SPS 2021 intensity ramp up and its implications for the kickers

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Acknowledgements:
M. Beck, A. Harrison, V. Kain, K. Kodama, L. Vega Cid, E. Veyrunes

Assumptions

Baseline:
4x72 bunches, 25ns structure;
Injection bunch length ~3ns, shortening during the ramp to ~1.6ns at flat top;
Scrubbing for 1.3e11 ppb so will probably target an intensity slightly above (no bunch shortening).

Possibly:
Eventually, depending on how things go, pushing forward into the LIU regime ⇨ a maximum of 2.6e11 - 2.8e11 ppb.
(This will not be for the start-up, but just to give an idea on where we will need to be heading for the coming years after LS2).

Overview

- Brief overview of SPS kicker modifications during LS2
- Reminder of interlock levels and limits for temperature and pressure
- Estimates for heating, cool down rates to help planning a schedule
- Required OP procedures and actions, expert contact persons during beam commissioning
- Beam commissioning for kickers

Modification of SPS kicker magnets during LS2

- MKP vented with dry nitrogen (will not be DC conditioned, only pulse conditioned).
- Neither MKE4 nor MKE6 vented.
- MKDV now consists of 3 magnets (was 2 prior to LS2, i.e. one new magnet). Ferrite yoke, not shielded, but conductors closer to beam than ferrite. Heating not expected to be an issue.

Operational scenarios

Temp. rise of MKE4, MKE6, MKD and MKP-S kicker magnets are not expected to limit SPS operation, even for HL-LHC type beams with 2.6e11 pb, 4 x 72b, 25ns (Inj. BL ~3ns, ⇨~1.6ns at flat top). **But MKP-L will limit operation:**

Confident: OK

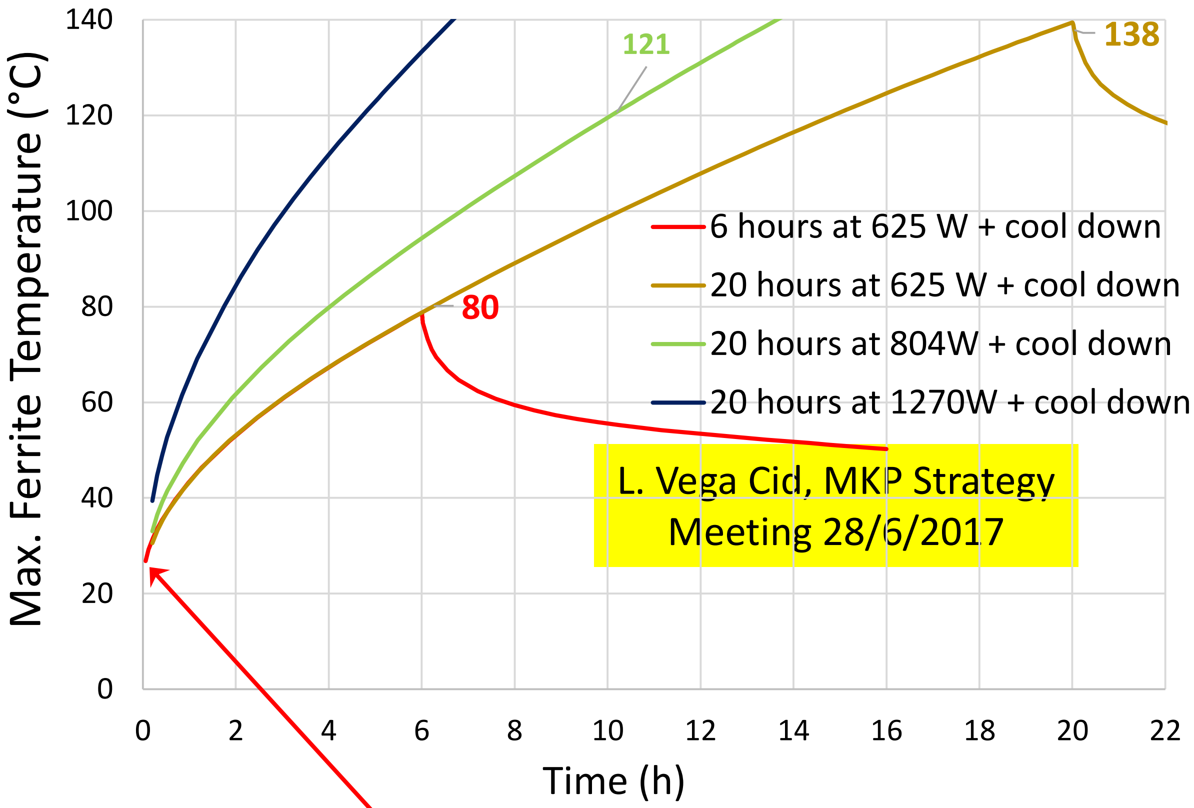
Could exceed Tc: rise of mis-kicking beam

Not OK

Risk of mechanical damage

Scenario		trains	Injected p/b	Exrtracted p/b	duty cycle	cycle type	module length [m]	resulting average power loss [W/m]	resulting average power loss per module [W/module]	duration (hours)	repetition	Ferrite Temperature
	2018 operation	3x48	1.33E+11	1.20E+11	50%	acceleration	0.7	149	104	1.5	every 12 hours	OK
	2018 MD	4x48	1.80E+11	1.80E+11	50%	flat bottom	0.7	164	115	10	once per week	OK
scrubbing week	2021 scrubbing	4x72	1.50E+11	1.50E+11	70%	flat bottom	0.7	239	167	continuous	continuous	OK
typical week	2021 operation	4x48	1.44E+11	1.30E+11	50%	acceleration	0.7	220	154	1.5	every 12 hours	OK
	2021 MD	4x72	1.67E+11	1.50E+11	50%	acceleration	0.7	443	310	10	once per week	OK
scrubbing week	2022 scrubbing	4x72	2.00E+11	2.00E+11	70%	flat bottom	0.7	424	297	continuous	continuous	Exceeds TC
typical week	2022 operation	4x48	1.67E+11	1.50E+11	50%	acceleration	0.7	296	207	1.5	every 12 hours	OK
	2022 MD	4x72	2.22E+11	2.00E+11	50%	acceleration	0.7	783	548	10	once per week	Close to TC
scrubbing week	2023 scrubbing	4x72	2.60E+11	2.60E+11	70%	flat bottom	0.7	717	502	continuous	continuous	Not OK
typical week	2023 operation	4x48	2.00E+11	1.80E+11	50%	acceleration	0.7	424	297	1.5	every 12 hours	Exceeds TC
	2023 MD	4x72	2.56E+11	2.30E+11	50%	acceleration	0.7	1074	752	10	once per week	Not OK
typical week	2024 operation	4x48	2.00E+11	1.80E+11	50%	acceleration	0.7	424	297	1.5	every 12 hours	Exceeds TC
	2024 MD	4x72	2.56E+11	2.30E+11	50%	acceleration	0.7	1074	752	10	once per week	Not OK

MKP-L: Predicted (max.) ferrite temperature versus time and dissipated power



Note: simulation starts at 25C

Assuming 10C/hr limit (manufacturer suggests 15C/hr for ferrite):

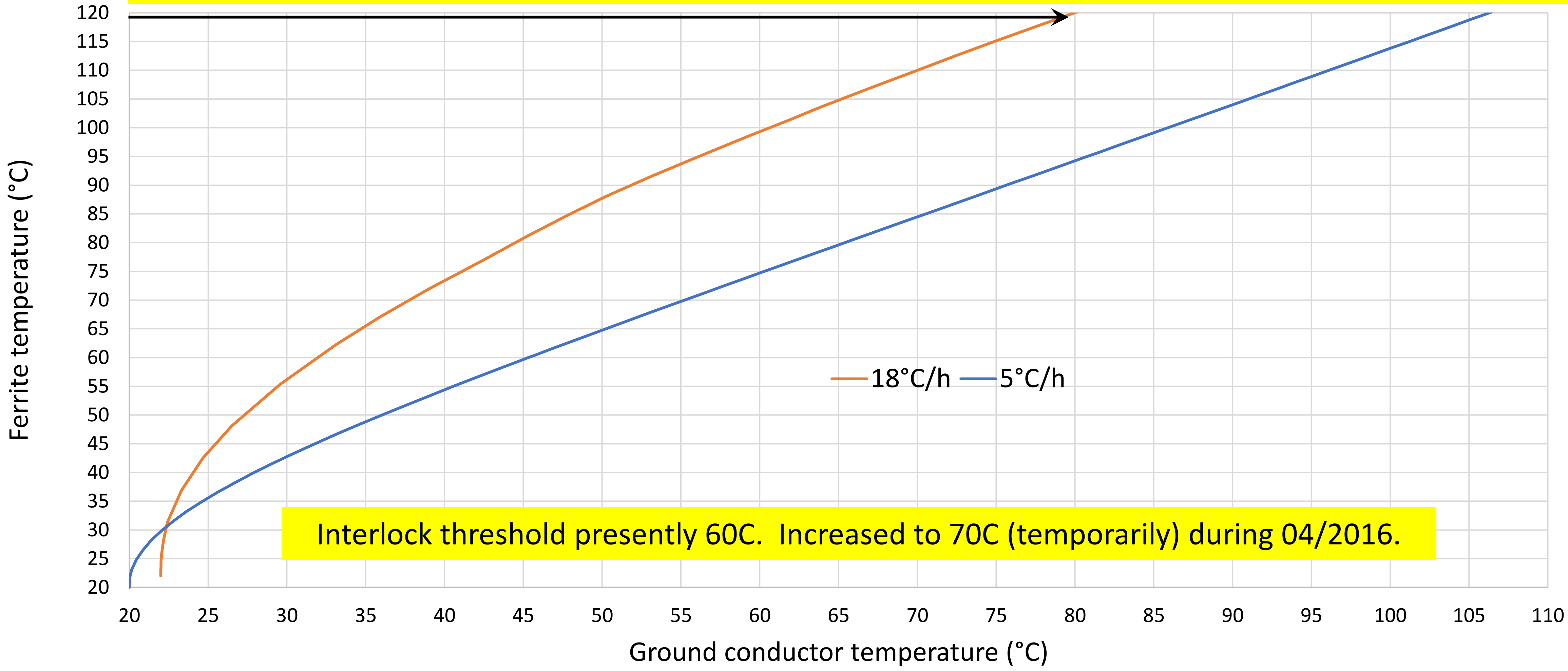
Time (hrs)	Temperature, 625W, [C]	dT/dt, 625W, (C/hr)	Temperature, 804W, [C]	dT/dt, 804W, [C/hr]
0	25		25	
0.5	37	**24.0**	41	**32.0**
1.5	48.5	**11.5**	56	**15.0**
3	61	**8.3**	72	**10.7**
6	80	**6.3**	95	**7.7**
10	100	5.0	121	**6.5**
~~20~~	~~138~~	~~3.8~~	~~170~~	~~4.9~~

