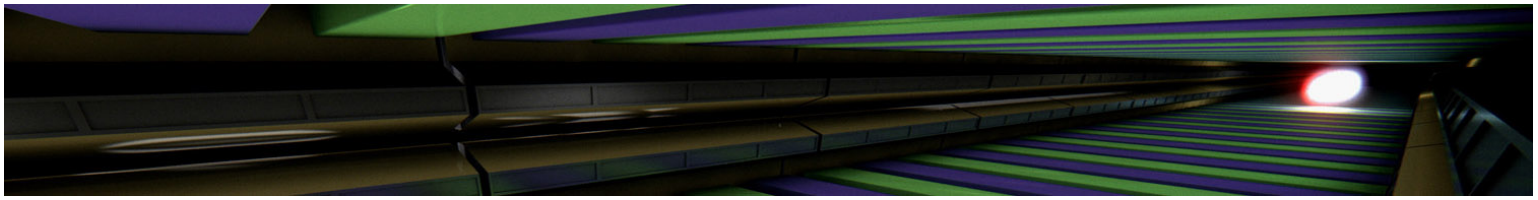


Confinement concepts for X-ray laser beams at the European XFEL

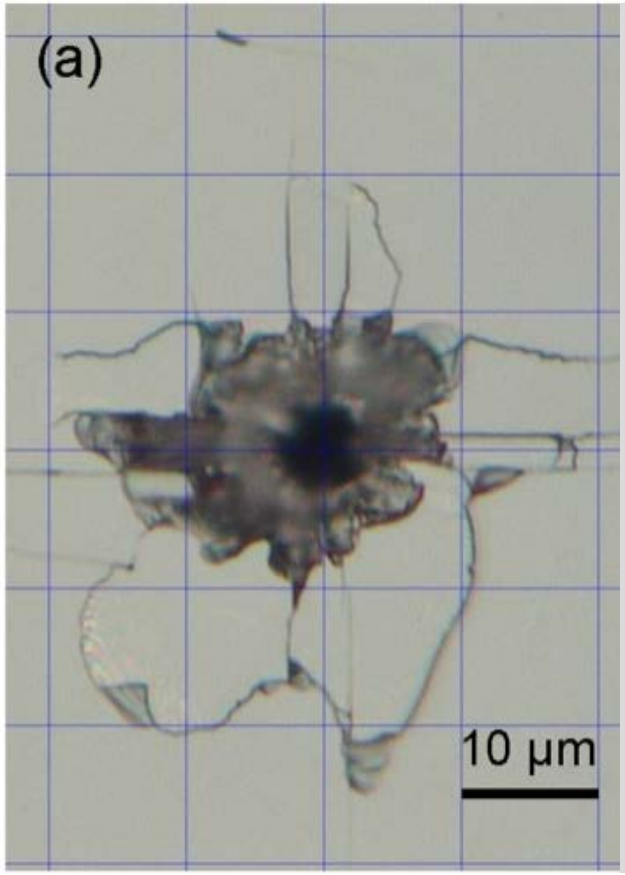
Harald Sinn

European XFEL, X-ray Optics

5.6.2015 RadSynch 2015

European XFEL

Beam damage from single shot (SACLA)



Sample: Silicon

Photon energy: 10 keV

Pulse energy: 0.1 mJ

Pulse duration: 20 fs

Focus: 1 µm FWHM

Crater diameter: 4 µm

Depth: 40 µm

Aspect ratio: 10

T. Koyama et al. Optics Express 21.015382 2007

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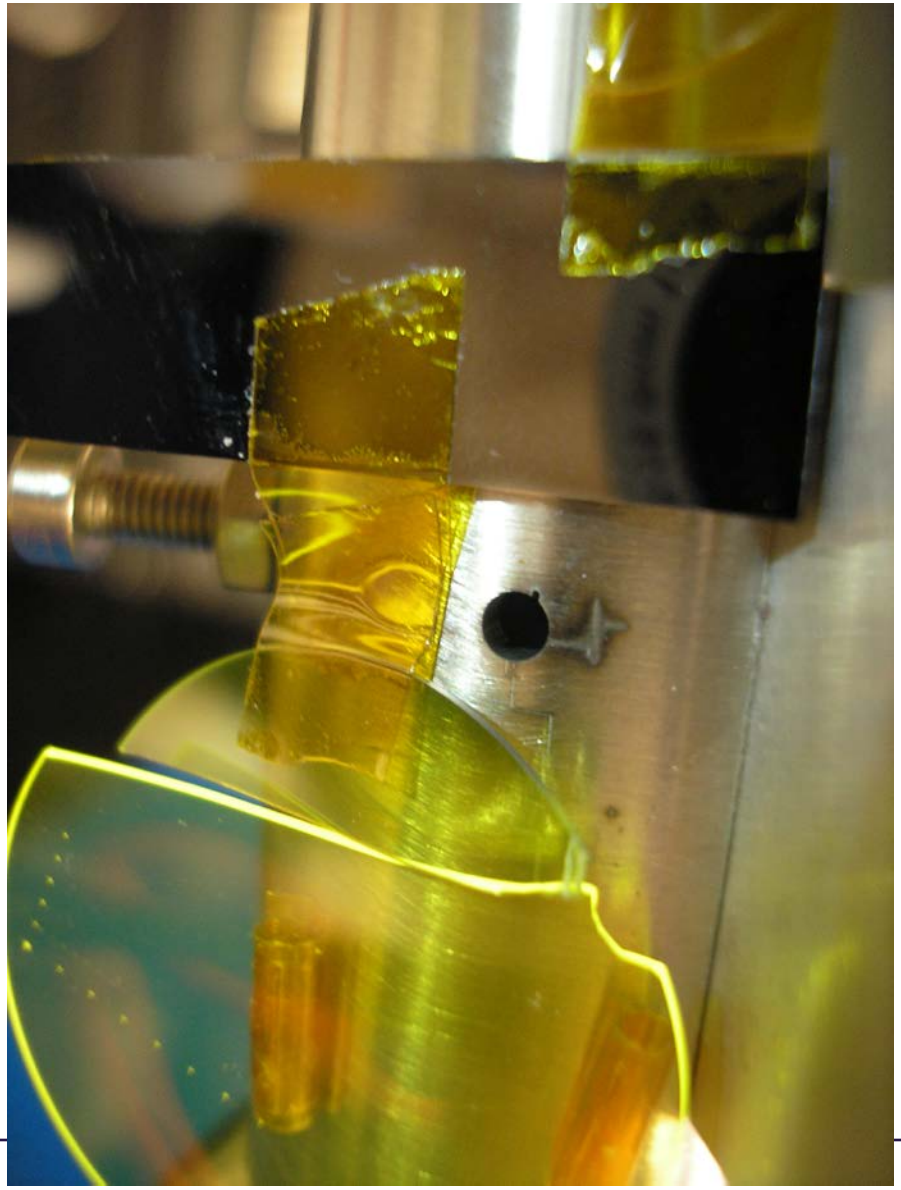
Alignment with X-ray laser beam (LCLS)



