Transverse Resonance Island Buckets as bunch separation scheme

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on behalf of the BESSY VSR team

2nd Workshop on Low Emittance Ring Lattice Design
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MAX IV, Lund, Sweden

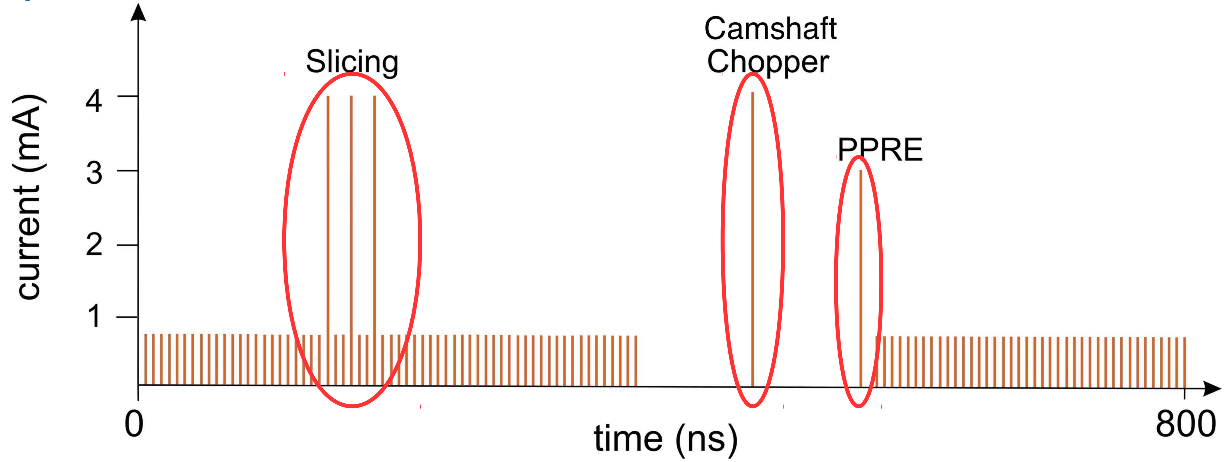
HZB Helmholtz Zentrum Berlin

Overview of talk

- Introduction and Motivation
- Established methods
  - MHz chopper, Pulse Picking Resonant Excitation (BESSY)
  - Vertical kick and cancel scheme (ALS)
- New approach at HZB (MLS and BESSY II)
  - **T**ransverse **R**esonance **I**sland **B**uckets - **TRIB**s
  - Experiences with (in-house) users at MLS and BESSY II
- Conclusion

Motivation: User demand - flexible fill pattern

BESSY II fill pattern – standard user mode

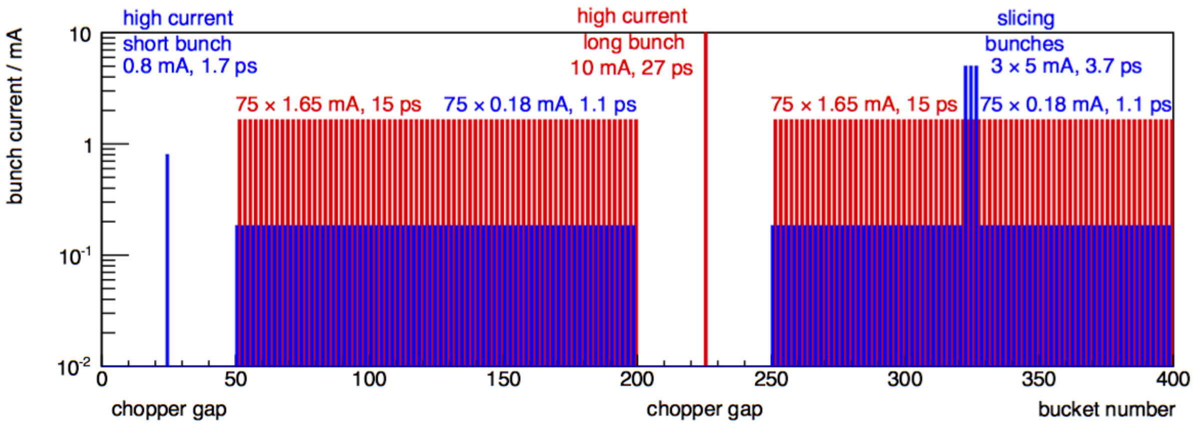


Users demands

- Single Bunch Mode with 1.25 MHz repetition rate
- Few Bunch Mode with 4 or 8 bunches, 5 to 10 MHz pulse repetition rate

C. Tusche, P. Goslawski et al.,
"Multi-MHz Time-of-Flight Electronic Bandstructure Imaging of Graphene on Ir(111)"
Applied Physics Letters, accepted and to be published

BESSY VSR fill pattern



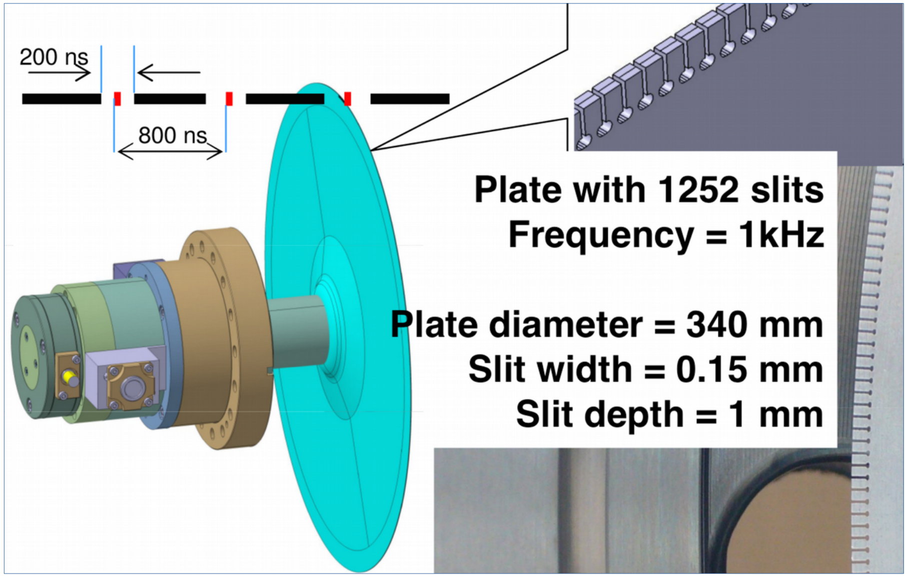
User demand:

Separation of short bunches

Established separation schemes at BESSY II

Phase locked MHz mechanical chopper

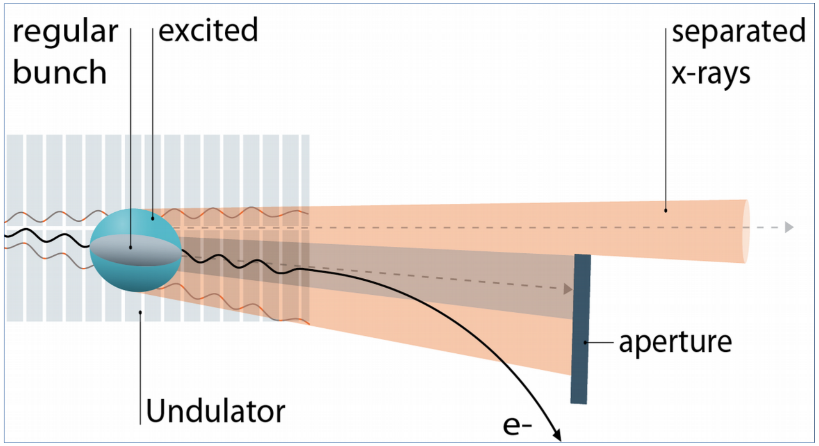
- Local separation of photons
- Needs an intermediate focus
- Phase locked within 2 ns
- Minimum gap of 100 - 200 ns
- At PM4 since 2015 in operation
  2nd at UE56 SGM, summer 2016



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

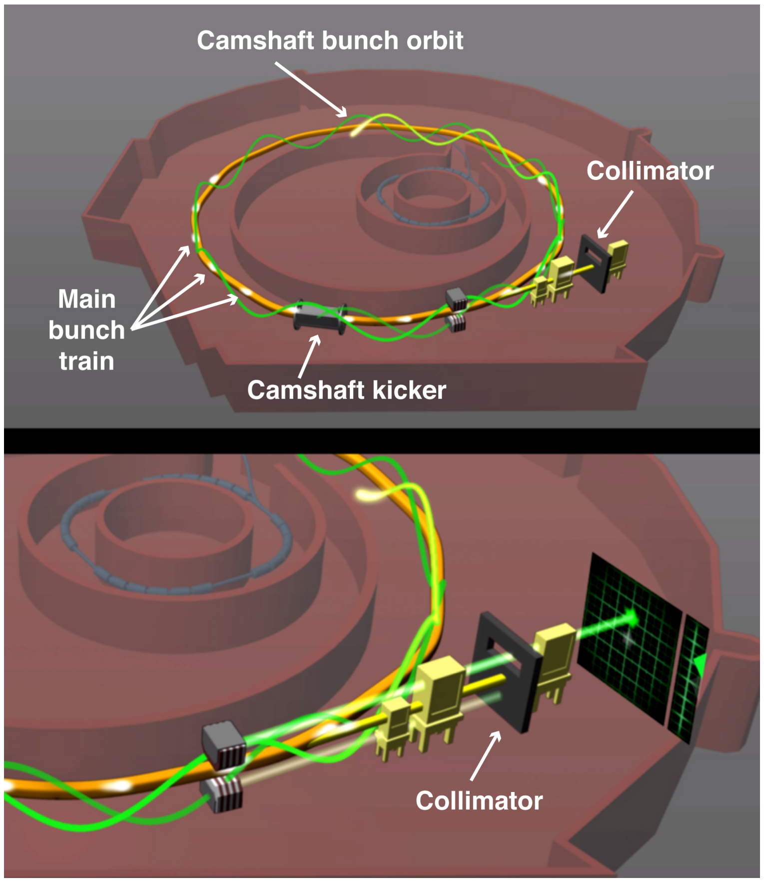


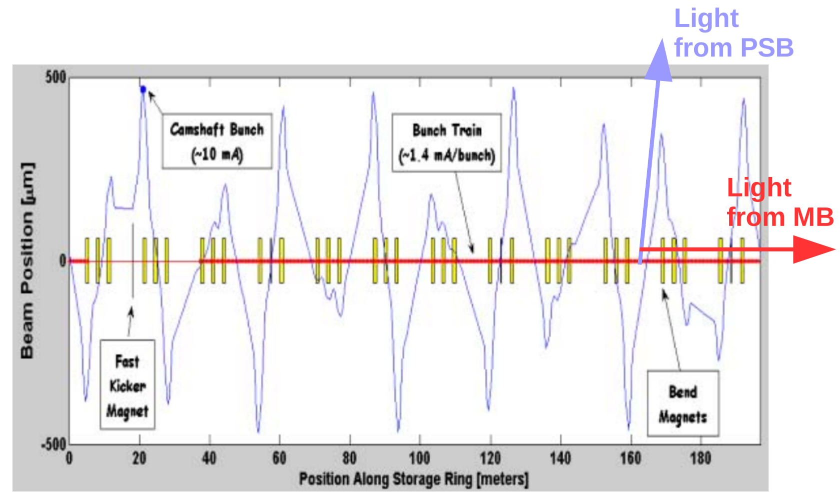
K. Holldack et al., Nature Com. 5, 4010, 2014

