Different operation regimes at the Karlsruhe Research Accelerator

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8th Low Emittance Ring Workshop (supported by the ARIES Project), Italy, 28 October 2020

Abstract-1

- The storage ring KArlsruhe Research Accelerator (**KARA** – former ANKA**)** at KIT operates in a **wide** energy range from **0.5** to **2.5 GeV**

- **Different** operation modes and lattice versions have been implemented at **KARA** ring:

- The **double bend achromat** (**DBA**) lattice with achromat straight sections (D=D′=0)

- The **theoretical minimum emittance** (**TME**) lattice with distributed dispersion and vertical tune Qu=2.69 (**USER-1** optics)

- **Modified TME (**theoretical minimum emittance) lattice with distributed dispersion (**USER-2** optics) and high vertical tune **Qy=2.801**

- Different versions of **low positive as well as negative momentum compaction factor** optics with highly **stretched dispersion** function

- The beam performance during user operation as well as at low alpha regimes was essentially improved

- Beam current up to **200 mA** is available for **USER** operation

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Abstract-2

- **Non-linear effects**, in particular, reduction of life time due to **residual** high order components of magnetic field generated by 2.5 T superconducting wiggler have been observed, studied and cured

- Based on good agreement between computer simulations and experiments, a new **User operation mode** at **high vertical tune Qy=2.801** **(modified TME lattice)** has been implemented and in operation

- Few options of **Low–α** optics have been simulated**,** tested and realized in a wide operational range of ring and now routinely used at 1.3 GeV for studies of beam bursting effects caused by coherent synchrotron radiation in THz frequency range

- Short bunches of a few **ps** pulse width are available at KARA

- A specific optics with **negative compaction factor** was simulated and implemented

- Regular operation and R&D studies at negative **α<0** are in active progress

- Studies of longitudinal motion at KARA have been performed with an objective to estimate feasibility of **filling** and **storing** of beam in **α-buckets**

- New experiments are planning

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Main results reported here:

1. E. Huttel *et al.*, "Operation with a low emittance optics at ANKA", in *Proc. Particle Accelerator Conf. (PAC'05)*, Knoxville, USA, May 2005, pp. 2467-2469

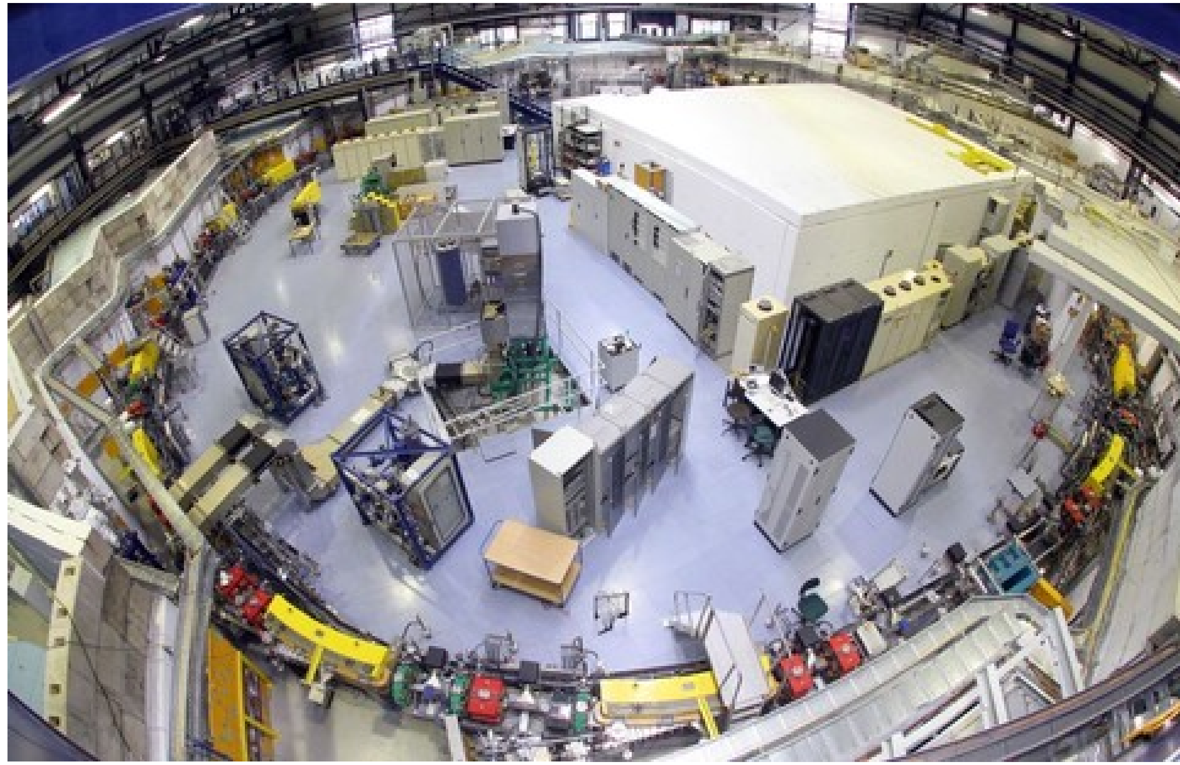
2. A. Papash, E. Blomley, J. Gethmann, E. Huttel, A.-S. Müller and M. Schuh, "High order magnetic field components and non-linear optics at the ANKA storage ring", *Proc. IPAC-17*, Copenhagen, Denmark, p.2586-2688 (2017).

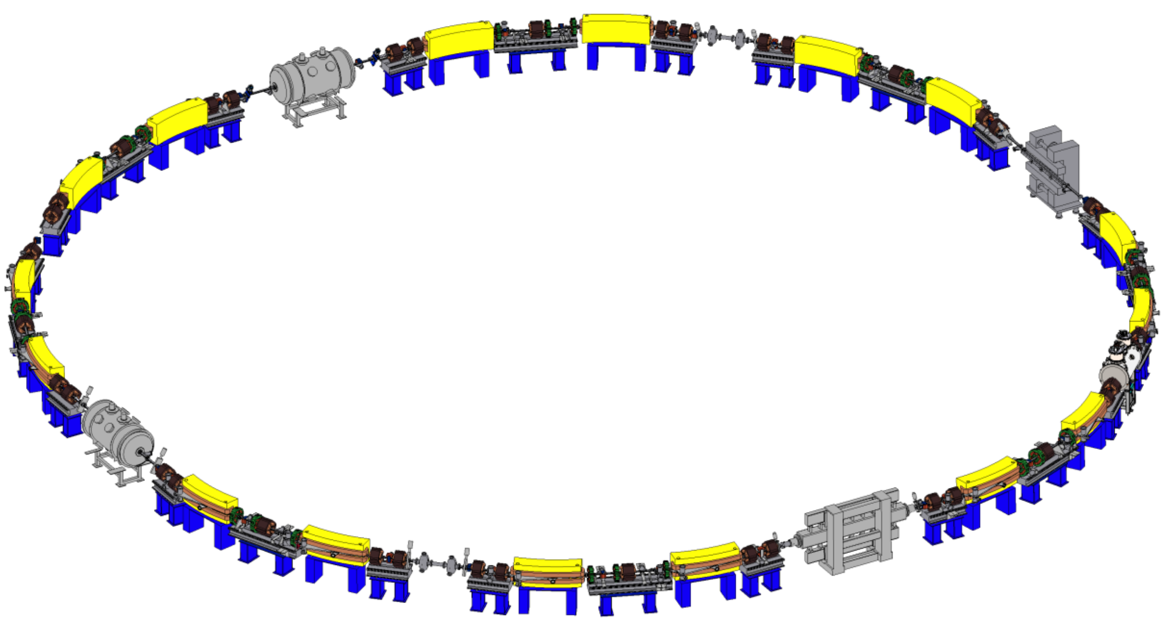
3. A. Papash, E. Blomley, M. Brosi, J. Gethmann, B. Kehrer, A.-S. Müller, P. Schönfeldt, M. Schuh and J. Steinmann, „Non-linear optics and low alpha operation at the storage ring KARA at KIT", *Proc. IPAC-18*, Vancouver, Canada, p.4235-4238 (2018)

4. P. Schreiber, T. Boltz, M. Brosi, B. Haerer, A. Mochihashi, A. Papash, M. Schuh and A.-S. Müller, „Status of operation with negative momentum compaction at KARA", *Proceed. IPAC-19,* Melbourne, Australia, p.878-881 (2019)

5. A. Papash, E. Blomley, T. Boltz, M. Brosi, E. Bründermann, S. Casalbuoni, J. Gethmann, E. Huttel, B. Kehrer, A. Mochihashi, A.-S. Müller, R. Ruprecht, P. Schreiber, M. Schuh and J. L. Steinmann, „New operation regimes at the storage ring KARA at KIT", *Proc. IPAC-19*, Melbourne, Australia, p.1422-1425 (2019)

KArlsruhe Research Accelerator
“KARA”
of the KIT
synchrotron light source





Parameters of KARA Ring and Beam

Table 1: Model parameters of KARA ring and beam

Parameter	**KARA**
Beam energy, GeV	0.5 to 2.5
Magnetic rigidity ***B·R***, T·m	1.67 to 8.339
Circumference, m	110.4
TME hor/vertical tunes Q_X / Q_Y	6.779 / 2.691
Mod **TME** tune operation Q_X / Q_Y	6.761 / **2.802**
Natural ε_x (nm·rad) **TME** / **DBA**	59 / 90
Long/short straight sections, m	5.604 / 2.236
Vacuum, tor / composition	10^{-9} / H_2+CO
Compact factor, –TME/mod TME –Low-α –Neg-α	$+9\cdot10^{-3}$ $+10^{-4}$ $-2\cdot10^{-3}$
RMS bunch length (user/low α), ps	21.6 / 2.4
Synch. frequency (user/low α), kHz	33.4 / 5
Natural Chromaticity ξ_X / ξ_Y	–12/–13
Chromaticity ξ_X/ξ_Y –TME –mod.TME –Low-α –Neg-α	+2/+6 +1/+1 +1/+1 –0.5/–6
SXT strength, Integrated, m^{-2} –TME –mod.TME –Low-α –Neg-α	+4.9 / –4 +4.3 / –3.3 +2.6 / –2 +2.3 / –1.5
RF frequency (MHz) / h_{RF}	500 / 184
CATACT / CLIC wiggler field, T	2.5 / 2.9
CATACT wiggler length / period	0.96 m / 48 mm
CLIC wiggler length / period	1.84 m / 51 mm
Residual oct. CATACT, $g_3(k_3\cdot L_W)$	≤120 T/m^3 (≤$20m^{-3}$)

Current/charge per bunch, mA/nC	(0.1÷1.5) / (0.037÷0.5)	
Damping time (hor/vert/long), ms	0.5 GeV	380/370/180
	2.5 GeV	3/3/1.5
SR Energy loss, keV/turn	1 (0.5) / 622 (2.5GeV)	
Natural energy spr. 0.5/2.5 GeV	$1.8\cdot10^{-4}$ / $9\cdot10^{-4}$	
Injected beam energy spread	$4\cdot10^{-4}$	
Injected beam emittance	150÷180 nm·r	

Span of Dispersion function is increased
from 0.7 m for TME lattice
up to 3 m for negative–α lattice

Table 2: Parameters of KARA optics at different operation conditions

Parameter	**modified TME**	**Low–α**	**Negative–α**
Comp. factor	**$\alpha = +9\cdot10^{-3}$**	**$\alpha = +1\cdot10^{-4}$**	**$\alpha = -7\cdot10^{-3}$**
Nat.emittance 0.5 GeV	2.4 nm·r	11.4 nm·r	18 nm·r
Nat.emittance 2.5GeV	58 nm·r	300 nm·r	460 nm·r
Dispersion	**+0.13…+0.71 m**	**–1.03…+1.44 m**	**–1.57…+1.65 m**
Natural width 0.5 GeV(rms)	σ_x=0.2 mm β_x=17 m	σ_x=0.5 mm β_x=22 m	σ_x=0.7 mm β_x=26 m
Inj.beam σ_x 0.5 GeV(rms)	σ_x=1.76 mm β_x=17 m	σ_x=2.03 mm β_x=22 m	σ_x=2.3 mm β_x=26 m
Natural width 2.5 GeV(rms)	σ_x=1.05 mm β_x=17 m	σ_x=2.7 mm β_x=22 m	σ_x=3.5 mm β_x=26 m

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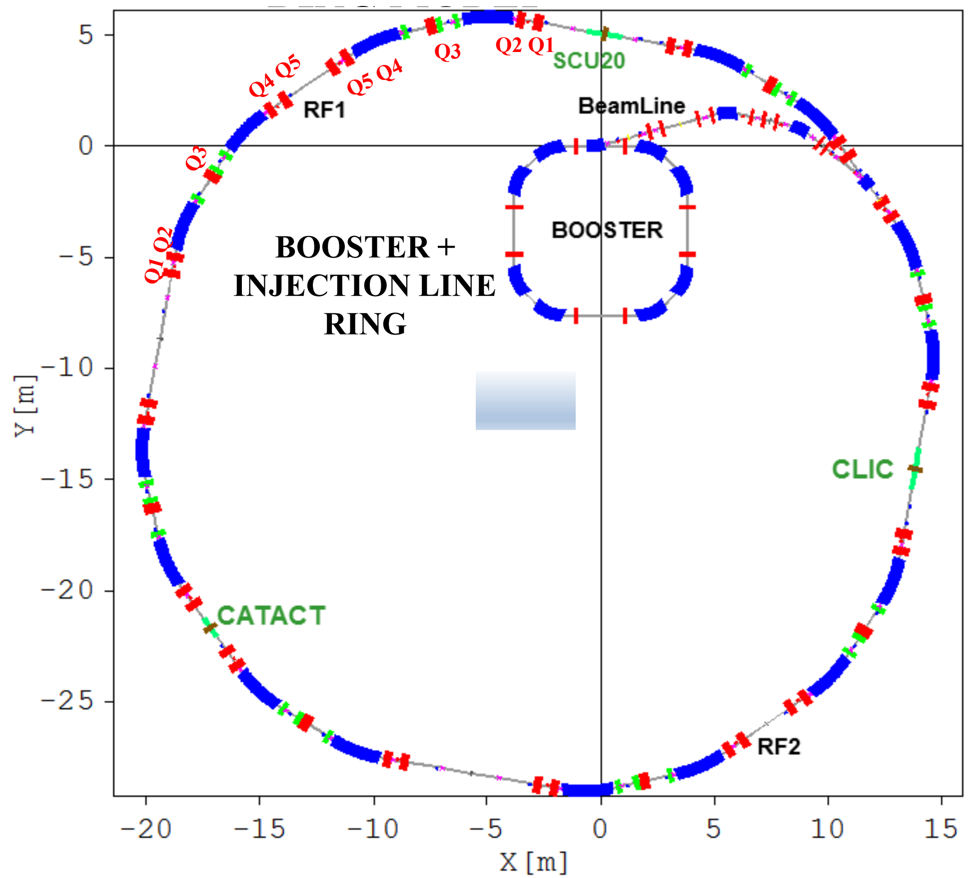
KARA Model

- KARA ring -- **four-fold** symmetry
- **8** double bend achromat sections (DBA)
- **16** bending magnets 22.5°
- **8** families of quads –
- **5** lenses at each family

- **4 long** and **4 short** straight sections are occupied by insertion devices (ID), RF stations, injection system
- flexible lattice allows a **variety** of operation regimes
- the **TME** mode with distributed dispersion **ε_x=56 nm**
- the **DBA** achromat (*D=0* in straights) **ε_x=87 nm**
- At present a **modified TME** optics with **high** vertical tune (**Q_y=2.81**) is applied for **USER** operation
- Beam up to 200 mA is stored and ramped from 0.5 to desired energy up to 2.5 GeV (**USER**)
- **Low–α** and **negative–α** operation modes - MP studies
- **Single**- and **multi**-bunch regimes – are available for all operation modes



- Computer model of ring, booster and injection line includes all magnetic elements, correctors, BPM, inj/extr kickers, septums, ID, collimators etc.
- The **computer code OPA** is used to simulate linear and high order dynamics at different operation modes

USER operation modes. Beam Current up to 200 mA, α= +9.3E-3

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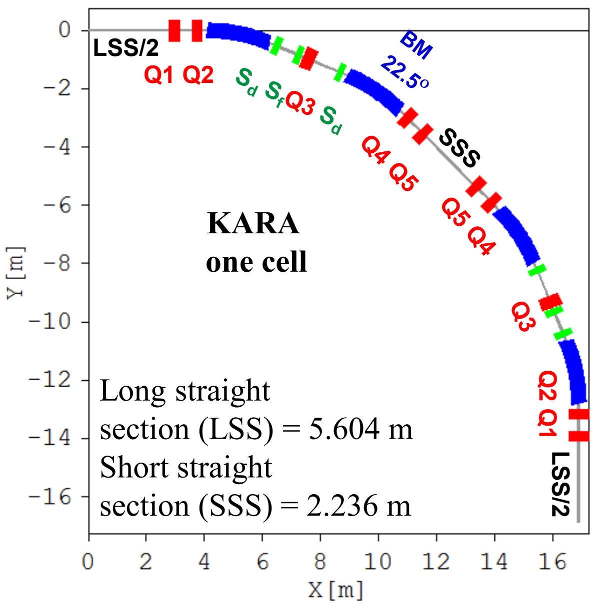
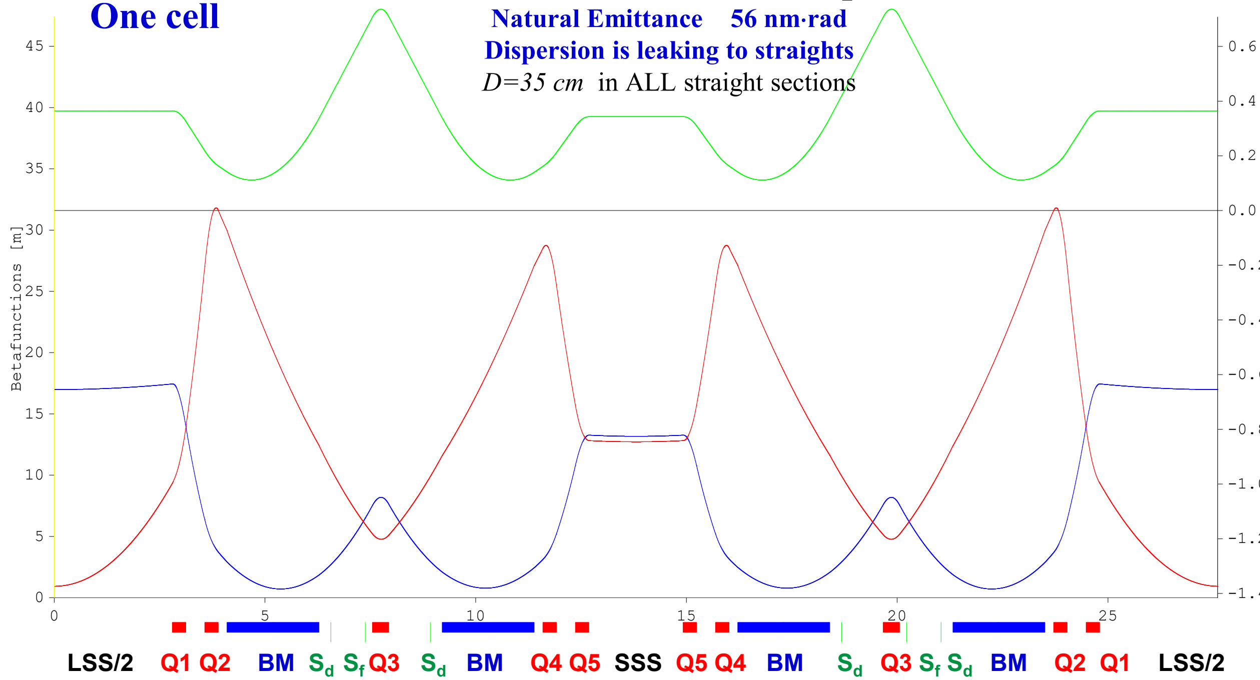
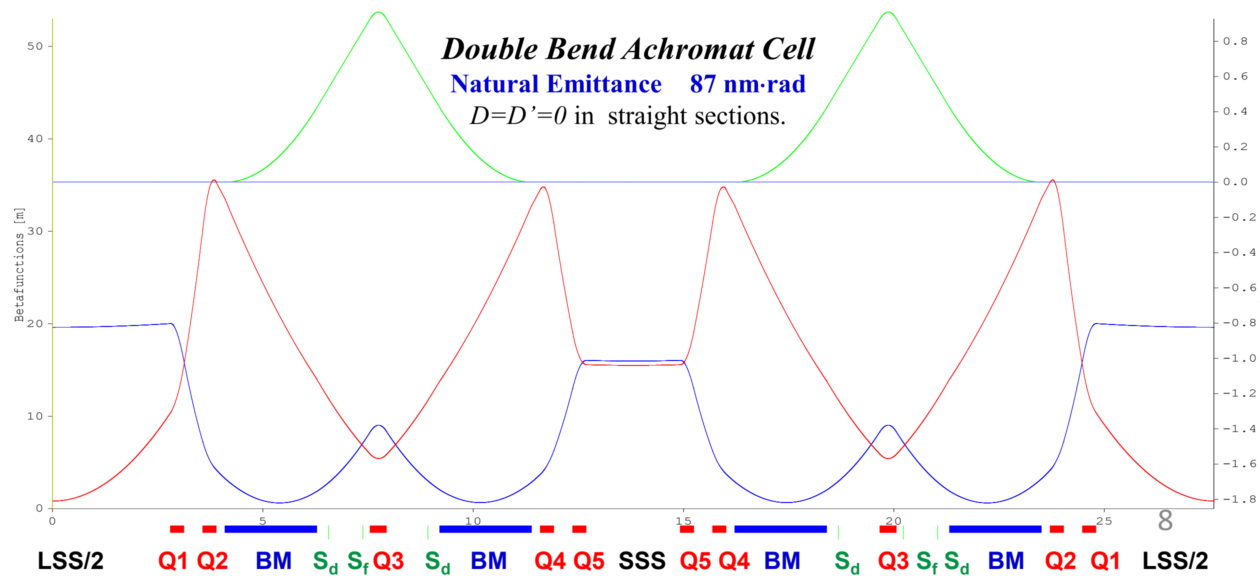
Ring lattice
One cell



TME Cell with Distributed Dispersion





- First, the 0.5 GeV beam from the booster is injected into a ring with TME/DBA optics and accumulated
- Second, beam is accumulated
- Third, stored beam is ramped to desired energy

Blue – horizontal betatron function
Red – vertical betatron function
Green - Dispersion

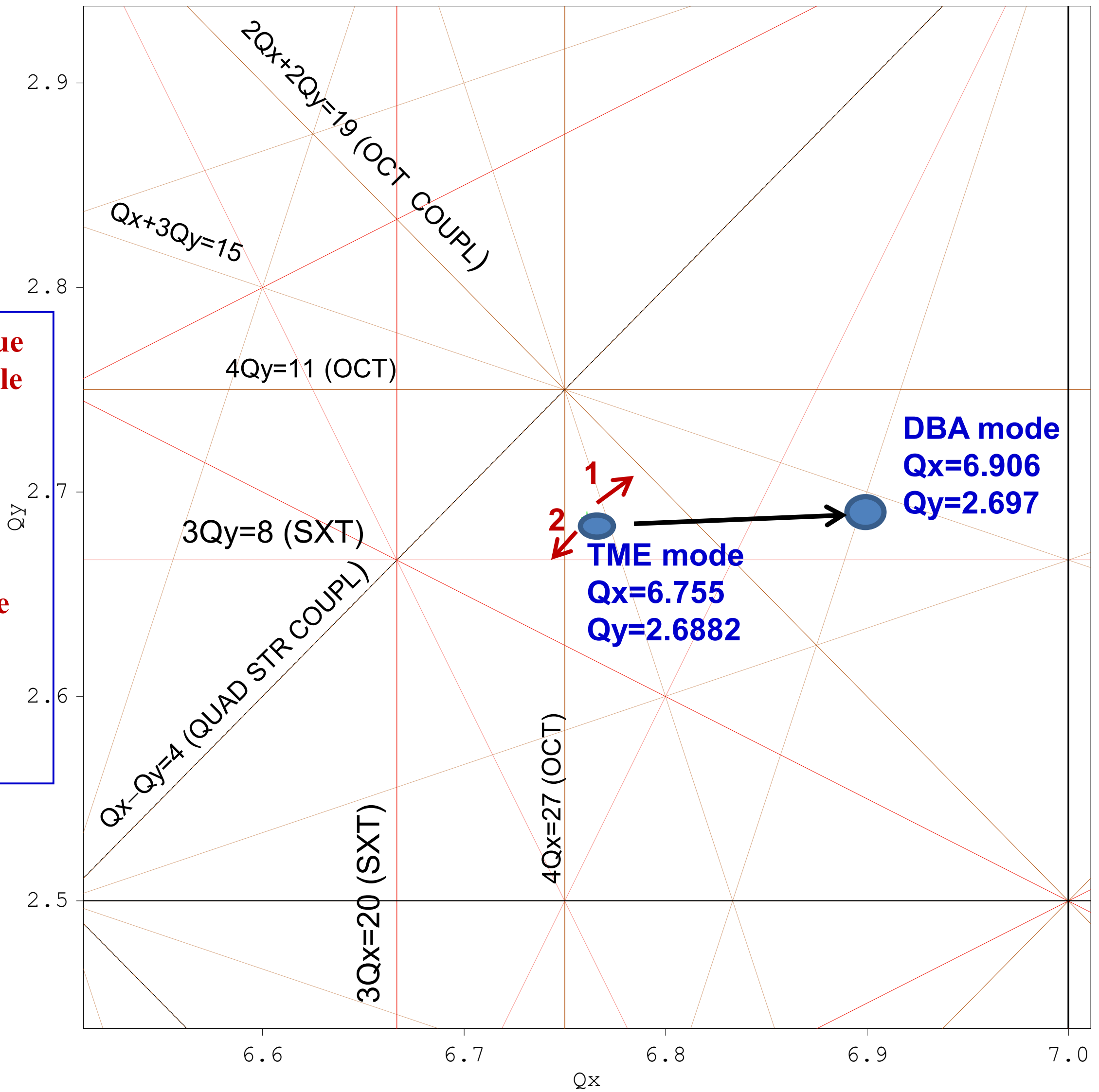
Betatron tune diagram of KARA ring

"On-line" transition of ring from TME to DBA lattice have been realized during CLIC tests

Tune diagram – up to 4[th] order incl. Skew resonances

1– reduced life time due to proximity of octupole Resonance excited by CATACT at high field (B=2.2-2.5 T)

2 – unstable operation close to SXT resonance Strong sextupoles create Large stop-band of resonance



Measured tunes are close to simulated one

Transition is accomplished by simultaneous Increase of quads current In order to keep tune ABOVE SXT resonance

Q3=+282.8…+294 A

Q3=+2.06….+2.14 m^{-2}

Q2= –366….–371 A

Q2= –2.26…–2.29 m^{-2}

- **Wiggler in KARA Model**

- PM wigglers, SC Undulator and two high field SC wigglers, namely, CATACT and CLIC are installed and operate at KARA ring

- The CATACT and CLIC wigglers are described in the KARA Model by **linear** approximation with dimensions and fields corresponding to the actual values

- The CLIC wiggler is located in the **long** straight section of KARA ring where the vertical betatron function is **small** (**βy < 0.8m**). Coherent shift of vertical tune is negligible (**ΔQy < 2.E-4)** and it is not compensated

- The CATACT wiggler is located in the **short** straight section of KARA ring where the vertical betatron function is **high** (**βy =13 m**) and coherent shift of the vertical betatron tune due to over-focusing at high field of CATACT wiggler (B_{CAT}=2.5 T) is **high** -- **$\Delta Q_Y \approx +0.04$**

- tune shift due to beam overfocusing by CATAC field is compensated to original value by **local reduction** of the strength of defocusing quadrupoles around the CATACT wiggler, (Pair of Q4 quads ahead and behind CATACT) exactly as in tests of the device

Transition to modified TME lattice
high vertical tune Qy=2.801

Motivation

- even though the coherent shift of the vertical betatron tune due to over-focusing by the CATACT wiggler poles was compensated locally
- and residual octupole components of wiggler does not exceed the design values
- A **lifetime** **reduction** from $T_{1/2}$=15 hours down to 12 hours was observed
- during the ramp of the **CATACT** wiggler at field level >**2.2 T**
- The **CLIC** wiggler does not influence the lifetime of the beam, even at high field level (**B_{CLIC}=2.9 T**) and without any compensation coils

CATACT SC wiggler at KARA hall

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- **Overfocusing in vertical plane caused by wiggler might be desribed**
  - **by coherent shift of vertical betatron tune to higher values.**
- **Shift is proporitonal to the value of the vertical beta-function averaged at wiggler location**

$$\Delta \nu_y = \frac{1}{8\pi}\left(B_w / B \cdot R\right)^2 \cdot L_w \cdot \overline{\beta}_y$$

Few methods to compensate beam over-focusing caused by wigglers

1) **LOCAL CORECTION – local REDUCTION of strength of vertical quads located around the wiggler. Tune is restored to original value while settings of other magnetic elements unchanged**

2) **GLOBAL correction. INCREASE strength of vertical quadrupoles to create minimum of vertical beta at wiggler position and limit beam distortion in vertical plane (reduce coherent tune shift and minimize beta-bit) caused by wiggler. -- Parameters of other quads MUST BE adjusted in order to COMPENSATE over-focusing in vertical plane**

