Design and commissioning experience with state of the art MPS for LEReC accelerator

S. Seletskiy (on behalf of LEReC team)

ERL 2019

BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

MPS subsystems experts

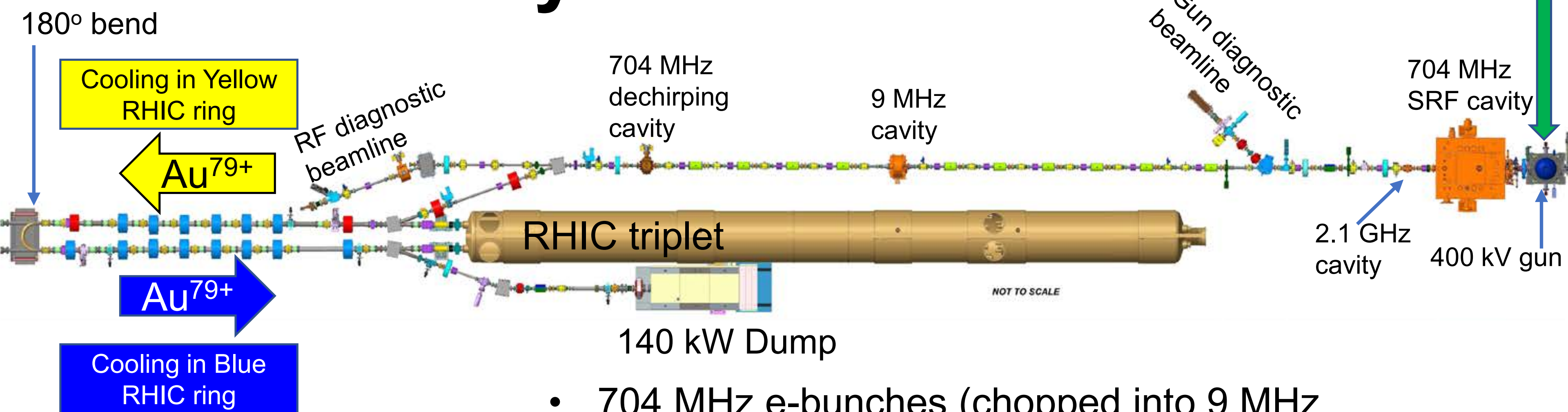
- Zeynep Altinbas – MPS engineer (MPS controller, MPS interaction with various subsystems etc.)
- Rob Hulsart – BPMs
- Toby Miller – diagnostics in general, insertable devices and BLMs in particular
- Matt Paniccia – FCTs
- Kevin Mernick – RF system and overall timing system
- Don Bruno – gun
- Patrick Inacker – laser
- Loralie Smart – vacuum system
- Sergei Seletskiy – conceptual design, coordination & administration

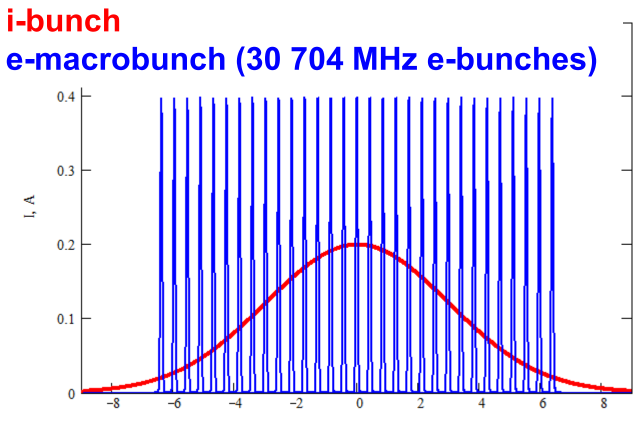
What is LEReC?

- Low Energy RHIC electron Cooler (LEReC) is the world's first RF-based ("bunched") electron cooler
- LEReC is the first electron cooler which is applied directly to the ions in the collider at top energy
- LEReC is the first electron cooler that utilizes the same electron beam for cooling ions in two consecutive cooling sections in two rings of the collider

- LEReC is an important part of low energy RHIC run dedicated to search of the QCD critical point in the nuclear matter phase diagram
- Since LEReC uses RF acceleration of the bunched beam it can be easily scaled for high energy applications

Accelerator layout





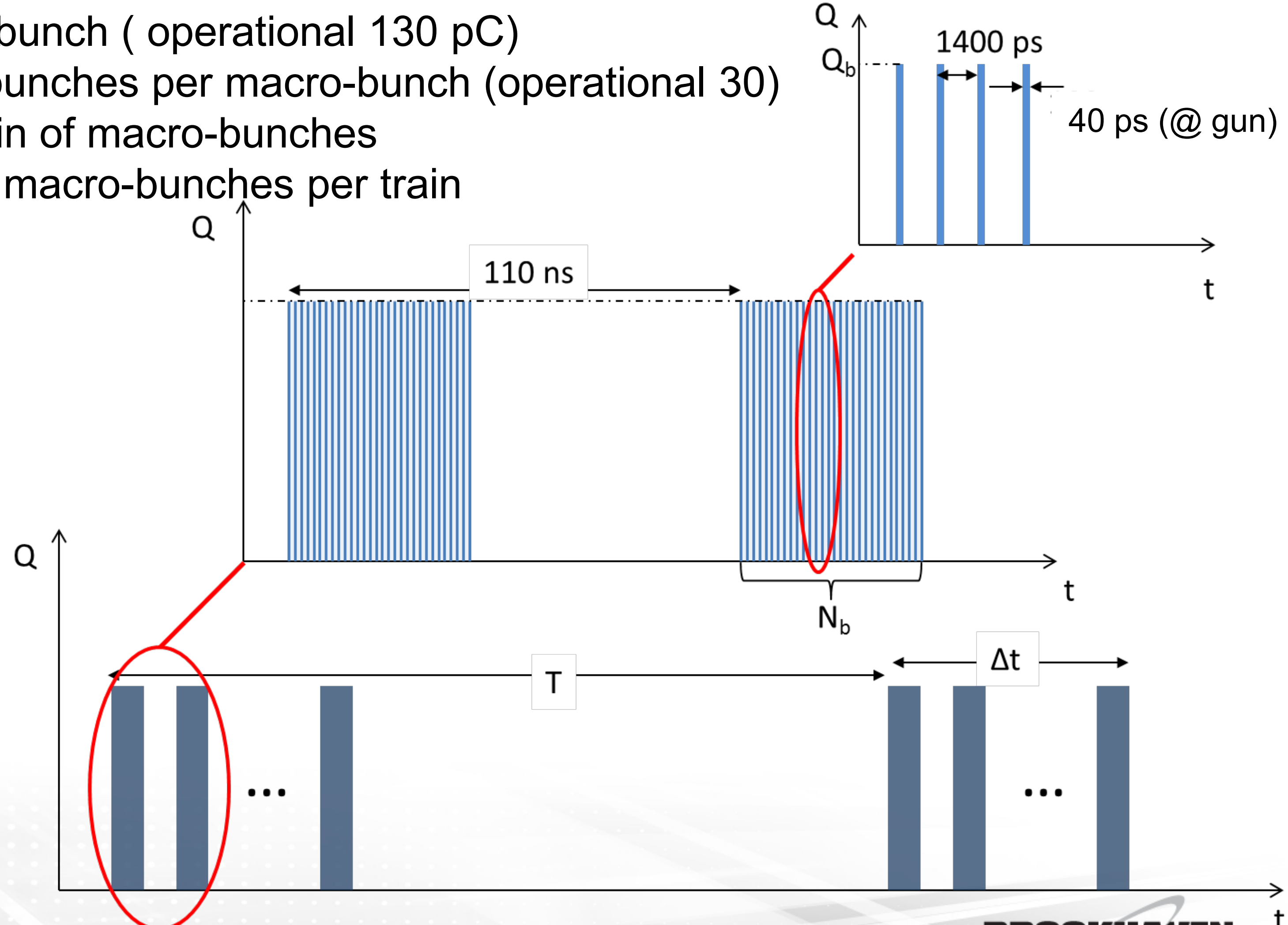
- 704 MHz e-bunches (chopped into 9 MHz macrobunches) are produced from photocathode and accelerated in gun to 400 keV
- Electrons are accelerated to design energy (1.6 MeV, 2 MeV, 2.6 MeV) in 704 MHz SRF Booster
- e-bunches are brought to Yellow and then Blue RHIC cooling sections (20 m long) where they co-travel with ion bunches with the same average velocity

