Simulated cleaning for HL-LHC layouts with errors

A. Marsili, R. Bruce, L. Lari, S. Redaelli

The HiLumi LHC Design Study (a sub-system of HL-LHC) is co-funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

Introduction

- Collimation cleaning simulations of ATS Beam 1
- Loss clusters downstream IR7
- Can be cured by 11 T dipoles + TCLD collimators
- Add error models of collimator alignment to simulations.
- See if TCLD still cure peaks around the ring (already the case without errors)

Outline

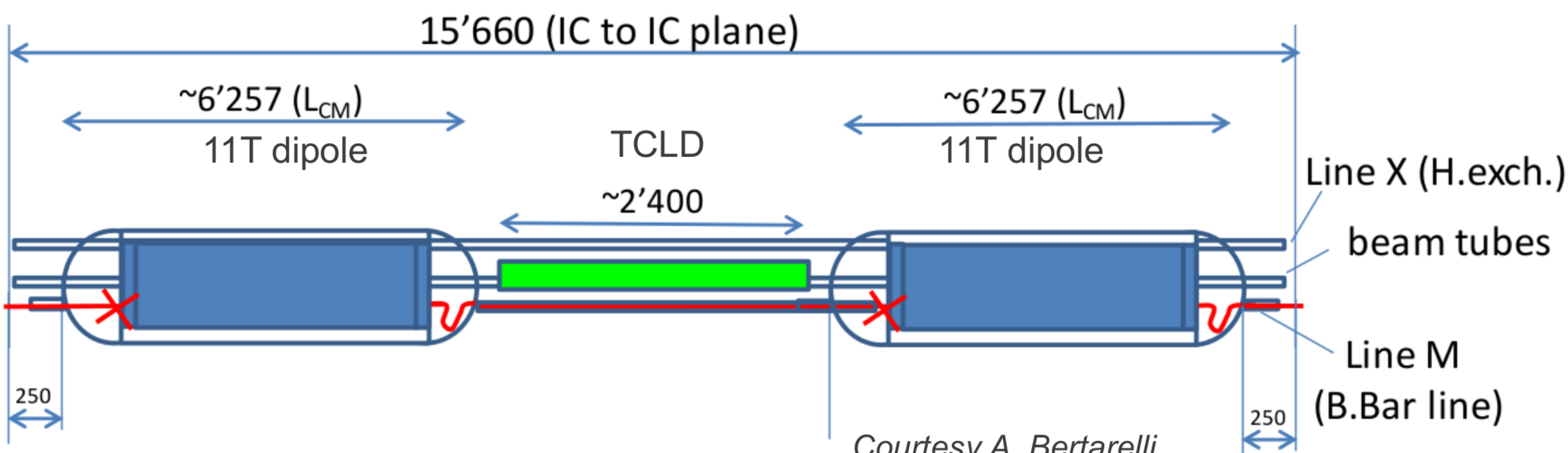
- Presentation of DS collimator layout
- Presentation of the different error models
  - Independent effects on simulations
- Combined error models
  - Global effects of TCRYO (TCLD)
  - Statistics
  - Non-flatness
- Local effect of TCRYO in IR7
  - Loss clusters
- Conclusion

Dispersion Suppressor Collimators (R. Bruce)

- IR7 dispersion suppressor (DS) is the limiting location in terms of collimation cleaning inefficiency
  - Dominating losses from protons that have undergone single diffractive scattering in TCP.
  - Energy offset large enough to hit the aperture in the arc, with high dispersion, but not large enough delta and betatron amplitude to hit the other collimators
- In the experimental IRs, off-momentum collisional debris lost in the DS. Maybe less critical (for protons – may still be needed for ions!) – considering presently only IR7 DS
- In both cases, the installation of additional collimators in the DS, TCLD, after the point where the dispersion is rising, could intercept these losses
- IR7 DS collimators are also beneficial for ions

Dispersion Suppressor Collimators (R. Bruce)

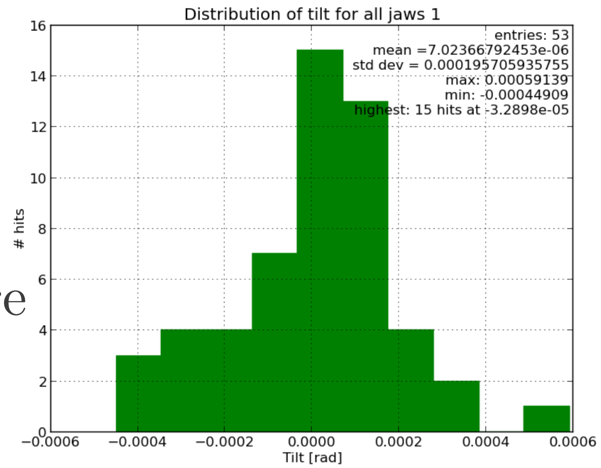
- Most promising layout option
  - replace an existing main dipole with two short 11T dipoles
  - Warm collimator installed in between the magnets
  - See talks V. Parma, A. Bertarelli in 2013 collimation review
- Considering a magnetic length of 5.5m (M. Karpinen) and an active collimator length of up to 1m



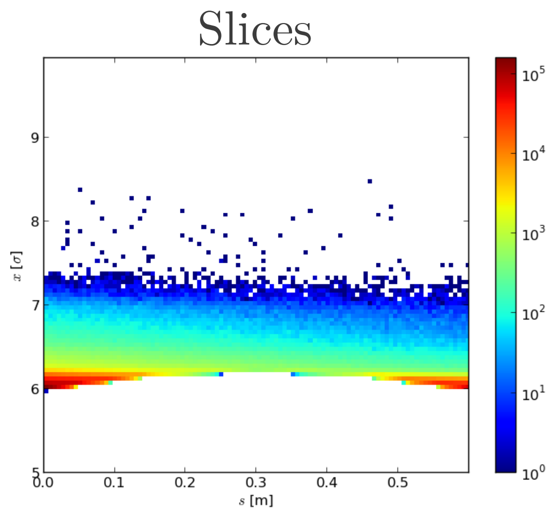
Courtesy A. Bertarelli

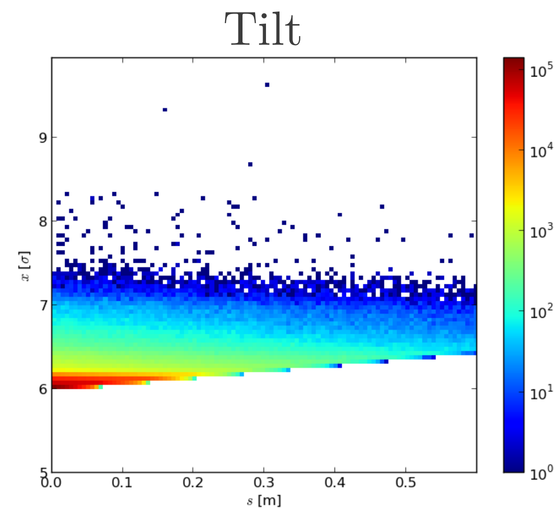
Error models in simulation

- Experimental data from C. Bracco's thesis
  - Will be updated by new data
- Gap: error on the size of the collimator gap
  - Standard deviation: 0.1σ
- Offset: error on the position of the beam centre
  - Standard deviation: 50 µm
- Tilt: error on the angle between jaw and beam
  - Standard deviation: 200 µrad
- Random distributions of errors controlled by a seed
- Slices: error on the flatness of the jaw (not random)
  - 2nd order polynomial: $4 \cdot 10^{-4}(\frac{s^2}{l} - s)$
  - fitted linearly by 4 slices



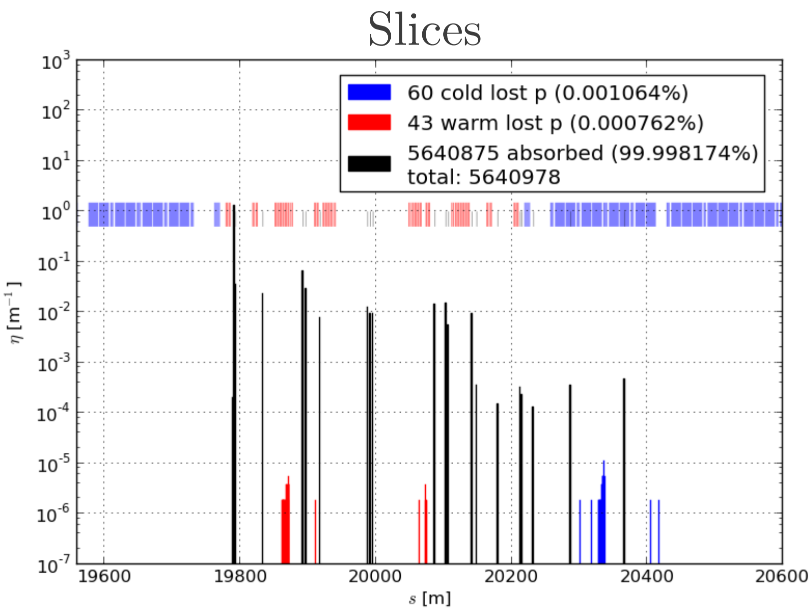
Example: impacts on the left jaw of the TCP

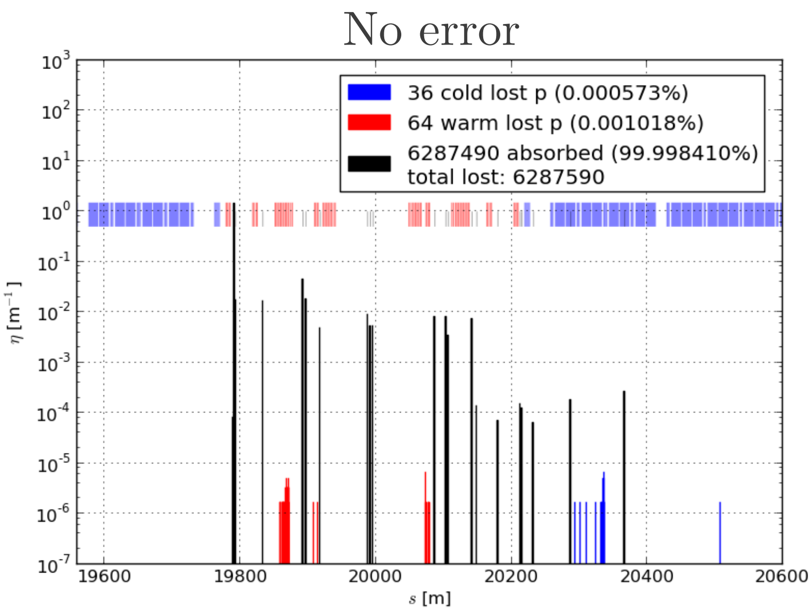




- Shape of the jaw is clearly visible
- With error on gap and offset, jaws not at 6 σ any more
- Distribution of losses in the collimator volume vary significantly
- Mismatch halo/primary decreases statistics
- Single seed is not meaningful
  $\rightarrow$ need systematic analysis based on appropriate statistics to identify real trends

Example: effect of the error on flatness





- Error on flatness (slices) decreases efficiency
- Error on slice has no random component (does not depend on a seed)

