Intensity Limitations from Existing Hardware in the HL-LHC era

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The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

Items under consideration

- Cryogenics
- Impedance & RF Heating
- Collimation
- Air Activation in Collimation Regions
- Injection & Dump Systems
- Vacuum
- RF

- Not covered
  - Radiation to electronics
  - Long term radiation damage to components

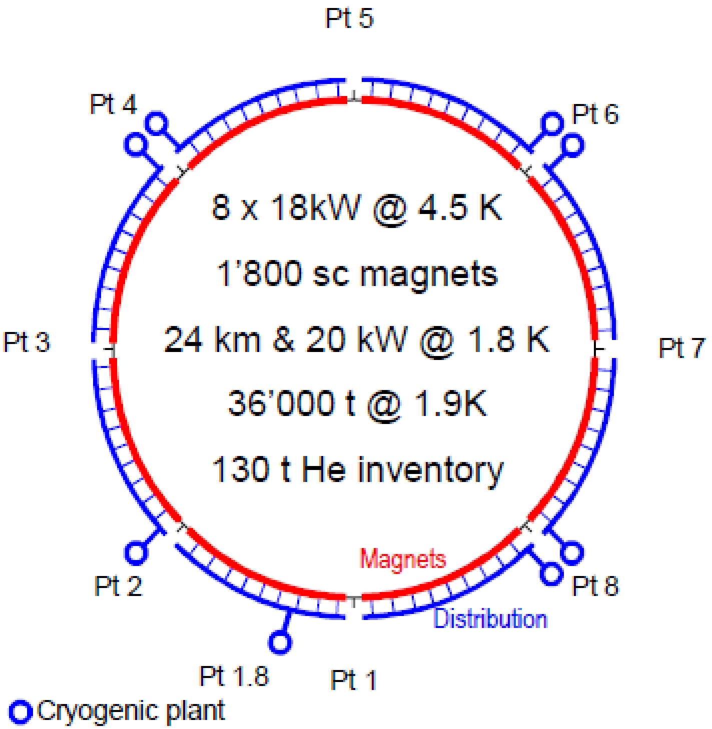
The Cryogenic System

1.8K dynamic heat load

- Secondaries (proportional to luminosity)
- Beam gas scattering (proportional to total current)
- Resistive heating (proportional to energy squared)

4.5K beam screen dynamic heat load

- Synchrotron radiation (proportional to E^4 & I_{tot})
- Image current (proportional to number of bunches, bunch length and square of bunch current)
- Electron cloud (an unknown!)

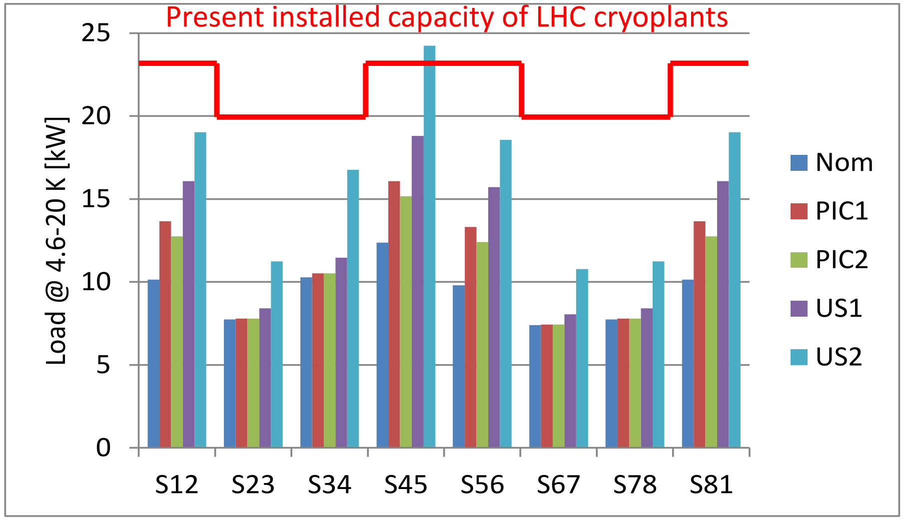


Parameters		Nominal	Above nominal PIC1	HL-LHC US2
E	[TeV]	7	7	7
Nb	[# p / bunch]	1.15E+11	1.24E+11	2.2E+11
nb	[-]	2808	2592	2592
L	[Hz/cm-2]	1E+34	3.71E+34	5E+34
σ	[ns]	1	1	1

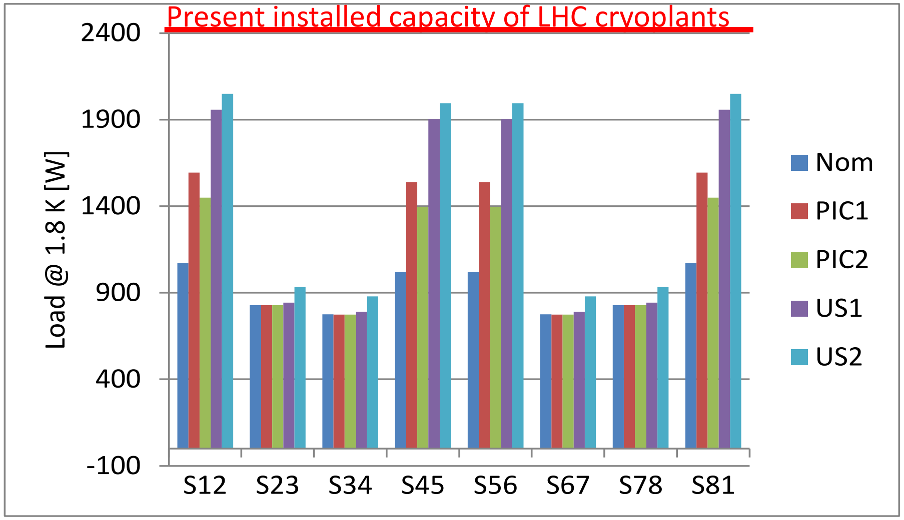
The Cryogenic System

Total load per sector (without e-cloud)

