Survey, Outlook and Perspectives

Short-Pulse Schemes in Storage Ring based Light Sources

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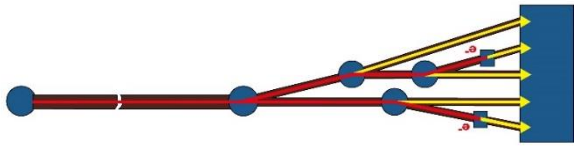
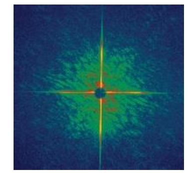
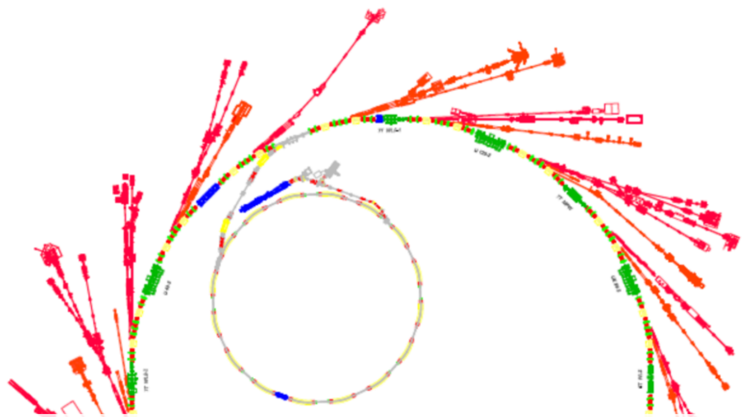
KfB-Perspektiven-Workshop
Strahlungsquellen
26. – 27.04.2018, Karlsruhe

Living in a world with FEL, providing fs (even as) pulses with > 10^{12} photons:





Why “short” pulses in storage rings?



And what is “short” in this context ?

100 ps – 10 ps – 1 ps – 100 fs – …

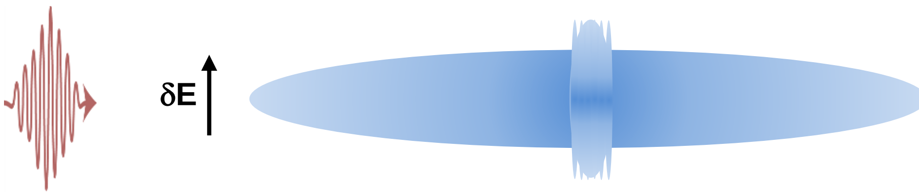
Short pulses in storage rings – Why?

- **generation of a continuous stream of broadband coherent radiation (CSR) in the THz / IR regime**
- **broad range of pulse repetition rates kHz – MHz – hundreds of MHz possible**
- **extremely stable pulses in the storage ring environment (pulse to pulse, day by day)**
- **can be used with the full suite of IDs and beamlines available**
- **users can select between short pulses (*and long pulses*) and high flux/brilliance**
- **many questions to be answered in the linear regime**
- **probing (radiation) sensitive samples**

“ordinary” electron bunch in SR

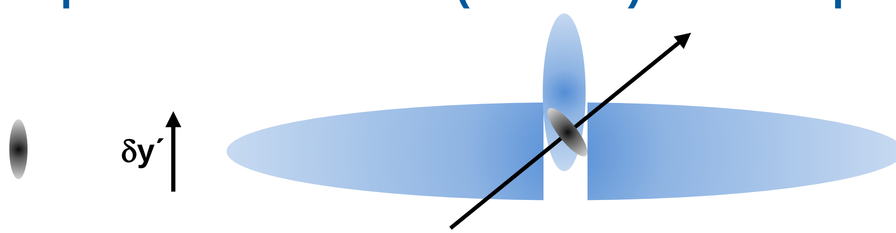
manipulation (seeding) with short (~ 50 fs) laser pulses

CHG coherent harmonic generation
EEHG echo enabled harmonic generation



laser slicing

manipulation with short (~ 100 fs) electron pulses



e^{-}-beam slicing

manipulation with transversal deflecting cavities (“crab cavities”)

transform

δE-s / δy´-s correlation

in a separation

photons from slice
↕
photons from bunch

~ 100 fs to ps photon pulses

at reduced intensity

“ordinary” electron bunch in SR

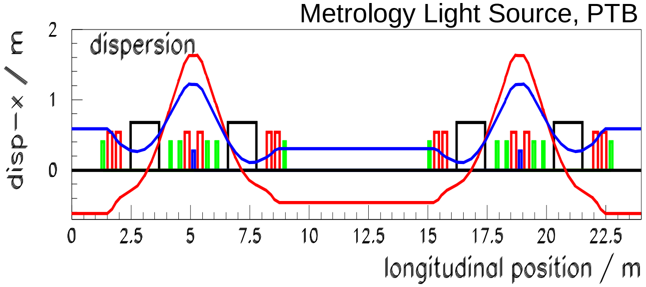
some 10 ps, some nC

$$\sigma_{bunch} \sim \sqrt{\frac{\alpha_c}{\dot{V}_{RF}}}\,, \quad I_{bunch} \sim \alpha_c$$

low-alpha operation

tuning the lattice – reducing momentum compaction factor α_c

Metrology Light Source, PTB



$$\frac{1}{10}\sigma_{bunch} \quad \text{requires} \quad \frac{1}{100}\alpha_c$$

$$\rightarrow \frac{1}{100} I_{bunch}$$

high RF gradient operation

sc cavities with high voltage @ higher frequencies – increasing V_{RF}

BESSY VSR
Helmholtz-Zentrum Berlin

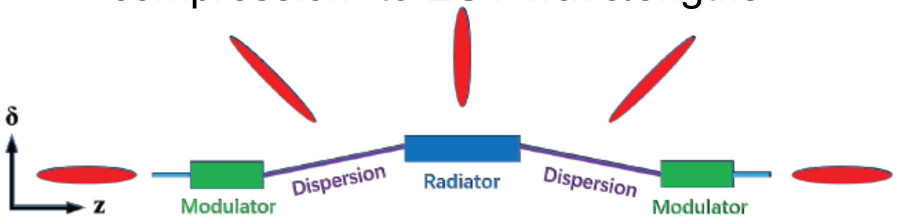
$$\frac{1}{10}\sigma_{bunch} \quad \text{requires} \quad 100 \times \dot{V}_{RF}$$

$$\rightarrow I_{bunch} = const.$$

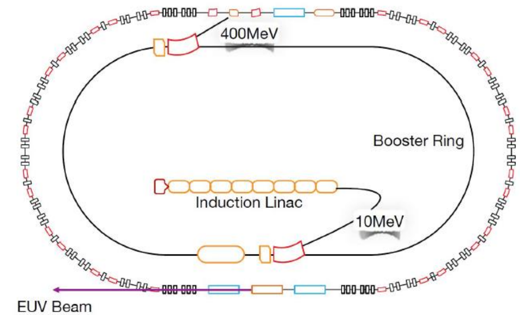
Steady State Micro Bunching SSMB → see talk C. Tang, TUB, (FLS18, THP2WB02)

graphics courtesy C. Tang, TUB

“compression” to EUV wavelengths



modulation on UV wavelength → SSMB in dedicated ring optics

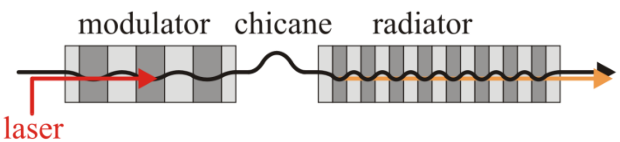


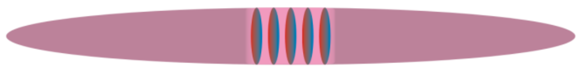
F. Ratner, A. Chao, PRL 105.15 (2010)

CHG, EEHG schemes → see talk S. Khan, TU Dortmund (FLS18, THP2WB04)

