CERN LEP3 MINI-WORKSHOP

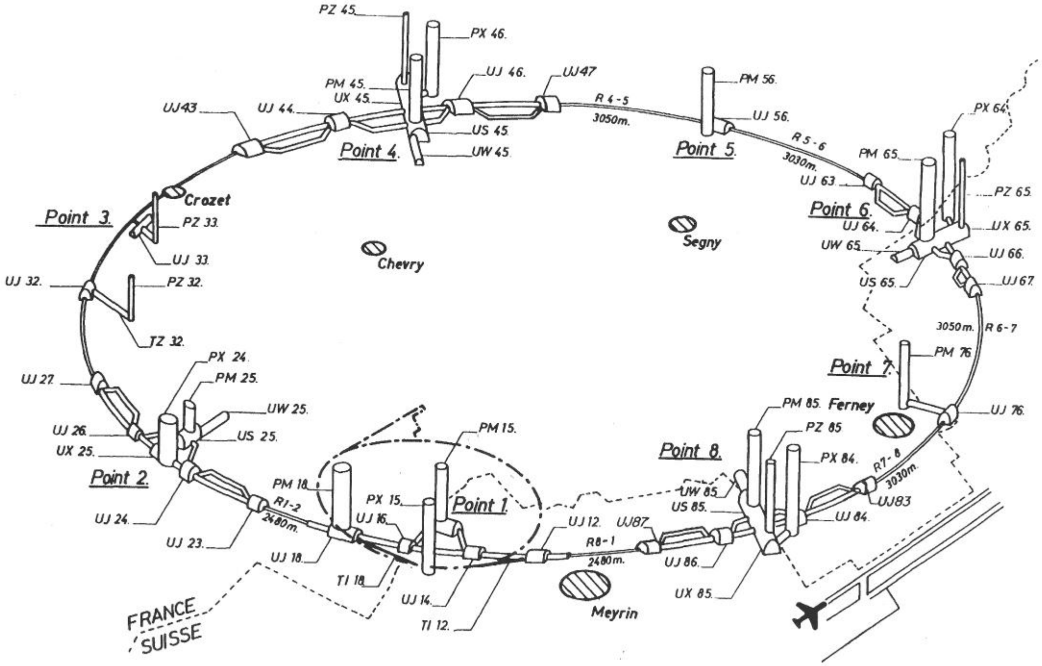
A brief recall of the LEP (radiation) history

(out of my memory and published papers)

Marco SILARI, ***DGS/RP***

Parameter	LEP1 (51.5 GeV)	LEP2 (100 GeV)	LEP3 (120 GeV)
Critical SR energy (keV)	98	716	1400
Radiated power, two beams (W/m)	62	1613	6000
Total SR power (MW)	1.2	22	100
E_{acc} [MV/m]		7.5	20
Effective RF length [m]		485	600
Beam current (mA)		4	7.2

A brief recall of LEP operational history



Typical maximum current per beam: 5 mA

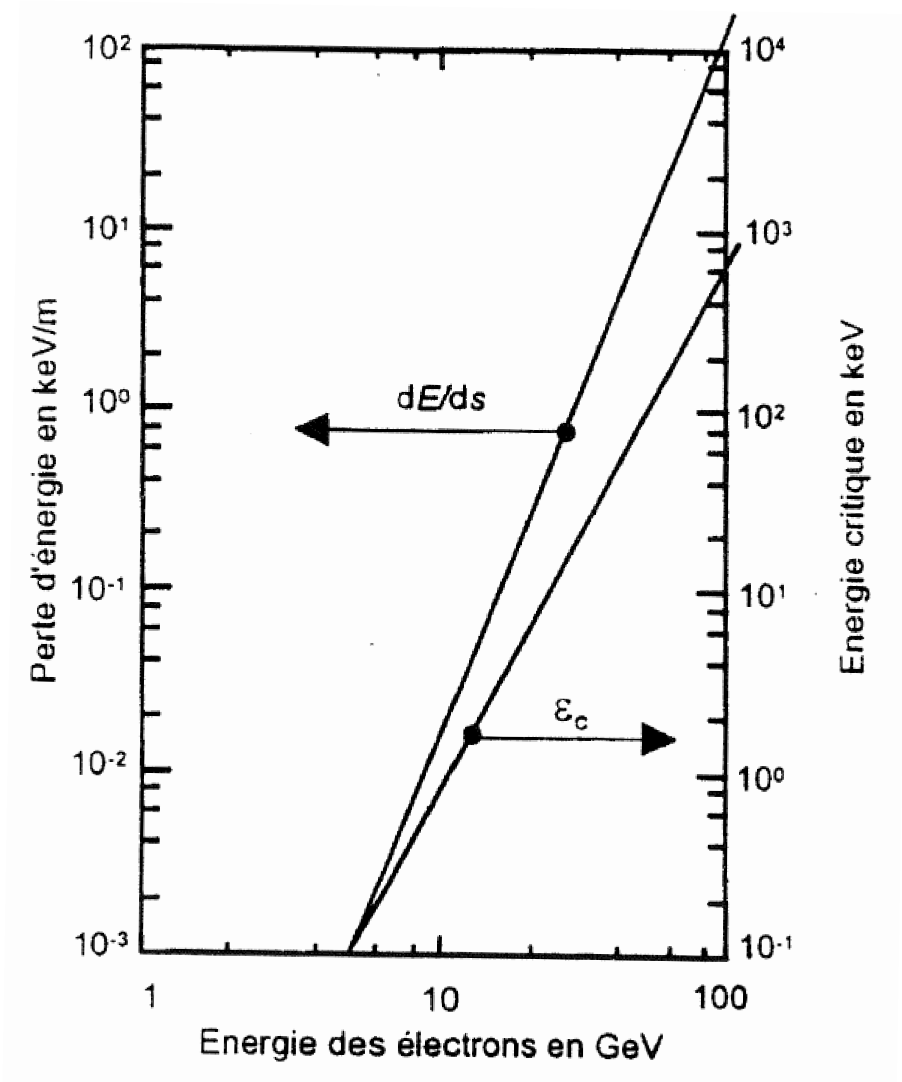
Coasting was lasting several hours

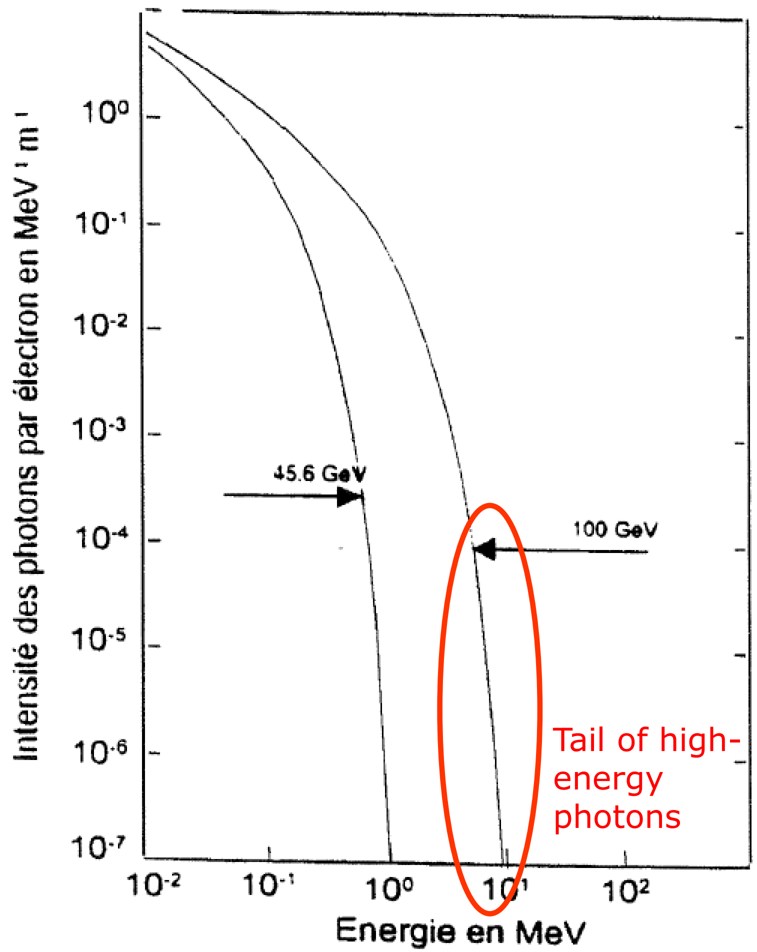
Total average beam current: 4 – 6 mA

- Start of operation: 1989
- 1989-95: 45 GeV per beam
- October 1995: 68 GeV
- June 1996: 80.5 GeV
- October 1996: 86 GeV
- 1997: 92 GeV
- 1998: 94.5 GeV
- 1999: 100 GeV
- 2000: 104 GeV

- Bremsstrahlung photons (from beam losses)
- Synchrotron radiation
  - The linear rate of energy loss increases with the E_e^4
  - The critical energy increase E_e^3
- Neutrons from photonuclear reactions
- Bremsstrahlung photons and neutrons from the operation of the s.c. RF cavities

Synchrotron radiation (up to 100 GeV)





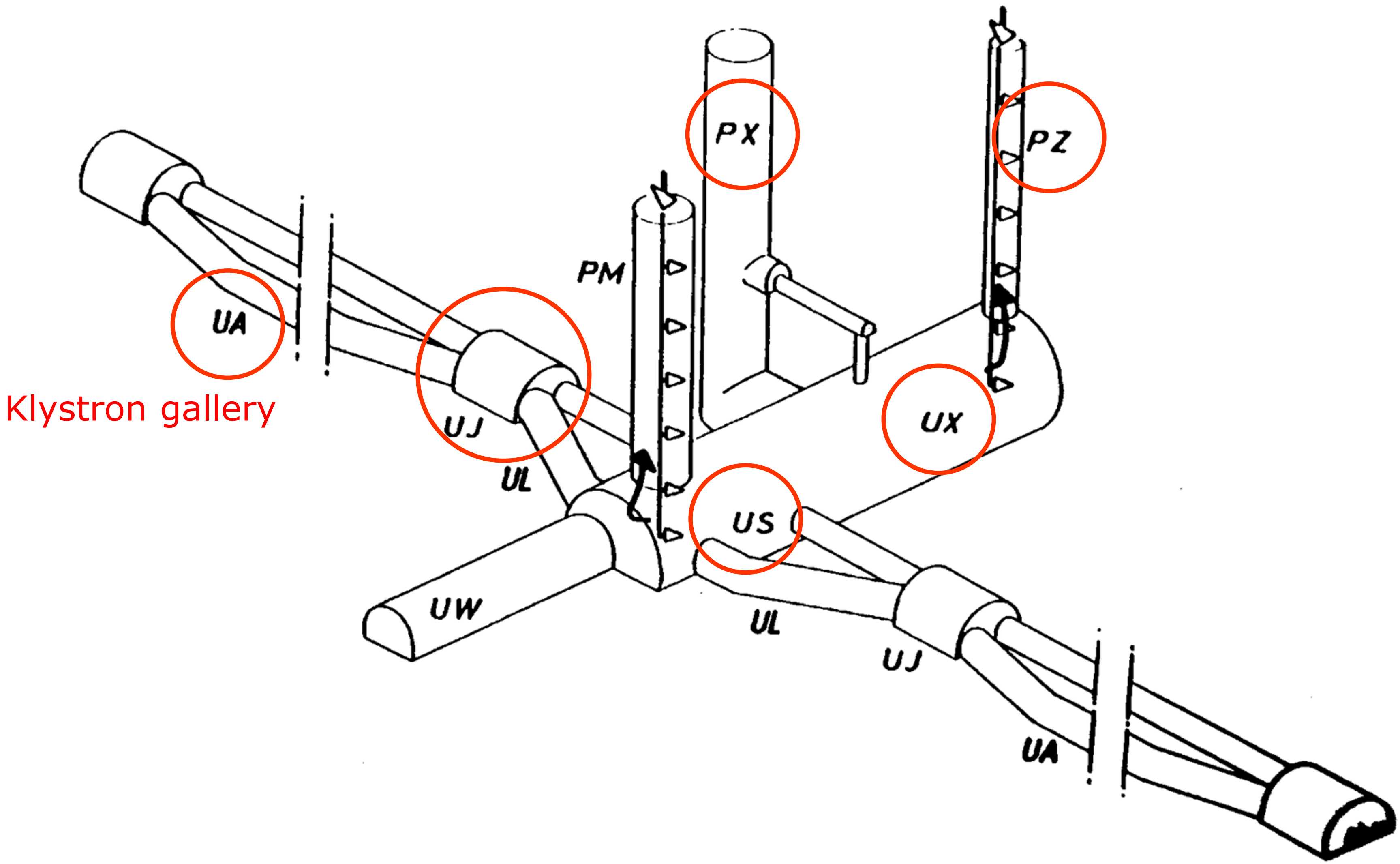
From the *Rapport définitif de sûreté* du LEP (1994)