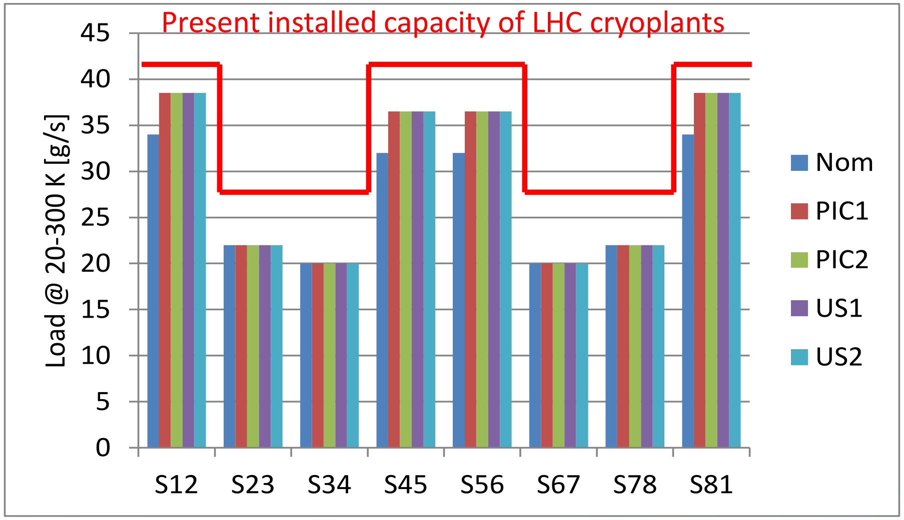
4.6 – 20 K



1.9 K



20 – 300 K



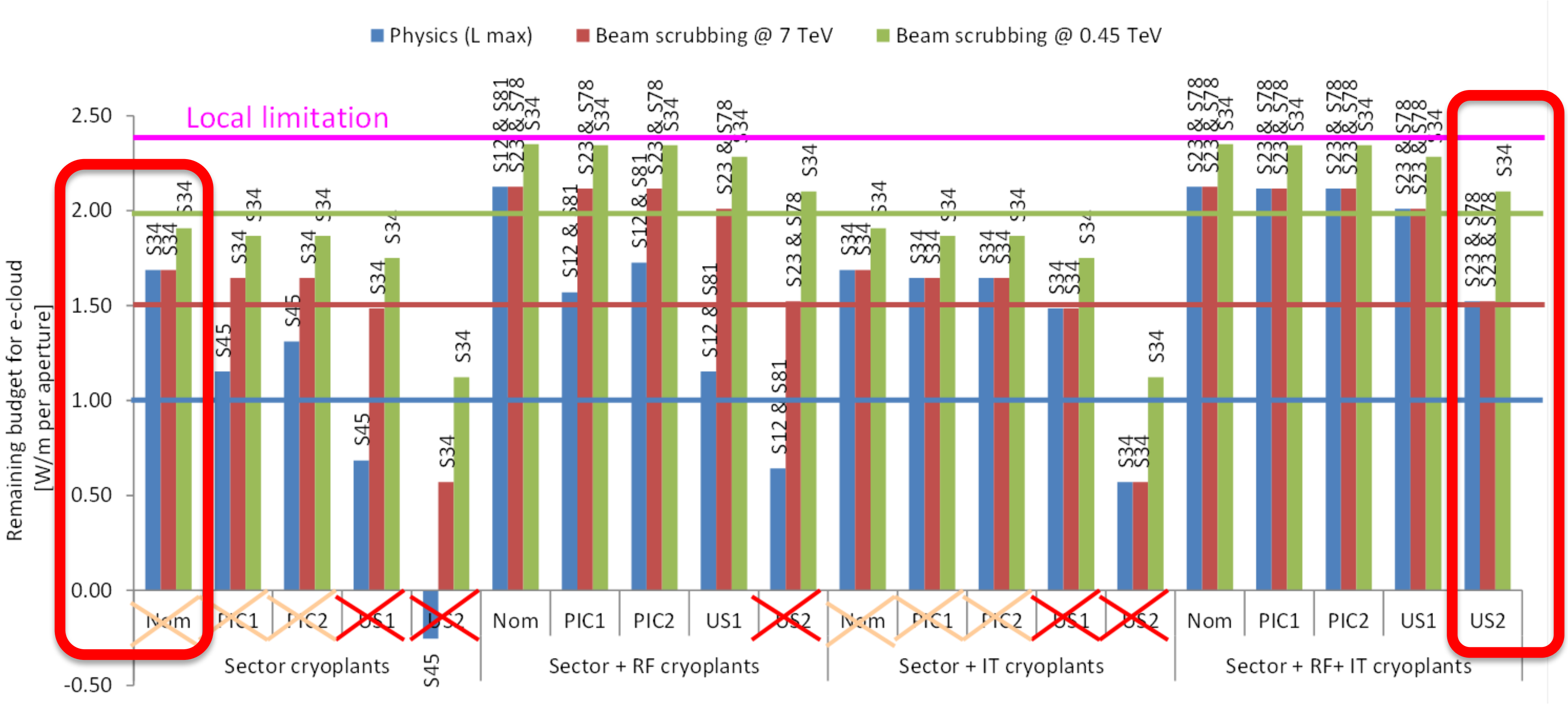
Ex-LEP cryo-plants feed low load sectors (23-34-67-78)

The Cryogenic System

Remaining cooling budget for e-clouds

Current hard limit for beam screen cooling (capillary size) is 2.4W/m per aperture

- Could run beam screen circuit at higher pressure
- Would lower overall capacity & therefore require addition of 8 new refrigerators

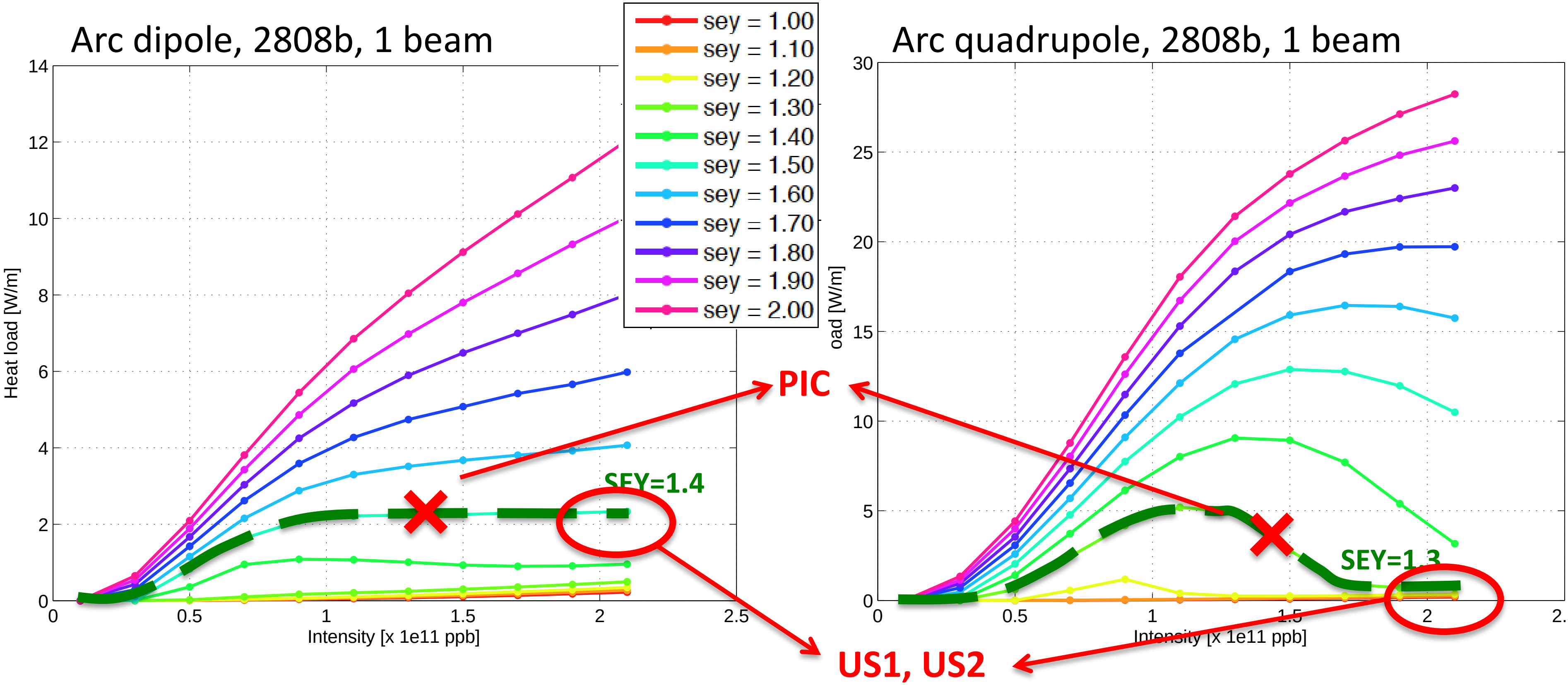


Now

HL-LHC

The Cryogenic System

Dependence of arc heat load on bunch intensity



⇒ Nonlinear behaviour

- ✓ Tends to level off above 1e11 ppb close to the threshold in dipoles
- ✓ Is strongly non-monotonic for quadrupoles

