Survey and Outlook

Short-Pulse Schemes in Storage Rings

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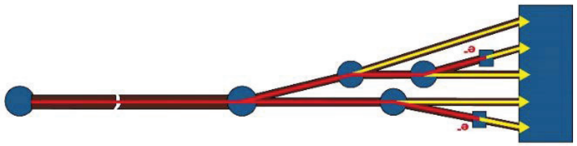
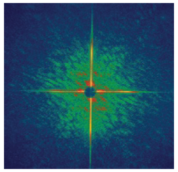
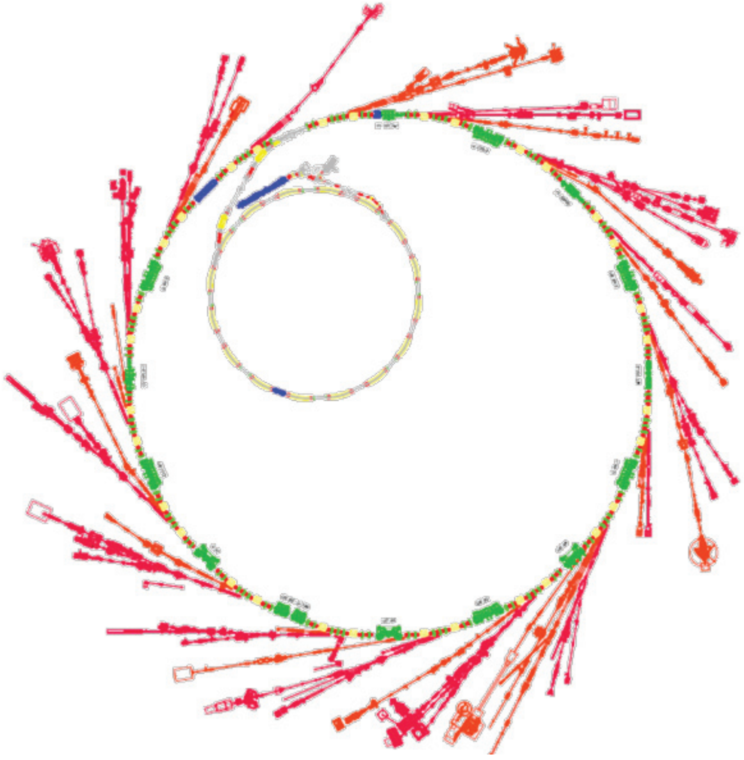
60th ICFA ABD Workshop
FLS2018, Shanghai
05. – 09.03.2018

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





Why "short" pulses in storage rings?



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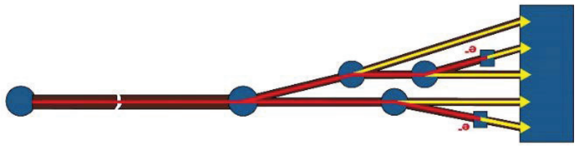

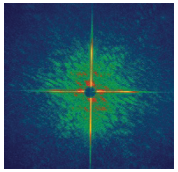

Why “short” pulses in storage rings?

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

Short pulse techniques for storage rings – manipulating the long bunch

“ordinary” electron bunch in SR

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

CHG coherent harmonic generation
EEHG echo enabled harmonic generation

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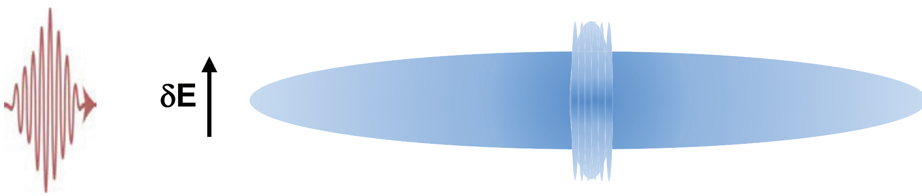

laser slicing

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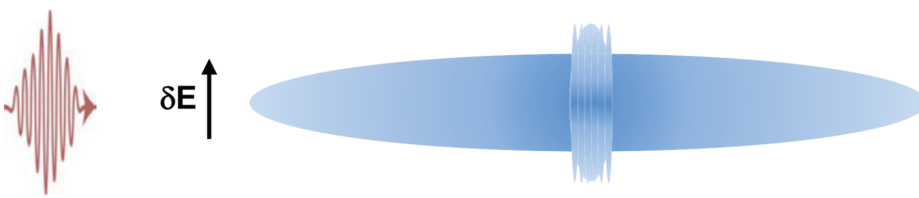

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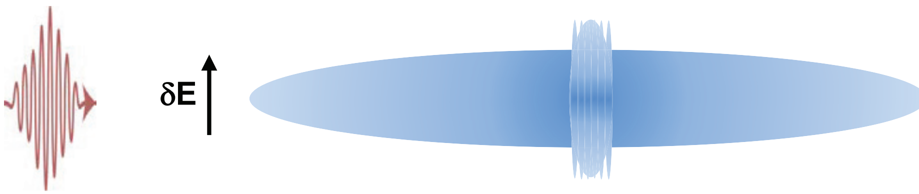

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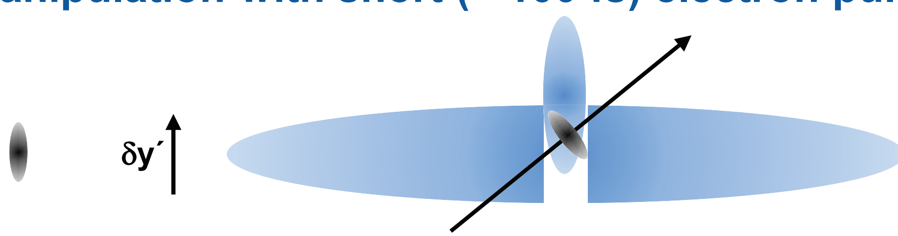

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manipulation with transversal deflecting cavities ("crab cavities")

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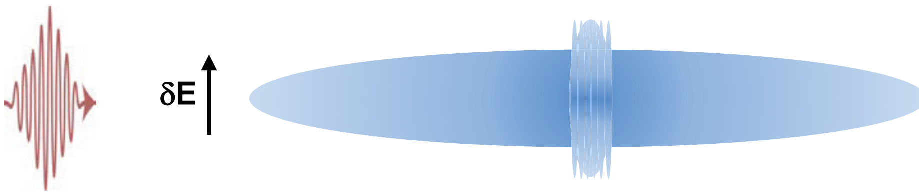

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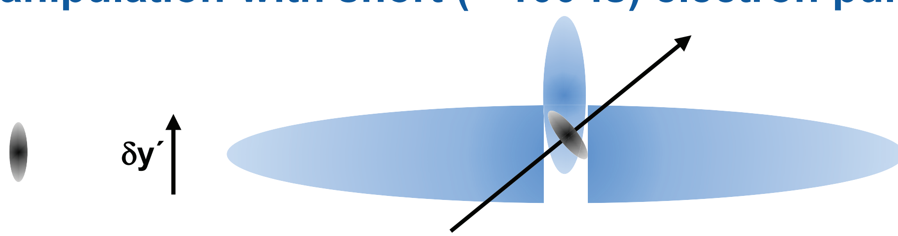

e⁻-beam slicing

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

Short pulse techniques for storage rings – shortening the long bunch

“ordinary” electron bunch in SR

some 10 ps, some nC

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

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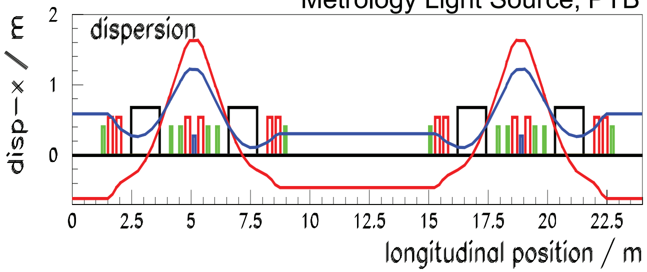
low-alpha operation

tuning the lattice – reducing momentum compaction factor α_c

Metrology Light Source, PTB



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

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

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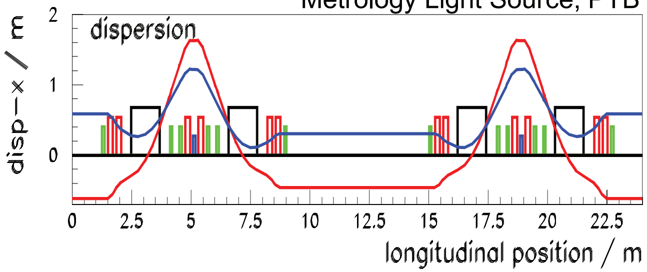

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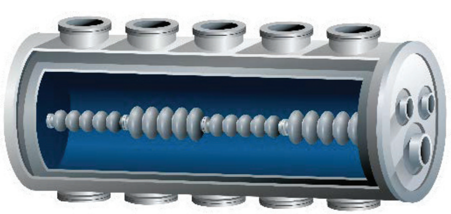
high RF gradient operation

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

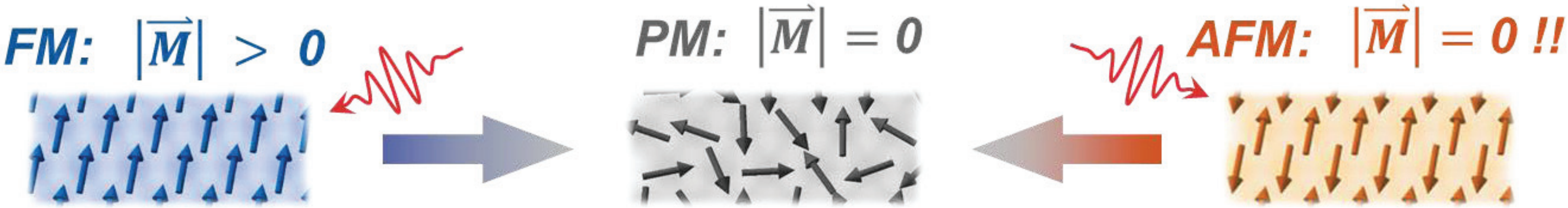


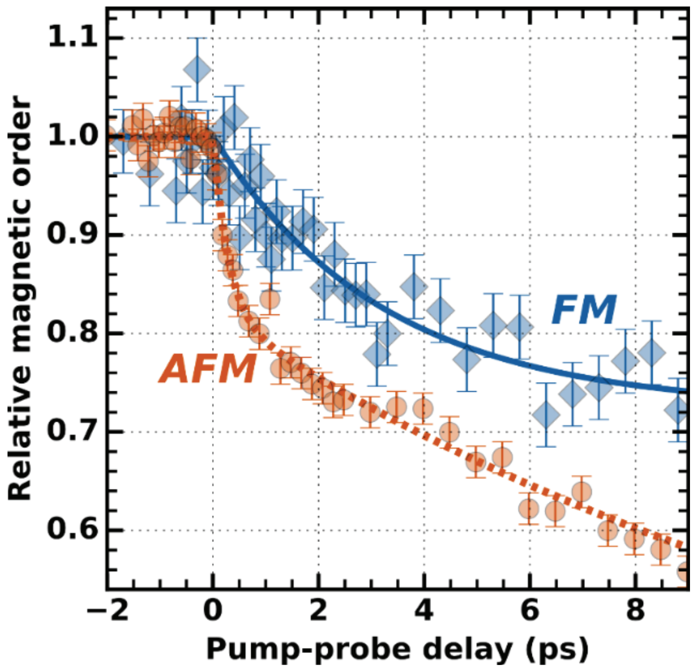
BESSY VSR
Helmholtz-Zentrum Berlin

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

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

Demagnetization of Dysprosium (ferromagnetic order versus anti-ferromagnetic order)
→ fast and energy efficient magnetic data storage



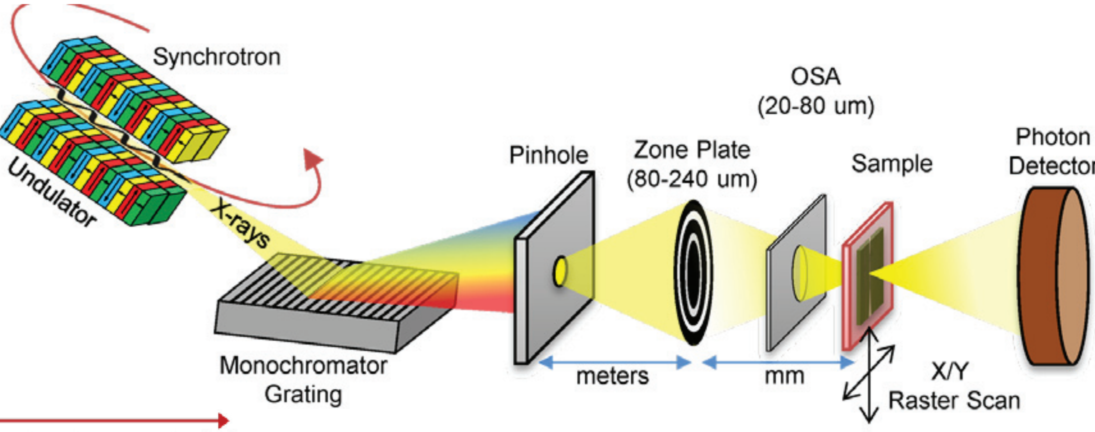


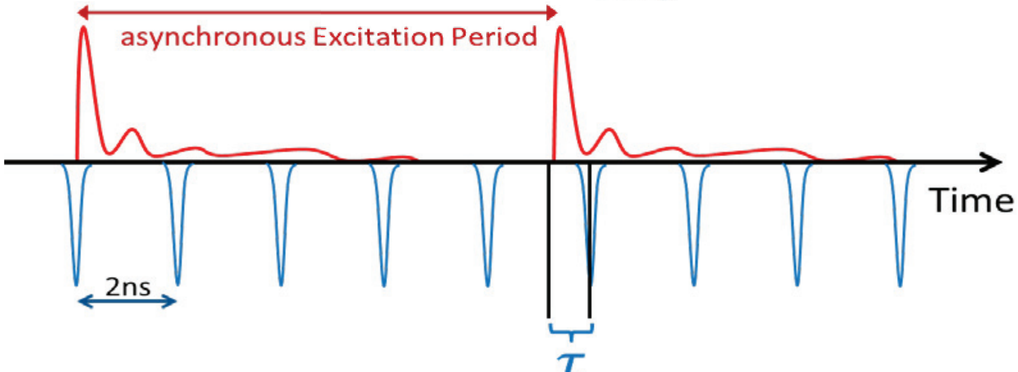
N. Thielemann-Kühn et al.,
Phys. Rev. Lett. 119, 197202 (2017).

example slicing facility
HZB / BESSY II

Short photon pulses in storage rings – Science example

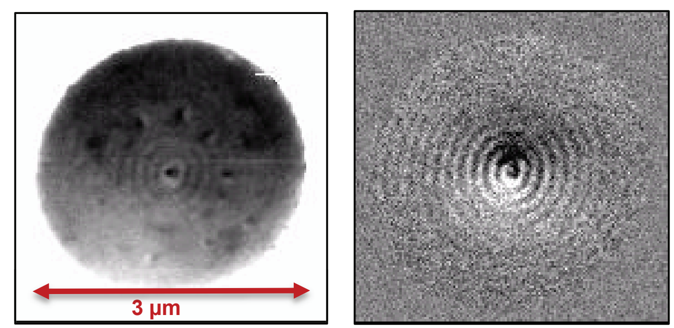
STXM: Scanning Transmission X-ray Microscope





- simultaneous acquisition of many time channels!
- all bunches contribute to all time channels (if N doesn‘t share dividers with the bunch number) !
- **Arbitrary low channel spacing**

direct observation of spin-waves



Raw Image **Normalized Image**

Chemically and magnetically sensitive microscopy with **~ 20 ps time** (defined by bunch-length, would **decrease with shorter bunches**) and < 20 nm spatial resolution

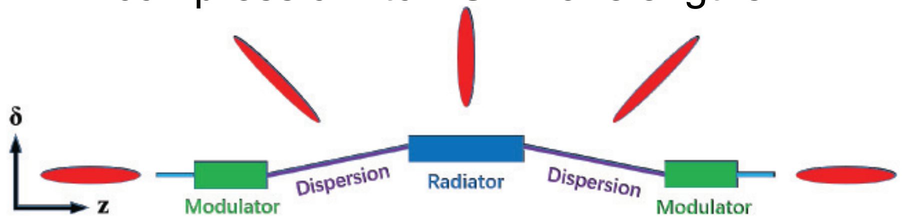
https://www.stuttgart.is.mpg.de/16275812/nanomagnetismus-im-roentgenlicht

Laser “seeding” schemes – imprinting short range density modulations

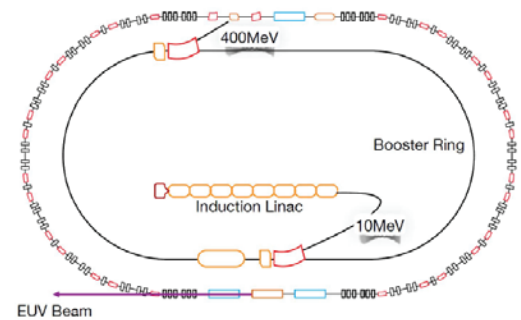
Steady State Micro Bunching SSMB → see talk C. Tang, TUB, (THP2WB02, next talk)

graphics courtesy C. Tang, TUB

“compression” to EUV wavelengths



modulation on UV wavelength → SSMB in dedicated ring optics



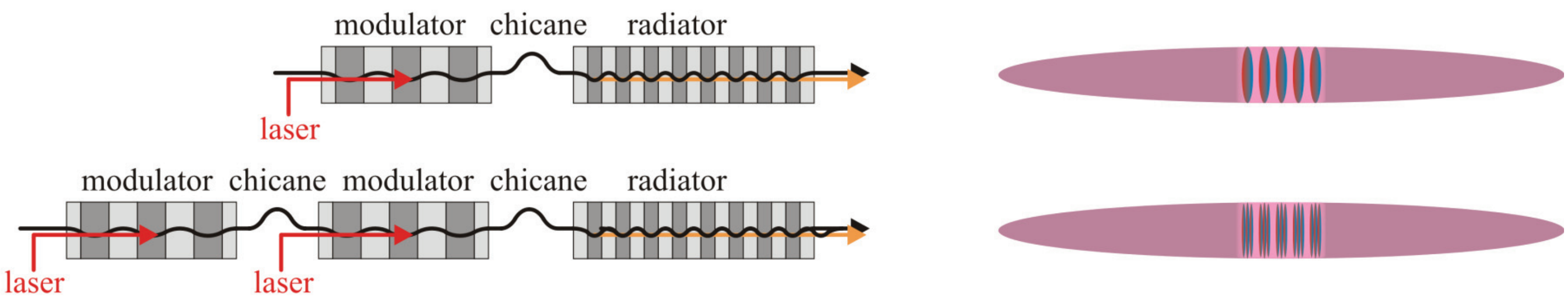
F. Ratner, A. Chao, PRL 105.15 (2010)

