Update on TAN design and energy deposition in the Matching Section of the HL-LHC IR1/5

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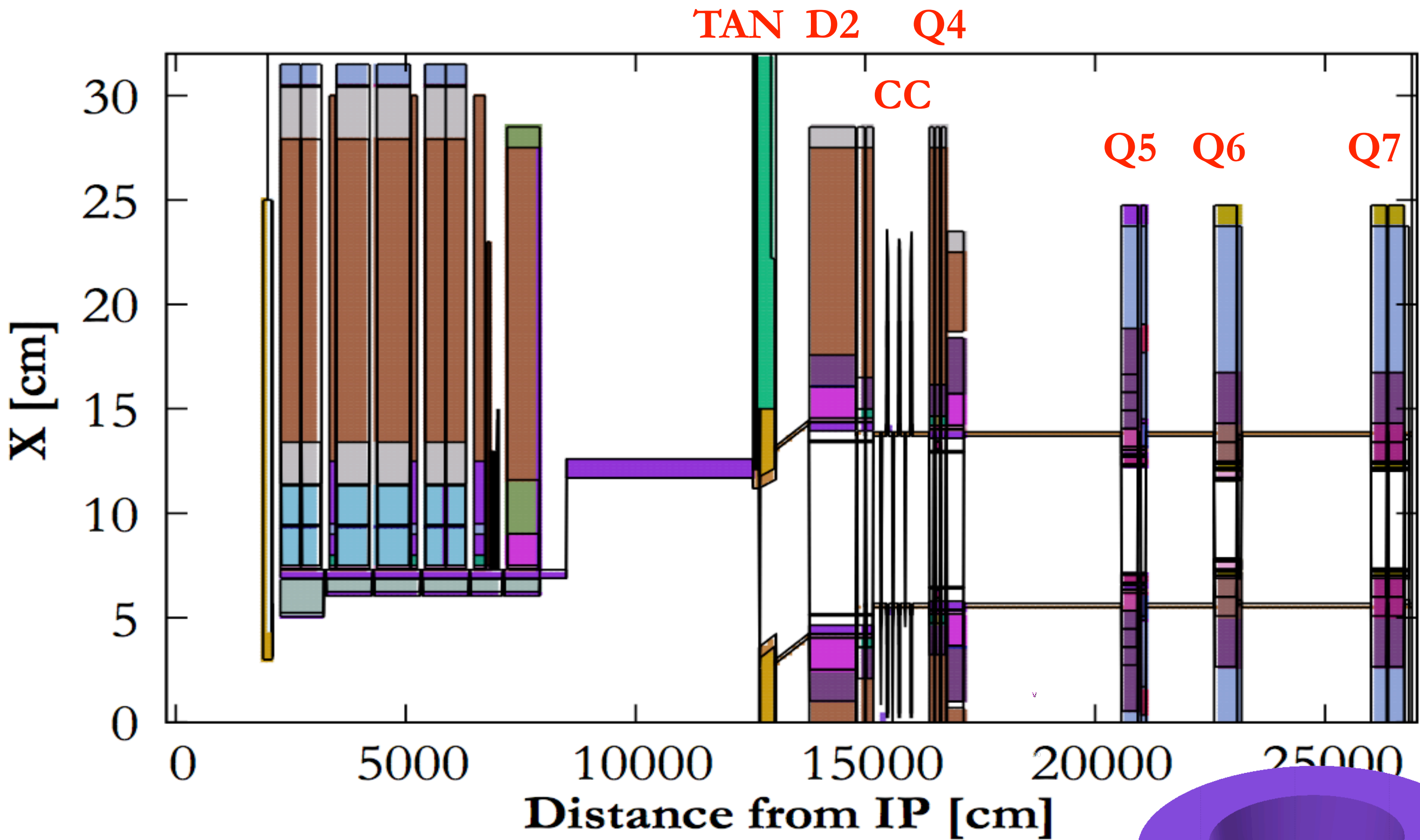
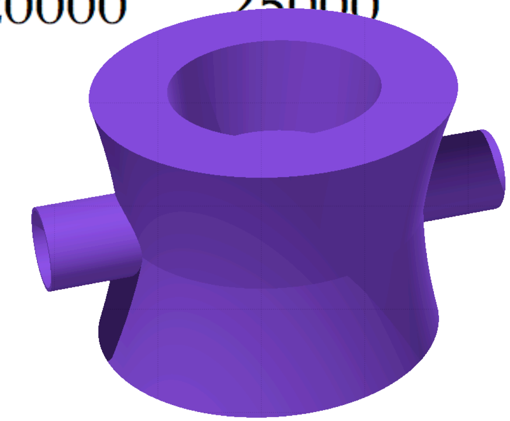
Objective

- HL-LHC peak power sensitivity in the Matching Section to:
  - optics round/flat/sround optics
  - horizontal/vertical crossing scheme
  - replace Q5 by MQYY (HL-LHC Q4)
  - implement shielding in D2, Q4, Q5 (tungsten absorbers)
  - TAN aperture (reducing)
  - TAN position (toward D2)

Many variables with strong interplay among them

HL-LHC beam-line model





- D2, Q4 and their associated correctors are new magnets (implementation according to specs available on WP3 site)
- Q5 is a MQY (present Q4)
- Q6 and Q7 are present magnets
- Crab cavities

Matching Section elements

New elements: 2-in-1

	HLLHC V1.0					Nominal V6.5			
Element	Length [m]	Coil Ap. [mm]	BS Ap. [mm]	Sep. [mm]	Shift [m]	Length [m]	Coil Ap. [mm]	BS Ap. [mm]	Sep. [mm]
TAN	3.7	n/a	Ellipse H oriented (41,37)	145	-15	3.7	n/a	Round: 26	160
D2	10	105	RE H oriented (41,36)	186	-15	9.45	80	RE H oriented: (31.3,26.4)	188
MCBRD	1.5 h 1.5 v		As D2	194	-15	Not present			
CRABS	3x 2.6	80	n/a	194	n/a	Not present			
Q4 and MCBY	3.5	90	RE pol. Oriented (32,37)	194	0.05	3.4	70	RE H oriented (24,28.9)	194
Q5	4.8	70	RE Q4 polarity or. (24,28.9)	194	11	4.8	56	RE pol. oriented	194

Q6-Q7 as in the present LHC machine

slide from R. De Maria, 2nd Joint HiLumi LHC-LARP Annual Meeting

High Luminosity LHC

Matching Section elements

New elements: 2-in-1

	HLLHC V1.0					
Element	Length [m]	Coil Ap. [mm]	BS Ap. [mm]	Sep. [mm]	Shift [m]	**Details about FLUKA implementation**
TAN	3.7	n/a	Ellipse H oriented (41,37)	145	-15	**truncated cone: see next slides**
D2	10	105	RE H oriented (41,36)	186	-15	4 mm CB with IR = 46.5 mm; 1 mm BS; **4.5 mm clearance BS-CB**
MCBRD	1.5 h 1.5 v		As D2	194	-15	as D2
CRABS	3x 2.6	80	n/a	194	n/a	**aperture 84 mm** (private communication from R. Calaga)
Q4 and MCBY	3.5	90	RE pol. Oriented (32,37)	194	0.05	4 mm CB with IR = 39 mm; 1 mm BS **1 mm clearance BS-CB**
Q5	4.8	70	RE Q4 polarity or. (24,28.9)	194	11	**Present Q4 (MQY):** 1.76 mm CB with IR = 31.49 mm 0.675 mm BS (25.225/30.025)

Q6-Q7 as in the present LHC machine

slide from R. De Maria, 2nd Joint HiLumi LHC-LARP Annual Meeting

High Luminosity LHC

Matching Section elements

New elements: 2-in-1

	HLLHC V1.0					
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Q4 and MCBY	3.5	90	RE pol. Oriented (32,37)	194	0.05	4 mm CB with IR = 39 mm; 1 mm BS **1 mm clearance BS-CB**
Q5	4.8	70	RE Q4 polarity or. (24,28.9)	194	11	**use a single MQYY (HL-LHC Q4)**

Q6-Q7 as in the present LHC machine

slide from R. De Maria, 2nd Joint HiLumi LHC-LARP Annual Meeting

HL-LHC IR optics features

name	$\beta^*_\times$ [m]	$\beta^*_\parallel$ [m]	$\theta_\times$ [μrad]	$\Delta_\parallel$ [mm]	$\times_{\text{plane}}$ IP1/5
injection: $\beta^*_{2,8} = 10$ m, $\theta_{\times 2,8} = 340\mu$rad					
inj	6.0	6.0	490	4	any
ATS phase advances, $\beta^*_8 = 3$ m					
presqueeze	3.0	3.0	590	1.5	any
presqueeze	0.44	0.44	360	1.5	any
Telescopic squeeze					
round	0.15	0.15	590	1.5	any
sround	0.10	0.10	720	1.5	any
flat	0.075	0.30	550	1.5	V/H
sflat	0.050	0.20	670	1.5	V/H
flathv	0.075	0.30	550	1.5	H/V
sflathv	0.050	0.20	670	1.5	H/V
ion, $\beta^*_{2,8} = 50$ cm					
ion	0.44	0.44	360	1.5	any

HL-LHC IR optics features

name	$\beta^*_\times$ [m]	$\beta^*_\parallel$ [m]	$\theta_\times$ [μrad]	$\Delta_\parallel$ [mm]	$\times_{\text{plane}}$ IP1/5
injection: $\beta^*_{2,8} = 10$ m, $\theta_{\times 2,8} = 340\mu$rad					
inj	6.0	6.0	490	4	any
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Telescopic squeeze					
round	0.15	0.15	590	1.5	any
sround	0.10	0.10	720	1.5	any
flat	0.075	0.30	550	1.5	V/H
sflat	0.050	0.20	670	1.5	V/H
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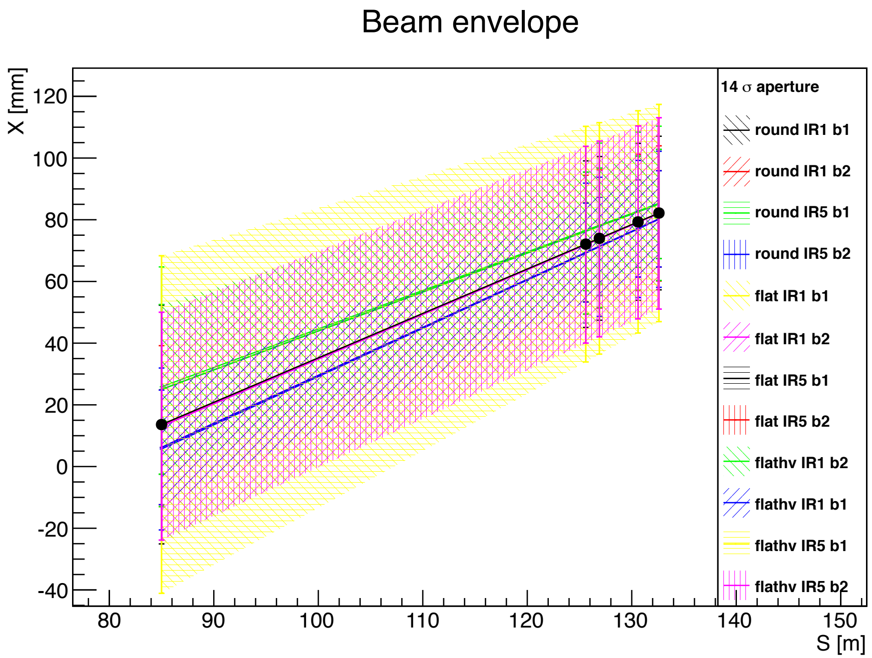
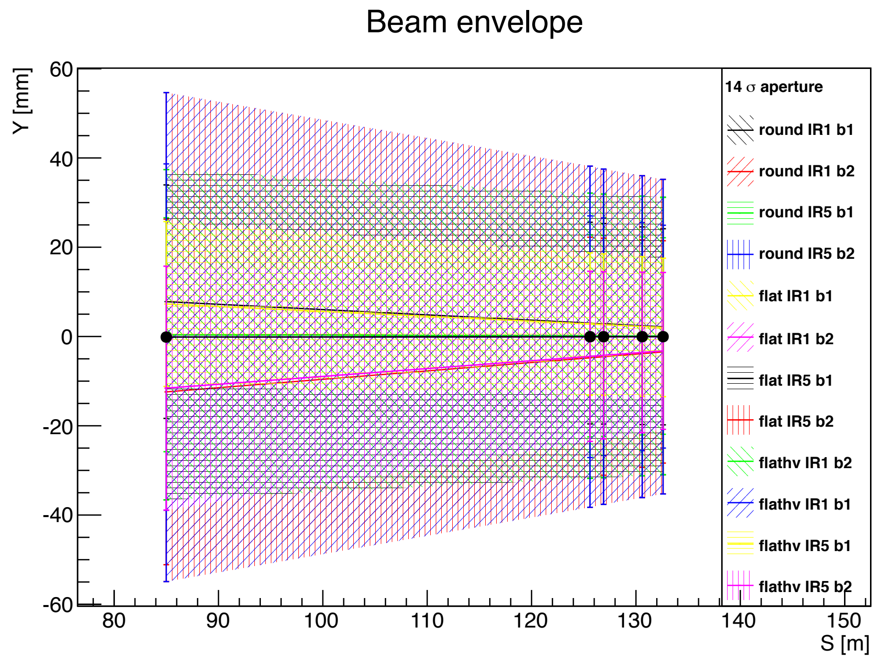
sflathv	0.050	0.20	670	1.5	H/V
ion, $\beta^*_{2,8} = 50$ cm					
ion	0.44	0.44	360	1.5	any

Highlighted optics have been used to define TAN aperture

TAN aperture





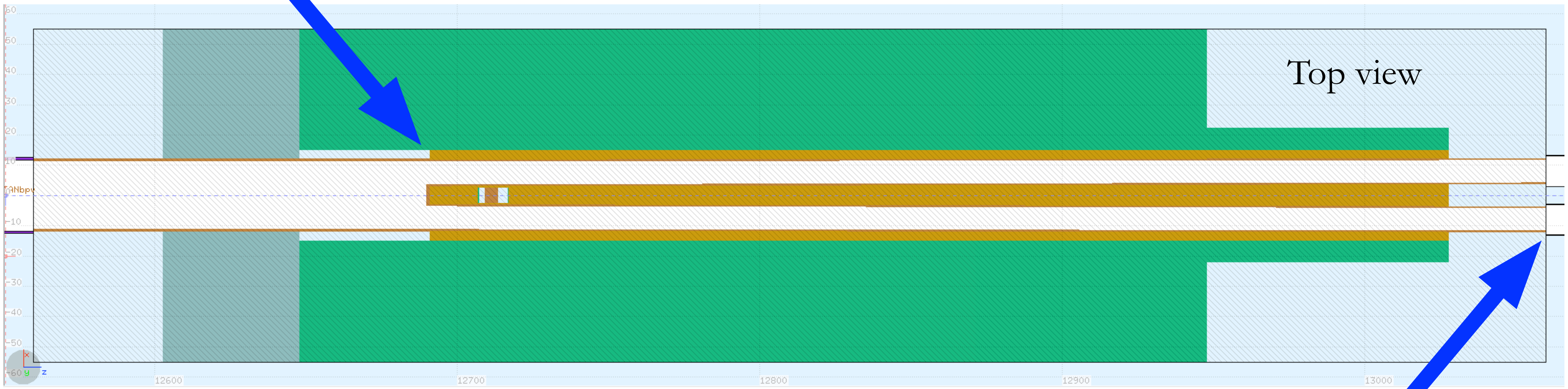
The following criterion was used to optimize the aperture:

- **TAN should not represent a bottleneck in the beam performance**
    1. Assumed emittance 3.75 μm
    2. 14σ aperture (slightly larger than the one in the Inner Triplet)
    3. Maximum beam envelop determined by round and flat optics

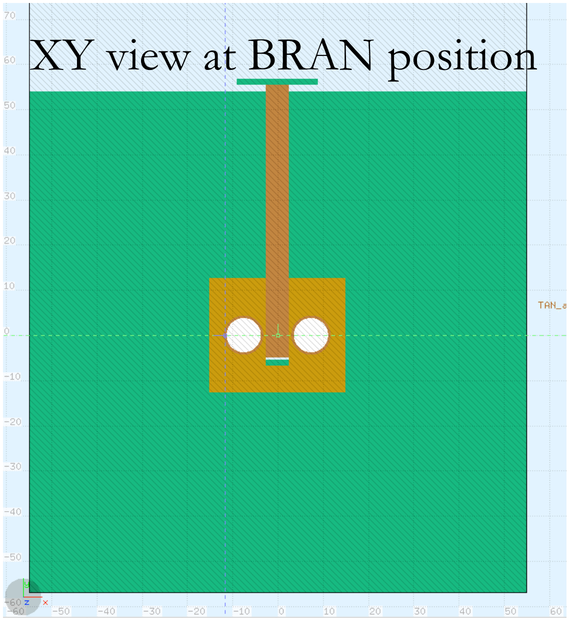
N.B. Here TAN aperture maximized, there are margins to reduce it (ideally improving the protection in both directions)

TAN model

s[m]/half-sep[mm]/radius[mm]
126.9/74/38



s[m]/half-sep[mm]/radius[mm]
130.6/79.3/37



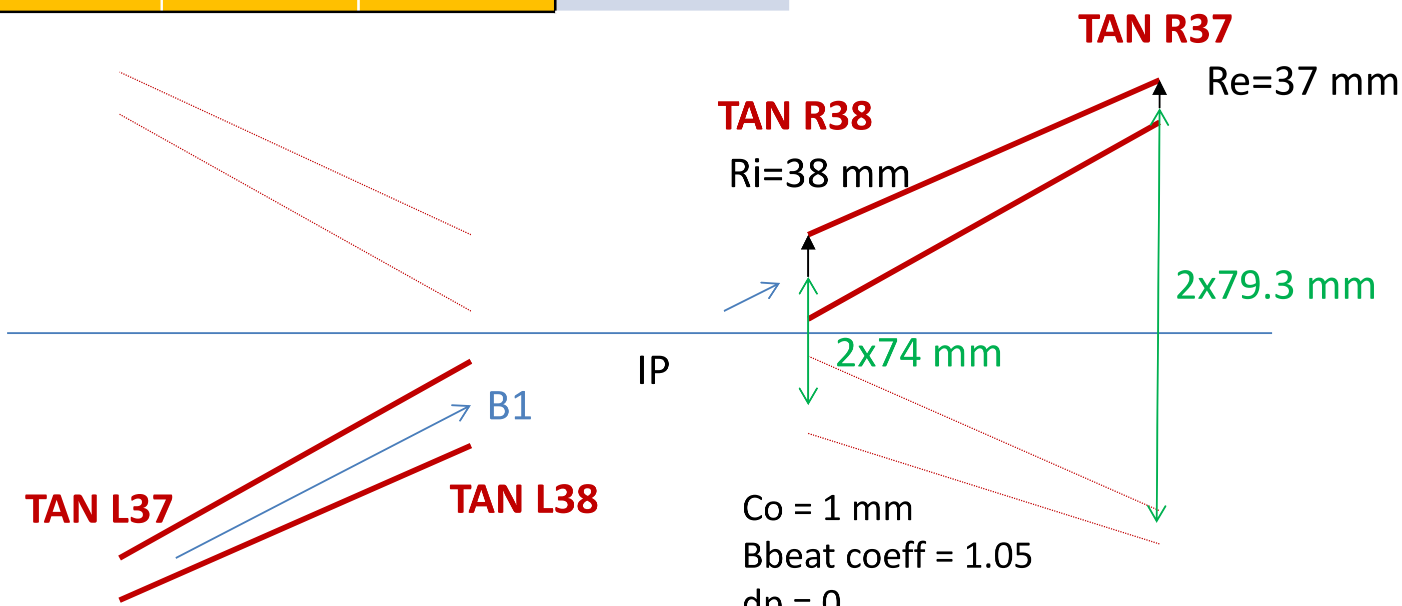
Adapted by present TAN FLUKA model

Beam pipes implemented as diverging truncated cones

IP1	n1 TANL37	n1 TANL38	n1 TANR38	n1 TANR37
ROUND	16.92	16.40	18.43	18.7
FLAT	15.26	15.36	13.18	13.37
IP5	n1 TANL37	n1 TANL38	n1 TANR38	n1 TANR37
ROUND	18.65	18.4	16.47	16.99
FLAT	13.44	13.25	15.42	15.28
Q2 R	12.19	Q2 F	11.92	

My numbers to compared with:
Round ➔13.88
Flat ➔11.13

Ellipse ➔ Rx=37 mm, Ry=33.3 mm
Beam pipe separation cte = 145 mm

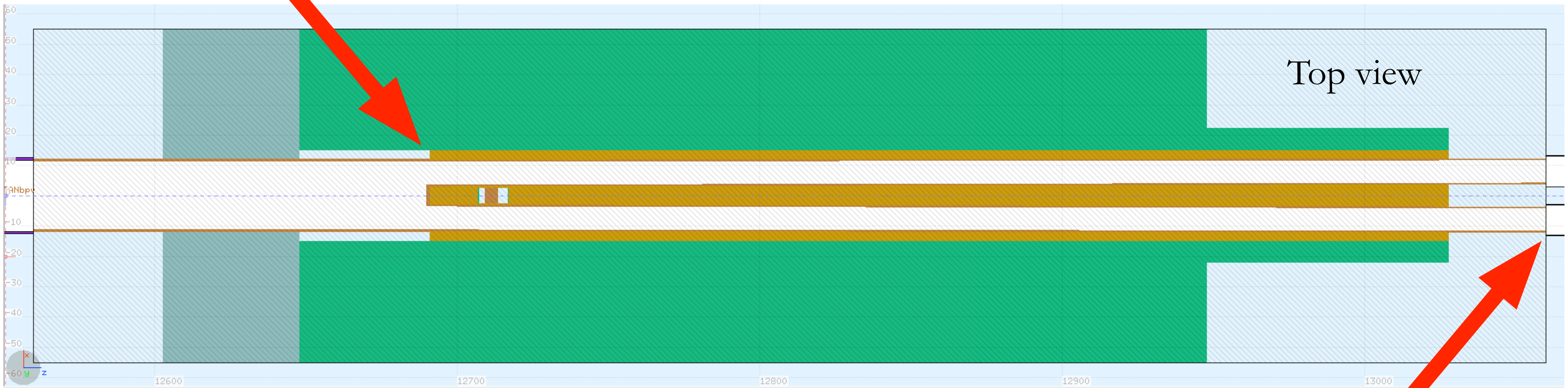


Co = 1 mm
Bbeat coeff = 1.05
dp = 0
e_n = 3.5 um rad
Halos = 6,6,6,6
Separation and crossing angles on

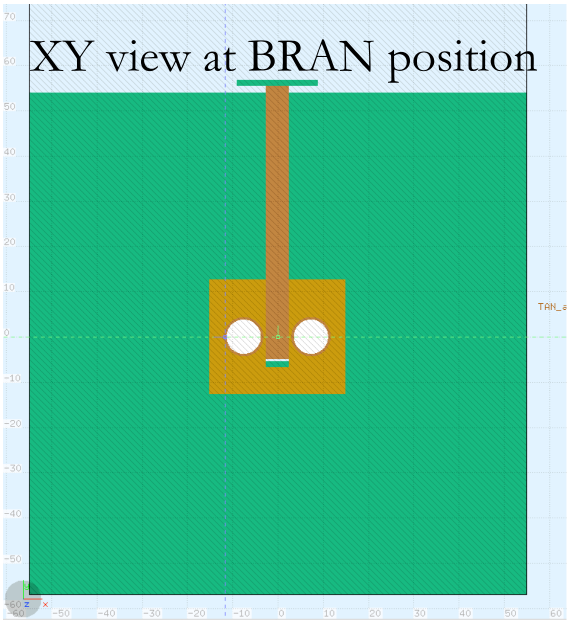
R. Alemany Fernandez

TAN model (+4 m toward D2)

s[m]/half-sep[mm]/radius[mm]
130.9/79.7/36.1

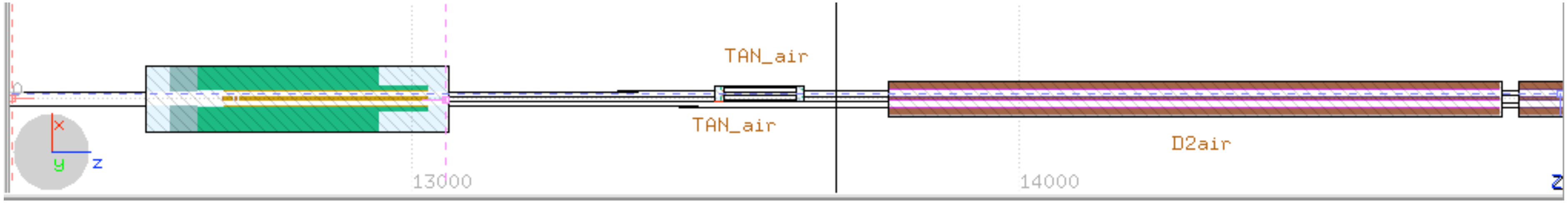


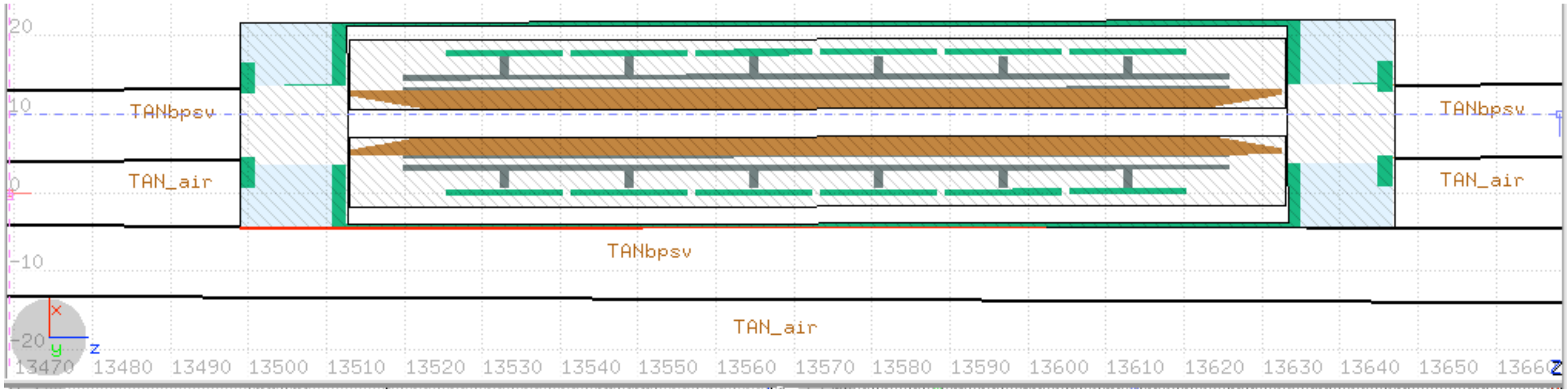
s[m]/half-sep[mm]/radius[mm]
134.6/85.1/34.4



