Slow Extraction in Electron Machines…

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…based on the experience at our in-house accelerator
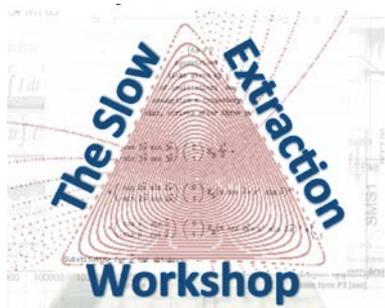
Darmstadt 02-Jun-2016

# Extraction at a 3rd Integer Resonance
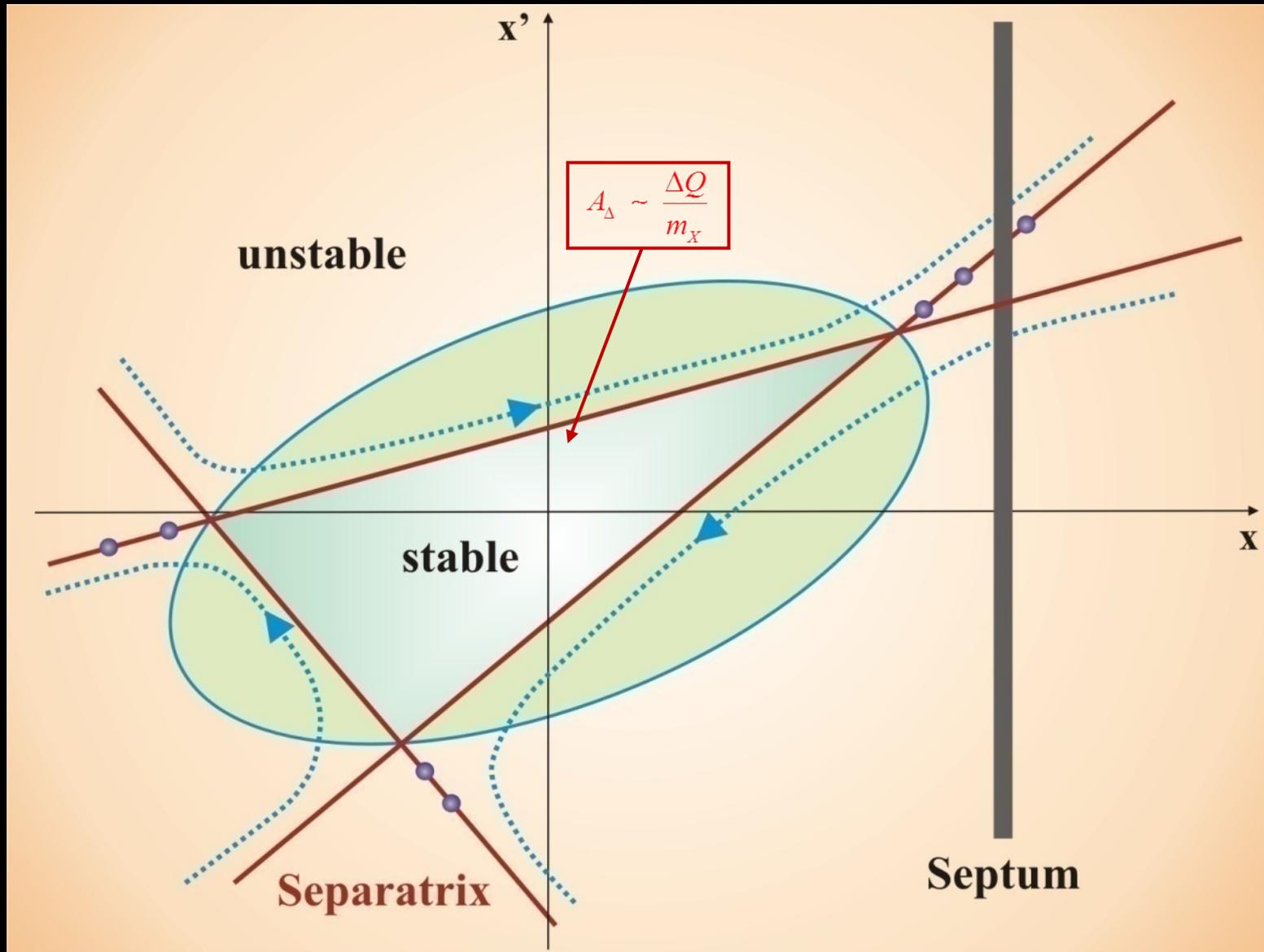
# Electron Stretcher Accelerator (ELSA)

FODO Lattice

Dipole
$R = 10,987\,\text{m}$

Quadrupole
QF

Dipole
$R = 10,987\,\text{m}$

Quadrupole
QD

1,73m   0,57m   5,1375m

$B_{max} = 1.07\ \text{T}\ \ @\ I = 3100\text{A}$

$g_{max} = 10\ \text{T/m}\ @\ I = 915\text{A}$

M20
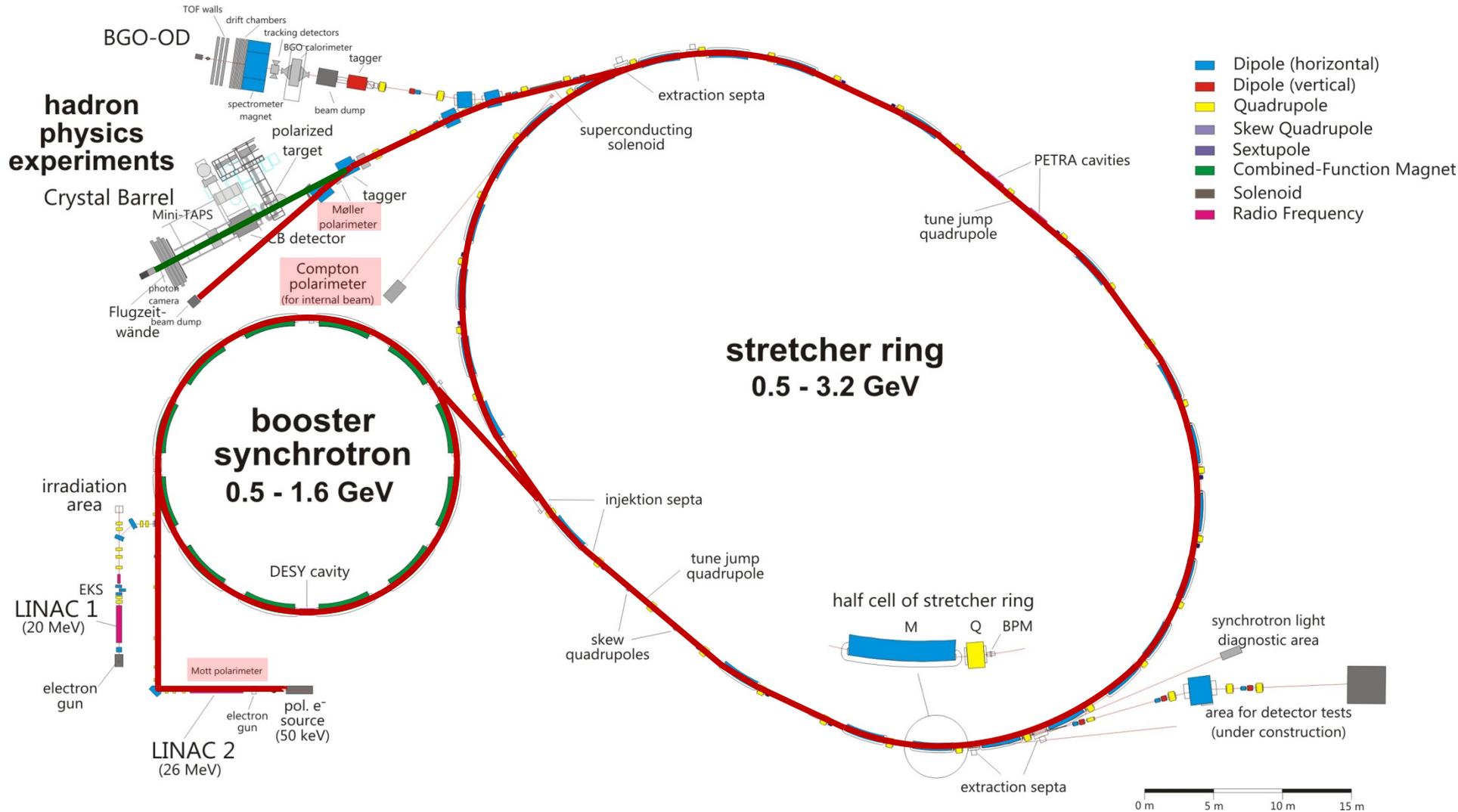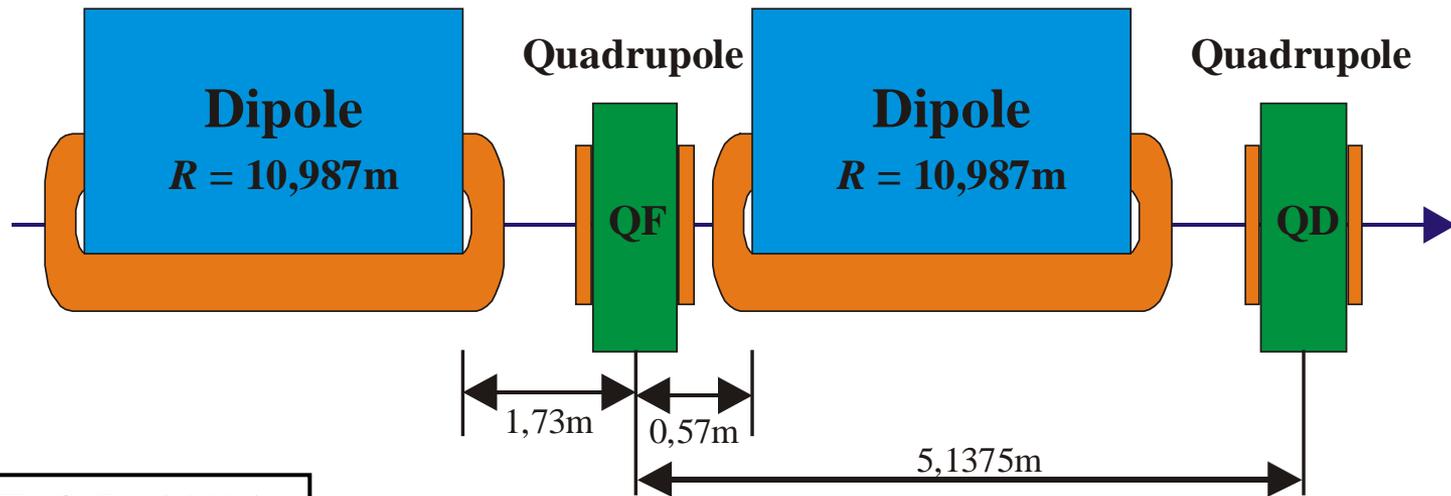
Resonance Excitation
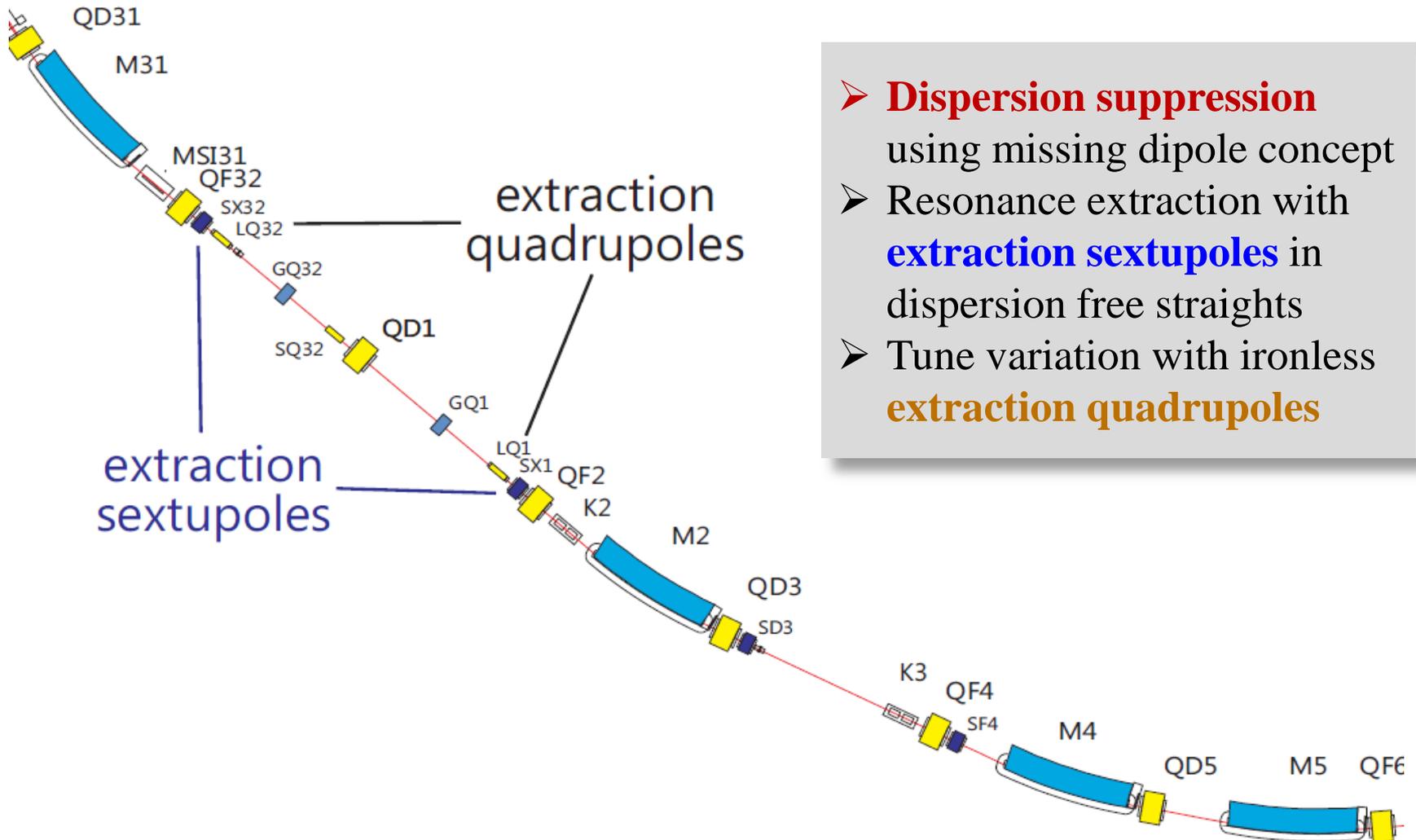
- **Dispersion suppression** using missing dipole concept
- Resonance extraction with **extraction sextupoles** in dispersion free straights
- Tune variation with ironless **extraction quadrupoles**

Dispersion Suppression
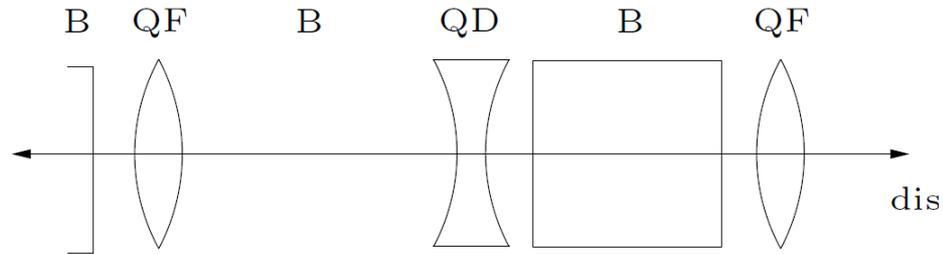
$Q_x = Q_z = 4,3:$
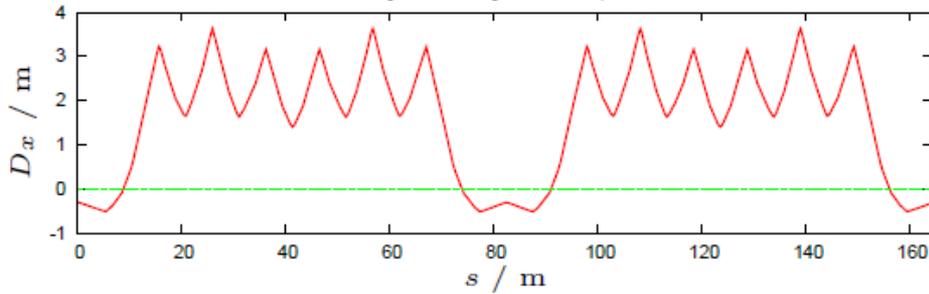
$Q_x = Q_z = 4,6:$
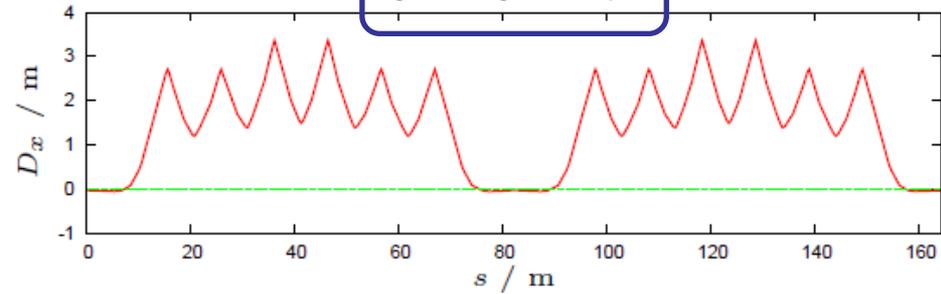
$Q_x = Q_z = 5,3:$
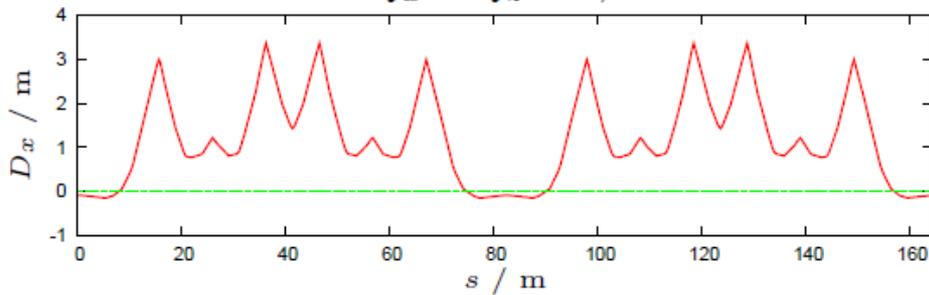
$Q_x = Q_z = 5,6:$
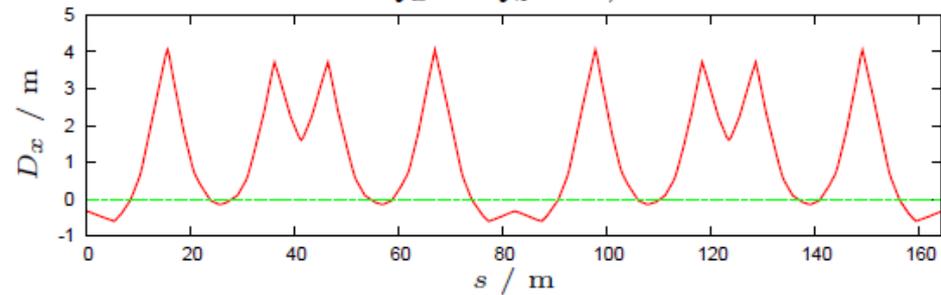
Choice of Betatron Tunes