Established separation scheme at ALS

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:

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

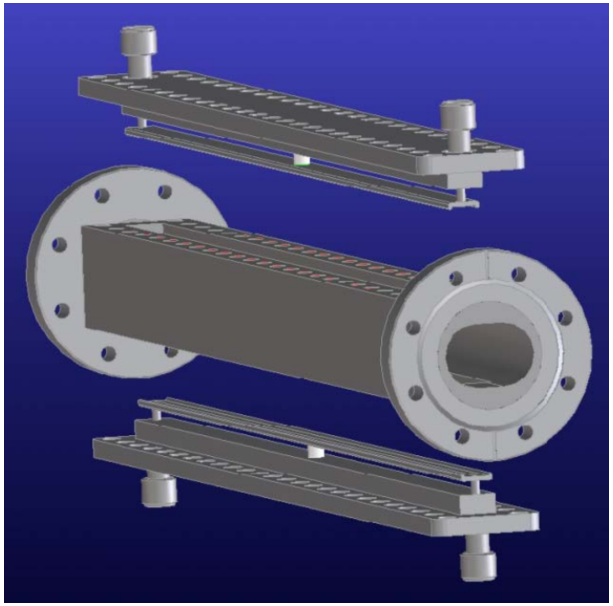
Various schemes possible:

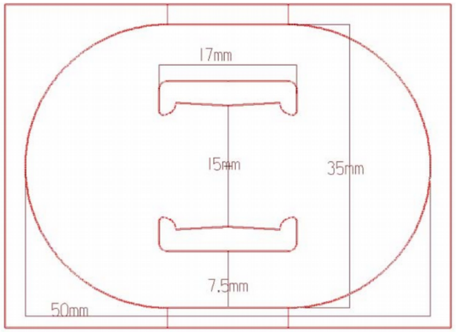
- Kick a chosen bunch each turn
- Kick at sub harmonics of the revolution frequency f_0 = 1.5 MHz to reduce bunch repetition rate

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

Established separation scheme at ALS

Pseudo single bunch scheme – kicker development challenging



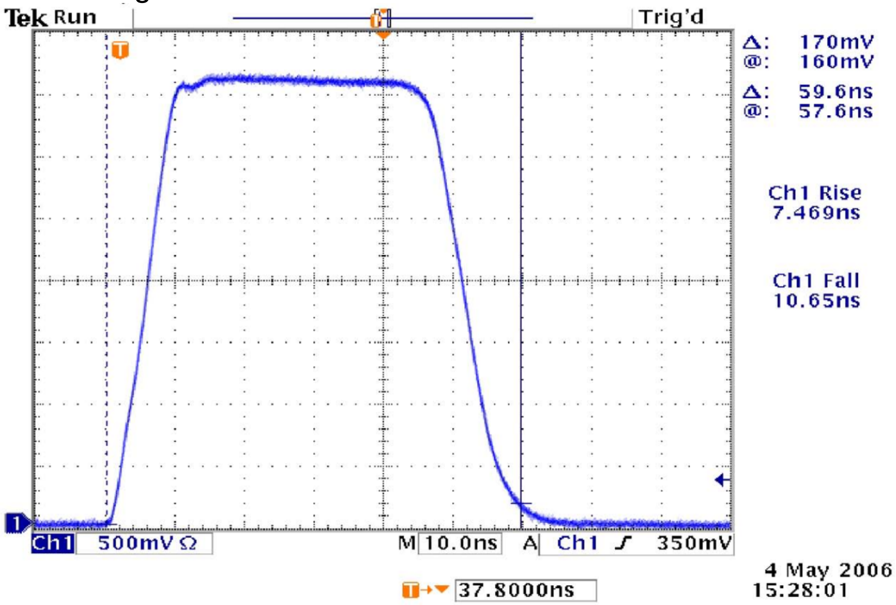


Transverse dimensions

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

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

Pulse length of 50 – 60 ns



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

Transverse **R**esonance **I**sland **B**uckets

- TRIBs -

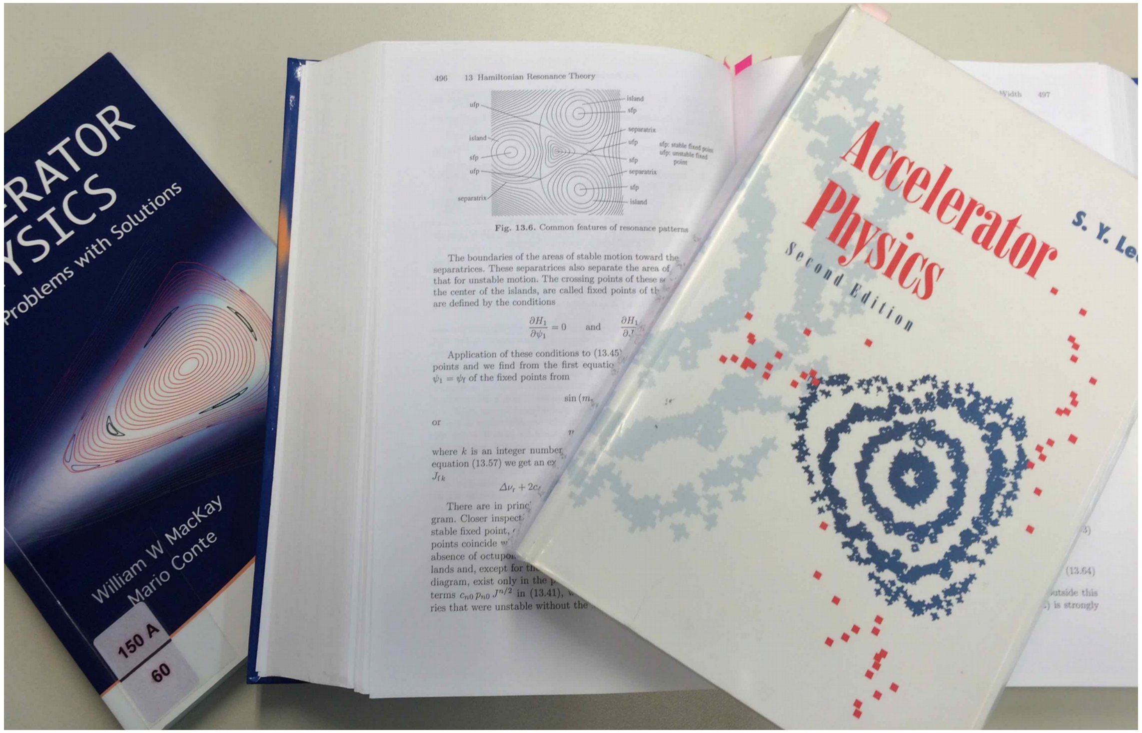
as bunch separation scheme

Method proposed by G. Wüstefeld

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

Transverse Resonance Island Buckets – 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.”

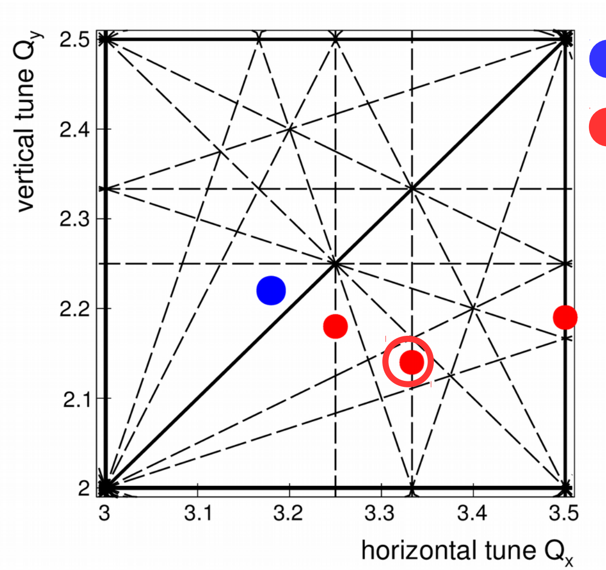
Application at hadron acc: Multiturn extraction

- 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

Transverse Resonance Island Buckets

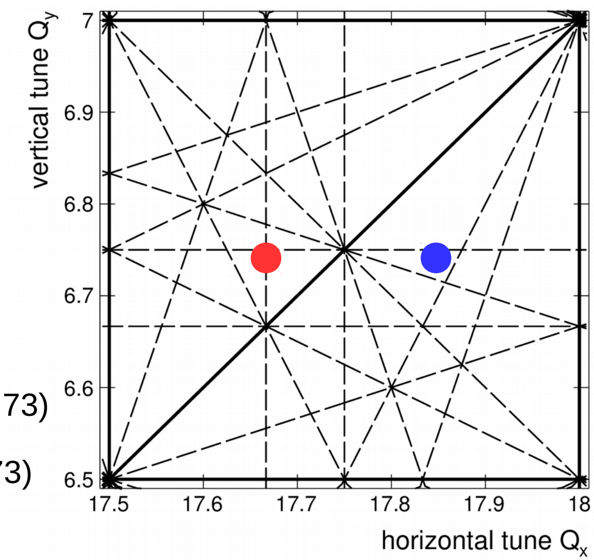
Island buckets at MLS



Working point (3.18, 2.22)

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

Island buckets at BESSY II



Working point (17.85, 6.73)

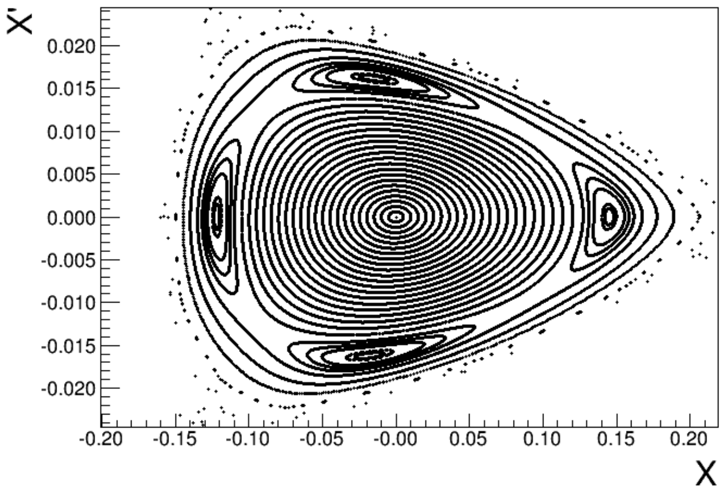
3[rd] order res. (17.66, 6.73)

