MEBT and Chopper Section

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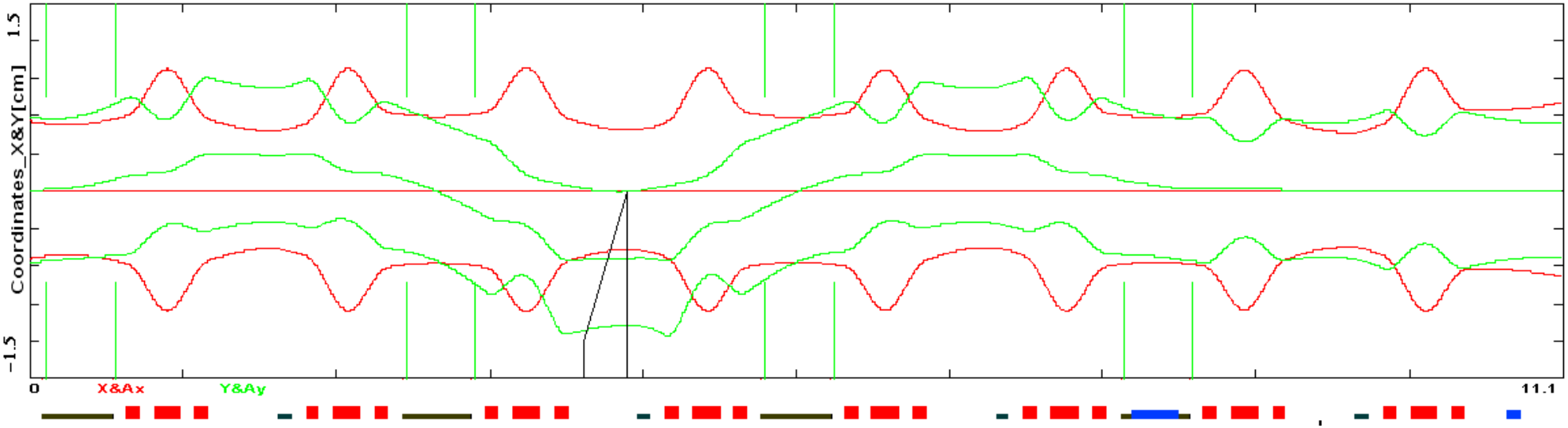
- Optics
- Kicker
- Beam dump

MEBT Optics

- Here and below we assume:
  - f_{RFQ}=162.5 MHz
  - ε_{n_rms}=0.25 mm mrad
  - Energy – 2.1 MeV (for easier comparison to BNL proposal)
    - Final choice (2.1 – 2.5 MeV?) needs to be done
- Four 50 cm kickers (installed in every second cell)
  - 90 deg. per cell $\Rightarrow$ 180 deg. between kickers
  - Small beam displacement in each kicker

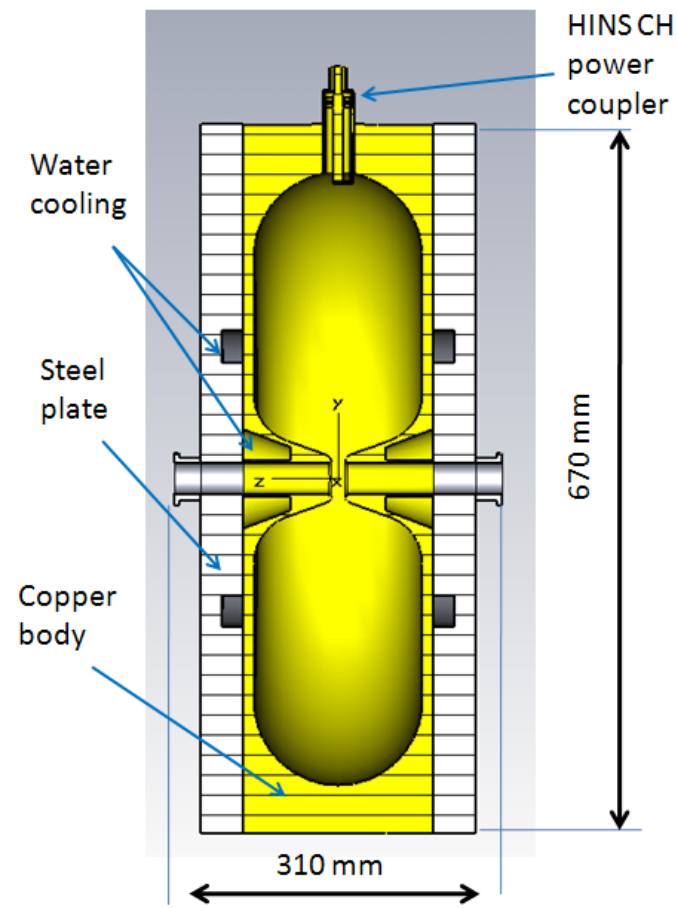
    $\Rightarrow$ Smaller aperture $\Rightarrow$ smaller voltage
  - Two kickers excite the motion and the other two damp it

    $\Rightarrow$ Beam current regulation with bipolar partial kicks
      - "+U" – no chopping;
      - "-U" – chop the bunch;
      - "0" – 50% beam current scraped
    - If all four kickers are used in phase => U→U/2



3σ beam size; V kick=±190 V, gap=±7.4 mm, I_{beam}=5 mA (linear SC), L_{tot}=11.1 m

- 4 cavities (installed in every 2-nd cell)
  - RF cavities are displaced from centers of straights to make space for the beam dump
  - Cavity transverse defocusing strongly affects optics
    - For f_{RF}=325 MHz, V≈40 kV
    - μ_L=90 deg (per two cells)



- 325 MHz is OK if $\varepsilon_L \leq 1$ μeV s
  - $\sigma_{\phi_max} \approx 18$ deg @ 1 μeV s & $I_{beam}=0$
  - Larger ε_L will require 162.5 MHz cavities with 2 times larger voltage (~82 kV)
    - For the same μ_L the low frequency RF will have the same effect on transverse focusing

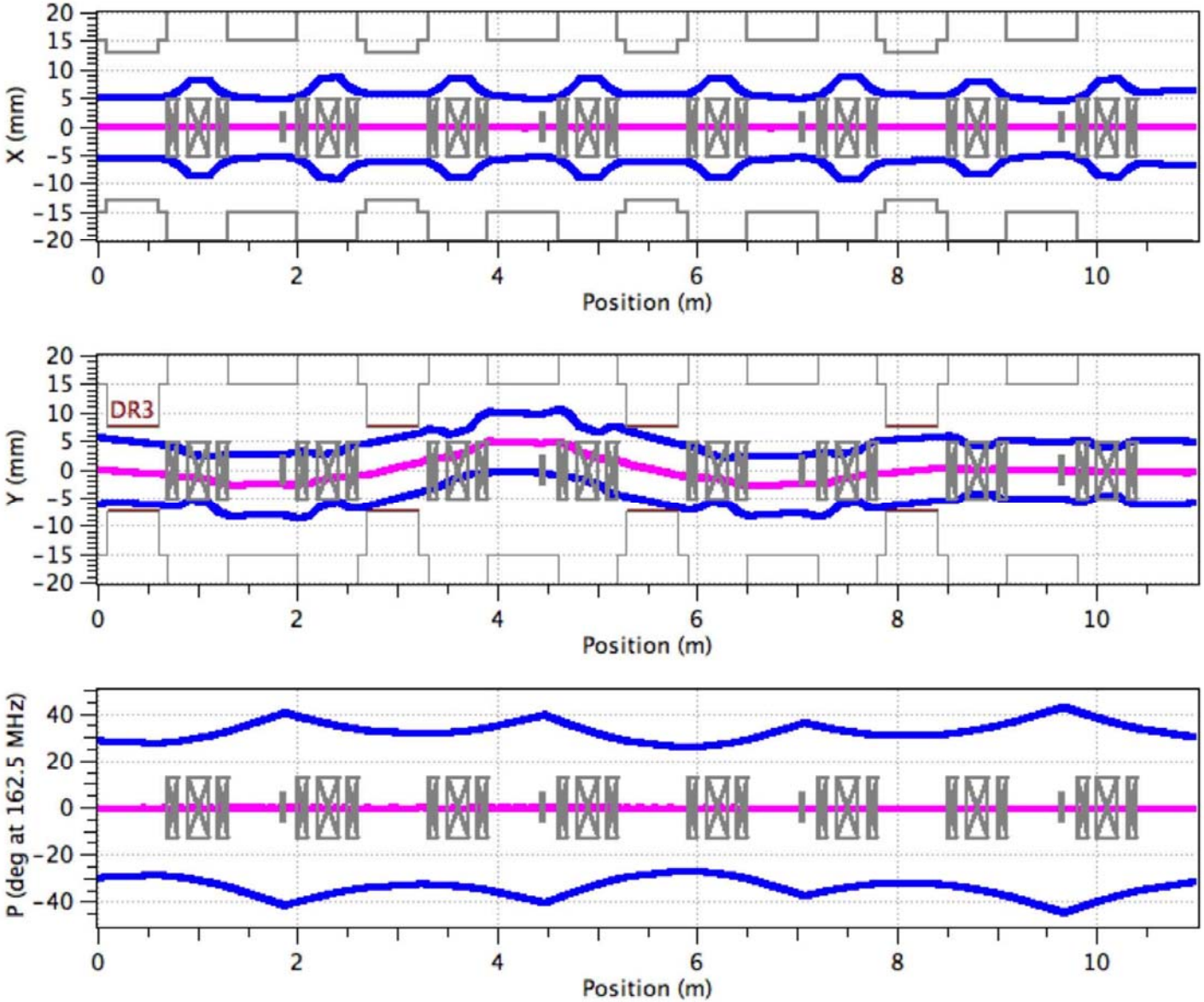
- Transverse and longitudinal focusing are beam current dependent

  ⇒ Independent control for each triplet and cavity

  - Matching beam envelope at MEBT entrance suppresses the beam envelope oscillations and emittance growth
  - Space charge increases the beam size

