CERN

Dust charging environment in accelerators: Synchrotron Radiation

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Workshop on Dust Charging and Beam-Dust Interaction in Particle Accelerators

13–15 Jun 2023
CERN
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https://indico.cern.ch/event/1272104/

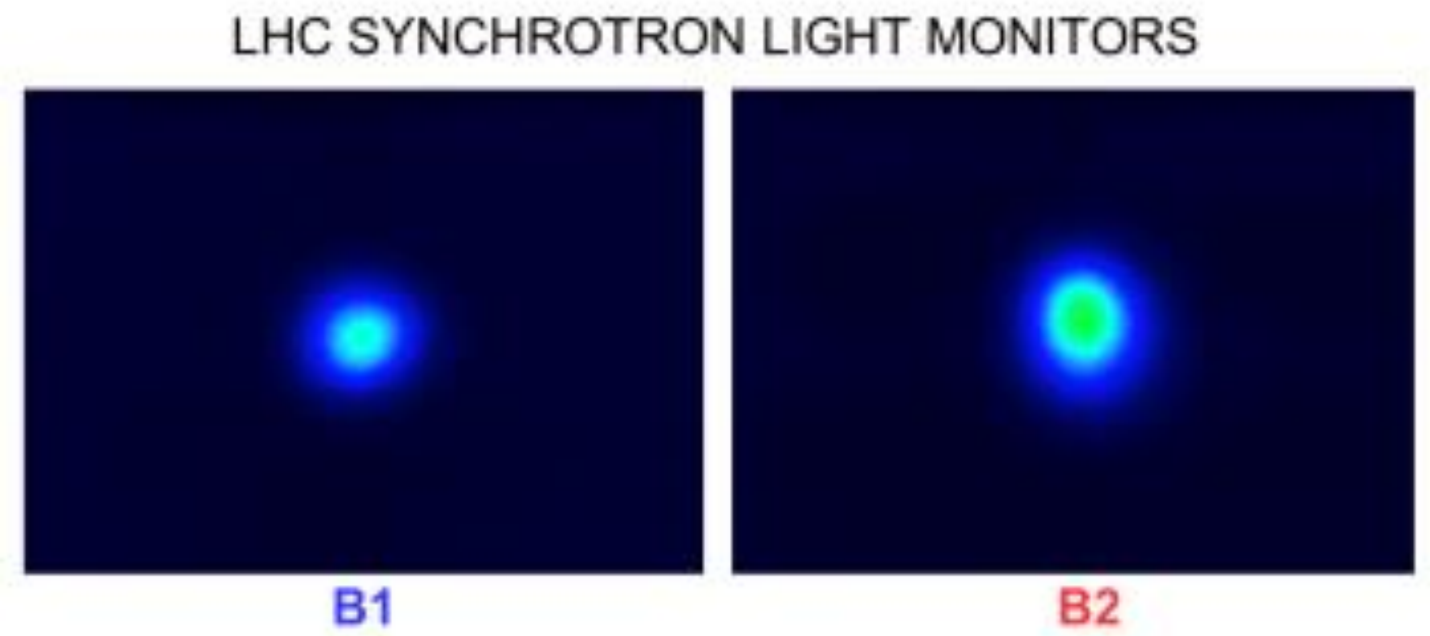
Outline

1. Synchrotron radiation properties
2. Photon interactions
3. Conclusions

1. SR properties

Synchrotron radiation: visible light

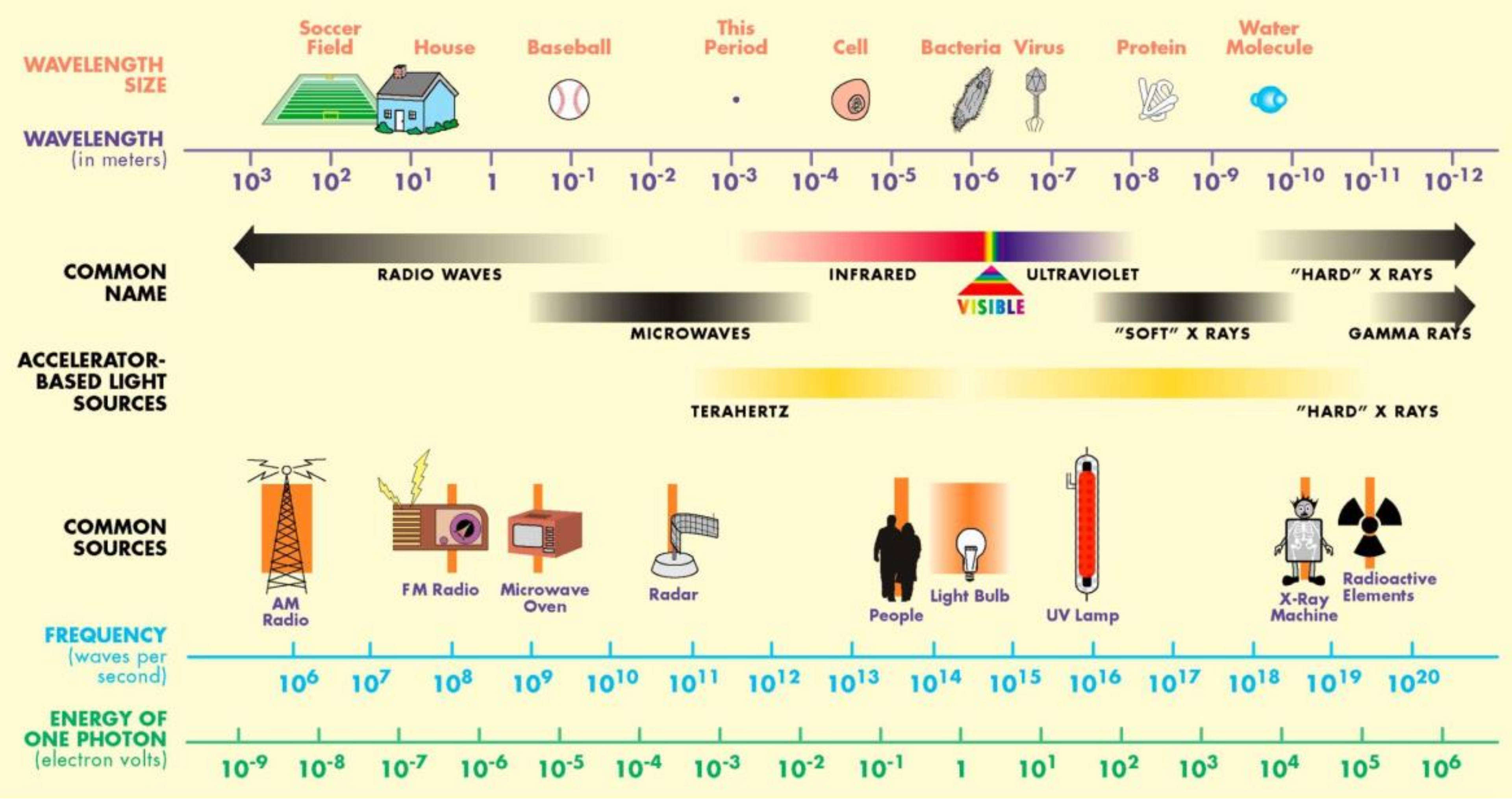
- In a synchrotron, charged particles can radiate light by synchrotron radiation
- This effect can be used for diagnostics purposes



CERN Control Centre LHC beams SR displays

- Particles lose energy by synchrotron radiation ➔ should be compensated by RF system
- Beam emittance shrinks upon emission of synchrotron radiation (damping rings/wigglers)

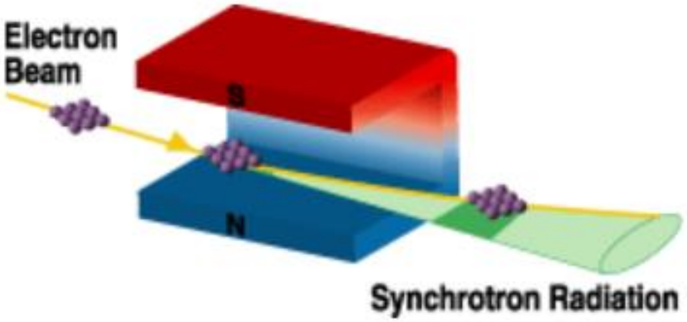
Electromagnetic Spectrum

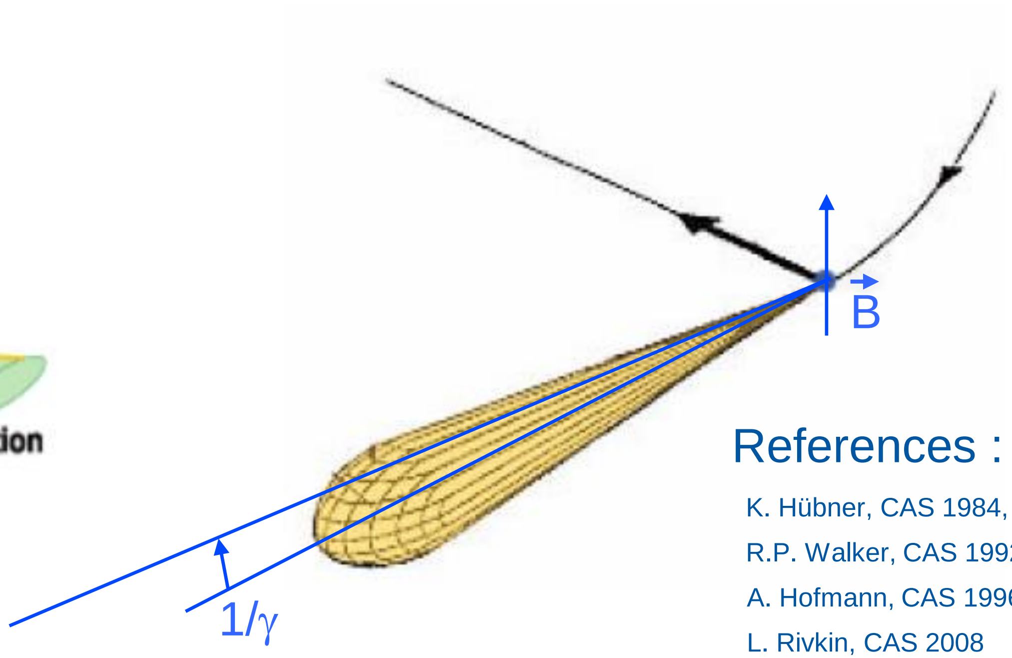


1 meV | 1 MeV

Synchrotron Radiation

- A charged particle which is accelerated generate radiation (*magnetic bremsstrahlung*)
- The power of the centripetal radiation is larger than the longitudinal radiation (factor γ^2)
- For a relativistic particle, the radiation is highly peaked (opening angle ~ 1/γ)
- **The radiation energy range from infrared to gamma rays: from meV to MeV**





References :

K. Hübner, CAS 1984, CERN 85-19

R.P. Walker, CAS 1992, CERN 94-01

A. Hofmann, CAS 1996, CERN 98-04

L. Rivkin, CAS 2008

Critical energy

- The critical energy ε_c splits the power spectrum in two equals parts: 50% above, 50% below ε_c

$$\varepsilon_c = \frac{3}{2}\frac{hc}{2\pi}\frac{\gamma^3}{\rho}$$

$$\text{Electrons}: \varepsilon_c[\text{eV}] = 2.218\ 10^3 \frac{\text{E[GeV]}^3}{\rho[\text{m}]}$$

$$\text{Protons}: \varepsilon_c[\text{eV}] = 3.5835\ 10^{-7} \frac{\text{E[GeV]}^3}{\rho[\text{m}]}$$