Beta functions and dispersion

Tune diagram

unstable

$$A_\Delta \sim \frac{\Delta Q}{m_X}$$

stable

Separatrix
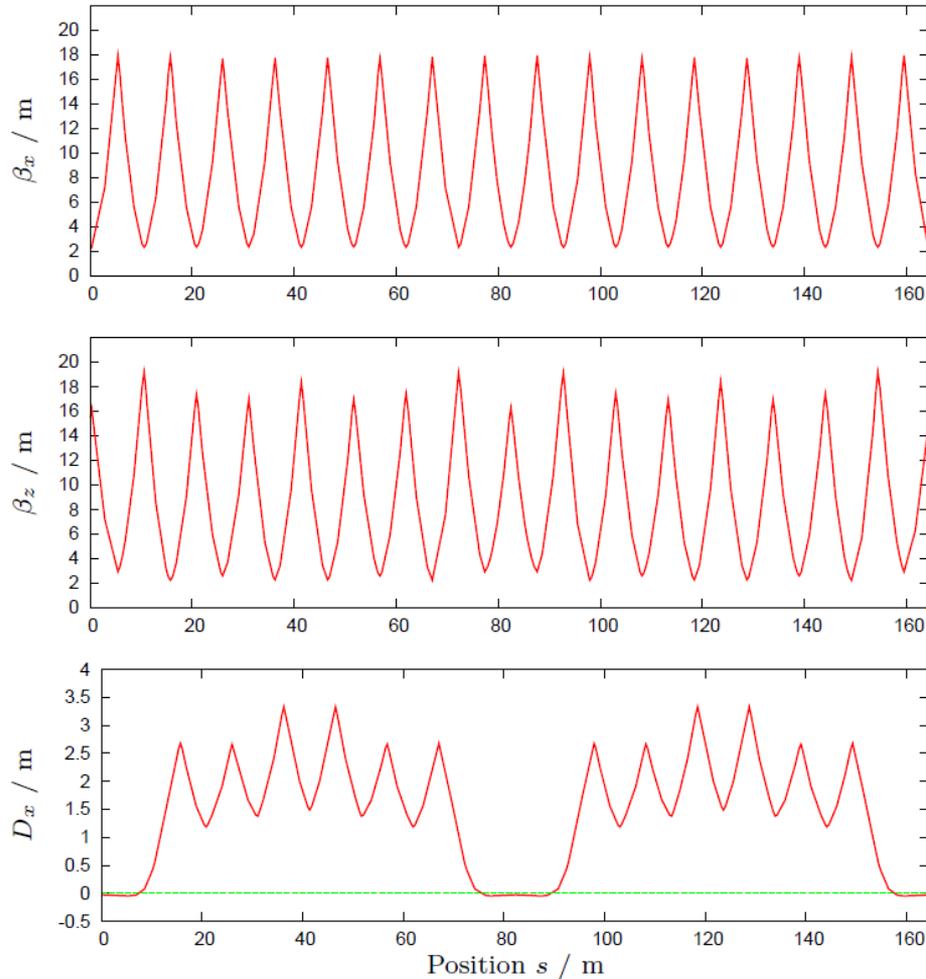
Septum
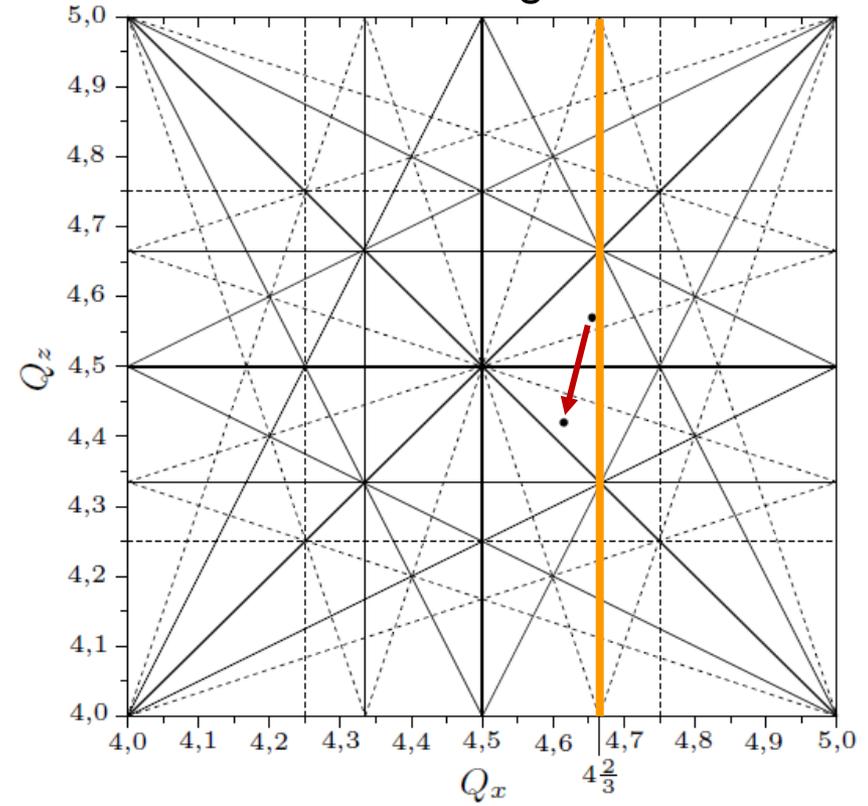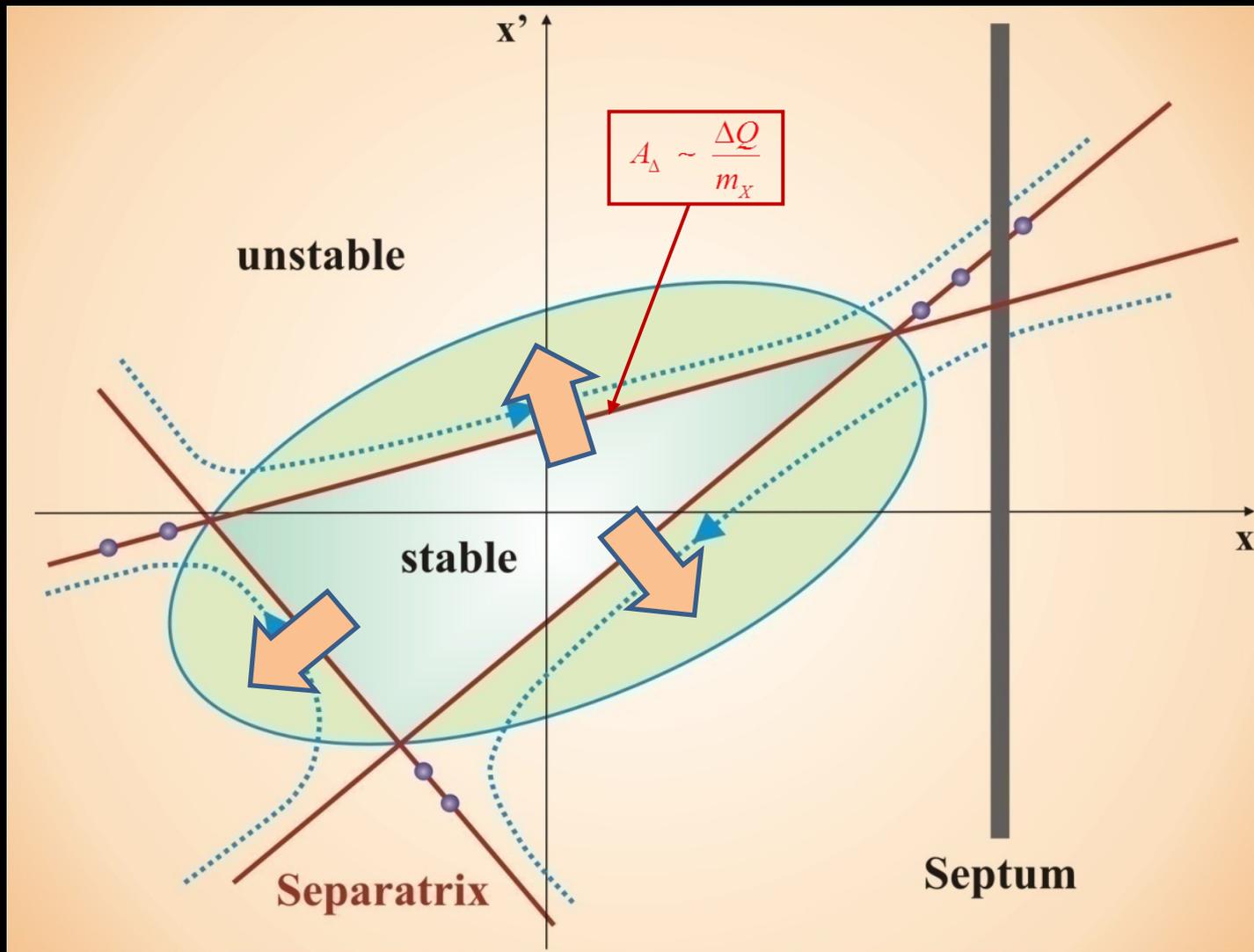
1/e damping times:

Injection (1.2 GeV): $\tau_x = 100$ **ms** / $\tau_s = 35$ **ms**

Extraction (3.2 GeV): $\tau_x = 5.2$ ms / $\tau_s = 2$ ms

Slow Beam Extraction

$$A_\Delta \sim \frac{\Delta Q}{m_x}$$

unstable

stable

Separatrix

Septum

x'

x

Sextupole Magnets (Extraction):
Excitation of a third integer resonance
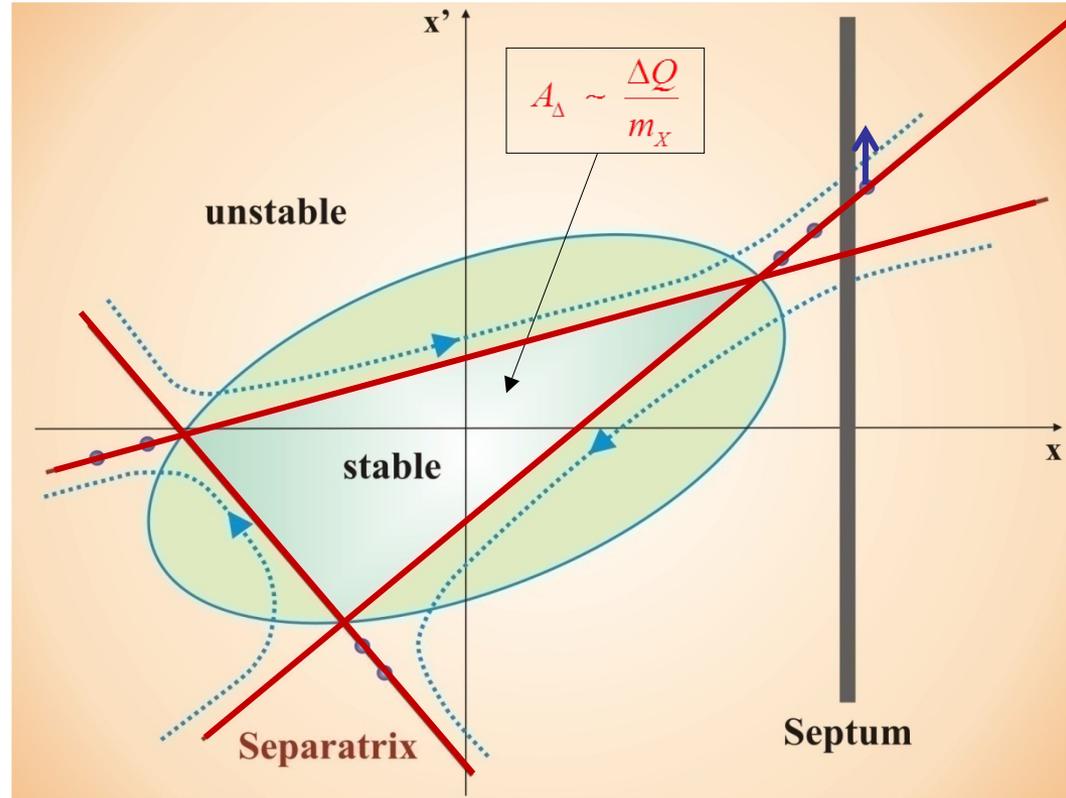
Ironless Quadrupole Magnets (Extraction):
Shift of the horizontal betatron tune close to a third integer value, "current feedback-loop"

Experiments

extr. quads

linpol γ

~ 0.5 nA

MSE22 QF22 M21 QD2

M22

MSE23 QD23

M23 extraction septa

QF24 superconducting
solenoid

M24

QD25

M25

QF26

M26

SD26
QD27

M27

ELSA

Intensity Stability

Stabilization of "overall" tagging rate (tagger-or)

Photon Camera
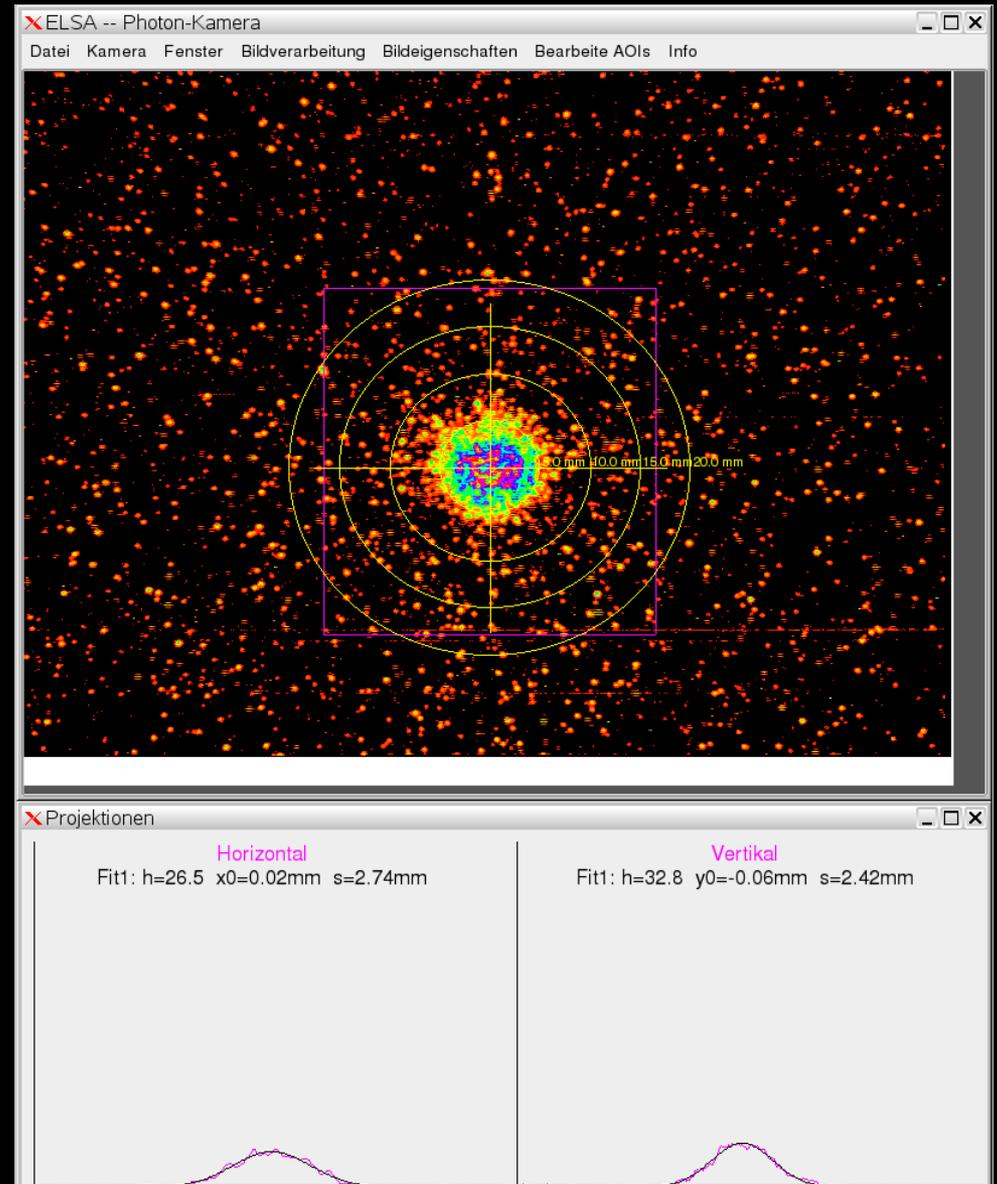
Position Measurement in the pA-Regime

$$P_{\text{noise}} = 4\,k_{\text{B}}\,T \cdot \Delta f$$

$$P_{\text{noise}} = 1{,}7 \cdot 10^{-20}\,\text{W/Hz} \cdot \Delta f$$
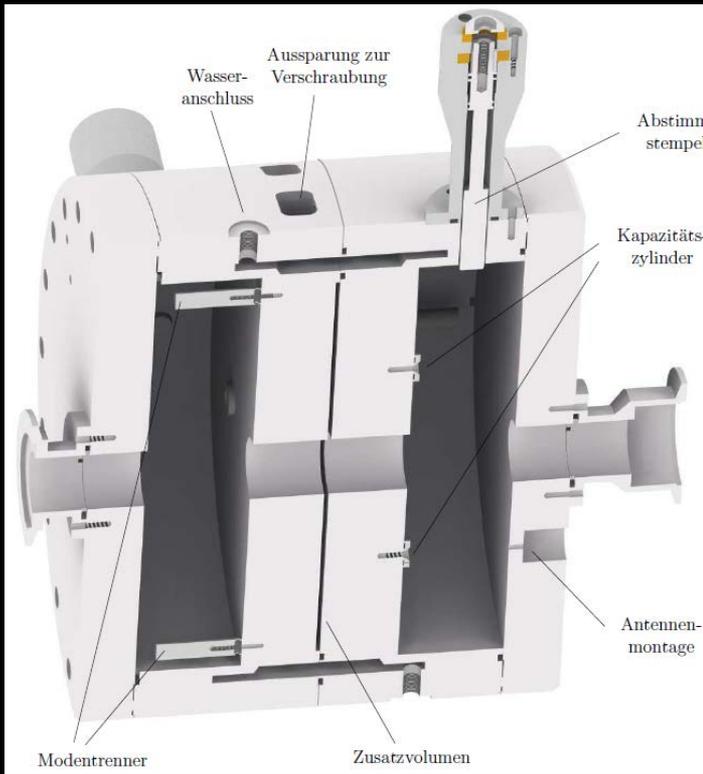
$$\Delta x < 50\mu\text{m} \;@\; I = 100\text{ pA},\; dx = 1\text{mm}$$