2÷3 mm pipe radius decrease
5÷6 mm increase in the beam pipe half-separation

TCL4 integration issue



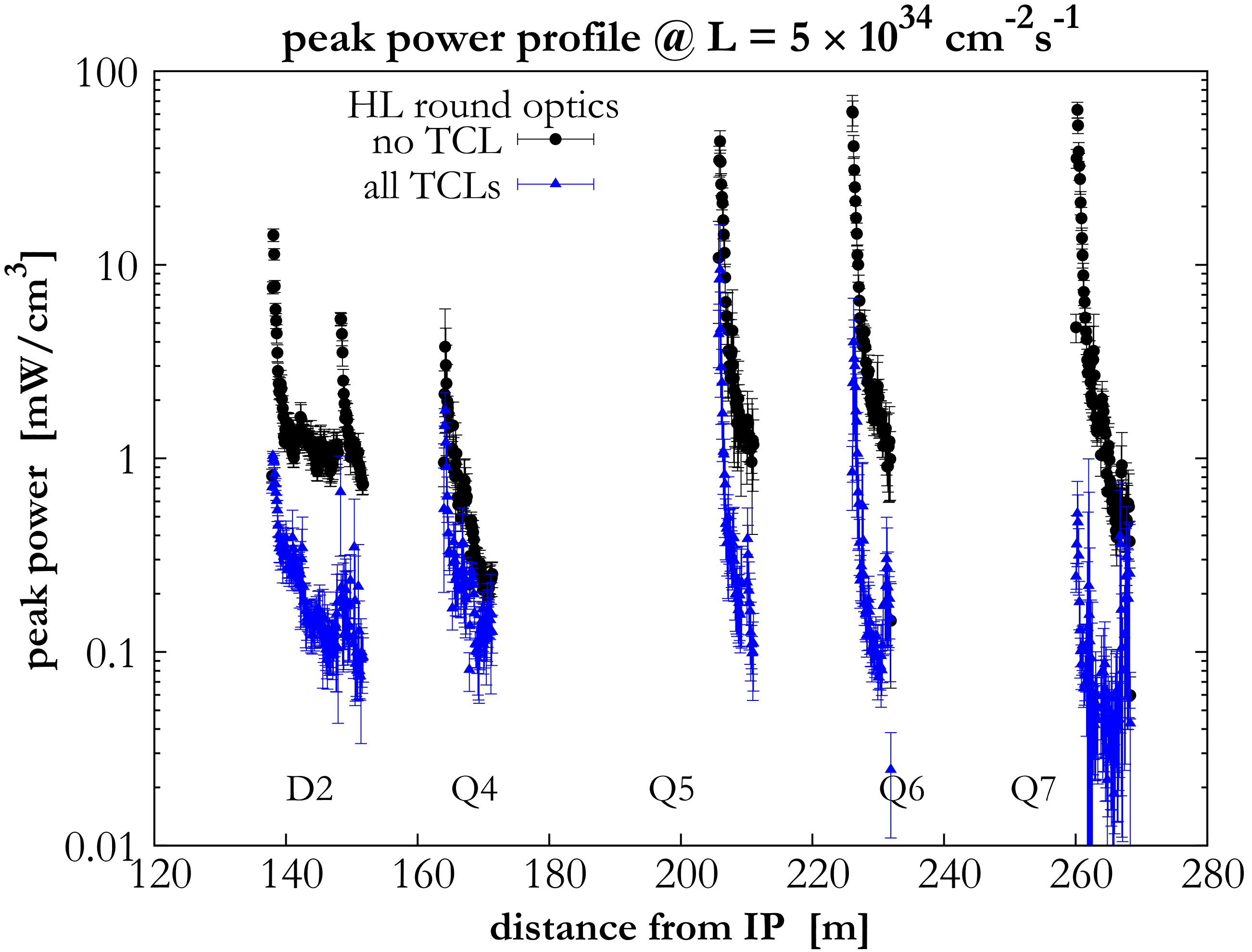


Not enough space to install the tank between the two beam pipes

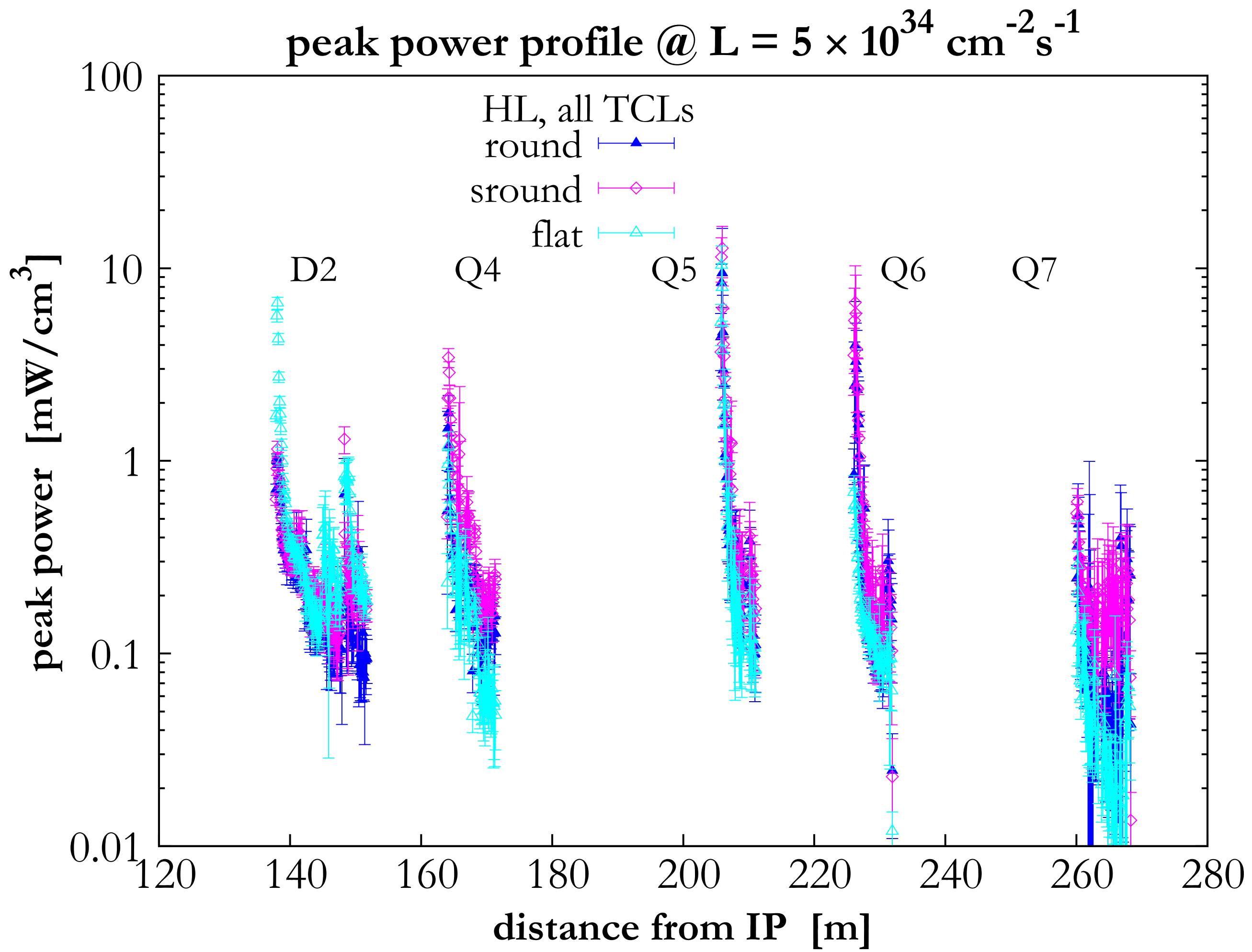
Only the jaws have been inserted in the model (<10% of total power)

Matching Section peak power

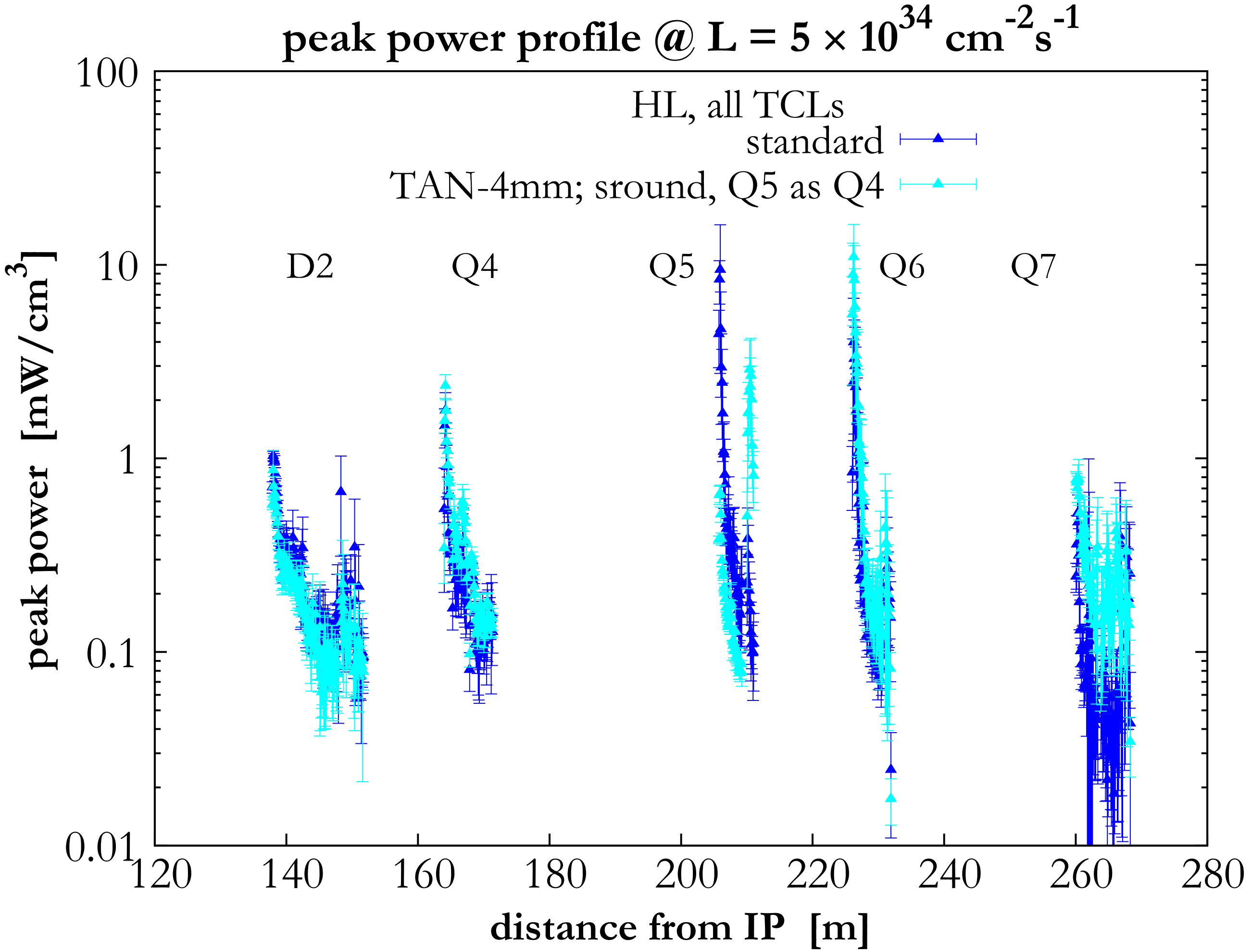
Spanning the range of TCL performance: no TCL vs TCL everywhere