Radiation issues

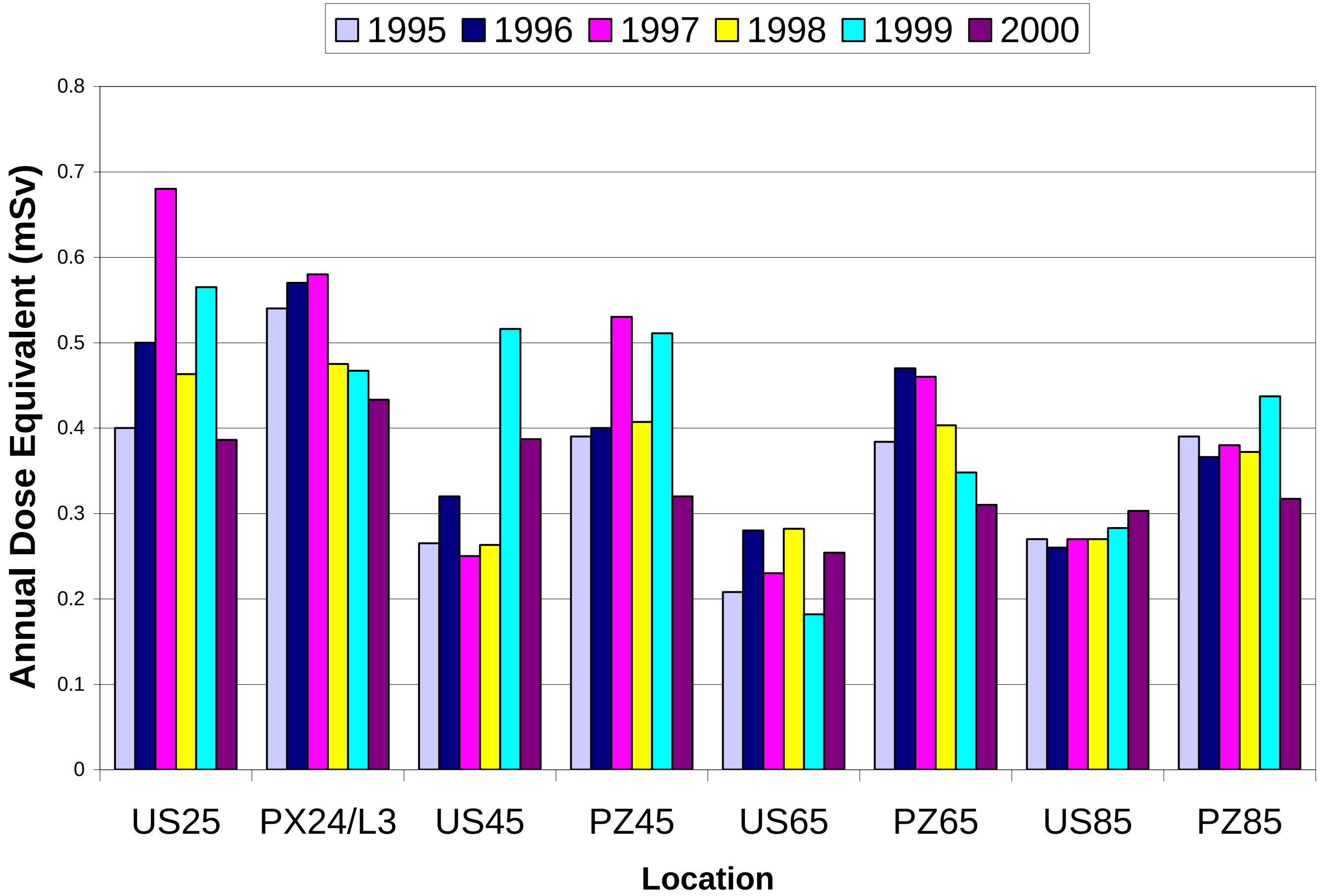
- Radiation shielding
  - Radiation doses on ground surface
  - Radiation doses in the underground accessible areas
- Synchrotron radiation and dose rates in the arcs during operation
- Radiation damage to equipment
- Transmission of radiation through ducts and labyrinths
- Radiation from the superconducting RF cavities
- Induced radioactivity (in the machine and in the experiments)
  - *Increased SR may play a major role in LEP3 versus LEP2*
  - Maintenance
    (including shipping of equipment outside CERN for repair)
  - Production of radioactive waste
  - Final decommissioning
  - *Induced activity in the cooling water was not a problem in LEP*

Radiation design studies may be needed for the SPS (and possibly PS)

