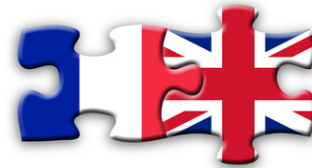


European X-ray Free Electron Laser (XFEL).

Début d'opération, expérience acquise et projets futurs .

Julien Branlard, for the LLRF team
Orsay, 10.07.2018

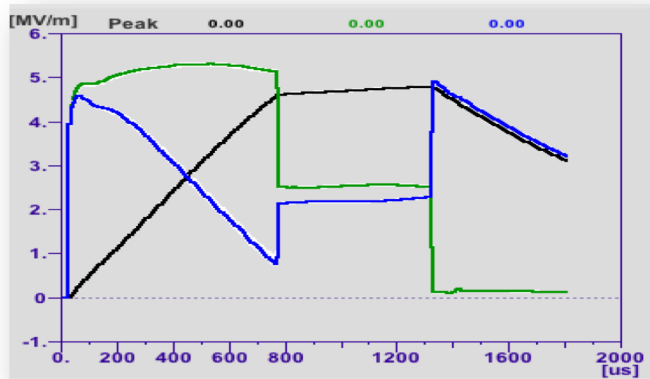


PLAN

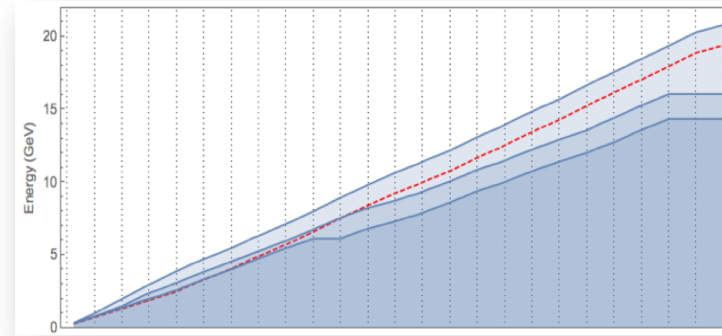
01. L'accélérateur European XFEL



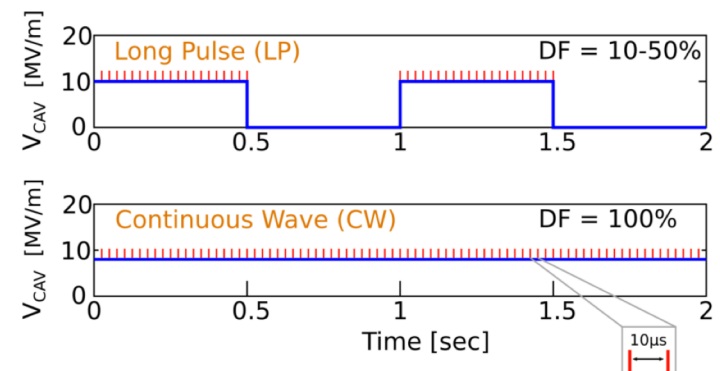
02. Highlights: RF commissioning



03. Highlights: Operation



04. Upgrade CW



INTRODUCTION

The European XFEL

INTRODUCTION: the European XFEL

European X-ray Free Electron Laser

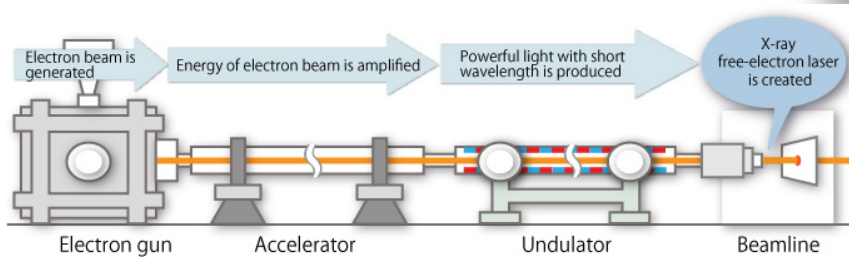
- Source rayons X pour utilisateurs
- Faisceau électrons 17.5 GeV
- 3 lignes photons (ondulateurs)
- Total de 6 expériences: hard (4) & soft (2) X-rays

L'accélérateur XFEL

- 1.3 GHz cavités supra (TESLA)
- Machine pulsée, 1.4 msec à 10 Hz
- 800 cavités SRF, coupleurs, tuneurs
- 101 cryomodules, 26 stations RF
- 2 ans: tests cavités / cryomodules + installation tunnel



You Tube watch online: <https://www.youtube.com/watch?v=p3G90p4glQA>



Le plus long linac supra en fonctionnement au monde



- Grande machine → “penser grand” (état d’esprit, approche générale)
- Répercussions à **tout niveaux**
 - Production
 - Test
 - Documentation
 - Stockage
 - Installation
 - Inventaire
 - Commissioning
 - Maintenance
 - ...
- Labo de recherche → **Compagnie de production de masse**

INTRODUCTION: contributions internationales

20 instituts de recherche et universités

11 pays (Europe, Russie)

80+ contributions *in-kind*



Wroclaw University of Technology

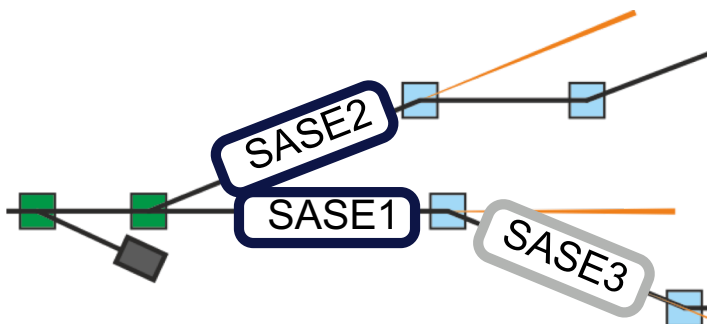
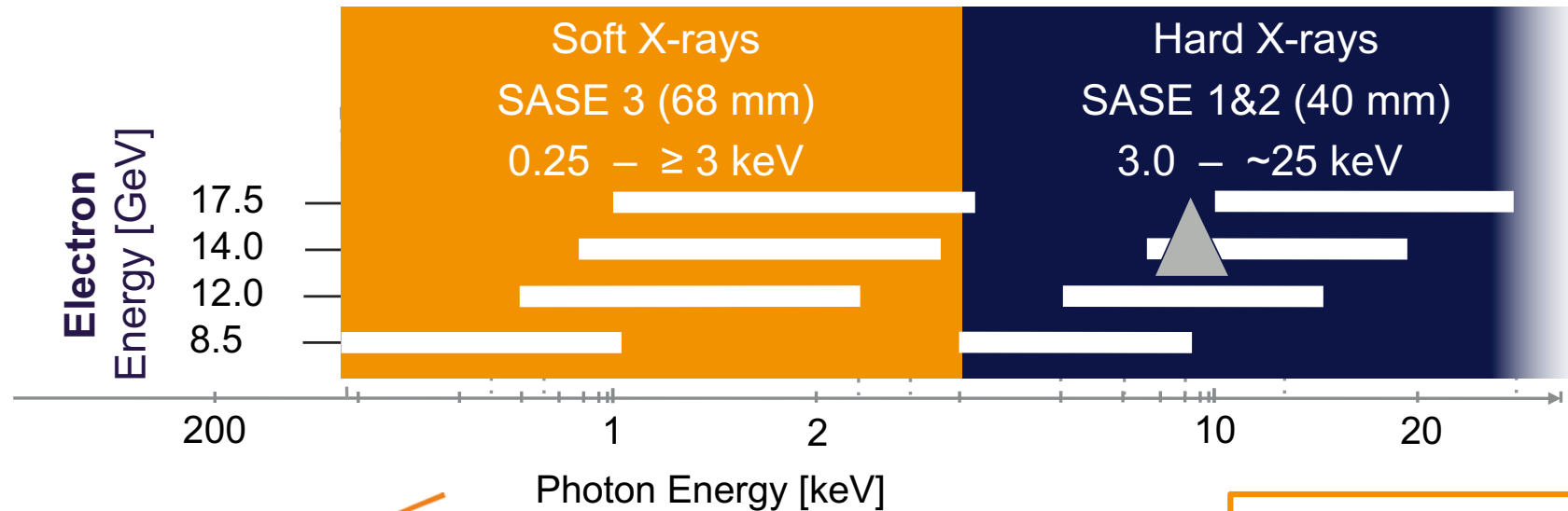


INTRODUCTION: contributions internationales

(source: <https://www.xfel.eu>)

Pays	Nb.	Valeur [k€]	Contributions (liste partielle)
Allemagne	36	429 447	<ul style="list-style-type: none">• Systèmes RF (haute puissance et bas niveau)• Cavités supraconductrices et vaisseaux cryo.• Tuneurs fréquence• Cryogénie et centrale cryogénique• Système de contrôle
Russie	13	42 043	<ul style="list-style-type: none">• Equipement cryogénique pour le Linac• Absorbeur faisceau• Electroaimants (température ambiante)• Structures transverses défectrices (TDS)
France	4	36 000	<ul style="list-style-type: none">• Coupleurs RF (production & conditionnement)• Assemblage cryomodules• Ecrans magnétiques
Italie	3	33 000	<ul style="list-style-type: none">• Cavités supraconductrices (production 50%)• Production vaisseaux cryogéniques (25%)• Production du module 3^{eme} harmonique (3.9GHz)
Pologne	5	18 390	<ul style="list-style-type: none">• HOM coupleur et absorbeurs• Tests verticaux cavités, tests horizontaux cryomodules
Suisse	2	8 835	<ul style="list-style-type: none">• Détecteurs de position faisceau (BPM)

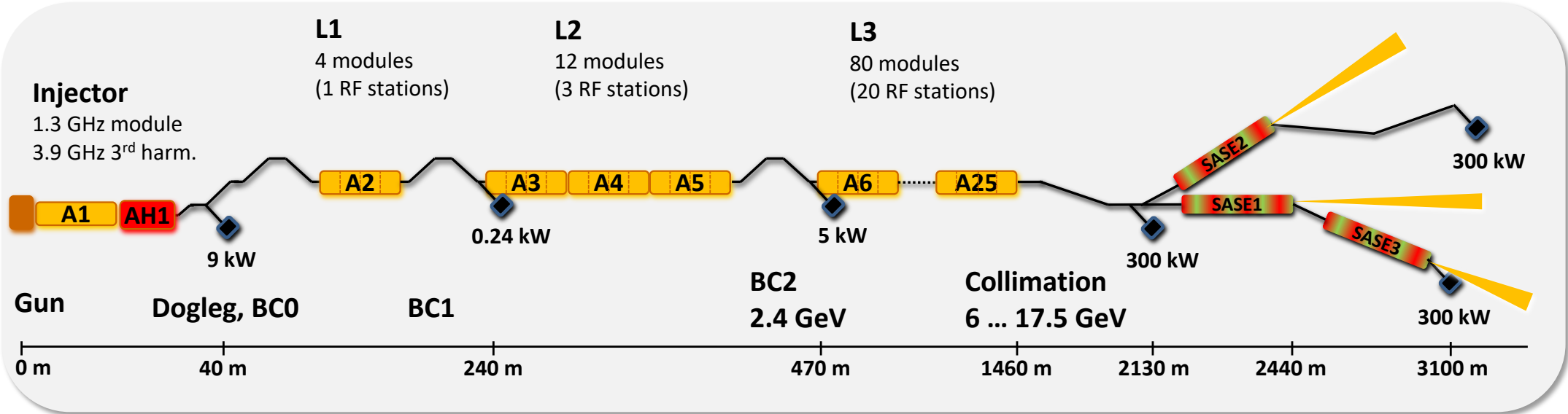
INTRODUCTION: energies photon de 0.25 keV à 25 keV



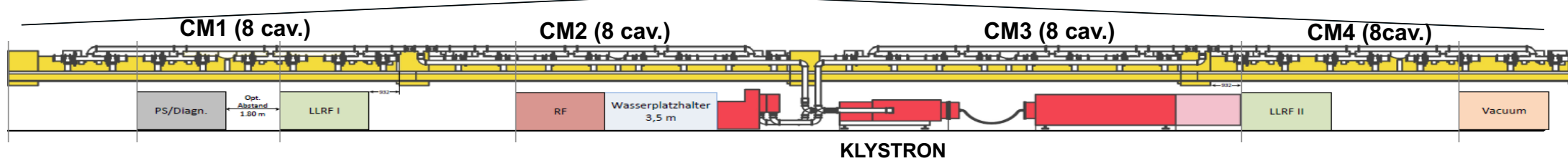
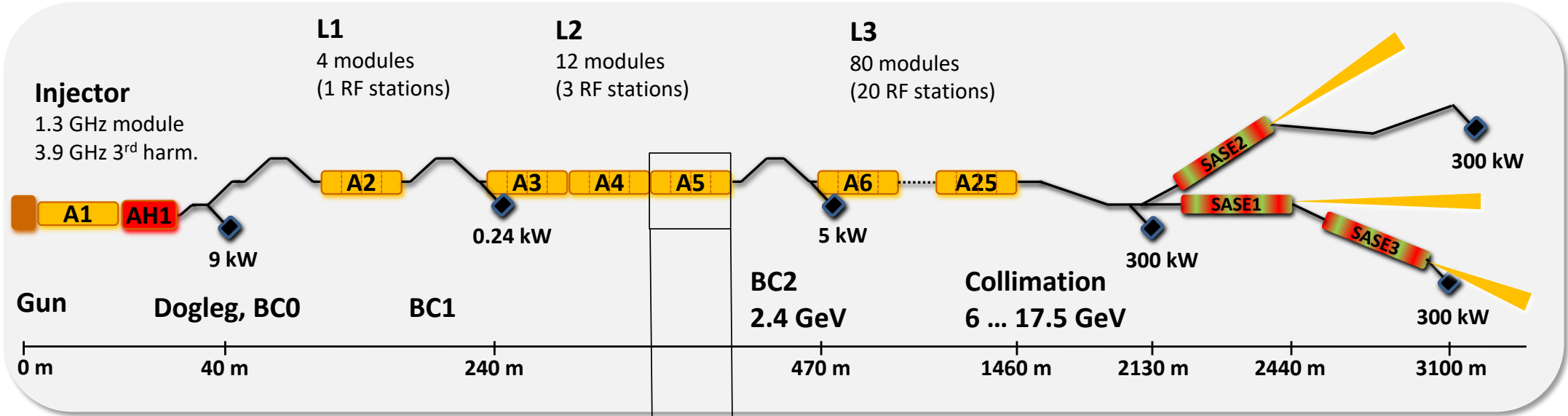
Working point during first user runs: 14 GeV electron beam energy and ~9.3 keV photon energy (SASE1).



INTRODUCTION: XFEL vue schématique



INTRODUCTION: une station RF



One RF station comprises:

- 1x 10 MW klystron
- 32x TESLA type cavities housed in 4 cryomodules
- 32x motorized power couplers
- 32x motorized tuners
- 64x piezo (actuator / sensor)
- 36x motorized phase shifters (1/ cav + 1/ cryomodule)
- 100+ RF channels (probe, forward, reflected)
- 600+ RF connections

x 26

COMMISSIONING

COMMISSIONING: mise en marche de l'XFEL

- **RF**
 - First RF
 - Required RF gradient and stability
- **Beam**
 - First beam
 - Required beam transmission at desired current
- **Photons**
 - First lasing
 - Required photon energy for user
- **Experiments**
 - Beam line
 - Experimental setup

Not covered in this talk



[MOXAA1] “Commissioning of the European XFEL Accelerator”, W. Decking, H. Weise

[THOAA3] “Installation and first Commissioning of the LLRF System for the European XFEL”, J. Branlard et al.



[MOZGBD2] “FEL Performance Achieved at European XFEL”, Matthias Scholz

COMMISSIONING RF

RF seulement

- **Vérifications initiales**
- **Vérif. signaux RF: Incidentés and Réfléchies**
- **Ajustement fréquence**
- **Vérif. signaux RF: Transmises**
- **Ajustement coupler**
- **1^{ere} calibration gradient (power-based)**
- **Opération asservissement (feedback)**



Prêt pour transport FAISCEAU

- **Etablir transport faisceau**
- **Ajustement phase cavités**
- **2^{eme} calibration gradient (beam-based)**

LLRF Milestones

LLRF system ready for commissioning ?

Cabling issues? Signal saturation ?

From parking position to resonance.

Cabling issues ? Signal saturation ?

Target $Q_L = 4.6e6$.

Coarse


Feedback, learning feedforward, ...

30 bunches, 0.5nC.

Using waveguide phase shifters.

Fine relative calibration. Absolute validation using energy server.

COMMISSIONING RF

<input checked="" type="checkbox"/>	12/16	Refroidissement à 4K 	2 weeks
<input checked="" type="checkbox"/>	01/17	Injector à 130 MeV (3 stations RF)	2 weeks
<input checked="" type="checkbox"/>	01/17	Linac 1 (+1 station RF)	1 month
<input checked="" type="checkbox"/>	02/17	Linac 2 (+3 stations RF)	2 weeks
<input checked="" type="checkbox"/>	02-04/17	Linac 3 (+15 + 3 stations RF)	2 months
<input checked="" type="checkbox"/>	04/17	Premier faisceau à travers la section onduleur (SASE1)	
<input checked="" type="checkbox"/>	05/17	Premier lasing	
<input checked="" type="checkbox"/>	05-08/17	SASE1 photon beamline + hall experimental	
<input checked="" type="checkbox"/>	09/17	Premiers utilisateurs (total 800 heures)	
<input checked="" type="checkbox"/>	2018	Commissioning continue + 2000 heures utilisateurs	
<input type="checkbox"/>	2019	Operation nominale avec 6 experiences + 4000 heures utilisateurs	

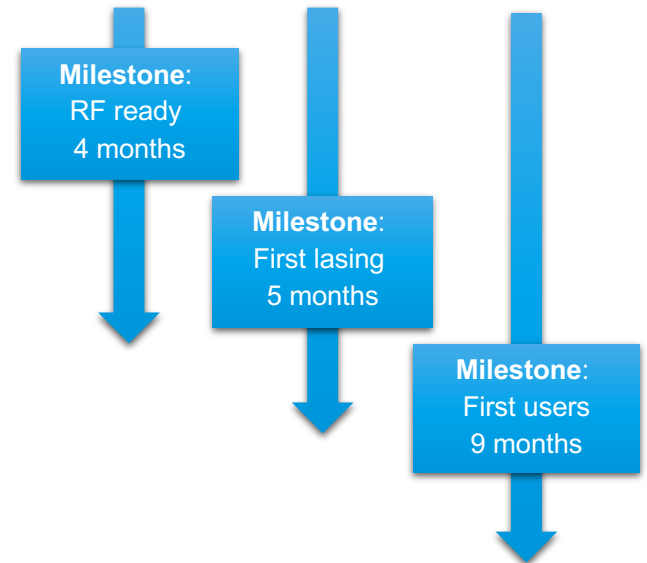


Photo: shutterstock.com

COMMISSIONING RF

Vérifications pre-commissioning

- Board
- Chassis
- Armoires



Grande machine → grande équipe

- 20 personnes
- dont 8 experts LLRF
- Plus contribution d'autres instituts



Procédure

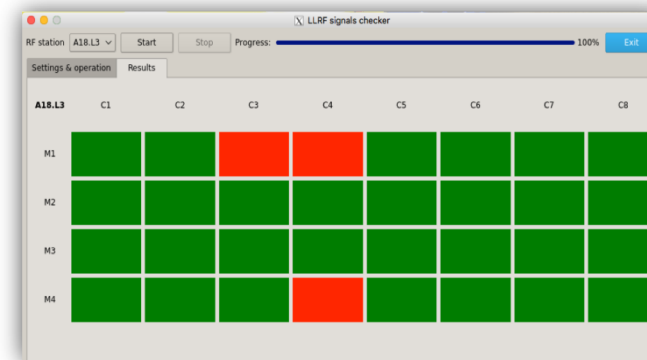
- Préparation et itération des procédures
- Check liste



Source: SmallBizClub.com

Automatisation

- Essentielle pour les machines à grande échelle
- Coûteux en temps mais retour sur investissement



COMMISSIONING RF

The screenshot displays the XFEL L3/CL/TLD control interface. At the top, it shows the operation mode as SASE1/3, TLD and the beam mode as Short. The personal interlock is set to XTL Beam Permission. The beam status is indicated as 'IN operation ON beam' for A6-A17 and 'IN operation but shifted OFF beam' for A18-A25. The magnets permission is grounded. The beam energy is 10381 MeV. Two LLRF control panels are shown: A10.L3 and A21.L3. A10.L3 is 'On Beam' and A21.L3 is 'Off Beam'.