flat/sround vs round optics



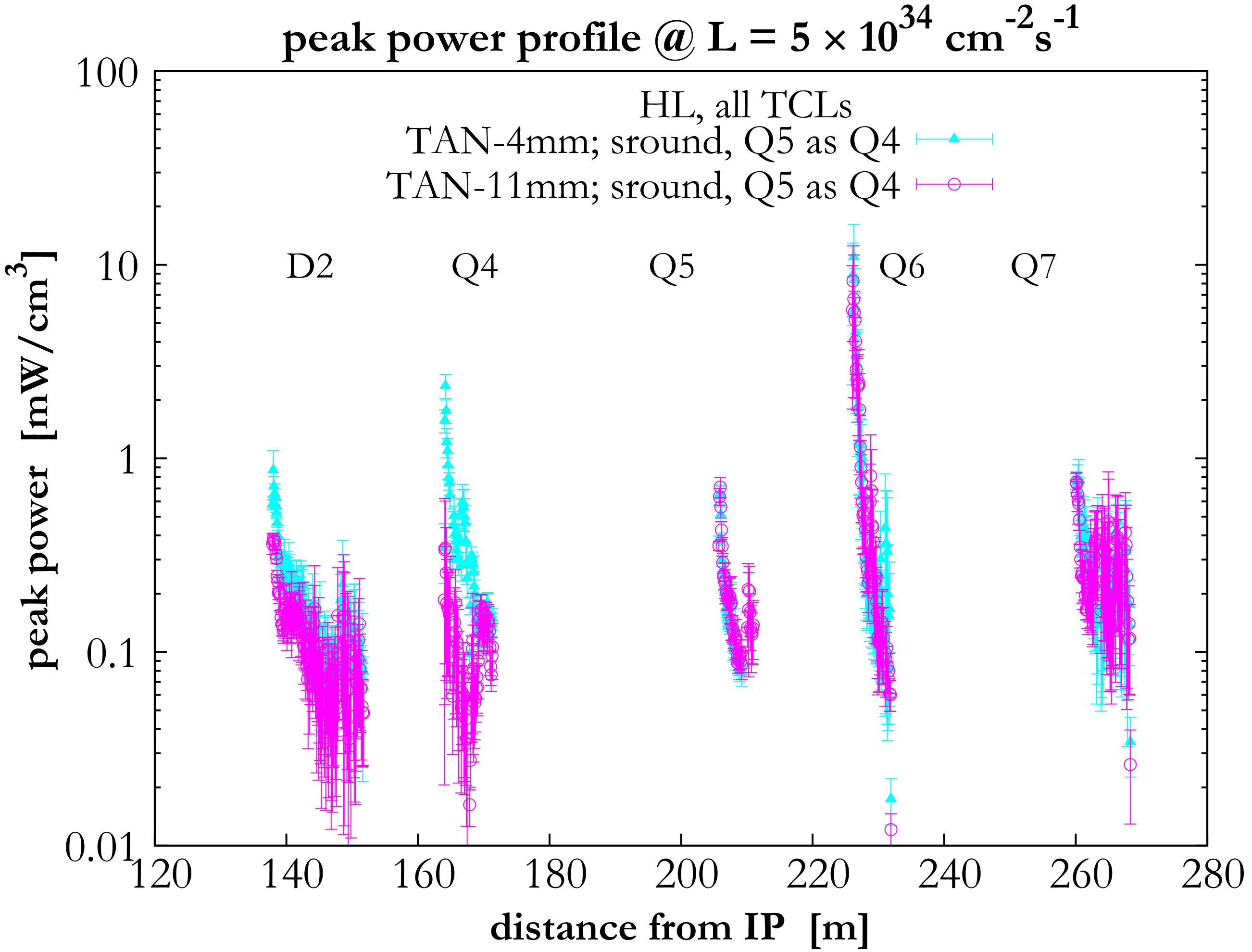
Reducing TAN aperture, Q5 as Q4



-10% radius reduction

Q5 aperture increase moves the problem on Q6

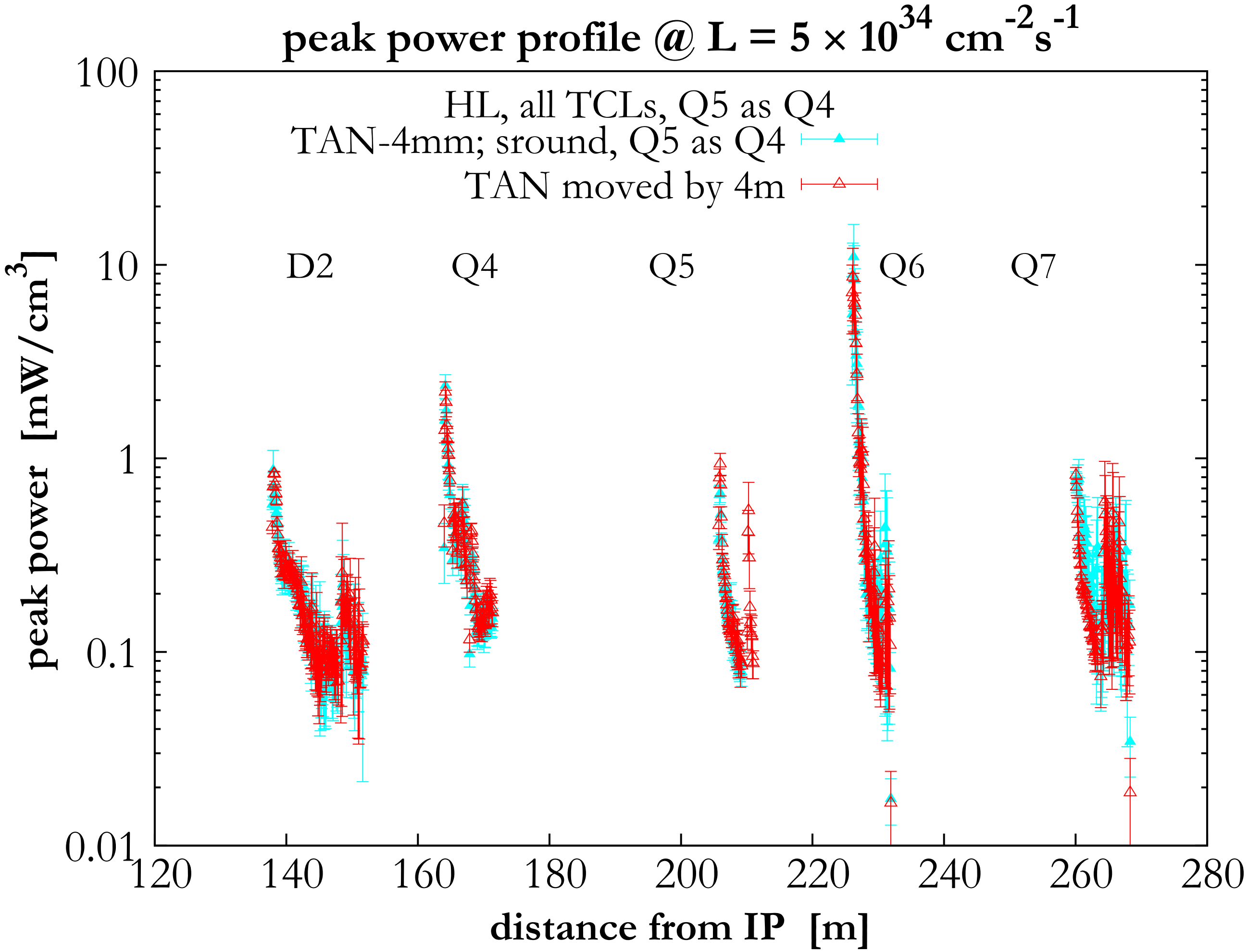
Further reducing TAN aperture



-30% radius reduction

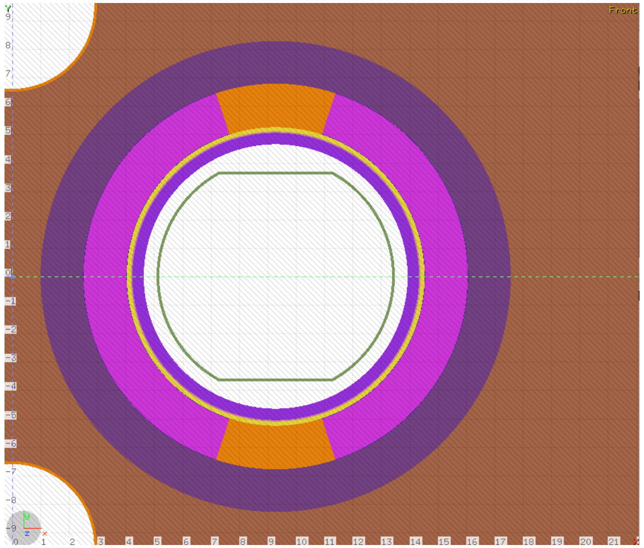
The effect of the reduction of the TAN aperture (reduction not realistic as considered in this extreme case) is, however, limited to D2-Q4

