ICFA

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Beijing, China

HF2014

Synchrotron radiation effects in the HF (FCC-ee) injector

Yannis PAPAPHILIPPOU, CERN

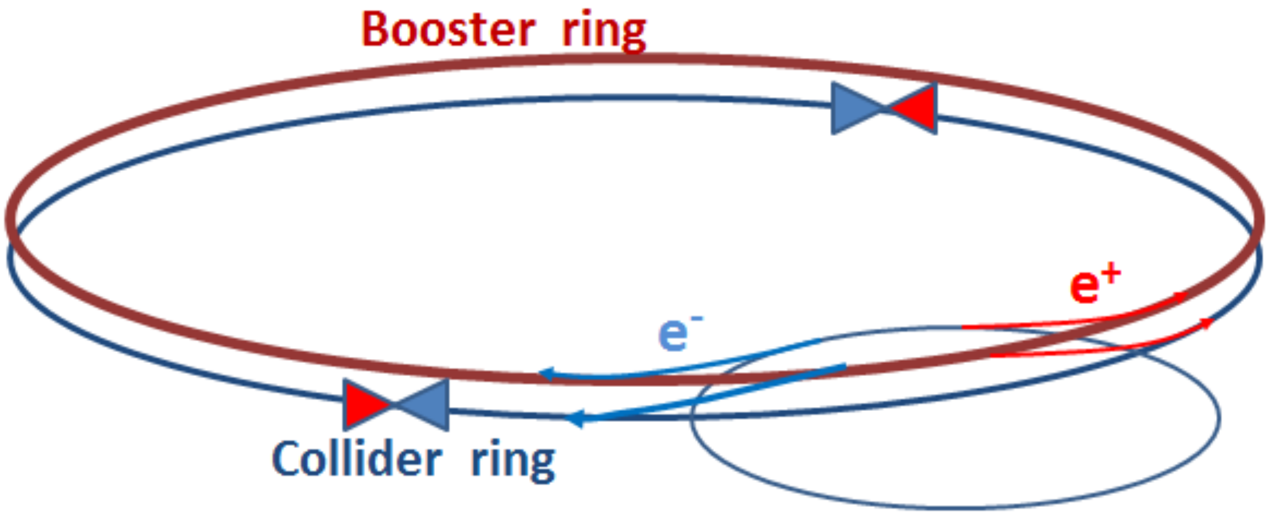
Outline

- Guidelines and tentative parameters for the FCC-ee injector
- Synchrotron radiation (SR) considerations
- SR in the Booster Ring
- SR in the SPS
- SR in the pre-injector
  - Positron production
- Outlook

Booster ring considerations

- Besides the collider ring(s), a booster of the same size (same tunnel) must provide beams for **top-up injection**.
  - Same size of RF system, but low power (~ MW).
  - Top up frequency ~0.1 Hz.
  - Booster injection energy ~20 GeV
  - Injector field at 20 GeV quite low
  - Long chicanes for by-passing experiments
- **Injector complex for e+ and e- beams of ~20 GeV**

J. Wenninger, FCC kick-off 2014



Target injector parameters

Parameter	Z	W	H	tt	LEP2
E [GeV]	45.5	80	120	175	104
I [mA]	1442	151	30	7	1
No. bunches	16700	4490	1360	98	4
Bunch population [10^{11}]	1.8	0.7	0.46	1.4	4.2
Lifetime [min]	298	73	29	21	434
Time between injections [sec]	361	88	35	25	263
Injected top-up bunch population [10^{11}]	601.2	62.9	12.5	2.7	0.34
Required particle flux for top-up [10^{11}p/sec]	**2.10**	**0.89**	**0.44**	**0.13**	**0.001**
Required particle flux for full filling [10^{11}p/sec]	**31.3**	**3.3**	**0.7**	**0.1**	**0.02**
Booster injector ramp rate [GeV/sec]	**5.2**	**12.2**	**20.4**	**31.6**	**17.1**

- For defining injector cycle and flux, assumed **2%** of current decay between top-ups
  - The top energy Fcc-ee defines the maximum time between injections/species (**25sec**)
  - Considering 50% duty factor (Interleaved e^+/e^- injection), injections should be made at a minimum rate of **~0.1Hz**
- For full collider filling (0.25mA/min for LEP), assumed **20min** of filling time and **80%** transfer efficiency along the injector chain
- Ramp rate for 0.1Hz injection considering linear ramp and short flat bottom and flat top (~100ms)
- Note that LEP2 injector parameters are obtained with the same assumptions

Possible FCC-ee injector scheme

- **LINACS** and positron production a downgraded version of the one for CLIC (or upgraded LIL/CTF3)
  - **2GHz, 50Hz repetition rate,** less than **10^9** p/b
- Trains with **3200 bunches** (320 for the Higgs and 98 for top production) injected **8 times** (7 for the top) in the SPS @ 10GeV in the required **50MHz** bunch structure and accelerated to 20GeV
  - Need new RF system in the SPS (50MHz?)
- SPS duty factor of **0.5** (apart for top) leaving time for fixed target proton physics
  - 5 cycles of 1.2s in a supercycle of 12s
- Injected into the booster ring (flat bottom of 6s or 2.4s) to be accelerated in **3s** to required extraction energy for FCC-ee
- **Filling time** for full filling **20min**
- **Top-up** compatible with lifetime (**25s** for FCC-ee top)

