Production of Coherent Synchrotron Radiation at ANKA Using Low-momentum-compaction Lattices

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LABORATORY FOR APPLICATIONS OF COHERENT SYNCHROTRON RADIATION

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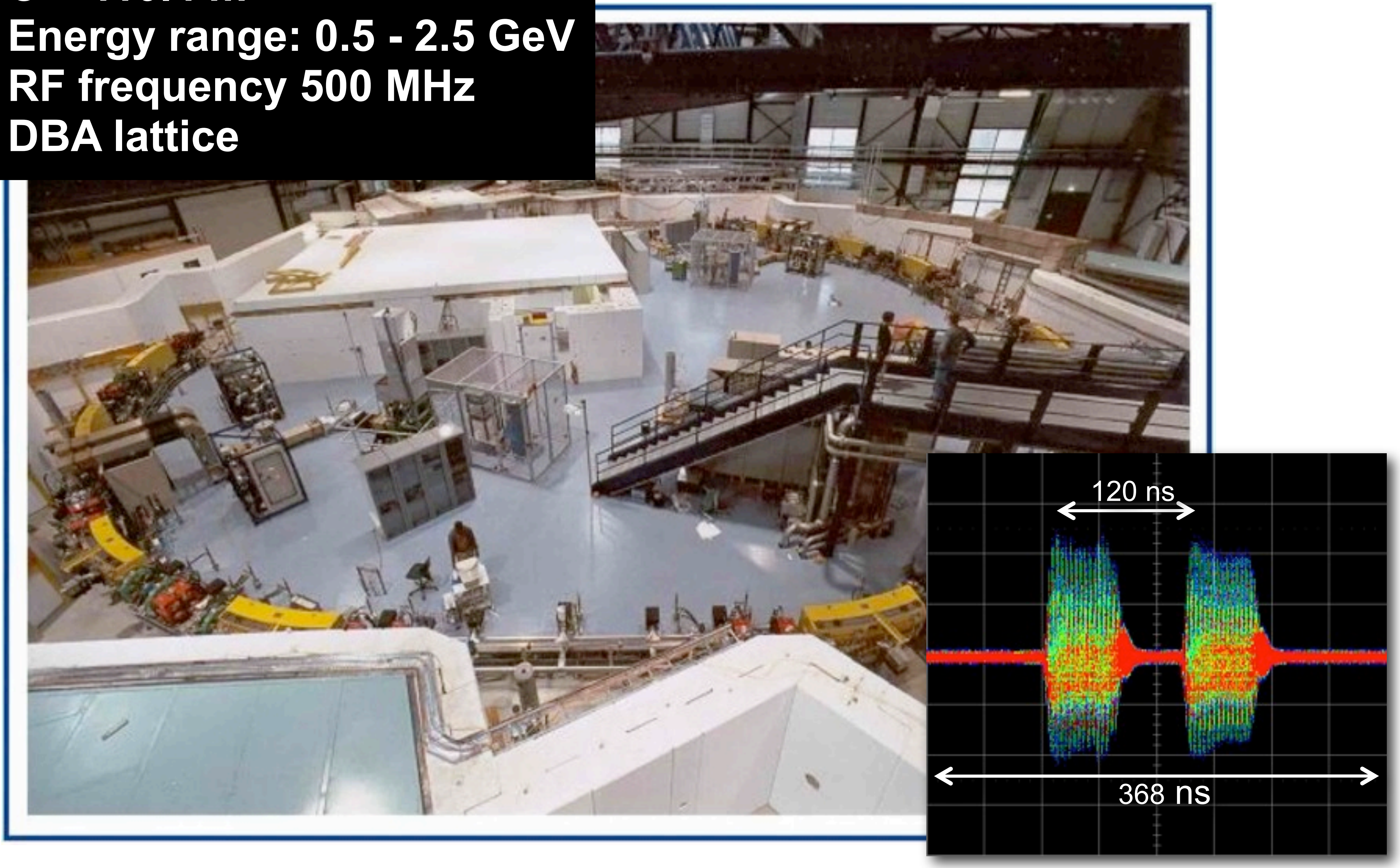
Overview

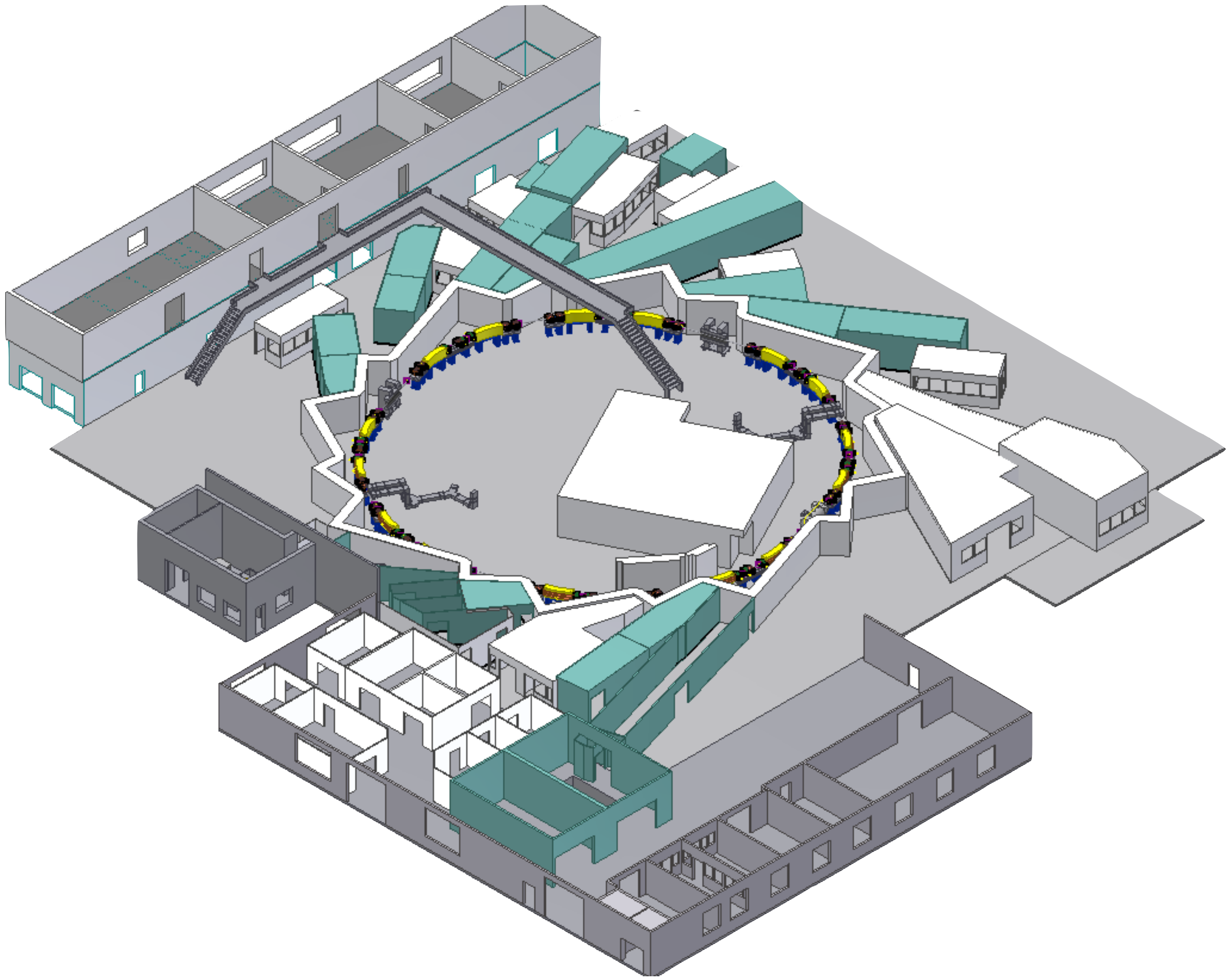
- Introduction
  - The ANKA storage ring
  - Low-alpha mode and CSR production
  - Stable vs. bursting emission
- Measurements with a hot electron bolometer (HEB)
- Measurements with a streak camera
- Spectral measurements
- Modeling the low-alpha mode with the Accelerator Toolbox

The ANKA storage ring

- C = 110.4 m
- Energy range: 0.5 - 2.5 GeV
- RF frequency 500 MHz
- DBA lattice



ANKA - Parameters



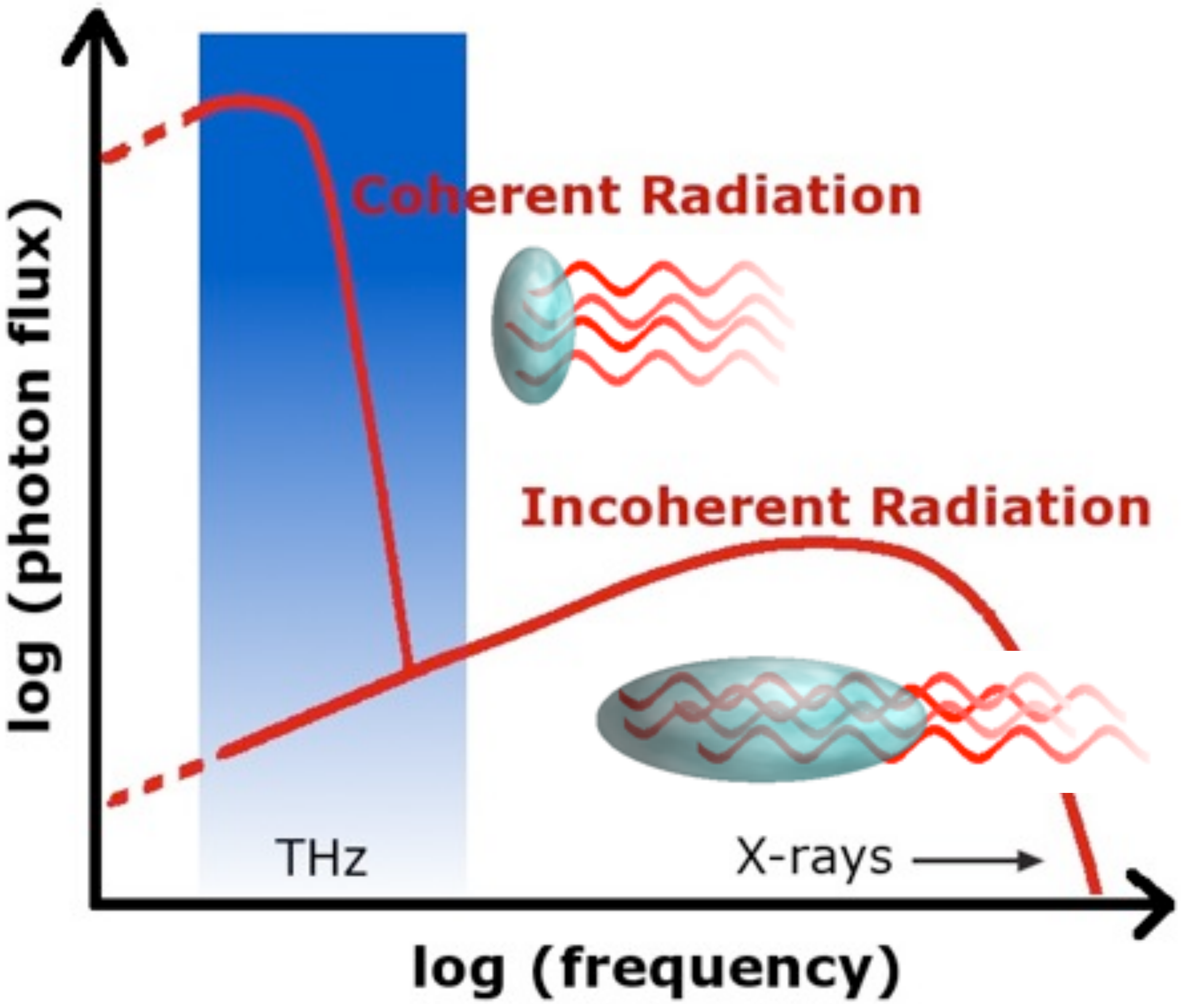
- **Normal operation:**
- Energy 2.5 GeV
- Current 120-200 mA
- Multi-bunch (3 trains with 30ish bunches each)
- **Natural bunch length $\sigma_{z,0} \approx 13$ mm**

- **Low-alpha mode:**
- Coherent THz radiation
- Energy 1.3 GeV
- Current ≈ 0.1 - 70 mA
- Single- or multi-bunch
- **Natural bunch length $\sigma_{z,0} \approx 0.3 - 4.5$ mm**

- **Beamlines:**
- 13 in operation
- 4 in construction / commissioning

Coherent synchrotron radiation (CSR)

- Short bunches emit usable coherent synchrotron radiation
- Enormous increase in power in comparison to incoherent emission
- Dedicated optics with negative dispersion in the long and short straight sections for flexible bunch length tuning
  - Low-α_c optics



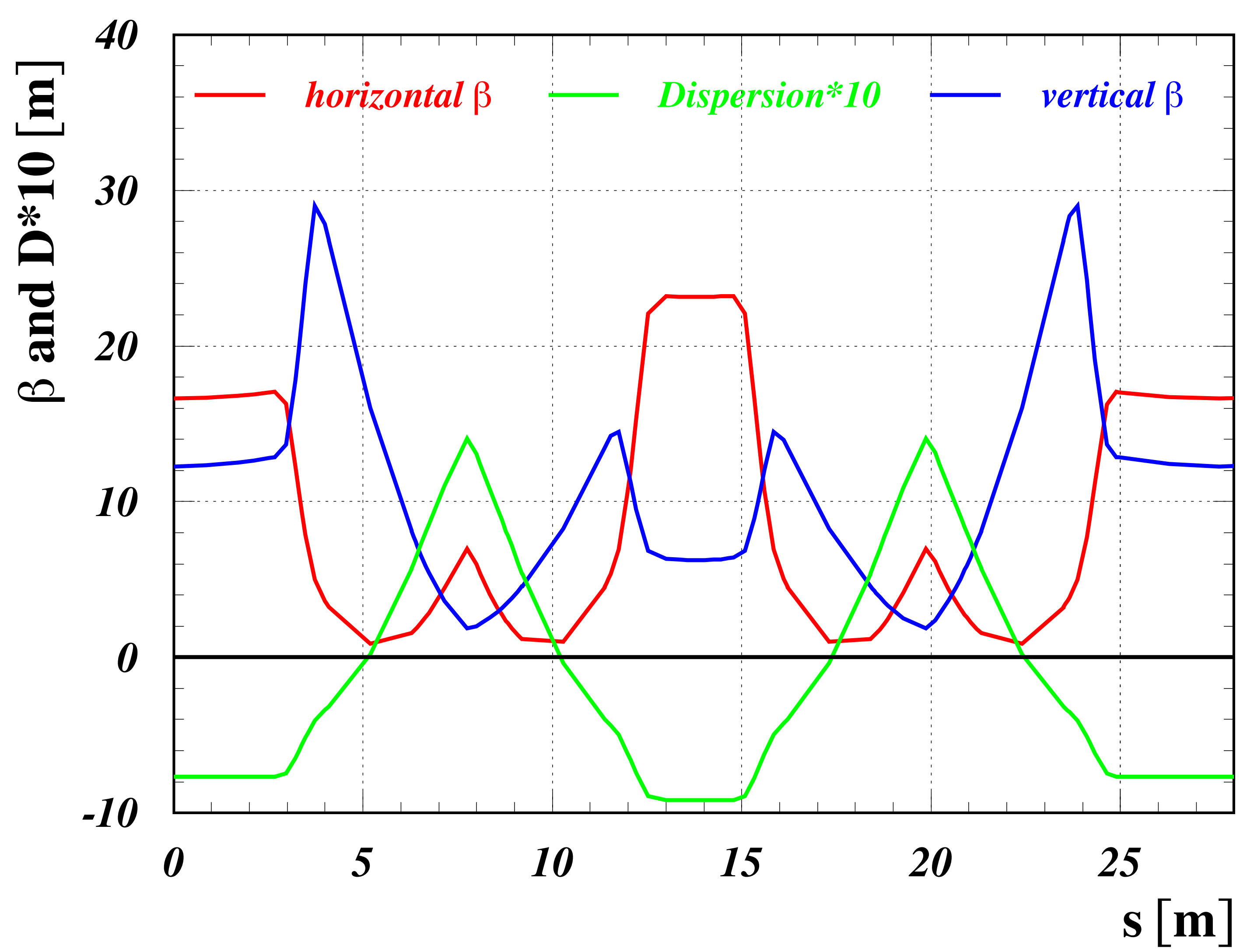
- Coherent radiation is produced in two regimes:
  - low power stable emission
  - high power radiation bursts

The low-alpha mode

- Low-alpha user operation: 12 days/year

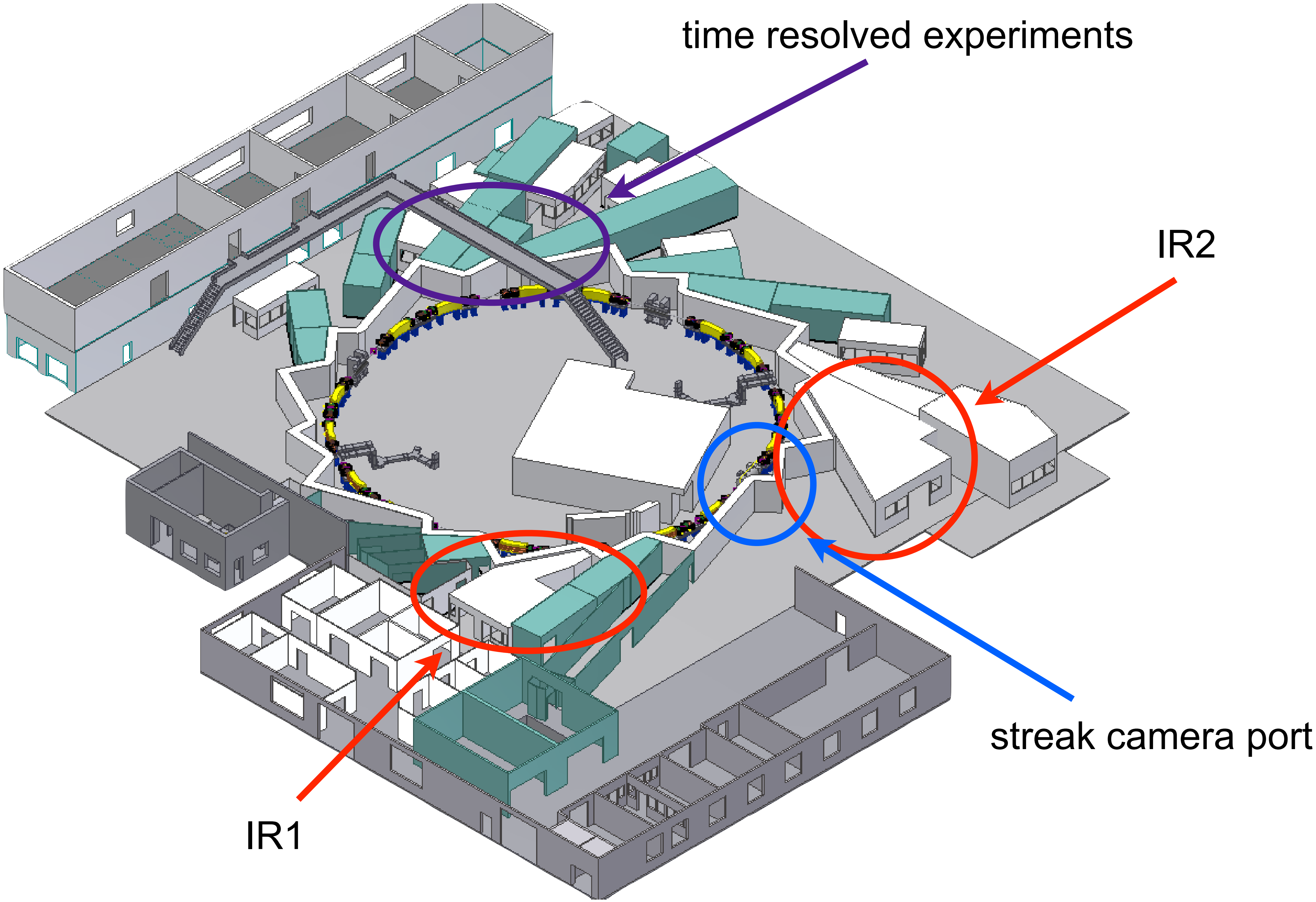
Operation procedure:

- Fill at 0.5 GeV
- Ramp energy (regular optics) to 1.3 GeV
- Low-α_c "squeeze"
  - change quadrupoles & sextupoles
  - orbit correction between steps



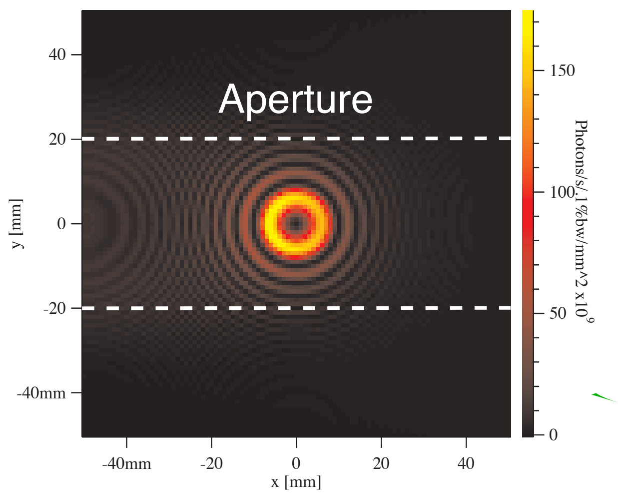
- Observed α_c range as derived from Q_s measurements:
  - from $8.5\ 10^{-3}$ to $2.4\ 10^{-4}$

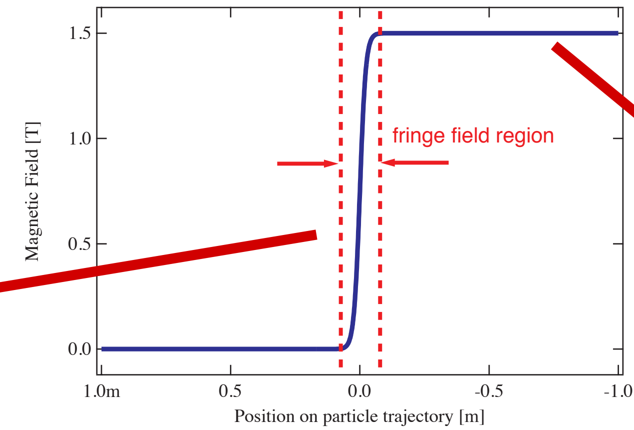
CSR for Users



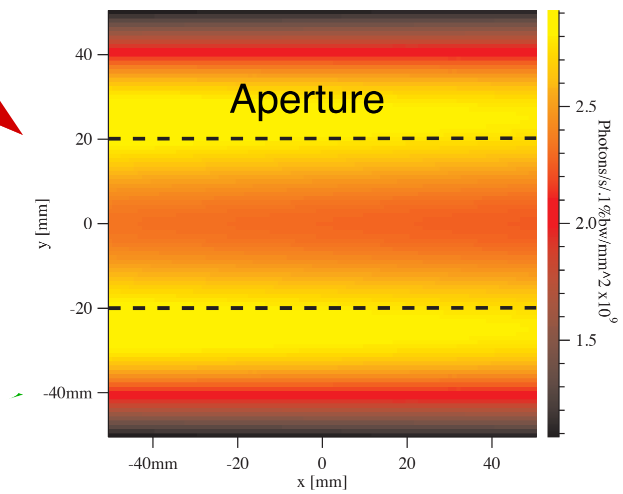
Synchrotron (Edge) Radiation at IR1

Source at ANKA–IR: fringe field

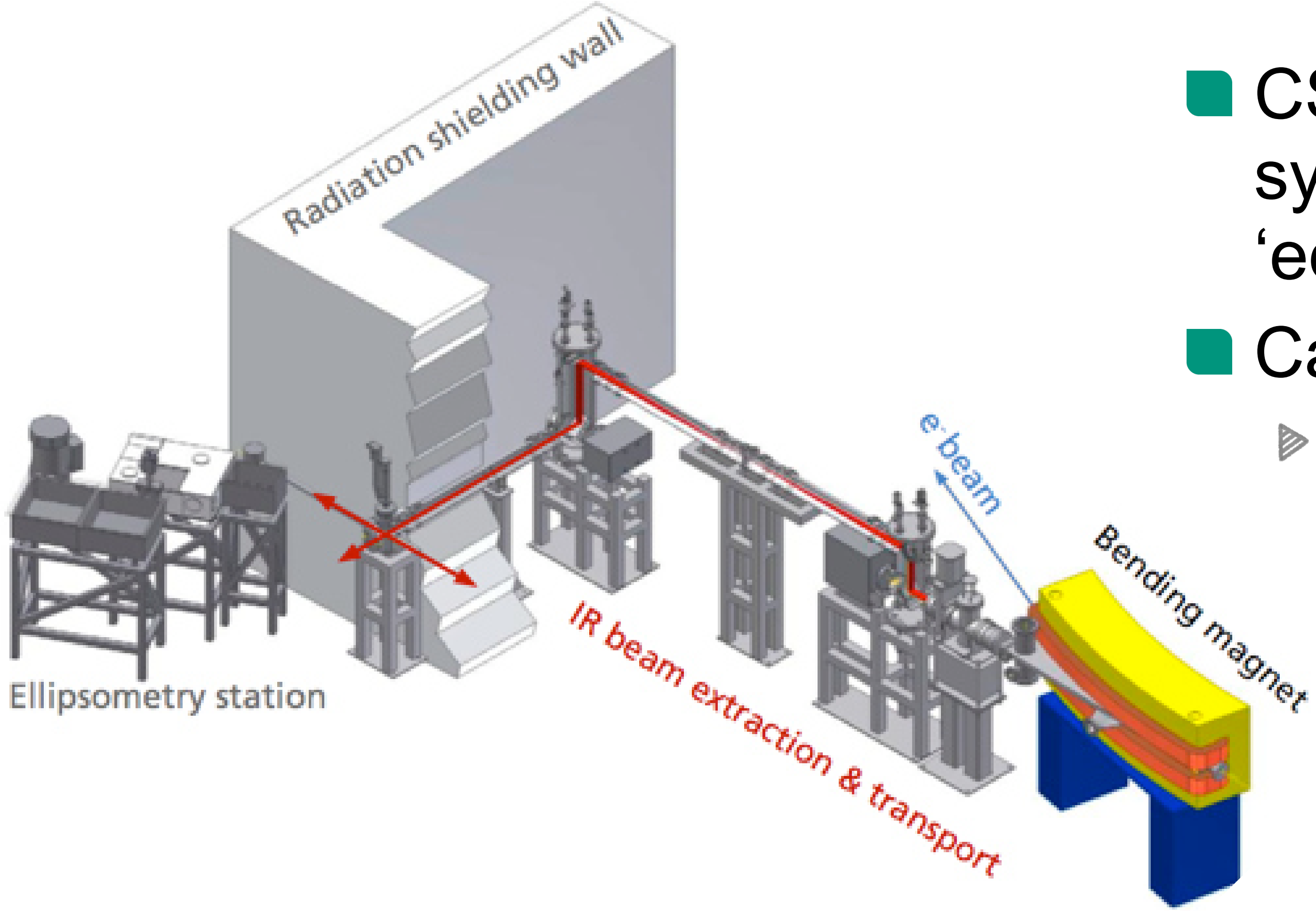




Main bending field as source



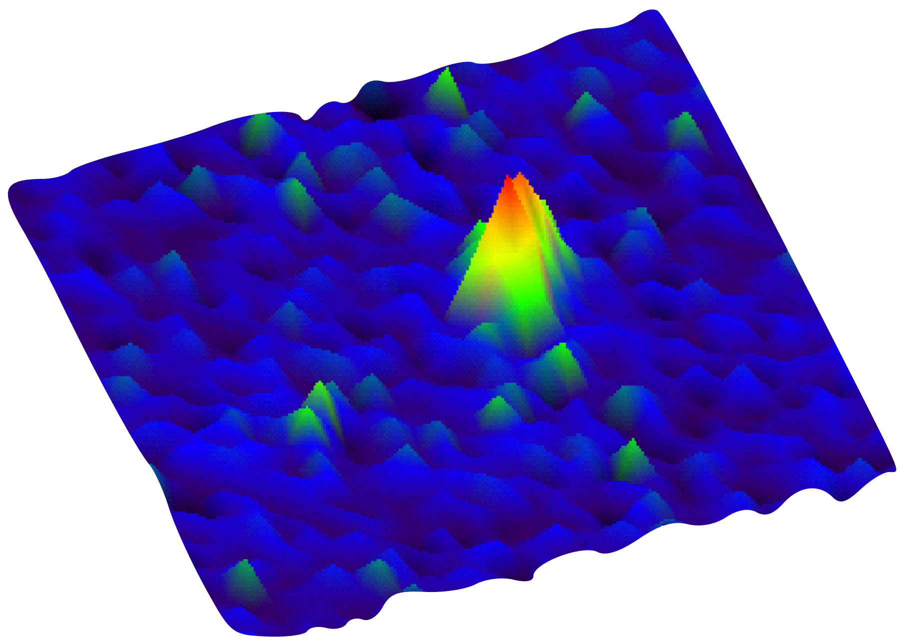
Courtesy Y.-L.Mathis



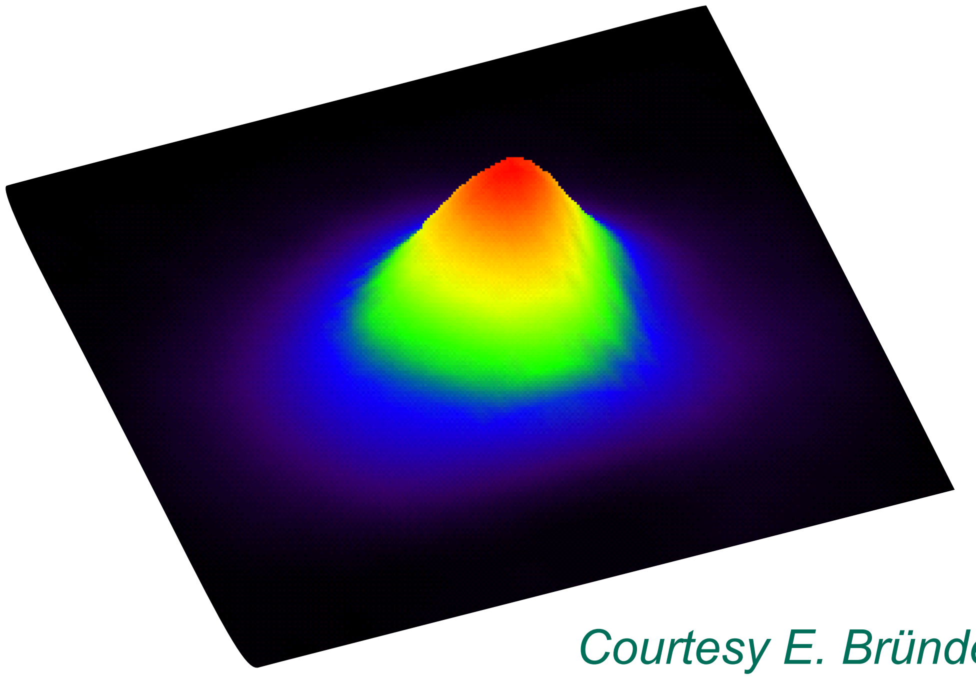
- CSR is observed as ‘regular’ synchrotron radiation but also as ‘edge’ radiation
- Can be an advantage for a beamline
  - lower frequencies observable for the same aperture

The THz Beam Profile

incoherent, $A_{max} \approx 0.1$ mV



coherent, $A_{max} \approx 2.9$ mV



Courtesy E. Bründermann, Ruhr Universität Bochum

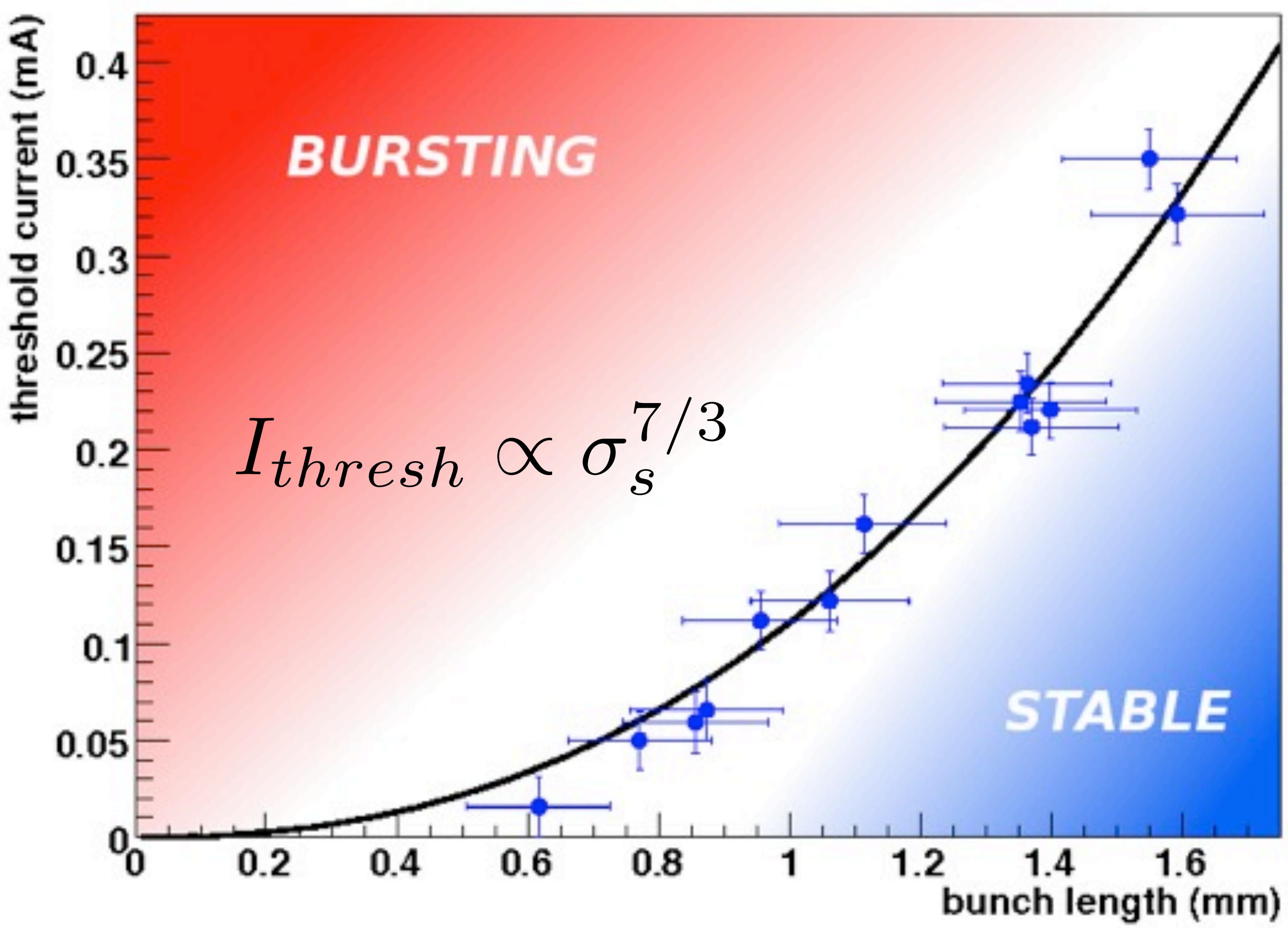
Setup of beam line and detector :

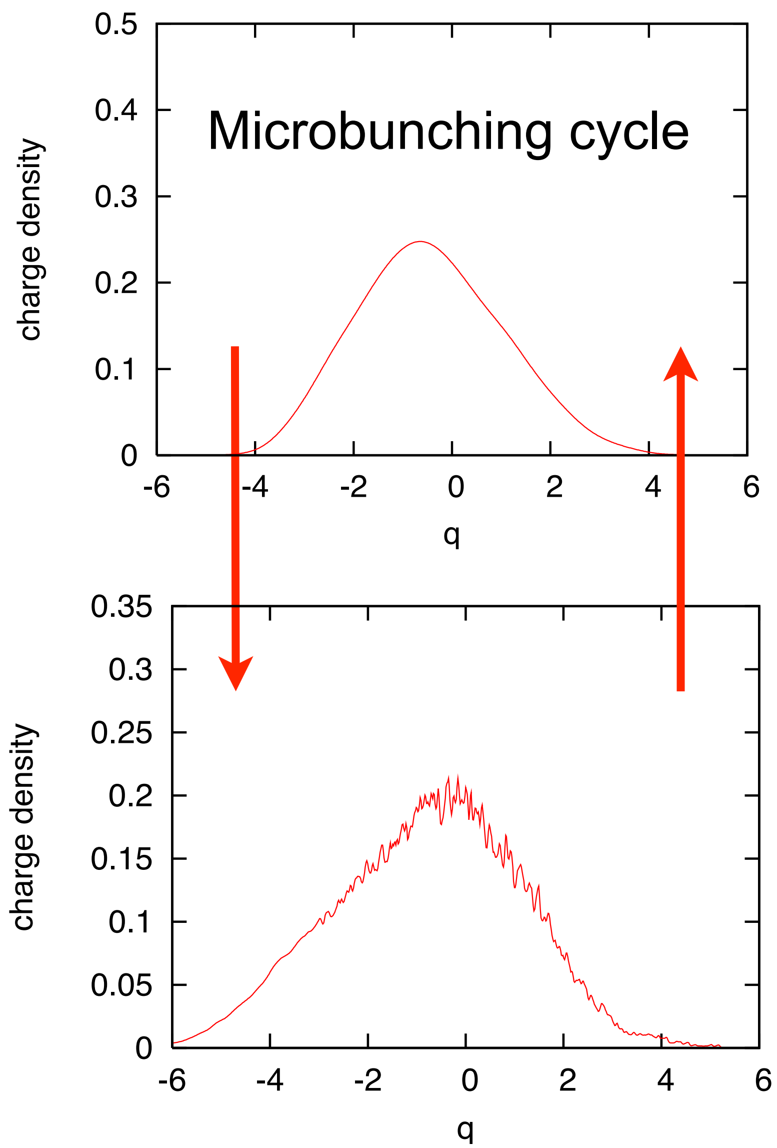
- measurement behind a Si or CaF2 vacuum window
- room temperature pneumatic (Golay) detector
- detector and aperture are mounted on a x-y imaging stage and scanned vs distance and lateral position relative to the vacuum window

