Bunch-by-Bunch Kicker and its Driver: 50 Ω choice

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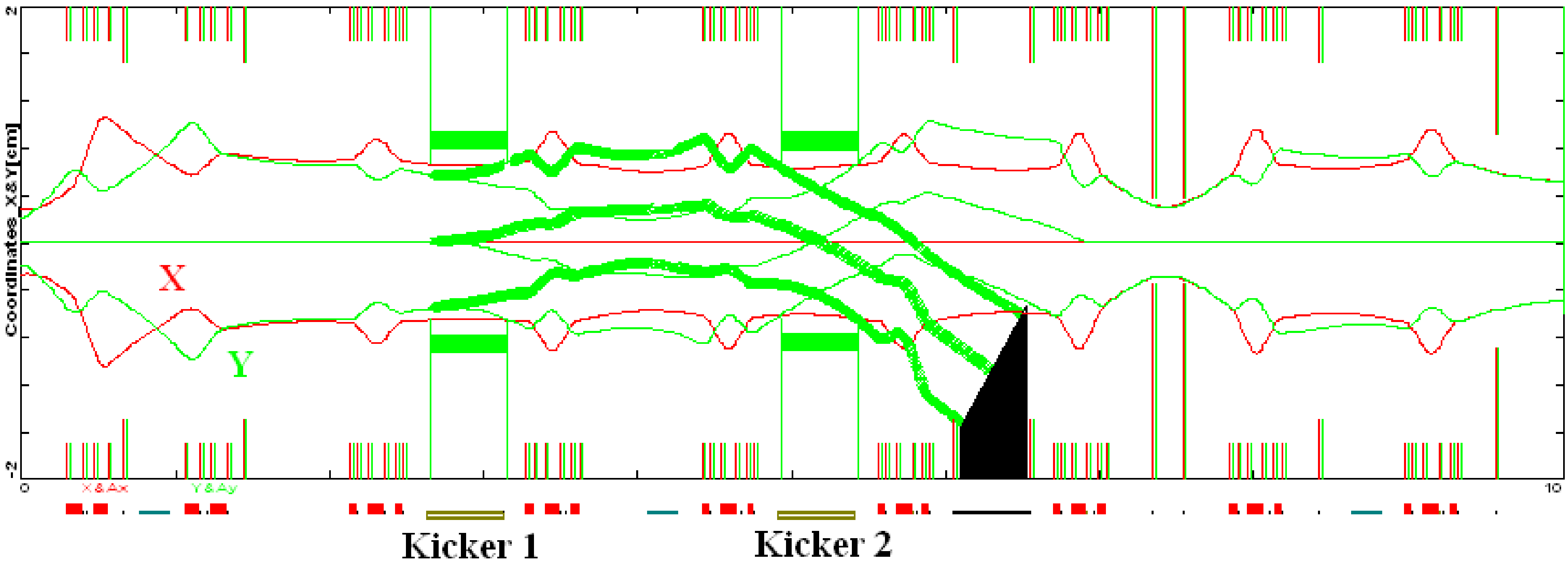
Requirements to Kickers



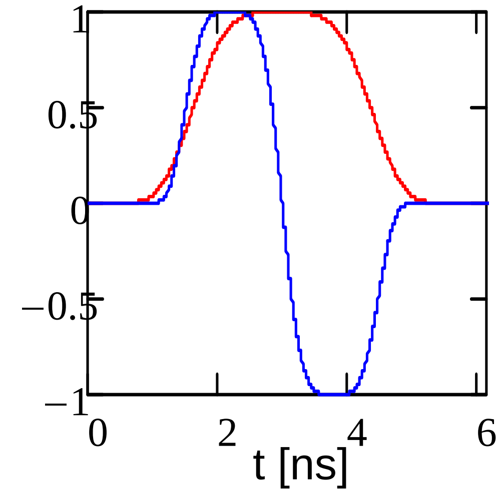
3σ beam size for the bunch passing through and bunch directed to the beam dump

- 2 kickers with 180° betatron phase advance between them
  - L=50 cm each, gap – 16 mm, U_{eff}=±250 V
  - Protecting electrodes stick in 1.5 mm (gap 13 mm)
    - isolated to detect beam halo which hits the kicker
- Beam is scraped before entering kicker section to prevent beam loss at kicker plates

Requirements to Kickers (continue)

- 6.1 ns between bunches
  - rms bunch length ≤15° => ±3σ = 90° or 1.5 ns – flat top
  - Bunch-to-bunch distance 13.4 cm
  - Wave velocity should match the beam velocity (β=0.067)
- Bandwidth ~0.5 GHz for unipolar kicks
- Bipolar kicks
  - Reduce the voltage of power amplifier by 2 times if "+U" - pass & "-U" - kill
    - But twice larger bandwidth ~1 GHz
  - Bipolar kicks major advantage
    - effective protection of kicker overheating by the beam
    - Absence of DC coupling

      ⇒ DC current is directly related to the beam loss
  - Beam current regulation is possible with partial scraping
    - Bunch-by-bunch regulation of kick strength

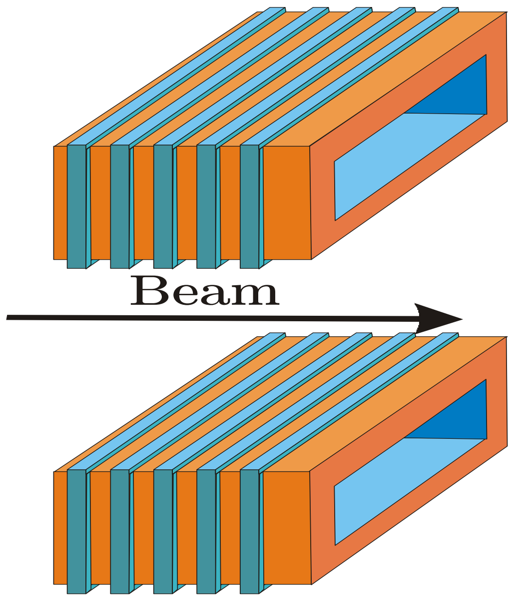


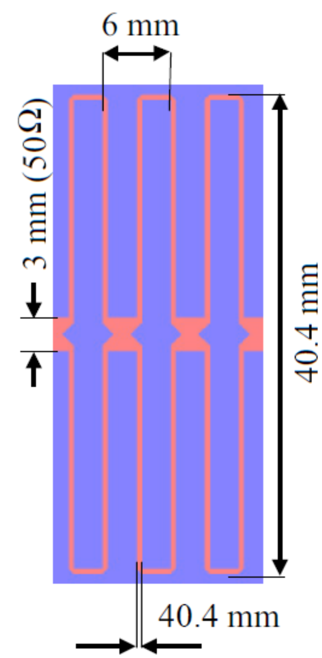
Challenges for Bunch-by-Bunch Chopper

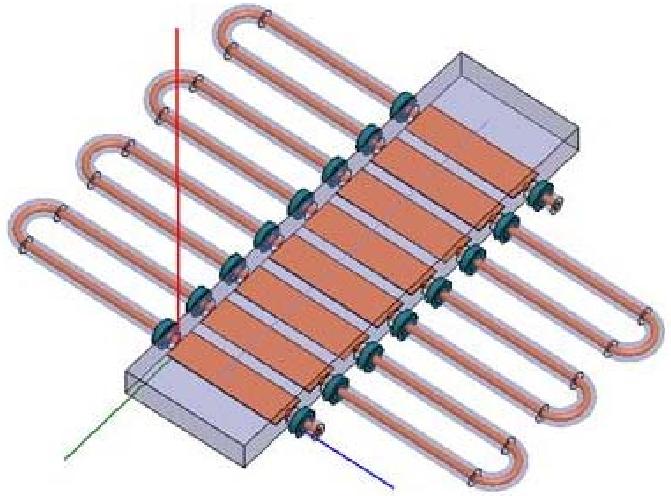
- Kicker
  - Small dispersion in a e.-m. structure decelerating wave to low β
  - Small reflections from discontinuities
  - Kicker have to be capable to withstand heating by beam halo
  - Have to be capable to withstand the power loss of e.-m. wave
- Power amplifier
  - Large power and bandwidth
    - Even state of the art systems are not good enough
  - Signal pre-distortion at the input allows one addressing the problem

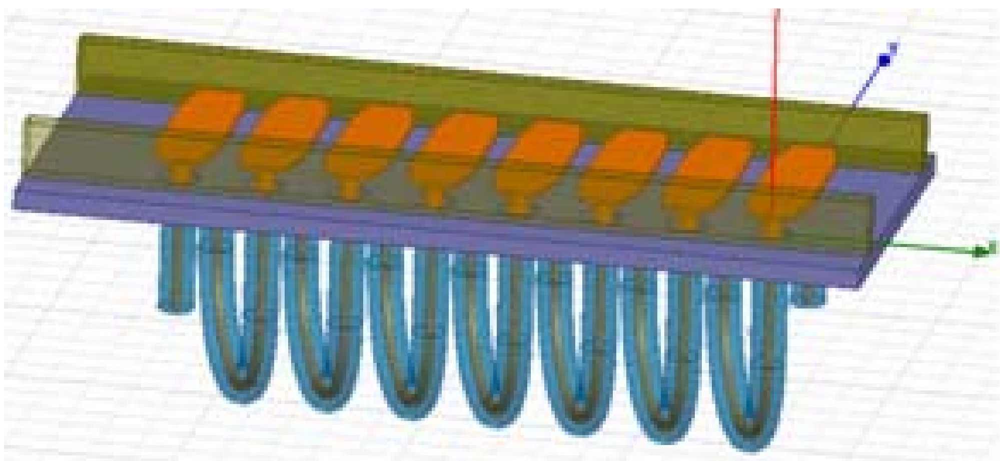
Possible Implementation for Kickers

- 2 ways to decelerate e.-m. wave
  - Spiral kickers
  - Meander
- Short plates can be connected by a coaxial delay lines to reduce coupling
- Major effects limiting the bandwidth
  - Coupling between stripes
  - Reflections from discontinuities
  - Losses in the conductor and dielectric