Tentative FCC-ee injector parameters

Accelerator	FCCee-Z		FCCee-W		FCCee-H		FCCee-tt	
Energy [GeV]	45.5		80		120		175	
Type of filling	Full	Top-up	Full	Top-up	Full	Top-up	Full	Top-up
LINAC # bunches	3200				320		280	
LINAC repetition rate [Hz]	50							
LINAC RF freq [MHz]	2000							
LINAC bunch population [10^8]	5.9	0.4	0.6	0.2	1.2	1.2	0.02	0.04
# of LINAC injections	8						7	
SPS/BR bunch spacing [MHz]	50							
SPS bunches/injection	80				8		7	
SPS bunch population [10^{10}]	2.35	0.16	0.25	0.08	0.49	0.49	0.10	0.14
SPS duty factor	0.5						0.29	
SPS / BR # of bunches	640/3200				64/320		49/98	
SPS / BR cycle time [s]	1.2 / 12						1.2 / 8.4	
Number of BR cycles	50	15	50	3	50	1	71	1
Transfer efficiency	0.8							
Total number of bunches	16700		4490		1360		98	
Filling time (both species) [sec]	1200	360	1200	72	1200	24	1193	16.8
Injected bunch population [10^{10}]	18	0.36	7	0.14	0.46	0.092	14	0.28

Booster Ring parameters

Top Energy [GeV]	45.5	80	120	175
Cycle time [s]	12			
Circumference [m]	100000			
Bending radius [m]	11000			
Injection energy [GeV]	20			
Dipole length	10.5			
Emittance @ injection [nm]	2.81	0.10	0.01	0.01
Emittance @ extraction [nm]	14.5	1.65	1.0	1.0
Bending field @ injection [G]	61			
Bending field @ extraction [G]	138	243	361	531
Energy Loss / turn @ injection [MeV]	1.287			
Energy Loss / turn @ extraction [MeV]	34.5	329.4	1667.6	7542.6
Long. Damping time @ injection [turns]	15543			
Long. Damping time @ extraction [turns]	1320	243	72	23
Average current [mA]	36.1	3.8	0.8	0.1
Average power @ injection [kW]	46.4	4.9	1.0	0.2
Average power @ extraction [MW]	1.24	1.26	1.26	0.88
Average power over 1 cycle [kW]	100	105	105	104
Power from dipoles @ extraction [W]	189	192	191	189
Power density on bends @ extraction [W/m]	18	18	18	13
Critical energy [MeV]	0.02	0.10	0.35	1.08
Radiation angle [μrad]	11.2	6.4	4.3	2.9

- "Similar" geometry as main ring to fit in the same tunnel
  - Need to by-pass experiments
- Low emittance @ extraction obtained quite naturally due to the small bending angle
  - Good for injection efficiency and top-up
- Ultra-low emittances @ injection if keeping the same optics as for collider
  - 10pm for higgs and top
  - Need detuned optics or working @ full coupling to avoid collective effects

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- Energy loss/turn determined by energy and ring geometry
  - Same as for the collider at extraction (~1MeV at injection)
- Bending field at injection of **61Gauss**
  - Has to remain low as energy loss/turn at flat top is already quite high
  - Compensation of eddy currents, hysteresis effects and appropriate shielding from FCC-ee main magnets is needed

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- Average current considered for full filling, from a fraction to ~**36mA**
- Average power at injection up to **46kW**
- Up to ~**1.3MW** at extraction
- Power density up to ~**18W/m**

