Exploring the essential Conditions Enabling Steady-State Microbunching

Joerg Feikes on behalf of the SSMB Collaboration*

* **Helmholtz-Zentrum Berlin:**
Jörg Feikes, Arnold Kruschinski, Ji Li, Markus Ries
Physikalisch-Technische Bundesanstalt (PTB):
Arne Hoehl, Roman Klein
Tsinghua University, Beijing:
Alex Chao, Xiujie Deng, Lixin Yan, Chuanxiang Tang, Wenhui Huang

DESY Accelerator Physics Seminar, December 12th, 2023

Outline

1. Steady State Microbunching
2. Proof of Principle Experiment
3. Bunching factor formula – experimental results
4. Energy widening effects in an isochroneous optic
5. Isochroneous optic in more detail
6. Stochastic quantum excitation
7. outlook

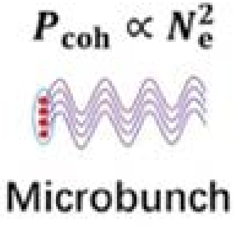
Coherent Radiation

- **Coherent Radiation** (CR) e.g. from e- is very powerful because its **intensity ~** $N_{electrons}^2$

(this is what makes **FELs** such powerful radiation sources)

CR can be obtained by reducing **bunch length** to values smaller than **radiation wave length** λ_{rad}

for CR in µm and sub-µm range ⟶ the e- have to be structured in **microbunches** (MB) ~ µm

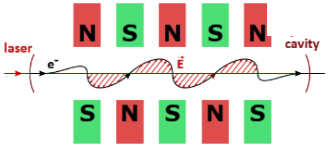


Microbunches

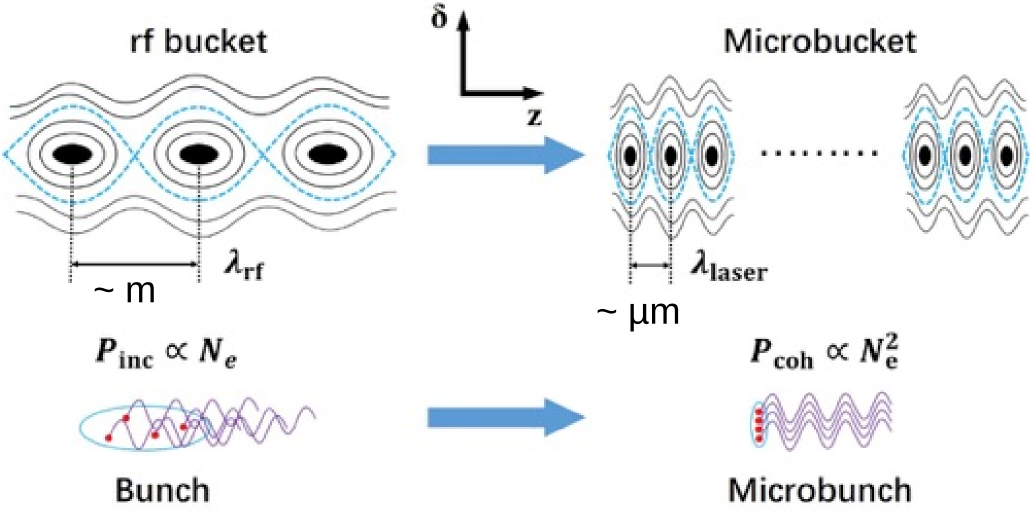
How can Microbunches be generated and maintained ?

substitute **RF cavity** ($\lambda_{\mathrm{rf}} \sim$ *m*) by **Laser Modulator** ($\lambda_{\mathrm{laser}} \sim$ µ*m*)

+ induction cell



+ optical cavity



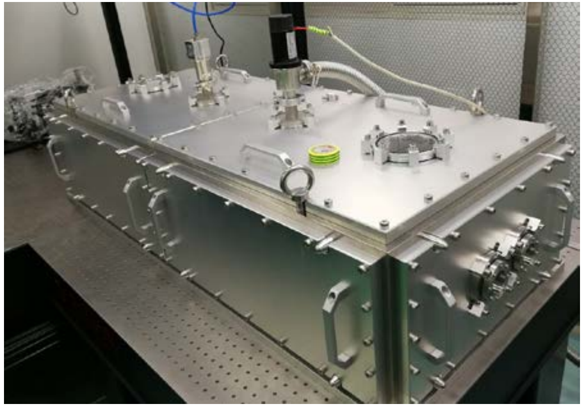
~ m

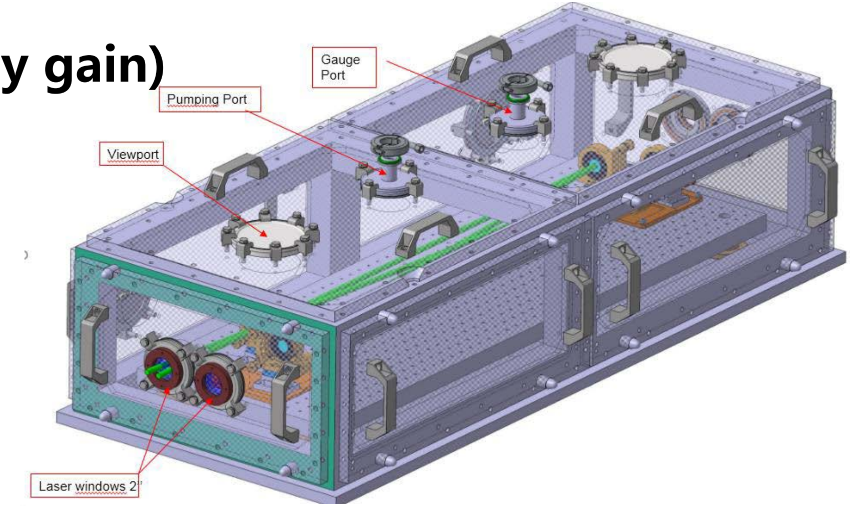
~ µm

by six orders smaller !

Optical Enhancement Cavity

- **The first OEC at Tsinghua (> 100 cavity gain)**



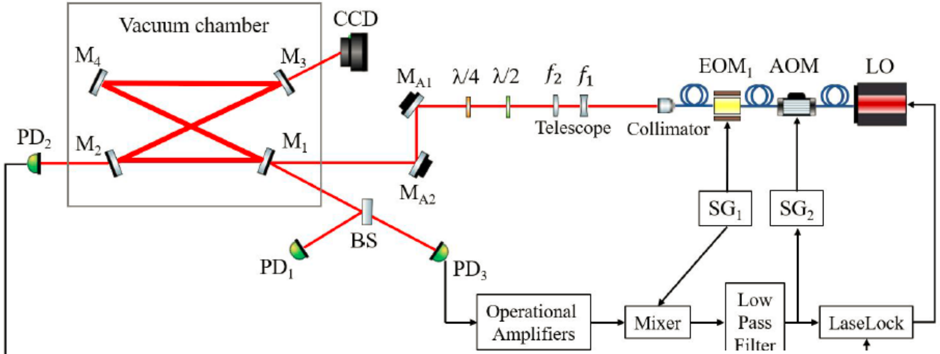


Designed for SSMB:

Wavelength ~ 1 um

CW Mode

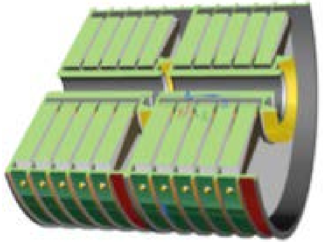
Stored power ~ 1 MW

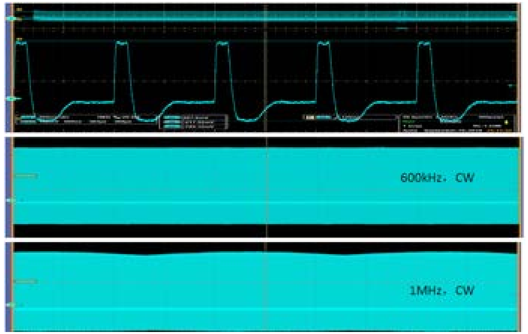


L. Yan. SSMB Online Workshop, 2020.

Induction Acceleration cell

THE INDUCTION ACCELERATION CELL IS USED TO SUPPLY THE OF RADIATION ENERGY LOSS ELECTRON BUNCHES





Achieved:

Voltage ~ 500 V

Pulse ~ 100 ns

Rep. Rate ~ 1 MHz

Current ~ 10 A

Courtesy Chuanxiang Tang

Example MLS: coherent power

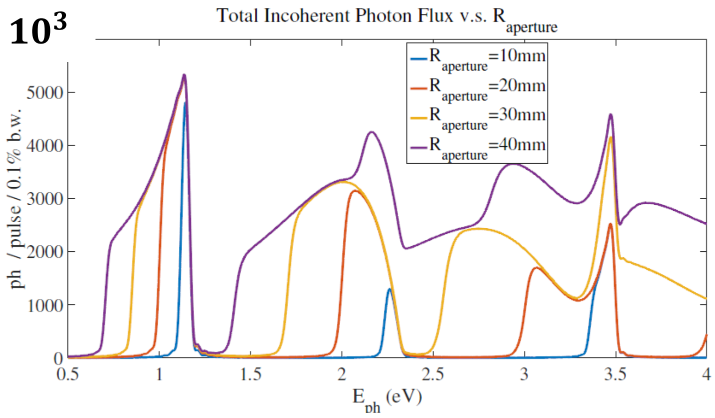
Comparing **number of photons** emitted by the U125 undulator at MLS from a **10µA single bunch** $(10^7\ e-)$
incoherent: bunch length =120µm, **coherent:** 10µA in 100 micro *bunches at 1064 nm distance*
Undulator gap set to first harmonic of 1064nm

Incoherent undulator radiation

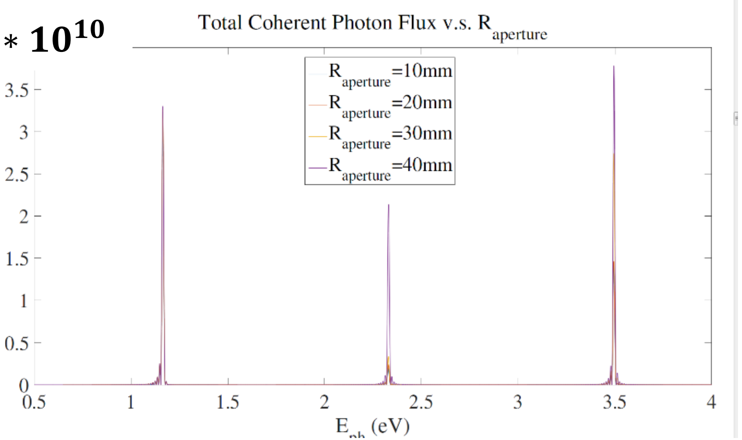
„Spectra“ calculation by Deng Xiujie

Coherent undulator radiation

$6 * 10^3$



$4 * 10^{10}$



These plots show number of emitted photons for one **single pulse**
but SSMB radiates over **many turns at repetition rates of MHz**

Steady-State Microbunching

Steady-**S**tate **M**icro**B**unching (SSMB)* aims for **microbunching** over **many turns** in storage rings

SSMB is not an FEL.

- FELs are **single-pass devices.**
- FEL mechanism is driven by an instability (self amplifying development of micro structures) -> no control
- Coherent emission leads to a **fast increase of the e- beam energy width** -> FEL process saturates

Instead for SSMB

- there is **no consecutive energy heating**/emittance growth.
  This is because of maintaining the very **precise turn-by-turn phase correlation** in the electron phase space
- **Laser modulator** is the key – causing microbunching and keeping it in steady-state
- the **Radiator** is only a **passive device**, much shorter than that in a high-gain FEL, e.g. a simple dipole

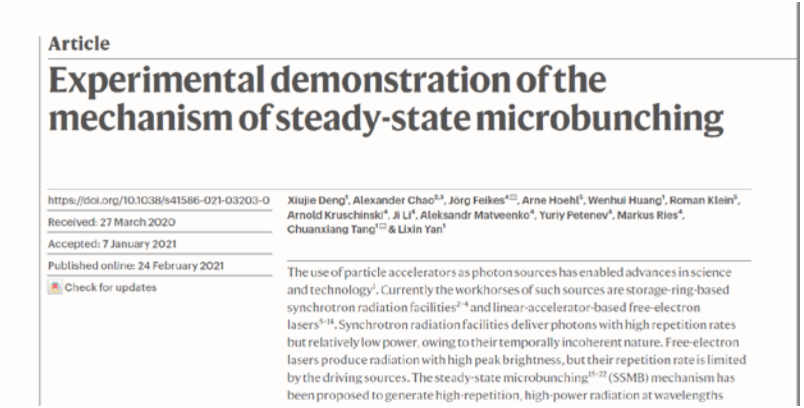
= **power emission in a 100m size storage ring comparable to a many km long SC FEL**

***Ratner, D. F. & Chao**, A. W. Steady-State Microbunching in a Storage Ring for Generating Coherent Radiation. *Phys. Rev. Lett.* **105**, 154801 (2010)

Proof-of-Principle Experiment

critical question: can a turn-by-turn phase correlation at 1 µm be maintained in a SR ?

This question was answered by **„Yes“** in a PoP experiment performed
at the **Metrology Light Source** (**MLS**) Berlin, Germany



Article

Experimental demonstration of the mechanism of steady-state microbunching

https://doi.org/10.1038/s41586-021-03203-0
Received: 27 March 2020
Accepted: 7 January 2021

Xiujie Deng[1], Alexander Chao[2,3], Jörg Feikes[4]✉, Arne Hoehl[5], Wenhui Huang[1], Roman Klein[5], Arnold Kruschinski[4], Ji Li[4], Aleksandr Matveenko[4], Yuriy Petenev[4], Markus Ries[4], Chuanxiang Tang[1]✉ & Lixin Yan[1]

The use of particle accelerators as photon sources has enabled advances in science and technology[1]. Currently the workhorses of such sources are storage-ring-based synchrotron radiation facilities[2–4] and linear-accelerator-based free-electron lasers[5–14]. Synchrotron radiation facilities deliver photons with high repetition rates but relatively low power, owing to their temporally incoherent nature. Free-electron lasers produce radiation with high peak brightness, but their repetition rate is limited by the driving sources. The steady-state microbunching[15–22] (SSMB) mechanism has been proposed to generate high-repetition, high-power radiation at wavelengths

Deng, X., Chao, A., Feikes, J. *et al.* Experimental demonstration of the mechanism of steady-state microbunching. *Nature* **590,** 576–579 (2021)

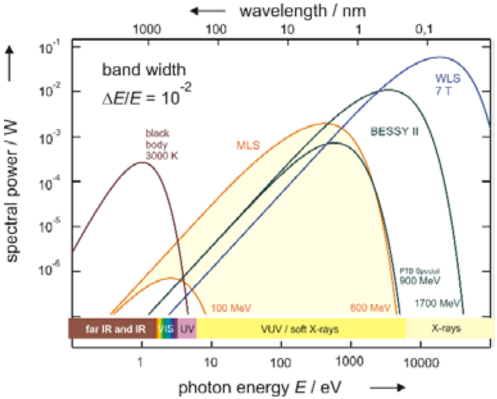
The Metrology Light Source

located south of Berlin, Germany

Circumference	48 m
Revolution frequency	f_{rev} = 6.25 MHz T_{rev} = 160 ns
Operational Energy	50 MeV **to** 630 MeV
Momentum Compaction Factor	$-5\times10^{-2} < \alpha < 5\times10^{-2}$
emittances at 250 MeV	30 nmrad (SSMB state)
RF frequency	500 MHz
Undulator	Single U125 λ_u = 125 mm

The MLS is a full time operating user machine

It is the first SR **optimized for low alpha** operation* by using a dedicated sextupole and octupole correction scheme.
Necessary condition for SSMB: **$|\alpha| \leq 2\times10^{-5}$**

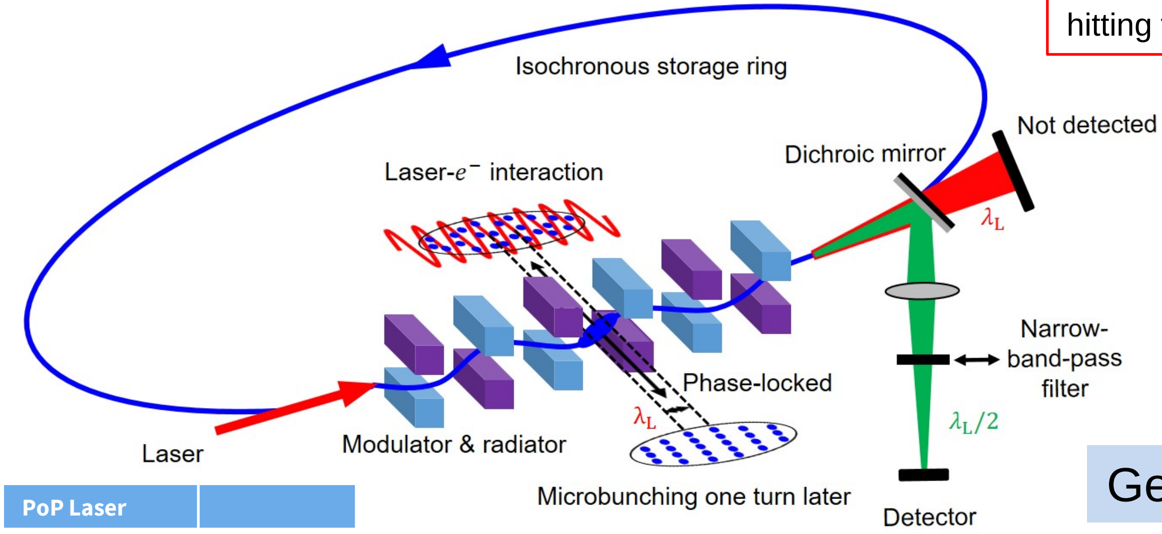


*Wüstefeld, G. et al. Metrology Light Source: The first electron storage ring optimized for generating coherent THz radiation. *Phys. Rev. ST Accel. Beams* **14**, 030705 (2011)

