Possibilities for Timing Experiments at the MAX IV Storage Rings

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MAX IV Laboratory, May 17, 2016

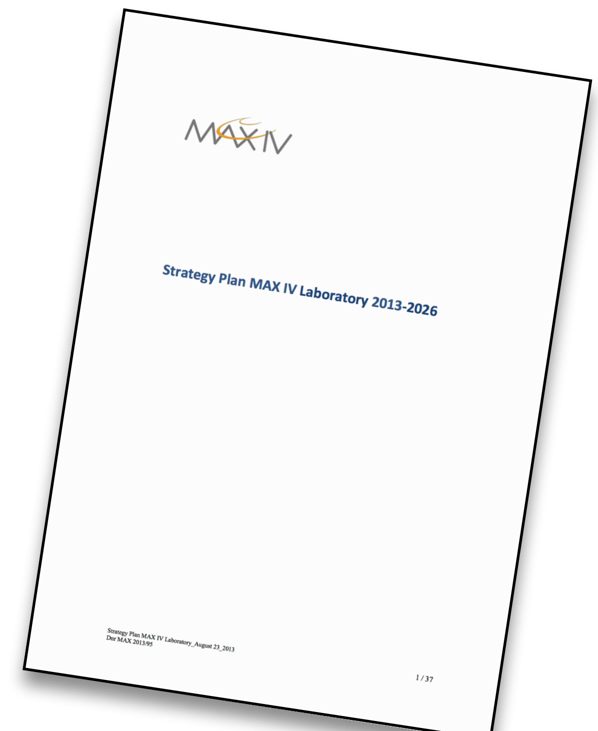
MAX IV

Introduction

- Assuming we commission to design specifications, what's ***the next big thing*** for the MAX IV storage rings?

➡Strategy Plan MAX IV Laboratory 2013-2026

- Storage ring upgrades call for
  - Electron beam stability improvements
  - Brightness & coherence improvements (3 GeV)
  - Fill pattern development → timing experiments

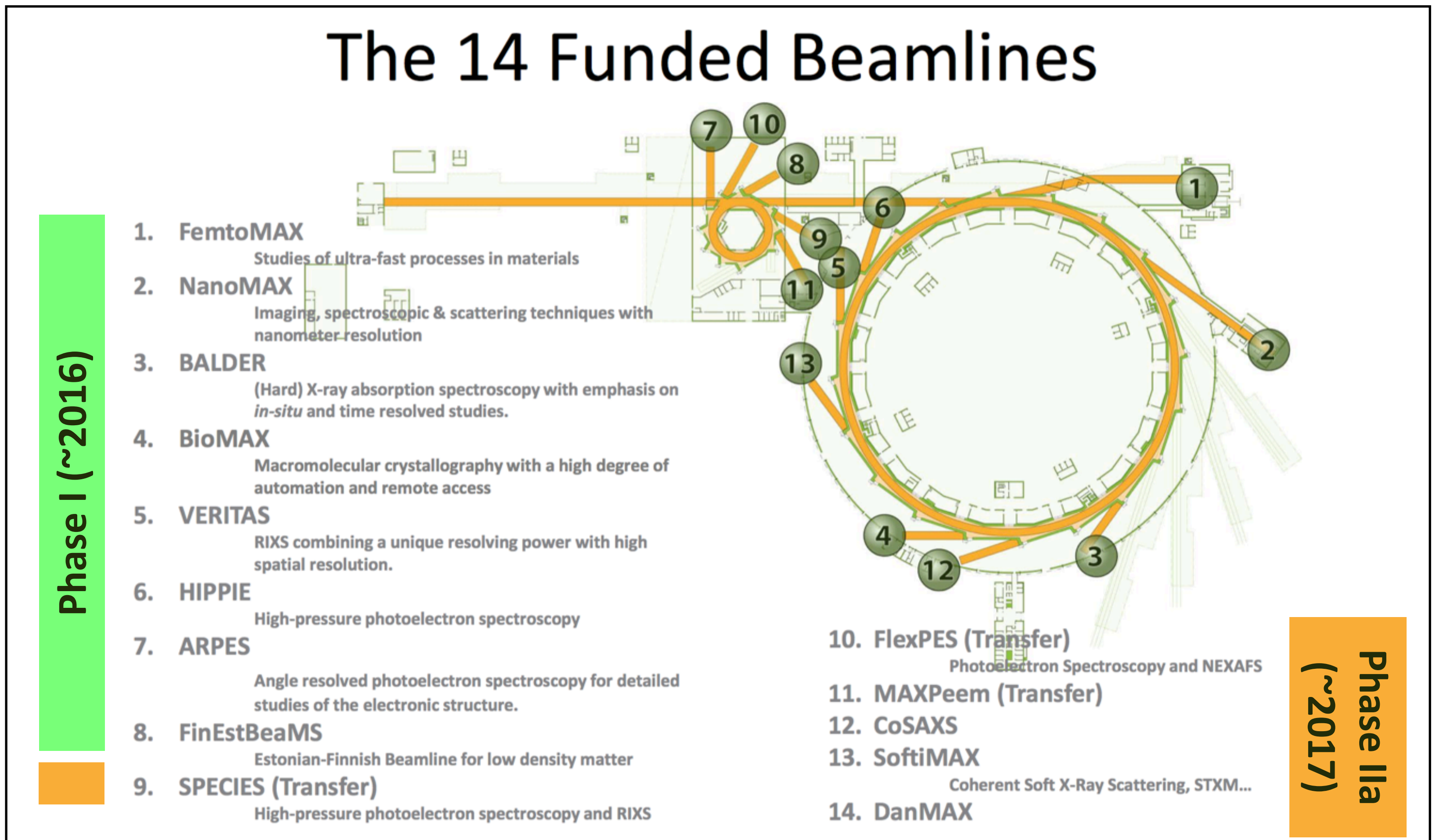

Strategy Plan MAX IV Laboratory 2013-2026

http://www.maxiv.lu.se/strategy_report

- Focus here will be on fill patterns and timing experiments *in the storage rings* (MAX IV baseline design already includes SPF)

Brief Facility Overview

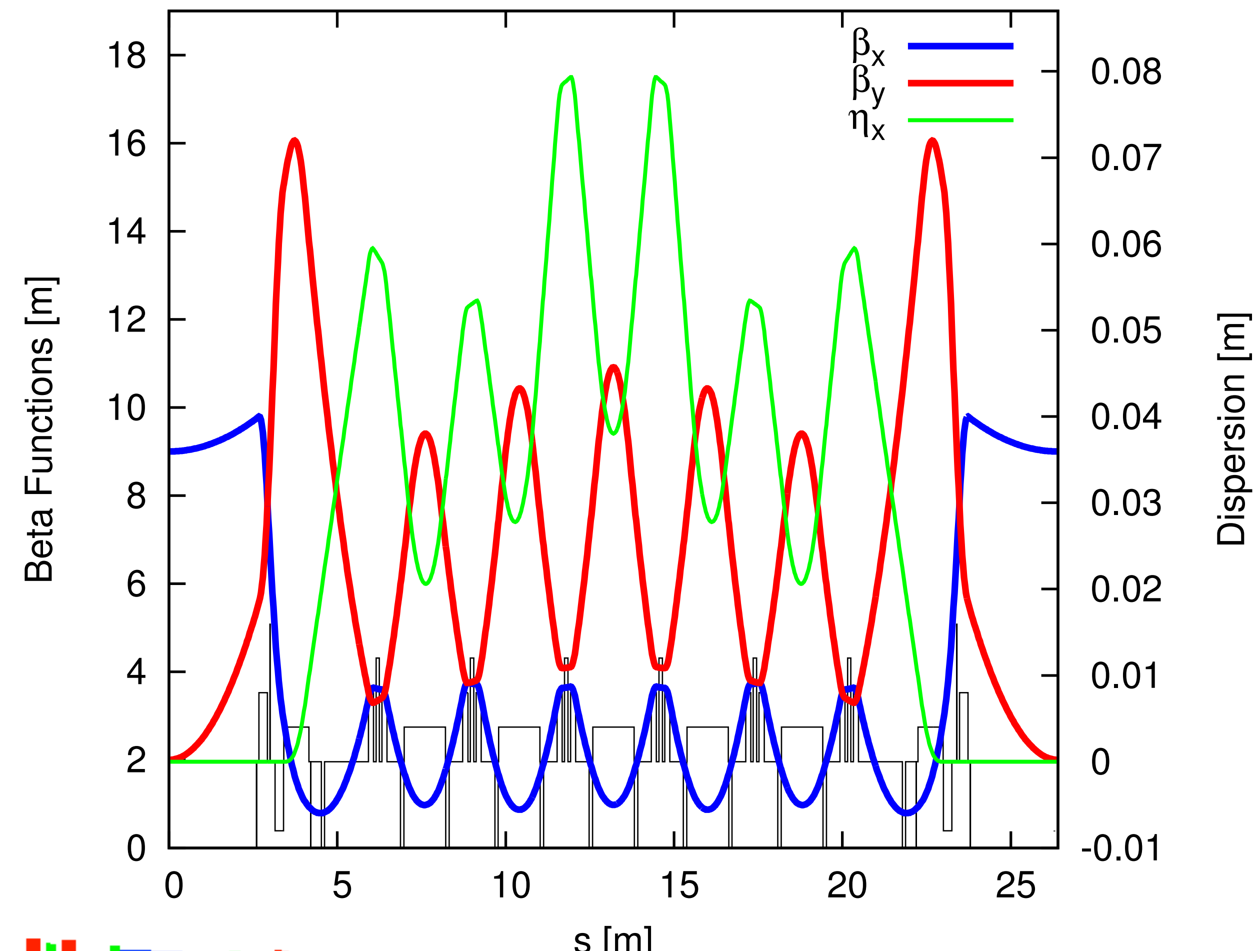
- MAX IV consists of two storage rings and a full-energy injector linac for top-off
- SRs @ 1.5 GeV and 3 GeV, ≈3.5 GeV linac also drives SPF/FEL
- User beamlines: 3 @ SPF, 10 @ 1.5 GeV SR, 19 @ 3 GeV SR