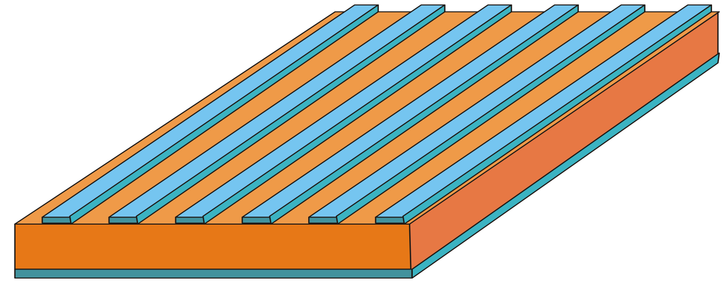






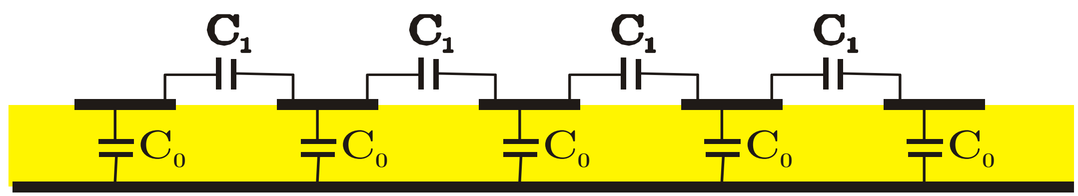
Simple analytical model

- Without coupling between nearby lines it can be considered as a transmission line
  - Dispersion is small and is
    - Dominated by loss in the conductor and dielectric



- Equations for parallel lines (coupling is on)

$$\begin{cases} \dfrac{\partial I_n}{\partial x} = -C_0 \dfrac{\partial U_n}{\partial t} + C_1 \left(\dfrac{\partial U_{n+1}}{\partial t} + \dfrac{\partial U_{n-1}}{\partial t} \right) \\ \dfrac{\partial U_n}{\partial x} = -L_0 \dfrac{\partial I_n}{\partial t} \mp L_1 \left(\dfrac{\partial I_{n+1}}{\partial t} + \dfrac{\partial I_{n-1}}{\partial t} \right) \end{cases}$$

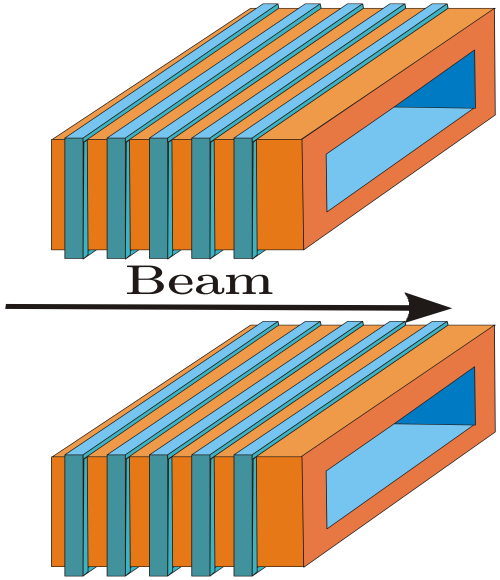


"-" if currents in nearby lines go in the same direction,
"+" – otherwise

C_0 & L_0 - capacitance & inductance per unit length

n – numerates lines

Helical versus meander kicker



- Dispersion equation for helical structure

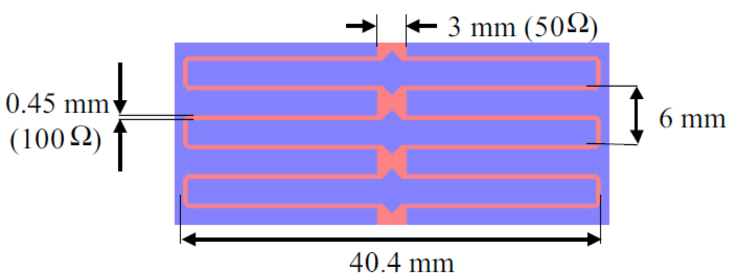
$$k \approx \frac{\omega}{v_L}\left[1-(\kappa_C-\kappa_L)\cos\left(\frac{\omega l}{v_L}\right)-2\kappa_C\kappa_L\cos^2\left(\frac{\omega l}{v_L}\right)\right]$$

l – length of a single turn

$\kappa_C = C_1 / C_0,\quad \kappa_L = L_1 / L_0$

- Dispersion equation for meander structure

$$k \approx \frac{\omega}{v_L}\left[1-(\kappa_C+\kappa_L)\frac{v_L}{2\omega l}\sin\left(\frac{2\omega l}{v_L}\right)\right]$$

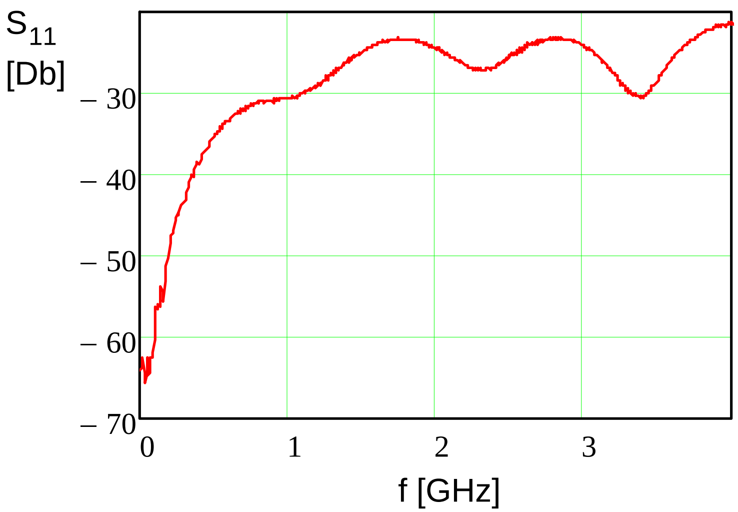


l – length of a stripe (kicker half width)

- For both kickers there are no problems worsen if $\omega \ll v_L / l$
  - i.e. small length helps but length cannot be smaller than the kicker gap
- Dispersion in helical structure is strongly suppressed if $\kappa_C = \kappa_L$
  - i.e. $\varepsilon = 1$

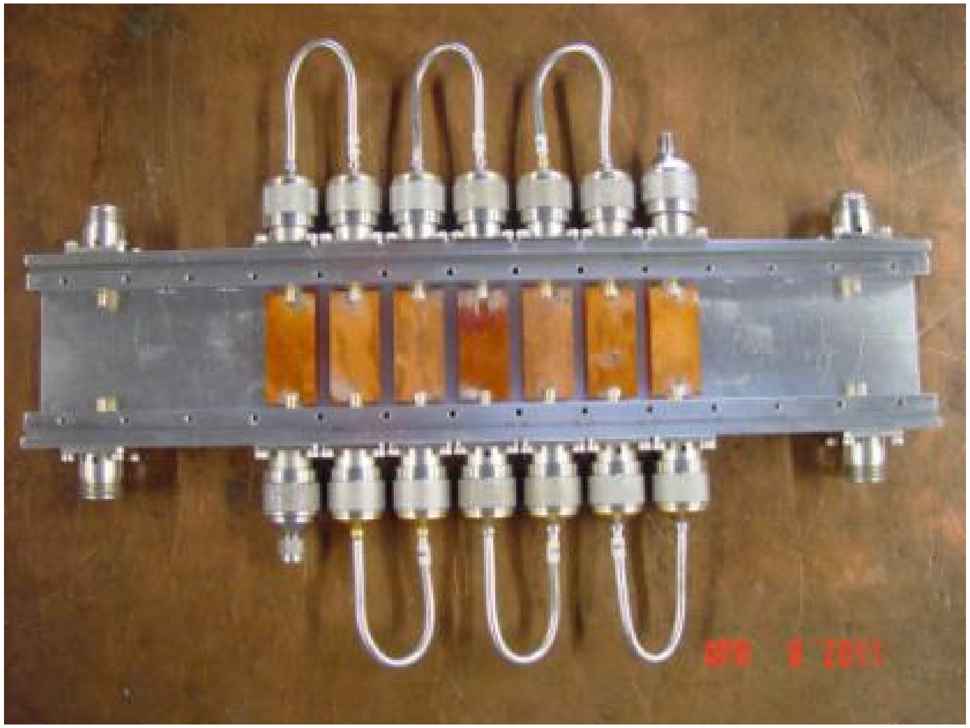
Kicker Prototype

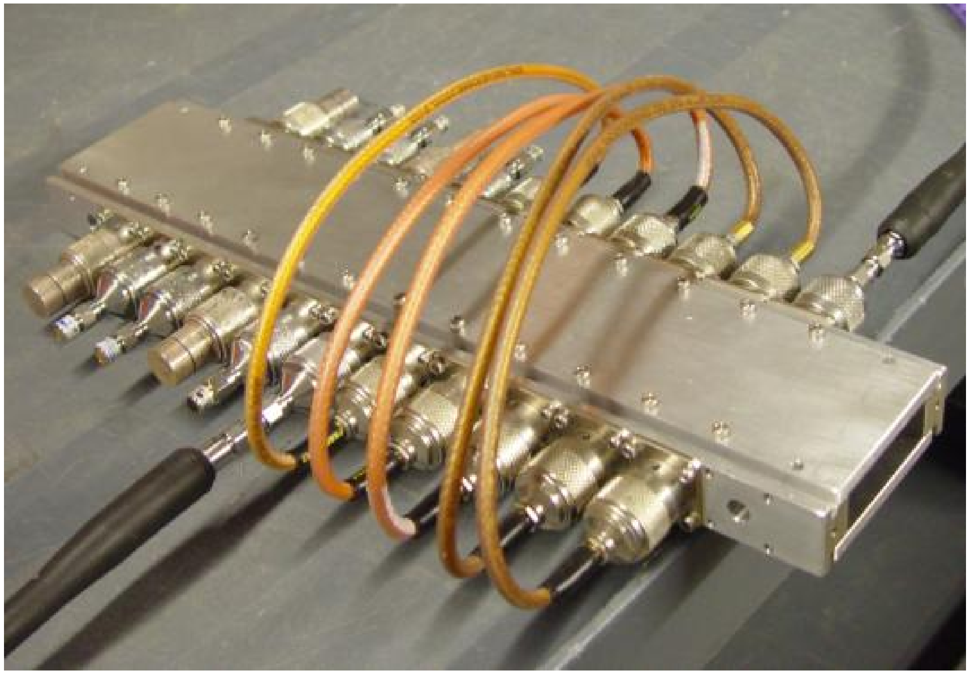
- First prototype (May 2011)
  - Verified both analytical estimates and e.-m. simulations
  - Excellent performance