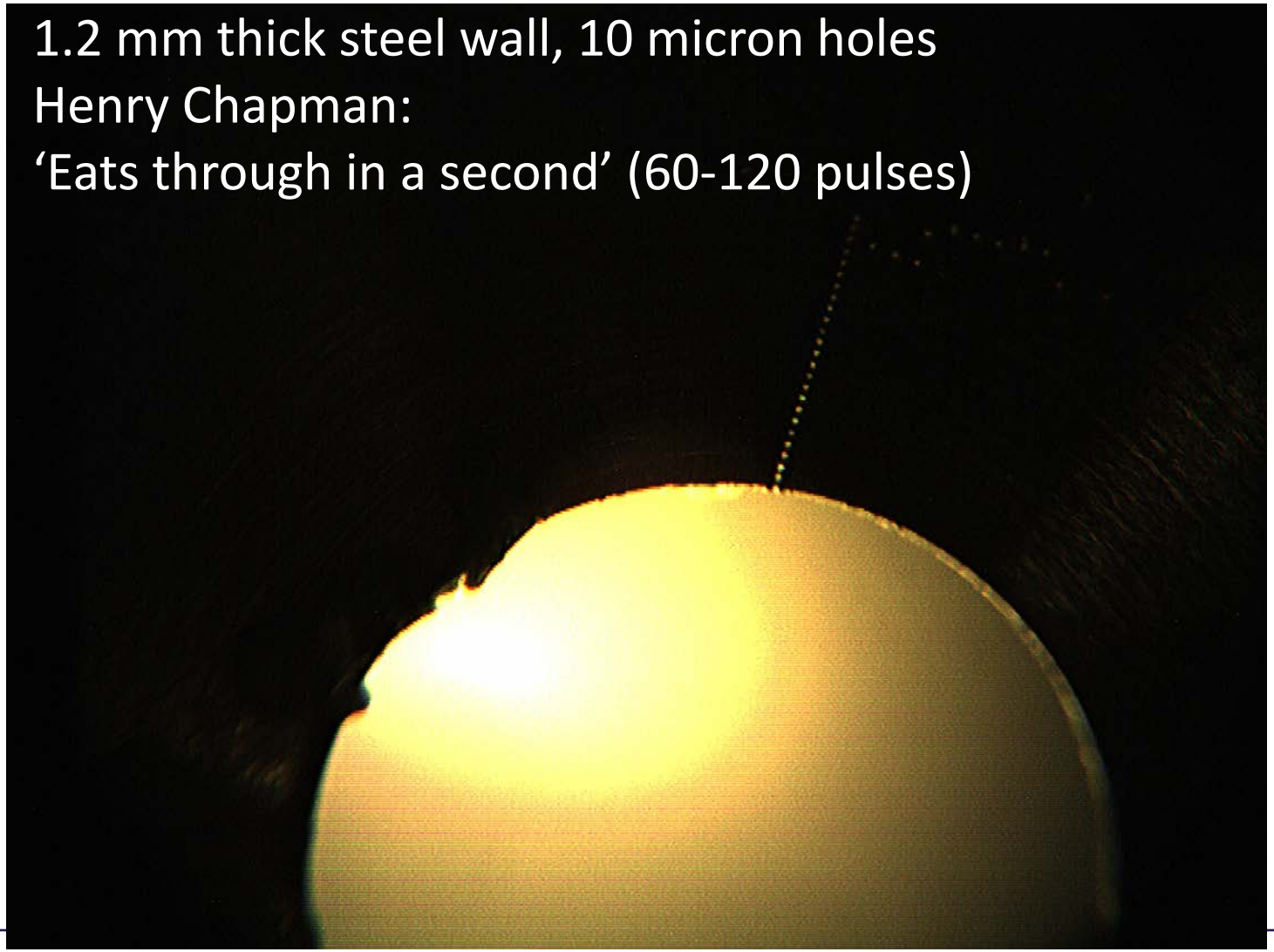
European XFEL

Alignment with X-ray laser beam

1.2 mm thick steel wall, 10 micron holes

Henry Chapman:

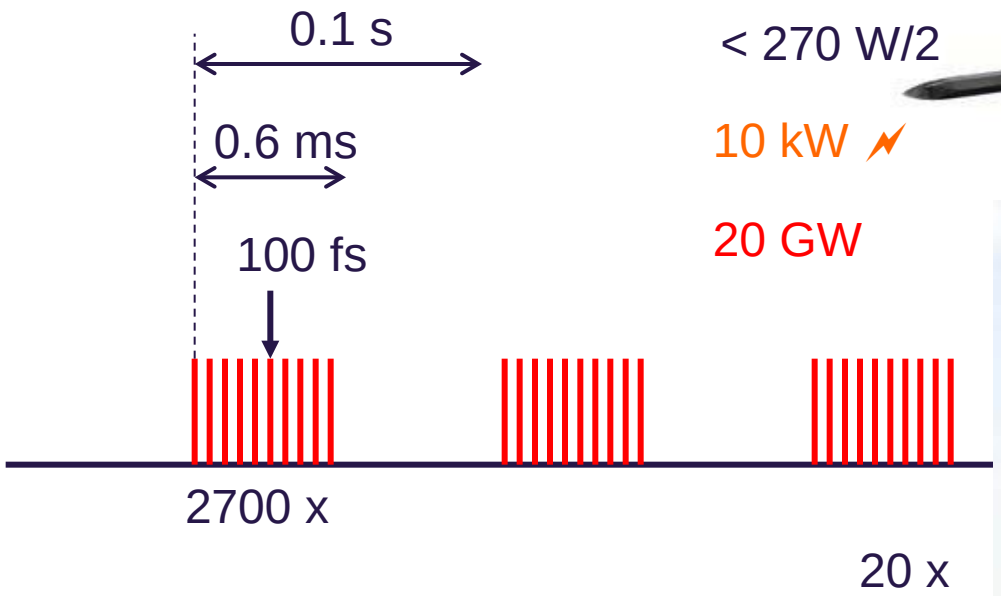
‘Eats through in a second’ (60-120 pulses)



