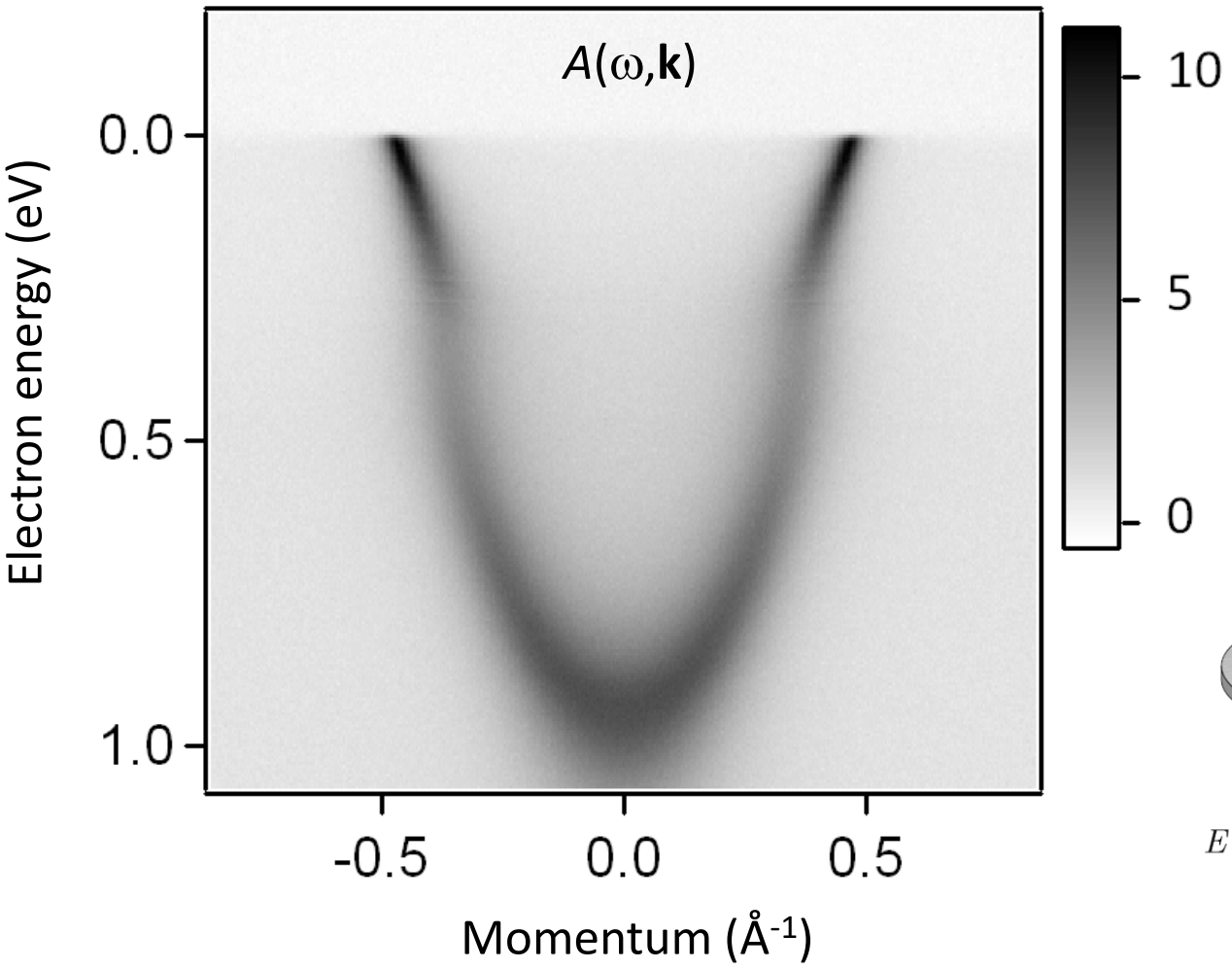
Курс:
Фізичні методи дослідження матеріалів

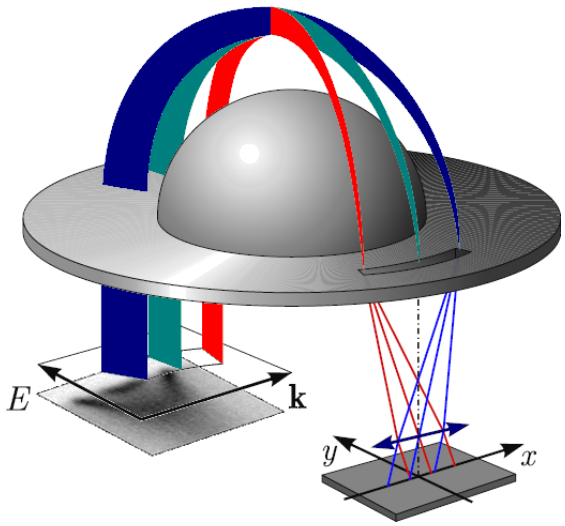
Тема:
ARPES+ та джерела фотонів, синхротнонні експерименти

Лектор: О. А. Кордюк

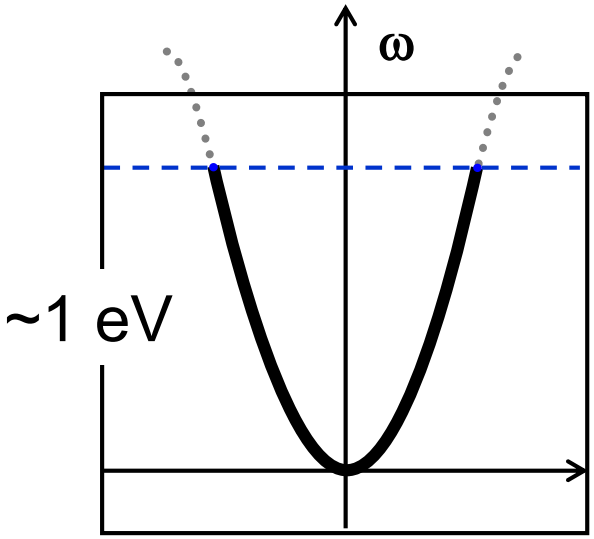
Electronic structure

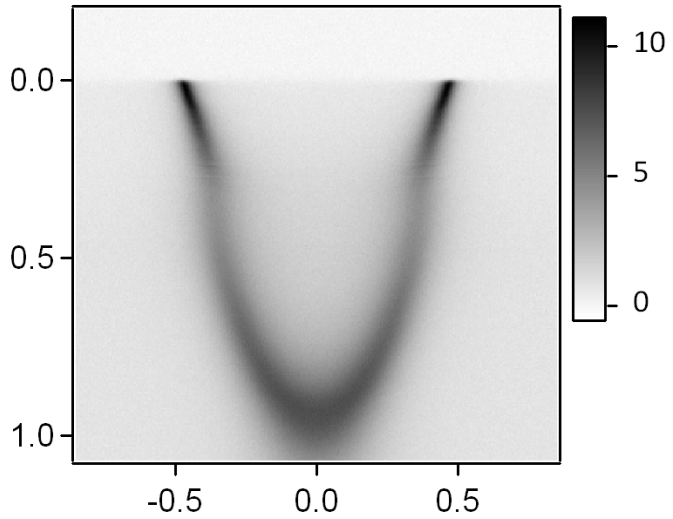
Electronic structure ≡ Electronic excitation spectrum ≡ Probability to find electron with momentum **k** and energy ω

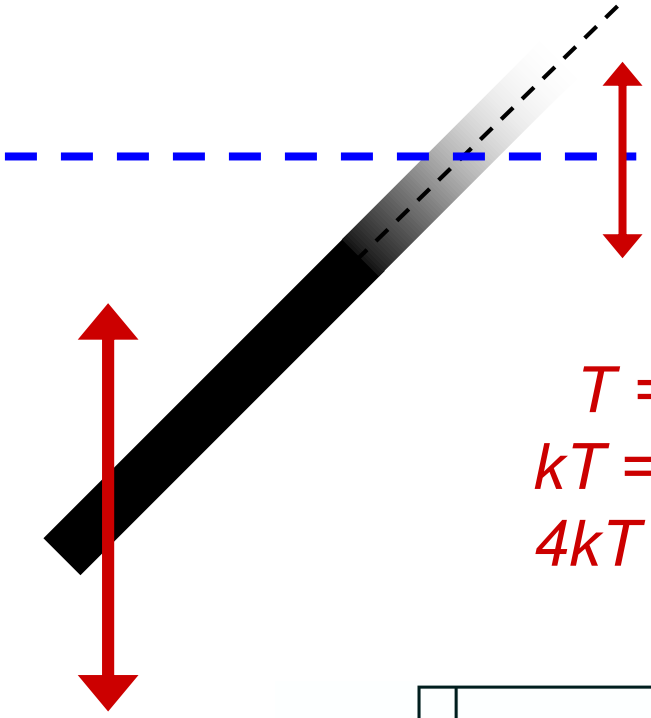




Energy scales





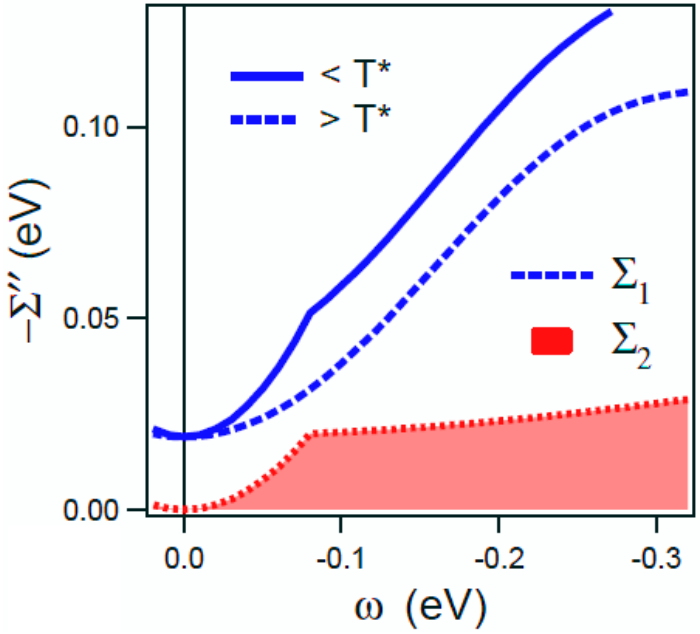


T = 300 K

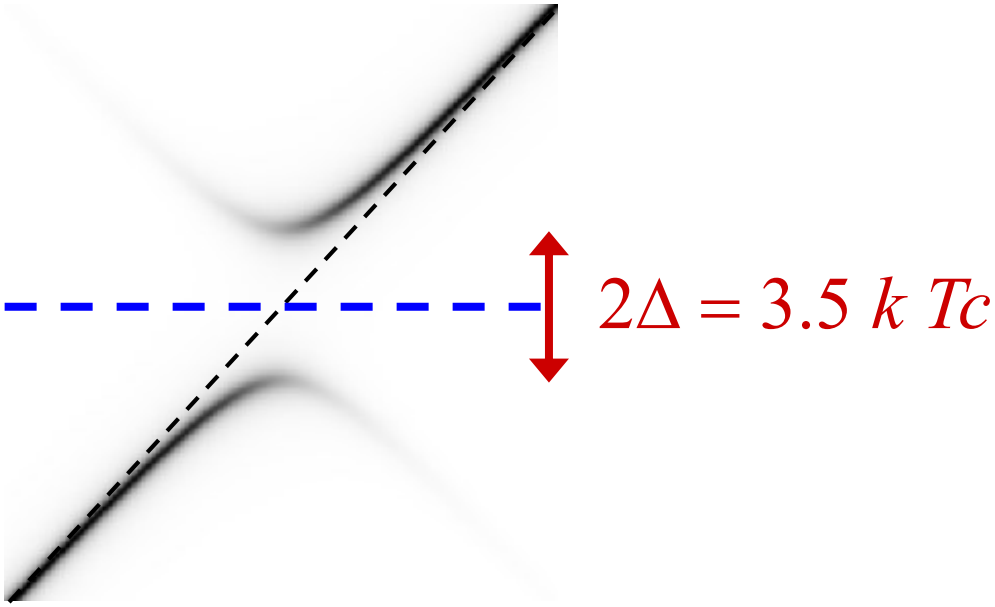
kT = 26 meV

$4kT$ ~ 0.1 eV

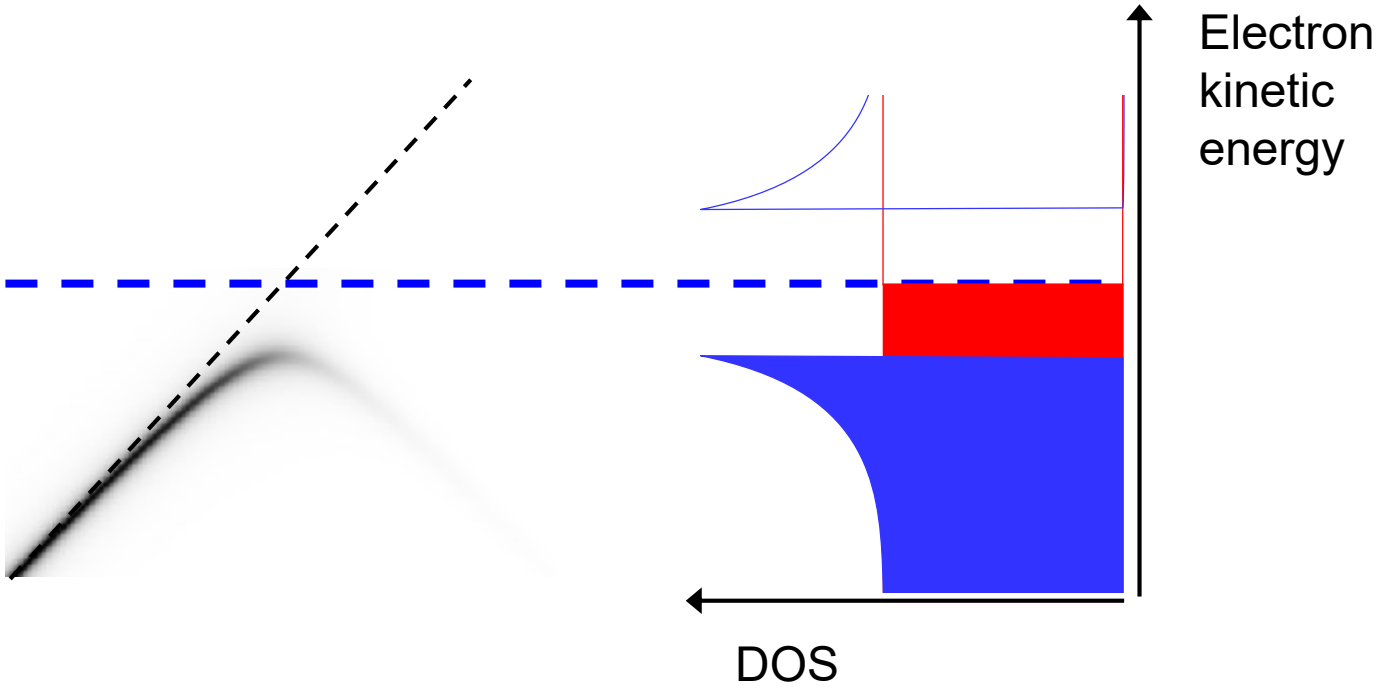
$2\Sigma'' \sim \alpha\,\omega^2 + \beta T^2$