Operation Mode: SASE1/3, TLD
Beam Mode: Short
Personal Interlock: XTL Beam Permission

IN operation ON beam (A6-A17)
IN operation but shifted OFF beam (A18-A25)
Not ready for beam operation hence shifted OFF beam (A21-A25)

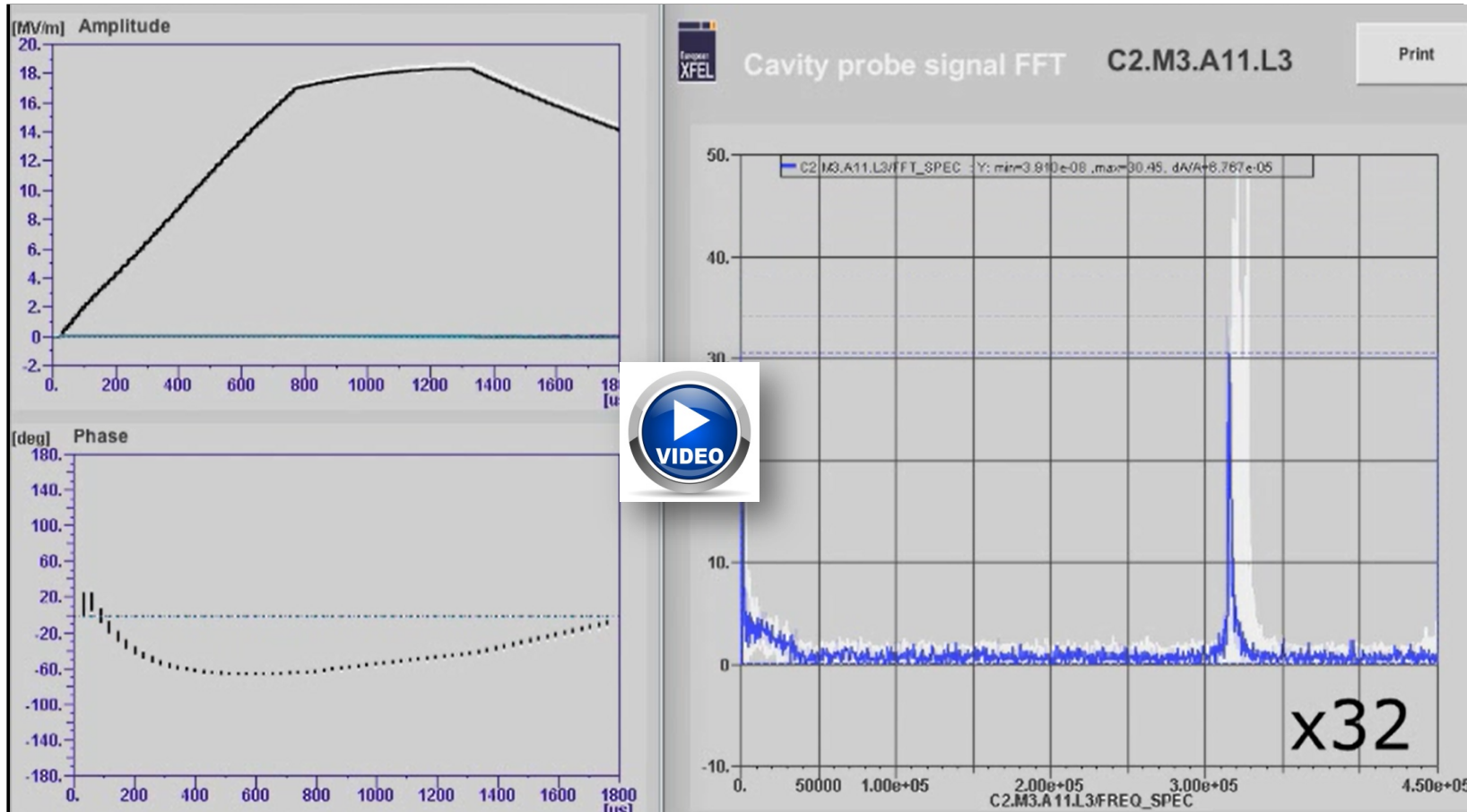
Magnets Permission
 LINAC Mode: [Green] [Yellow] [Red]
 Grounded [X]

Beam Status: 1 @ 99% (A6-A17), 1 @ 99% (A18-A20), 1 @ 97% (A21-A25)
 Energy: 10381 MeV

LLRF CONTROL A10.L3
 Main Control: Voltage 500.00 MV, Phase 0.00 deg, RF On/Off checked, FSM ON.
 Subsystems: Modulator, Kly Timing, RF Gate, Coupler, Quick Tune, Tuner, CPIM, PSM, RPC test, Watchdog.
 Status: **On Beam**

LLRF CONTROL A21.L3
 Main Control: Voltage 500.00 MV, Phase 0.00 deg, RF On/Off checked, FSM ON.
 Subsystems: Modulator, Kly Timing, RF Gate, Coupler, Quick Tune, Tuner, CPIM, PSM, RPC test, Watchdog.
 Status: **Off Beam**

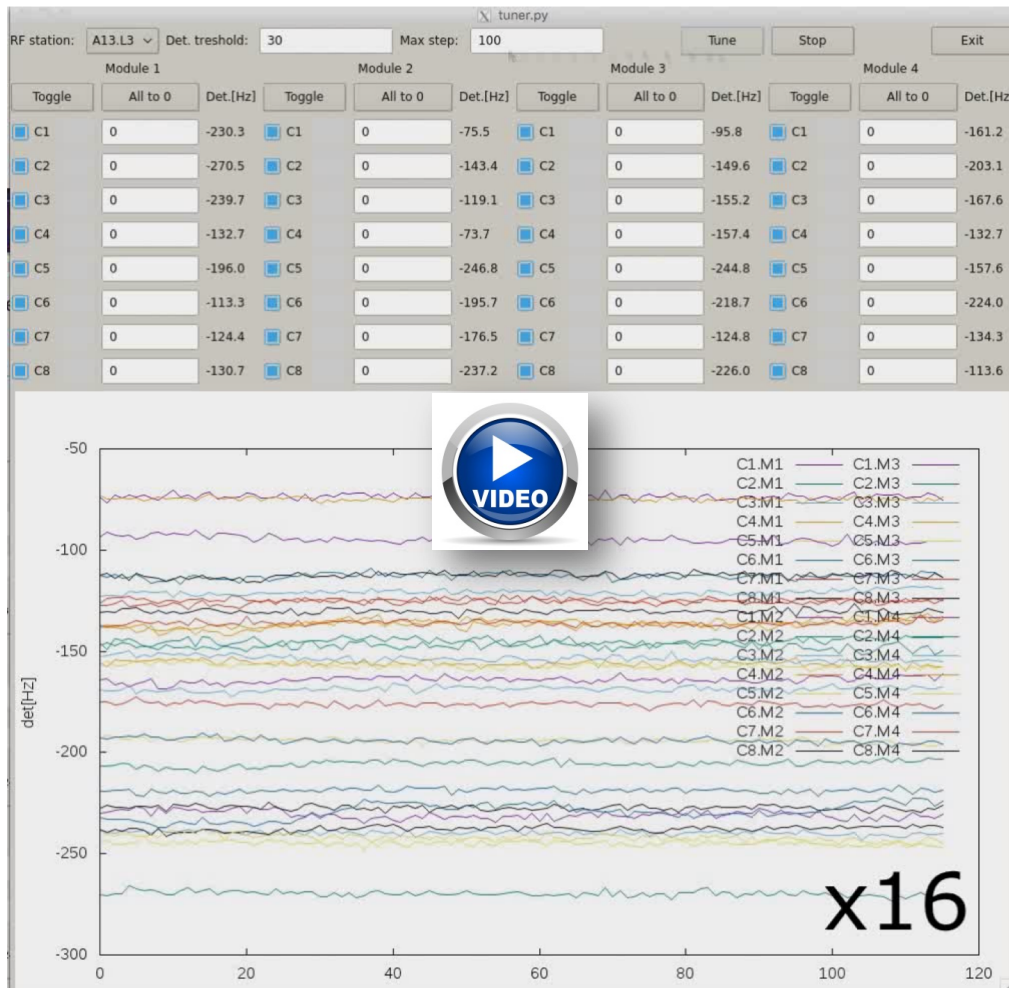
COMMISSIONING RF: outils d'automatisation



Premier ajustement fréquence des cavités (“coarse tuning”) depuis leur position de parking (~300-500 kHz en dessous de 1.3 GHz)

32 cavités ajustées en 2 heures environ (meilleur temps)

COMMISSIONING RF: outils d'automatisation



- Deuxième réglage fréquence (“fine tuning”)
- 32 cavités simultanément
- Environ 2 minutes pour 32 cavités
- Peut être utilisé sur plusieurs stations RF en parallèle

COMMISSIONING RF: outils d'automatisation

Vérification signaux RF (1/2)

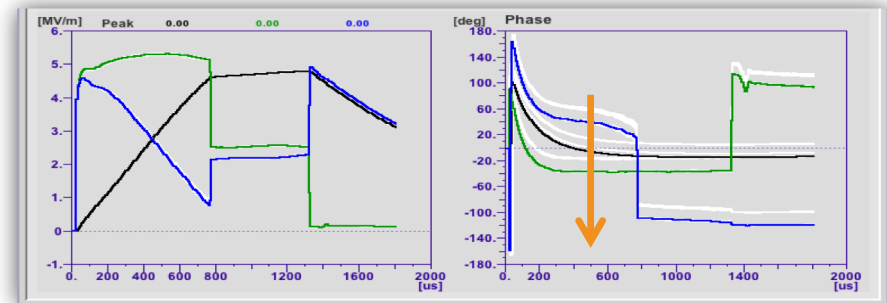
“Le jeux des 7 erreurs”



COMMISSIONING RF: outils d'automatisation

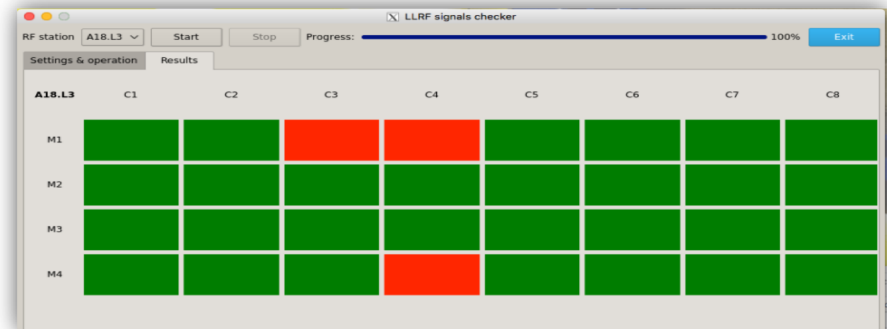
Vérification signaux RF (2/2)

- 3-4 mins par station RF
- Vérifie fonctionnalité ajusteur de phase (32x)
- Identifie erreurs câblage:
 - FORW ↔ REFL
 - C1 ↔ C2



Rappel:

- LLRF a 2500+ signaux RF
 - Transmis
 - Incident
 - Réfléchi
- x2 en comptant câblage int./ext.



Erreur de câblage

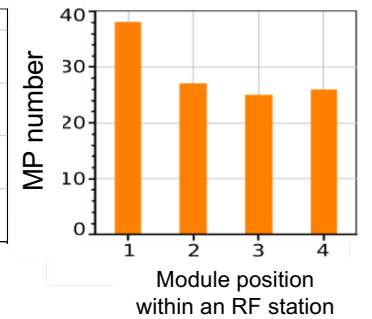
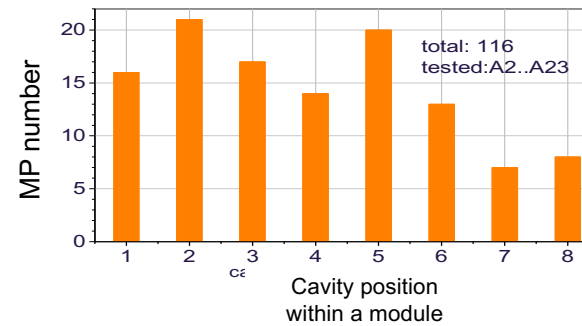
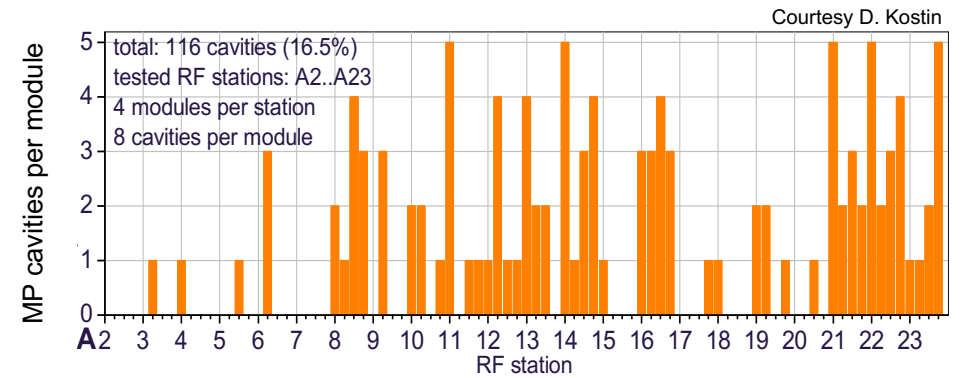
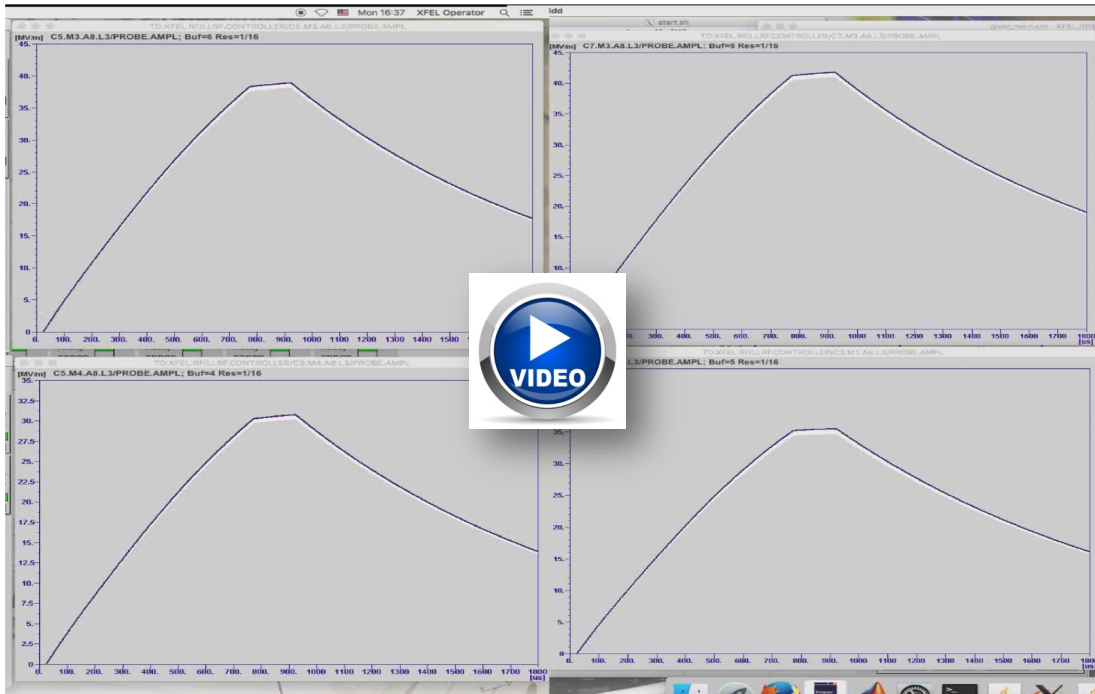
- **15 cas** (externes aux armoires) identifiés avant cool down
- **11 cas** (externes aux armoires) identifiés après cool down
- **0 cas** (interne aux armoires) identifiés jusqu'à présent

} < 1%

COMMISSIONING RF: conditionnement du multipacting

Multipacting (MP)

- Observé sur pratiquement toutes les stations RF testées jusqu'à présent (A2-A23)
- Apparaît vers 17-18 MV/m
- Conditionnable à chaque fois
- Conditionnement dure quelques heures par station (@10 Hz)

