Neutrino Factory Front End Studies

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Front end design

- progress on new front end components for neutrino factory
  - 1) adiabatic buncher
    - potential cost reduction
    - performance: use both signs
  - 2) ring coolers
    - potential cost reduction
    - performance: longitudinal emittance reduction

- problems with using ring coolers
  - 1) kicker (MC-256)
    - 50 ns risetime kicker
    - 12 m long injected bunch
    - 8 bunches at 201 MHz
  - 2) no specific design to prepare a suitable input beam
    - practical rings have C ~ 35 m
      - smaller: even worse injection problems
      - larger: give up economic advantage

- Goal

  try to design new front end that includes
  - 1) present RFOFO ring cooler (MC-273)
    - RFOFO has realistic field description
  - 2) compatible adiabatic buncher

  thinking ahead towards Study 3

- Properties of the input beam used in RFOFO ring simulations
  - ε_T = 12 mm
  - ε_L = 18 mm
  - 160 < p < 260 MeV/c
  - β_T = 30 cm (40 cm at end)
  - $L_C = -0.14\ 10^{-3}$ m GeV/c ($-0.72\ 10^{-4}$ m GeV/c at end)
  - Tr (without decays) = 0.73 after 15 turns

Outline of the system under study

- based on discussions at Collaboration Meeting (June)

1) FS2 target
2) tapered capture solenoid
3) modified adiabatic buncher
4) phase rotation
5) precooler
6) sign divider
7) present RFOFO ring cooler

- final merit factor based on output of RFOFO ring

Capture solenoid

- reexamined taper profile
- found FS2 B_S taper was optimal
- increased B_S from 1.25 to 2 T in the decay channel to improve performance
- matched radius at 2 T is 24 cm

R [cm]	Tr (after 38 m)
24	0.67
30	0.78

- kept acceptance radius at 30 cm
- FS2 taper reaches 2 T at 11.2 m from target

- Properties of the beam at end of 11.2 m taper [b3]

  ε_T = 22.8 mm
  ε_L = 3.82 m
  $< p_Z >$ = 425 MeV/c
  σ_{pZ} = 242 MeV/c
  β_T = 140 cm
  $L_C = 0.49\ 10^{-4}$ m GeV/c
  Tr = 0.93

Adiabatic buncher design

- designed following prescription of Dave N. (MC-269)
- first design had 11+39=50 m decay space and 50 m long buncher [b2]

  p_{REF} = 150, 269 MeV/c
  n_b = 10
  f: 400 -> 201.25 MHz
  100 x 50 cm cavities
  linear 0-12 MV/m gradient gave acceptable bunching

  400 MHz is largest reasonable frequency since λ_{RF} = 75 cm and R_{CAV}~ 29 cm

  try to keep 12 MV/m maximum gradient at 201 MHz (RFOFO ring value)

- discretized solution to 10 frequencies [b14]

  10 x 5 m long RF regions
  each region had 20 x 25 cm cavities
  f: 386 -> 201.25 MHz
  G: 0.6 -> 12 MV/m
  bunches beam nicely

  → beam spread out over 39 bunches, including tails

Second adiabatic buncher design

- eliminate 39 m decay region
- shorter buncher => higher gradient
  already at practical gradient limit ?
- DN algorithm would imply starting at higher frequency
  already at practical limit of 400 MHz
  => keep 1st buncher parameters
- bunches beam nicely
- beam spread out over 30 bunches, including tails

Properties of the beam at end of buncher [b19]

	whole beam	bunch train
ε_T [mm]	21.0	18.9
ε_L	7.99 m	139 mm
$< p_Z >$ [MeV/c]	325	208
σ_{pZ} [MeV/c]	215	$100 < p < 320$
β_T [cm]	110	71
L_C [m GeV/c]	$0.94\ 10^{-3}$	
Tr (from target)	0.88	0.34