- Operational beam current is 35-55 mA (baseline with trains); CW 85 mA (1.6 MeV), 67 mA (2 MeV)
- Operational beam power is <140 kW
- The smallest transverse RMS beam size in the LEReC (Merger beamline) is 0.25 mm

Time structure of LEReC beam

- Continuous sequence of 9 MHz macro-bunches or
- Trains (of length Δt) of 9 MHz macro-bunches repeated with frequency (f)

Q_b – charge per bunch (operational 130 pC)
N_b – number of bunches per macro-bunch (operational 30)
Δt – length of train of macro-bunches
N_{mb} – number of macro-bunches per train



Beam modes

Timing Pattern	Beam modes	Goals	Power
N_b = 30 N_b*N_{mb}*Q_b≤40nC f = 1 Hz	Low Current Mode (LCM); Q_b = 30 – 200 pC	Set beam optics & RF for nominal Q_b. Measure and fine-tune bunch parameters.	P ≤ 16 mW I ≤ 40 nA
N_b = 10,15,20,25,30 Δt ≤ 250 us T = 1 s – 5 s	RF Studies Mode (RFSM); Q_b ≤ 200 pC	RF fine-tuning. Study beam loading.	P ≤ 7 W I ≤ 3 uA
N_b = 30 N_{mb} = 1-6 f= 76 kHz	76 kHz Mode (76M) Q_b ≤ 200 pC	Obtain and optimize cooling of several ion bunches	P ≤ 7 kW I ≤ 2.7 mA
N_b = 30 f= 9 MHz	High current Mode (HCM); Q_b = 30 – 200 pC	Getting cooling of all ion bunches.	P = 142 kW I ≤ 55 mA
704 MHz CW	CW Mode (CWM); Q_b = 95 – 120 pC	Alternative to HCM.	P = 136 kW I = 68 - 85 mA

RFSM – has not been needed yet
CWM – is almost certainly obsolete
2.6 MeV – is obsolete. Hence, expected average power is reduced

MPS parameters

- We considered various failure scenarios resulting in the wrong power beam hitting various in-vacuum components: YAG screens, Vacuum Valves, Emittance Slits, Dumps, RF cavities and Vacuum Chamber
- As a result we identified the critical MPS parameters:

MPS Parameters	Value
Current threshold for ultimately safe operation mode (USOM)	**40 nA**
Reaction time (focused acute loss)	**40 us**
Tolerable routine distributed losses (halo scraping)	**100 uA**
Reaction time for small (up to 0.5 mA) distributed losses	**1 s**

The MPS reaction time was derived under assumption that beam optics studies are performed in LCM only and that in HCM the beam trajectory is kept in some reasonable range and that several critical magnet power supply currents are kept at operational values.