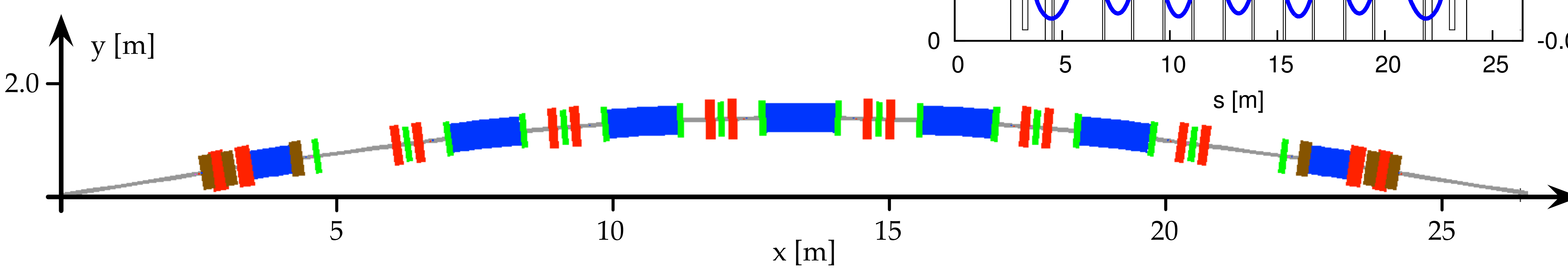


MAX IV 3 GeV SR Design Parameters

PRST-AB **12**, 120701 (2009)
PRST-AB **14**, 030701 (2011)
IPAC'**11**, THPC059, p.3029
JSR **21**, 862-877 (2014)

- MAX IV 3 GeV storage ring according to design:
  - 20-fold MBA lattice, 528 m, 500 mA with top-off
  - 7-bend achromat: 5×3° & 2×1.5°
  - U_0 = 364 keV/turn
  - ε_x = 328 pm rad, ε_y = 8 pm rad
  - ν_x = 42.20, ν_y = 16.28
  - β_x^* = 9 m, β_y^* = 2 m
  - σ_x^* = 54 µm, σ_y^* = 2-4 µm
  - ξ_x = -50.0, ξ_y = -50.2 → $\xi_{x,y}$ = +1

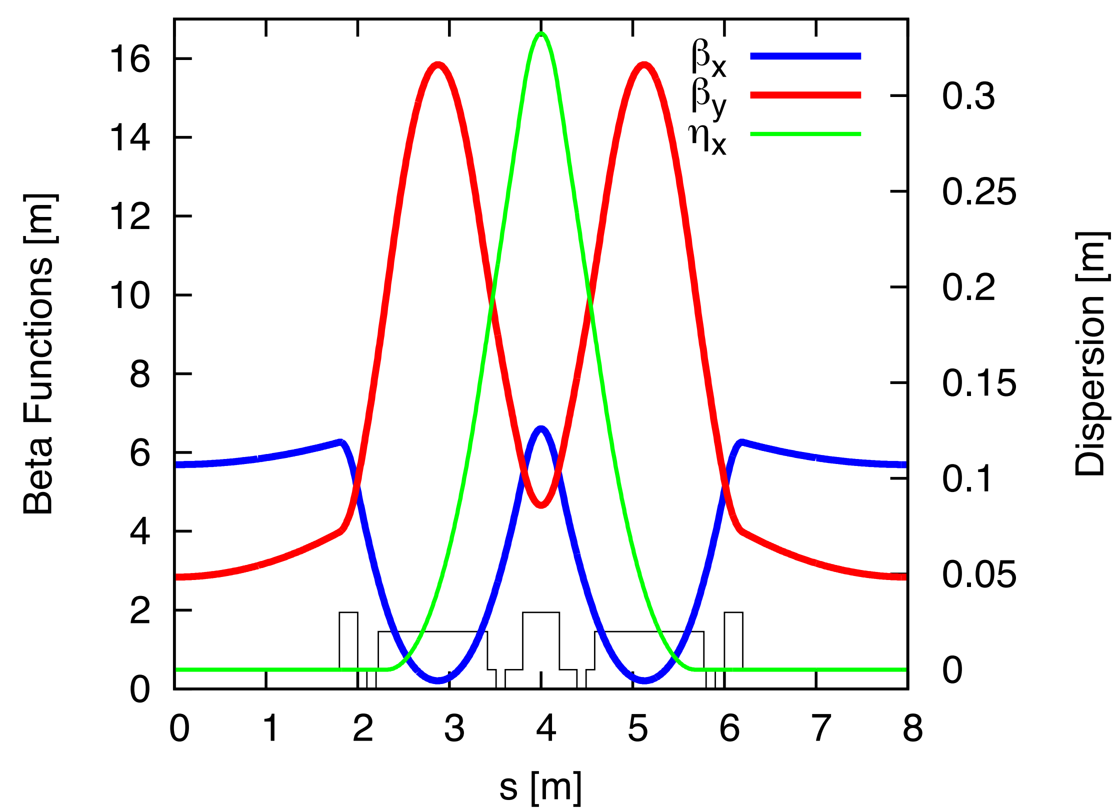


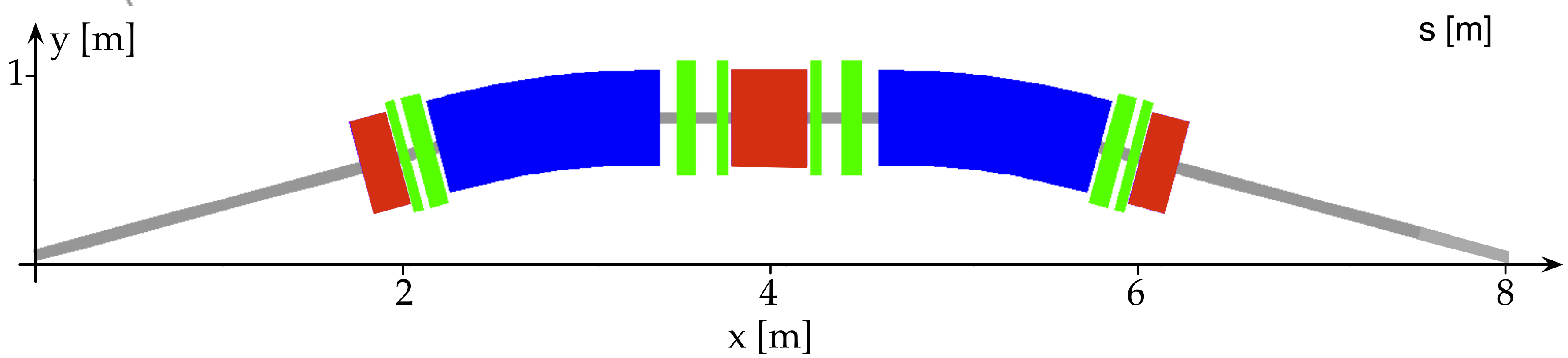


MAX IV 1.5 GeV SR Design Parameters

MAX IV **DDR** (Aug 2010)
IPAC'**11**, WEPO016, p.2430
IPAC'**12**, TUPPP024, p.1662

- MAX IV 1.5 GeV storage ring according to design:
  - 12-fold DBA lattice, 96 m, 500 mA with top-off
  - DBA 2×15°, integrated magnet design
  - U_0 = 114.1 keV/turn
  - ε_x = 5.98 nm rad, $\varepsilon_y \approx$ 60 pm rad
  - ν_x = 11.22, ν_y = 3.15
  - β_x^* = 5.7 m, β_y^* = 2.8 m
  - σ_x^* = 184 µm, $\sigma_y^* \approx$ 13 µm
  - ξ_x = -23.0, ξ_y = -17.1 → $\xi_{x,y}$ = +1



