Conceptual design of an SPS collimation system

M. Patecki, A. Mereghetti, D. Mirarchi, S. Redaelli

Outline

- Objectives for the SPS collimation system
- SPS beams
- Beam losses in the SPS
- Analysis of Beam Loss Monitors (BLM) data
- Comparison of 2 designs with nominal aperture:
  - Two-stage collimation
  - Scraper+Absorber at the maximum of the dispersion
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- Summary

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Objectives and challenges

- **Objectives:**
  - Passive machine protection
  - Concentration of losses in the designed locations
  - Reduction of activation of equipment
  - Functional for all SPS beams and optics (priority to HL-LHC beams)
- **Challenges:**
  - Avoid the movement of collimators between the cycles (common gap or small adjustment with orbit bump)
  - Fitting into (very limited) empty spots
  - Enough beam clearance -> large gaps to avoid consuming an usefull beam

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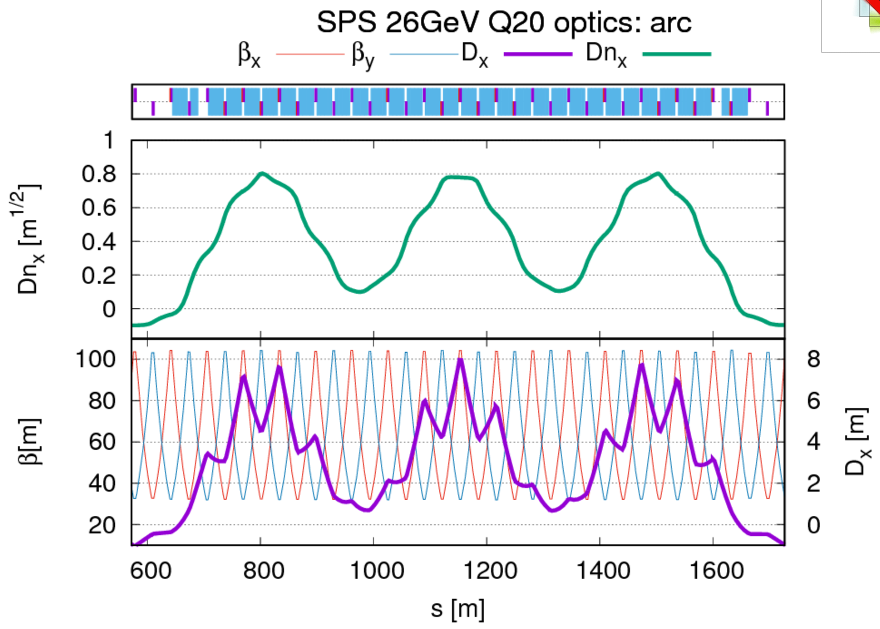
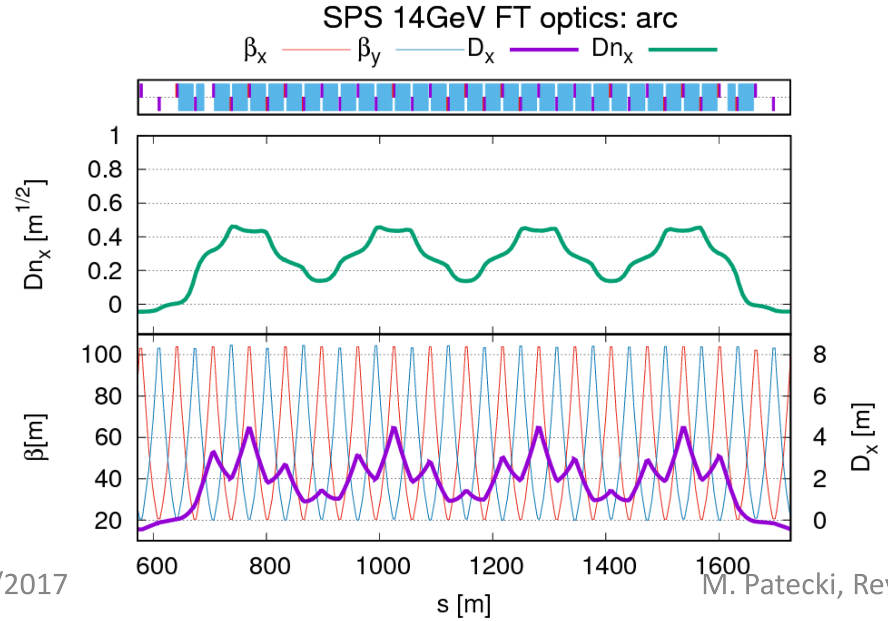
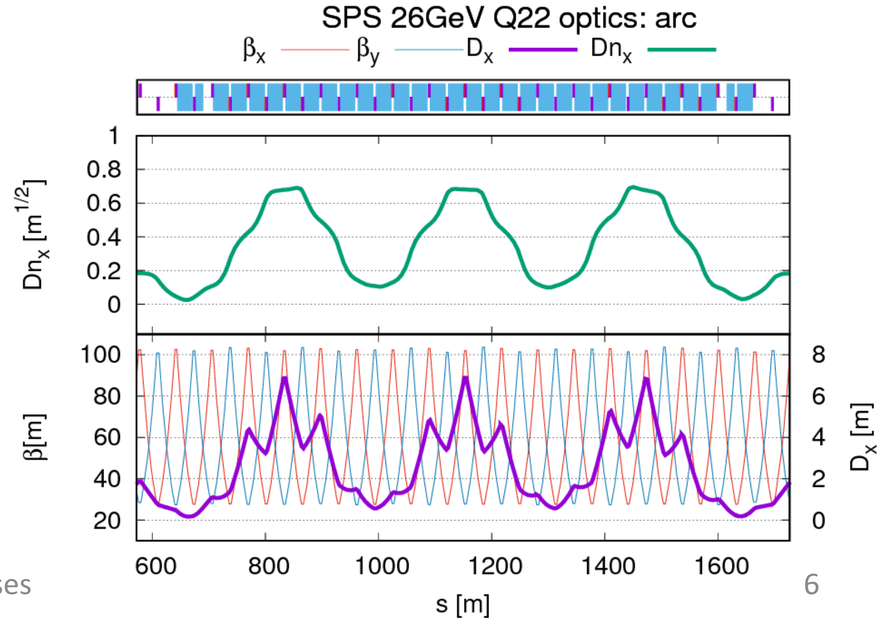
SPS beams

- LHC-type and fixed target
- Injection Energy (26GeV and 14 GeV)
- 3 types of optics: Q20, Q22, Q26
- Beams at slow extraction (special machine settings)
- Tables with beam parameters in extra slides







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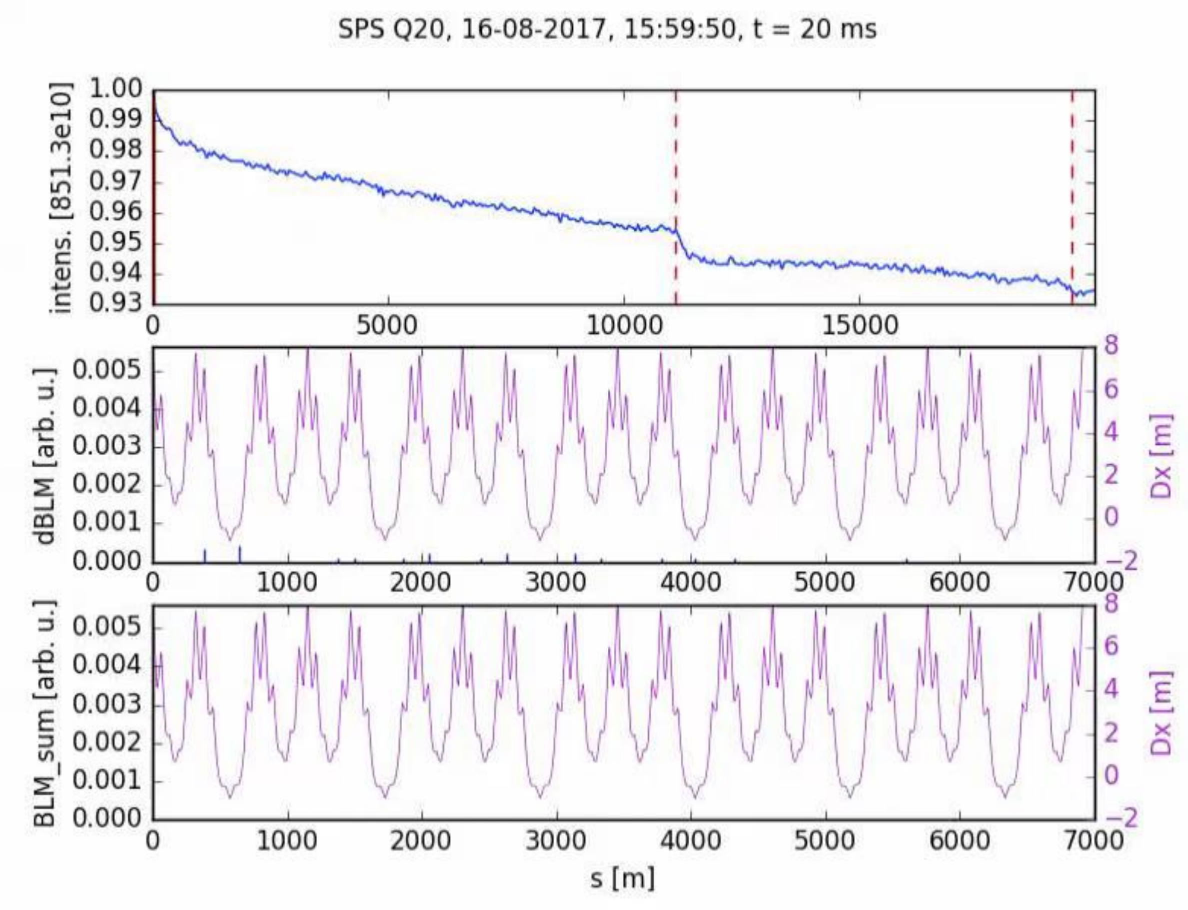
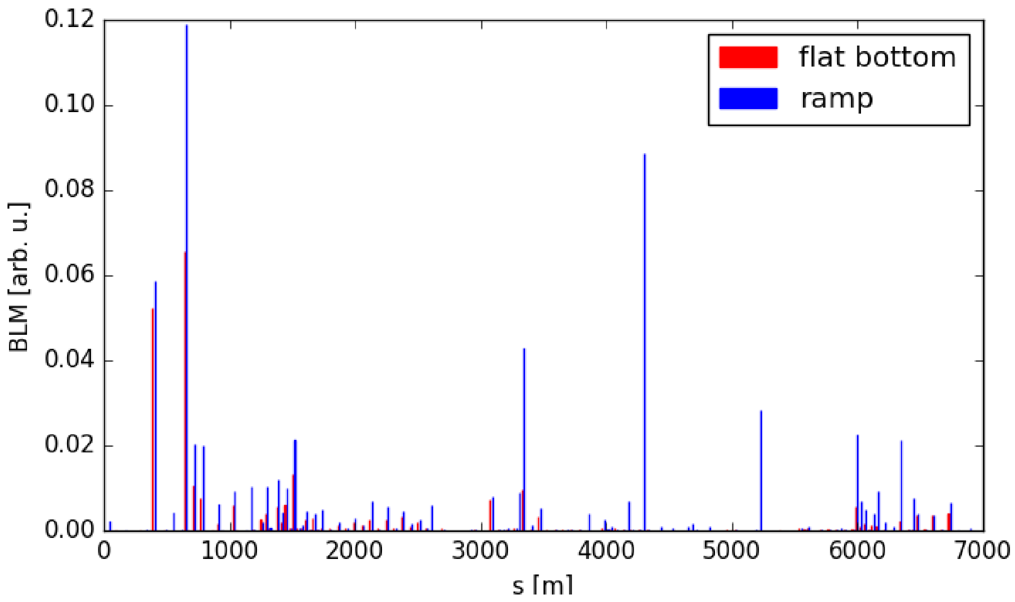
Losses in the SPS

- Injection and extraction losses
- **Off-momentum losses**
  - **Capture (bunch S-shape)**
  - **Flat bottom (full bucket)**
  - **During E ramp**
  - **In high dispersion regions**
- Transverse losses
  - Due to large beam size at injection energy
  - At aperture restrictions
- Scraping

Losses over the cycle





Assuming same response of all BLMs:

Loss [%]	BLM#	s [m]	element
17.7	133	643.4	MBA.12030
13.0	181	4291.1	MBA.42630
7.9	132	387.4	MBA.11230
6.5	169	3331.2	MBA.33230
4.7	97	5215.2	MDV.51907

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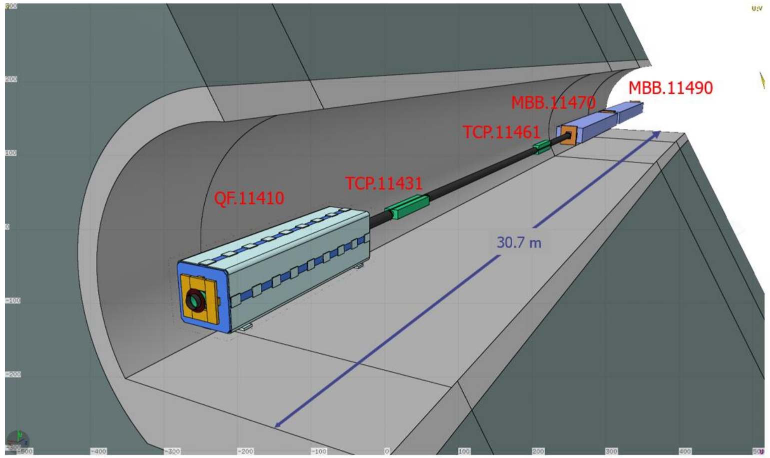
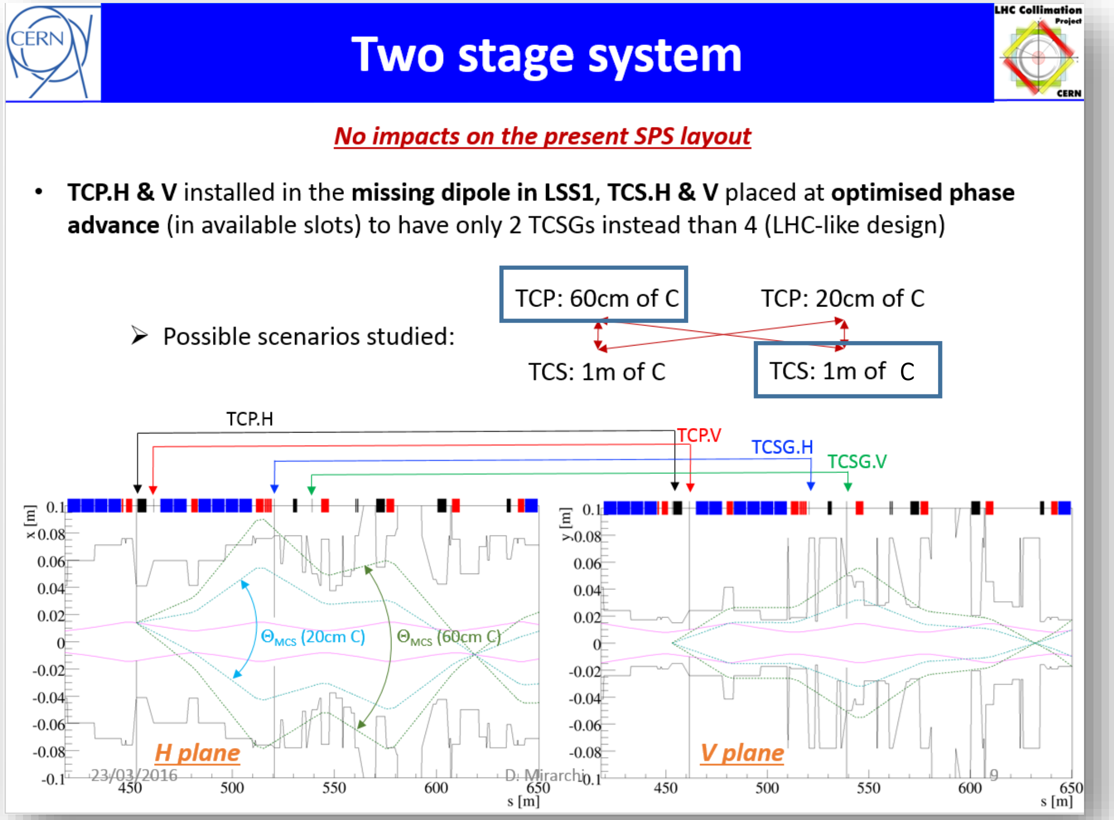
Two-stage collimation system
(Preliminary design by Daniele)

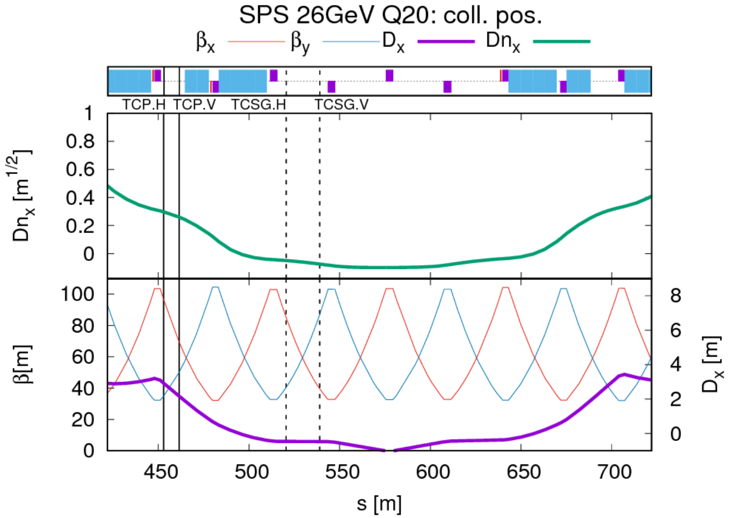
- Proposed by D. Mirarchi et al.:
  "SPS collimation first look and ideas." LIU-SPS, Beam Loss, Protection and Transfer Lines WG Meeting, 23.03.2016.
- Typical two-stage collimation system based on the betatron motion
  (correct phase advance between stages required).
- Primary collimators in the empty dipole slot; secondary coll. in the straight section.
- 4 collimators



Picture from: https://indico.cern.ch/event/609774/#17-fluka-simulations-of-sps-co



Optics at the collimators (Q20 & Q22)



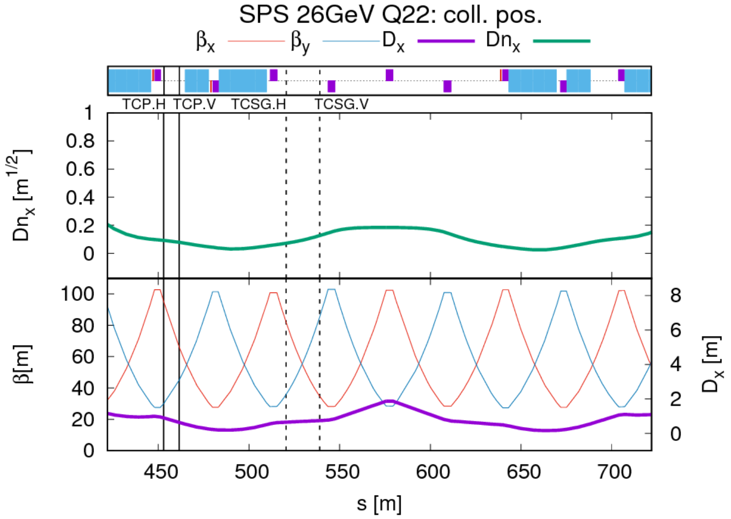


Table: Optics at the locations of the collimators.

case	coll	s [m]	μ_x [2π]	μ_y [2π]	β_x [m]	β_y [m]	D_x [m]
Q20	TCP.H	453.0	1.31	1.33	96.43	34.88	2.92
	TCP.V	461.5	1.33	1.37	69.45	50.07	2.17
	TCSG.H	520.5	1.51	1.53	85.18	40.41	-0.46
	TCSG.V	539.0	1.56	1.59	39.56	86.96	-0.47
Q22	TCP.H	453.0	1.44	1.47	95.08	30.00	0.90
	TCP.V	461.5	1.46	1.50	66.20	44.93	0.64
	TCSG.H	520.5	1.65	1.69	81.94	35.88	0.65
	TCSG.V	539.0	1.71	1.74	34.74	85.31	0.75

At the limit for off-momentum cleaning (Dx max: 8m)

Too low for off-momentum cleaning (Dx max: 7m)

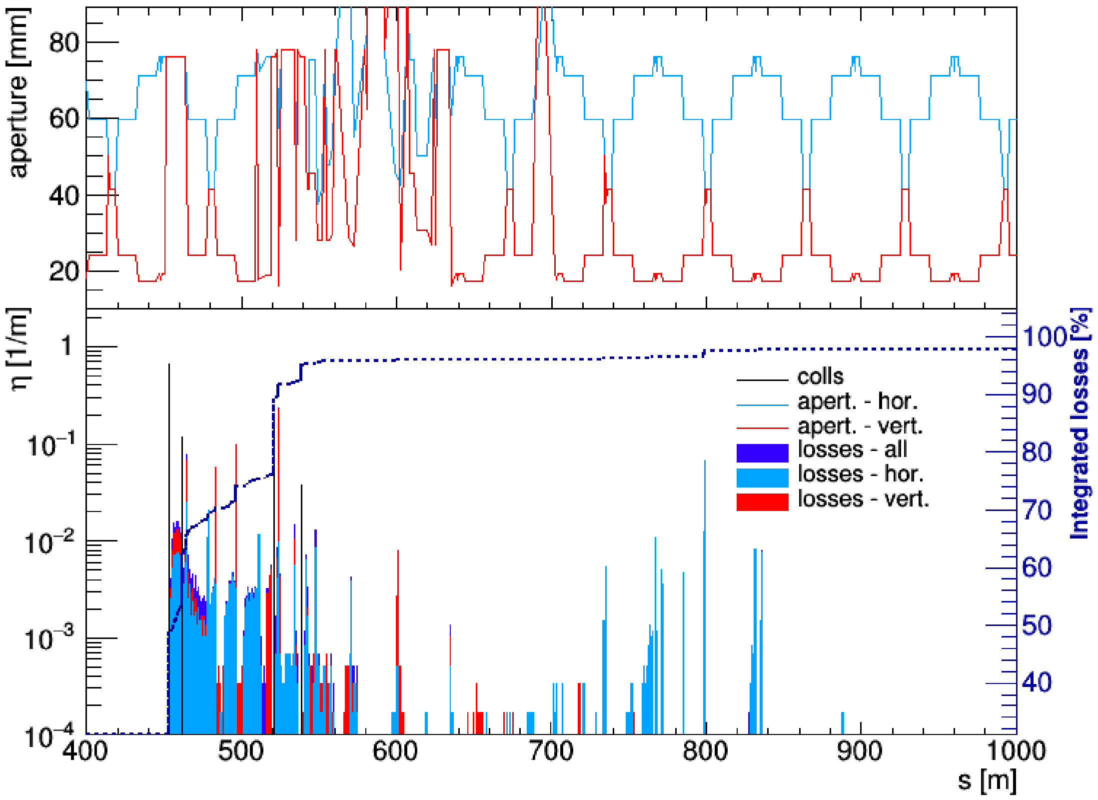
Original design by Daniele:

- Studied for Q20 & Q26 optics (there was no strong request for Q22 at that time)
- Half-gaps for primary collimators: $4\sigma_\beta$ (for ε=3.5 μm) (=14mm TCPH)
- This corresponds to $1.1\sigma_\beta$ + $D_x\delta_{bh}$ (for ε=1.89 μm)
- Half-gaps for secondary collimators: $5.5\sigma_\beta$ (for ε=3.5 μm)
- Impact parameter 6.5 μm
- Not an option for Q22 optics (D_x too low)

Two-stage collimation – loss map

<u>Modified design of Daniele:</u>

- Half-gaps for primary collimators: $4\sigma_\beta + D_x\,\delta_{bh}$ (for ε=1.89 µm) (=21.4 mm TCPH)
- Half-gaps for secondary collimators: $5.5\sigma_\beta + D_x\,\delta_{bh}$ (for ε=1.89 µm)
- Impact parameter 0.1 µm



