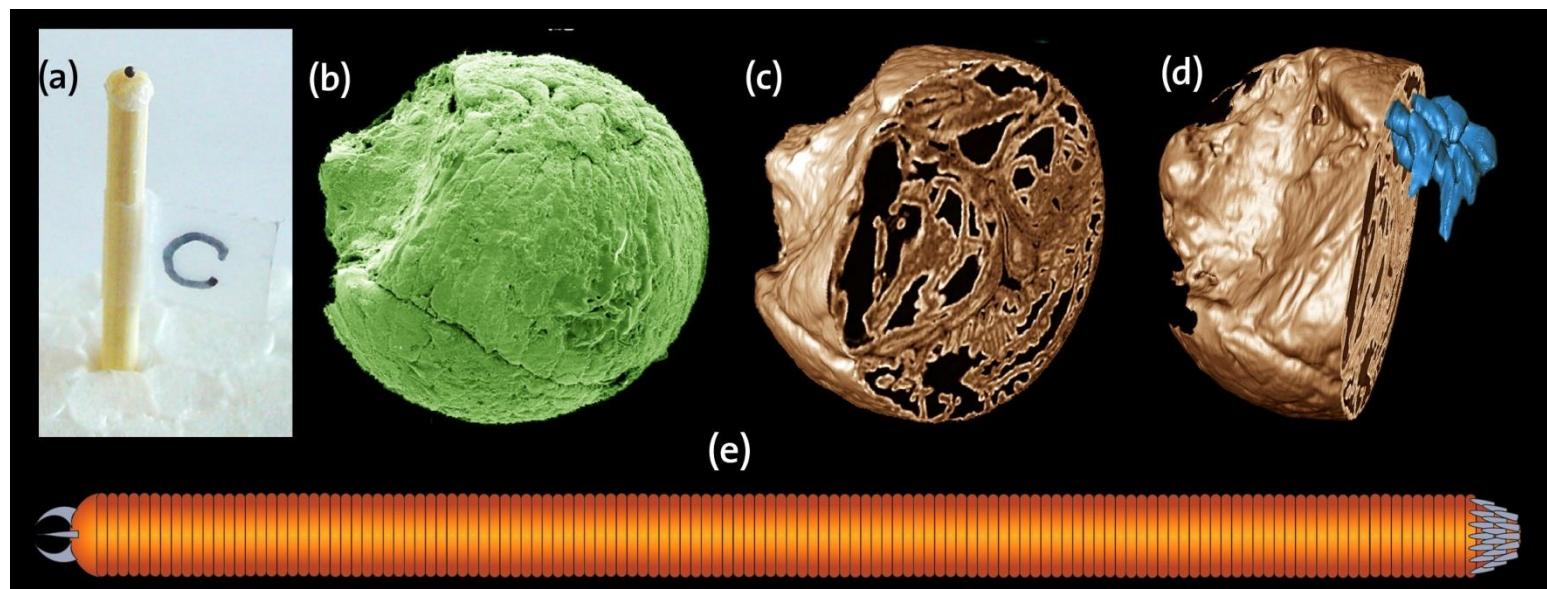
insufficient Blood Circulation  
 ⇒ Deficiency in Oxygen

⇒ Protein Deposits

⇒ Alzheimer

# Micro-Tomography

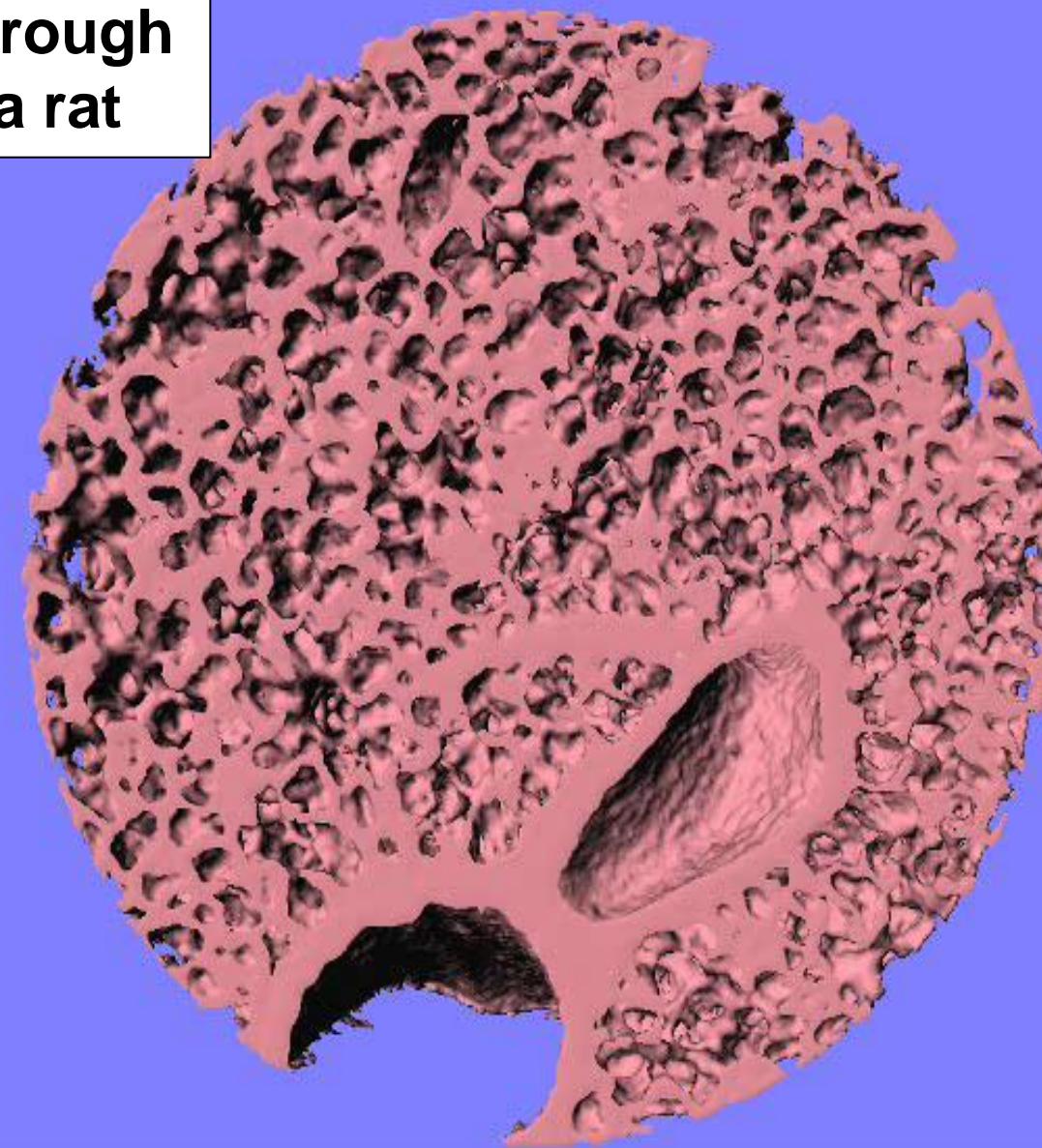
(M.Stampanoni)



Embryo of fossile Worm (*Markuelia secunda*), 500 Million years old

- a) black point on tooth pick
- b) from Analysis with Electron Scanning Microscope
- c) tomographic reconstruction at SLS
- d) Tail of Embryo (right)
- e) total Reconstruction (Head on left side)

## a voyage through the lung of a rat

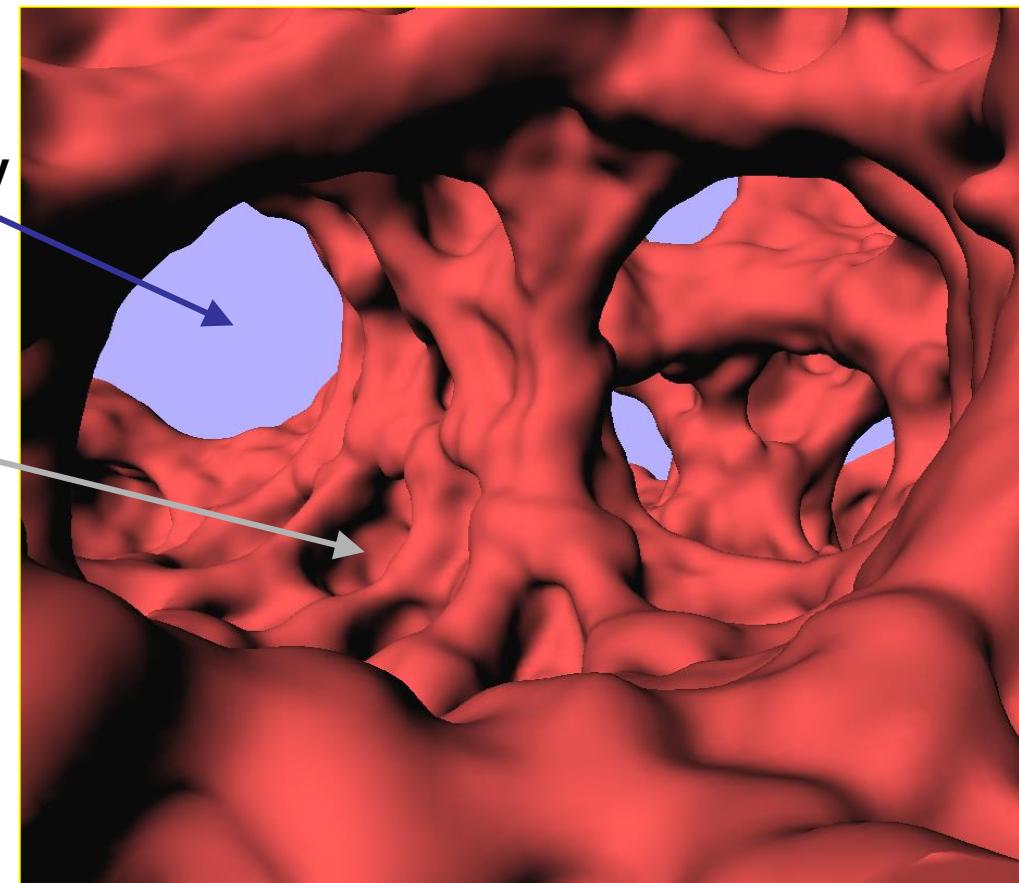


0.1 mm



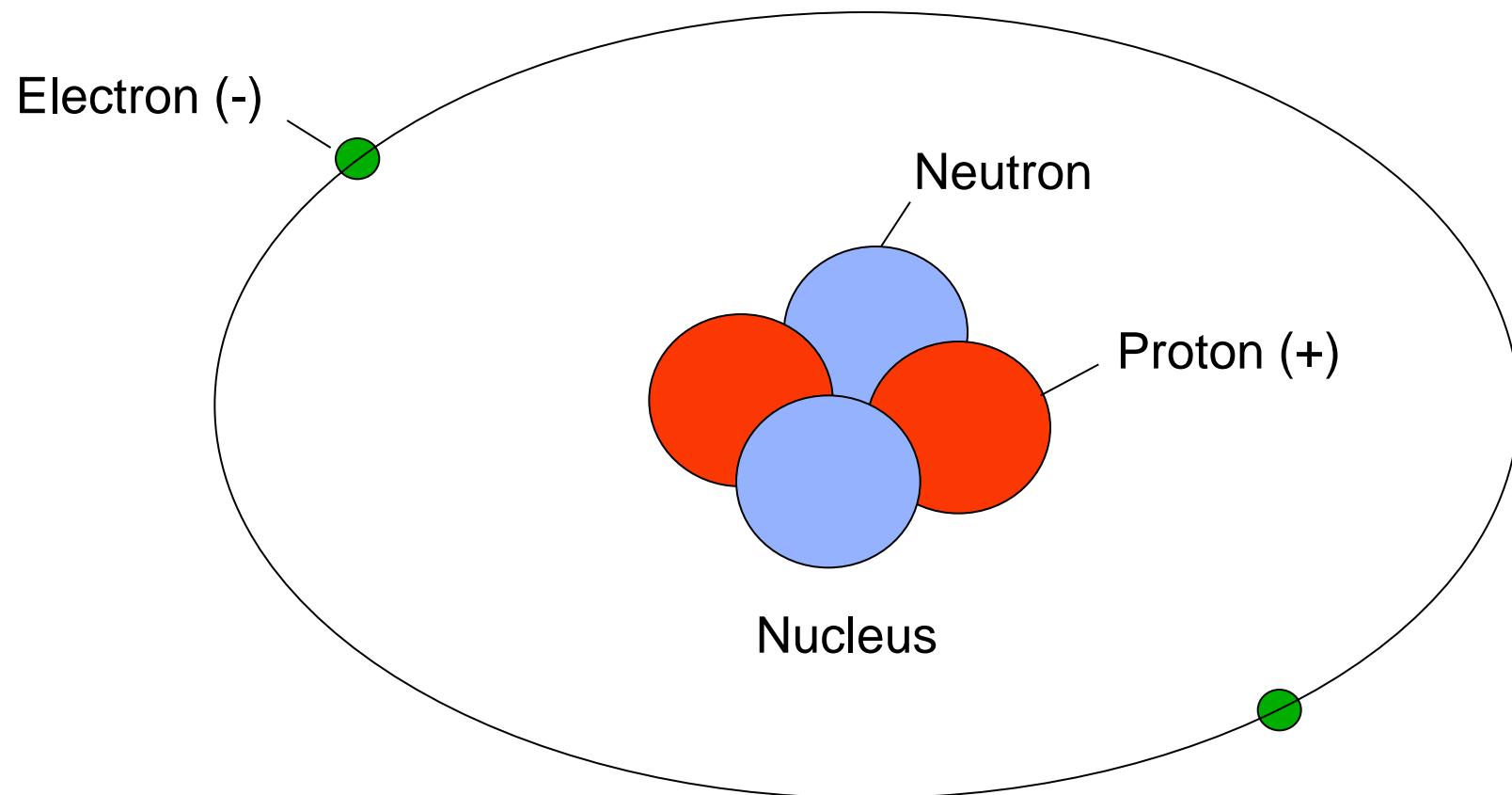
# X-ray Tomography

Gas exchange region in the lung of a rat



Prof. Schnitnny (Univ. Bern) et al  
Tomogram taken at beamline X04SA-MS, M. Stampanoni et al.

## Helium-Atom

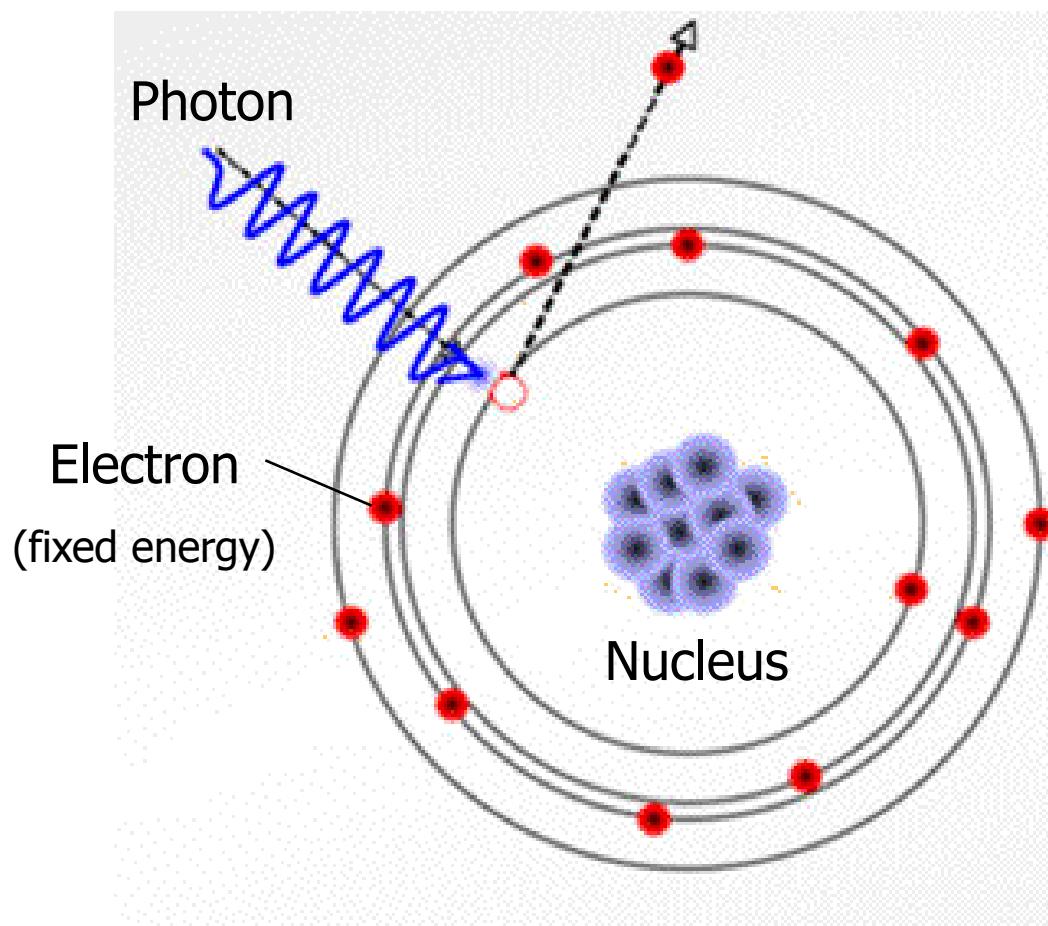


# Photo Effect

outgoing Electron

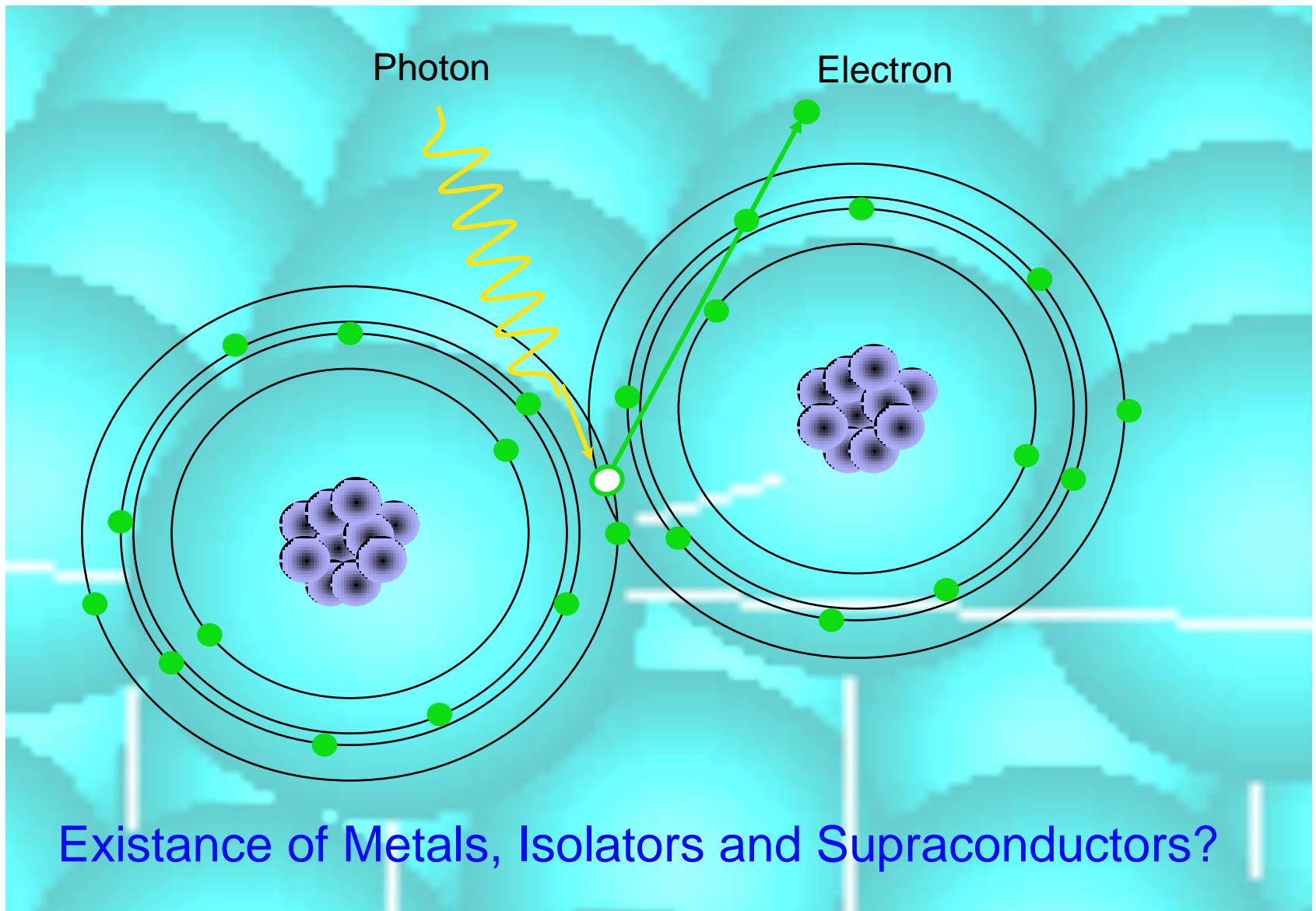
Photon in – Electron out

(Einstein 1905, Nobelprize 1921)

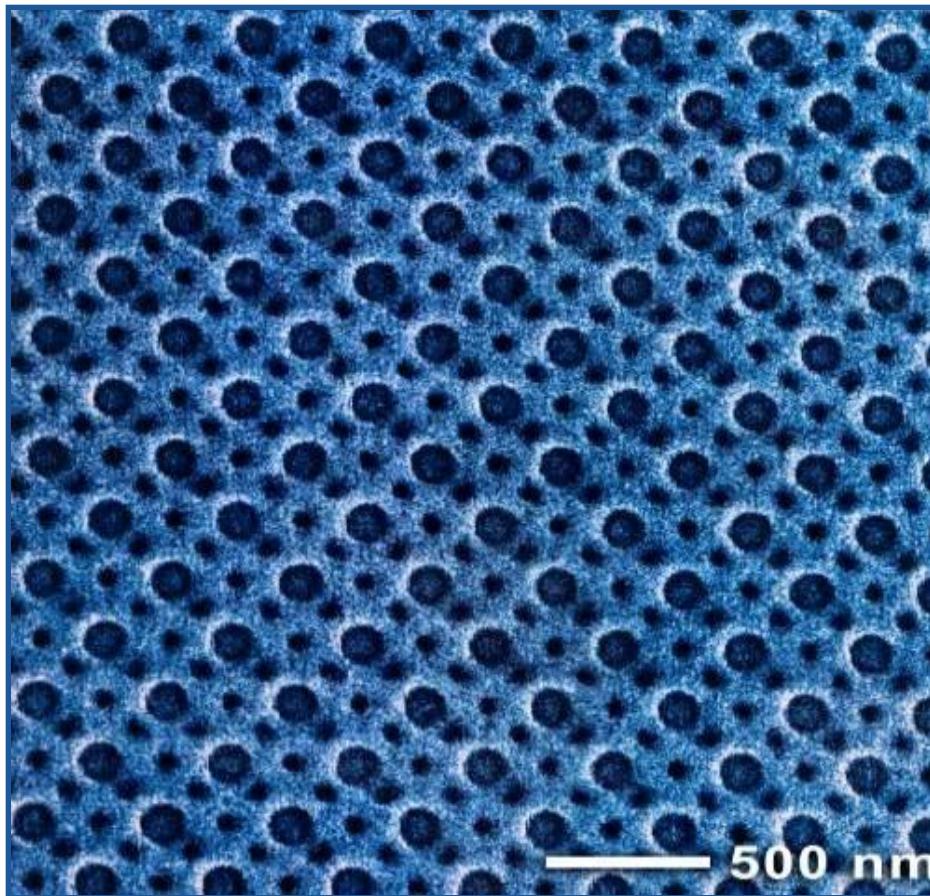


Energy Difference between  
Electron and Photon gives  
Binding Energy  
(specific for each Atom)

# chemical Bond



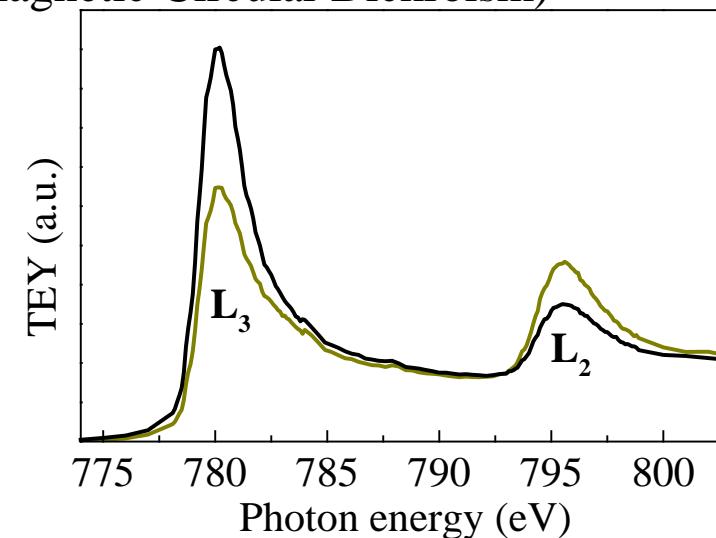
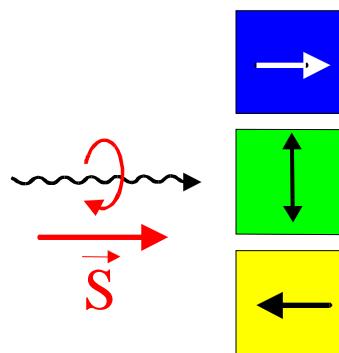
# Nanolithography



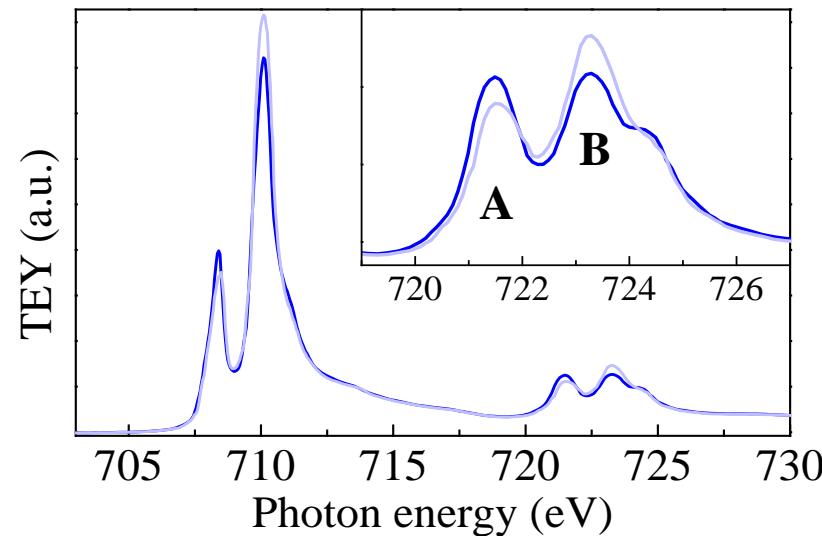
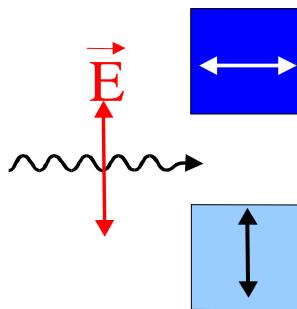
- Nano-pattern, formed with Synchrotron Light, useful for:
- Initiating Crystal Growth of Proteins
- Increasing the storage Capacity of Memory Discs
- Microfilters

# magnetic Microscopy

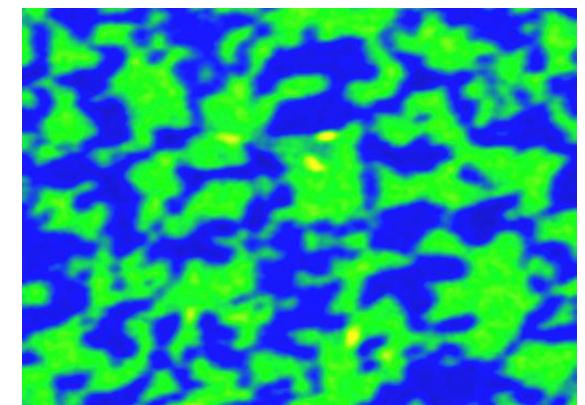
## XMCD (X-ray Magnetic Circular Dichroism)



