Position Pickups for the Cryogenic Storage Ring

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Low Current, Low Energy Beam Diagnostics Workshop
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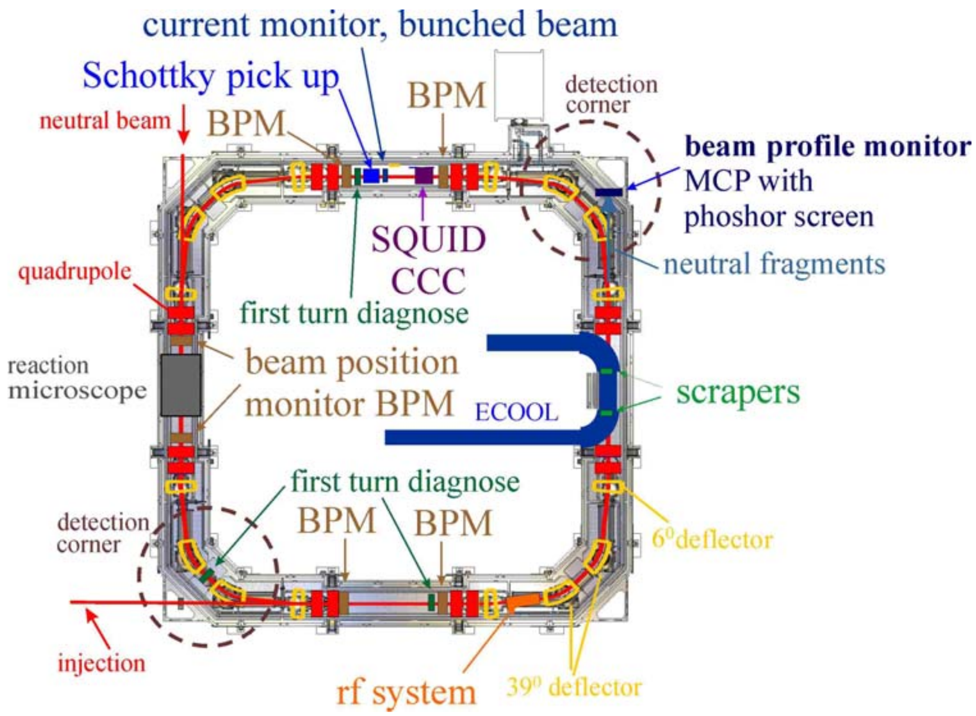
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Position Pickups at CSR



- closed orbit measurements, alignments of beam to experiments
- Beam Transfer Function / tune
- limited possibility of first turn diagnostics

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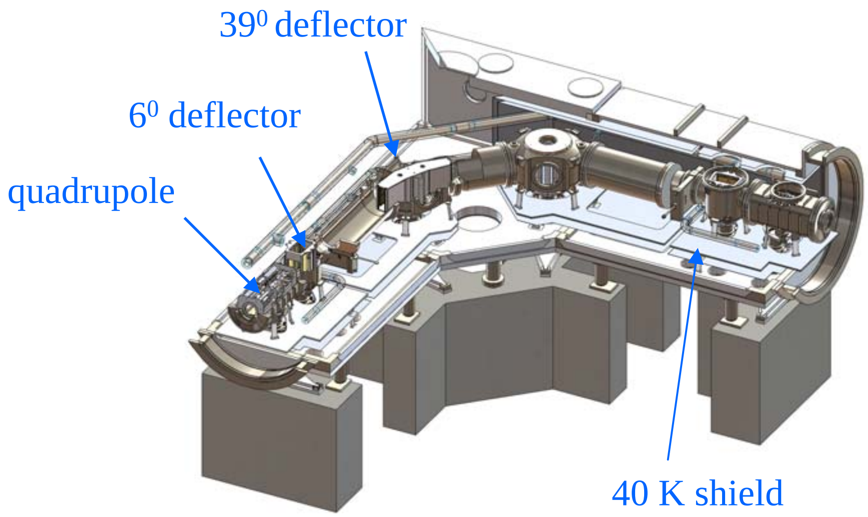
Problem statement

- Measure center of charge of the beam to < 0.5 mm precision
- Beam currents: 1 nA – 1 µA
- Ion mass: 1-100 amu
- Energy range (1^+ ions): 20 – 300 keV

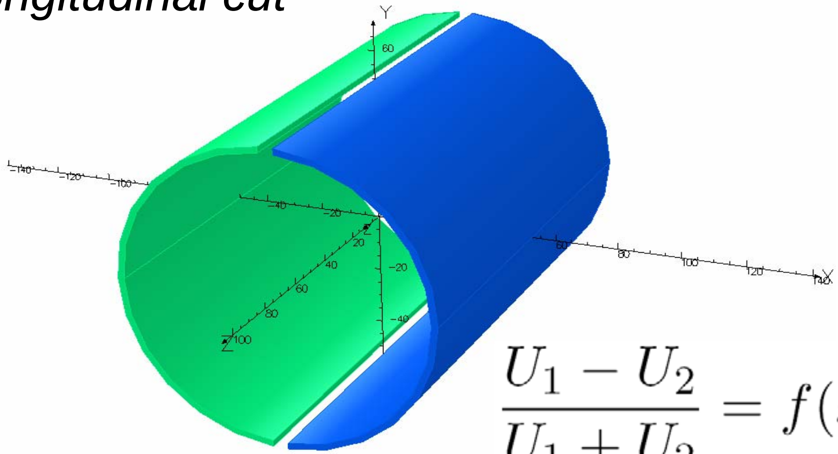
→ Frequencies 5 – 200 kHz

- Measurements with uncooled beams should be possible (no higher harmonics)
- Absolute position accuracy < 0.5 mm



