Collimation

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Acknowledgements to
Stefano Redaelli, the collimation team, the injection team, the dump team, the machine protection team, the BLM team, …

LHCCWG, May 3rd, 2006

Reference Material for Collimation

Reference material: **LHC design report (chapter 18).**
Chamonix and conference papers!

Recent talks at Chamonix and the LTC.

Outline of the LTC talk:

- Introduction
- Commissioning sequence and pre-requisites
- Beam-based calibration of collimators
- Deterministic set-up of collimators
- Interdependencies
- Empirical tuning and risks
- Recommendations for operational usage
- Conclusion

For the Commissioning WG

- Short introduction to definitions, baseline assumptions, collimation rules, …
- Encourage everybody to look at Chamonix papers and recent talks.
- Fill in Mike’s table…

Mike's Table

	Energy [GeV]	Bunches	Bunch Intensity	Total Intensity	Collimat ors	TCDQ	TDI	BLMs
pilot	450	1	5 e9	5 e9	All out	Out	Out	Passive
	7000							
super pilot	450	1	3 e10	3 e10				
	7000						-	
intermediate	450	12	3 e10	3.6 e11				
	7000						-	
43x43 initial	450	43	1 e10	4.3 e11				
	7000						-	
43x43	450	43	3 e10	1.2 e12				
	7000						-	

Complex System

- System is necessarily complex to provide the required excellent performance (2-3 orders of magnitude beyond TEVATRON).
- System now addresses for the first time all known issues.
- It is the only distributed LHC accelerator system that is staged: different phases, different installation campaigns, start-up with missing components, …
- We fully appreciate that it is difficult to understand and follow all the system aspects (also sometimes for us).

Phase	N_{coll}	Performance reach
1 (TL)	14	Ultimate intensity
1 (ring)	88	$\leqslant$ 40% nominal intensity
2 (ring)	30	$>$ 40% nominal intensity
3 (ring)	4	$>$ 50% nominal luminosity
4 (ring)	16	Reserve for ultimate efficiency

How to Read Acronyms

- **TC**… = **T**arget **C**ollimator
  - TCP = Primary collimator
  - TCSG = Secondary collimator Graphite
  - TCSM = Secondary collimator Metal
  - TCHS = Halo Scraper
- **TCL**… = **T**arget **C**ollimator **L**ong
  - TCLI = Injection protection (types A and B)
  - TCLP = Physics debris
  - TCLA = Absorber
- **TCD**… = **T**arget **C**ollimator **D**ump
  - TCDQ = Q4
  - TCDS = Septum
  - TCDI = Injection transfer lines
- **TD**… = **T**arget **D**ump
  - TDI = Injection

Scope of Collimation Commissioning

- Commissioning of the collimation system cannot be considered in an isolated way:
  - 200 database locations in the LHC and the transfer lines for collimators, absorbers, masks that are used for collimation, injection protection and dump protection.
  - 93% of them are in the collimation project but have important interplay with other devices.
  - **Here consider commissioning and set-up of all movable elements around the LHC! Many discussions on this over the last years and coherent concepts have been worked out.**
  - Work is a **collaborative effort between collimation project, injection project, dump project and BLM team: also later in the control room!**
- In the following consider all movable elements in the LHC as "collimators".

Commissioning Sequence and Prerequisites

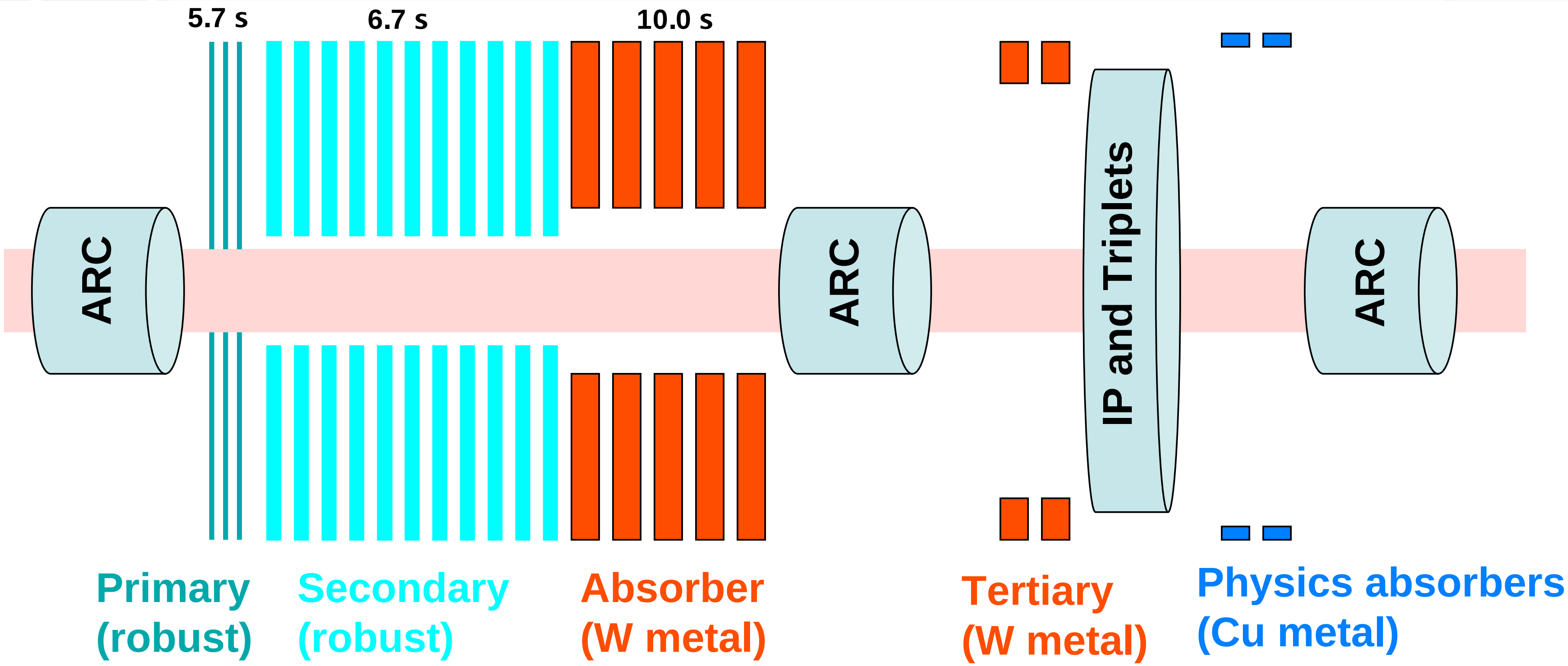
- Pre-requisites before setting up collimators:
  - Hardware commissioning of **collimators** completed.
  - Operational **interlock system**.
  - Working **injection systems**.
  - Working **beam dump systems**.
  - Defined and reasonably stable **orbit**.
  - Defined and reasonably stable **beta functions**.
  - Working **BLM's at all collimators** and a few critical loss locations.

(orbit and beta functions: **SC aperture**)

Commissioning Sequence Injection

1. Set-up of injection (injection project).
2. Set-up of injection protection (injection and collimation project).
3. **Declare injection safe ➔ reference values** (injection project).
4. Set-up of beam dump (dump project).
5. Set-up of dump protection (dump and collimation project).
6. **Declare beam dump safe ➔ reference values** (dump project).
7. Beam-based calibration of all ring collimators (collimation project).
8. Deterministic set-up of ring collimation (collimation project).
9. If necessary iterate over steps 1-8.
10. **Declare ring safe ➔ reference values.**
11. **Beam verification of protection and cleaning.**

Collimation at Injection



Relevant aperture limit is the arc!