Proof-of-Principle Experiment 2019

E=250 MeV, α = -2x10^{-5} (negative alpha)

Coherent radiation at the first harmonic λ_L=1064 nm could **not be detected** because the detector would be instantly destroyed by the strong Laser pulse hitting the bunches **160 ns** before the CR pulse

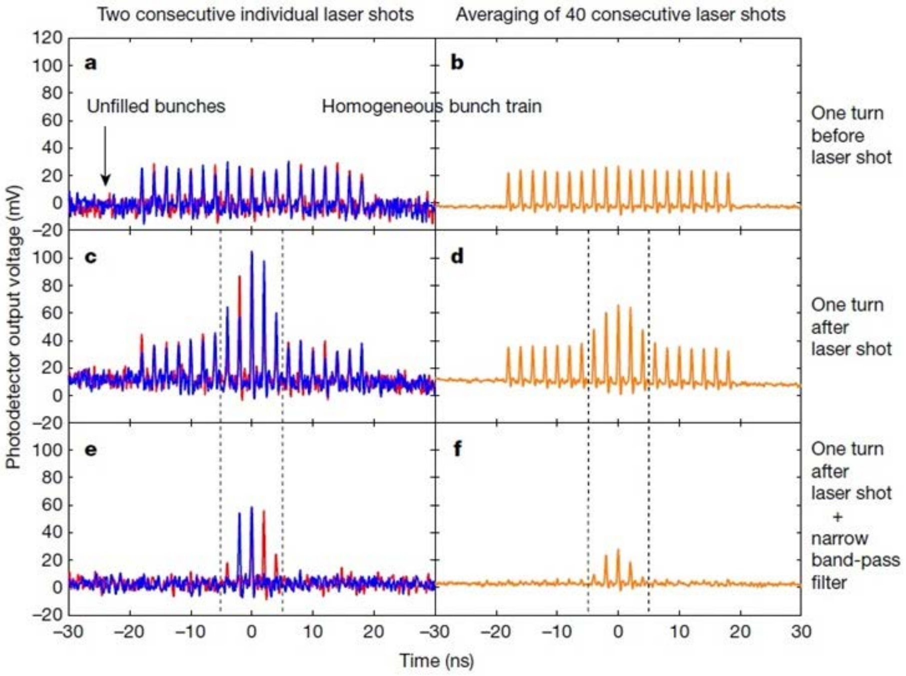


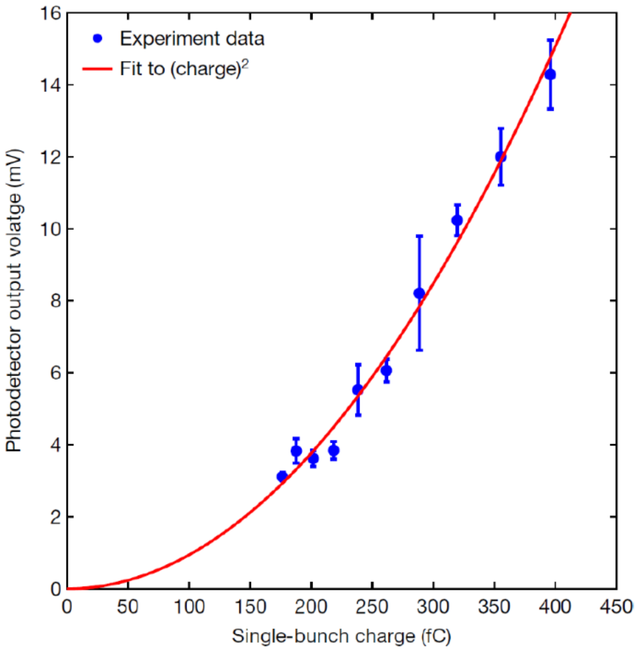
General Setup 2019/20

PoP Laser	
Wavelength	**1064 nm**
Pulse length	**5 ns** FWHM
Pulse energy	**~ 100 mJ**
Repetition rate	1.25 Hz

- Deteted signal (coherent radiation) of **the second harmonic λ_L= 532 nm** expected to be only **a few percent** of first harmonic.
- **Tolerances** on machine setting **much more tighter** for the second harmonic detection.

Coherent Radiation at second Harmonic



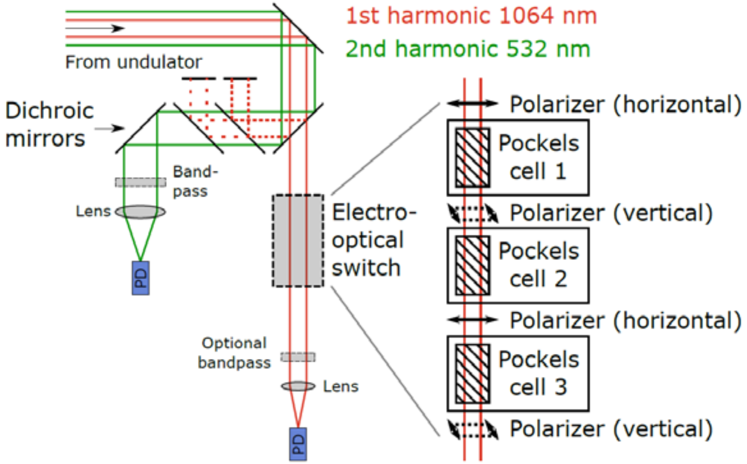


Success in 2019/2020 –proof of coherence after **one turn**

Extremely touchy to simultaneous precise setting of many relevant parameters

First Harmonic CR Detection Setup

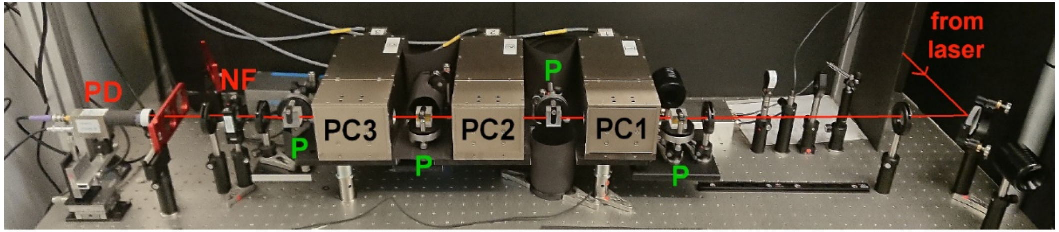
April 2021: first order CR detection scheme installed using electro-optical switches



Pockels cells are switched in such a way that the **laser pulse is blocked** while the **CR can pass 160 ns later**.

Three stages crucial to achieve 10^{-9} **attenuation** of Laser

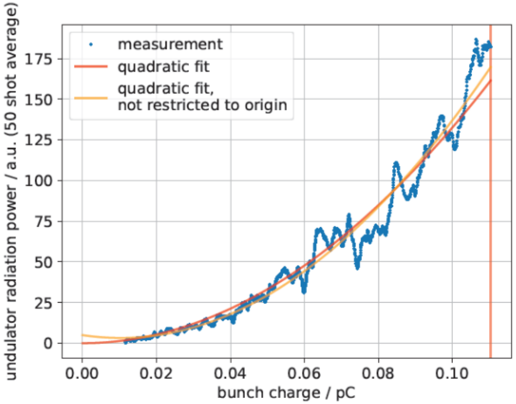
1^{st} and 2^{nd} harmonic CR are monitored in parallel



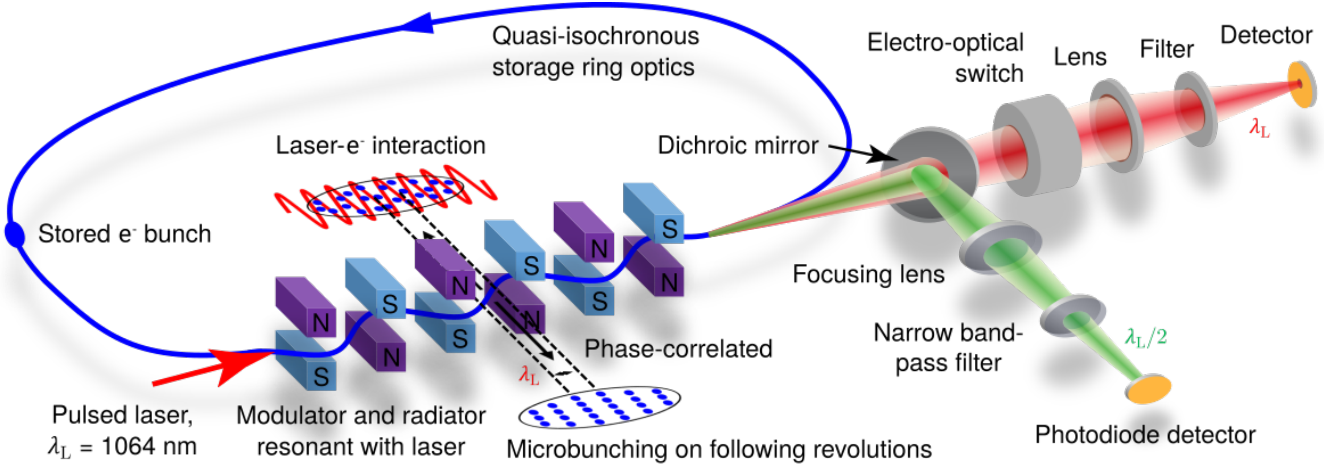
Pictures from Arnold Kruschinski, Master thesis