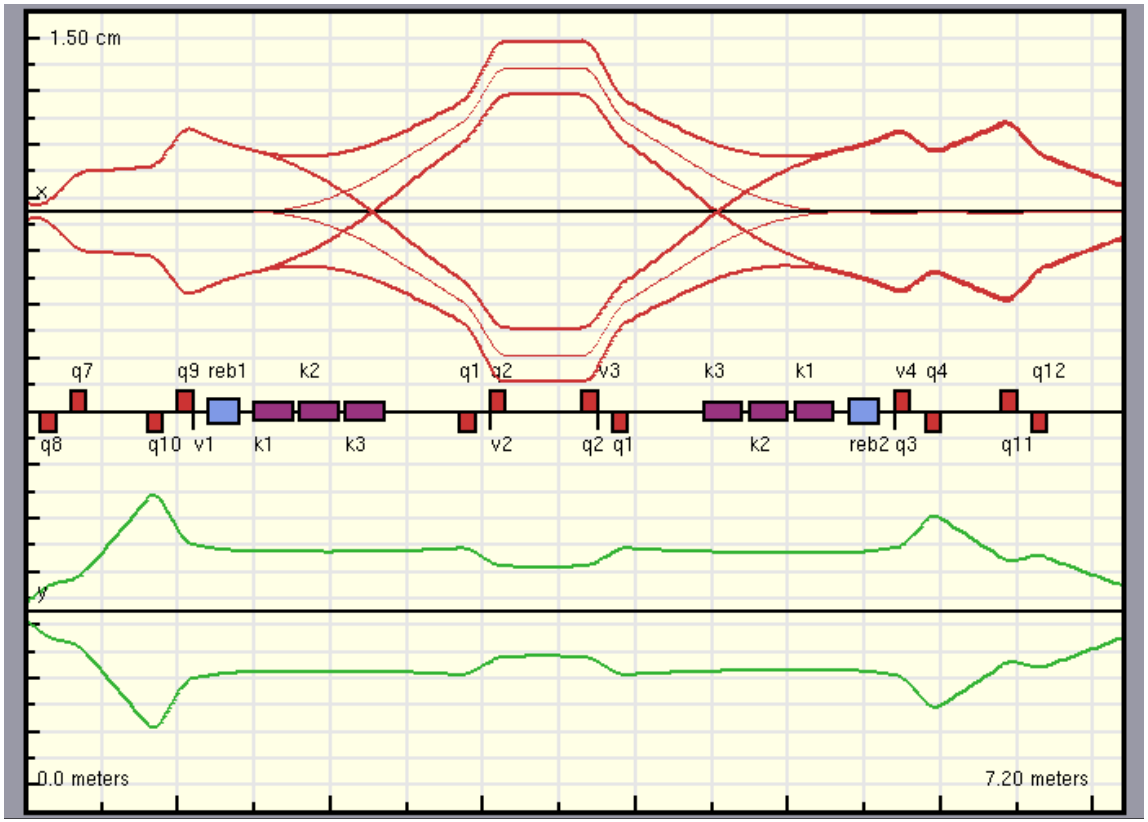
    ⇒ required kick grows by ~20-30% for 5 mA beam

MEBT Optics Simulations with Space Charge



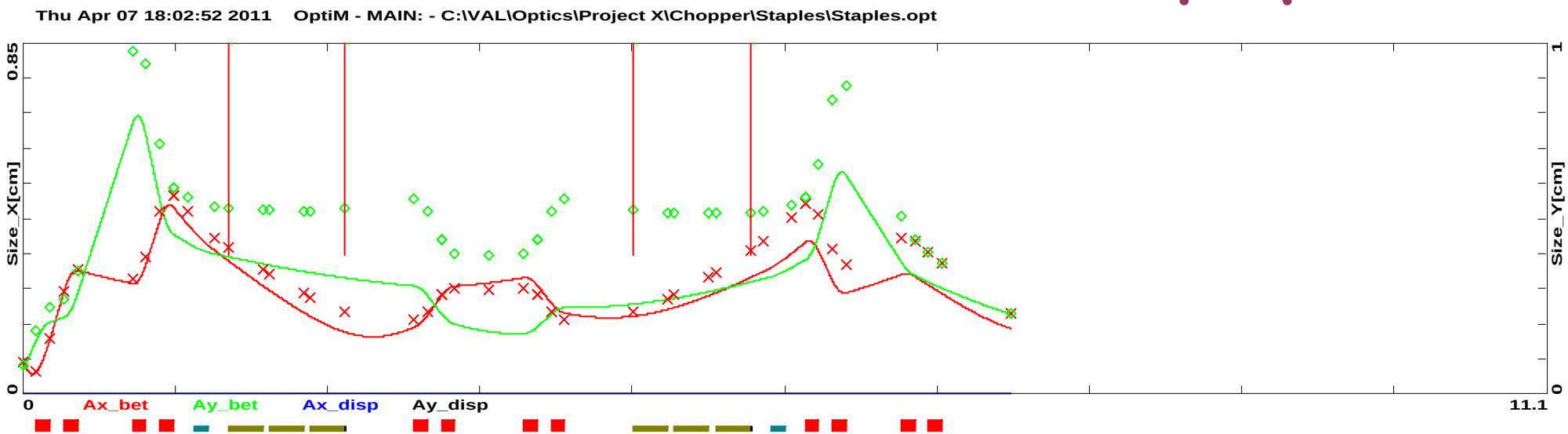
5 mA 162.5 MHz, 2.5 MeV

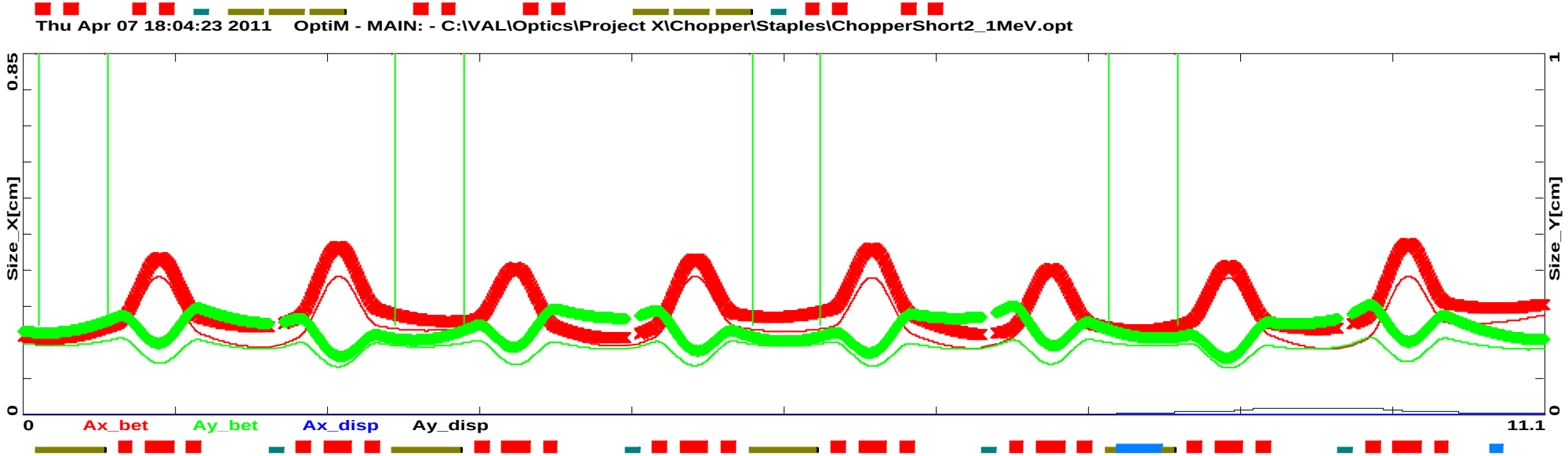
Alternative proposal (John Staples, LBNL)



- Similar to SNS chopper-antichopper
- Accommodates both narrow or wide bandwidth chopper schemes.
- Uses 12 quadrupoles, two 325 MHz rebunchers (blue)
- Three 25 cm choppers (purple) in tandem,each side of center, either NB or WB.
- "Flat" beam in 50 cm drift space in center for collimator(s).
- For wideband chopper, beam is offset in one direction to pass through, deflected in opposite direction to be stopped.
- For narrowband chopper, beam is deflected in both directions to be stopped, and goes straight through undeflected. Collimators symmetric across center.
- Overall length 7.2m, which includes matchers on each end: from RFQ and round beam to spoke structure on right to spoke cavity.
- The beam in the y-plane is slightly wider to reduce the power density.

1σ beam sizes for FNAL and LBNL proposals





LBNL (top): V kick=±285 V, gap=±10 mm, L_{tot}=7.2 m

FNAL (bottom): V kick=±190 V, gap=±7.4 mm, L_{tot}=11.1 m

vertical lines show 1/3 of kicker aperture, lines: I_b=0, crosses: I_b=5 mA

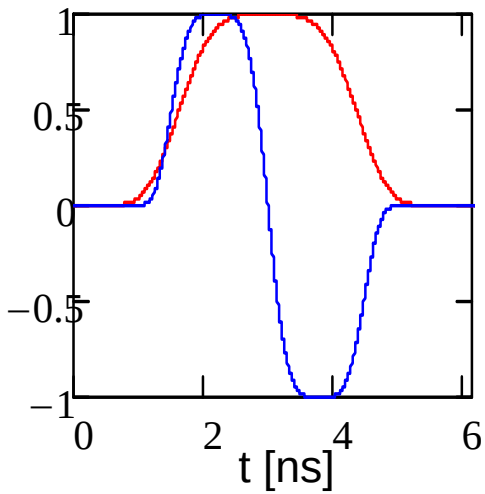
(the same longitudinal density is implied)

LBNL proposal

- Has shorter length
- Less quads and cavities
- 1.5 times larger distance between cavities
  - Smaller longitudinal acceptance
- More sensitive to the beam space charge
- Requires 12% larger integral kicker strength (looks that it can be better optimized?)
  - Requires 1.5 times larger single kicker strength
- Both designs show sufficiently small emittance growth and particle loss