	S [m]	Mod.	Orig..
All colls	**-**	**73.3**	**77.6**
TCP.H	453.0	48.7	42.7
TCP.V	461.5	8.8	9.5
TCS.H	520.5	13.0	19.2
TCS.V	539.0	2.7	6.0
drift	453 - 461	4.6	3.7
drift	462 - 465	3.0	2.7
MBB.11470	465.0	2.5	2.4
MBB.11490	471.4	0.9	0.9
MBB.11550	490.0	1.2	0.9
MBA.11570	496.7	3.2	2.0
MKQH.11679	523.7	2.7	3.3
MBA.11590	503.4	0.9	

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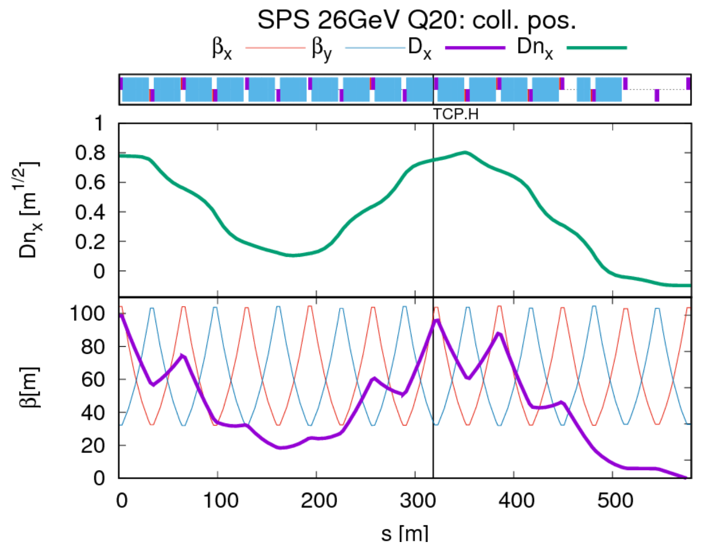
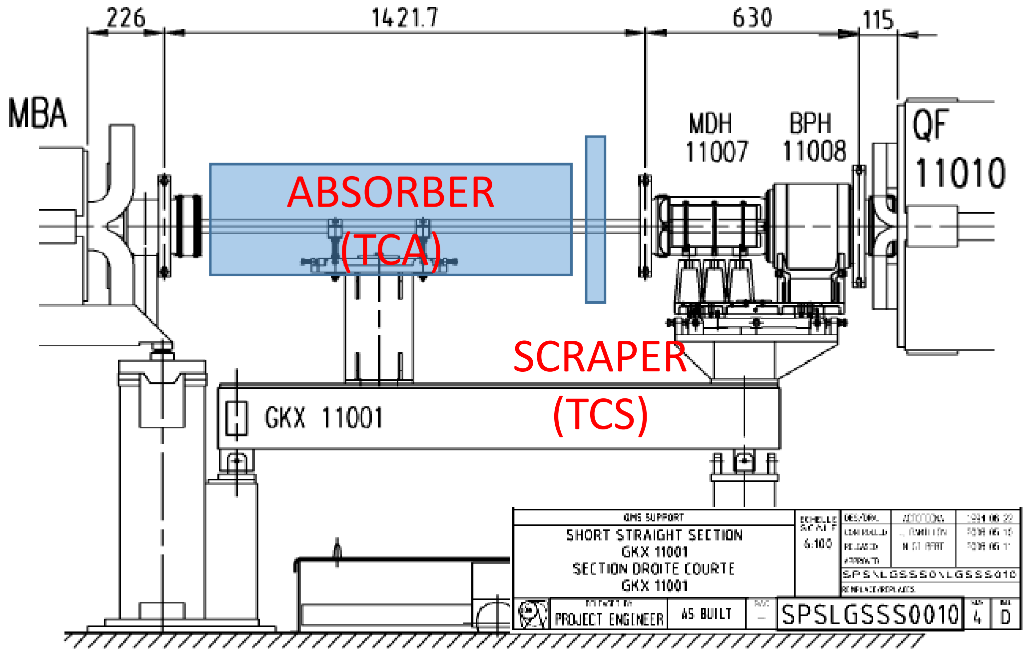
Scraper + Absorber @ Dx max

- Rather unusual design based on dispersion.
- Collimation insertion at the maximum of the dispersion for best off-momentum cleaning;
- Tight space limits using this location – in the arc, narrow vertical aperture, difficult to fit a secondary stage;
- Narrow scraper increases |dp/p| to send halo particles towards the absorber
- For 1cm of graphite about 3MeV E loss, corresponding to about δ_p=1.1e-4;
- Halo particles to hit the absorber front face with a large impact parameter (a few mm) and a large spread (a few mm);
- Scraper is not swept thorugh the beam. It is a short collimator with an adjustable opening.
- Only one collimation insertion.

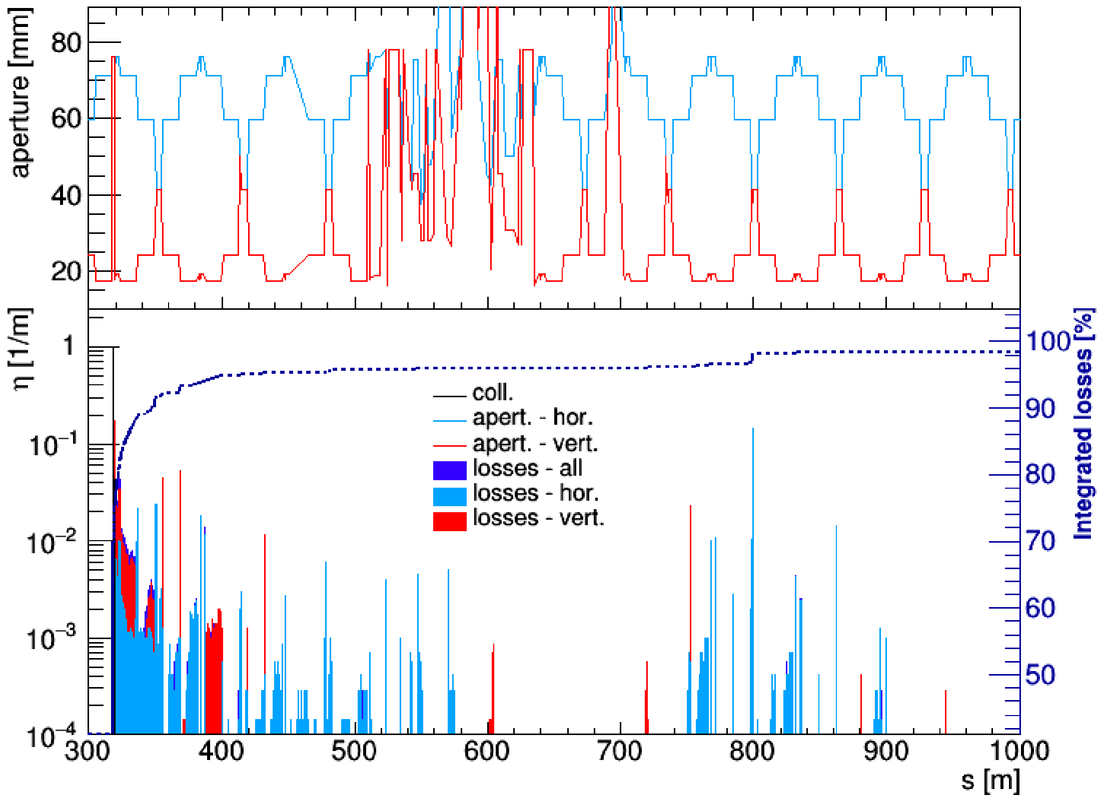




Settings:

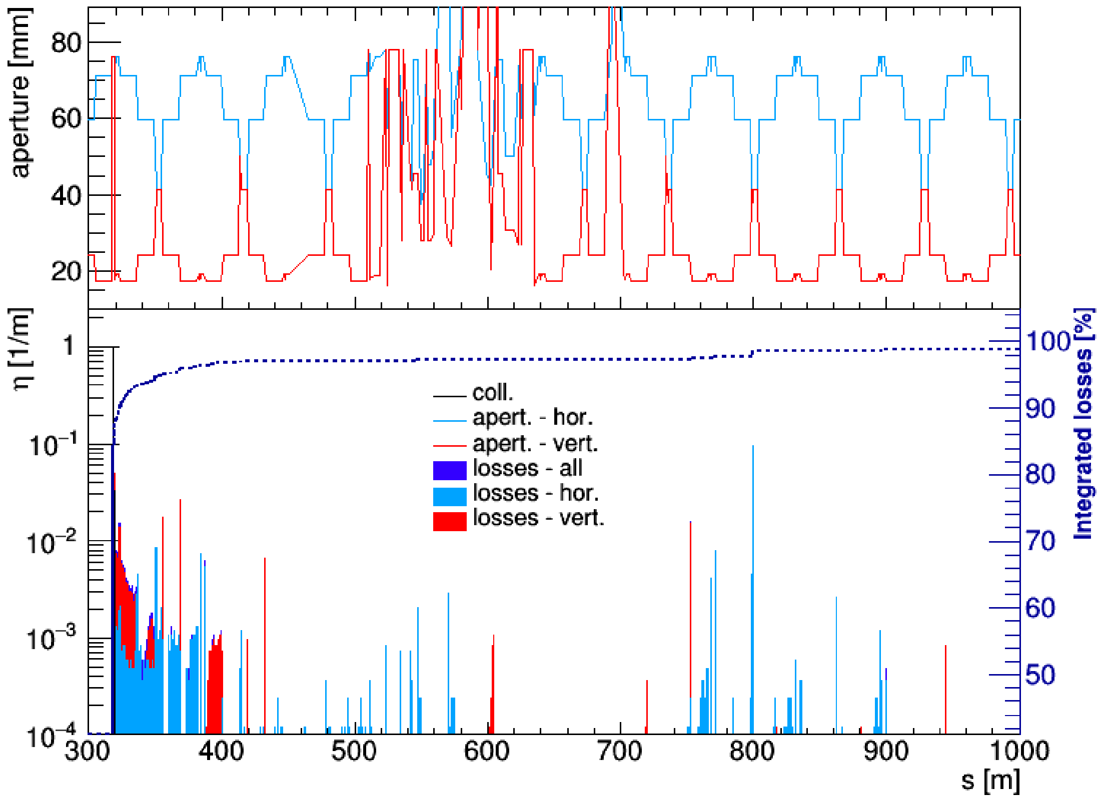
- TCS: 1cm, Gr or MoGr, half-gap: 5.0σ_β + $D_x \delta_{bh}$ (for ε=1.89 μm) = 41.7 mm
- TCA: 1m, MoGr or Cu, retraction 1.5mm w.r.t. TCS (0.6σ_β, δ_p=1.9e-4)
- Impact parameter: 0.1 μm

Scraper (MoGr) + Absorber (MoGr) – loss map



	S [m]	Losses [%]
All colls	**-**	**72.7**
TCA	318.4	69.6
TCS	319.0	3.1
MDH.11007	319.3	1.5
BPH.11008	319.6	1.2
QF.11010	320.0	5.2
MBA.11030	323.4	5.8
MBA.11050	330.0	2.7
MBB.11090	343.0	1.0
LSD.11105	350.8	1.5
BPCN.12508	799.5	1.0

Scraper (MoGr) + Absorber (Copper) – loss map



	S [m]	Copper	MoGr
All colls	**-**	**86.7**	**72.7**
TCA	318.4	83.9	69.6
TCS	319.0	2.8	3.1
MDH.11007	319.3	0.5	1.5
BPH.11008	319.6	<0.2	1.2
QF.11010	320.0	1.7	5.2
MBA.11030	323.4	3.0	5.8
MBA.11050	330.0	1.2	2.7
MBB.11090	343.0	0.5	1.0
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Comparison

Two-stage	S [m]	Mod.	Orig..
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Scr.+Abs.	S [m]	Copper	MoGr
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QF.11010	320.0	1.7	5.2
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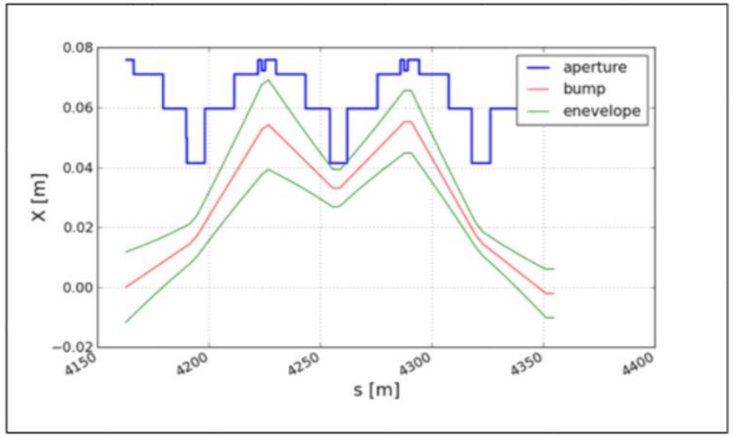
Measured horizontal aperture