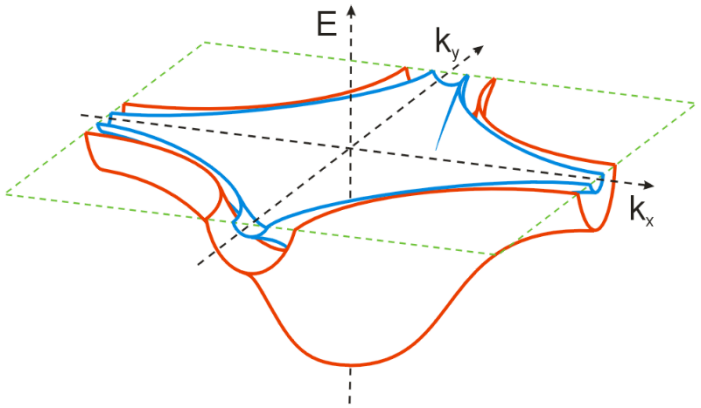
Energy scales: superconducting gap

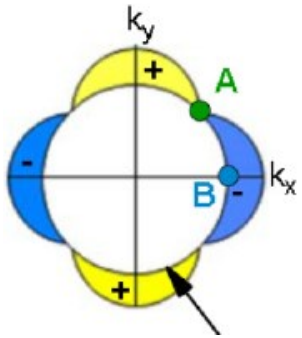


Energy scales: superconducting gap

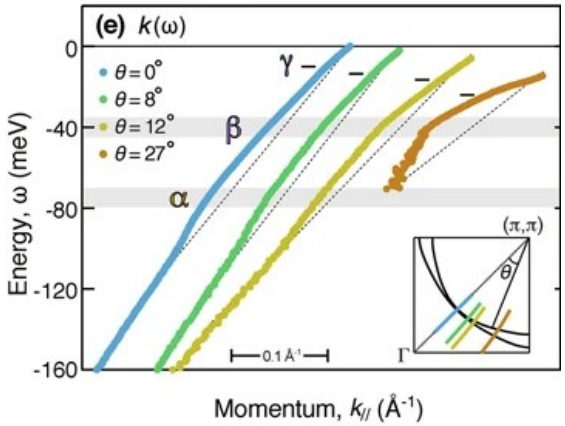


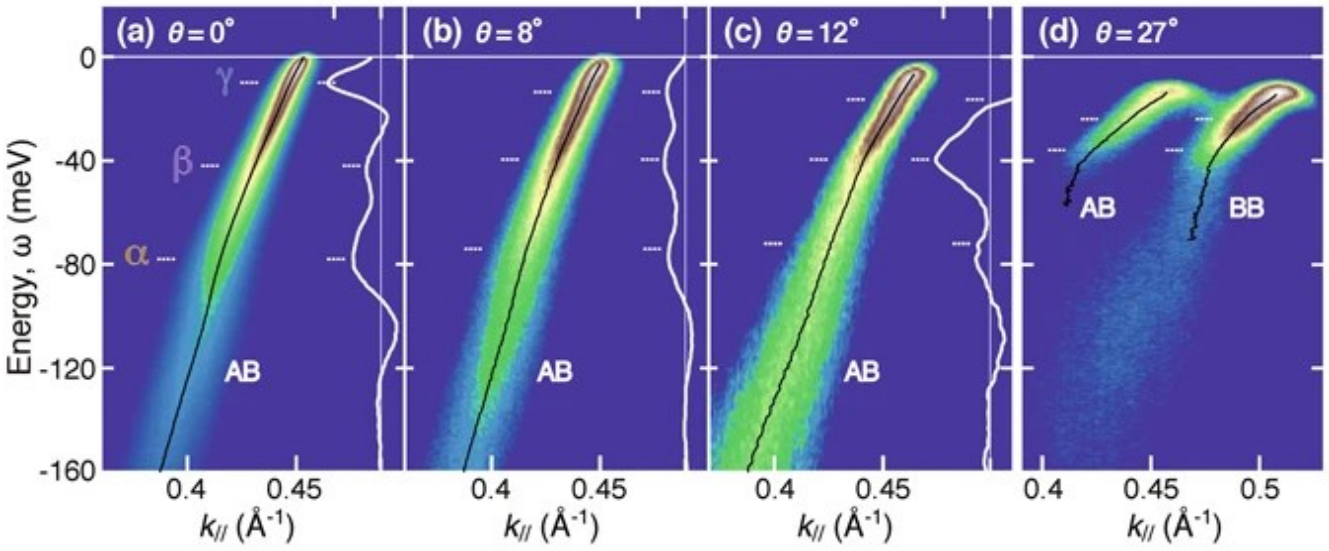
$$2\Delta = 3.5\ k\ Tc$$

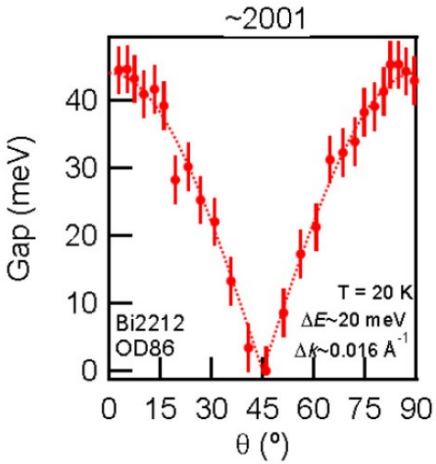




d-wave



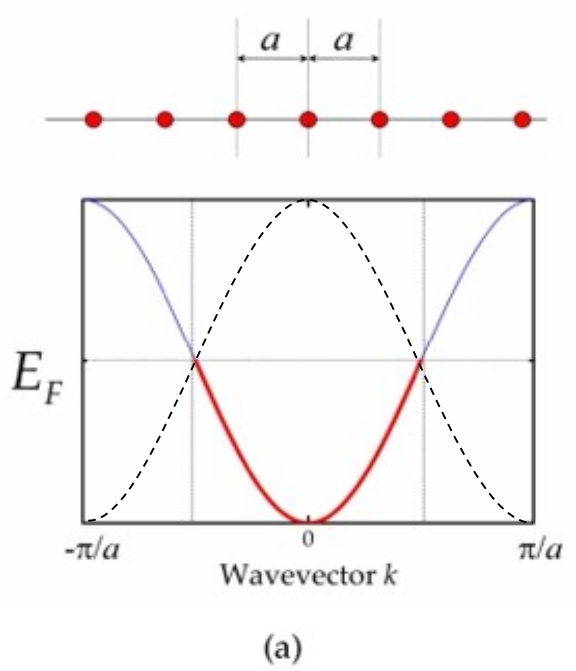


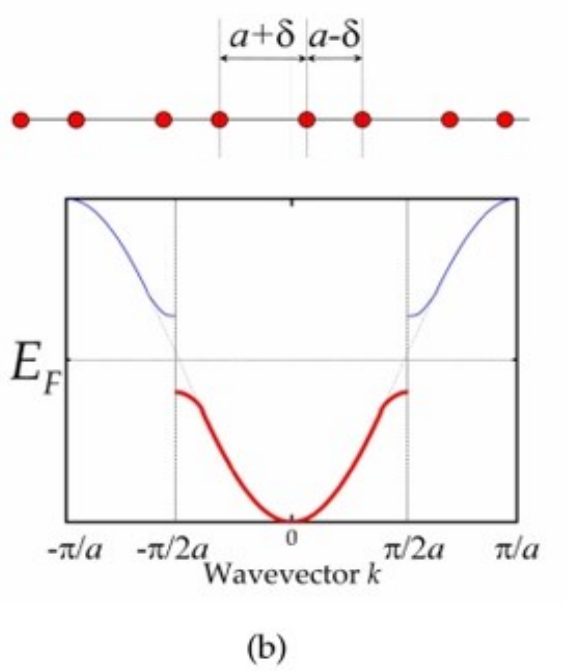


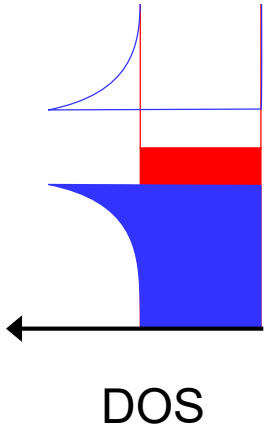
M. Hashimoto et al.
Nat. Phys. **10**, 483 (2014)

H. Anzai et al. *Sci. Rep.* **7**, 4830 (2017)

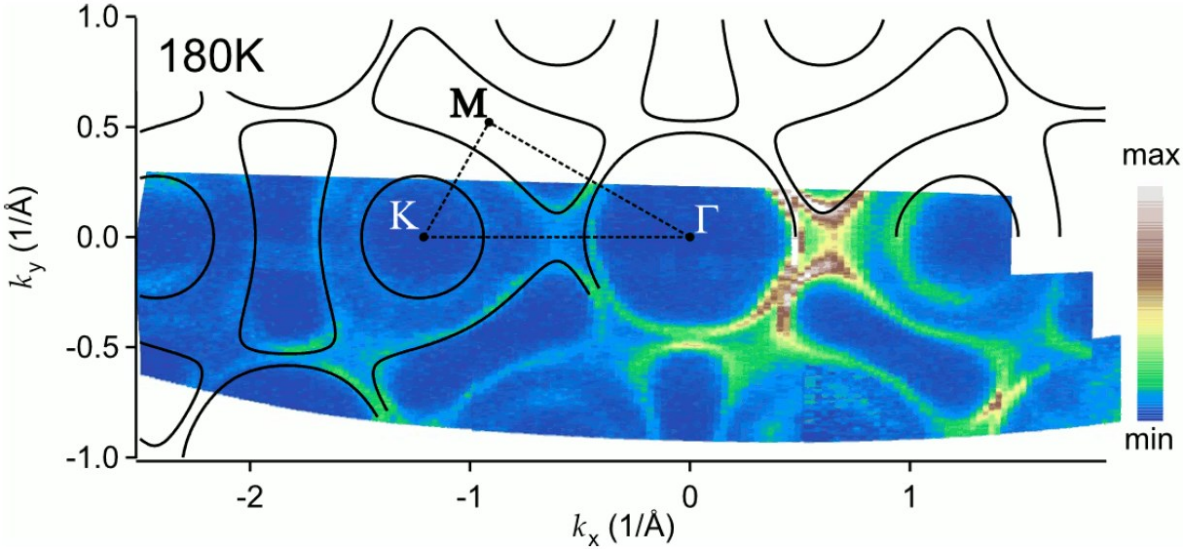
Peierls transition and Fermi surface nesting

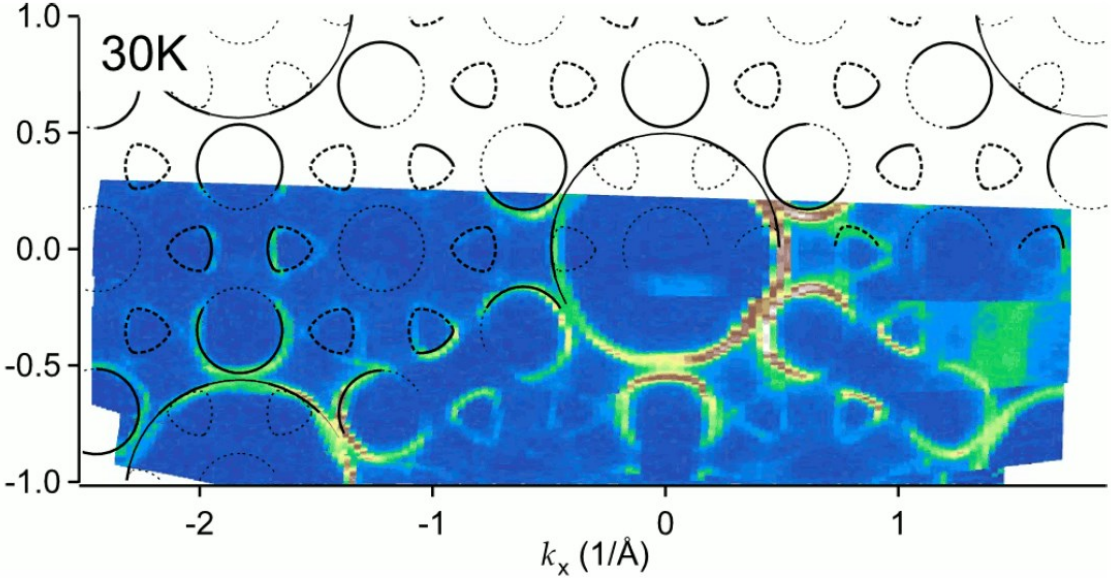




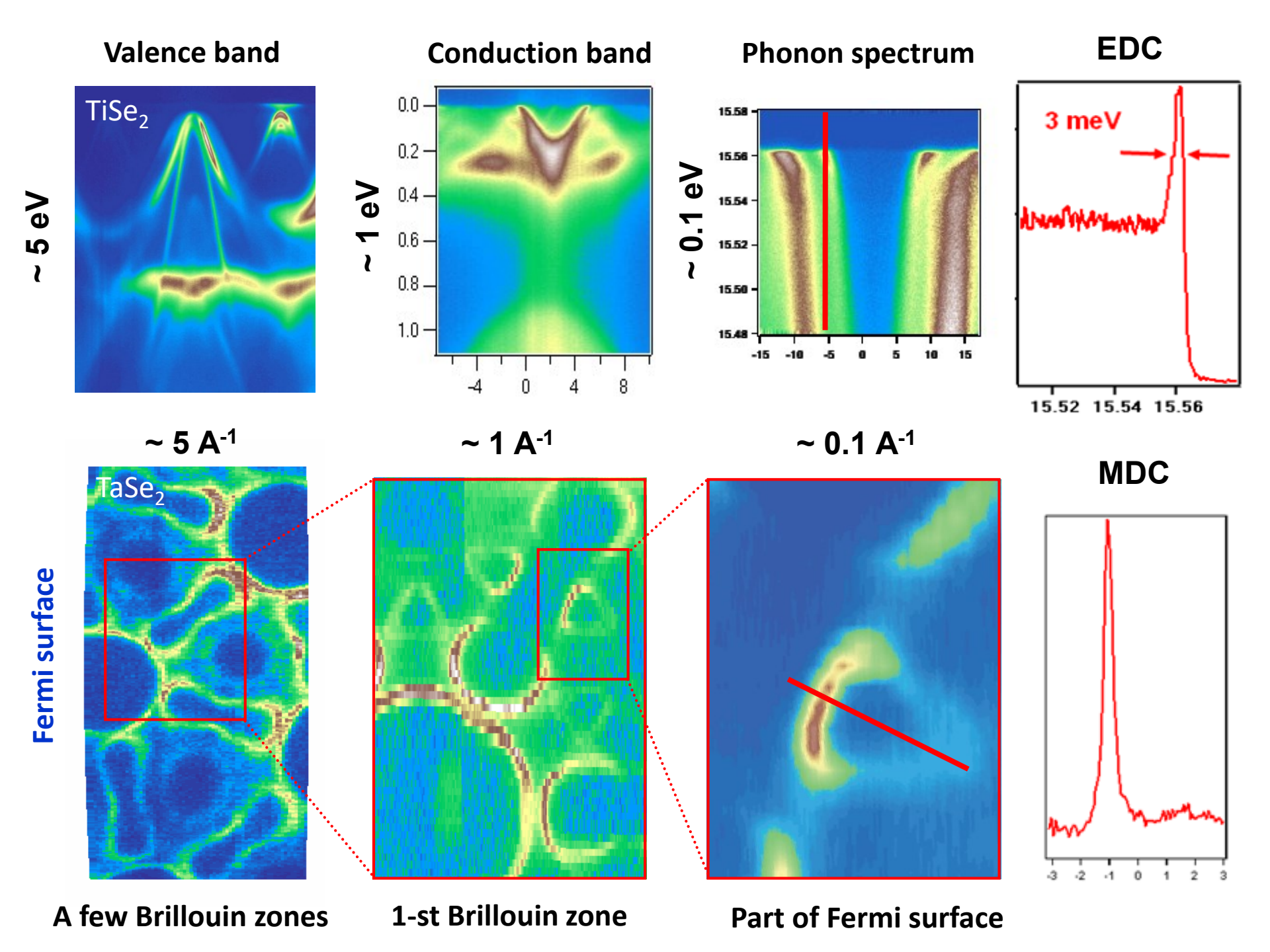


Pseudogap in TMD

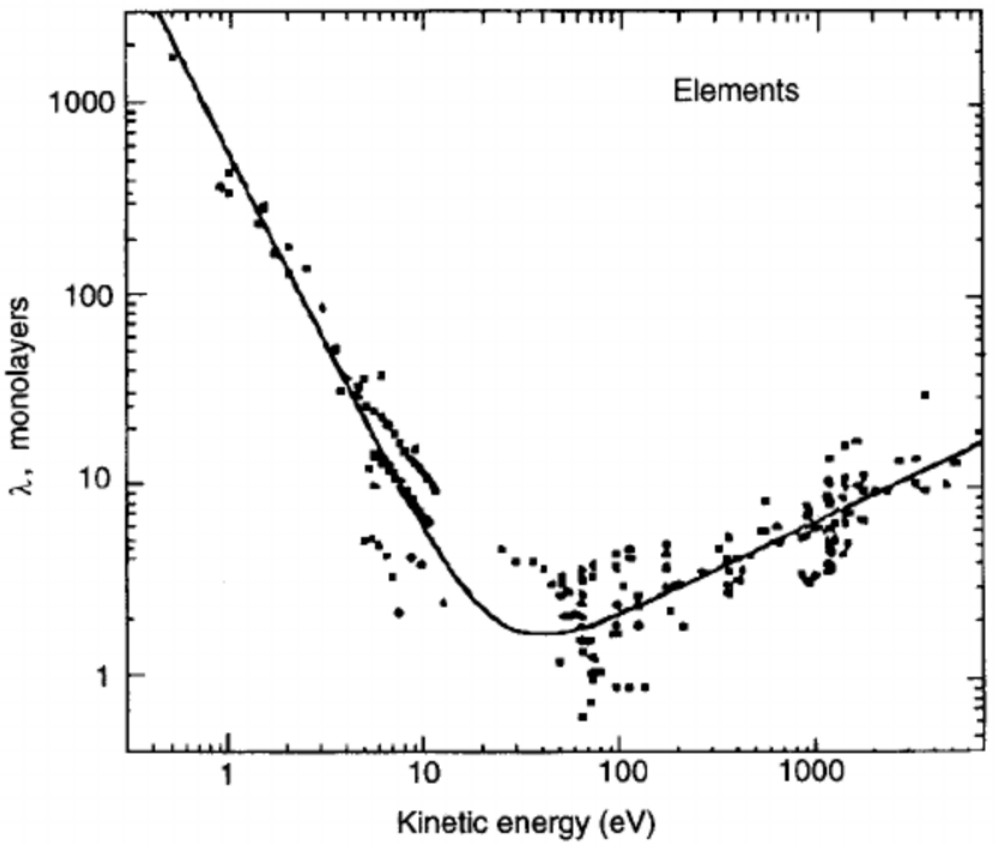




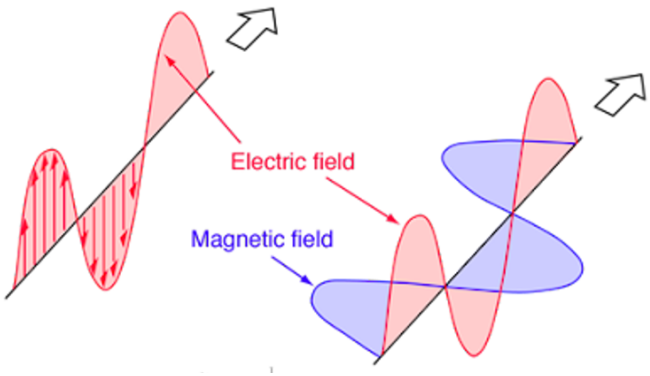
Borisenko PRL 2008
Evtushinsky PRL 2008

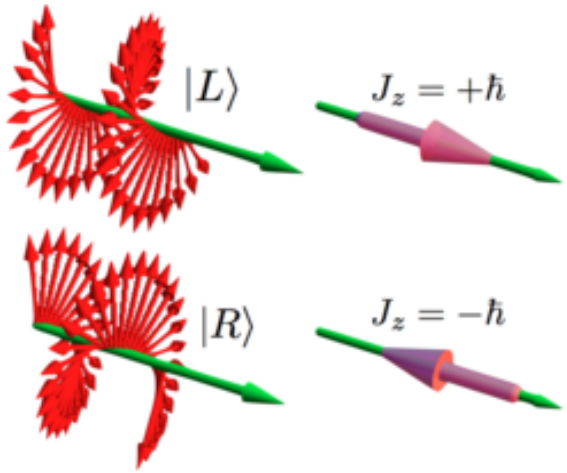

Valence band
Conduction band
Phonon spectrum
EDC
~ 5 eV
~ 1 eV
~ 0.1 eV
TiSe2
3 meV
15.52 15.54 15.56
~ 5 A-1
~ 1 A-1
~ 0.1 A-1
MDC
Fermi surface
TaSe2
A few Brillouin zones
1-st Brillouin zone
Part of Fermi surface