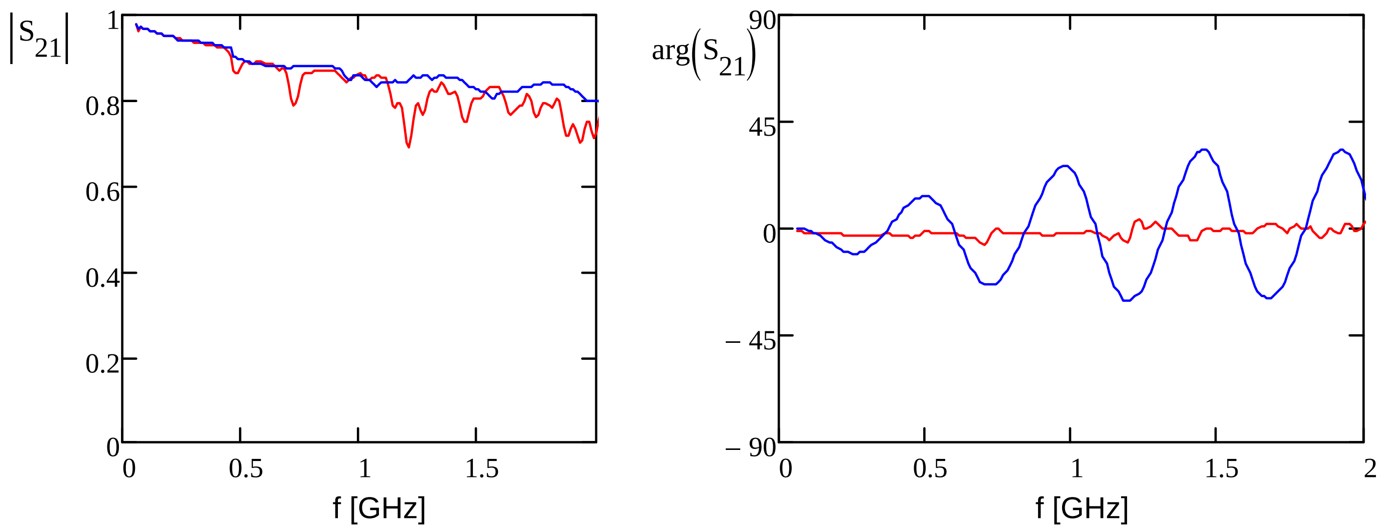
S11 for a single electrode (electrode length=40 mm, width=18 mm, step=23 mm

- Choice for the kicker structure
  - Separate plates (40 mm long, 20 mm period)
  - Helical connection

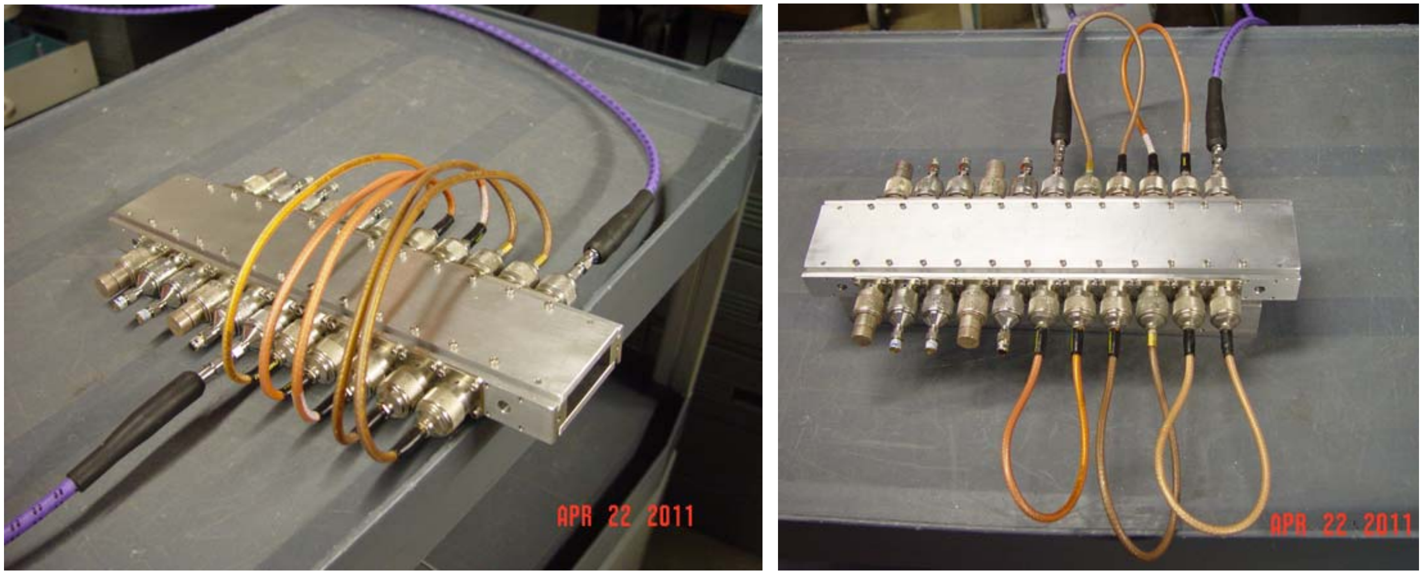




Kicker Prototype (continue)



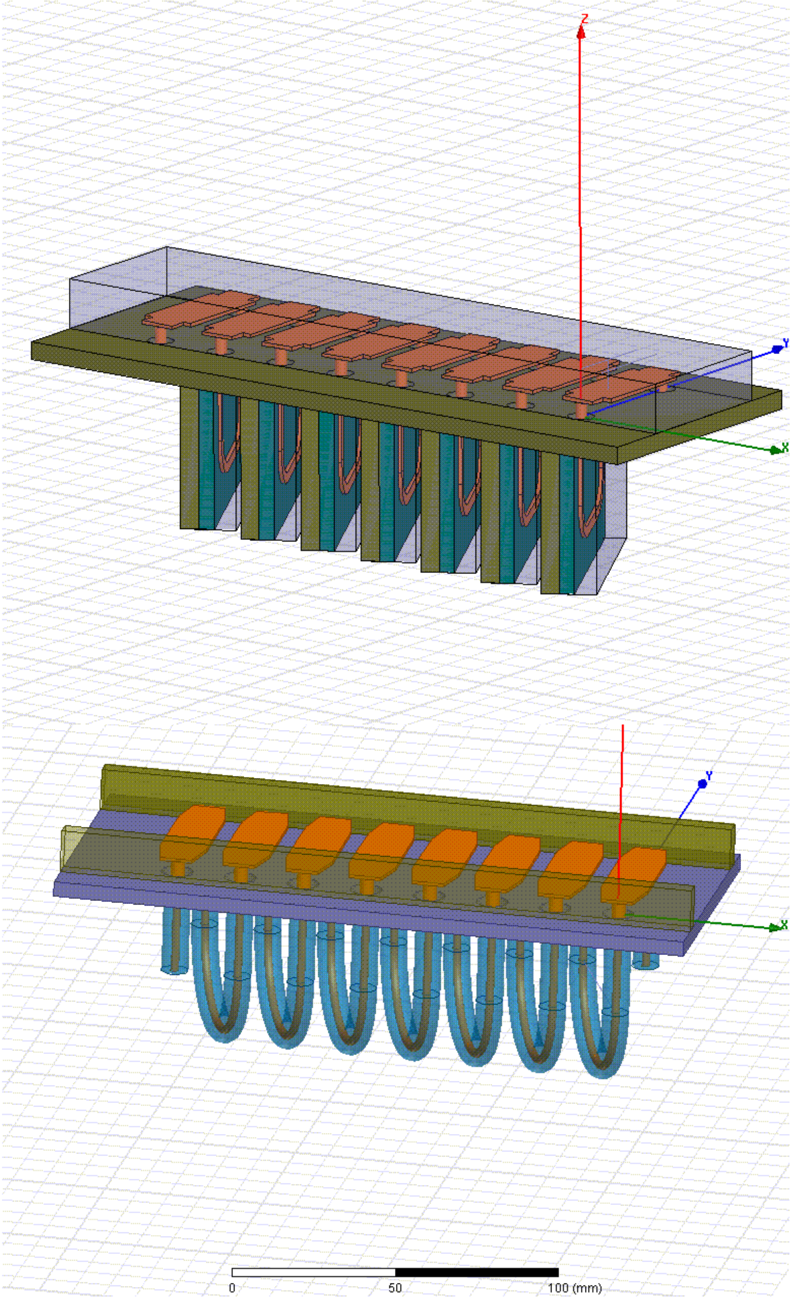
S21 for "helical" (red) and "meander" (blue) connections of 6 electrodes



- Obtained results proved the concept validity
  - Practical issues to be addressed (vacuum, high power, beam heating)