Protected by 3 stages of cleaning and absorption!

First and second aperture limits by robust collimators!

Then metallic collimators with good absorption but very sensitive!

Nominal Set-Up Injection (in s_b ,d=0)

3	a_{abs}	=	~ 10.0 s	Cleaning: Active absorbers in IR3 and IR7
3	a_{sec3}	=	9.3 s	d cleaning: secondary collimators IR3 (H)
3	a_{prim3}	=	8.0 s	d cleaning: primary collimators IR3 (H)
0	**a_{ring}**	**=**	**7.5 s**	**Ring cold aperture**
2	a_{prot}	≥	7.0 s	Dump (H) protection IR6 (TCDQ + TCS)
1	a_{prot}	=	6.8 s	Injection (V) protection IR2/IR8 (TDI, TCLI)
3	a_{sec}	=	6.7 s	b cleaning: secondary collimators IR7
3	a_{prim}	=	5.7 s	b cleaning: primary collimators IR7
1	a_{TL}	=	4.5 s	Transfer line collimators (ring protection at 6.9 s)

➔ Tight settings below "canonical" 6/7 s collimation settings!

Color code:
Green – robust
Blue – cold aperture
Red – non-robust

Influence of Imperfections

- The **required collimator settings** strongly depend on the **available cold aperture** and the **worst case beam lifetime** which must be survived without quench.
- The **available cold aperture** depends on the **orbit** and **beta beat** achieved during each stage of commissioning.
- **Orbit and beta beat** must be specified for **static** and **dynamic** contributions.
- Proposal: additional columns in the commissioning table to define the commissioning scenario for collimation.

Updated Table

	Energy [GeV]	Bunches	Bunch Intensity	Total Intensity	t min [h]	Max orbit (stat)[mm]	Max orbit (dyn) [mm]	Max db/b (stat) [%]	Max db/b (dyn) [%]	Aperture [s]	Collimators	TCDQ	TDI
pilot	450	1	5 e9	5 e9	?	?	?	?	?	?	All out	Out	Out
	7000												
super pilot	450	1	3 e10	3 e10	?	?	?	?	?	?			
	7000												-
intermediate	450	12	3 e10	3.6 e11	?	?	?	?	?	?			
	7000												-
43x43 initial	450	43	1 e10	4.3 e11	?	?	?	?	?	?			
	7000												-
43x43	450	43	3 e10	1.2 e12	?	?	?	?	?	?			
	7000												-

Detailed Commissioning Scenario

- A detailed commissioning scenario **depends on the additional parameters** listed in the previous table.
- This is **input required for detailed studies of collimation and machine protection**. We should not see this as output!
- Will be the **same in reality**: we will try to move collimators in until the beam operation is safe and number of quenches are minimized.
- Cannot move too far (typical limit is 4-5 s):
  - Start of beam scraping.
  - Strong sensitivity (losses, lifetime, …) to small beam changes.
- Once detailed scenarios have been agreed on:
  - Specify number of required collimators
  - Specify required settings
  - Specify tolerances
- **For the moment assume nominal parameters: 7.5 s aperture and 0.1 h beam lifetime!**

Running Without Cleaning at Injection

Expected quench limit for continuous losses:

450 GeV ➔ ~ **7.0×10^8 p/m/s**

Assume:

- Losses are fully deposited over 2 m of SC magnet (pessimistic).
- Minimum beam lifetime is 0.1 h.

Beam loss rate:

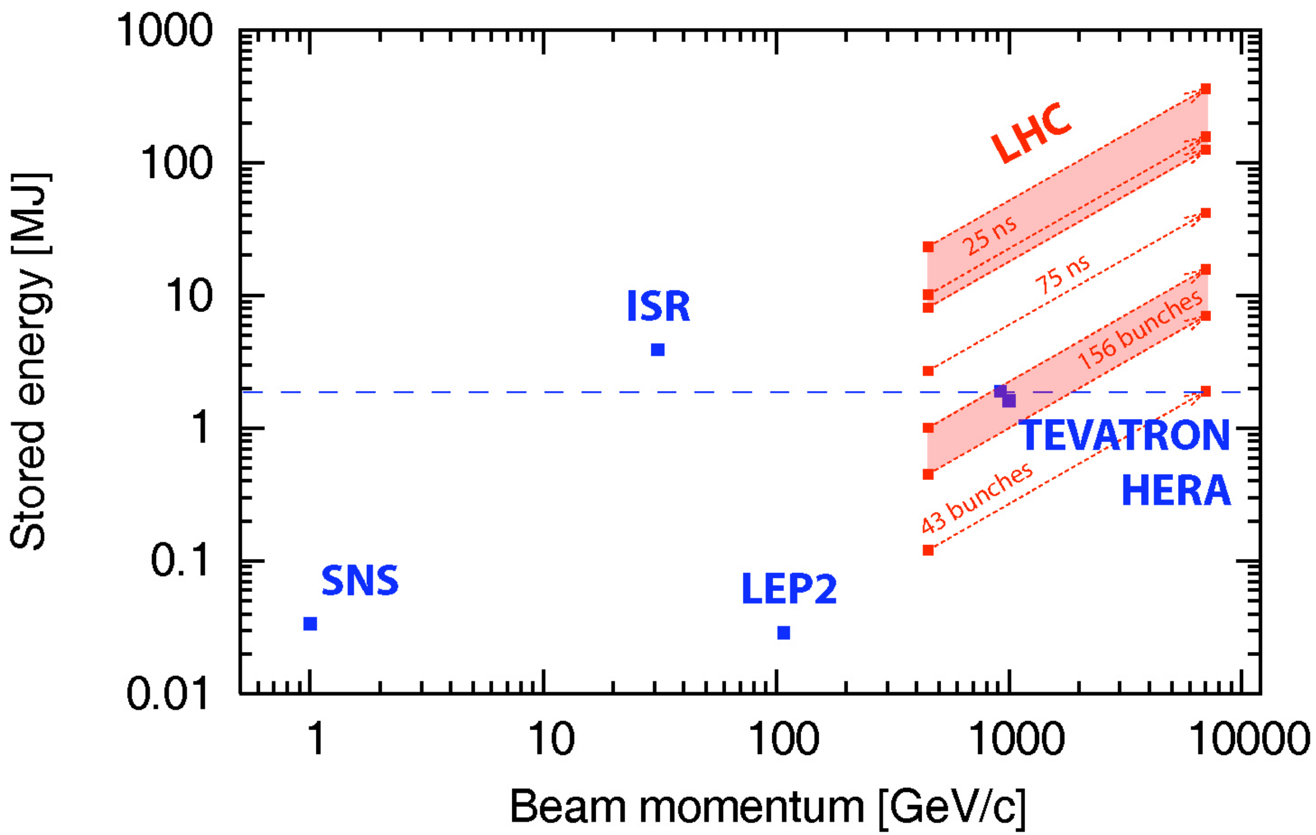
$$R_{loss} \approx I_{total} / t$$

Stored intensity required to provoke a quench without collimation under these conditions:

5.0×10^{11} p

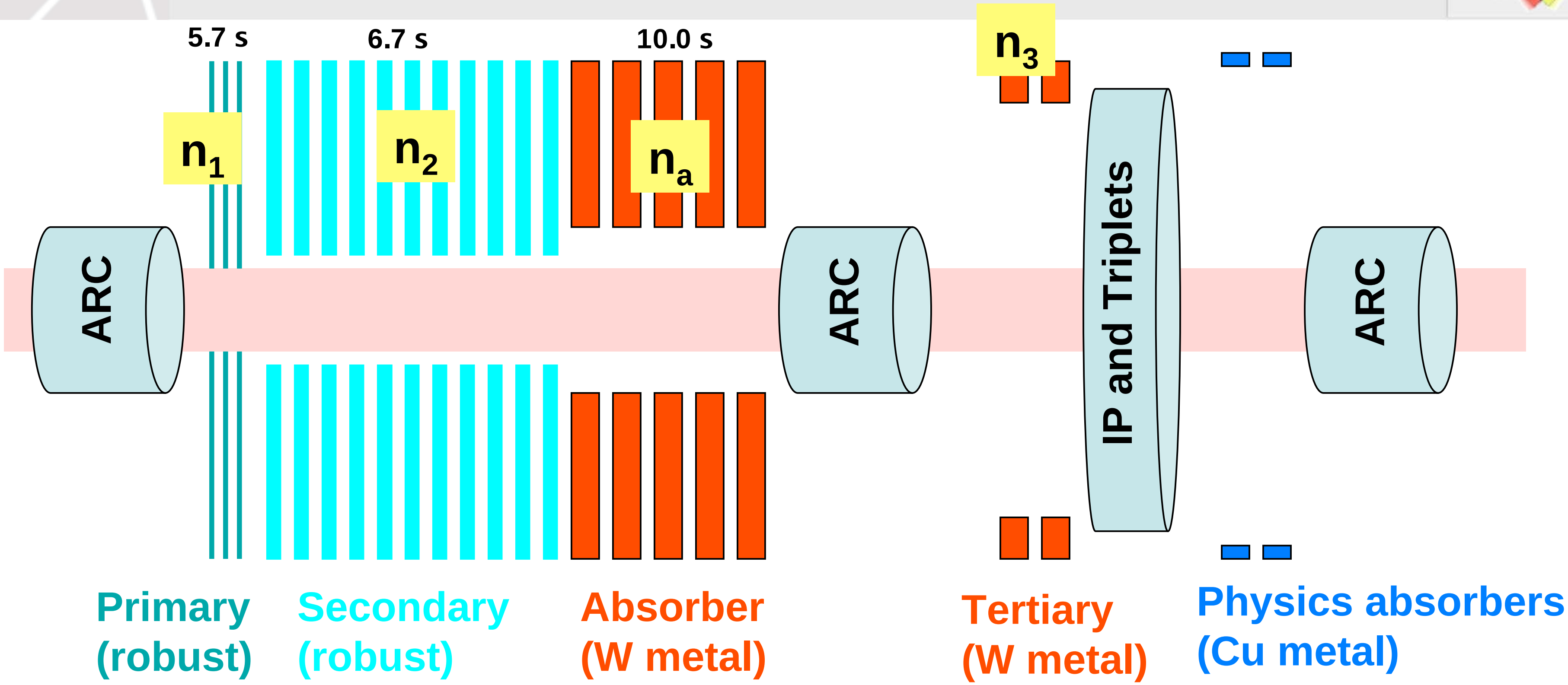
During early commissioning beam cleaning should be no issue (no surprise)!

Running Without Cleaning



Remember: HERA and TEVATRON need collimation mainly for background control!
They arrive at top energy with collimators open and without quenches!

Betatron Collimation at Injection



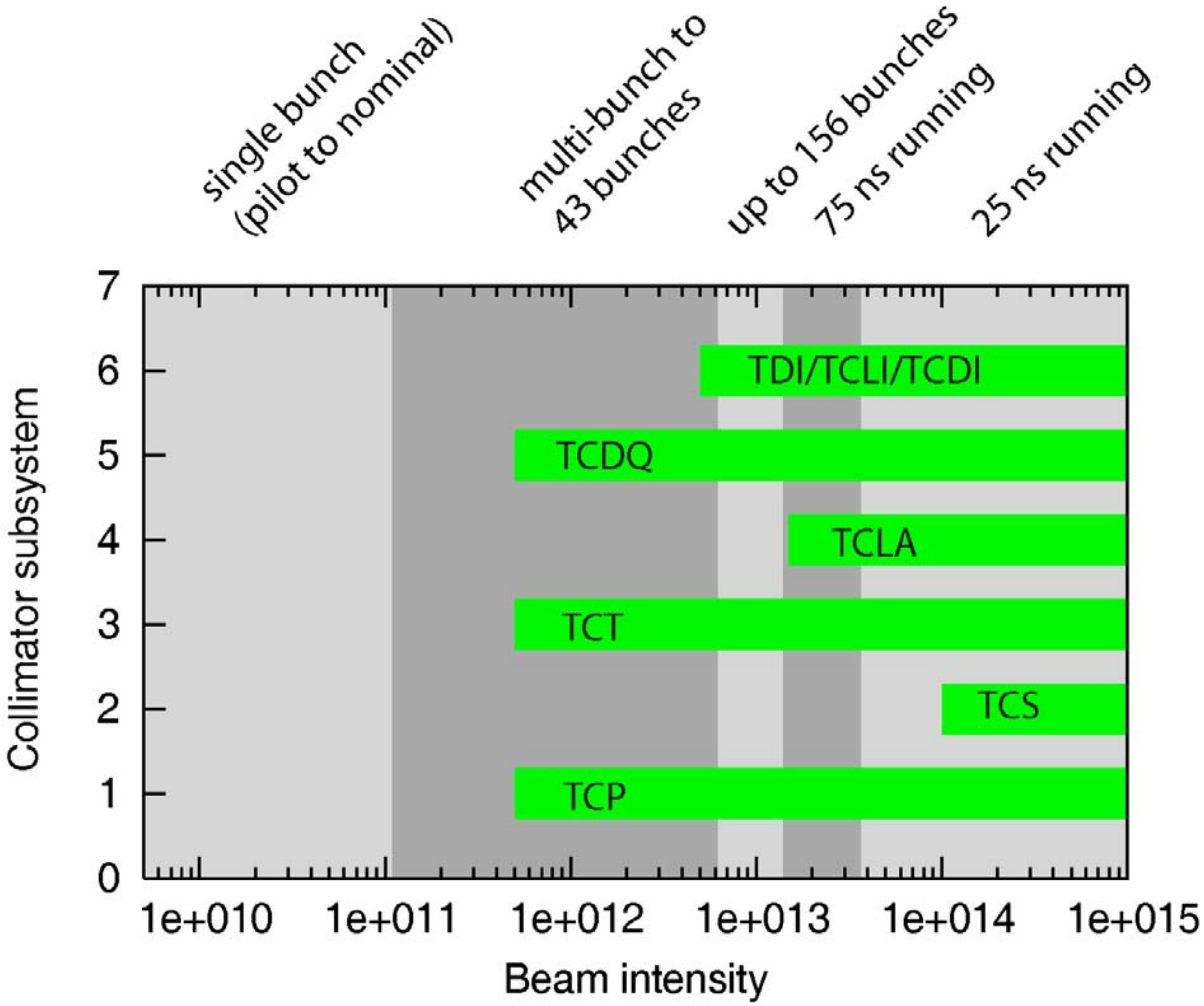
Relevant aperture limit is the arc!

Protected by 3 stages of cleaning and absorption!

First and second aperture limits by robust collimators!

Then metallic collimators with good absorption but very sensitive!

Required Systems at 450 GeV



Note:

- Based on **educated guesses**: Injection performance not yet as well studied as 7 TeV.
- Tighter requirements might arise!
- **Momentum cleaning** will likely have tighter requirements, depending on **capture losses at start of ramp**!

