8th DITANET Topical Workshop
on Beam Position Monitors
16-18 January 2012
Geneva, Switzerland

Beam Position Monitor for Low Energy Antiprotons at the USR

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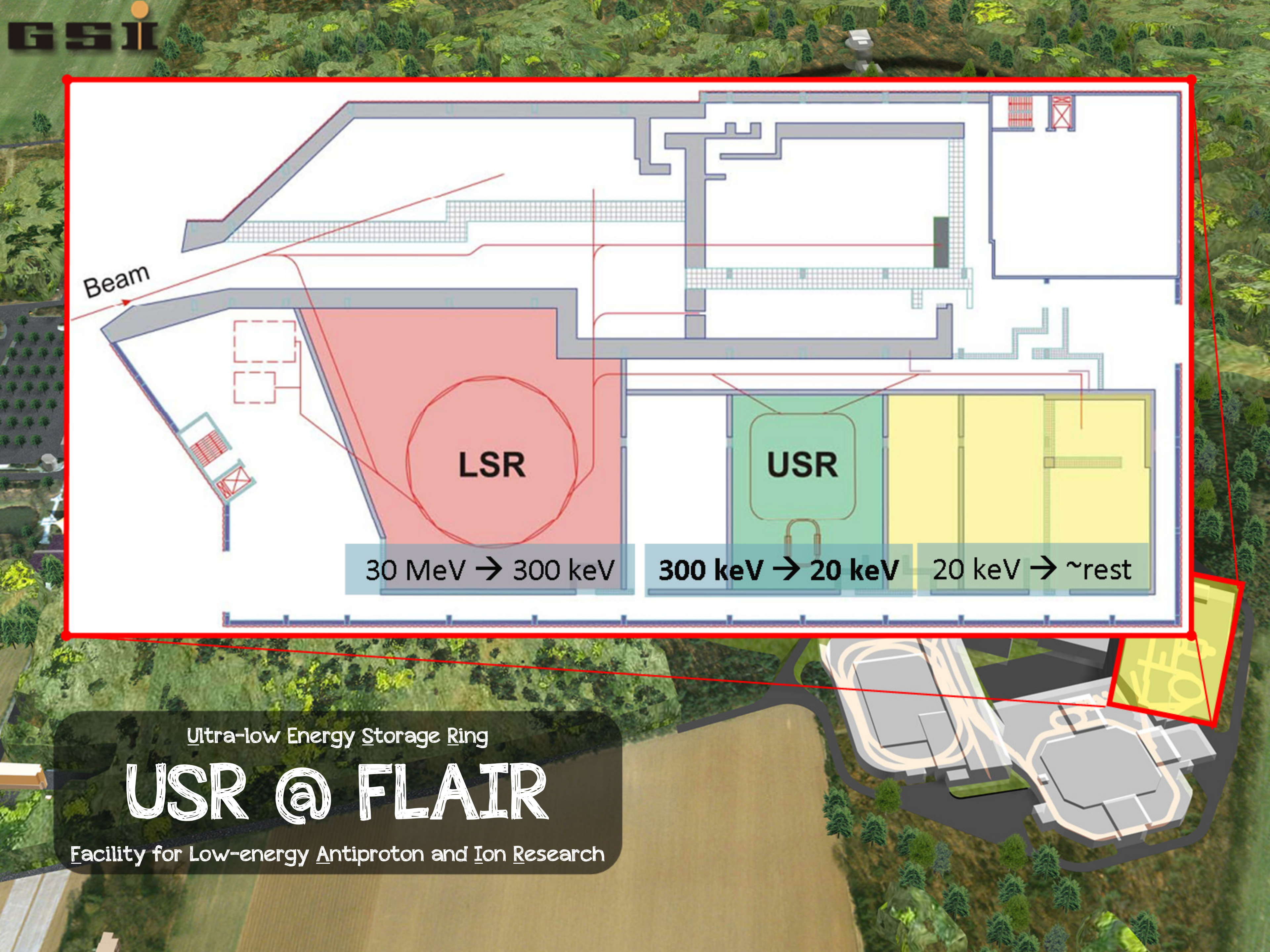
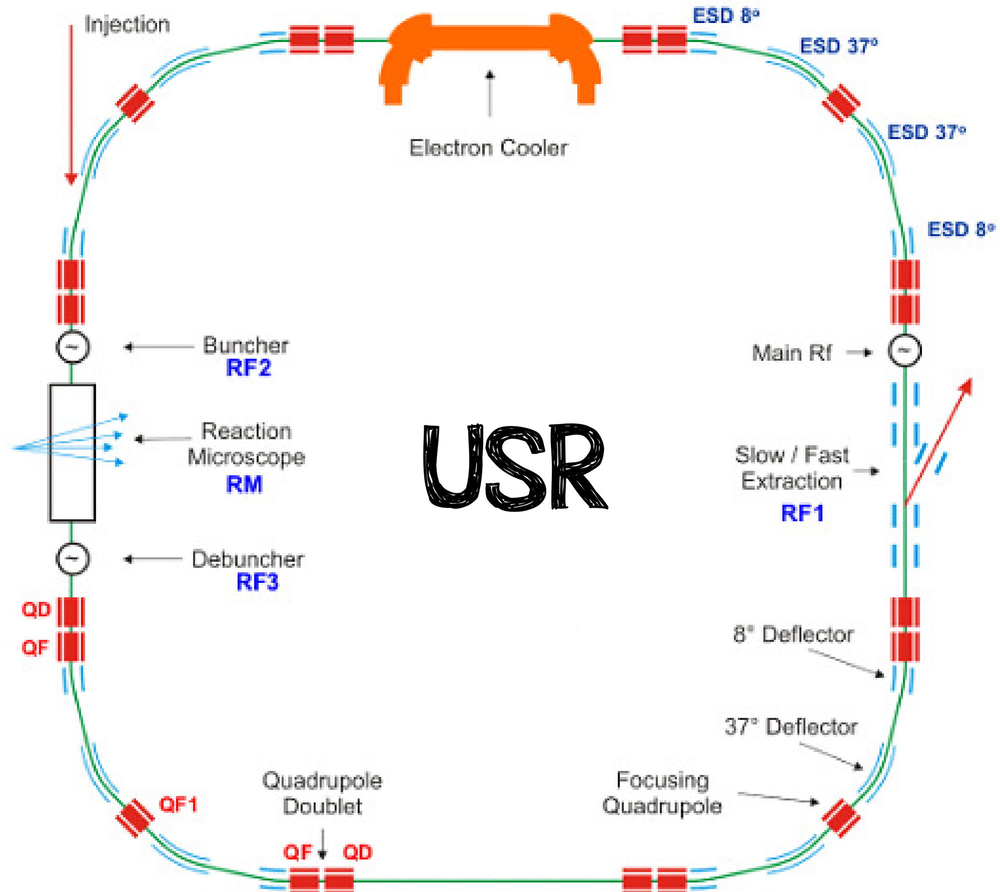
FAIR @ GSI
Facility for Antiproton and Ion Research

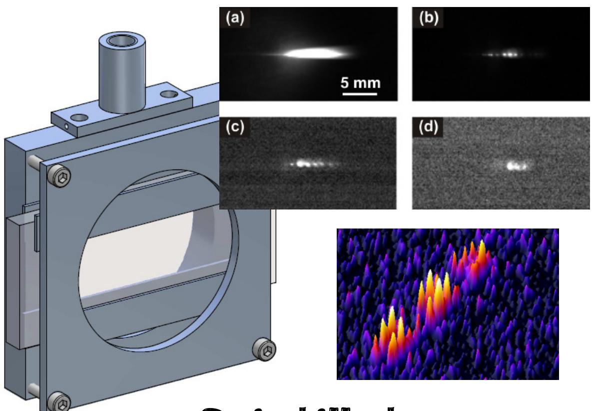

Beam
LSR
USR
30 MeV → 300 keV
300 keV → 20 keV
20 keV → ~rest
Ultra-low Energy Storage Ring
USR @ FLAIR
Facility for Low-energy Antiproton and Ion Research

Ultra-low Energy Storage Ring

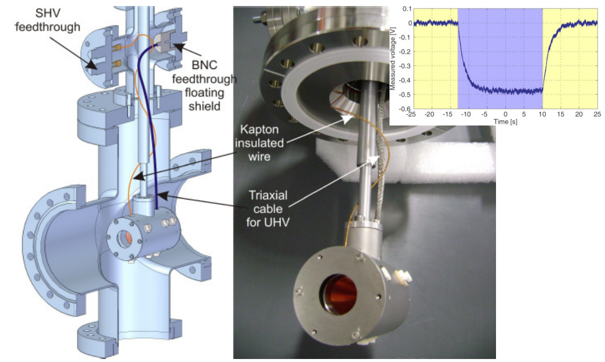
- Electrostatic ring
- Antiprotons & protons/ions
- Deceleration from 300 keV to 20 keV
- Space charge limit: 2×10^7 p @ 20 keV
- Average currents: ~100 nA to ~1 μA



Beam Instrumentation

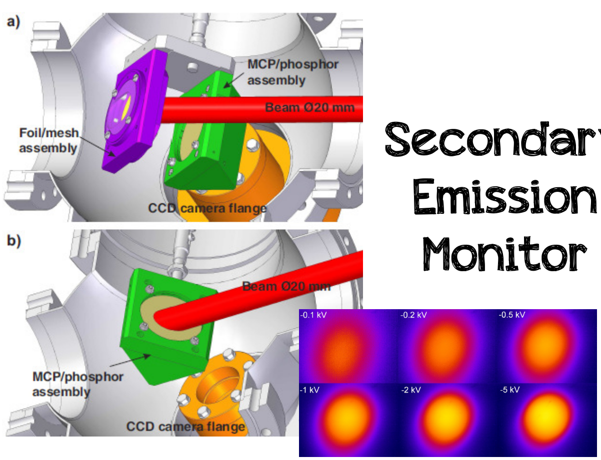


Scintillators



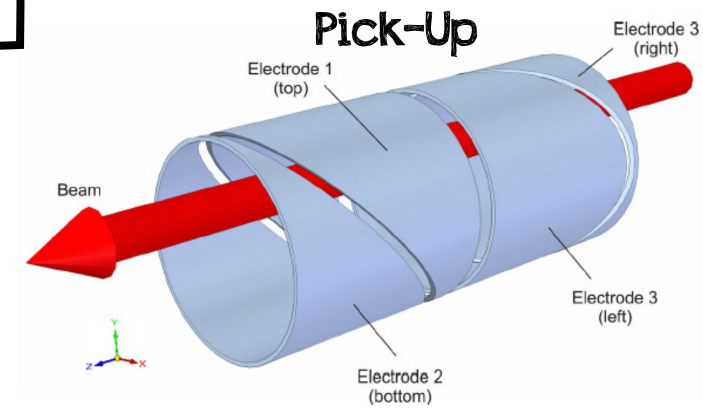
Faraday Cup

PhD Project

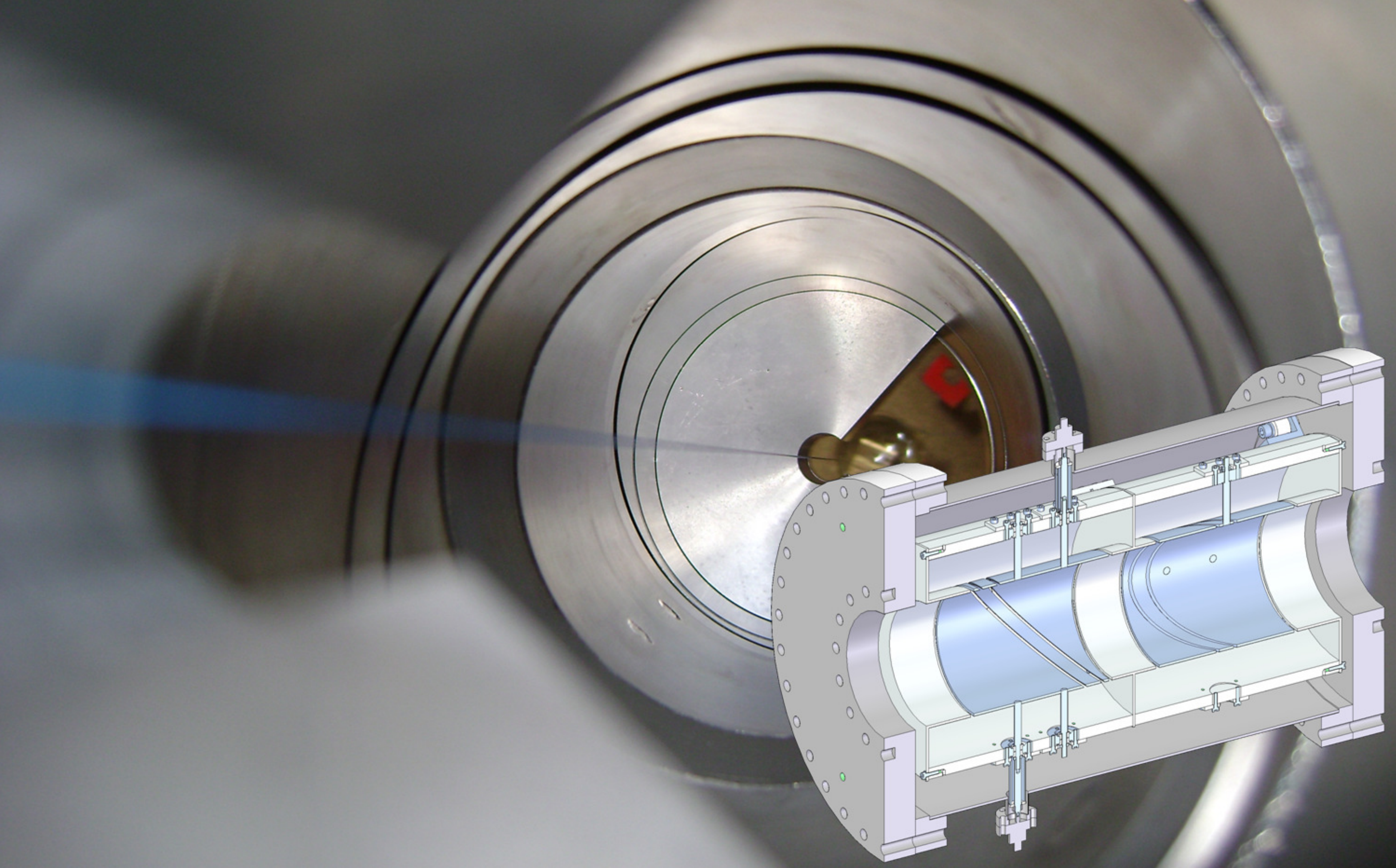


Secondary Emission Monitor

Capacitive Pick-Up



Capacitive Pick-Up



Problem Statement

- Beam currents: ~100 nA - ~1 μA
- Beam energies: 20 keV - 300 keV
- Rev. frequencies: ~50 kHz - ~200 kHz
- Both cooled and uncooled beams
- Resolution: <0.5 mm
- Accuracy: <0.5 mm