Parameter	Value
Mode	TM_{110}
Inner diameter	242 mm
Inner length	52 mm
Opening diameter	34 mm
Resonant frequency ν_0	1.499010 GHz
Shunt impedance $R_s/\Delta x^2$ (CST)	411 Ω/mm^2
Unloaded quality factor Q_0	11090
Coupling factor κ	0.89
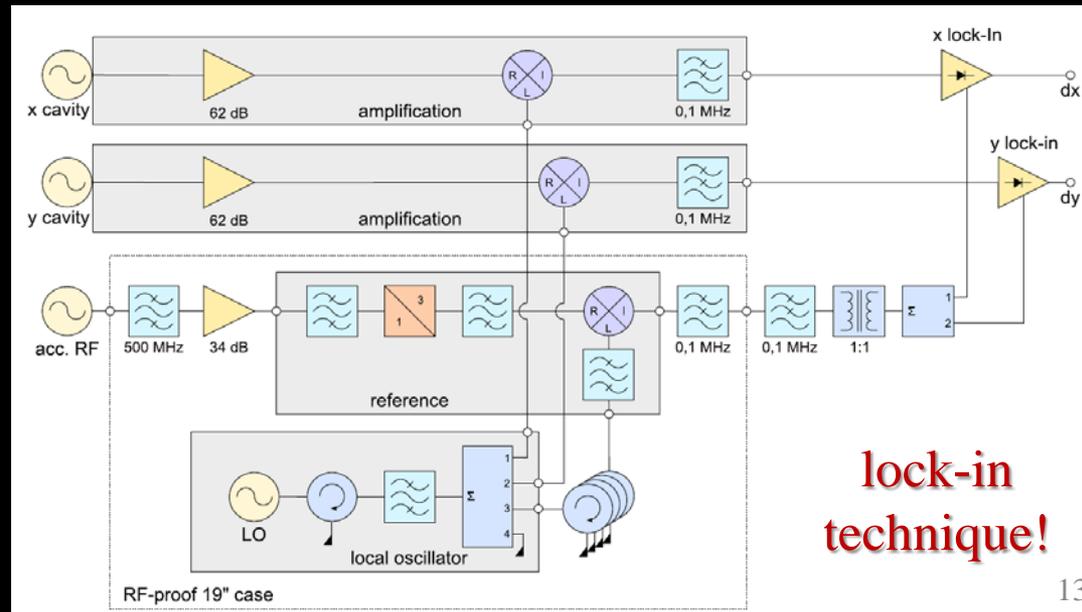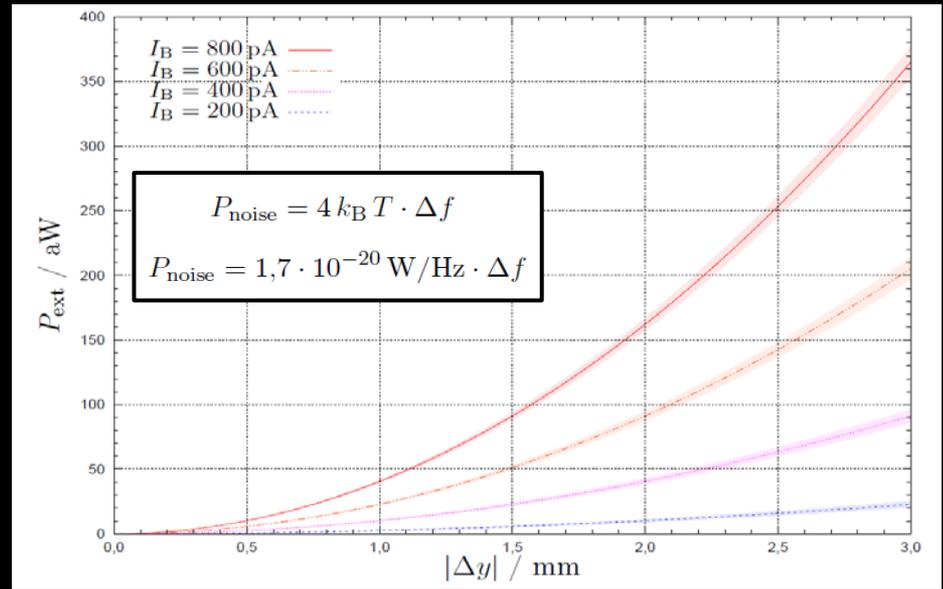
lock-in technique!

Strahllagemessung ELAN-Beamline

	Betrag	Phase	Mittel	Position		Mittel	
X	15.7 μV	-89 ⁰	-96 ⁰	-0.38 mm		-0.42 mm	
Y	54.6 μV	-88 ⁰	-89 ⁰	-1.68 mm		-1.69 mm	
I	Bunch-Faktor: 0.808			612 pA		604 pA	

Lock-In-Verstaerker

Zeitkonstante

◄ 30 ms ►

Status ● ● ●

Datenerfassung

Messung	Logging
AN	AN
AUS	AUS

Meldungen: Messung laeuft.

Mittelwerte, alle 5 Zyklen erfasst

Pos. / mm — x (gemittelt) — y (gemittelt)

500   Zyklusdauer: 5.28 s   1 Zyklen

Zeitliche Entwicklung waehrend der Extraktion

Letzte Extraktion, Ausleserate: ● 5.0 Hz

Pos. / mm — x — y — x-Fit

0.89 s + 0.20 s   Extraktionszeit: 4.01 s   4.68 s

Gemittelt ueber 10 von 10 Extraktionen

Pos. / mm — x (gemittelt) — y (gemittelt)

1.08 s   4.68 s

14
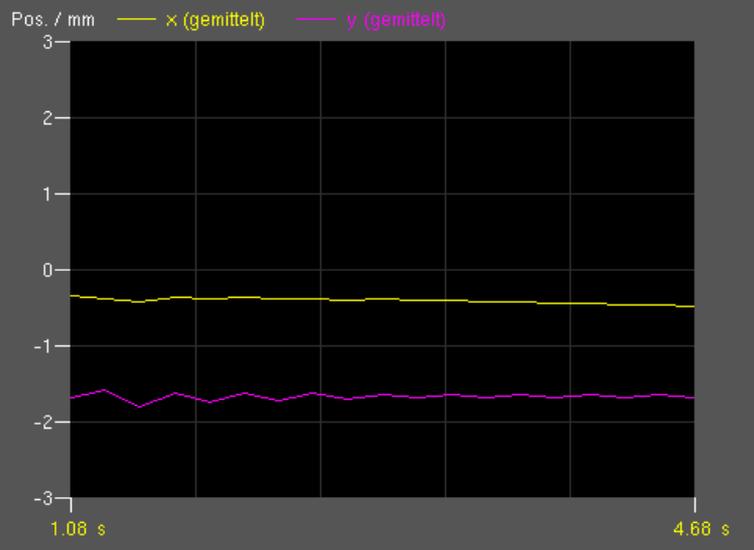
Spill Characteristics:

Beam Parameters:

- **Intensity:** adjustable, $\boxed{\textbf{0.1 fA} < \textit{\textbf{I}} < \textbf{ 1...10 nA}}$

Beam Parameters:

- **horz.:** affected by extraction, $\boxed{\textbf{have to be measured}}$

- **vert, long:** about the same as the internal values

Long-Term Stability:

- beam pointing stability $\leq$ 20 µrad $\leftrightarrow$ $\boxed{\textbf{photon-camera}}$

- beam position stability $\leq$ 0.2 mm $\leftrightarrow$ $\boxed{\textbf{RF-cavity}}$

Horizontal Emittance

$$A_\Delta \sim \frac{\Delta Q}{m_X}$$

Legend:
- Emittanzmessung mit automatisierter Mittelung
- Natürliche Emittanz bei 2,35 GeV
- Emittanzmessung ohne Mittelung

y-axis: Emittanz / nm rad

x-axis: Arbeitspunkt

Horizontal Emittance

$$A_\Delta \sim \frac{\Delta Q}{m_X}$$

Emittanzmessung mit automatisierter Mittelung

Natürliche Emittanz bei 2,35 GeV

Emittanzmessung ohne Mittelung

Emittanz / nm rad

Sextupolstärke / m^{-3}
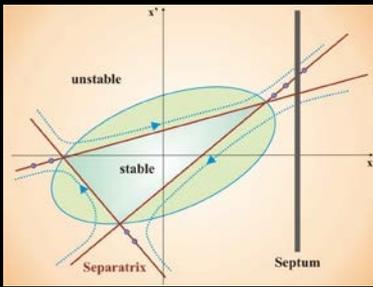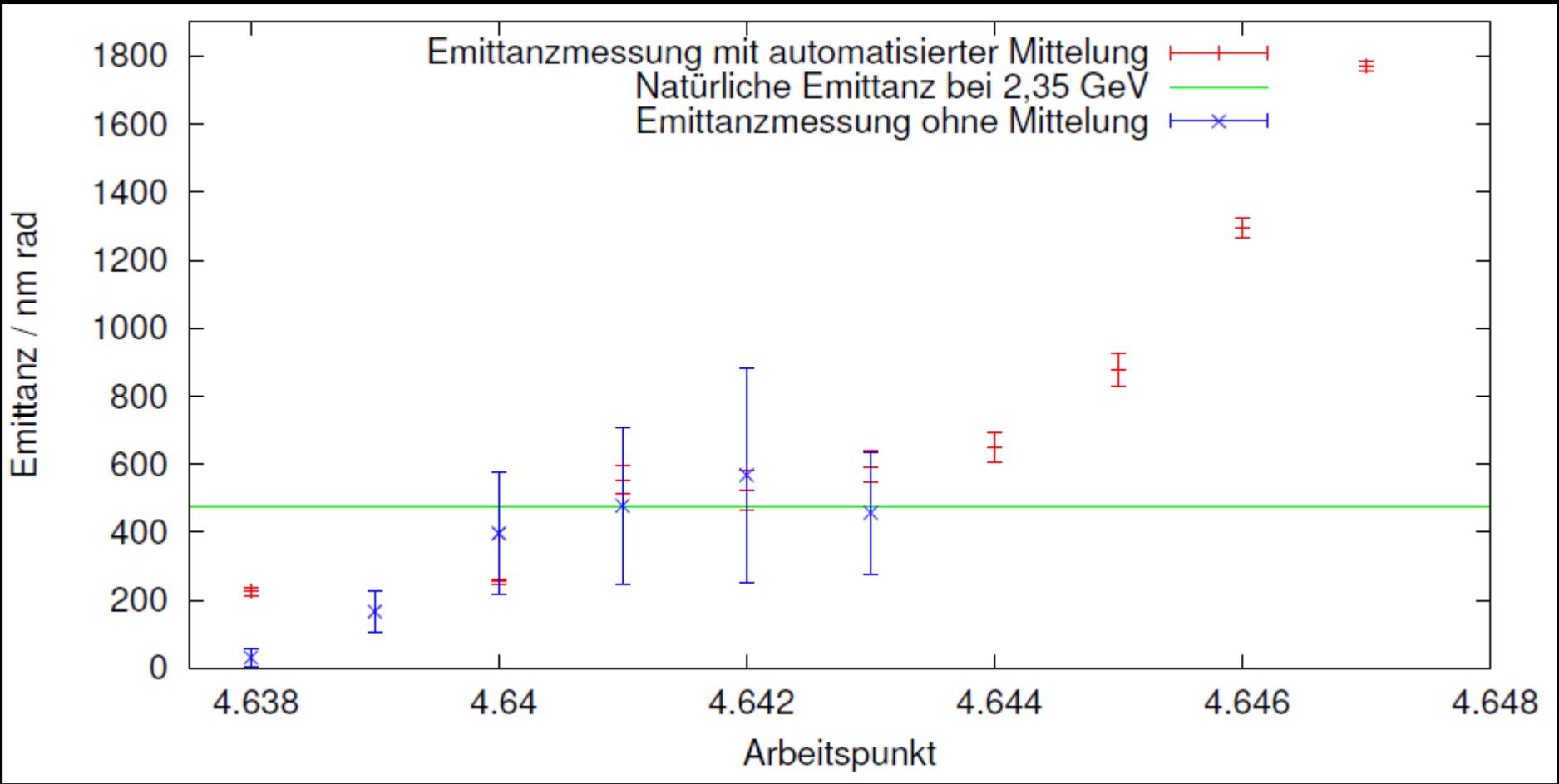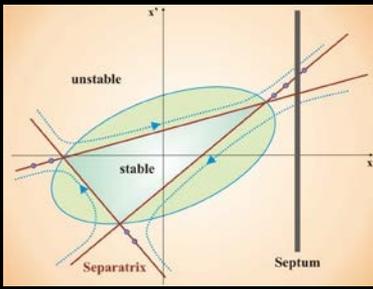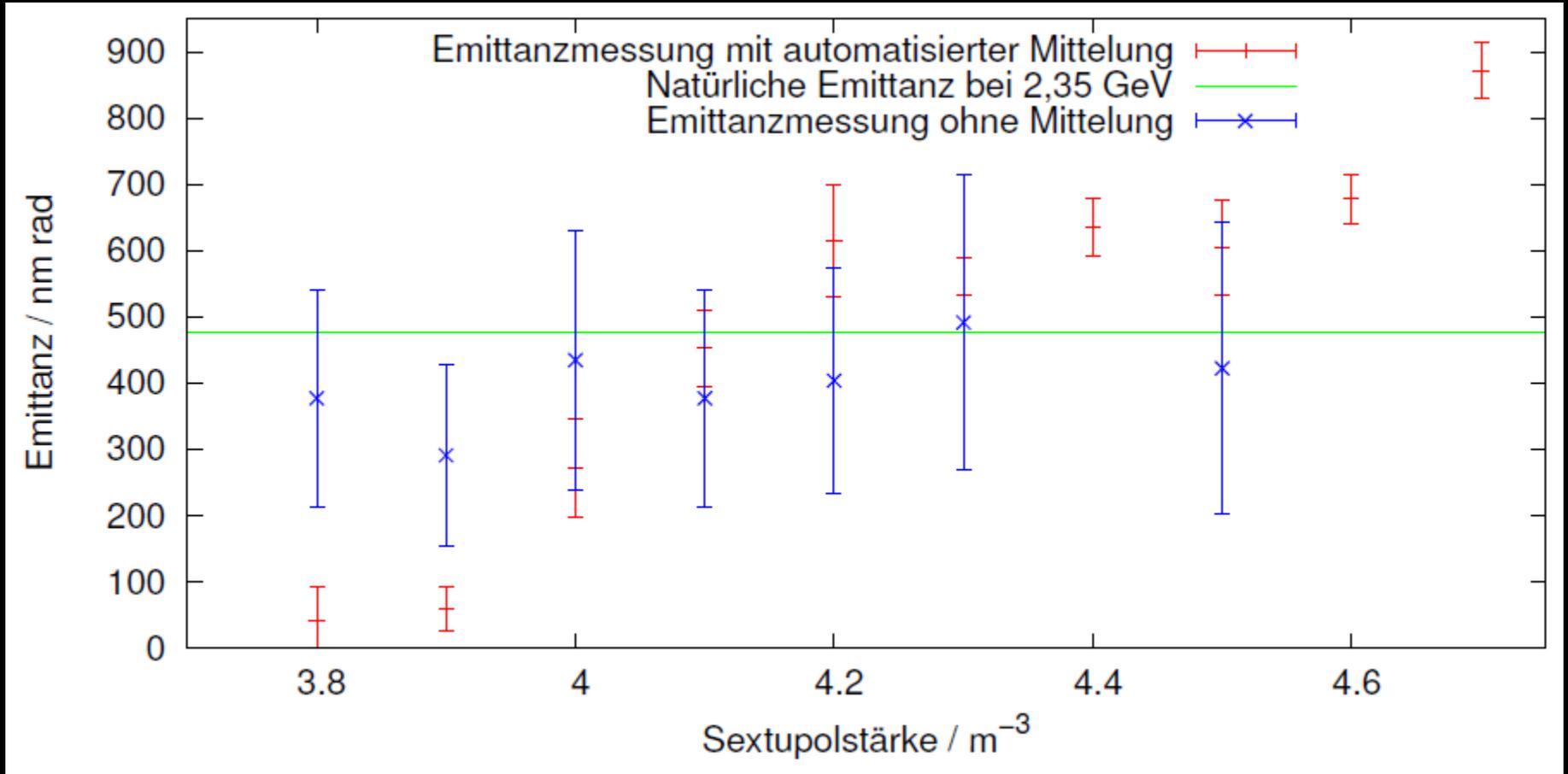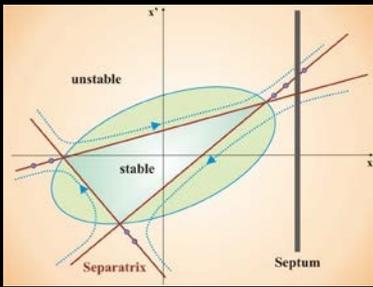
Horizontal Emittance
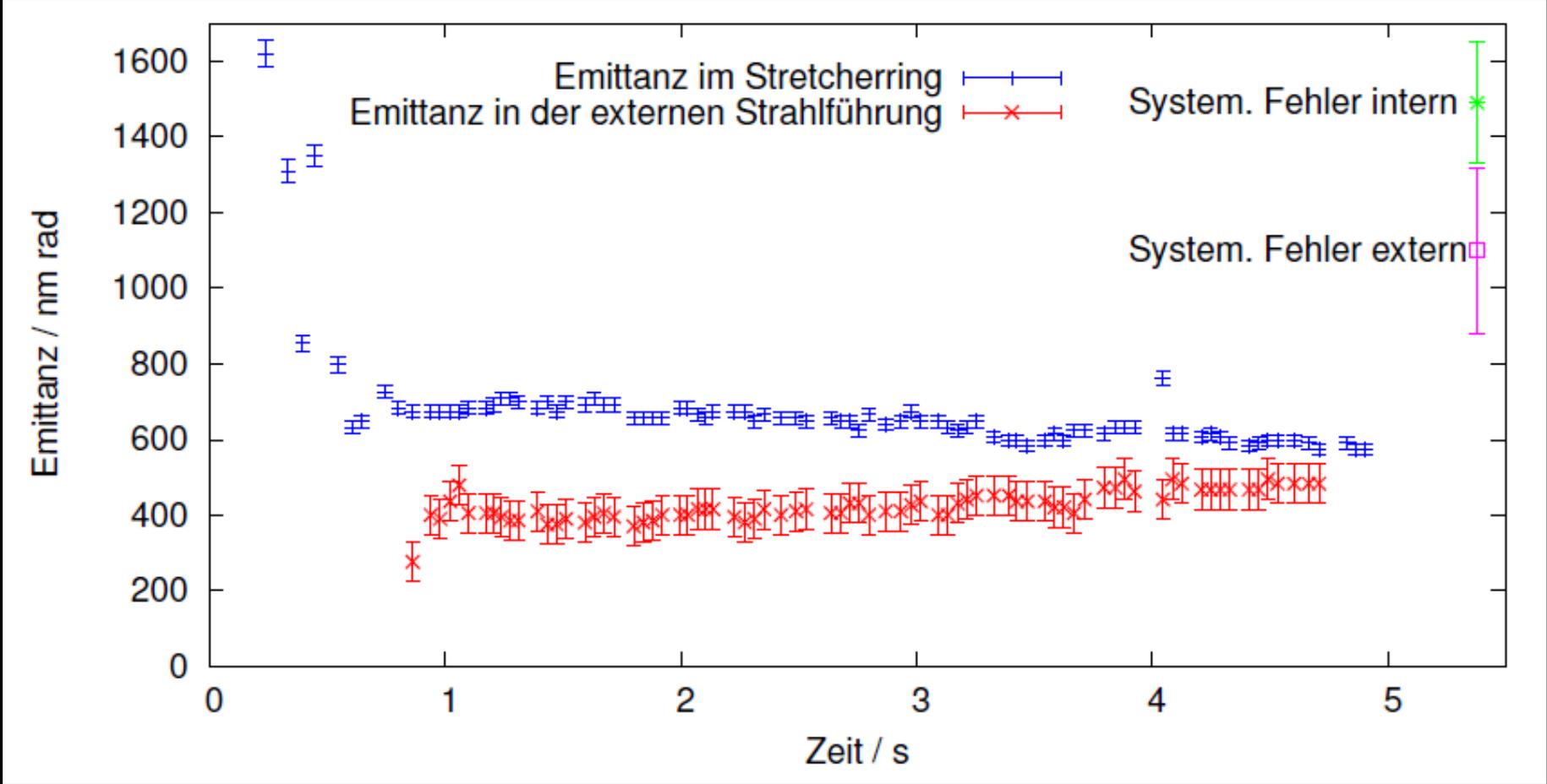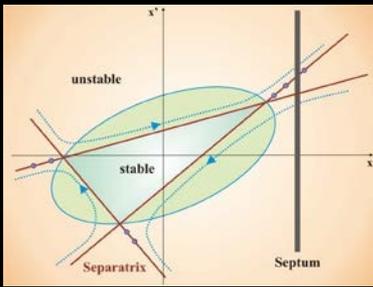
$$A_\Delta \sim \frac{\Delta Q}{m_X}$$

