Analysis of XFEL operation experience and ILC implications

Nick Walker
(on behalf of the XFEL SRF LINAC team)
DESY

DESY ILC Project Meeting
18th December, 2020

XFEL LINAC vs ILC (parameters)

		XFEL			ILC
		Design	Demonstrated	Routine	
Beam energy	GeV	8—17.5	↗ 17.6	11.5 | **14** | 16.5	125
Machine rep rate	Hz	10	10	10	5
N_{bunch}		2,700	>1,300	600—1,200	1,300 (2,600)
Beam rep rate	MHz	↗ 4.5	4.5	1.125—4.5	1.8 (2.7)
Bunch charge	pC	20—1,000	100—500	250	3,200
Beam Current (avg)	mA	≤ 5	< 2.25	0.6—1.3	5.8 (8.6)
Bunch length	fs	2-180	20, 50	20	1,000
Beam power	kW	500	80	40	6,000
Energy stability		$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$
Timing stability	fs		7	< 20	< 100
Average E_{acc}	MV/m	23.6	24.4	22.4	31.5 (35?)
Q_0		10^{10}	$\sim 10^{10}$	$\sim 10^{10}$	5×10^{9}
$\gamma\varepsilon_y$	µm	1	1.4	1.4	0.035

XFEL LINAC vs ILC (parameters)

		XFEL			ILC
		Design	Demonstrated	Routine	
Beam energy	GeV	8—17.5	↗ 17.6	11.5 | **14** | 16.5	125
Machine rep rate	Hz	10	10	10	5
N_{bunch}		2,700	>1,300	600—1,200	1,300 (2,600)
Beam rep rate	MHz	↗ 4.5	4.5	1.125—4.5	1.8 (2.7)
Bunch charge	pC	20—1,000	100—500	250	3,200
Beam Current (avg)	mA	≤ 5	< 2.25	0.6—1.3	5.8 (8.6)
Bunch length	fs	2-180	20, 50	20	1,000
Beam power	kW	500	80	40	6,000
Energy stability		$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$
Timing stability	fs		7	< 20	< 100
Average E_{acc}	MV/m	23.6	24.4	22.4	31.5 (35?)
Q_0		10^{10}	$\sim 10^{10}$	$\sim 10^{10}$	5×10^9
$\gamma\varepsilon_y$	µm	1	1.4	1.4	0.035

XFEL LINAC vs ILC (parameters)

		XFEL			ILC	
		Design	Demonstrated	Routine		
Beam energy	GeV	8—17.5	↗ 17.6	11.5 | **14** | 16.5	125	
Machine rep rate	Hz	10	10	10	5	👍
N_{bunch}		2,700	>1,300	600—1,200	1,300 (2,600)	👍
Beam rep rate	MHz	↗ 4.5	4.5	1.125—4.5	1.8 (2.7)	👍
Bunch charge	pC	20—1,000	100—500	250	3,200	
Beam Current (avg)	mA	≤ 5	< 2.25	0.6—1.3	5.8 (8.6)	
Bunch length	fs	2-180	20, 50	20	1,000	
Beam power	kW	500	80	40	6,000	
Energy stability		$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	👍
Timing stability	fs		7	< 20	< 100	👍
Average E_{acc}	MV/m	23.6	24.4	22.4	31.5 (35?)	
Q_0		10^{10}	$\sim 10^{10}$	$\sim 10^{10}$	5×10^{9}	👍
$\gamma\varepsilon_y$	µm	1	1.4	1.4	0.035	

XFEL LINAC vs ILC (parameters)

		XFEL			ILC	
		Design	Demonstrated	Routine		
Beam energy	GeV	8—17.5	↗ 17.6	11.5 | **14** | 16.5	125	
Machine rep rate	Hz	10	10	10	5	
N_{bunch}		2,700	>1,300	600—1,200	1,300 (2,600)	
Beam rep rate	MHz	↗ 4.5	4.5	1.125—4.5	1.8 (2.7)	
Bunch charge	pC	20—1,000	100—500	250	3,200	🤔
Beam Current (avg)	mA	≤ 5	< 2.25	0.6—1.3	5.8 (8.6)	🤔
Bunch length	fs	2-180	20, 50	20	1,000	🤔
Beam power	kW	500	80	40	6,000	🤔
Energy stability		$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	
Timing stability	fs		7	< 20	< 100	
Average E_{acc}	MV/m	23.6	24.4	22.4	31.5 (35?)	
Q_0		10^{10}	$\sim 10^{10}$	$\sim 10^{10}$	5×10^{9}	
$\gamma\varepsilon_y$	μm	1	1.4	1.4	0.035	

XFEL LINAC vs ILC (parameters)

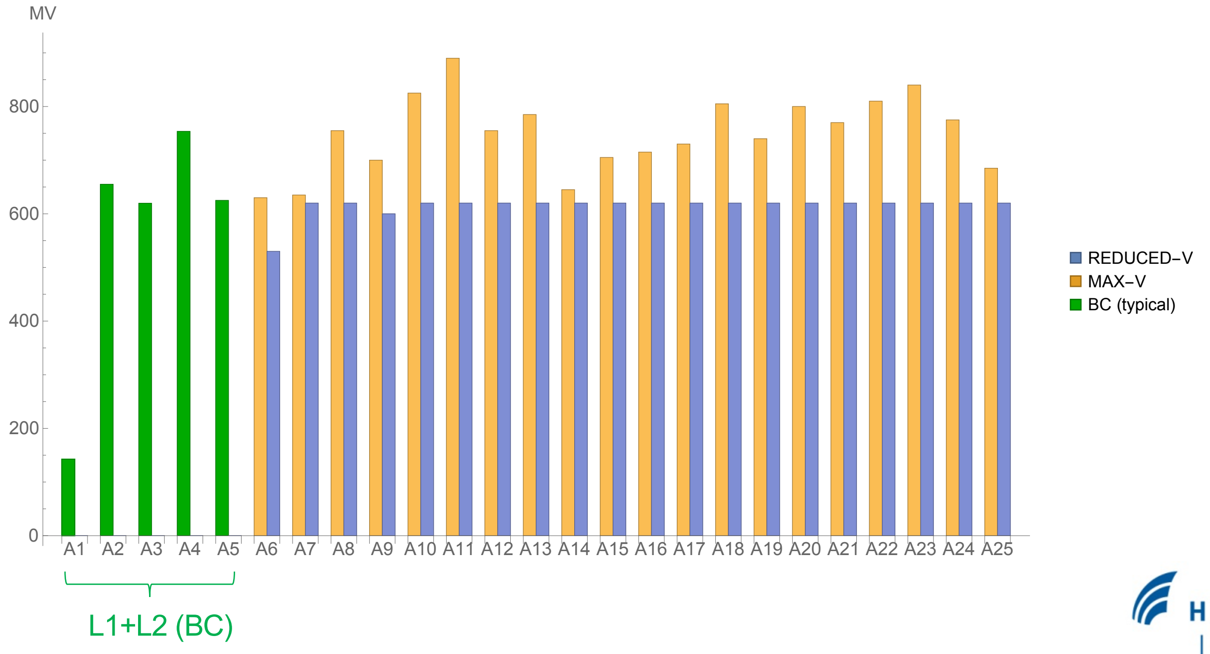
		XFEL			ILC
		Design	Demonstrated	Routine	
Beam energy	GeV	8—17.5	↗ 17.6	11.5 | **14** | 16.5	125
Machine rep rate	Hz	10	10	10	5
N_{bunch}		2,700	>1,300	600—1,200	1,300 (2,600)
Beam rep rate	MHz	↗ 4.5	4.5	1.125—4.5	1.8 (2.7)
Bunch charge	pC	20—1,000	100—500	250	3,200
Beam Current (avg)	mA	≤ 5	< 2.25	0.6—1.3	5.8 (8.6)
Bunch length	fs	2-180	20, 50	20	1,000
Beam power	kW	500	80	40	6,000
Energy stability		$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$
Timing stability	fs		7	< 20	< 100
Average E_{acc}	MV/m	23.6	24.4	22.4	31.5 (35?) 😮
Q_0		10^{10}	$\sim 10^{10}$	$\sim 10^{10}$	5×10^{9}
$\gamma\varepsilon_y$	µm	1	1.4	1.4	0.035 😮

