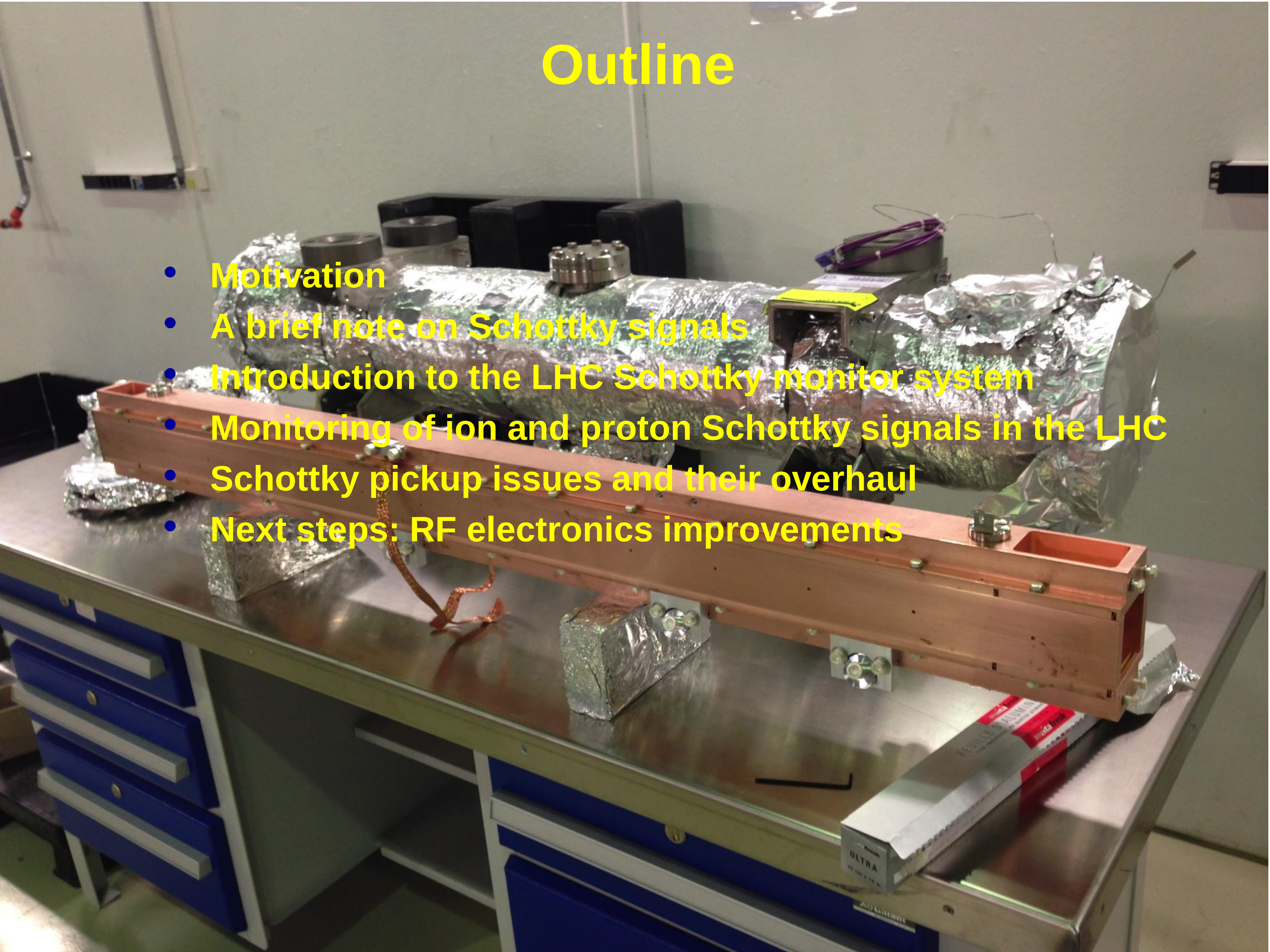
The LHC Schottky Monitor

– Review June 2014 –

Michael Betz

Manfred Wendt

BE-BI-QP



Outline

- Motivation
- A brief note on Schottky signals
- Introduction to the LHC Schottky monitor system
- Monitoring of ion and proton Schottky signals in the LHC
- Schottky pickup issues and their overhaul
- Next steps: RF electronics improvements

Motivation for Schottky Signal Monitoring: Beam Parameter Characterization

- **The Schottky signals allow to characterize some transverse beam parameters in a non-invasive way:**
  - **Incoherent Tune**

    $$q = \frac{1}{2} + \frac{f_2 - f_1}{2 f_{rev}}$$

  - **Momentum spread**

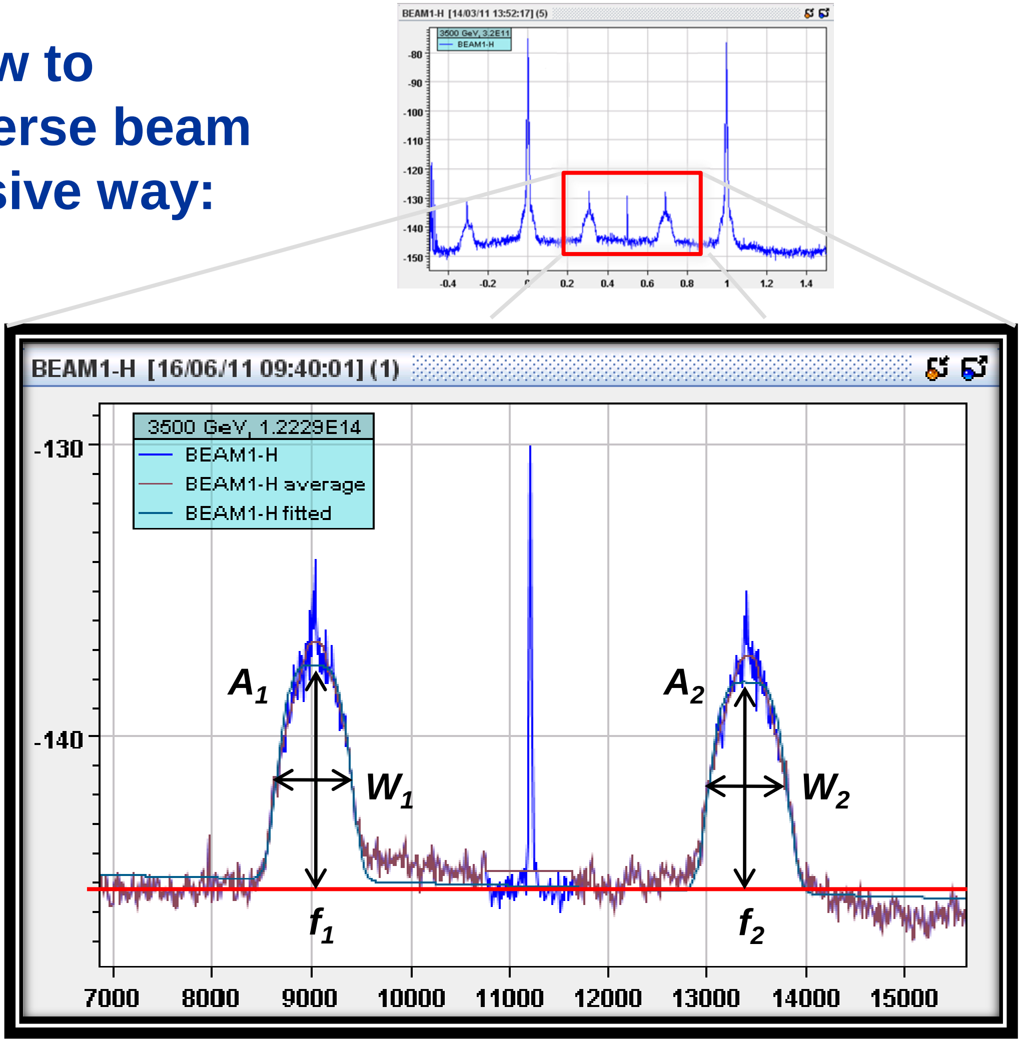
    $$\frac{\Delta p}{p} = \frac{1}{\eta} \frac{W_1 + W_2}{2 h f_{rev}}$$

  - **Chromaticity**

    $$\xi \propto \frac{W_1 - W_2}{W_1 + W_2}$$

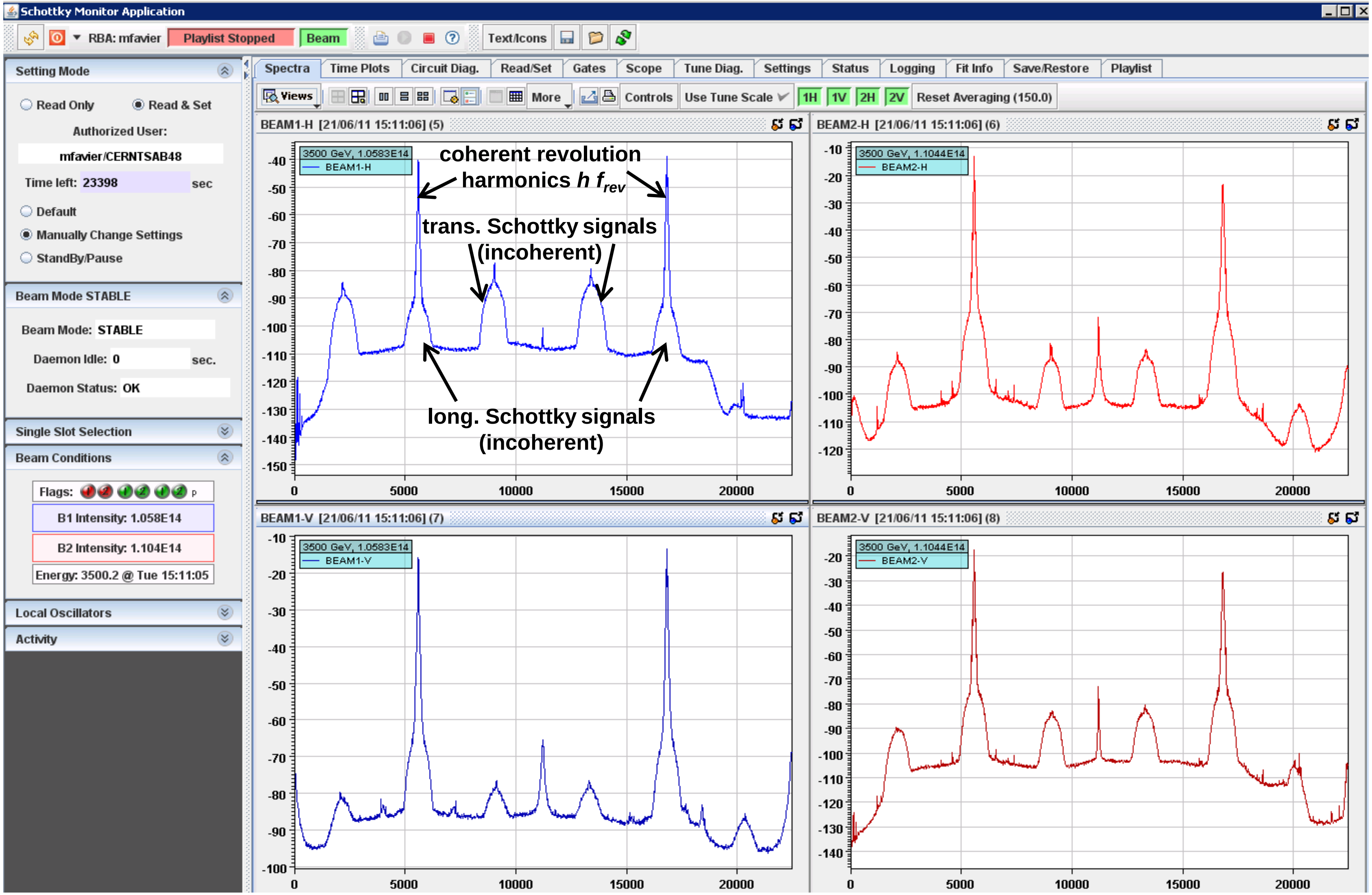
  - **Emittance**

    $$\varepsilon \propto A_1 W_1 + A_2 W_2$$



Zoom of the LHC proton Schottky signals (B1H, stable beam)

Typical Schottky Signals in 2010



Schottky Monitor Application

RBA: mfavier

Setting Mode

○ Read Only ● Read & Set

Authorized User: mfavier/CERNTSAB48

Time left: 23398 sec

○ Default

● Manually Change Settings

○ StandBy/Pause

Beam Mode STABLE

Beam Mode: STABLE

Daemon Idle: 0 sec.