The bursting stable threshold

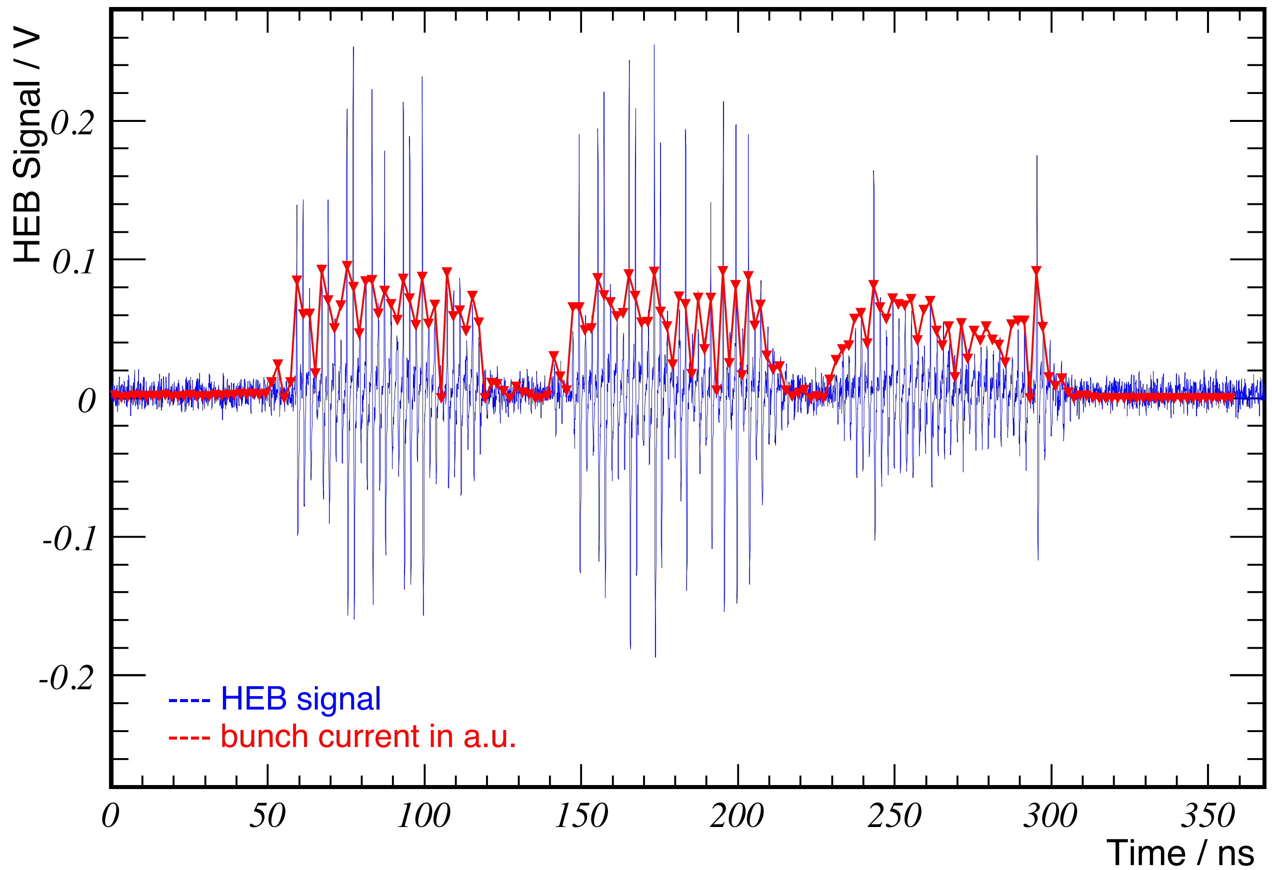
- Hight electron densities lead to microbunching instability
- Measured bursting stable threshold with Si bolometer
- Good agreement with theoretical prediction[+]:

[+]G. Stupakov and S. Heifets,
Phys. Rev. ST Accel. Beams 5, 054402 (2002)

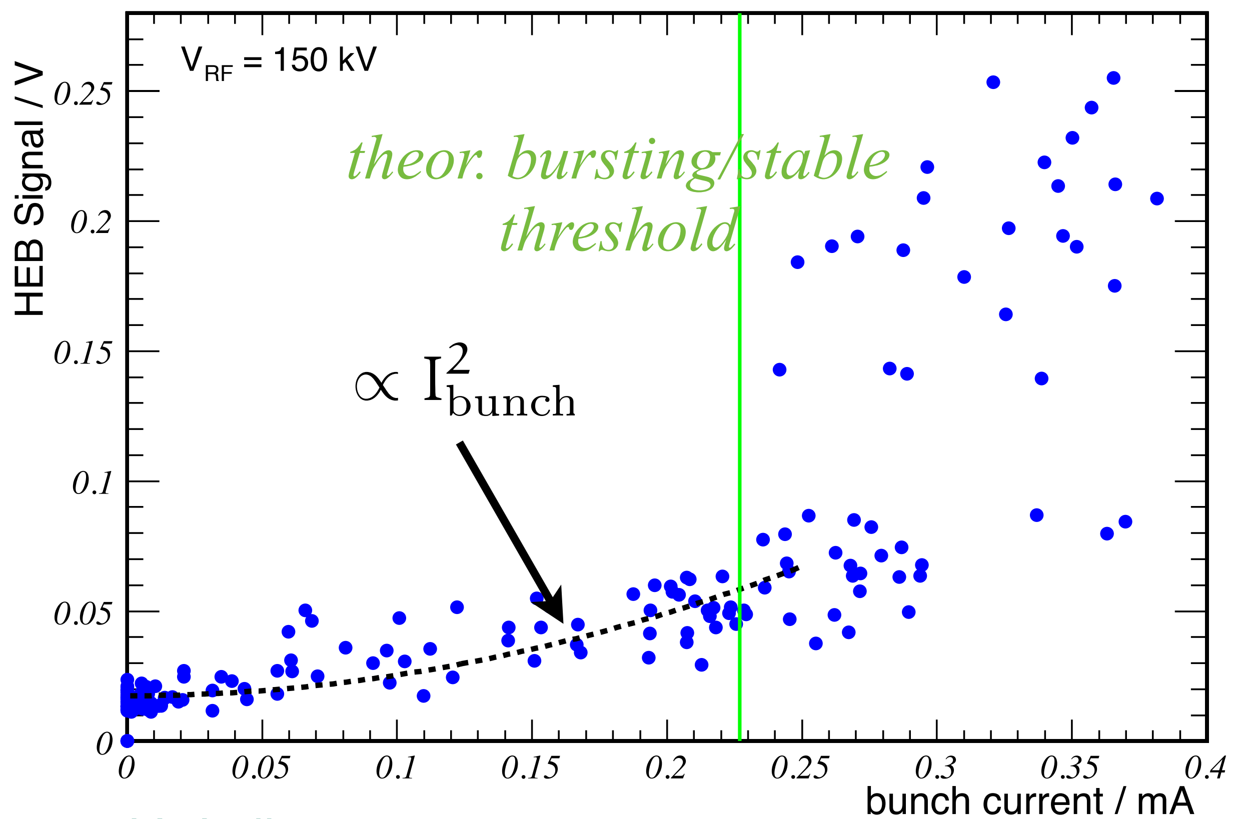




THz Signal and Beam Current

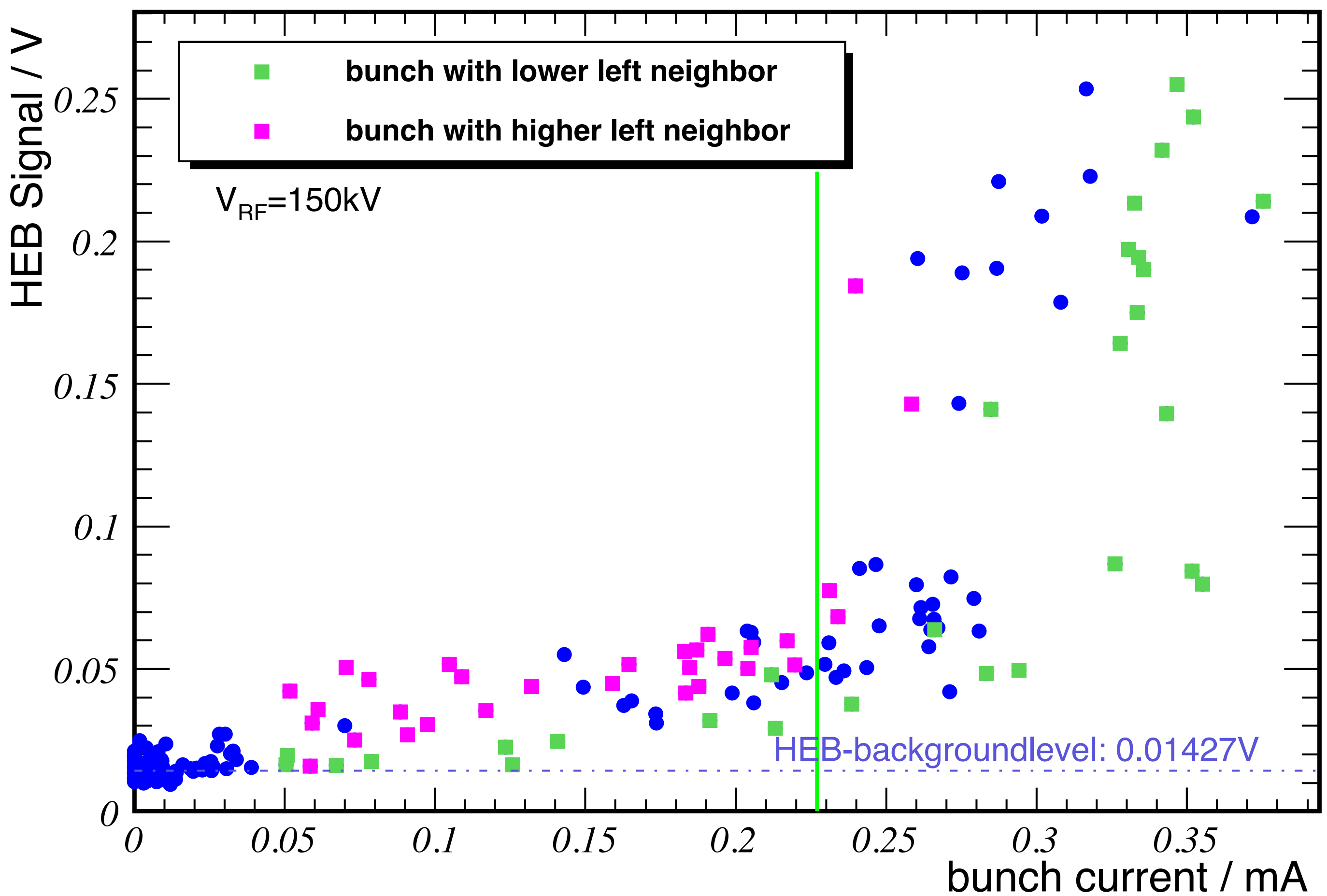


- The Hot Electron Bolometer (HEB) detects the THz signal of individual bunches
- Relative bunch currents from pickup

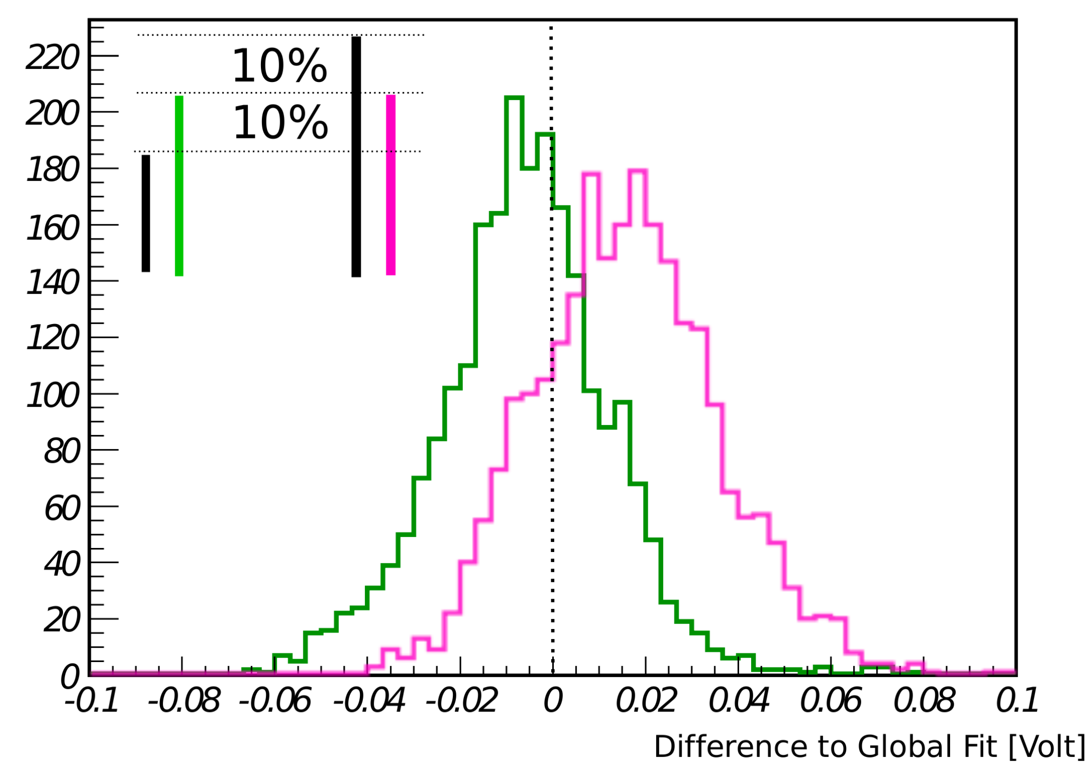


V. Judin

THz Signal and Beam Current



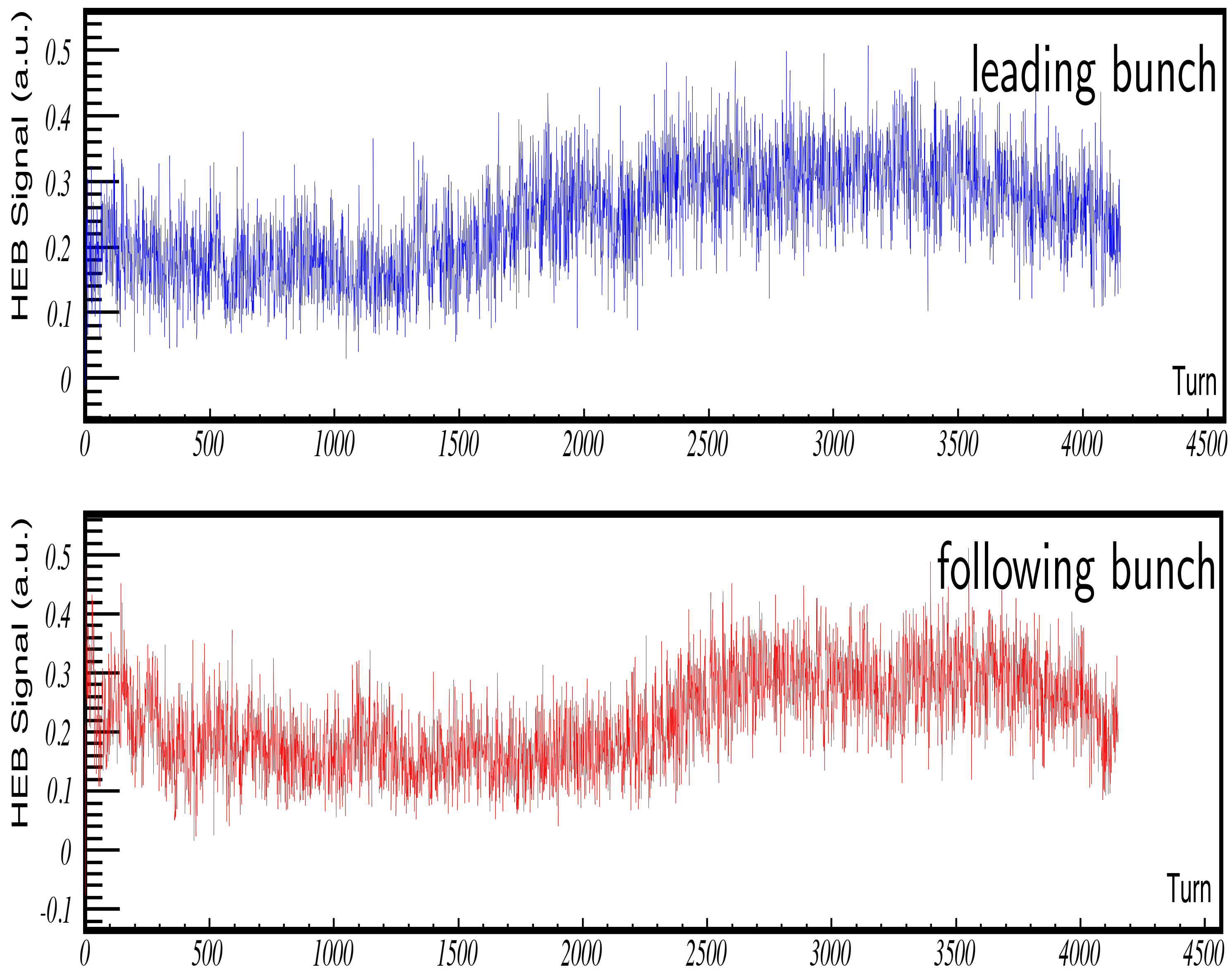
- A comparison shows a dependency of CSR on the current of the leading bunch
  - Investigations with tailor made filling pattern