Improved Setup

E=250 MeV, α < $2x10^{-5}$ change to **positive alpha**



Example for improved data taking:
Scan coherent power vs bunch charge

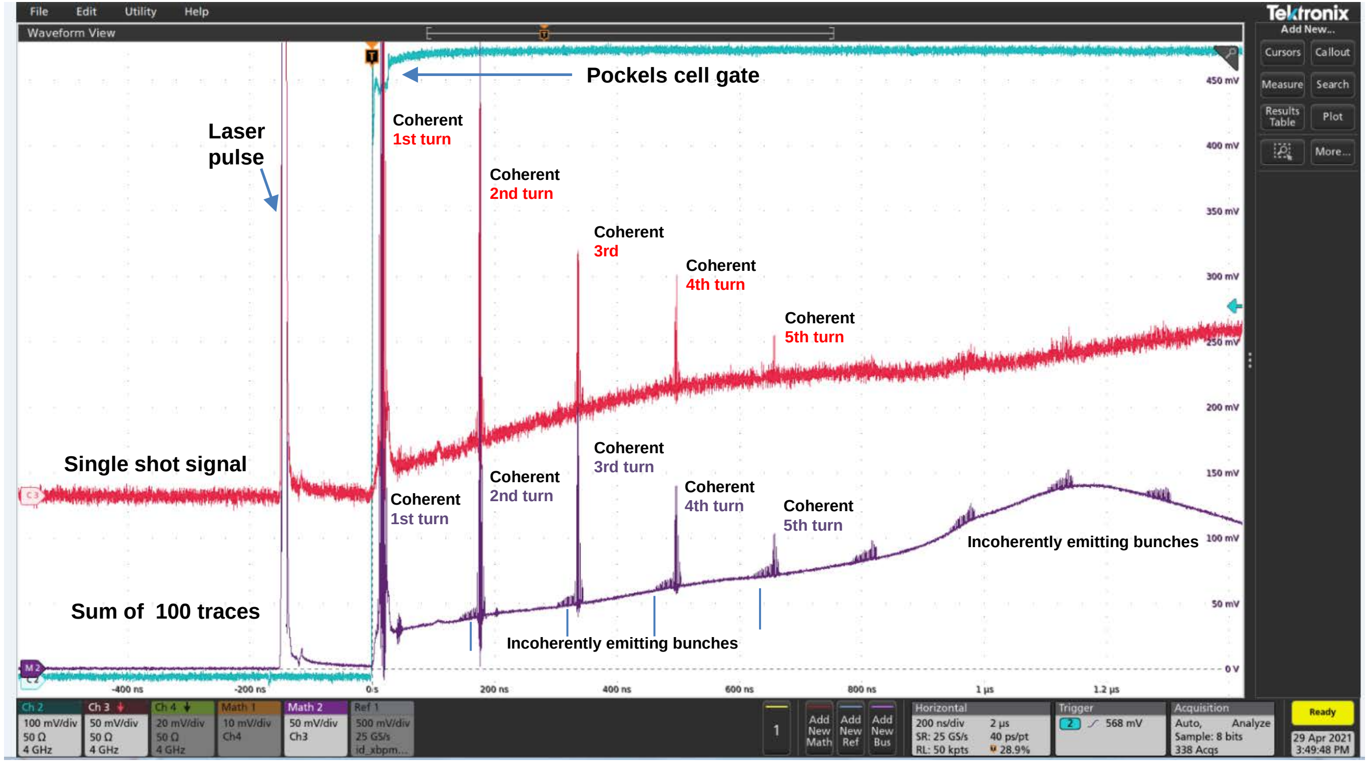


Improved Setup
in use since 2021

Coherent Radiation at first Harmonic

First test of new $\mathbf{1}^{st}$ order CR detection on 27th April 2021 gives huge success:

Strong coherent signals over many turns (> 5 µsec) -> allow systematic scans of parameter space



Ch 2: 100 mV/div, 50 Ω, 4 GHz

Ch 3: 50 mV/div, 50 Ω, 4 GHz

Ch 4: 20 mV/div, 50 Ω, 4 GHz

Math 1: 10 mV/div, Ch4

Math 2: 50 mV/div, Ch3

Ref 1: 500 mV/div, 25 GS/s, id_xbpm...

Horizontal: 200 ns/div, 2 µs, SR: 25 GS/s, 40 ps/pt, RL: 50 kpts, 28.9%

Trigger: 2, 568 mV

Acquisition: Auto, Analyze, Sample: 8 bits, 338 Acqs

29 Apr 2021 3:49:48 PM

Bunching factor

Parameter space of proper MLS setup enabling microbunching is extremely narrow !

Why ? -> lets have have a **closer look at the bunching factor** after modulating with one single Laser shot

$$\delta_{m+1} = \delta_m + A \, \sin\left(k_L z_m\right)$$

$$z_{m+1} = z_m - C_0\, \alpha(\delta_{m+1})\, \delta_{m+1}$$

$$\boxed{b(k) = \int_{-\infty}^{\infty} \mathrm{d}z\, e^{-ikz}\, \rho(z)}$$

δ = Δp/p momentum deviation

A = modulation amplitude = $\sqrt{\text{Laser power}}$ on turn 0

C_0 = orbit length for reference particle

k_L = Laser wave number

σ_δ = energy width

$\rho(z)$ = long. Bunch distribution

$\alpha(\delta) = \Delta C/C_0 / \delta$ momentum compaction factor

Bunching factor of **n-th harmonic** on **turn *m*** *(1-dimension)*

$$\boxed{b_{n,m} = J_n(nmk_L\alpha_0 C_0 A)\exp\left[-\frac{(nmk_L\alpha_0 C_0\sigma_\delta)^2}{2}\right]}$$

$$\boxed{P_{coherent} \sim |b_{n,m}|^2}$$

Why low alpha and low beam energy ?

$$\boxed{b_{n,m} = \underline{J_n}(nmk_L \boxed{\alpha_0} C_0 A) \exp\left[-\frac{(nmk_L \boxed{\alpha_0} C_0 \boxed{\sigma_\delta})^2}{2}\right]}$$

⇨ σ_δ, α_0 should be very small

(but α_0 not too small because J_n(x))

Standard optic -> SSMB optic → $|\alpha_0| = 3 * 10^{-2}$ -> $2 * 10^{-5}$ -> **1/1500**

Lowers **mean path length** change on one turn

Standard optic -> SSMB optic → z_{m+1}-z_m = **255 *μm* -> 0.17 *μm*** and below

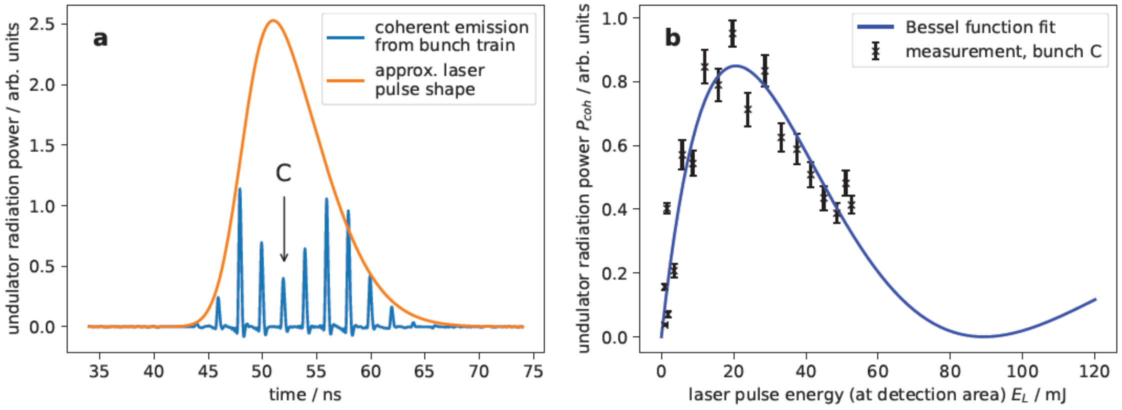
630 MeV -> 250 MeV → equilibrium energy width σ_δ= **4.5** $* 10^{-4}$ **-> 1.8** $* 10^{-4}$ -> **1/3**

Mean path length change on one turn due to longitudinal quantum excitation

630 MeV –> 250 MeV → z_{m+1}-z_m= **260 *nm* -> 26 *nm*** (~ $\gamma^{2.5}$) -> **1/10**

Impact of the Laser modulation depth

$$b_{n,m} = J_n(nmk_L\alpha_0 C_0 A)\exp\left[-\frac{(nmk_L\alpha_0 C_0\sigma_\delta)^2}{2}\right]$$



Arnold Kruschinski et al,
Next steps towards steady-state microbunching:confirming the theoretical foundation, to be publ

Fig. 2 Dependence of coherent emission power on laser modulation strength. a, coherent emission from individual bunches at maximum laser power one turn after modulation (data averaged over 20 consecutive laser shots). Approximate laser pulse shape is overlaid as a guide (shifted forward in time and scaled vertically to match coherent emission pulses). **b**, coherent emission of central bunch "C" for different laser pulse energies. Data points show average over 50 consecutive laser shots. Error bars represent standard error of the mean. The blue curve is a fitted function of the type $P_{coh} = a_1\left|J_1(a_2\sqrt{E_L})\right|^2$ with the Bessel function of the first kind J_1.

