Progress in synchrotron radiation studies and tools

Helmut Burkhardt (CERN) and Manuela Boscolo (INFN-LNF)

Contact for detector/experiments : Nicola Bacchetta

presented by M. Boscolo,

FCC-ee Physics Workshop (TLEP9), Pisa, Feb. 4th 2015

Introduction

- Synchrotron radiation fans in IR region for the BINP and CERN designs at top energy, 175 GeV / beam

- More on MDI for FCC-ee, concepts and generic simulations :
  - **Principles and scaling** presentation by M.B. **Oct. '13 at TLEP#6 CERN**
  - **Experience with backgr.** presentation by Helmut **March' 14 at EIC'14 JLAB**
  - **MDI for FCC-ee** presentation by Nicola **June '14 at TLEP#7 CERN**
  - **Losses in IR and Touschek** presentation by M.B. **Oct.'14 at HF2014 Beijing**
  - **IRChallenges** presentation by Helmut **Oct.'14 at TLEP#8 Paris**
  - **Synchrotron Rad. in IR** presentation by Helmut **Dec. '14 at VIDYO meet. No.11 CERN**

- Synchrotron Radiation is a big concern for FCC-ee, in addition there are other background sources that need careful studies

Background Sources

Two Main Classes:

- Synchrotron Radiation
- beam particles e+, e-, e+e- effects
  - Bhabha
  - Beamstrahlung
  - Touschek
  - beam-gas
  - pair production
  - ….

Both aspects deeply studied for present/past machines

- beam particles effects (better) studied at Factories
- SR manageable extrapolation from LEP experience

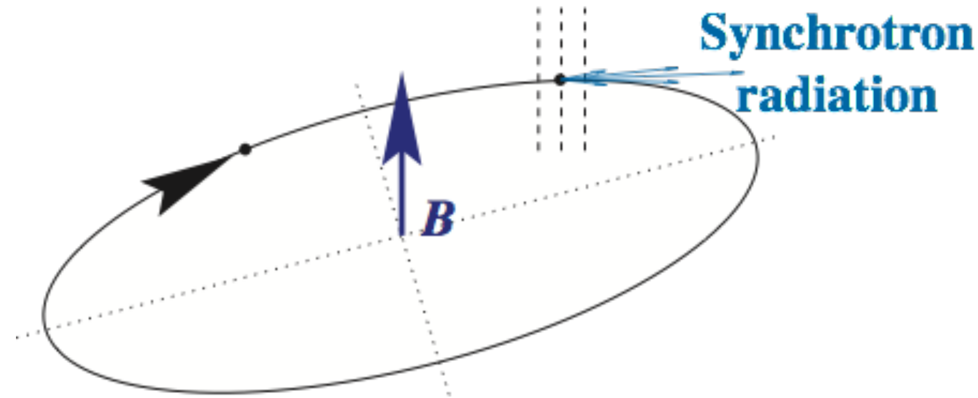
Synchrotron Radiation

$$E_c = \frac{3}{2}\frac{\hbar c\,\gamma^3}{\rho} = 2.96\times10^{-7}\mathrm{eV\,m}\,\frac{\gamma^3}{\rho}$$

$$\langle E_\gamma\rangle = \frac{8}{15\sqrt{3}}E_c \approx 0.308\;E_c$$

$$U_0 = \frac{e^2}{3\epsilon_0}\frac{\gamma^4}{\rho} \approx 6.0317\cdot10^{-9}\;\mathrm{eV\,m}\;\;\frac{\gamma^4}{\rho}$$

$$P_b = \frac{U_0\,I_b}{e}$$



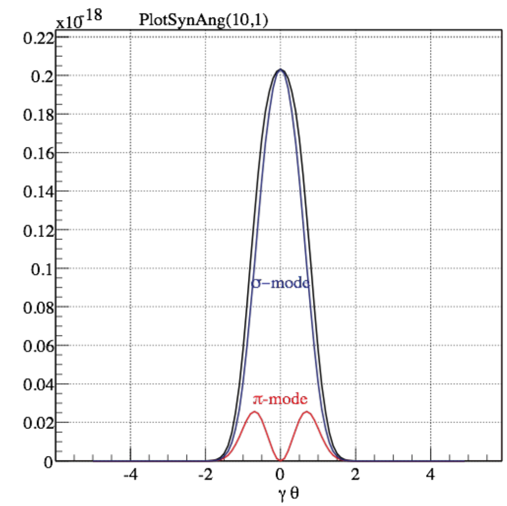
mean free path length λ between radiation

$$\lambda = \frac{\lambda_B}{B_\perp} \qquad \text{where} \quad \lambda_B = \frac{2\sqrt{3}}{5}\frac{mc}{\alpha e} = 0.16183\,\mathrm{Tm}$$

LEP2, TLEP, B ≃ O (0.1 T) O (1 m)

SynRad cone distribution mostly from bending angle O(mrad)

+ minor contribution from
beam divergence O(10 μrad)
and SynRad process



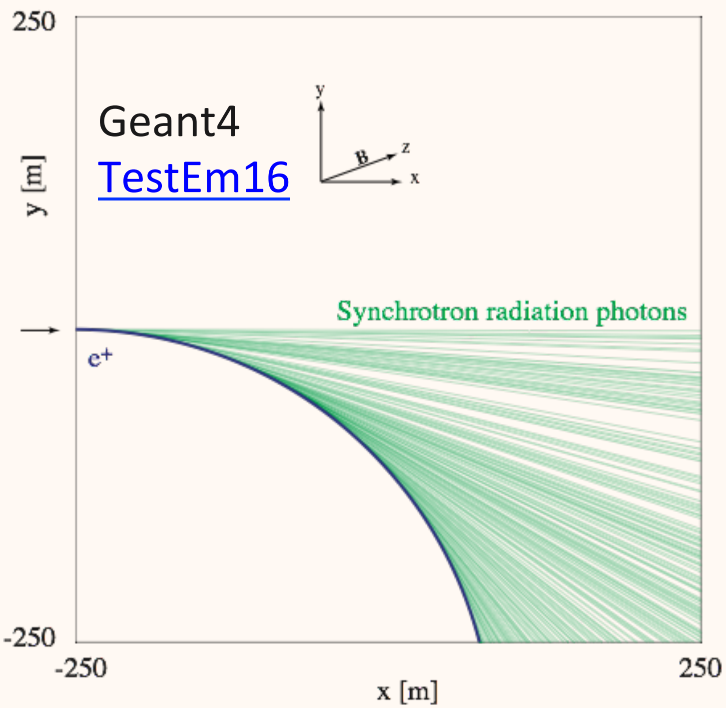
angular distribution (at E_c)
~ $1/\gamma$ = 3 μrad @ TLEP

Spectrum

Photon energy in units of the critical energy. $x = E_\gamma / E_c$

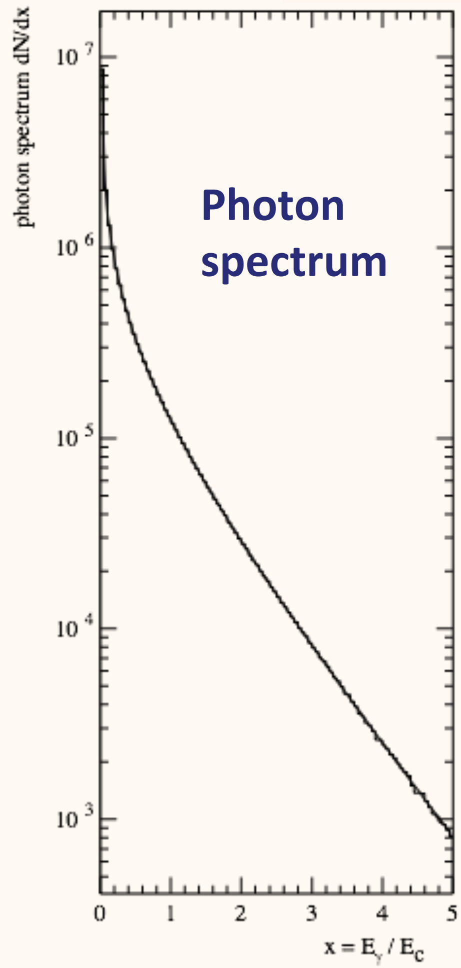
For hom. field over formation length : single spectrum