Pulsed beam at the European XFEL

Superconducting Linac, 10 Hz

XFEL pulse pattern: 99.4 % empty



< 270 W/2

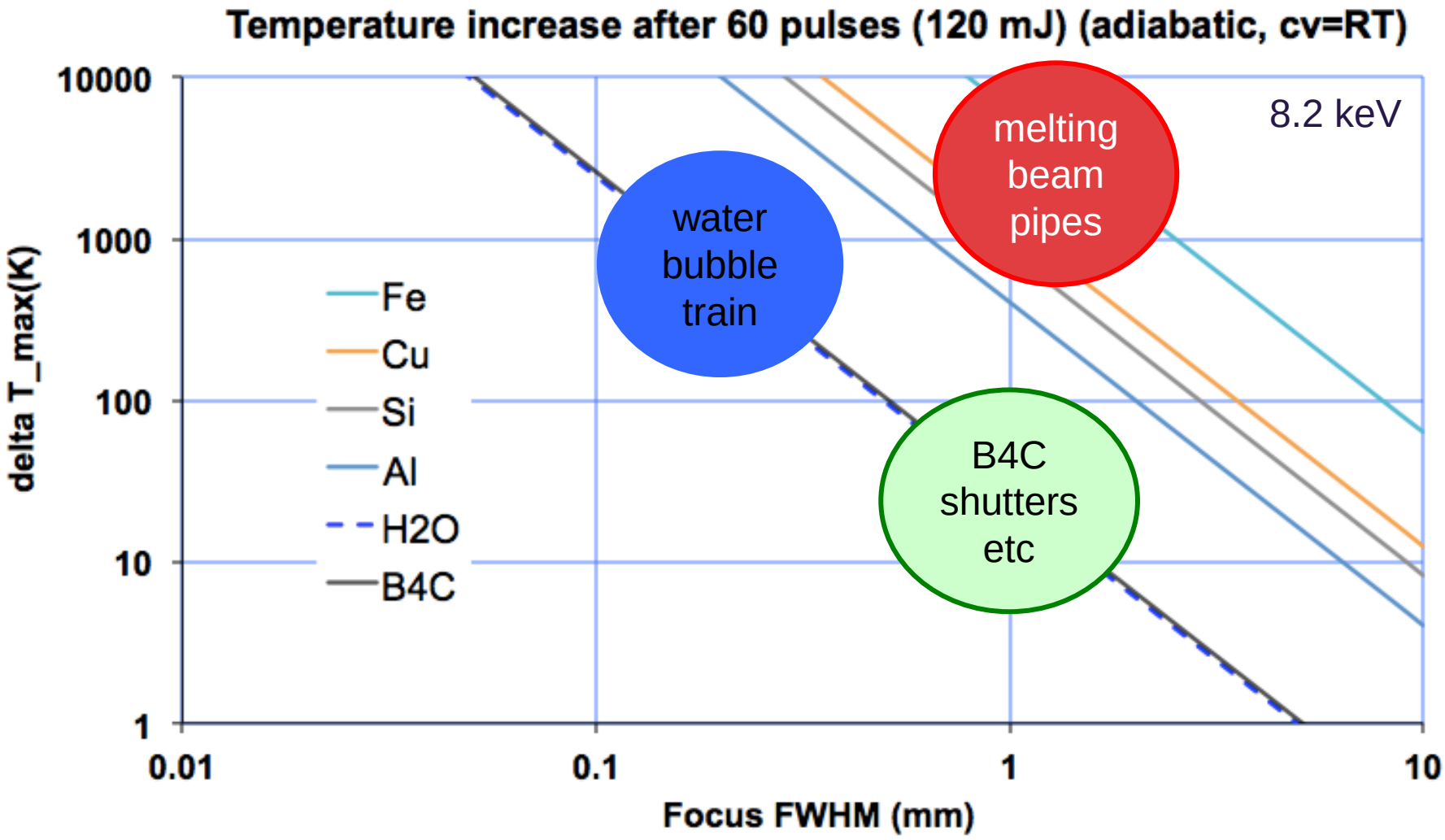
10 kW

20 GW

max. 27J/train, 10 Hz

European XFEL

Melting of steel, copper, …

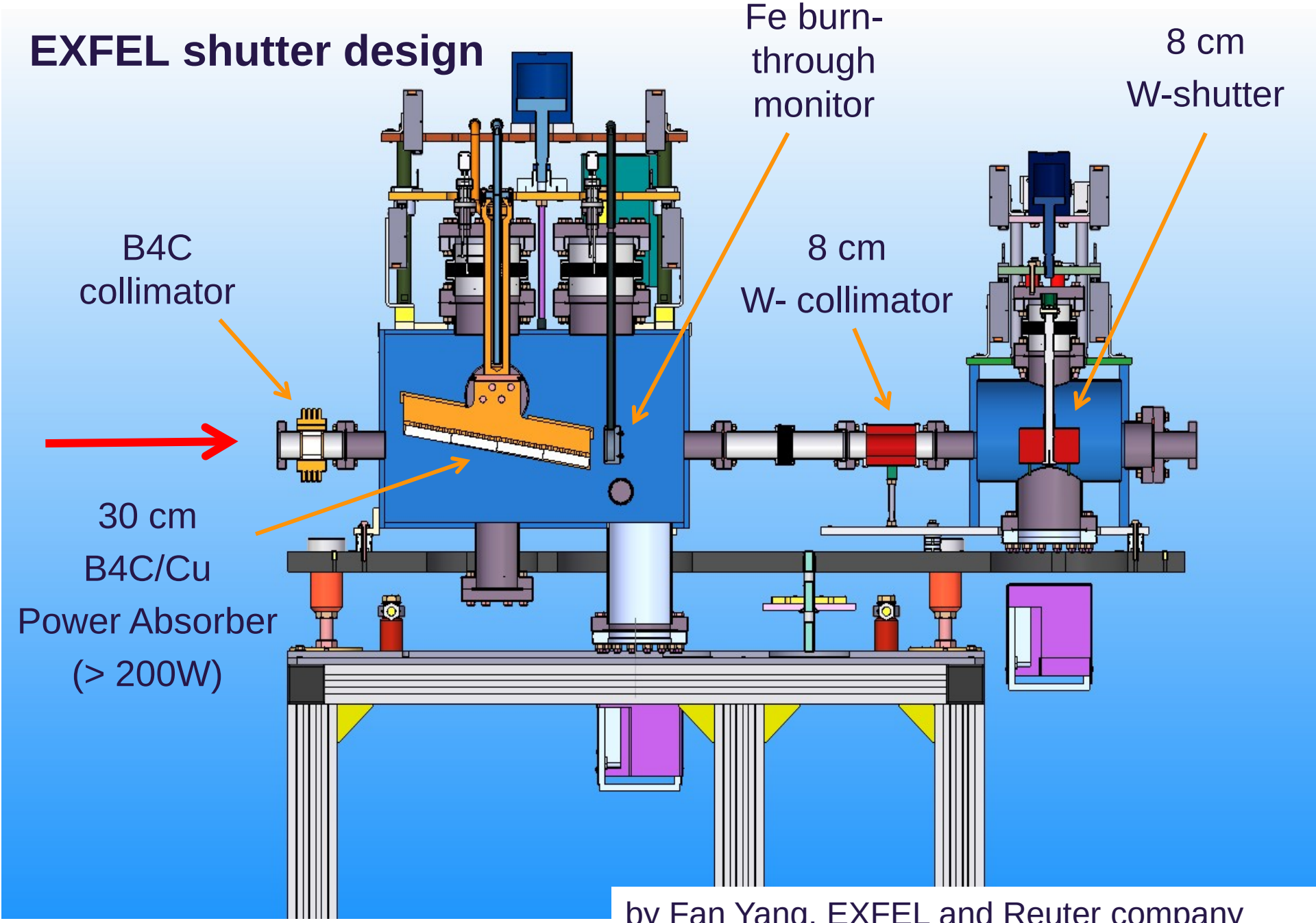


European XFEL

X-ray laser facilities beam safety considerations

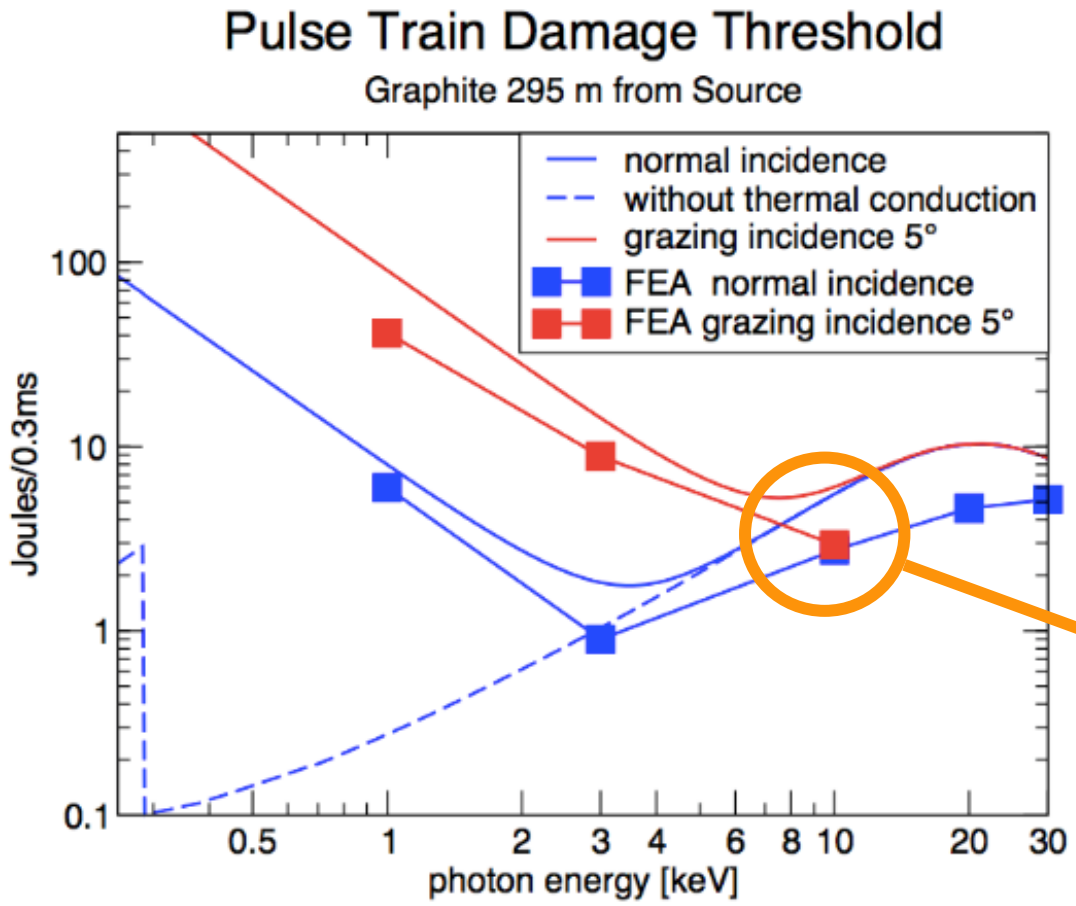
1. **X-ray laser beams can drill through any (solid) material**
2. **There is no theoretical upper power level**
3. **Optimize devices to single shot and pulse train requirements** *(as much as reasonably achievable)*
4. **Failure behavior should be part of device design** *(and should not compromise radiation safety!)*
5. **Limit beam on devices to safe operational limits:** *Safety limits science!*
6. **Tests with beam will be required** (to verify safety assumptions and extend operational limits)

EXFEL shutter design



by Fan Yang, EXFEL and Reuter company

Damage on shutters?



Limit:

2 J / pulse train

2 J / 2 mJ = 1000 pulses/train (facility limit: 2700)

Beam Modes

	≤ 0.1 nC	≤ 0.25 nC	≤ 1nC	> 1nC
Mode 1	1	1	1	1
Mode 2	600	200	30	1
Mode 3	2700	1350	200	10
Mode 4	2700	2700	< 2700	< 2700

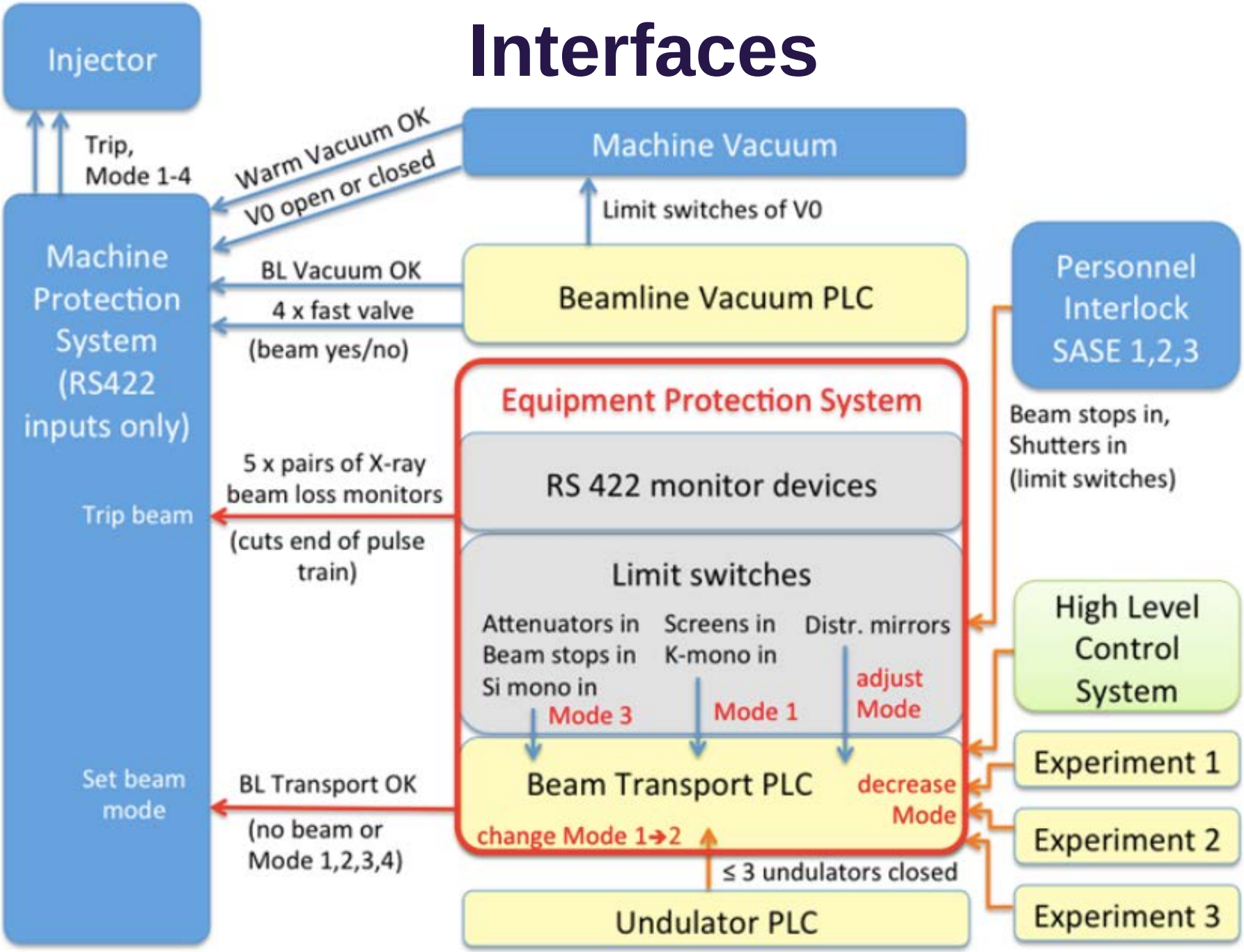
E-machine: screens, orbit unstable (?), Photons: screens