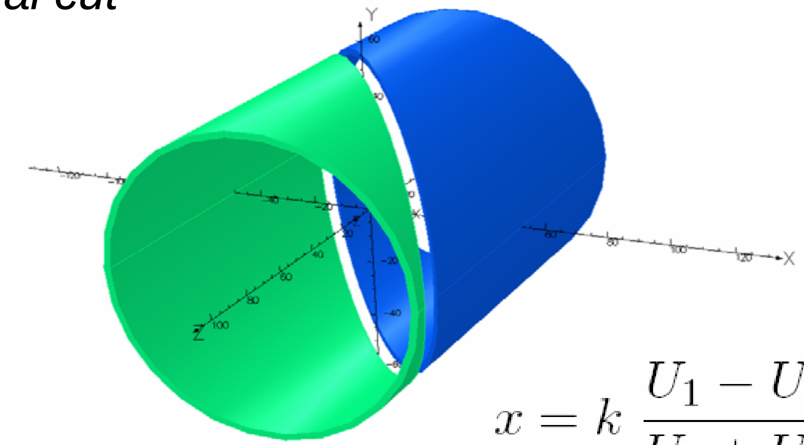
Comparison between longitudinally and diagonally slit pickups

Longitudinal cut



$$\frac{U_1 - U_2}{U_1 + U_2} = f(x, y)$$

Diagonal cut



$$x = k\,\frac{U_1 - U_2}{U_1 + U_2}$$

- Electrode shape – longitudinally or diagonally cut
- Beam Position Monitor vs. multi-purpose device
- Comparison of Δ/Σ for beams with 2 mm and 25 mm diameter located at x=25 mm and y=0 mm.

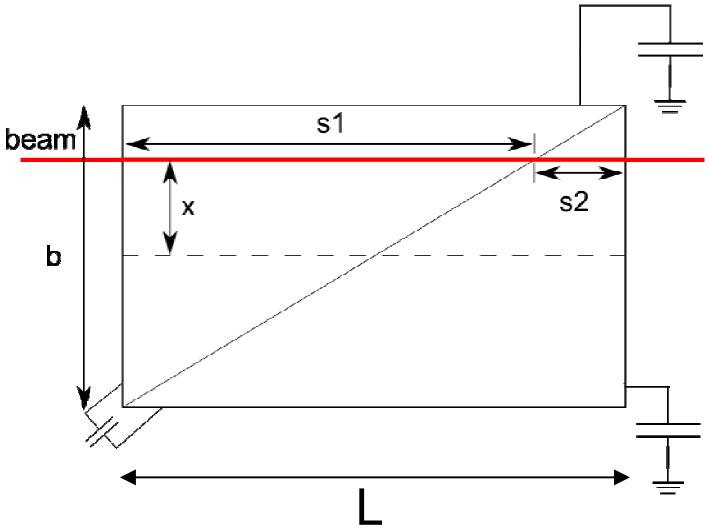
Diagonally cut pickup: no change in scaling factor

Longitudinally cut pickup: position dependance of scaling factor causes a systematic measurement error of Δx=0.05 mm.

Scaling factor of diagonally slit pickups

$$I_s = \omega \; I_b \; \triangle t$$

$$\longrightarrow I_s = \omega \; I_b \; \frac{L}{v}$$



$$x = k \; \frac{U_1 - U_2}{U_1 + U_2}$$

$$k = (1 + 2\, C_k/C)\; b/2 \longrightarrow C_k = 6 \text{ pF}, \;\; C = 60 \text{ pF} : \;\; k = 60\text{mm}$$

Example:

1 nA H^+-beam, f_0=200 kHz,

L=8 cm, v=0.025 c

$$\mathrm{U}_1 + \mathrm{U}_2 = \frac{1}{C} \; I_b \; \frac{L}{v} = 180 \text{ nV}$$

$$x = 0.5 \text{ mm} \longrightarrow \triangle U = 1.5 \text{ nV}$$

Measurement frequency

- Capacitive pickups can measure position of bunched beam only!

If beam coasts at frequency f, choose h x f to bunch the beam

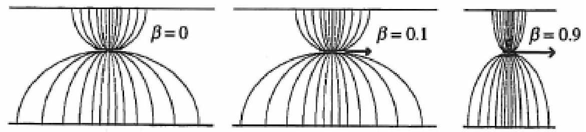
$$f_0 = \frac{1}{2\pi}\frac{1}{\sqrt{LC}}$$

Mass range	1-100 amu
Energy range (1^+ ions)	20 - 300 keV
Frequency range	5 kHz - 200 kHz
Intensity range	1 nA - 1 μA

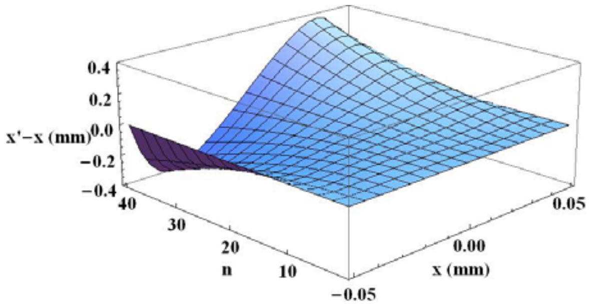
- Keep losses low due to L
- Required frequency shift should not be to high

→ Choose a frequency range much higher than the range of frequencies of the coasting beam!

But!