MEBT Kickers

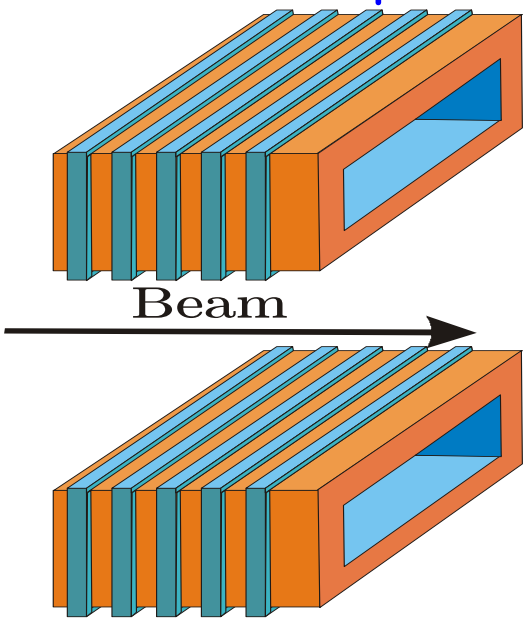
Requirements and Limitations

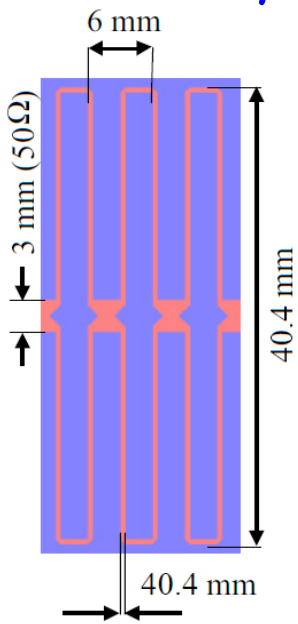


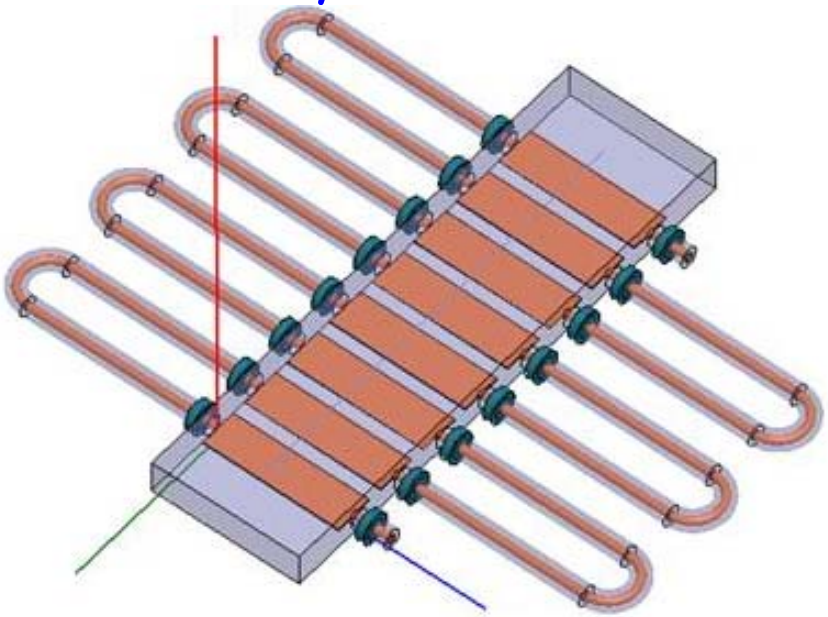
- 4 kickers:
  - L=50 cm (2*25 cm) , U_{eff}=±200 V (gap 15 mm)
- 6.1 ns between bunches
  - ⇒ Bunch-to-bunch distance 13.4 cm
  - ⇒ Wave velocity should match the beam velocity
  - ⇒ Bandwidth ~0.3 GHz for unipolar kicks
- Bipolar kicks
  - Allow the beam current regulation
- Reduce voltage of power amplifier in 2 times (power 4 times)
  - "+U" - pass & "-U" - kill
  - But twice larger bandwidth ~0.5 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

Possible Implementation for Kickers

- There are 3 ways to decelerate the wave
  - Coiled kicker (Spiral kickers for old "GHz scopes")
  - Meander (CERN proposal)
  - Short plates connected by a coaxial delay lines





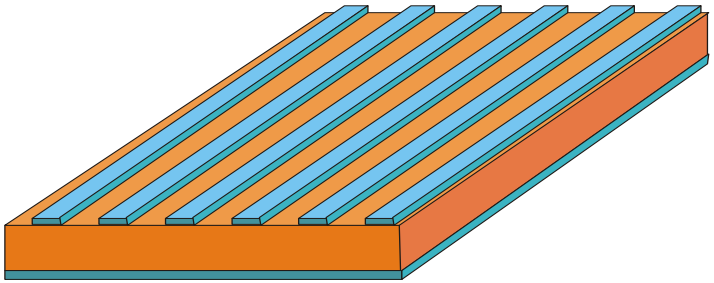


Major effects limiting the bandwidth

- Coupling between stripes
- Reflections from discontinuities
- Losses in the conductor and dielectric

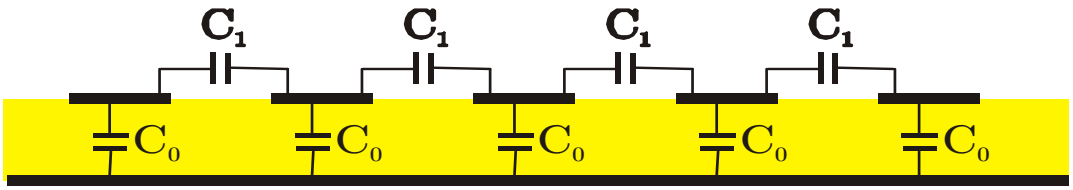
Simple analytical model for wave propagation

- In absence of coupling between nearby lines it can be considered as a transmission line
  - For a single line the dispersion is small and is dominated by loss in the conductor



- Equations for parallel lines (coupling is on)

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

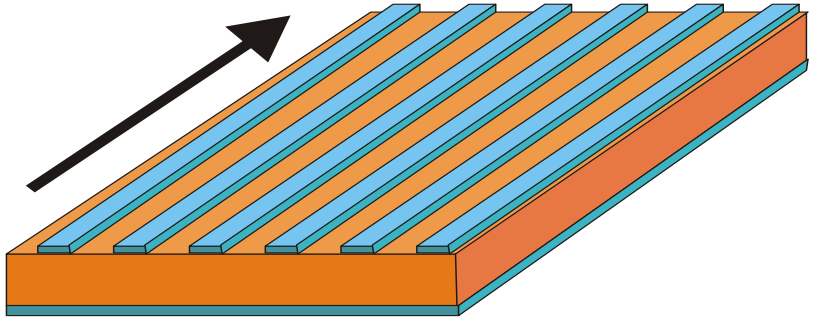


sign "-" if currents in nearby lines go in the same direction,
"+" – otherwise

- *C_0 & L_0 – capacitance & inductance per unit length*
- *n – numerates lines*

- For ε = 1 and waves propagating in the same direction in multiple lines the phase velocity is equal to c or

$$\boxed{c = \frac{1}{\sqrt{(C_0 - C_1)(L_0 + L_1)}}}$$



$\Rightarrow$ In the first order of perturbation theory
the inductive and capacitive coupling coefficients are equal

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

Coefficients of Potential & Coef.of Capacity

- Coefficients of potential S_{ik}: $\varphi_i = S_{ik} q_k$, $S_{ki} = S_{ik}$
  - For small strip width *(w << b, h)* S_{ik} is weakly affected by presence of other strips
- Coefficients of capacity

$$[C_{ik}] = [S_{ik}]^{-1} \quad , \qquad C_{ki} = C_{ik}$$

  - *C_{ik} decays faster than S_{ik} due to screening*
- Capacitive coupling coefficient

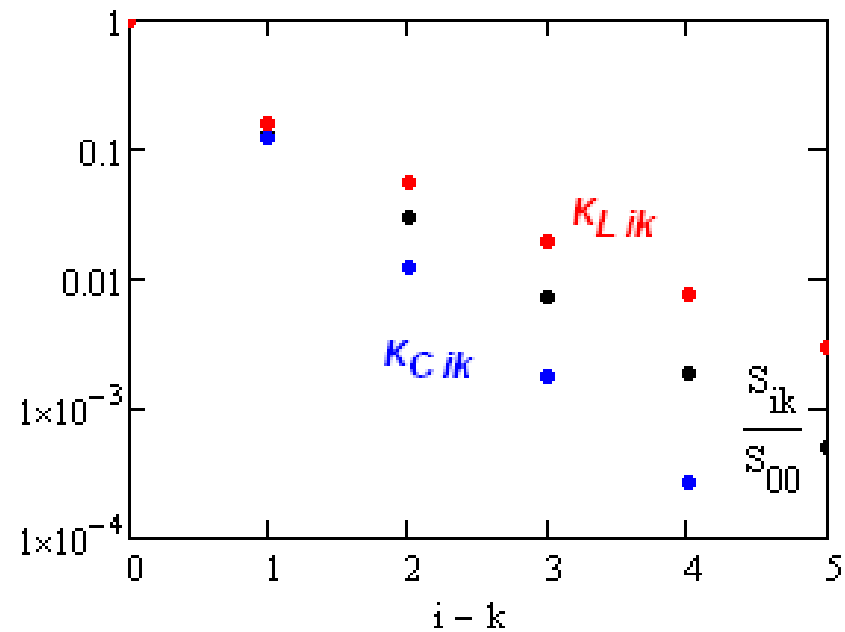
$$\kappa_{C_i} = -\frac{C_{k,k+i}}{C_{0,0}}$$

accounting nearby strips only

$$\kappa_C \equiv \kappa_{C_1} = -\frac{C_{0,1}}{C_{0,0}} \Rightarrow \quad C_0 \equiv C_{0,0} = \frac{C_{sngl}}{1 - 2\kappa_C{}^2}$$

- Inductance coupling coefficient

$$\kappa_{L_i} \equiv \frac{M_i}{L_0} = \frac{S_{k,k+i}}{S_{k,k}}\bigg|_{\varepsilon=1}$$