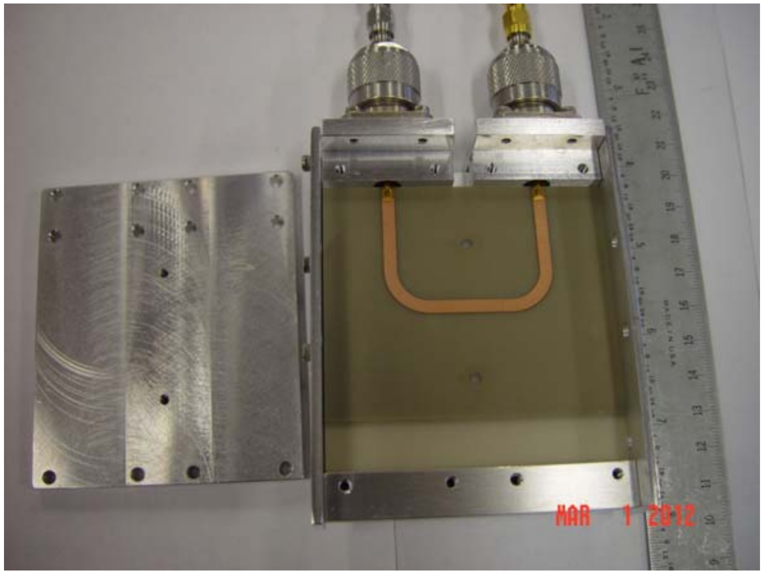
Work on Kicker Design

- Two implementations were perused
- Plan A
  - Copper line bonded to AlN substrate
    - Good thermal conductivity for AlN
    - Cooled through Cu ground plate
    - Each delay line is an individual unit screwed onto the ground plate
    - Recently stopped
- Plan B
  - Semi-rigid (hand-formable) cable
    - Outer conductor of coaxial cables is clamped on to the ground plate
    - Less loss in insulator => more suitable for 50 cm structure
    - Smaller thermal conductivity and maximum operational temperature for teflon insulator than AlN but still good enough
    - It is being implemented now!!!



Plan A

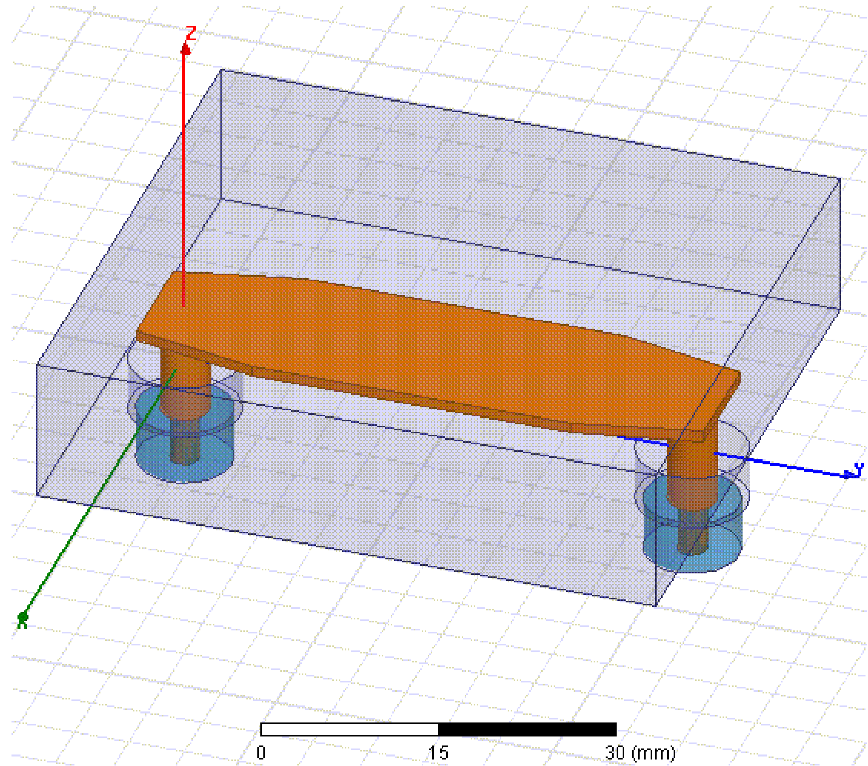
- Excellent thermal conductivity for
  - AlN - 170-200 W $m^{-1}K^{-1}$
  - Al_2O_3 - 18-35 W $m^{-1}K^{-1}$
    - 50 Ohm Al_2O_3 microstrip can handle 2 kW power in air
- Technical challenges
  - Direct bonding of copper is required to achieve small e.-m. loss
  - Bonding is commercially available
    - thin film, thick film, brazing, DBC (direct bond copper),
    - but low-loss is not easy
  - Joint between electrode and delay line to minimize reflections
- Purchased and received AlN samples.
  - Max. thickness of commercial DBC AlN can only be 1 mm,
  - Required thickness of 4 mm too expensive and requires too long time
- Measured insertion loss, impedance, delay time
  - Loss is too high at frequencies above 500 MHz for 50 cm structure

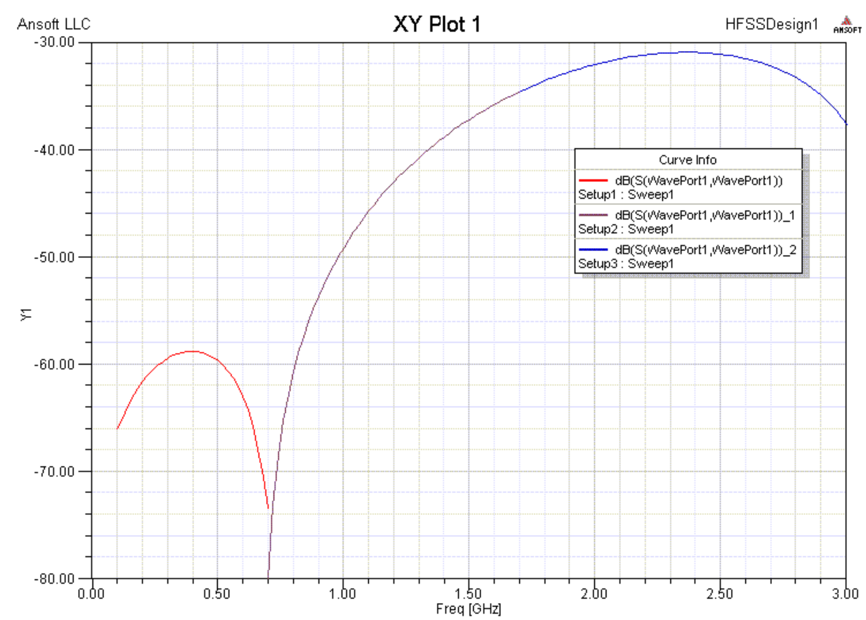


DBC AlN delay line

Plan B

- Cable: UT 390 (semi-rigid):
  4 kW Max. power,
  175 C Max. operating temp.
- Design of joint area between cable and electrodes has been completed.
- Design of joint between electrode and input power vacuum feedthrough has been completed.
- Teflon thermal conductivity is good enough: $\Delta T \sim 15\ C^o$ for 2 W/plate plus $\Delta T \sim 15\ C^o$ for 1 kW amplifier
  ⇨ Operating temperature $\leq 70\ C^o$
- Engineering effort is focusing on:
  - bend cable with minimum distortion of cross section to minimize reflection/dispersion
  - trim to right delay time etc.,
  - solder cable/feedthrough to electrodes
  - and meet vacuum spec.





S11

Power Amplifier

- Required power – 0.5 – 1 kW
    - Limited choice of amplifiers with ~1 GHz bandwidth
    - All designs are based on combination of outputs of many small power amplifiers
    - Gain is far from being good enough
    - After testing/checking a few brands we stopped at the SBA series (Teseq AG, Switzerland)
        - CBA 1G 150 was tested
        - CBA 1G 1000 is considered as an amplifier which satisfies all our requirements