Feedbacks running, MPS not, preferred commissioning mode

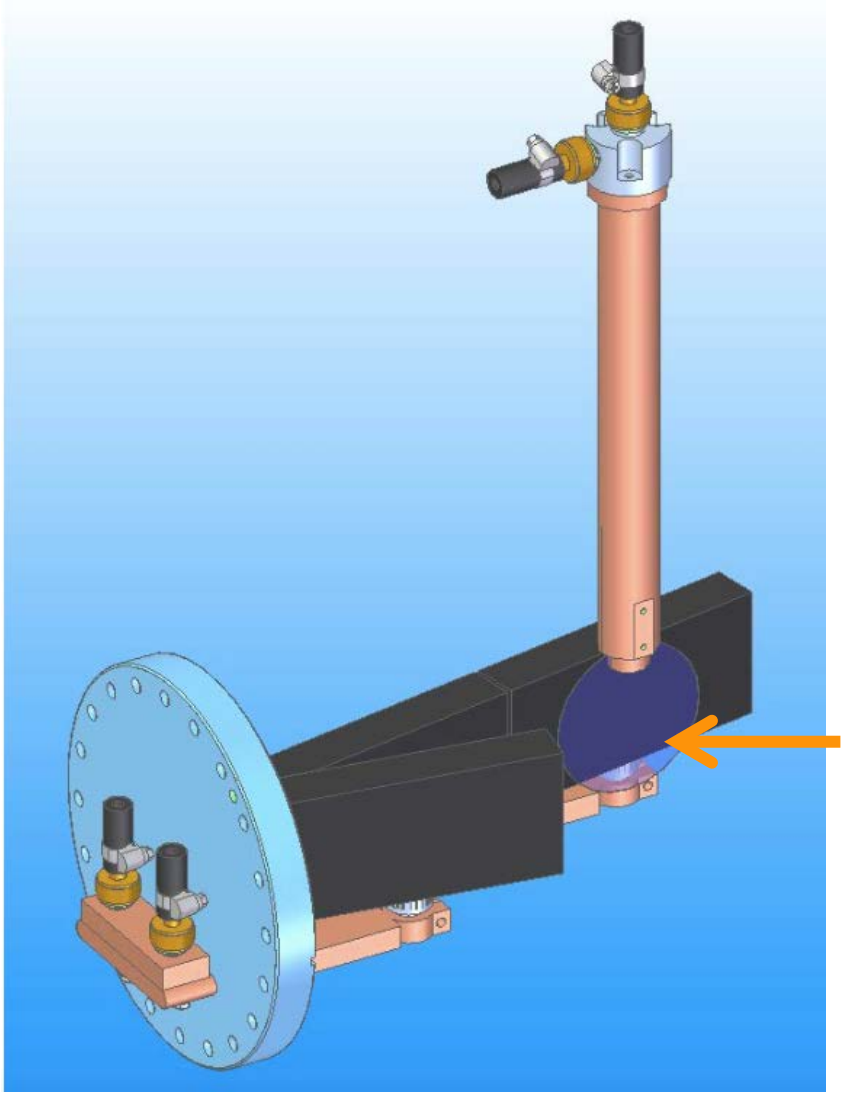
Photon systems: B4C absorbers stable

Full beam

Interfaces


Injector
Trip,
Mode 1-4
Machine Protection System (RS422 inputs only)
Warm Vacuum OK
V0 open or closed
Machine Vacuum
Limit switches of V0
BL Vacuum OK
4 x fast valve
(beam yes/no)
Beamline Vacuum PLC
Personnel Interlock SASE 1,2,3
Beam stops in,
Shutters in
(limit switches)
Equipment Protection System
5 x pairs of X-ray beam loss monitors
Trip beam
(cuts end of pulse train)
RS 422 monitor devices
Limit switches
Attenuators in
Beam stops in
Si mono in
Mode 3
Screens in
K-mono in
Mode 1
Distr. mirrors
adjust Mode
High Level Control System
Set beam mode
BL Transport OK
(no beam or Mode 1,2,3,4)
Beam Transport PLC
decrease Mode
change Mode 1→2
Experiment 1
Experiment 2
Experiment 3
≤ 3 undulators closed
Undulator PLC

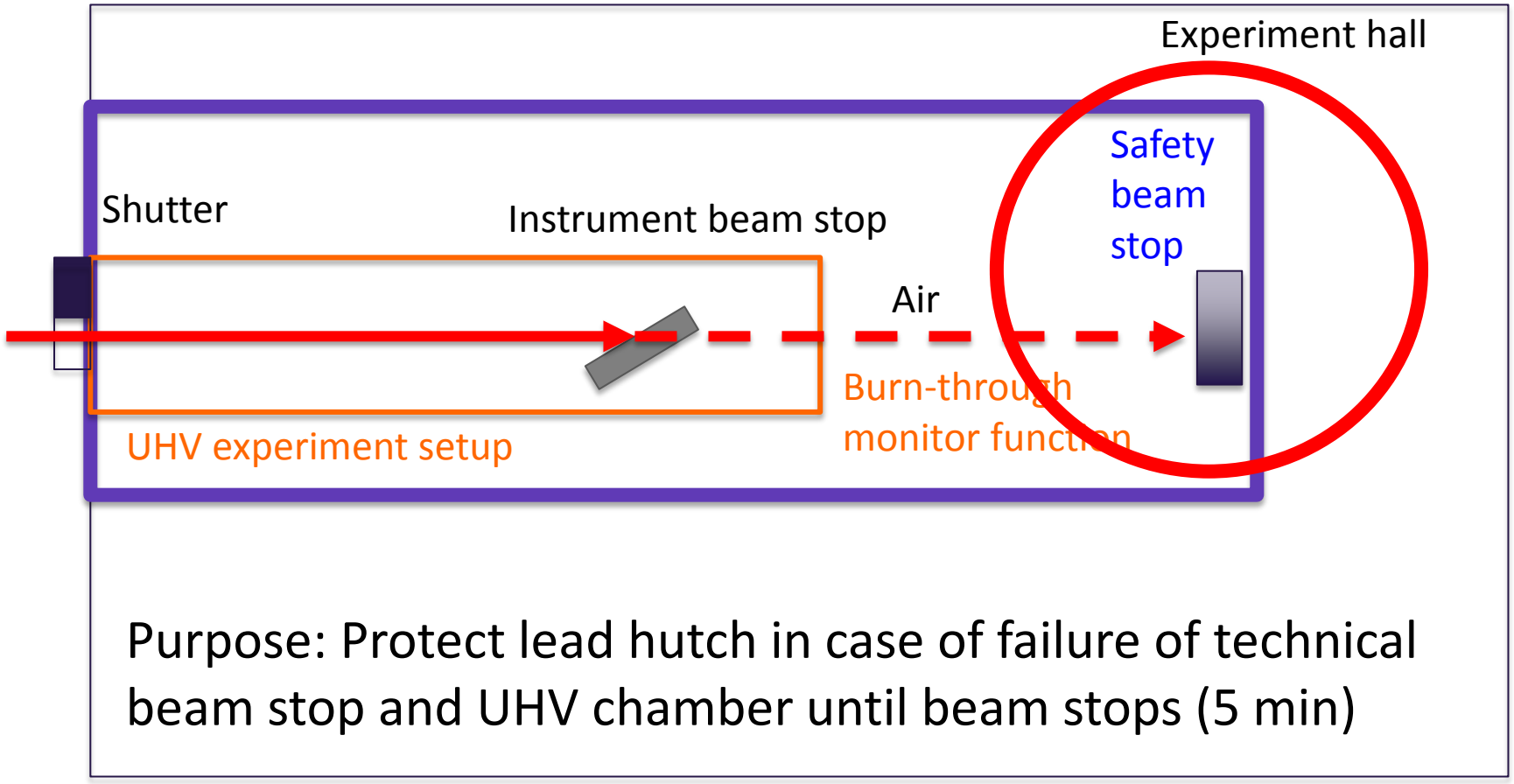
Can the full beam be stopped? Beam stop SPB instrument



10 cm diameter CVD diamond with 2° grazing incidence (3.5 mm aperture)

Can sustain full beam load in TDR operation envelope of SPB/SFX instrument

The safety beam stop concept



Purpose: Protect lead hutch in case of failure of technical beam stop and UHV chamber until beam stops (5 min)

