Mitigation of DS Losses with New 11 T Dipole Layout

E. Belli, R. Bruce, M. Giovannozzi, A. Mereghetti, D. Mirarchi, S. Redaelli

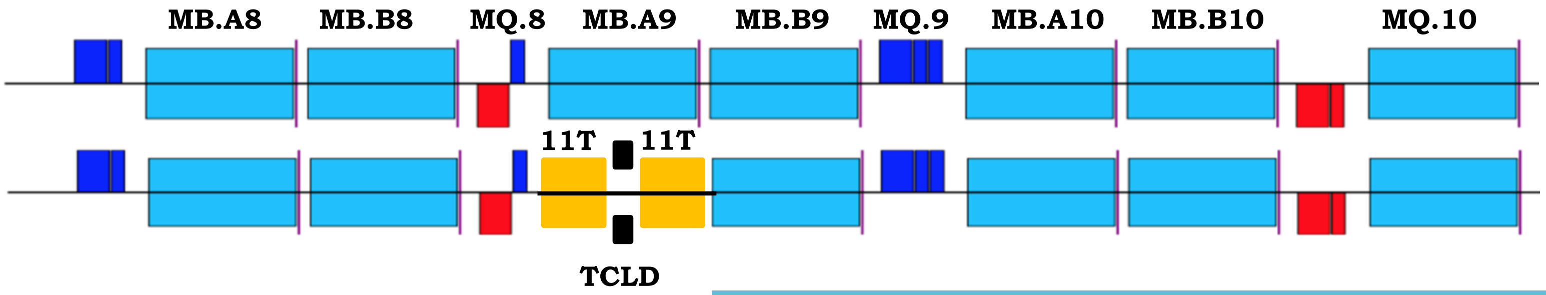
2019 HL-LHC Annual Meeting – FermiLab (US) – 14-16 Oct 2019

Outline

- Introduction and motivation
  - Mitigating present levels of energy deposition in module of 11 T dipole upstream of TCLD collimator in IR7
- Numerical simulations with SixTrack
  - Aperture scans
  - Local orbit bumps: 3 correctors and 4 correctors
  - Alternative collimator settings
- Conclusions

Motivation

- IR7 DS losses are the highest cold losses in LHC;
- With the higher intensities expected for HL-LHC, these losses could limit the machine performance, inducing magnet quench;
- Mitigation strategy: improve the collimation cleaning by substituting one standard dipole with a pair of 11 T magnets and a TCLD collimator per beam during LS2;



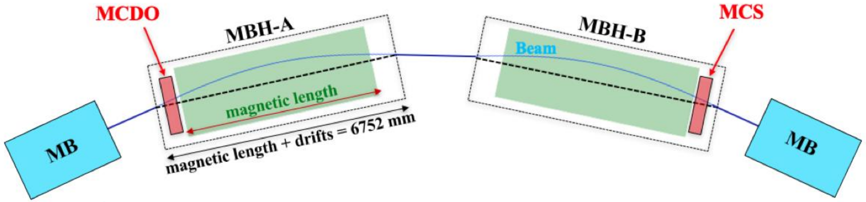
- Cell 9 is the optimal location in terms of local and global cleaning inefficiency [1];
- MB quench limit: ~20-30 mW/cm^3;
- 11 T peak power density: 48 mW/cm^3 vs a quench limit of ~70 mW/cm^3 [3];
- Possible ways to increase margin to quench?

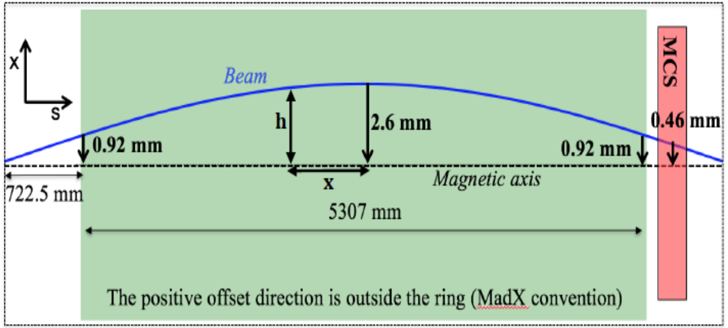
Peak power density in SC coils [mW/cm^3] [2]									
Protons					Ions				
Cells 8/9			Cell 11		Cells 8/9			Cell 11	
MB	MQ	11 T	MB	MQ	MB	MQ	11 T	MB	MQ
6.0	8.1	48	<0.3	<0.3	6.0	3.6	33	<0.003	<0.003

70% of quench limit

Simulation Set Up

- Standard SixTrack simulations for cleaning:
- HL-LHC optics v1.3, 7 TeV, β*=15cm;
- TCLD between 11 T dipoles at 16.6σ in cell 9;
- Sagitta in 11 T magnet (RBEND) taken into account as aperture offset in SixTRack survey file;





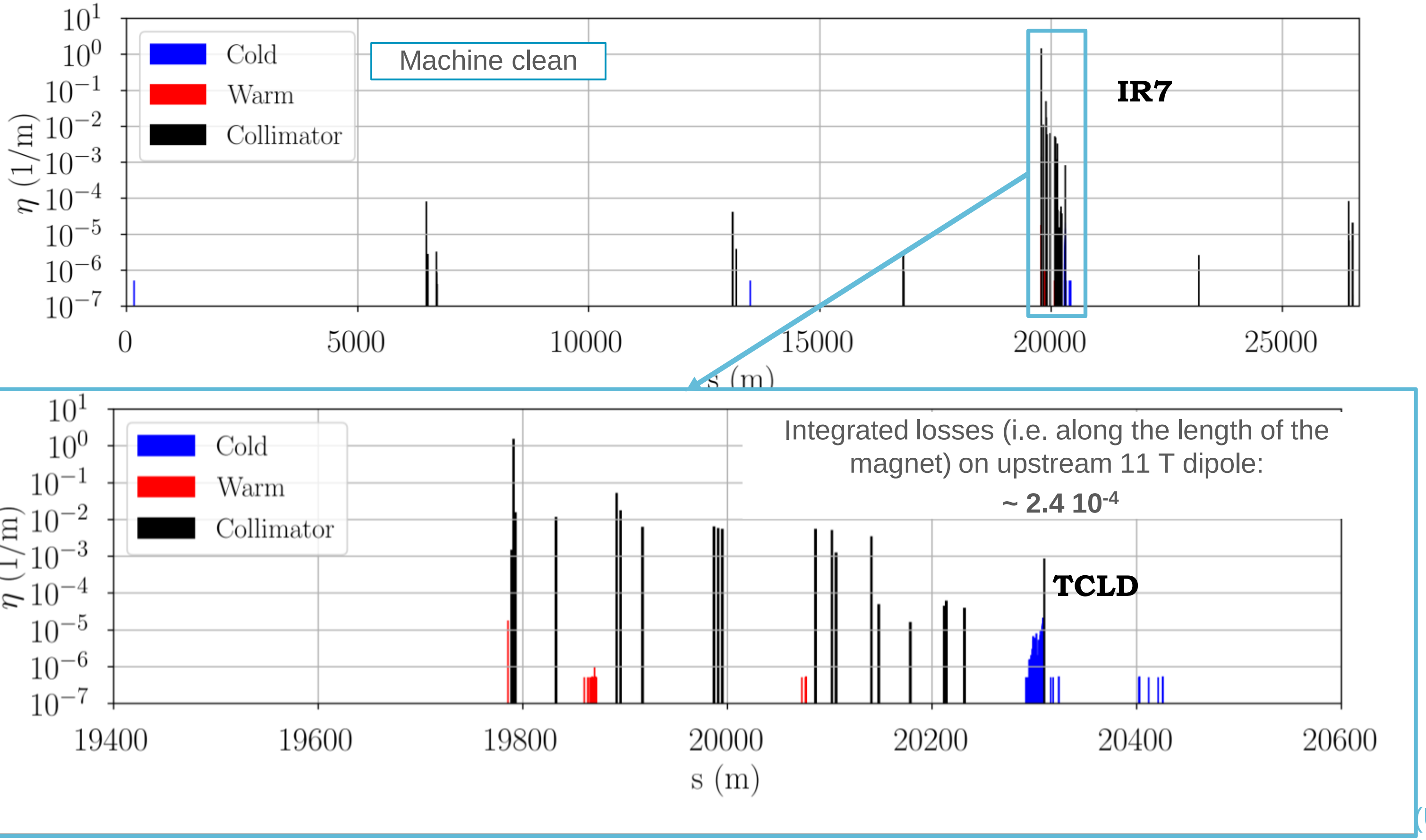
$$h = s + \sqrt{\rho^2 - x^2} - \rho$$

Collimation settings ($\varepsilon = 2.5\mu m$)	σ	Material
Primary (TCP) IR7	6.7	MoGr
Secondary (TCSG) IR7	9.1	MoGr
Absorber (TCLA) IR7	11.9	Inermet
Primary (TCP) IR3	17.7	CFC
Secondary (TCSG) IR3	21.3	CFC
Absorber (TCLA) IR3	23.7	Inermet
Tertiary (TCT) IR1	10.4	Inermet (V), CuCD (H)
Tertiary (TCT) IR5	10.4	Inermet (V), CuCD (H)
Tertiary (TCT) IR2	35.4	Inermet
Tertiary (TCT) IR8	17.7	Inermet
Secondary (TCSP) IR6	10.1	CFC
Dump prot. (TCDQ) IR6	10.1	CFC
TCL 4 IR1/5	14.2	Inermet
TCL 5 IR1/5	14.2	Inermet
TCL 6 IR1/5	14.2	Inermet

Simulation Studies

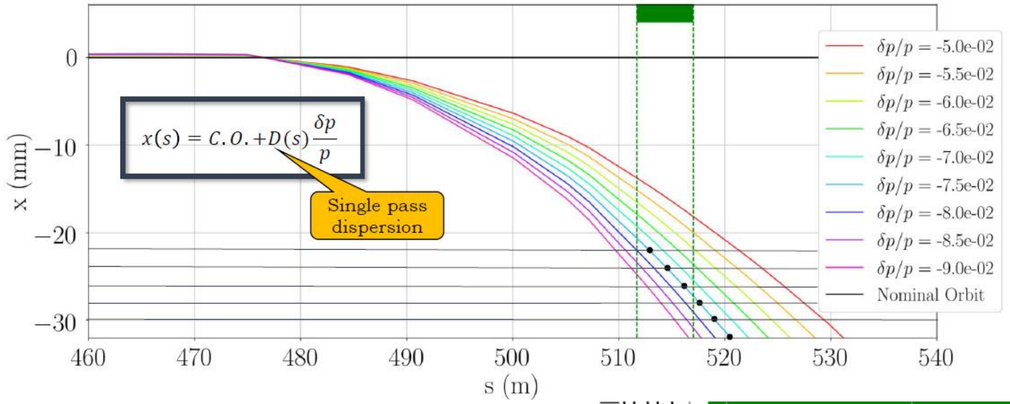
1. Aperture increase;
   - The aim is to mimic the alignment of the 11 T dipole towards the inside of the ring to gain in aperture;
2. Local orbit bump matched at the centre of the dipole:
   - 3 correctors – simplest bump option, to control beam position at 11 T dipole;
   - 3 correctors + trim power converters of 11 T – mitigation of max of local bump downstream of TCLD;
   - 4 correctors – more complete bump option, to control beam position and angle at 11 T dipole;
3. Playing with collimator settings:
   - Tighter TCSG and TCLA settings, to improve cleaning;
   - More relaxed TCP and TCSG settings, to reduce impact on impedance
4. Combinations of bump, misalignment and tighter TCSG settings as possible operational scenarios;

Reference Loss Map

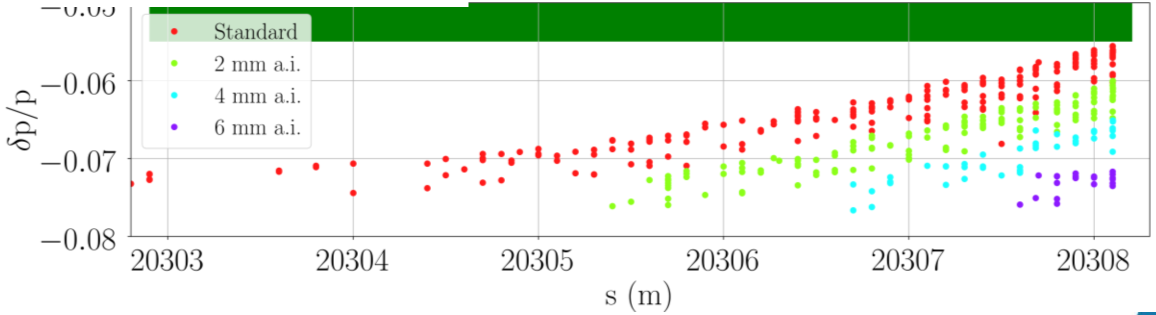


Aperture Scan

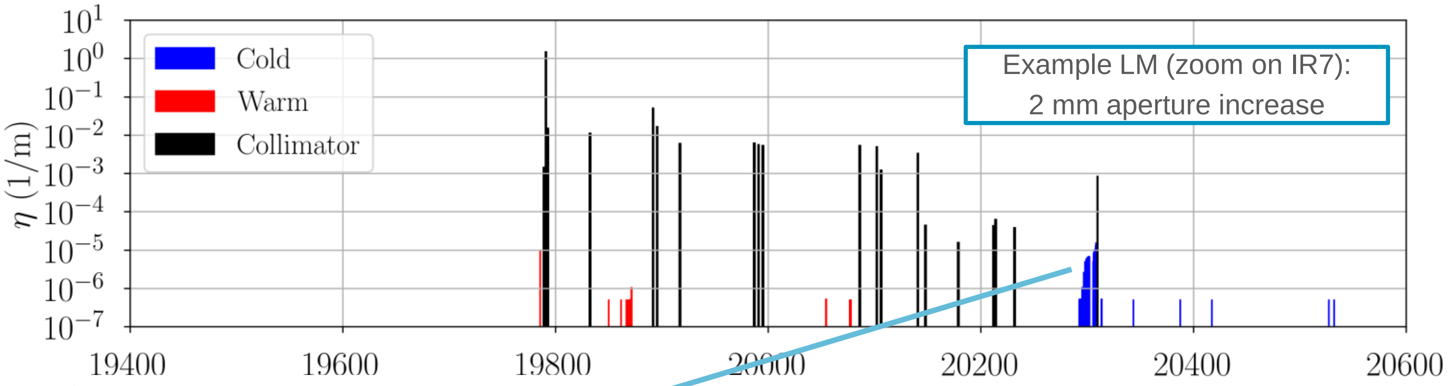
- Increase the horizontal aperture of the beam pipe at the 11 T magnet – standard half aperture: 22 mm;
- Aim: to emulate a misalignment of the magnet towards the inside of the ring;

