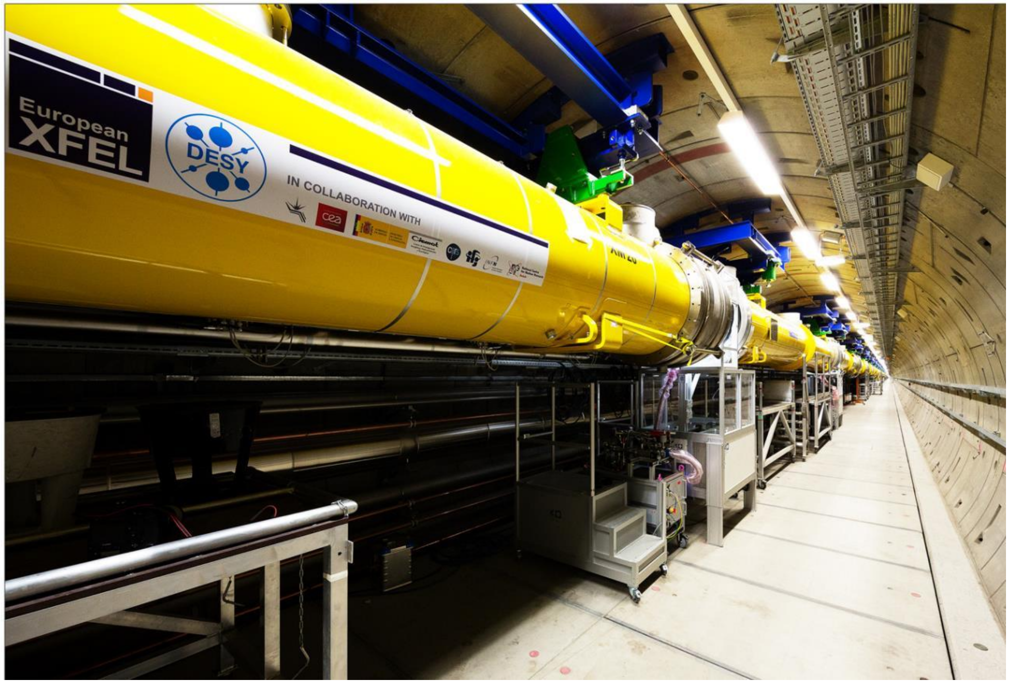
The European XFEL Project

O. Napoly, CEA-Saclay, Irfu/SACM

Outline

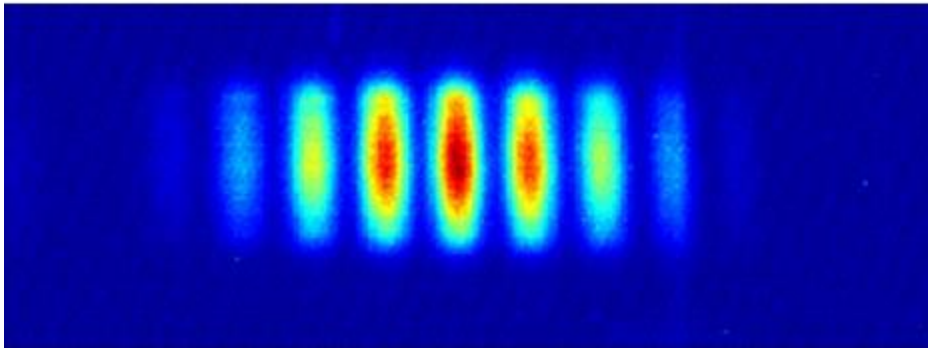
- Introduction to the XFEL goals
- The electron linac
- Cryomodule production and performance
- Conclusions

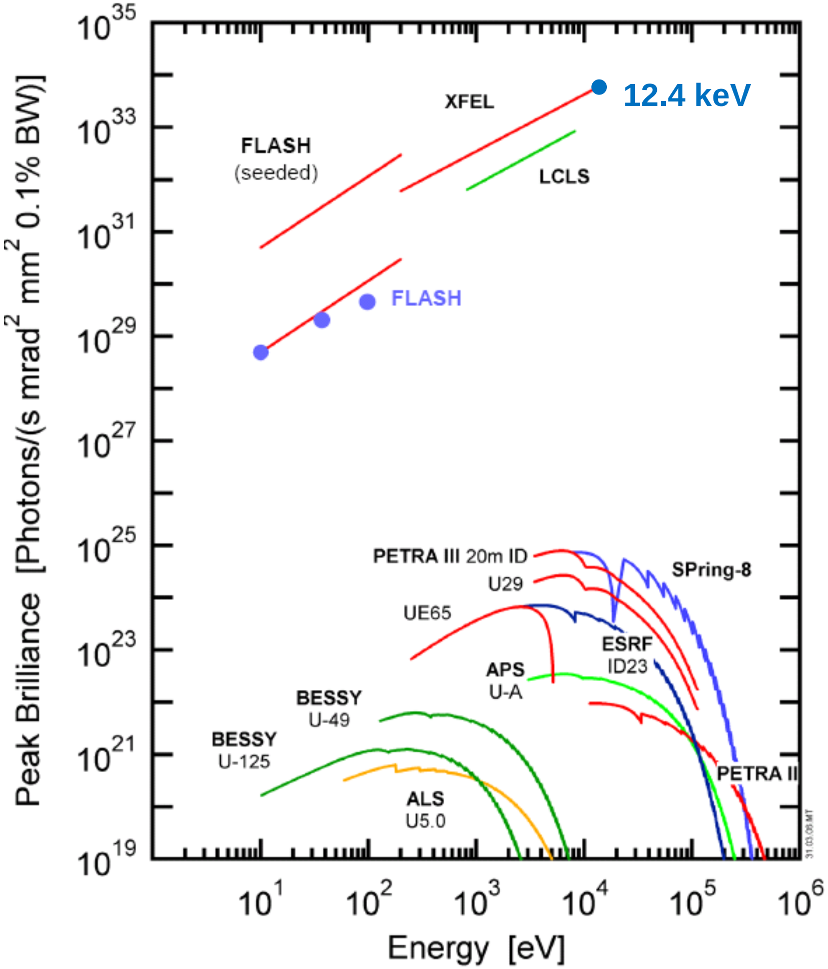


The European-XFEL Project

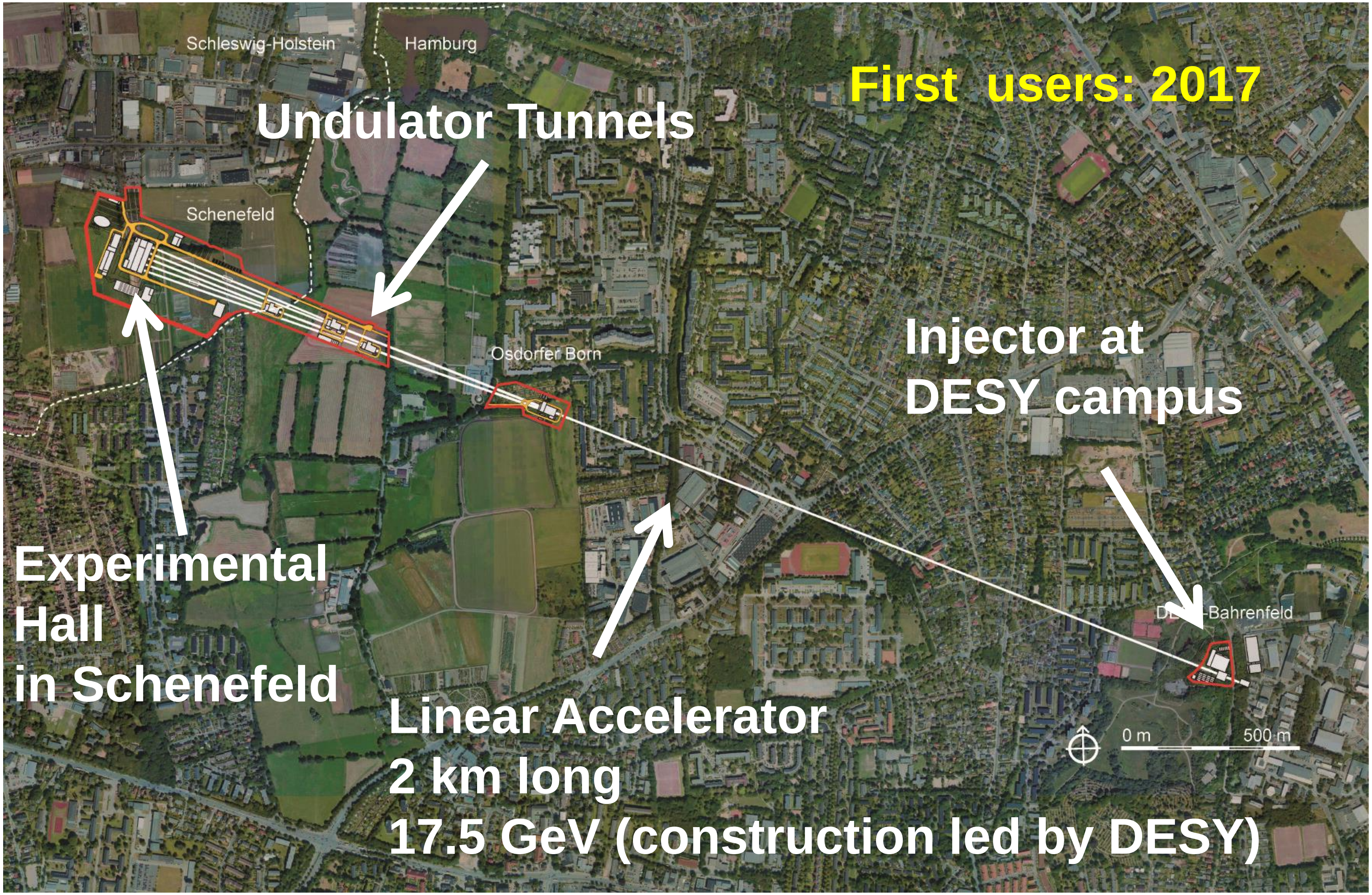
XFEL = X-ray Free Electron Laser

- 4^{th} generation light source
- FEL in SASE mode
- Tunable wave-length > 0.5 Å
- 10-100 fs light pulse duration
- Spatial coherence
- Cost : ~1 G€





The European XFEL Electron Accelerator

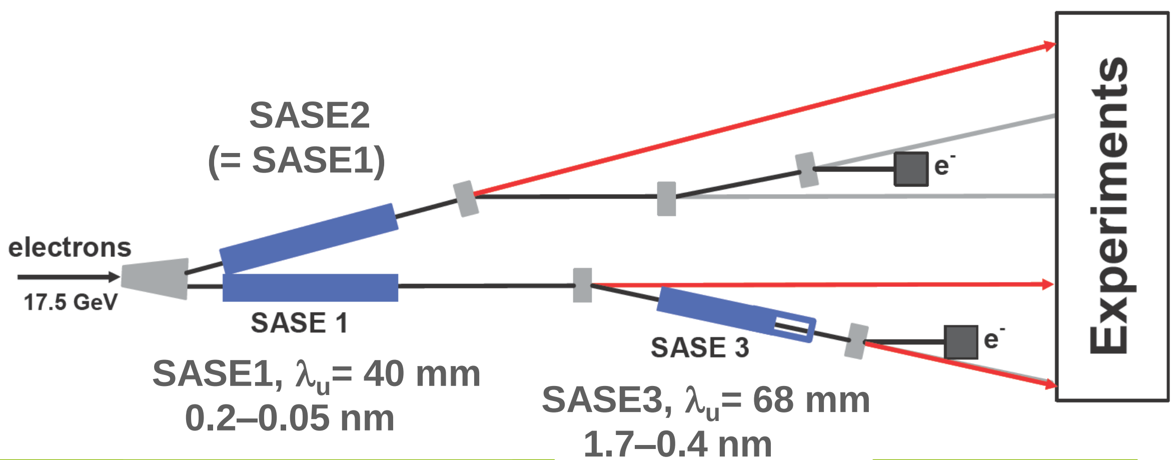


The Schenefeld Physics Campus

The European XFEL

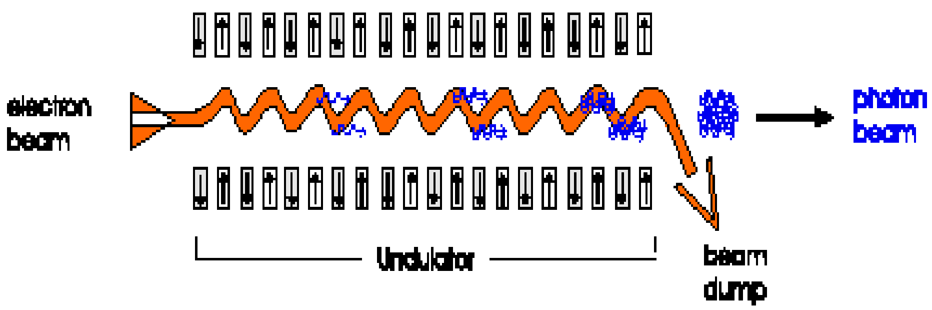
Some specifications

- Photon energy 0.25 → 25 keV
- Pulse duration ~ 10–100 fs
- Pulse energy few mJ
- Superconducting linac 17.5 GeV
- 10 Hz (27 000 b/s)
- 5 beamlines / 10 instruments
  - Start version with 3 BLs and 6 instruments
- Several extensions possible:
  - Self-Seeding
  - More undulators
  - More instruments
  - …..
  - CW operation



4th generation light sources

Self Amplification of Spontaneous Emission (SASE)
Free Electron Lasers (FELs) for hard X-Rays(~0.5 - 60 Å)