- 88 % of the emitted photons have an energy **lower** than the critical energy

- Magnetic rigidity:

$$B\,\rho = \frac{p}{e} \approx \frac{E}{e\,c} \qquad \frac{1}{\rho} \approx \frac{3}{10}\frac{B[T]}{E[GeV]} \qquad \varepsilon_c \propto \frac{E^3}{\rho} \propto B\,E^2$$

Dissipated power

- The average power emitted by the beam **per unit of length** is

$$P_0\,[\mathrm{W/m}] = \frac{e}{3\varepsilon_0 (m_0 c^2)^4} \frac{E^4}{2\pi\rho^2} I$$

$$P_0 \propto \frac{E^4}{\rho^2} I \propto B^2 E^2 I$$

- Electrons :

$$P_0\,[\mathrm{W/m}] = 88.57 \frac{E[\mathrm{GeV}]^4}{2\pi\,\rho[\mathrm{m}]^2} I[\mathrm{mA}]$$

- Protons:

$$P_0\,[\mathrm{W/m}] = 7.79\;10^{-12} \frac{E[\mathrm{GeV}]^4}{2\pi\,\rho[\mathrm{m}]^2} I[\mathrm{mA}]$$

- For the total dipole radiation power dissipated around the ring, **multiply by 2$\pi\rho$**

- Protons generate a lot less SR compared to electrons because there is a $1/m_0^4$ dependency in the formula for the radiated power, where m_0 is the rest mass of the radiating particle. Protons are 1836 times heavier than electrons, so the reduction factor is ~$8.8\cdot10^{-14}$

$$\frac{88.57}{7.79\times10^{-12}} = (1836)^4$$

With 1836 equals the ratio of proton to electron mass

Linear photon flux

- The photon flux per unit of length is given by :

$$\dot{\Gamma} = \frac{15\sqrt{3}}{8}\frac{P_0}{\varepsilon_c} = \frac{5\sqrt{3}e}{12\,h\,\varepsilon_0 c}\frac{\gamma}{\rho} I$$

$$\dot{\Gamma} \propto \frac{E}{\rho} I \propto B\, I$$

- Electrons :

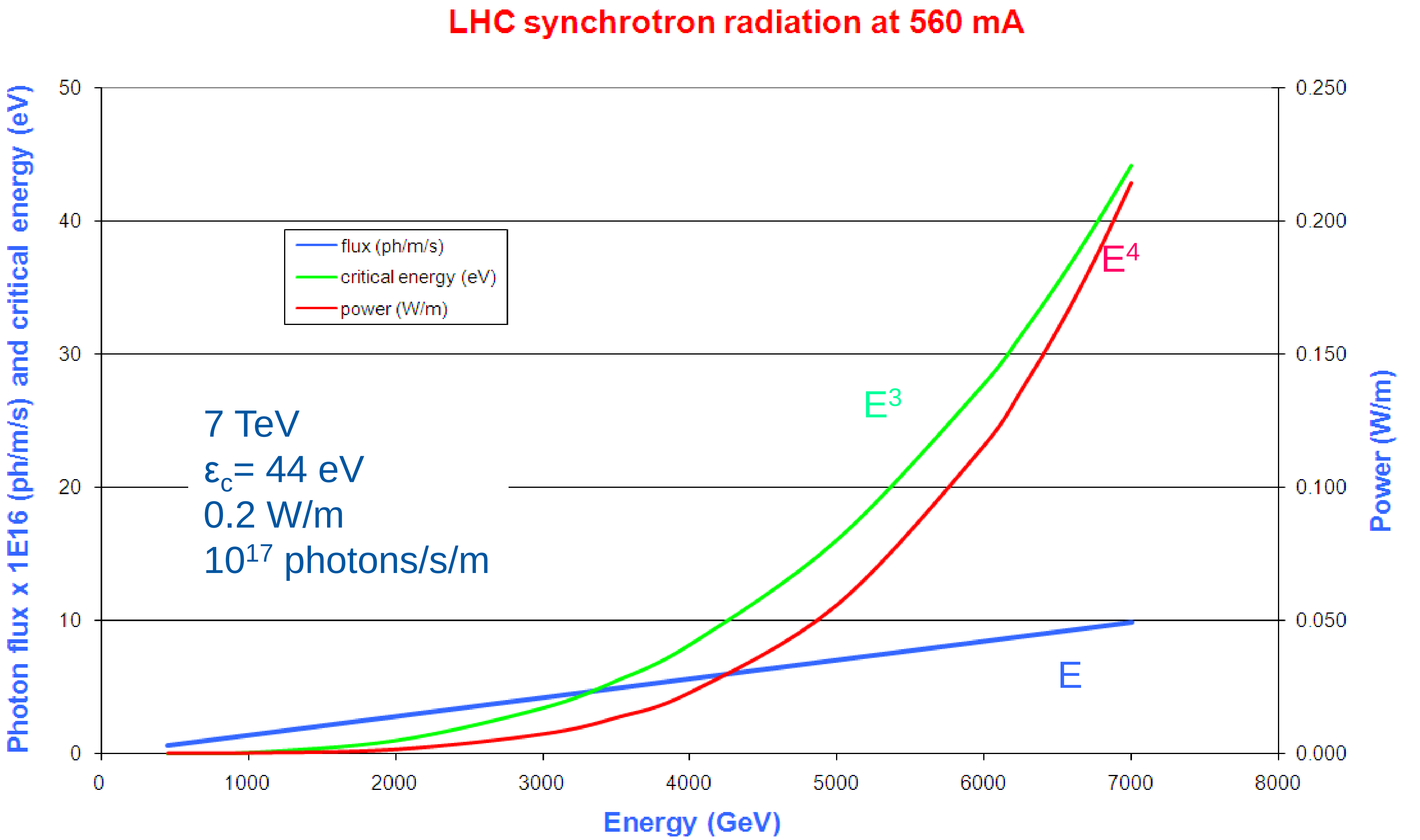
$$\dot{\Gamma}[\text{photons.m}^{-1}.\text{s}^{-1}] = 1.28810^{17}\frac{E[\text{GeV}]}{\rho[\text{m}]} I[\text{mA}]$$

- Protons:

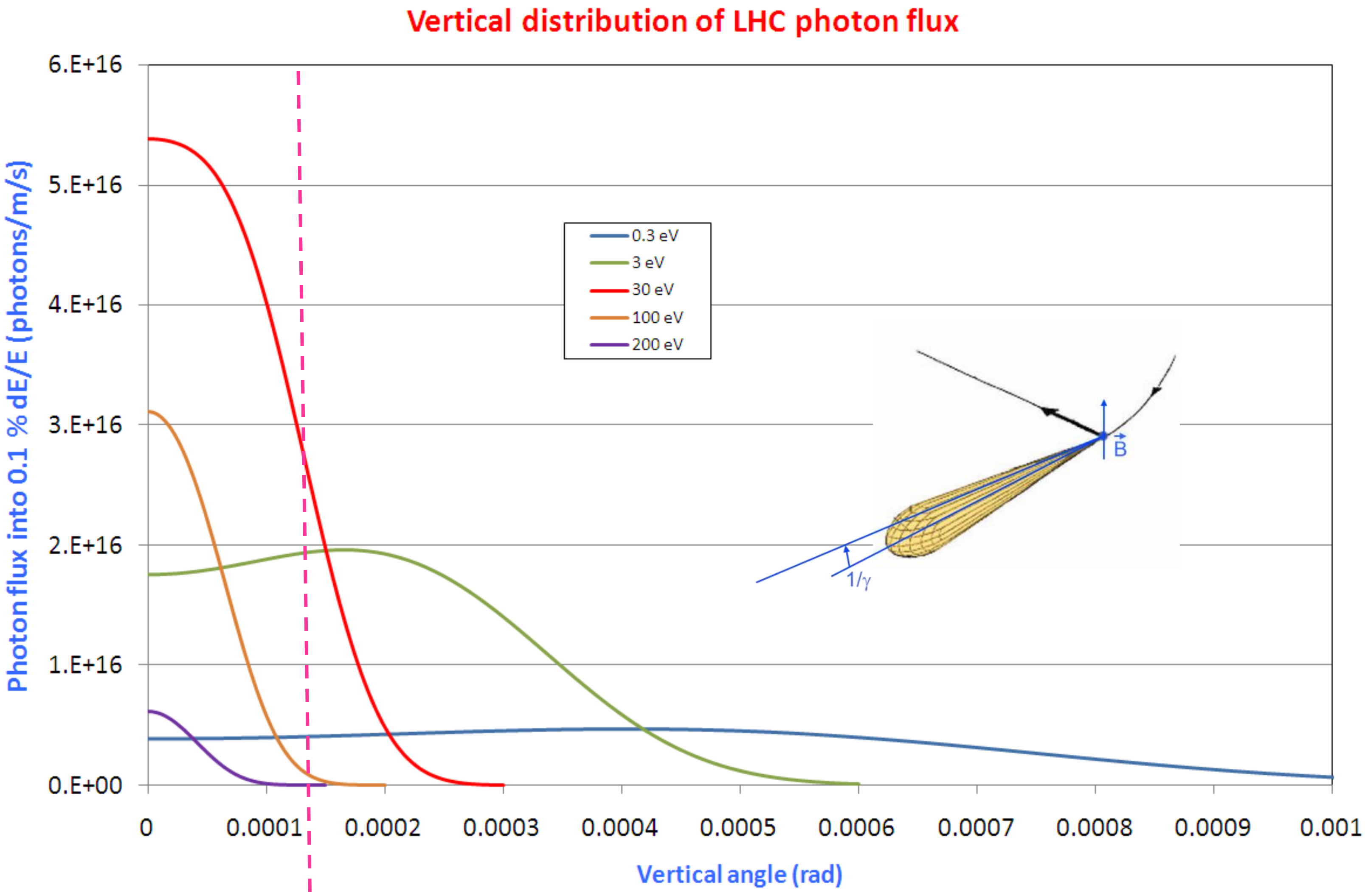
$$\dot{\Gamma}[\text{photons.m}^{-1}.\text{s}^{-1}] = 7.01710^{13}\frac{E[\text{GeV}]}{\rho[\text{m}]} I[\text{mA}]$$