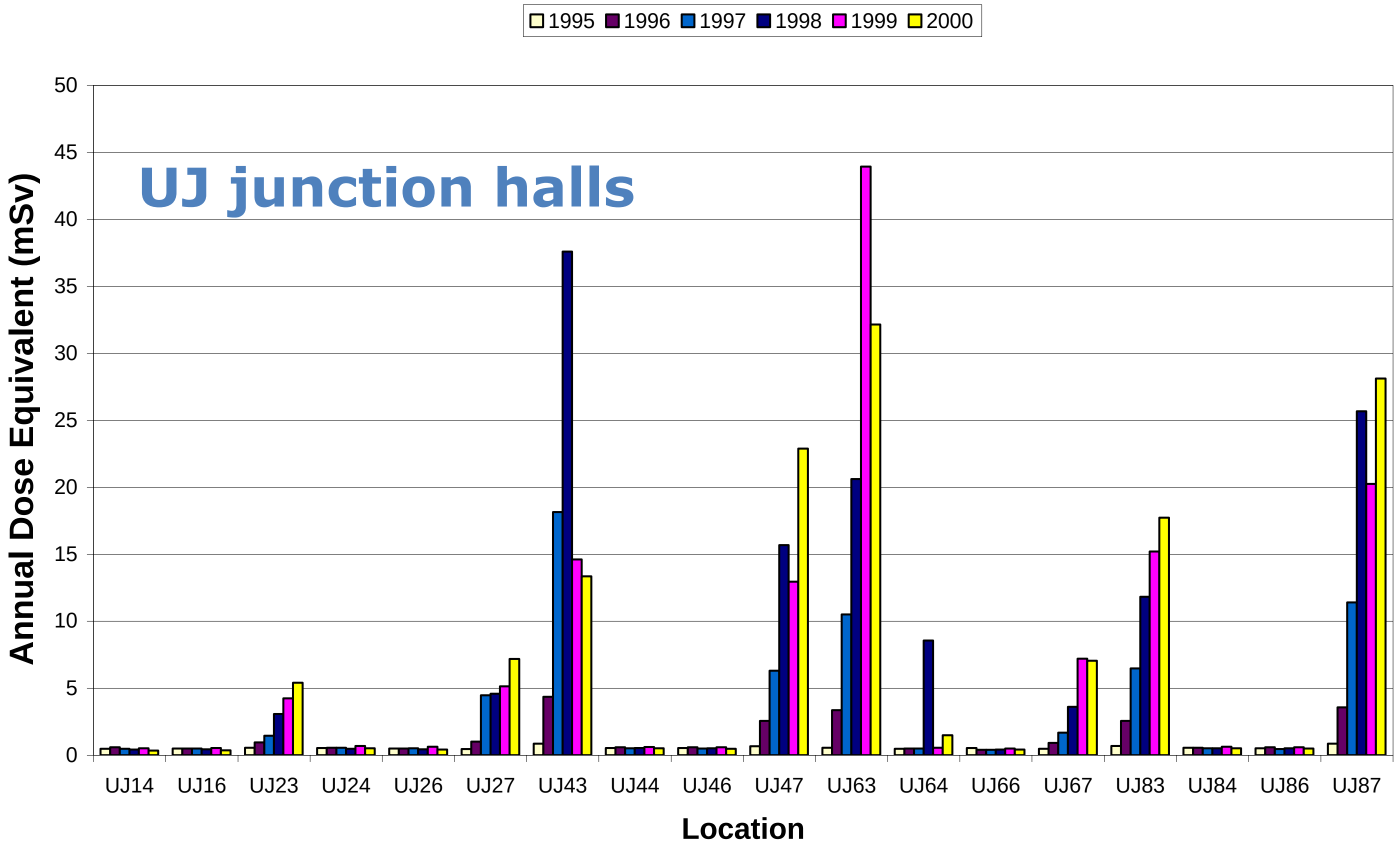
The underground LEP areas



Radiation doses (photons) in the underground areas

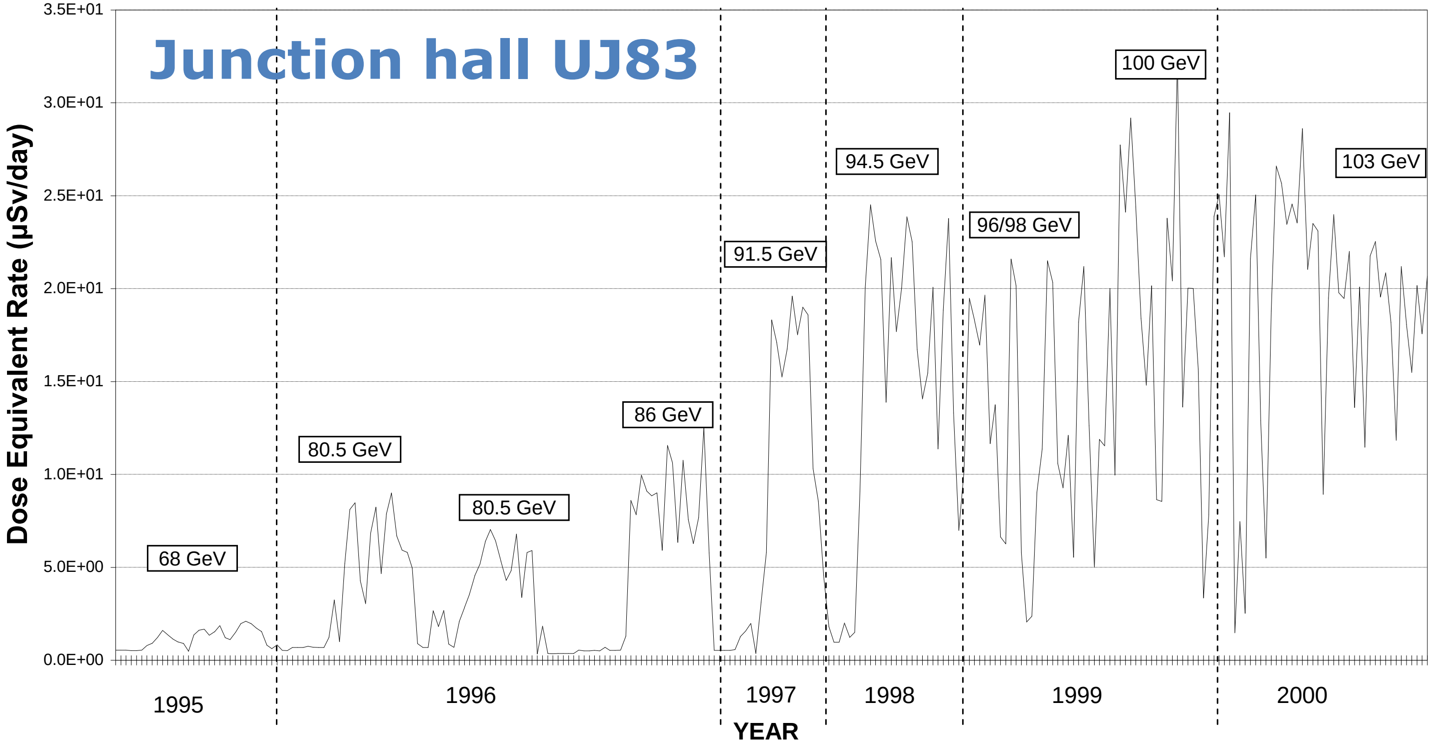


Radiation doses (photons) in the underground areas



UJ23, 27, 43, 47, 63, 67, 83 and 87 were close to the arcs , see the influence of the SR increase with beam energy

Radiation doses in the underground areas



Data are µSv per day, normalised to 1 mA total current of the circulating beams

Radiation levels in the LEP2 period (45 → 105 GeV)

Annual dose equivalent in the areas occupied by physicists in the experimental halls

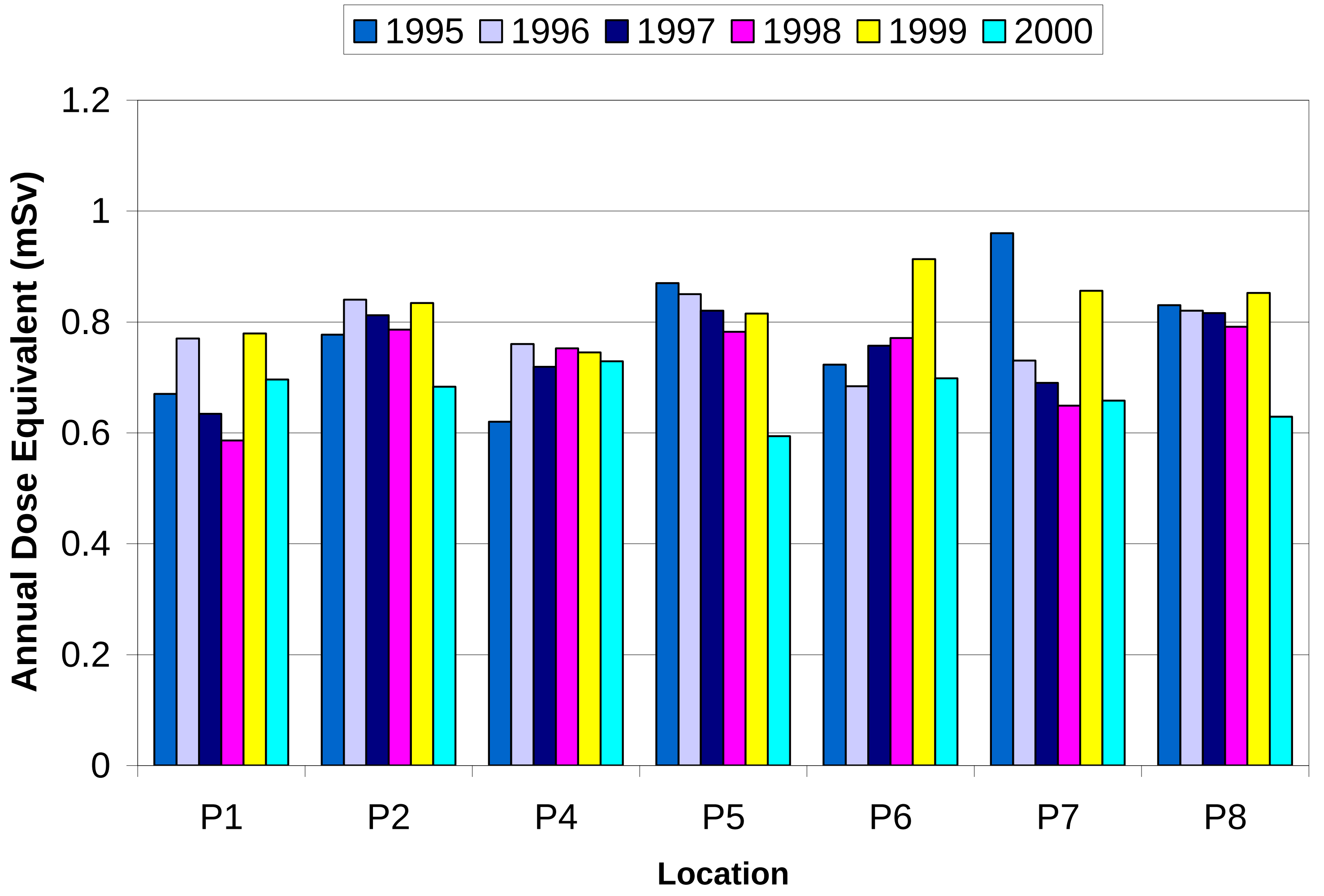
Year	Annual dose equivalent (mSv)		
	ALEPH	OPAL	DELPHI
1990	0.08 - 0.32	0.11 - 0.40	0.11 - 0.41
1991	0.17 - 0.32	0.21 - 0.40	0.08 - 0.41
1992	0.26 - 0.43	0.16 - 0.30	0.08 - 0.94
1993	0.29 - 0.46	0.26 - 0.37	0.15 - 0.36
1994	0.17 - 0.34	0.19 - 0.32	0.10 - 0.98
1995	0.17 - 0.40	0.18 - 0.30	0.14 - 0.33
1996	0.21 - 0.55	0.19 - 0.31	0.13 - 0.30
1997	0.06 - 0.41	0.20 - 0.38	0.13 - 0.48
1998	0.21 - 0.35	0.19 - 0.29	0.10 - 0.31
1999	0.19 - 0.51	0.16 - 0.50	0.14 - 0.52
2000	0.15 - 0.27	0.18 - 0.28	0.09 - 0.25

Annual dose equivalent at the bottom of the access pits PX

Year	Annual dose equivalent (mSv)			
	ALEPH PX46	OPAL PX64	DELPHI PX84	Surface
1990	0.40	0.40	0.41	0.80
1991	0.48	0.51	0.49	0.87
1992	0.46	0.44	0.41	0.90
1993	0.55	0.52	0.52	0.89
1994	0.41	0.37	0.39	0.83
1995	0.45	0.47	0.46	0.94
1996	0.48	0.47	0.45	0.75
1997	0.43	0.49	0.44	0.85
1998	0.47	0.43	0.43	0.81
1999	0.50	0.50	0.52	0.83
2000	0.39	0.39	0.36	0.68

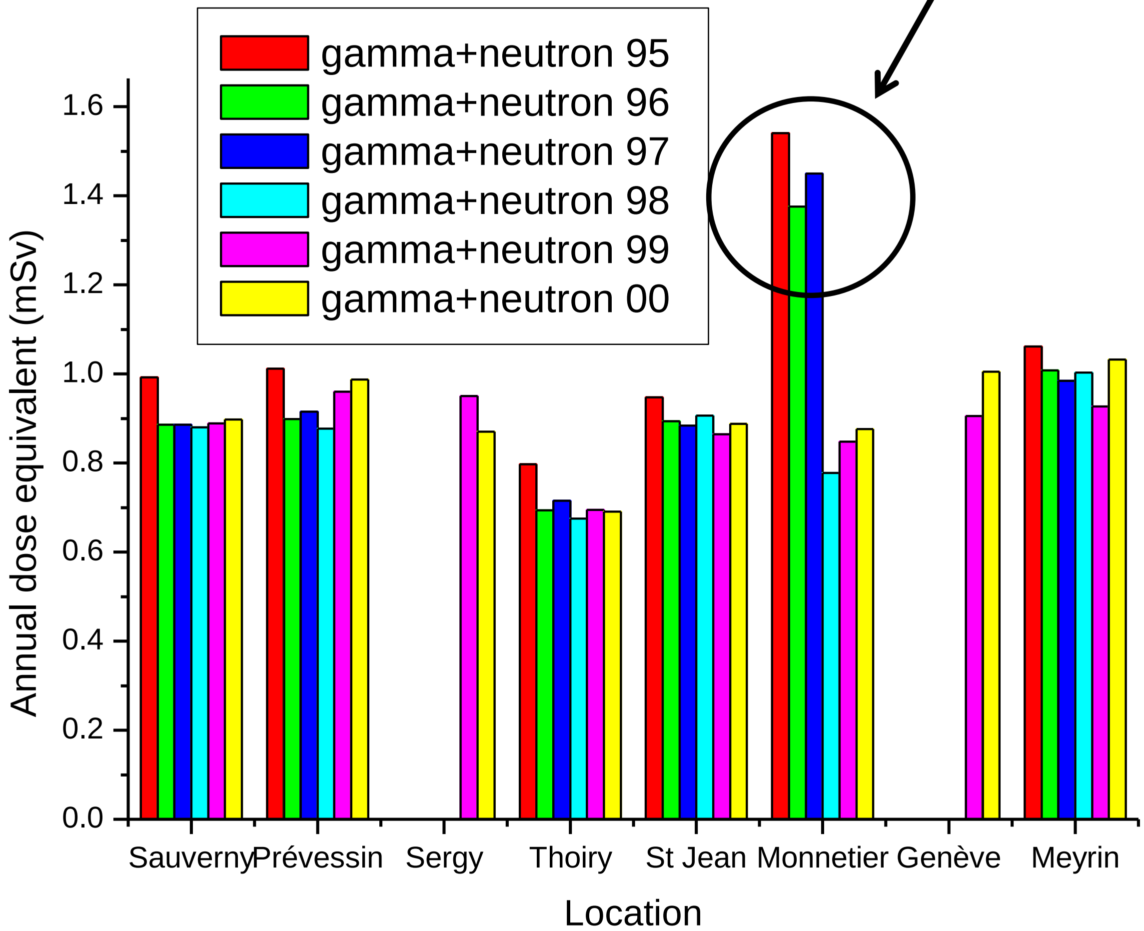
Annual dose equivalent in the underground 1/3 to 1/2 of values on ground surface