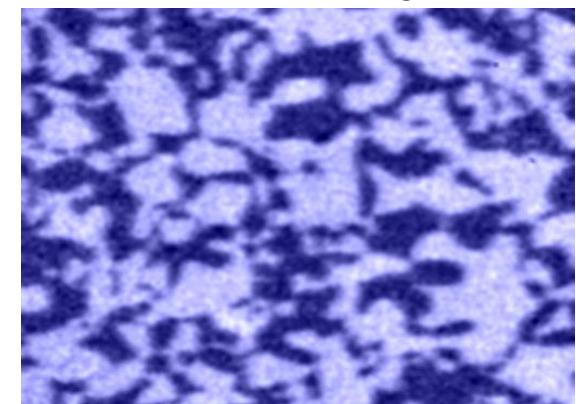
## XMLD (X-ray Magnetic Linear Dichroism)



**Co**

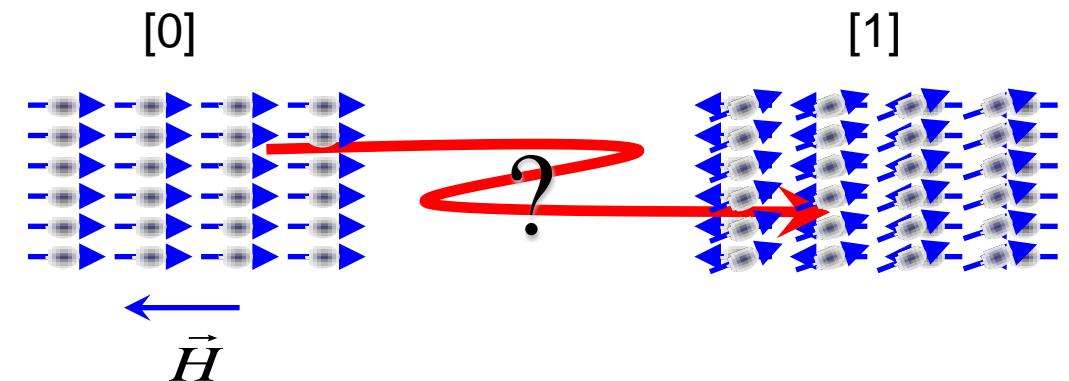


**LaFeO<sub>3</sub>**

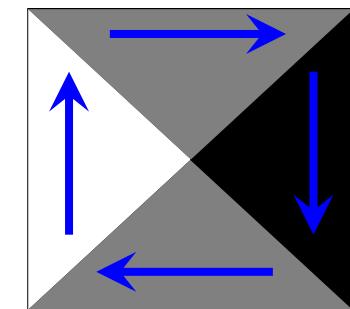


# Switching of magnetic domains

IBM / HITACHI (2005)  
Microdrive, 6 GByte, Pentium IV: 3GHz

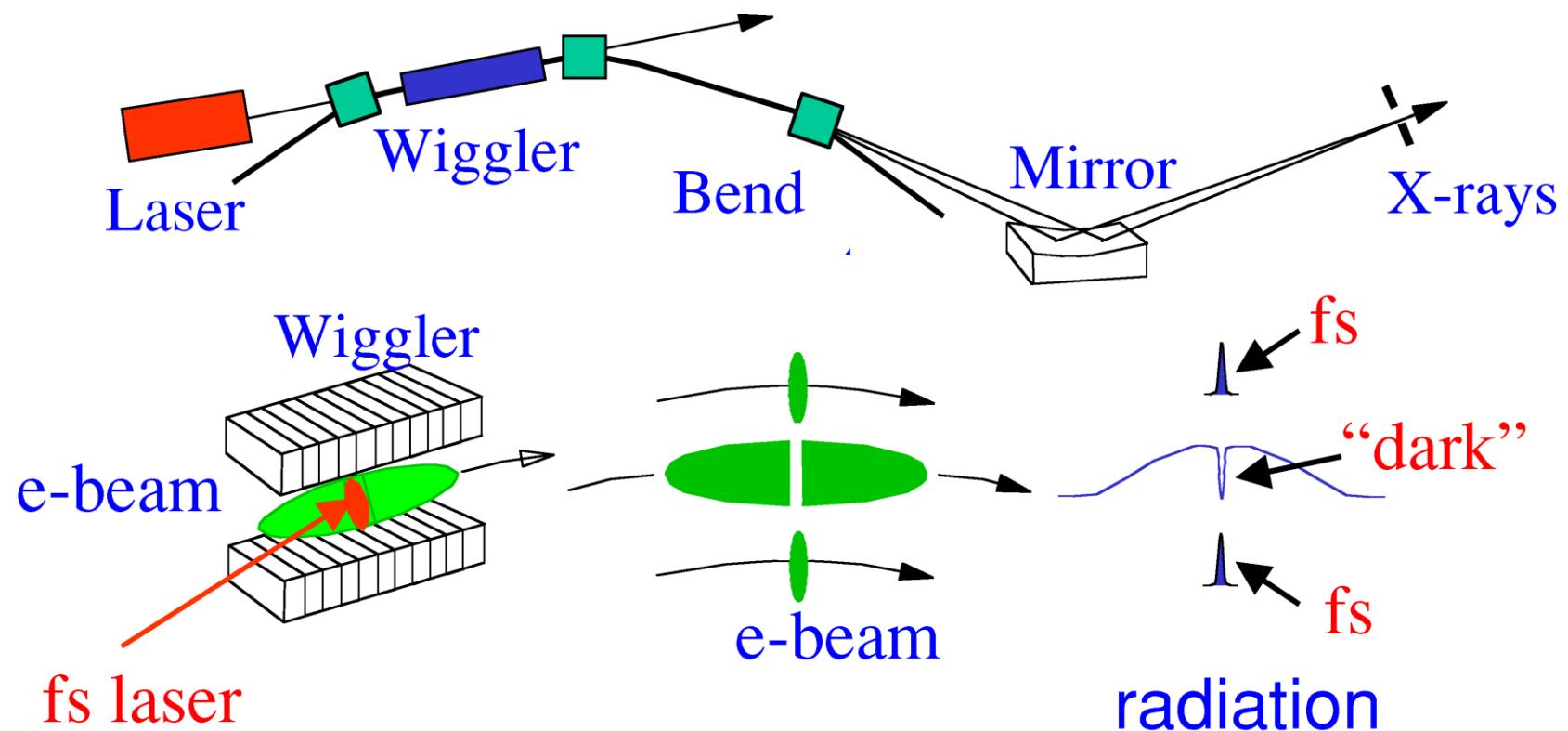


**Make movies of magnetic particles  
 $\mu\text{m}$  & sub-ns**

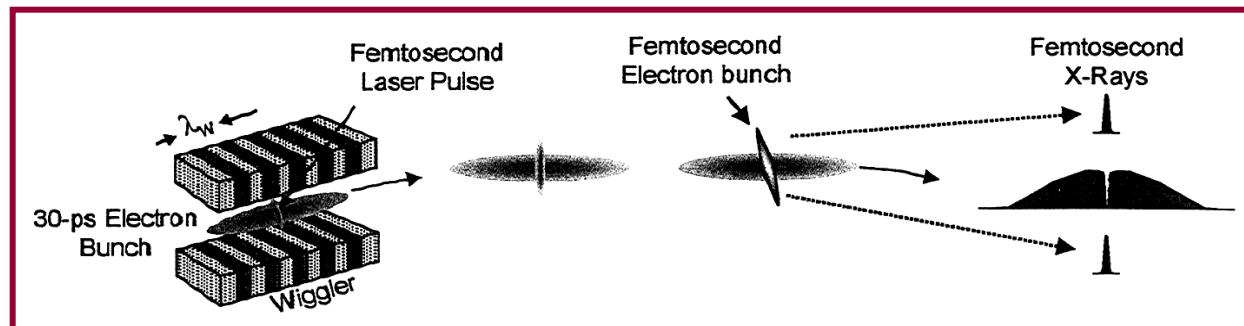


J. Raabe et al., PRL 94, 217204 (2005)

## Creating a fs pulse with a laser (ALS experiments)



# FEMTO: femtosecond X-ray pulses

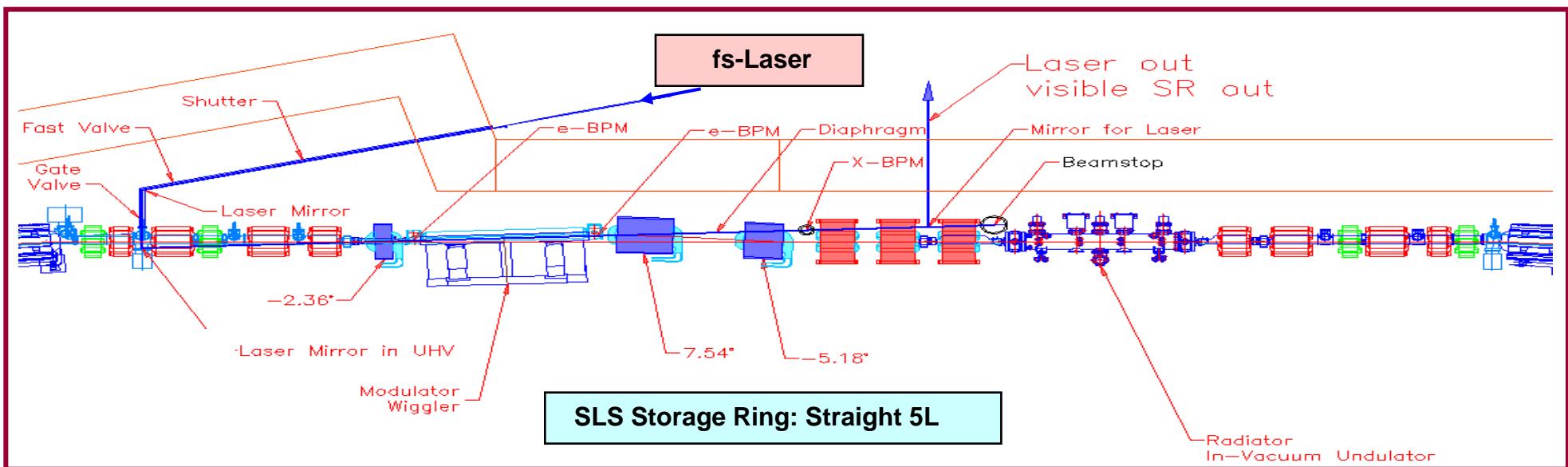


Principle:

Electron – Laser Interaction

Pulse Separation

Ultra-short X-rays

R.W. Schoenlein et al.,  
Science 287 (2000),  
2237.

Realization:

Modulator:  
WigglerAngular Dispersion:  
ChicaneRadiator:  
Vac UndulatorIn-  
100fs X-rays  
μXAS Beamline

## how fast are the electrons in the SLS?

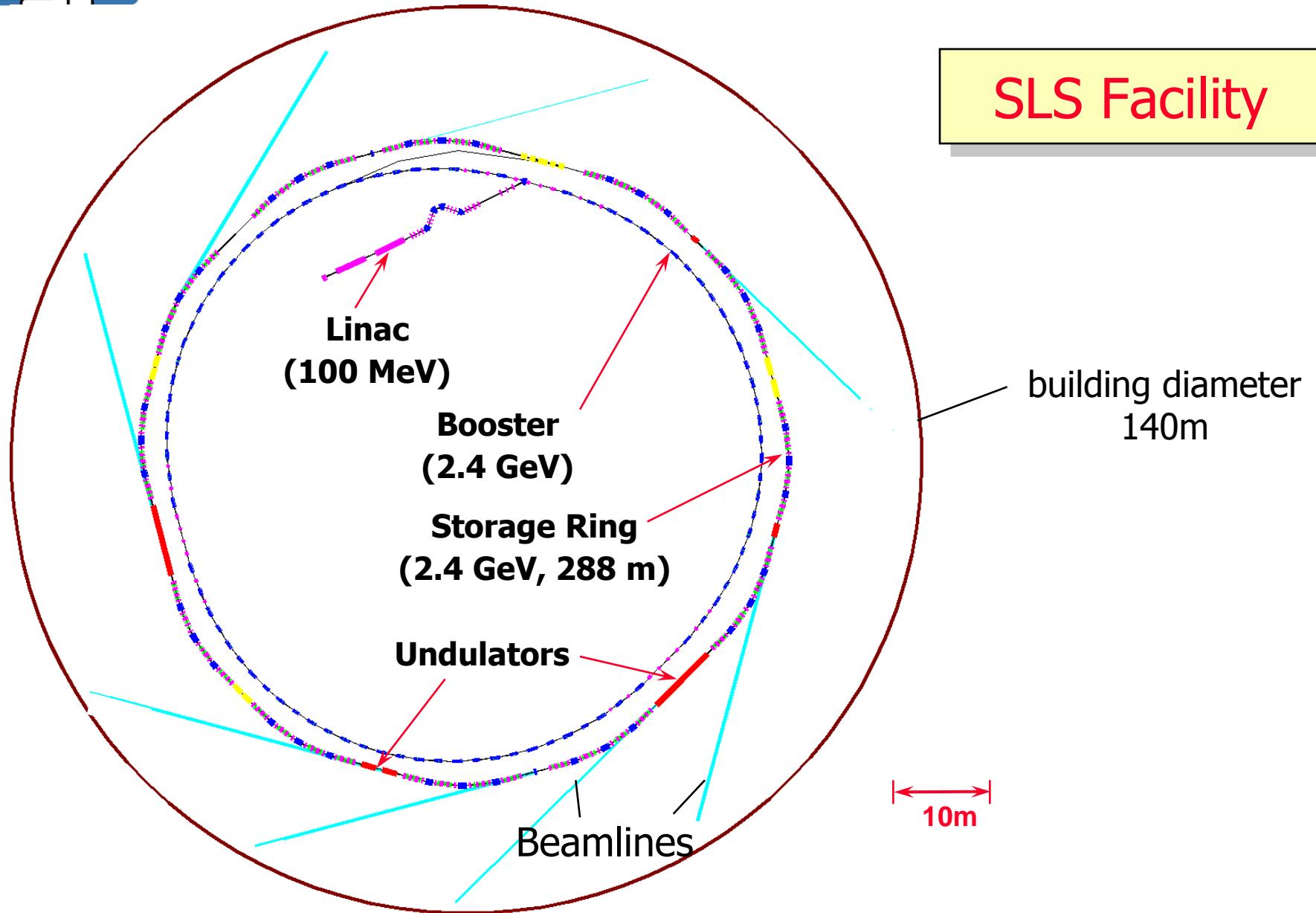
Generation of hard X-Rays requires very fast Electrons:

=> the electrons circulate with almost the speed of light:

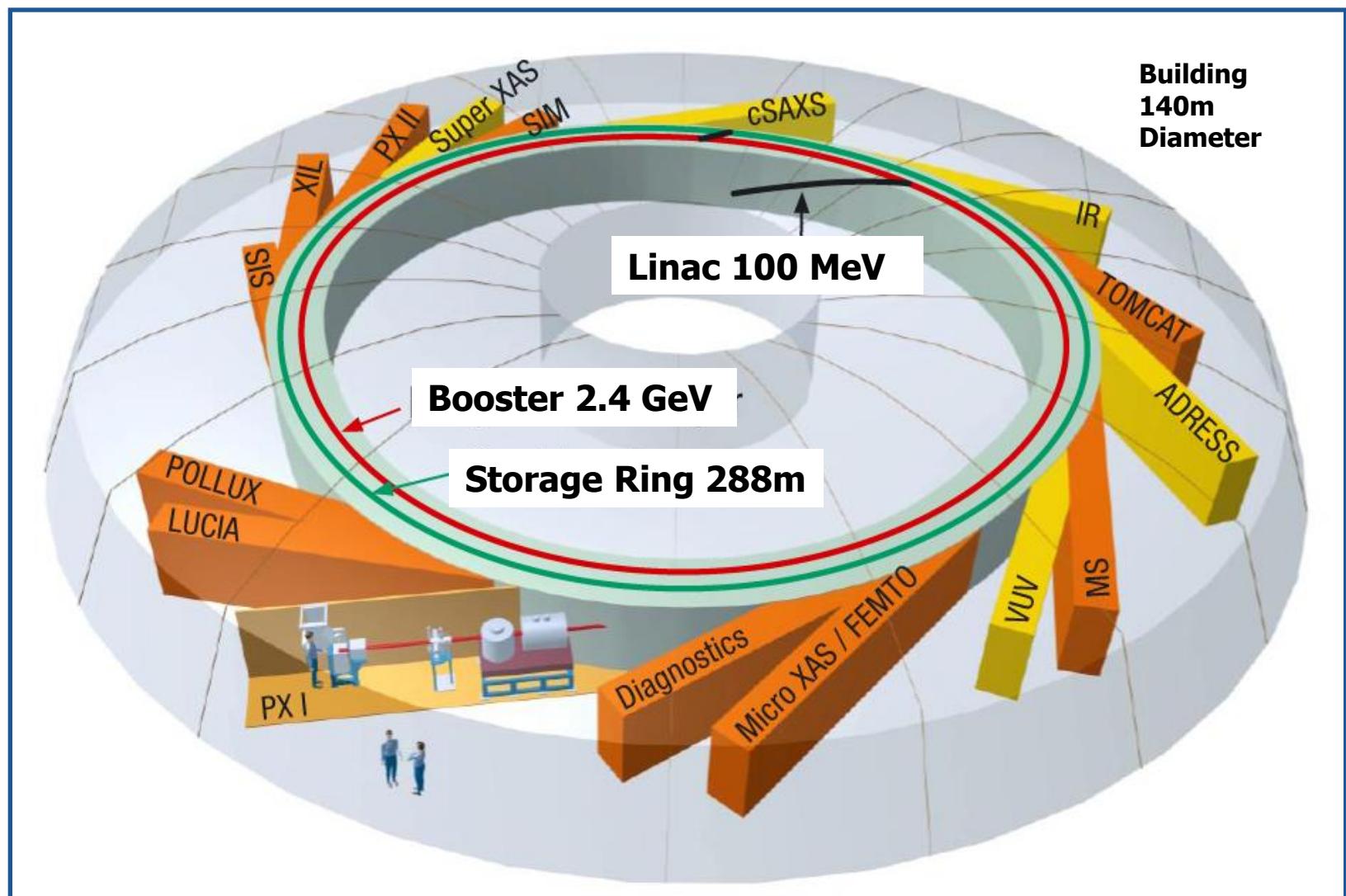
**1 Million turns per second in the Storage Ring !**

Race between electron and light to the moon (1.3 seconds):

**Electron looses by only 8m !**

**SLS Facility**

# SLS Layout

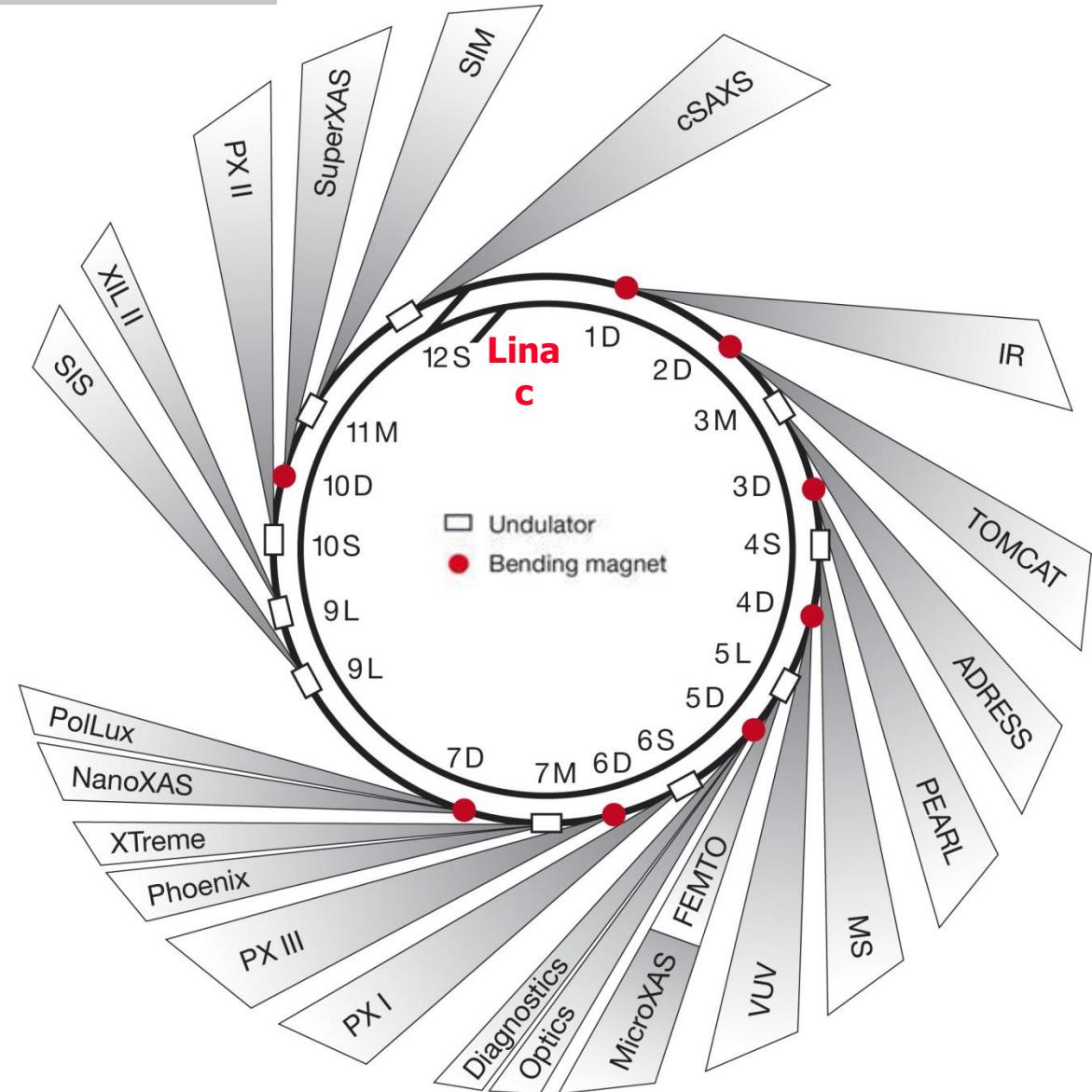


# SLS Beamlines

**2013:**

**21 Beamlines in Operation:**

**10 with Undulators**  
**3 from Superbends**  
**8 from Dipoles**



## 9 Beamlines from Insertions

No	Beamline	Insertions	Type	Experiments
3M	ADRESS	UE44	APPLE	Advanced Resonant Spectroscopy
4S	MS	W61	Wiggler	Material Sciences
5L	Femto / $\mu$ XAS	W138 / U19	Wiggler / In-Vac	Environmental/Material Science
6S	PX I	U19	In-Vac	Protein Crystallography
7M	LUCIA	UE54/Cavity	APPLE	Environmental/Material Science
9L	SIS	UE212	Twin ELM	Surfaces/Interfaces Spectroscopy
10S	PX II	U19	In-Vac	Protein Crystallography
11M	SIM	UE56	Twin APPLE	Surfaces/Interfaces Microscopy
12S	SAXS	U19	In-Vac	coherent small angle x-ray scattering

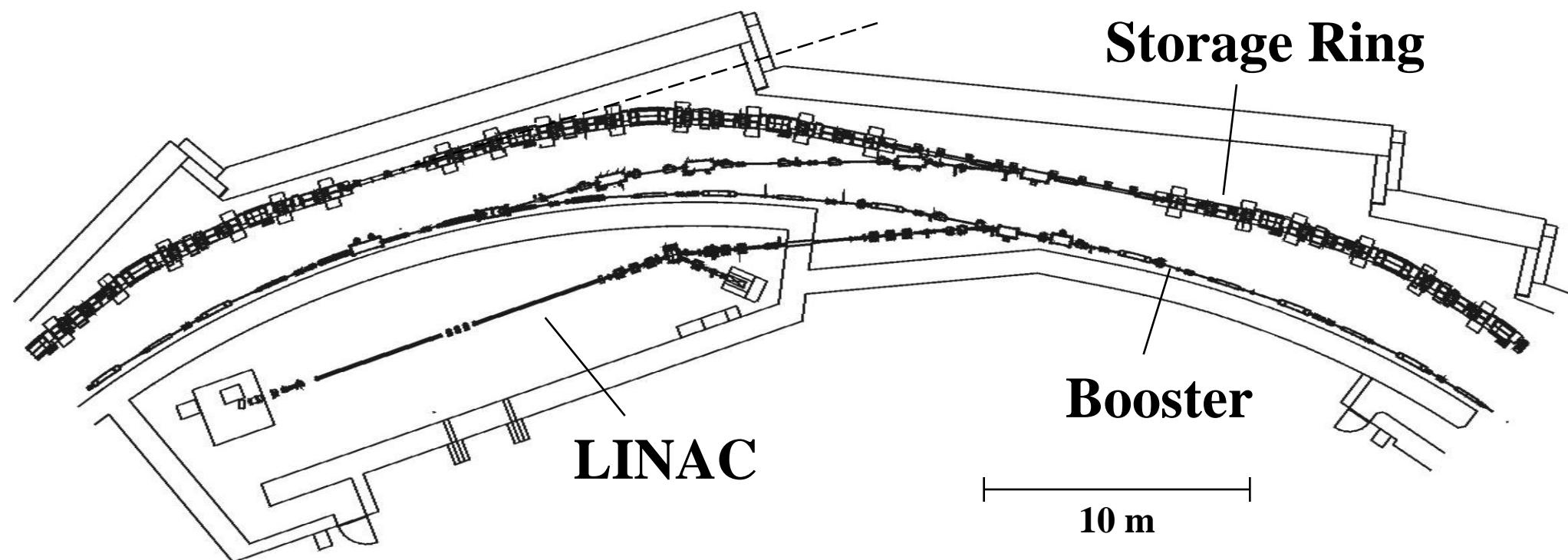
soft x-ray: flexible polarization

hard x-ray: small gap / small period, high harmonic operation

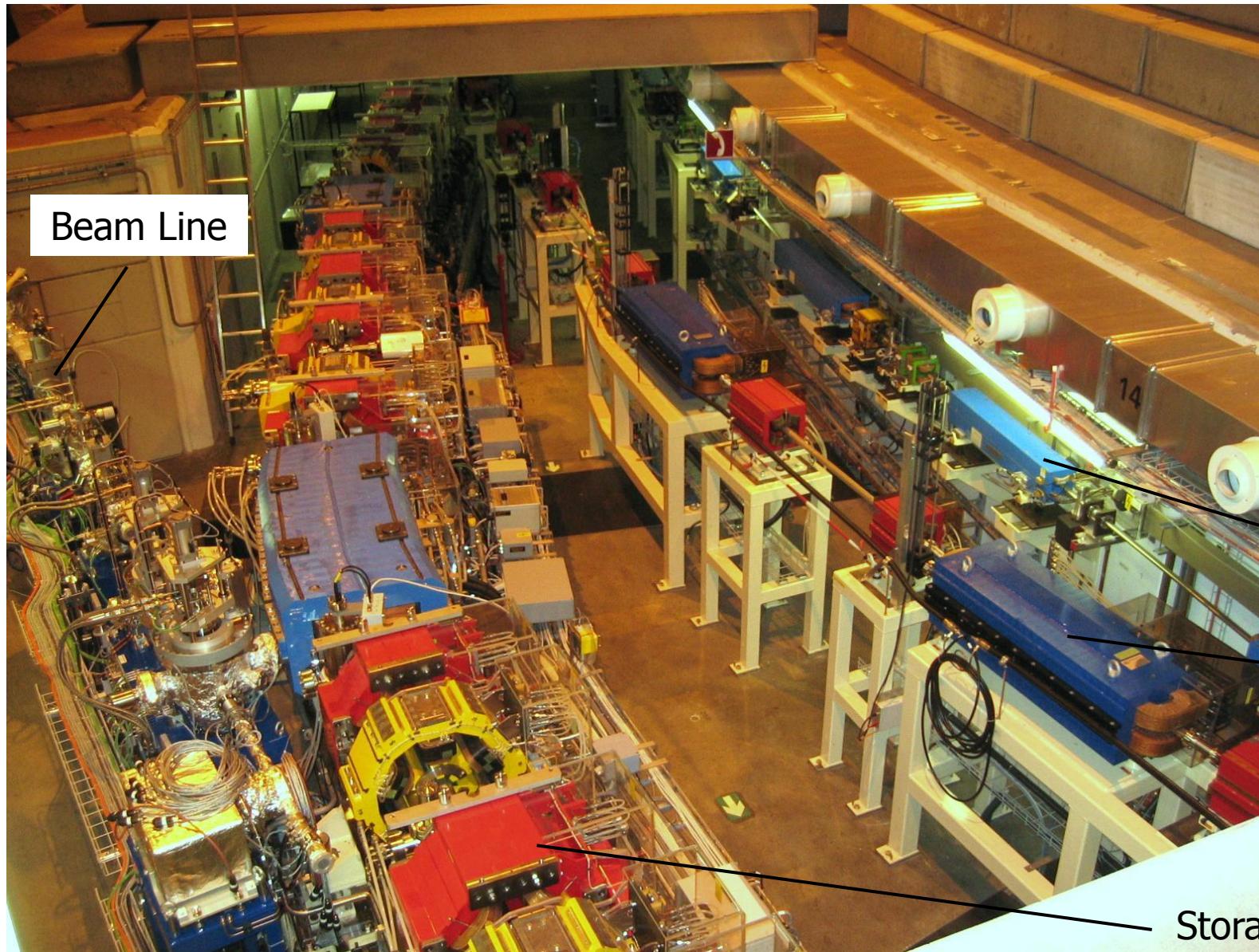
## 8 Beamlines from Dipoles

No	Beamline	Source	Experiments
1DC	IR	Dipole 1.4 T	Infrared Spectroscopy
2DA	TOMCAT	Superbend 2.9T	Tomography
4DA	VUV	Dipole 1.4 T	Combustion Reaction Analysis
5DA	OPTIC	Dipole 1.4 T	Test of optical components
5DB	DIAGNOSTIC	Dipole 1.4 T	Beam Diagnostic
6DA	PX III	Superbend 2.9T	Protein Crystallography
7DA	POLLUX	Dipole 1.4 T	Scanning Transmission X-ray Microscopy
10DA	SuperXAS	Superbend 2.9T	Absorption Spectroscopy