Daemon Status: OK

Beam Conditions

B1 Intensity: 1.058E14

B2 Intensity: 1.104E14

Energy: 3500.2 @ Tue 15:11:05

Reset Averaging (150.0)

BEAM1-H [21/06/11 15:11:06] (5)

BEAM2-H [21/06/11 15:11:06] (6)

BEAM1-V [21/06/11 15:11:06] (7)

BEAM2-V [21/06/11 15:11:06] (8)

coherent revolution harmonics $h\ f_{rev}$

trans. Schottky signals (incoherent)

long. Schottky signals (incoherent)

Bunched Beam long. Schottky Signals

- **Time difference τ to the synchronous particle (*f_{rev}*) due to synchrotron motion of *$n=1\dots N$* particles:**

random amplitude

$$\tau_n(t) = \hat{\tau}_n \sin(2\pi f_s t + \Psi_n)$$

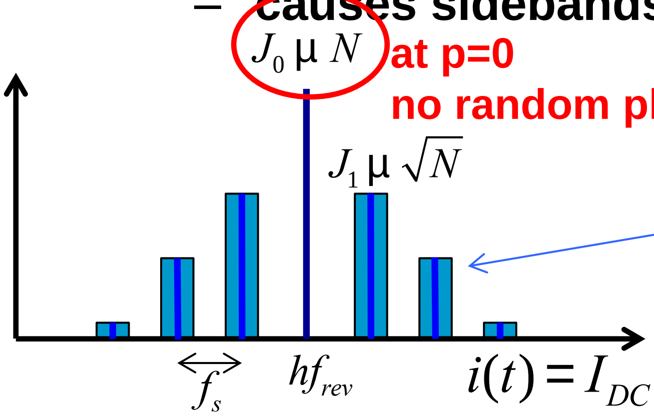
random phase

- **Schottky signal of the *n*th particle under phase modulation**

$$i_n(t) = zef_{rev} + 2zef_{rev}\sum_{h=0}^{\infty}\cos\{2\pi h f_{rev}[t - \hat{\tau}\sin(2\pi f_s t + \Psi)]\}$$

  - **causes sidebands around each *$h\,f_{rev}$* for bunched beams**

$$i_n = 2I_{DC}\sum_{n=1}^{N}\sum_{p=-\infty}^{\infty} J_p(2\pi h f_{rev}\hat{\tau}_n)\cos(2\pi h f_{rev} + 2\pi f_s t + p\Psi_n)$$



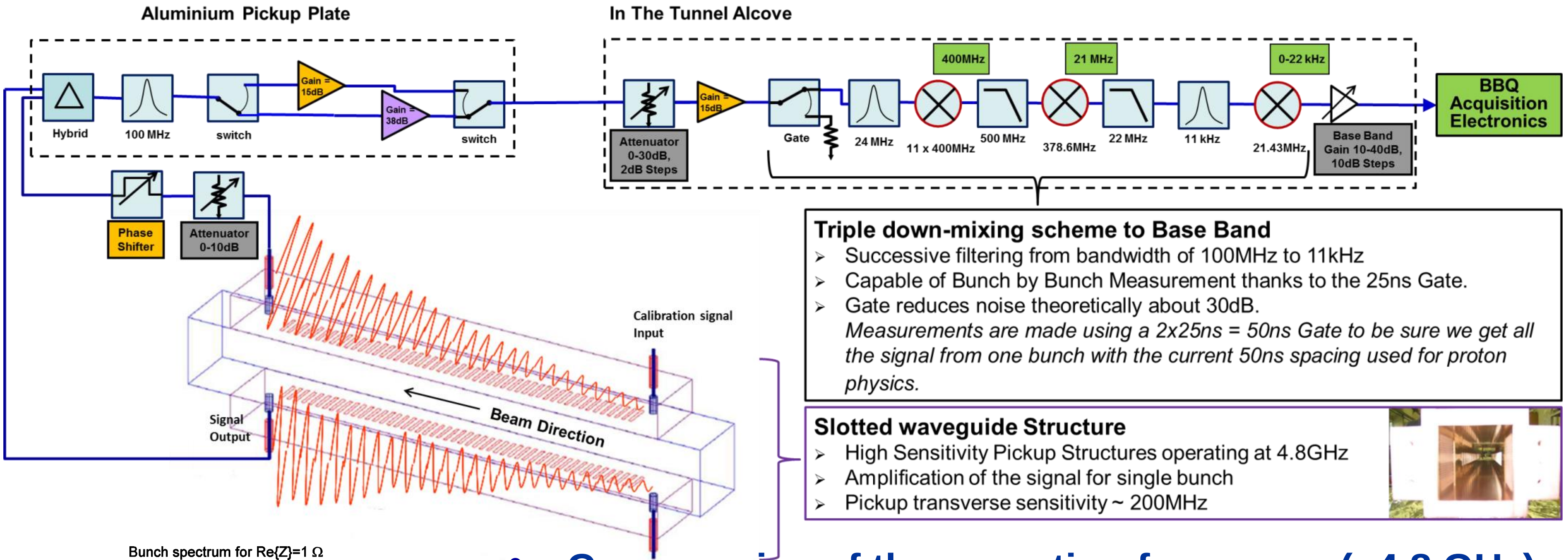
at p=0
no random phase!

Lines may broaden due to spread of f_s

$$I_{DC} = Nzef_{rev}$$

$$i(t) = I_{DC} + 2I_{DC}\sum_{h=1}^{\infty}\sum_{n-1}^{N}\sum_{p=-\infty}^{\infty} J_p(2\pi h f_{rev}\hat{\tau}_n)\cos(2\pi h f_{rev} t + 2\pi p f_s t + p\Psi_n)$$

LHC Schottky Monitor System

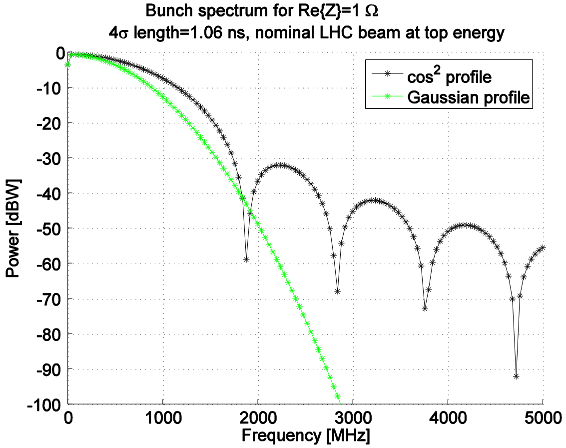


Triple down-mixing scheme to Base Band

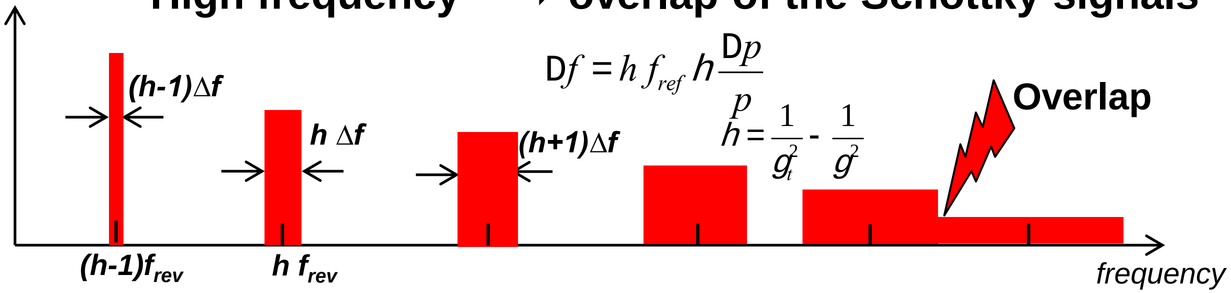
- Successive filtering from bandwidth of 100MHz to 11kHz
- Capable of Bunch by Bunch Measurement thanks to the 25ns Gate.
- Gate reduces noise theoretically about 30dB.
  Measurements are made using a 2x25ns = 50ns Gate to be sure we get all the signal from one bunch with the current 50ns spacing used for proton physics.

Slotted waveguide Structure

- High Sensitivity Pickup Structures operating at 4.8GHz
- Amplification of the signal for single bunch
- Pickup transverse sensitivity ~ 200MHz



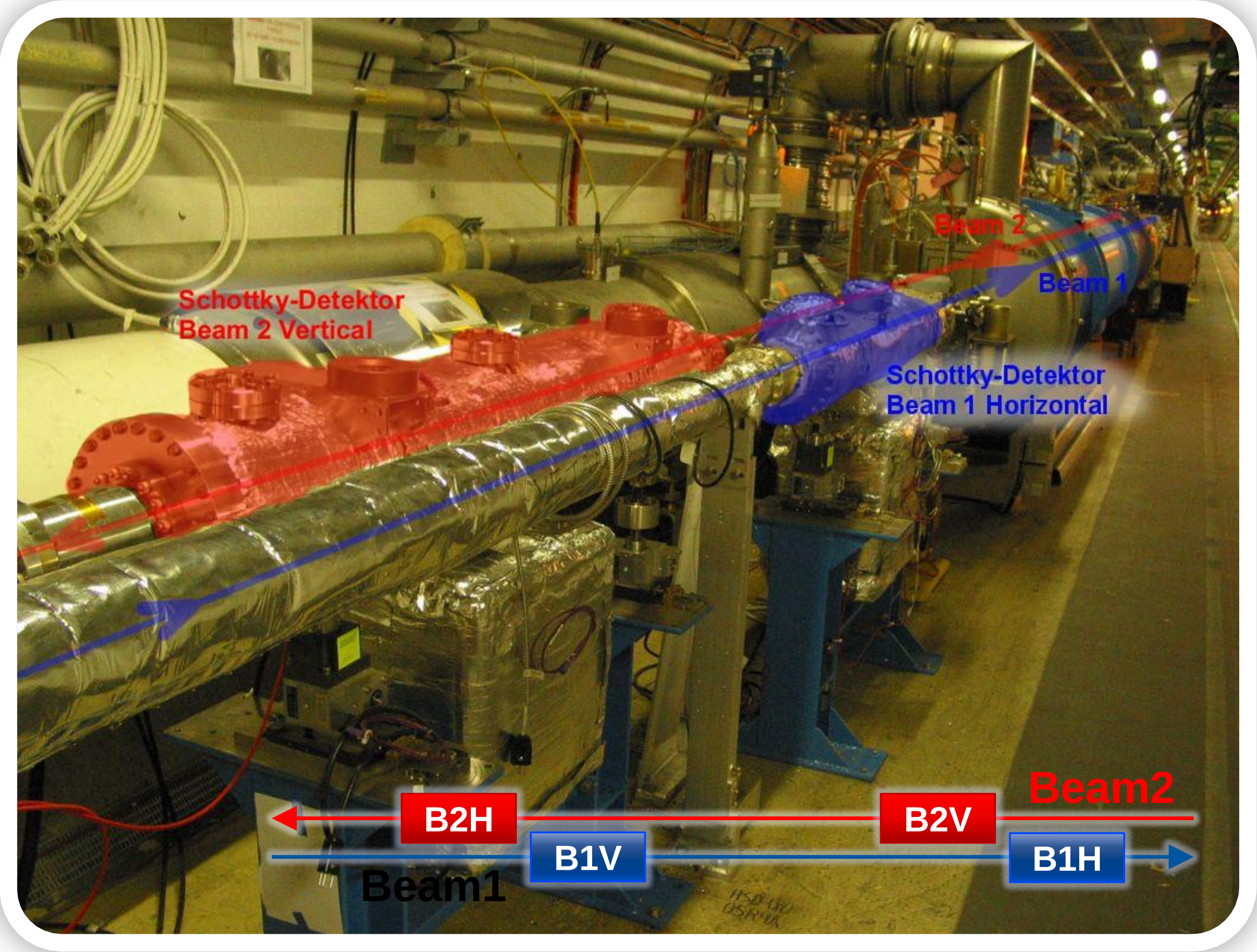
- **Compromise of the operation frequency (~4.8 GHz):**
  - **Low frequency ⟶ high level coherent signals**
  - **High frequency ⟶ overlap of the Schottky signals**



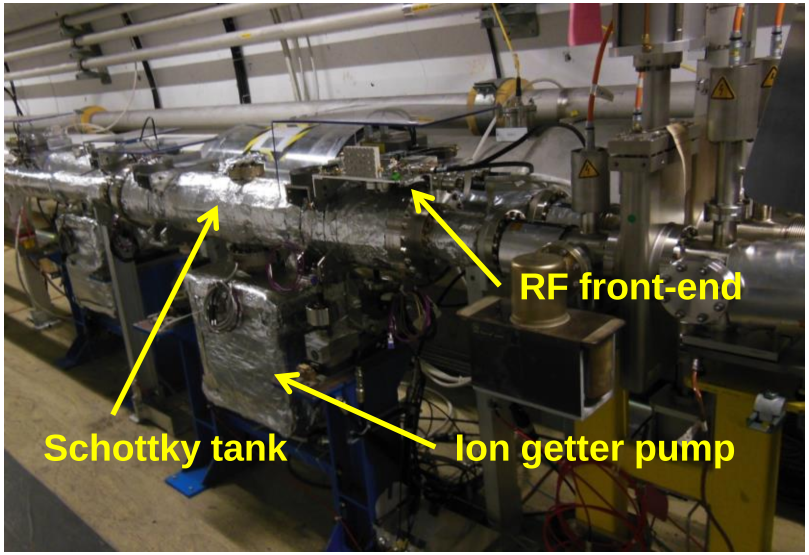
$$\Delta f = h f_{ref} \eta \frac{\Delta p}{p}$$

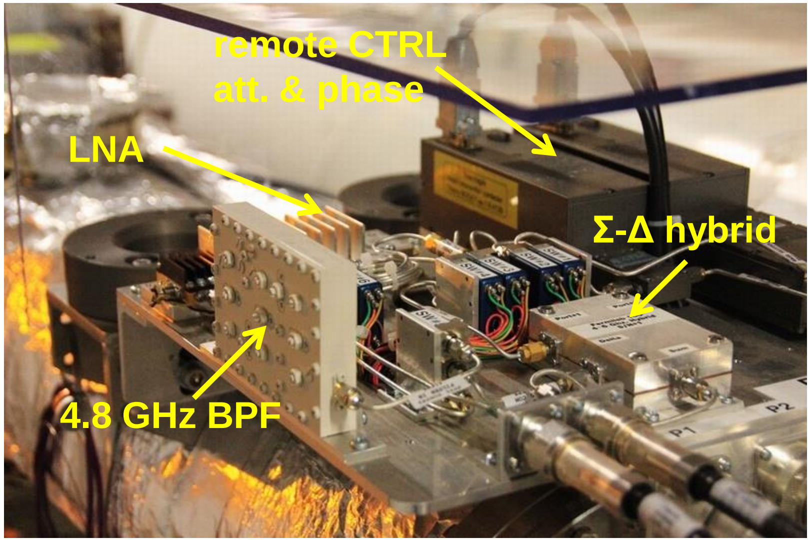
$$\eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}$$