⇒ But dependencies rely on assumptions on E_{max} and uniform SEY on the wall

The Cryogenic System

Estimates for e-cloud heat load

NOMINAL	**Available cooling [W/m/ap]**	**Meas 2012 [W/m/ap]**	**Scaling (N_{bun}= 2700)**	**Scaling factor (E=7 TeV + nominal filling)**	**Heat Load [W/m/ap] (SEY 2012)**	**Heat Load [W/m/ap] (dipoles fully scrubbed)**
Arc half-cell	2.4	0.4	x3.4	0.81x3.5(0.0) + 0.19x1.0	**4.3** **(x 1.8)**	**0.26** **(x 0.11)**

HL-LHC	**Available cooling [W/m/ap]**	**Meas 2012 [W/m/ap]**	**Scaling (N_{bun}= 2700)**	**Scaling factor (E=7 TeV + nominal filling)**	**Heat Load [W/m/ap] (SEY 2012)**	**Heat Load [W/m/ap] (dipoles fully scrubbed)**
Arc half-cell	2.4	0.4	x3.4	0.81x3.5(0.0) + 0.19x0.15	**4.1** **(x 1.72)**	**0.05** **(x 0.02)**

- Heat load will not get worse if intensity further increased
- Effect on Beam will get worse for higher intensity with same e-cloud

The Cryogenic System - Future

- Consolidation during LS1
  - Cu braid configuration on 6/8 IT
  - Increase maximum flow coefficient of SAM BS control valve
    - Should remove SAM limitations
- Main limitation
  - Heat loads on beam screen related to e-cloud
    - Extent unknown
    - Should not get worse if intensity is further increased
    - Max cooling of 2.4 W/m per aperture given by size of beam screen capillaries
    - Increasing beam screen pressure would require new cryoplants
- Future Requirements assuming triplet replacement

Hardware	Above Nominal	HL-LHC
New QRL line and Service Modules for IT	Y	Y
New QRL line and Service Modules for MS	N	Y
New QRL Service Modules for DS P1 & P5	N	Y
New Cryoplant for RF at P4	Y/N	Y
New Cryoplants for IT at P1 & P5	Y/N	Y

Instability Limits (impedance)

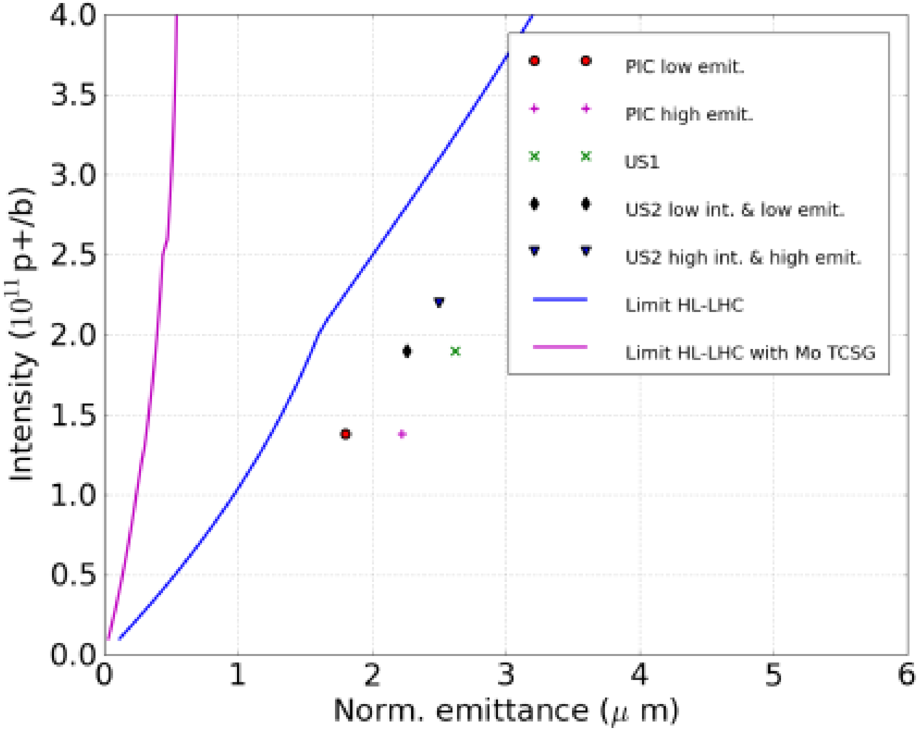
Longitudinal

- Impedance not an issue if we continue to blow-up the beams during ramp

Transverse

- Collimators are the largest source of impedance in the LHC (accounting for 90%)
- Possible limitation in minimum opening and β* reach
- Limited margin for all the scenarios based on extrapolations from 2012 (with positive octupole polarity)
- Impedance reduction with metallic collimators (Mo-C) required to provide safe margin
- Next Steps
  - Today - Estimate of machine impedance
    - N. Mounet
  - May 2014
    - initial estimate for intensity limitations
  - Nov 2014
    - report on beam intensity limitations

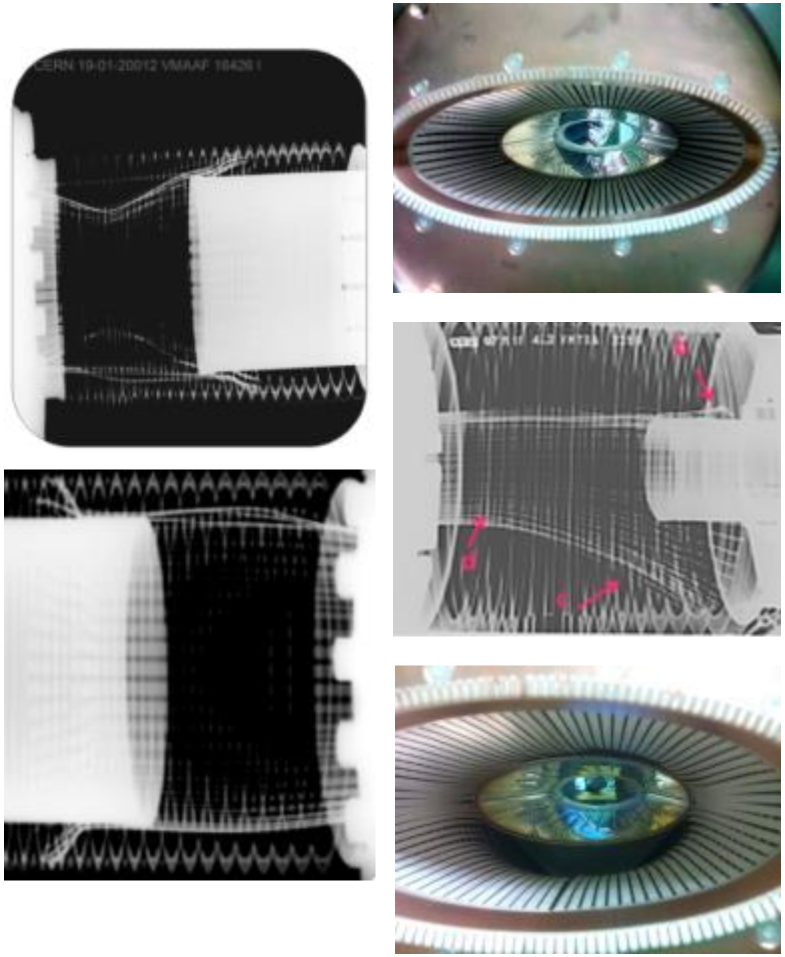
EFFECT OF CHROMATICITY, DAMPER, OCTUPOLES INCLUDED