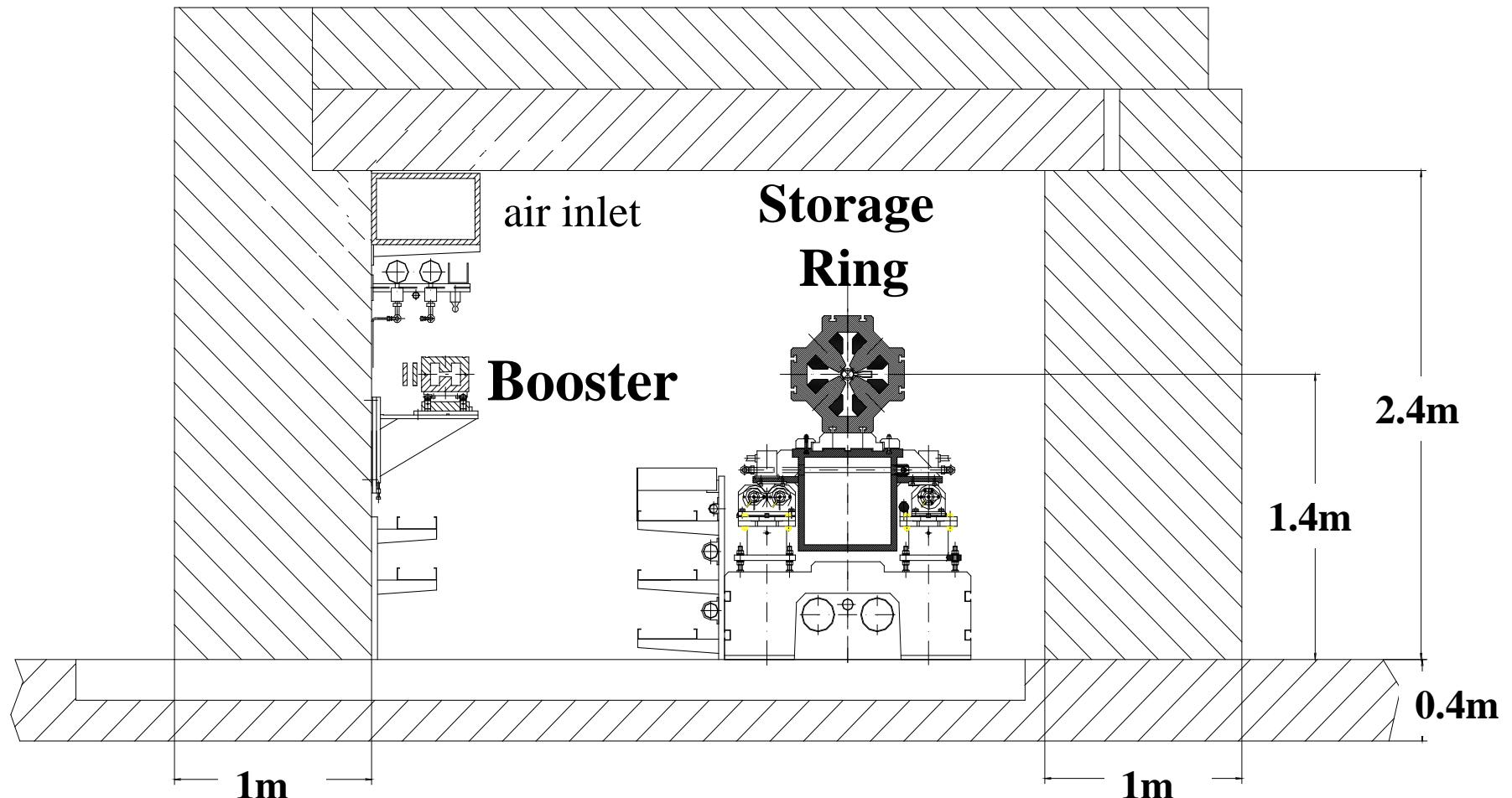
# Injection Region



# Photo of SLS Tunnel



# SLS Tunnel



## Radiation Dose

### natural Background

- Villigen :  $\approx 800 \mu\text{Sv/year}$   
( Davos , Locarno :  $\approx 1'500 \mu\text{Sv/year}$ )
- human, internal ( $\text{K}^{40}$  etc.)  $\approx 200 \mu\text{Sv/year}$
- medical Applications:  $\approx 1'000 \mu\text{Sv/year}$
- 8 h Flight:  $\approx 200 \mu\text{Sv}$

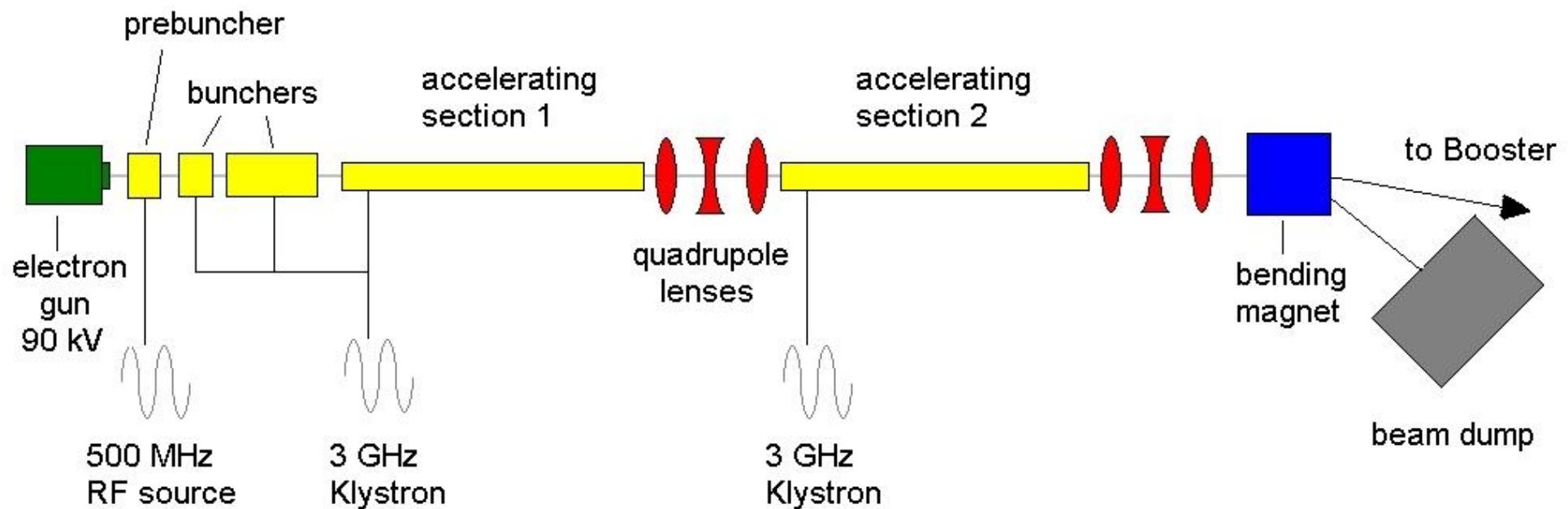
### Tolerance for SLS

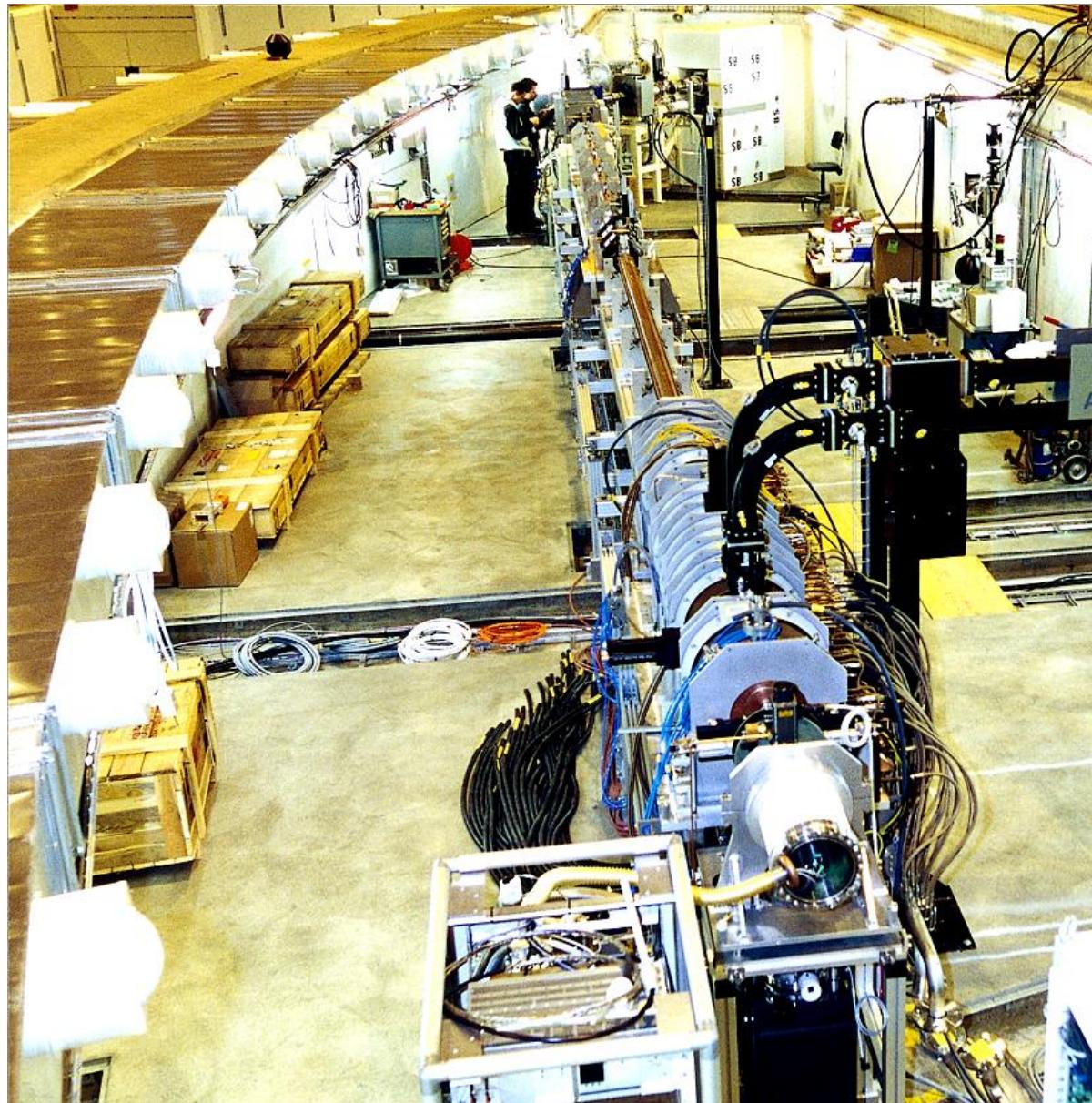
- outside PSI :  $< 50 \mu\text{Sv/year}$
- in SLS Building:  $< 1000 \mu\text{Sv/year}$

### Shielding of Accelerators

- Tunnel Walls : 1.0 - 1.3 m
- Tunnel Roof : 2 Concrete Layers of 0.4 m

# Layout 100 MeV Linac





# Linac

Electron Gun 90 keV

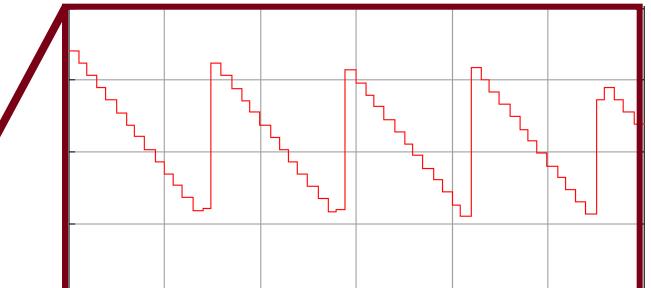
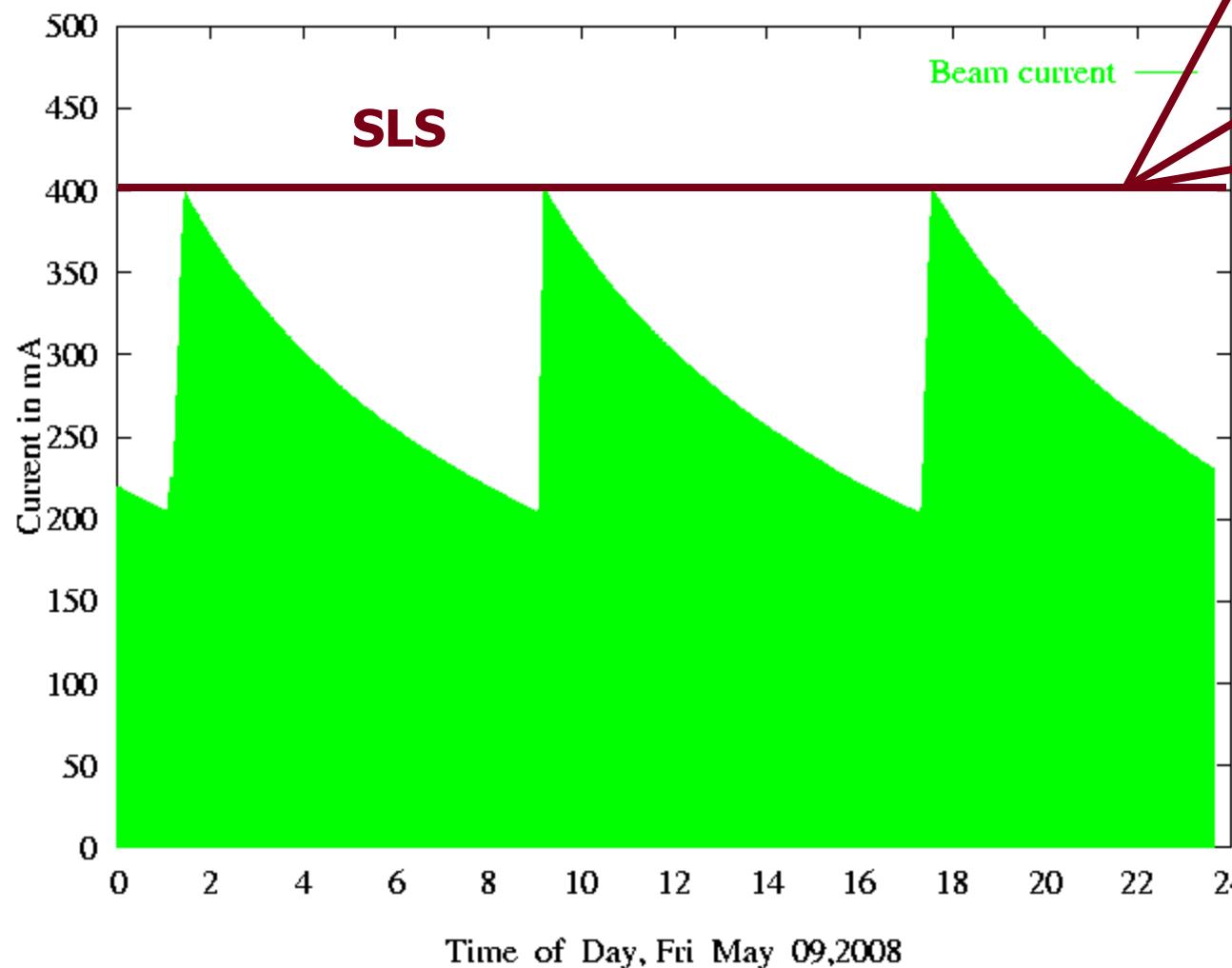
Linac (11m long) 100 MeV

## Booster Specialty

- Booster in same Tunnel as Storage Ring
  - Top-up Injection
- => large Circumference  
=> small Emittance
  - short refill every 2-3 min.  
=> constant Beam Current
- efficient Injection into Storage Ring,  
filling in 6 min.
  - => stable Temperatures on optical Components
- compact, economic Magnets
  - Energy Consumption < 20 kW
- simple Vacuum Chamber (30 x 20 mm)

## Lifetime vs. Top-up Injection

ALS Storage Ring Status  
230.140 mA



ALS (Berkeley , California):

Lifetime ~ 10 h ,

Refilling every 8 h

Current: **400 => 200 mA**

SLS (in 2008):

Lifetime ~8 h ,

not relevant !

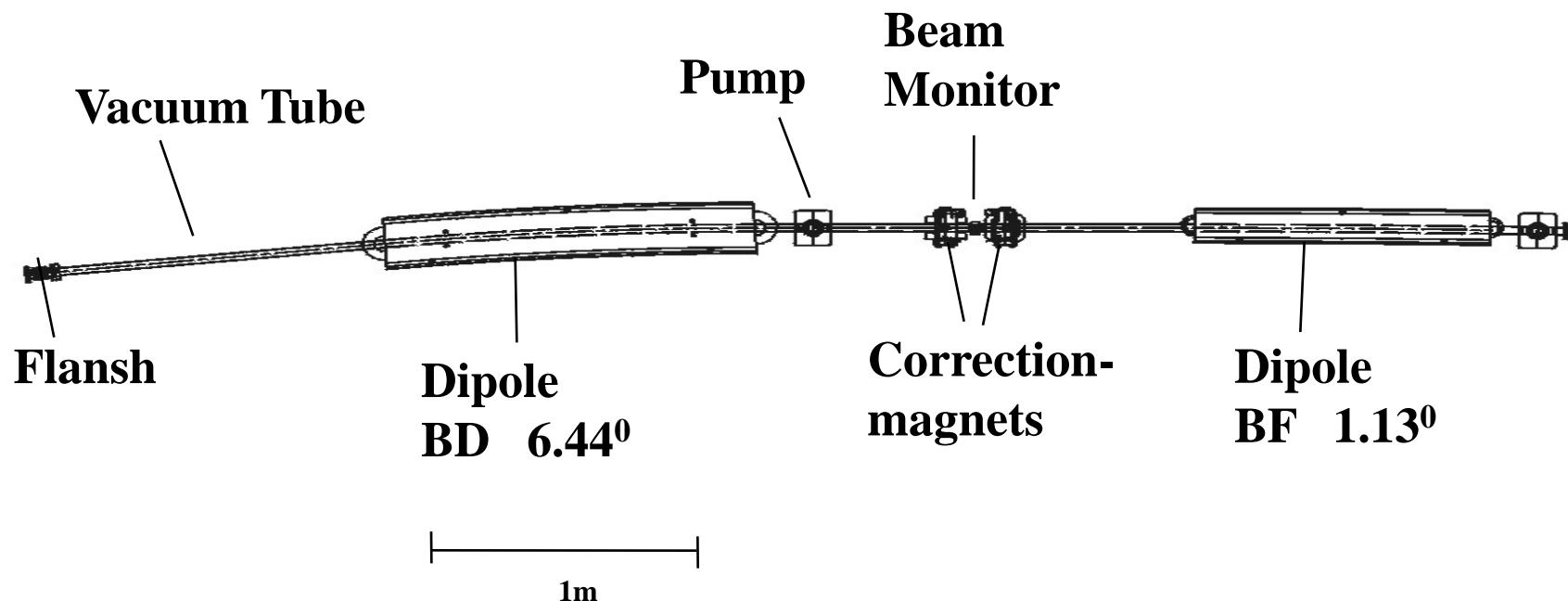
top-up every 2.5 min.