Radiation levels on ground surface at the eight LEP access points

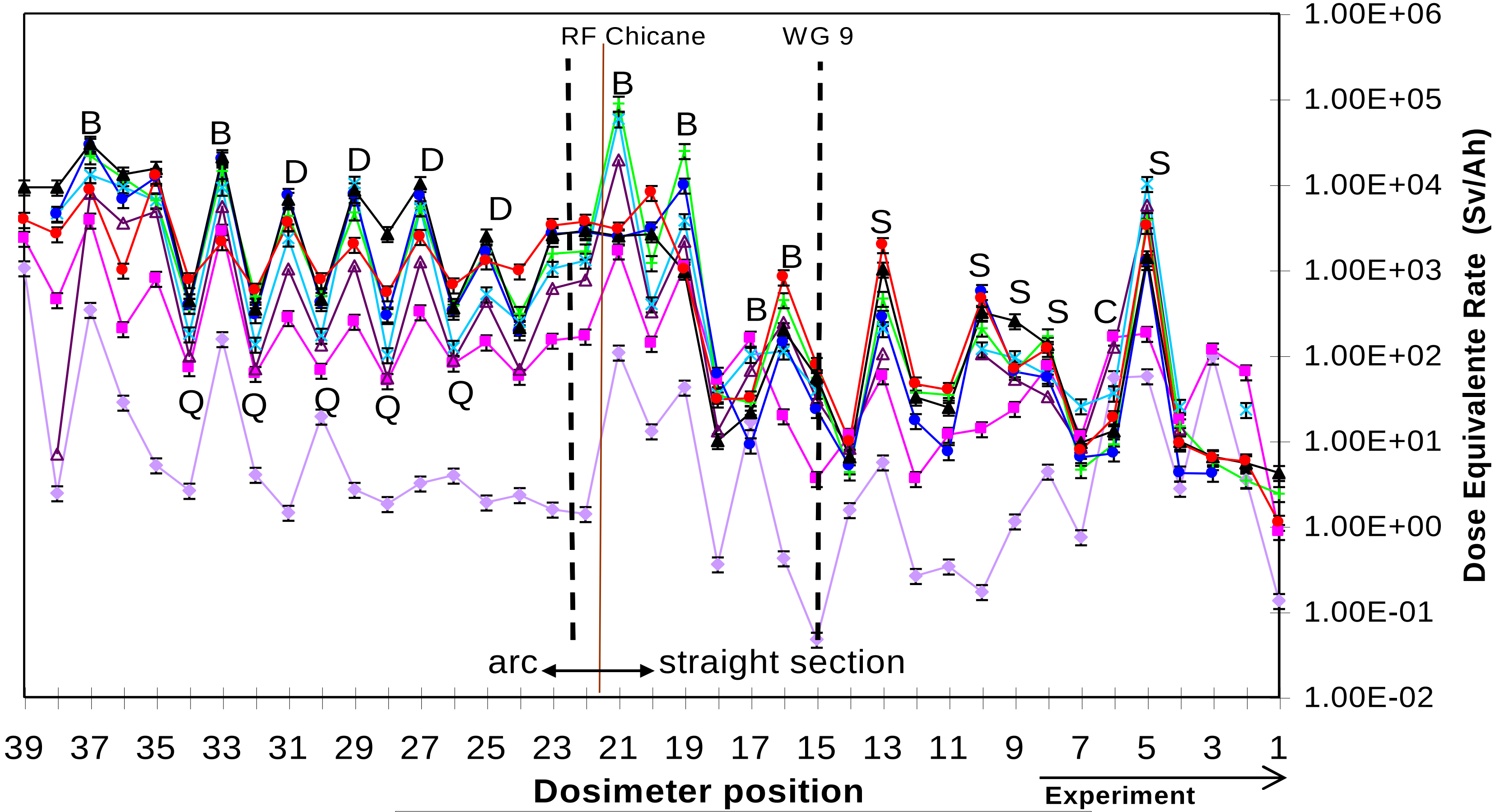


Radiation levels on ground surface around LEP

Radon (TLDs placed inside an ancient house with stone walls)



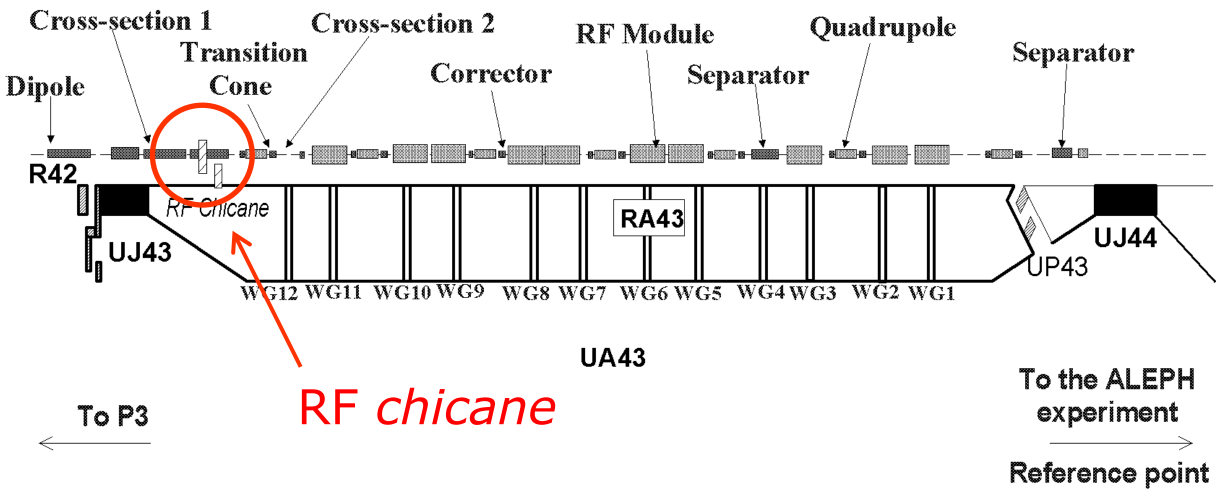
Radiation measurements in the arc and in the adjacent straight section

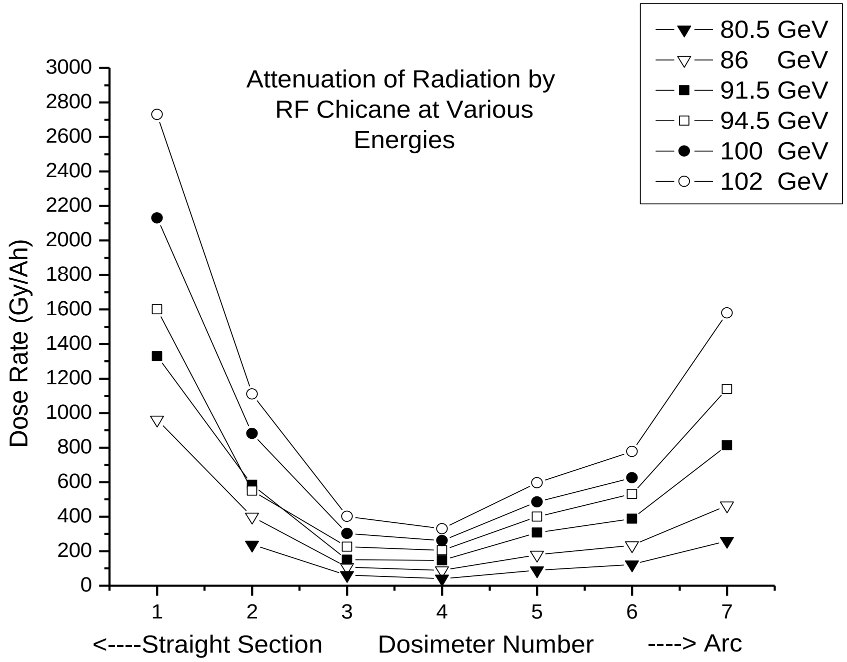


C = Collimator
S = Superconducting RF module

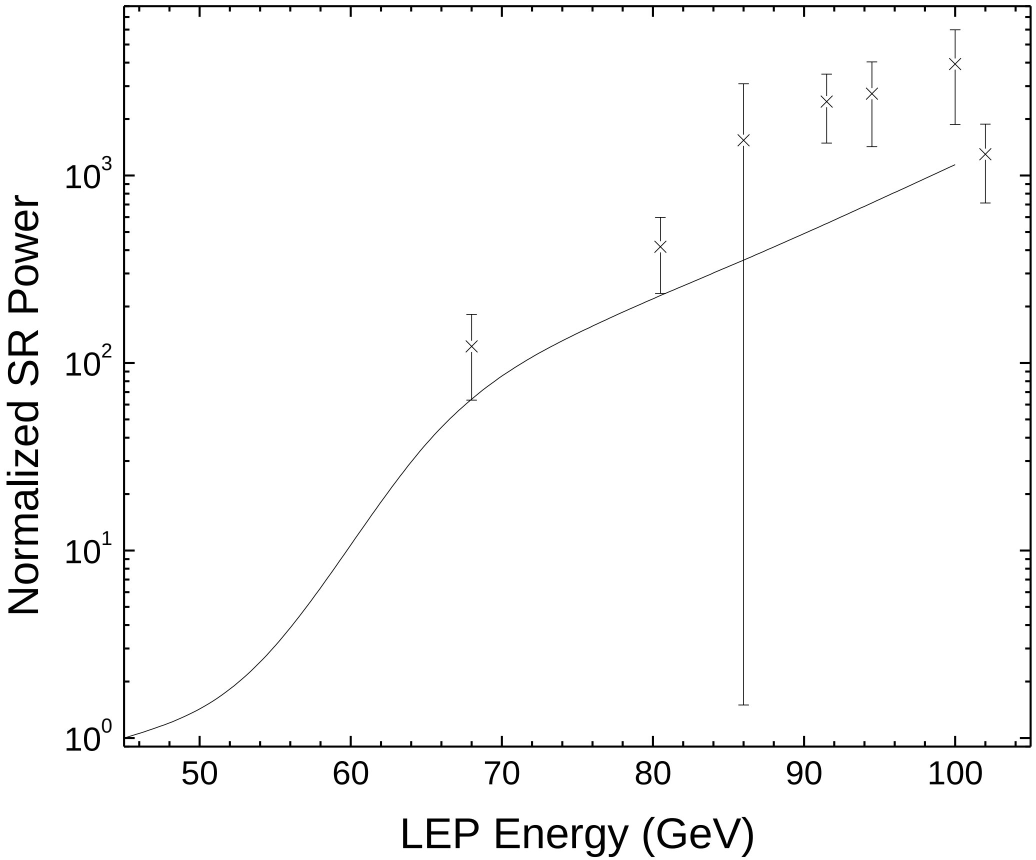
Q = Quadrupole
B = Bellow
D = Dipole

Radiation measurements in the arc and in the adjacent straight section





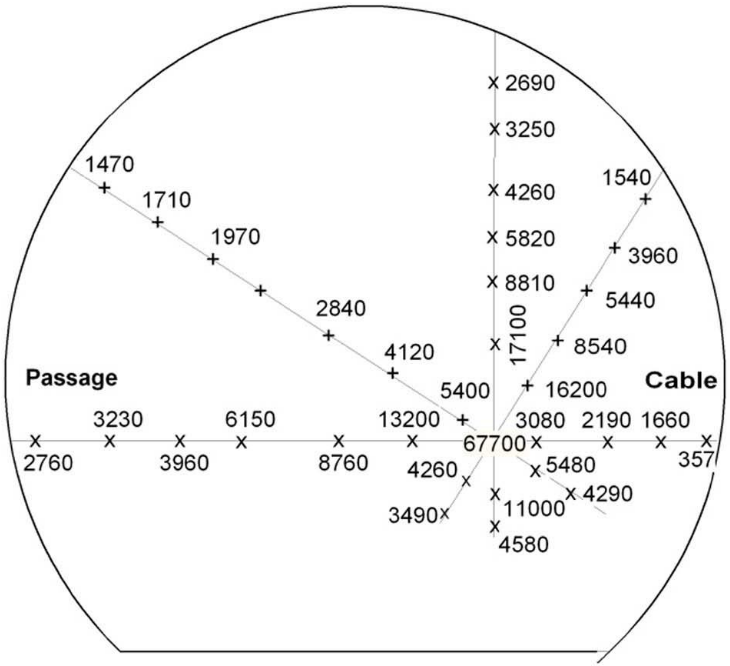
- The experimental data are the average of the integrated doses recorded with the PADs placed close to the dipoles
- Experimental data systematically overestimate the predictions by about a factor of 3 (except at 103 GeV)



