Chopping and Limitations to MEBT

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- MEBT optics
- Bunch-by-bunch kickers
- Beam Dump

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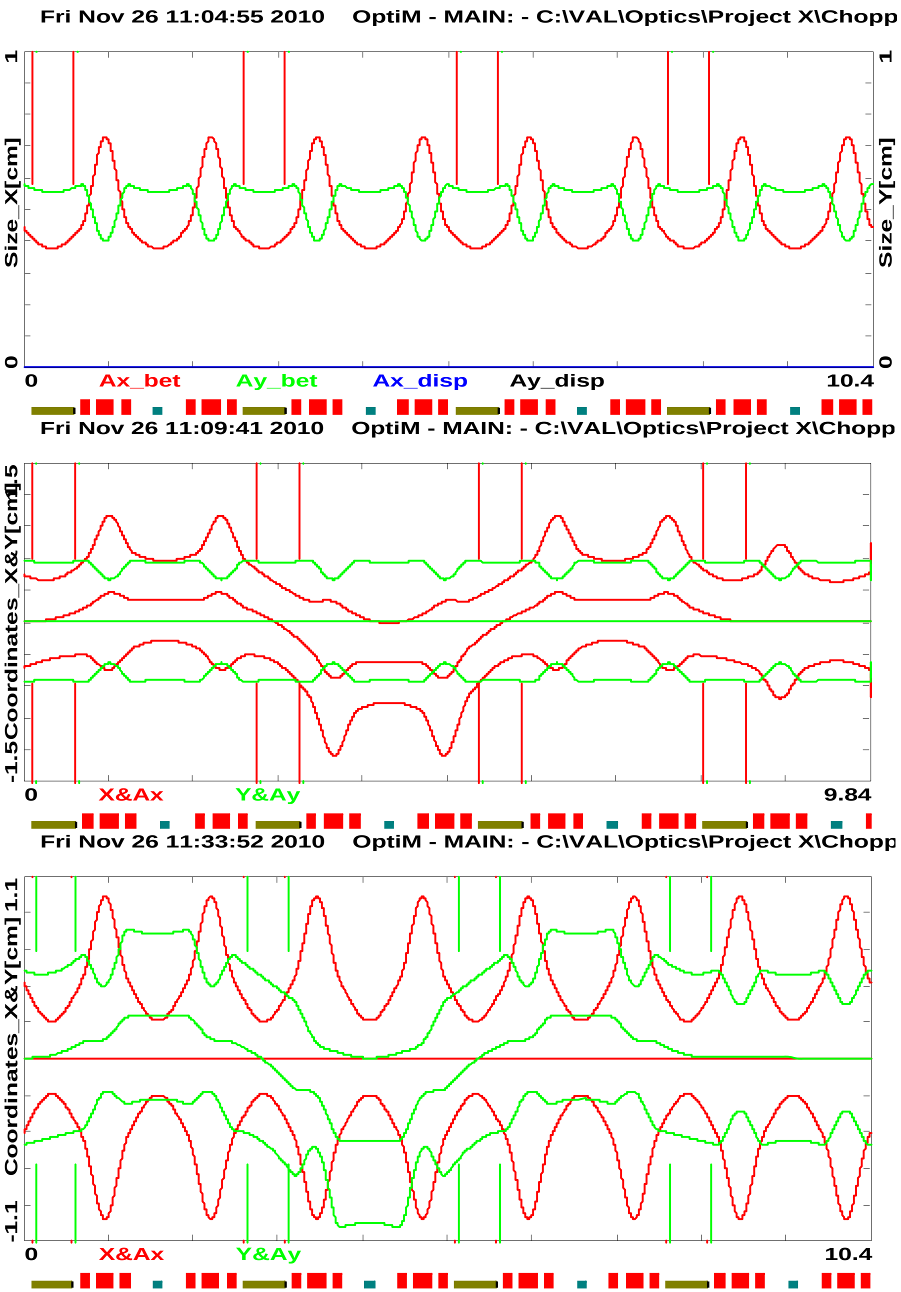
MEBT Optics

- Here and below we assume:
  - ε_{n_rms}=0.2 mm mrad
  - The beam collimator is located at x(y)=0
  - The scrapers are located at 3σ

Case without RF cavities

- Looks great
  - Perfectly periodic beam envelopes
- Vertical kick requires less voltage and therefore is preferable !!!

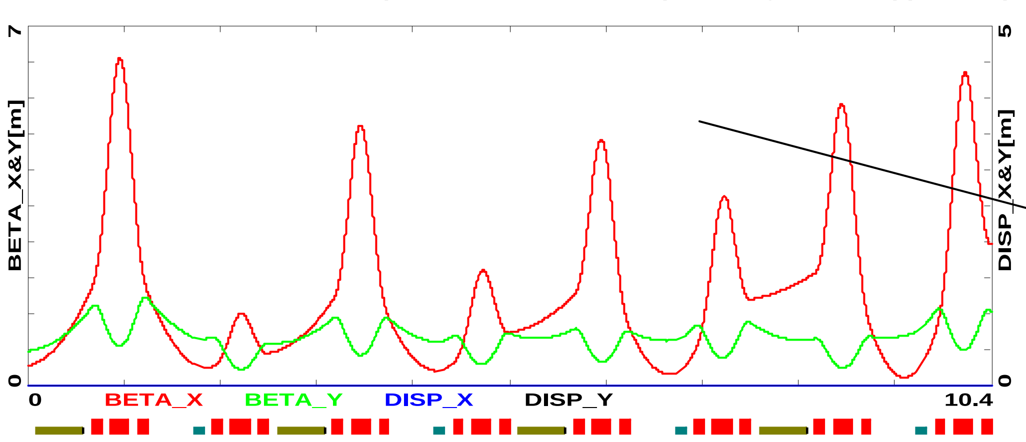


3σ beam size in absence of cavity focusing;
H kick ±200 V, gap ±5.8 mm, G=0.449 kG/cm;
V kick ±160 V, gap ±7.5 mm, G=0.585 kG/cm.

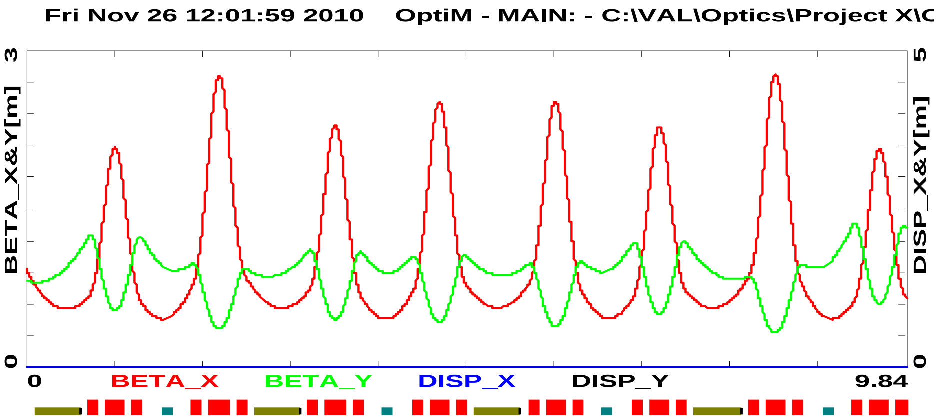
MEBT Optics (continue)

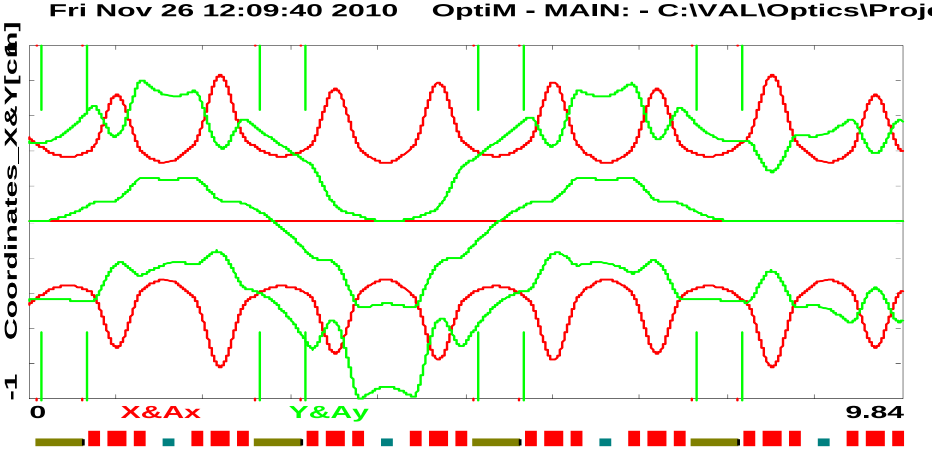
Effect of RF cavities

- Cav. $\perp$ focusing destroys the optics periodicity
- For f_{RF}=325 MHz & μ_L=90 deg
  - Cavity focusing: F=-260 cm
- RF cavities have to be moved from centers of RF straights to make space for beam dump
- It strongly amplifies β_x beating