CHG, EEHG schemes → see talk S. Khan, TU Dortmund (THP2WB04, last talk of today)

graphics courtesy S. Khan, TU Dortmund

CHG

EEHG



realising EEHG in a storage ring @ DELTA, TU Dortmund

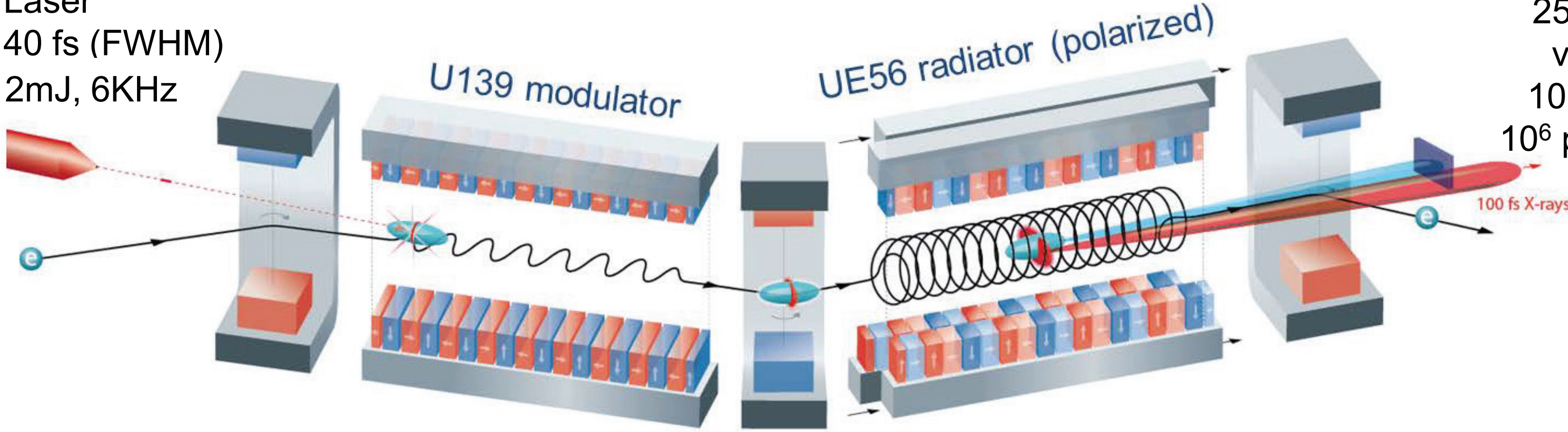
e.g. FEMTOSPEX Facility, BESSY II/HZB

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)

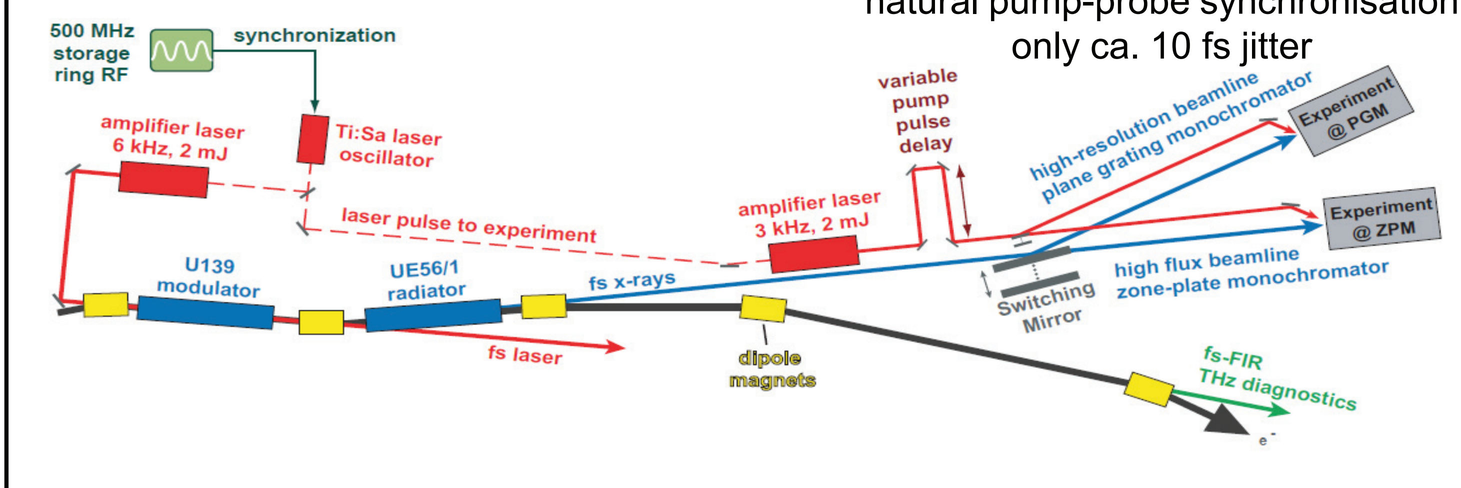
consecutive slicing on three, high charge, bunches

Laser
40 fs (FWHM)
2mJ, 6KHz



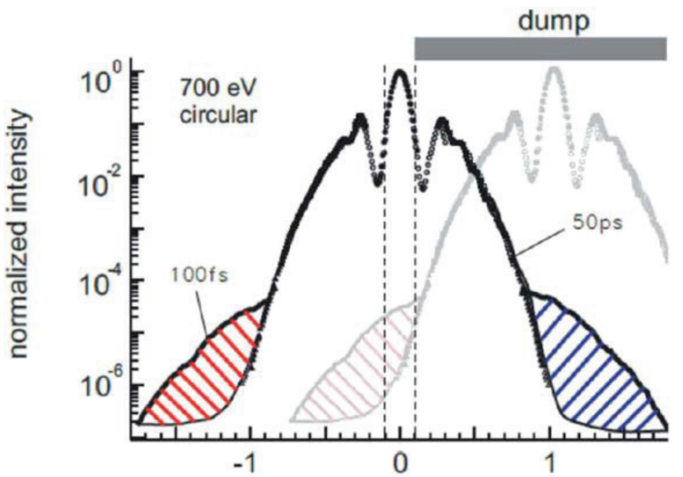
250 – 1400 eV
variable pol.
100 fs (FWHM)
10^6 ph/s/0.1% BW

natural pump-probe synchronisation
only ca. 10 fs jitter



Laser slicing – fast switching between short / long pulses

Fast switching with the Femto-Bump



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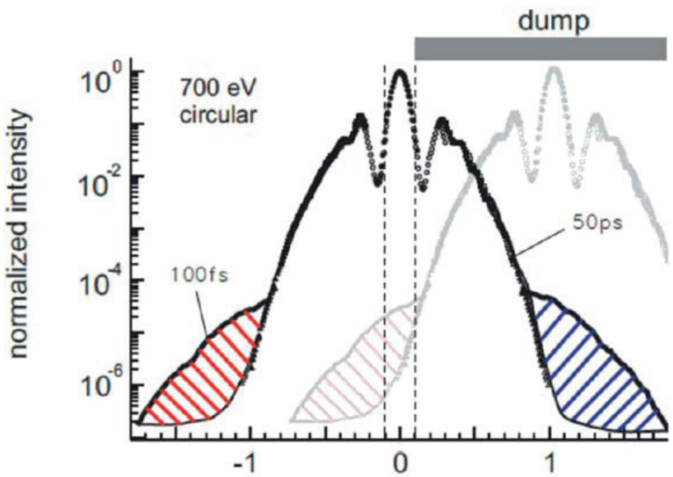

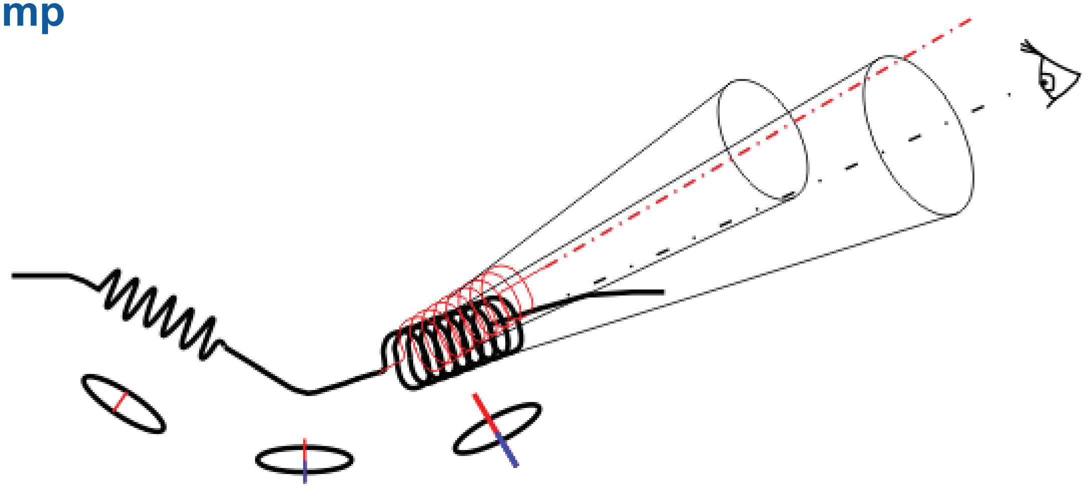

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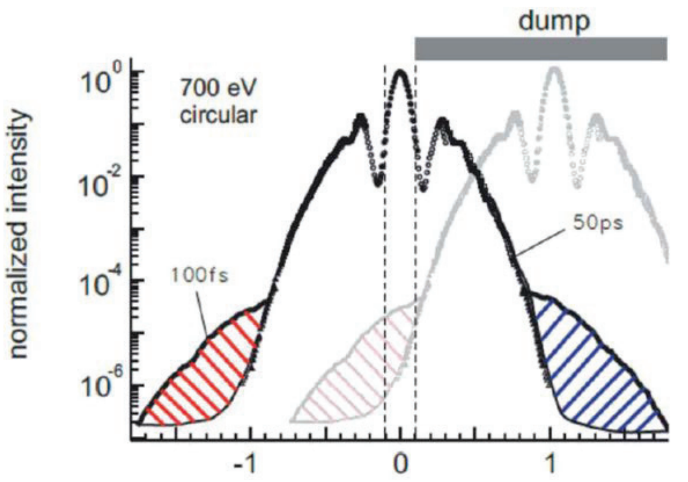

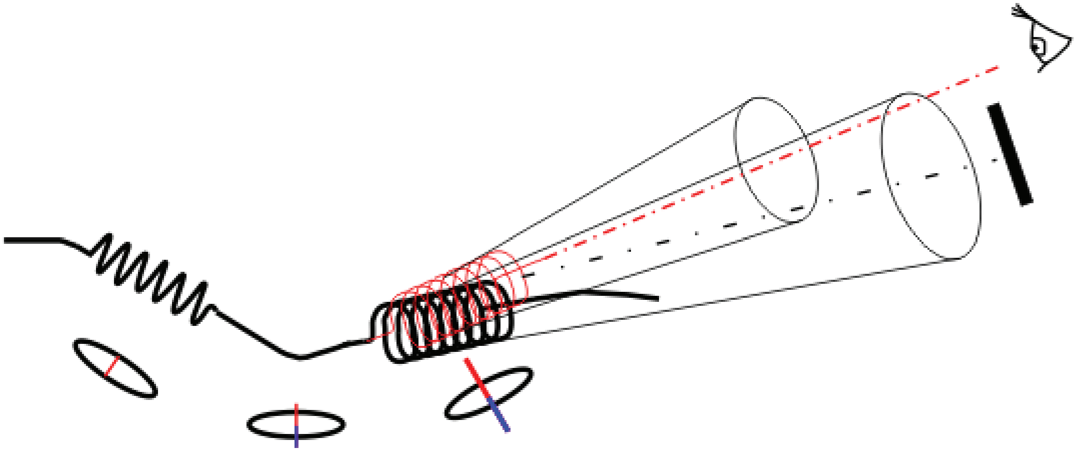

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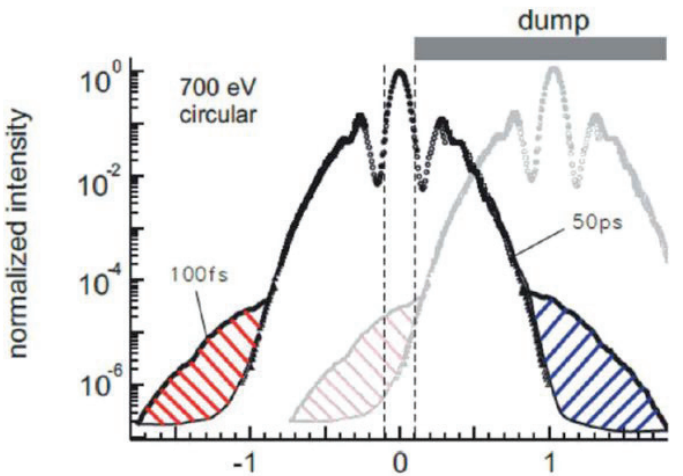
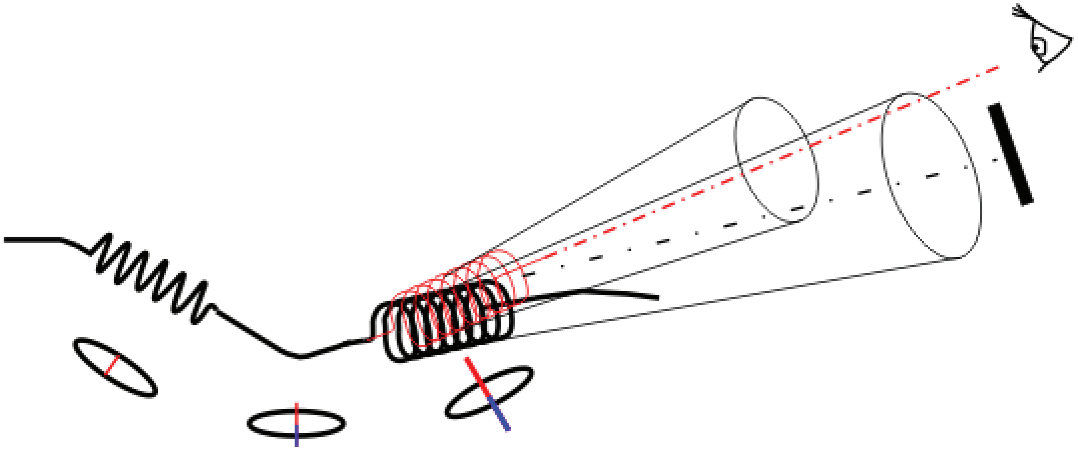




Laser Slicing Facilities:

ALS (pioneered)

BESSY II

SLS

SOLEIL

UVSOR (only beam tests for THz)

…

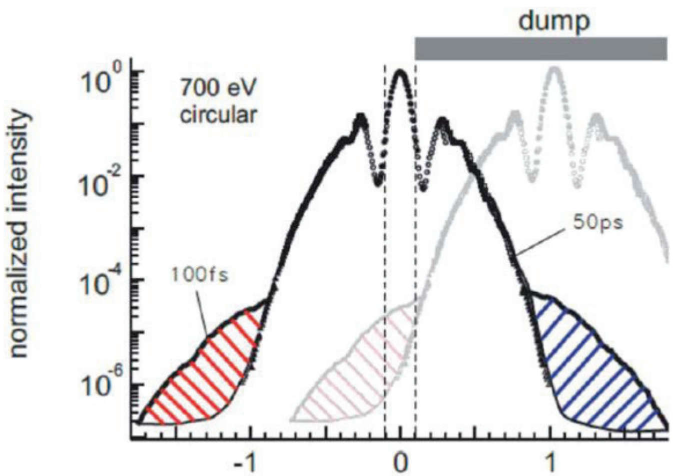
Resonance condition for modulation

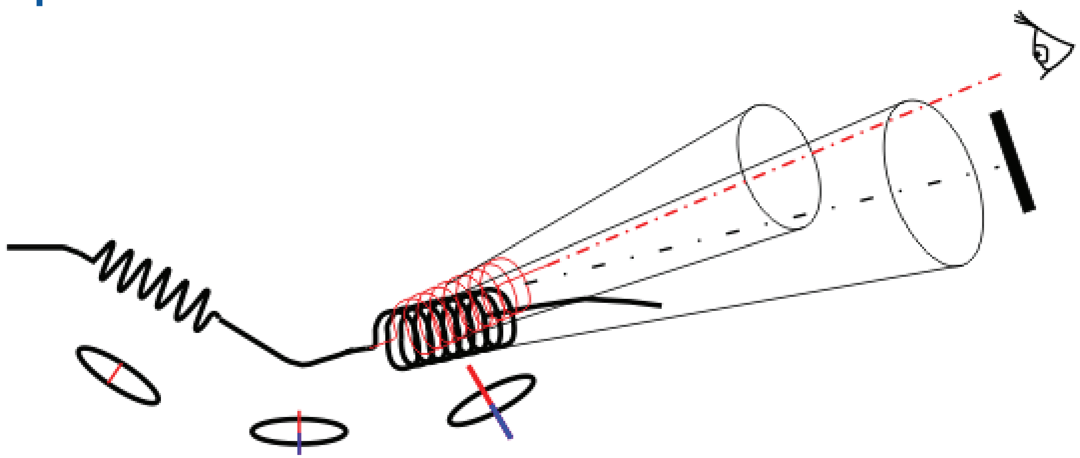
$$\lambda_{modulator} = \frac{2\lambda_{laser}\gamma^2}{1 + K^2/_2}$$

somewhat favours lower energy

Laser slicing – fast switching between short / long pulses

Fast switching with the Femto-Bump





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Pros

- some kHz rep. rate
- 100 fs (FWHM)
- extremely stable
- switching between short / long pulses
- intrinsic synchronisation ~ 10 fs