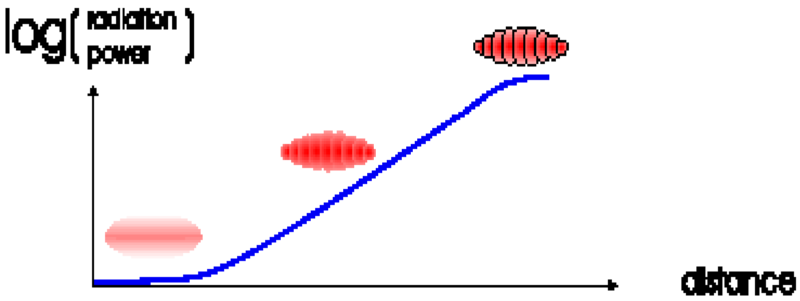


Basic Principle:

Self modulation of electron bunch density by own electro-magnetic field

⇒ micro-bunching

⇒ Electrons radiate in phase: $P \sim N^2$

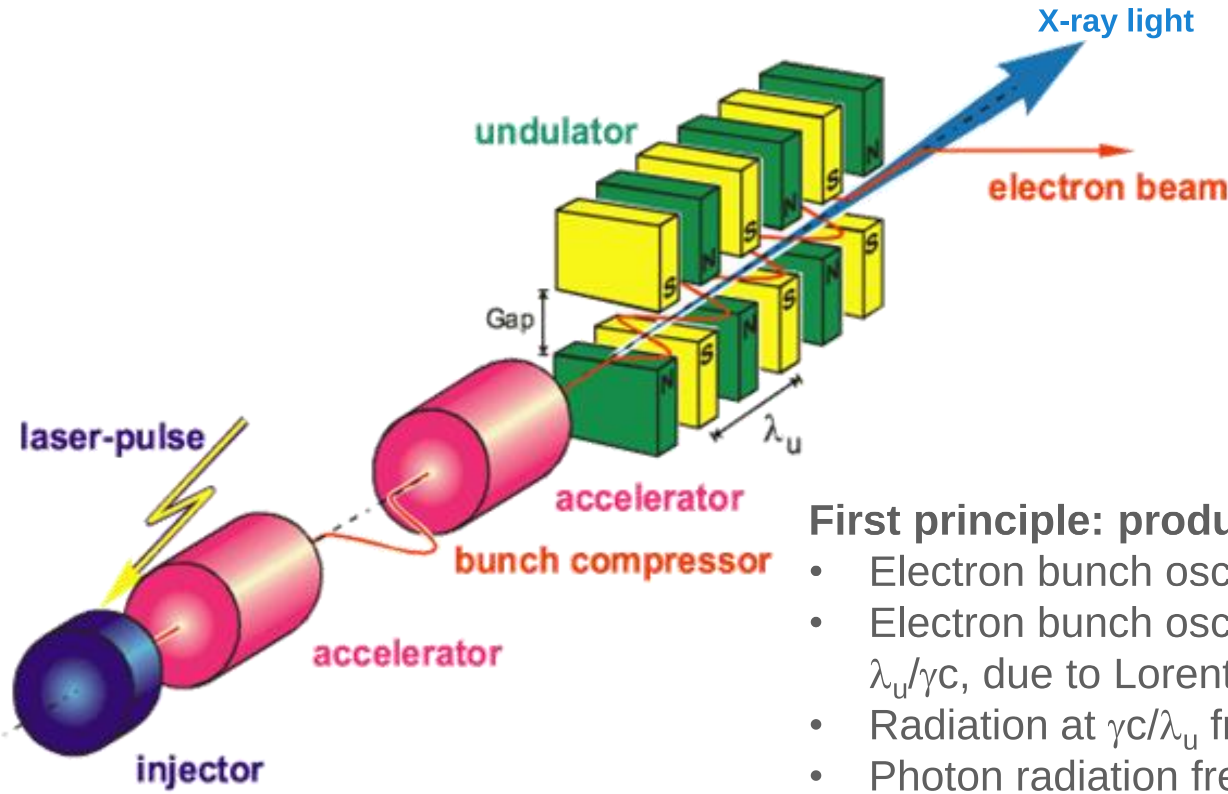


Need extremely good electron beam quality:

- Small emittance
- Small energy spread
- Large energy
- High particle densities

SASE – Self-Amplified Spontaneous Emission

Kondratenko, Saldin (1979)
Bonifacio, Pellegrini, Narducci (1984)



Need extremely good electron beam quality:

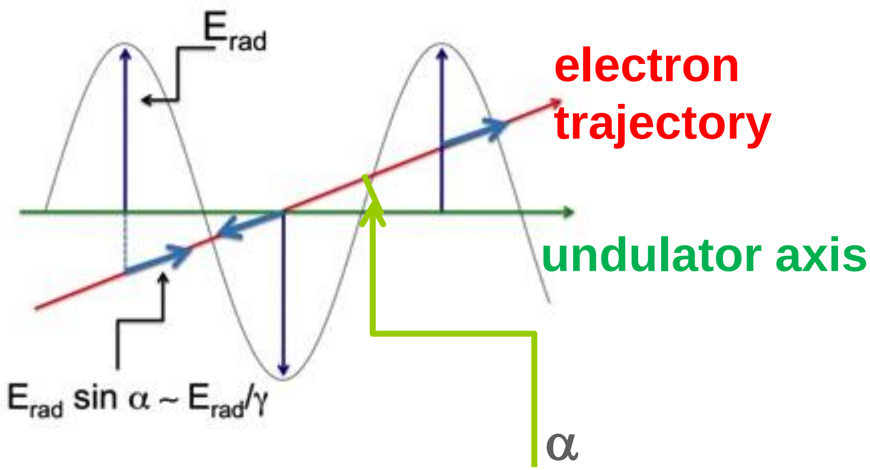
- Small emittance
- Small energy spread
- Large energy

γ=34x10^3 @ 17,5 GeV

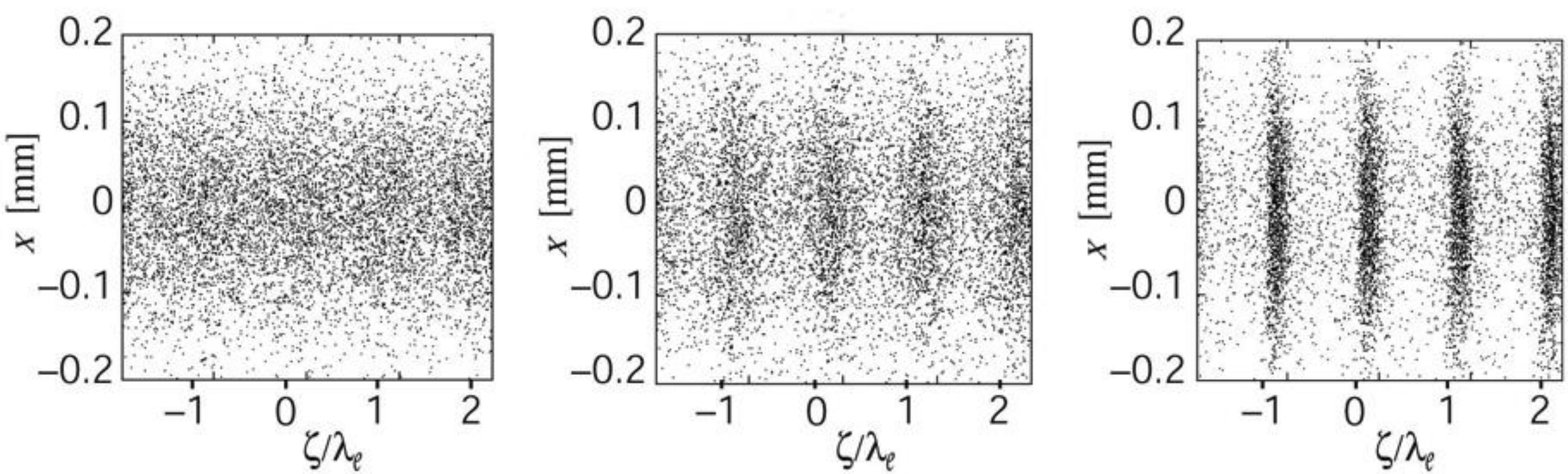
First principle: production of hard X-Rays

- Electron bunch oscillation period in lab frame is λ_u/c
- Electron bunch oscillation period in its rest frame is $\lambda_u/\gamma c$, due to Lorentz time dilatation
- Radiation at $\gamma c/\lambda_u$ frequency in rest frame
- Photon radiation frequency in lab frame is $\gamma^2 c/\lambda_u$ due to the relativistic Doppler effect.
- Wavelength ~ λ_u/γ^2 in laboratory frame

4^{th} generation light sources



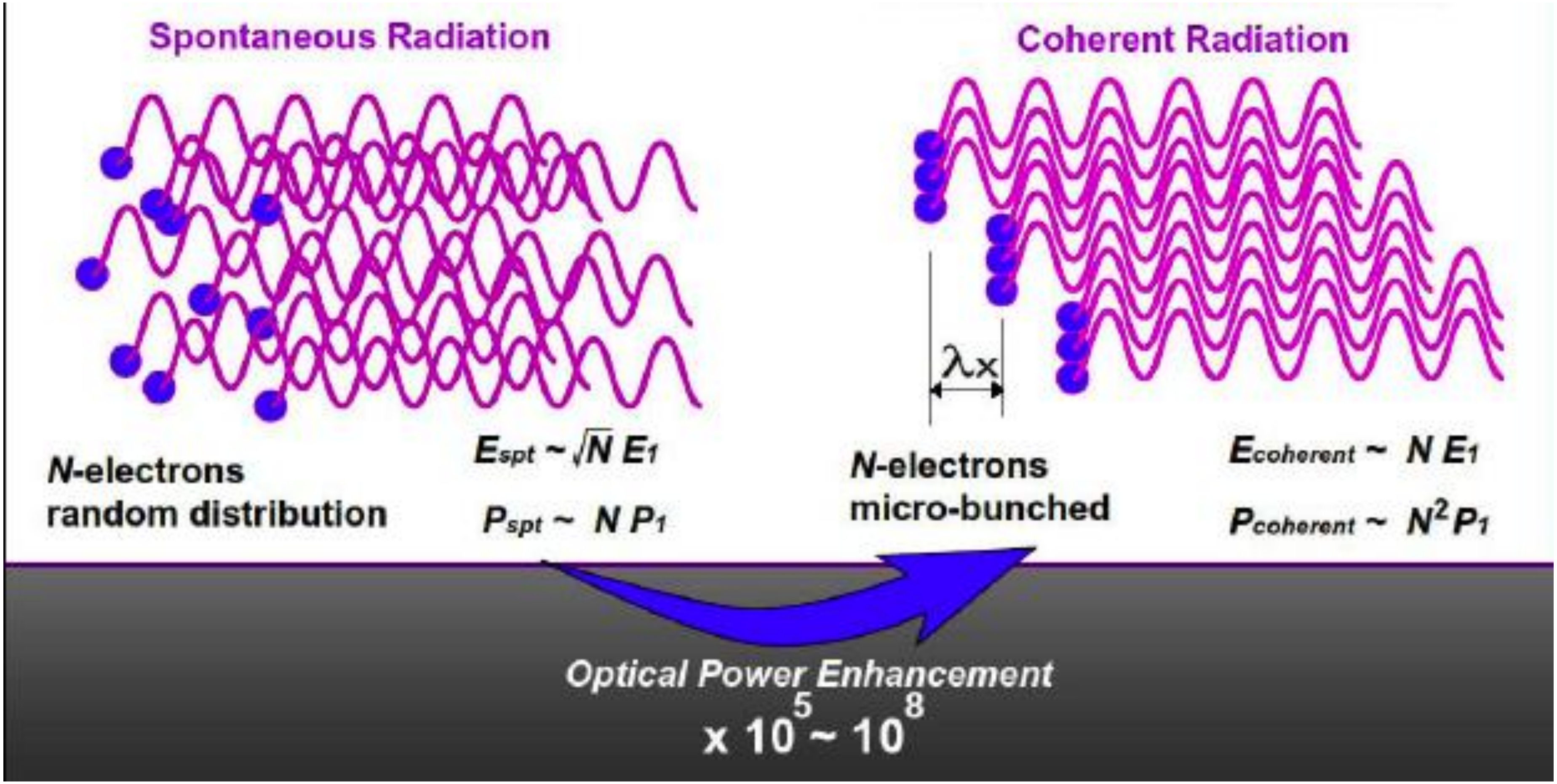
Second principle: 'micro-bunching'
Radiation electric field has a small component parallel to electron velocity, which can accelerate or decelerate electrons



4^{th} generation light sources

Third principle: coherent radiation *(T. Shintake)*

Micro bunches are coherent at the λ_X scale, they radiate as a 'macroscopic' charge