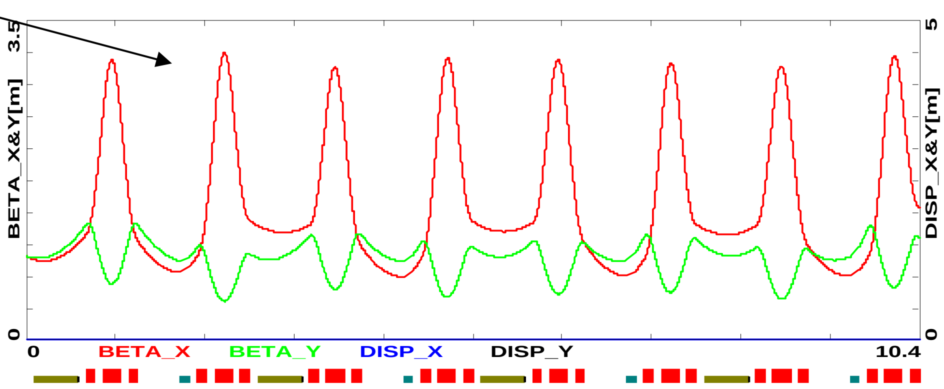


- Optics correction results in 2 times redaction of β_{xmax}





Symmetr. cav. pos.: 3σ beam size in absence of cavity focusing; G_F=0.522 & G_D=0.595 kG/cm μ_x=μ_y=2.01 V kick ±170 V, gap ±6.33 mm,



Asymmetric cavity location

MEBT Optics (continue)

- Correction of focusing requires
  - Vertical
    - Three families of defocusing quads
  - Horizontal
    - Each focusing quad is regulated independently

Major parameters of MEBT

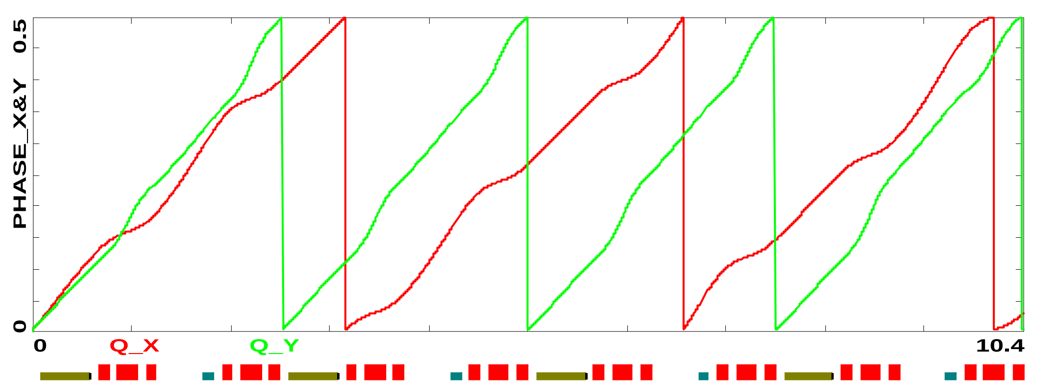
Beam energy	2.5 MeV
Beam current	5 mA
Longitudinal rms emittance	1 μeV s
Normalized rms ⊥ emittance	0.2 mm mrad
Norm. emittance ratio: $\varepsilon_L/\varepsilon_\perp$	1.6
Longitudinal phase advance	90 deg (per 2 cells)
Transverse phase advance	~90 deg (per 1 cell)
Bunch (RFQ) frequency	162.5 MHz
RF frequency	325 MHz
RF voltage	41 kV

Quad parameters

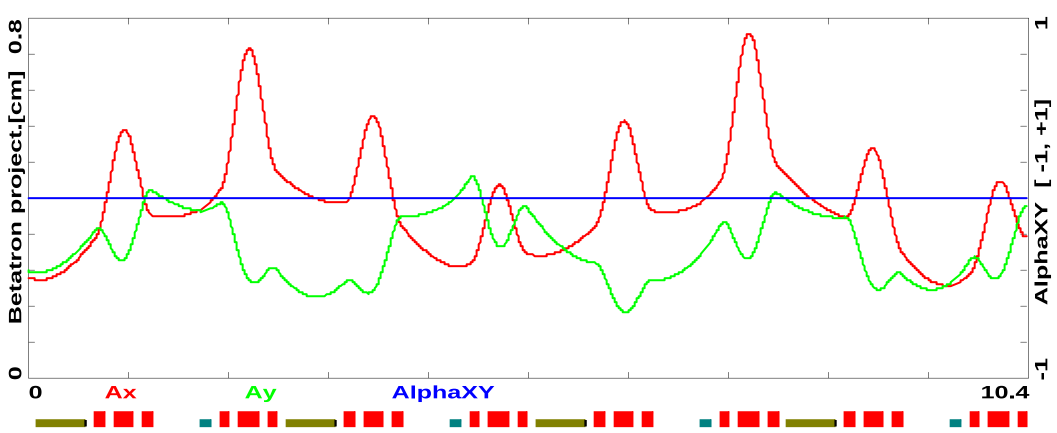
Name	L[cm]	G[kG/cm]
qD	10	-0.5308
qF1	20	0.4558
qD1	10	-0.5408
qD2	10	-0.6378
qF2	20	0.4698
qD	10	-0.5308
qD	10	-0.5308
qF3	20	0.4438
qD1	10	-0.5408
qD2	10	-0.6378
qF4	20	0.4718
qD	10	-0.5308
qD	10	-0.5308
qF5	20	0.4438
qD1	10	-0.5408
qD2	10	-0.6378
qF6	20	0.4718
qD	10	-0.5308
qD	10	-0.5308
qF7	20	0.4448
qD1	10	-0.5408
qD2	10	-0.6378
qF8	20	0.4558
qD	10	-0.5308

MEBT Optics with space charge

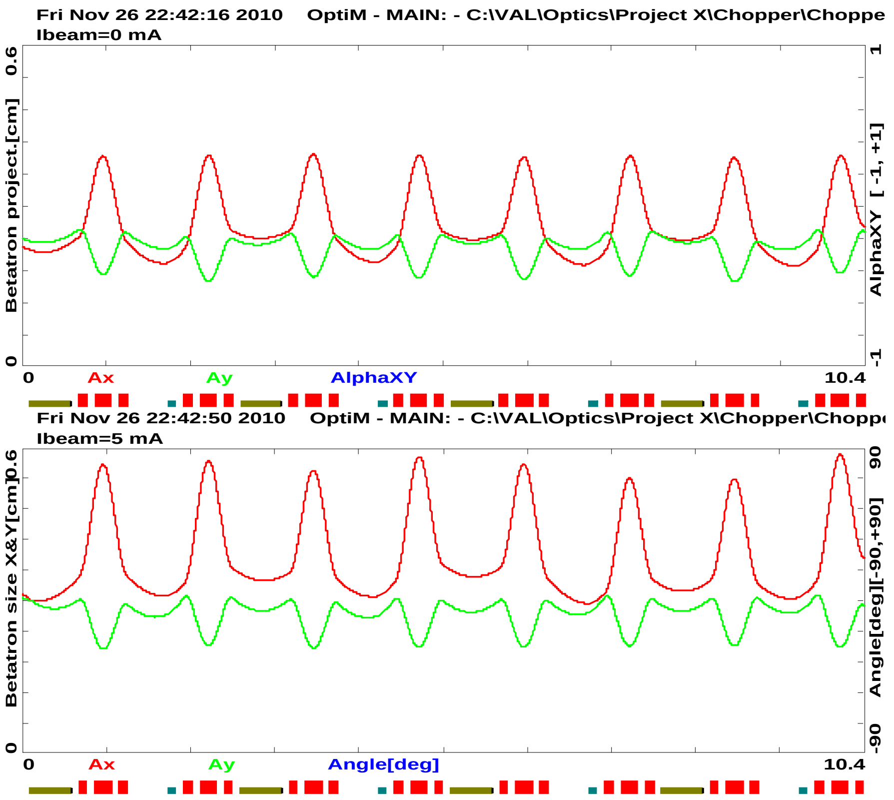
- Without space charge: $\mu_x \approx \mu_y \approx 90^\circ$