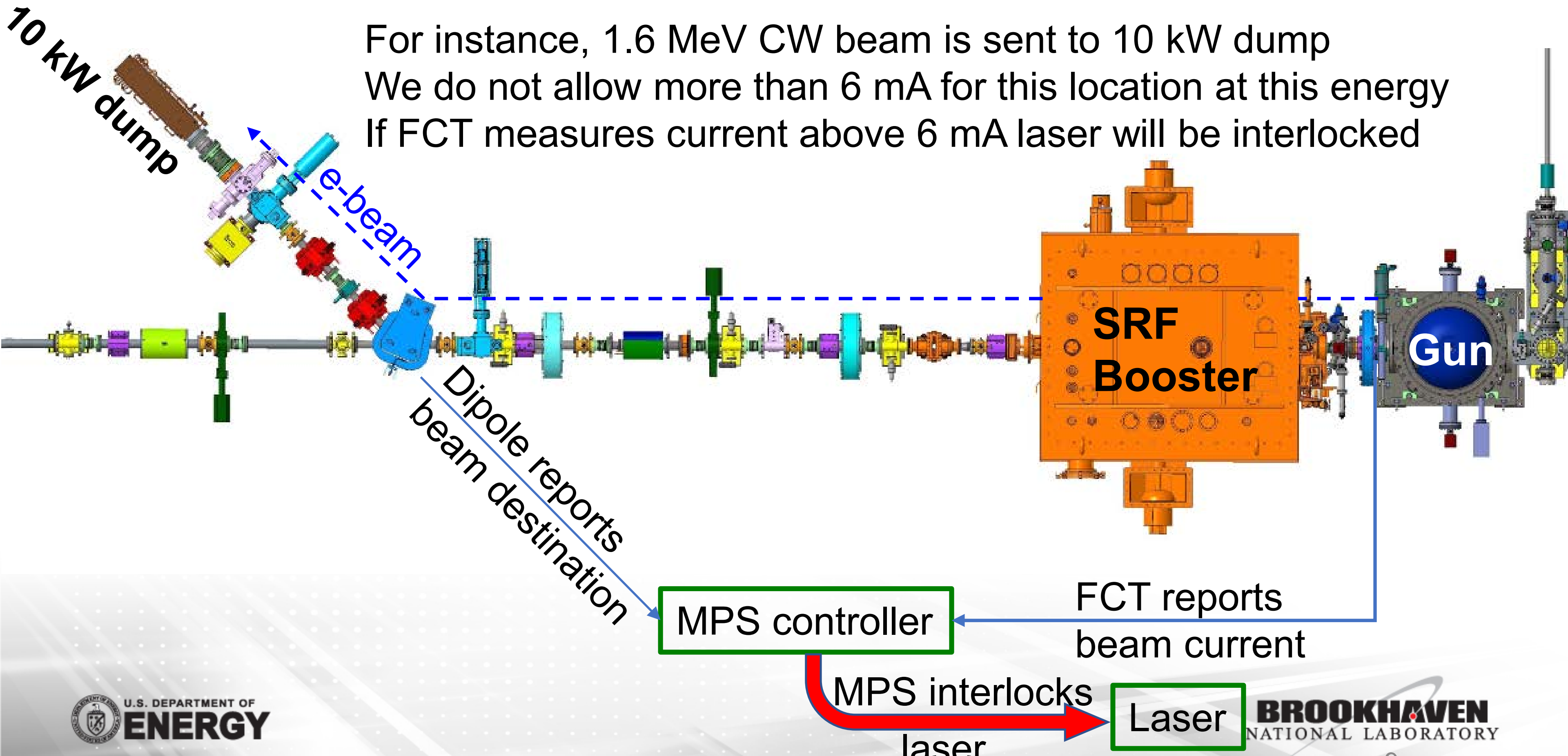
List of MPS devices

- Fast diagnostic (overall reaction time from fault detection to machine interlock <20 us): Requesting ½ of safe reaction time
  - Beam loss monitors (BLMs) – for fast loss detection
  - Fast current transformer (FCTs) – for measuring beam current. FCT processing scheme involves integrating charge accumulated in the 1 s moving window.
  - BPMs – to control beam trajectory
- Slow diagnostic:
  - Vacuum gauges
  - Dumps water flow and temperature
  - Beamline and dumps temperature
  - RF cavities "health" and compliance
  - Gun "health" and HVPS compliance
  - Insertable devices in/out status
  - Cryogenics temperature
- Monitoring bends to control beam trajectory and several critical solenoids to control focusing
- MPS interlocks the machine by blocking the photocathode laser beam

MPS Logic (I)

- MPS works with Machine Modes (MM)
- MM is defined by where the beam is supposed to land (determined from dipoles settings)
- Each MM has the safe current (SC) associated with it
- Actual beam current (ABC) is measured by the FCT
- If ABC > SC then the beam is interlocked

For instance, 1.6 MeV CW beam is sent to 10 kW dump
We do not allow more than 6 mA for this location at this energy
If FCT measures current above 6 mA laser will be interlocked

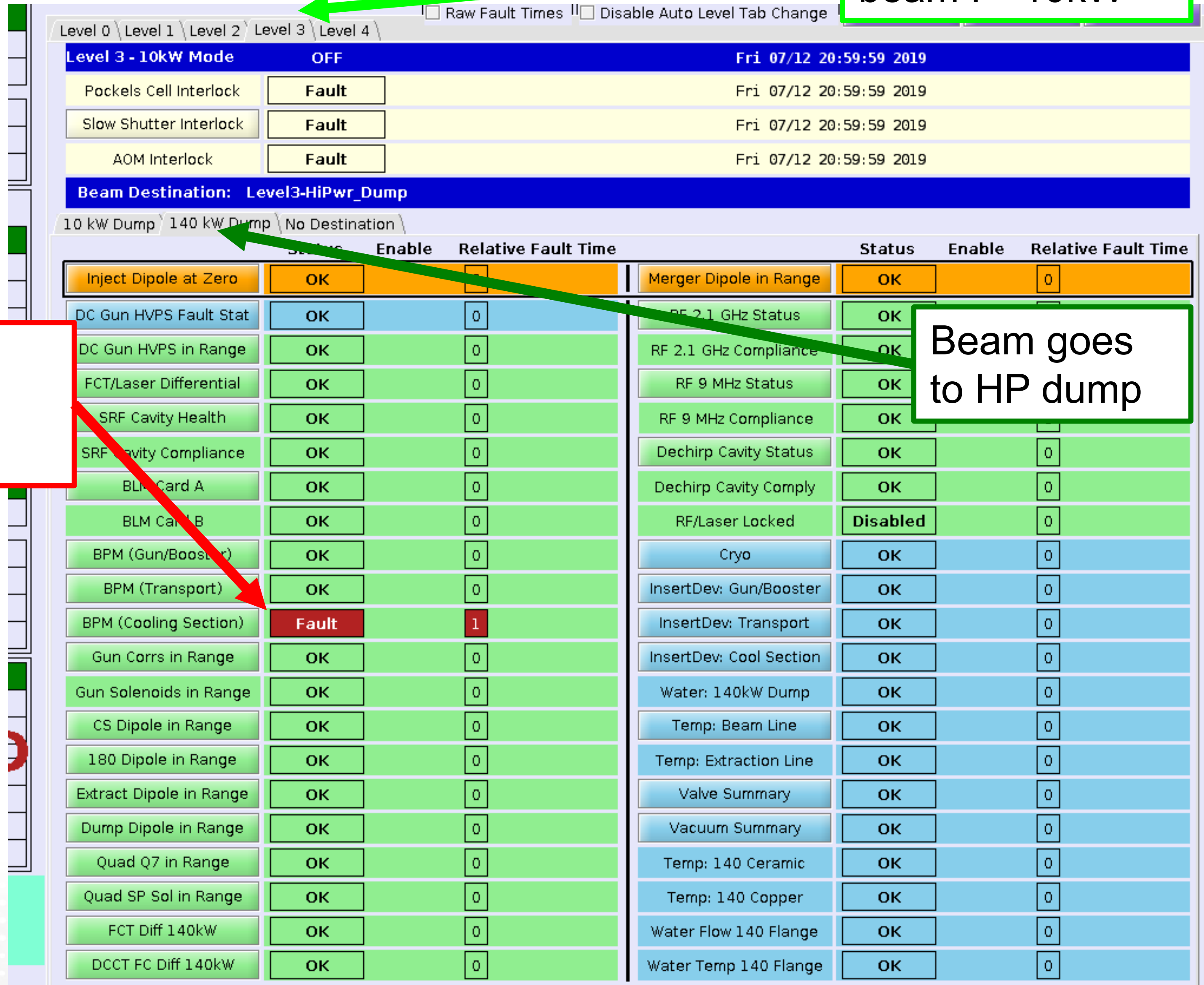


MPS Logic (II)