hv -> Photoelectron escape depth + Matrix elements

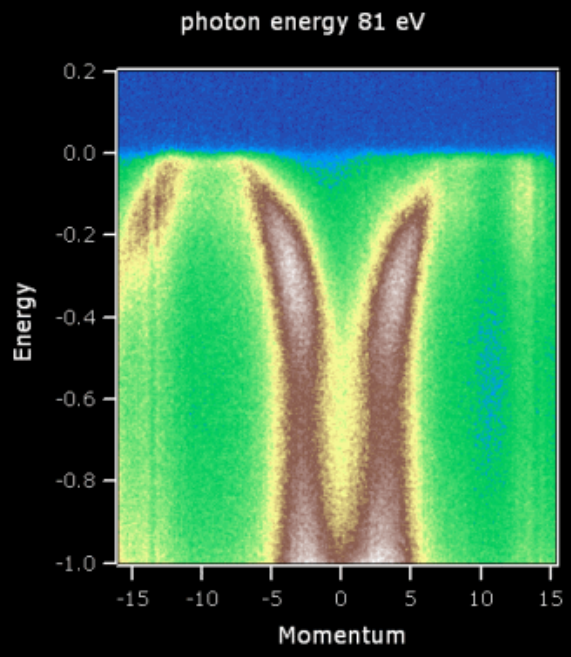


& Polarization

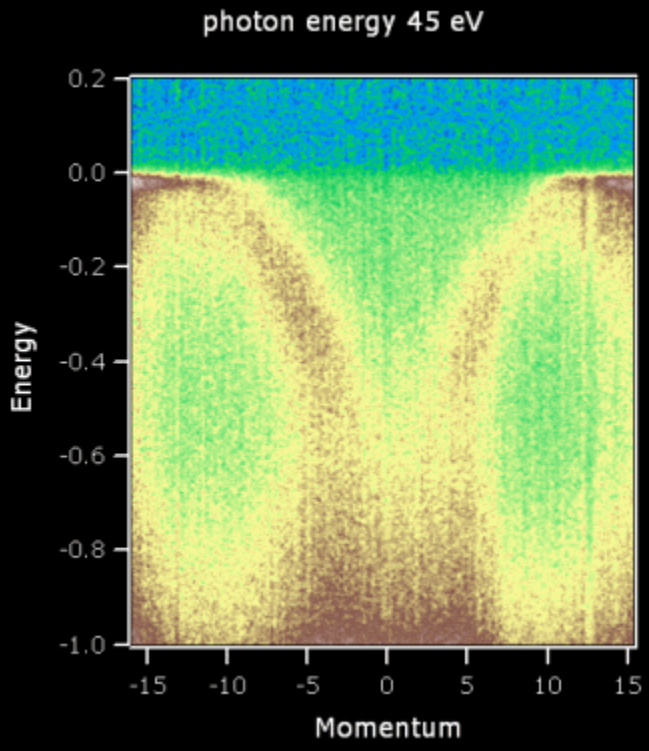


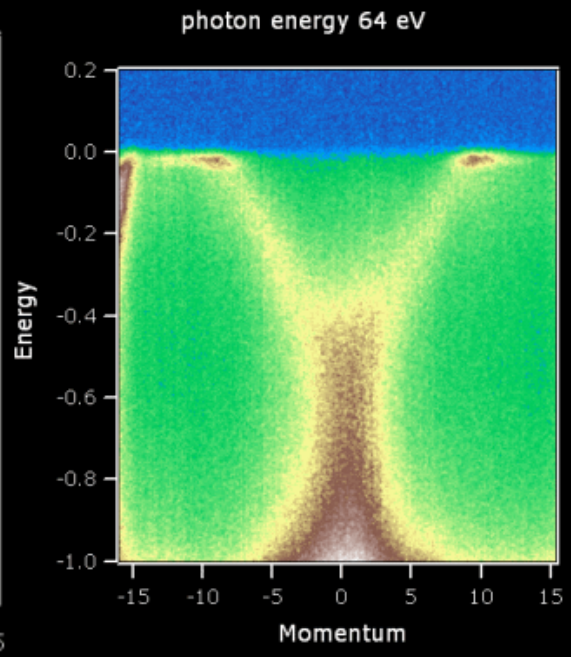


Photon energy – an important parameter



„Waterfalls“

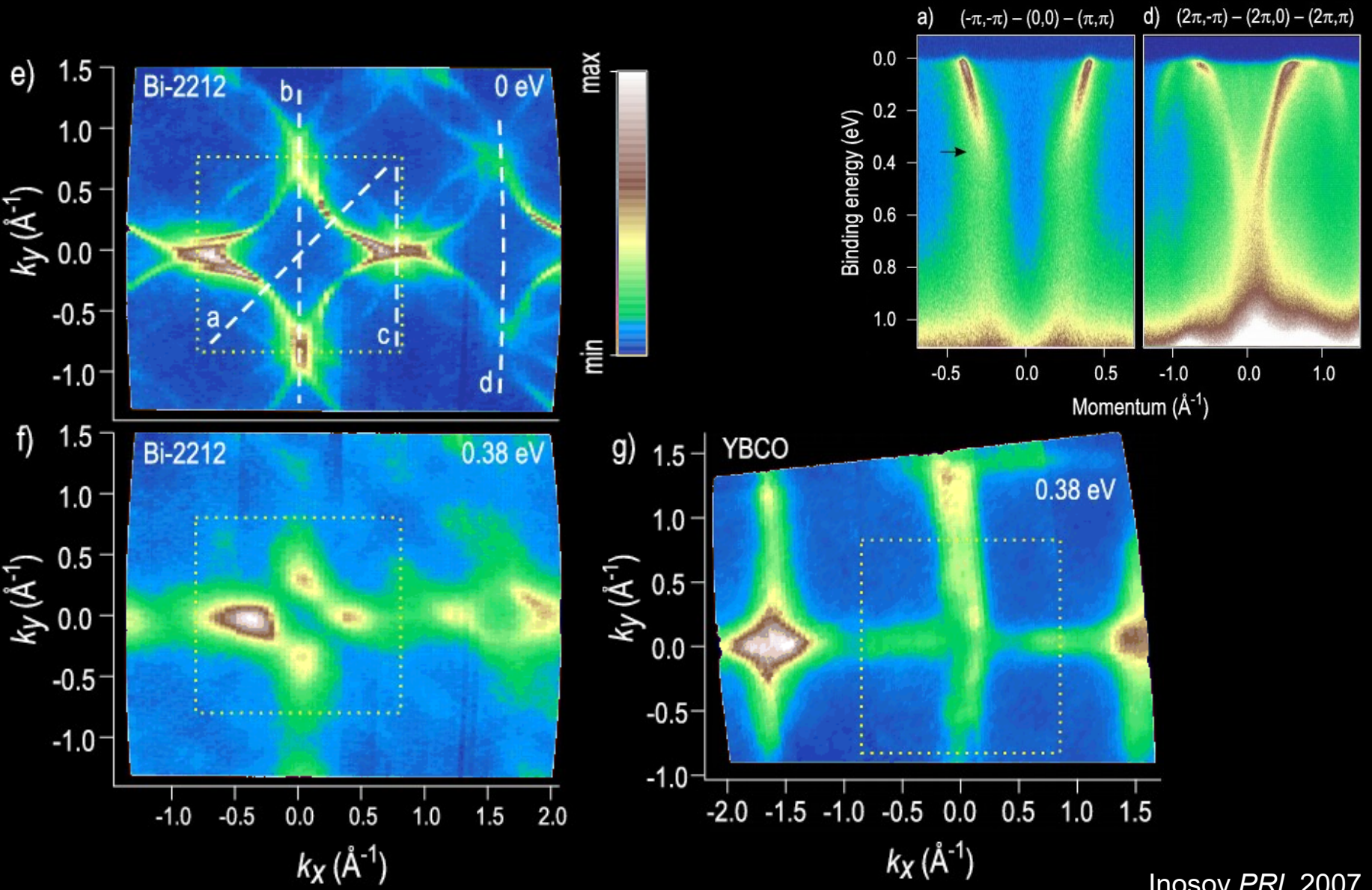




„Champagne glass“

Inosov *PRL* 2007, *PRB* 2008

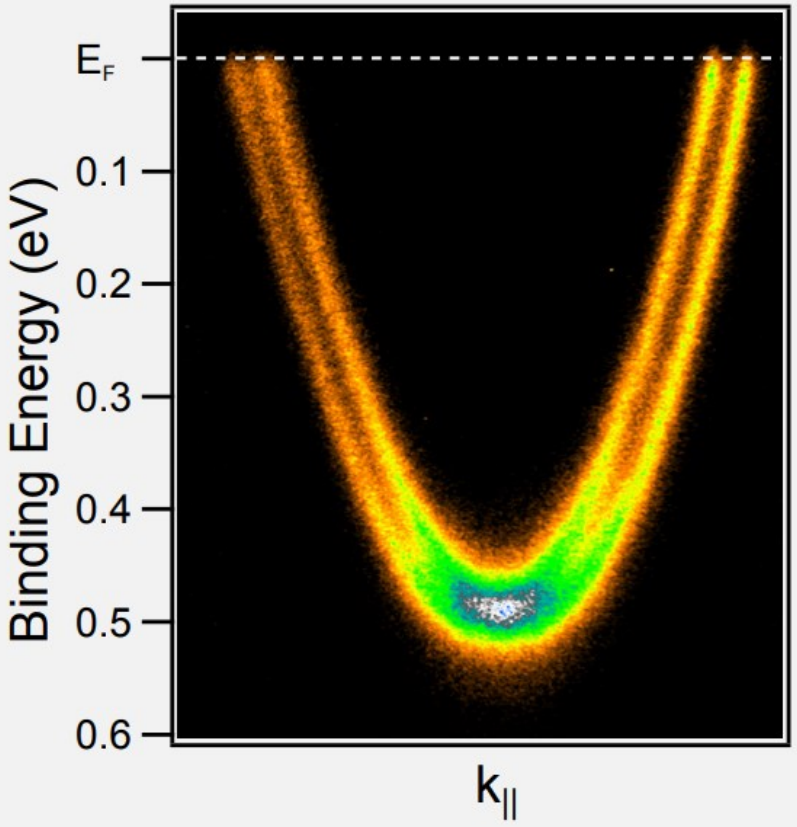
Waterfalls in cuprates



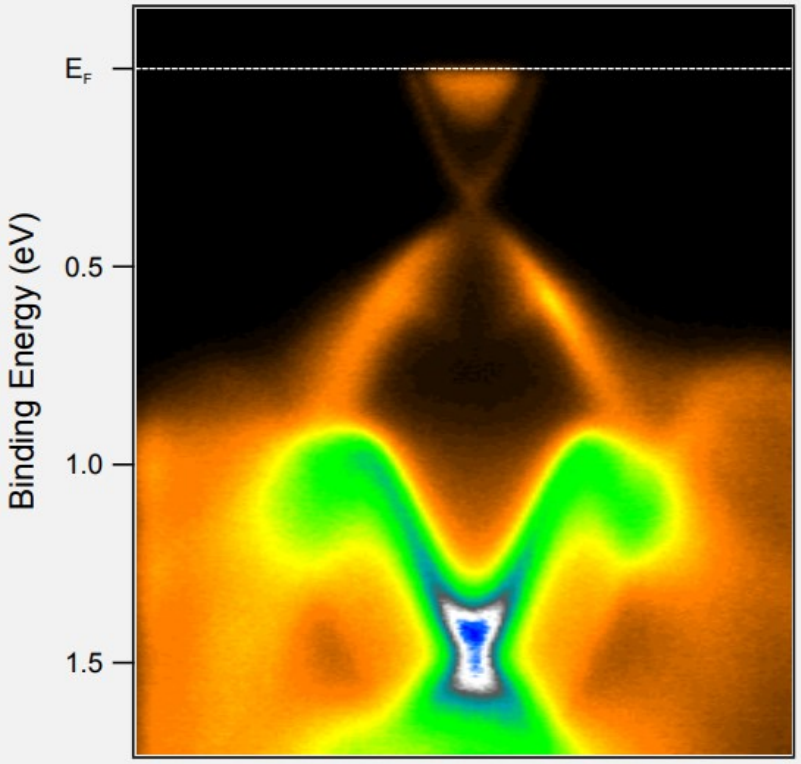
Inosov *PRL* 2007

Discharge Light Source with Quartz Capillary

Discharge Light Source with Quartz Capillary

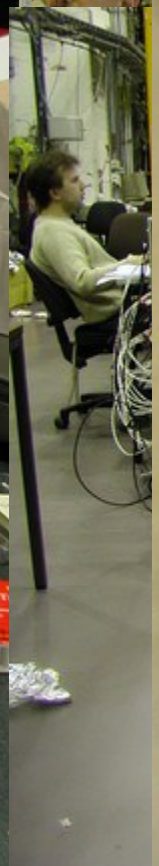


Au(111) surface state measured with a UVLS and TMM 304 at T=23 K

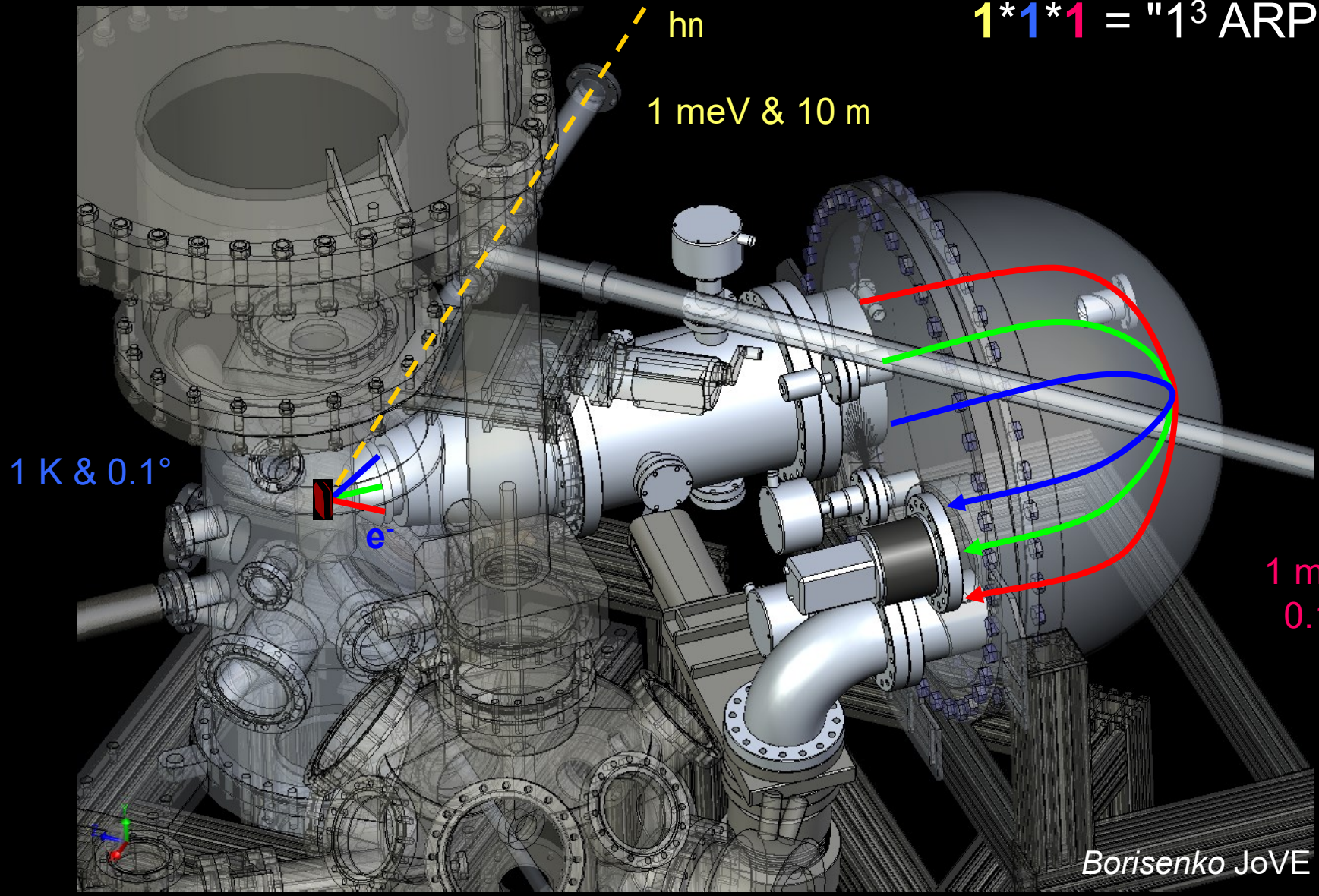


Γ point of Bi_2Te_3, A topological insulator. Raw data from PHOIBOS 225 2D-CCD with UVLS and TMM 304 at T=70K.

