Resonance Islands at Storage Rings

(Transverse)

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DESY, Zeuthen, Germany

Overview of the talk: Resonances at Storage Ring

- Short definition of the ‘word’ Resonance (at Storage Rings)
  - Longitudinal Resonance
  - Transverse Resonances
    - Linear and Non-Linear
- Transverse Resonance Island Buckets – TRIBs at BESSY II / VSR and MLS
  - Studies, Experiments, Applications and Ideas

Resonances at Storage Rings

Resonance(s)

- System with the possibility to oscillate
  - repelling force (linear and non-linear)
  - natural (eigen)frequency, resonant frequency
- Driving external force
  - when periodic, even when weak, large amplitudes of the oscillating system

    -> resonance disaster

at Storage Rings

- Beam / Particle
  - transverse (Quadrupols) and longitudinal (Cavities)
  - three (pseudo)harmonic oscillators: Qx, Qy, Qs

$$Q_x = n + \frac{f_x}{f_0}$$

- Perturbation by magnetic imperfections, misalignements, …
  - periodic with revolution frequency due to <u>circular accelerator</u>

    -> beam blow up or even loss

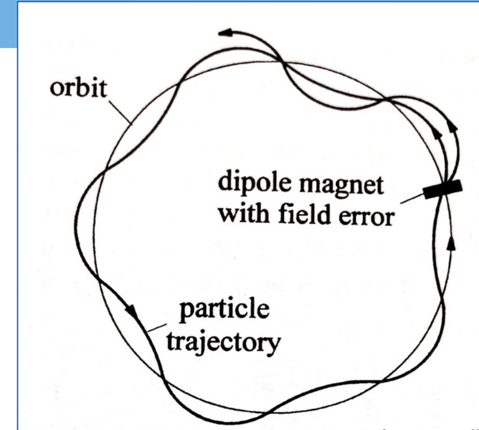
In general:
Resonances are bad! Avoid them!

Resonances at Storage Rings

Resonances at Storage Rings

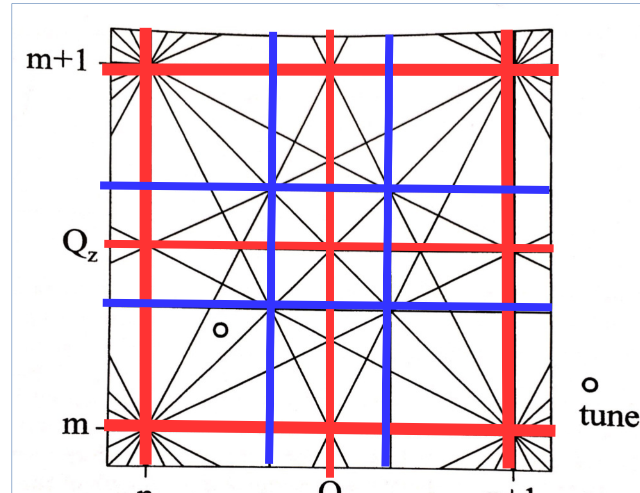
- If Tune Q = 0,1,2, …, n, integer -> perturbation in phase with revolution frequency

Driving field	Resonance condition
dipole	Q = p
quadrupole	Q = p/2
sextupole	Q = p/3



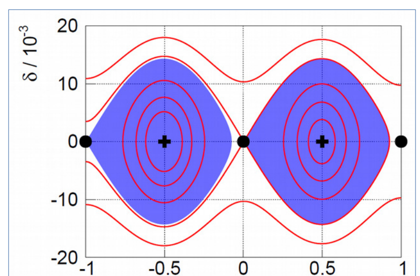
from K.Wille

- Transverse resonances: $\boxed{mQ_x + nQ_y = p}$
  - **Linear:** Dipole and Quadrupolmagnets integer and half-integer resonance
  - **Nonlinear:** Sextupole (third order resonance) and higher orders

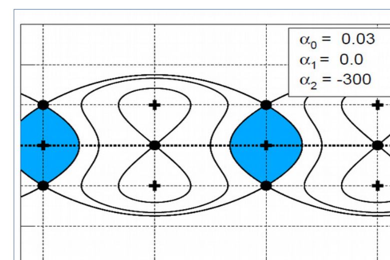


from K.Wille

- Longitudinal Resonances: Qs -> 0
  - See low alpha, G. Wüstefeld, J. Feikes and PhD theses M. Ries



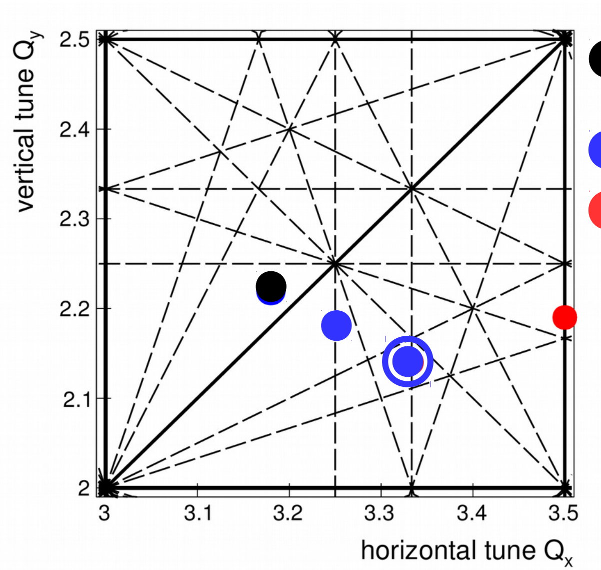
from PhD M.Ries



from PhD M.Ries

Resonances (TRIBs) at BESSY and MLS

Island buckets at MLS



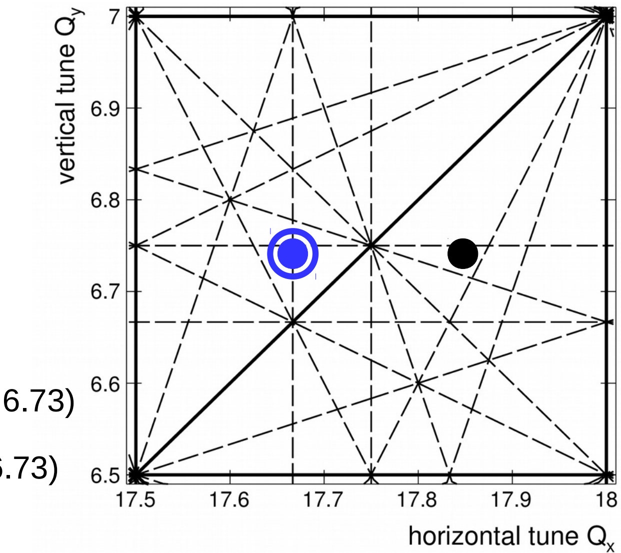
Working point (3.18, 2.22)

4th order res. (3.25, 2.18)
3rd order res. (3.33, 2.14)
2nd order res. (3.50, 2.19)

Island buckets at BESSY II

Working point (17.85, 6.73)

3rd order res. (17.66, 6.73)

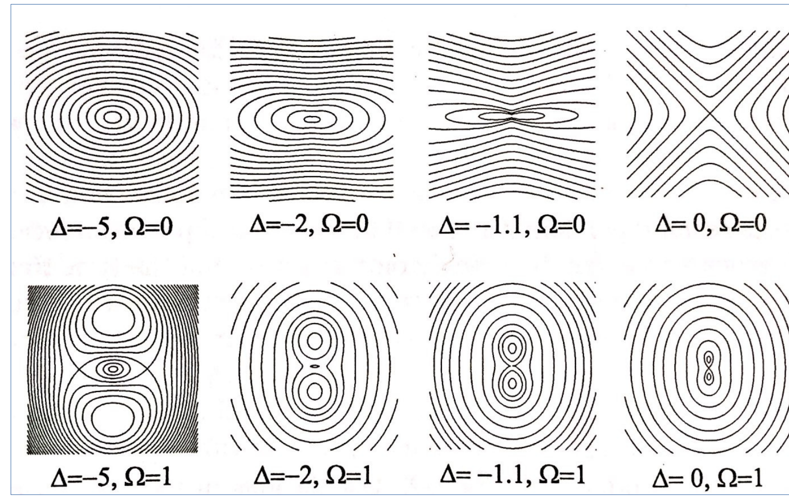


Operating machine close to horizontal resonance

- Only small de-tuning needed to move close to resonance
- Minor impact on linear beam optics expected
- No big changes of beta function and dispersion

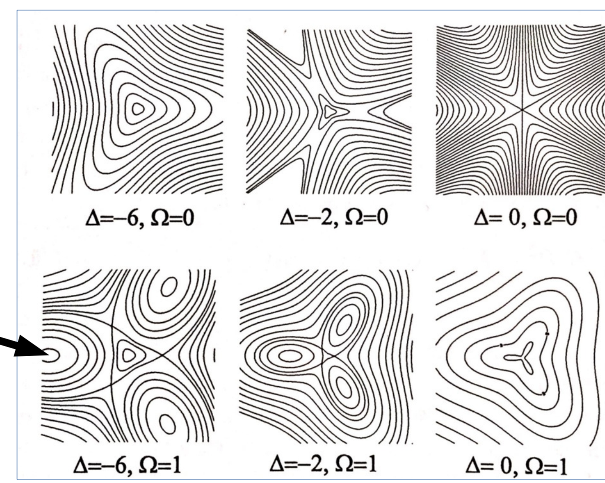
Transverse Resonances at Storage Rings

- Deformation of the transverse phase space (x,x') or in action angle variables (J,ψ)
  - Stable and unstable fixed points, separated by separatrix
- Phase space motion for a half integer resonance



from H.Wiedemann

- Phase space motion for a third order resonance

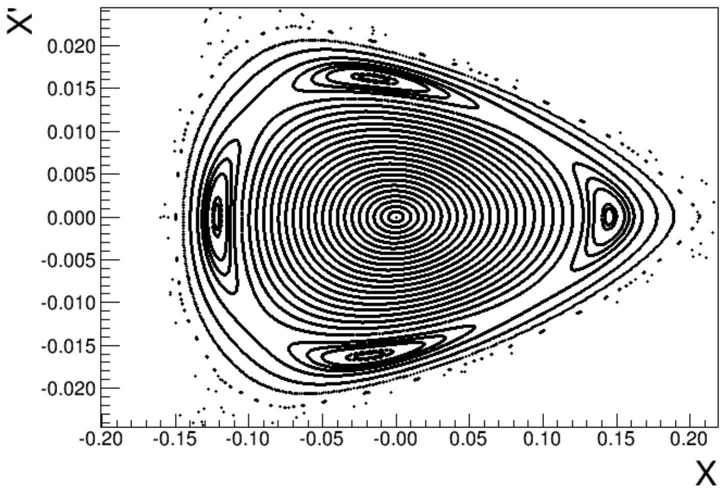


ISLAND Bucket

Transverse Resonance Island Buckets
- TRIBs -

TRIBs and the additional orbit

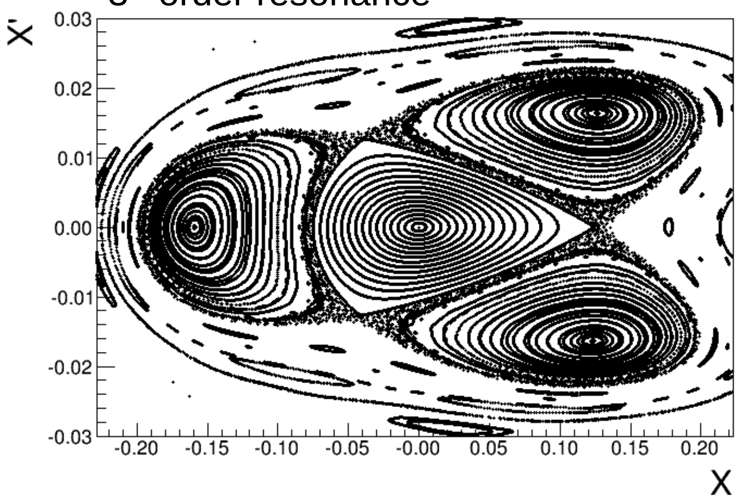
4th order resonance



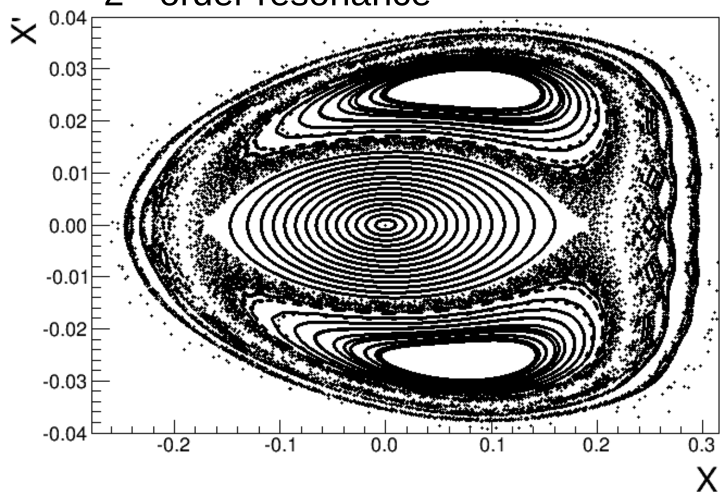
(x, x') phase space simulations

- Near resonance additional stable buckets
- Number of buckets = n, order of resonance
- 2nd stable orbit winding around the standard orbit closing after n revolutions