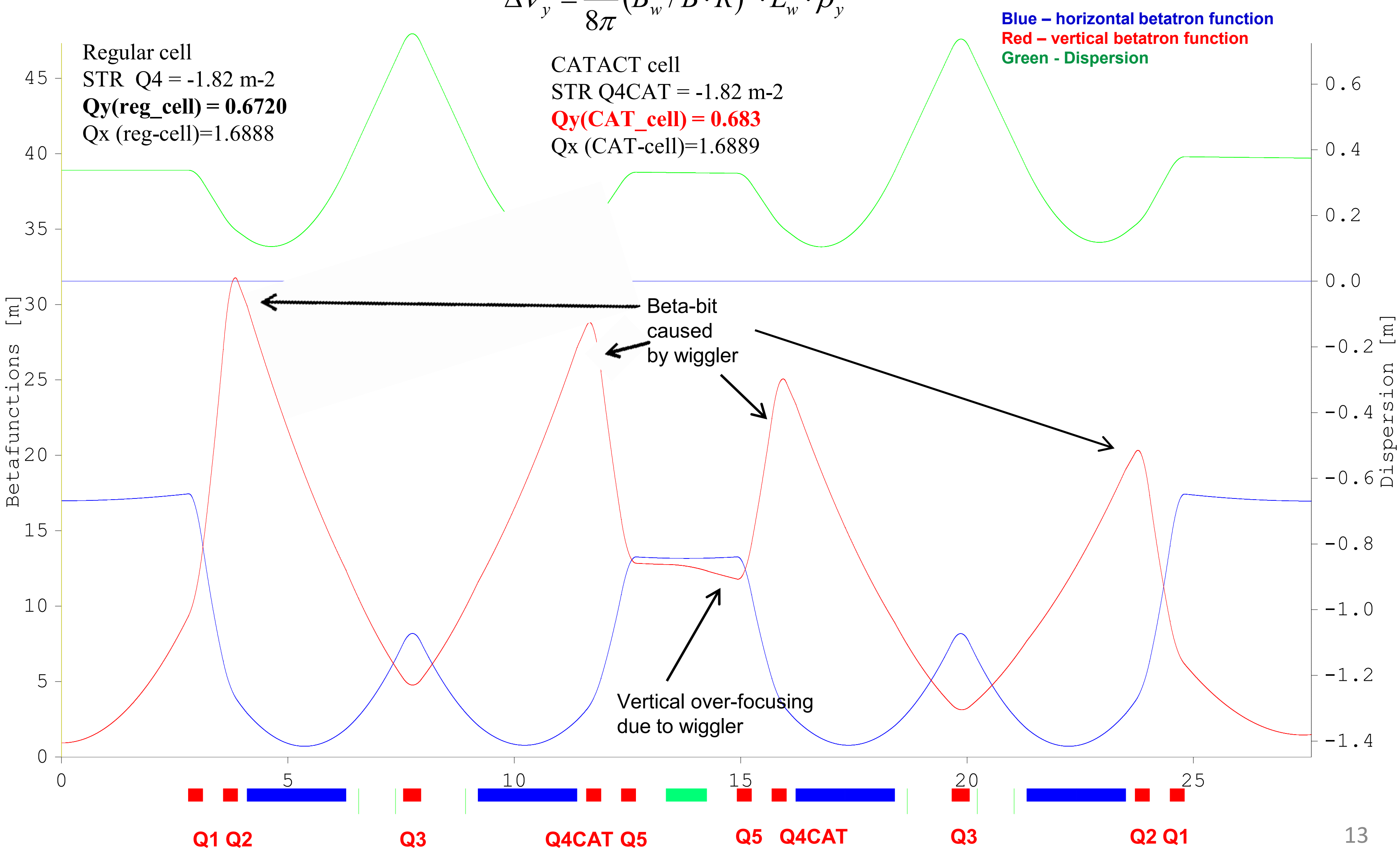
- **Option (2) is applied at MAX-IV 3 GeV ring where value of βy in the long straight sections is high (βy=5m) and life time of a beam would be limited by small gaps of permanent magnet wigglers (4 mm). Local reduction of βy at position of wigglers benefits beam life time**

- **Option (1) is applied at KARA**

KARA lattice. CATACT ON B=2.5 T
Tune shift BEFORE COMPENSATION

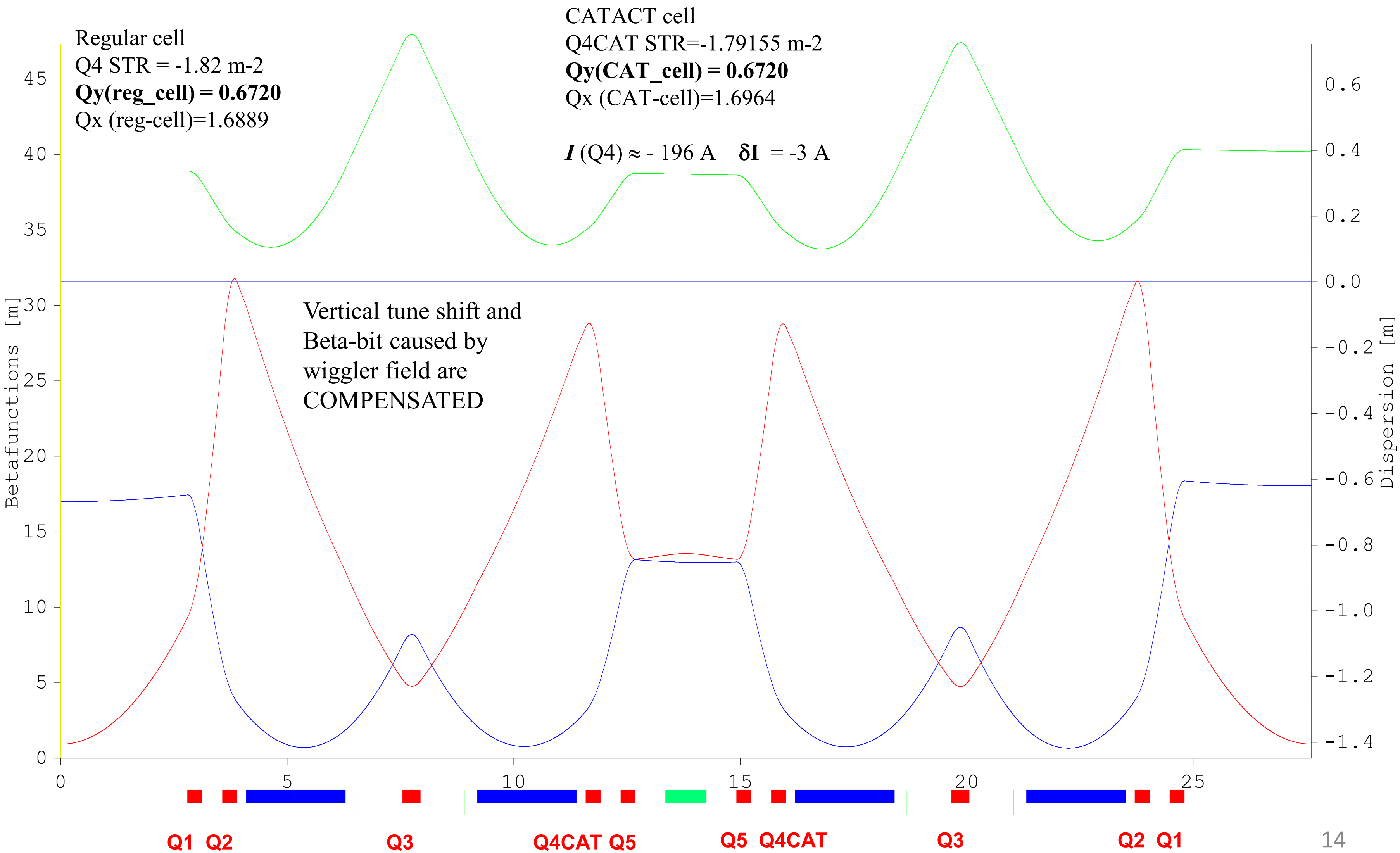
wiggler field cause local over-focusing in vertical direction, vertical tune shift and beta-bit
Local compensation of vertical tune shift should be applied

$$\Delta \nu_y = \frac{1}{8\pi}(B_w / B \cdot R)^2 \cdot L_w \cdot \overline{\beta}_y$$



CATACT Wiggler field B=2.5 T. Tune shift is COMPENSATED

LOCAL compensation of vertical tune shift is accomplished
by REDUCTION of strength of vertical quads located around the wiggler



Dynamic Aperture of KARA ring

at USER operation

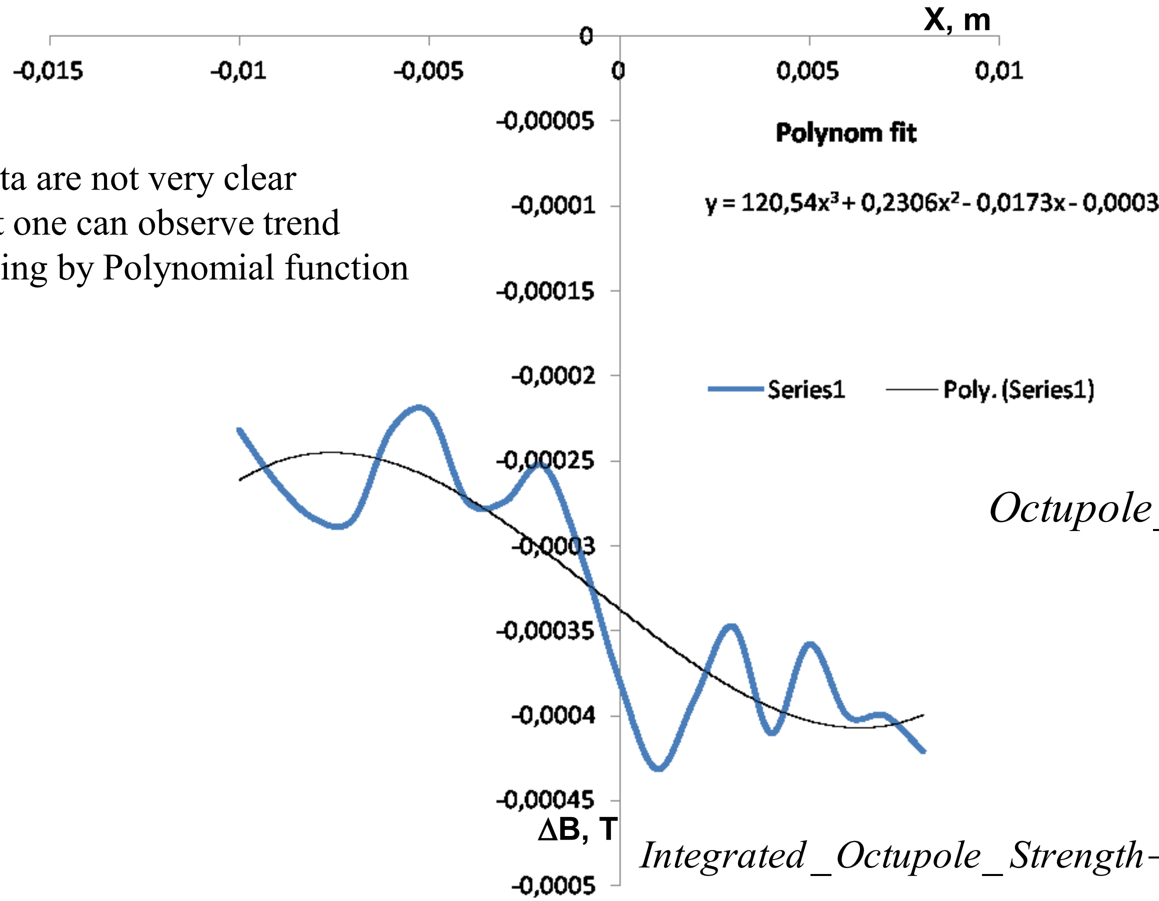
and

influence of high order components

of wiggler residual field

Measurements of the CATACT magnetic field

(CATACT FAT report, Budker INP, Dec 2013)



Data are not very clear
but one can observe trend
fitting by Polynomial function

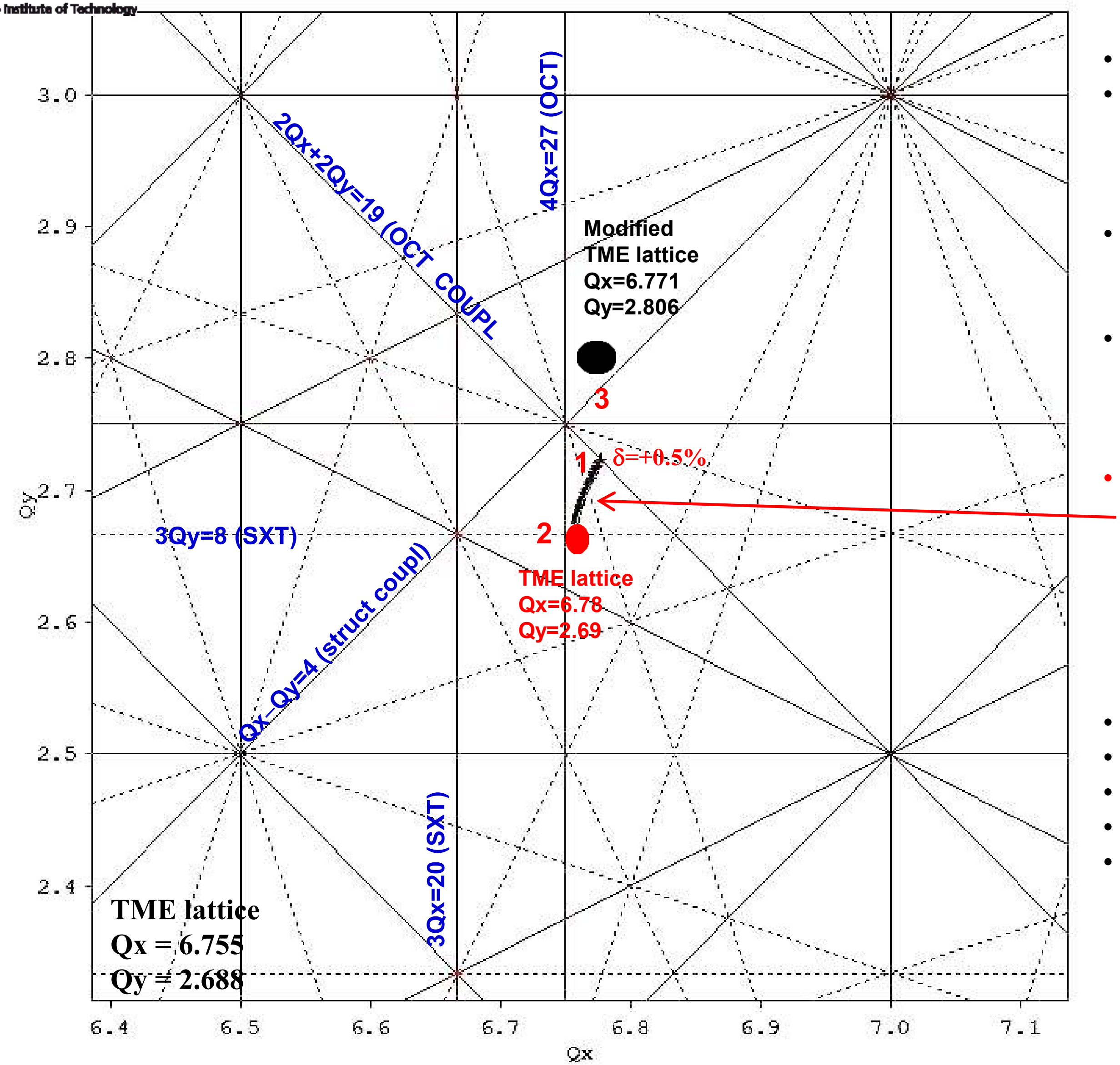
$$Octupole\_Gradient - \left(\frac{\partial^3 B}{\partial y^3} = 120 T/m^3 \right)$$

$$Integrated\_Octupole\_Strength - \left(K_{OCT} \cdot L_w = \left(\frac{1}{B \cdot R} \right) \cdot \frac{\partial^3 B}{\partial y^3} \cdot L_w \approx 15 m^{-3} \right)$$

RESIDUAL Integrated Octupole gradient of CATACT wiggler measured during BINP Factory tests does not exceed tolerances set by design specifications

GRADIENT(oct)·L < 100 T/m²

Tune diagram of KARA ring. TME lattice at high chroma



- TME lattice. Ring operation at
- Qy=2.69 is suffered from proximity to SXT resonance
  - Qy=8/3 (2,667)

- Also coupling octupole resonance is excited by CATACT wiggler at B>2 T

- TME lattice. Ring operates at **high positive CHR +2/+6** to supress HEAD-TAIL instability

- **Tune shift at HIGH chromaticity +2/+6 push OFF-MOMENTUM particles towards high order resonance driven by residual octupole component of CATACT wiggler field. Particles with momentum offset cross OCT RES**

- Cure:
- reduced chromaticity (+1,+1)
- and modified TME lattice at
- high vertical tune (Qy=2.801)
- limits influence of SXT/OCT reasonances

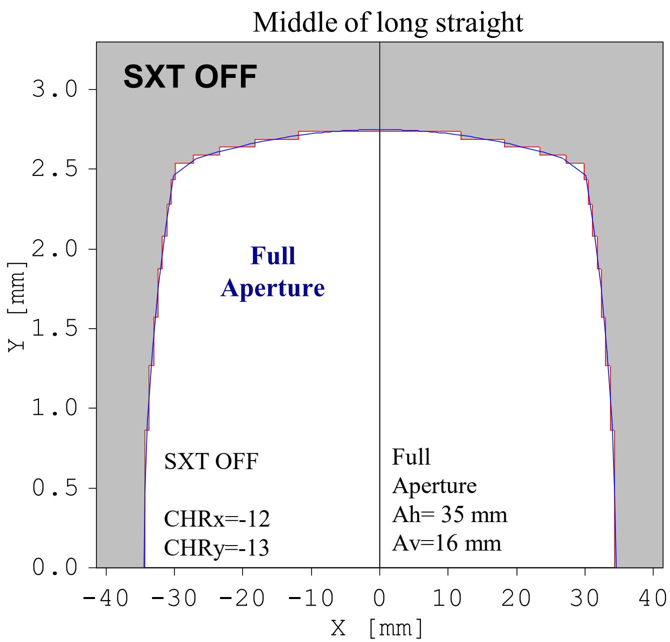
Tune diagram –
up to 4th order incl.
Skew resonances

1 – reduced life time
Cross coupl Oct Res
for off-mom. δ=+0.5%
excited by CATACT
at B >2 T and

2 – unstable operation
close to SXT resonance
Strong sextupoles create
Large stop-band
of resonance

3 -- Reduction of life time
Cross coupl Str res
Qx-Qy=4
Excited by field Errors
& misalignments of
QUADRUPOLES

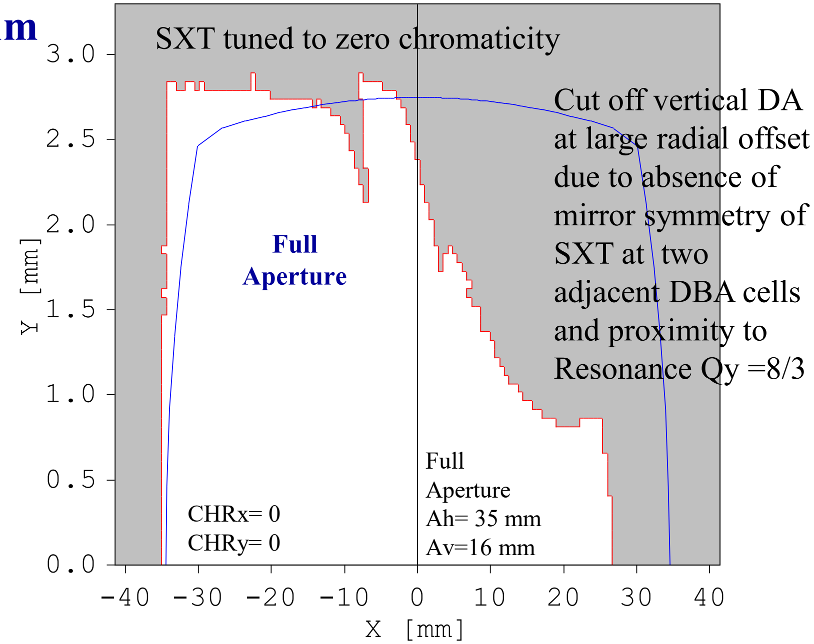
Dynamic Aperture of KARA ring
TME lattice
ON-momentum

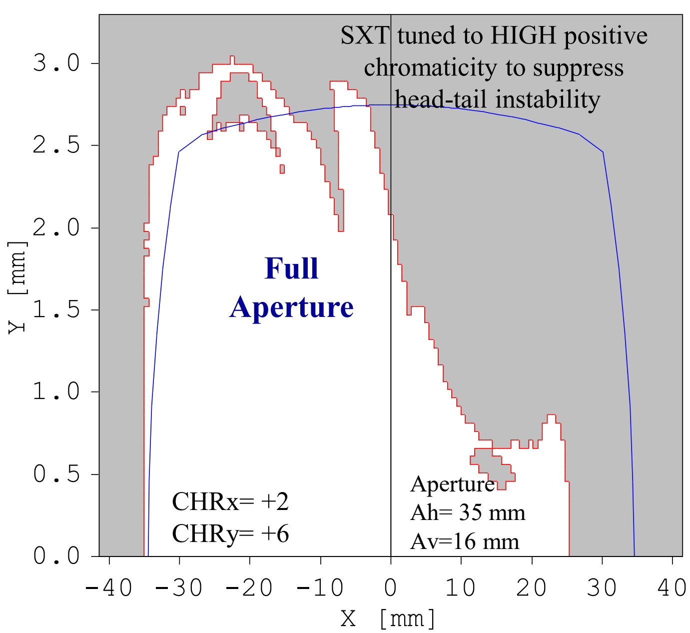


CATACT OFF

Qx=6.755
Qy=2.688

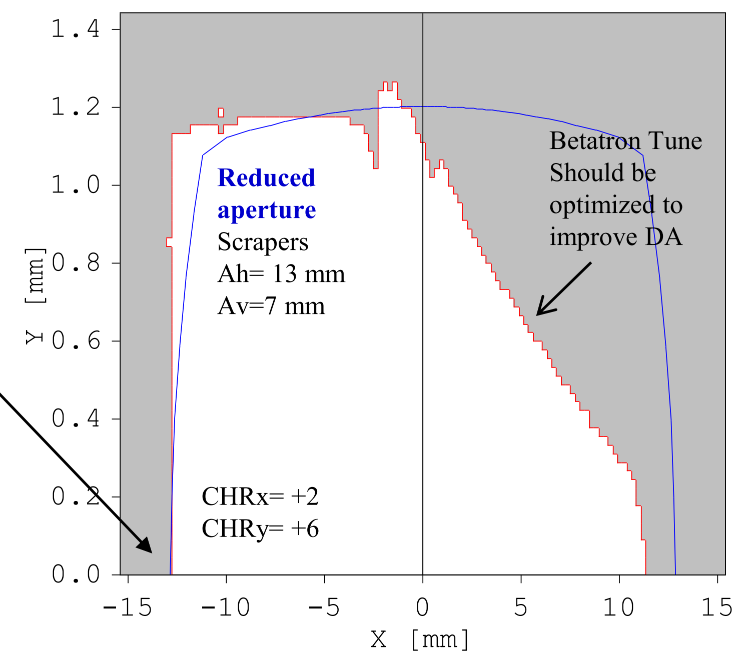
Blue polygon – contour of vacuum chamber normalized to the max value of beta-function





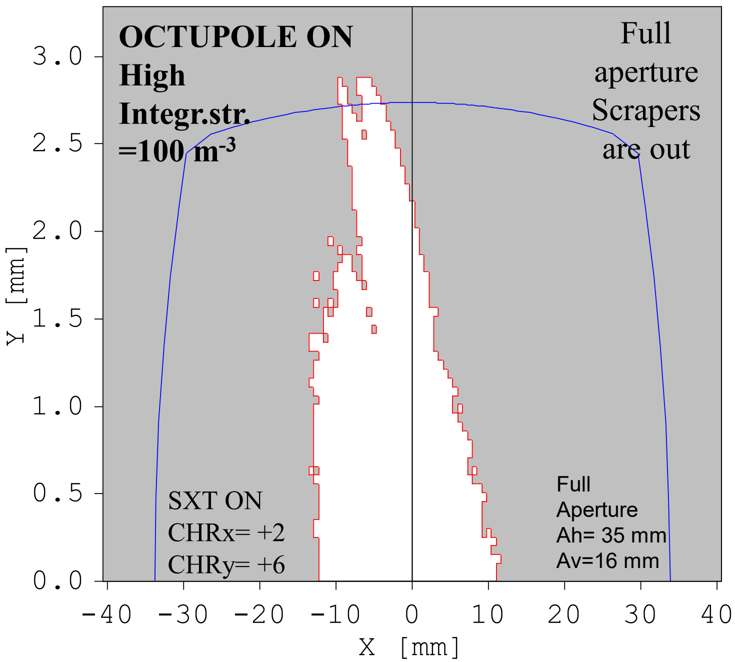
Scrapers reduce vacuum chamber aperture

Ah= 13 mm
Av=7 mm



Dynamic Aperture
TME lattice Qy=2.688
ON-momentum

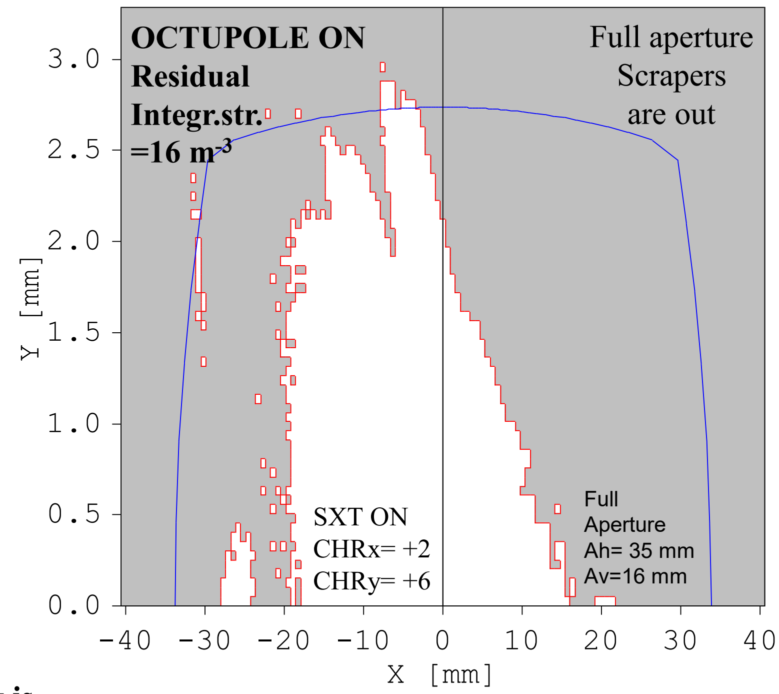
On-momentum DA Δp=0

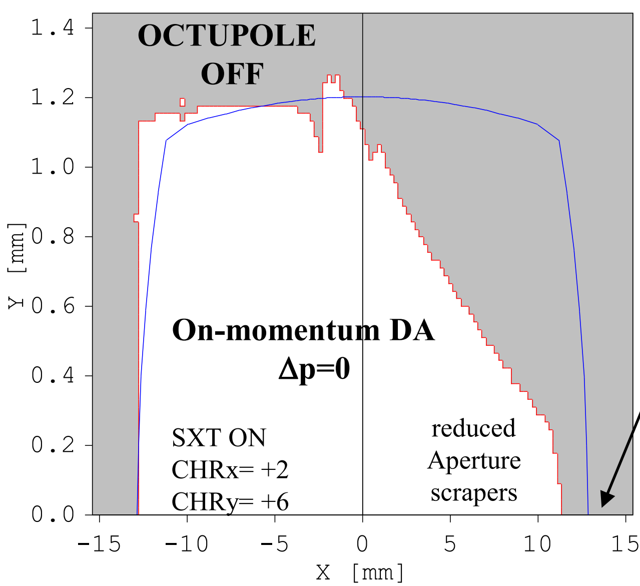


CATACT ON
B= 2.5 T

In case of large deviation off ring axis (ΔX > 15 mm) **HIGH (100m-3)** Octupole component of magnetic field drastically reduces Dynamic Aperture (and life time) due to ADTS

On-momentum DA Δp=0

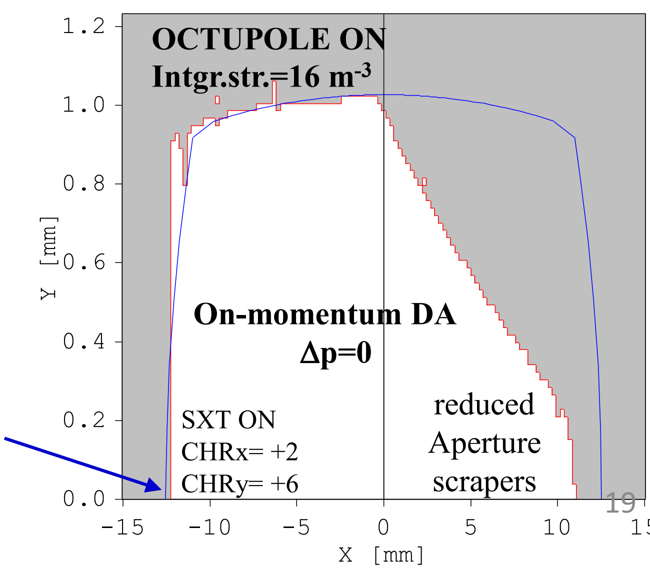




DA of KARA ring is already limited by scrapers reducing aperture to Ah= 13 mm Av=7 mm

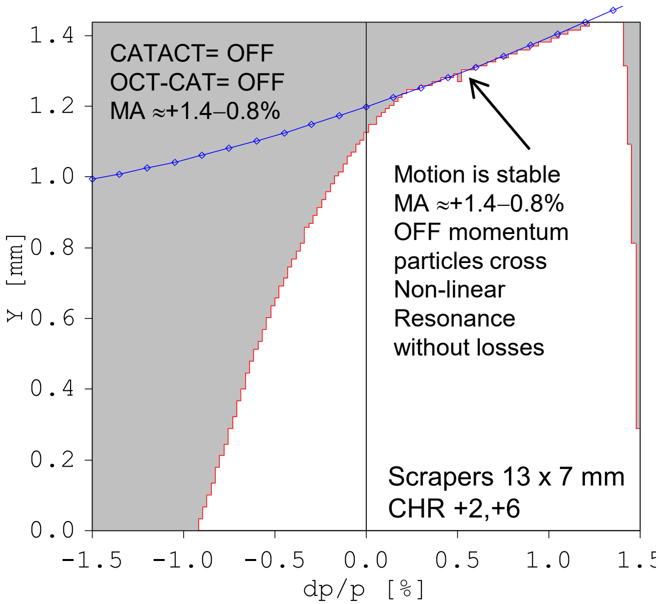
Effect of WEAK (16 m-3) residual OCTUPOLE component of CATACT field is NOT VISIBLE for ON-momentum particles

BUT !