To a first approximation, heating rates are proportional to average dissipated power.
Thus, for 300W, extrapolating:

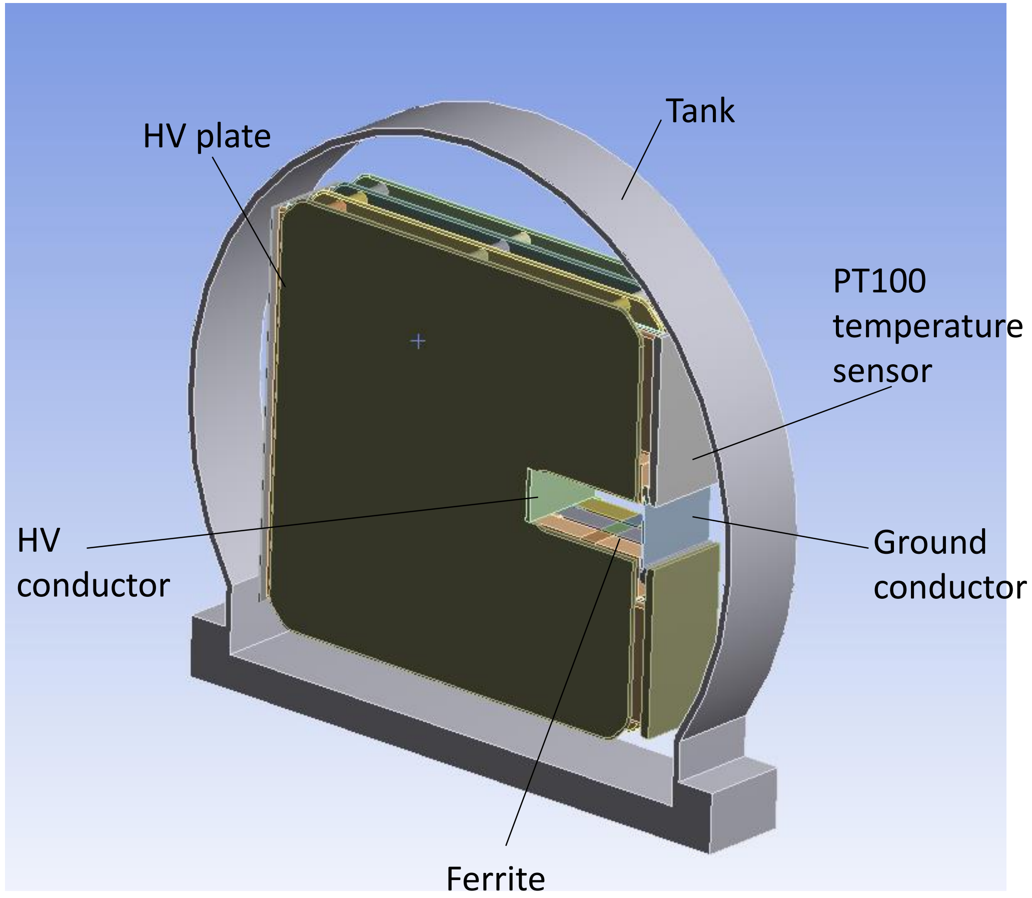
Time (hrs)	Temperature, 300W, [C]	dT/dt, 300W, (C/hr)
0	25	
0.5	31	**12.0**
1.5	36.75	**5.8**
3	43	4.2
6	52.5	3.2
10	62.5	2.5
~~20~~	~~81.5~~	~~1.9~~

MKP-L: Predicted (max.) temperatures for 2 heating rates

No direct correlation between measured temperature (on Ground conductor) and Ferrite temperature….:



MKP-L Kicker Magnet (1)

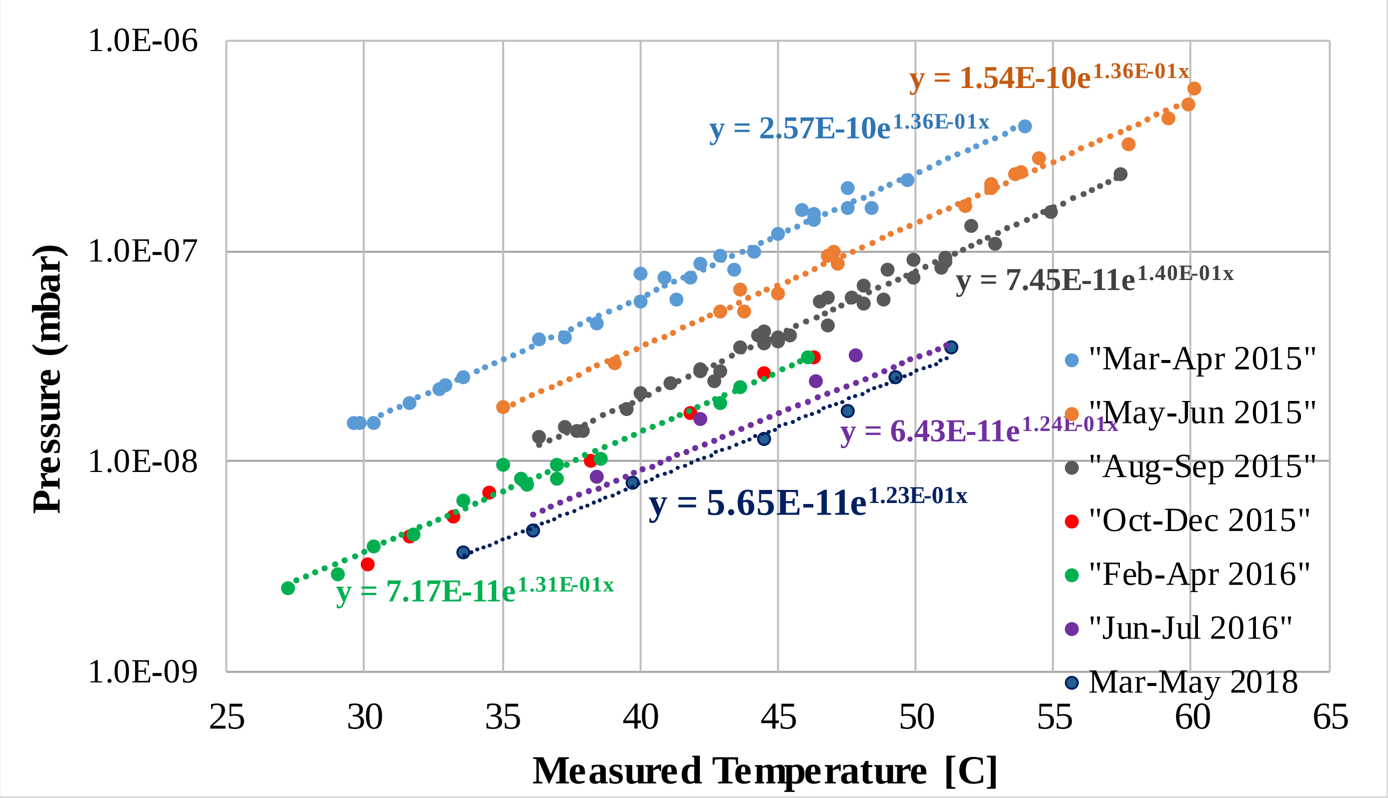


- Curie temperature of ferrite would be exceeded under some scenarios ⇨ mis-injected beam…..
- PT100 does not measure well ferrite temperature – for a given ferrite temperature, PT100 reading depends upon rate of heating…..
- High rate of heating (e.g. 30C/hr for 800W/module) in ferrite legs could lead to mechanical damage:
  - Cracking of ferrite 'legs' – already observed (but reason for cracking unknown);
  - Local chipping of ferrite 'legs'

- Will need to gain experience, during high intensity operation of SPS kicker magnets, in particular with MKP-L, to calibrate thermal models.