V. Judin

CSR of Adjacent Bunches

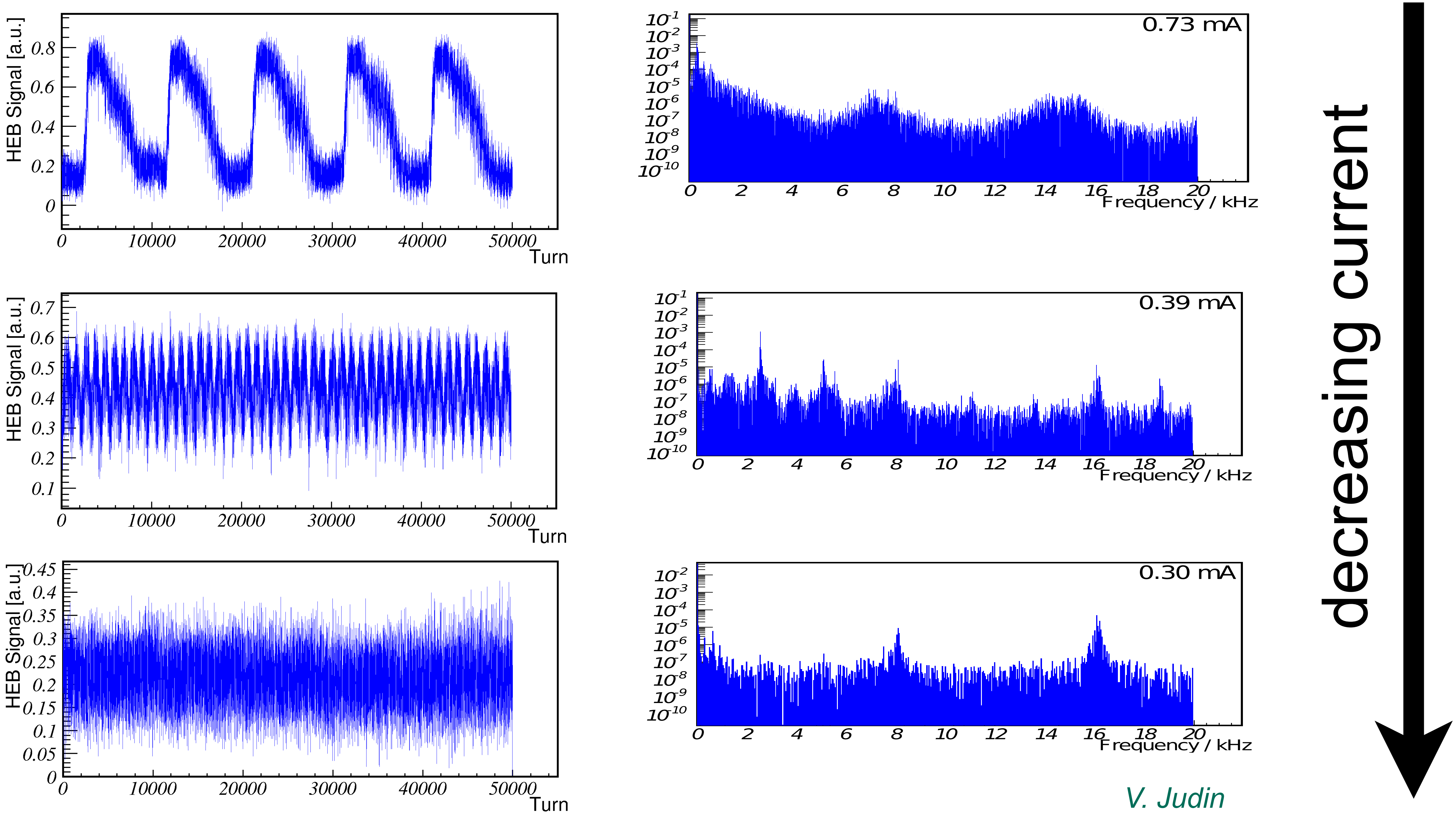
- Correlated bursting?



V. Judin

- Effect is under systematic investigation

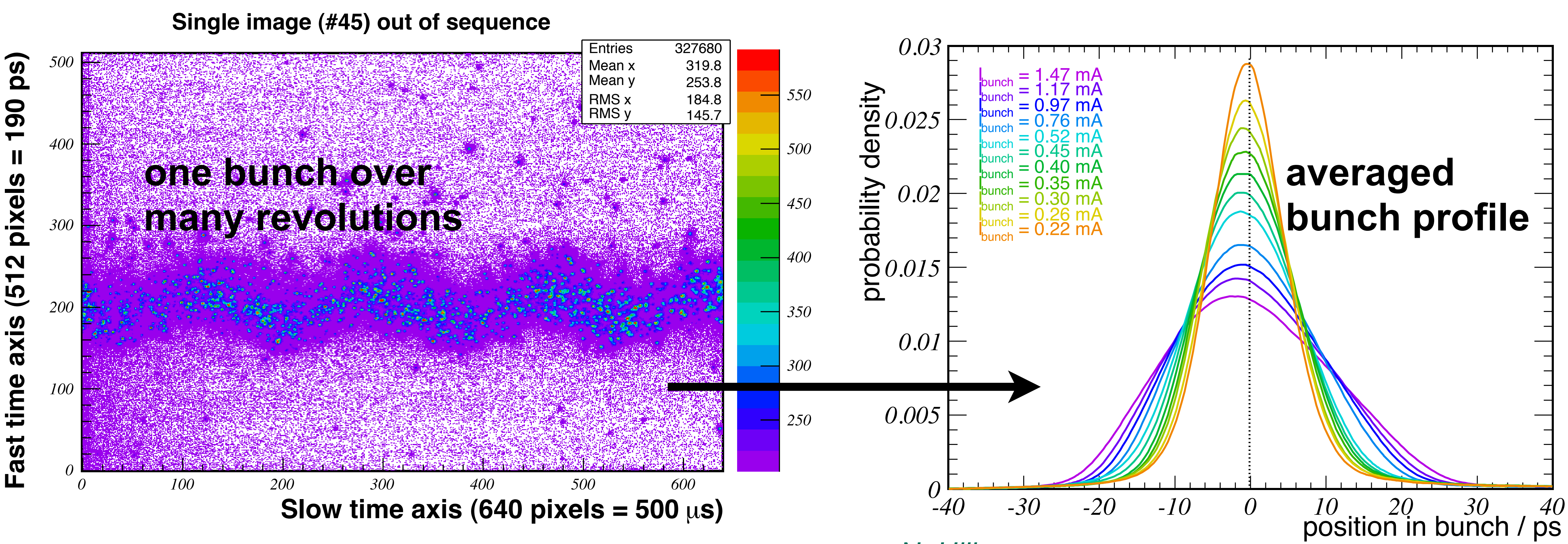
Radiation Bursts



- Bursting behavior dependent on electron density

Streak Camera

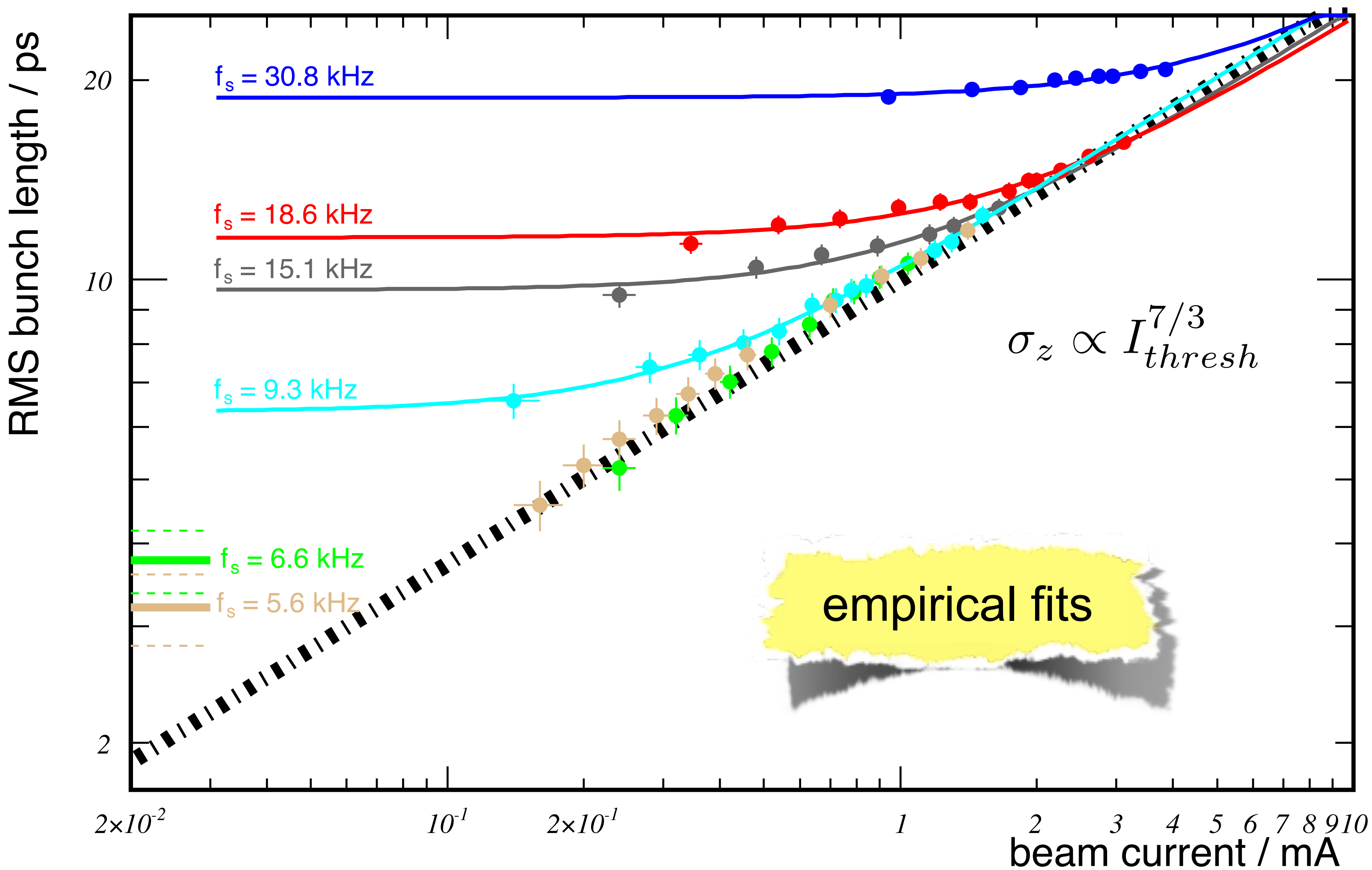
- Double-sweep synchroscan streak camera from Hamamatsu
- Optical port at IR beamline, now new dedicated beam port
- Recording of sequences of 500 consecutive images
- Correct for oscillations



N. Hiller

Bunch length

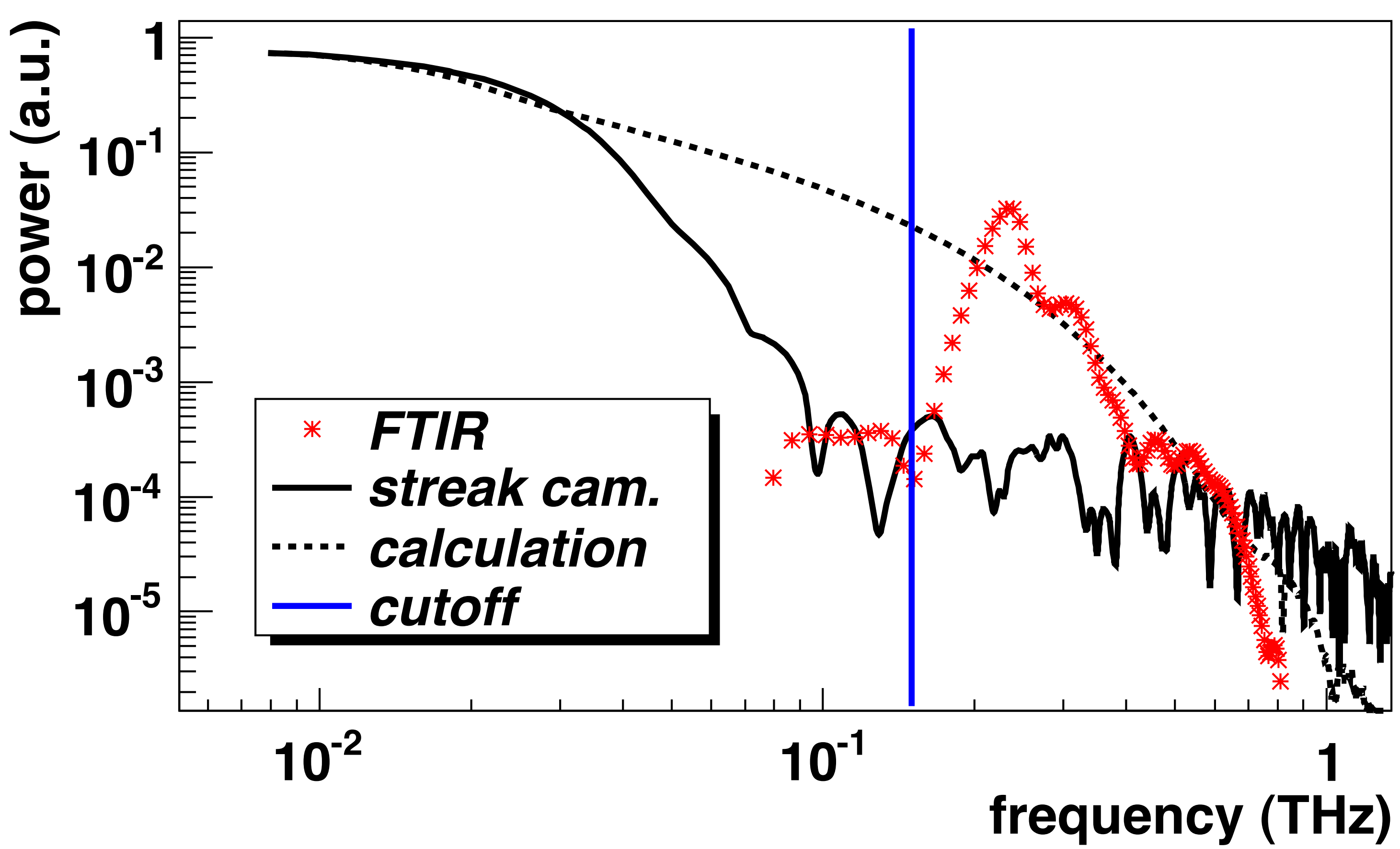
- Low currents: Converging to the zero current bunch length
- Above bursting stable threshold: Turbulent bunch lengthening



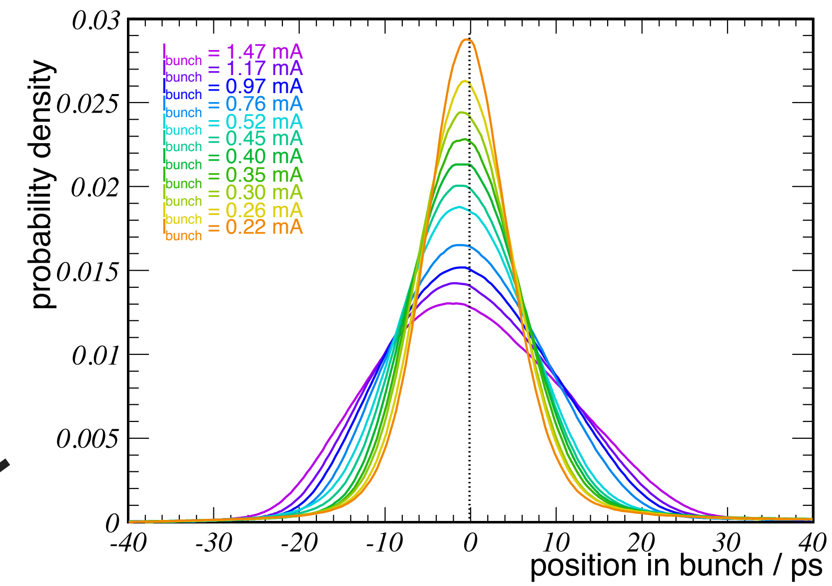
N. Hiller

Measured and Expected Spectra

- CSR spectra are proportional to Fourier transform of the electron distribution
- Spectral measurements with a Michelson Interferometer
- Expectation from streak cam. measurement below cutoff
- Explanation: substructure or stronger deformation
  - Single shot measurement needed