Required Collimator Settings
(assuming multi-batch injection)

	Energy [GeV]	Bunches	Bunch Intensity	Total Intensity	Collimators	TCDQ	TDI	BLMs
pilot	450	1	5 e9	5 e9	All out	Out	Out	Passive
	7000							
super pilot	450	1	3 e10	3 e10	All out	Out	Out	
	7000						-	
intermediate	450	12	3 e10	3.6 e11	n_1 = 6 n_2=out? n_a = out? n_3 = 30	n_{tcdq} = 10	Out	
	7000						-	
43x43 initial	450	43	1 e10	4.3 e11	as above	as above	Out	
	7000						-	
43x43	450	43	3 e10	1.2 e12	as above	as above	Out	
	7000						-	

Pushing Collimator Settings Early

(assuming multi-batch injection)

	Energy [GeV]	Bunches	Bunch Intensity	Total Intensity	Collimators	TCDQ	TDI	BLMs
pilot	450	1	5 e9	5 e9	All out	Out	Out	Passive
	7000							
super pilot	450	1	3 e10	3 e10	All out	Out	Out	
	7000						-	
intermediate	450	12	3 e10	3.6 e11	n_1 = 6 n_2=out? n_a = out? n_3 = 30	n_{tcdq} = 10	Out	
	7000						-	
43x43 initial	450	43	1 e10	4.3 e11	as above	as above	Out	
	7000						-	
43x43	450	43	3 e10	1.2 e12	n_1 = 5.7 n_2= 6.7 n_a = 10.0 n_3 = 30	n_{tcdq} = 9	N_{tdi} = 6.8	
	7000						-	

Set-Up Procedure for Collimators

- Please refer to the recent presentation at LTC!
- Basic philosophy:
  - Establishing machine reference conditions.
  - Beam-based calibration of collimators for reference machine. Can (should) be done with full beam for beam scenarios listed in table.
  - Setting of collimators to target positions.
  - Checks on adequate protection and cleaning (generate error scenarios, generate high beam losses, …).
  - Machine is declared safe for protection and cleaning (massive quenches cause damage as well) with the given reference machine.
  - Reference machine condition (safe set-up) is maintained by automatic machine protection systems (orbit interlocks, feedback, …) and EIC's.
  - In case reference condition cannot be re-established (beta changes, …) work on new safe set-up must be done (repeat set-up).
- Not so clear (for me at least): Protection against off-momentum injection! How to check and where is it lost?

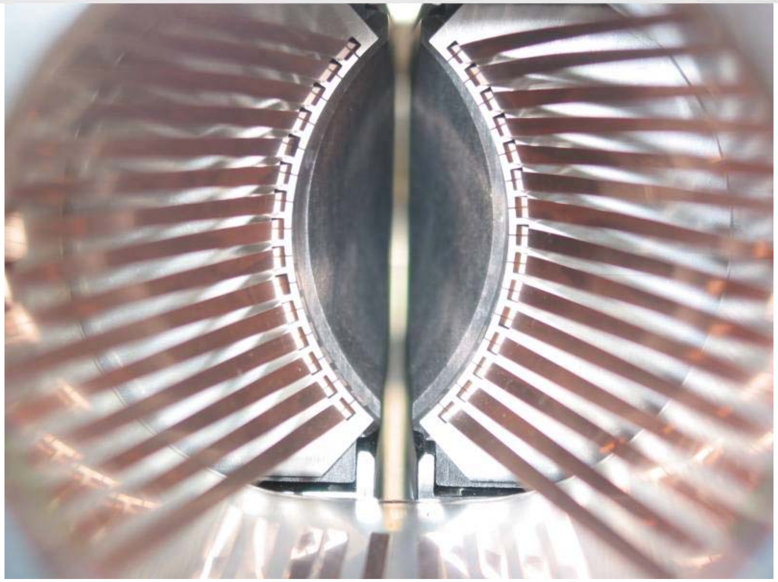
Beam-based Calibration of Collimators

- Target collimator jaw settings are expressed in normalized (nominal emittance) beam size around the orbit. For example a **horizontal collimator at n_{coll}**.
- **Real jaw positions x_{jaw} then depend for each collimator on:**
  - Local orbit at the center of the collimator.
  - Local beta functions at the collimator.

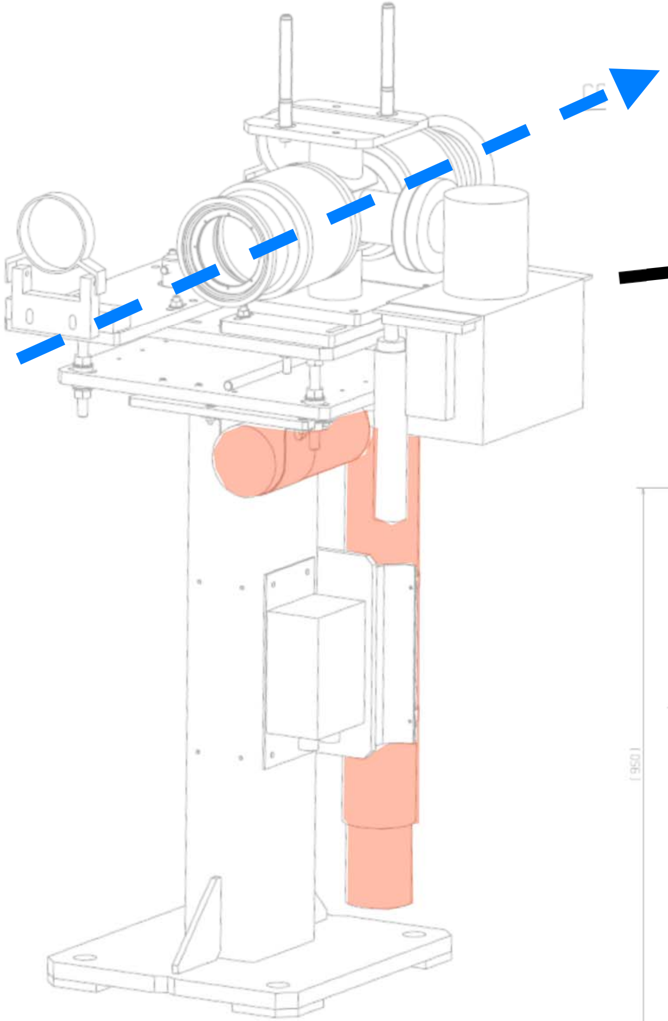
$$x_{jaw} = x_{beam}(s) \pm n_{coll} \sqrt{\beta_x(s)\ \varepsilon_x}$$

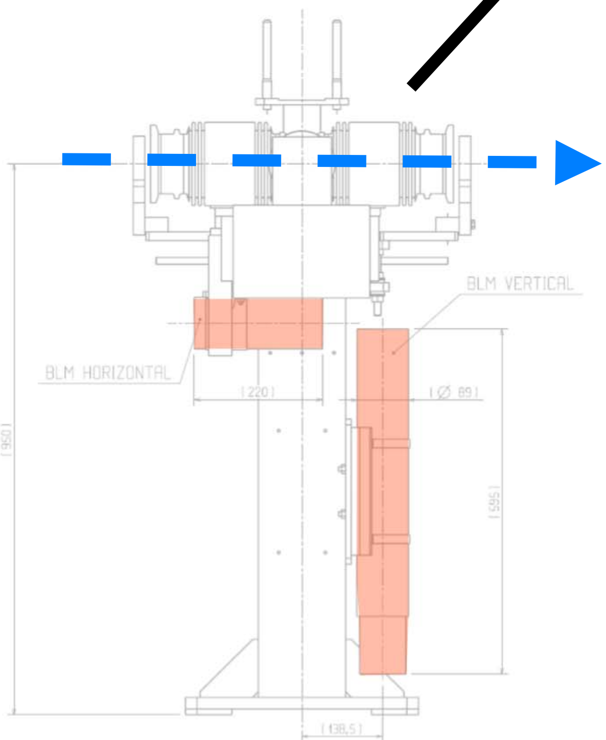
- How to determine the correct jaw positions ➔ **collimator calibration** for obtaining local orbit and beta values!

