Experience and future plans for running concurrently multiple experiments with Free Electron Lasers

For Diling Zhu, Aymeric ROBERT

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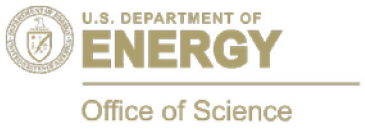
Linac Coherent Light Source



Layout

- How to define the success of an “X-ray” User Facility ?
- What is “Multiplexing”
  - Performing multiple experiments at the same time.
- Multiplexing Concepts:
  - Multiplexing with Electrons : feeding multiple undulators with one linac
  - Multiplexing with Photons : feeding multiple experiments from one undulator
- Current Multiplexing schemes at LCLS
- Future plans with X-ray gratings
- Conclusion

Acknowledgments

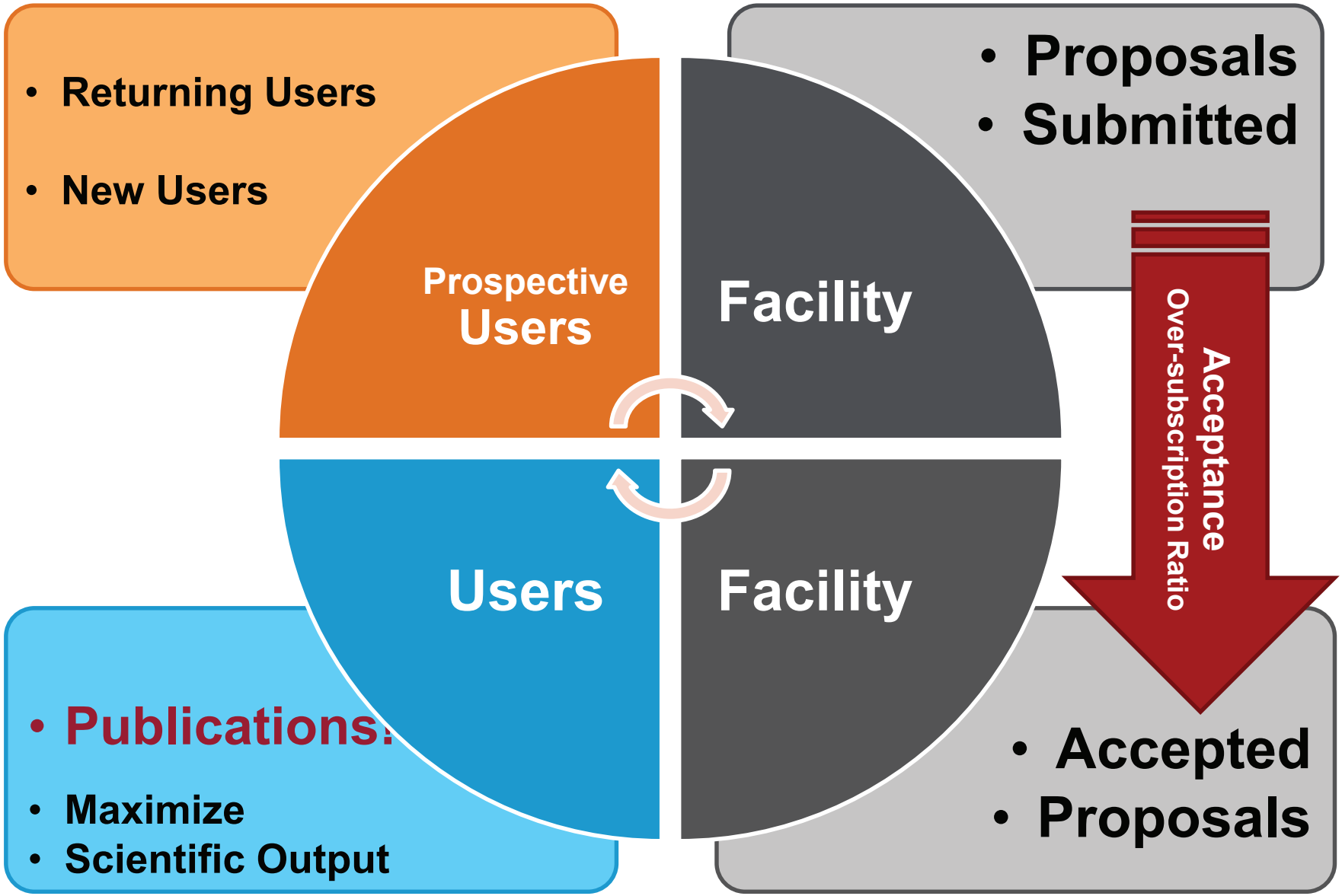
- **Thin Diamonds and Large Offset Monochromators**
  - Y. Feng, D. Zhu and the LCLS HXR Department (LCLS)
  - Y. Shvydko, S. Stoupin, Advanced Photon Source (ANL)
  - S. Terentiev , V. Blank, TISCNM (Russia)

- **CXI Refocusing**
  - S. Boutet and the LCLS FXI Department (LCLS)

- **Hard X-ray Mirrors**
  - D. Cocco, L. Zhang and the LCLS Optics Eng. Team (LCLS)

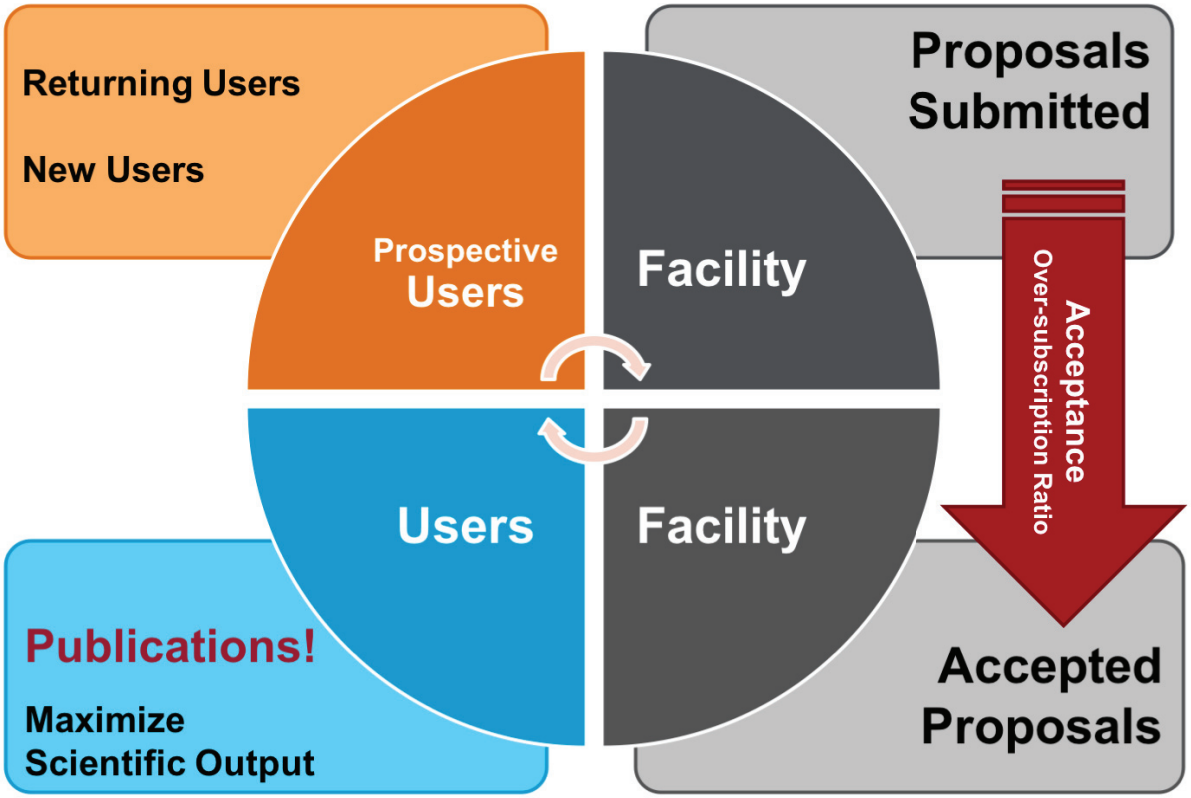
- **Gratings**
  - M. Chollet, B. Arnold, A. Sakdinawat, K. Li, J. Hastings, HXR Department and LCLS Optics Eng. Team (SLAC & LCLS)
  - C. David, Paul Scherrer Institut (Switzerland)