XFEL LINAC Voltage Configurations

	Energy (GeV)	Config	Off-crest phase	Margin to on crest (MV)	Recover by phase alone
Typical user run	14.5	Reduced-voltage configuration	20°	690	1 station
Low-energy user run	11.5	Reduced-voltage configuration	44°	3190	>1 station
High-energy user run	16.5	High-voltage configuration	21°	925	1 station
Maximum demonstrated energy	17.6	High-voltage config (no margin)	on-crest		

Reduced-V is a *High Reliability & Availability* mode

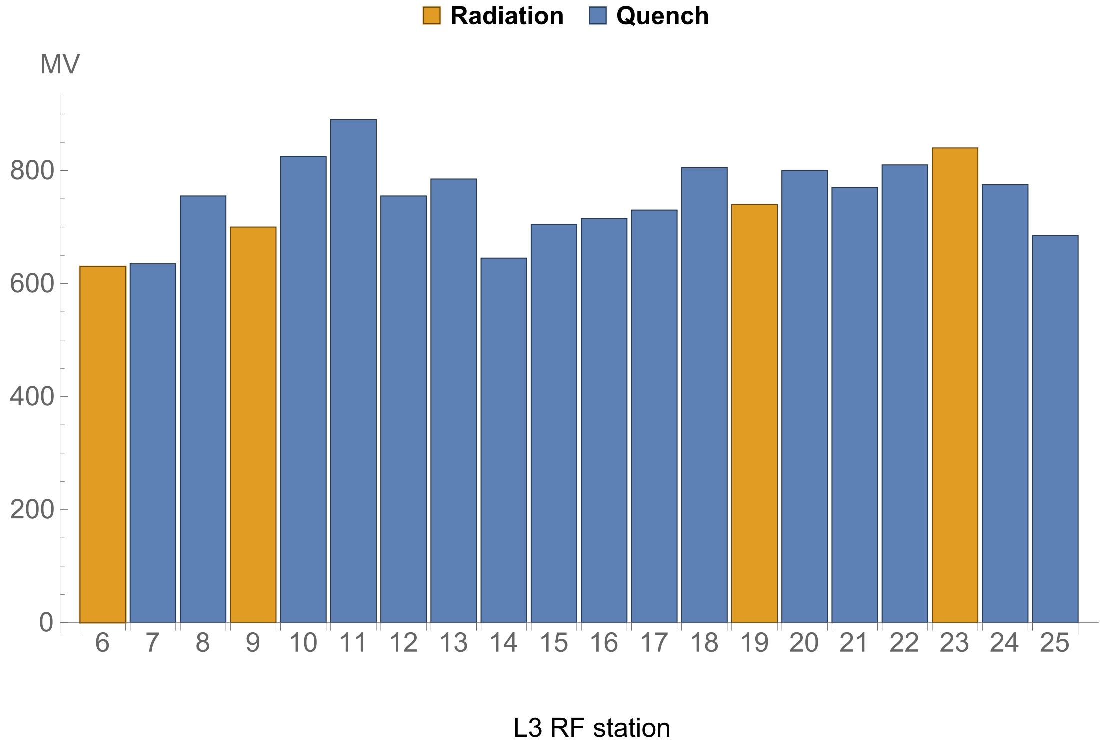
- power de-rated
- reduced radiation (dark current)



Maximum Energy Performance

- Maximum station voltage limited by
  - Quench (generally one limiting cavity ~0.5 MV/m margin)
  - Excessive radiation due to dark current
  - 22 / 640 (L3) cavities operationally detuned

- With all **L3 stations on phase ➔ 17.6 GeV**
  - Bunch compressor (L2+L3) at 2.4 GeV (nominal)
  - No operational overhead (longer trip recovery)
  - Not offered as a user run mode (yet!)
  - 16.5 GeV mode allows for one L3 station to fail.