V. Kain, Measured Q20 aperture limits at QDs and possible physical explanation/solution, https://indico.cern.ch/event/673312/:

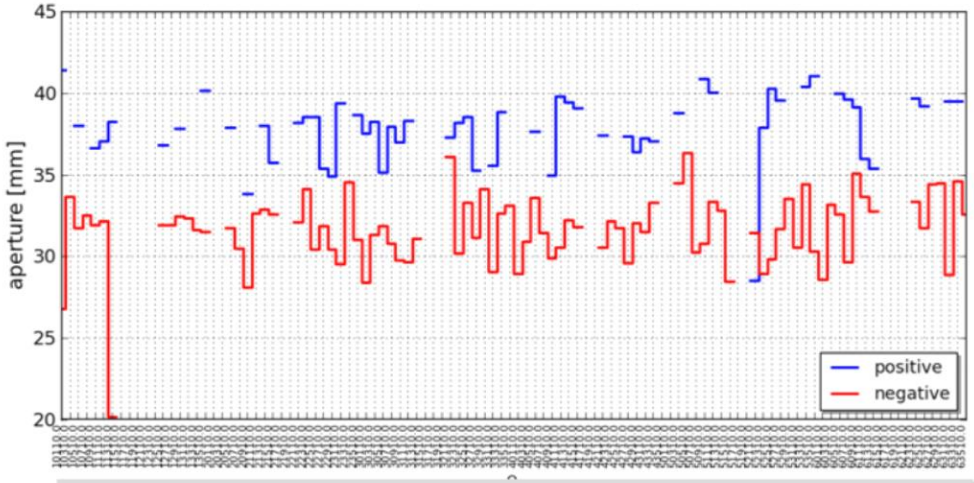
Measurement of mechanical aperture at QDs in H

- Measured at all QDs except locations *17 and *19
- Measurement at 14 GeV, Q26 with 4C bump
- Interpolate orbit at QD location and correct measured max. bump amplitude



Result in mm

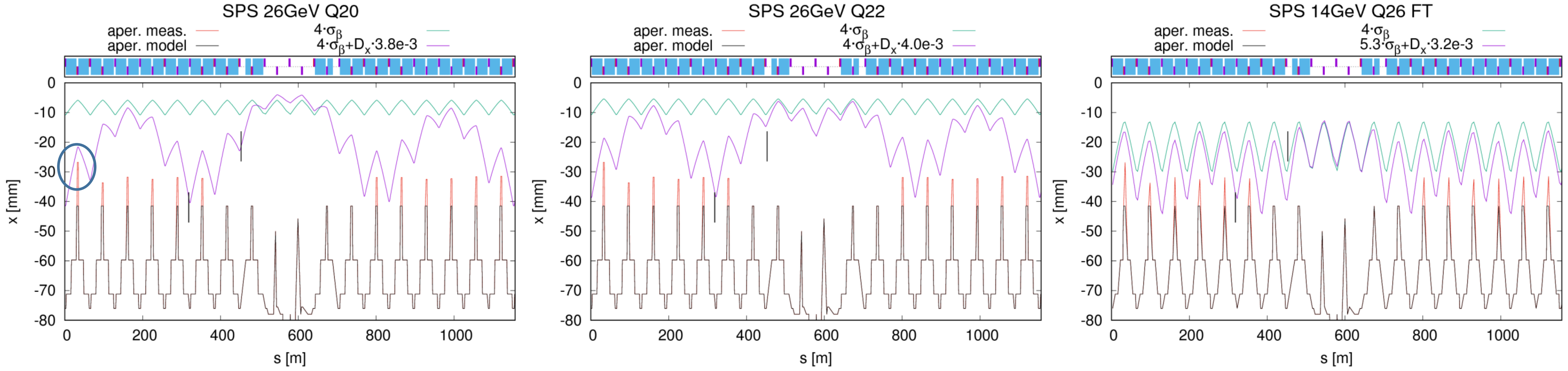
- Systematically smaller aperture towards the inside than towards the outside. Aperture on paper 41.5 mm



If there is no line, either no measurement or aperture never reached. Max. possible 4C bump = 40 mm @ QD.

Beam size vs. measured aperture

- Fitting a whole RF bucket very challenging in high dispersion regions
- Q20 is the most affected (largest dispersion)
- Makes it difficult to fit the collimator between beam envelope and mechanical aperture
- S+A and TCP.H marked at 318m and 453m, respectively.
- Common opening for S+A.
- TCP.H requires changing the gap between Q20 and Q26-fixed-target.



Collimation efficiency with meas. aper.

Two-stage coll.

- Primary vertical collimator cut: $4\sigma_\beta$
- Secondary collimators retracted by 1 σ_β.
- Cleaning efficiency drops with measured aperture.
- **Cleaning efficiency fully recovered by applying a tighter cut.**

	Two-stage coll. system			
	Coll. cut H [mm]	model aper	meas. aper.	meas. aper. +5mm
Q 20	$2\sigma_\beta + D\delta_{bh}$ = 16.4	76% (2%)	76% (2%)	76% (2%)
	$3\sigma_\beta + D\delta_{bh}$ = 18.9	76% (3%)	52% (21%)	65% (9%)
	$4\sigma_\beta + D\delta_{bh}$ = 21.5	74% (3%)	2% (45%)	4% (36%)

Legend:
no bracket: absorbed in colls.
in bracket: max. localised loss

Some examples of loss maps in extra slides.

Collimation efficiency with meas. aper.

Scraper+Absorber

- No problem for Q22.
- Tight aperture at QDs spoils the cleaning efficiency in Q20 optics.
- Decreasing the gaps helps in Q20.
- Efficiency recovered if the aperture is increased by 5mm.
- Cleaning efficiency improved with Copper.
- **Half-gap of about 37mm for both Q20 and Q22.**

		Absorber: MoGr			Absorber: Copper		
	Coll. cut [mm]	model aper	meas. aper.	meas. aper. +5mm	model aper	meas. aper.	meas. aper. +5mm
Q 20	$2\sigma_\beta + D\delta_{bh}$ = 33.9	74% (5%)	69% (5%)	73% (5%)	87% (3%)	83% (3%)	87% (3%)
	$3\sigma_\beta + D\delta_{bh}$ = 36.5	73% (5%)	65% (5%)	72% (5%)	87% (3%)	**78% (4%)**	86% (3%)
	$4\sigma_\beta + D\delta_{bh}$ = 39.1	72% (6%)	57% (8%)	71% (6%)	86% (3%)	**69% (8%)**	85% (4%)
Q 22	$2\sigma_\beta + D\delta_{bh}$ = 32.1	no need to check	76% (5%)	no need to check	no need to check	no need to check	no need to check
	$3\sigma_\beta + D\delta_{bh}$ = 34.6		75% (5%)				
	$4\sigma_\beta + D\delta_{bh}$ = 37.2	75% (5%)	74% (5%)		89% (3%)	89% (3%)	

Some examples of loss maps in extra slides.

Legend:
no bracket: absorbed in colls.
in bracket: max. localised loss

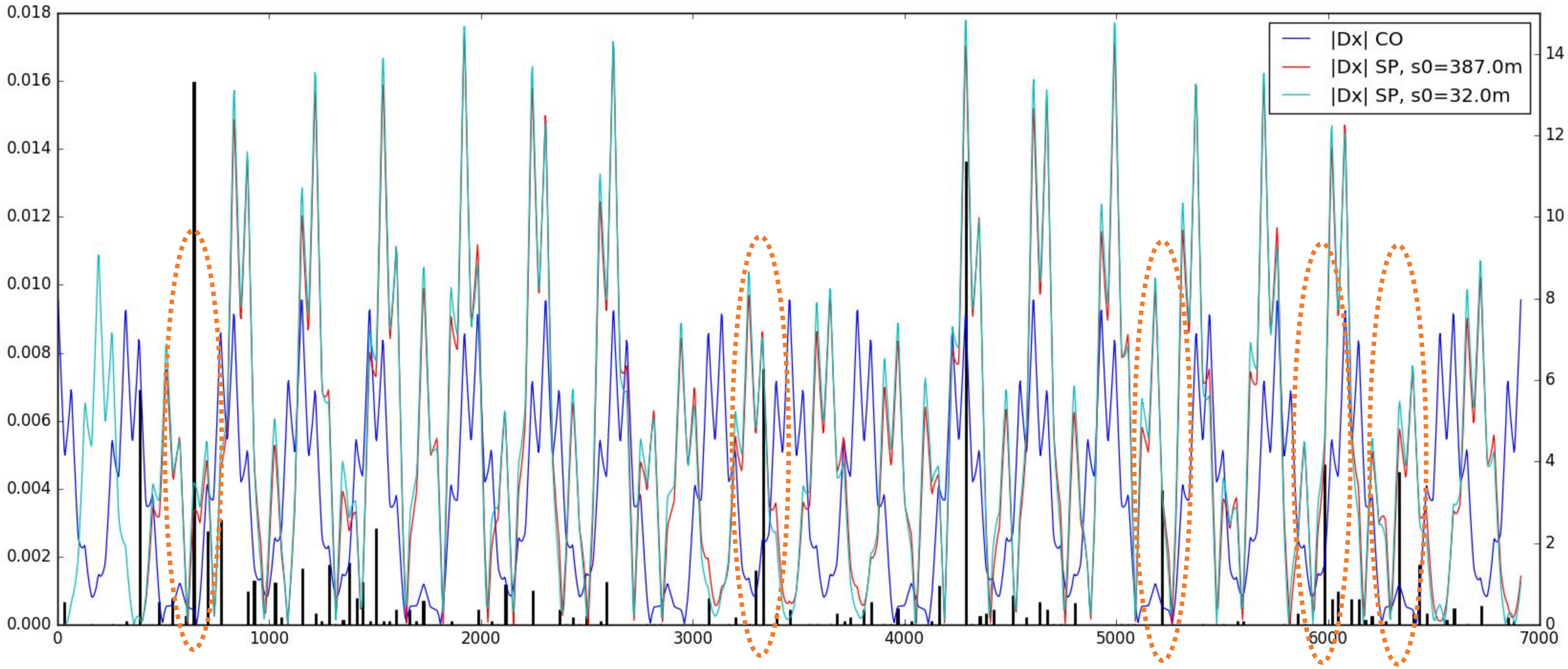
	$\varepsilon_{N,x}$ $[\mu m]$	β_x $[m]$	D_x $[m]$	δ_{bh} $[10^{-3}]$	$\delta_{p,1\sigma}$ $[10^{-3}]$	σ_β $[mm]$	$D_x\delta_{bh}$ $[mm]$	$D_x\delta_{p,1\sigma}$ $[mm]$
Q20	1.89	100	7.5	3.8	1.5	**2.6**	**28.6**	**11.3**
Q22	1.89	98.7	6.7	4.0	1.5	**2.6**	**26.9**	**10.1**

Objectives and challenges - summary

- **Objectives:**
  - Passive machine protection ✓ - only H plane tested so far
  - Concentration of losses in the designed locations ✓
  - Reduction of activation of equipment ? – E deposition study with FLUKA
  - Functional for all SPS beams and optics (priority to HL-LHC beams) ✓/ ✓ (S+A)/(2stage)
- **Challenges:**
  - Avoid the movement of collimators between the cycles (common gap or small adjustment with orbit bump) ✓/✗
  - Fitting into (very limited) empty spots ✓
  - Enough beam clearance -> large gaps to avoid consuming an usefull beam ✓/ ✓

Extra slides

Single pass dispersion



More detailed study might be needed.