Current: **402 => 400 mA**

# Booster

## FODO-cell

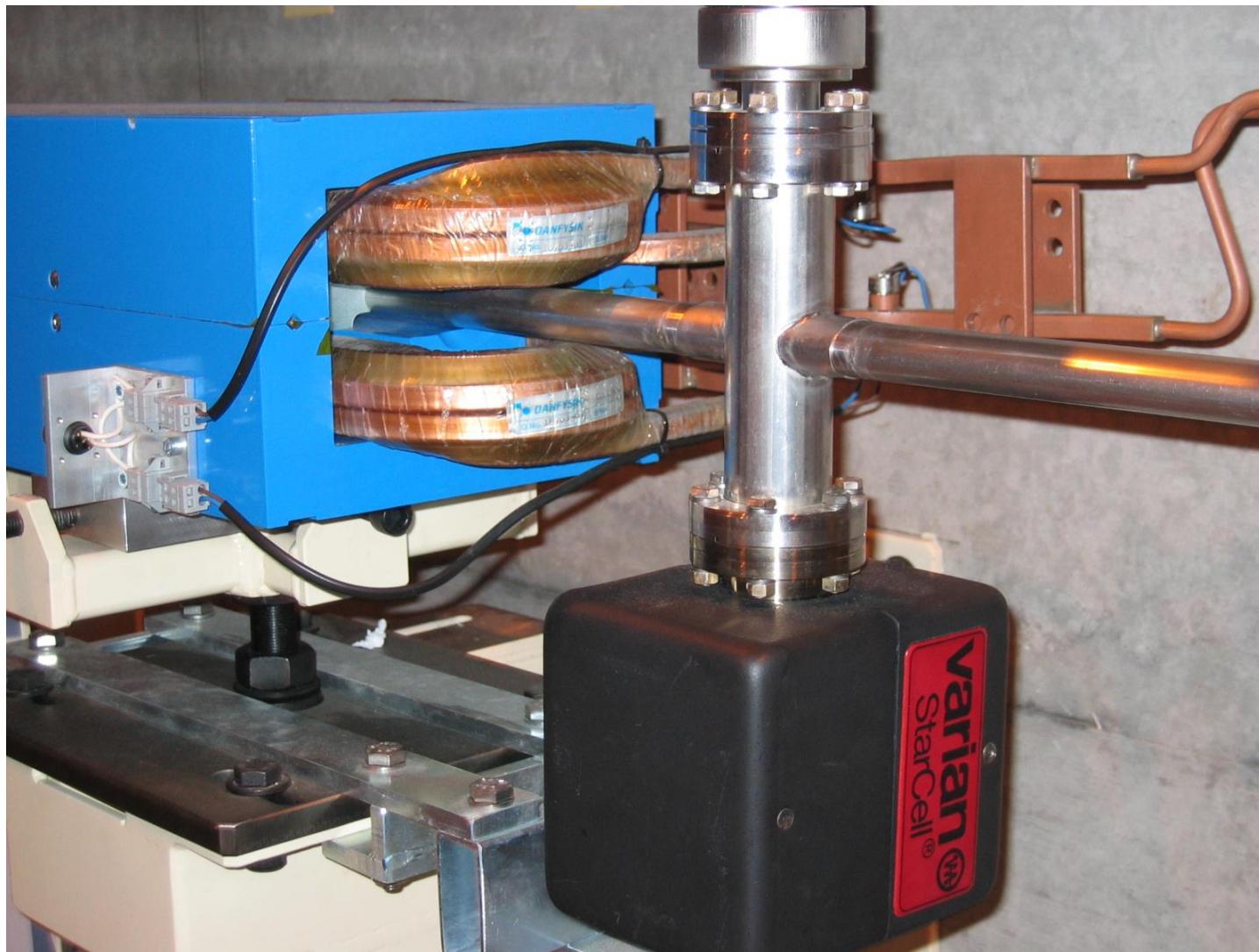
### 5.4m long



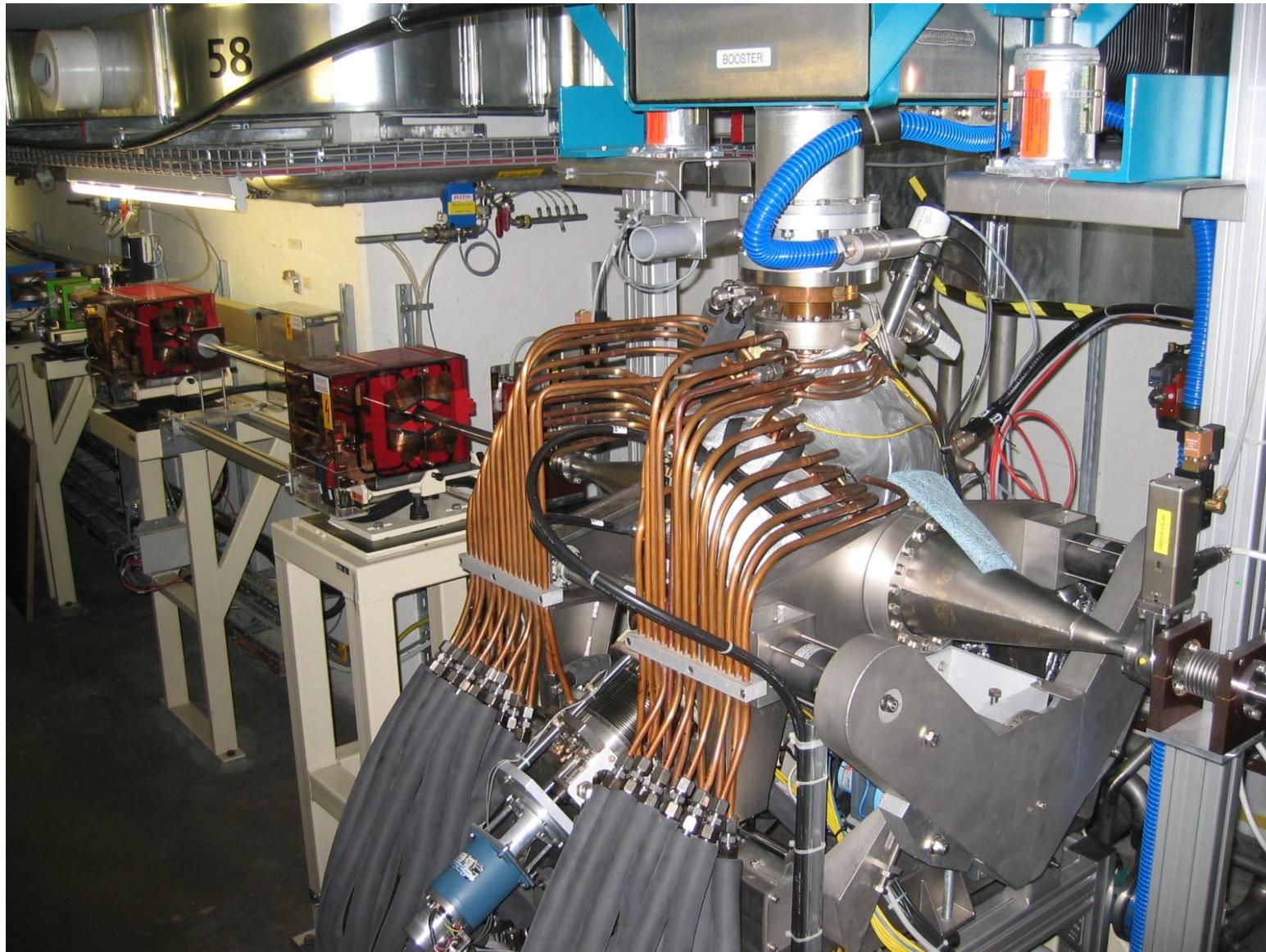
# Booster



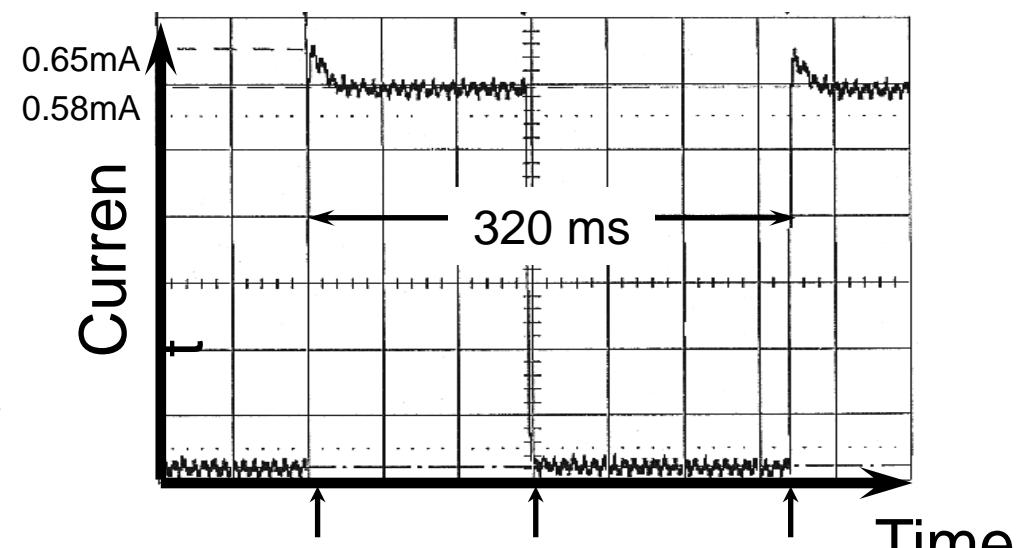
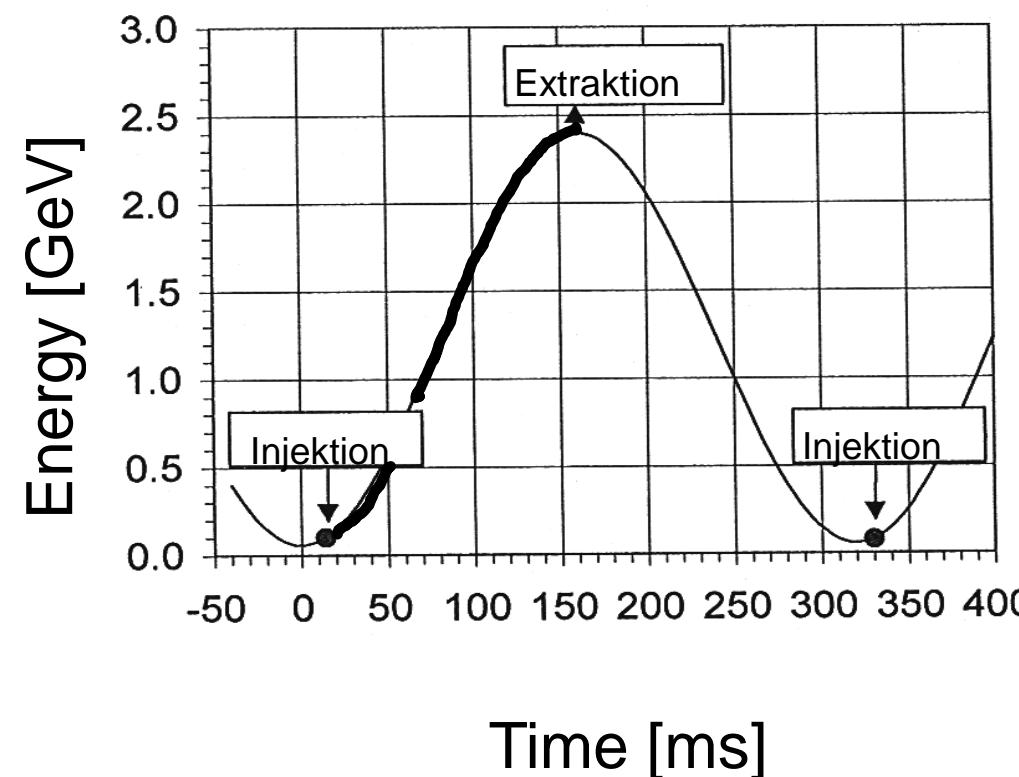
# vacuum pump in booster



# Booster cavity



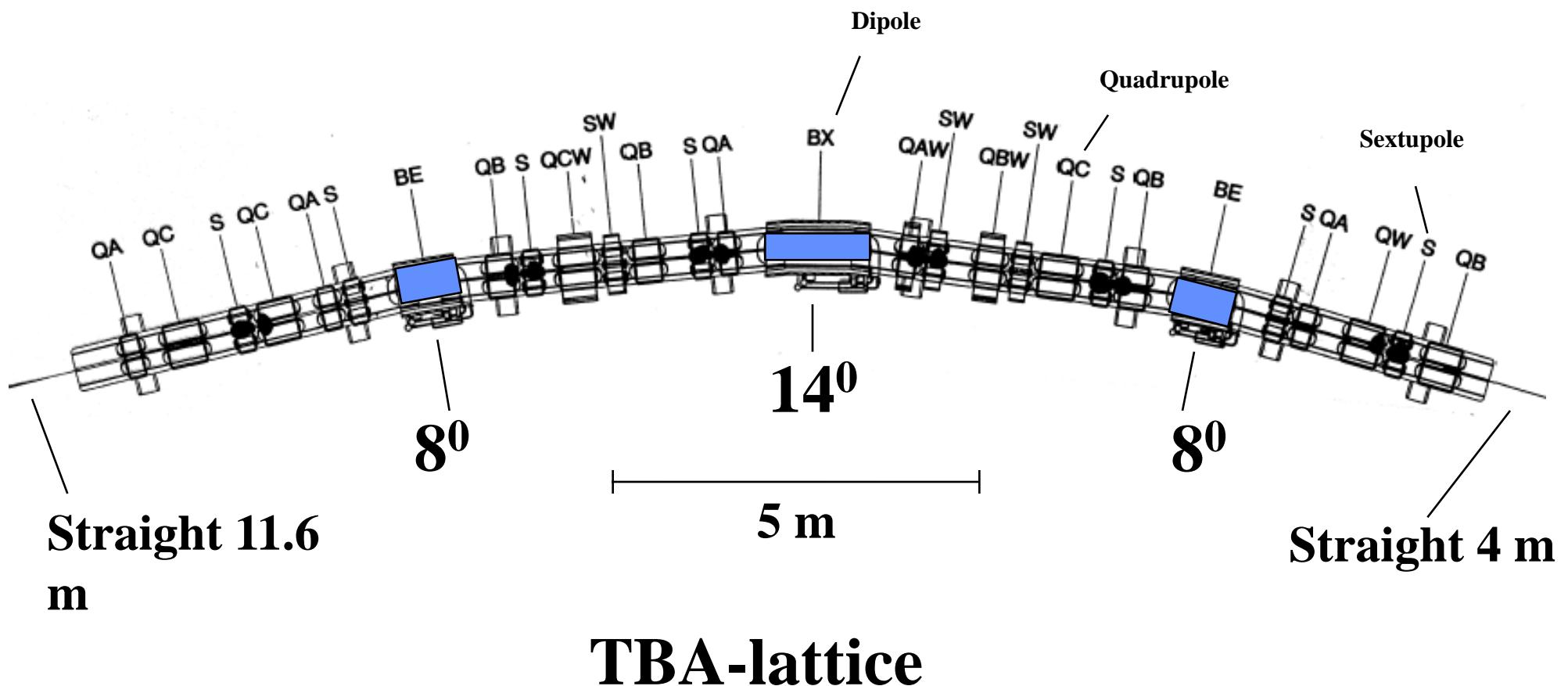
## Acceleration in Booster



## Parameter of 2.4 GeV Storage Ring

circumference	288 m
12 straights	3x11.7m, 3x7m, 6x4m
current	400 mA
emittance	5 nm
lattice	Triple Bend Achromat
tunes $Q_x , Q_y$	20.44 , 8.74
momentum compaction	$0.6 \cdot 10^{-3}$
RF frequency	500 MHz
peak RF voltage	2.6 MV
radiation loss / turn	500 keV
energy spread (rms)	$9 \cdot 10^{-4}$
damping times (x, y, E)	9 , 9 , 4.5 ms

# SLS 30° Arc



(T<sub>riple</sub> B<sub>end</sub> A<sub>chromat</sub>)

## Parameter Storage Ring

### Storage ring

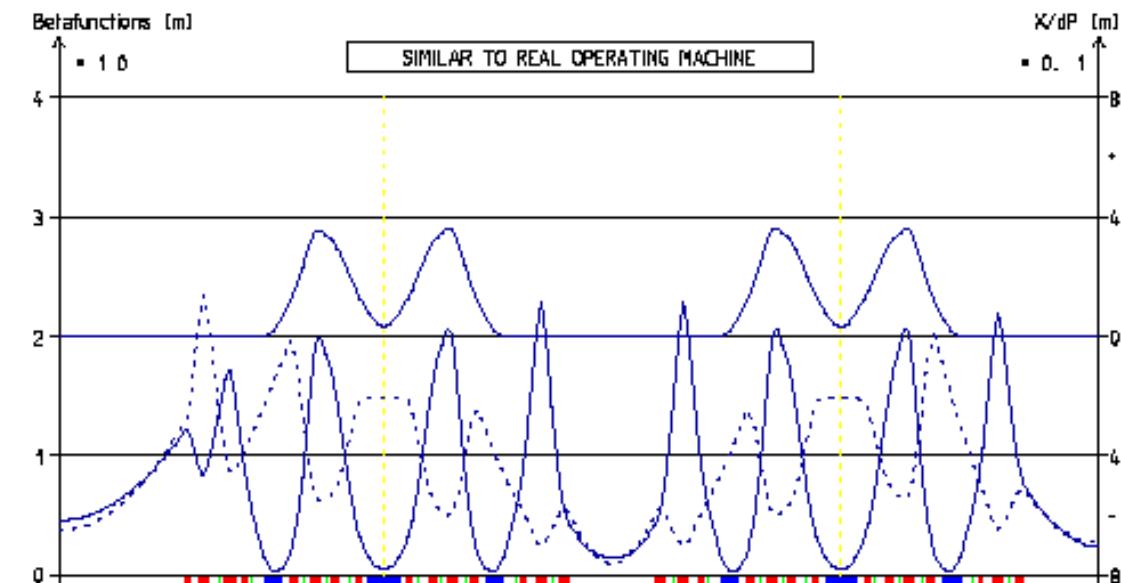
**12 TBA:**  $8^\circ/14^\circ/8^\circ$

**12 straights:**

3 x 11 m

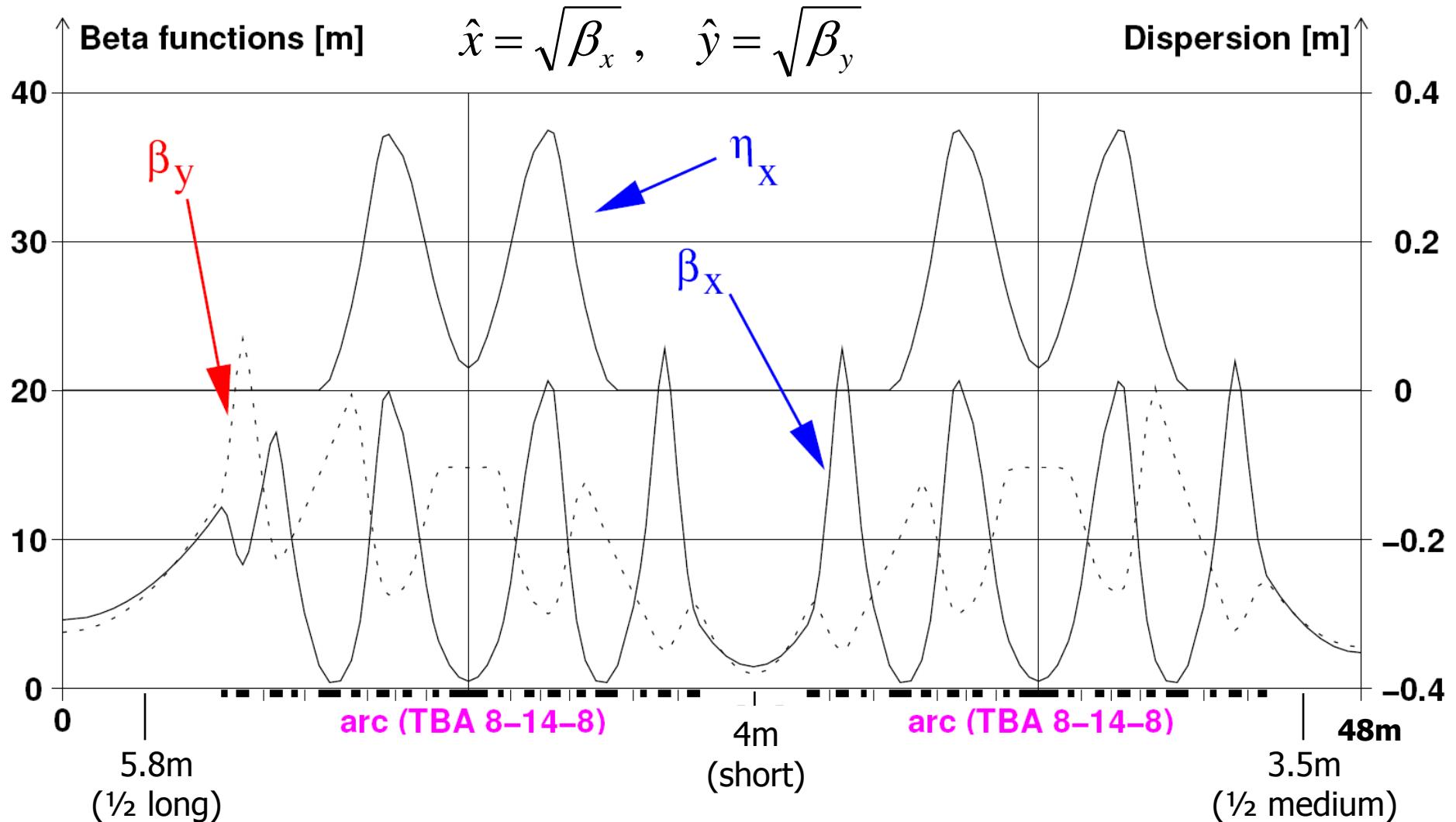
3 x 7 m

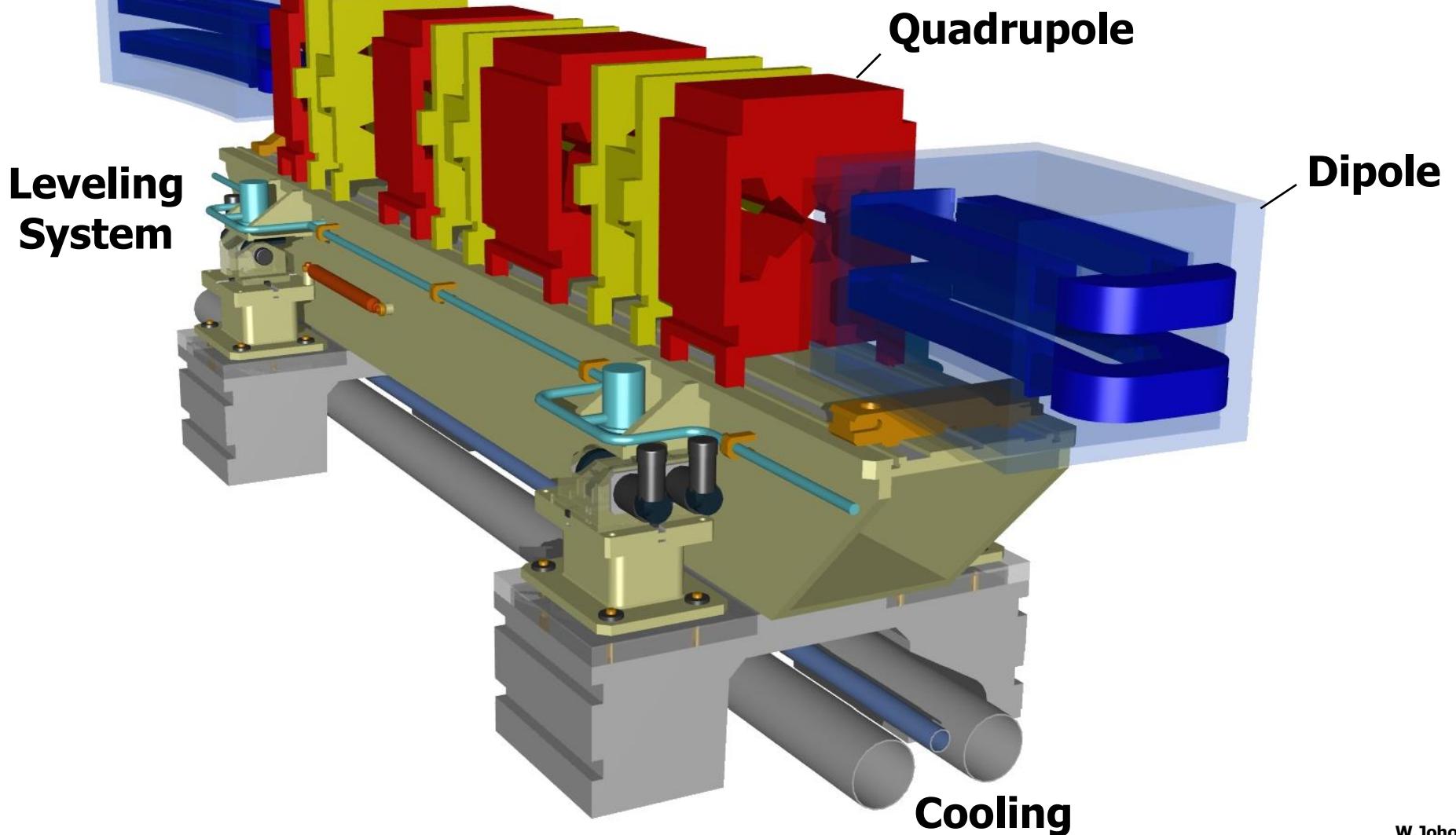
6 x 4 m



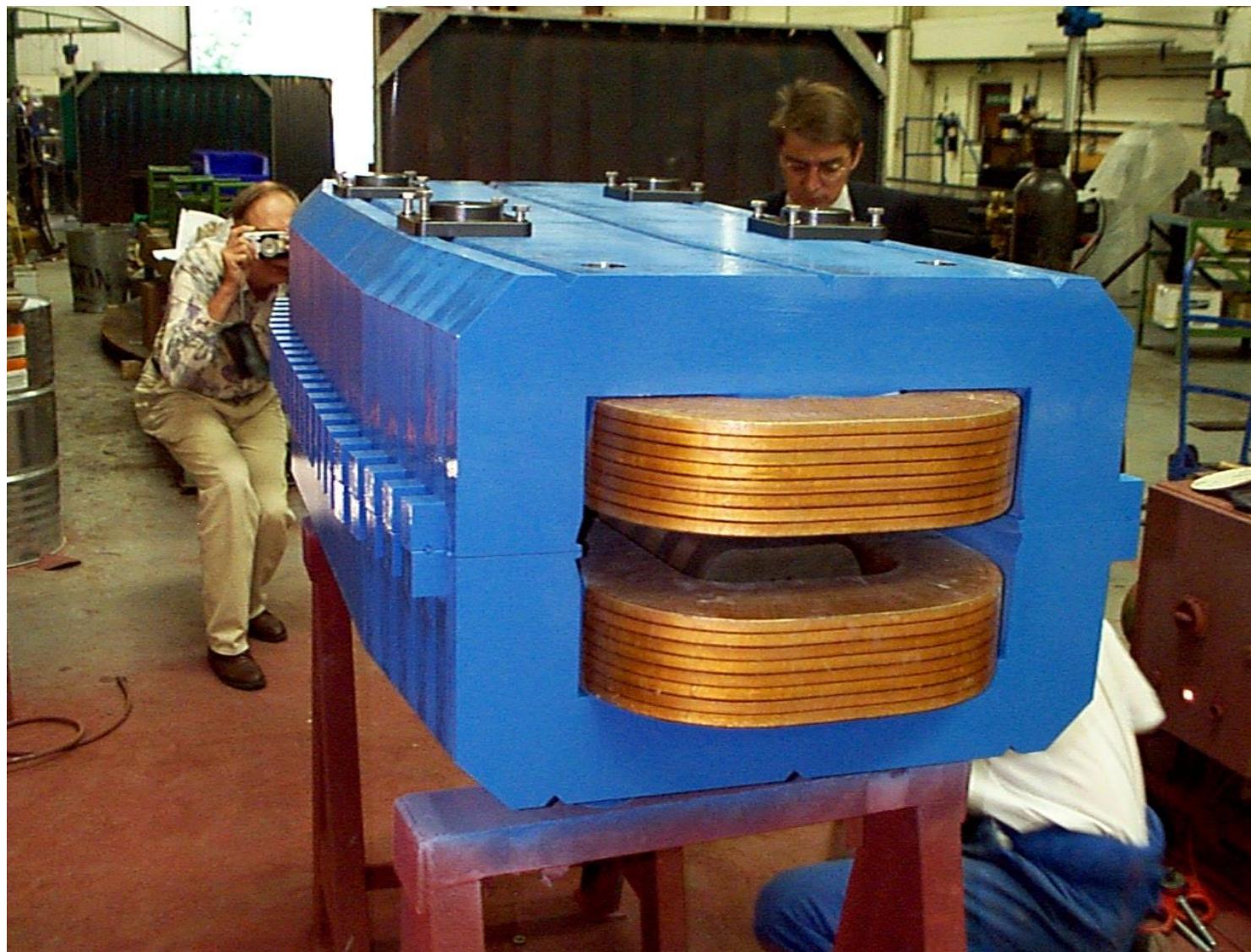
Energy	<b>2.4 GeV</b>	Momentum compact.	$6.3 \cdot 10^{-4}$
Emittance	<b>5 nm rad</b>	Radiation loss per turn	512 keV
Circumference	288 m	Damping times	9 / 9 / 4.5 ms
RF frequency	500 MHz	Relative energy spread	$8.9 \cdot 10^{-4}$
Tunes	<b>20.41 / 8.17</b>	Bunch length (rms)	3.5 mm
Chromaticities	<b>-66 / -21</b>	Beam current	<b>400 mA</b>

# Lattice functions over 2 arcs à 30°



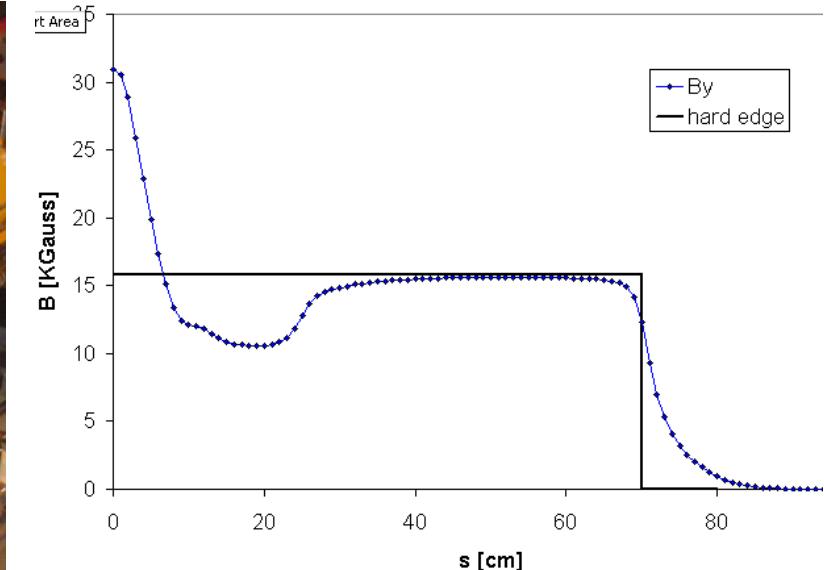
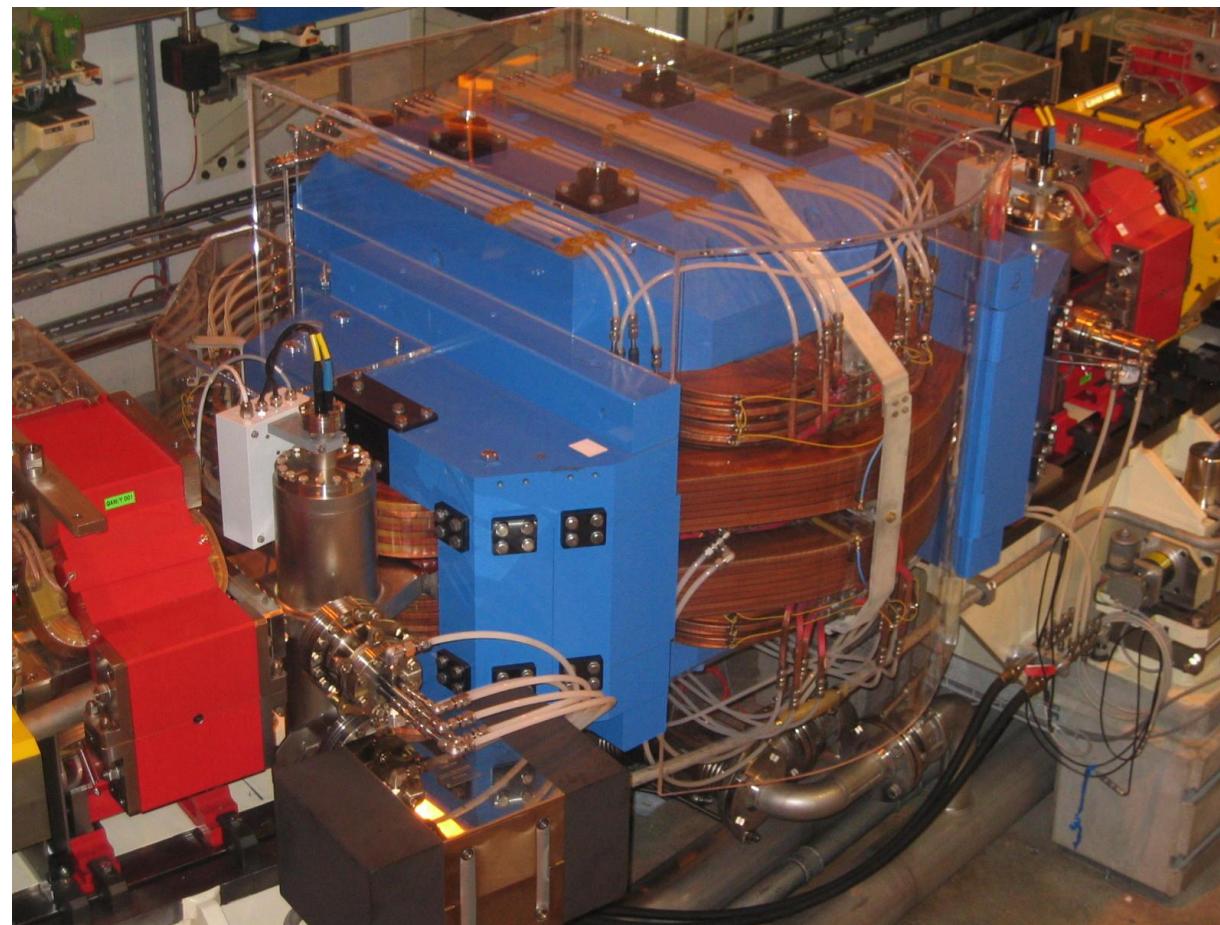
**SLS Girder**