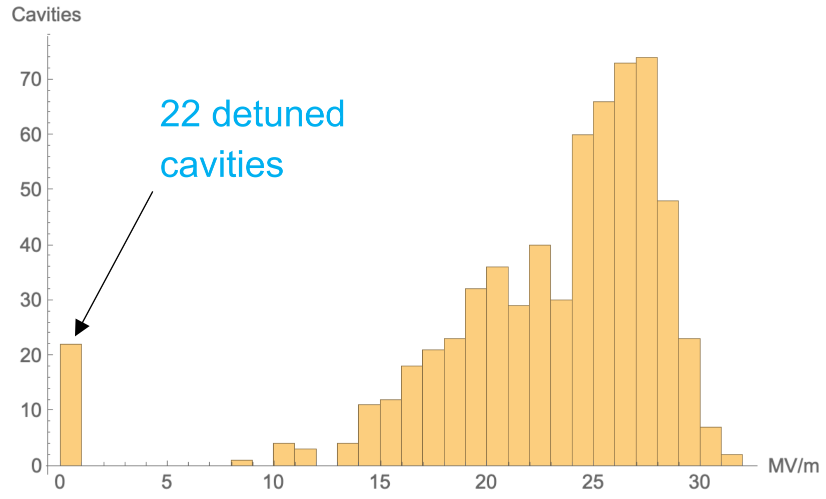


ILC: 1 GV per RF station (on average)

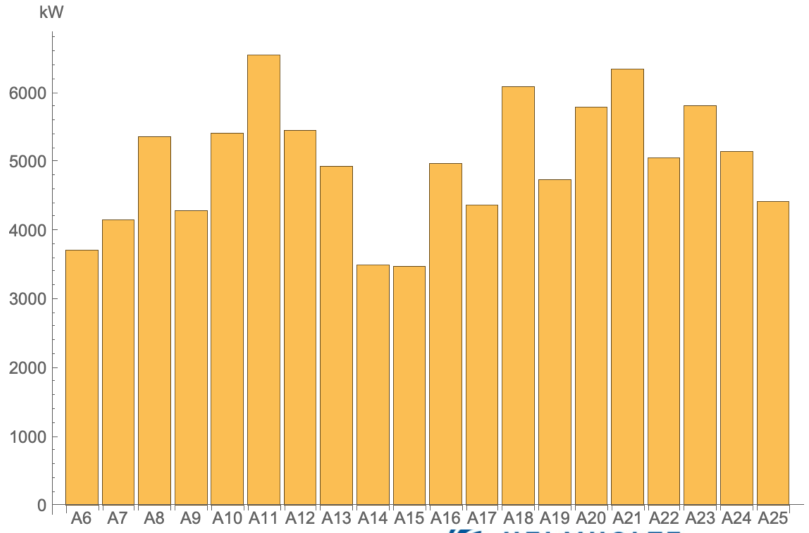
RF performance at HIGH-V (L3)

- Average gradient
  - 24.4 ±4 MV/m
    - ▶ Design goal 23.6 MV/m
    - ▶ 23.0 MV/m including detuned cavities

Gradient



Klystron
Power



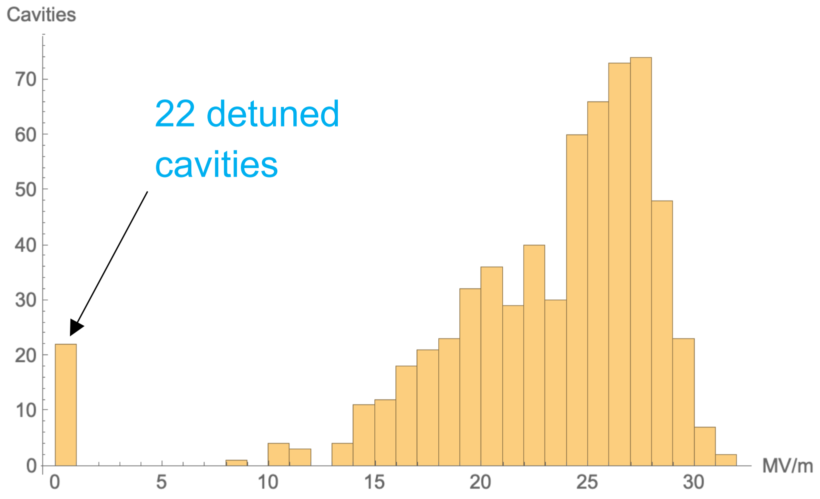
RF performance at HIGH-V (L3)

- Average gradient
  - 24.4 ±4 MV/m
    - ▶ Design goal 23.6 MV/m
    - ▶ 23.0 MV/m including detuned cavities

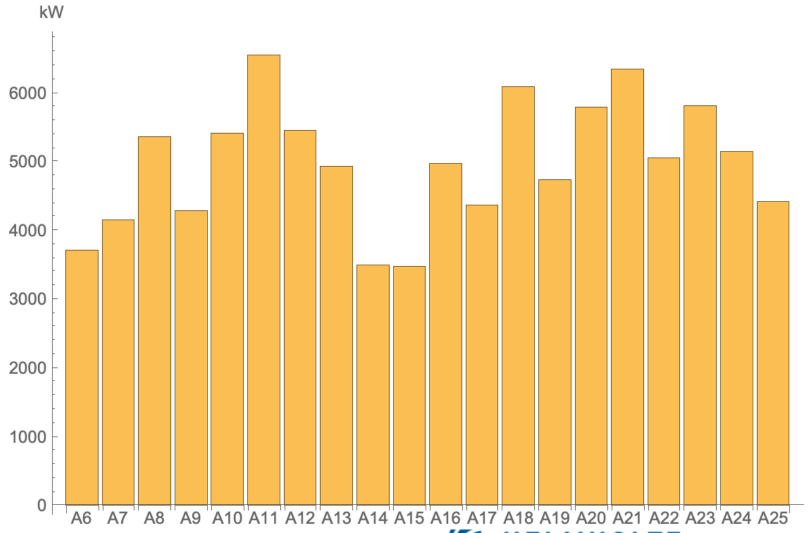
During recent 16.5 GeV run: 23.4 MV/m (22.6 MV/m)