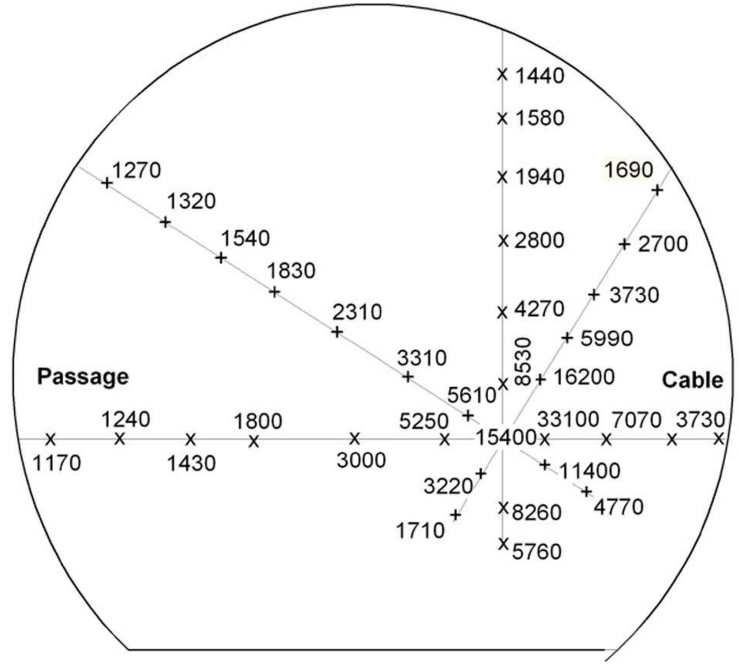
Normalized radiation levels (dose/integrated current) in the arcs increased up to the ninth power of the lepton energy:

- SR raises with 4th power or energy
- Energy of emitted X-rays increases with energy, making the **Pb shielding** of the vacuum chamber less effective

LEP energy = 80.5 GeV



Cross-section 1 in the arc 11.55 m from the RF chicane

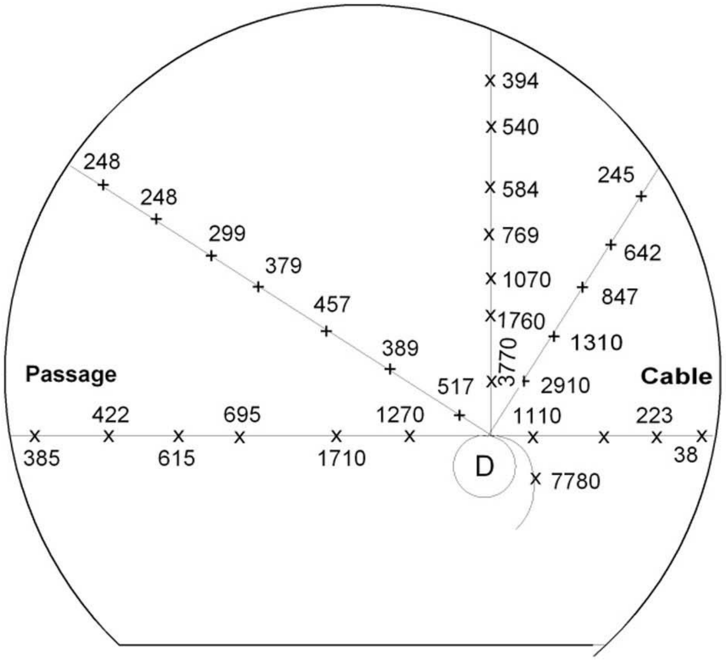


RA43

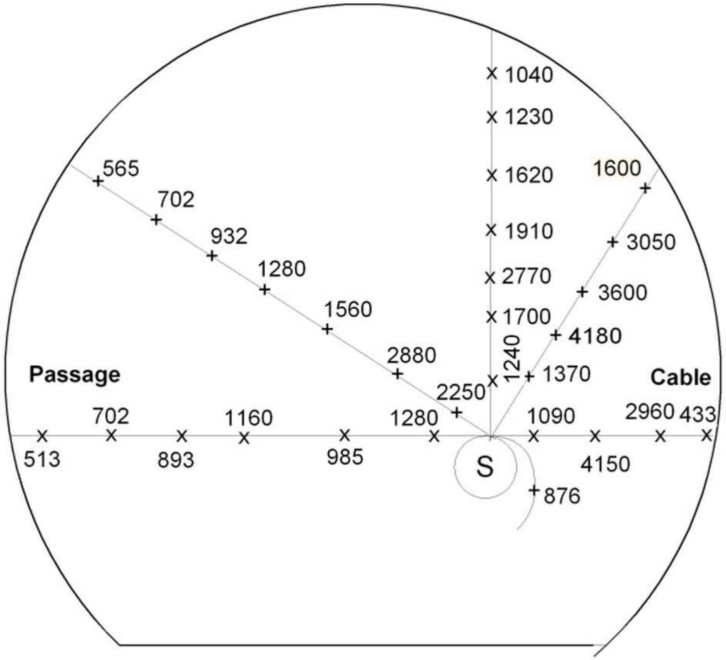
Cross-section 2 in the straight section 11.55 m from the RF chicane

Units of Measurement : Sv/Ah

LEP energy = 103 GeV



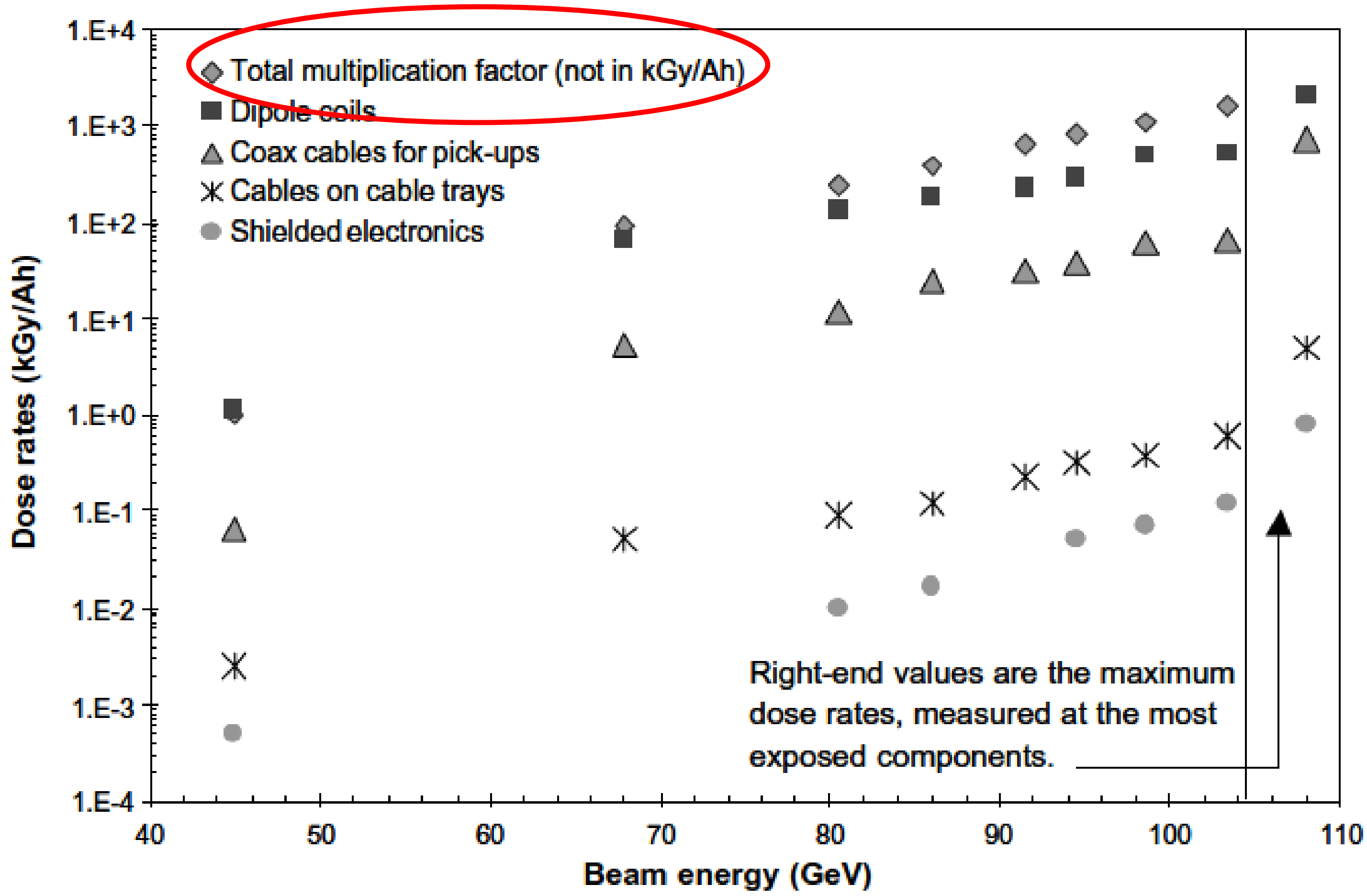
Cross-section 1 in the arc 6.4 m from the RF chicane



Cross-section 2 in the straight section RA43 29.1 m from the RF chicane

Units of Measurement : Sv/Ah

Radiation levels in the arcs



Evolution of the dose rates (kGy/Ah) in the arcs as a function of the beam energy (GeV)