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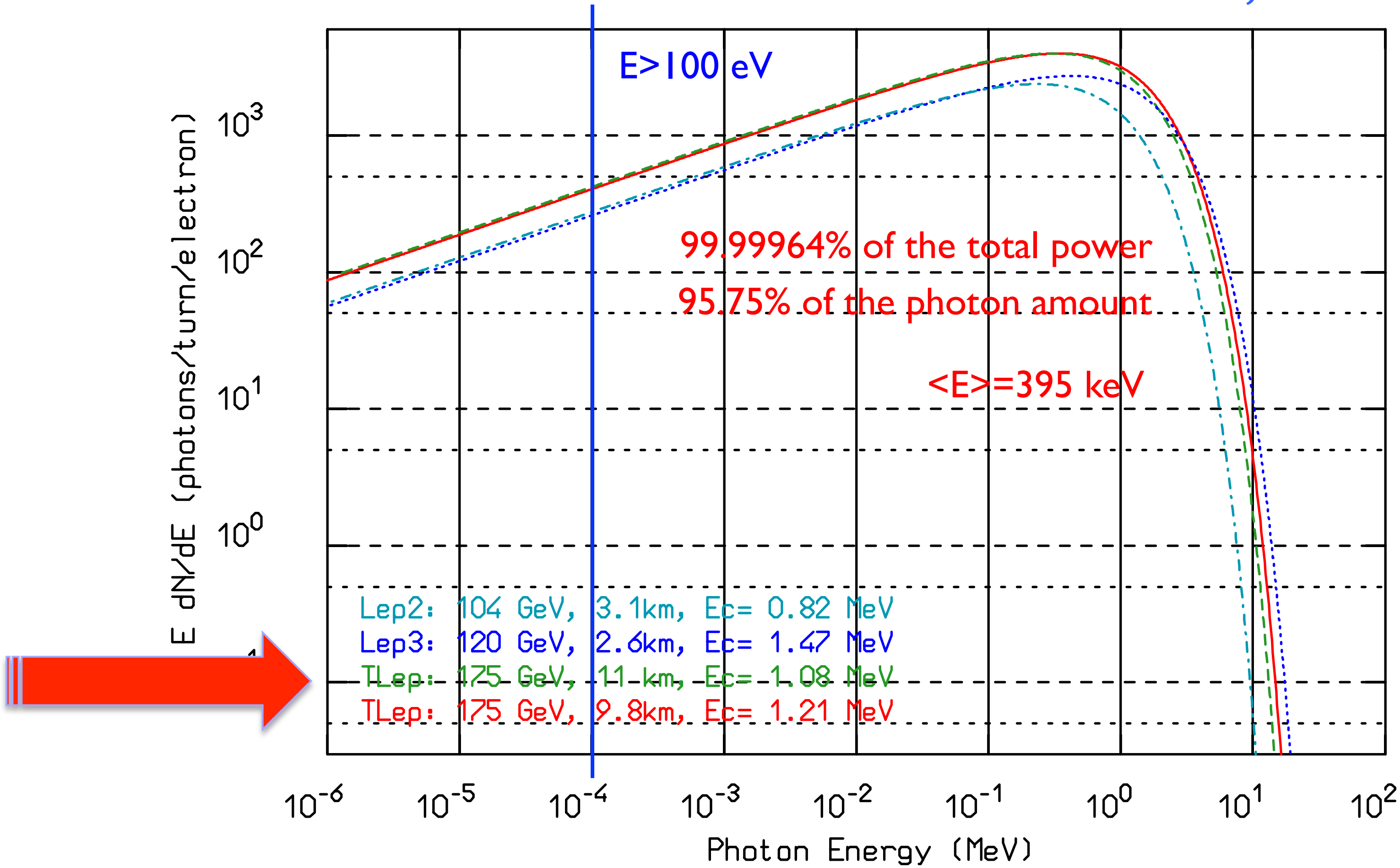
- Critical energies @ extraction as for the collider (up to **1.1MeV** for highest energy)
- Vertical radiation angle of a few μrads
- Needs demanding shielding, absorption scheme and vacuum chamber design

