MDI studies for FCC-hh

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RD_FA Collaboration Meeting - Bologna - 03/04.07.2017

INFN Contribution to FCC

- European Circular Collider is a project which objective is to develop the conceptual design of a future hadron collider beyond LHC, as an international collaborative effort under European leadership

- I.N.F.N. has an important role in different Work Packages of this project, with several sections and laboratories involved
- Publications:
  - *"Beam dynamic issues in the FCC, Proceedings of HB2016"*, Malm, Sweden (2016)
  - Periodic EuroCirCol deliverables
  - Posters @IPAC2017 (Copenaghen) and @FCCWeek2017 (Berlin)
  - Peer reviewed paper *"Synchrotron radiation backgrounds for the FCC-hh experiments"* @IPAC2017, IOPScience

Synchrotron Radiation in the experiments for FCC-hh

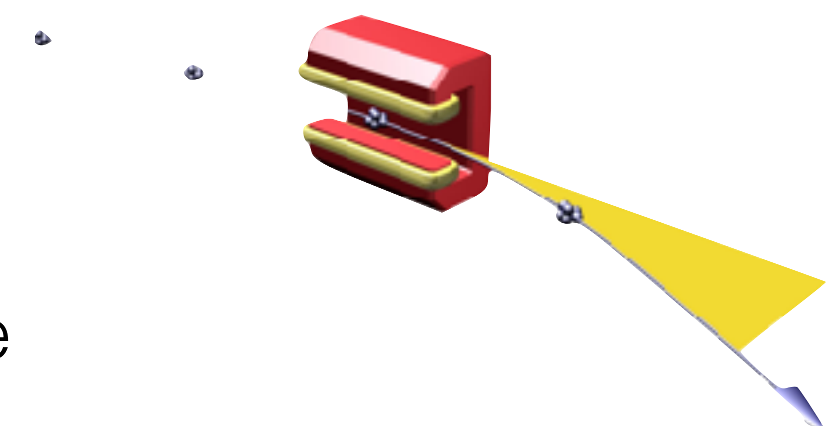
Starting Points

- Synchrotron Radiation (SR) power radiated per beam depends strongly on particle's Lorentz Gamma factor, and hence on particle mass:

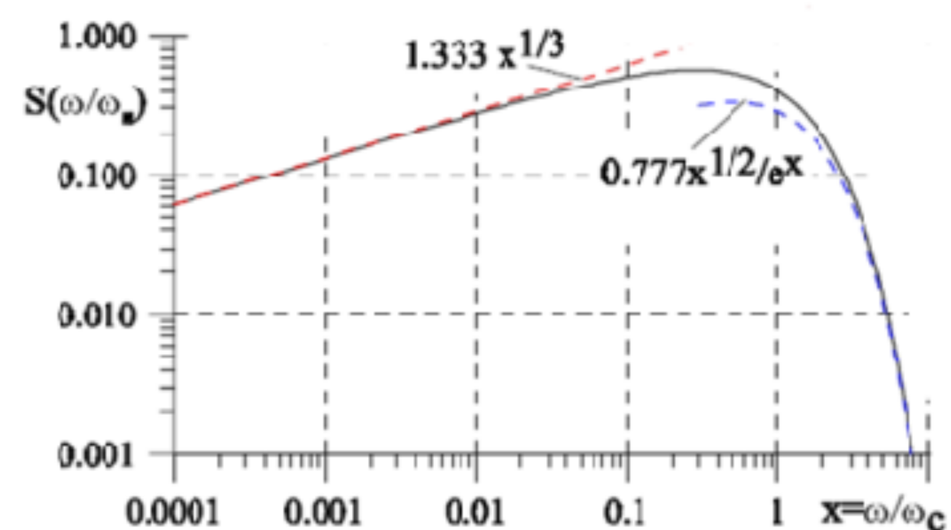
$$P \propto \gamma^4 \rightarrow P \propto m^{-4}$$

➜ while synchrotron radiation is a major concern for electron beams, for protons beams it is usually negligible:

$$P_p \sim 10^{-13} \times P_e$$



- However, in Very High Energy p-p colliders the effect starts to be visible, and should be carefully evaluated



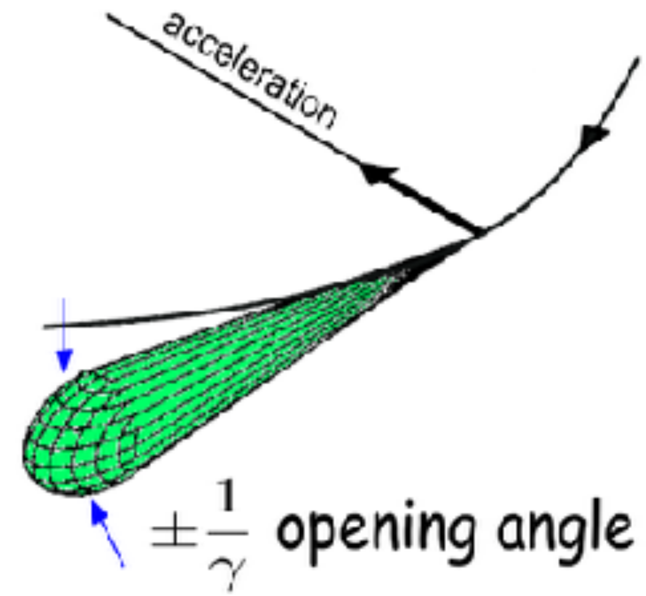
Starting Points

- The synchrotron radiation **cone** is very **narrow**:

$$\gamma_p = \frac{E_p}{m_p} = \frac{50TeV}{938MeV} \sim 5 \times 10^4$$

$$\frac{1}{\gamma_p} \sim 1.9 \times 10^{-5} rad \sim 10^{-3} deg$$

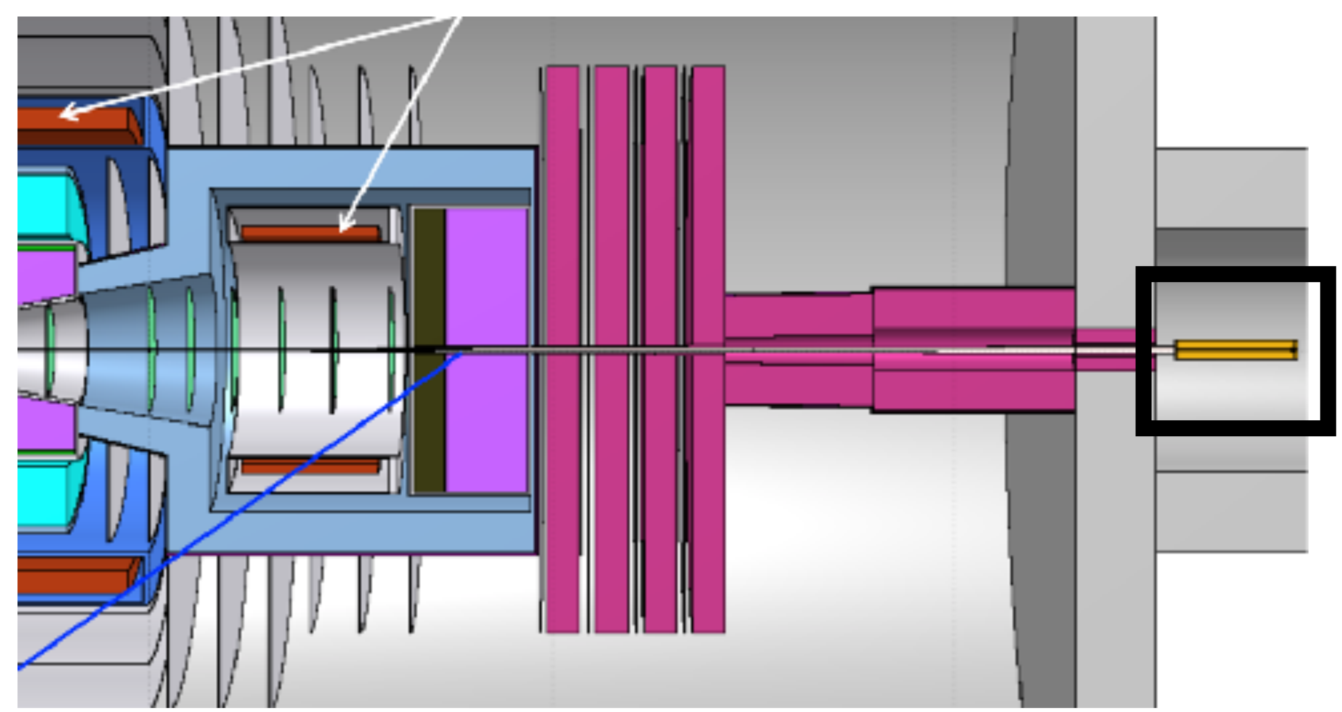
$$\theta_{BEND} = 3 \times 10^{-4} rad$$



  ➡ We assume the SR to be "pencil beam"-like (lying on horizontal plane only)

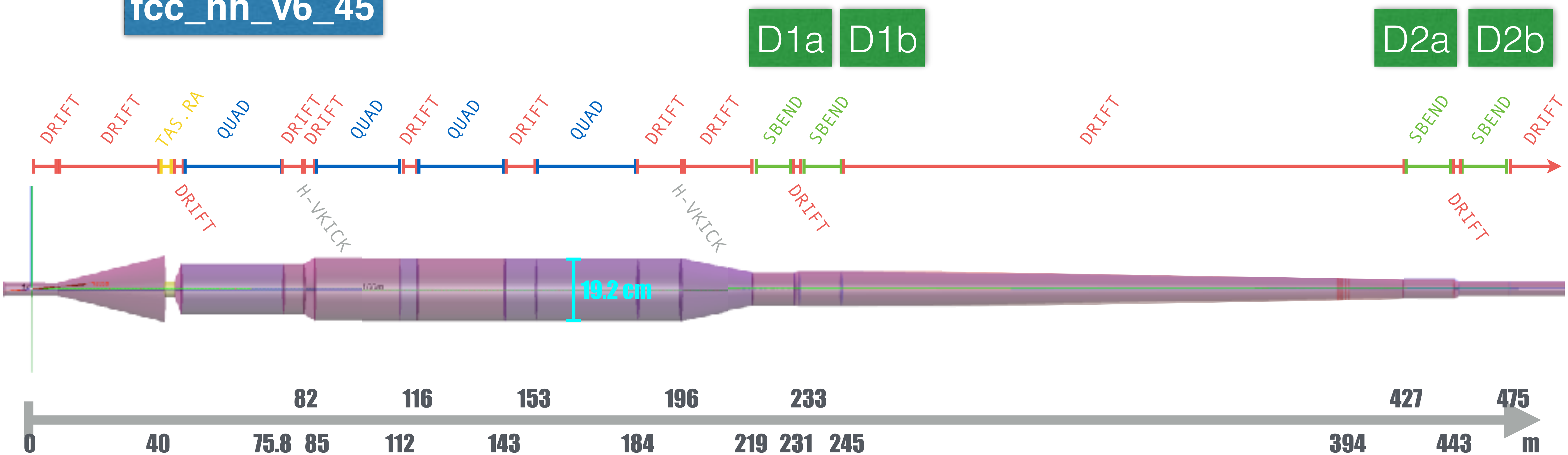
- Only particles entering the TAS can in principle reach the experiments