Drop will be studied in Jan start up

Gradient

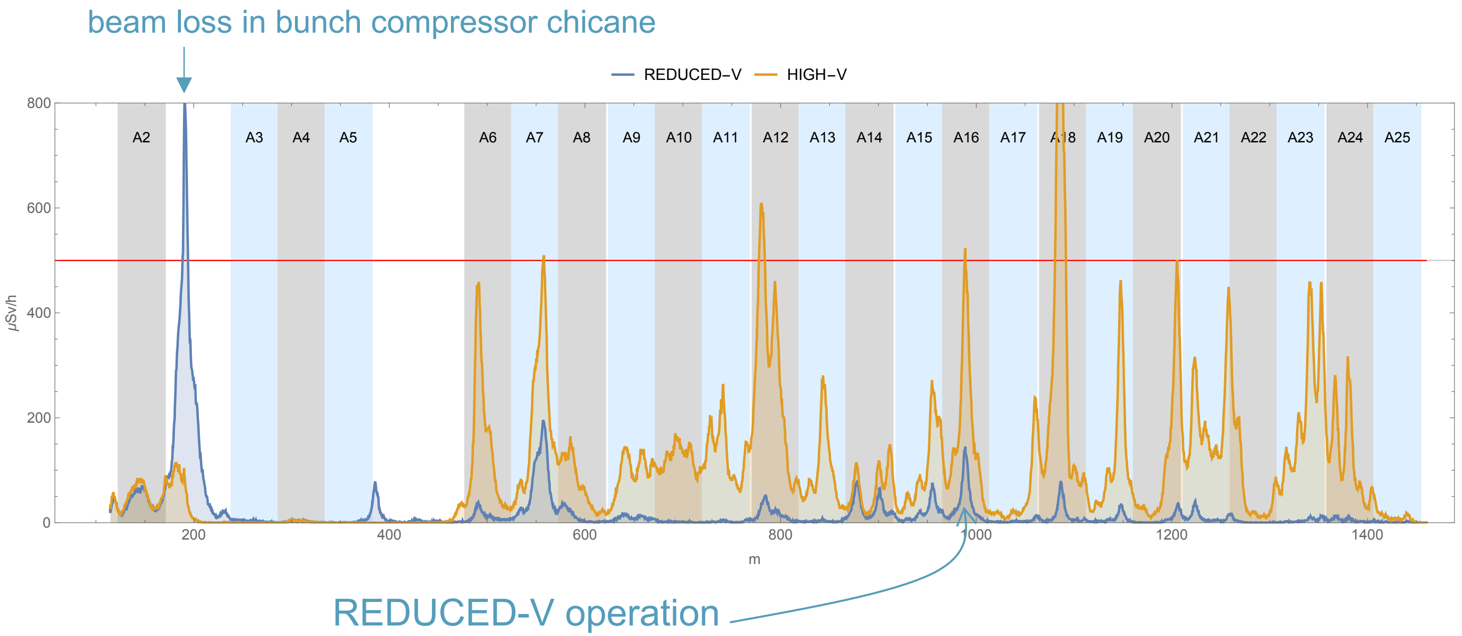


Klystron Power



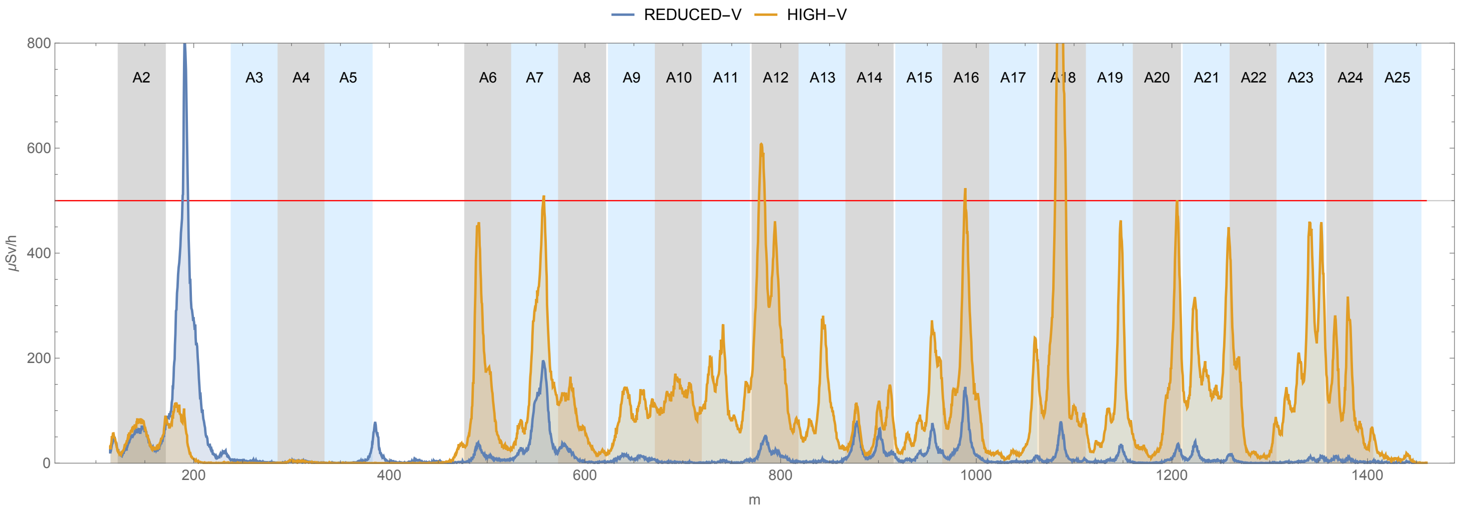
Radiation (Dark Current)

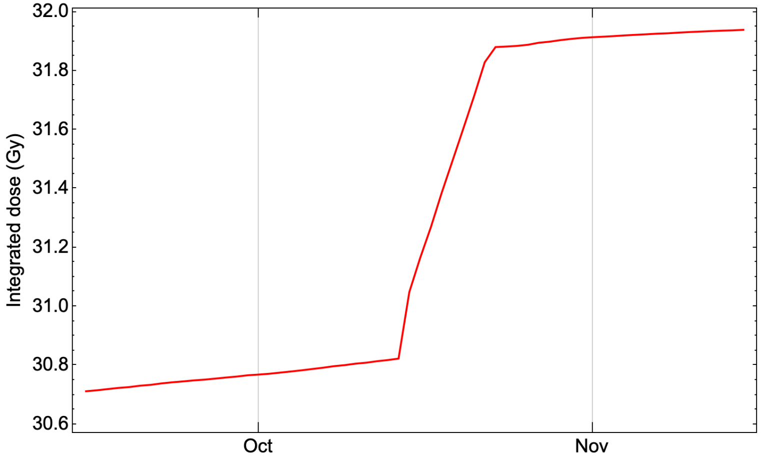
- All RF stations (modules) generate dark current to some degree
  - voltage dependent
- We routinely monitor radiation levels during operation
  - Distributed “real time” dosimetry
    - Continuous (rolling averaged)
    - Gamma radiation
    - Outside and inside electronics racks
  - Tunnel radiation profiles
    - Via our roving robot MARWIN
    - As needed (aiming at once per week)
    - Gamma and neutron radiation
- MARWIN neutron signal is used to define max operation voltage
  - ≤ 500 uSv/h
  - A6, A9, A19 and A23



Radiation (Dark Current)

- All RF stations (modules) generate dark current to some degree
  - voltage dependent
- We routinely monitor radiation levels during operation
  - Distributed “real time” dosimetry
    - Continuous (integrated, rolling averaged)
    - Gamma radiation
    - Outside and inside electronics racks
  - Tunnel radiation profiles
    - Via our roving robot MARWIN
    - As needed (aiming at once per week)
    - Gamma and neutron radiation
- MARWIN neutron signal is used to define max operation voltage
  - ≤ 500 uSv/h
  - A6, A9, A19 and A23