E. Métral, N. Mounet

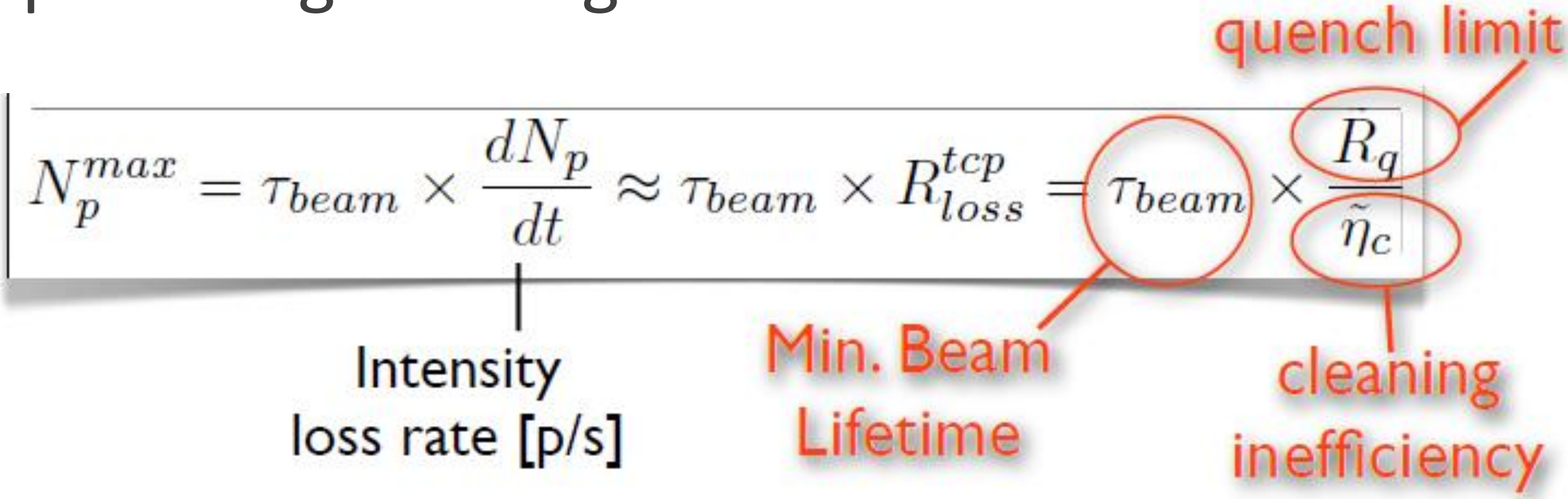
RF Heating

- Main limitations to date were non-conformities
- Conclusion of RF contact task force (2012)
  - For cases studied no problem with impedance for conforming RF fingers observed
  - No limitation expected for HL-LHC parameters
- Known Limiting Items
  - Injection kicker (MKI)
    - Foreseen upgrade might not be good enough to go beyond nominal
  - Injection Protection (TDI)
    - Already not adequate for current power loss
  - Other considerations
    - Ferrites
      - Effective but need efficient cooling
    - Power extracted by beam instrumentation systems
    - New devices
      - Synchrotron light extraction mirror redesigned
      - Beam gas vertex detector tank for emittance measurements carefully simulated



Collimation

- How many particles can be injected without quenching the magnets?



$$N_p^{max} = \tau_{beam} \times \frac{dN_p}{dt} \approx \tau_{beam} \times R_{loss}^{tcp} = \tau_{beam} \times \frac{\tilde{R}_q}{\tilde{\eta}_c}$$

quench limit

Intensity
loss rate [p/s]

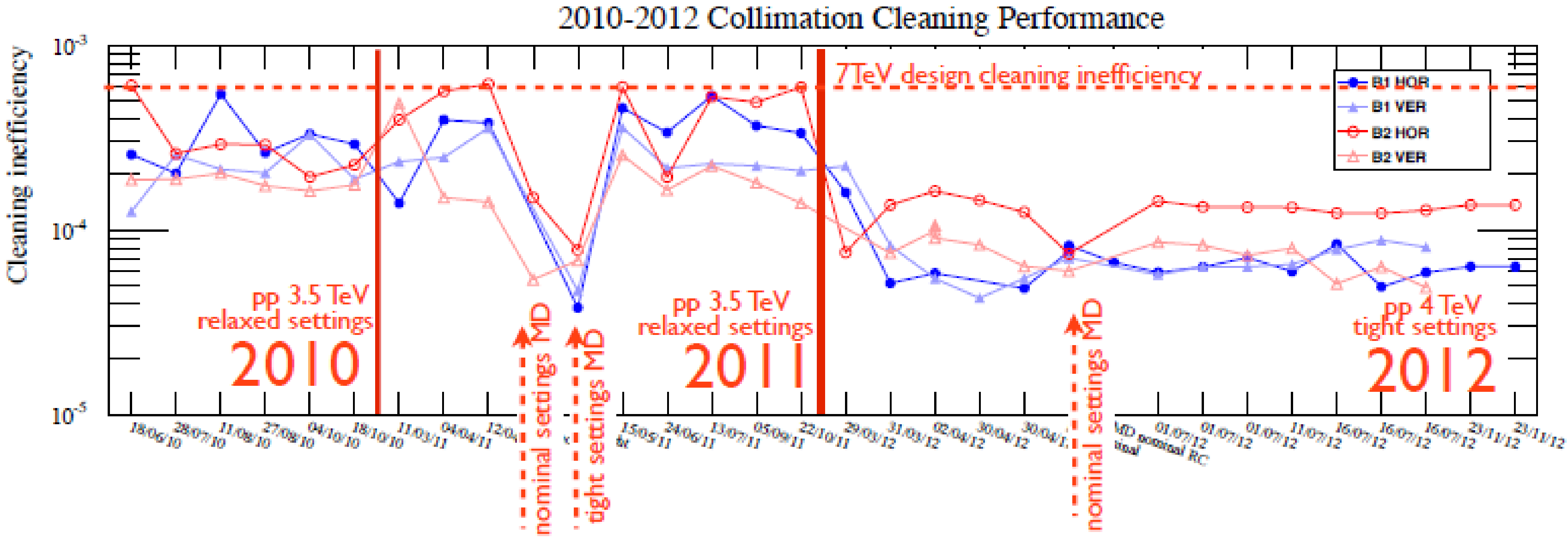
Min. Beam
Lifetime

cleaning
inefficiency

$$R_{loss}^{tcp} = \frac{\tilde{R}_q}{\tilde{\eta}_c}$$

The maximum loss at the primary is determined by the maximum loss allowed at the cold magnets (quench limit) divided by the cleaning inefficiency.