Result of bunching

bunched μ in whole train in Δp band = 33.7 % (from target)

bunched μ in bunches 4-11 in Δp band = 27.3 %

all non-e^- in bunches 4-11 = 36.7 %

used in downstream simulations

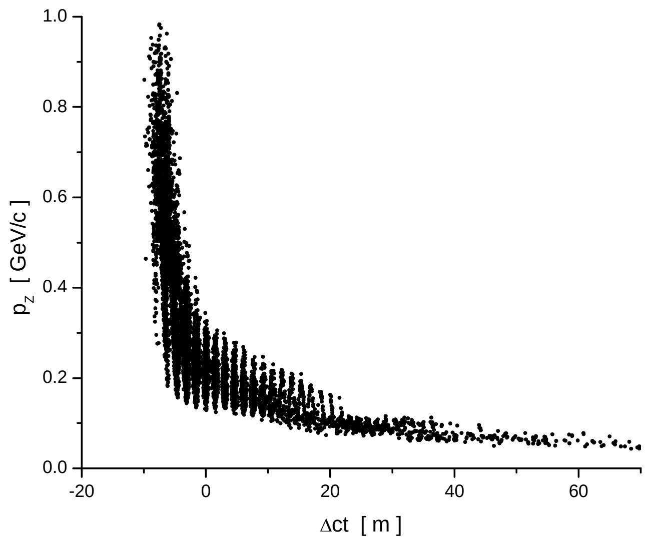
ε_T = 19.9 mm

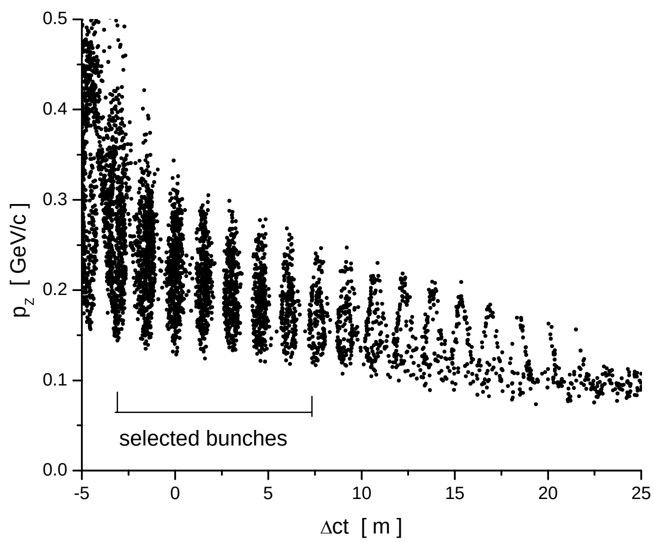
ε_L = 103 mm

Direct injection into RFOFO ring

Tr = 0.037 from target

(x 1.15 for μ / p)


1.0
0.8
0.6
0.4
0.2
0.0
p_z [GeV/c]
-20
0
20
40
60
Δct [m]


0.5
0.4
0.3
0.2
0.1
0.0
p_z [GeV/c]
selected bunches
-5
0
5
10
15
20
25
Δct [m]

Phase rotation

- try to improve transmission

(1) constant frequency 201 MHz [b18]
vary G, L , φ
try to get <p_{FRONT}> = <p_{END}> of selected bunches
inject into RFOFO: Tr = 0.030 from target

(2) beat frequency [b13]
10 m section alternating 196 and 206 MHz
vary f_i, G_i, φ_i
optimum G = 12 MV/m, $\varphi = -110^o$
inject into RFOFO: Tr = 0.015 from target

(3) vernier buncher (Juan G.) [b21]
12.3 m long, 3 T channel
f: 203.6 -> 195.8 MHz
G = 10 MV/m
β_T = 62 cm
inject into RFOFO: Tr = 0.044 from target

- vernier phase rotation helped a little
- needs more work
- but last 5 m of my buncher is 201 MHz, 12 MV/m = rotator?

Matching

(1) design match between buncher and RFOFO
- 4 x 2.75 = 11 m long
- no field reversals
- taper B_S: 2 -> 2.8 T (peak value in RFOFO)
- include 201 MHz, 12 MV/m RF in each cell
- taper φ: 5 -> 20^o
- include LiH blocks to keep <p> constant

Properties of the beam at end of match [b20]
- ε_T = 19 mm
- ε_L = 127 mm
- β_T = 56 cm
- r(x, p_X) = 0.03 (upright ellipse)
- r(y, p_Y) = 0.02
- Tr = 0.36 from target

inject into RFOFO: Tr = 0.044 from target
- (same as vernier phase rotation)