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 Resonance Island Buckets

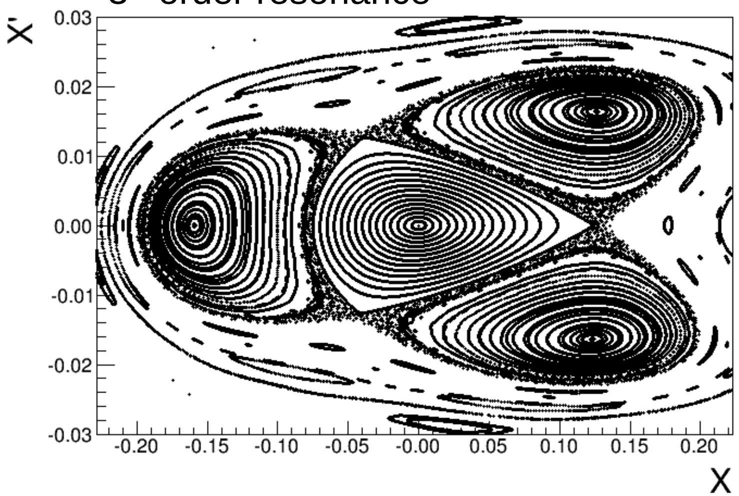
4th order resonance



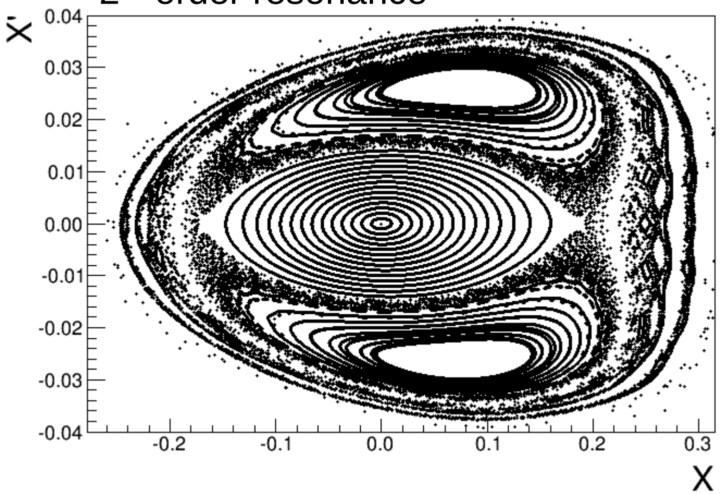
(x, x') phase space simulations

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

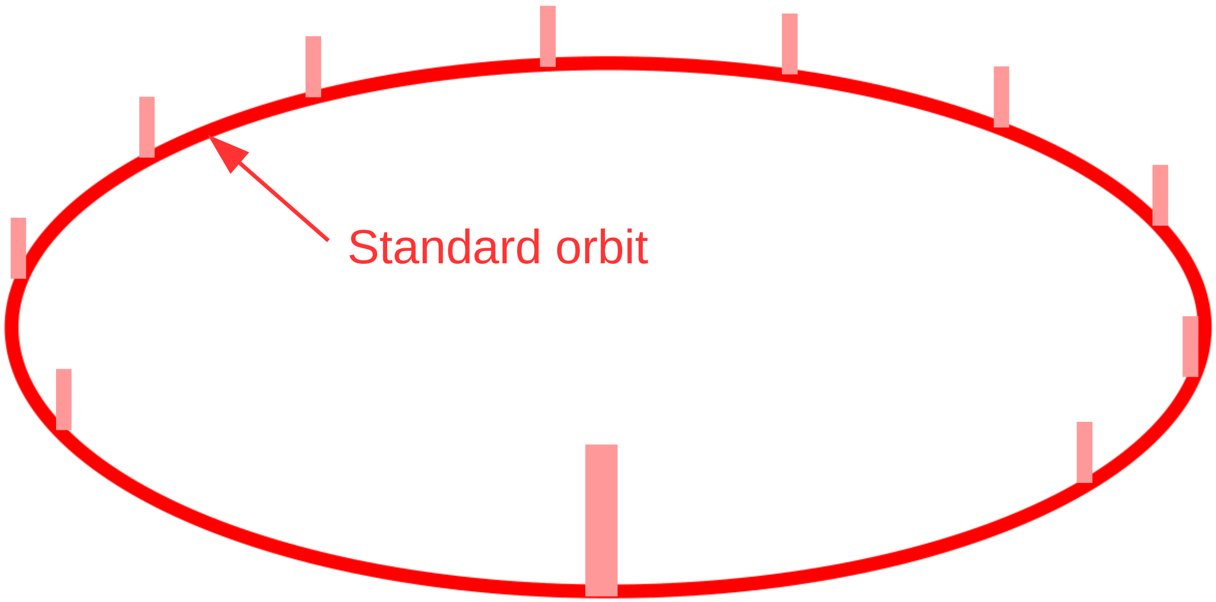
3rd order resonance



2nd order resonance



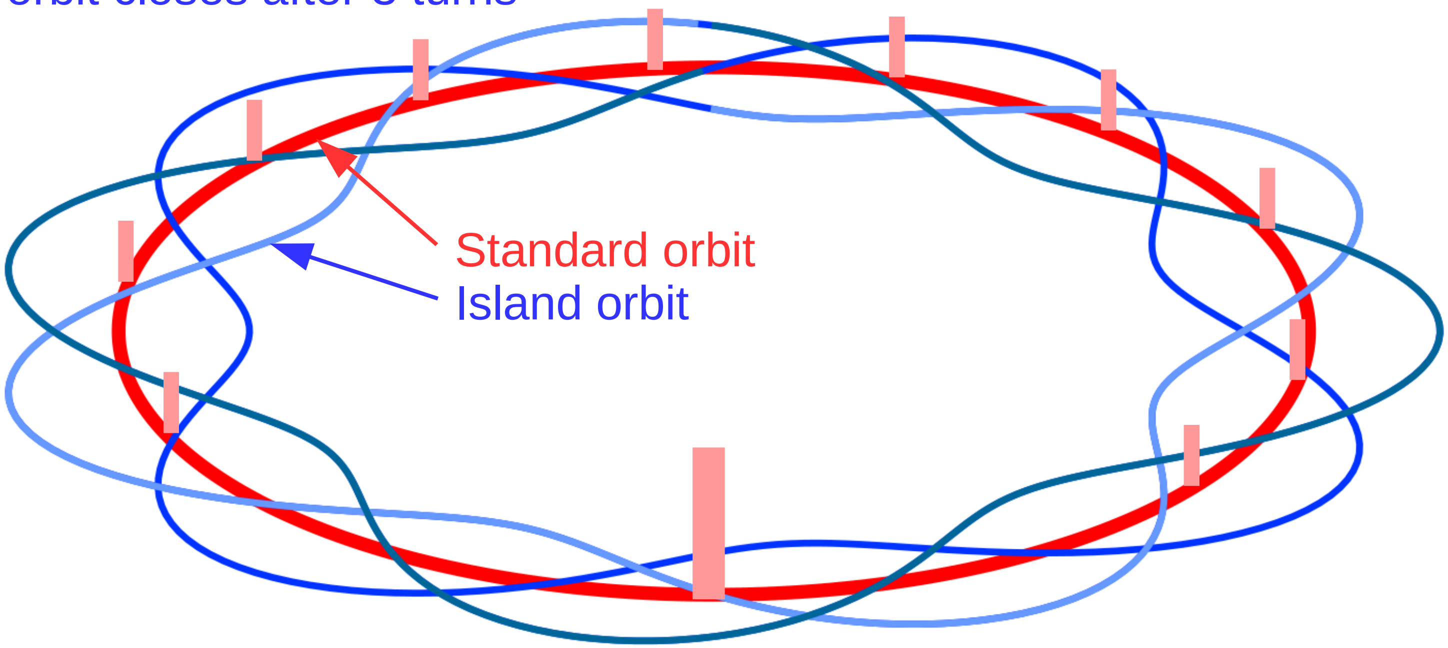
Separation scheme using transverse resonance island orbit



Transverse Resonance Island Buckets

Separation scheme using transverse resonance island orbit

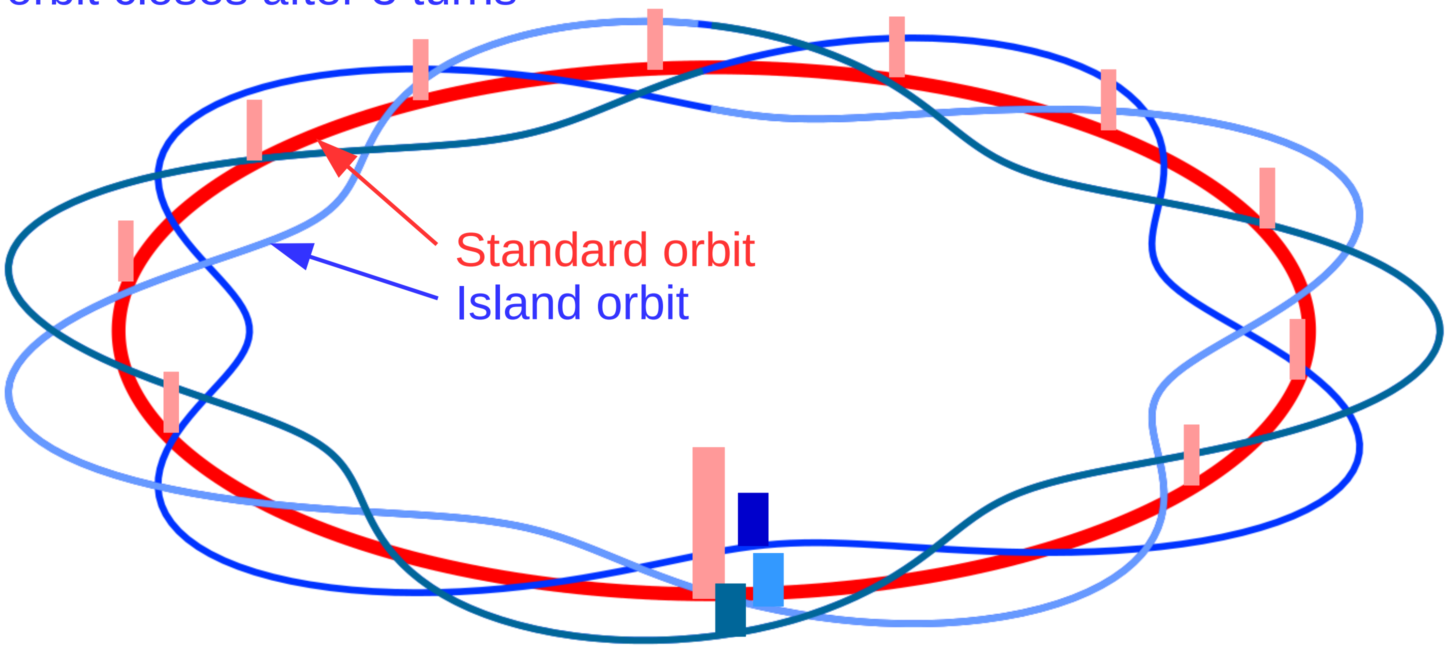
3rd order resonance
Island orbit closes after 3 turns