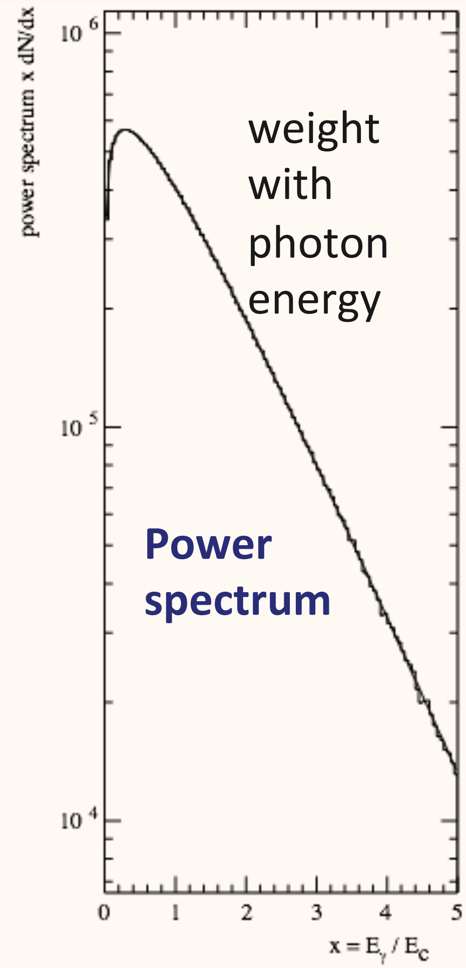
$$\frac{d^2N}{ds\,dx} = \frac{\sqrt{3}\,\alpha}{2\pi}\,\frac{eB_\perp}{mc}\int_x^\infty K_{5/3}(\xi)\,d\xi$$



10 GeV e+ moving initially in x-direction, bend downwards on a circular path by a 0.1 T magnetic field in z-direction. Geant4 TestEm16

This year : generalized to long live charged particle in Geant4 10.1 released 5/12/2014

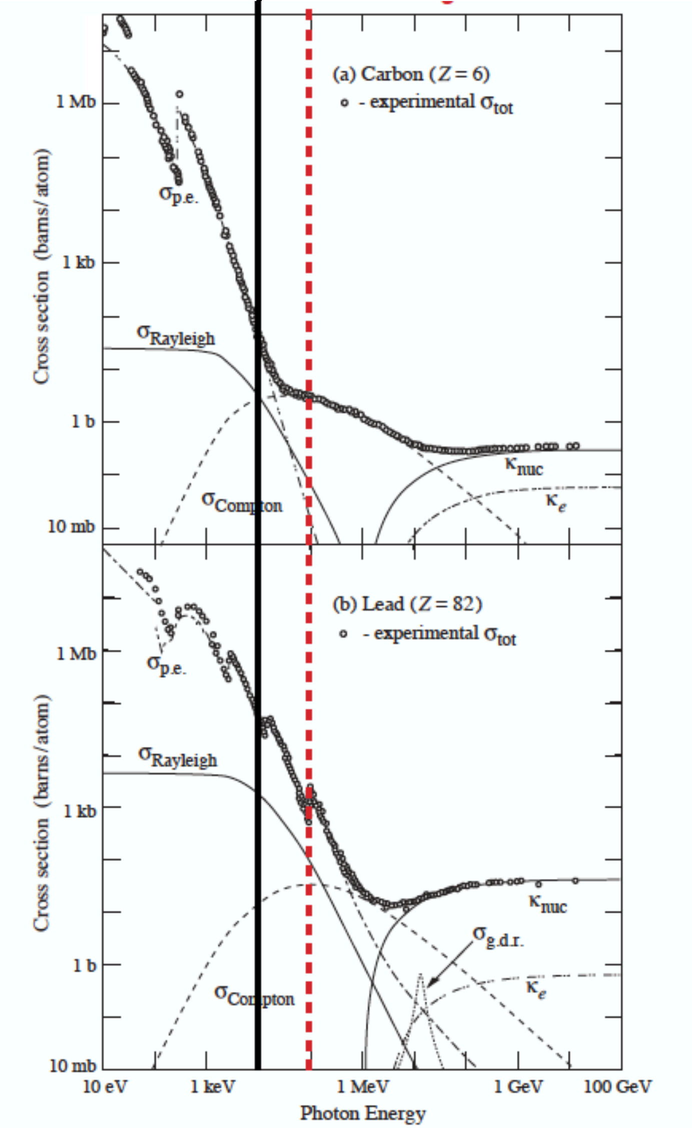




Ref.: H.B., CERN-OPEN-2007-018, Geant4 physics-manual   Implemented as process G4SynchrotronRadiation

Spectrum and absorption

✔ < 10 keV | very difficult above 100 keV



Typical mean (0.3 E_c) photon energies

B-factories (and **FCC-hh**) mostly below 10 keV

LEP1 : 21 keV
LEP2 : 320 keV (arc, last bend 10× lower)

TLEP : ~ 350 keV (arc, 175 GeV)
-> very similar to LEP2
difficult to collimate

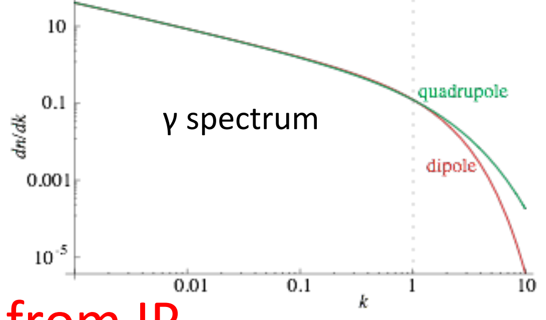
Enormous photon flux, MWs of power
can get kW locally, melt equipment, detectors..

Aim as for LEP2 :
do not generate hard synchrotron radiation anywhere close to the IR

Approach for FCC-ee IR challenges

Challenge: maximize performance (integrated luminosity) for experiments **for good** or at least tolerable **experimental (background, stability) conditions.**

H.B. Chapter 5.2 Landolt-Börnstein New Series I/21C



Some key points :

Minimize synchrotron radiation in the IR region =>

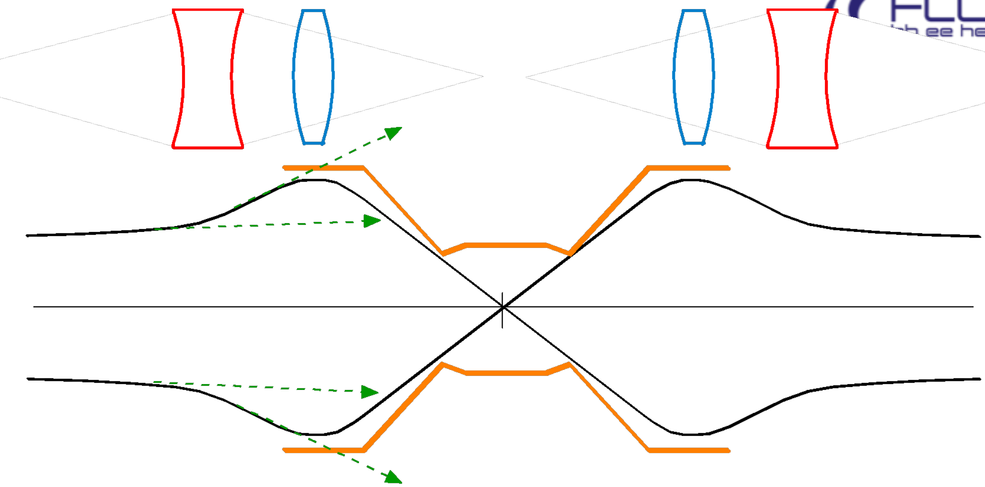
- **Bends** as weak as possible and as far as possible from IP
- **Quads** have to be strong and close to IP,
  Minimize offset from quad axis
  Careful with vertical halo/tails