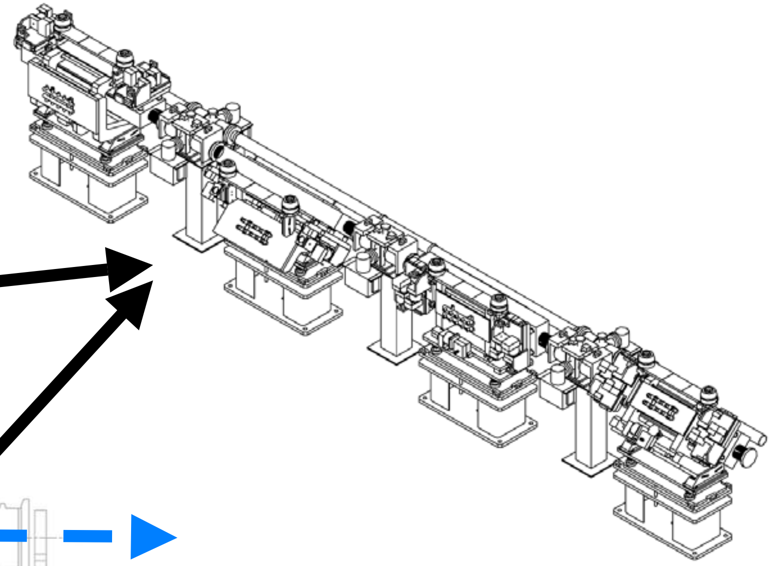
The LHC phase 1 collimator



BLM's for Observing Beam Loss

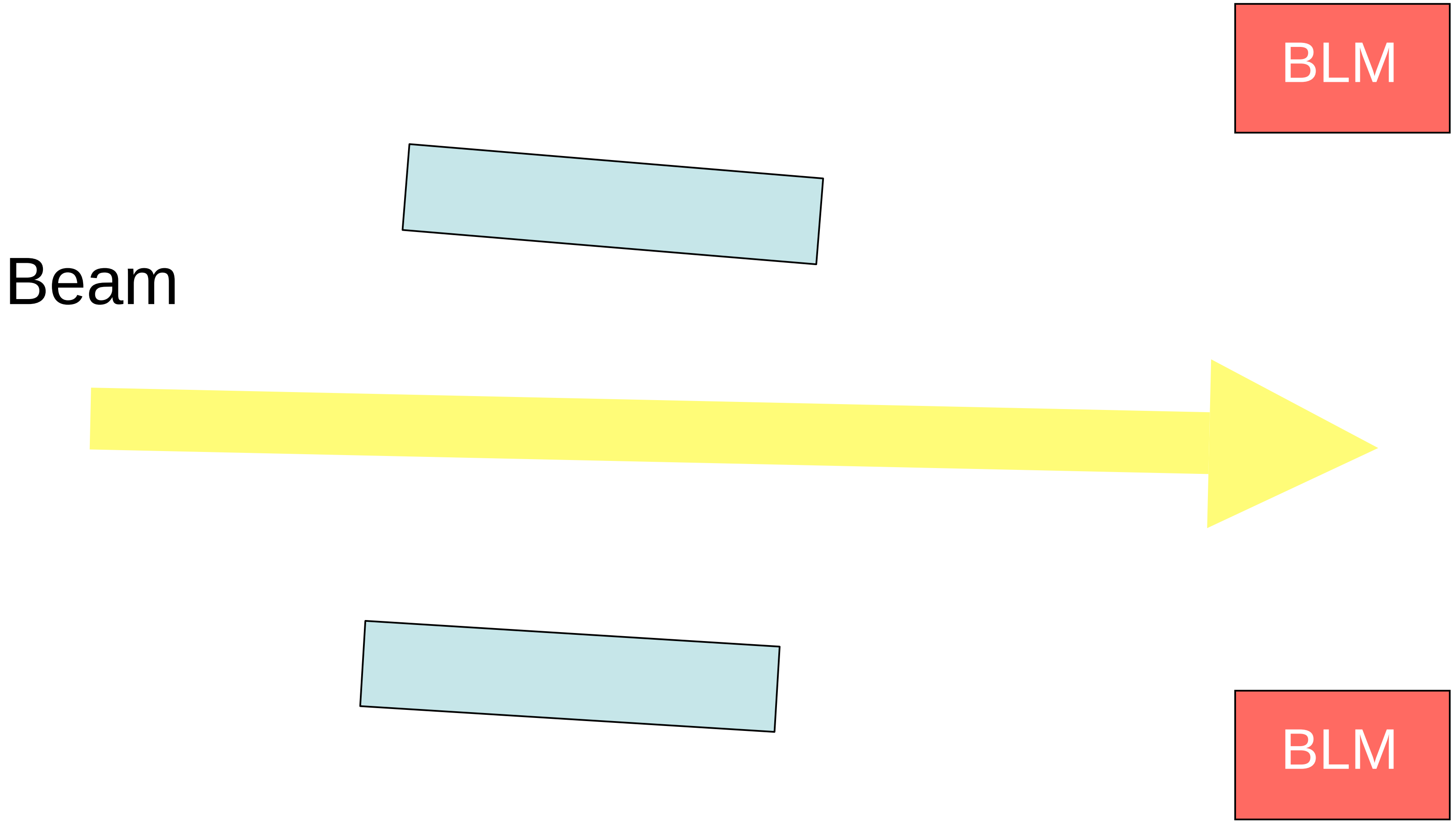




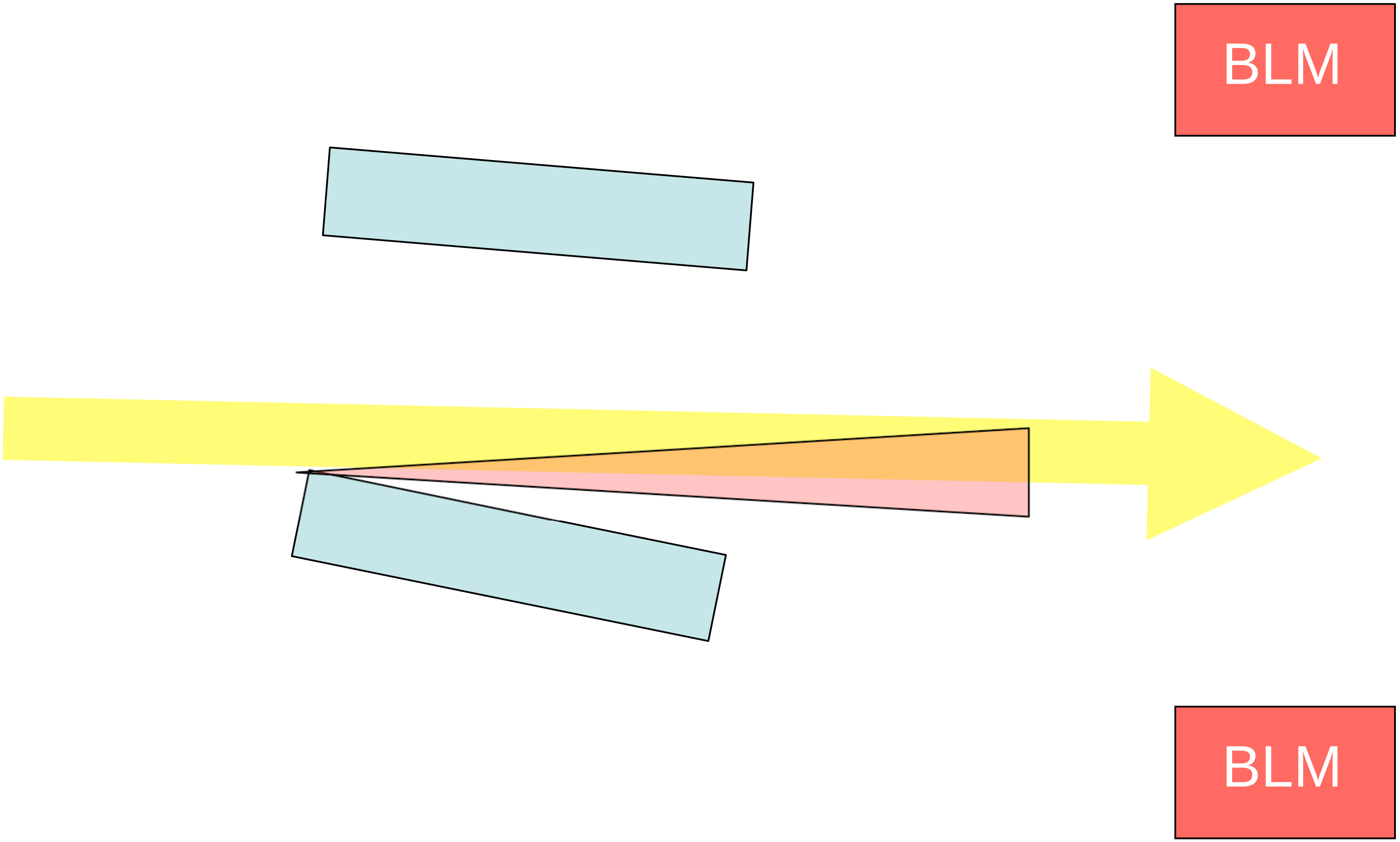


Every collimator has
2 dedicated BLM's.