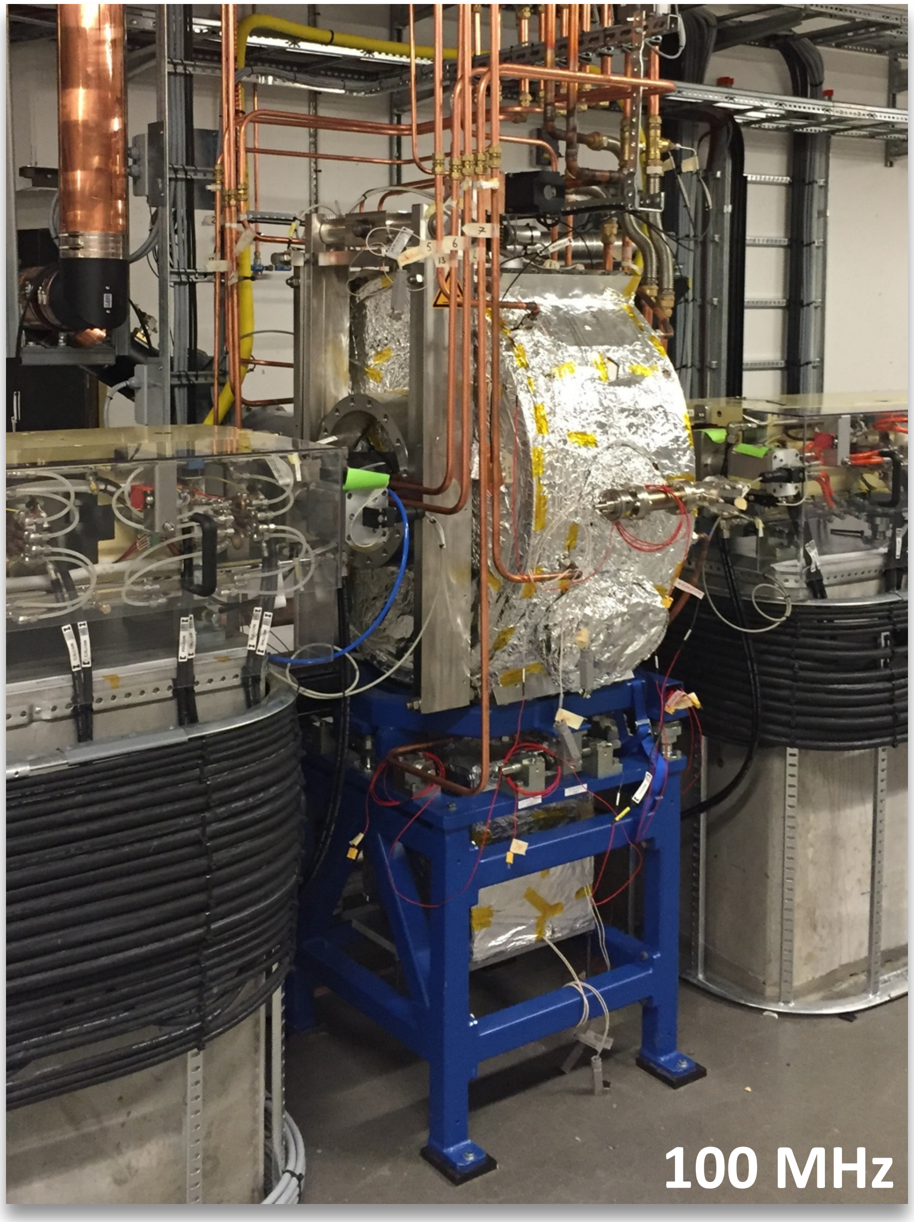


Storage Ring RF

IPAC'**11**, MOPC051, p.193

JSR **21**, 862-877 (2014)

- MAX IV storage rings originally designed for high average brightness & multibunch users → time-resolved experiments directed towards SPF
- SRs employ 100 MHz main RF system → uniform fill, ***no*** ion clearing gap (***5 nC/bunch***), ***top-off*** injection from linac (supports SB & MB injection → up to 100 ns trains)



1.5 GeV SR

Main RF Frequency	**99.931 MHz**
No. of Main Cavities	**2**
Max. Cavity Voltage	**280 kV**
Harmonic number	**32 (2^5)**

3 GeV SR

Main RF Frequency	**99.931 MHz**
No. of Main Cavities	**6**
Max. Cavity Voltage	**300 kV**
Harmonic number	**176 ($2^4 \times 11$)**

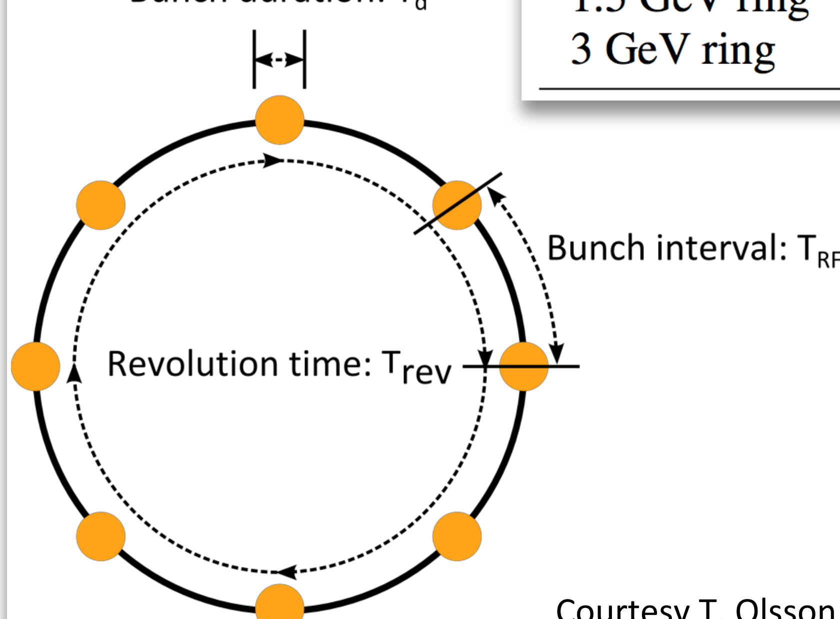
Storage Ring RF (cont.)

SRI **2015**, THU-P-021

- Storage rings achieve ≈MHz repetition rates while 100 MHz RF system renders 10 ns bunch spacing & long bunches
- Bunch length further increased by passive Landau cavities at the 3rd harmonic (roughly a factor 5 depending on cavity tuning ***and fill pattern***)

TABLE 1. Time structure for the MAX IV storage rings and SPF.

	Single-bunch repetition rate [Revolution time]	Bunch interval	Bunch length (bare lattice at maximum main cavity voltage)
SPF	100 Hz	10^7 ns	0.1 ps (FWHM)
1.5 GeV ring	3.13 MHz [0.32 μs]	10 ns	~49 ps (RMS) (w/o HCs) to ~213 ps (RMS) (HCs)
3 GeV ring	0.57 MHz [1.76 μs]	10 ns	~29 ps (RMS) (w/o HCs) to ~165 ps (RMS) (HCs)



Courtesy T. Olsson

MHz rep rates

10 ns bunch spacing
vs. 2 ns in conventional 500 MHz RF systems

30–220 ps (9–66 mm) RMS
depending on harmonic cavities

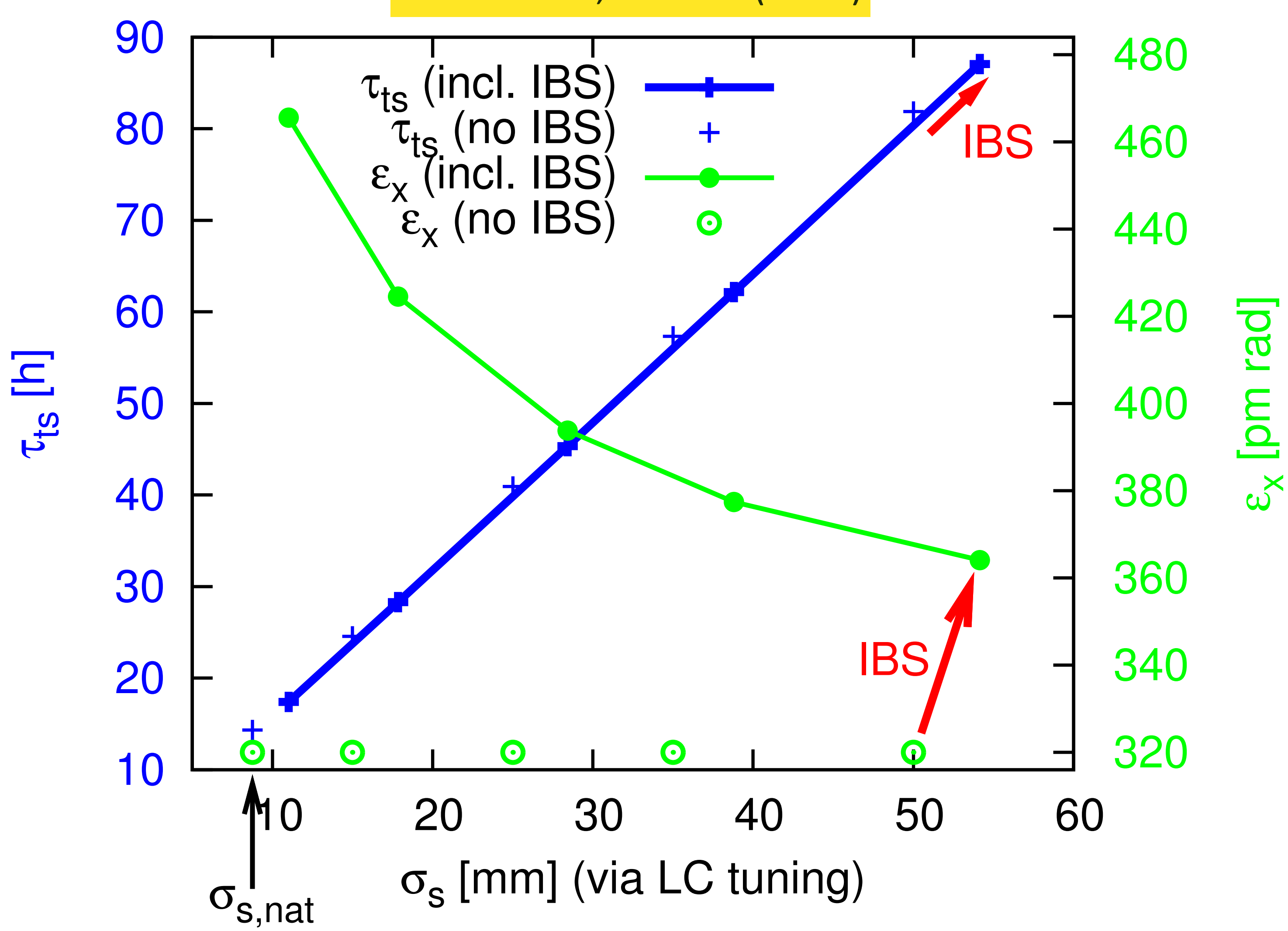
Storage Ring RF (cont.)