Drilling a cone through metal plate with fixed aspect ratio

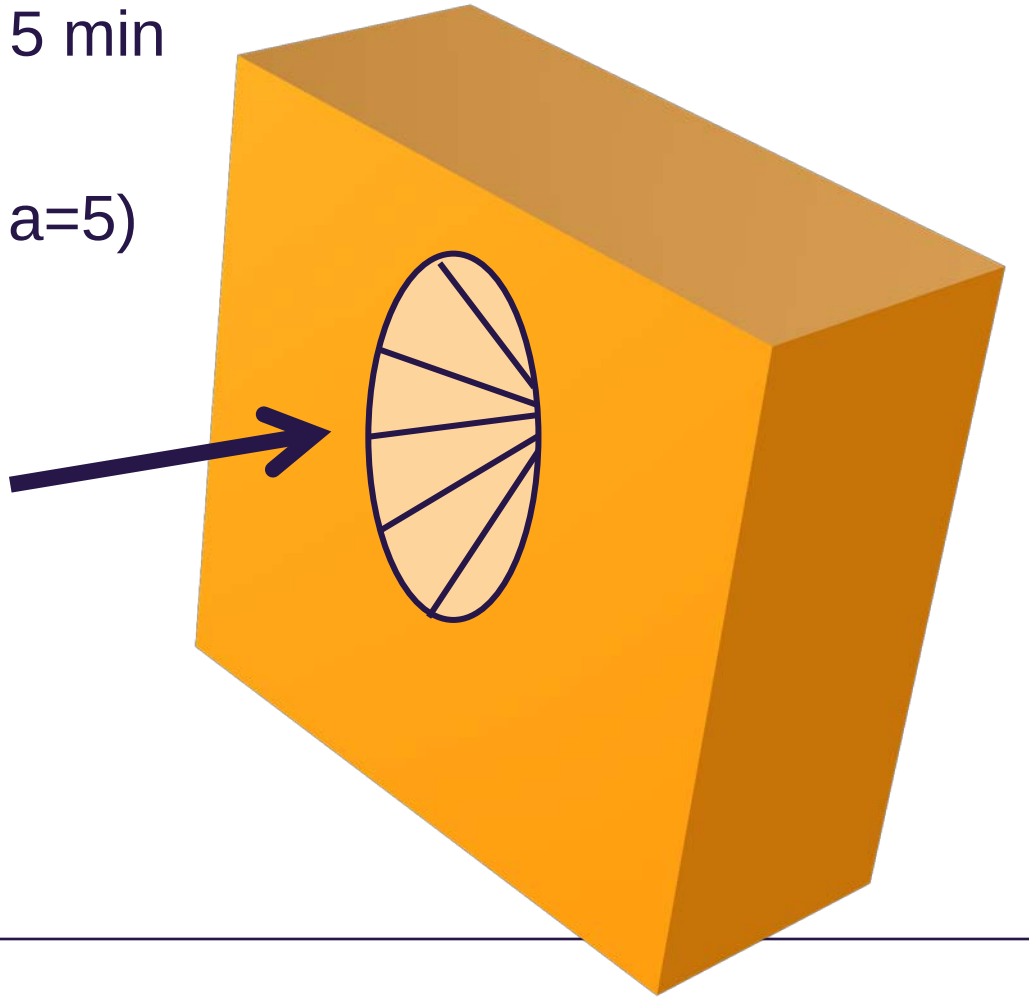
Assumption: Energy evaporates material

Requirement: Should last > 5 min

Cone: Volume = 1/3 π r^2 h

Aspect ratio : h = a 2r (e.g. a=5)

h ≅ $Vol^{-1/3}$



Assumed maximum beam load condition

Upper boundary to M. Yurkov calculations
(1.5 x SASE saturation for 1 nC):

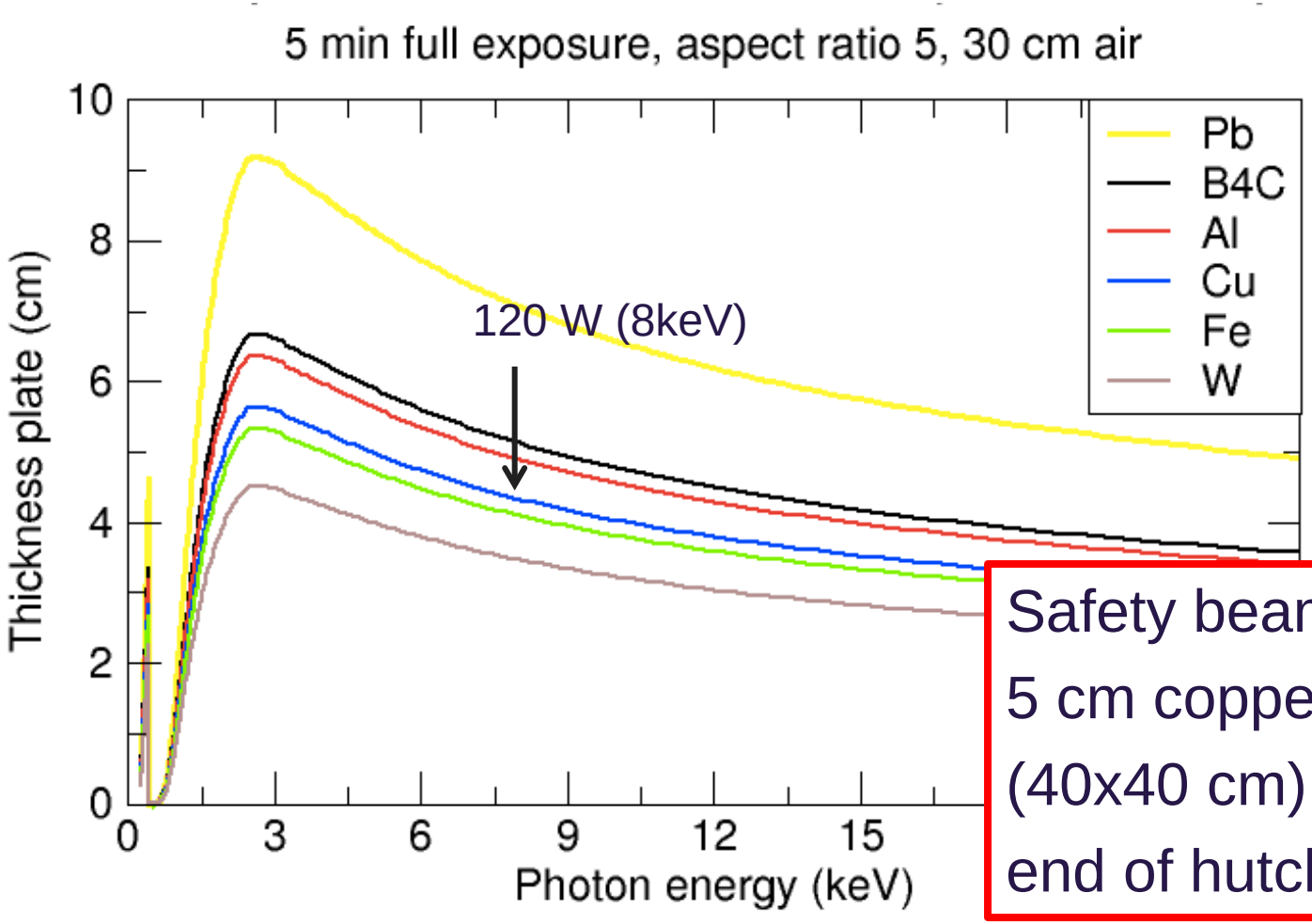
$$E_{pulse} = \frac{36\ mJ}{E_{photon}[keV]}$$

E_{photon}	< 3keV	3 keV	5 keV	8 keV	12 keV	16 keV	24 keV
E_{pulse}	≤ 15 mJ	12 mJ	7 mJ	4.5 mJ	3 mJ	2 mJ	1.5 mJ

E_{photon}	< 3keV	3 keV	5 keV	8 keV	12 keV	16 keV	24 keV
$E_{pulsetrain}$	40 J	32 J	19 J	12 J	8 J	6 J	4 J
$P_{average}$	400W	320W	190W	120W	80W	60W	40W