Momentum acceptance of KARA ring
TME lattice Qy=2.688

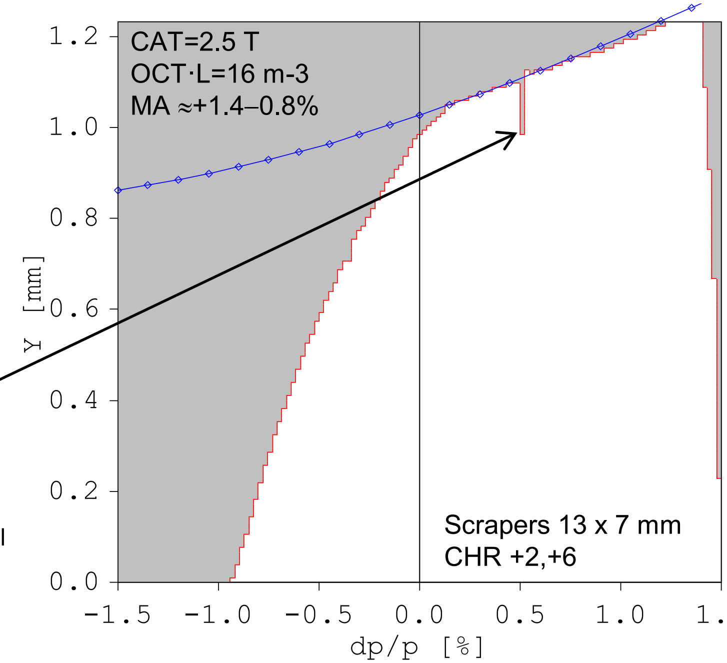
OFF-momentum

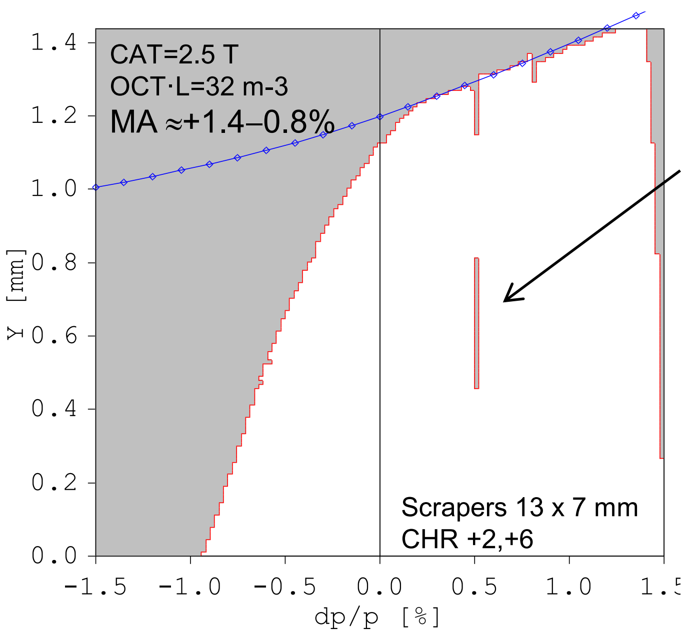


CATACT ON
B= 2.5 T

Resonance
2Qx+2Qy=19
driven by octupole
Field component
appears
for OFF-Momentum
particles at
δp/p≈+0.5%

Octupole strength
does not exceed
tolerances on residual
components set by
CATACT specs

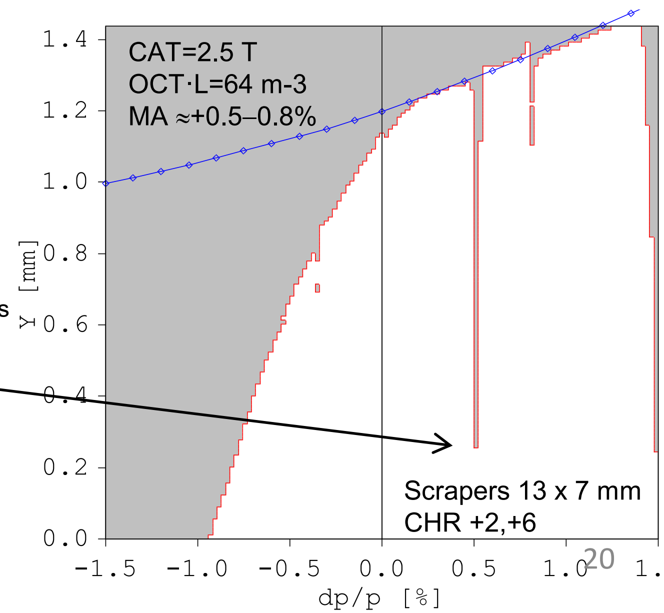




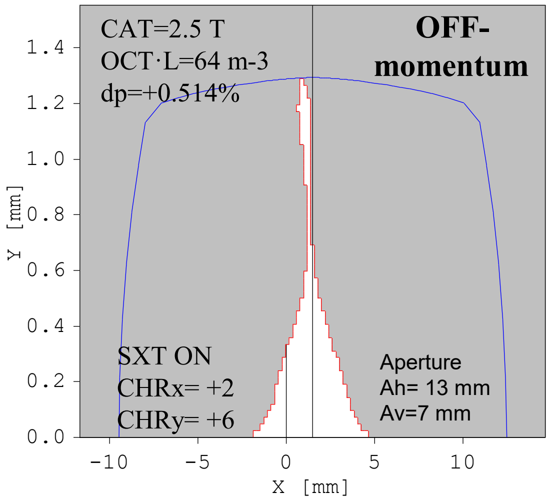
for OFF-Momentum
particles at
δp/p =+0.5%
Resonance
grows at high octupole
strength

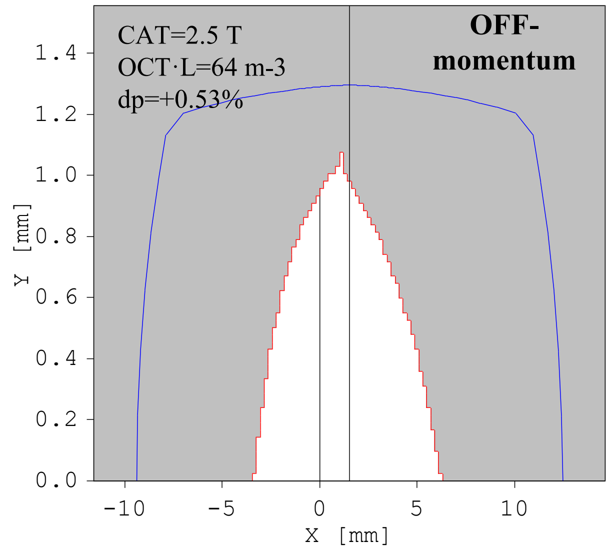
At high Strength
of octupoles components
drive resonance
2Qx+2Qy=19

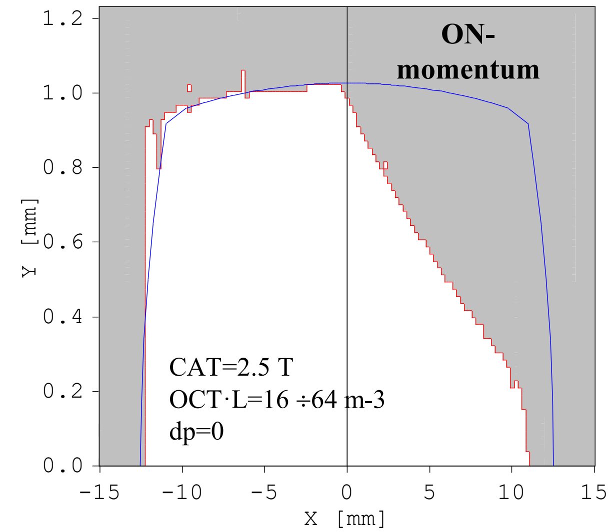
The DA is SHRUNK
to < 0.2 mm
for OFF-Momentum
particles δp/p =+0.5%



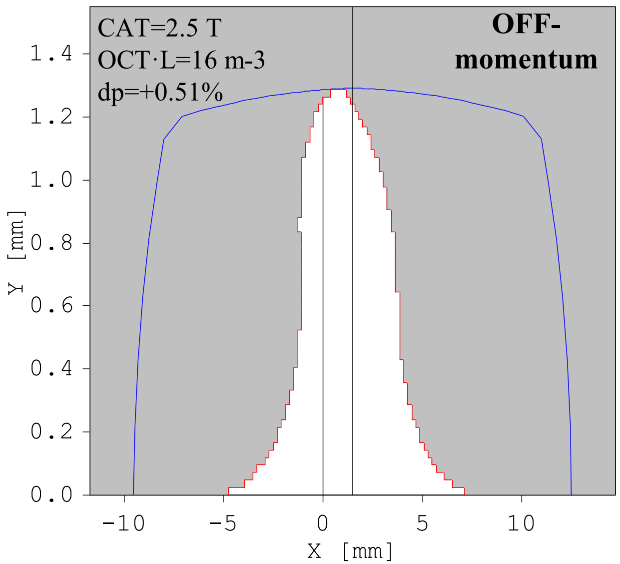
DA at different momentum offsets. TME lattice Qy=2.688
CATACT ON. B= 2.5 T

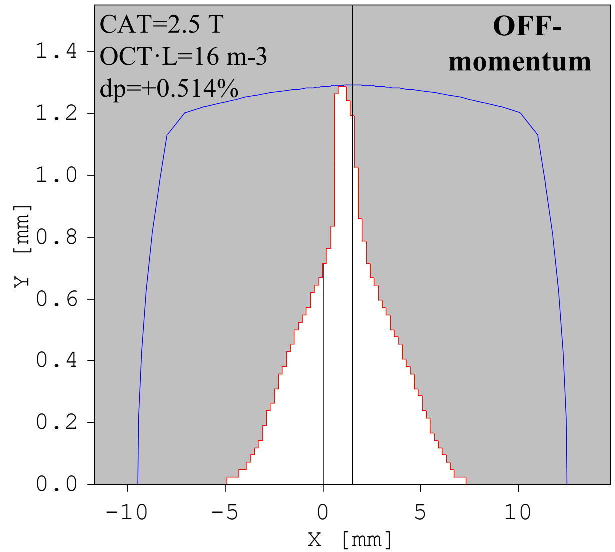


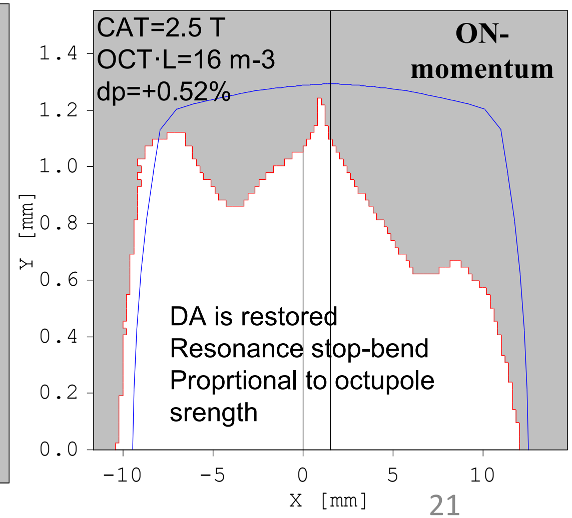




- IF strength of Octupole component exceeds tolerance in few times the OFF –momentum DA might srhinks to Zero and beam might be LOST.
- Life time of beam is defined at high beam current by Touschek inelastic scattering with large momentum deviation
- while KARA acceptacne is limited by RF to <±1%.
- At high chromaticity the OCTUPOLE resonance appears at dp=+0.51% when off-momentum DA shrinks but not to ZERO







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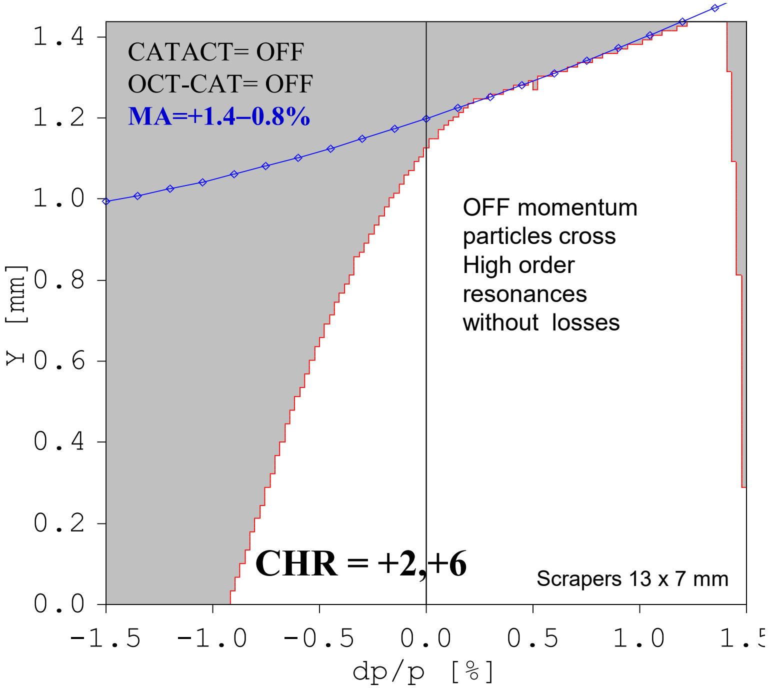
Momentum acceptance. TME lattice Qy=2.688
Effect of Chromaticity



CATACT ON
B= 2.5 T

Qy = 2.688

Resonance
2Qx+2Q=19
Driven by octupole
Component of CATACT
shrinks DA for particles
with momentum offset

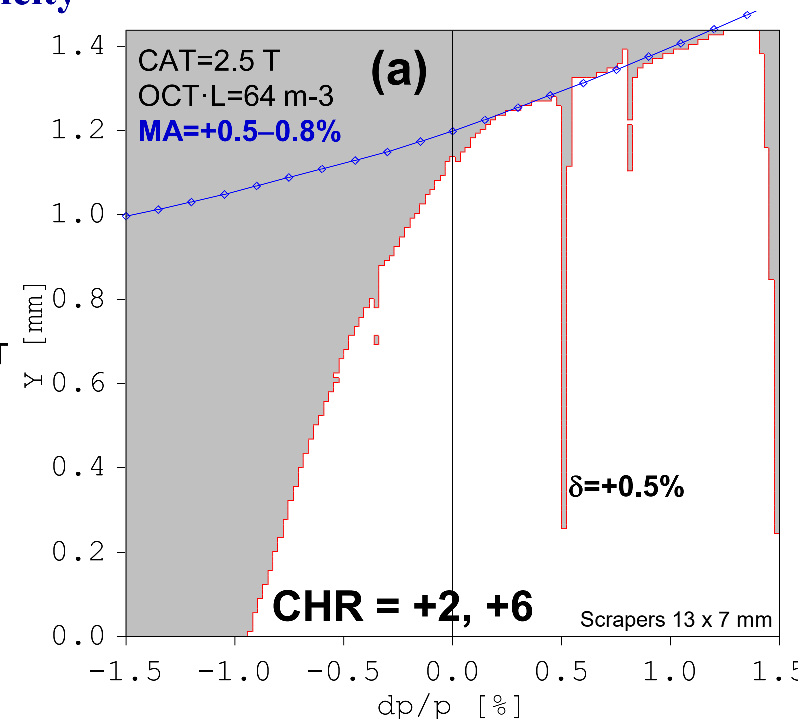
(a) δp/p = +0.51%
CHR = +2,+6

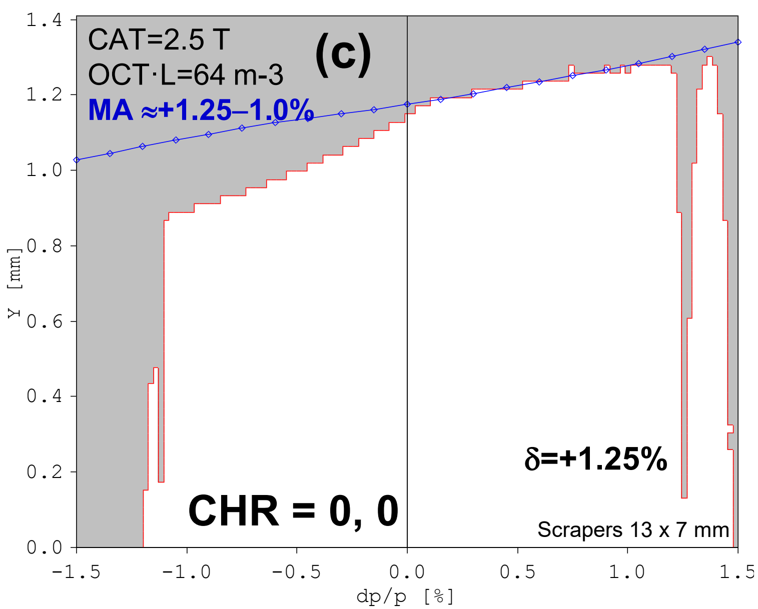
(b) δp/p = +0.9%
CHR = +1,+1

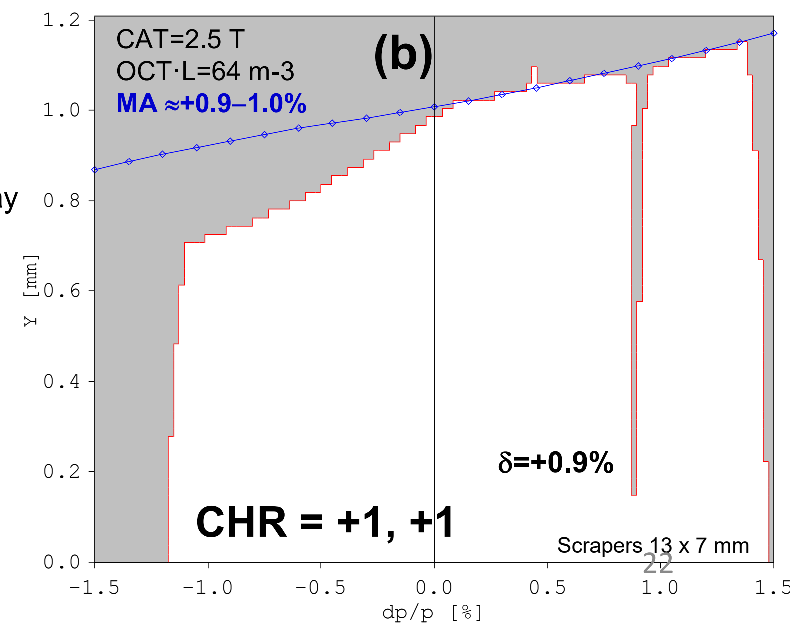
(c) δp/p = +1.24%
CHR = 0, 0

When Chromaticity
is reduced
the Momentum offset of
resonance is shifted away
From reference energy

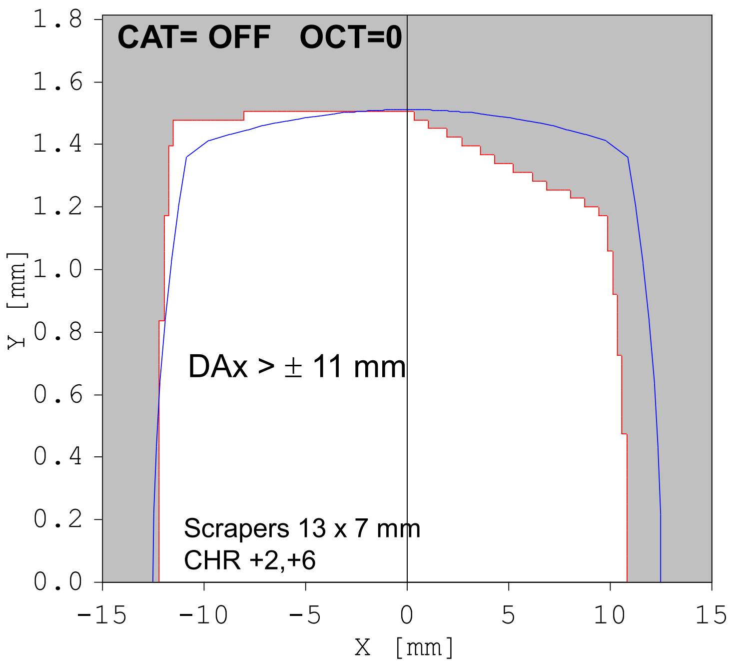
The life time is
RESTORED
by reducing
of Chromaticity
at 2.5 GeV and
Feedback ON
while CATACT
at top field level
B=2.5 T







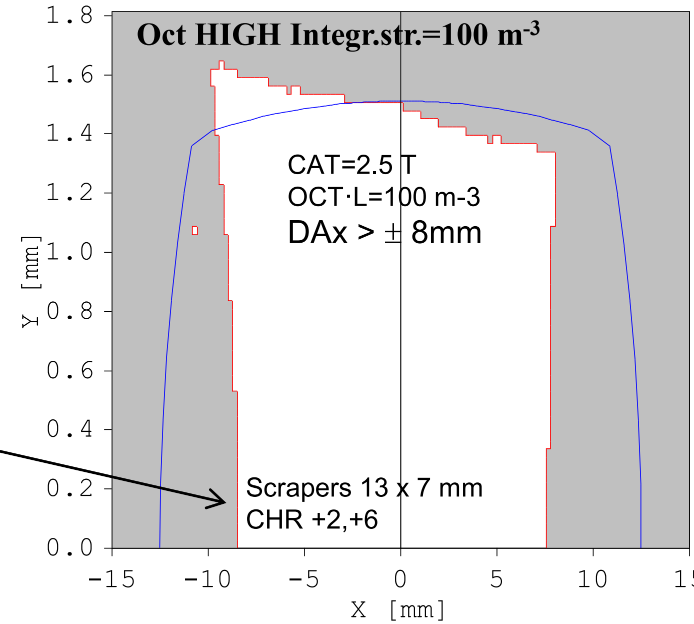
Dynamic Aperture. ON-momentum modified TME lattice Qy=2.801

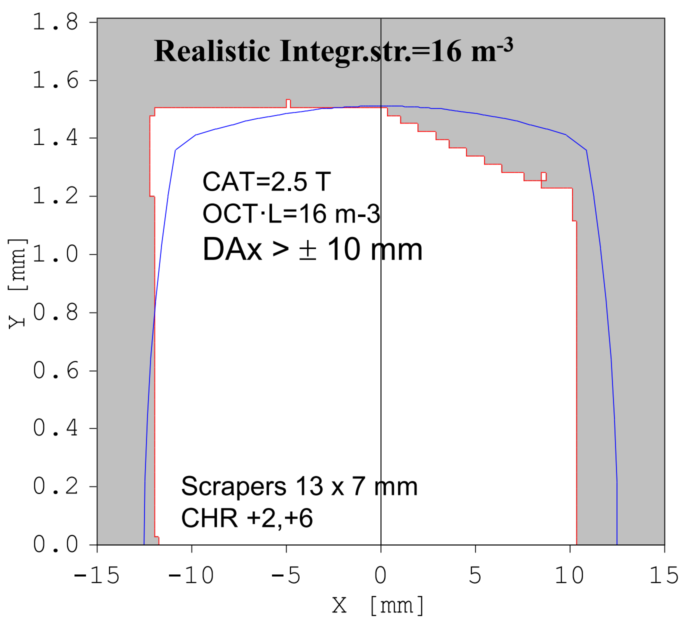


CATACT ON
B= 2.5 T

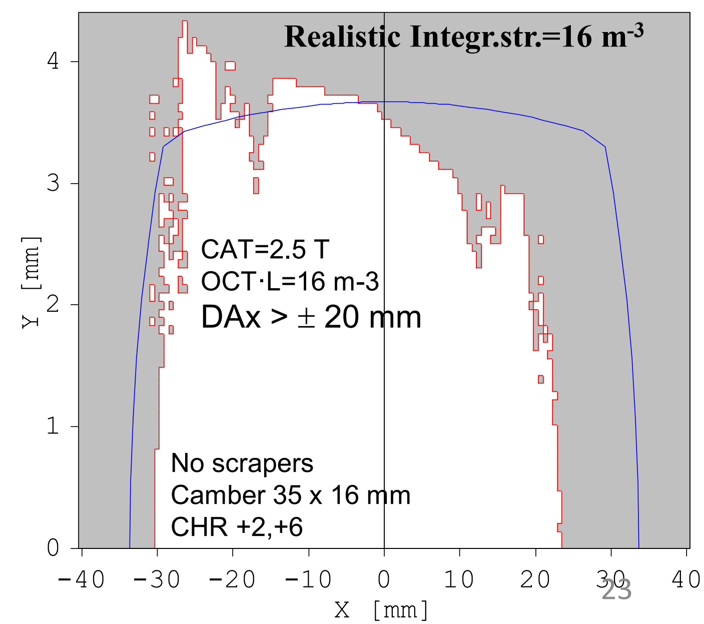
High tune
Qy = 2.801

Life time might be Slightly reduced at high integr. octupole OCT·L > 100 m-3





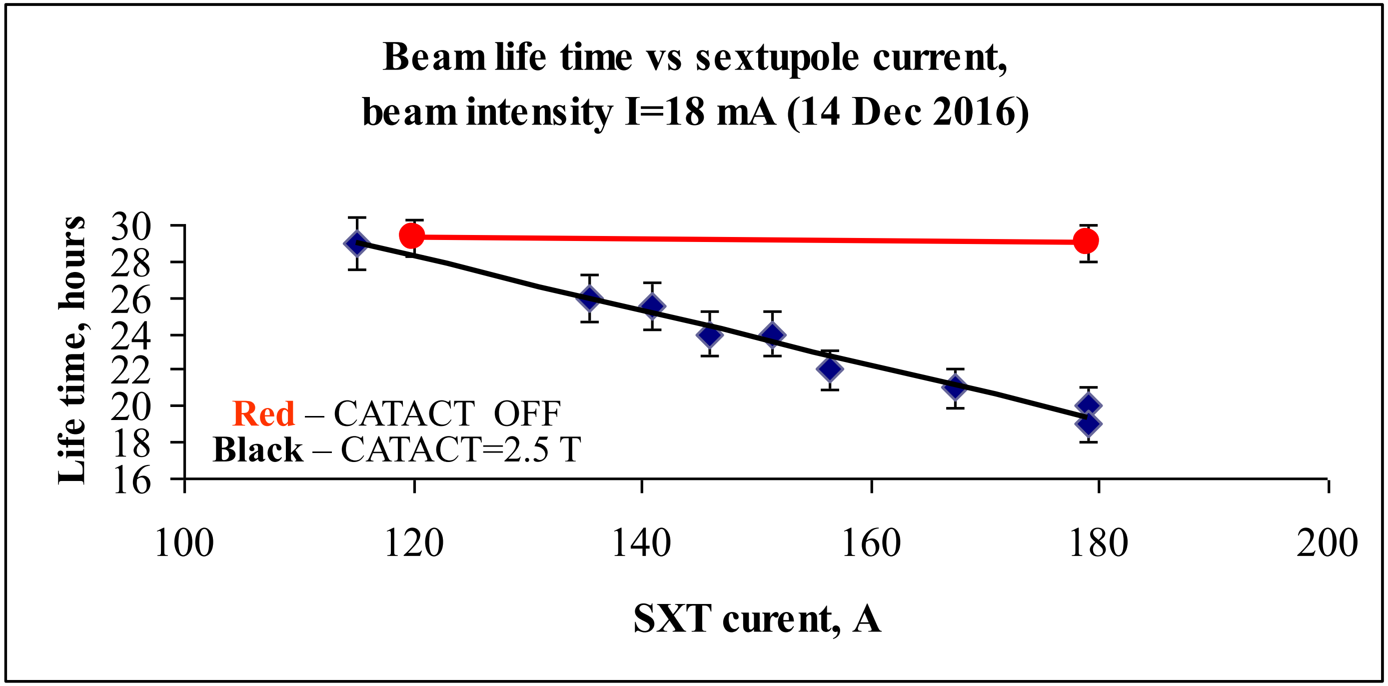
At
Hight tune
no CATACT
neither CLIC
with small residual
octupole components
set by tolerances
OCT*L< 100T/m3
will NOT restrict
ring operation



Ring tests. Variation of chromaticity

Life time measurements at 2.5 GeV

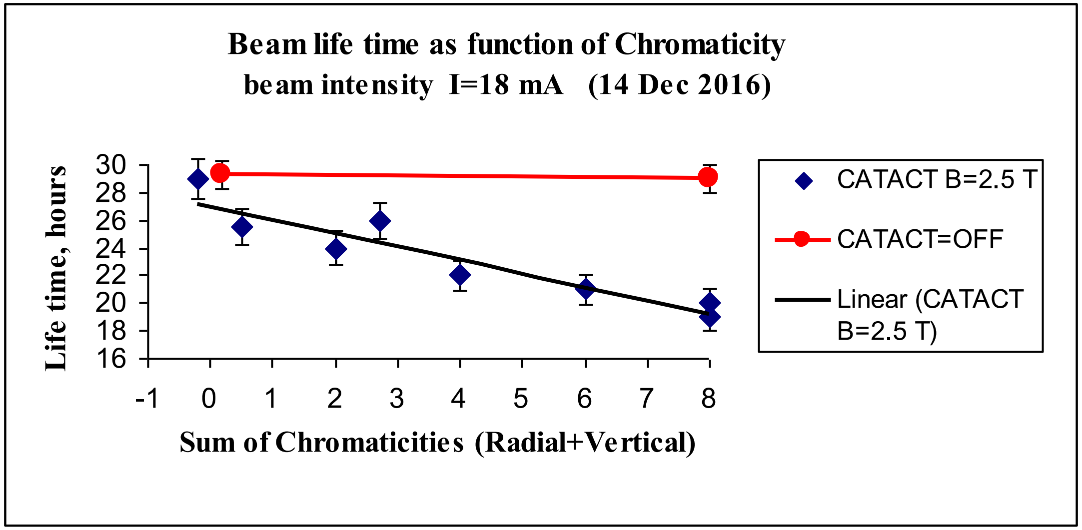
TME lattice Qy=2.69



Life time (hours) as function of current of vertical sextupole.
I=18 mA. Beam tests 15 Dec 2016

- Increasing of current of vertical sextupoles leads to growth of vertical chromaticity
- At high chromaticity particles on **halo** of energy distribution hit octupoles resonance
- excited by residual octupole component of CATACT wiggler at high field level B>2.2 T
- At higher chroma less momentum offset to hit OCT resonance. More particles are lost
- Life time is reduced

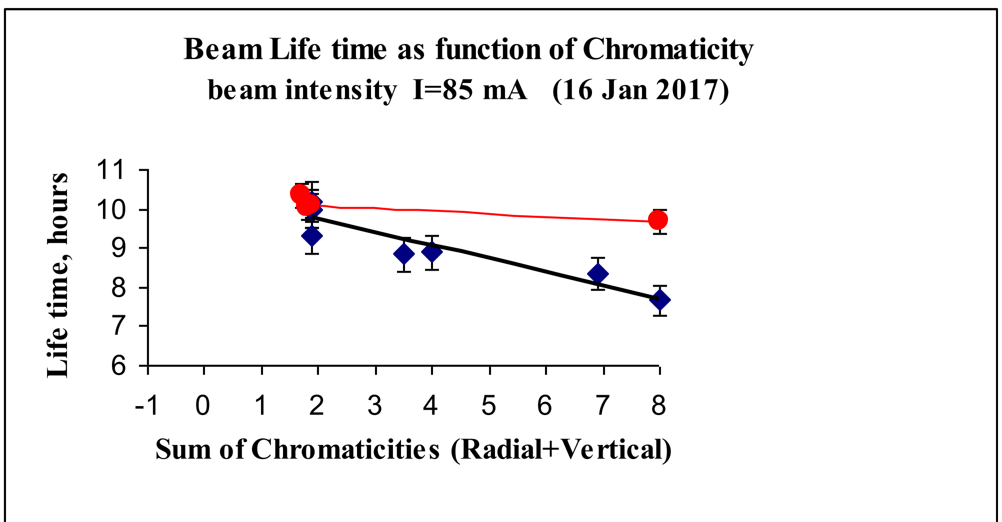
Ring tests. Life time measurements.
TME lattice. 2.5 GeV   Qy=2.69



Red – **CATACT OFF**
Blue – **CATACT=2.5 T**

Dependence of Life time on chromaticity (sum of CHR=$\xi x + \xi y$). E=2.5 GeV.