IPAC'**11**, MOPC051, p.193

JSR **21**, 862-877 (2014)

- Passive LCs are indispensable in our SRs since they
  - ensure sufficient Touschek lifetime
    (limiting interruption to SPF operation)

PRST-AB **17**, 050705 (2014)



Storage Ring RF (cont.)

IPAC’**11**, MOPC051, p.193

JSR **21**, 862-877 (2014)

- Passive LCs are indispensable in our SRs since they
  - ensure sufficient Touschek lifetime
    (limiting interruption to SPF operation)
  - damp instabilities

Threshold currents(mA) in MAX IV 3 GeV ring considering different effects

effect / plane	ξ	Z_{geom} HC off	Z_{geom} HC on	Z_{geom} + RW HC off	Z_{geom} + RW HC on	Z_{geom} + RW_{5IDs} HC on
Longitudinal	-	620	970	-	-	-
Horizontal	0.0	2010	2020	120	140	-
	1.0	>2050	17100	150	3500	-
	1.2	5040	21900	-	-	-
Vertical	0.0	920	710	40	40	-
	1.0	2200	10400	-	950	380
	1.2	3170	15100	50	1250	540

*in mA

Harmonic cavity is crucial for successful operation!

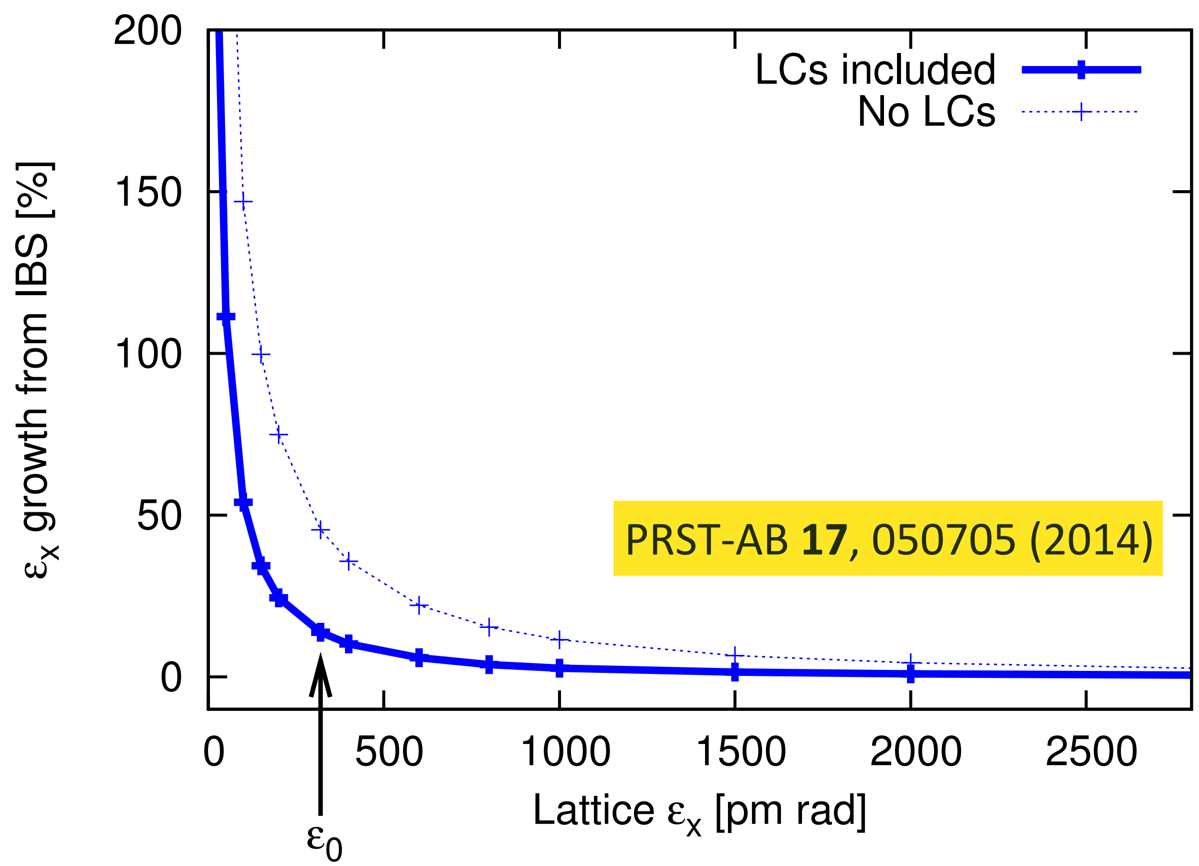
LER workshop, September 2014   Galina Skripka

Storage Ring RF (cont.)

IPAC'**11**, MOPC051, p.193

JSR **21**, 862-877 (2014)

- Passive LCs are indispensable in our SRs since they
  - ensure sufficient Touschek lifetime
    (limiting interruption to SPF operation)
  - damp instabilities
  - conserve ultralow-emittance at high bunch charge (3 GeV SR)



So why timing experiments at storage rings?

- Storage rings are unprecedented in terms of *stability* and *repetition rate* while serving many users *simultaneously*
- Some user groups interested in timing experiments would benefit from repetition rates ≈10^4 times higher than SPF
- This implies fill patterns and operation modes that go beyond the original MAX IV design, e.g. single-bunch, camshaft, hybrid, etc. → this can perturb operation of the LCs and hence jeopardize storage ring performance

➡ ***What can we do to be able to serve both single-bunch and multi-bunch users simultaneously at our ring(s)?***

Timing Experiments at MAX IV SRs

SRI **2015**, THU-P-021

- Launched collaboration between
  - MAX IV Machine Division
  - LU: *Stacey Sörensen* (Synchrotron Radiation Research) ➔ *Raimund Feifel* (FASM, GU)*, Teresia Olsson* (grad student, accelerator physics) & *Christian Stråhlman* (grad student, beamline instrumentation)
  - Nordic timing user community
- Organized three topical events in Lund:
  - two meetings with users (Mar & Sep 2014)
    - user community informed about possibilities & difficulties
    - collected user cases for timing experiments

Timing Experiments at MAX IV SRs (cont.)