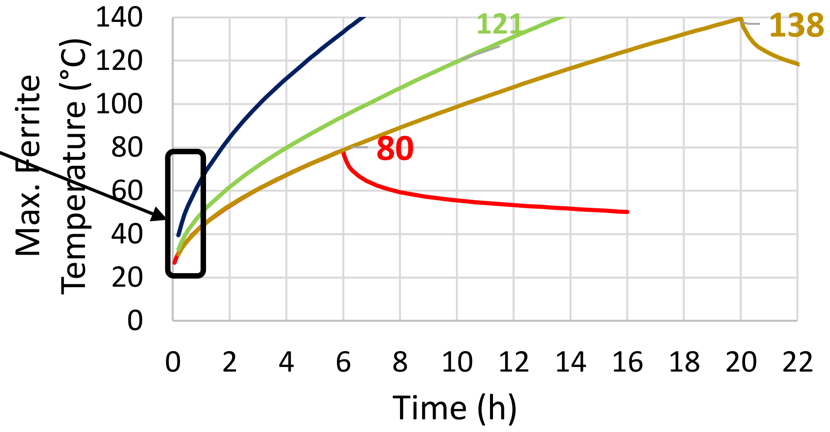
MKP-L Kicker Magnet (2)

- SPS kicker magnets are NOT designed to be bakeable:
  - Elevated temperature of ferrite will lead to high outgassing, and hence higher risk of electric breakdown during injection;
  - ‘Continuous’ 2021 scrubbing will heat ferrite (~100C expected ⇨ ~85C measured) which will result in high-outgassing and possible risk of breakdown during injection, e.g.
    85C measured expected to give: ⇨ background pressure of 2e-6mbar (66C ⇨ 2e-7 mbar, 77C ⇨ 7e-7 mbar).
  - With time, outgassing will slightly reduce for a given ferrite temperature.



Possible short-term 'mitigation' of issues for MKP-L

- Thermal studies launched to study possible means of reducing risk of mechanical damage, e.g.:
  - Reduce initial power dissipation in ferrite by decreasing initial power deposition (e.g. 3 batches instead of 4) with high intensity beams;



- Risk of mis-injection of beam, into SPS, could be reduced following high-intensity scrubbing/operation by pulsing MKP kicker magnets, with increasing voltage, when SPS is empty:
  a) Used to validate that MKP-L temperature < Curie temperature, by measuring pulse properties of kicker magnets ⇨possibility to change MKP-L temperature interlock threshold;
  b) (Re-)condition MKP kicker magnets before injection into SPS.

- Controls to allow the above pulsing could possibly be implemented during YETS 2021/22 (fixed pulse width, only vacuum interlock, …) – budget required…
  - IPOC analysis to be fully defined for short pulse & long read-back cables;
  - Require Python script for analysis of IPOC data.

Longer-term 'mitigation' of issues for MKP-L

- MKP-L with serigraphy designed and will be prototyped…. This MKP-L has ~order of magnitude less beam induced heating – hence, no thermal issues expected. Therefore, ferrite outgassing is also expected to be greatly reduced since temperature rise will be limited:
  - Theoretical calculations show that serigraphy should not degrade field rise-time (to be confirmed on the prototype);
  - Mechanical robustness to be verified on the prototype MKP-L;
  - Impedance to be verified on a prototype MKP-L;
  - HV performance to be verified on the prototype MKP-L;
  - Alumina carrier of serigraphy may cause ecloud issues: possible solution (verified on LHC MKIs and on liners in SPS) is to coat alumina with Cr2O3;
  - Estimating price for upgrading a 4 module MKP-L;
  - Initial planning shows that:
    - 2 module prototype MKP-L could be assembled, measured and tested by autumn 2020;
    - If prototype is verified: Upgraded 4 module spare MKP-L would be ready for installation during YETS 2021-2022.

Temperature and Pressure Interlock Thresholds

Temperature of MKE4, MKE6 and the MKD kicker magnets are not expected to directly limit SPS operation, even for HL-LHC type beams with 2.6e11 pb, 4 x 72b, 25ns. However, background pressure at elevated temerature may be an issue (especially where nagnets have not previously been at the high temperature).

MKE4 & MKE6

Temperature interlock thresholds:

- Circulating beam 90 C (SW)
- Extraction beam 70 C (SW)

Vacuum interlock threshold for both MKE4 & MKE6: no SW interlocks . 1e-6/5e-7 mbar (HW).

MKP

Temperature interlock threshold: 60 C (to be increased to 70 C)

Vacuum interlock thresholds:

- MKP-S (MKP1,2,3): 2.1e-7 mbar (SW). 6e-7/5e-7 mbar (HW)
- MKP-L (MKP4), Physics: 2.1e-7 mbar (SW). 8e-7/7e-7 mbar (HW)
- MKP-L (MKP4), MD or Scrubbing: 7.1e-7 mbar (SW). 8e-7/7e-7 mbar (HW)
- MKP-L (MKP4), Max: 5.1e-7 mbar (SW). 8e-7/7e-7 mbar (HW)

MKD

Temperature interlock threshold: no interlock

Vacuum interlock threshold: no SW interlock. 5e-7/3e-7 mbar (HW)

MKQ

Temperature interlock threshold: no interlock

Vacuum interlock threshold: no SW interlock. 1e-6/9e-7 mbar (HW)

Required OP procedures and actions

Temperature

- MKP: if temperature approaches interlock threshold, reduce average power deposition in magnet (e.g. for a given scrubbing intensity, increase super-cycle duration).
- MKE: no major issues expected: hence, if an issue, contact expert.
- MKD: no major issues expected. Heating will cause background pressure increase. If an issue, contact expert.

Pressure

- MKP:
  - if pressure approaches interlock threshold, this could be due to both ecloud and background pressure due to heating. Reducing average power would reduce background pressure – but a long thermal time constant.
  - If magnets breakdown when pulsed, magnets need to be reconditioned. In absence of automatic procedure, needs to be done in BA1 by piquet.
- MKE4/6: no major issues expected in 2021. But background pressure will increase with temperature, due to outgassing
  - if pressure approaches interlock threshold ask expert to check pressure due to ecloud and temperature
  - if magnets breakdown when pulsed, magnets need to be reconditioned by piquet.
- MKD: new MKDV will require (potentially long) conditioning: hence, if an issue, contact expert. After extended scrubbing or high intensity MD, is pressure > 1e-8 mbar, magnets need to be reconditioned, in situ, by piquet.

Expert contact persons during beam commissioning

MKP
Generator: Peter BURKEL
Magnet: Mike BARNES
Controls: Nicolas VOUMARD
ABP: Francesco VELOTTI

MKE4/6
Generator: Peter BURKEL
Magnet: Mike BARNES
Controls: Christophe LOLLIOT
ABP: Francesco VELOTTI

MKQ
Generator: Peter BURKEL
Magnet: Peter BURKEL
Controls: Lorane ALLONNEAU
ABP: Francesco VELOTTI

MKDH
Generator: Viliam SENAJ
Magnet: Vasco NAMORA
Controls: Pieter VAN TRAPPEN
ABP: Francesco VELOTTI

MKDV
MKDV Generator: Viliam SENAJ
MKDV Magnet: Gael BELLOTTO
MKDV Controls: Pieter VAN TRAPPEN
ABP: Francesco VELOTTI

Conclusions (to end of 2021)