Transverse Resonance Island Buckets

Separation scheme using transverse resonance island orbit

3rd order resonance
Island orbit closes after 3 turns



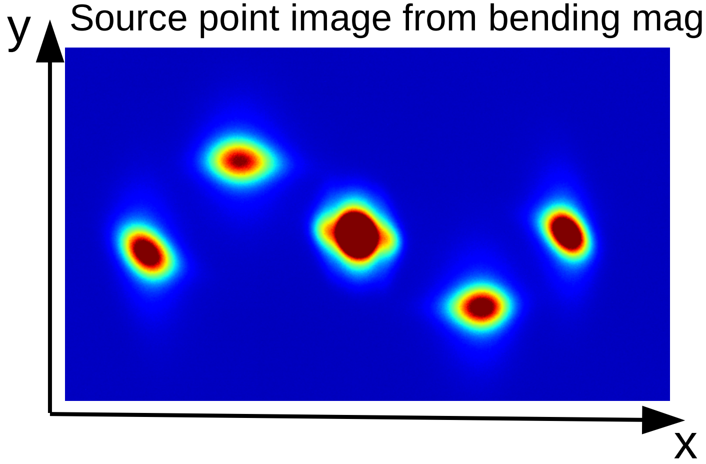
Beam separation at beamlines

- 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)

Transverse Resonance Island Buckets

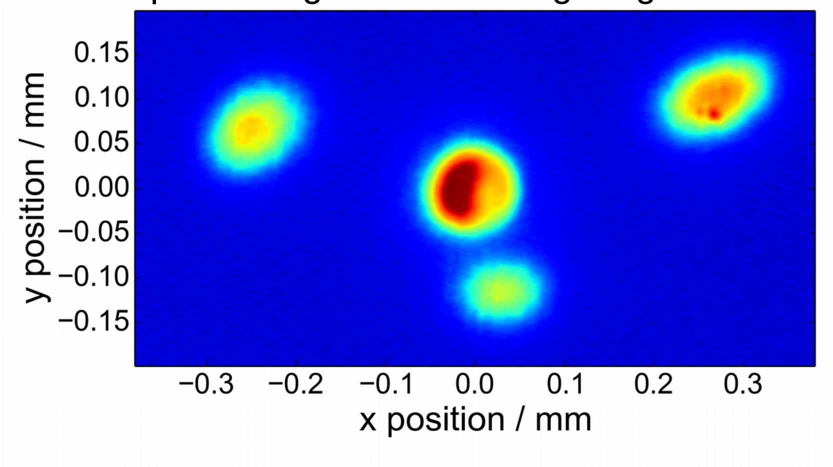
Island buckets at MLS

4th order resonance
Source point image from bending magnet



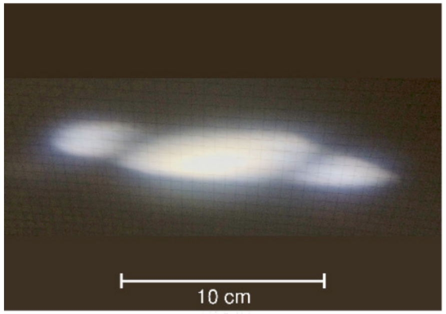
Island buckets at BESSY II

3rd order resonance
Source point image from bending magnet

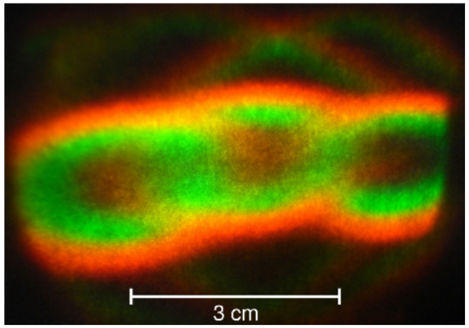


Island buckets at photon beamlines

3rd order resonance
Bending magnet beamline



Undulator beamline



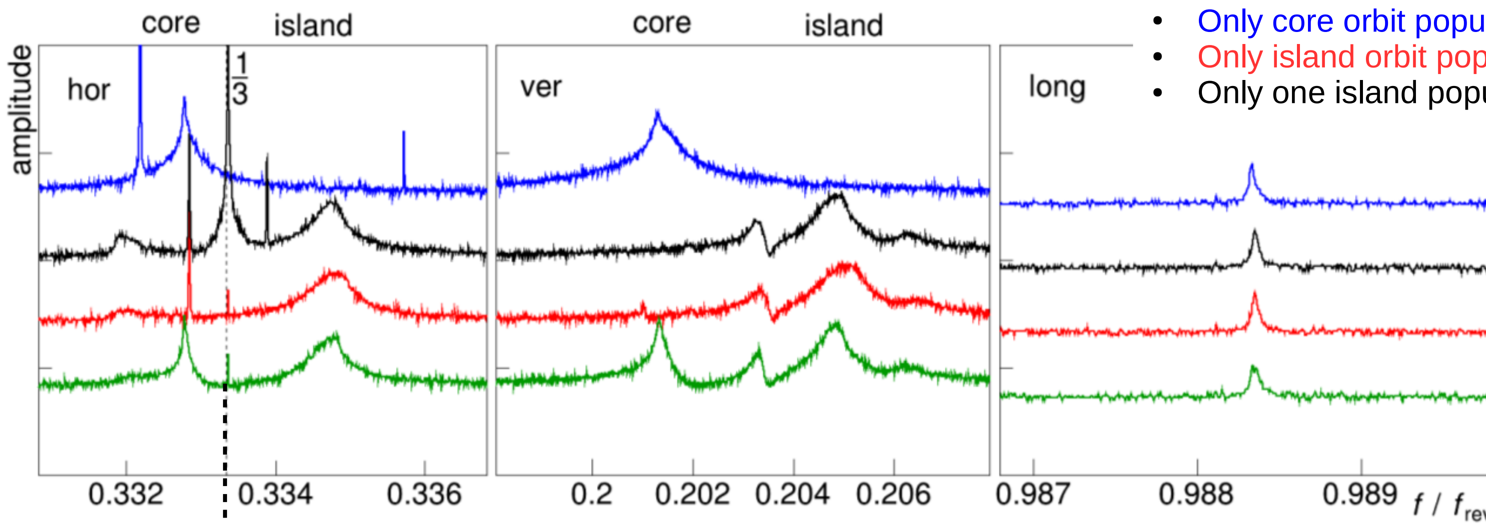
How to generate islands

- 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

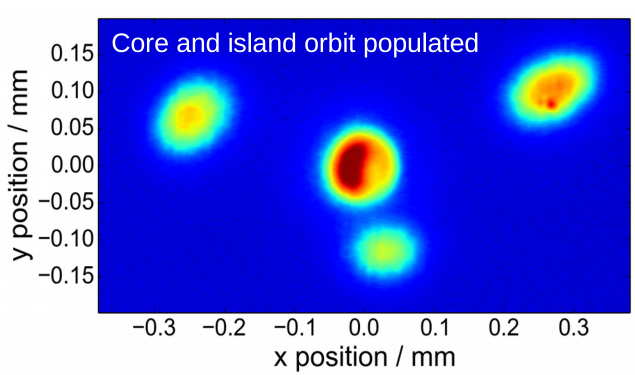
Transverse Resonance Island Buckets

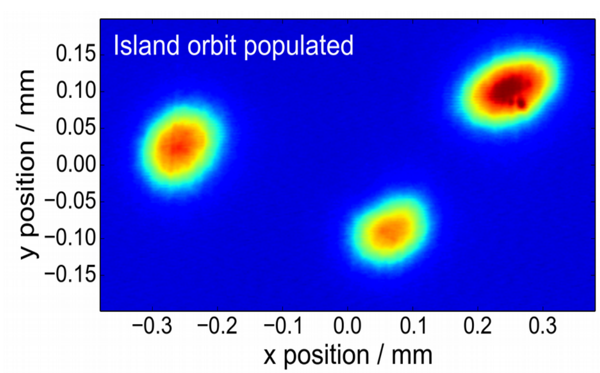
Tunes and current manipulation

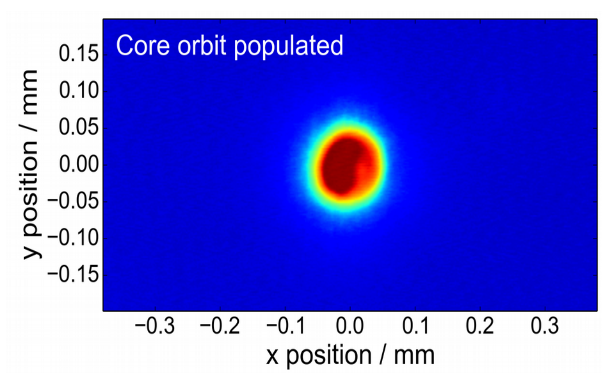
- Core and island orbit populated
- Only core orbit populated
- Only island orbit populated
- Only one island populated