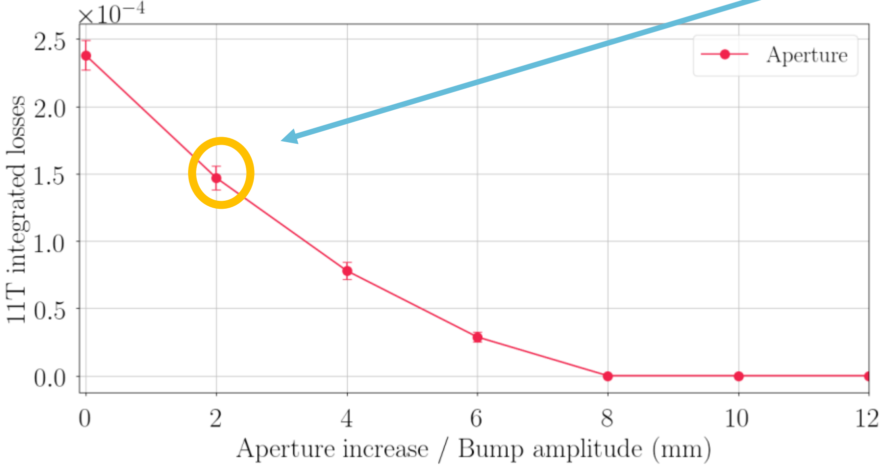


- Losses in the IR7 DS are typically dominated by off-momentum protons (mostly single diffractive), with δ of few %;
- Enlarging the aperture (i.e. shifting it transversally towards the inside of the ring) could allow to shift losses towards the downstream TCLD;



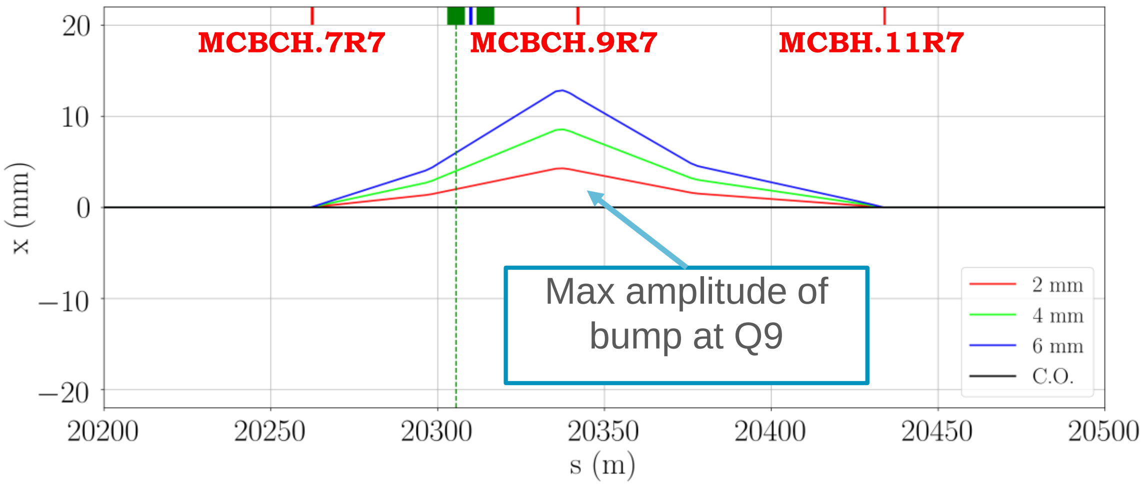
Aperture Scan: Results





- Already a reduction of losses by 38 % with 2 mm aperture increase
- No losses in 11 T dipole with 8 mm aperture increase and larger;

3 Magnets Local Orbit Bump



3 values of bump explored, limited by the peak of the orbit bump at Q9:

- 6mm @ 11 T → 13 mm @ Q9;
- 4mm @ 11 T → 9 mm @ Q9;

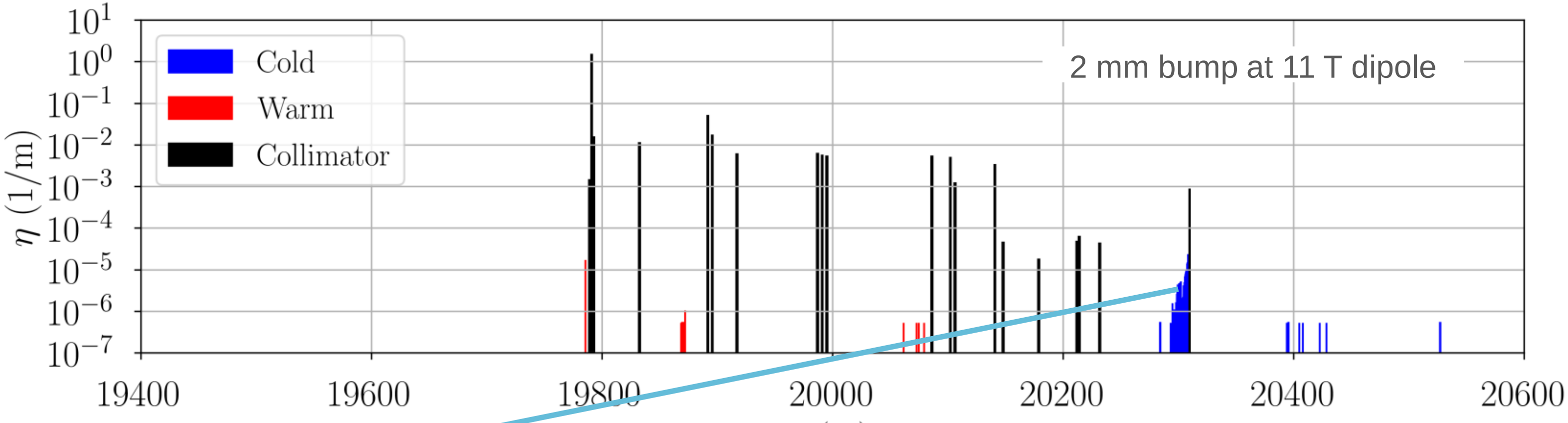
To be compared with 22 mm (current aperture);

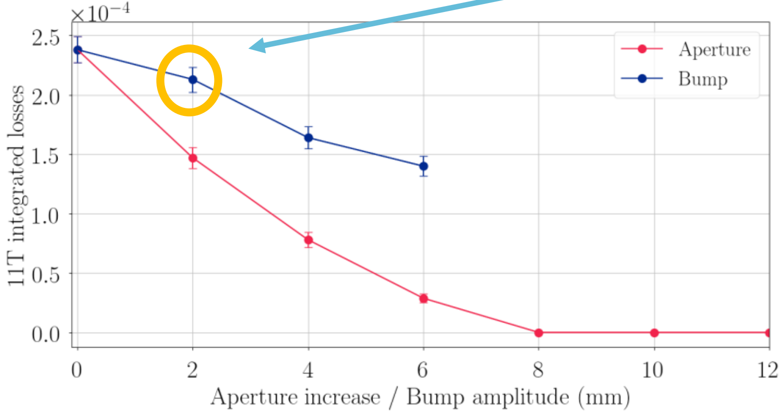
Required kick [μrad]	Bump amplitude [mm]		
Correctors	2	4	6
MCBCH.7R7	39.1	78.2	117.3
MCBCH.9R7	9.3	18.6	27.9
MCBH.11R7	30	60	90

The use of 11 T trip power converter (PCs) can mitigate these points (see later);

MCBH.11R7 out of strength;

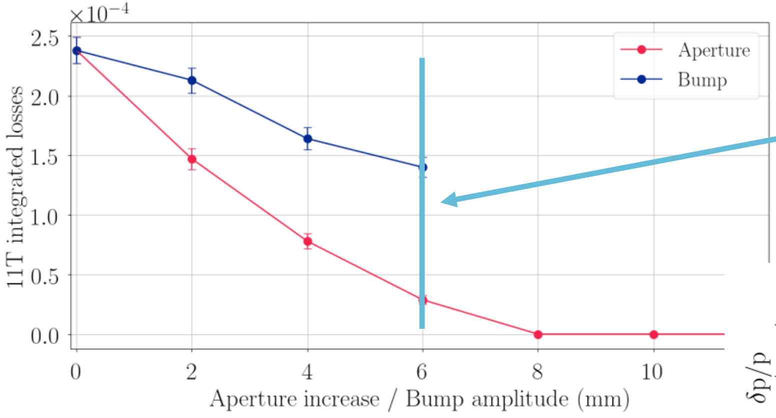
3 Magnets Local Orbit Bump: Results



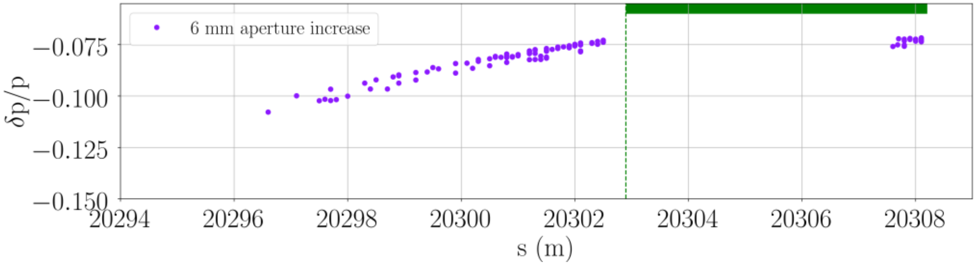


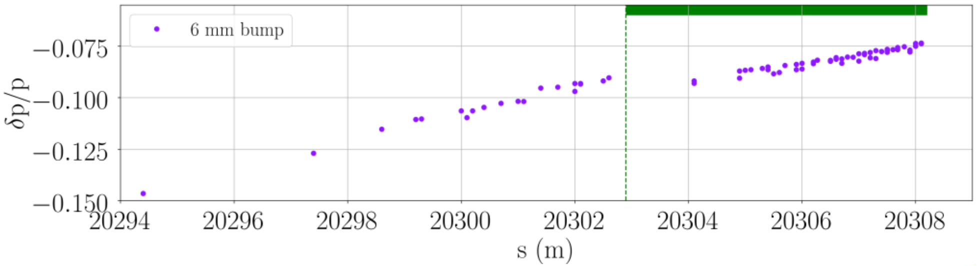
- Already a reduction of losses by 10% with 2 mm orbit bump at 11 T dipole;

Aperture Increase vs Orbit Bump



Higher losses with orbit bump than with the corresponding aperture increase

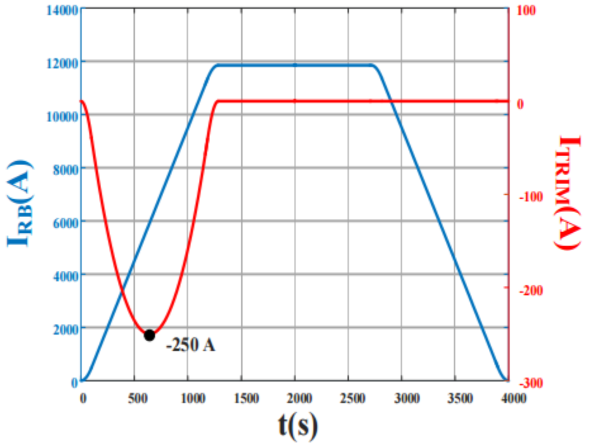




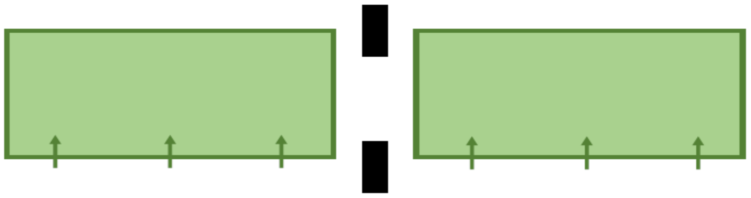
The bump longitudinally shifts particles that would have been lost upstream

Trim Power Converter of 11 T Dipole

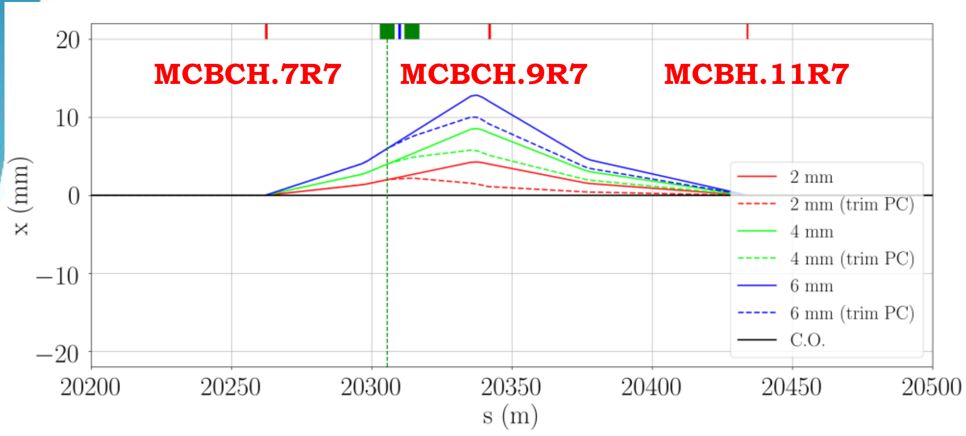
- Transfer function of 11 T magnets is slightly different than that of the MBs;
  - Trim Power Converter connected to the 11 T magnets in series to inject or extract current from 11 T dipoles to compensate the difference on the transfer function;
- Nominal current of 11 T magnet: $I_{nom,11T}$=11850 A;
- Deflection angle of 11 T magnet is half of the bending angle of a nominal dipole: θ_{11T}=2.55 μrad;
- Rating of trim PC: 250 A;
- Modelled in MAD-X as three h-kickers per magnet;