Cons

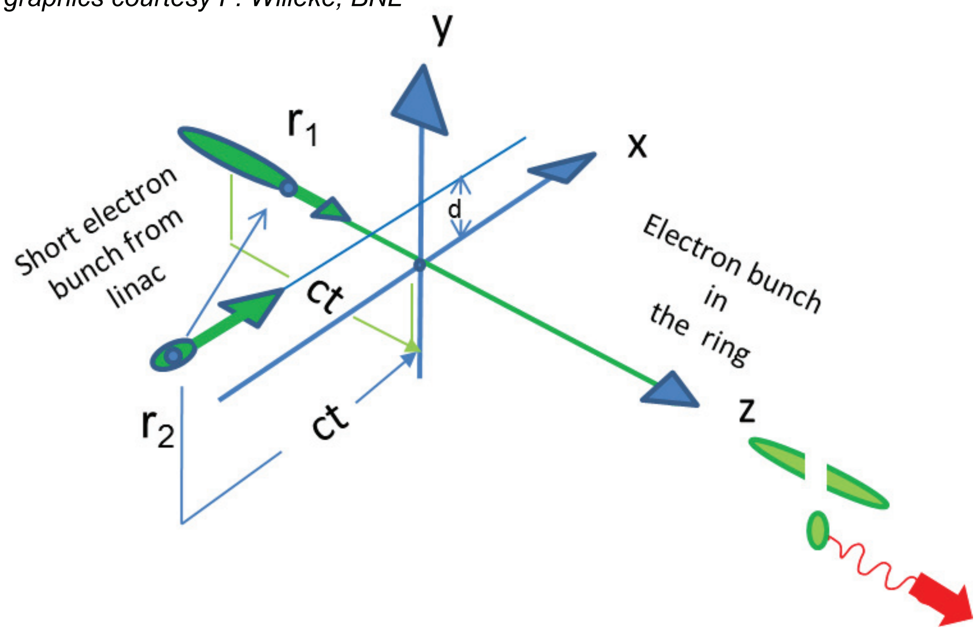
- low number of photons
- rep. rate limited due to “regeneration” of sliced bunches

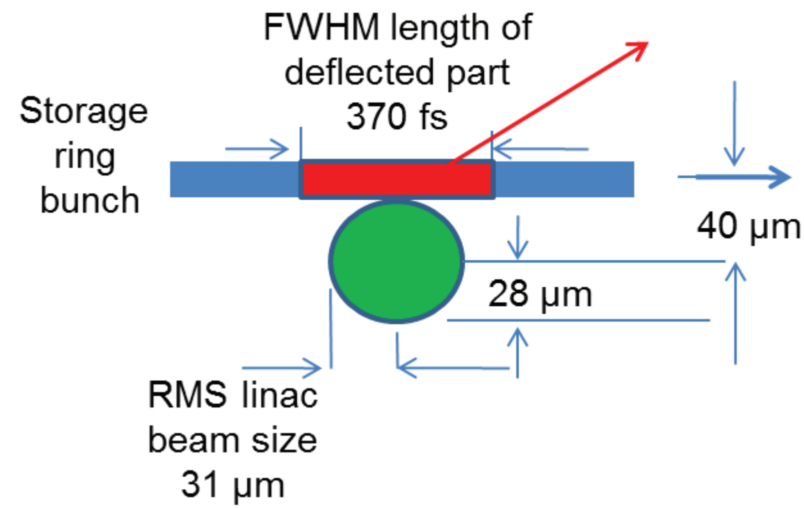
Electron beam slicing – basic principle

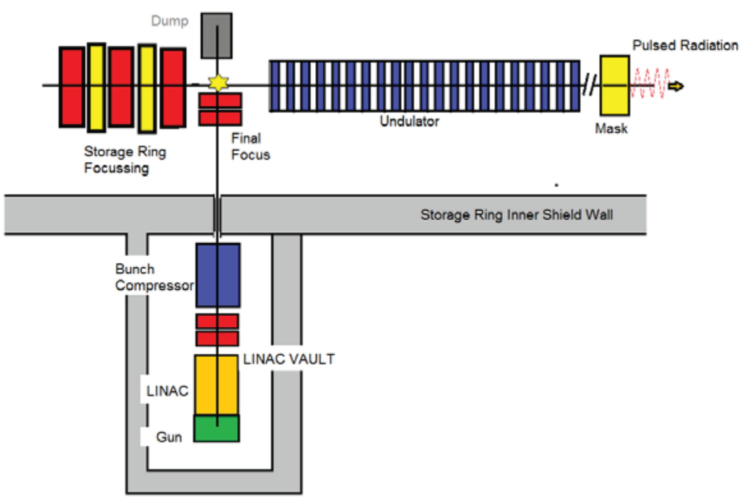
Design Study for electron beam driven slicing @ NSLSII, F. Willeke, L.H. Yu, et al.

graphics courtesy F. Willeke, BNL

F. Willeke et al, IPAC2013, 1134







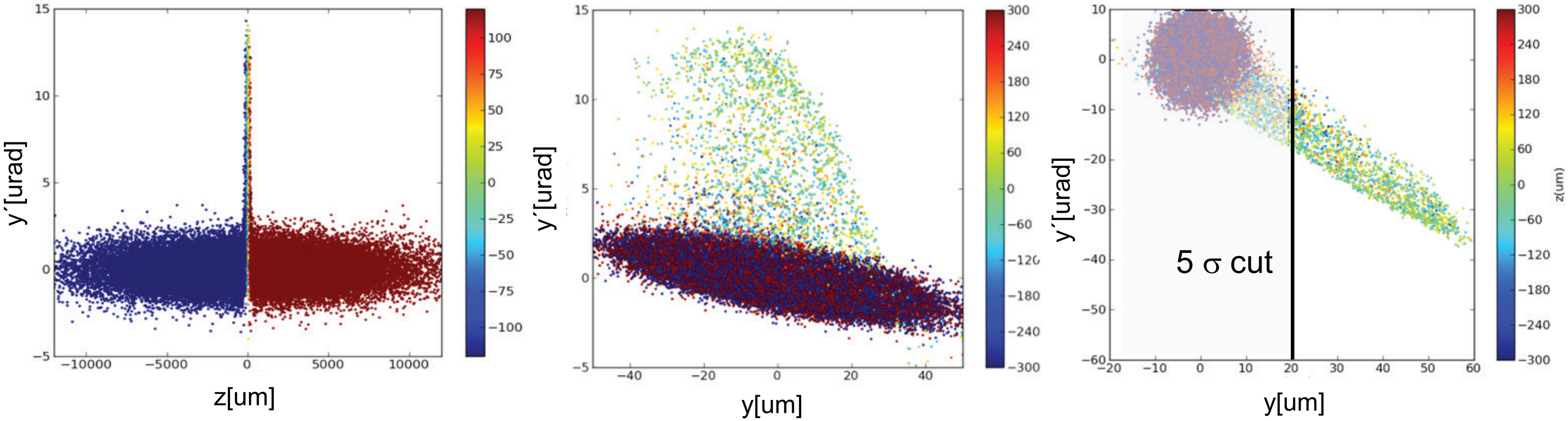
Kick beam:

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

Electron beam slicing – expected performance

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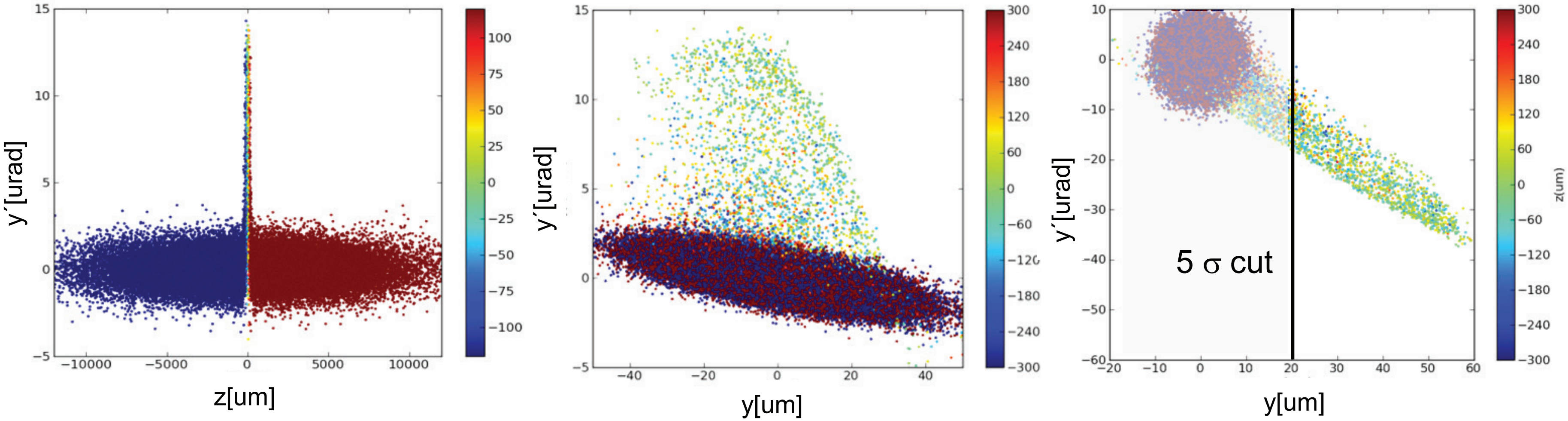

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Pros

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

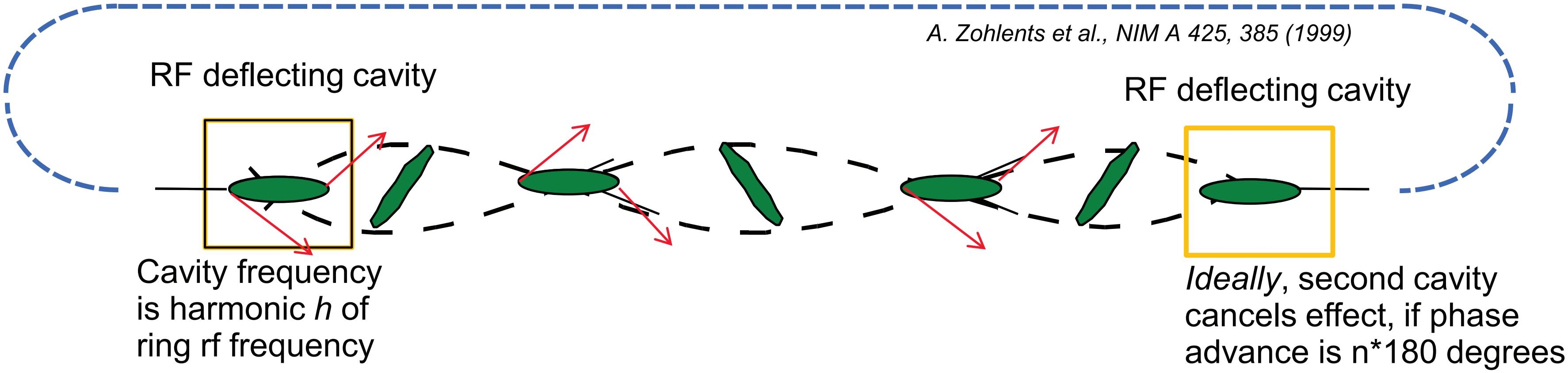
Cons

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

Deflecting the beam – basic principle

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

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



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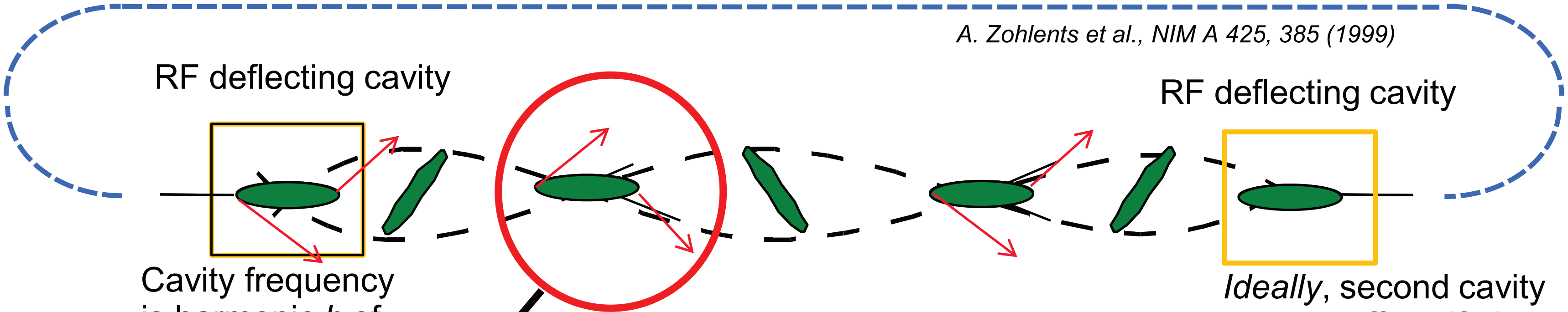
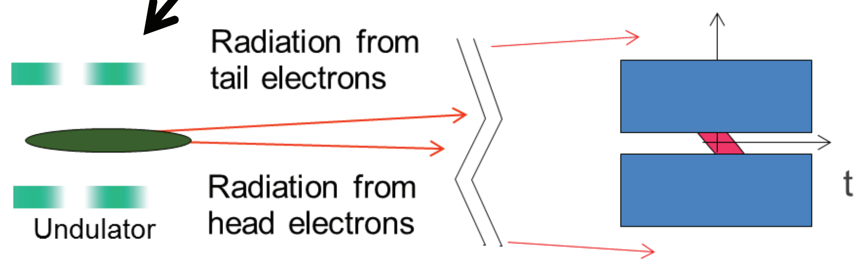


Cavity frequency is harmonic *h* of ring rf frequency

Ideally, second cavity cancels effect, if phase advance is n*180 degrees



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

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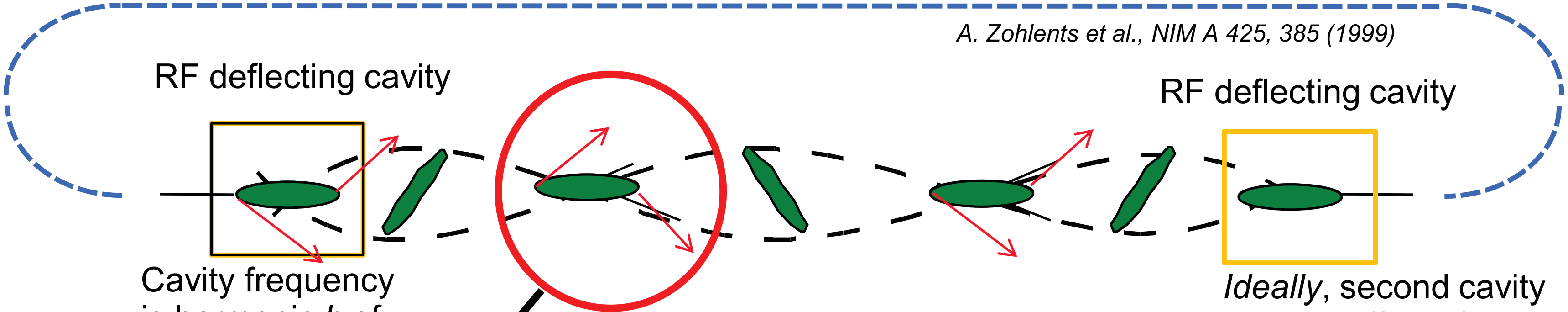
A. Zohlents et al., NIM A 425, 385 (1999)



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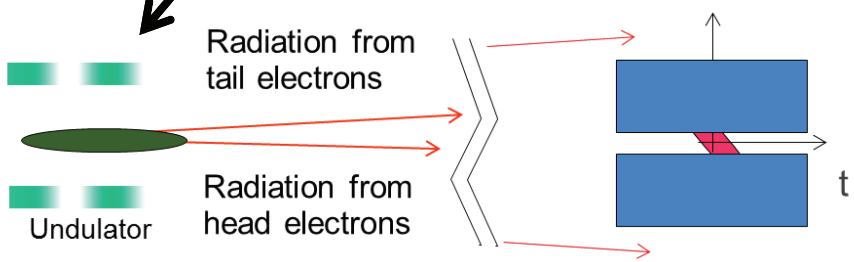

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For 1% transmission:

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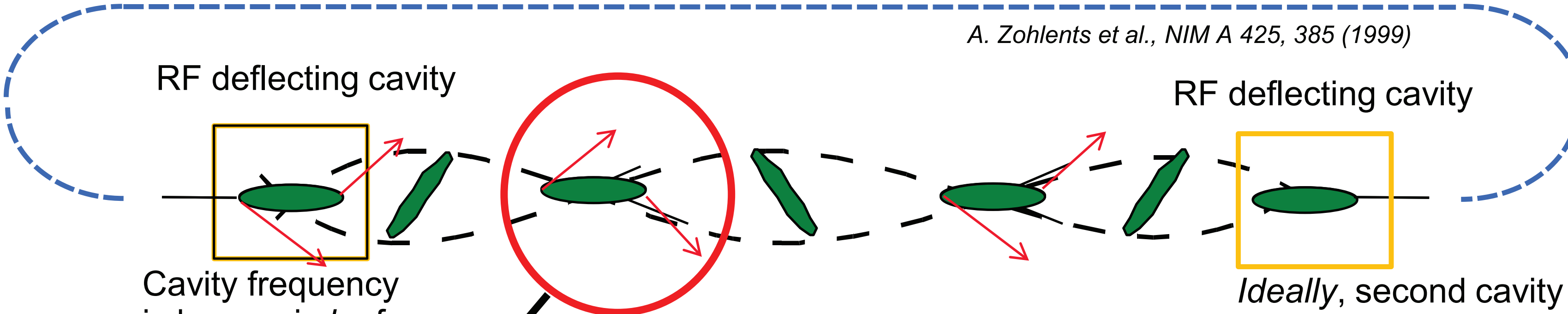
graphics courtesy A. Zohlents, M. Borland, APS/ANL



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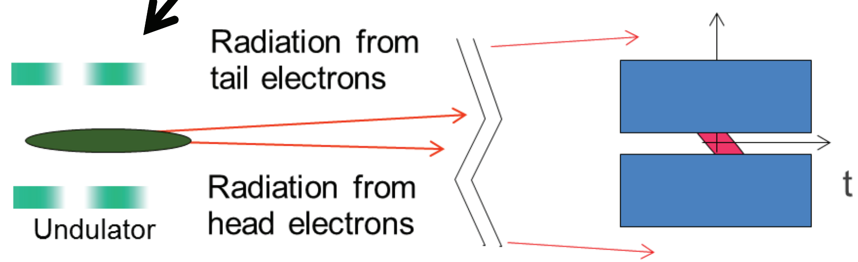

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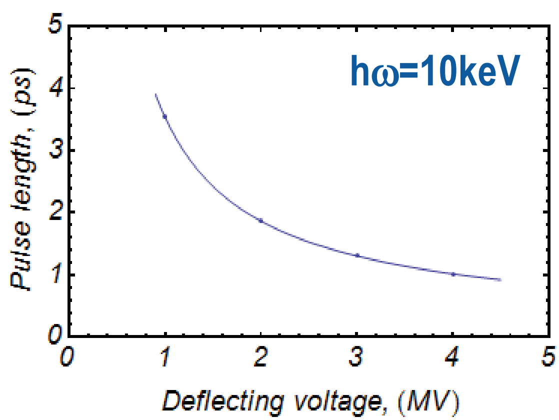

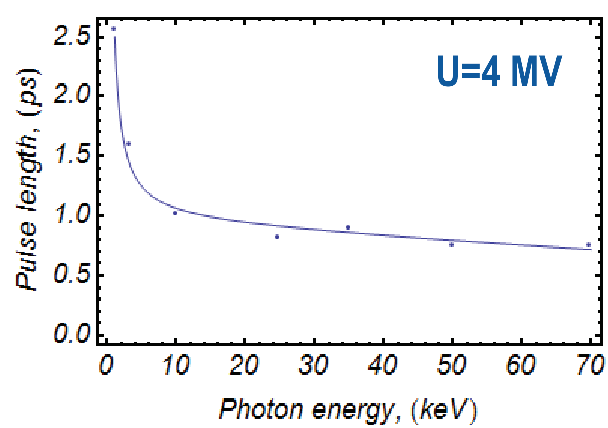

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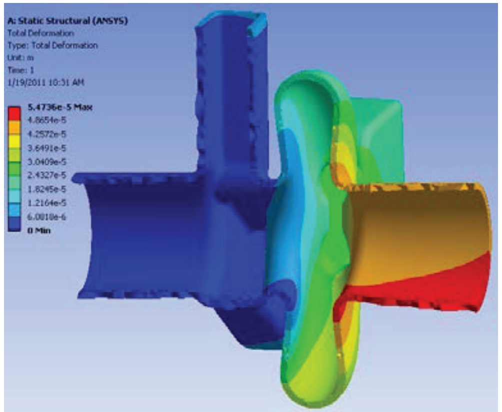
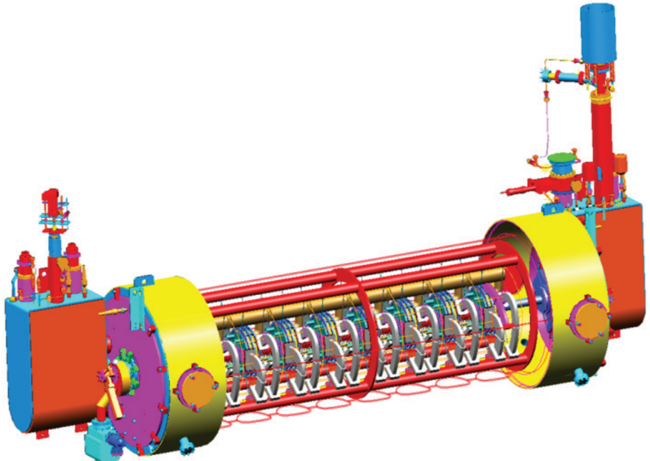
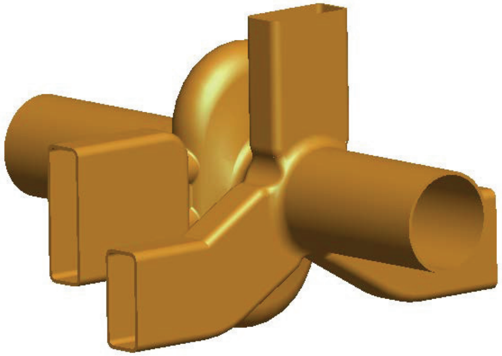




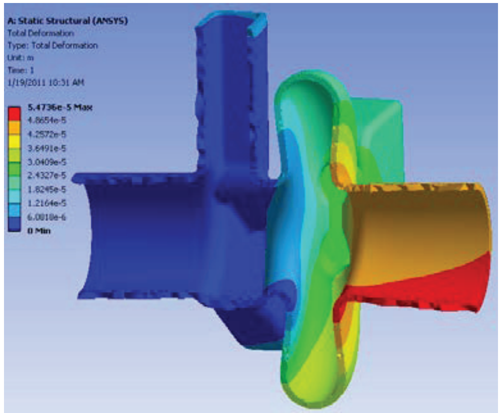


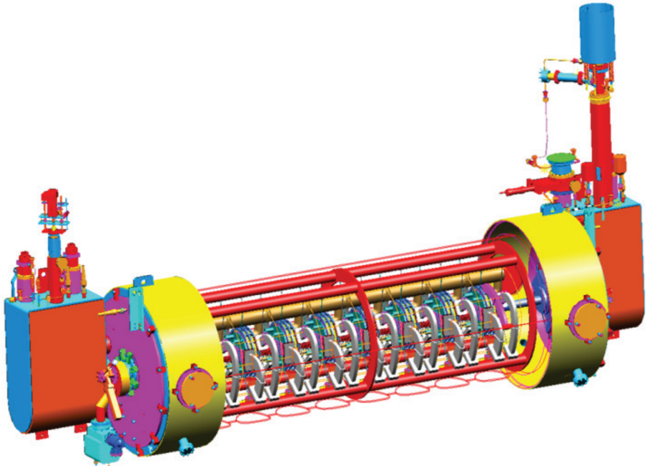
SPX project, ANL-JLAB-SLAC-LBNL-(Tsinghua-PKU) collaboration

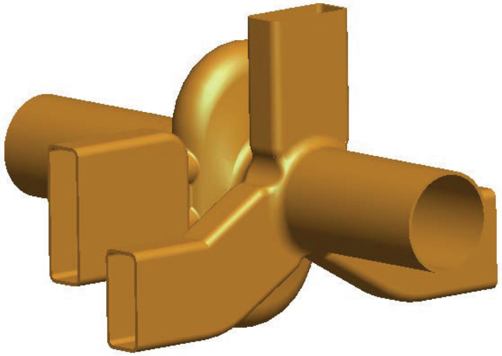
G. Waldschmidt et al., SRF2013 1098

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, …

Deflecting the beam – basic principle







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- rather high intensity (> 1% of full bunch; with "compression" even higher)

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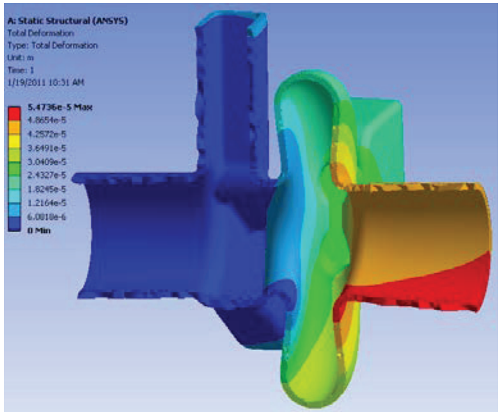

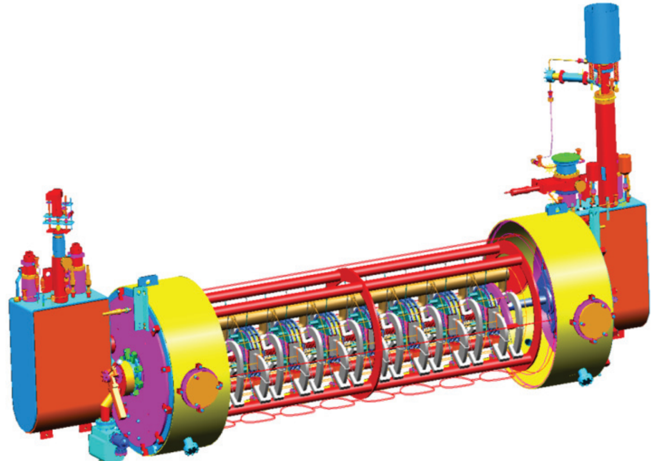

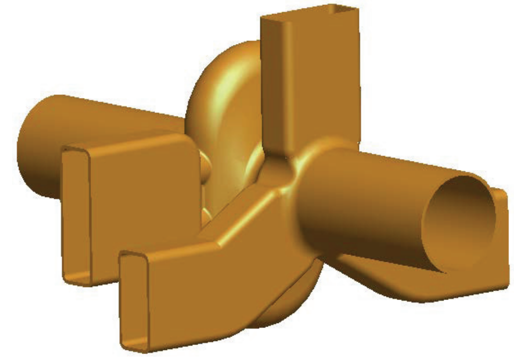

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Cons

- 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 electron pulses in storage rings – low alpha operation

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

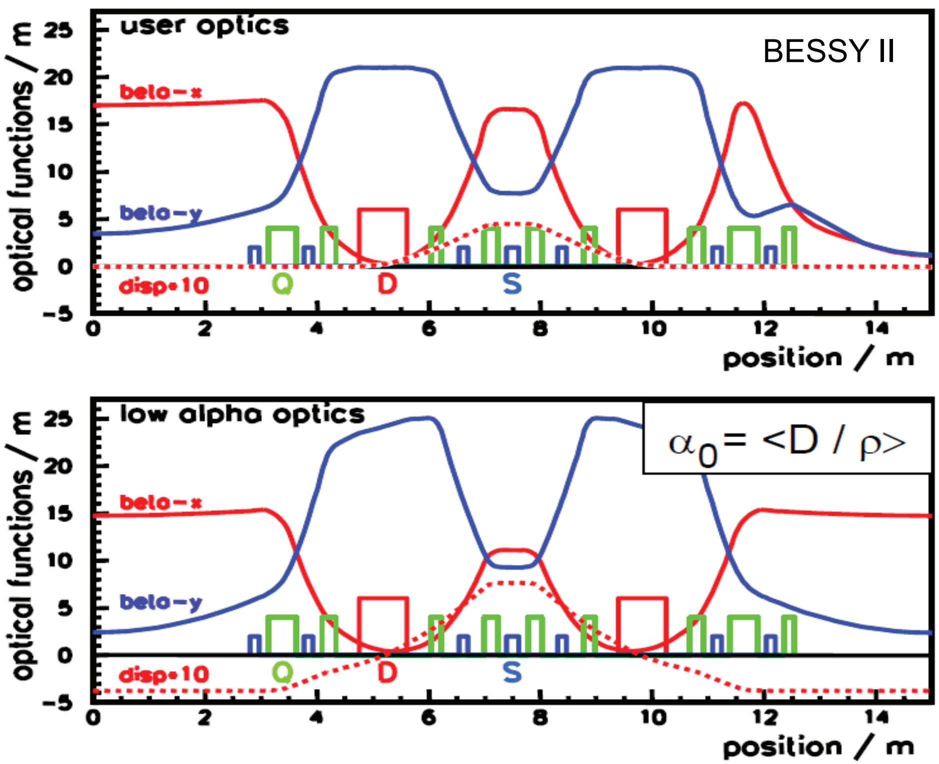
Fundamental interest in generating short electron pulses for generation of intensive, broadband, stable THz radiation (CSR)
but also great interest for beam studies (bursting thresholds) *(see e.g. talk J. Steinmann, TUP2WD03)*

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

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

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

quadrupoles → α_0
sextupoles → α_1
octupoles → α_2



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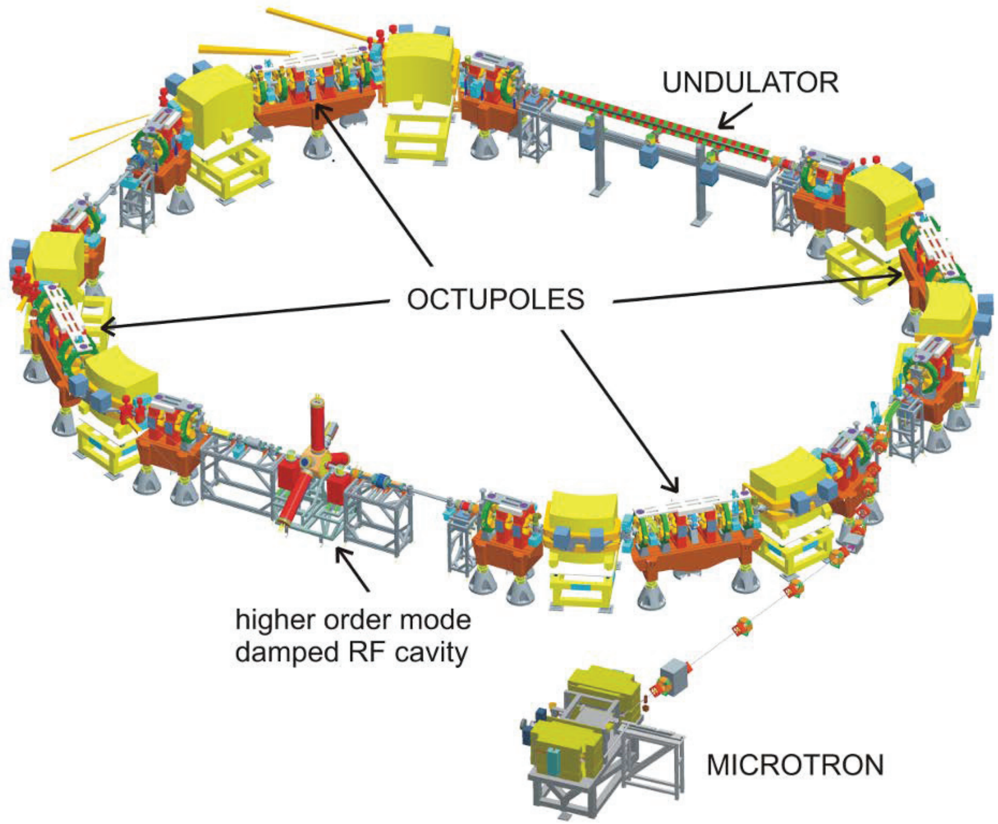

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MLS - Metrology Light Source
(developed and operated by HZB, BESSY)

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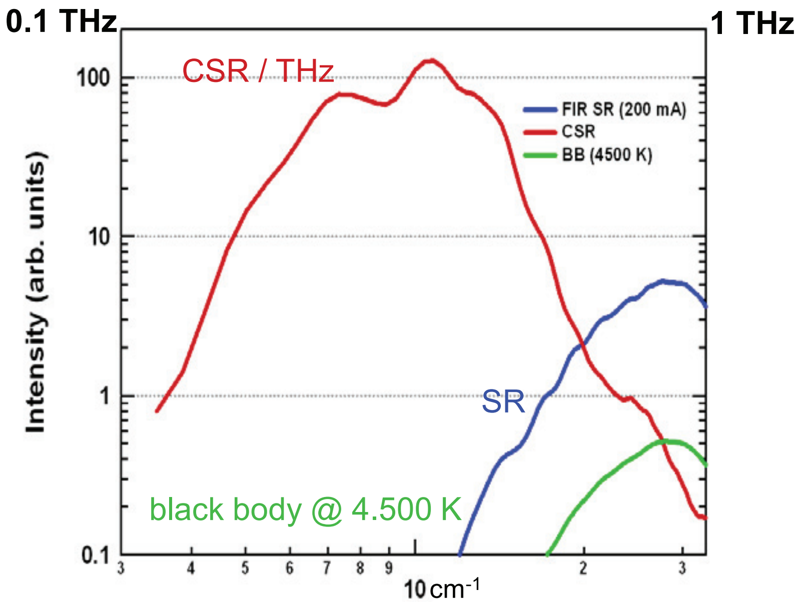