- 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

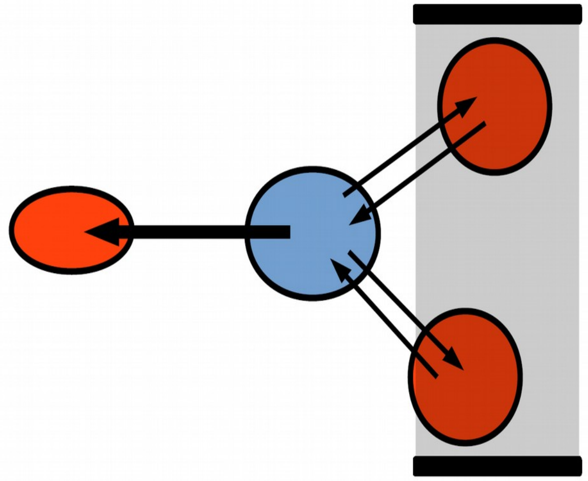




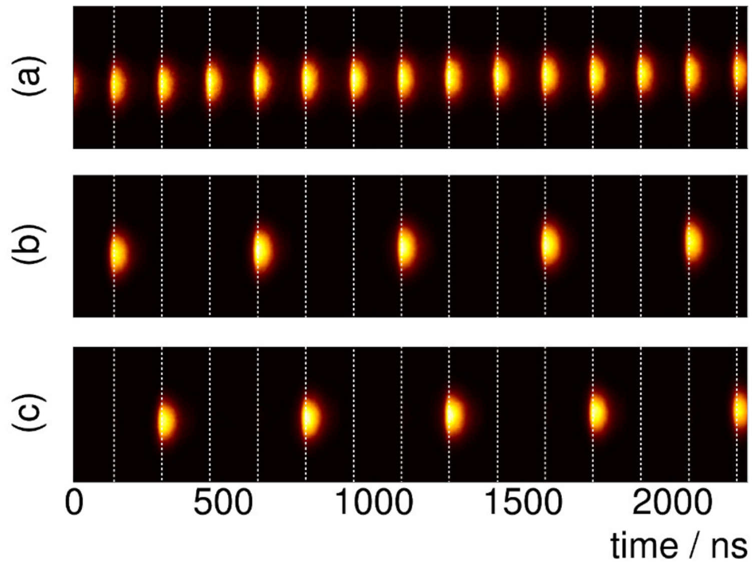


Current manipulation, sub-revolution frequency (MLS)

- 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

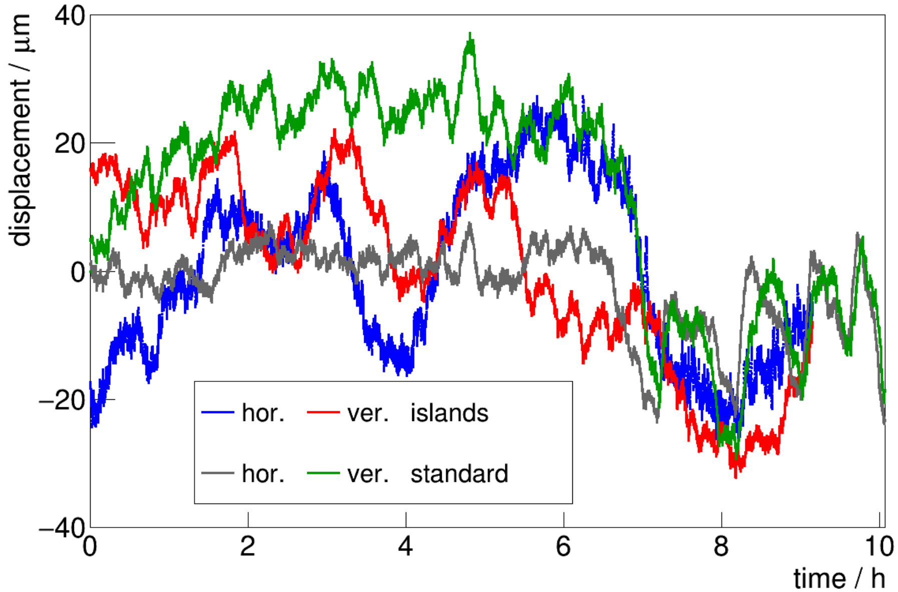
Application:

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

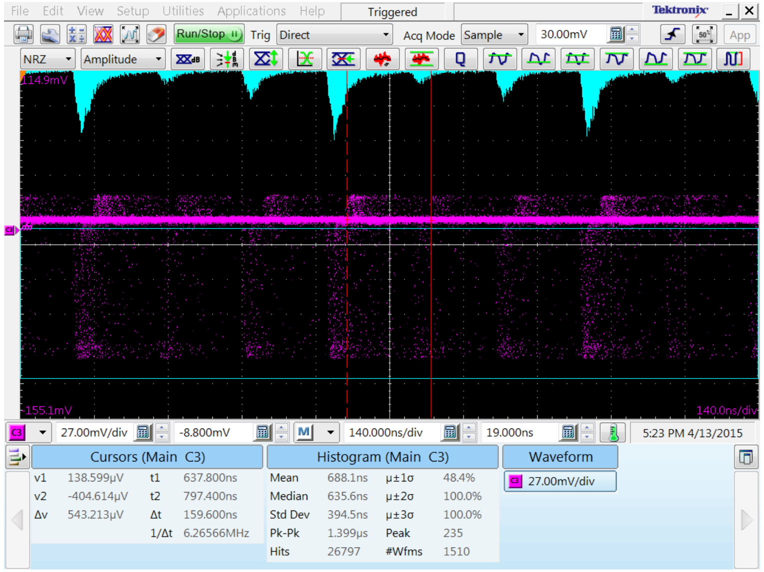
User experiments with TRIBs at the MLS

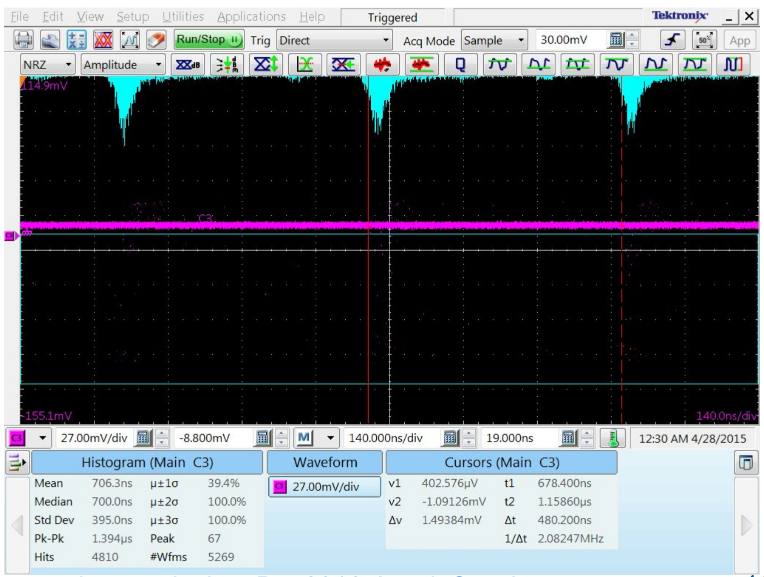
Sub revolution frequency

- 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





User experiments with TRIBs at 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?

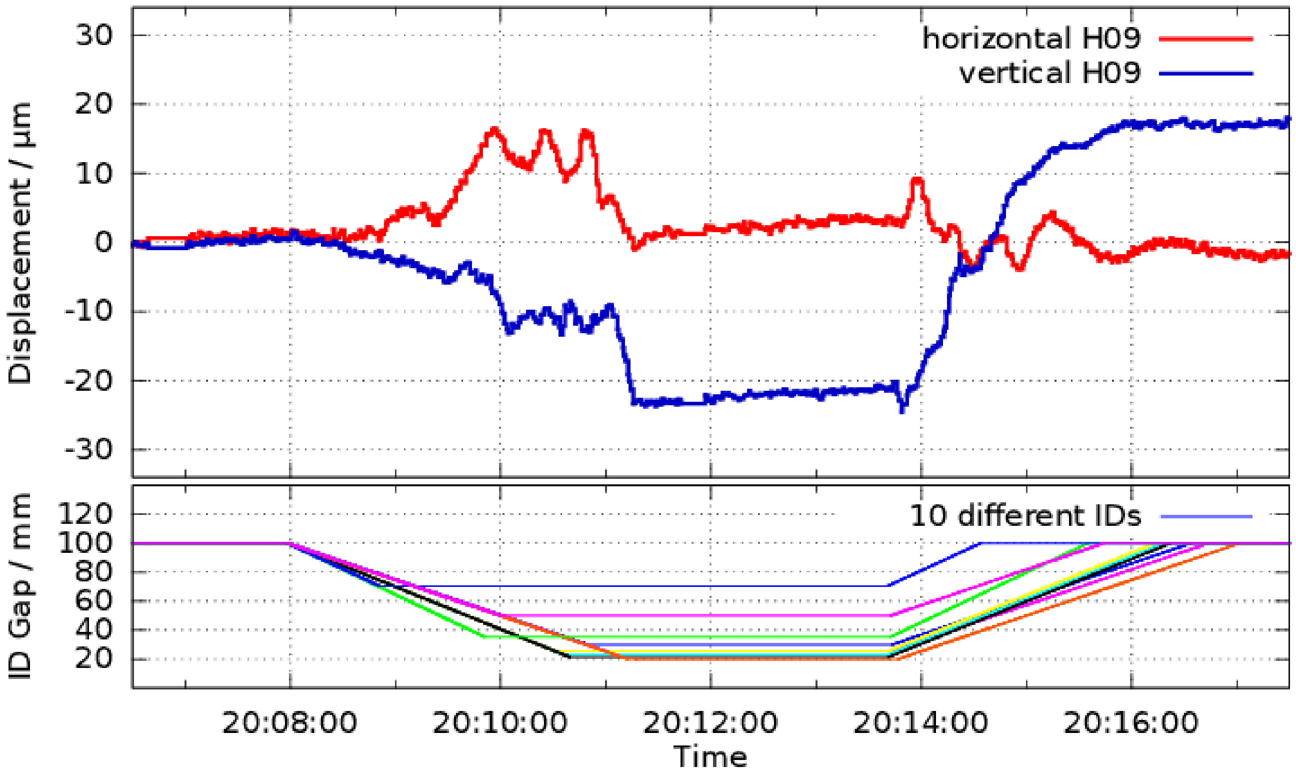
✓

Fall 2016

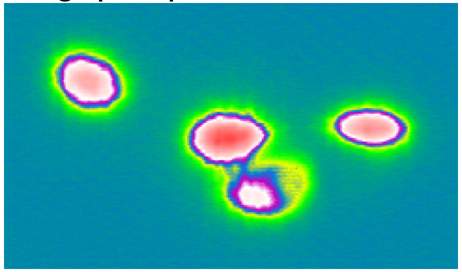
- **Injection - TopUp operation possible?**
  - Injection Efficiency (>90%) and Lifetime (>5h@300mA) ?
  - Difference between new working point (17.66) and old one (17.84)? (synchrotron source points from standard orbit)
  - Impact of radiation from island orbit on standard orbit?