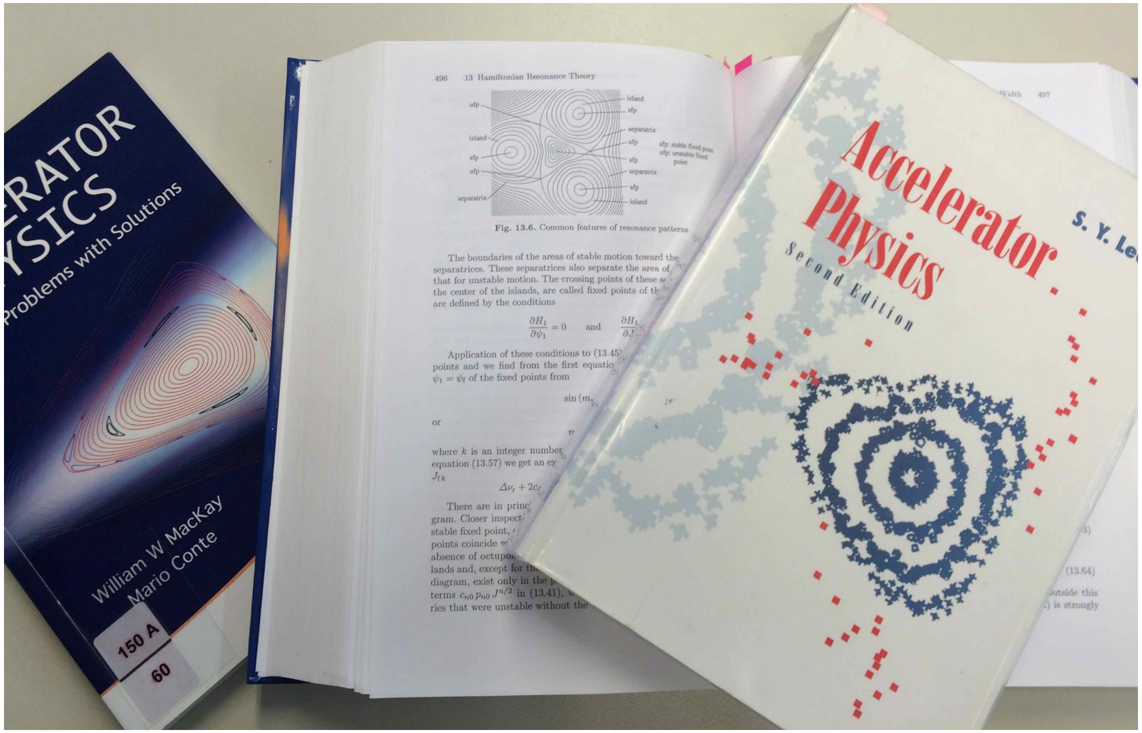
3rd order resonance



2nd order resonance



TRIBs - Not new



No application at Lightsources so far

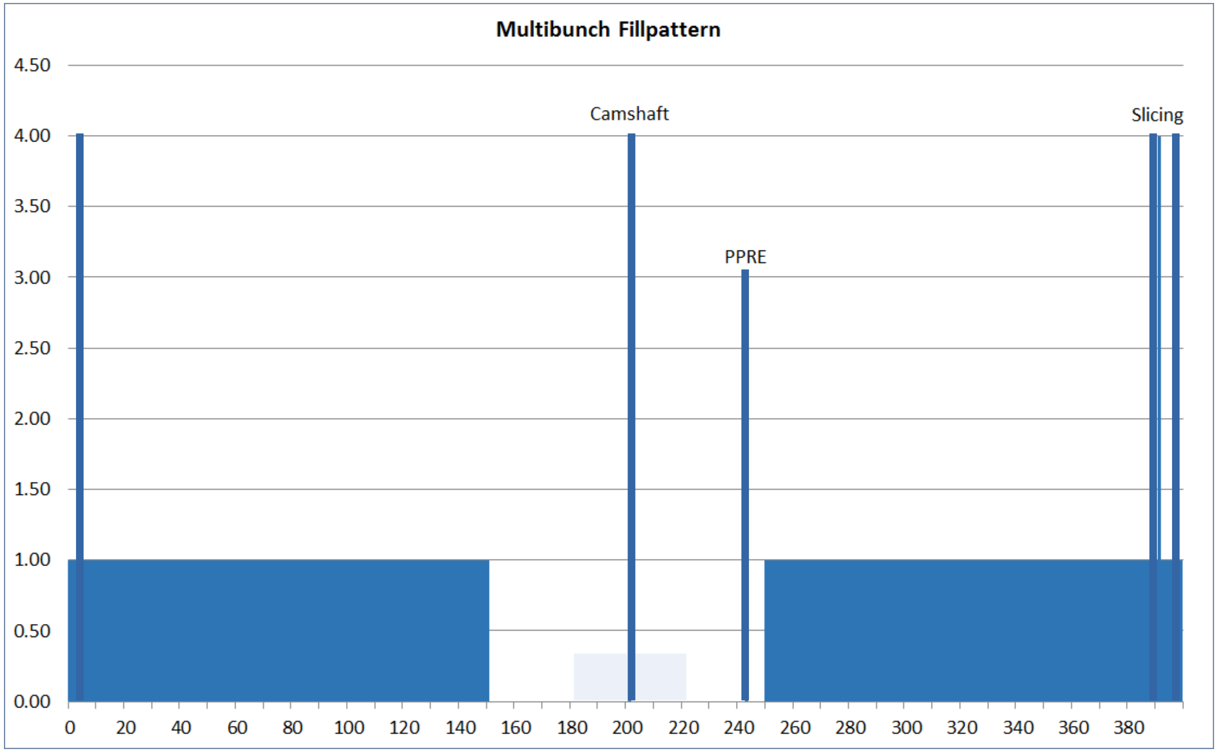
- Do not store beam on resonance
- “Accelerator operators are keen to avoid low order strong resonances because of visibly short lifetime.”
- “Accelerator physicists are eager to apply their skill to correct or compensate the resonance for minimizing their effects on the beams.”

Application (unstable fix points) Multiturn (slow) extraction

- R.Cappi and M.Giovannozzi, “Multiturn extraction and injection by means of adiabatic capture in stable islands of phase space”, Phys. Rev. ST Accel. Beams 7, 024001 (2004)

Stable 2nd island orbit for bunch separation
Aim: Multiple beam storage with island buckets

See – https://www.helmholtz-berlin.de/quellen/bessy/betrieb-beschleuniger/betriebsmodi_en.html
or google: BESSY II operation modi



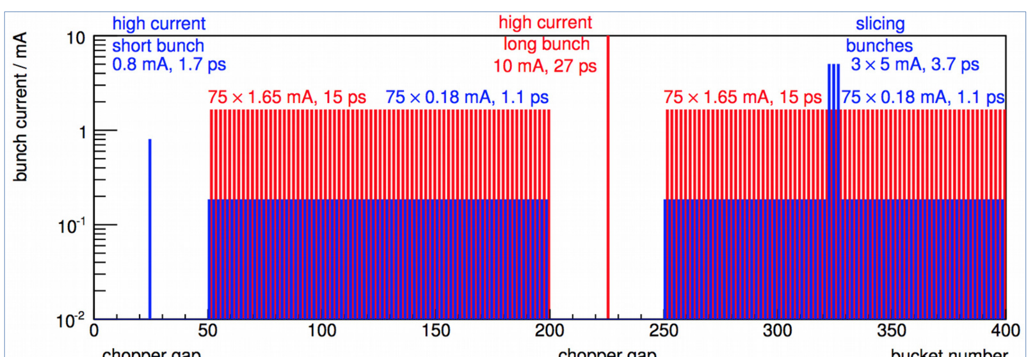
Hybrid Multibunch Fill

- MultiBunch train of 300 buckets
  > Average brilliance
- SingleBunch in ion clearing gap
  > Time resolved exp.
- Pulse Picking Resonant Excitation
  > ARTOF (reduced intensity)
- Three Slicing bunches
  > Ultra short photon pulses (100 fs)

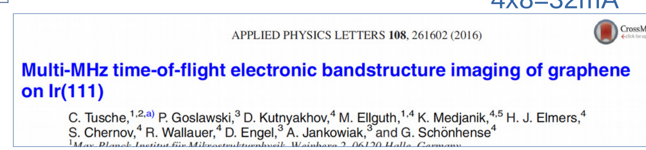
Rep.rate: 800ns, 1.25MHz
1x15mA

- And Single Bunch Mode
  And **Few Bunch Mode**

Rep.rate: 200ns, 5.0MHz
4x8=32mA



Future BESSY VSR fill pattern


APPLIED PHYSICS LETTERS 108, 261602 (2016)

Multi-MHz time-of-flight electronic bandstructure imaging of graphene on Ir(111)

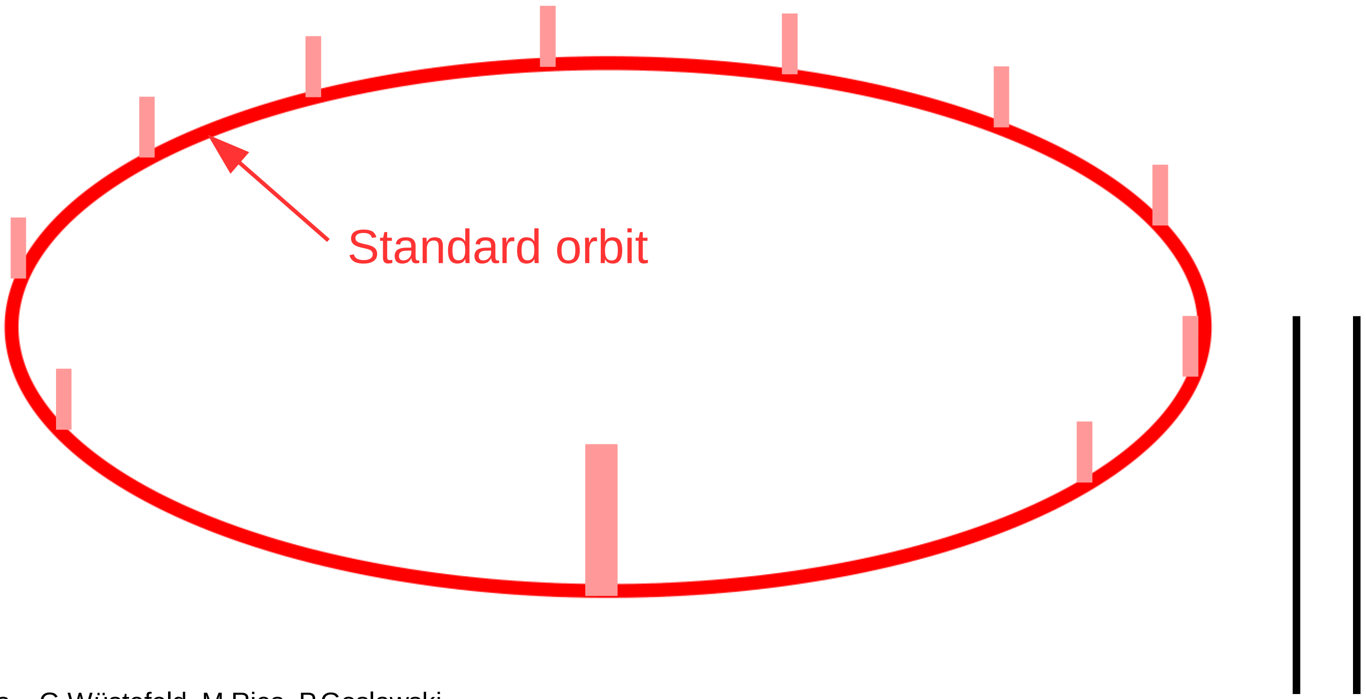
C. Tusche,[1,2,a)] P. Goslawski,[3] D. Kutnyakhov,[4] M. Ellguth,[1,4] K. Medjanik,[4,5] H. J. Elmers,[4] S. Chernov,[4] R. Wallauer,[4] D. Engel,[3] A. Jankowiak,[3] and G. Schönhense[4]

Common Verbundforschungsprojekt (Uni Mainz, Uni München):
PhD to get TRIBs understood and running

Bundesministerium für Bildung und Forschung

TRIBs - Additional Orbit

Separation scheme using transverse resonance island orbit



Driving forces behind TRIBs – G.Wüstefeld, M.Ries, P.Goslawski

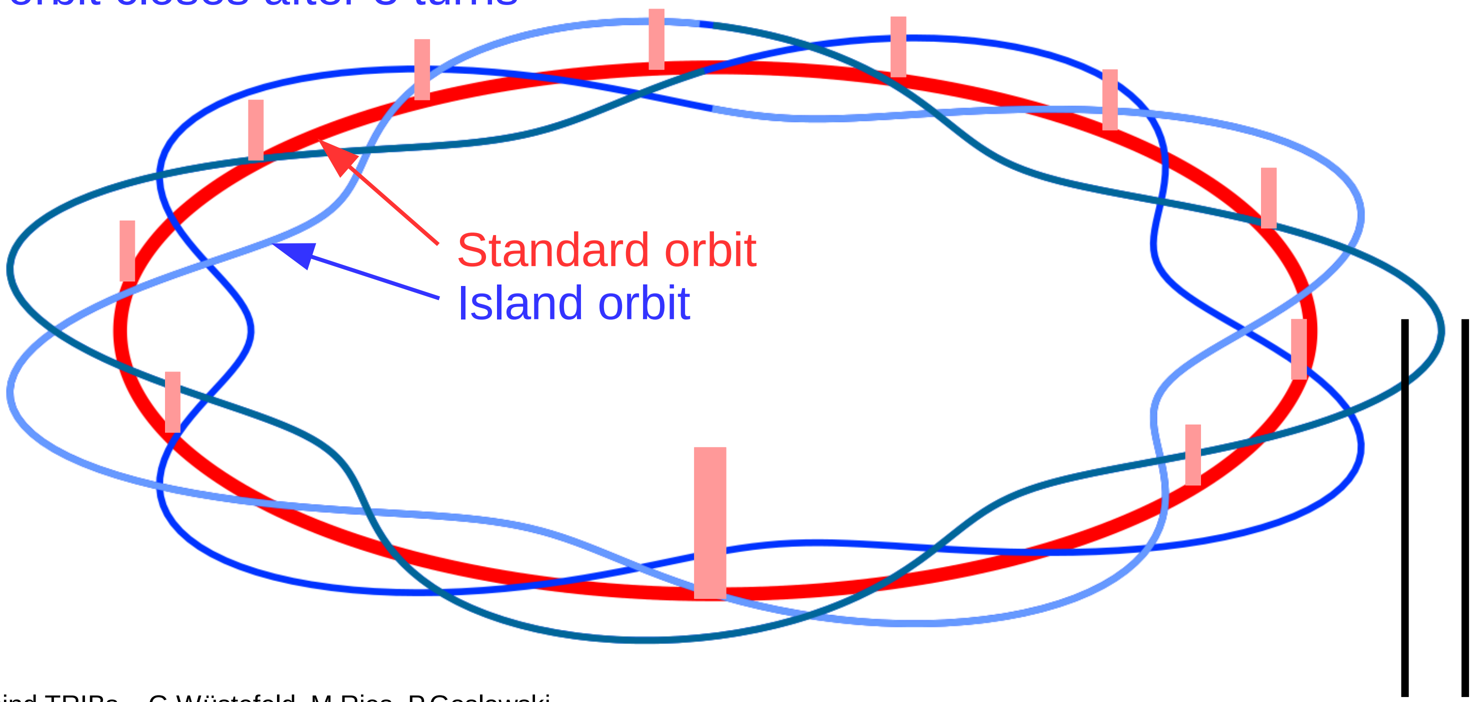
M. Ries et al., “Transverse Resonance Island Buckets at the MLS and BESSY II” Proceedings of IPAC2015, Richmond, VA, USA, MOPWA021

P. Goslawski et al., “Resonance Island Experiments at BESSYII for User Applications” Proceedings of IPAC2016, Busan, Korea, THPMR017

P. Goslawski et al., “Status of Transverse Resonance Island Buckets as Bunch Separation Scheme“, Proceedings of IPAC2017, Copenhagen, Denmark, WEPIK057