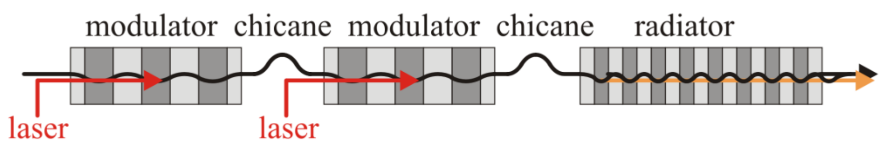
graphics courtesy S. Khan, TU Dortmund

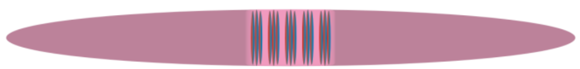
CHG

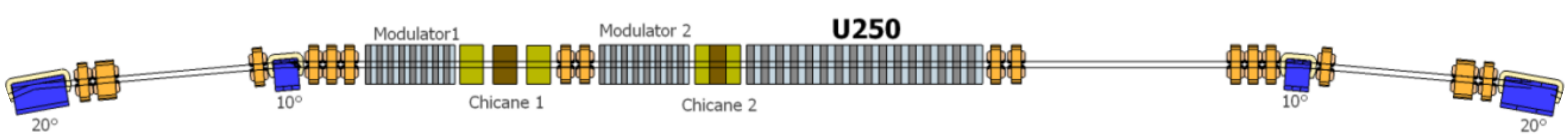




EEHG







realising EEHG in a storage ring @ DELTA, TU Dortmund

e.g. FEMTOSPEX Facility, BESSY II/HZB

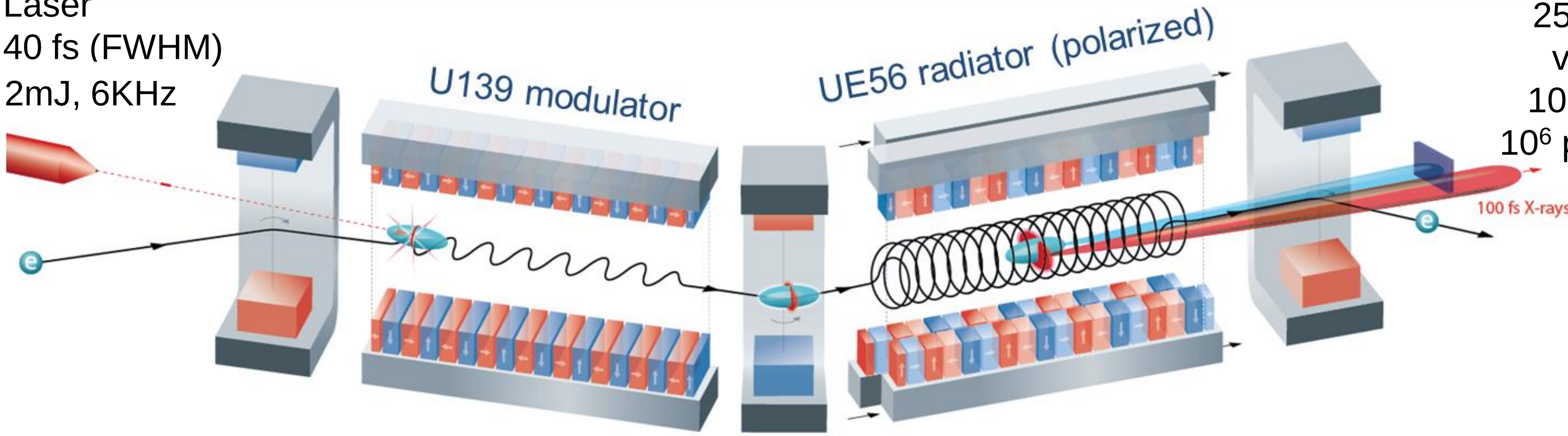
graphics from K. Holldack, HZB

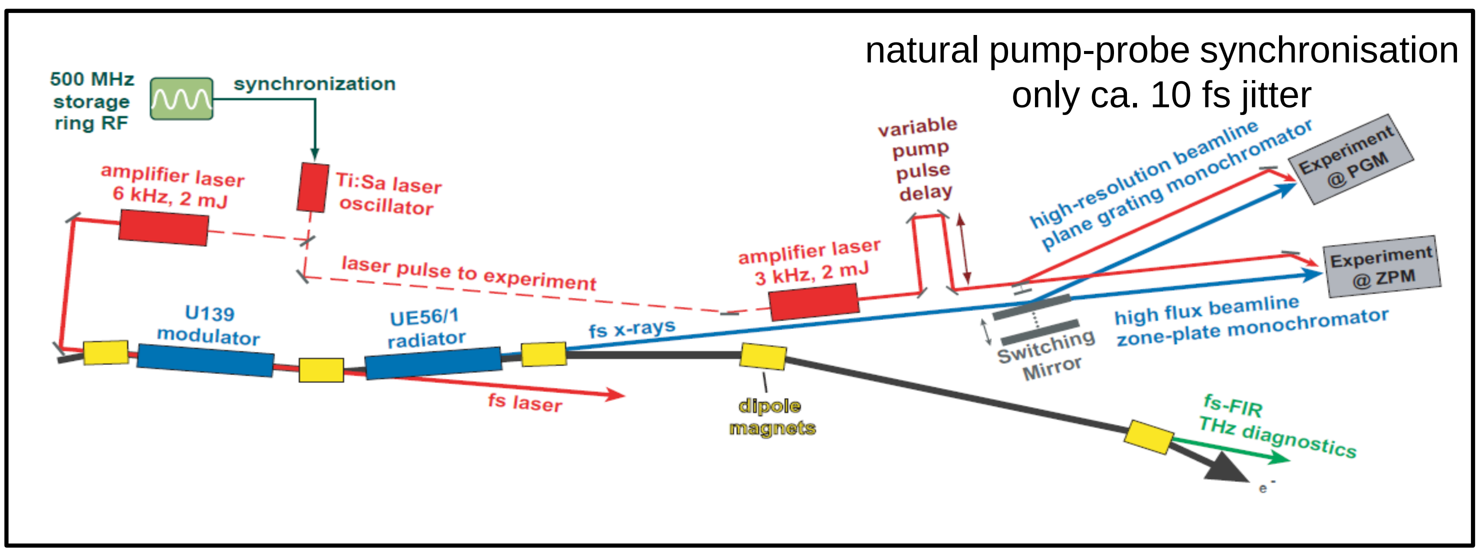
A. Zohlents et al., PRL 76 (6) 912 (1996) (basic principle)
R.W. Schoelein et al., Science, March 24, (2000) 2237
S. Khan et al.,PRL 97 (7), 074801 (2006)
K. Holldack et al., JSR, ISSN 1600-5775 (2014)

consecutive slicing on three, high charge, bunches

Laser
40 fs (FWHM)
2mJ, 6KHz

250 – 1400 eV
variable pol.
100 fs (FWHM)
10^6 ph/s/0.1% BW





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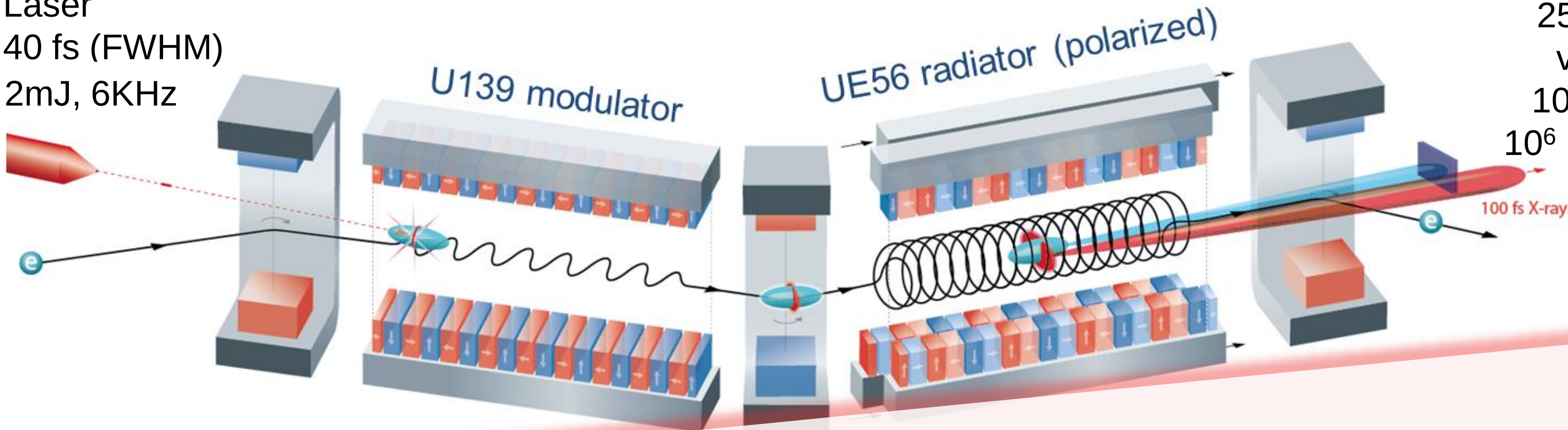