Low-β effect



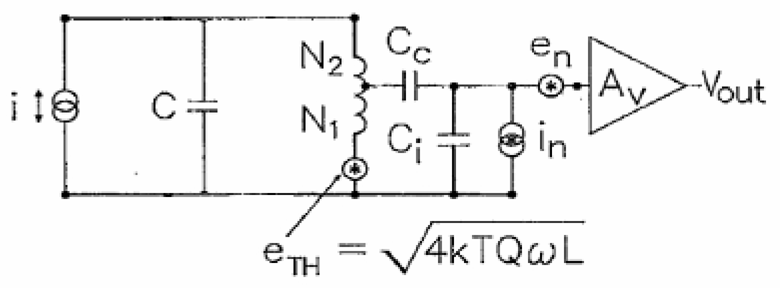
Systematic error due to the low-β effect

Cannot bunch to too high harmonics (h<40)!
Chose 200 – 400 kHz as appropiate

Calculation of the Signal-to-Noise ratio

Sources of noise:

- Thermal noise: $U_n = \sqrt{4\, k\, T\, Z}$
- Voltage noise of amp: E_n
- Current noise of amp: $I_n\, Z$



Impedances:

$$\alpha = \frac{N_1}{N_1 + N_2}\,\frac{C_c}{C_c + C_i}$$

$$Z_{\text{non-resonant}}(\omega) = \frac{1}{\omega\, C}$$

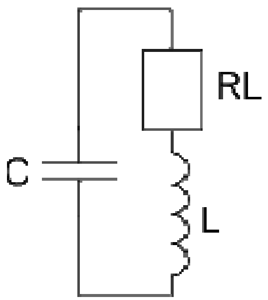
$$Z_{\text{resonant}}(\omega = \omega_0) = \frac{Q}{\omega\, C}$$

S/N optimized if: $\dfrac{E_n}{I_n} = Z_{\text{source}}$

$$S/N = \sqrt{\frac{I_{\text{S}}^2\, Z^2}{(4\, k\, T\, Z + I_n^2\, Z^2\, \alpha^2 + E_n^2/\alpha^2)\, \triangle f}}$$

Inductance

Impedance at resonance

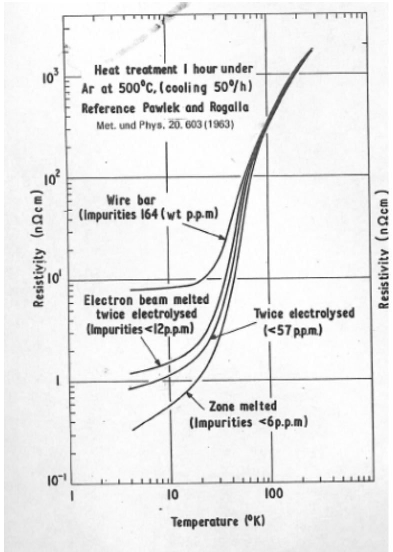


$$\omega_0 = \frac{1}{\sqrt{L\,C}}$$

$$Z(\omega = \omega_0) = \frac{1}{R_L}\,\frac{L}{C}$$

Capacity budget

element	C [pF]	source
electrode	20	Tosca calculation
feedtrough[1]	5	estimate
switches (relays)	2.5	datasheet
cables	?	
coil	10	estimate
variable capacity diode	5	datasheet
amplifier	15	data sheet/estimate



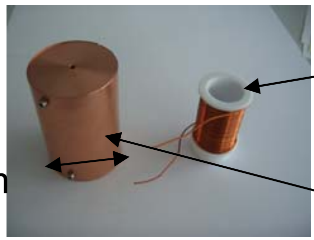
The electrical resistivity of heat treated copper

Coils made from copper wire

C=70 pF, 400 kHz

→ L=2.2 mH

→ N~400

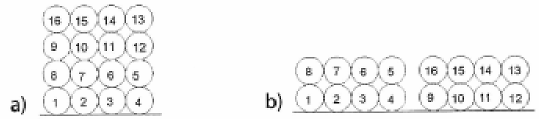


5 cm

Teflon body (ε=2)

Copper shielding

Reduction of capacity by chamber winding



Examples (H. Kracke):
Copper coil,
L=2.2 mH, Cs=8.3 pF,
RL=22 Ohm @ 4K

$$\rightarrow Q = 250\ (400\mathrm{kHz})$$

- RRR=66
- Coupling to resonator probably to strong

$$R_{Coil} \approx \frac{\rho\, l}{2\,\pi\, r\, \delta}, \quad \delta = \sqrt{\frac{2\,\rho}{\mu\,\omega}}$$

Superconducting coil (copper shielding),RL=5 Ohm @ 4K

$$\rightarrow Q = 1100\ (400\mathrm{kHz})$$

Superconducting coil (super cond. shielding),RL=1.7 Ohm @ 4K

$$\rightarrow Q = 3300\ (400\mathrm{kHz})$$

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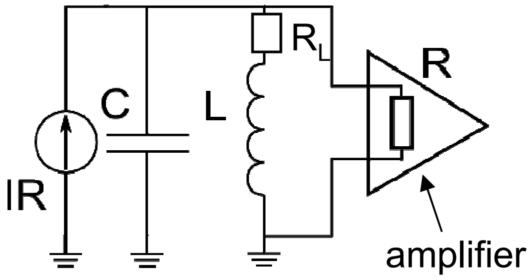
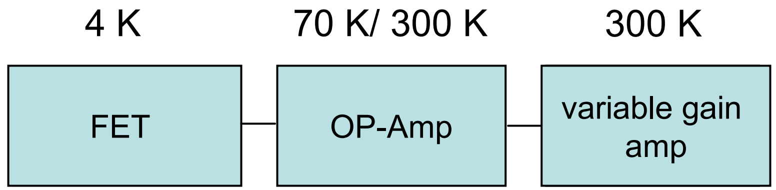
Cryo-amplifiers

Use cryo-amplifiers to be as close as possible to signal source!