Success of an "X-ray" User Facility



Success of an "X-ray" User Facility : Equations/Graphs

SLAC



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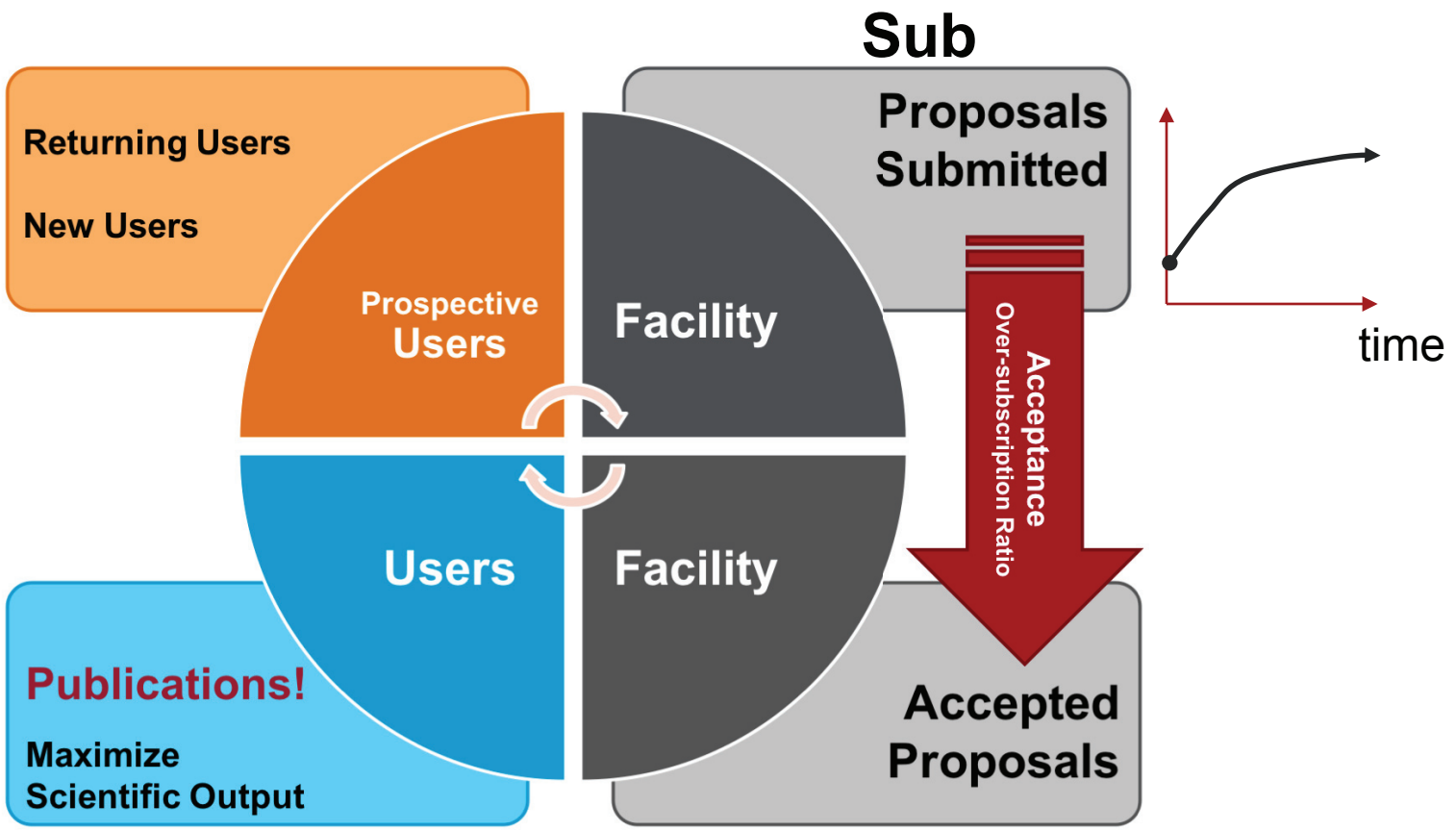

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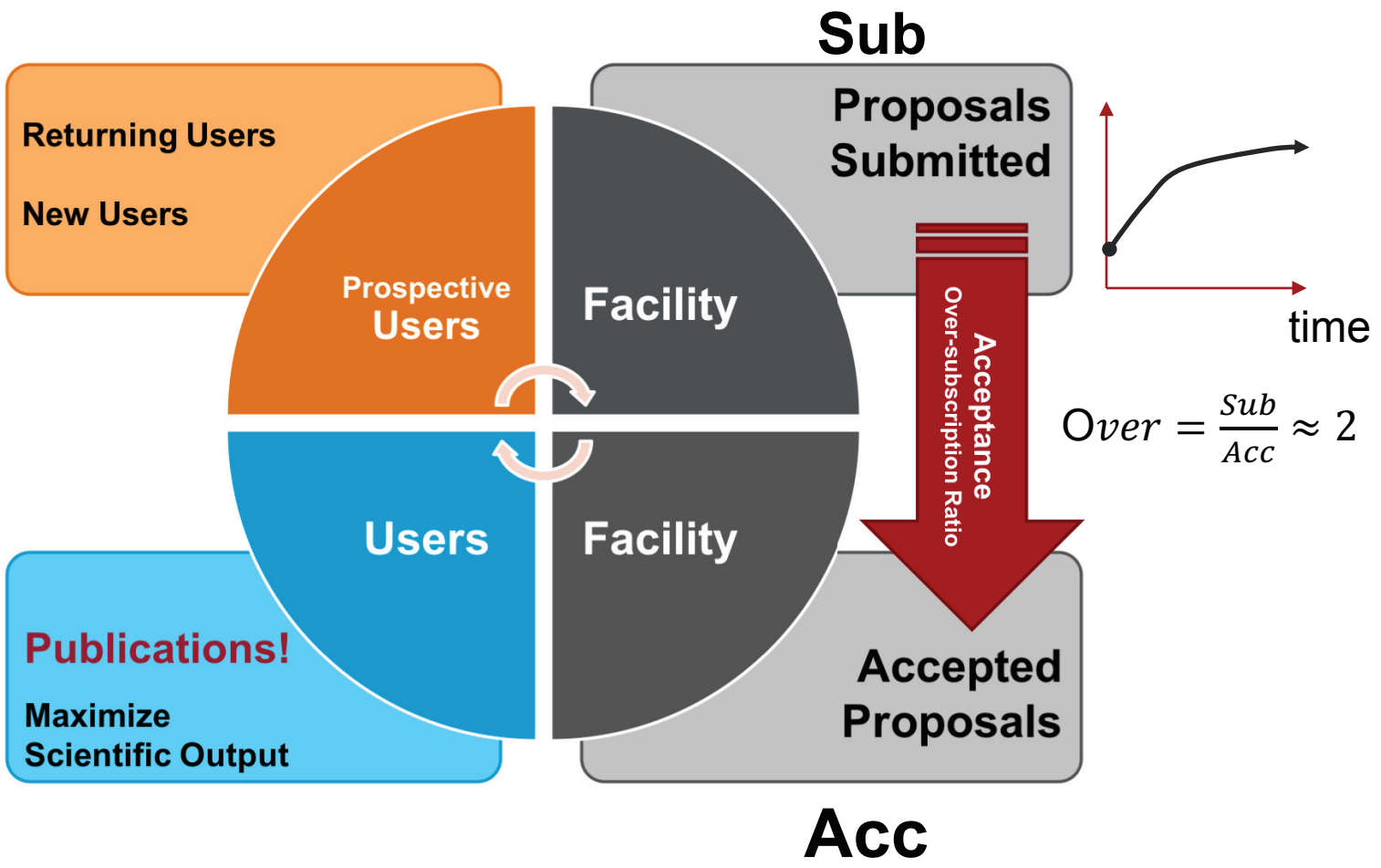