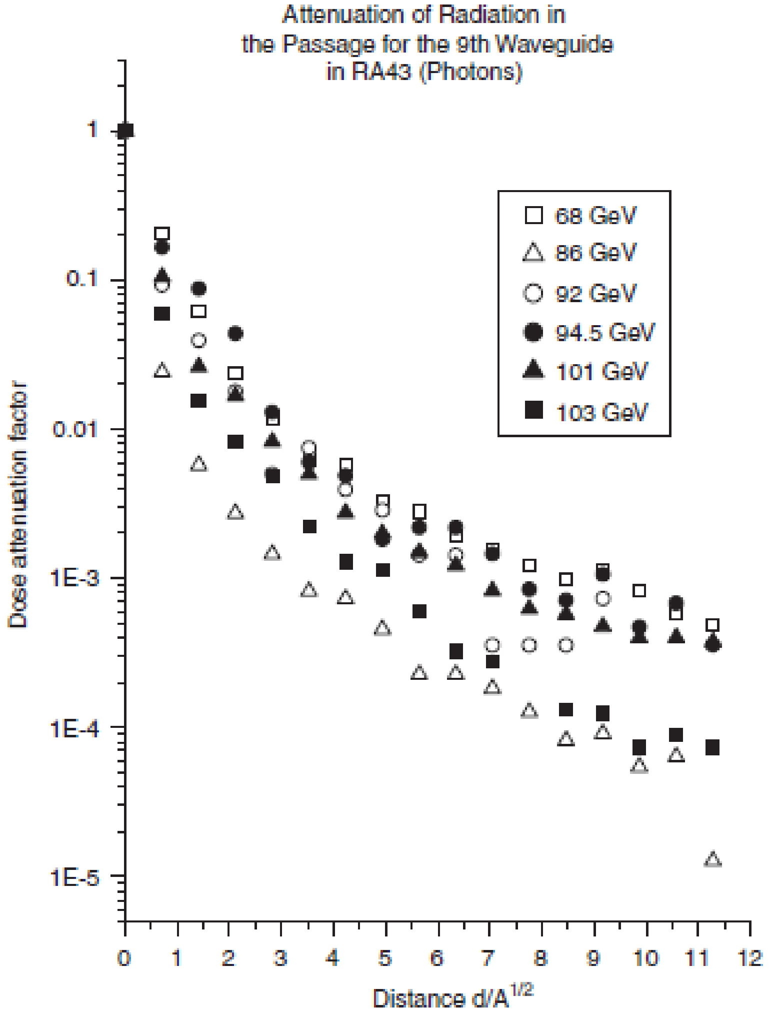
- Longitudinal dose distribution **much more uniform** over the arcs than in proton accelerators
- Doses as high as **22 MGy** were reached (even up to 100 MGy for the dipole of cell 161 at injection)
- During the 1999/2000 shut down, a campaign took place to cut the extremities of the control cables which came close to the beam pipe
- At the decommissioning in 2001, some control cables were found severely damaged at places where absorbed doses exceeded some **300 kGy**
- Total integrated dose on the **dipole coils** over the lifetime of LEP ≈ 10^7 Gy, ***a factor 5 below*** the dose where severe radiation damage of the coil insulation would have been expected

- **Damage on standard optical fibre cables** was observed immediately at the startup even at 45 GeV and the cables could no longer be used after only a few weeks. More radiation-hard glass fibre cables were installed in the main drains **below 40 cm of concrete**
- These cables accumulated a radiation dose of **less than 100 Gy** except at some places below the access plates and where they came close to the equipment, they stayed operational until the end of the run in 2000
- The **radiation dose limit** for a large number of cable insulating materials is 0.2–0.5 MGy and for pure epoxy resins 2–5 MGy
- The dose absorbed by the organic materials due to the **neutrons** accounted for less than 1% of the total ionizing dose
- Production of O_3, NO and NO_2 by radiation could cause corrosion

Transmission of radiation through the waveguide ducts

Position	80 GeV	86 GeV	94.5 GeV	100 GeV	103 GeV
	UA/RA	UA/RA	UA/RA	UA/RA	UA/RA
WG1	$4.7\ 10^{-5}$	$4.2\ 10^{-4}$	$6.6\ 10^{-2}$	$1.9\ 10^{-1}$	$2.5\ 10^{-1}$
WG2	—	$6.5\ 10^{-4}$	$3.1\ 10^{-1}$	$1.3\ 10^{-1}$	$4.2\ 10^{-1}$
WG3	$1.2\ 10^{-5}$	$4.4\ 10^{-4}$	$1.3\ 10^{-1}$	$8.4\ 10^{-2}$	$2.1\ 10^{-1}$
WG4	—	$4.9\ 10^{-5}$	$3.7\ 10^{-3}$	$2.0\ 10^{-2}$	$1.1\ 10^{-1}$
WG5	$3.3\ 10^{-6}$	$3.4\ 10^{-4}$	$3.2\ 10^{-2}$	$5.5\ 10^{-2}$	$3.7\ 10^{-1}$
WG6	—	$4.9\ 10^{-4}$	$9.6\ 10^{-2}$	$3.5\ 10^{-1}$	$2.4\ 10^{-1}$
WG7	—	$4.7\ 10^{-4}$	$7.2\ 10^{-2}$	$2.5\ 10^{-1}$	$4.7\ 10^{-2}$
WG8	—	$7.5\ 10^{-4}$	$1.4\ 10^{-1}$	$2.9\ 10^{-2}$	$9.0\ 10^{-2}$
WG9	—	$1.0\ 10^{-4}$	$4.8\ 10^{-2}$	$6.8\ 10^{-3}$	$1.2\ 10^{-1}$
WG10	$2.5\ 10^{-6}$	$2.2\ 10^{-4}$	$1.5\ 10^{-2}$	$2.9\ 10^{-2}$	$1.6\ 10^{-1}$
WG11	$4.3\ 10^{-6}$	$8.2\ 10^{-6}$	$3.6\ 10^{-2}$	$1.7\ 10^{-3}$	$2.3\ 10^{-3}$
WG12	$1.1\ 10^{-5}$	$2.1\ 10^{-5}$	$6.0\ 10^{-2}$	$9.1\ 10^{-4}$	$1.8\ 10^{-2}$

- Dose rates in UA at 103 GeV of the order of tens of uSv/h



Attenuation of photons in WG

Transmission of radiation through the waveguide ducts

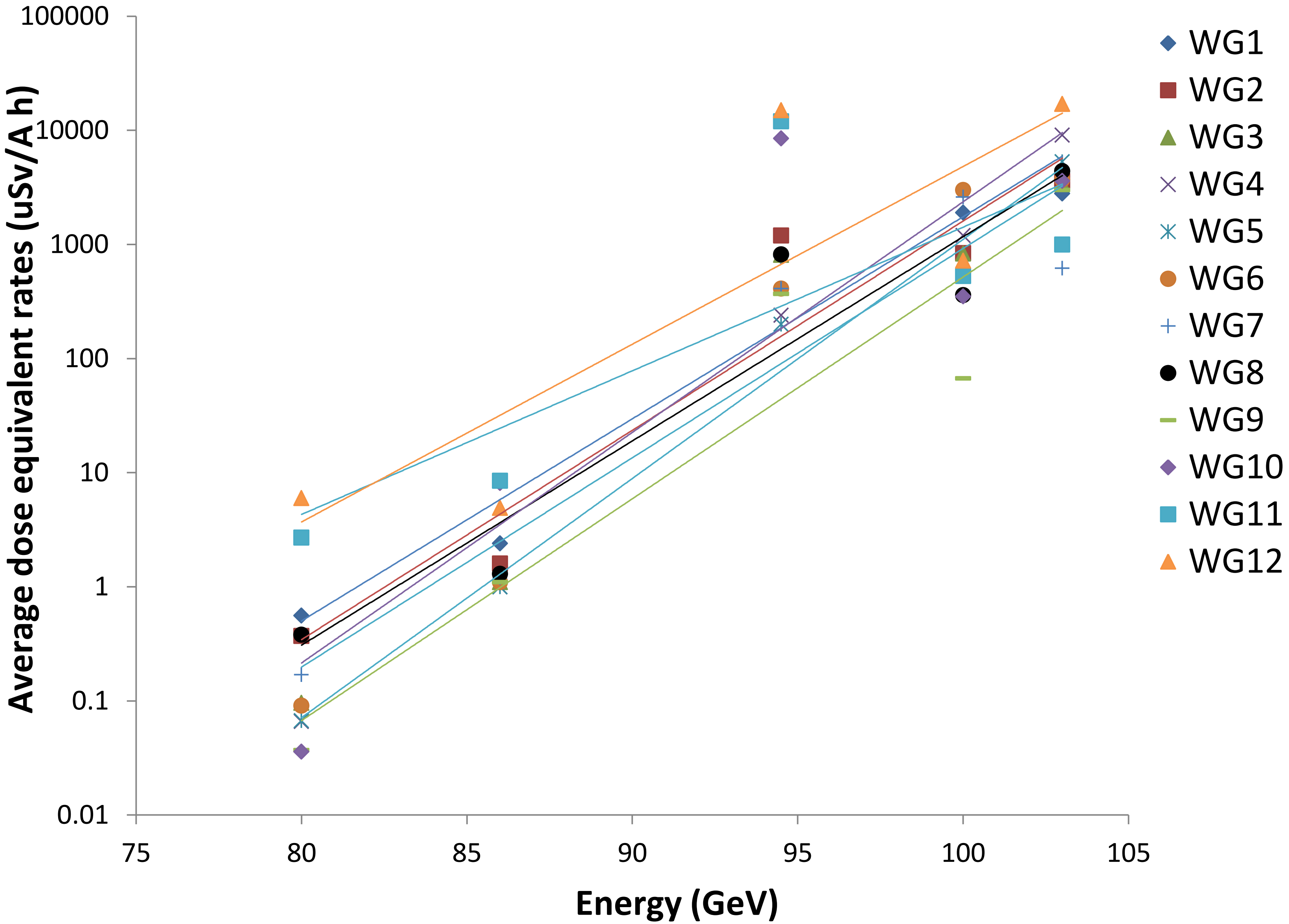
Average dose equivalent rates at the entrance and exit of the waveguide ducts in RA43/UA43

Position	80 GeV		86 GeV		94.5 GeV		100 GeV		103 GeV	
	RA (mSv/A h)	UA (μSv/A h)	RA (mSv/A h)	UA (μSv/A h)	RA (mSv/A h)	UA (μSv/A h)	RA (mSv/A h)	UA (μSv/A h)	RA (mSv/A h)	UA (μSv/A h)
WG1	12	5.6×10^{-1}	5.8	2.4	12	7.9×10^{2}	9.8	1.9×10^{3}	11	2.8×10^{3}
WG2	—	3.7×10^{-1}	2.5	1.6	3.8	1.2×10^{3}	6.5	8.4×10^{2}	8.5	3.6×10^{3}
WG3	7.9	9.6×10^{-2}	2.5	1.1	6.4	8.1×10^{2}	9.8	8.3×10^{2}	16	3.4×10^{3}
WG4	—	6.6×10^{-2}	21	1.0	66	2.4×10^{2}	59	1.2×10^{3}	87	9.1×10^{3}
WG5	20	6.7×10^{-2}	3.0	1.0	6.2	2.0×10^{2}	9.6	5.3×10^{2}	14	5.3×10^{3}
WG6	—	9.1×10^{-2}	2.3	1.1	4.3	4.1×10^{2}	8.5	3.0×10^{3}	15	3.7×10^{3}
WG7	—	1.7×10^{-1}	2.5	1.2	5.7	4.1×10^{2}	10	2.6×10^{3}	13	6.2×10^{2}
WG8	—	3.8×10^{-1}	1.8	1.3	5.7	8.2×10^{2}	12	3.6×10^{2}	49	4.4×10^{3}
WG9	—	3.7×10^{-2}	11	1.1	7.6	3.7×10^{2}	9.9	67	25	3.0×10^{3}
WG10	14	3.6×10^{-2}	36	8.1	5.8×10^{2}	8.5×10^{3}	12	3.5×10^{2}	22	3.6×10^{3}
WG11	6.3×10^{2}	2.7	1.0×10^{3}	8.5	3.5×10^{2}	1.2×10^{4}	3.2×10^{2}	5.3×10^{2}	4.3×10^{2}	1.0×10^{3}
WG12	5.7×10^{2}	6.0	2.3×10^{2}	4.9	2.5×10^{2}	1.5×10^{4}	8.0×10^{2}	7.2×10^{2}	9.4×10^{2}	1.7×10^{4}