SRI **2015**, THU-P-021

SRN **Vol.28, No.5,** 2015

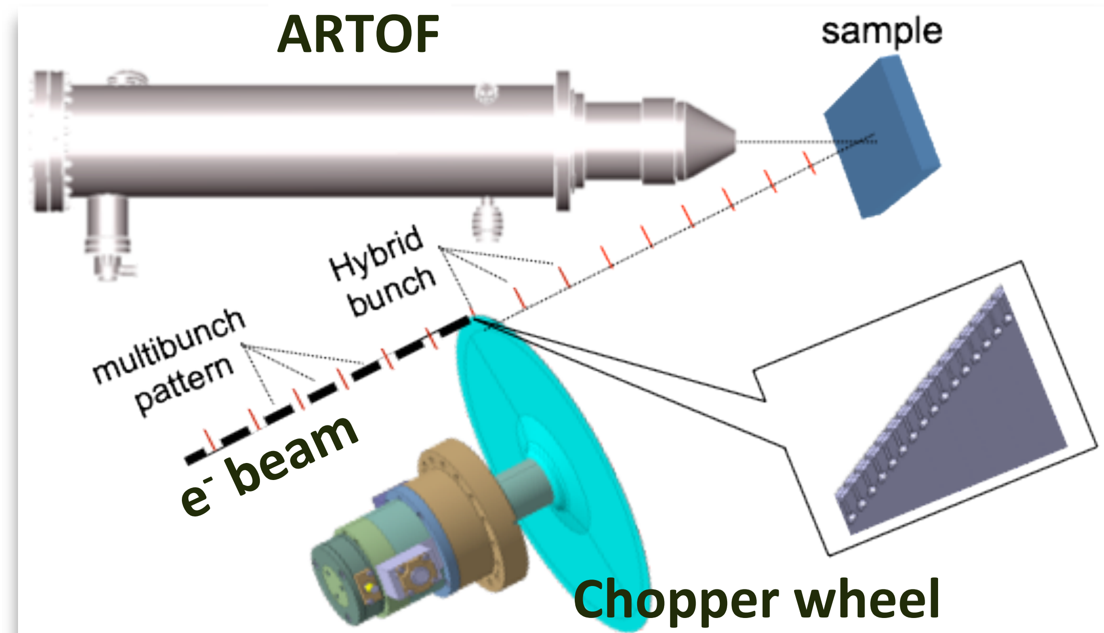
- Launche
  - MAX I
  - LU: *St* ... *nd Feifel* (FASM, ... *hristian Stråhl*
  - Nordi
- Organize
  - two m
    - user
    - colle
  - one workshop with focus on machine implementation (Mar 2015) "Workshop on Timing Modes for Low-Emittance Storage Rings"

http://indico.maxiv.lu.se/event/60/

Timing Experiments at MAX IV SRs (cont.)

SRI **2015**, THU-P-021

- Discussions with users on:
  - Pulse lengths & interval between pulses
  - Photon energy & intensity
  - Synchronization with lasers and choppers
- User interest for:
  - Electron time of flight, multi-coincidence
  - Ion time of flight, multi-coincidence
  - Short x-ray pulses for electron ARToF
  - Pump-probe exp. with laser synchronization
  - Time-resolved exp. implementing gated detectors
  - Time-resolved luminescence experiments (lifetime from ns to µs)



Picture from Ruslan Ovsyannikov

MHz Chopper @ BESSY II
Enables *1.25 MHz repetition rate* at beamline
Requires camshaft bunch in *200 ns window*

Opt. Lett. **40,** 2265 (2015)

Timing Experiments at MAX IV SRs (cont.)

SRI **2015**, THU-P-021

- User meetings resulted in
  - report to MAX IV Directors

    http://indico.maxiv.lu.se/event/60/material/0/0.pdf
  - three typical user cases of interest

Coincidence & TOF (choppers/camshaft?)

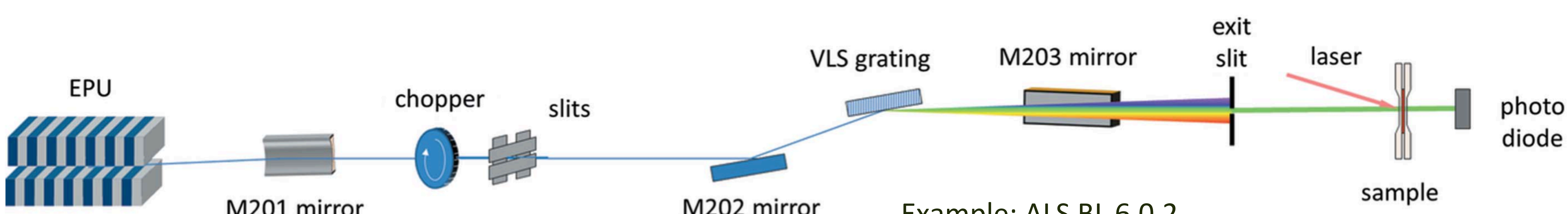
Rep. Rate at Experiment	**10–100 kHz**
Pulse Interval	**≥ ±150 ns for synchr.**
RMS Pulse Length	**< 500 ps**
No. ph/s (within 1% BW)	**≈10^7**

Pump-probe (using gating & opt. choppers)

Rep. Rate at Experiment	**≈ MHz**
Pulse Interval	**±130 ns for synchr.**
RMS Pulse Length	**≈100 ps (→ time res.)**
No. ph/s (within 1% BW)	**≈10^{14}**

ARTOF (camshaft?)

Rep. Rate at Experiment	**≈ MHz**
Pulse Interval	**≈100 ns**
RMS Pulse Length	**10 (optimal) – 200 ps**
No. ph/s (within 1% BW)	**≈10^7**



Example: ALS BL 6.0.2
(from JSR **22**, 729-735, 2015)

Timing Experiments at MAX IV SRs (cont.)

- There are many possibilities to shorten bunch lengths in the rings (e.g. femto-slicing, high-order RF, non-integer harmonic RF, LCs in bunch shortening mode, injection of short bunches from linac, low-alpha optics)

- However, overall users interest appears to be greatest for adequate time structure, decreasing bunch length has lower priority

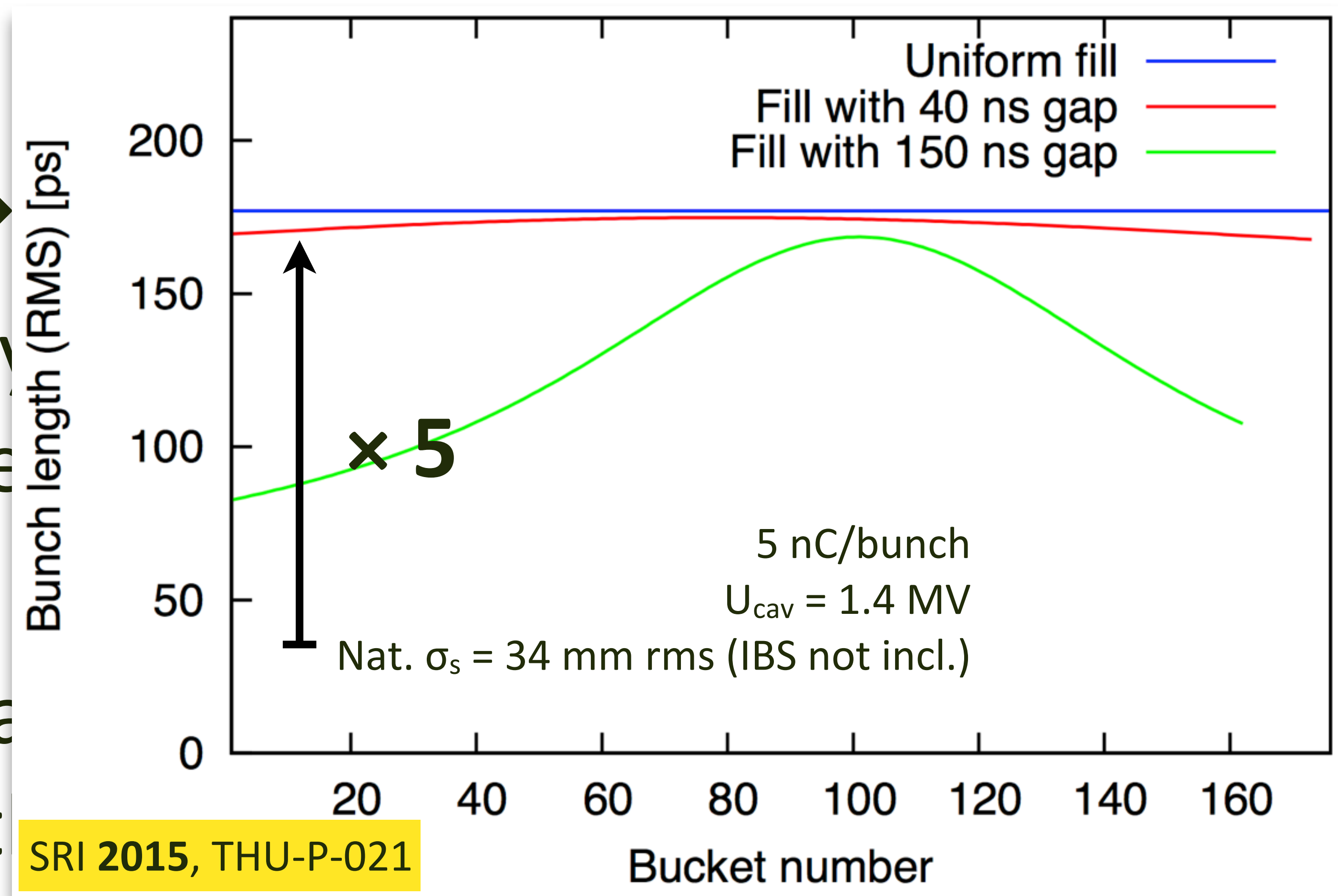
- From this we derive the following staged approach:
  - **Single-bunch / hybrid / camshaft** (requires FP control, LC transient issues?)
  - **Resonant pulse picking** (enables simultaneous multi-bunch users)
  - **Pseudo single bunch** (increase intensity)
  - ...worry later about shorter pulse lengths

Fill Pattern Tailoring

- MAX IV SRs can operate in SB or few-bunch mode (linac can inject in both modes) → mainly of use in 1.5 GeV SR (32 bunches, 3.12 MHz)
- Camshaft/hybrid modes would enable timing experiments with choppers (mechanical or optical) and/or gated detectors → mainly of use in 3 GeV SR (176 bunches, 568 kHz)
- However, gaps in FP → transients in passive LCs → variation of bunch lengths and phases along bunch train (→ variation of lifetime & emittance)

Fill Pattern Tailoring (cont.)