Beam current 18 mA   Beam tests 15 Dec 2016



Red – **CATACT OFF**
Blue –**CATACT=2.5 T**

Life time as function of chromaticity (total=$\xi x + \xi y$). E=2.5 GeV.

Beam current = 85 mA   Beam tests 16 Jan 2017

Measures to counteract life time reduction caused by residual high order components of magnetic field of wiggler

- **Shift working point** to avoid crossing of octupole resonance 2Qx+2Qy=19 for particles with momentum offset less than ±1%

- **Reduce chromaticity** to +1 +1 to shift ersonance conditions away of working point

- „**Resonance scan**“ at BESSY helps to define parasitic

- skew quadrupole field due to WGL by Crossing   Qx+Qy = N

- pseudo Octupole field by crossing 4Qy=N

- pseudo skew octupole components by crossing 2Qx+2Qy=M

- M=19 in case of KARA ring

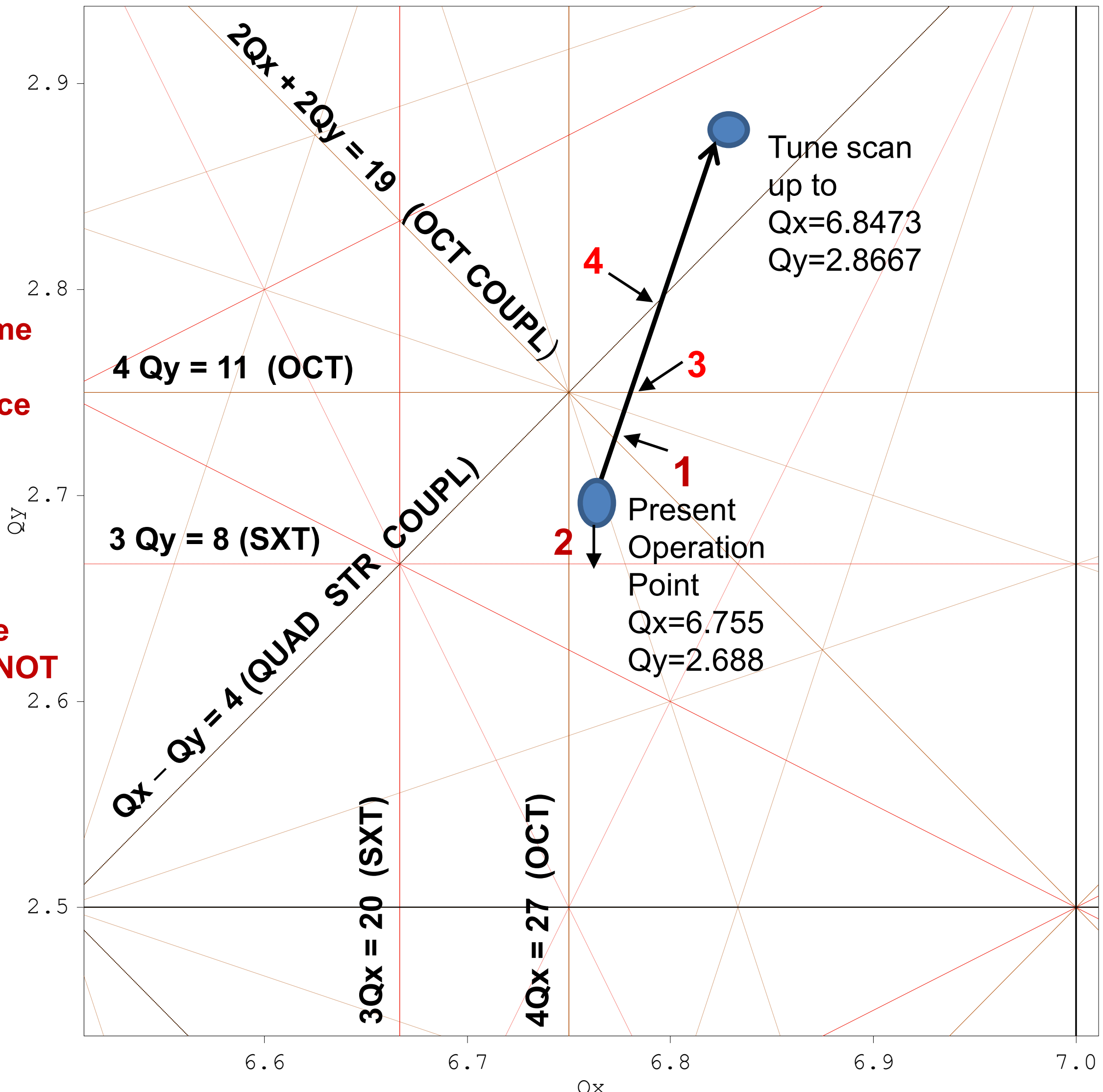
Resonance scan of betatron tunes

Ring tests 15, 16 Feb 2017

Betatron tunes were scanned from low to high values and life time has been measured

3

reduction of life time while crossing octupole Resonance
4Qy=11
is NOT observed because of the CATACT field is FLAT in horizontal plane and octupole component does NOT produced in X direction



1– reduced life time while Crossing coupled Octupole Resonance
2Qx+2Qy=19
excited by CATACT at high field level (B=2.2-2.5 T)

2 – unstable operation close to SXT resonance Strong sextupoles create Large stop-band of resonance

4

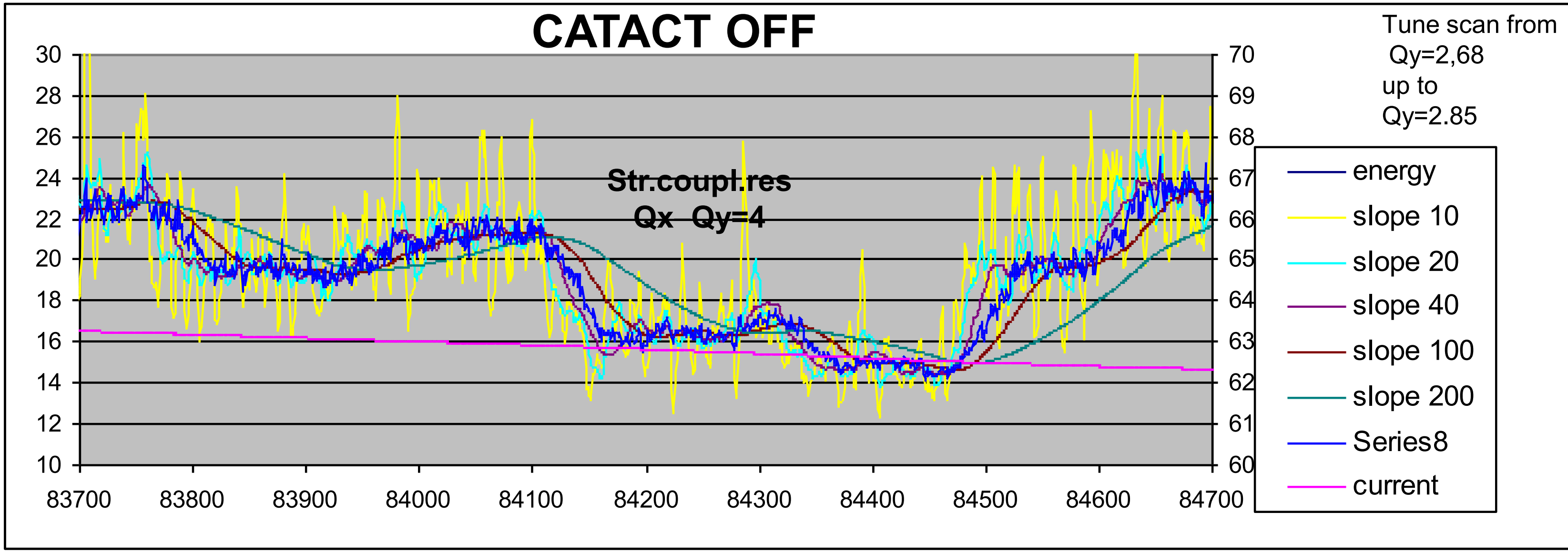
Reduction of life time While crossing coupled Structure resonance
Qx-Qy=4
Excited by field Errors & misalignments of QUADRUPOLES

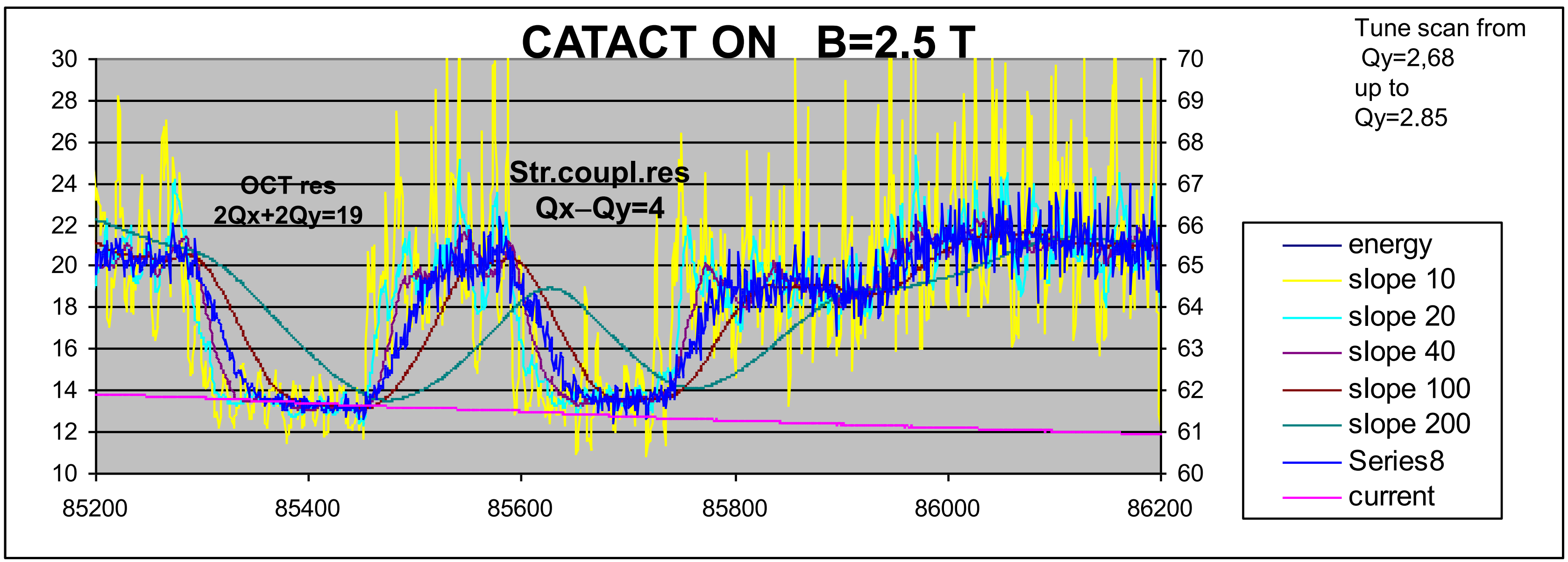
Tune diagram – up to 4th order incl. Skew resonances

Life time during "Resonance scan"

Data acquisition at high chromaticity +2,+6

2.5 GeV

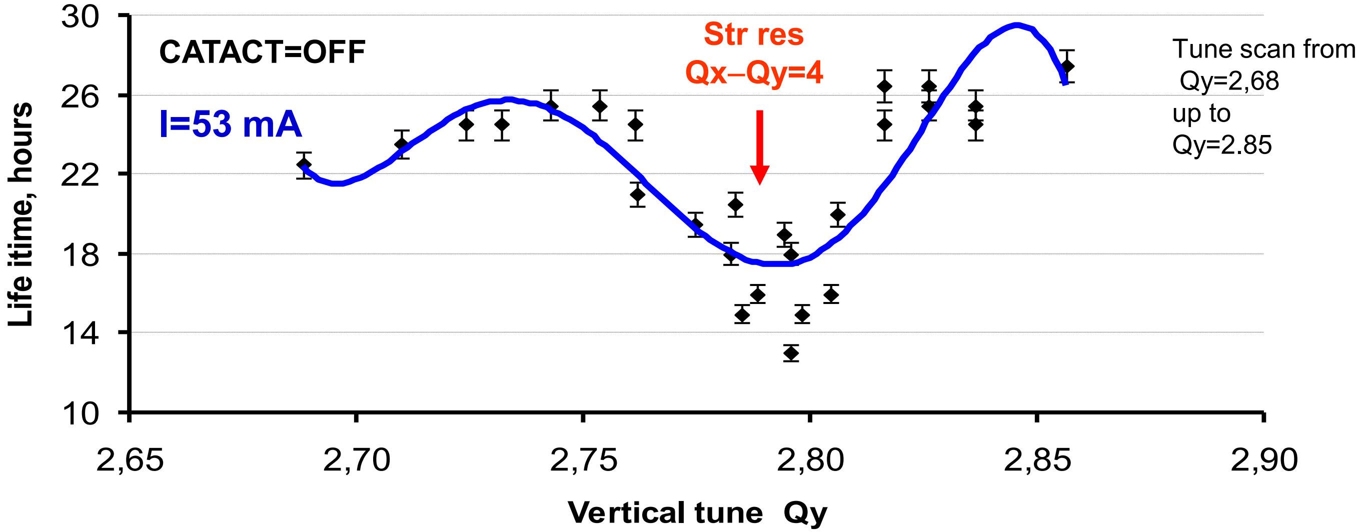


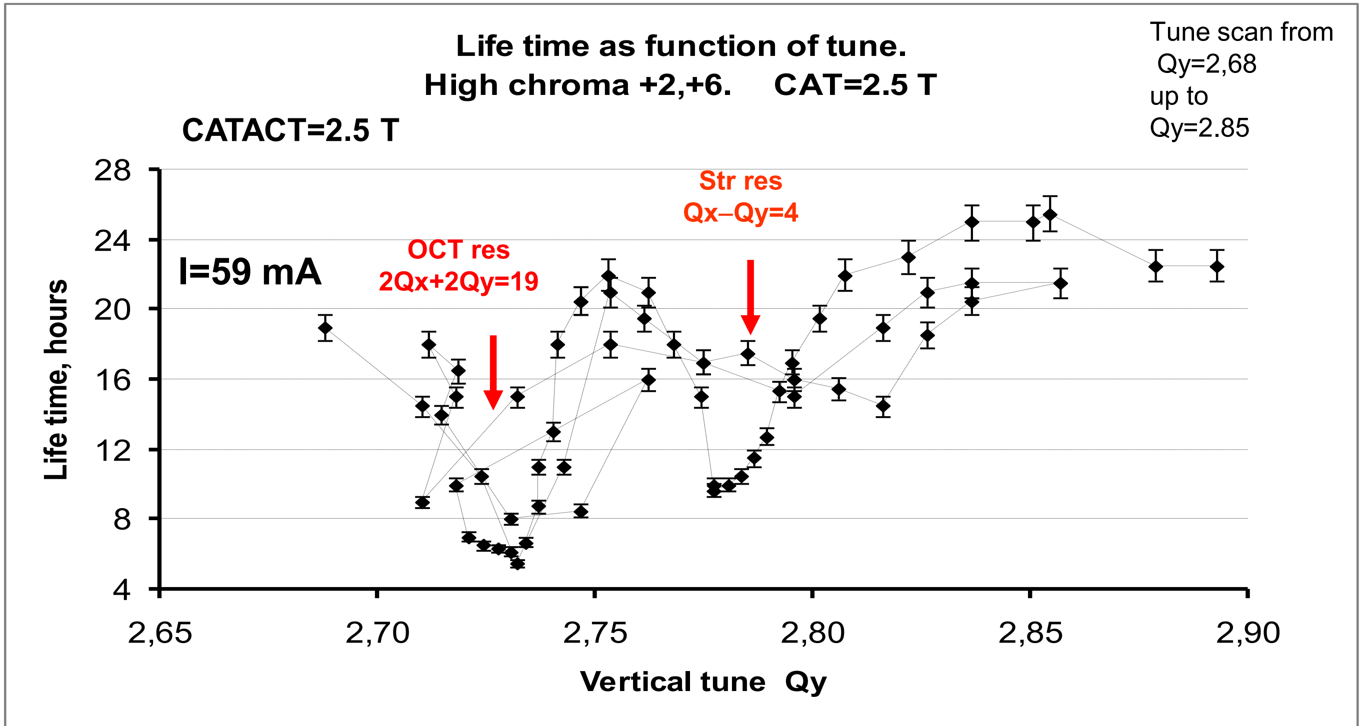


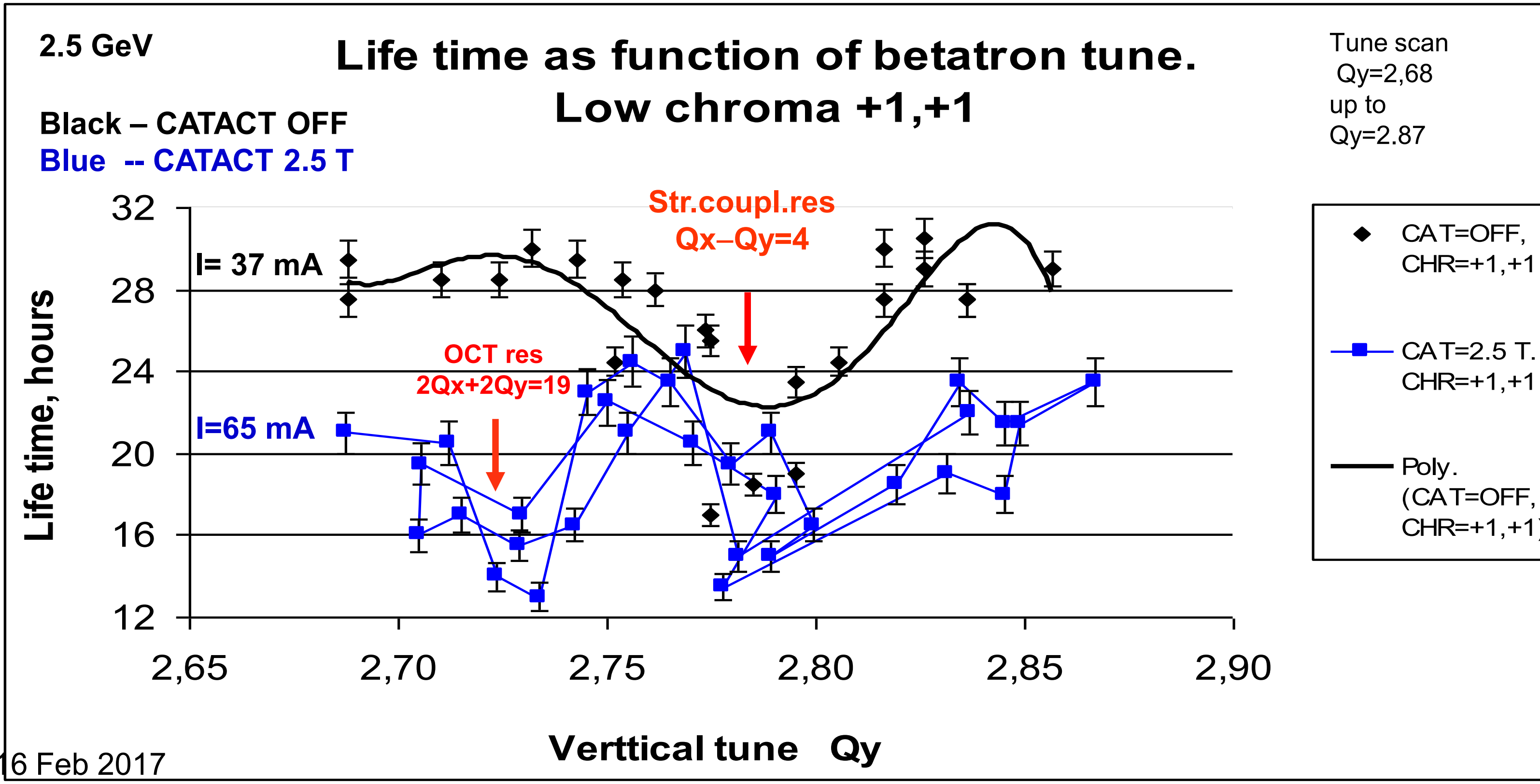
Time, sec

2.5 GeV

Life time as function of betatron tune.
High chroma +2,+6. CATACT OFF

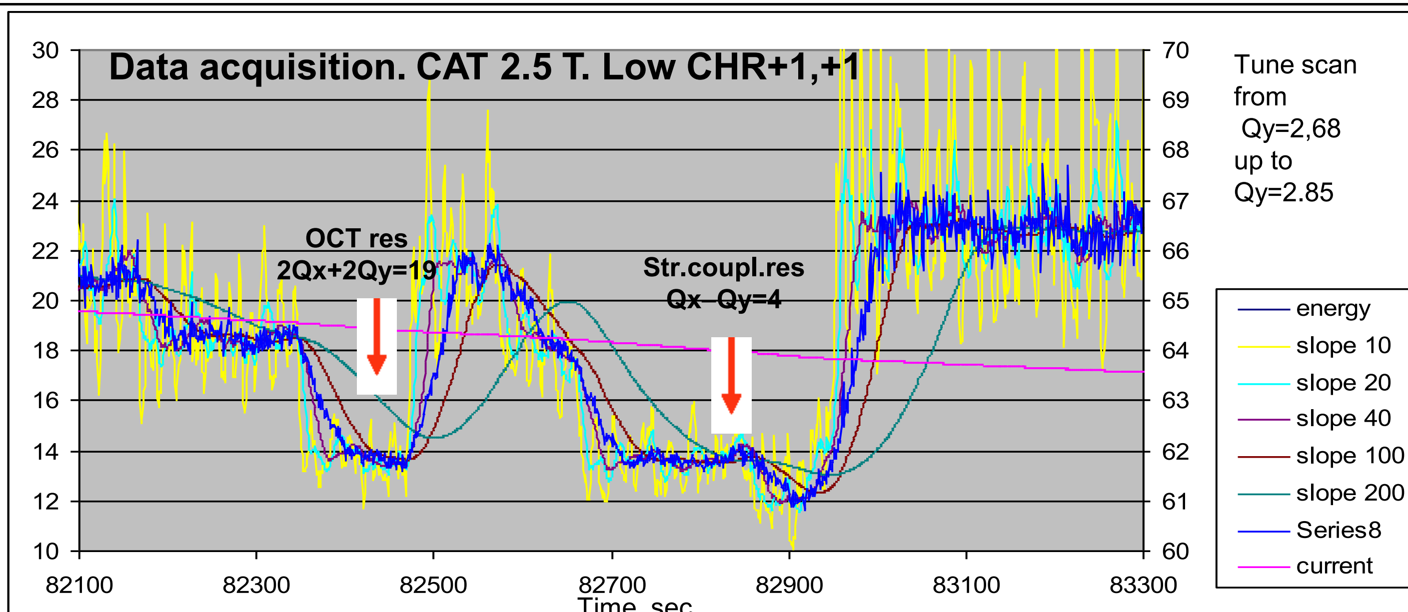




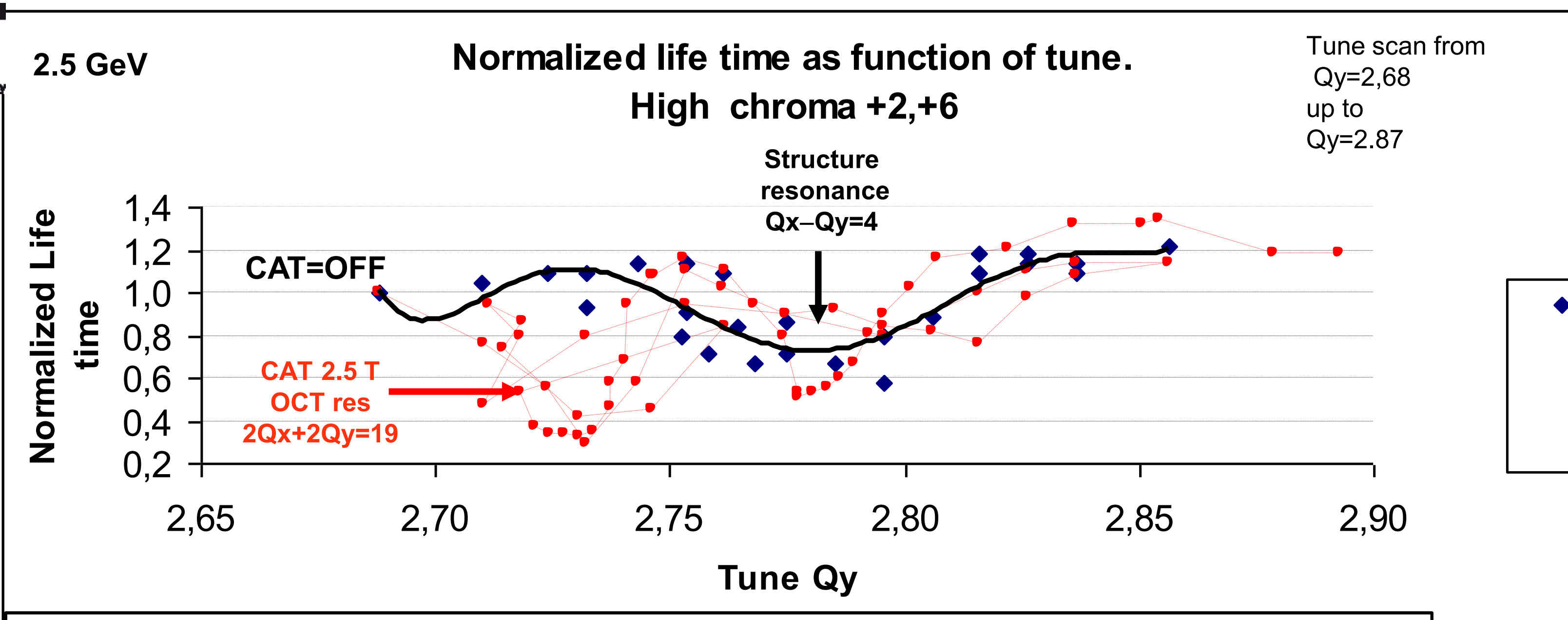


15,16 Feb 2017

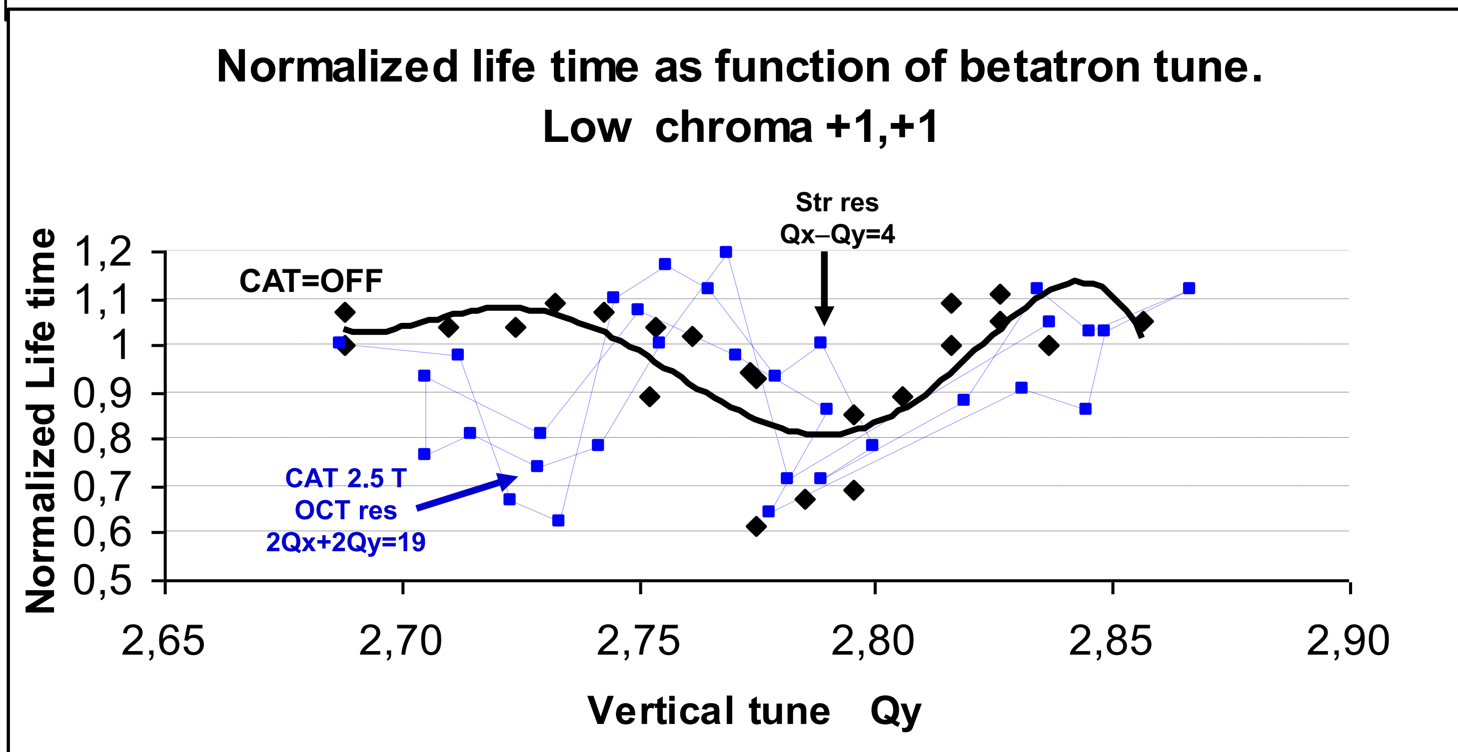
10 data points slope
20 data points slope
40 data points slope
100 data point slope
200 data point slope



2.5 GeV



Tune scan from
Qy=2,68
up to
Qy=2.87



Tune scan from
Qy=2,68
up to
Qy=2.85

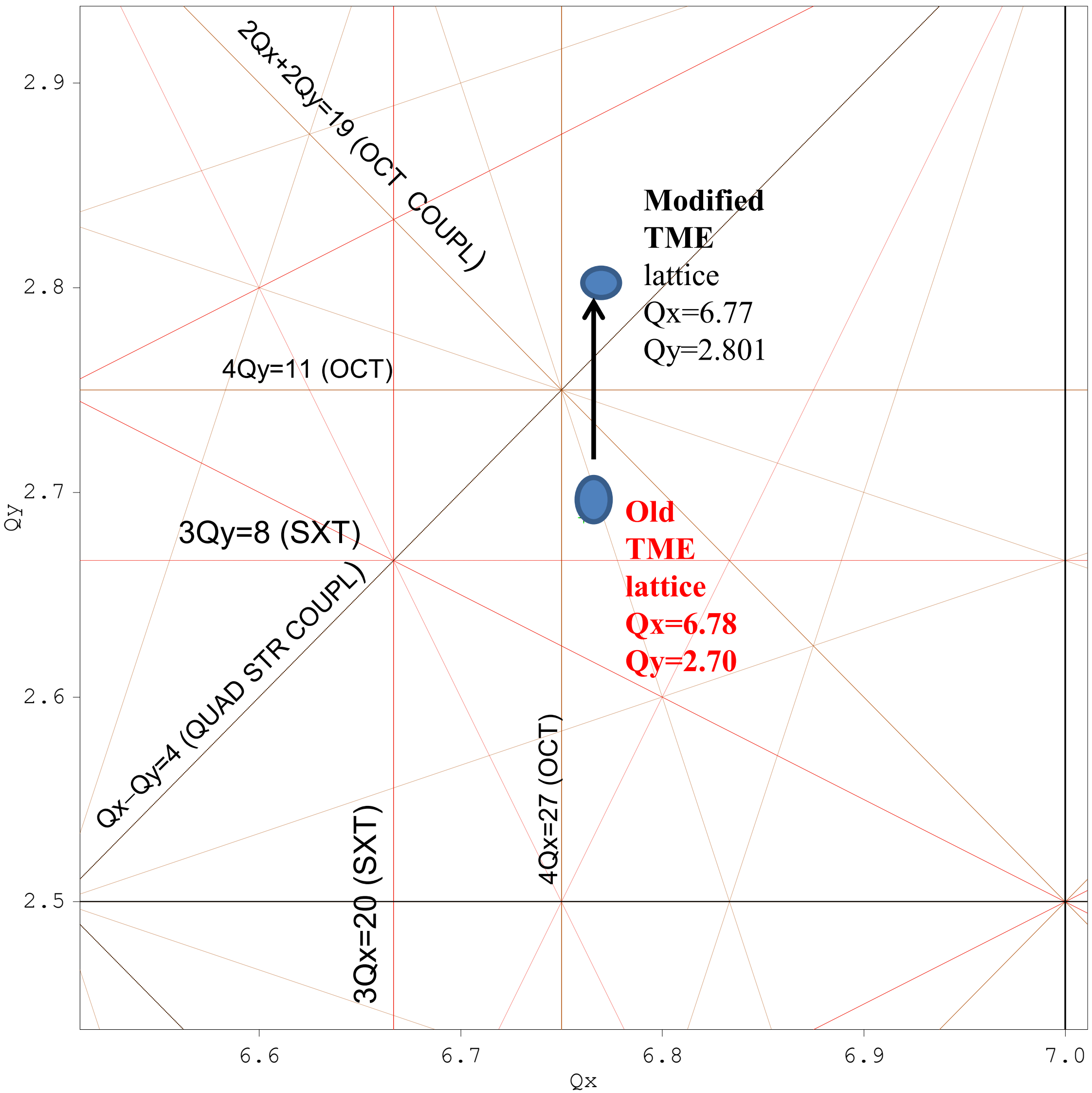
At low chroma LT reduction is still present but much less

Operation at high vertical tune improves KARA performance even at high field level (2.5 T) of CATACT wiggler
Life time was restored

First, the 0.5 GeV beam from the booster is **injected** into **modified TME** optics at **high** vertical tune

Second, beam is accumulated

Third, **stored** beam is **ramped** to desired energy.