Collimation – Cleaning Efficiency



Excellent stability of cleaning performance observed

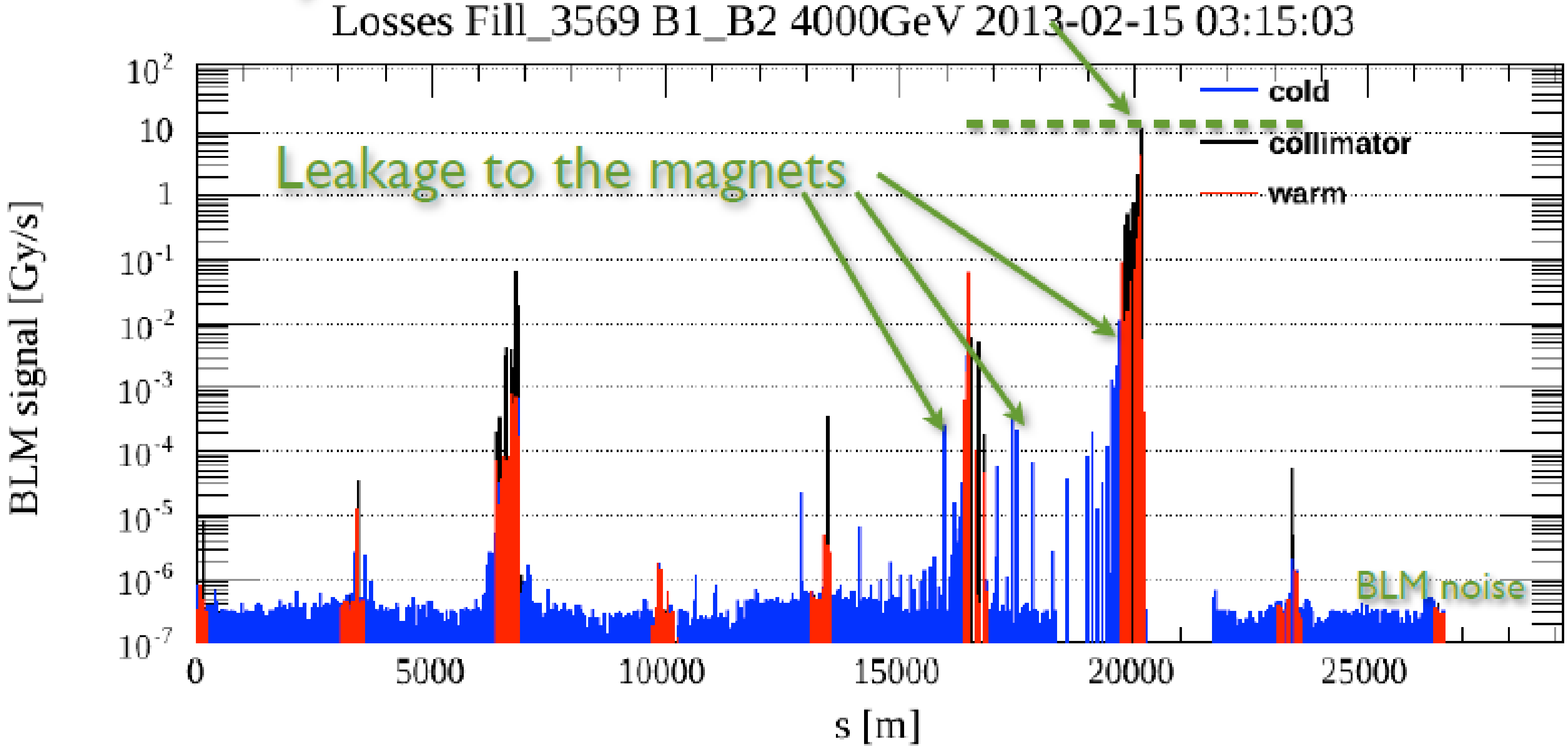
Achieved with only one alignment campaign per year (March 2012) IR3/IR7
In 2012 with tight settings the **cleaning improved from 99.97% to 99.993%**

Cleaning for Tight Settings: 1.2×10^{-4}

Collimation – Quench Limit

1.05MW in IR7! No Quench!