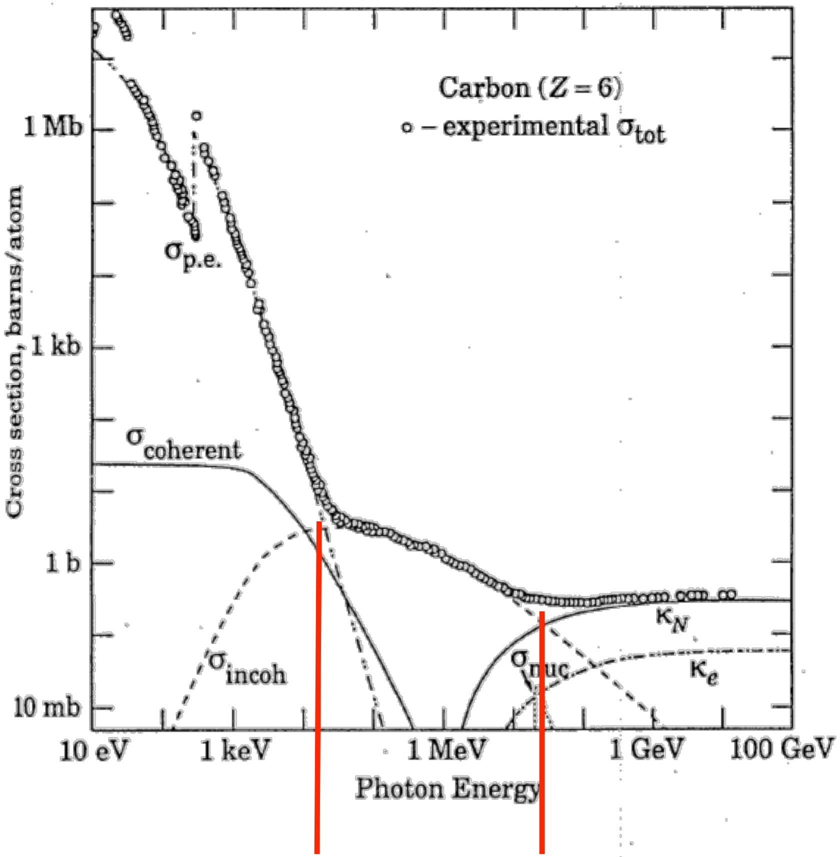
Synchrotron Radiation

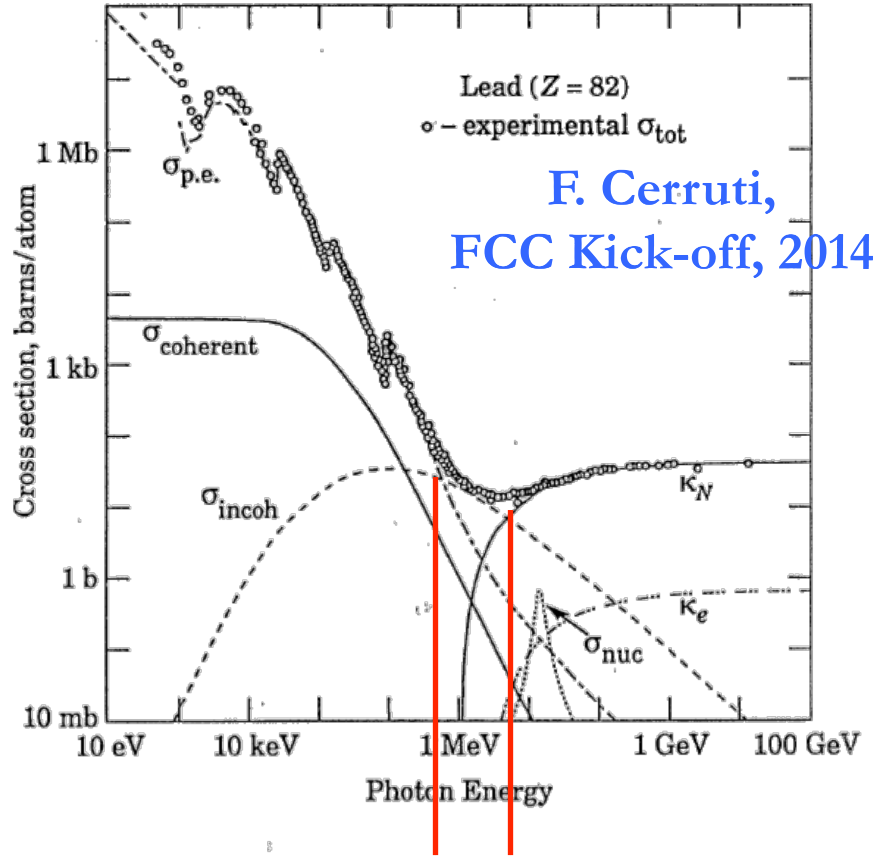
F. Cerruti, FCC Kick-off, 2014



- Critical energy ranging from a few keV at injection (20GeV) to around ~1MeV at flat top (as for collider)

Photon Cross Section





F. Cerruti, FCC Kick-off, 2014

Photoelectric dominated | Compton dominated | Pair dominated

Photoelectric dominated | Compton dominated | Pair dominated

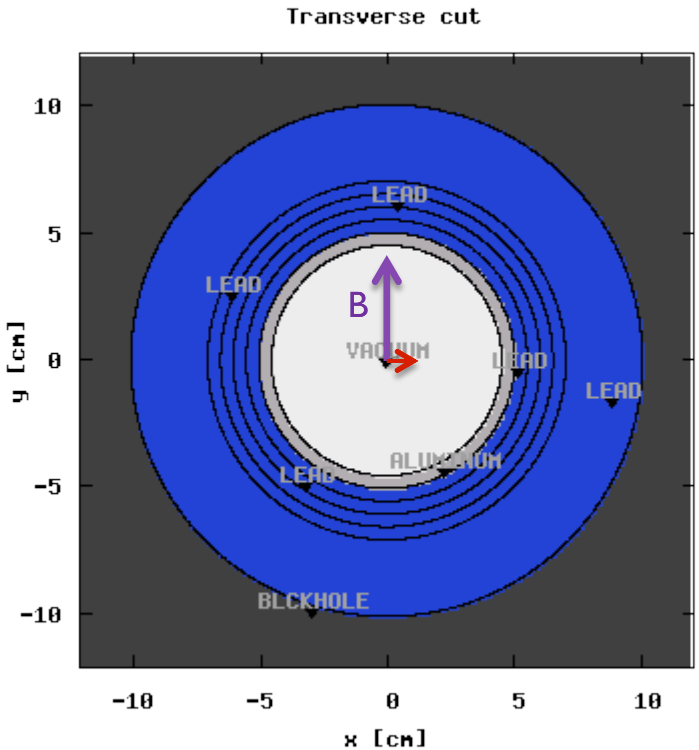
$\sigma_{p.e.}$=photoelectric σ_{incoh}=Compton $\sigma_{coherent}$=Rayleigh σ_{nuc}=photonuclear