  ➡ We focus on particles **entering the TAS**



BEAM PIPE SCHEME FROM MAD-X

optics used:
fcc_hh_v6_45



- B=4.27 T
- L=12.5 m
- Θ=-0.3 mrad
- E_C=1.146 keV
- N_γ/proton=0.1795
- P=32 W
- E_{TOT}=6.34 TeV

- B=3.56 T
- L=15 m
- Θ=0.3 mrad
- E_C=0.95 keV
- N_γ/proton=0.1795
- P=27 W
- E_{TOT}=5.28 TeV

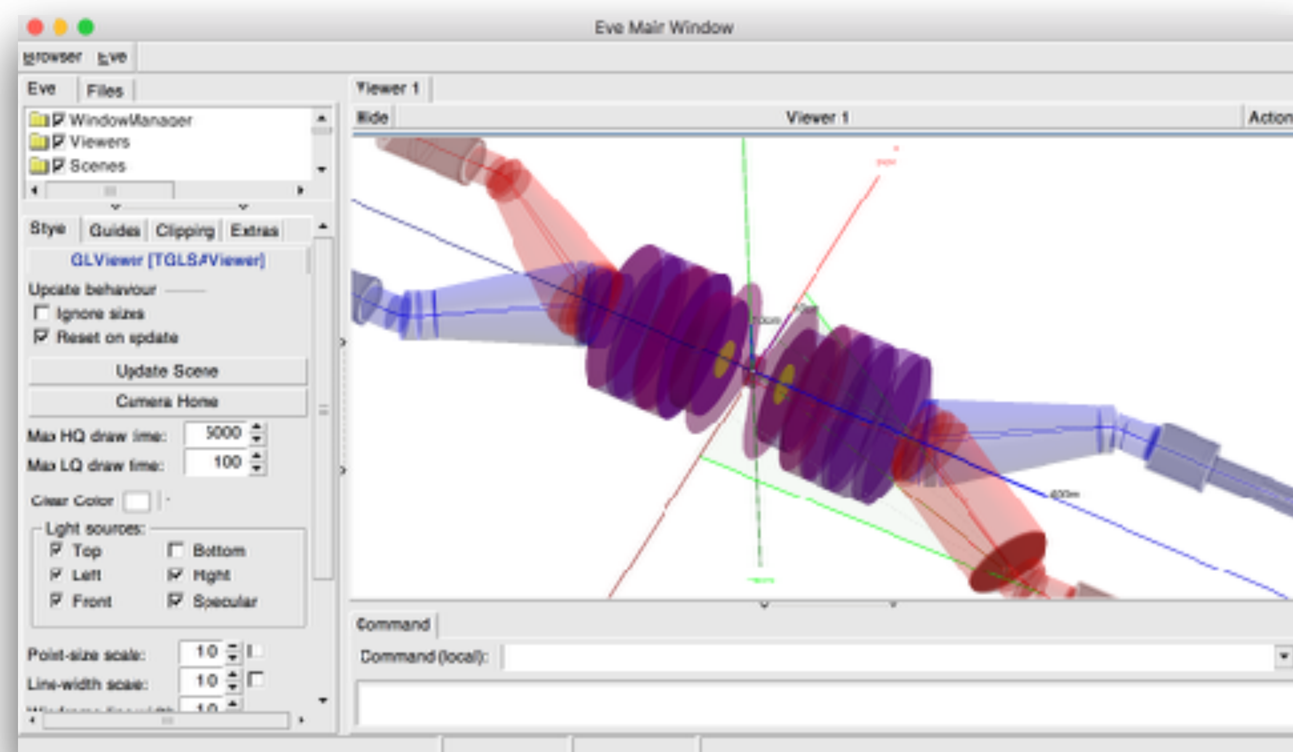
- 5486 Bends in the lattice:
  - All but 4 “strong” (~16T)
  - 4 “soft” (~4T) near the IP

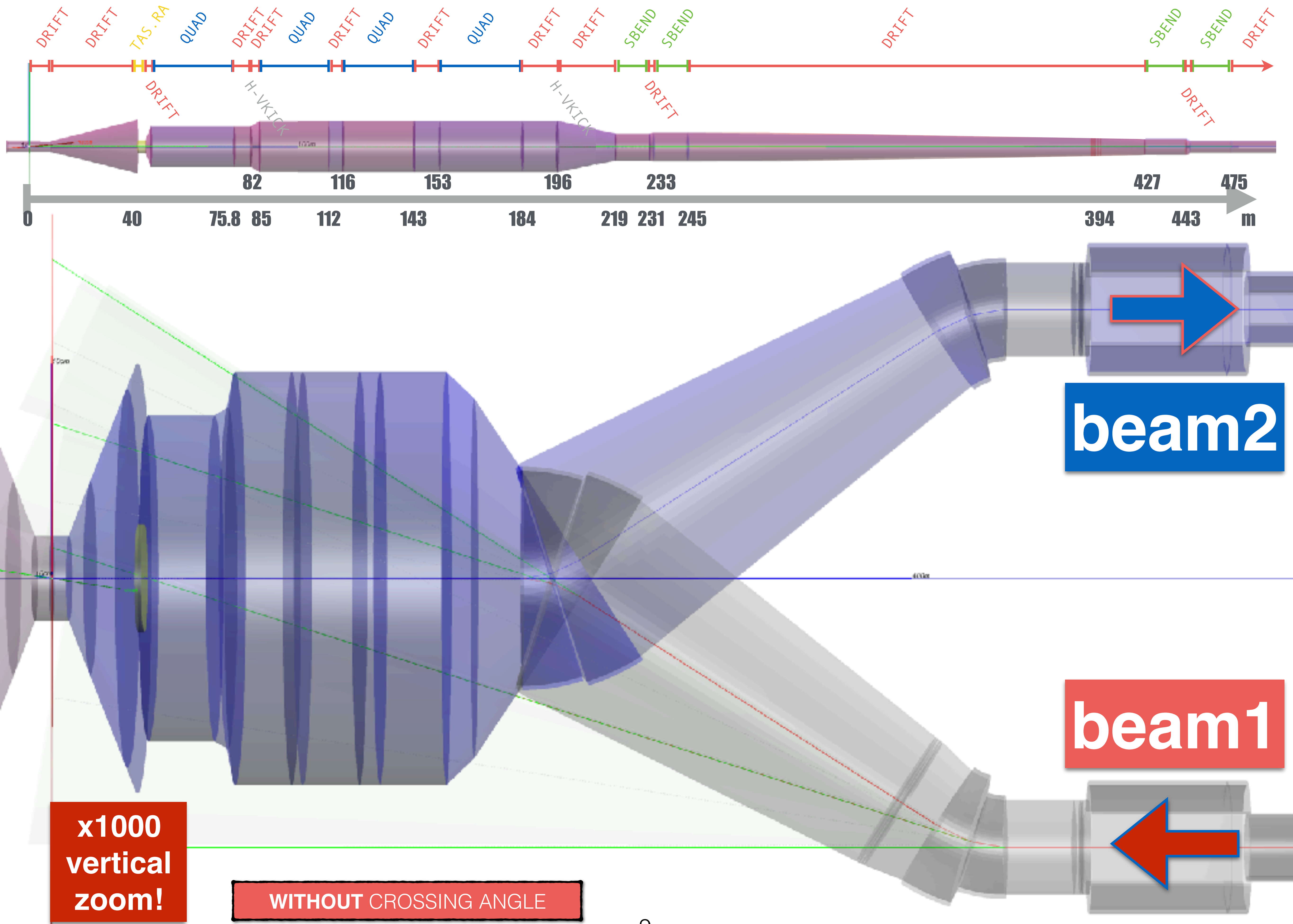
First approach: MDISim

MDISim Tool

- Developed by *Helmut Burkhardt* (CERN), is a set of C++/Root classes that allow to:
  - Run MAD-X on the desired lattice of the FCC
  - Read MAD-X output, plot the lattice
  - **Calculate Synchrotron Radiation** (Power Radiated, Critical Energy..) and plot it over the geometry using Root's TEve
- Import geometry and SR in Geant4 to perform full simulation