2700 pulses/train

Required thickness of safety beam stop



Safety beam stop:
5 cm copper plate (40x40 cm) at the end of hutch

Other aspect ratios

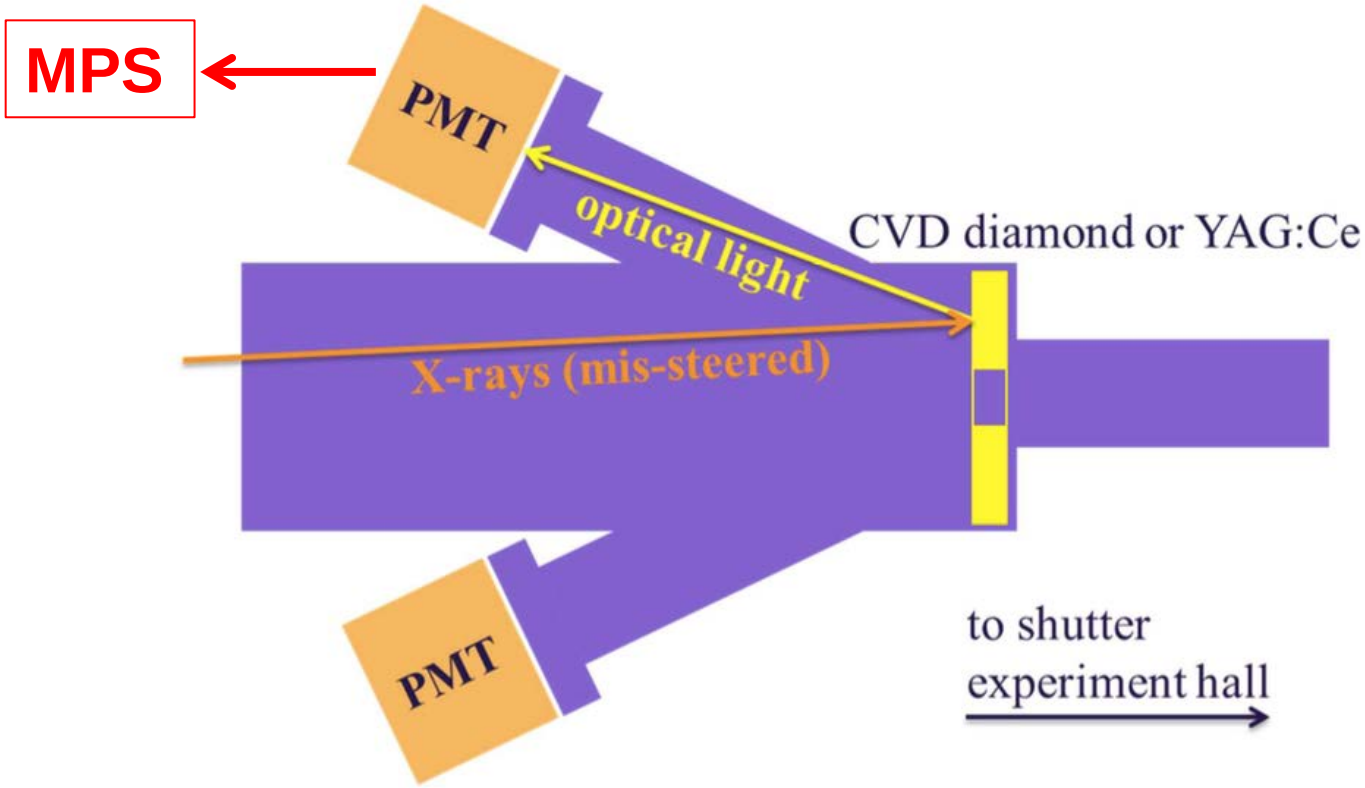
10: 3 min,

50: 1 min,

100: 40 sec (assuming full efficiency)

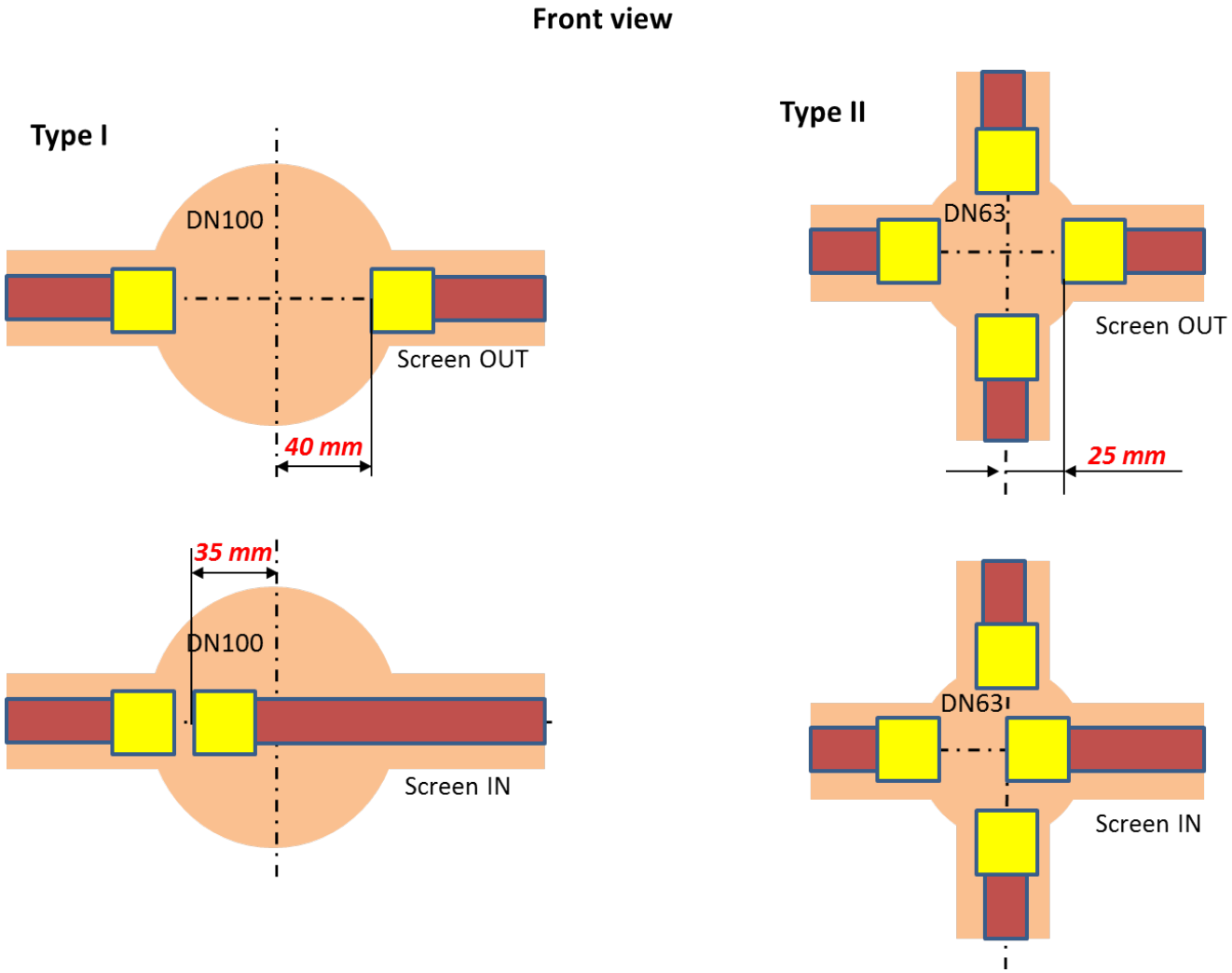
Fast shutdown of beam: The Photon Beam Loss Monitor concept