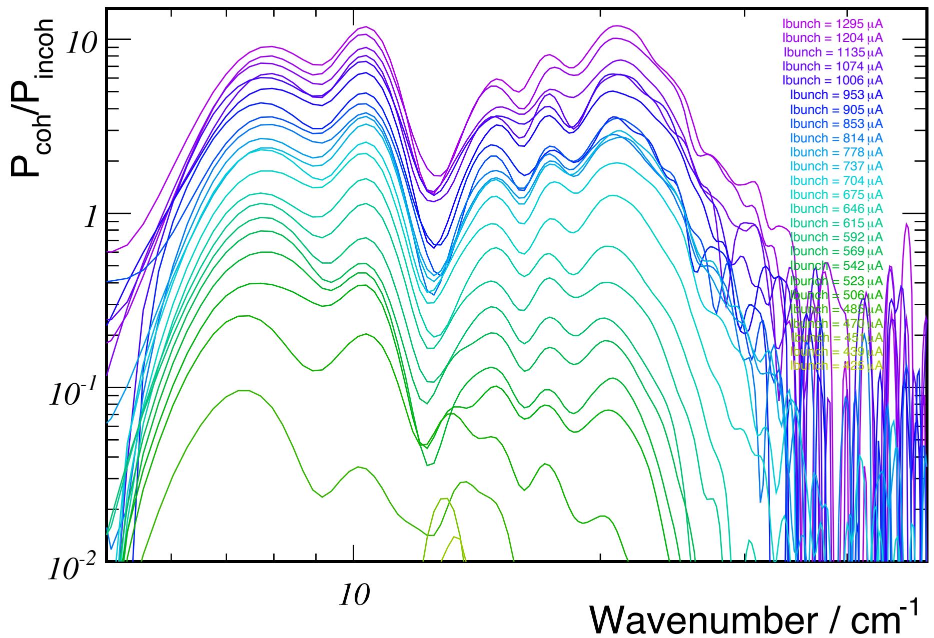


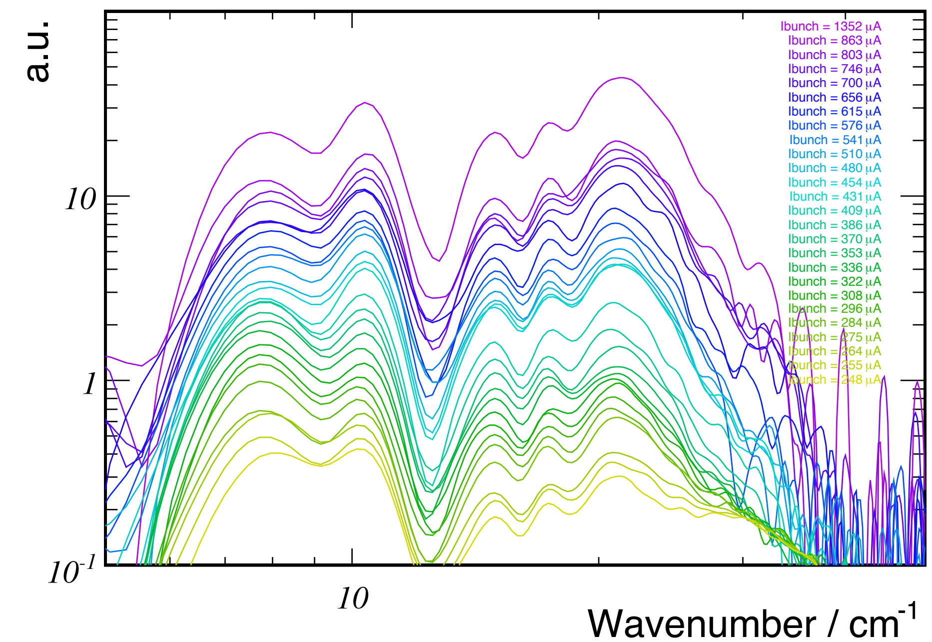
FFT



Coherent Radiation

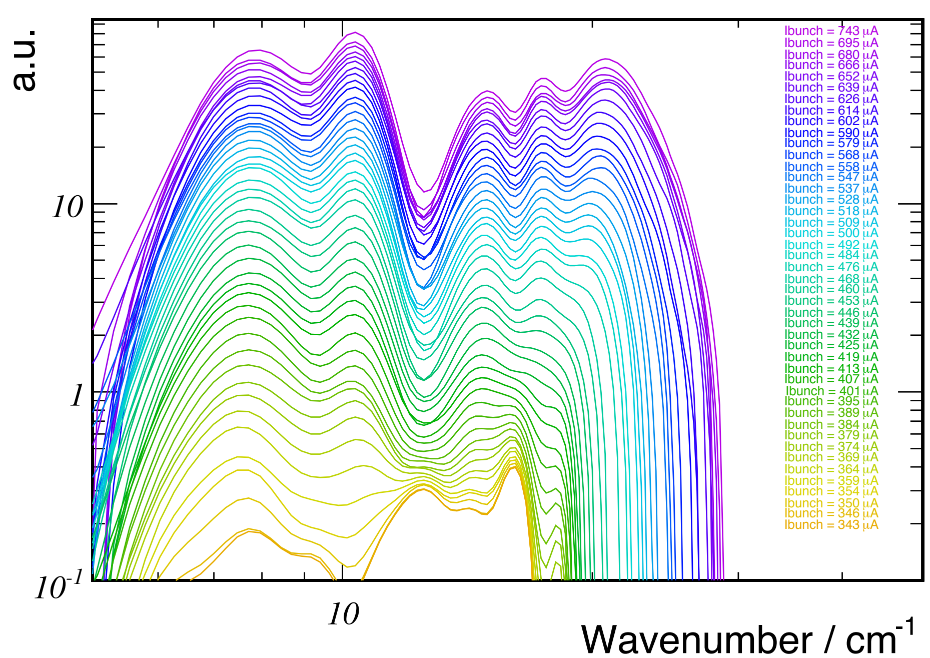
- Comparison of single and multi-bunch fillings

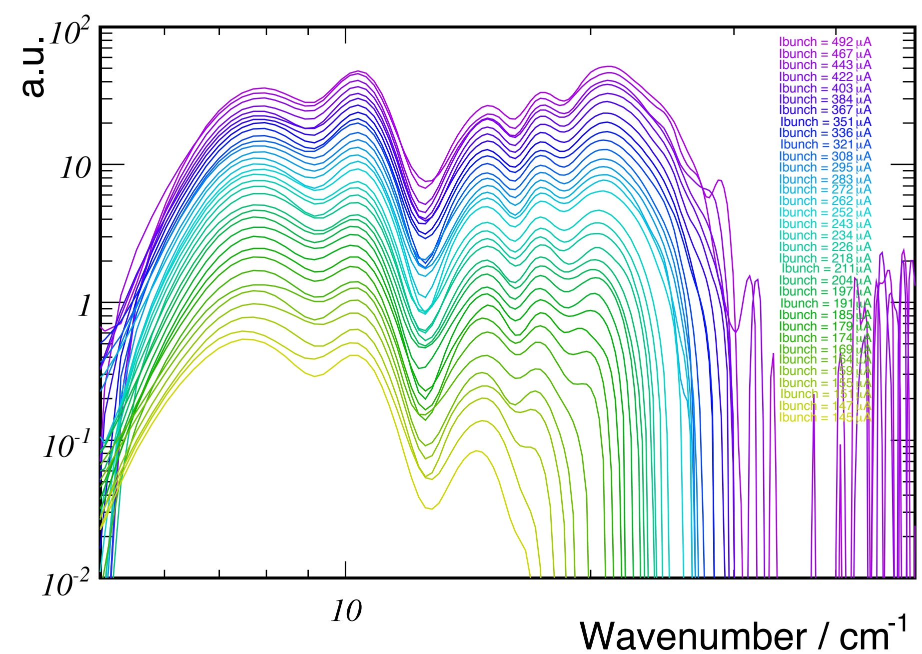




Filter #2 < 35 cm^{-1}

single bunch





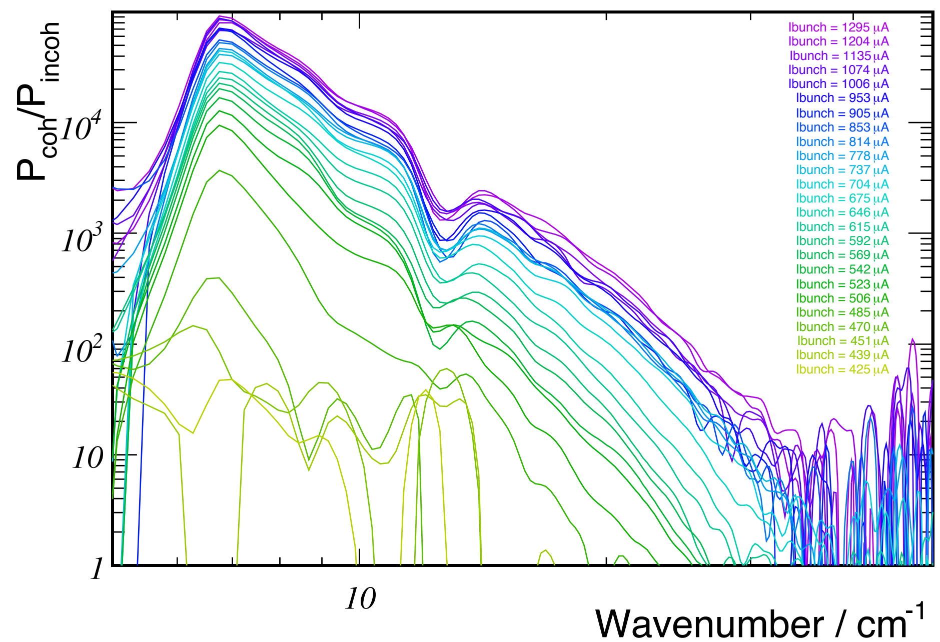
multi bunch

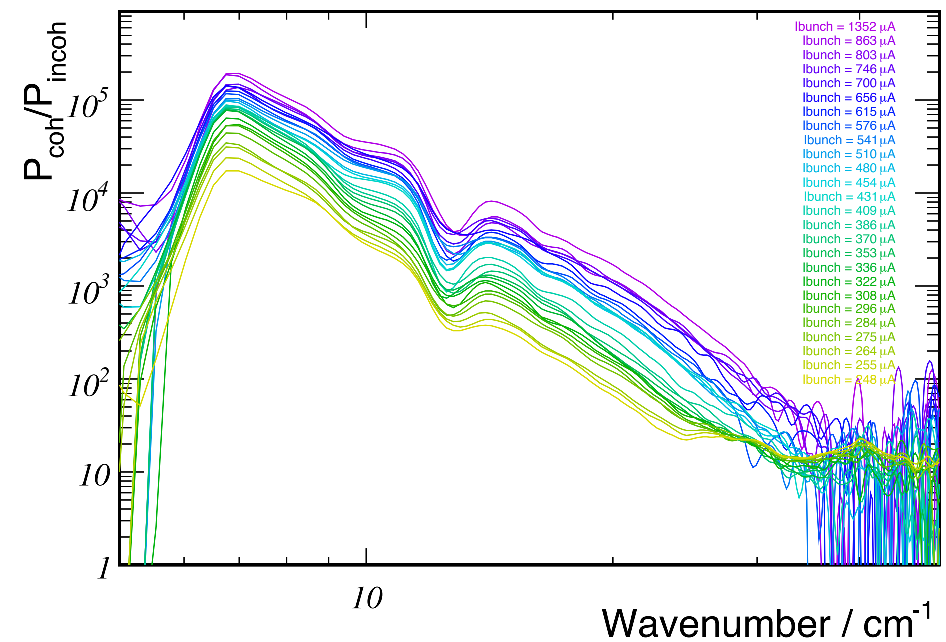
fs = 9.6 kHz / 5.3 ps

fs = 6.6 kHz / 3.8 ps

Gain Curves

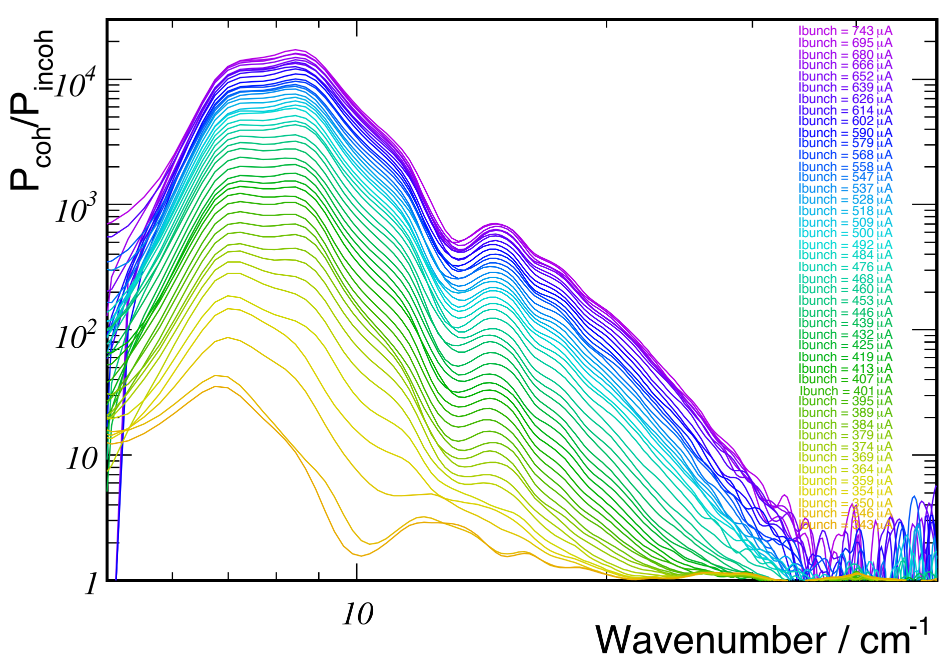
- Comparison of single and multi-bunch fillings

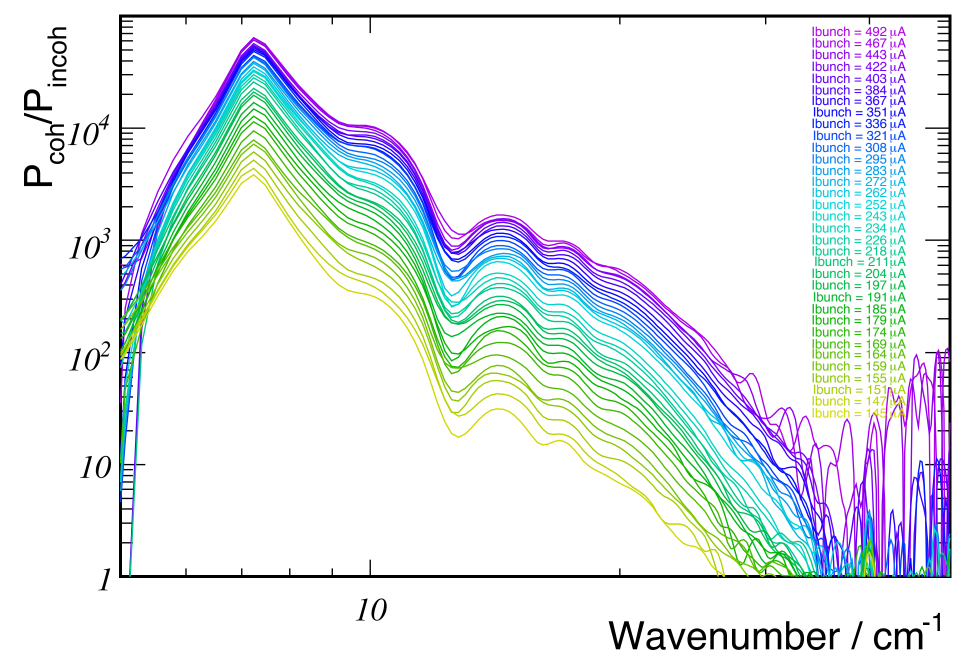




single bunch

Filter #2 < 35 cm^{-1}



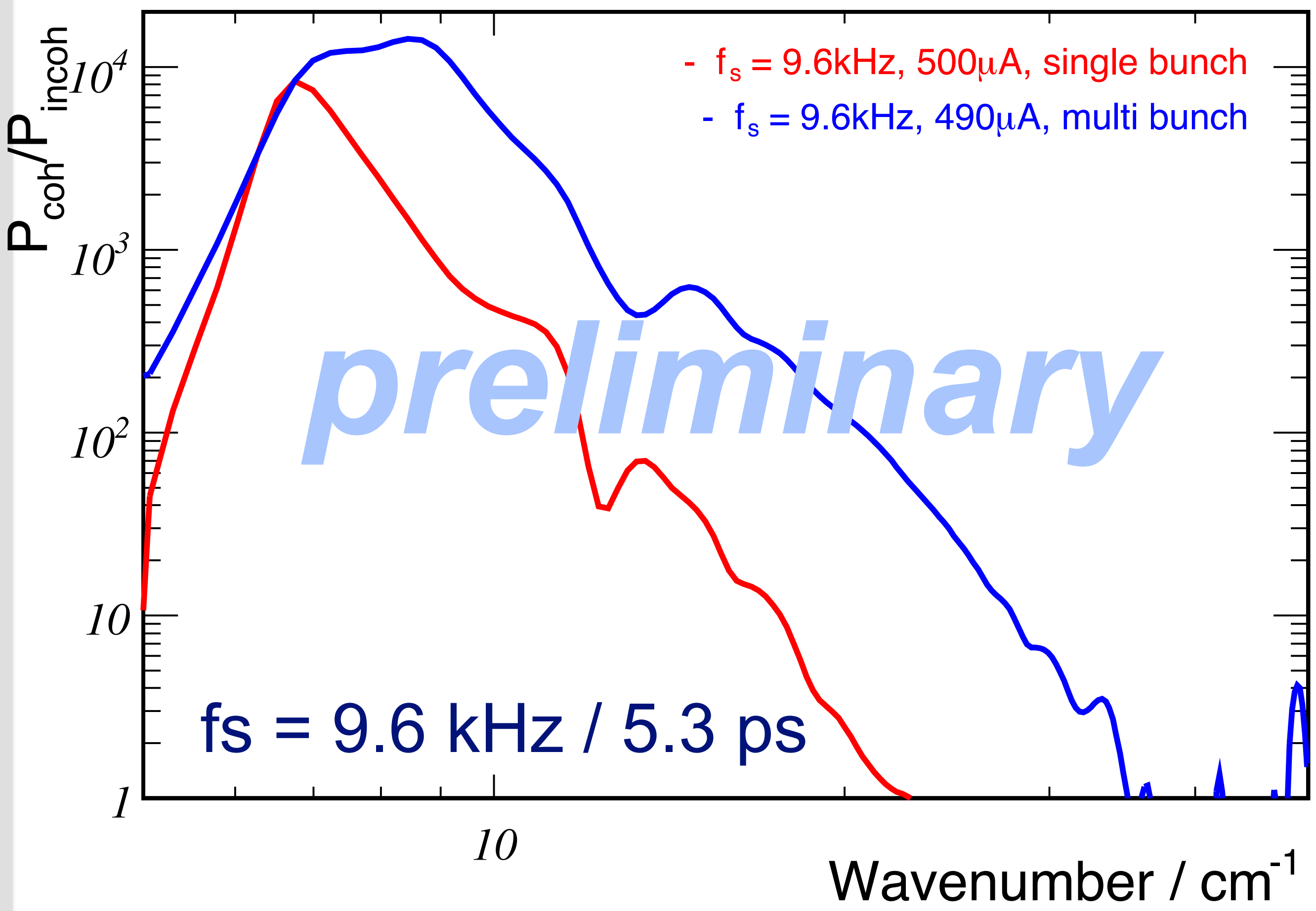


multi bunch

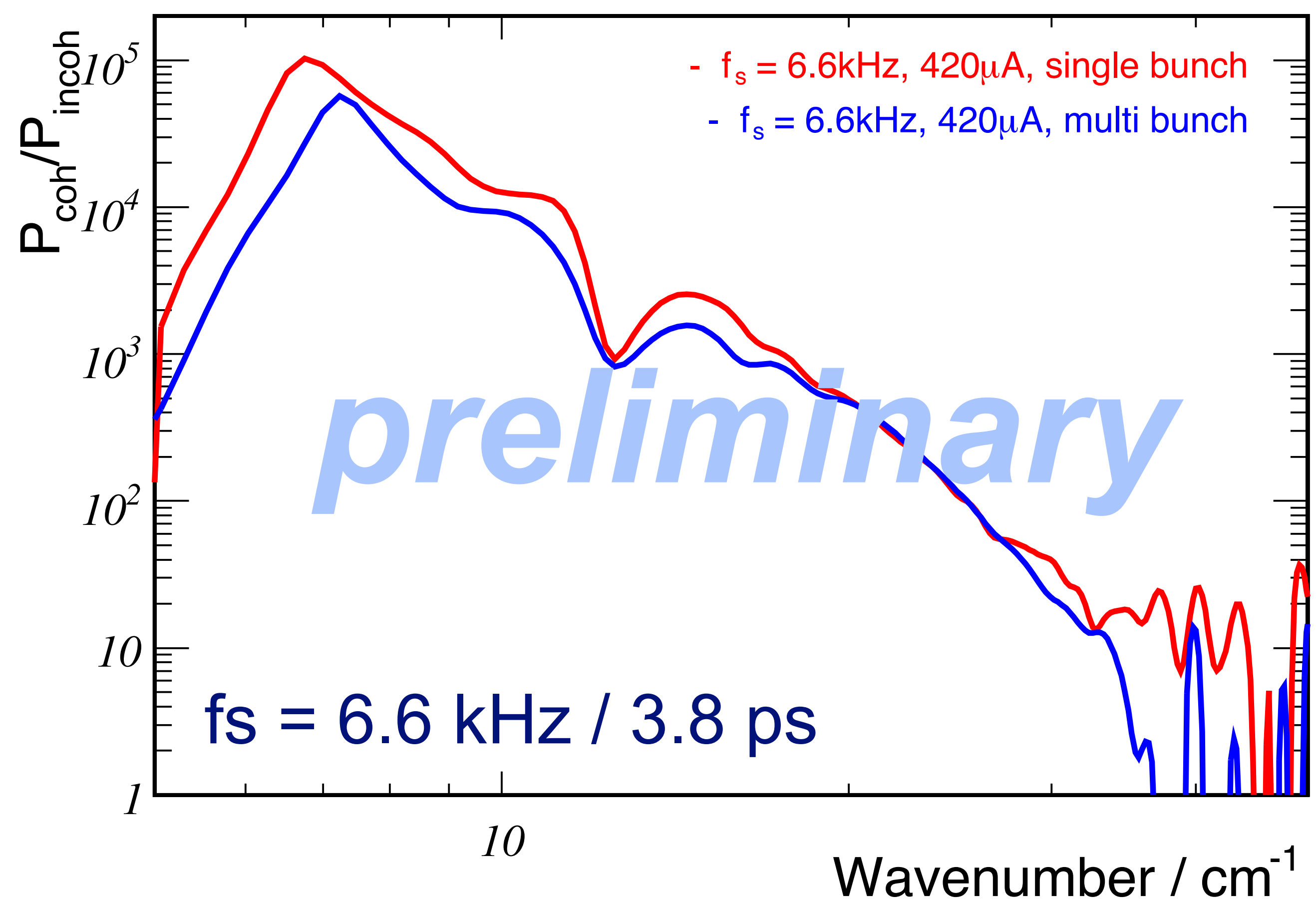
fs = 9.6 kHz / 5.3 ps

fs = 6.6 kHz / 3.8 ps

Observations



- Multi bunch gain curve seems to lie significantly higher than single bunch curve for similar single bunch current for longer bunches
- For shorter bunches, the curves are closer