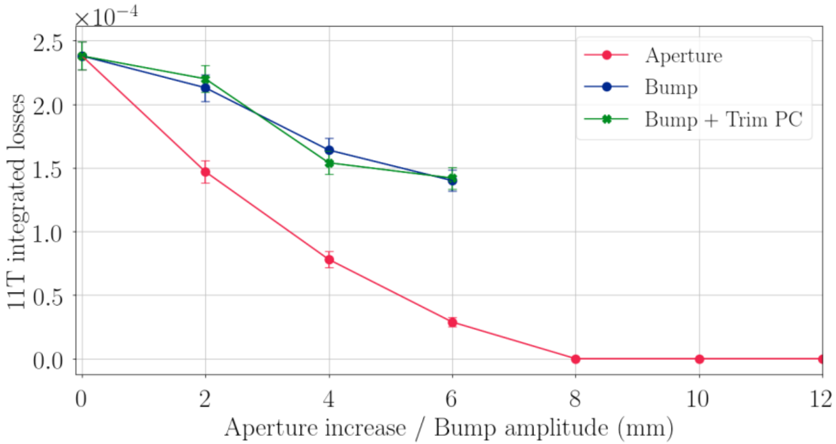


$$-\frac{I_{trim}}{I_{nom,11T}}\boldsymbol{\theta_{11T}} < \theta < \frac{I_{trim}}{I_{nom,11T}}\boldsymbol{\theta_{11T}} \quad \approx \pm\mathbf{53.8}\ \boldsymbol{\mu rad}$$



Local Orbit Bump and Trim PC of 11 T Dipole

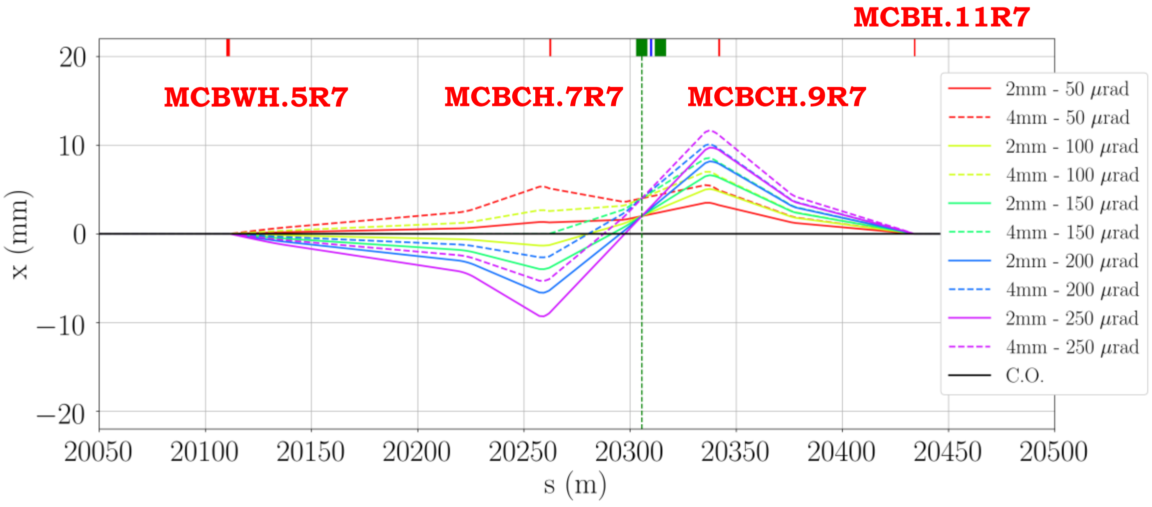




Required kick [μrad]	Bump amplitude [mm]		
Correctors	2	4	6
MCBCH.7R7	39.6	78.7	117.8
MCBCH.9R7	64.7	74	83.3
MCBH.11R7	8.3	38.4	68.4 ✓

4 Magnets Local Orbit Bump

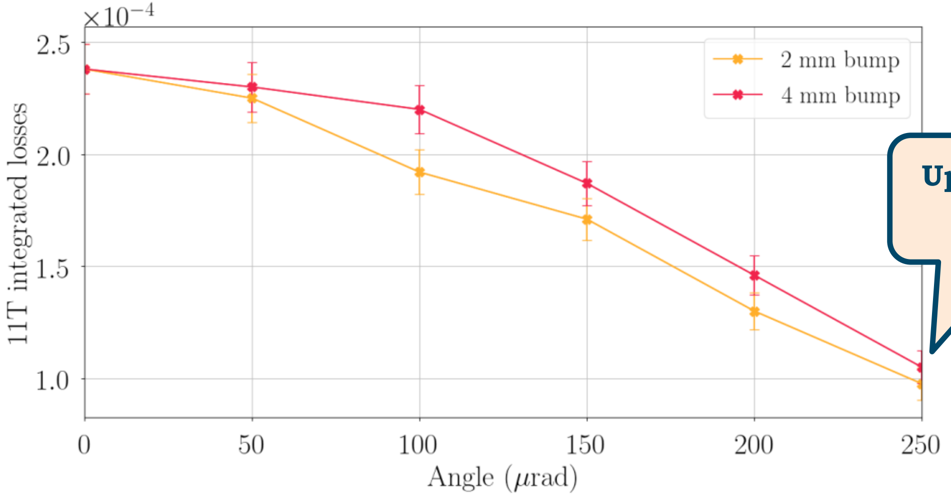
- Four magnets allow to control both position and angle of the beam;
- Evaluating performance for 2/4 mm bump for different angles



Required kick [μrad]	Angle [μrad]									
Correctors	50		100		150		200		250	
	2 mm	4 mm	2 mm	4 mm	2 mm	4 mm	2 mm	4 mm	2 mm	4 mm
MCBWH.5R7	7.5	30.15	-7.5	15.1	-22.5	53.9	-37.6	-15	-52.6	-30
MCBCH.7R7	32.3	51	45.9	64.6	59.4	78.1	72.9	91.7	86.5	105.3
MCBCH.9R7	19.9	61	-1.25	39.9	-22.4	18.7	-43.6	-2.5	-64.8	-23.7
MCBH.11R7	24.2	36.7	35.8	48.4	47.4	60	59	71.6	70.6	**83.2**

4 Magnets Local Orbit Bump - Results

- Four magnets allow to control both position and angle of the beam;
- Evaluating performance for 2/4 mm bump for different angles

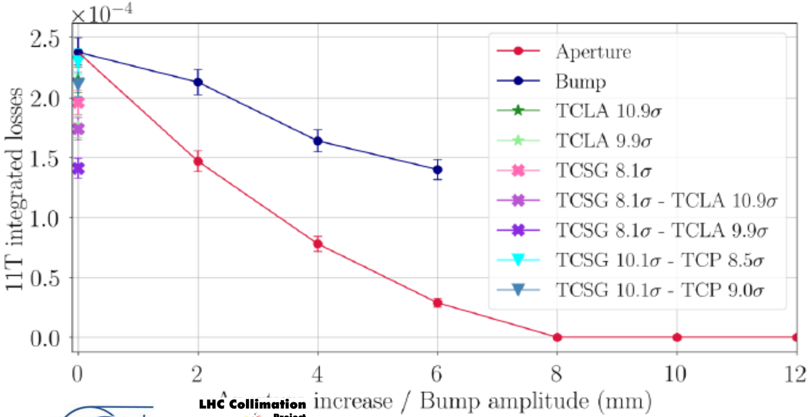


Up to 60% loss reduction

Required kick [μrad]	Angle [μrad]									
Correctors	**50**		**100**		**150**		**200**		**250**	
	2 mm	**4 mm**	**2 mm**	**4 mm**	**2 mm**	**4 mm**	**2 mm**	**4 mm**	**2 mm**	**4 mm**
MCBWH.5R7	7.5	30.15	-7.5	15.1	-22.5	53.9	-37.6	-15	-52.6	-30
MCBCH.7R7	32.3	51	45.9	64.6	59.4	78.1	72.9	91.7	86.5	105.3
MCBCH.9R7	19.9	61	-1.25	39.9	-22.4	18.7	-43.6	-2.5	-64.8	-23.7
MCBH.11R7	24.2	36.7	35.8	48.4	47.4	60	59	71.6	70.6	**83.2**

Varying IR7 Collimator Settings

- To improve cleaning:
  - TCLAs with -1σ and -2σ wrt HL-LHC baseline;
  - TCSGs with -1σ wrt HL-LHC baseline;
  - Mixed;
- To relax impact on impedance:
  - TCPs more opened by 1.8σ, and TCSGs at 1.6σ retraction;
  - TCPs more opened by 2.3σ, and TCSGs at 1.1σ retraction;

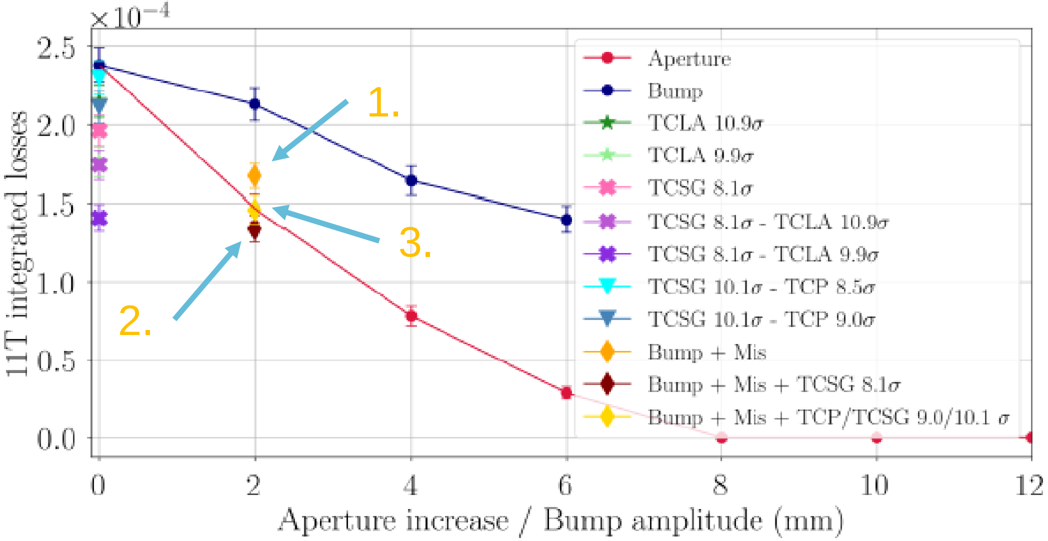


Collimation settings ($\varepsilon = 2.5\mu m$)	σ	Material
Primary (TCP) IR7	6.7	MoGr
Secondary (TCSG) IR7	9.1	MoGr
Absorber (TCLA) IR7	11.9	Inermet
Primary (TCP) IR3	17.7	CFC
Secondary (TCSG) IR3	21.3	CFC
Absorber (TCLA) IR3	23.7	Inermet
Tertiary (TCT) IR1	10.4	Inermet (V), CuCD (H)
Tertiary (TCT) IR5	10.4	Inermet (V), CuCD (H)
Tertiary (TCT) IR2	35.4	Inermet
Tertiary (TCT) IR8	17.7	Inermet
Secondary (TCSP) IR6	10.1	CFC
Dump prot. (TCDQ) IR6	10.1	CFC
TCL 4 IR1/5	14.2	Inermet
TCL 5 IR1/5	14.2	Inermet
TCL 6 IR1/5	14.2	Inermet

Promising results with tighter settings but impact on impedance should be evaluated!

3 Possible Operational Scenarios

1. 2 mm local orbit bump + 1 mm misalignment of 11 T dipole towards the inside of the ring;
2. 2 mm local orbit bump + 1 mm misalignment + IR7 TCSGs at 8.1σ;
3. 2 mm local orbit bump + 1 mm misalignment + IR7 TCPs/TCSGs at 9σ/10.1σ;



Conclusions

- Installed in cell 9, TCLD provides a good global and local cleaning inefficiency but with a higher power density in the upstream 11 T dipole (~50 mW/cm^3 predicted for protons, t=0.2 h);
- Standard SixTrack simulations performed to find possible ways to decrease power load on upstream 11 T dipole:
  - 3 correctors local orbit bump
    - 40% loss reduction in the case of 6 mm bump, but MCB current out of strength and max orbit shift not negligible compared to aperture;
  - 3 correctors local orbit bump + trim PCs of 11 T dipole
    - Max orbit reduced and current within the budget for 6 mm bump;
  - 4 correctors local orbit bump
    - 60% loss reduction in the case of 2 mm bump and 250 mrad angle
  - Collimator settings:
    - 1s reduction for TCSG and 2s reduction for TCLAs allows reducing losses by 40% - solution viable only if margins for impedance are demonstrated;
  - Three possible operational scenarios seem promising with loss reduction by 40%
    - Energy deposition studies on-going (see next presentation)

HiLumi
HL-LHC PROJECT

Thanks a lot!