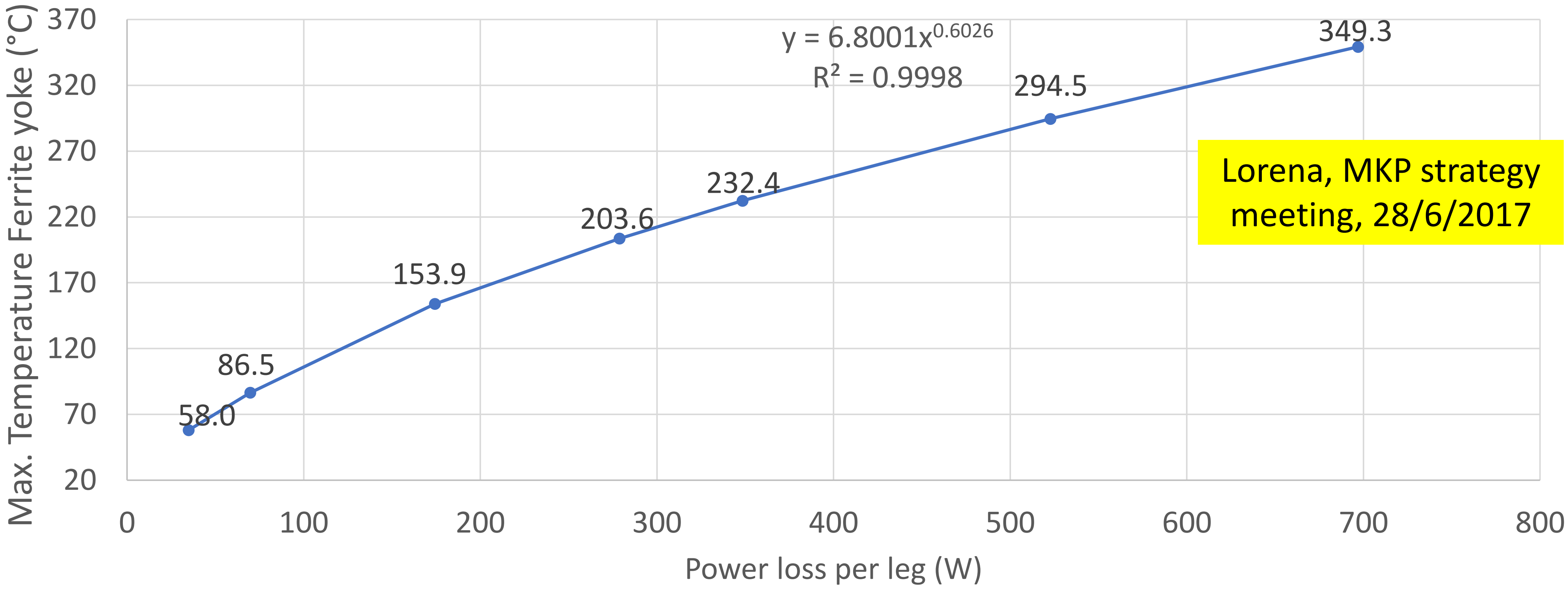
- No thermal issues expected for MKP-S, MKE or MKD kicker magnets
- MKP-L expected to be OK, thermally, during 2021 scrubbing and operation
  - However, ‘continuous’ 2021 scrubbing will heat ferrite (~100C expected ⇨ ~85C measured) which will result in high-outgassing and possible risk of breakdown during injection
- For MKP-L small risk of mechanical damage during 2021 MD – mitigating measures under study
- Prototyping of MKP-L with serigraphy (for mitigating heating) ongoing:
  - Prototype MKP-L could be measured and tested by autumn 2020;
  - If prototype is verified: upgraded 4 module spare MKP-L would be ready for installation during YETS 2021-2022.

Thank you for your attention.

Questions ?

Spare slides

Steady state calculations



- The maximum temperature reached in the yokes can be calculated with this graph for different scenarios.
- The results are pessimistic due to the long thermal time constant of the magnet: several hours are needed to reach the steady-state regime.

Operational scenarios

Temperature rise of MKE4, MKE6, MKD and MKP-S kicker magnets are not expected to limit SPS operation, even for HL-LHC type beams with 2.6e11 pb, 4 x 72b, 25ns. **But MKP-L will limit operation:**

Confident: OK

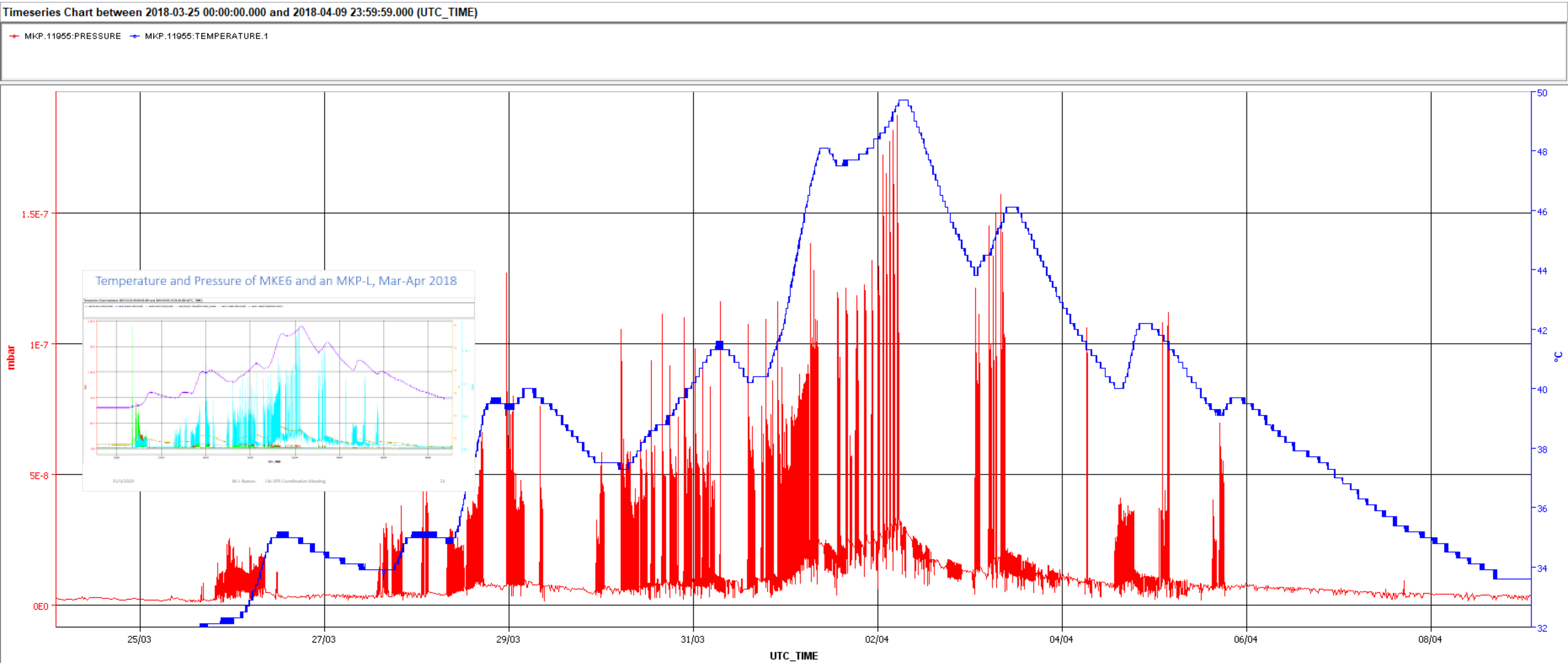
Could exceed Tc: rise of mis-kicking beam