SR Monte Carlo : H.B. CERN-OPEN-2007-018 integrated in G4

- **For FCC the approach has been to start developing the software tools**

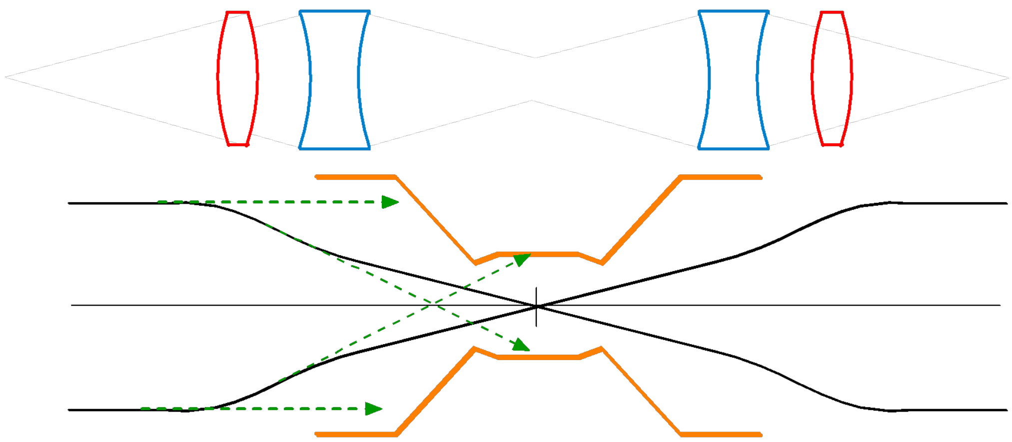
SR from the final focusing magnets

SR from the last vertical focusing magnet can usually be shielded from the IP detector beam pipe. This is more difficult when the photons penetrate the beam pipe



Vertical beam focusing
(side view)

SR from the last horizontal focusing magnet is more difficult to block because the beam is over-focused in order to compensate for the defocusing from the last quadrupole



Horizontal beam focusing
(plan view)

[M. Sullivan, HF2014, Beijin, 9-12 Oct. 2014]

MDISim: generic tool for IR studies

- MAD-X lattice and survey (geometry), if available with apertures: basis
- ROOT: main geometry and interface tool
- With extra library to read MAD-X tfs files and calculate derived machine parameters (SynRad)

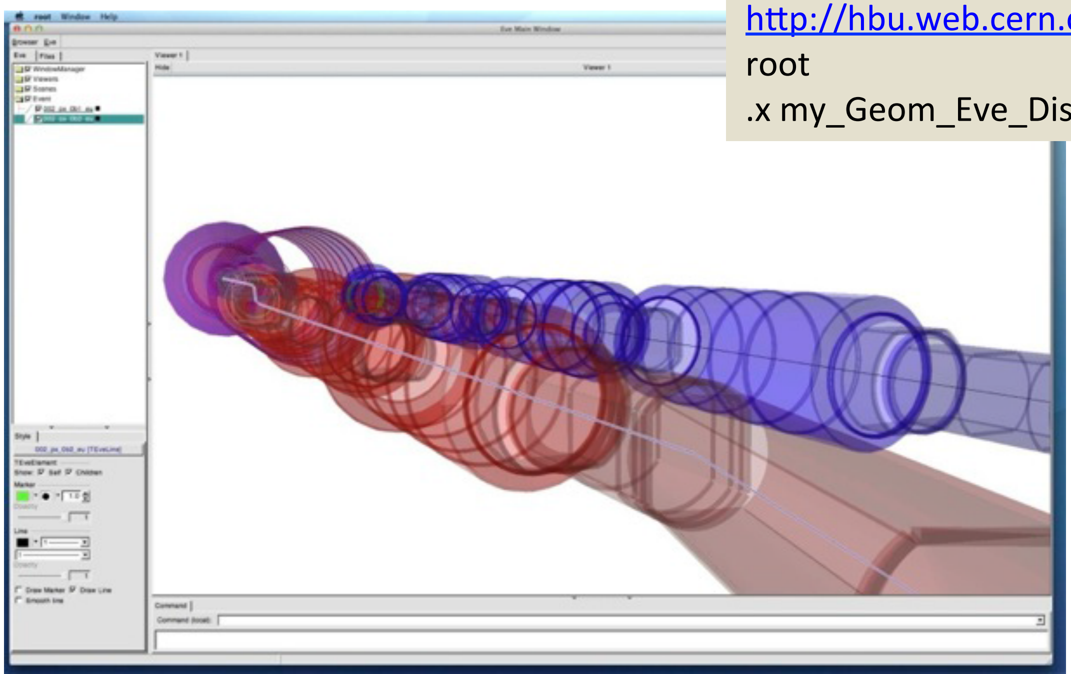
Step 1 : Construct tables (ntuples) with detailed information element by element

transformation of Courant-Snyder machine coordinates to Euclidian detector coordinates

Display geometry and optionally accelerator tracks

- **Step 2 :** geometry display based on MAD-X aperture information using the EVE (Event Visualization Environment)
- **Step 3 :** accelerator tracking (several options, example here is MAD-X, LHC IR geometry)

Run our demo :
http://hbu.web.cern.ch/hbu/Geom/my_Geom_Eve_Display.C
root
.x my_Geom_Eve_Display.C



Export/import Geometry; ROOT to Geant4

ROOT

gGeoManager->Export("LHC_IR_5.gdml"); // export the whole geometry in gdml, or xml, C, root

GEANT4, straightforward to import ROOT geometry - which can be full machine

```
  in DetectorConstruction.cc
G4GDMLParser parser ; parser.Read("FCC-hh.gdml");
fBox=parser.GetWorldVolume();
```

Loop over imported volumes and set magnetic field and additional parameters if required

```
G4LogicalVolumeStore* lvs = G4LogicalVolumeStore::GetInstance();
for( auto lvciter = lvs->begin(); lvciter != lvs->end(); ++lvciter ) // loop over imported geometry modules
{
  G4MagField* ThisField = new G4MagField(localfieldValue); // set the local field
  G4FieldManager* fLocalFieldManager = new G4FieldManager(ThisField);
  fLocalFieldManager->SetDetectorField(ThisField);
  if(localfieldValue!=0)
  {
    fLocalFieldManager->CreateChordFinder(ThisField);
    fLocalFieldManager->GetChordFinder()->SetDeltaChord(accuracy); // adjust field tracking accuracy
  }
  else fLocalFieldManager->SetDetectorField(NULL);
  G4bool forceToAllDaughters = true; // use field for daughter modules
    if(VolName=="top") forceToAllDaughters=false; // except for top volume which cover all other volumes
  lvciter->SetFieldManager(fLocalFieldManager, forceToAllDaughters);
}
```