- **Hypothesis:**
  effects from the ring impedance are more significant if the CSR effect is less pronounced

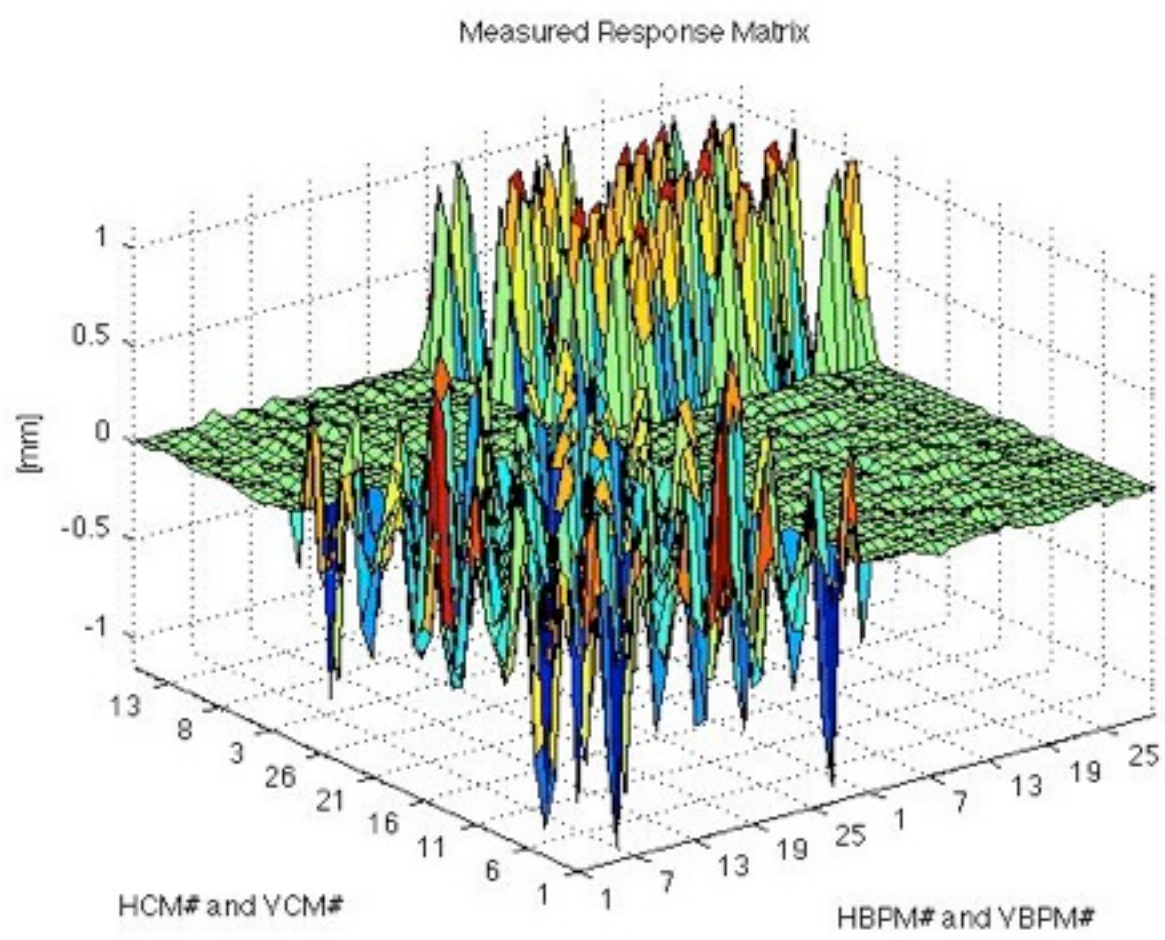
Modeling the low-alpha mode with AT

	measured f_s	model α_0
A	30.7 kHz	$8.5 \cdot 10^{-3}$
B	29.2 kHz	$7.8 \cdot 10^{-3}$
C	24.2 kHz	$5.7 \cdot 10^{-3}$
D	8.5 kHz	$0.74 \cdot 10^{-3}$
E	6.7 kHz	$0.46 \cdot 10^{-3}$

5 different low-alpha optics modeled

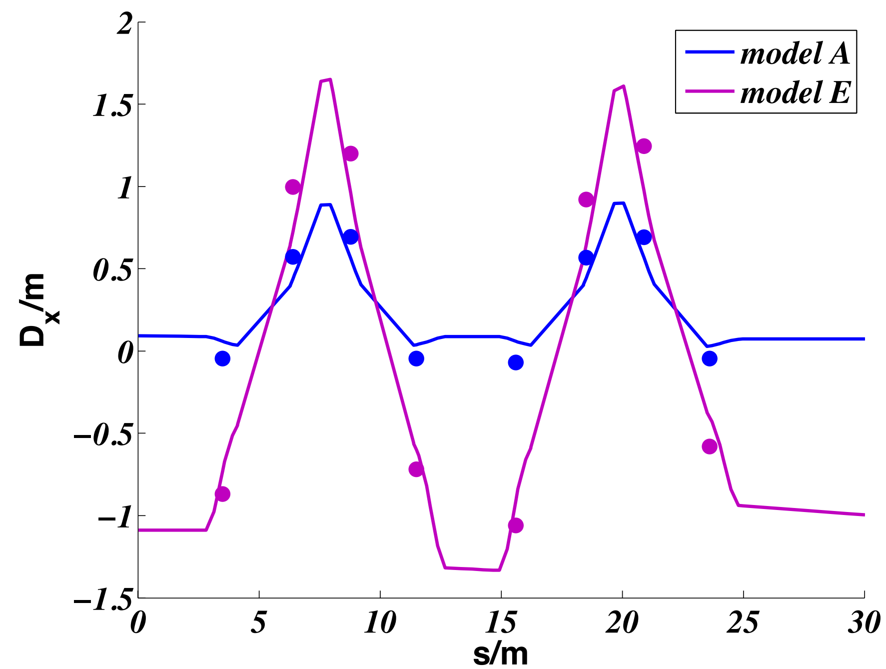
Measurements for each model:

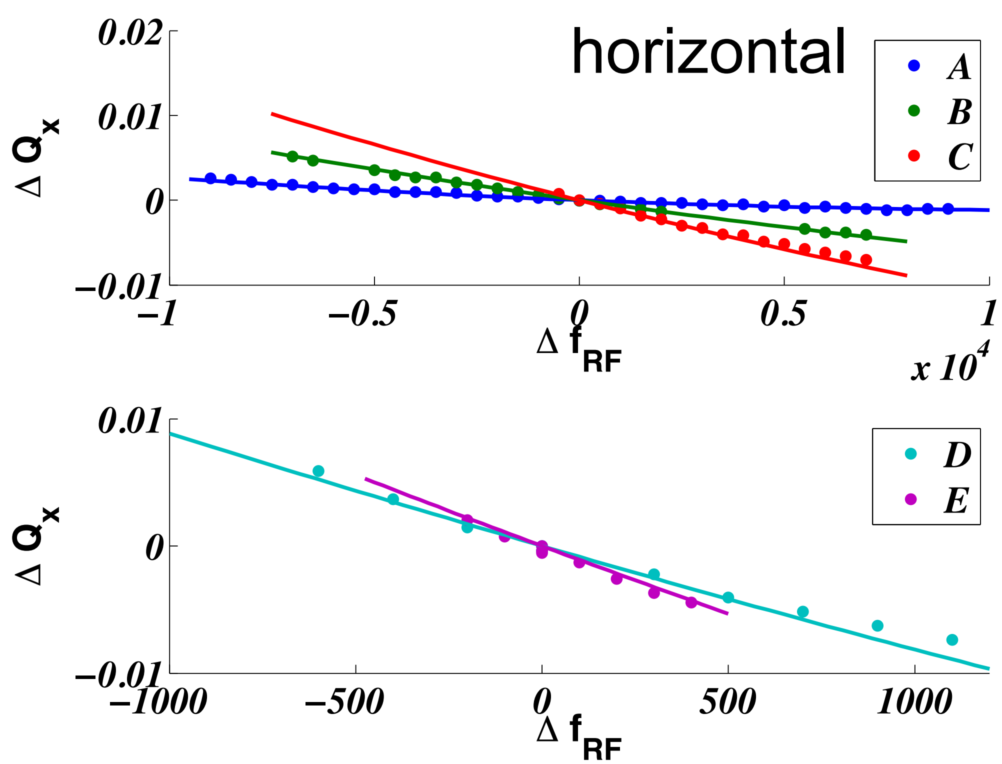
- Tunes: Q_x, Q_y, Q_s
- Orbit response matrix
- Dispersion
- Chromaticity

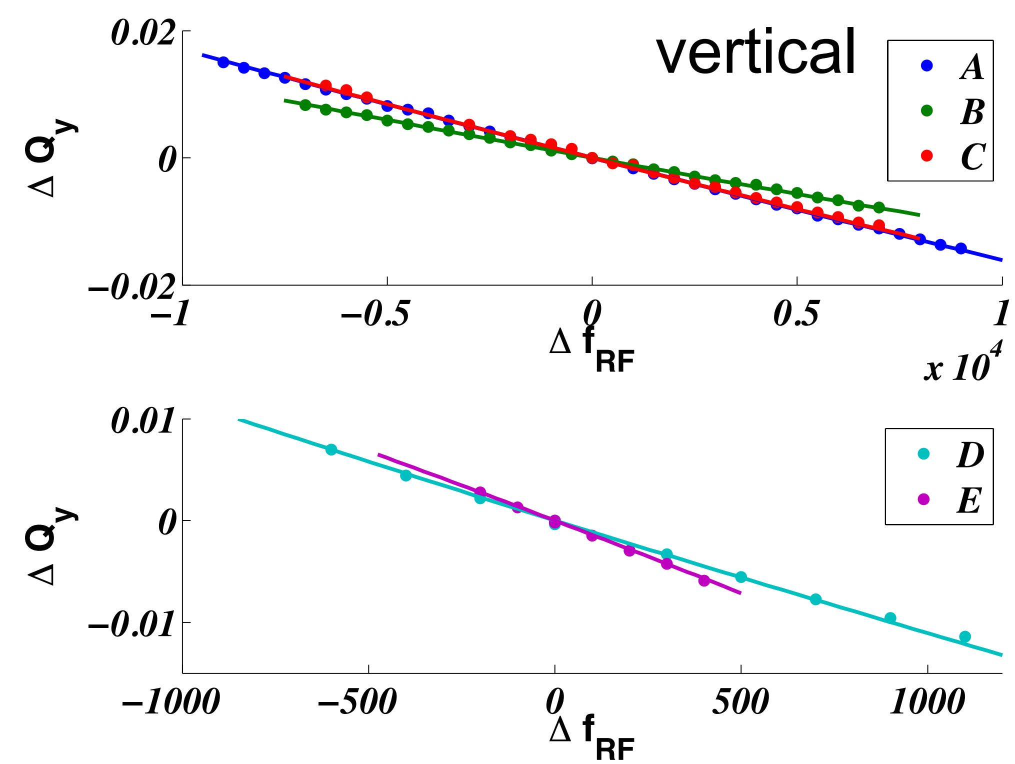


LOCO fits and Chroma fits

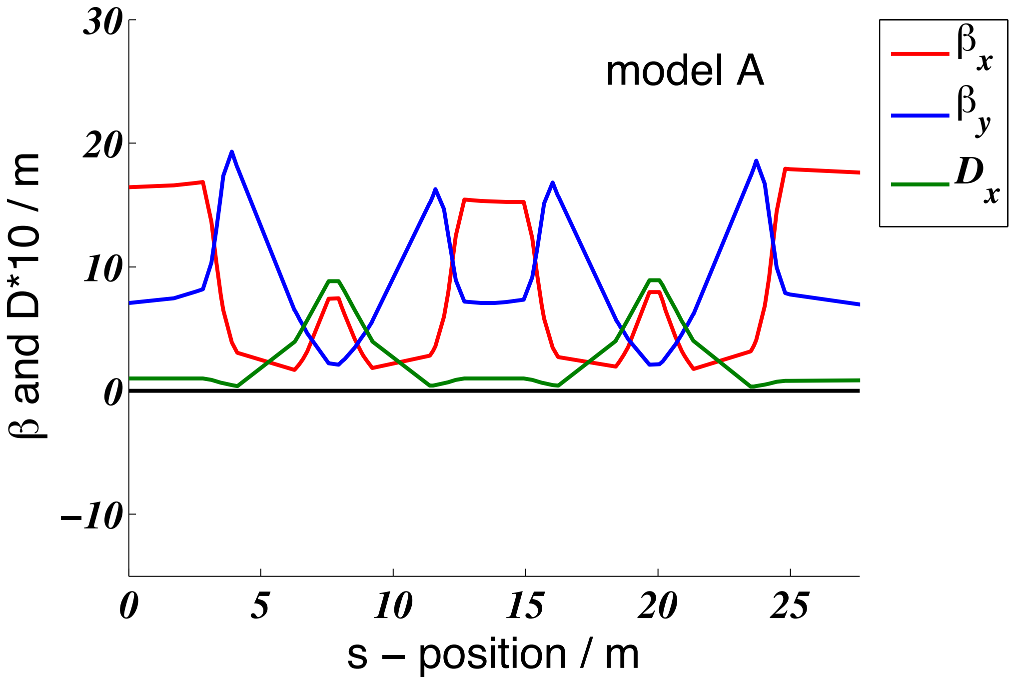
- Magnet strength calculated from currents settings
- Correction of quadrupole strength:
  - LOCO fit of response matrices and dispersions
- Additional quadrupole components
  - fit of tunes and chromaticity curve shapes
- Correction of sextupole strength
  - fit of chromaticity values