RADCON monitors

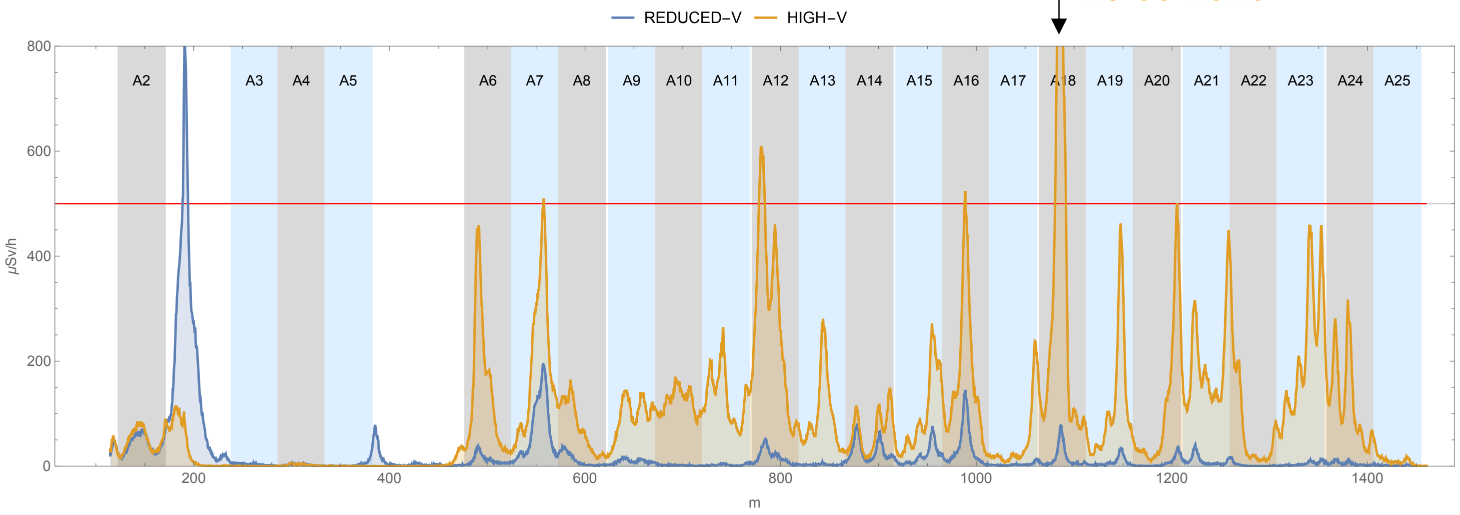
Example of FE onset in **A24** (14.10.2019)

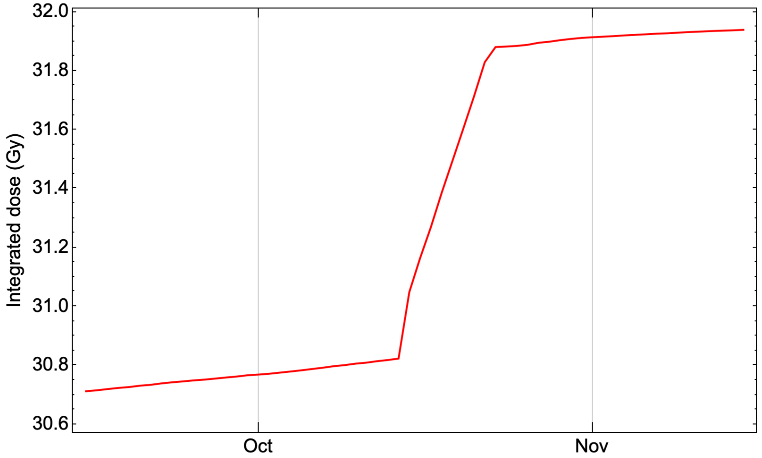
(→ one cavity removed from ops)

Radiation (Dark Current)

- All RF stations (modules) generate dark current to some degree
  - voltage dependent
- We routinely monitor radiation levels during operation
  - Distributed “real time” dosimetry
    - Continuous (integrated, rolling averaged)
    - Gamma radiation
    - Outside and inside electronics racks
  - Tunnel radiation profiles
    - Via our roving robot MARWIN
    - As needed (aiming at once per week)
    - Gamma and neutron radiation
- MARWIN neutron signal is used to define max operation voltage
  - ≤ 500 uSv/h
  - A6, A9, A19 and A23

A18.M3.C4
detuned
23.09.2020





RADCON monitors

Example of FE onset in **A24** (14.10.2019)

(→ one cavity removed from ops)