References

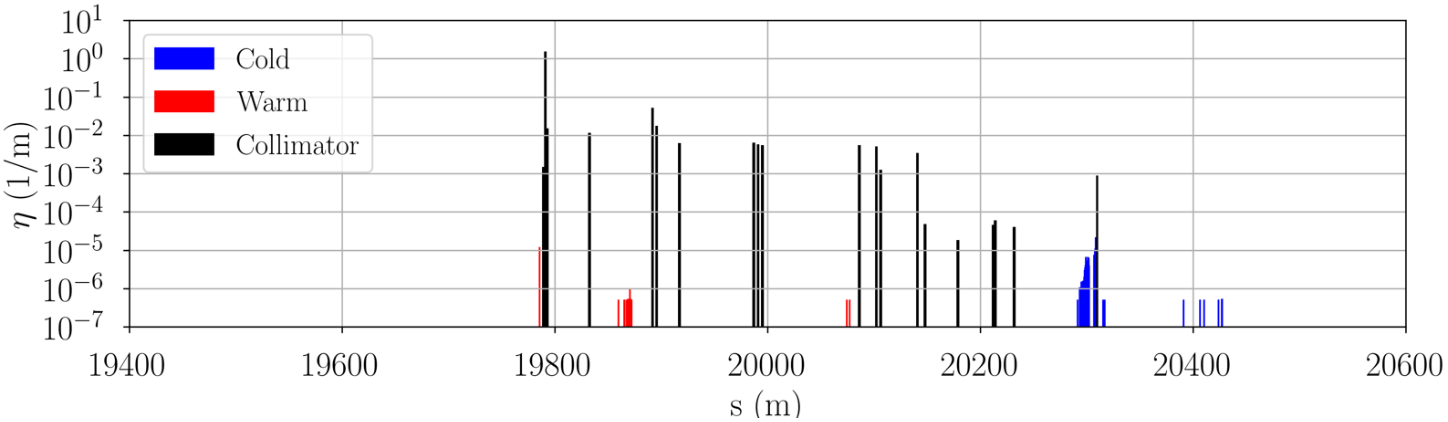
[1] D.Mirarchi, "Optimisation of TCLD position for HL-LHC", ColUSM #94, 29 Sep 2017.

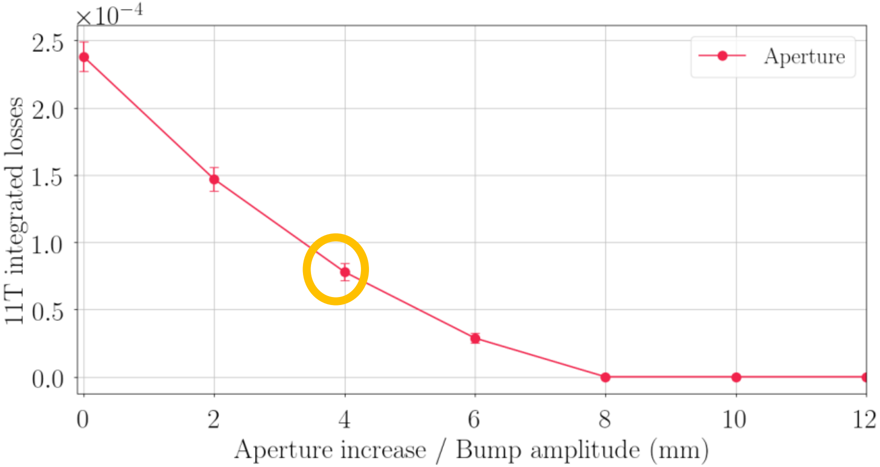
[2] C. Bahamonde Castro, "Energy deposition from collimation losses in the DS region at P7", 8th HL-LHC Collaboration Meeting, 17 Oct 2018.

[3] L. Bottura, "Quench performance and assumptions: magnets and cryogenics", International Review of the HL- LHC Collimation System, 11 Feb 2019.