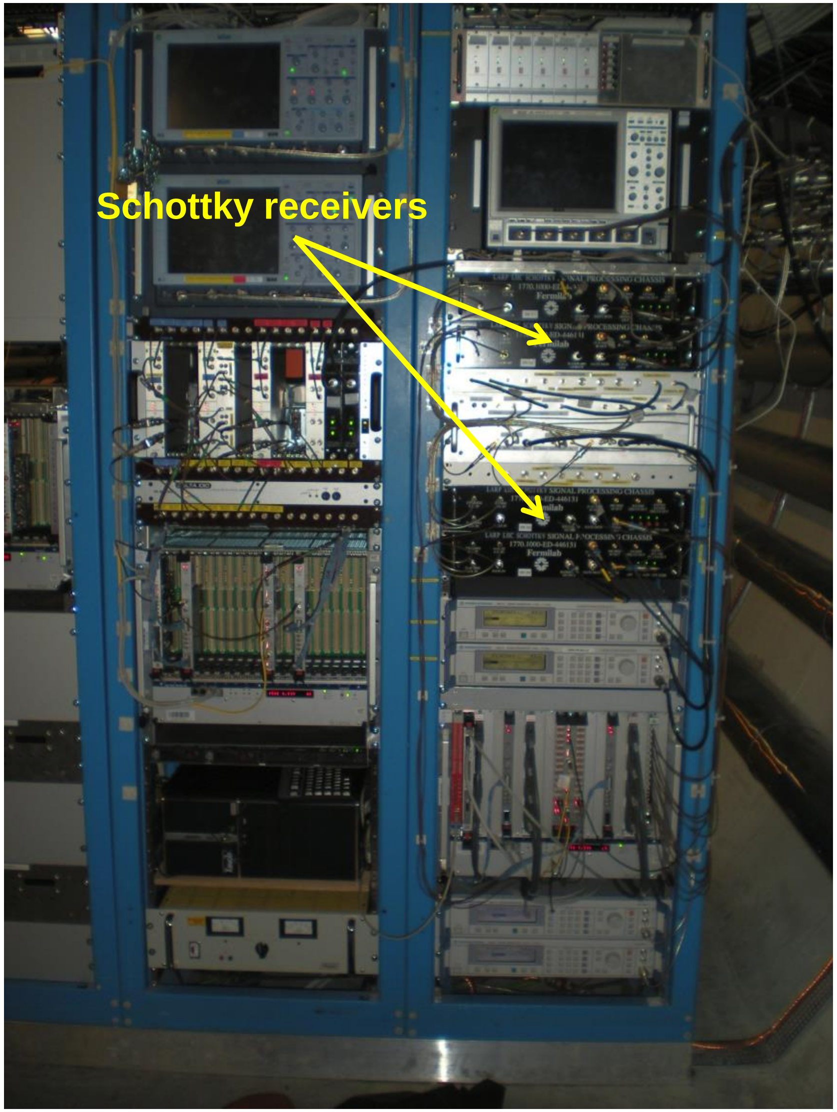
Schottky Monitor Hardware



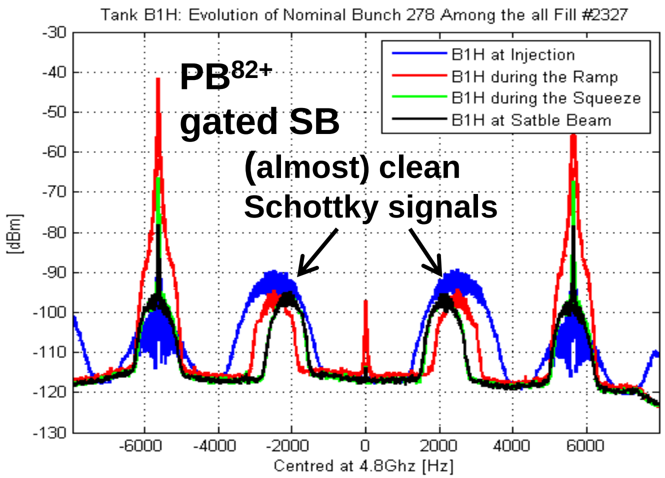
Schottky Monitor Hardware (cont.)





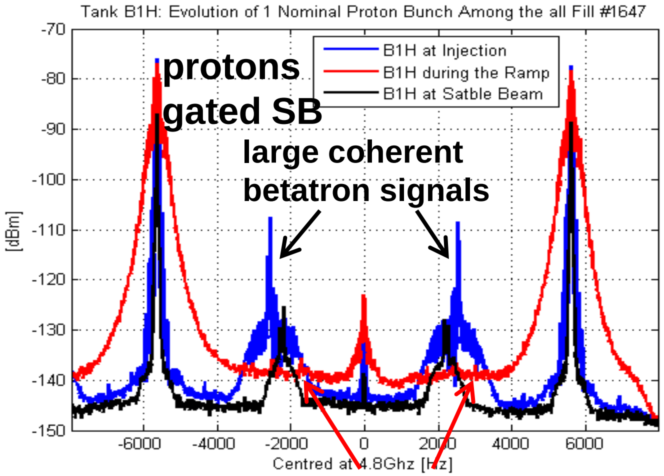


LHC Schottky Signals



PB^{82+} gated SB

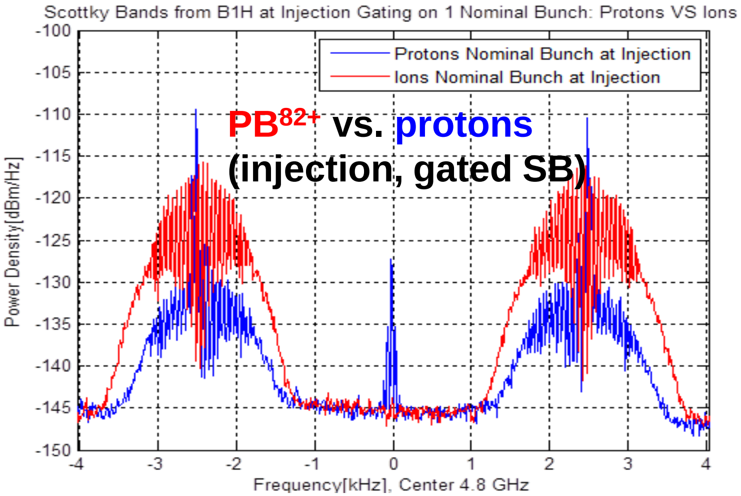
(almost) clean Schottky signals



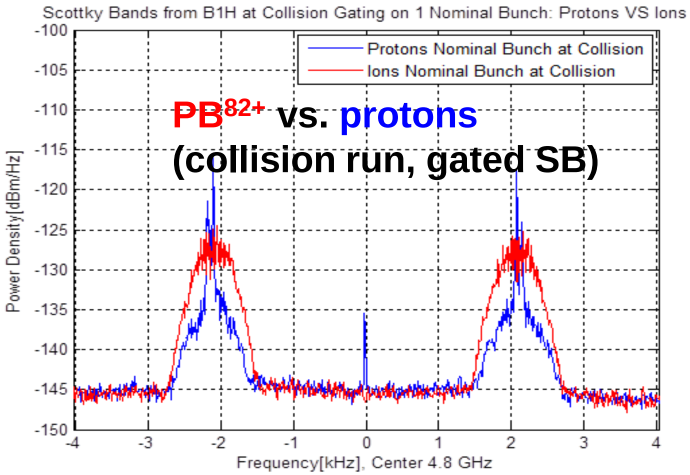
protons gated SB

large coherent betatron signals

no Schottky signals during the ramp!

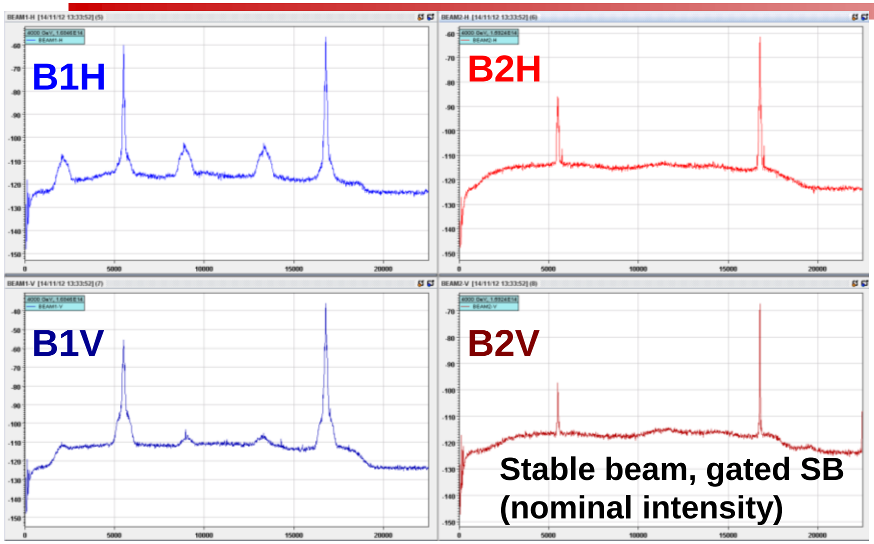


PB^{82+} vs. protons (injection, gated SB)

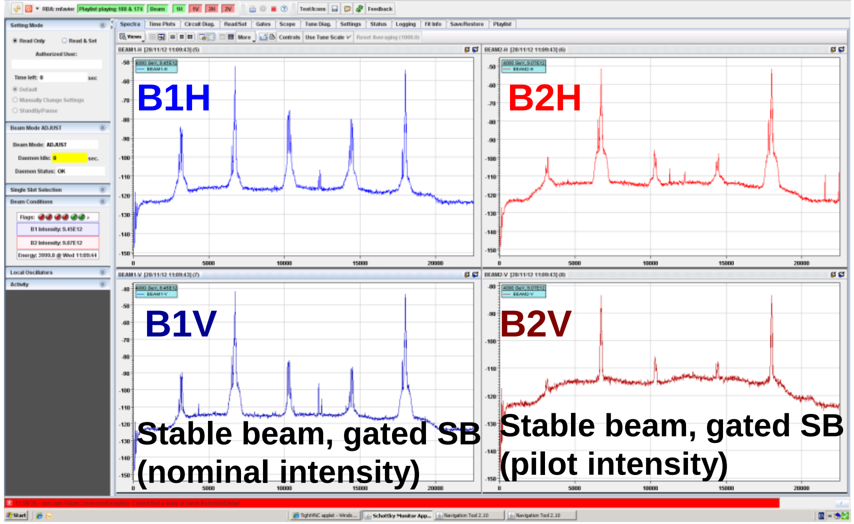


PB^{82+} vs. protons (collision run, gated SB)

Proton Schottky Signals Nov. 2012

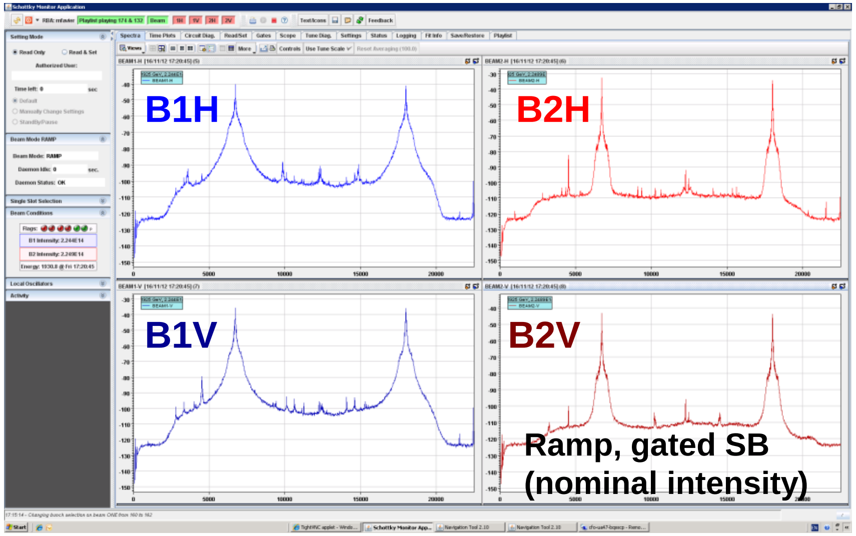


Stable beam, gated SB
(nominal intensity)

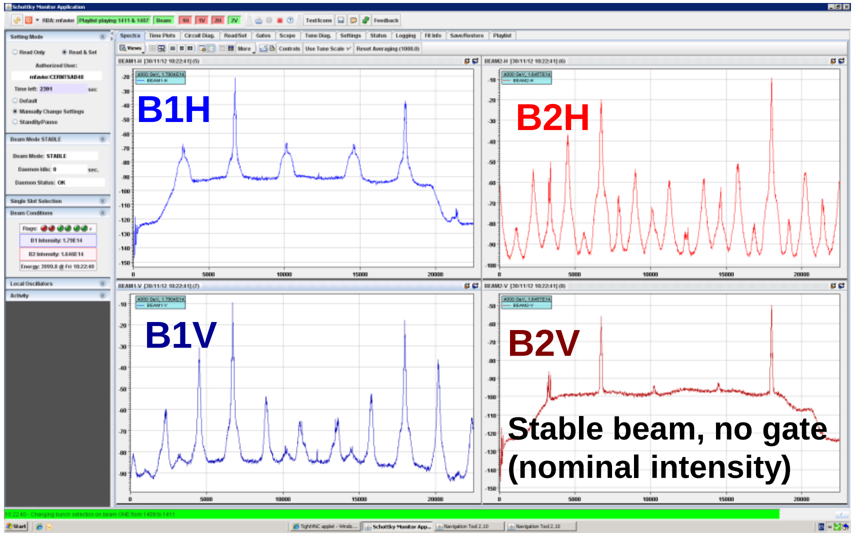


Stable beam, gated SB
(nominal intensity)

Stable beam, gated SB
(pilot intensity)



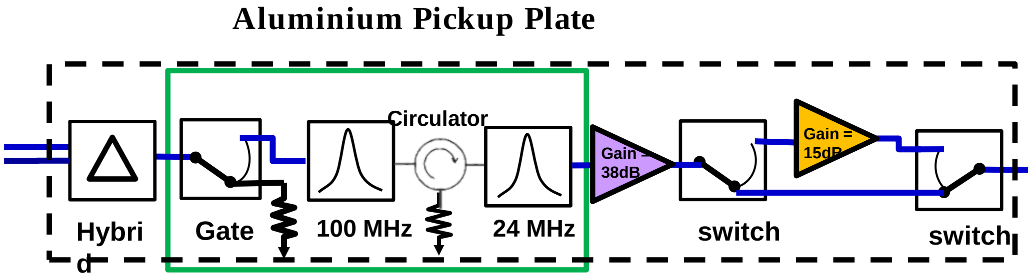
Ramp, gated SB
(nominal intensity)

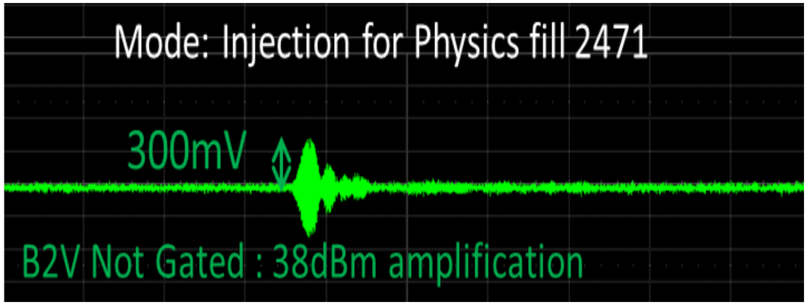


Stable beam, no gate
(nominal intensity)