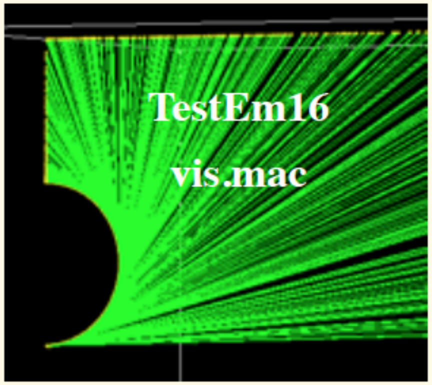
Synergies with FCC-hh

Contact to MDI FCC-hh detector : Werner Riegler, CERN

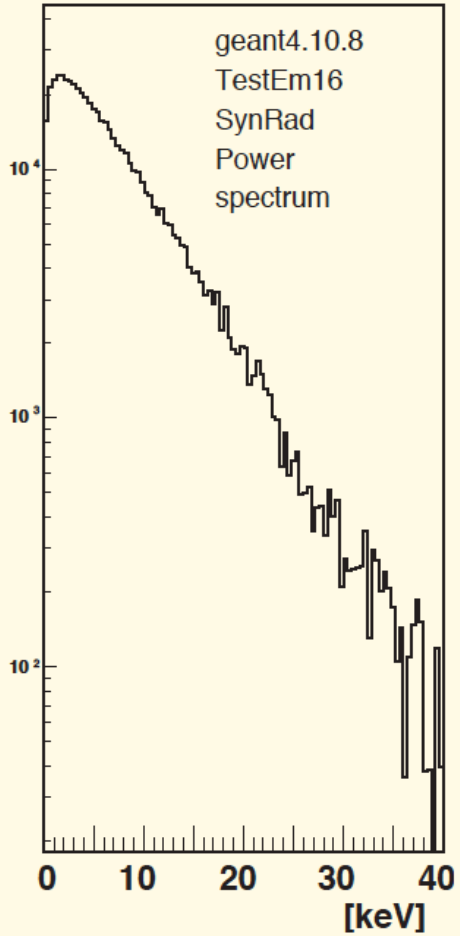
Generic geometry / field interfaces can be applied equally to ee, hh (and LHeC Peter Koska et al.)

Synchrotron radiation in FCC also relevant for hh

G4SynchrotronRadiation now works for all long lived charged particles proton, ions ..



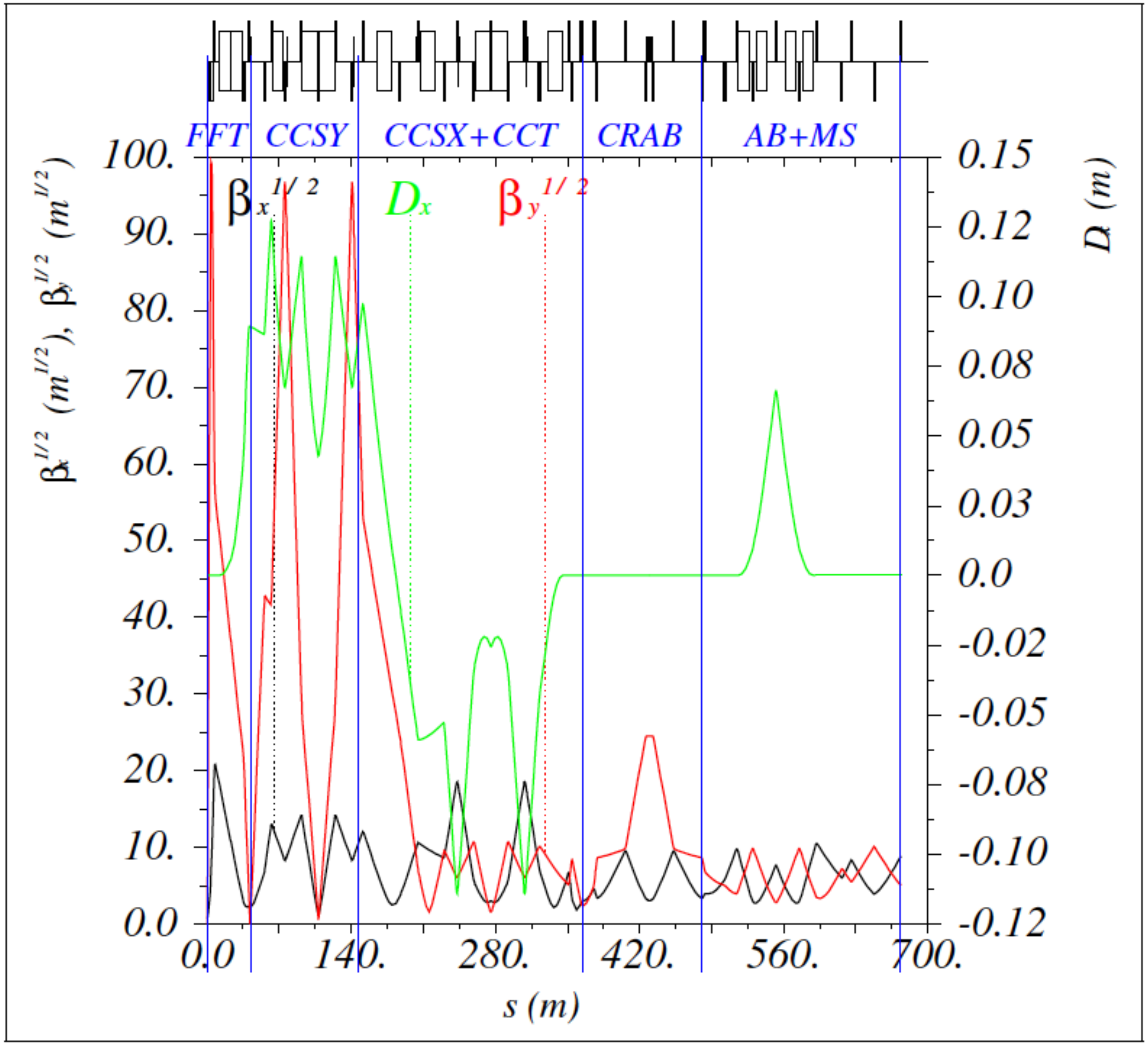
Presented at annual
Geant4 collaboration meeting
Sept. 2014 in Okinawa
Status and Validation of Standard EM Physics
by Vladimir Ivanchenko
for the G4 EM standard WG



FCC example
100 TeV pp collisions
50 TeV/beam
20 Tesla magnetic field
3 MW in proton synchrotron radiation

Ecrit = 5.4 keV
comparable to B-factories

Interaction Region optical functions



TLEP Optics with Crab Waist - BINP

(TLEP_V14_IR_6-13-2)

MDISIM output

red color : energy over 100 keV, and within 200 m of IP

bends

iele	NAME	KEYWORD	S	L	Angle	Emean	ngamBend	rho	B	BETX	SIGX	divx	Power
			m	m		keV		m	T	m	mm	mrad	Watt
13	L.MB0	SBEND	22.56	10.5	0.001	348.64	3.6071	1.05e+04	0.055594	122	0.4646	0.02834	3.349e+04
15	L.MB1	SBEND	33.66	10.5	0.0037	1290	13.346	2.84e+03	0.205698	14.21	0.1586	0.02834	4.585e+05
39	L.MB2	SBEND	73.68	10.5	0.0037674	1313.5	13.59	2.79e+03	0.209446	78.22	0.372	0.01655	4.753e+05
59	L.MB3	SBEND	107.2	14.5	0.0051804	1307.9	18.686	2.8e+03	0.208551	2.024	0.05984	0.03686	6.508e+05
65	L.MB4	SBEND	123.5	14.5	0.0051804	1307.9	18.686	2.8e+03	0.208551	185.1	0.5723	0.03686	6.508e+05
91	L.MB5	SBEND	179.7	14.5	0.00063536	160.41	2.2918	2.28e+04	0.025578	6.146	0.1043	0.01713	9789
105	L.MB6	SBEND	221.5	14.5	0.0002393	60.415	0.86319	6.06e+04	0.00963366	84.76	0.3873	0.005598	1389
129	L.MB7	SBEND	274.6	14.5	-0.0031537	796.19	11.376	4.6e+03	-0.126959	8.549	0.123	0.01494	2.412e+05
135	L.MB8	SBEND	291	14.5	-0.0031537	796.19	11.376	4.6e+03	-0.126959	26.96	0.2184	0.01494	2.412e+05
161	L.MB9	SBEND	345.5	14.5	-0.0028026	707.57	10.109	5.17e+03	-0.112827	19.14	0.184	0.01956	1.905e+05
235	L.MB10	SBEND	526.5	10.5	0.0011018	384.13	3.9743	9.53e+03	0.0612522	18.23	0.1796	0.02132	4.065e+04
241	L.MB11	SBEND	543.5	10.5	0.0011018	384.13	3.9743	9.53e+03	0.0612522	23.68	0.2047	0.01544	4.065e+04
247	L.MB12	SBEND	571.8	10.5	0.0011018	384.13	3.9743	9.53e+03	0.0612522	7.454	0.1148	0.01544	4.065e+04
253	L.MB13	SBEND	588.8	10.5	0.0011018	384.13	3.9743	9.53e+03	0.0612522	86.85	0.392	0.02132	4.065e+04
273	MB1.A1C1.DS	SBEND	686.4	10.5	0.00048843	170.29	1.7618	2.15e+04	0.0271539	35.99	0.2523	0.01122	7989
275	MB2.A1C1.DS	SBEND	697.5	10.5	0.00048843	170.29	1.7618	2.15e+04	0.0271539	16.97	0.1733	0.01122	7989
282	MB3.A1C1.DS	SBEND	711.4	10.5	0.00048843	170.29	1.7618	2.15e+04	0.0271539	36.24	0.2532	0.01122	7989
284	MB4.A1C1.DS	SBEND	722.5	10.5	0.00048843	170.29	1.7618	2.15e+04	0.0271539	73.12	0.3597	0.01122	7989
292	MB5.A1C2.DS	SBEND	736.4	10.5	0.00048843	170.29	1.7618	2.15e+04	0.0271539	35.99	0.2523	0.01122	7989
294	MB6.A1C2.DS	SBEND	747.5	10.5	0.00048843	170.29	1.7618	2.15e+04	0.0271539	16.97	0.1733	0.01122	7989