- LEP : 3 10^{16} ph/m/s
- LHC : 1 10^{17} ph/m/s

Scaling with energy



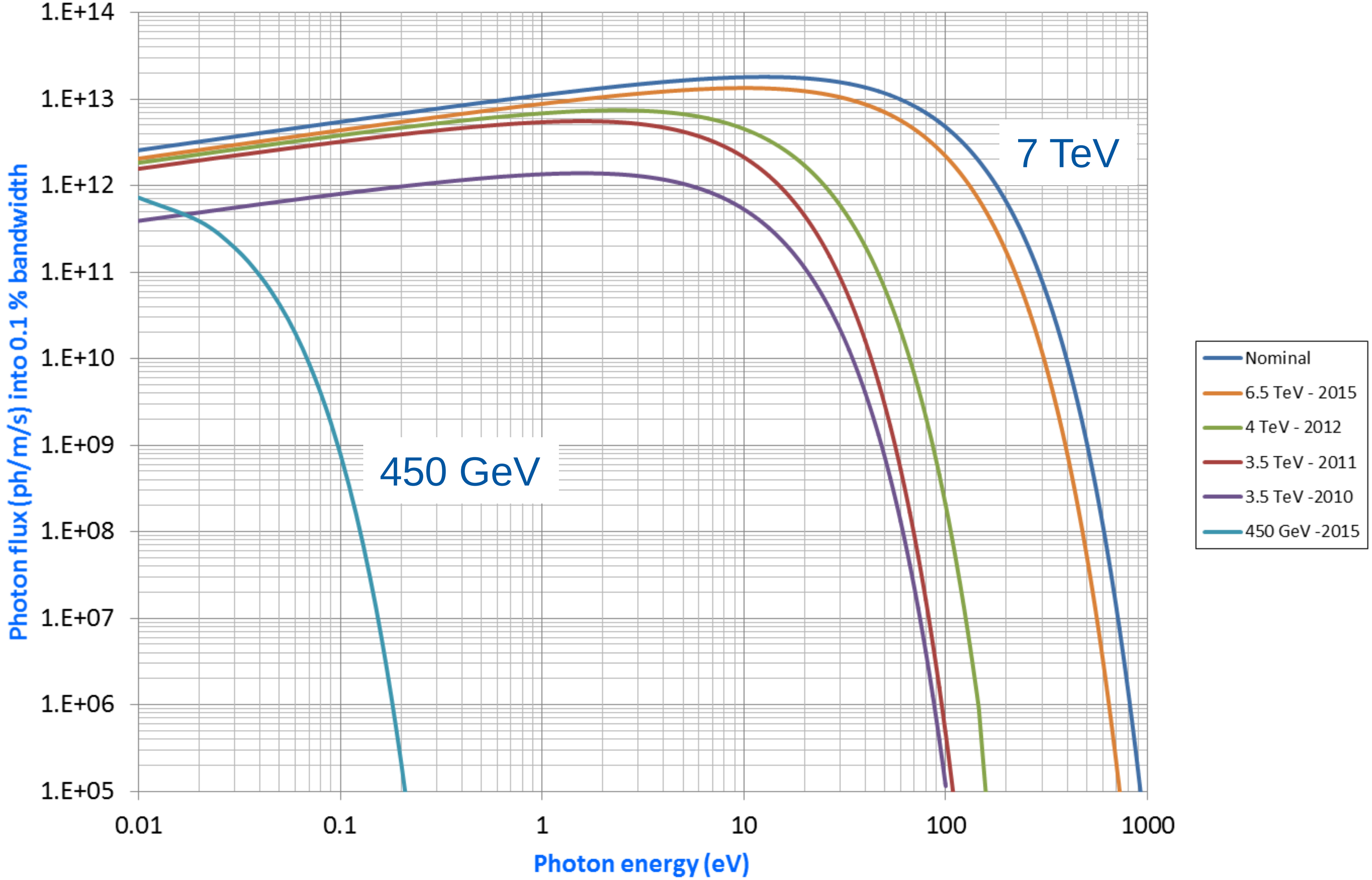
Energy distribution in the vertical plane



1/γ = vertical opening angle = 0.13 mrad ➔ 1.3 mm at 10 m

LHC SR Spectrum : from IR to UV

- With nominal parameters : 7 TeV and 585 mA
- 2010, 2011, 2012 and 2015 spectra



LEP SR spectrum: harder spectrum, X-rays & gamma rays

- LEP: electron-positron collider; was installed in the (now) LHC tunnel before LHC; same circumference (26.8 km)

LEP (CERN): (high-energy e+ e- COLLIDER)

ρ = 2963 m

I = 4 mA

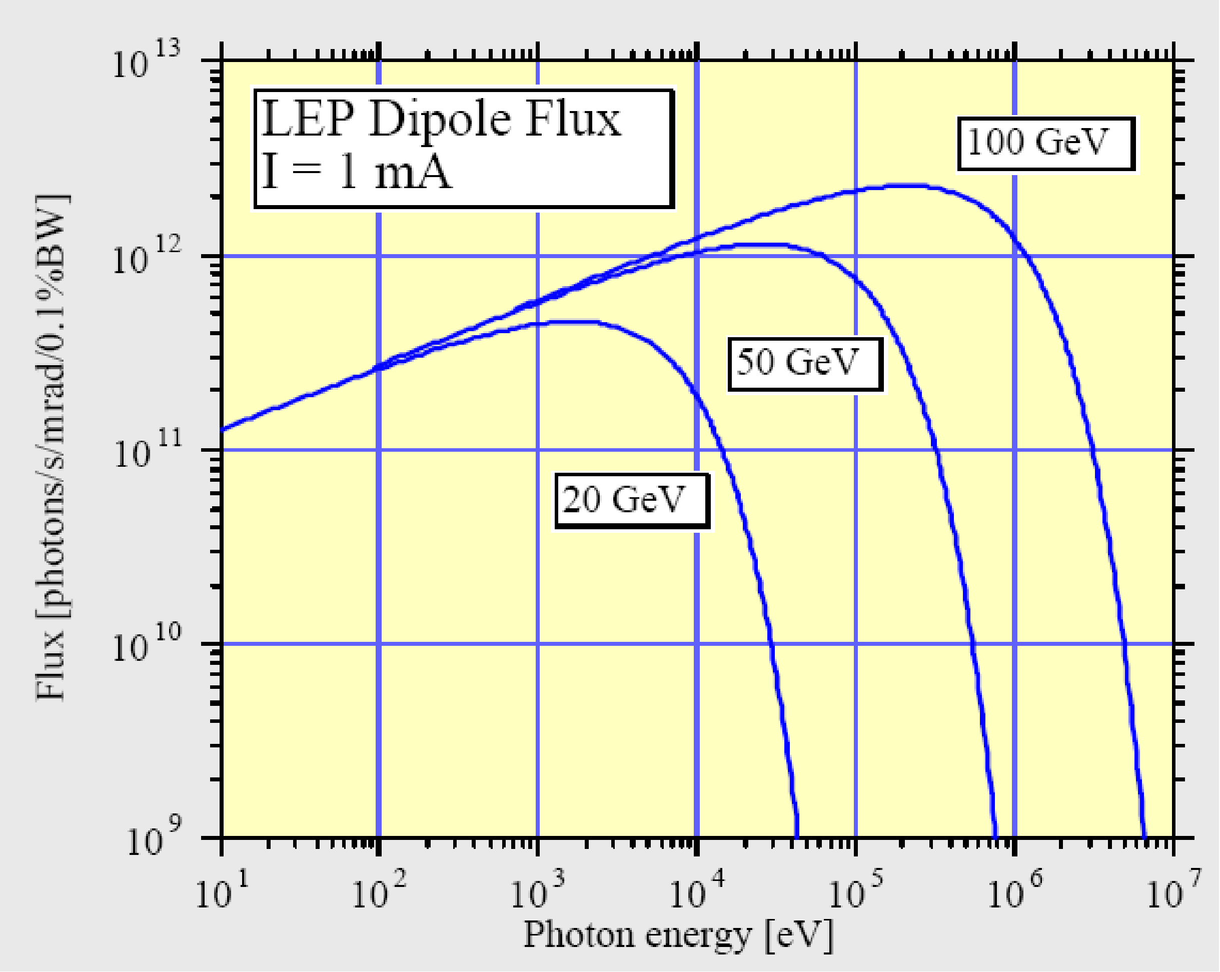
E = 100 GeV (up to 104)

ε_c = 748.6 keV ←

F = 1.736·10^{16} ph/s/m

P = 0.642 kW/m

1/γ = 5.11 μrad → **0.511 mm @100 m**

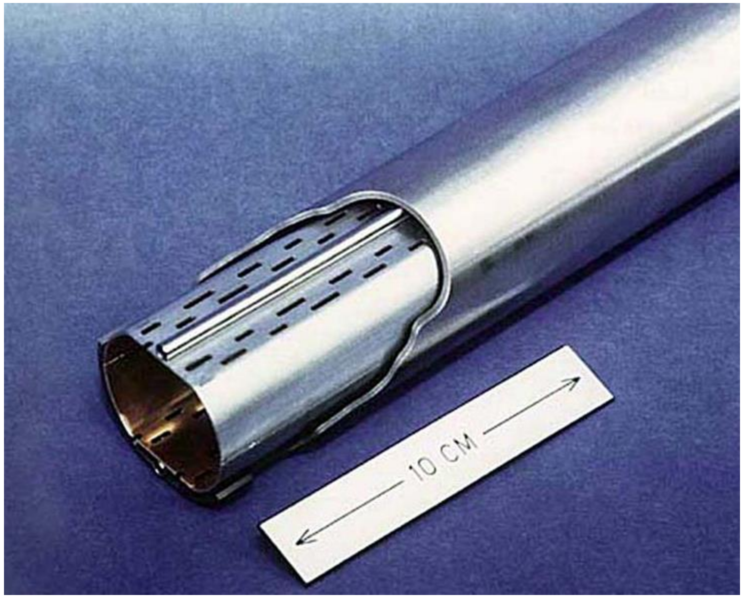


SR impact on different type of machines …

		Soleil	KEK-B		LEP			LHC	
			LER	HER	Inj.	1	2	Inj.	Col.
Particle		e^-	e^+	e^-	e^-	e^-	e^-	p	p
Beam current	mA	500	2600	1100	3	3	7	584	584
Energy	GeV	2.75	3.5	8	20	50	96	450	7000
Bending radius	m	5.36	16.31	104.46	2962.96			2784.302	
Power	W/m	14 030	20 675	5 820	0.8	30	955	0	0.2
Critical energy	eV	8 600	5 800	11 000	6 000	94 000	660 000	0	44
Photon flux	photons/m/s	$3\ 10^{19}$	$7\ 10^{19}$	$1\ 10^{19}$	$3\ 10^{15}$	$7\ 10^{15}$	$3\ 10^{16}$	$7\ 10^{15}$	$1\ 10^{17}$
Dose at 3000 h	photons/m	$4\ 10^{26}$	$8\ 10^{26}$	$1\ 10^{26}$	$3\ 10^{22}$	$7\ 10^{22}$	$3\ 10^{23}$	$7\ 10^{22}$	$1\ 10^{24}$

- In LEP, and all synchrotron light sources, the evacuation of the **power is an issue**
- The LHC operates at 7 TeV with ~ 0.6 A. **Power evacuation is an issue for the cryogenic system (1 kW/arc), due to the low carnot efficiency at low temperature**
- **The critical energy varies from a few 10 eV to 660 keV**. Strongly bound molecules can be desorbed

… heavy consequences on design



Courtesy N. Kos CERN TE/VSC

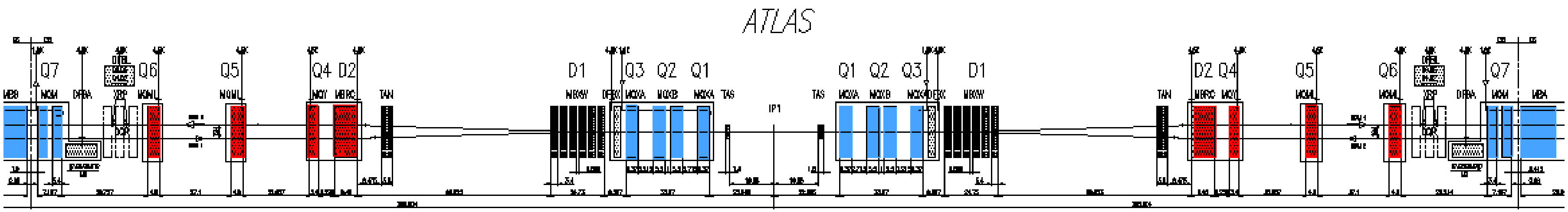
Courtesy N. Kos CERN TE/VSC

LHC Design

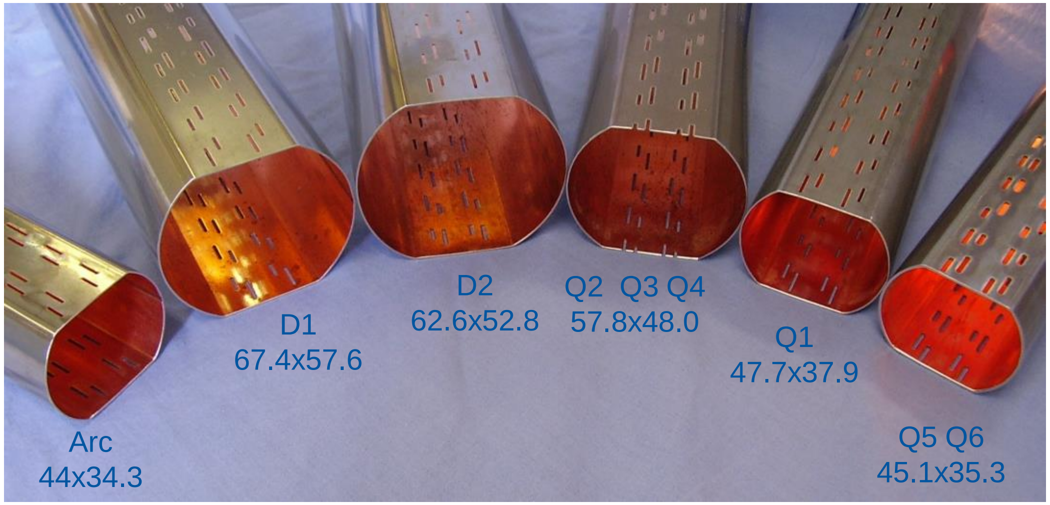
(CERN LHC Vacuum group)