and moving the TAN

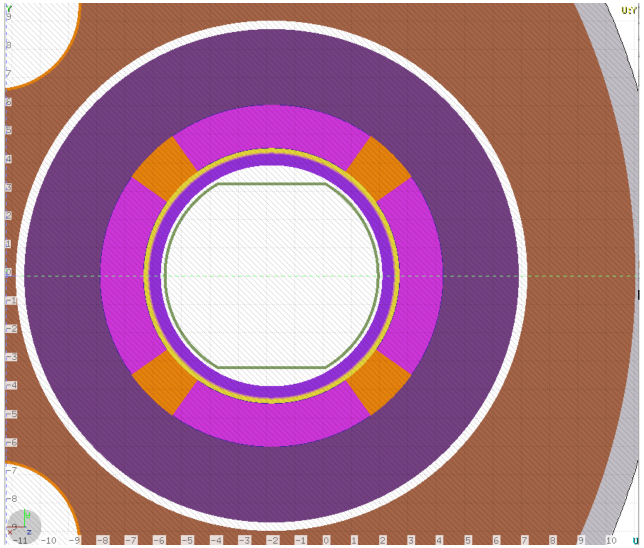


Beam screen with tungsten absorbers

D2



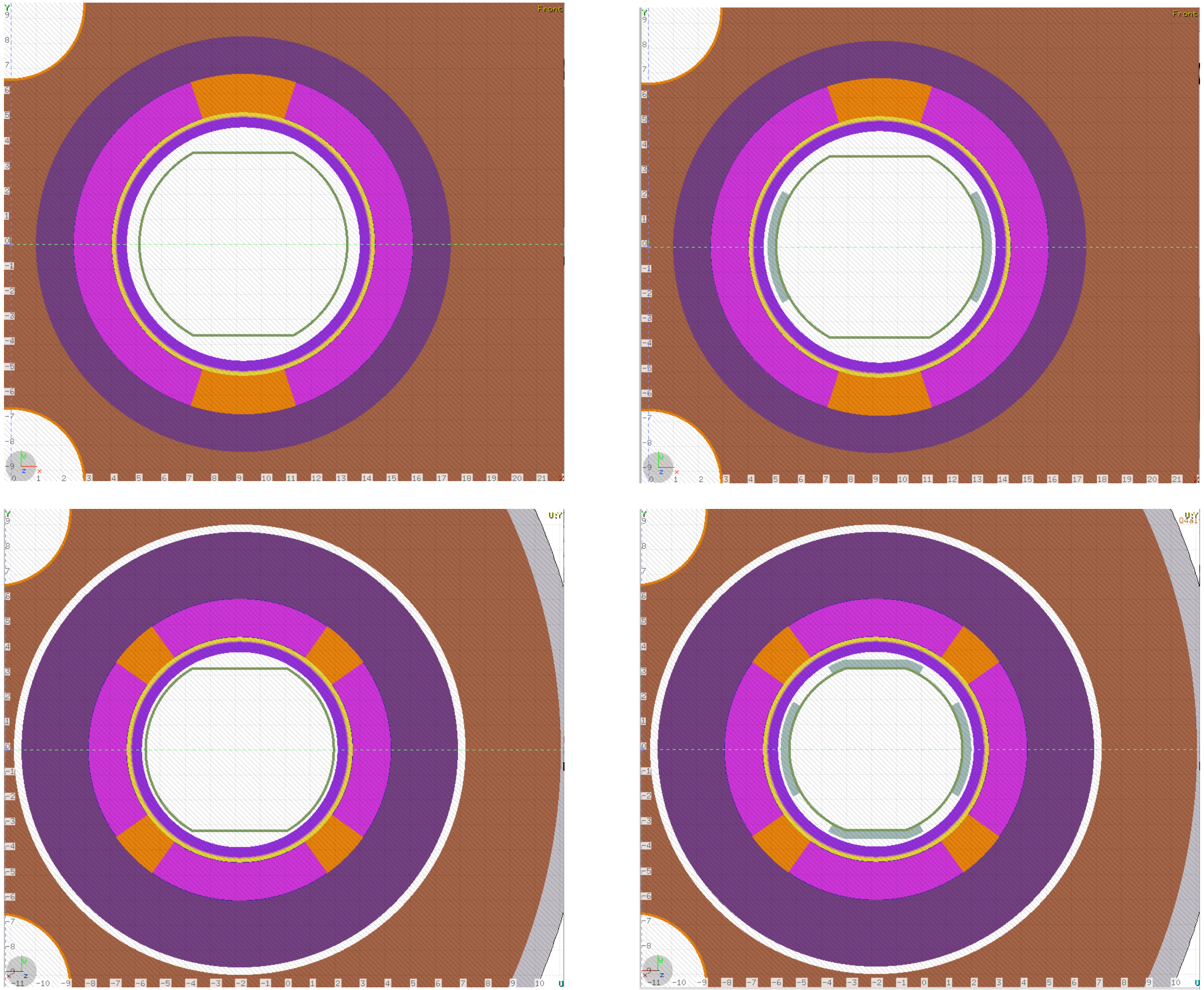
Q4/5



Beam screen with tungsten absorbers

D2

Q4/5

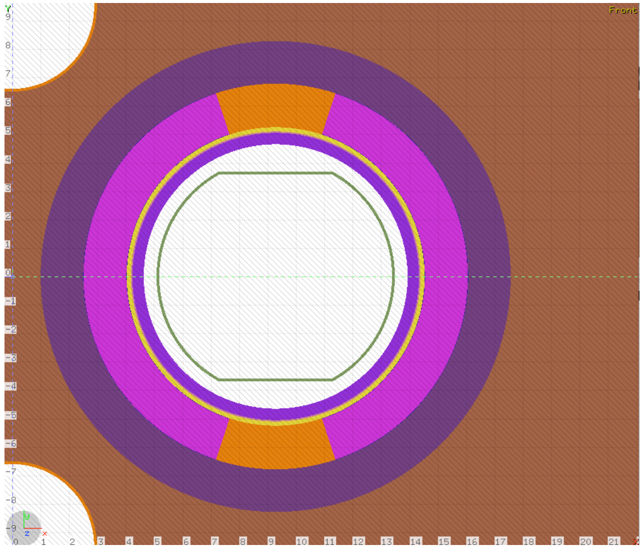


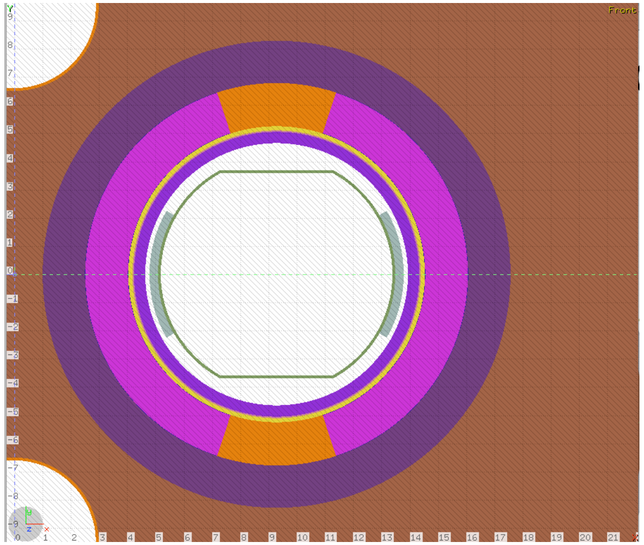
3 mm tungsten absorbers

covering $\pm 30^{\circ}$ from the mid-planes

Beam screen with tungsten absorbers

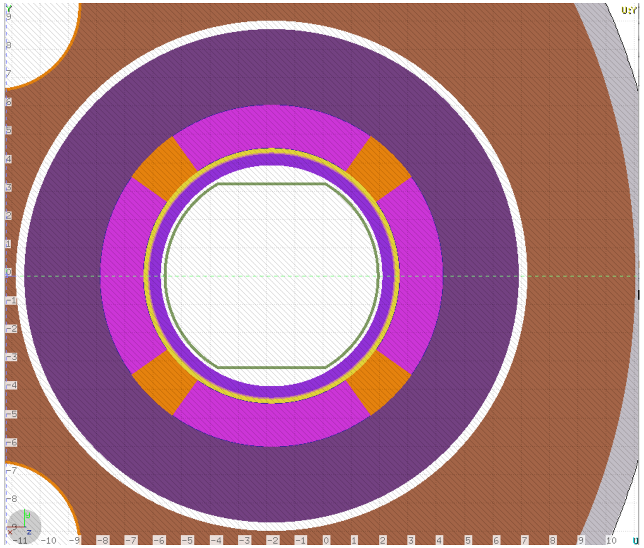
D2

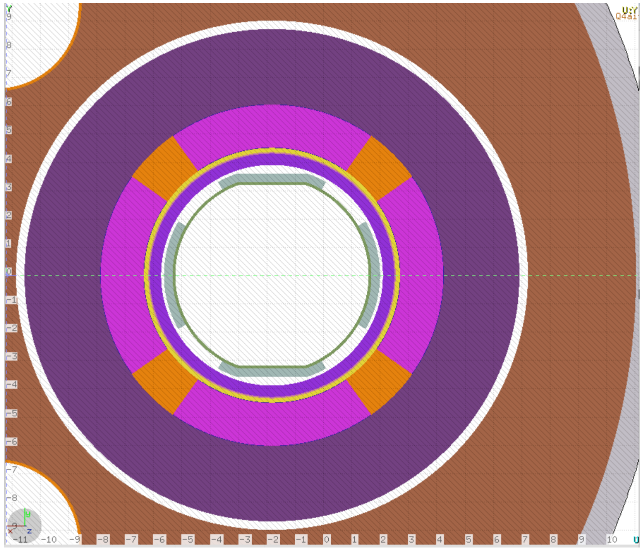




no aperture loss

Q4/5



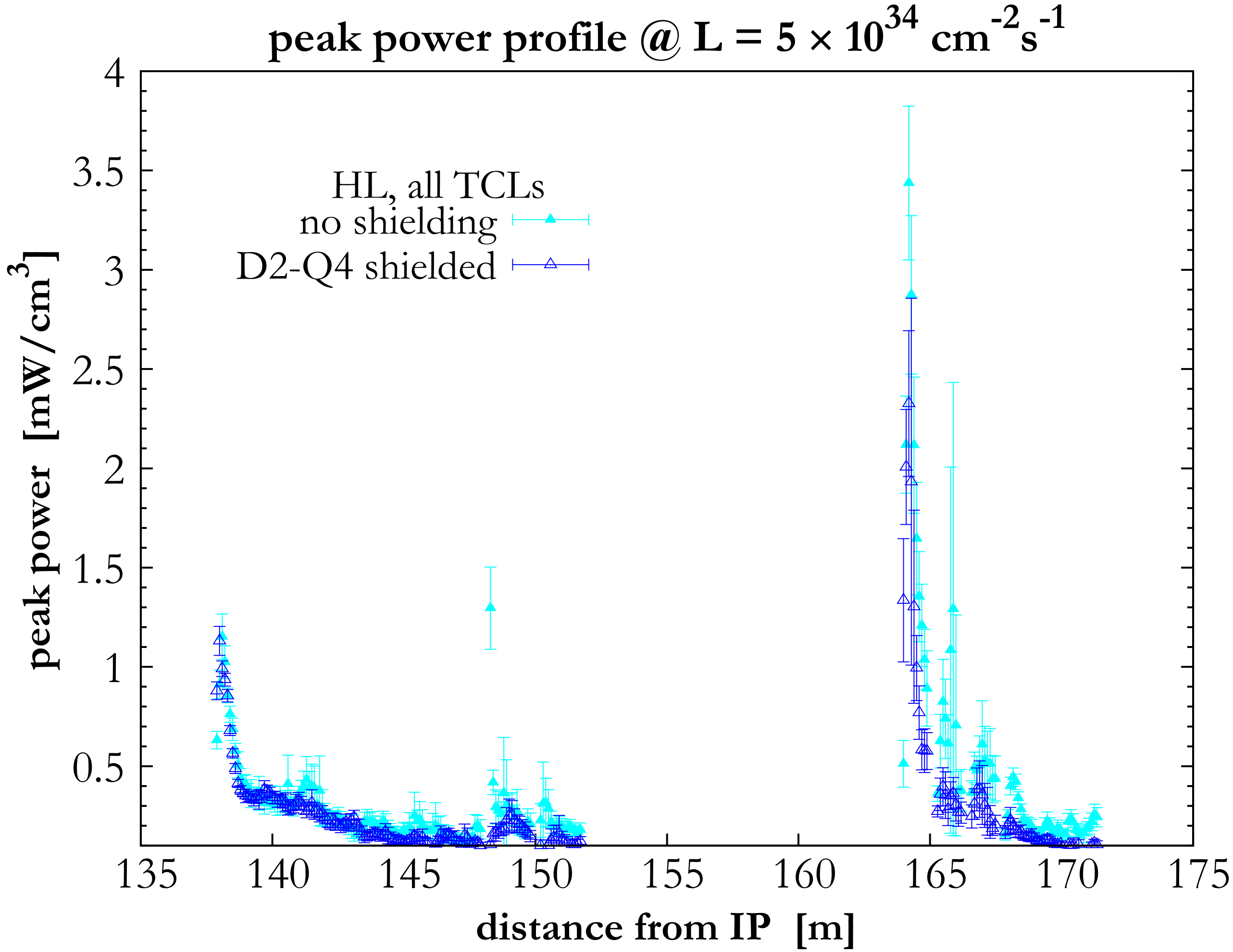


lost 3+3 mm along the major of the RECTELLIPSE

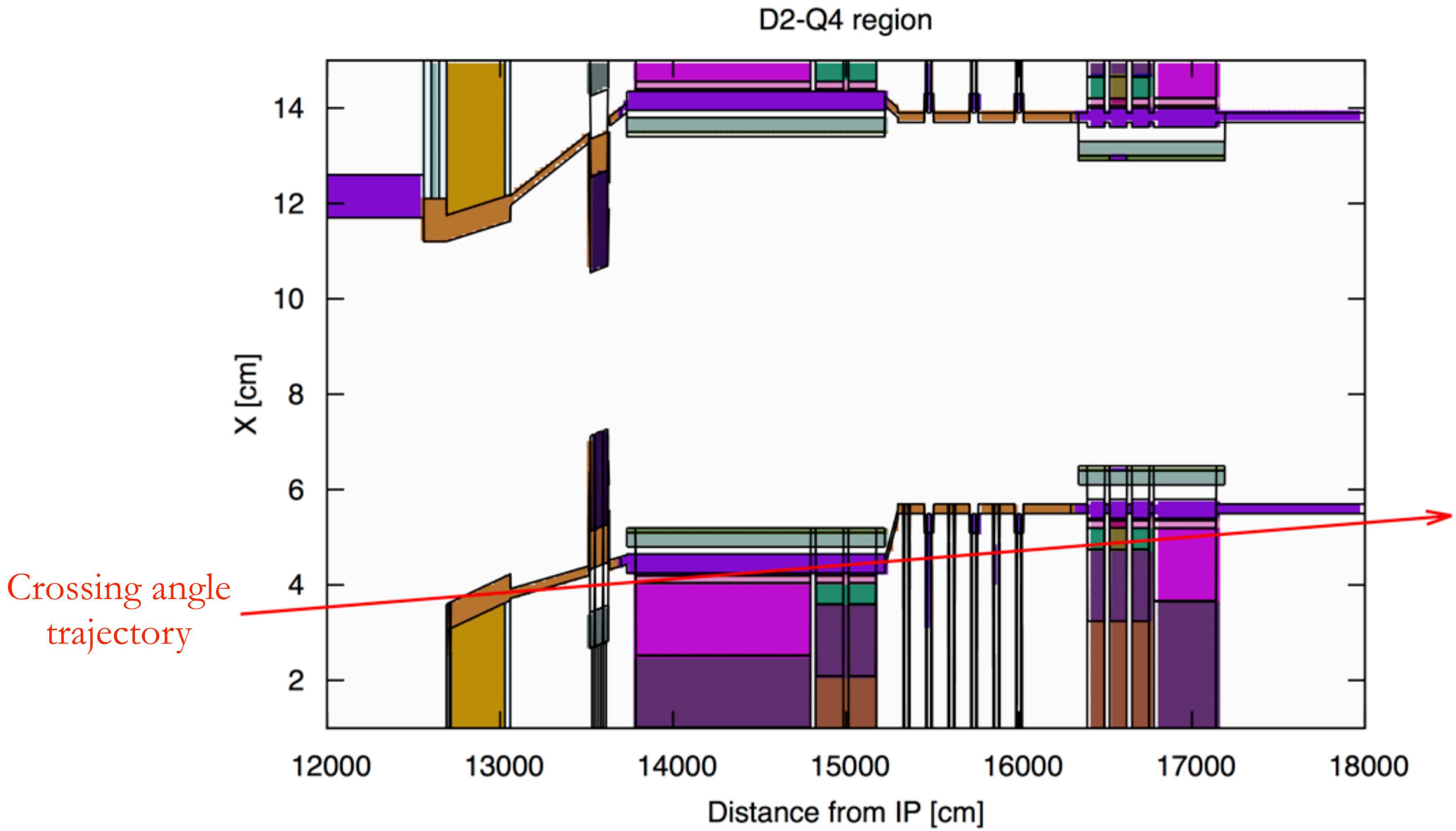
3 mm tungsten absorbers

covering $\pm 30^{\circ}$ from the mid-planes

Effectiveness of the shielding

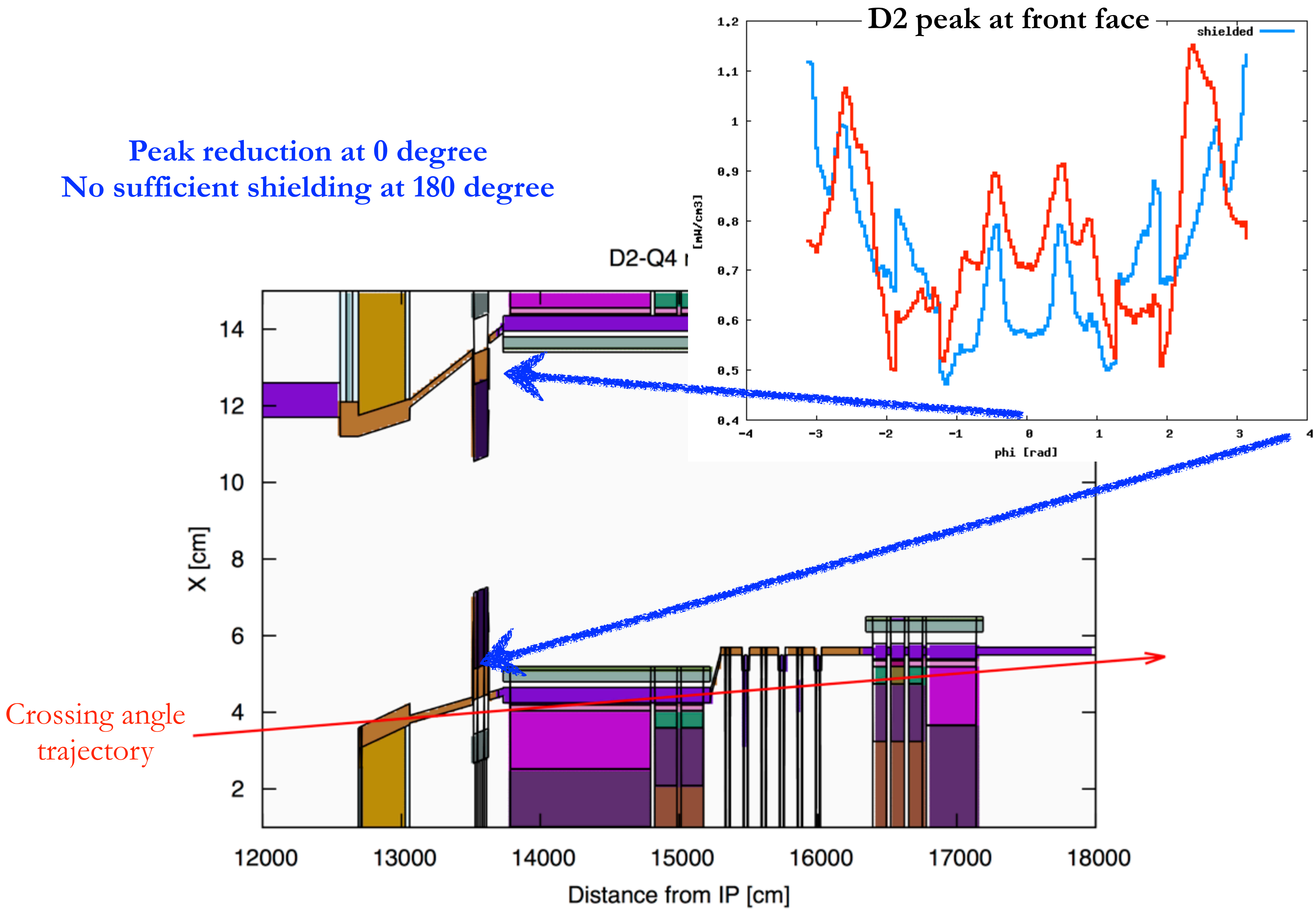


Peak reduced by ~30% on the Q4, but really limited on D2 (see next slide)

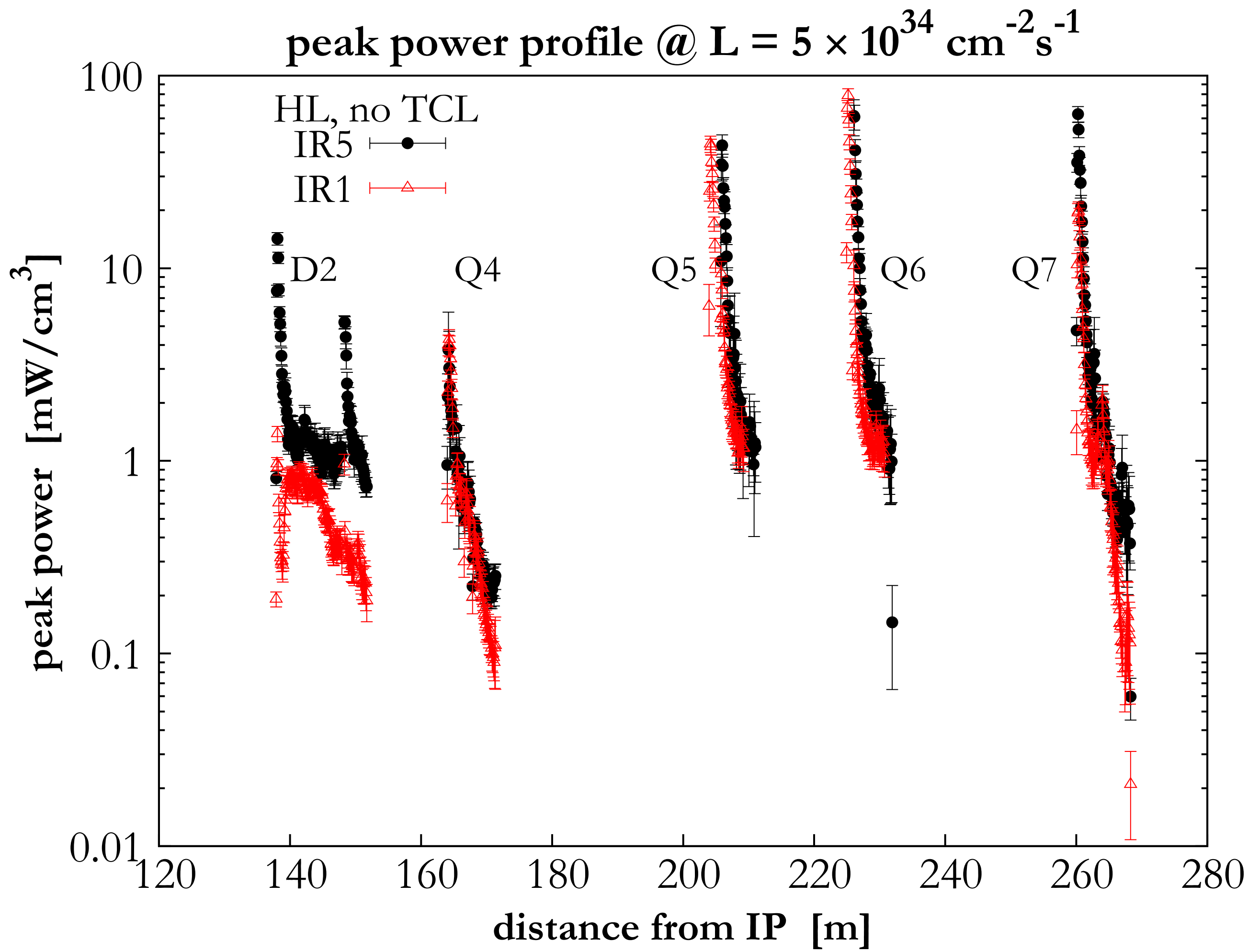


D2-Q4 region
X [cm]
14
12
10
8
6
4
2
12000
13000
14000
15000
16000
17000
18000
Distance from IP [cm]
Crossing angle trajectory