from summing up energy loss the 1660 bends U0sum=2.149 GeV PowSum= 57.234 MW

Quads, at 1 sigmax, horizontal

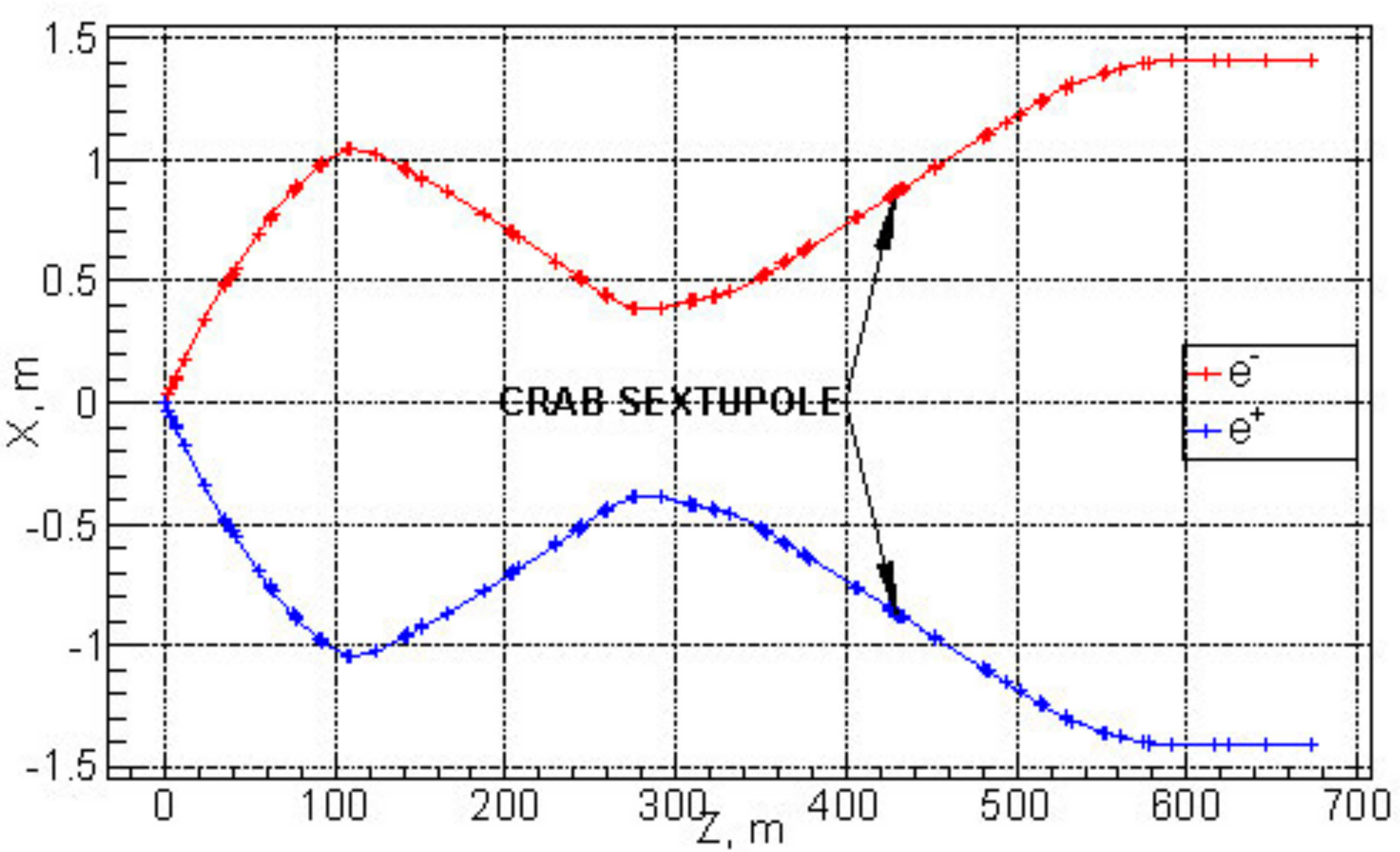
iele	Element	s	betx	sigx	divx	K1L	k0	L	x	Angle	Emean	ngam	Power
		m	m	mm	mrad	m-2	m-1	m	mm		keV		Watt
5	L.MQ0_1	3.8	41.5	0.2709	0.006531	-0.29142	7.8947e-05	1.8	8.6833e-32	0.000142104	289.004	0.512589	3944.81
7	L.MQ0_2	5.6	183	0.5684	0.003113	-0.29142	0.00016565	1.8	1.7717e-31	0.000298166	606.395	1.07553	17367.2
9	L.MQ1_1	7	393	0.8338	0.002122	0.15977	0.00013321	1	2.5822e-31	0.000133211	487.651	0.480509	6239.69
11	L.MQ1_2	8	433	0.8752	0.002022	0.15977	0.00013984	1	2.7024e-31	0.000139835	511.902	0.504405	6875.72
17	L.MQ2_1	35.7	7.16	0.1126	0.01571	-0.06095	6.8626e-06	1	5.8903e-20	6.86259e-06	25.1222	0.0247543	16.56
19	L.MQ2_2	36.7	5.8	0.1013	0.01747	-0.06095	6.1735e-06	1	7.0102e-20	6.17354e-06	22.5998	0.0222688	13.4015

from summing up energy loss in the 1562 quads U0Sum=0.00390576 GeV plane=x PowSum=104.006 kW

Optics files in /afs/cern.ch/eng/fcc/ee/TLEP_V14_IR_6-13-2/ by Anton Bogomyagkov et al
as presented by Anton and Dmitry last Dec.: https://indico.cern.ch/event/356596/