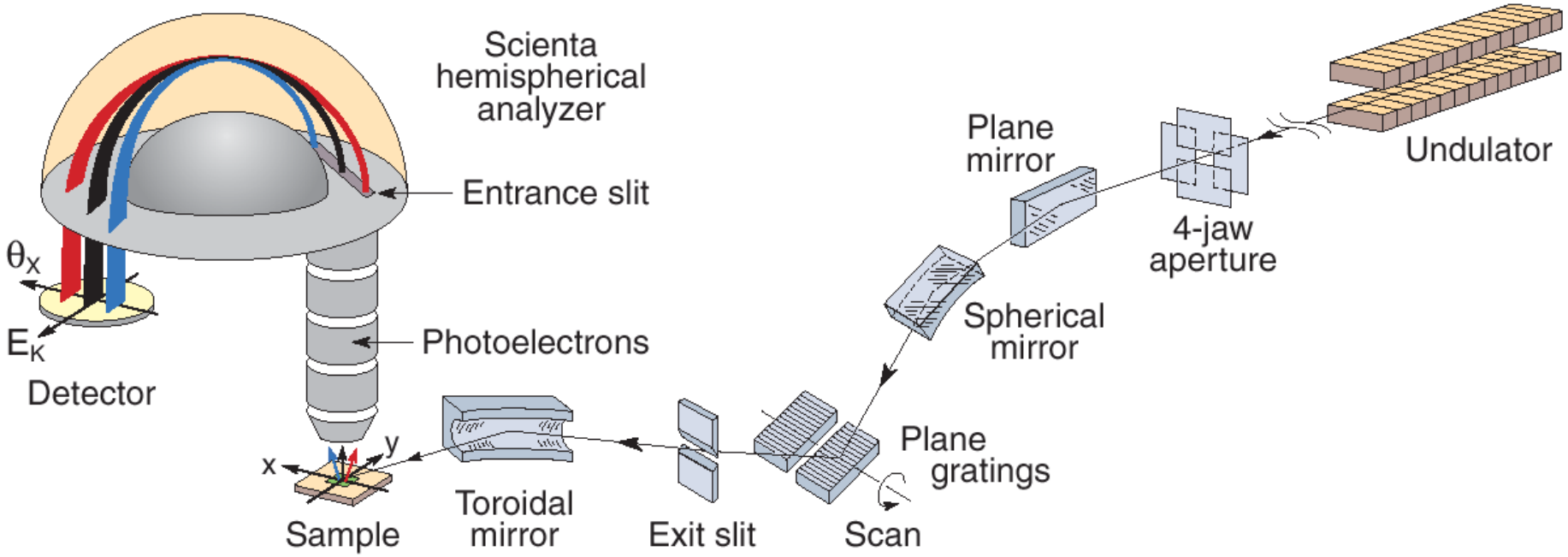
...travelling chamber



ARPES anatomy



ARPES with Synchrotron Light



Damascelli *RMP* 2003

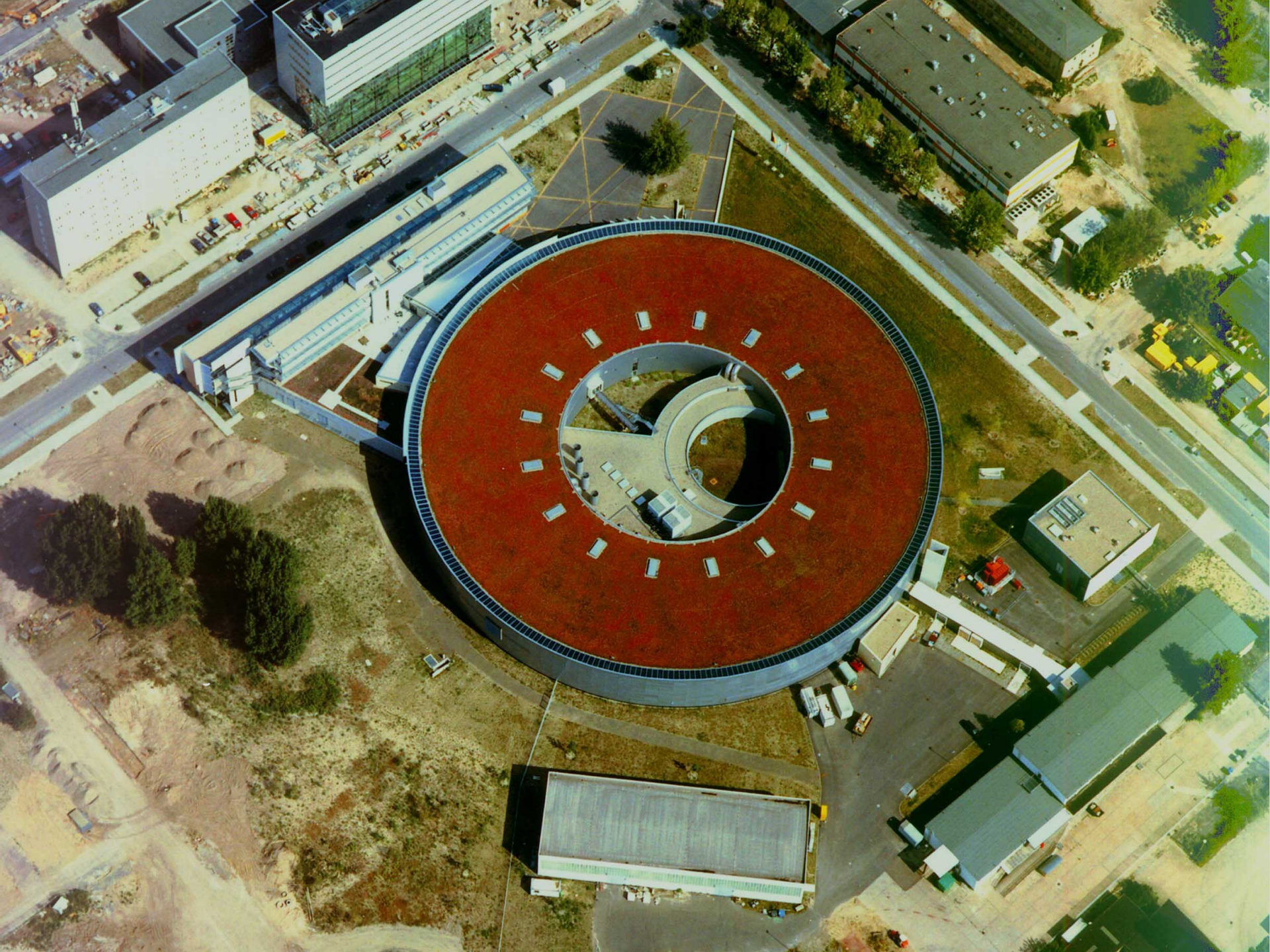
ARPES =

analyzer + manipulator (10^6 €)
+ sinchrotron

- New direction:
  time resolved ARPES,
  XFEL

Synchrotrons


BESSY

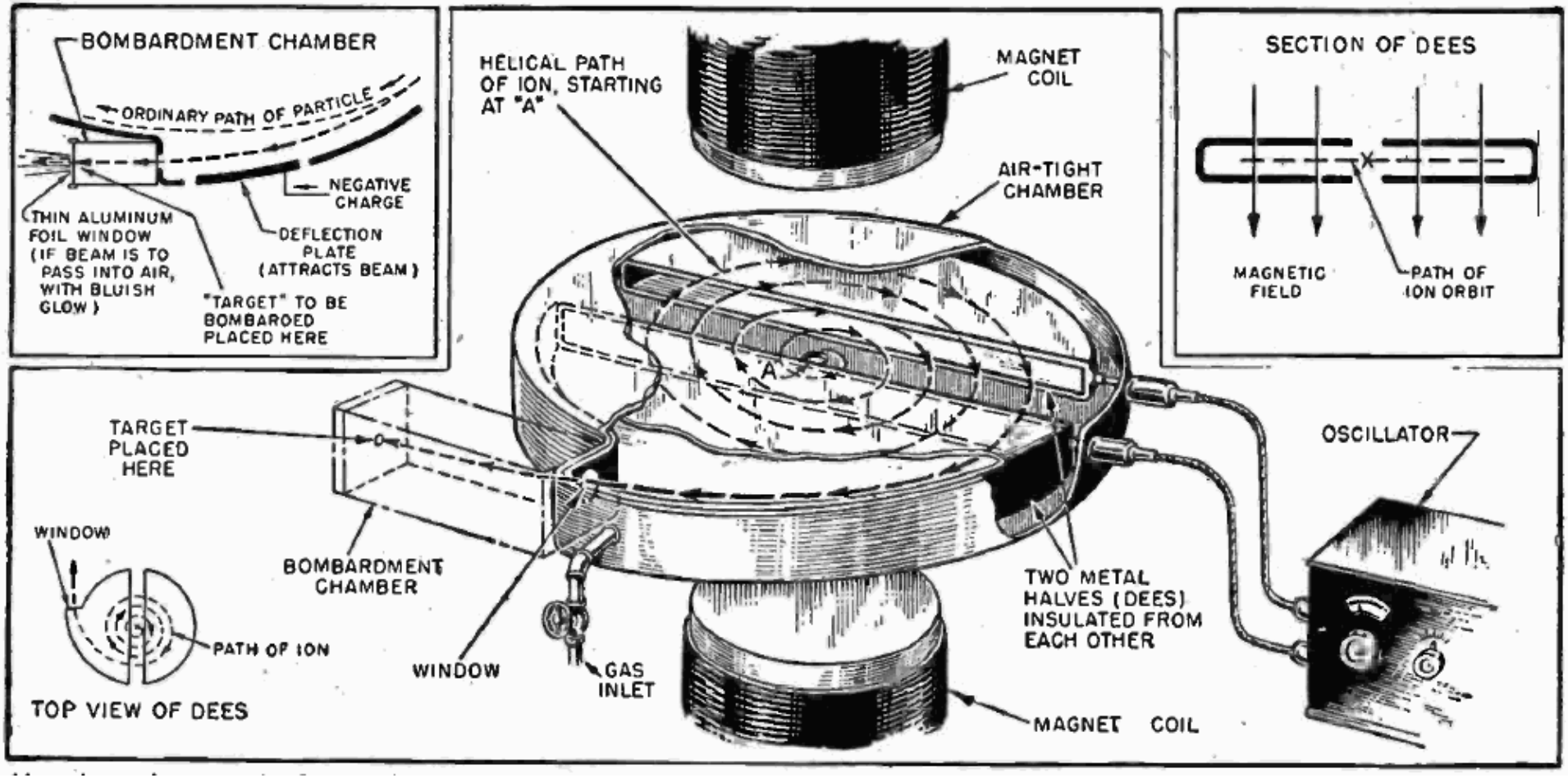



SLS


SINQ

Cyclotron

резонансний циклічний прискорювач
нерелятивістських заряджених частинок



https://en.wikipedia.org/wiki/Cyclotron

Cyclotron

$$f = \frac{qB}{2\pi m}$$

cyclotron resonance frequency

$$F_C = \frac{mv^2}{r}$$

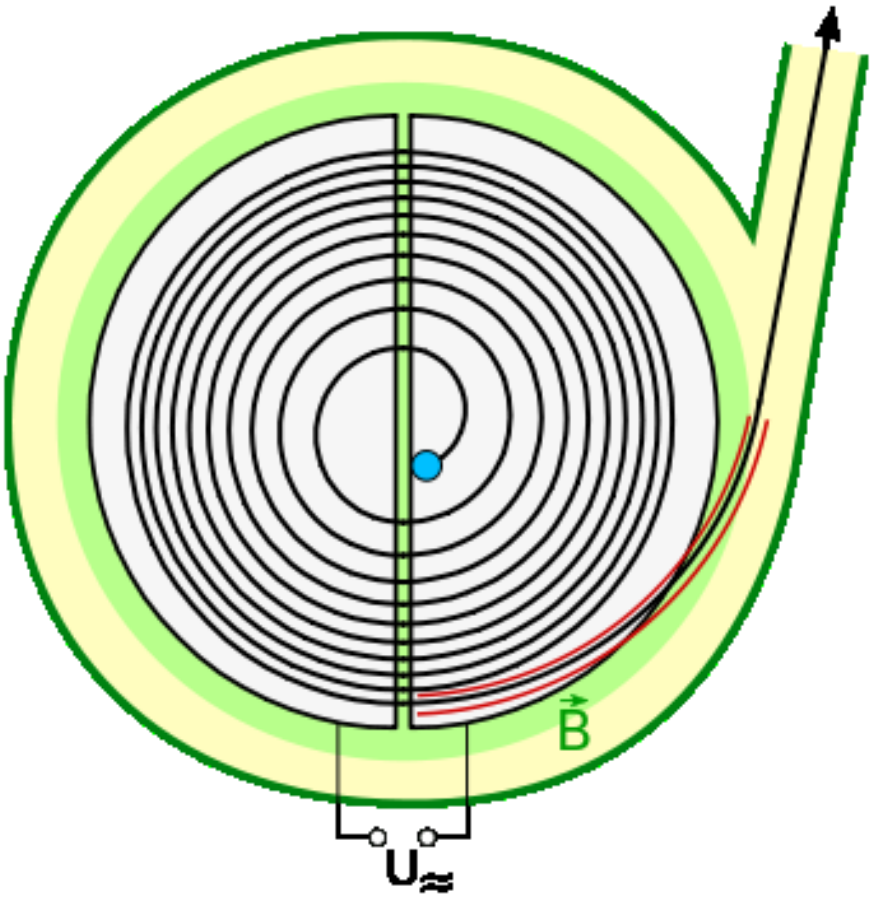
centripetal force

$$F_B = qvB$$

Lorentz force

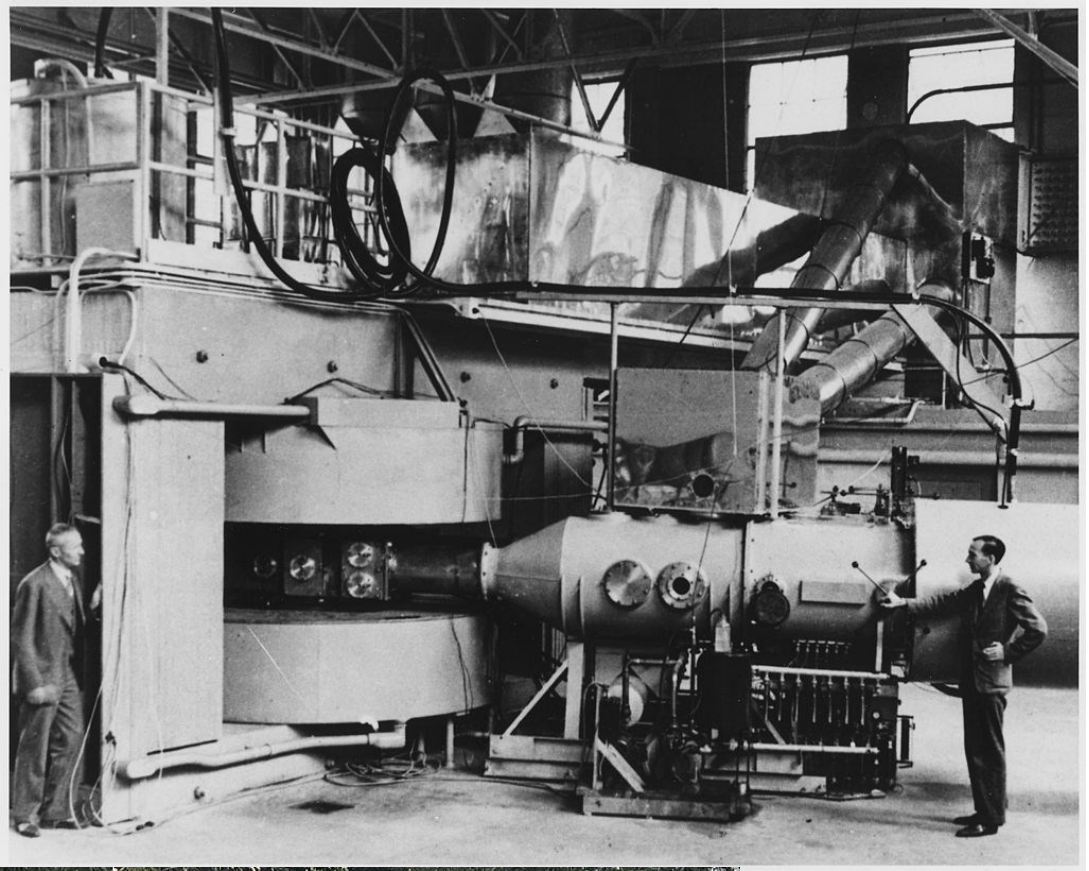
$$v = \frac{qBR}{m}$$

$$E = \frac{1}{2}mv^2 = \frac{q^2 B^2 R^2}{2m}$$



about 2 T for ferromagnetic electromagnets

Lawrence's 1946 synchrocyclotron:
D = 4.67 m



Lawrence's 60-inch cyclotron, with magnet poles 60 inches (1.5 meters) in diameter, at the University of California Lawrence Radiation Laboratory, Berkeley, in August, 1939, the most powerful accelerator in the world at the time.