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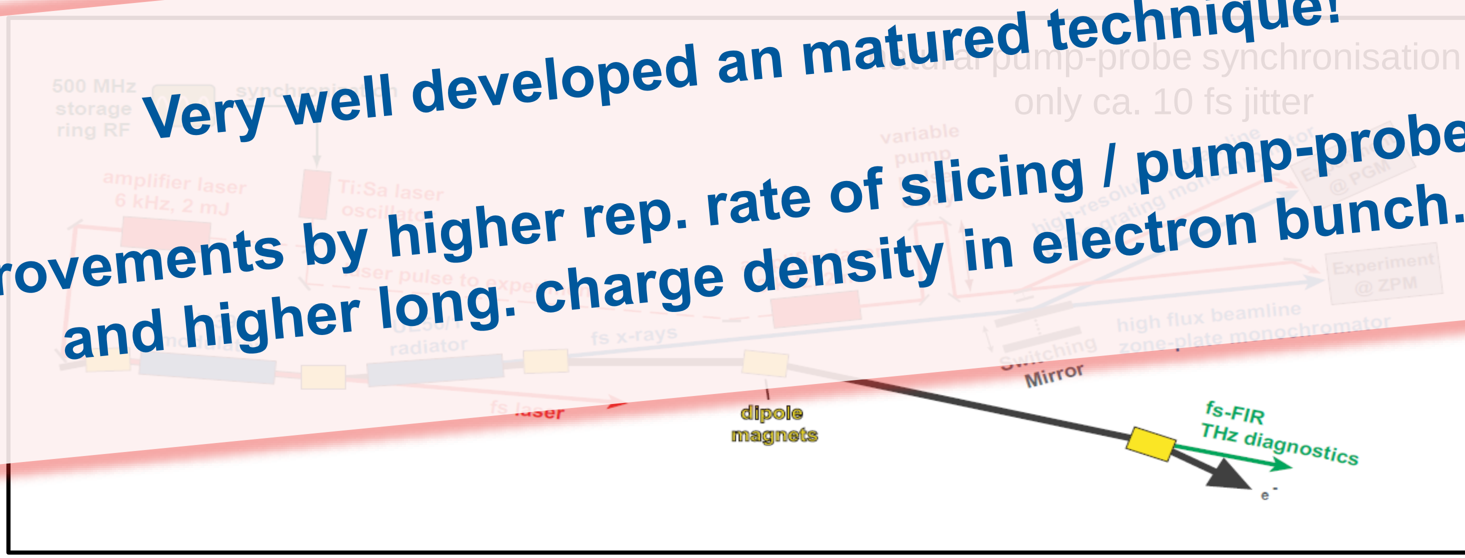


Very well developed an matured technique!

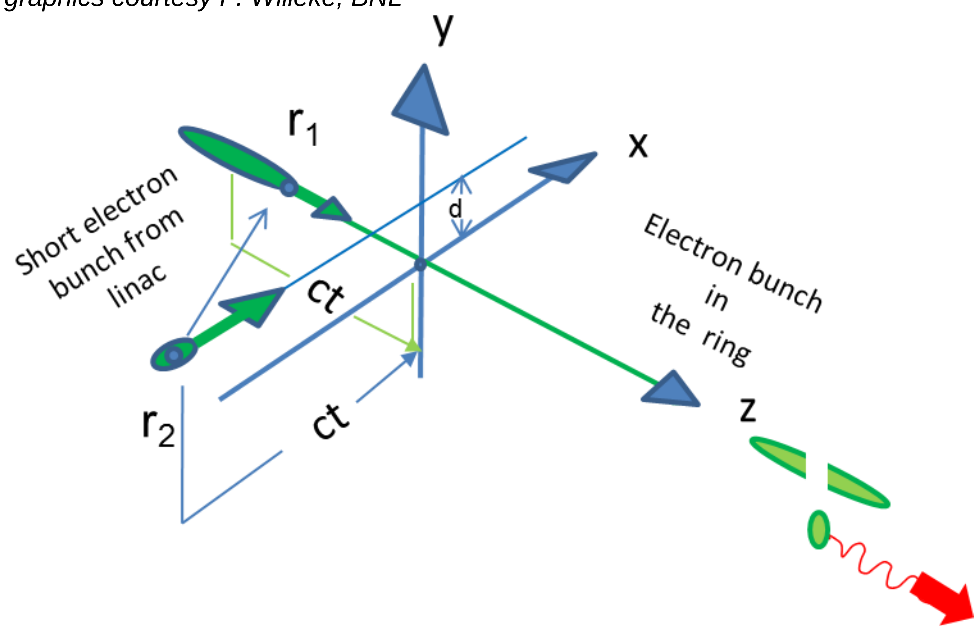
Improvements by higher rep. rate of slicing / pump-probe laser and higher long. charge density in electron bunch.

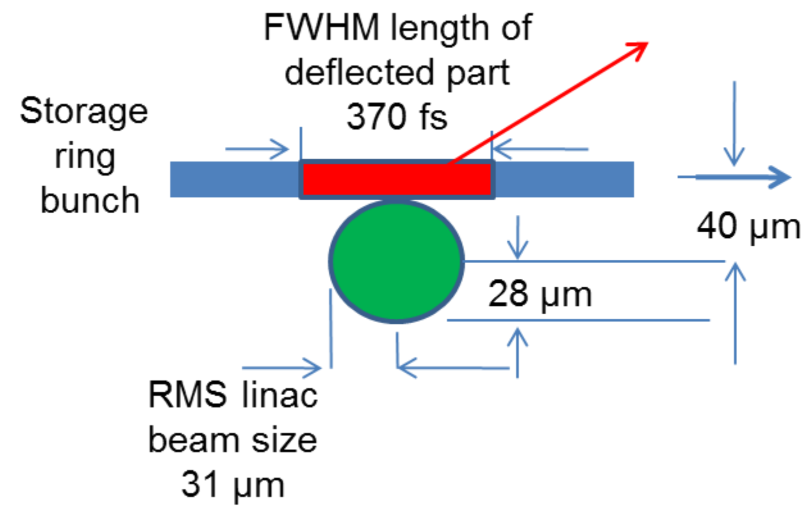
Electron beam slicing – basic principle

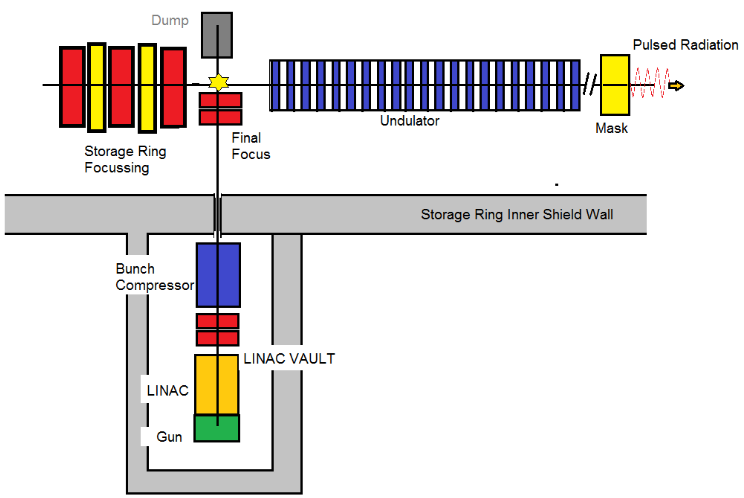
Design Study for electron beam driven slicing @ NSLSII, F. Willeke, L.H. Yu, et al.

graphics courtesy F. Willeke, BNL

F. Willeke et al, IPAC2013, 1134







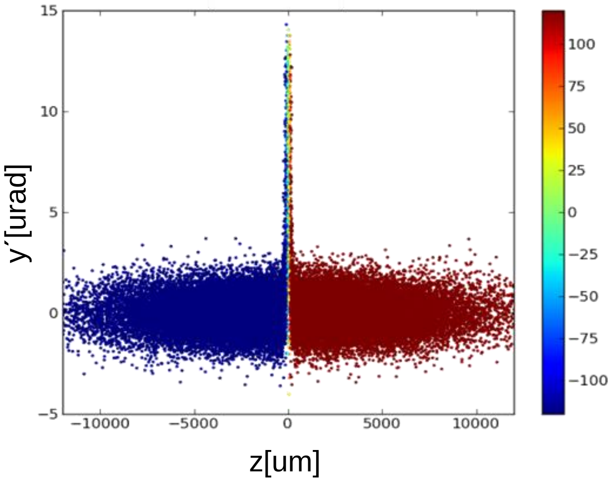
Kick beam:

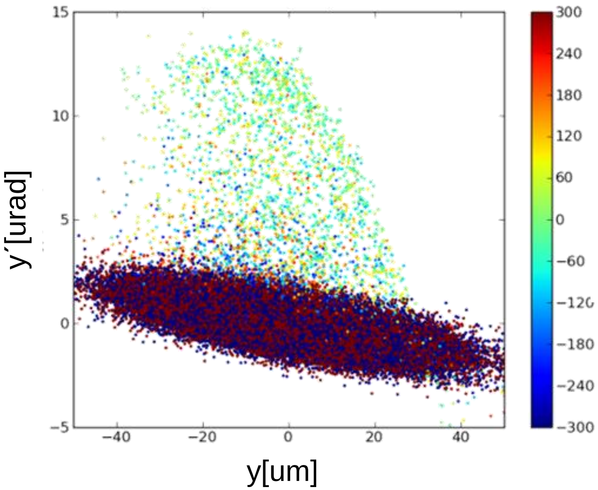
5 MeV, 50 pC, 150 fs, ε_n=5 μm

30 μm beam size requires 2 mm beta-function (linac with photo RF gun)