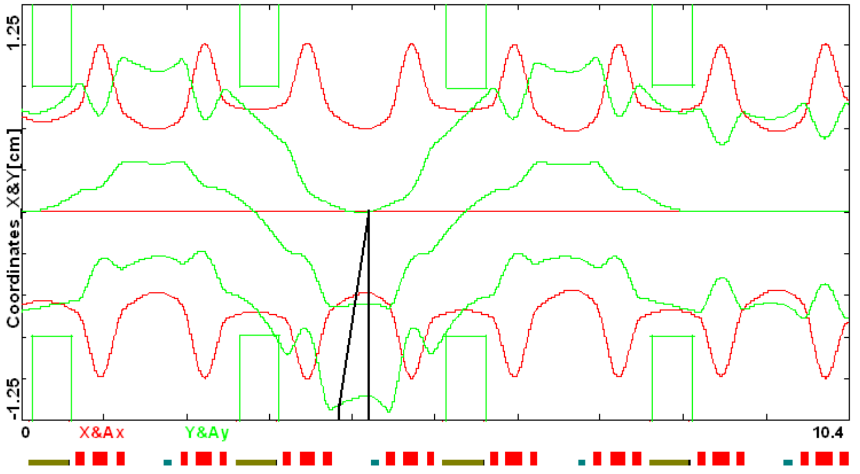
- If not tuned the space charge yields large beam envelope oscillations



- Matching at MEBT entrance strongly suppresses the oscillations



Beam envelopes √2σ for
0 mA - top, 5 mA bottom



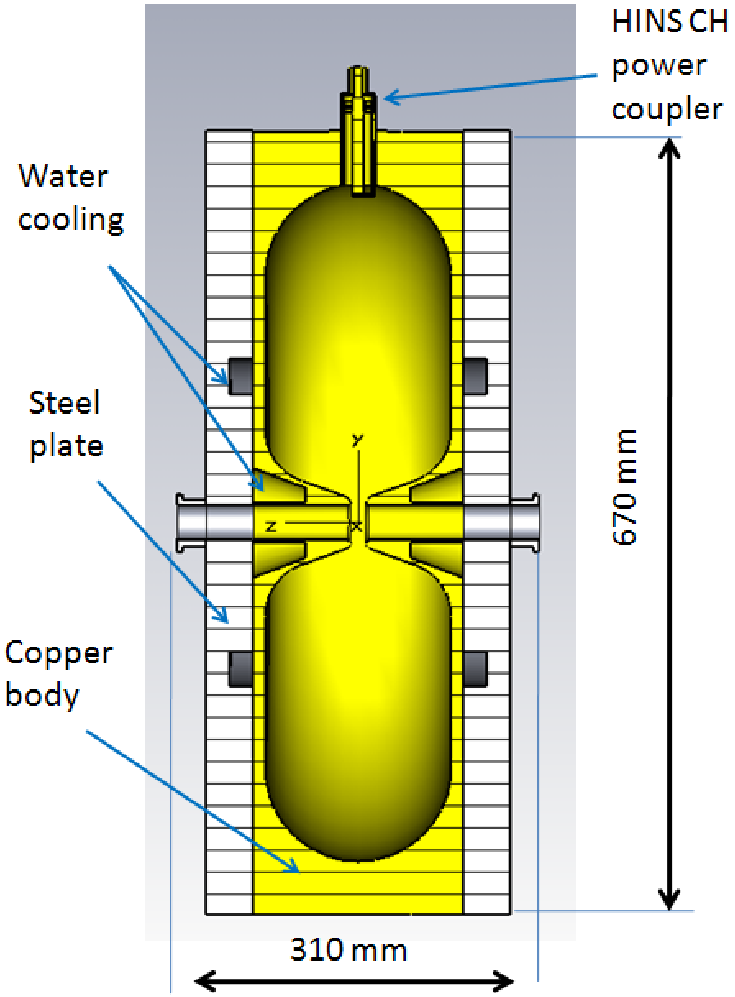
3σ beam envelopes; 0 mA scaled to 5 mA
V kick ±230 V, gap ±7.4 mm,

MEBT Optics (continue)

- Period structure

Name	qD	drift	qF	drift	qD	drift
Length [cm]	10	10	20	10	10	70

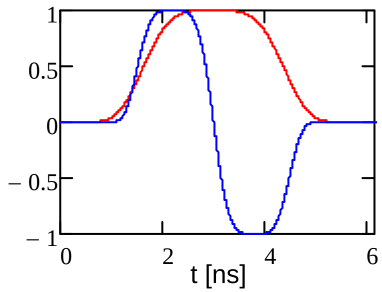
  - ♦ Quads: $G < 0.7$ kG/cm; aperture: Ø = 4 cm, $B_{tip} < 1.4$ kG
- RF cavities
  - ♦ 325 MHz looks good if the longitudinal emittance ≤1 μeV s
    - σ_{ϕ_max} = 18 deg @ 1 μeV s & I_{beam}=0
  - ♦ Period 260 cm, V=41 kV, μ_L=90 deg.
    - Larger emittance will require 162.5 MHz cavities with 2 times larger voltage (~82 kV)
    - For the same μ_L the low frequency RF will have the same effect on transverse focusing



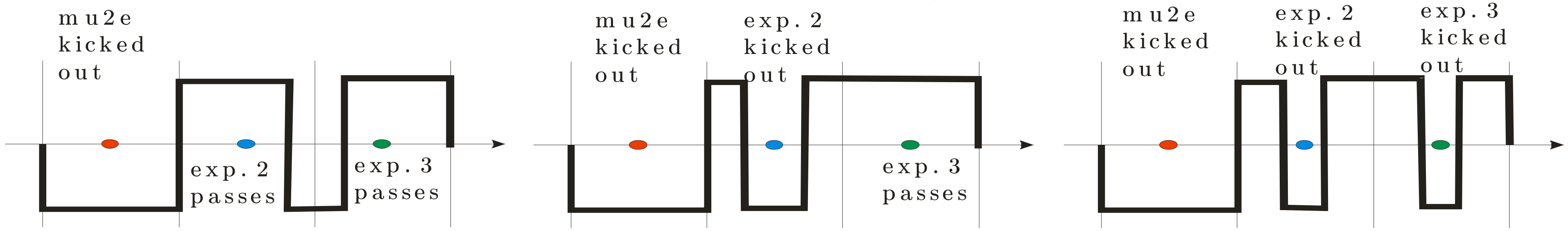
Summary for MEBT optics

- Kicker requirements: L=50 cm, V_{eff}=±250 V, gap 15 mm
  - Almost 2 times reduction of kicker voltage is related to
    - Using vertical kick instead of horizontal - 1.25 times
    - Reduction of emittance from 0.4 to 0.2 mm mrad ~1.4 times
  - Space charge increases the beam size
    - ⇒ required kick grows by 1.35 times from 0 to 5 mA (170 -> 230 V)
- Beam dump - large beam power (up to 12.5 kW)
  - Allocated space for RF cavity and beam dump is 70 cm
  - It is tight
    - Can be alleviated by shortening quads => total length of triplets
      - a design is required to see how much can be gained

- Bipolar kicks: "+" – no chop; "-" – chop; "0" – half bunch chop
  - It allows the beam current regulation
  - It reduces the voltage of power amplifier by 2 times
  - Allows to use an amplifier without DC coupling but requires twice larger bandwidth
    - Absence of DC coupling => effective protection of kicker overheating by the beam halo with detecting DC current



- Longitudinal tails of RFQ can limit the beam extinction
  - It can be addressed by pulse shape adjustments for one experiment (mu2e) but can be done for all experiments
  - It will be easier for a single polarity (entire bucket) kick
  - Simulations are needed to make a quantitative conclusion

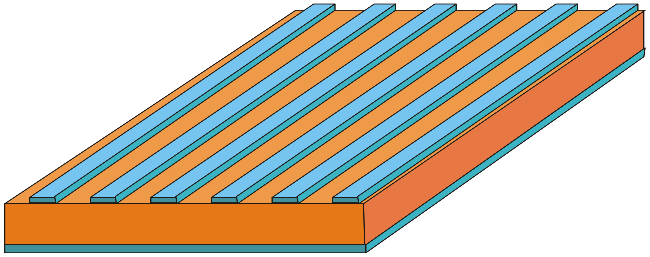


Bunch-by-Bunch Kickers

- 4 kickers: L=50 cm (2*25 cm) , U_{eff}=±250 V (gap 15 mm)
- 6.1 ns between bunches
  - ⇒ Bunch-to-bunch distance 13.4 cm
  - ⇒ Bandwidth ~0.3 GHz for bipolar kicks
  - ⇒ The pulse velocity should match the beam velocity
- There are 3 ways to decelerate the wave
  - ♦ Spiral (old GHz scopes)
  - ♦ Meander (CERN proposal)
  - ♦ short kickers connected by a coaxial delay lines
- The major reasons limiting the bandwidth are
  - ♦ coupling between stripes
  - ♦ reflections from discontinuities
  - ♦ losses in the conductor and dielectric

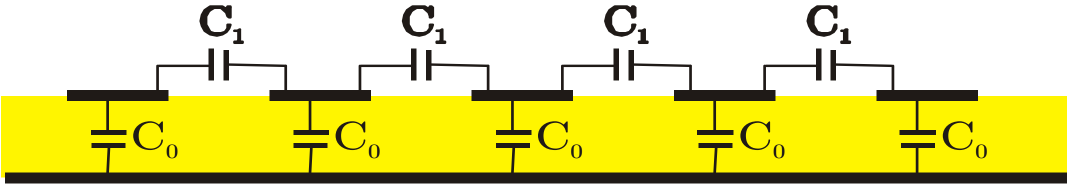
Simple analytical model for signal propagation