# Dipole-Magnet



Deflection  $14^0$   
Field 1.4 T  
Length 1.4m  
Weight 3 Tonns

# Superbend

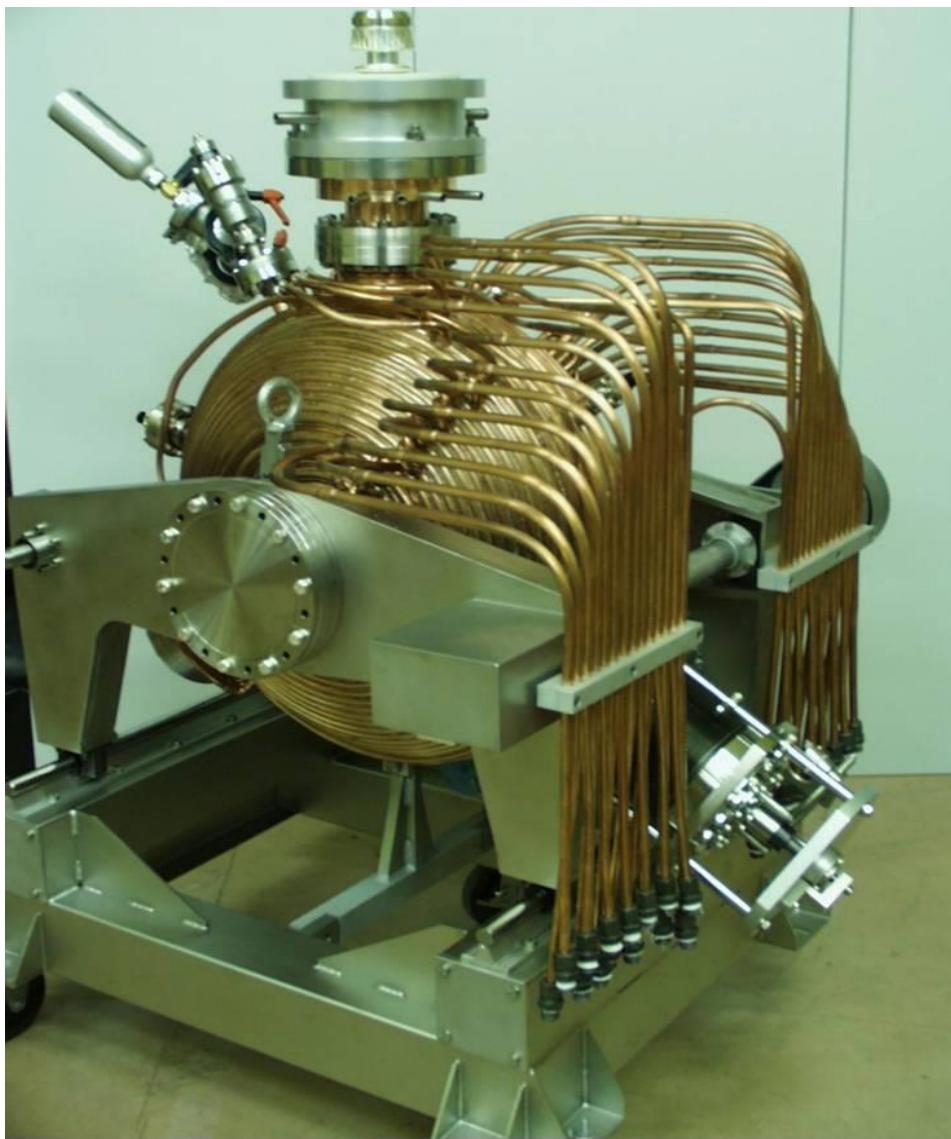


bending angle  $14^0$

center cone with 3 T

critical energy = 11.5 keV

end regions with 1.5 T

**RF-Cavity**

circulating Electrons generate  
200 kW of X-Rays

This Power has to be  
refurbished by an RF-System

Cavity = Resonator, made of Copper,  
Frequency 500 MHz

4 Cavities in Storage Ring,  
1 Cavity in Booster

600 kV Voltage  
55 kW Power Loss/Cavity

## SLS Vacuum system

- electrons have to circulate for hours in storage ring  
=> ultrahigh vacuum
- stainless steel vacuum chamber ,  
preconditioned at 250° during 4 days
- constant cross section avoids beam instability
- Ante-chamber reduces desorption by synchrotron radiation
- vacuum chamber is connected to the girder only at the  
**Beam Position Monitors** (> floats inside the magnets)

## Accelerator Components

- 600 Magnets
- 300 Vacuum Pumps
- 150 Beam Monitors
- 5 RF Cavities
- 600 m Vacuum Tubes
- 50 km Power Cables
- 500 km Signal Cables
- 3 MW Power Consumption

# Spectrum of Synchrotron Radiation

## Dipole Magnet with Field B:

Spectral Flux  $\sim [E \cdot I \cdot G_1]$ , E = Energy, I = Current

$$G_1(x) = x \int_x^\infty K_{\gamma_3}(x') dx'$$

$$x \equiv \frac{\varepsilon}{\varepsilon_c}, \quad \varepsilon = \text{Photon-Energy}$$

$$\text{crit. Energy: } \varepsilon_c = 665 \text{ eV} \cdot E^2 [\text{GeV}] \cdot B [\text{T}]$$

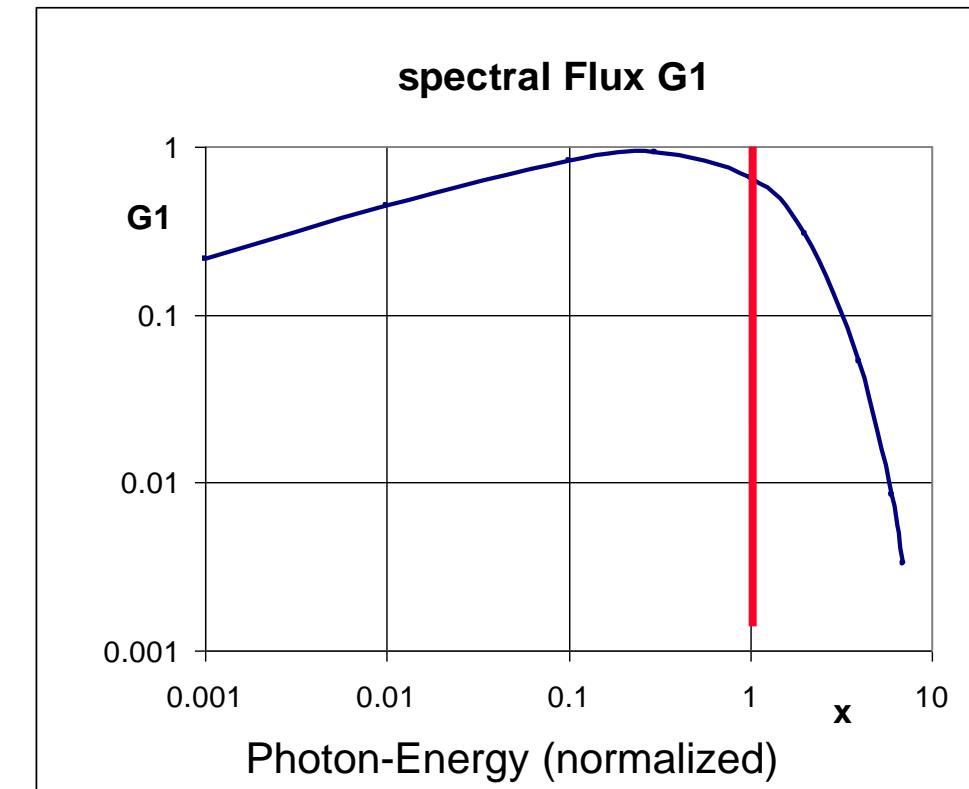
(SLS : 5.4 keV for normal dipol, 11.5 keV for Superbend)

Approximation:  $G_1 \approx A x^{1/3} g(x)$

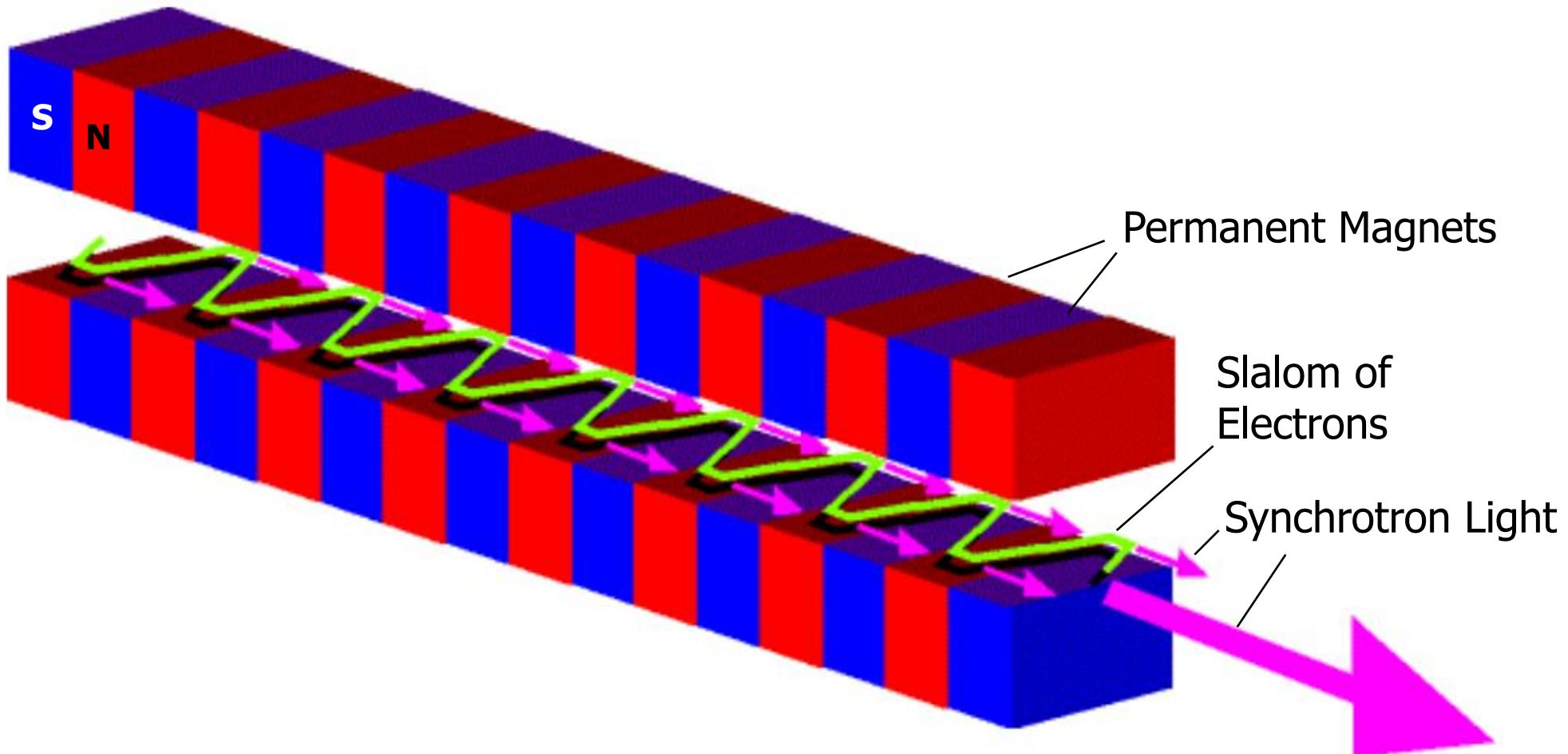
$$g(x) = \left[ \left( 1 - \left( \frac{x}{x_L} \right)^N \right)^{\frac{1}{S}} \right]$$

$$A = 2.11, \quad N = 0.848$$

$$x_L = 28.17, \quad S = 0.0513$$



## Slalom Race in Undulator



# fast Electrons in magnetic field generate Synchrotron Light

**moving light source**



**Doppler effect**

**shift to higher frequencies**  
 $\Rightarrow$  short wavelength  $\lambda$

**narrow light cone**  
 $\Rightarrow$  strong collimation  
 (laserlike)

**slalom course in undulator**

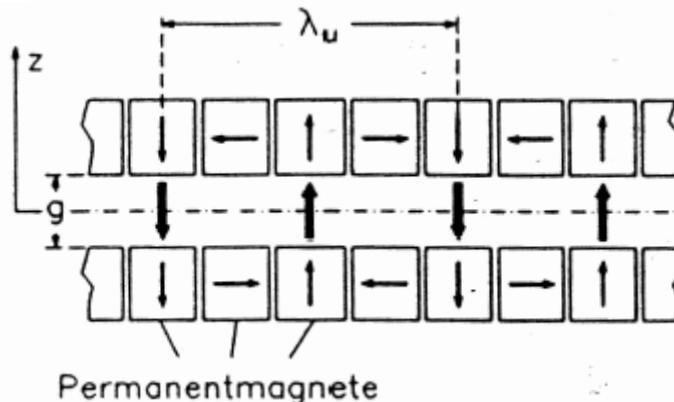


**positive Interference**

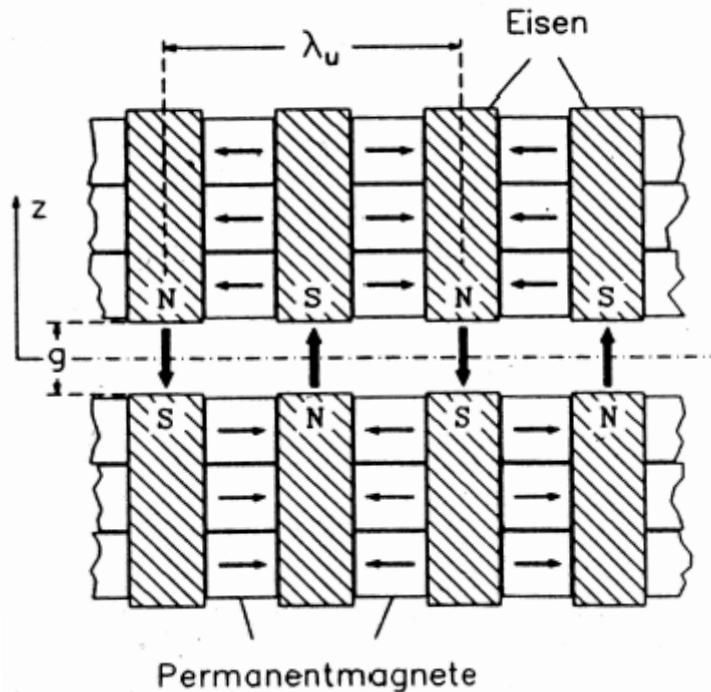
period  $\lambda_u$  gives sharp  
 spectral lines at harmonics  $n$   
 $\Rightarrow$  high brightness

$$\lambda \sim \lambda_u (c - v_e) \sim n \lambda_u / E_e^2$$

- $\Rightarrow$  short wavelength  $\lambda$  requires high electron energy  $E_e$
- $\Rightarrow$  large storage ring



Hybrid-Undulator



## Undulators à la Halbach

An Undulator forces an Electron on a Slalom course.

Revolution in the Construction of Undulators:

Klaus Halbach, Berkeley, proposed 1980

## Permanent Magnets (PM)

=> allows short Periods  $\lambda_u$  (15-60 mm)

PM-Material: SmCo , NdFeB

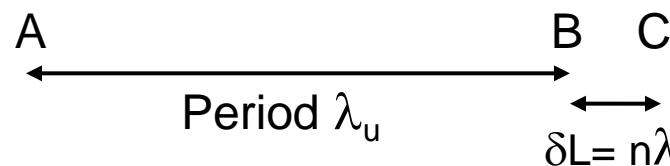
a Pencil made with PM corresponds to  
15'000 Amp-Turns !!

Variation of Field with Magnet Gap g  
=> Variation of Wavelength  $\lambda$

## Selection of Wavelength $\lambda$ in an Undulator

In an Undulator there is a Race between the Electron  
(on a Slalom Course) and an emitted Photon!

N	S	N(orthpole)	S(outhpole)
---	---	-------------	-------------



Electron  $v \equiv \beta c$

Photon  $c$

At A an Electron emits a Photon 1 with Wavelength  $\lambda$ .

At B it emits another Photon 2 with the same  $\lambda$ .

By that time Photon 1 is already at C, ahead by  $\delta L$ .

If  $\delta L$  corresponds to  $n\lambda$ , then this wavelength is amplified through **positive Interference**.

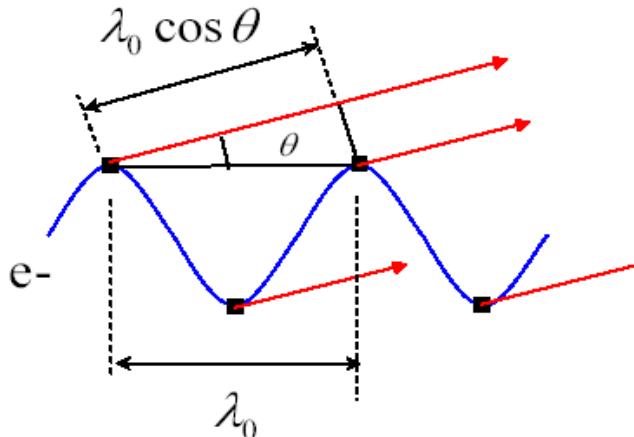
$$\delta L \equiv n\lambda \approx (1 - \beta) \lambda_u, \quad 1 - \beta \approx \frac{1}{2\gamma^2}$$

$$\lambda = \frac{\lambda_u}{2n\gamma^2} \left(1 + \frac{K^2}{2}\right)$$

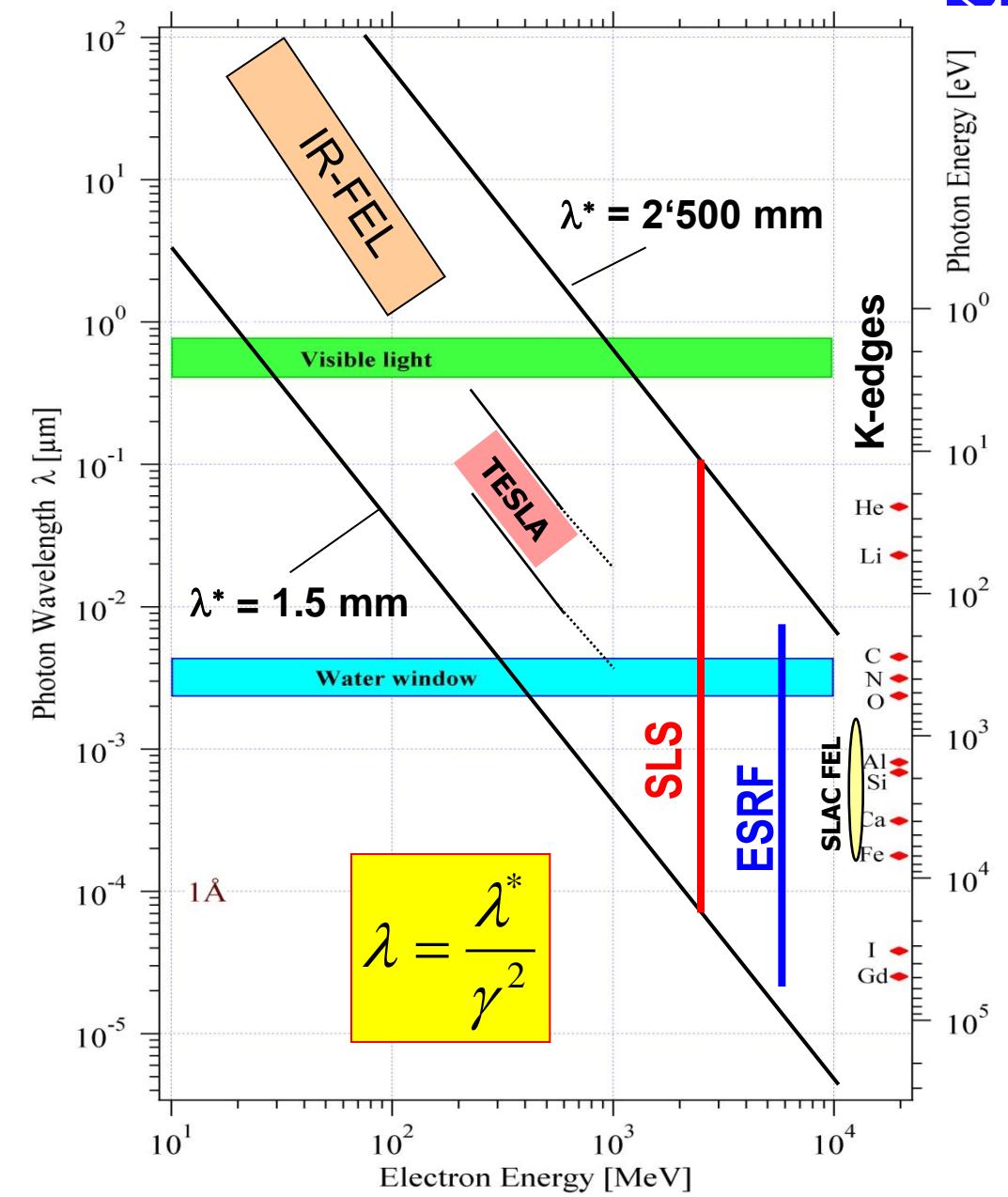
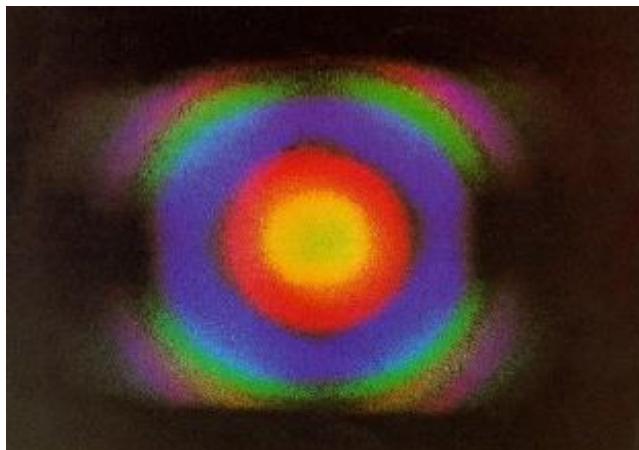
↑  
Detour by Slalom

$$K = 0.0934 \lambda_u [mm] B [T]$$

## Undulator Radiation



$$\lambda^* = \frac{\lambda_u}{2n} \left( 1 + \frac{K^2}{2} + \gamma^2 \theta^2 \right)$$



## SLS Undulators

- In-Vacuum Undulators: Period = 19 mm, min. gap = 5 mm

**X-Rays: 3-20 keV (13th harmonic)**

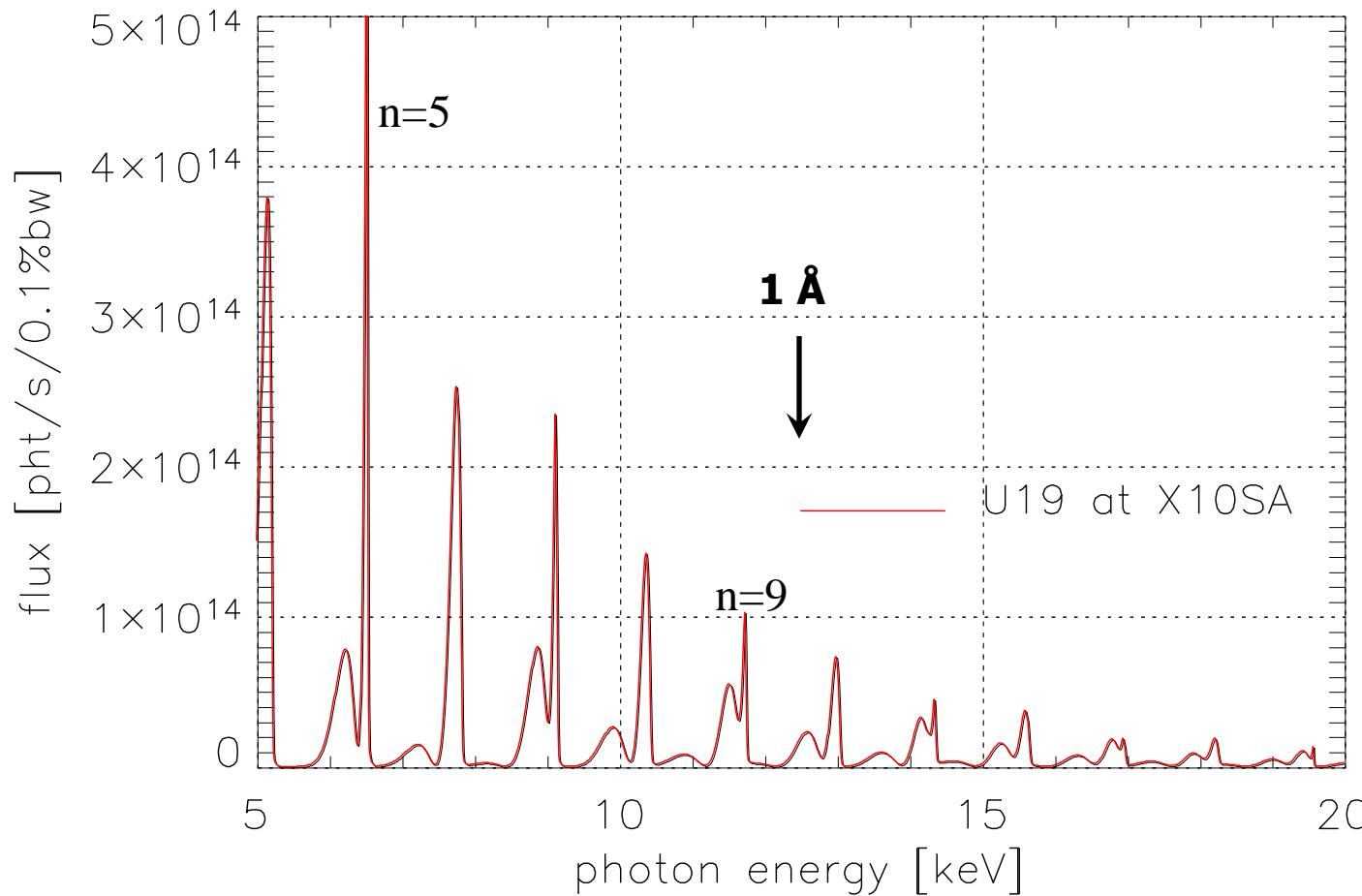
- Apple II Type Twin Undulators: Period = 56 mm