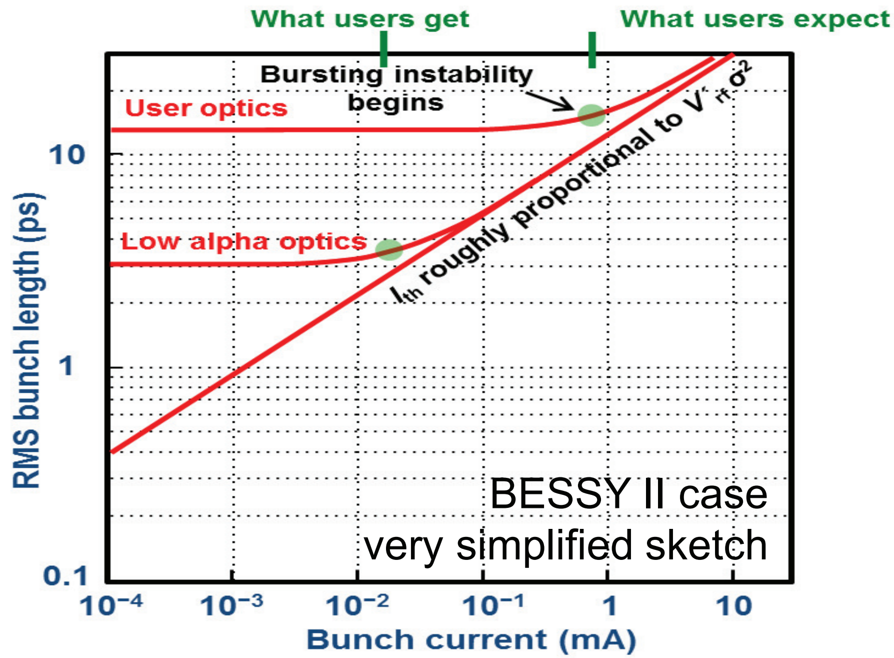

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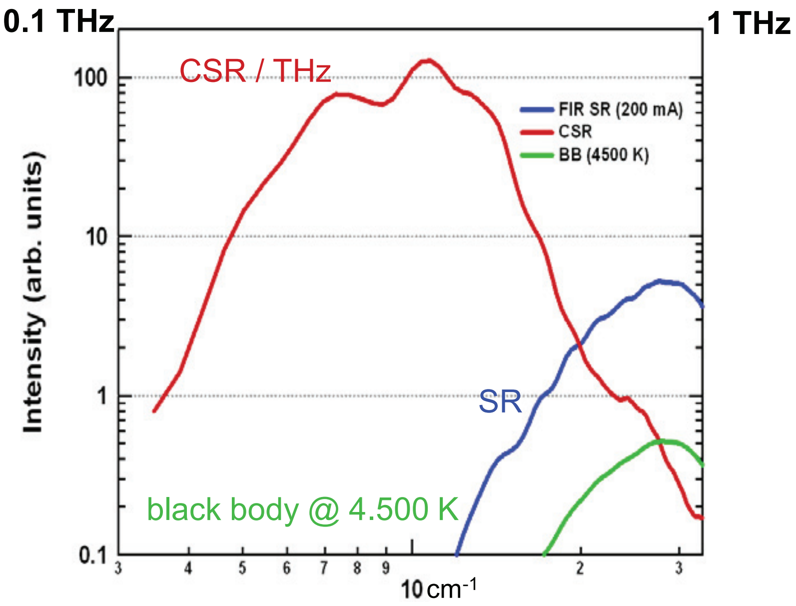

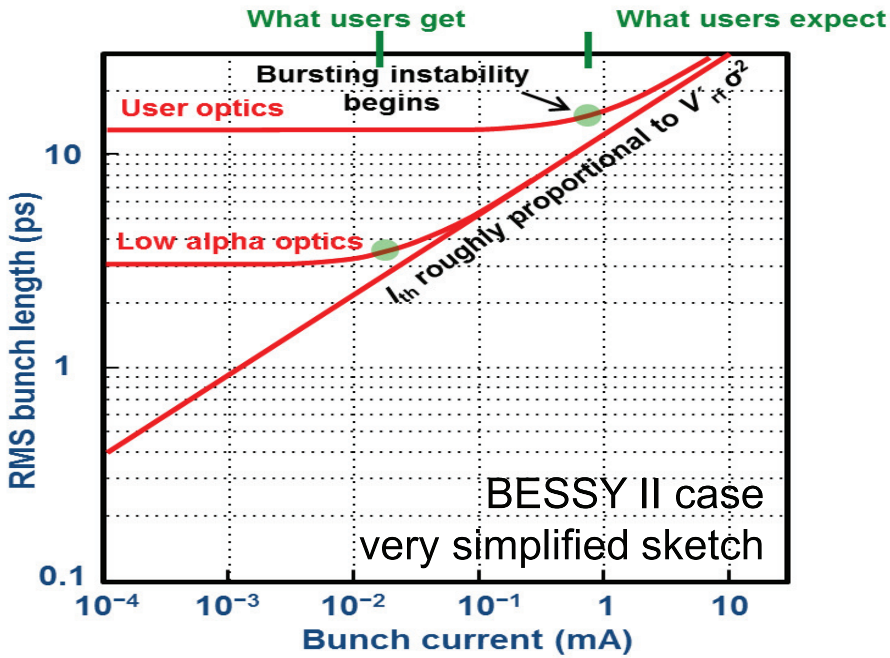

Facilities operating low-alpha
ALS, KARA (fka ANKA), ALS
BESSY II, DIAMNOND, Elettra
MLS, NewSUBARU, SLS, SOLEIL
SPEAR, SRS, …

BESSY II, SOLEIL ca. 12 dedicated days/a

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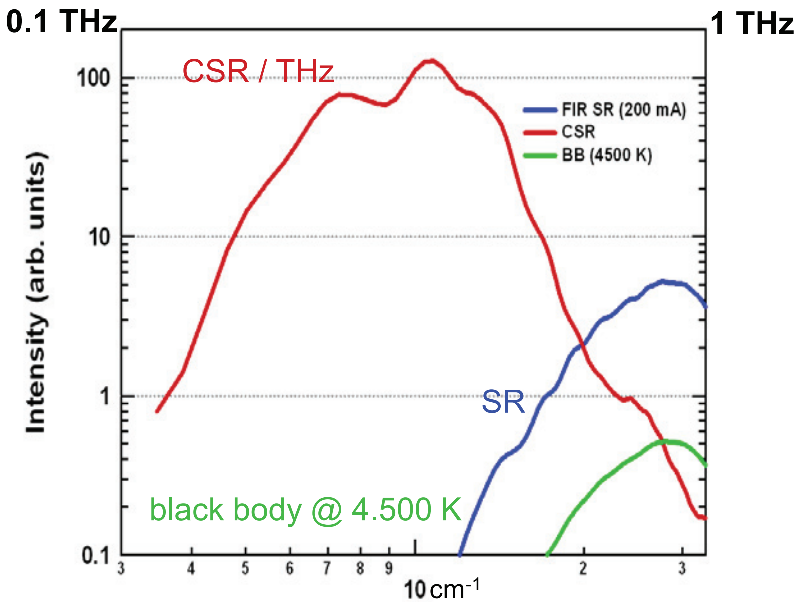

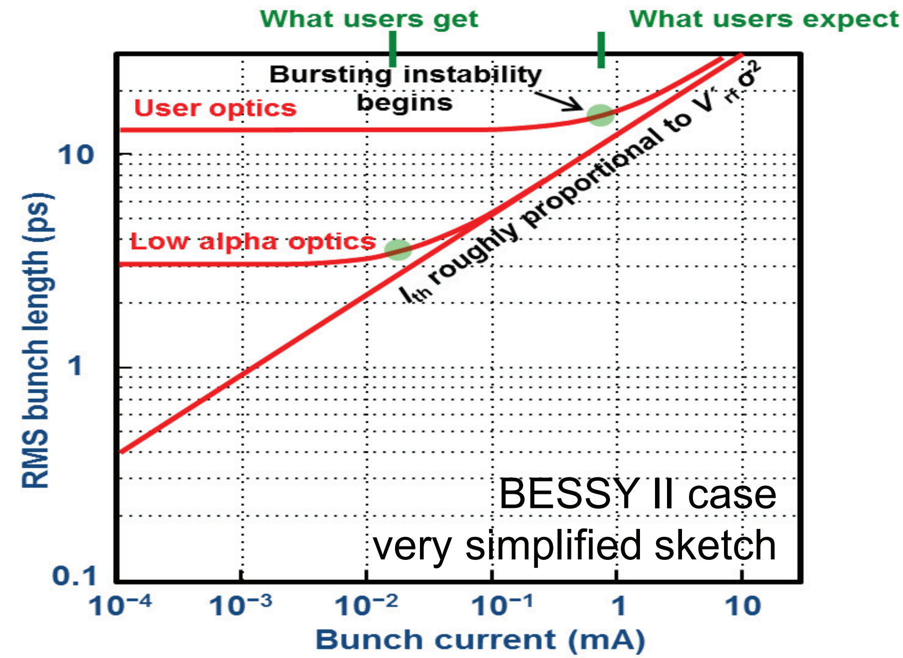

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- pulse lengths ps and below
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- or at higher currents → intensive bursts
- no significant investment

Cons

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- orbit very sensitive to RF freq. changes

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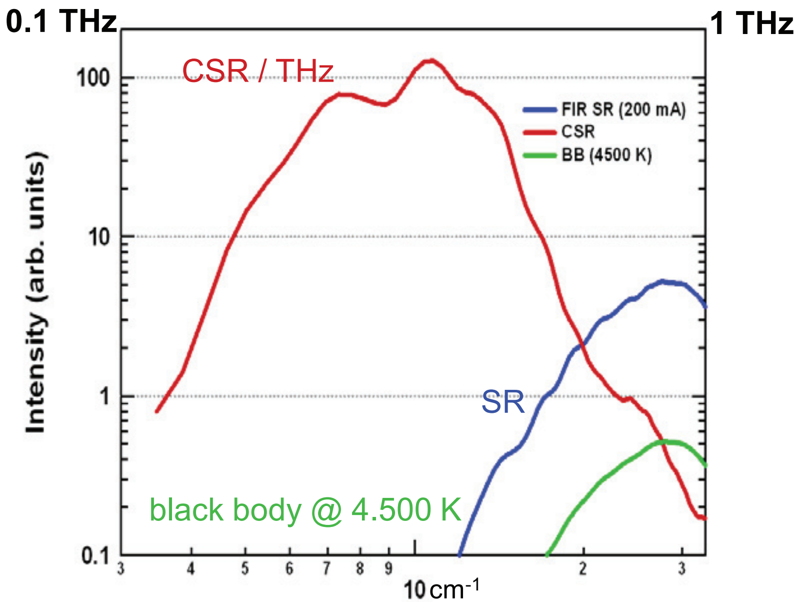

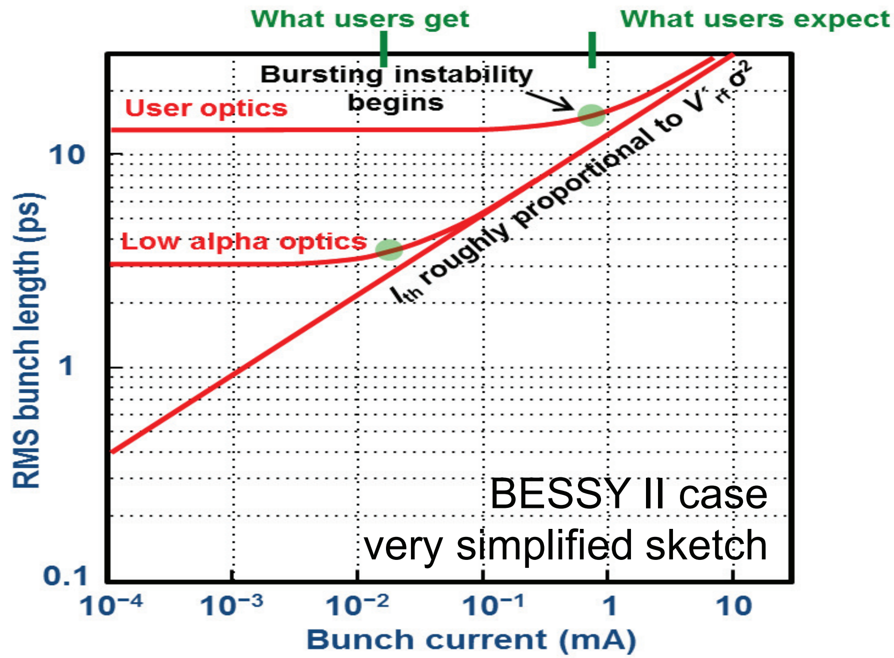

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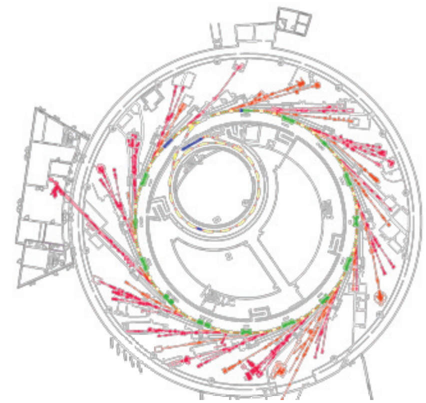
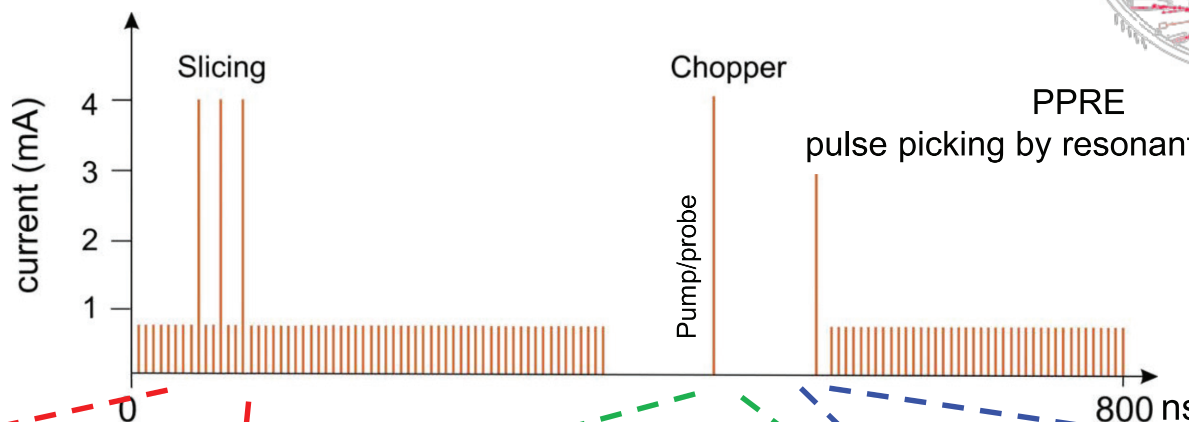
In the case of $\alpha \rightarrow 0$ and I → 0 the minimum bunch length is limited (~ 300 fs) by a) quantum excitation and partial $\alpha \neq 0$ b) transverse-longitudinal coupling

(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

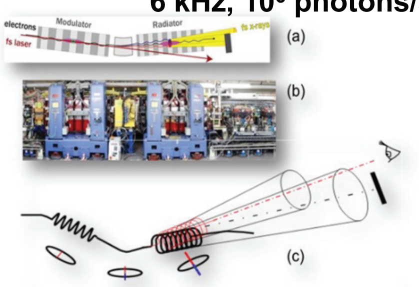
Energy/current	1.7GeV / 300mA
Emittance	6 nm rad
Pulse length	15 ps (rms)
Circumference	240



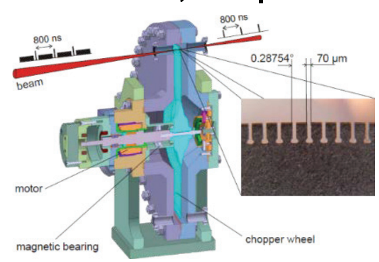


PPRE
pulse picking by resonant excitation

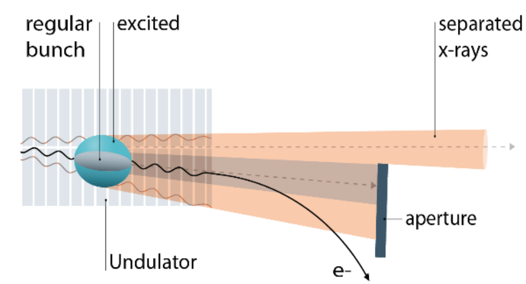
100 fs
6 kHz, 10^6 photons/s



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



20 ps
1.25 MHz, 10^9 photons/s



R. Müller et al, IPAC2016 / IPAC2017

Short pulses – using high voltage, high frequency cavity systems

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Today: short pulses, low flux in low-alpha

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1.5 MV @ 500 MHz rf-systems = 2π 0.75 MV GHz

→ reduce α by 100 = low-alpha operation with 1/10 bunch length

→ limited average current (~ 1/100)

→ rather “dark” operation mode

Future: short pulses, high flux

supply additional high voltage at

high frequency: 32 MV @ 1.5 GHz

→ short 1.9 ps pulses with same
current as in standard user op.

