Results of the LHC DCCT* Calibration Studies

Thanks also to the BCNGW members

Lumi days 2012-02-29

*DCCT = DC Current Transformer
This talk presents the results of the DCCT studies published in note CERN-ATS-Note-2012-026 PERF

- Motivation
- The DCCT system
- DCCT error sources divided in 3 categories
  - Internal effects
  - Sensitivity to external factors
  - Calibration method
- Difference between systems A and B
- Results
- Conclusion
Motivation

• DCCT is the only instrument which accurately measures the total beam intensity
• All other instruments measuring the intensities per bunch (e.g. FBCT, BPTX, WCM, LDM) are normalized to the DCCT
• A good knowledge of the DCCT uncertainty is crucial for all luminosity measurements

In 2010 the DCCT uncertainty was estimated at 2% per beam (see note CERN-ATS-Note-2011-004 PERF), dominating the luminosity uncertainty

Studies performed during 2010/2011 to better understand the DCCT behavior and characterize its systematic uncertainties
DCCT system

Located on a straight section at point 4

Two independent systems per ring (A and B)

Designed an constructed at CERN

Acquired in 4 ranges with 12-bit bipolar ADC
Each range signal: 0 – 5V = 0 – 2047 ADC bins

<table>
<thead>
<tr>
<th>Range</th>
<th>Full scale (charges)</th>
<th>LSB weight Charges/bin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$5 \cdot 10^{14}$</td>
<td>$2.5 \cdot 10^{11}$</td>
</tr>
<tr>
<td>2</td>
<td>$5 \cdot 10^{13}$</td>
<td>$2.5 \cdot 10^{10}$</td>
</tr>
<tr>
<td>3</td>
<td>$5 \cdot 10^{12}$</td>
<td>$2.5 \cdot 10^{9}$</td>
</tr>
<tr>
<td>4</td>
<td>$5 \cdot 10^{11}$</td>
<td>$2.5 \cdot 10^{8}$</td>
</tr>
</tbody>
</table>
Sources of errors

**DCCT Error Sources**

- Internal Effects
  - Baseline
  - Noise
- Internal Effects
  - Linearity
  - Stability
- From Surrounding RF
- EMC
- From Surrounding Magnetic Fields
  - Bunch Length Dependence
  - Bunch Position Dependence
  - Bunch Pattern Dependence
- Sensitivity to External Factors
  - Cross Talk between Rings
- Calibration Method
  - Methodology and Current Leak
  - Current Source Accuracy
  - Calibration Rods Position Dependence
Noise – baseline correction

Noise level and floating baseline require a baseline correction between measurements

• Baseline correction **method verified and validated**
• Typical error on **baseline correction**: $\pm 1 \times 10^9$ charges (envelope)
• If baseline not corrected and not analyzed:
  (analyze offset after dump for 2011 physics fills)

Fourier analysis of noise shows **no frequency peak**:
Long term fluctuations of baseline

Measure signal stability over 2×12 hours with and without current (measured in-situ)

• No difference observed with various injected intensities
• Measure RMS and peak-to-peak (P2P) variations with 1 min. and 1 hour average (longer average of 1 hour reduces the fluctuations compared to 1 min.)

![Graph showing stability over time](image)

<table>
<thead>
<tr>
<th>Range</th>
<th>Averaging time</th>
<th>Absolute RMS (LSB)</th>
<th>Absolute RMS (charges)</th>
<th>Absolute P2P (LSB)</th>
<th>Absolute P2P (charges)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 min.</td>
<td>± 0.1</td>
<td>±2.3 \cdot 10^{10}</td>
<td>± 0.4</td>
<td>±1.1 \cdot 10^{11}</td>
</tr>
<tr>
<td>2</td>
<td>1 min.</td>
<td>± 0.1</td>
<td>±2.2 \cdot 10^{9}</td>
<td>± 0.4</td>
<td>±1.0 \cdot 10^{10}</td>
</tr>
<tr>
<td>3</td>
<td>1 min.</td>
<td>± 0.3</td>
<td>±6.7 \cdot 10^{8}</td>
<td>± 0.9</td>
<td>±2.4 \cdot 10^{9}</td>
</tr>
<tr>
<td>4</td>
<td>1 min.</td>
<td>± 2.5</td>
<td>±6.3 \cdot 10^{8}</td>
<td>± 9.4</td>
<td>±2.3 \cdot 10^{9}</td>
</tr>
<tr>
<td>1</td>
<td>1 hour</td>
<td>± 0.01</td>
<td>±2.8 \cdot 10^{9}</td>
<td>± 0.03</td>
<td>±7.3 \cdot 10^{9}</td>
</tr>
<tr>
<td>2</td>
<td>1 hour</td>
<td>± 0.02</td>
<td>±5.2 \cdot 10^{8}</td>
<td>± 0.05</td>
<td>±1.1 \cdot 10^{9}</td>
</tr>
<tr>
<td>3</td>
<td>1 hour</td>
<td>± 0.2</td>
<td>±4.8 \cdot 10^{8}</td>
<td>± 0.4</td>
<td>±1.1 \cdot 10^{9}</td>
</tr>
<tr>
<td>4</td>
<td>1 hour</td>
<td>± 1.9</td>
<td>±4.7 \cdot 10^{8}</td>
<td>± 4.1</td>
<td>±1.0 \cdot 10^{9}</td>
</tr>
</tbody>
</table>