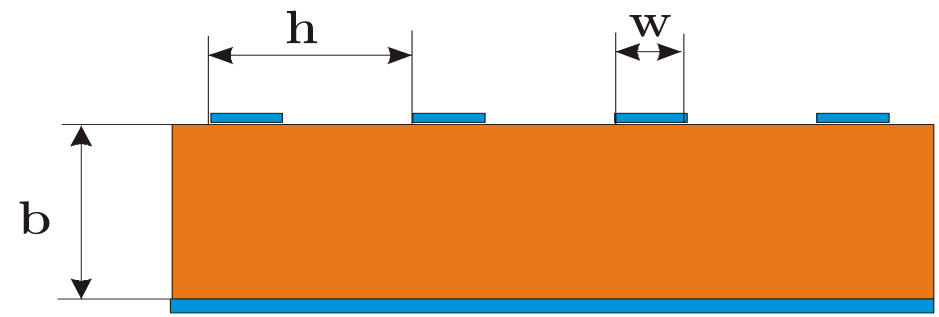
CERN meander

ε=9.6, b_1=3 mm, b_2=7 mm

Capacitance and Inductance of single stripe

- For $w < b$ ($h \to \infty$) the capacitance per unit length of a single stripe is

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



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

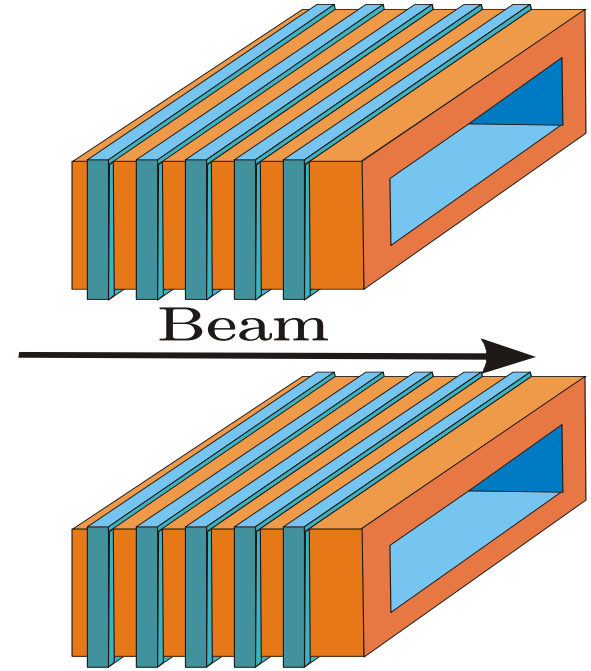
=> $$L_0 = \frac{2}{c^2}\ln\left(\frac{32b}{\pi w}\right), \quad w < b$$

- The wave velocity for uncoupled strip:
  - not $\propto$ to $1/\sqrt{\varepsilon}$

$$v_L = \frac{1}{\sqrt{C_0 L_0}} \approx c\sqrt{\frac{2}{\varepsilon+1}\frac{\ln\left(\frac{16}{\pi}\frac{\varepsilon+1}{\varepsilon}\frac{b}{w}\right)}{\ln\left(\frac{32}{\pi}\frac{b}{w}\right)}}, \quad w < b$$

Coiled kicker

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



Looking for a solution in the form:

$$\begin{pmatrix} U(s,t) \\ I(s,t) \end{pmatrix} = \begin{pmatrix} U_0 \\ I_0 \end{pmatrix} e^{i(\omega t - kx)}$$

and taking into account boundary conditions

$$\begin{cases} U_{n+1}(s,t) = U_n(s+l,t) \\ I_{n+1}(s,t) = I_n(s+l,t) \end{cases}$$

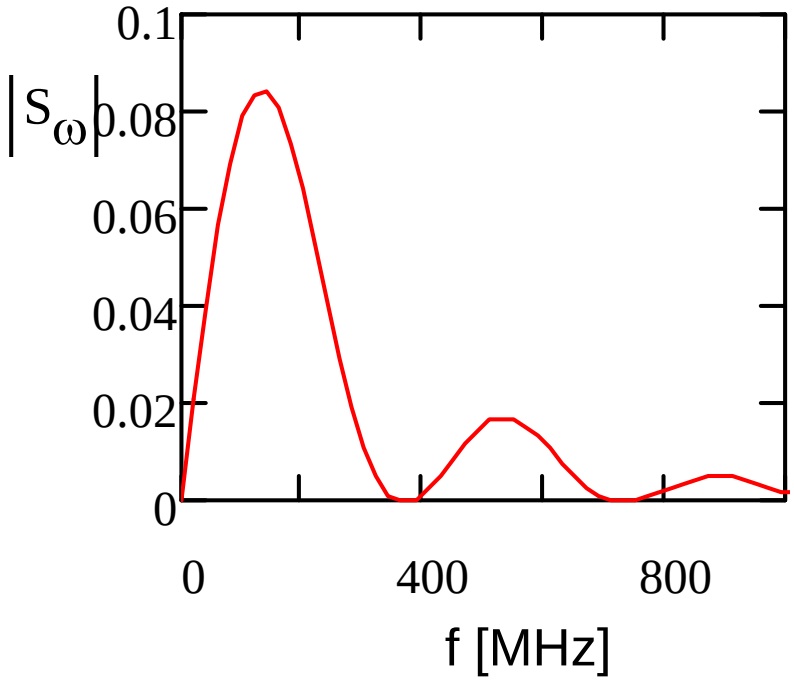
one obtains the dispersion equation

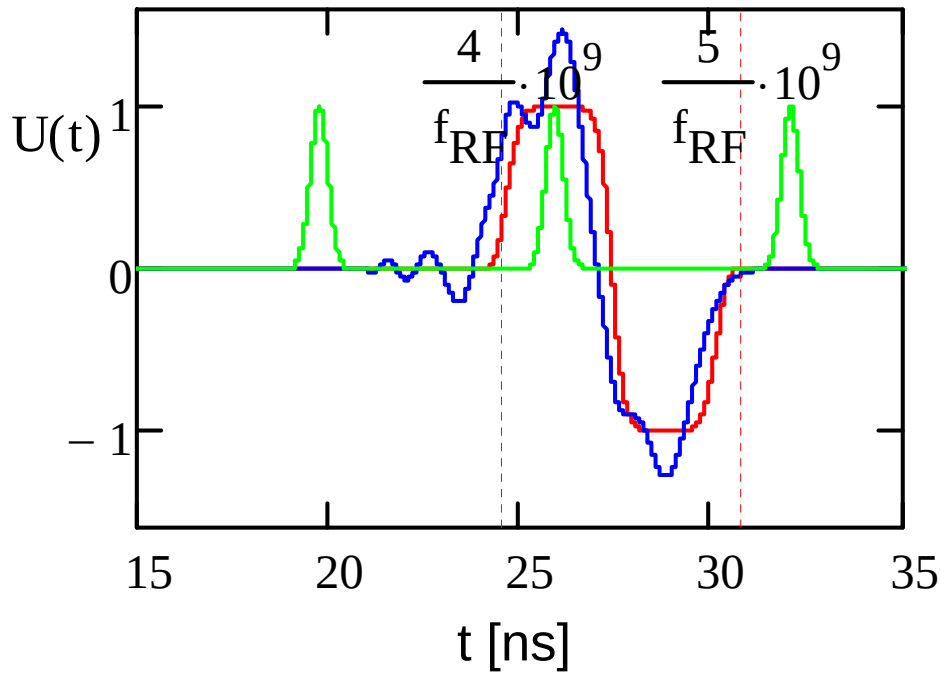
$$\boxed{k \approx \frac{\omega}{\mathrm{v}_L}\left[1 - (\kappa_C - \kappa_L)\cos\left(\frac{\omega l}{\mathrm{v}_L}\right) - 2\kappa_C\kappa_L\cos^2\left(\frac{\omega l}{\mathrm{v}_L}\right)\right]}$$

l – length of a single turn

ε – is dielectric permittivity

Coiled kicker (continue)

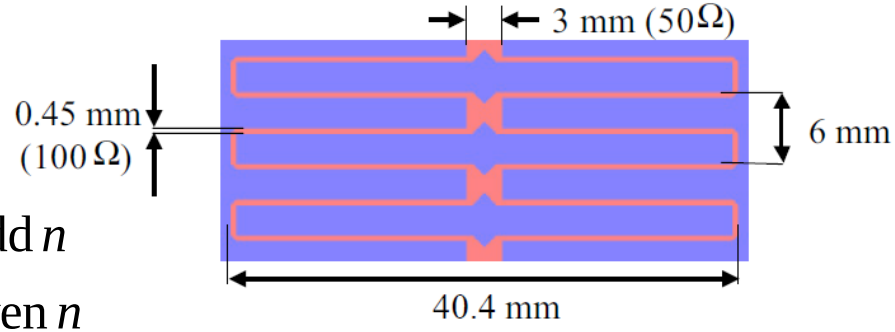




turn length - l=6.7cm, k_C = 0.053, k_L = 0.14, ε=3.5, h=6.5 mm, total length – 25cm

- Coupling coefficient was set to obtain sufficiently small pulse distortions
  - $\kappa \leq 0.1$ => large distance between turns => large kick attenuation
    - Reduction of one turn length would help but is limited by kicker width (i.e. beam size)

Meander kicker



Looking for solution in the form:

$$\begin{pmatrix} U(s,t) \\ I(s,t) \end{pmatrix} = \begin{pmatrix} U_1 e^{-ik_n x} + U_2 e^{ik_n x} \\ I_1 e^{-ik_n x} + I_2 e^{ik_n x} \end{pmatrix} e^{i(\omega t - mn)}, \quad k_n = \begin{cases} |k|, & \text{odd } n \\ -|k|, & \text{even } n \end{cases}$$

and taking into account the boundary condition:

$$\begin{cases} U_n(l/2,t) = U_{n+1}(l/2,t) \\ I_n(l/2,t) = I_{n+1}(l/2,t) \end{cases}$$