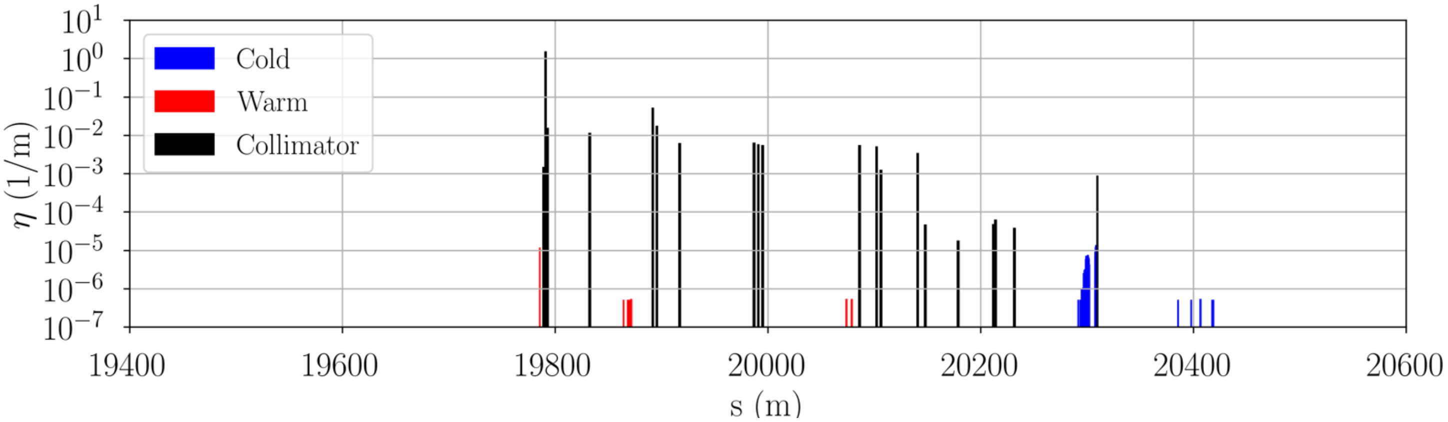
CERN

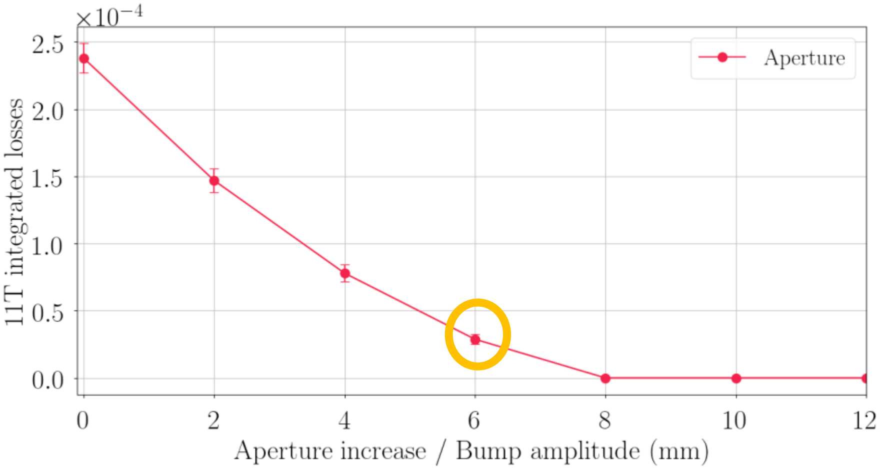
Aperture Scan – 4 mm Aperture Increase



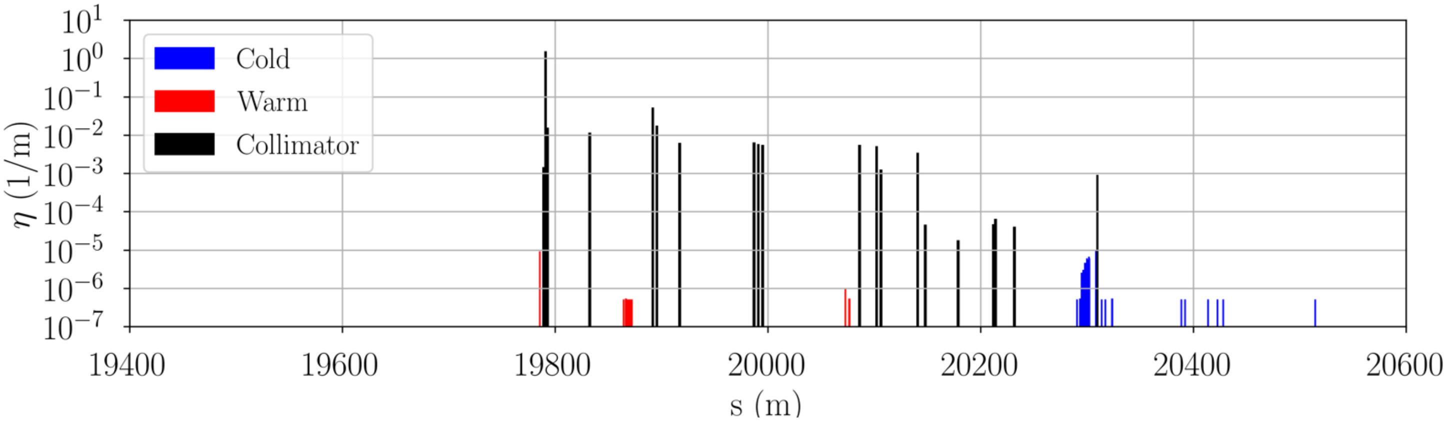


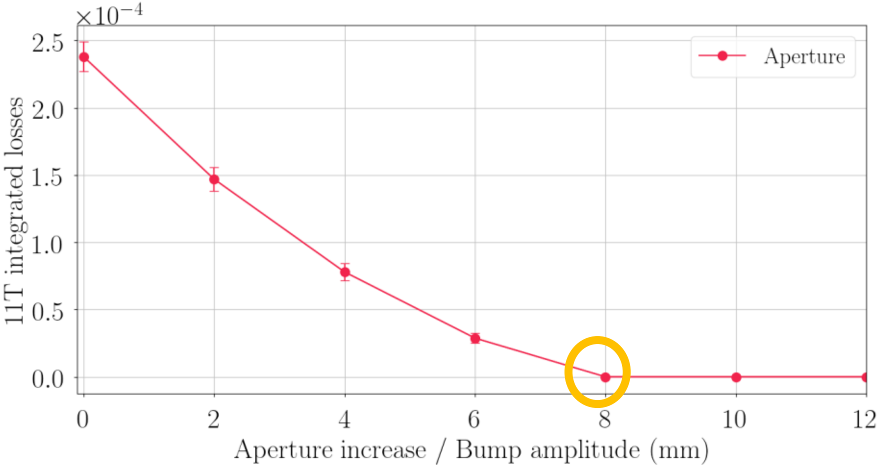
Aperture Scan – 6 mm Aperture Increase



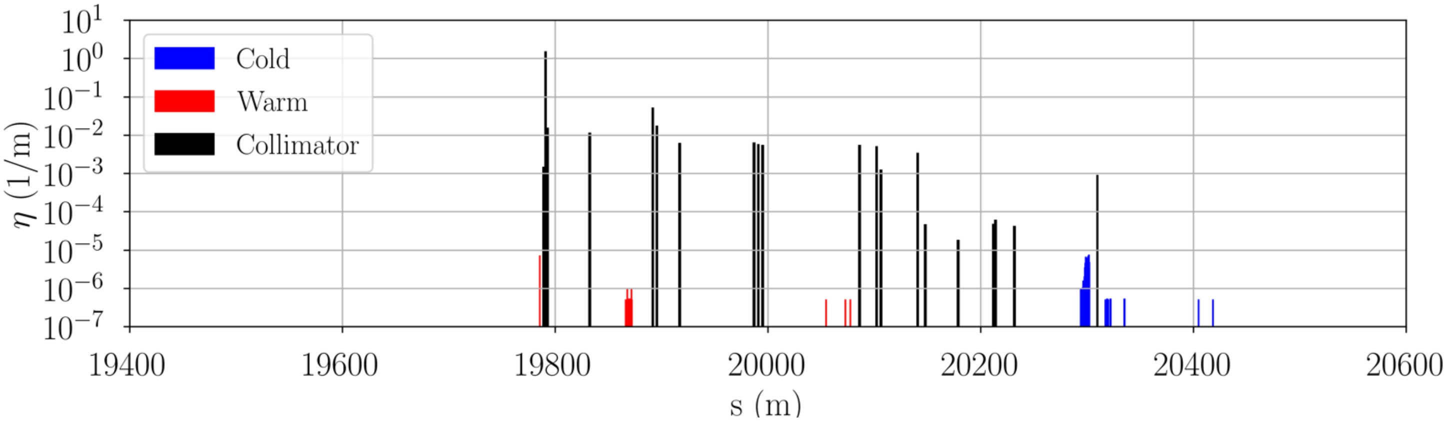


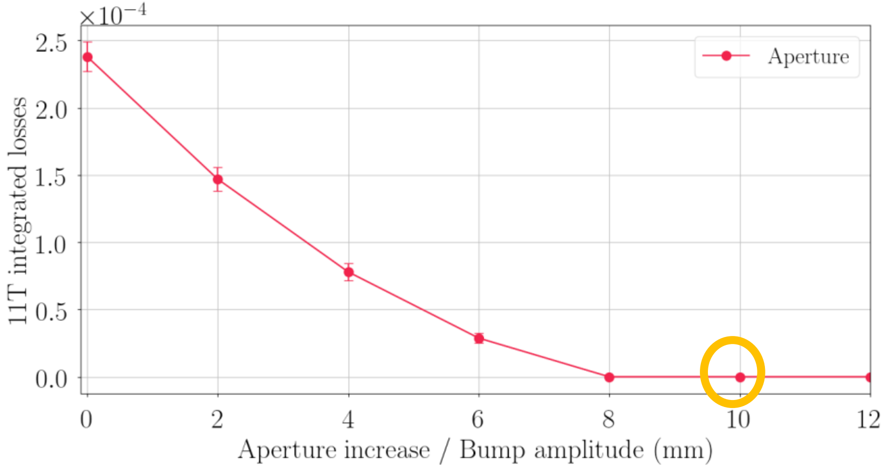
Aperture Scan – 8 mm Aperture Increase



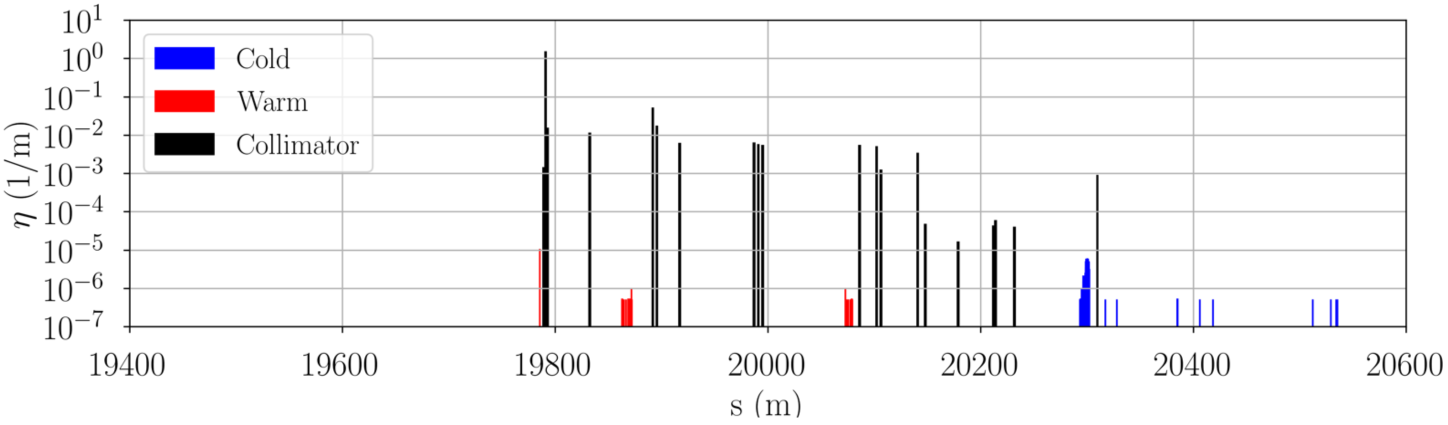


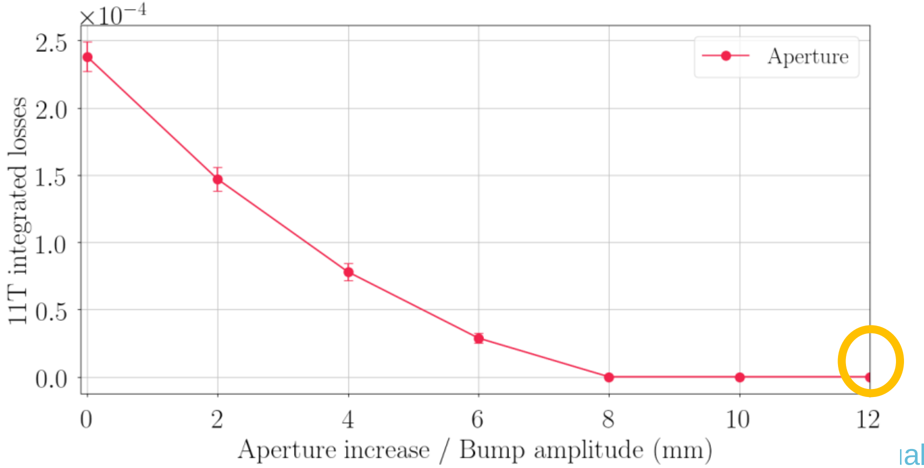
Aperture Scan – 10 mm Aperture Increase





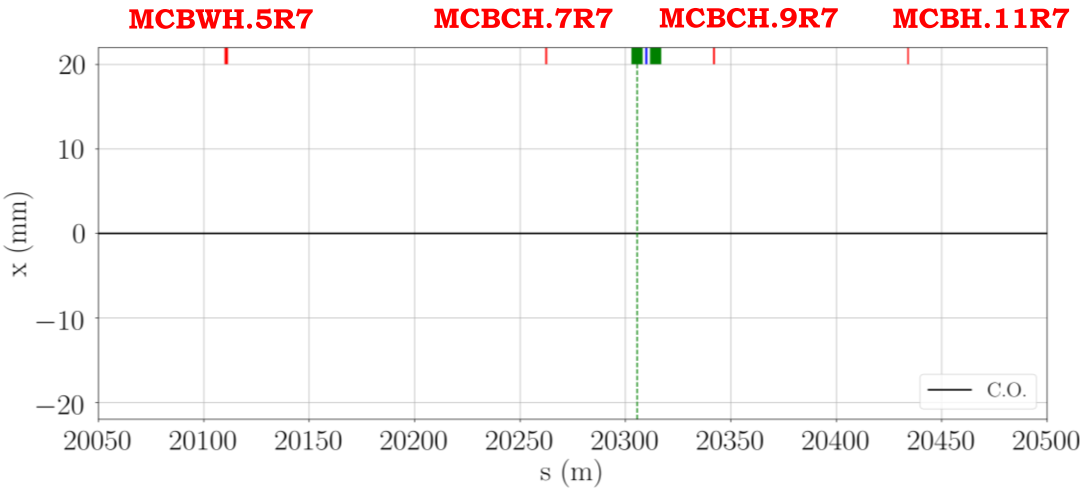
Aperture Scan – 12 mm Aperture Increase





Local Orbit Bump at 11 T Magnet

- At least 3 correctors required to control the bump position and close it;
- 4-magnets local bump to control both position and angle;



Magnet type	$B[T]$	$L_{mag}[m]$	$I_{max}[A]$
MCBCH @1.9K	3.11	0.904	100
MCBH @1.9K	2.93	0.647	55
MCBWH	1.1	1.7	500

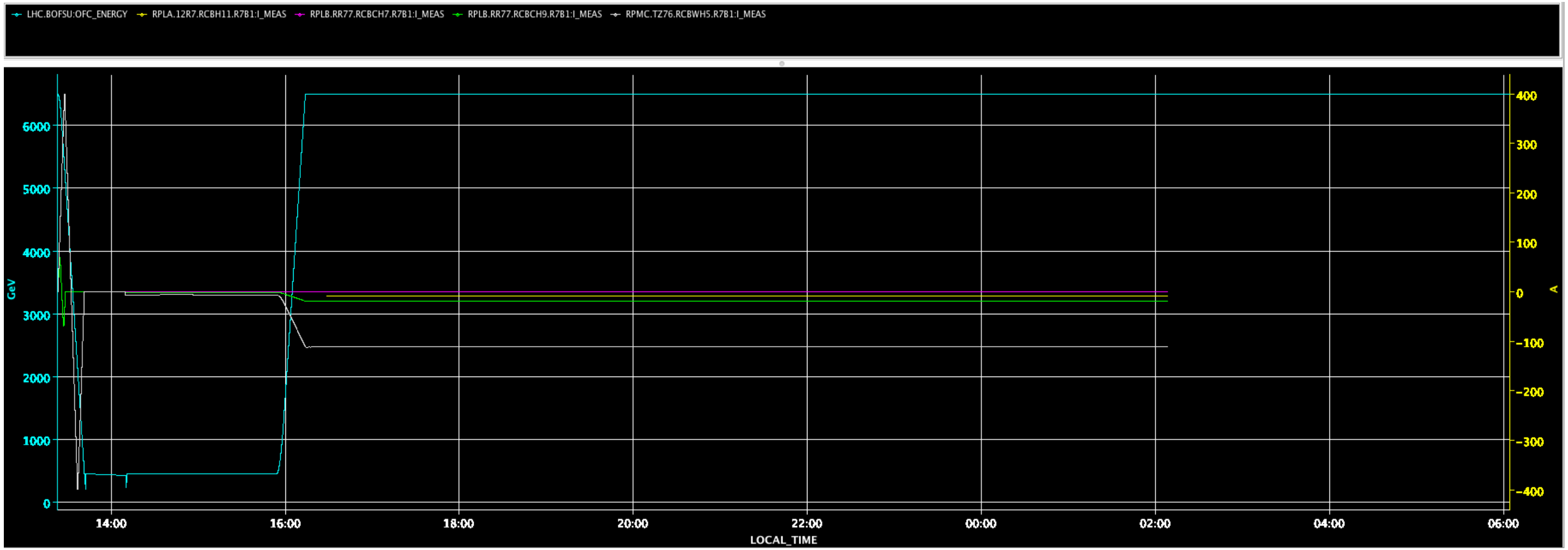
$I = I_{max}$ →

θ_{max} [μrad] @ 7 TeV
132.54
89.37
80.14

$$\theta[rad] = 0.3 \frac{L_{mag}[m] \cdot B[T]}{p[GeV/c]} \frac{I\,[A]}{I_{max}[A]}$$

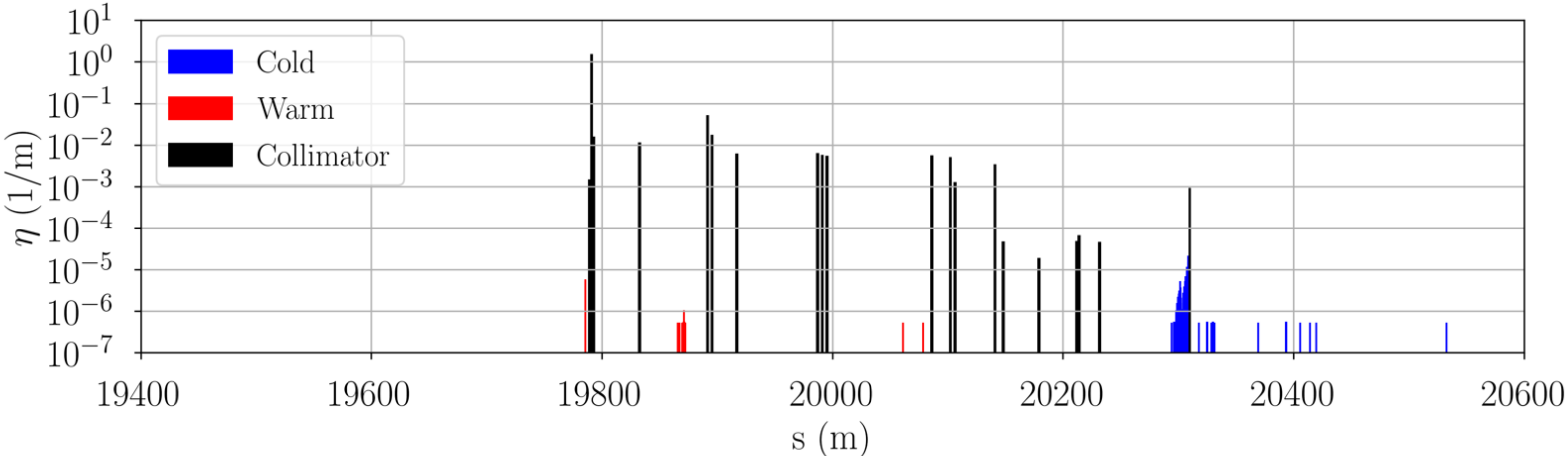
HiLumi HL-LHC PROJECT · CERN · LHC Collimation Project CERN

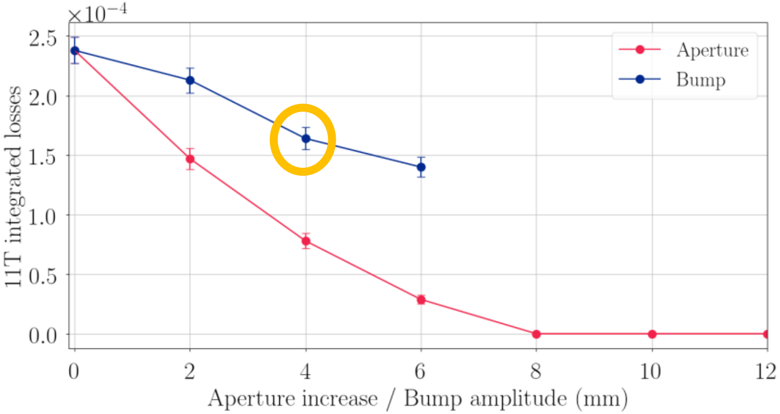
Local Orbit Bump: Correctors Budget



Magnet type	$I[A]$	θ [μrad] @ 7 TeV	θ_{av} [μrad]
MCBWH.5R7	-111.35	-17.8	≈62
MCBCH.7R7	0.5	0.6	≈132
MCBCH.9R7	-18.88	-22.7	≈109
MCBH.11R7	-8.88	-13.1	≈76