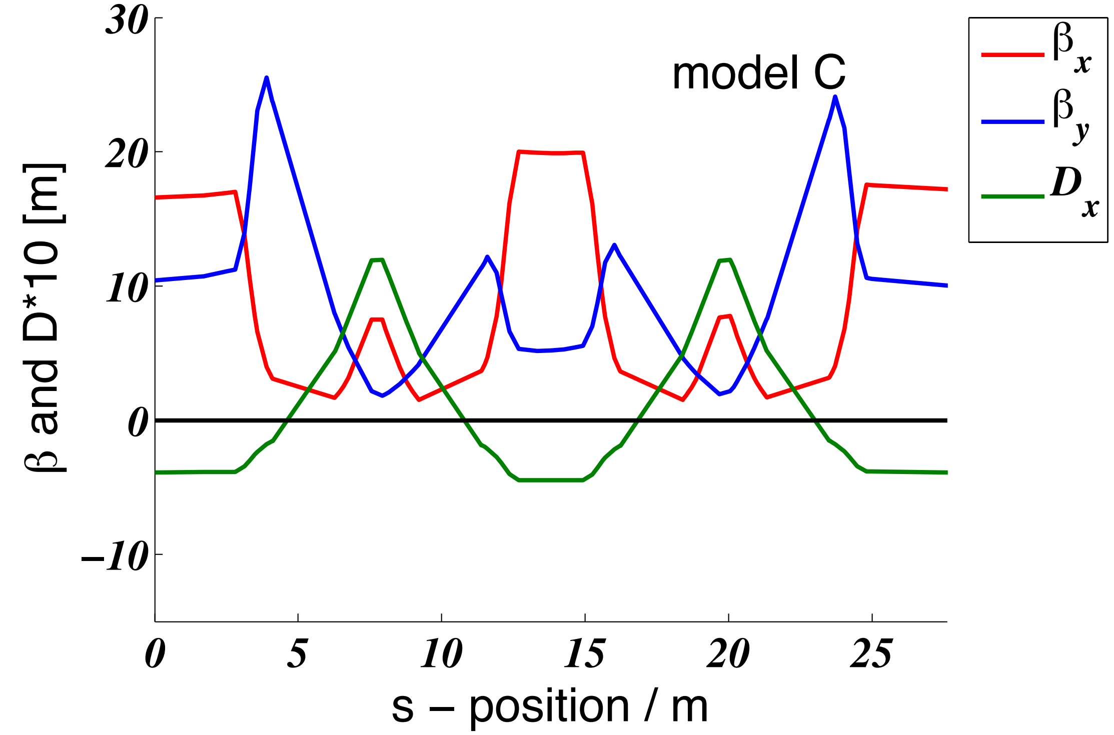


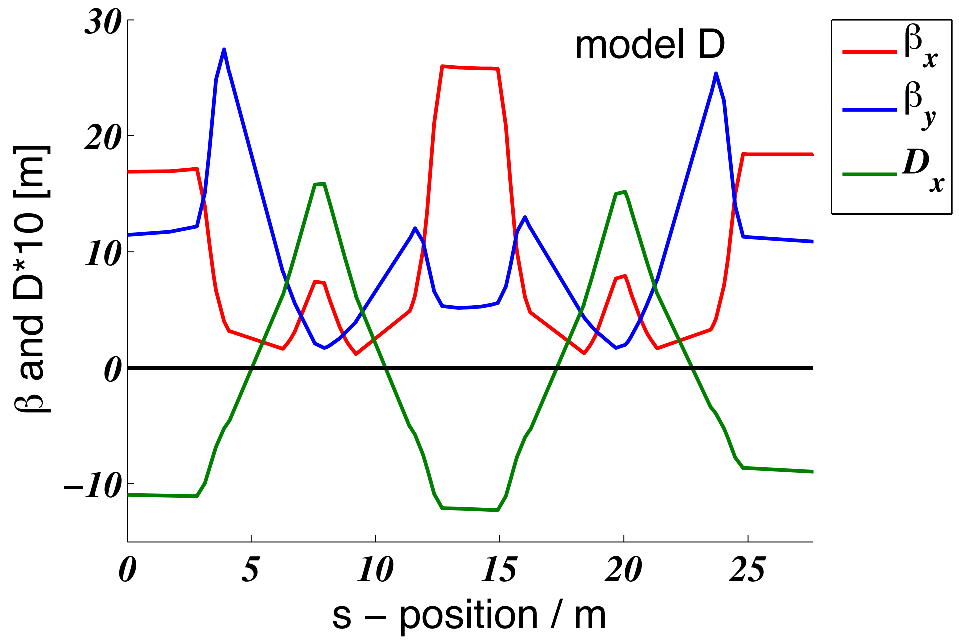


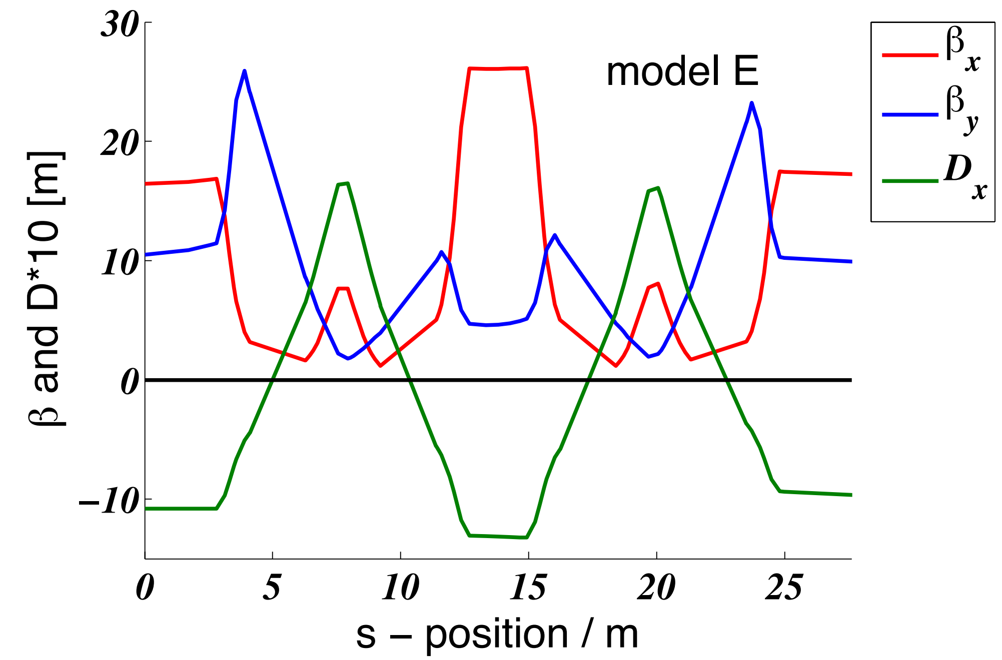


Optics functions

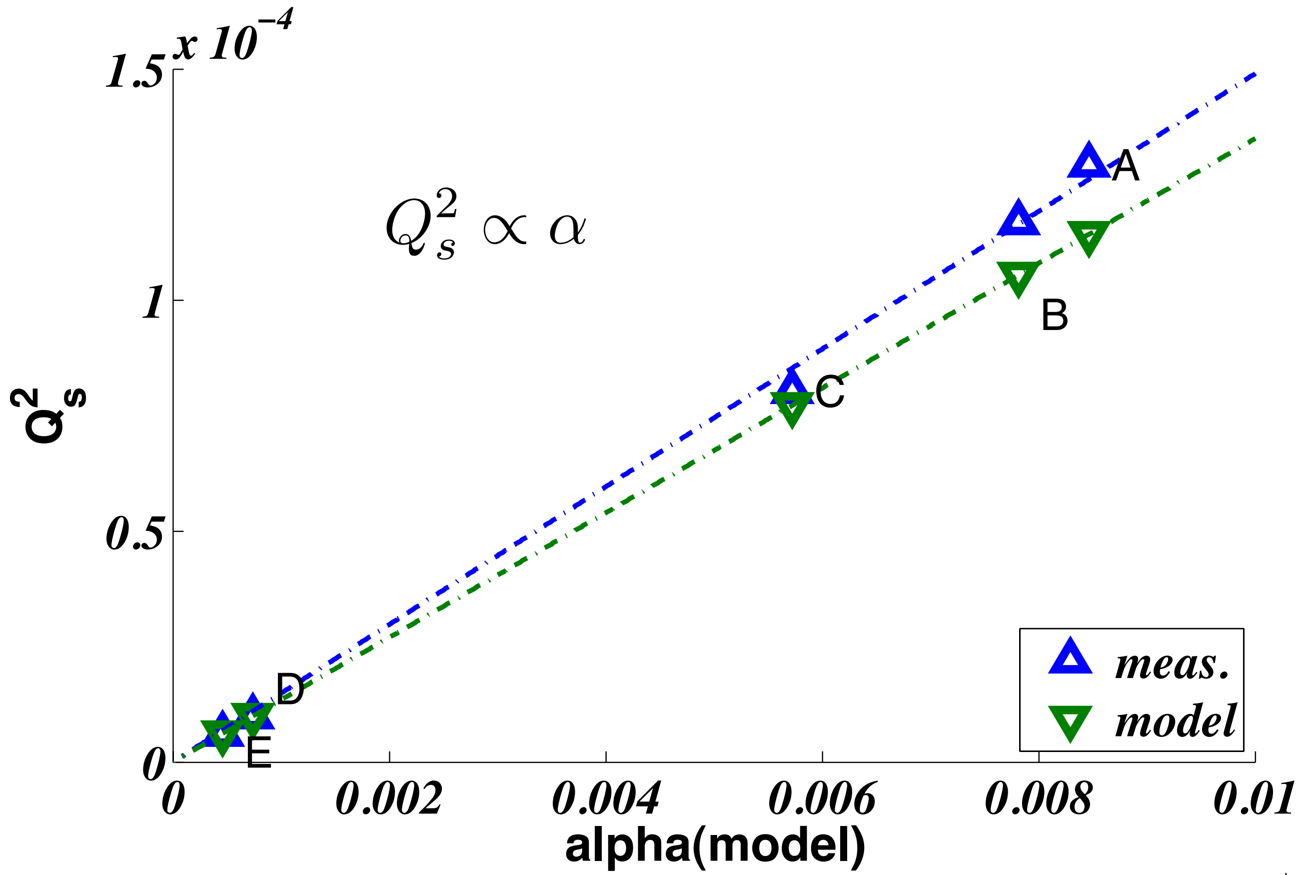








Tunes

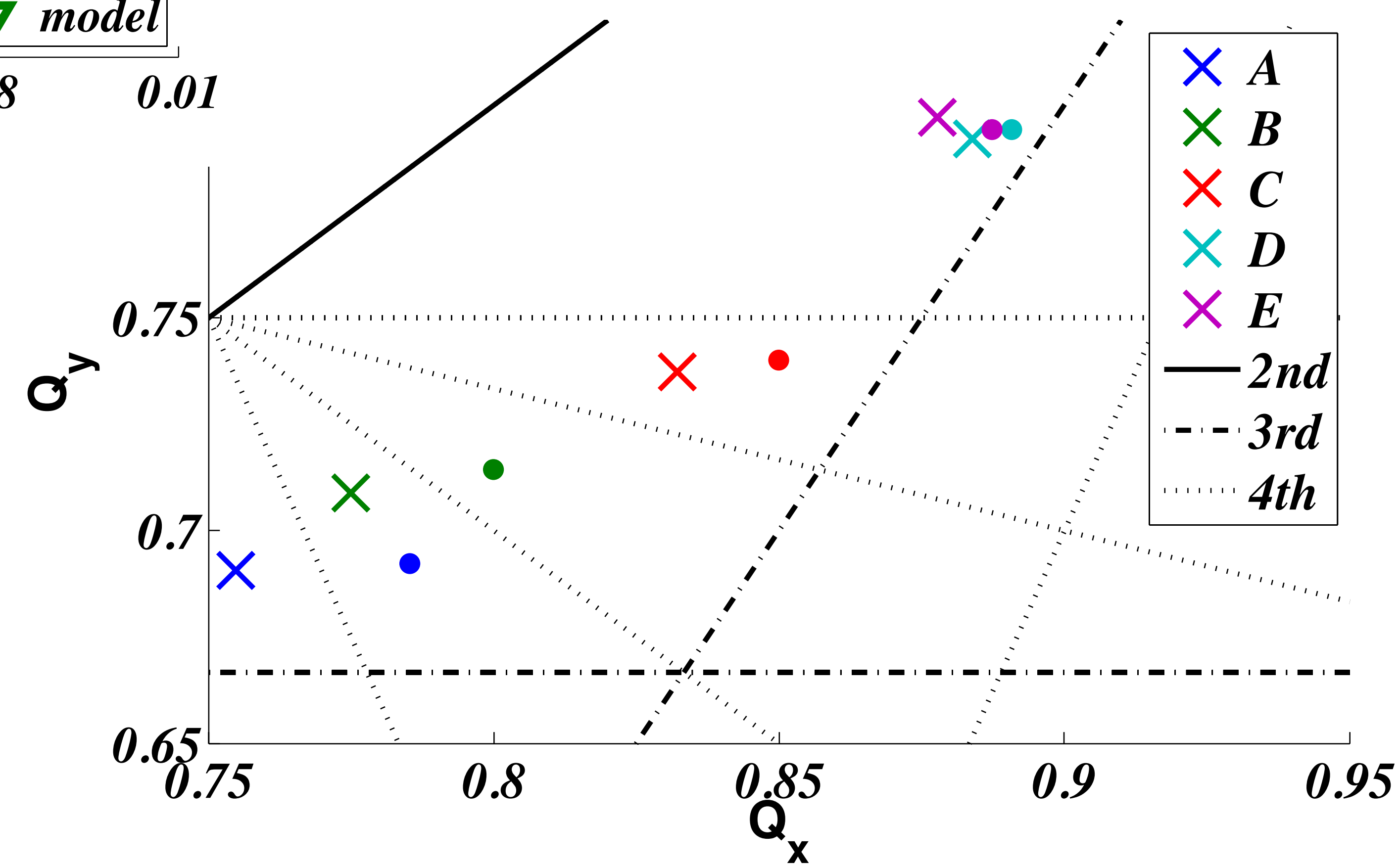


Synchrotron tune:

- approximate the measurements
- no impact seen in AT of higher order terms on synchrotron tune

Betatron tunes:

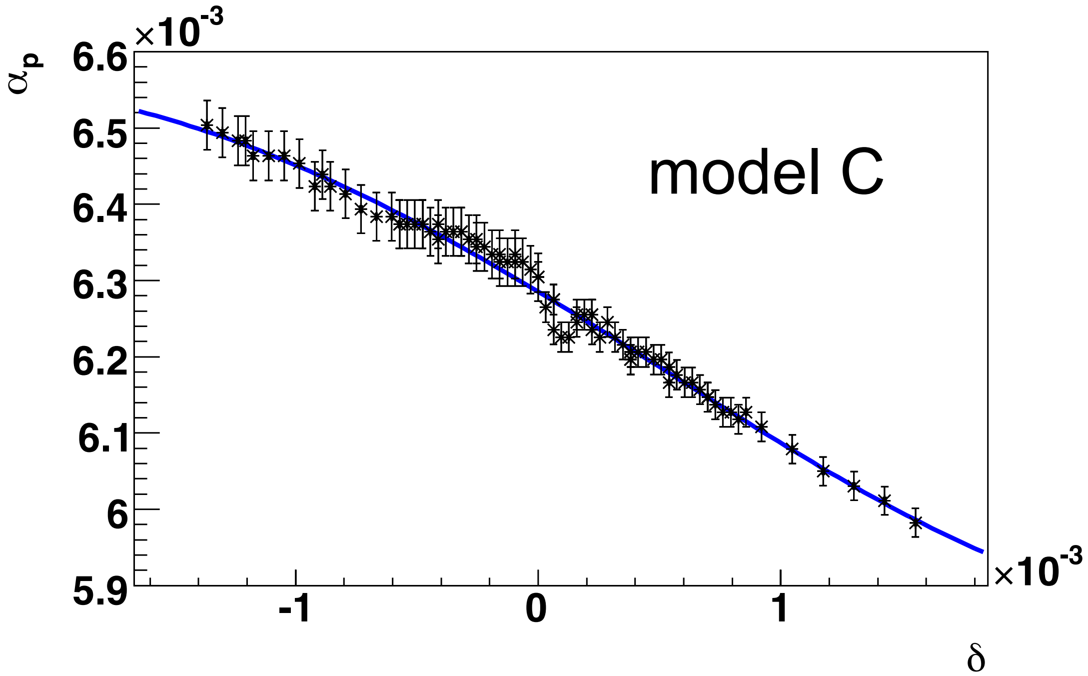
- approximate the measurements
- best agreement for lowest α
- largest difference in the horizontal betatron tune
  - emphasis in modeling on sychrotron tune

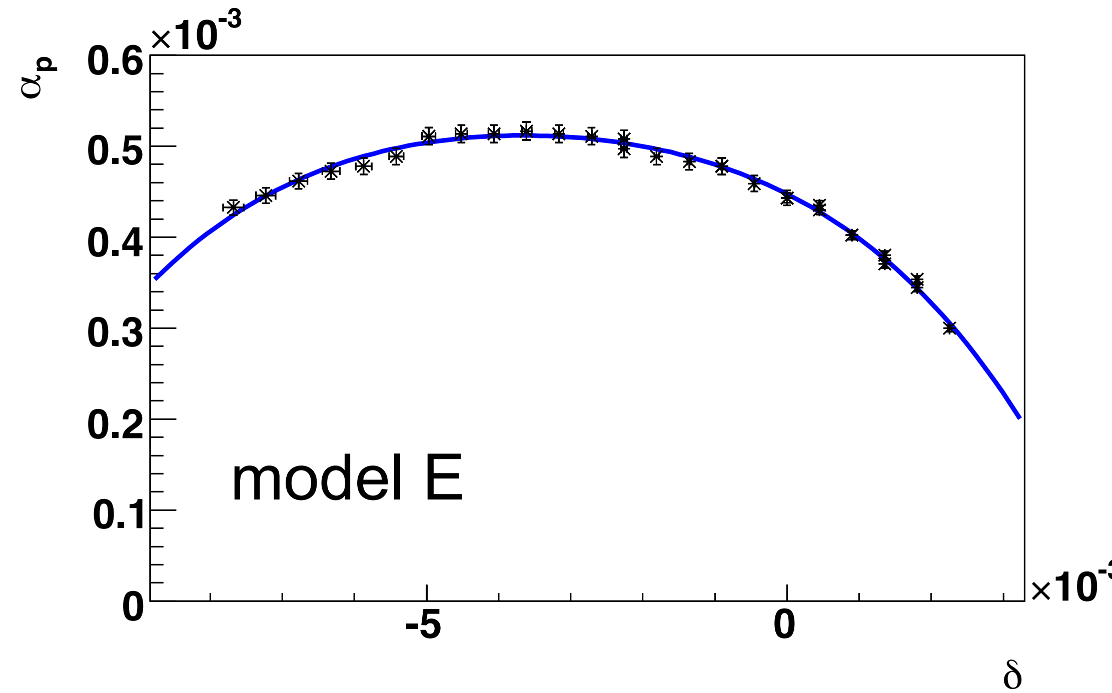


Higher order alpha

$$f_s(f_{RF}) \to \alpha_p(dp/p) = \alpha_p(\delta)$$

$$\alpha_p = \frac{dL/L}{dp/p} \qquad \alpha_c = \frac{\Delta L/L_0}{\Delta p/p_0} \qquad \Longrightarrow \qquad \alpha_p = \frac{1+\delta}{1+\alpha_c\delta}\frac{d(\alpha_c\delta)}{d(\delta)}$$