Peak reduction at 0 degree
No sufficient shielding at 180 degree

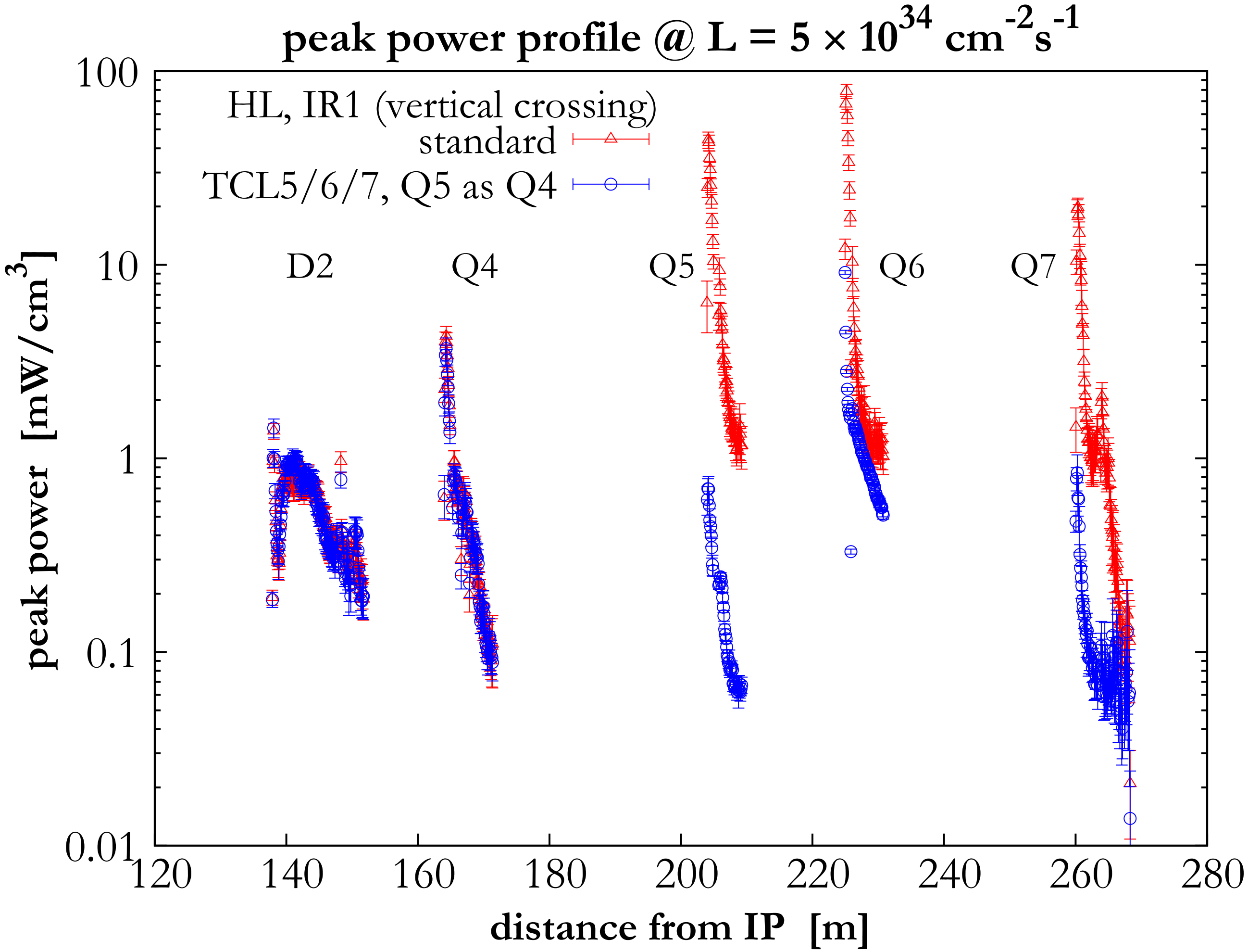


A look at IR1



No TCL

IR1 with TCL5/6/7 and Q5 as Q4



No TCL4

Q6 still critical from the protection point of view

Final remarks

- HL-LHC layout is challenging in the protection of the Matching Section elements
  (putting aside the 5× in luminosity, one should bear in mind that the beam is larger and that the separation between the beam trajectory and the neutral cone is strongly reduced§)

- Positive outcome
  - Q5 as MQYY (HL-LHC Q4) reduces the peak power at about 1 mW/cm^3 @ 5×10^{34} cm^{-2}s^{-1}
  - but what about Q6 (~10 mW/cm^3 @ 5×10^{34} cm^{-2}s^{-1})?

- TAN aperture/move and beam screen shielding turn out to have a limited impact
  - power peak are located at the IP-side of the MS magnets
  - leakage between TAN and TCL4

Reserve slides

Basic parameters

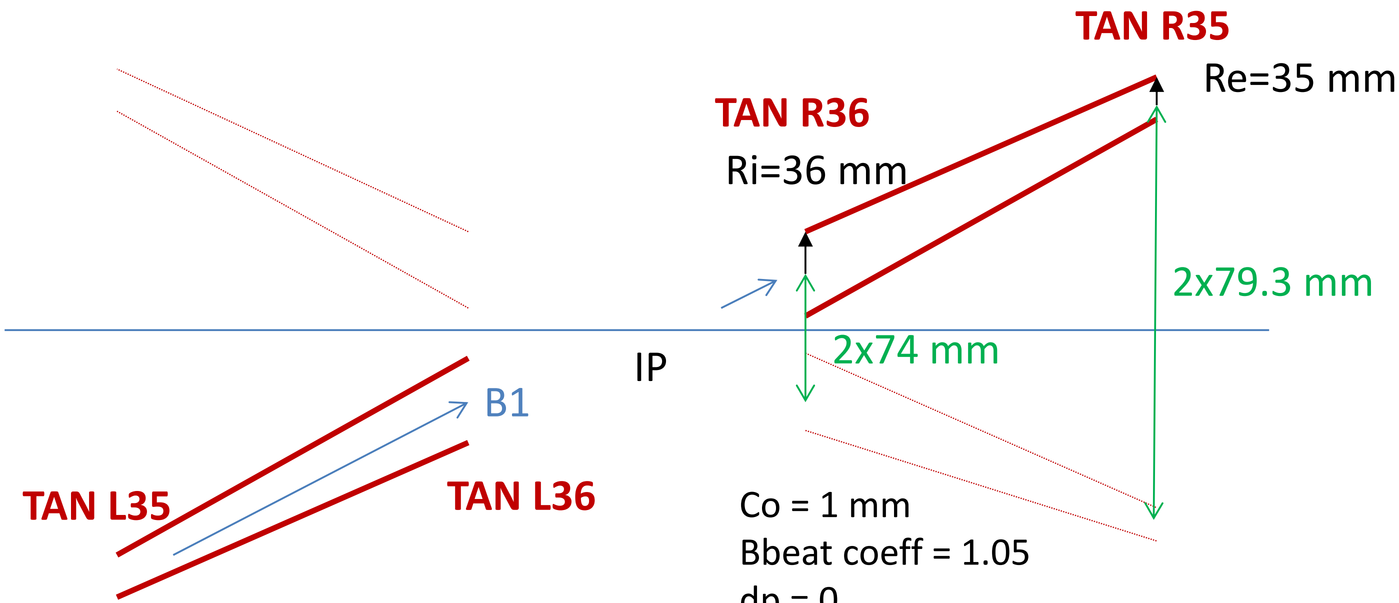
- 85 mb proton-proton cross-section at $\sqrt{s}$ = 14 TeV
- Normalization:
  - dose at 3000 fb^{-1} and
  - power density at $L = 5 \times L_0 = 5 \times 10^{34}\ cm^{-2}\ s^{-1}$
- DPMJET III as event generator
- Binning scoring: $\Delta z \simeq 10$ cm, $\Delta\phi = 2^0$
  - $\Delta r \simeq 3$ mm for dose scoring
  - Entire radial cable for power scoring

IP1	n1 TANL35	n1 TANL36	n1 TANR36	n1 TANR35
FLAT	14.36	14.50	12.45	12.60

IP5	n1 TANL35	n1 TANL36	n1 TANR36	n1 TANR35
FLAT	12.67	12.51	14.54	14.38
Q2 ROU	12.19	Q2 FLAT	11.92	

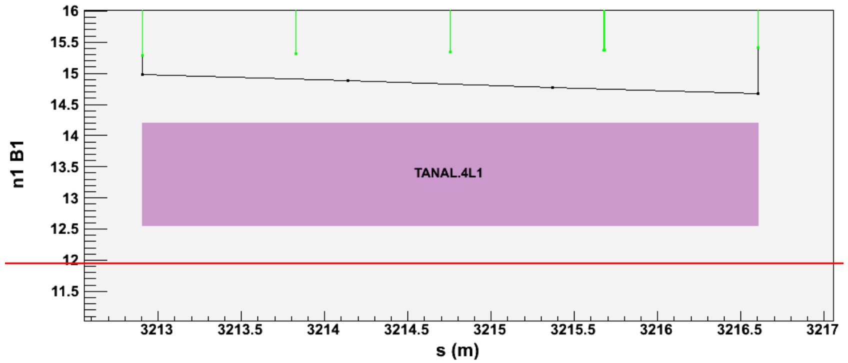
My numbers to compared with:
Round ➔13.88
Flat ➔11.13

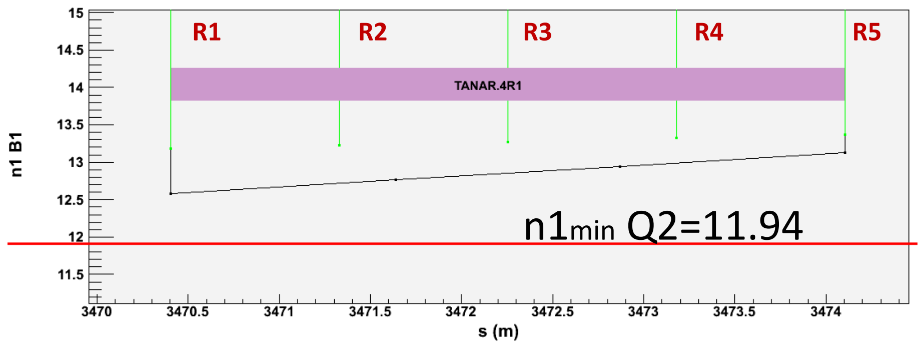
Ellipse ➔ Rx=37 mm, Ry=33.3 mm
Beam pipe separation cte = 145 mm

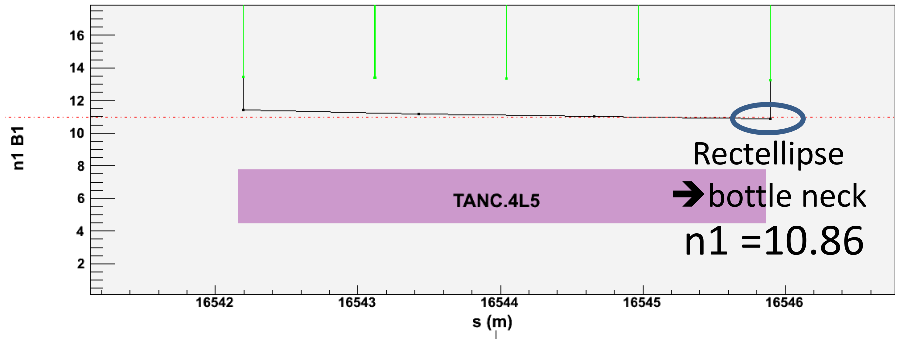


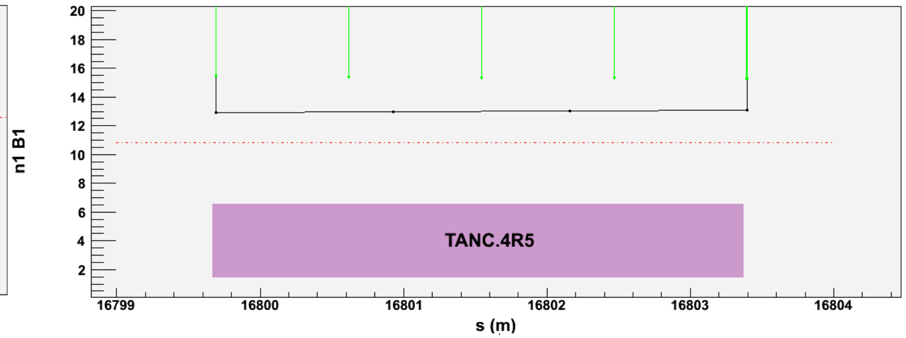
Co = 1 mm
Bbeat coeff = 1.05
dp = 0
e_n = 3.5 um rad
Halos = 6,6,6,6
Separation and crossing angles on