Separation scheme using transverse resonance island orbit

3rd order resonance
Island orbit closes after 3 turns



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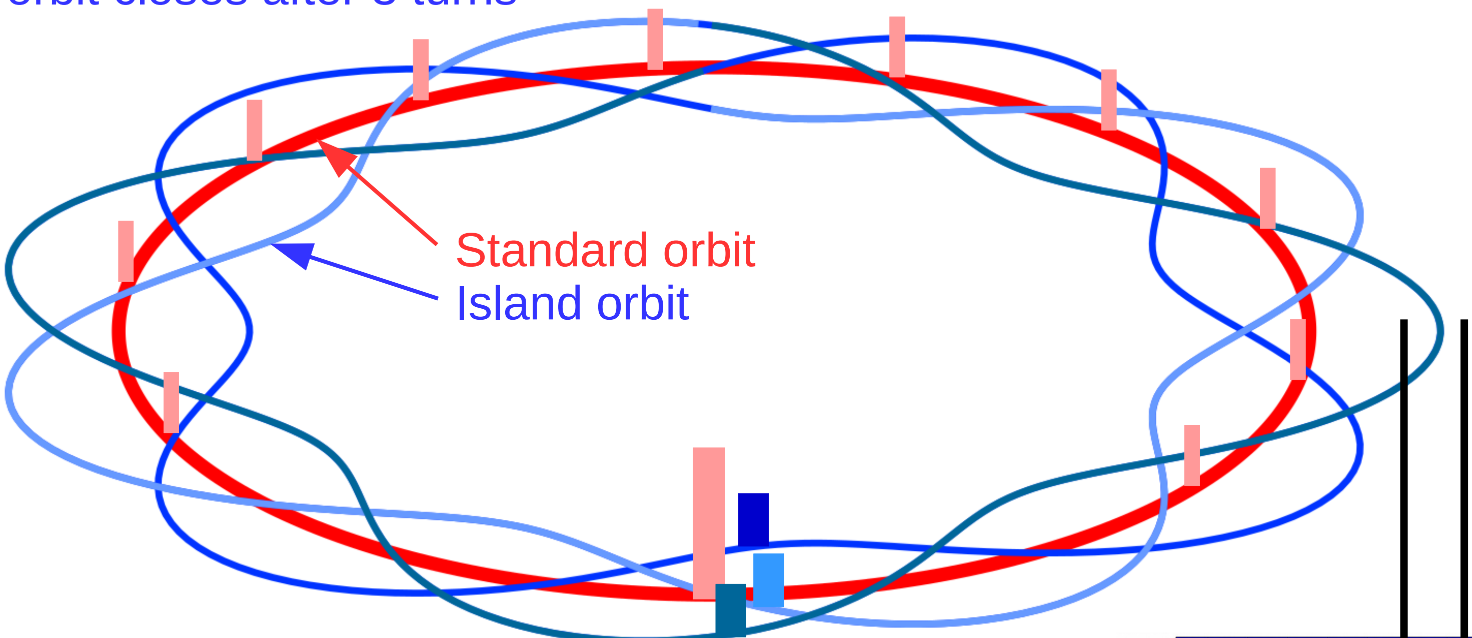
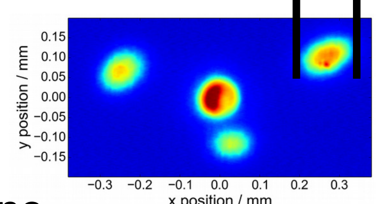




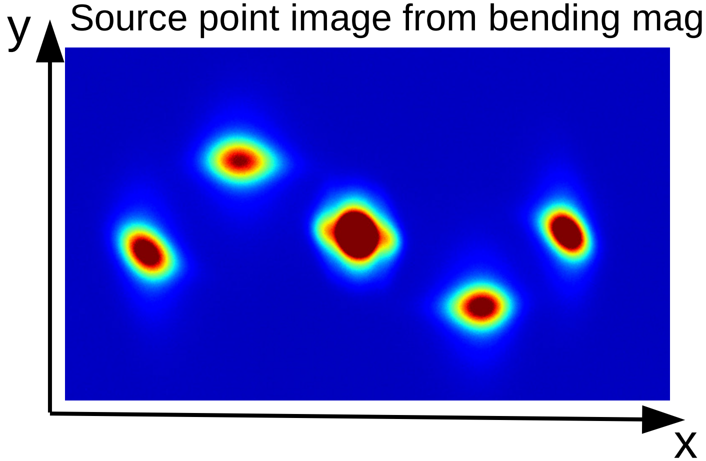
Beam separation at beamlines

- Spectral monochromators use vertical plane as dispersion plane, so a horizontal separation would be favourable
- No big changes at beamlines necessary (in contrast to vertical kicking)

M. Ries et al., Proceedings of IPAC2015, Richmond, VA, USA, MOPWA021

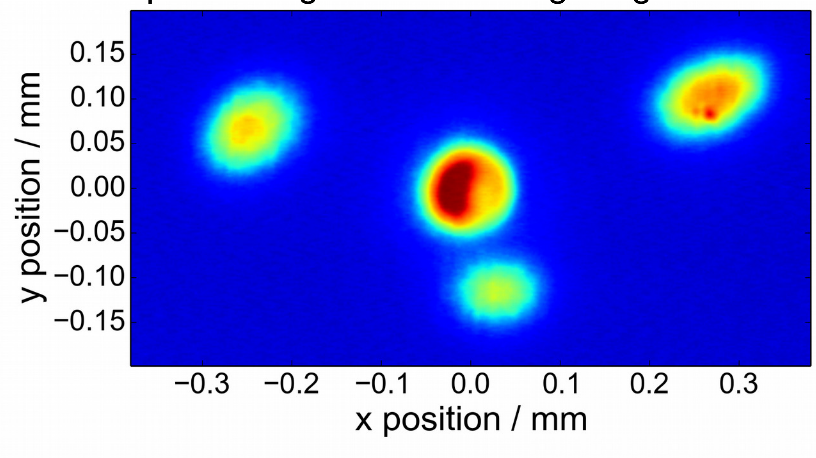
Island buckets at MLS

4th order resonance
Source point image from bending magnet



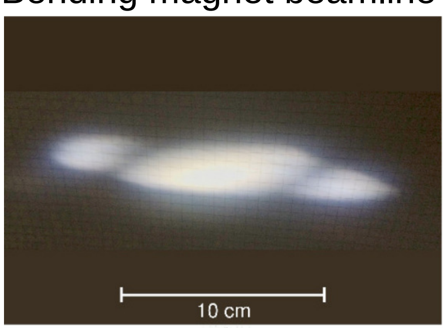
Island buckets at BESSY II

3rd order resonance
Source point image from bending magnet

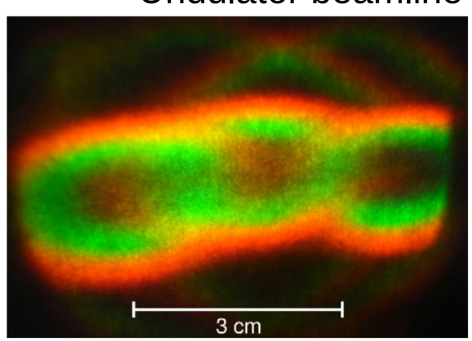


Island buckets at photon beamlines

3rd order resonance
Bending magnet beamline



Undulator beamline



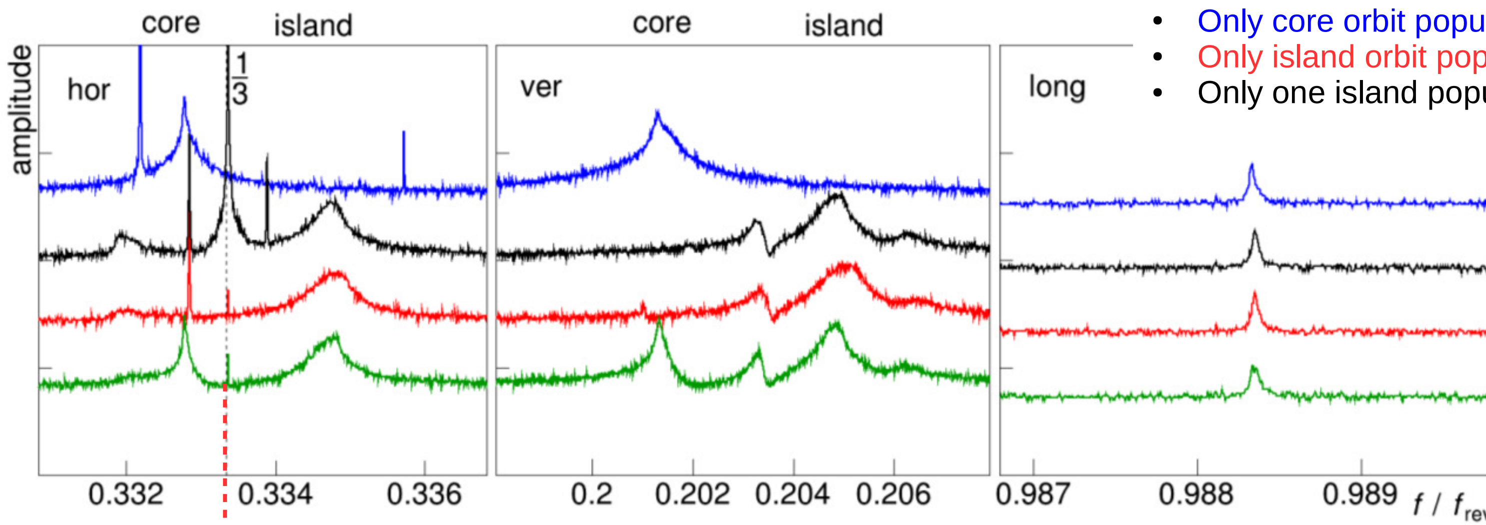
How to generate islands

- Move tune towards resonance and manipulate x,x' phase space using chromatic and harmonic sextupoles
- Lifetime, loss rate, tune, source point
- Tune shows deformation near resonance
- Core and island have different tunes separated by resonance

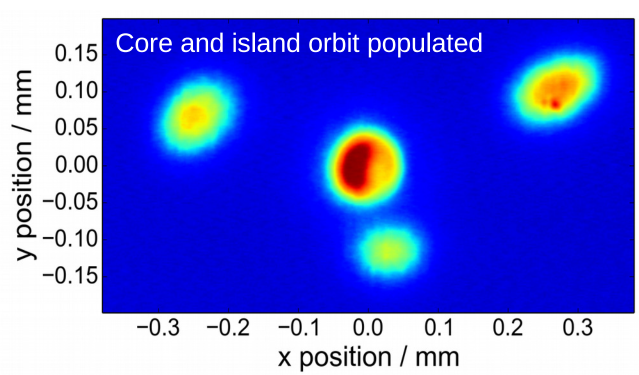
Tunes and current manipulation

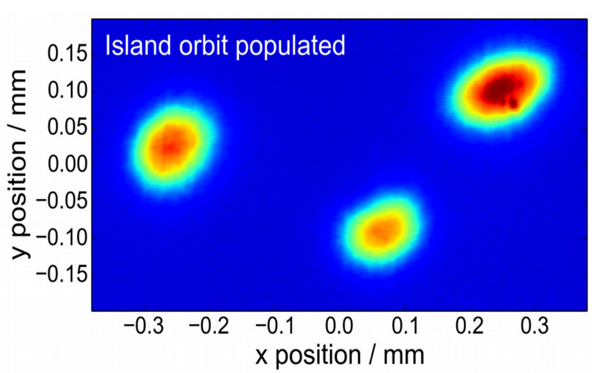
M. Ries et al., Proceedings of IPAC2015, Richmond, VA, USA, MOPWA021

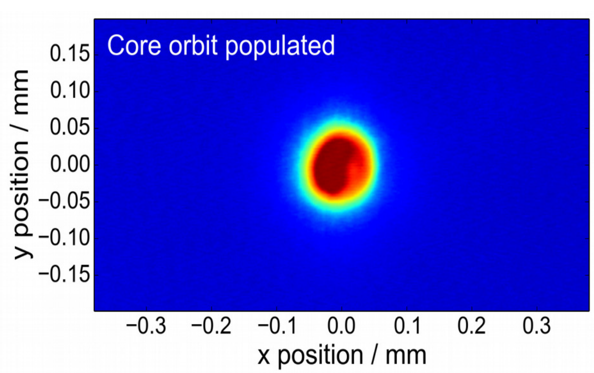
- Core and island orbit populated
- Only core orbit populated
- Only island orbit populated
- Only one island populated



- Current diffusion between core and island orbit, back and forth -> quasi static equilibrium
- Core (or island) tune is resonantly excited to clear core (or island) orbit from current
- With bunch selective excitation -> Placing arbitrary bunches on island orbit, arbitrary fill pattern







TRIBs BESSY II - Towards realistic user operation

Proof of principle experiments

Since 2015

- Island operation compatible with
  - High current operation (300 mA)
  - IDs: moving undulator gaps and SC devices (7T MPW)

Fall 2015

- **Separation** - **good enough?**
  Electron separation -> Photon pulse separation?
  - Align island orbit on dipole/ID beamline
  - Purity, Diffusion rates, SNR
  - Usable at all beamlines at the same time ?
  - Impact of radiation from island orbit on standard orbit?

Fall 2016

- **Injection - TopUp operation possible?**
  - Injection Efficiency (>90%) and Lifetime (>5h@300mA) ?
  - Difference between new working point (17.66) and old one (17.84)? (synchrotron source points from standard orbit)
  - Impact of radiation from island orbit on standard orbit?

TRIBs BESSY II - Separation (Oct2015)

First experiments with in-house users at BESSY II

Island buckets as separation scheme?

- One bending magnet beamline (**PM4**)
- Four ID beamlines (**UE56-1, UE112**, UE49, UE46)

Many thanks to
K. Holldack, R. Ovsyannikov, G. Schiwietz
F. Kronast, E. Schierle,
M. Mast, C. Jung, F. Schäfer

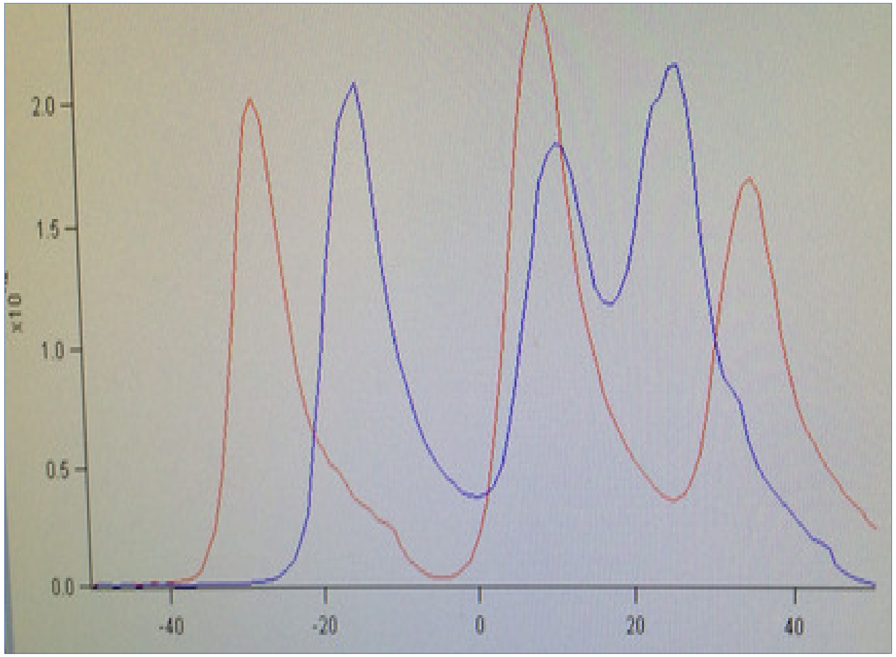
- When all current is pushed in island orbit, photon flux of the core beam vanishes completely at most beamlines
  - Beamline acceptance of most undulator beamlines ≈ 0.2 mrad
  - Orbit separation is much larger of about ≈ 0.3 mrad
  - Synchrotron radiation opening angle: $\boxed{\theta = \frac{1}{\gamma} = \frac{1}{3327} = 0.3\,\mathrm{mrad}}$