Resonance Condition

$$\lambda_r = \frac{\lambda_u (1 + K^2)}{2\gamma^2}$$

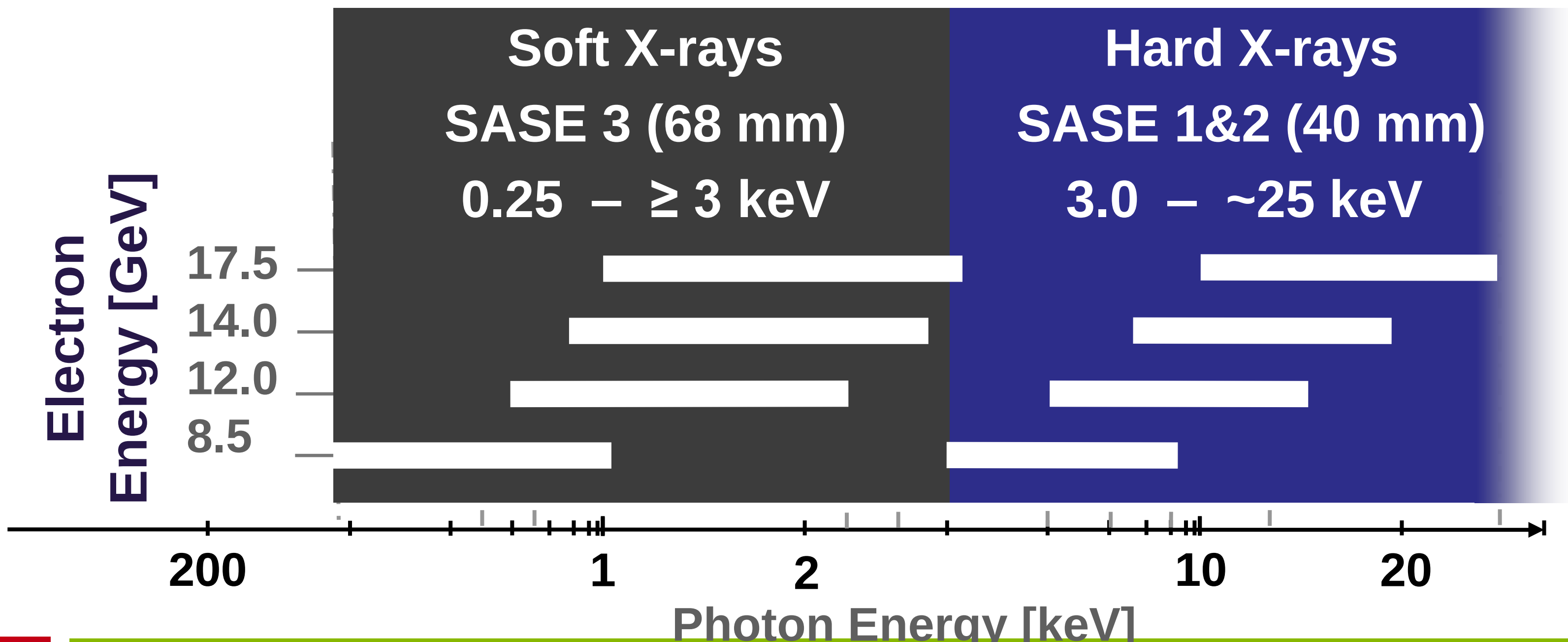
λ_r: 1x10^{-10} m

λ_u: 40-68 mm

K: 1- 9

$$K = 0.094 B_0[T] \lambda_u[mm]$$

European XFEL aims at 0.25 to 25 keV

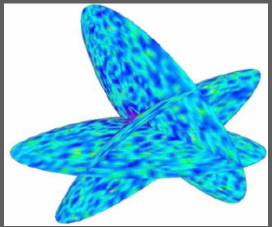


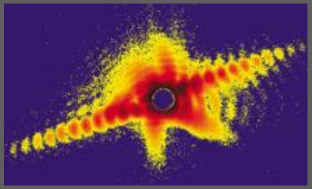
Six “day-one” scientific instruments

Hard X-rays

SPB/SFX: Single Particles, Clusters, and Biomolecules
Serial fs Crystallography

- Structure determination of single particles: atomic clusters, bio-molecules, virus particles, cells.



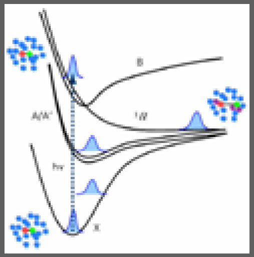


MID : Materials Imaging & Dynamics

- Structure determination of nano-devices and dynamics at the nanoscale.

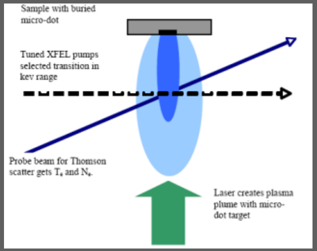
FXE : Femtosecond X-ray Experiments

- Time-resolved investigations of the dynamics of solids, liquids, gases



HED : High Energy Density Matter

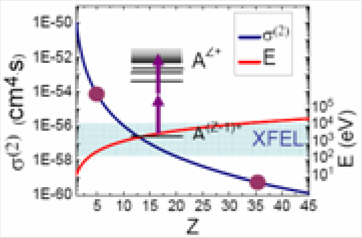
- Investigation of matter under extreme conditions using hard X-ray FEL radiation, e.g. probing dense plasmas



Soft x-rays

SQS: Small Quantum Systems
Investigation of atoms, ions, molecules and clusters in intense fields and non-linear phenomena

SCS: Soft x-ray Coherent Scattering/Spectroscopy
Electronic and real structure, dynamics of nano-systems and of non-reproducible biological objects

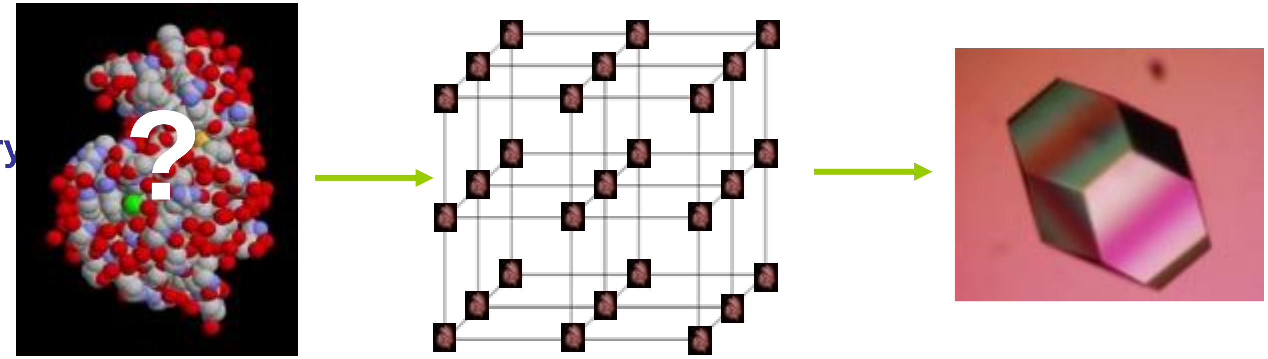


Application to Biology : bio-crystallography

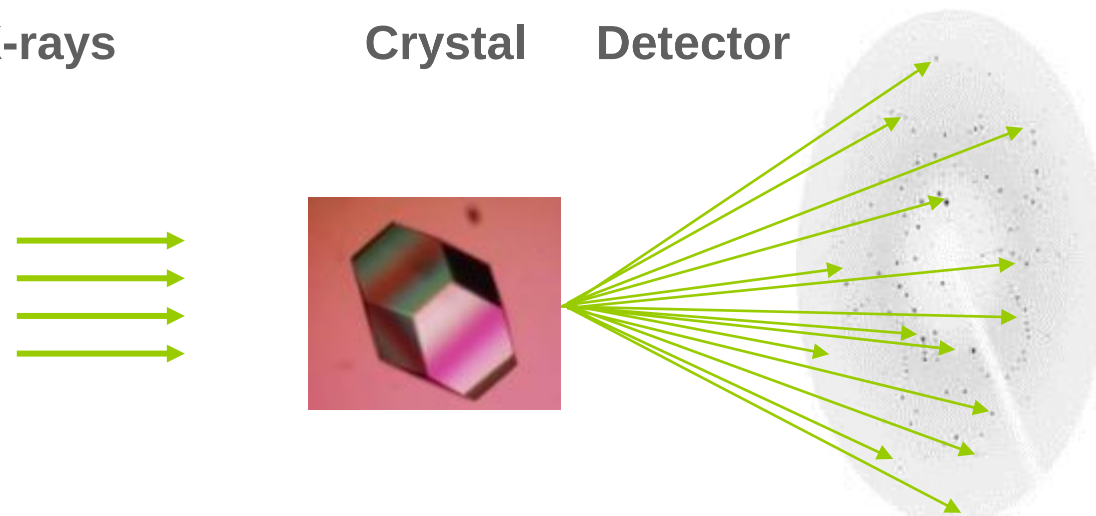
Courtesy M. Altarelli

Applied to larger and larger complex molecules:

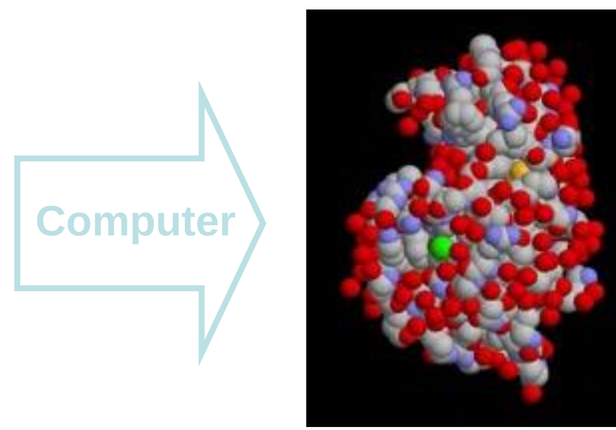
Lysozyme
(Enzyme from poultry



X-rays **Crystal** **Detector**



Determination of the atomic structure of the molecule!



Limits of Synchrotron (3rd generation) for Bio-crystallography

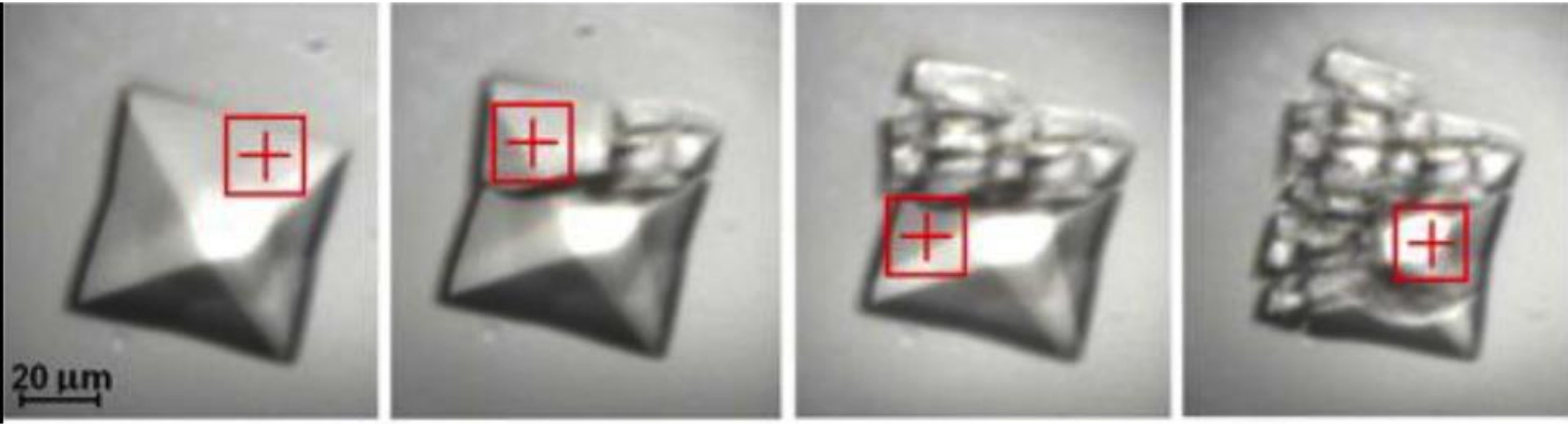
Courtesy M. Altarelli

In spite of its extraordinary success, synchrotron bio-crystallography meets some limitations:

Need for crystals > (10-100 μm)^3

Radiation damage limits resolution… freezing a partial remedy

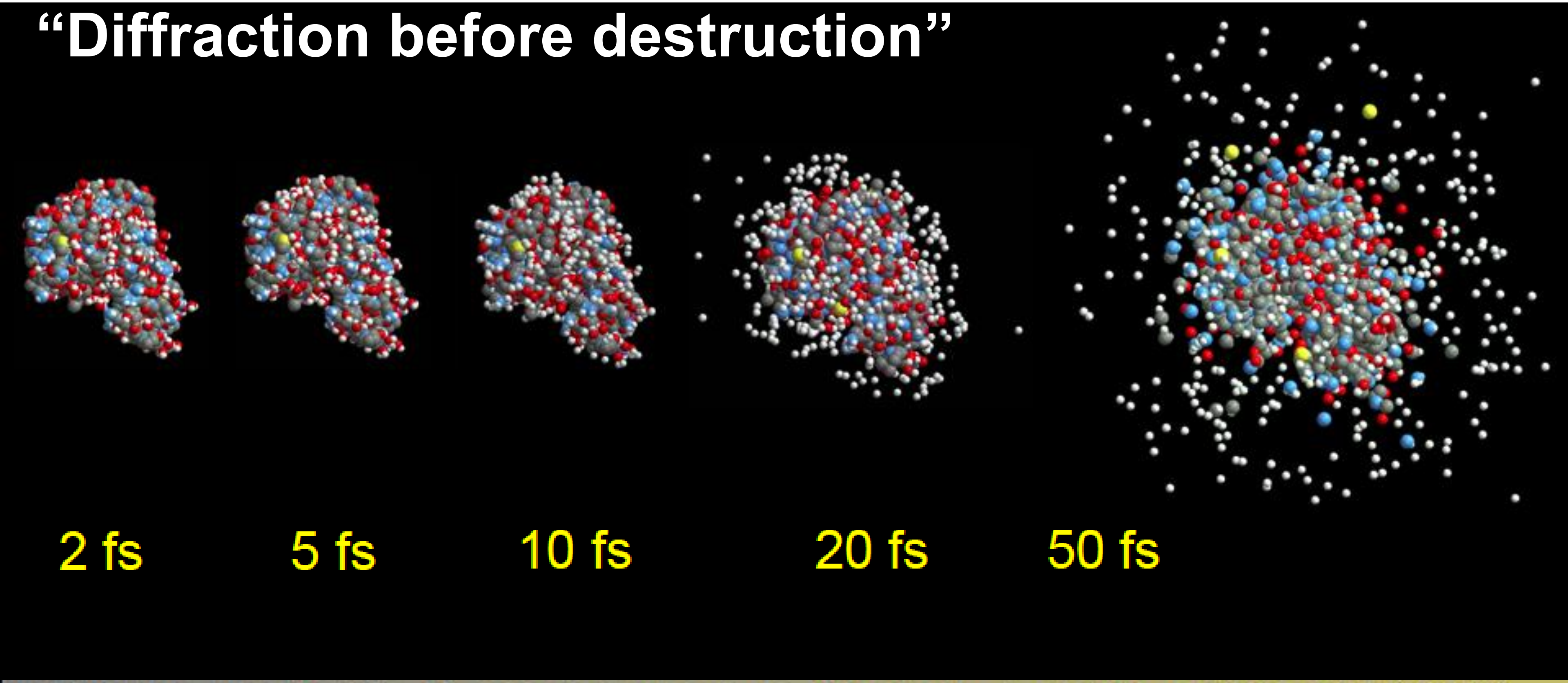
Crystal of Bovine Enterovirus 2 (BEV 2), 0.5 s, 10^8 ph/μm^2
D. Axford et al., Acta Cryst D68, 592 (2012)



SASE FEL short pulses

Courtesy M. Altarelli

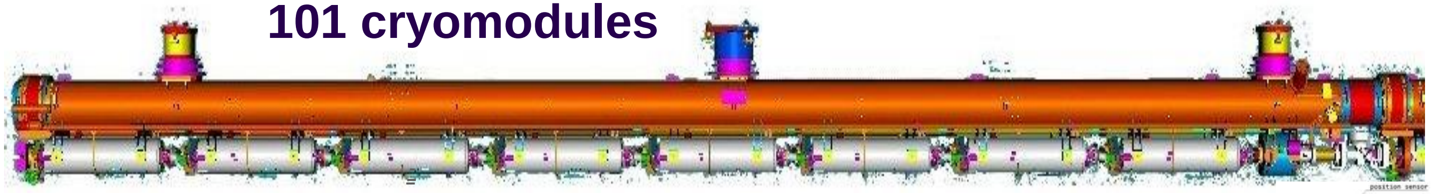
Speed may be the answer!