Realistic error models for LHC collimators

—

Global effect

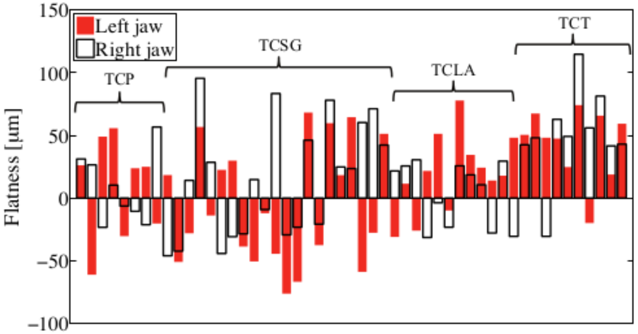
TCRYO & other collimators

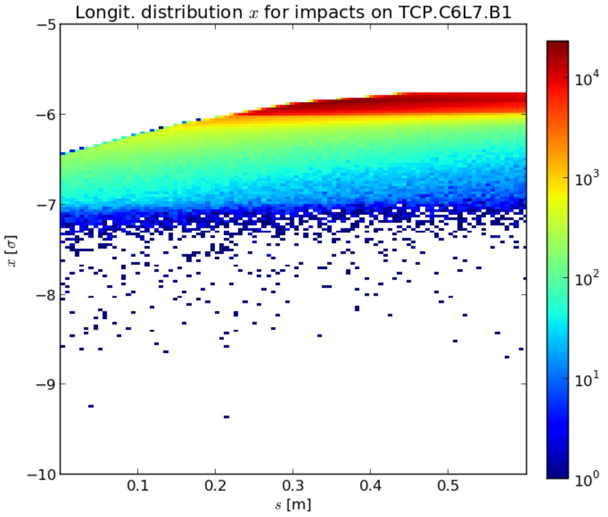
- 2 TCRYO: open, or set at 15 σ
- Worst case situation, to compare with the no-error case (10 and 15 σ)
- Reality should be in between two cases
- Simulations: 100 cm jaws
  - current model is 80 cm
  - both values give similar cleaning (FLUKA)
- Global inefficiency strongly dependent on the presence of the TCRYO

Type	Setting
TCP IR7	6
TCSG IR7	7
TCLA IR7	10
TCP IR3	12
TCSG IR3	15.6
TCLA IR3	17.6
TCL	10
TCSTCDQ	7.5
TCDQ	8
TCT IR1/5	8.3
TCT IR2/8	12.0

Combined error models

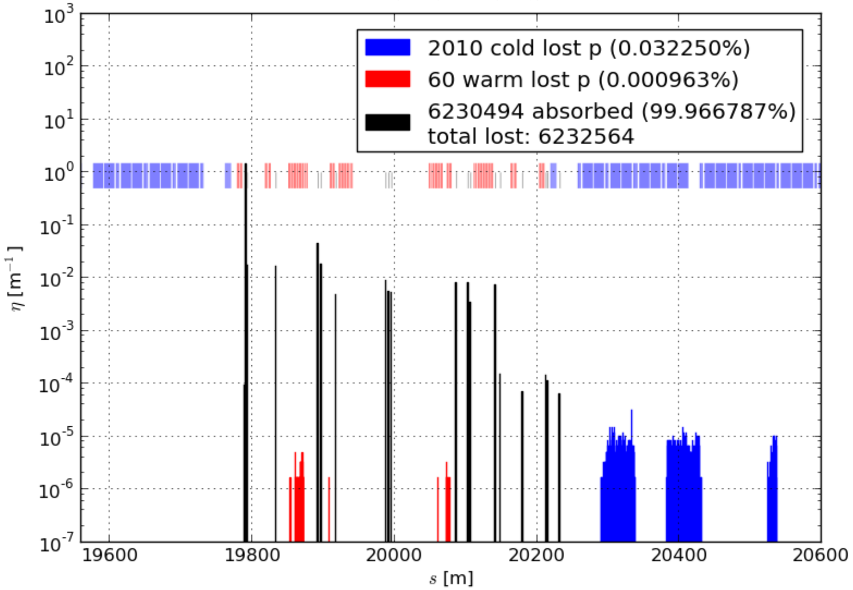
- All considered errors at the same time
- Error on flatness:
  - Mostly deformed towards the beam (2/3)
  - Both cases simulated
  - Average absolute flatness: 40.3 ± 22.2 µm
  - Modelled as parabola with maximum: 10 ppm (worst case scenario)
- Several seeds for the random errors
- Example shows non-flatness + tilt



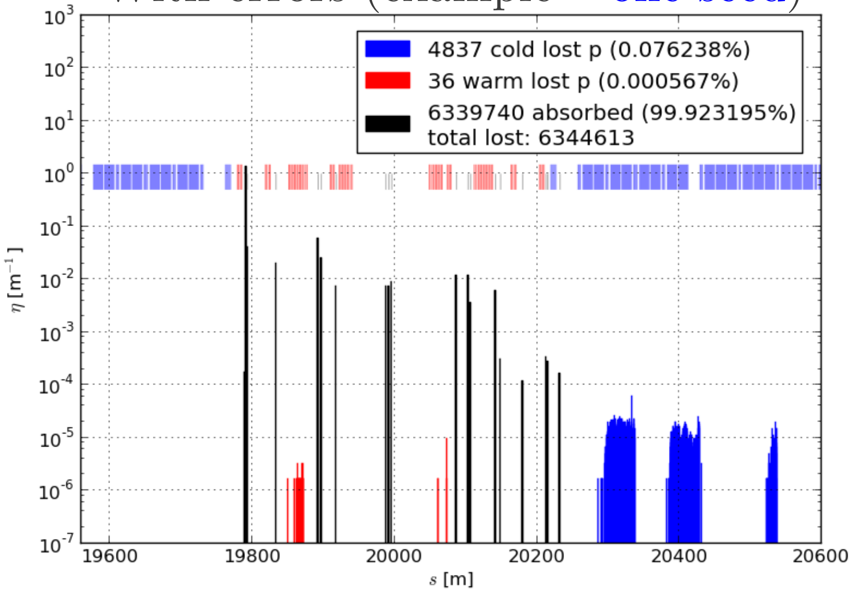


Loss maps IR7, no TCRYO with and without errors

No errors



With errors (example – one seed)



Global inefficiency: 3.225e-4

Loss clusters under 1e-5

Global inefficiency: 7.624e-4

Loss clusters above 1e-5

Cleaning deteriorates with error models

Statistics

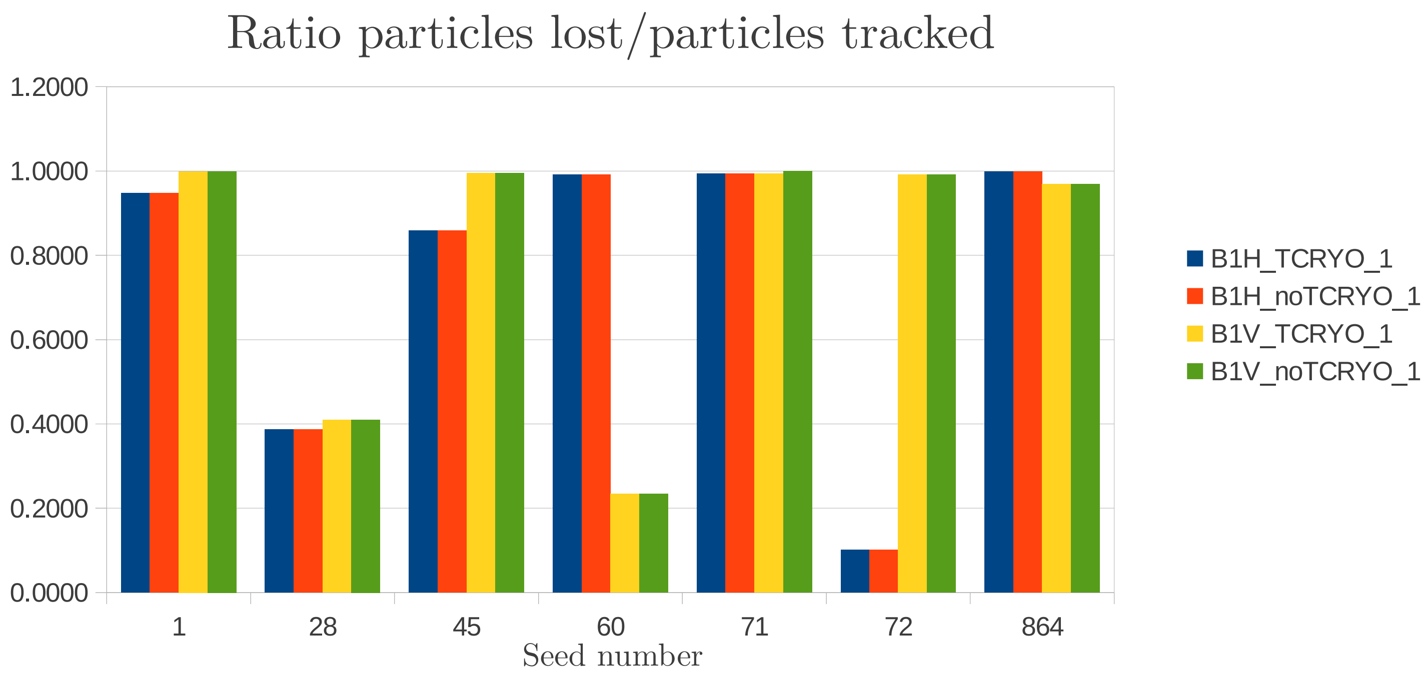
- Ratio particles lost / particles tracked

	Hor, no TCRYO	Ver, no TCRYO	Hor, TCRYO	Ver, TCRYO
Mean	6.756e-4	5.086e-4	1.753e-5	1.441e-5
Std. Dev.	1.659e-4	1.065e-4	1.144e-5	4.497e-6
Error	6.27e-5	4.025e-5	4.326e-6	1.7e-6

- Global inefficiency

	Hor, no TCRYO	Ver, no TCRYO	Hor, TCRYO	Ver, TCRYO
Mean	6.756e-4	5.086e-4	1.753e-5	1.441e-5
Std. Dev.	1.659e-4	1.065e-4	1.144e-5	4.497e-6
Error	6.27e-5	4.025e-5	4.326e-6	1.7e-6