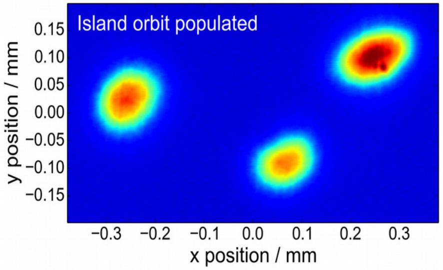
Bending magnet beamline PM4

- Intermediate focus and moveable slit (because of MHz chopper)
- Source point mapped by a horizontal scan of first mirror
- Displacement of outer island spots of 0.5 mm at a source size of 0.1 mm -> 4σ separation
- Once only single bunch in island end-stations sees a clean 1.25 MHz signal
- ARTOF on gold with SB in island orbit in parallel to MB fill on standard orbit

First scan

Second scan after improving beam separation

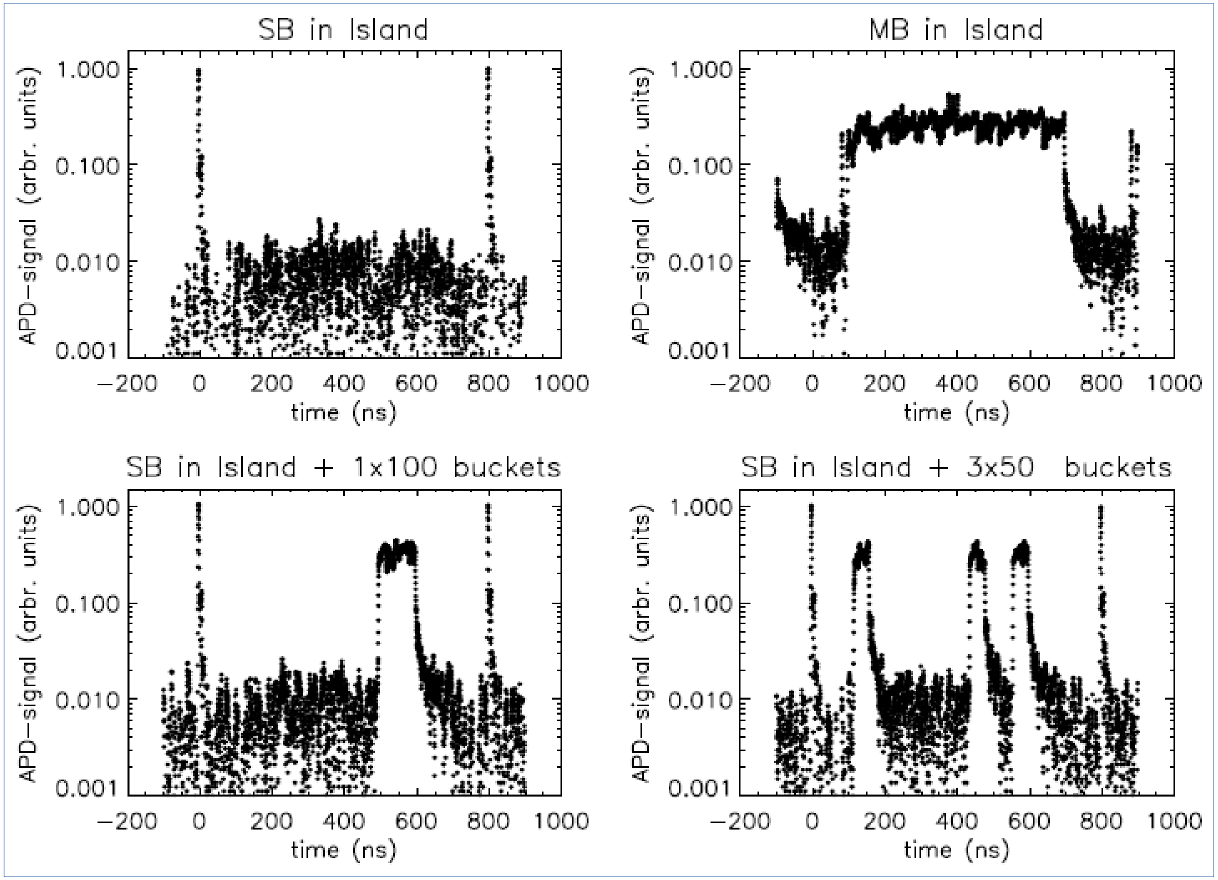




ID UE56-1 ZPM vertical polarized

- Signal measured with avalanche photodiode, fast enough to resolve fill pattern
- Photons of 3rd undulator harmonic, 831eV linear vertical polarised

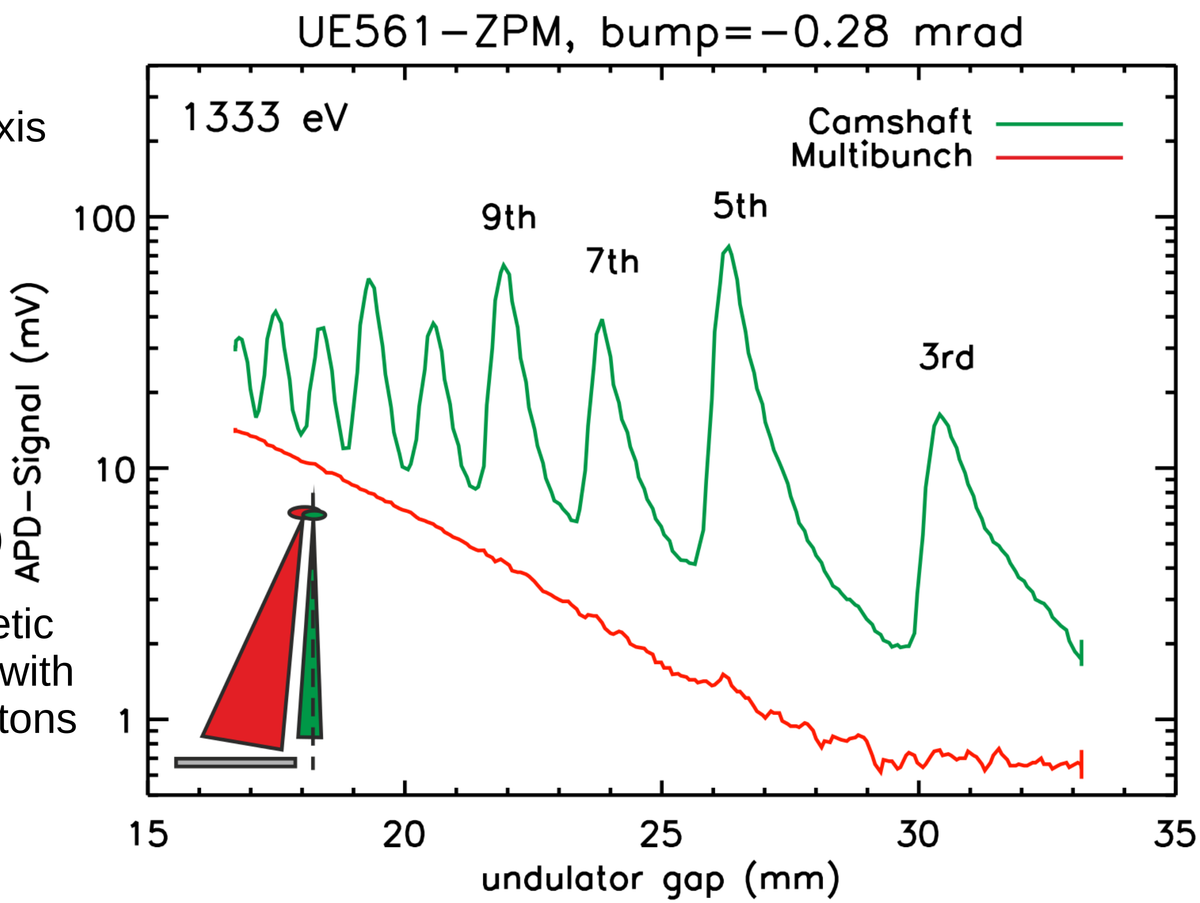
- Align island orbit on ID axis
  - Orbit bump of 0.23 mrad
  - Pinhole displacement of 0.8 mm
- Signal ratio SB/MB: Purity -> 100
- Arbitrary fill pattern within seconds



ID UE56-1 ZPM elliptical polarised

- UE56 operated in elliptical mode (shift 25), elliptical polarised 1333eV
- Only Camshaft in island orbit, photons of 5th undulator harmonic

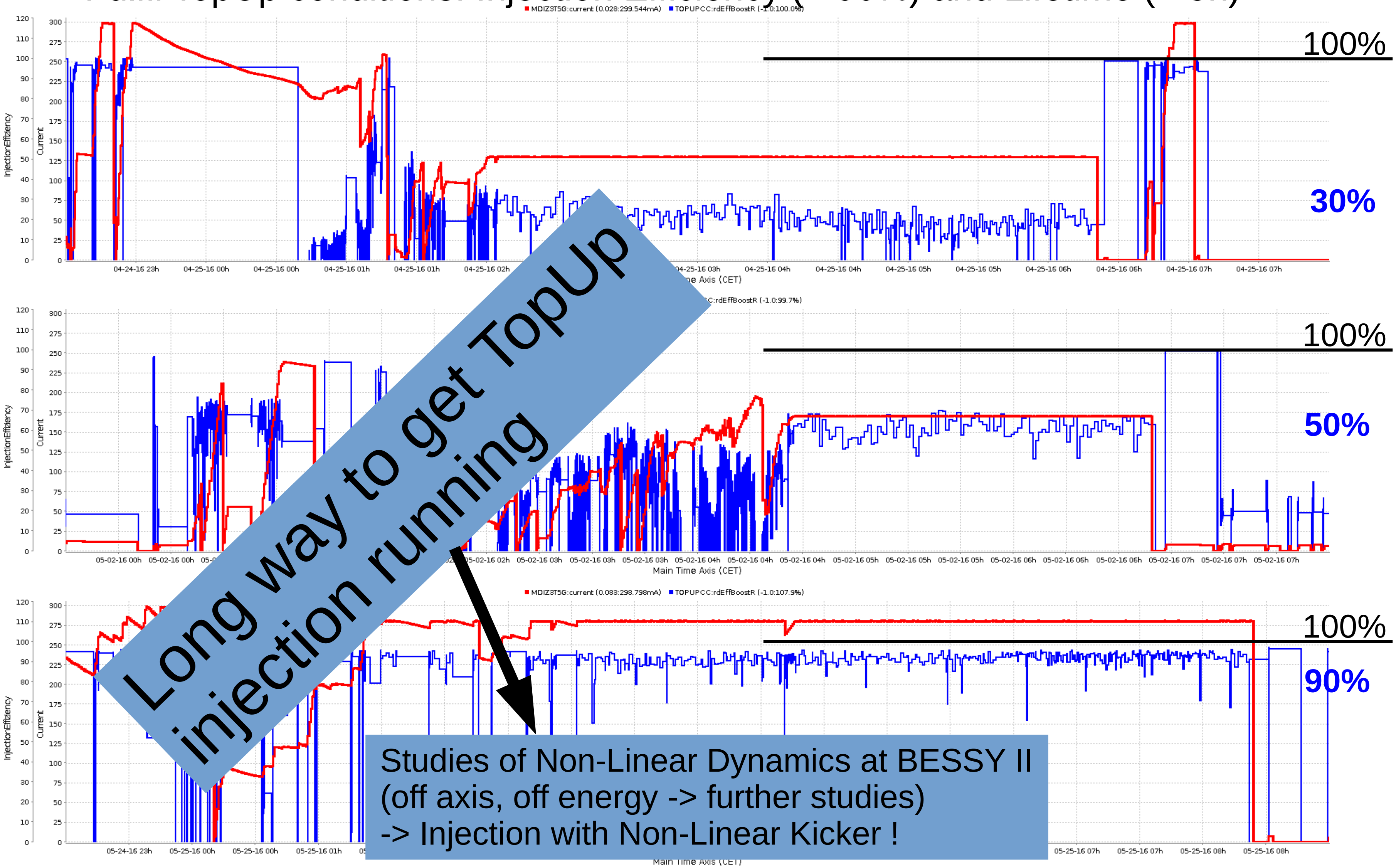
- Orbit bump with 0.28 mrad to align island orbit on ID axis
- Camshaft from island orbit shows undulator spectrum while MB fill from standard orbit is far off axis and blocked by aperture
- Purity -> 100 (5th harmonic)
- Time resolved X-ray magnetic circular dichroism (XMCD) with camshaft island bunch photons



Further developments of island buckets at BESSY II

– Current
– Injection Efficieny

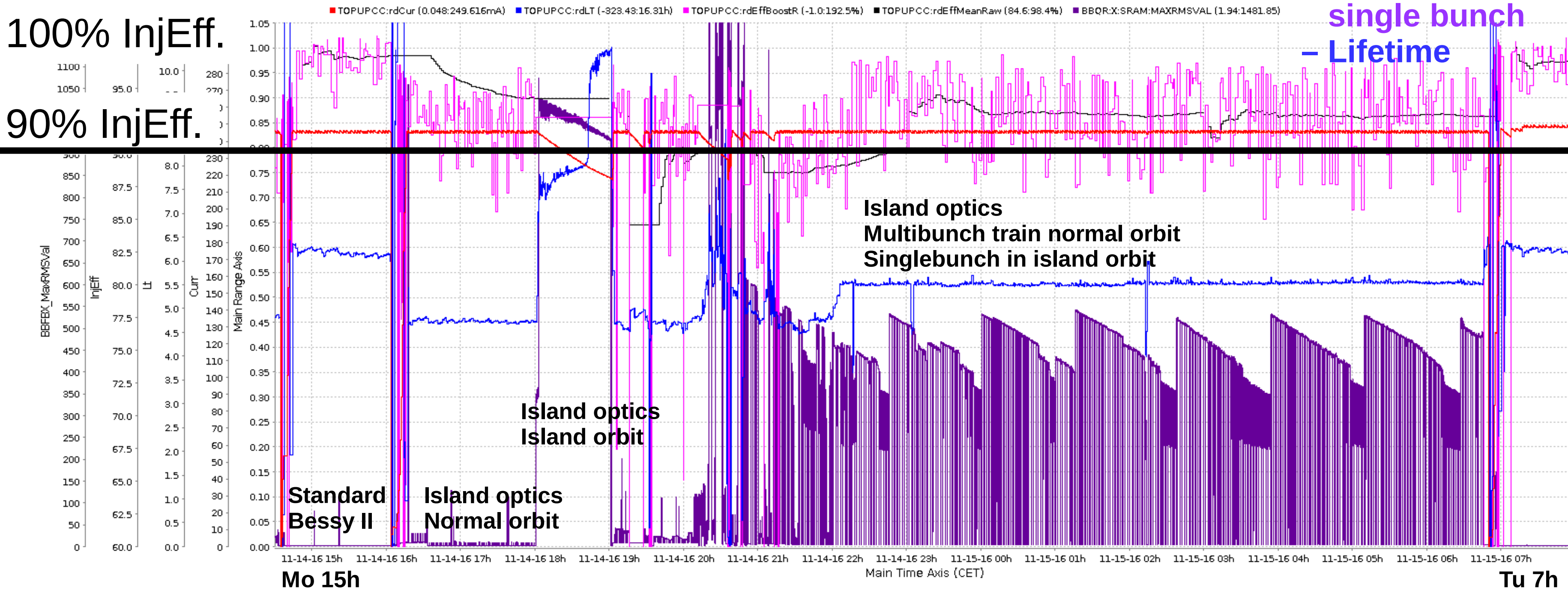
- Fulfil TopUp conditions: Injection Efficiency (> 90%) and Lifetime (> 5h)



Studies of Non-Linear Dynamics at BESSY II
(off axis, off energy -> further studies)
-> Injection with Non-Linear Kicker !