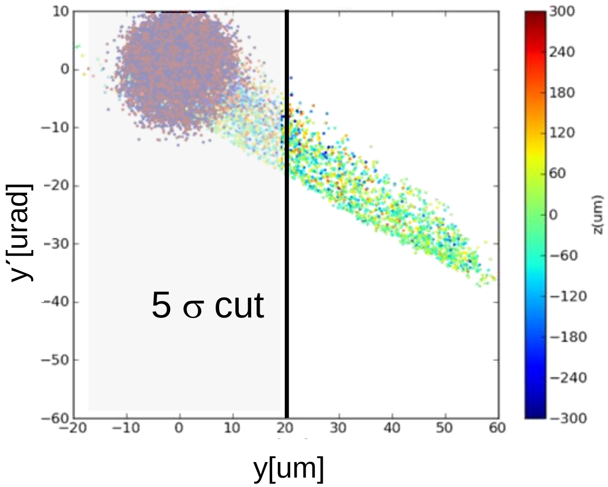
→ kick angle 3.3 μrad over sliced beam (for 5 σ separation @ β_y =25m, NSLSII beam)

Phase Space at kick-point





at radiator



ca. 5.2 x 10^4 photons/sec/0.1%BW/bunch/mA (U20)

rep. rate defined by linac technology
nc ~ 100 Hz – kHz, sc ~ up to many MHz

Pros

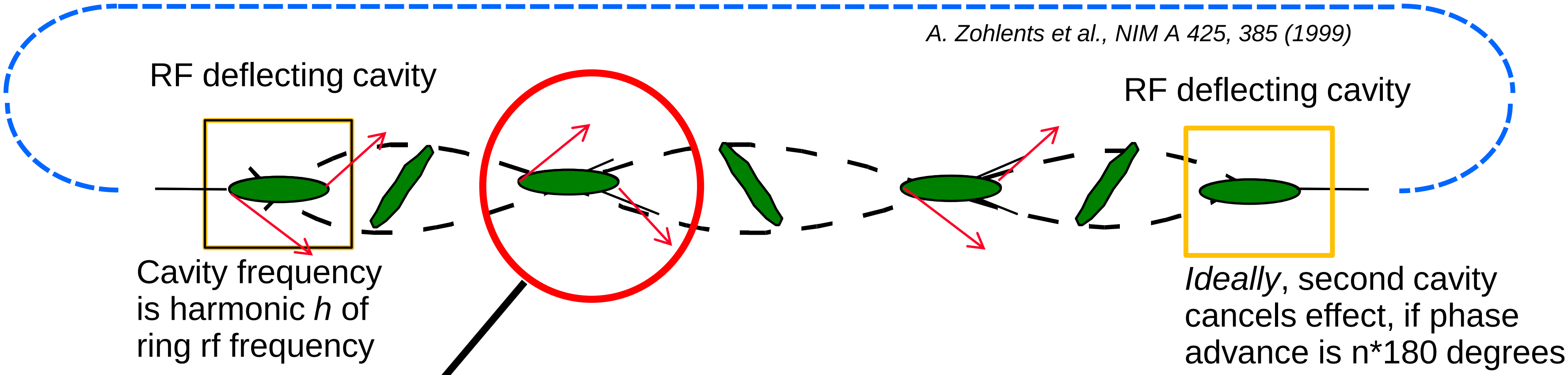
- ~ 100 fs pulse length
- more photons/pulse than laser slicing and possibly higher rep. rate

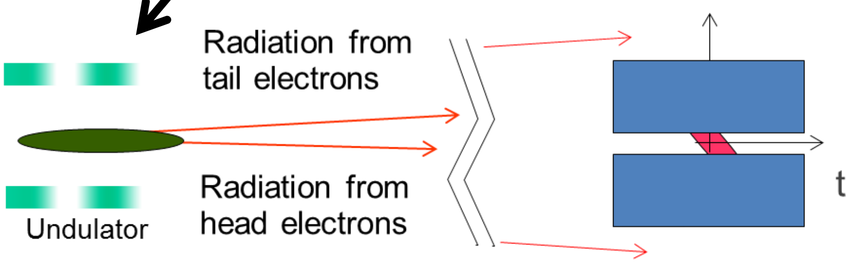
Cons

- challenging e-beam parameter / linac
- complex technology
- rep. rate limited due to regeneration of sliced bunch / increase in ε_y (mitigation by 2nd kick -> 2nd linac)
- no intrinsic synchronisation for pump-probe

Localised transverse chirp concept, A. Zohlents et al., APS/ANL

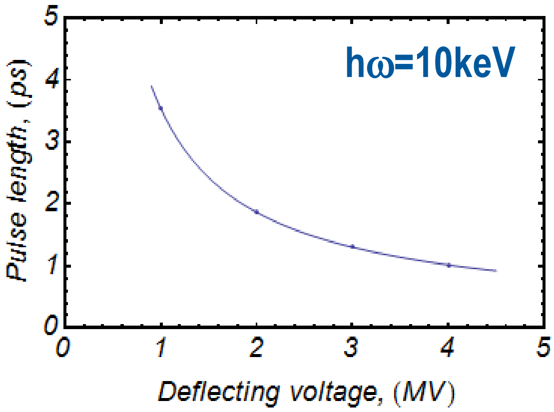
graphics courtesy A. Zohlents, M. Borland, APS/ANL

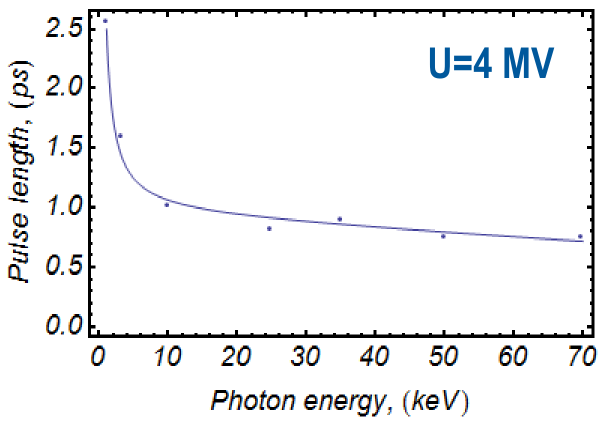




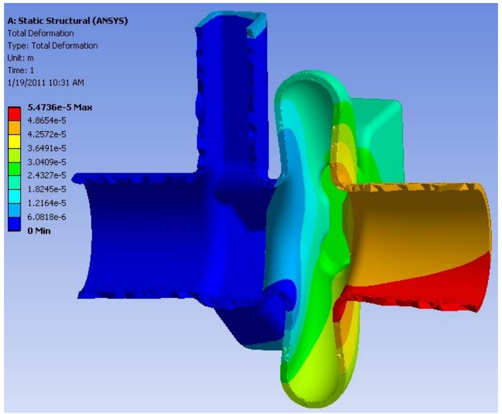
Pulse can be **sliced** (short but lower intensity) or **compressed** (at given wavelength, “full” intensity) with asymmetric cut crystal

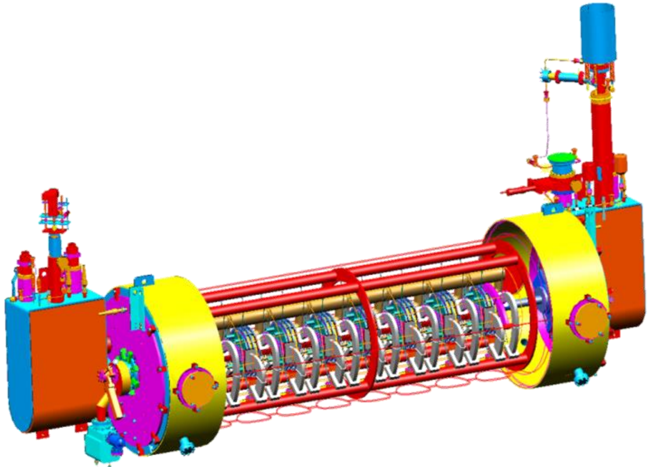
For 1% transmission:



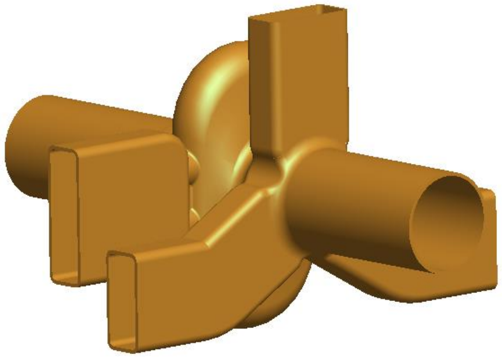


Deflecting the beam – basic principle





SPX project, ANL-JLAB-SLAC-LBNL-(Tsinghua-PKU) collaboration



G. Waldschmidt et al., SRF2013 1098

2 cryo modules, 8 sc cavities each, 4 MV total voltage, 2815.486 MHz (8th harmonic)
Need 6.5 kW / cell and very stable LLRF (< 0.07 °) for "perfect" cancellation of kick
(make it transparent outside the crabbed area) and efficient HOM damping to avoid CBI, …

Pros

- ps pulses in high energy storage rings with full rep. rate
- parallel to high current, standard user operation
- rather high intensity (> 1% of full bunch; with "compression" even higher)

Cons

- all bunches are tilted
- localised scheme (only limited number of BL benefit)
  can be overcome → later this talk
- complex technology; demanding requirements on cw sc crab cavities

Short bunches by reducing momentum compaction → proper optics tuning (dispersion)