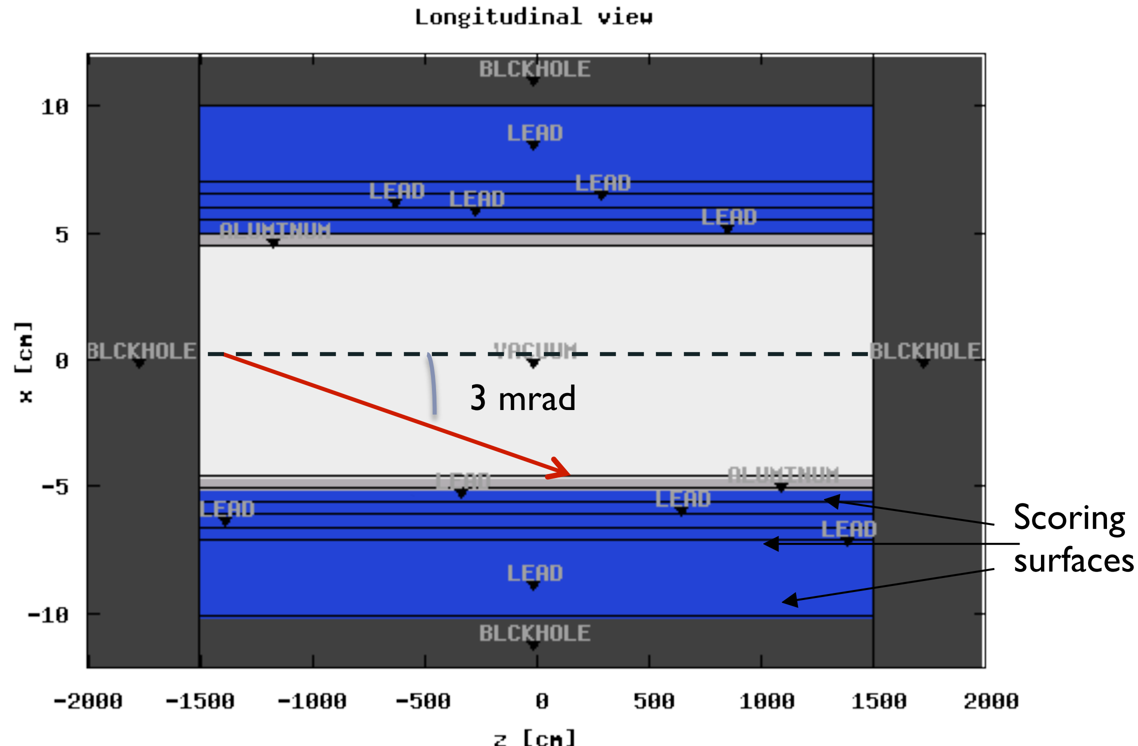
κ_N=pair production, nuclear field κ_e=pair production, electron field

- In the photons energy of interest, cross section is Compton dominated, but tails extend to photo-nuclear reactions

Shielded beam chamber

Chamber shielding for collider





- ❑ Beam chamber: round IR = 4.5 cm
- ❑ Aluminum pipe: thickness = 0.5 cm
- ❑ Lead shielding: thickness = 5.0 cm

F. Cerruti, FCC Kick-off, 2014

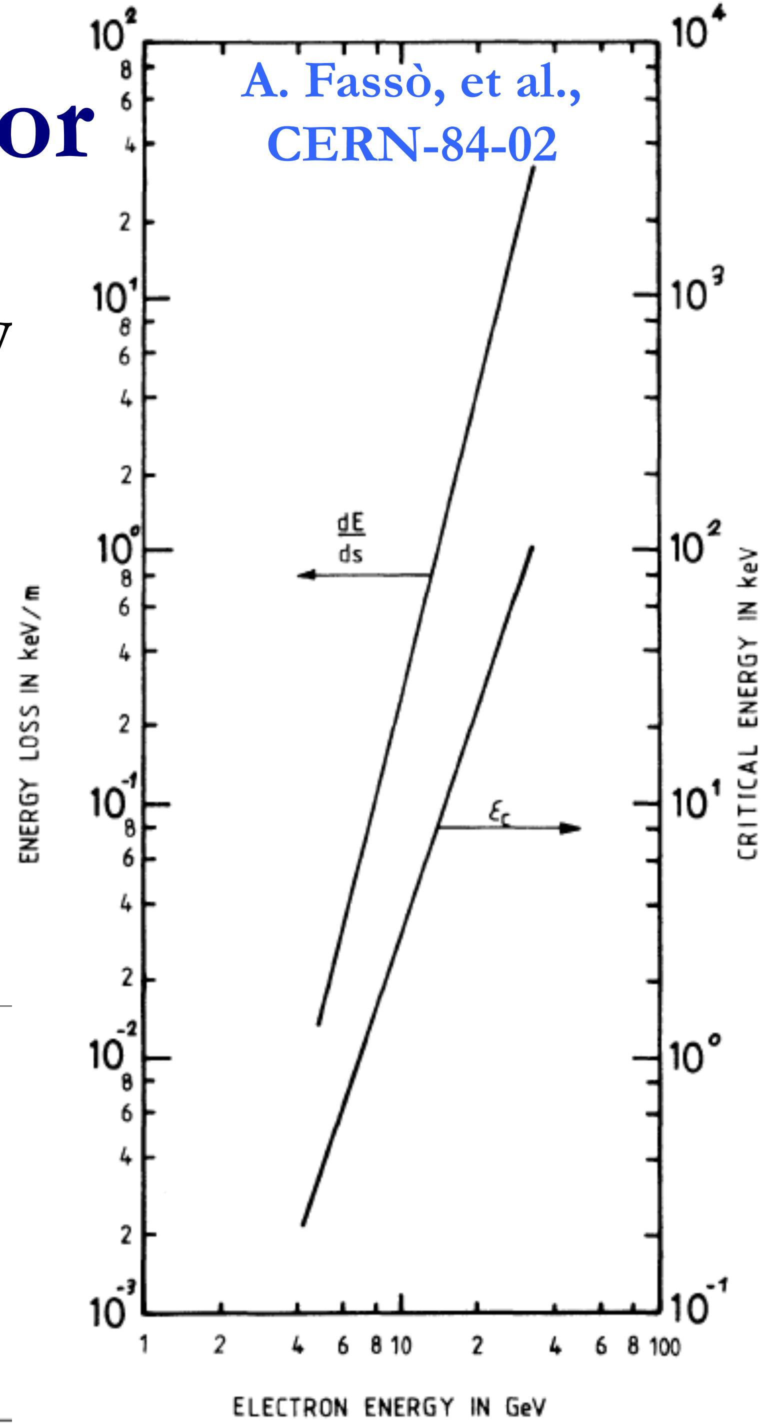
- Booster ring will need absorbers in front of dipoles but also beam pipe shielding
- Thickness to be defined according to radiation power needs (18W/m @ top energy, for each dipole) but still in the MW range for the whole ring at extraction
- Escaping power should be evaluated and included in tunnel activation estimations (production of ozon, neutron dose,…)