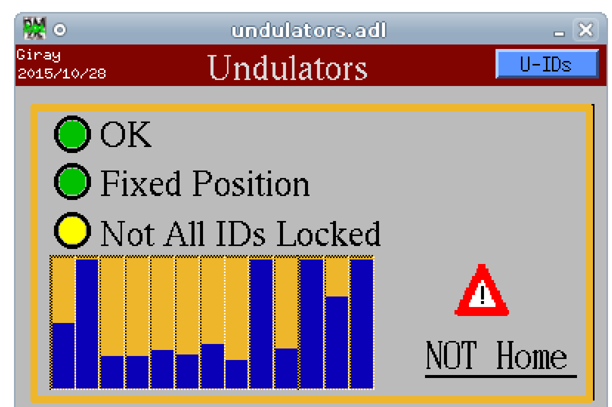
November 2016 – Proof of principle Experiments
TRIBs in TopUp with open beamshutters and most IDs closed!

– Current
– Injection Efficieny
– Island Signal single bunch
– Lifetime



Result:

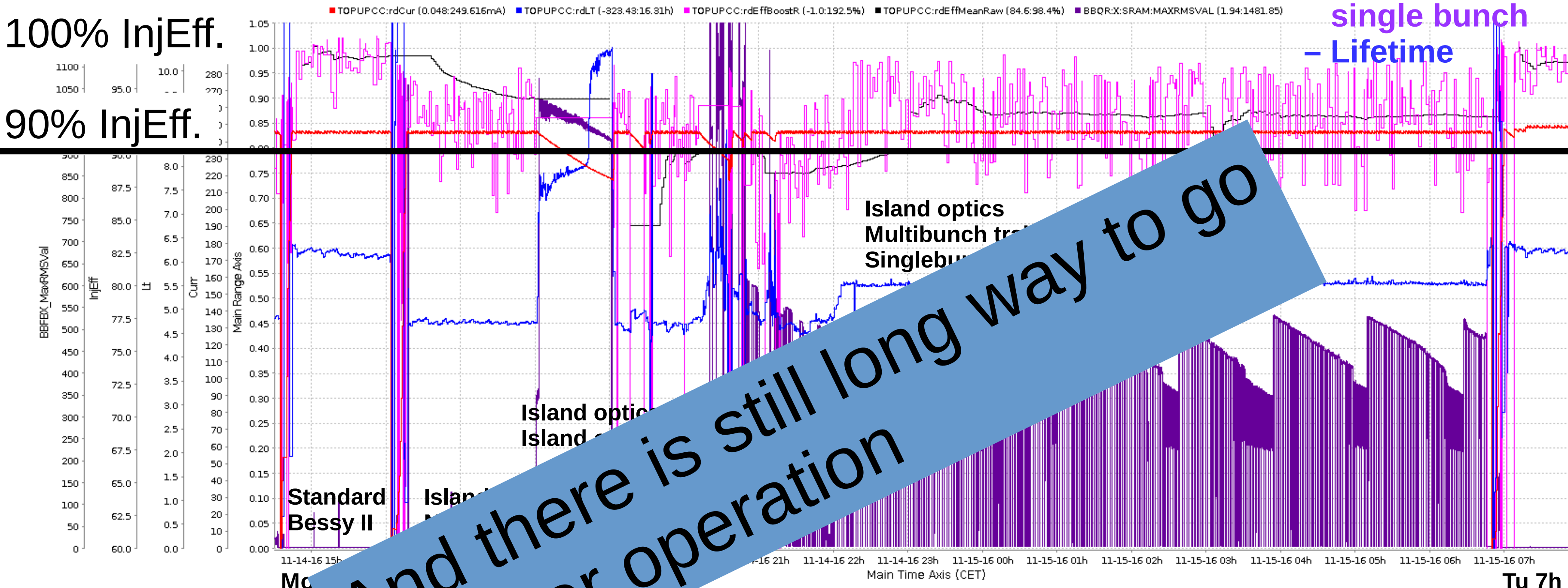
- Island optics with single bunch on island orbit over night (8h) in TopUp with open beamshutters and 9 IDs and some dipoles beamlines participating
- Stable operation, but improvable !
  -> balance between Separation and Injection !
- Many techniques not prepared for island operation, for example: ID correction



TRIBs BESSY II with TopUp

November 2016 – Proof of principle Experiments
TRIBs in TopUp with open beamshutters and most IDs closed!

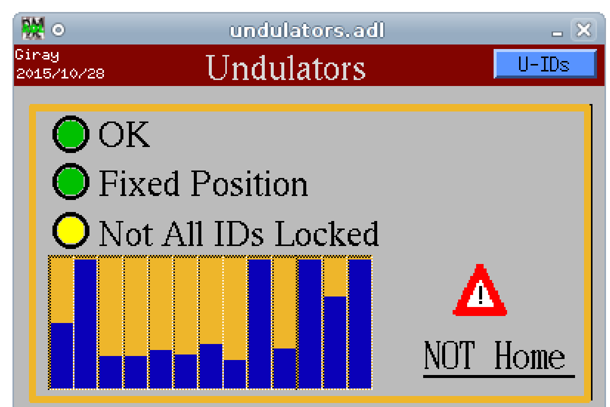
– Current
– Injection Efficieny
– Island Signal single bunch
– Lifetime



And there is still long way to go for user operation

Result:

- Island optics with single bunch on island orbit over night (8h) in TopUp with open beamshutters and 9 IDs and some dipoles beamlines participating
- Stable operation, but improvable ! -> balance between Separation and Injection !
- Many techniques not prepared for island operation, for example: ID correction



Further steps

- Deeper understanding of island orbit -> characterisation
- More common experiment during machine startup and beamline commissioning
  - Transparent Injection and Separation

- **TWIN Orbit User Test (user shift) KW8, 19-25 February**
  purple in beamtime schedule

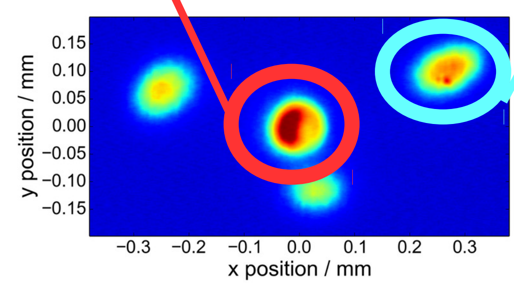
Access – no beam	Accelerator Start-up	Few Bunch Mode user shift	Low-alpha user shift	Multi bunch user shift	ID/beamline Con

Beamtime	2017 / 2																												
Month	January																												
Week	1 *							2 *							3							4							
operation-mode	MC							MB							MB							MB							
Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
early shift (7:00-15:00)																													
late shift (15:00-23:00)																													
night shift (23:00-7:00)																													

Beamtime	2017 / 2																			2018 / 1								
Month	February																											
Week	5				6 *							7 *							8 *							9		
operation-mode	MB				SB							MC							TO							M		
Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	1	17	18	19	20	21	22	23	24	25	26	27	28
early shift (7:00-15:00)																												
late shift (15:00-23:00)																												
night shift (23:00-7:00)																												

Standard orbit
Multibunch Fill

Island orbit
SB or FewBunch



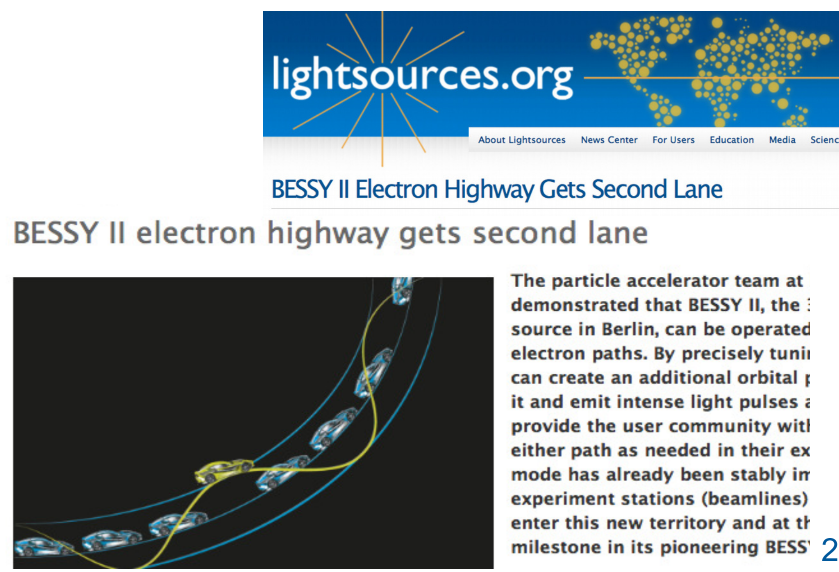
More information or want to participate:
> User office: A. Vollmer, F. Staier
> paul.goslawski@helmholtz-berlin.de

Summary: TRIBs – Applications, Ideas, Speculations

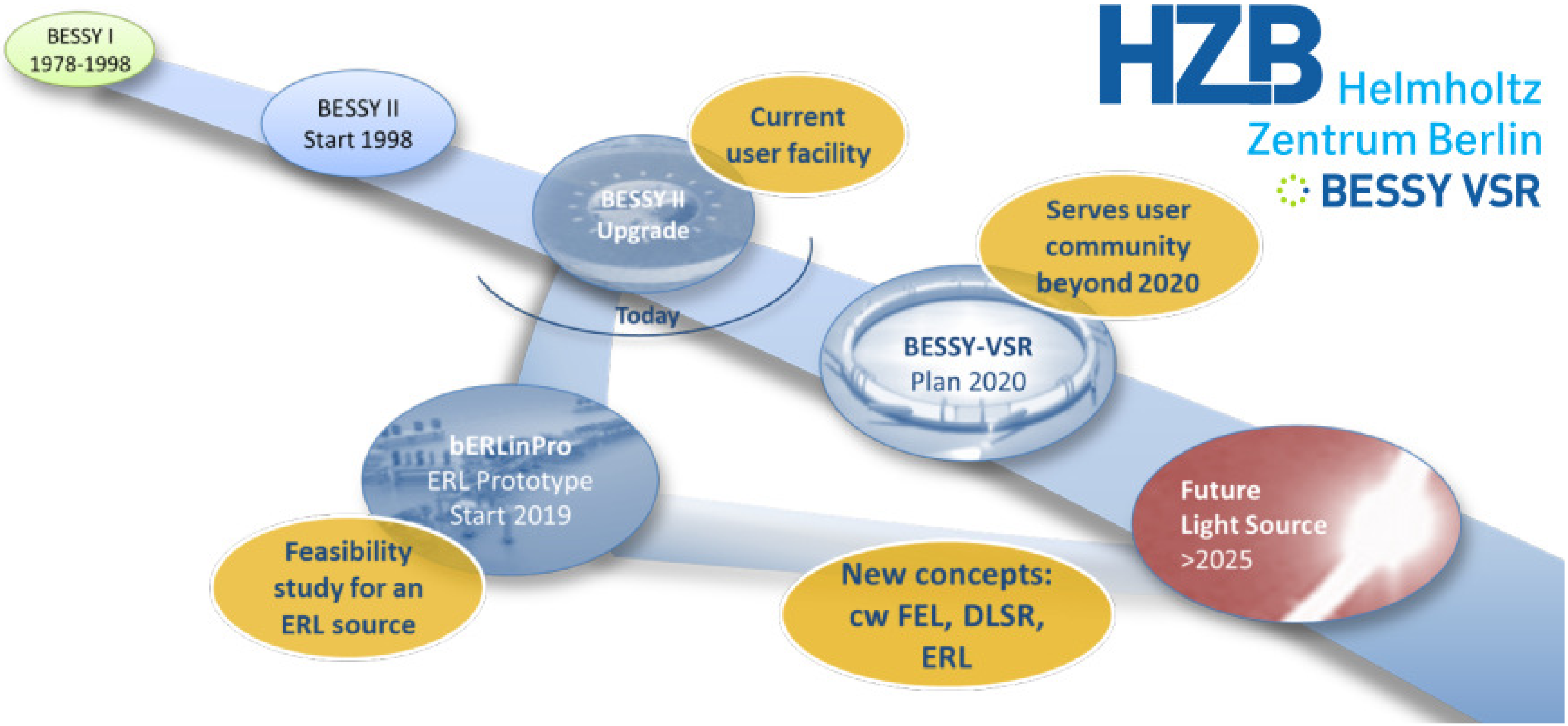
What is/may be possible with TRIBs

- **Separation scheme**, two stable orbits in one machine, 2nd lane, 2nd fillpattern
  - Increasing revolution frequency; Combine with TOPUP
    - Established user operation at decaying machine with one ID (MLS)
    - Studies towards user operation in a 3rd generation lightsource, TOPUP injection, many IDs (BESSY II / VSR)
- **Injection scheme for low ε machines**
  - Fundamental rule of injection:
  - Injected beam always at large amplitudes (x – horizontal)
- **One ID with two (or more) beamlines**
- **Different energies from the 2nd orbit -> experiment**

It is not possible to re-inject particles into an already occupied volume of phase space without losing the particles already present. K.Wille, p.142, (2000)



Thank you for your attention



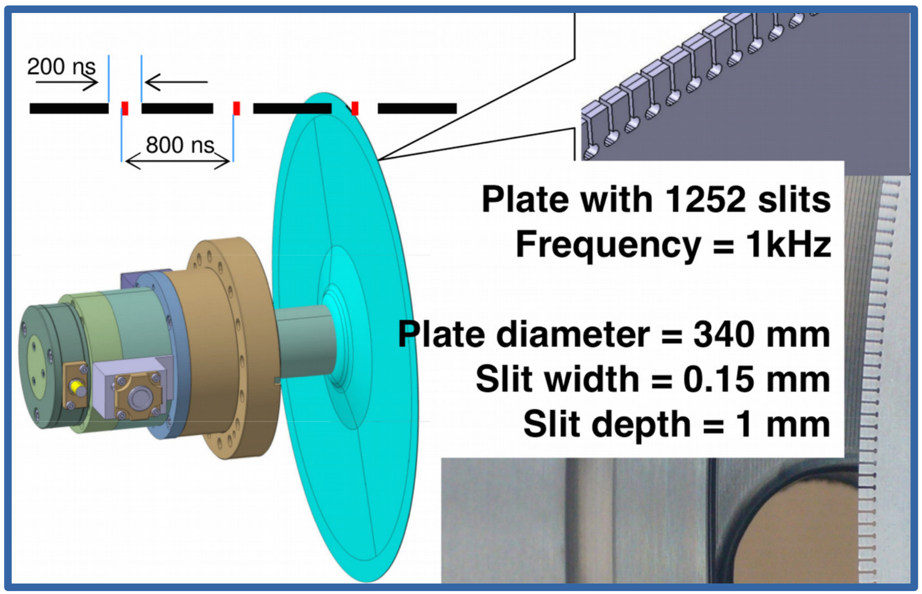
A BIG THANKs to all colleagues who contributed to this work!
electrons + warm and sc heartware, photons + beamline scientists hardware, IDs, user groups, communication, administration