Considerations on statistics

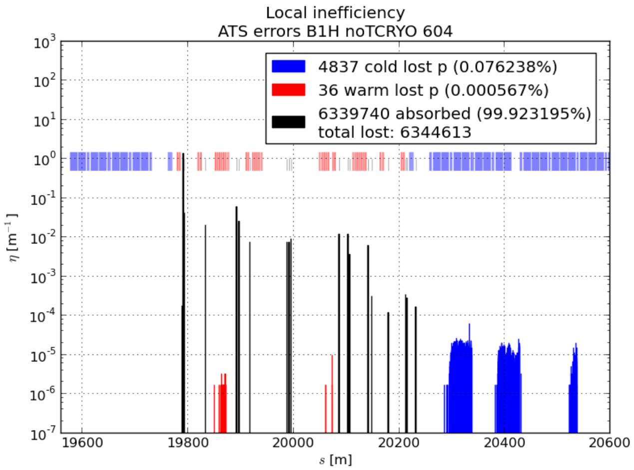


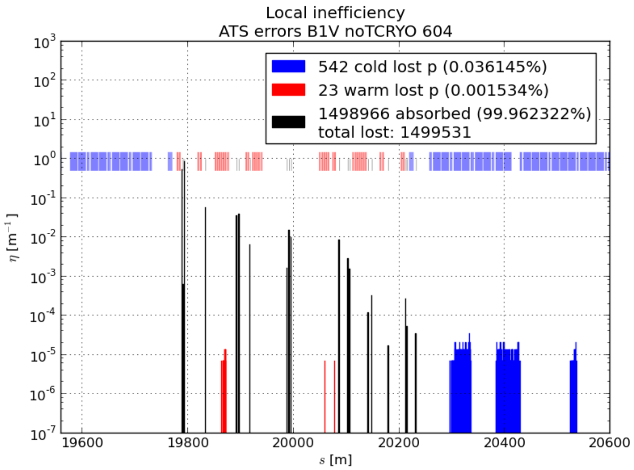
- In some cases, alignment errors ⇔ mismatch halo/collimator

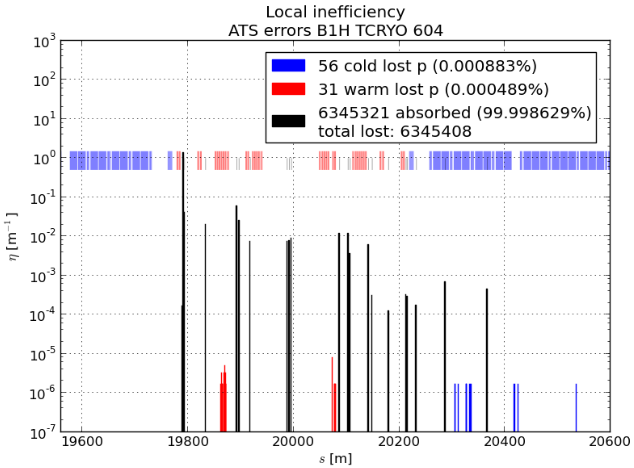
  ⇔ different collimator setting

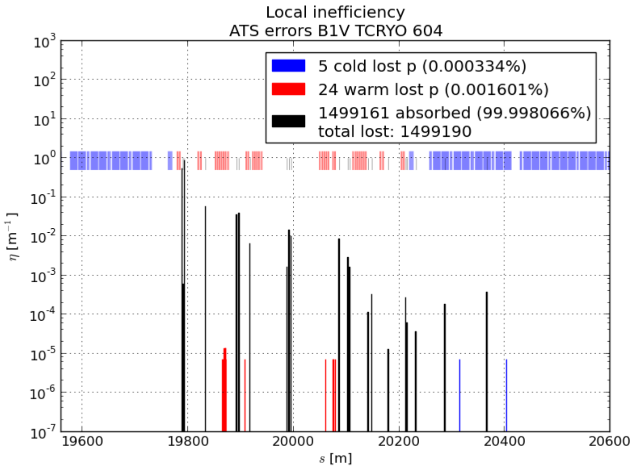
  ⇒ decrease of the statistics

Loss maps for four cases (same seed)





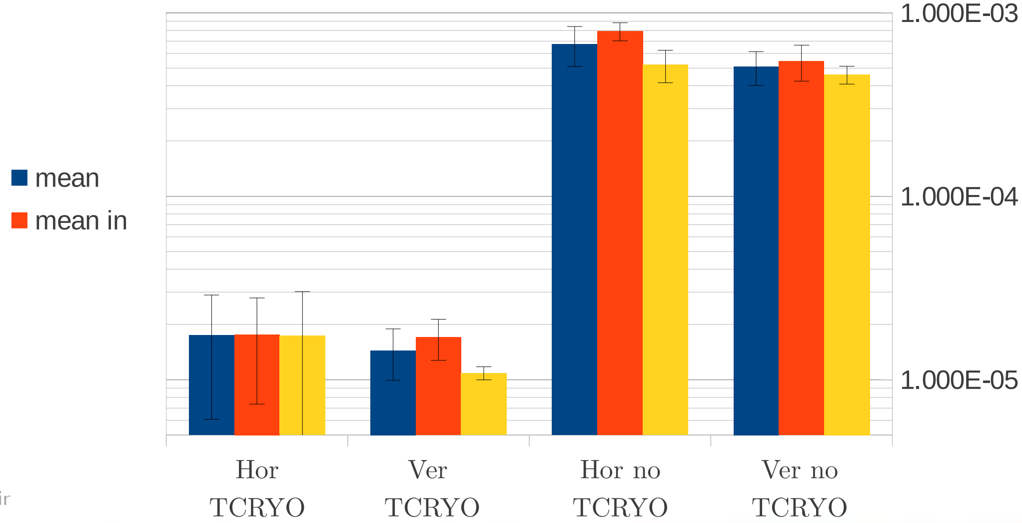


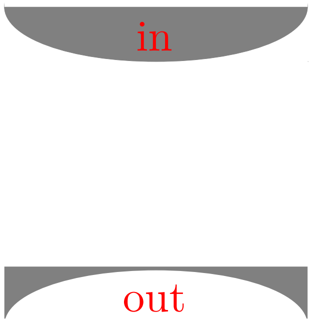


Even with errors and at 15σ, the TCLD provide a good protection

Observations on non-flatness

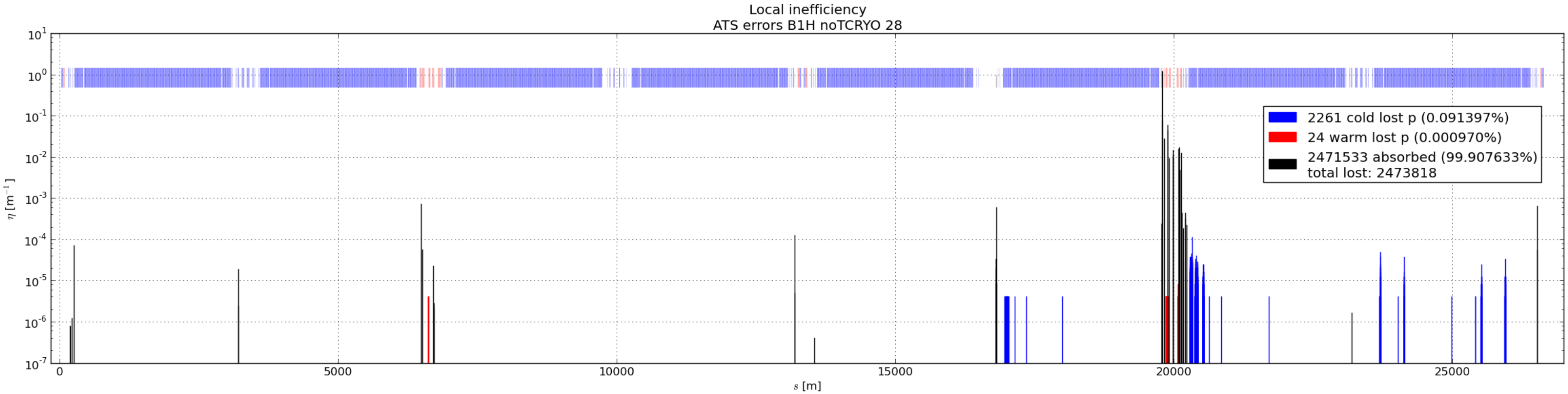
- 2^{nd} order polynomial, two options: towards the beam, or away.
- Half of simulations in one case, half in the other
- Same maximum deformation
- On average, the deformation towards the beam provides a better cleaning efficiency (more material than other case)

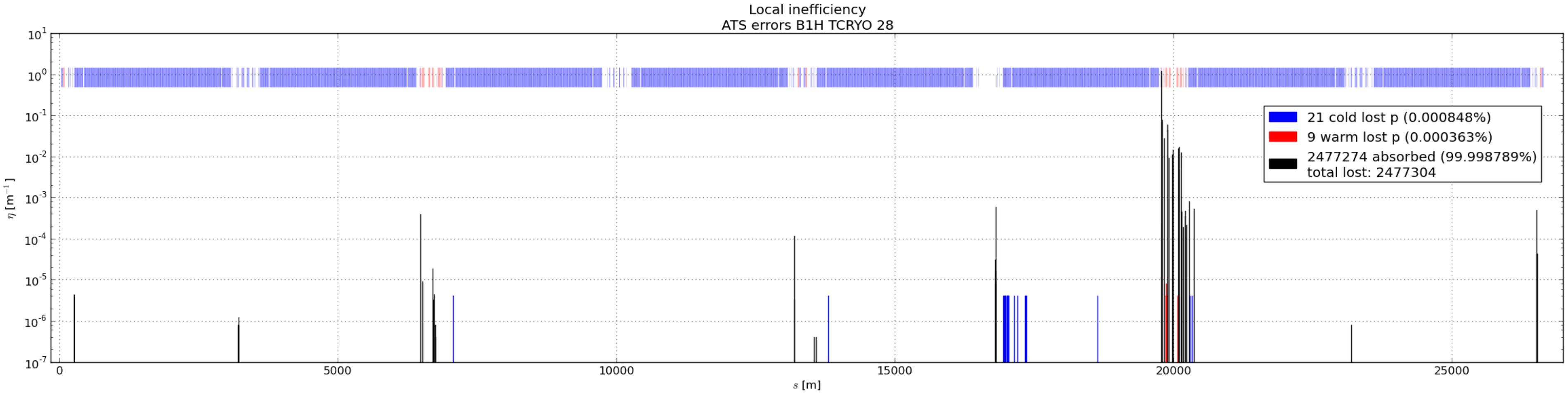




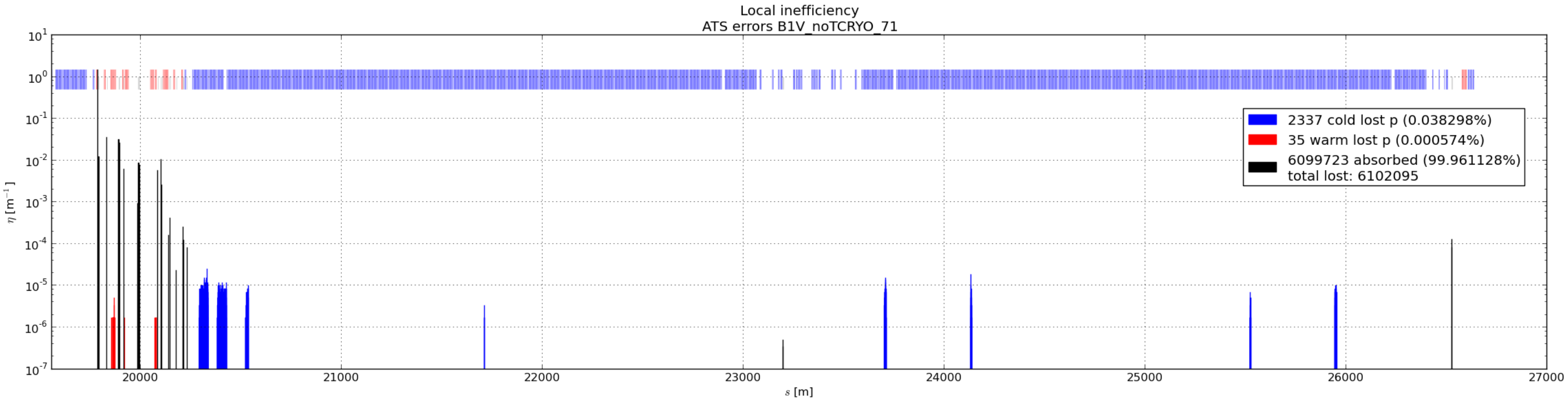
Local effect of the TCRYO (TCLD) on loss clusters