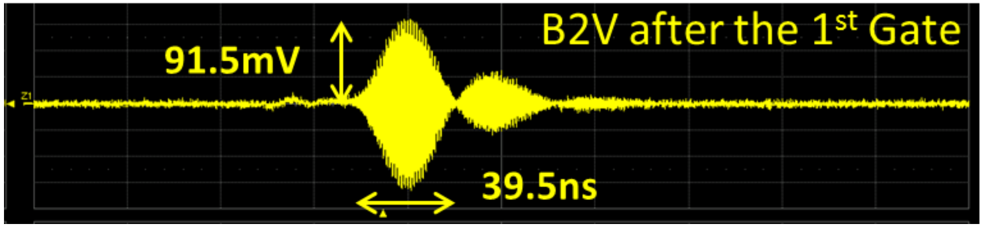
Modifications of B2V

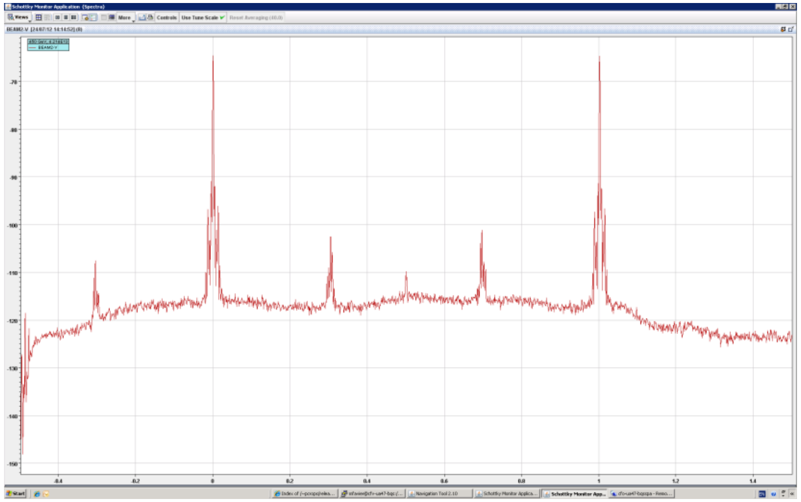
- Additional gate switch
- Additional BPF
  - Improve S/N and avoid VNA saturation





- Time domain signals before and after modification
  - Proton bunch at injection
  - Coherent signal level reduction factor 3x



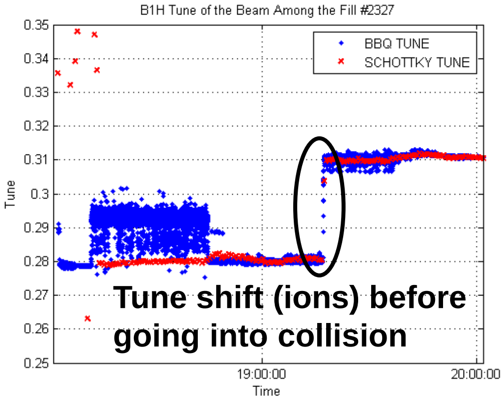


- Reduced coherent signal levels
  - By ~15…20 dB
- No S/N improvement
  - No Schottky signals visible

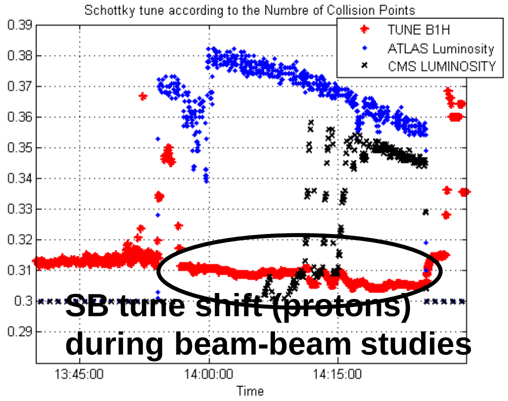
Observations

- Clean, reliable Schottky signal observed for PH^{82+} ions under all conditions
  - Signal power scales with the charge: z=82
  - No longitudinal RF gymnastics on the ramp
- Proton Schottky signals are (too) low,
  and suffer from high coherent signal contents
  - Large coherent revolution and betatron harmonics
    - ➢ Saturate and degrade front end VNA
  - No Schottky signal on the ramp and 1st part of the collision run
    - ➢ Schottky signals vanish due to controlled long. beam blow-up
- Proton Schottky signals turn out to be unreliable
  - Large signal variations from run to run
  - Monitor B1H shows the best behavior,
    the other pickups show insufficient S/N ratio.
  - Tuning of amplitude & phase balance was limited to B1H
    - ➢ The optimized balance is very narrow band
- RF front-end modifications show some improvement
  - Modifications on the B2V gating reduced the coherent signal levels
    - ➢ However, no significant S/N improvement
  - Replacement of B2H VNA improved the S/N ratio
    - ➢ Verified with NF measurement.

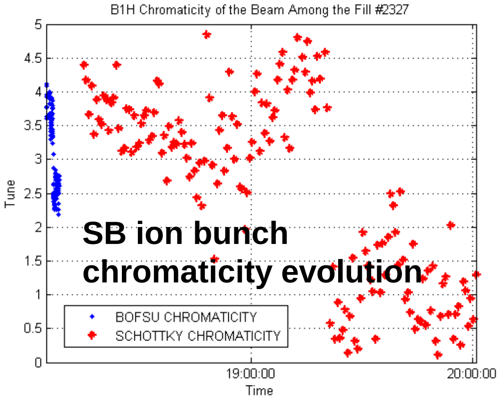
Beam Parameter Monitoring



Tune shift (ions) before going into collision



SB tune shift (protons) during beam-beam studies

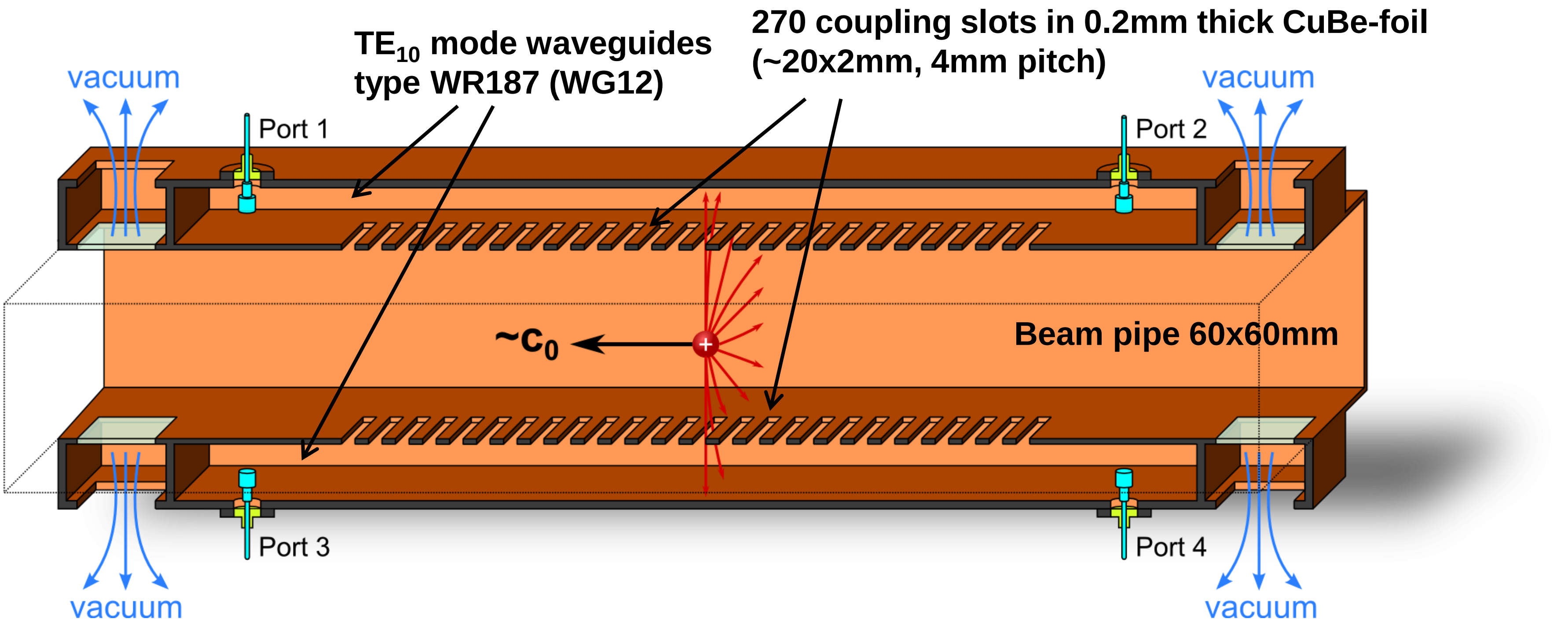


SB ion bunch chromaticity evolution

- **Successful monitoring of ion beam parameters**
  - **Single bunch tune and chromaticity observations**
  - **Slow update rate due to high averaging needs**
- **Limitation of the monitoring of proton beam parameters**
  - **Successful single bunch tune observations**
  - **No data during ramp!**
  - **Requires better S/N ratio of the hardware**
- **Need more flexibility on fitting routines**
  - **E.g. change of frequencies, span, amplitudes, and other settings**

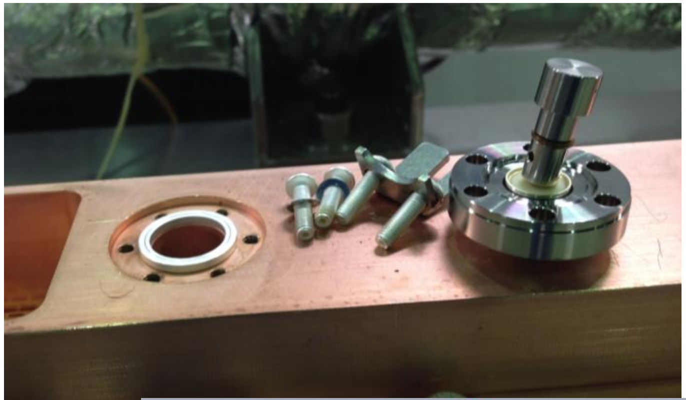
Schottky Pickup

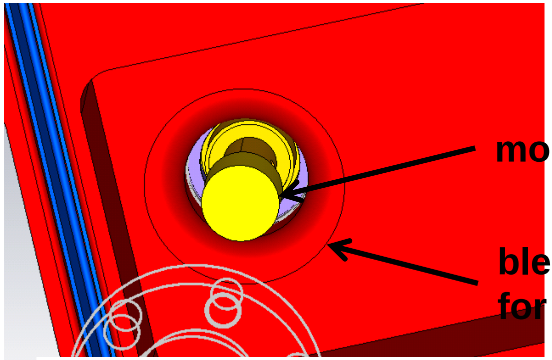
- **Forward hybrid waveguide coupler**
  - **TEM beam field excites TE_{10} WG mode**
- **Symmetric arrangement of horizontal / vertical couplers**
  - **Any asymmetry will degrade the performance, i.e. limit the common mode suppression!**
- **Waveguide-to-coaxial couplers: Signal output ports 1 & 3**
  - **Ports 2 & 4 are used for calibration and test signals**



Pickup Issue: WG-Coax Coupler

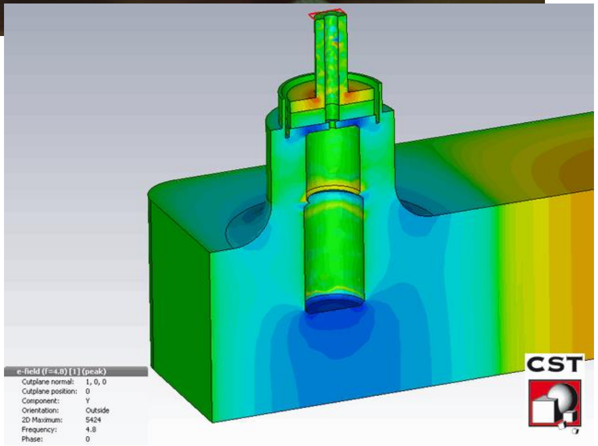
- **Waveguide-to-coaxial coupler has large return losses (S11)**
  - **Partially fixed during initial assembly**
  - **Redesign of the WG-coaxial coupler (Ms.Sc. thesis Matthias Ehret)**



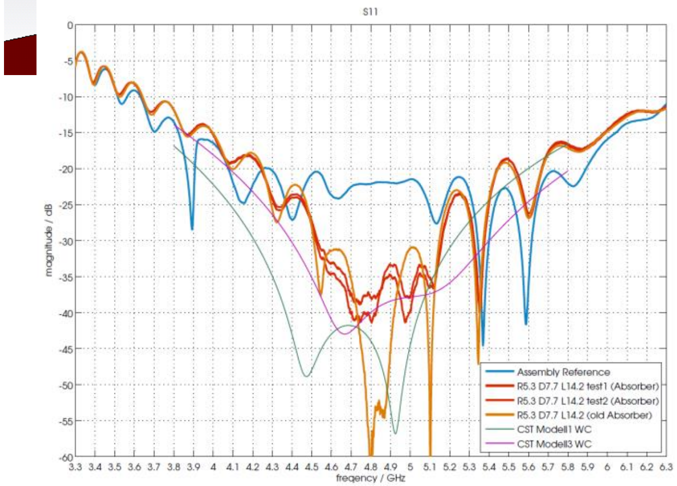


modified pin extension

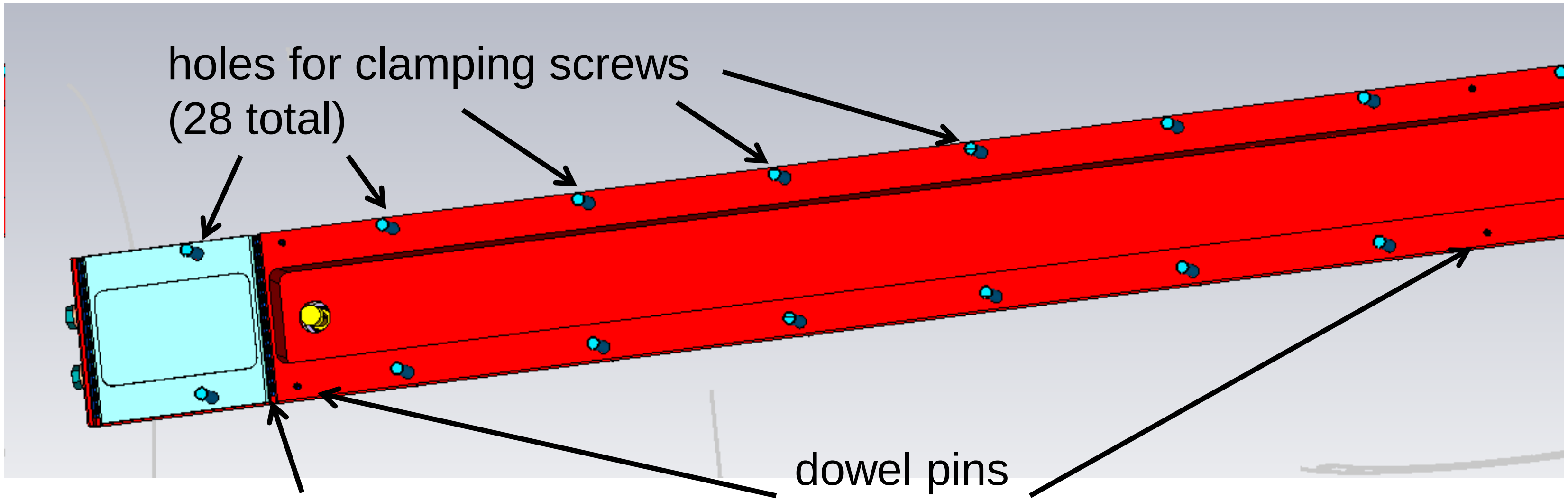
blended through hole for feedthrough



e-field (f=4.8) [1] (peak)
Cutplane normal: 1, 0, 0
Cutplane position: 0
Component: Y
Orientation: Outside
2D Maximum: 5424
Frequency: 4.8
Phase: 0