Vertical Emittance

$$A_\Delta \sim \frac{\Delta Q}{m_X}$$
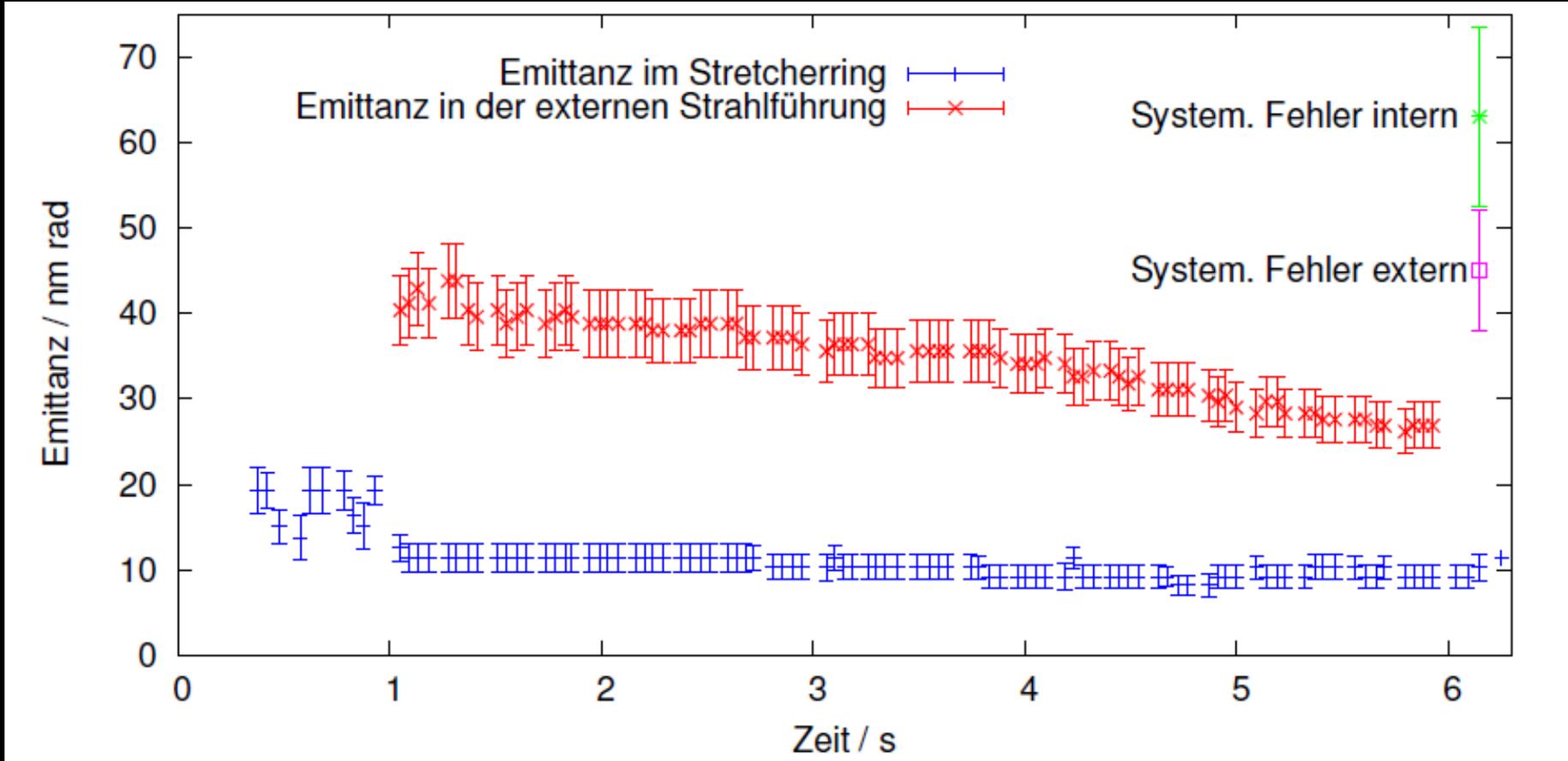
Experimental R&D
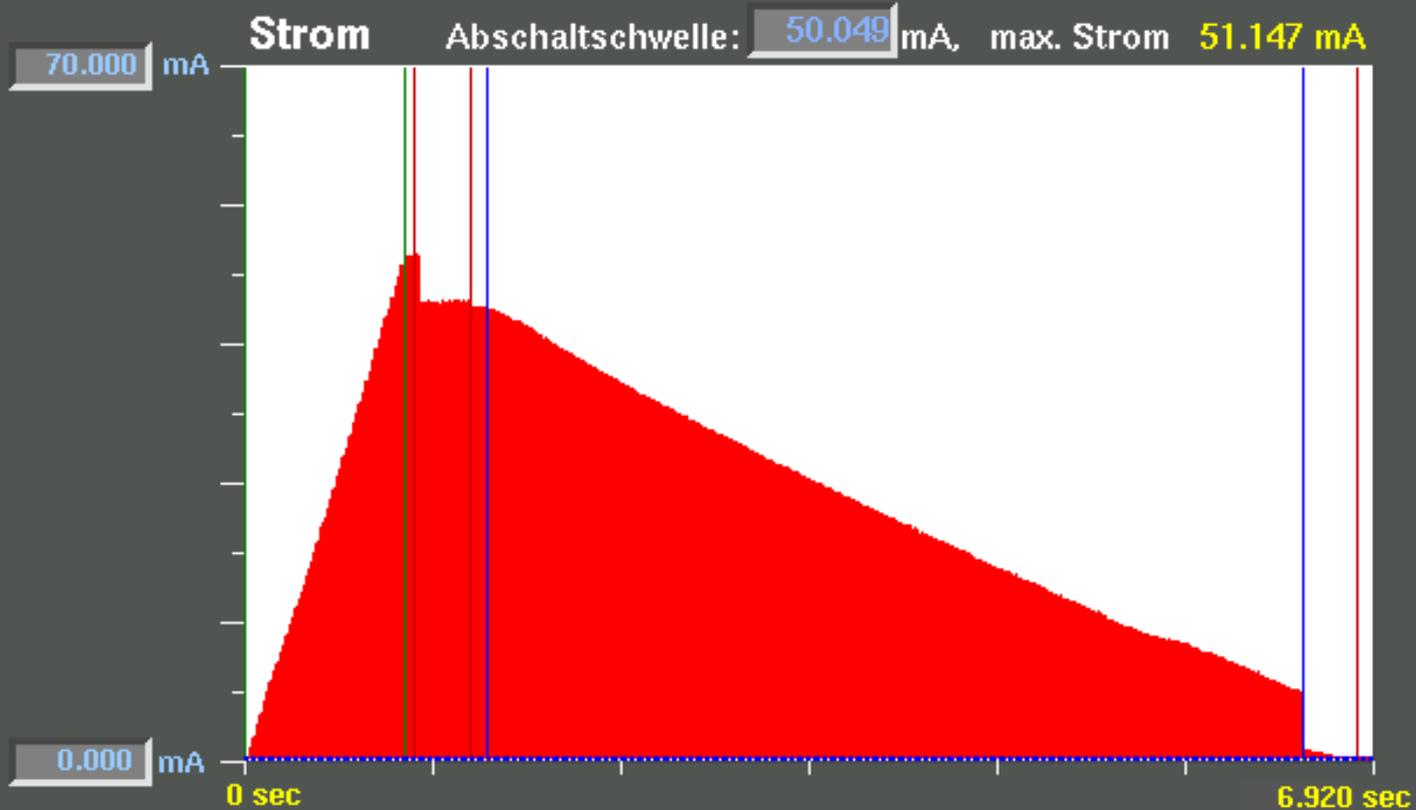
Resonance Scan

Requirements:

- **Precise setting of the tunes ($\Delta Q_x < 10^{-4}$)**

  – ironless air core quadrupole magnets

- **Precise measurement of the tunes ($dQ_x < 10^{-4}$)**

  – dedicated 3D bunch by bunch feed-back system

- **Precise measurement of the beam loss**

  – dedicated beam loss monitoring system

- **Fully automatized parameter setting and data taking**

@ $Q_s = 0.0488$
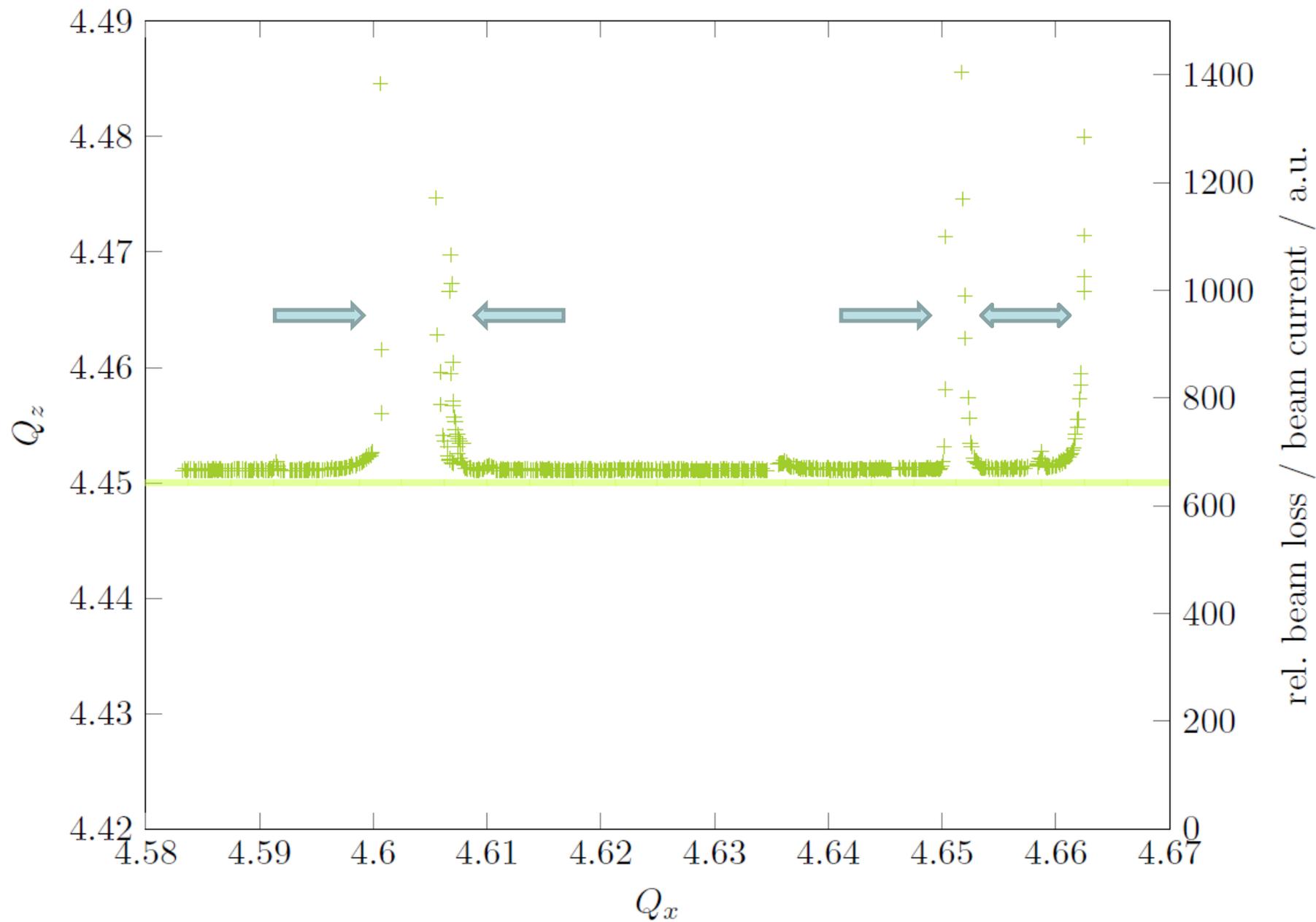
@ $Q_s = 0.0488$
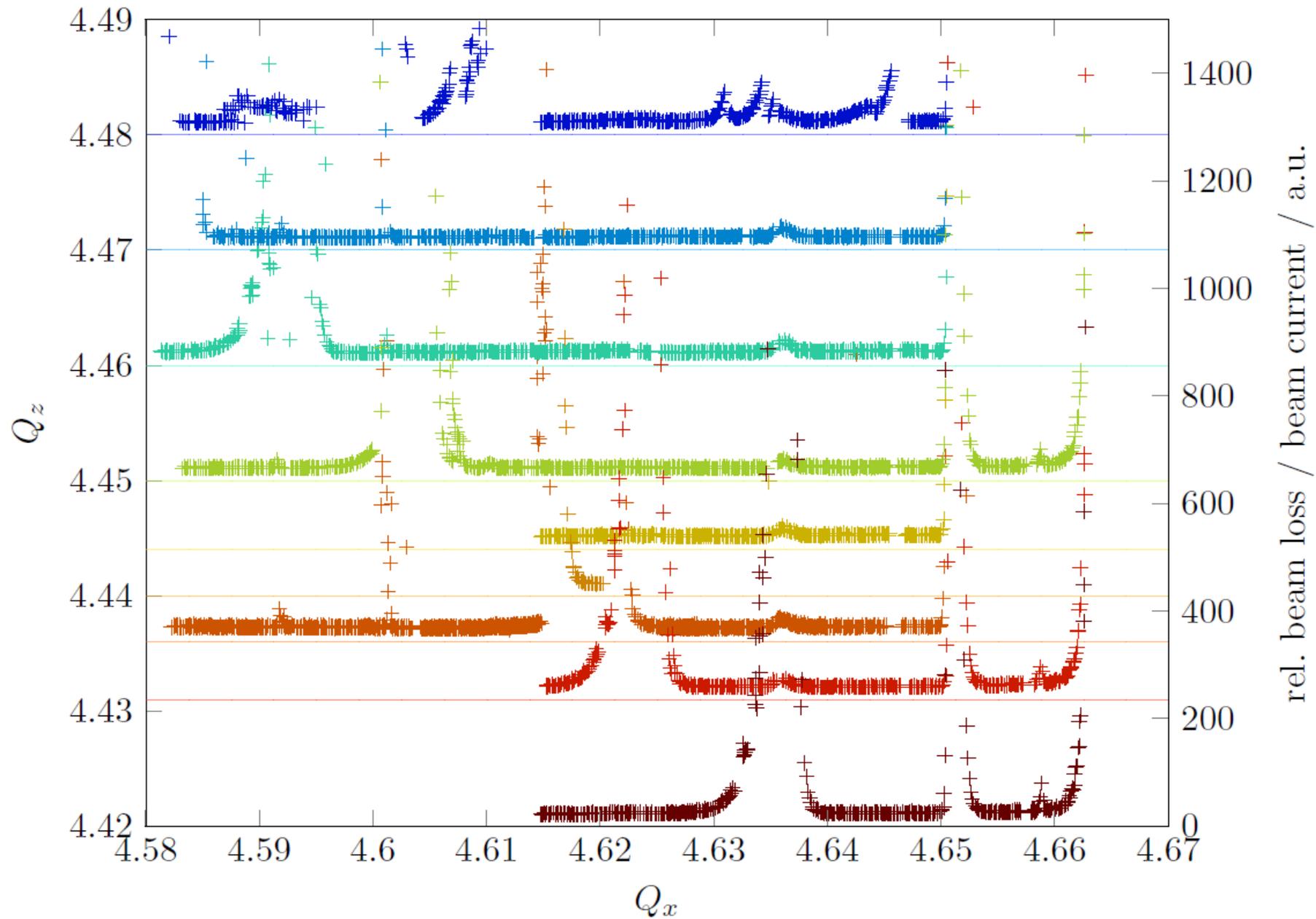
@ $Q_s = 0.0488$
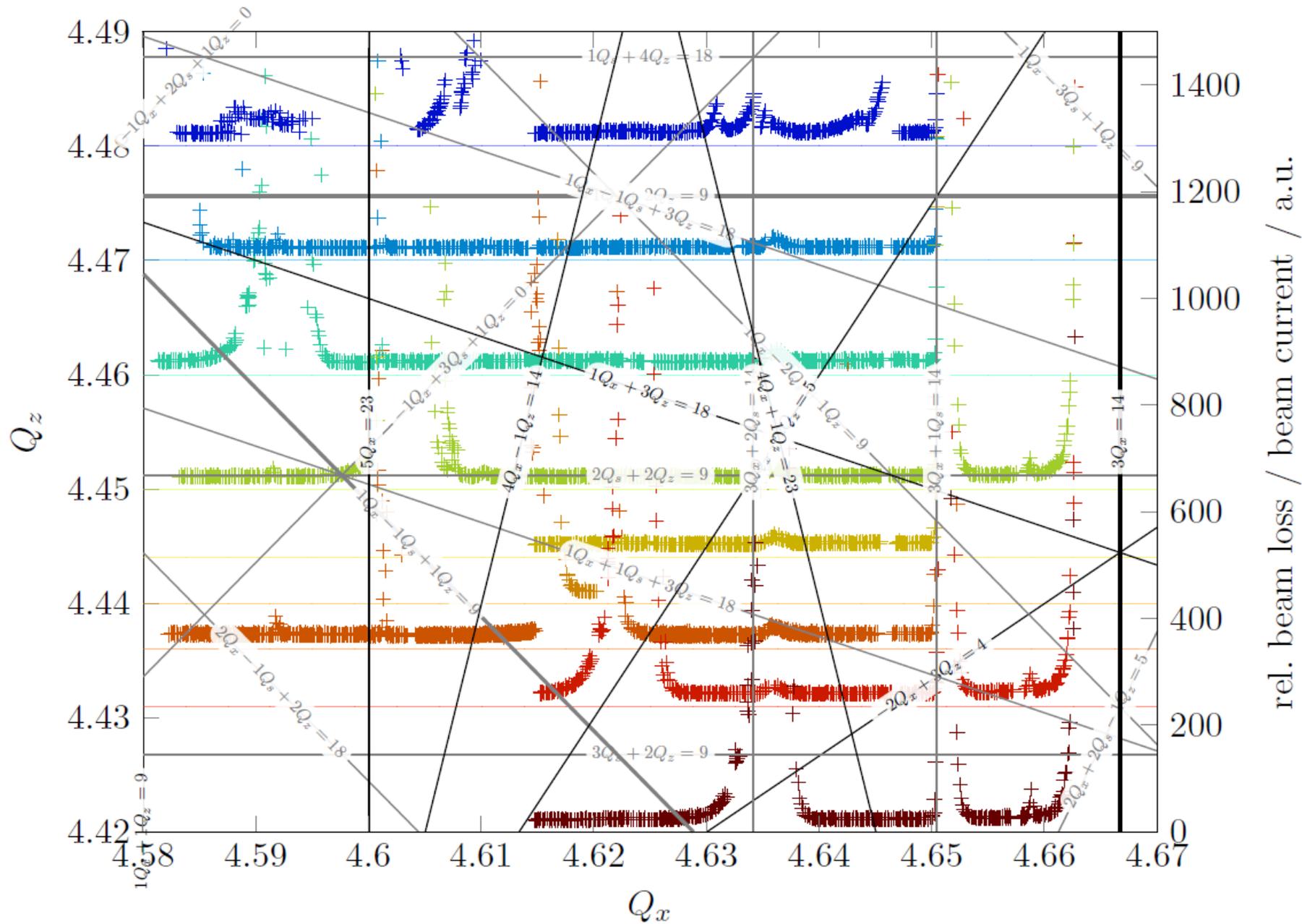
@ $Q_z = 4.431$
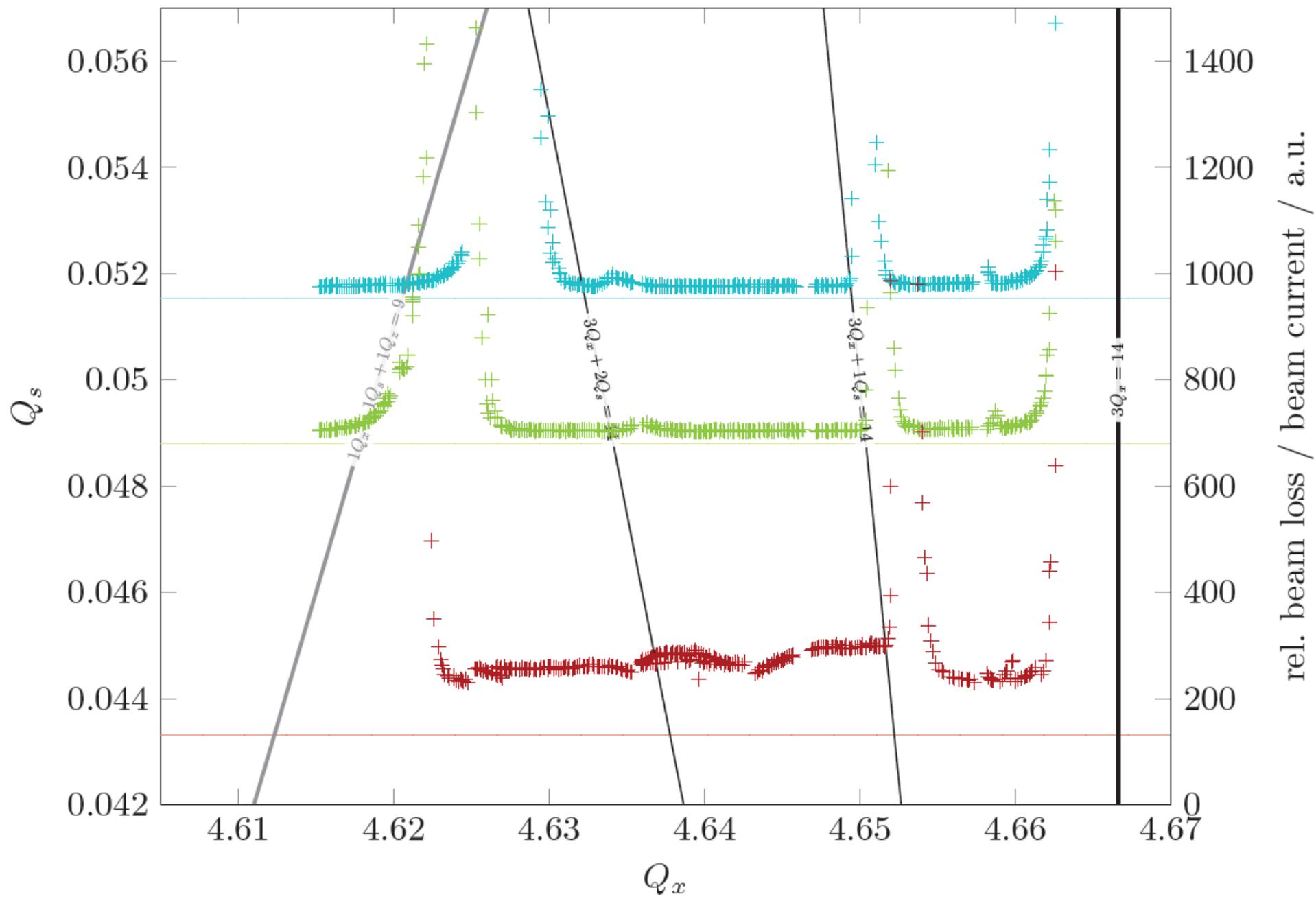
@ $Q_s = 0.0488$
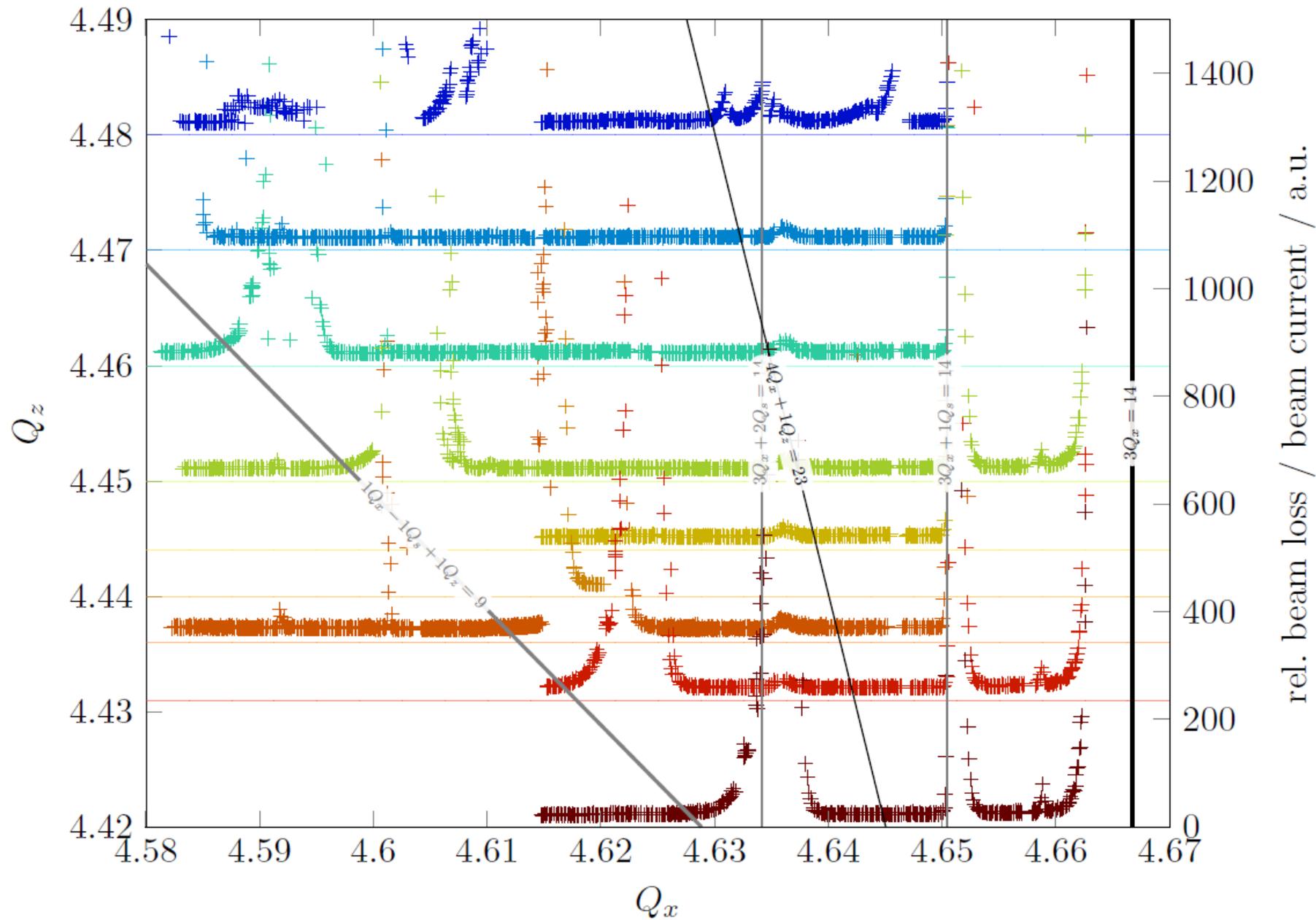
@ $Q_s = 0.0488$, $m_{ex} = 2$
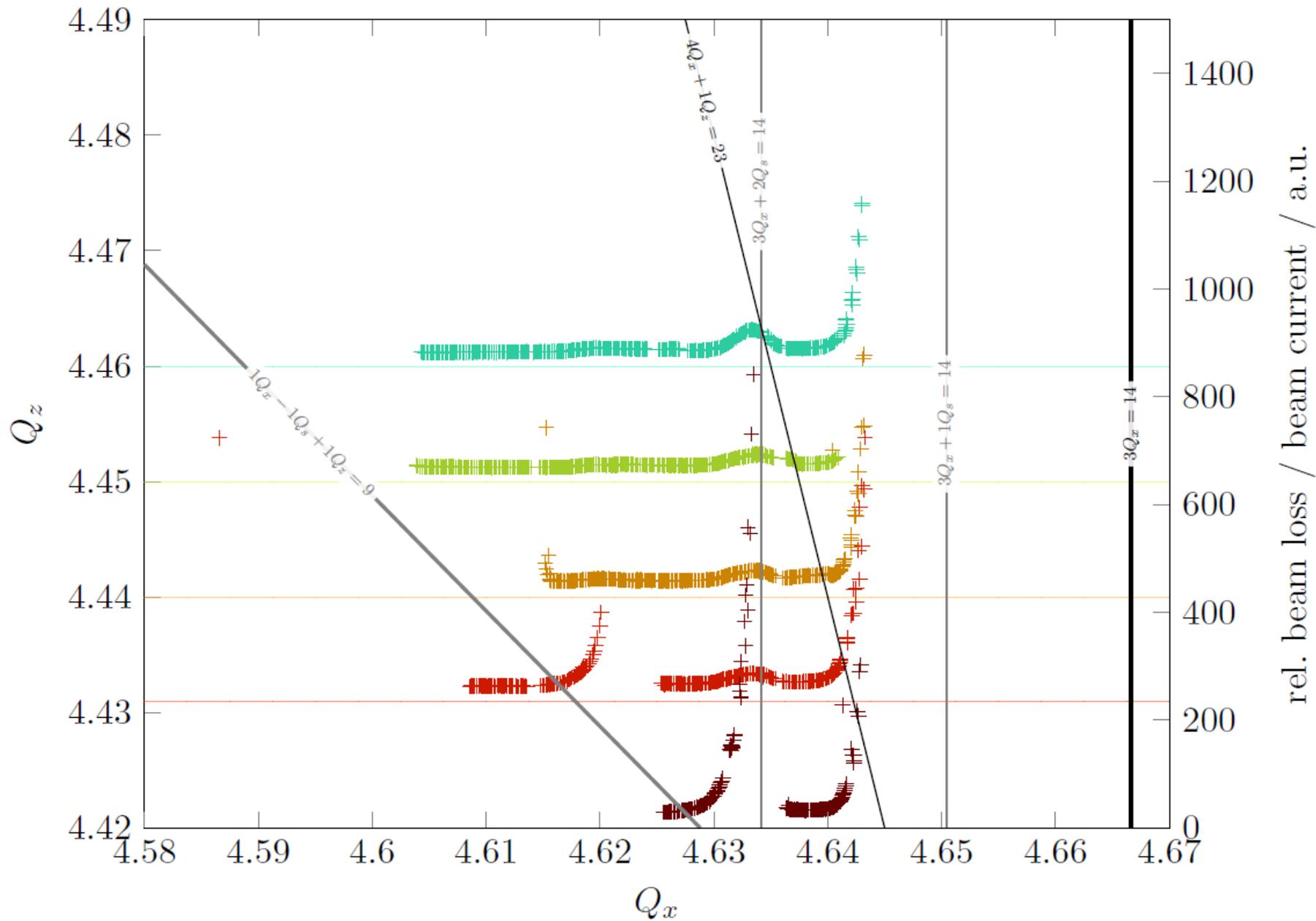
Choice of Optimum Tunes

Tune diagram

tunes in Boostermode @ $Q_s = 0.0488$
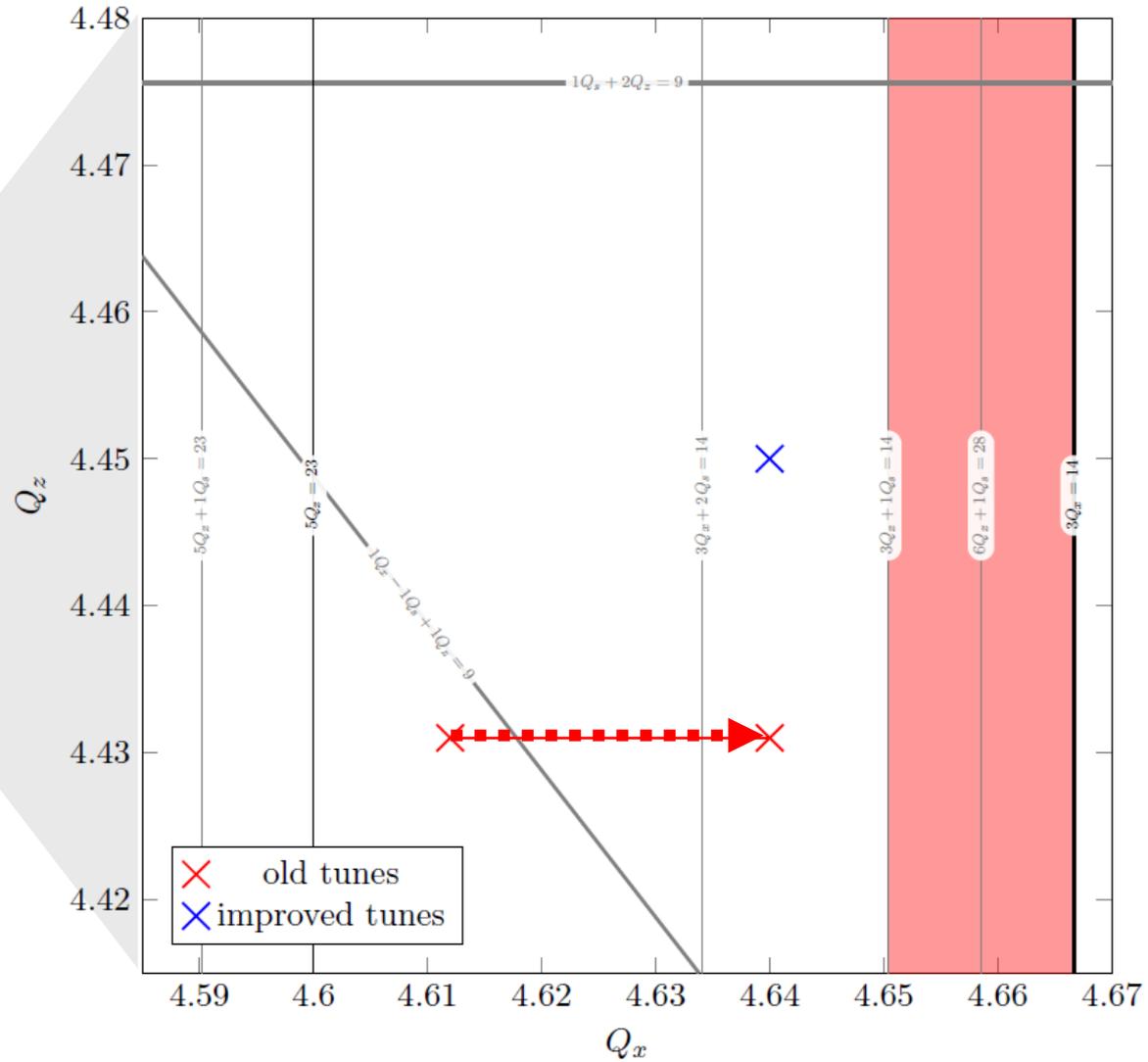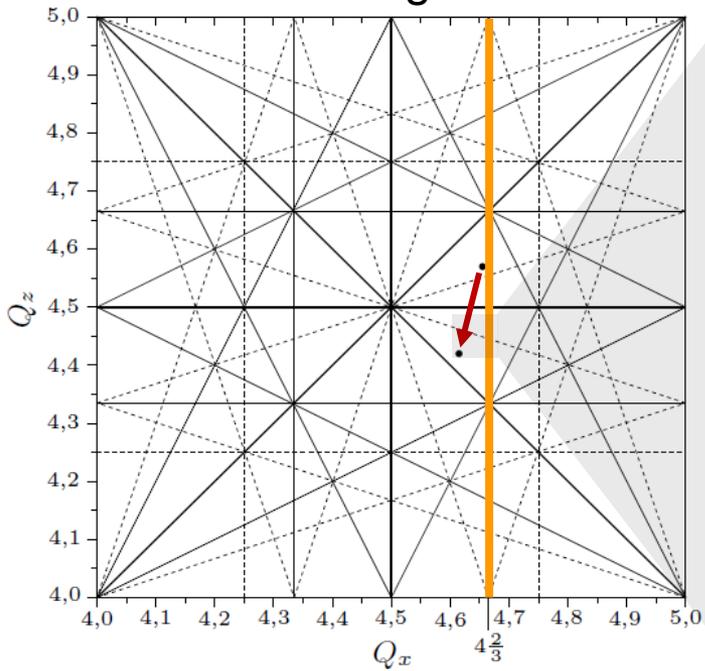
SR based Intensity Monitoring

H$_2$O cooled copper pick-off mirror

OSR

bending di...