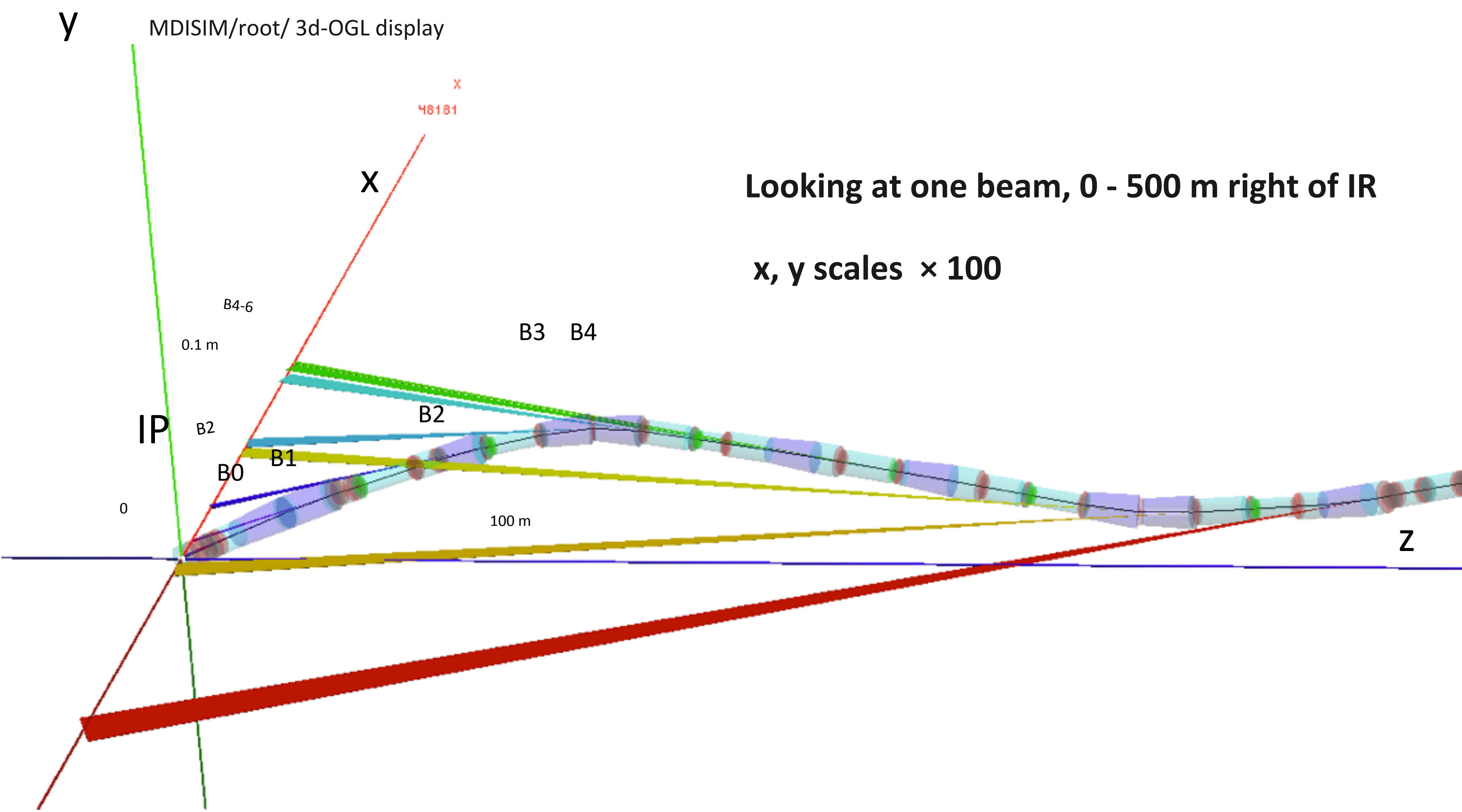
FCC-ee crab-waist IR

A. Bogomyagkov



SynRad bend cones

TLEP_V14_IR_6-13-2 **BINP**



TLEP Optics - CERN

(TLEP_V12A)

MDISIM output

red color : energy over 100 keV, and within 200 m of IP

bends

iele	NAME	KEYWORD	S (m)	L (m)	Angle	Emean (keV)	ngamBend	rho (m)	B (T)	BETX (m)	SIGX (mm)	divx (mrad)	Power (Watt)
14	BMVC	SBEND	129	47.26	0.002	154.92	7.2143	2.36e+04	0.024704	315.4	0.5597	0.005639	7368
24	BMVC	SBEND	273.8	47.26	0.002	154.92	7.2143	2.36e+04	0.024704	101.8	0.318	0.00564	7368
26	BMVC	SBEND	322.1	47.26	0.002	154.92	7.2143	2.36e+04	0.024704	315.4	0.5597	0.005639	7368
36	BMVC	SBEND	466.8	47.26	0.002	154.92	7.2143	2.36e+04	0.024704	101.8	0.318	0.00564	7368
39	BMHC	SBEND	503	35.19	−0.002	208.03	7.2143	1.76e+04	−0.0331727	21.71	0.1468	0.006974	9893
49	BMHC	SBEND	611.6	35.19	−0.002	208.03	7.2143	1.76e+04	−0.0331727	100.1	0.3153	0.006973	9893
51	BMHC	SBEND	647.8	35.19	−0.002	208.03	7.2143	1.76e+04	−0.0331727	21.71	0.1468	0.006974	9893
61	BMHC	SBEND	756.4	35.19	−0.002	208.03	7.2143	1.76e+04	−0.0331727	100.1	0.3153	0.006973	9893
79	MB1.A3C1.DS	SBEND	808.8	10.5	0.00049583	172.87	1.7885	2.12e+04	0.0275653	36.2	0.1896	0.008248	2038
81	MB2.A3C1.DS	SBEND	819.9	10.5	0.00049583	172.87	1.7885	2.12e+04	0.0275653	17.59	0.1322	0.008248	2038
88	MB3.A3C1.DS	SBEND	833.8	10.5	0.00049583	172.87	1.7885	2.12e+04	0.0275653	36.26	0.1898	0.008233	2038
90	MB4.A3C1.DS	SBEND	844.9	10.5	0.00049583	172.87	1.7885	2.12e+04	0.0275653	71.82	0.2671	0.008233	2038
98	MB5.A3C2.DS	SBEND	858.8	10.5	0.00049583	172.87	1.7885	2.12e+04	0.0275653	35.5	0.1878	0.008334	2038
100	MB6.A3C2.DS	SBEND	869.9	10.5	0.00049583	172.87	1.7885	2.12e+04	0.0275653	17.04	0.1301	0.008334	2038
107	MB7.A3C2.DS	SBEND	883.8	10.5	0.00049583	172.87	1.7885	2.12e+04	0.0275653	36.37	0.19	0.008385	2038
109	MB8.A3C2.DS	SBEND	894.9	10.5	0.00049583	172.87	1.7885	2.12e+04	0.0275653	73.15	0.2695	0.008385	2038
119	MB9.A3C3	SBEND	908.8	10.5	0.00099166	345.74	3.5771	1.06e+04	0.0551306	36.11	0.1894	0.008386	8152
121	MB10.A3C3	SBEND	919.9	10.5	0.00099166	345.74	3.5771	1.06e+04	0.0551306	17.09	0.1303	0.008386	8152
130	MB11.A3C3	SBEND	933.8	10.5	0.00099166	345.74	3.5771	1.06e+04	0.0551306	36.29	0.1898	0.00838	8152
132	MB12.A3C3	SBEND	944.9	10.5	0.00099166	345.74	3.5771	1.06e+04	0.0551306	72.99	0.2692	0.00838	8152

from summing up energy loss the 6592 bends U0sum=7.801 GeV PowSum=51.4238 MW

Quads, at 1 sigmax, horizontal

iele	Element	s (m)	betx (m)	sigx (mm)	divx (mrad)	K1L (m-2)	k0 (m-1)	L (m)	x (mm)	Angle	Emean (keV)	ngam	Power (Watt)
3	Q4	3.07	16.7	0.129	0.007701	−0.6072	7.8304e-05	1.0741	3.9205e-21	8.41039e-05	286.651	0.303374	573.256
5	Q3	6.31	127	0.3545	0.002801	0.27506	9.7521e-05	1.2351	1.3913e-20	0.00012045	356.999	0.434479	1022.47
8	Q2	65.4	28.7	0.1688	0.005882	−0.038944	6.5752e-06	1	2.412e-20	6.5752e-06	24.0701	0.0237176	3.76329
10	Q1	80.8	101	0.3168	0.003135	0.033179	1.0511e-05	1	4.0143e-20	1.05115e-05	38.4799	0.0379163	9.61782
13	QDV	81.8	102	0.318	0.003123	−0.014755	4.6918e-06	0.5	4.0051e-20	2.34588e-06	17.1753	0.00846191	0.958055
15	QFV2	130	312	0.5568	0.001784	0.02951	1.6431e-05	1	5.3019e-18	1.64308e-05	60.149	0.0592681	23.4999
19	QDV2	178	8.04	0.08934	0.01112	−0.02951	2.6363e-06	1	8.399e-18	2.63629e-06	9.65078	0.00950944	0.604971
23	QFV2	227	315	0.5597	0.001774	0.02951	1.6517e-05	1	2.2837e-17	1.65167e-05	60.4635	0.059578	23.7463
25	QDV2	275	102	0.318	0.003123	−0.02951	9.3835e-06	1	1.0464e-17	9.38351e-06	34.3507	0.0338476	7.66444