          Price ~$200K for 1 kW,

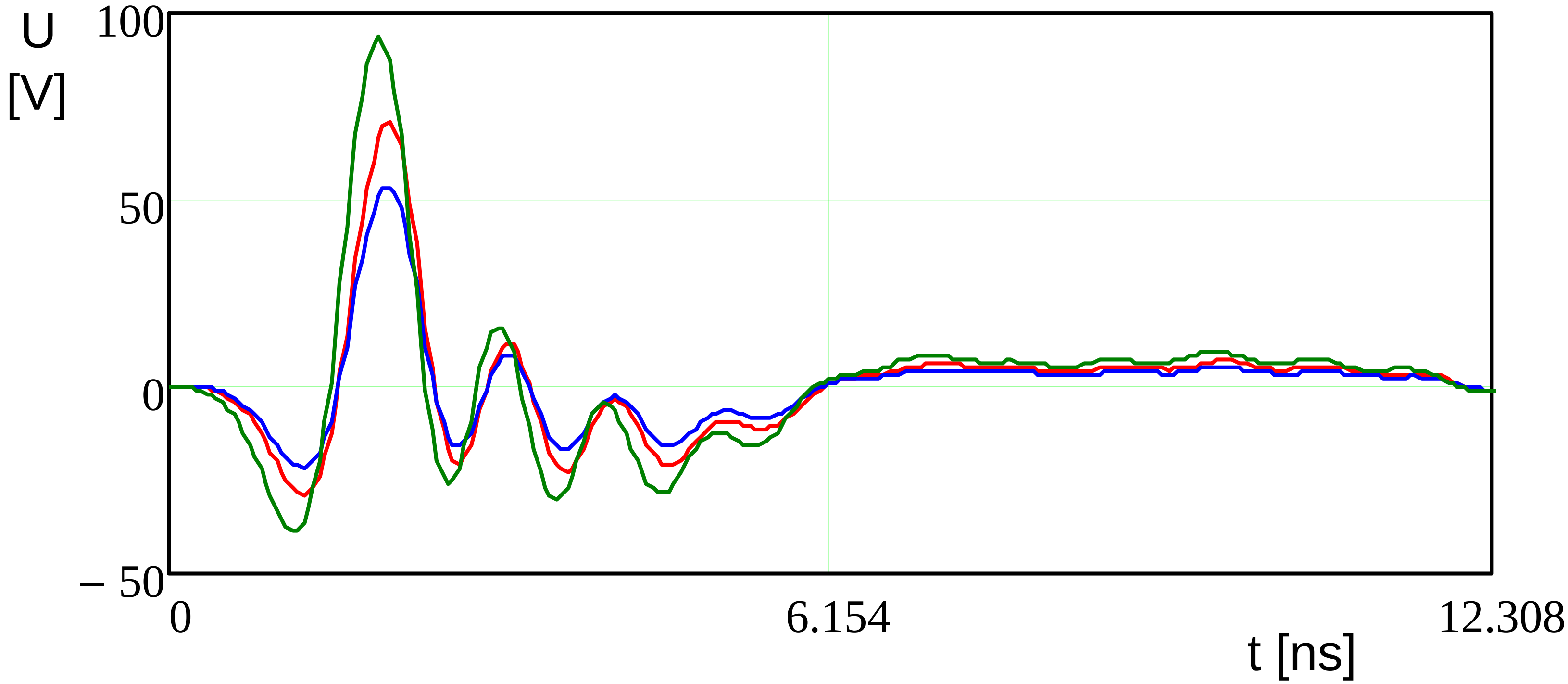
          4 amplifiers are required

CBA 1G 150

- Class A linear and low distortion design
- High reliability gallium arsenide technology
- Mismatch tolerant and unconditionally stable
- Wide instantaneous bandwidth
- Typical 2 dB compression data (as described in IEC 61000-4-3) provided
- Three year parts and labour warranty

CBA 1G 1000

Power Amplifier tests (CBA 1G 150 – 150 W)

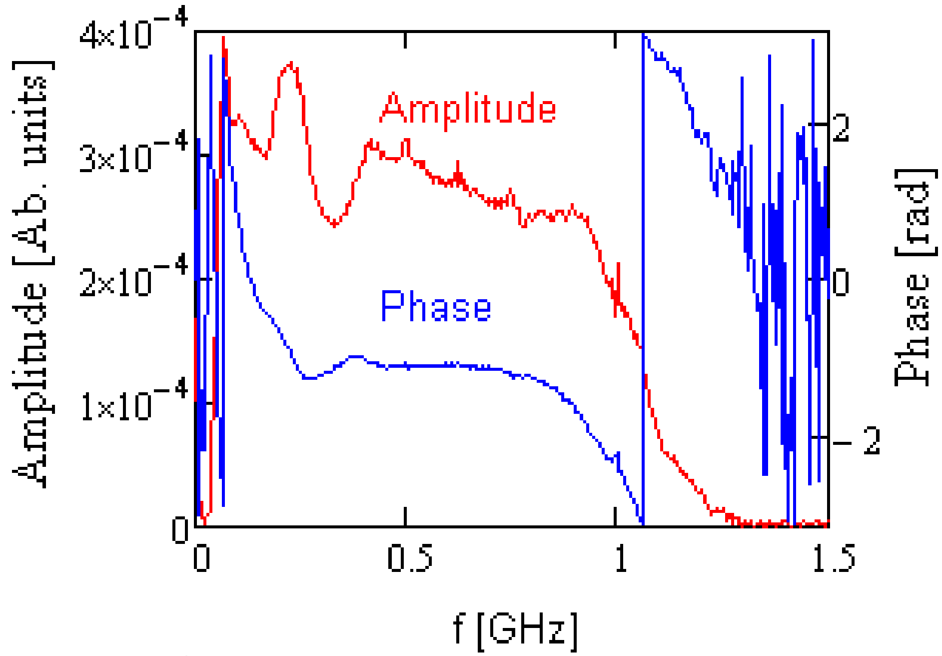


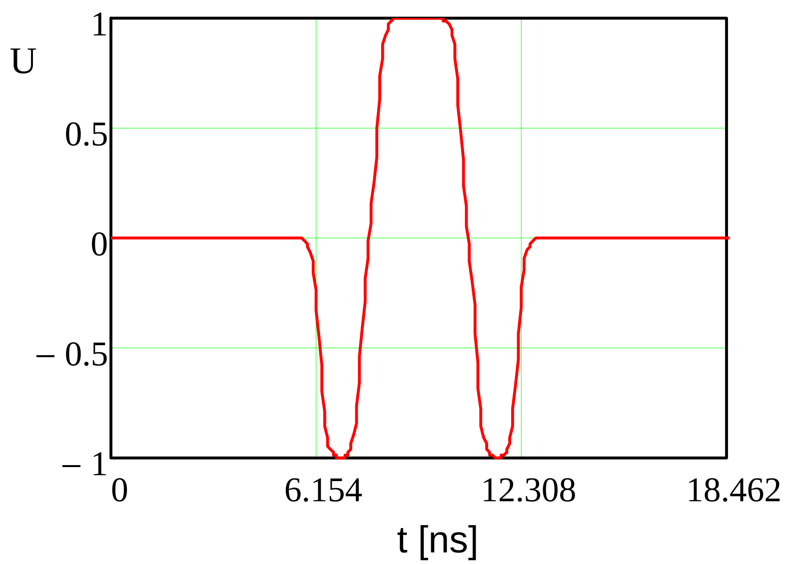
Impulse response of the amplifier

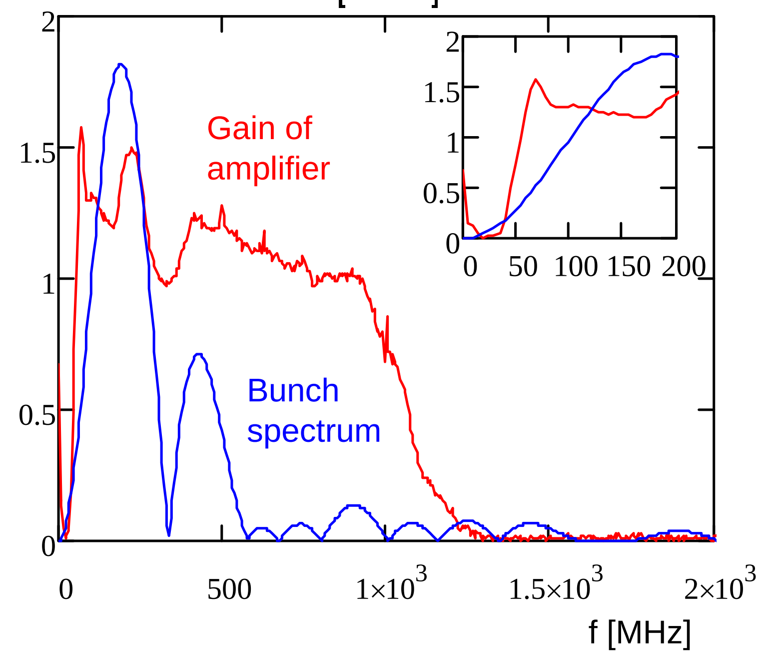
- Good linearity of the response with driving amplitude
- Duration of the response is about one bucket length (~6.1 ns)
  - It makes direct use of amplifier impossible
- Signal pre-distortion at the amplifier input addresses the problem
  - Chase Scientific DA-14000 4.0 GS/sec PCI Based Arbitrary Waveform Generator Card was used

Forming Pulses with Flat Top

- The amplifier bandwidth is 0.05 – 1 GHz (at half maximum)
- To reduce coupling between nearby pulses a single bunch spectrum has to have a small content at low frequency
- High frequency of upper band boundary allows one to have fast transition between positive and negative voltages and makes triple pulse as a good candidate
- Rise and fall times are chosen to make the bunch spectrum be inside amplifier band