- In the absence of coupling between nearby lines it can be considered as a transmission line
  - Dispersion is small
    - 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 and L_0 are capacitance and inductance per unit length; n – numerates lines

- If the same signals are propagated simultaneously in all lines the propagation speed is the same as in a single line

  ⇒ In the first order of perturbation theory the inductive and capacitive coupling coefficients are equal $\kappa = \dfrac{C_1}{C_0} = \dfrac{L_1}{L_0}$

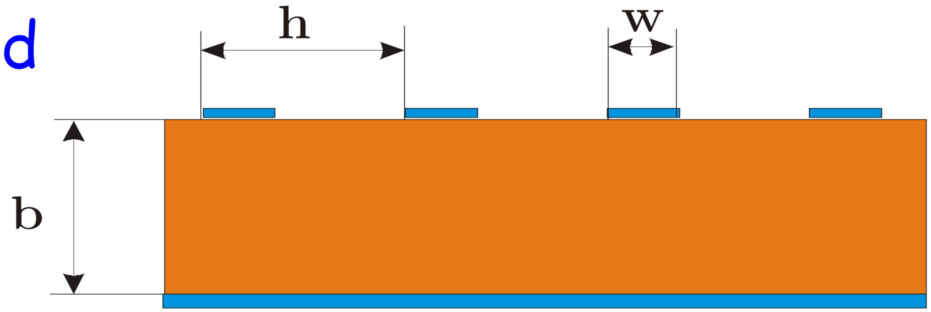
Coupling between stripes

- Capacitance per unit length of a single stripe is (Gelmont, et.al.,1995)

$$C_0 \approx \frac{1+\varepsilon}{2}\begin{cases} \left[\ln\left(\dfrac{\sqrt{\cosh\left(\alpha(b,w,\varepsilon)\right)}+1}{\sqrt{\cosh\left(\alpha(b,w,\varepsilon)\right)}-1}\right)\right]^{-1}, & \tanh\left(\alpha(b,w,\varepsilon)\right)\le 1/\sqrt{2}\,, \\ \dfrac{1}{\pi^2}\ln\left(2\dfrac{\sqrt{\cosh\left(\alpha(b,w,\varepsilon)\right)}+\sqrt{\sinh\left(\alpha(b,w,\varepsilon)\right)}}{\sqrt{\cosh\left(\alpha(b,w,\varepsilon)\right)}-\sqrt{\sinh\left(\alpha(b,w,\varepsilon)\right)}}\right), & \tanh\left(\alpha(b,w,\varepsilon)\right)\ge 1/\sqrt{2}\,, \end{cases} \qquad \alpha(b,w,\varepsilon)=\frac{\pi w\varepsilon}{4b(1+\varepsilon)}.$$

  - ♦ for *w<< b, h* it can be simplified

$$C_0 \approx \frac{\varepsilon+1}{4}\left[\ln\left(\frac{16}{\pi}\frac{\varepsilon+1}{\varepsilon}\frac{b}{w}\right)\right]^{-1}, \quad L_0 = \frac{2}{c^2}\ln\left(\frac{32b}{\pi w}\right)$$

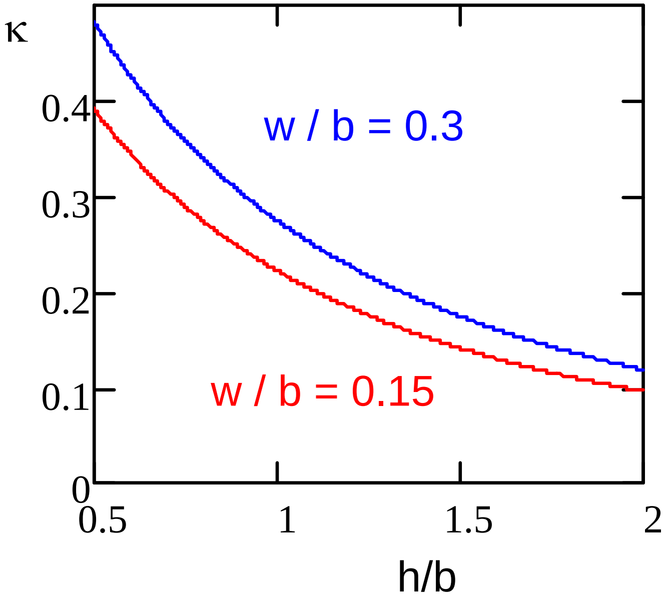


- Then, the coupling coefficient is

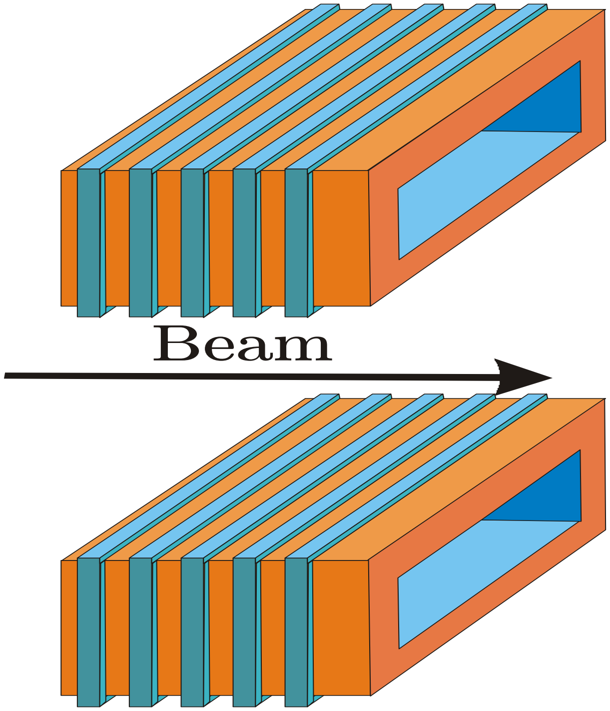
$$\boxed{\kappa \approx \ln\left(\sqrt{1+(2b/h)^2}\right)\Big/\ln\left(\frac{32b}{\pi w}\right), \quad w \ll b,h}$$

- A desire to have good kicker efficiency ($U_{eff} \geq 0.7U_0$) requires h ≤ b

  => $\kappa \geq$ **0.15**



Coiled kicker



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

one obtains the dispersion equation

$$\boxed{k \approx \sqrt{\varepsilon}\frac{\omega}{c}\left[1 + 8\kappa^2 \cos\left(\sqrt{\varepsilon}\frac{\omega l}{c}\right)\sin^2\left(\sqrt{\varepsilon}\frac{\omega l}{2c}\right)\right]}$$

l – length of a single turn

ε – is dielectric permittivity (assume $\varepsilon \gg 1$)

Impedance of the line is frequency dependent too

$$Z(\omega) \approx Z_{line}\left[1 + 2\kappa\cos\left(\sqrt{\varepsilon}\frac{\omega l}{c}\right)\right], \quad Z_{line} = Z_0\frac{\sqrt{\varepsilon}}{4\pi C_0}$$

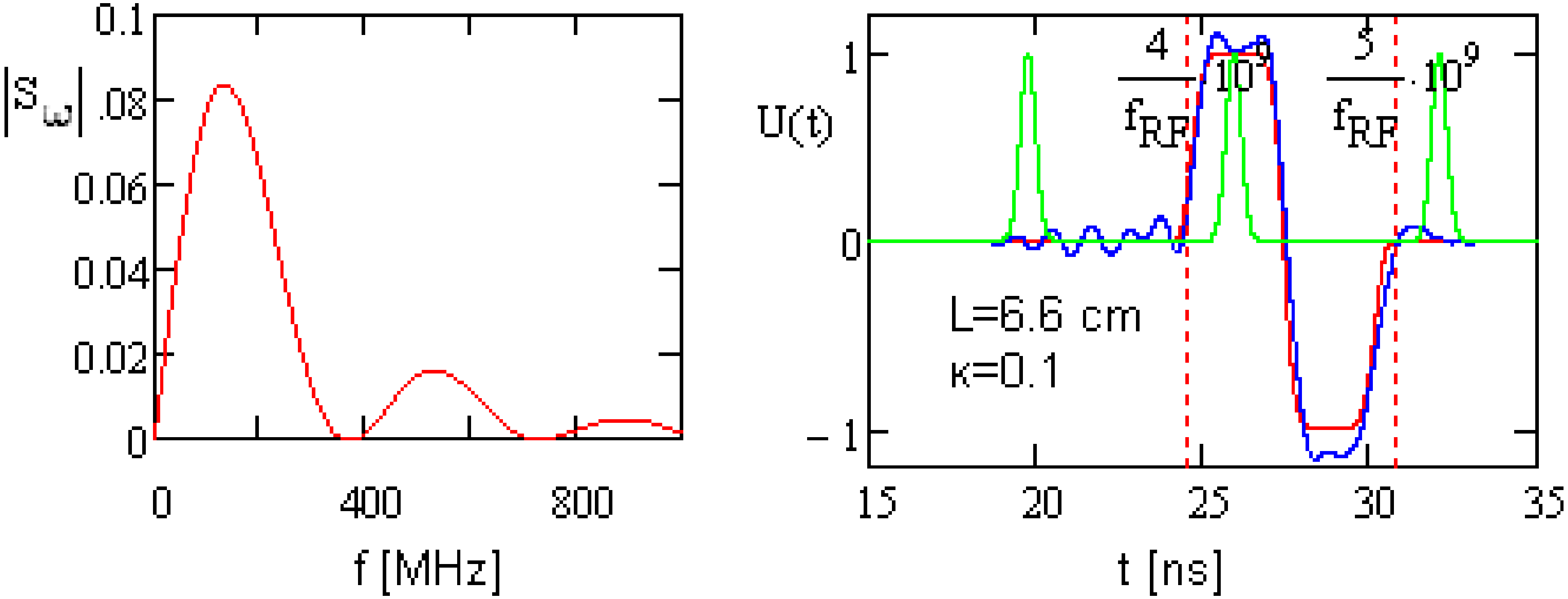
Reflections modulate the wave amplitude propagating along beam