SPS beams

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Table 1: HL-LHC beam parameters in the SPS

Parameter	Unit	HL-LHC Standard Low Energy	HL-LHC Standard High Energy	LIU-SPS 80b Low Energy	LIU-SPS 80b High Energy	HL-LHC BCMS Low Energy	HL-LHC BCMS High Energy
Energy	GeV	26	450	26	450	26	450
Bunch intensity	10^{11} p/b	2.57(1)	2.43(2)	2.57(1)	2.43(2)	2.57(1)	2.43(2)
Number of bunches per batch		288		320		288	
Batch length	ns	7800		8600		8200	
Total intensity per batch	10^{13} p+	7.00(3)		7.78(3)		7.00(3)	
Bunch spacing	ns	25		25		25	
Number of trains per batch		4		4		6	
Number of bunches per train		72		80		48	
Train spacing	ns	225		225		225	
Train length	ns	1175		1975		1175	
Emittance H (norm.)	μm	1.90(4, 5)		1.90(4, 5)		1.55(4, 5)	
Emittance V (norm.)	μm	1.90(4, 5)		1.90(4, 5)		1.55(4, 5)	

(1) : At flat-bottom before capture, assuming 5% reduction after capture

(2) : At flat-top before scraping, assuming 2.32×10^{11} at injection into LHC and including 5% reduction for scraping and injection losses

(3) : At flat-top energy

(4) : At extraction from SPS, allowing 10% emittance growth for SPS-LHC transfer and LHC injection process

(5) : Worst-case assumptions so as to ensure that there is an inherent safety factor in the subsequent calculations

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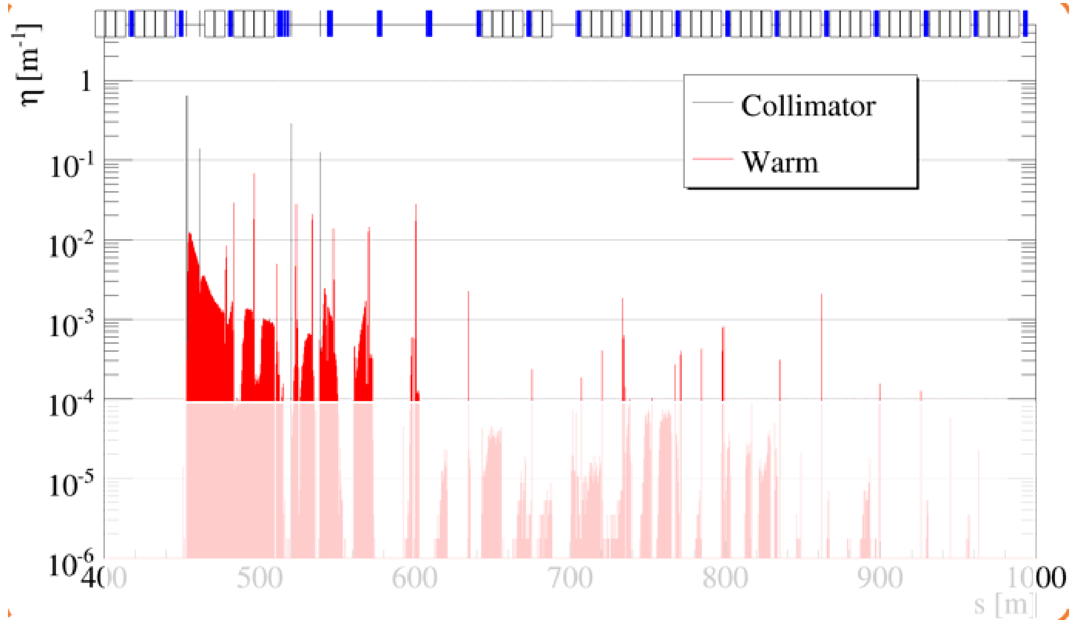
Table 2: SFTPRO Beam Parameters in the SPS

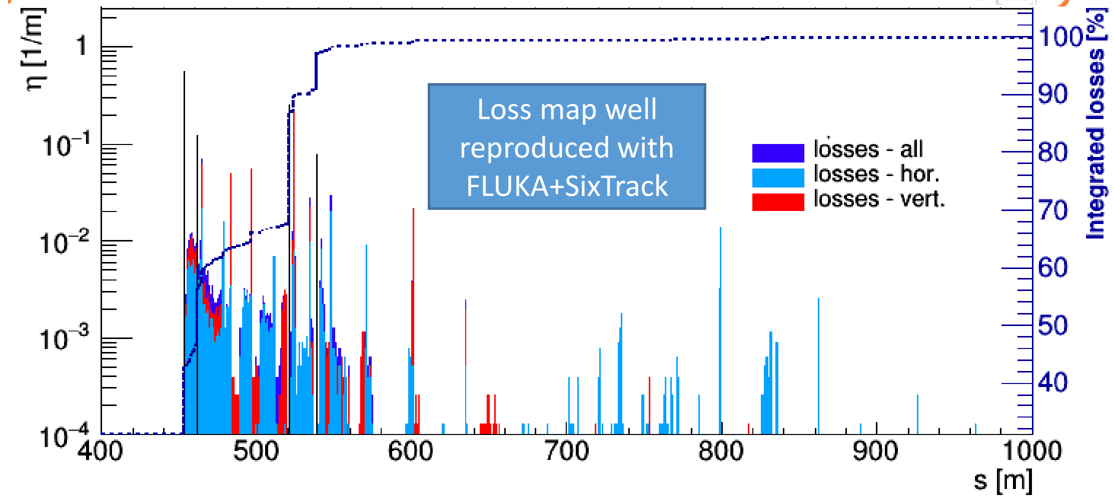
Parameter	Unit	SPS-FT North Low Energy	SPS-FT North High Energy	SPS-FT SHiP Low Energy	SPS-FT SHiP High Energy
Energy	GeV	14	400	14	400
Bunch intensity	10^{10} p/b	1.47(1)	1.40	1.12(1)	1.07
Number of bunches per batch		4200		4200	
Batch length	ns	22100		22100	
Total intensity per batch	10^{13} p+	5.88(2)		4.49(2)	
Bunch spacing	ns	5		5	
Number of trains per batch		2		2	
Number of bunches per train		2100		2100	
Train spacing	ns	1100		1100	
Train length	ns	10500		10500	
Emittance H (norm.)	μm	8.0		8.0	
Emittance V (norm.)	μm	5.0		5.0	

(1) : At flat-bottom before capture, assuming 5% reduction after capture

(2) : At flat-top energy

Two-stage collimation – loss map





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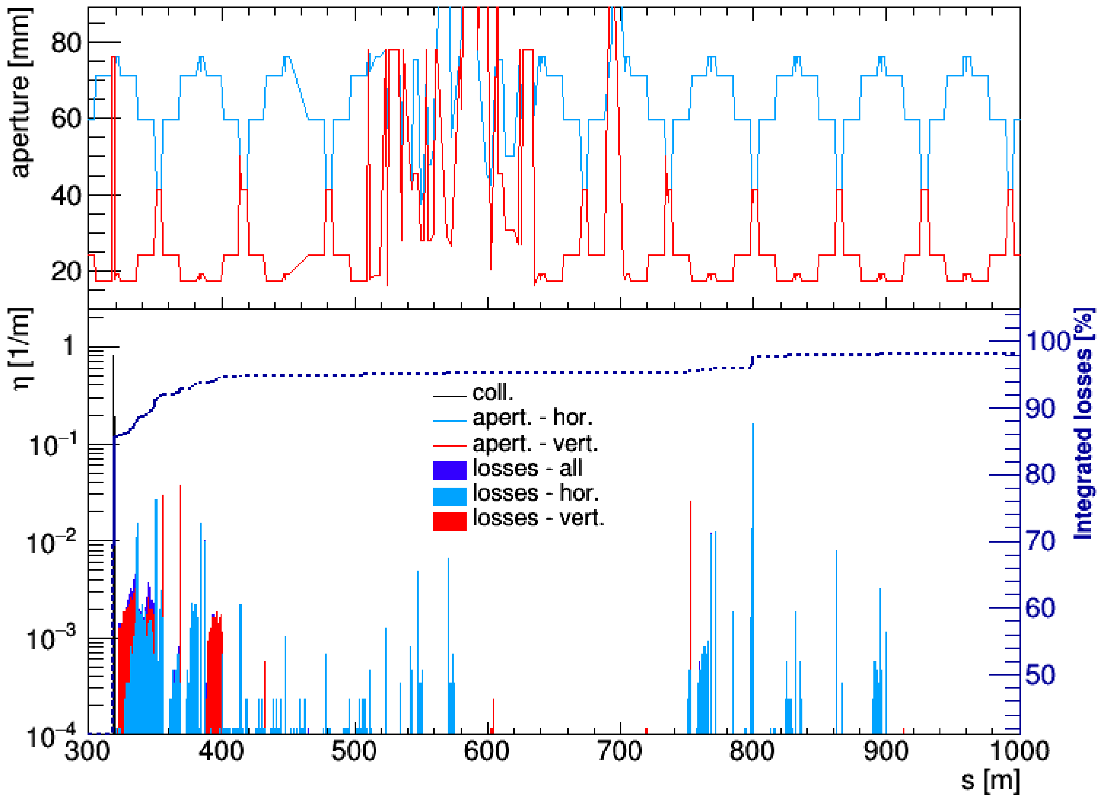
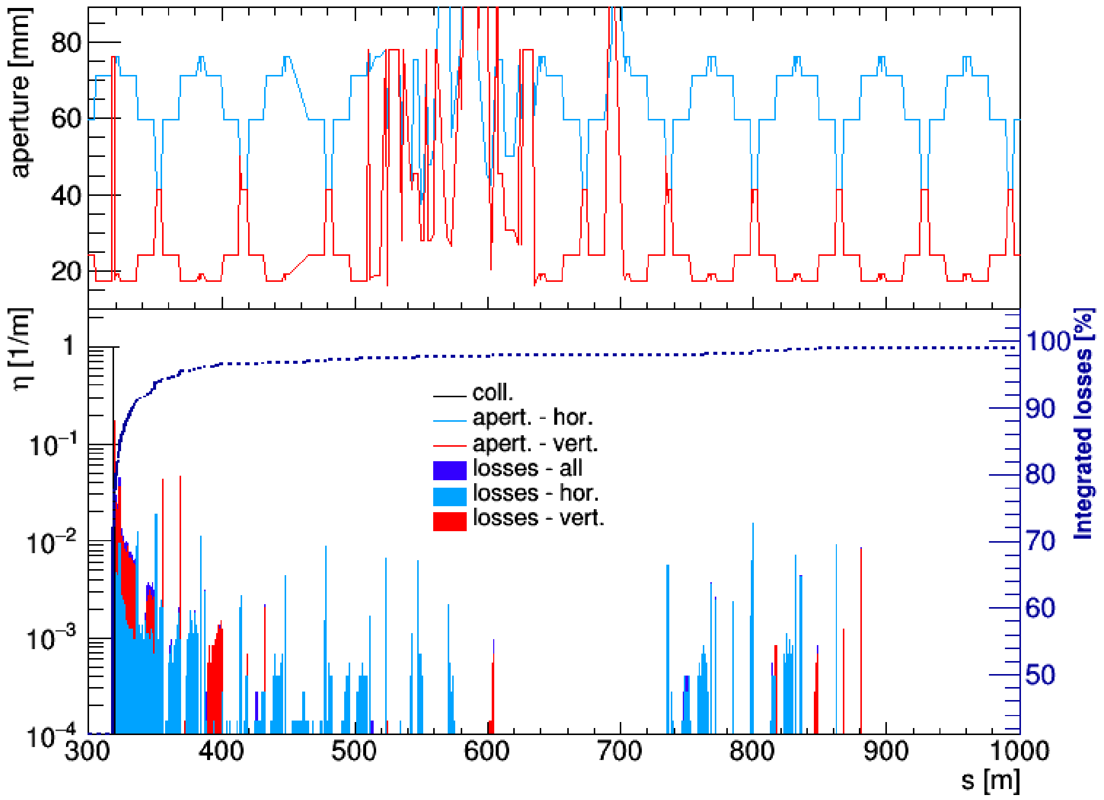
Scraper (MoGr) + Absorber (MoGr) 450GeV, Q20



	S [m]	r1.5mm	r1.0mm	r0.5mm
All colls	**-**	**85.6**	**86.4**	**87.0**
TCA	318.4	69.1	76.0	82.0
TCS	319.0	16.5	10.4	5.0
MBA.11030	323.4	0.5	0.5	0.5
MBA.11050	330.0	1.5	1.4	1.4
MBB.11090	343.0	1.0	1.0	1.0
LSD.11105	350.8	1.7	1.6	1.5
BPCN.12508	799.5	1.3	1.4	1.3