SPS as LEP injector

- Energy loss/turn up to **20MeV** at 20 GeV
- Critical energy in the range of a few to **25 keV**
- Power density of around 2W/m at maximum energy (0.45mA of average current)
- Most of it absorbed by SS vacuum chamber
  - Radiation dose in the shadow of proton operation
- Shielding (lead collar of 10mm) placed in MBB magnets for protecting vacuum flanges and magnet coil insulation

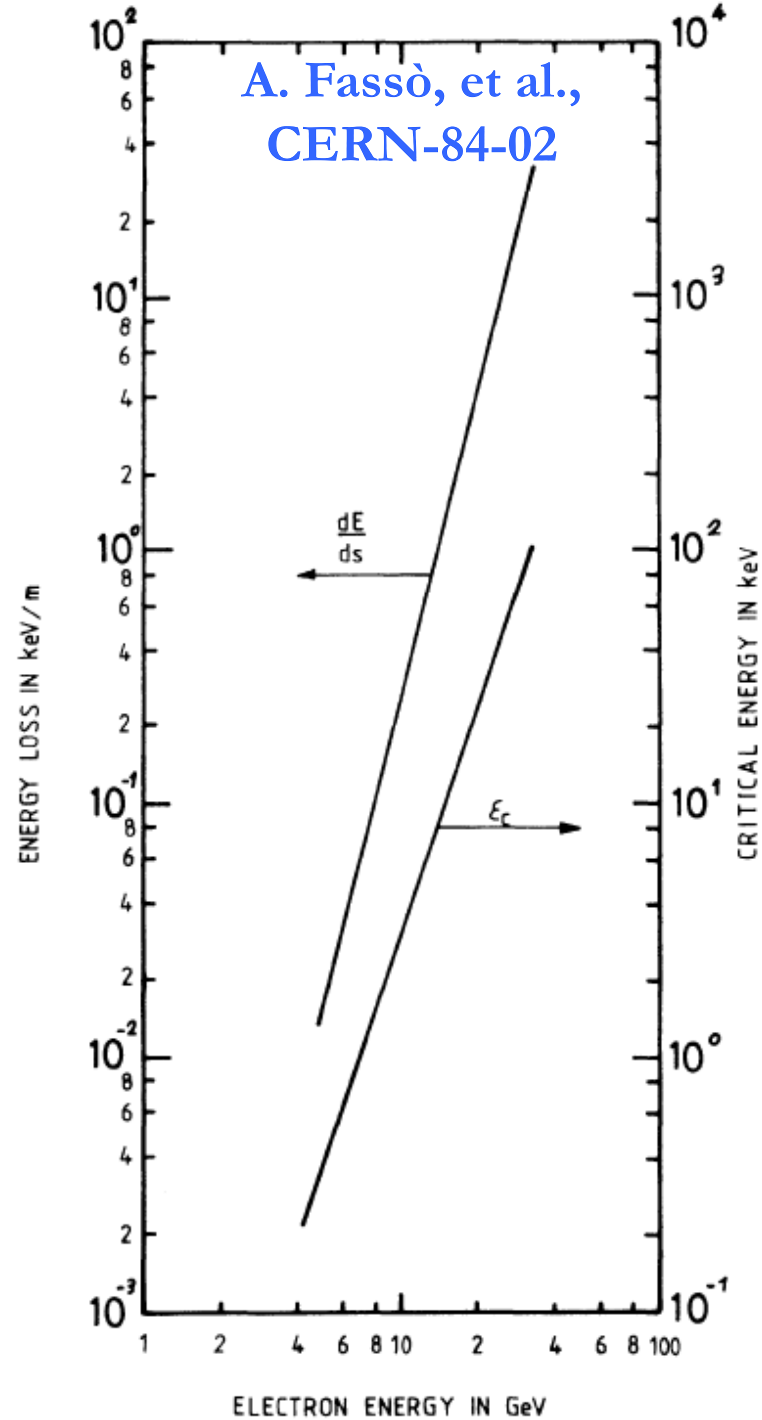
Maximum energy	20	GeV
Number of electrons or positrons per SPS pulse	6.4×10^{10}	
Mean radius of SPS	1100	m
Current of circulating $e^{\pm}$ (each beam)	0.445	mA
Bending radius of main ring magnets	741.3	m
Energy loss for one $e^{\pm}$ per turn	19.1	MeV
Energy loss per path length in dipole	4.1	keV/m
Power loss per path length in dipole	1.82	W/m
Critical energy of synchrotron radiation	23.9	keV
Superperiod of SPS magnet cycle	15	s
Number of $e^{\pm}$ cycles per superperiod ($2\,e^{+}, 2\,e^{-}$)	4	