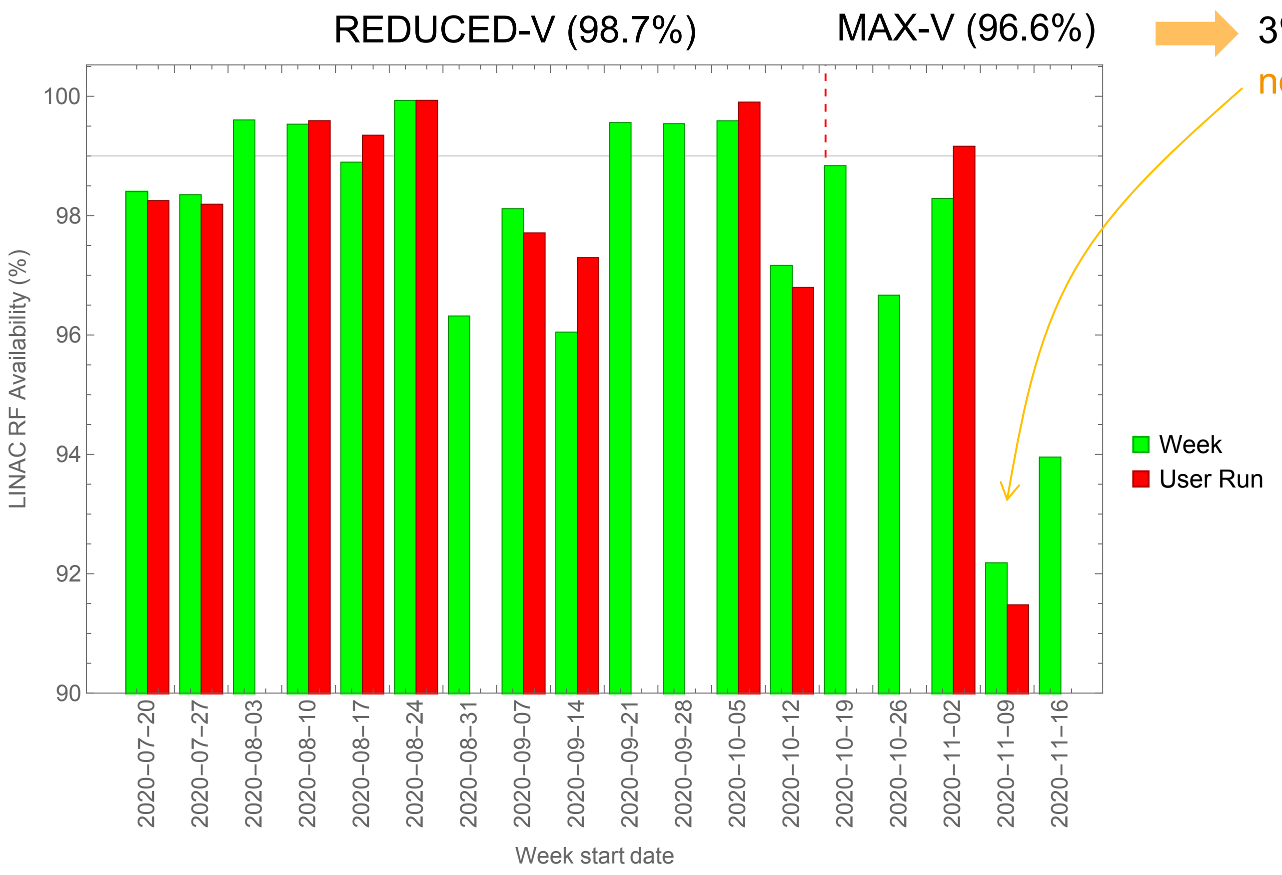
Detuned cavities (23)

➡ Degraded during operation

(Also A6 → reduced voltage)

Station	Count	Cavity	Reason	Date detuned	Comment
A4	1	M4.C4	Coupler (T70K)		
A6	3	M3.C1	High FE/X-Ray		AMTF
		M3.C5	MGTF (quench)		
		M3.C6	MGTF (quench)		
A7	3	M1.C7	MGTF (quench?)	21.11.2018	Operationally degradation observed on 02.11.2018
		M2.C3	MGTF (quench)		
		M2.C7	High FE/X-Ray		AMTF
A8	3	M4.C1	MGTF (quench)		
		M4.C4	MGTF (quench)		
		M4.C5	MGTF (quench)		
A10	1	M1.C3	Low-field quench		AMTF
A12	3	M2.C2	MGTF (quench)		
		M3.C8	MGTF (quench)		
		M4.C1	Coupler (T70K)		
A14	1	M3.C5	Excessive cryogenic losses		
A16	1	M2.C1	Coupler (T70K)		
A18	1	M4.C4	AMTF WDS spec error		
	2	M3.C4	High FE/X-Ray	23.09.2020	MARWIN neutron >500uSv/h
A20	1	M4.C1	Coupler (T70K)		
A21	2	M3.C4	Low-field quench		AMTF
		M4.C2	MGTF (quench)		
A22	1	M4.C3	High FE/X-Ray	14.01.2020	MARWIN neutron >500uSv/h
A24	1	M2.C7	High FE/X-Ray	14.10.2019	FE event (activation)
Total	**23**				