$R = 10.88$

optical box beneath

magnification
$M=0.125$

$f=500$

alignment laser

motorized

CCD

Synchrotronlicht während eines ELSA-Zyklus

Counts x 10
2500

1250

0

e$^-$ extraction event rate
2 kHz

ELSA current < 35 nA

0 s   integrationszeit jeweils 20 ms   4880 s

ELSA-Zyklus

beam position control (CCD)

5.0 mm   10.0 mm
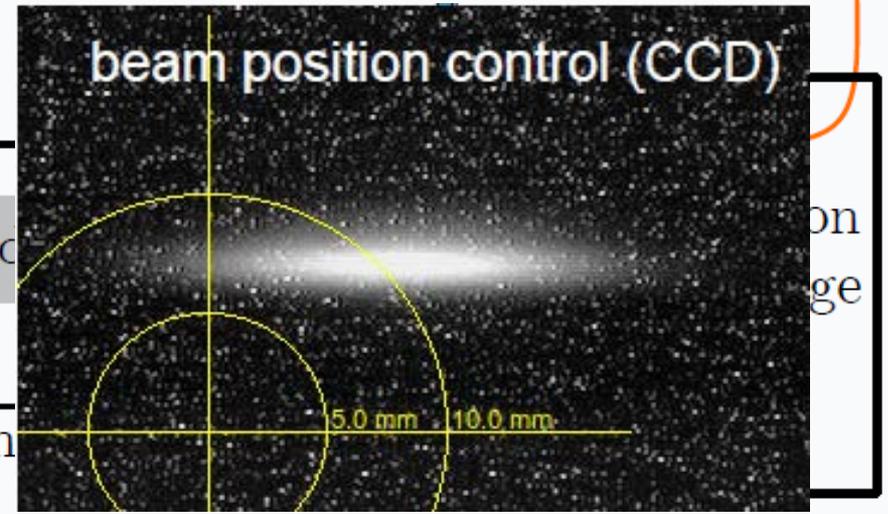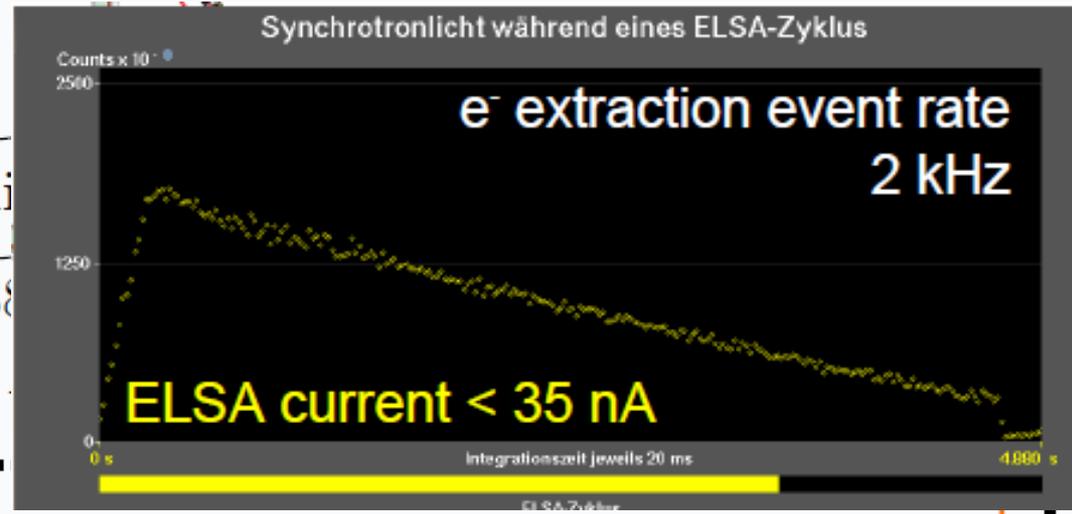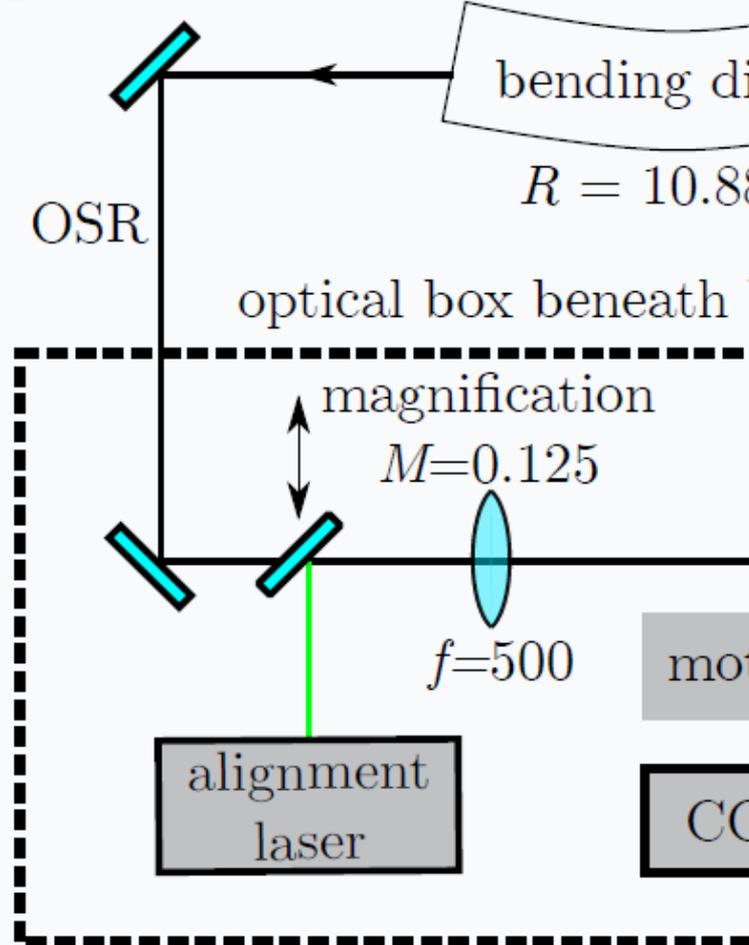
Ultra-low Current Injection

Control of Synchrotron RF Generator

- Wait for next accelerator cycle
- Accelerator running?
- Problem with RF generator? → Reset RF generator
- RF power much too high? → Decrease coarse gain
- RF power much too low? → Increase coarse gain
- No. of injections < lower threshold? → Decrease fine gain
- No. of injections > upper threshold? → Increase fine gain
- program generator synchrotron RF

calibration LED

photomultiplier Photonis XP2262

collimation

attenuation

pulses from photomultiplier → NIM discriminator

counter TTL output
men M41 module

veto inp.

injection trigger

timing module

readout every 20 ms

counts > nominal value?

true

set veto signal

software

VME system

LINAC

Typical Performance

Extraction rates of 100 Hz to 1 MHz

Summary

Slow electron extraction at a 3rd integer resonance

- resonance excitation with sextupoles in dispersion free straights

- shrinking of phase stable triangle with ironless quadrupoles

- in case of synchro-betatron coupling extraction at $3Q_x+Q_s = n$ possible

Stabilization of beam parameters

- intensity: feed-back on extraction quadrupoles ($\leftarrow$ intensity signal)

- pointing: feed-back on extraction septum ($\leftarrow$ quadrupole current)

Dynamic range

- ext. currents 0.1 fA $< I <$ 10 nA depending on fill of the storage ring

Appendix

… spares …

Beam Loss Monitoring System

QF

QD

32x

pin diodes
below shielding

7 cm

BERGOZ
Beam Loss Monitor (BLM)

BLM   BLM   BLM

BLM   BLM   BLM

BSC   BSC   BSC

RS485-BUS

cycle trigger

control
system   Linux PC
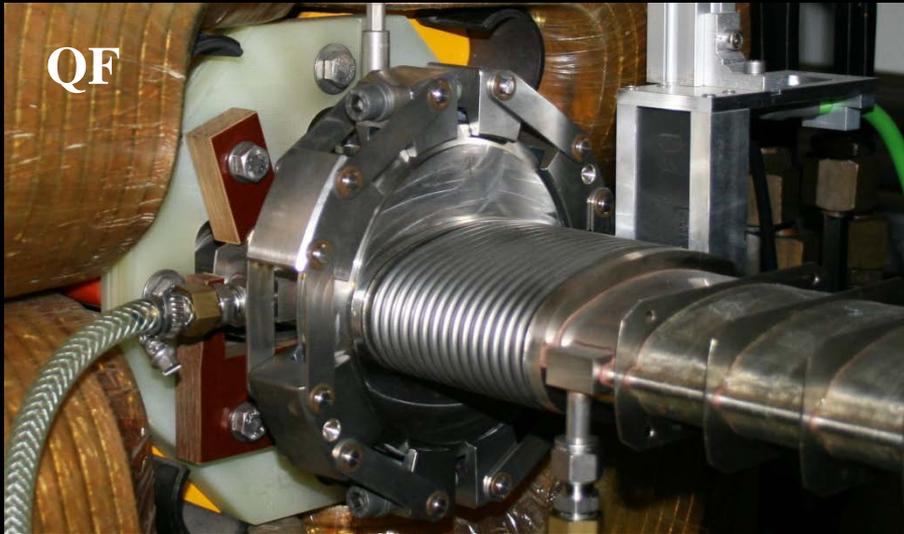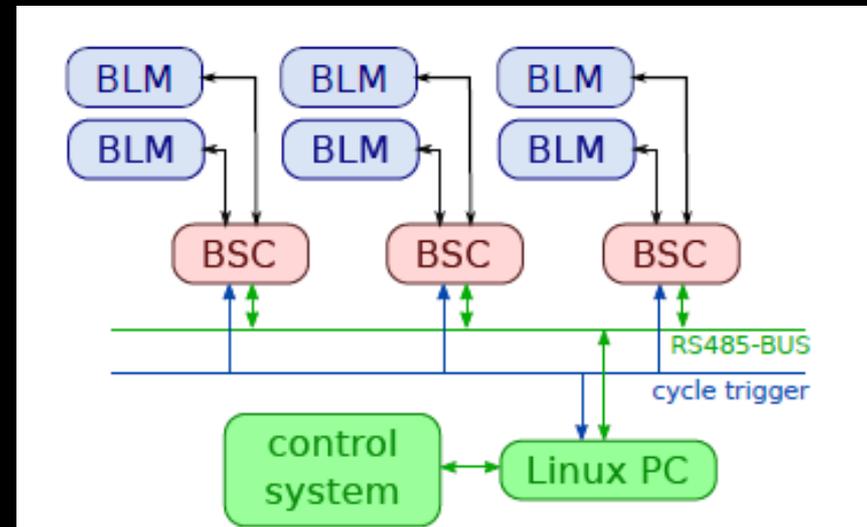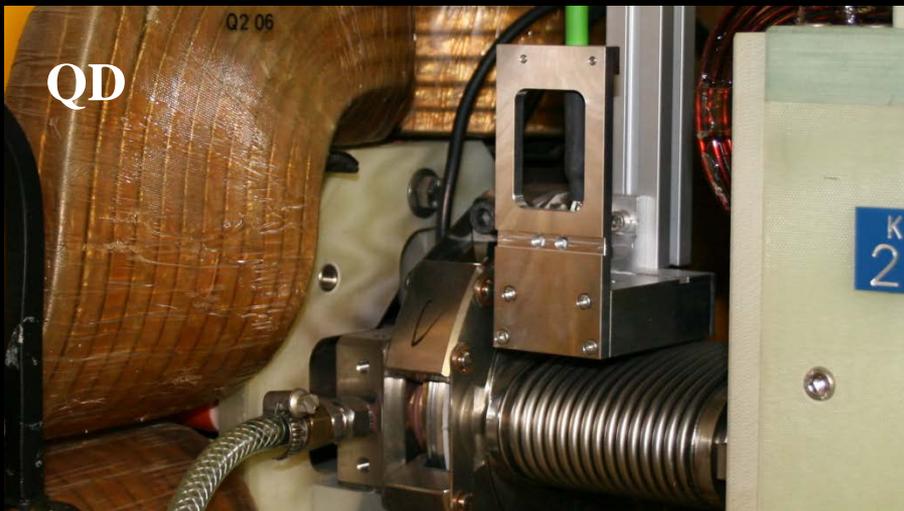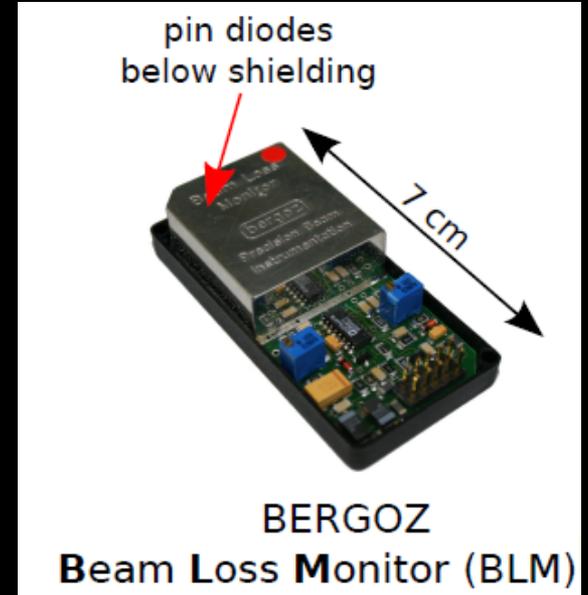
Bunch by Bunch Feedback

System Layout:

©DIMTEL, Inc.
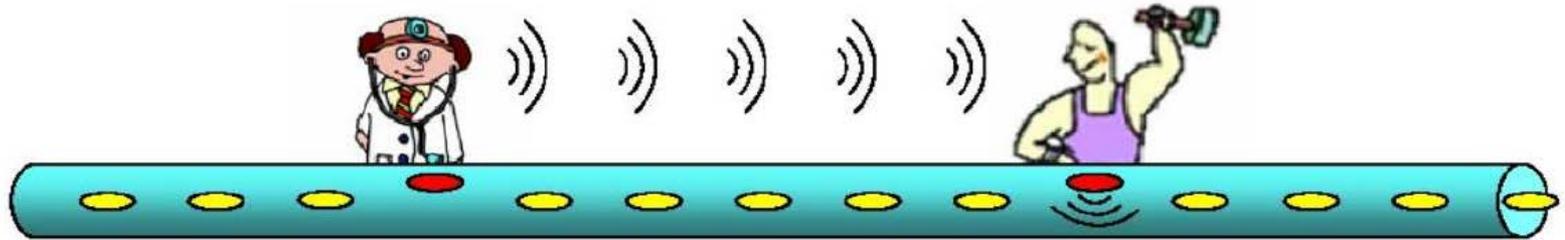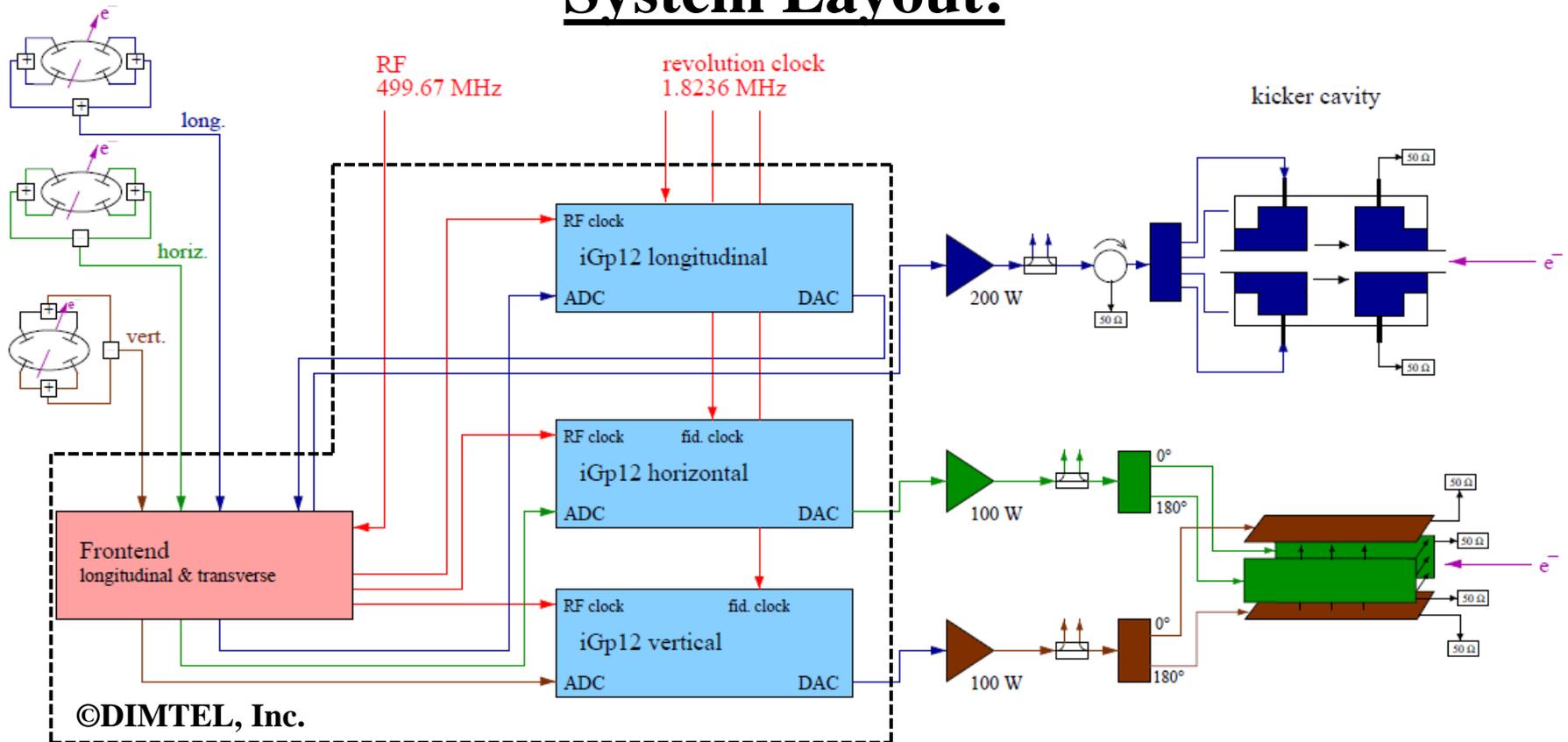
Broad-Band Kickers

(developed and constructed in-house)

Longitudinal: Kicker Cavity
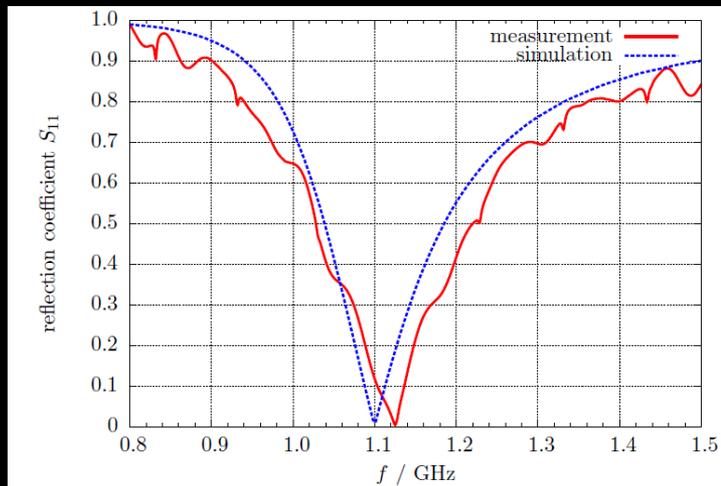
$$\nu = 1.13 \text{ GHz}$$

$$Q_L = 3.78$$

$$R_S = 387 \ \Omega$$

$$BW = 255 \text{ MHz}$$
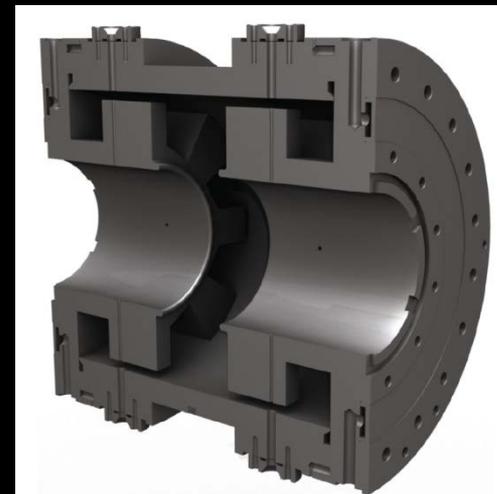
Transverse: Stripline Kicker

$$f = 0 - 250 \text{ MHz}$$
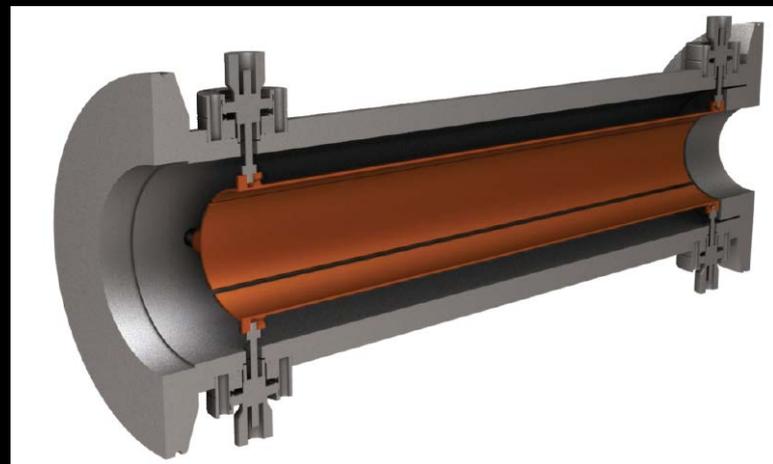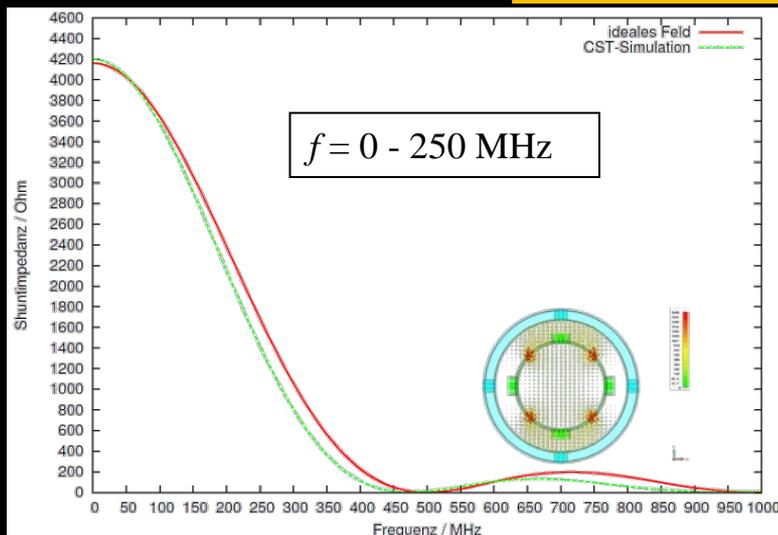
Feedback based Tune Measurement