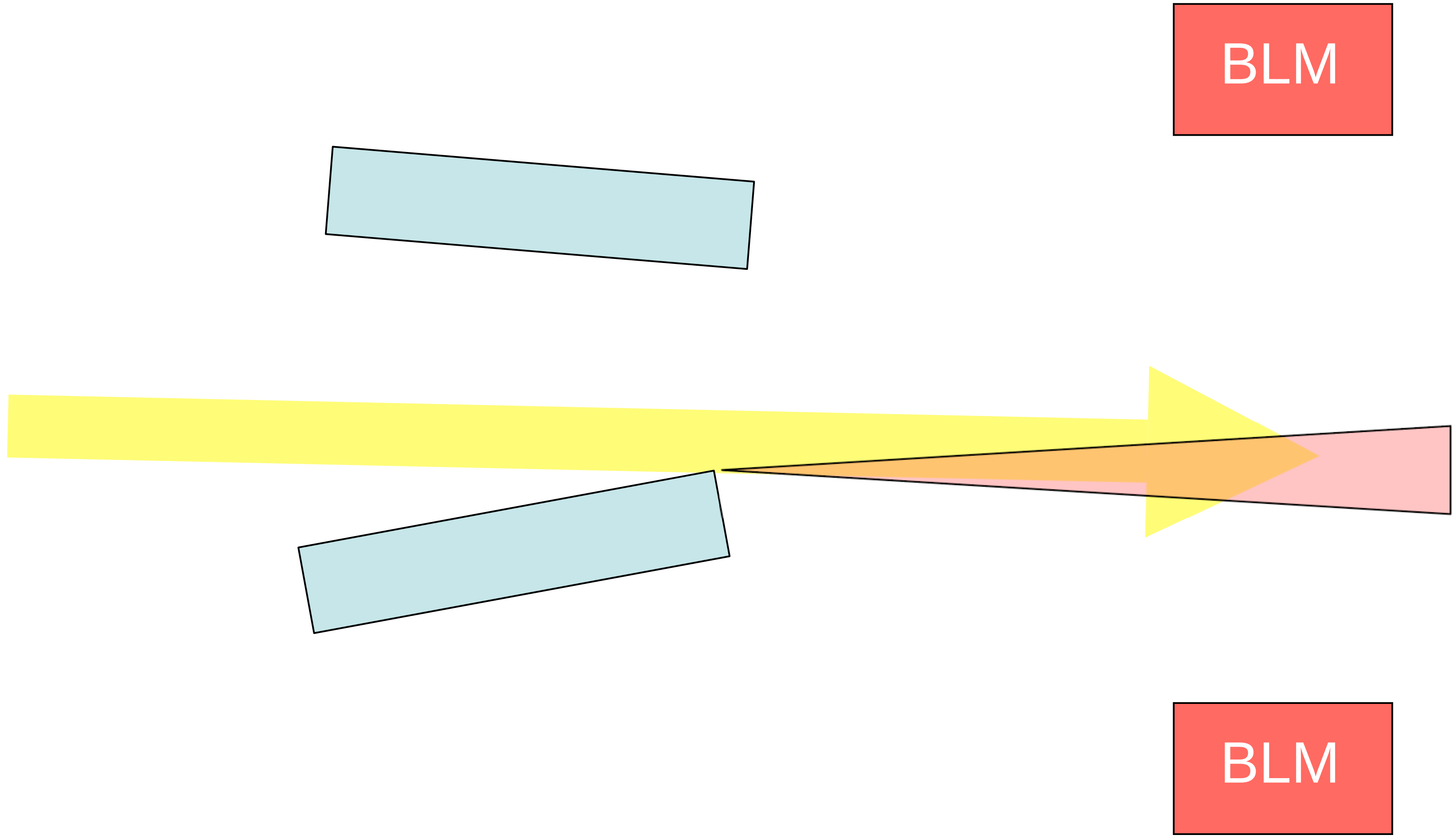
Set-up of single collimator



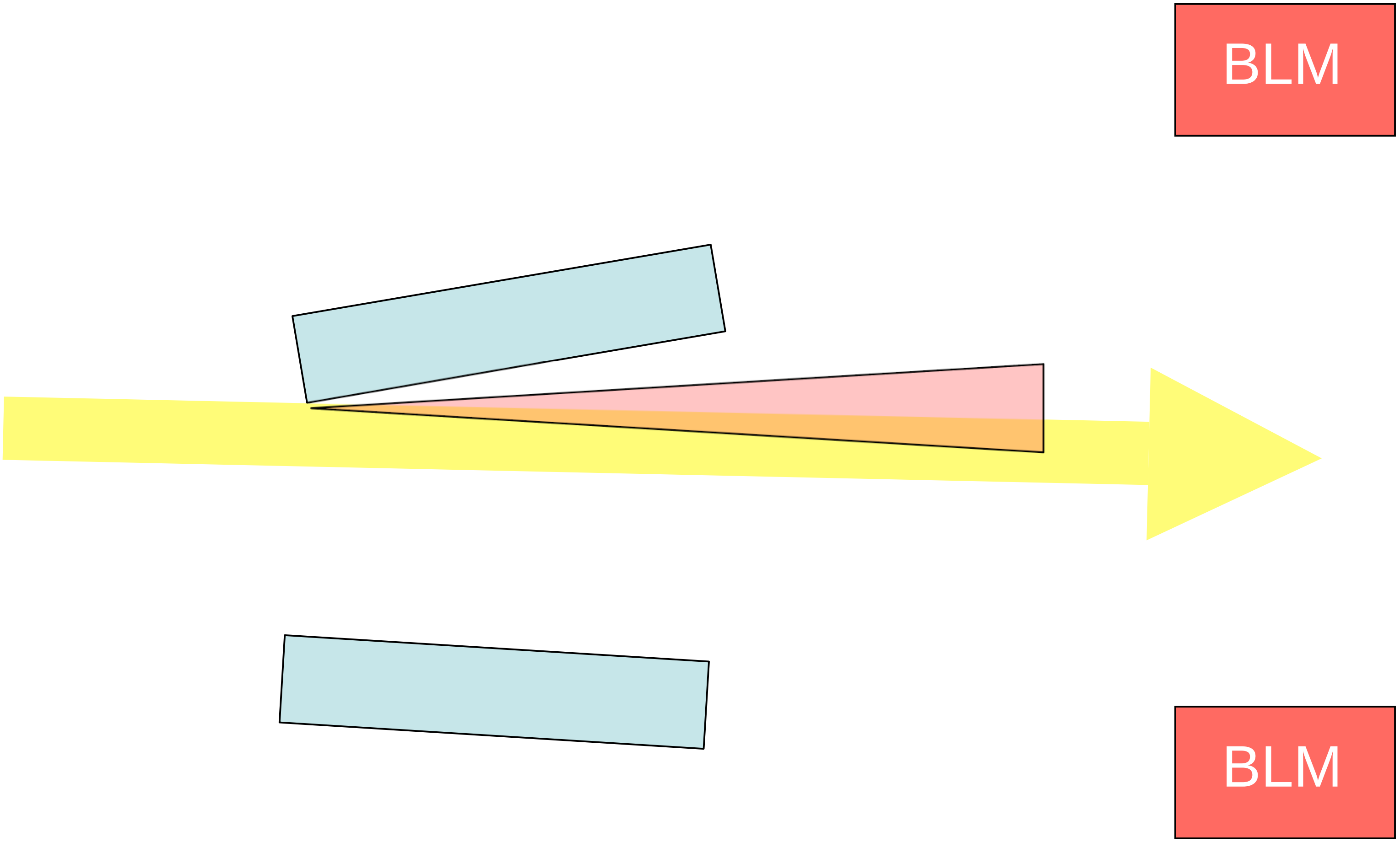
Set-up of single collimator



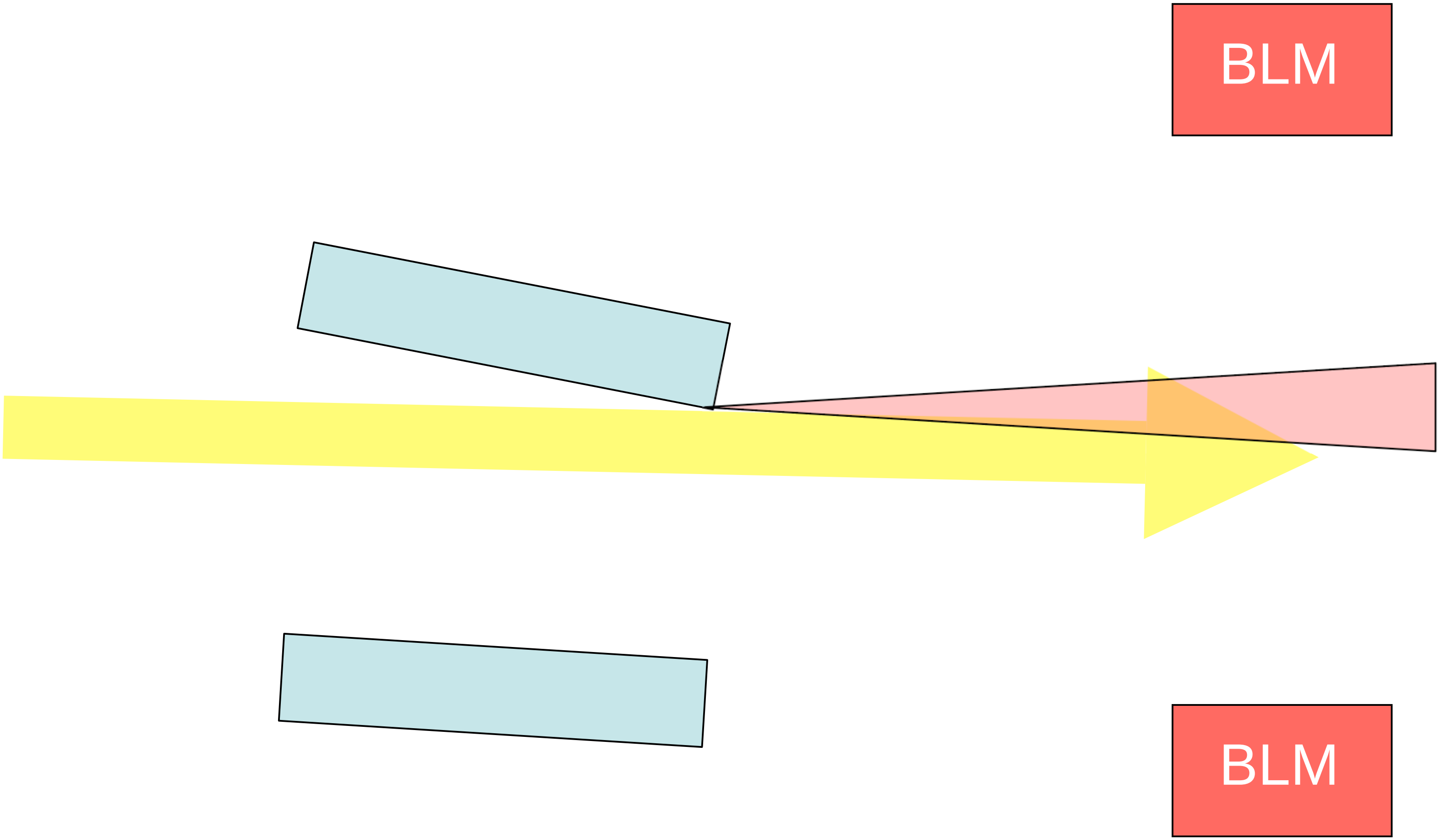
Set-up of single collimator



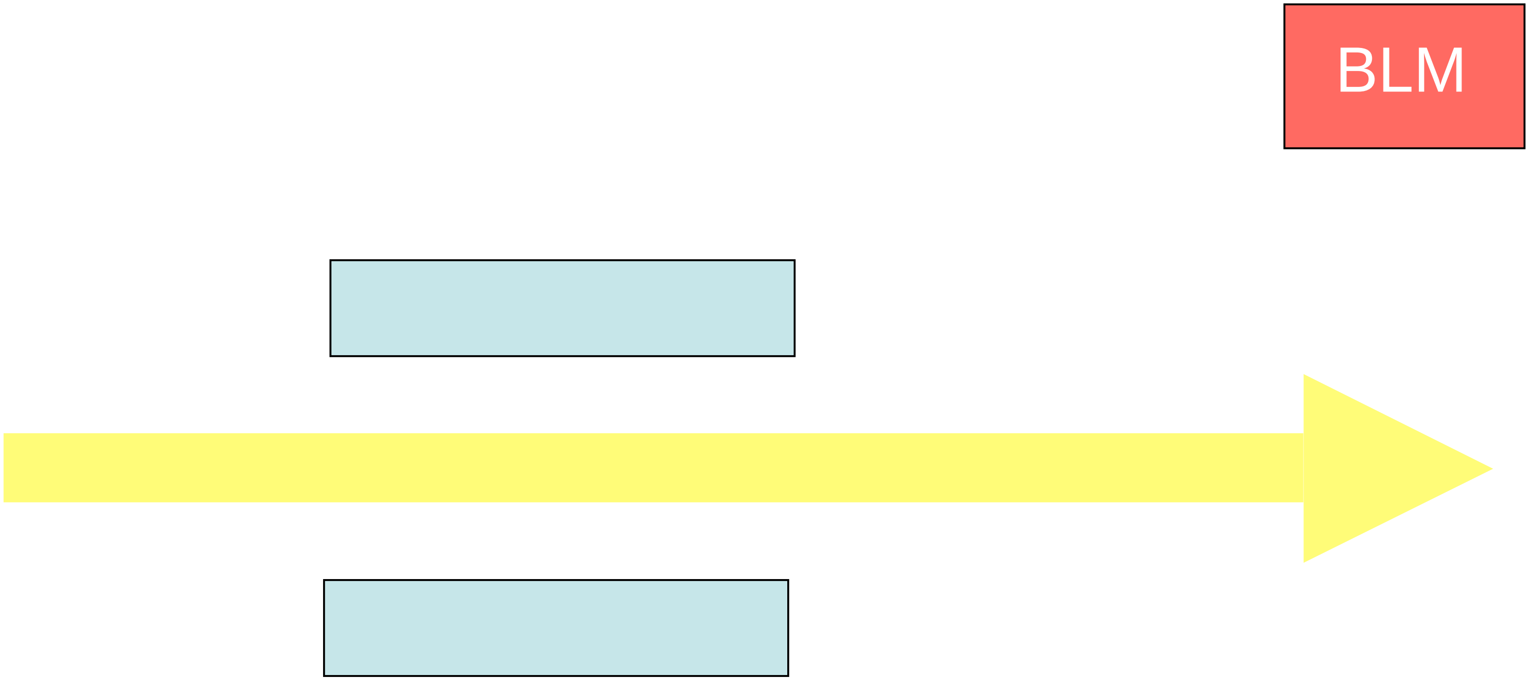
Set-up of single collimator

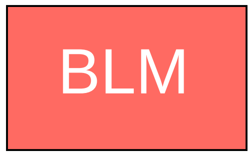


Set-up of single collimator



Set-up of single collimator





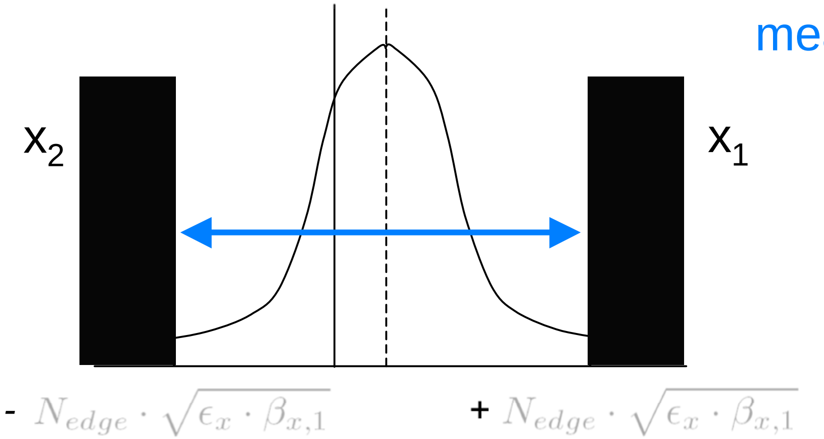
Calibrated center and width of gap, if beam extension is known (e.g. after scraping).

Advance with experience! Rely on BLM system...

Result from Collimator Calibration

Collimator

$$\Delta x = x_1 - x_2$$



← Get beam offset from measured jaw positions

Measure half gap →

$$G_{x,1} = N_{edge} \cdot \sqrt{\epsilon_x \cdot \beta_{x,1}}$$
$$G_{x,2} = N_{edge} \cdot \sqrt{\epsilon_x \cdot \beta_{x,2}}$$
$$G_{x,3} = N_{edge} \cdot \sqrt{\epsilon_x \cdot \beta_{x,3}}$$

Local beta functions at collimators

$$G_{x,1} = N_{edge} \cdot \sqrt{\epsilon_x \cdot \beta_{x,1}}$$
$$G_{x,2} = N_{edge} \cdot \sqrt{\epsilon_x \cdot \beta_{x,2}}$$
$$G_{x,3} = N_{edge} \cdot \sqrt{\epsilon_x \cdot \beta_{x,3}}$$

$\Rightarrow$

$$\beta_{x,1} = \frac{G_{x,1}^2}{N_{edge}^2 \cdot \epsilon_x}$$
$$\beta_{x,2} = \frac{G_{x,2}^2}{N_{edge}^2 \cdot \epsilon_x}$$
$$\beta_{x,3} = \frac{G_{x,3}^2}{N_{edge}^2 \cdot \epsilon_x}$$