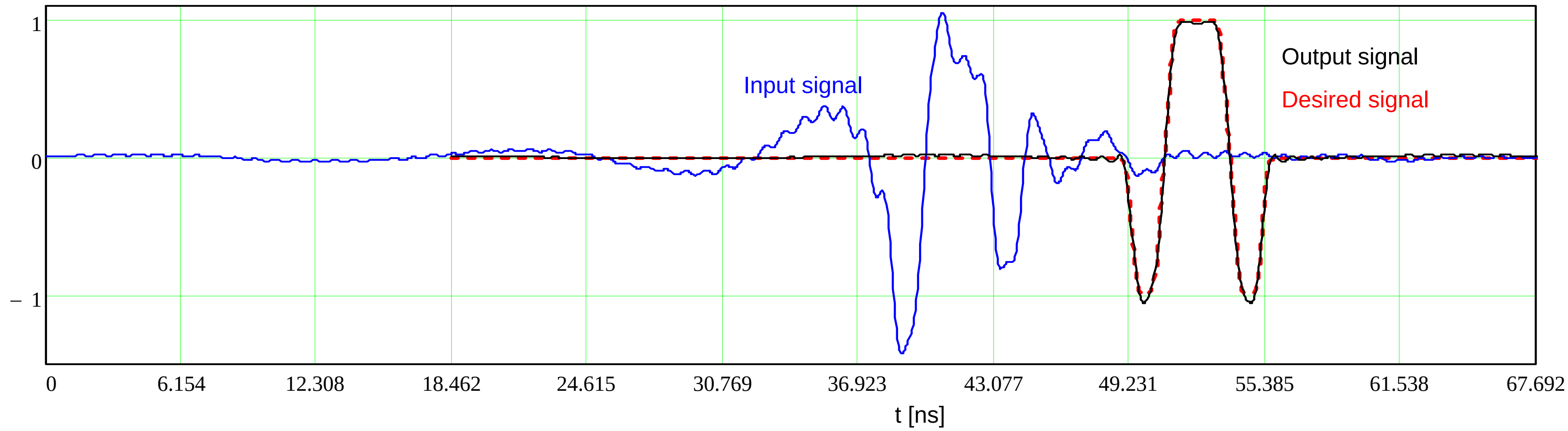






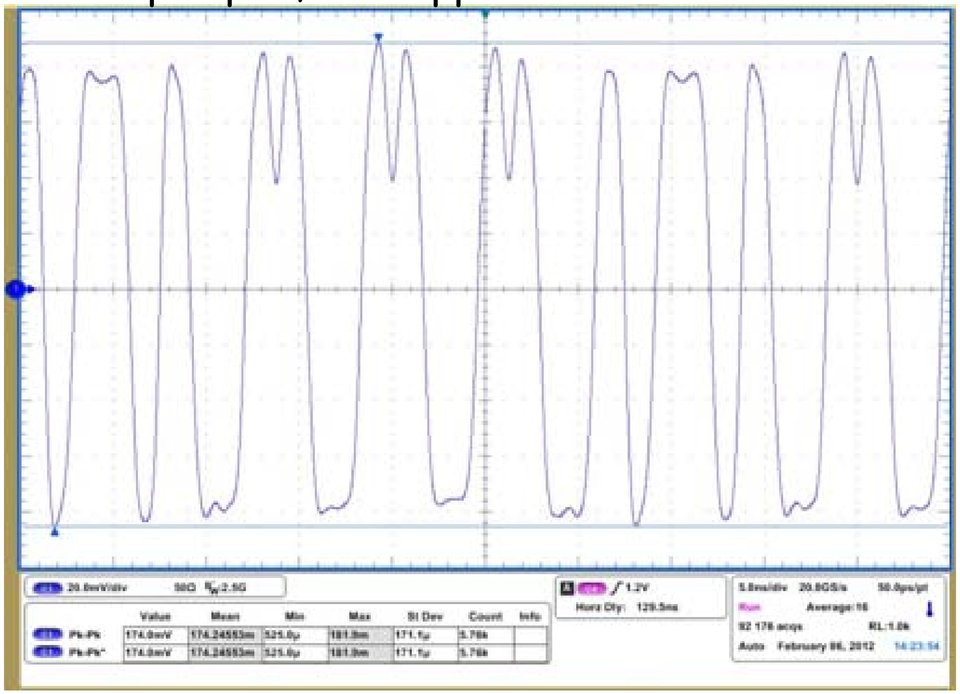
Forming Pulses with Flat Top (continue)

- Desired dependence of voltage on time at the amplifier input (for one pulse) was obtained from the desired signal shape making the following transformations
    - FFT of desired pulse
    - Removing content outside of amplifier band
    - Multiplying obtained spectrum by inverse of amplifier gain
    - Performing inverse FFT
- The dependence of voltage on time for multiple pulses (bunches) was obtained by summing signals of single pulse with 1 bucket delay time for each next pulse
    - The signal polarity was not changed for bunches to be killed
    - The signal polarity was changed for pulses assigned to pass