Q	$Z(M\Omega)$
250	1.4
1100	6.1
3300	18.5





Requirements

- DC input impedance high enough to not to lower quality factor
- Low Voltage noise
- Very low Current noise
- Cryo-capable
- Low power consumption

Example data of comm. available amplifier

- R=22.7 M
- E_n=8 nV/√Hz
- I_n=8 fA/√Hz
- GaAs-Technology
- 10 mW

GaAs FET cryo-capable!

Benefits from Resonant Amplification (I)

Noise

resonant

Q	$Z(M\Omega)$	U_n (nV)	E_n (nV)	$I_n\ Z$ (nV)	Total Noise (nV)
250	1.4	175	80	111	222
1100	6.1	367	80	489	617
3300	18.5	630	80	1438	1572

f=400 kHz

RBW=100 Hz

non-resonant

$$Z_{\text{non-resonant}} \approx \frac{1}{\omega\ C} = 5.6\ \text{k}\Omega$$

U_n=11 nV, E_n=80 nV, $I_n\ Z$=0.4 nV, Total Noise=80.7 nV

Signal

$$I_s = \omega\ I_b\ \Delta t$$

Beam current to signal current calculation

$$\rightarrow I_s = \omega\ I_b\ \frac{L}{v}$$

$$\rightarrow I_s = 2\ \pi\ h\ I_b\ \frac{L}{C_0}$$

$$h = 1 \rightarrow I_s/I_b = 2\ \pi\ \frac{L}{C_0} = 1.4\%$$

f=400 kHz, h=20, Q=250, l=0.08 m, $C_0 = 35$ m, $I_b = 1$ nA

U_{resonant}=200 μV → S/N=59 dB

$U_{\text{non-resonant}}$=0.8 μV → S/N=20 dB

S/N improvement 39 dB

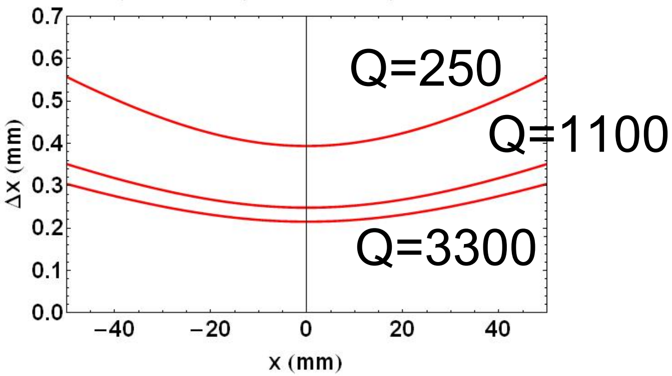
Benefits from Resonant Amplification (II)

$$x = k\,\frac{U_1 - U_2}{U_1 + U_2} \;\rightarrow\; \triangle x = k\sqrt{\left(\frac{2\,U_2}{(U_1+U_2)^2}\,U_{\mathrm{noise}}\right)^2 + \left(\frac{-2\,U_1}{(U_1+U_2)^2}\,U_{\mathrm{noise}}\right)^2}$$

$$\triangle x < 0.25mm \rightarrow S/N > \frac{2\,k}{\triangle x} = 400,\, f = 400\mathrm{kHz},\;\; h = 2 \rightarrow Q = 1100$$