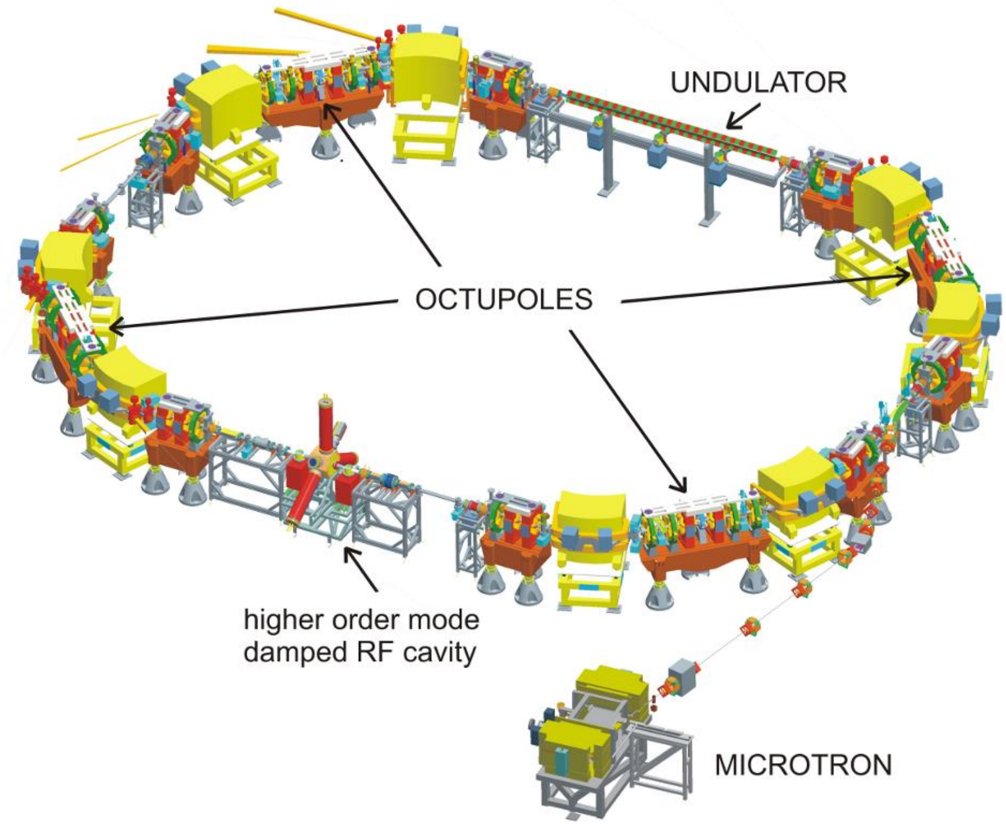
Fundamental interest in generating short electron pulses for generation of intensive, broadband, stable THz radiation (CSR)
but also great interest for beam studies (bursting thresholds) *(see e.g. talk J. Steinmann, TUP2WD03)*

$$\sigma \sim \delta_0 \sqrt{\frac{\gamma}{\omega_0} \cdot \frac{\alpha}{\dot{V}_{RF}}} \qquad I \sim \alpha$$

$$\alpha = \frac{\delta L / L_0}{\delta p / p_0} = \frac{1}{L_0} \int ds \, \frac{D(s)}{R(s)}$$

$$\alpha(\delta) = \alpha_0 + \alpha_1 \delta + \alpha_2 \delta^2 +$$

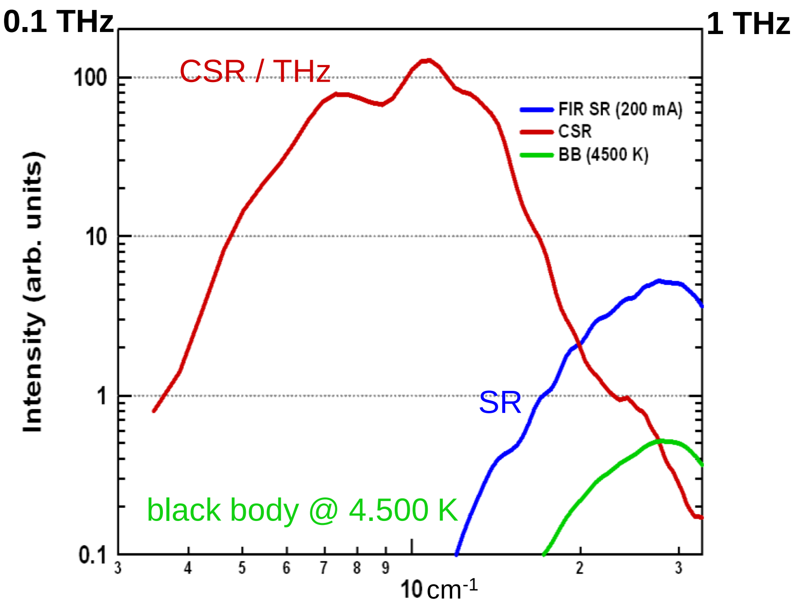
quadrupoles → α_0
sextupoles → α_1
octupoles → α_2

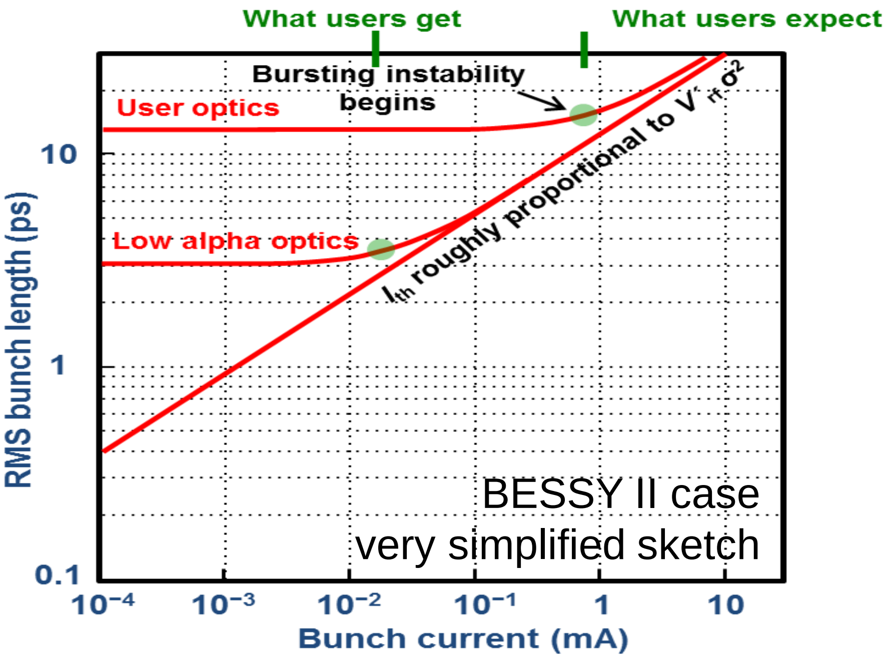


J. Haissinski, IL Nuevo Cimento Vol. 18 BN1, (1973)
C. Pelligrini, D. Robin, NIM A 301, 27 (1991)
M. Abo-Bakr et al., PRL 88, 254801 (2002) (first stable CSR)
J.M. Byrd et al., PRL 89, 224801 (2003) (bursting CSR)
G. Wüstefeld et al., EPAC2008, 26

MLS - Metrology Light Source
(developed and operated by HZB, BESSY)

Short electron pulses in storage rings – low alpha operation





Facilities operating low-alpha

ALS, KARA (fka ANKA), ALS
BESSY II, DIAMNOND, Elettra
MLS, NewSUBARU, SLS, SOLEIL
SPEAR, SRS, …

BESSY II, SOLEIL ca. 12 dedicated days/a

Pros

- pulse lengths ps and below
- all pulses short
- when properly tuned → very stable THz/CSR
- or at higher currents → intensive bursts
- no significant investment