High current operation and moving ID gaps

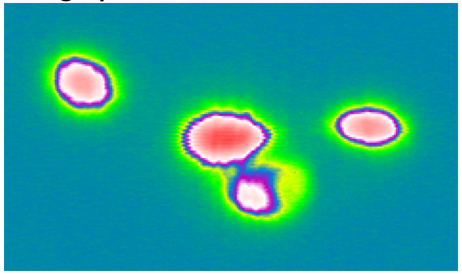
- High current operation possible ➡ 300mA (all in core or island)
- Closing gaps of 10 undulators ➡ Position change of ±20 µm
    - Without orbit correction and tune feedback, but with feedforward for standard optic



ID gaps open, 200mA



ID gaps closed, 200mA



Transverse Resonance Island Buckets – Separation

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, M. Mast, F. Schäfers, E. Schierle

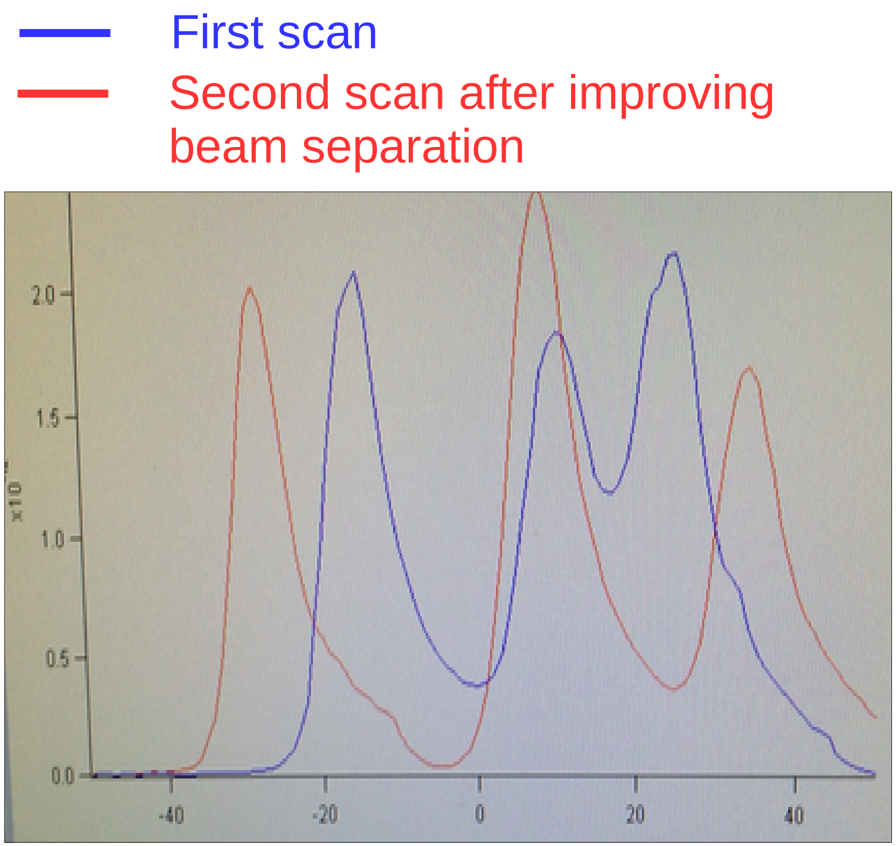
- When all current is pushed in island orbit, photon flux of the core beam vanishes completely at most beamlines
  - Beamline acceptance of most undulator beamlines ≈ 0.2 mrad
  - Orbit separation is much larger of about ≈ 0.3 mrad
  - Synchrotron radiation opening angle:

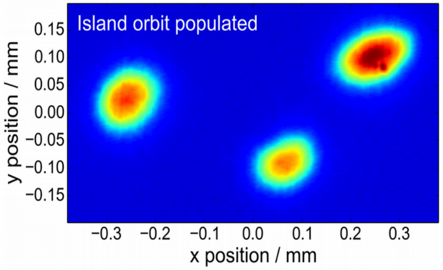
$$\theta = \frac{1}{\gamma} = \frac{1}{3327} = 0.3\,mrad$$