Connects directly to E-machine MPS, shuts down beam after 30-50 pulses



by Natalia Gerasimova, EXFEL

PBLM after every beam steering element



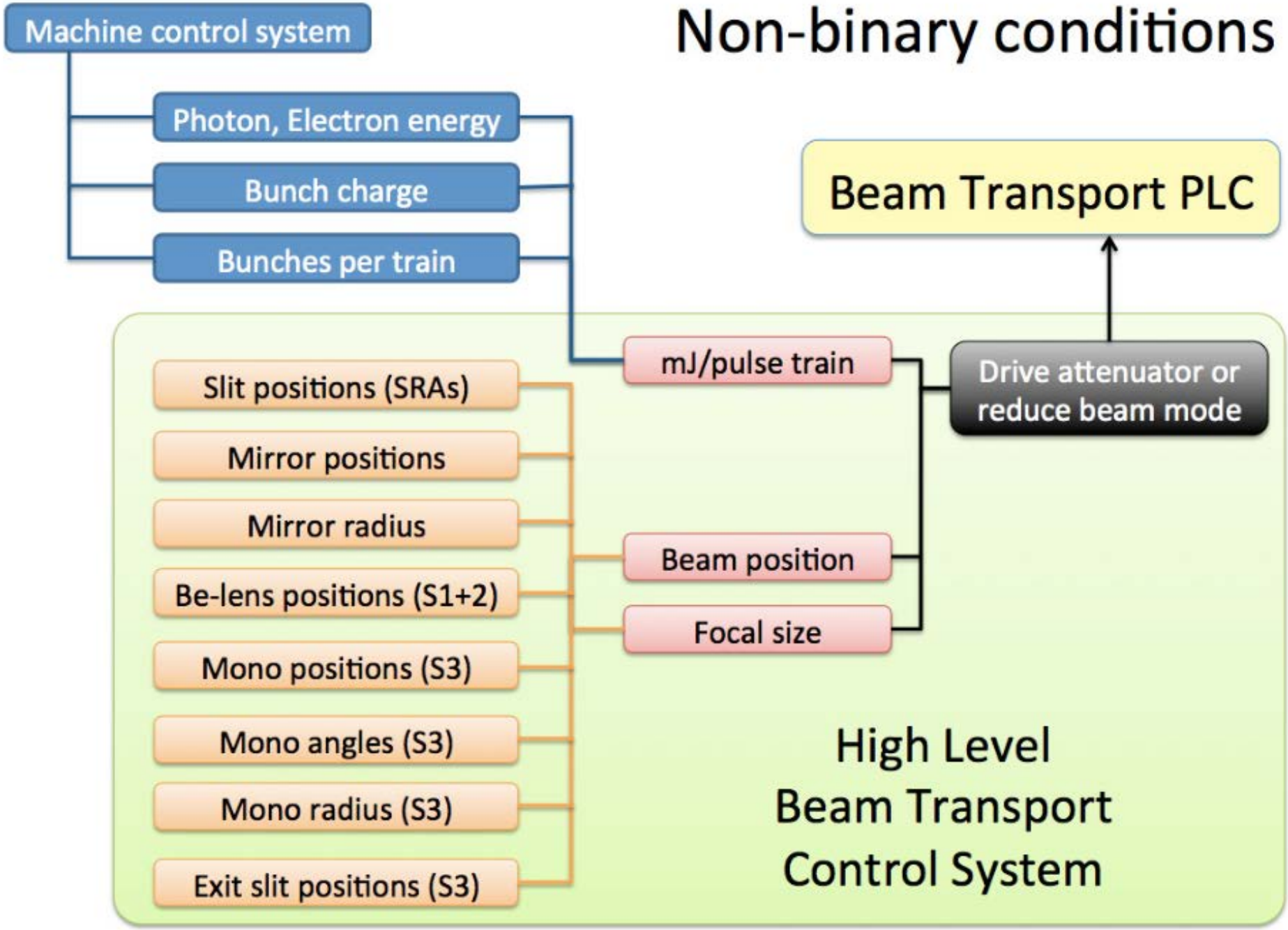
by Natalia Gerasimova, EXFEL

European XFEL

Summary of beam containment concepts

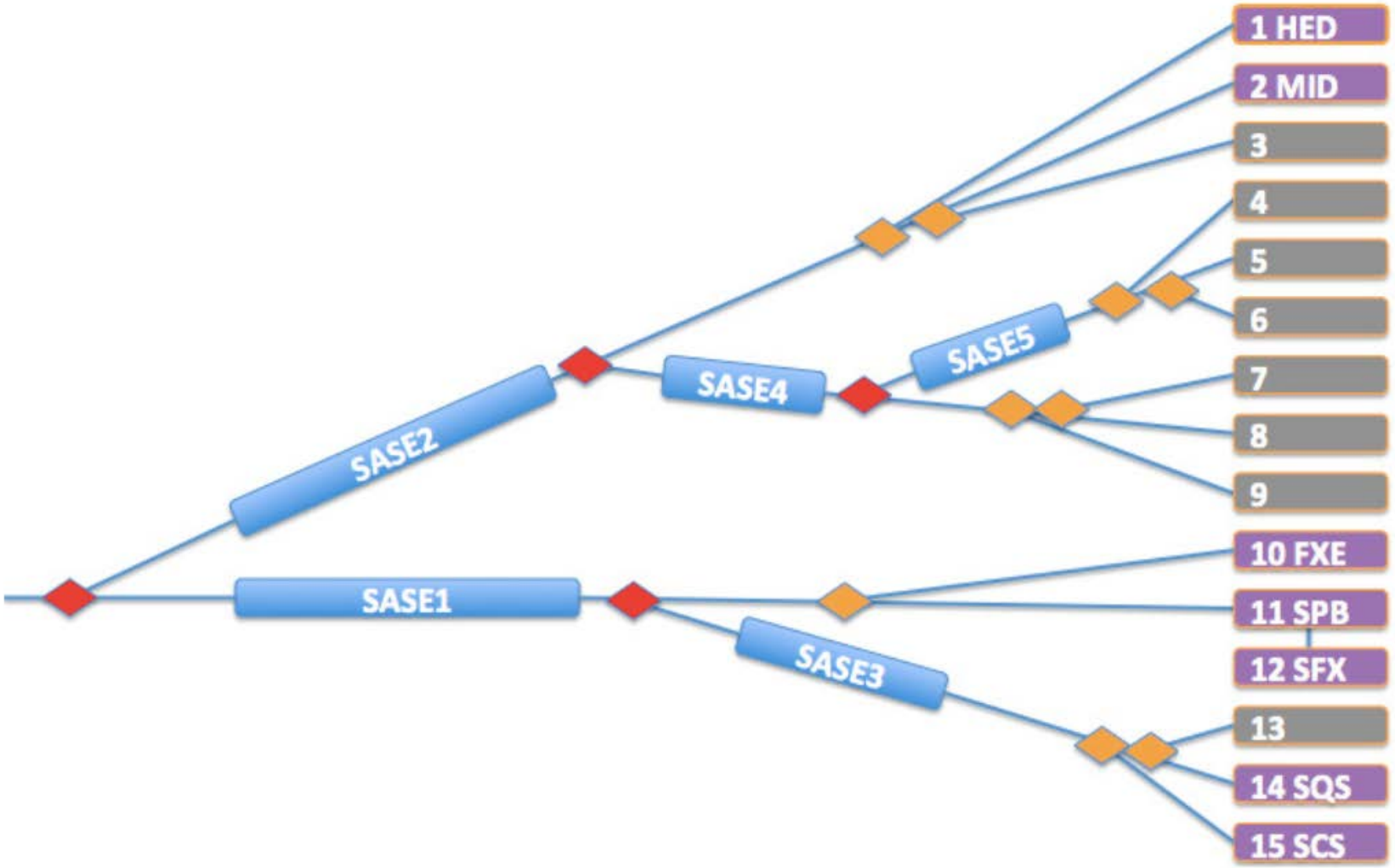
- Radiation safety concept is independent of specific instrument configuration (focusing, beam stop).
- Integrity of (accelerator) vacuum will be destroyed before radiation shielding will be exposed to EXFEL beam
- Beam modes can reduce beam power via MPS, when certain elements are inserted (screens, shutters).
- Fast shut-off possible through photon beam loss monitors (photomultiplyers) via MPS
- At the end of each instrument is a 5 cm thick copper plate (or >80 cm concrete)
- Experiments to test assumptions of beam containment must be made in early operation phase

Non-binary conditions



European XFEL

Photon beam distriubtion

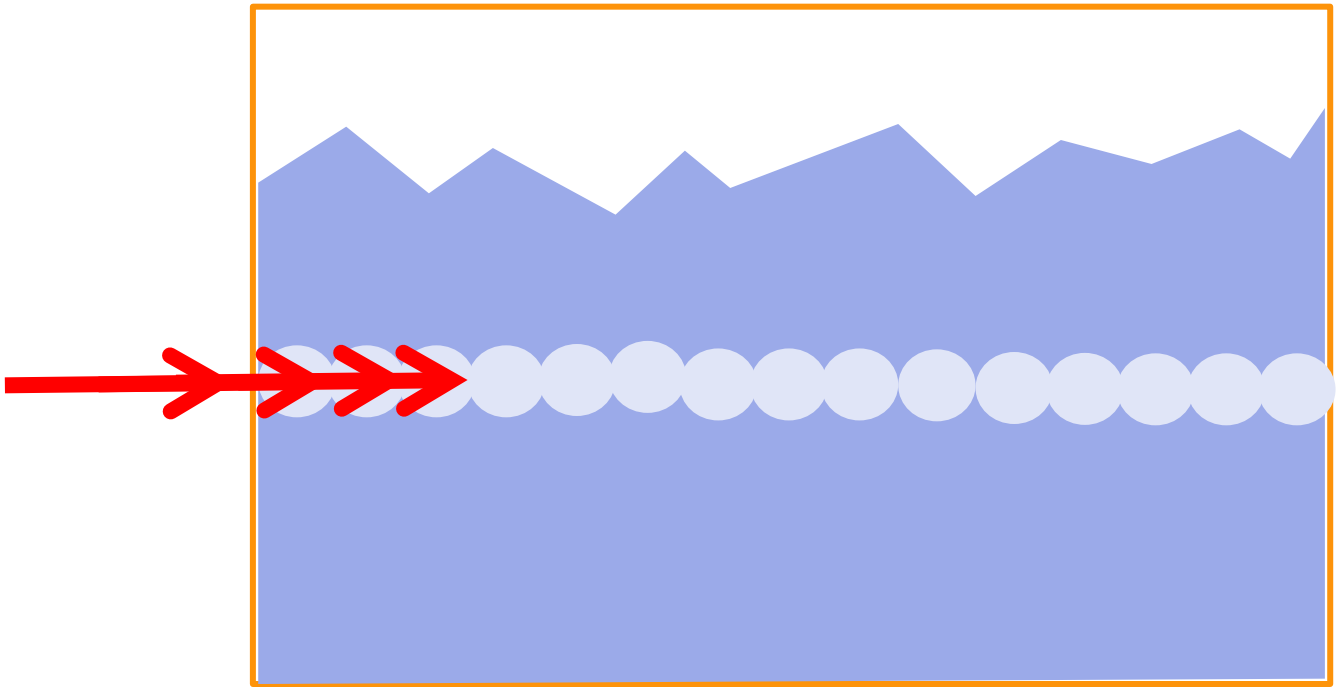


LCLS I solutionCutting with optical lasers

Will not work for high repetition rate due to ‘bubble-train’ formation

Beam 100 Hz

Bubble train through water (?)