one obtains the dispersion equation

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

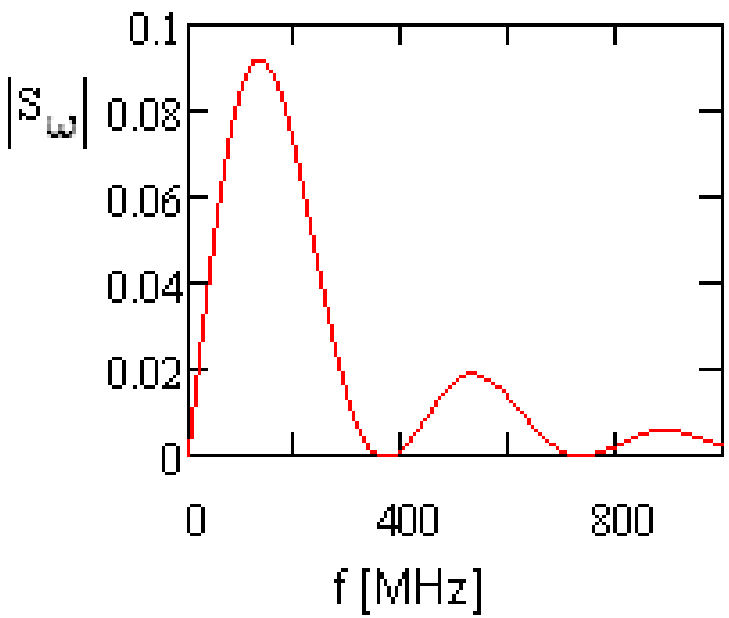
l – length of a stripe

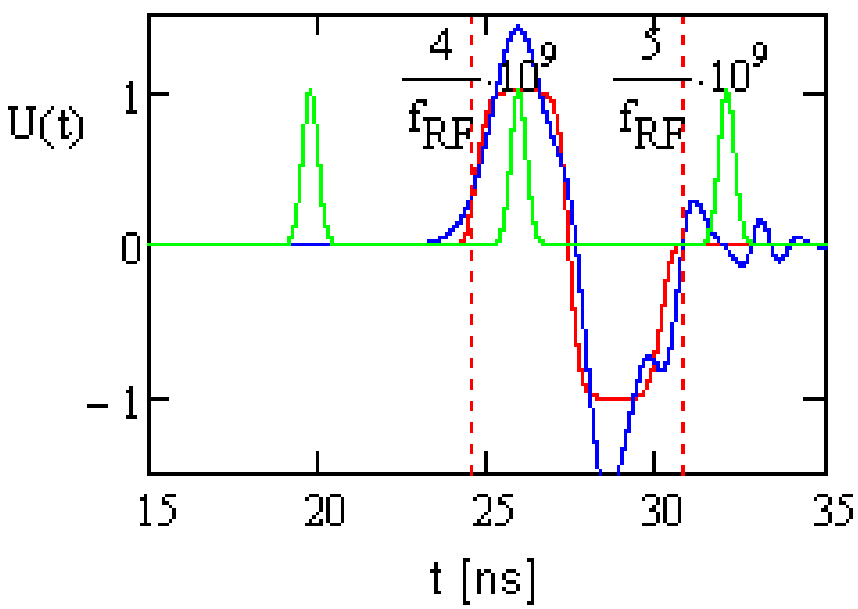
ε – is dielectric permittivity

- Same as for the coiled kicker the kicker impedance is frequency dependent
  - Reflections from kicker and its termination affect wave smearing less than dispersion

Meander kicker (continue)

- Unlike for the coil kicker the dispersion correction is $\propto \kappa_L + \kappa_C$ not to $\kappa_L - \kappa_C$
  - i.e. much larger effect for the same coupling
- However shorter period (more than 4 times) helps
  - It moves problems to higher frequencies
- Still looks that it does not address Project X needs



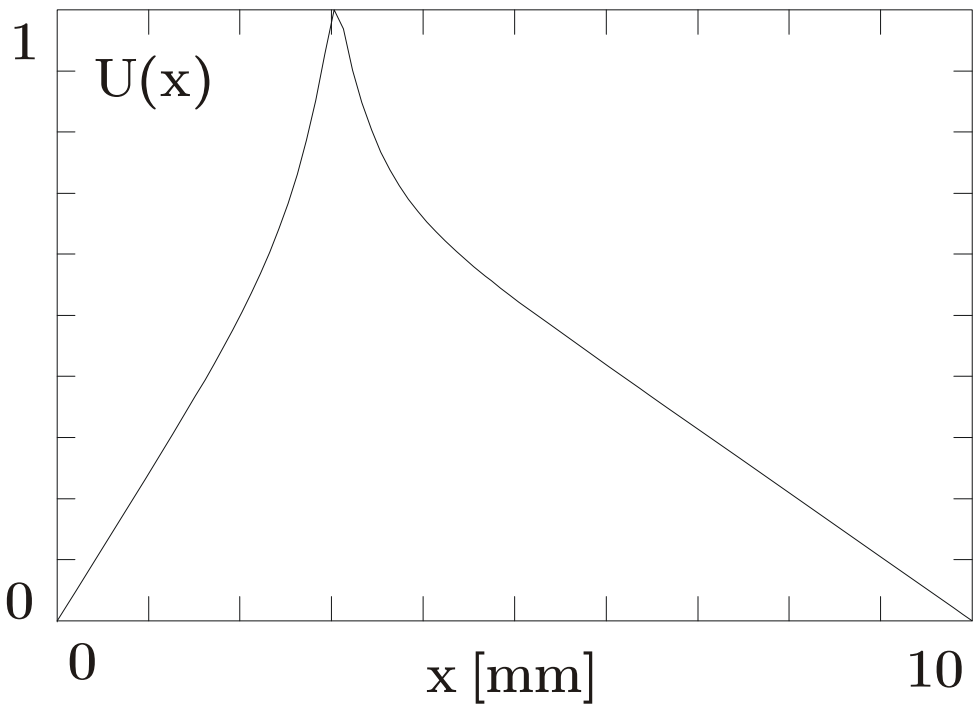


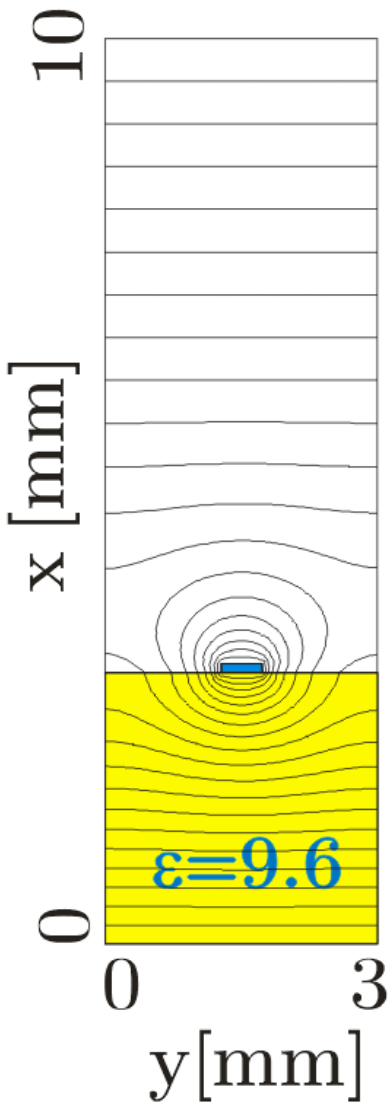
Pulse spectrum and propagation for the CERN kicker proposal adjusted to Project X needs; Ltot=25 cm, h = b = 2 mm, l = 22 mm, ε = 9.6

Problems with CERN meander kicker

- Dielectric is directly visible by the beam and can be charged by its tails

  $\Rightarrow$ Uncontrolled beam displacement
- Hardly can achieve the desired bandwidth
- Bad kicker efficiency: ~60% ($U_{eff} \geq 0.6U_0$)