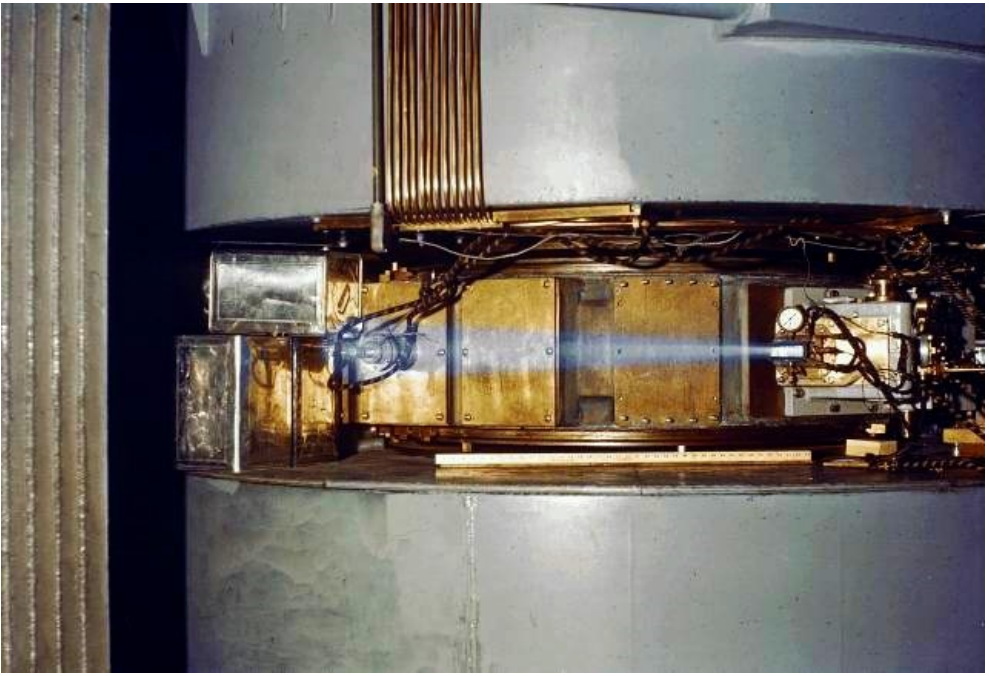
Was used it to discover plutonium, neptunium, and many other transuranic elements (1951 Nobel Prize in chemistry).

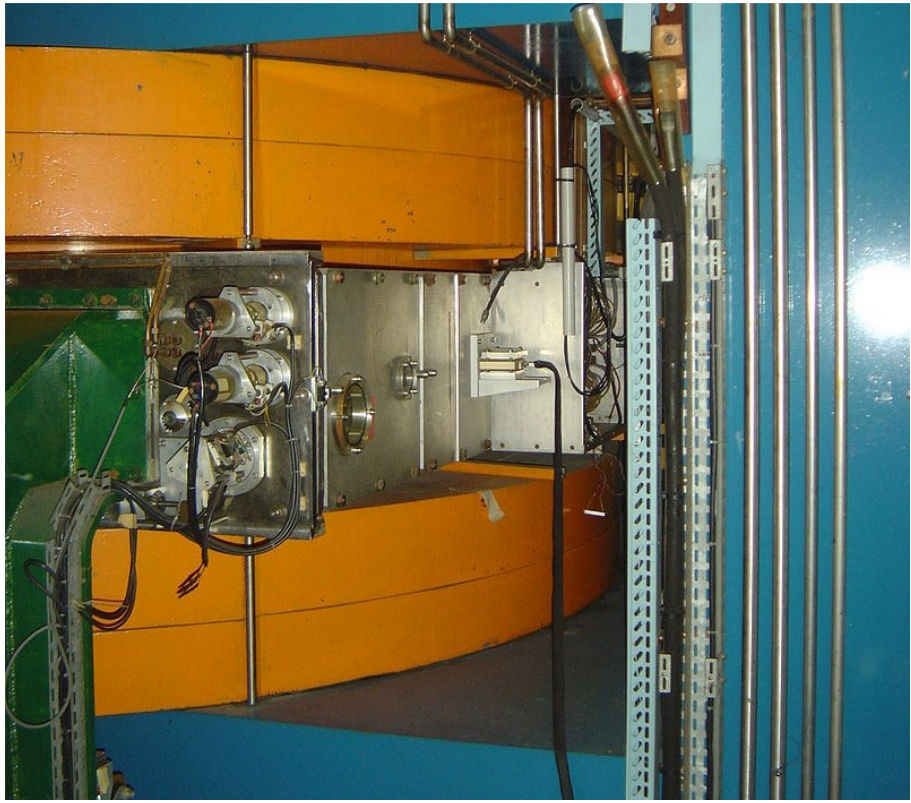
A modern cyclotron used for radiation therapy. The magnet is painted yellow.

https://en.wikipedia.org/wiki/Cyclotron

Synchrocyclotron =
Cyclotron + relativistic frequency correction

$$\omega = 2\pi f = \frac{qB}{\gamma m_0} = \omega_0 \sqrt{1 - \left(\frac{v}{c}\right)^2}$$





Superconducting Ring Cyclotron (SRC) to accelerate heavy ions:

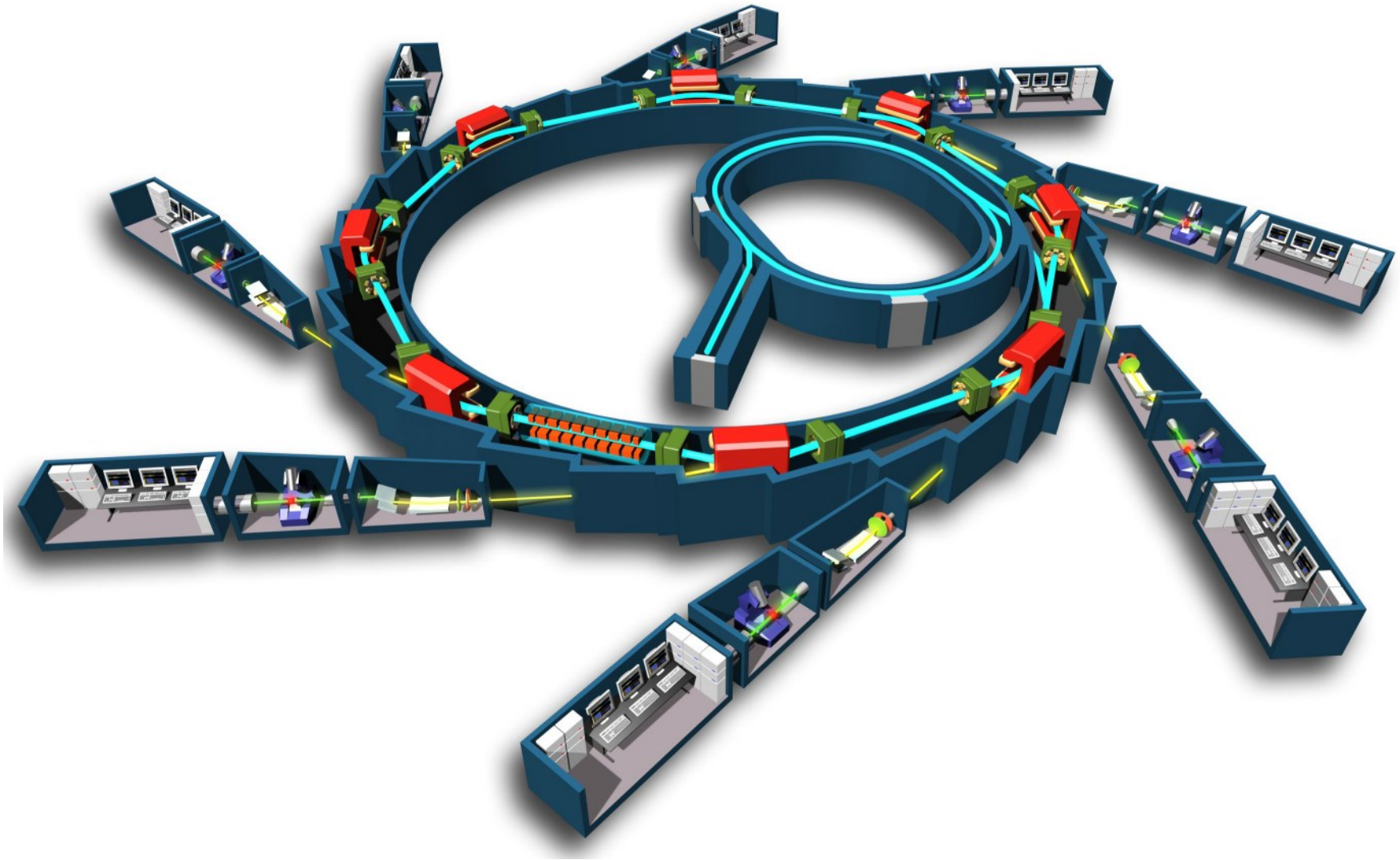
six separated superconducting sectors, 19 m in diameter and 8 m high.
Maximum magnetic field is 3.8 T. The total weight is 8,300 t.
Maximum beam radius ~ 5 m.

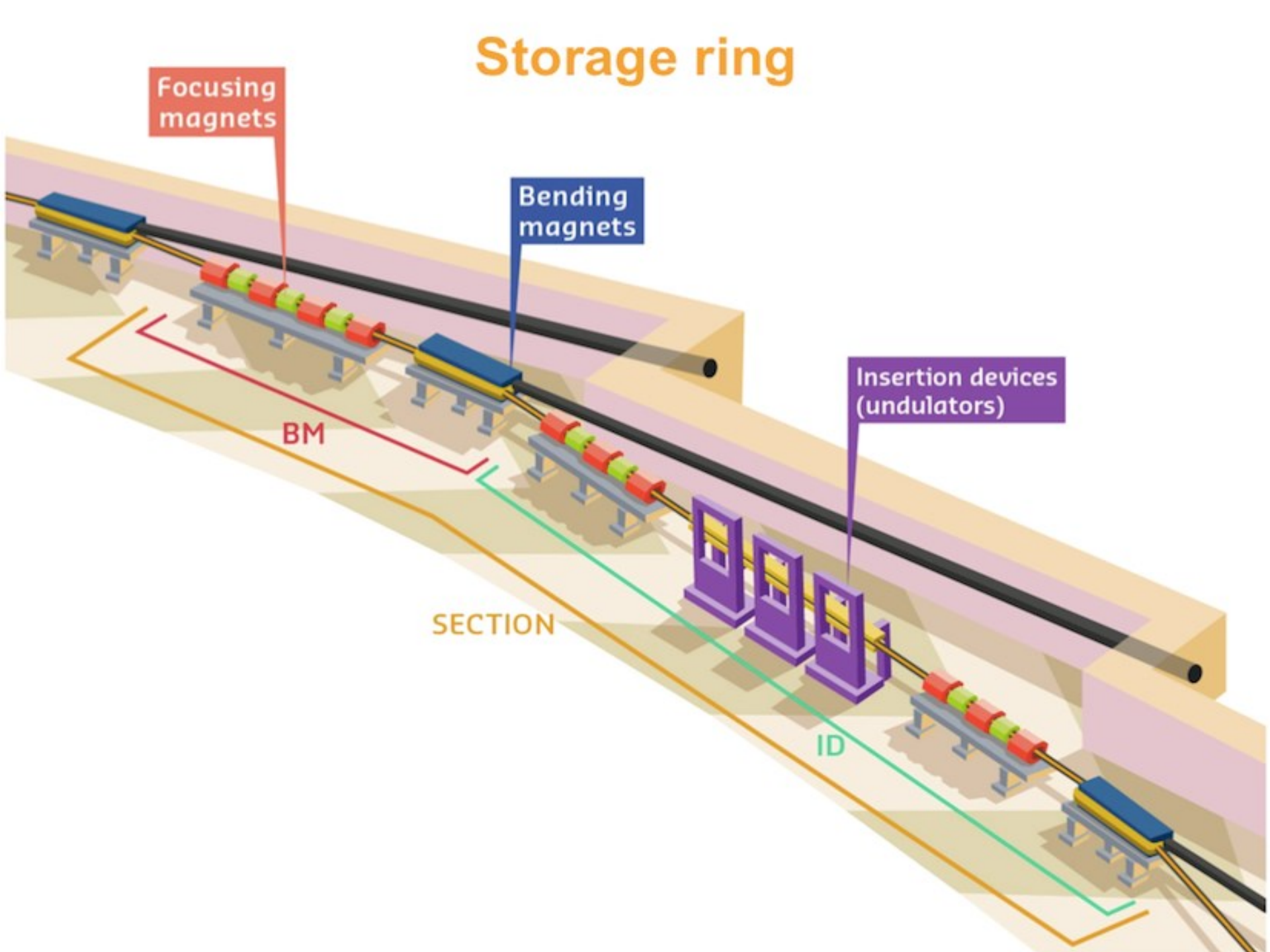
Accelerates uranium ions to 345 MeV per atomic mass unit.

TRIUMF, Canada's national laboratory for nuclear and particle physics, houses the world's largest isochronous cyclotron:

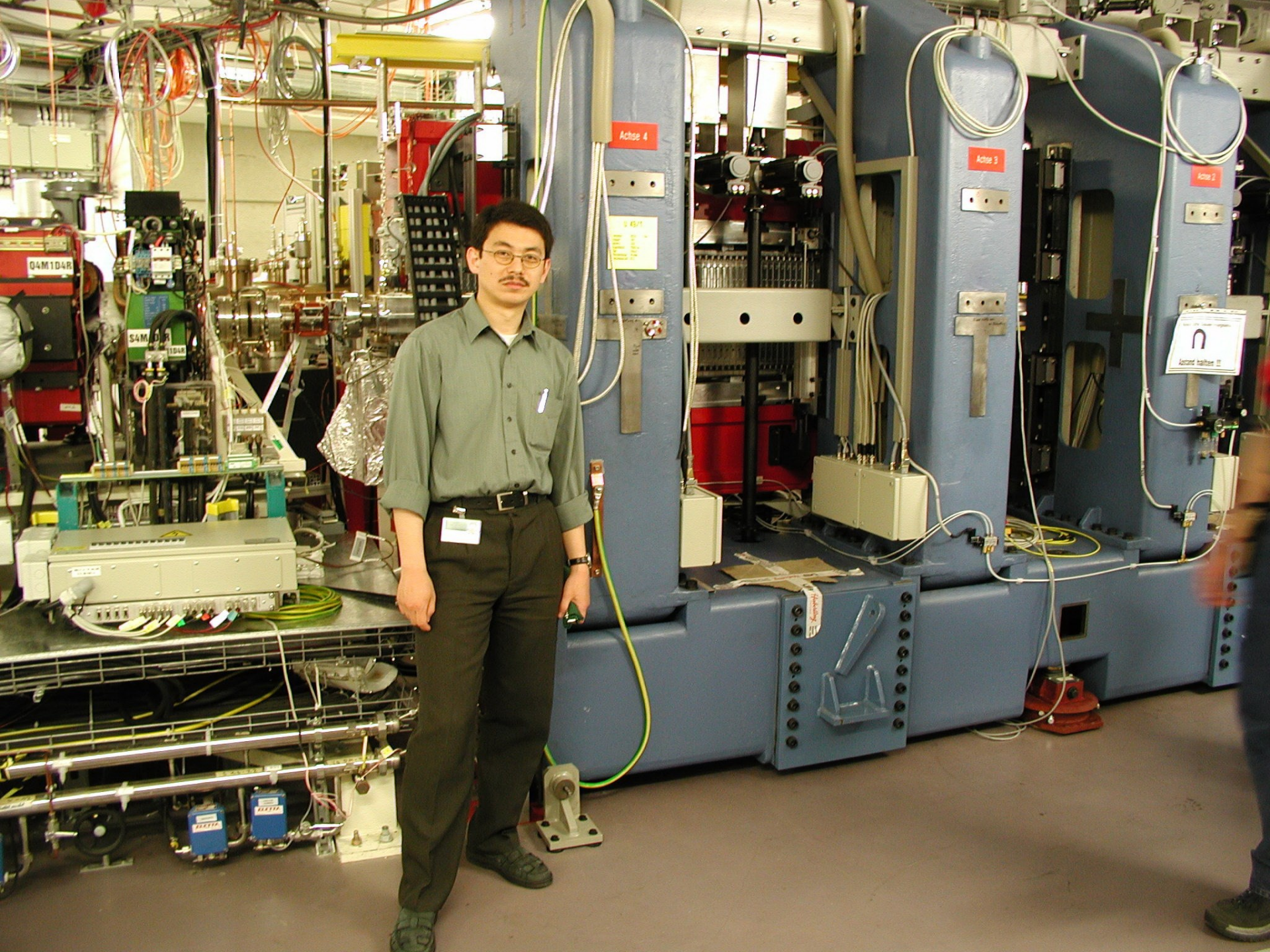
The 18 m diameter, 4,000 t main magnet produces a field of 0.46 T while a 23 MHz 94 kV electric field is used to accelerate the 300 μA beam. Its large size is a result of using negative hydrogen ions rather than protons.