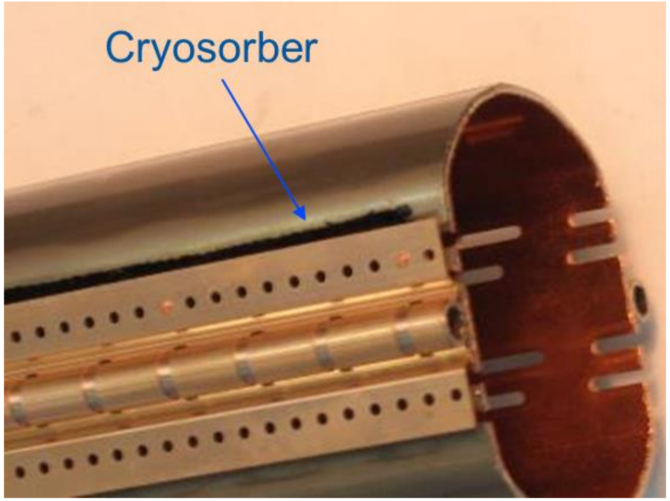
- Perforated Cu colaminated beam screen to intercept the SR power (~ 1 kW/arc) protecting the 1.9 K cold bore and to allow a distributed pumping

Long Straight Section Zoo



- Focusing inner triplets located around experiments operate at 1.9 K
- Matching sections operate at 4.5 K ➔ beam screen with cryosorbers

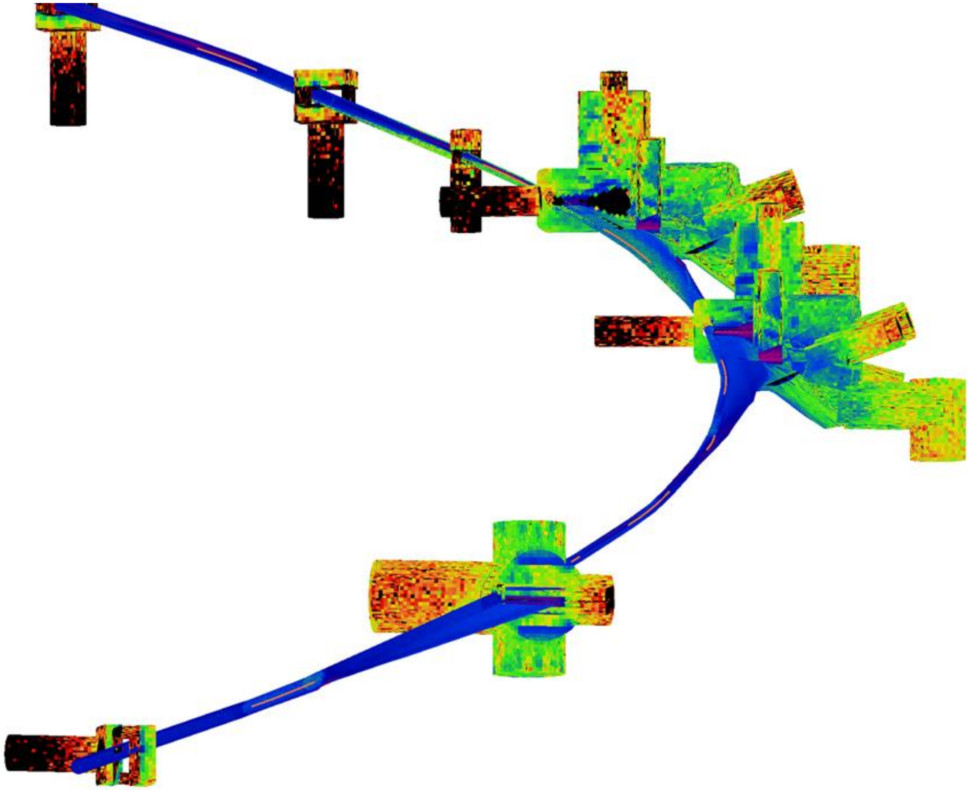




Beam Screen for the LHC Long Straight Sections, edms 334961

Ray tracing

• Ray tracing programs are used to compute photon flux and power dissipation in specific geometries e.g. SynRad+



https://molflow.docs.cern.ch/

Ray tracing of synchrotron radiation in a real machine
courtesy R. Kersevan

SR parameters for next CERN machines

		LHC		FCC-ee				FCC-hh
		LHC	HL-LHC	Z	WW	ZH	ttbar	
Particle		p p		$e^- e^+$				p p
Beam current	mA	584	1120	1390	147	29	5.4	500
Energy	GeV	7 000		45.6	80	120	182.5	50 000
Bending radius	m	2801		10760				2801
Power	W/m	0.2	0.4	730				35.7
Power	kW/beam	4	7	$50\ 10^3$				$2.3\ 10^3$
Critical energy	keV	0.044		20	106	356	1253	4.3
Vertical angle	µrad	134		11	6	4	3	19
SR size at 10 m	mm	1.3		0.011	0.06	0.04	0.03	0.19
Incidence angle	mrad	4		3.3				2
SR path length	m	11.4		35.9				20.5
Photon flux	photons/m/s	$1\ 10^{17}$	$2\ 10^{17}$	$8\ 10^{17}$	$1\ 10^{17}$	$4\ 10^{16}$	$1\ 10^{16}$	$2\ 10^{17}$
Dose at 3000 h	photons/m	$1\ 10^{24}$	$2\ 10^{24}$	$8\ 10^{24}$	$1\ 10^{24}$	$5\ 10^{23}$	$1\ 10^{23}$	$2\ 10^{24}$

2. Photon interactions

Photon interaction with matter

- Photons emitted by synchrotron radiation interact with the vacuum chamber material

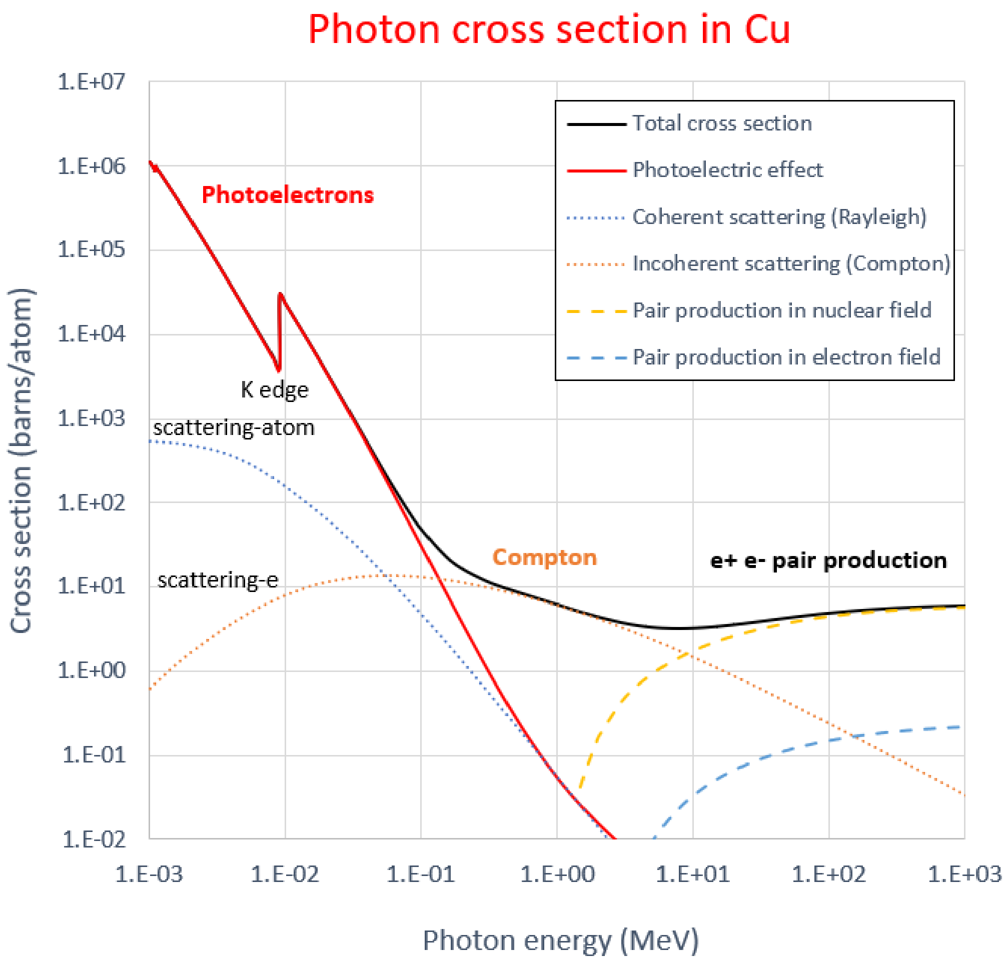
- Penetration depth ~ 5 nm in metals

- LHC, Ec = 44.1 eV
- Sync rad machine, Ec = 5-10 keV
- Super KEKB HER, Ec = 7.3 keV
- FCCee Z, Ec = 0.6 keV
- FCCee W, Ec = 32.7 keV

➔ Photoelectrons dominated

- LEP2, Ec = 0.7 MeV
- FCCee H, Ec = 0.3 MeV
- FCCee tt, Ec = 1.3 MeV

➔ Compton dominated



http://physics.nist.gov/xcom

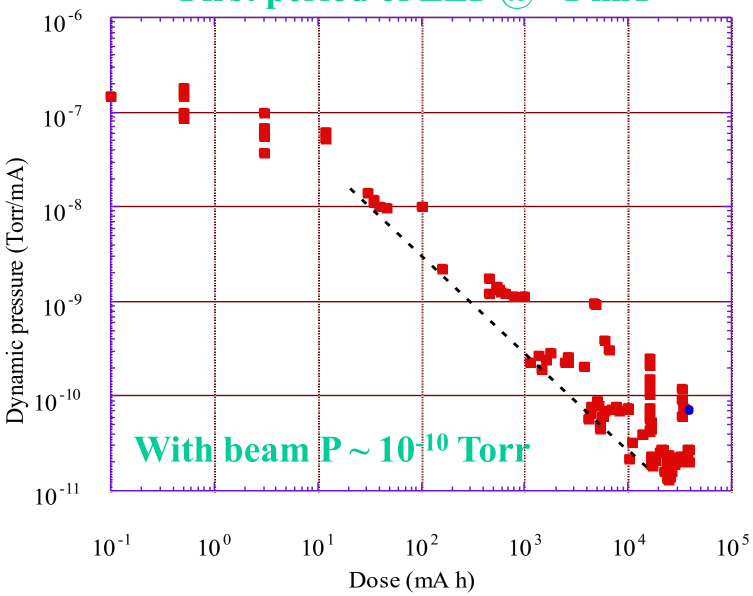
A. Molecular desorption

Photon Stimulated Desorption

- The observed dynamic pressure decreases by several orders of magnitude with photon dose: "photon conditioning"
- The photon desorption yield is characterised by η_{photon}