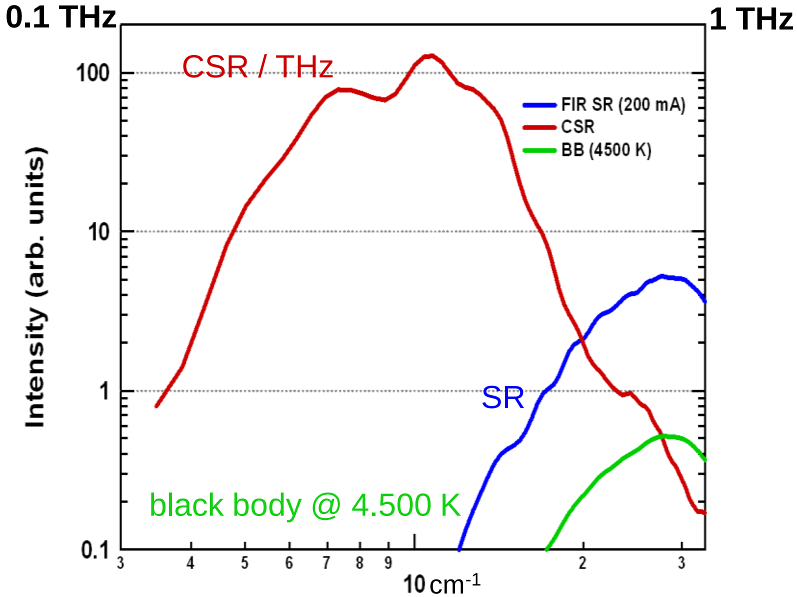
Cons

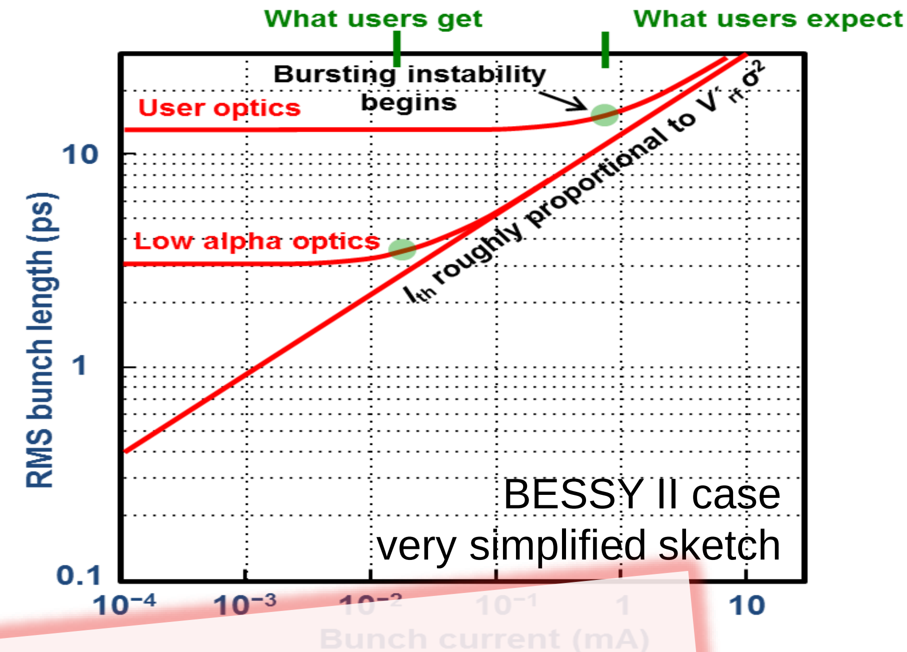
- too low beam current for other users
- orbit very sensitive to RF freq. changes

In the case of $\alpha \rightarrow 0$ and $I \rightarrow 0$ the minimum bunch length is limited (~ 300 fs) by a) quantum excitation and partial $\alpha \neq 0$ b) transverse-longitudinal coupling

(BESSY II case: P. Goslawski et al., IPAC2014 216, see also next talk THP2WB02 by C. Tang, TUB)

Short electron pulses in storage rings – low alpha operation





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Very well developed an matured technique!

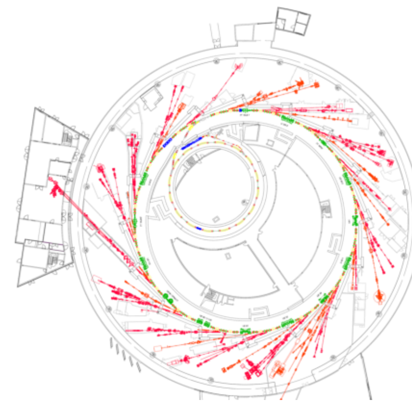
Still many things to be understood!
(e.g. negative low-alpha operation, thresholds, …)

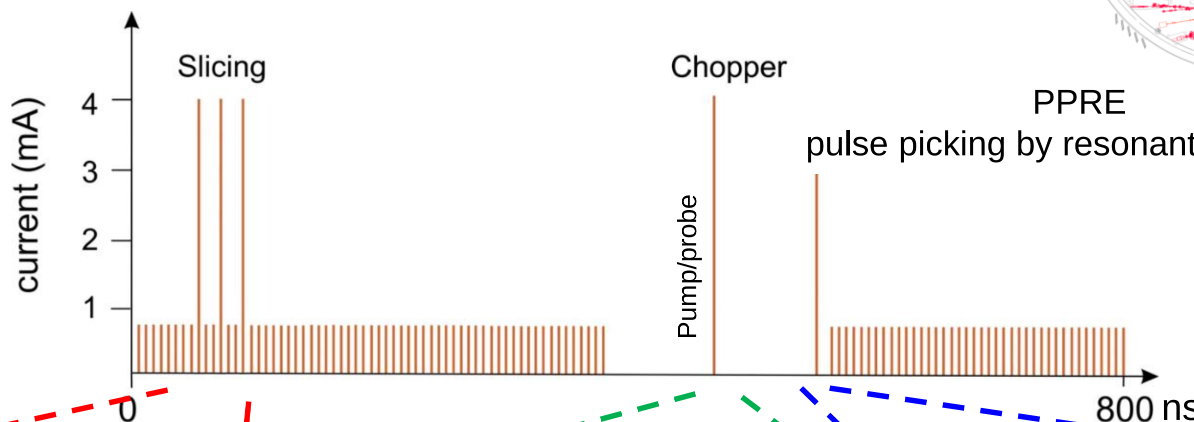
In the case of $\alpha \rightarrow 0$ and $I \rightarrow 0$ the minimum bunch length is limited (~ 300 fs) by a) quantum excitation and partial $\alpha \neq 0$ b) transverse-longitudinal coupling

(BESSY II case: P. Goslawski et al., IPAC2014 216, see also next talk THP2WB02 by C. Tang, TUB)

Standard multi-mode fill pattern (40 weeks / a) @ BESSY II

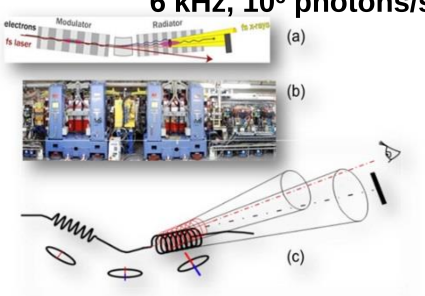
Energy/current	1.7GeV / 300mA
Emittance	6 nm rad
Pulse length	15 ps (rms)
Circumference	240



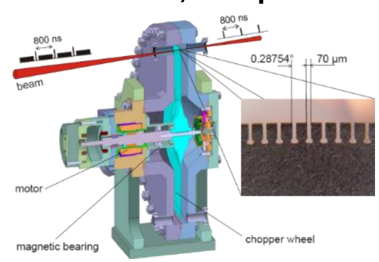


PPRE
pulse picking by resonant excitation

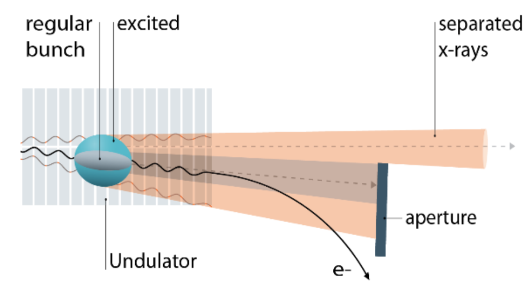
100 fs
6 kHz, 10^6 photons/s



20 ps
1.25 MHz, 10^{13} photons/s

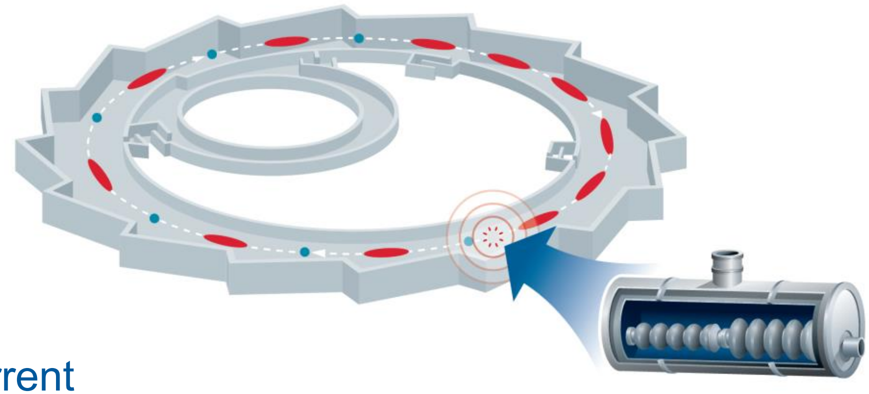


20 ps
1.25 MHz, 10^9 photons/s



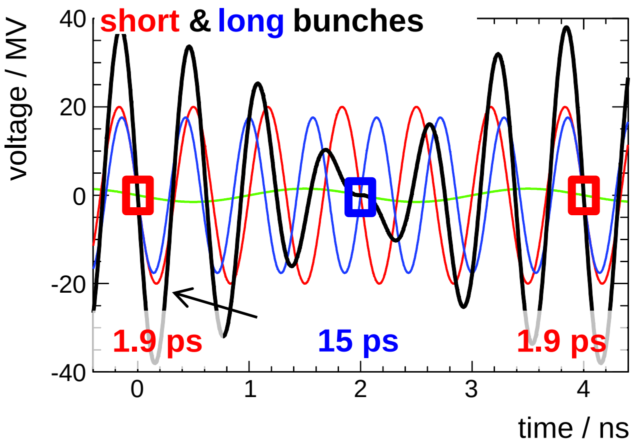
R. Müller et al, IPAC2016 / IPAC2017

$$\sigma \propto \delta_0 \sqrt{\frac{E_0}{\omega_0} \cdot \frac{\alpha}{\omega_{rf} V_{rf}}} \qquad I \propto \alpha$$



high voltage (20 MV/m) cw multi-cell SC cavities allow to increase the total voltage gradient by two orders of magnitude
→ ca. 1/10 bunch length @ constant bunch current

Combining two RF systems with different frequencies (1.5 GHz & 1.75 GHz) generates long and short buckets, which can be filled individually to generate optimized fill pattern.