Synchrotron

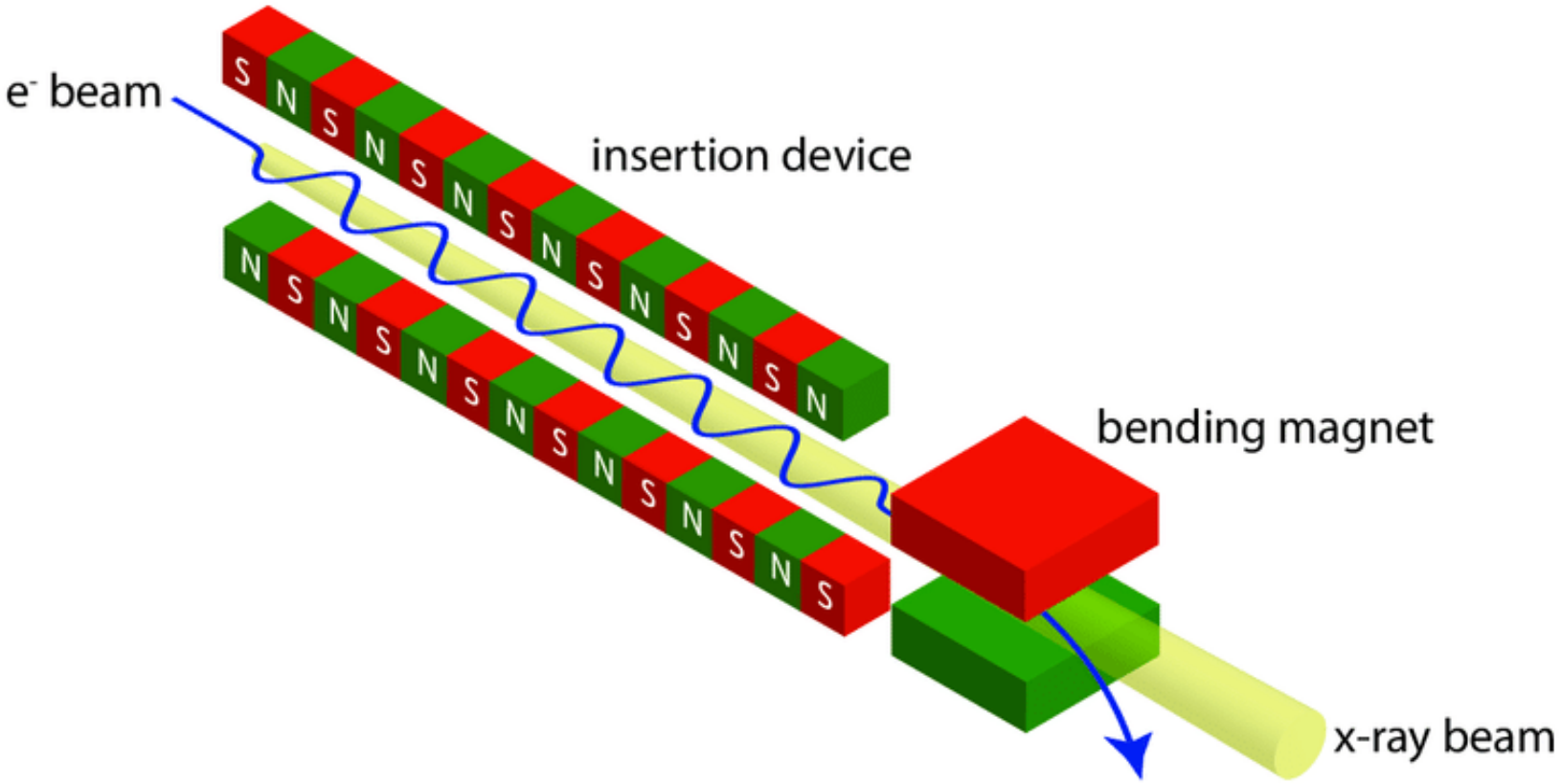



Storage ring
Focusing magnets
Bending magnets
Insertion devices (undulators)
BM
SECTION
ID

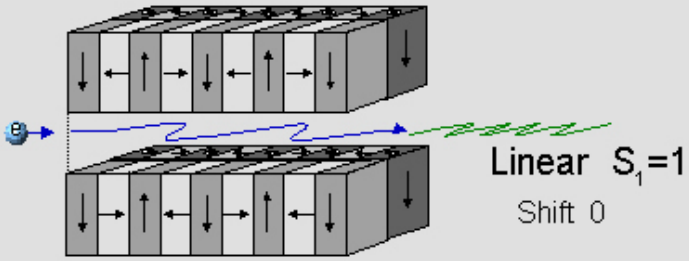

Achse 2
UE 45

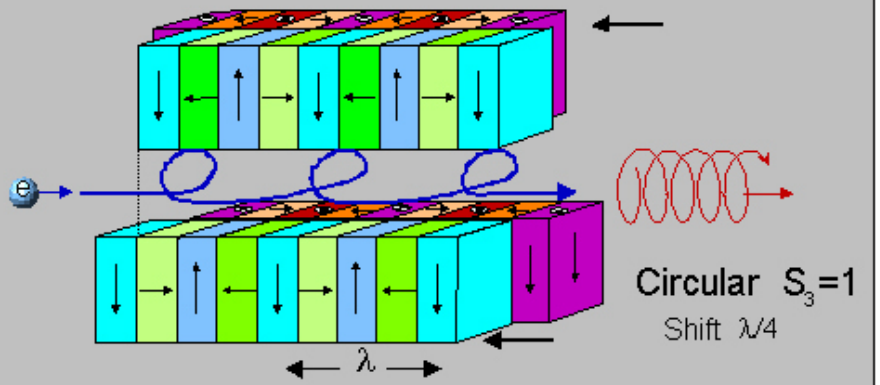

Achse 4
Achse 3
Achse 2
Q4M1D4R

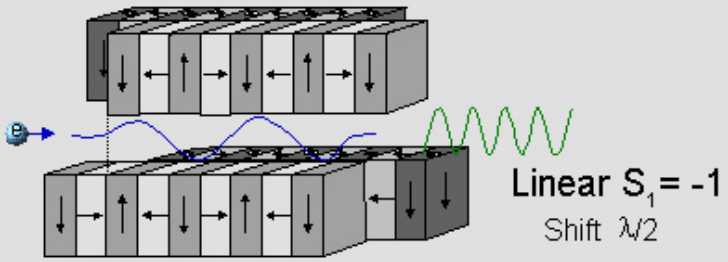
Insertion device (undulator)