Tune diagram –
up to 4th order incl.
Skew resonances

After successful tests vertical betatron tune at User operation as well as at low-α operation has been increased from

Qy = 2.69 ÷ 2.71

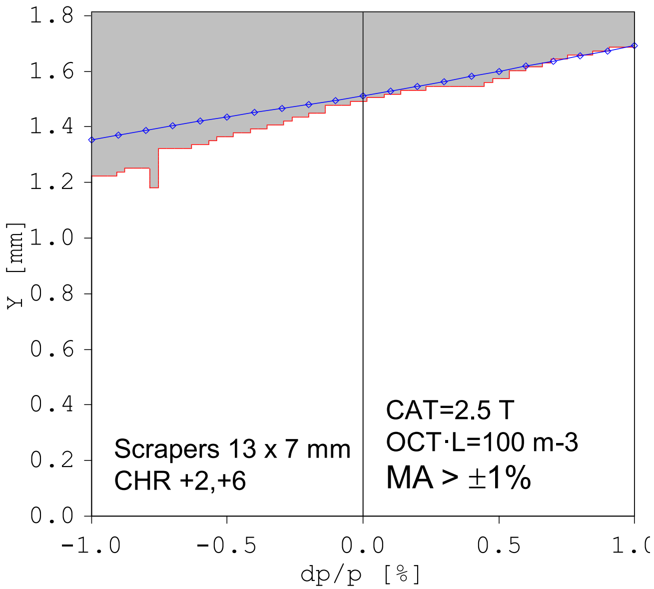
to

Qy = 2.801 ÷ 2.81

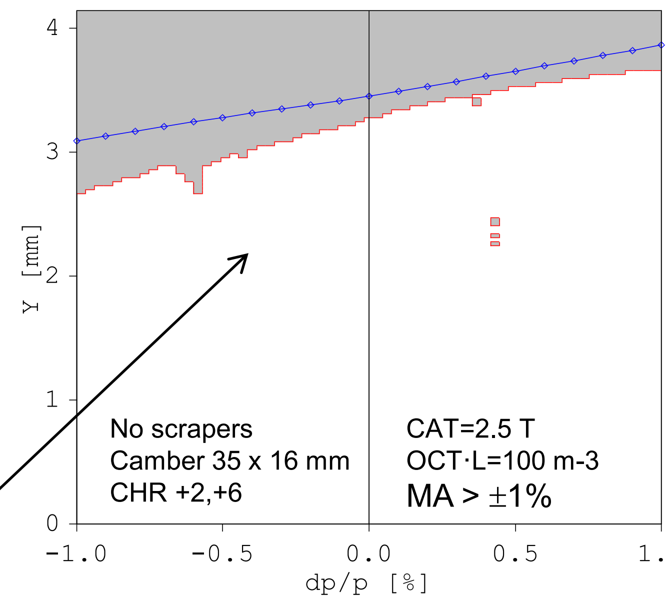
while values of betatron functions and Dispersion have been almost unaffected

Karlsruhe Institute of Technology

Dynamic Aperture for OFF-momentum particles Modified TME lattice Qy=2.81



CATACT Wiggler ON B= 2.5 T

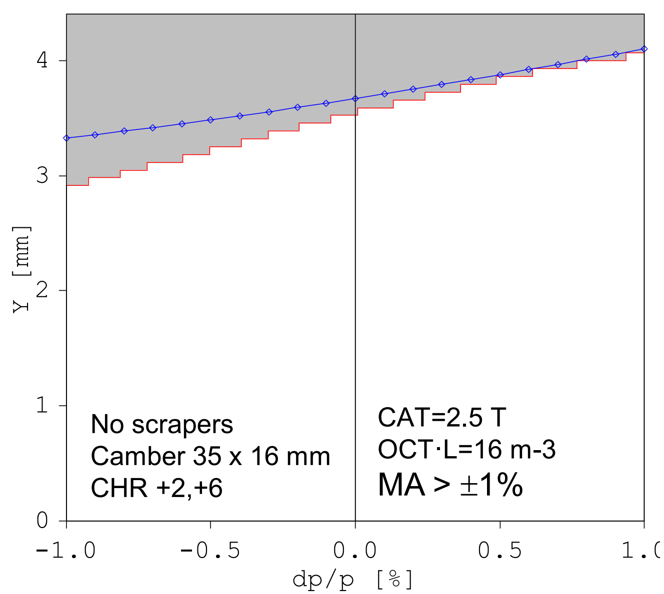


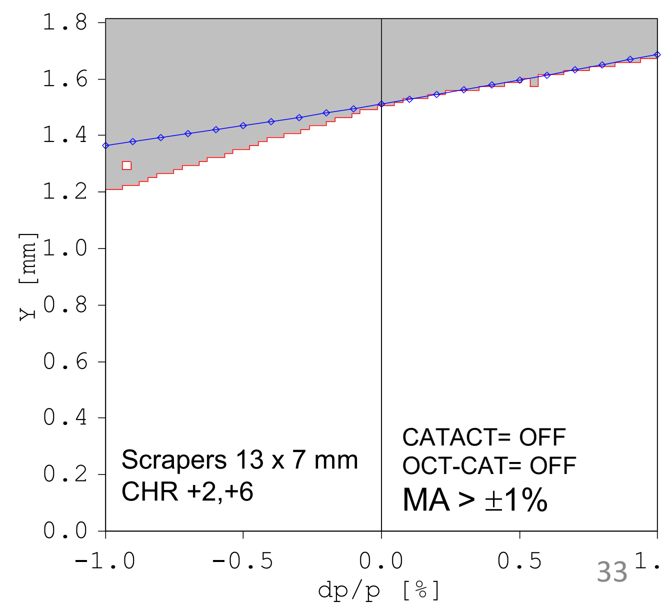
High tune is chosen away of Octupole resonances

Motion is stable for ON- momentum and OFF-momentum particles

No distortion of Phase space
even at HIGH INTGR.
OCTUPOLE Strentgh

- 100 m-3 and large
- oscilation amplitude
- KARA operates at safe
- margins of SCrapers





Merit of modified TME lattice at high vertical tune

New quads settings at high vertical betatron tune $Q_y = 2.801$ are established at injection energy (0.5 GeV), during RAMP (0.5 – 2.5 GeV) and at TOP energy (2.5 GeV)

modified ramp tables with new quads settings allow:

(1) stay away from the sextupole resonance $Q_y = 8/3 = 2.667\ldots$

(2) improve operation conditions (life time, stability)

(3) escape reduction of life time caused by combination of (a) + (b) + (c) +(d)

(a) high order (octupole) field components
of wiggler $B_w = 2.2 \div 2.5$ T
(b) proximity of old tune $Q_y = 2.69\ldots$ to coupling octupole resonance $2Q_x + 2Q_y = 19$
(c) proximity of old tune to sextupole resonance $Q_y = 2.666\ldots$
(d) High chromaticity $\xi_{x,y} = +2,+6$

(4) new quads settings are adjusted to minimize shaking of betatron tunes during RAMP procedure wheen current of bends and quadrupole magnets is increased in few times (~5 times)

(5) reduced deviation of betatron tune during ramp helps to operate fast Bunch-by-Bunch Feedback system during injection, ramp, at TOP and stabilize beam current and suppress instabilities

Modified TME lattice
Tests

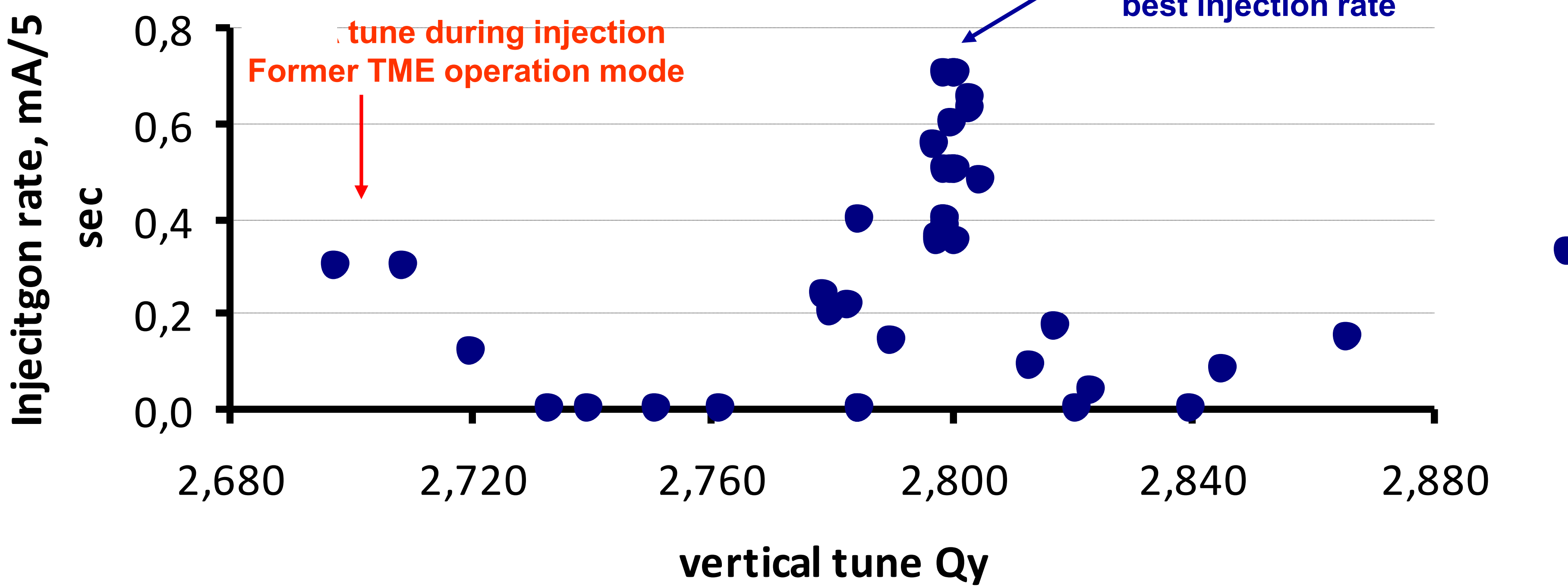
Beam injection
and
energy ramp
from 0.5 to 2.5 GeV
at high betarton tune
Qy = 2.801

SEARCH for new injection point with high Qy and best injection rate

Injection rate as function of betatron tune

Looking for best injection rate at high tune

Modified TME lattice with high vertical tune best injection rate

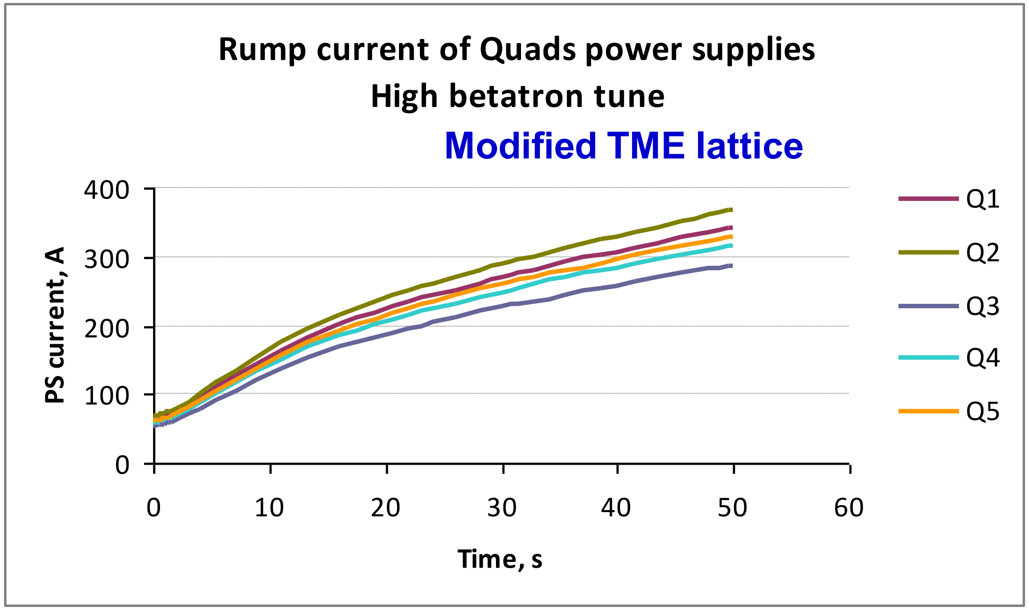


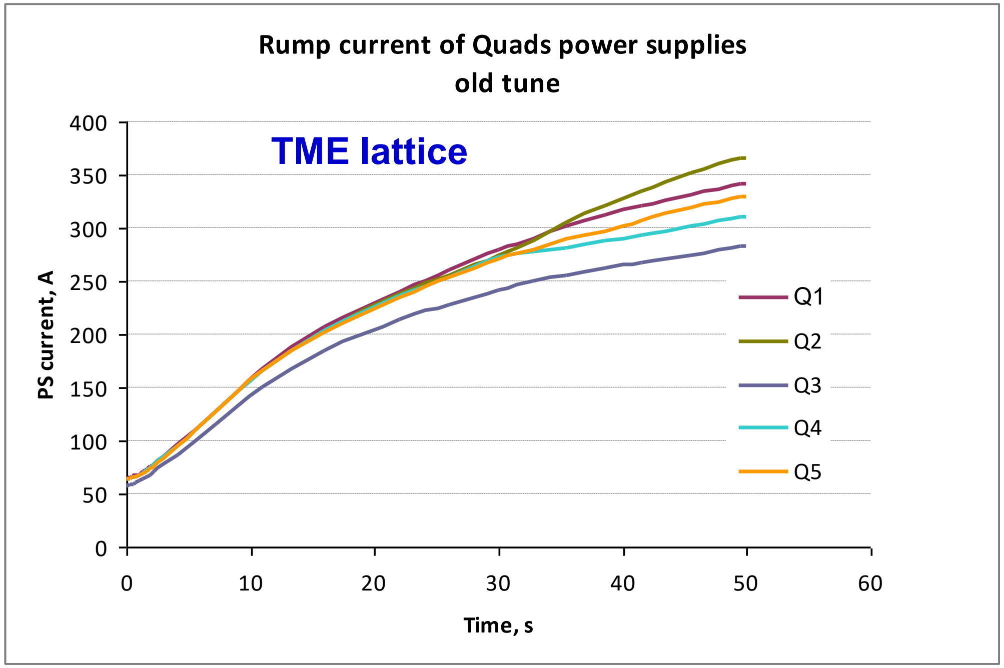
- Highest Injection rate of 0.7 mA/5 sec has been achieved at Qy=2.801 and Qx = 6.75 (27/4)
- This operation point provides best Life time at 2.5 GeV and minimum of Resonance Driving terms (RDT)

- Phase dependent RDT are minimized by periodicity of 4 fold symmetry of KARA ring
- One can explore possible benefits of KARA operation at radial tune 6.75

Ramping curves

Ramping curves were modified to keep Qx,y UNCHANGED during energy increase





(1) 0.5 GeV beam from the booster is injected into modified TME optics at high vertical tune Qy=2.801

(2) beam is accumulated

(3) stored beam is ramped to desired energy

(4) measure tune shifts during ramp

(5) simulate modifications of Quad strength to fix tunes

(6) estimate <u>small</u> variations of current of Q coils

(7) Apply new settings at ramp tables

(8) next iteration…

Shift of betatron tunes $\Delta Q_{x,y}$ produced by ONE single quadrupole of effective length L_Q is a product of strength variation (proportional to relative change of coil current) and value of beta-function at quadrupole location. Tune shift caused by small change of quad current might be roughly estimated by following formulas

$$\Delta Q_X \approx +\frac{L_Q}{4\pi}\cdot\bar{\beta}_X\cdot\frac{\Delta I_Q}{I_Q} \qquad \Delta Q_Y \approx -\frac{L_Q}{4\pi}\cdot\bar{\beta}_Y\cdot\frac{\Delta I_Q}{I_Q} \qquad (6.12)$$

where $\bar{\beta}_{X,Y}$ is average value of beta-function over quads length.

Normalized tune shifts at different energies are presented in **Table #6.2.** BBB fast feedback data are taken by direct measurements of betatron tunes shifts at ANKA ring.

Table 6.2. Rate of betatron tune shift due to coil current variation

ameter	**q3** k_3 **(m^{-2}) A**	**q4** k_4 **(m^{-2}) A**	**tune Qx**	**tune Qy**	$\frac{\Delta Q_X}{\Delta Iq3}$ **A^{-1}**	$\frac{\Delta Q_Y}{\Delta Iq3}$ **A^{-1}**	$\frac{\Delta Q_X}{\Delta Iq4}$ **A^{-1}**	$\frac{\Delta Q_Y}{\Delta Iq4}$ **A^{-1}**
=0.5 GeV **BBB**	+2.06 57.2	–1.82 64.0	6.771	2.698	**+0.07**	**–0.035**	**–0.028**	**+0.106**
=0.74 GeV ıroportion	+2.06 86.4	–1.82 95.1	6.771	2.698	**+0.047** $A_E=0.5A_{0.5}/E$	–0.024	–0.019	+0.085
=1.0 GeV 'roportion	+2.06 115.5	–1.82 126.9	6.771	2.698	**+0.035** $A_E=0.5A_{0.5}/E$	–0.018	–0.014	+0.0625
=1.3 GeV ıroportion	+2.06 150.3	–1.82 165.3	6.771	2.698	**+0.027** $A_E=0.5A_{0.5}/E$	–0.015	–0.011	+0.048
=1.6 GeV ıroportion	+2.06 184.1	–1.82 203.4	6.771	2.698	**+0.022** $A_E=0.5A_{0.5}/E$	–0.013	–0.009	+0.039
=2.1 GeV ıroportion	+2.06 249.5	–1.82 276.9	6.771	2.698	**+0.0167** $A_E=0.5A_{0.5}/E$	–0.011	–0.0063	+0.030
=2.5 GeV **BBB**	+2.06 282.8	–1.82 310.0	6.771	2.698	**+0.0147**	**–0.0091**	**–0.005**	**+0.025**

Rate of tune shift for intermediate values of beam energy is estimated by interpolation formula

$$\frac{dQ}{dI}(E)=\frac{dQ}{dI}(E_i)+(E-E_i)\cdot tg\left[\frac{\frac{dQ}{dI}(E_{i+1})-\frac{dQ}{dI}(E_i)}{E_{i+1}-E_i}\right]$$

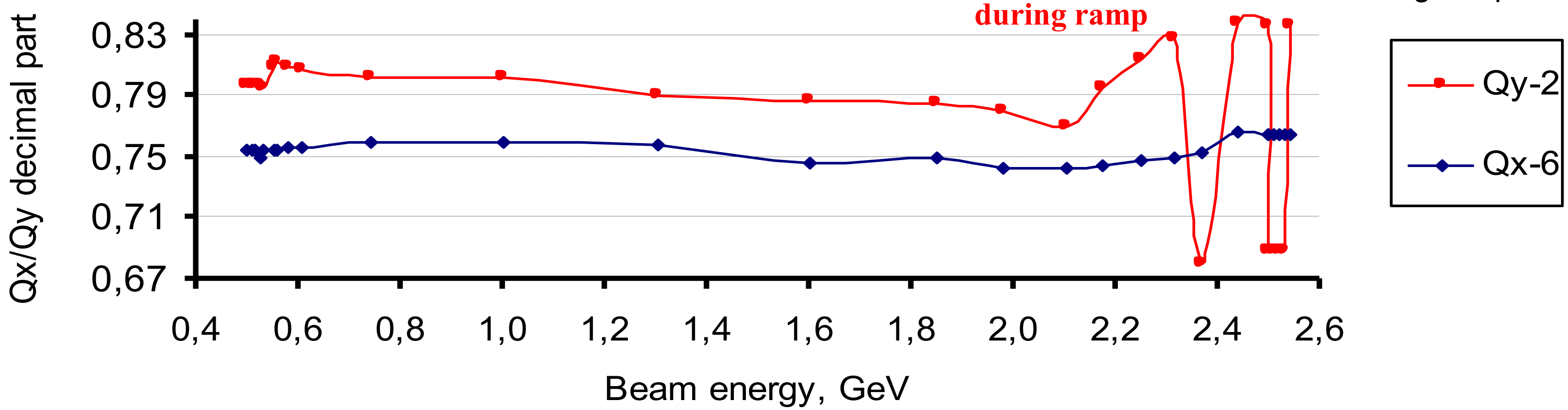
Betatron tunes during ramp. High Qy mode

Q4 quad strength is increased in proportion k=65/64 to Q4 strength at USER mode ramp

(170mA at 0.5GeV - 110 mA at 2.5 GeV) 17 March 2017

Before correction Vertical tune drifting a lot during ramp

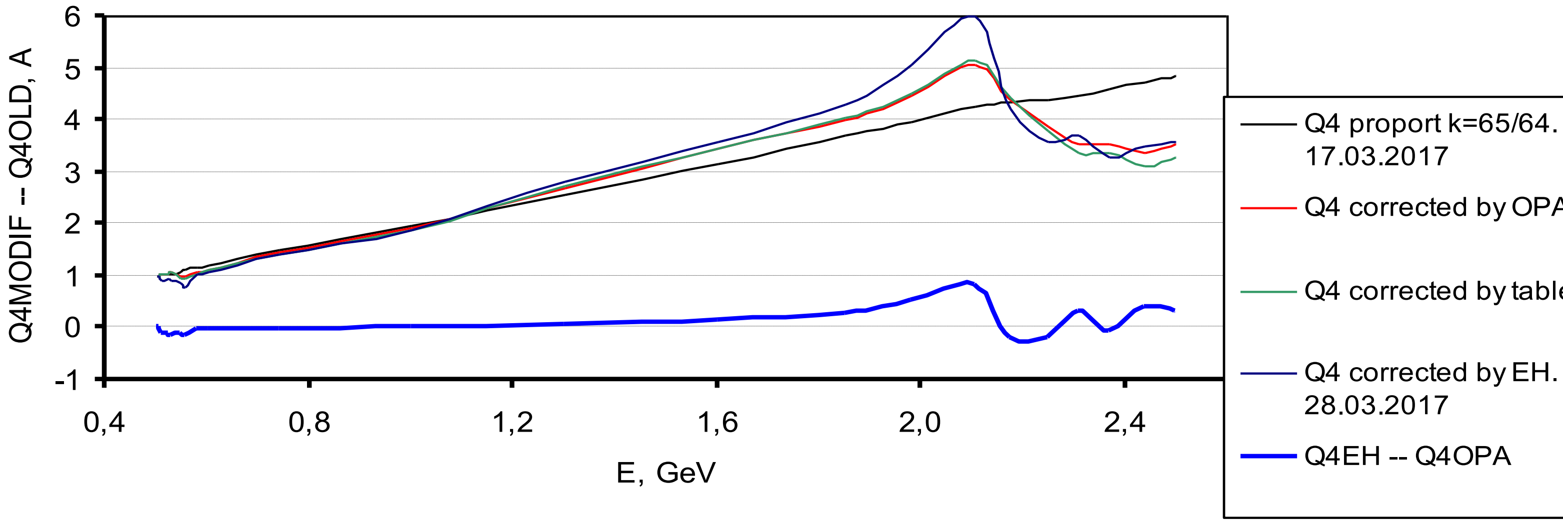
Tunes have been shaking during ramp



One should deviate Ramping curves from Direct proportion In order to fix tunes

Adjusting of Q4 quad at ramp to stabilize high vertical tune Qy=2,8

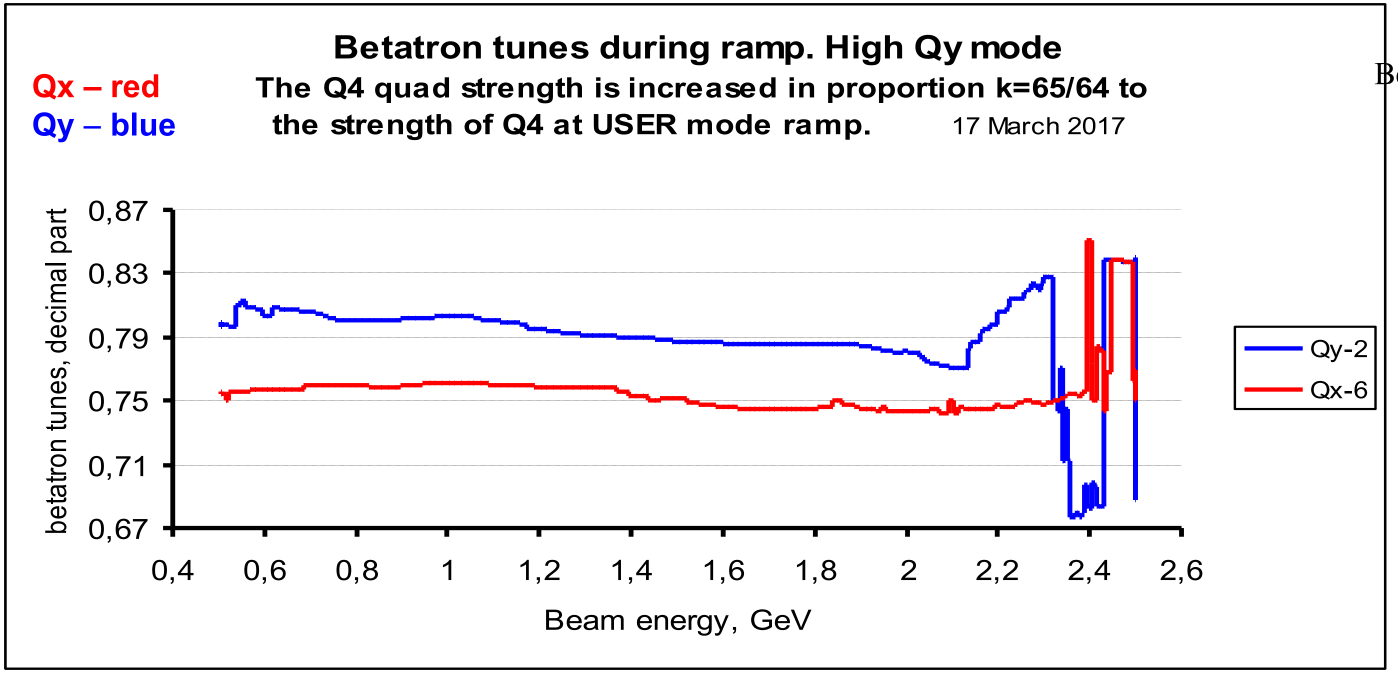
Corrections to ramp table to keep Qy CONST during increasing of beam energy