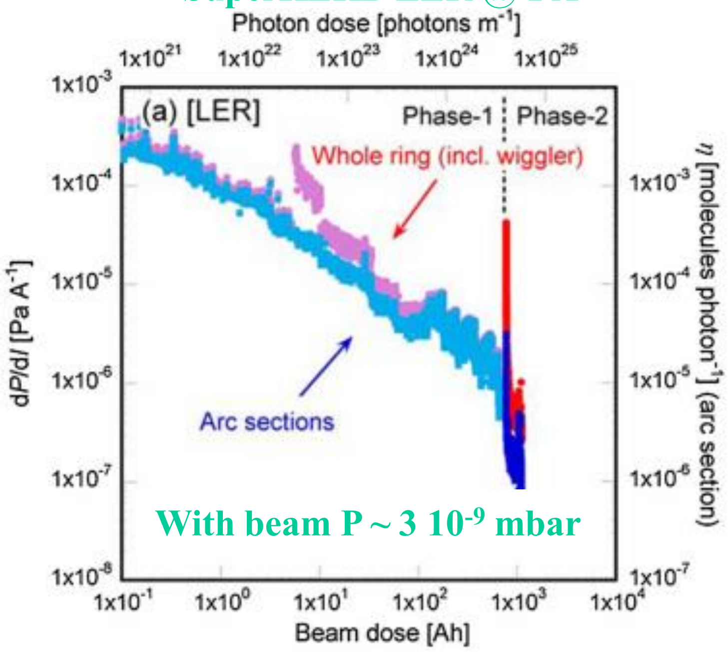
$$P = P_o + P_{Dyn} = \frac{Q + \eta_{Photons}\dot{\Gamma}_{Photons}}{S}$$

First period of LEP @ ~1 mA



O. Gröbner. Vacuum 43 (1992) 27-30

SuperKEKB LER @ 1 A



Y. Suetsugu et al., J. Vac.Sci.Technol. A37 021602 (2019)

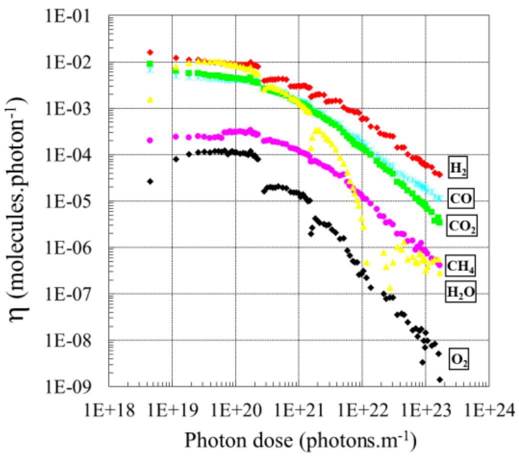
Photon Desorption Yield

- Initial yield ~ 10^{-3} – 10^{-2} molecules/photon
  - Rapid decrease with dose until ~ 10^{-7} - 10^{-6} molecules/photon at 10^{25}-10^{26} ph/m
  - Several monolayers (1 to 15) of gas can be desorbed

- Photoelectric effect with linear yield till 5 keV, then Compton dominated above 100 keV

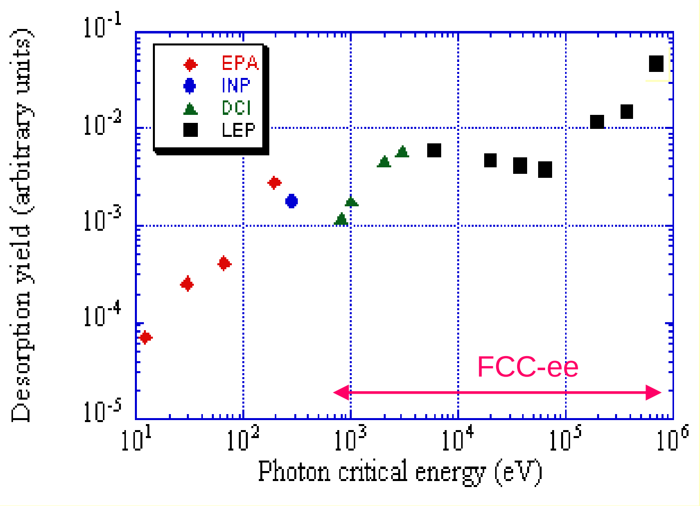
- Large yield for physisorbed/condensed gases

Unbaked stainless-steel 3.75 keV



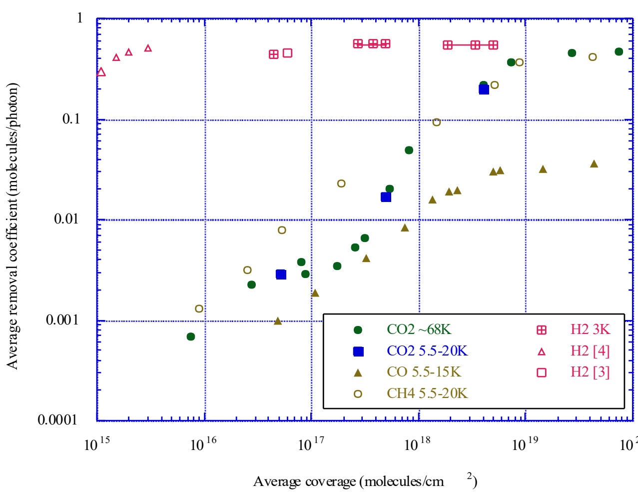
C. Herbeaux et al.
JVSTA 17(2) Mar/Apr 1999, 635

As a function of critical energy



O. Gröbner. CAS 99-15

Unbaked Stainless steel 250-300 eV Perpendicular incidence

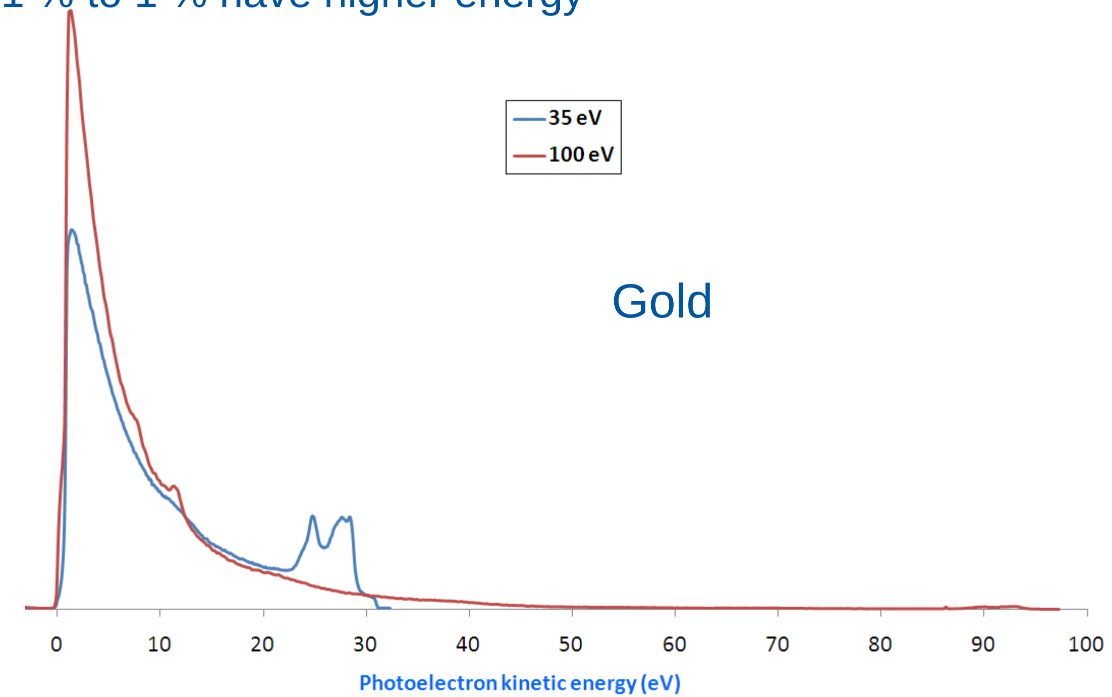


V. Anashin *et al.*,
Vacuum 53 (1-2), 269, (1999)

C. Photoelectrons

Photoelectrons

- **Photoelectric effect** : when a photons irradiates a surface with enough energy, it produces electrons
- The energy of emitted electrons varies from : 0 eV to ($h\nu - W_f$) eV
- Most of the electrons are secondary electrons (Ec < 20 eV) produced in the material
- A few 0.1 % to 1 % have higher energy



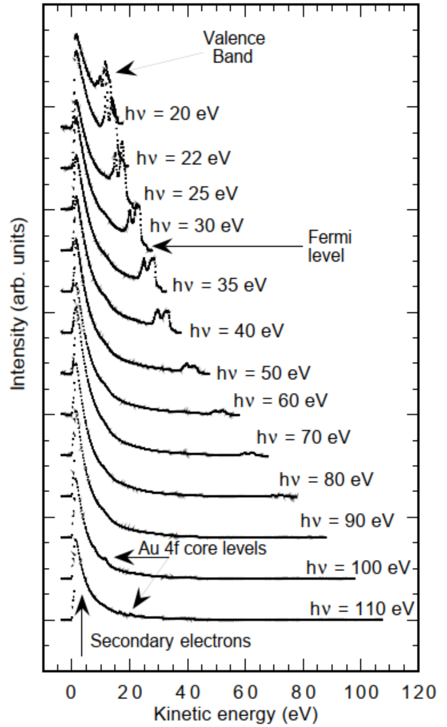
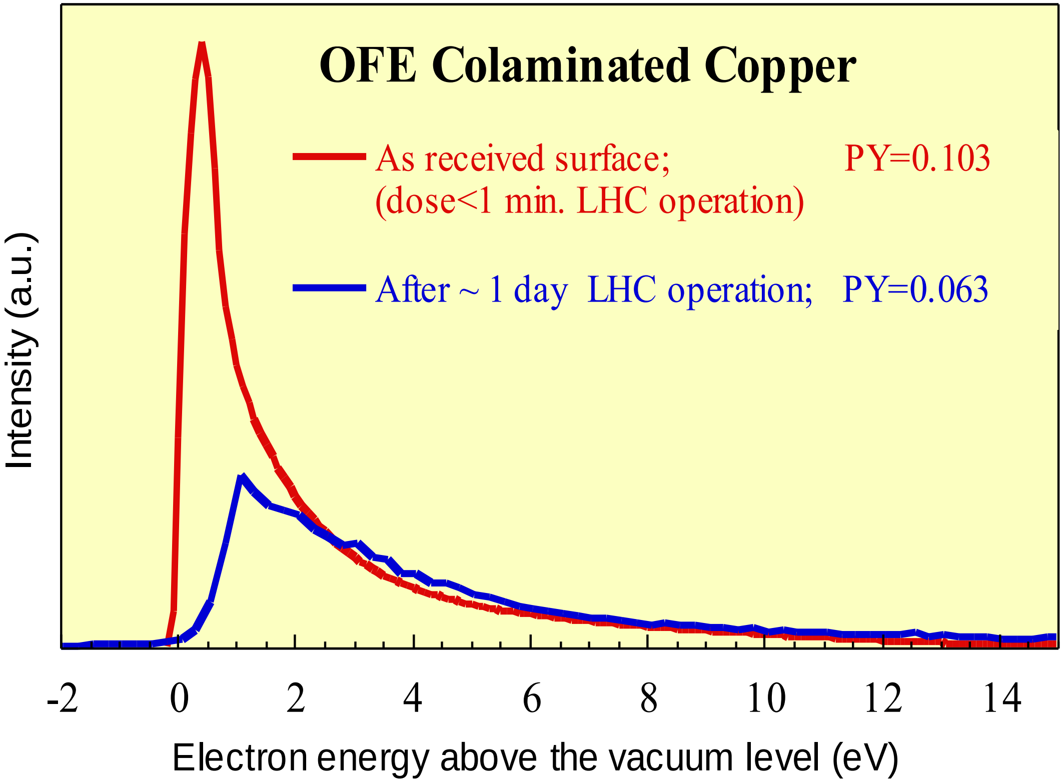


FIG. 3. A complete series of EDCs taken from the Au sample as a function of photon energy. Each EDC is shifted vertically for clarity.