Transverse Resonance Island Buckets – Separation

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

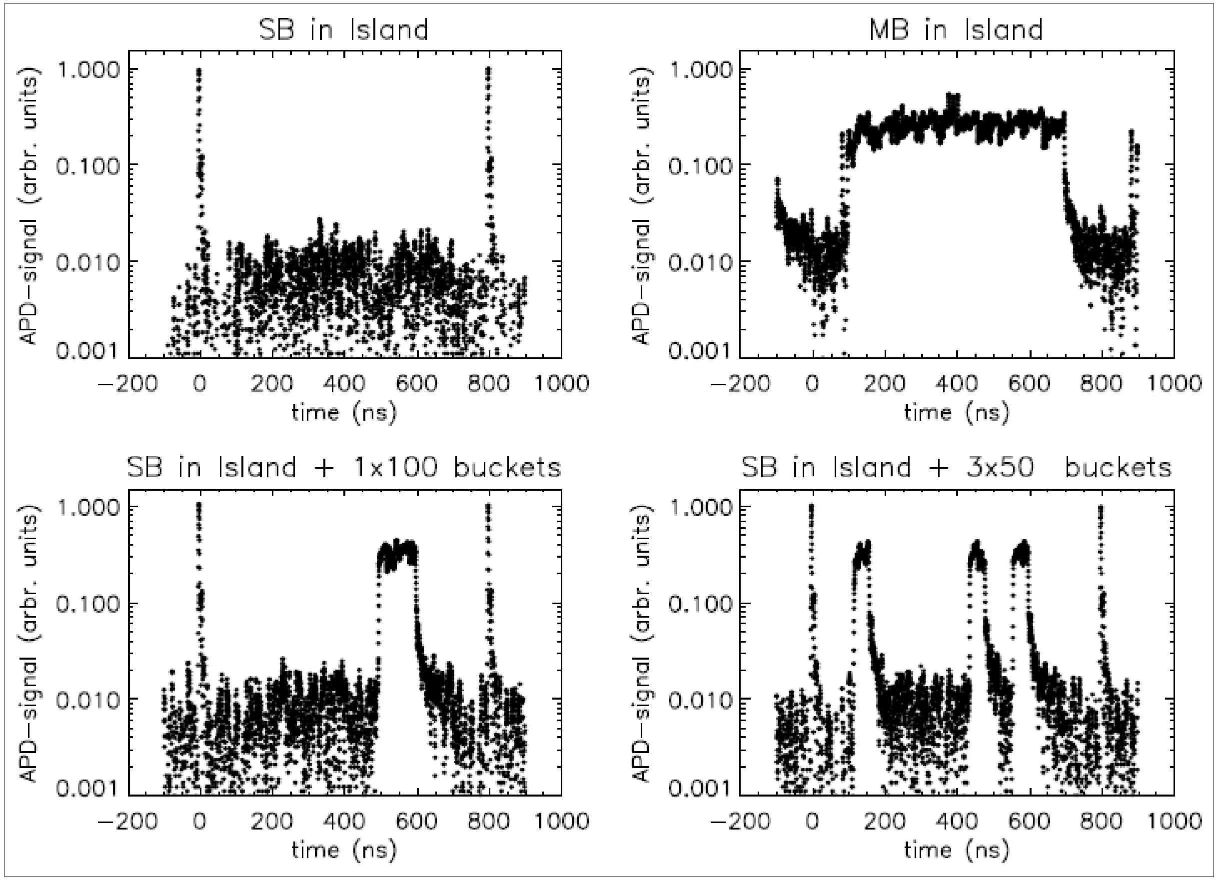




ID UE56-1 ZPM vertical polarised

- 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

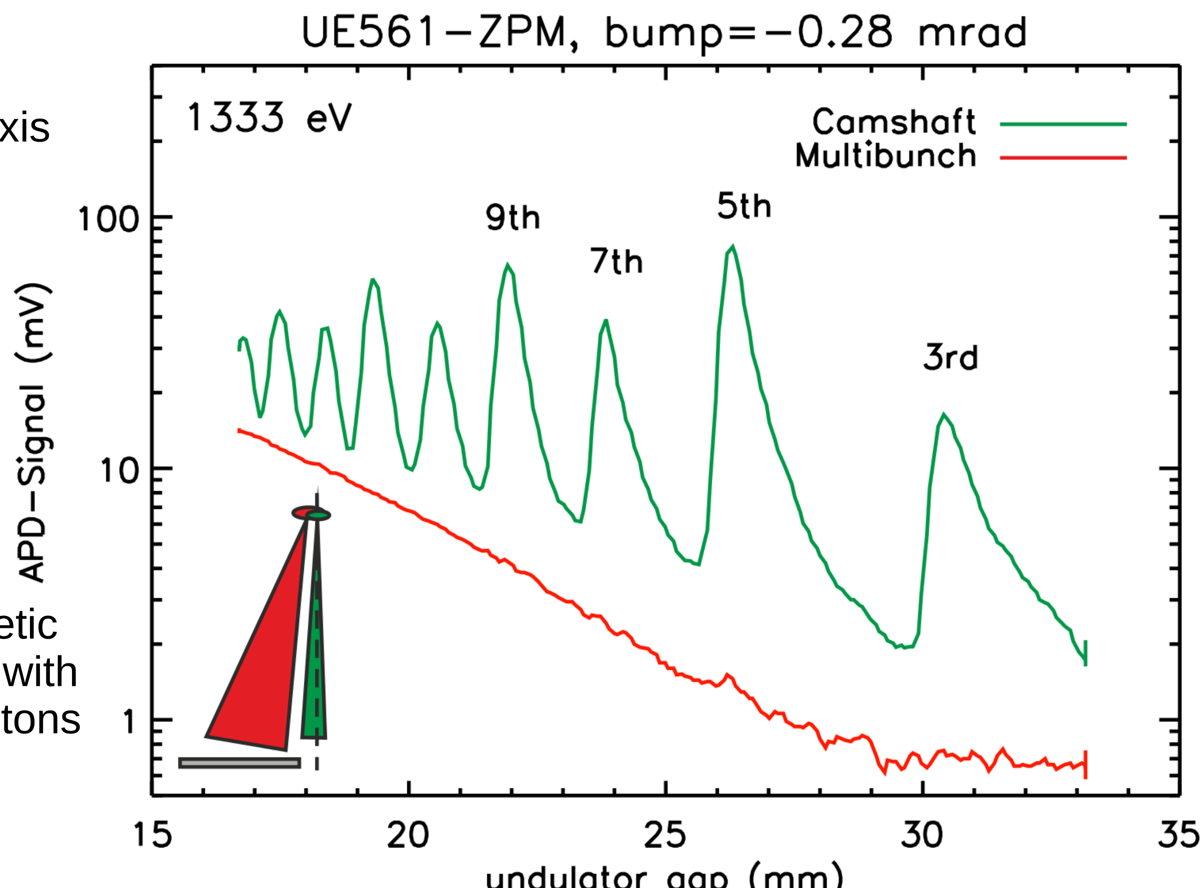


Transverse Resonance Island Buckets – Separation

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

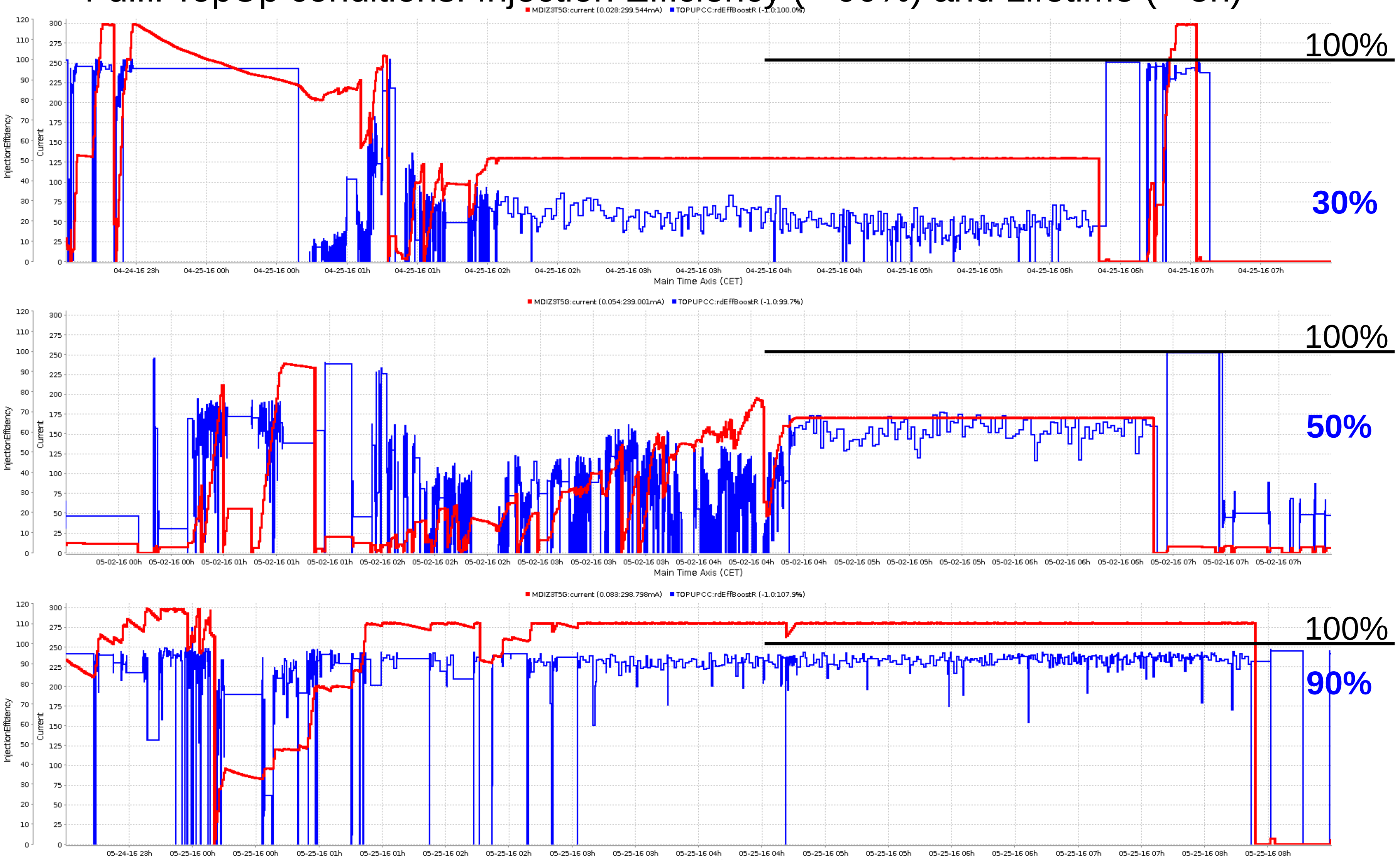
- Orbit bump with 0.28 mrad to align island orbit on ID axis
- Camshaft from island orbit shows undulator spectrum while MB fill from standard orbit is far off axis and blocked by aperture
- Purity > 100 (5th harmonic)
- Time resolved X-ray magnetic circular dichroism (XMCD) with camshaft island bunch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



Further developments of island buckets at BESSY II

– Current
– Injection Efficieny

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



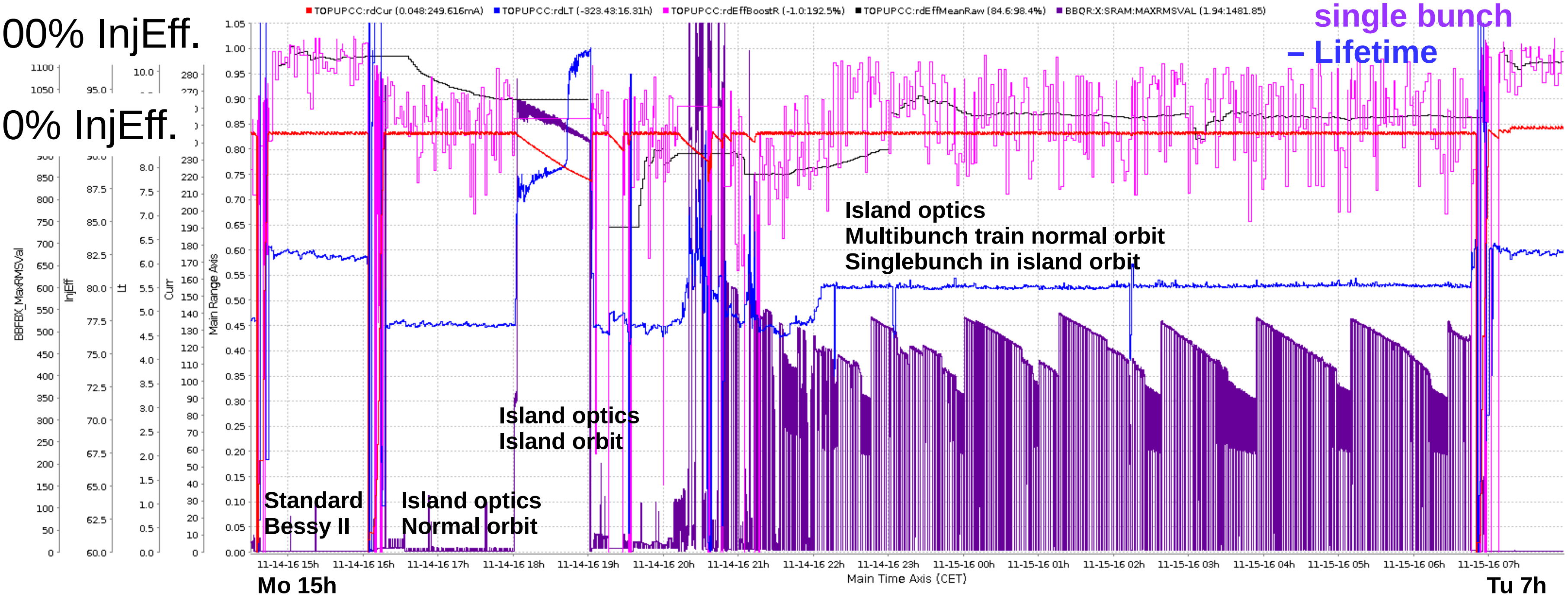
TRIBs with TopUp at BESSY II

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

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

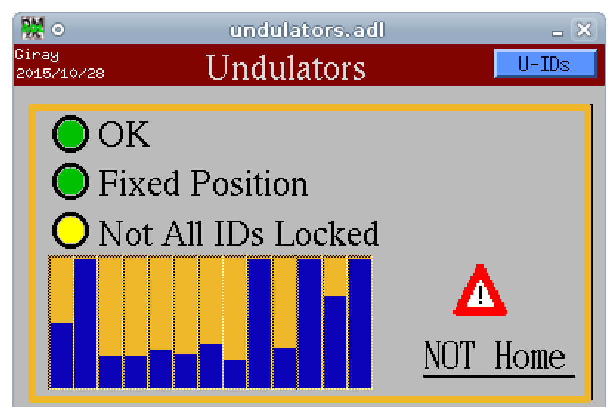
100% InjEff.

90% InjEff.



Result:

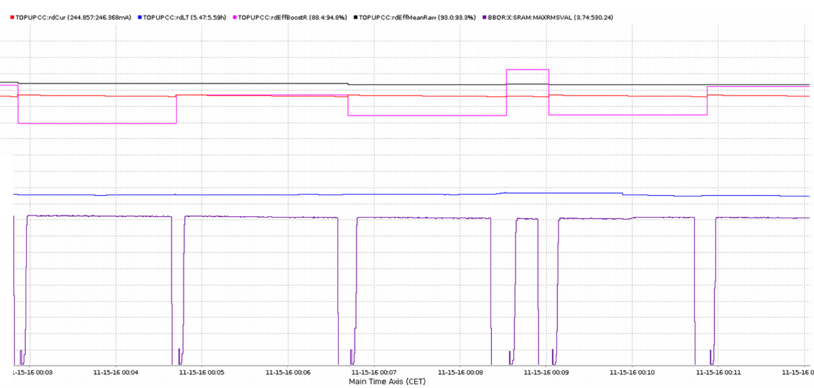
- Island optics with single bunch on island orbit over night (8h) in TopUp with open beamshutters and 9 IDs and some dipoles beamlines participating
- Stable operation, but improvable !
  > balance between Separation and Injection !
- Many techniques not prepared for island operation, for example: ID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