Beam modes	MPS operation
Low Current Mode (LCM); I ≤ 40 nA	Allowed: everything Monitored: HVPS, BLMs, Vacuum, RF health & compliance
RF Studies Mode (RFSM); I ≤ 3 uA	Allowed: RF YAG exposure to beam Monitored: HVPS, BLMs, Vacuum, IDs, BPMs, Gun-Booster mags, RF YAG wheel, RF health & compliance
HCM or CWM (P ≤ 10 kW); 76 kHz mode	Prohibited: going to RF line Monitored: HVPS, BLMs, Vacuum, IDs, BPMs, Gun-Booster mags, RF health & compliance
High current Mode (HCM); CW Mode (CWM); P > 10 kW	Prohibited: going to RF line, going to 10 kW line Monitored: HVPS, BLMs, Vacuum, IDs, BPMs, Gun-Booster mags, RF health & compliance

MPS Logic (III)

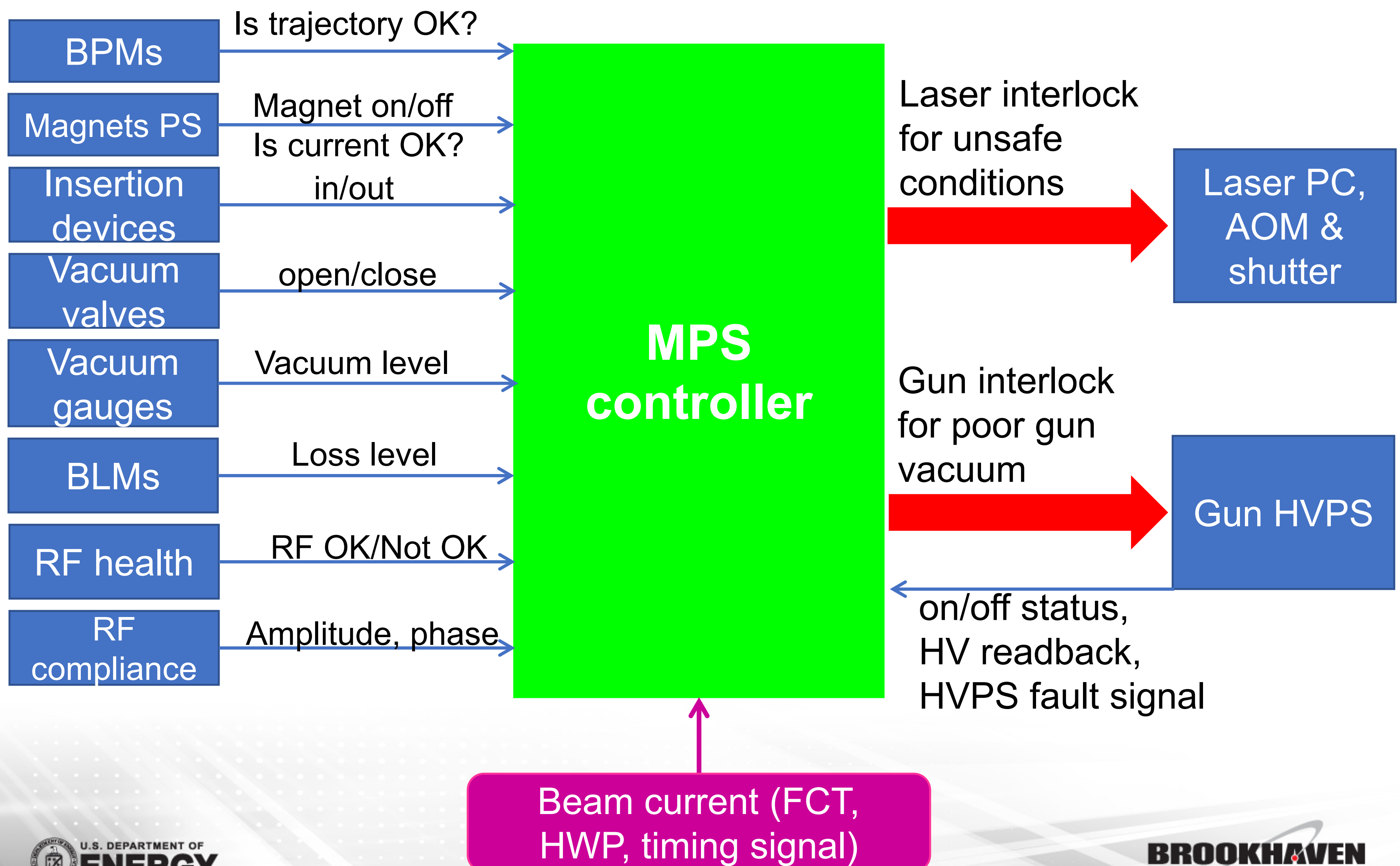
It's HCM but beam P<10kW



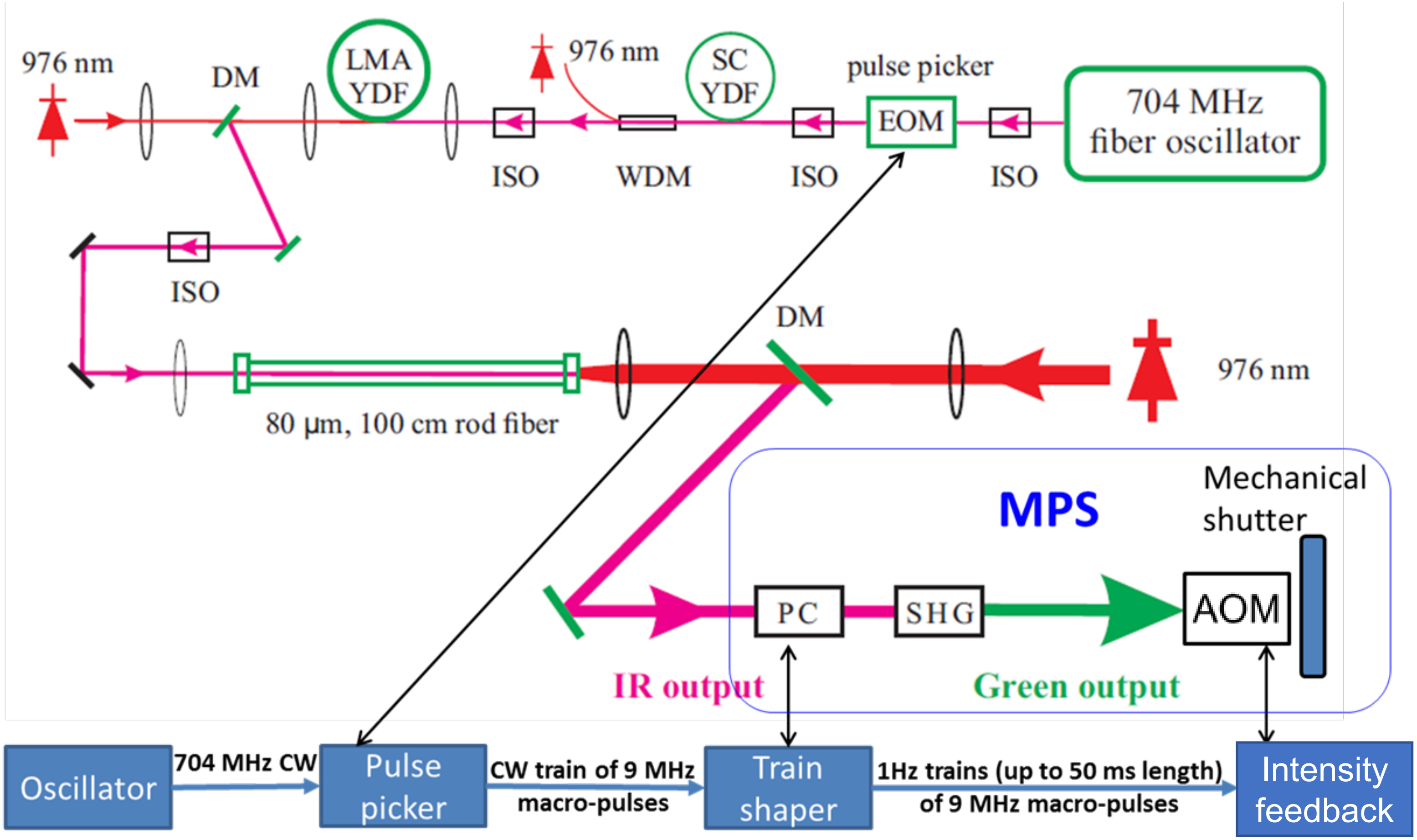
MPS tripped on beam position in cooling section

Beam goes to HP dump

MPS Logic (IV)


BPMs
Is trajectory OK?
Magnets PS
Magnet on/off
Is current OK?
Insertion devices
in/out
Vacuum valves
open/close
Vacuum gauges
Vacuum level
BLMs
Loss level
RF health