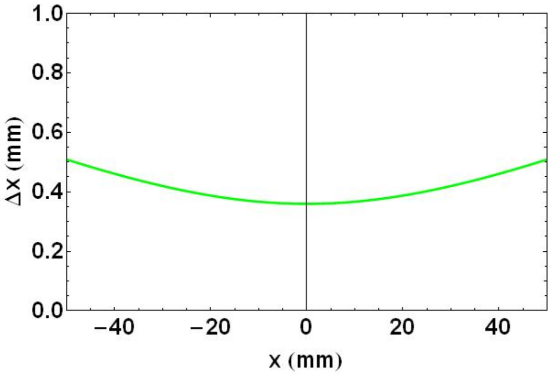
Position dependence of position error

resonant

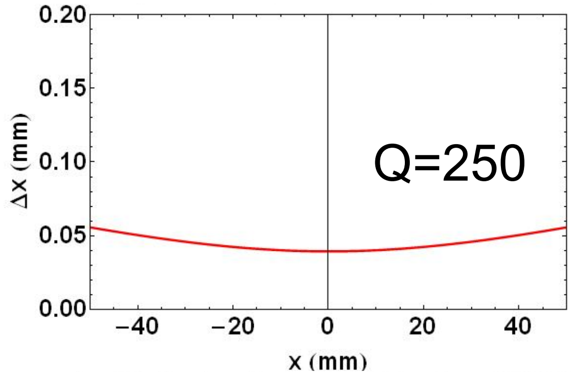


I_b=1 nA,
f=400kHz,
h=2,
α=1,
Δf=100 Hz

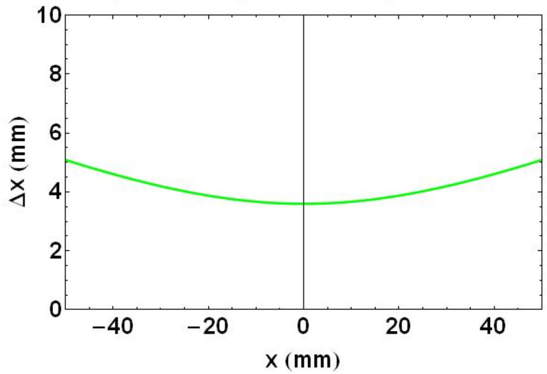
non-resonant



I_b=0.1 μA,
f=400kHz,
h=2,
α=1,
Δf=100 Hz



I_b=1 nA,
f=400 kHz,
h=20,
α=1,
Δf=100 Hz



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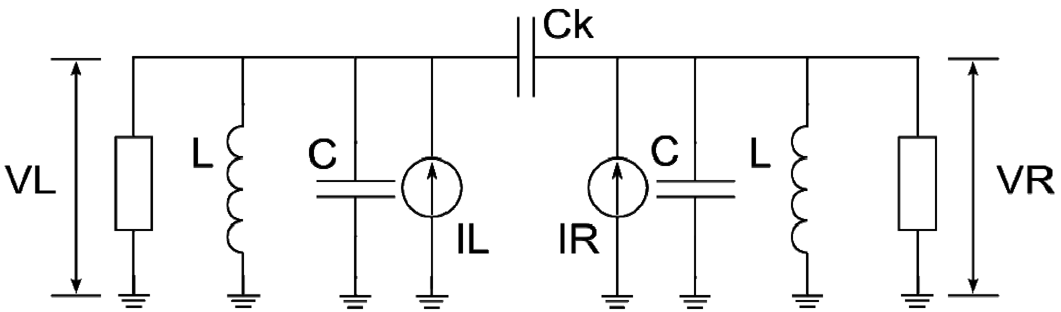
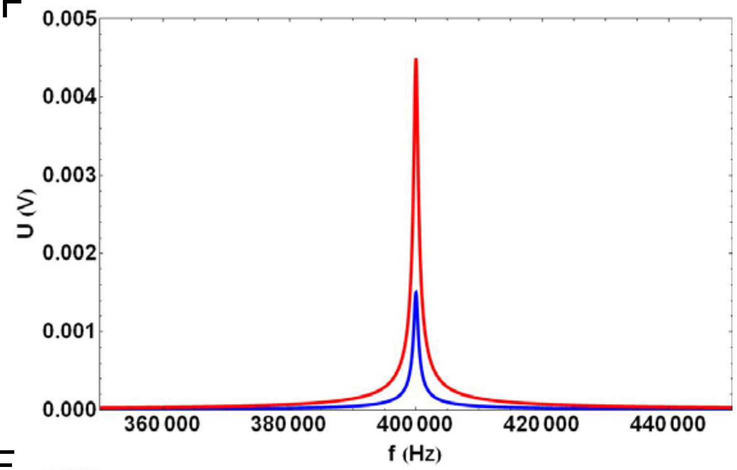
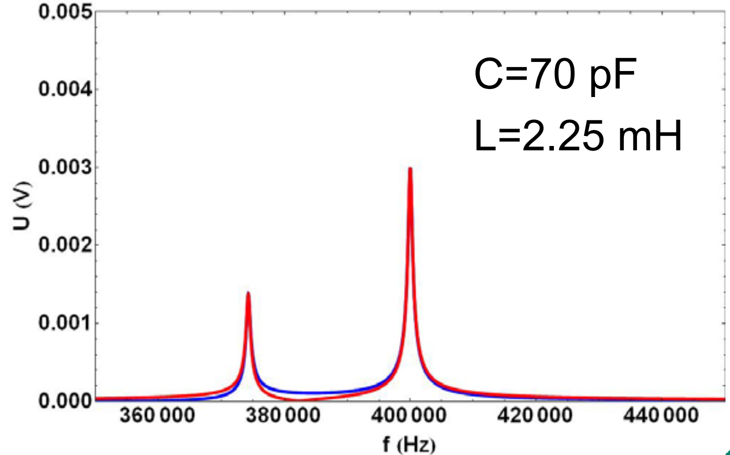
Effects of coupling



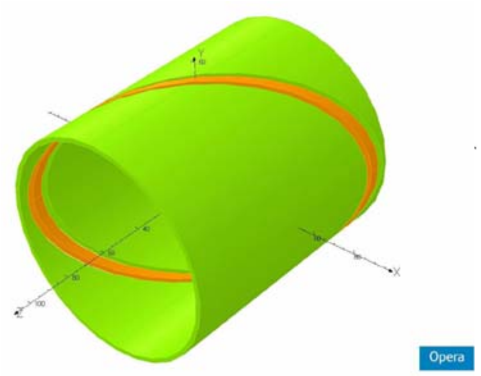
Ck=0 pF



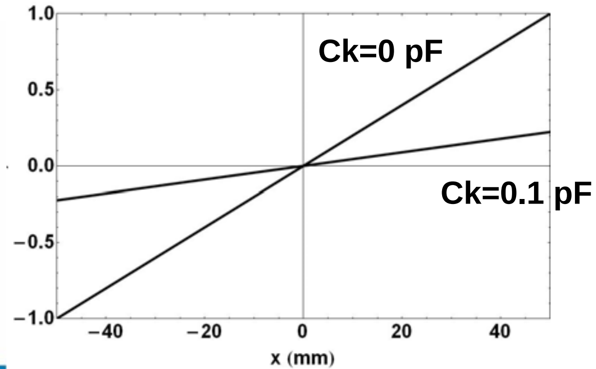
Ck=5 pF



Guard Ring: 6 pF → 4 pF



Not sufficient!



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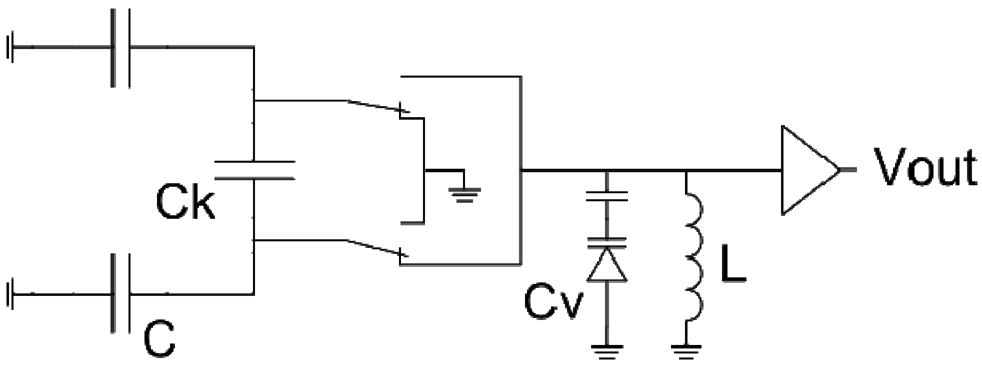
Amplification circuit