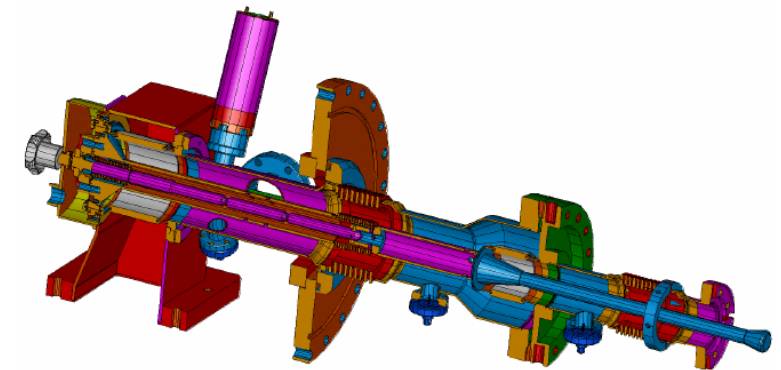
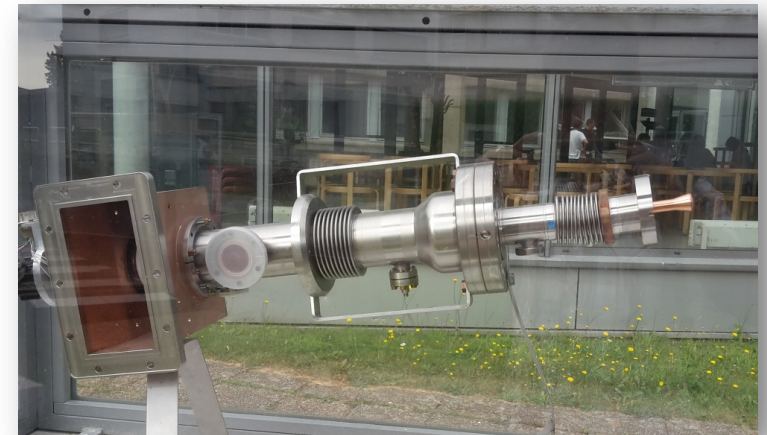


COMMISSIONING RF: problèmes de coupleurs

5 sur 720 coupleurs shuntés après tests dans le tunnel < 1%

- A4.M4.C4 coupler problem: T70K [shorted]
- A12.M4.C1 coupler problem: T70K [shorted]
- A16.M2.C1 coupler problem: T70K [shorted]
- A20.M4.C1 coupler problem: T70K [shorted]
- A21.M2.C5 coupler problem: T70K [shorted]

Courtesy D. Kostin



N	position	module	coupler part	status	comments
1	A4.M4.C4	XM72	CPI-CP-024	shorted	T70K → 200K, high e-1 signal (discharge), cold part problem. AMTF: push-rod replaced, no other problems.
2	A12.M4.C1	XM53	THRI-WP-706	shorted	T70K → 150K, discharge, warm part problem. No problem / observations in AMTF.
3	A13.M2.C8	XM51	THRI-WP-683	OK	high e-2 signal – conditioned.
4	A16.M1.C1	XM69	THRI-CP-880	OK	high e-1 signal – conditioned.
5	A16.M2.C1	XM60	CPI-CP-028	shorted	T70K → 150K high e-1/2 signals, cold part problem. Problem seen in AMTF, T70K → 115K (some overheating).
6	A16.M2.C2	XM60	CPI-WP-030	OK	high e-2/3 signals – conditioned.
7	A16.M4.C7	XM66	THRI-WP-323	OK	high e-2/3 signals – conditioned.
8	A19.M3.C4	XM-2	AC3H26	testing	T70K overheating – no discharge. Observed in AMTF as well.
9	A19.M3.C6	XM-2	AC3H38	OK	conditioned (5hr) up to 150kW FT-pulse (25MV/m)
10	A20.M4.C1	XM65	THRI-WP-470	shorted	high T70K, cpl.vac. increased, high e-2 signal bursts, warm part problem.
11	A21.M2.C5	XM92	THRI-WP-155	shorted	T70K overheating – no discharge. WP was already replaced in AMTF – same problem.

5 FPCs are not conditionable and showing T70K overheating – shorted / disconnected from RF.

COMMISSIONING RF: field emission

9 sur 720 cavités normalement detunées

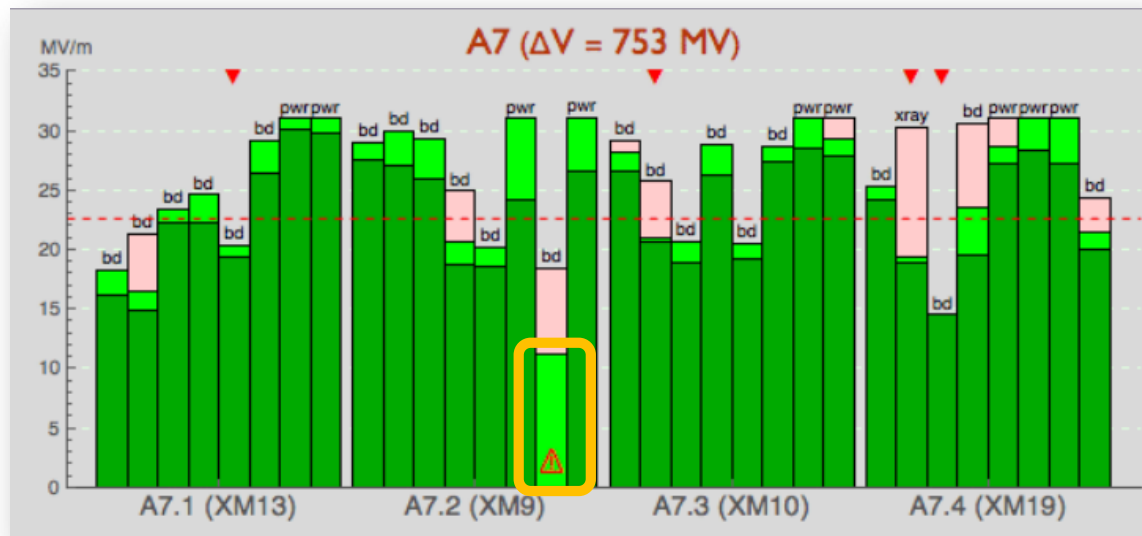
1.25 %

5 jugées inutilisables après tests à AMTF

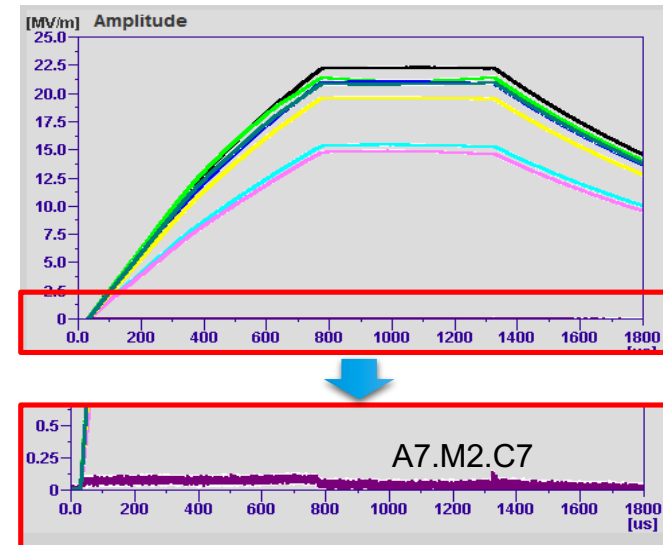
- A6.M3.C1 high FE/X-ray (limite 10 MV/m)
- A7.M2.C7 high FE/X-ray (limite 11 MV/m)
- A10.M1.C3 low Eacc BD (no FE) (limite 13 MV/m)
- A18.M4.C4 high FE/X-ray (23 MV/m limit + wrong P_{FORW})
- A21.M3.C4 high FE/X-ray

4 détunées après tests dans le tunnel

- A12.M2.C2 low Eacc BD (limite le VS)
- A12.M3.C8 low Eacc BD (limite le VS)
- A14.M3.C5 high FE/Xray
- A21.M4.C2 low Eacc BD (limite le VS)



Courtesy N. Walker



COMMISSIONING RF: combien de cavités par station RF

- Seulement **13 / 22** stations RF utilisent toutes les 32 cavités (~60%)

data from 05.02.2018

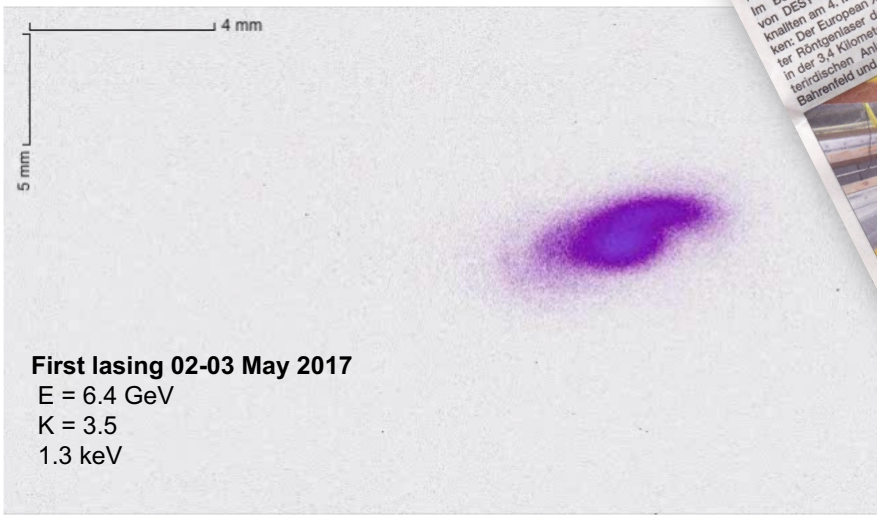
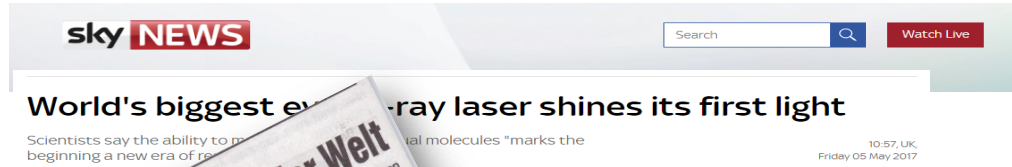
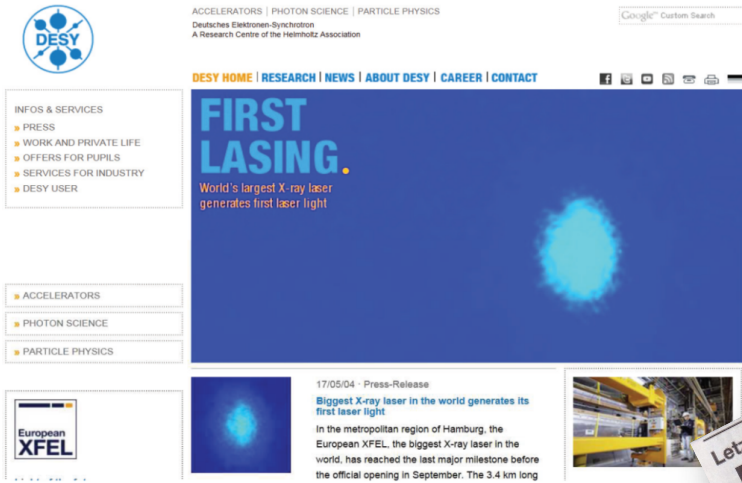
Linac Station	L1		L2		L3																	
	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	A21	A22	A23
Cav. in operation	32	32	31	32	31	31	32	32	31	32	29	32	31	32	31	32	31	32	32	29	32	32
AMTF gradient	867	983	989	924	827	753	843	827	860	939	880	843	748	770	919	842	911	858	948	923	870	919
Typ. operation	616	593	593	593	710	630	718	700	750	740	600	701	620	630	780	600	740	540	650	800	660	750
Ratio to AMTF	71%	60%	60%	64%	86%	84%	85%	85%	87%	79%	68%	83%	83%	82%	85%	71%	81%	63%	69%	87%	76%	82%
Avg gradient	19.3	18.5	19.1	18.5	22.9	21.0	22.4	21.9	24.2	23.1	19.4	21.9	20.0	20.3	26.0	18.8	23.9	16.9	21.0	26.7	20.6	23.4

2.4 GeV at BC2

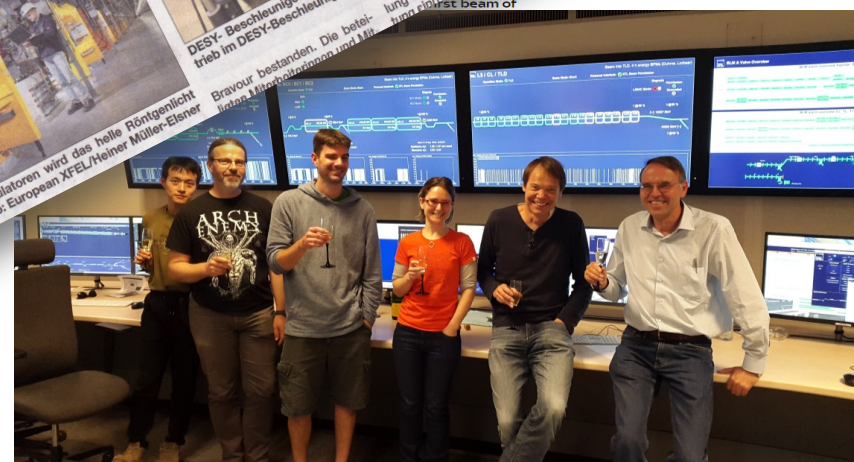
14 GeV

- **14 GeV**
 - ~ 80% du gradient maximum mesuré en test horizontal (AMTF)
 - Gradient moyen: 21.4 MV/m

Mai 2017: premiers résultats: LASING!



First lasing 02-03 May 2017
 $E = 6.4 \text{ GeV}$
 $K = 3.5$
 1.3 keV



Mai 2017: rencontre utilisateurs

Plus de 1000 participants



Sept. 2017: Inauguration



OPERATION

OPERATION: Sept. 2017 - Premiers utilisateurs

Deux huttes expérimentales servies

- SPB/SFX
- FXE

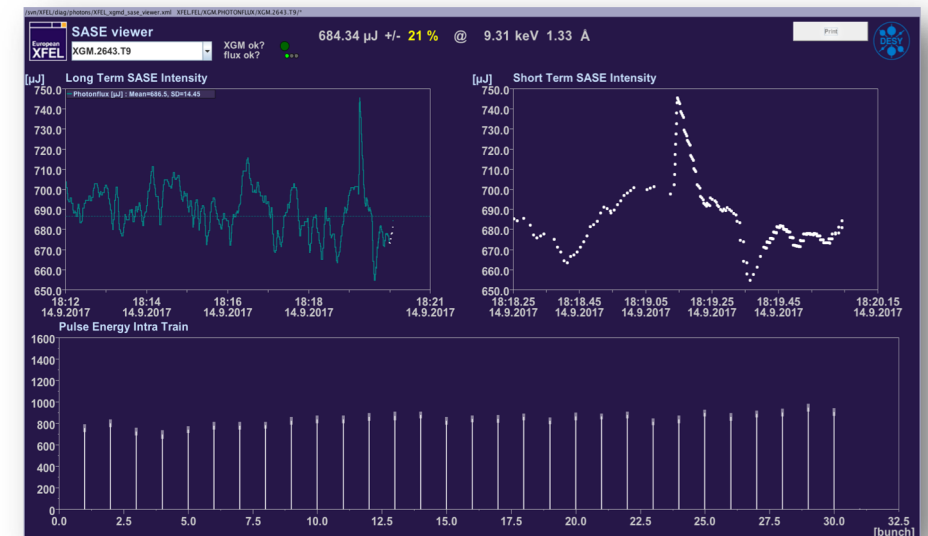
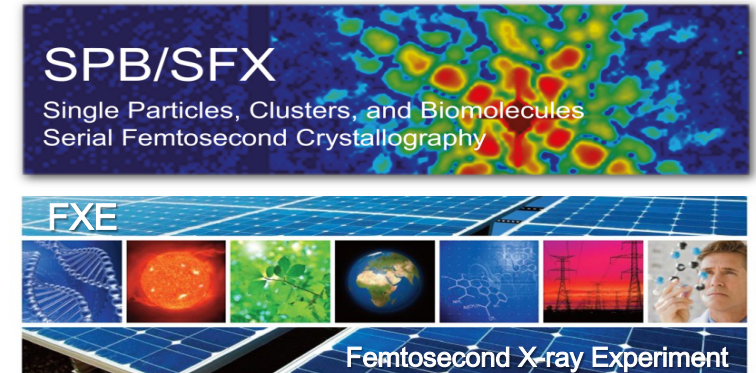
Paramètres accélérateur

- Energie: 14 GeV
- Faisceau: 1-30 paquets d'e⁻, 500 pC

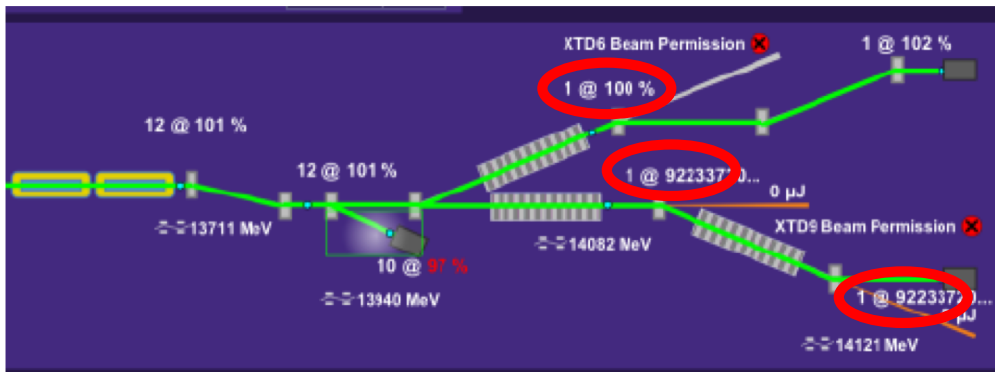
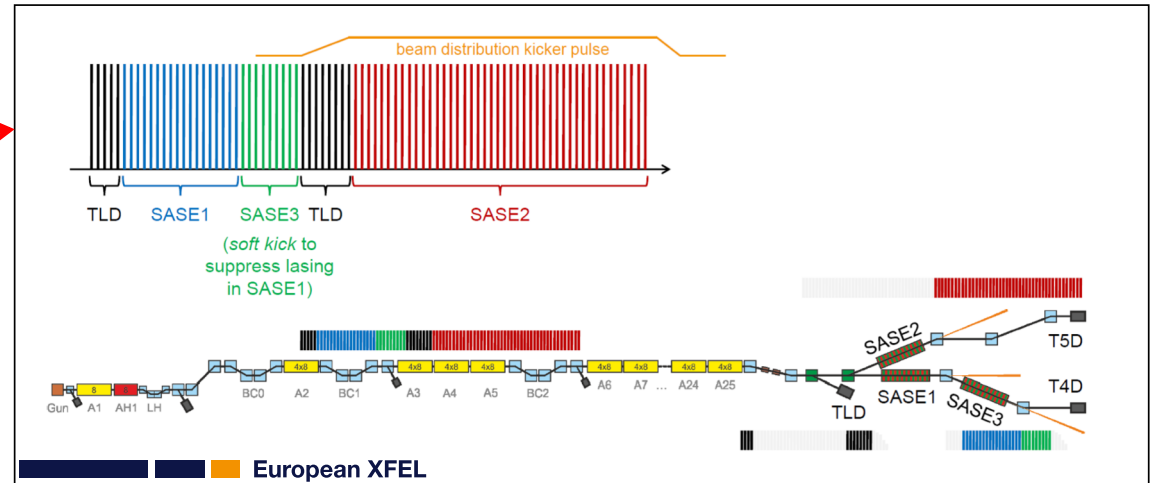
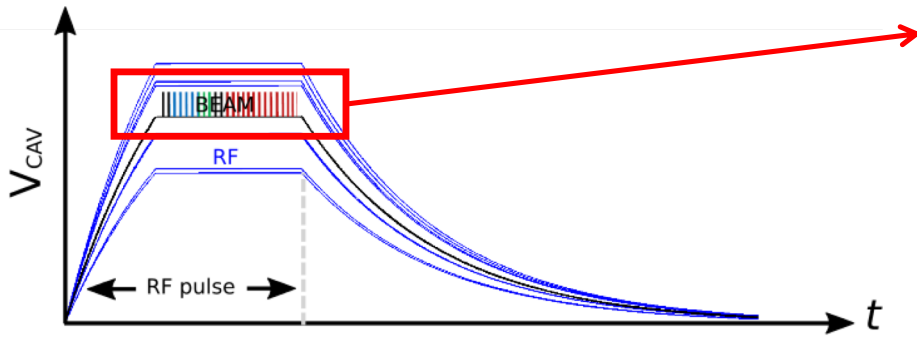
Paramètres onduleurs