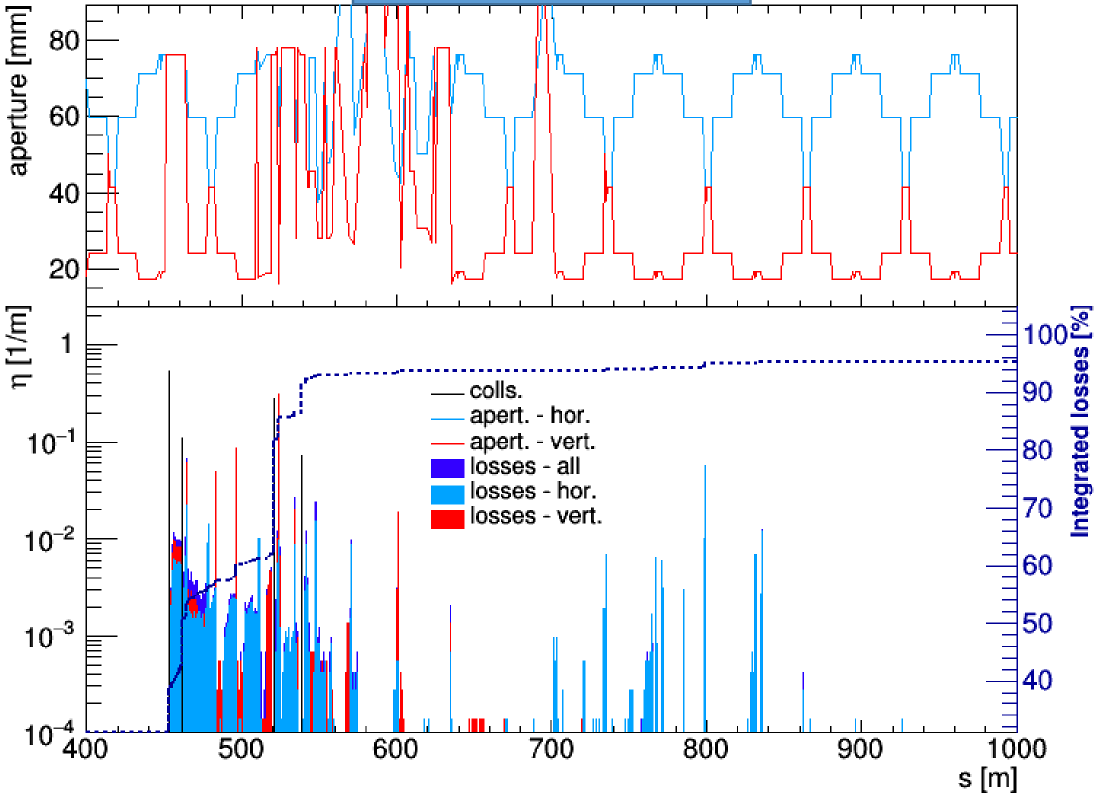
Scraper (MoGr) + Absorber (MoGr) Q22, 26GeV



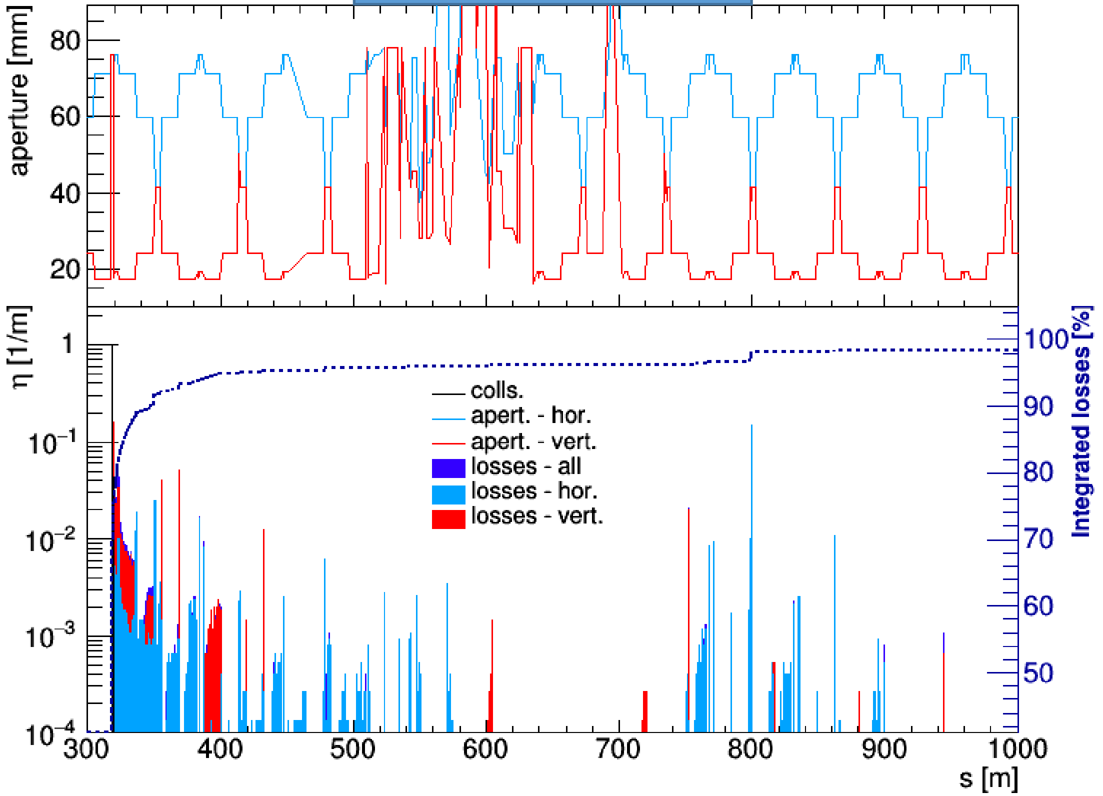
	S [m]	Q22	Q20
All colls	**-**	**74.7**	**72.7**
TCA	318.4	72.9	69.6
TCS	319.0	1.8	3.1
MDH.11007	319.3	1.5	1.5
BPH.11008	319.6	0.8	1.2
QF.11010	320.0	5.4	5.2
MBA.11030	323.4	6.1	5.8
MBA.11050	330.0	2.6	2.7
MBB.11090	343.0	1.1	1.0
LSD.11105	350.8	1.3	1.5
BPCN.12508	799.5	<0.2	1.0

Validation of cleaning efficiency with a constant E loss per turn

Mod. Dan. design

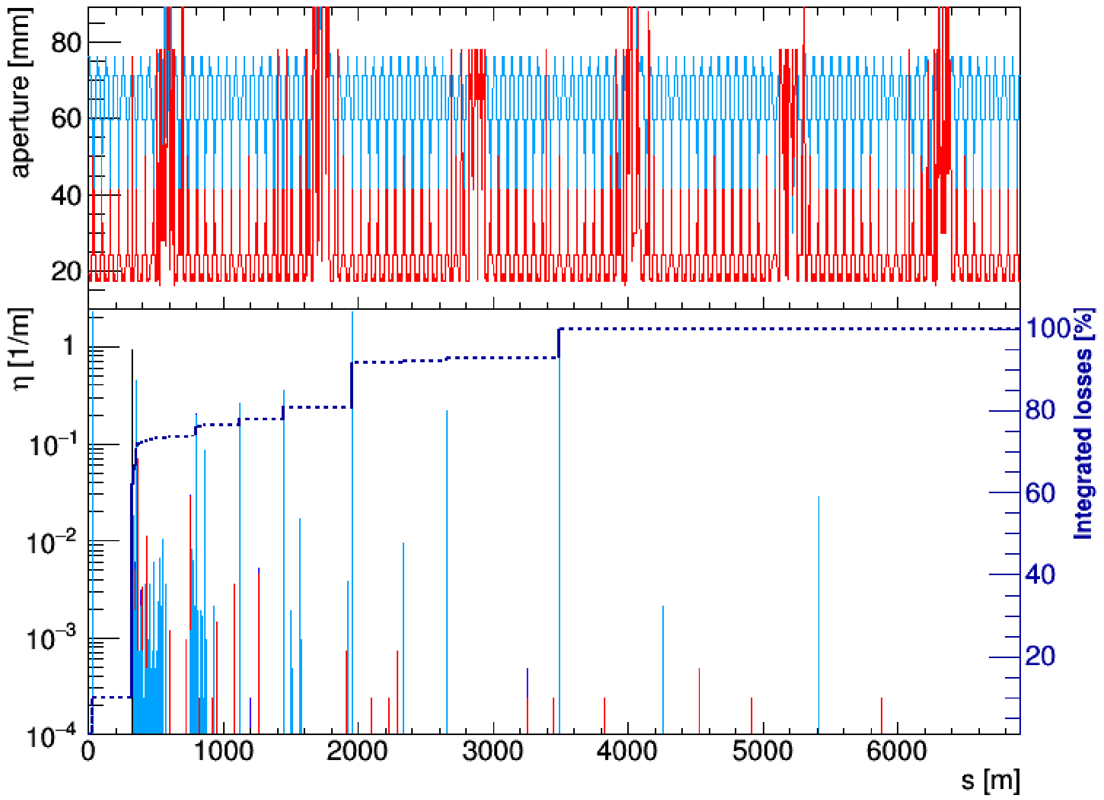


Scr.+Abs. MoGr



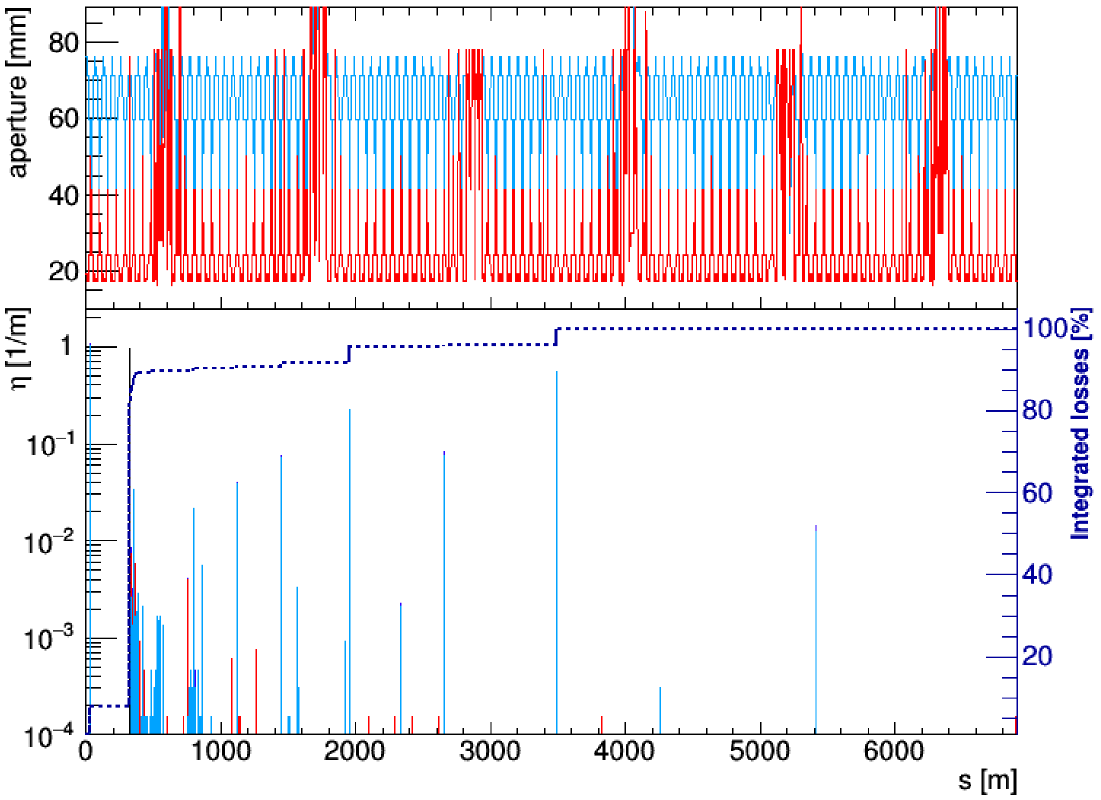
- Constant E loss 1keV/turn, at the beginning of every next turn
- 10 000 turns
- Same loss pattern as for halo initialized at the collimator