Back Up

TRIBs - Established separation schemes at BESSY II

Phase locked MHz mechanical chopper

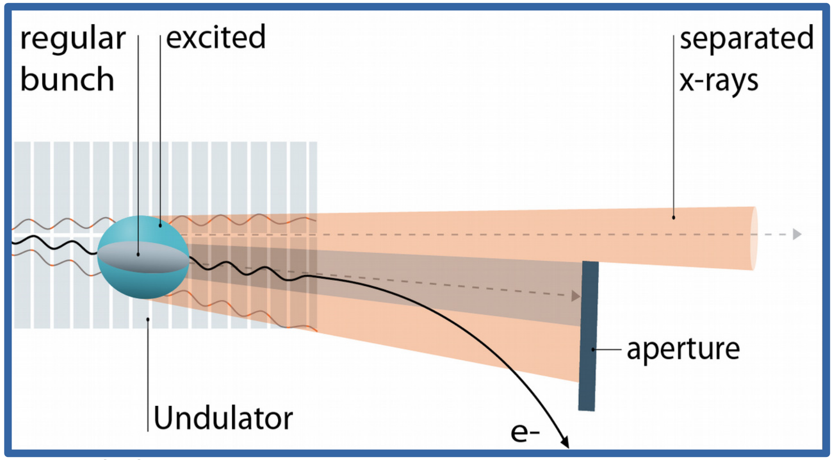
- Local separation of photons
- Needs an intermediate focus
- Phase locked within 2 ns
- Minimum gap of 100 - 200 ns
- At PM4 since 2015 in operation
  2nd at UE56 SGM, summer 2016



FZ Jülich

Pulse Picking Resonant Excitation (PPRE)

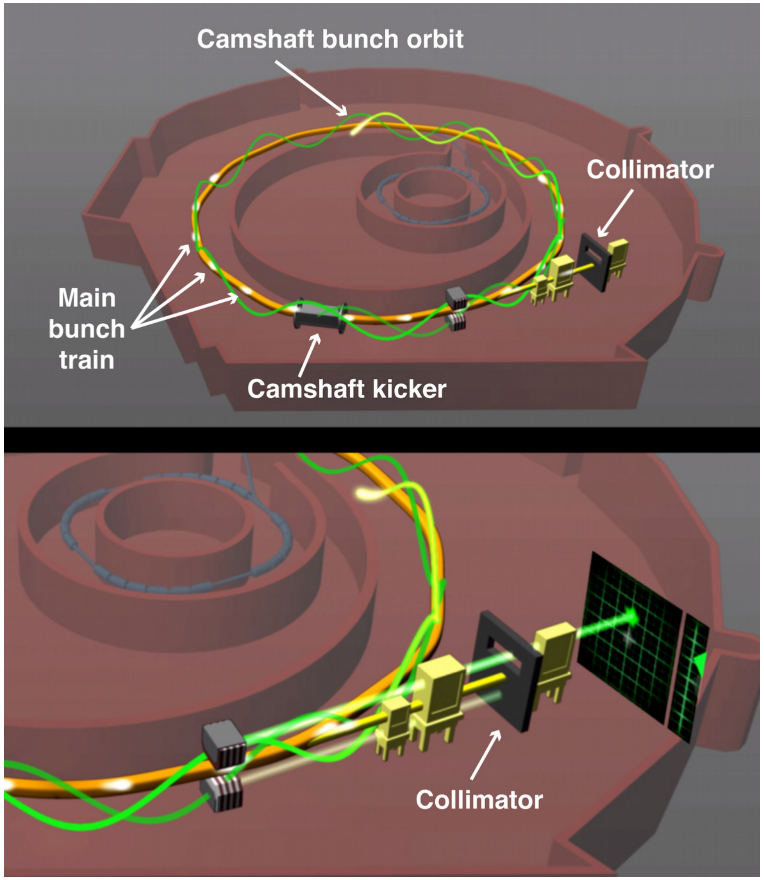
- One bunch is weakly excited, separation in horizontal plane
- At desired beamline MB radiation is blocked by local orbit bump and aperture (typically 0.5 mrad)
- SB photons in beamline with reduced intensity
- Ratio of SB to MB, Purity up to 1000
- No gap needed

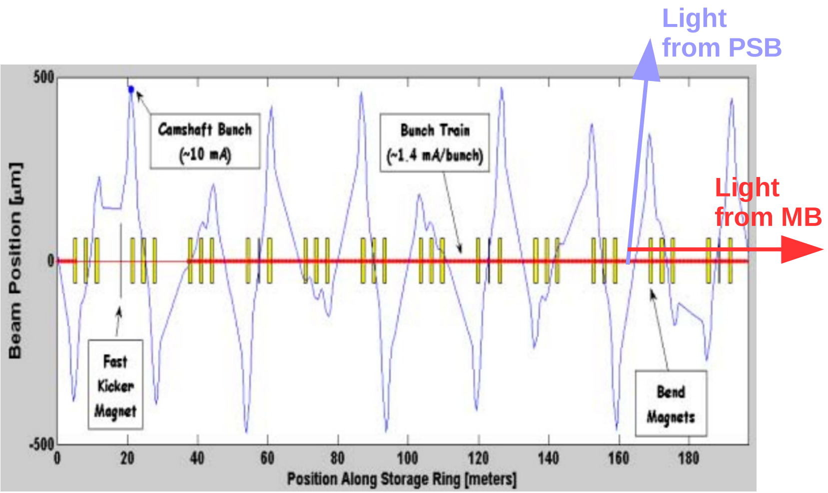


K. Holldack et al., Nature Com. 5, 4010, 2014

Pseudo single bunch scheme

- Separation in the vertical plane by a vertical kick (and cancel)





Orbit distortion at position i from kick Θ at position k:

$$\Delta y_i = \frac{\Theta \sqrt{\beta_i \beta_k}}{2\sin(\pi Q)} \cos(|\mu_i - \mu_k| - \pi Q)$$

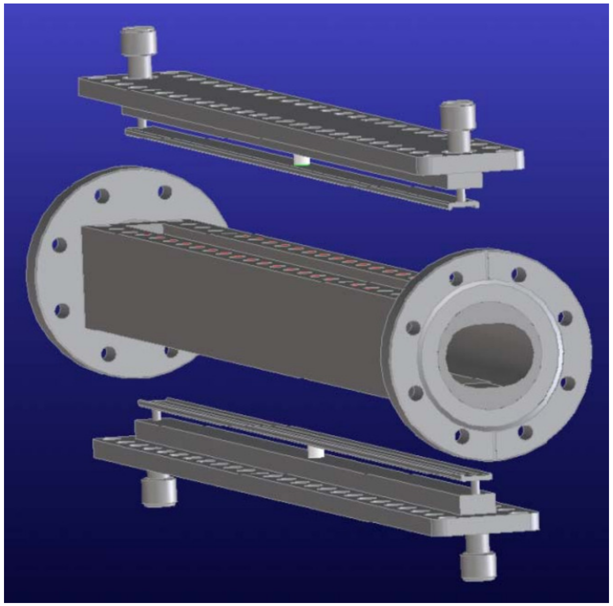
Various schemes possible:

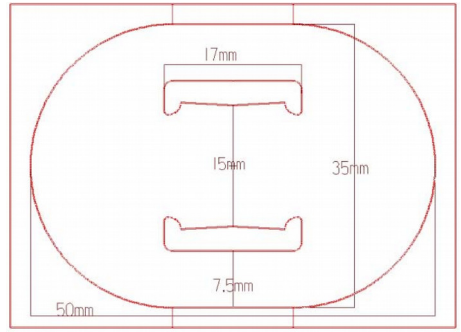
- Kick a chosen bunch each turn
- Kick at sub harmonics of the revolution frequency f_0 = 1.5 MHz to reduce bunch repetition rate

C. Sun et al., PRL 109, 264801 (2012)

TRIBs - Established separation scheme at ALS

Pseudo single bunch scheme – kicker development challenging

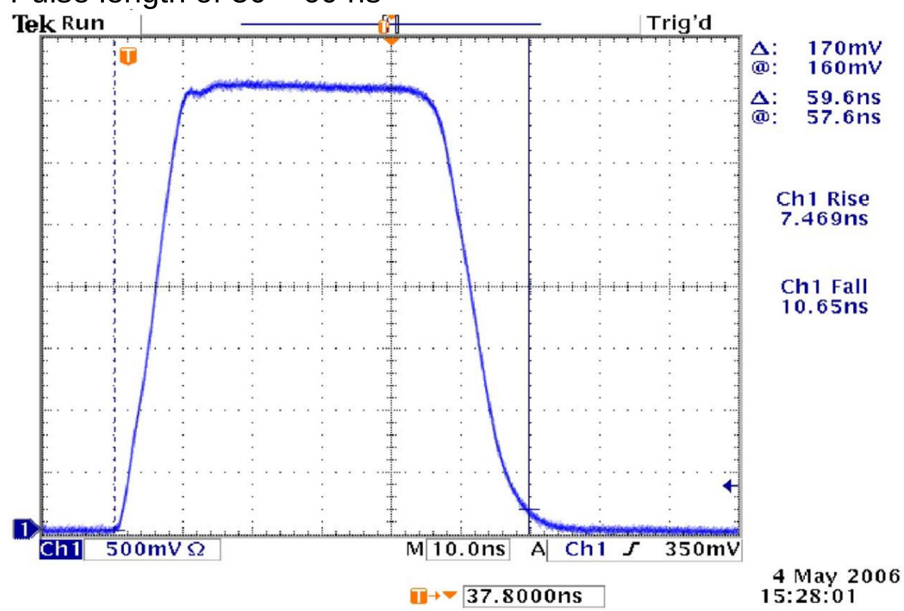




Transverse dimensions

Kicker parameters	
Length	0.6 m
Strength	70 µm rad
Rep. rate	1.5 MHz
Pulse length	50 – 60 ns

Pulse length of 50 – 60 ns



- Successfully demonstrated at ALS
- Gap of 50 ns required
- Technical realisation challenging
- Dedicated beamline separating photon beams vertically

S. Kwiatkowski et al., Proc. Of EPAC 2006, Edingburgh, Scotland

FewBunch Mode: One more motivation for TRIBs

APPLIED PHYSICS LETTERS 108, 261602 (2016)

Multi-MHz time-of-flight electronic bandstructure imaging of graphene on Ir(111)

C. Tusche,[1,2,a)] P. Goslawski,[3] D. Kutnyakhov,[4] M. Ellguth,[1,4] K. Medjanik,[4,5] H. J. Elmers,[4] S. Chernov,[4] R. Wallauer,[4] D. Engel,[3] A. Jankowiak,[3] and G. Schönhense[4]
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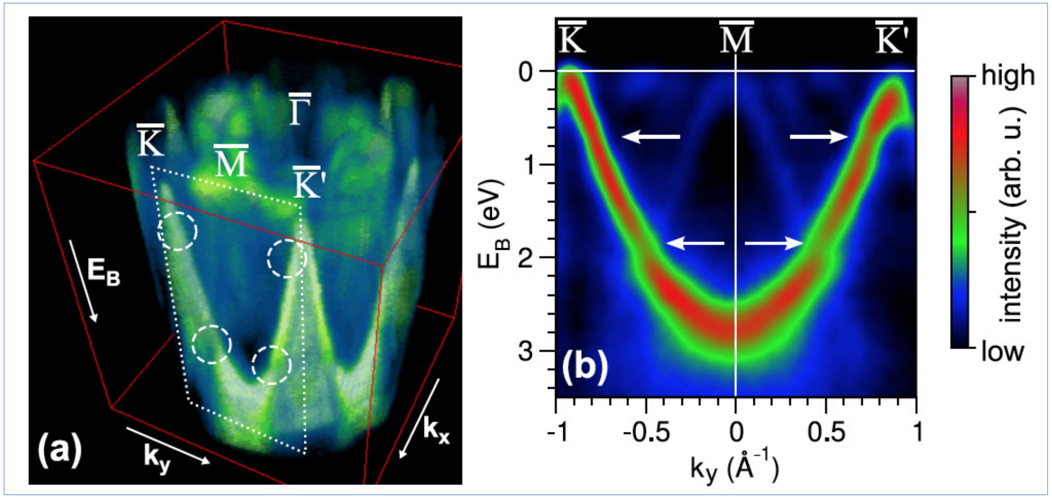
(Received 2 March 2016; accepted 13 May 2016; published online 27 June 2016)

In the quest for detailed spectroscopic insight into the electronic structure at solid surfaces in a large momentum range, we have developed an advanced experimental approach. It combines the 3D detection scheme of a time-of-flight momentum microscope with an optimized filling pattern of the BESSY II storage ring. Here, comprehensive data sets covering the full surface Brillouin zone have been used to study faint substrate-film hybridization effects in the electronic structure of graphene on Ir(111), revealed by a pronounced linear dichroism in angular distribution. The method paves the way to 3D electronic bandmapping with unprecedented data recording efficiency. *Published by AIP Publishing*. [http://dx.doi.org/10.1063/1.4955015]



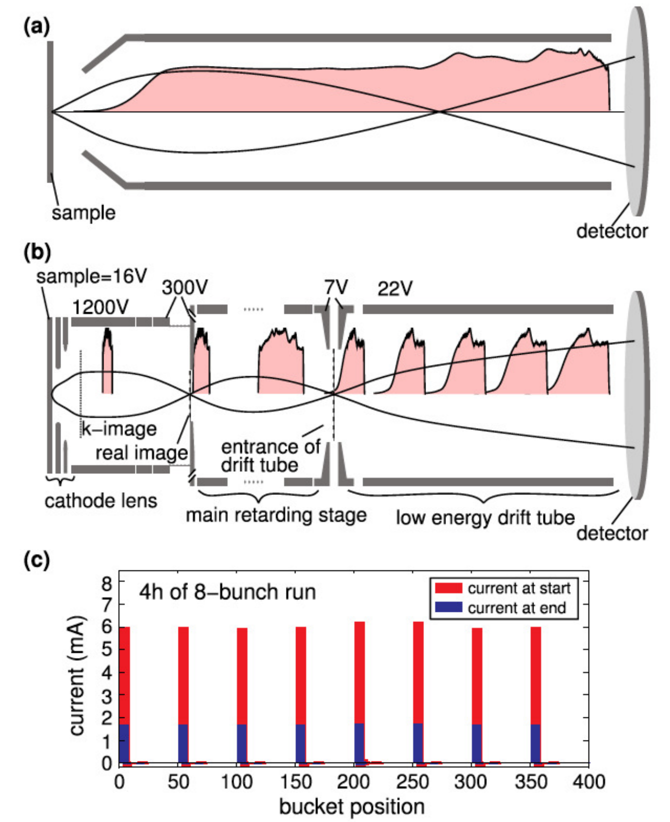


FIG. 1. (a) Working principle of a ToF spectrometer. Photoelectrons (black lines) from the sample are focused on the (x, y, τ)-resolving detector. The underlaid spectrum indicates the emitted electron distribution dispersed in time. (b) Layout of the ToF momentum microscope. The k-image is formed by the cathode lens and projected onto the detector. Emission spectra from several bunches travel through the field free drift tube at the same time. (c) Fill pattern and current distribution at the beginning and end of the 4 h long 8-bunch run.