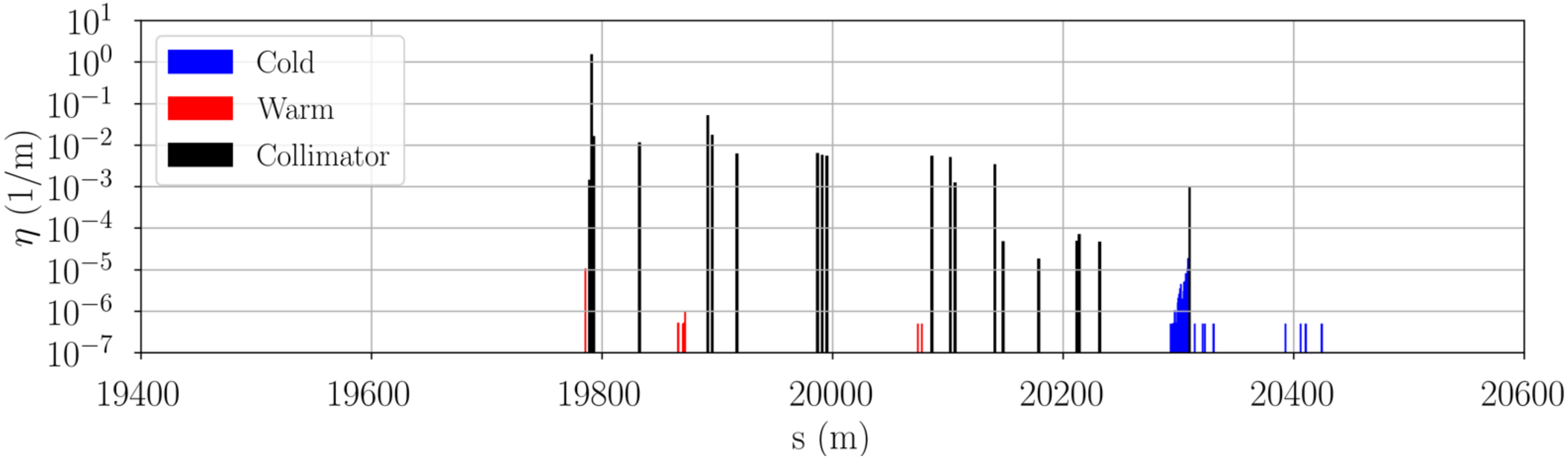
3 Magnets Local Bump – 4 mm Orbit Bump

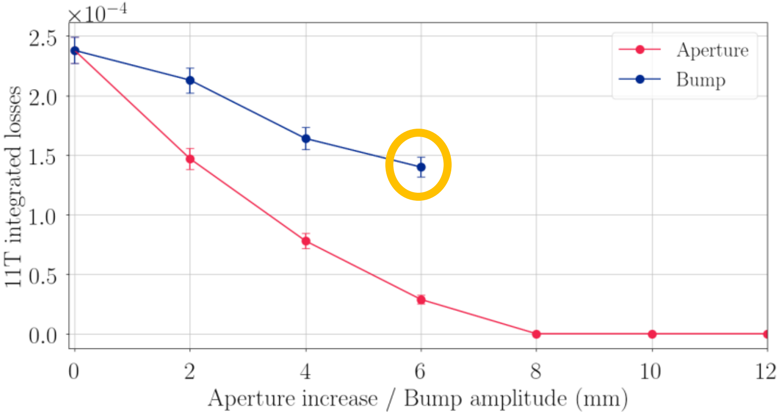




30% losses reduction

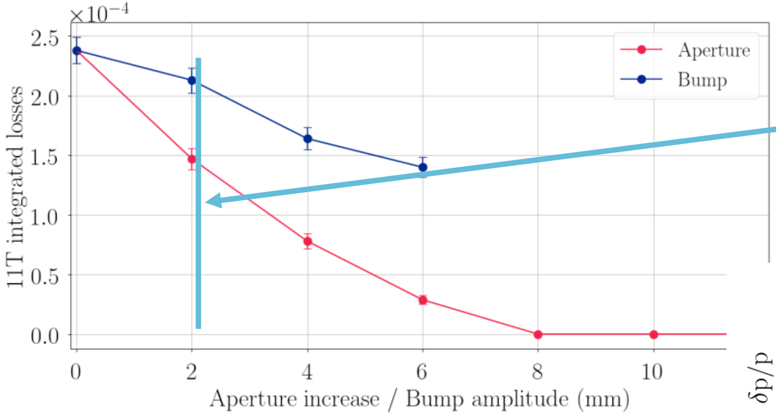
3 Magnets Local Bump – 6 mm Orbit Bump



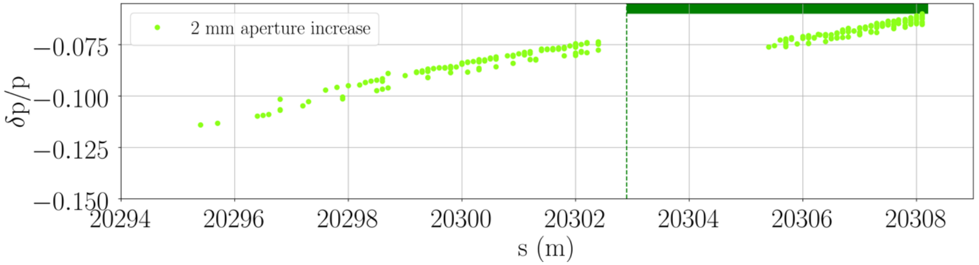


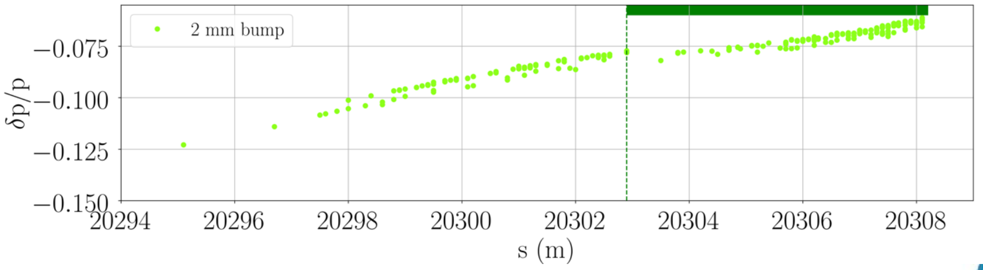
40% losses reduction

Aperture Increase vs Orbit Bump (2 mm)



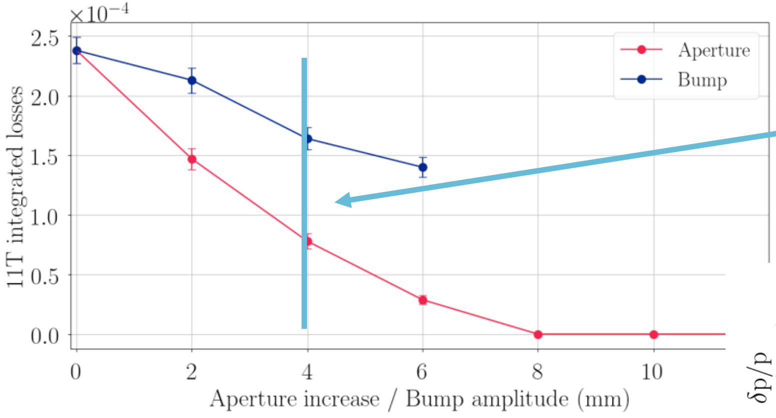
Higher losses with orbit bump than with the corresponding aperture increase



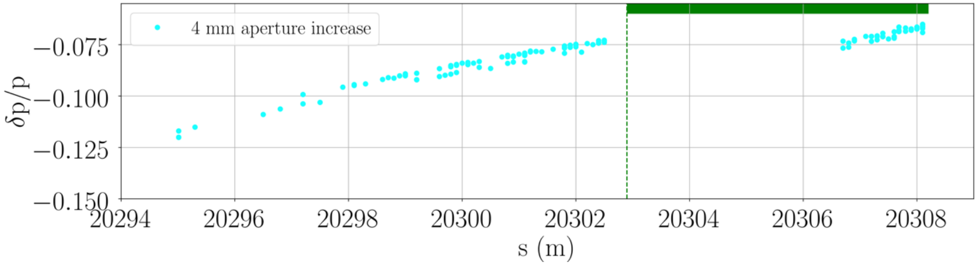


The bump longitudinally shifts particles that would have been lost upstream

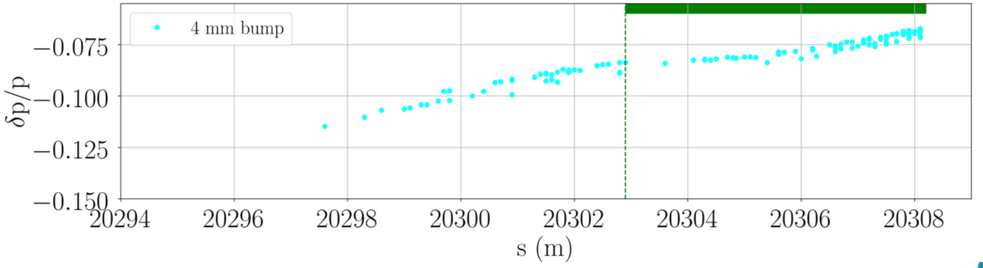
Aperture Increase vs Orbit Bump (4 mm)



Higher losses with orbit bump than with the corresponding aperture increase

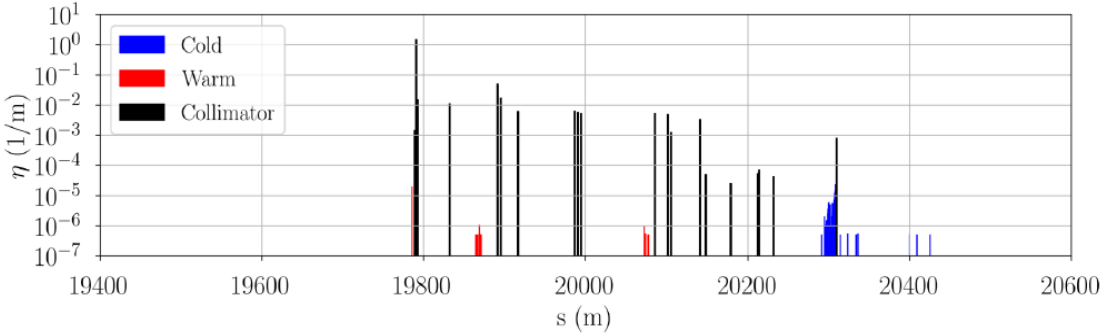


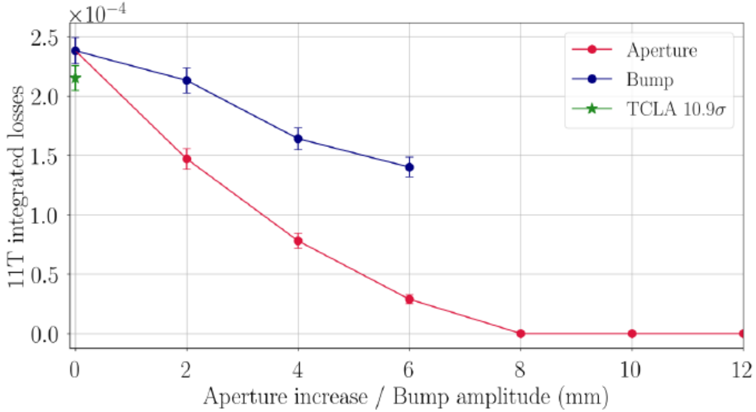
The bump longitudinally shifts particles that would have been lost upstream



Tighter TCLA Settings – -1σ

	σ
Primary (TCP) IR7	6.7
Secondary (TCSG) IR7	9.1
Absorber (TCLA) IR7	10.9
Primary (TCP) IR3	17.7
Secondary (TCSG) IR3	21.3
Absorber (TCLA) IR3	23.7
Tertiary (TCT) IR1	10.4
Tertiary (TCT) IR5	10.4
Tertiary (TCT) IR2	35.4
Tertiary (TCT) IR8	17.7
Secondary (TCSP) IR6	10.1
Dump prot. (TCDQ) IR6	10.1
TCL 4 IR1/5	14.2
TCL 5 IR1/5	14.2
TCL 6 IR1/5	14.2

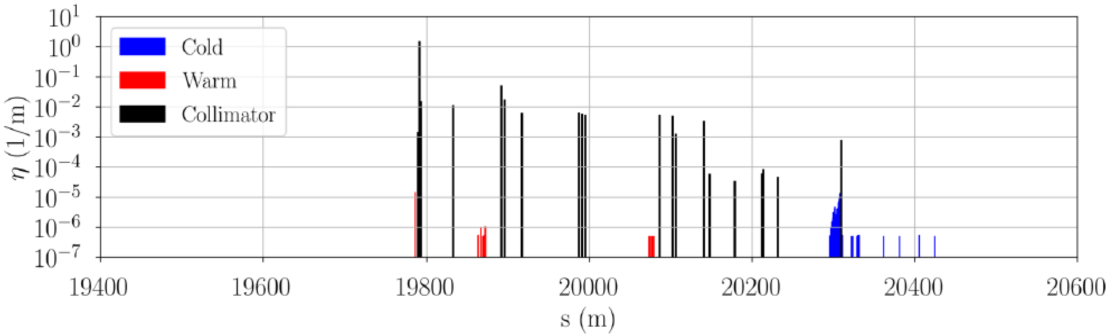


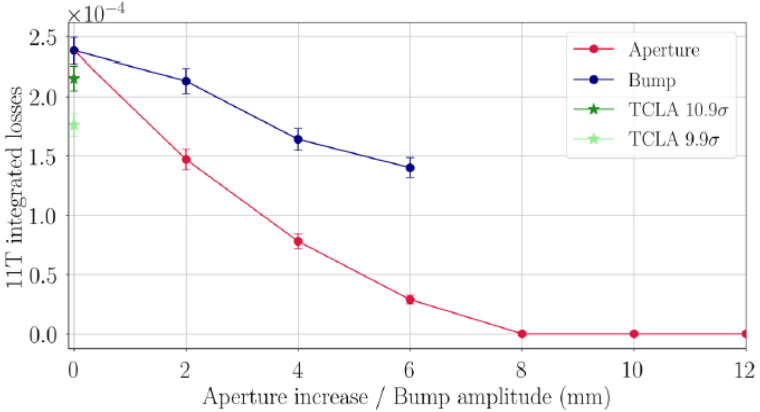


10% losses reduction

Tighter TCLA Settings – -2σ

	σ
Primary (TCP) IR7	6.7
Secondary (TCSG) IR7	9.1
Absorber (TCLA) IR7	9.9
Primary (TCP) IR3	17.7
Secondary (TCSG) IR3	21.3
Absorber (TCLA) IR3	23.7
Tertiary (TCT) IR1	10.4
Tertiary (TCT) IR5	10.4
Tertiary (TCT) IR2	35.4
Tertiary (TCT) IR8	17.7
Secondary (TCSP) IR6	10.1
Dump prot. (TCDQ) IR6	10.1
TCL 4 IR1/5	14.2
TCL 5 IR1/5	14.2
TCL 6 IR1/5	14.2