Diagonally Cut Pick-Up

$$x = k_x(x,y) \cdot \frac{\Delta U_x}{\Sigma U_x}$$

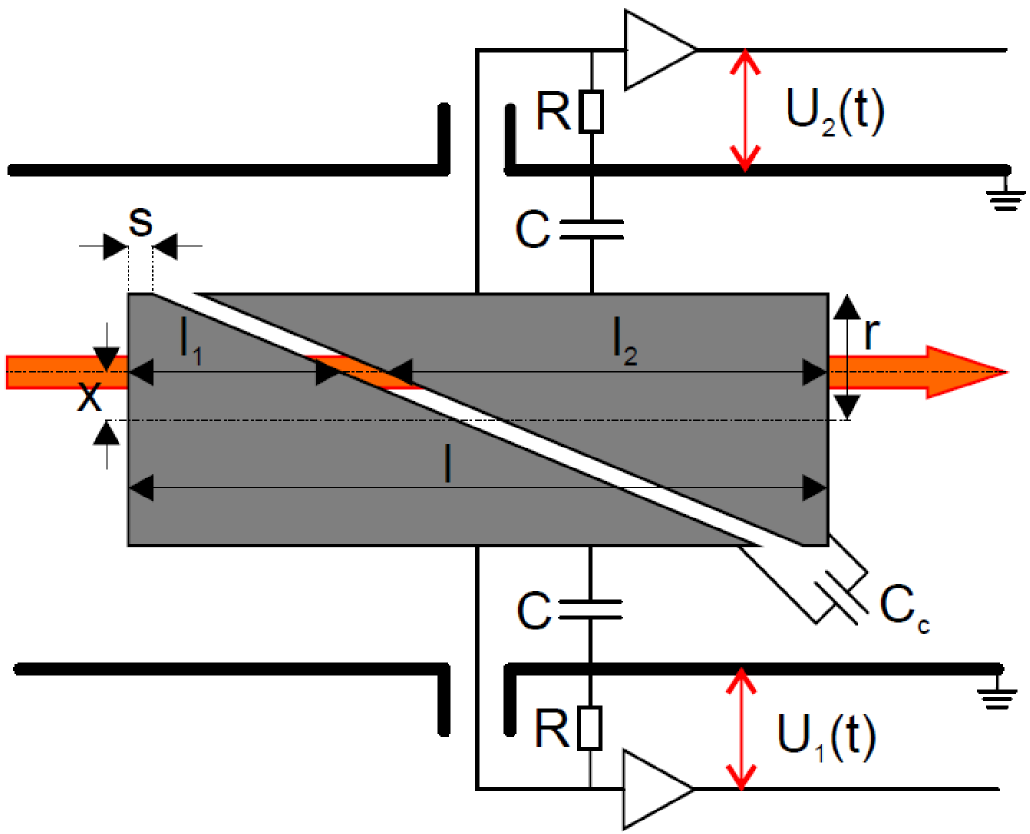
$$y = k_y(x,y) \cdot \frac{\Delta U_y}{\Sigma U_y}$$

$$\Sigma U = U_1 + U_2$$

$$\Delta U = U_1 - U_2$$

Diagonal cut:

$$k_x(x,y) = k_y(x,y) \equiv k = \text{const}$$



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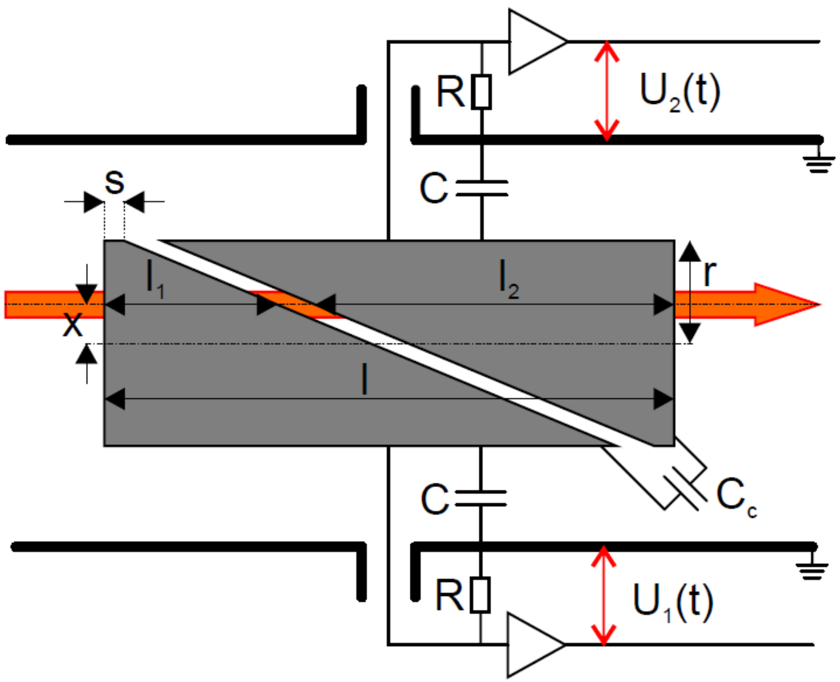
Diagonal cut:

$$k_x(x,y) = k_y(x,y) \equiv k = \text{const}$$

$$k = \frac{r}{1 - 2 \cdot s/l} \cdot (1 + 2 \cdot \frac{C_c}{C})$$

$$\hat{U} = \frac{1}{2} \cdot \frac{l}{C \cdot v} \cdot \bar{I}$$



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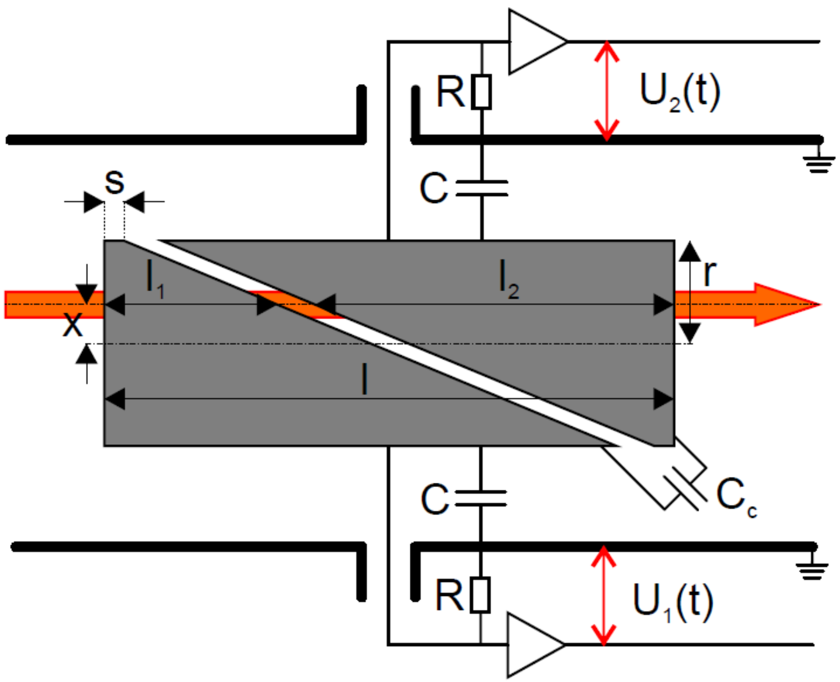

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<u>USR example:</u>

N = 2×10^7, v = 0.006 c, I = 140 nA

l = 100 mm, C = 100 pF

ΣU = 75 μV

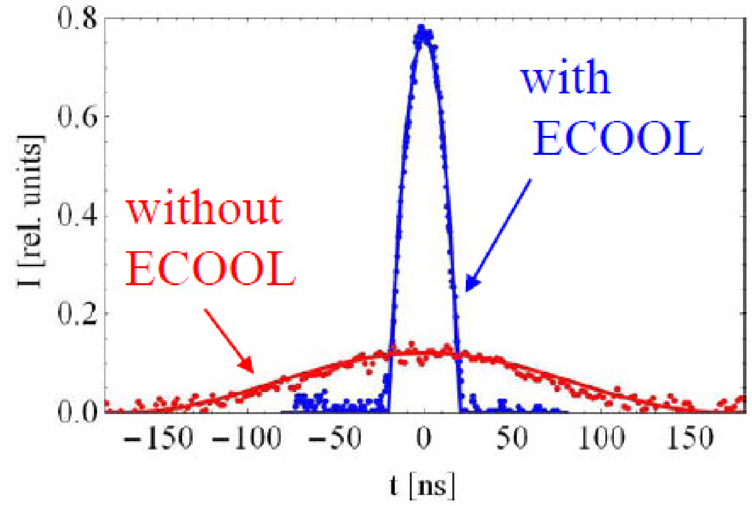
k = 100 mm, x = 0.5 mm

ΔU = 375 nV

ΔU = 750 nV/mm

Uncooled and Cooled Beams

$$I(t) = \sum_{n=0}^{\infty} I_n \cos(2 \cdot \pi \cdot n \cdot f_{RF} \cdot t)$$

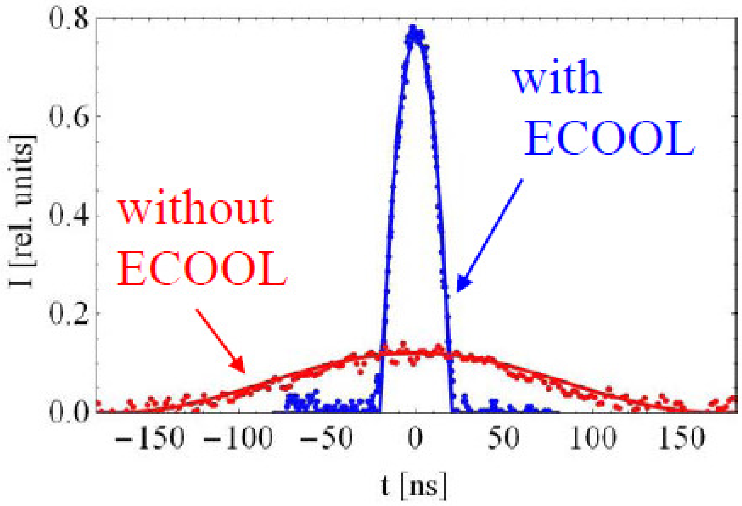


Uncooled and Cooled Beams

$$I(t) = \sum_{n=0}^{\infty} I_n \cos(2 \cdot \pi \cdot n \cdot f_{RF} \cdot t)$$

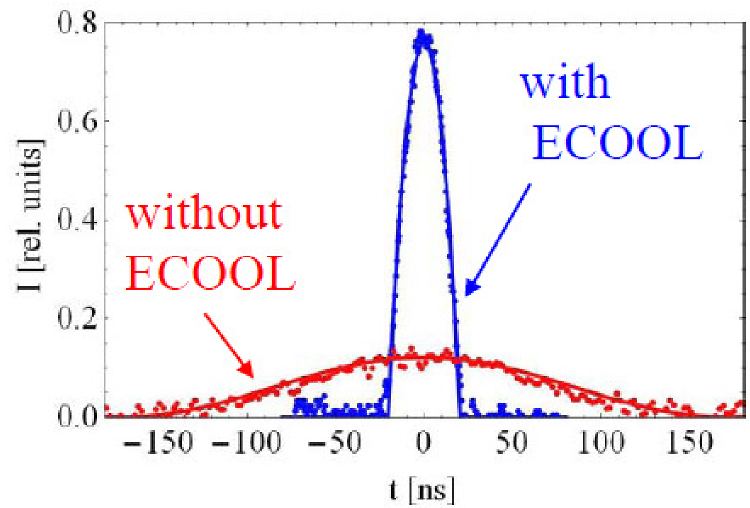
Uncooled beams:

$$I(t) = 2 \cdot \bar{I} \cdot \cos^2(\pi \cdot f_{RF} \cdot t)$$



Uncooled and Cooled Beams

$$I(t) = \sum_{n=0}^{\infty} I_n \cos(2 \cdot \pi \cdot n \cdot f_{RF} \cdot t)$$