Not OK

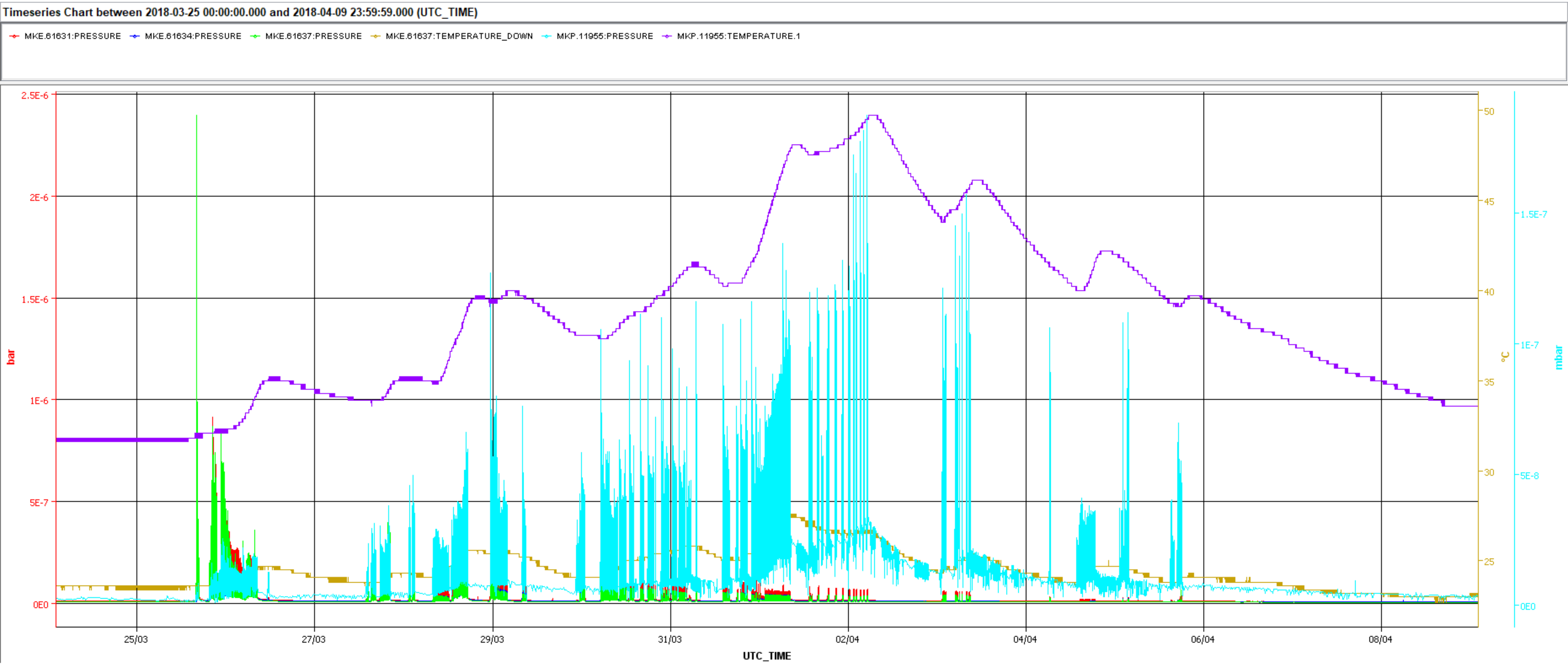
Risk of mechanical damage

Scenario		trains	Injected p/b	Exrtracted p/b	duty cycle	cycle type	module length [m]	resulting average power loss [W/m]	resulting average power loss per module [W/module]	duration (hours)	repetition	Ferrite Temperature	Continuous OP (Plot 1) [C]	T+
	2018 operation	3x48	1.33E+11	1.20E+11	50%	acceleration	0.7	149	104	1.5	every 12 hours	OK	74	53.6
	2018 MD	4x48	1.80E+11	1.80E+11	50%	flat bottom	0.7	164	115	10	once per week	OK	78	63.7
scrubbing week	2021 scrubbing	4x72	1.50E+11	1.50E+11	70%	flat bottom	0.7	239	167	continuous	continuous	OK	98	
typical week	2021 operation	4x48	1.44E+11	1.30E+11	50%	acceleration	0.7	220	154	1.5	every 12 hours	OK	93	55.3
	2021 MD	4x72	1.67E+11	1.50E+11	50%	acceleration	0.7	443	310	10	once per week	OK	142	87.1
scrubbing week	2022 scrubbing	4x72	2.00E+11	2.00E+11	70%	flat bottom	0.7	424	297	continuous	continuous	Exceeds TC	138	
typical week	2022 operation	4x48	1.67E+11	1.50E+11	50%	acceleration	0.7	296	207	1.5	every 12 hours	OK	111	57.1
	2022 MD	4x72	2.22E+11	2.00E+11	50%	acceleration	0.7	783	548	10	once per week	Close to TC	200	115.5
scrubbing week	2023 scrubbing	4x72	2.60E+11	2.60E+11	70%	flat bottom	0.7	717	502	continuous	continuous	Not OK	190	
typical week	2023 operation	4x48	2.00E+11	1.80E+11	50%	acceleration	0.7	424	297	1.5	every 12 hours	Exceeds TC	138	60.8
	2023 MD	4x72	2.56E+11	2.30E+11	50%	acceleration	0.7	1074	752	10	once per week	Not OK	242	161.7
typical week	2024 operation	4x48	2.00E+11	1.80E+11	50%	acceleration	0.7	424	297	1.5	every 12 hours	Exceeds TC	138	60.8
	2024 MD	4x72	2.56E+11	2.30E+11	50%	acceleration	0.7	1074	752	10	once per week	Not OK	242	161.7

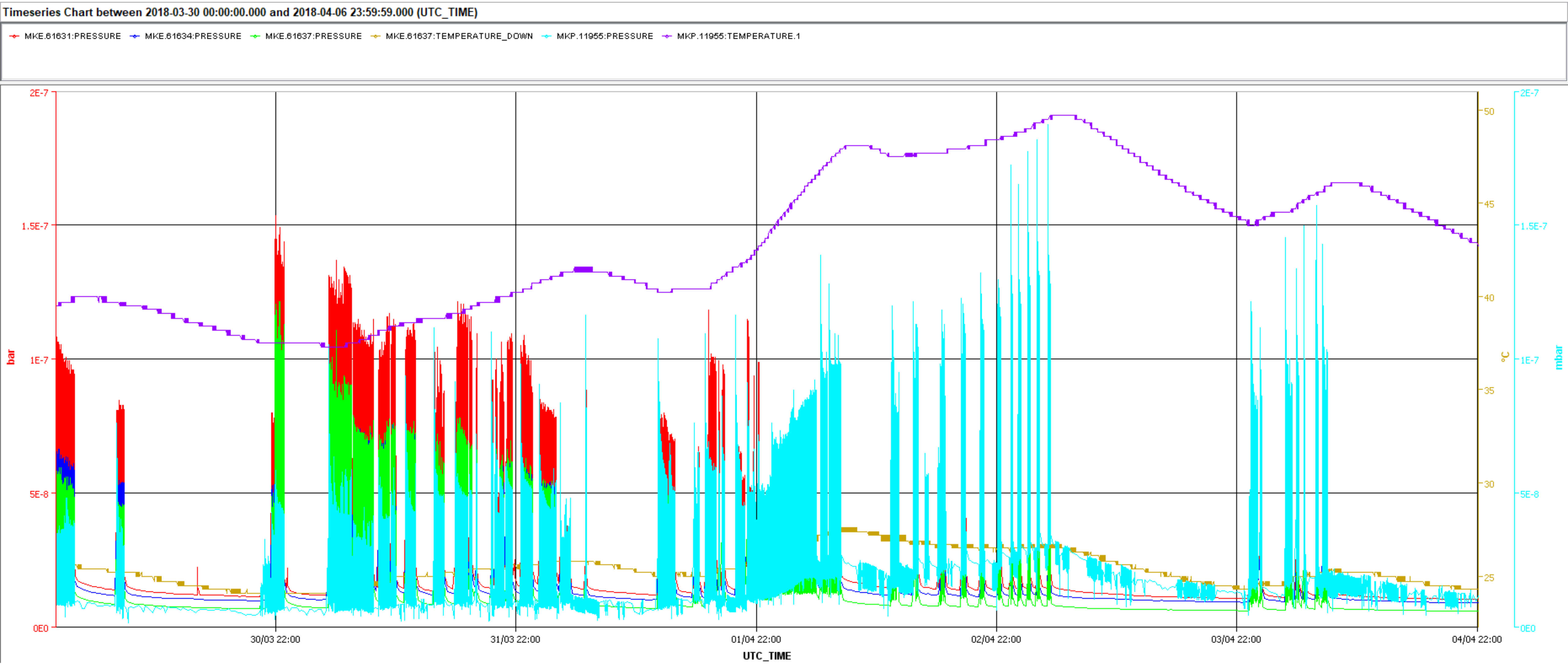
Temperature and Pressure of an MKP-L, Mar-Apr 2018



Temperature and Pressure of MKE6 and an MKP-L, Mar-Apr 2018

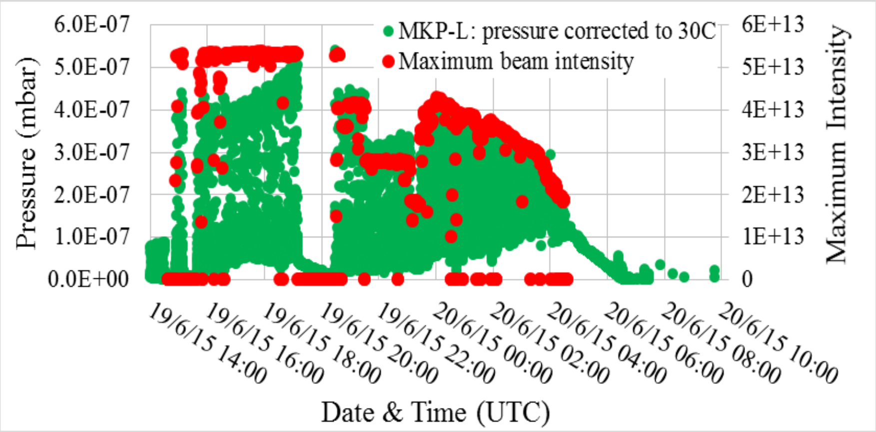


Temperature and Pressure of MKE6 and an MKP-L, Mar-Apr 2018

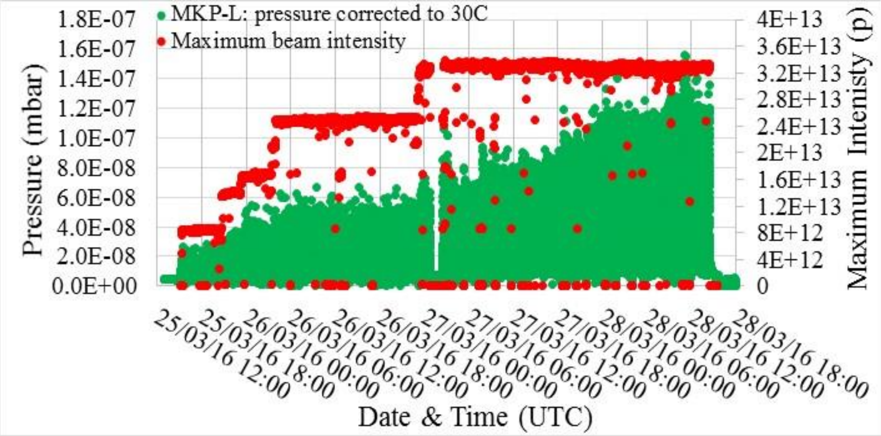


Fast Pressure Rise Corrected for Temp.

19/06/15 to 20/06/15 (25ns scrubbing run):



25/03/16 to 28/03/16 (25ns scrubbing run):



- Normalized pressure, corrected to 30˚C measured, is **~1x10^{-20} mbar/proton**.
- Operation at an elevated temperature seems to have reduced subsequent outgassing.

- Normalized pressure, corrected to 30˚C measured, is **~4x10^{-21} mbar/proton**. Hence some limited conditioning over the last 9 months.