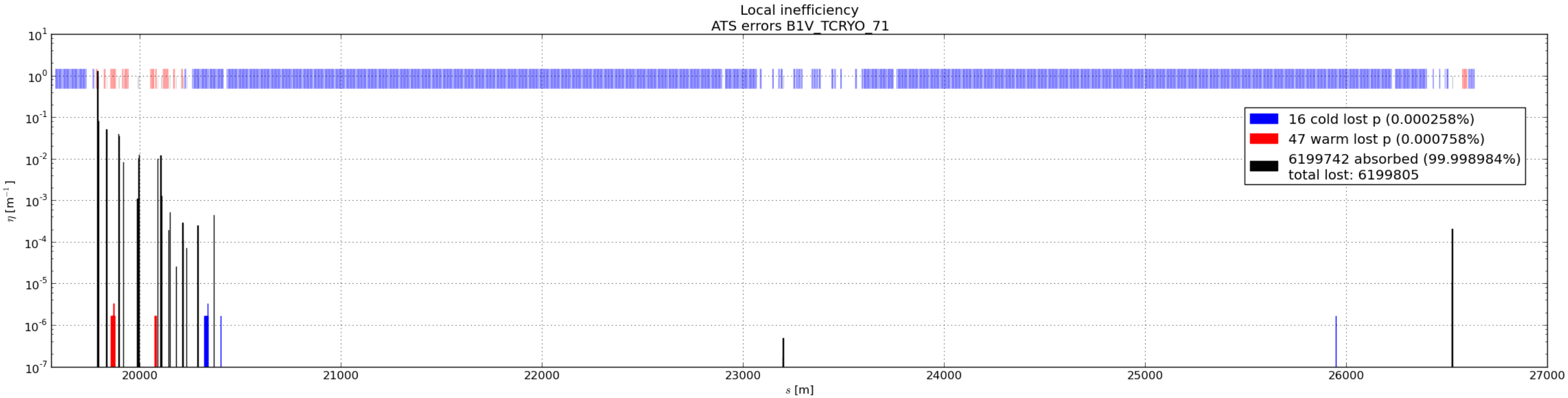
Effect of the TCRYO (both cases with error models, one seed)



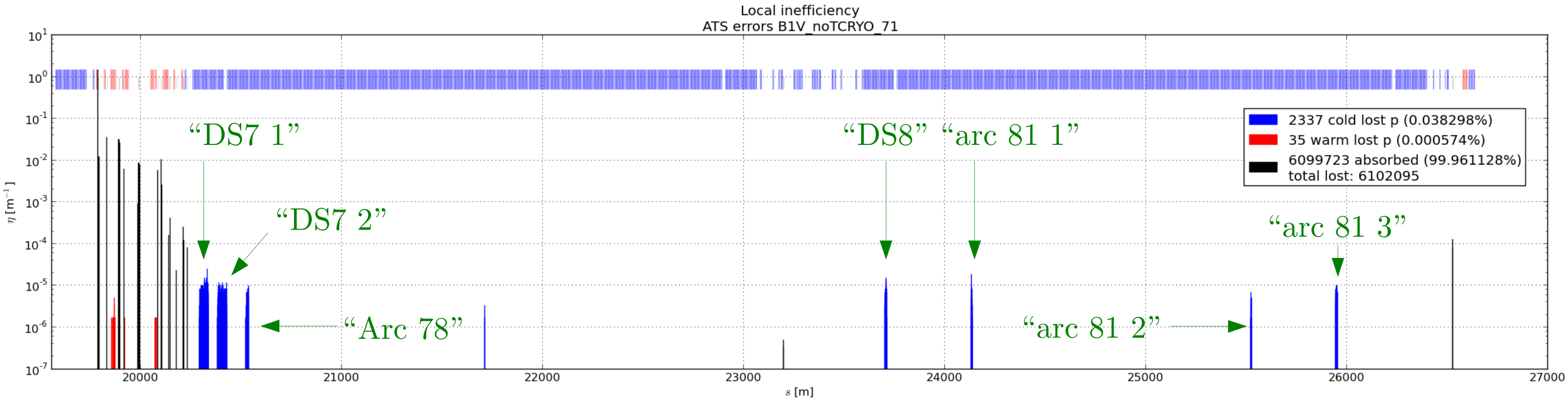


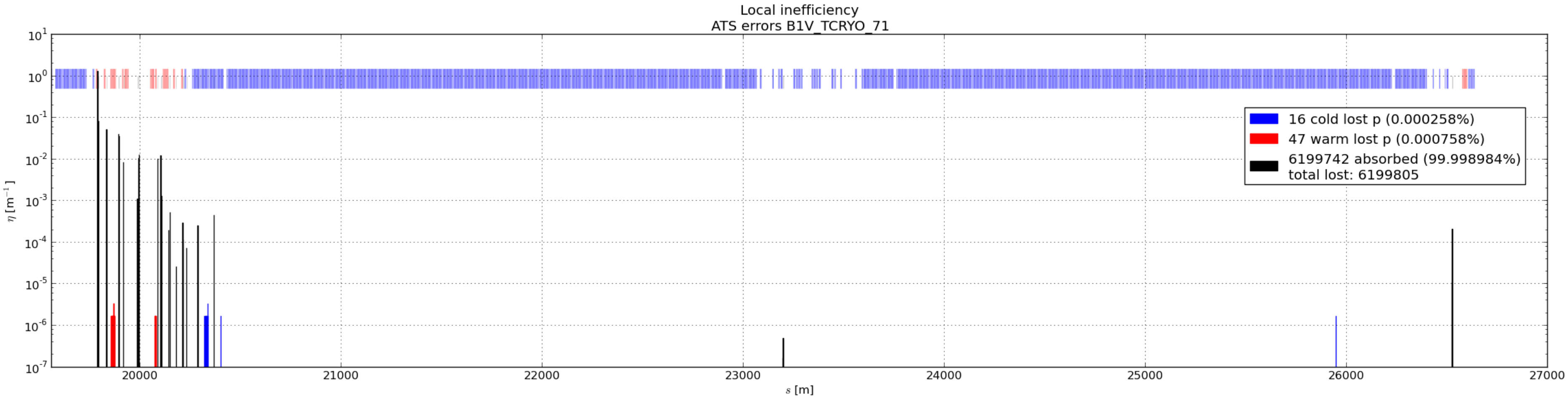
Losses in the arcs (other seed)



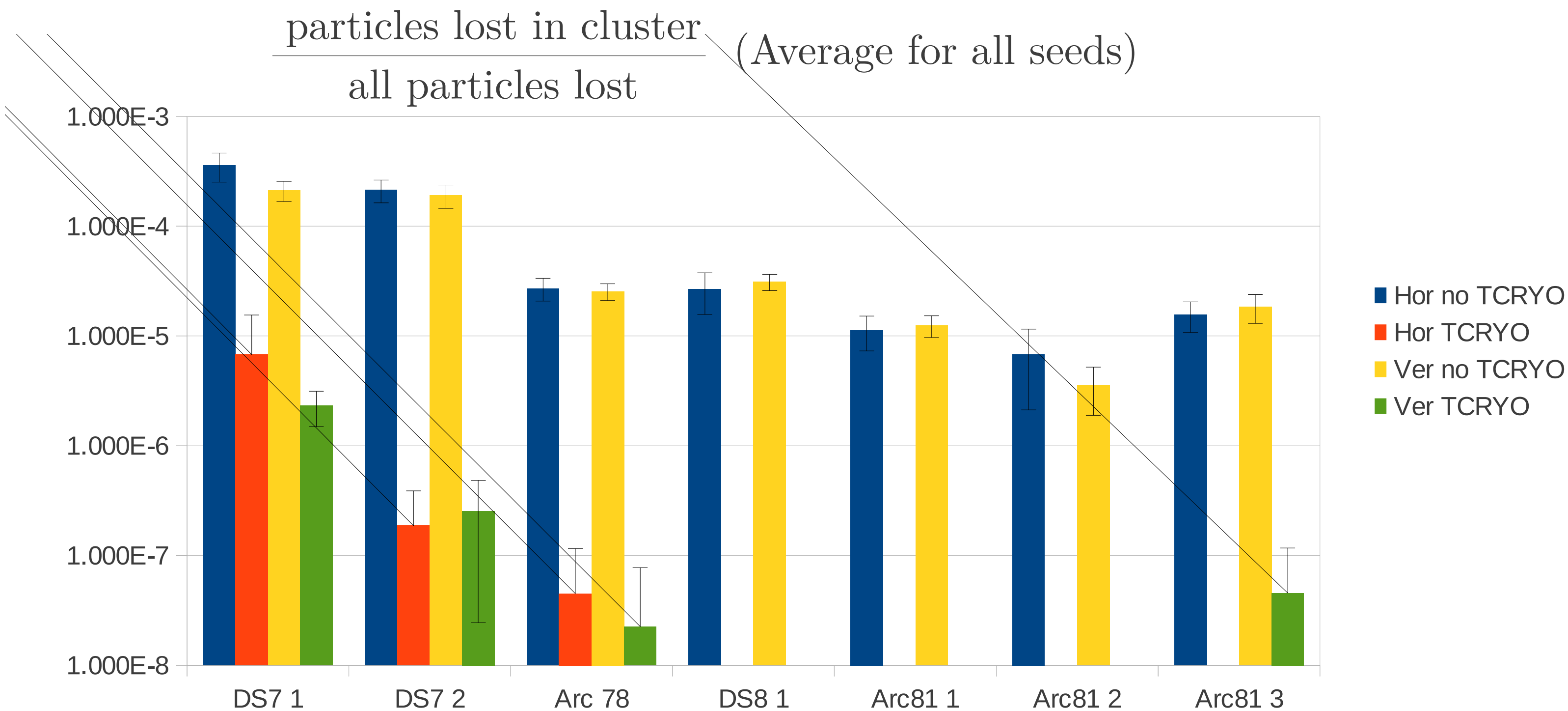


Loss clusters: names





Effect of the TCRYO for each cluster



- With TCRYO, most clusters disappear: local inefficiency is less than 1/6.4e-6
- Min. ratio corresponding to the improvement in local inefficiency (first 3 clusters):

Gain H	53.01	988.44	339.413
Gain V	91.6	732.71	546.2

Conclusions

- Cleaning performance with and without DS collimation was studied for different error models together
- Error models deteriorate cleaning efficiency
- Worst case situation: considered errors + setting at 15 σ
- Even in worst case, global efficiency improves by factor 30 to 45
- The efficiency estimated from the number of protons hitting the cold aperture downstream IR7 improved by a factor x100
  (cf A. Lechner's presentation on energy deposition, earlier)
- Catching off-momentum leakage close to IR7 make
  the overall losses around the ring less sensitive to machine imperfections

310 000 jobs, 2e12 particles, 800 years of CPU

Thank you !