RF OK/Not OK
RF compliance
Amplitude, phase
MPS controller
Laser interlock for unsafe conditions
Laser PC, AOM & shutter
Gun interlock for poor gun vacuum
Gun HVPS
on/off status, HV readback, HVPS fault signal
Beam current (FCT, HWP, timing signal)

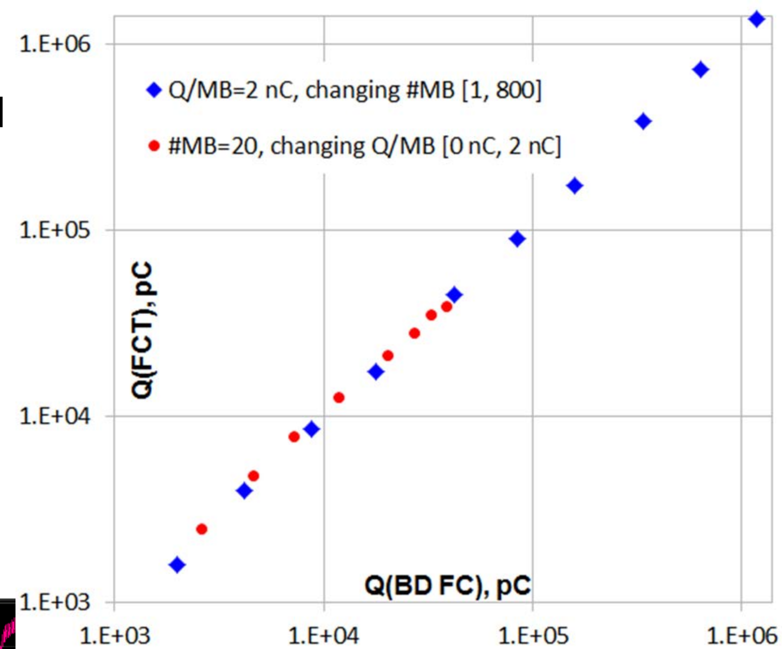
MPS – Laser interface

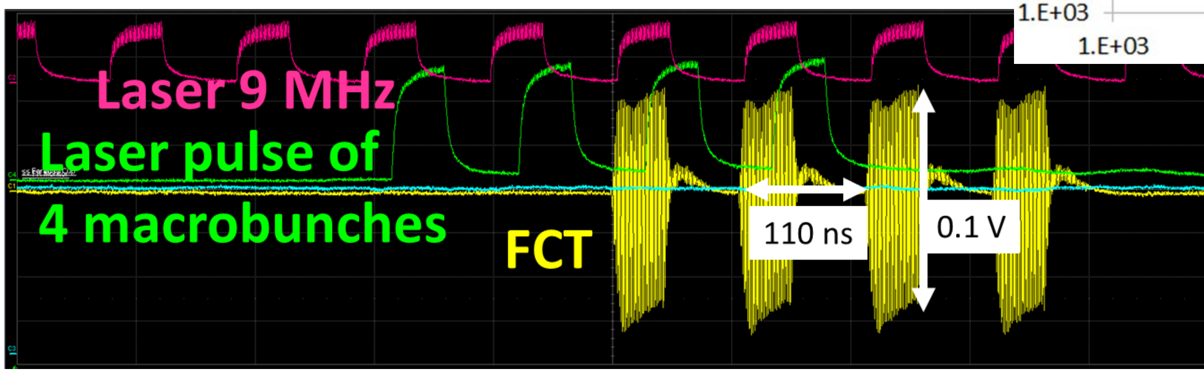


- The MPS is interlocking the machine by switching off the (train shaping) Pockels cell and the intensity feedback AOM and by closing the mechanical shutters
- The measured closing time of AOM is 130 ns

Current measurements

- Fast current transformer (FCT) is always engaged and providing the current measurements to the MPS.
- First laser-produced e-beam was obtained on May 5th 2017, FCT signal was observed right away.
- Beam-based calibration of the FCT involved comparing its response to the beam charge measured with FCs and later with DCCT.
- The FCT reliably determines and sets MPS current levels as long as charge/bunch ≥ 0.7 pC.