@ 300 K	GaAs FET Switch	HF Relay
On resistance	3.9 Ω	0.2 Ω
Off resistance	200 kΩ	10^{10} Ω
Capacity	15 pF	2.5 pF
Life time (cycles)	–	100 10^6
Switching time	4 ns	1 ms
State hold power	6.4 mW	32 mW



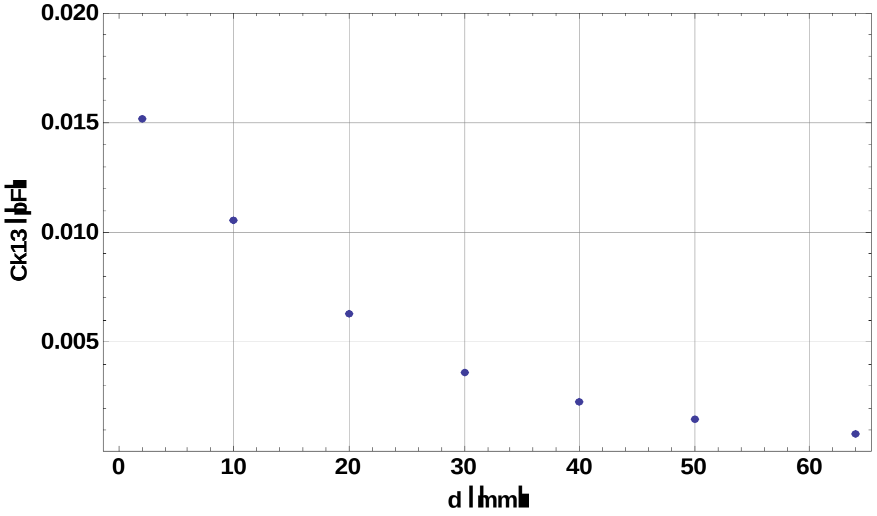
- Testet two relay changers in liquid nitrogen -> switched for >150 10^6 times.
- Switching power changed from 32 mW (300 K) -> 4 mW (77 K)
- Change of On resistance over life time?
- Is through resistance the same for the two ways in a changer?

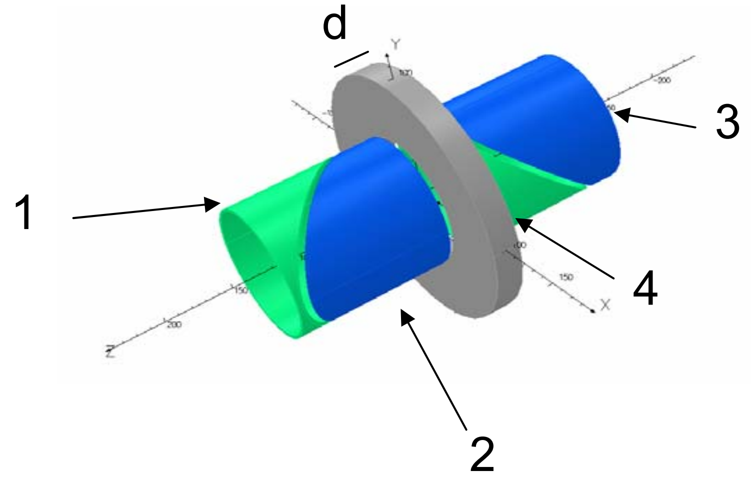
$$U_{signal} \propto \frac{1}{R_L} \rightarrow$$

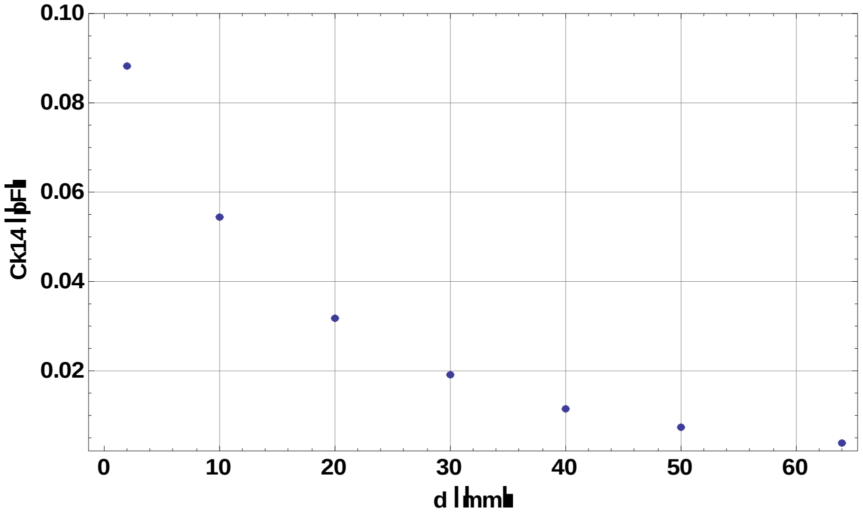
RL=20 Ohm (Q=275), comparability 10^{-3}