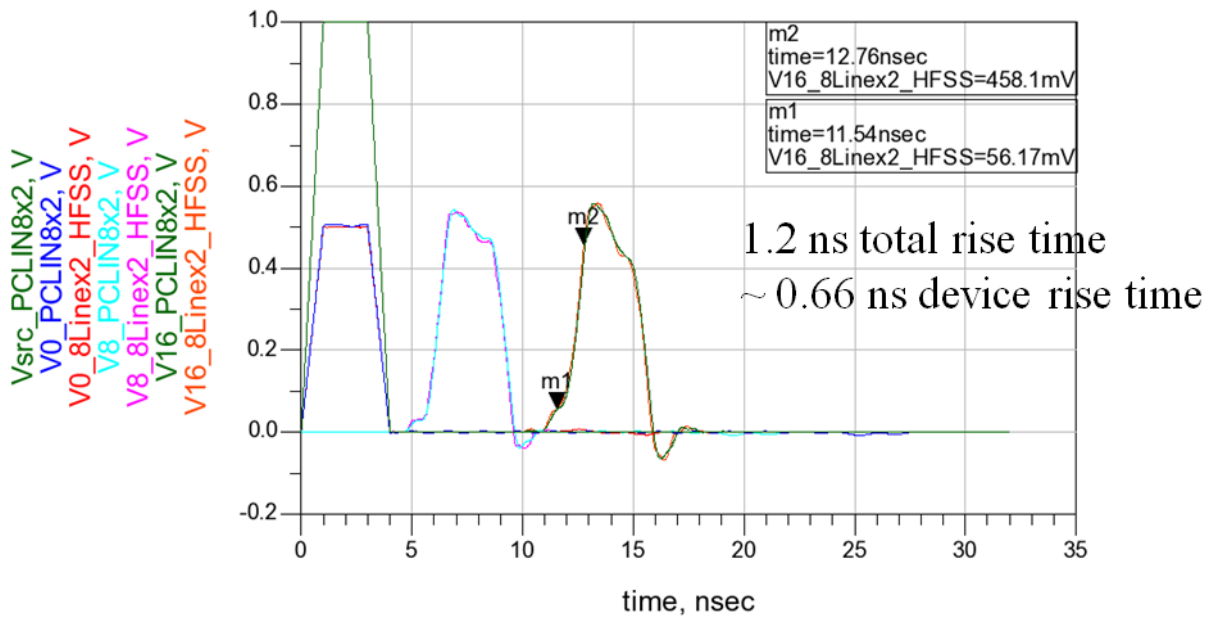


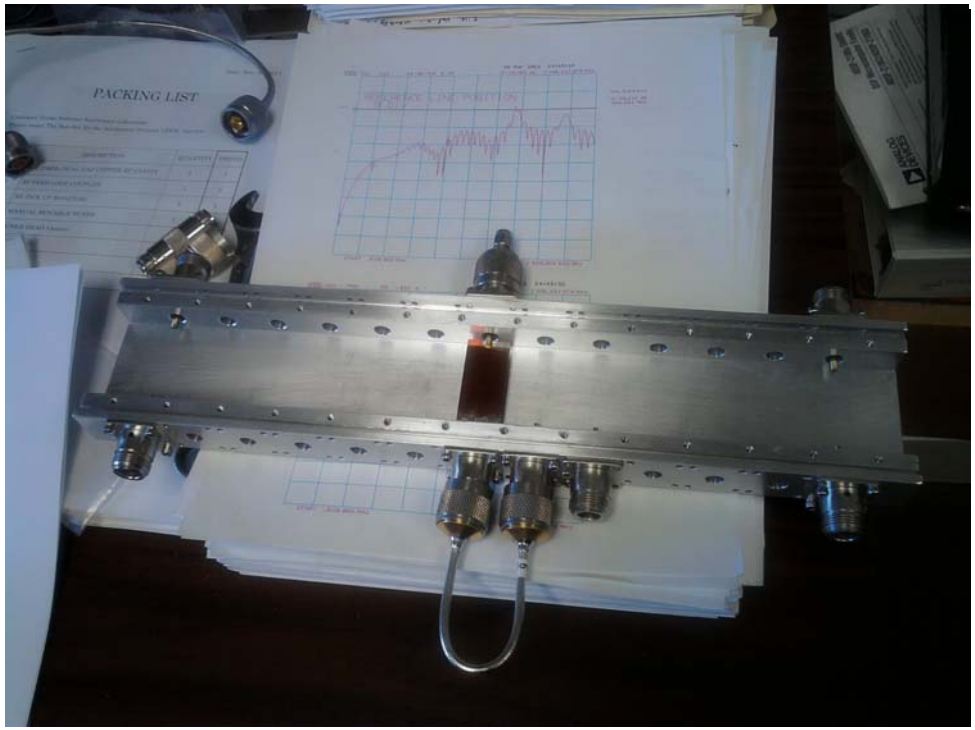


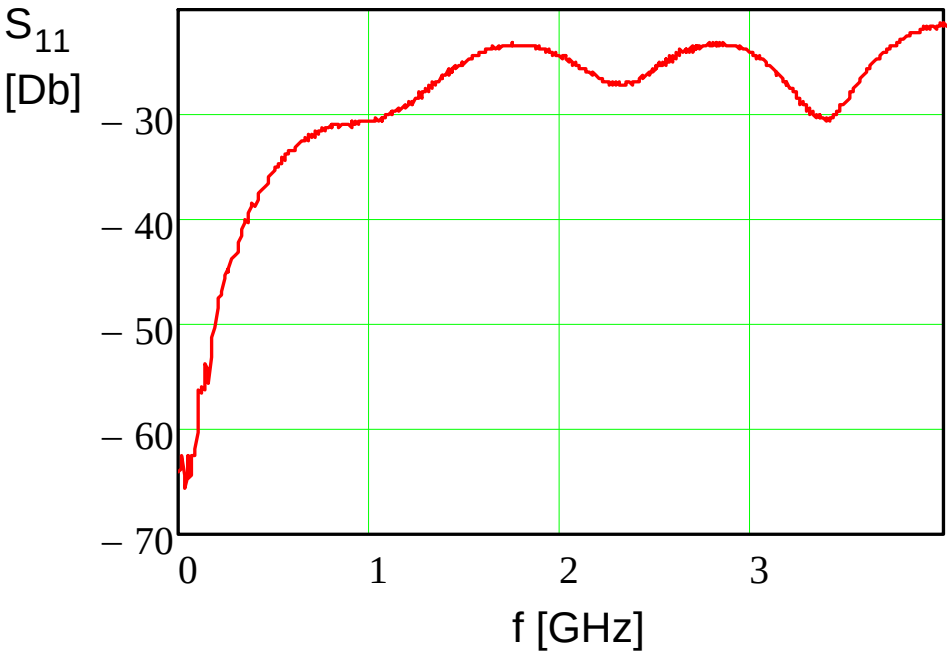
Alternative Approach for Chopper Design

- No dielectric => No charging of the surface
- "RF cable" connection between stripes
  - Smaller effective coupling between lines
    - Local coupling can be increased => More effective kicks !!!
  - Water or air cooling of stripes is possible
- Expected problems
  - Reflections at the transitions
- Tests of prototype based on the cable delays is going on
  - Tests of single and 7 of 11 electrodes are very encouraging
  - Complete kicker test within next 2 weeks

16 Striplines, 4 ns pulse / 1 ns rise time

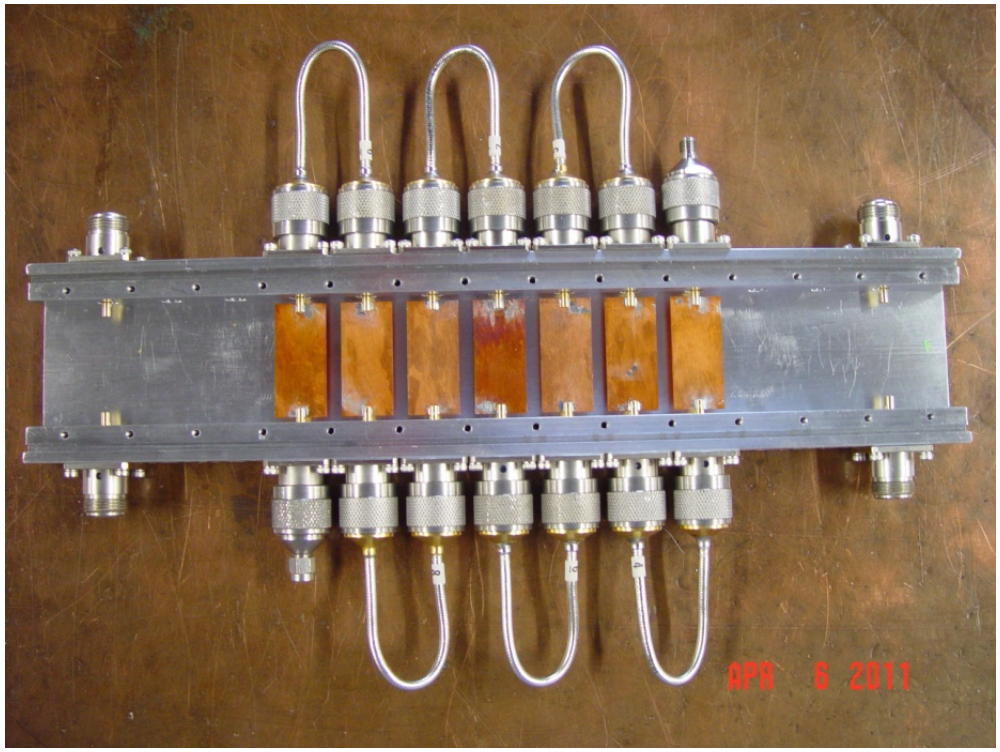




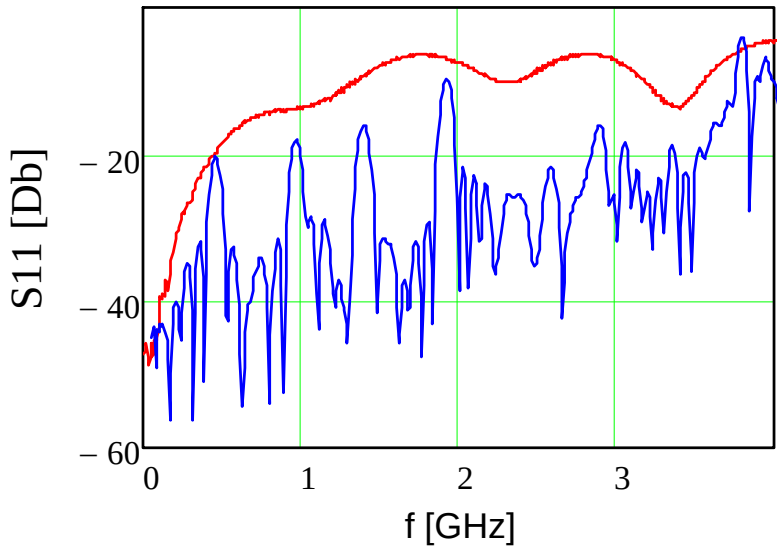


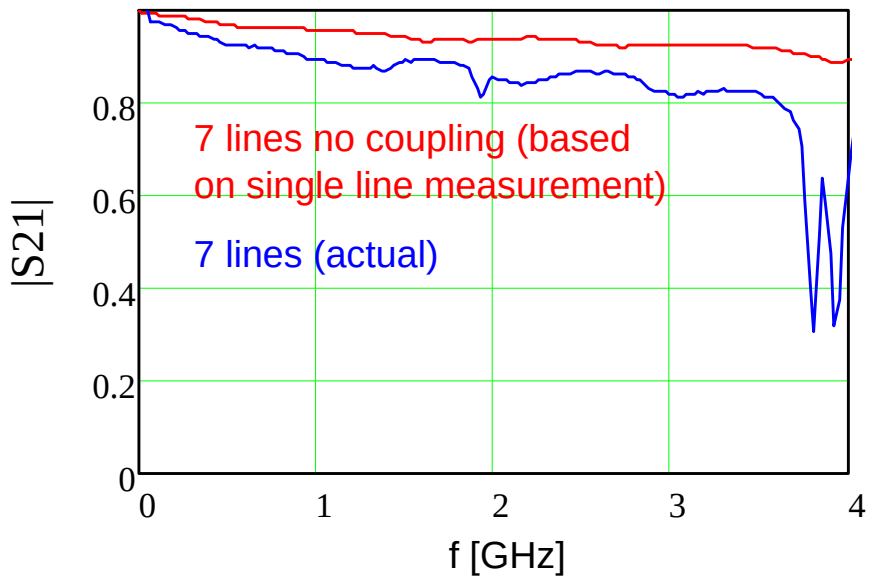
S_{11} for a single electrode (electrode length=40 mm, width=18 mm, step=23 mm.)