- Energie SASE jusqu'à 750 μJ
- Longueur d'onde ~1.3 Å
- Energie photon ~9.2 keV

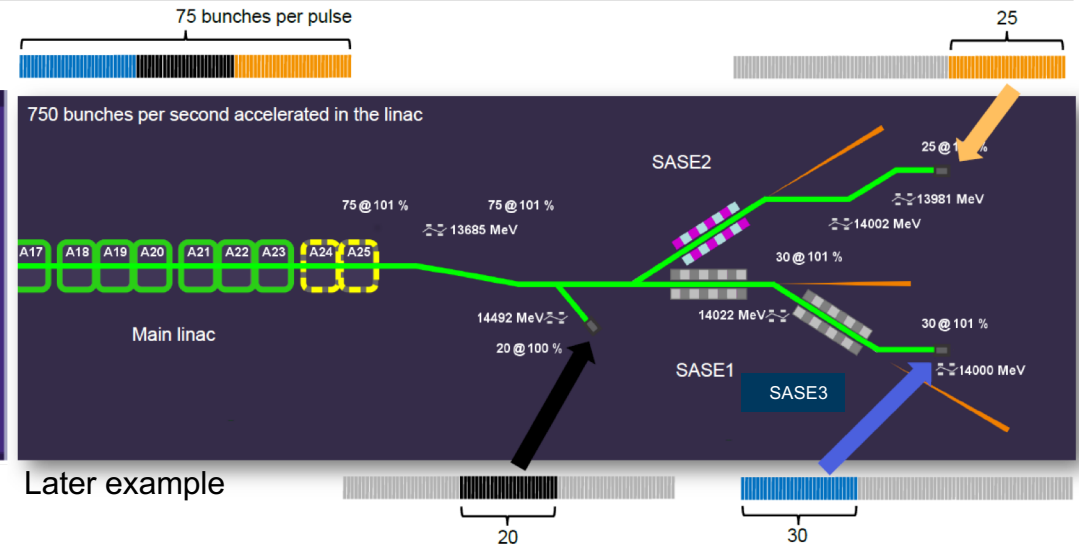
Puissance et disponibilité du faisceau au delà des attentes 😊



OPERATION: Mars 2018 – Faisceau multi-ligne

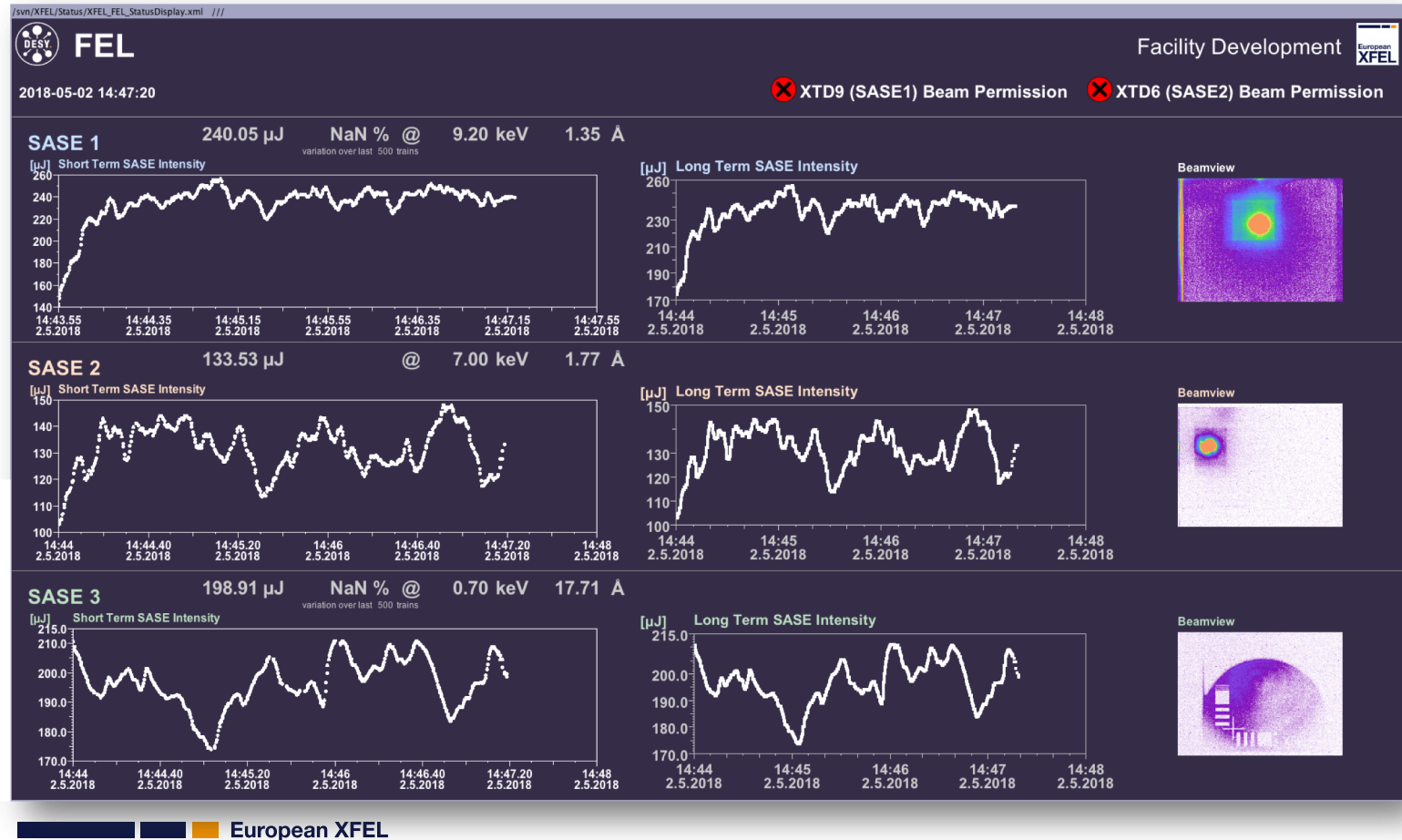
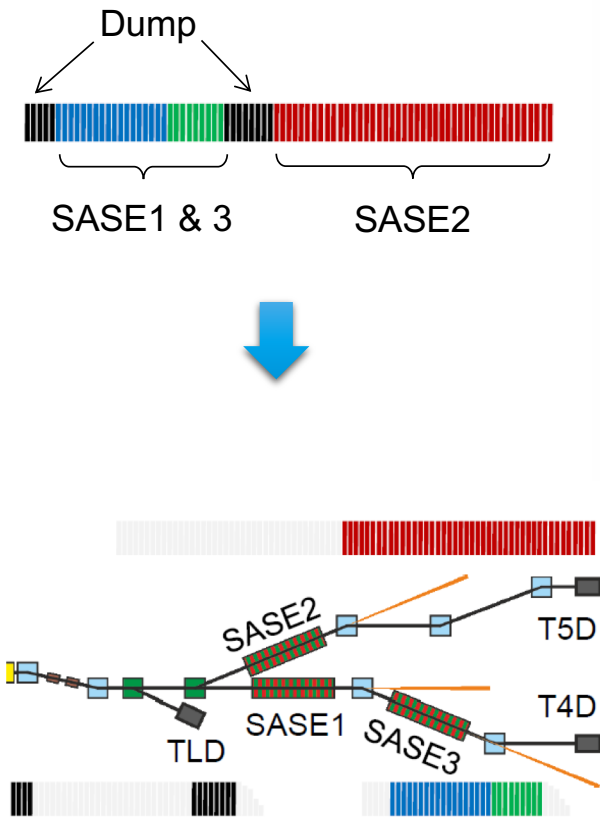


15.03.2018

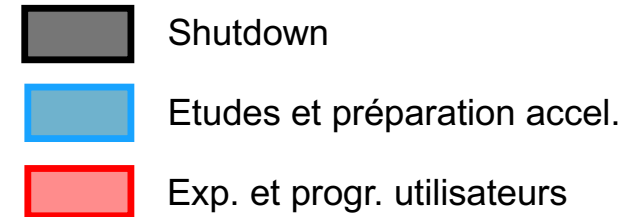
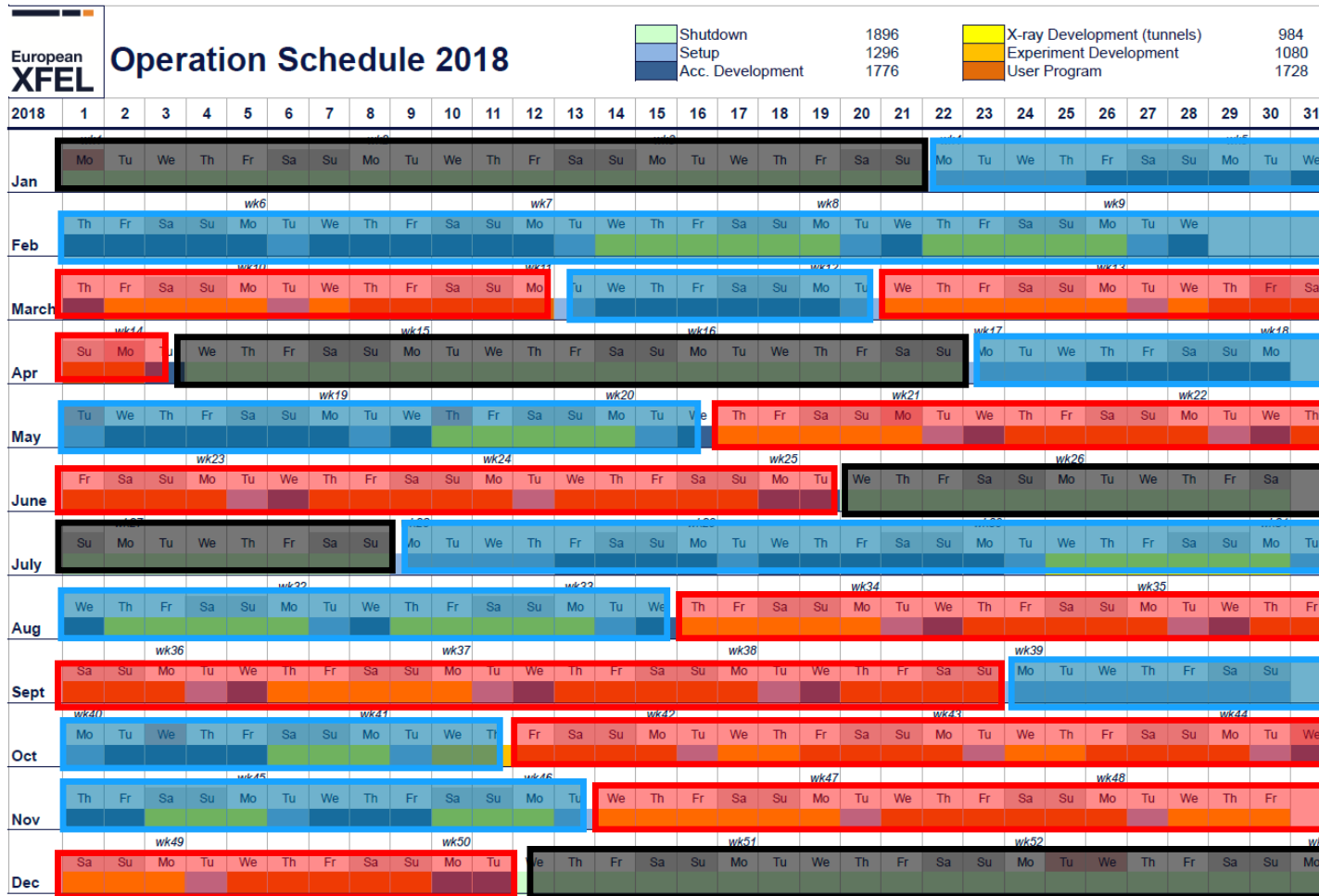


Later example

OPERATION: Mai 2018 – Premier lasing simultan  SASE1/2/3



OPERATION: XFEL planning



2018

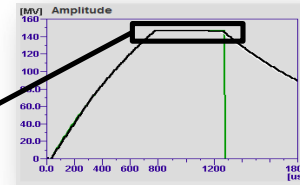
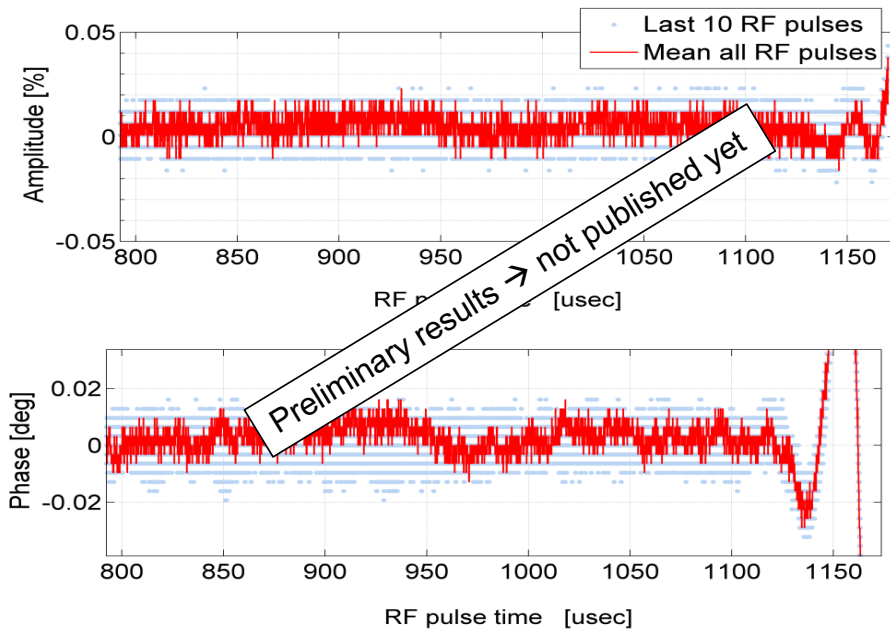
- 6800 h. d'opération
- 1600 h. programme utilisateurs

2019

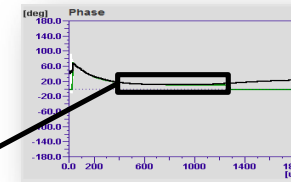
- 6700 h. d'opération
- 4800 h. programme utilisateurs

OPERATION: performance RF

Stabilité (in-loop)



Intra-pulse $\sigma(dA/A) = 0.0057 \%$
 Pulse-to-pulse $\sigma(dA/A) = 0.0056 \%$



Intra-pulse $\sigma(dP) = 0.0051 \text{ deg.}$
 Pulse-to-pulse $\sigma(dP) = 0.0024 \text{ deg.}$

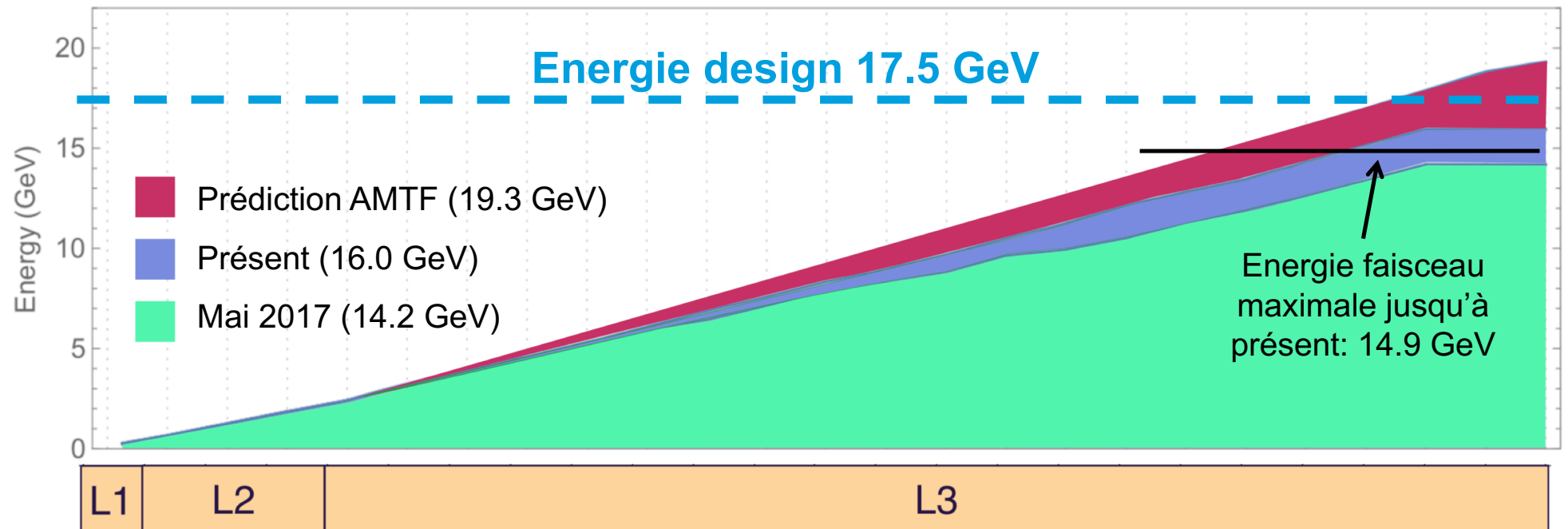


Spécifications:

$\sigma(dA/A) = 0.01 \%$ ✓
 $\sigma(dP) = 0.01 \text{ deg.}$ ✓

Courtesy S. Pfeiffer

OPERATION: quête du gradient maximum



- **23** stations sur les **25** disponibles ont été mise en service (les 2 dernières cette semaine)
- L'énergie faisceau maximale démontrée jusqu'à present est de **14.9 GeV**
- **14.0 GeV** typiquement pour les utilisateurs.