link




DRIFT
DRIFT
TAS.RA
QUAD
DRIFT
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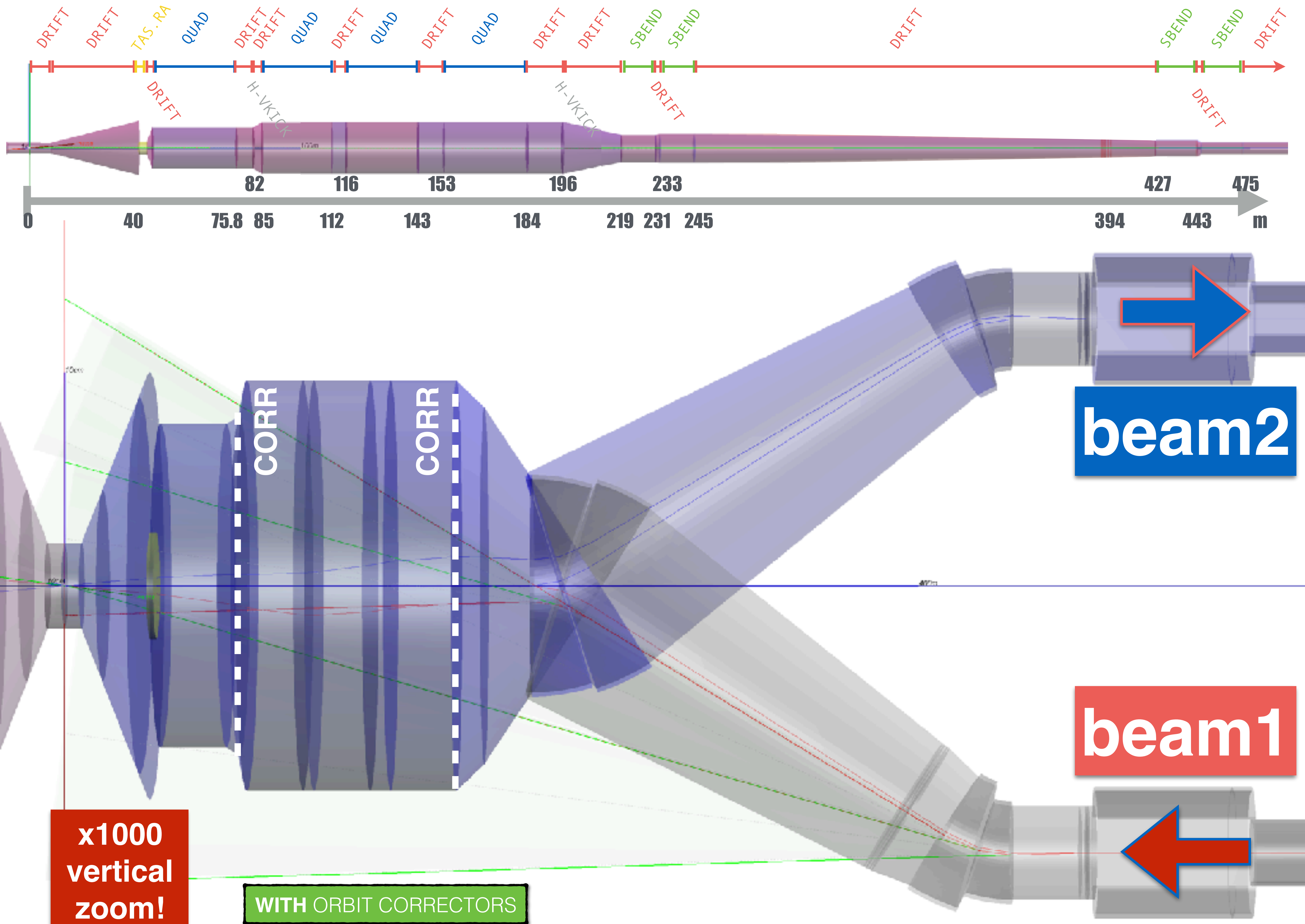
DRIFT
DRIFT
82
116
153
196
233
427
475
0
40
75.8
85
112
143
184
219
231
245
394
443
m
beam2
beam1
x1000 vertical zoom!
WITHOUT CROSSING ANGLE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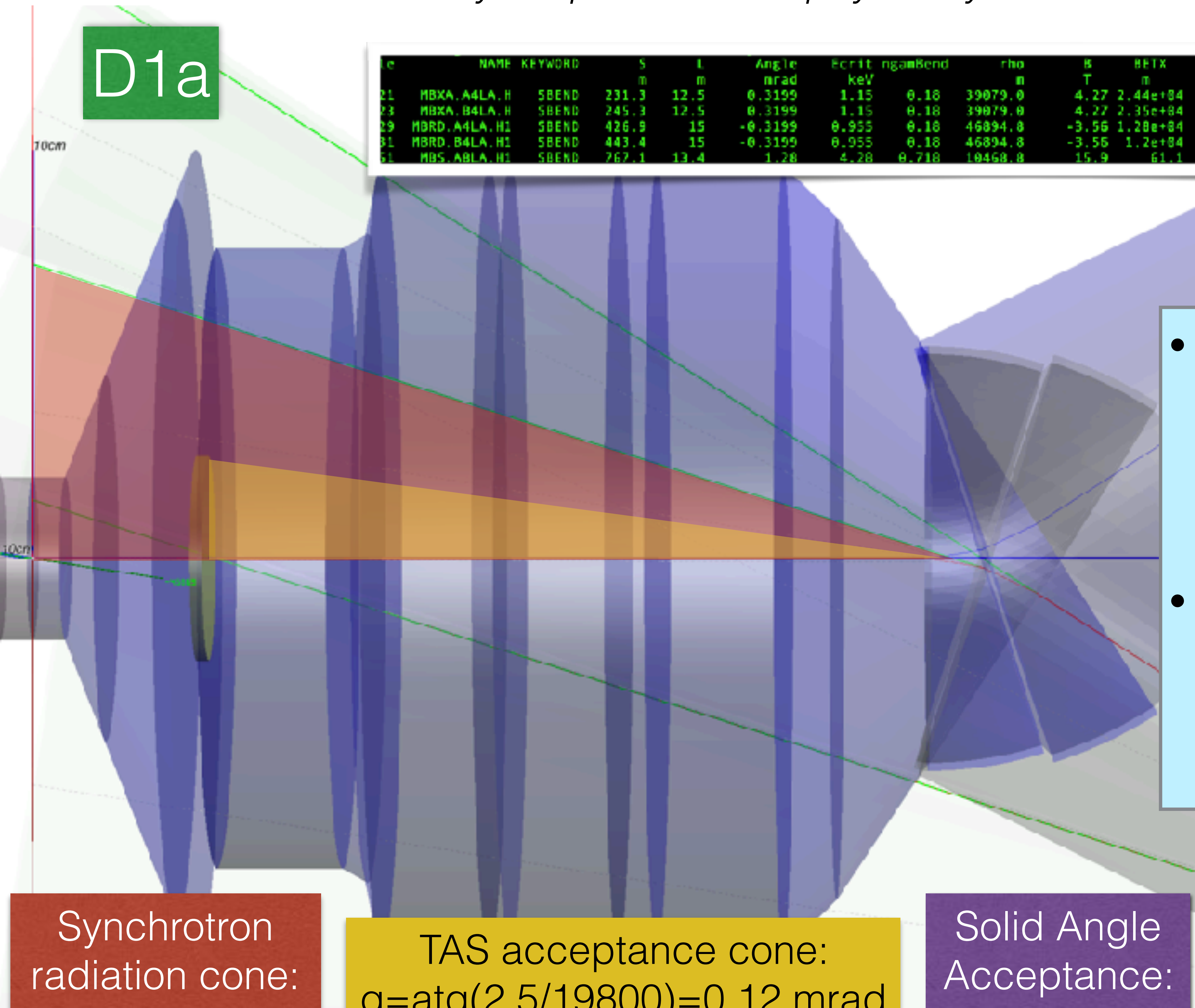
H-VKICK
DRIFT
DRIFT
82 116 153 196 233 427 475
0 40 75.8 85 112 143 184 219 231 245 394 443 m
CORR
CORR
beam2
beam1
x1000 vertical zoom!
WITH ORBIT CORRECTORS

Solid angle evaluation

“How many SR photons can physically enter the TAS aperture?”



le	NAME	KEYWORD	S	L	Angle	Ecrit	ngamBend	rho	B	BETX	SIGX	divx	Power	frac>10MeV	ngam*npart	Egamtot	Em
			m	m	mrad	keV		m	T	m	mm	mrad	kW			GeV	
21	MBXA.A4LA.H	SBEND	231.3	12.5	0.3199	1.15	0.18	39079.0	4.27	2.44e+04	1	0.00141	0.0322	0	1.8e+10	6.34e+03	0.
23	MBXA.B4LA.H	SBEND	245.3	12.5	0.3199	1.15	0.18	39079.0	4.27	2.35e+04	0.984	0.00141	0.0322	0	1.8e+10	6.34e+03	0.
29	MBRD.A4LA.H1	SBEND	426.9	15	-0.3199	0.955	0.18	46894.8	-3.56	1.28e+04	0.728	0.00141	0.0268	0	1.8e+10	5.28e+03	0.
31	MBRD.B4LA.H1	SBEND	443.4	15	-0.3199	0.955	0.18	46894.8	-3.56	1.2e+04	0.705	0.00141	0.0268	0	1.8e+10	5.28e+03	0.
51	MBS.A8LA.H1	SBEND	767.1	13.4	1.28	4.28	0.718	10468.8	15.9	61.1	0.0582	0.000879	0.481	0	7.18e+10	9.46e+04	1

- MDISim gives the total SR power emitted in each element of the lattice
- From geometry the fraction of this power entering the TAS can be evaluated

Synchrotron radiation cone: θ=0.3 mrad

TAS acceptance cone: α=atg(2.5/19800)=0.12 mrad

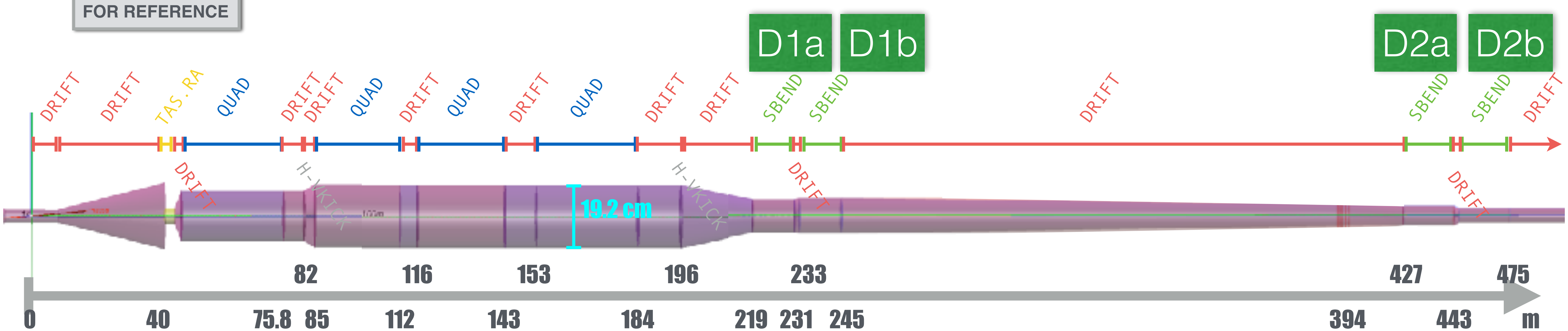
Solid Angle Acceptance: f=α/θ=40%

MDISIM Output

iele	NAME	KEYWORD	S	L	Angle	Ecrit	ngamBend	rho	B	BETX	SIGX	divx	Power	frac>10MeV	ngam*npart	Egamtot	Emean
			m	m	mrad	keV		m	T	m	mm	mrad	kW			GeV	keV
21	MBXA.A4LA.H	SBEND	231.3	12.5	6.3199	1.15	0.18	39079.8	4.27	2.46e+04	1.01	0.00142	0.0322	0	1.8e+10	6.34e-03	0.353
23	MBXA.B4LA.H	SBEND	245.3	12.5	6.3199	1.15	0.18	39079.8	4.27	2.36e+04	0.987	0.00142	0.0322	0	1.8e+10	6.34e-03	0.353
29	MBRD.A4LA.H1	SBEND	426.9	15	-6.3199	0.955	0.18	46894.8	-3.56	1.29e+04	0.73	0.00142	0.0268	0	1.8e+10	5.28e-03	0.294
31	MBRD.B4LA.H1	SBEND	443.4	15	-6.3199	0.955	0.18	46894.8	-3.56	1.21e+04	0.707	0.00142	0.0268	0	1.8e+10	5.28e-03	0.294
51	MBS.A8LA.H1	SBEND	767.1	13.4	1.28	4.28	0.718	10466.8	15.9	61.1	0.0502	0.000877	0.481	0	7.18e+10	9.46e-04	1.32