R. Neutze, R. Wouts, D. van der Spoel, E. Weckert, J. Hajdu, Nature **406** (2000)

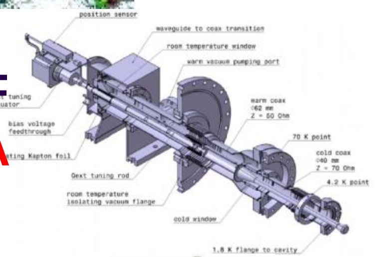
Linac Supraconducteur

101 cryomodules



808 cavités
1.3 GHz / 23,6 MV/m

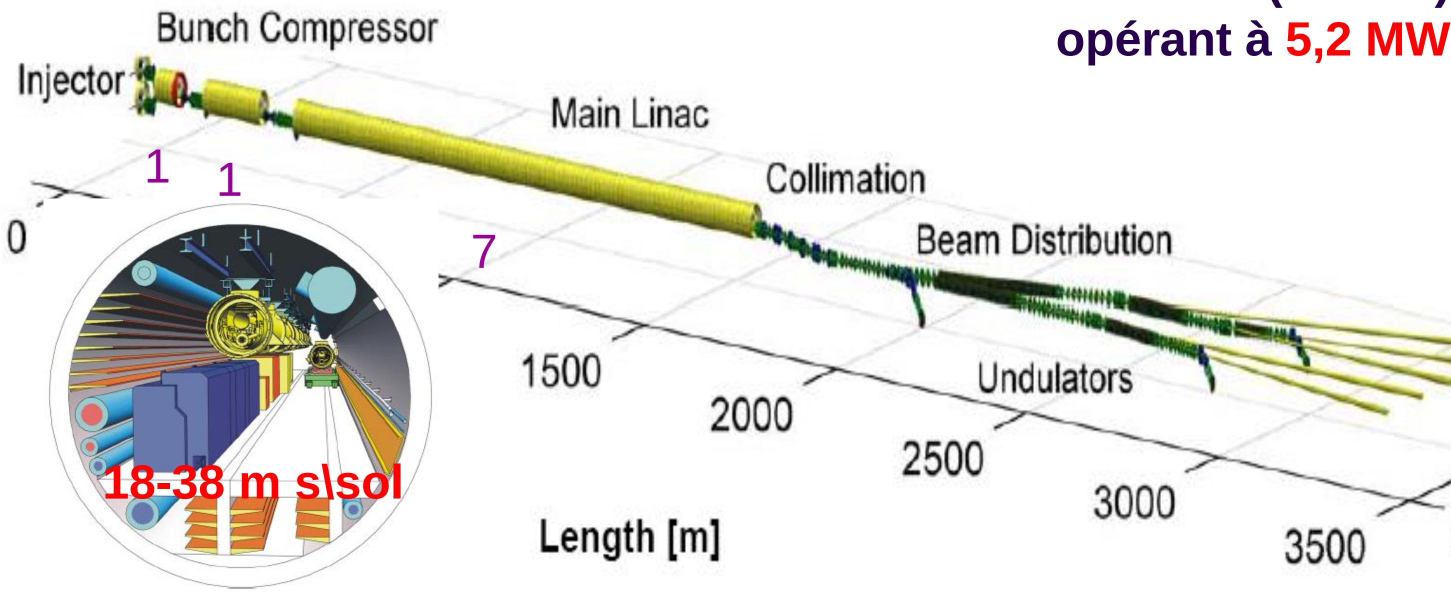
808 coupleurs RF
120 kW @ 5 mA



26 stations RF (10 MW)
opérant à 5,2 MW

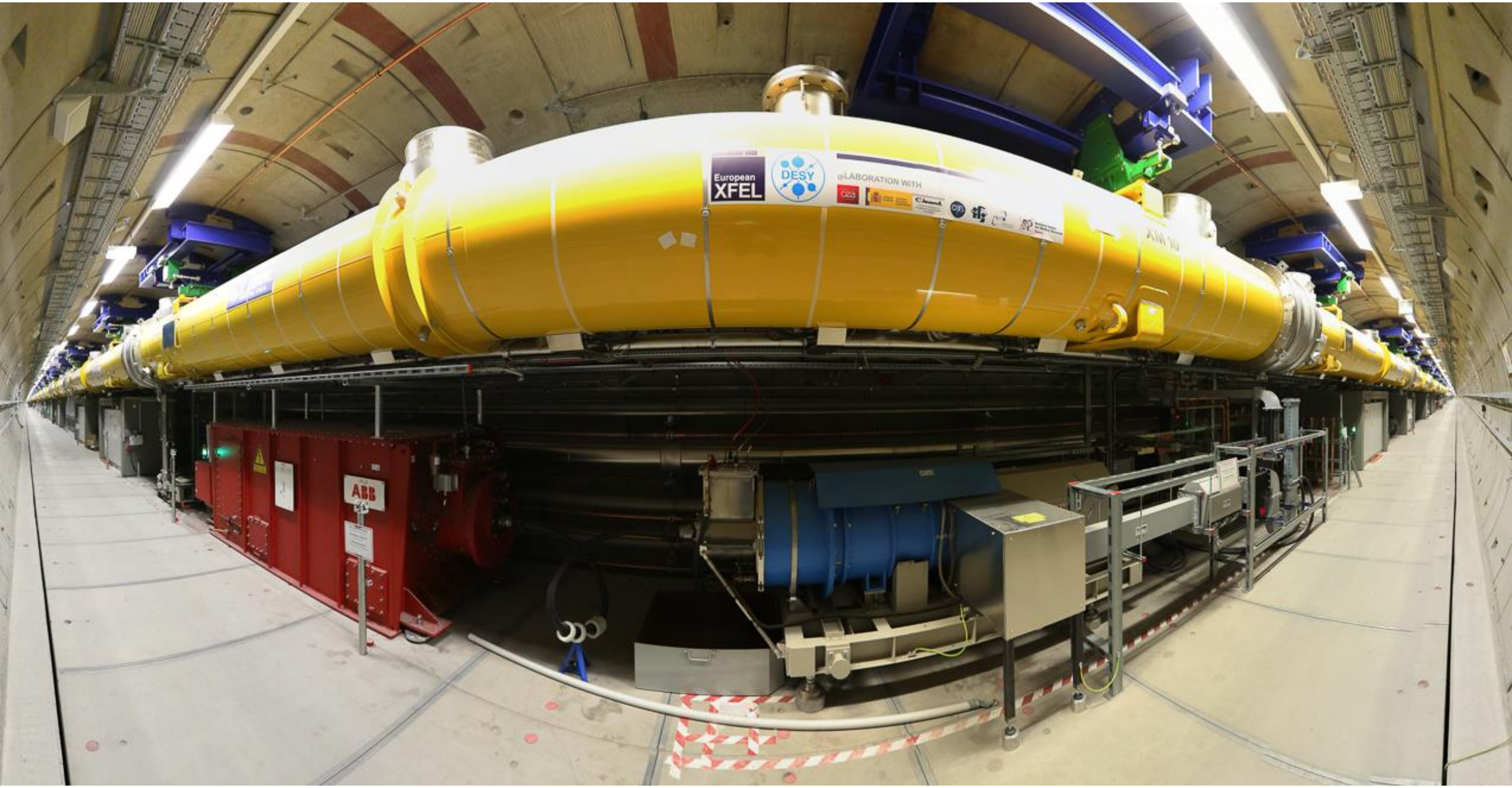
Thales

Toshiba

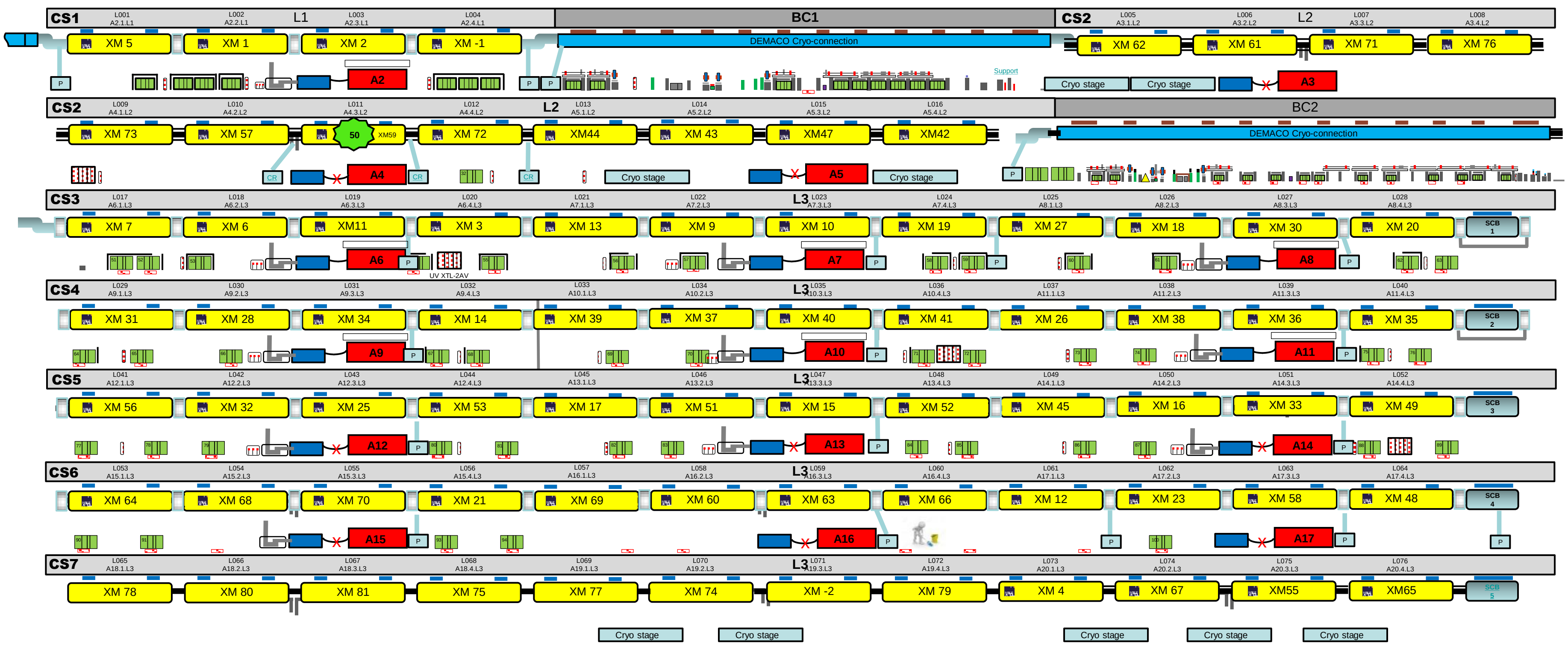


1 secteur cryogénique (12 modules) : 120 W @2K, 204 W @5-8K, 1,4 kW @40-80K

Almost one Kilometer of Cold Linac



Installation Status Linac Tunnel



Status 15.04.2016

76 Modules installed

next 4 Modules in prep.