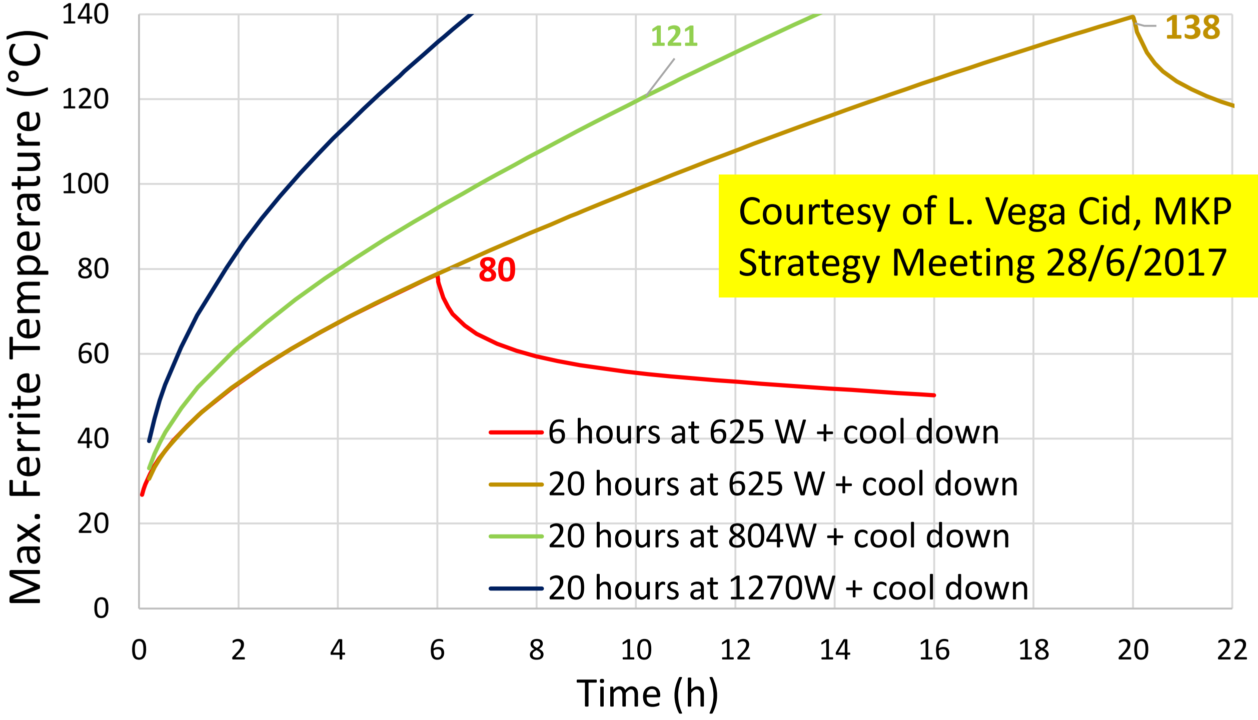
- In general the corrected pressure and beam intensity curves have the same shape, indicating that the fast pressure rise is attributable to multipacting;
- Methods of reducing SEY are being considered (e.g. LESS and aC) – but would need extensive testing (HV, UFOs, etc.);
- Studies of multipacting commenced by G. Rumolo et al to determine whether it would be expected for MKP-L.

Temperature rise of MKP

Note: MKP-L dissipation is 3-4 time greater than MKP-S, thus only MKP-L temperature is expected to heat significantly.

- For 1.6e11 ppb, 4 x 72b, 25ns, accelerated (taking into account changing beam spectrum): ~650W/MKP-L;
- For 2.2e11 ppb, 4 x 72b, 25ns, accelerated (taking into account changing beam spectrum): ~1200W/MKP-L;