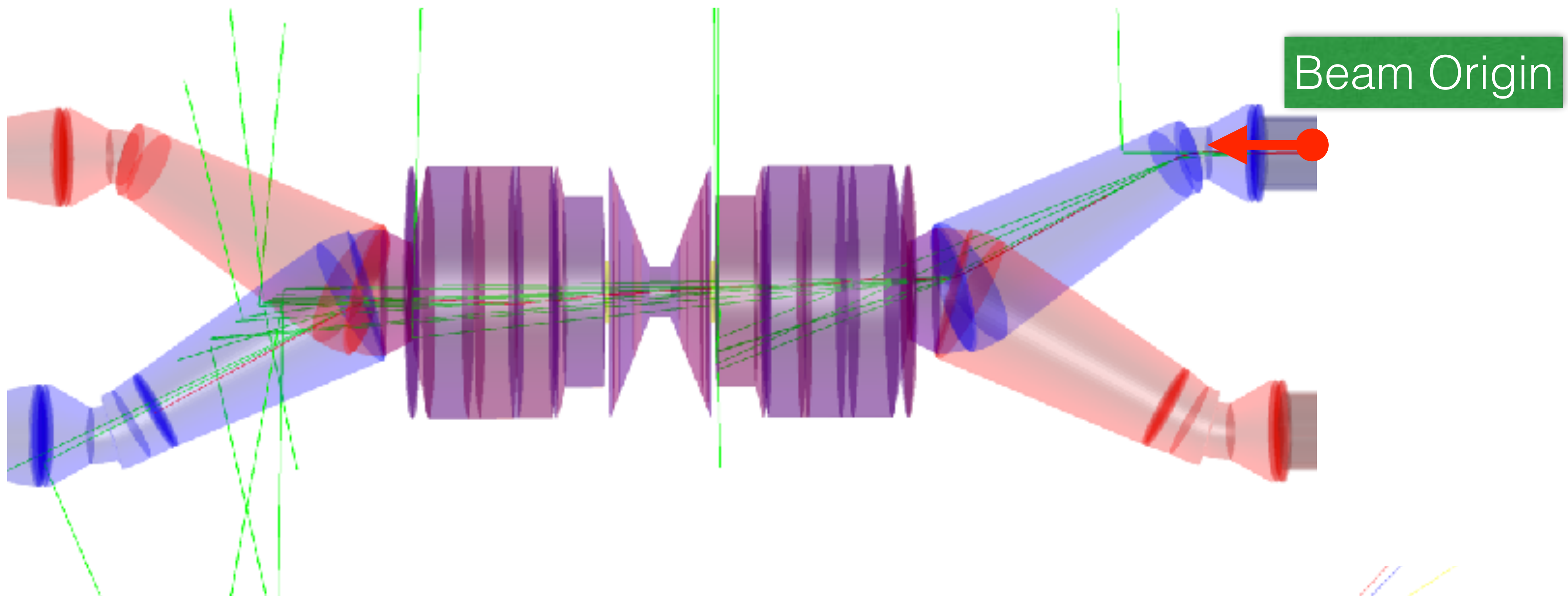
						WITHOUT Crossing Angle			WITH Crossing Angle		
el.	S (m)	B (T)	E_{crit} (keV)	$N_{\gamma TOT}$ (J)	P (W)	f_{TAS} (%)	E_{TAS} (J)	P_{TAS} (W)	f_{TAS} (%)	E_{TAS} (J)	P_{TAS} (W)
D1a	231	-4,3	1,146	1,8E+10	32	40	4,0E-07	12,8	77,0	7,7E-07	24,6
D1b	235	-4,3	1,146	1,8E+10	32	0	—	—	—	—	—
D2a	427	3,6	0,955	1,8E+10	27	15,3	1,3E-07	4,1	8,0	6,8E-08	1,2
D2b	443	3,6	0,955	1,8E+10	27	0	—	—	—	—	—
D3	767	15,9	4,279	7,2E+10	480	—	TOT	17W	–	TOT	26W

FOR REFERENCE



MDISim Tool

- MDISim allows to create a geometry (.gdml) file to be imported in GEANT4
- It is then possible to perform a full physics simulation

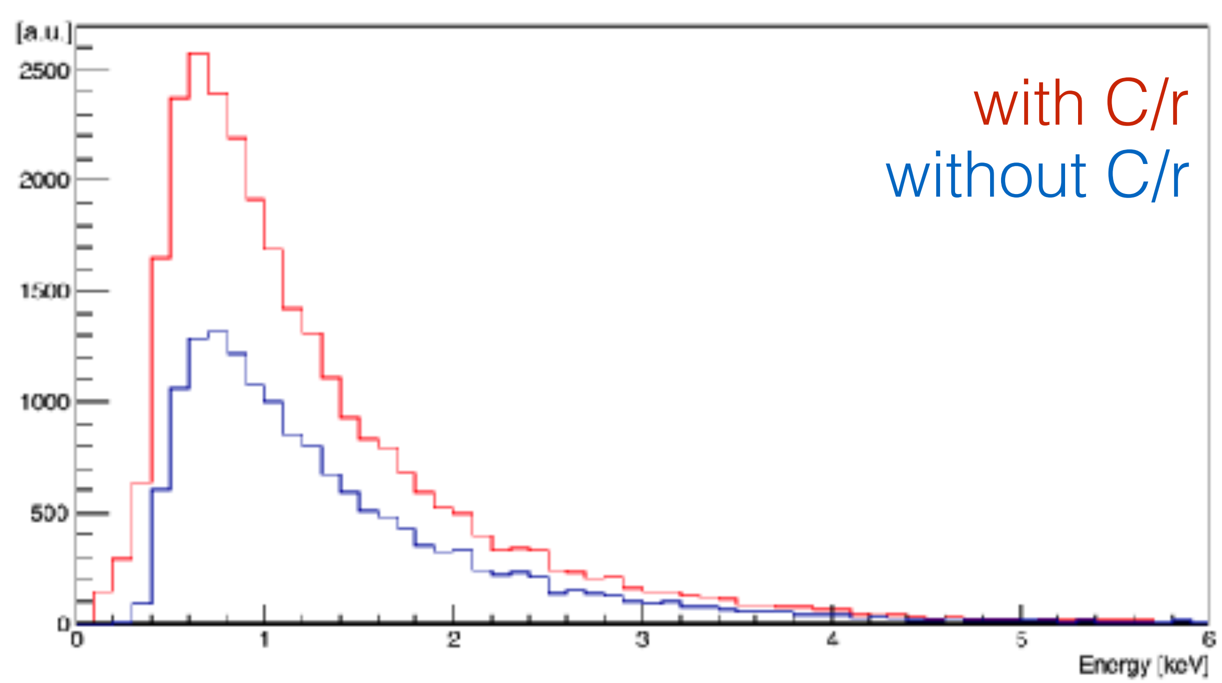


GEANT4 Simulation

- Amount of power entering the TAS:

El.	P [W]	$f_{\not{C}r}$ [%]	$P_{\not{C}r}$ [W]	f_{Cr} [%]	P_{Cr} [W]
$D1_A$	32	40	13	77	25
$D1_B$	32	0	0	0	0
$D2_A$	27	15	4	17	5
$D2_B$	27	0	0	0	0
TOT	-	-	17	-	30

- Spectrum of photons entering the TAS:

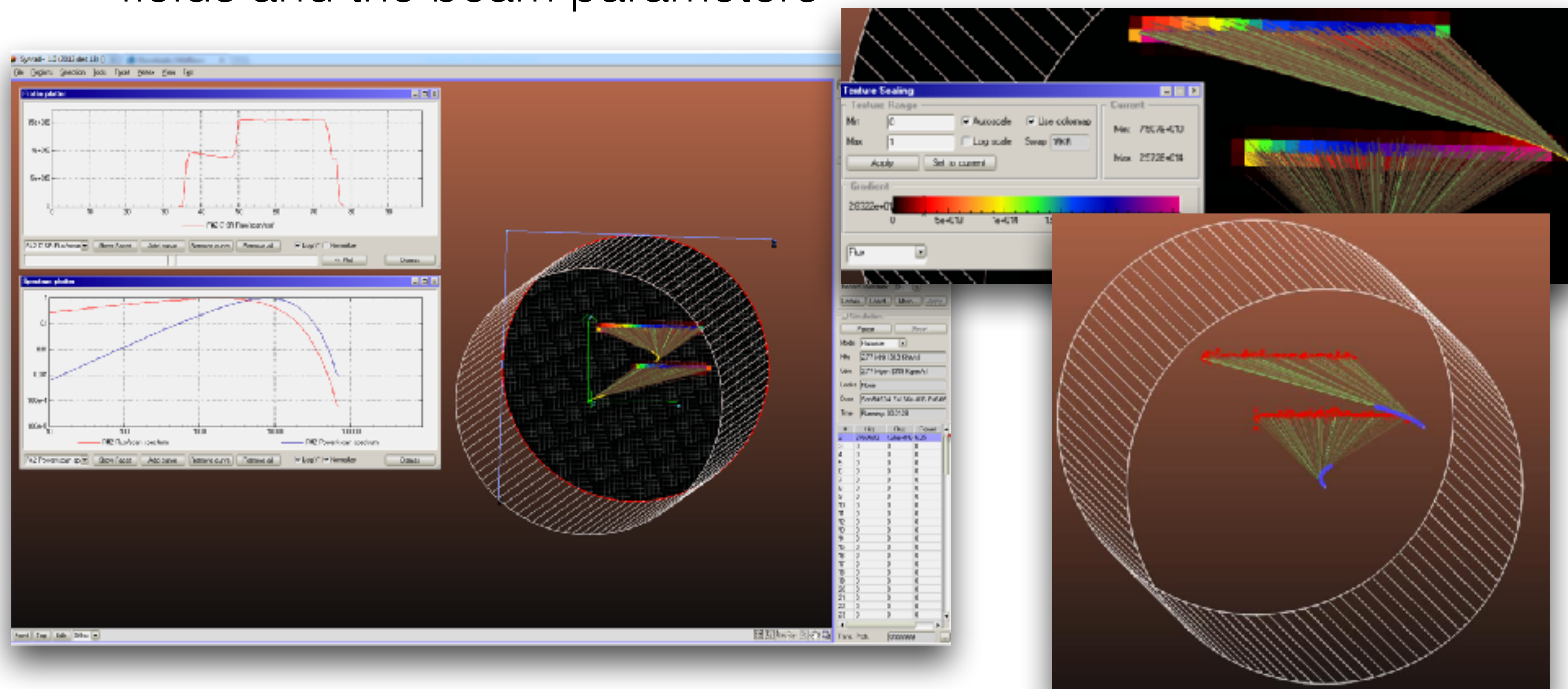


A dedicated simpler GEANT4 simulation suggests that due to the low energy of these photons **we expect about 1 photon per bunch to traverse** the beam pipe and enter the detector region