R. Cimino *et al.* , Phys. Rev. ST Accel. Beams 2, 063201 (1999)

EDC under LHC SR irradiation

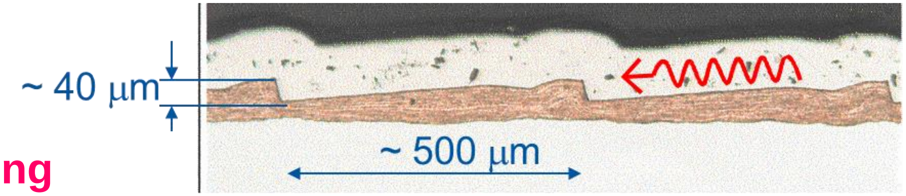
- EDC: Electron distribution curve
- SR dose reduce the amount of low energy photoelectrons
- The total yield is decreased by 40 % after 1 day of nominal LHC operation



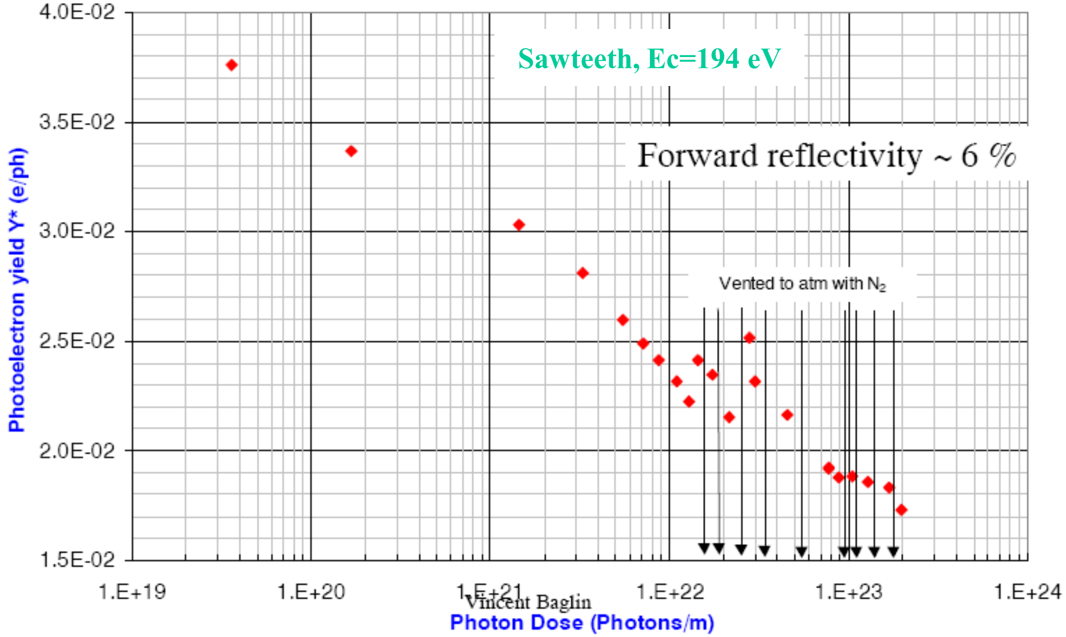
R. Cimino *et al.* Phys. Rev. AB-ST 2 063201 (1999)

Photoelectrons for a LHC type beam screen

- Sawtooth structure
- At 194 eV critical energy (“11.5 TeV LHC”)
- The Photoyield decrease with **beam conditioning**
- From 4 to 1 % under perpendicular incidence



Courtesy N. Kos CERN TE/VSC

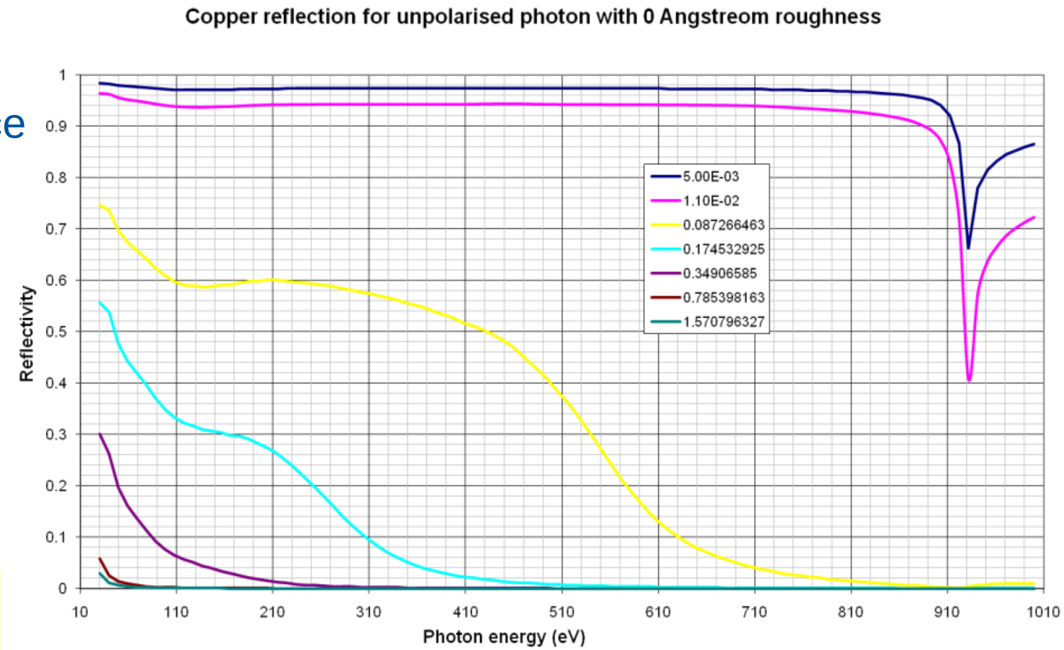


V. Baglin *et al.*, Chamonix, 2001

B. Reflectivity

Photon reflectivity

- From 1 to 80% forward reflectivity
- Low reflectivity at perpendicular incidence
- High reflectivity at grazing incidence *i.e.* this is the case of SR in accelerators
- In LHC, 5 mrad gives more than 95% reflection
- Copper adsorption at 920 eV

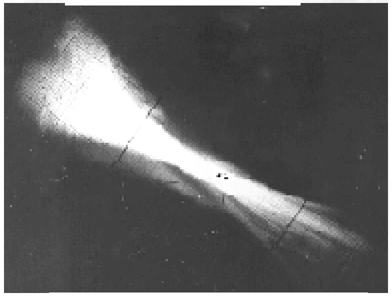


Henke databook

Material	Status	45 eV R (%)	194 eV R (%)
Cu roll bonded	as-received	80.9	77.0
Cu roll bonded air baked	as-received	21.7	18.2
Cu electroplated	as-received	5.0	6.9
Cu sawtooth	as-received	1.8	-
	150°C, 9 h	1.3	1.2
	150°C, 24 h	1.3	1.2
TiZr film	as-received	20.3	17.1
	120°C, 12 h	19.5	16.7
	250°C, 9 h	19.9	17.4
	350°C, 10 h	20.6	16.9
	CO saturated	20.7	-

V. Baglin *et al.*, Trieste, 1998

DCI, Ec=3 keV



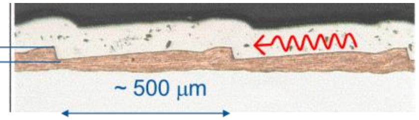
O. Gröbner *et al.*, 24-4-1988

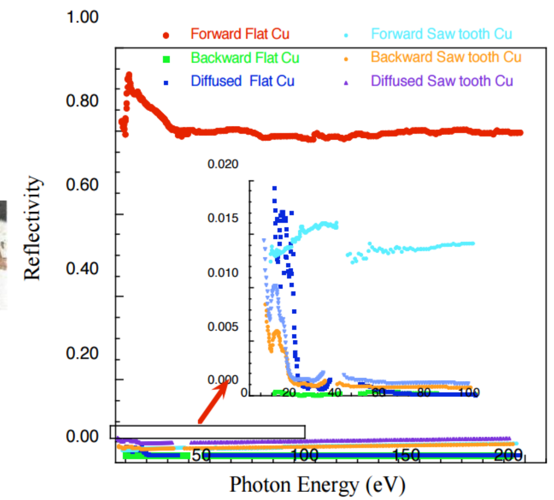
➔ In complex geometries, ray tracing is done with e.g. SynRad

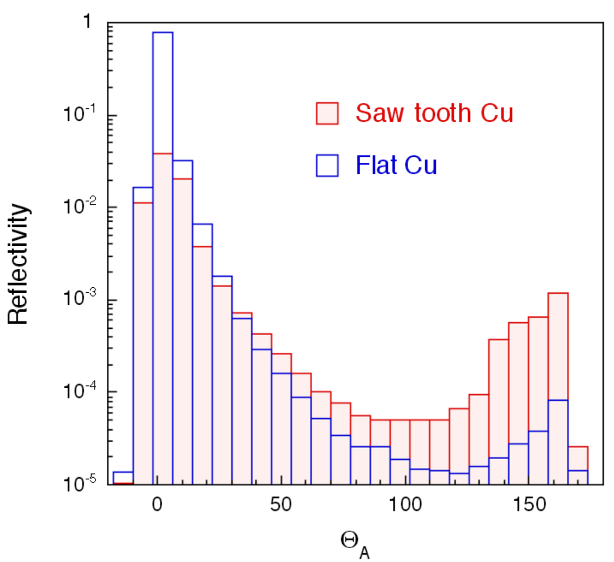
Photon reflectivity of LHC type material

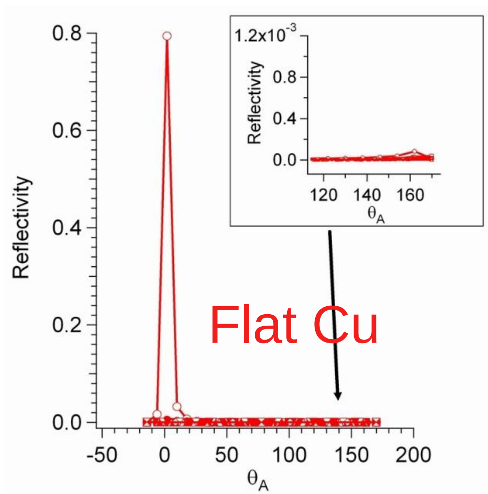
- The saw tooth structure reduces the forward reflectivity but increases diffused reflectivity

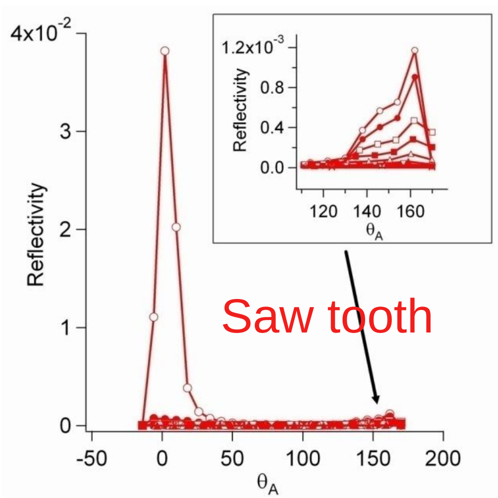
	Flat sample	Saw-tooth sample
Forward scattering	80 %	4 %
Back scattering	0 %	2 %
Diffused	2 %	4 %
Total	82 %	10 %