Energy widening effects at low alpha

single particle effects **limiting the smallest achievable bunch length**

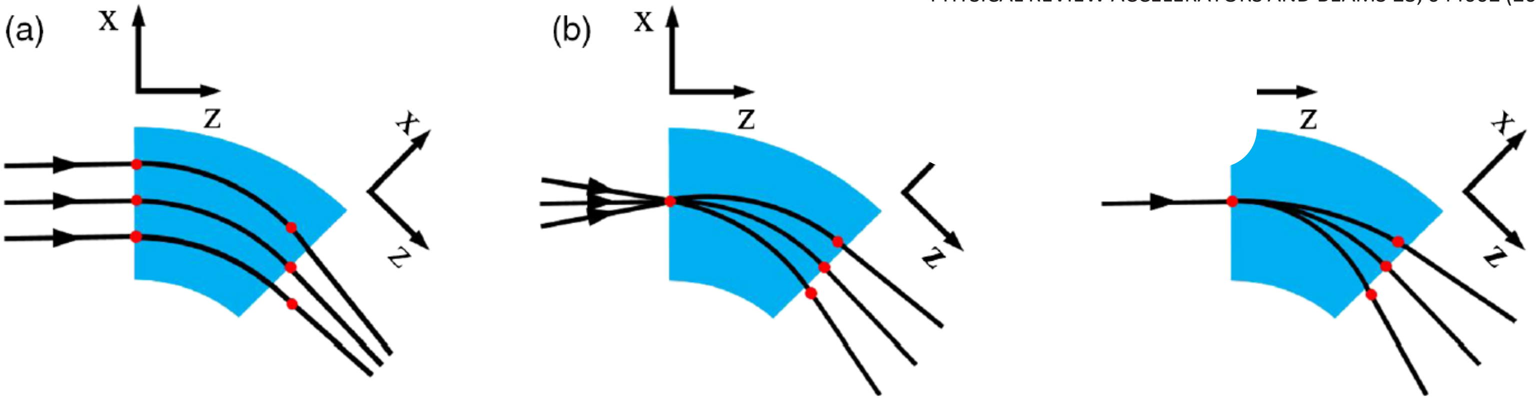
when operating at a **very low value** of **momentum compaction factor**

1. first order transverse-longitudinal coupling
2. second order transverse-longitudinal coupling
3. longitudinal quantum excitation („partial alpha effect“)

First order long-trans coupling

- Particles with different betatron amplitudes and phases pass bending magnets on different trajectories, resulting in a longitudinal displacement differences (Shoji, Wüstefeld, Huang, Chao et al.):

Deng et al, **Single-particle dynamics of microbunching**
PHYSICAL REVIEW ACCELERATORS AND BEAMS 23, 044002 (2020)



Linear transverse-longitudinal coupling induced by a bending magnet. Particles with different horizontal positions (a) and angles (b) pass the horizontal bending magnet along different paths, resulting in longitudinal coordinate differences. Particles with different energies (c) also pass the horizontal bending magnet along different paths, resulting in horizontal position and angle differences.

First order long-trans coupling

Drift of longitudinal position on m-th revolution

$$\Delta z_{B,m} = \sqrt{4\epsilon_x \mathcal{H}_x \sin^2(m\pi\nu_x) + 4\epsilon_y \mathcal{H}_y \sin^2(m\pi\nu_y)}.$$

Here, $\nu_{x,y}$ are the horizontal and vertical betatron tunes (number of transverse oscillations per revolution), $\epsilon_{x,y}$ are the transverse beam emittances and $\mathcal{H}_{x,y}$ are the horizontal and vertical chromatic functions at the modulation point defined as

$$\boxed{\mathcal{H}_{x,y} = \gamma_{x,y} D_{x,y}^2 + 2\alpha_{x,y} D_{x,y} D'_{x,y} + \beta_{x,y} D'^2_{x,y}}$$

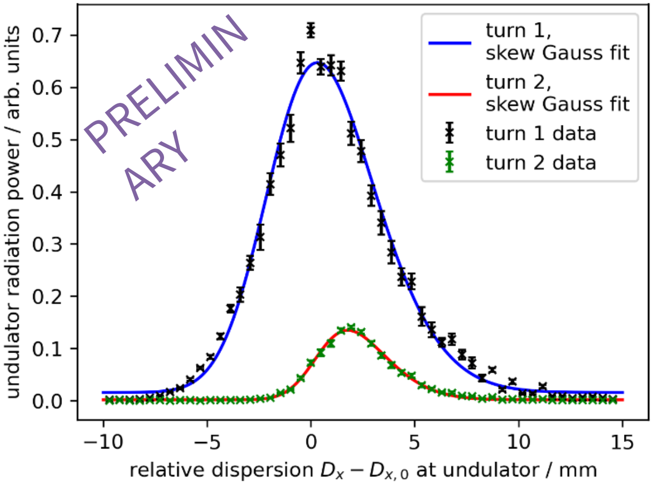
Only when **Dispersion and Dispersion angle** are simultaneously reduced down to a **few mm** then micro bunching and coherent emission become possible

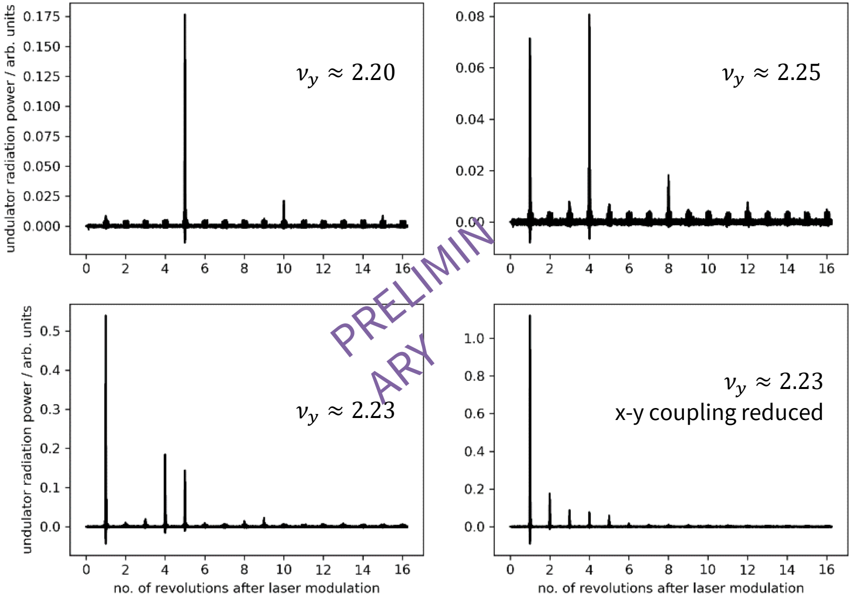
RECENT RESULTS : TRANSVERSE-LONGITUDINAL COUPLING

Bunching factor on
m-th revolution

$$\mathrm{b}_m = J_1(mk_L\alpha_0C_0A)\cdot\exp\left[-\frac{k_L^2}{2}\left\{(m\alpha_0C_0\sigma_\delta)^2+4\epsilon_x\boxed{\mathcal{H}_x}\sin^2(m\pi\nu_x)+4\epsilon_y\mathcal{H}_y\sin^2\boxed{(m\pi\nu_y)}\right\}\right]$$

GAUSSIAN DEPENDENCE ON DISPERSION ($\mathcal{H}_x \sim D_x^2$ @ UNDULATOR)