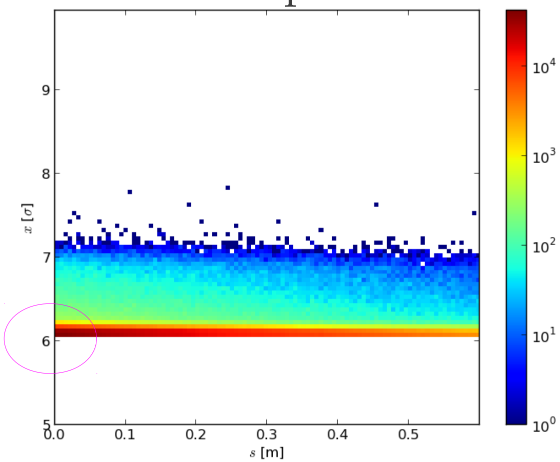
cern.ch

Spare slides

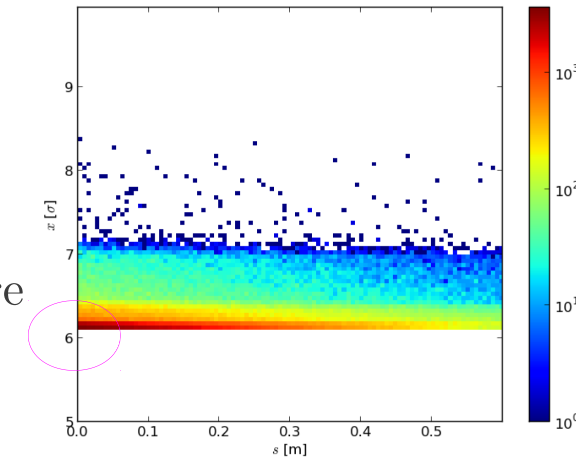
Example: impacts on the left jaw of the TCP

Setting: 6 σ

Gap

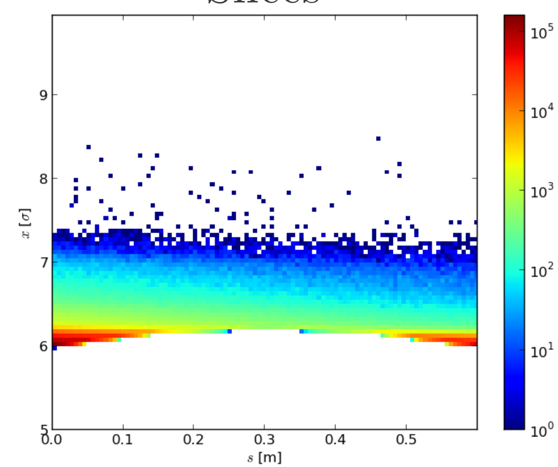


Offset

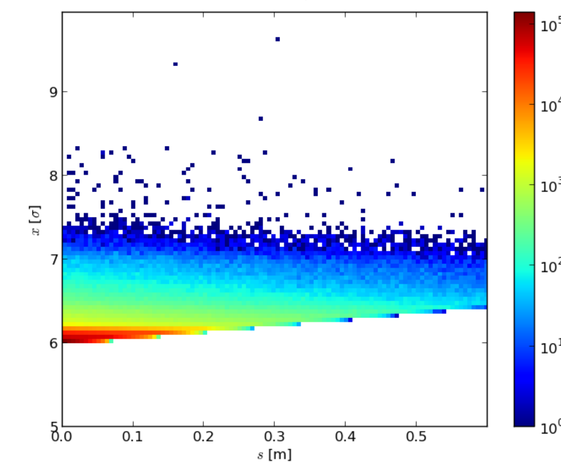


Not 6 σ any more

Slices

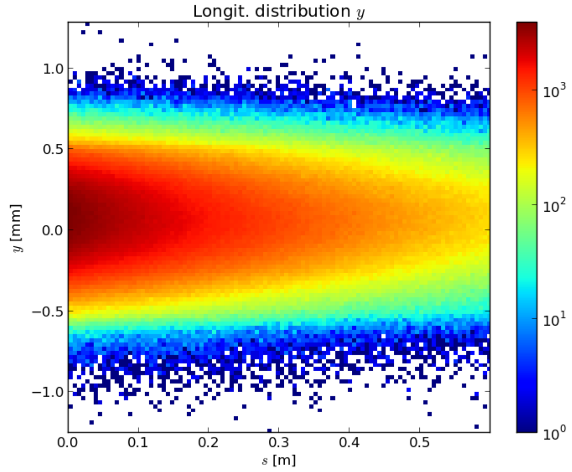


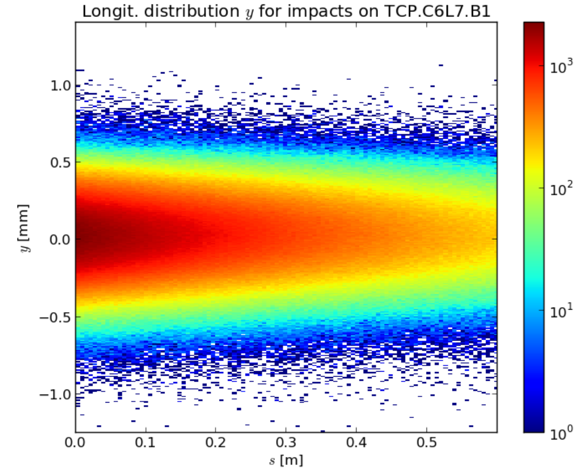
Tilt

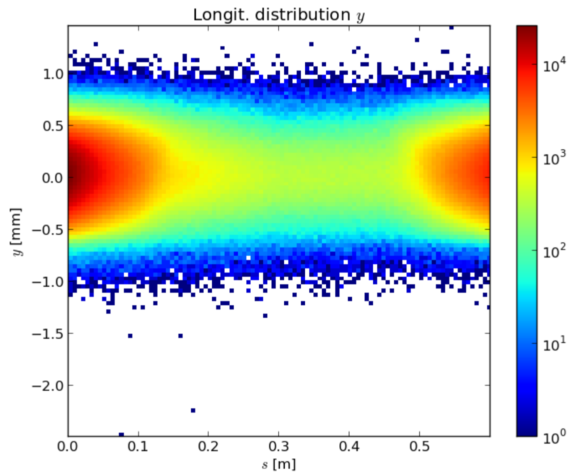


Shape of the jaw is clearly visible

Impacts on the TCP (vertical plane)

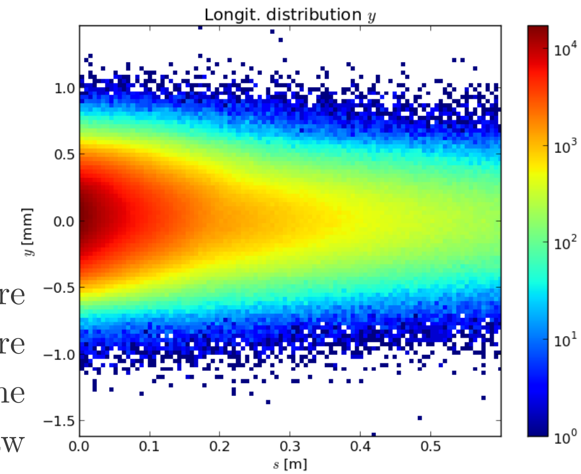




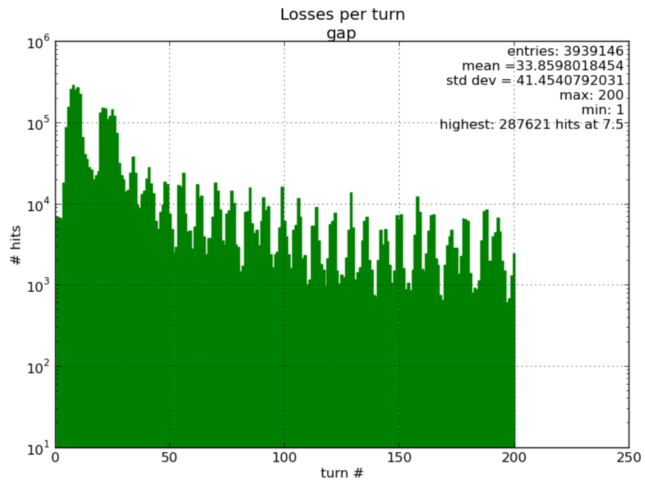


Slices are clearly visible

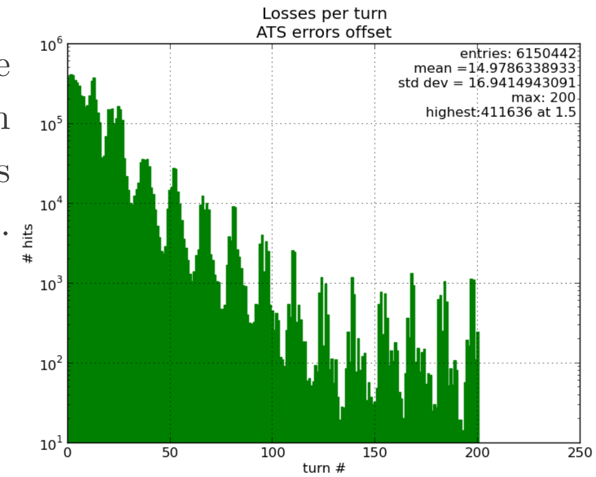
With tilt, more particles are absorbed at the beginning of the jaw

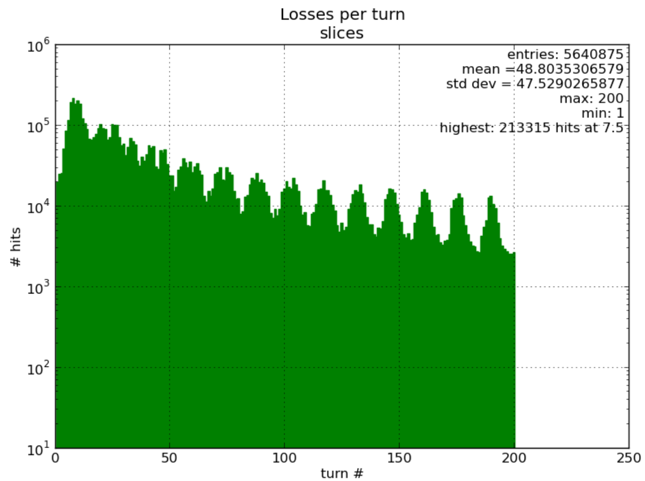


Distributions of losses per turn

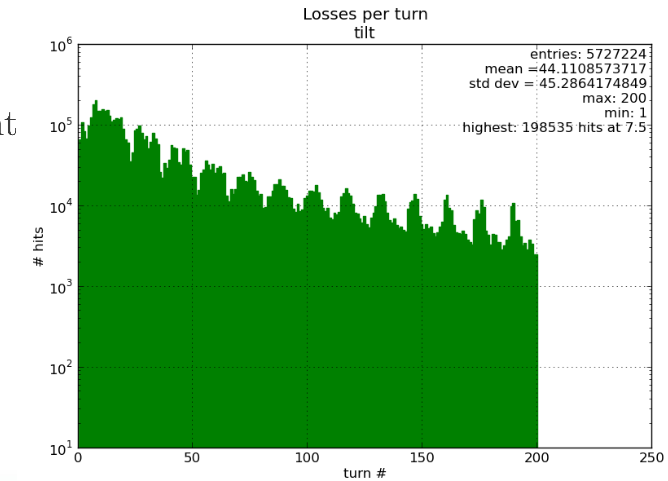


With offset error, one jaw is used more than the other, but cleaning is still good.