$$\boxed{U(\omega) \approx U_0\left[1 + \kappa\cos\left(\sqrt{\varepsilon}\frac{\omega l}{c}\right)\right]}$$

Wave reflected from termination weakly interacts with beam

Coiled kicker (continue)

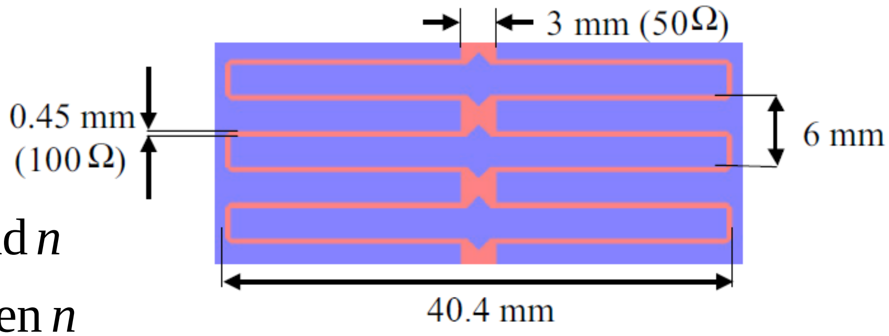
- Phase modulations, $\exp(-i\,k(\omega)\,s)$, affect the pulse propagation stronger than the wave reflections from the kicker due to frequency dependent mismatch
    - Damping due to finite resistivity makes only small correction



turn length - l=6.6 cm, k = 0.1, ε=3.5, h=9 mm, total length – 50 cm

- Coupling coefficient was set to obtain sufficiently small pulse distortions
    - $\kappa \le 0.1$ => large distance between turns => large kick attenuation
        - Reduction of one turn length would help but is limited by kicker width (i.e. beam size)
    - Therefore the coiled kicker does not look promising

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

$$\boxed{\mu(\omega) \approx \sqrt{\varepsilon}\frac{\omega l}{c} - \kappa \sin\left(2\sqrt{\varepsilon}\frac{\omega l}{c}\right)}$$

l - length of a stripe (kicker half width)

ε - is dielectric permittivity (assume ε>>1)

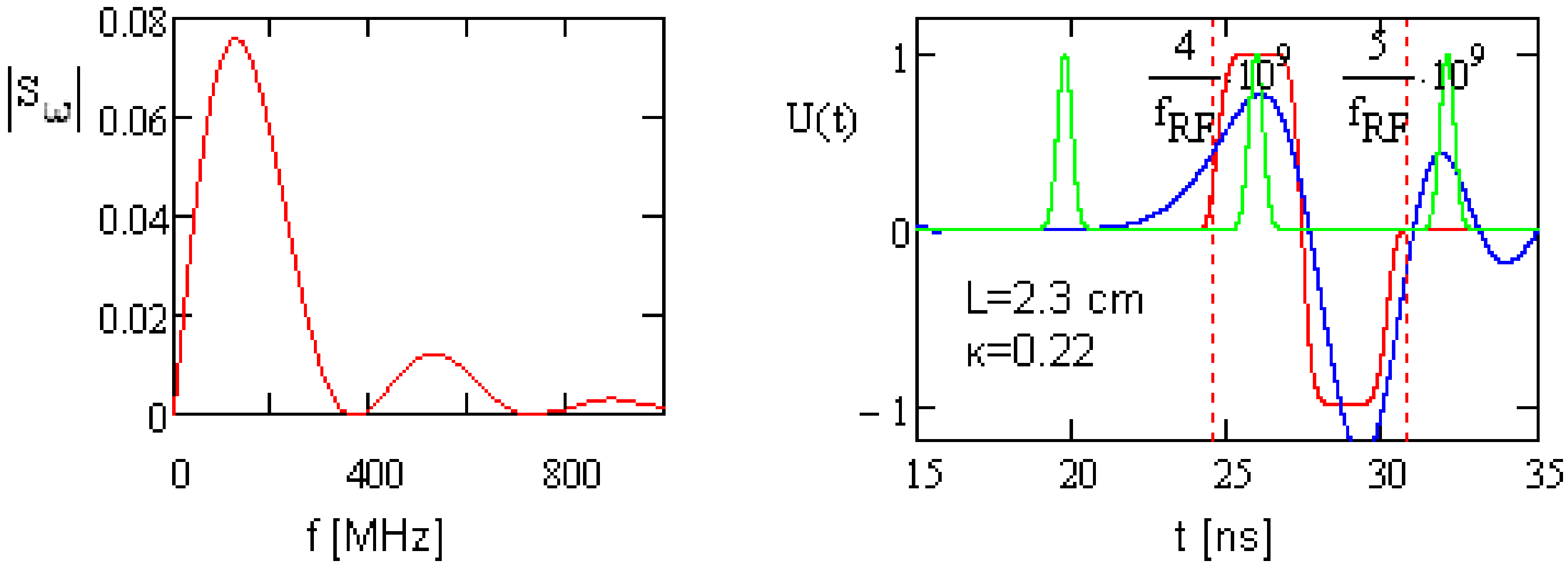
In the first order the line impedance and wave reflections are the same as for coiled kicker

$$Z(\omega) \approx Z_{line}\left[1 + 2\kappa\cos\left(\sqrt{\varepsilon}\frac{\omega l}{c}\right)\right], \quad Z_{line} = Z_0 \frac{\sqrt{\varepsilon}}{4\pi C_0}$$

$$\boxed{U(\omega) \approx U_0\left[1 + \kappa\cos\left(\sqrt{\varepsilon}\frac{\omega l}{c}\right)\right]}$$

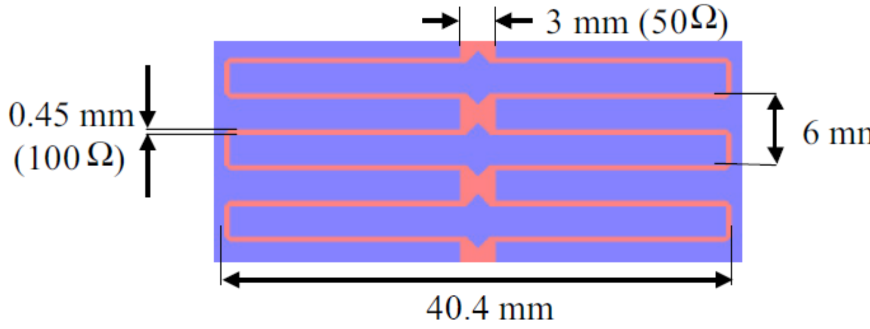
Meander kicker (continue)

- The same as for coiled kicker the wave reflected from termination weakly interacts with beam
- Not as for coil kicker the dispersion correction is $\propto \kappa$, not to κ^2
  - i.e. much larger effect for the same coupling
- However much shorter period (more than 4 times) helps
  - It moves problems to higher frequencies
- Still looks that it does not address Project X needs