< 0.1% for VdM scans
24 hours stability with high current

Measure signal stability over 24 hours with high current (measured in-situ)

- No thermal effect observed due to possible heating of electronic components
- Stable within ±0.01%
- Digitalization artifacts of 12-bit ADC visible with low noise signal

Problem for short time average at high intensity
Linearity away from calibration point (3 measurements in-situ)

• Non-linearity observed ≈1 ADC bit
• DCCT underestimates intensity below the calibration point
• More measurements with alternate 16-bit ADC and new 24-bit ADC
• Non-linearity due to 12-bit ADC

Lowest value in a range:
At 8% of range:
\[ \frac{2^{12}/2 \times 0.08}{2^{12}/2} = 164 \text{ bins} \]
error: ± 1 bin = 0.63%

Error negligible close to calibration point
At 80% of range:
error: ± 1 bin = 0.06%
Scaling factor stability

6 precise calibrations performed in 2011 during technical stops spanning 9 months

Principle: scaling factor = injected charges (current)/ADC bins
Is this value stable over the year?

- Only 2 measurements available in 2010 with one deviation of 1.6%
- Method has been improved
- Precise calibration performed during all TS in 2011
- Tunnel temperature: ±2 °C over the year
- No seasonal effect observed
- Two different current sources provide consistent results

Uncertainties:
± 1 LSB for ranges 1,2,3 (0.06% at 80% of range)
± 4 LSB for range 4 (0.24% at 80% of range)

Other plots in appendix
Cross-talk between rings

Observe DCCT signal on empty ring while high intensity beam is dumped in the other ring.

Dump at high intensity (beam 2)

Observe DCCT with empty beam 1

No cross-talk observed
Verify dependence on bunch position (MD fill 1910)
Reminder: FBCT is sensitive to position

Normal intensity decay unaffected by beam position
Interference from magnetic field

Verify correlation between LHC energy (i.e. magnetic field) and DCCT signal after dump for all physics fills in 2011

No interference with magnetic field observed
Interference from RF

Study interference with LHC RF cavity field using physics fills in 2011

No difference in offset Rfon – Rfoff (using 86 fills with a clear RF step)

No interference with LHC RF cavity field observed

- DCCT (beam 1 sys A)
- average region

RF “step”
Bunch pattern dependence (1/2)

• In 2010 a dependence on bunch pattern was discovered
• Problem was identified and reproduced in laboratory
• Corrected during winter shutdown 2010/2011
• DCCT bunch pattern misbehavior due to
  • Train of several close bunches combined with
  • High intensity
    i.e. the large mean intensity of a bunch train is
    source of problems
• VdM fills with single bunch injection were not affected

Laboratory setup to test the modifications:
Generate and inject current with a bunch pattern simulating a train injection
Verify:
\[ \frac{I_{\text{pattern}}}{I_{\text{DCCT}}} = \text{constant for all pattern} \]
Problem visible with low intensity

Test at maximal intensity
Instrumentation limits accuracy

New hardware tested with intensities equivalent to a filled machine with 50 ns injection
Observed deviation of ±0.1% is taken as uncertainty for bunch pattern dependence
Instrumentation and hardware components are probably limiting the accuracy

Additional tests performed (plots in appendix):
Sensitivity to an injected RF sine wave (laboratory measurement)
Sensitivity of bunch length and beam debunching (MD fill 30 June 2011)
Current source accuracy (calibration)

Calibration performed with precise current source

- 2 DC Current sources available: Yokogawa 7651 and GS200
- Measurement accuracy limited by lab equipment
- 4-wire setup with soldered connections

Uncertainty of ±0.05% is assumed for the current source

Tested: position of calibration rods do not influence the DCCT response
Calibration methodology and current leak

What can go wrong during the calibration?