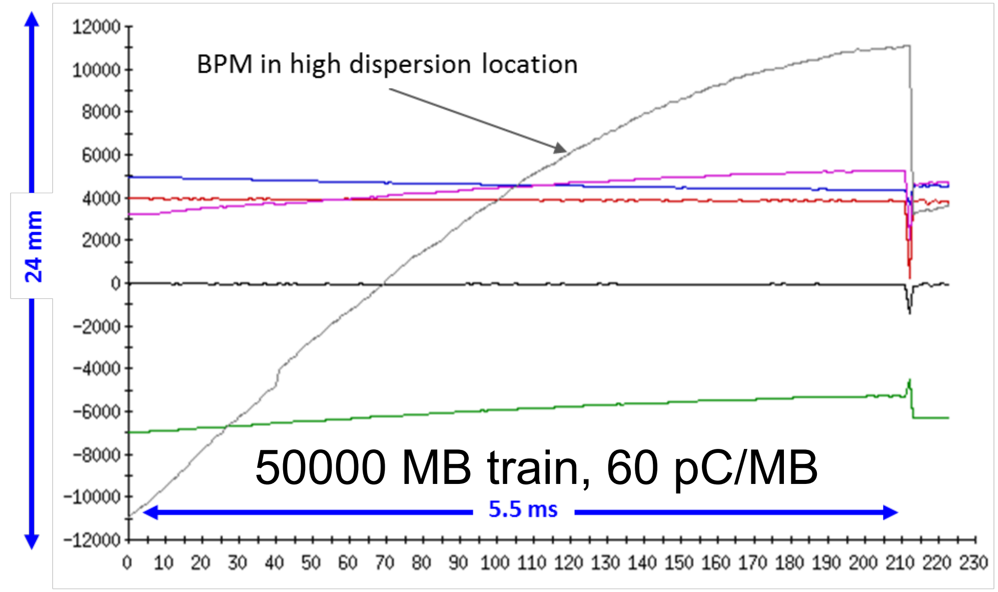


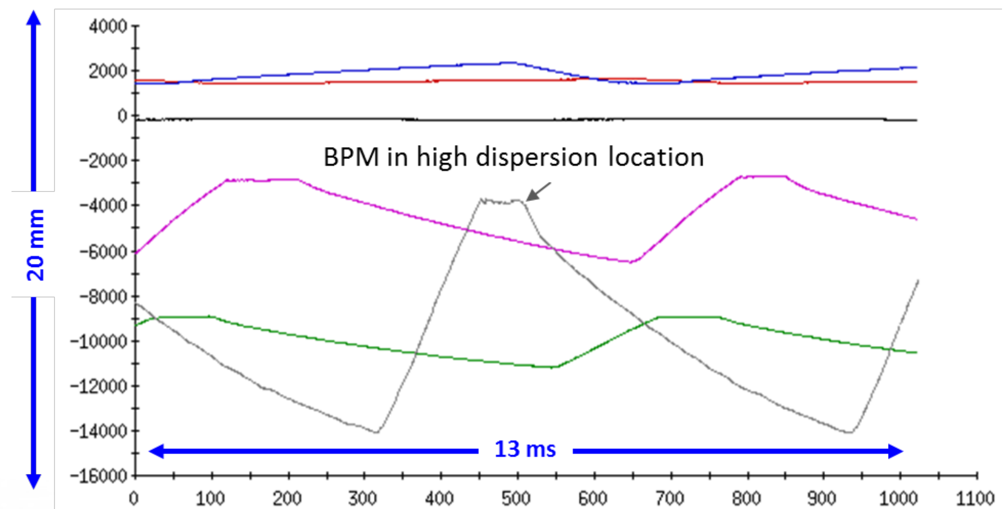


- For the sake of superfluity, when CW settings are detected (half-wave plate is inserted and laser shutter is open) we automatically assume that we are in HCM
- We do the same for 76M – whenever MPS detects that timing system is set to 76 kHz and that the shutter is open the HCM is assumed.

BPMs

- BPMs have been reliably interlocking the MPS whenever the beam trajectory was moved out of the allowed range both in the pulsed and in the CW modes.
- For instance, BPMs were interlocking the MPS because of trajectory change along the train of macrobunches due to the beam loading or due to instability of the gun PS.

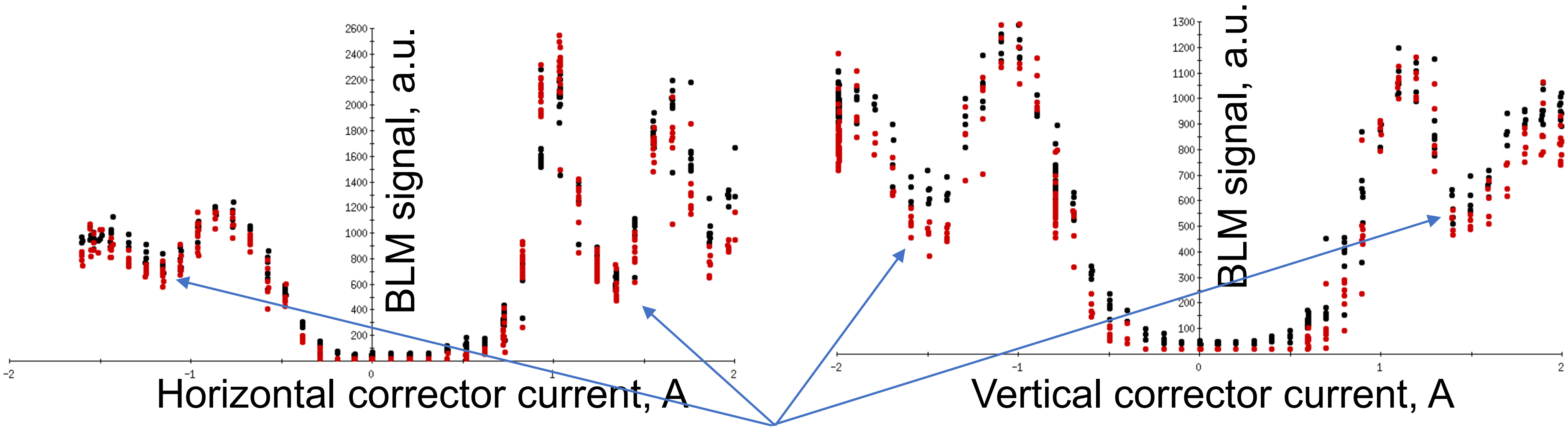




CW, 2.8 mA, regulation loop malfunctioning

BLMs

- Beam loss monitors (BLMs) are PMTs retrofitted with few feet long scintillating fiber
- BLMs cover the whole accelerator
- BLMs detect losses in all directions



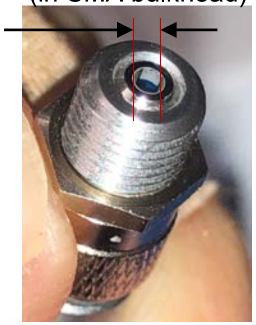
Partial shielding of losses by the magnet

- We set BLMs to trigger the MPS trip at the radiation levels equivalent to the loss of 40 nQ pulsed beam on the insertable devices. Although this setting might be too conservative, it did allow us to operate 30 mA beam.
- The only nuisance was that during the RHIC injections (when injection lattice is not optimized) BLMs were triggered by ion losses causing LEReC MPS trips.