**flexible Polarisation Modes, 90-3000 eV**

- Electromagnetic Twin Undulator UE212: Period = 212 mm

**VUV- and soft X-Rays: 10-800 eV**

## Spectrum of Undulator U19



**in-Vacuum Undulator**

**Protein Crystallography**  
**(Clemens Schulze)**

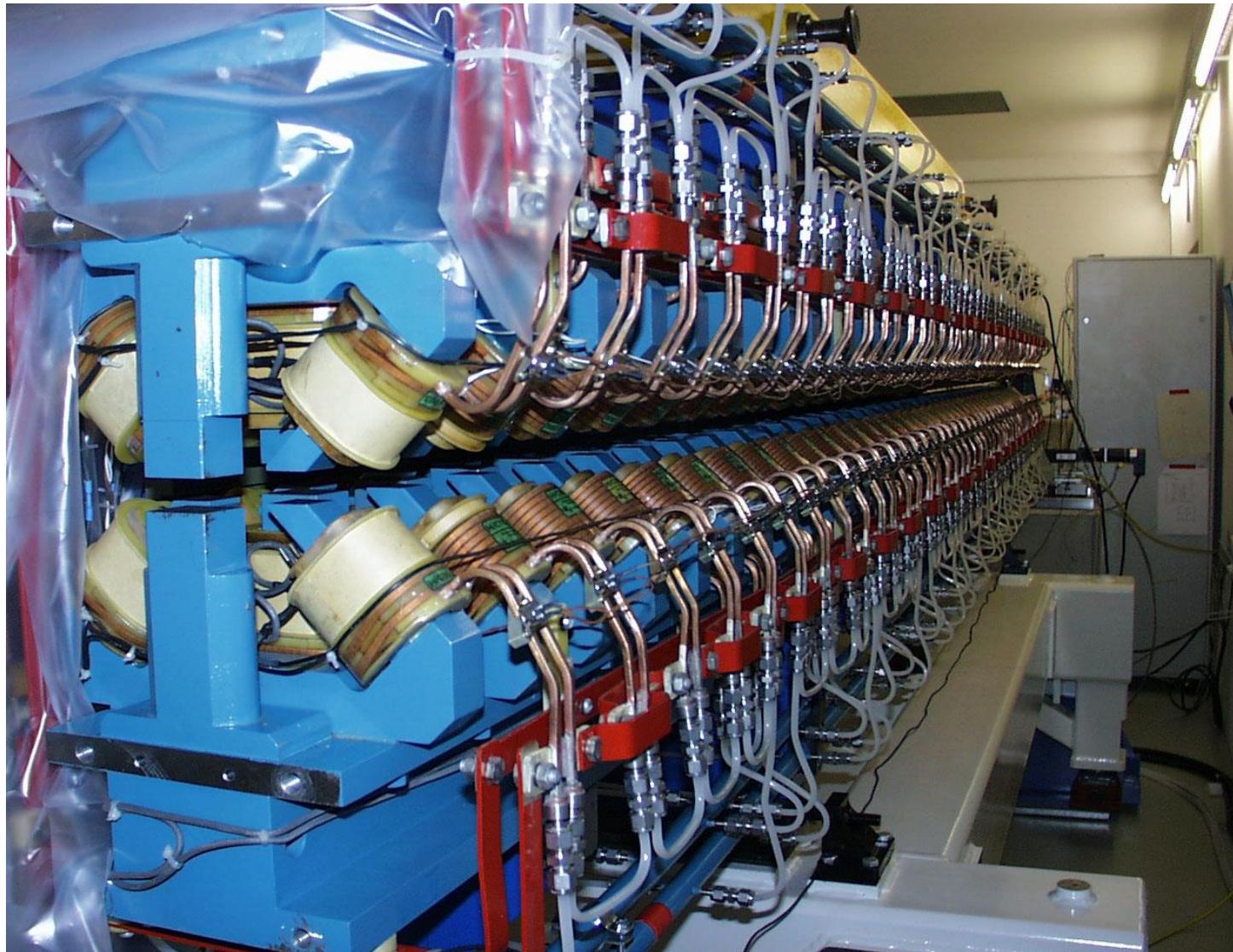
# Undulator UE56



Permanent Magnets  
62 Periods à 56mm

helical Fields give  
circular and linear  
Polarisation

# Undulator UE212



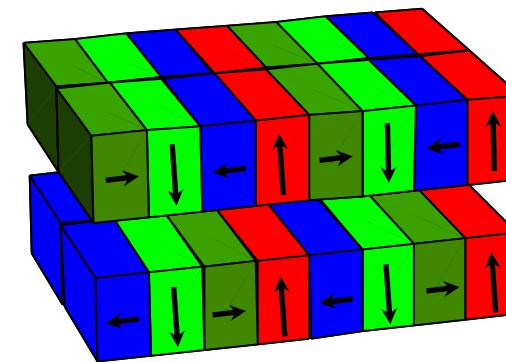
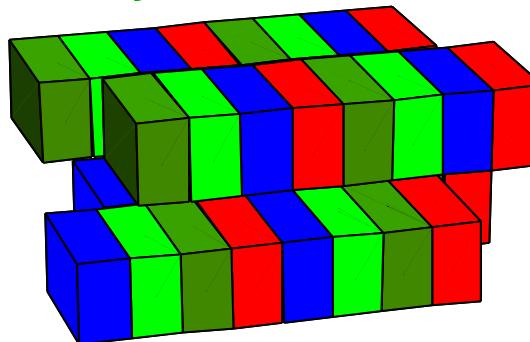
Electromagnets

2\*21 Periods à  
212mm

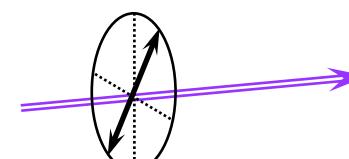
helical Fields give  
circular and linear  
Polarisation

# Elliptical undulatc

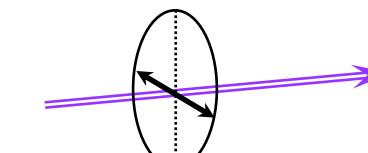
shift 0

shift  $\pi/2$   
asymmetric

linear 0 - 90°

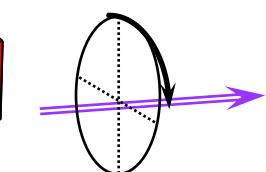
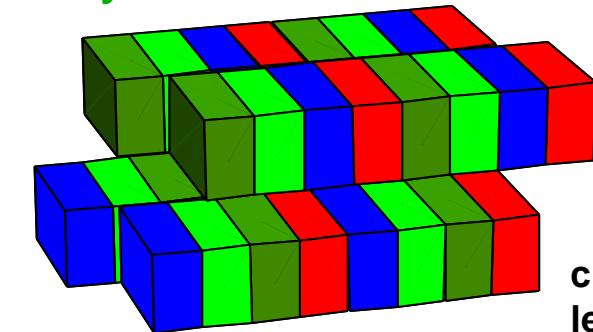
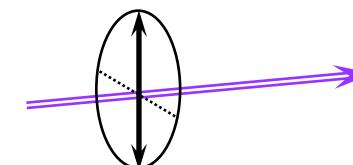
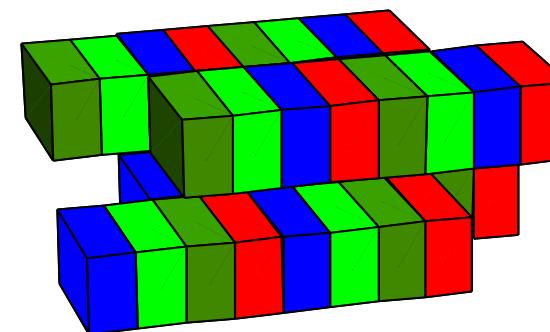


nearly polarised light



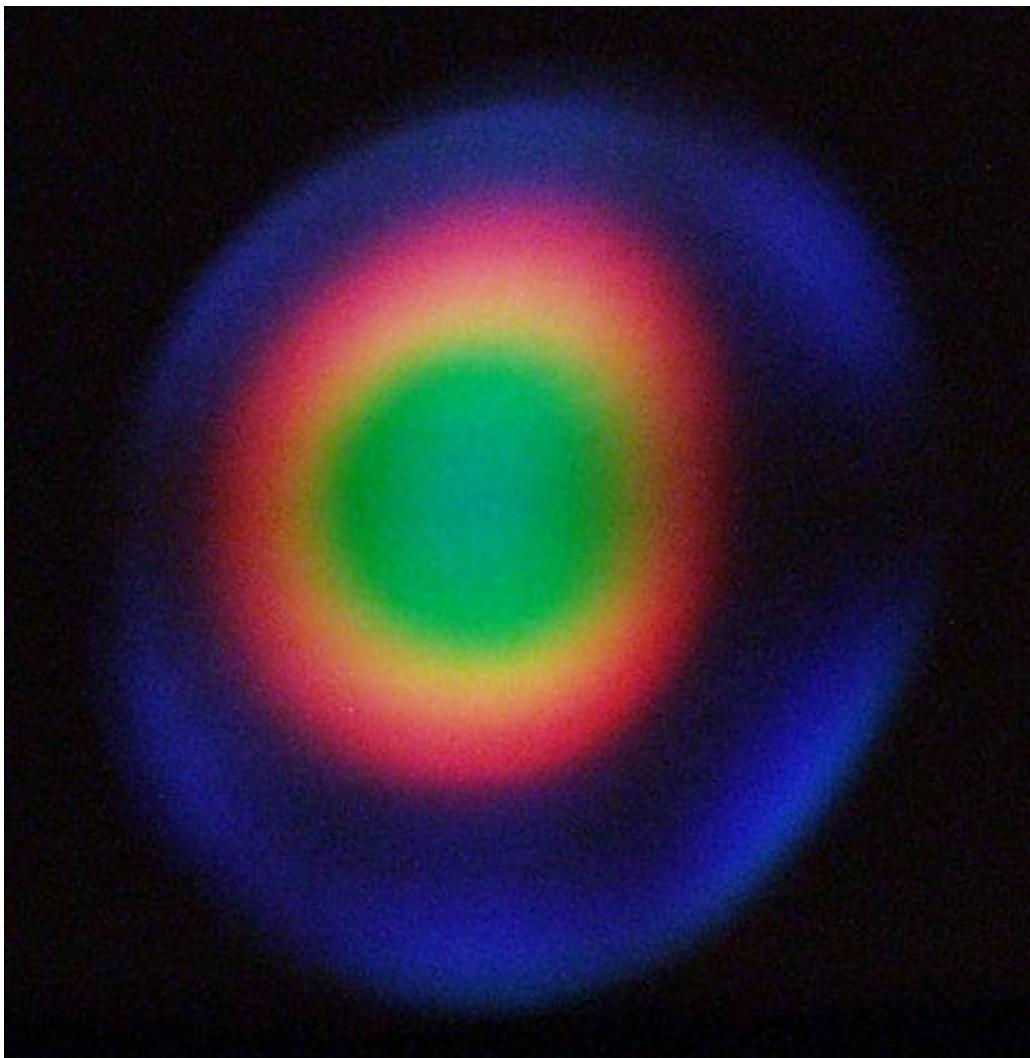
horizontal

symmetric

circular  
left or right  
(helicity + or -)shift  $\pi$ 

vertical

## Light Cone



Light Cone from Wiggler W138

1. harmonic,  $K=18$  ( $B=1.4$  T)

# Brightness of a Light Source

Source area,  
 $S$

$S$



Angular  
divergence,  
 $\Omega$

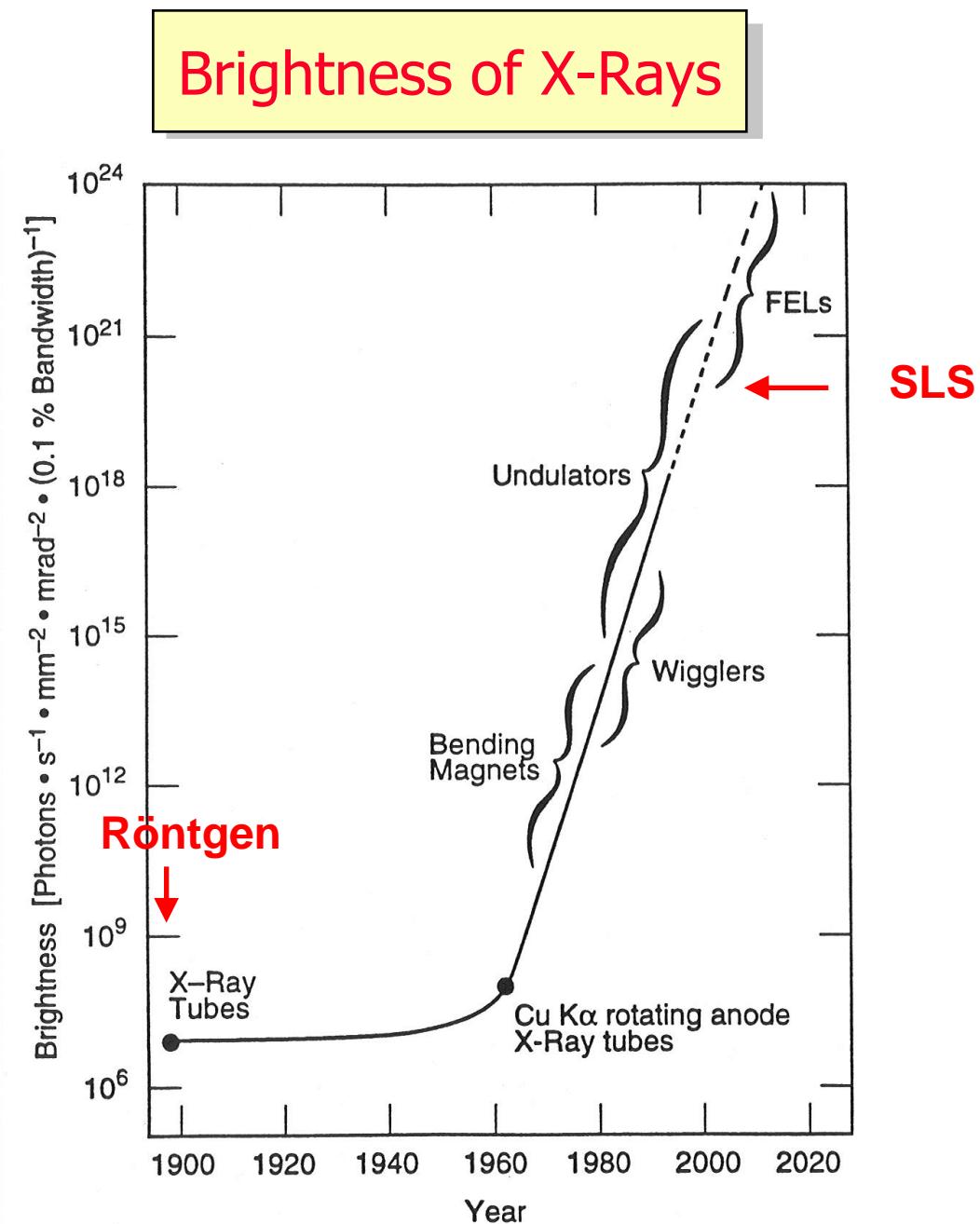
Flux,  $F$

$$\text{Brightness} = \frac{F}{S \cdot \Omega}$$

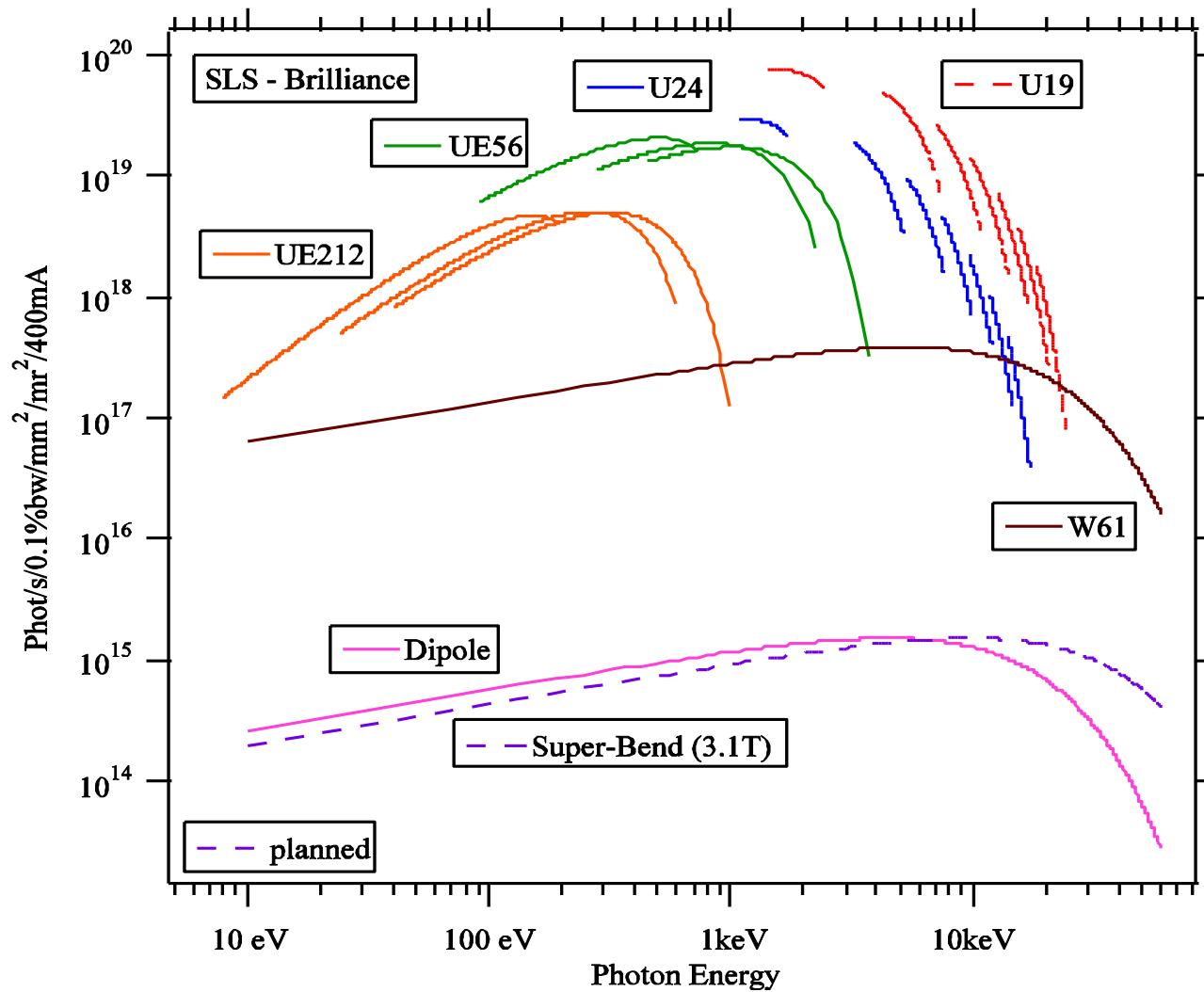
high Brightness

- Investigation of small Microprobes (Cristals < 20 µm)
- small Beam Divergence
  - => compact Mirrors, small Aberrations
- short Measuring-Time (ca. 15 min/crystal)
- high Coherence => Imaging with Phase Contrast

**'Brightness'= performance of a light tower**



## Brightness at 2.4 GeV and 400 mA



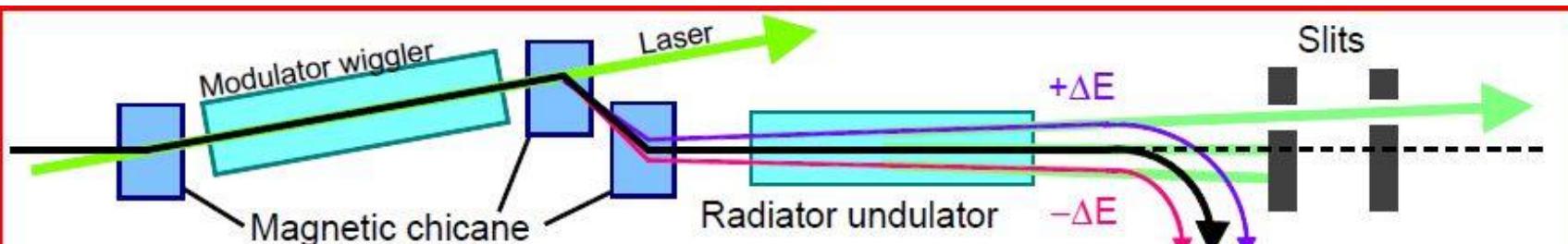
U19: 5 – 6 mm gap

Peak Brilliance at 1-2 keV

max. Energy  $\approx$  20 keV

(13. harmonic)

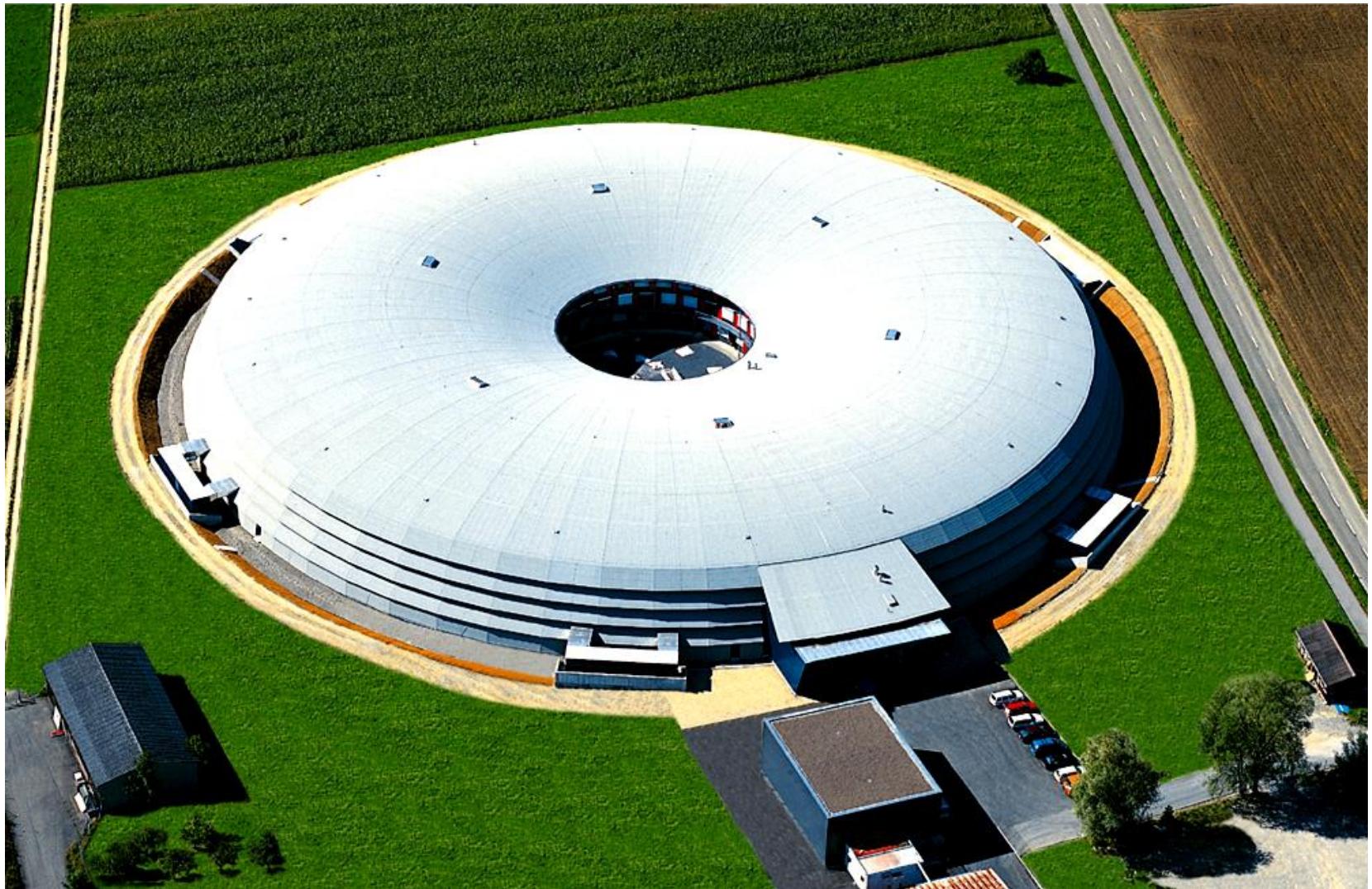
## Short Pulses



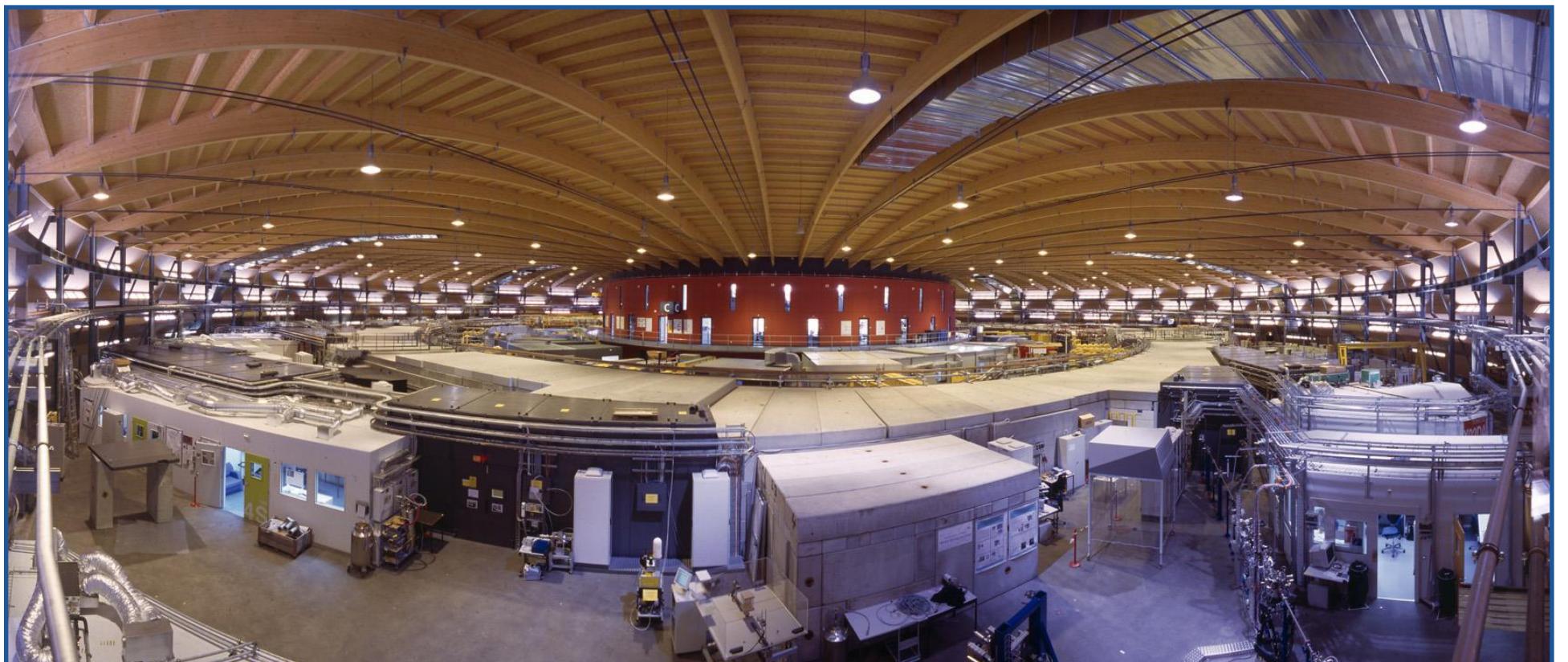
### Laser beam slicing FEMTO @ SLS

- ◆ Operation since 5 years. High scientific output.
- ◆ Compatible with other SLS users.
- ◆ X-ray pulse length **150 fs FWHM**.
- ◆ Photon energy ...4...8... keV.
- ◆ Temporal stability **30 fs rms** over one week.
- ◆ Flux up to  **$3 \cdot 10^5$  photons / s / 0.1%BW**.
- ◆ Repetition rate **2 kHz**.
- ◆ **upgrade:** → **10 ( 20 ? 100 ?? ) kHz**.

SLS Photo

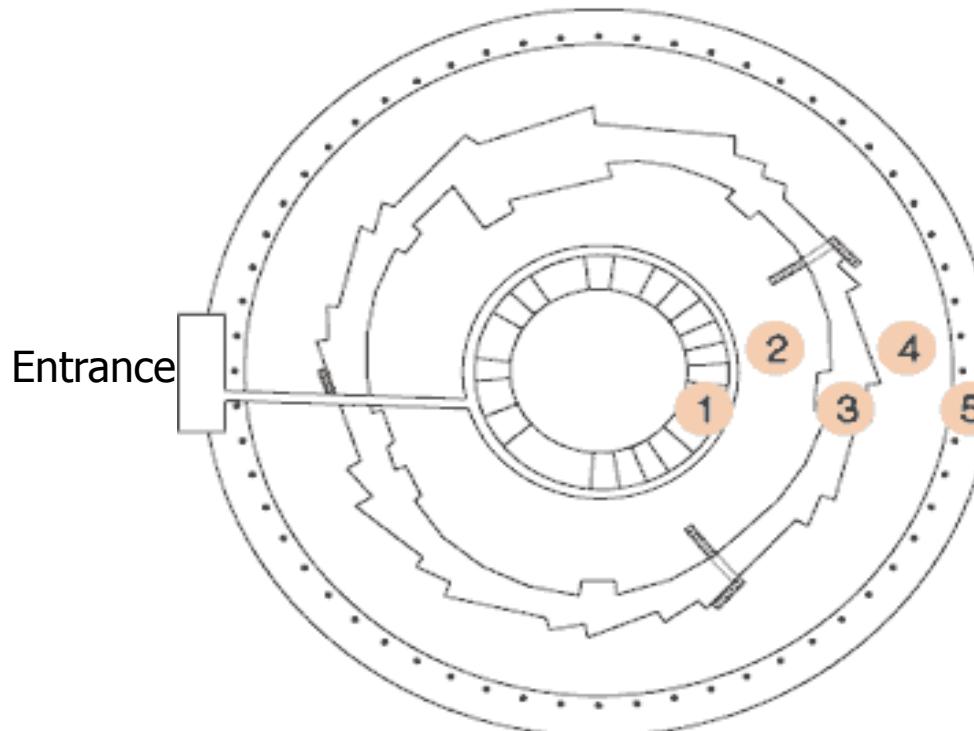


## SLS Building



an architectural Juwel !