PowSum=91.4409 kW

Based on tlep_v12a_cern_full_ring.madx from Roman Martin received by email on 10/12/2014

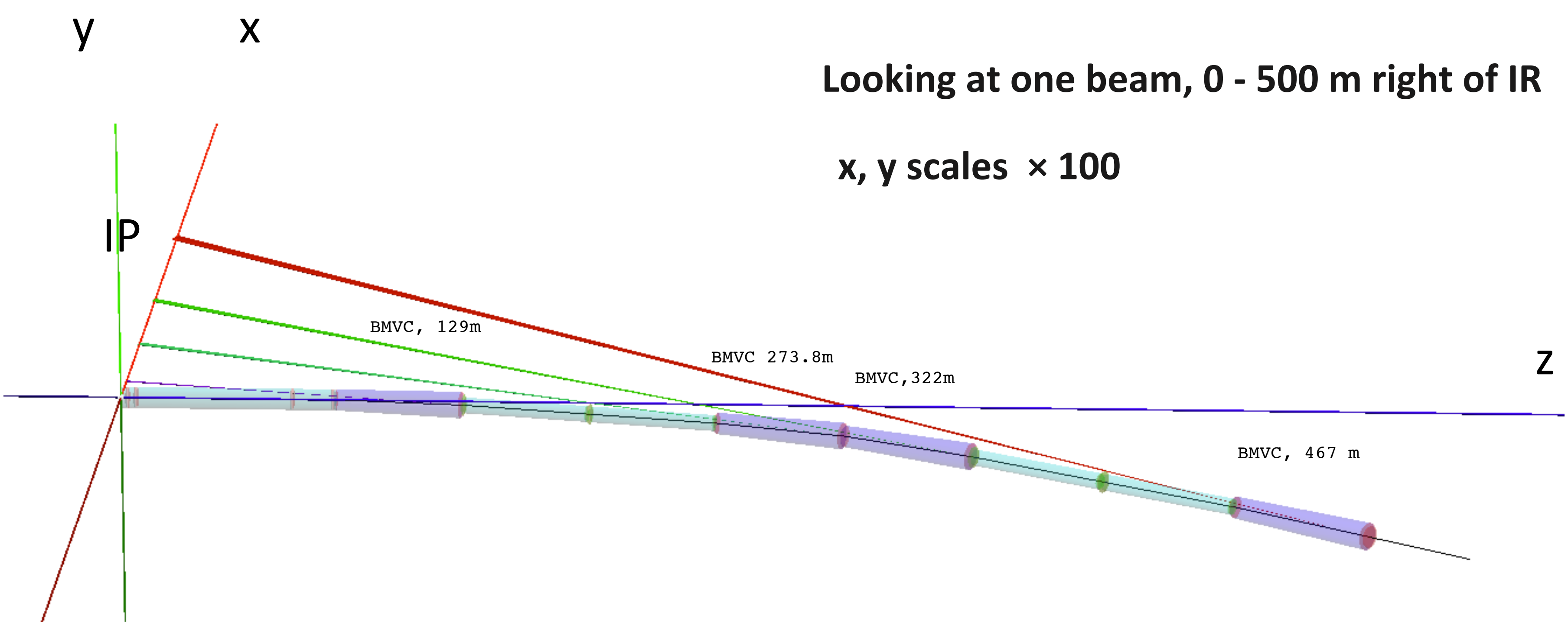
SynRad bend cones for CERN optics

TLEP_V12A

MDISIM/root/ 3d-OGL display

Looking at one beam, 0 - 500 m right of IR

x, y scales × 100



Synchrotron Radiation

Concerns:

- compatibility of stay-clear apertures with effective masking of incoming SR
- edge scattering from upstream SR masks
- backscattering from downstream aperture limitations

Beam Particle Effects

- Beam-gas
- Touschek

Machine Induced Backgrounds
single beam effect, losses in the whole tunnel

- Radiative Bhabha
- Beamstrahlung

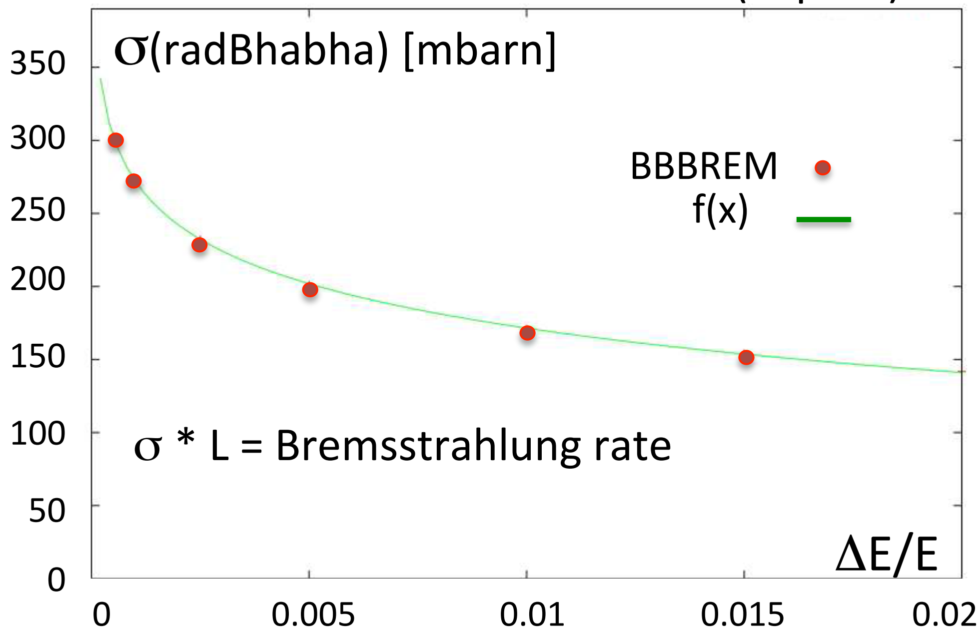
IP backgrounds, mainly losses at IP,
multiturn tracking needed for low-angle scatterings