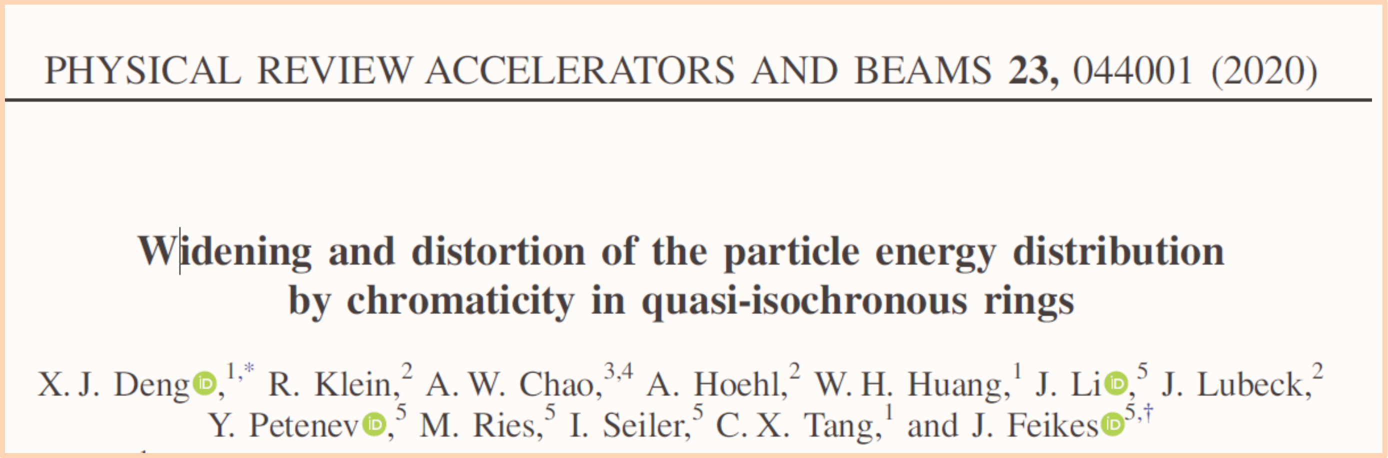
Confirmation of theoretical prediction is crucial, as proposed SSMB schemes will take advantage of transverse-longitudinal coupling!

Arnold Kruschinski et al, *Next steps towards steady-state microbunching:confirming the theoretical foundation,* to be published

Second order transverse coupling

Second order transverse coupling effect:

- Confirmed experimentally at MLS
- Instructive energy widening effect
- Is suppressed by very acurate **compensation of horizontal chromaticity**



PHYSICAL REVIEW ACCELERATORS AND BEAMS **23,** 044001 (2020)

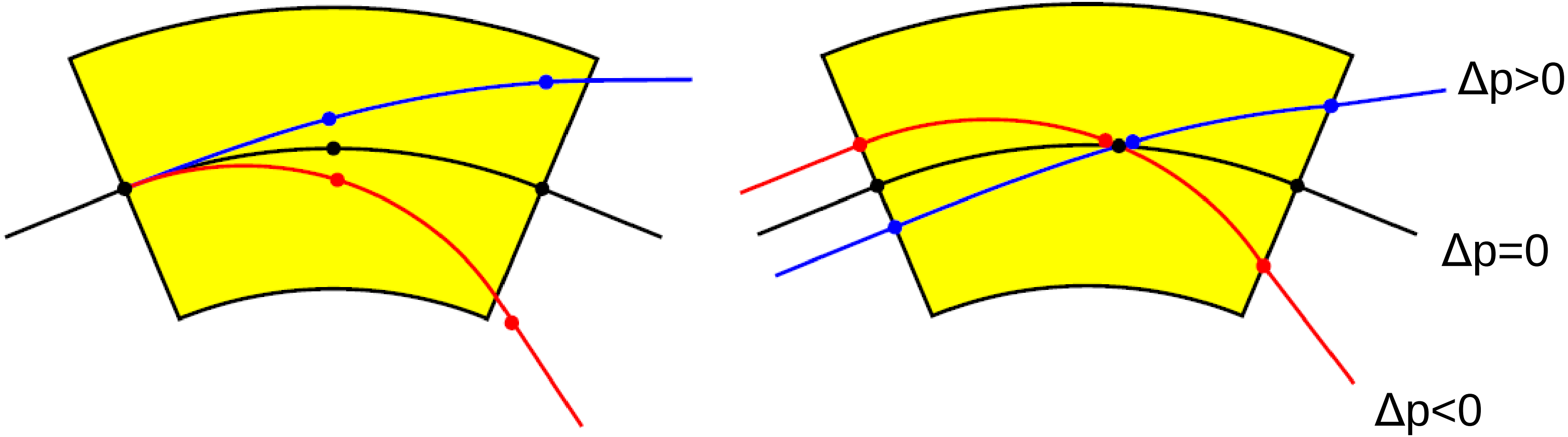
Widening and distortion of the particle energy distribution by chromaticity in quasi-isochronous rings

X. J. Deng,[1,*] R. Klein,[2] A. W. Chao,[3,4] A. Hoehl,[2] W. H. Huang,[1] J. Li,[5] J. Lubeck,[2]
Y. Petenev,[5] M. Ries,[5] I. Seiler,[5] C. X. Tang,[1] and J. Feikes[5,†]

Chromatic orbits in isochronic DBA optic

$$\alpha_0 = \frac{1}{C_0} \oint \frac{D_0(s)}{\rho(s)} \mathrm{d}s$$

$$\int_0^{L_{\mathrm{dip}}} \frac{D(s)}{\rho(s)} \mathrm{d}s = 0 \quad \forall \quad \text{dipoles},$$



(a) DBA lattice path length

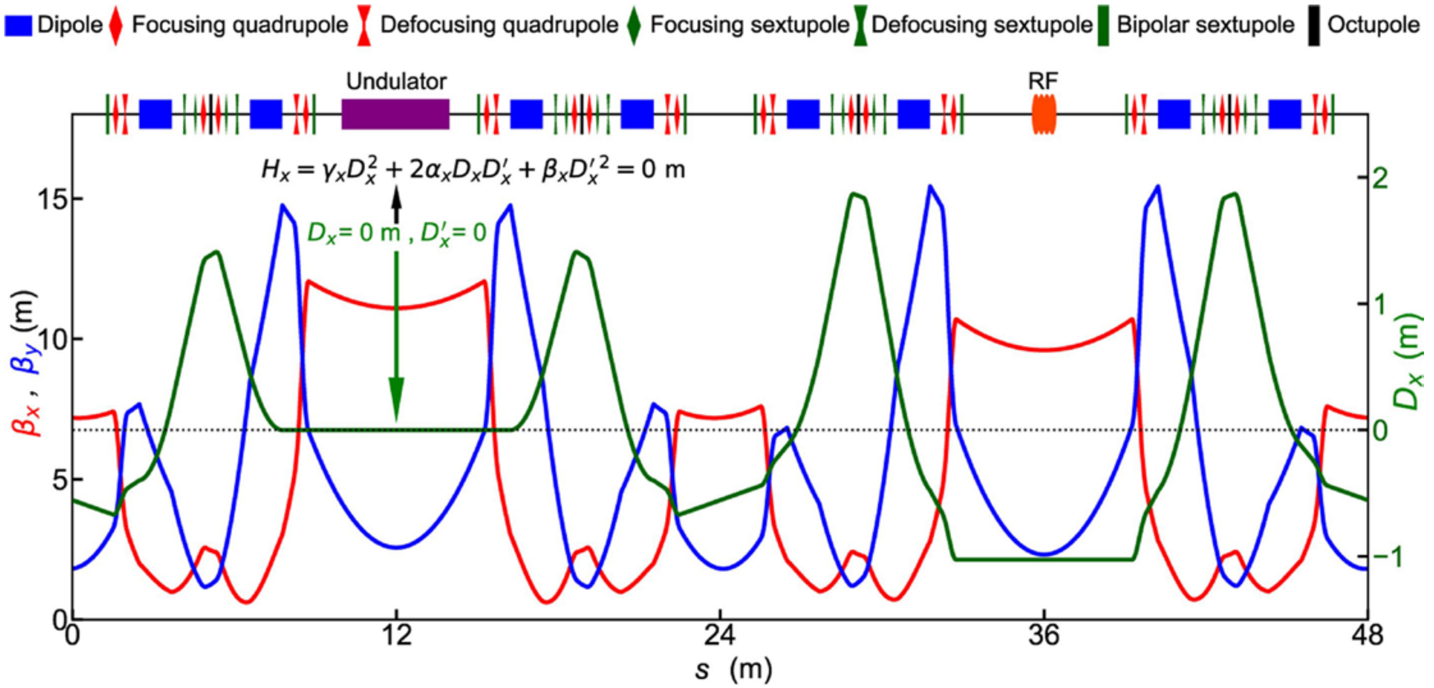
(b) isochronous lattice path length

M. Ries, *Nonlinear momentum compaction and coherent synchrotron radiation at the Metrology Light Source*, Ph.D. thesis, Humboldt-Universit�at zu Berlin, Germany (2014).