R. Alemany Fernandez

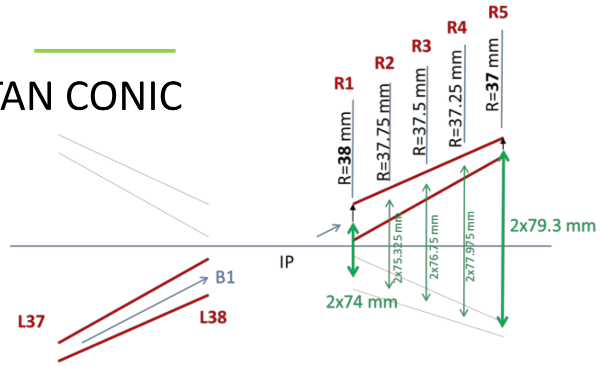




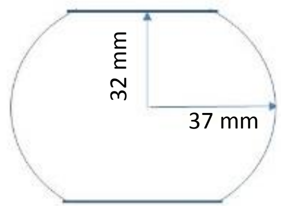




TAN CONIC



RECTELLIPSE



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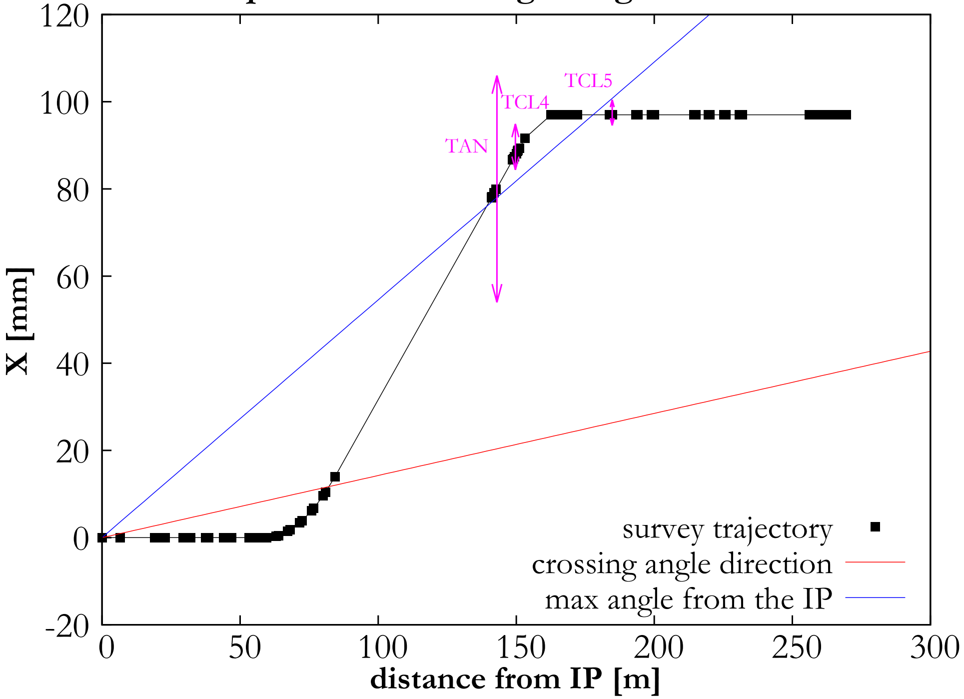
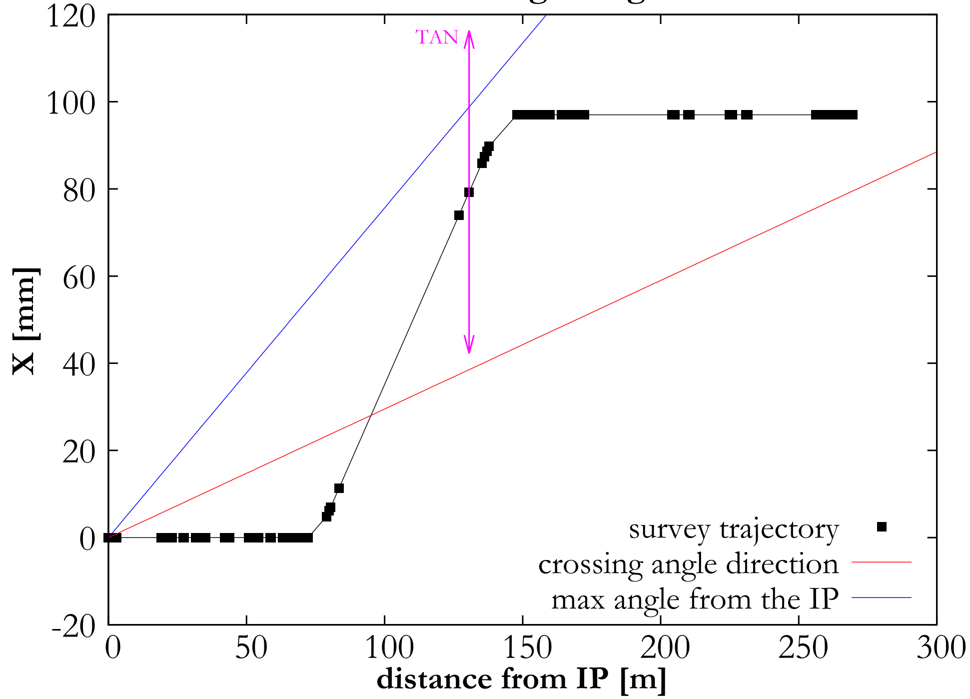
HL-LHC vs LHC

present LHC Long Straight Section



HiLumi LHC Long Straight Section



26 mm aperture **+ 42%** → 37 mm aperture (at TAN end)

maximum beta values at TAN location:
~1.6 km (V6.503 optics)

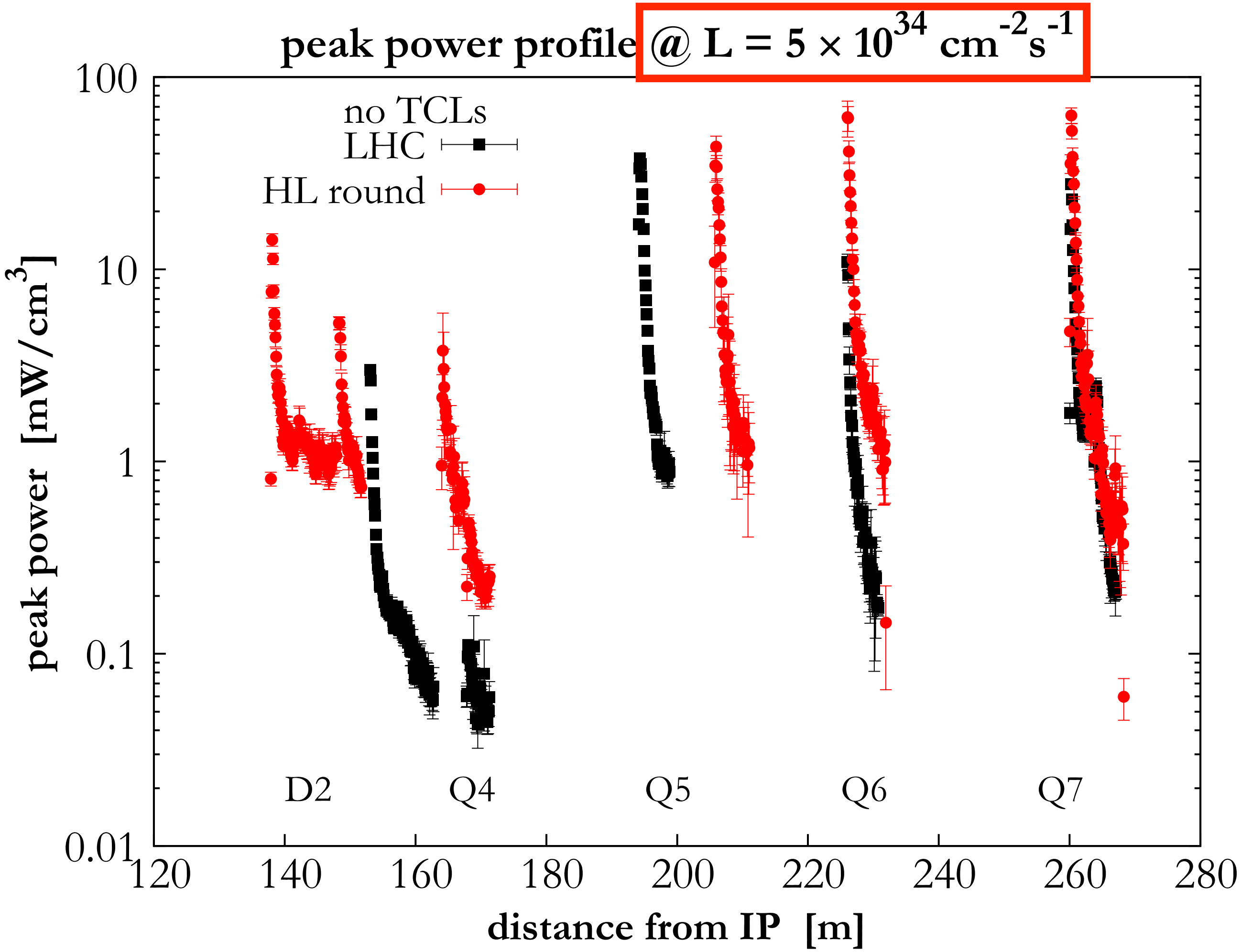
×4÷10 →

maximum beta values at TAN location:
~7-8 km (round optics)
~15 km (flat)

TAN aperture increase seems to be “reasonable” if compared to β increase

Lost the beam separation between the proton beam trajectory and the neutral cone coming from collision at IP

Comparison with LHC (no TCL)



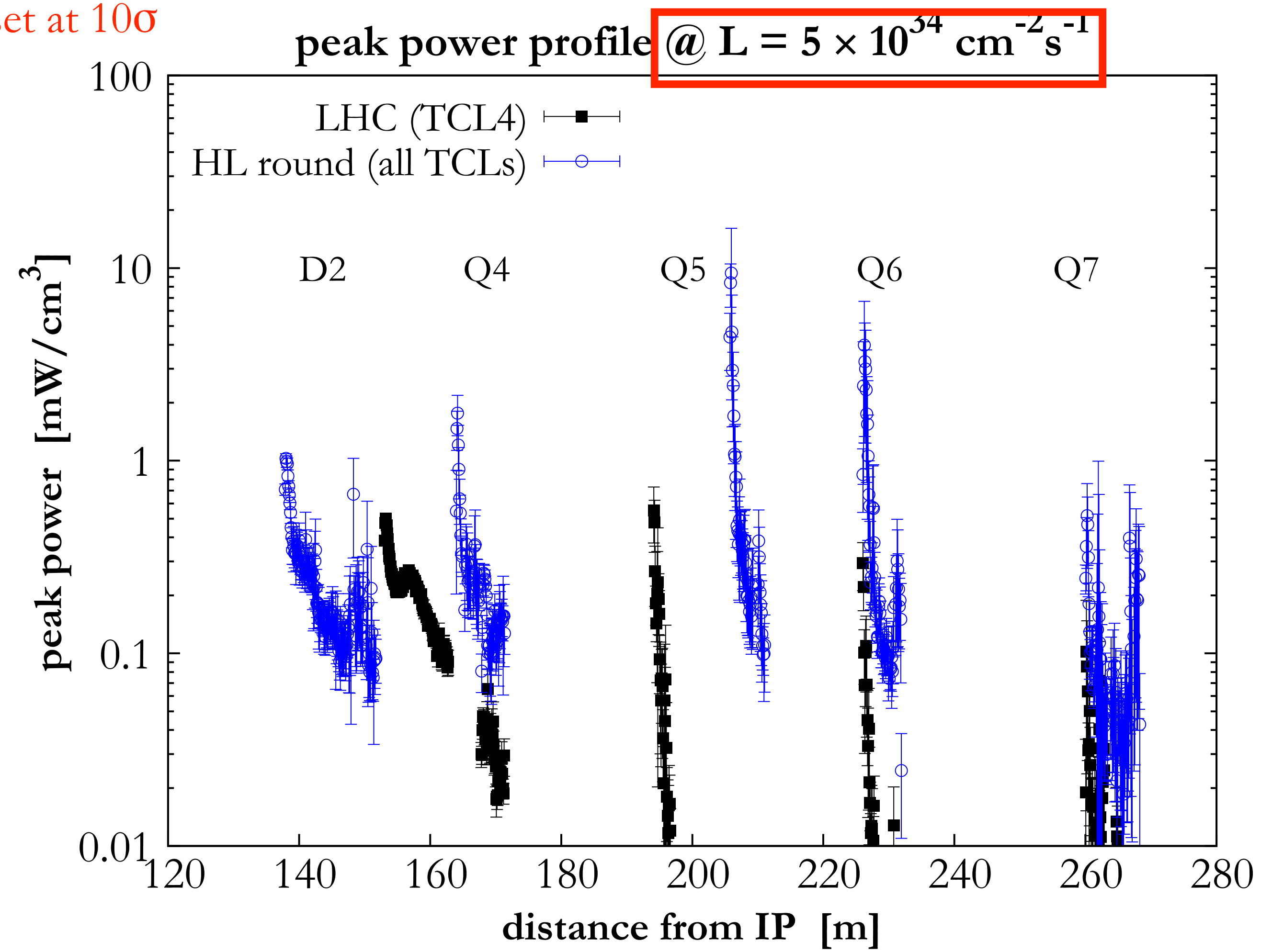
At same luminosity, there is a factor 5÷50 increase in the D2, Q4 and Q6 peak loads

Q4 correctors are not shown for LHC case

85 mb proton-proton cross-section at $\sqrt{s}$ = 14 TeV has been used for the normalization

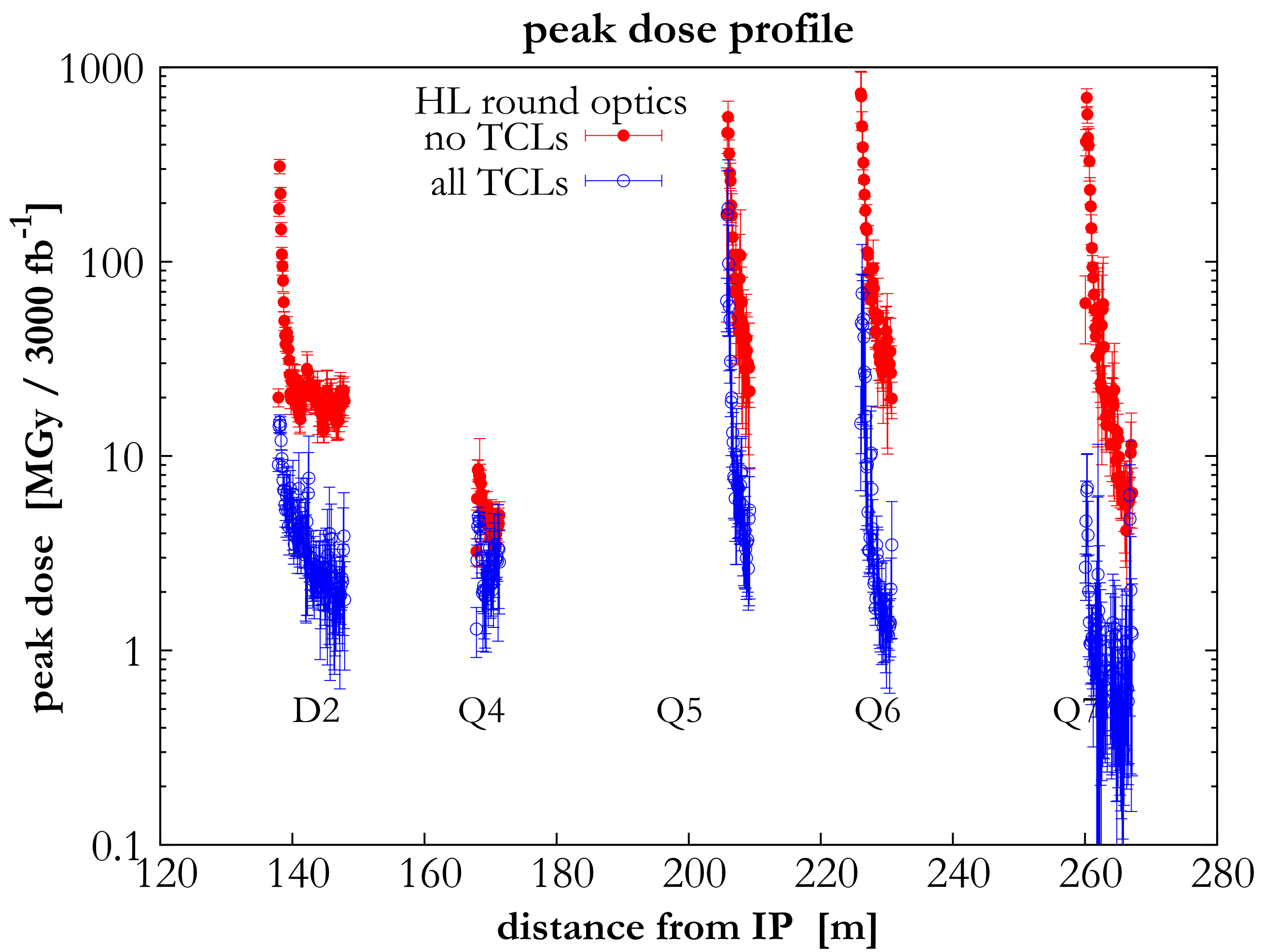
Comparison with LHC (with TCL)