Team of Architects from Bern  
(Gartenmann, Werren, Jöhri, Marchand )



Zones:

- 1 Office Building (3 Floors)
- 2 Technical Galery
- 3 Tunnel (Storage Ring, Linac and Booster)
- 4 Area for Beam Lines
- 5 Outer Ring (60 Columns, Air Inlet System)

## Building Concept

- separate annular Ring (40 cm) for Floor of Tunnel und Beam Lines (Zones 3, 4)  
=> decouples Tunnel and Exp. Floor from Rest of Building
- very stable Temperatures in Tunnel und Hall

=> **stable Conditions for  
Electron Beam and Beam Lines**

## Building Parameter

outer Diameter	138 m
Height	14.3 m
Area	14'000 m <sup>2</sup>
Columns, Roof Beams	60
Length of Roof Beams	43 m
Crane	16 t
Circumference Storage Ring	288 m
Tunnel, inner Height	2.4 m

Office Building:

3 Floors with Offices for 80 Persons, Control Room, Labs

## Building Specifications

- Base Ground: Glacial Gravel and Sand,  
only removal of ground for leveling!
- separate annular Concrete Ring Floor (Cast in one Piece)  
for Tunnel and Beam Lines
- differential Settlement: < 0.2 mm/year over 10 m
- Tolerance on Vibrations: < 0.5  $\mu\text{m}$  (up to 50 Hz)
- recessed Windows in Building Walls  
=> no direct Sun Light on Floor

## Wooden Roof



Aufnahmedatum  
18. November 1998  
PSI / SLS

## Temperature Stability

=> vital for stable Beams !

### Tunnel



$25^{\circ} \pm 0.03^{\circ}$

- Air Conditioning: 5 Units à  $6'000\text{m}^3/\text{h}$
- 150 Jets for stable Air Circulation
- 40kW Cooling, 90kW Heating (Shutdown)

### Hall



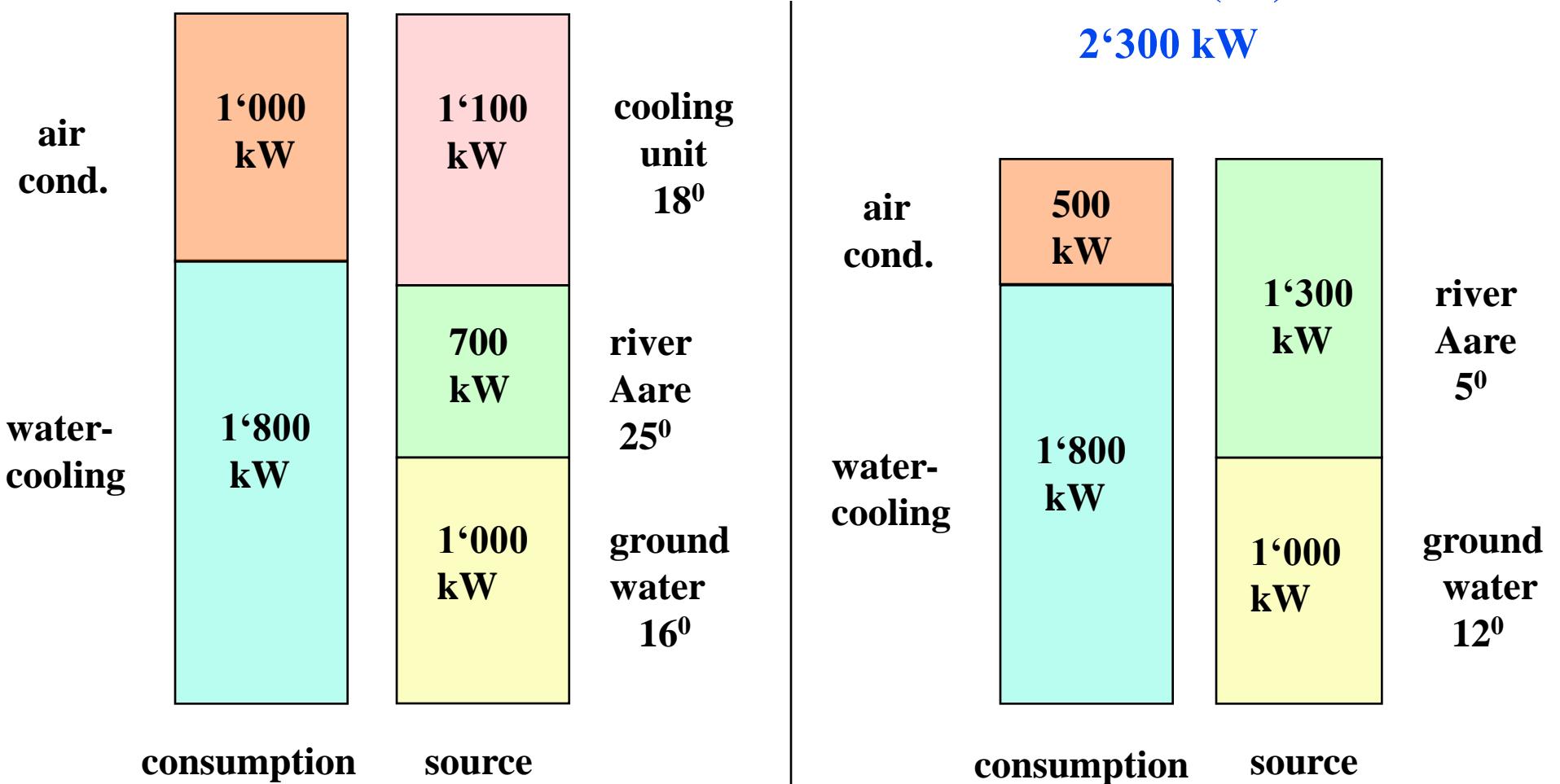
$24^{\circ} \pm 0.2^{\circ}$  (Summer and Winter)

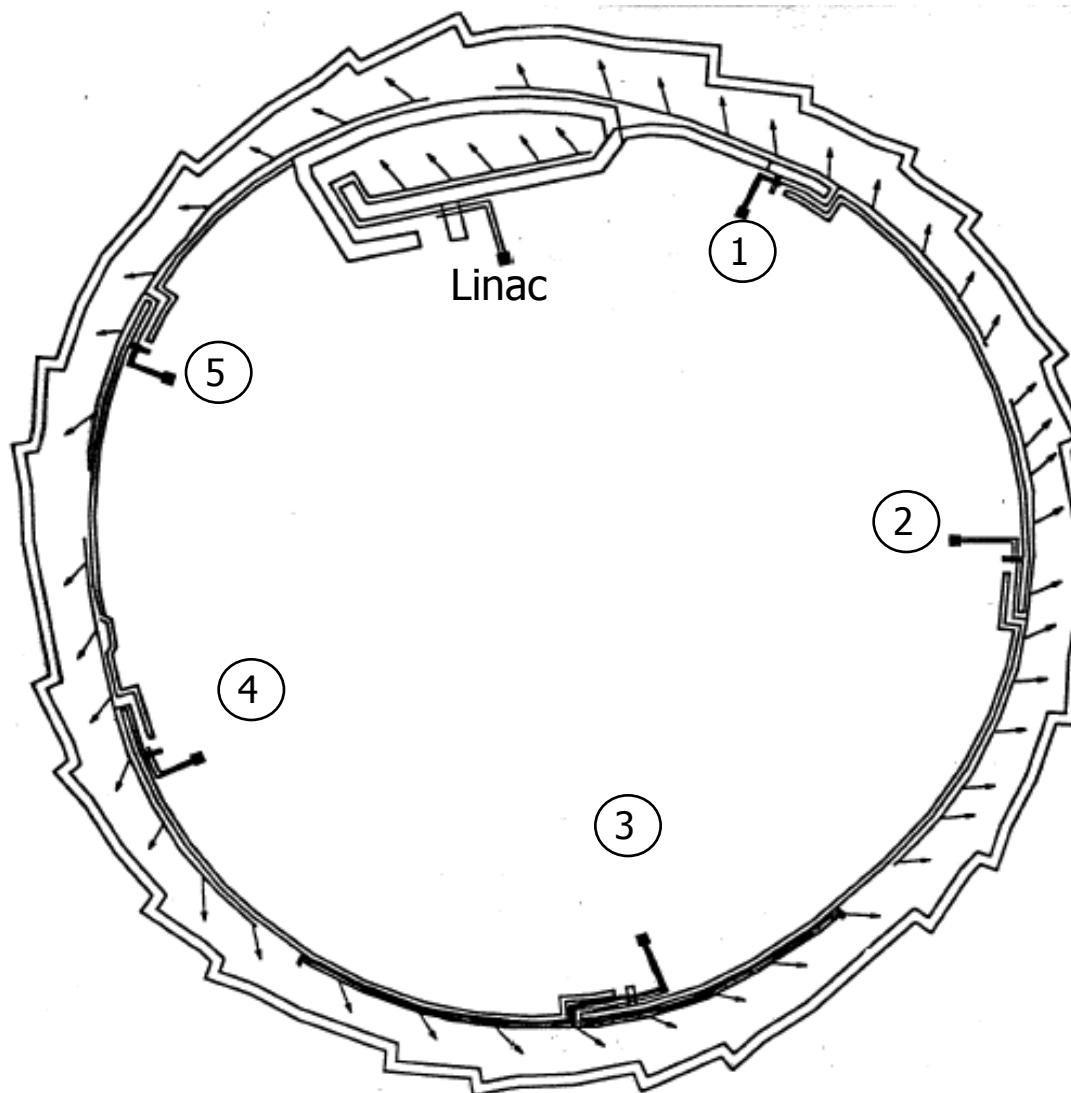
- Air Conditioning: 6 Units à  $50'000\text{m}^3/\text{h}$
- 800kW Cooling Power
- gentle Air Inlet on 55% of outer Circumference

## Cooling of SLS

**Summer ( $35^0$ )**

**2'800 kW**





## Airconditioning in SLS Tunnel

Air Jets produce a helical Air Flow

**Tunnel** ( $3'100 \text{ m}^3$ ):

5 Cooling Units, 150 Jets

total:  $30'000 \text{ m}^3/\text{h}$

40 kW Cooling, 90 kW Heating

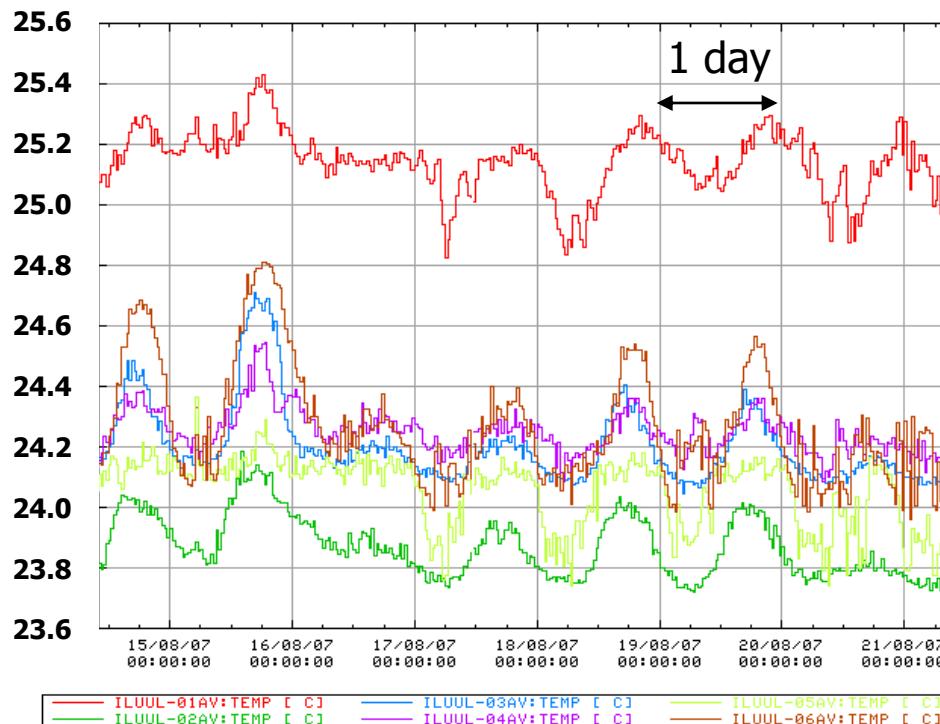
$T=25^\circ \pm 0.03^\circ$

**Linac:** 1 Cooling Unit,  
20 Jets

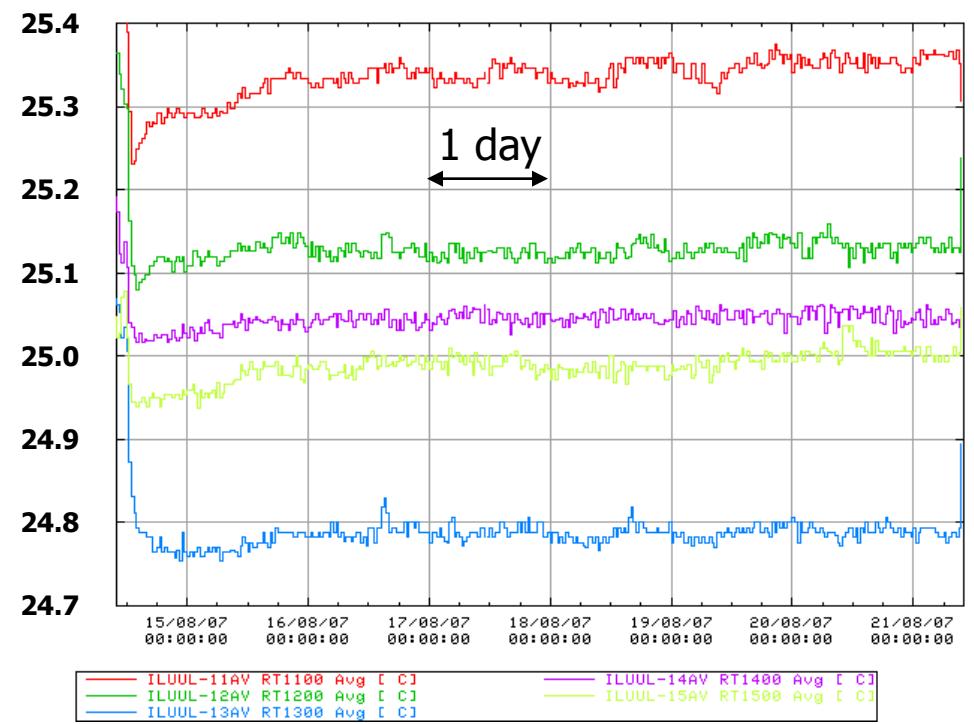
# Stability of Temperature Exp.Hall and Beam Tunnel

7 days in August 2007

Hall Temperature [ $^{\circ}\text{C}$ ] of 6 Sectors



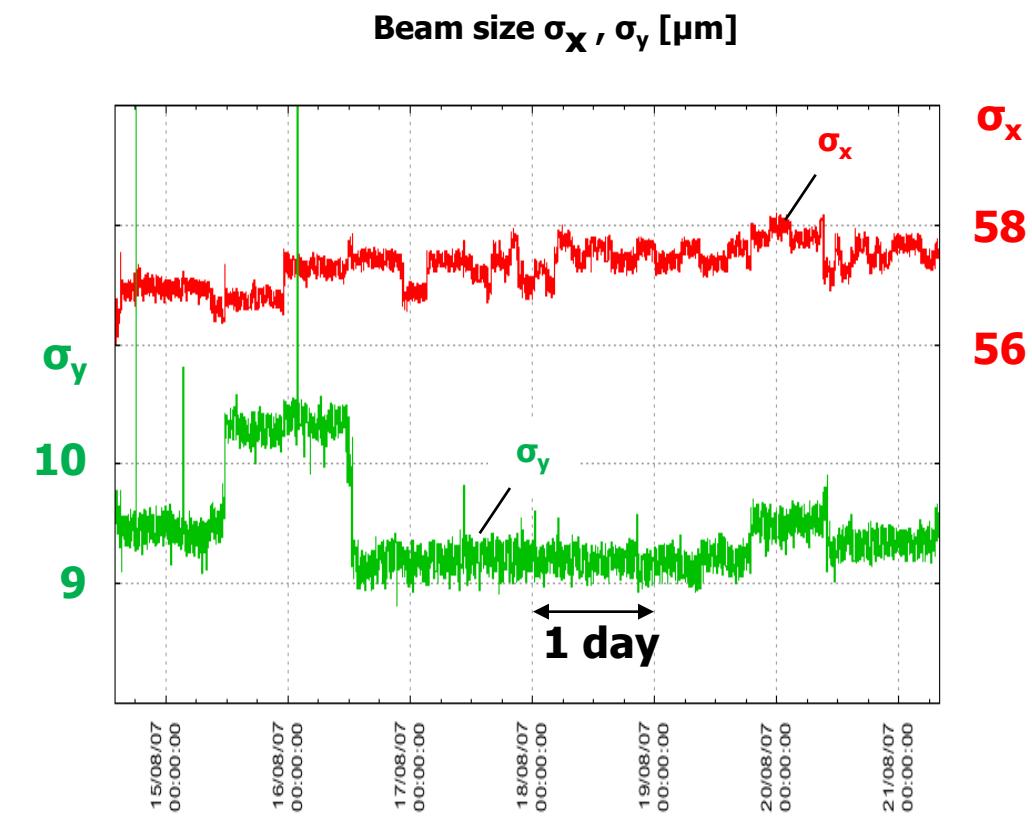
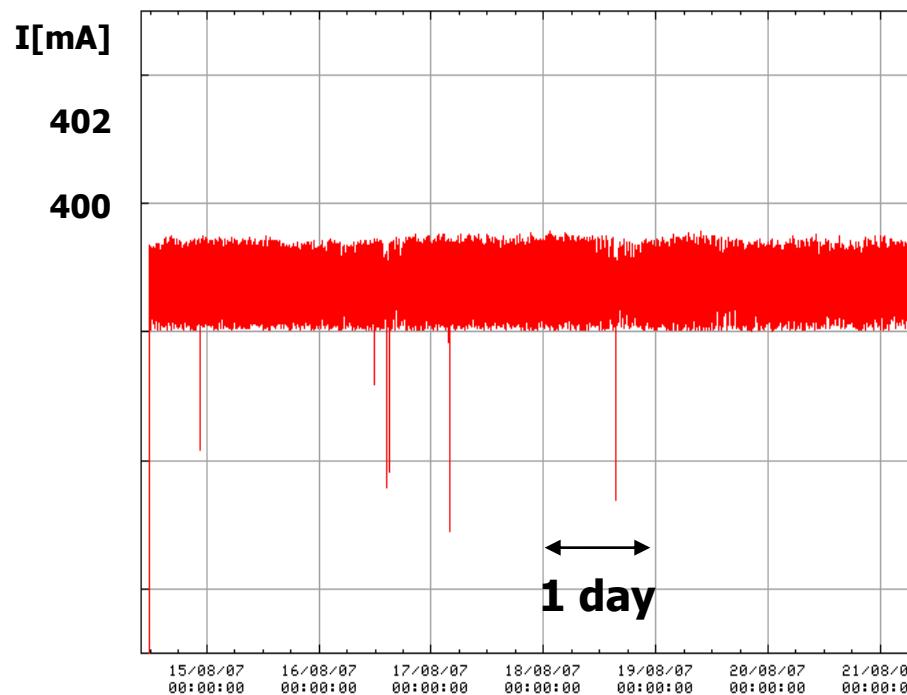
Tunnel Temperature [ $^{\circ}\text{C}$ ] of 5 Sectors



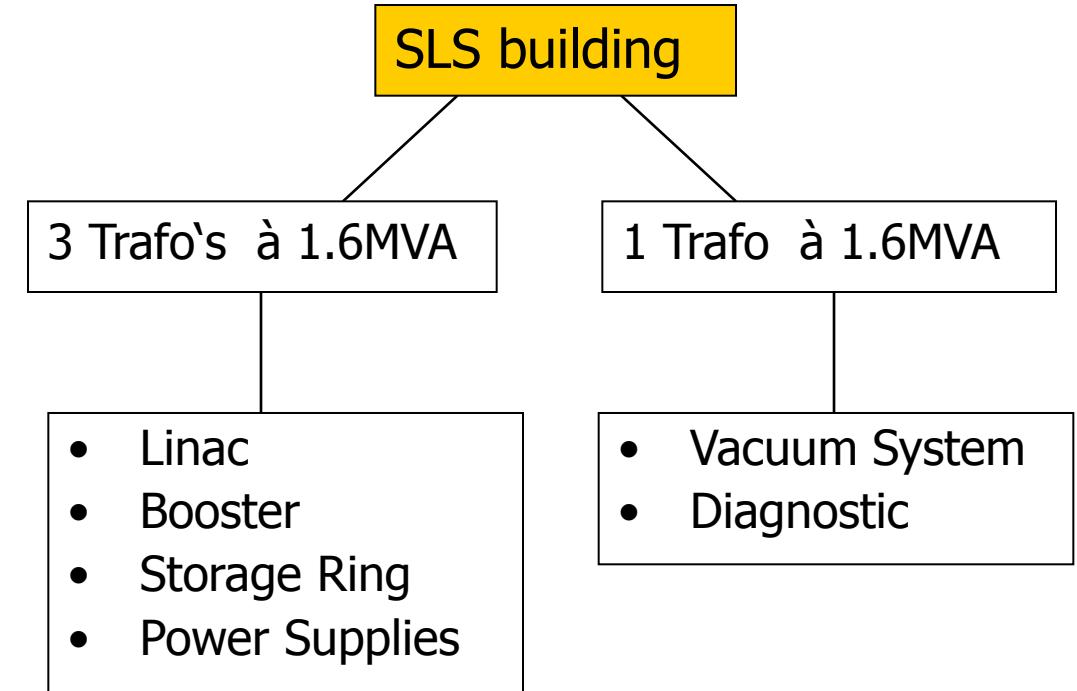
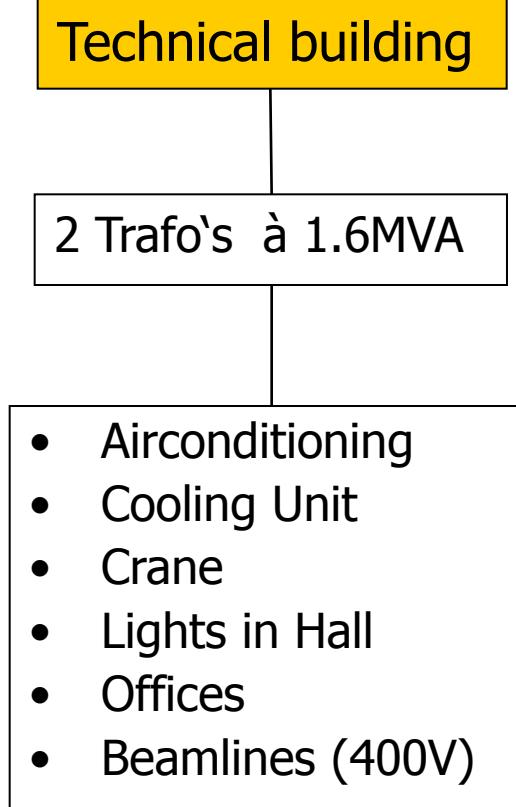
# stable beams with top-up

7 days in August 2007 , without interruptions!

top-up every 2.5 min.  
Beam current 400-401.5 mA



## SLS Electro Concept



- **installed Power: 9.6 MW**
- **consumed Power: 3-3.5 MW**

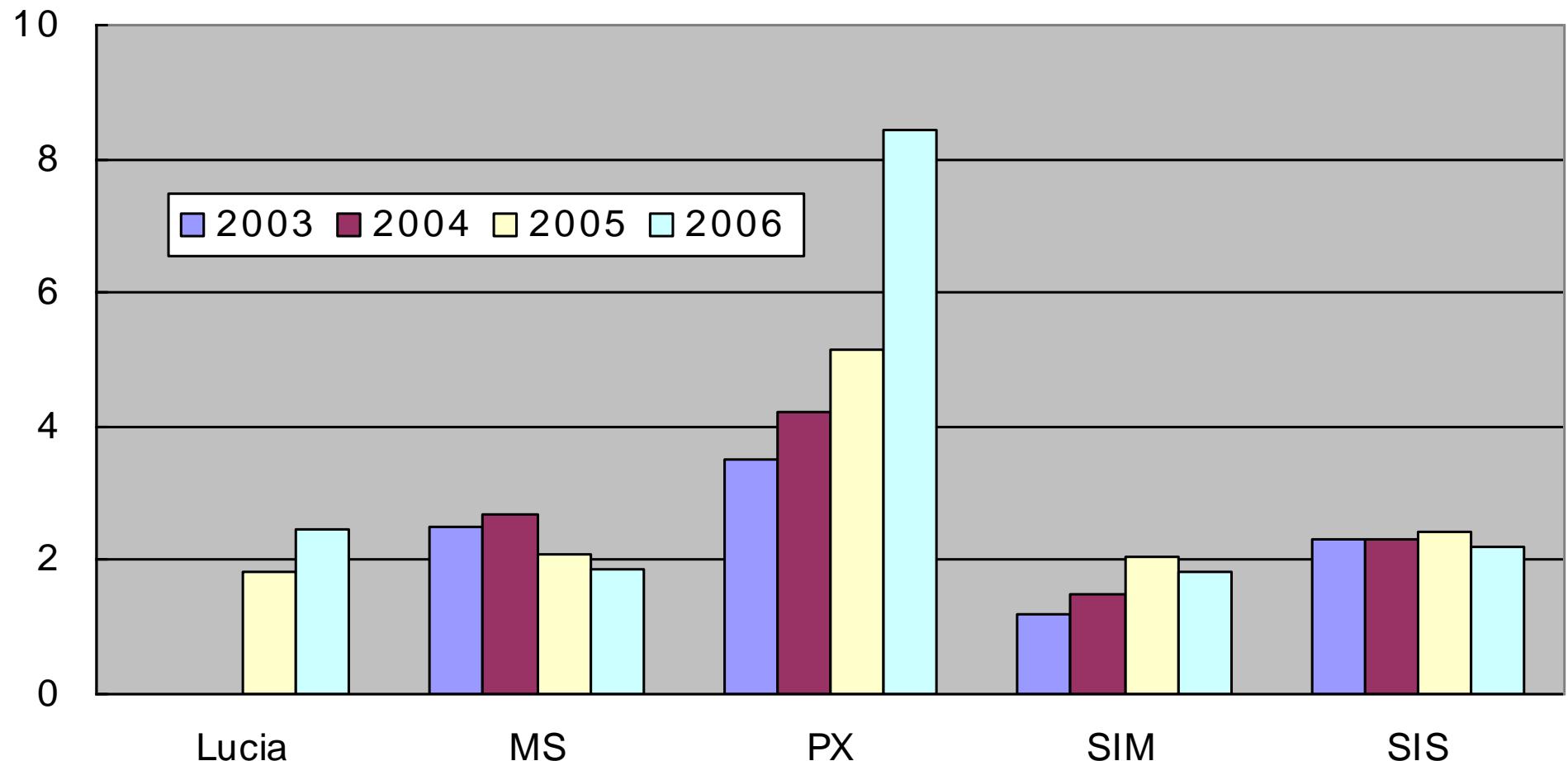
## SLS Users

### Institutes

### Industry

- ETH Zürich, ETH Lausanne
- Universities  
(CH und abroad)
- PSI
- Research Labs  
(IBM Rüschlikon, EMPA,  
Max Planck Institute Munich,...)
- Novartis
- Hoffmann-LaRoche

# Overbooking of SLS Beamlines



## Experimental Trends

### 1. Protein Crystallography

Crystals as small as  $5 \times 5 \mu\text{m}$

(The Swiss Chemical Companies finally woke up!)