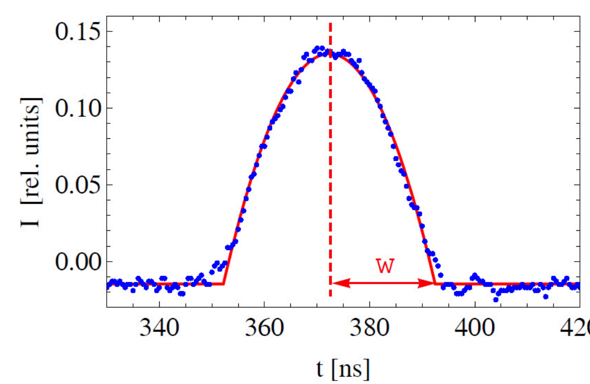


Uncooled beams:

$$I(t) = 2 \cdot \bar{I} \cdot \cos^2(\pi \cdot f_{RF} \cdot t)$$

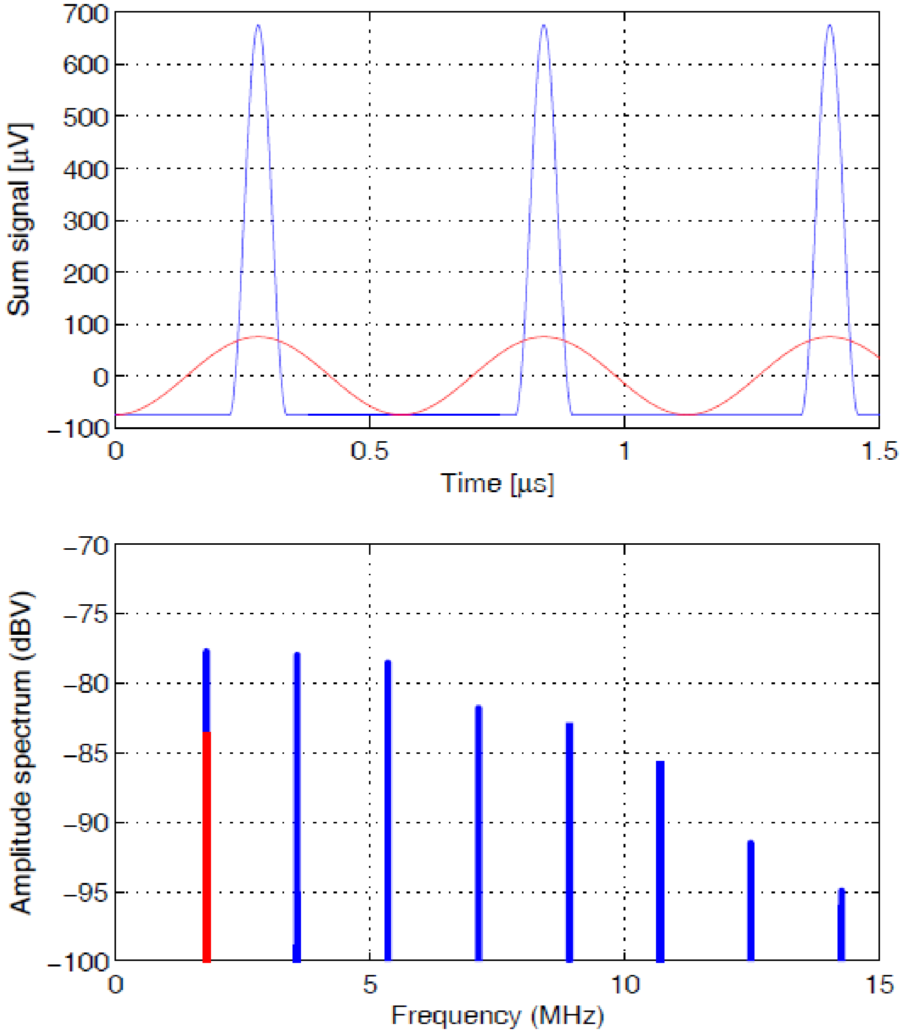
Cooled beams:

$$w = L_{ring} \cdot \sqrt[3]{\frac{3 \cdot \left(1 + 2 \cdot \ln \frac{R}{r}\right) \cdot \bar{I}}{2^4 \cdot \pi^2 \cdot c^4 \cdot \epsilon_0 \cdot \gamma^2 \cdot h^2 \cdot \beta^4 \cdot U_{RF}}}$$



Ref.: M. Grieser et al., *Acceleration, Deceleration and Bunching of Stored and Cooled Ion Beams at the TSR, Heidelberg*, HIAT09, Venezia, Italy, 2009.

Uncooled and Cooled Beams



<u>USR example:</u>

E = 300 keV, N = 2×10^7, h = 10

ΣU_{pk-pk} = ~150 µA
ΔU_{pk-pk} = ~1.5 µA/mm

ΣU_{pk-pk} = ~750 µA
ΔU_{pk-pk} = ~7.5 µA/mm

Noise Estimation

$$U_{noise} = \sqrt{\left(e_{th}^2 + |Z|^2 \cdot i_{amp}^2 + e_{amp}^2\right) \cdot \Delta f} \qquad Z = \left(R^{-1} + i\omega C\right)^{-1}$$

thermal contribution: e_{th}^2

amplifier contribution: $|Z|^2 \cdot i_{amp}^2 + e_{amp}^2$

S/N

U_{noise} = 1 nV/√Hz	Δf	ΔU @ 0.1 mm	ΔU @ 0.5 mm	$\Sigma U_{uncooled}$	ΣU_{cooled}
Bunch structure	>20 MHz	0.02	0.09	33	170
Bunch by bunch	~2 MHz	0.06	0.3	100	530
Turn by turn	~200 kHz	0.2	0.9	330	1700

Δf << 200 kHz: closed orbit measurements

Position Uncertainty

$$\sigma_x = \sqrt{\left(\frac{\delta x}{\delta U_1} \cdot U_{noise}\right)^2 + \left(\frac{\delta x}{\delta U_2} \cdot U_{noise}\right)^2}$$

$$\sigma_x = 2 \cdot k \cdot U_{noise} \cdot \frac{\sqrt{U_1^2 + U_2^2}}{(U_1 + U_2)^2}$$

Assumption:

U_{noise} → dominant uncertainty contribution

Position Uncertainty

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$$\sigma_x(x = 0) = \frac{k}{\sqrt{2}} \cdot \frac{U_{noise}}{U_{electrode}}$$

$$\hat{U} = \frac{1}{2} \cdot \frac{l}{C \cdot v} \cdot \bar{I} = \frac{1}{2} \cdot \frac{l}{L} \cdot \frac{N \cdot e}{C}$$

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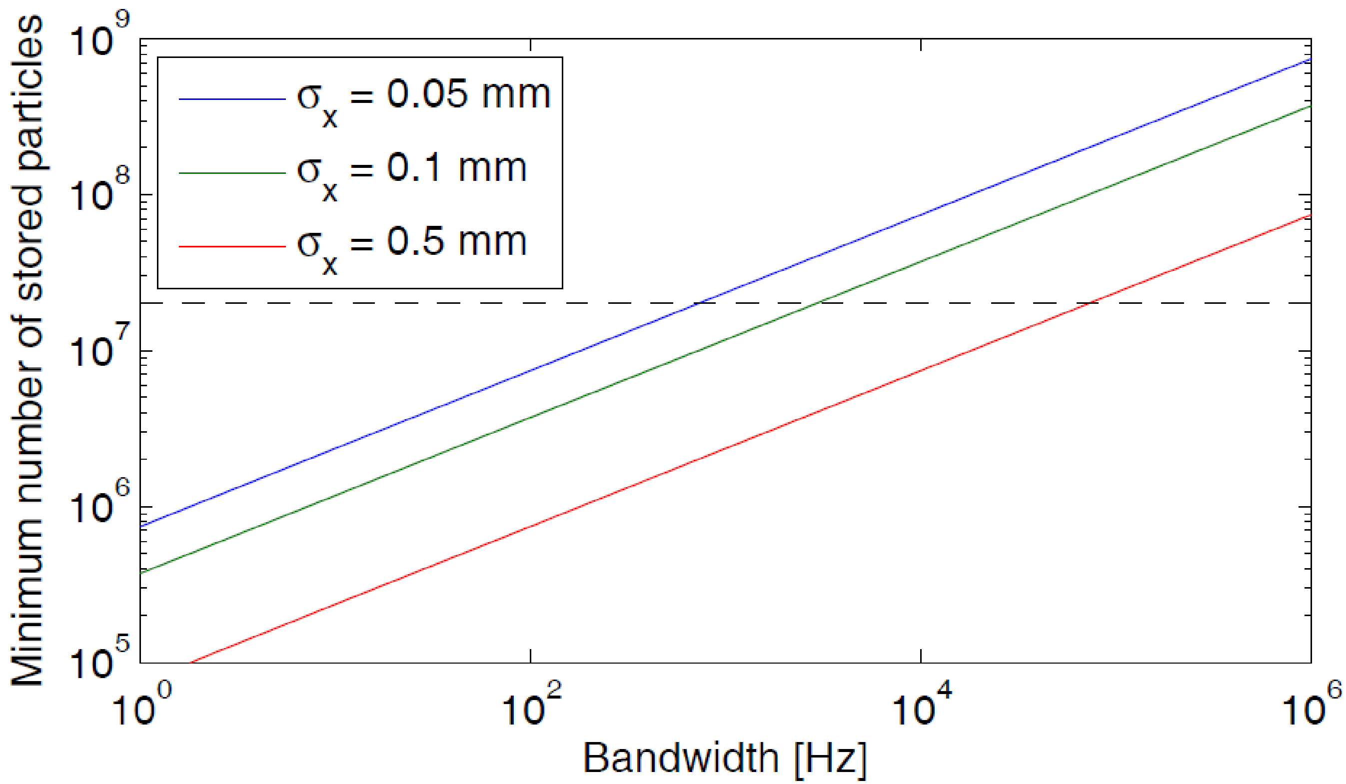


$\Delta f < 1$ kHz

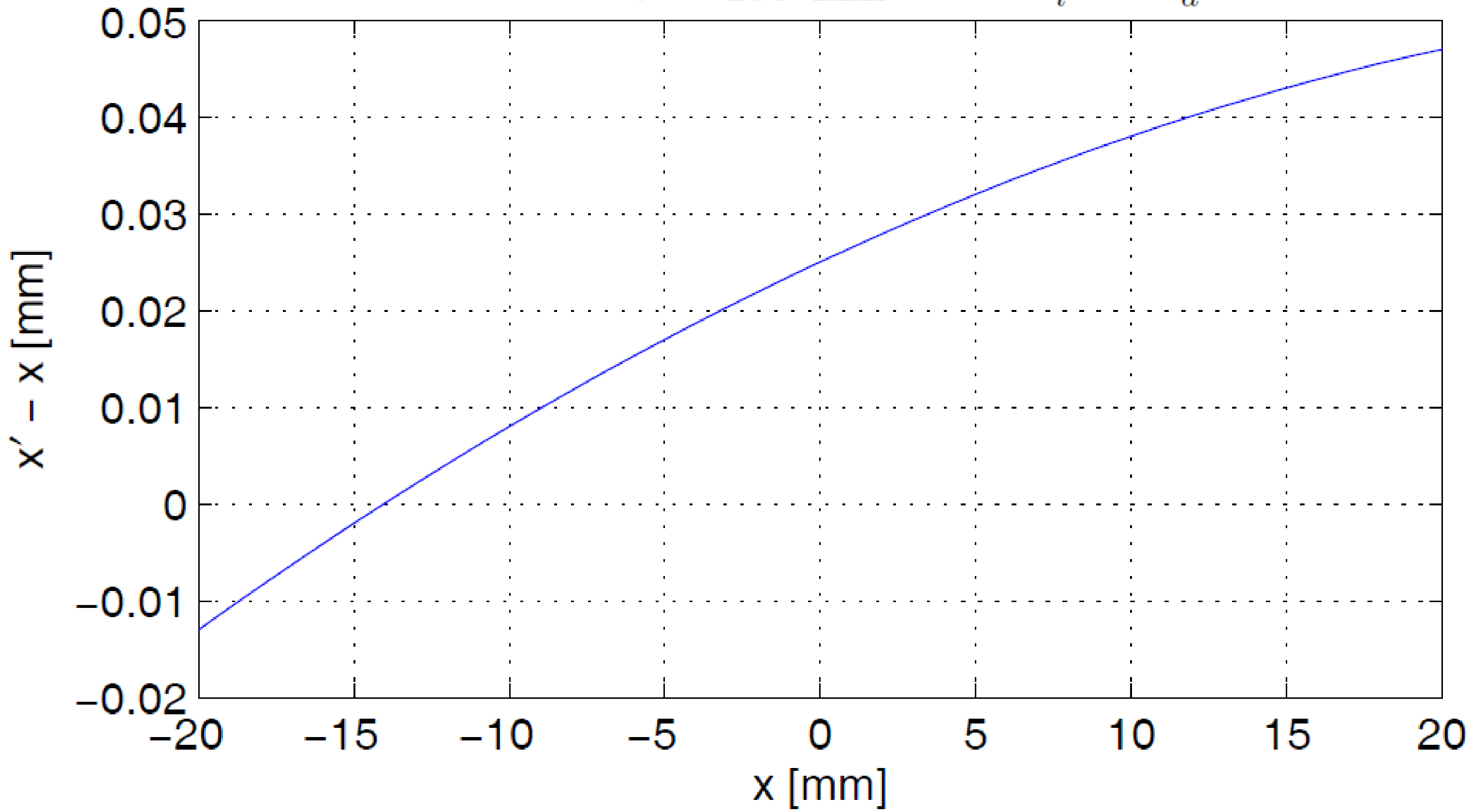
Mechanical Tolerances

$$l_{left} = l \qquad l_{right} = l - \Delta_l$$

$$d_{left} = d \qquad d_{right} = d + \Delta_d$$

$$x' = k \cdot \frac{\Delta U}{\Sigma U} \cdot \frac{2 + \frac{\Delta_l}{l} \cdot \left(\left(\frac{\Delta U}{\Sigma U} \right)^{-1} - 1 \right)}{2 + \frac{\Delta_l}{l} \cdot \left(\frac{\Delta U}{\Sigma U} - 2 \right) + \frac{\Delta_d}{d} \cdot \left(\frac{\Delta U}{\Sigma U} - 2 \right)}$$

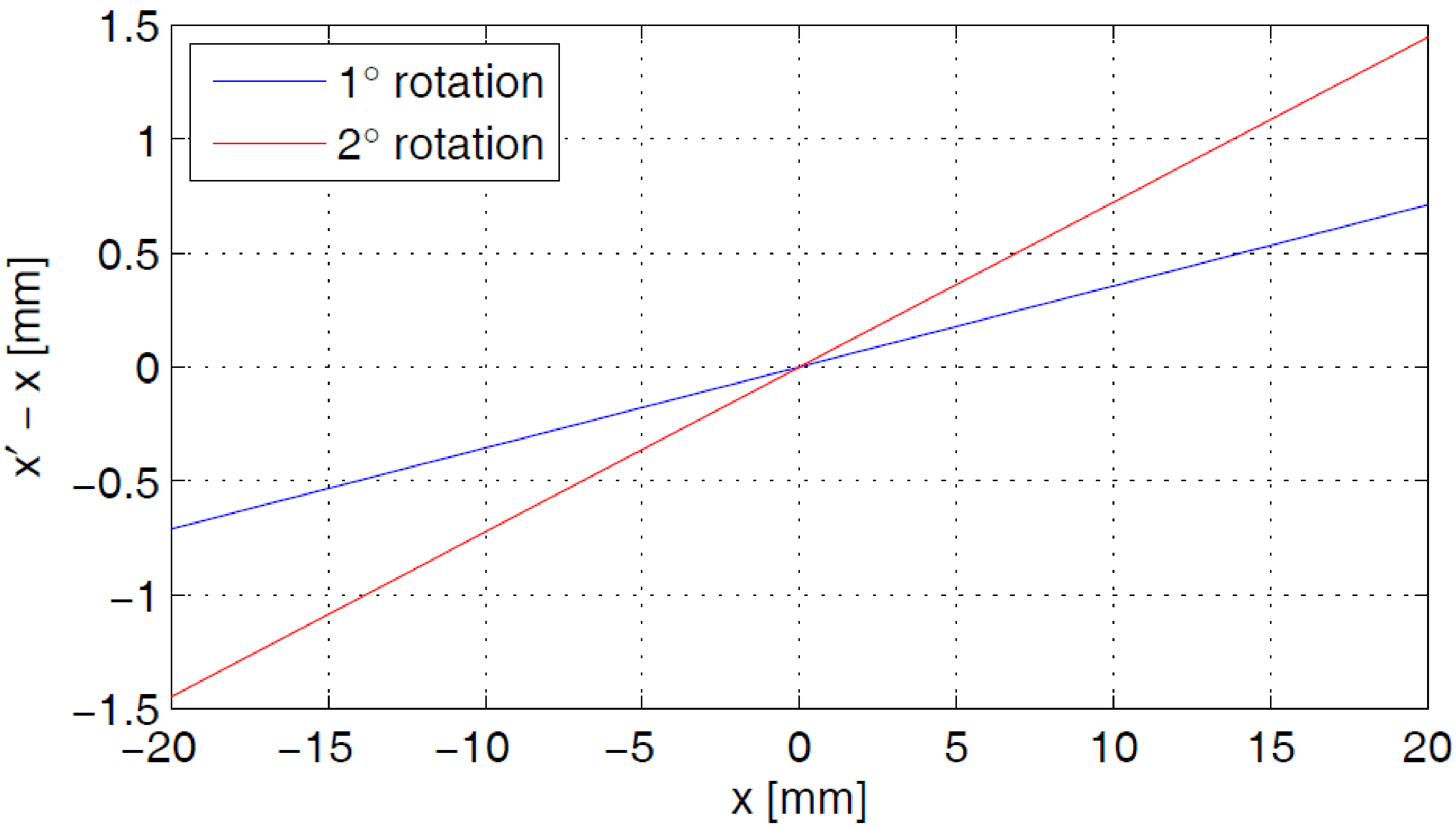
$d = 100$ mm $\quad l = 100$ mm $\quad \Delta_l = \Delta_d = 0.1$ mm