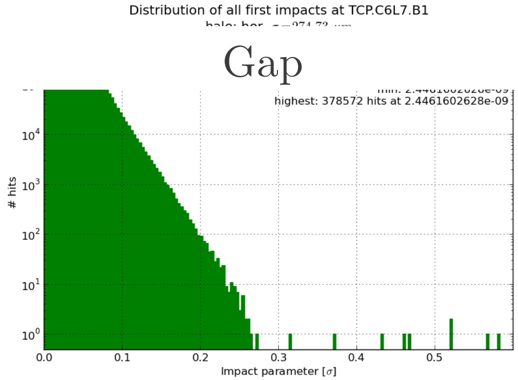


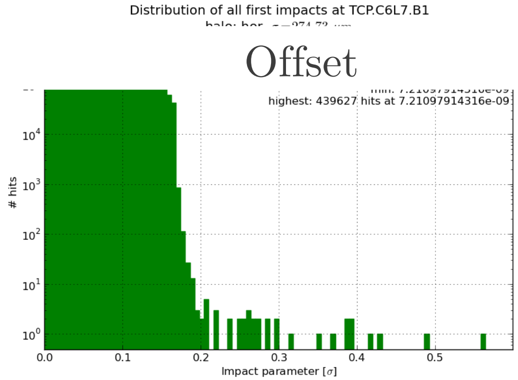


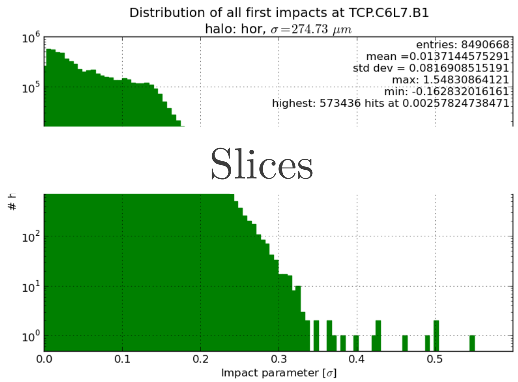
Cleaning is less efficient (for this specific seed)

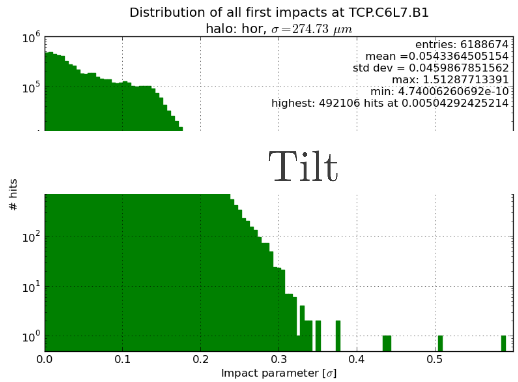


First impacts on TCP.C6L7.B1



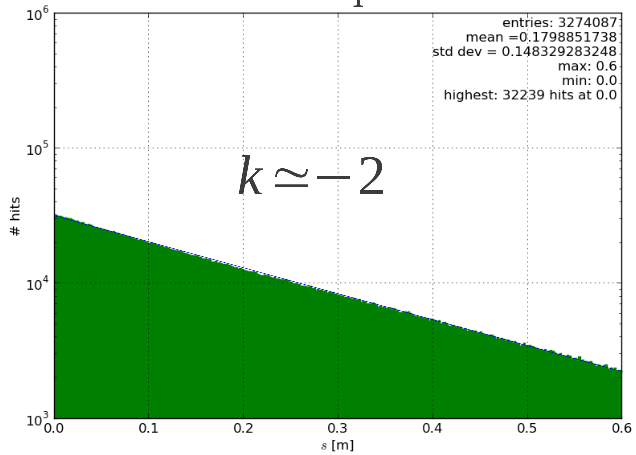




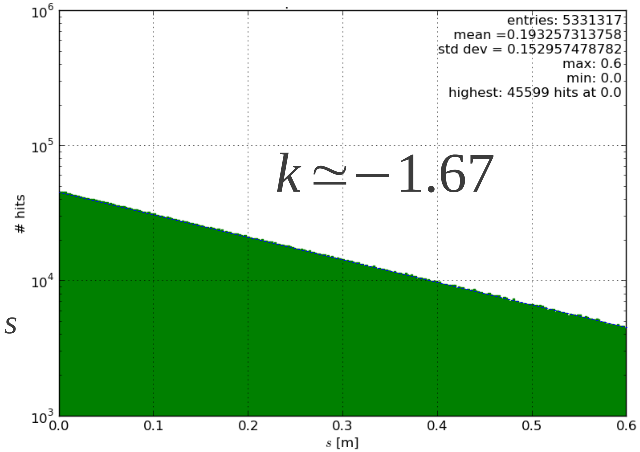


Longitudinal distribution of particles absorbed in TCP.C6L7.B1

Gap



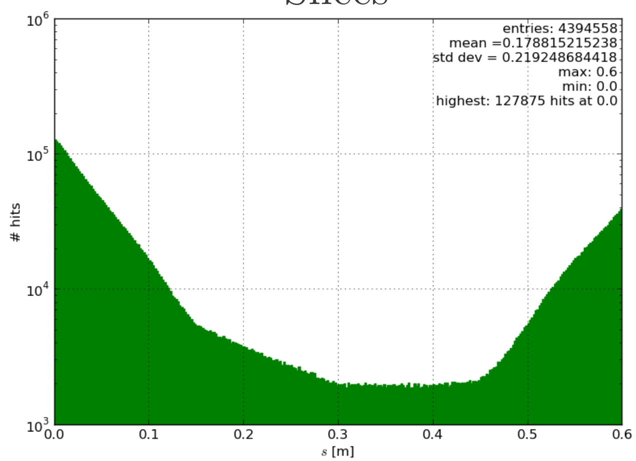
Offset



More particles are absorbed with gap than with offset

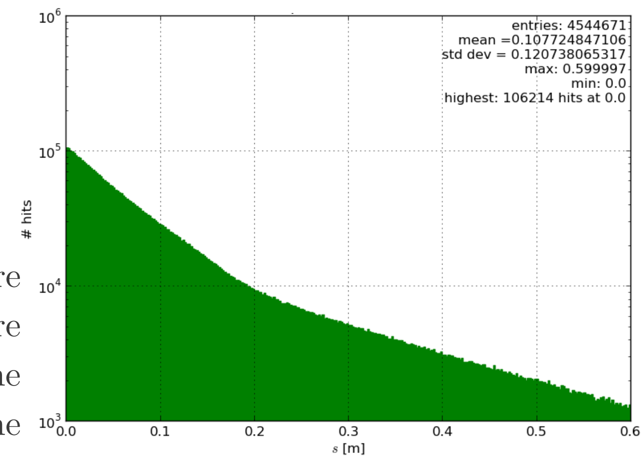
$$N \simeq N_0 \cdot 10^{k \cdot s}$$

Slices



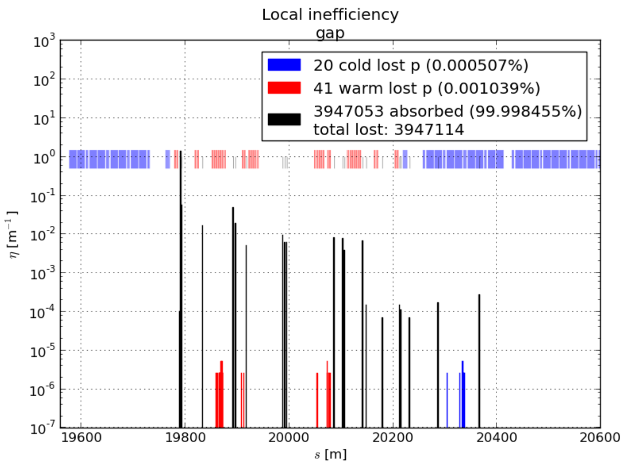
Slices are clearly visible

Tilt

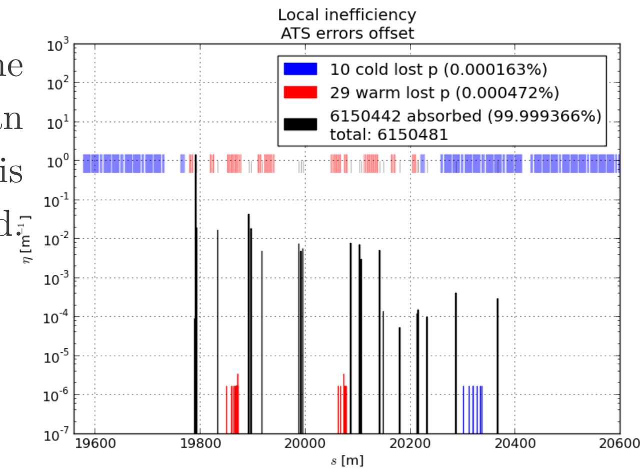


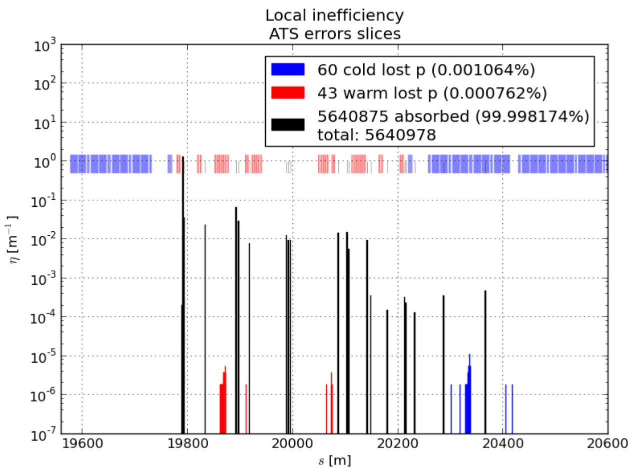
With tilt, more particles are absorbed at the beginning of the jaw

Loss maps of IR7

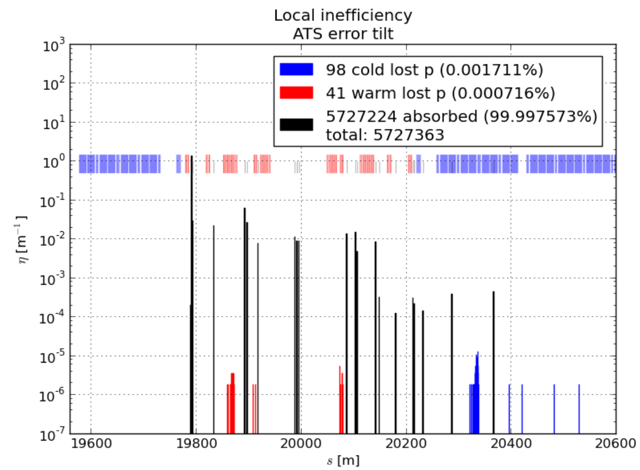


With offset error, one jaw is used more than the other, but cleaning is still good.