More difficult for skew collimators!

Measure gap ➔ **beta beat**

Measure gap, the emittance and the normalized edge ➔ **absolute beta**

This feature is the result of:

Having two opposite jaws: not possible for TEVATRON or RHIC!

Direct measurement of gap with calibration during production!

Interdependencies (Draft)

	Quench propability	MP	Halo distribution	Collimators	Impedance	Lifetime	Background
TCP	critical	critical	important		critical	important	secondary
TCS	critical	critical	important		critical	important	secondary
TCLA	critical	critical	important		critical	important	secondary
TCT	critical	critical	important		critical	important	secondary
TCDQ	critical	critical	important		important	Important	secondary
TDI, TCLI	critical	critical	important		important	important	secondary
Orbit	important	critical	secondary	critical	secondary	important	secondary
Optics	important	critical	secondary	critical	important	important	secondary
Crossing angle	important	critical	important	critical	secondary	important	secondary
Tune	secondary	important	critical	important		important	secondary
Coupling	secondary	important	critical	important		important	secondary

LHC is a very complicated machine!

Each action can have many (unexpected) side-effects!

How to Overcome Possible Beam Loss Limitations During Commissioning?

1. **Increase available aperture** for the beam (work on orbit and beta beat).
2. **Improve stability** of the machine (lower loss rates).
3. **Improve cleaning efficiency** (close collimators ➔ reduce tolerances, increase impedance, increase complexity).
4. **Decrease intensity**.

Sorted in order of priority for collimation/machine protection!

Solution 4 reduces the performance and is only the last resort! It is the easy way!

For above ~ 5-10% of nominal intensity we need to work hard on all topics 1-3! Don't cut too many corners in the early commissioning!

For detailed scenarios: **Need estimate on beta beat and orbit during different phases of commissioning!**

Conclusion

- Basic collimation scenarios exists and table was filled in.
- Major input must be specified (orbit, beta beat, loss rates, …) for detailed studies which then provide more details: available aperture, number of collimators required, settings, operational tolerances.
- Strategy should be defined on major commissioning goals:
  – As fast as possible to collisions even with reduced aperture?
  – Get close to nominal design parameters (aperture) before attacking further problems: minimizes overall time for higher luminosity running.
- Extended table will help in defining our goals and reference scenarios for each step.