FewBunch Mode: One more motivation for TRIBs

The present experiment has triggered a discussion about establishing a “few bunch” operation mode optimizing the time structure for most efficient use in the BESSY II community, which is still ongoing.

Besides the ToF momentum microscope, another user group also profits from the 8-bunch fill, gaining a factor of 4 in intensity and improving their signal to noise ratio by a factor of 2.

In the future, separation concepts for simultaneously providing optimized time structures of the photon source suggest a most efficient use of ToF momentum microscopy at modern synchrotron sources. For instance, operating the storage ring close to a resonance and using non-linear effects provides a second orbit resulting in a multi-beam machine. By exciting individual bunches, the second orbit can be populated at will. Currently, the proof of principle experiments are conducted at BESSY II, and might pave the way to offer a “few bunch” mode simultaneously to a multibunch fill.

→ Few (4) Bunches in TOPUP available

→ New bunch separation scheme

Transverse
Resonance
Island
Buckets

> TRIBs

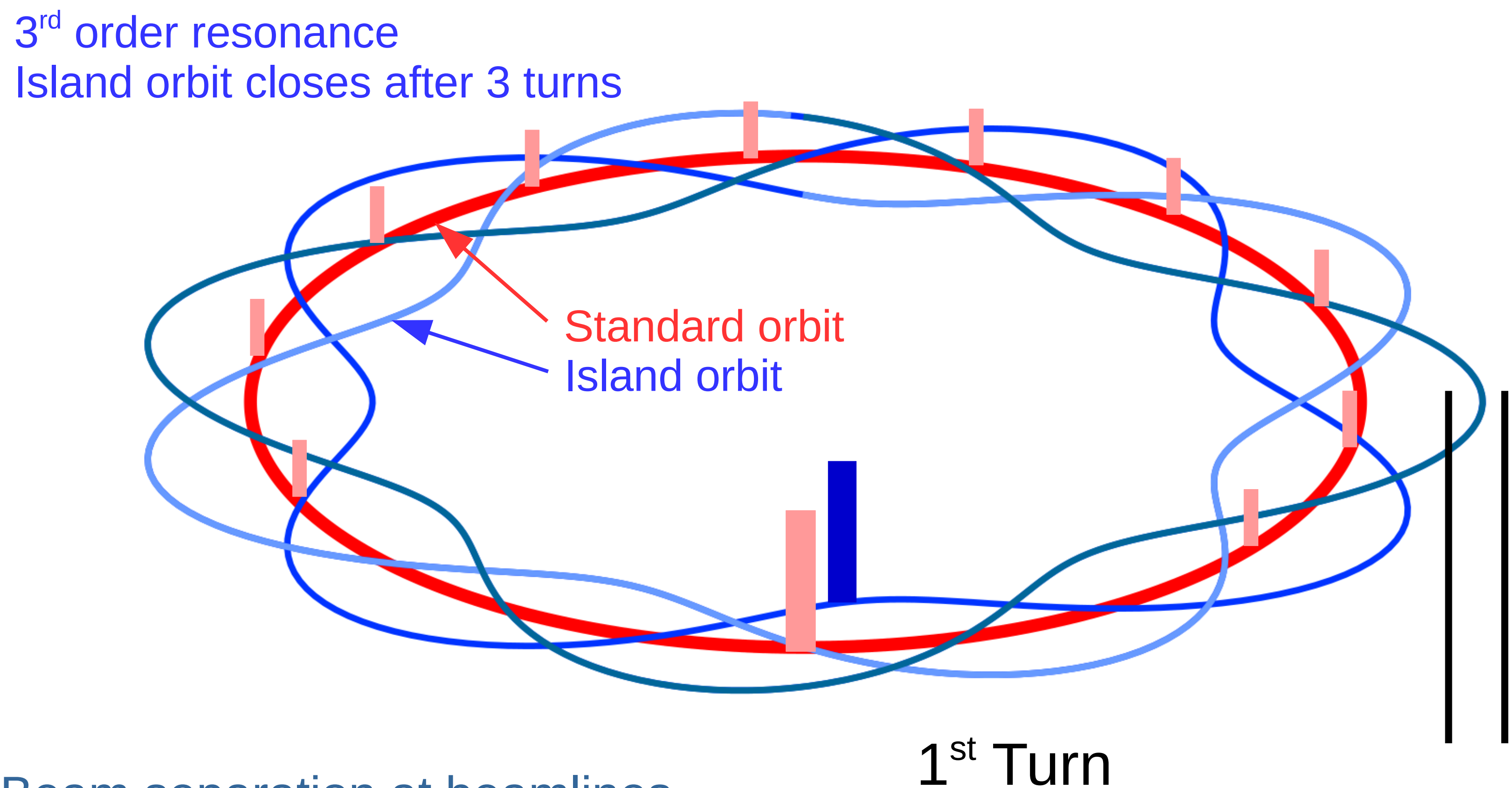
Aim: “All” :) Many fillpatterns simultaneously !
Strengthen the VARIABLE in BESSY VSR !

Common Verbundforschungsprojekt (Uni Mainz, Uni München):
PhD to get TRIBs understood and running

Bundesministerium für Bildung und Forschung

TRIBs - Additional Orbit

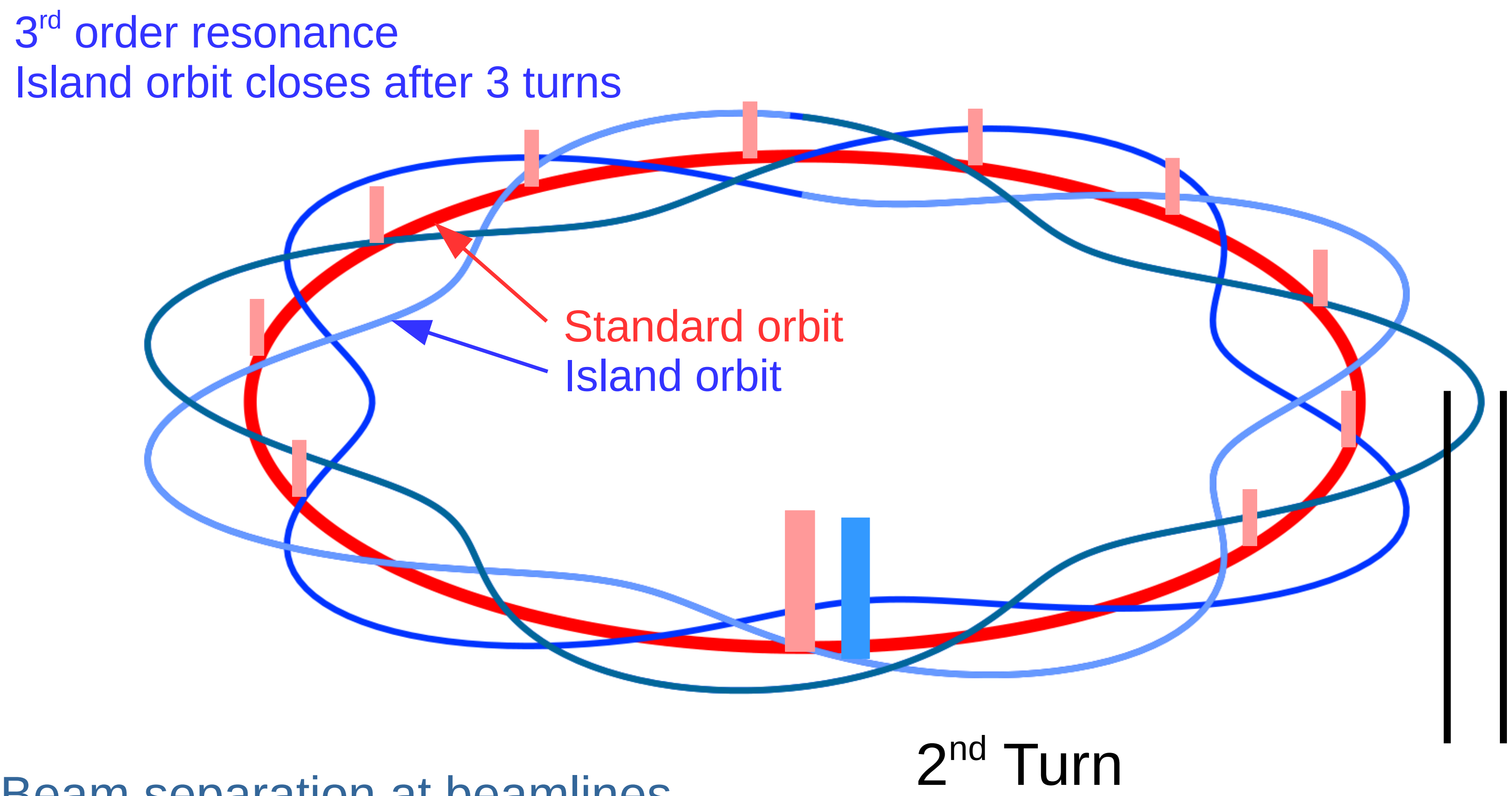
Separation scheme using transverse resonance island orbit



Beam separation at beamlines

- Spectral monochromators use vertical plane as dispersion plane, so a horizontal separation would be favourable
- No big changes at beamlines necessary (in contrast to vertical kicking)

Separation scheme using transverse resonance island orbit



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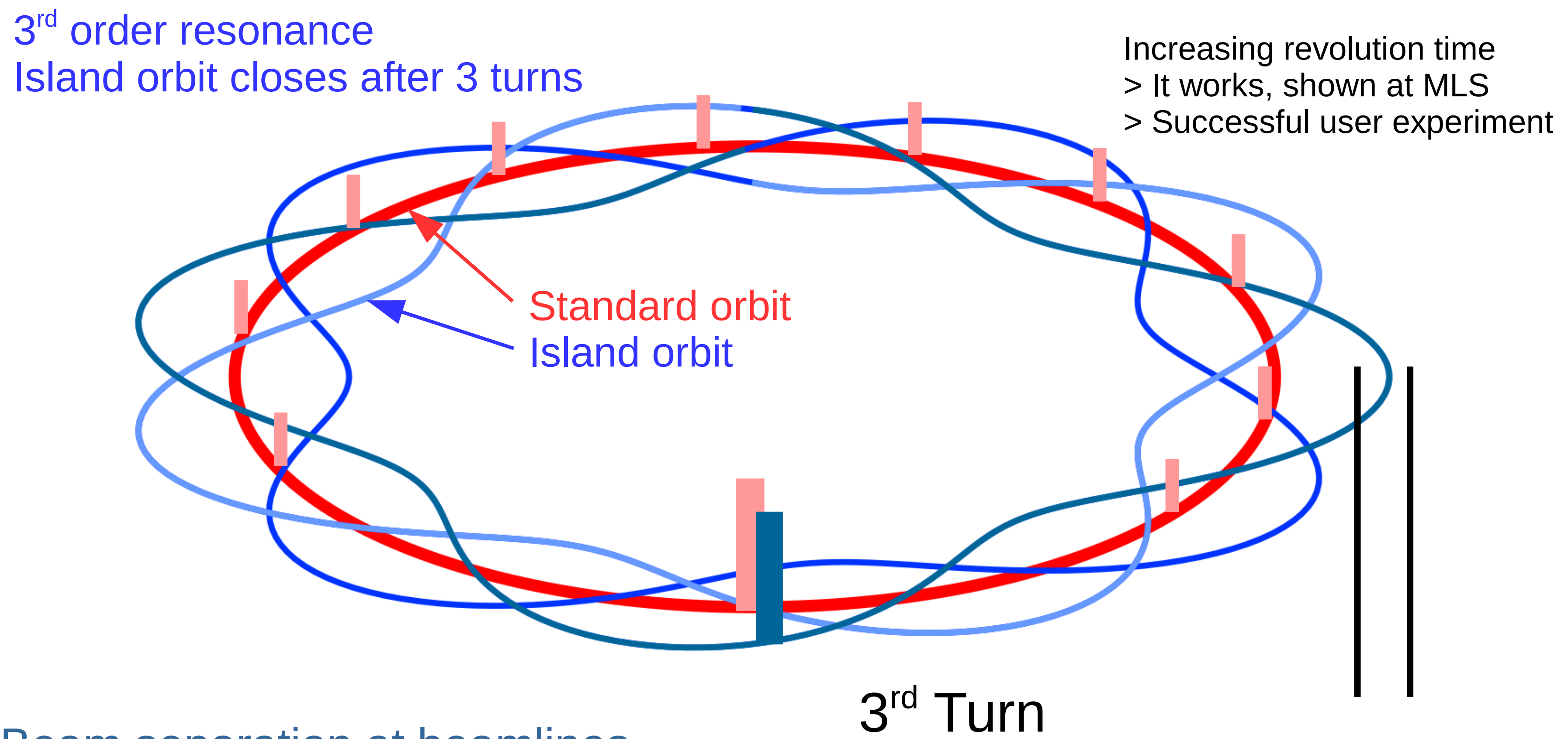
Separation scheme using transverse resonance island orbit



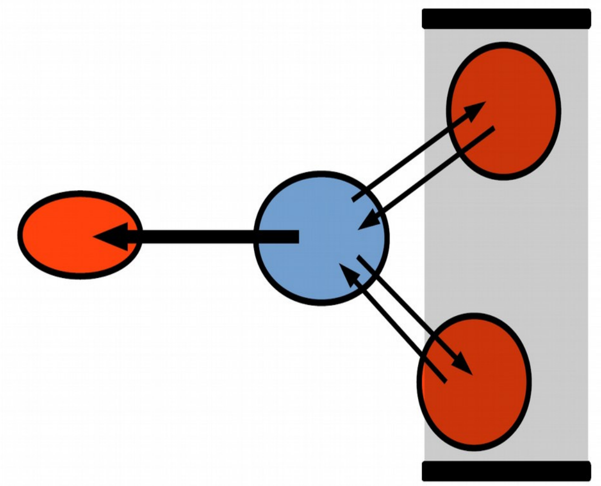
Beam separation at beamlines

- Spectral monochromators use vertical plane as dispersion plane, so a horizontal separation would be favourable
- No big changes at beamlines necessary (in contrast to vertical kicking)