- MAX IV SRs … de (linac can inject in both modes) → … .12 MHz)
- Camshaft/hy… periments with choppe… ted detectors → … Hz)
- However, ga… → variation of bunch lengt… tion of lifetime & emittance)



- Model & develop mitigation measures in collaboration with N. Milas (LNLS) & R. Nagaoka, F. Cullinan (SOLEIL)

Fill Pattern Tailoring (cont.)

- MAX IV SRs ... de (linac can inject in both modes) → ... .12 MHz)
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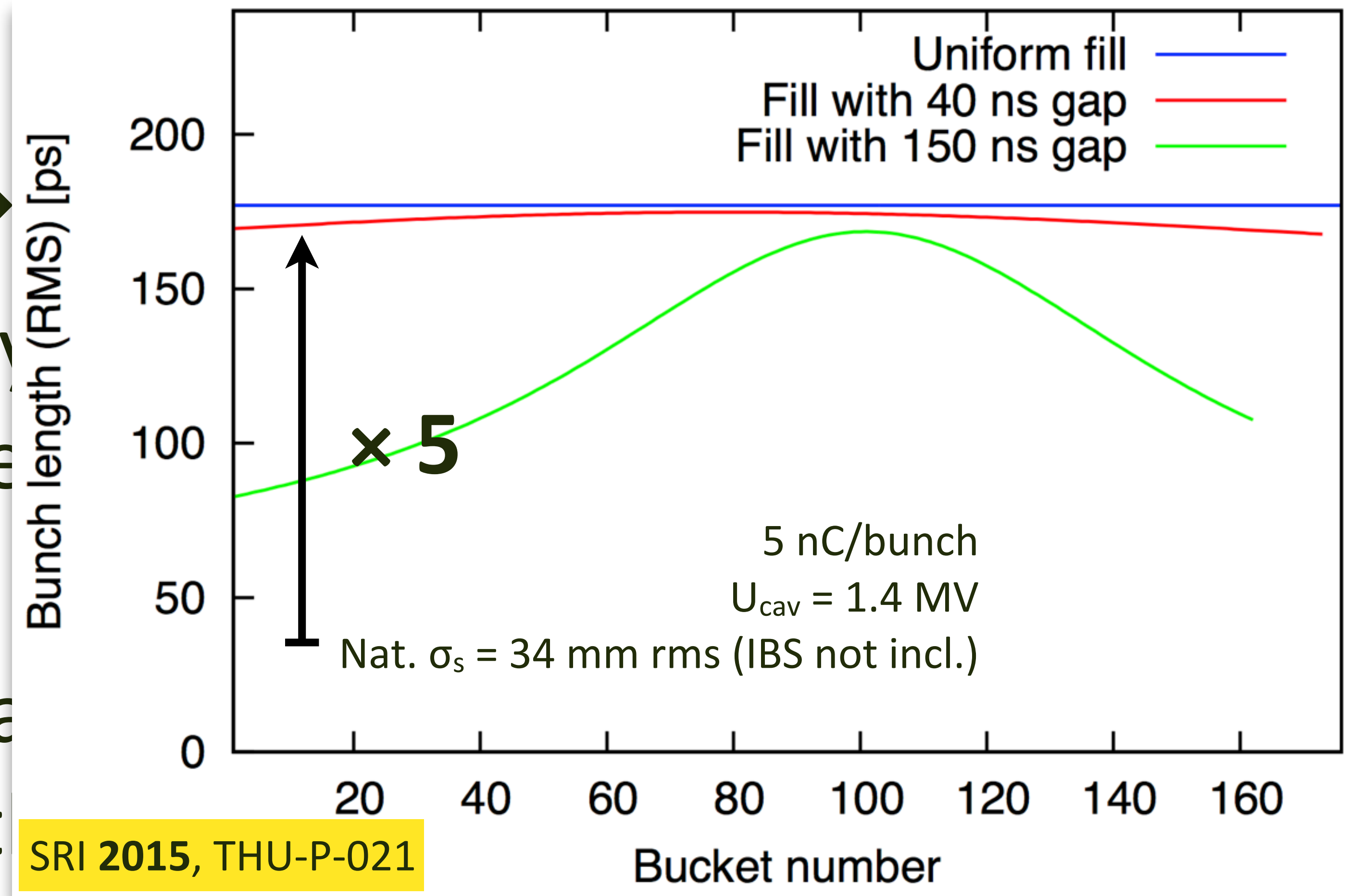


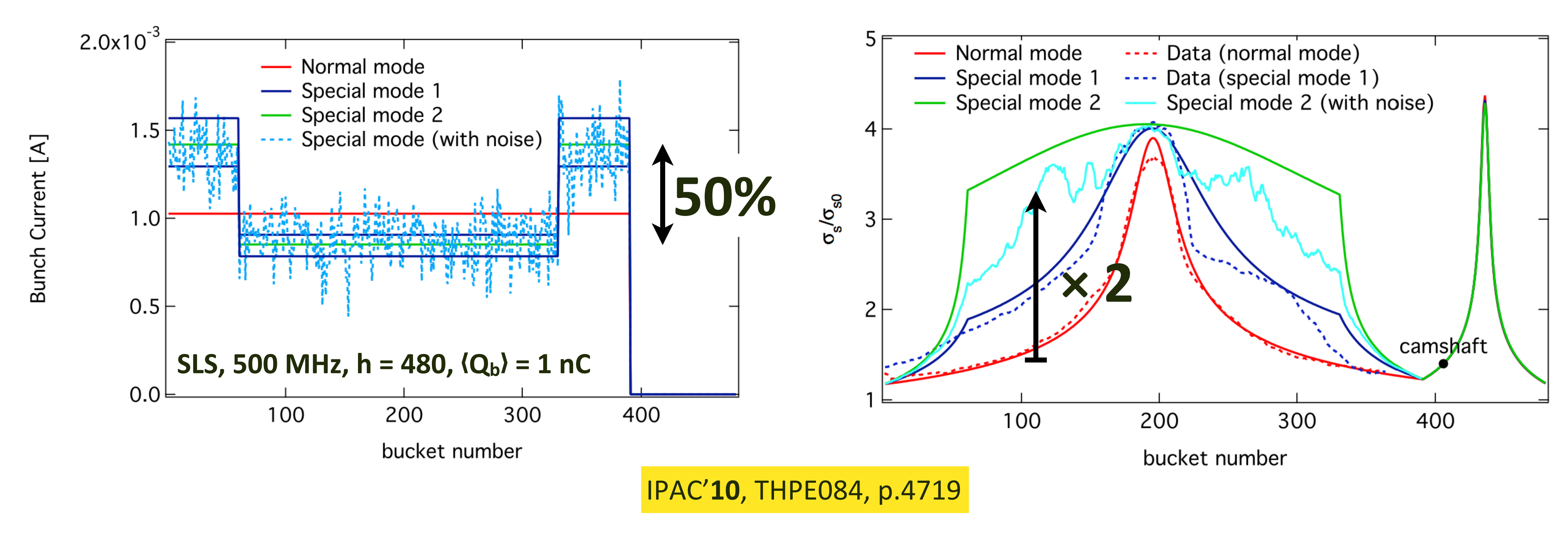
SRI **2015**, THU-P-021

- Model & develop mitigation measures in collaboration with N. Milas (LNLS) & R. Nagaoka, F. Cullinan (SOLEIL)
  – bunch profile measurements in MAX II (benchmarking of models)

IPAC’**16**, WEPOW036

IPAC’**16**, WEPOW037

Fill Pattern Tailoring (cont.)