Scraper (MoGr) + Absorber (MoGr) meas. aper. $4\sigma_\beta + D\delta_{bh}$



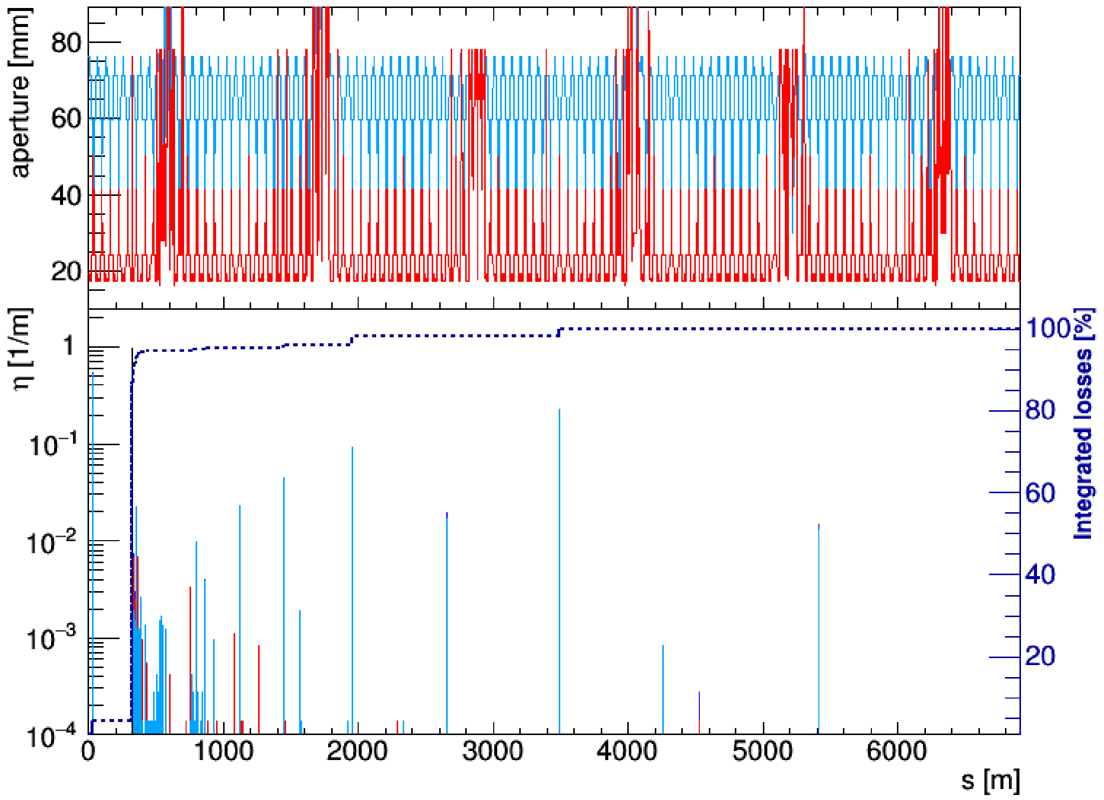
	S [m]	Losses [%]
All colls	**-**	**56.7**
TCA	318.4	55.2
TCS	319.0	1.5
QD.10110	32.0	7.7
MDH.11007	319.3	1.2
BPH.11008	319.6	1.9
QF.11010	320.0	4.8
MBA.11030	323.4	4.3
MBA.11050	330.0	2.3
MBB.11090	343.0	1.5
QD.11110	352.0	2.2
QD.22510	1951.9	4.0
QD.40110	3487.7	4.0

Scraper (MoGr) + Absorber (Cu) meas. aper. $4\sigma_\beta + D\delta_{bh}$



	S [m]	Losses [%]
All colls	**-**	**69.0**
TCA	318.4	67.6
TCS	319.0	1.4
QD.10110	32.0	7.8
QF.11010	320.0	1.8
MBA.11030	323.4	3.4
MBA.11050	330.0	1.7
MBB.11090	343.0	1.0
QD.11110	352.0	1.2
QD.22510	1951.9	3.7
QD.40110	3487.7	3.9

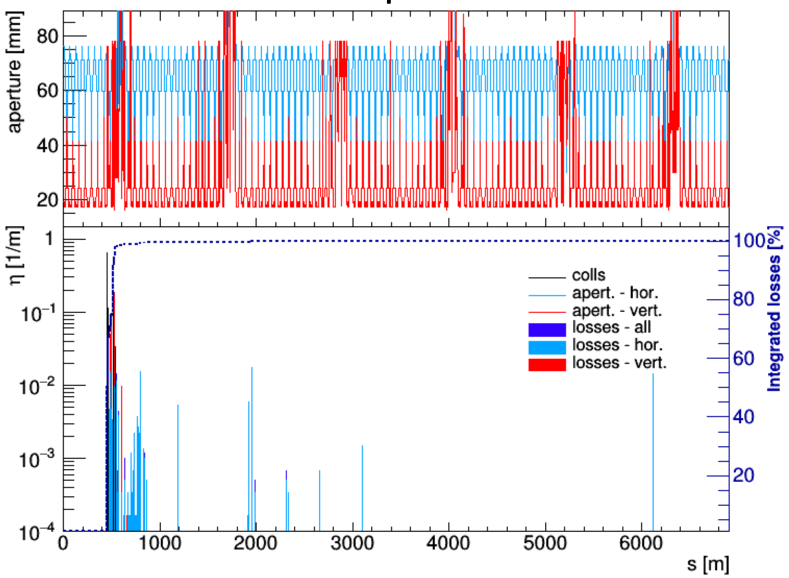
Scraper (MoGr) + Absorber (Cu) meas. aper. $3\sigma_\beta + D\delta_{bh}$



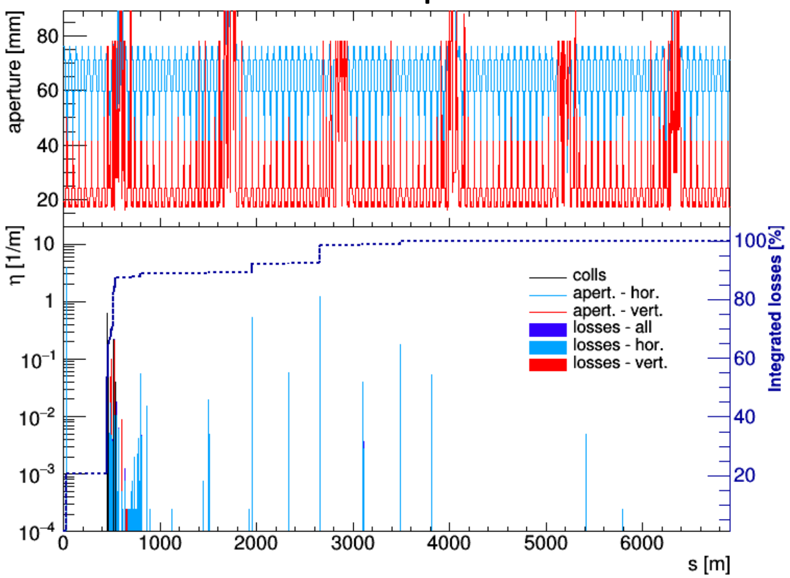
	S [m]	Losses [%]
All colls	**-**	**78.2**
TCA	318.4	76.8
TCS	319.0	1.4
QD.10110	32.0	4.4
QF.11010	320.0	1.8
MBA.11030	323.4	3.0
MBA.11050	330.0	1.6
MBB.11090	343.0	1.0
QD.11110	352.0	1.0
QD.22510	1951.9	1.8
QD.40110	3487.7	1.8