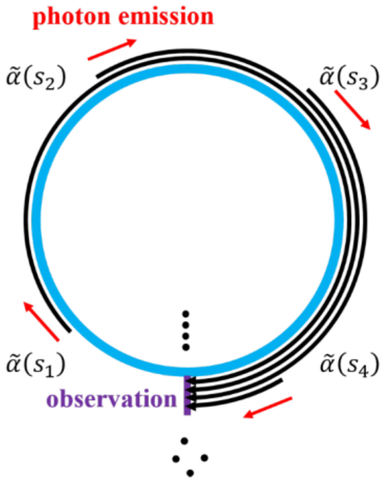
Isochronous SSMB optic

Positive and negative Dispersion on one **complete** turn cancel exactly

$\longrightarrow \alpha_0 \approx 0$



“Partial alpha” effect in isochronous optic



The Dispersion on path from **random photon emission point *s*** to a fixed observation point **does not cancel** !

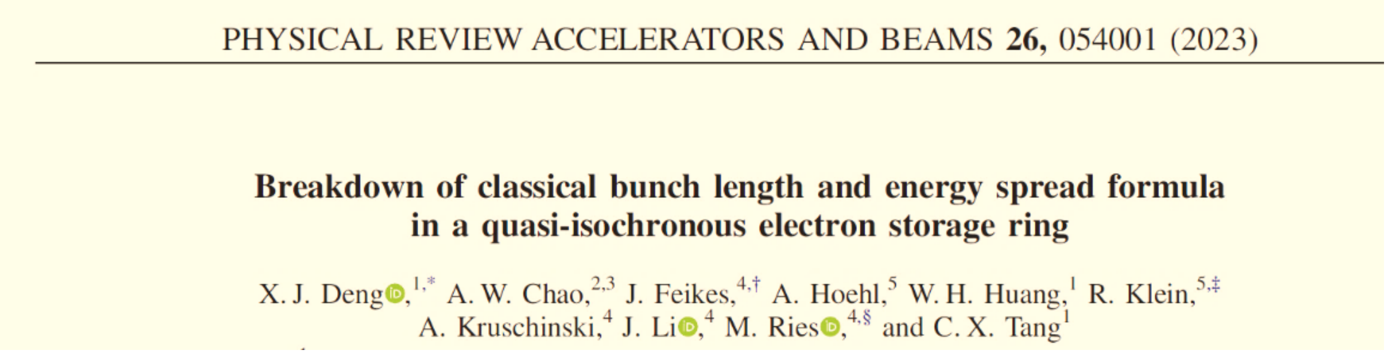
$\tilde{\alpha}$ *(s)* = *„partial α(s)“* is **non-zero** -> **stochastic excitation** (**l**ong **q**uantum **e**xcitation)

-> Increasing **energy spread and bunch lengthening** at very low *α*

$$\sigma_\tau = \sqrt{\sigma^2_{\tau,\ \mathrm{Sands}} + \sigma^2_{\tau,\ \mathrm{lqe}}}$$

$\sigma_{\tau,lqe} \sim$ Variance{$\tilde{\alpha}$ (s)}

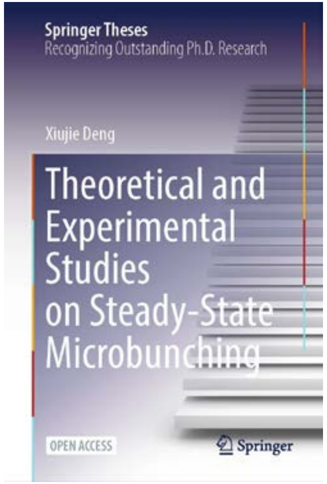
The „partial alpha effect“ was confirmed and quantified at MLS



PHYSICAL REVIEW ACCELERATORS AND BEAMS **26,** 054001 (2023)

Breakdown of classical bunch length and energy spread formula in a quasi-isochronous electron storage ring

X. J. Deng,[1,*] A. W. Chao,[2,3] J. Feikes,[4,†] A. Hoehl,[5] W. H. Huang,[1] R. Klein,[5,‡] A. Kruschinski,[4] J. Li,[4] M. Ries,[4,§] and C. X. Tang[1]



Springer Theses
Recognizing Outstanding Ph.D. Research

Xiujie Deng

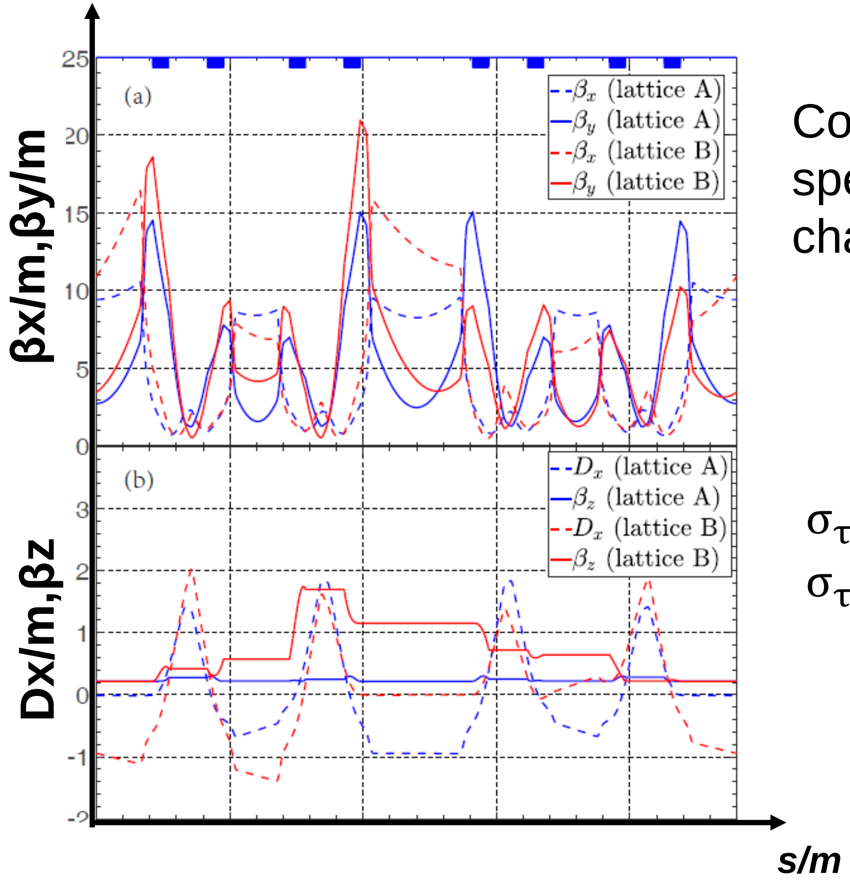
Theoretical and Experimental Studies on Steady-State Microbunching

OPEN ACCESS

Springer

But: **former theoretical description had to be extended to correctly fit the experimental data**

Courant-Snyder formalism of longitudinal dynamics, X. J. Deng, A. W. Chao, et al,
Phys. Rev. Accel. Beams 24, 094001 –2021



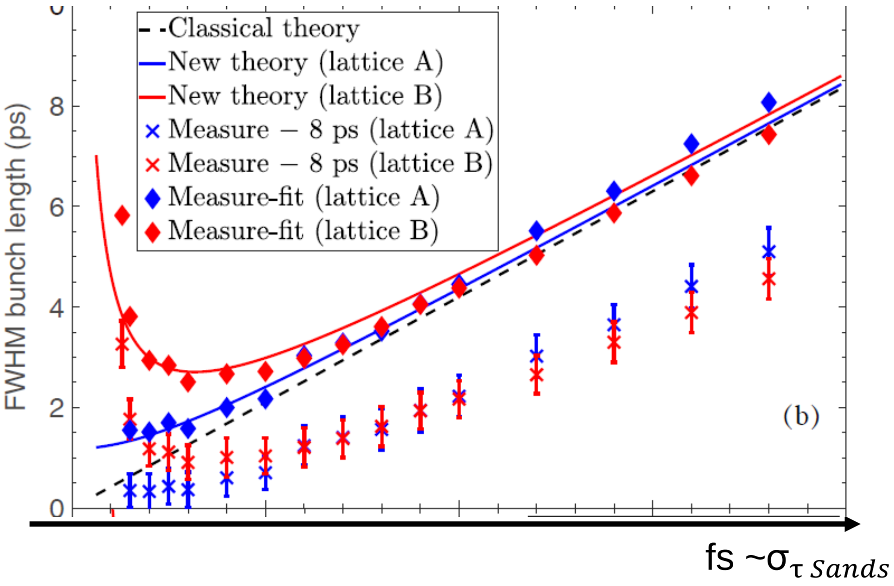
Comparing the **low alpha user optics** with a specially designed **„partial alpha optic“** characterized by stronger varying $\tilde{\alpha}$(s)