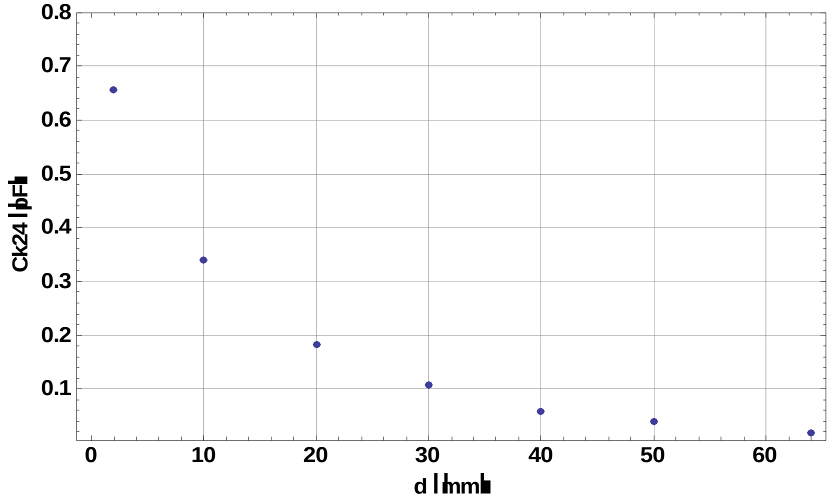
Difference of through resistance <0.02 Ohm

Dependence of coupling on width of middle guard ring

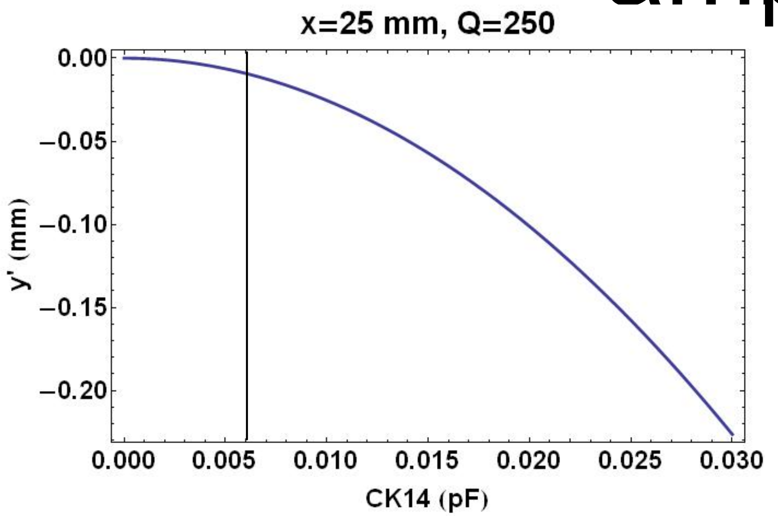


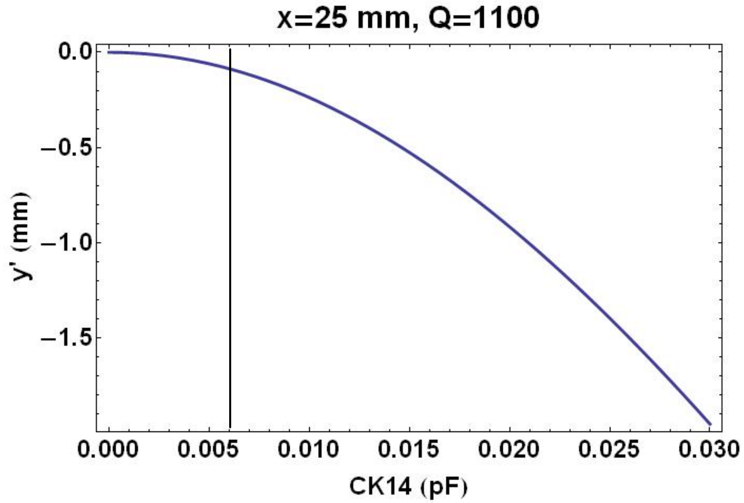


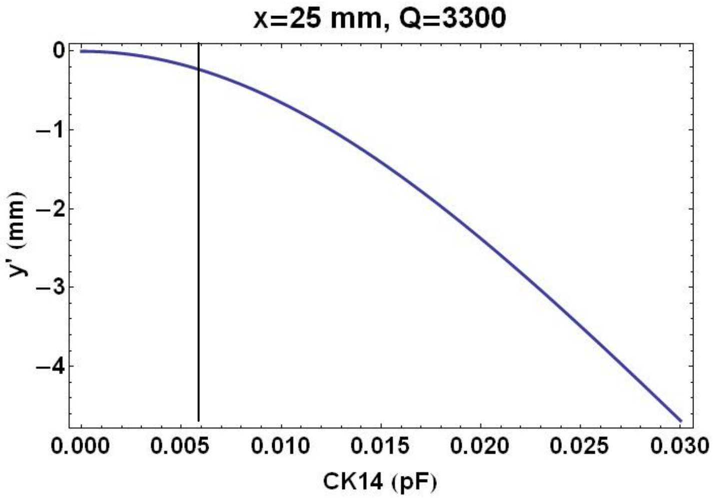




Coupling between pickups - resonant amplification

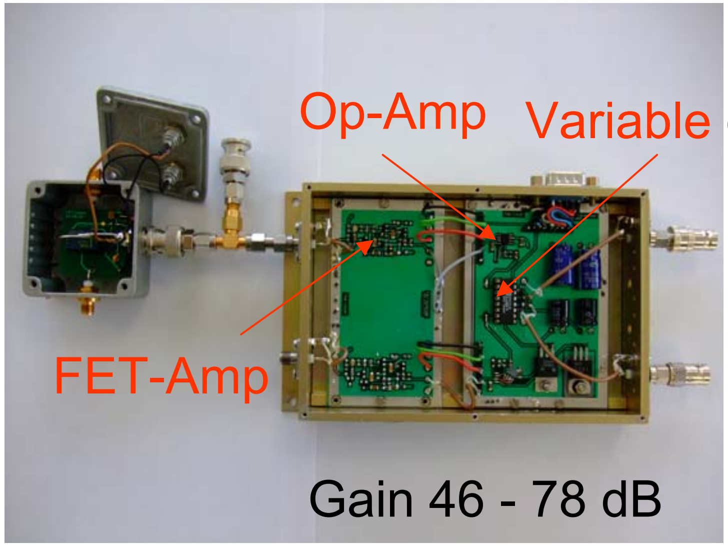






If simultaneous measurement of one electrode is required the guard ring separating one pickup from the other should have a thickness > *6 cm*.