11 Gy/s at the TCP.B6R7.B2 in IR7

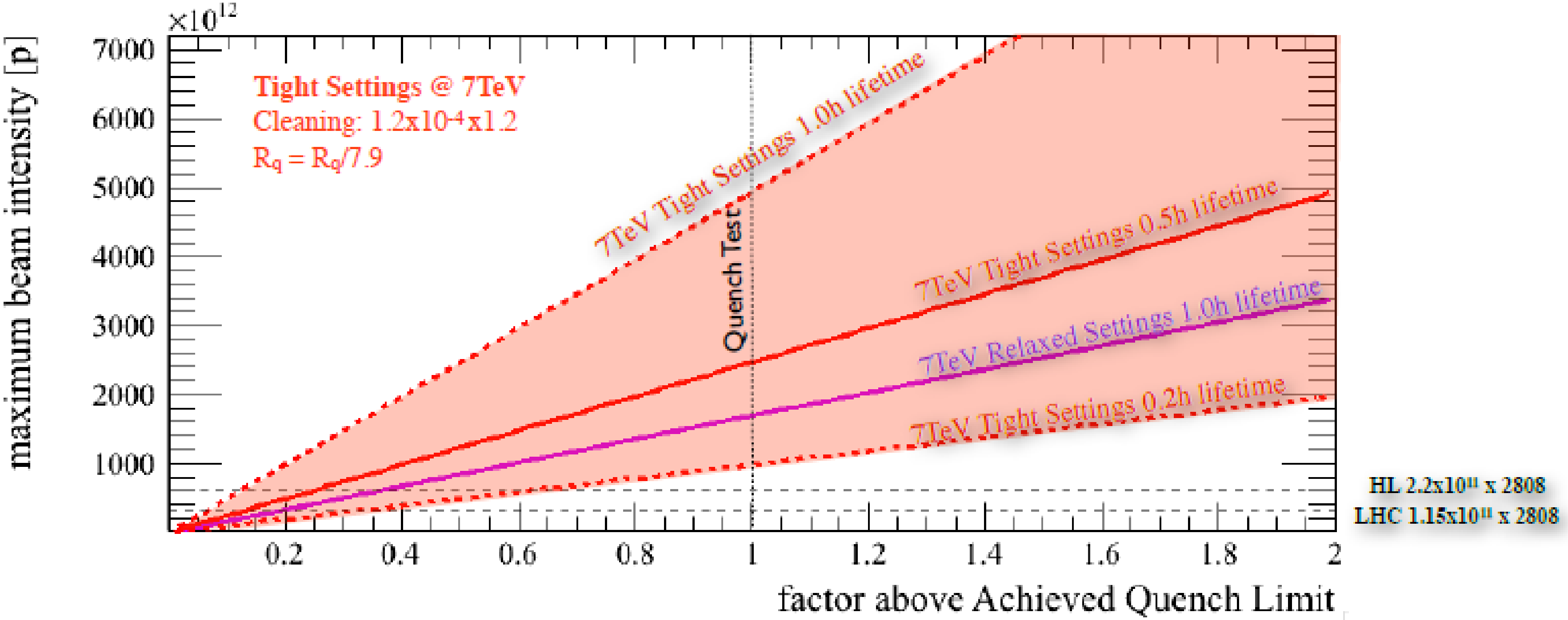


Leakage to the magnets

BLM noise

very relaxed collimator settings to allow more leakage

Collimation – Beam Lifetime

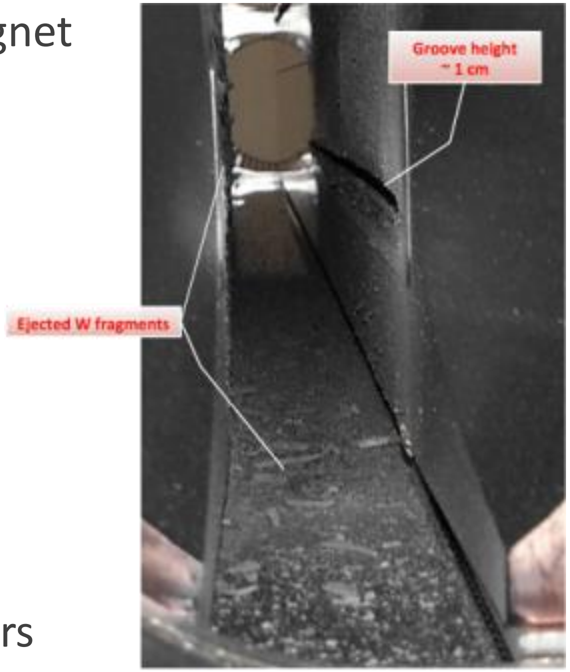


	Min. Lifetime [hours]	Nmax [protons]	Nmax/N_{LHC}	Nmax/N_{HL}
7 TeV Tight Settings	0.2	9.9E+14	3.1	1.6
	0.5	2.5E+15	7.6	4.0
	1.0	4.9E+15	15.3	8.0

Additional factor ~2 from updated quench margin estimates

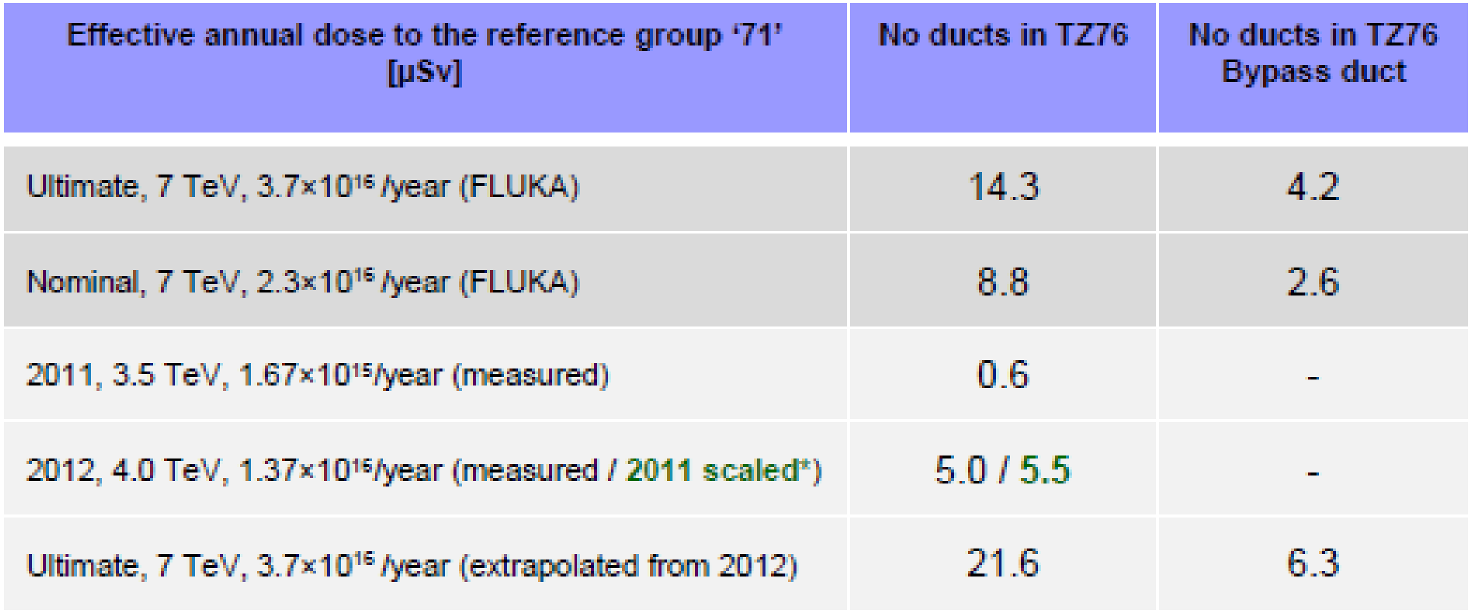
Collimation - Conclusions

- Need to find good low-impedance solution for jaw material or collimator impedance will be the limitation
- Quench limit seems factor 3-4 higher than foreseen
  - 5mJ/cm^3 $\Rightarrow$ 20-50mJ/cm^3
  - Would allow operation at 3-6 times nominal intensity
  - More likely to damage collimators than quench
  - 500kW over 10s - original design to maintain flatness & hierarchy
  - BLM thresholds need to be set to protect collimator not magnet
- Robustness in case of asynchronous dump – 2 limits
    - 2×10^{10} at 7 TeV - jaw properties recovered by vertical movement
    - 1×10^{11} at 7 TeV - complete replacement required
  - Separation of TCDQ & tertiary (TCT) determines β^* reach
  - Robust TCT required
- IR debris
  - New TCL collimators in LS1 – no limitation before LS3
  - Ions – DS limitation – OK until LS2
- Warm magnet lifetime linked to energy deposited on collimators