→ forced low-alpha mode permits
even ~ 400 fs

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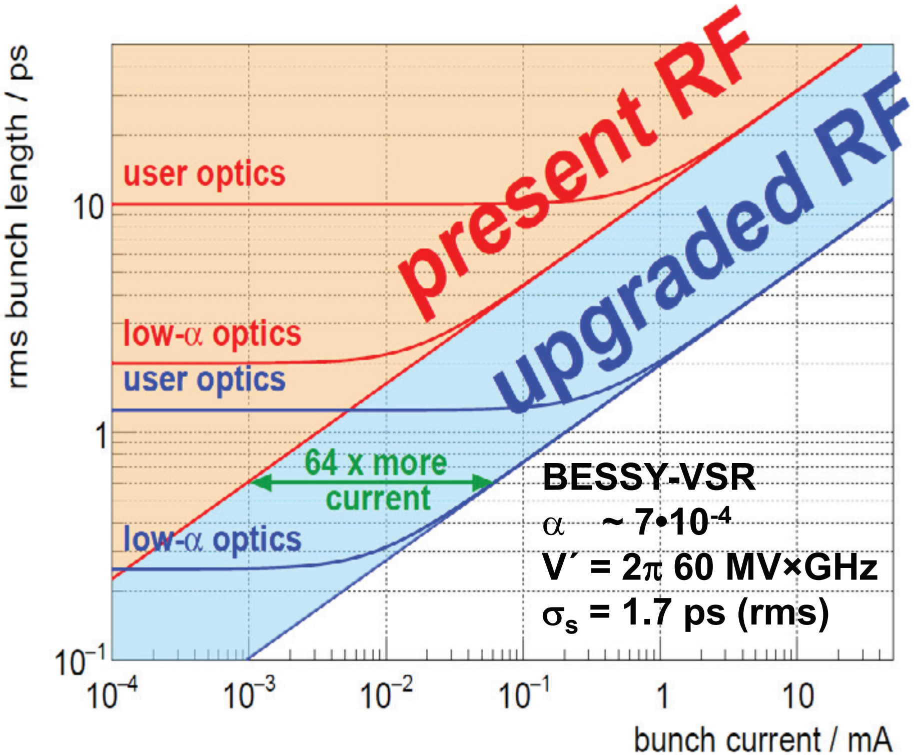

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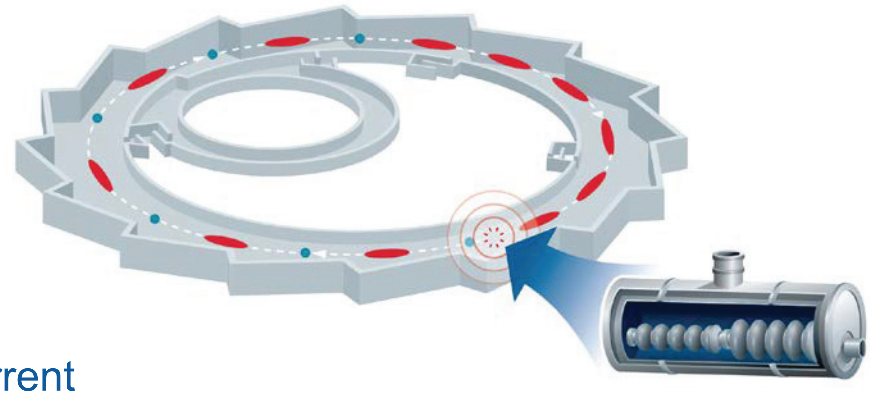
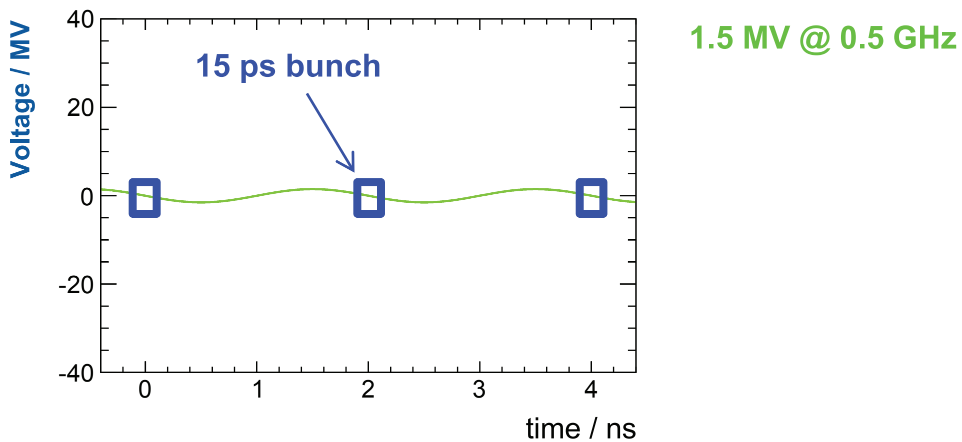


high voltage (20 MV/m) cw multi-cell SC cavities allow to increase the total voltage gradient by two orders of magnitude
→ ca. 1/10 bunch length @ constant bunch current

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.



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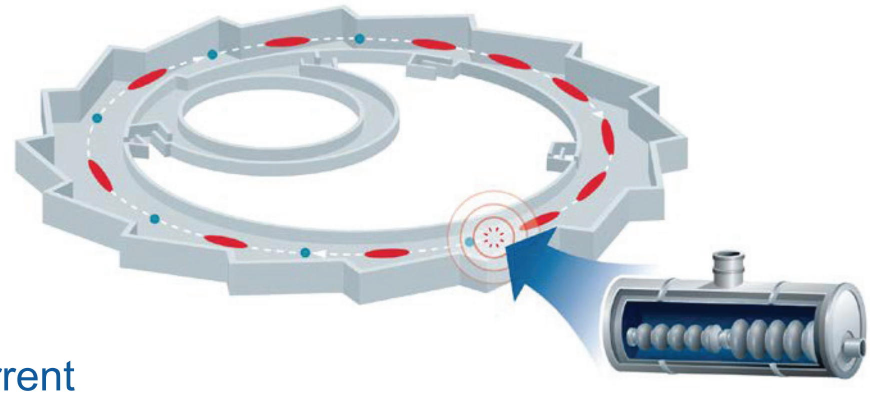

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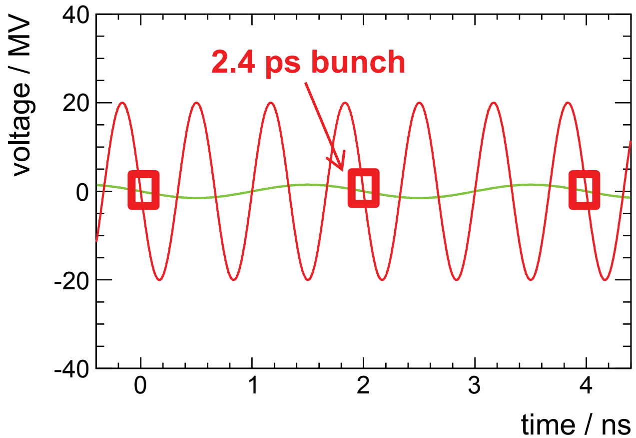

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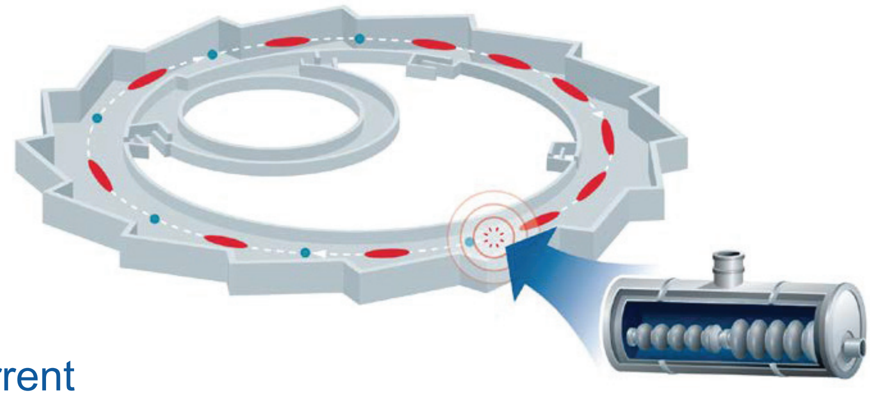

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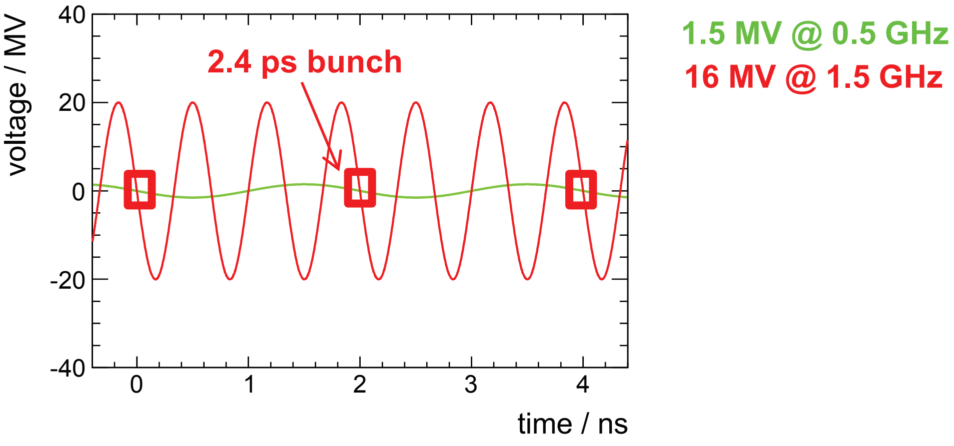

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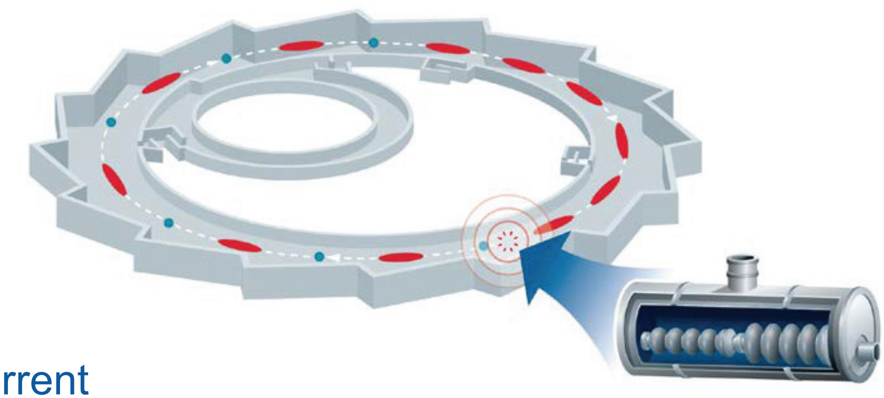

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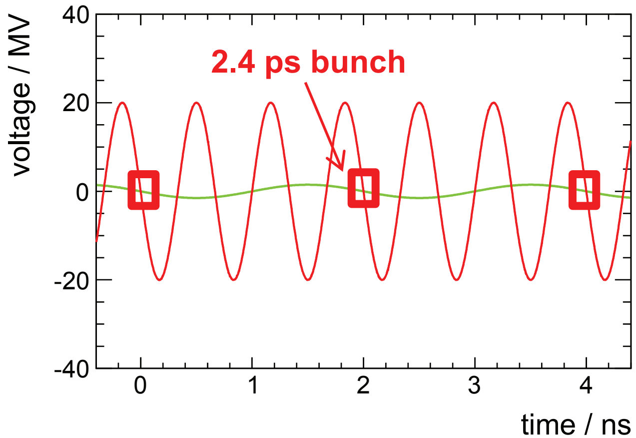

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16 MV @ 1.5 GHz

J. Feikes, P. Kuske, G. Wüstefeld EPAC2006

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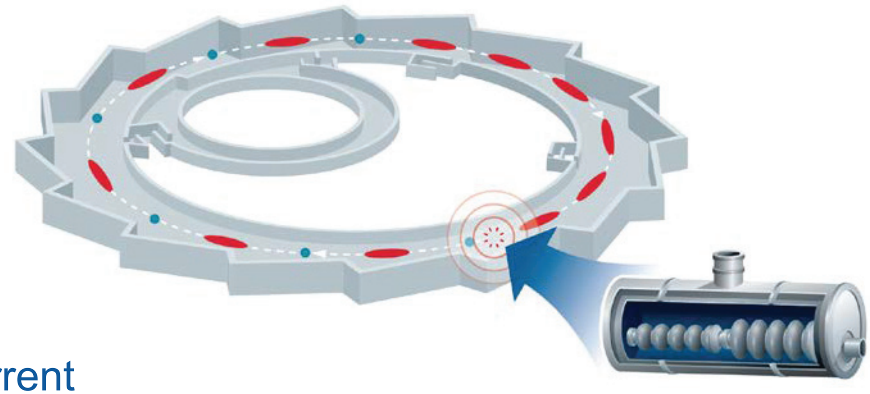

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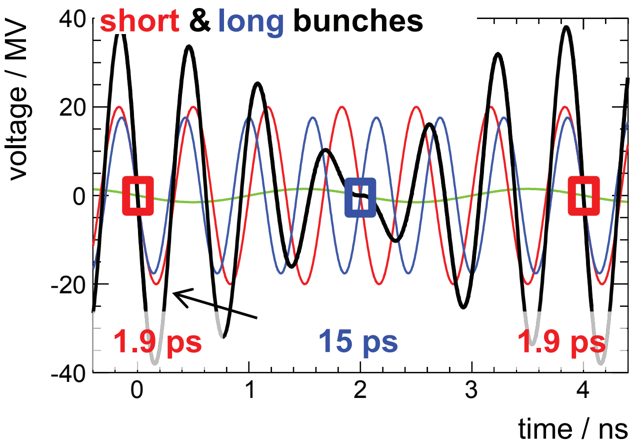

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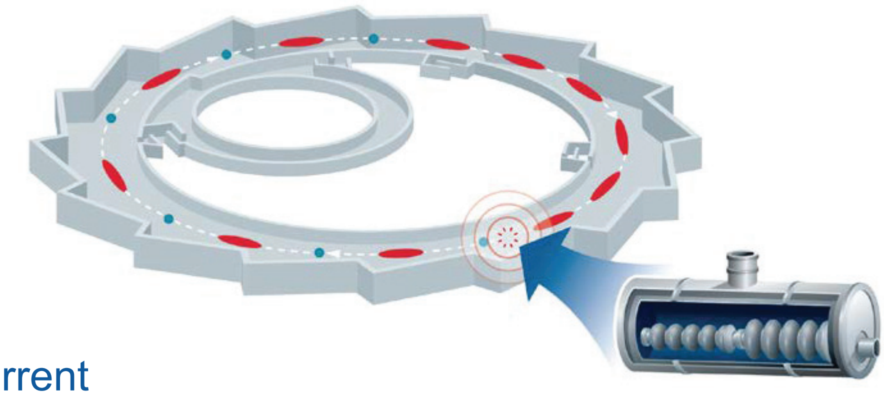

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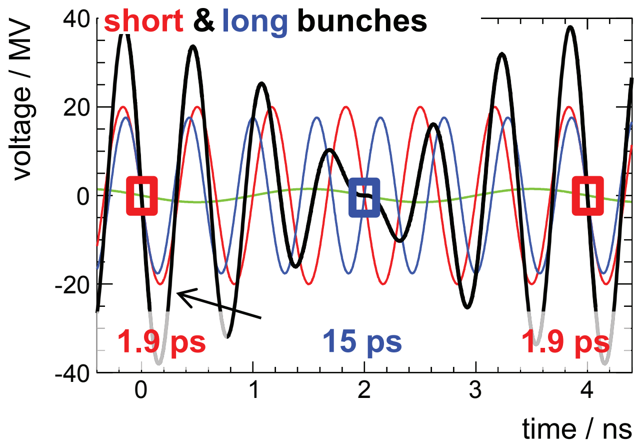

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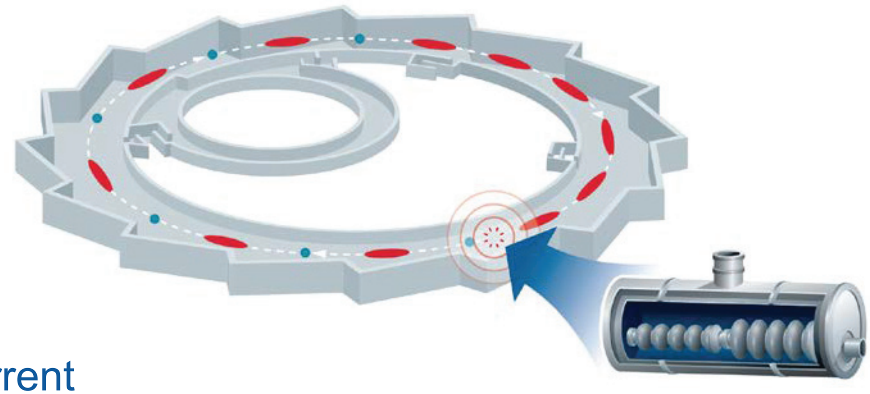

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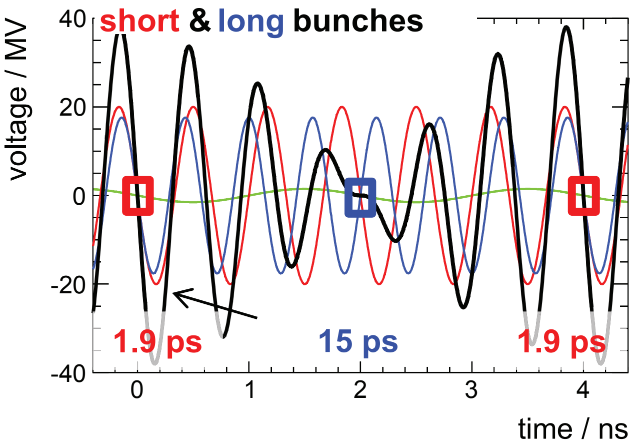

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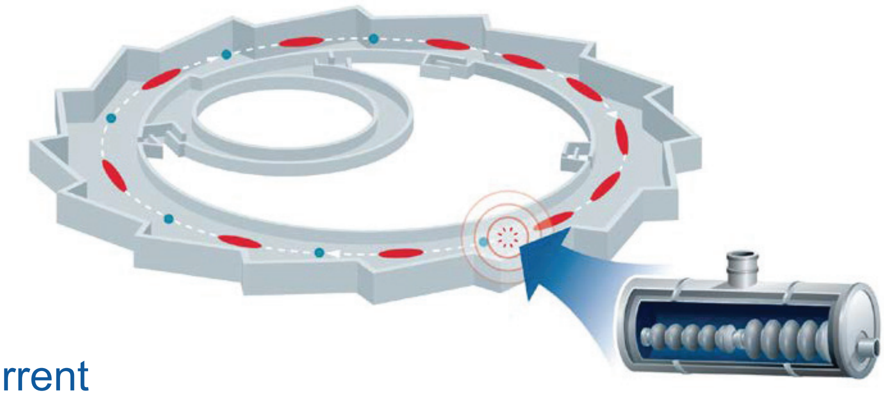