TCL half-gap set at 10σ



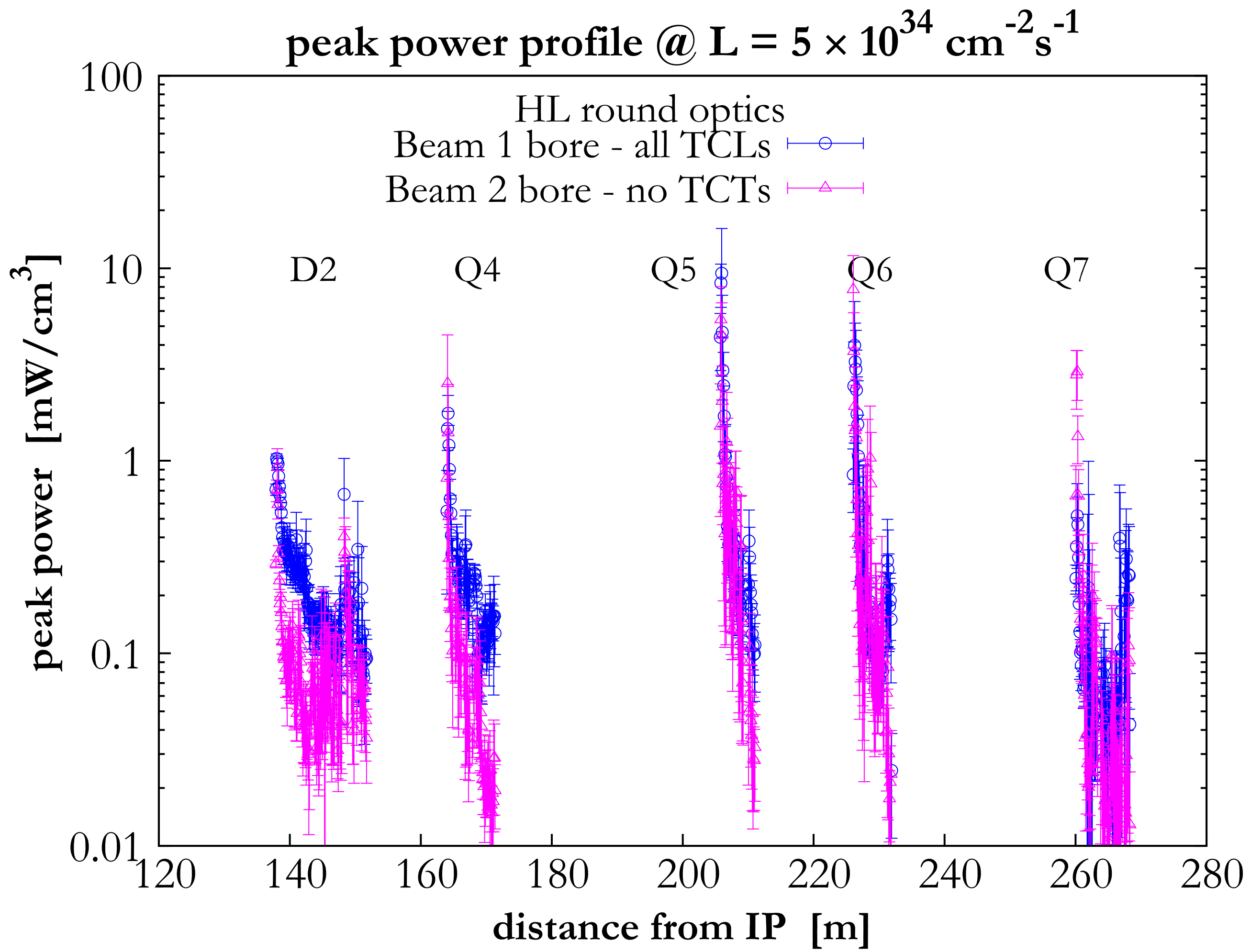
- **For the present LHC, TCL4 is sufficient to keep peak load <1mW/cm³**
- **For the HL case, even in the presence of a TCL in front of each magnet, the energy deposition results in peak loads in the range of 1 ÷ 10 mW/cm³**
- **TCL less effective in limiting magnet energy deposition because of the larger aperture (at a fixed number of σ)**

Peak dose



- **As for long term damage, ~100 MGy/3000 fb^{-1} (!) would be reached on the Q5 and Q6**

Looking at beam 2 bore



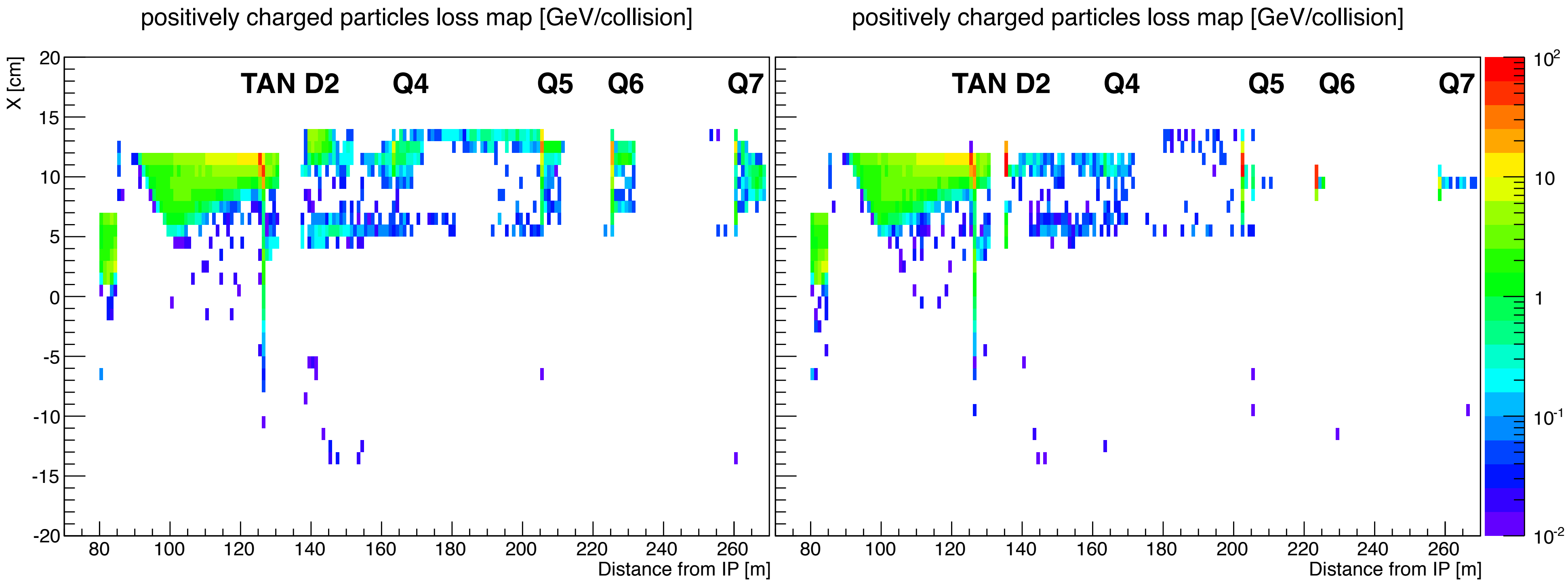
- **Beam 2 bore is also resulting in high energy deposition.**
- **TCTs will serve also as "TCL" but it depends on where they are located**

Total power

Power [W]	TAN	TCL4	D2	Q4	TCL5	Q5	TCL6	Q6	TCL7	Q7
LHC, hor, TCL4 @ 10^{34} cm^{-2} s^{-1}	205	35	4	0.3	-	0.2	-	<0.1	-	<0.1
HL round, vert, no TCL, @ 5×10^{34} cm^{-2} s^{-1}	1210	-	60	20	-	40	-	45	-	20
HL round, hor, no TCL, @ 5×10^{34} cm^{-2}s^{-1}	930	-	145	35	-	80	-	90	-	55
HL round, hor, all TCLs @ 5×10^{34} cm^{-2}s^{-1}	935	245	45	15	115	15	40	9	6	3
HL flat, hor, all TCLs @ 5×10^{34} cm^{-2}s^{-1}	990	265	60	9	80	13	35	8	4	3

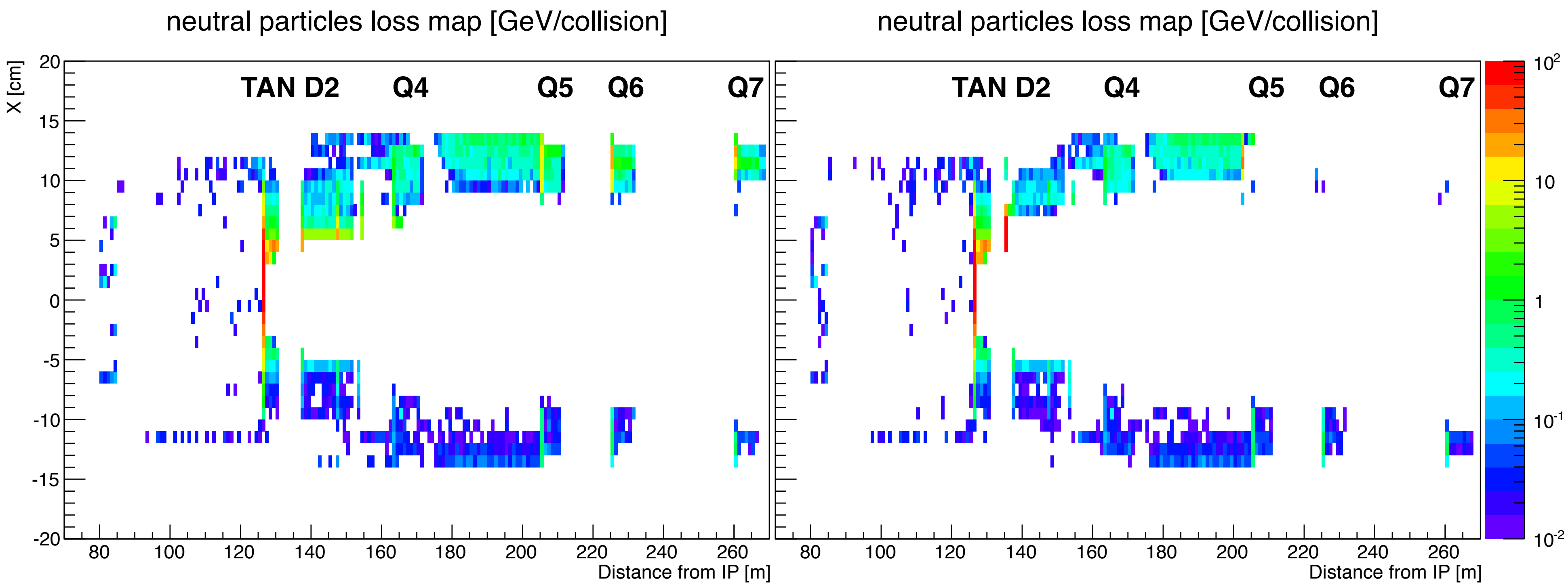
- **TAN will absorb even 1.2 kW (less shielding from the upstream elements)**
- **Looking at D2 (as example), the increase of heat load does not scale with the luminosity**

HL-LHC IR5 loss map



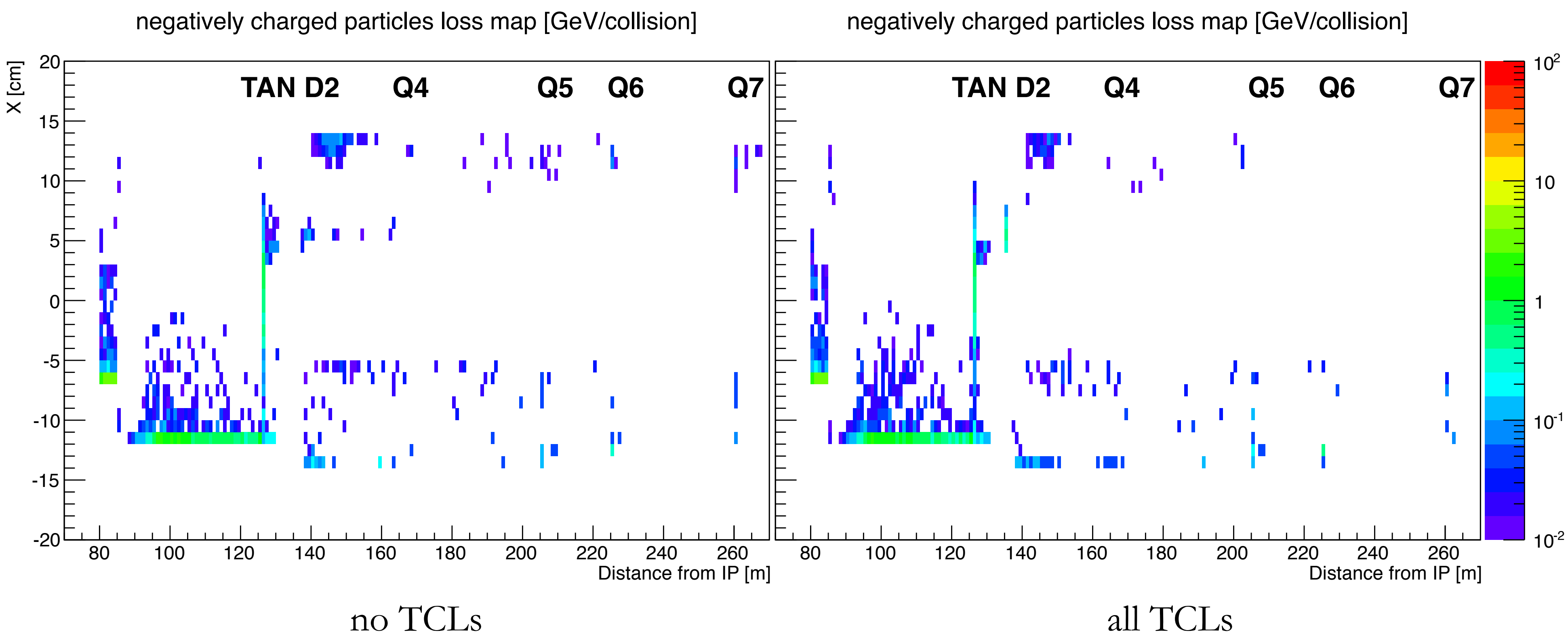
no TCLs

all TCLs



no TCLs

all TCLs


negatively charged particles loss map [GeV/collision]
negatively charged particles loss map [GeV/collision]
TAN D2
Q4
Q5
Q6
Q7
X [cm]
Distance from IP [m]
no TCLs
all TCLs