RF Systems Availability

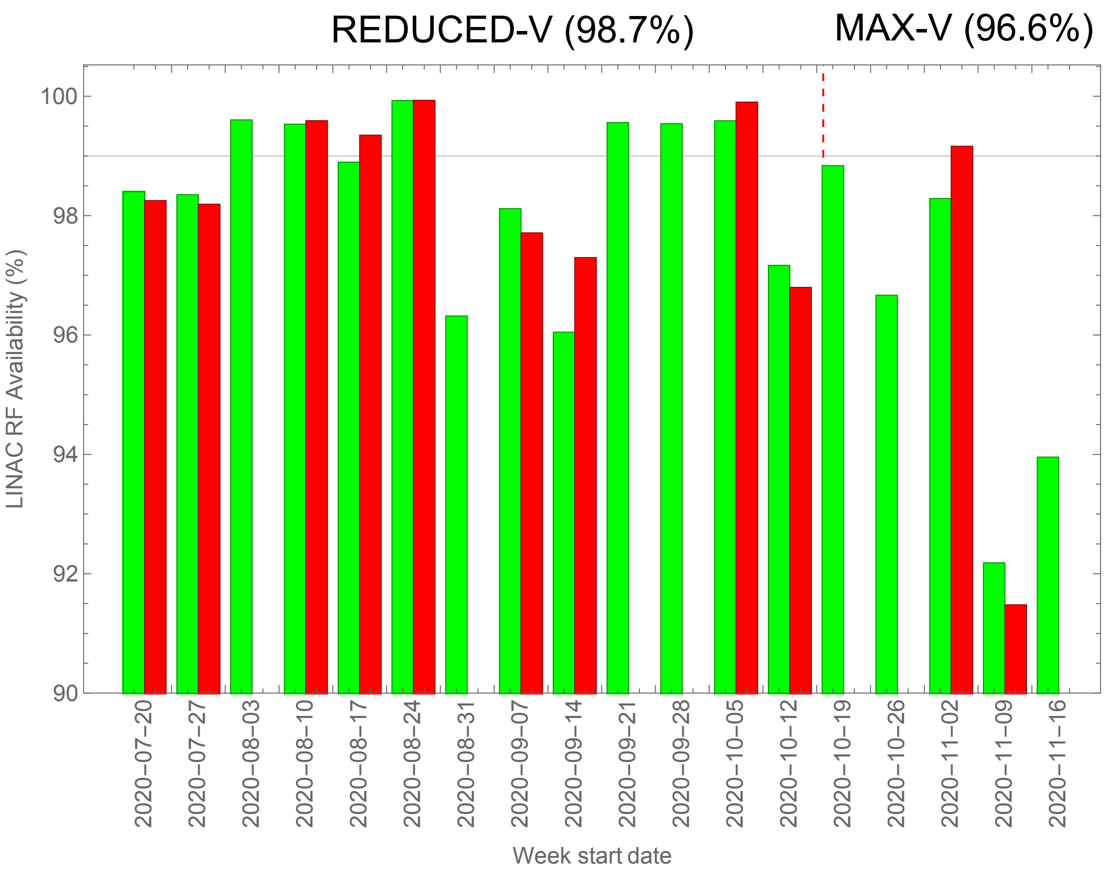


3% drop due to single klystron problem
not related to high-v operation

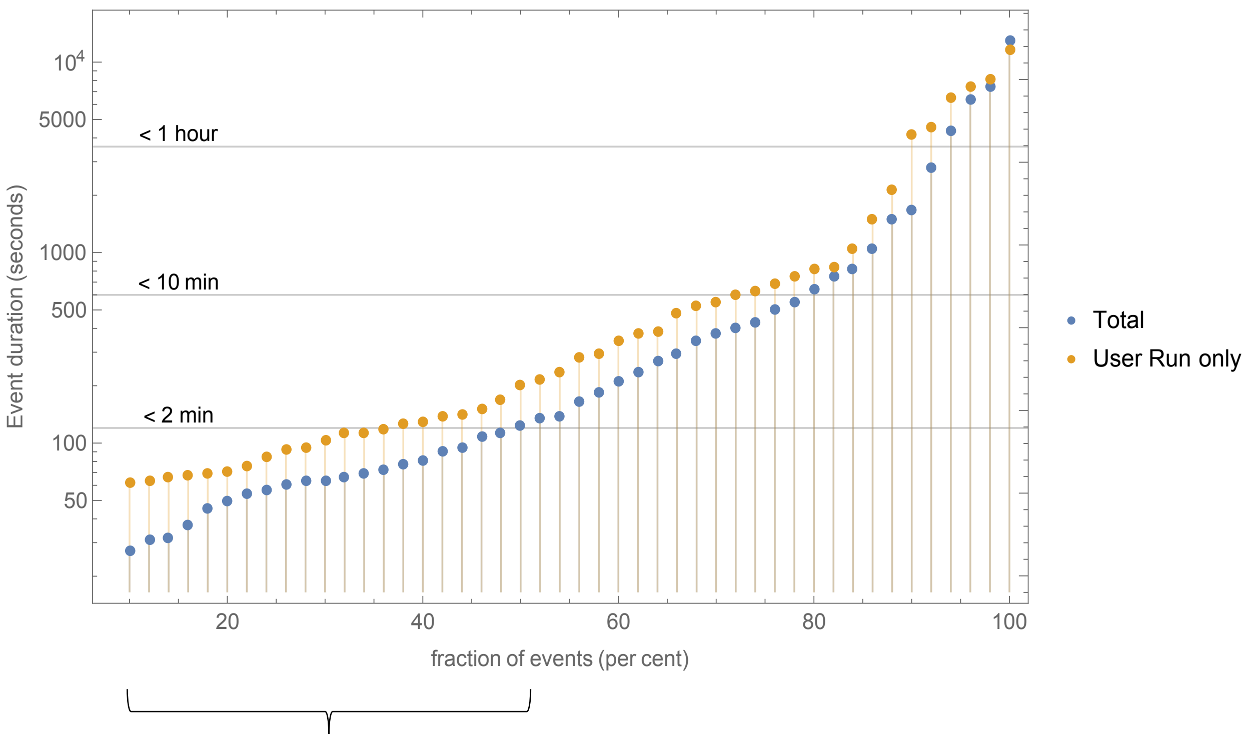
SRF LINACS are very reliable

(But HPRF is derated)

RF Systems Availability



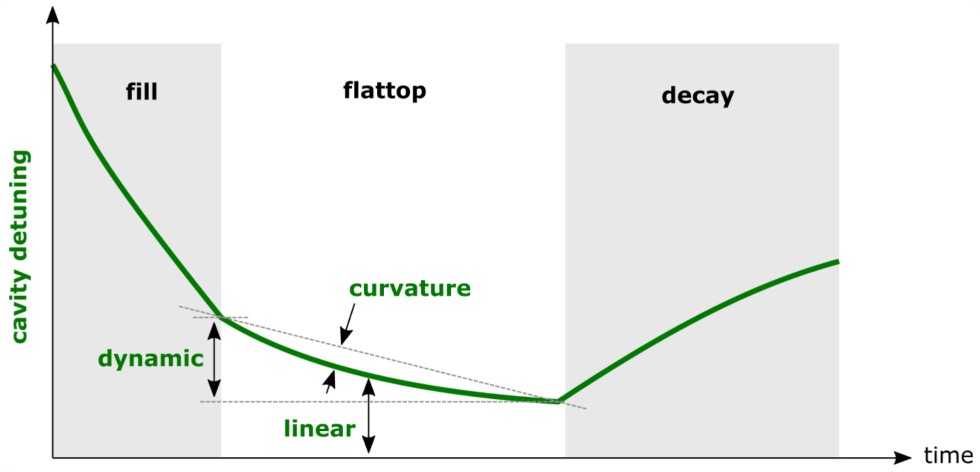
Trip Downtime Distribution

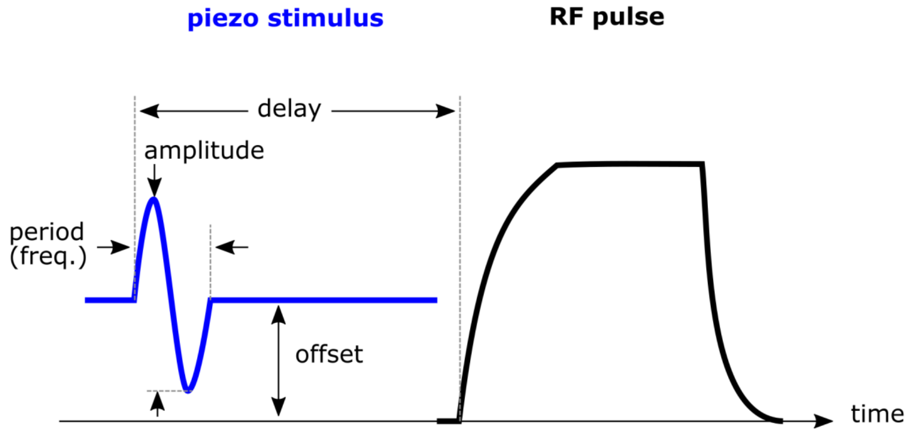


Automated trip recovery (FSM)

Piezo Systems
A high-visibility addition to the LLRF systems

- Piezo systems dynamically maintain individual cavity “on resonance” during the beam pulse (RF flat top)
  - Lorentz force detuning (LFD)
- Track slow frequency drifts
- Direct RF benefits
  - “flat” cavity voltage across flat top
    - ► stable operation close to quench limits
  - Reduction of forward power
  - Easier tuning and trip recovery
    - ► related to first point
- Now operational on all 776 cavities