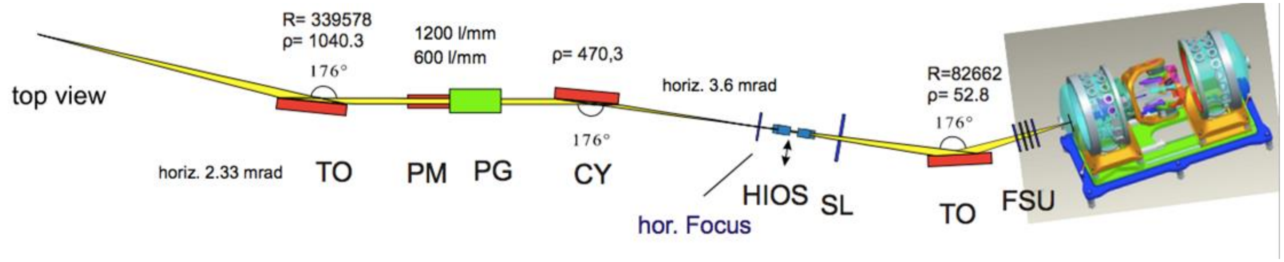




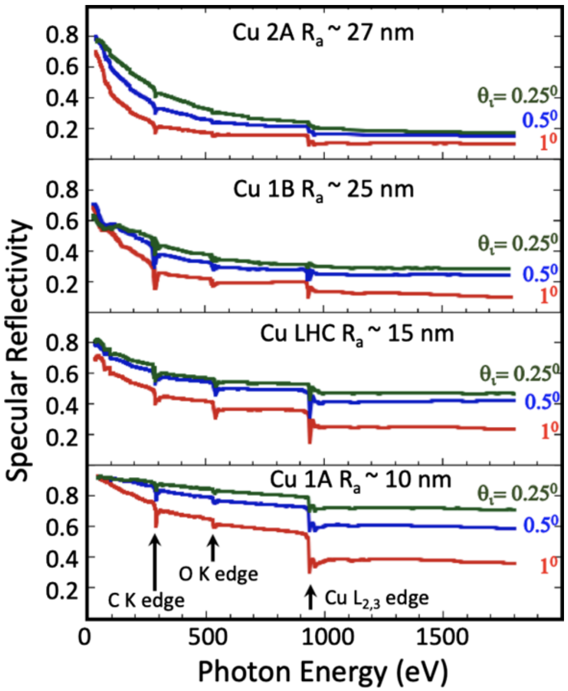
N. Mahne *et al.* App. Surf. Sci. 235, 221-226, (2004)

Refined reflectivity measurements

- Dedicated instrument for 3D mapping of photon interaction with matter at BESSY-II synchrotron



- LHC:
  - Roughness ~ 15 nm,
  - Incidence angle 4 mrad (=0.25˚)
- FCC hh or ee:
  - Incidence angle 2 mrad
- Forward reflectivity: 0.2-0.9 in a wide photon range
- Surface roughness is a key factor



E. La Francesca et al. Phys. Rev. Accel. Beams 23, 083101 (2020)

D. Photoionisation

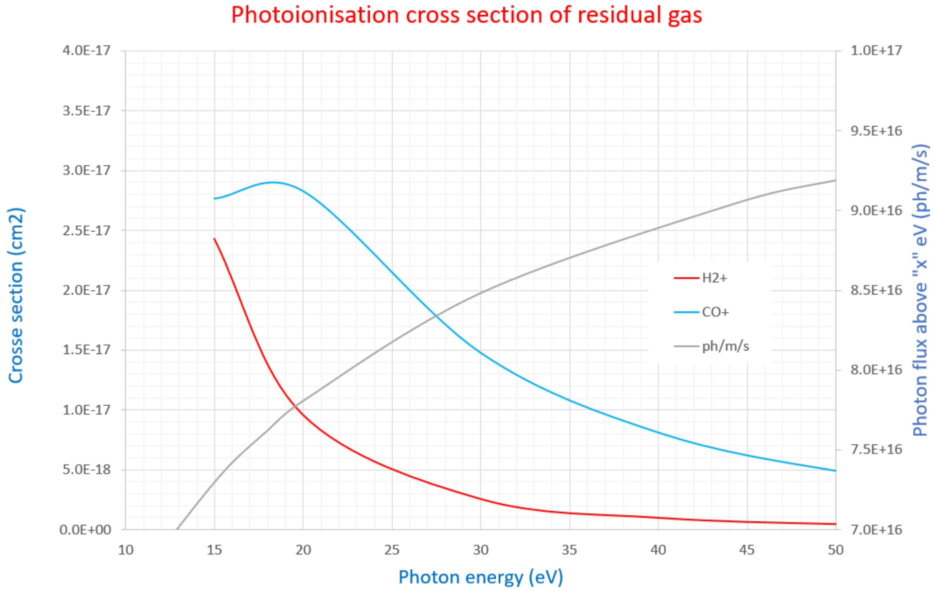
Photoionisation of residual gas

- Ionisation threshold ~ 15 eV

- cross section ~ 10^{-21} m^2
  - Range 15-30 eV

- Photon flux in the range ~ 10^{16} ph/m/s
- Path length ~ 10 m
  - $\dot{\Gamma} L$ ~ 10^{17} ph/s

- Gas density: 10^{15} H_2/m^3 (4 10^{-8} mbar)



Y. Miyahara. Jap. J of Appl. Phys. 26 (1987) 1544-1546

$$\dot{\Gamma}_{\text{ion, ph}} = \sigma_{ion,ph} \dot{\Gamma} L \text{n} \;\cong\; 2\;10^{11}\ \text{ions/m/s}$$

- Remark: Ionisation of the residual gas by the 7 TeV proton beam

$$\dot{\Gamma}_{\text{ion, proton}} = \sigma_{ion,proton} \frac{I}{e} \text{n}$$

  - cross section ~ 10^{-22} m^2
  - for LHC: I = 0.6 A; I/e ~ 4 10^{18} proton/s; so:

$$\frac{\dot{\Gamma}_{\text{ion, ph}}}{\dot{\Gamma}_{\text{ion, proton}}} = \frac{\sigma_{ion,ph}}{\sigma_{ion,proton}} \frac{\dot{\Gamma} L}{I/e} \cong \frac{1}{4}$$

Conclusion

- Synchrotron radiation is emitted in the magnetic field in a highly peaked vertical angle;

- SR is characterised by the critical energy, power and photon flux

- The photon energy spans from IR to UV (in LHC) and X-rays, gamma rays for FCCs
  - Photon flux and power have significant impact on the machine design

- Photons irradiating a surface:
  - emit photoelectrons
  - stimulate molecular desorption
  - may be reflected

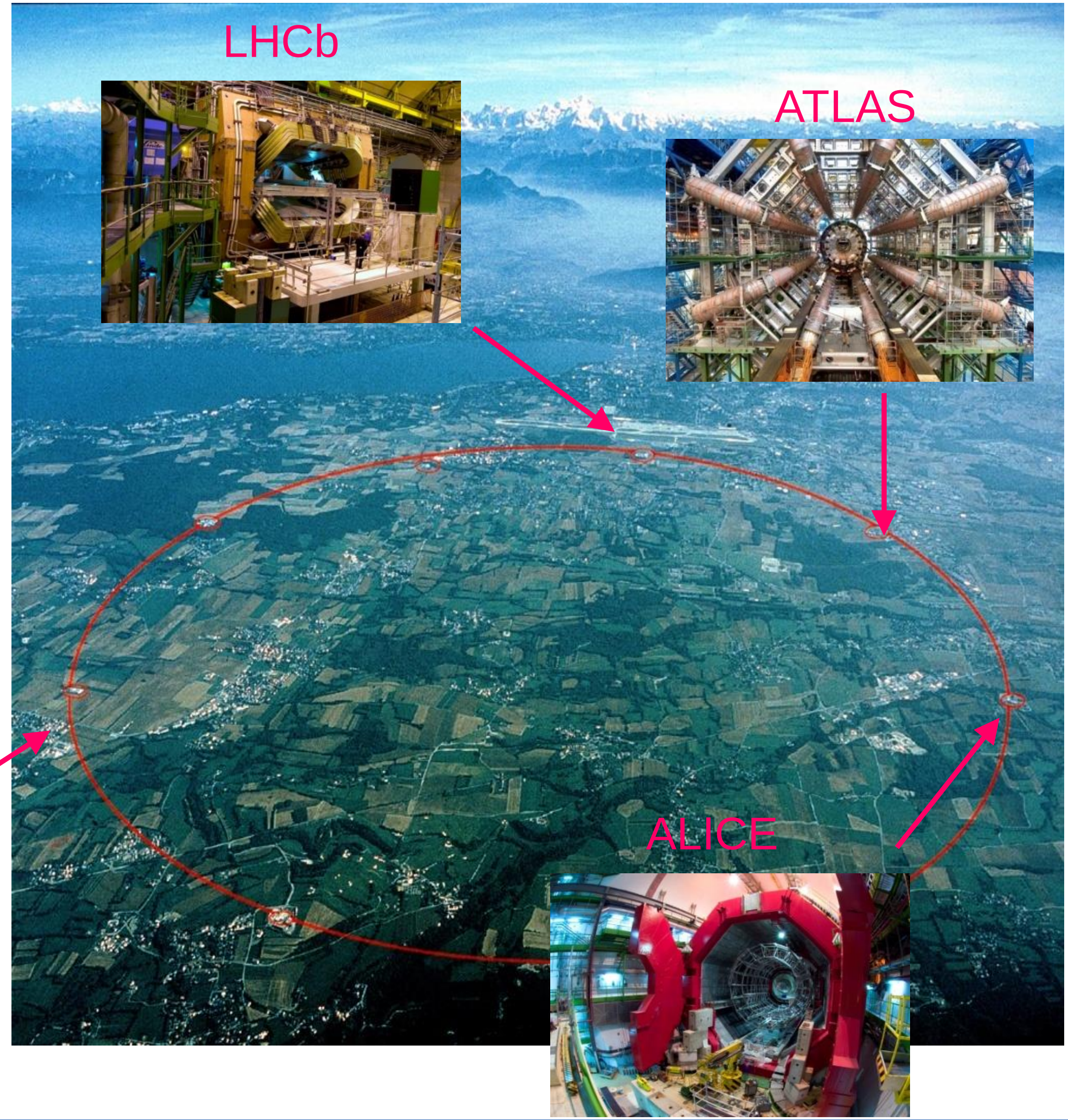
- Photons ionise the residual gas along their path

Thank you for your attention !!!