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY

BLMs operation and upgrade



- Up to this point we used 1 mm diameter scintillating plastic optical fibre (POF) and it worked fine.
- Yet it was noticed that increased power of testing in CW mode has caused ~17% darkening in some of the fibers.
- An undoped quartz fiber was tested and found to have a response of 85% of that of the POF; which can be compensated for with increased bias voltage. Thus, a 1.5 mm quartz fiber in armoured sheath with SMA terminations is ordered in 16 lengths of 3 – 13 m to replace the POF covering the entire 100 m of the LEReC beam line.

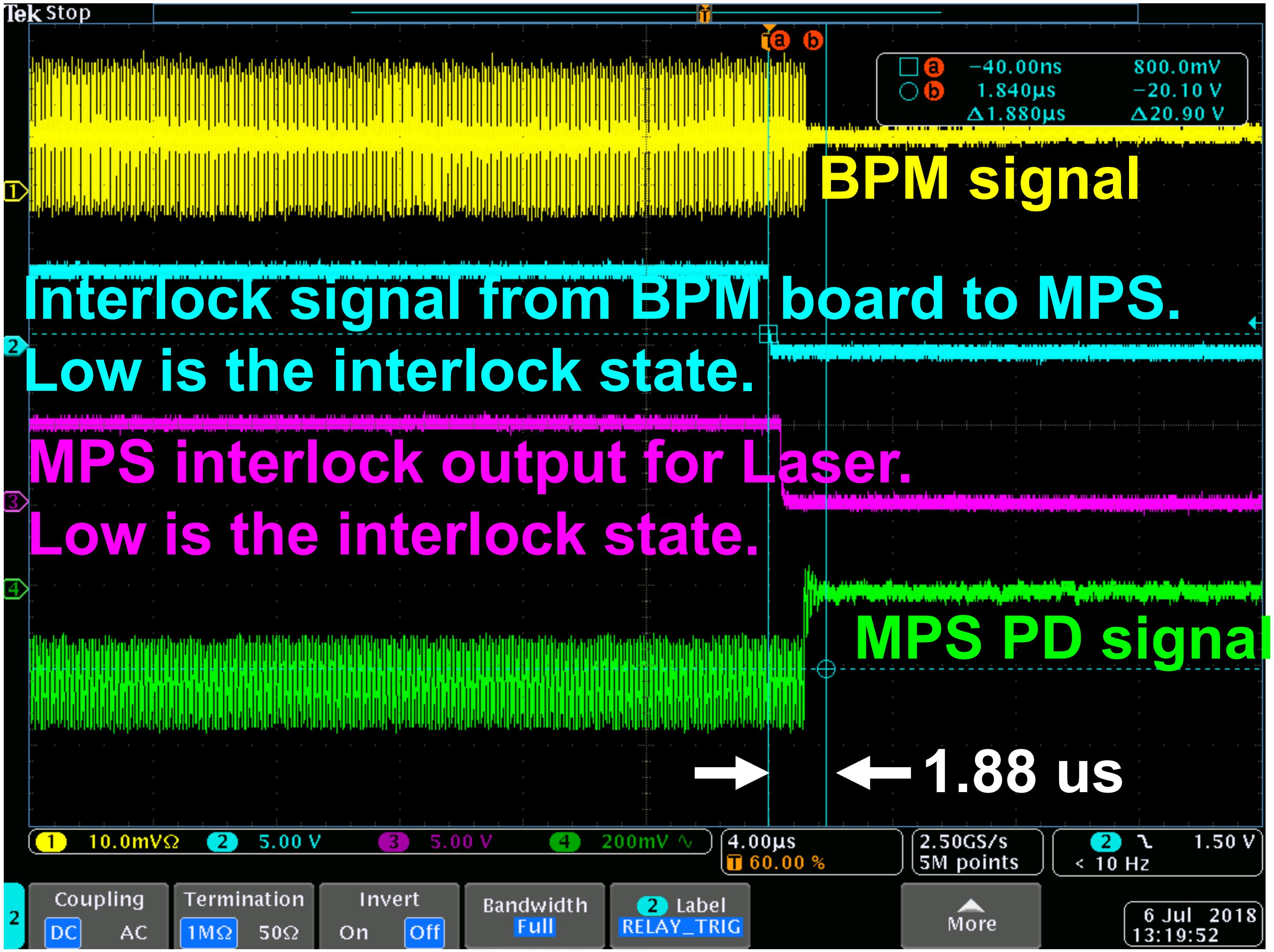
- A test of the Libera BLM board was made with one of the BLMs. Libera was locked to the RHIC revolution frequency clock. This allowed the capture of the LEReC macrobunch structure in the beam loss data.
- Libera BLM can be used to sample the beam only in the RHIC abort gap (effectively sampling ~1us out of every RHIC turn) so as to be insensitive to the RHIC beam losses and only sensitive to the LEReC beam losses. This method may be used in the future to mitigate MPS trips during RHIC injection losses.

Response time of fast diagnostics

An example of measurement for BPMs:

The fault condition was created at the BPM and the reaction time was measured from the delay between the BPM-registered fault and the disappearance of the signal on the MPS PD.

MPS controller response time is 500 ns (blue trace to purple trace). The time from an interlock to 'no-beam' condition, is within 2 μs. Adding 3μs of processing and cable delay time we get 5μs for the overall MPS reaction time.