- 7 lines were recently measured

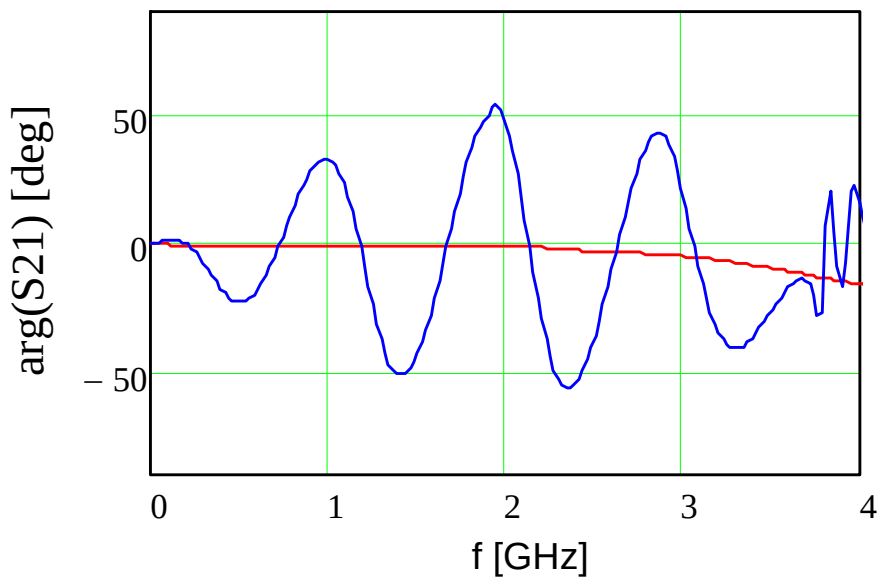


Comparison of network analyzer measurements for 1 and 7 electrodes



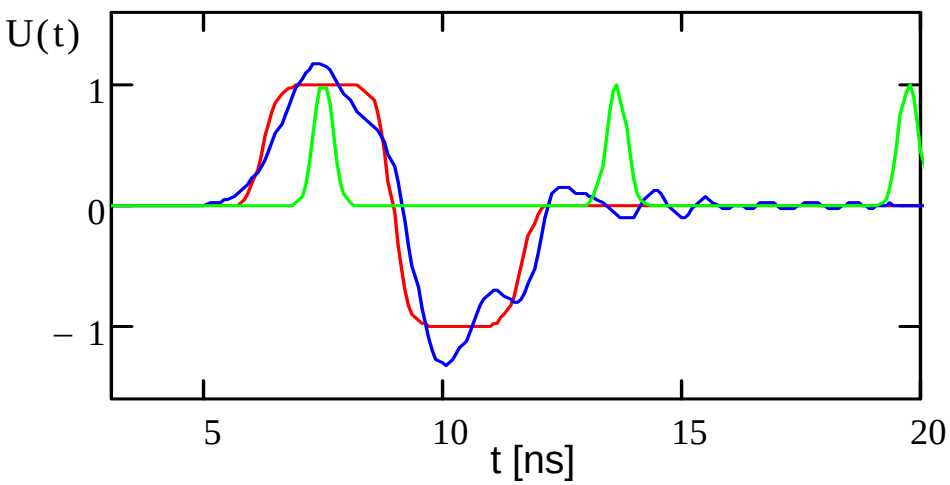


- Reflection from the kicker with 7 electrodes is smaller than it could be expected from single line measurement
- S21 magnitude is damped faster because of damping in the cable
- Phase is strongly affected by coupling between lines



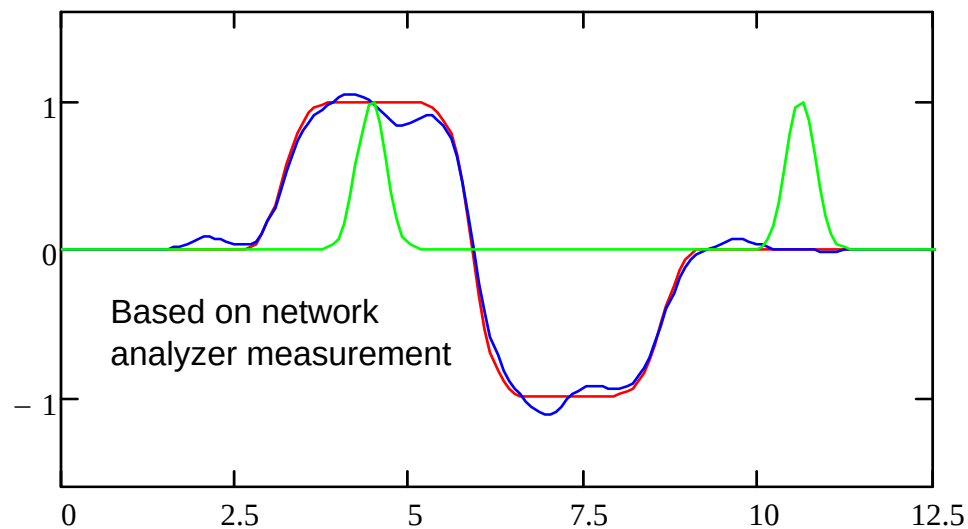
Measurements with 7 of 11 electrodes

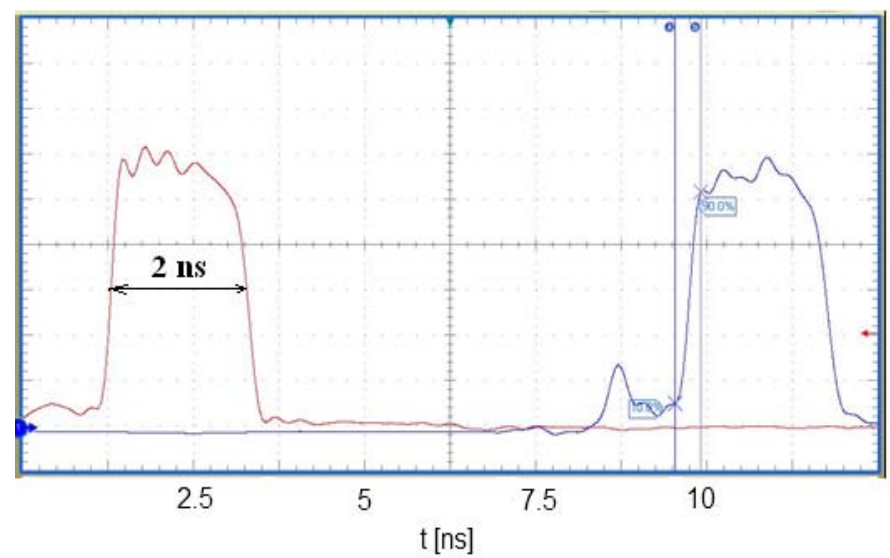
- Very good results for 16 cm kicker
- It is already clear that the prototype of 25 cm kicker will satisfy the requirements
- Much better than CERN meander



Simulation of signal distortion after 16.1 cm of CERN meander

- Next step is a design of actual kicker
  - Vacuum & Cooling

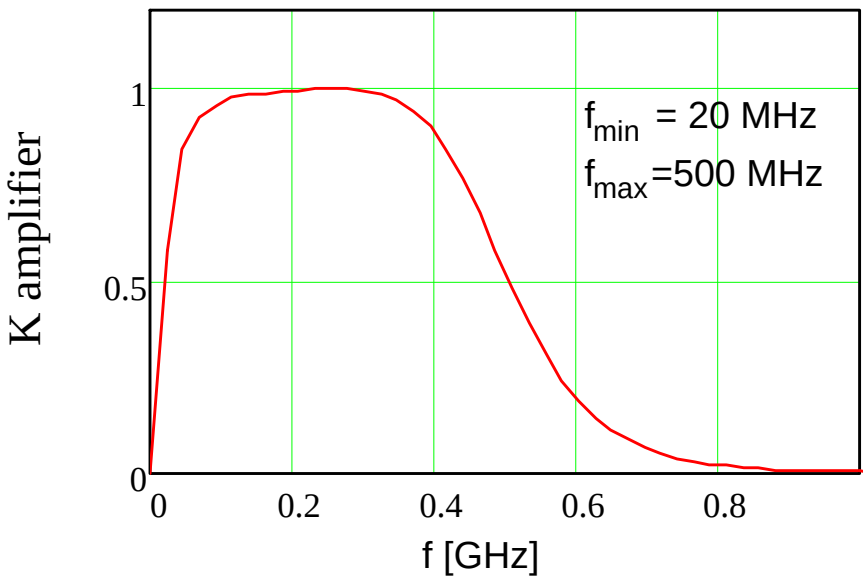


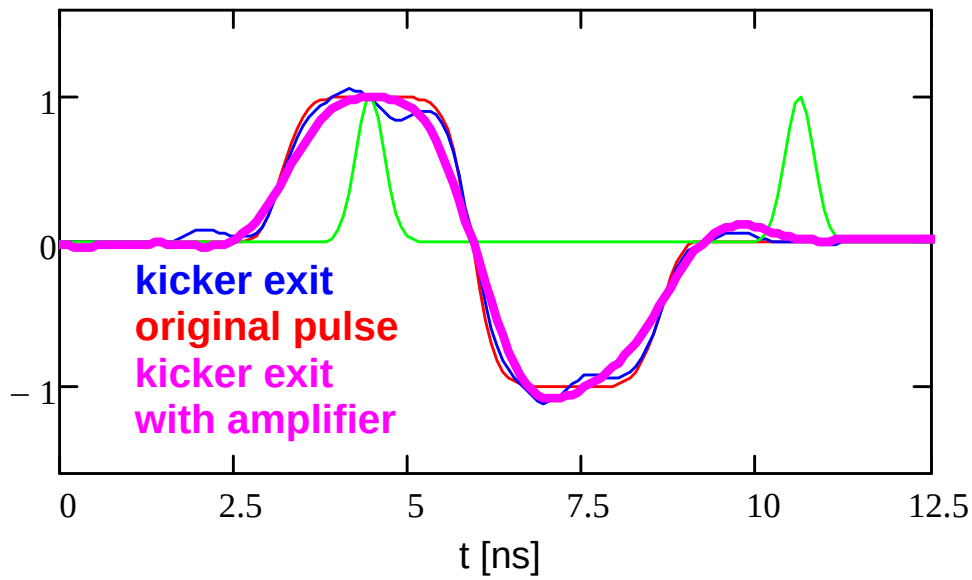


Comparison of network analyzer and direct scope measurements for 7 lines (L_{tot}=16.1 cm)

High Power Amplifier

- 0.5 kW amplifier is required to make 200 V
- Frequency band of 20 – 500 MHz is sufficient to make good bipolar pulse
- If necessary an equalizer can be designed to correct for the phase and amplitude distortions of power amplifier
  - It can also make partial correction to the dispersion introduced by kicker
  - Longer kicker (25→50 cm) looks possible if an equalizer is used