### 2. Microscopy of surfaces

30 nm resolution, (e.g. magnetic domains)

### 3. Micro Spectroscopy

### 4. Micro Tomography

=> Top up and submicron stability (with FOFB)  
is absolutely essential!

## Milestones

First Ideas	1991	Start of Building:	2.June 1998
„Giessbach-Meeting“ (Users support SLS)	Oct. 1994	Building finished:	1.July 1999
ETH-council approves SLS	Sept. 1995	Beam in Linac:	23.March 2000
Parlament approves SLS	<b>18.June 1997</b>	Beam in Booster:	8.Aug. 2000
		Beam in Storage Ring	<b>13.Dec. 2000</b>
		goal of 400 mA reached	5.June 2001
		=> Begin Experiments:	2.Aug. 2001

## Budget SLS (1997)

Building + Land 38 MFr.

Infrastructure, Labs, Ringtunnel 25 MFr.

Storage Ring, Booster, Linac 68 MFr.

4 Beam Lines (2007: 8+3) 28 MFr.

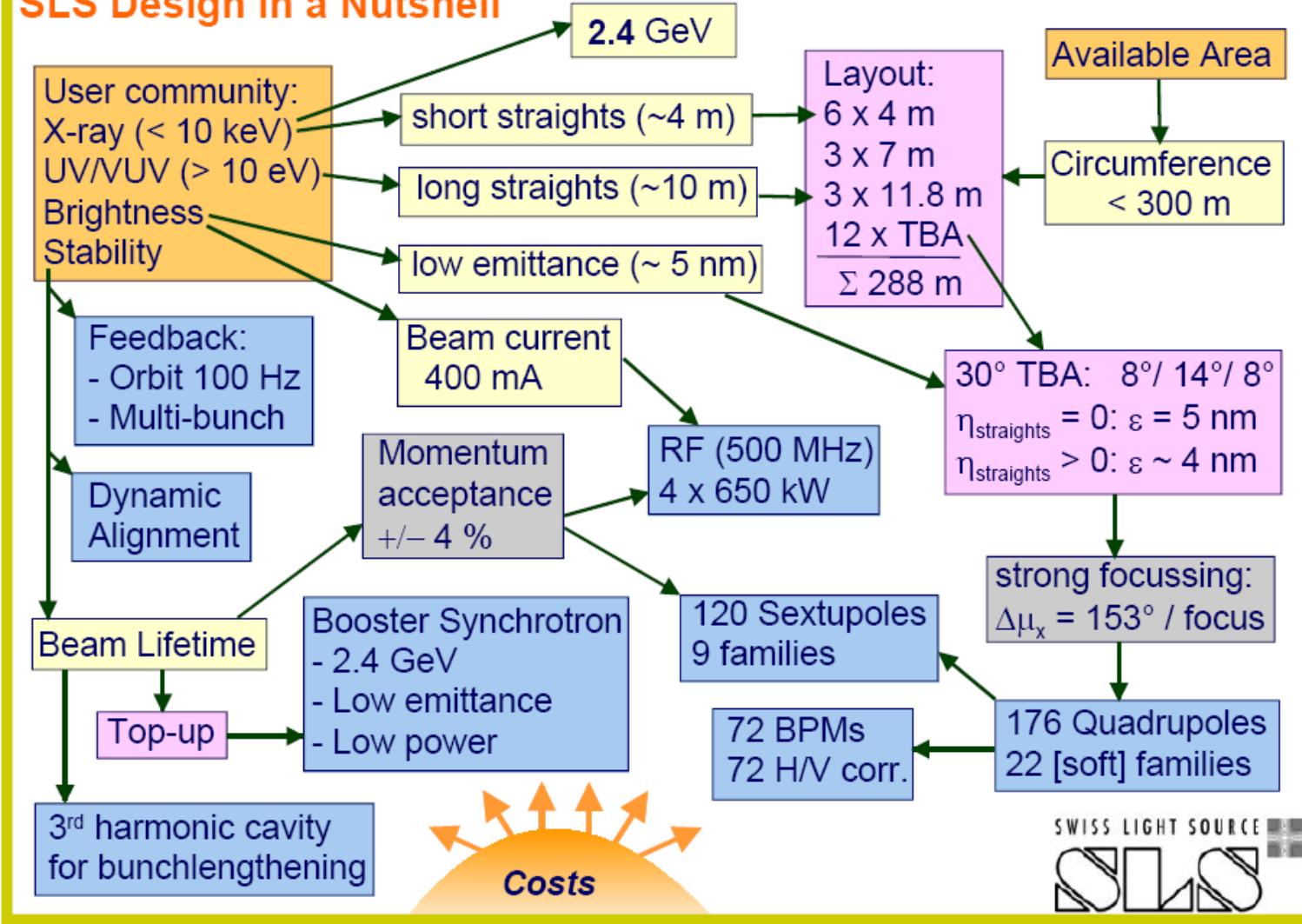
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Total Costs for SLS 159 MFr.

plus 400 man years

# SLS Summary (A.Streun)

## SLS Design in a Nutshell



copy of SLS ?  
(à la Andreas Streun)

## SLS-Design

If we would have to do it again...

*higher performance at lower costs !*

Explore new options:

- **Reduced spectral range:** dedicated VUV xor Xray rings
- **Emittance < 1 nm:** longitudinal gradient bends, multi-cell achromats
- **Reduced flexibility:** predictable magnetic fields and beam dynamics
- **Combined magnets:** D+Q, D+Q+S (SLS-booster), Q+S+O (MAX-4)
- **Higher multipoles:** Octupoles ( $dQ/dJ$ ,  $d^2Q/dp^2$ ) and decapoles ( $d^3Q/dp^3$ ) ?
- **Dynamic alignment:** The magnet *is* the girder.
- **Reduced apertures:** where's the limit? (acceptances, resistive wall....)

## New Light Sources (à la A. Streun)

### Is there a future for new storage ring light sources ?

Users for: high brightness **and not** time resolved ?

Era of national work horses: large, flexible, “conservative”, many different users

New projects: MAX-4, NSLS-2, ESRF-2,...

Lattice trends:

- Reduced spectral range: dedicated VUV **xor** Xray rings
- Emittance < 1 nm
- Reduced flexibility: predictable magnetic fields and beam dynamics
- Combined magnets: D+Q+S (SLS-booster), Q+S+O (MAX-4)
- Octupoles ( $dQ/dJ$ ,  $d^2Q/dp^2$ ) and decapoles ( $d^3Q/dp^3$ ) ?
- The magnet **is** the girder.
- Reduced apertures: where's the limit? (acceptances, resistive wall....)
- → Possible cost savings

## SwissFel Project

Combination of advantages of

### Laser

- extremely short pulses
- extremely high intensity
- monochromatic light
- coherence

### X-rays

- very short wavelenghts  
=> details of very small structures
- transparency of materials
- adjustment of wavelength  
to specific elements

## Free Electron Laser

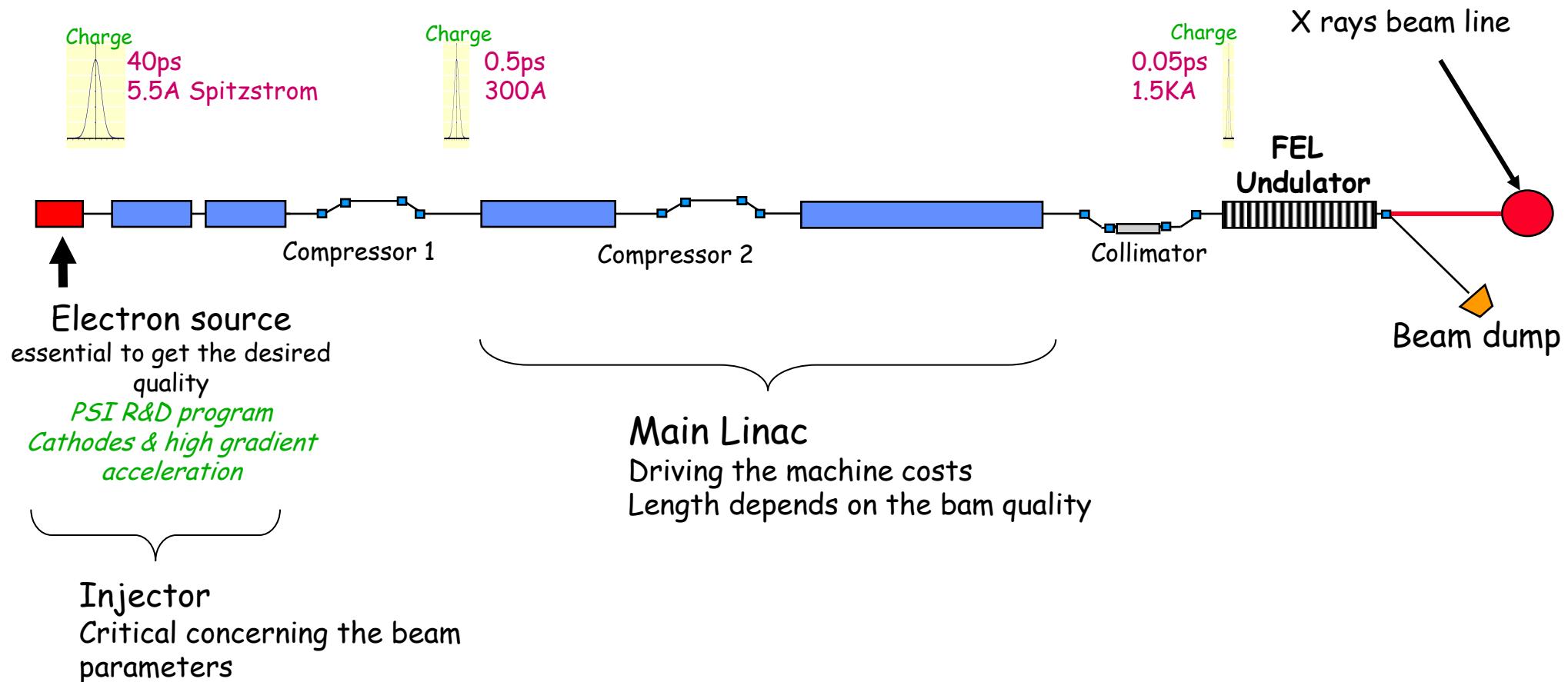
excellent beamquality of electron gun

- ⇒ microbunches of electrons in undulator
- ⇒ extremely short and intense X-ray flashes
- ⇒ „film of dancing molecules“

=> new research topics in  
Physics, Chemistry, Biology, Material Science

**=> PSI remains internationally competitive**

## Typical FEL layout



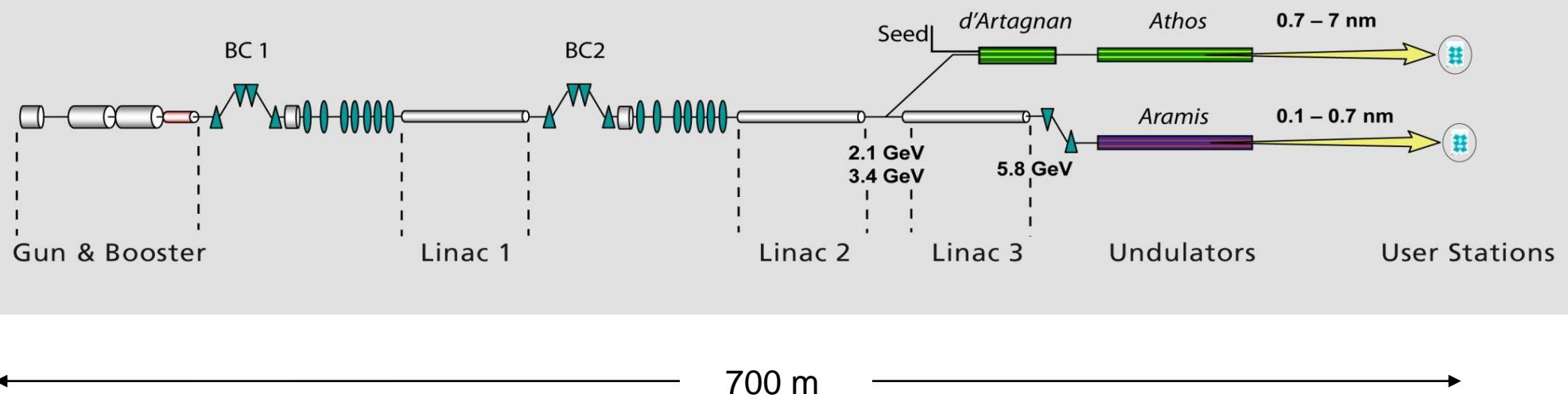
The FEL is a very high brightness light source  
Fully coherent with very short photon pulse ~50 fs

# Layout

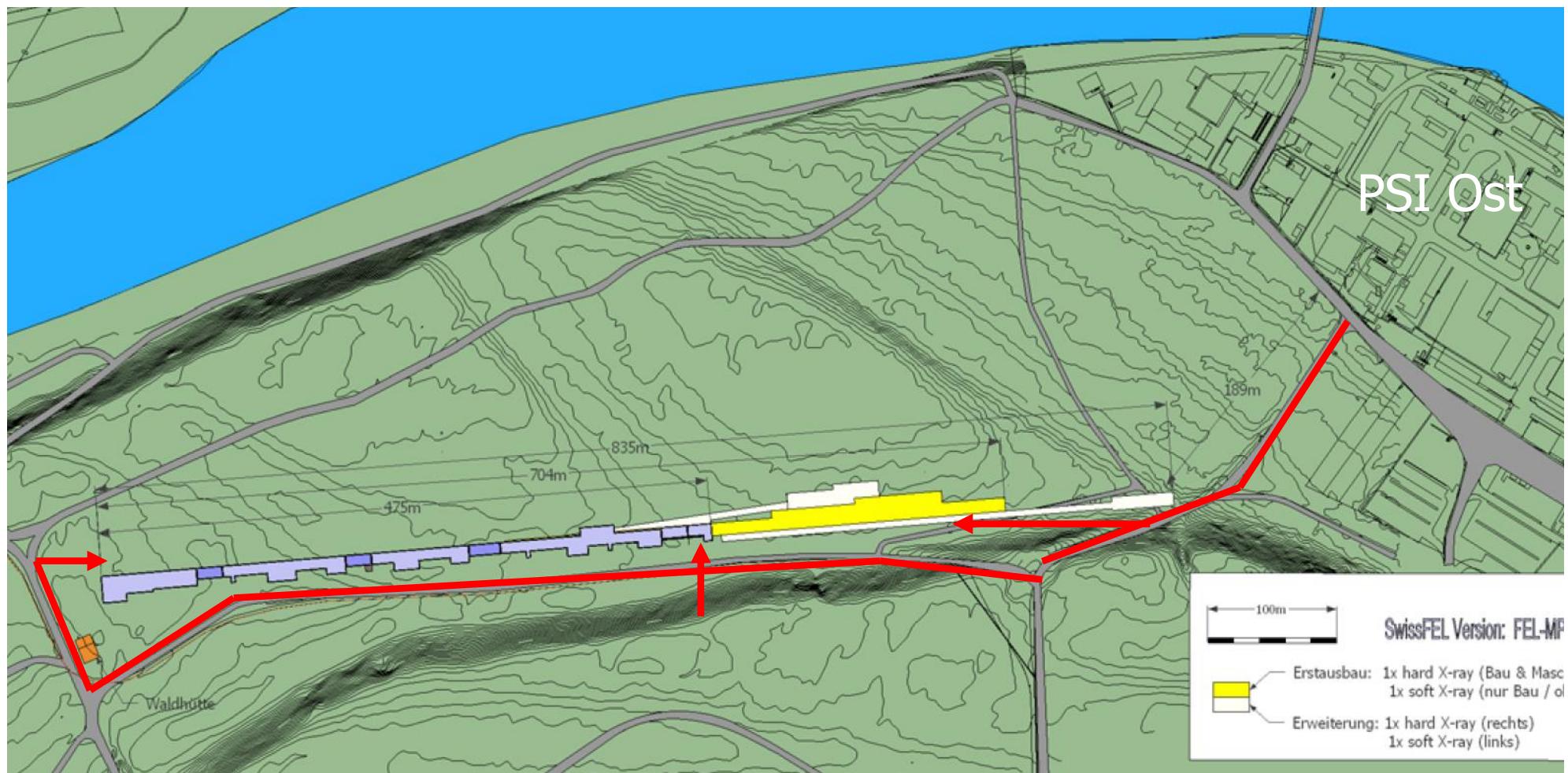
## Electron Injector

## Linear- Accelerator

## Free Electron Laser Experiments



# SwissFEL Würenlingen



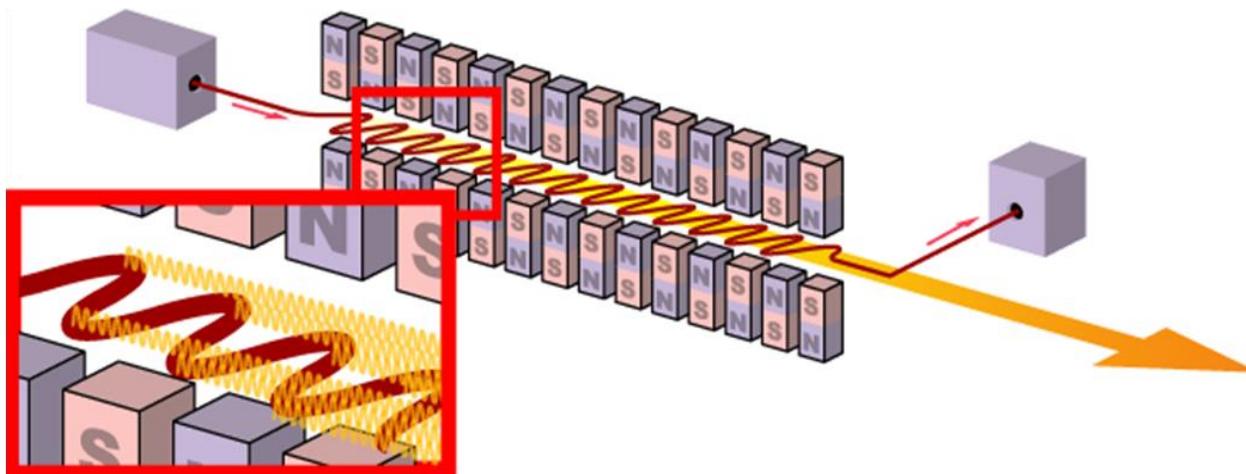
# SwissFEL

## SwissFEL

the next large facility at PSI

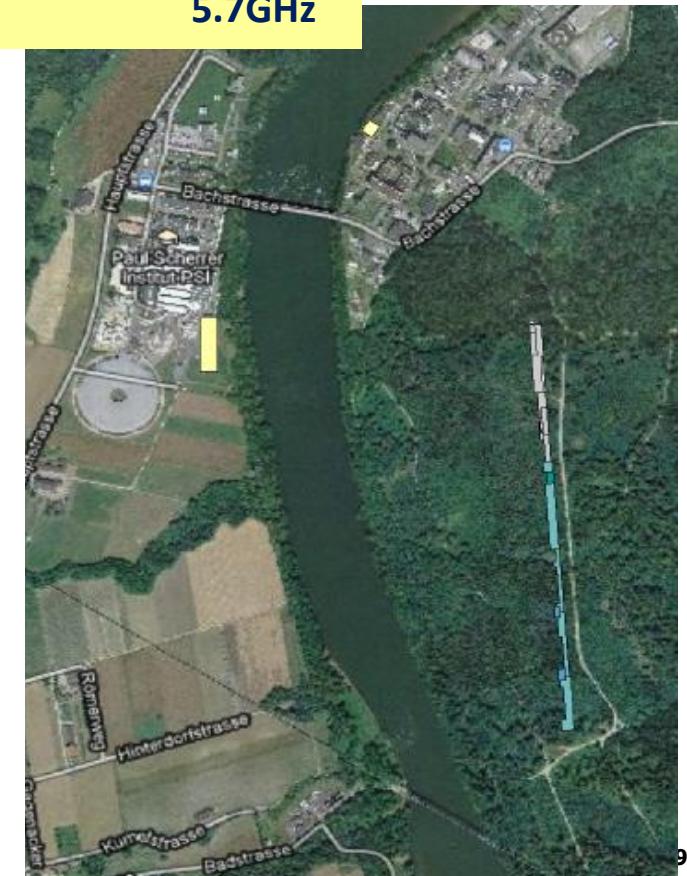
### SwissFEL key parameters

Wavelength range	1 Å - 70 Å
Pulse duration	1 fs - 20 fs
Electron Energy	5.8 GeV
e <sup>-</sup> Bunch charge	10-200 pC
Repetition rate	100 Hz
acc. structures	5.7GHz



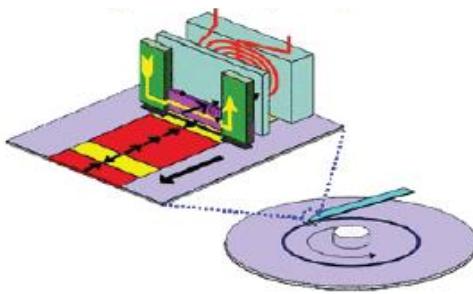
### FEL principle

Electrons interact with periodic magnetic field  
of undulator magnet to build up an  
extremely short and intense X-ray pulse.



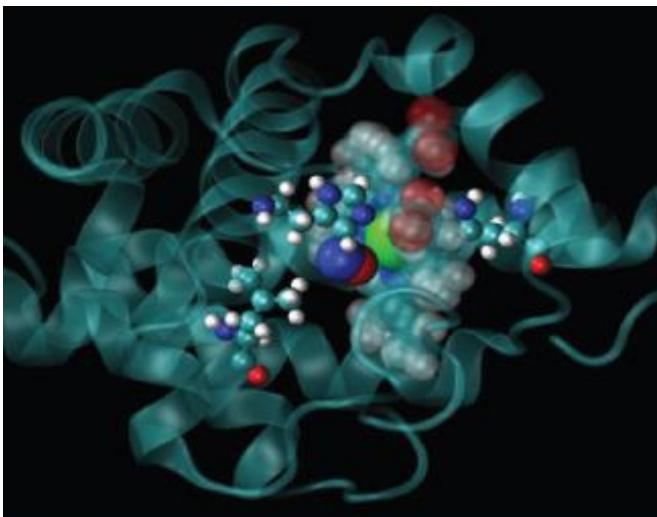
## Magnetism:

materials and processes for  
tomorrow's information technology



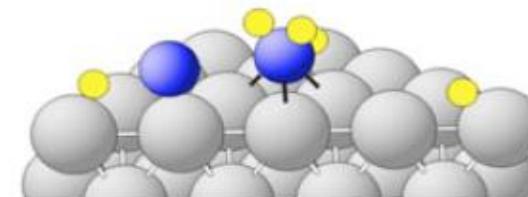
## Biochemistry:

shedding light on the processes of life

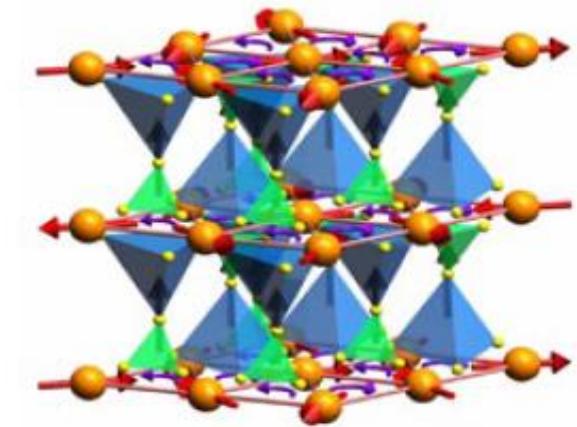


## SwissFEL Science (R.Abel)

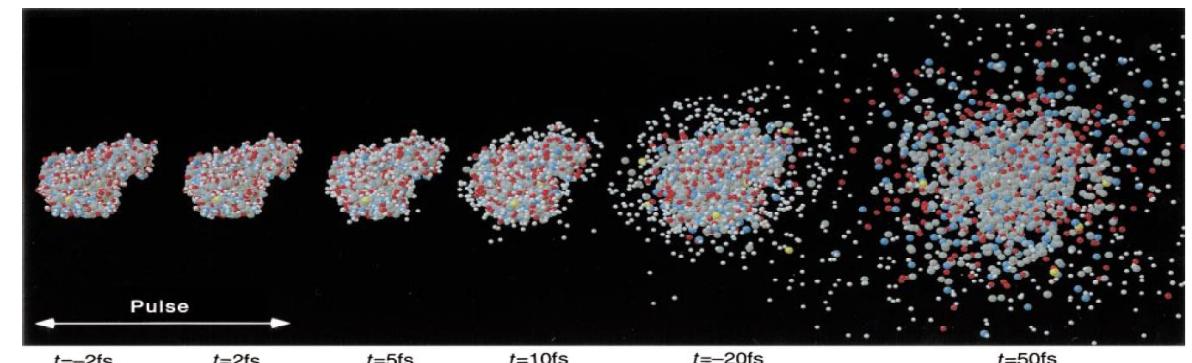
**Catalysis and  
solution chemistry:**  
for a clean environment and  
a sustainable energy supply



**Correlated electrons:**  
the fascination of  
new materials



**Coherent diffraction:**  
flash photography of matter



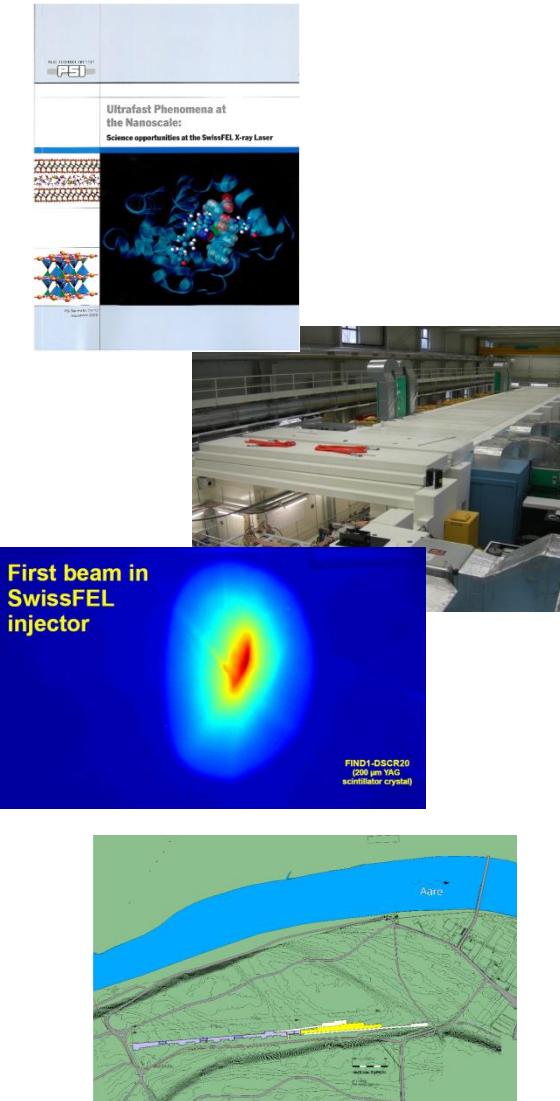
# „Probes“ for Research in Physics, Chemistry, Biology, new Materials

- Neutrons
- Muons
- Synchrotron Light
- X-ray Flashes

=> **this combination of top facilities  
is worldwide unique !**

# SwissFEL Milestones

4 MeV gun:	in operation
Scientific Case:	September 2009
Local community:	January 2010
ETH Board:	March 2010
Start „Bewilligungsverfahren“:	March 2010
250 MeV injector:	First beam March 2010
Inauguration 250 MeV inj.	August 24th 2010
Documents for BFI:	October 2010
Parliament decision:	2012
Start of construction:	2013
Aramis operation:	2017
Athos operation:	2018



<http://www.swissfel.ch>