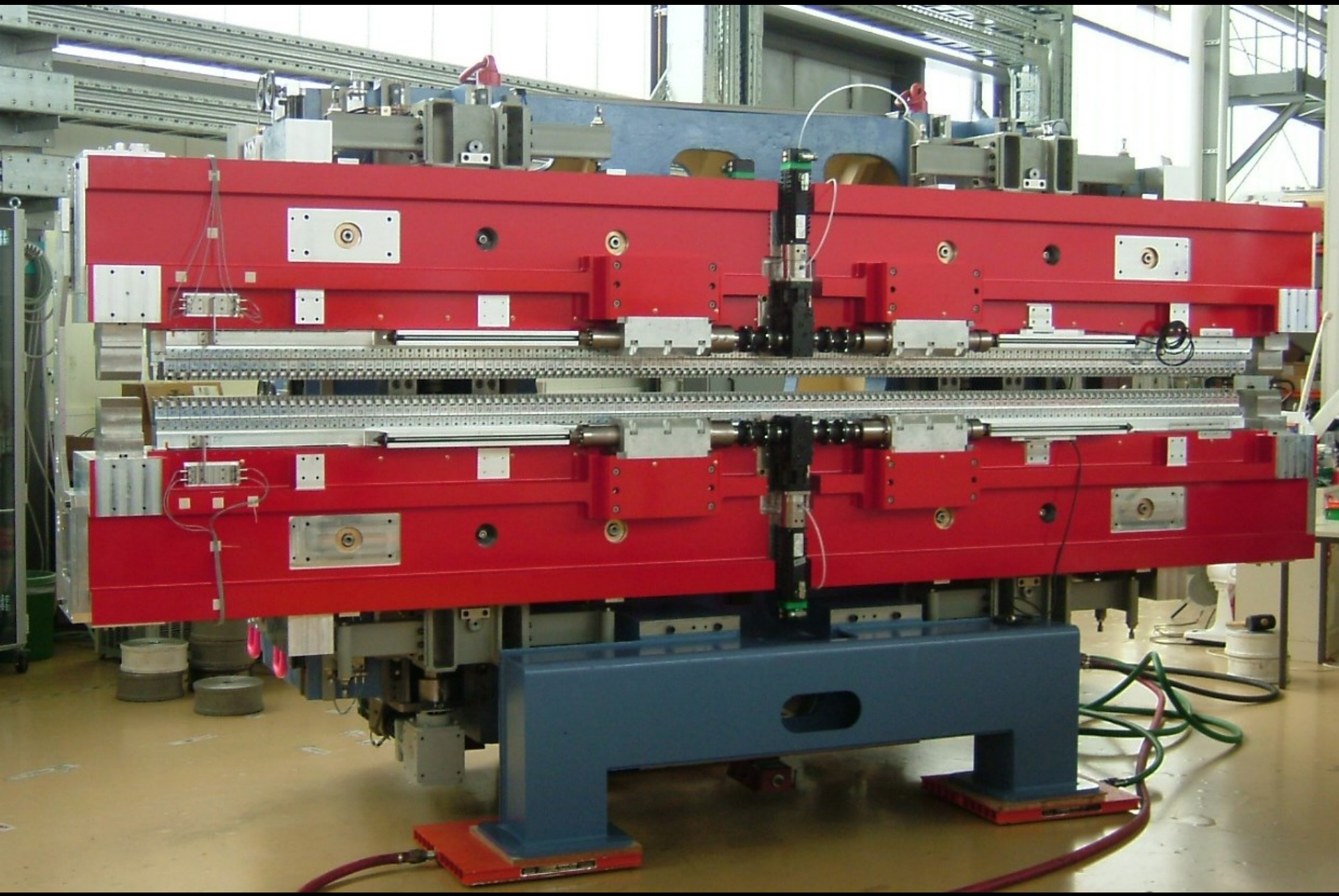


BESSY Undulator UE 56



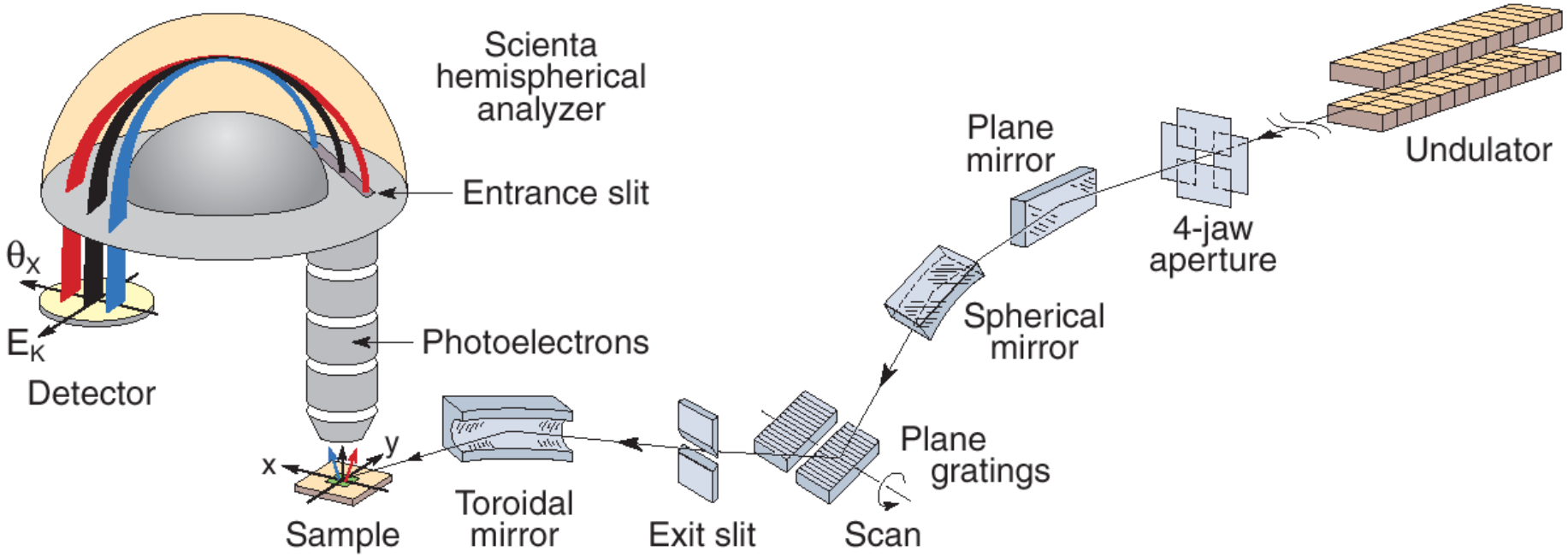




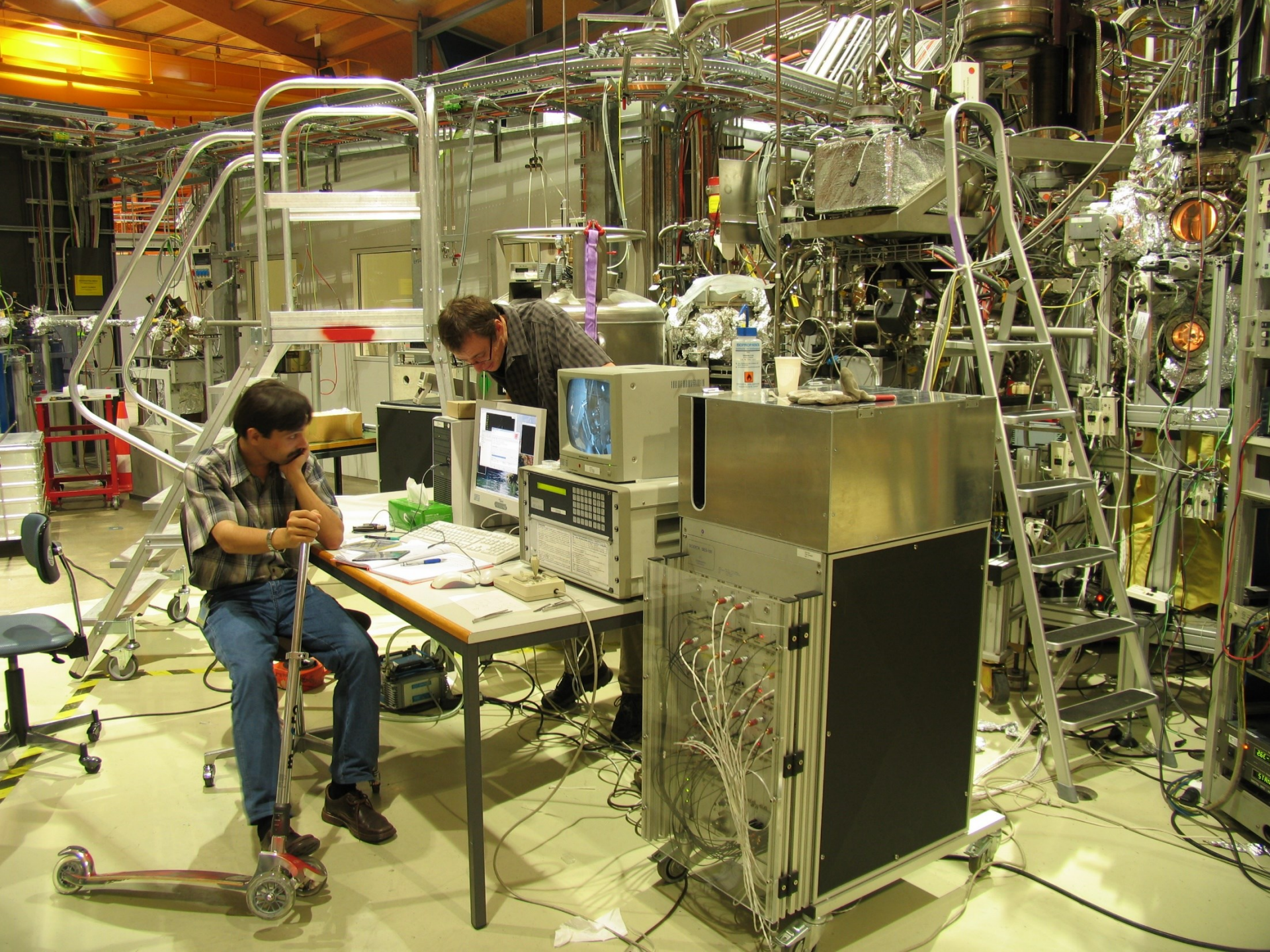



PFEIFER
Seil- und Hebetechnik
18t
M&S
030/3325044
Maschinentransporte

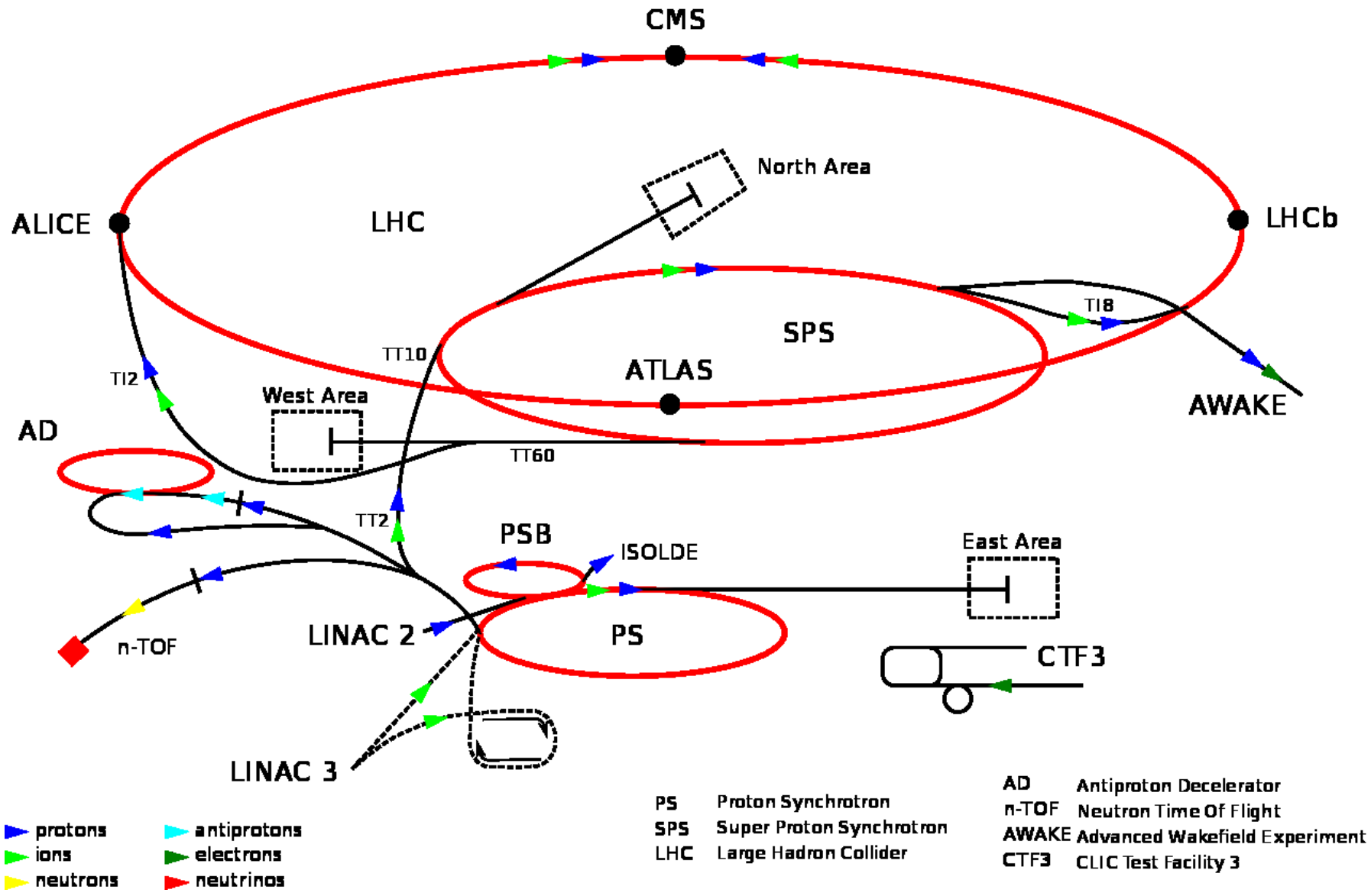
ARPES with Synchrotron Light



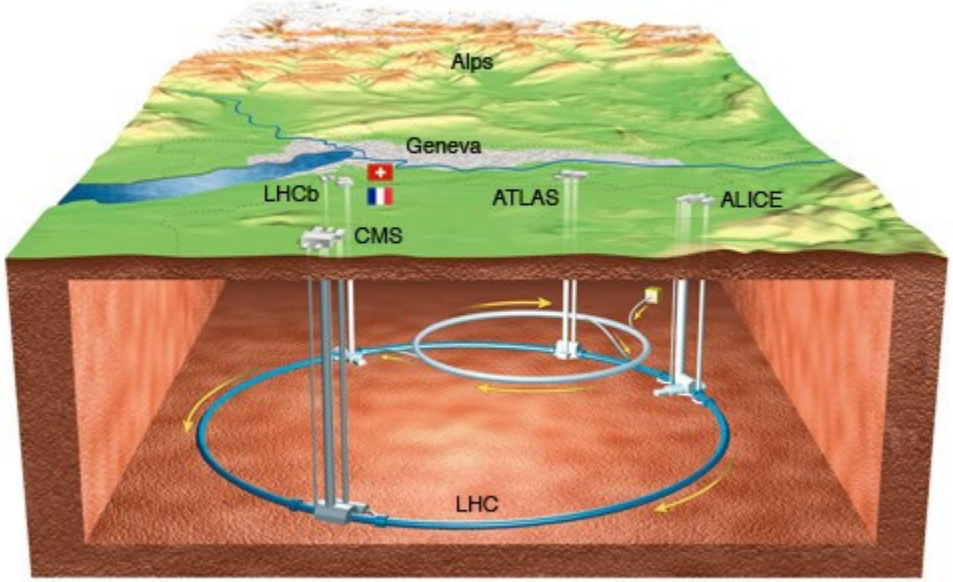
Damascelli *RMP* 2003



Proton synchrotron



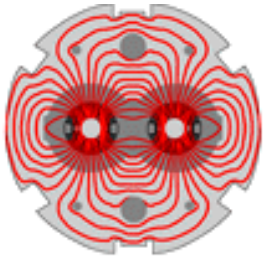
Large Hadron Collider (LHC)



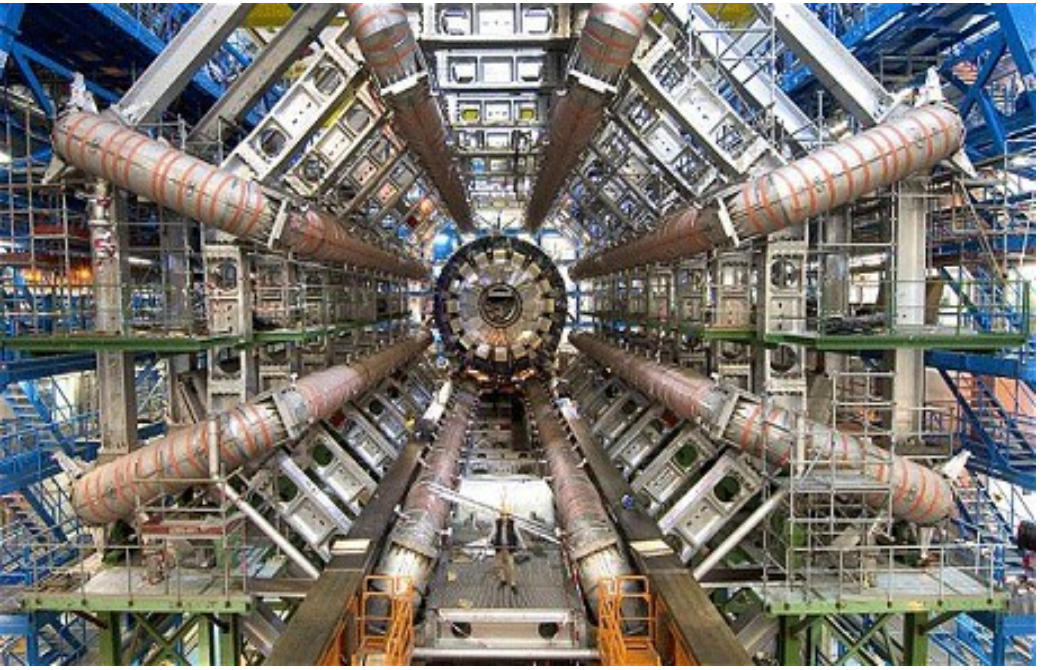
1998 – 2008
7.5 billion euros (approx. $9bn)

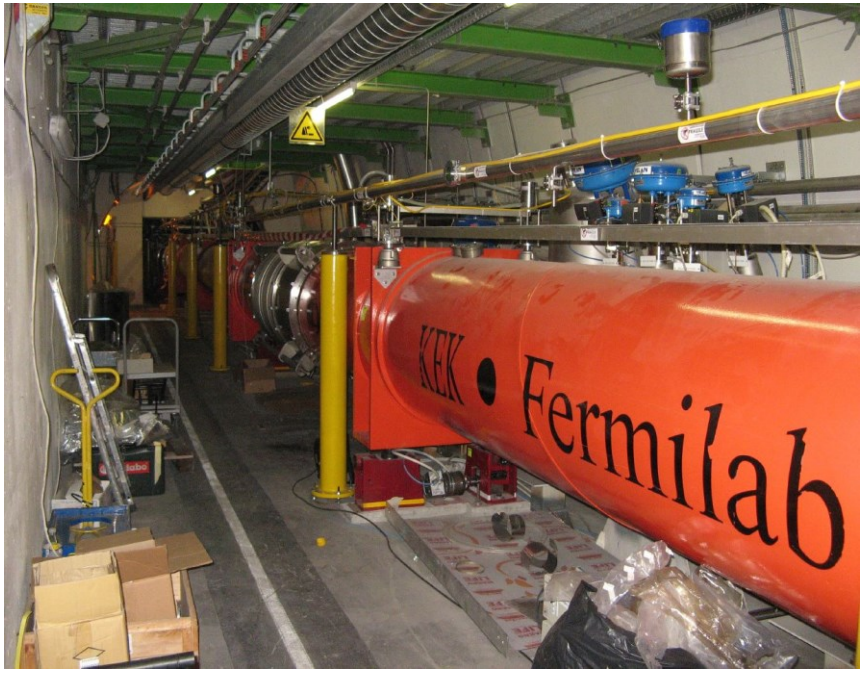
27 km in circumference, 175 m deep

3.5 TeV per beam in 2010 and 2011
4 TeV in 2012
upgrades to 6.5 TeV mid-March 2015

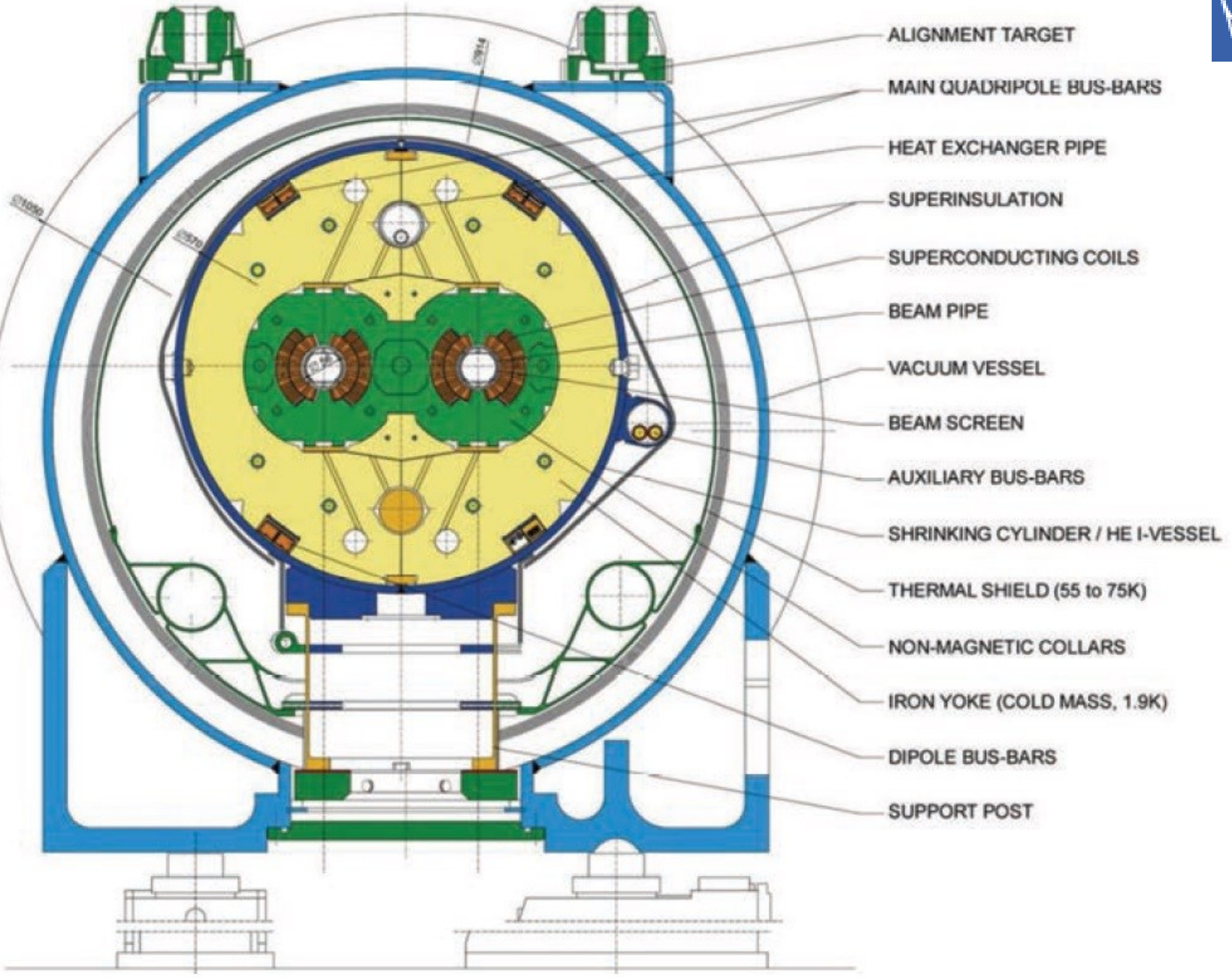


Великий адронний колайдер





10 000 надпровідних магнітів,
1200 тон кабелю з NbTi при 1.9 K
більше (130 тон LHe)

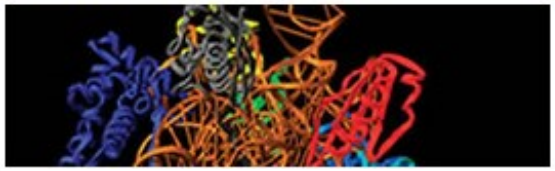

ALIGNMENT TARGET
MAIN QUADRIPOLE BUS-BARS
HEAT EXCHANGER PIPE
SUPERINSULATION
SUPERCONDUCTING COILS
BEAM PIPE
VACUUM VESSEL
BEAM SCREEN
AUXILIARY BUS-BARS
SHRINKING CYLINDER / HE I-VESSEL
THERMAL SHIELD (55 to 75K)
NON-MAGNETIC COLLARS
IRON YOKE (COLD MASS, 1.9K)
DIPOLE BUS-BARS
SUPPORT POST