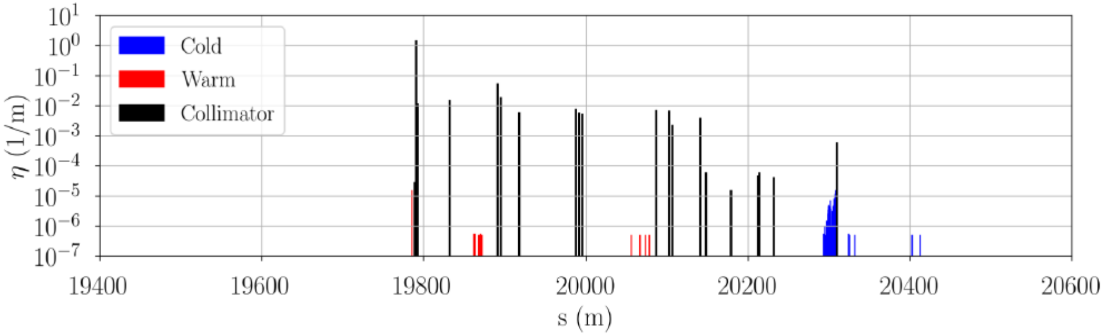


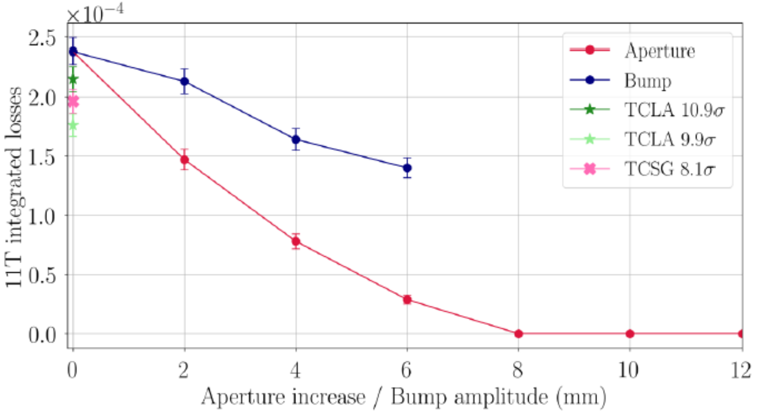


26% losses reduction

Tighter TCSG Settings – -1σ

	σ
Primary (TCP) IR7	6.7
Secondary (TCSG) IR7	**8.1**
Absorber (TCLA) IR7	11.9
Primary (TCP) IR3	17.7
Secondary (TCSG) IR3	21.3
Absorber (TCLA) IR3	23.7
Tertiary (TCT) IR1	10.4
Tertiary (TCT) IR5	10.4
Tertiary (TCT) IR2	35.4
Tertiary (TCT) IR8	17.7
Secondary (TCSP) IR6	10.1
Dump prot. (TCDQ) IR6	10.1
TCL 4 IR1/5	14.2
TCL 5 IR1/5	14.2
TCL 6 IR1/5	14.2

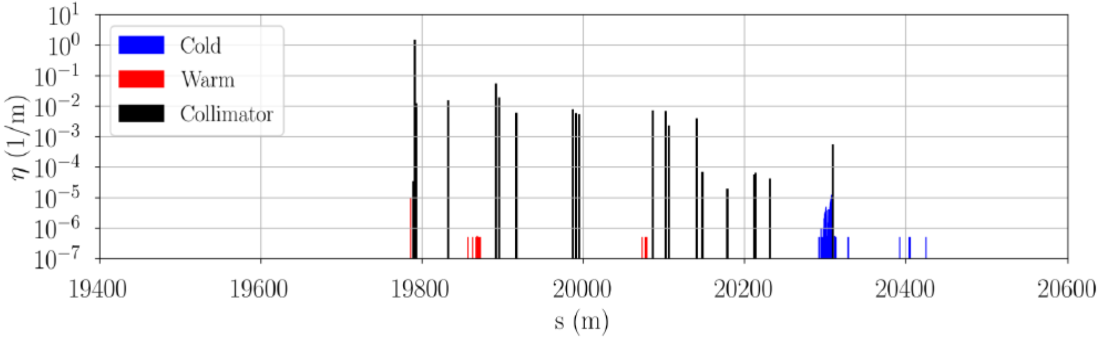


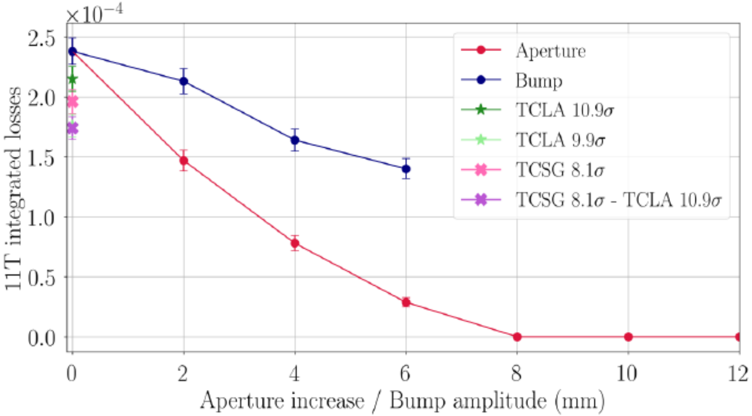


20% losses reduction

Tighter TCSG and TCLA Settings – -1σ

	σ
Primary (TCP) IR7	6.7
Secondary (TCSG) IR7	**8.1**
Absorber (TCLA) IR7	**10.9**
Primary (TCP) IR3	17.7
Secondary (TCSG) IR3	21.3
Absorber (TCLA) IR3	23.7
Tertiary (TCT) IR1	10.4
Tertiary (TCT) IR5	10.4
Tertiary (TCT) IR2	35.4
Tertiary (TCT) IR8	17.7
Secondary (TCSP) IR6	10.1
Dump prot. (TCDQ) IR6	10.1
TCL 4 IR1/5	14.2
TCL 5 IR1/5	14.2
TCL 6 IR1/5	14.2

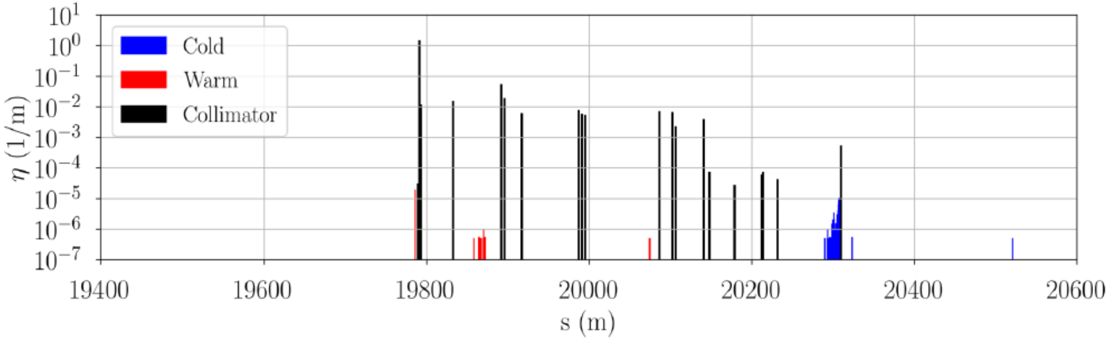


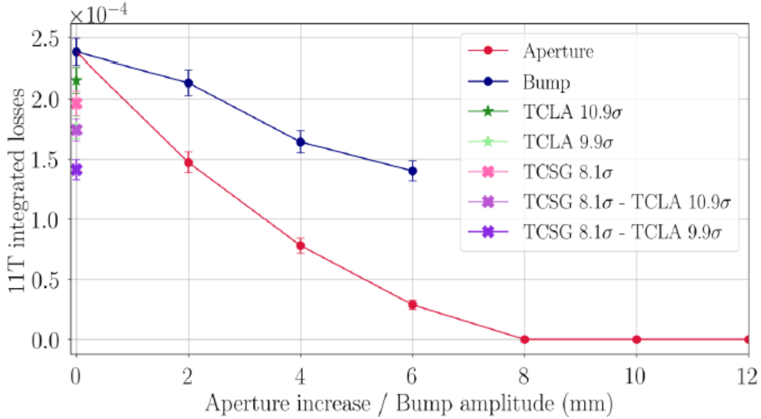


27% losses reduction

Tighter TCSG (-1σ) and TCLA (-2σ) Settings

	σ
Primary (TCP) IR7	6.7
Secondary (TCSG) IR7	**8.1**
Absorber (TCLA) IR7	**9.9**
Primary (TCP) IR3	17.7
Secondary (TCSG) IR3	21.3
Absorber (TCLA) IR3	23.7
Tertiary (TCT) IR1	10.4
Tertiary (TCT) IR5	10.4
Tertiary (TCT) IR2	35.4
Tertiary (TCT) IR8	17.7
Secondary (TCSP) IR6	10.1
Dump prot. (TCDQ) IR6	10.1
TCL 4 IR1/5	14.2
TCL 5 IR1/5	14.2
TCL 6 IR1/5	14.2

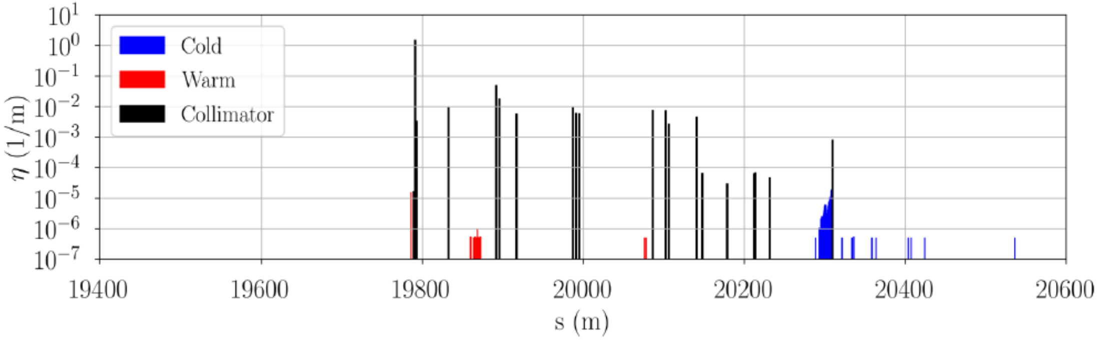


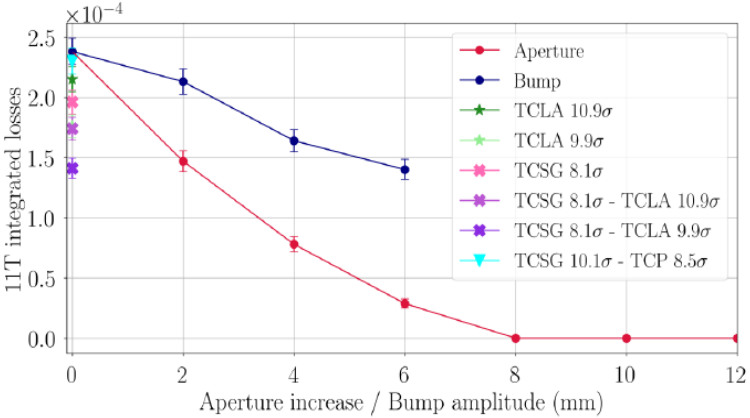


40% losses reduction

More Relaxed TCP/TCSG Settings – 1.6σ Retraction

	σ
Primary (TCP) IR7	8.5
Secondary (TCSG) IR7	10.1
Absorber (TCLA) IR7	11.9
Primary (TCP) IR3	17.7
Secondary (TCSG) IR3	21.3
Absorber (TCLA) IR3	23.7
Tertiary (TCT) IR1	10.4
Tertiary (TCT) IR5	10.4
Tertiary (TCT) IR2	35.4
Tertiary (TCT) IR8	17.7
Secondary (TCSP) IR6	10.1
Dump prot. (TCDQ) IR6	10.1
TCL 4 IR1/5	14.2
TCL 5 IR1/5	14.2
TCL 6 IR1/5	14.2

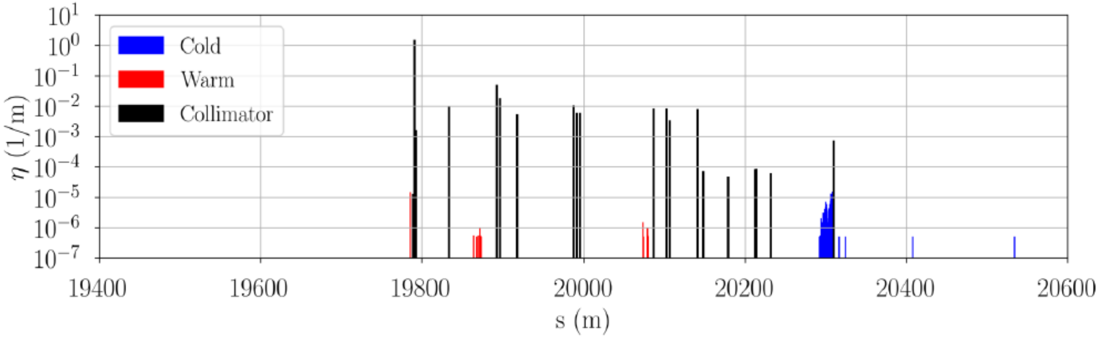


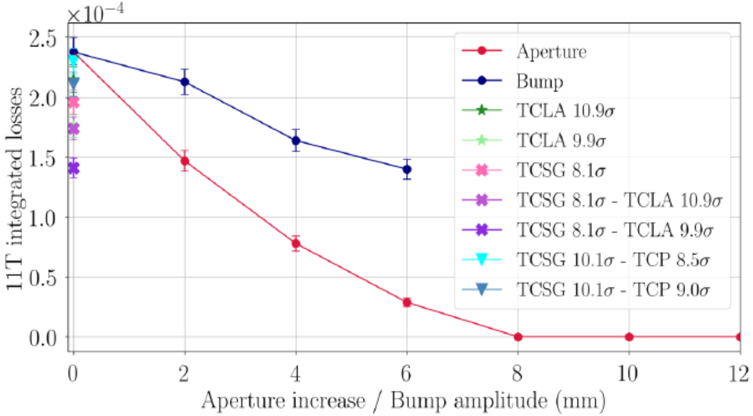


3% losses reduction (within error bars)