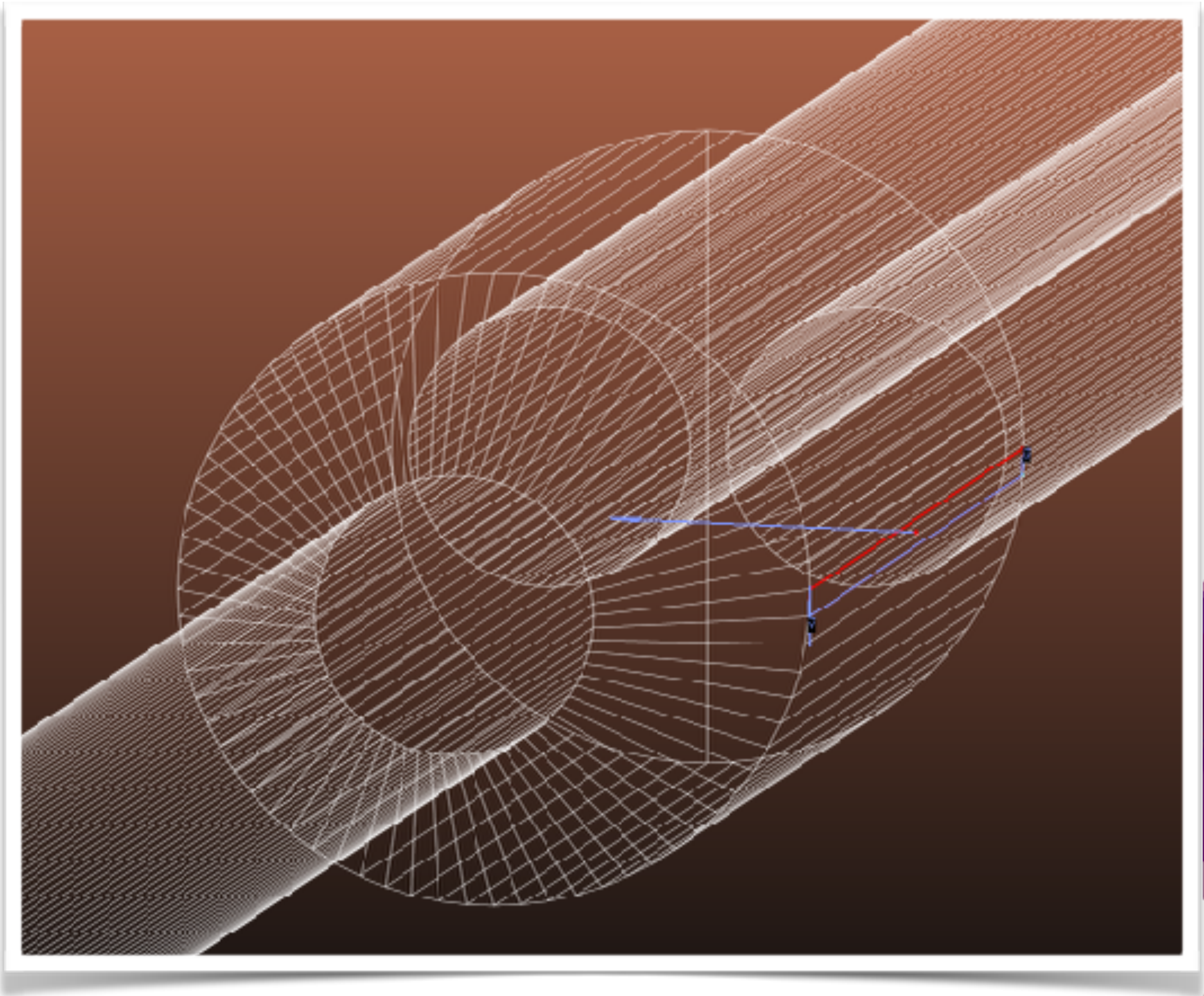
Second approach: SynRad

Synrad Software

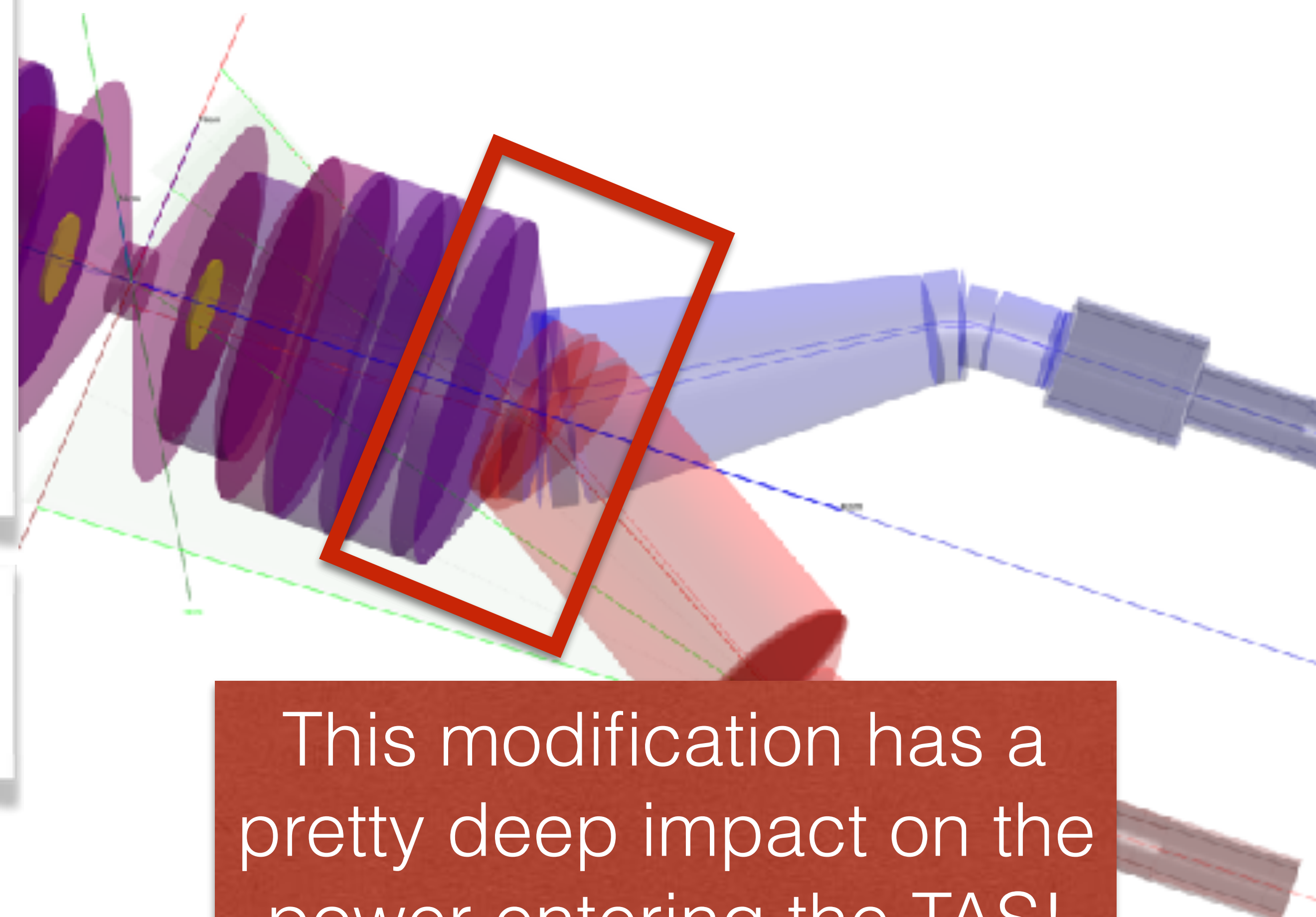
- Synrad is a software developed by *Roberto Kersevan* @ CERN able to **generate** and **trace photons** to calculate flux and power distribution on a surface caused by Synchrotron radiation link
- Needs as input the geometry (in CAD-like format), the magnetic fields and the beam parameters



modifications to the geometry wrt pure optics



LHC was used as a reference for recombination chamber and beam pipe, making a sort of "projection"

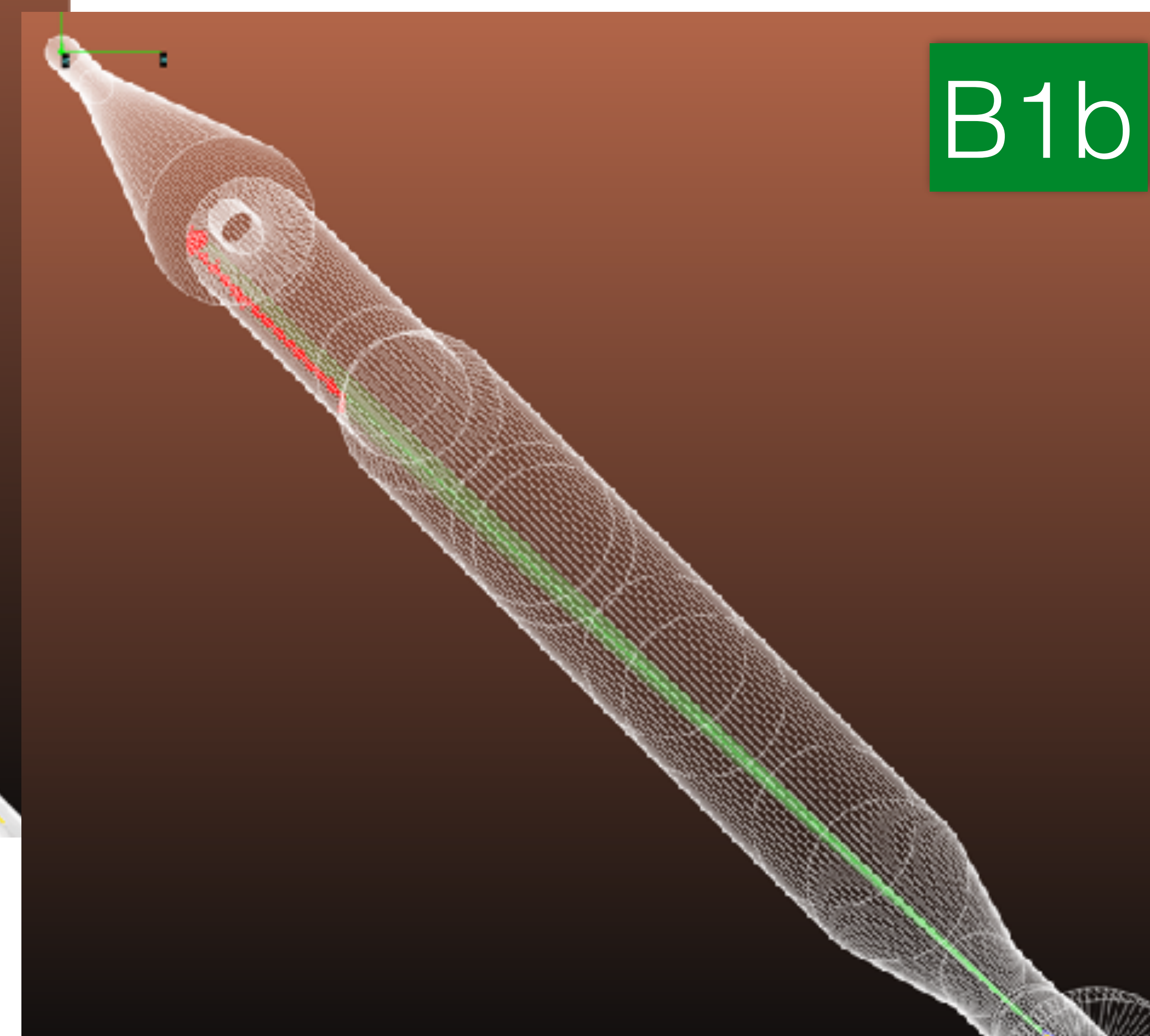


This modification has a pretty deep impact on the power entering the TAS!