Piezos – impact on beam dynamics

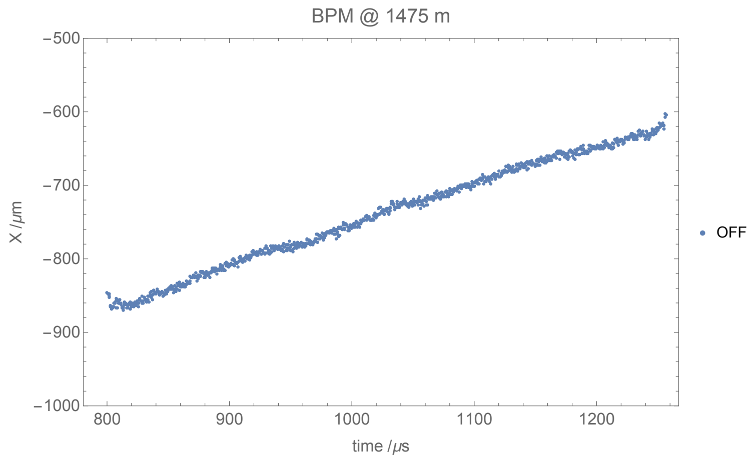
An added benefit

- Transverse kicks from cavity HPC and misalignments (tilts)

RF Station: $\frac{d}{dt}\sum_{i=1}^{32}\tilde{V}_i = 0$ LLRF VSUM control

But $\frac{d}{dt}\tilde{V}_i \neq 0$

⇒ time-dependent transverse kicks along bunch train



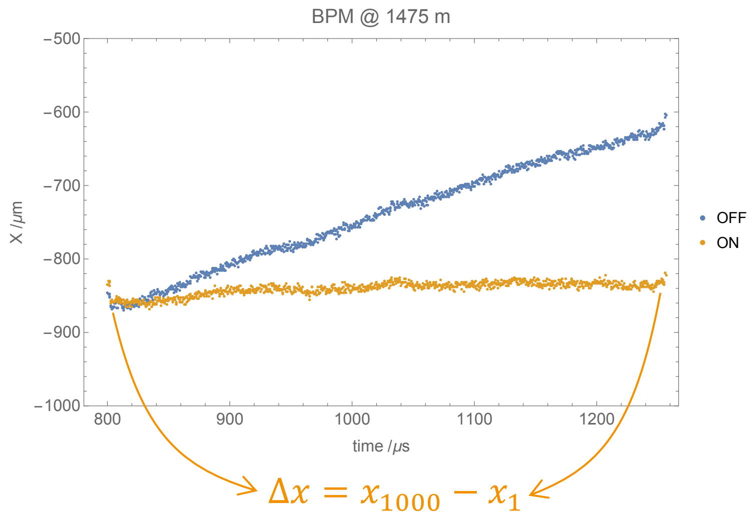
Piezos – impact on beam dynamics
An added benefit

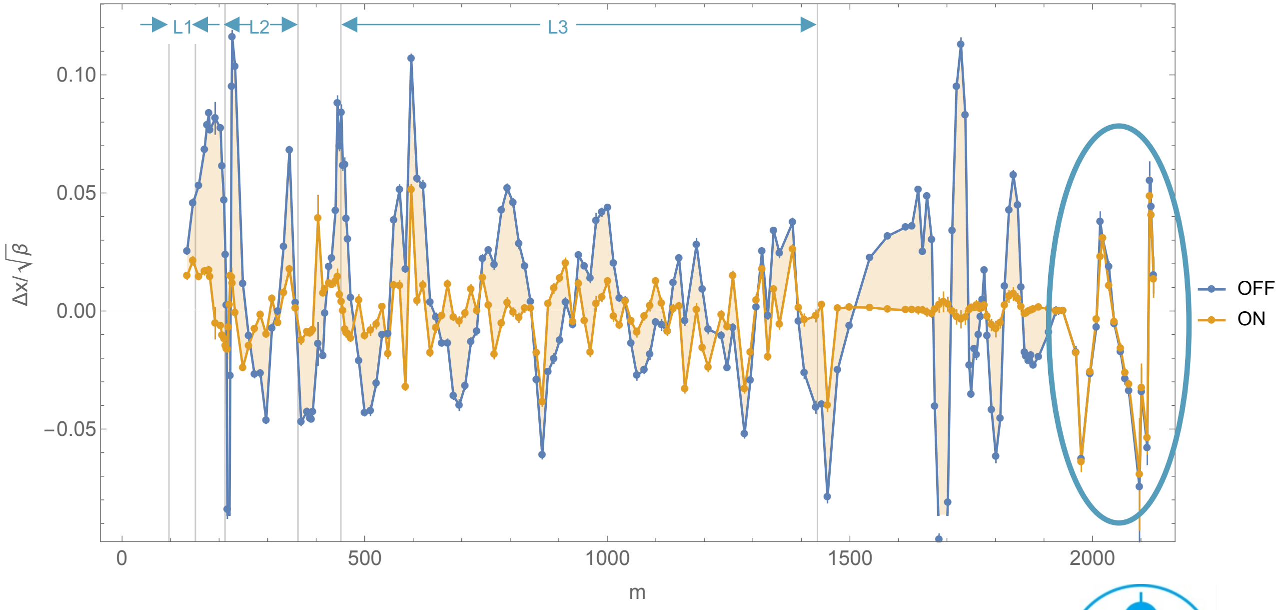
- Transverse kicks from cavity HPC and misalignments (tilts)

RF Station: $$\frac{d}{dt}\sum_{i=1}^{32}\tilde{V}_i = 0$$ LLRF VSUM control

But $$\frac{d}{dt}\tilde{V}_i \neq 0$$

⇒ time-dependent transverse kicks along bunch train





Quick summary

- XFEL has successfully tested ILC tech.
- But many parameters remain elusive
  - Elephant in the room: average accelerating gradient
- Availability RF is now >90 (>99)
  - Highly automated systems
  - And the hard work and diligence of many people.

Quick summary

- XFEL has successfully tested ILC tech.
- But many parameters remain elusive
  - Elephant in the room: average accelerating gradient
- Availability RF is now >90 (>99)
  - Highly automated systems
  - And the hard work and diligence of many people.

To answer the remaining ILC questions, we need to build it

😀

Thanks for your attention