OPERATION: performance RF (Juin 2018)

Courtesy M. Omet

RF station	AMTF [MeV]	XFEL [MeV]	XFEL / AMTF	Limitation
A9	827	700	84%	Field emission
A10 ♦	860	770	90%	M3.C8 quenches at 19.8 MV
A11	939	900	96%	Coupler heating
A12 ♦	880	710	81%	M2.C5 quenches at 25.8 MV, high rad.
A13 ♦	843	750	89%	M4.C1 quenches at 25.4 MV
A14	748	620	83%	Soft quenching and probably field emission at M3.C5 and M3.C7
A15	770	710	92%	M4.C2 quenches at 19.4 MV
A16 ♦	919	830	90%	M3.C8 quenches at 27.0 MV
A17 ♦	842	750	89%	M3.C8 quenches at 25.0 MV
A18	911	850	93%	M1.C1 quenches at 27.8 MV
A19 ♦	858	703	82%	M3.C8 quenches at 18 MV
A20	920	620	67%	Waveguide sparking
A21 †	893	870	97%	Missing piezo operation, otherwise M1.C5 quenching at 30.3 MV
A22	870	845	97%	M3.C5 quenches at 19.9 MV
A23	919	700	76%	Waveguide sparking

♦ Amélioration possible en modifiant le système de guide d'onde

† Dégradation du gradient de la cavité (M4.C2: > 31 MV → 22.3 MV) → exclue du VS

study finished

study on-going

Encore 9 stations RF à étudier

OPERATION: problèmes d'irradiation ?



- Relevés TLD réguliers
- Détecteurs dark current en ligne
- Mesures hebdomadaires (MARWIN)



Cas isolés

- Échanges de SSDs (4x)
- Composants nécessitant reprogrammation (4x)
- Connection Ethernet défailante (2x)



OPERATION: problèmes d'irradiation ?

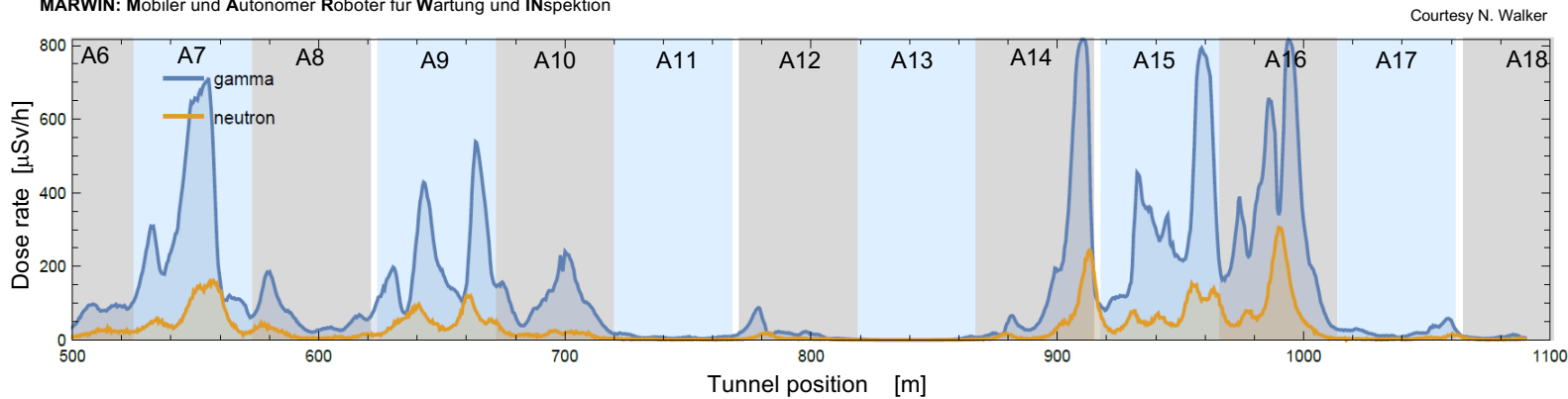
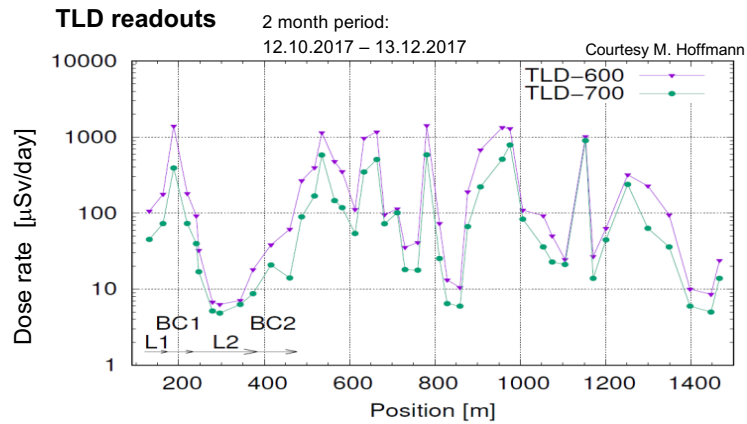
Radiation

- Détecteur en ligne
- Mesures régulières
- XFEL : MARWIN

Limite pour composants électroniques : 1 Gray / an



MARWIN: Mobile and Autonomous Robot for Maintenance and INSpection



Film: M. Omet

OPERATION: machine availability

Quelle disponibilité?

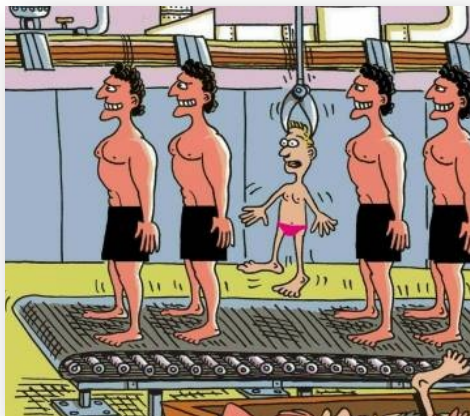
- Dispo. RF
- Dispo. faisceau
- Dispo. photon



Source: fabulesslyfrugal.com

Développement outils

- Détection des fautes (10 Hz)
- Sauvegarde données
- Comprendre la faute et prendre des contre mesures



Analyse des fautes

- Définir et trier par catégories
- Identifier la cause (« root cause »)
- Définir et mesurer le temps de récupération



Source: pinterest.com

Maintenance

- Surveiller la « santé » du système
- Analyse de risques
- Maintenance préventive

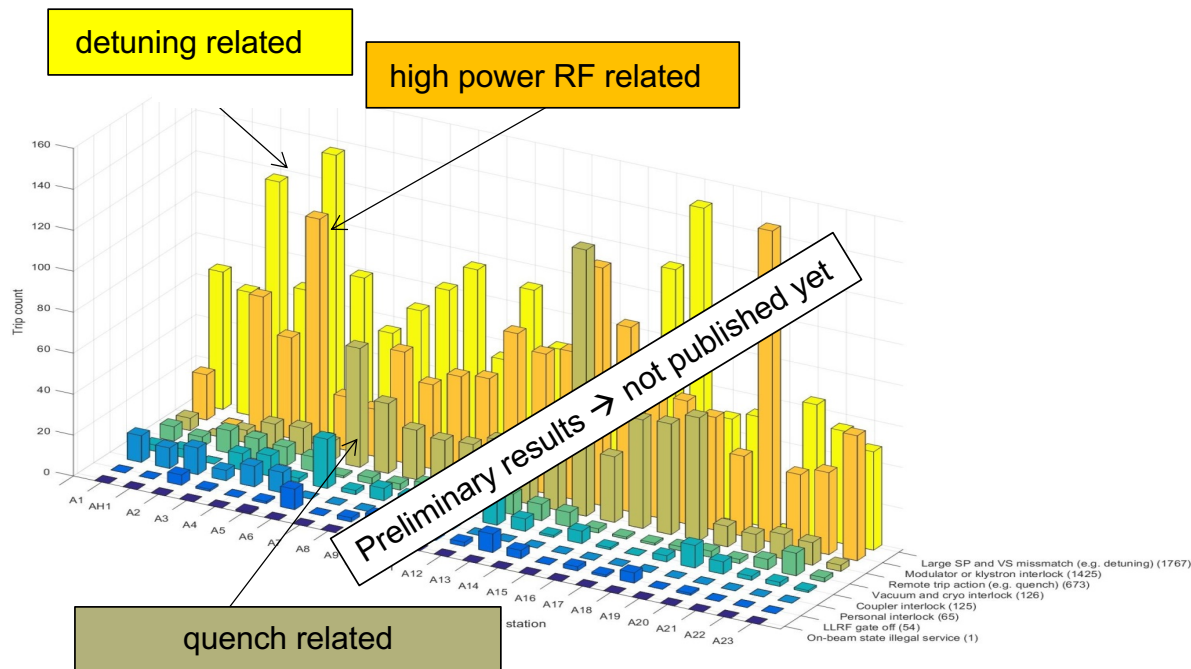


Source: cartoonstock.com

OPERATION: first look at machine availability

Première analyse 2017

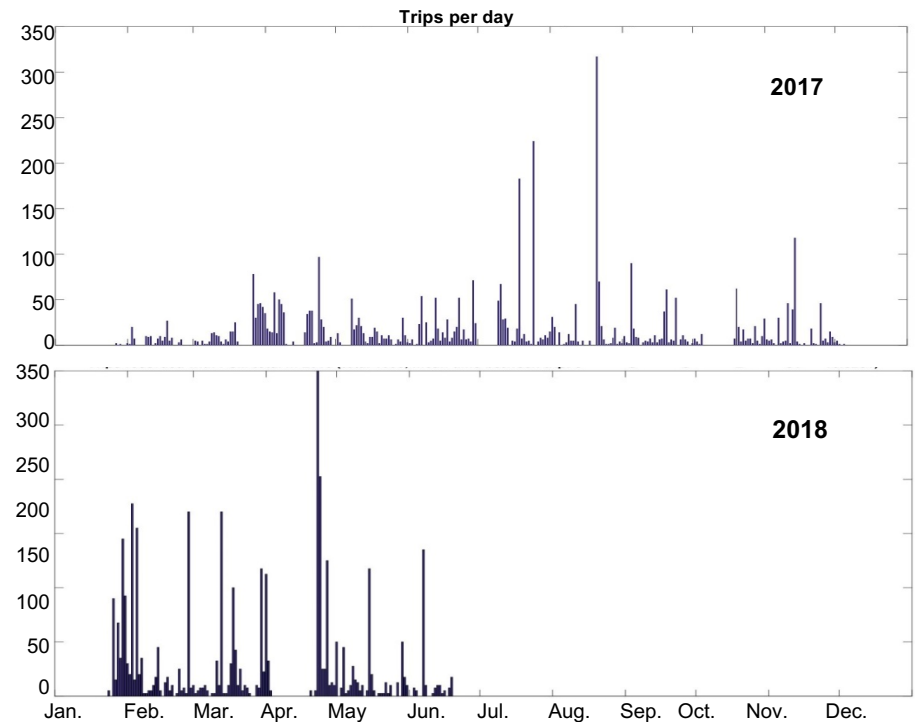
- Source des données: fichiers log de FSM
- Nombre total de fautes: **4236**
- 8 catégories de fautes



Courtesy M. Omet

Premières conclusions:

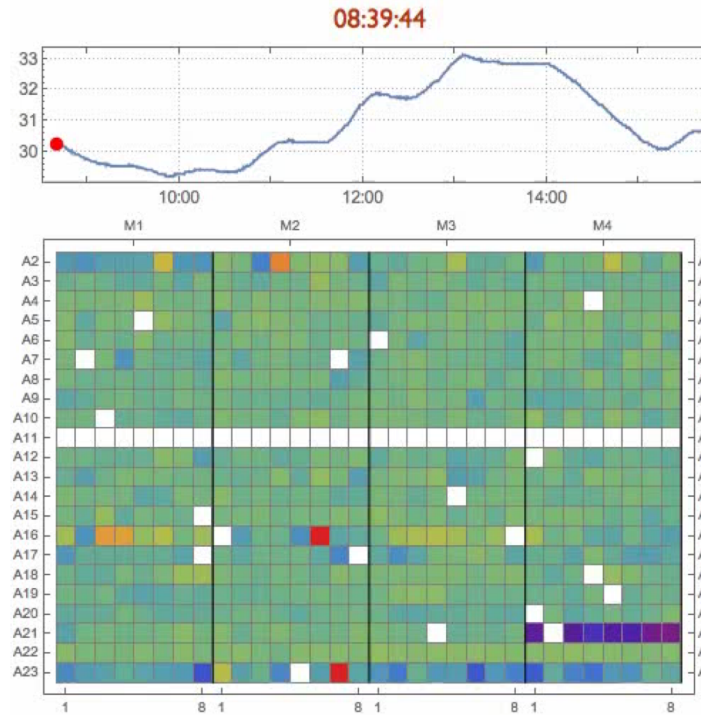
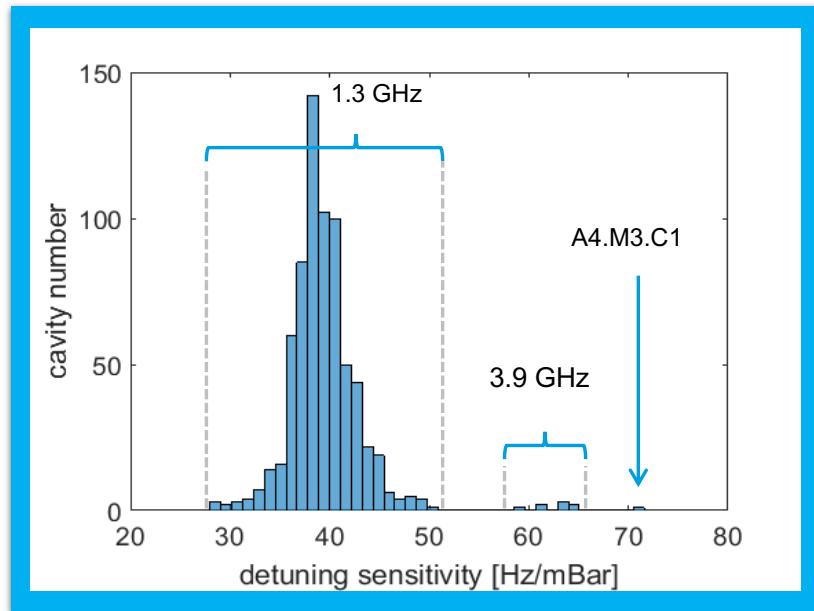
- Les outils ne sont pas appropriés
- Trop de “fausses alarmes”
- L’analyse des fautes prend beaucoup de temps



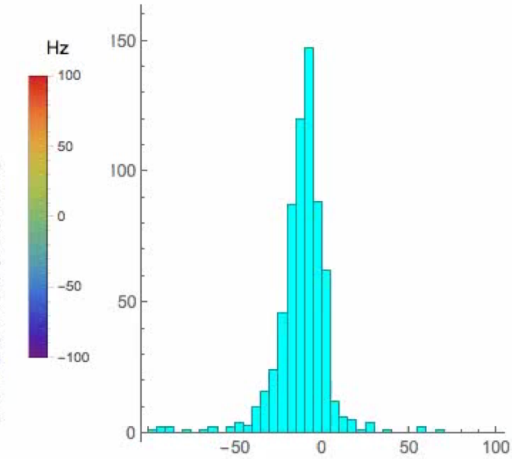
OPERATION: cavity detuning vs He pressure

Objectifs:

- Mesurer les variations fréquence des cavités en fonction de la pression Hélium
- Etablir une zone de tolérance raisonnable des fluctuations pression Hélium.