strongly dependent on momentum acceptance

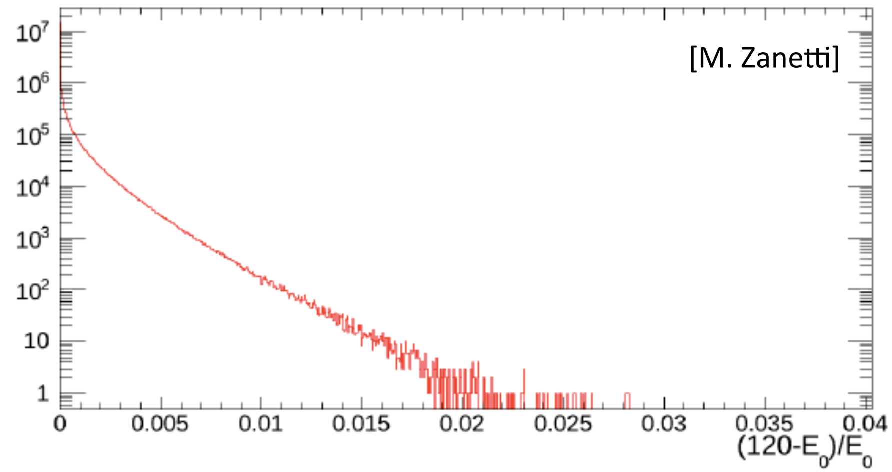
- e+e- pairs

Dependence on Energy Acceptance

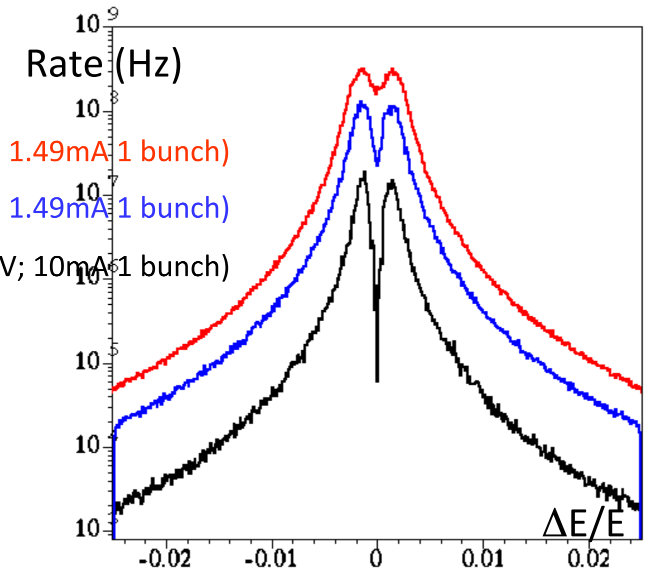
Radiative Bhabha Cross-section (SuperB)



Beamsstrahlung rate (FCC-ee)



Touschek particles/ second



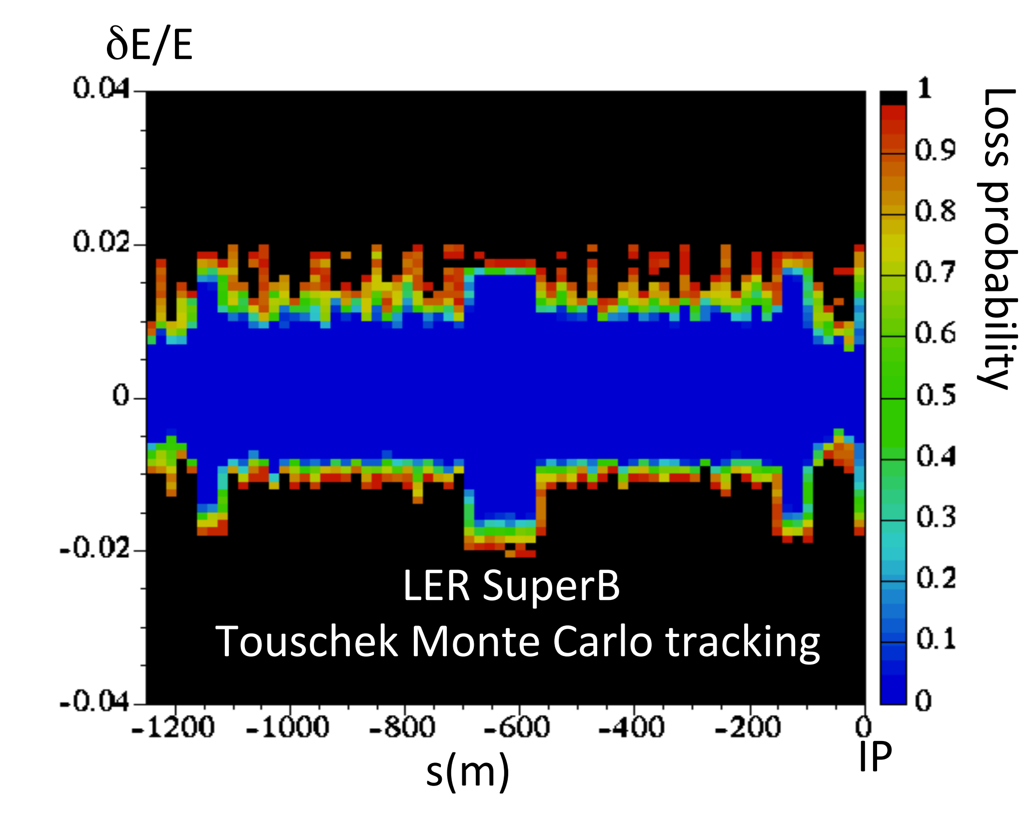
Lifetime estimated for these effects usually assumes ring's energy acceptance

Momentum aperture

- Crucial for all sources inducing a $\delta E/E$

like Touschek, rad Bhabha, beamstralung (HE)

- Best determined with full tracking



Not just an *s* dependent momentum aperture

A.Xiao,M.Borland, PAC07 p.3457

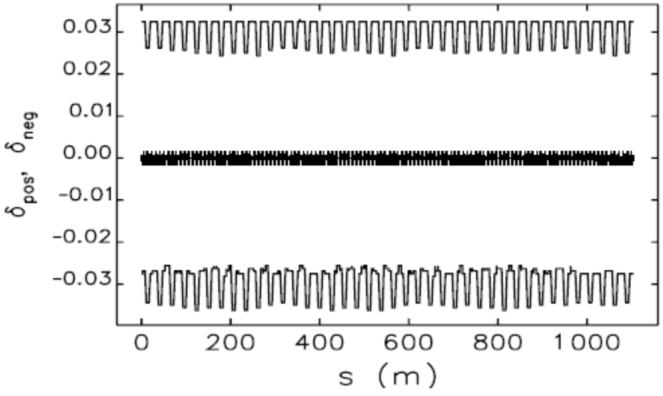
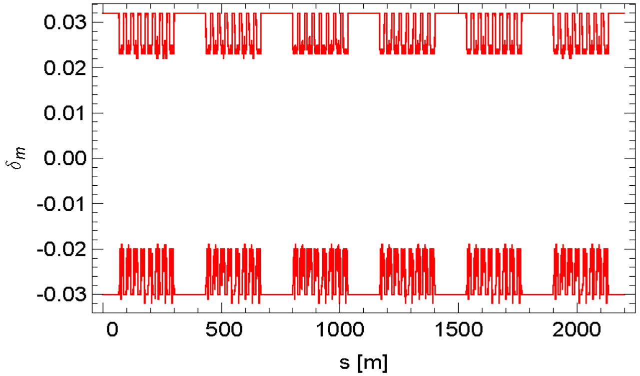


Figure 1: Momentum aperture of the APS.

momentum aperture



PEP-X Y. Cai, SLAC
FLS-2012, March 2012

Pair production: e^+e^- (and $\mu^+\mu^-$)

- $e^+e^- \rightarrow e^+e^- e^+e^-$
- It can be studied with GUINEA-PIG generator
- can be high production rate but particles have low energy and loop in the solenoid field
- relevant for which sub-system?
  - typically low energy curling e^+e^- relevant for vertex detector and first layers of tracking devices
- first guess at generator level (with magnetic fields)
- full simulation with Geant4 needed for detailed study
- Same statements are valid for $\mu^+\mu^-$ production ($e^+e^- \rightarrow e^+e^- \mu^+\mu^-$) to be checked at these energies

Conclusions

- Synchrotron radiation in the IR region is a major issue for TLEP @ top energy
- Photon energy very similar to LEP2 where this was acceptable with IRs designed for low synrad + ~100 collimators and local masks, (L ~ 1.e32cm-2s-1)
- **Work for FCC-ee / TLEP only started --- much more to do on IR synchrotron radiation and beam particle effects**