Misalignment

Rotation by a small angle α

$$x' = k \cdot \frac{\Delta U}{\Sigma U} \cdot \frac{1 + \frac{l}{d} \cdot \alpha}{1 - \frac{l}{d} \cdot \alpha}$$



Signal Quantization

Quantization step size: $U_q = \frac{2 \cdot U_{adc}}{2^b - 1}$

Number of bits: b

Input range: $\pm U_{adc}$

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$$b > \log_2 \left(\frac{2 \cdot U_{adc}}{U_{min} \cdot G} + 1 \right)$$

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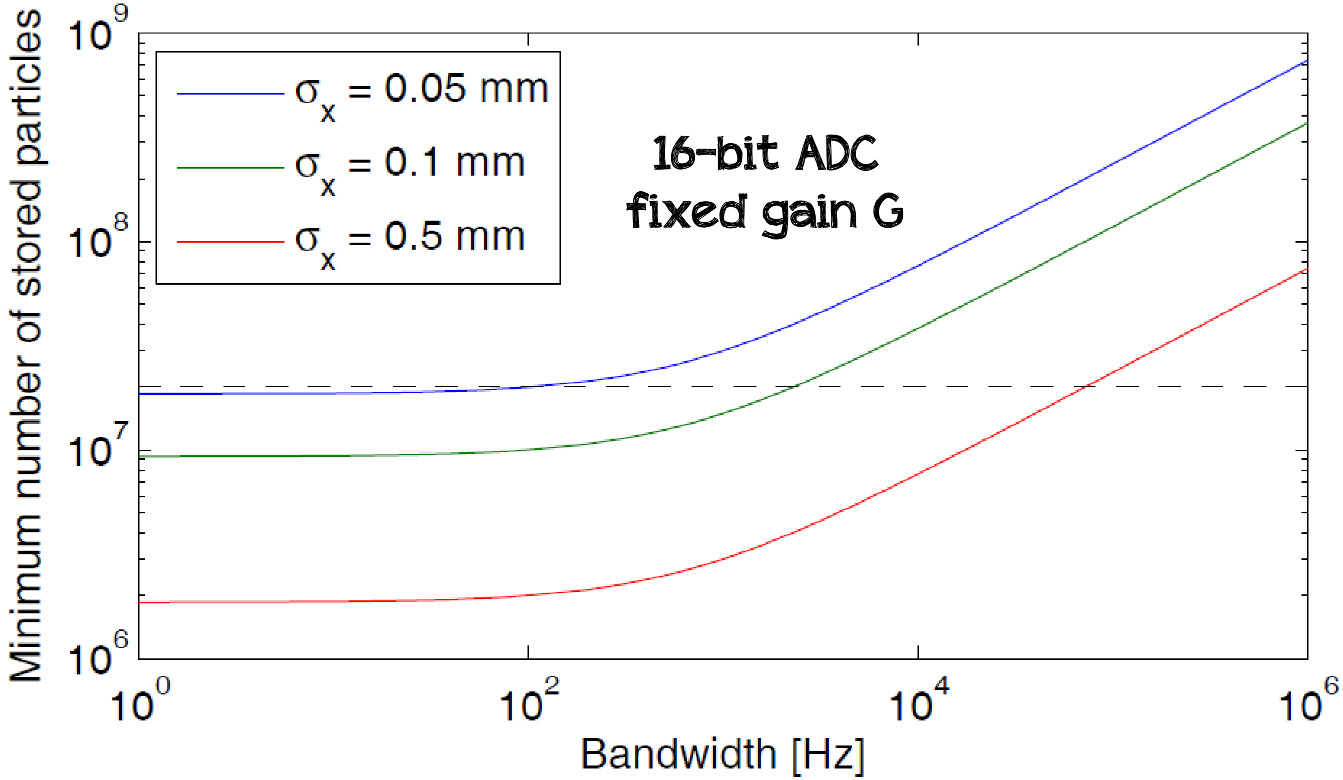
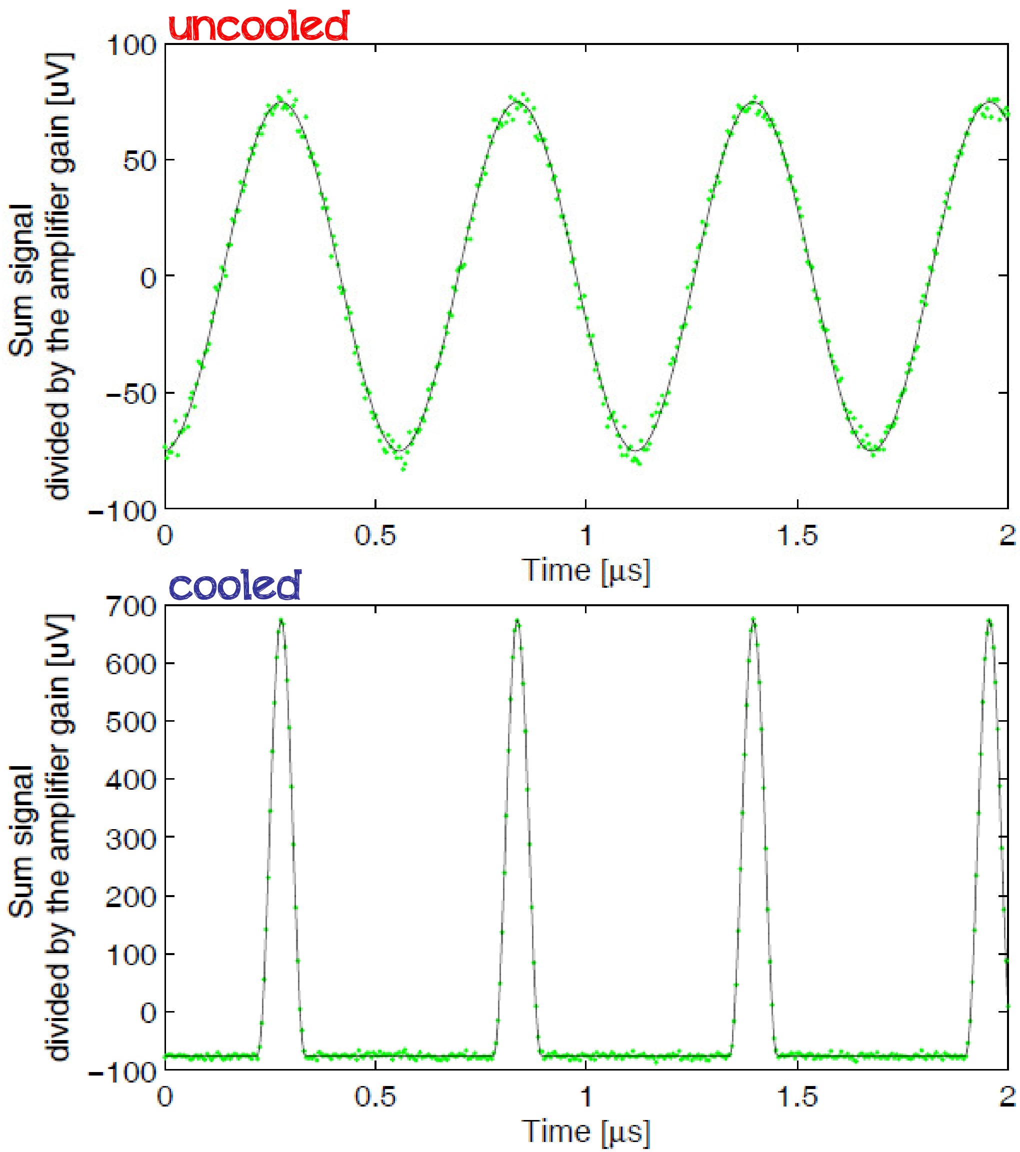