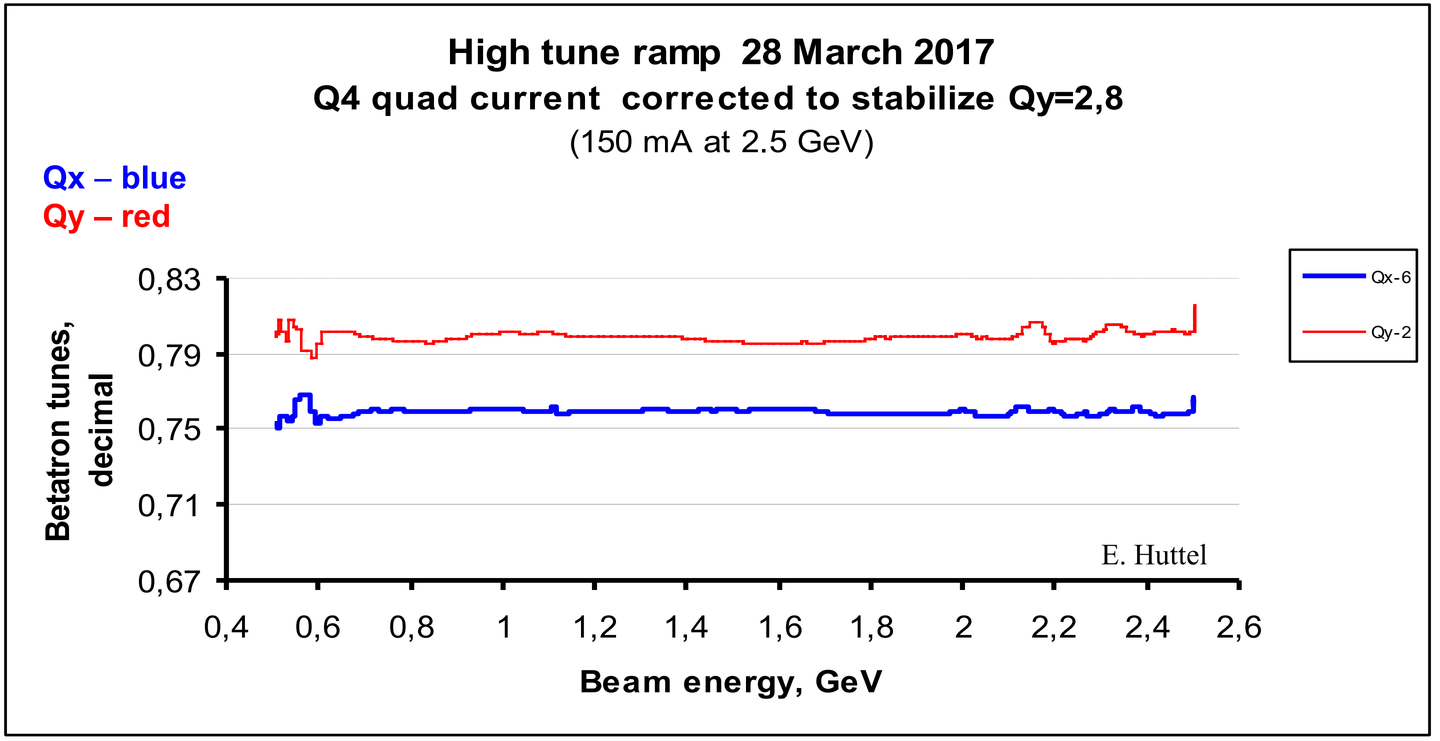
New ramp tables were established to operate ring at high vertical tune Qy=2.81

Basic idea- ramp beam energy and keep betatron tune **fixed**

Quads strength was estimated by OPA, Quads current by proportion



Before correction of ramp table Tunes are drifting a lot during ramp



After adjusting of Quads current during ramp Qx, Qy tunes were fixed at ALL energies

Short bunches at KARA

low momentum compaction factor optics

$$\sigma_0 = \frac{\alpha^{(1)} C}{2\pi \cdot \Omega_S} \cdot \frac{\delta p}{p_0} = \frac{\delta p}{p_0} \sqrt{\frac{\alpha^{(1)} \cdot C_0^2 E_0 \beta_0^2}{2\pi \cdot h_{RF} e U_0 \cos(\varphi_S)}}$$

We found new settings of KARA elements for ramp-squeezing tables at low–α operation with high betatron tune Q=2.801 and measured beam parameters at different operation conditions

Different versions of KARA optics

Modified TME mode (USER)

(1) 0.5 GeV beam from the booster is **injected** into **modified TME** optics of ring at **high** vertical tune Qy=2.801

(2) beam is accumulated (~30 minutes)

(3) Ring is **ramped** to desired energy and **stored** beam circulates ~24 hours

low–α mode

(4) low-α **stepwise squeezing** is applied to modified TME
- increase of Q3 strength to stretch ***D***
- Dispersion crosses zero at azimuth of bending magnets

(5) Q1,2,4,5 adjusted to keep Qx, Qy

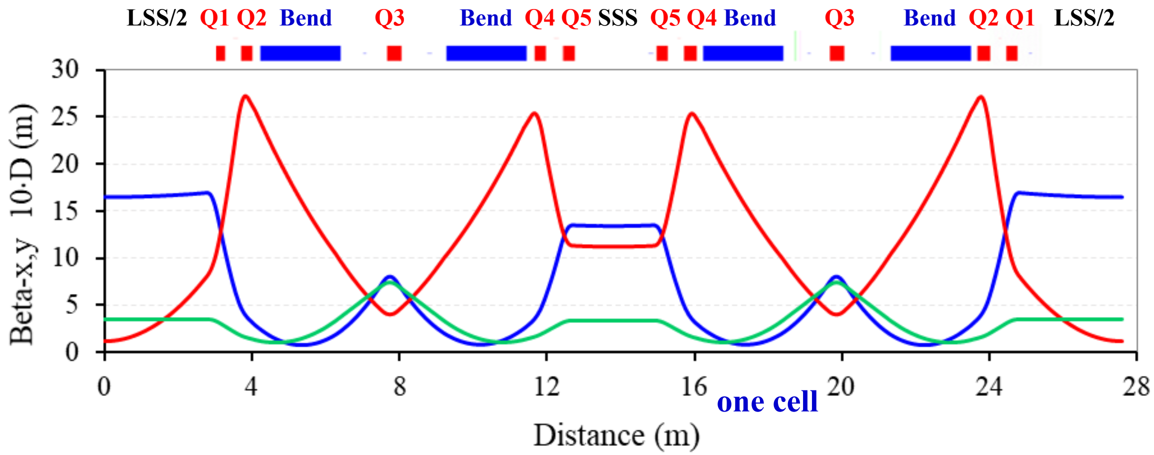
(6) Orbit correction after each step

(7) Span of ***D*** grows to +1.4…–1 m in order to compensate positive and negative contribution of dispersion inside bending magnets

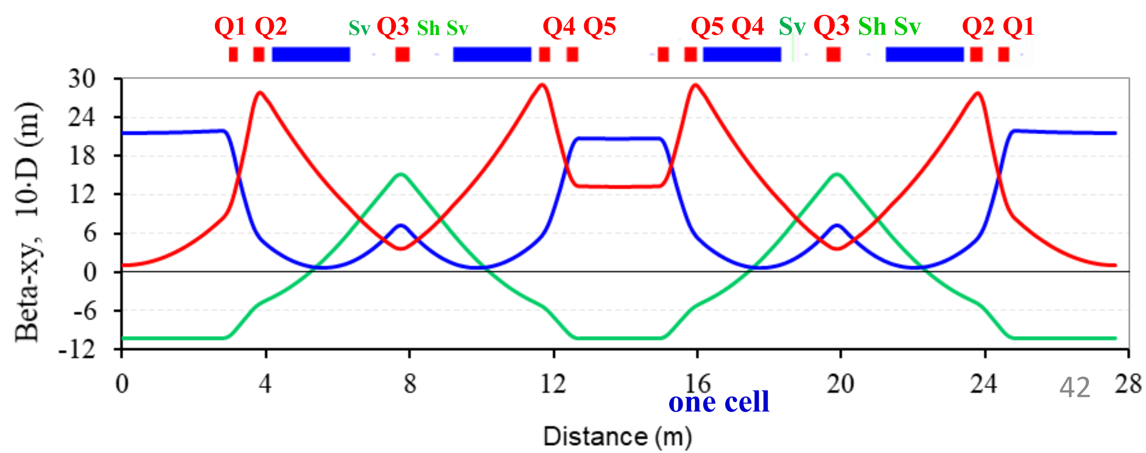
(8) Compaction factor at low-α is reduced ~100 times – down to $1\cdot10^{-4}$

The origin is at the middle of long straight section (θ_0=0).
The **horizontal**/**vertical** beta-functions – **blue**/**red** color
dispersion – **green**.

Modified TME lattice
D = +0.13 to +0.71 m, Dstr = 0.35 m



Low compaction factor optics α=+1·E-4 (positive)
***Dispersion* is stretched from**
+1.44 m (Q3) to –1.03 m (straights)



Low–α lattice with stretched dispersion to reduce momentum compaction factor ~100 times

squeezing procedure applied **to modified TME** optics Qy=2.81

$$\alpha^{(1)} = \frac{\partial L / L}{\partial p / p} = \frac{1}{L_0} \oint \frac{D}{\rho} ds$$

Q3 **UP**
Span of ***D*** grows
+1.4…to –1 m

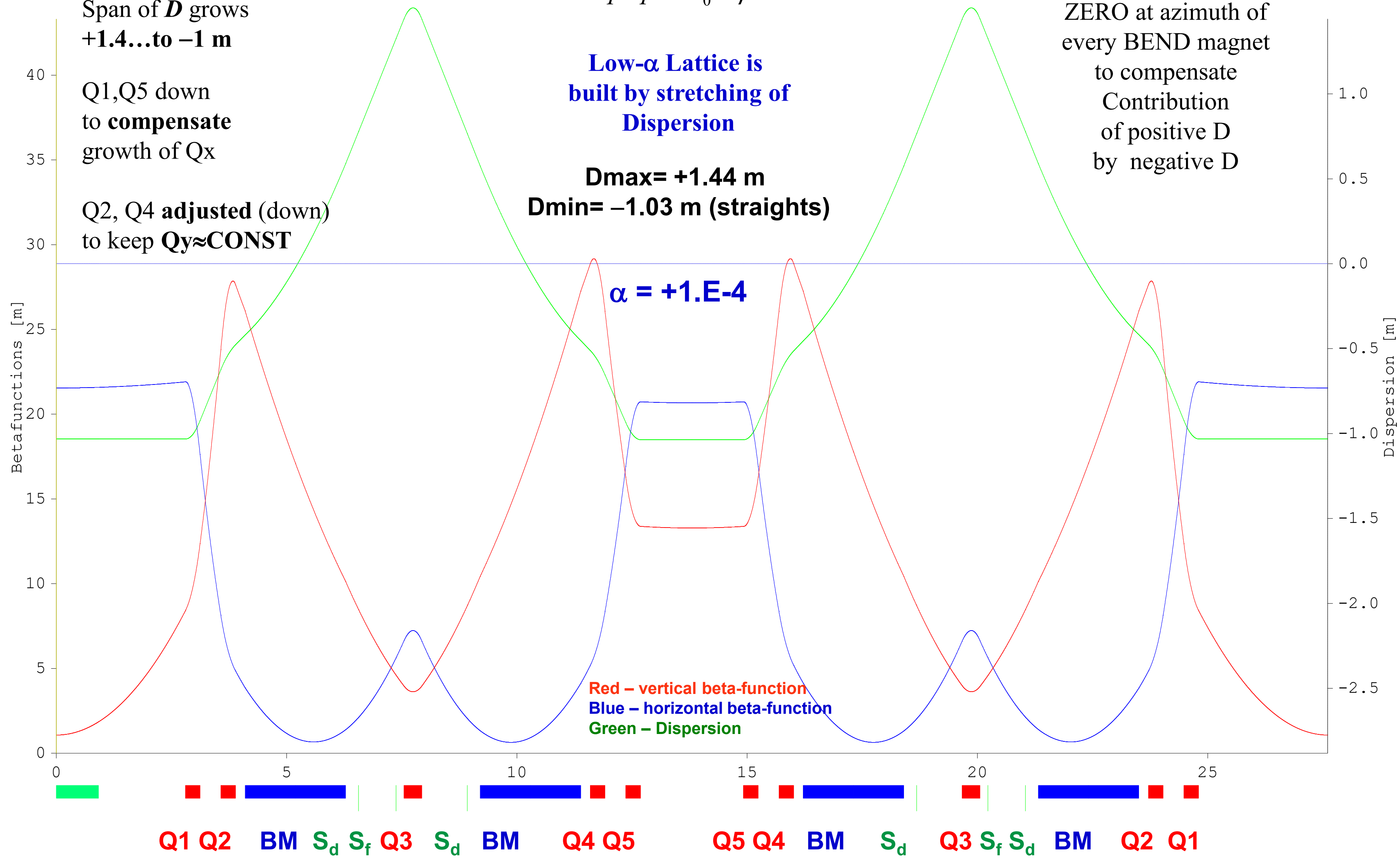
Q1,Q5 down
to **compensate**
growth of Qx

Q2, Q4 **adjusted** (down)
to keep **Qy≈CONST**

Low-α Lattice is built by stretching of Dispersion

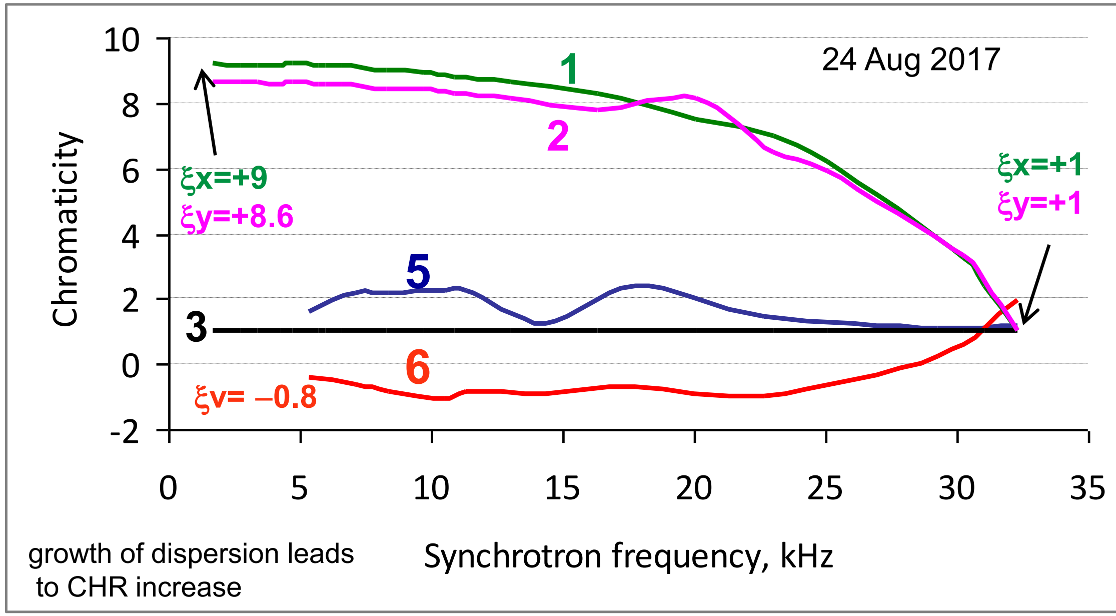
Dmax= +1.44 m
Dmin= –1.03 m (straights)

Dispersion crosses ZERO at azimuth of every BEND magnet to compensate Contribution of positive D by negative D



Merit of SXT strength reduction during low–α squeeze (Tests 1.3 GeV 24.08.2017)

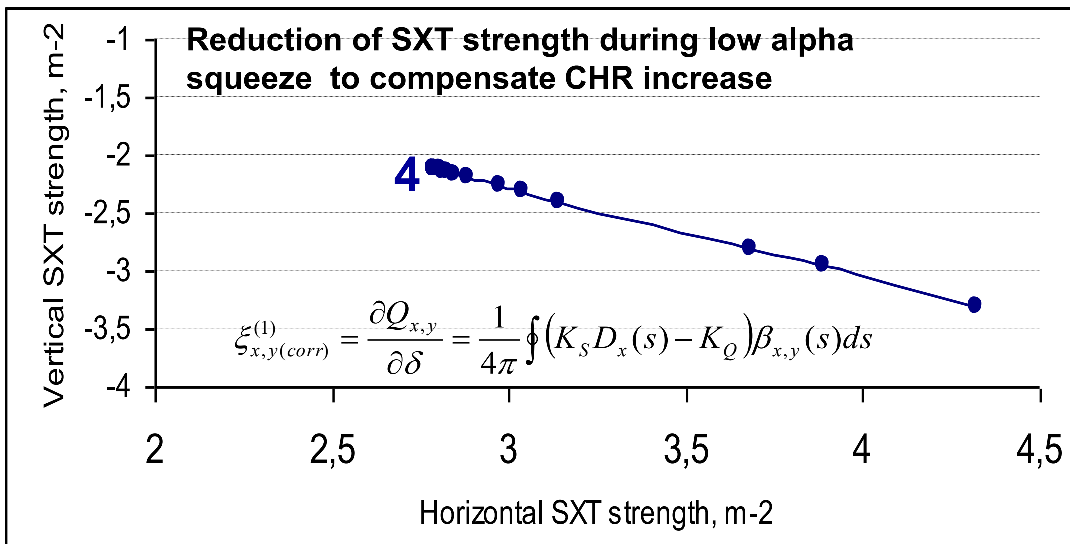
Predicted by simulations
High SPAN of Disperion leads to essential growth of **chromaticity** during low–α Squeeze if sextupole **strength** is FIXED
curve 1 – kSF=+4,3 m-2 = const
curve 2 – kSD =–3,3 m-2 = const
Growth of chromaticity adds to beam Losses due to reduced MA
LT further reduced



Strength of sextupoles was subsequently reduced in synchronism with stepwise reduction of synchrotron tune in order to **compensate** growth of CHR
curves 3,4 - simulations,
cuvres 5, 6 - measured

Curve 3
CHR is fixed during low–α squeeze (ξh,v = +1,+1) **by stepwise** reduction of SXT strength, see curve 4
Curve 4
kSF=+4,3 down to +2,8 m-2
kSD =–3,3 down to –2,1 m-2

Curve 5 and **curve 6** – CHRh and CHRv measured during low–α squeeze at 1.3 GeV
5 – ξh ≈ +1 to +2 (ISF = 76 A down to 61 A)
6 – ξv ≈ +2 to –0,8 (ISD = 70 A down to 54 A)

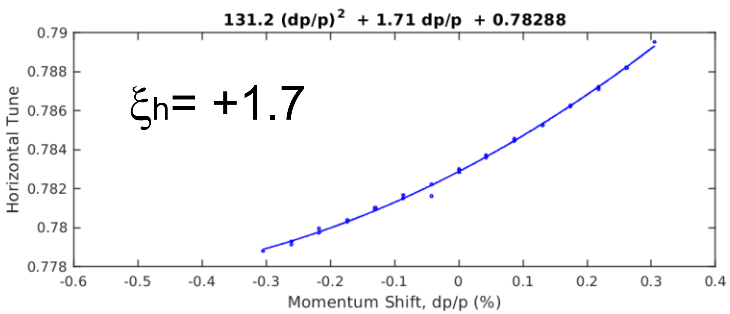


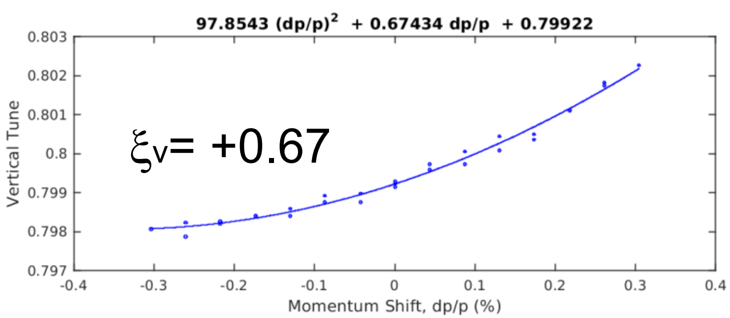
$$\xi^{(1)}_{x,y(corr)} = \frac{\partial Q_{x,y}}{\partial \delta} = \frac{1}{4\pi}\oint \left(K_S D_x(s) - K_Q\right)\beta_{x,y}(s)ds$$

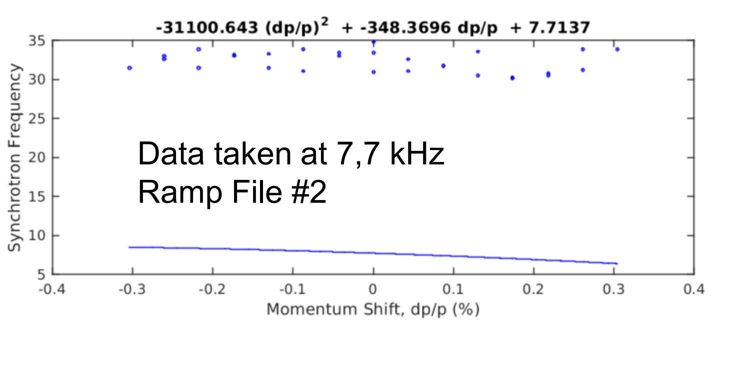
We adjust SXT settings in the squeeze table in order to keep **small posiive** CHRh,v =+1÷+2

Correction of SXT strength to keep CHR slightly positive during low-alpha squeeze at 1.3 GeV (Tests 16-19 October 2017)

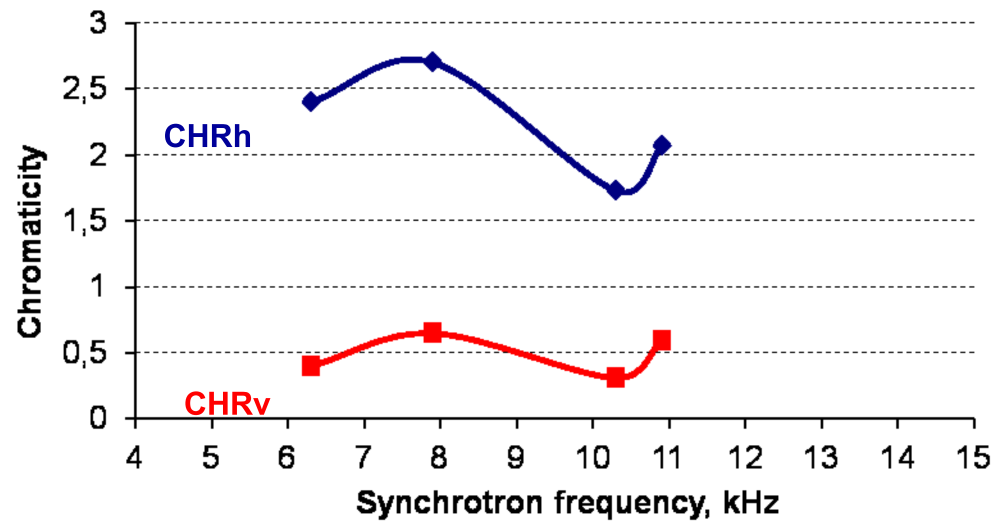
Chroma measurements of corrected ramp/squeeze file #2 (reduced SXT strength). Julian Gethmann 19 Oct 2017



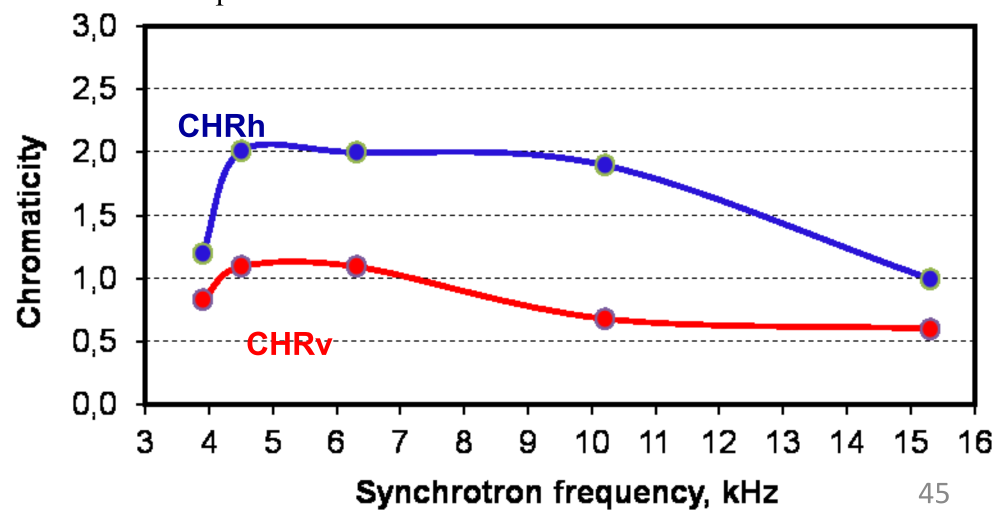




SXT strength corrected to keep positive chromaticity



SXT strength adjusted to optimize chromaticity during squeeze.
Ramp file #2 from 16 October 2017



Life time during low–α squeezing procedure at 1.3 GeV. KARA tests.

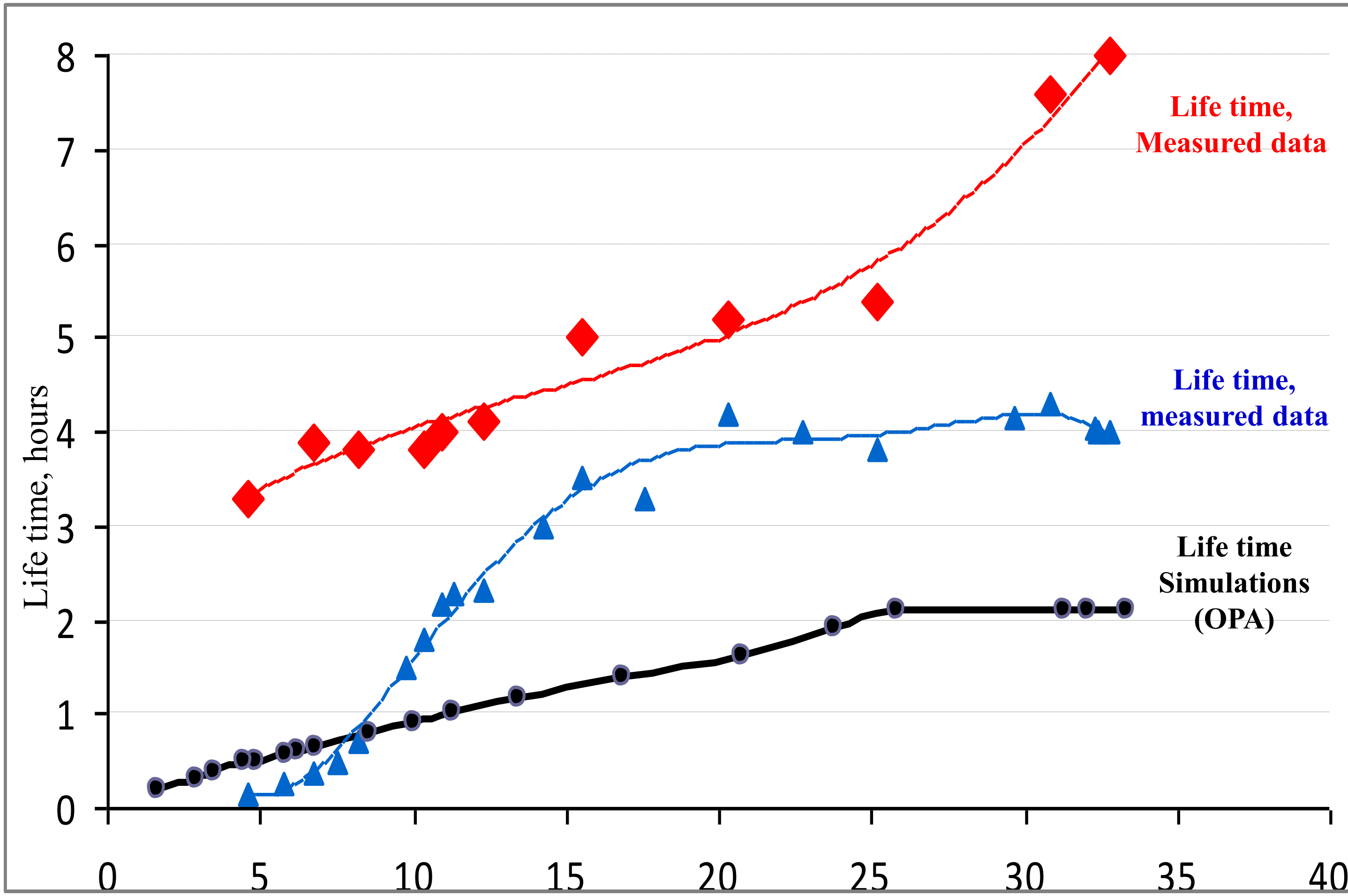
$$\xi^{(1)}_{x,y(corr)} = \frac{\partial Q_{x,y}}{\partial \delta} = \frac{1}{4\pi}\oint \left(K_S D_x(s) - K_Q\right)\beta_{x,y}(s)ds$$

black curve -OPA simulations
High span of dispersion reduces MA and leads to the smooth reduction of Life Time

Blue curve - growth of chromaticity adds to beam losses. SXT strength is FIXED and CHRx,y grows from+2,+1 at modified TME (Fs=34 kHz) to +9,+9 at low–α (Fs=5 kHz) Life time **sharply drops** at small compaction factor

Red curve -- SXT strength is subsequently reduced during squeeze in synchronism with stepwise reduction of Fs - to compensate growth of CHR and keep it slightly positive $\xi x \approx +2$, $\xi y \approx +1$
Life time is reduced smoothly – in agreement with OPA simiulations (similar slope)

After correction of ring optics life time at low-α improved from few minutes **(blue triangles)** to ~3 hours (**red rombes**)