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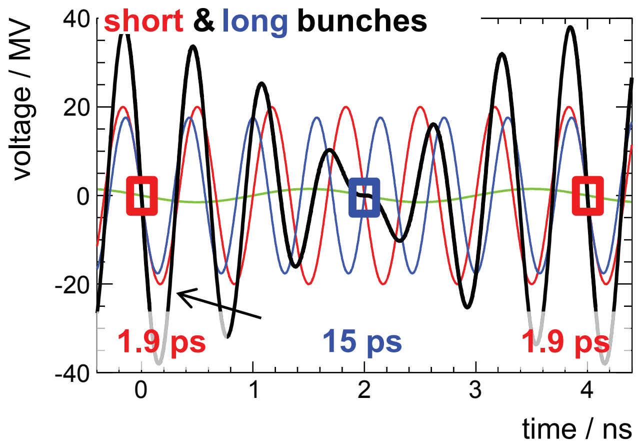

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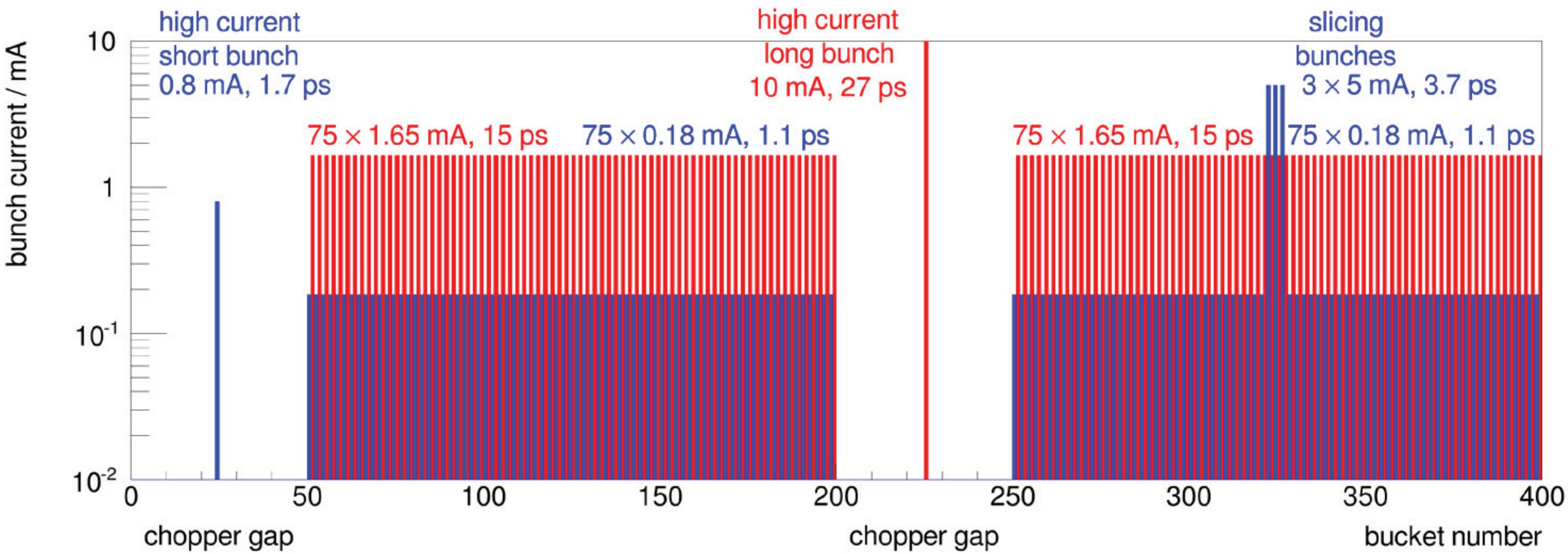
VSR – variable pulse length storage ring

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

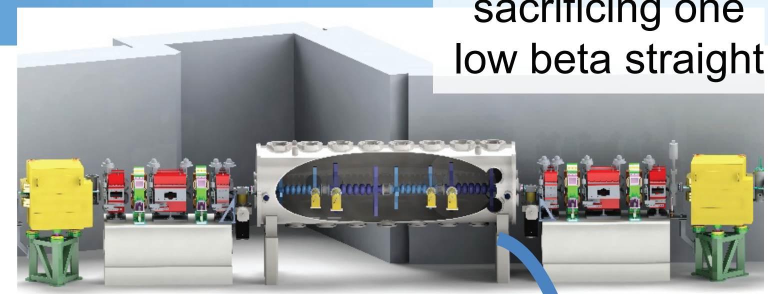
multi functional / multi user hybrid mode

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)

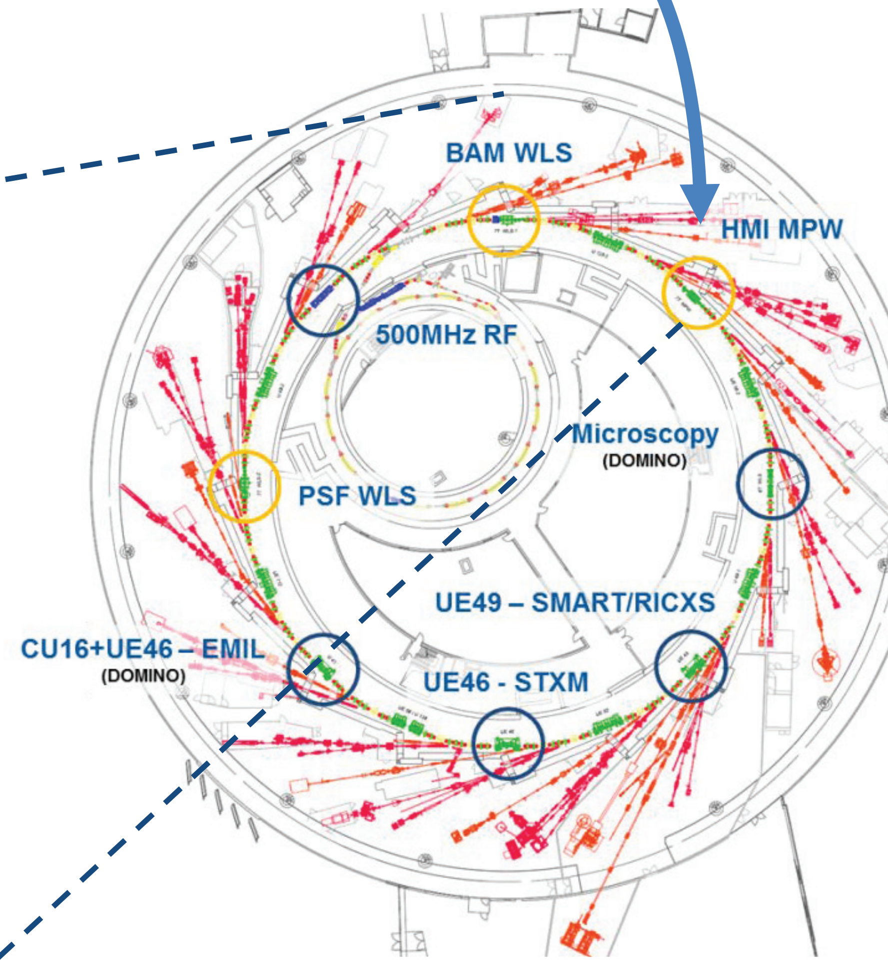
Technical realisation

sacrificing one low beta straight

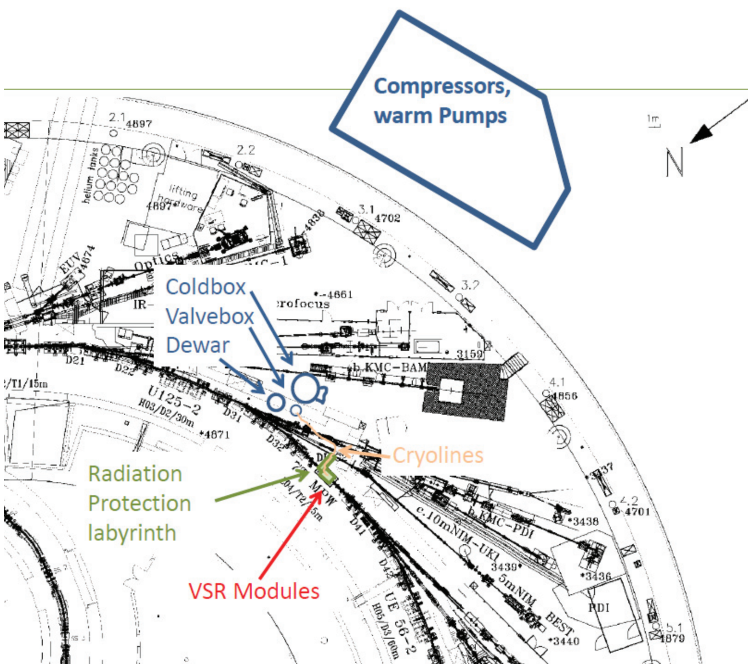


One cryo-module with:
2 x 4 cell @ 1.5 GHz & 2 x 4 cell @ 1.75 GHz
operating at **1.8 K LHe** temperature
active length: **1.50 m** with **20 MV/m**
total gradient: **2π 50 MV×GHz (x 60 increase)**

A. Velez, A. Neumann, F. Glöckner, J. Knobloch et al. HZB



Installation of 1.8 K Cryo-System



BESSY-VSR – Time line

doi:10.5442/R0001

2015

- Technical Design Study ready
- Scientific evaluation
  result: “outstanding” project
- Full support by German Committee for Research with SR

2016

- Exploring funding sources
- Start of 2 R&D projects for SRF cavity development and bunch2bunch beam diagnostic (3a, 3.0 Mio€)

2017

- Successful applied for EFRE funding (via State of Berlin)
  → 7.5 Mio€ of the necessary funding = SupraLab@HZB
- 11.8 Mio€ granted by Helmholtz Association
- 10.0 Mio€ HZB funds

>> BESSY VSR fully funded << – total invest ca. 30 Mio€

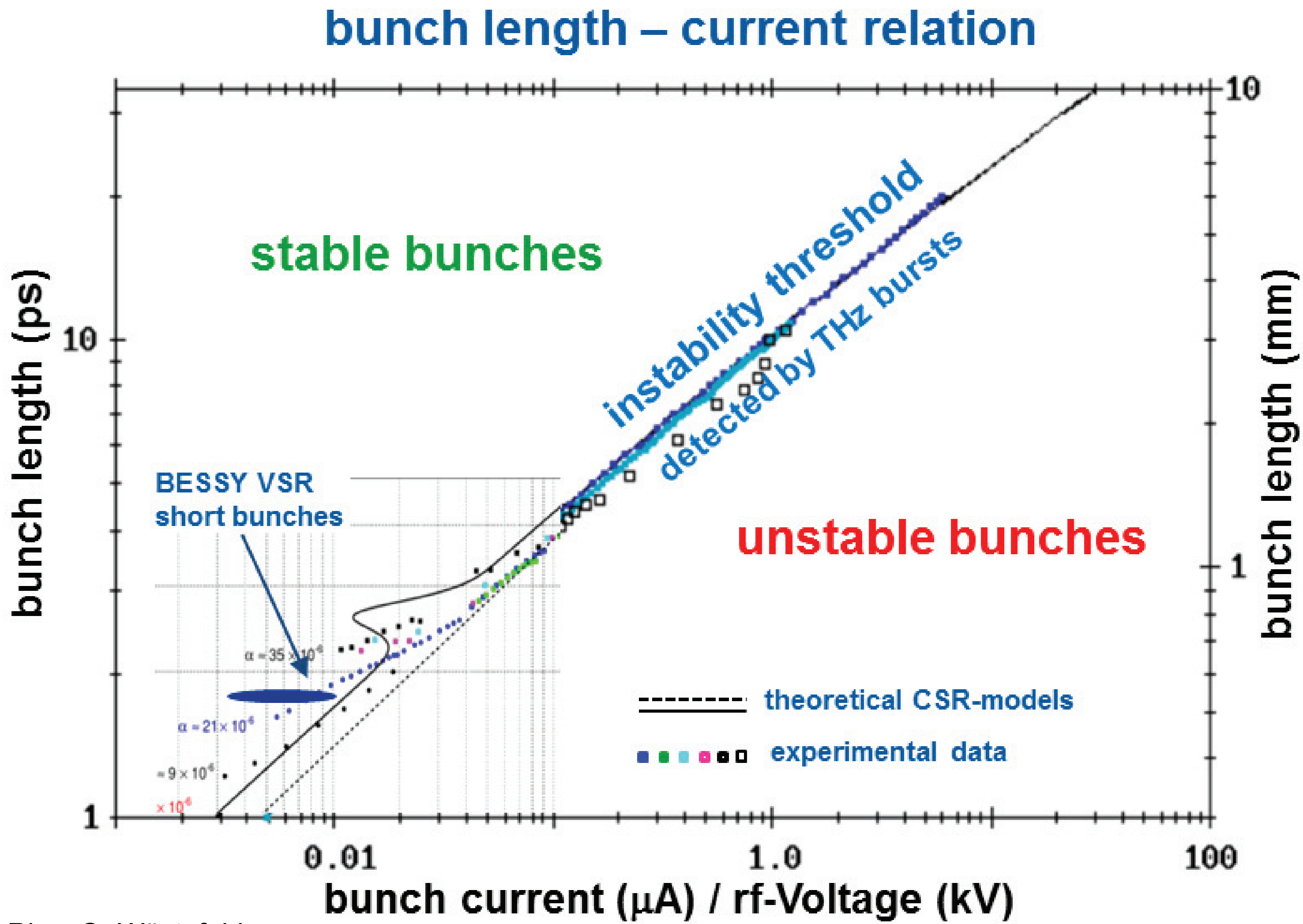
2018	2019	2020	2021	2022
tendering cavities & SSA transmitter	**installation & commissioning cryo-plant**	**prep. phase cryo-module 2 x 1.5 GHz (assembly, test, beam test)**	**full BESSY VSR 2 x 1.5 GHz & 2 x 1.75 GHz (assembly, test, user operation)**	

implementation within “standard” shutdowns 2018 – 2021 + ca. additional 15 weeks

P. Schnizer, M. Ries, FLS2018, WEP2PT010

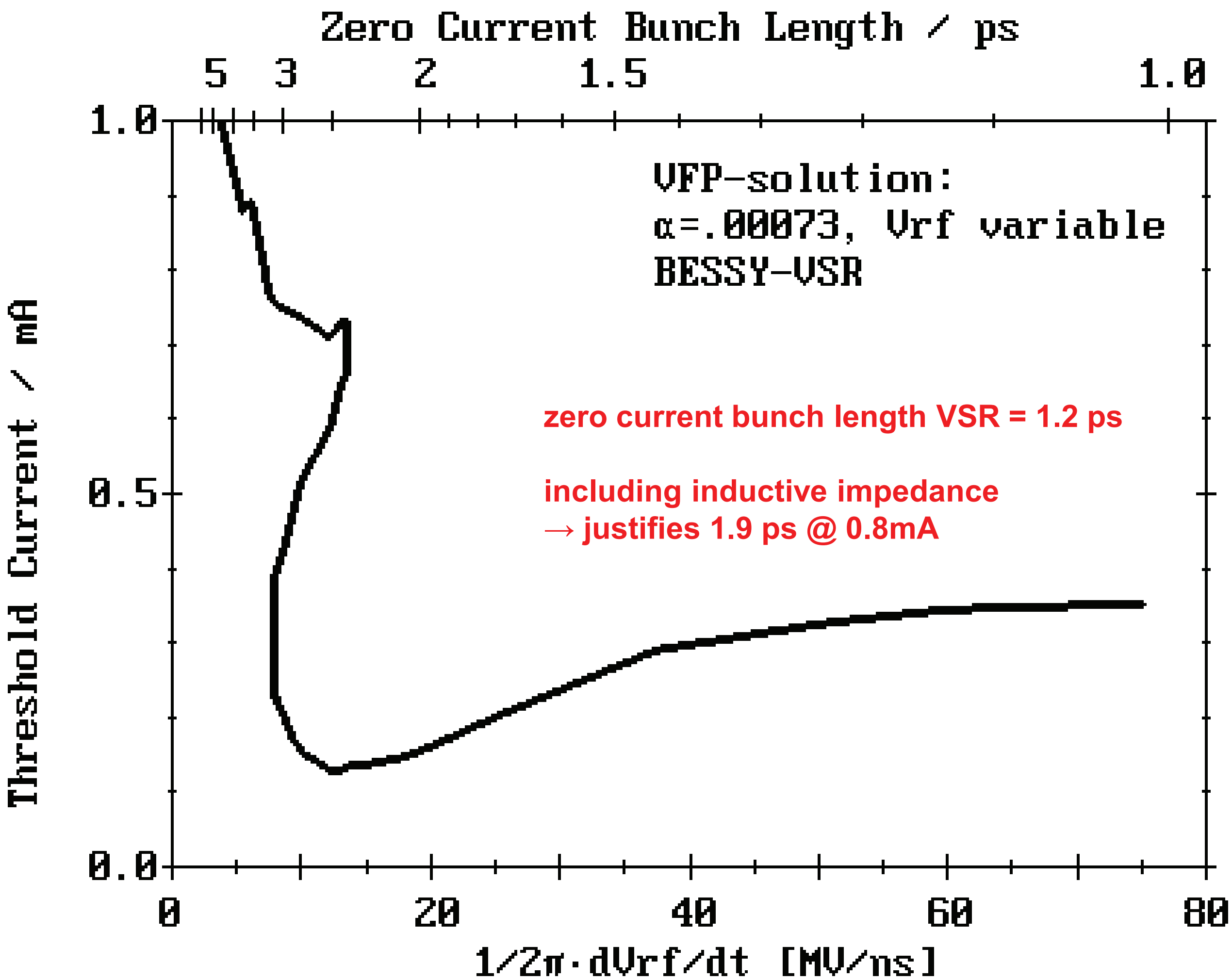
Highly charged short bunches are limited by the <u>CSR bursting instability</u>