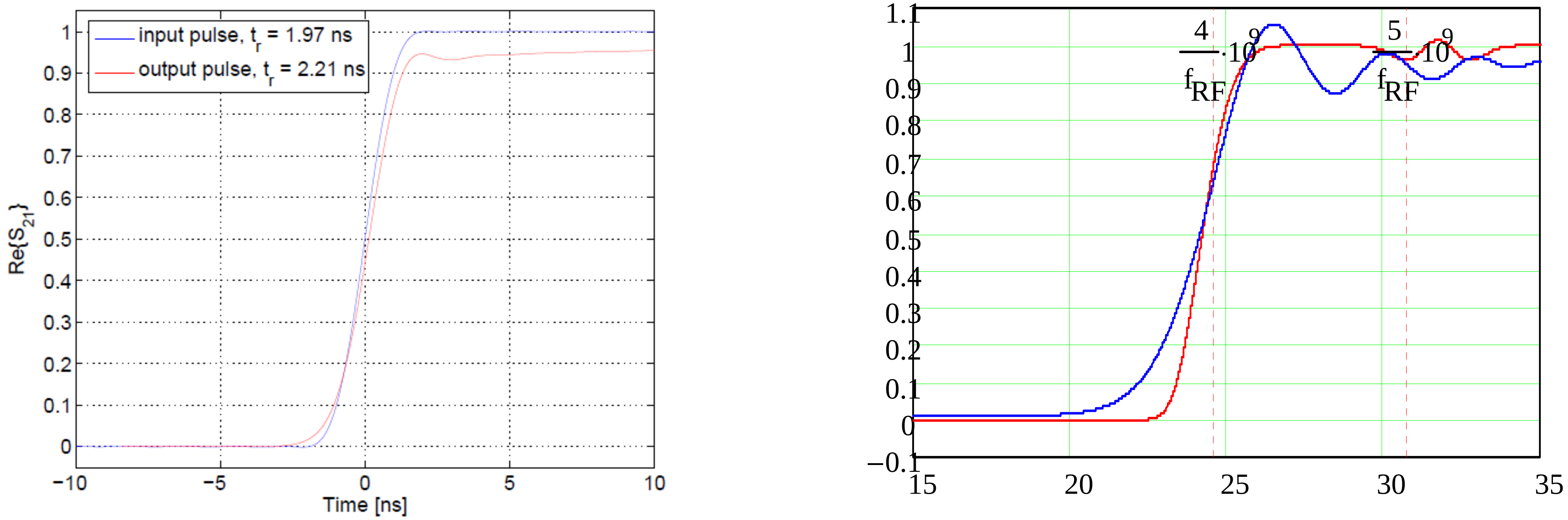


Pulse spectrum and propagation for the CERN kicker proposal adjusted to project X needs, L_{tot}=50 cm, h = b = 3 mm, l = 23 mm, ε = 9.6

CERN proposal for meander kicker

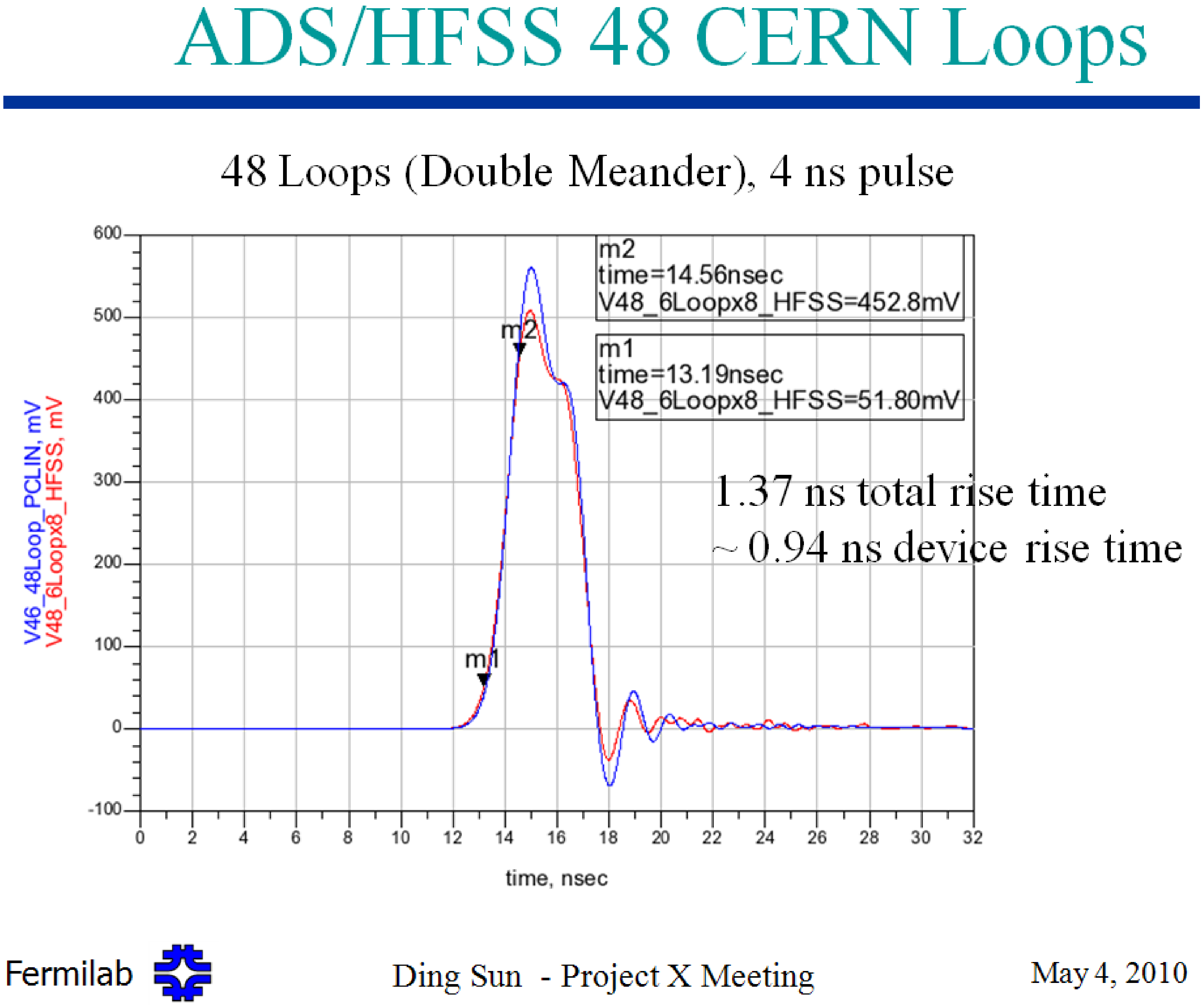


- Total kicker length 40 cm
  - two 100 Ω lines
- Demonstrated rise time ~ 3 ns
  - They claim 1 ns (definition?)
- The above analytical estimate looks less optimistic (~5 ns)
  - It correctly predicts that the wave propagates faster by 1.9 times because of strip-to-strip coupling
    - κ = 0.19 - analytical estimate
    - κ = 0.25 – fitted from wave propagation speed



Measured and calculated wave shape at the kicker end

CERN proposal for meander kicker (continue)



ADS/HFSS 48 CERN Loops

48 Loops (Double Meander), 4 ns pulse

1.37 ns total rise time

~ 0.94 ns device rise time

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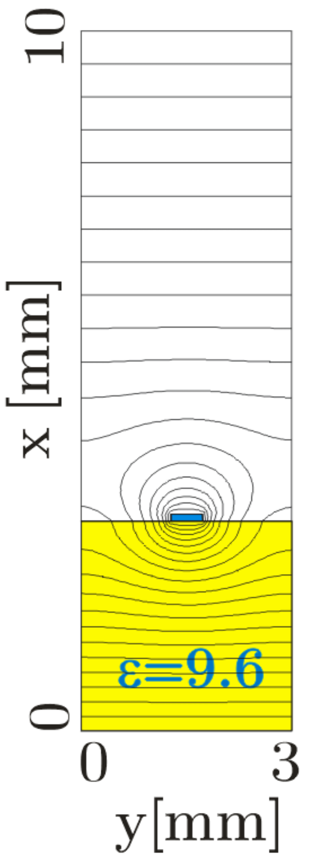
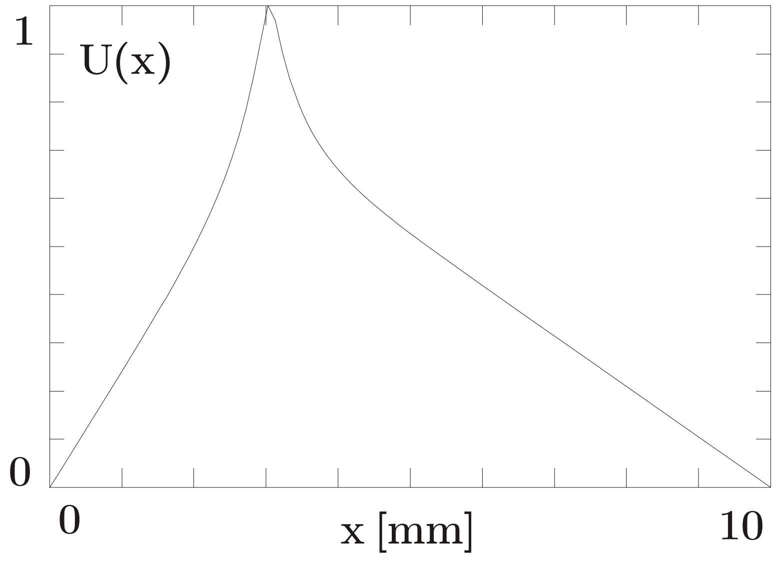
Total length of 48 loops is 28.8 cm; single polarity pulse fits into 6 ns