α = +1.E-4 Synchrotron frequency Fs, kHz α = +9.E-3

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Direct injection into

Positive low–α lattice

and

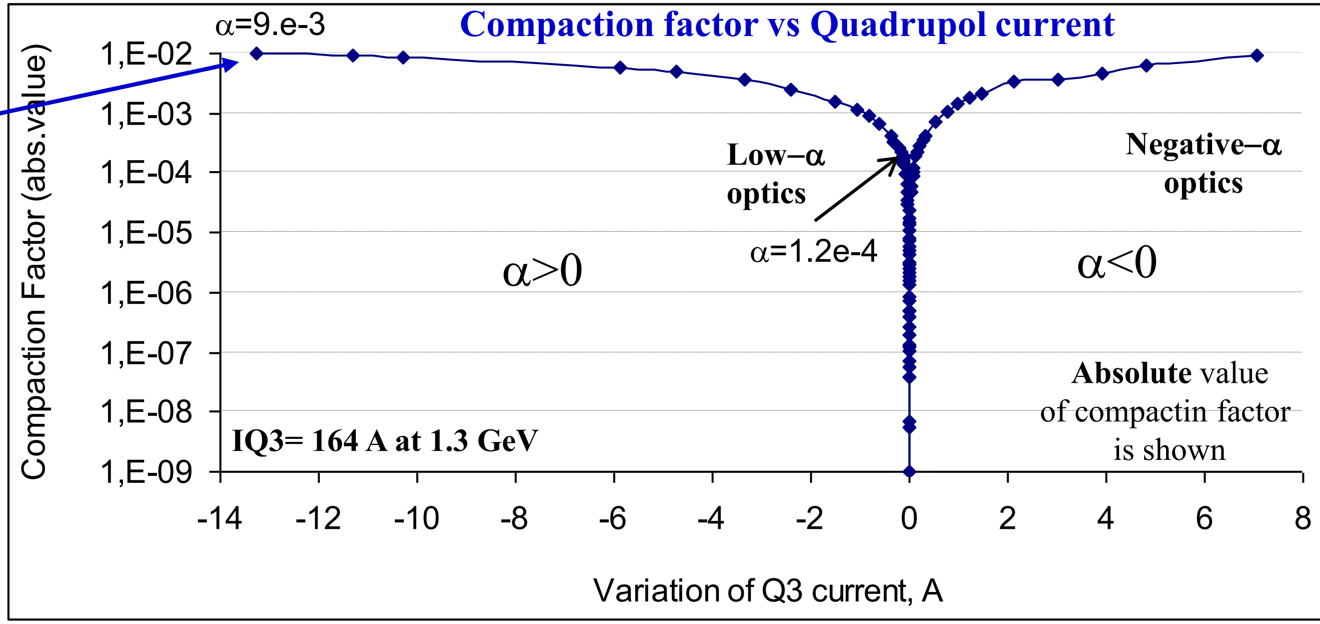
Procedure development

of

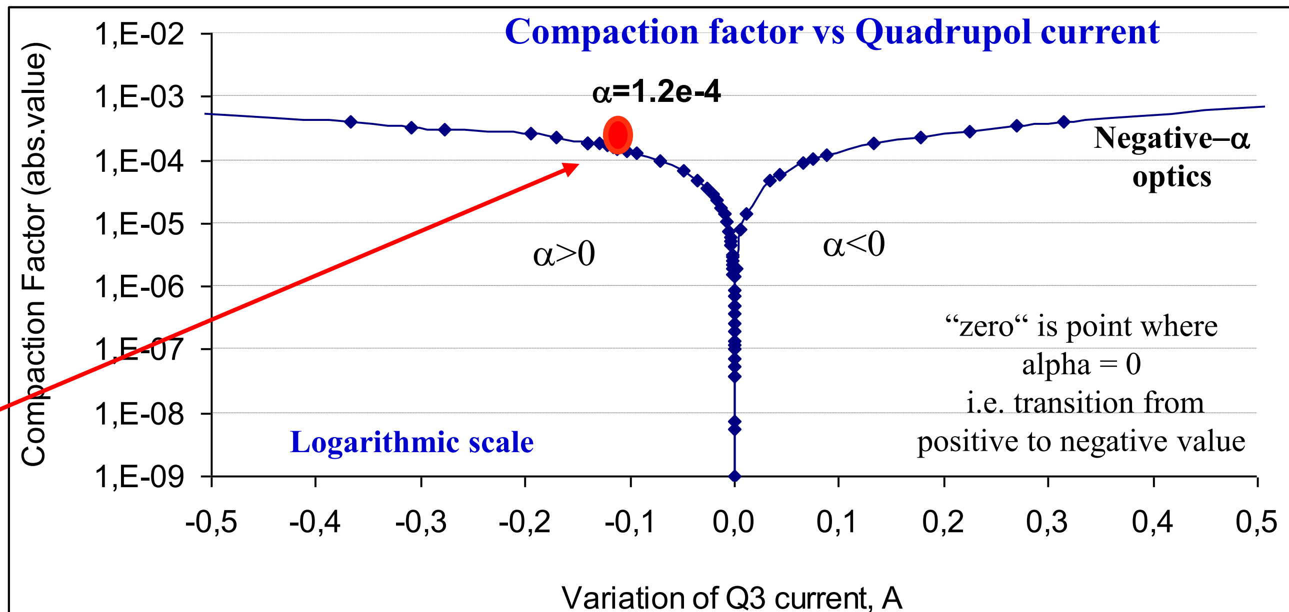
NEGATIVE–α optics

Modified TME operation mode

Transition of momentum compaction factor from positive to negative value leads to beam loss due to instability

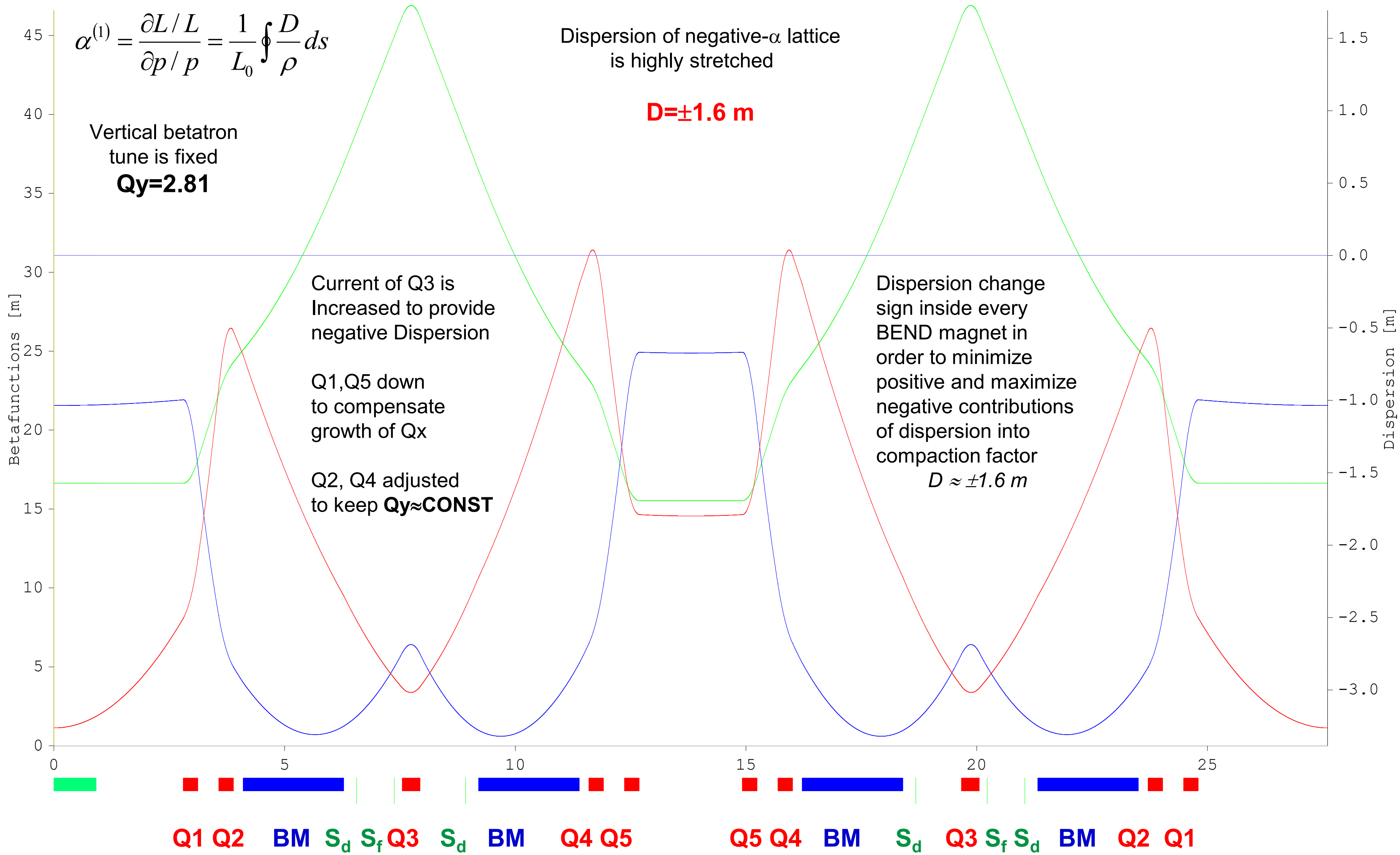


Low–α operation mode of KARA



KARA lattice (one cell) at NEGATIVE Compaction Factor

α = –6.1E-3



Green – Dispersion
Red – vertical beta-function
Blue – horizontal beta-function

- **transfer** from positive low–α to negative–α mode is **not possible** at any energy because crossing of zero value of the momentum compaction factor leads to instability and loss of the beam at KARA

- to operate at negative–α, **direct** **injection** of 0.5 GeV beam from the booster into negative–α lattice is **mandatory**

- First we **simulate** and **tested** **new** **positive low–α lattice** for **direct injection** of 0.5 GeV beam after the booster

- Then, we **simulate** and **tested** **negative–α** optics for **direct injection** at 0.5 GeV. Linear optics at negative–α is similar to positive low–α lattice just ***D*** is stretched slightly more and RF phase of Booster is shifted at 180°

- Special algorithm of **step-wise** change of quads current was developed using KARA Model and applied to build up **new** **positive low-α** lattice at 0.5 GeV from modified TME lattice while keeping betatron tunes **fixed**

- **slight increase** of Q3 strength at each step of squeezing procedure in order to **stretch dispersion**

- tiny **reduction** of Q1 and Q5 focusing quads -- to decrease horizontal tune Qx and restore it original value

- the radial tune Qx is restored, but vertical tune Qy **grows** slightly above original value

- small reduction of Q2 and Q4 defocusing quads **restores** vertical tune Qy

- At each **step** the compaction factor is **reduced** while tunes are kept almost **unchanged**

- Variation of quads current is **monotonic** (Q3 **UP** while Q1,2,4,5 **DOWN**) and **hysteresis** effects are **avoided**

- At Qx,y=const the **fast feedback** system stabilizes the beam during stretching.

- Same algorithm was applied to **extrapolate** settings for **negative–α** optics (**α = –6.E-3)** and inject beam directly

- Similar procedure but in **REVERSED** order to **REDUCE** abs. value of neg**–α** to **α = –1.E-3**

Momentum Acceptance of KARA lattice at different operation modes

OPA simulations

at modified **TME mode**
MA of ring lattice **±2%** is reduced by scrapers to **±1.3%** while at 2.5 GeV RF limits MA to **±1%**

RF defines total MA at top operation (USER)

Due to high span of ***D*** at **low-α** the MA of lattice is reduced to **±0.7 %**

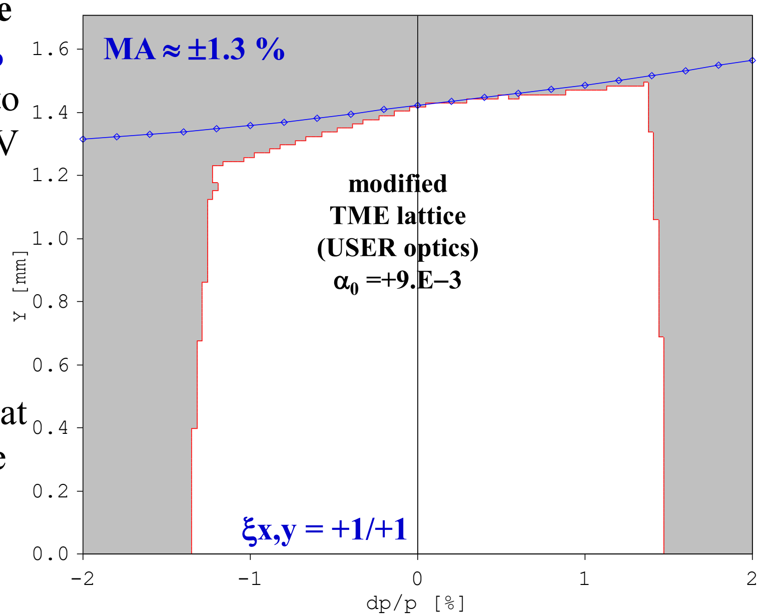
$$MA_L \sim \frac{1}{|D_\pm|}$$

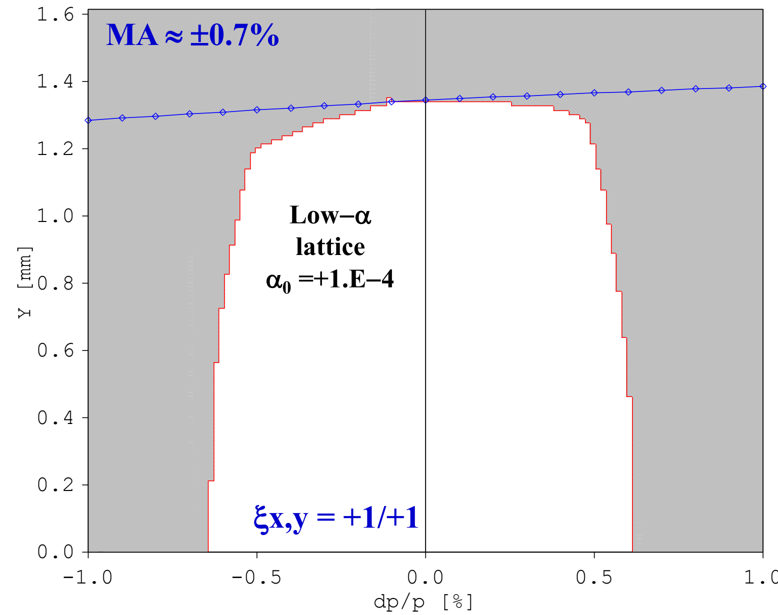
MA of KARA lattice is even less at **negative–α**

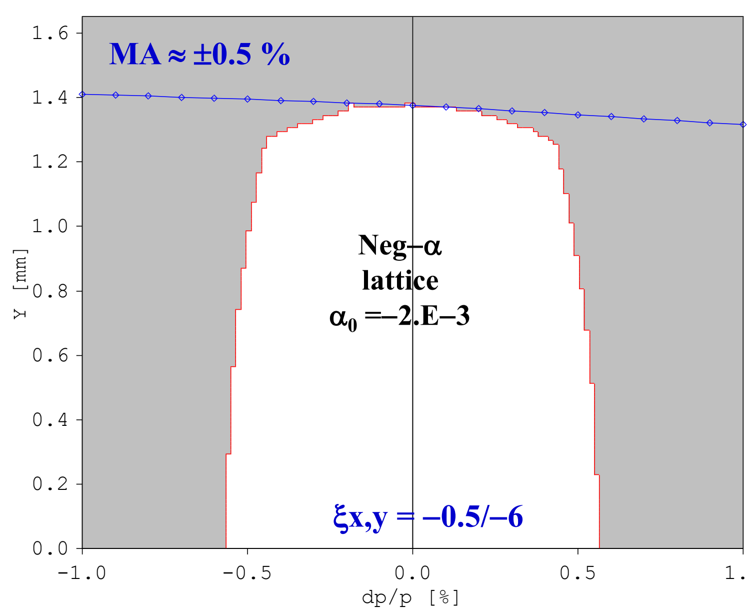
Reduced acceptance of lattice limits total MA at low/neg–α

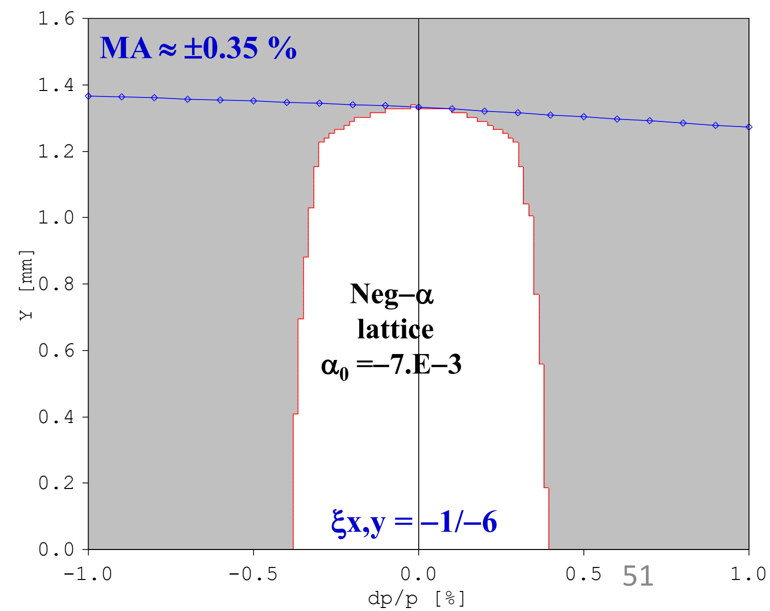
As consequence, the Life Time drops

Scrapers Aperture
Ah= ±13 mm
Av=±7 mm









- At 0.5 GeV the Touschek effect gives main contribution to beam losses for all described lattices. According to simulations for modified TME lattice at 0.5 GeV, the calculated life time is ~1.5 h at low beam current (0.1 mA/bunch) and 0.26 MV RF voltage amplitude. Results of simulations agree with experimental data. For same conditions, but at negative−α optics simulations predict **reduction** of life time to $T_{1/2} < 0.3$ hour.

- Applying of **high** RF voltage is **excessive** during **injection** into **negative−α** optics as well as into new positive low−α lattice. At 0.5 GeV the energy losses due to synchrotron radiation are < 1 keV/turn

- The **high** RF voltage leads to bunch **compression** causing **growth** of intra-beam scattering rate and **reduced Touschek** life-time

- Simulations predict increase of life time of 0.5 GeV beam in 3 to 4 times by reduction of RF voltage from 260 kV down to ~20 kV for negative−α mode

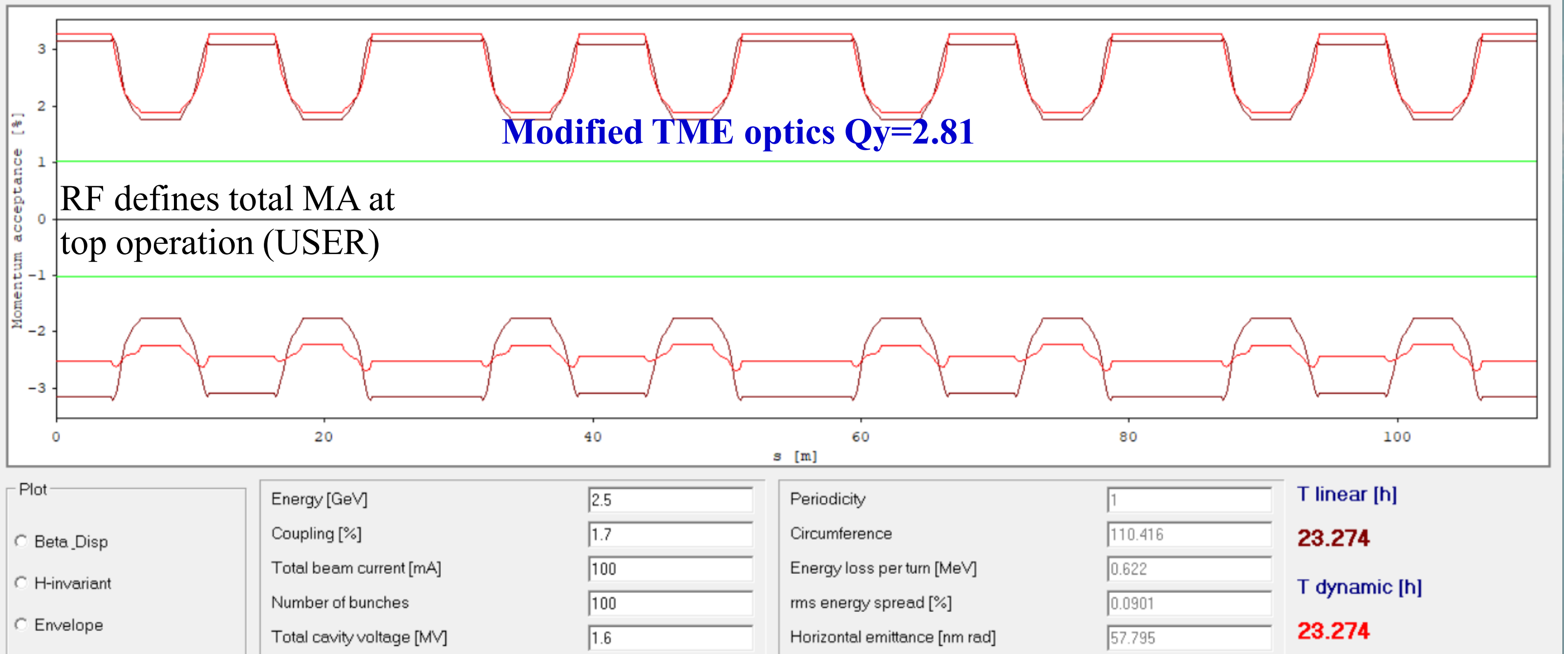
- During direct injection into negative−α lattice as well as into positive low−α lattice the amplitude of RF voltage was **decreased** from 260 kV down to 30−50 kV and life time was **restored** from ~20 minutes to $T_{1/2} \approx 1.5$ hour

- Current of bending magnets and RF frequency have been optimized to get a good injection rate at negative−α (as well as positive low−α) injection tests

KIT Karlsruhe Institute of Technology

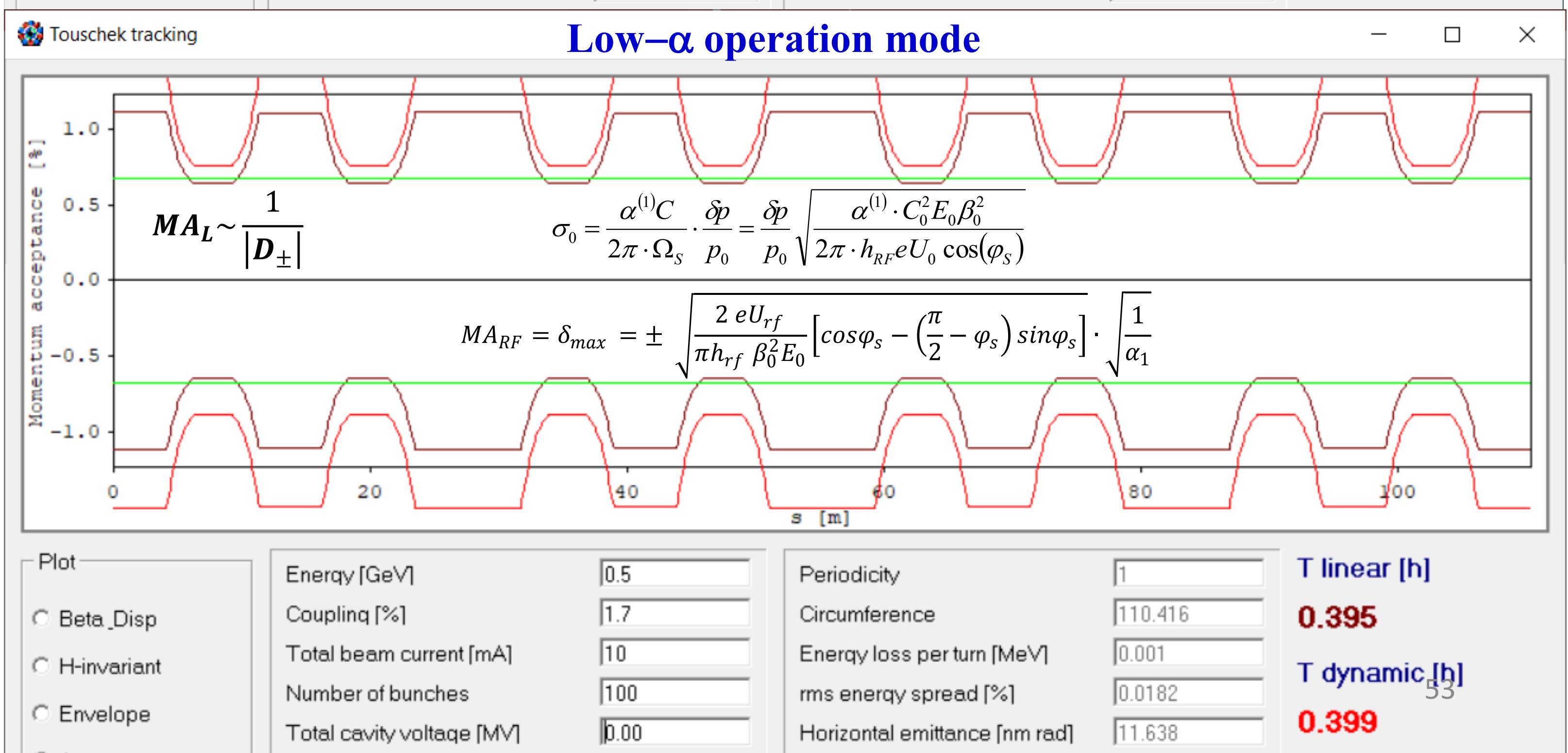
MA of ring lattice at modified TME mode is **±2% (red)** and it is reduced by scrapers to **±1.3%**

RF limits MA to **±1% (green)** at E=2.5GeV at max available U=1.6 MV



at **Low–α** the MA of lattice is reduced to **±0.7% (red)** due to high span of ***D.***
MA(RF)>MA(lat)

Excessive RF voltage is **decreased** during direct injection into **Low–α** optics in order to elongate bunch, reduce Touschek loss rate and improve Life Time

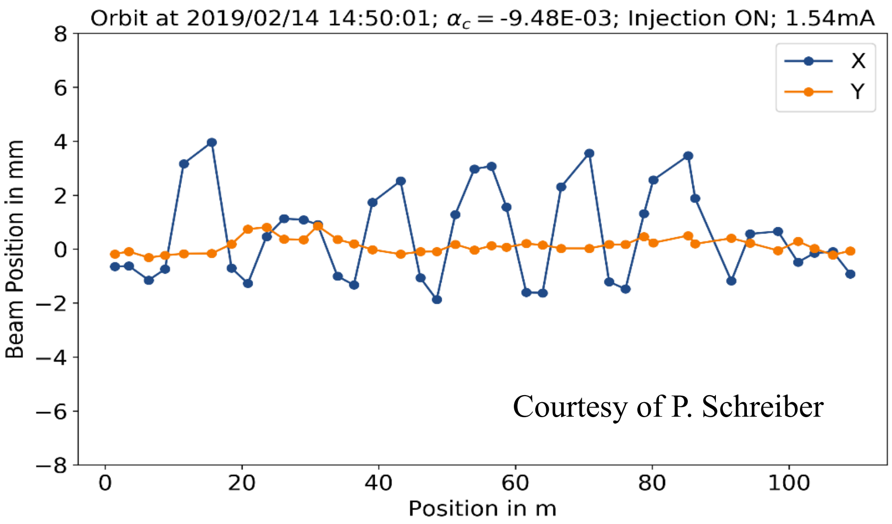


- good injection rate at KARA when beam trajectory is captured by high dispersion pattern
- injection rate drops to zero if span of radial oscillations is reduced by adjusting of RF frequency

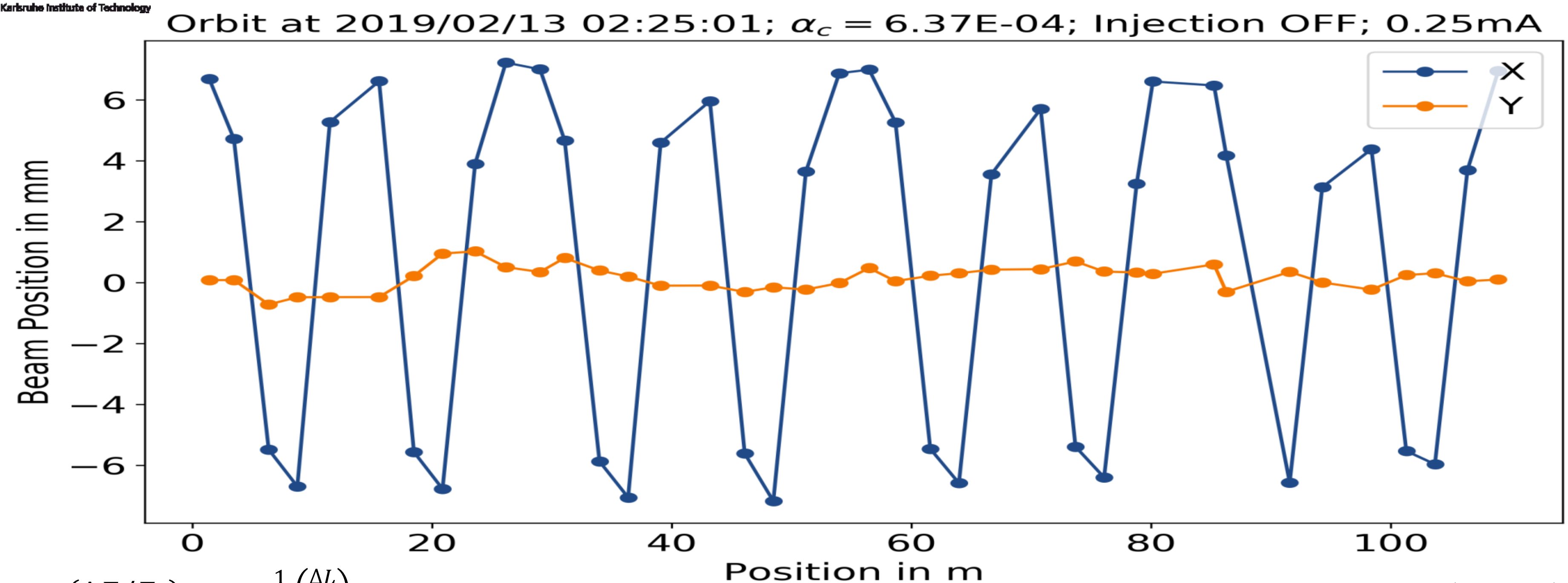
- $(\Delta E/E_0)_{COD} = \frac{1}{\alpha}\left(\frac{\Delta L}{L_0}\right)_{COD}$

- $\Delta A_x = D_{max} \cdot (\Delta E/E_0)_{COD}$

  COD - Closed Orbit Distortions



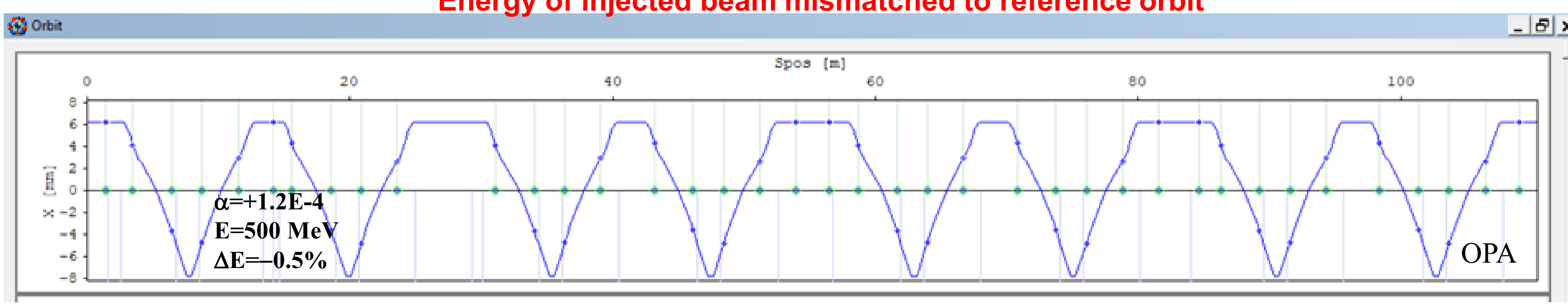
- Beam trajectory was reproduced in simulations
- **Energy offset** between injected beam and reference orbit (magnetic rigidity of ring) could cause effect of orbit mismatching
- at **negative–α** and single bunch operation up to **0.8–1 mA/bunch** of beam have been stored so far
- at negative–α and multi-bunch operation total beam current is limited by transverse mode coupling instability (TMCI) as well as by micro-bunching instability.
- Further tests and simulations are in progress to improve injection rate, minimize span of orbit oscillations and increase beam current



$$(\Delta E/E_0)_{COD} = \frac{1}{\alpha}\left(\frac{\Delta L}{L_0}\right)_{COD}$$

$$\Delta A_x = D_{max} \cdot (\Delta E/E_0)_{COD}$$

Energy of injected beam mismatched to reference orbit



Orbit oscillations of beam in the horizontal plane of the KARA storage ring with low–α. Random position errors (Closed Orbit Distortions) of magnets generate residual orbit lengthening and associated energy mismatching magnified by low–α: (a) measured data [4]; (b) Beam with energy offset δ = –0.5% (OPA simulations).