IPAC'**10**, THPE084, p.4719

- Model & develop mitigation measures in collaboration with N. Milas (LNLS) & R. Nagaoka, F. Cullinan (SOLEIL)
  - bunch profile measurements in MAX II (benchmarking of models)
  - e.g. tailor FP to reduce transients (theoretical studies)

IPAC'**16**, WEPOW036

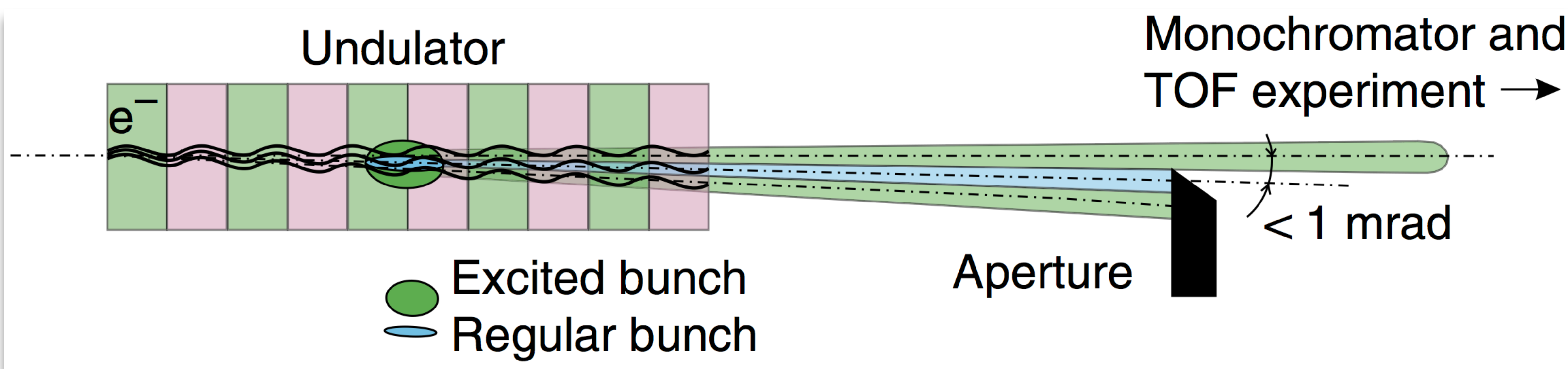
IPAC'**16**, WEPOW037

http://www.maxiv.lu.se/science/accelerator-physics/current-projects/timing-modes-in-the-max-iv-storage-rings/

Resonant Pulse Picking

Nat. Commun. **5:4010** (2014)

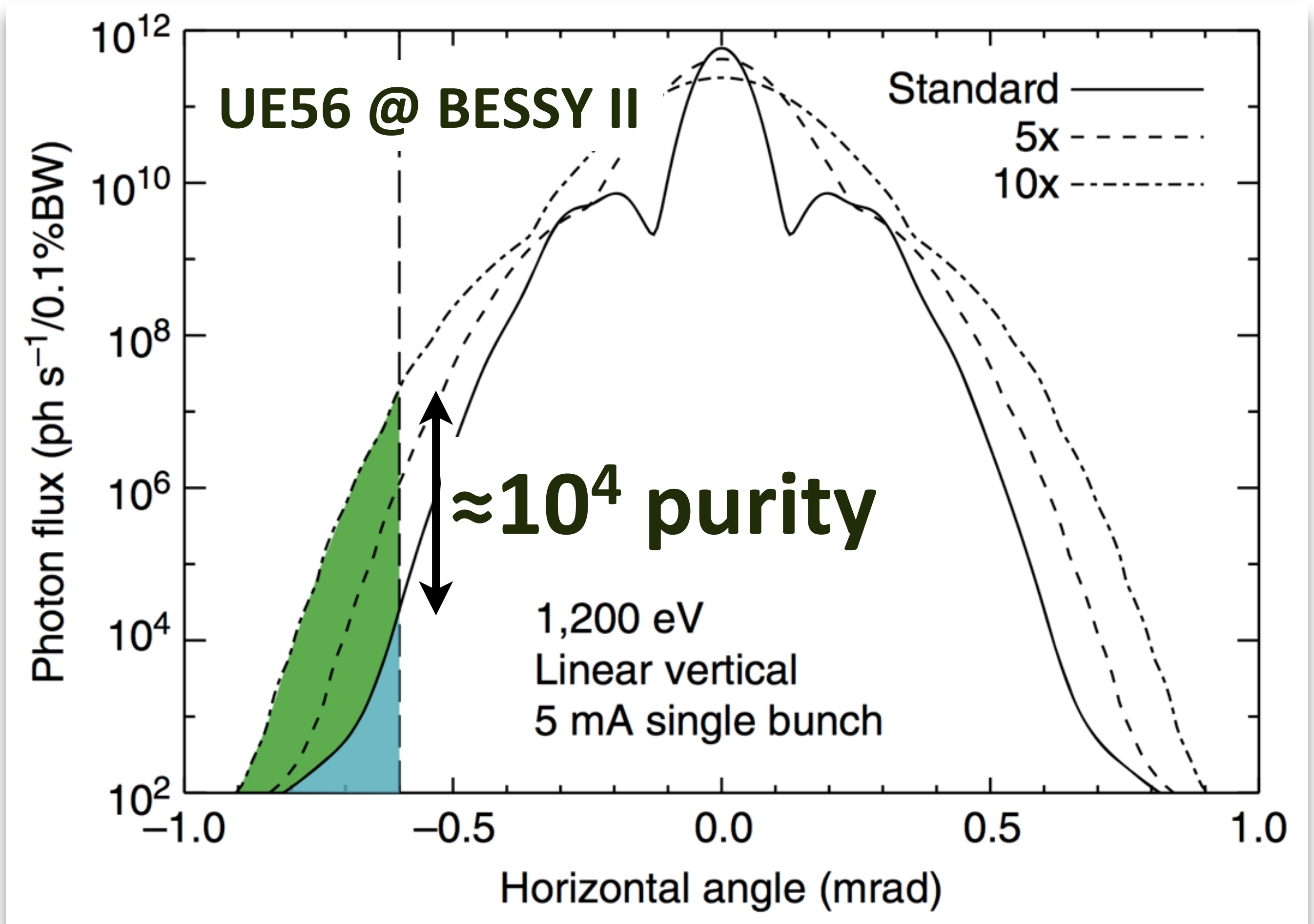
- Developed at BESSY II, in user operating since 2014
- Quasi-resonant excitation of a single bunch → incoherent betatron oscillations → emittance increase
- Aperture @ BL ensures only photons from the increased divergence of this bunch reach sample (can be combined with closed orbit bump) while all other BLs receive multi-bunch light



Resonant Pulse Picking (cont.)

Nat. Commun. **5:4010** (2014)

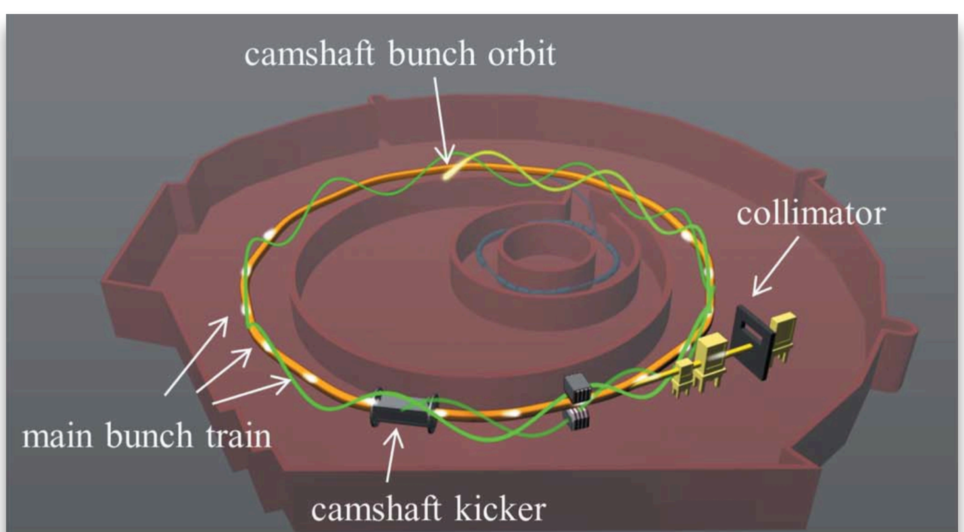
- Excitation and bump applied in horizontal plane ➔ preserve vertical plane for monochromatization
- Achievable intensity is trade-off between excitation strength, bump amplitude vs. aperture, and desired pulse purity
- BESSY II: 10^7-10^9 ph/s/0.1%
- Excitation an be performed with stripline kicker for BxB FB ➔ option to run w/o gap
  - NB: BL needs to be able to handle high heat load on aperture
  - NB: Excitation always on, photons from excited bunch visible to other BLs too

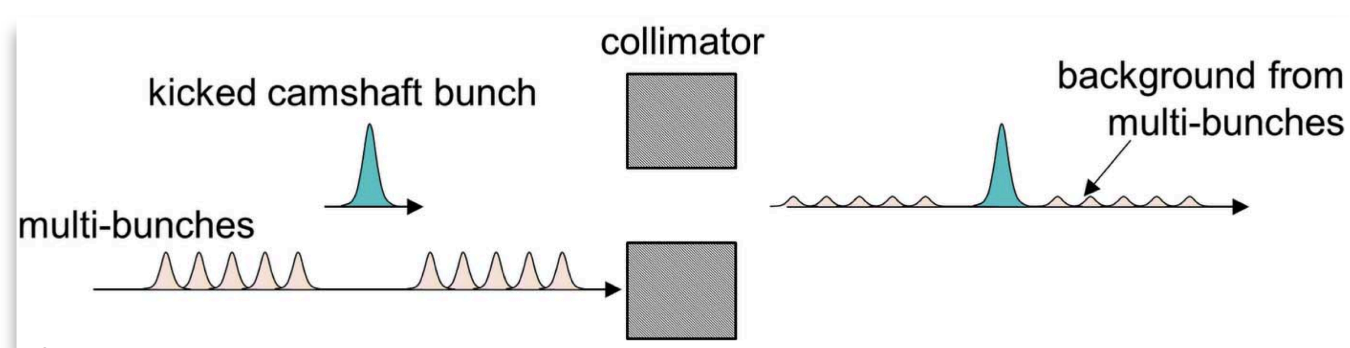


Pseudo Single Bunch

PRL **109**, 264801 (2012)
JSR **22**, 729-735 (2015)
PRST-AB **18**, 120702 (2015)

- Developed at Berkeley for ALS user operation in 2012
- ***Kick-and-cancel scheme***: bunch is kicked onto a separate closed orbit & after a few turns kicked back → angular/spatial separation of radiation emitted from this single bunch
- Aperture @ BL ensures only photons from the this displaced bunch reach sample (can be combined with closed orbit bump) while all other BLs receive multi-bunch light → 10^3 suppression (>10^5 with chopper)





Pseudo Single Bunch (cont.)