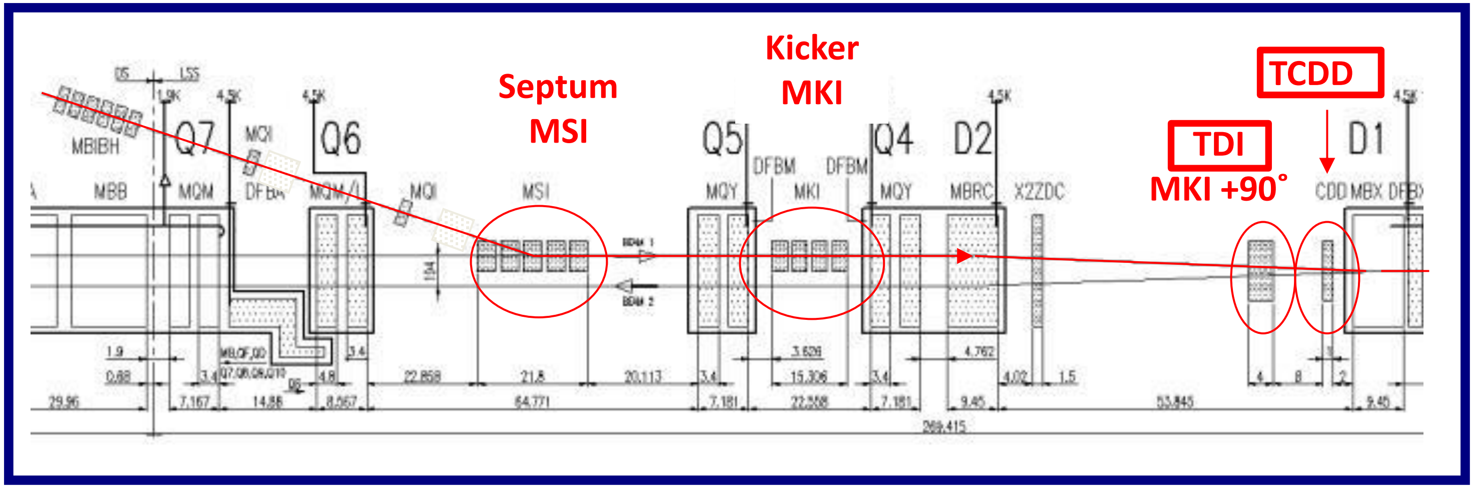
Air activation in Collimation Regions

- Released activity in 2012 corresponds to about 5μSv to the reference group of population which is in good agreement with the prediction of 5.5μSv
- Installation of ventilation doors (ongoing) and later use of air bypass ducts will reduce the released activity by about a factor of 3 if they work as designed
- Scaling of measured activities and losses to ultimate and taking into account the installed doors gives an annual dose to the reference group of 6.3μSv.
- Our CERN objective is to stay below 10μSv/year.



Effective annual dose to the reference group '71' [μSv]	No ducts in TZ76	No ducts in TZ76 Bypass duct
Ultimate, 7 TeV, 3.7×10^{16} /year (FLUKA)	14.3	4.2
Nominal, 7 TeV, 2.3×10^{16} /year (FLUKA)	8.8	2.6
2011, 3.5 TeV, 1.67×10^{15}/year (measured)	0.6	-
2012, 4.0 TeV, 1.37×10^{16}/year (measured / 2011 scaled*)	5.0 / 5.5	-
Ultimate, 7 TeV, 3.7×10^{16} /year (extrapolated from 2012)	21.6	6.3

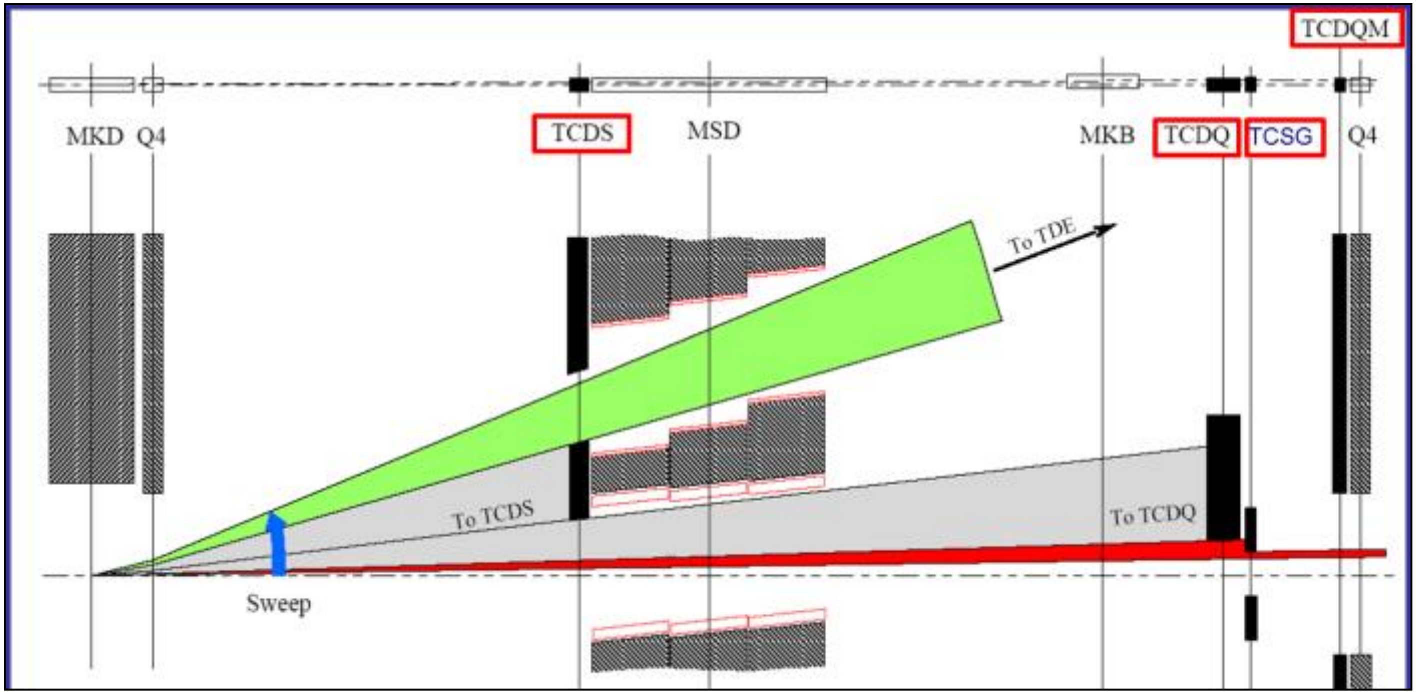
Injection Protection



TDI

- Primary injection absorber
- Must be able to withstand injection kicker failure & impact of one LHC batch without damage
- Will be replaced in LS2 to go higher than nominal, taking into account impedance issues

Dump System Protection

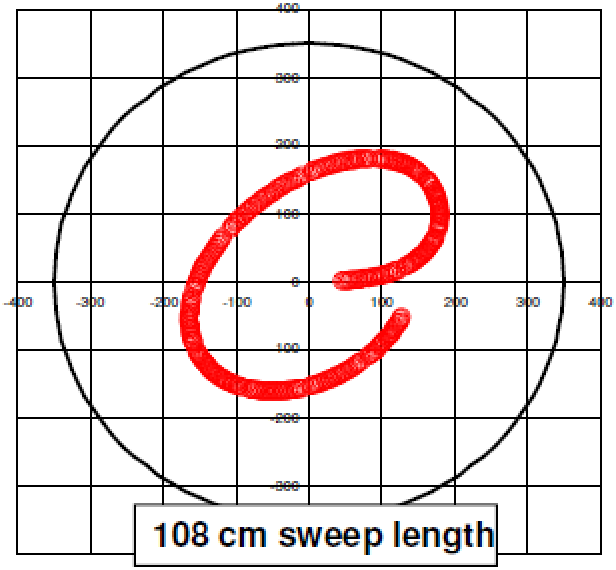


- TCDQ
  - Replaced by three module unit in LS1
  - Should then already be HL-LHC compatible
- TCDS
  - Probably limited to ULTIMATE intensity
  - Ti part of the diluter will deform plastically above this

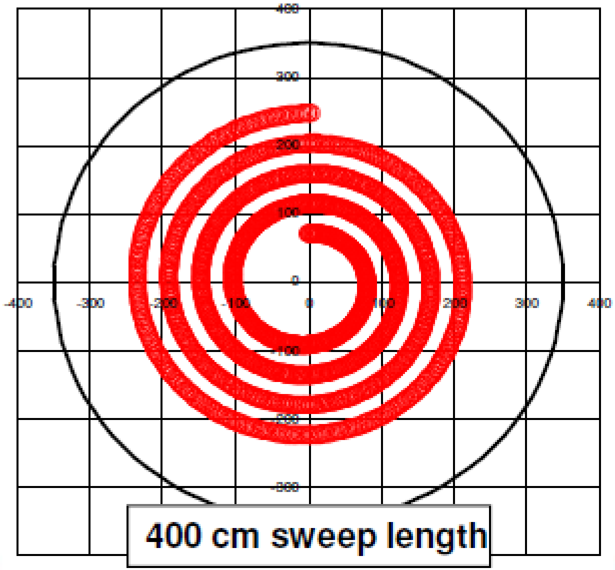
Dump Block

OK for ULTIMATE intensity

- Going above will:
  - Require dilution kicker upgrade
    - Increase sweep length by increasing the frequency
    - Requires more MKB tanks
  - Check of N_2 gas handling system
    - Pressure might be too high after repeated dumps
  - Check of windows & BTVDD screen