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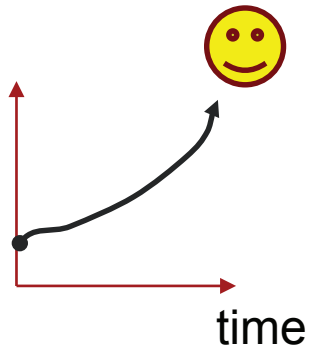
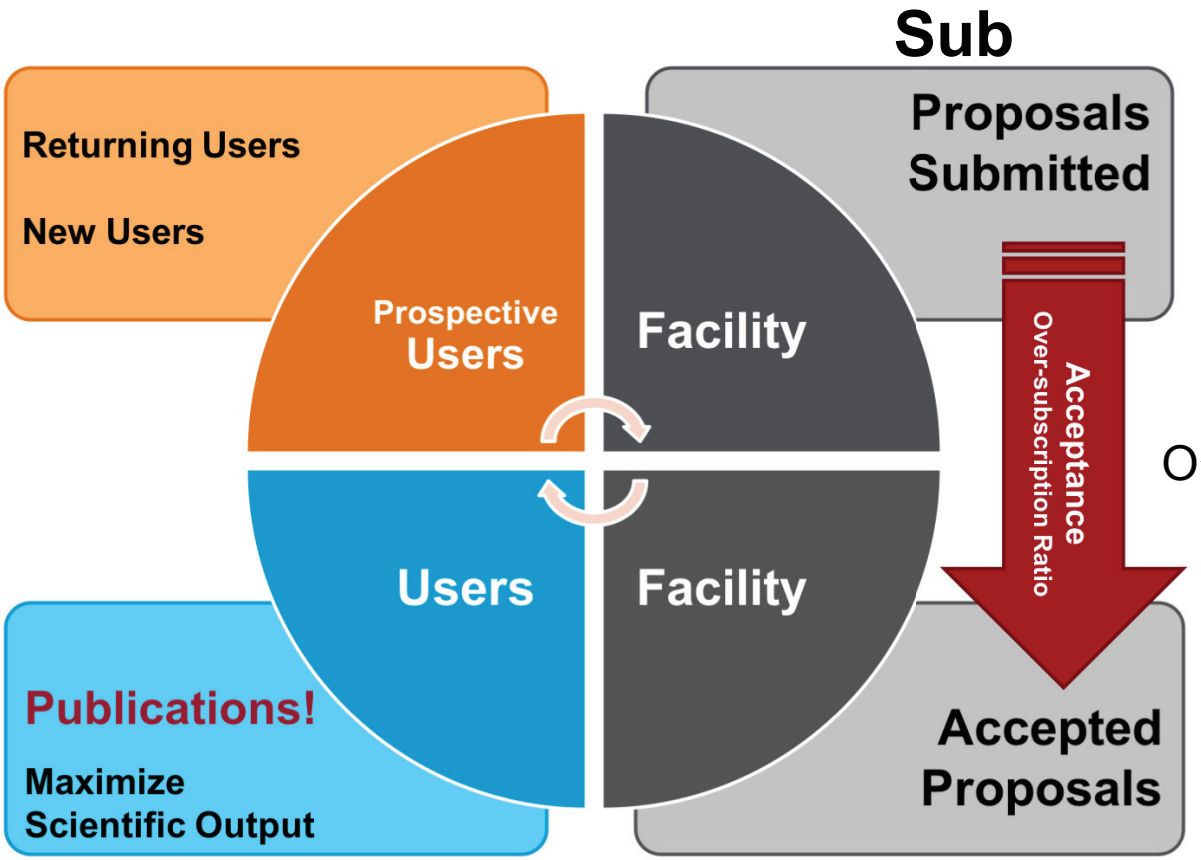
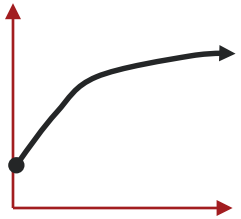






$$Over = \frac{Sub}{Acc} \approx 2$$

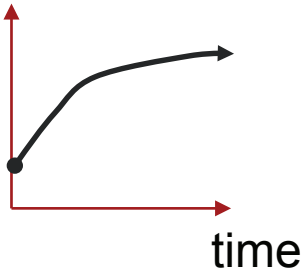
$N_p \geq Acc$

Acc

Success of an "X-ray" User Facility : Equations/Graphs

SLAC

$$\frac{New}{Nu} > 10\%$$



Nu=Rec+New

Sub

Returning Users

New Users

Proposals Submitted

Prospective Users

Facility

Acceptance
Over-subscription Ratio

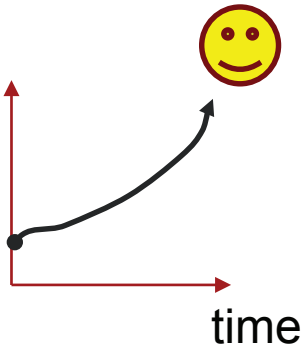
Users

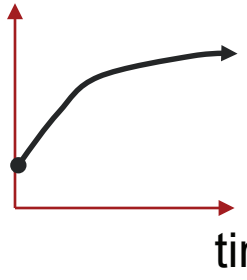
Facility

Publications!

Maximize Scientific Output

Accepted Proposals





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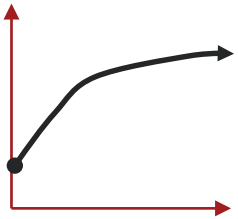

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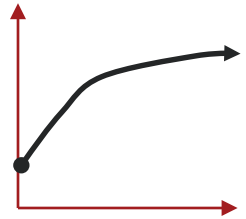

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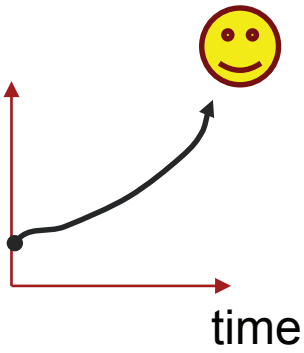


$N_p \geq Acc$

Acc

$\frac{Budget}{N_P} \to 0$

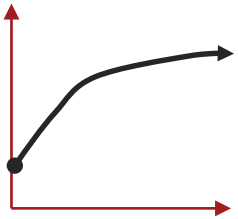
Funding Agency = Budget

$\frac{Budget}{Acc} \to 0$

Success of an "X-ray" User Facility : Equations/Graphs

SLAC

$\frac{New}{Nu} > 10\%$



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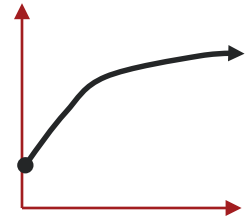

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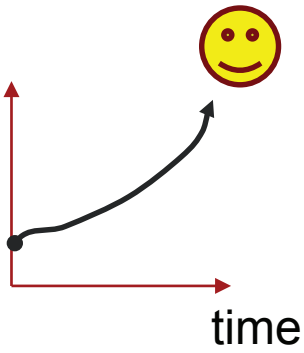

$N_p \geq Acc$

Acc

Multiplexing !