Beam Dump

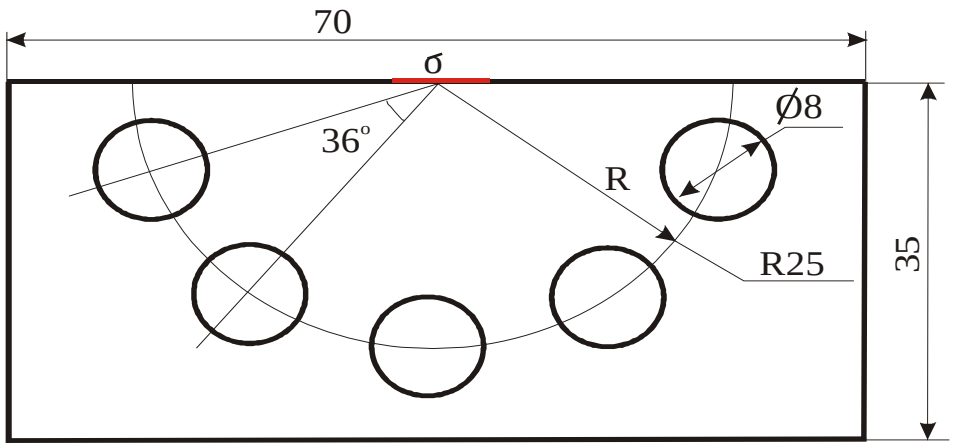
- Beam dump - large beam power (up to 12.5 kW)
  - Allocated space for RF cavity and beam dump is 70 cm
  - It is tight!!!
- Normally water accepts the power density ≤ 60 W/cm^2
  - Heat removal requires large aria of water channels
- For Gaussian heating profile

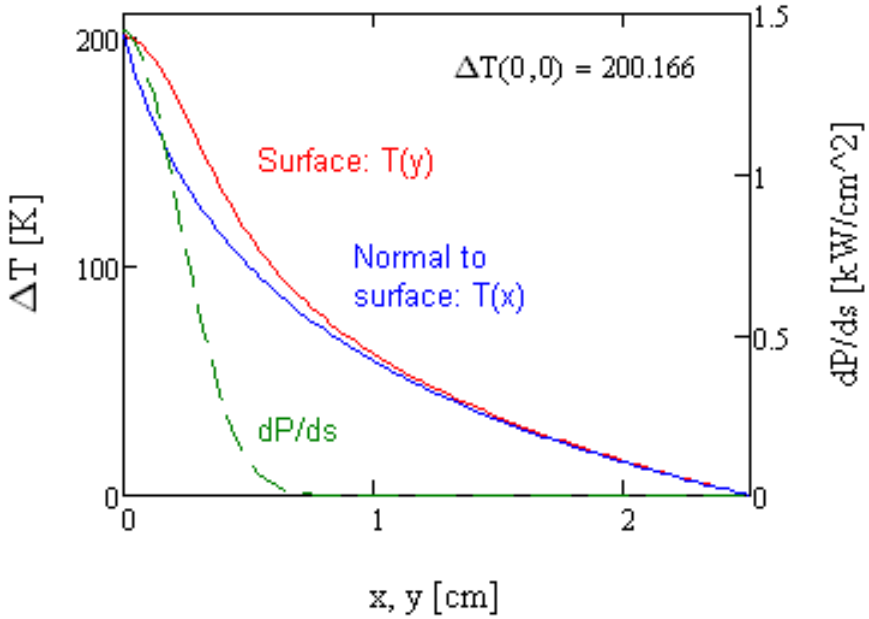
  with σ = 2.2 mm and

  linear power density ***dQ/dL***=800 W/cm

  the temperature drop in copper ~200 K (R=2.5 cm)

$$\Delta T \simeq \frac{1}{\pi\kappa}\frac{dQ}{dL}\ln\frac{1.89R}{\sigma}$$





- Temperature gradient in damp material introduces stresses and should be minimized
- Copper looks as a good material due to its high thermal conductivity
- However the temperature difference of 200 K results large stresses
  - ΔT=40 K @ stress yield
  - i.e. we are factor of 5 above stress yield

Length of the beam dump	30 cm
Beam dump angle to beam	29 mrad
Max. linear power density	**0.8 kW/cm**
Water pressure drop	2 atm.
Water pipes connection	serial
Total length of pipes	2 m
Water flow	0.3 l/s
Power density (water-to-Cu)	64 W/cm^2
Water ΔT (inlet-to-outlet)	9.5 C°
ΔT (water-to-Cu)	27 C°
Inlet water temperature	50 C°
Peak temperature	**290 C°**

- The stress can be relieved by deformations
  - Half of the stress is absorbed by settling material to the mean temperature
  - Mechanical design should minimize stresses (thin slits normal to beam direction)
  - No significant pulse load
    - ΔT=30 K for 5 ms interruption
    - Heat penetration (diffusion) rate $\sqrt{d\overline{x^2}/dt}$ $\approx$ 1 cm/$\sqrt{s}$

Beam Dump Lifetime

- Proton (H^-) beam damages the dump surface
  - Sputtering
    - amplified by oblique incidence: ~0.15 mm/year
  - Blistering
    - It will be mitigated by remelting
- High speed vacuum pumping is required to keep vacuum in MEBT cavities
- Differential pumping is required to keep good vacuum in SC cavities
- Insulators in close dump vicinity have to be protected from the direct flux of sputtered material

Conclusions

- Bunch-by-bunch chopping has been significantly alleviated with appropriate choice of MEBT optics
- Bunch-by-bunch chopper with 162.5 MHz RFQ looks OK
  - Present understanding of bunch-by-bunch kickers does not support 352 MHz RFQ
  - The kicker with plates and delay lines looks as a good solution
- 10 kW beam dump requires careful design work
  - There is no obvious show stoppers for the beam dump design
  - Beam dump spattering is not a problem but prevents using thin films on the dump face (radiation reduction, etc.)
    - It can pollute normal conducting and SC cavities
- 500 W amplifier with 20-500 MHz bandwidth is required to drive 200 V at the kicker plates
  - Present systems have parameters close to the desired ones
  - An imperfection of amplifier gain (both phase and amplitude) can be corrected by equalizer

Backup viewgraphs

Sputtering estimate

- The beam energy is sufficiently high and small scattering angle approximation can be used
- Using Thomas-Fermi model for calculating the energy transfer to an atom above I_a one obtains the cross section:

$$\sigma \approx \pi r_p^{\,2} Z^2 \frac{\left(m_p c^2\right)^2}{I_a E}\left(1+0.9\left(1.174\frac{Z^{4/3} r_p}{a_0}\frac{m_p c^2}{\sqrt{4AI_a E}}\right)^{2/3}\right)^{-2}$$

⇨ Sputtering probability per incoming proton - $W \approx \dfrac{\sigma^2}{a_{lat}^{\,2}\theta}$

$r_p \approx 1.53\cdot10^{-16}$cm, $a_0 \approx 0.53\cdot10^{-8}$ cm, $m_p c^2$ = 938 MeV, E=2.5 MeV;

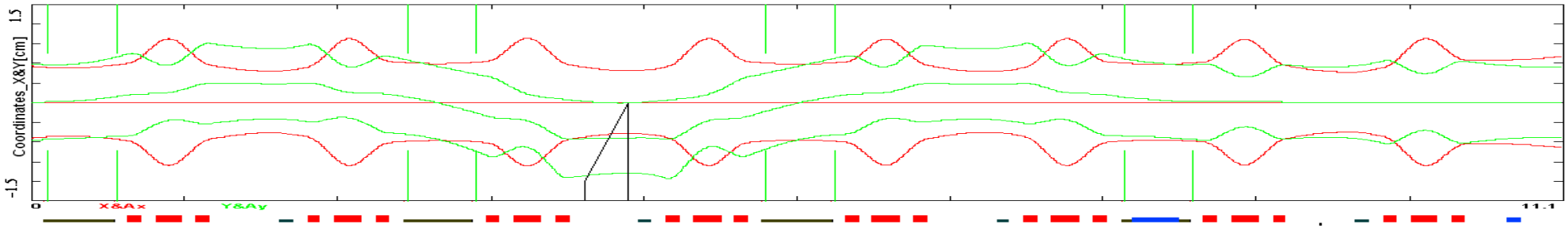
for Cu: Z = 29; A = 65.5; I_a = 3.3 eV; $a_{lat} \approx 2.3\cdot10^{-8}$ cm (atom-to-atom dist.)

⇨ W = $5.3\cdot10^{-3}$ for θ = 29 mrad (1.7 deg)

- There is no reliable exper. data on sputtering by 2.5 MeV prot.
  - Comparison to simulations points out ~2 times overestimate
  - for θ=1 deg.: modeling by T. Sizyuk (Purdue univ.) - W = $4.3\cdot10^{-3}$
    above estimate - W = $8.8\cdot10^{-3}$
- Applicability condition: incident angle is larger than the scattering angle: $\theta \gg \sqrt{I/E}$ (θ >> 1 mrad)

MEBT Beam Instrumentation

- Optics measurements with differential orbits
  - BPMs & dipole correctors & cavities
- Beam envelope measurements
- Beam loss measurements
  - + kicker protection
- Protection of beam dump and other collimators



8+ BPMs (in each triplet; 3 coordinates)

| | | | | | | | |

4 profile monitors (3 sizes, 45 deg. phase advance, have to be upstream collimator)

| | | |

2 beam current monitor + beam current measurements for all collimators

| |

Limitations on Possible Choice of Beam Instrumentation

- BPMs (4 plates in one device)
  - have to be located inside quads to save space
  - all 3 coordinates have to be reported
- Profile measurements
  - Desirable to be able to do measurements for both p's and H^-
  - Should take small longitudinal space (~5-7 cm)
    - Transverse profile
      - IPM
        - CW, 10^9 electrons/cm/s @ 10^{-9} Torr & 5 mA
      - Light excited by beam in residual light atoms
        - CW, 10^6 photons/cm/s @ 10^{-6} Torr & 5 mA
      - Wires
        - pulsed beam, tungsten wire, 4 μs, 60 Hz, ΔT~400 C
    - Longitudinal
      - Laser profile monitor (for H^- only)
      - Wire monitor (pulsed beam)
      - Laser profile monitor based on a change of beam ionization with optical excitation of residual gas atoms by laser (not tested, CW)