TRIBs with TopUp at BESSY II

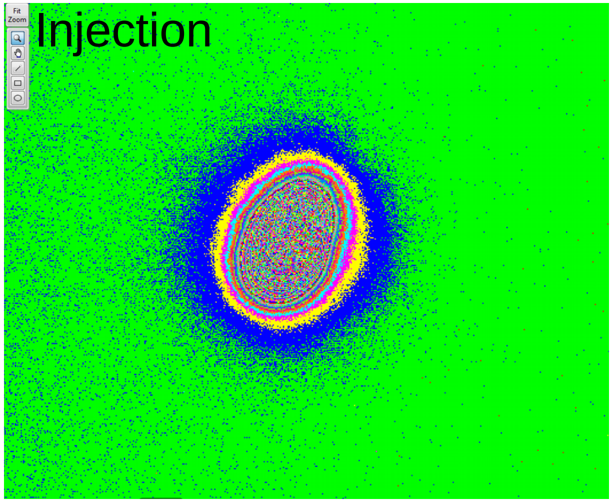
Injection in TRIBs optics

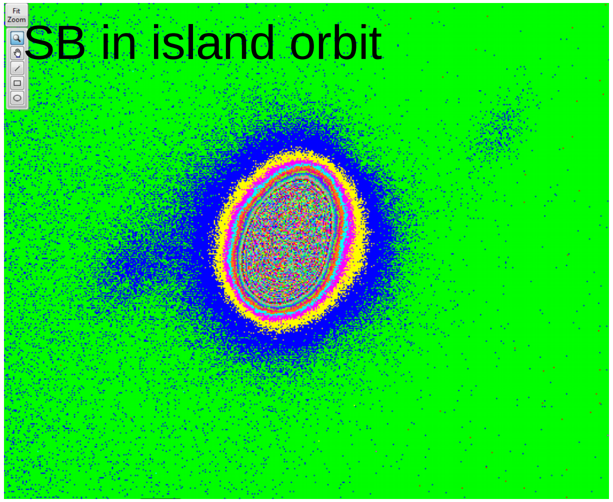
- Injection every 90-110 sec
- For injection all current pushed into standard bucket/orbit by horizontal sinusoidal excitation
- No SB (single bunch) signal from island orbit for 10 sec
- Average Injection Efficiency over night of 93 %
- Operation with FastOrbitFeedback running



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

Source point imaging systen





Bending magnet beamline
ArTOF user signal

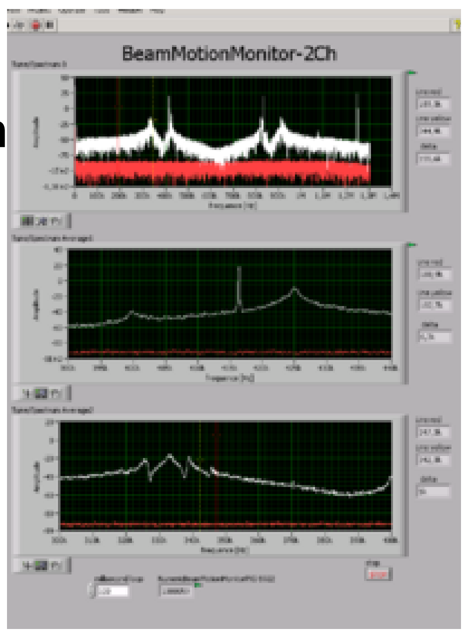
Data taking
Single bunch in island orbit

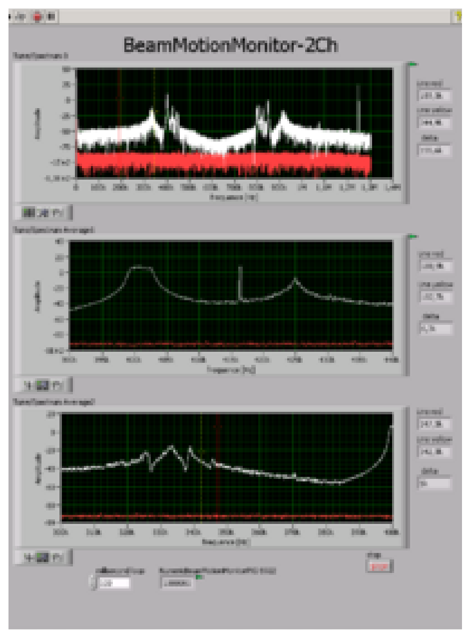
Injection
All current in standard orbit

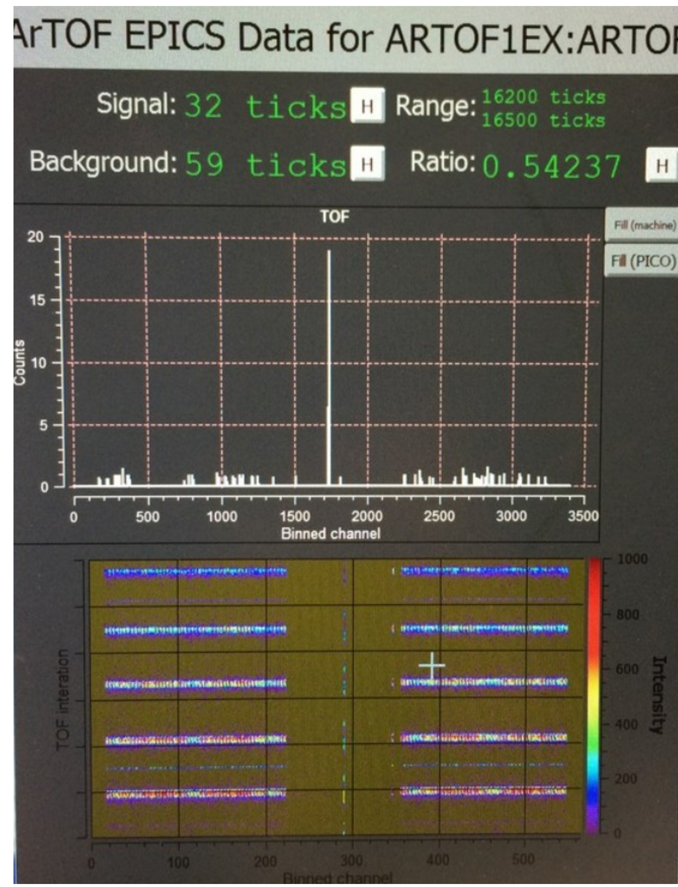
Beam spectrum

X

Y







Conclusion and Outlook

Islands at MLS

- Island buckets operation successfully established at MLS
- At nominal beam current (200 mA) and good lifetime, (decay mode, no injection)
- Operation at sub harmonic revolution frequency by populating only one island
- Successful user experiments

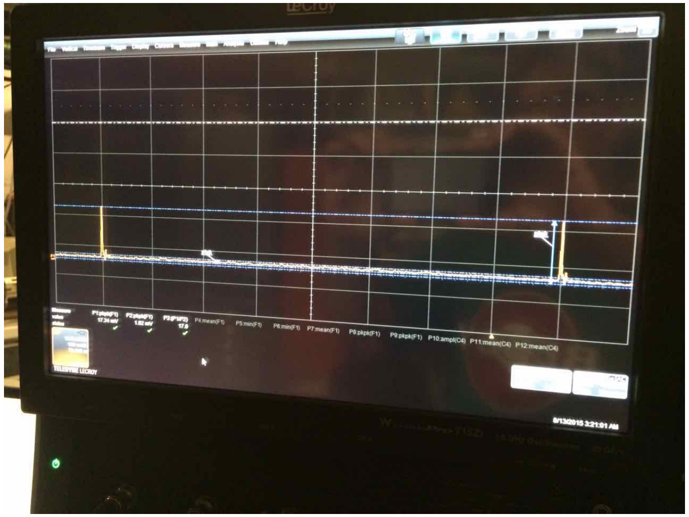
Islands at BESSY II

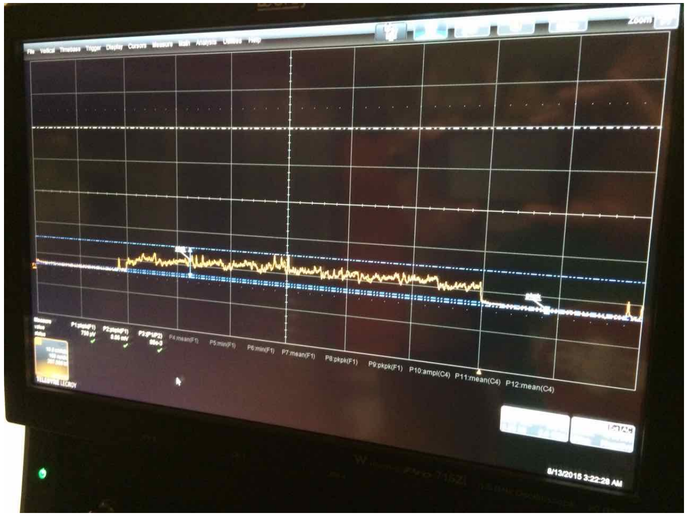
- Island buckets at horizontal 3rd order resonance are under investigation as as separation scheme at BESSY II
- Good separation has been achieved (IDs, sc IDs, bends)
- TopUp Injection in core orbit works
- > Balance separation and injection

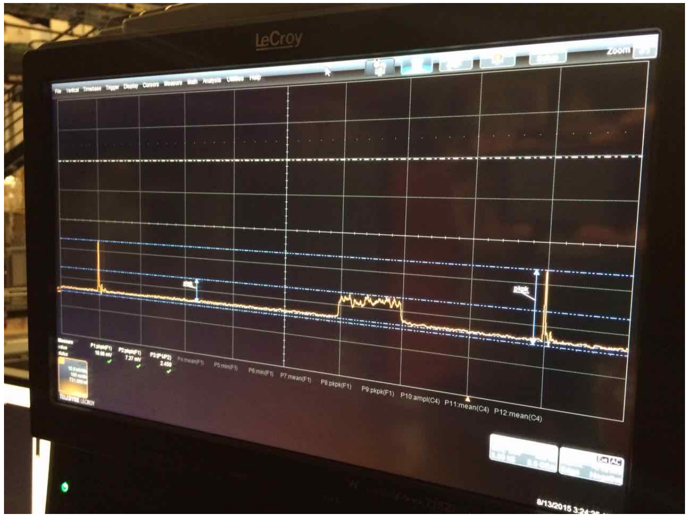
Resonant islands - an option for BESSY II and VSR !?

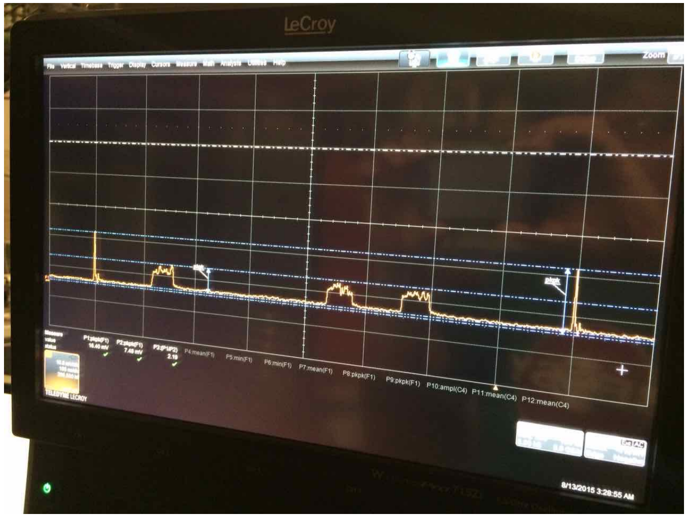
1) As bunch separation scheme of short bunches
2) Avoid transient beam loading, i.e., no shift of bunches along filling and improved Touschek lifetime

Thank you for your attention









The End