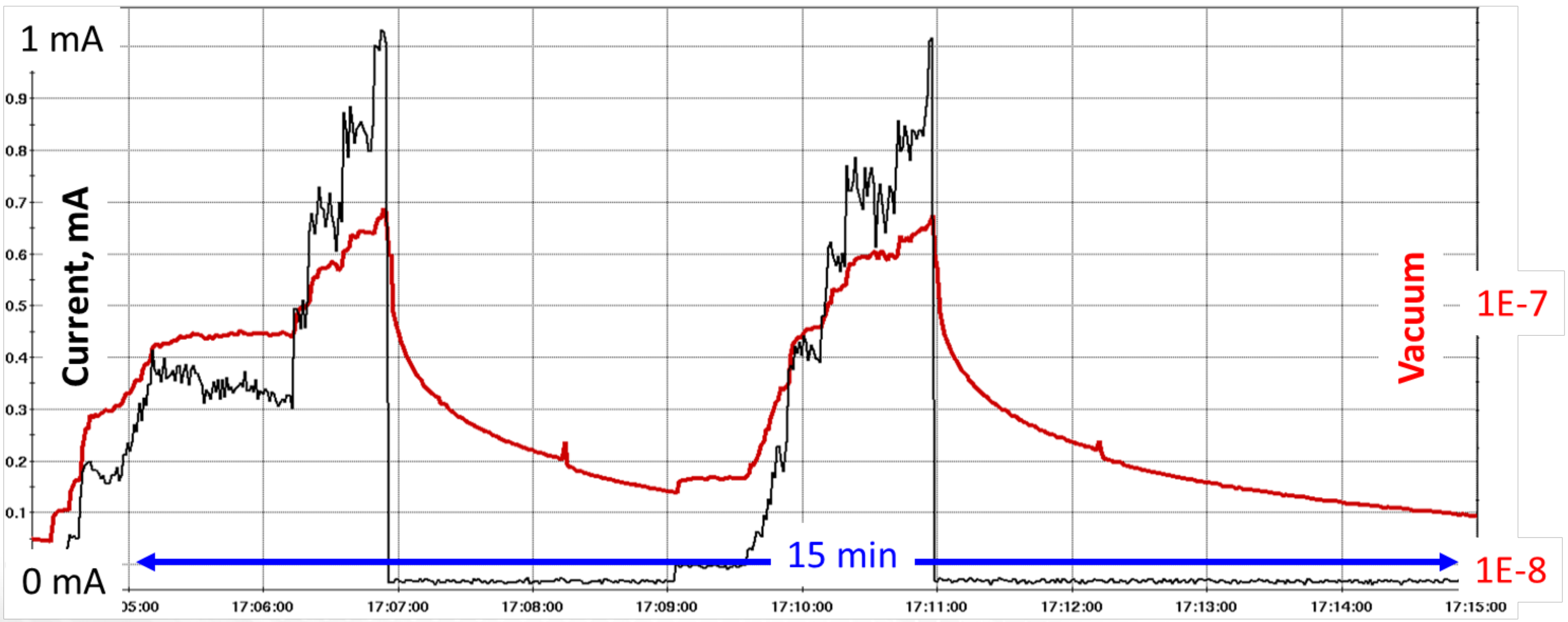


U.S. DEPARTMENT OF ENERGY

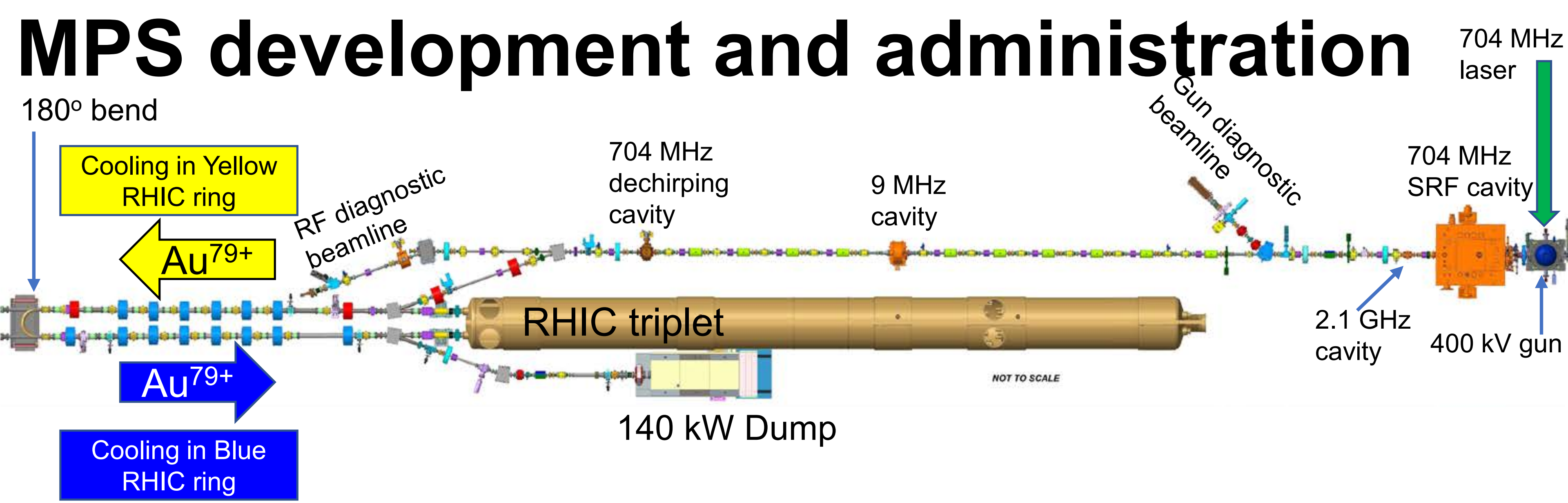
BROOKHAVEN NATIONAL LABORATORY

Slow diagnostics

- The vacuum gauges, readback of the magnets PS currents, readback of position of various insertion devices, Gun HVPS readback and beamline and dump temperatures worked reliably trough 2017-2019 gun, accelerator and cooling commissioning.



MPS development and administration



- MPS prototype (having all main features of the present system) was developed for 2017 gun commissioning. It included gun and 7 m beamline to the diagnostic dump.
- MPS for the full LEReC was developed and commissioned in 2018 as a part of accelerator commissioning.
- In 2019 MPS was operated with some minor modifications (as compared to 2018) during commissioning of electron cooling.
- Evolution of the MPS had the following features:
  - The system became less “configurable” (all vacuum gauges and all BLMs are always monitored no matter the beam destination)
  - Duplicating levels of protection were added for some critical features (current measurement, SRF Booster protection etc.)
- MPS is checked first without and then with the beam before each run.

A few lessons we learned

- Of course, the MPS is designed to be fail-safe. It is important to double-check that every part of every subsystem interacting with the MPS is fail-safe too.

- Commissioning of such an accelerator as LEReC (actual R&D, both from engineering and physics point of view, which must be turned into an operational machine in a record time) requires frequent adjustments to various machine parameters affecting the MPS. No matter how inconvenient it is, never allow access to the MPS and MPS-related settings to anyone but people who have detailed understanding of the system intricacies.

- Having redundancy in the system is important.

Conclusion

- LEReC is an unconventional and a sophisticated accelerator that requires a sophisticated MPS for safe operations.

- LEReC MPS was designed, developed and deployed during 2017-2018 commissioning of accelerator and was fully operational during 2019 electron cooling commissioning.

- Each and every part of the LEReC MPS has been battle-tested. It is ready for LEReC transition to operations.