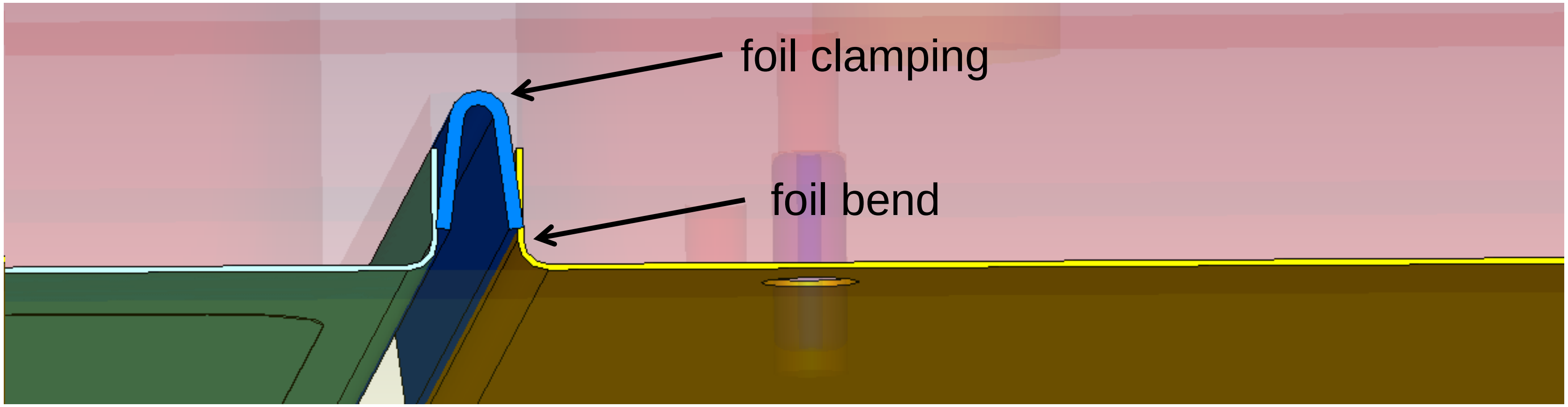
Pickup Issue: Warped Foil



holes for clamping screws
(28 total)

foil clamping
groove

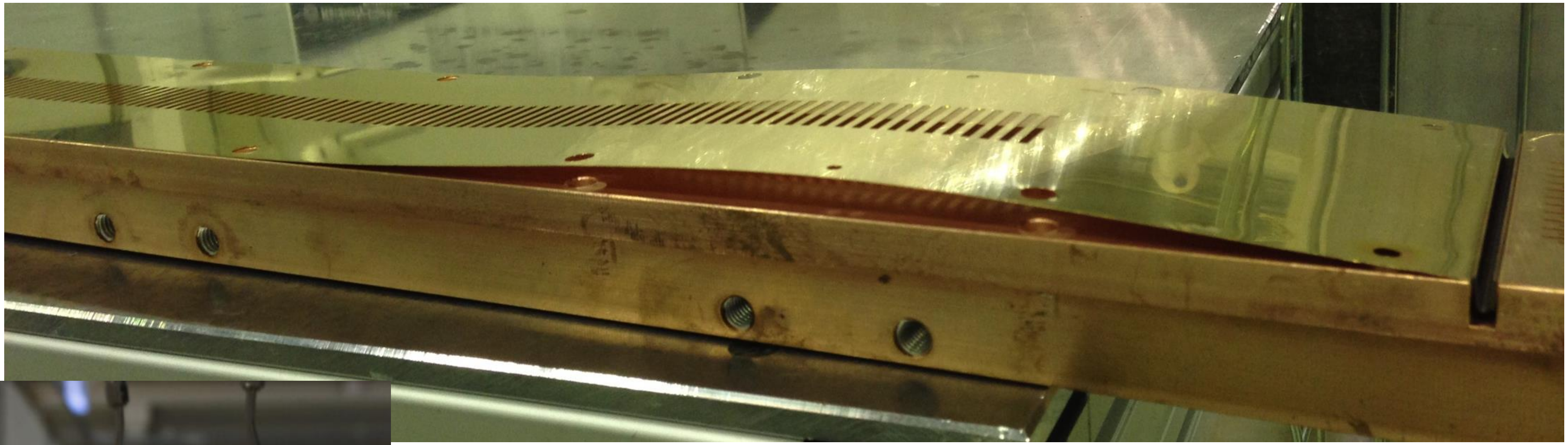
dowel pins
(6 total)



foil clamping

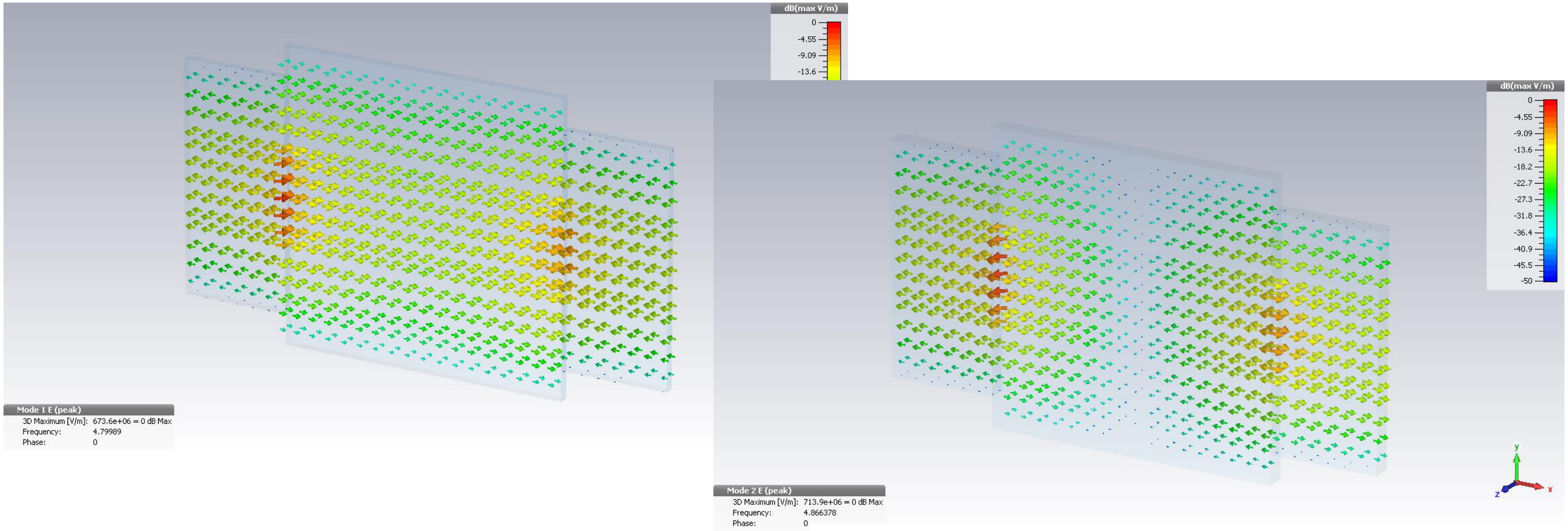
foil bend

Pickup Issue: Warped Foil (cont.)



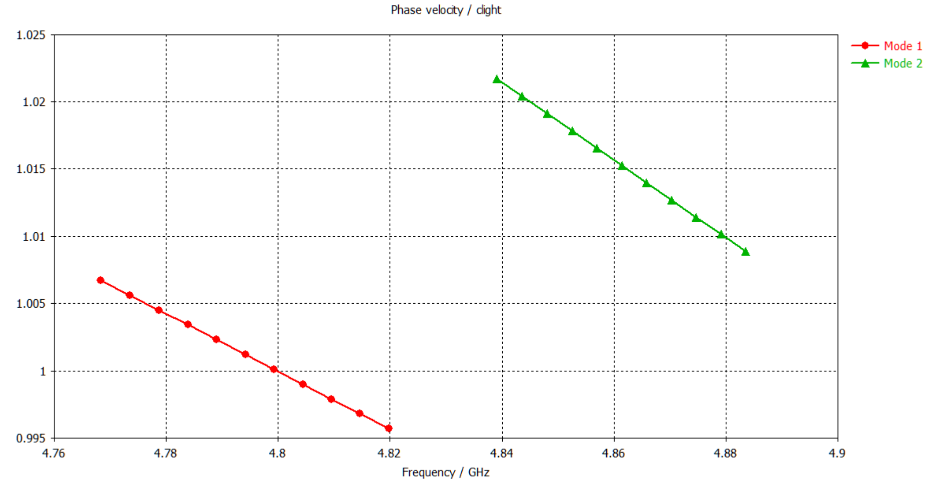
- **Seems to be caused by elongation of the foil during bake-out:**
  - **Thermal expansion coefficient (µm/m/K)**
    SS 316L: 16.2 (original design)
    AlSi1MgMn: 23.4 (LHC)
    CuBe foil: 17.0
  - **(AlSiMgMn – CuBe) x 1.4m x 150 K = 1.3 mm**

Verify EM Analysis



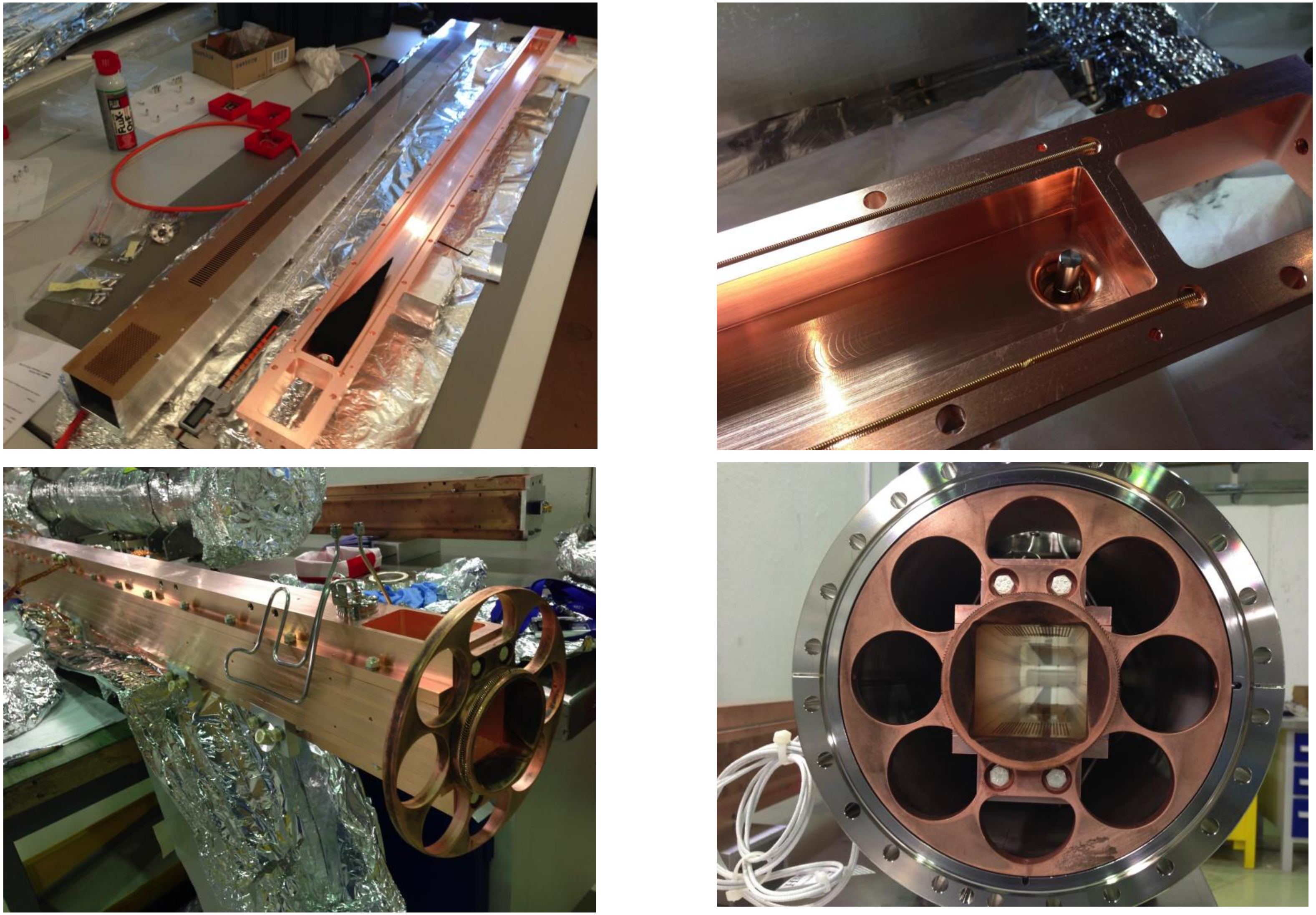
Mode 1 E (peak)
3D Maximum [V/m]: 673.6e+06 = 0 dB Max
Frequency: 4.79989
Phase: 0