Courtesy of M. Beck, MKP Strategy Meeting 13/4/2017

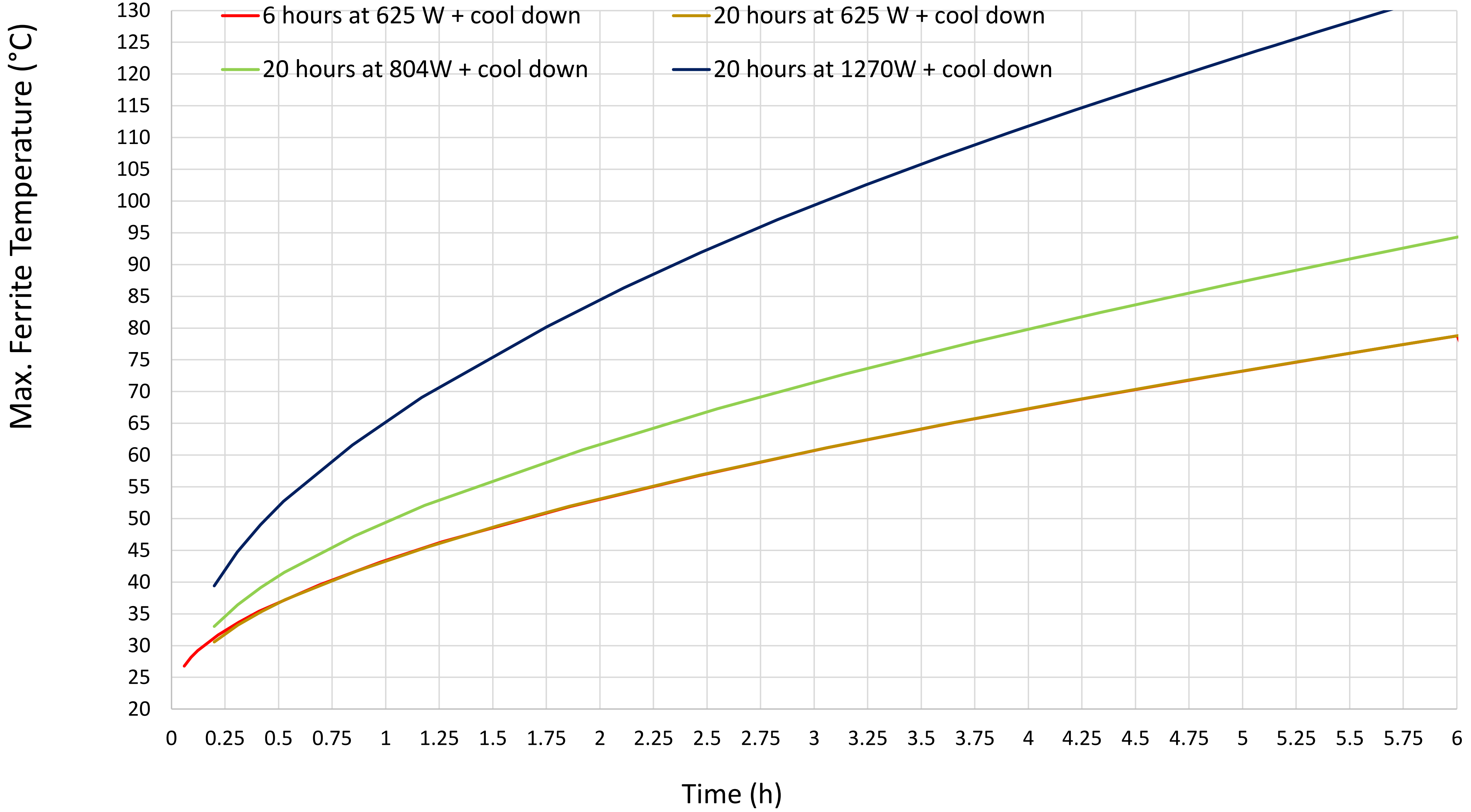


Courtesy of L. Vega Cid, MKP Strategy Meeting 28/6/2017

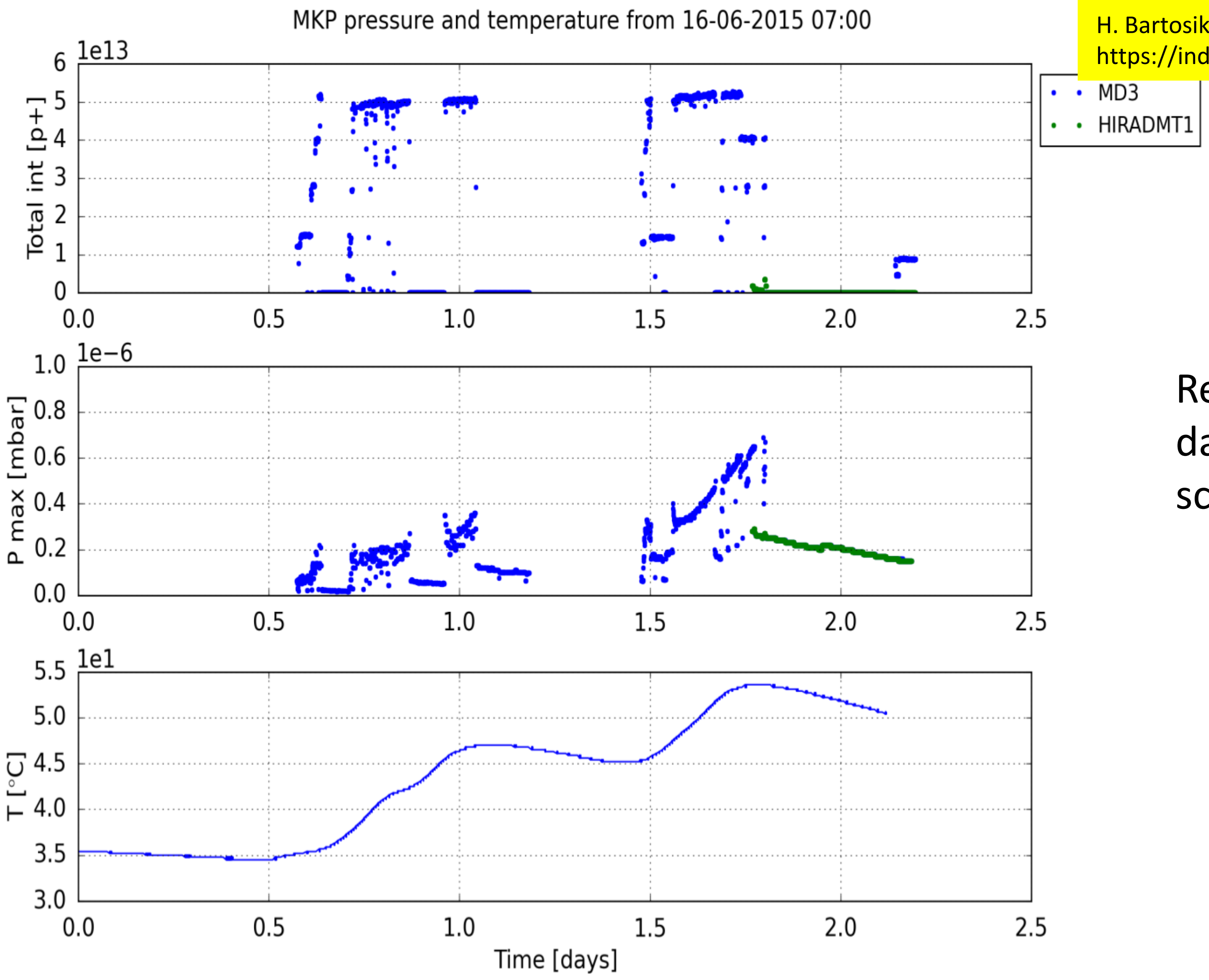
Starting with ferrite at ambient temperature:

- For 1.6e11 ppb, 4 x 72b, 25ns, accelerated (650W) ⇨ ~15hrs.
  - Require 2hrs without beam to cool by ~20C.
  - Can then scrub at this intensity again for ~4hrs.
- For 2.2e11 ppb, 4 x 72b, 25ns, accelerated (~1200W) ⇨ ~4hrs.
  - Require 2hrs without beam to cool by ~20C.
  - Can then scrub at this intensity again for ~2hrs.

MKP: Lorena predictions 13/4/2017



Operational limitations from MKPL in 2015



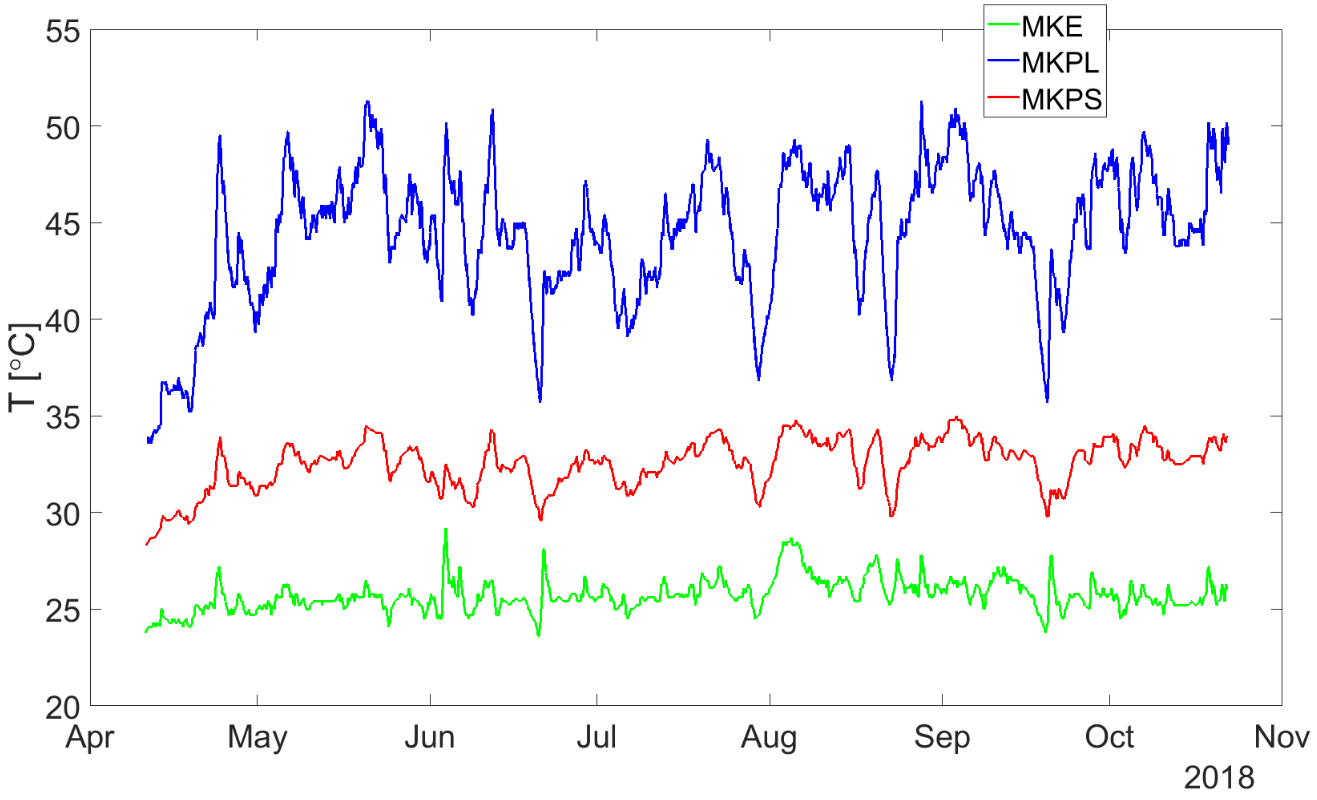
H. Bartosik, LIU-SPS BD WG meeting, 19/12/2019, https://indico.cern.ch/event/870931/

Reached close to 55° after 2 days of high intensity scrubbing in 2015

Operational limitations from MKPL in 2018

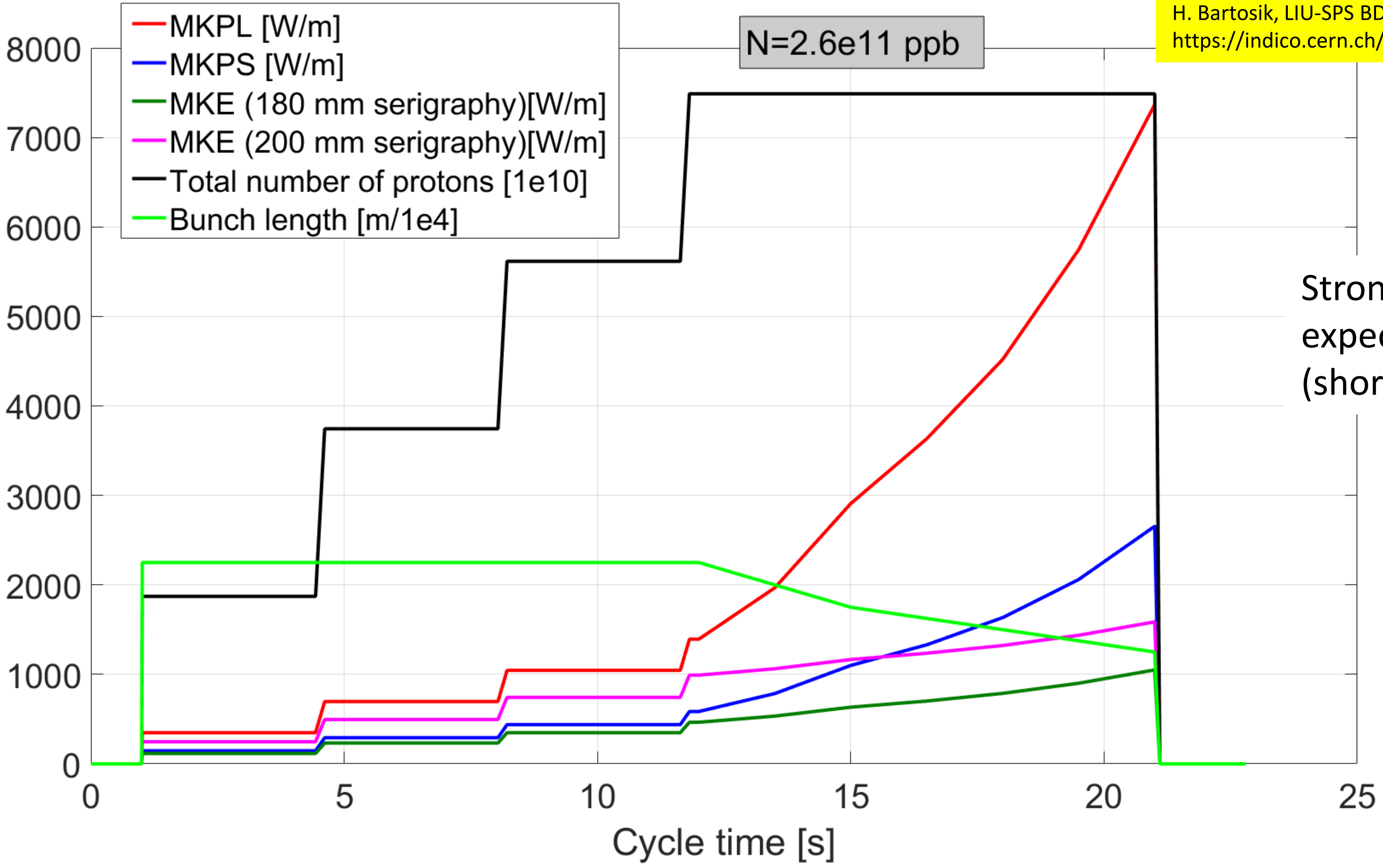
H. Bartosik, LIU-SPS BD WG meeting, 19/12/2019, https://indico.cern.ch/event/870931/