108 cm sweep length



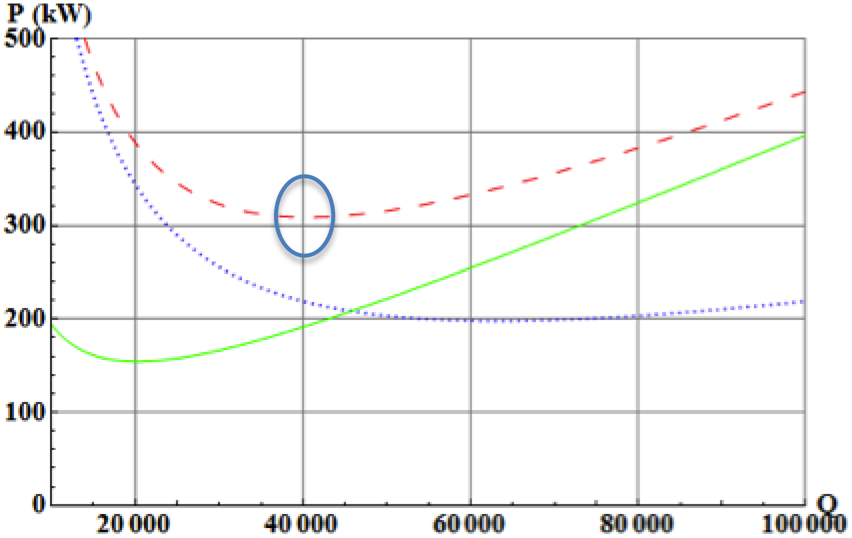
400 cm sweep length

Vacuum

- Only hard limitation is ion induced instability limit at 2.3A
  - Determined by beam screen pumping (size of holes)
- Fast pressure transients
  - Currently leads to the closure of sector valves near collimator locations
  - Needs new interlock strategy
    - Make system immune to short transients
    - Evaluation required of risk & impact of missing real vacuum leak compared to risk of exercising the complete beam dump system
  - Hollow electron lens could mitigate by controlling time distribution of losses
- Thermal induced desorption
  - Increased outgassing – order of magnitude pressure increase every 50°C
  - Collimators
    - Expect pressure rise & larger radiation dose to neighbouring equipment
    - Adds to flux impacting on magnets (i.e. quench limit)
  - RF heating
    - Issue for experimental background

RF System Limits – Present Scheme

- RF/LLRF is currently setup to minimize transient beam loading effects
- Would need at least 300 kW of klystron forward power at ultimate intensity
- Klystrons saturate at 200 kW with present DC parameters (ultimately 300 kW).
- The present scheme cannot be extended much beyond nominal.



Required klystron power for
1.15e11 ppb, 25 ns, 7 TeV,
1.7e11 ppb, 25 ns, 450 GeV,
1.7e11 ppb, 25 ns, 7 TeV

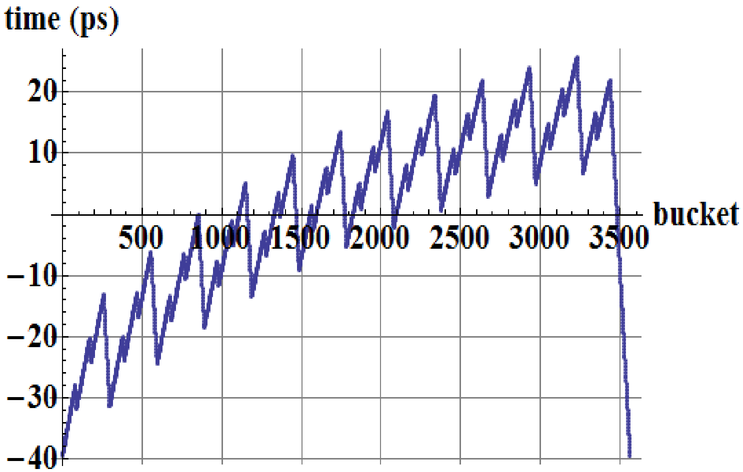
RF System Limits – Proposed Scheme

Phase modulated RF voltage

- Cavity phase modulated by transient beam loading
- Klystron drive kept constant over one turn
- Needed klystron power becomes independent of the beam current.
- For Q_L=60k, need only 105 kW for 12 MV total
- Stability not modified
- Displacement of luminous region acceptable to experiments

During filling

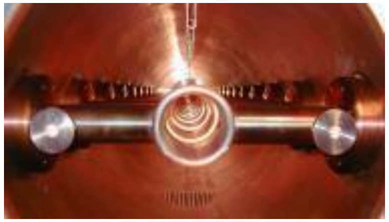
- Keep cavity phase constant for clean capture
  - Possible to use present scheme thanks to reduced total voltage (6 MV) required.



Modulation of the cavity phase by the transient beam loading in physics. 2835 bunches, 1.7 10^{11} p/bunch, 1.5 MV/cavity, QL=60k, full detuning (-7.8 kHz).

RF System Limits – Conclusions

- Phase modulated RF voltage allows intensity independent operation
  - Used for Ramp & 7 TeV
  - Will affect other possible HL-LHC systems
    - 800MHz needs same modulation ⇒ more power ⇒ more expensive
    - Crab cavities require prohibitively more power
      - Need to live with bunches receiving transverse kicks ⇒ offset collisions
- Limitation becomes RF power required at injection
  - Close to limit at HL-LHC intensities
- Current injection intensity limitation given by SPS RF
  - Limited to just above nominal at 25ns spacing
  - Accepting 10% longer bunches would allow an increase of bunch intensity to ~1.45×10^{11} if increased capture losses acceptable in LHC
  - Going to ultimate intensities & beyond
    - Requires upgrade to SPS RF and LLRF systems



Summary

- **Cryogenics**
    - If limited will be due to e-cloud heat load – increasing intensity will not make it worse
- **Impedance**
    - Not much margin with current collimators – needs new secondary collimator material/coating
- **RF Heating**
    - MKI and TDI will need redesign to go beyond nominal
- **Collimation**
    - Might be limited by collimator damage threshold due to continuous losses
- **Air Activation in Collimation Regions**
    - Ultimate should be OK but keeping below 10μS/year may not be possible with HL-LHC
- **Injection & Dump Systems**
    - TDI – needs redesign to reach ULTIMATE
    - TDE – OK for ULTIMATE – probable upgrade of system required to go higher
- **Vacuum**
    - Hard limit due to ion induced instability in arc beam screen well above HL-LHC parameters
    - Interlock due to fast losses will need to be revisited post LS1
- **RF**
    - With new scheme limit is at injection but should be able to cope with 2.2×10^{11} per bunch
    - New scheme has impact on other HL-LHC items – 800MHz & crab cavities

High
Luminosity
LHC

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