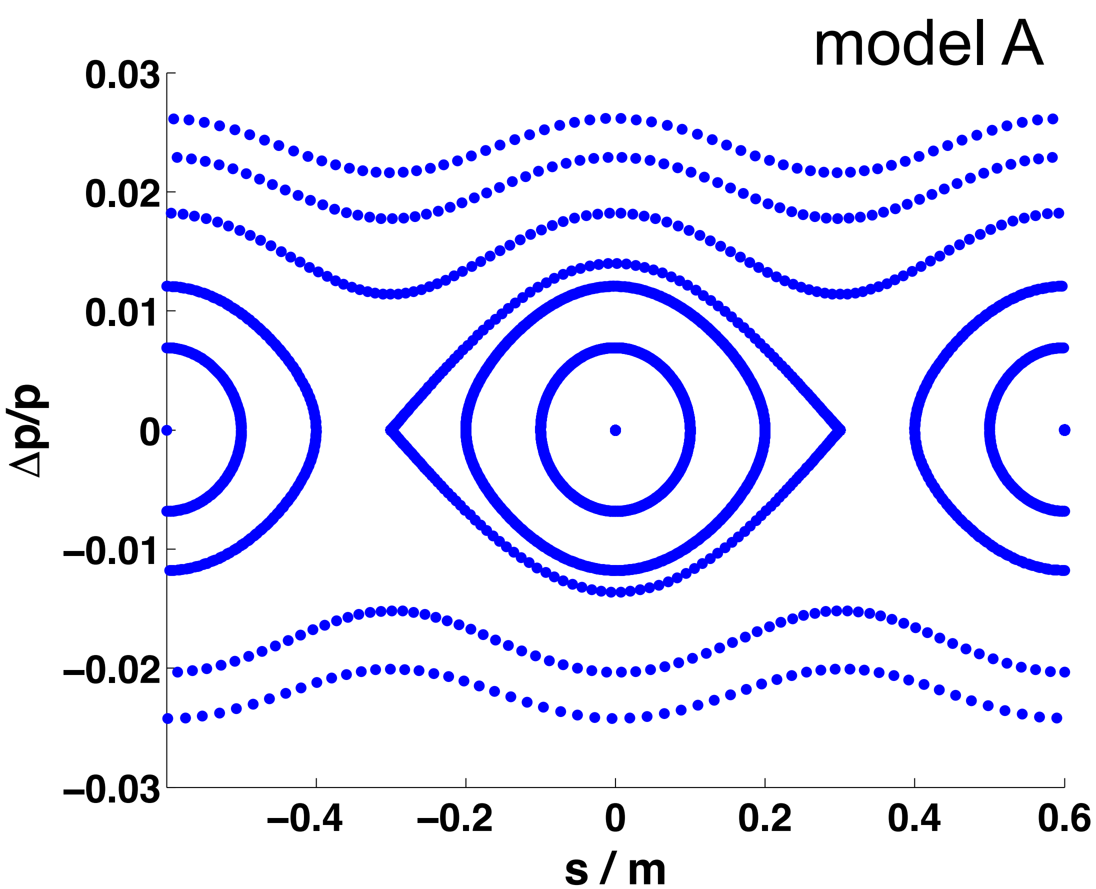


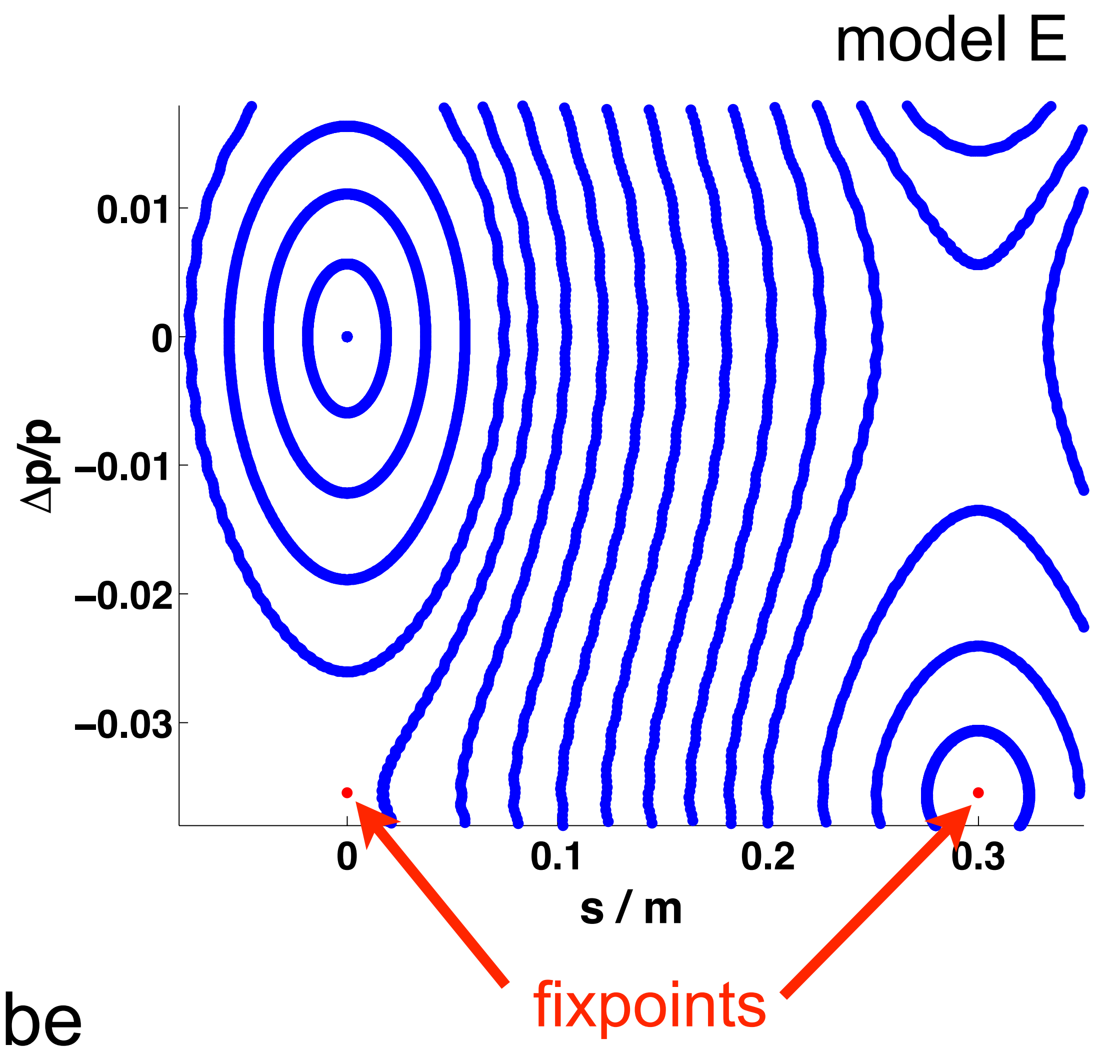
$$\Rightarrow \alpha_c \quad = \quad \alpha_0 + \alpha_1\delta + \alpha_2\delta^2 + \alpha_3\delta^3 + ...$$

$$\alpha_0 \quad = \quad +(6.28 \pm 0.0014)\cdot 10^{-3}$$
$$\alpha_1 \quad = \quad -(99 \pm 6)\cdot 10^{-3}$$

$$\alpha_0 \quad = \quad +(0.447 \pm 0.004)\cdot 10^{-3}$$
$$\alpha_1 \quad = \quad -(20 \pm 1)\cdot 10^{-3}$$
$$\alpha_2 \quad = \quad -(2,710 \pm 300)\cdot 10^{-3}$$
$$\alpha_3 \quad = \quad -(190,000 \pm 90,000)\cdot 10^{-3}$$

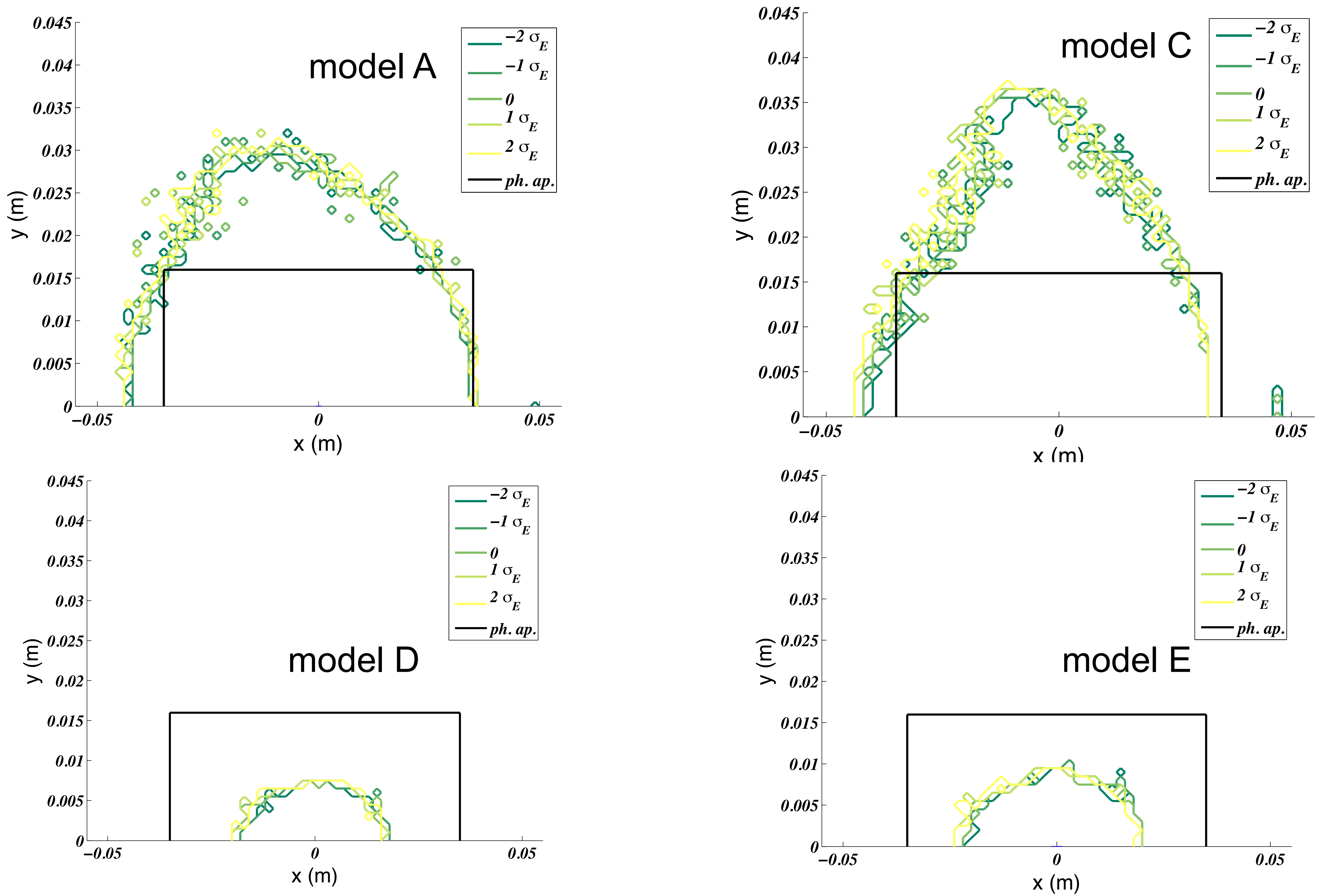
Longitudinal phase space



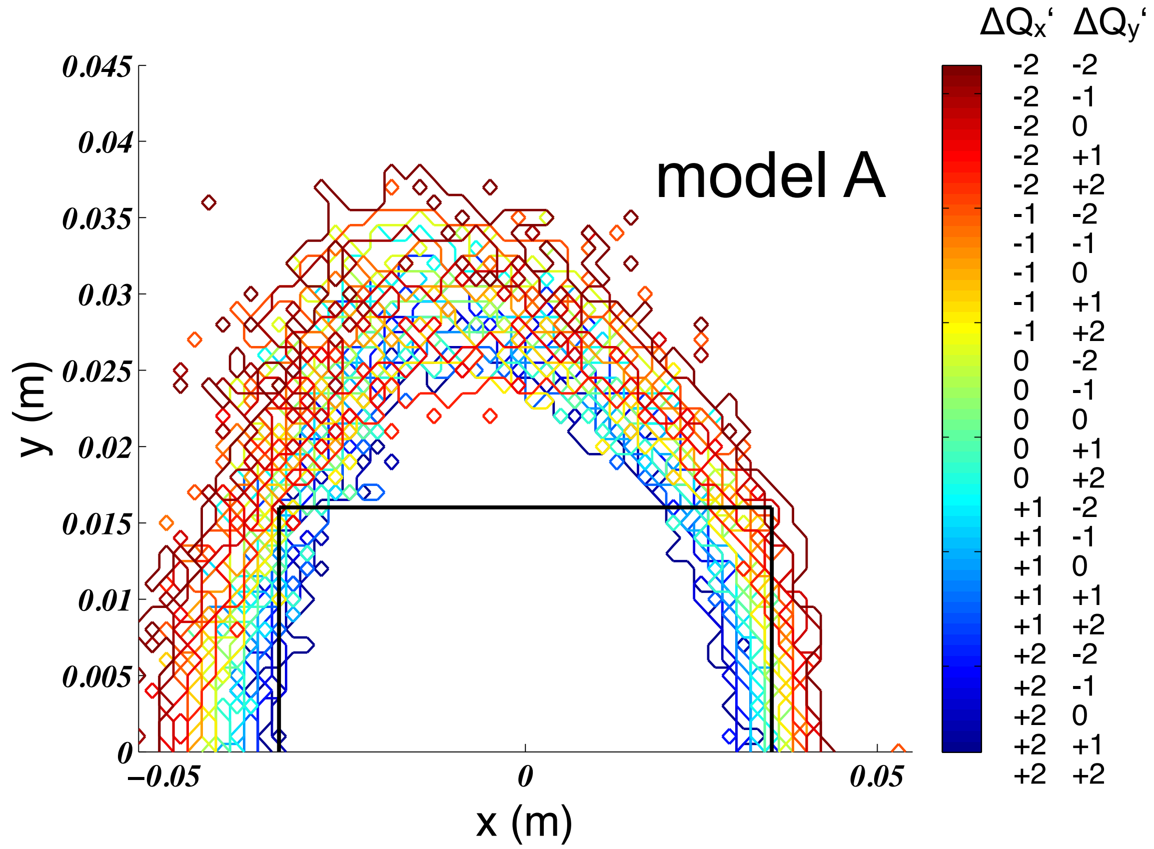


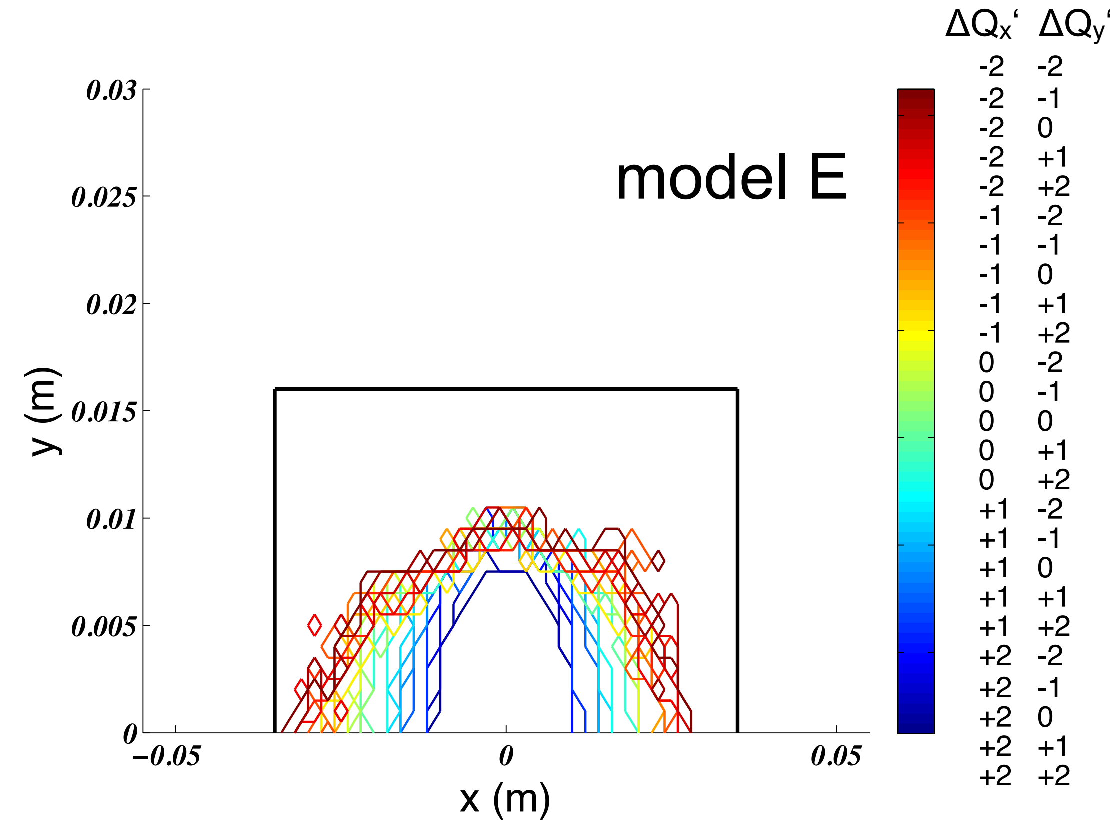
- Low α_0 → higher order terms have to be considered
- Additional fixpoints at: $\left.\frac{\Delta p}{p}\right._{fix} \approx \frac{\alpha_0}{\alpha_1} = -0.036$
- Measurement: $\frac{\alpha_0}{\alpha_1} = -0.023 \pm 0.001$

Dynamic aperture



DA for different chromticities





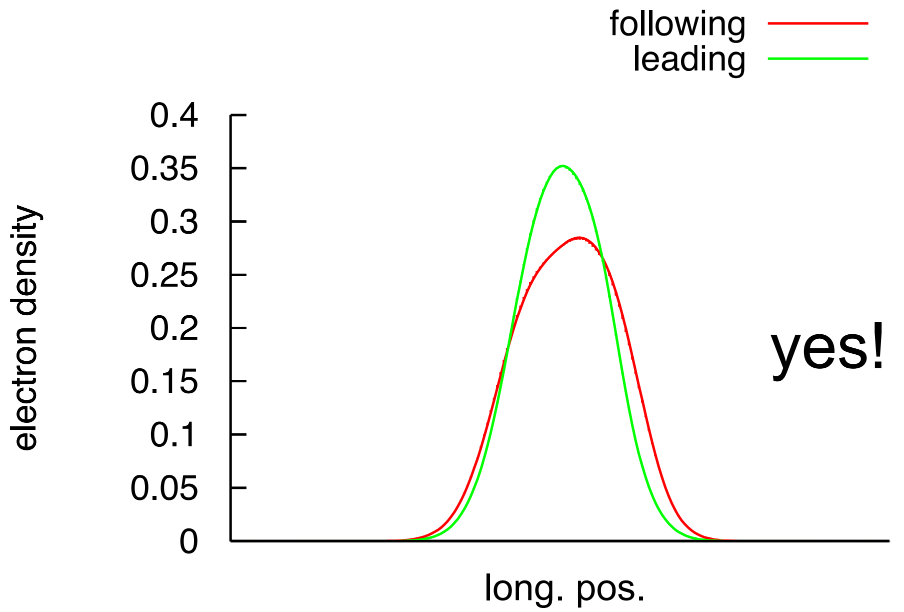
- Small chromaticities enlarge dynamic aperture
- Low α_0 optics are more sensitive to chromaticity changes

Summary

- Regular low-alpha user operation
- Characterized the properties of the CSR
  - calculated and observed bursting/stable threshold
  - investigated radiation behavior with HEB
- Bunch shape and length measurements with streak camera
- Spectral measurements, comparison multi and single bunch
- Beam based modeling of the low-alpha mode
  - higher order momentum compaction
  - second stable fixpoints in long. phase space
  - dynamic aperture investigation

Outlook

- Simulations of microbunching instability and bursting behavior with a Vlasov-Solver
  - Bunch to bunch interaction?



- HEB leading bunch analysis, bursting triggering with additional wake fields
- Single shot measurements of electron distribution with electrooptical sampling