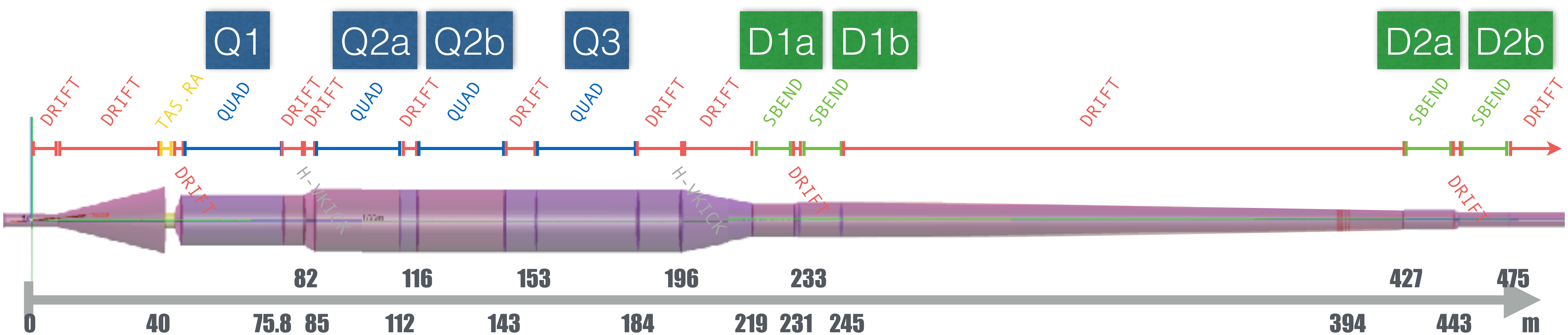
- So I evaluated with SynRad the **power entering the TAS** from the various magnetic elements in both cases *with* and *without* the *Crossing Angle*

here showing

No Crossing Angle



Power (W)	No Crossing Angle		Crossing Angle	
	MDISim	SynRad	MDISim	SynRad
D2b	0	0	0	0
D2a	4,1	0,08	1,2	1E-03
D1b	0	0	0	4E-05
D1a	12,8	5,02	24,6	5,75
Q3	—	0	—	1,24
Q2b	—	0,139	—	2,19
Q2a	—	0	—	1E-04
Q1	—	0,0113	—	e-6
TOT	**16,9**	**5,3**	**25,8**	**9,2**



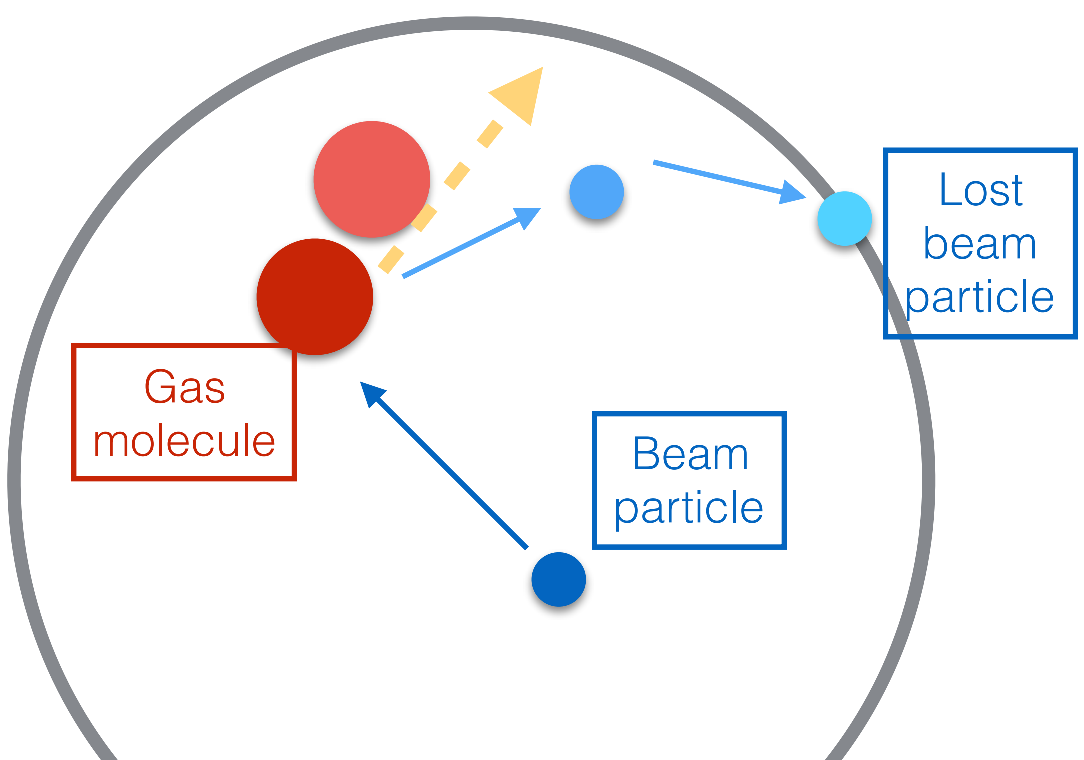
Conclusions on Synchrotron Radiation

- **Synchrotron Radiation** emitted in the last bends (500m from the IP) **<u>is not an issue</u>**:
    - The emitted Power is IN TOTAL **~100 W** (=upper limit in all beam conditions)
    - The **fraction** of this power **entering the TAS** is **~10 W with/without crossing angle**
    - Orbit correctors contribute for ~ W (~10x lower than bends)
    - The emitted photons, even if numerous (**~10^{10}** per bunch), have a **critical energy** of **1keV**
    - They are **safely stopped** within the pipe
- Substantial agreement between the 2 codes

Other MDI studies

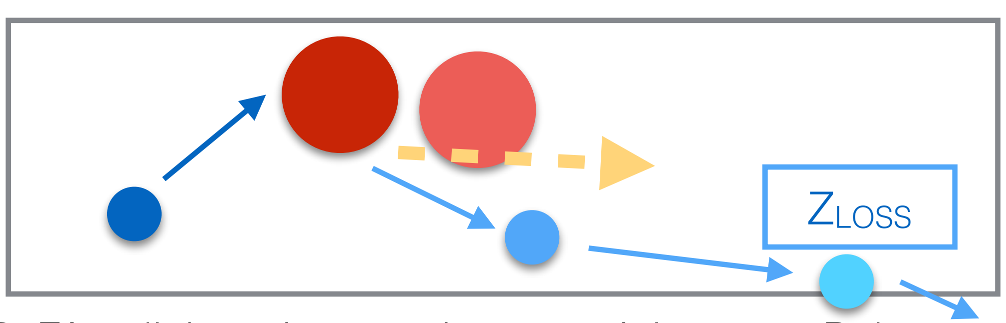
Other MDI Studies

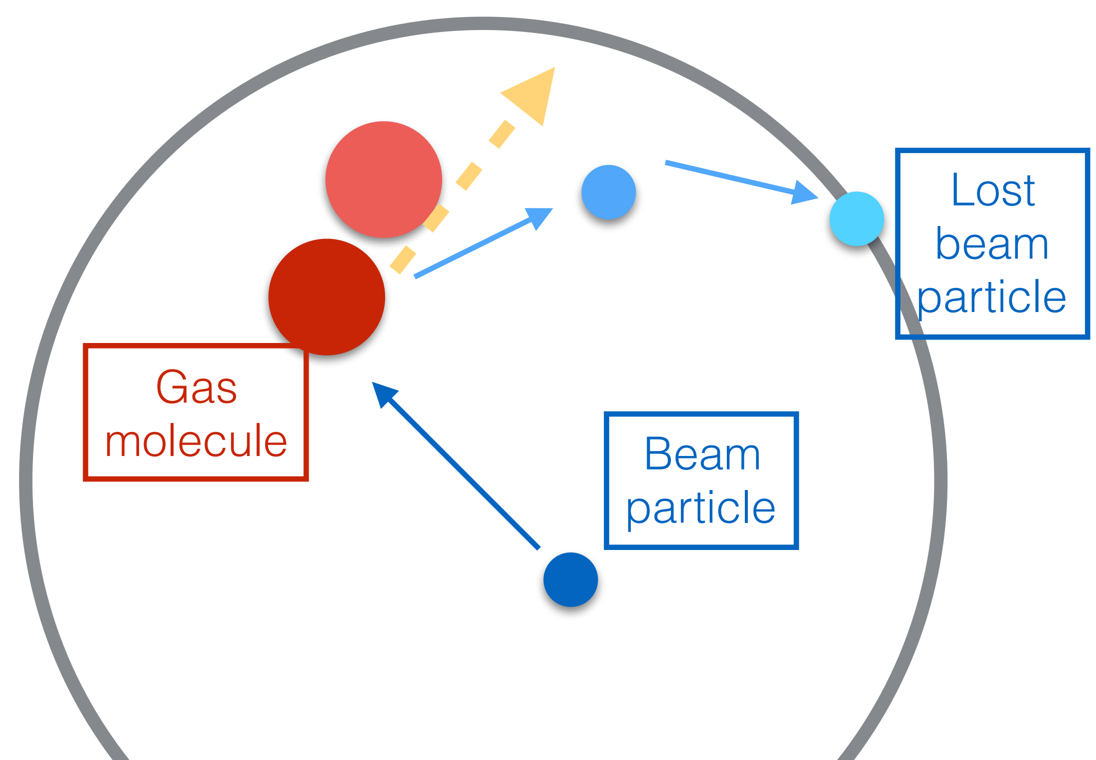
- The tool developed and tested for Synchrotron Radiation studies opens the way to several others possible applications
  - We now have in **GEANT4** the beam pipe geometry and the beam characteristics
- **Beam Gas studies:**
  - Very rare process, due to very low density of Vacuum in the pipe
  - However, within certain limits, can be “enlarged” by rising this density