A. Fassò, et al., CERN-84-02



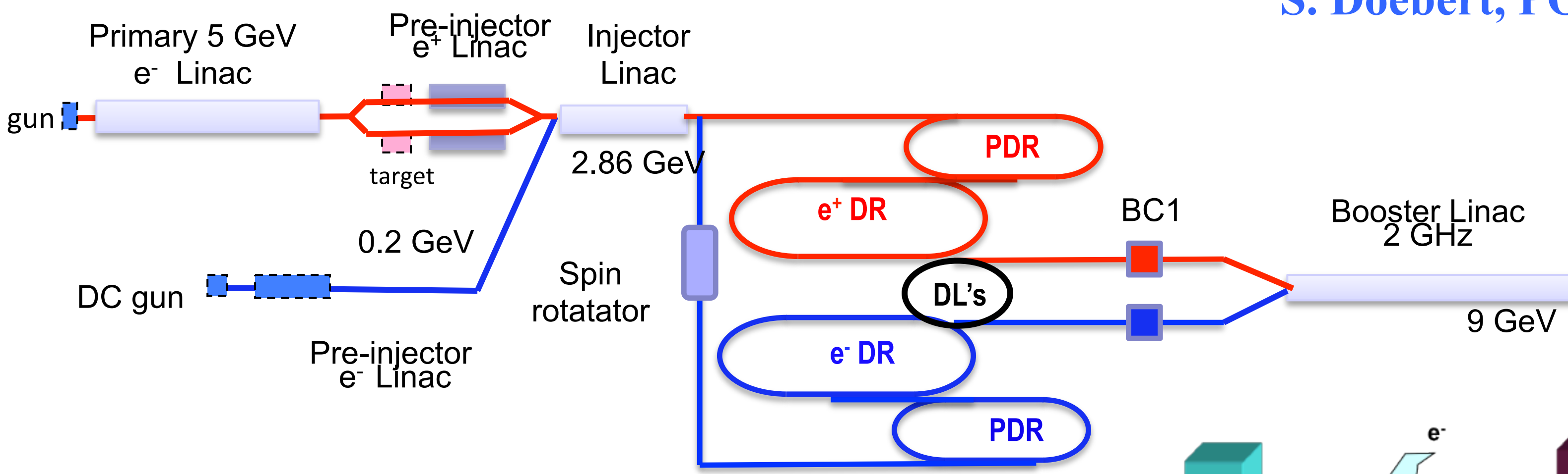
Synchrotron Radiation in the SPS

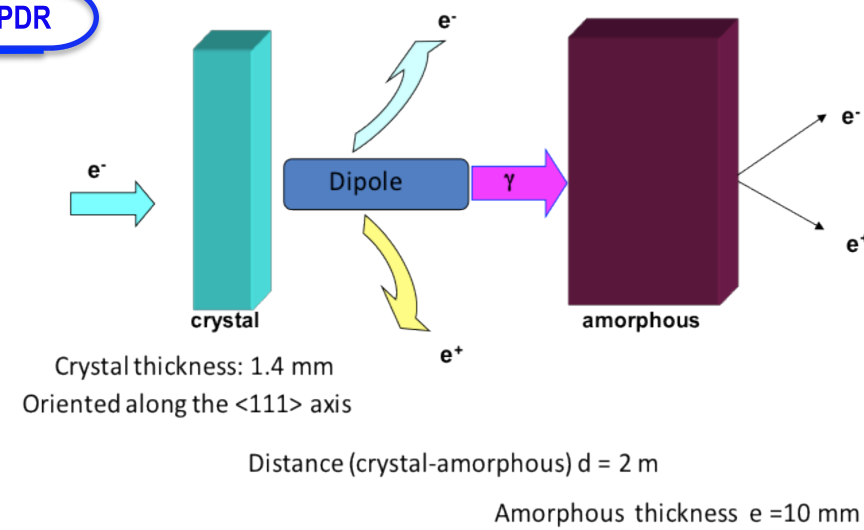
- Energy loss/turn up to **20MeV** at 20 GeV
- Critical energy in the range of a few to **25 keV**
- Average power from 124kW (injection) to ~**2MW** (extraction) for Z production (highest average current, of around 104mA)
- This corresponds to ~**3kW** for each dipole or ~**430W/m**
  - Need absorption scheme, and maybe shielding, i.e new vacuum pipe,..
- Electron cloud and ions!!!