The total contribution of orbit oscillations to the orbit lengthening of the KARA storage ring is given by

$$\left(\frac{\Delta L}{L_0}\right)_{COD} = 740\left(\frac{x_{cod}^2}{L_0^2}\right) + 0.5\left(\frac{x_{cod}^2}{\rho^2}\right) \tag{74}$$

Because the quadratic terms of misalignment errors cause oscillations of a beam around a reference trajectory, the orbit length, and average orbit radius, are different from the reference ideal orbit. As a consequence, the beam energy deviates from nominal value by

$$(\Delta E/E_0)_{COD} = \frac{1}{\alpha}\left(\frac{\Delta L}{L_0}\right)_{COD} \tag{82}$$

For 'user operation', when the value of momentum compaction factor is relatively high and dispersion function is always positive, one can compensate small energy offsets by variation of the RF frequency and center orbit. During low–α operation, energy offsets grow essentially even at small orbit misalignment and the amplitude of orbit oscillations at low–α is magnified by high values of a stretched dispersion function

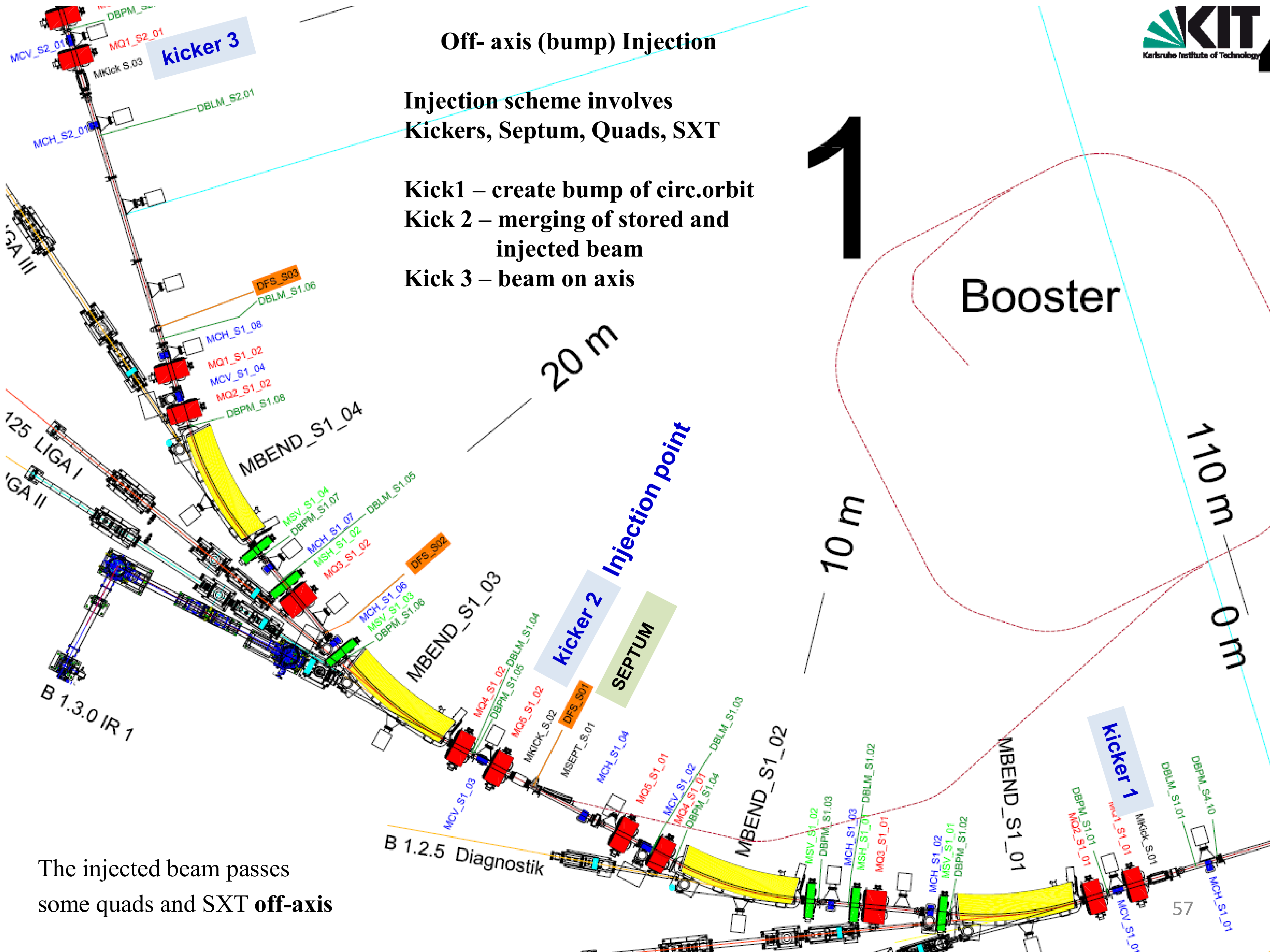
$$\Delta A_x = D_{max} \cdot (\Delta E/E_0)_{COD} \tag{83}$$

During low–α experiments at the KARA storage ring, beam orbit oscillations with span $\Delta A_x \approx \pm 8$ mm have been measured**.** We've estimated the energy offset due to COD errors and misalignments to be as high as $\Delta E \approx -0.5\%$

Off- axis (bump) Injection

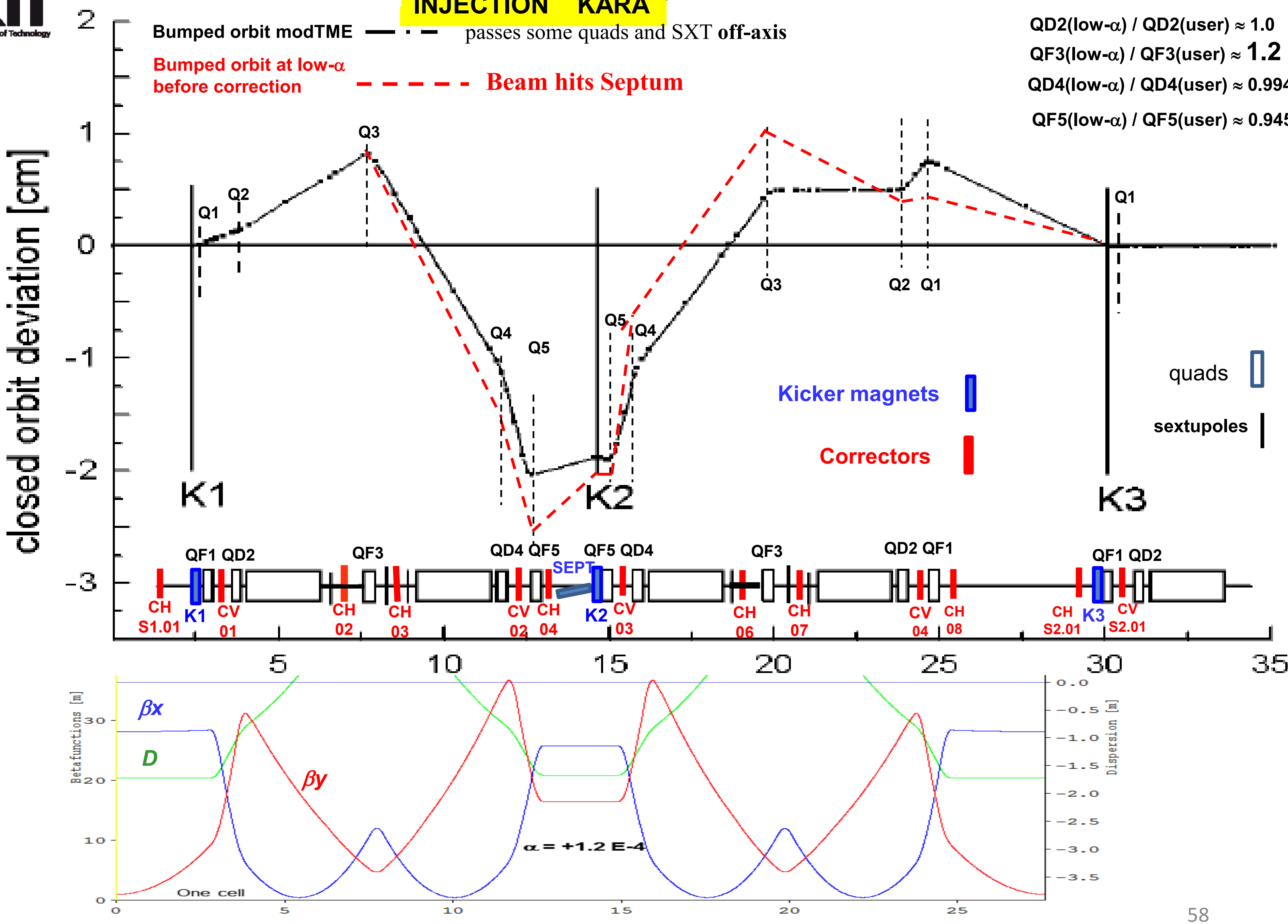
Injection scheme involves Kickers, Septum, Quads, SXT

Kick1 – create bump of circ.orbit
Kick 2 – merging of stored and injected beam
Kick 3 – beam on axis



The injected beam passes some quads and SXT **off-axis**

INJECTION KARA



KARA injection at low-positive/negative–α operation modes

- **Off-axis** Injection scheme of KARA ring involves septum, three kicker magnets
- few quads and SXT located in injection sector of ring

- The injected and stored bumped beam passes some quads and sextupoles **off-axis**

- In order to **stretch** dispersion and create negative contribution of dispersion function at low–α and even more at negative–α optics, **strength** of Q3 quads should be essentially **increased**

- Beam **hits** septum after first turn, if kickers settings will **not be changed** from TME optics to new positive low–α lattice and same for negative–α lattice

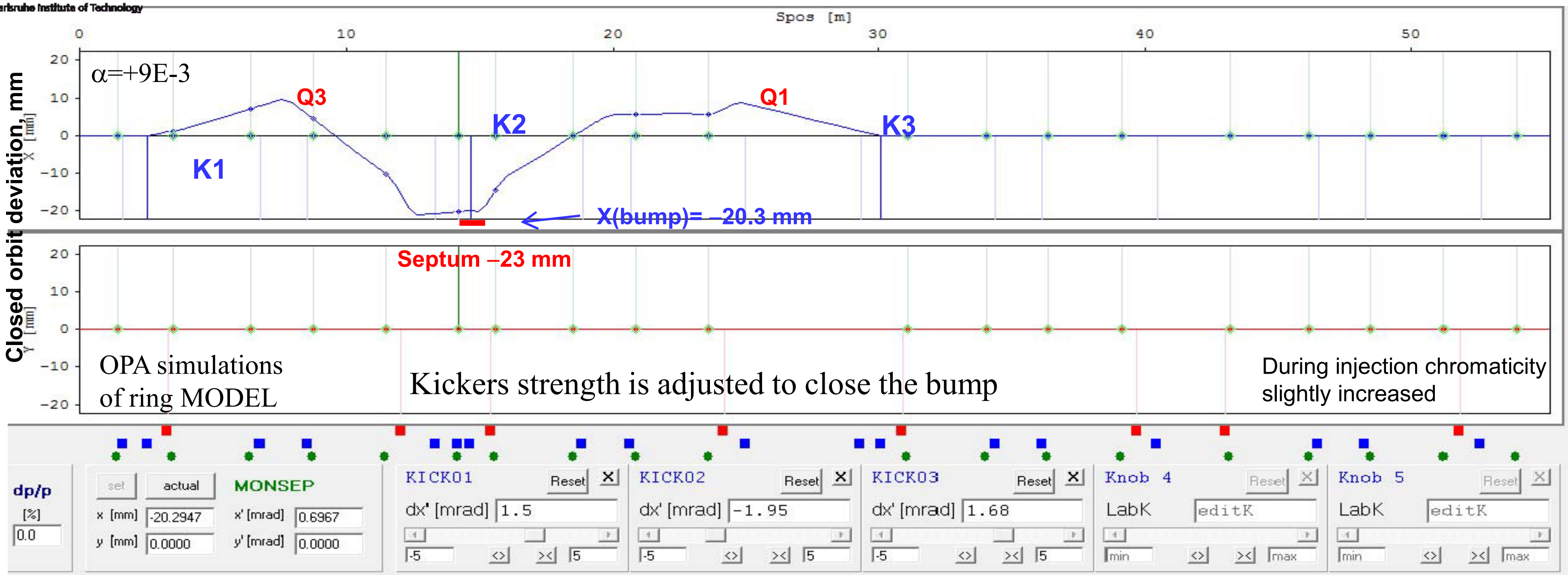
- Field strengths of all three kickers were **calculated** in **KARA model** and have been subsequently **reduced** during tests

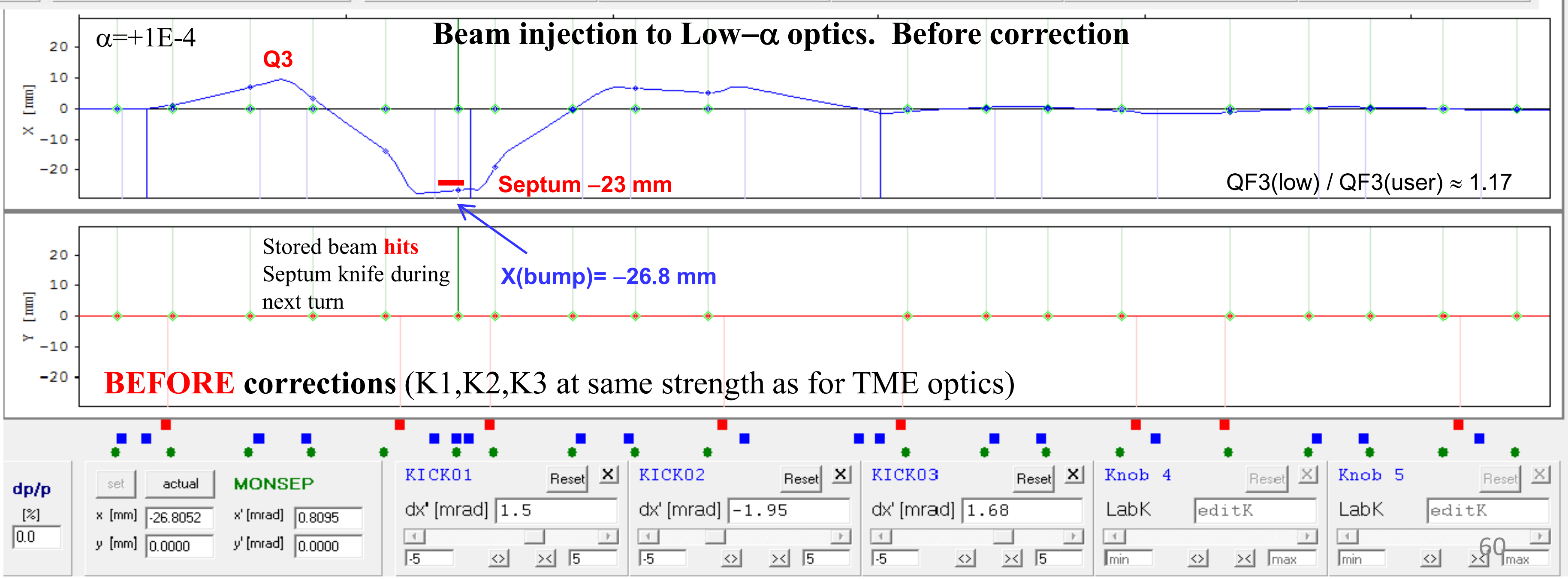
- Beam was successfully stored at the **new positive low-α mode**

- Based on model predictions and experience gained at direct injection of 0.5 GeV beam into the **new positive low–α** optics, settings of all quads, kickers, sextupoles and some correctors have been calculated by Model and **tailored** for injection into the **negative-α** lattice

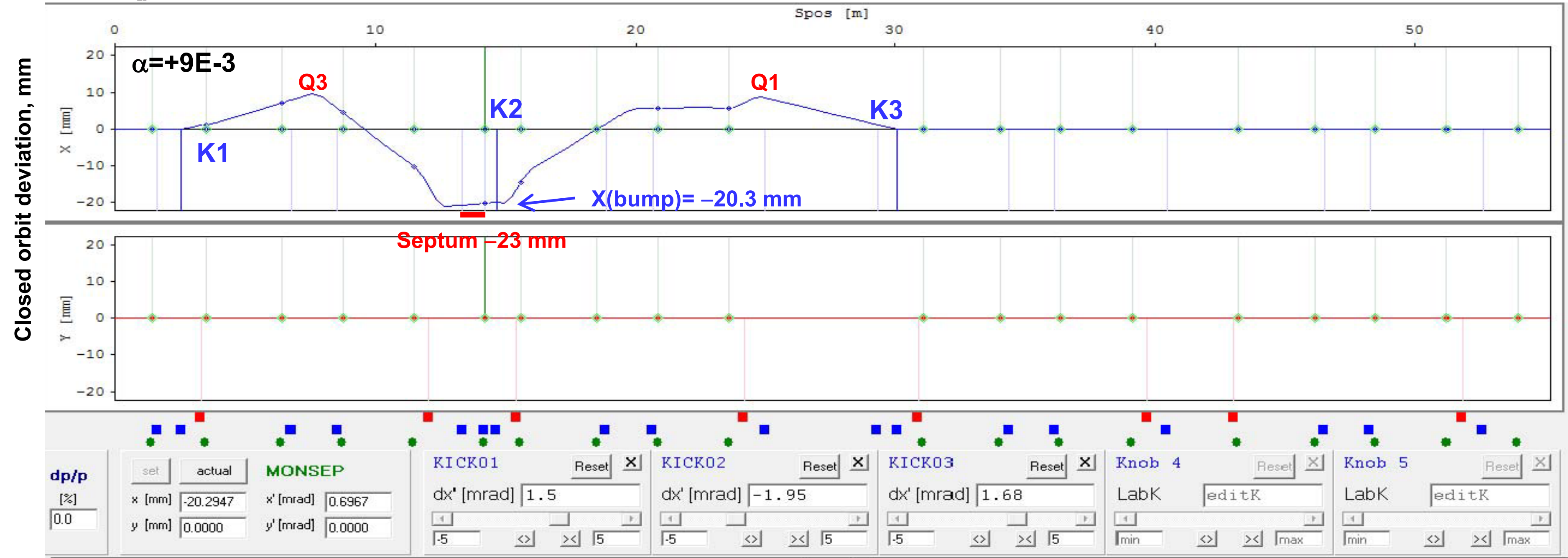
- Finally, the beam has been stored at **negative-α** optics of KARA ring

Beam injection. Modified TME optics

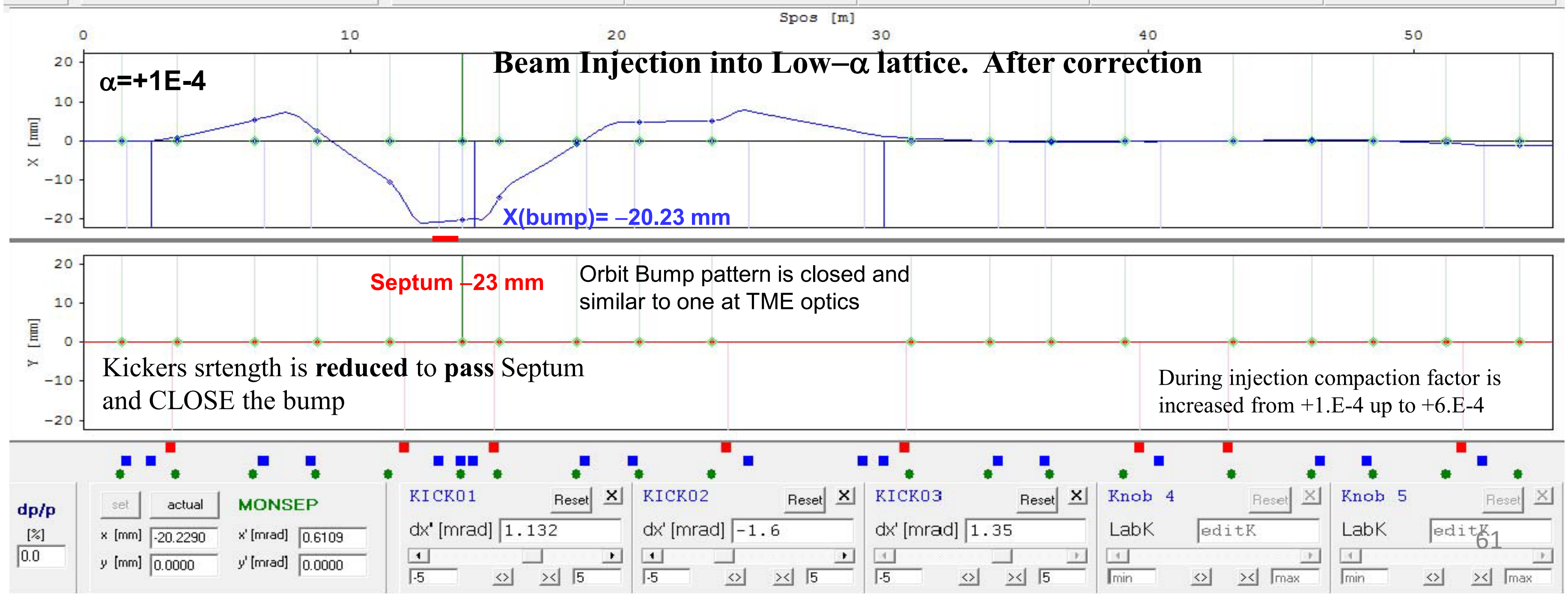




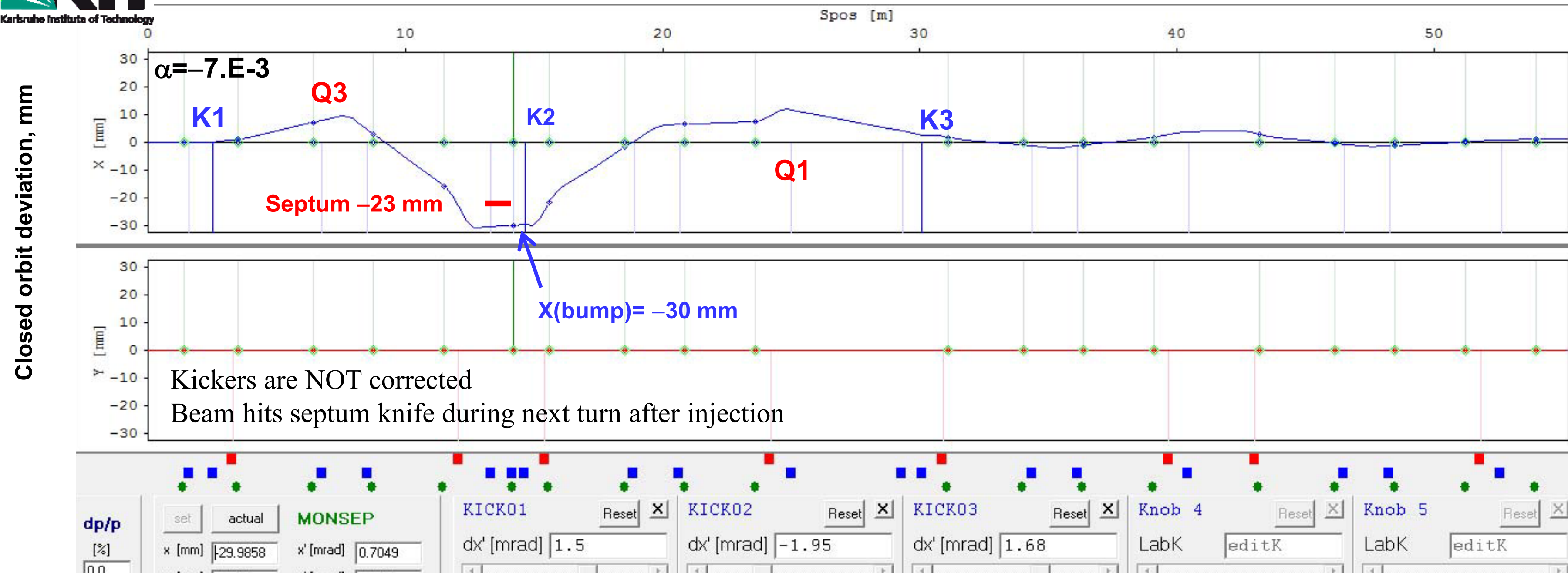
Beam injection. Modified TME optics

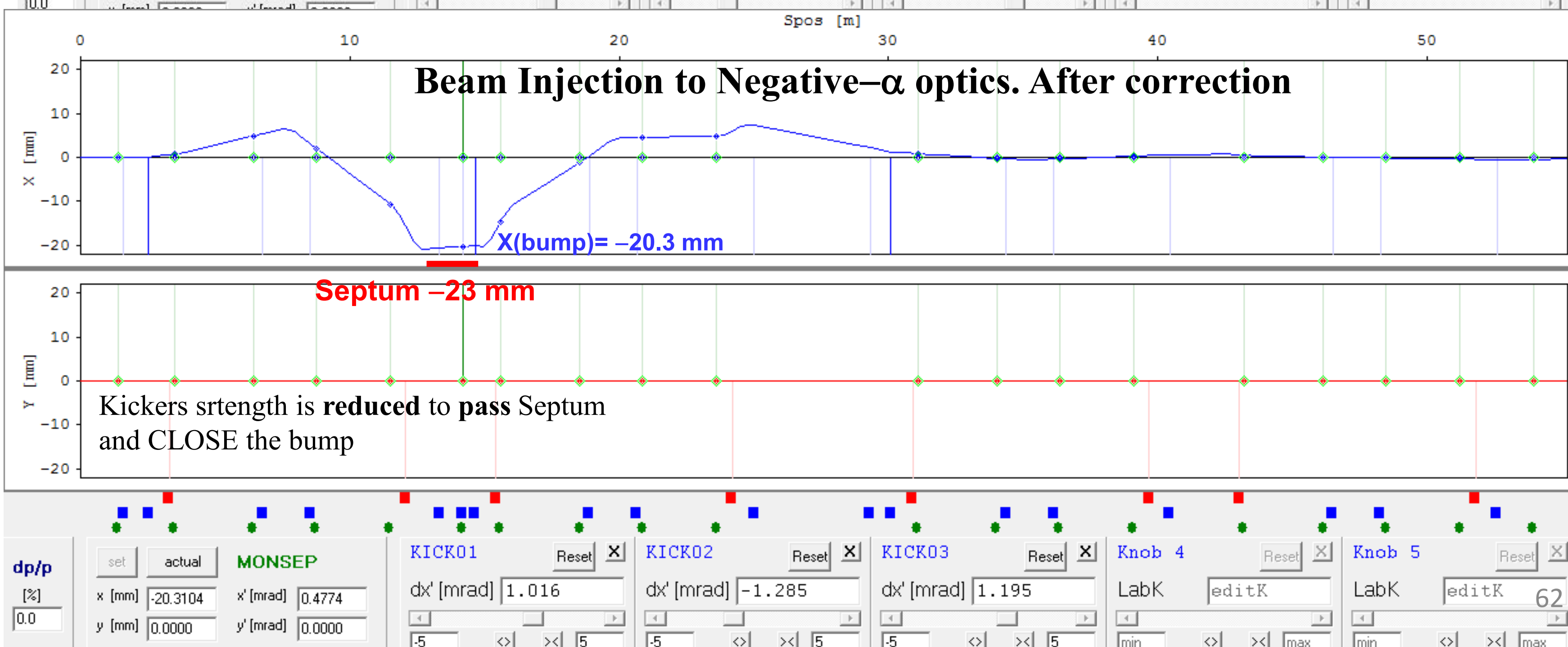


Beam Injection into Low–α lattice. After correction



Beam Injection to Negative–α optics. Before corection





CONCLUSION AND OUTLOOK

- Different operation modes were successfully tested and are in operation at KARA ring
- Life time reduction associated with residual high order non-linear components of wiggler magnetic field has been restored
- Ring performance, life time, and beam current are essentially improved
- Parameters of direct injection into low positive and negative momentum compaction factor optics have been simulated and experiments were performed
- Tests on negative alpha are in progress to deliver a contribution for R&D of future light sources

THANKS