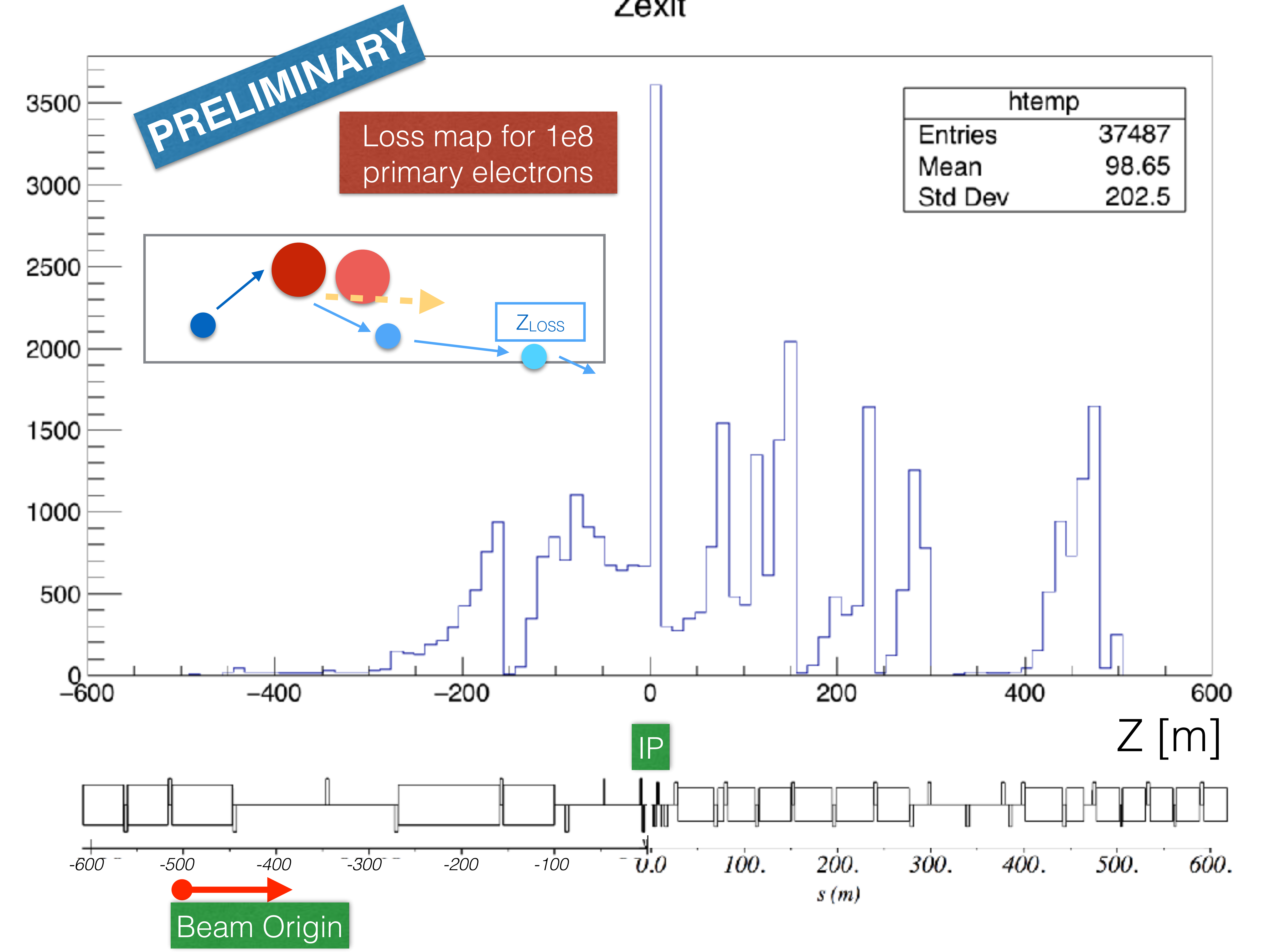


Beam Gas studies in GEANT4

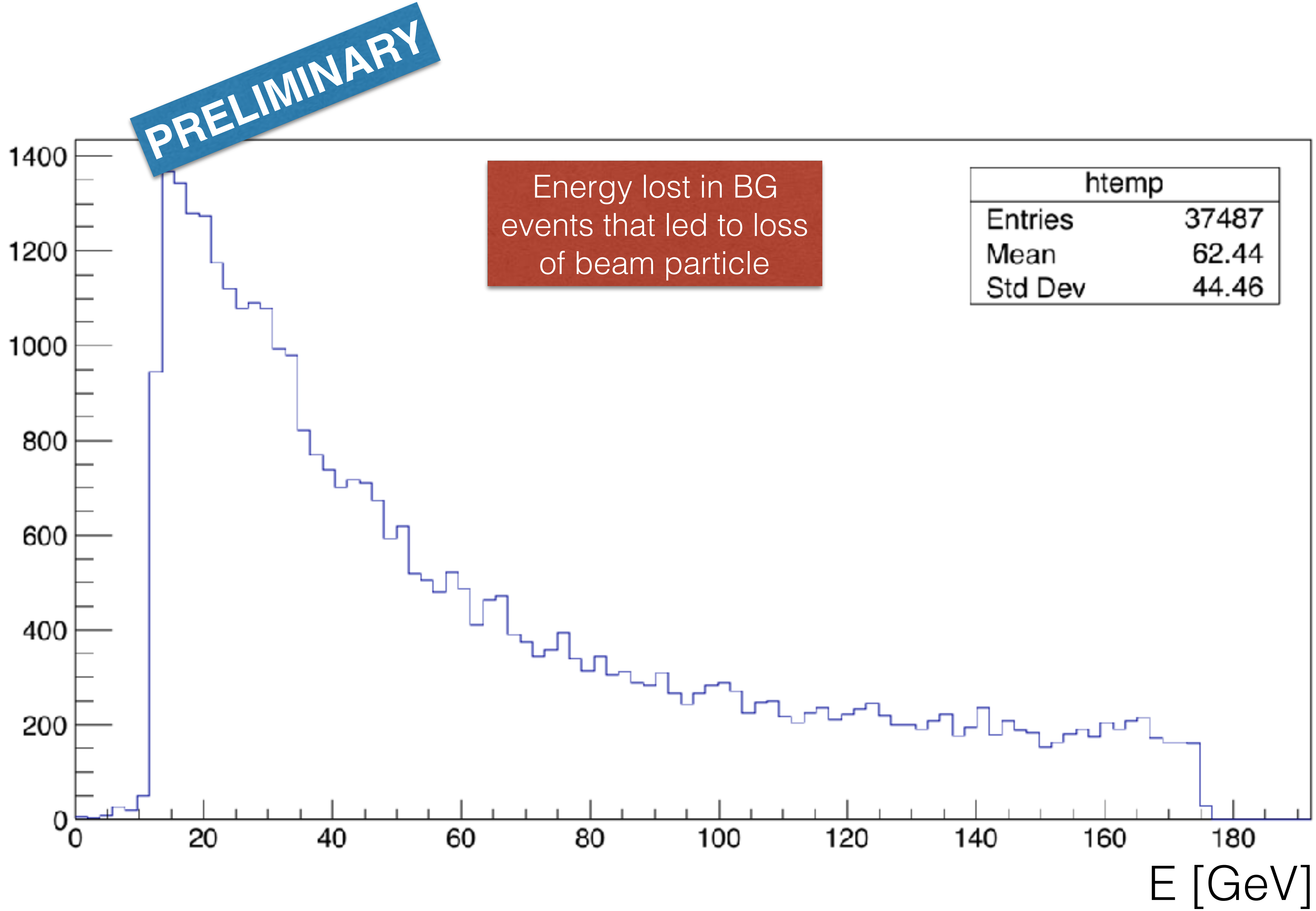
- (Inelastic) **Beam Gas studies** for **FCC-ee**:
  - A primary electron (realistic, 175GeV) beam is generated 500m from the IP
  - Rising the Vacuum **density** of about **10 orders of magnitude** it is possible to start to see some Beam-Gas interactions
  - Event recognition:
    - Primary electron undergoes *"eBrem"* process with >1GeV energy transfer
    - The primary electron is then lost in the pipe







Zexit
PRELIMINARY
Loss map for 1e8 primary electrons
htemp
Entries 37487
Mean 98.65
Std Dev 202.5
ZLOSS
Z [m]
IP
s (m)
Beam Origin


PRELIMINARY
Energy lost in BG events that led to loss of beam particle
htemp
Entries 37487
Mean 62.44
Std Dev 44.46
1400
1200
1000
800
600
400
200
0
0
20
40
60
80
100
120
140
160
180
E [GeV]

Conclusions

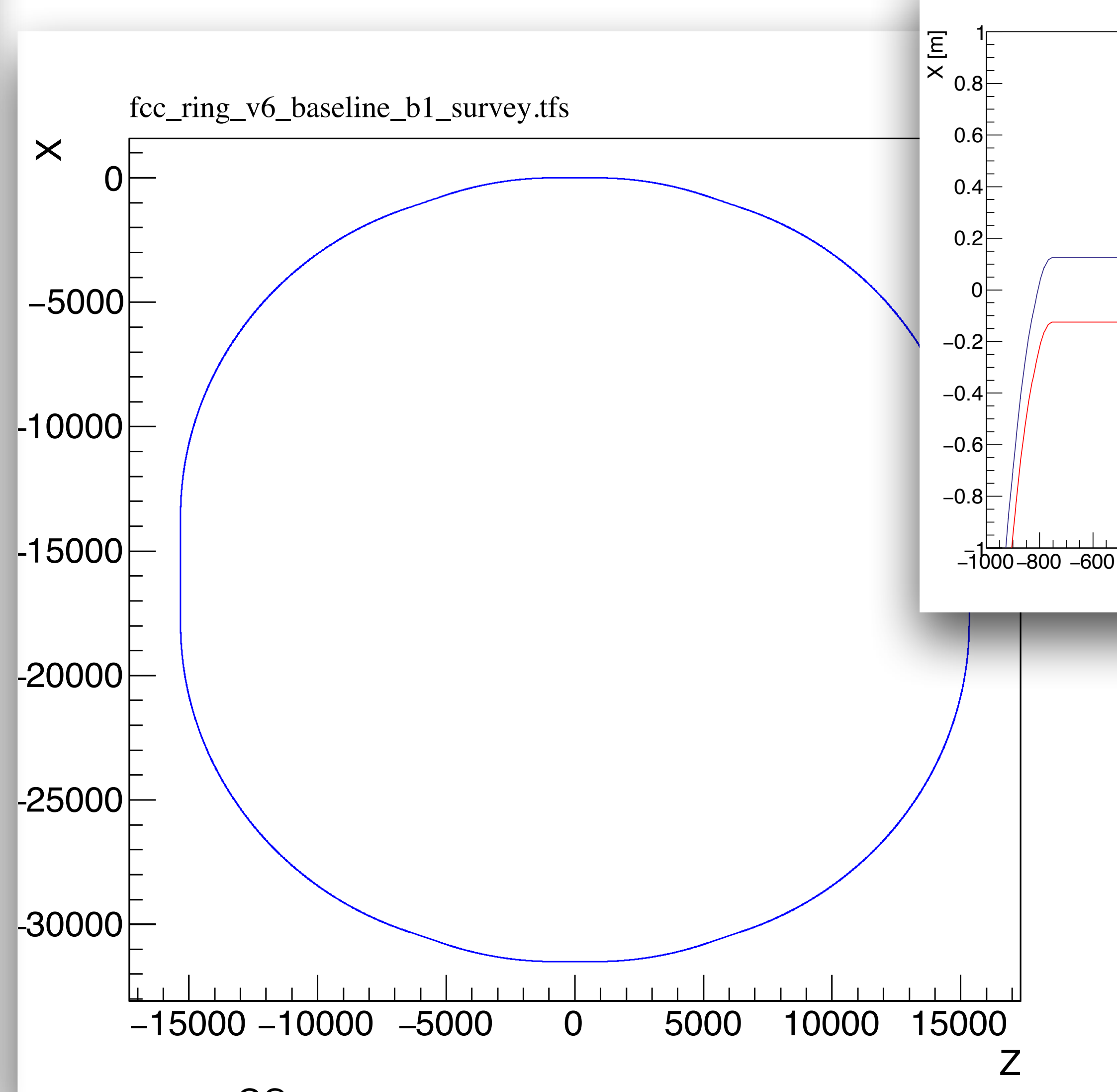
- A **tool** to import in GEANT4 geometry of the pipe and beam characteristics was developed
  - Tested and validated for **Synchrotron Radiation** studies
    - SR power into the experiments is **not an issue** for FCC-hh
    - The study will have to be **updated** from time to time with the last optics, in view of a coherent CDR
  - Very powerful! Can give access to a whole series of other studies
    - **Beam-Gas** (also for FCC-hh)…
  - Much flexible, not only applicable to FCC, but also to LEMMA…