Back up slides

The CERN Large Hadron Collider (LHC)

- 26.7 km circumference
- 8 arcs of 2.8 km
- 8 long straight sections of 575 m
- 4 experiments
- 7 TeV / beam
- 90% of the machine is held at cryogenic temperature: 1.9-20K



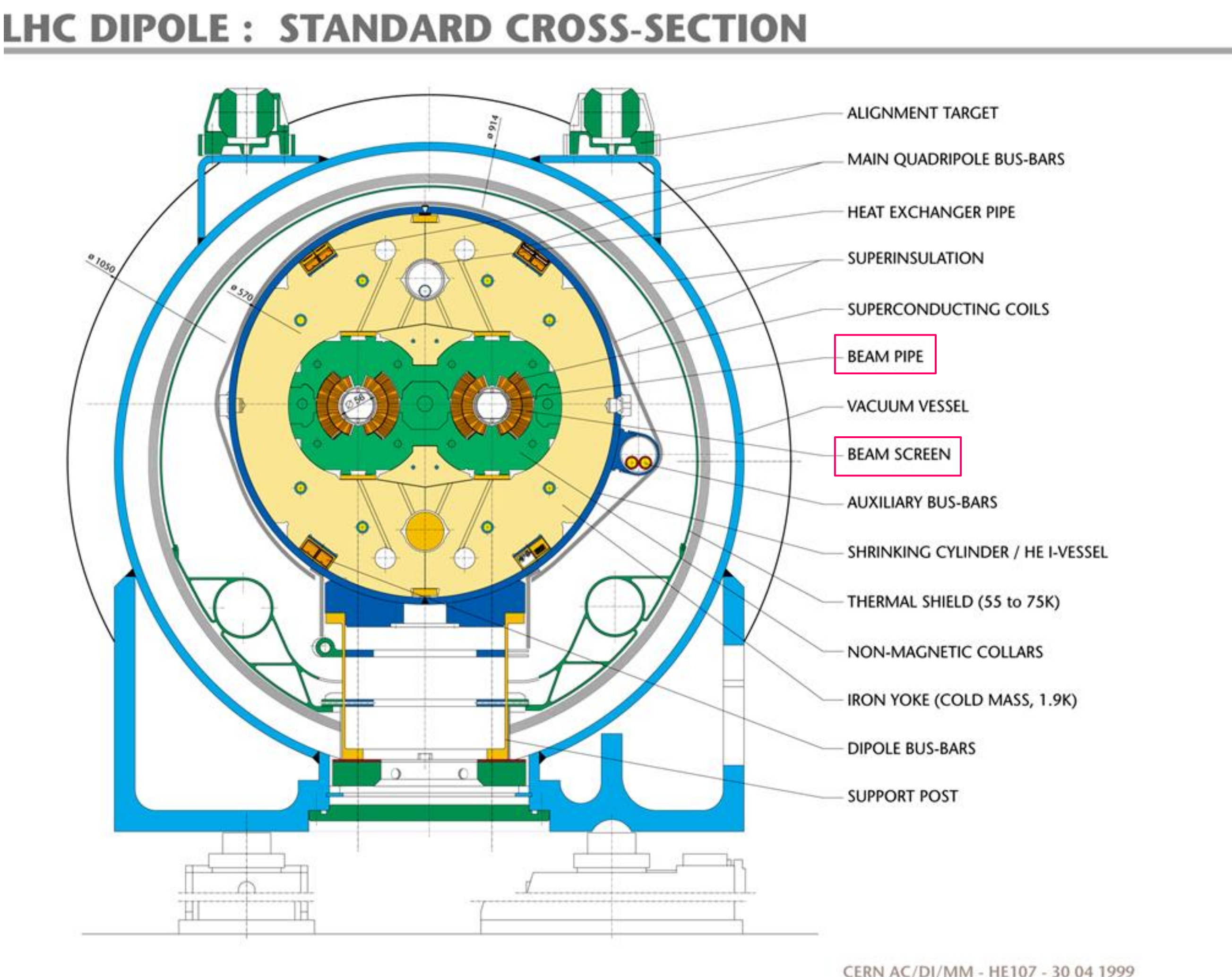
CMS

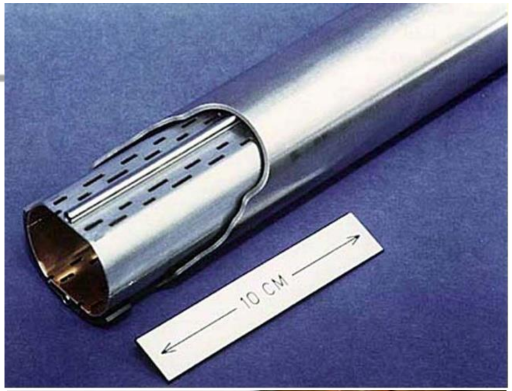
LHC Nominal Design Parameters

Circumference	26.7	km
Beam energy at collision	7	TeV
Beam energy at injection	0.45	TeV
Dipole field at 7 TeV	8.33	T
Luminosity	1×10^{34}	$cm^{-2}.s^{-1}$
Beam current	0.584	A
Protons per bunch	1.15×10^{11}	
Number of bunches	2808	
Nominal bunch spacing	24.95	ns
Normalized emittance	3.75	μm. rad
Total crossing angle	285	μrad
Energy loss per turn	6.7	keV
Critical synchrotron energy	44.1	eV
Radiated power per beam	3.6	kW
Stored energy per beam	362	MJ
Stored energy in magnets	11	GJ
Operating temperature	1.9	K

LHC Dipole Vacuum System

- Cold bore (CB) at 1.9 K which ensures leak tightness
- Beam screen (BS) at 5-20 K which intercepts thermal loads (~ 1.4 kW/arc for SR + Resistive wall)



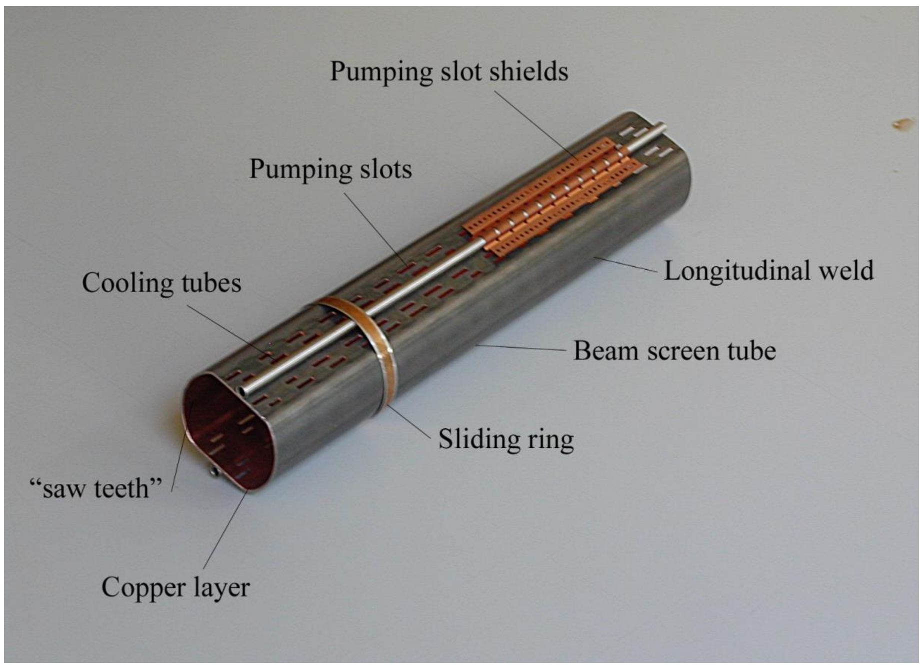


Courtesy N. Kos CERN AT/VAC

LHC Beam Screens Functionalities

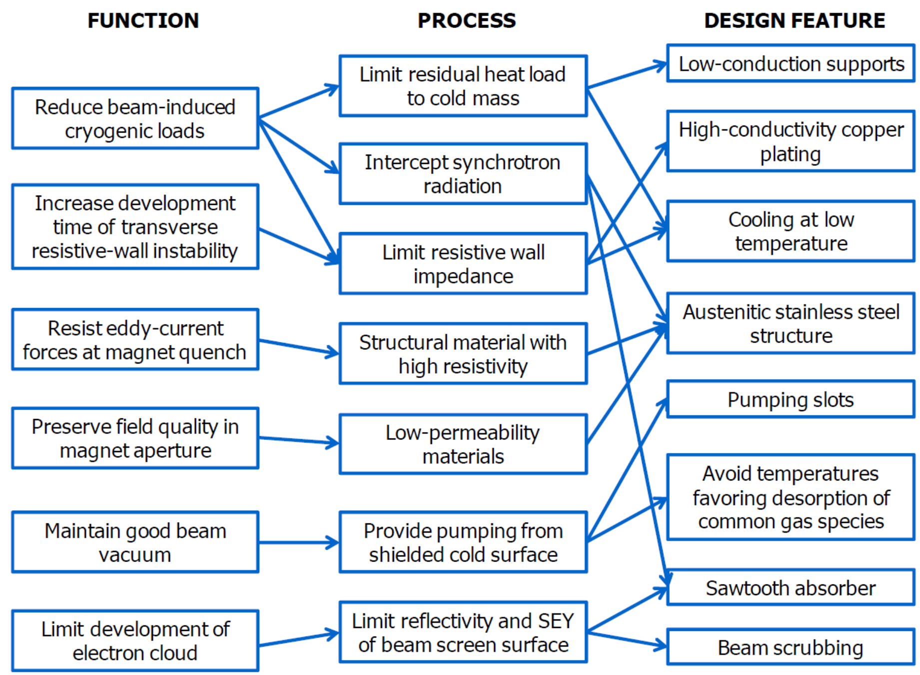
- An innovative and complex system, produced at several 10 km scale !

- Intercept the heat load induced by the circulating beam (impedance, synchrotron radiation, electron cloud)
- Operate between 5 and 20 K (high RRR)
- Pumping holes to control the gas density



Courtesy N. Kos CERN TE/VSC

Functional design map of beam screen



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LHC Vacuum System Principle

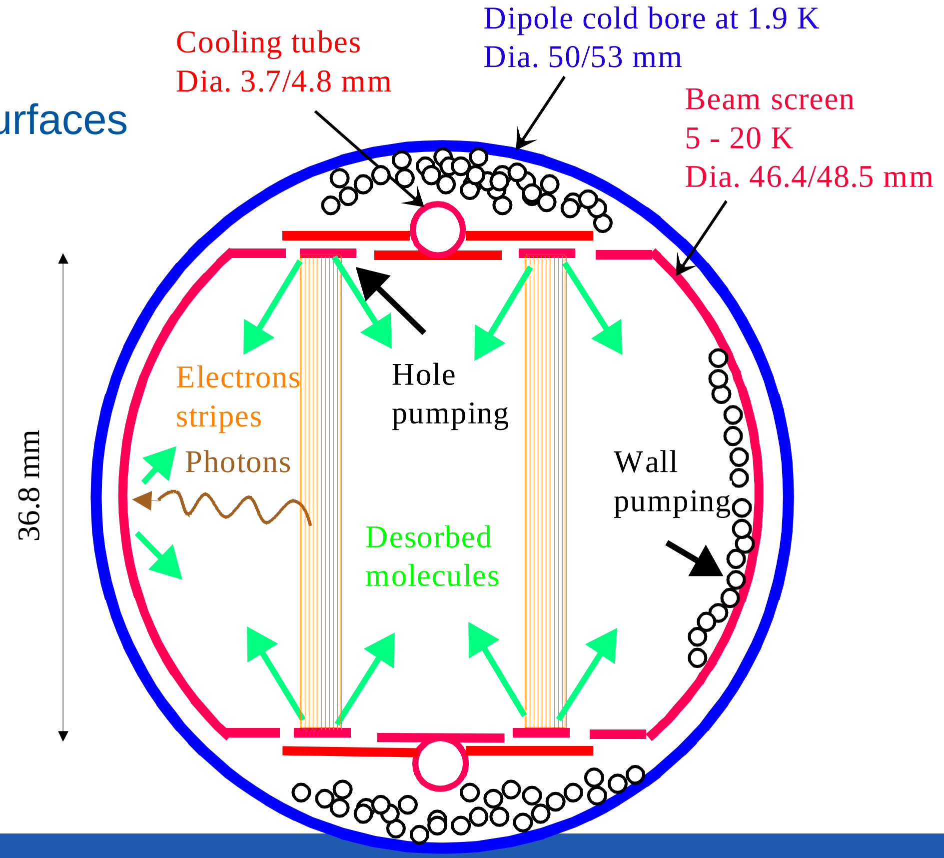
- Molecular desorption stimulated by photon, electron and ion bombardment
- Desorbed molecules are pumped on the beam vacuum chamber
- 100 h beam life time (nuclear scattering) equivalent to ~ 10^{15} H_2/m^3 (10^{-8} Torr H_2 at 300 K)

In cryogenic elements

- Molecular physisorption onto cryogenic surfaces (weak binding energy)

- Molecules with a low recycling yield are first physisorbed onto the beam screen (CH_4, H_2O, CO, CO_2) and then onto the cold bore

- H_2 is physisorbed onto the cold bore



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