⇨ unstable bunches are not lost, they <u>blow up in energy spread and length</u>



P. Kuske, M. Ries, G. Wüstefeld

CSR-driven longitudinal instability of short bunches – predictions of VFP-solver with parallel plate model for BESSY VSR (in black)



P. Kuske, IPAC2017, THPAB007
P. Kuske, IPAC2013, WEOAB102

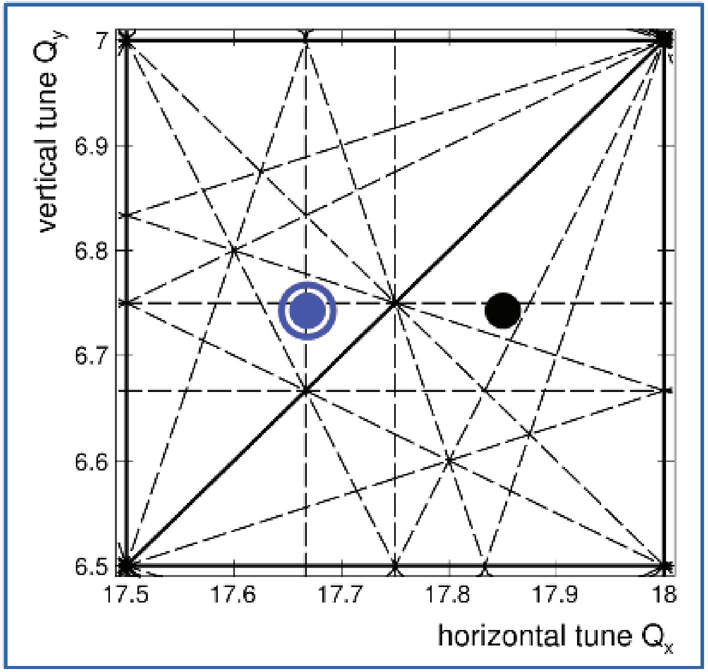
Transverse Resonance Island Buckets (TRIBs) – bunch separation

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

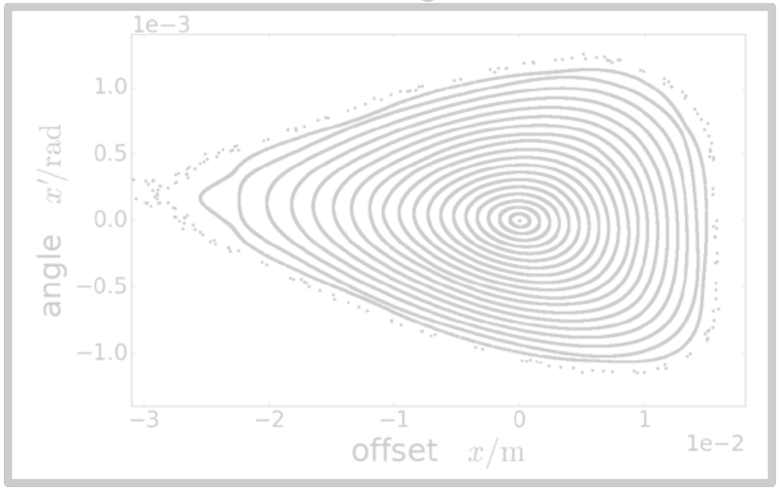
- Operating machine close to horizontal 3rd order resonance
- Minor impact on linear beam optics expected



● 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)

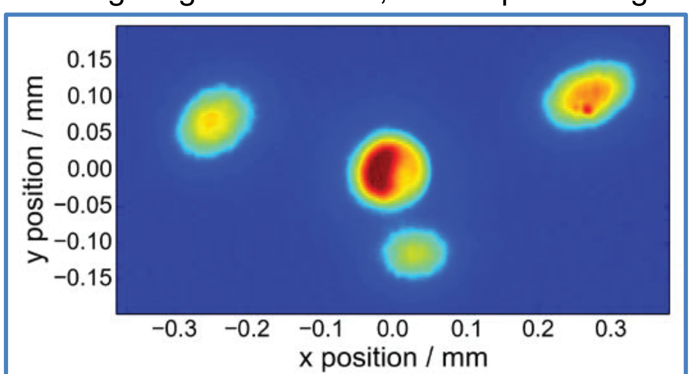
TRIBs at BESSY II
Proof of Principles Studies:

- 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

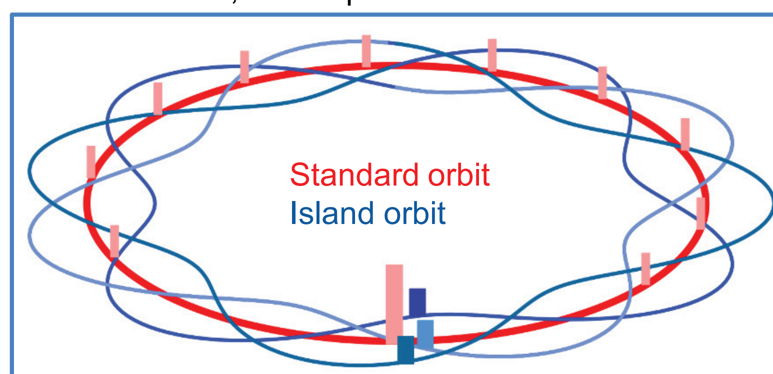
Bending magnet beamline, source point image



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

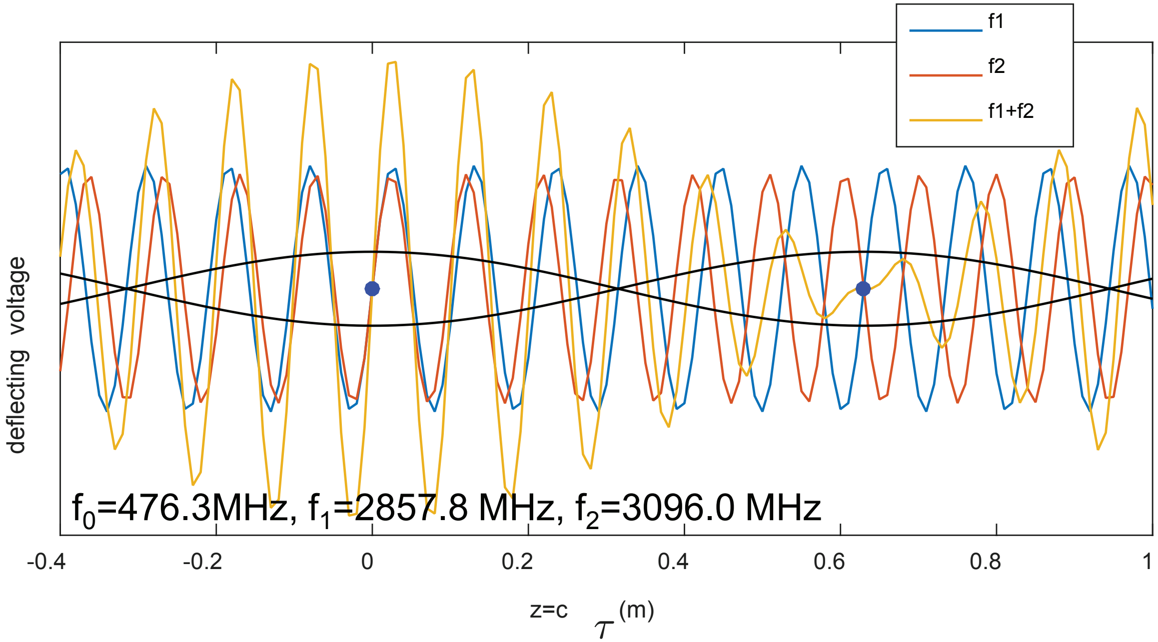
TRIBs Scheme, 2nd fill pattern stored on 2nd orbits



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.

Deflecting the beam – 2f steady state transverse RF chirp

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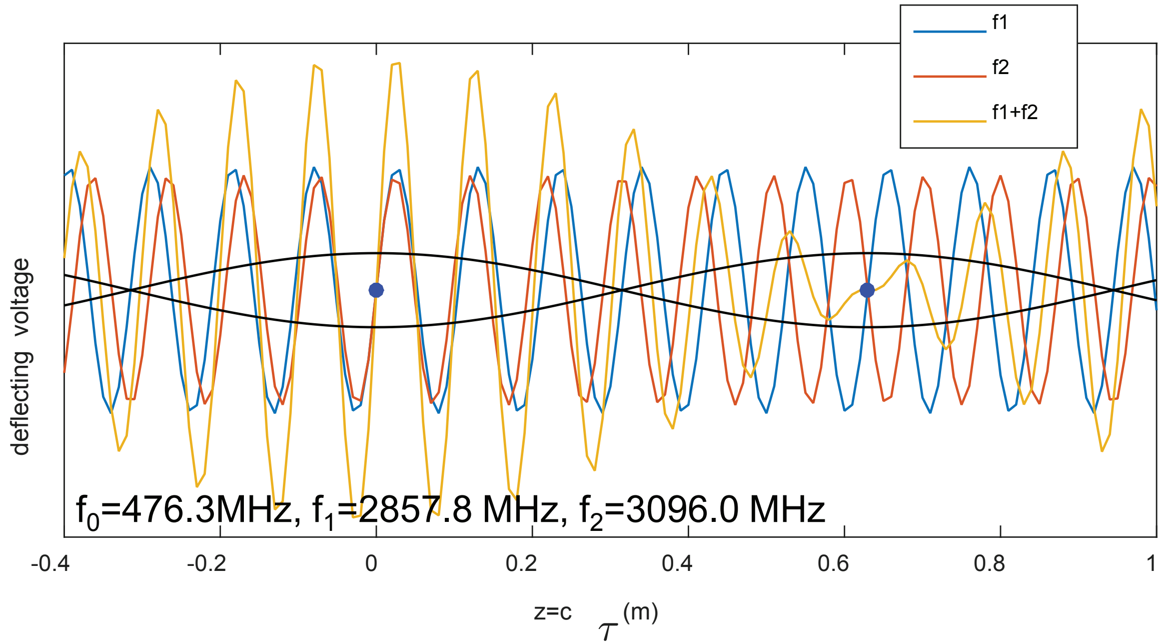

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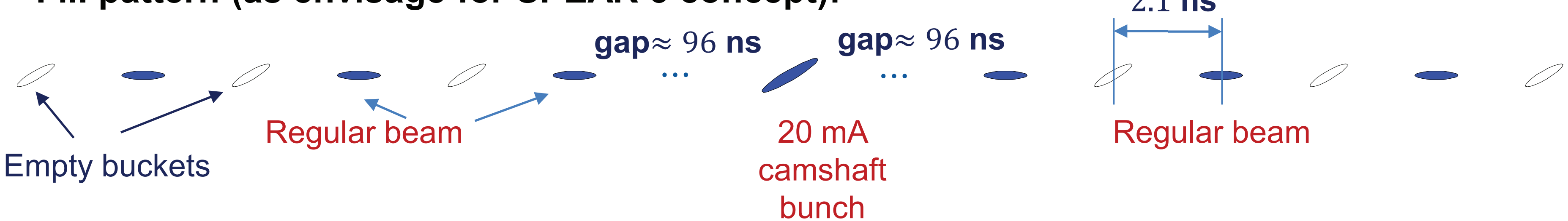
Fill pattern (as envisage for SPEAR 3 concept):



Comparison – 2f steady state transverse RF chirp ↔ VSR

2f steady state transversal RF chirp	longitudinal beating potential / VSR
- ps photon pulse length - alternating standard and tilted buckets - natural separation of short slices and main beam - no increase in long phase space density (no lifetime / IBS issues)	- ps short electron bunches = real increase in longitudinal charge density (supports improved slicing, CSR/THZ generation) - alternating short and long buckets - full set of separation modes possible (longitudinal, horizontal, vertical = chopper, RPPX, pseudo single bunch, TRIBs (?)) - no coupling to transverse phase space
- separation only vertical - separation depends on longitudinal position in ring - pulse length is wavelength depending - coupling to none tilted bunches in case of insufficient cancellation of kicks (e.g. due to transient beamloading; RF stability) - some influence on vertical emittance - reduced intensity – only fraction of bunch is used - need crab cavities at n and n+1/2 harmonic	- increased long. charge density (Touschek / IBS issues) - injection issues into short bunches - technological very challenging to press 2x2x4cell sc cavities in one straight and to operate them

Summary

There is the need for short bunches in storage rings

→ ps level (and below), at rep. rates from kHz to many MHz

Many different schemes exists, new are coming up

→ slicing, low-alpha, transverse RF chirp, VSR, …

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Are short pulses possible in DLSR?

As the VSR scheme or the steady state RF chirp scheme spans up a fill pattern with alternating “standard” and “manipulated” buckets, which can be filled at will, it could be possible to provide also for DLSR catered fill pattern, with special treated bunches, for the generation of short photon pulses in the ps regime.

This requires detailed studies of the impact of these schemes on DLSR operation and the properties of these “manipulated” buckets in terms of lifetime, IBS, …

to be continued …

Light matters!

THANK YOU FOR YOUR ATTENTION

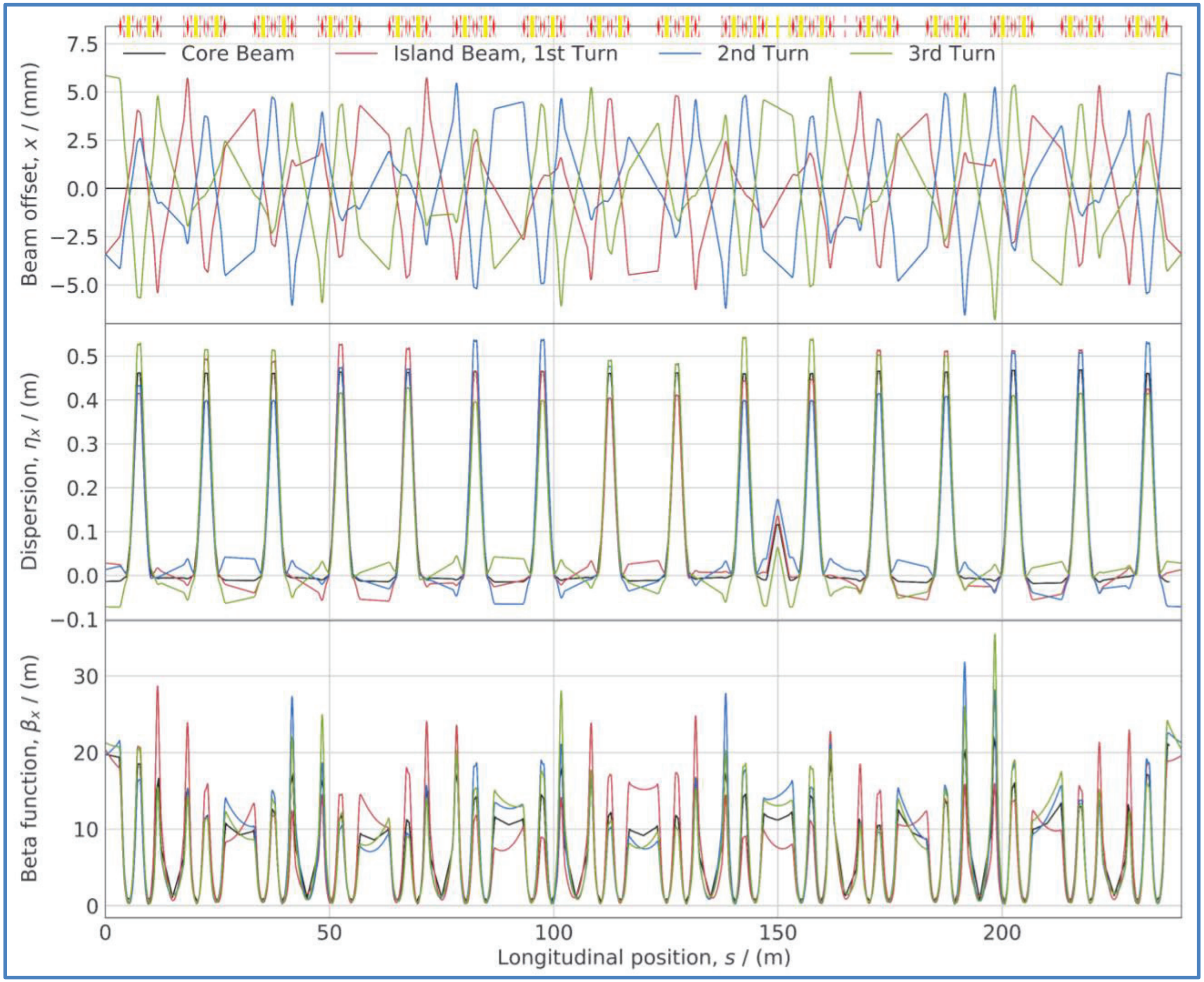
Many thanks to all colleagues for providing material:

A. Chao/SLAC, X. Huang/SLAC, S. Kahn/DELTA,
A.-S. Müller/KIT, F. Willeke/BNL, A. Zohlents/ANL
and P. Goslawski, K. Holldack, P. Kuske, R. Müller, M. Ries, U. Schade, G. Wüstefeld / BESSY II, HZB

TRIBs at BESSY II – Separation and Twiss Parameters of TRIBs orbit

F. Kramer, HZB und HU Berlin, PhD thesis in preparation

Horizontal beam offset
Dispersion function
Beta function



Equilibrium Emittance:

BESSY II std. :	7 nm rad
TRIBs core orbit:	8 nm rad
TRIBs island orbit:	9 nm rad