Accuracy of current source: verified

Methodology of the calibration procedure and software: verified with independent method

Current leak between the surface racks and DCCT’s in the tunnel: same calibration with source on the surface or in the tunnel

(see all 16 plots in the appendix)
Difference between systems A and B

What was observed so far:

- **Noise level and baseline:** $O(1\text{ LSB})$
- **Baseline stability:** $O(1\text{ LSB})$
- **Scaling factor stability:** $O(1\text{ LSB})$
- **Non-linearity:** $O(1\text{ LSB})$
- **Bunch pattern dependency:** 0.1%
- **Current source accuracy:** 0.05%

In a first approximation DCCT accuracy limited by:
- Intrinsic noise level and baseline fluctuations.
- Resolution of 12-bit ADC

**DCCT Errors**

- No other systematic effect has been observed

**Independent systems A and B**

- Should agree within ±1 LSB or within expected noise fluctuations

**Analyze all injections steps** for physics fills in 2011

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2012-02-29
Colin Barschel
Difference between systems A and B

Limited by noise level

Limited by 12-bit ADC

Overall difference between systems A and B confirms accuracy observed during all studies

9 injection steps in 2011, possible cause: asynchronous range change 2->1 (not a concern)
Results

Source of uncertainties without any measurable effect

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Range</th>
<th>Relative error (%)</th>
<th>Absolute error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-talk between beams (Sec. 4.1)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Noise change during dump of other beam</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sensitivity to injected RF sine wave (Sec. 4.2.3)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>No resonance found between 1 kHz - 110 MHz</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sensitivity to LHC energy (Sec. 4.4.1)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>No correlation observed with LHC energy</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sensitivity to LHC RF system (Sec. 4.4.2)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>No correlation observed with LHC RF cavity field</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Thermal effect during 24 hours under load</td>
<td>&lt; 0.01%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>No systematic drift of day/night effect (Sec. 3.4.2)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Current leak during calibration from surface</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>No difference between the source on the surface or in the tunnel (Sec. 5.3)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Methodology of calibration procedure</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>No difference between “self” calibration and standard BI procedure (Sec. 5.3)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Seasonal fluctuations of calibration factors</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Calibrations stable within expected ADC bit accuracy, verified over 9 month (Sec. 3.6)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Off-center position of calibration rods (Sec. 5.2)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Bunch position dependence (MD)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>No dependence found with beam movement during MD (Sec. 4.3)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Bunch pattern dependence (MD)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>No dependence found during beam debunching with RF off (Sec. 4.2.2)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Results

Summary of the DCCT uncertainties given as an envelope error
Multiply final number by 0.683 to interpret as 1-σ error

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Range</th>
<th>Relative error (%)</th>
<th>Absolute error</th>
<th>Correlated btw. beams</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current source precision</td>
<td></td>
<td>± 0.05%</td>
<td>± 1 · 10^9 e</td>
<td>yes</td>
</tr>
<tr>
<td>Baseline correction</td>
<td>1</td>
<td>(± 6 · 10^10 e)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>(± 7 · 10^9 e)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>(± 4 · 10^9 e)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>(± 4 · 10^9 e)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-linearity of 12-bit ADC</td>
<td></td>
<td>± 1 LSB</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>Long term stability of baseline</td>
<td>1</td>
<td>± 1.1 · 10^11 e</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>± 1.0 · 10^10 e</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>± 2.4 · 10^9 e</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>± 2.3 · 10^9 e</td>
<td></td>
<td></td>
</tr>
<tr>
<td>observed fluctuations within 2 × 12 hours</td>
<td>1</td>
<td>(± 7.3 · 10^9 e)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>(± 1.1 · 10^9 e)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>(± 1.1 · 10^9 e)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>(± 1.0 · 10^9 e)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long term stability of calibration</td>
<td>1,2,3</td>
<td>± 1 LSB</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>envelope observed within 8 month (Sec. 3.6)</td>
<td>4</td>
<td>± 4 LSB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bunch pattern dependence (laboratory test)</td>
<td></td>
<td>±0.1%</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>accuracy limited by instrumentation (Sec. 4.2.1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Difference between system A and B</td>
<td>1,2,3</td>
<td>± 1 LSB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>observed during all physics injections 2011</td>
<td>4</td>
<td>± 10 LSB</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The highest accuracy is reached with ranges 1-3 close to the calibration point
Conclusion