Damping of Instabilities:

Coherent Signal:

FB on
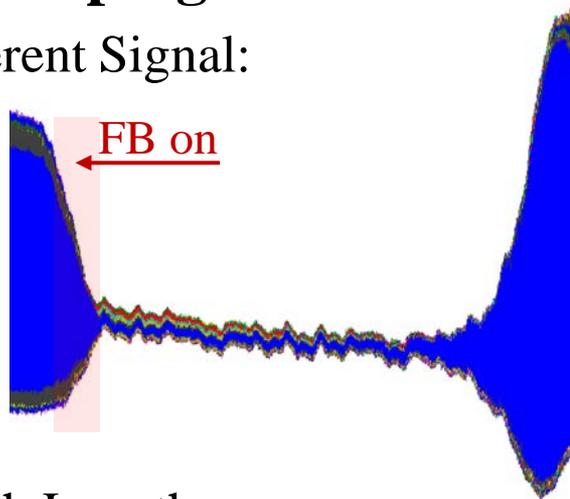
Bunch Length:
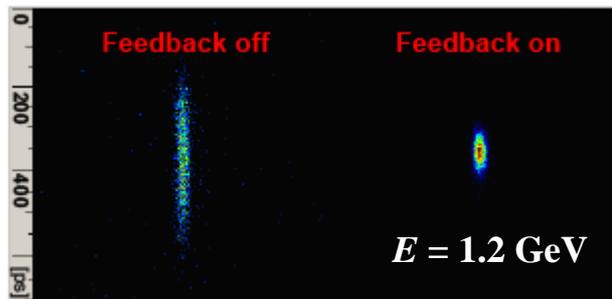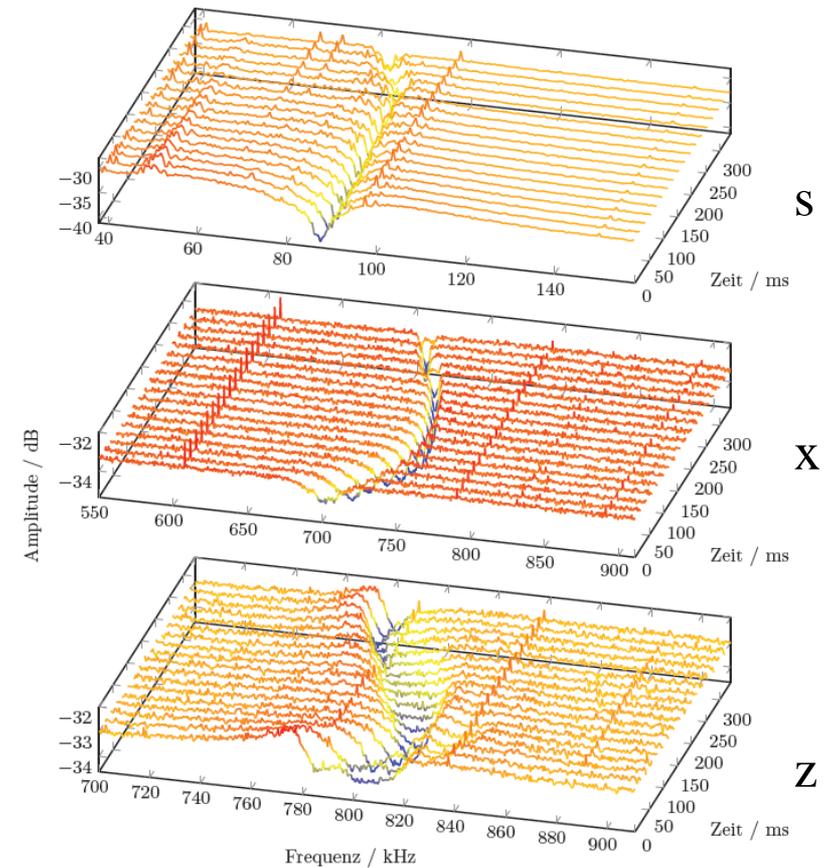
Allows stable operation of ELSA with currents up to 200mA!

Horizontal tune fit

Gaussian fit: horizontal beam spectrum

$f_x = (649.467 \pm 0.049)\,\text{kHz}$

$Q_x = 5 - f_x / f_{rev} = 4.643\,85 \pm 0.000\,03$
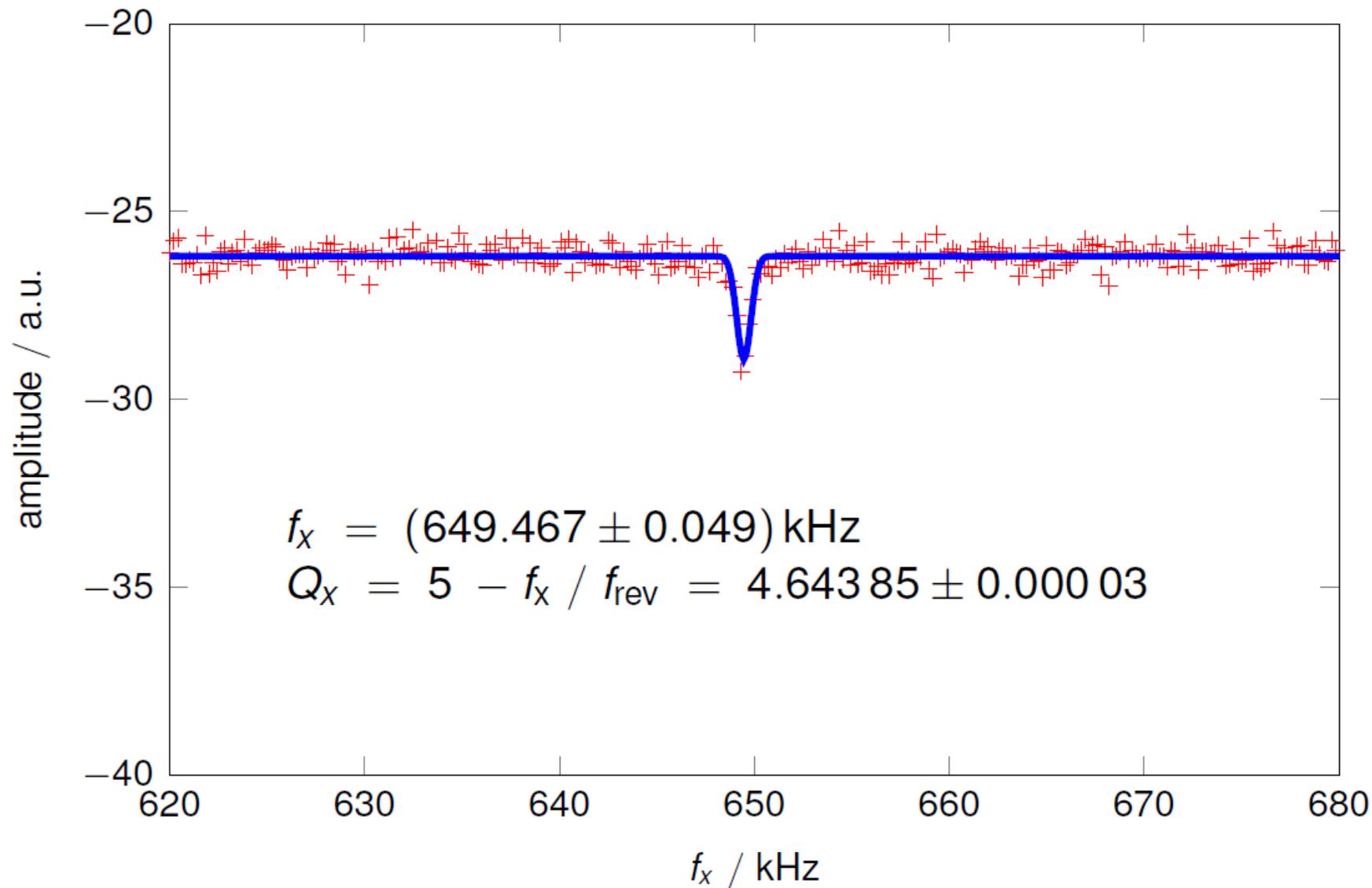
Vertical tune fit

Gaussian fit: vertical beam spectrum

$$f_z = (833.107 \pm 0.141)\,\text{kHz}$$
$$Q_z = 4 + f_z / f_{rev} = 4.456\,85 \pm 0.000\,08$$
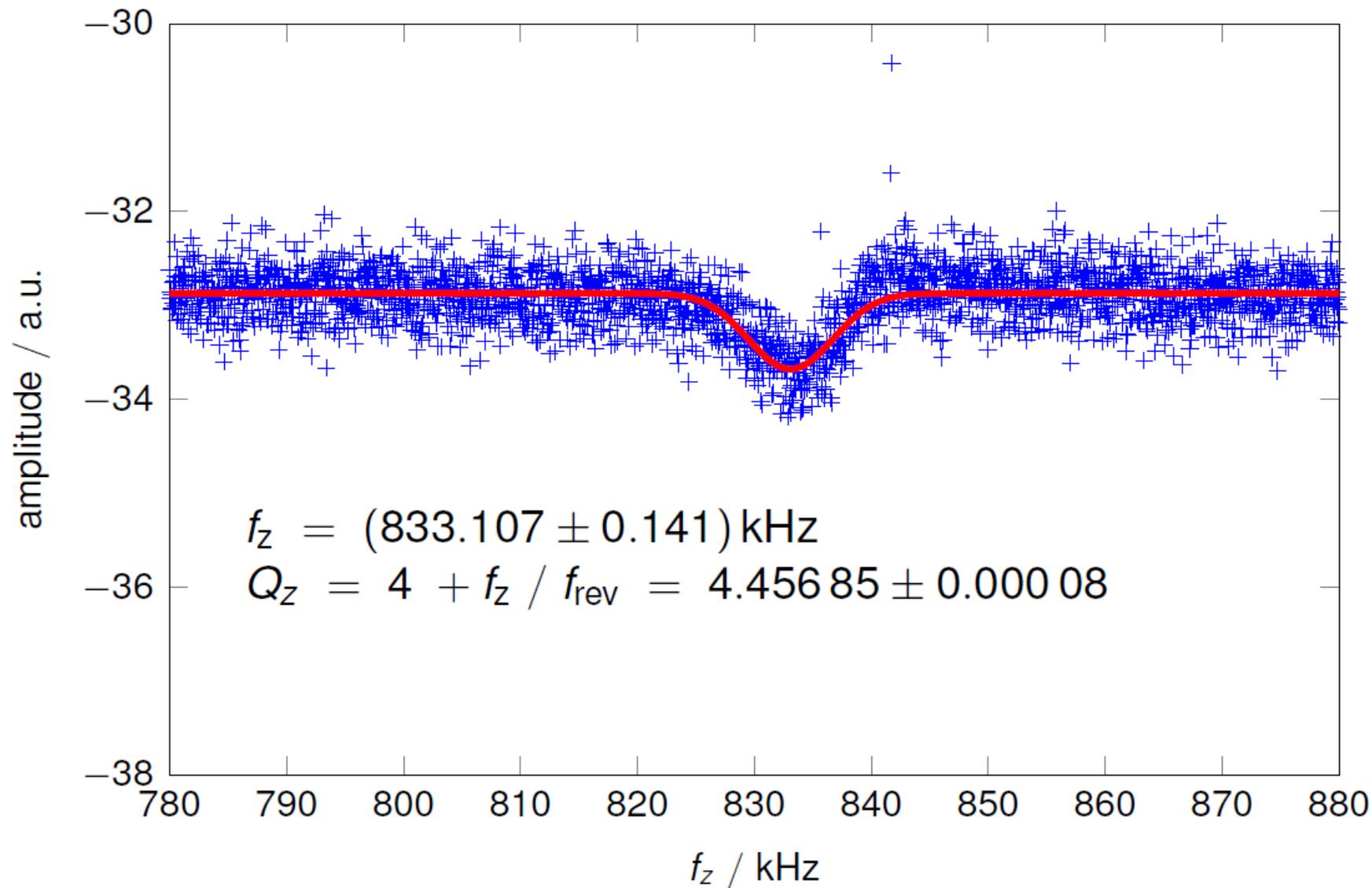
Resonance scan: cooking

set values:

- Q_x $\Delta = 0.0001$
- Q_z $\Delta = 0.01$
- Q_s $\Delta = 0.00274$ (5 kHz)

measurements:

- Q_x^M
- Q_z^M
- Q_s^M
- Loss (normalized to beam current)

additional parameters

(kept constant)

- Energy
- M_f (F sextupole strength)
- M_d (D sextupole strength)
- M_x (extraction sextupole strength)
- Septum$_{position}$
- Septum$_{angle}$
- …
- *weekday?*

Tune Dependencies

Measurement principle

```
┌──────────────┐      ┌─────────────────────────┐      ┌─────────────────┐
│   refill,    │      │  preparation:           │      │ wait for current│
│ energy ramp  │ ───→ │  - set Qₓ, Q_z, Q_s     │ ───→ │   I < 35 mA     │
│              │      │  - configure feedback   │      │                 │
└──────────────┘      │  - diag. trigger config │      └─────────────────┘
```

$$preparation: \quad - \text{set } Q_x, Q_z, Q_s$$

$$\text{wait for current } I < 35\,\text{mA}$$

```
┌──────────────────┐            ┌──────────────────────┐
│    adjust Qₓ     │ ────────→  │  fire diag. trigger  │
└──────────────────┘            │ ⇒ BLM measurement    │
                                └──────────────────────┘
```

$$\text{adjust } Q_x$$

$$\Rightarrow \textbf{BLM measurement}$$

```
┌─────────────────────┐    ┌──────────────────┐    ┌──────────┐
│ prep. for injection:│ ←  │ data acquisition │ ←  │ wait 2 s │
│ - Qₓ, Q_z, Q_s setup│    │                  │    │          │
│ - feedback config.  │    └──────────────────┘    └──────────┘
└─────────────────────┘
```

$$\text{prep. for injection:} \quad - Q_x, Q_z, Q_s \text{ setup} \quad - \text{feedback config.}$$