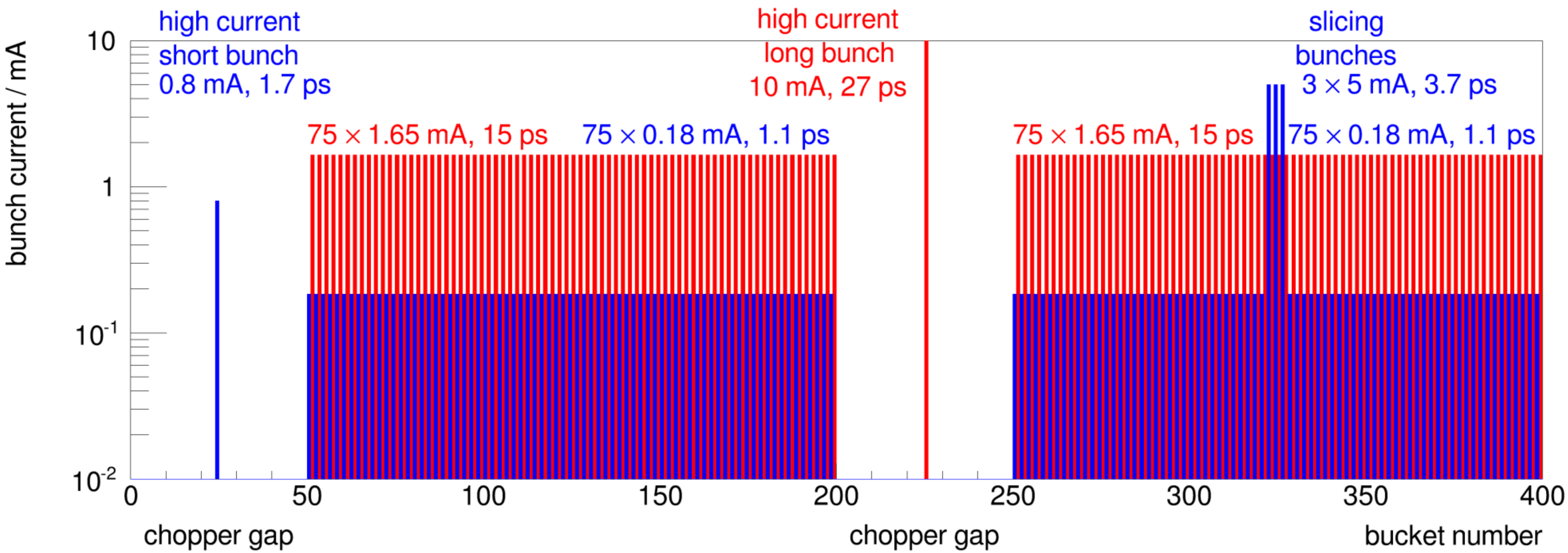


1.5 MV @ 0.5 GHz
16 MV @ 1.5 GHz
14 MV @ 1.75 GHz

J. Feikes, P. Kuske, G. Wüstefeld EPAC2006
G. Wüstefeld, A. Jankowiak, J. Knobloch, M. Ries, IPAC2011

VSR – variable pulse length storage ring

BESSY VSR – catered fill pattern of long and short electron bunches



- 300 mA average current
- camshaft single bunches (short and long) in gaps
- 100 ns gaps → for single bunch separation by chopper

in low alpha mode
400 fs @ 0.04 mA / bunch

multi functional / multi user hybrid mode

ps short single bunch, high current single bunch, slicing bunches, high average brilliance, background of intense CSR/THz radiation

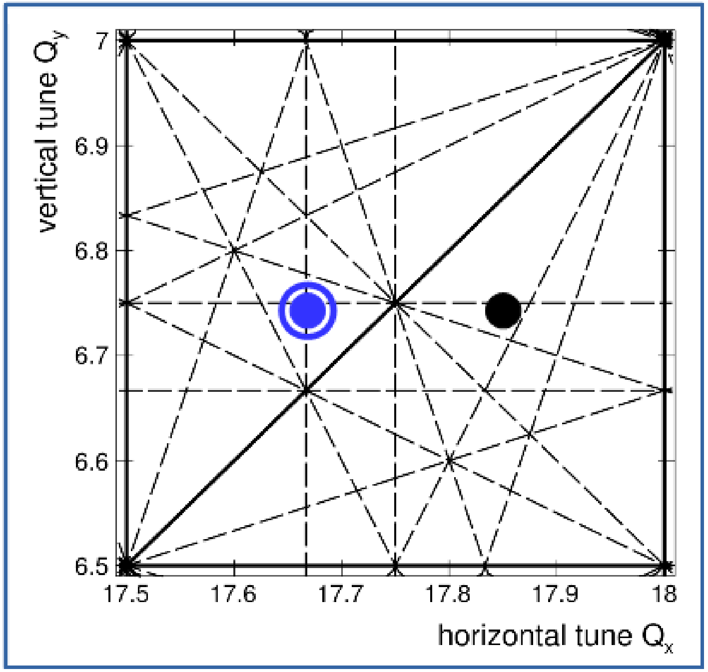
preserving the emittance (no optics changes)

TRIBs = Transverse Resonance Island Buckets

M. Ries et al., IPAC2015, 138
P. Goslawski et al., IPAC2017, 3059

TRIBs at BESSY II
A new Bunch Separation Scheme

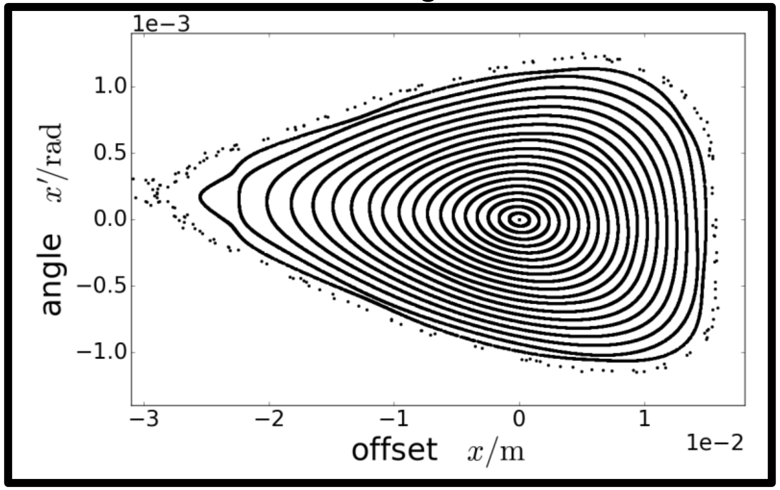
- Operating machine close to horizontal 3rd order resonance
- Minor impact on linear beam optics expected



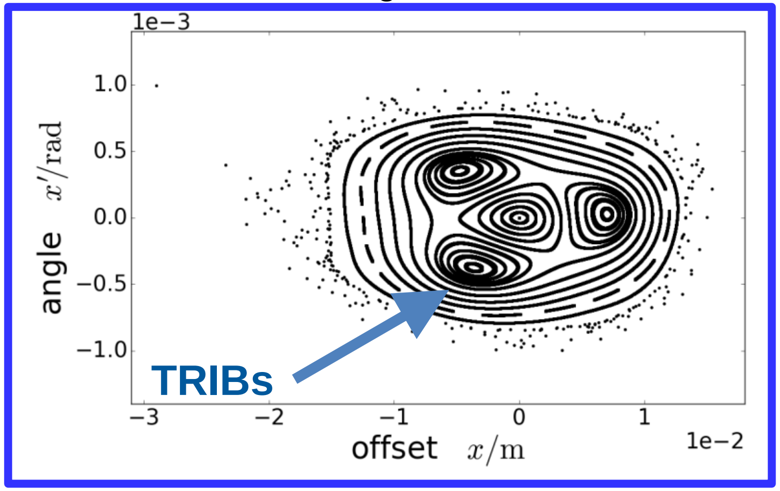
● BESSY II working point (17.85, 6.73)
● BESSY II TRIBs at 3rd order (17.66, 6.73)

2nd stable fix point & orbit

BESSY II standard setting



BESSY II TRIBs setting at 3rd order resonance



TRIBs – It is real (@BESSY II and @MLS)