Two stage coll. with meas. aper. $3\sigma_\beta + D\delta_{bh}$

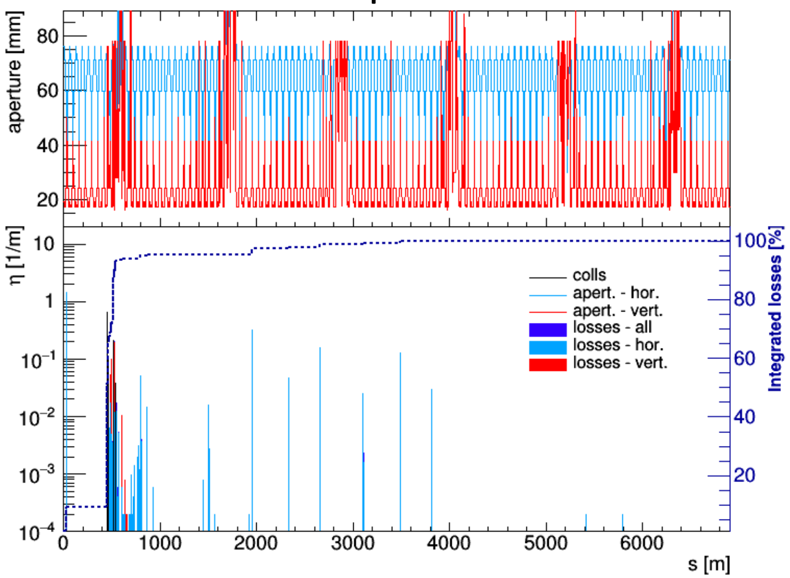
model aperture



measured aperture

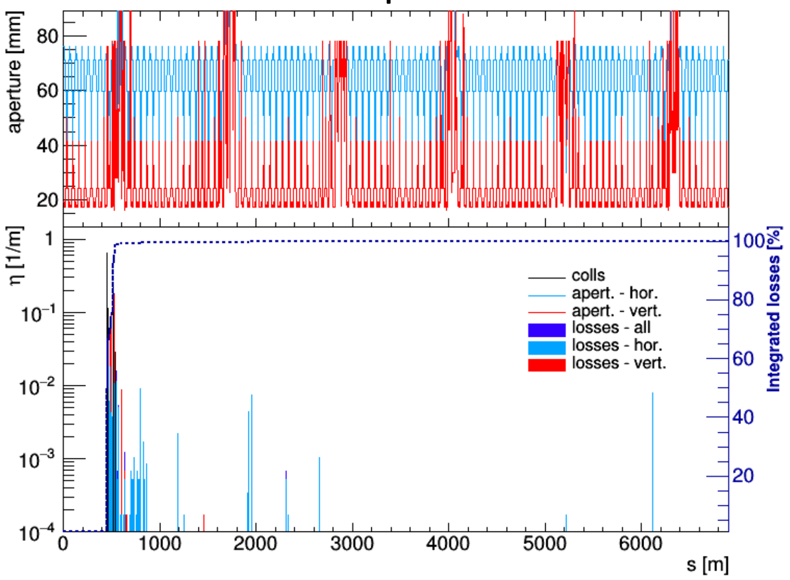


measured aperture+5mm

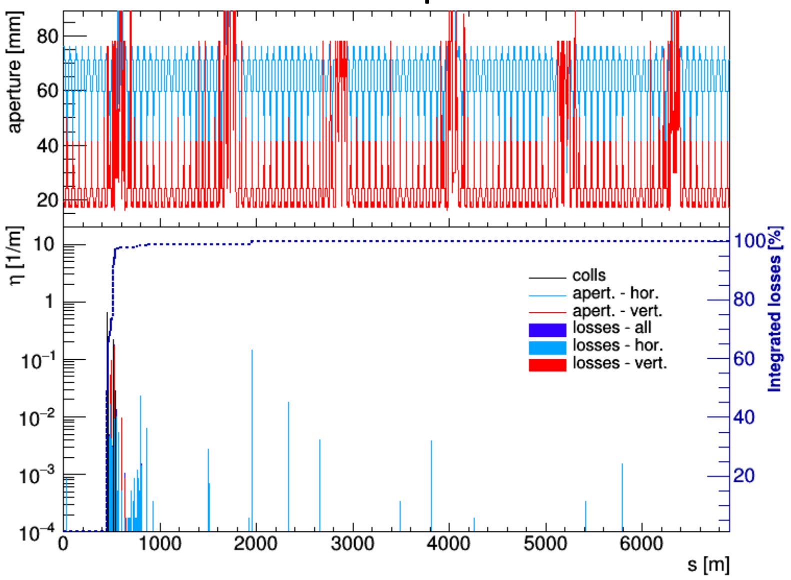


Two stage coll. with meas. aper. $2\sigma_\beta + D\delta_{bh}$

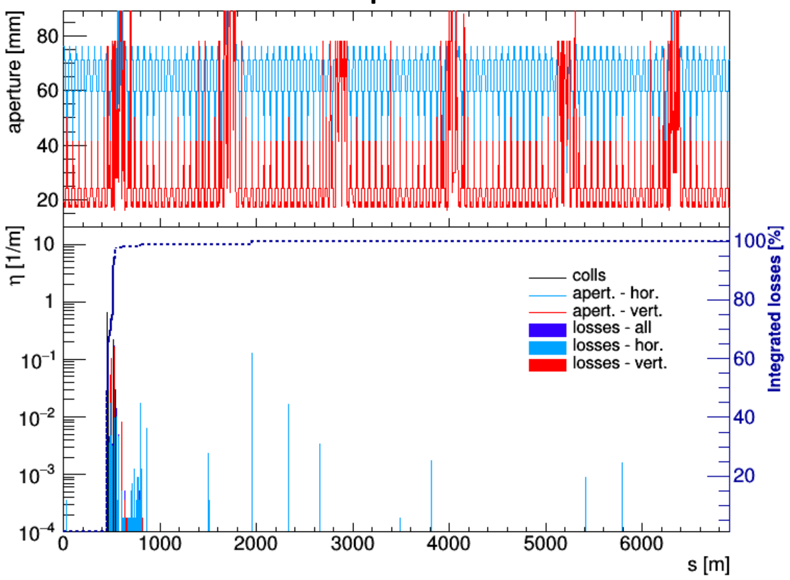
model aperture



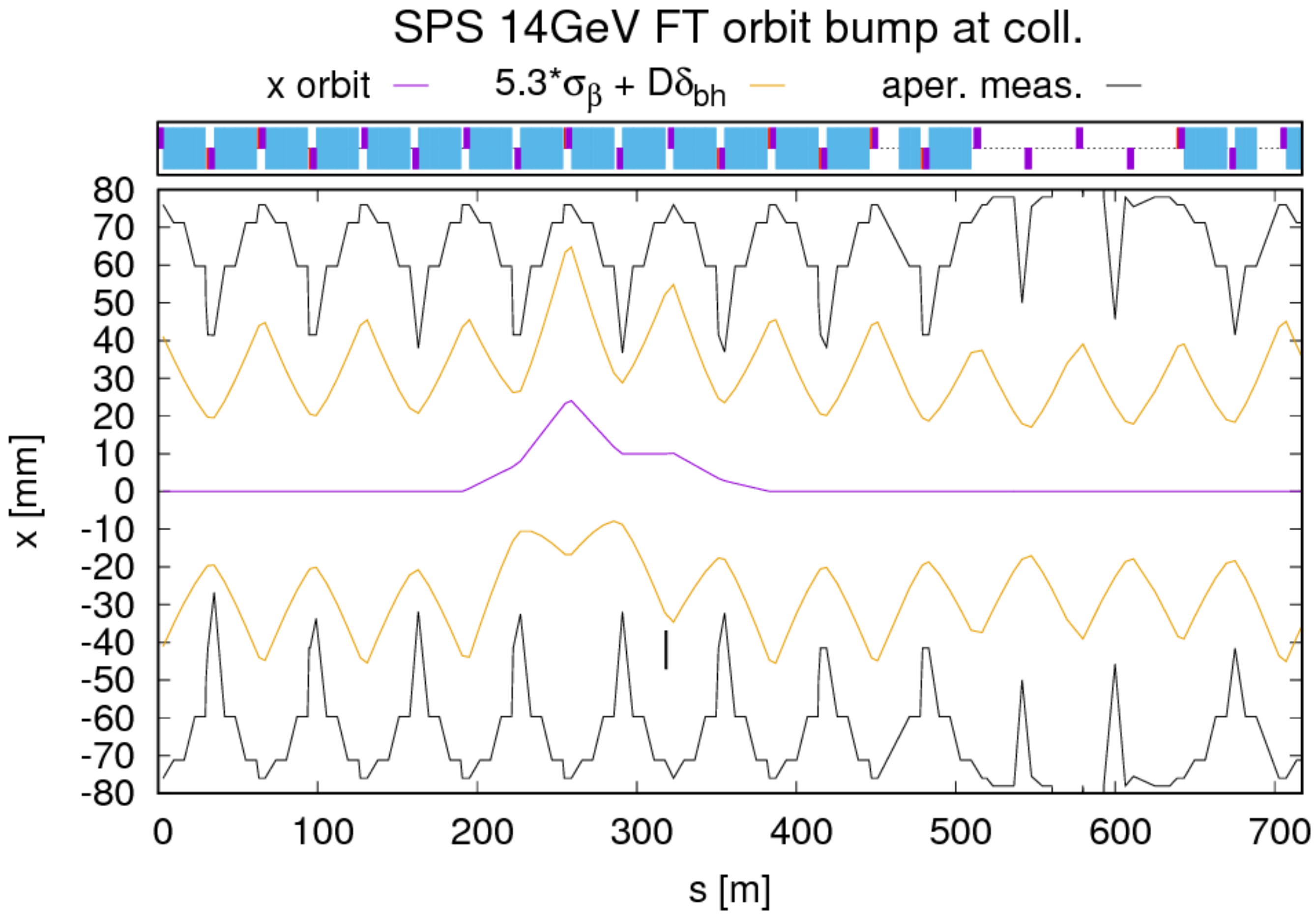
measured aperture



measured aperture+5mm



Fixed target beams, 14GeV, Q26 – avoiding the collimator with 10mm orbit bump

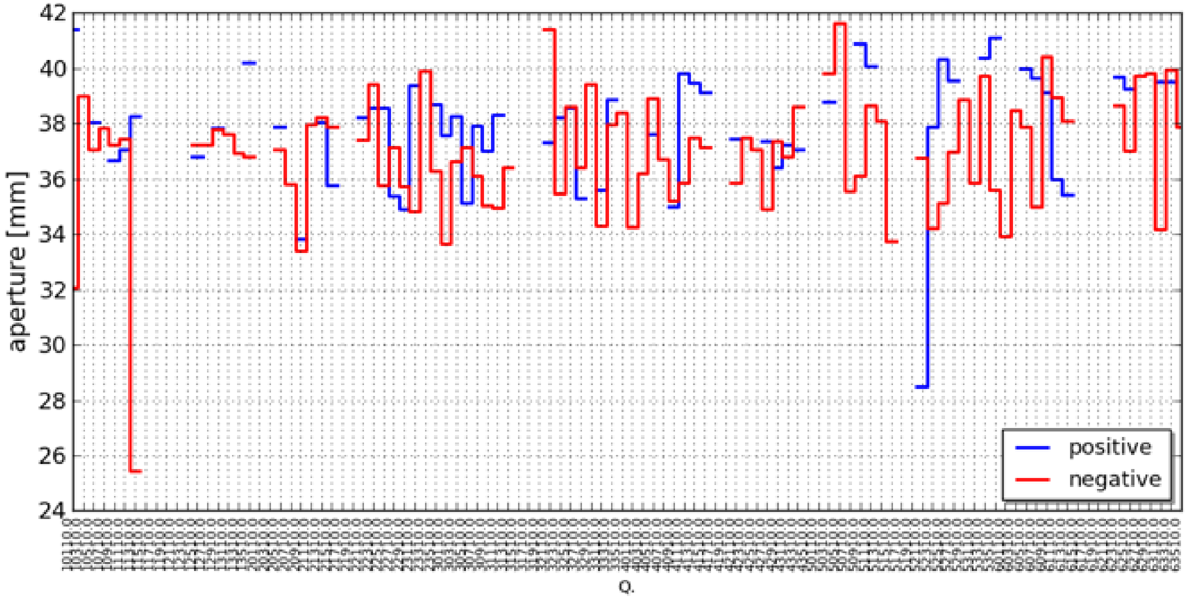


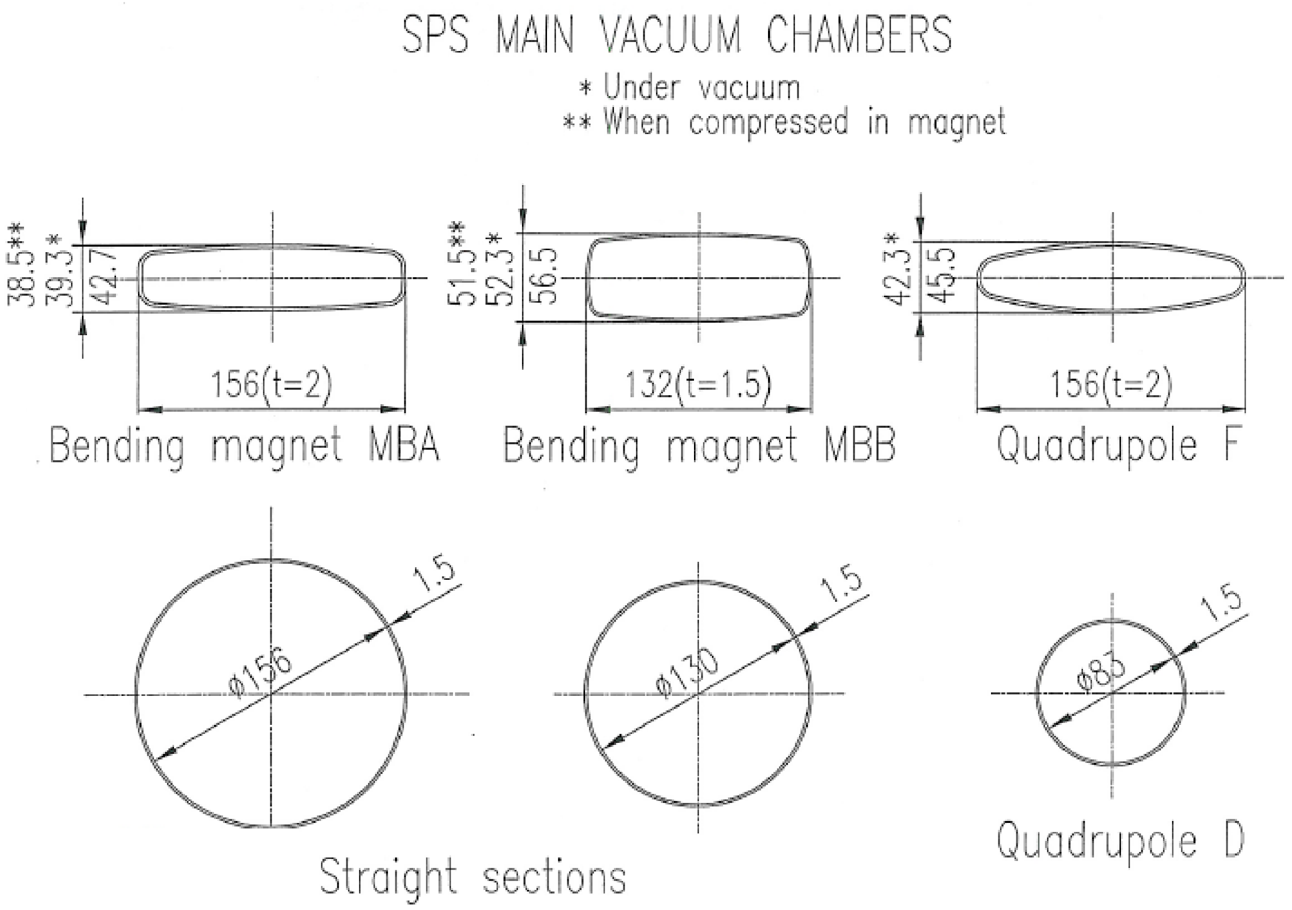
Measured horizontal aperture +5mm

V. Kain, Measured Q20 aperture limits at QDs and possible physical explanation/solution, https://indico.cern.ch/event/673312/:

Aperture measurements correcting for 5.3 mm

- Difference between negative and positive aperture less pronounced
- Possibly a few locations with pumping port shield flange on QD-MBB transition installed wrongly




SPS MAIN VACUUM CHAMBERS
* Under vacuum
** When compressed in magnet
38.5**
39.3*
42.7
156(t=2)
Bending magnet MBA
51.5**
52.3*
56.5
132(t=1.5)
Bending magnet MBB
42.3*
45.5
156(t=2)
Quadrupole F
ø156
1.5
ø130
1.5
ø83
1.5
Straight sections
Quadrupole D

Bucket height

$$\delta_{\mathrm{bh}} = \sqrt{\frac{2\mathrm{eV}}{\pi \beta_0^2 \mathrm{E}_0 \mathrm{h} \left|\eta\right|}}$$

Bucket height at injection for Q20, Q22, Q26 and fixed target (FT).

	Q20	Q22	Q26	FT
RF V [MV]	4.5	3.5	3.0	2.5
δ_{bh} $[10^{-3}]$	3.70	4.03	5.13	3.17

Beam size vs. measured aperture

- Fitting a whole RF bucket very challenging in high dispersion regions
- Q20 is the most affected (largest dispersion)