CLIC Main Beam Injector LINACS

S. Doebert, POSIPOL 2013



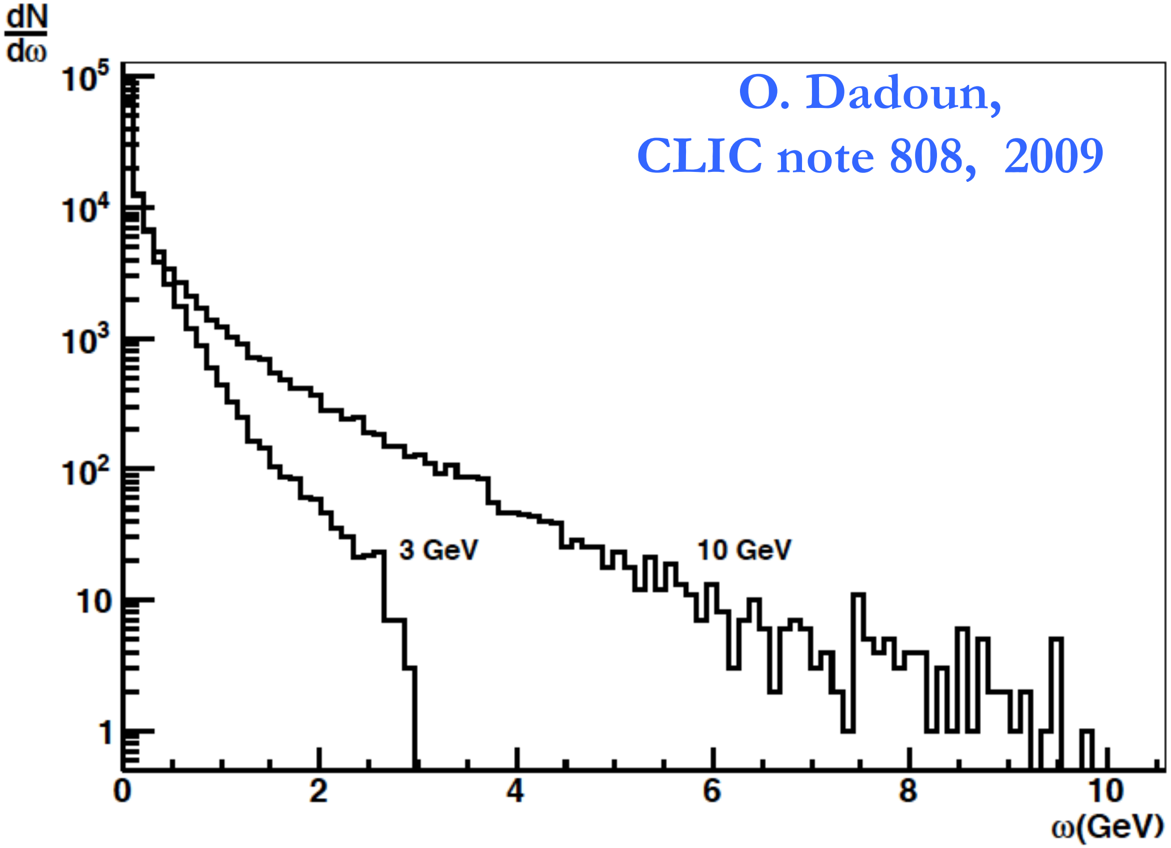


- Common injector linac
- All linac's at 2 GHz, bunch spacing 1 or 2 GHz before the damping rings
- Hybrid positron sources for positron production
- Needs **shielding** around the target area

Target Parameters Crystal		
Material	Tungsten	W
Thickness (radiation length)	0.4	χ_0
Thickness (length)	1.40	mm
Energy deposited	~1	kW

Target Parameters Amorphous		
Material	Tungsten	W
Thickness (Radiation length)	3	χ_0
Thickness (length)	10	mm
PEDD	30	J/g
Distance to the crystal	2	m

Positron production for CLIC - Crystal



- Photon distribution for incident electron beam of 3 and 10 GeV after tungsten crystal, peaked at lower energies (majority of the photons below 100MeV)
- No issue with power deposited on crystal (below 1% of incident electron beam power

E_{e^-}(GeV)	P_{e^-}(kW)	t(cm)	N_γ/e^-	$\bar{E}_\gamma$(MeV)	P_γ(kW)
10	190	0.10	22.5	304	130
5	90	0.14	20.0	160	58
4	72	0.15	18.5	136	45
3	54	0.16	15.5	115	32

Positron production for CLIC - target

O. Dadoun,
CLIC note 808, 2009

E_{e^-} (GeV)	Yield	P(kW)	Pedd(J/g)
3	1.04	7.9	10.30
4	1.50	10.8	16.90
5	1.95	13.4	24.27
10	4.14	22.4	59.81

- For amorphous tungsten target Peak Energy deposition density limited below 35J/g
- Compromise should be found between incident electron parameters (energy, charge), required positron yield, distance between crystal and converter, target thickness and adiabatic matching device (AMD) parameters

Outlook

- Synchrotron radiation power in Booster ring is much lower than in collider but with similar critical energy
  - Absorbers and shielding are necessary
- Synchrotron radiation power in the SPS is much higher and necessitates absorbers and shielding
- Vacuum chamber design for both rings may become complex (anti-chambers, coatings for SEY reduction and pumping, eddy current considerations,…)
- Pre-injector has requirements typical to electron linacs
- Positron production system necessitates careful design for required yield but also associated power deposition (damage) and shielding (radiation)

感谢您的关注

Thank you for your attention