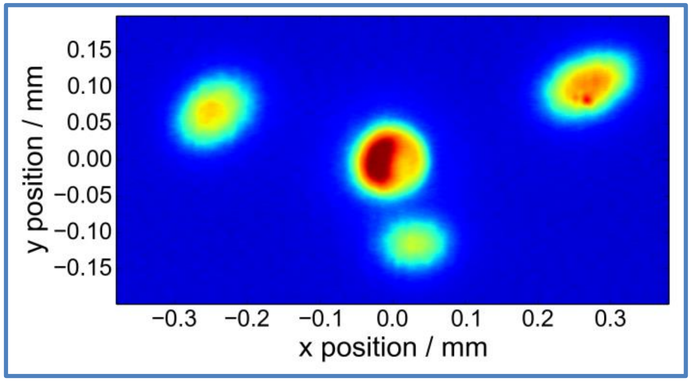
TRIBs at BESSY II
Proof of Principles Studies:

- Current can be shuffled between both orbits without losses
- Separation at user beamlines is promising
- TopUp injection is possible (if all current is stored on core orbit)

Succesful Twin Orbit User Test Week 19. – 25. February 2018

- performance on central orbit not detoriated
- excellent separation on second orbit
- injection process to be optimized

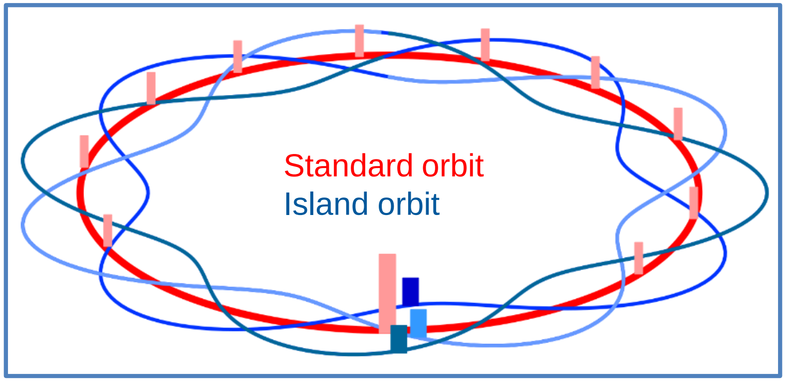
Bending magnet beamline, source point image



TRIBs - the long term objective:

- Verify if TRIBs bunch separation scheme could be a realistic operation mode for storage ring light sources
- Possible bunch separation scheme for short and long bunches at BESSY VSR
- Strengthen timing user community: 2nd fill pattern, tailored for timing experiments stored on 2nd orbit

TRIBs Scheme, 2nd fill pattern stored on 2nd orbits



Steady state two-frequency crab cavity scheme for short photon pulse generation

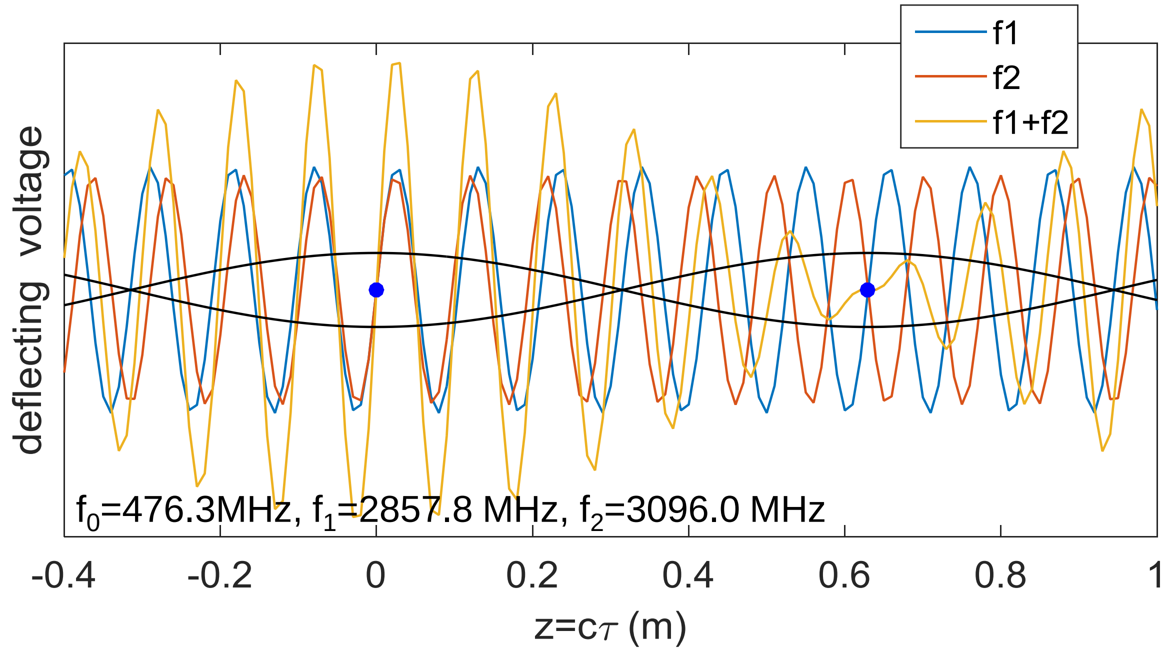
A. Zohlents (ANL), X. Huang et al (SLAC)

graphics courtesy X. Huang (SLAC)

A. Zohlents, NIM A 798 (2015) 111-116

X. Huang, PRAB 19, 024001 (2016)

Two crab cavities of two different frequencies located in one cryo-module (inspired by VSR scheme) → imprints static, transverse chirp around the ring



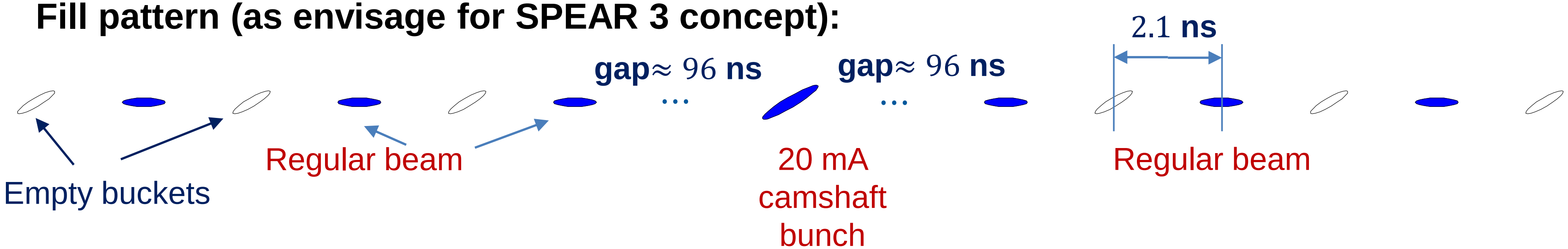
Two frequencies:

$$f_1 = nf_0,$$

$$f_2 = \left(n + \frac{1}{2}\right) f_0$$

Half of the buckets are tilted in $y - z$ plane, the other half are un-affected.

Fill pattern (as envisage for SPEAR 3 concept):



Signifikanter Bedarf an kurzen Pulsen in Speicherringen

→ ps (und kleiner) mit Wiederholraten von kHz bis zu vielen MHz

Es gibt erprobte Schemata und neue werden entwickelt

→ Slicing, low-alpha und neuTransversaler HF chirp, variable Pulslängen, Erzeugung stabilen Mikrobunchings, EEHG, …

Erzeugung kurzer Pulse auch in DLSR (diffraktionslimitierte Speicherringe) von großem Interesse

VSR ähnliche Schemata sollten es ermöglichen auch in DLSR Füllmuster zu erzeugen, die neben hochbrillanten langen Elektronenpaketen zusätzlich einige kurze Elektronenpakete für zeitaufgelöste Experimente erlauben.

Alex Chao, SLAC

"Die Physik und Technologie von DLSR ist verstanden. Das 100% Kohärenzlimit im Angström Bereich ist in Reichweite.
Die aufregendsten Möglichkeiten und die spannendste Physik liegt im longitudinalen Phasenraum!"

Kurze Pulse in Speicherringen – Warum?

- **Erzeugung von breitbandiger kohärenter Synchrotronstrahlung (CSR) im THz und Infrarot Bereich.**
- **Kurze Pulse mit kHz – MHz – vielen MHz Wiederholrate.**
- **Ultra stabile Pulsparameter in Speicherring Qualität (Puls zu Puls, Tag zu Tag, …)**
- **Nutzung des ganzen Spektrum der in einem Speicherring verfügbaren Strahlrohre (Dipole, Wiggler, Undulatoren)**
- **Nutzer können wählen zwischen kurzen Pulsen und hohem Fluss / Brillanz / Kohärenz**
- **Viele wissenschaftlichen Fragestellung lassen sich (nur) bei niedrigen Intensiäten, im linearen Anregungsbereich der Proben, beantworten.**
- **Zeitaufgelöste Charakterisierung (strahlungs-) empfindlicher Proben.**

Light matters!

THANK YOU FOR YOUR ATTENTION

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