Average -10.0 Hz



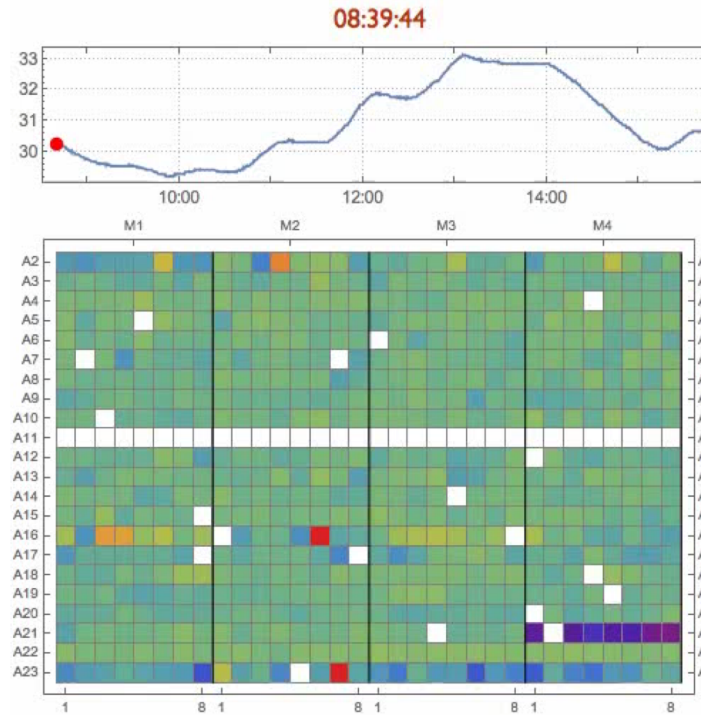
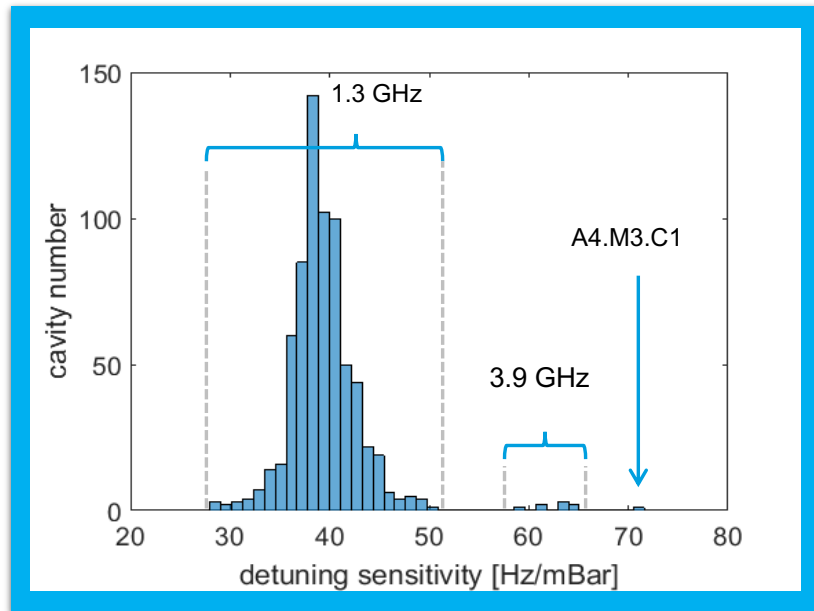
Film: N. Walker

Cavity 1.3 GHz : 40 Hz/mBar
 Cavity 3.9 GHz : 62 Hz/mBar
 +/- 3mBar threshold ⇔ 20% power overhead

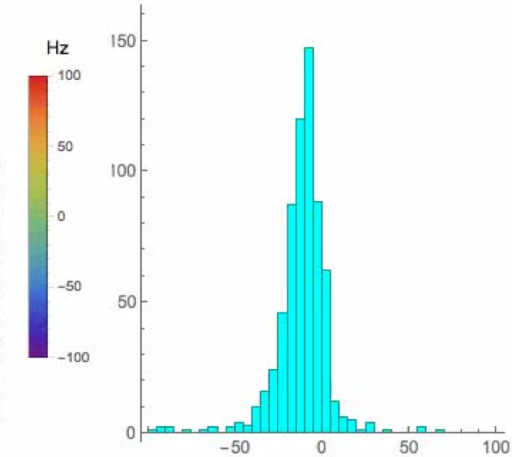
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Average -10.0 Hz



Film: N. Walker

Cavity 1.3 GHz : 40 Hz/mBar
 Cavity 3.9 GHz : 62 Hz/mBar
 +/- 3mBar threshold ⇔ 20% power overhead

Continuous Wave (CW) upgrade

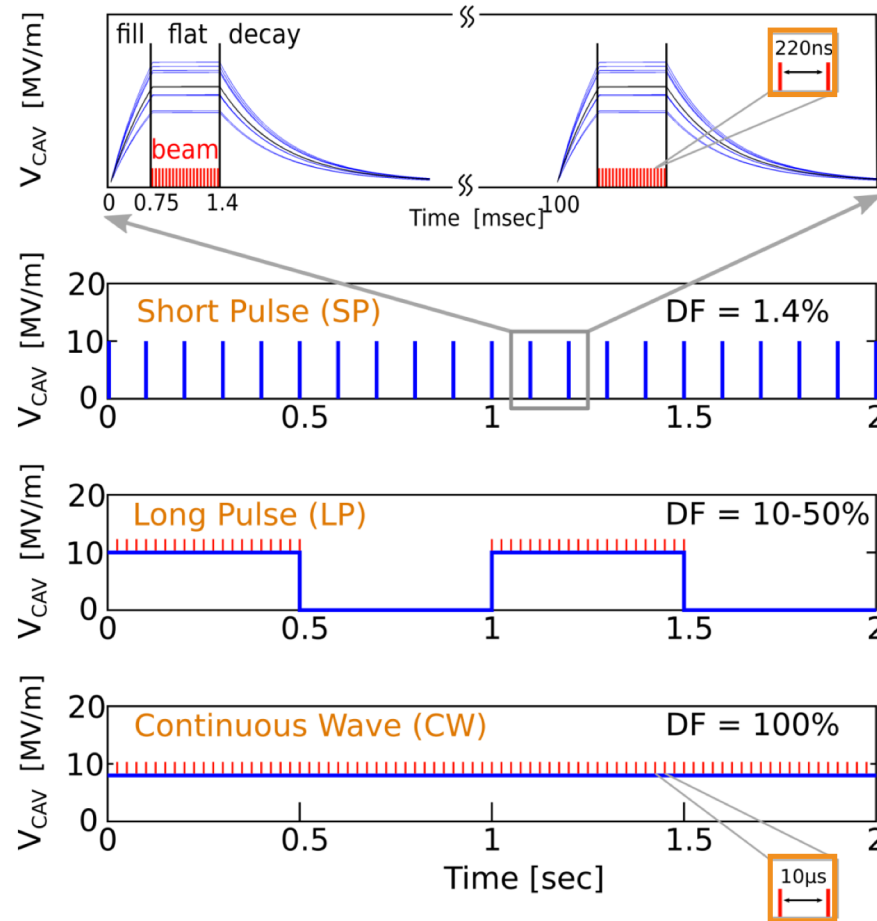
CW UPGRADE: motivation for CW Operation

Avantages d'une opération RF continue (CW)

- Plus facile à l'injection (laser)
- Plus facile à la détection (détecteurs)
- Pas d'effet transitoires

Avantages d'une opération pulsée longue (LP)

- Accélération encore relativement efficace (duty factor DF = 10-50%)
- Permet des gradients plus élevés qu'en CW à charge thermique égale



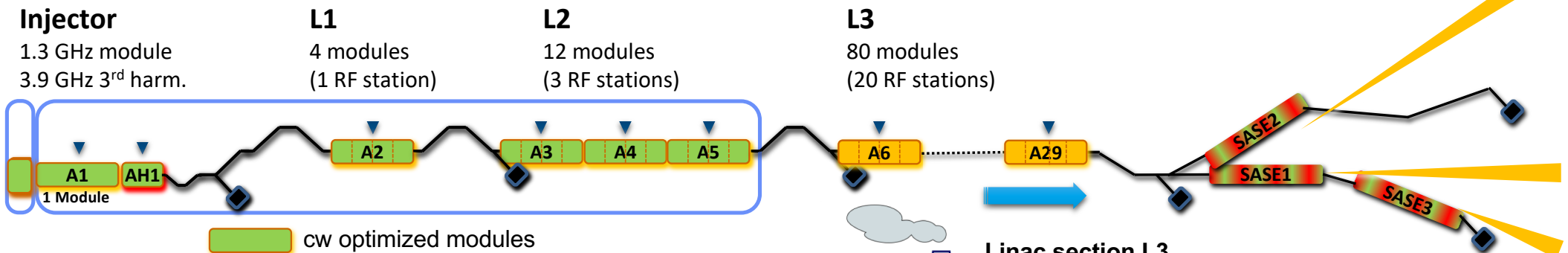
FLASH.
Free-Electron Laser FLASH

$E = 17.5 \text{ GeV}$
 $N_{\text{bunch}}/\text{s} = 27\text{k}$

$E = 10 \text{ GeV}$
 $N_{\text{bunch}}/\text{s} = 50\text{k}^*$
*up to 500 kHz for 20pC

$E = 8 \text{ GeV}$
 $N_{\text{bunch}}/\text{s} = 100\text{k}^*$
*up to 1 MHz for 20pC

CW UPGRADE: modification du XFEL en CW



1 – Remplacer les 17 premiers cryomodules

- Capacité de refroidissement augmentée
- Utilisation de cavités à plus haut facteur de qualité (N infusion? Grain large?)

2 – Installer des sources de puissance CW

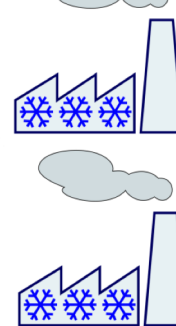
- 1x IOT par station RF

3 – Doubler la station cryo (coût principal)

- 2.5 → 5kW

4 – Installer un canon à électrons CW:

- RF gun upgrade (sans doute SRF)



Linac section L3

- operated at moderate CW gradients
- lengthened by former A2 ... A5
80 + 12 modules
24 RF stations

➔ **Expected energy 8 GeV !**

- The former front-end cryomodules can be installed at the end of the linac to **lengthen L3** (+4 RF stations)
- No further action required in L3 (>1km)
- The upgraded XFEL would be capable of **short pulse long pulse AND continuous wave** operation

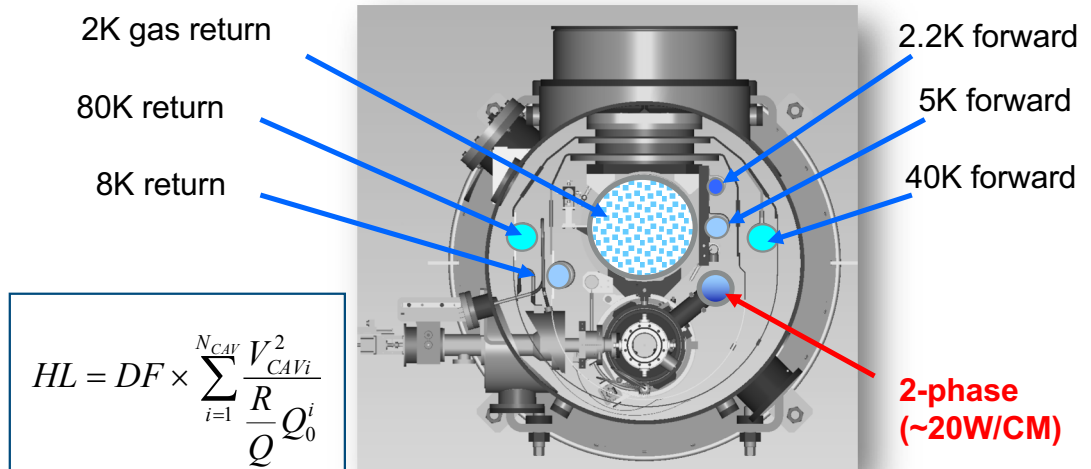
CW UPGRADE: challenges of high duty-factor operation

Higher dynamic heat load

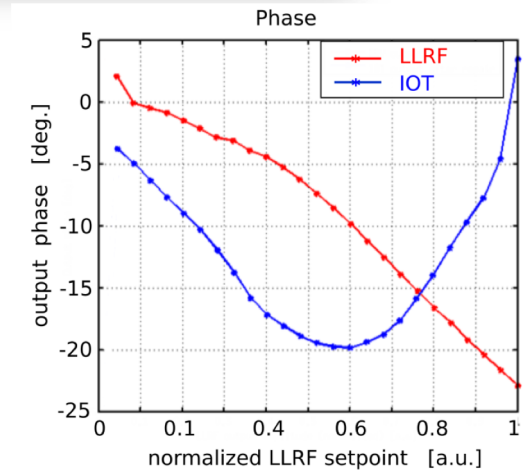
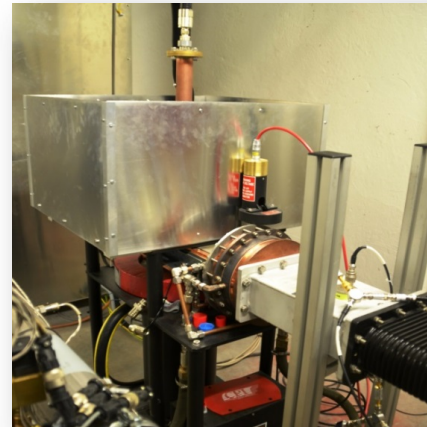
- 20W max for current XFEL cryomodules (CM)
- Limit set by the 2-phase pipe

CW capable RF sources

- Inductive Output Tube (IOT)
 - More compact than solid state amplifiers
 - Take energy from mains only when delivering power
- Strong non-linearities during fill time



$$HL = DF \times \sum_{i=1}^{N_{CAV}} \frac{V_{CAVi}^2}{R} \frac{Q^i}{Q_0}$$



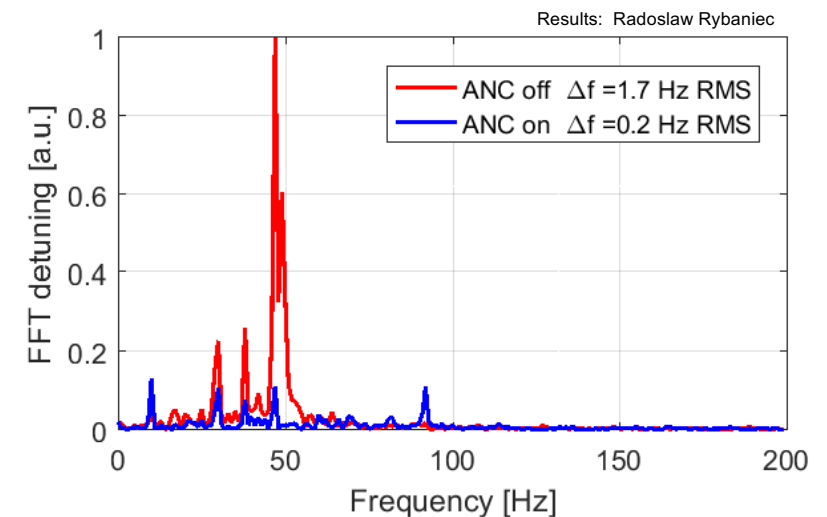
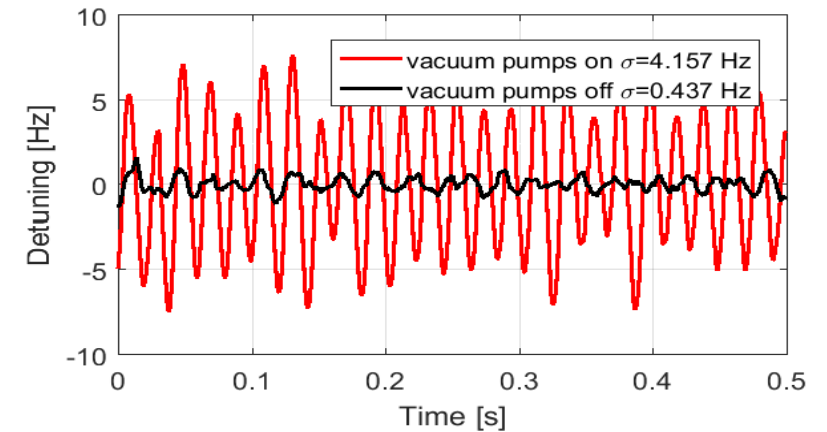
CW UPGRADE: quelques résultats: suppression microphonie

Sources microphoniques

- Principalement **pompes à vide**
- Fréquences dominantes autour de **30 Hz** et **49 Hz** pour la plupart des cavités
- Fluctuations du bain d'Hélium
- Effet décuplé pour les Q_L élevés

Suppression microphonie

- Techniques d'Active Noise Cancellation (**ANC**) permettent de filtrer les fréquences destructives



CW UPGRADE: quelques résultats: régulation RF

Control en Vector Sum (8 cavités , 1 IOT)

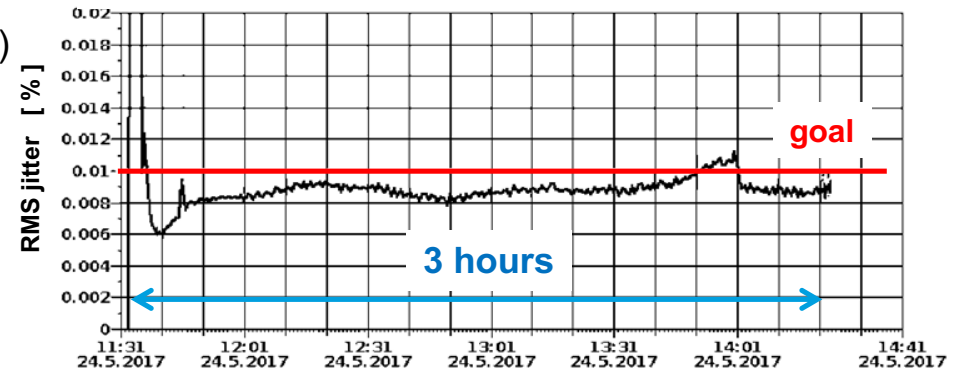
- $E_{ACC} = 15 \text{ MV/m}$ $Q_L = 1.5\text{-}3 \times 10^7$ (43-22 Hz half bandwidth)
- Regulation performance (May 2017)
 - $dA/A = 0.008 \%$ $dP = 0.008 \text{ deg.}$
- $E_{ACC} = 16 \text{ MV/m}$ $Q_L = 3 \times 10^7$ (22 Hz half bandwidth)
- Regulation performance (Dec. 2017)
 - $dA/A = 0.007 \%$ $dP = 0.010 \text{ deg.}$



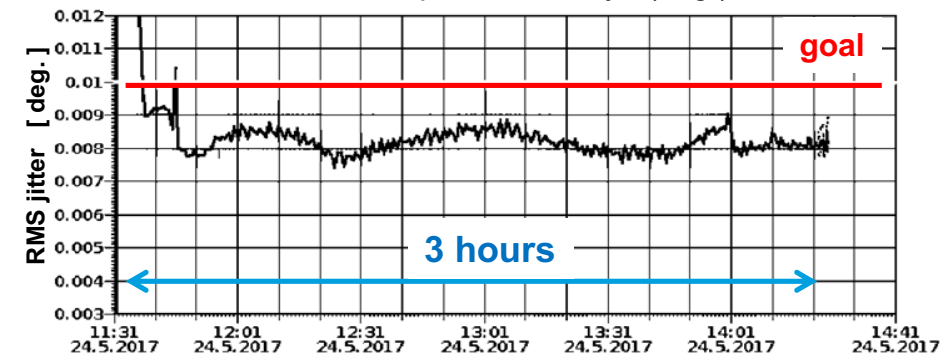
Control en mode individuel (1 cavity, 1 IOT)

- $E_{ACC} = 16 \text{ MV/m}$ $Q_L = 8.2 \times 10^7$ (8 Hz half bandwidth)
- Regulation performance (Dec. 2017)
 - $dA/A = 0.015 \%$ $dP = 0.017 \text{ deg.}$

Vector sum amplitude stability (dA/A)



Vector sum phase stability (deg.)