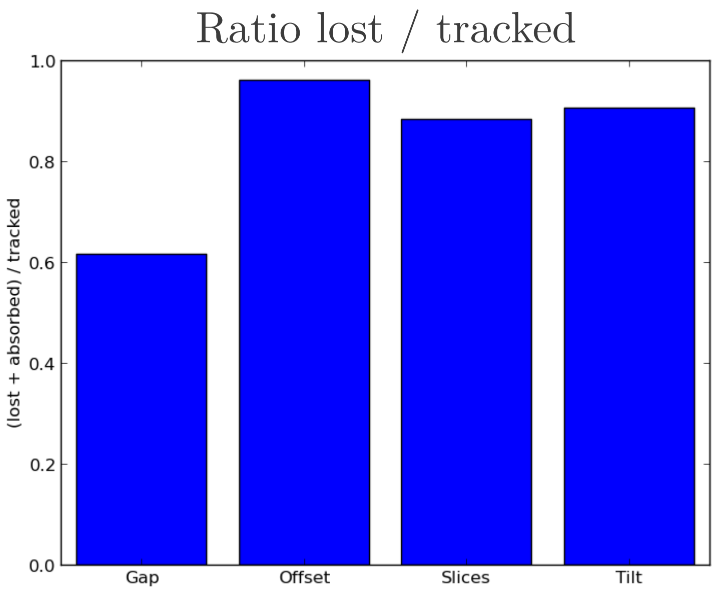


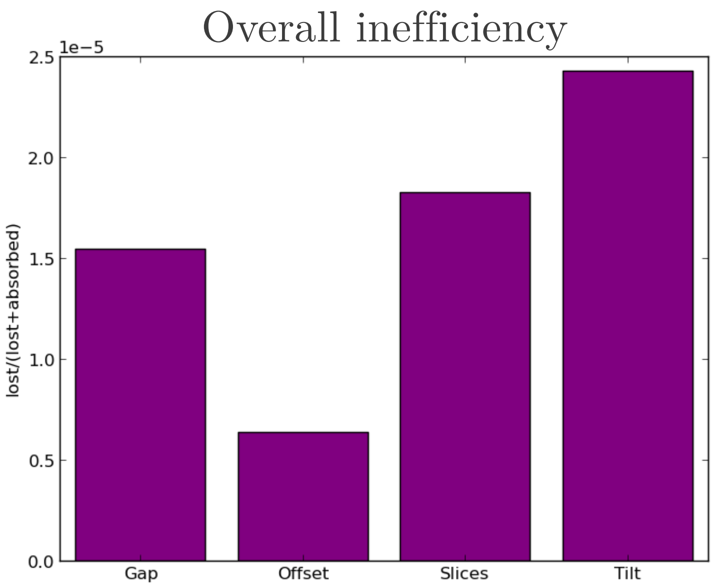


(Could do with more statistics or without TCRYO)



Statistics





- Error on gap = bigger collimator setting
- Offset = favouring one jaw
- Slices and tilt have similar effect: less material

- Offset gives best cleaning
- Tilt gives worst cleaning
- Slices = higher order of tilt (better cleaning)

Statistics

Gap

- Tracked: 6 400 000
- Lost: 3 947 114 (61.67 %)

Offset

- Tracked: 6 400 000
- Lost: 6 150 481 (96.10 %)

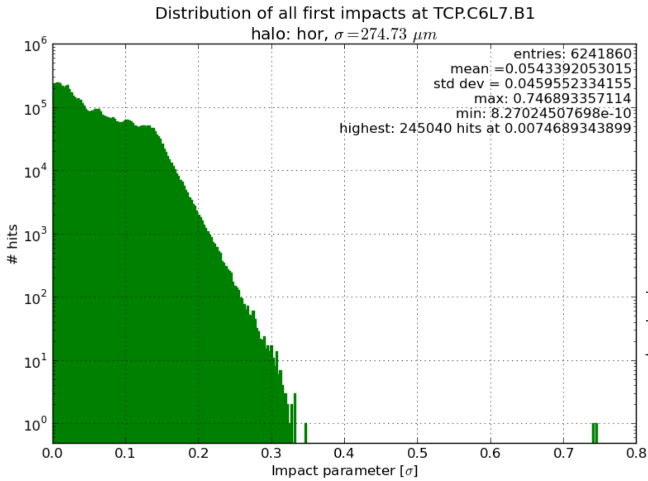
Slices

- Tracked: 6 393 600
- Lost: 5 640 978 (88.23 %)

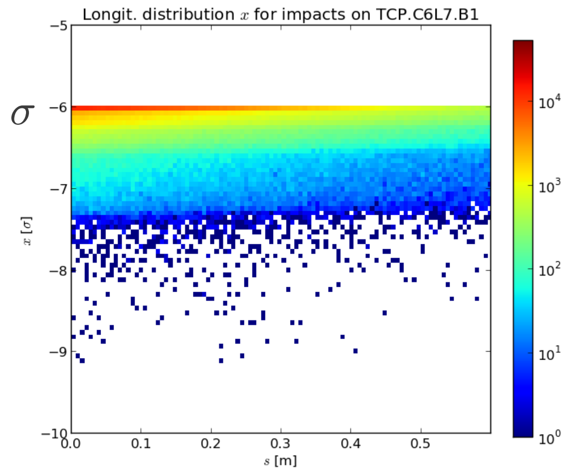
Tilt

- Tracked: 6 329 600
- Lost: 5 727 363 (90.48 %)

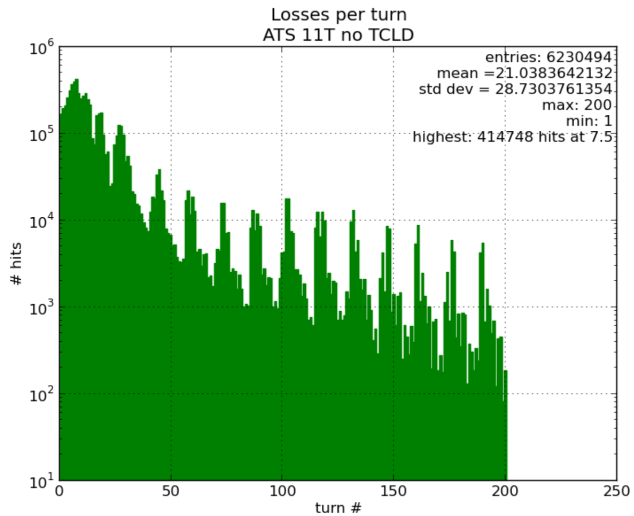
No error, Horizontal B1 (for reference)



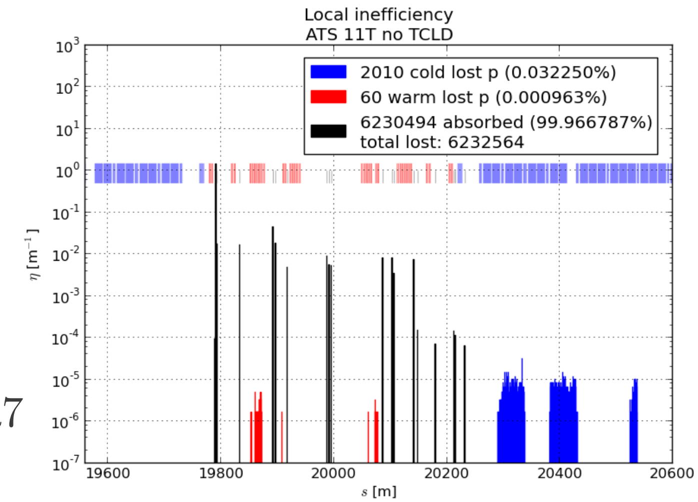
Flat jaw at exactly 6 σ



Many first impacts between 0 and 0.15 σ

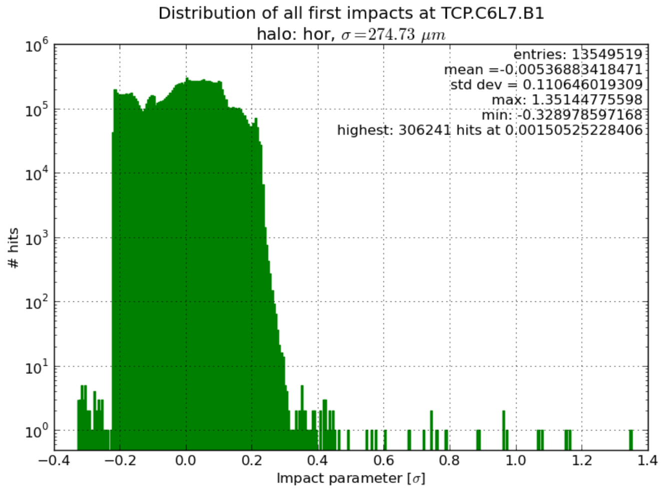


Losses per turn

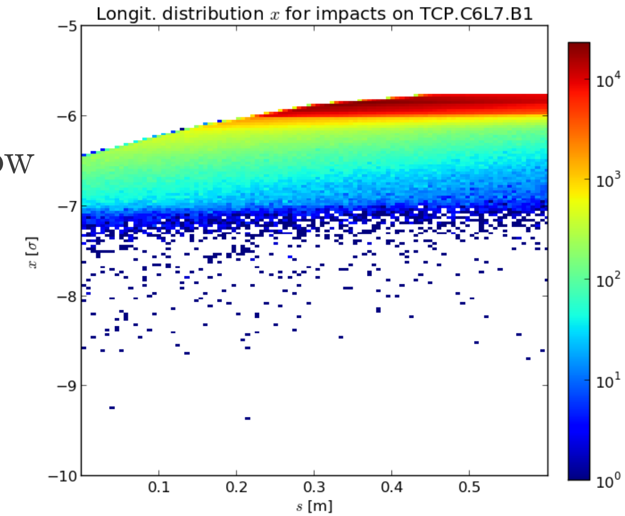


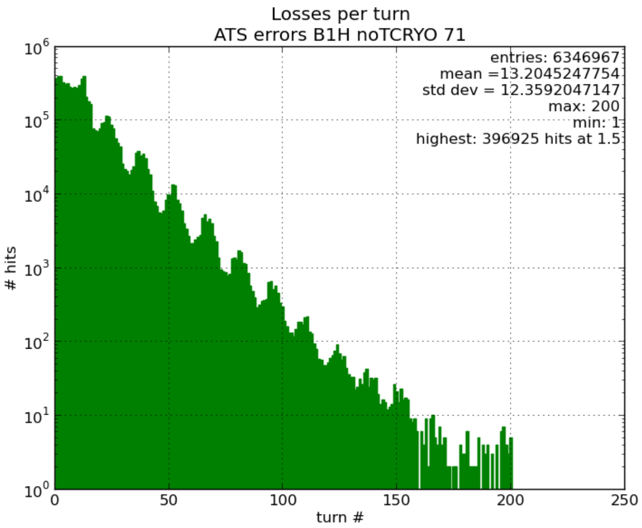
Loss maps IR7

Result example:
B1 horizontal, no TCRYO



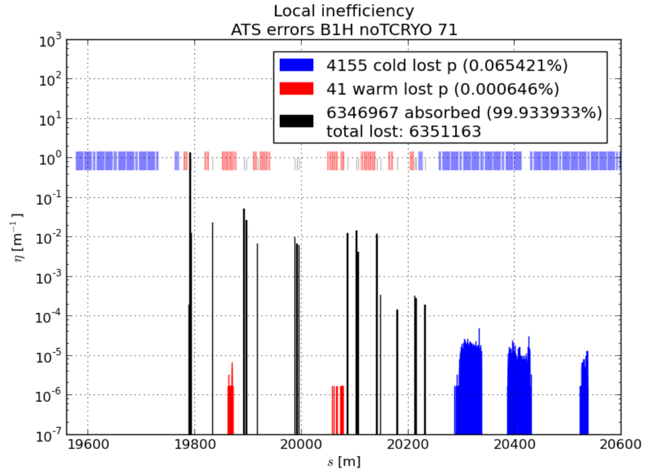
Impacts on primary show non-flatness + tilt