Mode 2 E (peak)
3D Maximum [V/m]: 713.9e+06 = 0 dB Max
Frequency: 4.866378
Phase: 0



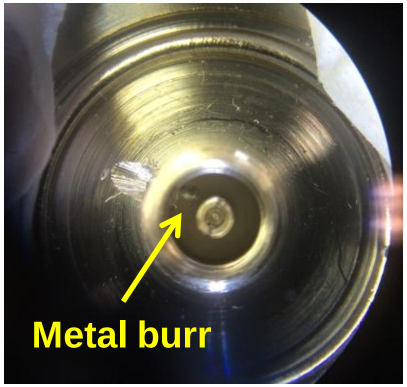
- **Eigenmode analysis**
  - **Single cell, periodic boundaries**
  - **Adapt slot dimensions**
    - Δ-mode: $v_p=c_0$ @ 4.8GHz
    - Single cell phase advance (23.06^0) matched to TE10 WG-mode

Schottky Pickup Remanufacturing



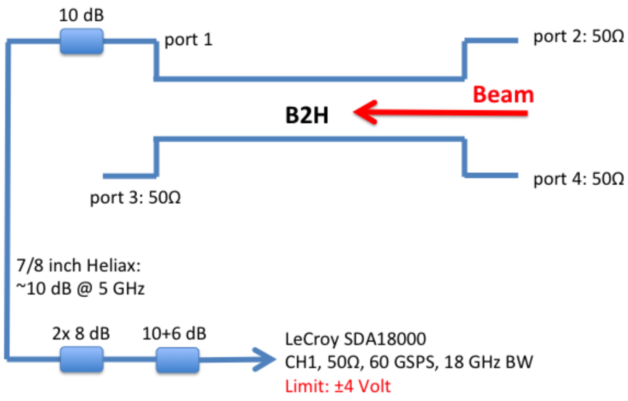
Pickup Status

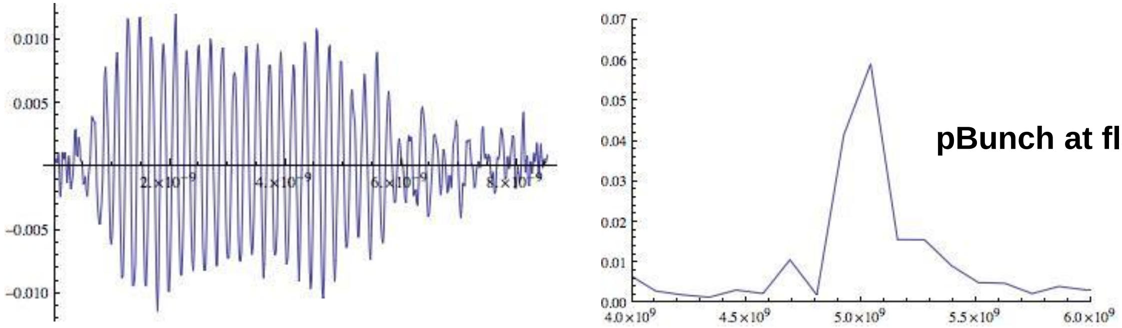
- **All four Schottky beam pickups have been remanufactured**
  - **All waveguide and beampipe parts made out of Cu**
    - Canted coil spring to improve RF contact of the sandwich construction
  - **New CuBe coupling foils with integrated pumping area**
  - **Modified / improved WG-to-coaxial couplers**
    - Careful RF optimization of each coupler
  - **Final check of all components**
    - RF feedthroughs, cables, slotted foil, etc.
- **Some observations**
  - **No warping of coupling foils after baking procedure (200 C)!**
  - **RF characteristics are very sensitive to tolerances!**
    - Very critical is the WG-coaxial coupling area!
    - Remaining stress in Cu and CuBe parts!
  - **Outgassing issues**
    - Two monitors are vacuum certified and installed
    - Two monitors did not passed the outgassing limits!



Next Steps…

- **Finalize Schottky pickup installation**
  - Will be done in June 2014
- **RF electronics modifications (one system only!)**
  - New fast gate switch (based on KEK design)
  - Tunable input BPF (YIG)
  - Tunable 1st LO
  - New LNA
- **Control of amplitude/phase balance**
  - Expand remote control to all systems
- **Control and GUI software improvements**





pBunch at flat top (stored), ~1e10 ppb

Intro and Outline

Some of the issues with the current receiver chain

The center frequency is not adjustable

Degradation of the first amplifier in the chain (over months)

Dynamic range could be further optimized

The whole chain can probably be simplified

(at the moment there's 7 amplifiers!)

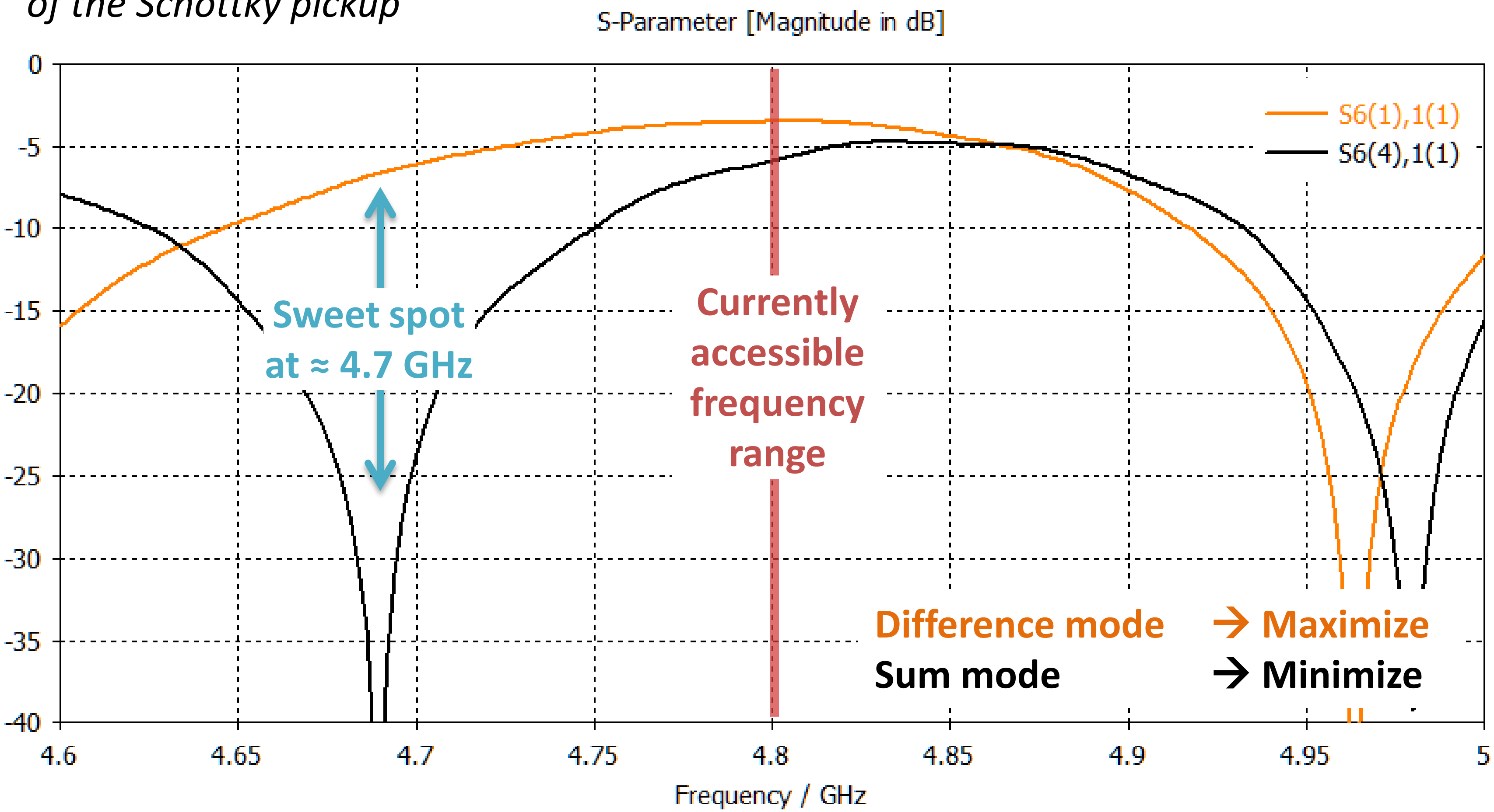
Synchronization signal to the low level RF introduces phase noise

What we want to do about it

1) A fast gating switch placed at the beginning of the chain
2) Adjustable preselector filter in the frontend
3) Adjustable 4.4 GHz Local Oscillator for the first mixer

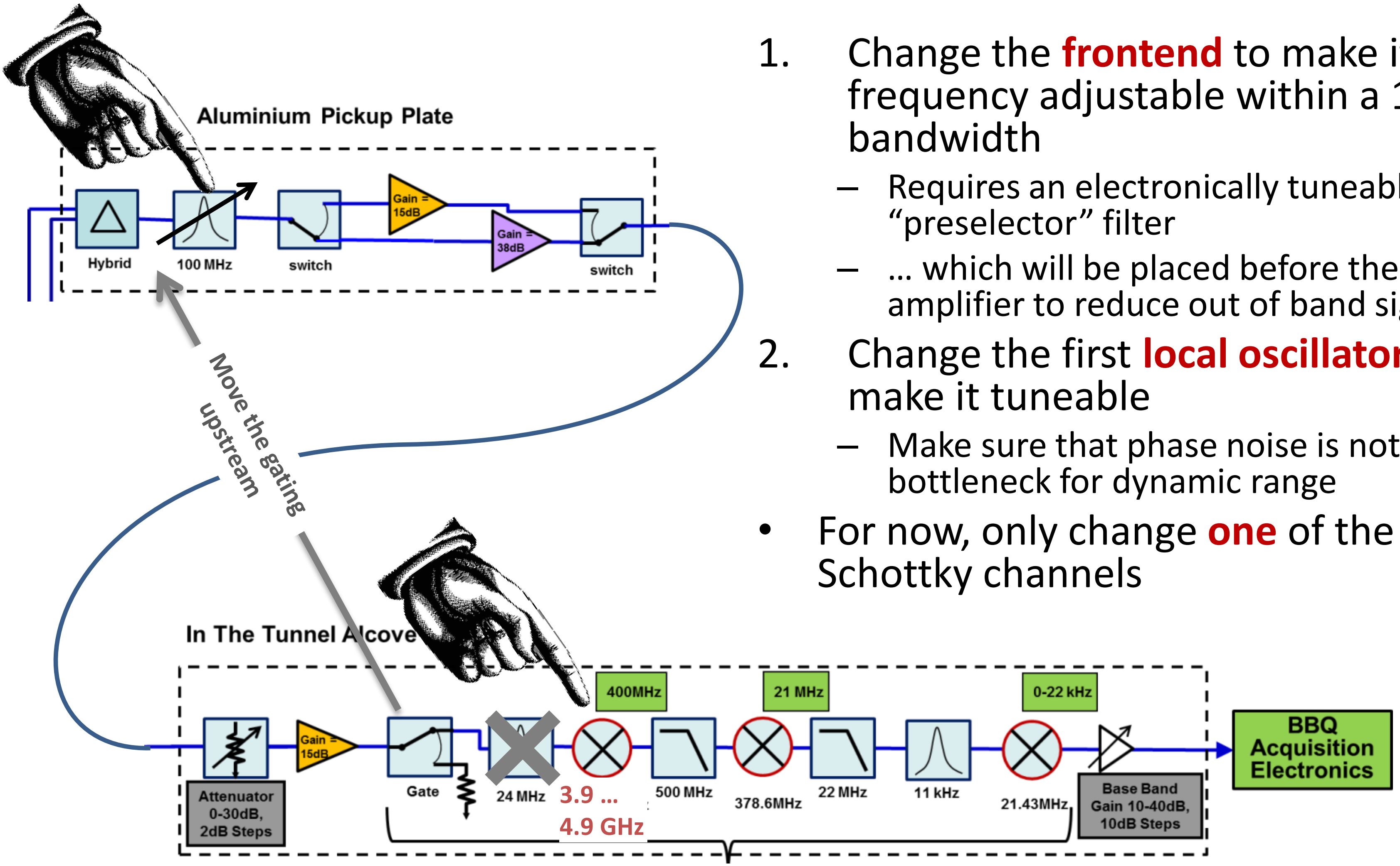
Why we want an adjustable center frequency

CST microwave studio simulation of the Schottky pickup



Currently the Schottky receiver is centered at 4.8 GHz and **not adjustable**
However we expect the best “Signal to Noise” from the pickup at ≈ 4.7 GHz

Proposed changes to the receiving chain



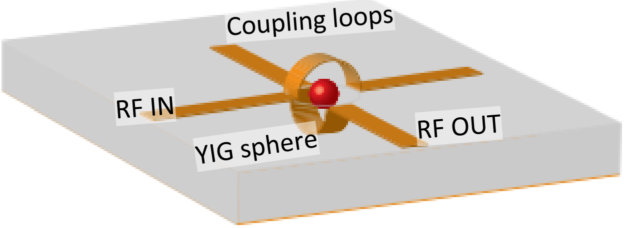
1. Change the **frontend** to make it frequency adjustable within a 1 GHz bandwidth
   - Requires an electronically tuneable “preselector” filter
   - … which will be placed before the first amplifier to reduce out of band signals
2. Change the first **local oscillator** to make it tuneable
   - Make sure that phase noise is not a bottleneck for dynamic range