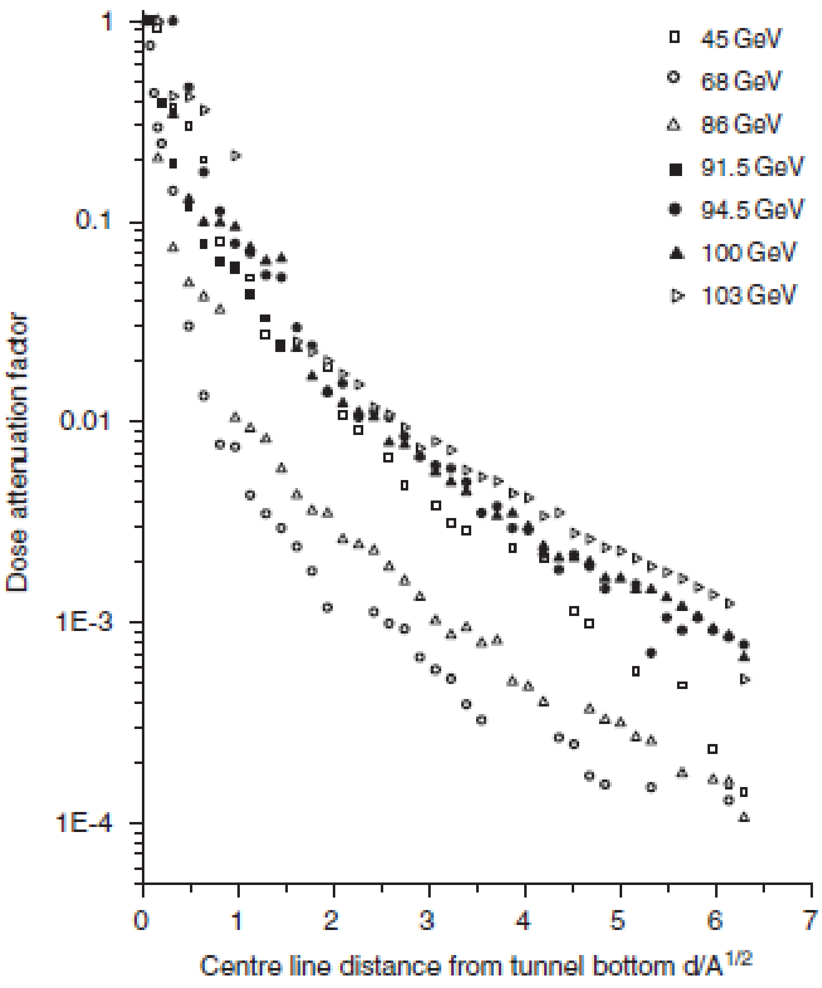
WG 1 is towards ALEPH (interaction point 4), WG 12 is towards the arc (Fig. 5). Values are normalised to 1 A h of total circulating beam current.

The radiation intensity did not change significantly in the LEP tunnel with increasing beam energy, whilst increased dramatically on the UA side of the ducts, indicating a decrease in the attenuation properties of the duct (in one case by 5 orders of magnitude!)

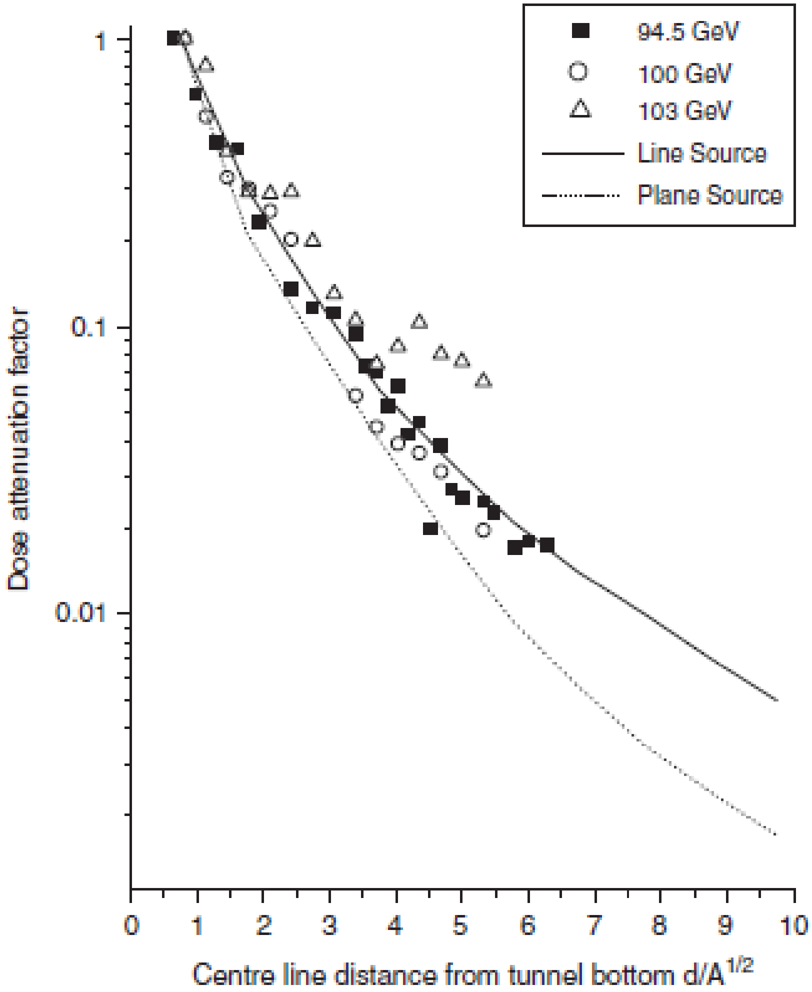
Transmission of radiation through the waveguide ducts