1 RF-Station ready

6 RF-Stations under commissioning

9 RF-Station in preparation

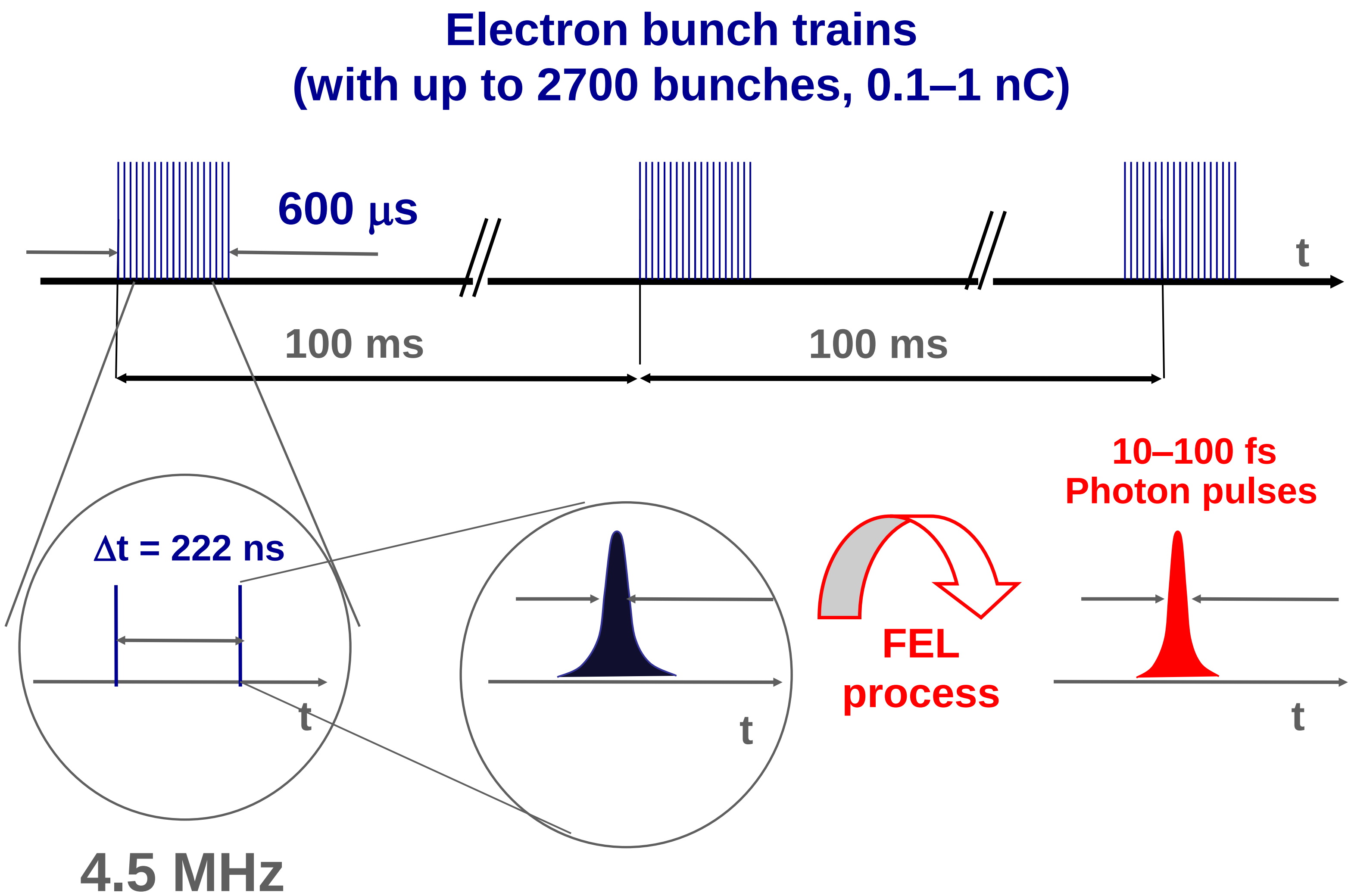
L'Accélérateur XFEL

- **Accélérateur linéaire supraconducteur à électrons**
- Haute énergie : 17,5 GeV
- Taux de répétition : 10 Hz
- Impulsion : 650 µs de faisceau,   1,4 ms de RF
- Intensité moyenne : 0,25-5 mA (0,02 - 1 nC / 200 ns)
- Intensité crête : 5 kA (un paquet)
- Emittance normalisée : 1,4 Pi mm.mrad

E-beam parameters

Quantity	Value
electron energy	8/12.5/14/17.5 GeV
macro pulse repetition rate	10 Hz
RF pulse length (flat top)	600 μs
bunch repetition frequency within pulse	4.5 MHz
bunch charge	0.02 – 1 nC
electron bunch length after compression (FWHM)	2 – 180 fs 90 fs
Slice emittance **(relates to gun RF power)**	0.4 - 1.0 mm mrad
beam power	500 kW

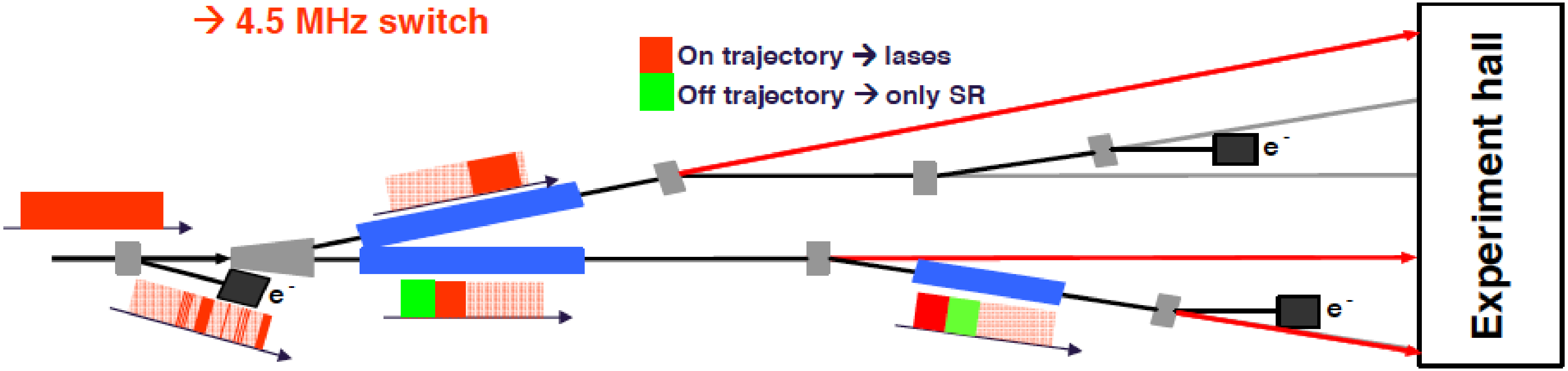
European XFEL Facility—Time Structure



Serving many instruments at one time

Dedicate & distribute electron bunches to instruments

- Operate accelerator as continous as possible
  - → **stability / performance**
- Distribute electron bunch train on two lines
  - → **10 Hz switch (few μs duration)**
- Switch on/off lasing for SASE 1/ SASE 3 line (optional)
  - → **4.5 MHz switches**
- Determine exact bunch pattern
  - → **4.5 MHz switch**



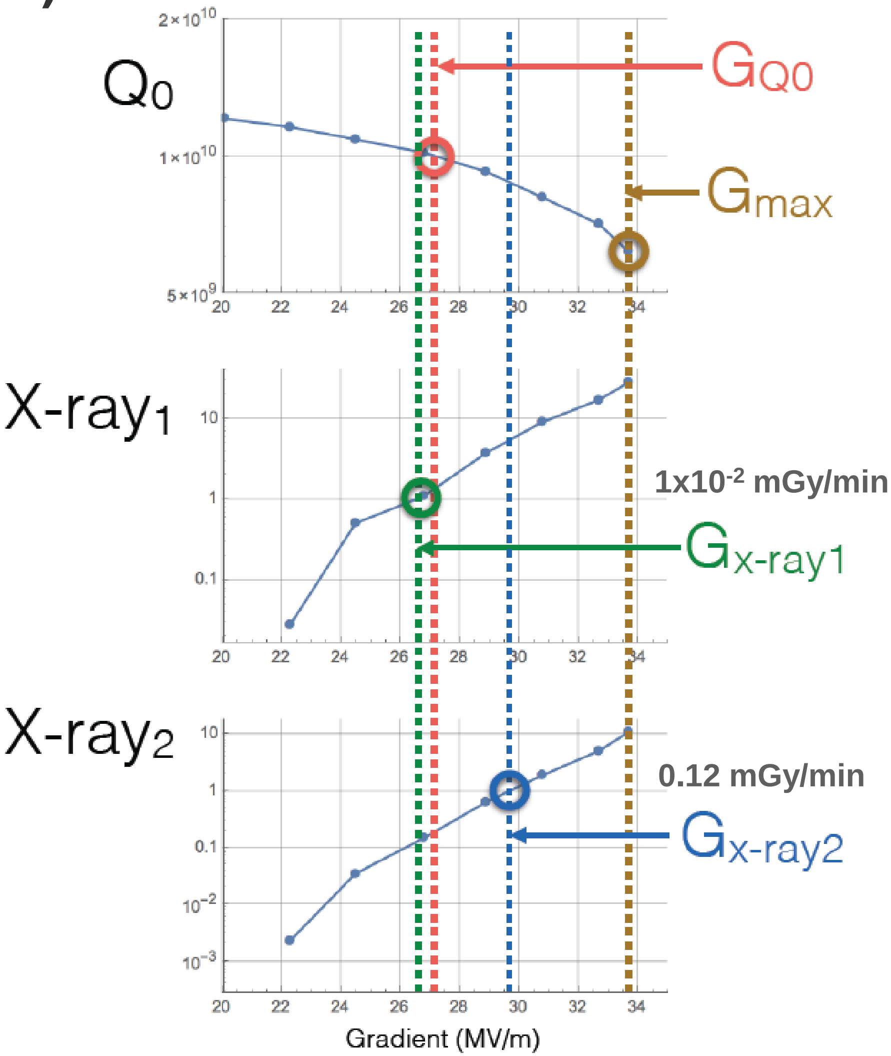
Electron bunch distribution : 27.000 bunches/sec to 3 (5) beamlines; in average 10-20 Hz and ~800 (500) pulses/train; using kicking methods to make bunches lase only in dedicated undulator

Champ accélérateur (‘gradient’) G maximal vs. G utile

- Minimum of the following gradient values:
  - MAX (i.e. quench)
  - $Q_0 = 10^{10}$
  - X-ray 1 (top) threshold
  - X-ray 2 (bottom) threshold

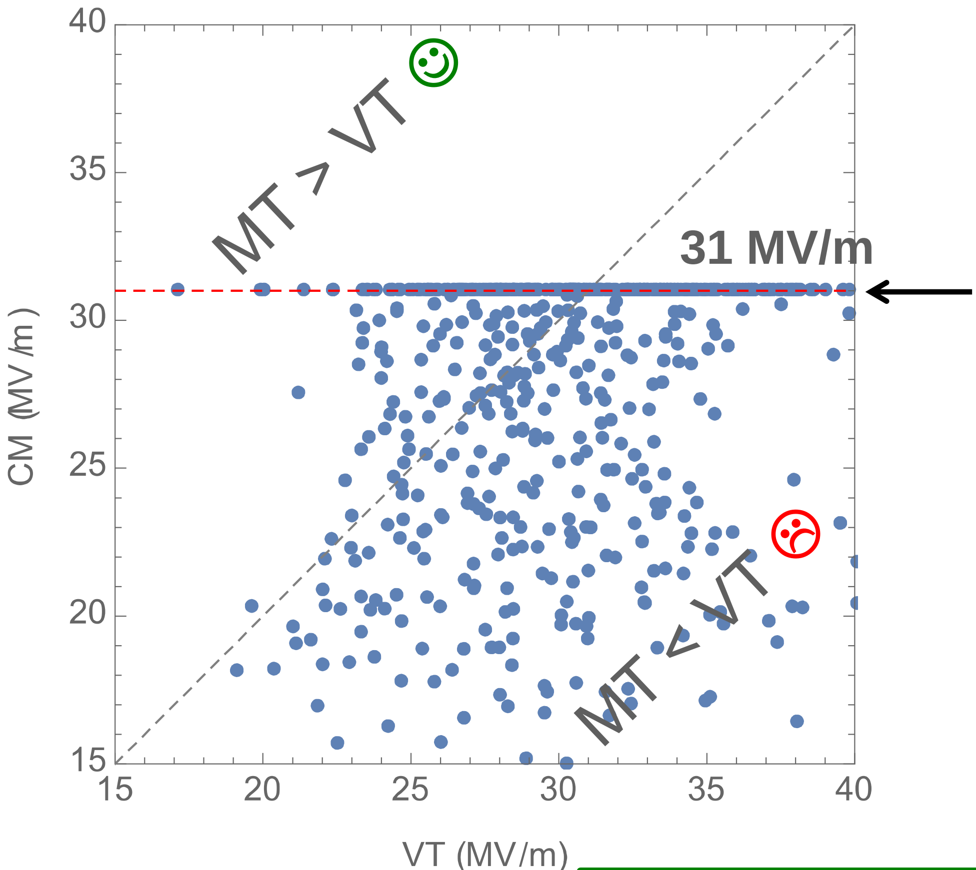
$$Q_0 = \omega_{RF} W / P_{diss}$$

In this example, usable gradient is limited by FE ($X\text{-ray}_1$) to ~27 MV/m



Courtesy M. Wiencek, N. Walker

"Usable" Gradient (up to XM79)



E-XFEL Module Assembly 'Phase Diagram'

RF Test and Linac operation limited to 31 MV/m to protect the RF distribution system

	N_{cavs}	Average	RMS	min	max
VT	615.	30.2	4.6	11.2	43.7
CM	615.	27.6	4.6	10.5	31.