Complications with CERN meander kicker proposal

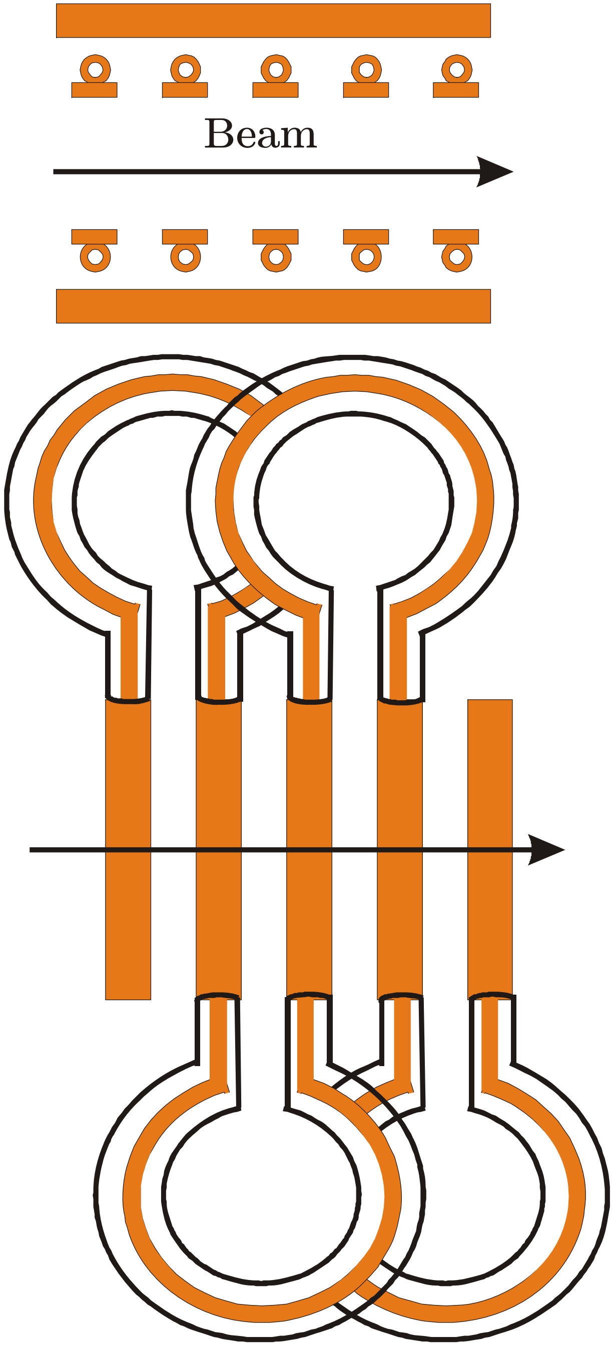


- Hardly can achieve the desired bandwidth (time resolution)
- Bad kicker efficiency: ~60% ($U_{eff} \geq 0.6U_0$)
  - Large ε and ρ = 100 Ω
    - ⇨ small stripe width
    - ⇨ ~30% loss of the kick due to small width
  - Additional 15% are lost due to stripe resistivity
    - wave damping ~30% to the line end (40 cm)
    - corresponding heating is negligible, ΔT≈ 1.5 C^o
- Dielectric is directly visible to the beam and can be charged by its tails
  - Reproducibility???
  - Discharges can result in a kicker damage

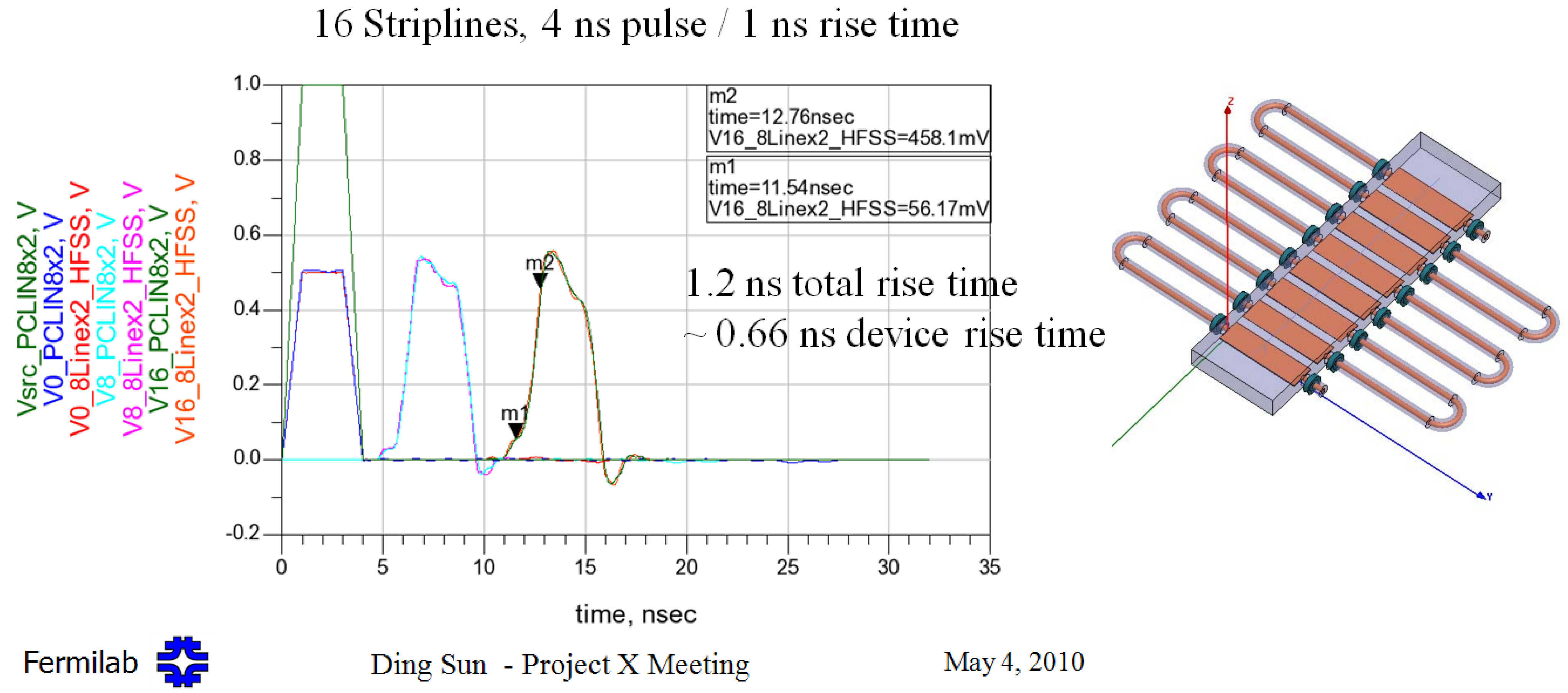


Alternative Approach for Chopper Design (Ding Sun)

- Details
  - No dielectric
    - No charging of the surface
  - "RF cable" connection between stripes
  - Smaller effective coupling between lines
  - More effective kicks
  - Water or air cooling of stripes is possible
- Expected problems
  - Reflections at the transitions
- Construction of prototype based on the cable delays is started



Alternative Approach for Chopper Design (continue)



16 Striplines, 4 ns pulse / 1 ns rise time

m2
time=12.76nsec
V16_8Linex2_HFSS=458.1mV

m1
time=11.54nsec
V16_8Linex2_HFSS=56.17mV

1.2 ns total rise time

~ 0.66 ns device rise time

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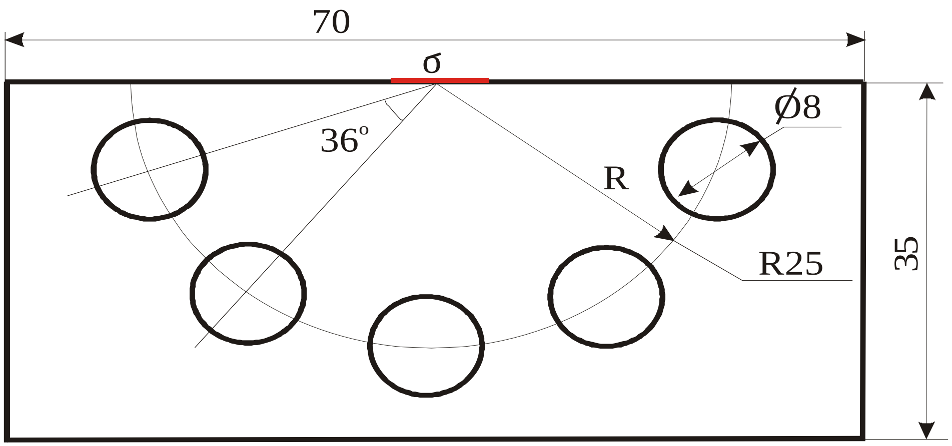
Step – 16 mm, total length for the 16 strip-lines kicker is 26 cm, 2 kickers in 1 straight