$$I < 25\,\text{mA}$$
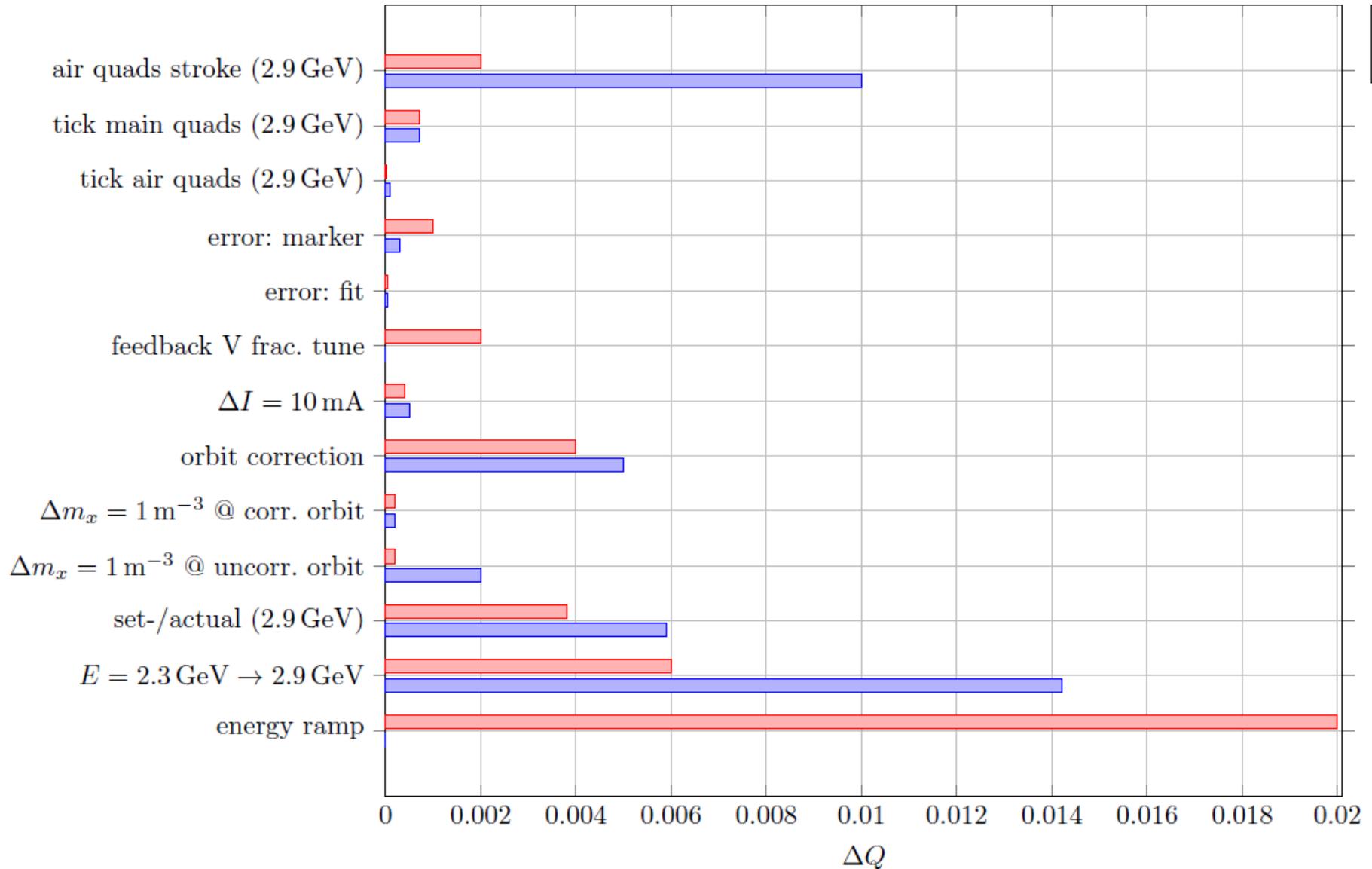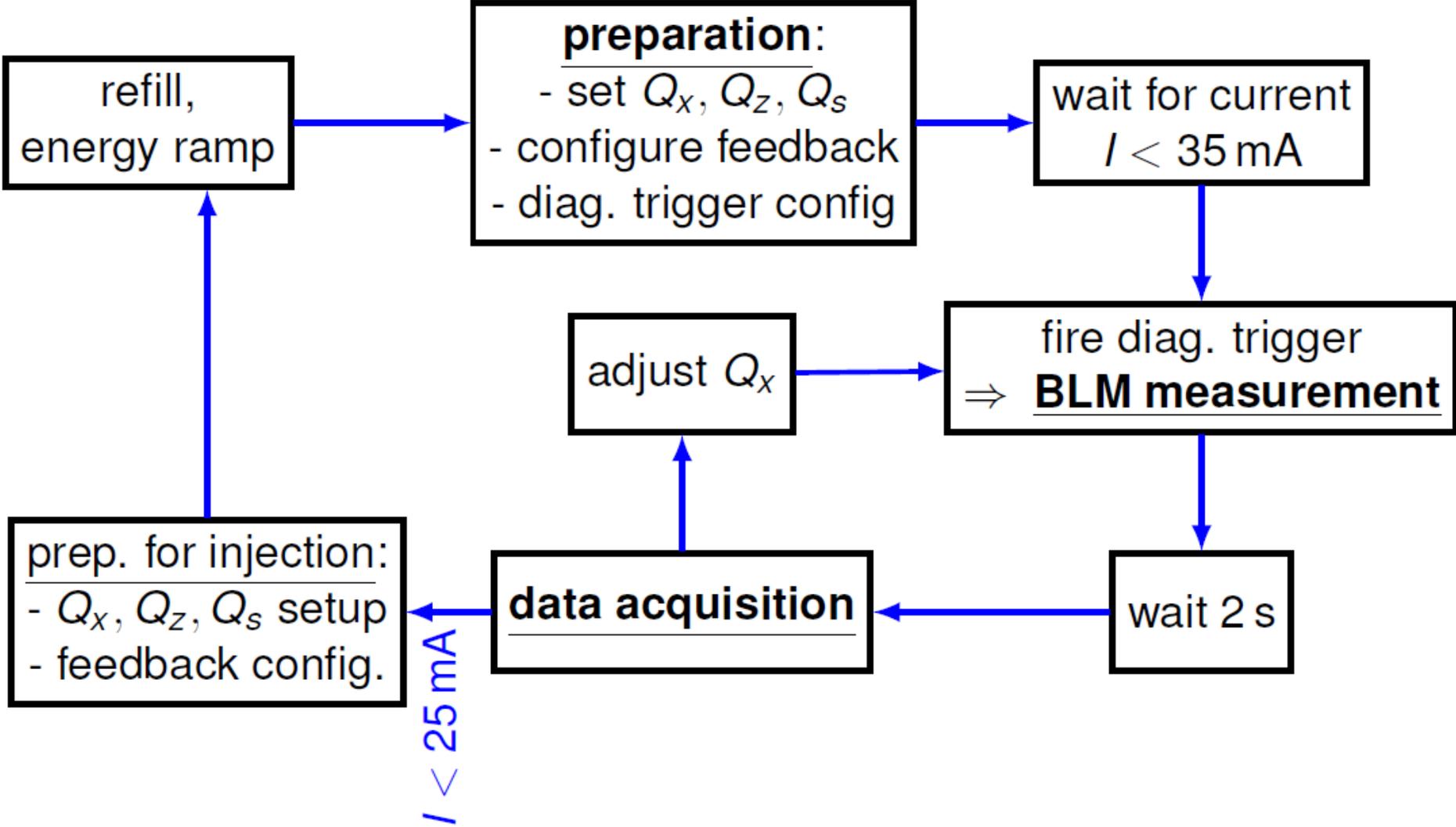
Setting Q_x with air core quadrupoles
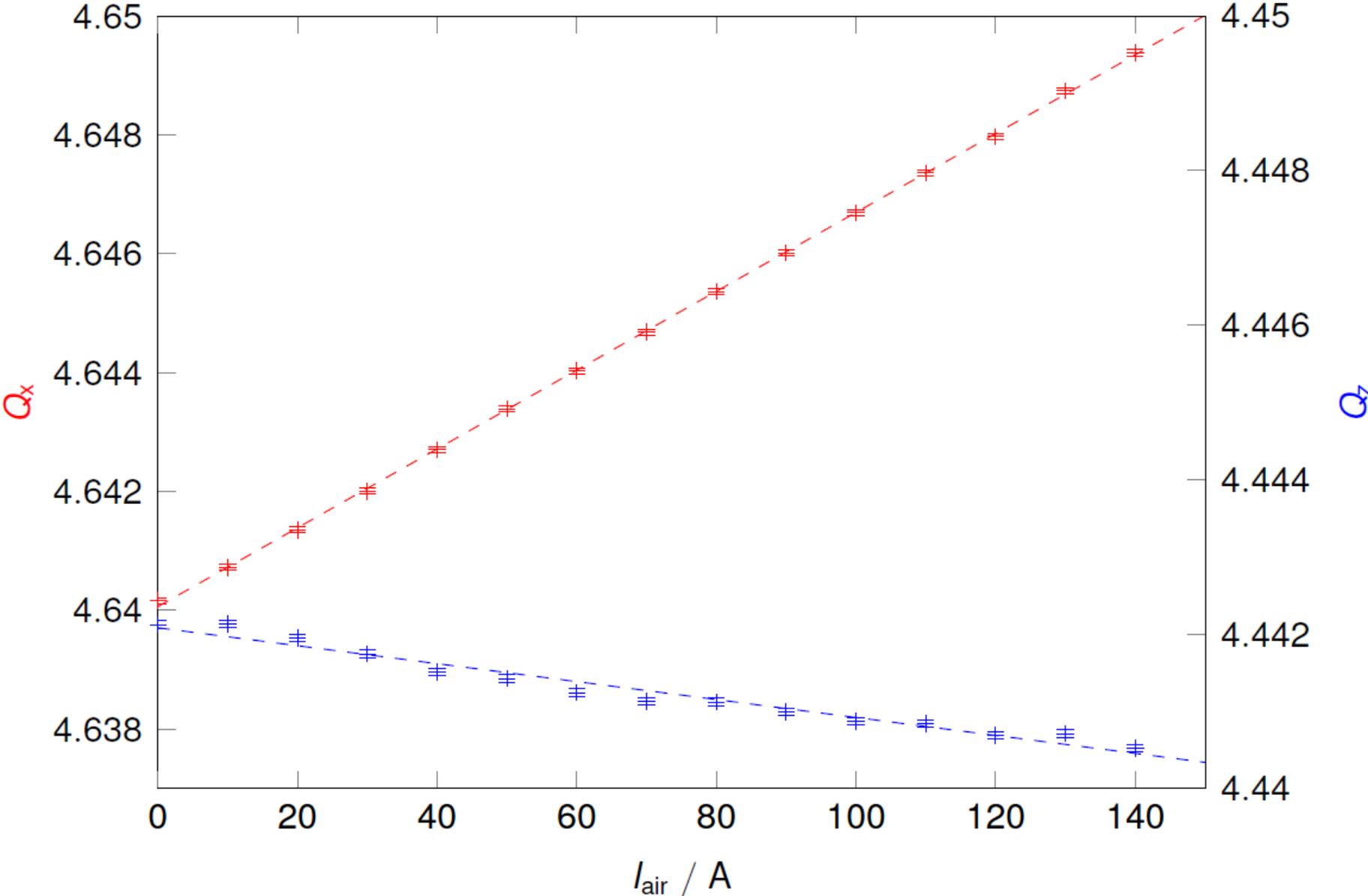
Horz. Phase Space with MAD-X

Legend:
Teilchen mit Startablage x= 0,3 mm
Teilchen mit Startablage x= 0,7 mm
Teilchen mit Startablage x= 1,1 mm
Teilchen mit Startablage x= 1,15 mm
Teilchen mit Startablage x= 1,4 mm

Y-axis: horizontale Winkelablage x' / rad
X-axis: horizontale Ablage x / m

$m_x = 4\text{m}^{-3}$, $L=28.7\text{cm}$
$Q_x = 4.6585$
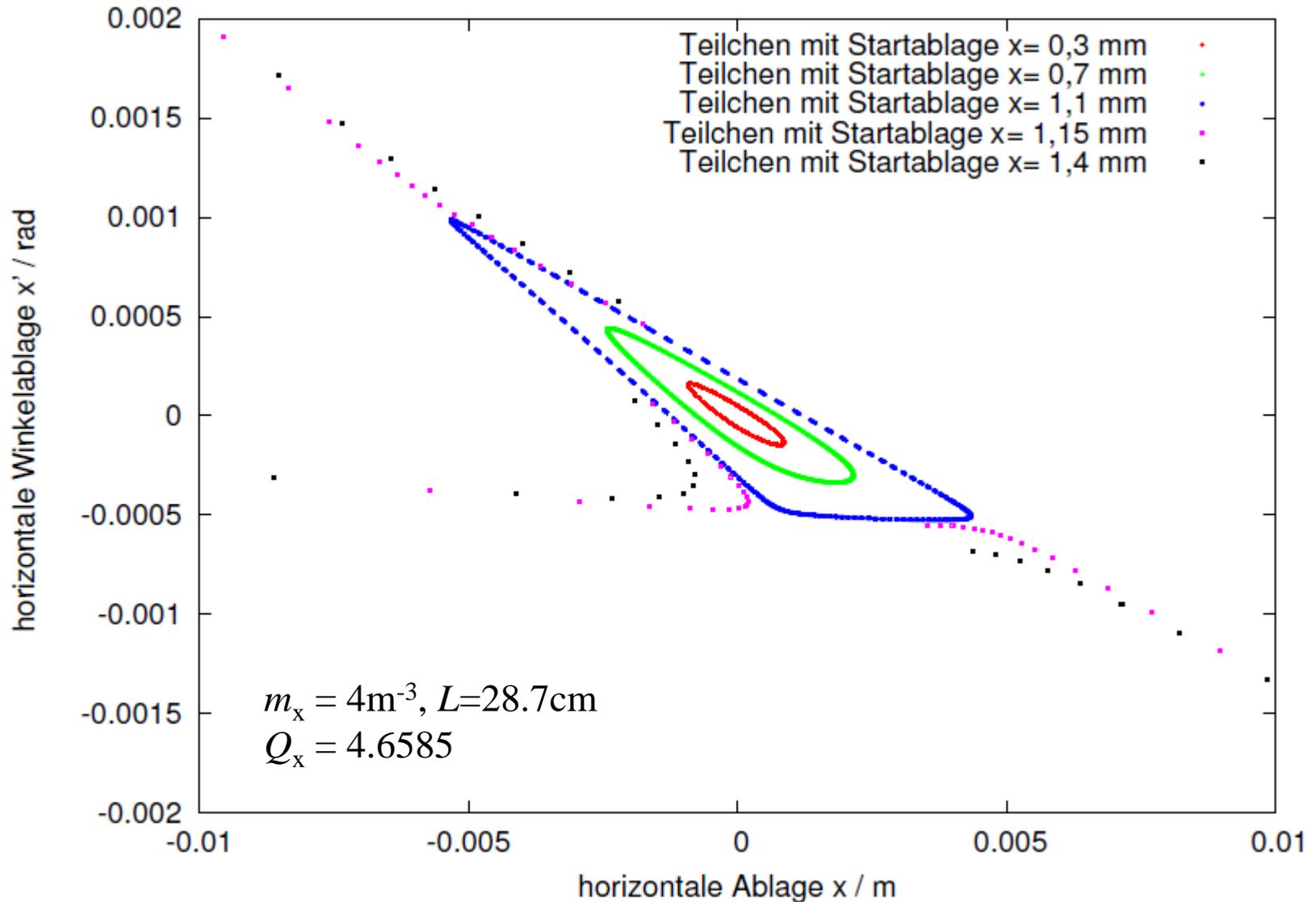
RF Control & Stabilization
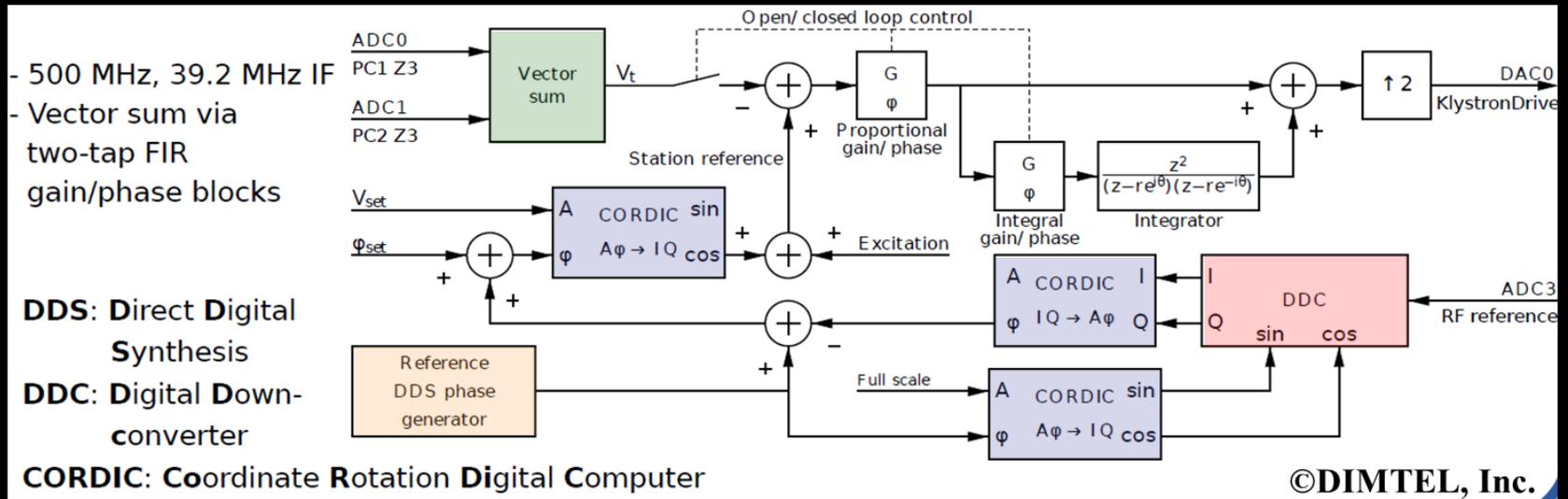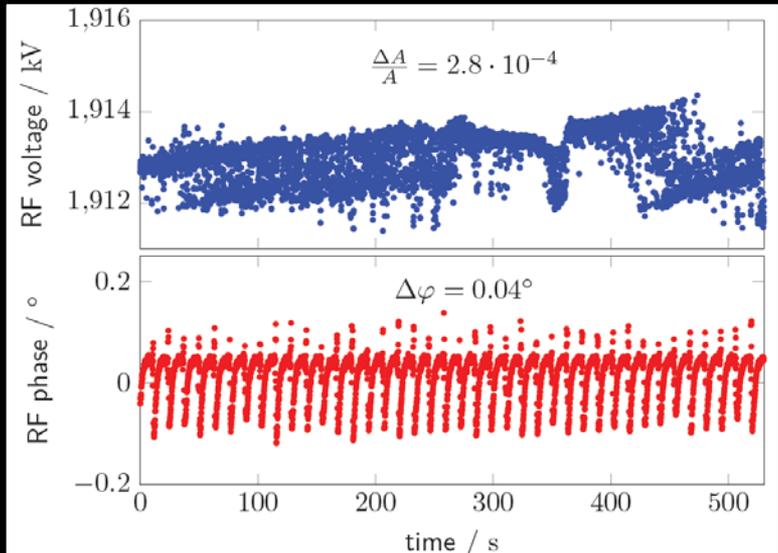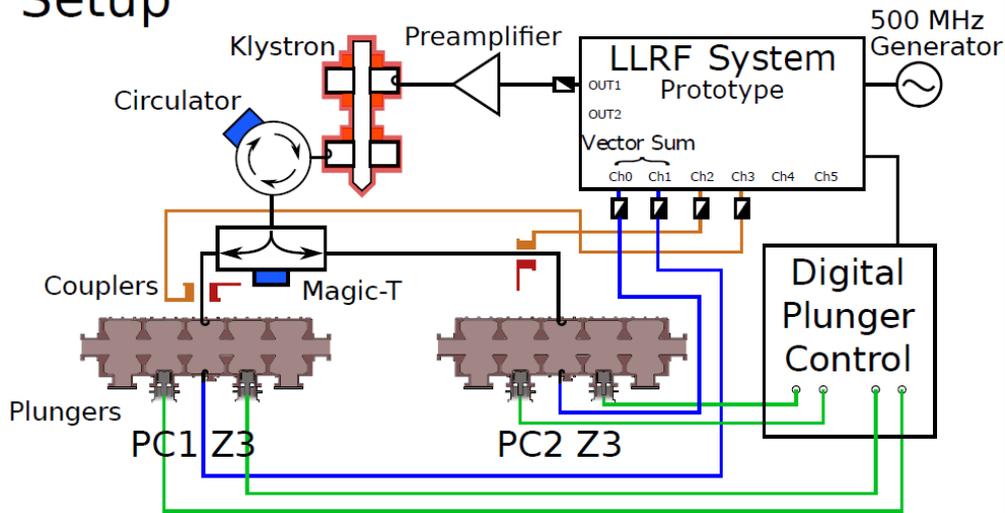
ELSA - Zyklusdefinition für **Boostermode**

Bitte alle Energieangaben in GeV und alle Zeitangaben in Sekunden machen.

Zyklusstart	Rampstart	Rampstop	Extr.Start	Extr.Stop	Zyklusstop
0.0 s	**1.060 s**	**1.393 s**	**1.493 s**	**6.487 s**	**6.920 s**

6.01 GeV/s   -6.01 GeV/s

3.200

Extraktions-
Energie (GeV)

Injektions-
Energie (GeV)

1.200

$$TV = \frac{\text{Extraktionszeit}}{\text{Zykluszeit}}$$

$$= \frac{4.994 \ \text{s}}{6.920 \ \text{s}}$$

$$= \ 72.160 \ \%$$

Strahlstrom

Inj.	Dämpfzeit	Rampphase	Extr.Prep.	Extraktionsphase	Rampphase	Inj. Prep.
7	0.100	0.333	0.100	4.994	0.333	0.100	s

Injektions-
schüsse

7

*

Injektions-
phasen

=

Injektionen
insgesamt

49

**Booster
Definition...**

davon
Korr.-Präp.-
Zeit

0.050

**Timing-
Einstellung
berechnen**

Einstellungen
speichern

☺ Timing/Triggersystem ist gesetzt .

Einstellungen
restaurieren

Injektions-
versatz:

78.000 nsec

Aktuelle Einstellung einfrieren ?   JA   NEIN

ELSA Boostermode (Einstellungen) ⊕

Rampen-Vorgaben:

Rampen-Modell:　◄　**LINEAR**　►

◄　［Graph: linear ramp］　►

Auflösung (ΔT):　◄　**0.300　msec**　►

Aktionen:

| Berechnen & Setzen |
| Löschen |
| Magnete normieren |
| Korrekturen & Optionen |
| Übersicht Korrekturen |

Rampen-Schritte:　**2648**

| grosse Bruecke |

Arbeitspunkte

	Injektion	Extraktion
Qx	◄　4.6120　►	◄　4.6270　►
		I(QF): 612.106 A
Qz	◄　4.4310　►	◄　4.3850　►
		I(QD): 561.509 A
Qs	0.0488	0.0500
	Qs:　86000 Hz	Qs:　91180 Hz

| Arbeitspunktmessung (Feedback) |　| Q-Diagramm | pdf |

Rampenstatus

HF-Rampe　🟢
Korrektor-Status　🟢

🔴 Fehler / aus
🟢 statisch
🟢 Rampbetrieb
🟡 Sättigung
⭕ aus

Sextupole

	Injektion	Extraktion
mF	◄　3.5000　m^{-3}　►	◄　0.0000　m^{-3}　►
		I(SF):　0.000　A
mD	◄　2.5000　m^{-3}　►	◄　0.0000　m^{-3}　►
		I(SD):　0.000　A
mX	◄　0.0000　m^{-3}　►	◄　2.7000　m^{-3}　►
		I(SX):　92.320　A

Wert 0.0 bedeutet, dass der Injektionswert über-nommen wird.

| HF-Rampe... |
| Rampen-Status... |
| Korrektorrampen... |　| libclo |
| Luftquadrupole... |

🙂　**Rampen berechnet und gesetzt.**

Accelerator Cycle