Signal Quantization



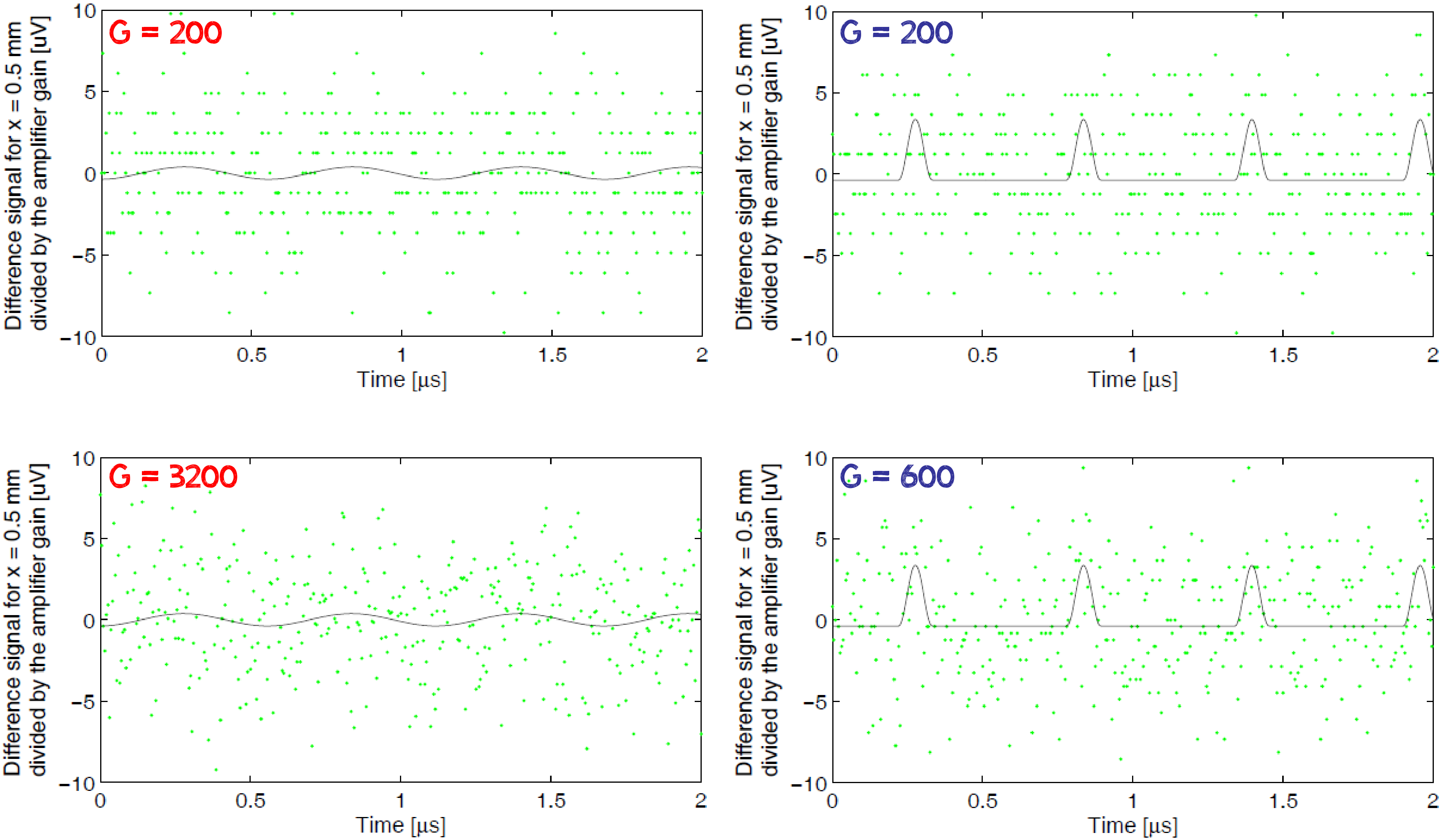
__Example:__

12 bit ADC, 200 MS/s, G = 200, ADC input range ±500 mV, 20 MHz bandwidth

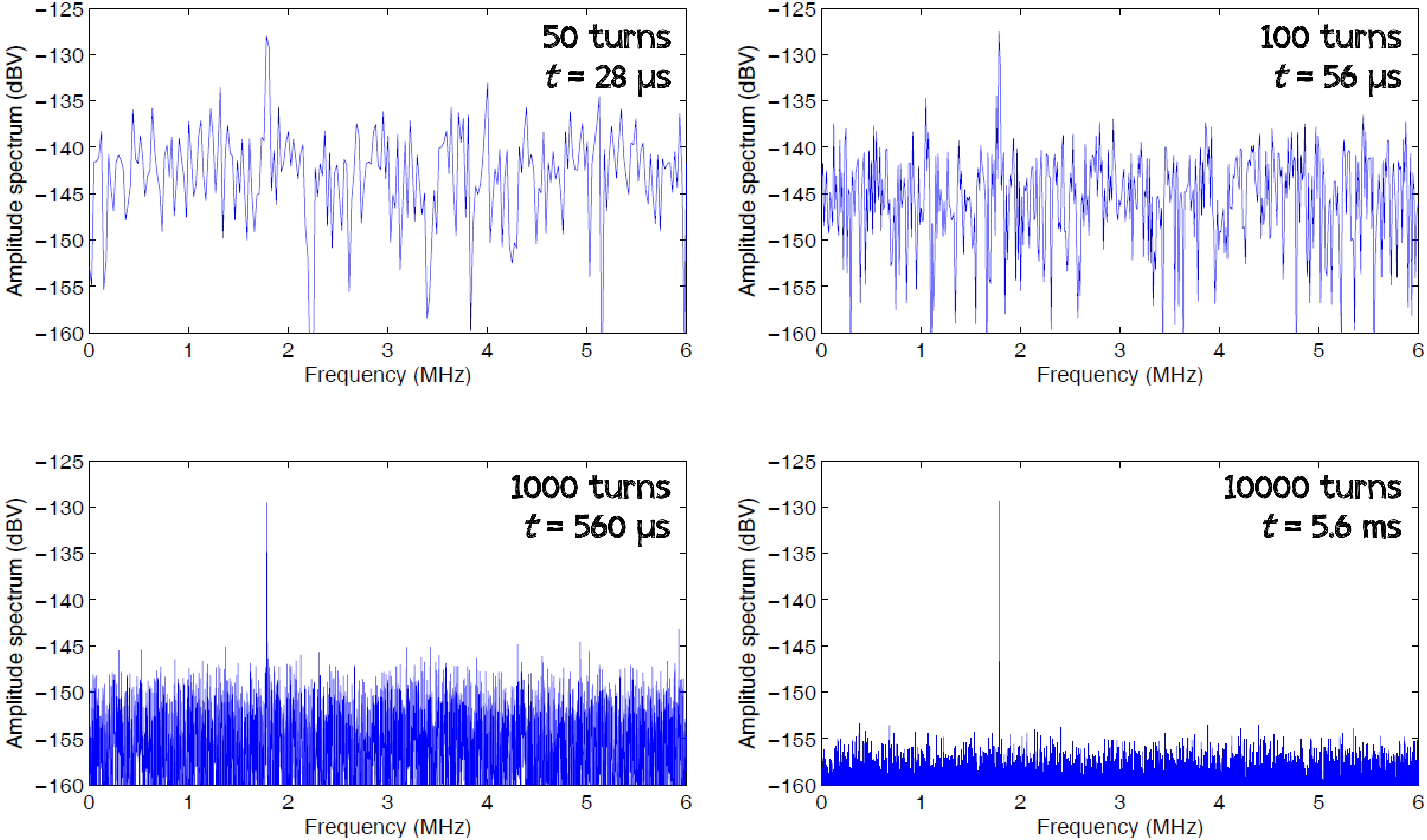
Noise:

- thermal
- amplifier
- ADC

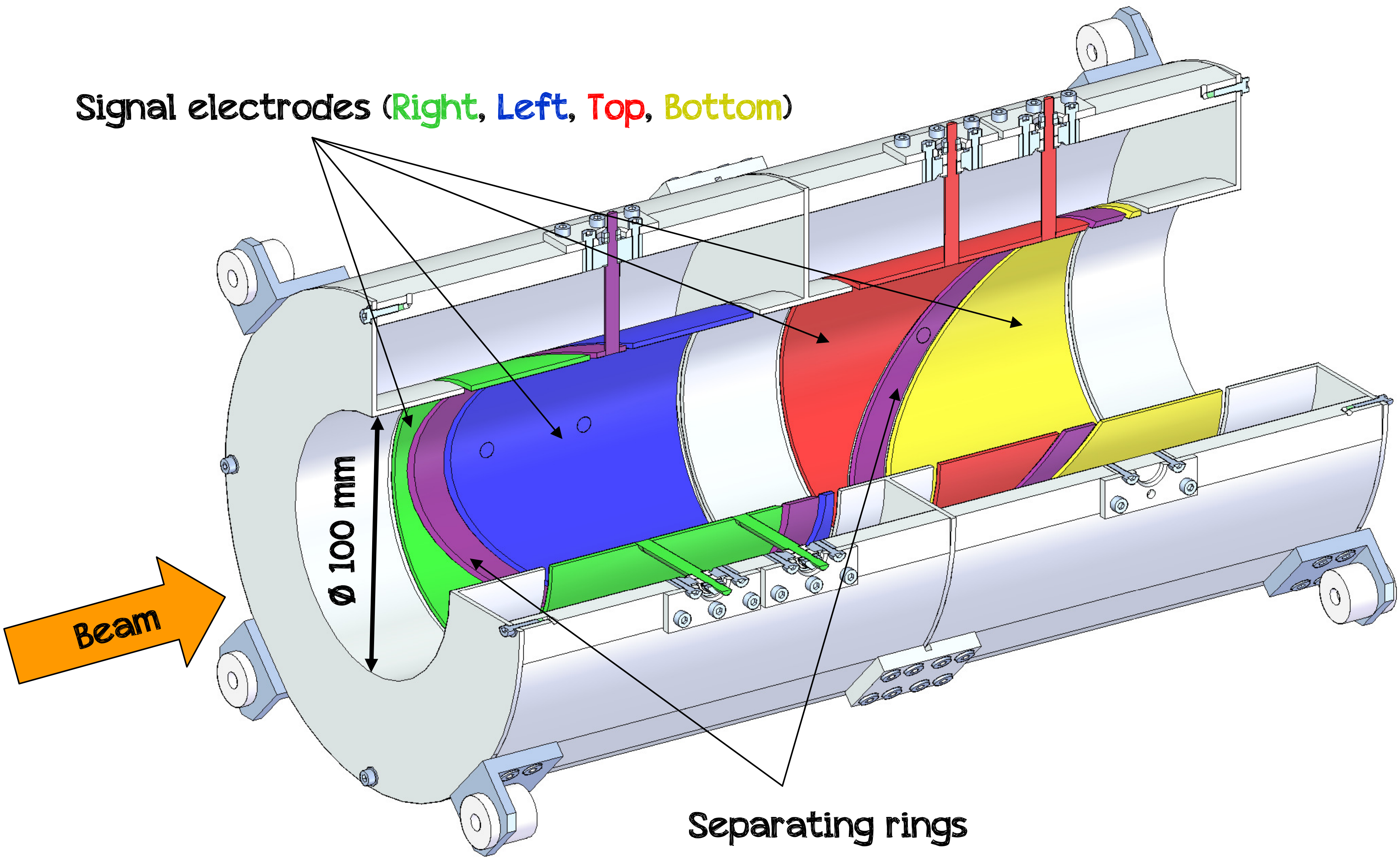
Signal Quantization



Spectrum


50 turns
t = 28 μs
100 turns
t = 56 μs
1000 turns
t = 560 μs
10000 turns
t = 5.6 ms
Amplitude spectrum (dBV)
Frequency (MHz)
−125
−130
−135
−140
−145
−150
−155
−160
0
1
2
3
4
5
6

Pick-Up Prototype



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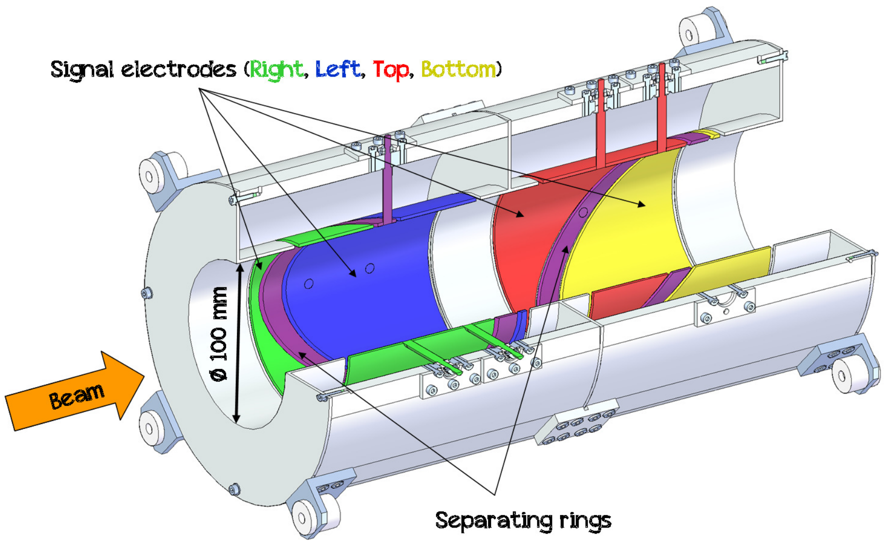
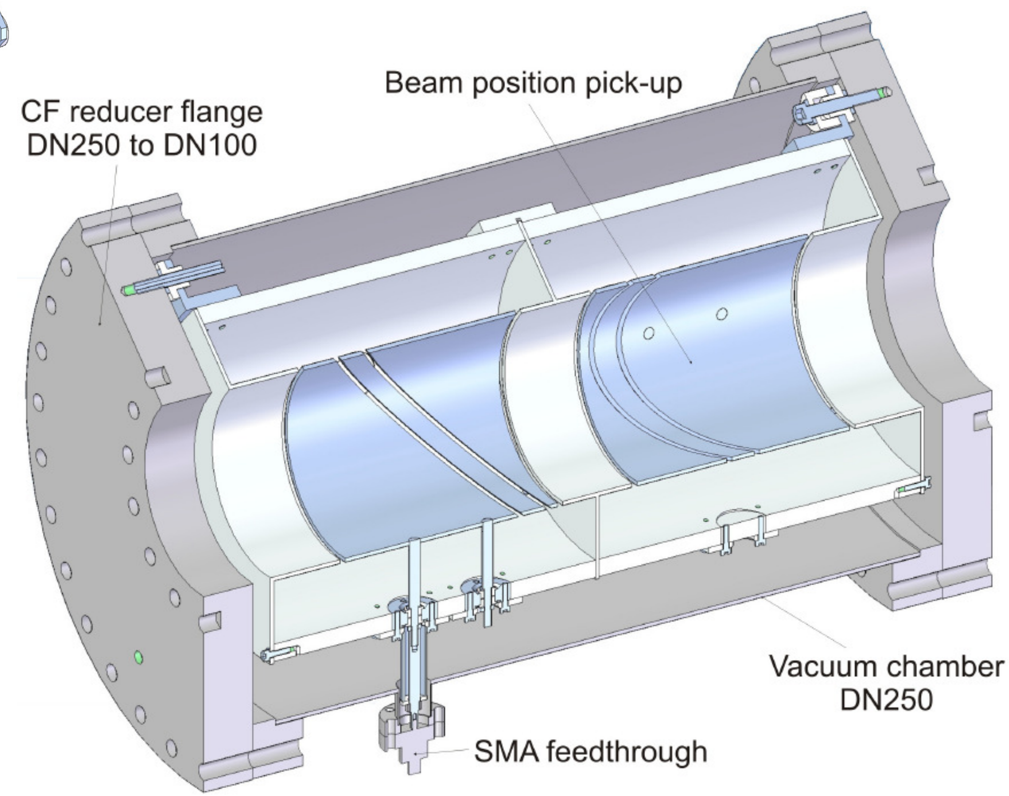
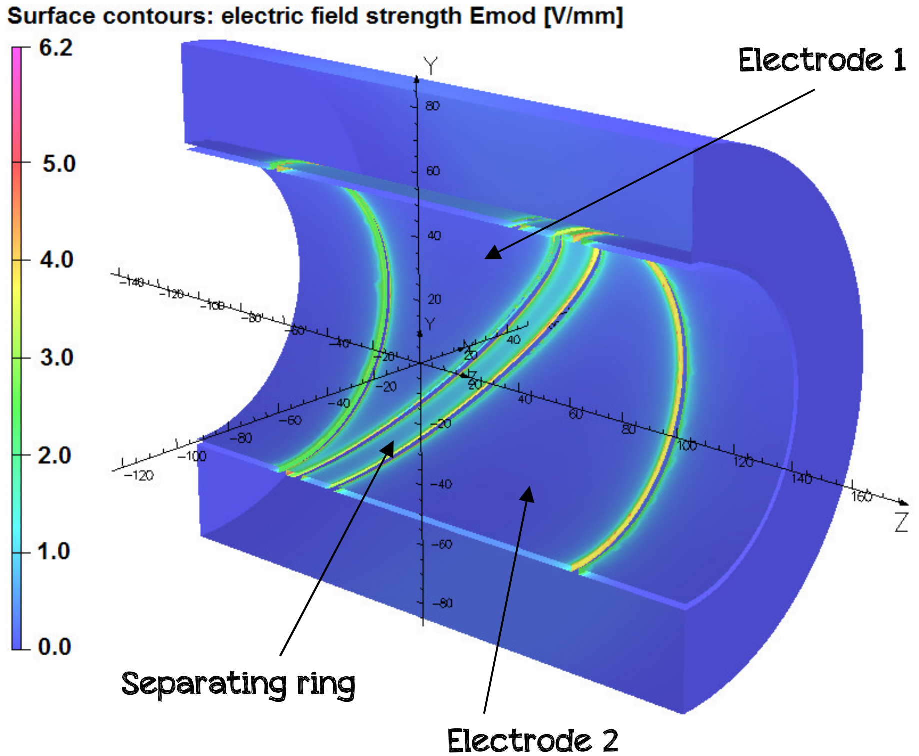