(2) design 2nd match between vernier phase rotator and RFOFO
- similar to above, but B_S: 3 -> 2.8 T
- inject into RFOFO: Tr = 0.044 from target

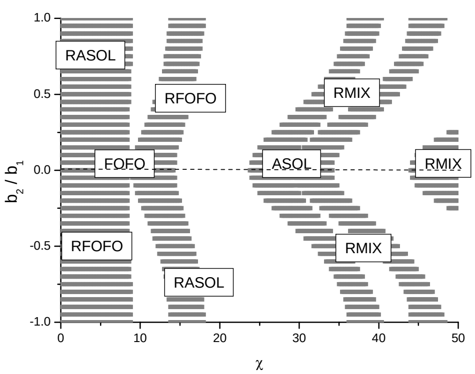
(3) rerun phase rotator at 2 T (same as buncher) [b21]
- taper B_S: 2 -> 4 T to get β_T = 41 cm going into RFOFO
- inject into RFOFO: Tr = 0.044 from target

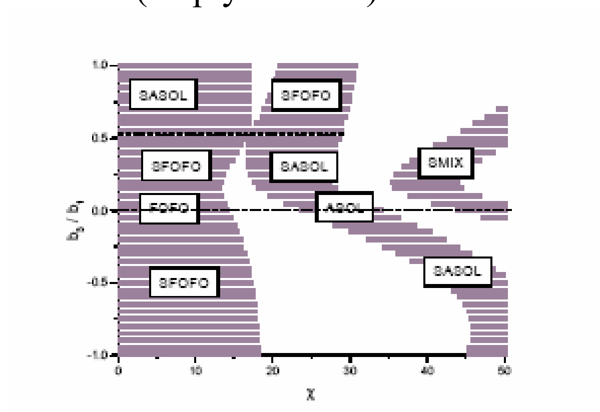
Precooler

- there is mismatch between output of buncher and RFOFO acceptance
  x5 mismatch in ε_L
  x2 in ε_T

  ⇨ we need 6D precooler
  can't be a ring because of kicker problem
  e.g. snake, helix, spiral
  choose snake so all bending is in one plane

- try FOFO focusing channel in 1st passband
  length = 36 m
  $B_S = b_S \sin kz$
  $b_S = 2$ T, $\lambda_B = 2.4$ m
  Tr = 100% for p > 100 MeV/c (empty channel)





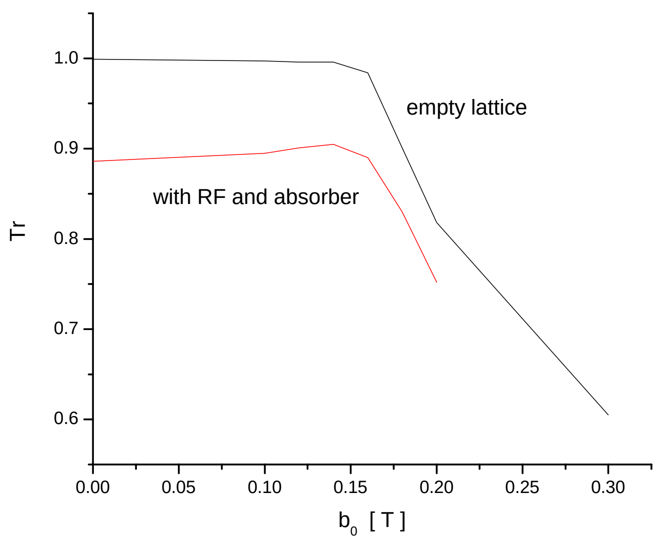
$$\chi = \frac{eB_o\lambda_B}{p}$$

RF: use 201 MHz, 12 MV/m , 25^o, 2x 33 cm cavities per 1.2 m lattice cell

ABS: 40 cm per lattice cell, 55^o wedges

Add dipole field

$B_Y = b_0 \cos kz$
increasing B_Y decreases channel transmission
$b_0 = 0.14$ T gives peak transmission with RF+ABS
D_X, $D_{X'}$, $D_{Y'} \sim 0$
$D_Y \sim 10$ cm



Simulate: buncher -> precool -> RFOFO

Properties of the beam at end of precool [b22]