Test Measurements



Data acquisition with SiS3300
14 bit ADC,
$f_{sampling}$=80 MHz,
average over 4800 periodes

Noise measurement

$$E_{ni}^2 = U_n^2 + E_n^2 + I_n^2 \; R_s^2$$

I_n~150 fA/√Hz
E_n~3 nV/√Hz
R_n=20 kΩ

C^{6+} beam, f_0=509.33 kHz, h=6,
C_0=55 m, $l = 0.08$ m

$\triangle x < 0.5mm \rightarrow S/N >= 520$

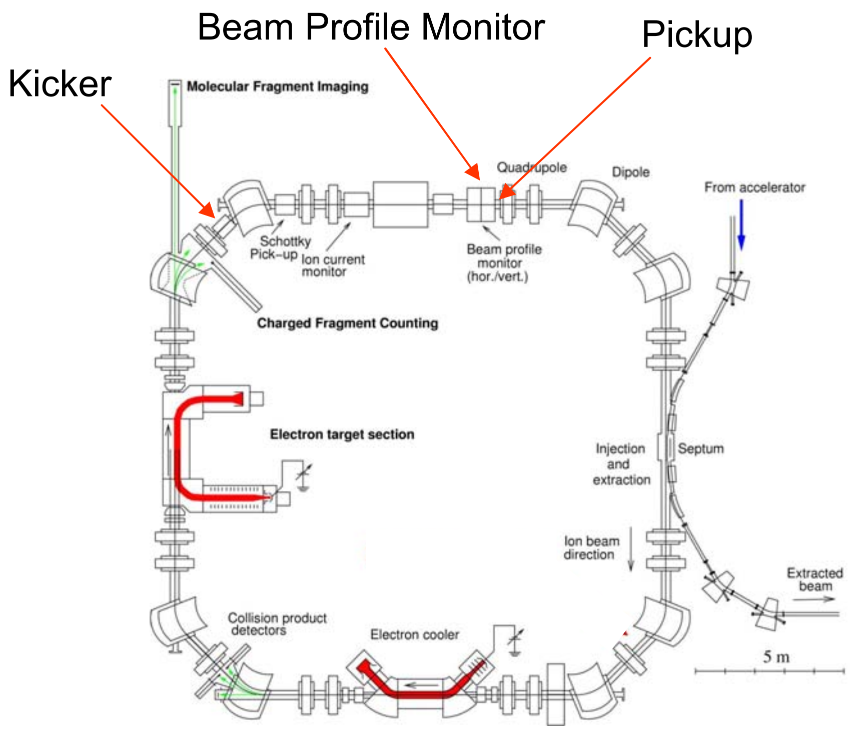
L=19.9 µH
R_L=3.3 Ω
Q=116 @ f_0=3,056 MHz
$Z(\omega_0)$=44.2 kΩ

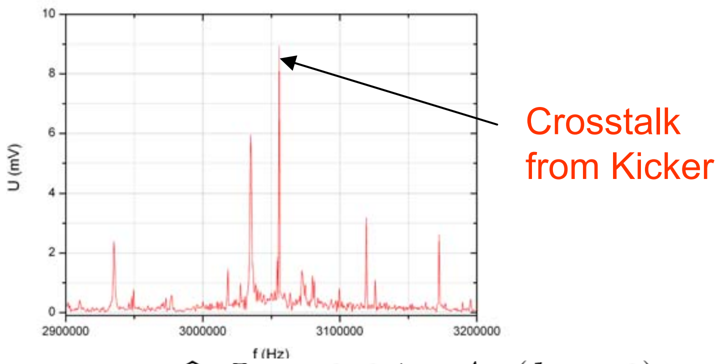
Minimum current ($\triangle f = 625$ Hz):

- resonant: $I_b = 0.1 \; \mu A$
- non-resonant: $I_b = 1.7 \; \mu A$

S/N improvement: 18 dB

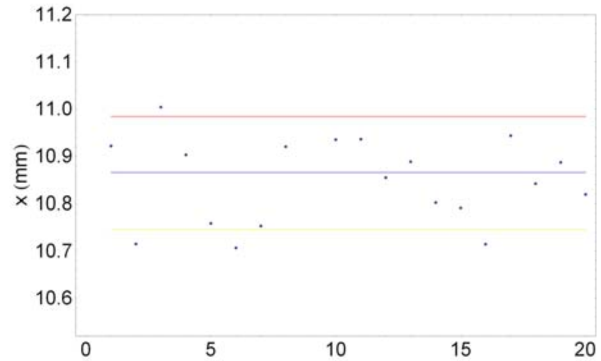
Test Measurements





$U_{\text{kicker crosstalk}} \mathrel{\widehat{=}} I_b = 0.04\ \mu A \quad (h = 6)$

C^{6+} beam, f_0=509.33 kHz, h=3,
C_0=55 m, $l = 0.08$ m, No. of measurements N=20



Results:

- Current: $I_b = 0.5\ \mu A$
- $\overline{x} = 10.86$ mm
- $\triangle\overline{x} = 0.03$ mm
- Measured Standard Deviation: $s = 0.12$ mm
- Calculated Standard Deviation: $s = 0.07$ mm

Calculated Standard Deviation for non-resonant amplification: $s = 1.2$ mm

Thank you for listening!

And many thanks to the CSR team for support!