Capacitance Simulations

Opera 3D, Tosca
Electrostatic Solver



1. No separating ring:

$C = 13.7$ pF
$C_c = 3.1$ pF

$C_c/C = 0.22$

$k = 78$ mm

2. Grounded ring:

$C = 18.8$ pF
$C_c = 1.2$ pF

$C_c/C = 0.06$

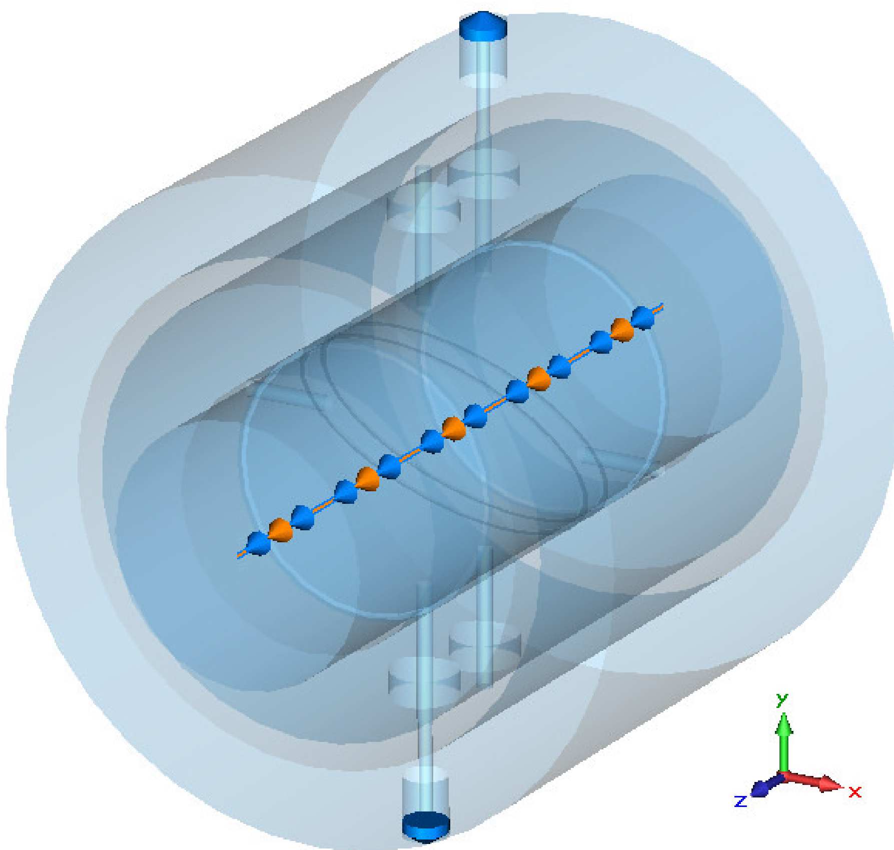
$k = 60$ mm

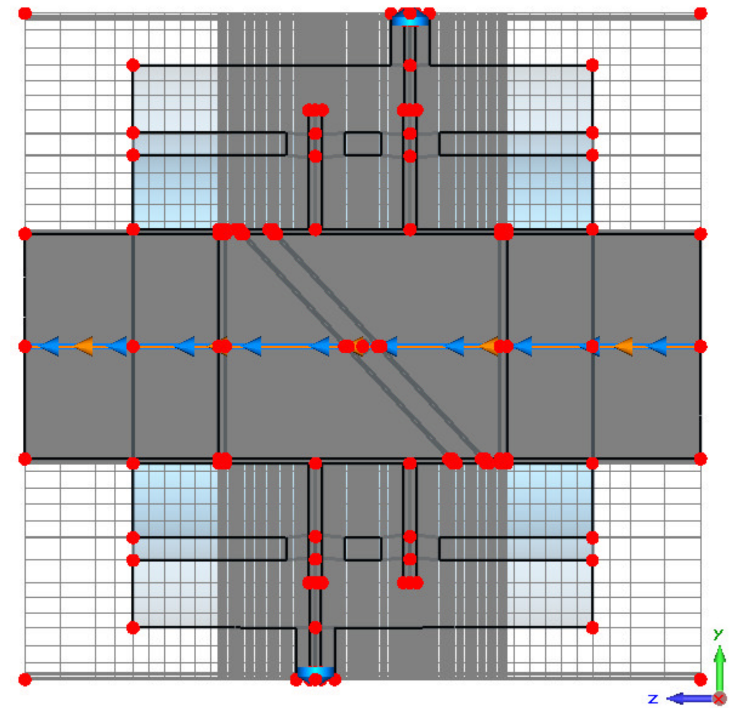
Capacitance insensitive to a small tilt of the separating ring.

Real C increased by the contribution of the connections and the amplifier.

Pick-Up Response Simulations

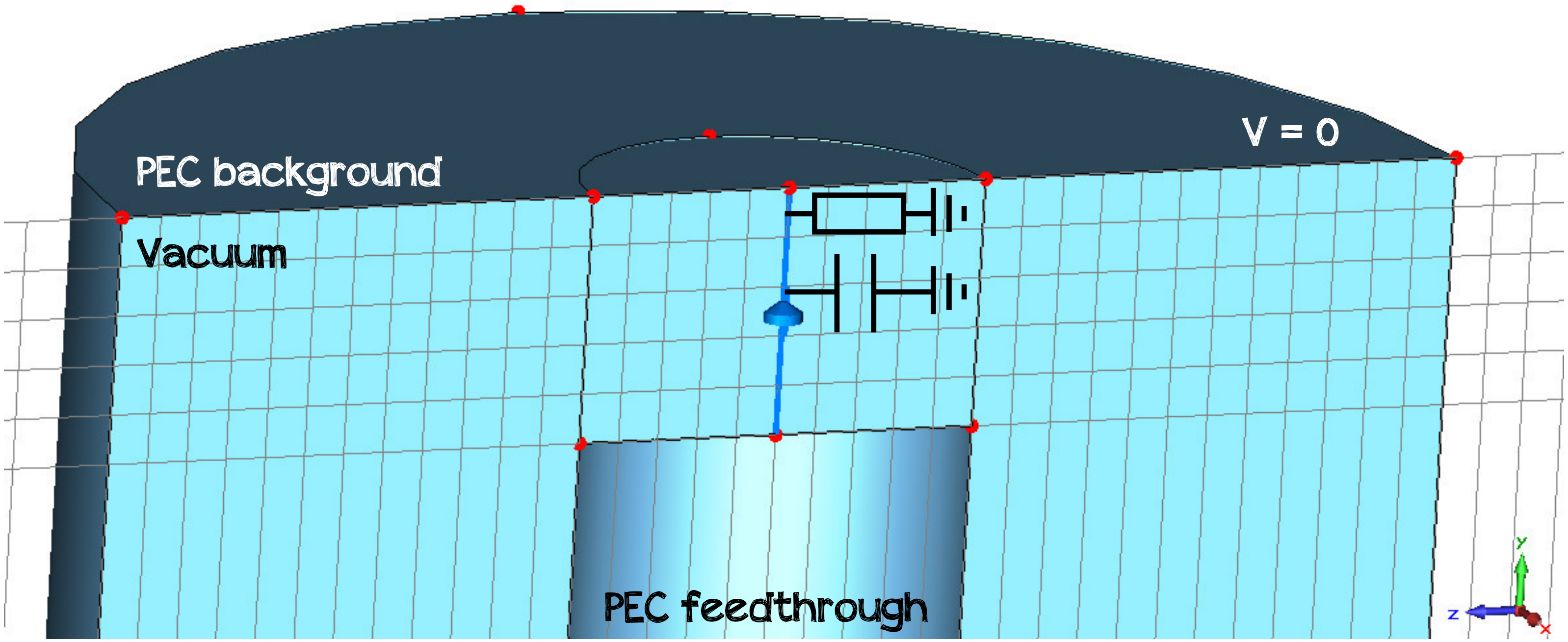
CST Particle Studio
Wakefield Solver





~7×10^6 mesh cells (already reduced by a factor of 2 by a symmetry plane)

Pick-Up Response Simulations



Voltage monitored at lumped components attached to the feedthroughs with *C* and *R* of the amplifier input

Pick-Up Response Simulations

With the ring:

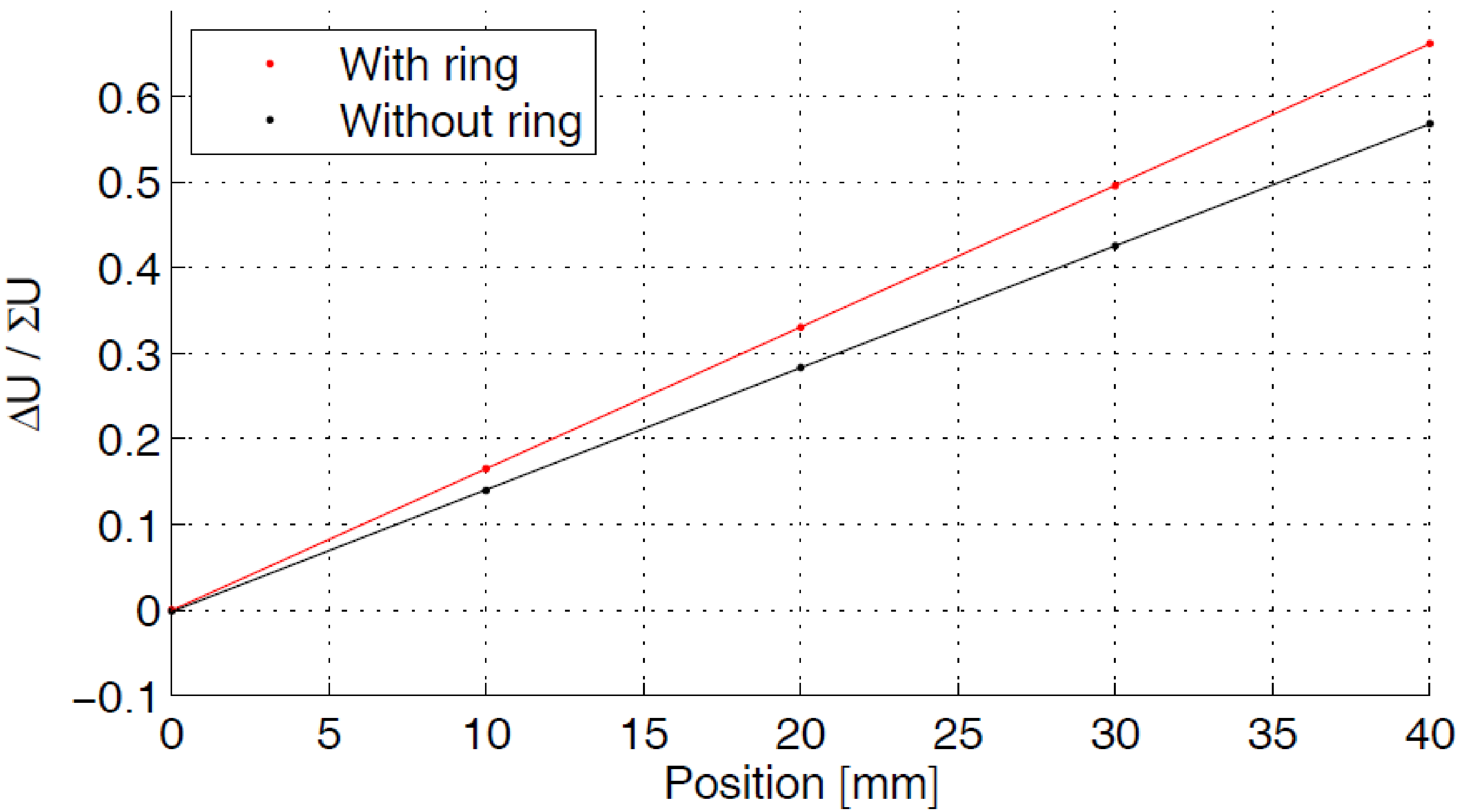
k = 60.4 mm ± 0.1 mm

x_0 = 0.03 mm ± 0.02 mm

Without the ring:

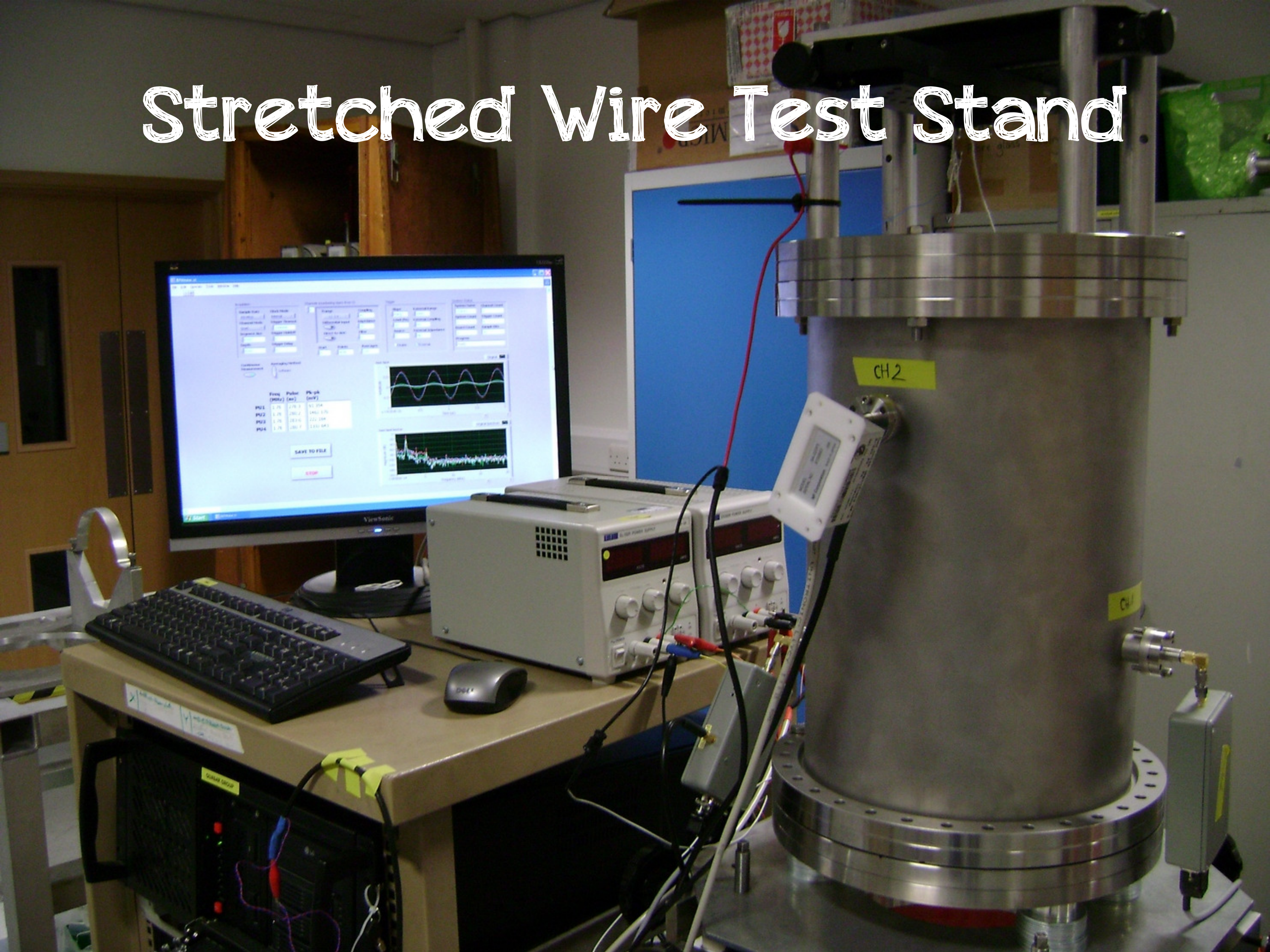
k = 70.1 mm ± 0.1 mm

x_0 = 0.15 mm ± 0.04 mm

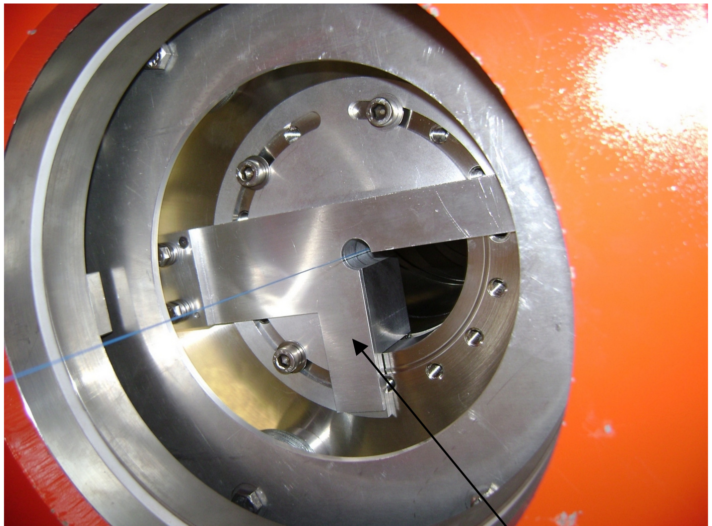


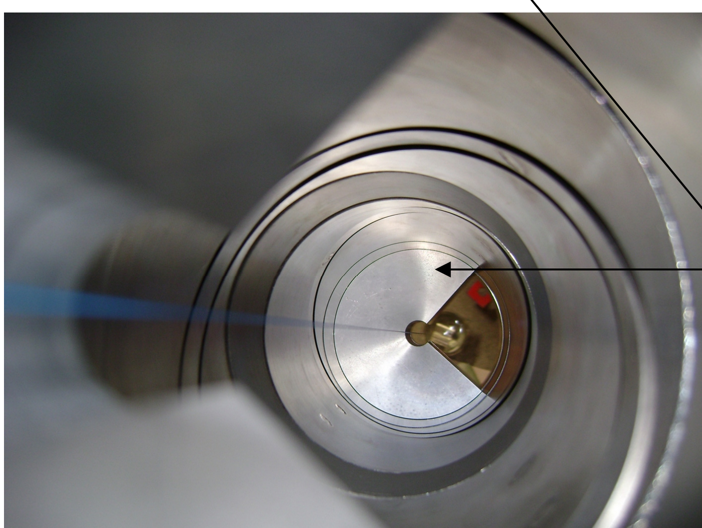
$\beta = 1$

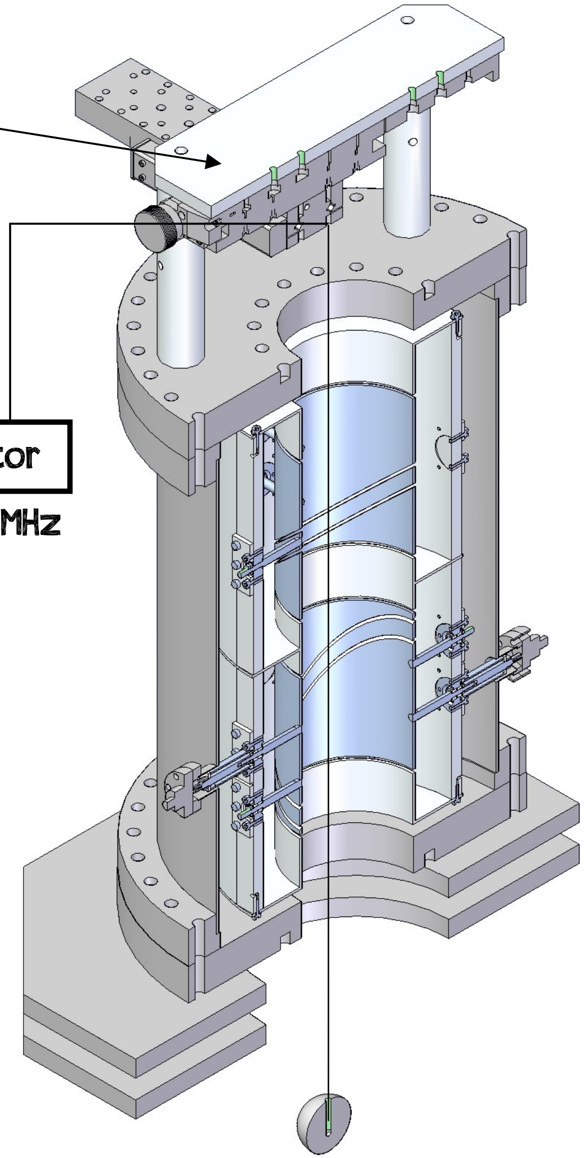
Stretched Wire Test Stand



Stretched Wire Test Stand



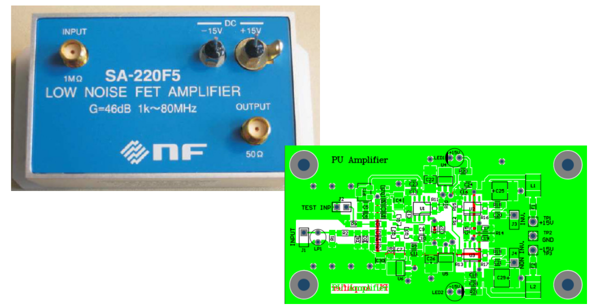




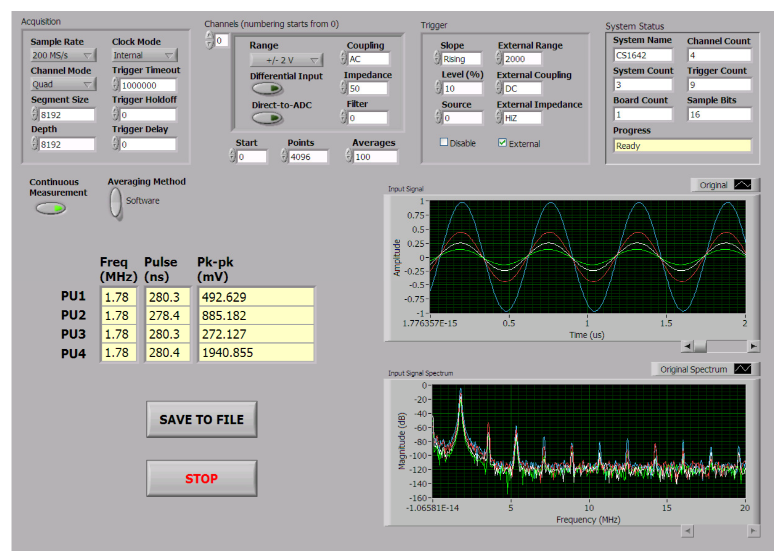
Stretched Wire Test Stand

PU → **amp** → **LP filter** (optional) → **ADC** → **LabView**

PU amps	NF SA-220F5	MSL, A. Paal
Input impedance	1 MOhm ‖ 57 pF	5 MOhm ‖ 30 pF
Input noise	0.5 nV/√Hz	0.9 nV/√Hz
Voltage gain	46 dB	54 dB



Digitizer	CS1642
Channels	4
Resolution	16 bit
Sampling	200 MS/s
Bandwidth	125 MHz
Memory	128 MB



Measurements vs. Simulations

With the ring:

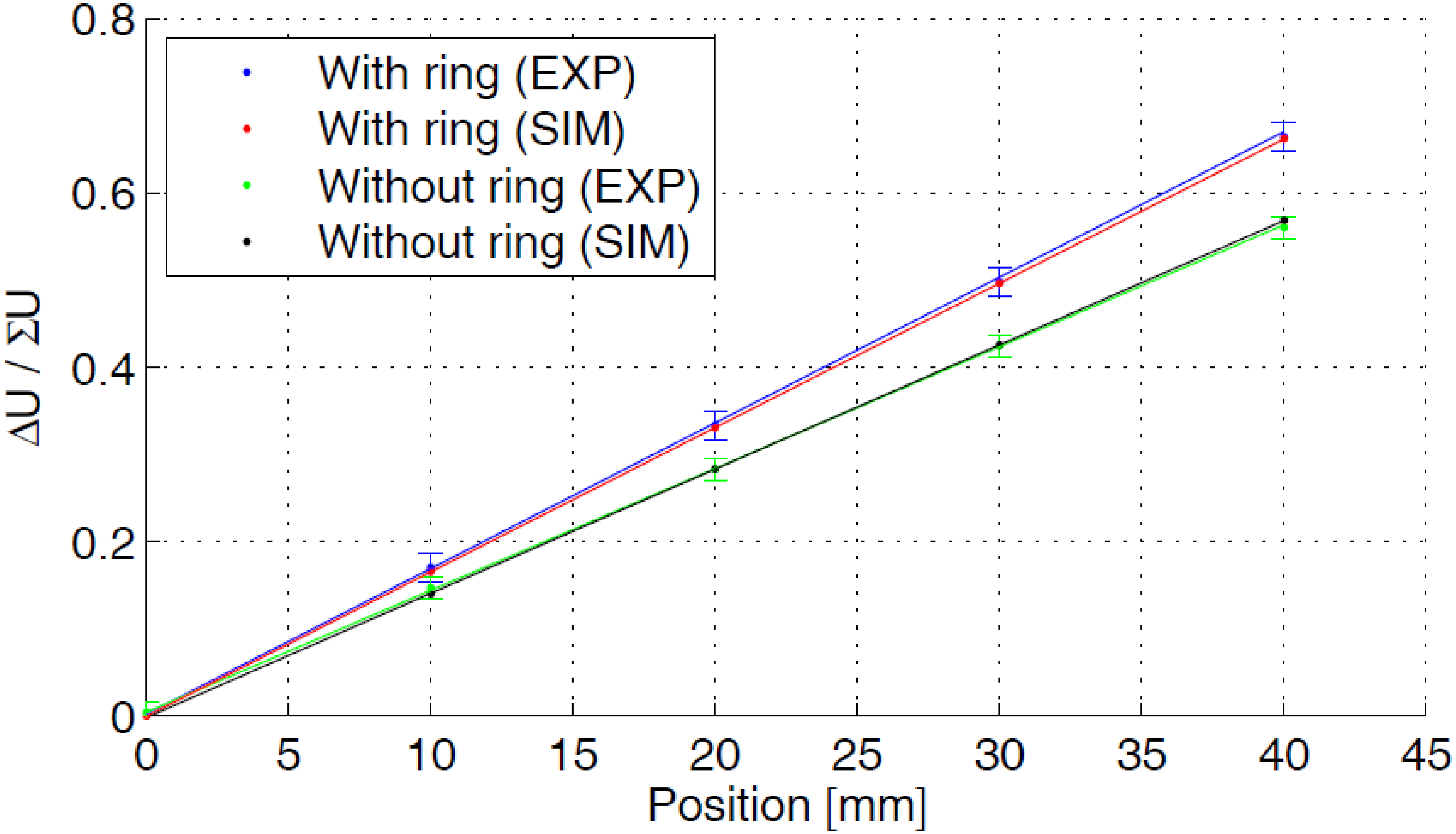
k = 59.8 mm ± 0.1 mm

x_0 = -0.1 mm ± 0.1 mm

Without the ring:

k = 71.5 mm ± 0.1 mm

x_0 = -0.3 mm ± 0.2 mm



Separating Ring

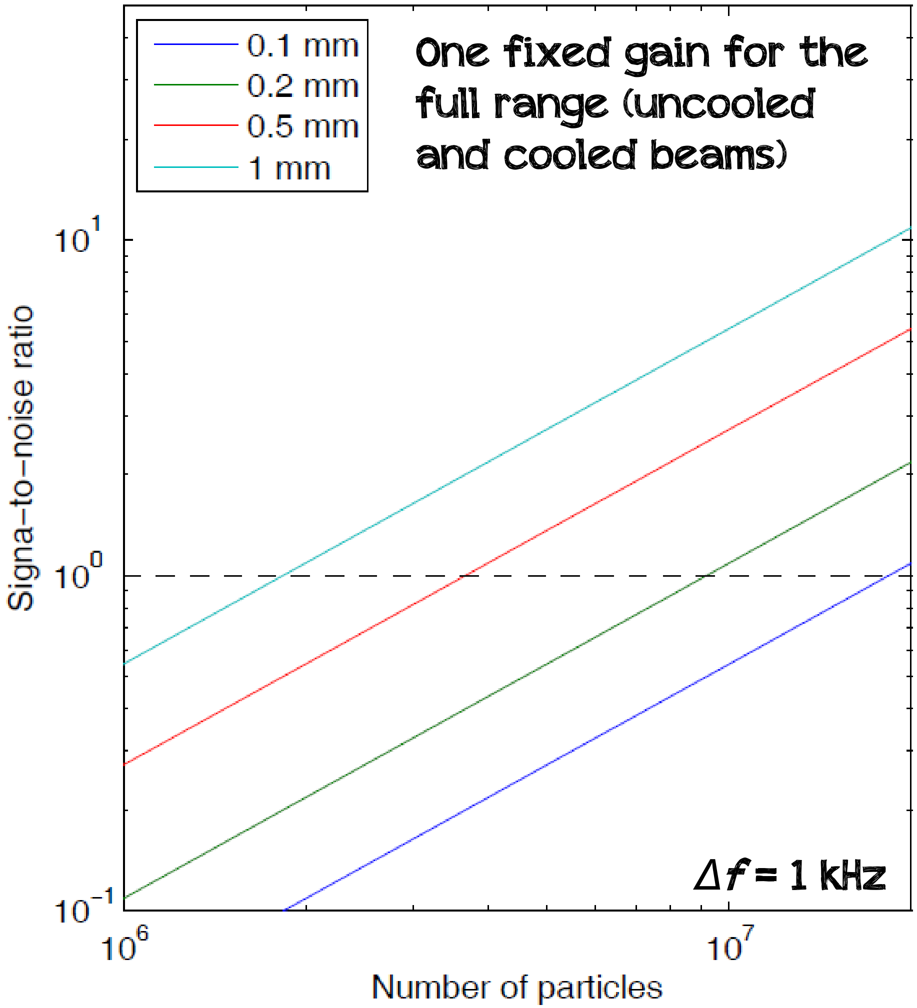
Improvement in sensitivity...