$\frac{Budget}{N_P} \to 0$

Funding Agency = Budget

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Synchrotron Storage Rings vs. FELs

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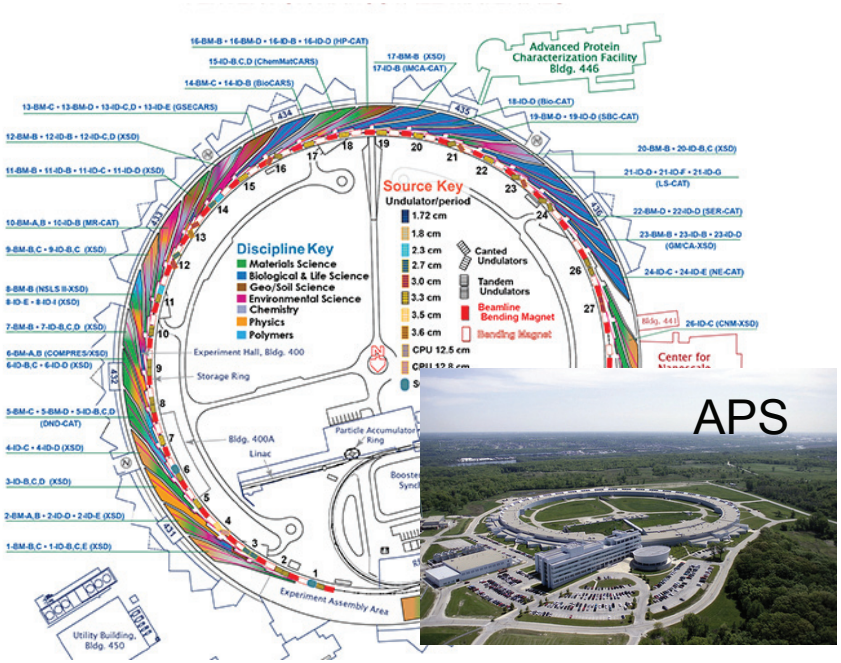
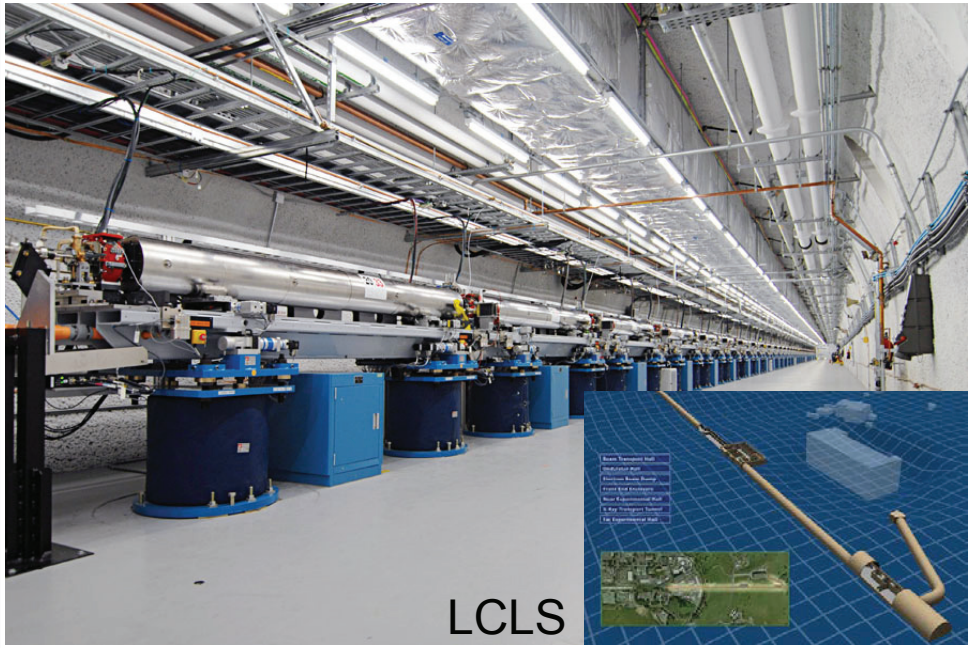
Storage Rings



FELs



Ultimate e-recycling

- Top-up
- MANY IDs & BMs
- Independent operation
- ~ 1 instrument per Undulator

Single-Path Undulator

- Chaotic
- Very limited number of Undulators
- Possibly several instruments per undulator

Multiplexing : more than 1 experiment by sharing same linac

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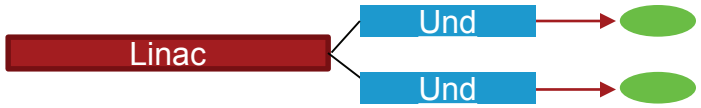
Performing more than 1 experiment by sharing the same linac

- **Sharing the Electrons**
  - Two undulators in parallel
    - e-beam switching with reduced rep-rate in each undulator



Tanaka et al : demonstrated successfully at SACLA with BL3, BL2

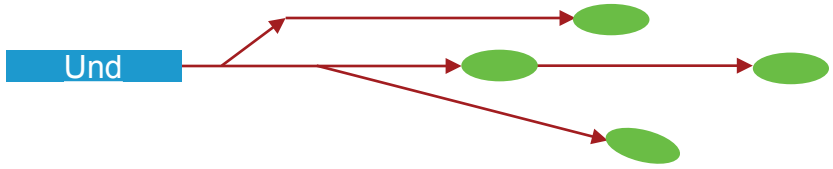
  - Two undulators in tandem
    - e-beam recycling

Decking et al : demonstrated at Eu-XFEL with SASE 1 and 3

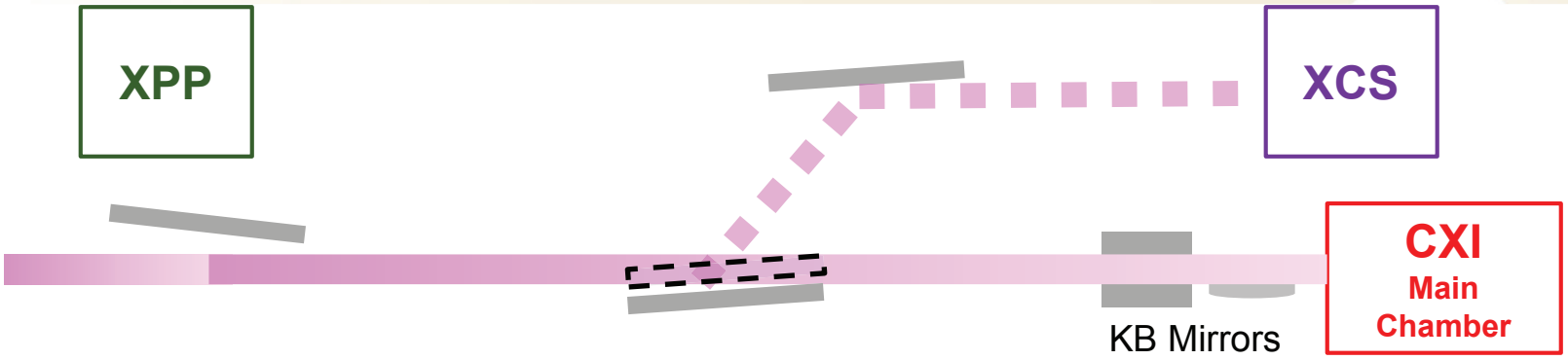
- **Sharing the X-rays**

(i.e. more than 1 experiment at a time from a single undulator)

  - Intermittent splitting & fast switching
  - Recycling the X-rays
  - Splitting
    - Spectral Splitting
    - Spatial Splitting