- Reached high temperatures even without dedicated scrubbing, just from nominal operation and high intensity studies on Thursdays



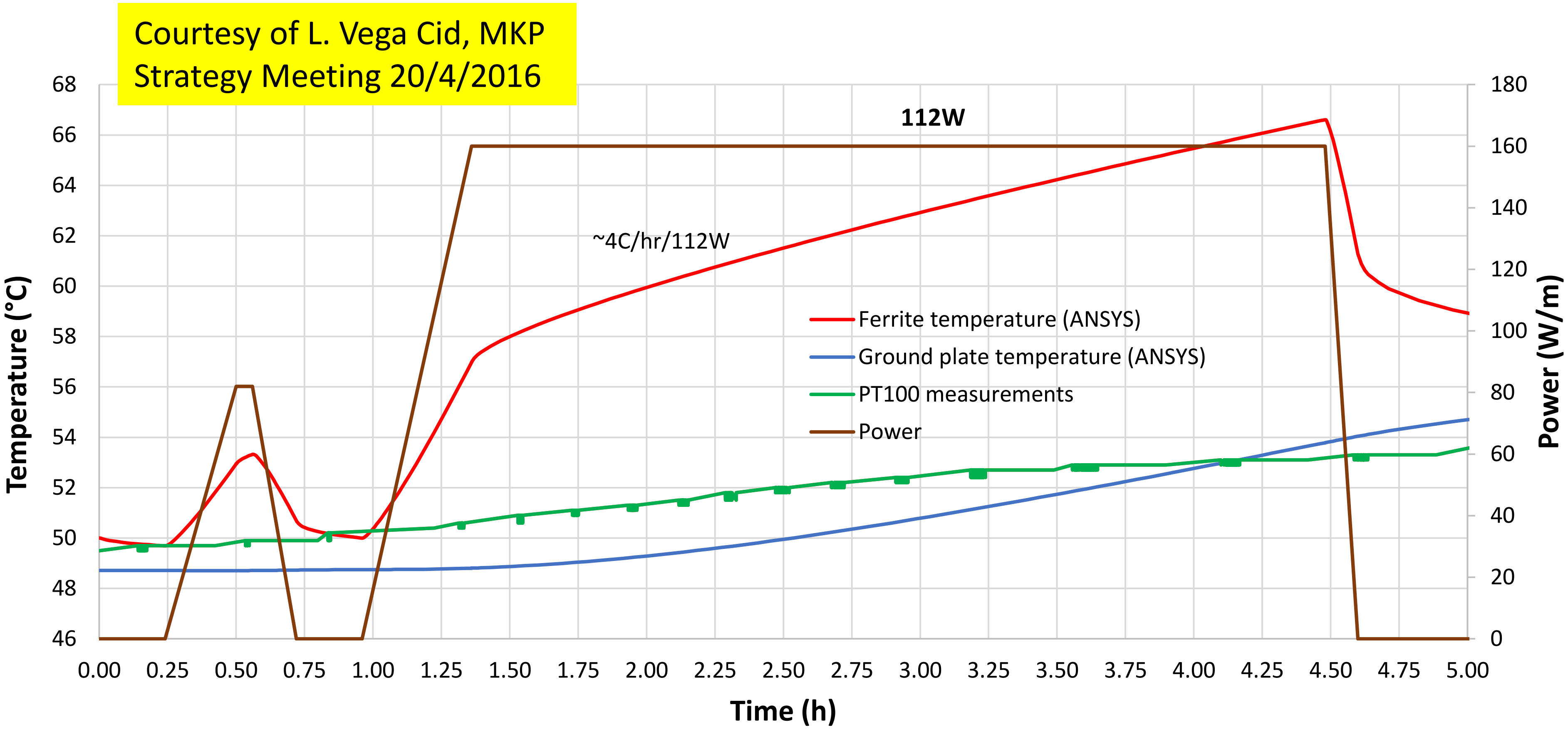
Power loss in kickers along cycle

H. Bartosik, LIU-SPS BD WG meeting, 19/12/2019, https://indico.cern.ch/event/870931/

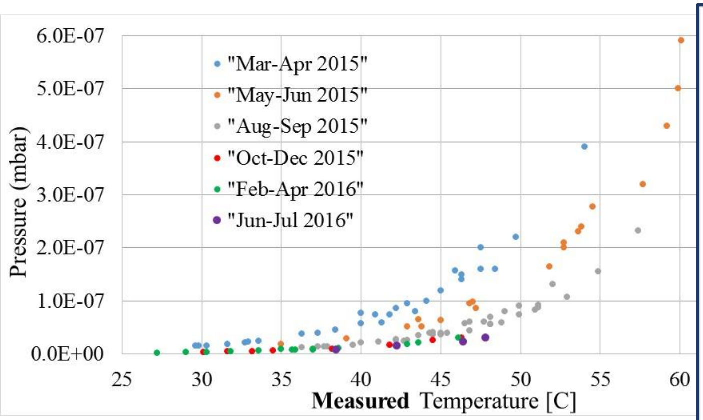


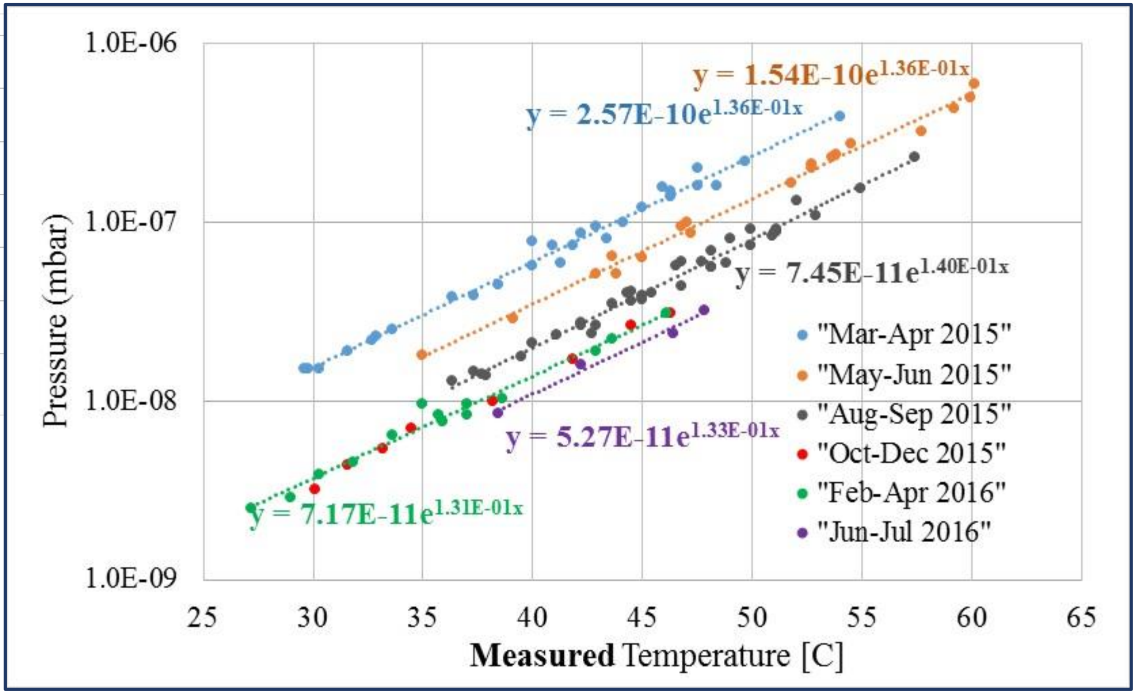
Strong heating of MKPL expected at high beam energy (short bunches)

Predicted heating of MKP-L



MKP-L Outgassing due to Heating





Since LS1 there have been periods of significant vacuum pressure rise in the MKP-L. The high pressure results in an important increase in the electrical breakdown rate. However:

- For a given measured temperature, **there has been a reduction in pressure by a factor of 5-6 between Mar-Apr. 2015 and Jun-Jul 2016 (5.5 at 40˚C).**
- Thermal treatment of Peraluman plates could not be carried out on MKP-L exchanged during LS1: **vacuum tests on plates show no difference in outgassing for sample plates which did and didn't undergo thermal treatment**.