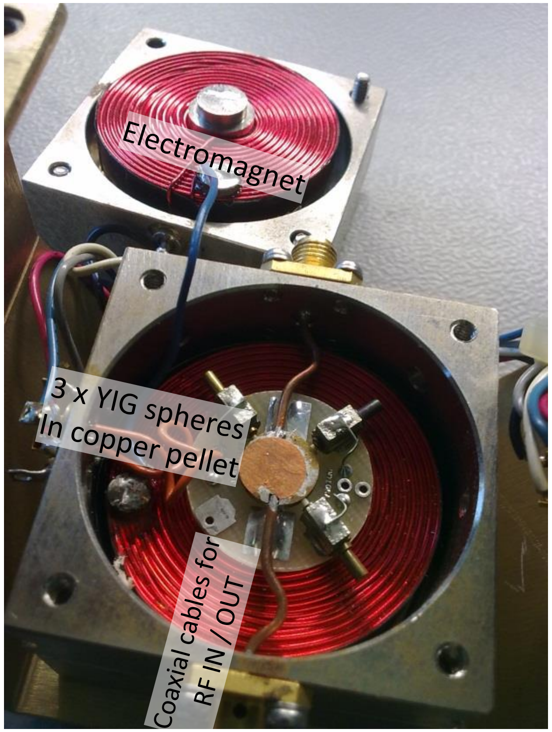
- For now, only change **one** of the four Schottky channels

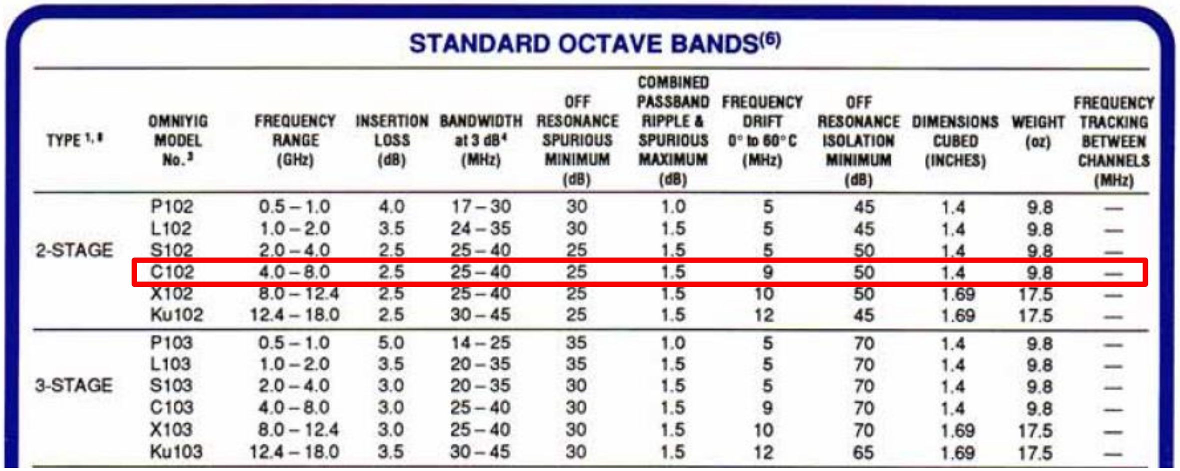
A YIG – filter as preselector

- YIG = Yttrium iron garnet (ferrite)
- Magnetically tunable bandpass filter
- Readily available:
  - 4 – 8 GHz frequency range
  - 25 MHz bandwidth
  - 2.5 dB insertion loss

- **Proposed Signal path:**
  Pickup → Gating switch → YIG filter → Low noise amplifier …



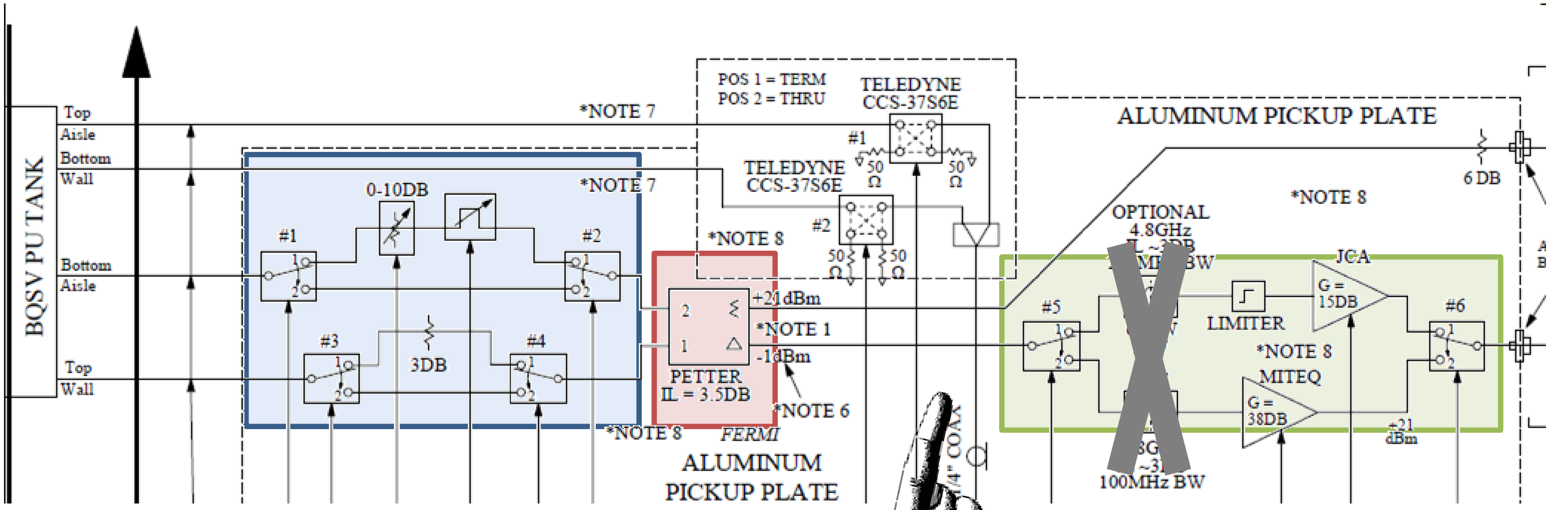




STANDARD OCTAVE BANDS(6)

TYPE [1,5]	OMNIYIG MODEL No.[3]	FREQUENCY RANGE (GHz)	INSERTION LOSS (dB)	BANDWIDTH at 3 dB[4] (MHz)	OFF RESONANCE SPURIOUS MINIMUM (dB)	COMBINED PASSBAND RIPPLE & SPURIOUS MAXIMUM (dB)	FREQUENCY DRIFT 0° to 60° C (MHz)	OFF RESONANCE ISOLATION MINIMUM (dB)	DIMENSIONS CUBED (INCHES)	WEIGHT (oz)	FREQUENCY TRACKING BETWEEN CHANNELS (MHz)
2-STAGE	P102	0.5 – 1.0	4.0	17 – 30	30	1.0	5	45	1.4	9.8	—
	L102	1.0 – 2.0	3.5	24 – 35	30	1.5	5	45	1.4	9.8	—
	S102	2.0 – 4.0	2.5	25 – 40	25	1.5	5	50	1.4	9.8	—
	C102	4.0 – 8.0	2.5	25 – 40	25	1.5	9	50	1.4	9.8	—
	X102	8.0 – 12.4	2.5	25 – 40	25	1.5	10	50	1.69	17.5	—
	Ku102	12.4 – 18.0	2.5	30 – 45	25	1.5	12	45	1.69	17.5	—
3-STAGE	P103	0.5 – 1.0	5.0	14 – 25	35	1.0	5	70	1.4	9.8	—
	L103	1.0 – 2.0	3.5	20 – 35	35	1.5	5	70	1.4	9.8	—
	S103	2.0 – 4.0	3.0	20 – 35	30	1.5	5	70	1.4	9.8	—
	C103	4.0 – 8.0	3.0	25 – 40	30	1.5	9	70	1.4	9.8	—
	X103	8.0 – 12.4	3.0	25 – 40	30	1.5	10	70	1.69	17.5	—
	Ku103	12.4 – 18.0	3.5	30 – 45	30	1.5	12	65	1.69	17.5	—

A closer look at the Frontend



Phase and amplitude matching of the top and bottom signal “Electrical center adjustment”

90 deg **hybrid**: subtracts both signals

2 signal paths with different filters / amplifiers

Insert gating switch and the YIG filter here

Get rid of non - adjustable filters downstream

Consequences of this modification

- Main advantage:
  frequency adjustable frontend

- Furthermore the first amplifier will see less “out of band” signal power
  less degradation, improved dynamic range

3 dB bandwidth of the filters upstream of the first amplifier

Old: 200 MHz[1] or 60 MHz[2]
New: 25 MHz

But:

- the Insertion Loss (IL) of any component in front of the first amplifier will readily add to the **system noise figure**
- **Maximum input power to the YIG filter is +10 dBm**

Insertion loss before the first amplifier

Old: 2 dB
(fixed filters)

New: 2.5 dB + xx dB
(YIG filter + Gate)

---

[1] RTX 4809B200L2.0A50
[2] RTXCF4809B 60L2.0A50

A closer look at the first local oscillator (LO)

Old configuration:

400 MHz reference signal
→ Frequency multiplier * 11
→ 4.4 GHz LO signal

- Automatically locked to the cavity RF
- Cheap (10^3 CHF)
- **But:** always fixed frequency ratio

Output phase noise[1] [dBc] =
Phase noise of reference [dBc]
* 20 log(11)

New configuration:

400 MHz reference signal
→ fractional PLL RF source
→ 4.4 GHz LO signal

- Adjustable output frequency
- Not so cheap (10^4 CHF)
- Frequency locking needs to be fine-tuned to optimize phase noise
- **Not clear if similar phase noise performance can be achieved**

Output phase noise depends on the quality of the internal oscillator (VXCO) and the phase noise of the reference signal. The PLL loop-bandwidth determines which one dominates

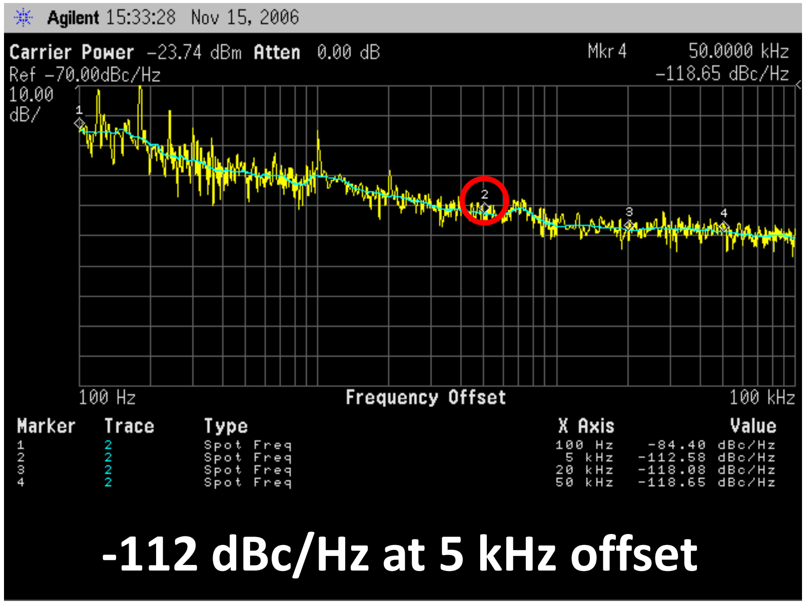
---

[1] *Fundamentals of Spectrum Analysis (Christoph Rauscher)*

Phase noise at 4.8 GHz

Old configuration:

PSP7102 Comb generator



Agilent 15:33:28 Nov 15, 2006

Carrier Power -23.74 dBm **Atten** 0.00 dB Mkr 4 50.0000 kHz

Ref -70.00dBc/Hz -118.65 dBc/Hz

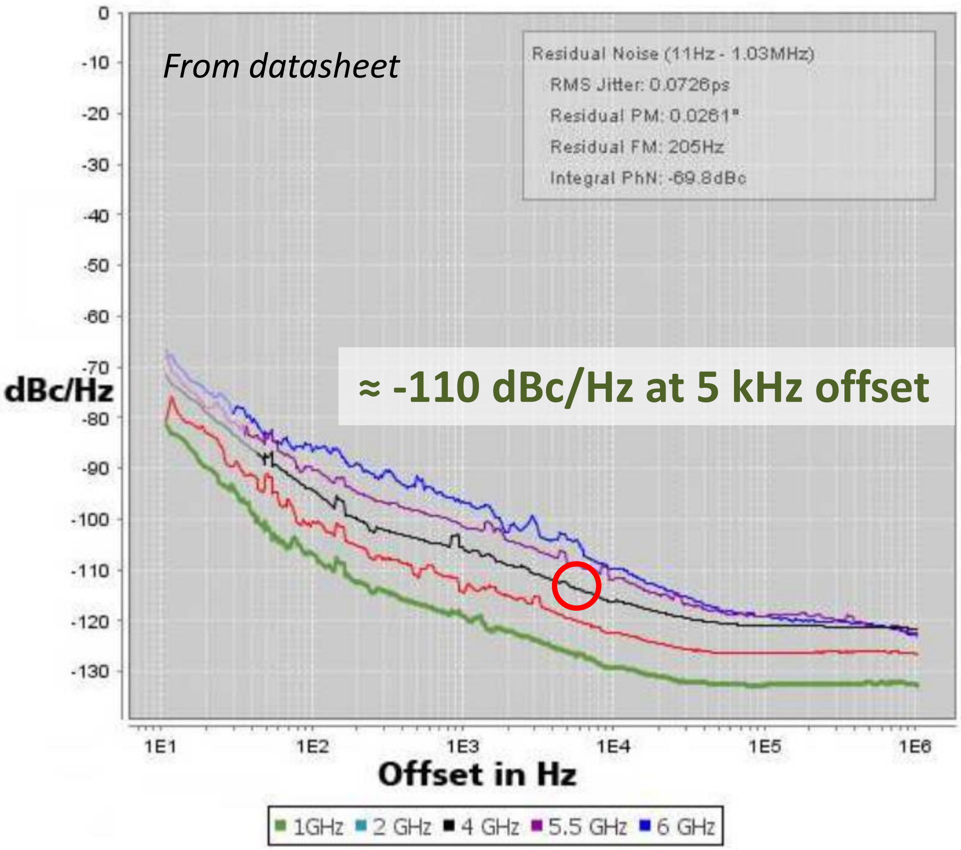
```
Marker   Trace   Type                      X Axis        Value
1        2       Spot Freq                 100 Hz     -84.40 dBc/Hz
2        2       Spot Freq                   5 kHz   -112.58 dBc/Hz
3        2       Spot Freq                  20 kHz   -118.08 dBc/Hz
4        2       Spot Freq                  50 kHz   -118.65 dBc/Hz
```

-112 dBc/Hz at 5 kHz offset

Measured at CERN, 15.04.2006
Input signal: 400 MHz
from a HP8341A

New configuration:

Anapico APSIN6010HC
(as an **example** for a mid-range RF source)



From datasheet

Residual Noise (11Hz - 1.03MHz)
RMS Jitter: 0.0726ps
Residual PM: 0.0261°
Residual FM: 205Hz
Integral PhN: -69.8dBc

≈ -110 dBc/Hz at 5 kHz offset

Looks promising!