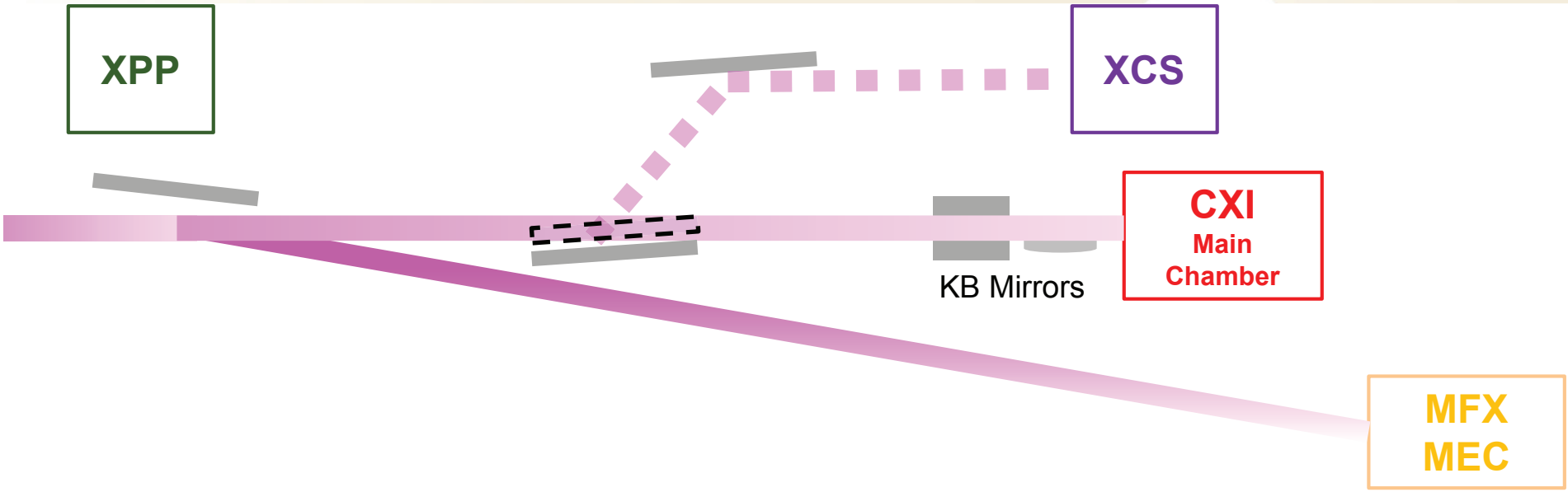


X-ray Multiplexing (1) : Fast Switching



- **Fast Switching : no need for hour-longs downtime**
  - 10 minute switching
  - MFX Single Mirror
  - XCS Periscope : 2 mirrors

X-ray Multiplexing (1) : Fast Switching



- **Fast Switching : no need for hour-longs downtime**
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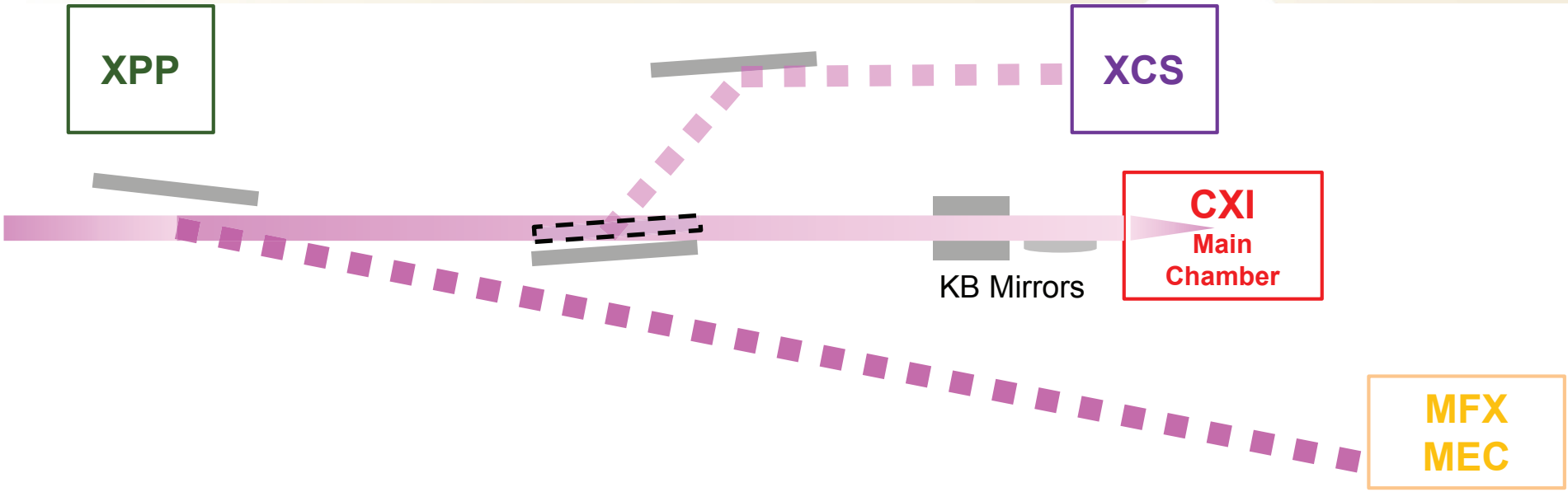
  - XCS Periscope : 2 mirrors

X-ray Multiplexing (1) : Intermittent Switching



- **Intermittent Switching : MEC vs CXI or XCS**
  - MEC operation with long pulse laser
  - 1 shot every several minutes

X-ray Multiplexing (2) : X-ray recycling

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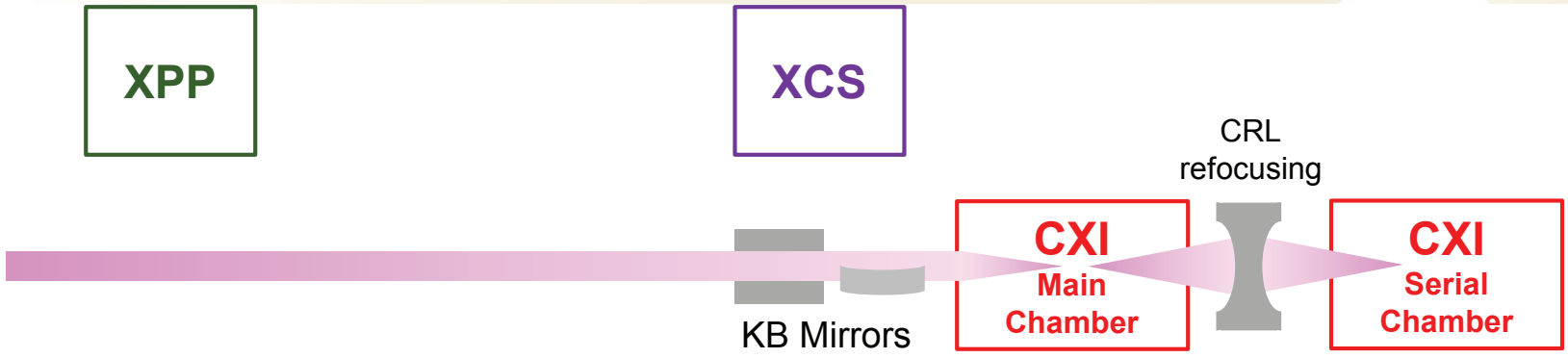
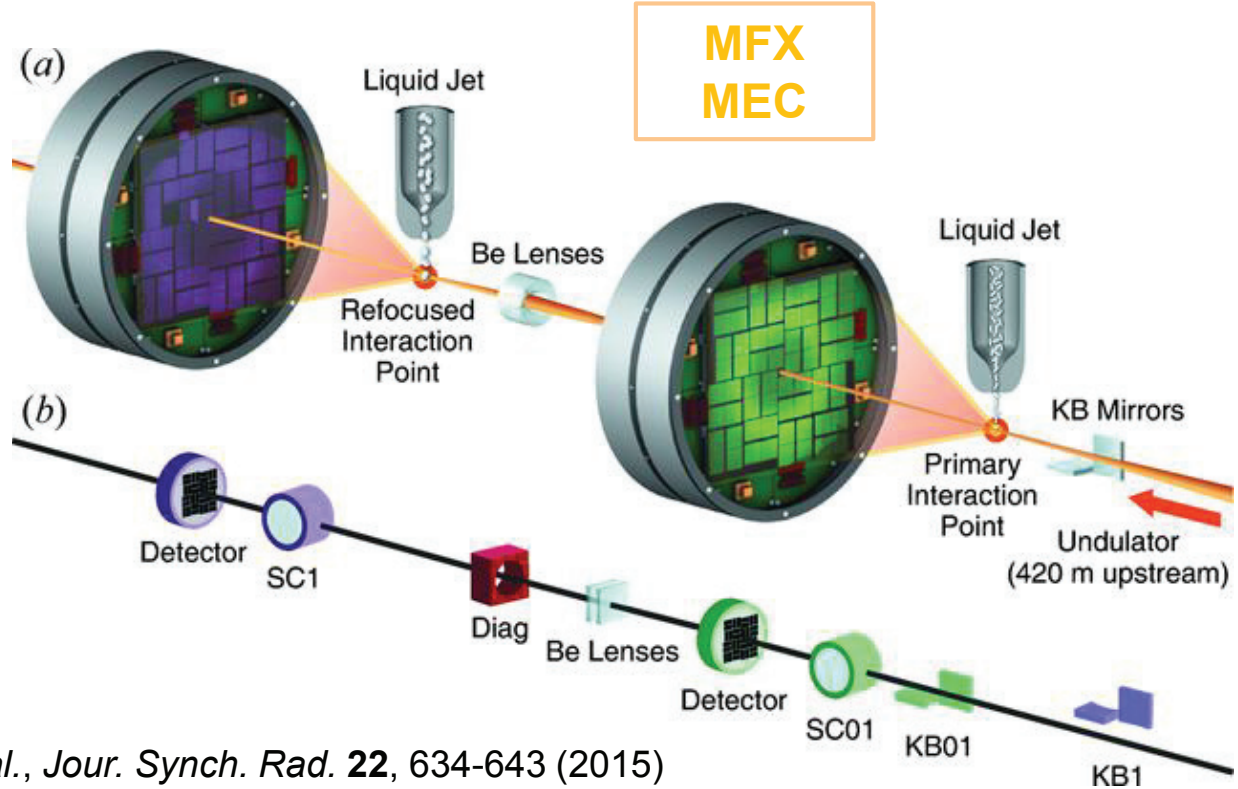