$\sigma_{\tau,lqe}$~ Variance{$\tilde{\alpha}$ (s)}

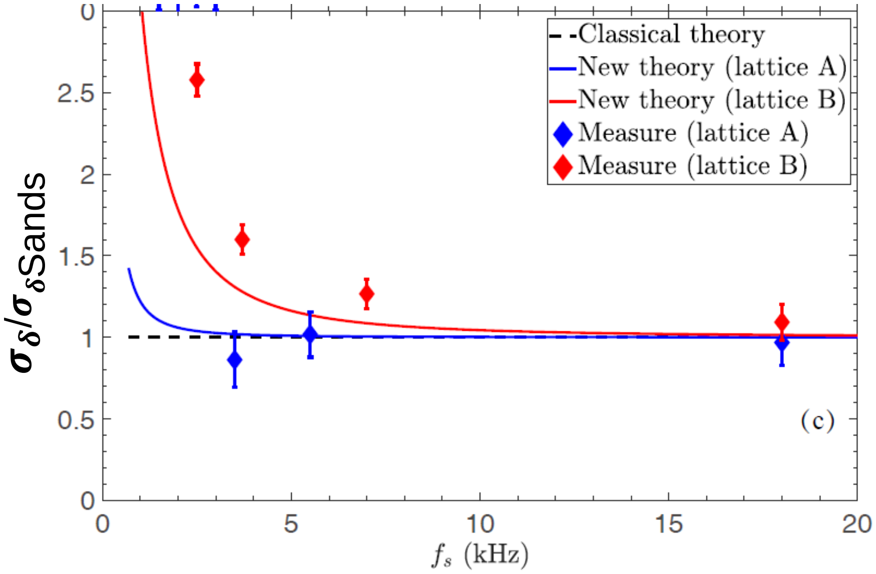
$\sigma_{\tau,lqe}$ = 115 fs in standard low alpha = **lattice A**
$\sigma_{\tau,lqe}$ = 470 fs in partial alpha optic = **lattice B**

$$\sigma_\tau = \sqrt{\sigma^2_{\tau,\ \mathrm{Sands}} + \sigma^2_{\tau,\ \mathrm{lqe}}}$$

“Partial alpha” effect, exp. Data



Bunch length -> Streak camera



Energy width -> Compton Backscattering

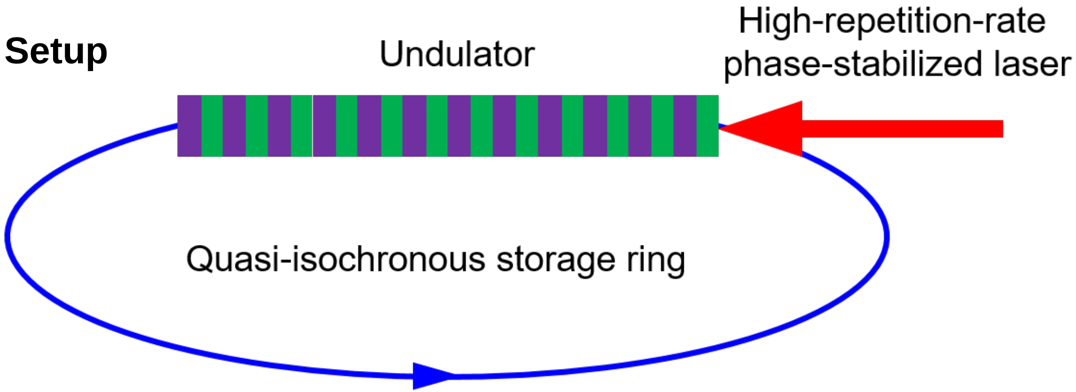
Impact of partial alpha effect

- longitudinal quantum excitation is **the limiting effect** for some SSMB source
- can not be mitigated
- Strong guideline for the design of a proper SSMB lattice:
  many dipoles with **small bending angles** to minimize Variation of α(s)
- limits use of e- beam to ~ 100ns before SSMB is suppressed by the increasing energy spread

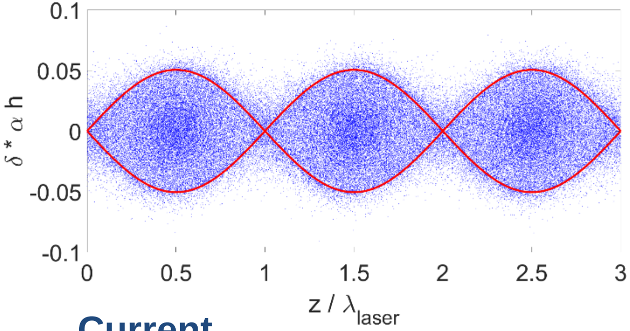
PoP Phase II

ON THE BASIS OF PHASE I, THE NEXT STEP IS TO SUSTAIN THE MICROBUNCHING FOR MULTIPLE (~ 1000) TURNS TO REACH A QUASI-STEADY STATE, BY REPLACING THE LASER USED IN PHASE I WITH A HIGH-REPETITION PHASE-LOCKED LASER

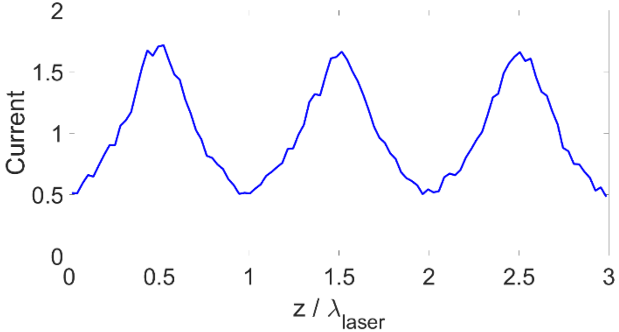
Setup



Phase space



Current



- **Dedicated laser system development complete**

Courtesy Chuanxiang Tang

Summary

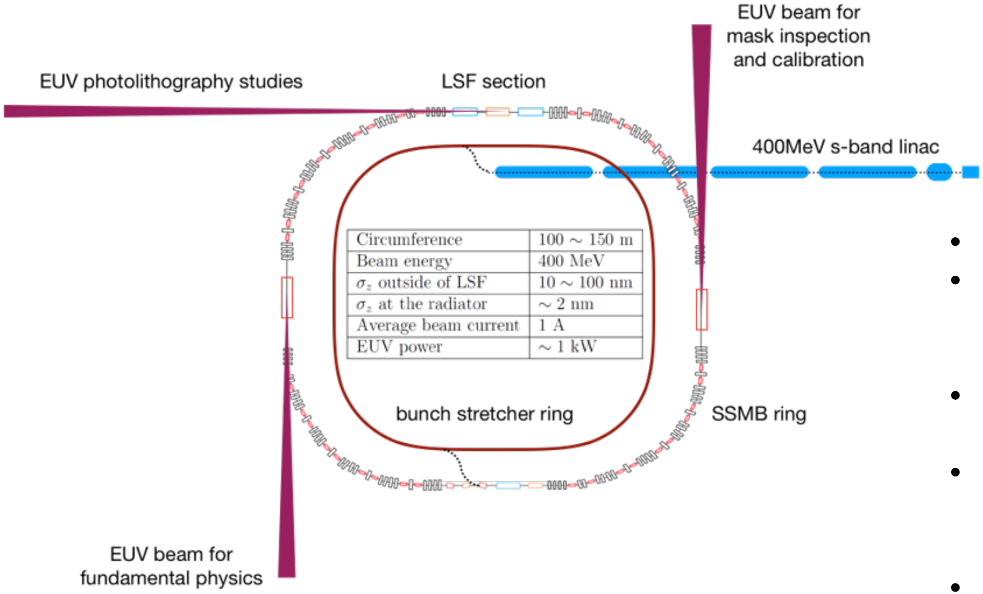
- SSMB:
  - Understanding of complex dynamics achieved
  - Quantitative studies confirm theory → Transverse-longitudinal coupling → long. quantum exc.
  - All recipes are now available to develop a SSMB source

- Next SSMB PoP phase in preparation:
  - Modulate electron beam turn-by-turn for up to 1000 revolutions to achieve a quasi-steady state
  - High repetition rate laser under construction and optimization by Chinese collaboration partners

Future perspective: Tsinghua EUV SSMB Ring

Aiming for 3 nm microbunches @ 400 MeV for the first time in a storage ring

Status: under in-depth study + technical development -> trying to get fund



Circumference	100 ~ 150 m
Beam energy	400 MeV
σ_z outside of LSF	10 ~ 100 nm
σ_z at the radiator	~ 2 nm
Average beam current	1 A
EUV power	~ 1 kW

Courtesy Chuanxiang Tang from
1^{st} SSMB Lightsource Online Workshop,
7-9 December 2020 Shanghai
http://indico-cdex.ep.tsinghua.edu.cn/event/38/
-> interested will find many details to this project here !

Some potential applications:

- High-power EUV radiation for **EUV lithography**
- Energy-tunable high-flux narrowband EUV photons for condensed matter physics e.g. **angle-resolved photoemission spectroscopy**
- Ultrahigh-power deep ultraviolet and infrared for atomic and molecular physics
- high power radiation for ultrashort (sub-femtosecond to attosecond) photon pulses and pulse trains with **definite phase relations**
- nonlinear phenomena and dynamical properties of materials can be driven and studied by **high-peak and average-power terahertz radiation**