Courtesy N. Walker

Qualification des cryomodules

Courtesy D. Reschke

Production des Cryomodules

La contribution du CEA à European-XFEL:

assemblage de 103 cryomodules

sur le site de Saclay et l'infrastructure du CEA

↓

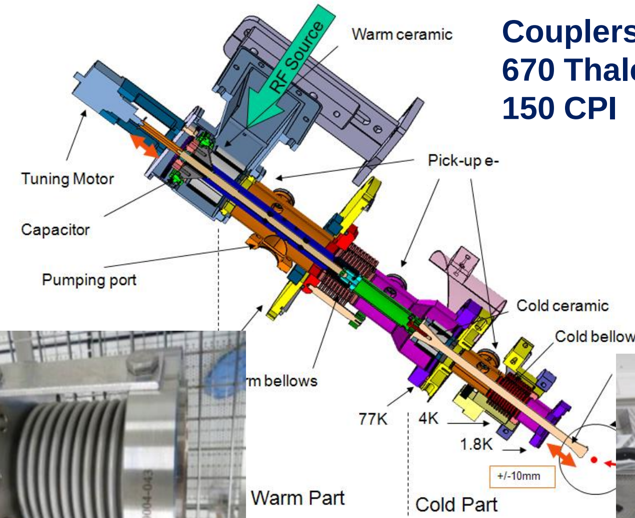
opéré par un contractant industriel Alsyom:

→ Objectif de production : 1 module / semaine

→ Objectif de performance : E_{acc} > 23,6 MV/m

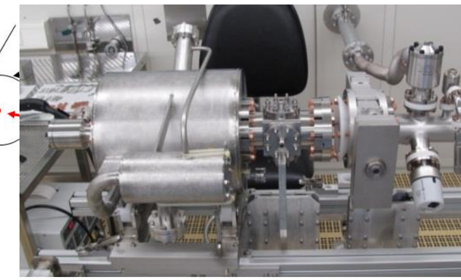
⇒ Objectif global: V_{acc} > 196 MV par semaine

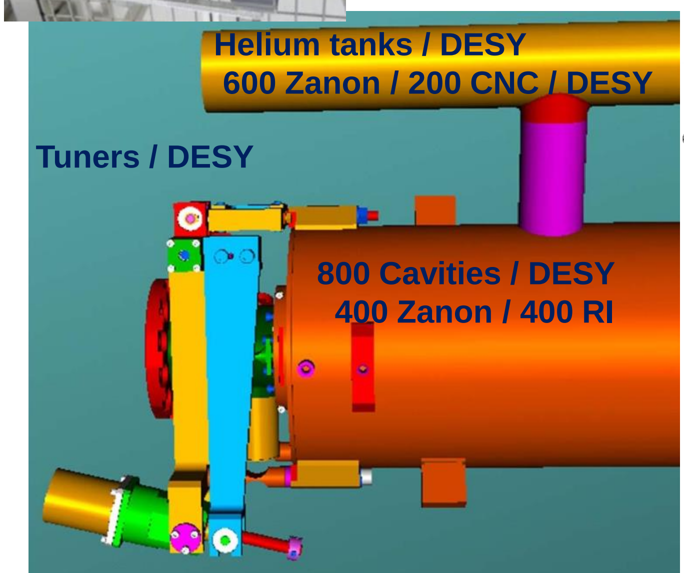
Industrialisation des composants / Transferts

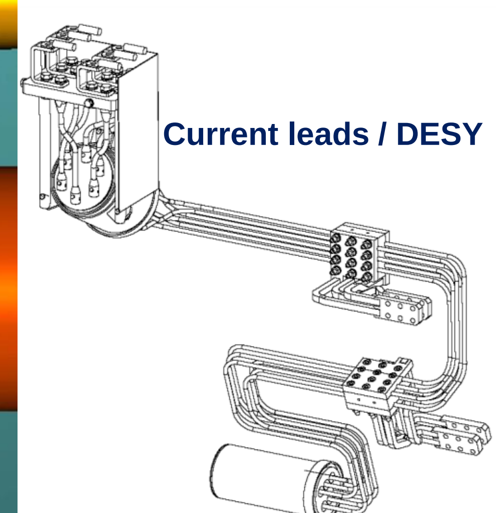


Couplers / IN2P3
670 Thales-RI
150 CPI

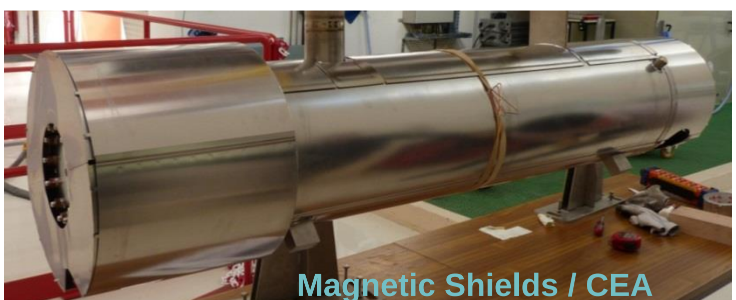
Quadrupole-BPM / DESY
103 Magnets / Ciemat
BPM / 72 DESY – 31 CEA
206 Gate Valves / DESY



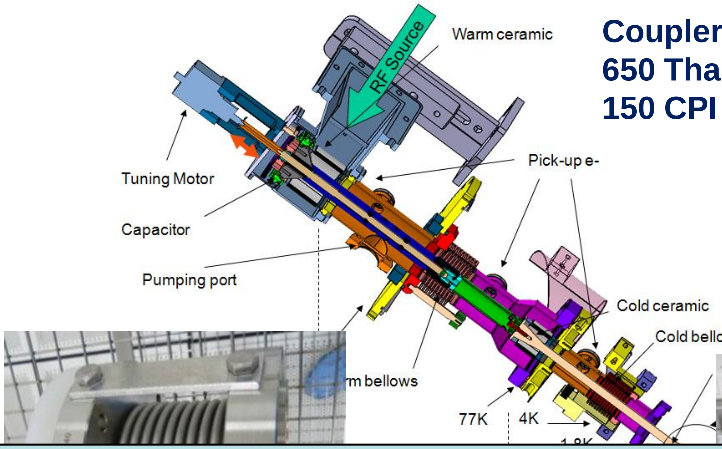




Current leads / DESY

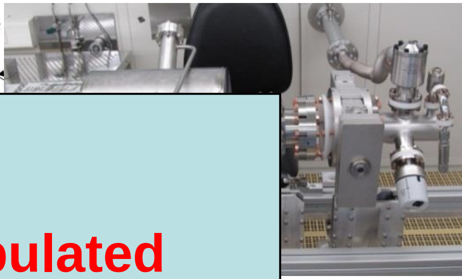


Component Industrialization / Handover



Couplers / IN2P3
650 Thales-RI
150 CPI

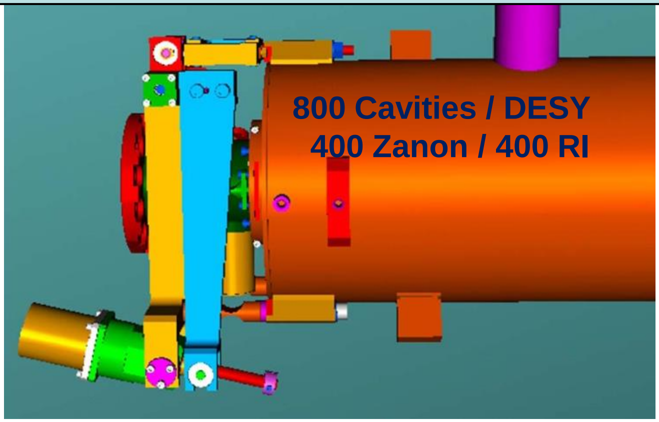
Quadrupole-BPM / DESY
103 Magnets / Ciemat
BPM / 72 DESY – 31 CEA
206 Gate Valves / DESY



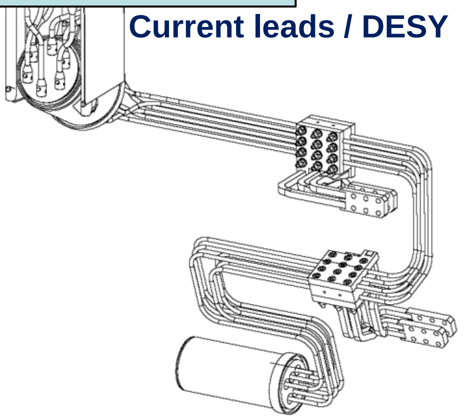
9 422 components integrated

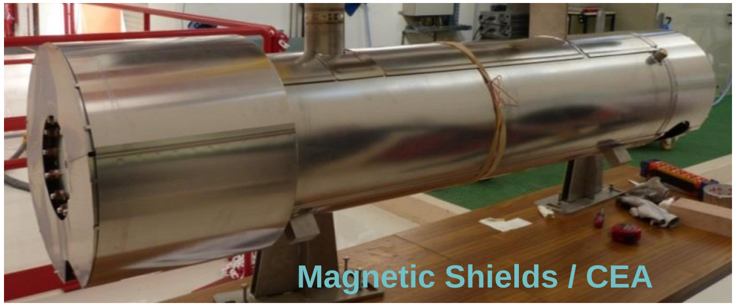
and more that 12 400 individual parts manipulated

per cryomodule.