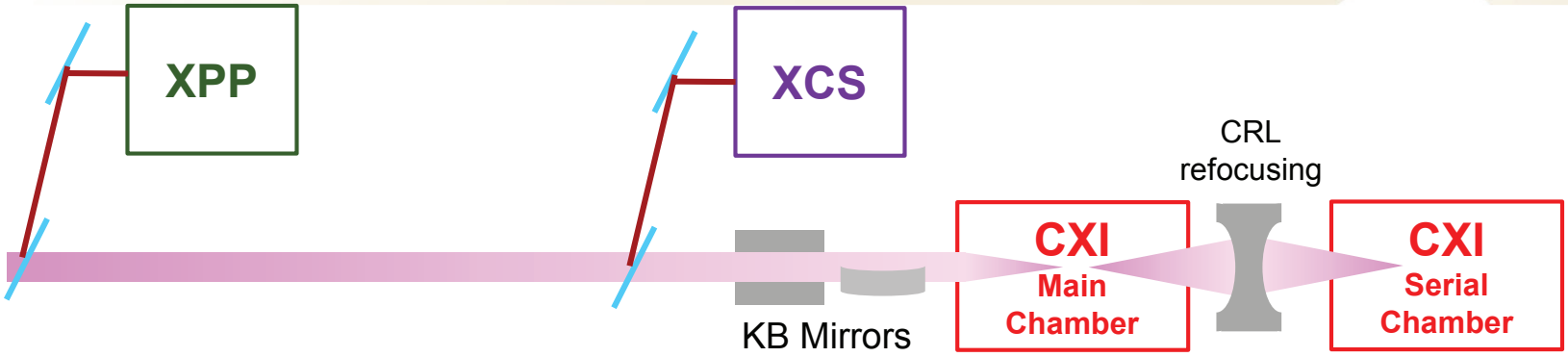
Recycling X-rays

- Reuse the “spent” beam from the upstream experiment into a second independent experiment.
- Structures were obtained from each of the data sets from independent experiments.



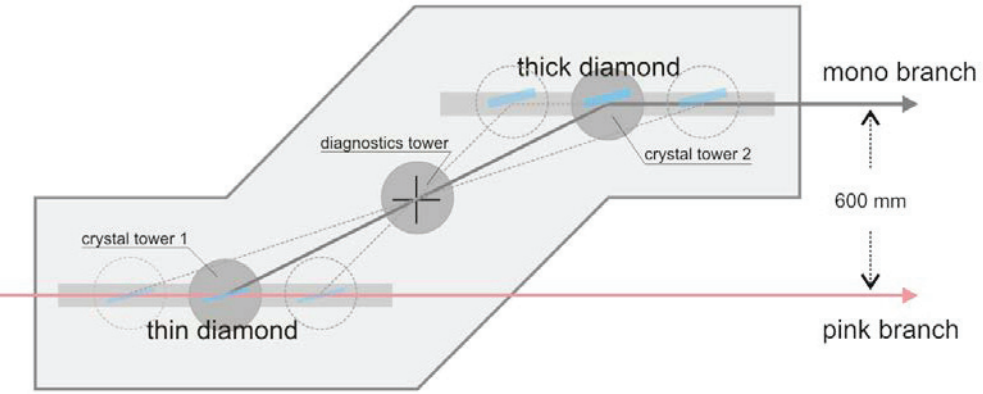
Boutet *et al.*, *Jour. Synch. Rad.* **22**, 634-643 (2015)

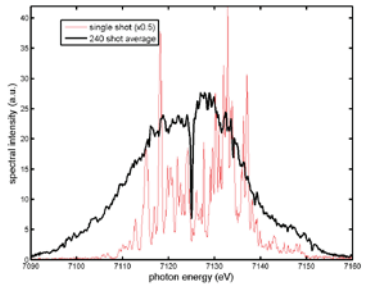
X-ray Multiplexing (3) : Spectral Splitting

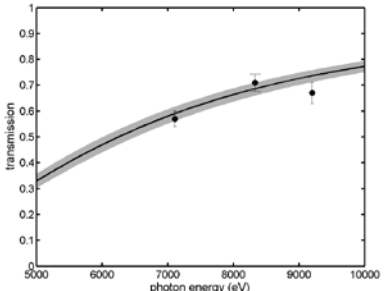


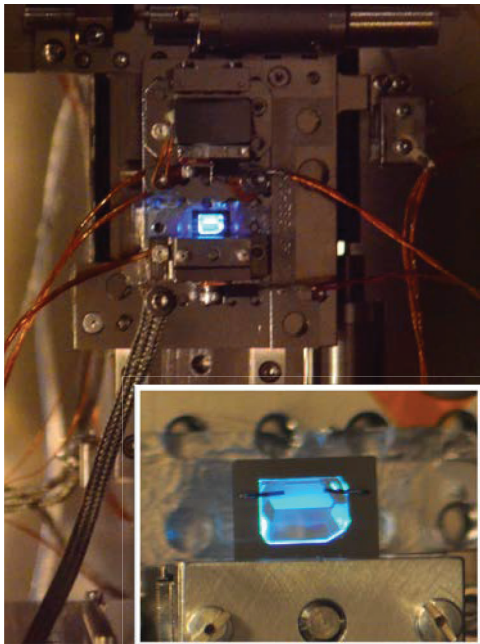
- **Spectral Splitting**
  - Large Offset diamond monochromators