Why is phase noise critical

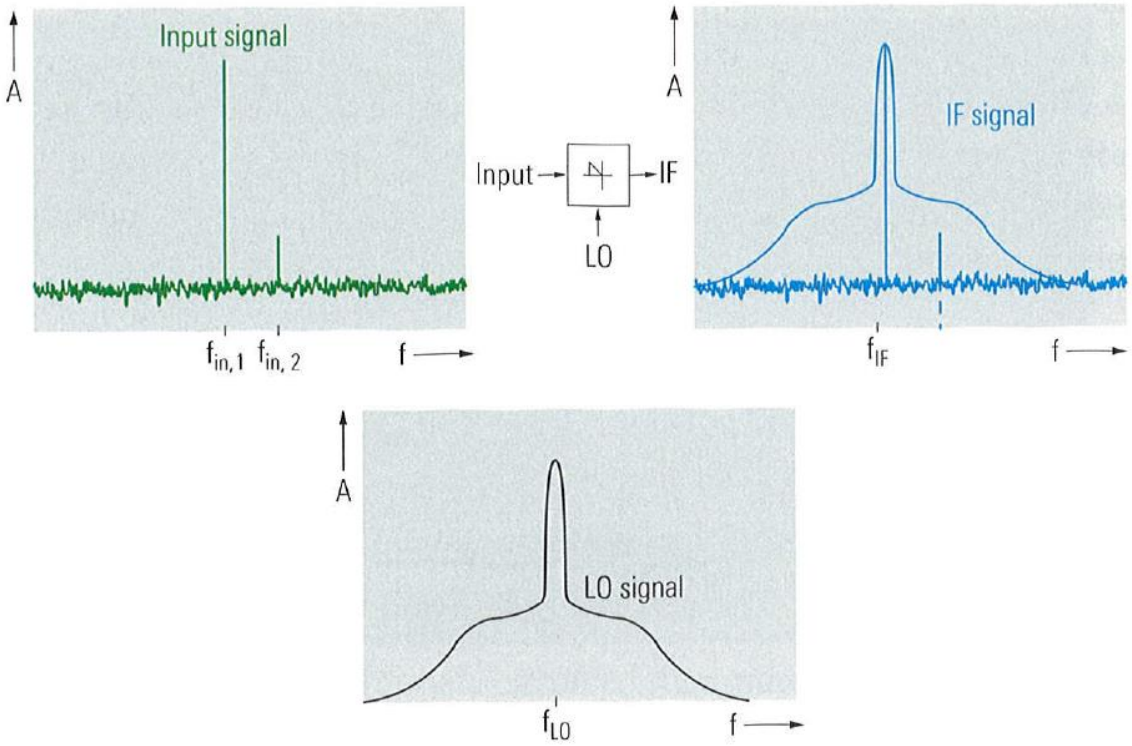


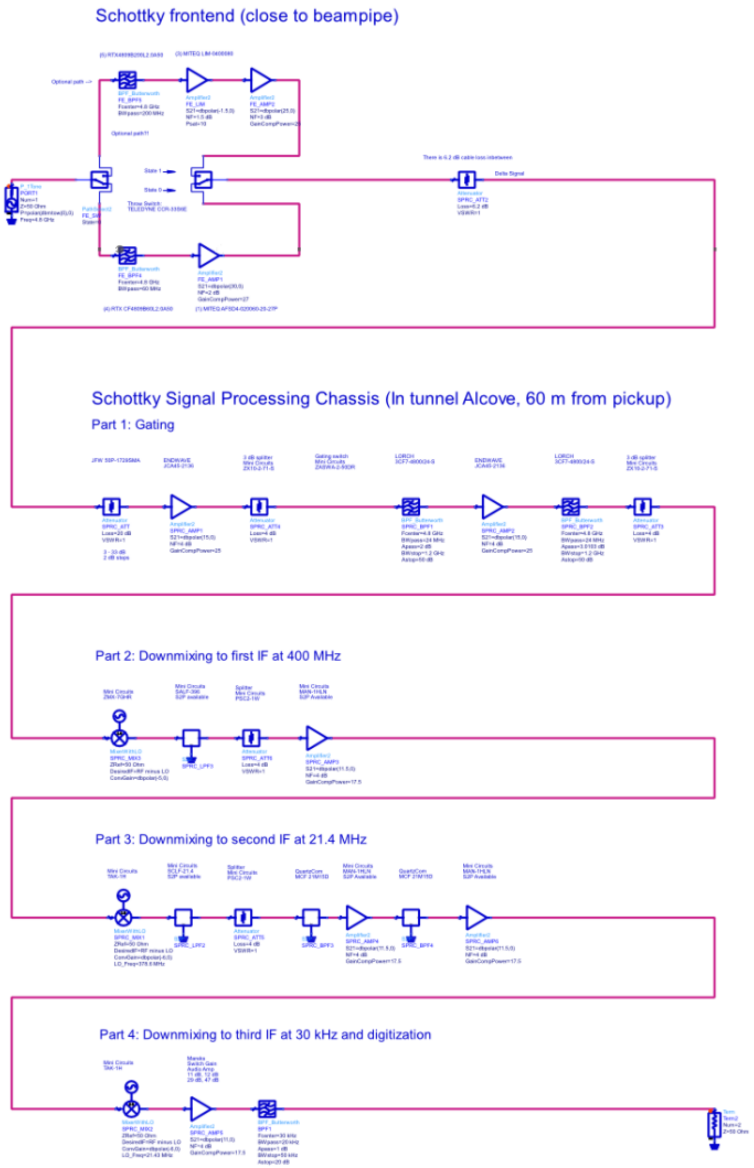
Fig. 5-12 *Internal phase noise transferred onto input signal by reciprocal mixing*

Source: Fundamentals of Spectrum Analysis (Christoph Rauscher)

An ADS simulation of the entire Schottky chain

- Can be used to
  - identify bottlenecks
  - estimate the signal and noise levels for each amplifier along the chain
  - Fine-tune the gain of each stage to avoid saturation

- Models based on VNA measurements (in progress) and datasheets



An example: saturating components

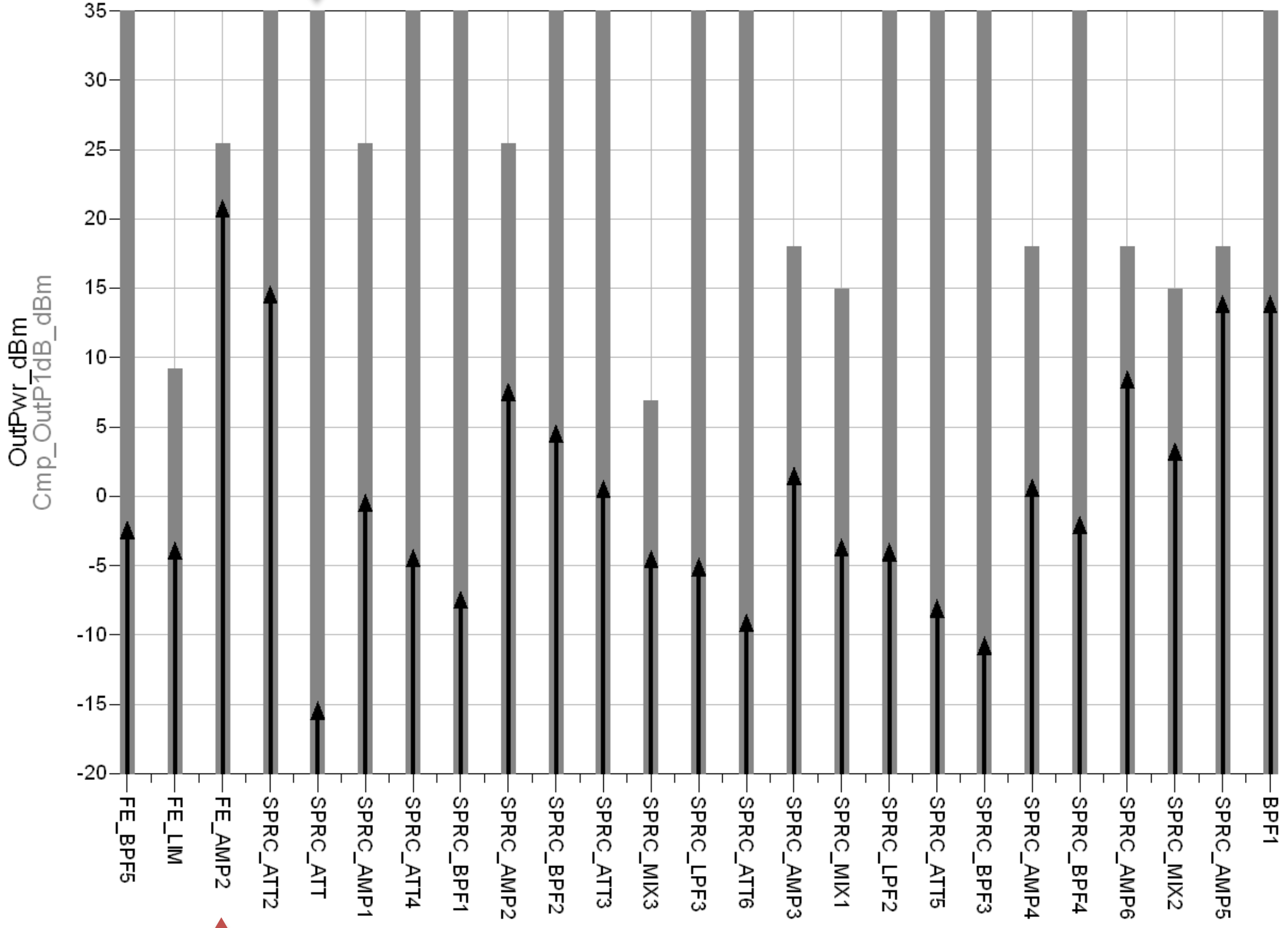
Input signal:
0 dBm, 4.8 GHz, CW

Black arrows:
Output power of each component

Grey bars:
1 dB compression point of each component

For large dynamic range we want to maximize the distance between them!

Variable attenuator had to be set to -30 dB to prevent saturation of subsequent components



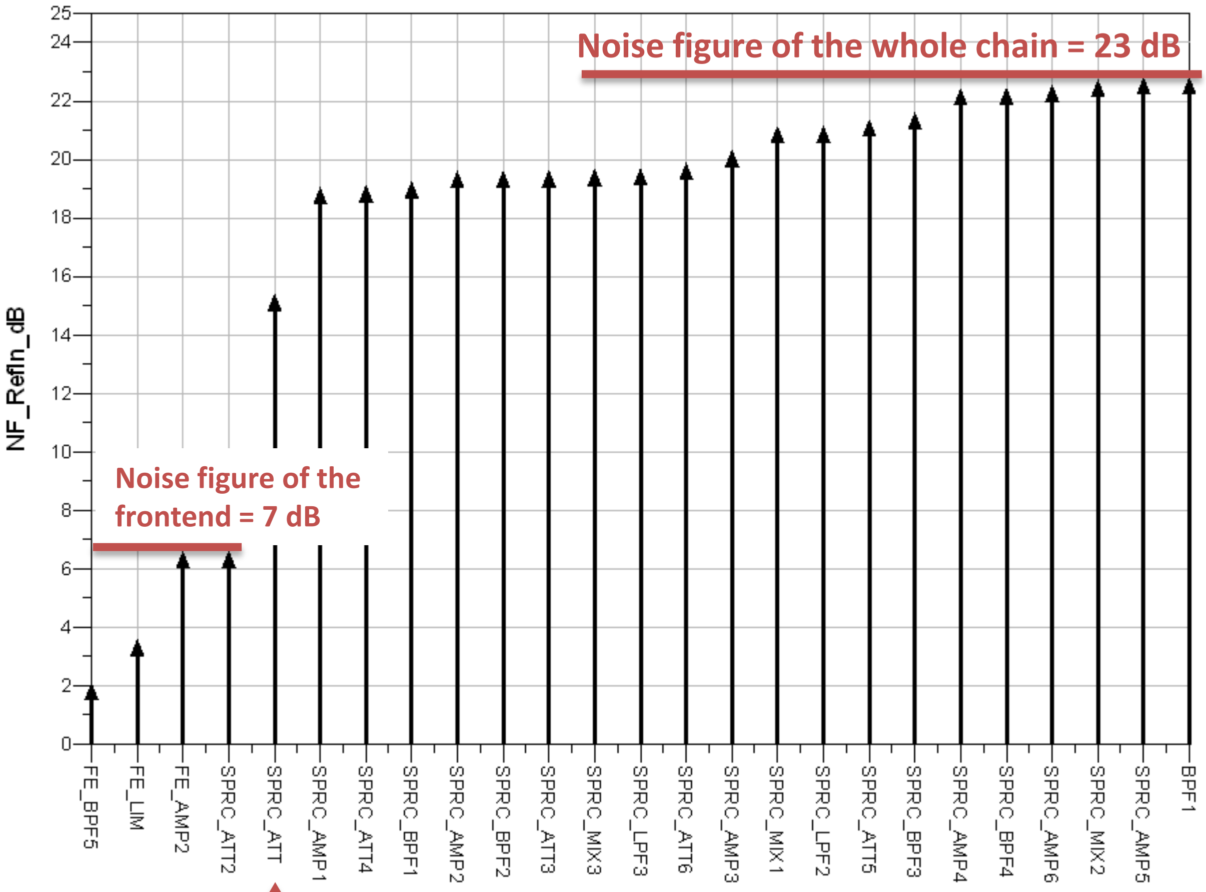
First amplifier has too much gain for a 0 dBm input signal

An example: system noise figure along the chain

Noise figure (NF):
Degradation of the signal to noise ratio due to the added noise of each component

NF = lower limit on dynamic range
(signal vanishes in noise)

The plot shows the NF measured from the beginning of the chain to the output of each component



Noise figure of the whole chain = 23 dB

Noise figure of the frontend = 7 dB

Largest noise contribution from variable attenuator, which had to be set to -30 dB to prevent saturation of subsequent amplifiers