CCTV

European XFEL

European X-ray Free Electron Laser

TINY STRUCTURES



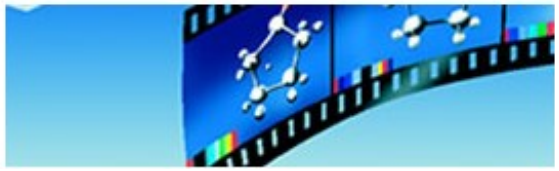
Examples

- Deciphering the structure of biomolecules
- Exploring the nanoworld in 3D

Experiment stations

SPB, SCS and MID

ULTRAFAST PROCESSES

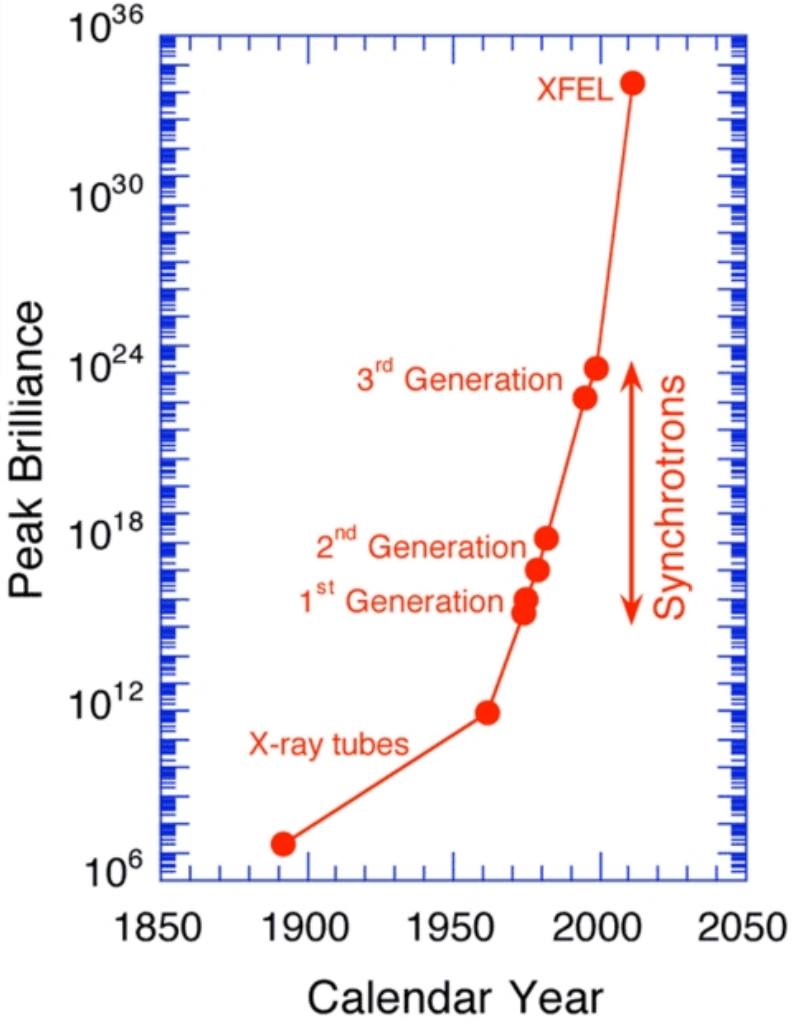


Examples

- Filming chemical reactions
- Unravelling magnetization

Experiment stations

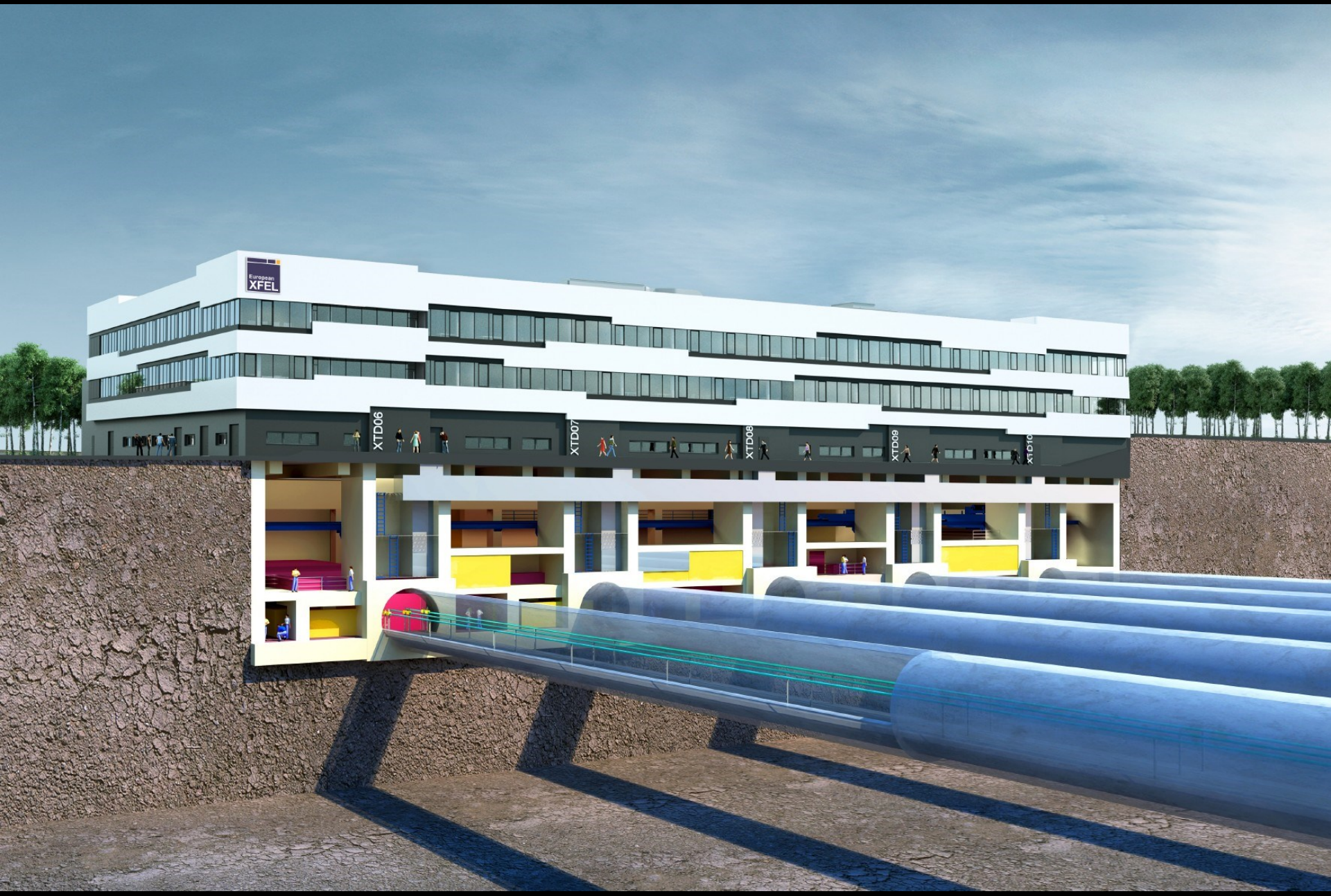
SPB, MID, FXE, HED, SQS, SCS



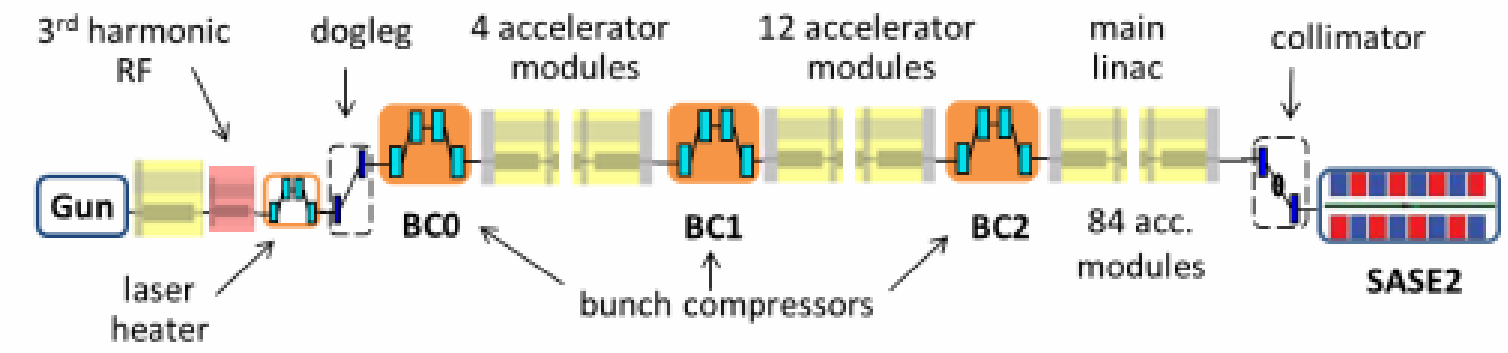
2009-2015: ~ 1 000 000 000 €

European XFEL

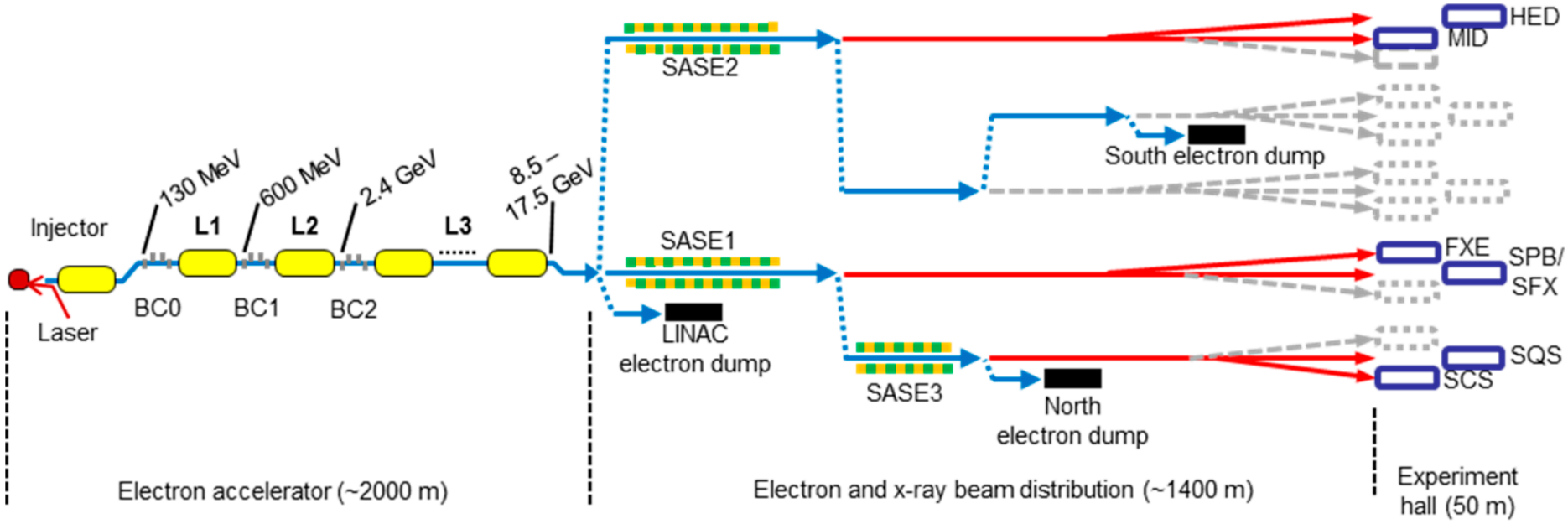
European X-ray Free Electron Laser


European
XFEL
XTD06
XTD07
XTD08
XTD09

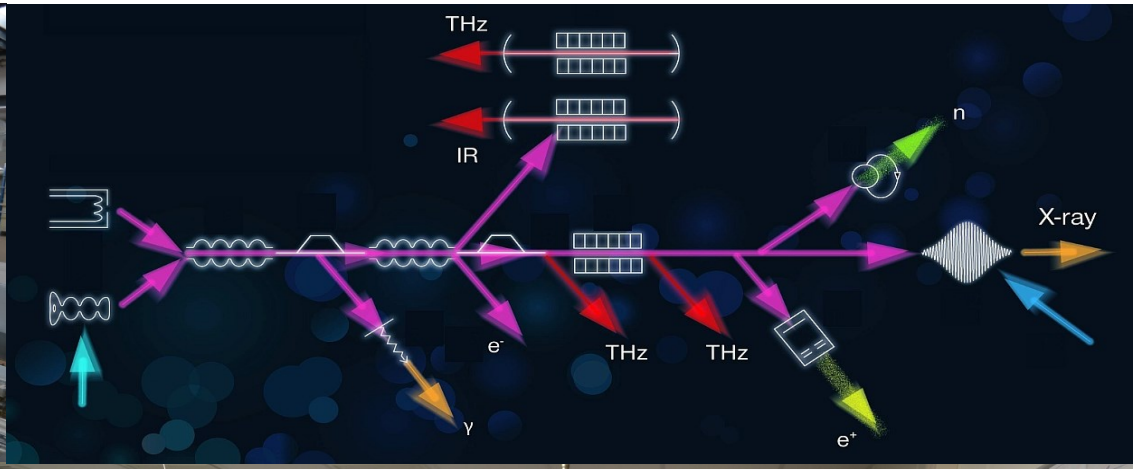
European XFEL

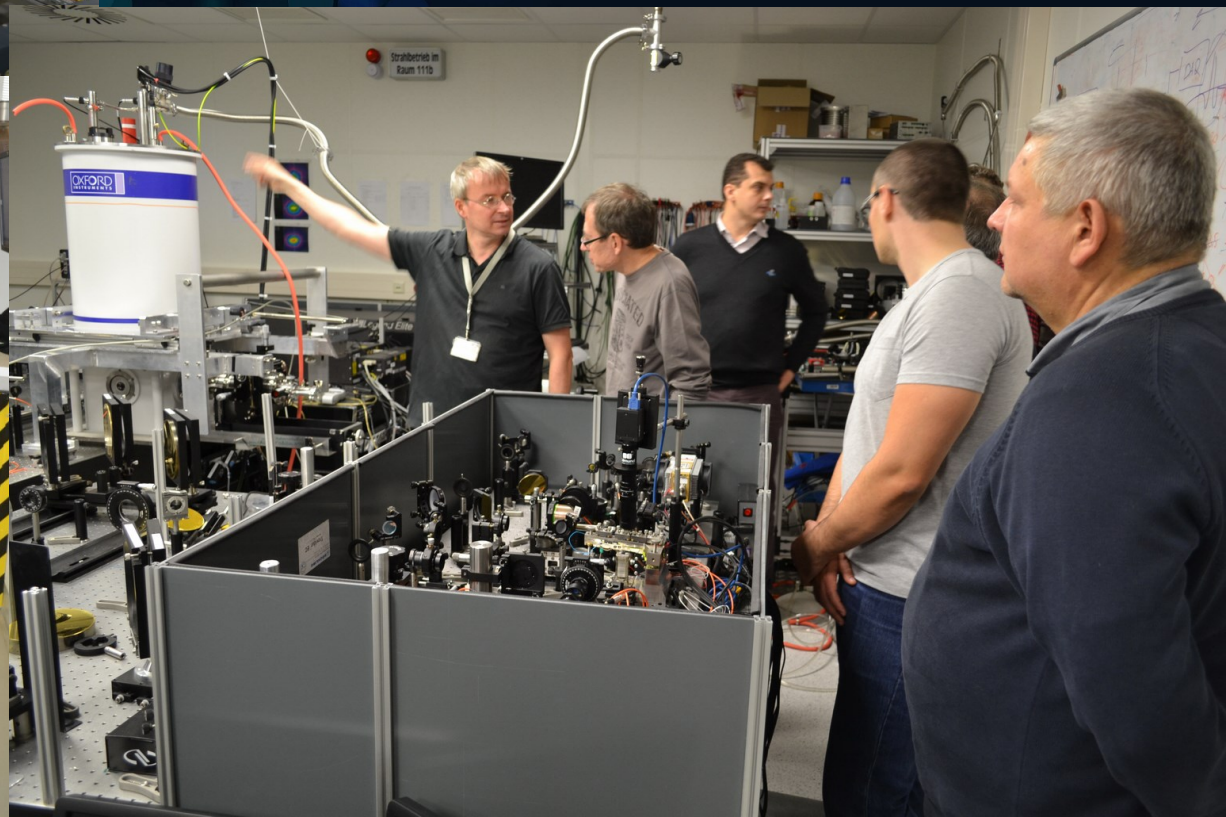


	R_{56} = 60-120 mm	R_{56} = 60-120 mm	R_{56} = 30-100 mm
σ_s = 2 mm	σ_s = 1 mm	σ_s = 0.1 mm	σ_s = 0.01-0.02 mm
I_{peak} = 50 A	I_{peak} = 100 A	I_{peak} = 1 kA	I_{peak} = 5-10 kA
Q = 1 nC	E = 130 MeV	E = 600 MeV	E = 2400 MeV



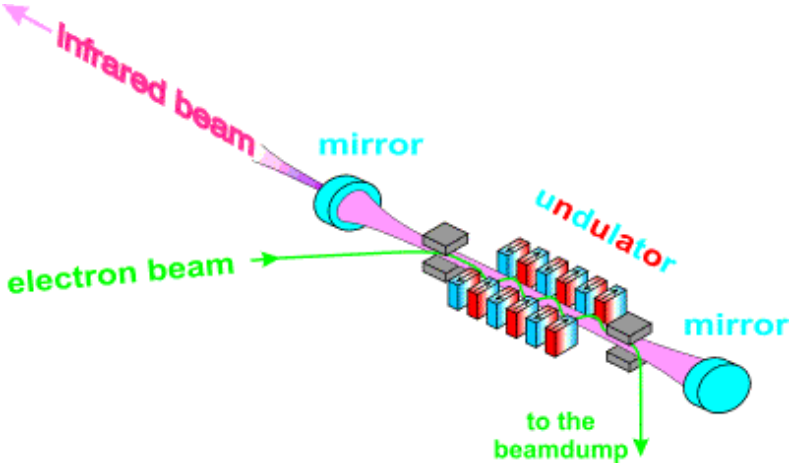
ELBE. Institute of Radiation Physics





ELBE. Institute of Radiation Physics

ELBE (**E**lectron **L**inac for beams with high **B**rilliance and low **E**mittance)



Radiation

Undulator	U27	U100
Wavelength [µm]	4 - 22	18 - 250
Average output power [W]	0.1 - 40	0.1 - 40
Pulse energy [µJ]	0.01 - 3	0.01 -3

Electron beam

Kinetic energy [MeV]	12 - 34
Bunch charge [pC]	77
Bunch repetition rate [MHz]	13
Average beam current [mA]	1
Long. beam emittance [keV*ps]	50
Transverse beam emittance [mm*mrad]	13

Undulators

Undulator	U27	U100
Undulator period [mm]	27.3	100
Number of periods	2*34	38
Undulator parameter	0.3 - 0.7	0.5 - 2.7

Synchrotron Light

BESSY (Berlin)

Emile Rienks
Rolf Follath
Andrei Varykhalov
Serguei Molodtsov

SLS (PSI Villigen)

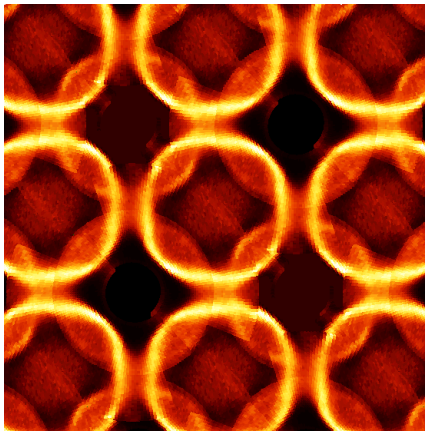
Ming Shi
Vladimir Strocov
Luc Patthey
Joel Mesot

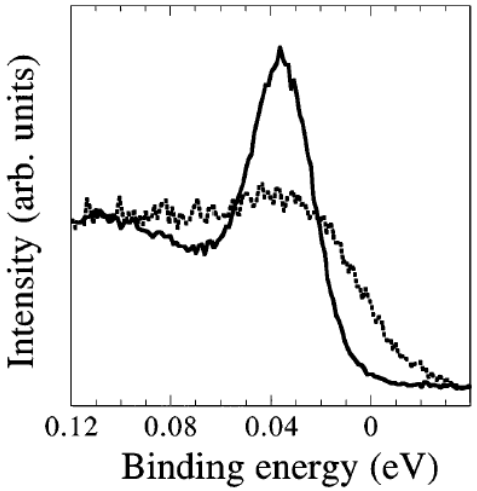
ELETTRA (Trieste)

Alexei Barinov
Pavel Dudin
Stefano Turchini

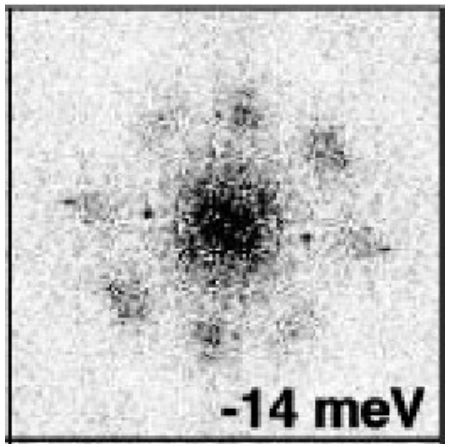
Modern momentum resolving techniques

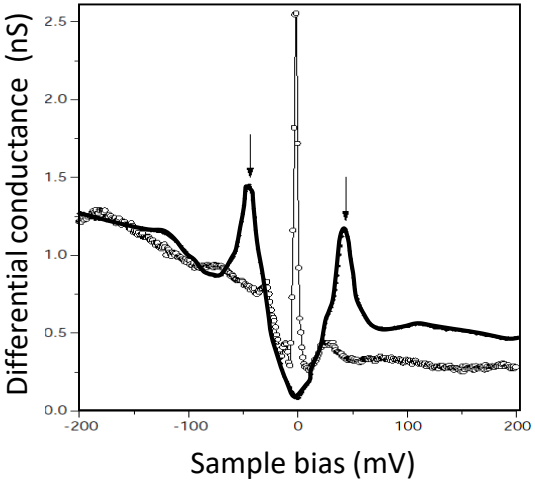
ARPES





STS





INS