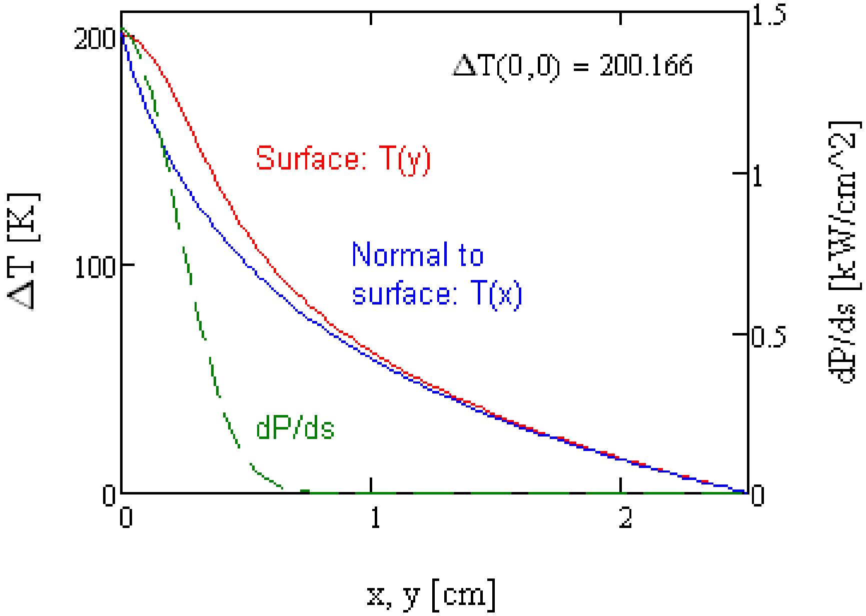
- Rise time is at the boundary of acceptable for double polarity pulse
- Kicker efficiency is much better than for CERN meander
  - 300 V peak (1 kW) amplifier look adequate for powering one side of the kicker (required effective kicker voltage ±230 V)
- First tests are expected within 2 months

Beam Dump

- For 5 mA beam the total beam power is 12.5 kW
- Water can accept the power density dP/ds ≤ 60 W/cm^2
  - Heat removal requires large aria of water channels
- Temperature gradient in damp material introduces stresses and should be minimized
- For Gaussian heating profile with σ = 2.2 mm and the linear power density **dQ/dL**=800 W/cm the temperature difference in copper ~200 K (R=2.5 cm)

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





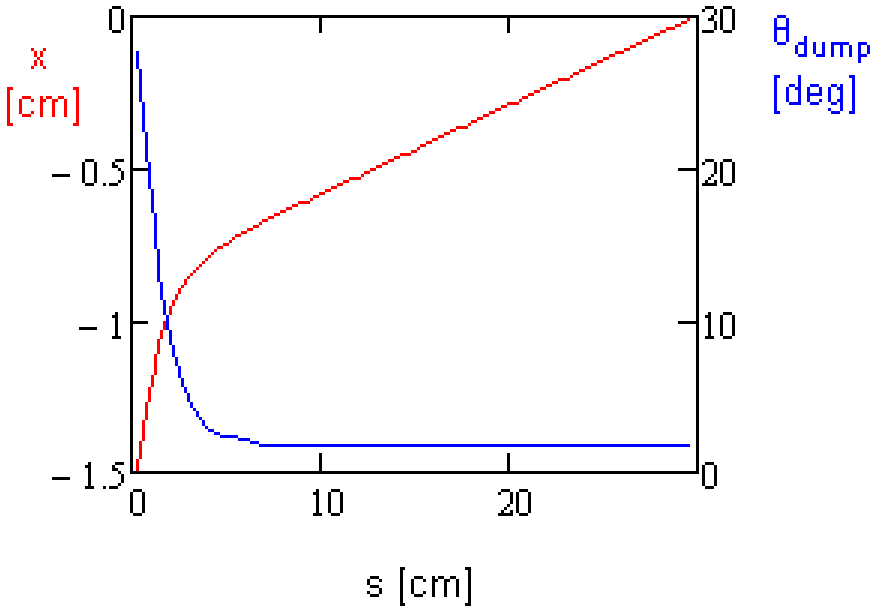
Beam dump (continue)

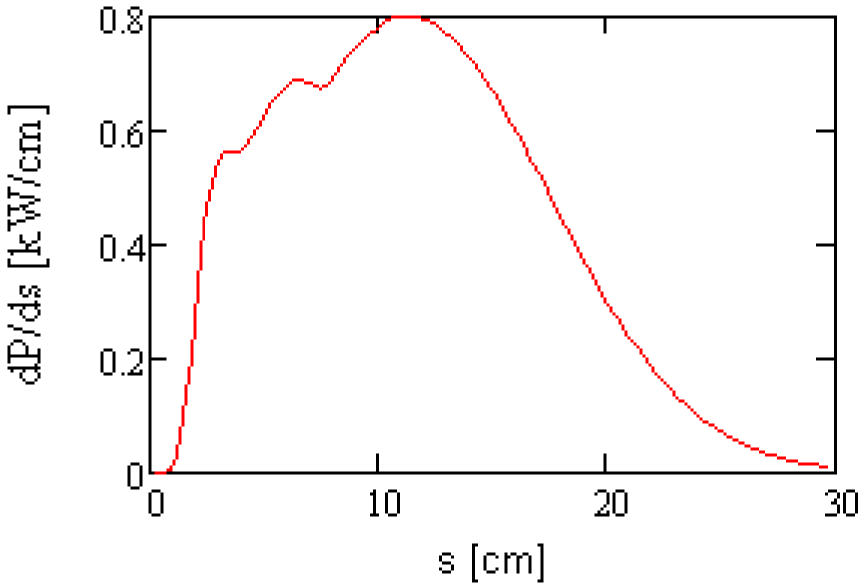
Length of the beam dump	30 cm
Beam dump angle to beam	29 mrad
Max. linear power density	**0.8kW/cm**
Water pressure drop	2 atm.
Water pipes connection	serial
Total length of pipes	2 m
Water flow	0.3 *l*/s
Power density (water-to-Cu)	64 W/cm^2
Water ΔT (inlet-to-outlet)	9.5 C°
ΔT (water-to-Cu)	27 C°
Inlet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

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

Beam Dump Space Limitations

- 700 mm drift is allocated for the RF cavity and the beam dump
  - 300 mm cavity
  - 300 mm beam dump
    - 3σ scraping
    - Dump face is bend at the entrance to reduce the dump length
  - 100 mm interfaces





Beam Dump Lifetime

- Proton (H^-) beam destroys the dump surface
  - Sputtering
    - amplified by oblique incidence - estimate: ~0.15 mm/year
  - Blistering
    - Will be mitigated by
      high temperature of the dump face
      remelting of blistered material - Dump face should look up
- Dump activation and neutron production
  - Not negligible
    - Would not happen for Cu at E < 2.1 MeV or with higher Z material
  - Sputtering limits usefulness of thin layer of high Z material
  - Thermal stresses do not allow thick layer
- 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 dump vicinity have to be protected from the flux of sputtered material

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 - $W \approx \frac{\sigma^2}{a_{lat}{}^2 \theta}$

$r_p \approx 1.53 \cdot 10^{-16}$ cm, $a_0 \approx 0.53 \cdot 10^{-8}$ cm, $m_p c^2$ = 938 MeV, E=2.5 MeV;

for Cu: Z = 29; A = 65.5; I_a = 3.3 eV; $a_{lat} \approx 2.3 \cdot 10^{-8}$ cm (atom-to-atom dist.)

⇨ W = $5.3 \cdot 10^{-3}$ 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 = $4.3 \cdot 10^{-3}$
    above estimate - W = $8.8 \cdot 10^{-3}$
- Applicability condition: incident angle is larger than the scattering angle: $\theta \gg \sqrt{I/E}$ ($\theta \gg 1$ mrad)

Conclusions

- Now we better understand requirements to the RFQ beam parameters (emittances, beam current)
  - RFQ design and simulations will follow
  - 10 mA RFQ current greatly complicates the beam bump design
    - Looks impossible without liquid metal jet (reliability?) or significant MEBT lengthening with consecutive negative effect on the beam dynamics
- Reduction of transverse emittance and better understanding of optics reduced the kicker voltage to a manageable level, P≤1 kW
- Present understanding of bunch-by-bunch kickers does not support 352 MHz RFQ (162.5 looks OK)
  - The choice of the kicker type is not quite clear yet