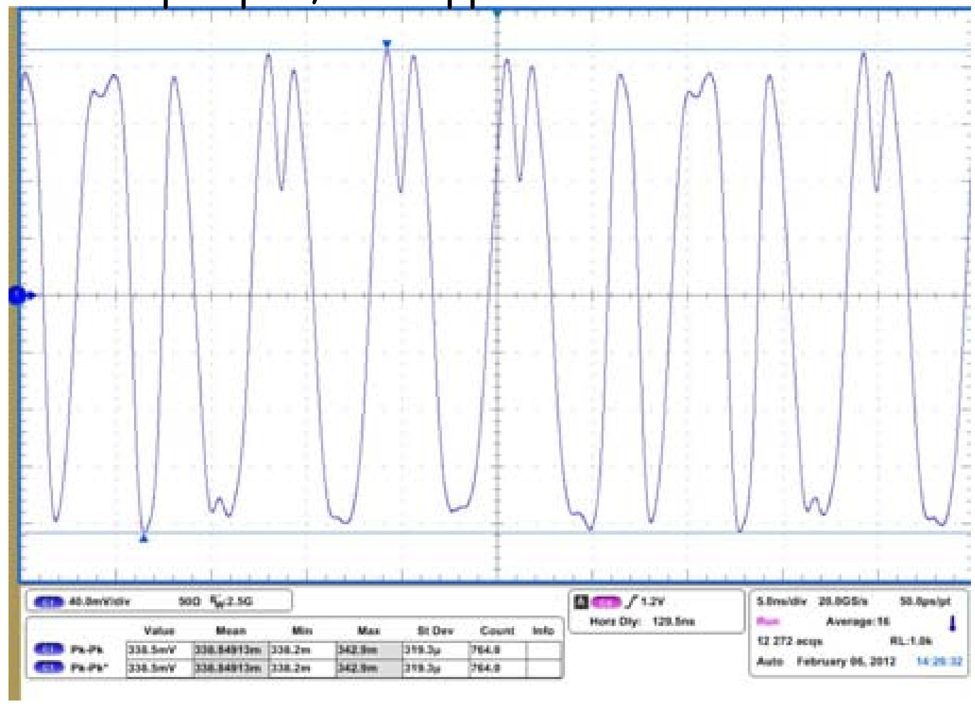


Five pulses test

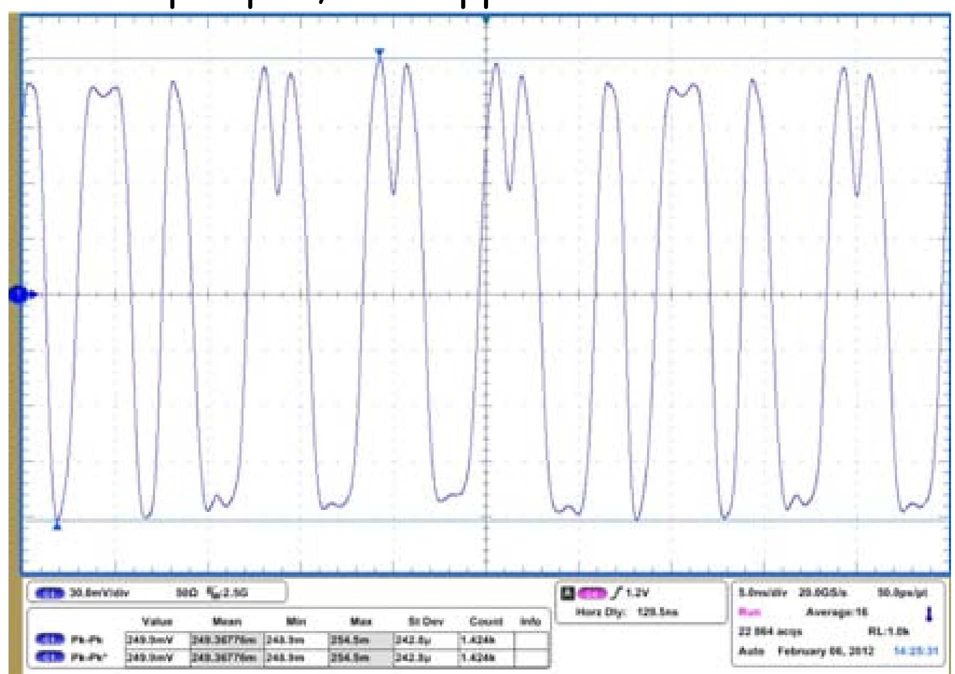
6 dB input pad, 123 Vpp out



3 dB input pad, 177 Vpp out

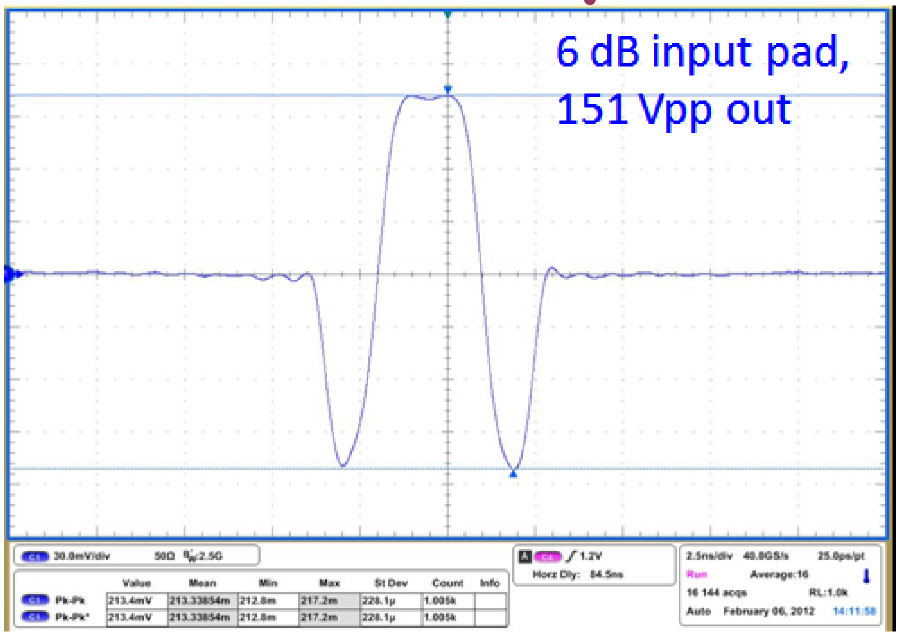


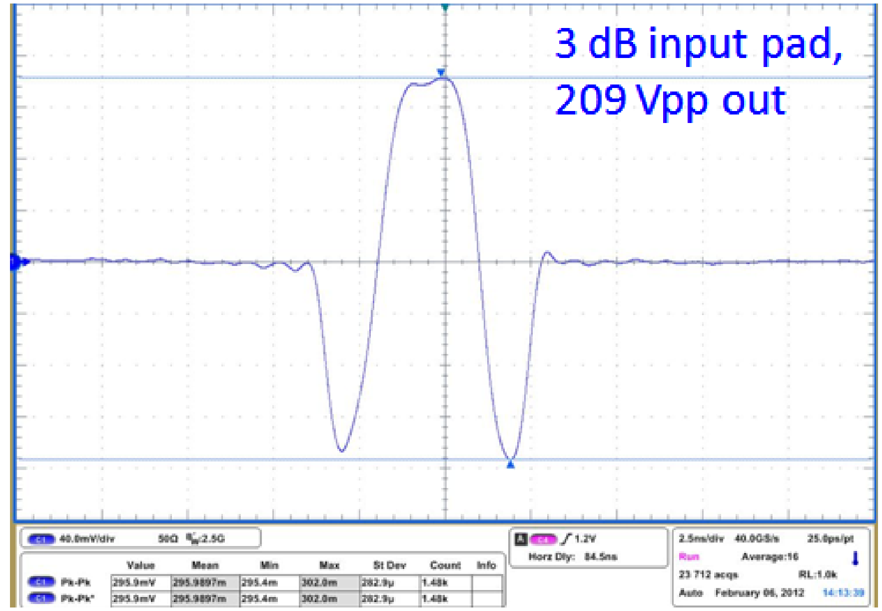
0 dB input pad, 240 Vpp out



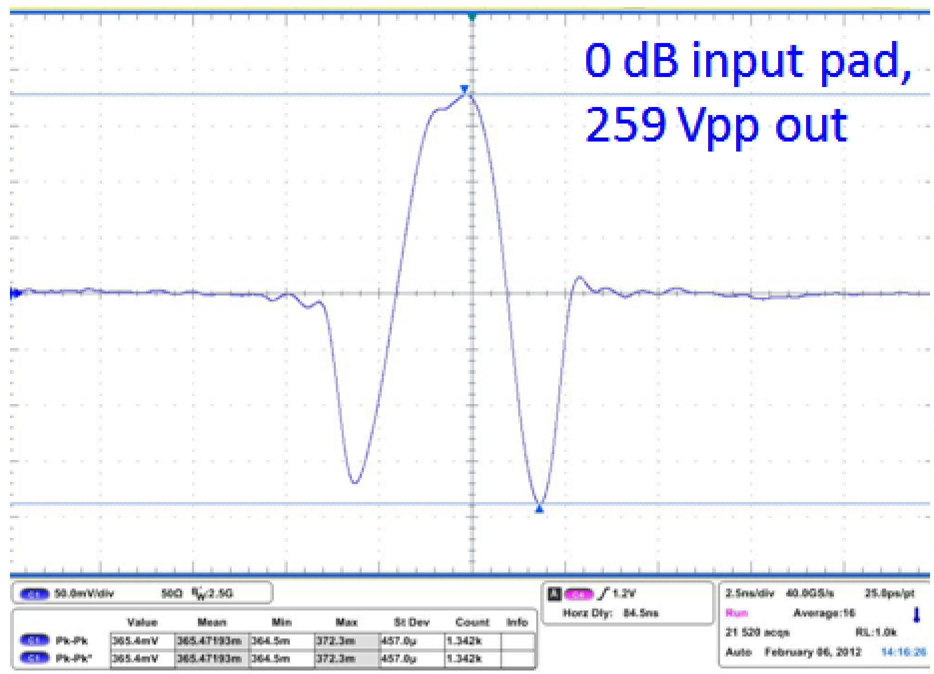
- 150 W amplifier makes almost half of the required voltage
- 1 kW amplifier should deliver±310 V
  - i.e. it has 25% margin, most of which will be absorbed by loss of kicker efficiency and the wave damping along the kicker

Gain nonlinearity

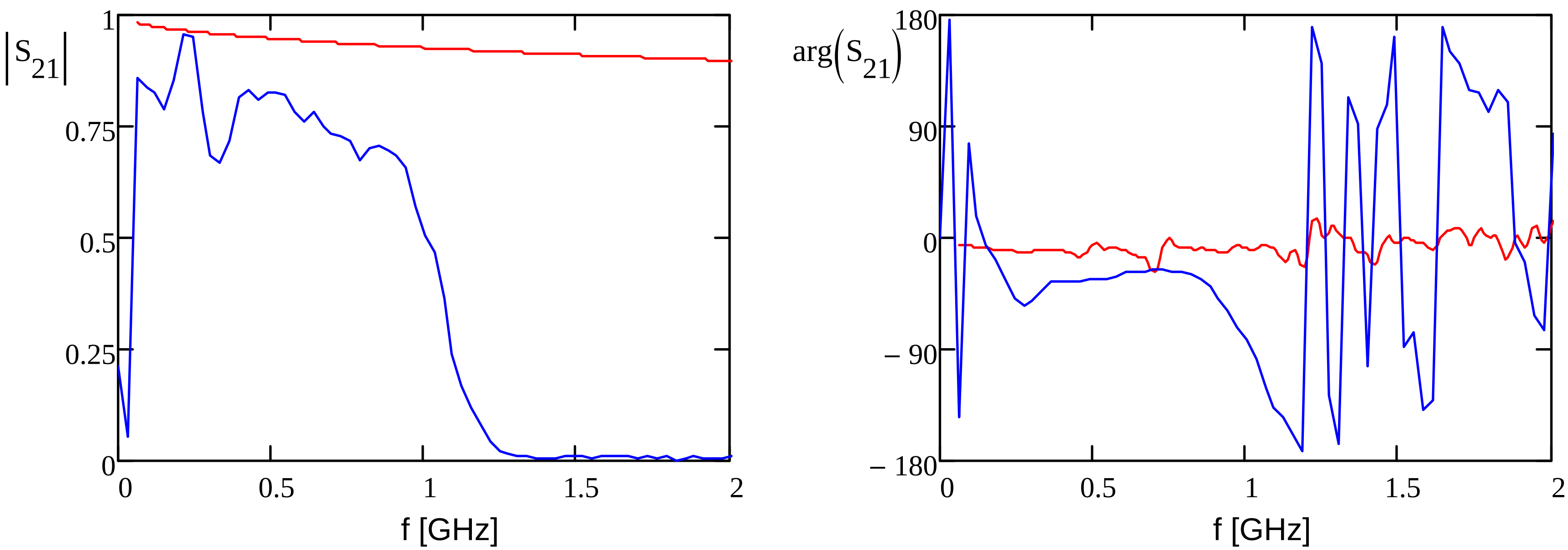




- Gain nonlinearity at high power can be compensated by iterative algorithm correcting shape of the pre-distorted pulses



Gain Correction for Kicker and Amplifier

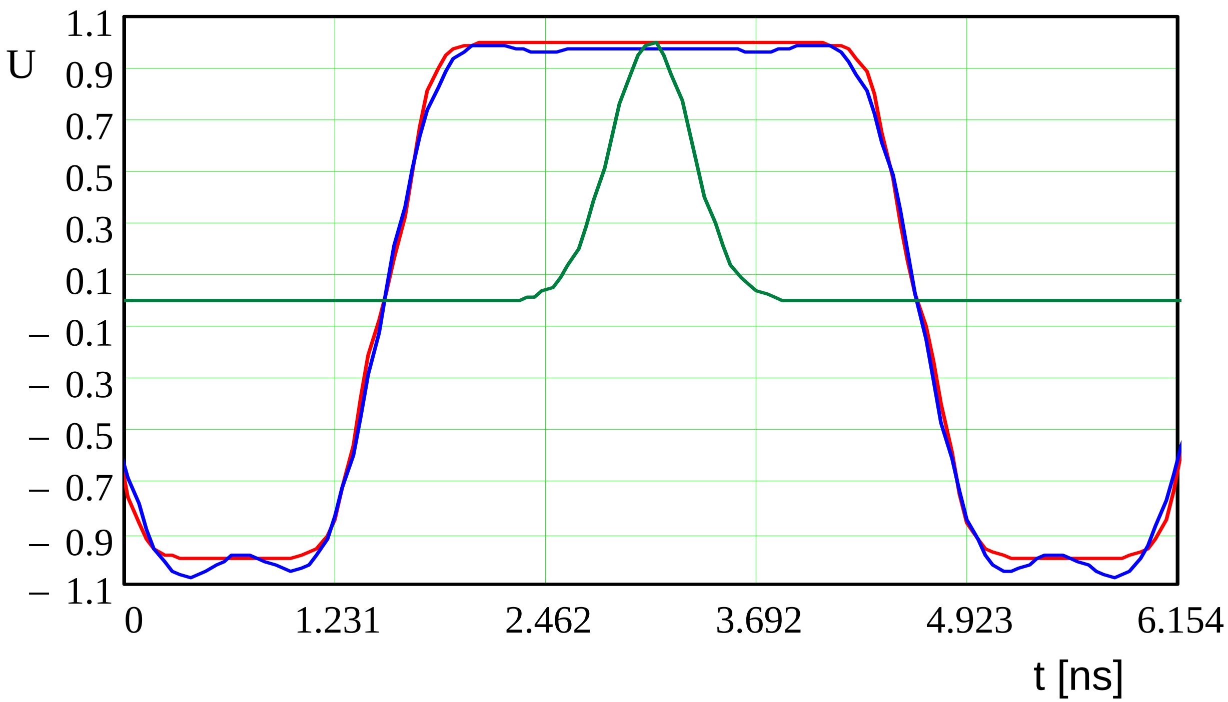


S_{21} for the kicker (red) and power amplifier (blue). S_{21} for the kicker is a projection of 6 electrode measurements to 25 electrodes

- Signal pre-distortion can additionally correct for dispersion in the kicker and connecting cables as well as reflections at transitions

Conclusions

- Design of 50 Ω kicker satisfies all requirements for the bunch-by-bunch Project X chopper operating at 162.5 MHz bunch rate
- All engineering problems look to be addressed
- Test of the full scale prototype is expected in the fall of this year
- Pulse pre-distortion allows us to use a commercial power amplifier
  - Tests performed with 150 W amplifier proved validity of the concept and exhibited excellent results