CONCLUSION

RESUME

Présentation générale de l'European XFEL

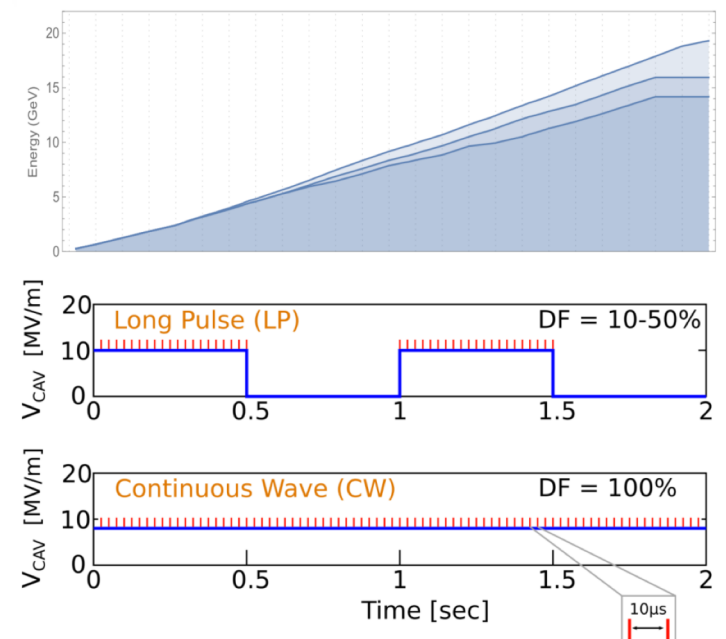
- Contributions internationales
- Quelques points forts de la mise en marche (01 – 09/2017)
- Mise en marche RF, condition présente et difficultés rencontrées

L'XFEL en fonctionnement

- Développement multi ligne pour le faisceau
- Efforts pour atteindre l'énergie maximale
- Premiers essais d'analyse de disponibilité de l'accélérateur
- Quelques exemples d'expériences

R&D vers un fonctionnement en continu

- Plans pour l'upgrade
- Challenges du CW
- Résultats préliminaires



Plans à court et moyen termes

Utilisateurs

- Premiers utilisateurs **soft X-ray** beamline SASE3 – fin 2018
- Transition: plus d'heures utilisateurs, moins développement accélérateur
 - 1200h mise en place expérience + 1600h opération utilisateur

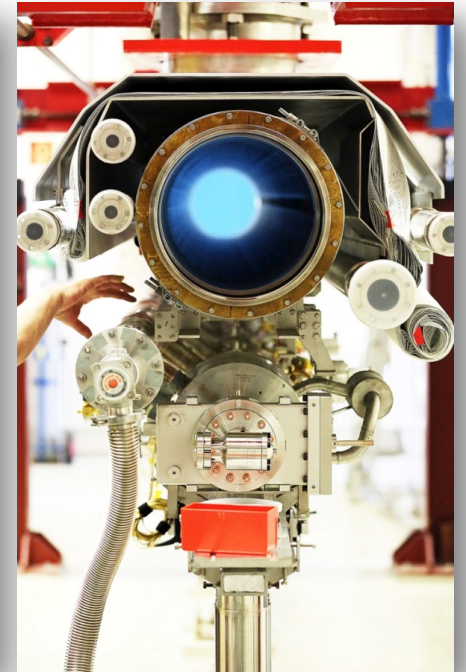
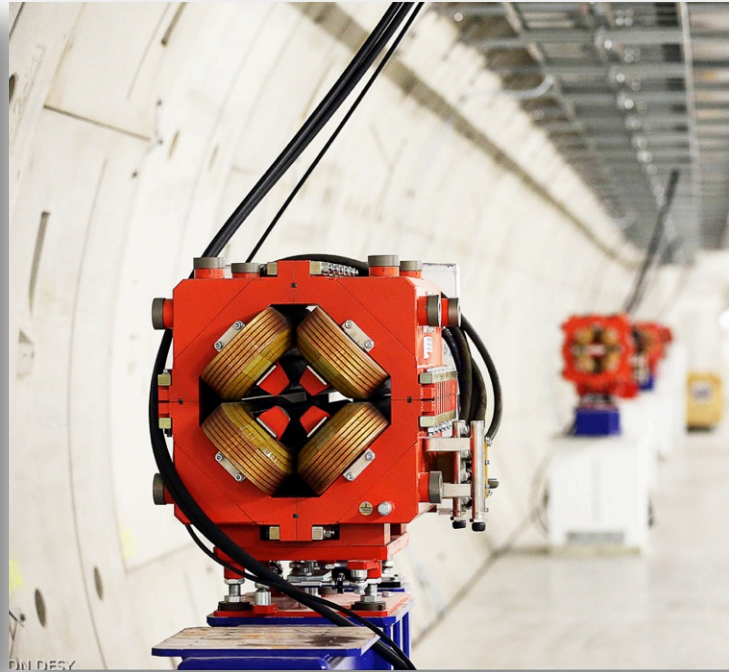
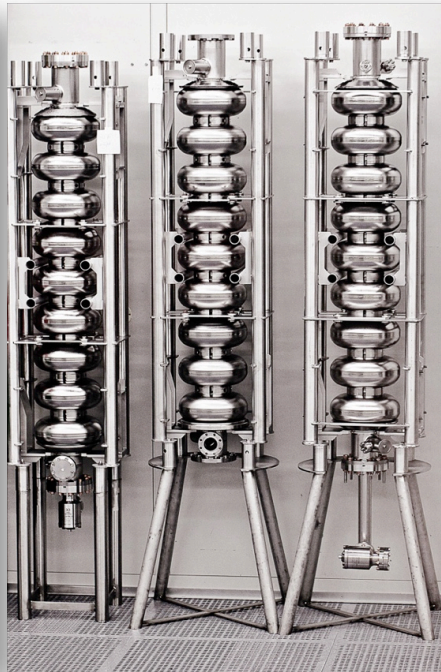


Objectifs performance machine

- Démontrer accélération faisceau à **l'énergie de design** (~17.5 GeV) – été 2018
- Accélération du **nombre maximum** de paquets d'électrons (2700) – fin 2018
- Augmenter l'énergie photon jusqu'à **15 keV**
- Meilleure compréhension de la **disponibilité** de l'accélérateur
- Objectifs stabilité sont atteints, à court terme. Long terme ?
- **Rapidité de démarrage** après shut down
- « Jouer un peu » avec l'accélérateur ?



Merci pour votre attention!



DESY.

Contact

Deutsches Elektronen-Synchrotron

www.desy.de

Julien Branlard

MSK

julien.branlard@desy.de

+49 (0) 40 8998 1599

BACK UP SLIDES

CW UPGRADE: R&D tests en continuous wave

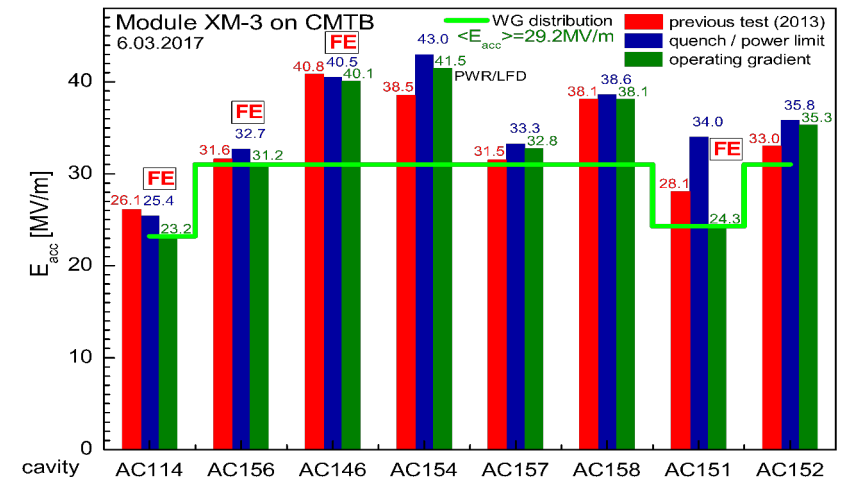
Cryomodule Test Bench (CMTB)

- Test facility capable of short pulse, long pulse and CW operation
- Adjustable power distribution (per cavity)
- Inductive output tube (IOT) up to 100 kW
- Cool down to 2K and 1.6K
- Dedicated LLRF system for single cavity and vector sum regulation



XM-3 XFEL pre-series cryomodule

- Contains **7 large grain cavities**
- Individual gradients up to **> 40 MV/m**
- Modified couplers to achieve high Q_L (**up to 10^8**)
- Demonstrated $Q_0 = 4.7 \times 10^{10}$ @ 1.8K 7 MV/m
 $Q_0 = 4.1 \times 10^{10}$ @ 1.8K 14 MV/m

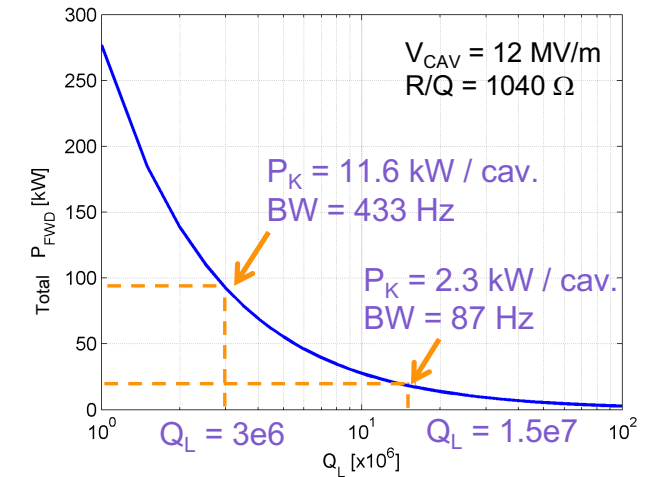


CW UPGRADE: challenges of high duty-factor operation (2/2)

Operating cavities with narrow bandwidth

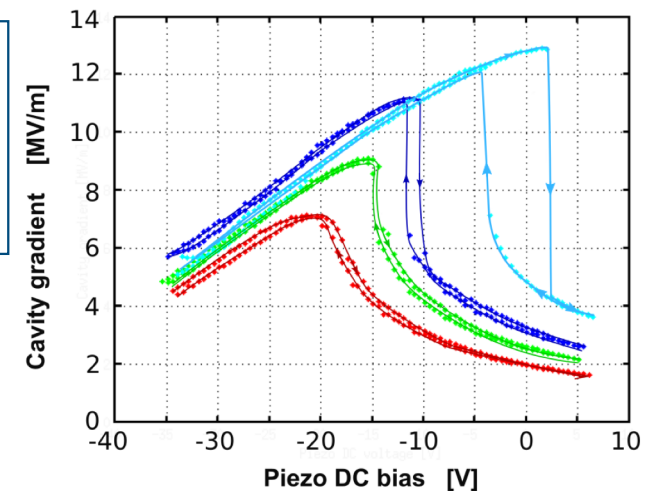
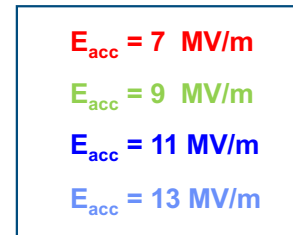
- With higher loaded quality factor Q_L , less power is required to achieve same gradient
- Side effect: cavity bandwidth is reduced
- Microphonics are the dominating detuning effect

$$V_{CAV} = \sqrt{4P_K \frac{R}{Q} Q_L}$$



Static drops

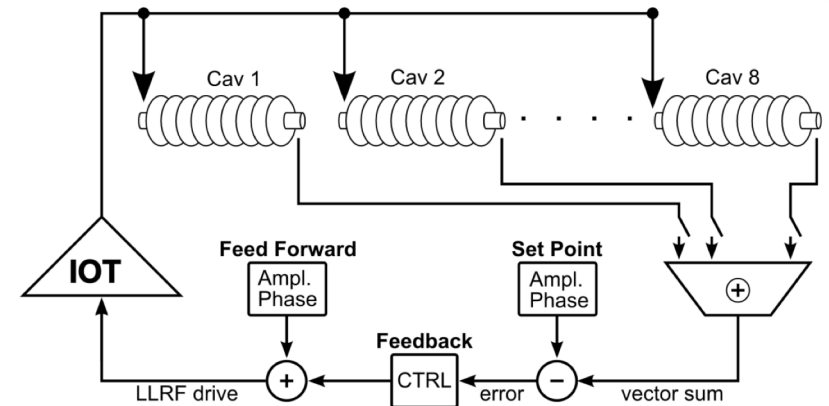
- Detuning as a function of piezo DC bias shows hysteresis behavior
- Effect increases with gradient
- Can lead to domino effect detuning in vector sum control
- Single cavity jump can cause drastic reaction of RF feedback, leading to instabilities



CW UPGRADE: R&D control gradient et fréquence

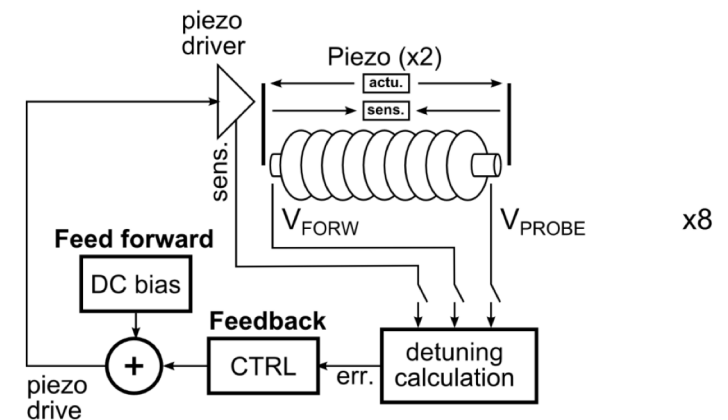
RF feedback

- Applied around individual cavities or to the vector sum
- Proportional / integral feedback controller
- Goal is to maintain gradient amplitude and phase
 - $dA/A \leq 0.01\%$
 - $dP \leq 0.01$ deg.



Piezo feedback

- Each cavity is equipped with a dual piezo frequency tuner
- Applied around individual piezo electric element
- Proportional / integral feedback controller
- Goal is to keep cavity on resonance to meet phase stability requirements
 - $\Delta f \ll$ cavity half bandwidth



OPERATION: LLRF system, isolated failures

- **SSDs exchange**
 - RAID redundancy lost, slow writing to disk
 - 5 occurrences so far:
 - *FLASH: 20 occurrences in 6 years*
- **Device needs to be reprogrammed**
 - MCH (x1)
 - TCK7 (x1)
 - *FLASH: 2-3 occurrences*
- **Lost Ethernet communication with device**
 - 1 occurrence so far: (Nov. 2017 TMCB REFM-OPT)
 - *FLASH: 5-6 times (PDU)*



radiation related ?

COMMISSIONING: tool automation

- Power-based calibration

- Dynamic range optimization

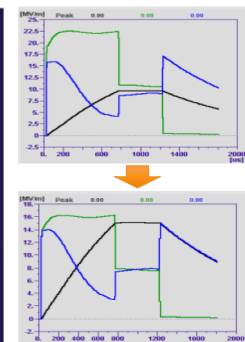
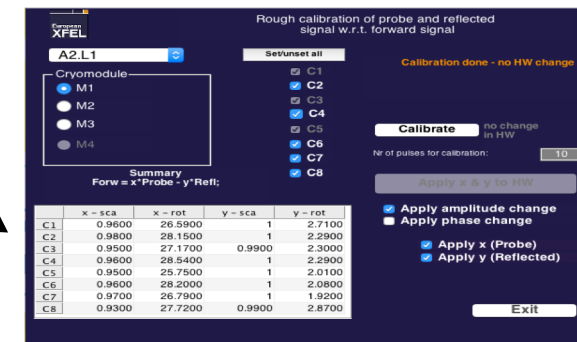
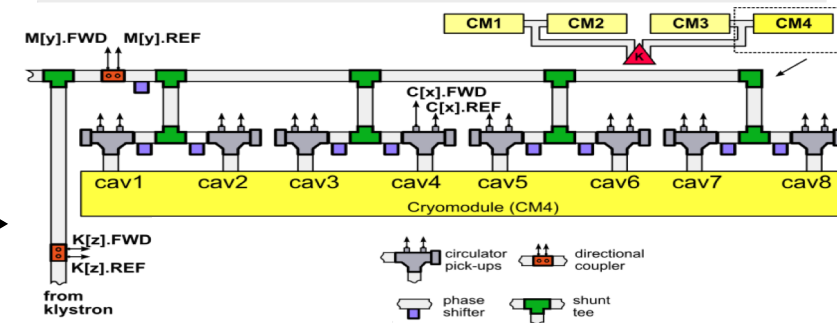
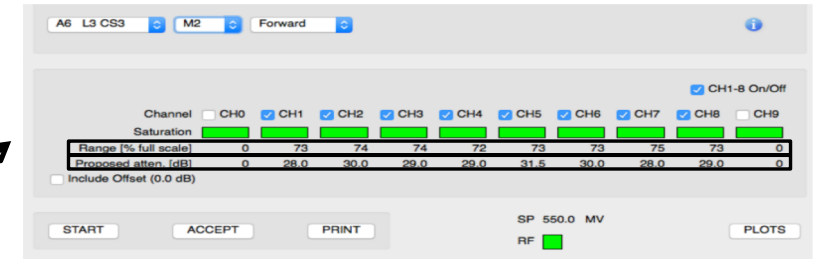
“Adjust attenuation so that available signal uses the optimal range of the digitizers”