Current leads / DESY





Cryomodule Factory

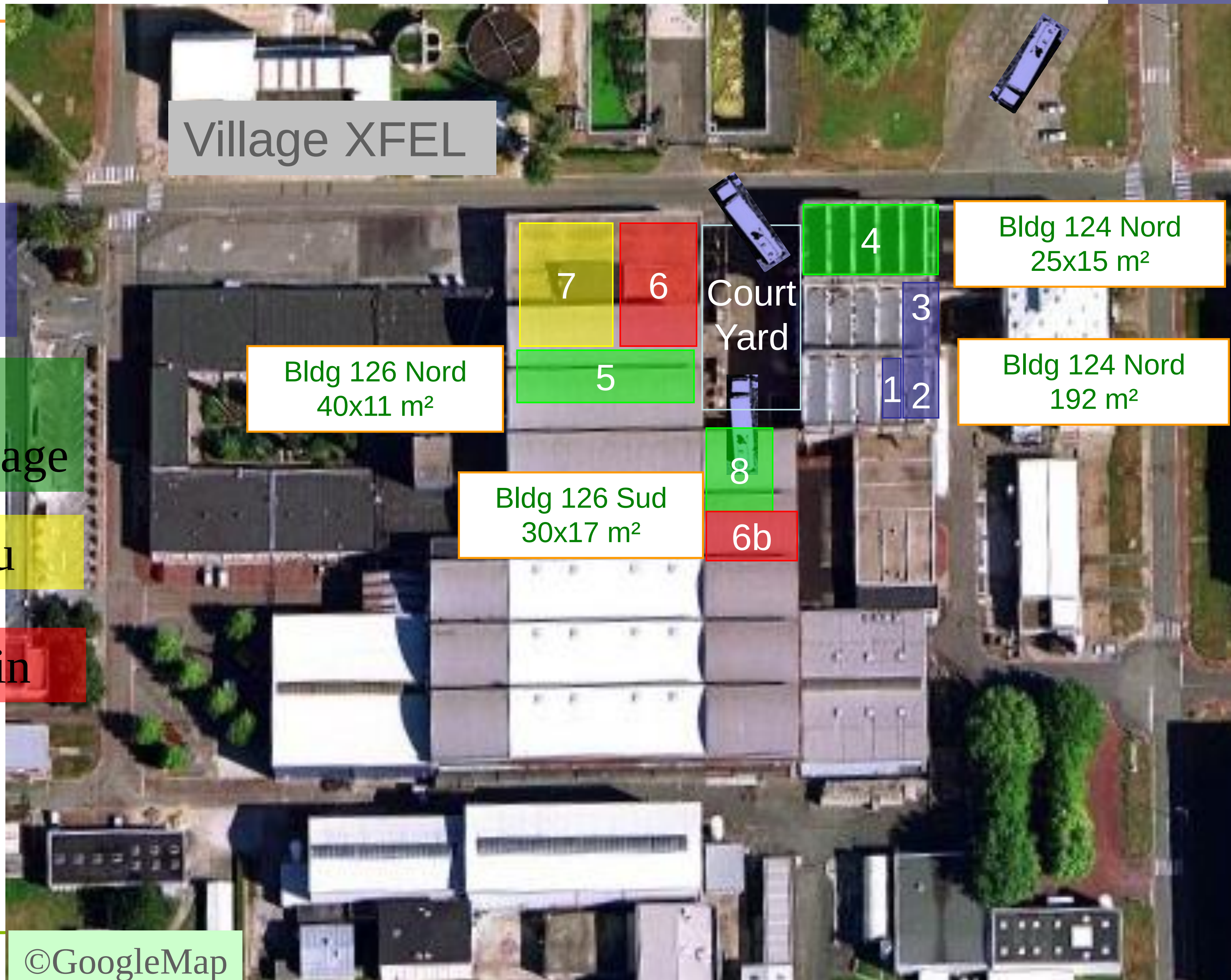
Bâtiment d'Intégration: 2300 m²

Salles blanches

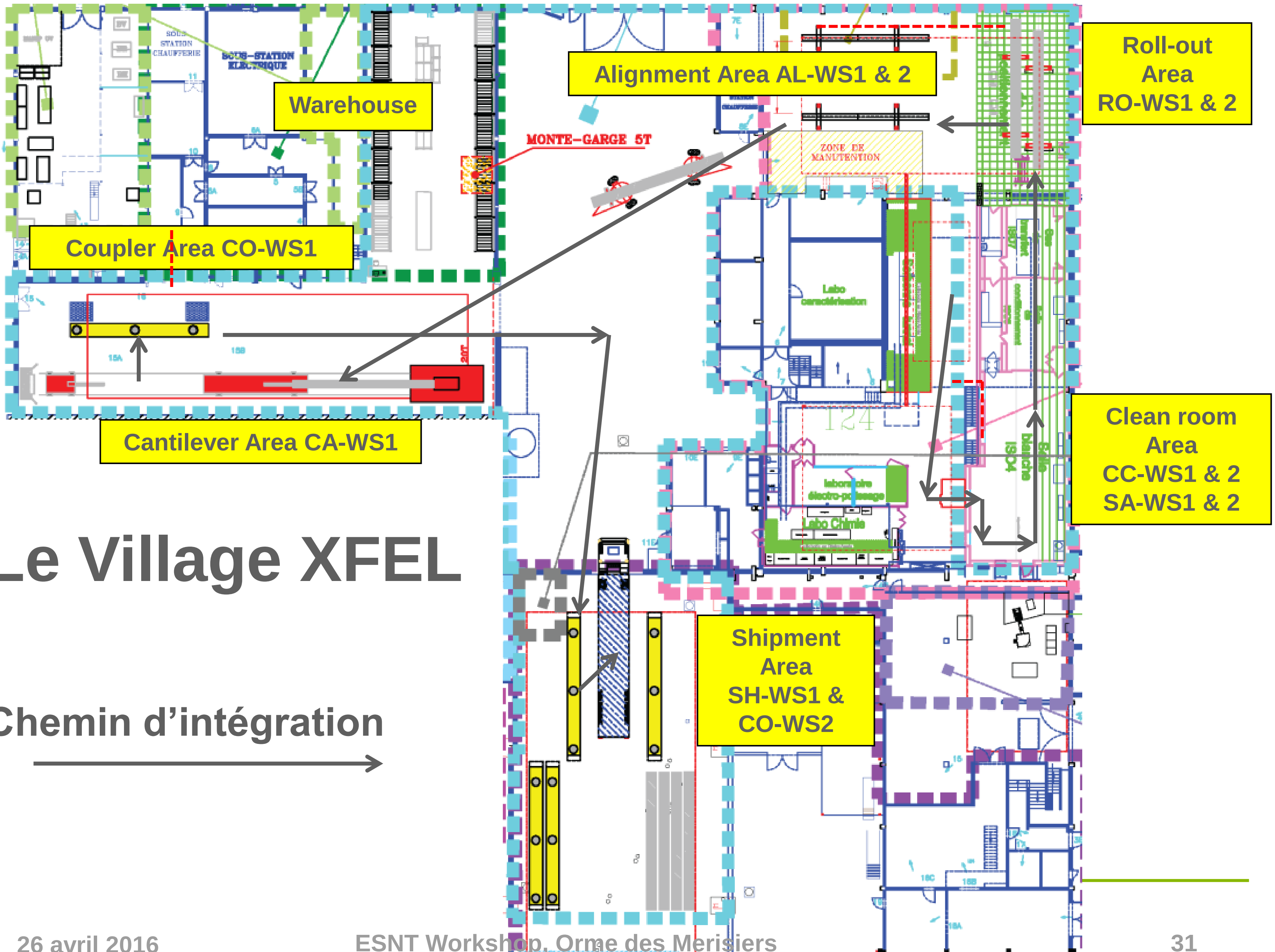
Halls Assemblage

Bureau

Magasin



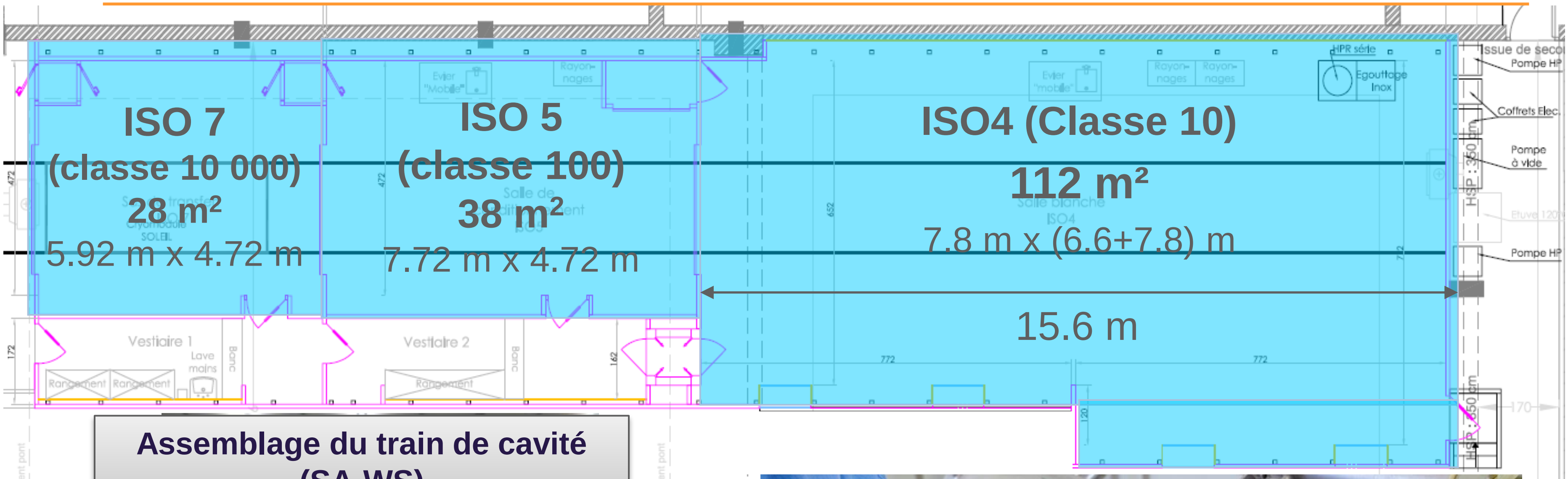
Halls d'Assemblage: Stations de Travail



Le Village XFEL

Chemin d'intégration →

Salle Blanche XFEL



Assemblage du train de cavité (SA-WS)

Assemblage du coupleur froid (CC-WS)

Station d'Intégration de la Masse Froide

Assemblage de la masse froide (RO-WS)

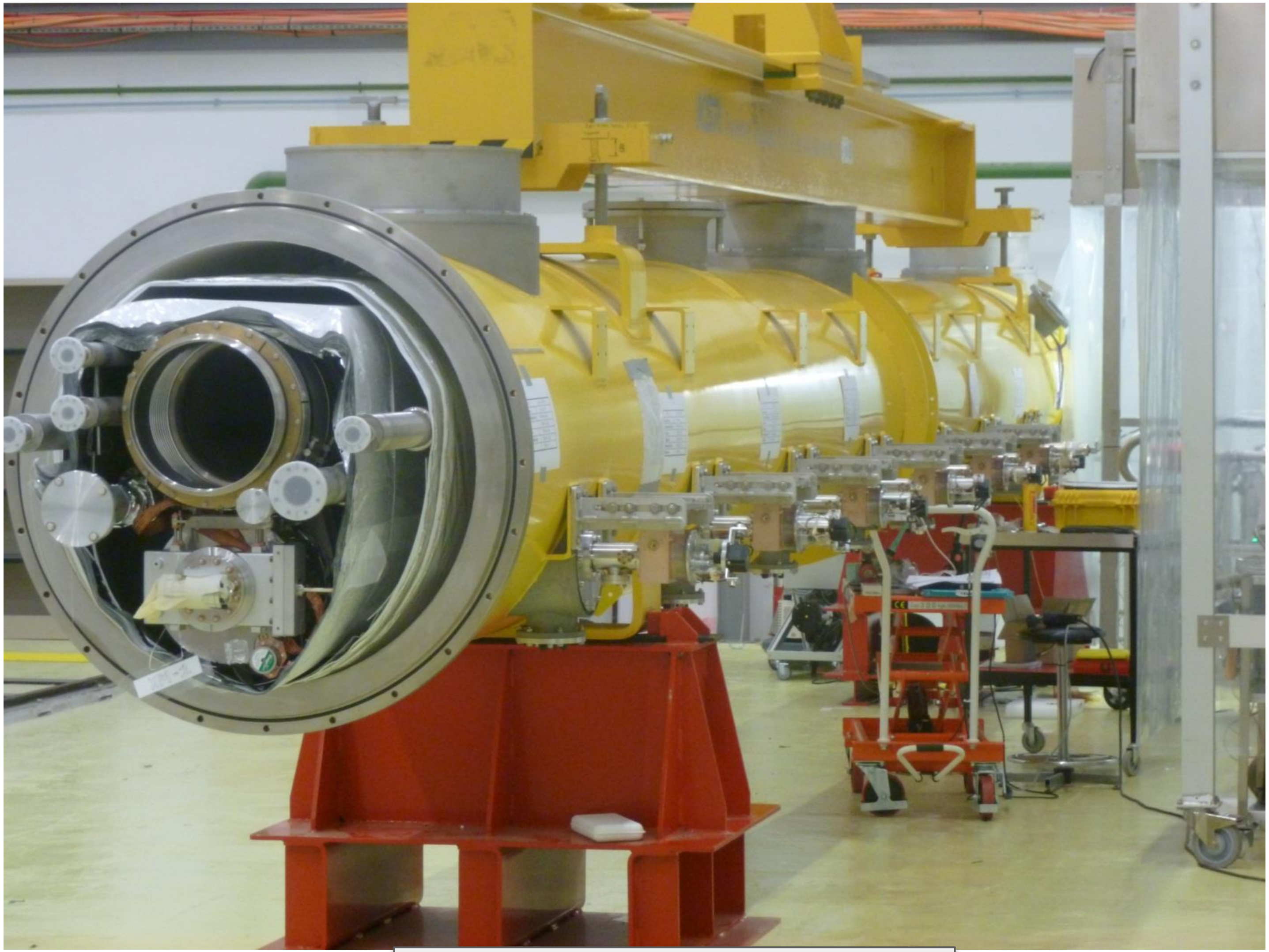
Stations d'Alignement

Stations Masse froide (RO-WS) et Alignement des cavités (AL-WS)

Station Enfourneur

XM1 (enfourneur) le 14/02/2014

Station Coupleurs Chauds



Assemblage des coupleurs chauds (CO-WS)

Stations de Travail Enfourneur et Coupleurs Chauds

XM1 (Enfourneur) and XM-1 (Coupleurs chauds) le 14/02/2014

Station Expédition

Expédition (SH-WS)

Chargement (SH-WS)

Expédition des Cryomodules de Série

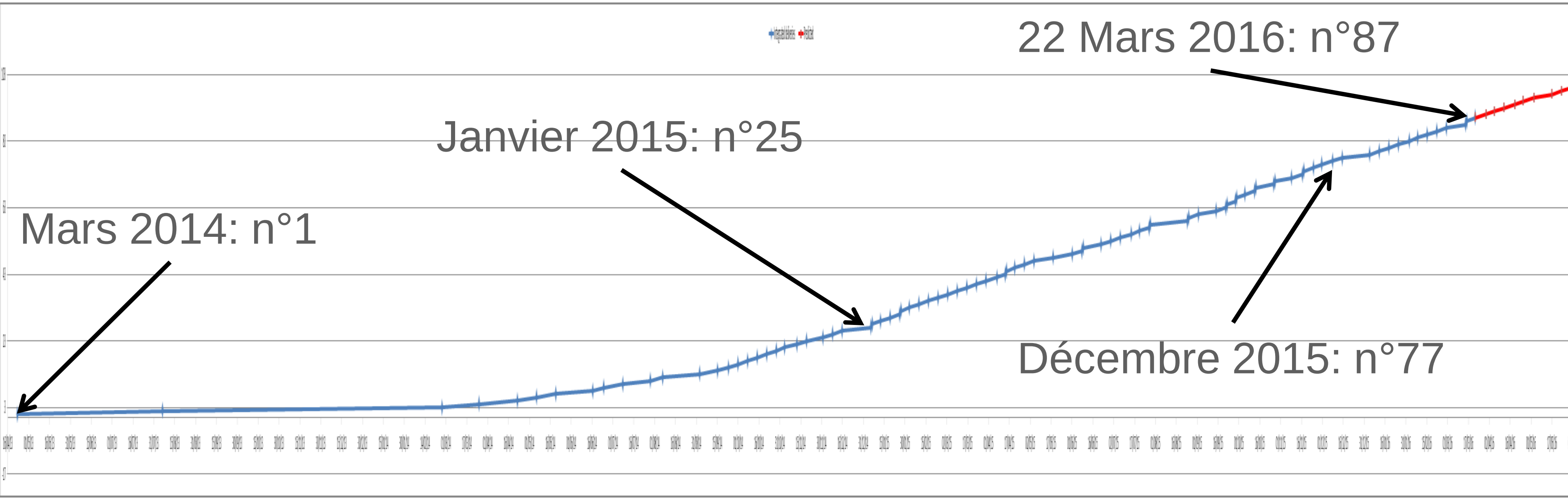
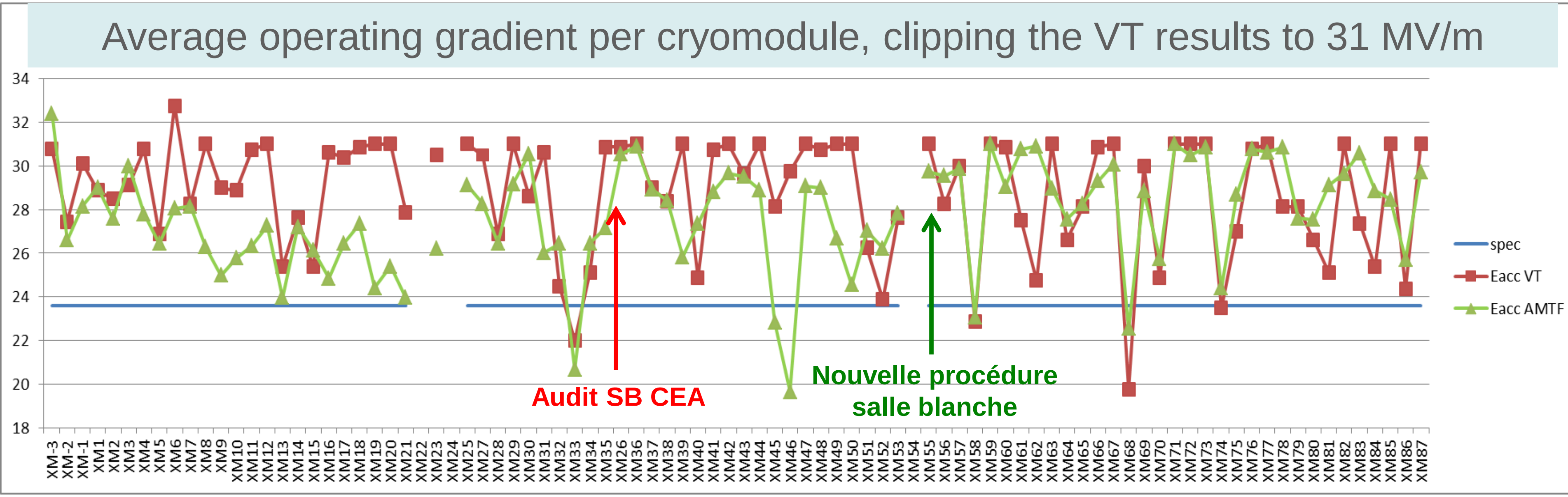


Figure: *expédition des cryomodules de série, de XM1 à XM100*

- **93 cryomodules livrés à DESY à ce jour** (XM-3, XM-2, XM-1 inclus).
- Depuis Janvier 2015, la cadence d’expédition est de **4 jours**.
- Le linac inclut les modules de pré-séries XM-2 et XM-1, mais pas XM-3
- L’expédition de XM100 est prévue le **5 juillet 2016**

Performance des Cryomodules (1/2)