PRL **109**, 264801 (2012)

JSR **22**, 729-735 (2015)

PRST-AB **18**, 120702 (2015)

- KAC scheme allows users to set variable repetition rate
- PSB KAC relies on kicker performance
  - ALS achieved so far: 1 kV within 40 ns at 1.25 MHz → excite in vertical plane
  - in principle: bunch spacing determines required kicker rise/fall time
  - but in practice: pulse length of kicker determines required gap in FP

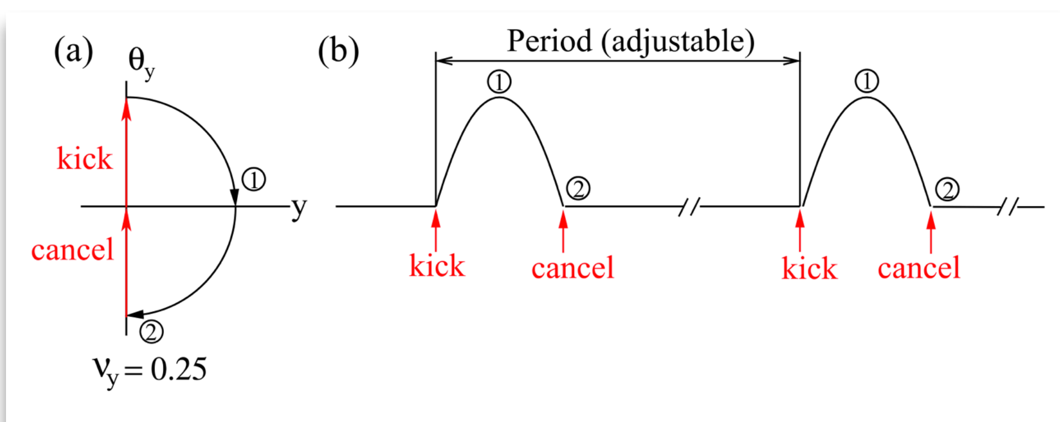
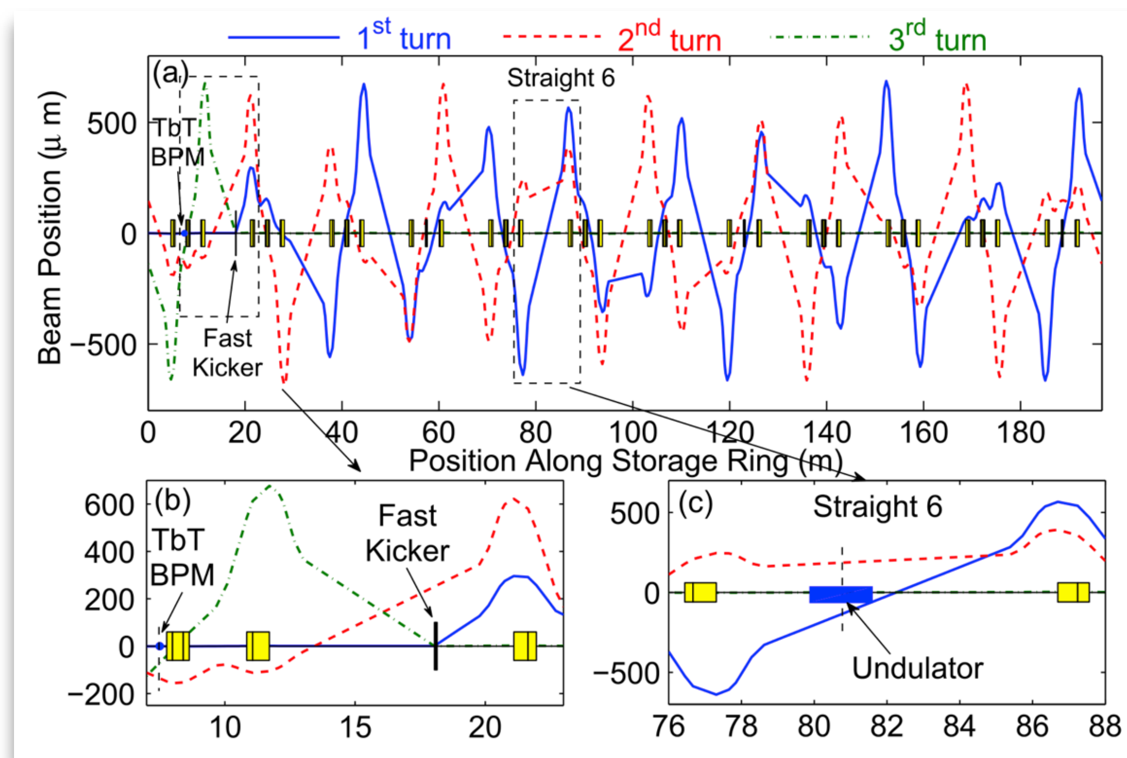


FIG. 2 (color online). Schematic of the kick-and-cancel mode: (a) Phase space, (b) PSB pulses with adjustable frequency.



Possible Strategy for MAX IV SRs

- Transients are a real issue for our rings → most likely we will have to tailor FP to sufficiently counteract transients in LCs
- Leverage MAX IV's 10 ns natural bunch spacing → PPRE w/o gap and/or relaxed PSB kicker requirements
- Massive global R&D effort on fast injection kickers → operate PSB kicker with little or no gap at all?

- Possible immediately: run 1.5 GeV SR in SB/2-bunch mode
  - bunch length can be as short as 50 ps rms (depending on RF settings)
  - requires time splitting with MB users
  - variable repetition rates can be achieved with chopper
  - spectral range sufficient? (TOF users so far @ lower energies)

Possible Strategy for MAX IV SRs (cont.)

- Mid-term development: PSB or PPRE in 3 GeV SR (many SS's)
  - PSB renders variable repetition rate and preserves ultralow emittance (possibly not a concern for ARTOF users)
  - PPRE does not require dedicated kicker & lower intensity can be of advantage for some users (e.g. ARTOF)
  - PPRE light available simultaneously at all BLs, PSB only at some
  - Both methods compatible with MB users → no time splitting

- Ideally, develop kicker with ≈20 ns pulse that achieves ≈10σ displacement → ≈100 μrad (roughly 1kV, 1 cm gap, 1m length)
- Such a kicker could also be beneficial for BxB on-axis injection → hard, low-DA optics, round beams, new IDs, etc.

Possible Strategy for MAX IV SRs (cont.)

- Challenge for both PSB & PPRE: design apertures capable of accepting SB photons while dissipating massive MB heat load
- So far unaddressed requests:
  - long-pulse, soft radiation (LCs in 1.5 GeV SR not effective in 2-bunch mode)
  - short, hard radiation (LCs required in 3 GeV SR) → shorter (unstretched) camshaft bunches created naturally by proper positioning within gap and exploiting transients in LCs?
  - pulses significantly shorter than natural bunch lengths (≈30ps)

➡ We have more than enough interesting open questions to work on in the coming years, but we're confident we could be serving timing users at our SRs in the near future

Summary & Outlook

- Few-bunch mode in MAX IV 1.5 GeV SR realizable right away
- Ongoing modeling efforts to
  - understand measured bunch profiles in MAX II
  - quantify transients in LCs driven by FP variations/interruptions
  - quantify longitudinal properties of camshaft bunches
  - develop mitigation measures for transient behavior
  - develop possible PPRE & PSB schemes at MAX IV
  - characterize photon yield & properties from such schemes
- Investigation of improvements in BL instrumentation → e.g. choppers, gated detectors, energy resolution in ARTOF spectrometer, etc.

IPAC'**16**, WEPOW036

IPAC'**16**, WEPOW037

Summary & Outlook (cont.)

- Experimental effort to apply and characterize excitation with stripline kickers as required for PPRE
  - ~~MAX III measurements?~~ (shutdown Dec 2015)
  - with BxB FB in 3 GeV SR once available (→ ideally with APD @ BL)
- Development of a new fast kicker system enabling e.g. PSB
  - funding proposal to SSF rejected Feb 2015
  - however, considered an important enabler for various SR improvements → will continue to pursue topic & seek funding

➡ Continued R&D on both the accelerator and the BL instrumentation side should enable timing experiments at the MAX IV SRs (and other ultralow-emittance SRs) in the future