- Forward power calibration

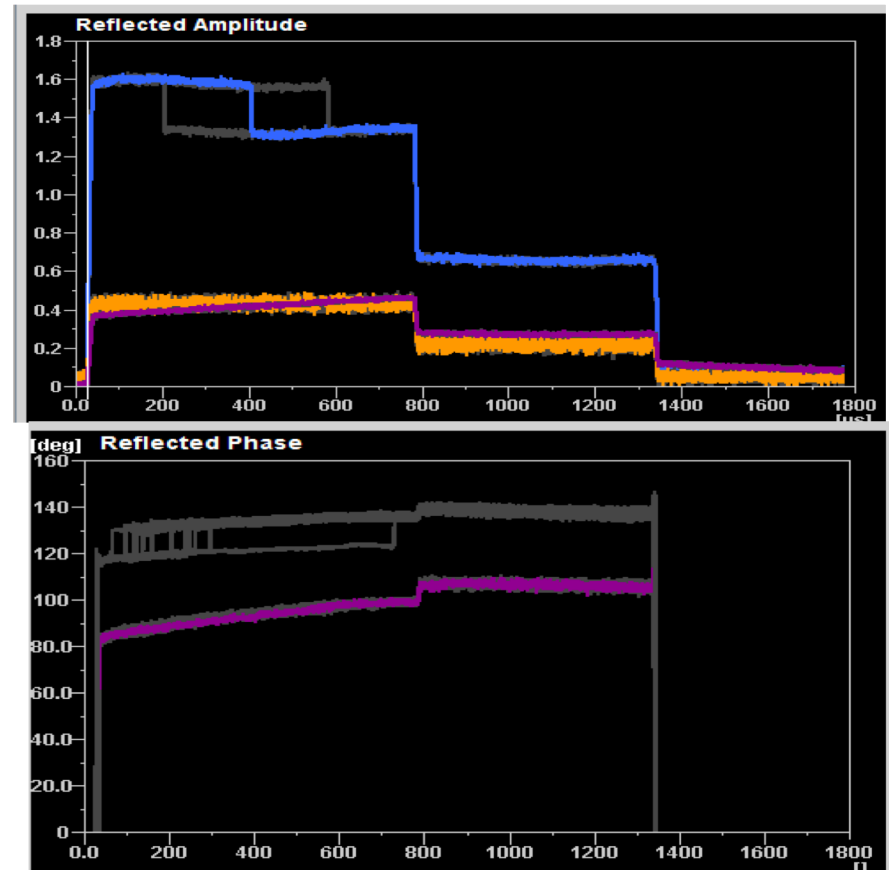
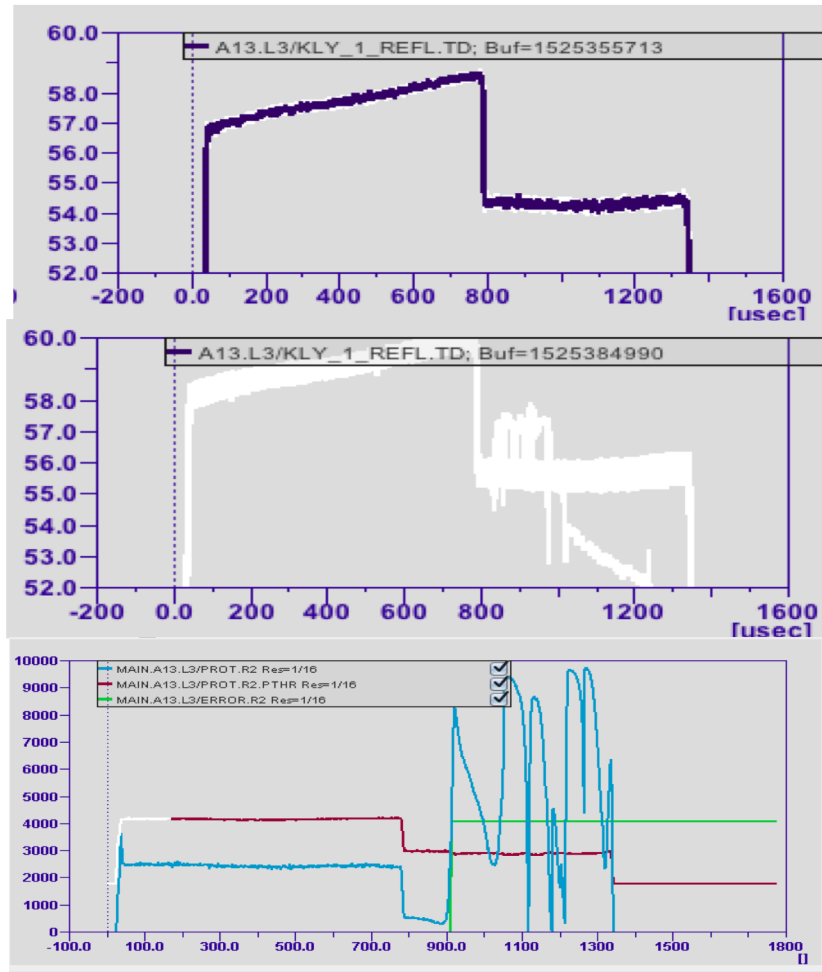
“Scale forward power signals so they read actual kW, based on the power meter measurements”

- Probe and Reflected signal calibration

“Scale reflected and probe signals so that Probe = Forward – Reflected”

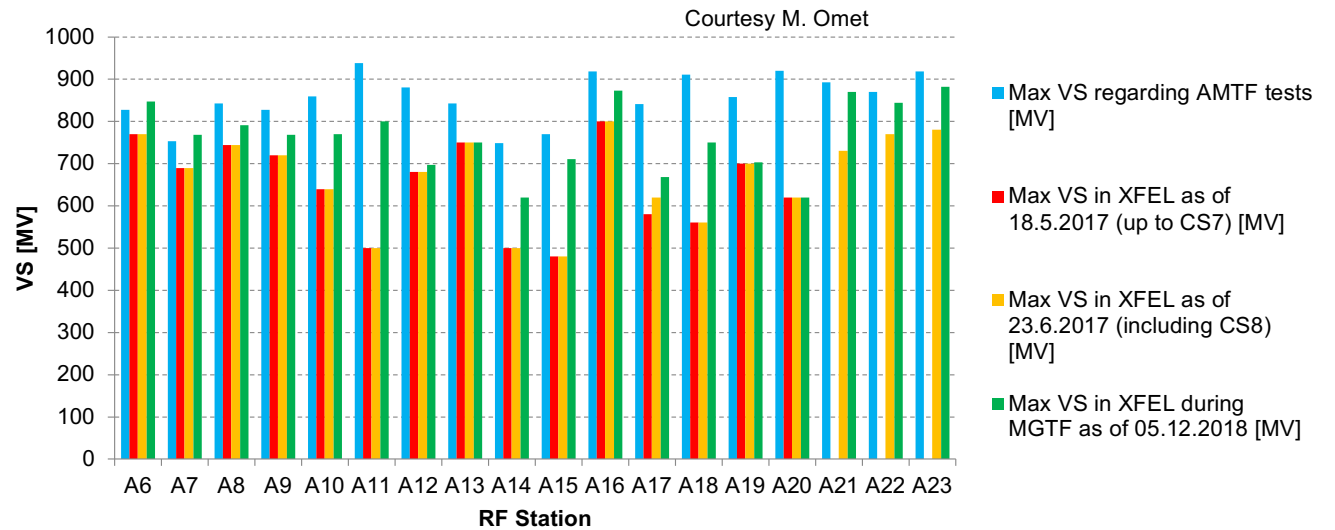
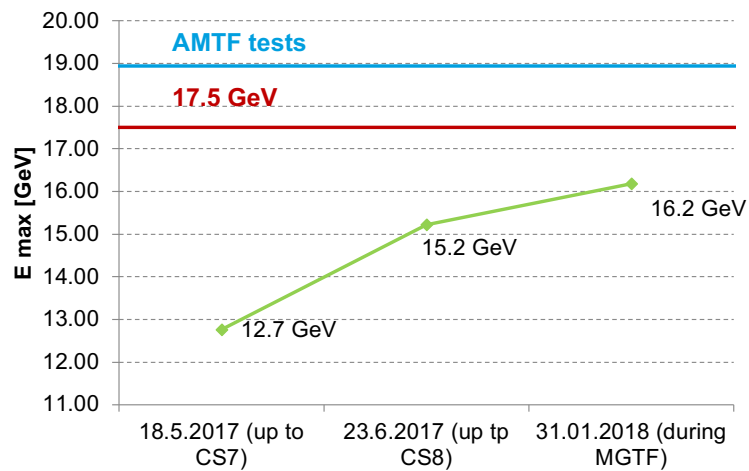


OPERATION: waveguide sparks



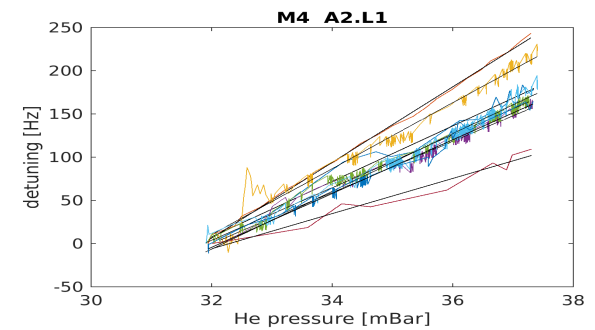
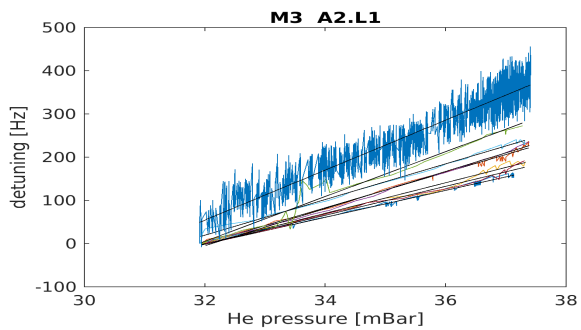
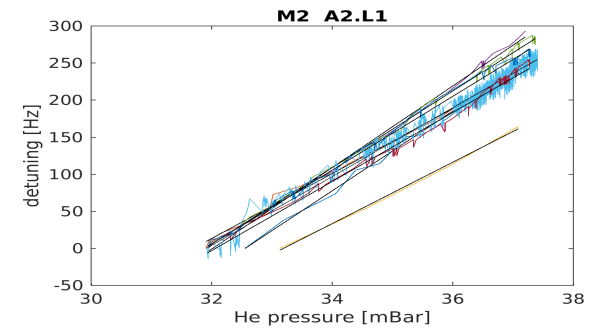
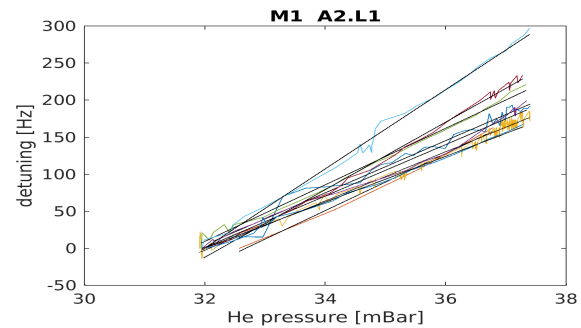
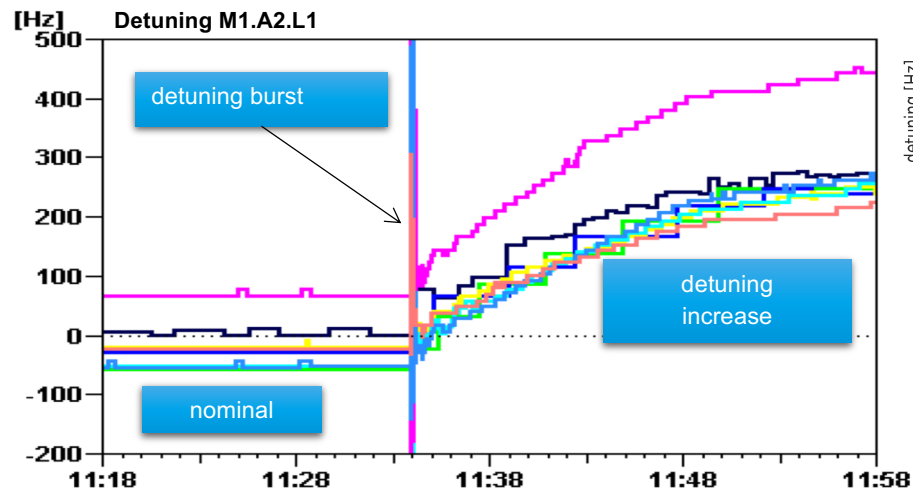
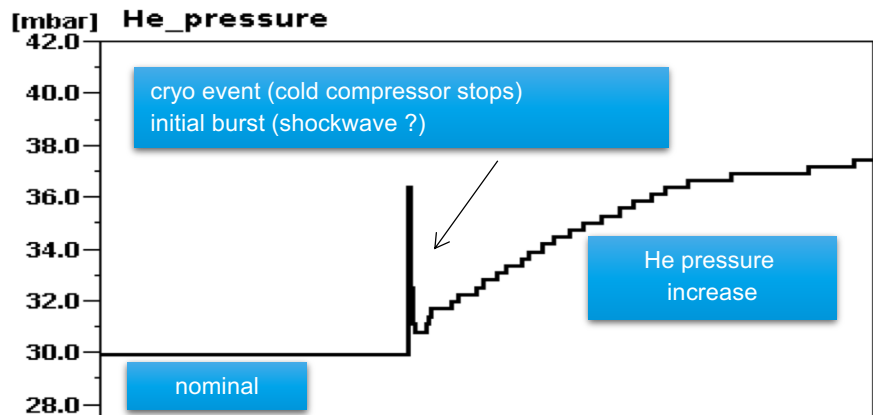
Data from A13 – 7.11.2017 12:48

OPERATION: Energy reach



- On-going effort to assess the maximum operation gradient for every RF station
- CS9 soon to be commissioned (A24, A25)

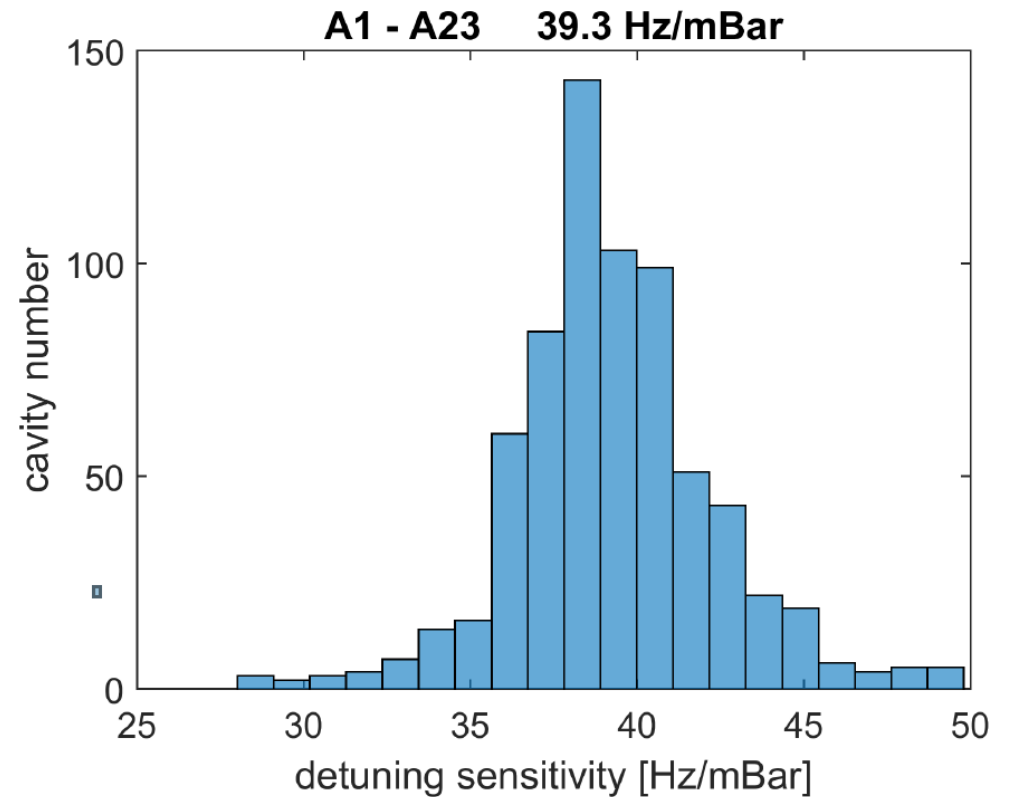
OPERATION: He pressure – RF tuning correlation



$$\left\langle \frac{df}{dP} \right\rangle = 40 \text{ Hz/mBar}$$

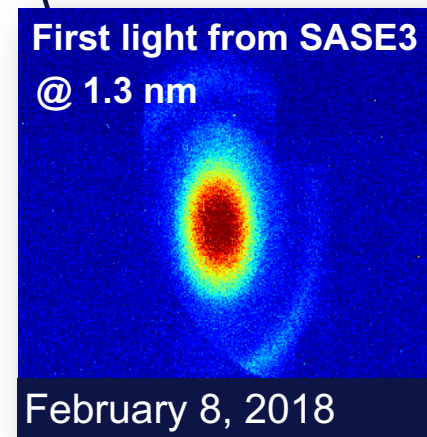
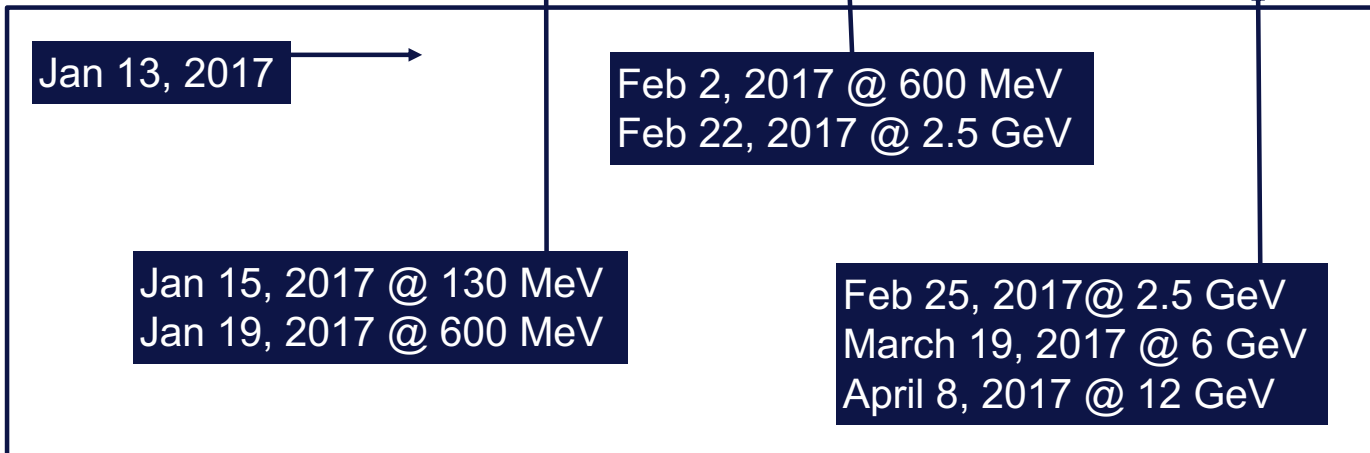
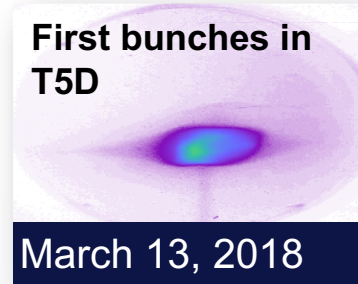
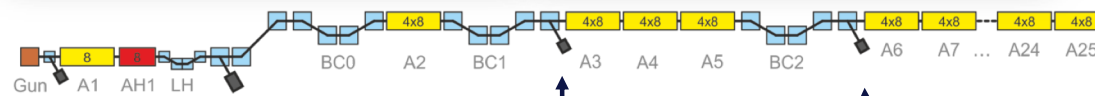
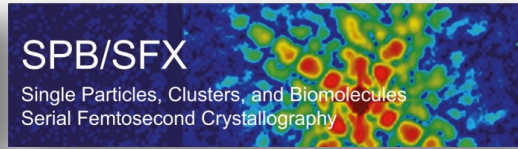
Cavity Detuning vs He Pressure

- Results
 - On average 40 Hz/mbar
 - 1 sigma = 3 Hz/mBar
 - Acceptable detuning +/-130 Hz corresponds to +/- 3.25 mBar pressure change
- Current pressure stability of +/-3 mBar corresponds to a detuning of +/-120 Hz
- Special case of AH1
 - On average 62 Hz/mBar
 - 1 sigma = 2 Hz/mBar
 - Current pressure stability of +/-3 mBar corresponds to +/- 186 Hz of detuning, which is acceptable



Commissioning timeline

First user runs started in September 2017 (SASE1 beamline)



IPAC'17 talk by Winni Decking