MFX
MEC





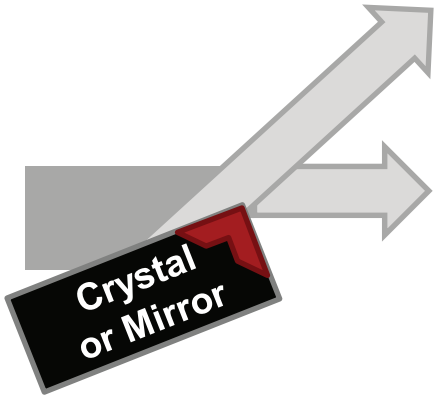


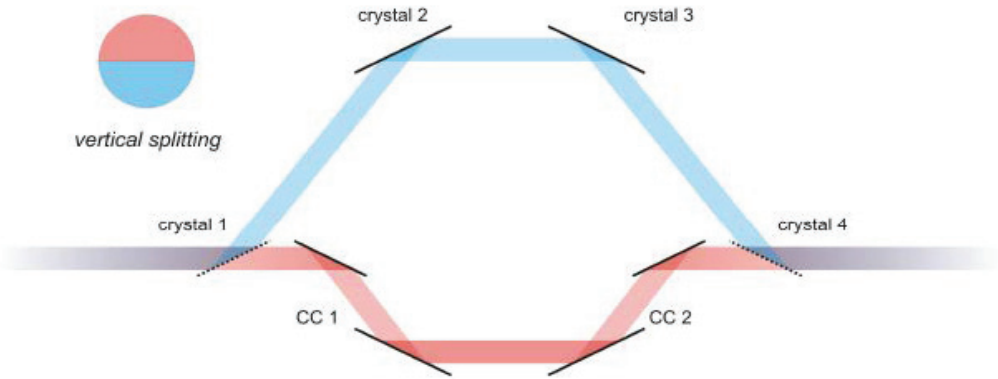


Feng et al., *Proc SPIE* 87780b (2013)
Stoupin et al., *J. Appl. Cryst.* **47**, 1329 (2014)
Zhu et al., *Rev. Sci. Inst.* **85**, 063106(2014)
Feng et al. J. Synch. Rad. **22** 626 (2015)

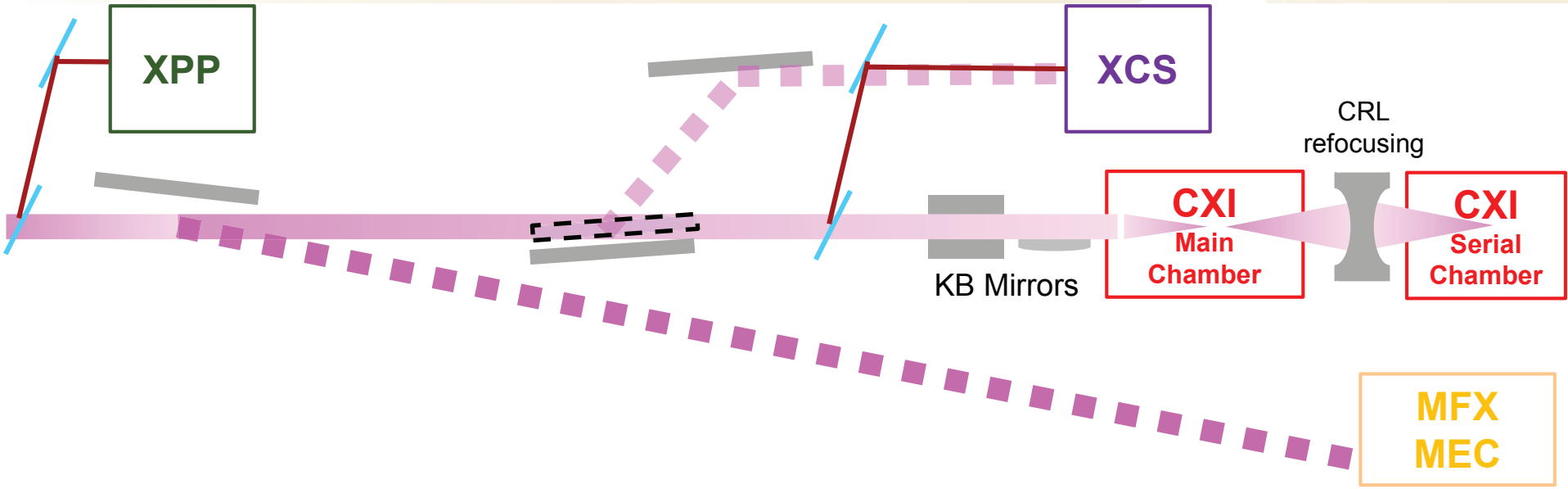
X-ray Multiplexing (4) : Spatial Splitting

- **Not in use currently at LCLS or elsewhere as multiplexing option**
- **First used at FLASH with soft X-ray mirrors**
  - (Mitzner & Zacharias et al.)
- **Concerns about coherent diffraction features from the edge**
- **Has been successfully used recently in X-ray Optics**
  - **Pioneered with hard X-rays and crystals with Split and delay at SACLA**
    - Osaka et al., *Opt. Express.* **21**, 2823 (2013), *Proc SPIE* **921009** (2014)
  - **Also with crystals and Split and delay at LCLS**
    - Zhu & Sun et al., *Proc SPIE* **10237** (2017)





X-ray Multiplexing : All multiplexing options for hard X-rays



- **Ultimately if all experiment agree on a single X-ray energy**
  - **Monochromatic beam at XPP and XCS**
  - **Pink beam at**
    - **Or CXI/XCS tradeoff**
    - **CXI and CXI refocusing**
    - **Intermittent at MEC or MFX**

Current Impact on LCLS Schedule

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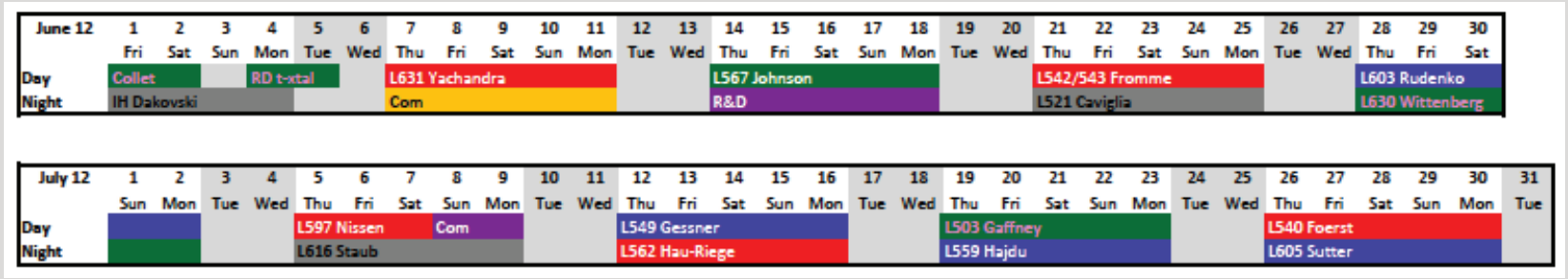
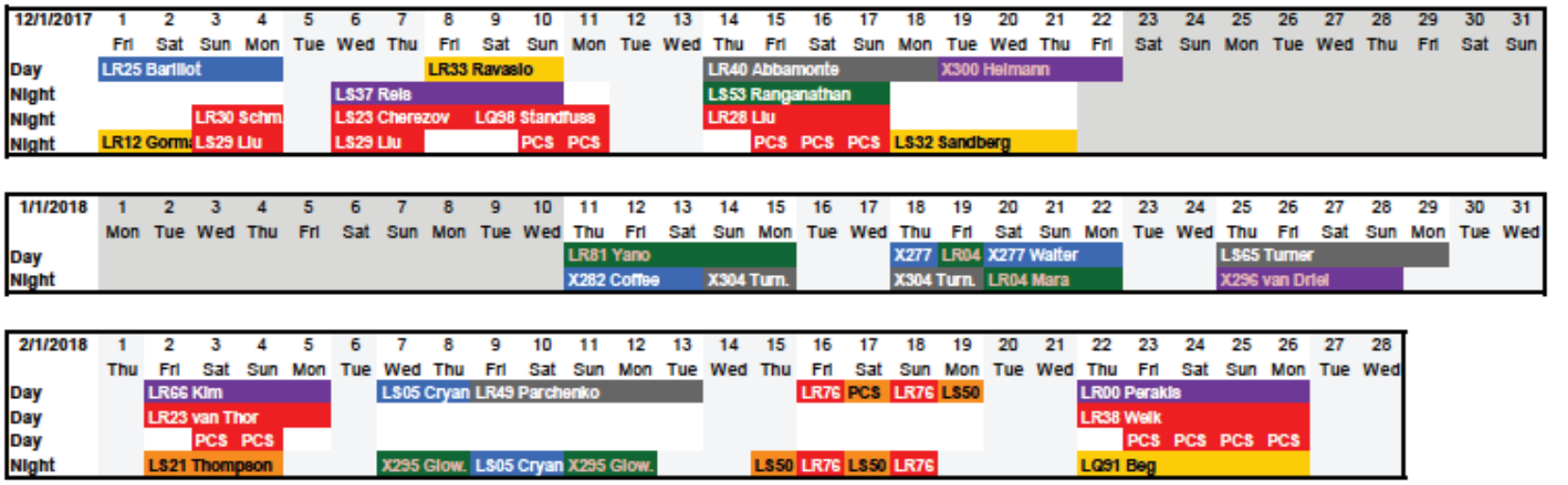
Without Multiplexing : No more than 2 experiments per day