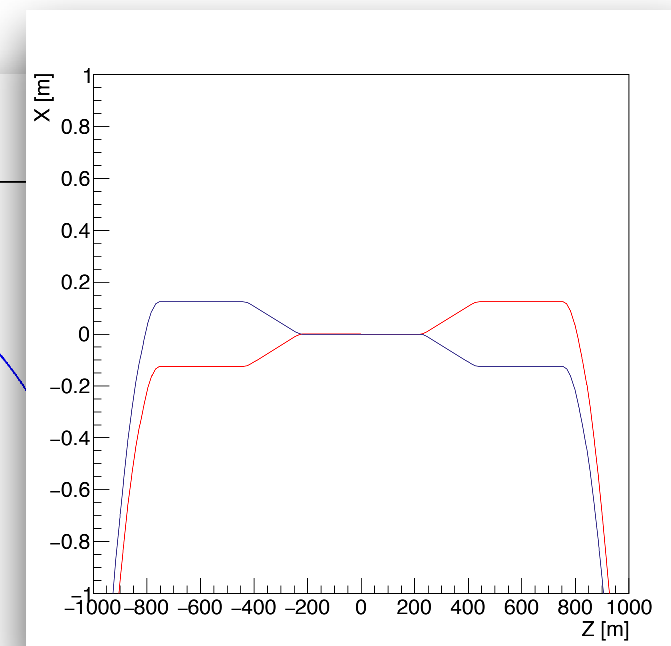
backup

Beam parameters

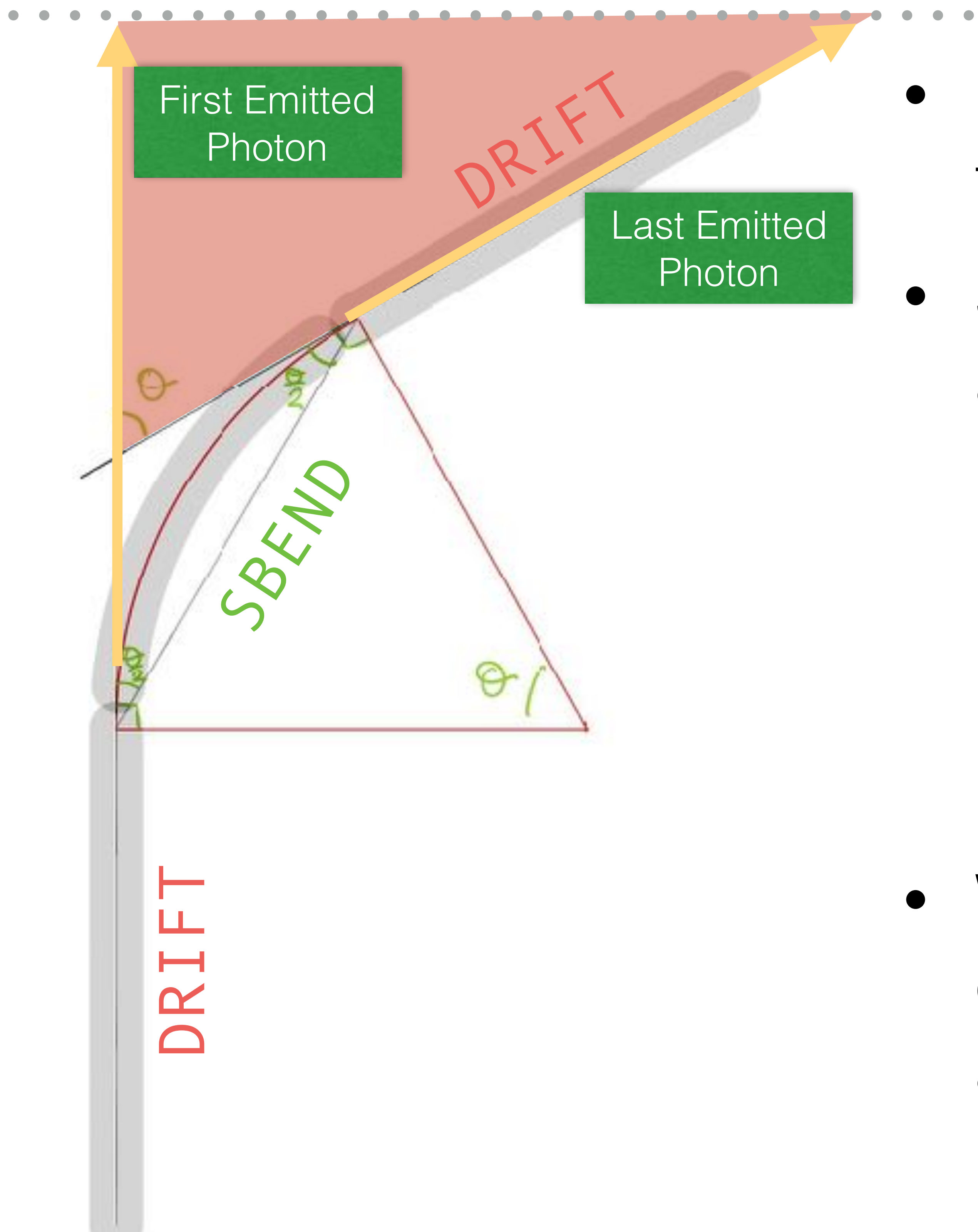
```
@ NAME                 %05s "TWISS"
@ TYPE                 %05s "TWISS"
@ SEQUENCE             %08s "FCC_RING"
@ PARTICLE             %06s "PROTON"
@ MASS                 %le          0.938272046
@ CHARGE               %le                    1
@ ENERGY               %le                50000
@ PC                   %le     49999.9999911965
@ GAMMA                %le     53289.4486339626
@ KBUNCH               %le                10600
@ BCURRENT             %le  4.79502351385978e-05
@ SIGE                 %le                    0
@ SIGT                 %le                    0
@ NPART                %le         100000000000
@ EX                   %le  4.12839700312689e-11
@ EY                   %le  4.12839700312689e-11
@ ET                   %le                    1
@ LENGTH               %le     100170.614199044
@ ALFA                 %le  0.000101112451618679
@ ORBIT5               %le                   -0
@ GAMMATR              %le     99.4483723902716
@ Q1                   %le       111.3103836898
@ Q2                   %le      108.319735822487
@ DQ1                  %le     0.704766620174269
@ DQ2                  %le      2.53678571482396
@ DXMAX                %le      15.1732173929165
@ DYMAX                %le      14.9243069125305
@ XCOMAX               %le    0.0137550431615374
@ YCOMAX               %le    0.0137449902569815
@ BETXMAX              %le     79717.6528109933
@ BETYMAX              %le     80231.1846763345
@ XCORMS               %le  0.000356215756222975
@ YCORMS               %le  0.000359222411426776
@ DXRMS                %le      1.83029943789494
@ DYRMS                %le     0.736053497810314
@ DELTAP               %le                    0
@ SYNCH_1              %le     10.1229915726241
@ SYNCH_2              %le  0.000600932166177875
@ SYNCH_3              %le  5.73672334655025e-08
@ SYNCH_4              %le   9.2355347923506e-08
@ SYNCH_5              %le  1.16651985634425e-09
```

- 50 TeV protons
- Optics version:
  - *fcc_hh_v6_45*





PHOTON DISTRIBUTION



- Neglecting the aperture of the SR cone..
- SR Photons are emitted in an area of θ
    - same angle as the bending magnet!
    - we refer to this area as “cone”
- We assume photons are emitted isotropically in this area

Beam parameters

	FCC-hh Baseline	FCC-hh Ultimate
Luminosity L [$10^{34}cm^{-2}s^{-1}$]	5	20-30
Background events/bx	170 (34)	<1020 (204)
Bunch distance Δt [ns]	25 (5)	
Bunch charge N [10^{11}]	1 (0.2)	
Fract. of ring filled η_{fill} [%]	80	
Norm. emitt. [μm]	2.2(0.44)	
Max ξ for 2 IPs	0.01 (0.02)	0.03
IP beta-function β [m]	1.1	0.3
IP beam size σ [μm]	6.8 (3)	3.5 (1.6)
RMS bunch length σ_z [cm]	8	
Crossing angle [σ□]	12	Crab. Cav.
Turn-around time [h]	5	4

source: FCCweek16

Beam parameters

parameter	FCC-hh		SPPC	HE-LHC* *tentative	(HL) LHC
collision energy cms [TeV]	100		71.2	>25	14
dipole field [T]	16		20	16	8.3
circumference [km]	100		54	27	27
# IP	2 main & 2		2	2 & 2	2 & 2
beam current [A]	0.5		1.0	1.12	(1.12) 0.58
bunch intensity $[10^{11}]$	1	1 (0.2)	2	2.2	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25	25	25
beta* [m]	1.1	0.3	0.75	0.25	(0.15) 0.55
luminosity/IP $[10^{34}\ cm^{-2}s^{-1}]$	5	20 - 30	12	>25	(5) 1
events/bunch crossing	170	<1020 (204)	400	850	(135) 27
stored energy/beam [GJ]	8.4		6.6	1.2	(0.7) 0.36
synchrotr. rad. [W/m/beam]	30		58	3.6	(0.35) 0.18

source: FCCweek16