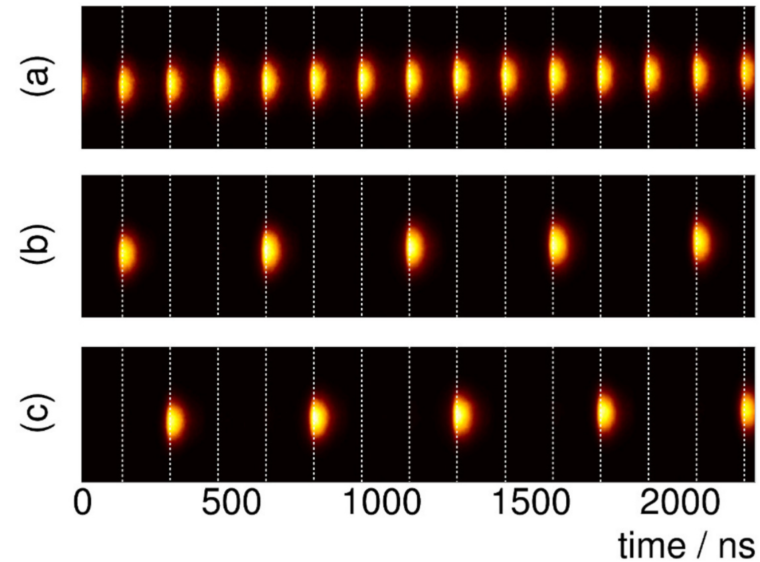
M. Ries et al., Proceedings of IPAC2015, Richmond, VA, USA, MOPWA021

Current manipulation, sub-revolution frequency (MLS)

- How to populate only one island?
- Non linearity of kicker
- Kick (or pause) every 3rd turn: 2.083 MHz instead of 6.25 MHz pause-pause-kick



Streak camera with aperture to select photons of one island



a) islands equally populated, kick every turn
b, c) only single island populated, kick-kick-pause pause every 3rd turn

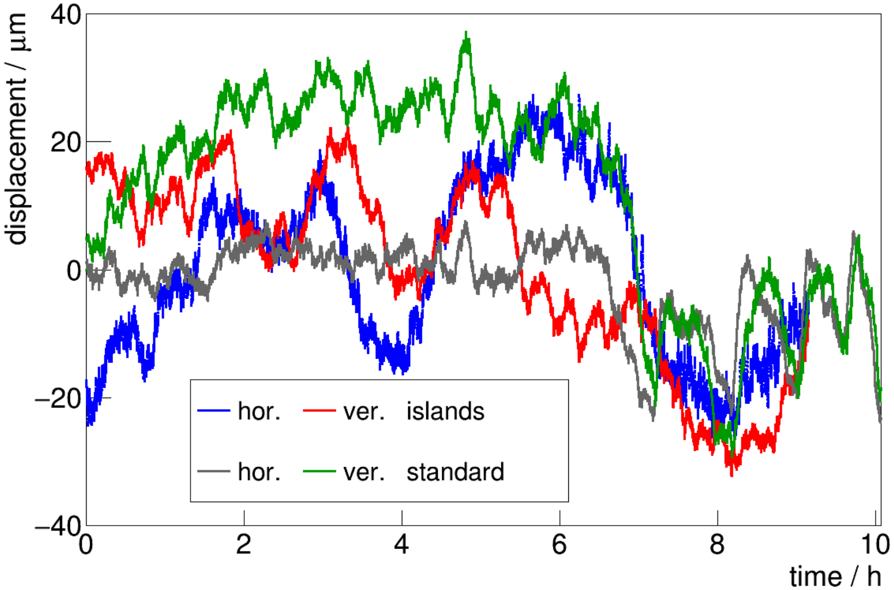
Application:

- Increase revolution time for TOF exp.
- Useable to test bunch resolved diagnostics

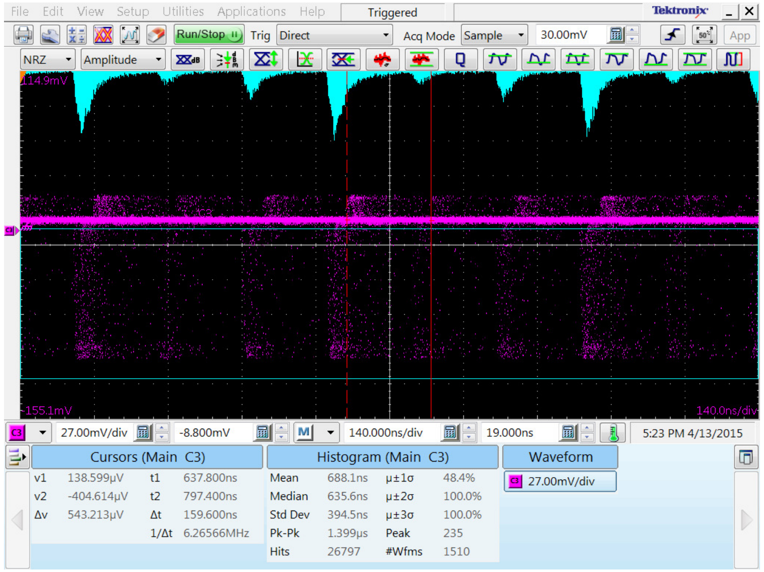
Sub revolution frequency

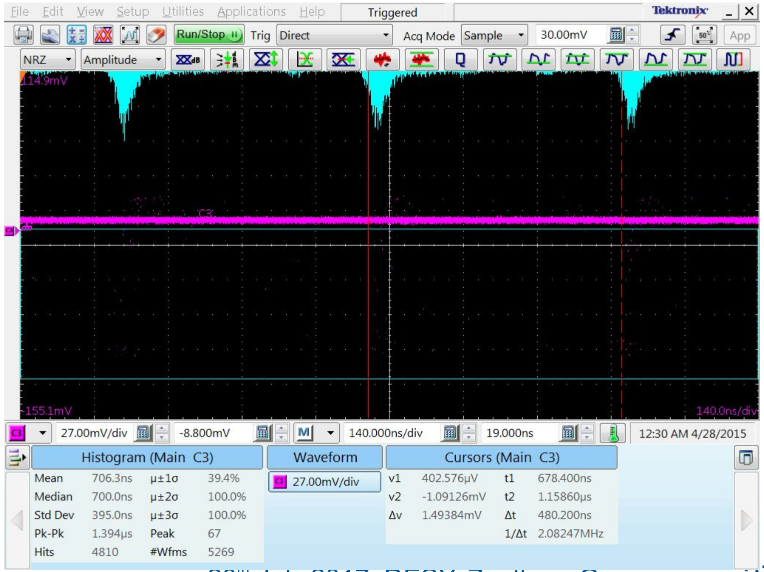
M. Ries et al., Proceedings of IPAC2015, Richmond, VA, USA, MOPWA021

- Reduced revolution frequency of 6.25 MHz to 2.083 MHz by populating only one island (revolution time 160 ns → 480 ns)
- Two successful user runs of 10 h each in decay mode for ARTOF experiments
- Vertical and horizontal position of source point monitor, without orbit correction
  → good long term stability of island orbit



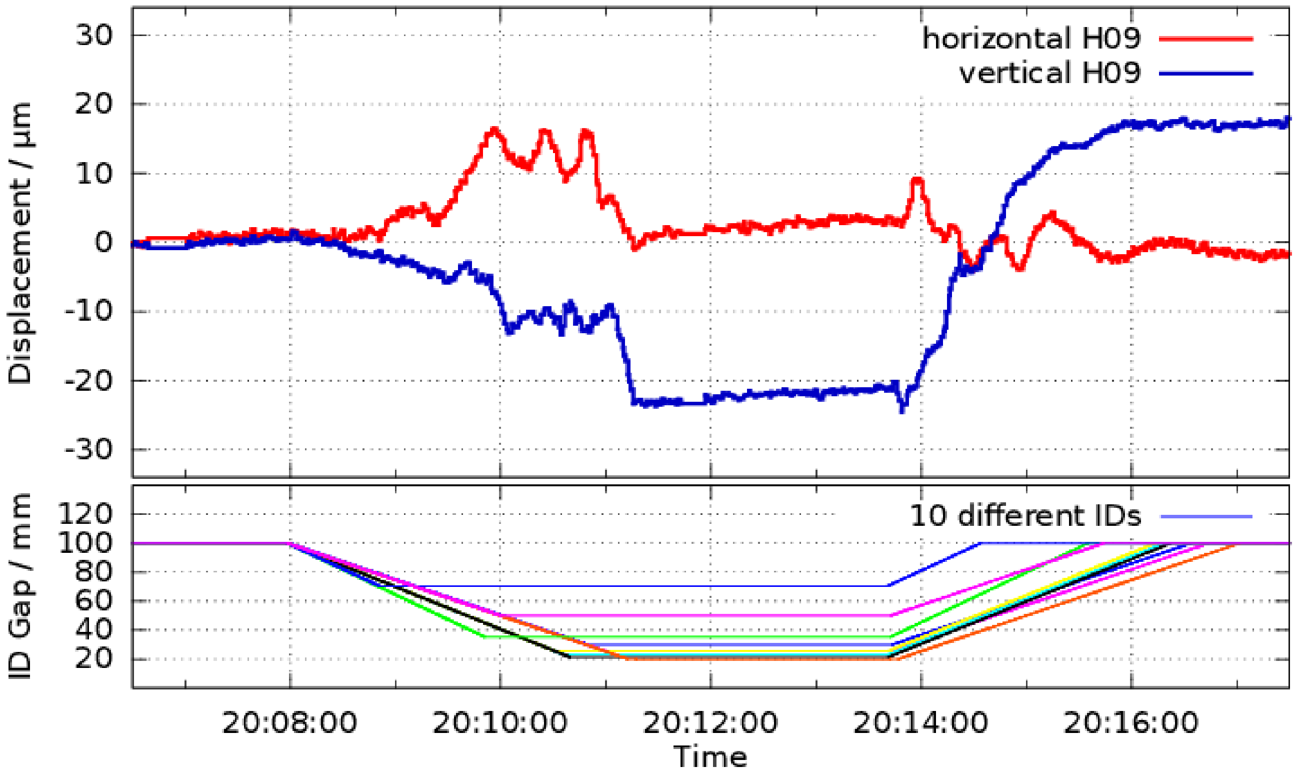
Signal measured at ID beamline with channeltron



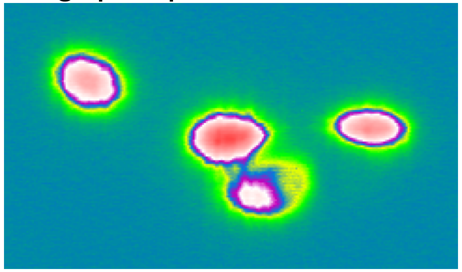


High current operation and moving ID gaps

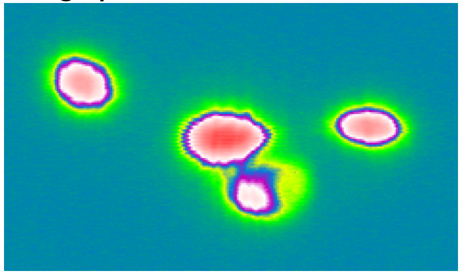
- High current operation possible ➞ 300mA (all in core or island)
- Closing gaps of 10 undulators ➞ Position change of ±20 µm
  - Without orbit correction and tune feedback, but with feedforward for standard optic



ID gaps open, 200mA



ID gaps closed, 200mA

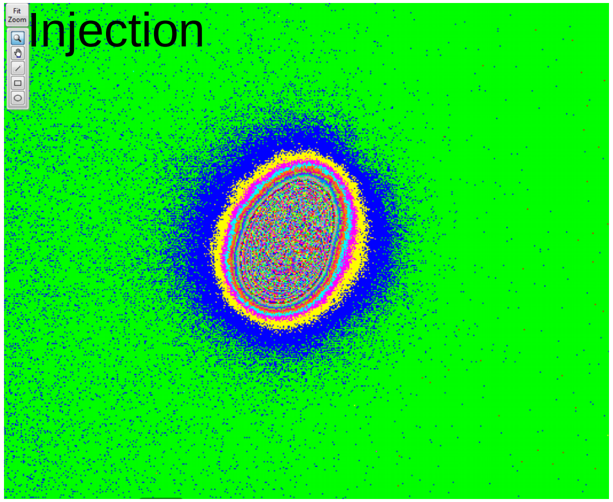


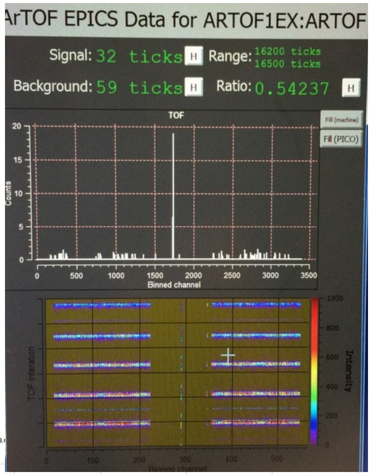
TRIBs BESSY II - TopUp Injection

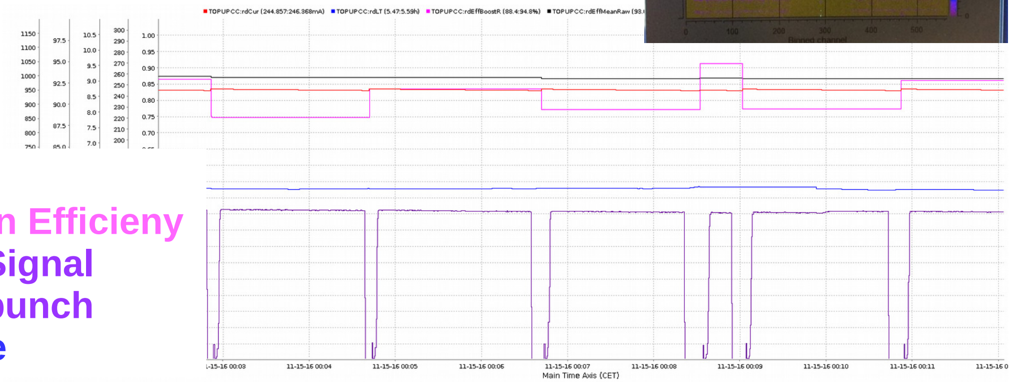
Injection in TRIBs optics

- Injection every 90 - 110 sec
- For injection all current pushed into standard bucket/orbit by horizontal sinusoidal excitation
- No SB (single bunch) signal from island orbit for 10 sec
- Average Injection Efficiency over night of 93 %
- Operation with running FastOrbitFeedback

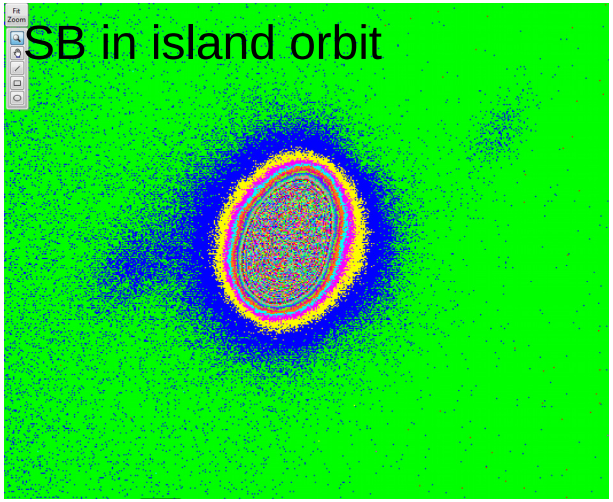
Source point imaging system







– Current
– Injection Efficieny
– Island Signal single bunch
– Lifetime



Thank you for your attention !

A BIG THANKs to all colleagues who contributed to this work!
electrons + warm and sc heartware, photons + beamline scientists hardware, IDs, user groups, communication, administration