Backup slides

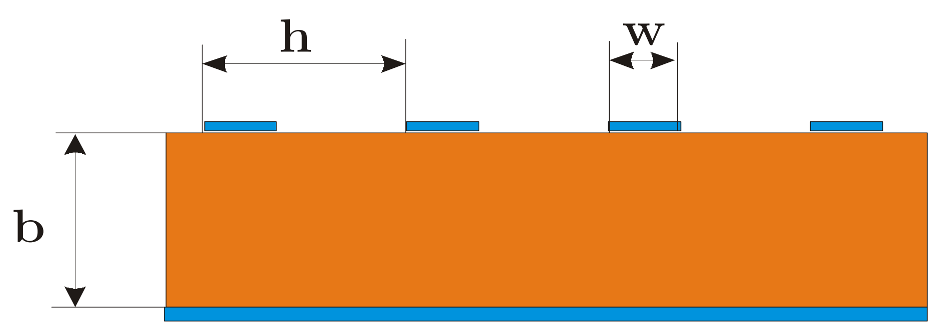
Simple analytical model (continue)

- If the same signals are propagated simultaneously in all lines the propagation speed is the same as in a single line
  - $\Rightarrow$ In the first order of perturbation theory for $\varepsilon = 1$ the inductive and capacitive coupling coefficients are equal

$$\kappa_C = \frac{C_1}{C_0}, \quad \kappa_L \approx \frac{L_1}{L_0}, \quad \kappa_C \approx \kappa_L$$

- Capacitance per unit length of a single stripe is
  - for w < b ($h \to \infty$) it can be simplified

$$C_0 \approx \frac{\varepsilon+1}{4} \frac{1}{\ln\left(\frac{16}{\pi}\frac{\varepsilon+1}{\varepsilon}\frac{b}{w}\right)}$$

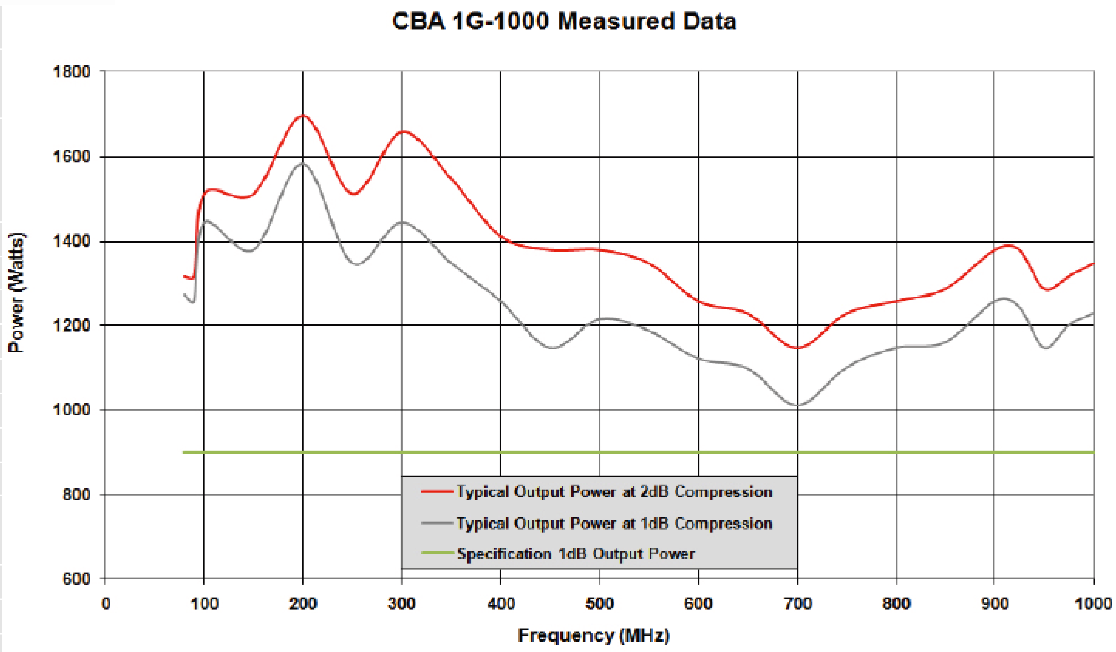


- Inductance per unit length
  - Does not depend on ε
  - It is inversely proportional to C_0 for $\varepsilon = 1$

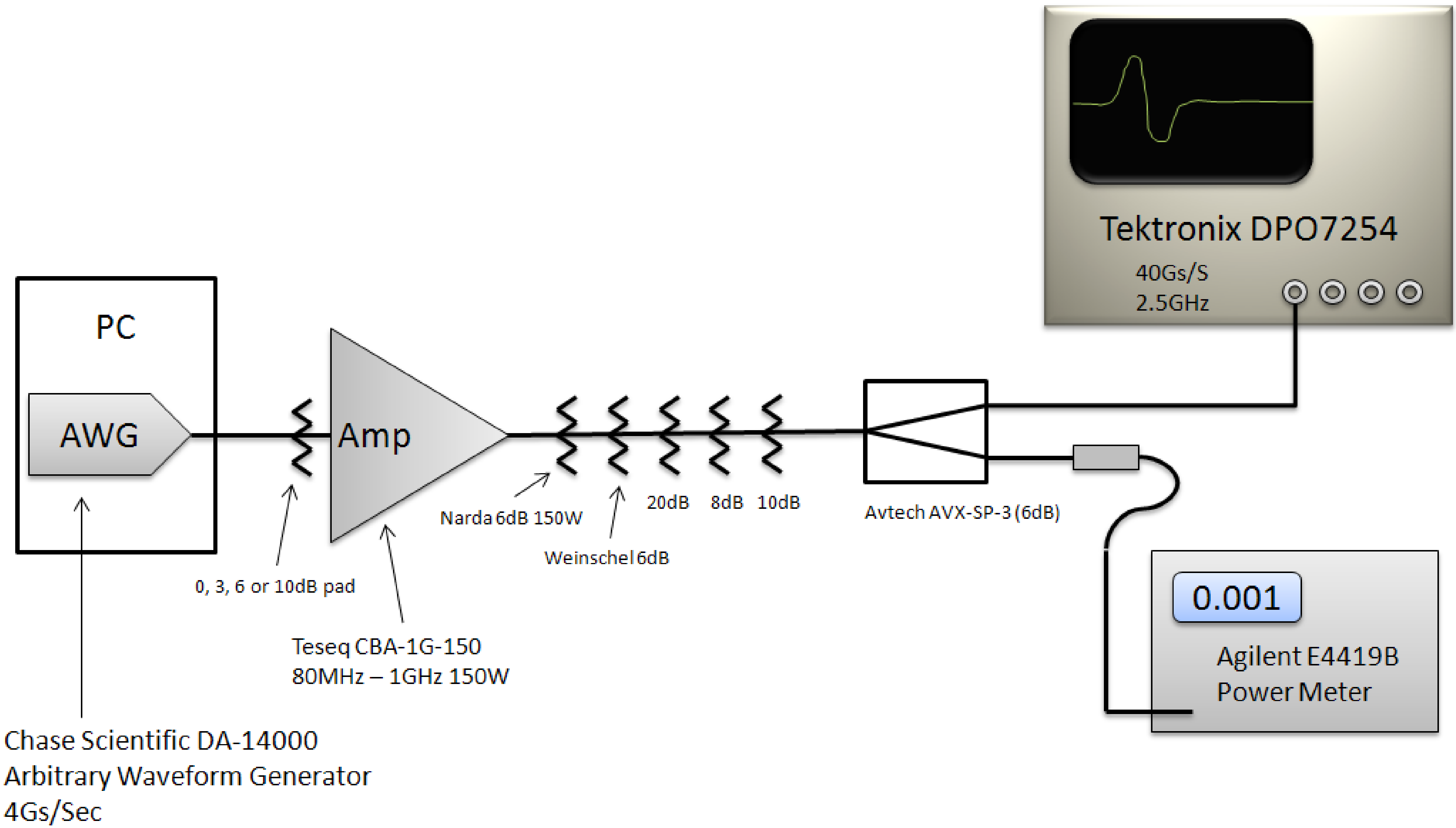
CBA 1G-1000
80 MHz TO 1 GHz 1000 WATT CLASS A BROADBAND AMPLIFIER

Technical specifications

Frequency range (instantaneous)	80 to 1000 MHz
Rated output power	1000 W minimum (1400 W typical 80 MHz to 500 MHz)
Output power at 1 dB gain compression	800 W minimum (1200 W typical 80 MHz to 500 MHz) (1000 W typical 80 MHz to 1 GHz)
Gain	61 dB
Third order intercept point (see note 1)	70 dBm
Gain variation with frequency	±3 dB
Harmonics at 800 W output	better than -20 dBc
Output impedance	50 Ohms
Stability	Unconditional
Output VSWR tolerance (see note 2)	Infinite any phase
Input VSWR	2:1
RF connector style	Input type N female Output 7/16 female
Safety interlock	BNC female, s/c to mute
USB interface	Optional
Supply voltage	170 to 264 Vac
(see options for three phase configuration)	
Supply frequency range	45 to 63 Hz
Supply power	<6 kVA
Mains connector	Appropriate IEC60309 plug (see options)
Conducted and radiated emissions	EN 61326 Class A
Conducted and radiated immunity	EN 61326: 1997 table 1
Mains harmonic currents	EN 61000-3-2
Voltage fluctuations and flicker	EN 61000-3-3
Safety	EN 61010-1
Case dimensions	34U rack, 800 mm deep
Mass	200 kg
Operating temperature range	0 to 40°C
Options (select at time of ordering)	
341-826	Three phase plus P.E. delta connection no neutral (4 pin plug), voltage range applies Line to Line
341-926	Three phase, neutral plus P.E. star connection (5 pin plug), voltage range applies Line to Neutral



Test Setup


Tektronix DPO7254
40Gs/S
2.5GHz
PC
AWG
Amp
Narda 6dB 150W
20dB
8dB
10dB
Avtech AVX-SP-3 (6dB)
Weinschel 6dB
0, 3, 6 or 10dB pad
0.001
Agilent E4419B
Power Meter
Teseq CBA-1G-150
80MHz – 1GHz 150W
Chase Scientific DA-14000
Arbitrary Waveform Generator
4Gs/Sec