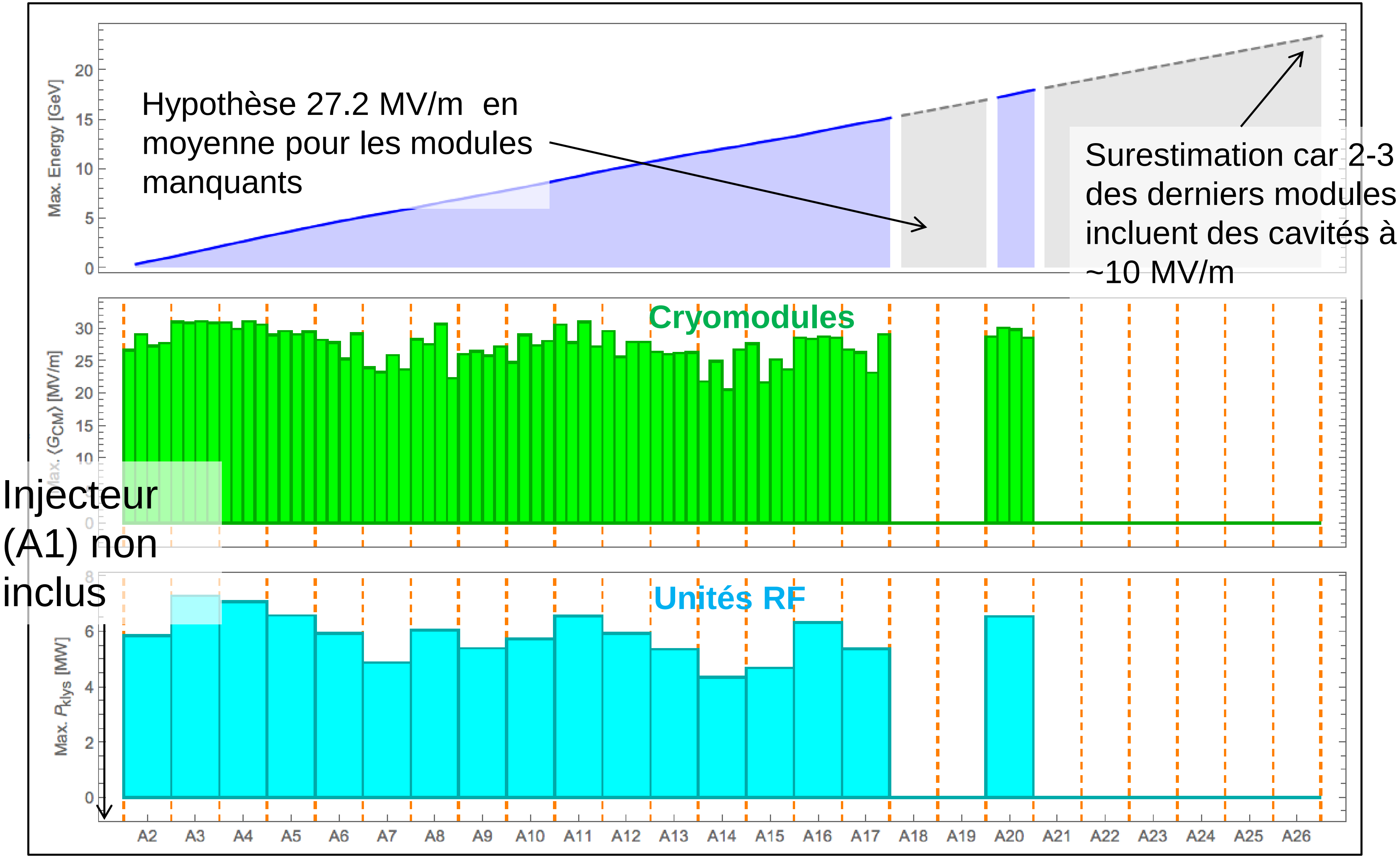
1st sample of 32 series CM
ΔE_{op} = -2.3 MV/m

2nd sample of 19 series CM
ΔE_{op} = -1.8 (-0.8) MV/m

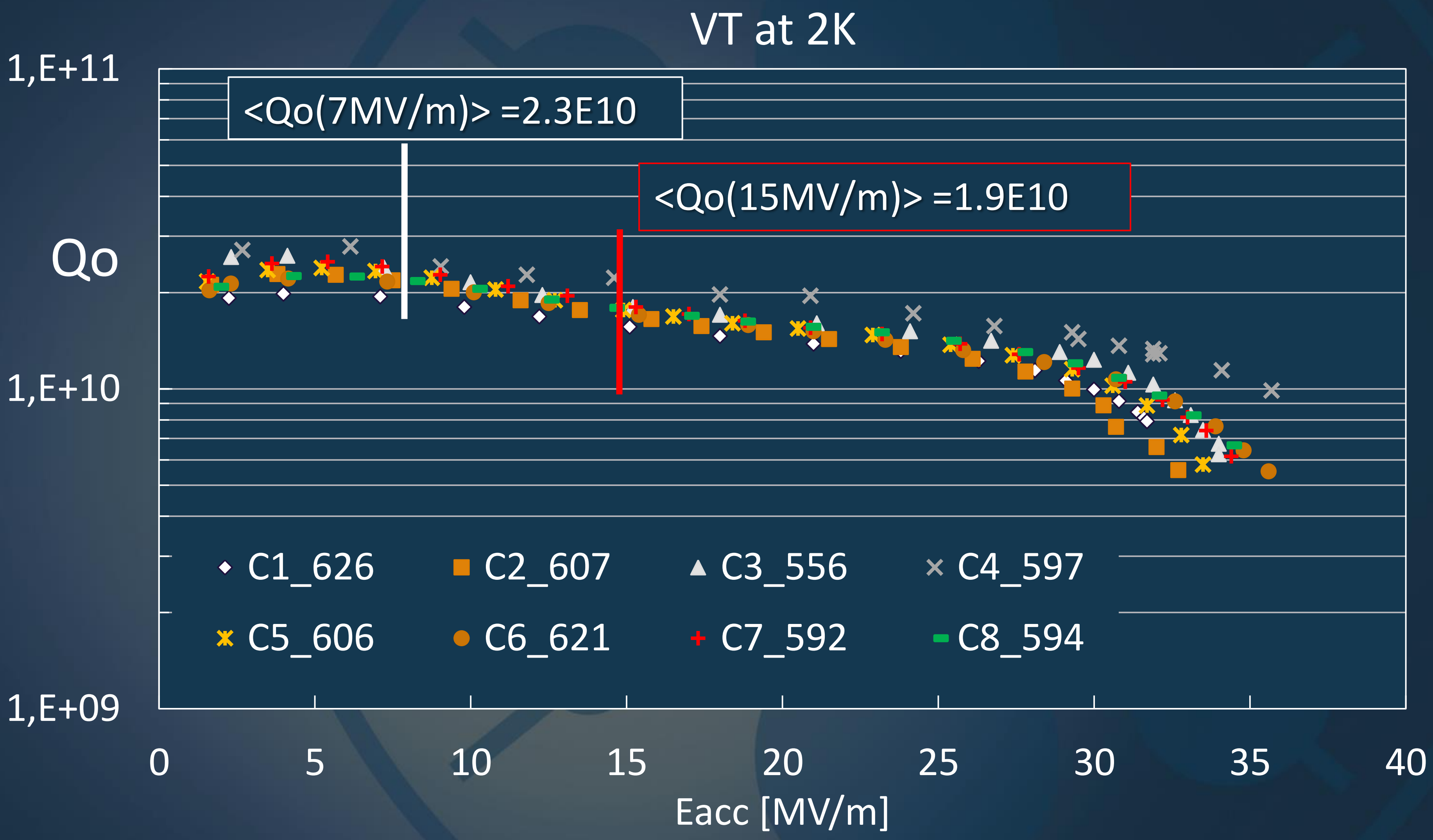
last 33 series CM
ΔE_{op} =+0.6 MV/m

- All but 5 of 85 tested modules are on XFEL specs (23.6 MV/m), 6 modules need(ed) repair.
- Average gradient is 17% above specs : **$\langle E_{acc} \rangle$ = 27.7 MV/m**.
- Significant gradient degradation from XM6 to XM23, while CEA and Alsyom put all their effort in achieving production goal of 1 CM/week: an audit of string and module assembly was conducted by CEA on XM26
- A simplification of the clean room procedures was introduced at XM54: **no degradation after**

Extrapolation de l'Energie du LINAC



XM4 cavities:



XM4 cavities: sp test at CMTB (Denis Kostin)

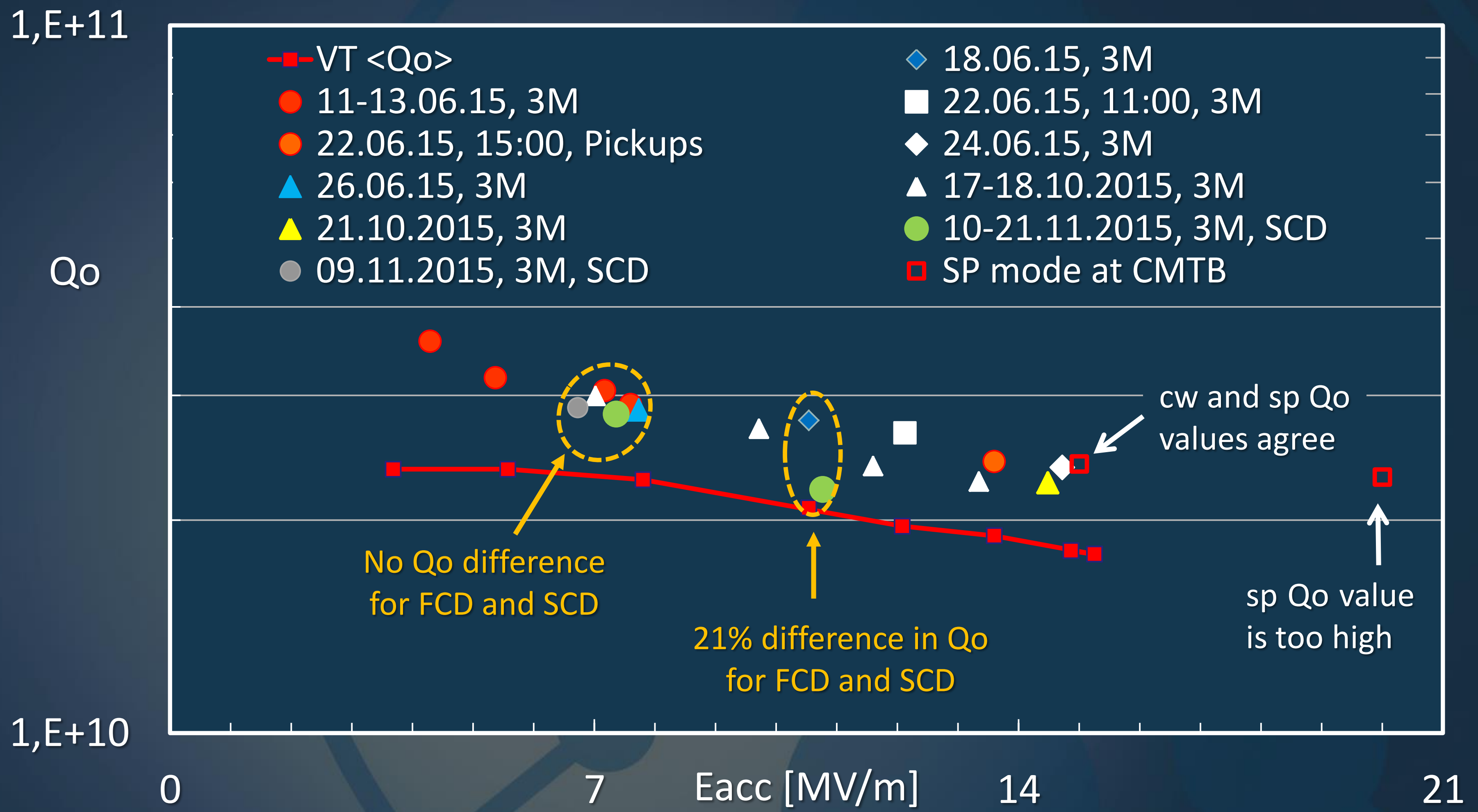
Gradients

Cavity	Max Eacc [MV/m]	Max oper. Eacc [MV/m]	Operation Limit
C1_0626	33.5	31.0	PWR
C2_0607	34.8	31.0	PWR
C3_0556	31.1	30.6	Quench
C4_0597	34.5	29.9	X-ray > 10^{-2} mGy/min
C5_0606	**39.0**	31.0	PWR
C6_0621	24.4	23.9	Quench
C7_0592	**22.0**	21.5	Quench
C8_0594	35.1	31.0	PWR

Qo(2K)

Eacc [MV/m]	15	20.5
<Qo> [10^{10}]	2.4	2.3 (?)

cw tests at 2K, FCD & SCD



In most of runs 3 methods (3M) were used to determine E_{acc} (to minimize an error): Read out of pickups (calibrated the sp mode), $\{P_{in}, Q_{load}\}$ for each cavity, and IOT (P_{IOT}*0.95/8).

Conclusions

- E-XFEL Cryomodule Assembly at Saclay went through 4 main phases:
  1. Mastering the process [T1/2008 – T1/2013]
  2. Mastering the infrastructure and tooling [T3/2010 – T1/2013]
  3. Mastering the handling of non-conformities, both *imported*-PRODUCT and PROCESS-*generated* non-conformities [T3/2012 – T3/2014]
  4. 'Mastering' the industrial operator
     - Productivity [T1/2014 – T4/2014]
     - Quality Assurance [T4/2014 – ongoing]

  This process depends inevitably on the early availability of the cryomodule components: '*Practice makes perfect*'
- The difficulties of coupler assembly had been under-estimated by CEA
  1. e.g. cavity vs. coupler assembly includes 1 vs. 12 individual parts, ~100 vs. ~1000 fastening hardware.
  2. about 8 couplers (both cold part and warm part) have been destroyed due to bad manipulation and/or bad assembly.
- Better module RF performance correlated to Clean Room practice and procedures.

Thank you for your attention