Losses per turn

Deteriorated cleaning



All results
ratio lost/sent

Horizontal		Vertical	
B1H_TCRYO_1	0.948362313675	B1V_TCRYO_1	0.99958140625
B1H_TCRYO_28	0.387117461746	B1V_TCRYO_28	0.409967397023
B1H_TCRYO_45	0.858202029936	B1V_TCRYO_45	0.995526890262
B1H_TCRYO_604	0.991569156916	B1V_TCRYO_604	0.23448292042
B1H_TCRYO_71	0.994606975843	B1V_TCRYO_71	0.994606975842
B1H_TCRYO_72	0.101252688575	B1V_TCRYO_72	0.991525985394
B1H_TCRYO_864	0.998737560012	B1V_TCRYO_864	0.96894203125
B1H_noTCRYO_1	0.94838546875	B1V_noTCRYO_1	0.999586479796
B1H_noTCRYO_28	0.387040431975	B1V_noTCRYO_28	0.410120500401
B1H_noTCRYO_45	0.858190458617	B1V_noTCRYO_45	0.995600456478
B1H_noTCRYO_604	0.991544090068	B1V_noTCRYO_604	0.234395476941
B1H_noTCRYO_71	0.994557244688	B1V_noTCRYO_71	0.999950019664
B1H_noTCRYO_72	0.10121171875	B1V_noTCRYO_71	0.991446644664
B1H_noTCRYO_864	0.99874	B1V_noTCRYO_864	0.968934310905

All results
Global inefficiency

Horizontal		Vertical	
B1H_TCRYO_1	3.52735023308e-05	B1V_TCRYO_1	1.67260310504e-05
B1H_TCRYO_28	1.21100855214e-05	B1V_TCRYO_28	1.03132477105e-05
B1H_TCRYO_45	9.47893216183e-06	B1V_TCRYO_45	2.18342806374e-05
B1H_TCRYO_604	1.37108902765e-05	B1V_TCRYO_604	1.9344153163e-05
B1H_TCRYO_71	8.64301518656e-06	B1V_TCRYO_71	1.0161609921e-05
B1H_TCRYO_72	3.55083483215e-05	B1V_TCRYO_72	1.21390772504e-05
B1H_TCRYO_864	7.98048255631e-06	B1V_TCRYO_864	1.03206413634e-05
B1H_noTCRYO_1	0.00067203027777	B1V_noTCRYO_1	0.000483655358329
B1H_noTCRYO_28	0.00092473932545	B1V_noTCRYO_28	0.000679880499836
B1H_noTCRYO_45	0.000803848992371	B1V_noTCRYO_45	0.000638847020963
B1H_noTCRYO_604	0.00076864350904	B1V_noTCRYO_604	0.000376926494664
B1H_noTCRYO_71	0.000661103169435	B1V_noTCRYO_71	0.000388870117545
B1H_noTCRYO_72	0.000410817789955	B1V_noTCRYO_72	0.000510983787218
B1H_noTCRYO_864	0.000488040197733	B1V_noTCRYO_864	0.000481025404114

LHC Collimation Project CERN

All results - clusters

H/V	TCRYO	seed	total lost	DS7 1	DS7 2	Arc 78	DS8 1	Arc81 1	Arc81 2	Arc81 3		DS7 1	DS7 2	Arc 78	DS8 1	Arc81 1	Arc81 2	Arc81 3
h	noTCRYO	1	6069667	1769	1477	210	296	85	8	145		2.914E-4	2.433E-4	3.460E-5	4.877E-5	1.400E-5	1.318E-6	2.389E-5
h	noTCRYO	28	2474334	1257	696	87	71	41	32	53		5.080E-4	2.813E-4	3.516E-5	2.869E-5	1.657E-5	1.293E-5	2.142E-5
h	noTCRYO	45	5488025	2442	1399	170	122	68	59	83		4.450E-4	2.549E-4	3.098E-5	2.223E-5	1.239E-5	1.075E-5	1.512E-5
h	noTCRYO	71	6351163	2441	1246	147	110	72	44	77		3.843E-4	1.962E-4	2.315E-5	1.732E-5	1.134E-5	6.928E-6	1.212E-5
h	noTCRYO	72	647755	116	91	12	22	2	0	8		1.791E-4	1.405E-4	1.853E-5	3.396E-5	3.088E-6	0.000E+0	1.235E-5
h	noTCRYO	604	6344613	2711	1498	178	141	78	72	96		4.273E-4	2.361E-4	2.806E-5	2.222E-5	1.229E-5	1.135E-5	1.513E-5
h	noTCRYO	864	6391936	1759	941	125	87	59	29	60		2.752E-4	1.472E-4	1.956E-5	1.361E-5	9.230E-6	4.537E-6	9.387E-6
	Hor no TCRYO										mean	3.586E-4	2.142E-4	2.715E-5	2.669E-5	1.127E-5	6.831E-6	1.563E-5
											std dev	1.061E-4	5.033E-5	6.361E-6	1.097E-5	3.946E-6	4.711E-6	4.844E-6
h	TCRYO	1	6067091	137	3	0	0	0	0	0		2.258E-5	4.945E-7	0.000E+0	0.000E+0	0.000E+0	0.000E+0	0.000E+0
h	TCRYO	28	2477304	2	0	0	0	0	0	0		8.073E-7	0.000E+0	0.000E+0	0.000E+0	0.000E+0	0.000E+0	0.000E+0
h	TCRYO	45	5485902	10	1	0	0	0	0	0		1.823E-6	1.823E-7	0.000E+0	0.000E+0	0.000E+0	0.000E+0	0.000E+0
h	TCRYO	71	6363575	9	1	1	0	0	0	0		1.414E-6	1.571E-7	1.571E-7	0.000E+0	0.000E+0	0.000E+0	0.000E+0
h	TCRYO	72	647758	12	0	0	0	0	0	0		1.853E-5	0.000E+0	0.000E+0	0.000E+0	0.000E+0	0.000E+0	0.000E+0
h	TCRYO	604	6345408	9	3	1	0	0	0	0		1.418E-6	4.728E-7	1.576E-7	0.000E+0	0.000E+0	0.000E+0	0.000E+0
h	TCRYO	864	6390642	5	0	0	0	0	0	0		7.824E-7	0.000E+0	0.000E+0	0.000E+0	0.000E+0	0.000E+0	0.000E+0
	Hor TCRYO										mean	6.765E-6	1.867E-7	4.496E-8	0.000E+0	0.000E+0	0.000E+0	0.000E+0
											std dev	8.794E-6	2.007E-7	7.109E-8	0.000E+0	0.000E+0	0.000E+0	0.000E+0
v	noTCRYO	1	6396074	1282	1182	148	182	66	22	88		2.004E-4	1.848E-4	2.314E-5	2.845E-5	1.032E-5	3.440E-6	1.376E-5
v	noTCRYO	28	2621359	744	685	84	105	39	15	75		2.838E-4	2.613E-4	3.204E-5	4.006E-5	1.488E-5	5.722E-6	2.861E-5
v	noTCRYO	45	6368657	1631	1600	199	232	109	24	157		2.561E-4	2.512E-4	3.125E-5	3.643E-5	1.712E-5	3.768E-6	2.465E-5
v	noTCRYO	71	6102095	1071	842	122	137	50	19	90		1.755E-4	1.380E-4	1.999E-5	2.245E-5	8.194E-6	3.114E-6	1.475E-5
v	noTCRYO	72	6344624	1414	1193	157	199	78	30	108		2.229E-4	1.880E-4	2.475E-5	3.137E-5	1.229E-5	4.728E-6	1.702E-5
v	noTCRYO	604	1499531	212	204	31	46	21	0	21		1.414E-4	1.360E-4	2.067E-5	3.068E-5	1.400E-5	0.000E+0	1.400E-5
v	noTCRYO	864	6198079	1266	1127	163	177	66	25	100		2.043E-4	1.818E-4	2.630E-5	2.856E-5	1.065E-5	4.034E-6	1.613E-5
	Ver no TCRYO										mean	2.121E-4	1.916E-4	2.545E-5	3.114E-5	1.249E-5	3.544E-6	1.842E-5
											std dev	4.429E-5	4.556E-5	4.412E-6	5.306E-6	2.828E-6	1.656E-6	5.406E-6
v	TCRYO	1	6397321	18	0	0	0	0	0	0		2.814E-6	0.000E+0	0.000E+0	0.000E+0	0.000E+0	0.000E+0	0.000E+0
v	TCRYO	28	2618019	5	0	0	0	0	0	0		1.910E-6	0.000E+0	0.000E+0	0.000E+0	0.000E+0	0.000E+0	0.000E+0
v	TCRYO	45	6366275	21	2	0	0	0	0	1		3.299E-6	3.142E-7	0.000E+0	0.000E+0	0.000E+0	0.000E+0	1.571E-7
v	TCRYO	71	6199805	12	1	0	0	0	0	1		1.936E-6	1.613E-7	0.000E+0	0.000E+0	0.000E+0	0.000E+0	1.613E-7
v	TCRYO	72	6343228	18	3	1	0	0	0	0		2.838E-6	4.729E-7	1.576E-7	0.000E+0	0.000E+0	0.000E+0	0.000E+0
v	TCRYO	604	1499190	1	1	0	0	0	0	0		6.670E-7	6.670E-7	0.000E+0	0.000E+0	0.000E+0	0.000E+0	0.000E+0
v	TCRYO	864	6201229	17	1	0	0	0	0	0		2.741E-6	1.613E-7	0.000E+0	0.000E+0	0.000E+0	0.000E+0	0.000E+0
	Ver TCRYO										mean	2.315E-6	2.538E-7	2.252E-8	0.000E+0	0.000E+0	0.000E+0	4.548E-8
											std dev	8.190E-7	2.294E-7	5.517E-8	0.000E+0	0.000E+0	0.000E+0	7.192E-8
											Gain H	53.014894	1147.5923	603.73221	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
											Gain V	91.606326	754.91179	1129.9859	#DIV/0!	#DIV/0!	#DIV/0!	404.96905