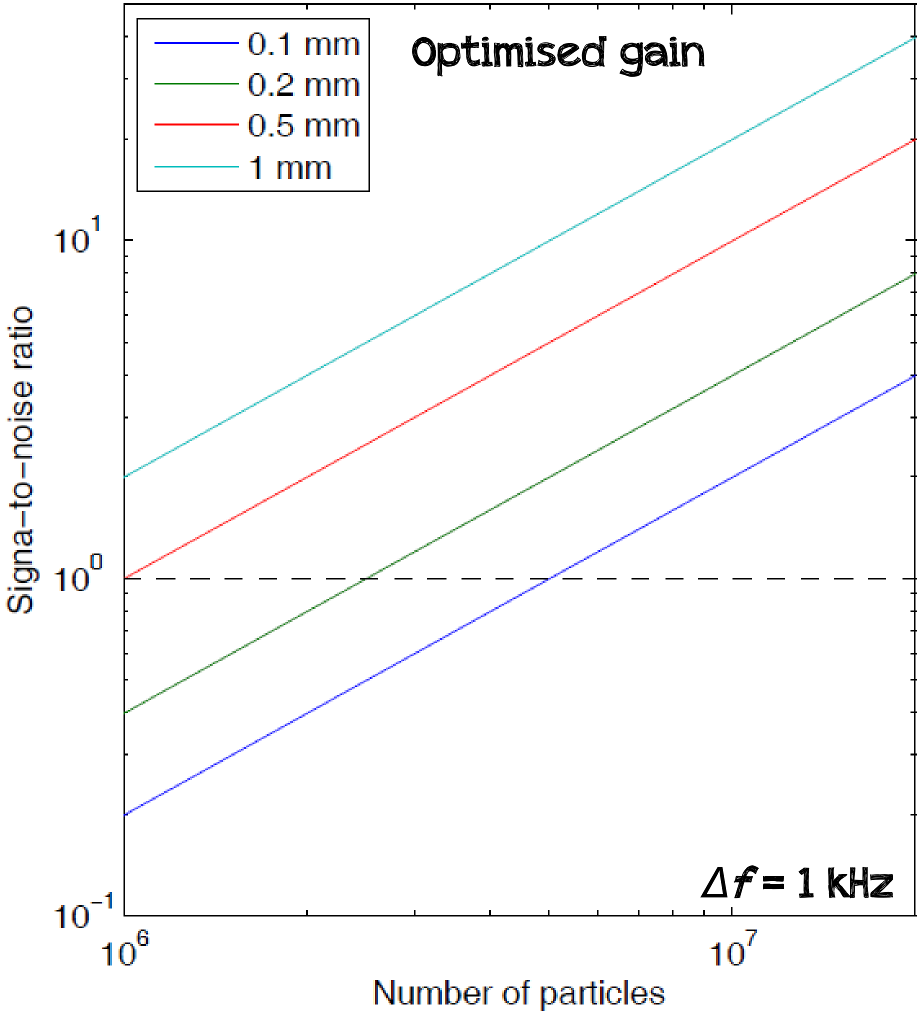
k => ~115% k

...but at the cost of the signal strength

U => ~80% U

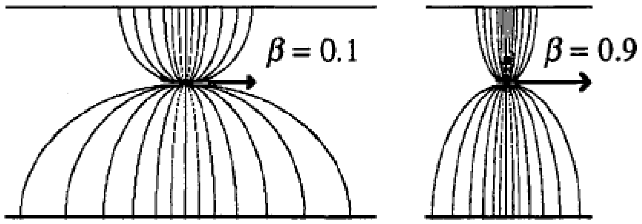
Position Resolution

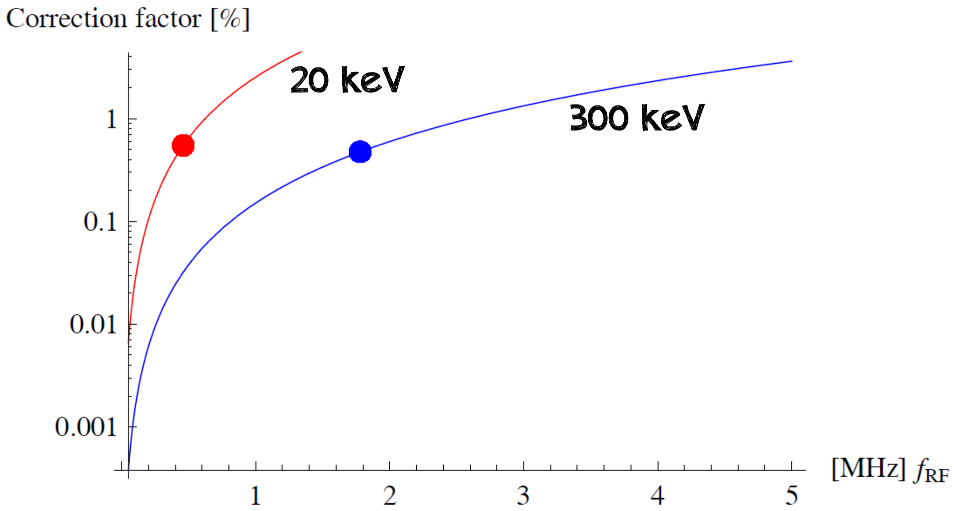


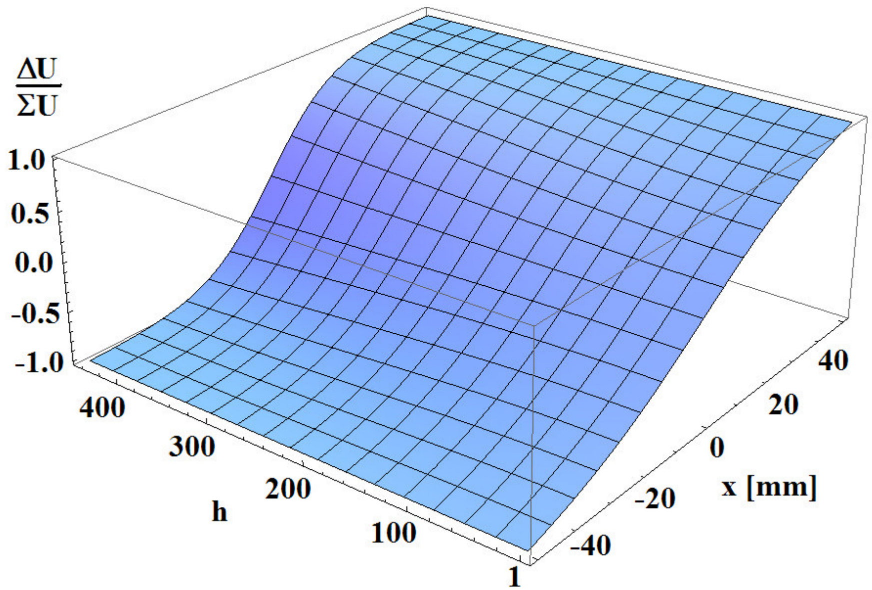


Low β Beams

- Theoretical calculations: difference below 0.5%-1% for low frequencies (RF harmonic numbers)
- Preliminary CST simulations: difference not bigger than a few percent (mesh size?), further studies needed





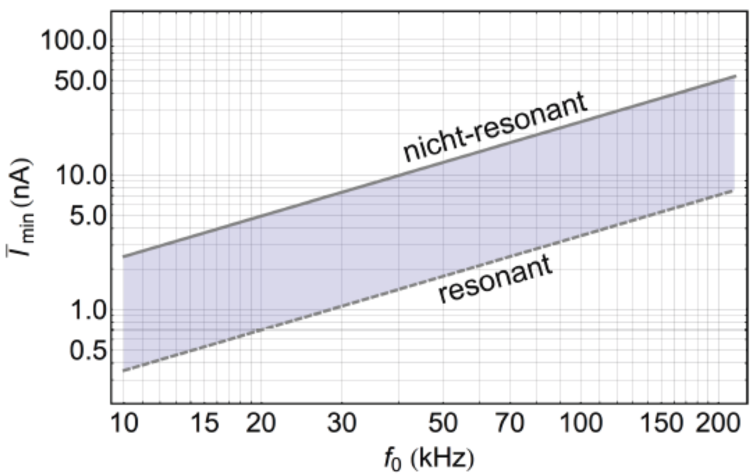


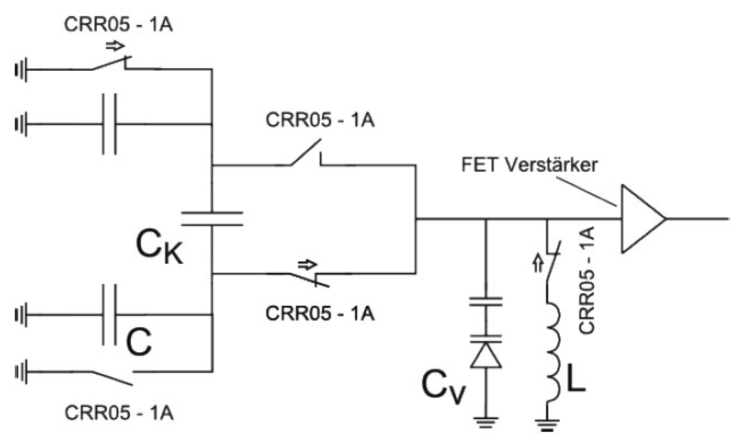
Prototype Status

- Diagonal cut => linear response
- Sensitivity: ~0.1 mm (depending on the bandwidth and gain), closed orbit measurements only (<1 kHz)
- Mechanical accuracy: <0.5 mm
- Tested only with a stretched wire and simulated for $\beta = 1$

Perspectives

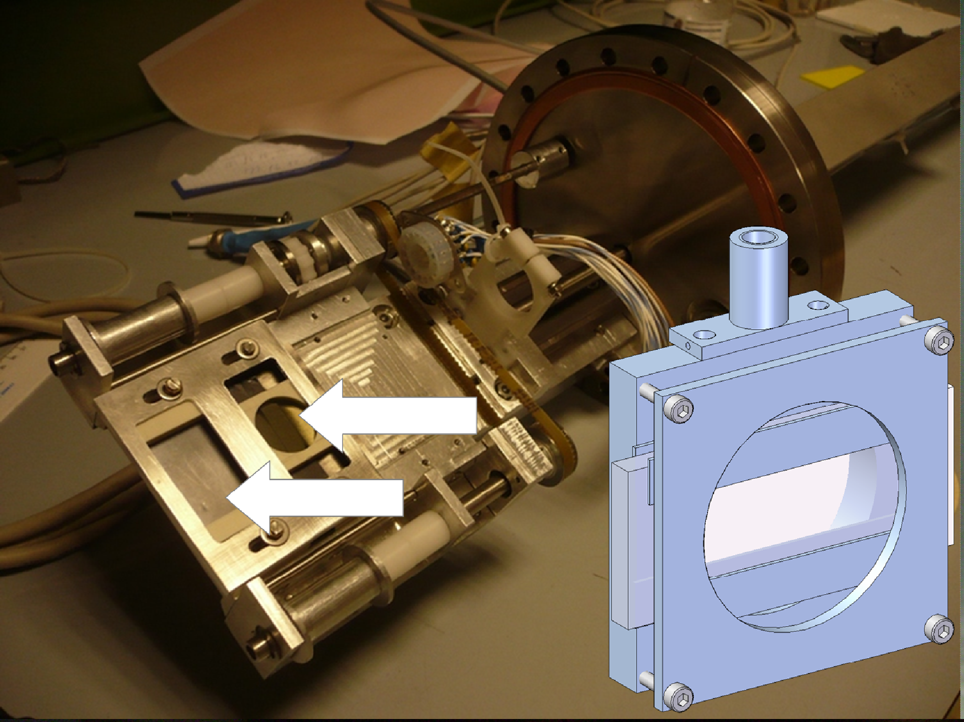
- Systematic simulations for $\beta << 1$
- Sensitivity can be improved with a resonant circuit (one order of magnitude)

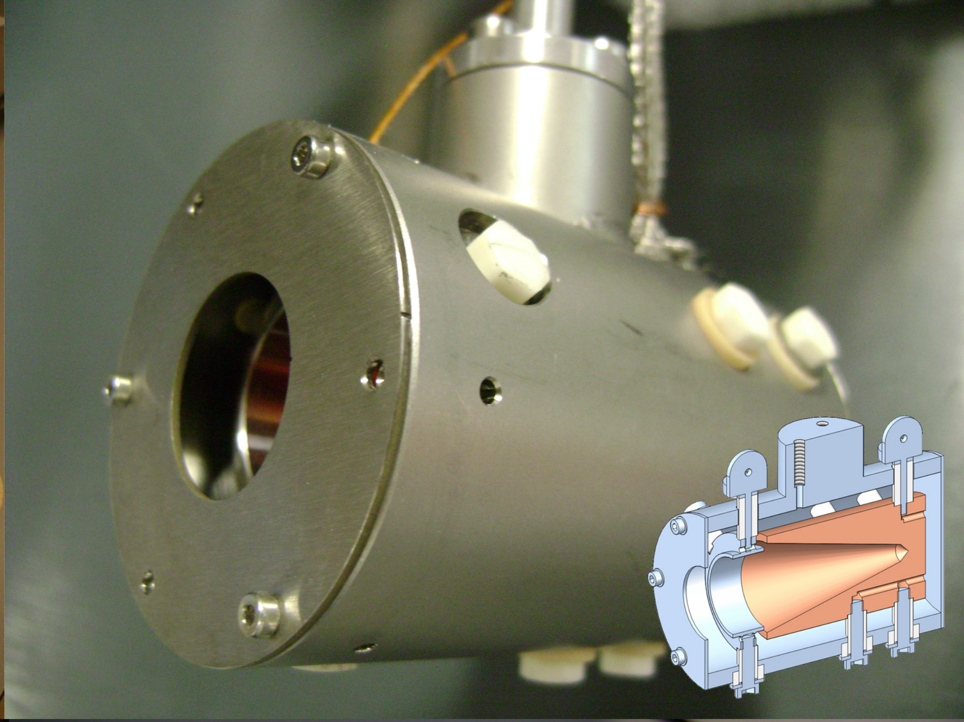




- Beam current measurements, etc.

Ref.: F. Laux, *Entwicklung von kapazitiven Positions-, Strom- und Schottkysignal-Messsystemen für den kryogenen Speicherring CSR*, PhD Thesis, University of Heidelberg, 2011.





Thank you for attention