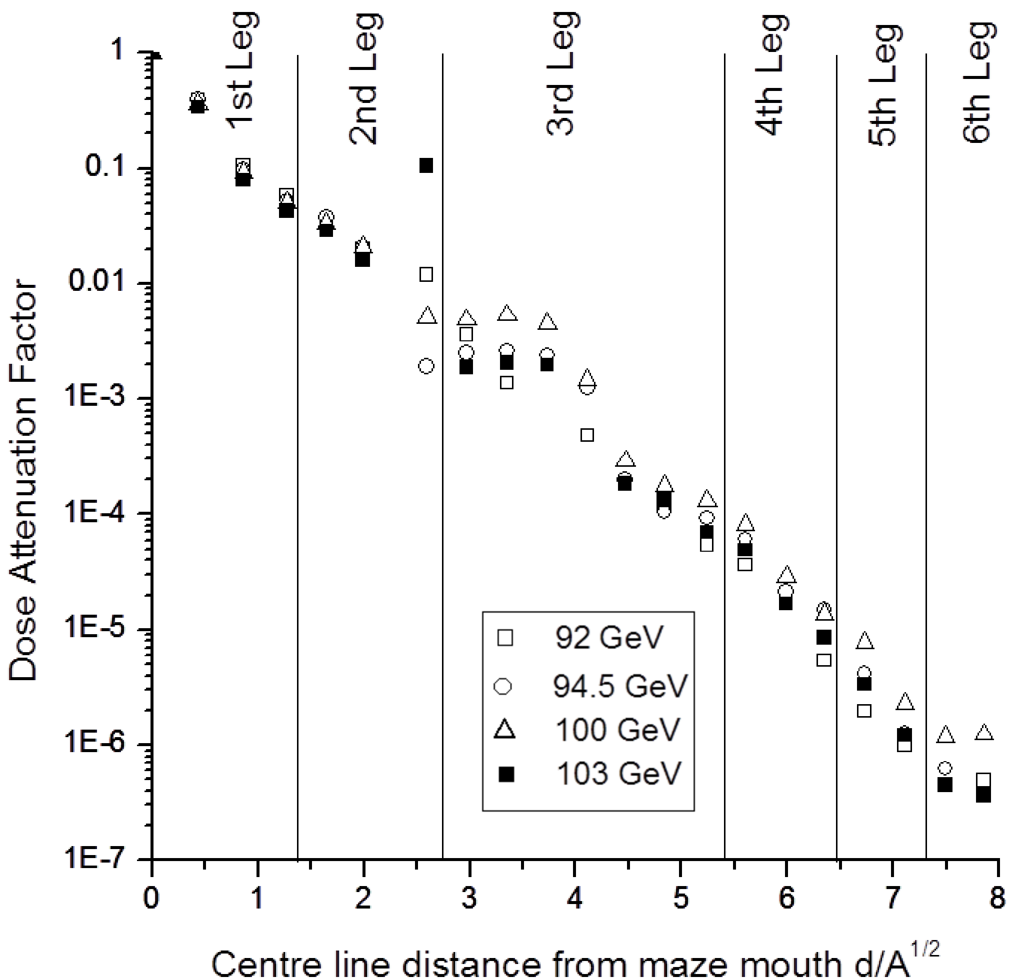
Photons

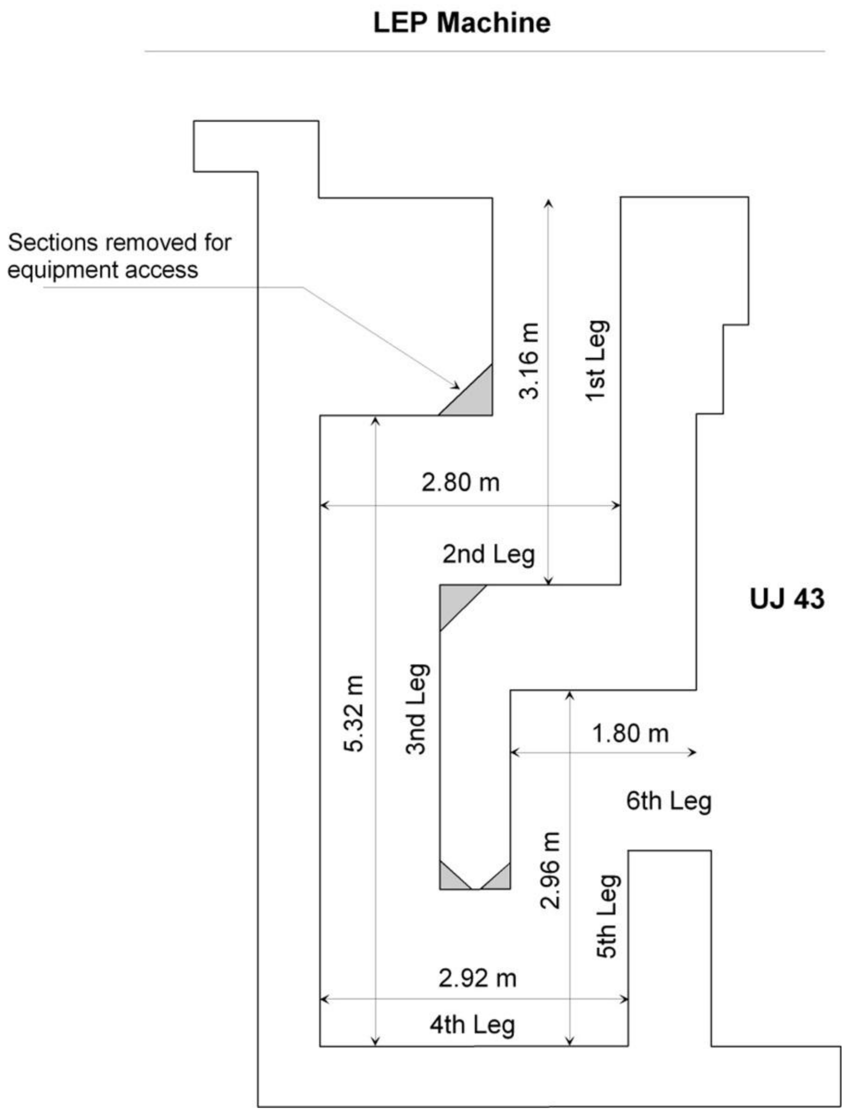


Neutrons



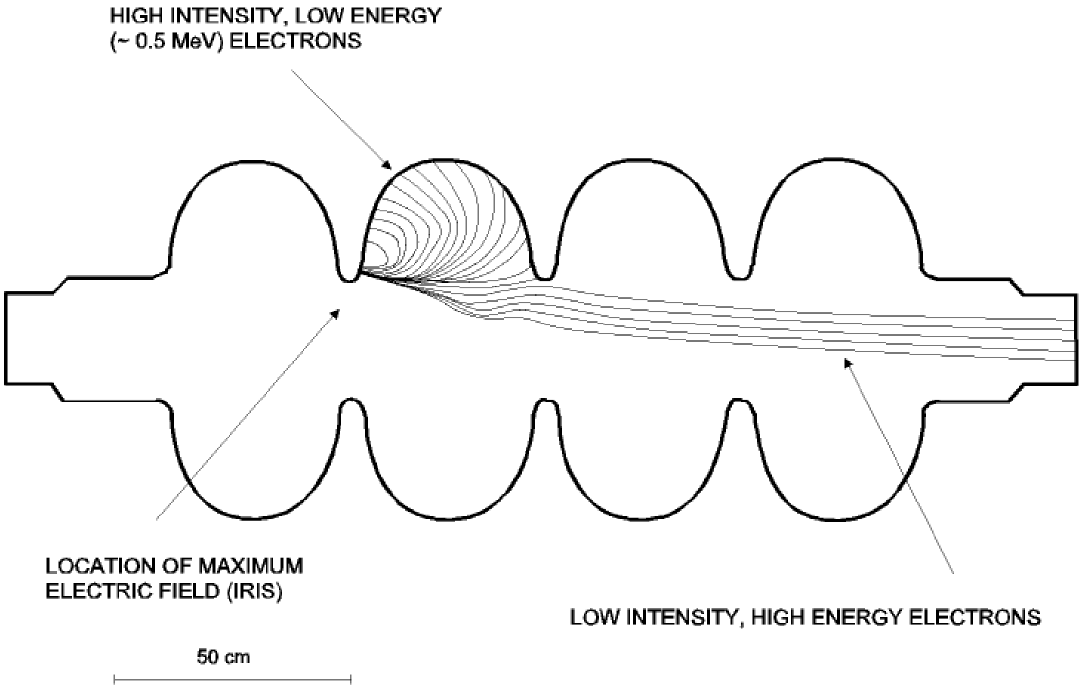
Transmission of radiation through the access maze in UJ43



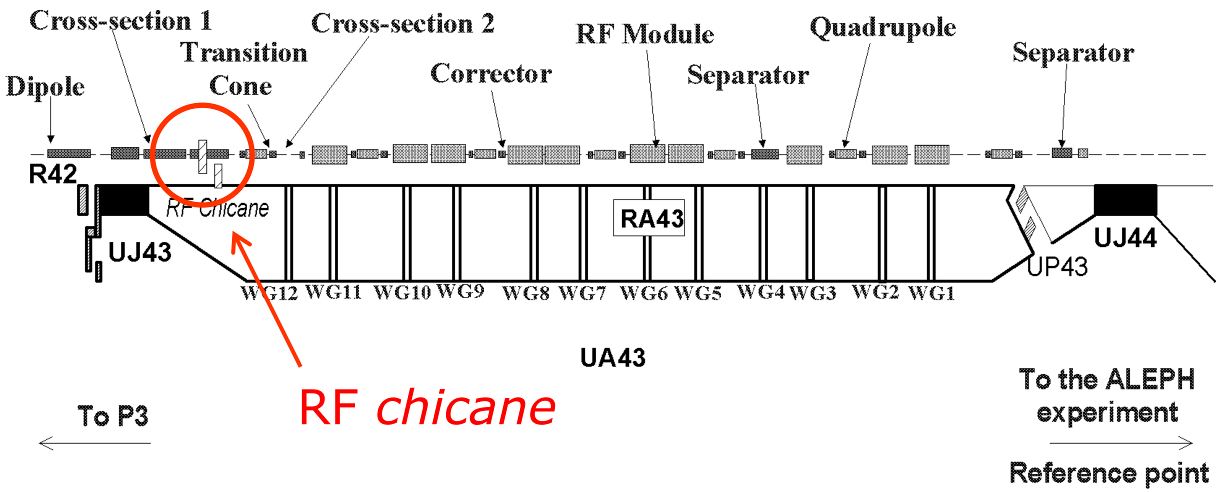


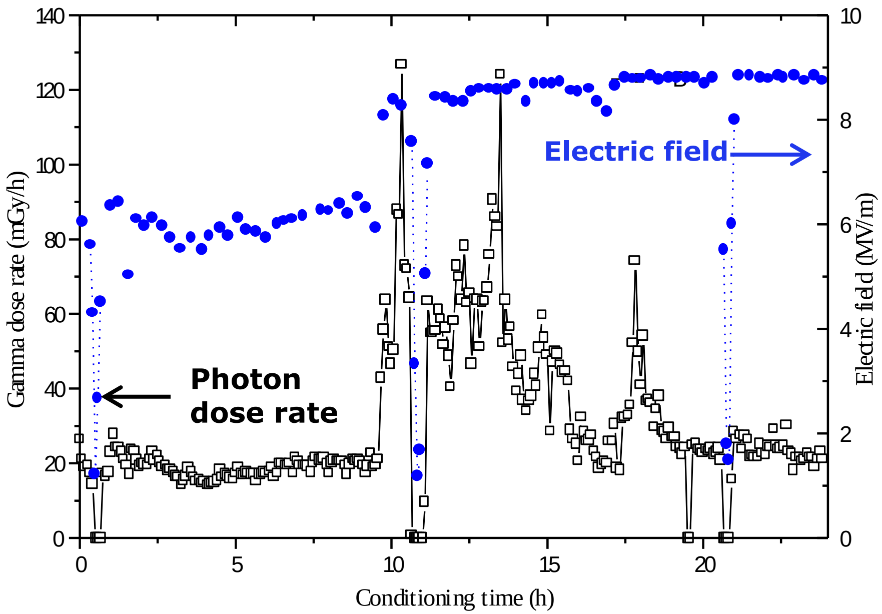
Stray radiation from the s.c. RF cavities

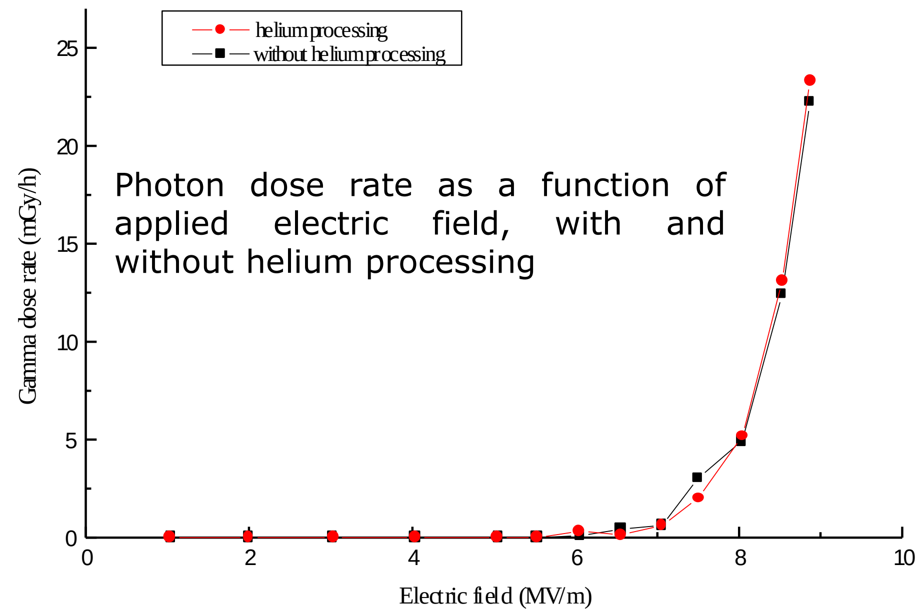
- 72 s.c. modules, 4 cavities / module
- Total accelerating voltage 40 MV (klystron power 150 MW)
- Prompt photon dose rate during conditioning on cavity axis close to the exit cone: from a few Gy h^{-1} to hundreds of Gy h^{-1}
- Prompt neutron dose rate: a few 10^{-3} of the photon dose
- Induced radioactivity



Stray radiation from s.c. RF cavities







Photon dose rate as a function of applied electric field, with and without helium processing

Total specific activity (Bq/g) in various regions of the LEP dipoles induced by synchrotron radiation for a beam energy of 100 GeV

Decay time (days)	Al (vacuum chamber)	Pb (shield)	Iron-concrete (dipole)
0	$3.38\ 10^{-1}$	$6.41\ 10^{-1}$	$3.56\ 10^{-2}$
1	$1.29\ 10^{-1}$	$4.53\ 10^{-1}$	$5.14\ 10^{-3}$
7	$3.64\ 10^{-2}$	$7.43\ 10^{-2}$	$3.75\ 10^{-3}$
30	$3.44\ 10^{-2}$	$4.36\ 10^{-3}$	$3.52\ 10^{-3}$
365	$1.76\ 10^{-2}$	$5.17\ 10^{-4}$	$1.96\ 10^{-3}$
3650	$4.30\ 10^{-4}$	$4.77\ 10^{-7}$	$9.96\ 10^{-5}$

LEP decommissioning, about **30,000 tons** from the LEP machine and **10,000 tons** from the experiments → ***mostly conventional scrap***

Induced radioactivity in the LEP experiments essentially **zero** (except for the Far Forward Monitors)

Present amount of radioactive waste stored at CERN: about 10,000 tons

References

A. Fasso et al., Radiation problems in the design of the Large Electron-Positron collider (LEP), CERN Yellow Report 84-02 (1984).

K. Goebel (Ed.), The radiological impact of the LEP project on the environment, CERN Yellow Report 81-08 (1981).

A. Fassò, J.C. Gaborit, M. Höfert, F. Pirotte and M. Silari, Radiation levels in LEP, 1989-1995, Nucl. Instr. and Meth. A384, 531-538, 1997.

M. Silari, S. Agosteo, J-C. Gaborit and L. Ulrici, Radiation produced by the LEP superconducting RF cavities, Nucl. Instr. and Meth. A 432, 1-13, 1999.

M. Silari and L. Ulrici, Investigation of induced radioactivity in the CERN Large Electron Positron collider for its decommissioning, Nucl. Instr. and Meth. A 526, 510-536, 2004.

H. Schonbacher and M. Tavlet, Absorbed doses and radiation damage during the 11 years of LEP operation, Nucl. Instr. and Meth. B 217, 77-96, 2004.

J-C. Gaborit, M. Silari and L. Ulrici, Radiation levels in the CERN Large Electron Positron collider during the LEP 2 phase (68 – 105 GeV), Nucl. Instr. and Meth. A 565, 333-350, 2006.