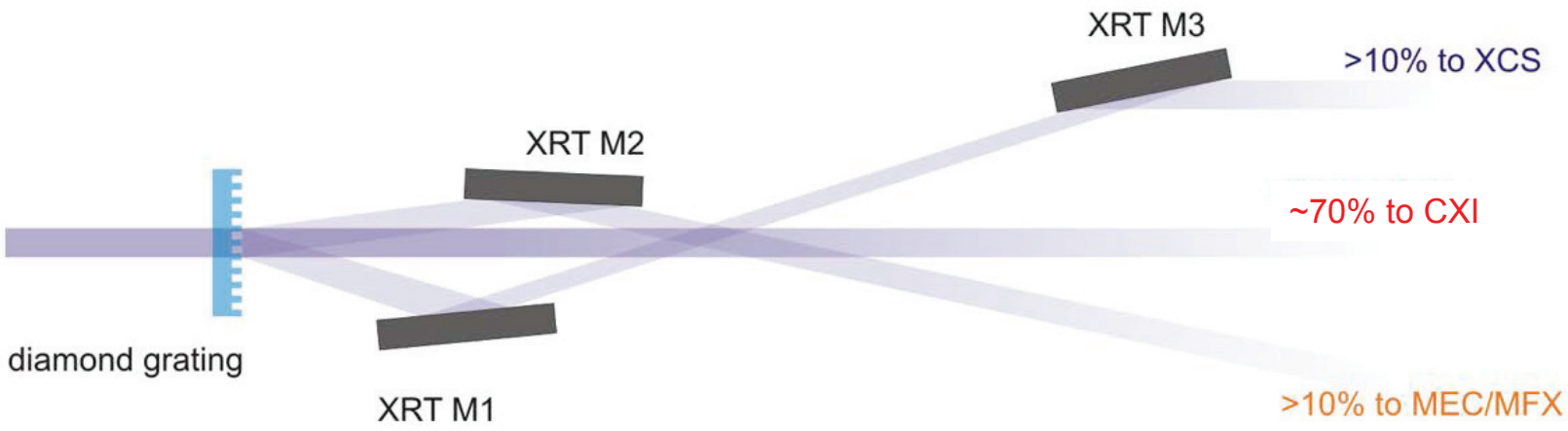


With Multiplexing : Minimum 2 experiments per day (when X-ray photon energy can be in common)

Adding 20-30% more experiments !



Future : Grating based FEH Multiplexing



- **Increase available beamtime : up to 3 instruments in pink simultaneously**
- **Installation is straight forward using existing components**
  - 10m at the beginning of the XRT is enough to create 2mm separation. Direct beam can go through while 1rst order gets picked up by either M1 or M2.

Basic Grating Parameters

Grating material: diamond (polycrystaline)
Grating period: ~600nm
bar height: 4-5 micron
First order diffraction efficiency: 10%-15%

Energy range: >8 keV, optimized for 9.5 keV
First order diffraction angle: ~ 200-300 urad to reach 2-3mm offset at M1/2 mirrors

Fabrication and modeling of diamond grating beam splitter

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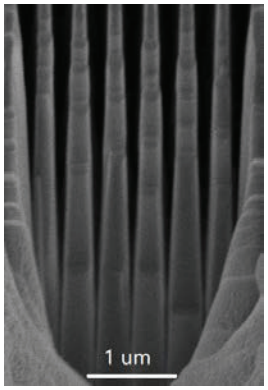
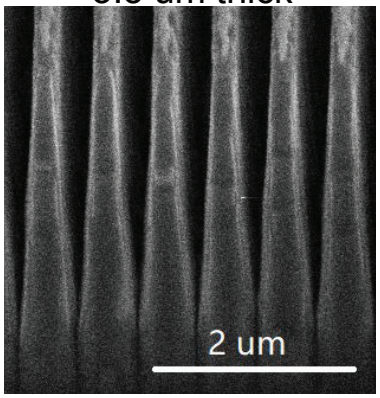
Cross-sectional SEM images of fabricated diamond gratings

200 nm half-pitch
5 um thick

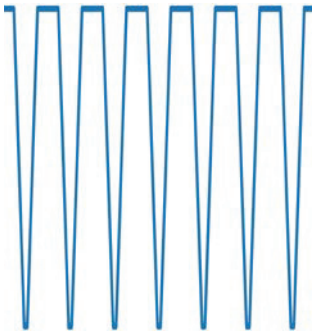


300 nm half-pitch
3.5 um thick

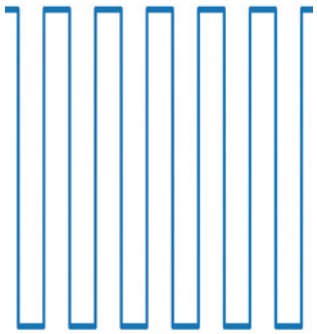


Tapered as-fabricated profiles alter the diffraction efficiencies

Tapered as-fab profile



Binary profile



Calculated Performance at 9.5 keV

Period, Thickness	Diffraction Angle	Profile	Calculated Diffraction Efficiency	
			0th order	± 1st order
400nm, 5μm	0.33 mrad	tapered as-fab	56.8%	19.50%
		binary	32%	27.60%
600nm, 3.5μm	0.22 mrad	tapered as-fab	77.8%	9.1%
		binary	60.5%	16.10%

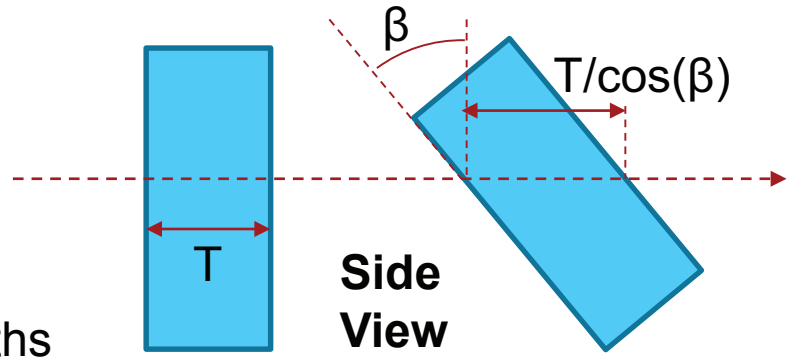
"Approximately equal" beam splitting (30%) requires a thickness of about 5μm for binary profile, and around 7~8 μm for the tapered as-fab profile.

Courtesy Kenan Li

X-ray gratings : Benefits

- True splitting :
  - Same spectral property in the direct and 1st order branches
  - e.g., SACLA/SwissFEL/XFEL spectrometer setup using grating as beam sampler for timing & spectral diagnostics (collaboration with C. David@PSI)

- Intensity ratio is tunable between 1st order side branched and 0th order transmitted
  - by adjusting the effective height w/o changing grating pitch.
  - But it reduced the acceptance



- Minor modification of the existing beam paths

- Easy to align, relatively cheap

- Compatible with LCLS-II-HE and the planned increase of heatload

Conclusion

- Success of User Facilities is driven by the support of a strong user community that has reasonable access

- Multiplexing can be obtained by using the electrons or the photons :
  - e-beam : recently demonstrated
  - X-ray : routinely used at LCLS and maturing.

- Combination of both e- and X-ray multiplexing is most probably the most appropriate, as it offers more possibility to multiplex experiments with different photon energies.