Absorption length water: 0.9 mm at 8 keV, 60 x 0.9 = 54 mm

European XFEL

Enthalpy of vaporisation of X-ray beamstops

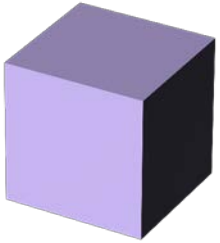
	B4C	Al	Fe	Cu	Pb	W
kJ/mol	560	293	347	300	178	800
molar volume cm^3/mol	22.01	10	7.09	7.11	18.26	9.74
kJ/cm^3	25.44	29.3	49.84	42.19	9.74	82.13
eV/atom	5.80	3.03	3.60	3.11	1.84	8.29

SASE3 beam power

SASE3: 270W X-ray beam power over 5 min

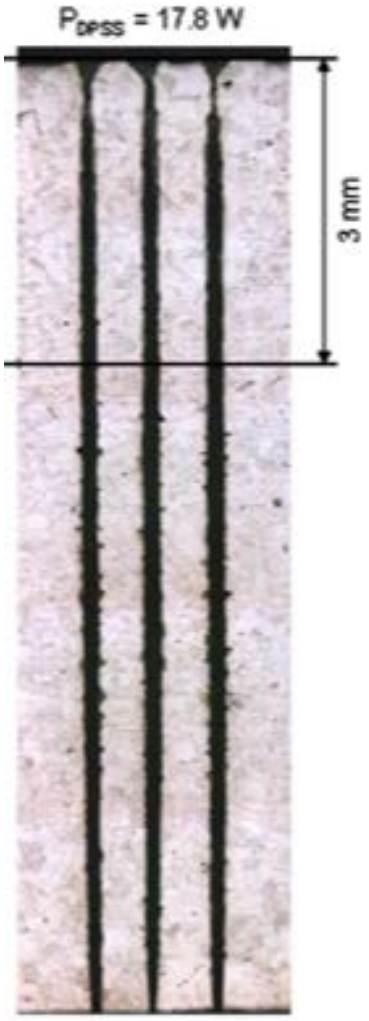
270J/s * 300 s = 81.000 J (=19.4 kcal)

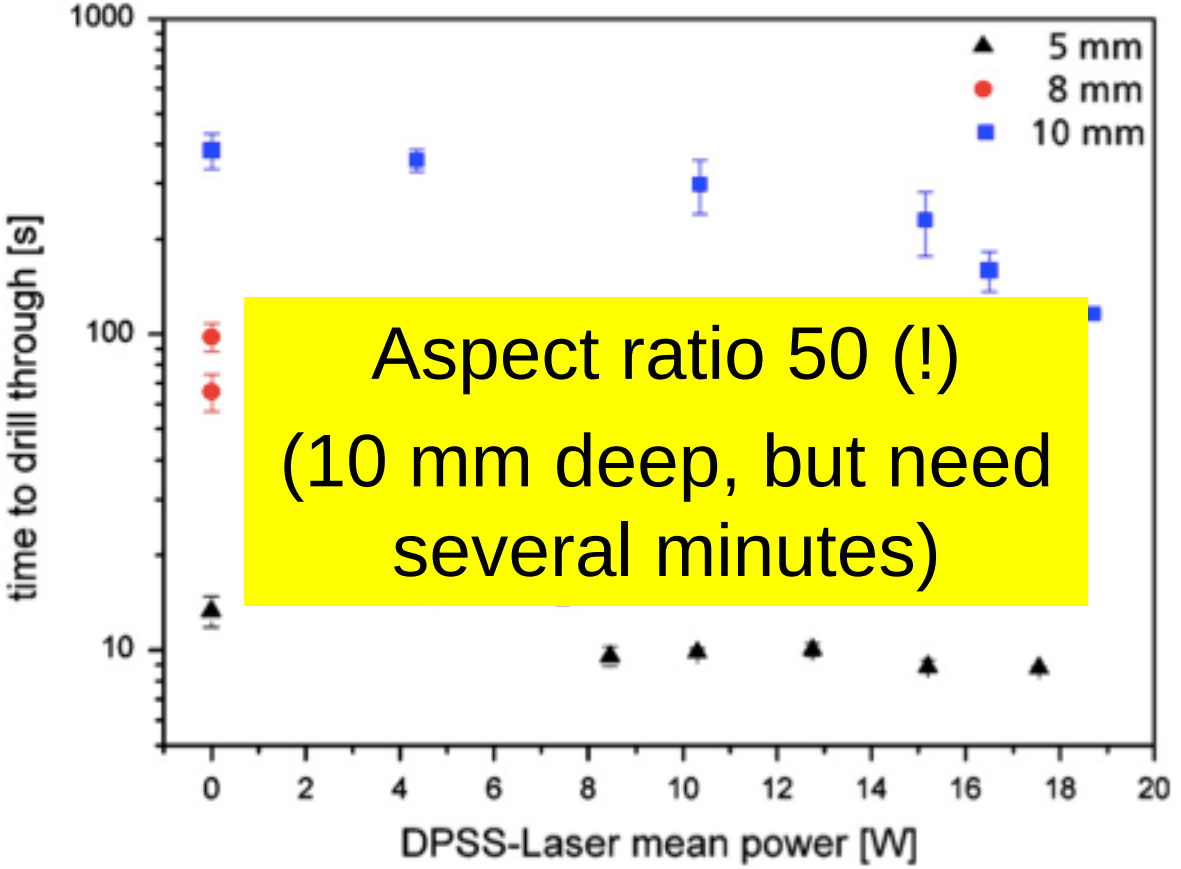
Eat Butterkeks: 21.6 kcal



Evaporate 1 cm^3 of Tungsten: 19.6 kcal

Drilling with optical lasers





Aspect ratio 50 (!)

(10 mm deep, but need several minutes)

Two Nd:YAG lasers: 0.5 ms + 17 ns pules superposed

M. Brajdic et al. Optics and Lasers in Enigneering 46 (2008) 648-655

Cut through 40 mm steel plate

Aspect ratio 5
40 mm deep
but 1600W!

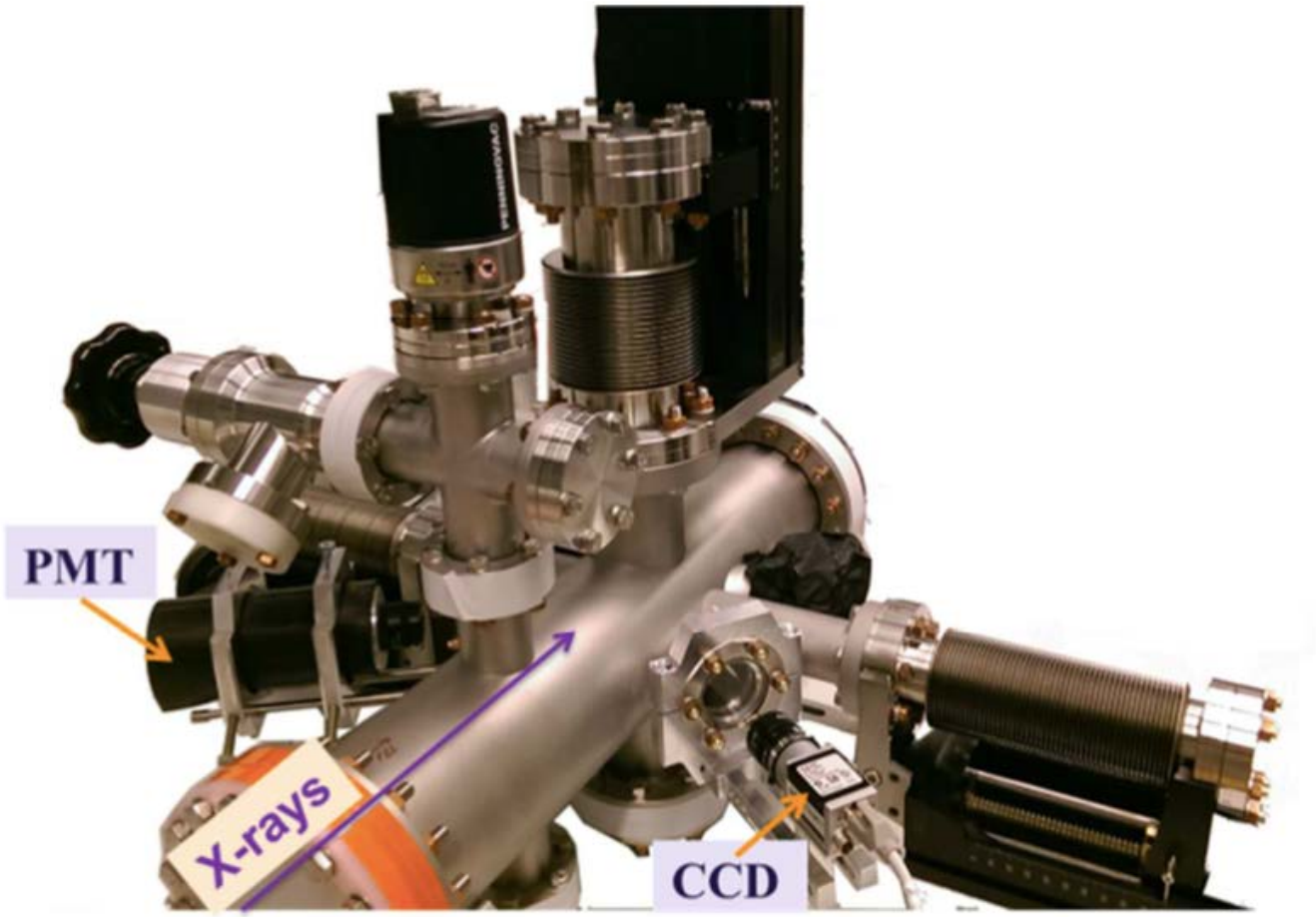
Figure 3. Profile cut and cut surface finish obtained in 40mm-thick, 250 grade mild steel plates with Nd:YAG laser power of 1.6 kW.

Click here to enlarge image

From: www.industrial-lasers.com

European XFEL

PBLM prototype



by Natalia Gerasimova, EXFEL

European XFEL

Shutter for optics hutches