• The studies allow us to better understand the DCCT uncertainties and exclude many possible sources of error
• With ideal conditions (e.g. during a van der Meer fill) the DCCT uncertainties are reduced down to 0.2% per beam or 0.34% on the beam product
• The DCCT uncertainties are not dominating the luminosity error anymore

• A new 24-bit acquisition system is now installed and will acquire the DCCT in parallel to the present system in 2012 (still in test mode but useful for comparison).
Additional plots (appendix)
Examples

**Example fill 1783**
Total intensity \( \approx 3.2 \times 10^{12} \) protons
Acquired in range 3

**Example of low intensity fill**
Total intensity \( \approx 4 \times 10^{10} \) protons
Acquired in range 4

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### Example fill 1783

<table>
<thead>
<tr>
<th>Source of uncertainty (per beam)</th>
<th>Relative error (%)</th>
<th>Correlated btw. beams</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current source precision</td>
<td>± 0.05</td>
<td>yes</td>
</tr>
<tr>
<td>Bunch pattern dependence (laboratory test)</td>
<td>± 0.1</td>
<td>yes</td>
</tr>
<tr>
<td>Non-linearity of 12-bit ADC</td>
<td>± 0.08</td>
<td>yes</td>
</tr>
<tr>
<td>Baseline correction</td>
<td>± 0.03</td>
<td>no</td>
</tr>
<tr>
<td>Long term stability of baseline on range 3</td>
<td>± 0.08</td>
<td>no</td>
</tr>
<tr>
<td>Long term stability of calibration on range 3</td>
<td>± 0.08</td>
<td>no</td>
</tr>
<tr>
<td>Difference between system A and B on range 3</td>
<td>± 0.08</td>
<td>no</td>
</tr>
</tbody>
</table>

**Total error per beam** ± 0.20
**Correlated error per beam** (± 0.138) yes
**Uncorrelated error per beam** (± 0.143) no

**Total error on beam product** ± 0.34

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### Example of low intensity fill

<table>
<thead>
<tr>
<th>Source of uncertainty (per beam)</th>
<th>Relative error (%)</th>
<th>Correlated btw. beams</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current source precision</td>
<td>± 0.05</td>
<td>yes</td>
</tr>
<tr>
<td>Bunch pattern dependence (laboratory test)</td>
<td>± 0.1</td>
<td>yes</td>
</tr>
<tr>
<td>Non-linearity of 12-bit ADC</td>
<td>± 0.63</td>
<td>yes</td>
</tr>
<tr>
<td>Baseline correction</td>
<td>± 2.50</td>
<td>no</td>
</tr>
<tr>
<td>Long term stability of baseline on range 4</td>
<td>± 2.5</td>
<td>no</td>
</tr>
<tr>
<td>Long term stability of calibration on range 4</td>
<td>± 2.5</td>
<td>no</td>
</tr>
<tr>
<td>Difference between system A and B on range 4</td>
<td>± 6.25</td>
<td>no</td>
</tr>
</tbody>
</table>

**Total error per beam** ± 7.6
**Correlated error per beam** (± 0.63) yes
**Uncorrelated error per beam** (± 7.6) no

**Total error on beam product** ± 10.8
The DCCT system
DCCT baseline subtraction method defined in note CERN-ATS-Note-2011-004 used in 2010

- random time position with 9 days of data
- random gap length 1h – 40h
- $I_{\text{measured}} = 1h$ window (centered in gap)
- Offset calculation: 2h before and after gap
  $$I_{\text{interpolated}} \pm \text{P2P error}$$

Method is reasonable:
79% of interpolated < 1 sigma error
Automatic offset correction

DCCT offset after dump (range 1)

DCCT offset after dump (range 2)

DCCT offset after dump (range 3)

DCCT offset after dump (range 4)
Linearity with alternate ADC

Compare DCCT linearity with alternate ADC

Reference response of NI ADC:
For each equivalent DCCT range use equivalent source current and ADC voltage (with appropriate resistance)
e.g. Range 1:
Source current = 0 – 200 mA
NI ADC voltage ≈ 0 – 5 V (R = 25 Ω)