More Relaxed TCP/TCSG Settings – 1.1σ Retraction

	σ
Primary (TCP) IR7	9.0
Secondary (TCSG) IR7	10.1
Absorber (TCLA) IR7	11.9
Primary (TCP) IR3	17.7
Secondary (TCSG) IR3	21.3
Absorber (TCLA) IR3	23.7
Tertiary (TCT) IR1	10.4
Tertiary (TCT) IR5	10.4
Tertiary (TCT) IR2	35.4
Tertiary (TCT) IR8	17.7
Secondary (TCSP) IR6	10.1
Dump prot. (TCDQ) IR6	10.1
TCL 4 IR1/5	14.2
TCL 5 IR1/5	14.2
TCL 6 IR1/5	14.2



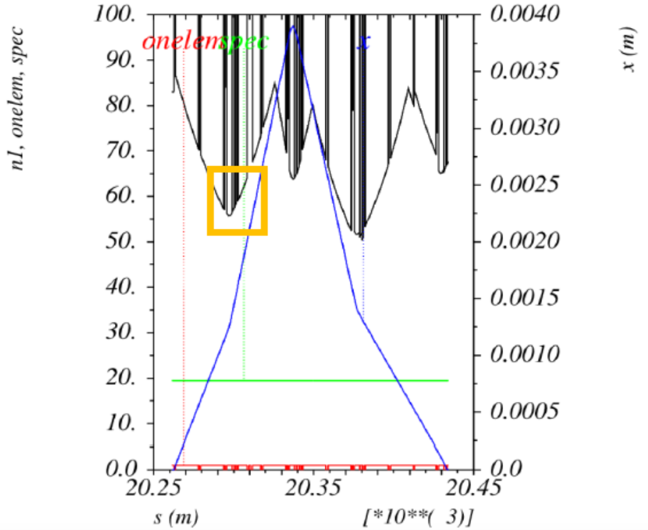


11% losses reduction

Aperture Check for 1st Option

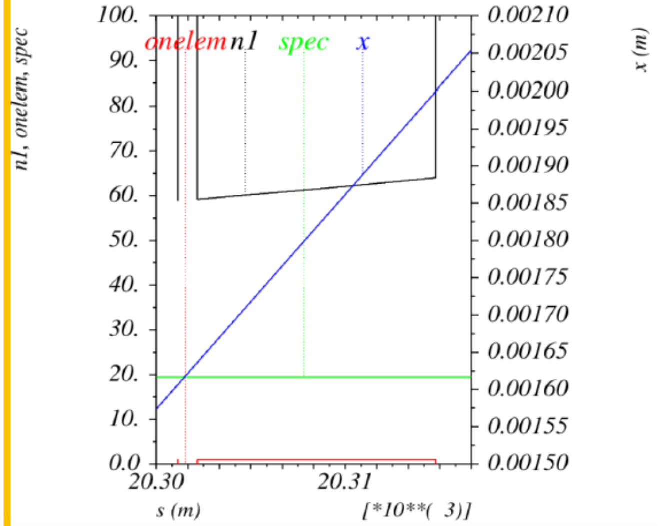
MAD-X n1 method for computing the available aperture in units of RMS beam size

Halo parameters	(6,6,6,6)
Momentum offset	$2 \cdot 10^{-4}$
Fractional beam size change from β-beating	1.1
Radial closed orbit excursion	2 mm
Relative parasitic dispersion	0.1



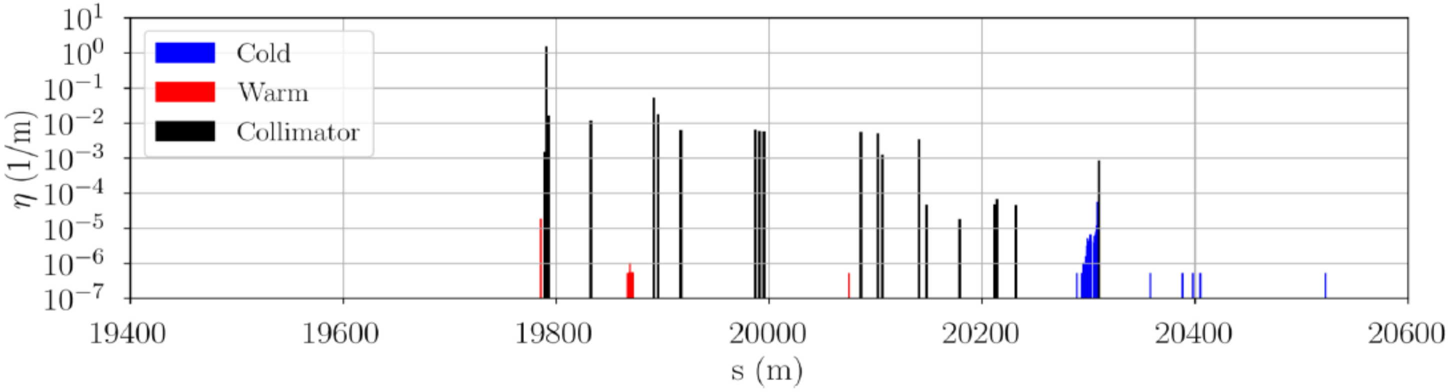
In the center of the 11T dipole

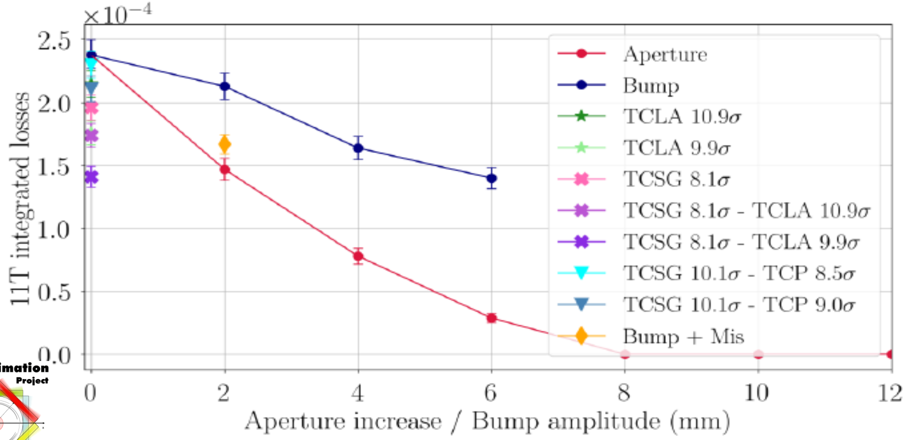
- $\beta \approx 23.9$ m → $\sigma \approx 89.4 \mu m$
- 3.6 mm (shift + misalignment) ≈ 40 σ



1st Possible Operational Scenario

2 mm bump + 1 mm misalignment of 11 T dipole towards the inside of the ring.

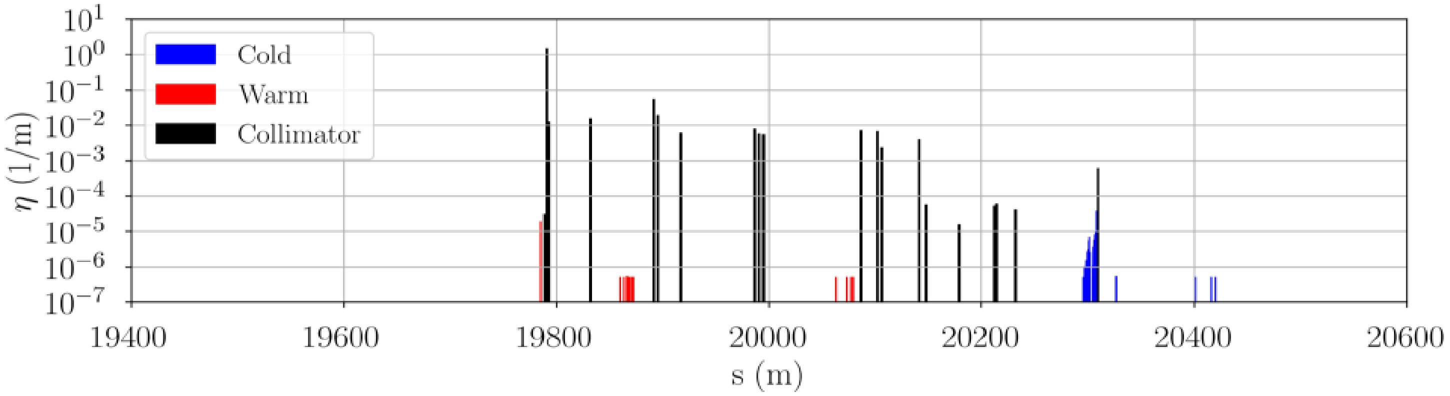


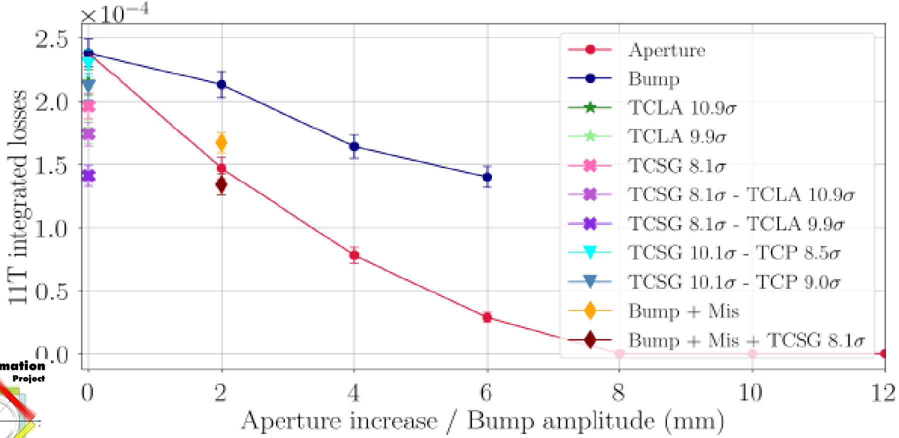


30% losses reduction

2nd Possible Operational Scenario

2 mm bump + 1 mm misalignment + TCSGs at 8.1σ

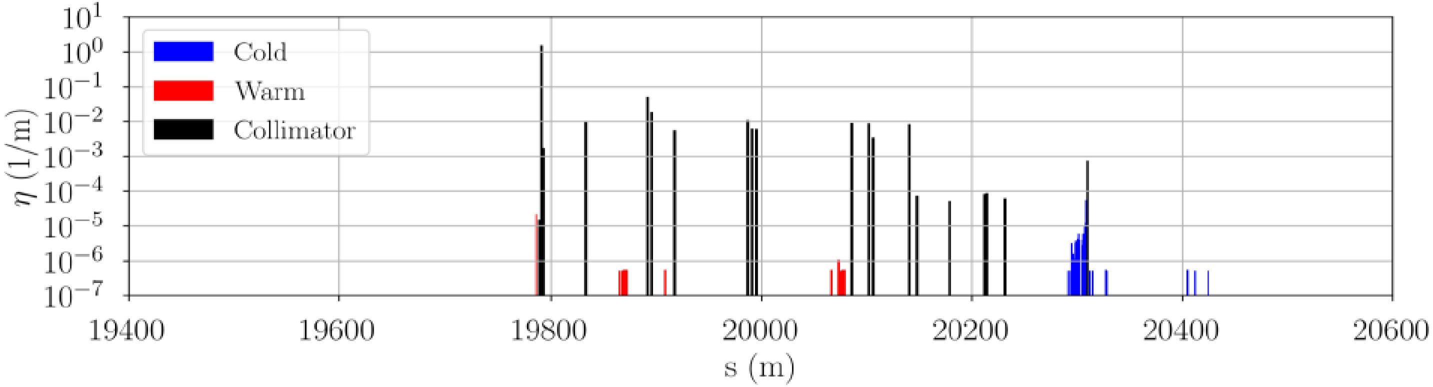


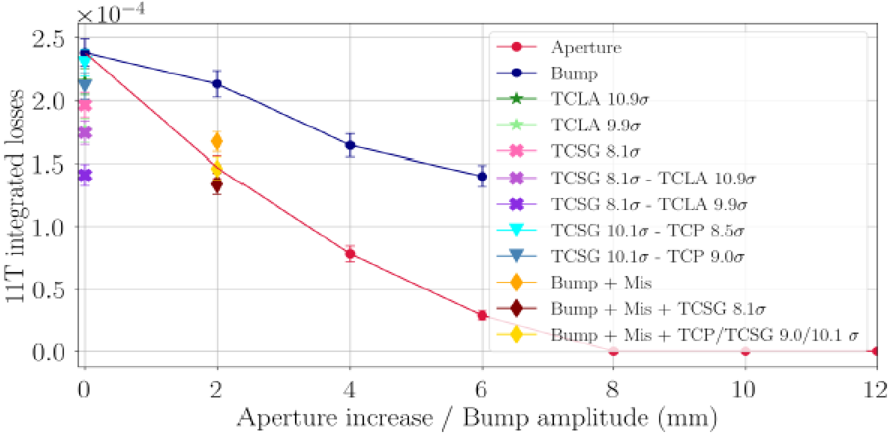


45% losses reduction

3rd Possible Operational Scenario

2 mm bump + 1 mm misalignment + TCPs/TCSGs at 9σ/10.1σ





40% losses reduction