Acquire linearity measurement with two ADCs:
• LHC ADC (default 12 bit)
• NI ADC 16 bit
• Compare NI vs. DCCT measurement

DCCT follows lab reference
⇒ Non-linearity due to 12 bit ADC
24-bit scaling factor

DCCT scaling factors sys A beam 1

DCCT scaling factors sys A beam 2

DCCT scaling factors sys B beam 1

DCCT scaling factors sys B beam 2

Fit: 61286000; $\chi^2$/DoF:1.6
Fit error: $\pm 7800$
$\pm 0.1$
measurement 1
measurement 2
measurement 3

Fit: 61434000; $\chi^2$/DoF:1.8
Fit error: $\pm 7800$
$\pm 0.1$
measurement 1
measurement 2
measurement 3

Fit: 61356000; $\chi^2$/DoF:2.9
Fit error: $\pm 7800$
$\pm 0.1$
measurement 1
measurement 2
measurement 3

Fit: 61454000; $\chi^2$/DoF:0.51
Fit error: $\pm 7800$
$\pm 0.1$
measurement 1
measurement 2
measurement 3
Calibration system B

Absolute scale calibration (system B beam 1)

Absolute scale calibration (system B beam 2)
RF switched off: beam fully unbunched after ≈10 minutes (FBCT drops to zero)
DCCT signal is unaffected by bunch structure
Interference with LHC magnets

![Graphs showing interference with LHC magnets.](image-url)
Study interference with LHC RF cavity field for physics fills in 2011

No difference in offset \( R_{\text{fon}} - R_{\text{off}} \) (using 86 fills with a clear RF step)
Bunch pattern setup

Setup (lab DCCT, new electronics/HF by-pass):
• Inject different bunch pattern trough DCCT beam pipe
• Pattern with $\nu=11$ kHz creates current $>0$ seen by DCCT
• Acquire average current as INPUT (voltage over 50 $\Omega$)
• Acquire DCCT signal as OUTPUT

Verify ratio $I_{\text{pattern}}/I_{\text{DCCT}}$ = constant for all pattern

1 LHC revolution 0.089 ms

One revolution 1/11245 s
Verify DCCT sensitivity to RF
1 circulating bunch can be shown as RF wave (next slide)

Inject RF trough DCCT with coaxial antenna
• Current visible by DCCT = zero (AC current)
• Frequency sweep to detect possible resonances
• Sweep is logarithmic (more time at low frequencies)
• 1 kHz – 250 kHz at ≈ 30 mW (unamplified)
• 250 kHz – 110 MHz at ≈ 10 W

Is injected RF power comparable to a single bunch?
Next slide: compare RF power to bunch intensity
RF power to bunch size

Suppose 1 bunch with

\[ T = \frac{1}{\nu_{rev}}; \quad Q = N \cdot e; \quad \sigma_t = \frac{\sigma_z}{c} \]

\[ I(t) = Q \cdot \sum_{n=-\infty}^{\infty} \frac{1}{\sqrt{2\pi}\sigma_t} e^{-\frac{(t-nT)^2}{2\sigma_t}} \]

\[ I(\nu) = Q \cdot \nu_{rev} \cdot e^{-\nu^2 \cdot \sigma_t^2 \cdot 2\pi^2} \sum_{k=-\infty}^{\infty} \delta(\nu - k\nu_{rev}) \]

\[ I_{RF}(t) = I_{peak} \cdot \cos(2\pi\nu_0 t) \]

\[ I_{RF}(\nu) = I_{peak} \cdot \frac{1}{2} (\delta(\nu - \nu_0) + \delta(\nu + \nu_0)) \]

\[ I_{peak} = \sqrt{2} \cdot I_{RMS} = \sqrt{\frac{2P}{R}} \]

\[ Q \cdot \nu_{rev} \approx \frac{1}{2} I_{peak} \]

\[ N_{10W} \approx \frac{0.6}{2} \cdot \frac{1}{10^4} \cdot \frac{1}{1.6 \cdot 10^{-19}} \approx 1.6 \cdot 10^{14} \text{ protons} \]

\[ N_{30mW} \approx \frac{35 \cdot 10^{-3}}{2} \cdot \frac{1}{10^4} \cdot \frac{1}{1.6 \cdot 10^{-19}} \approx 10^{12} \text{ protons} \]
• No resonance found between
• 1 kHz – 110 MHz
• Deviation from zero (or 80 mA) is compatible with noise level

$I=0$
(most sensitive range 4)

$I=80$ mA range 2