ε_T = 17.7 mm (start at 19.9)
ε_L = 96 mm (start at 103)
β_T = 91 cm
Tr = 0.20 from target

rate of cooling(??) is very low
probably just an expensive beam collimator

inject into RFOFO: Tr = 0.031 from target

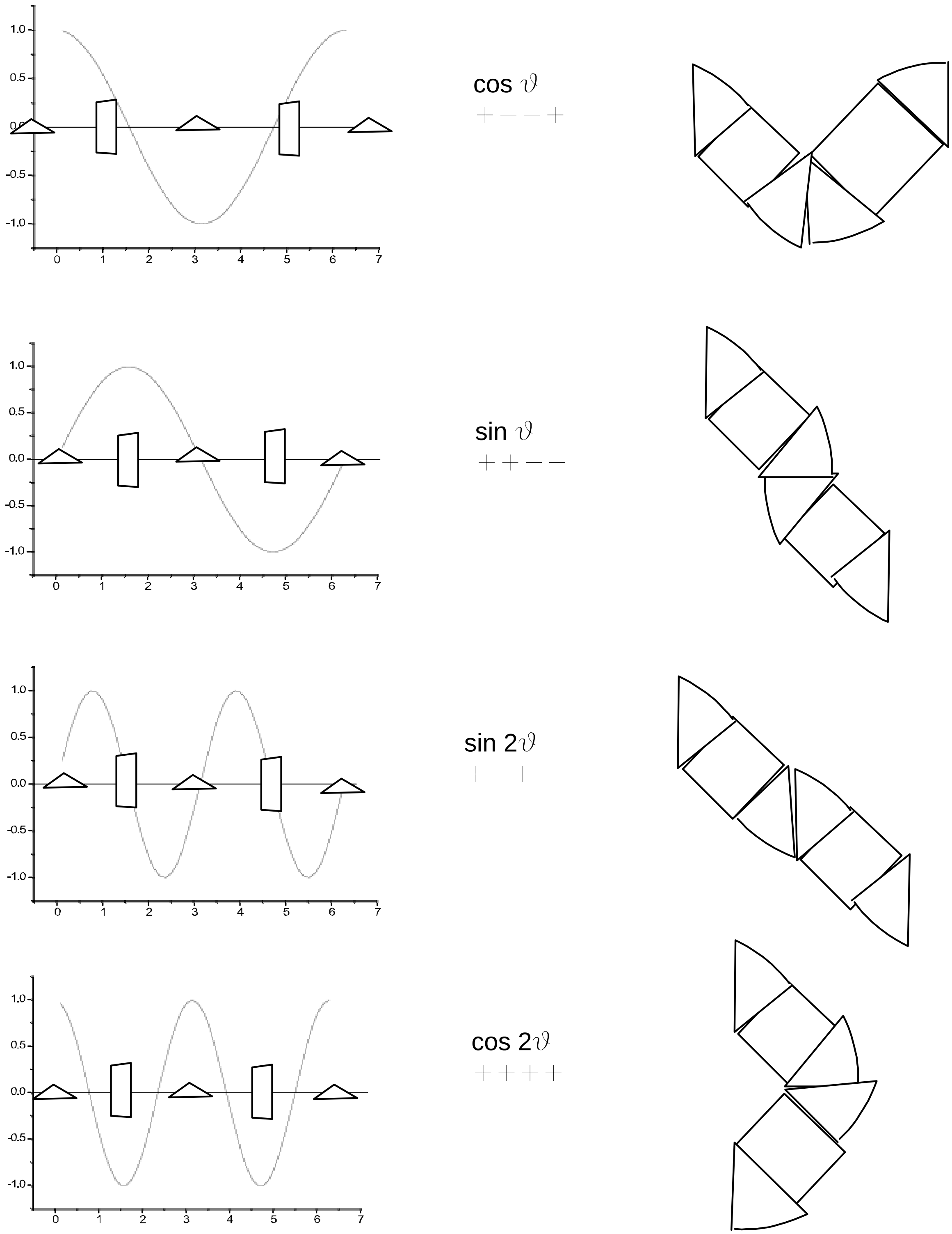
Tried other dipole configurations
require net beam motion from left to right

B_Y / b_0	Scott's notation
cos kz	+ - - +
sin kz	+ + - -
-sin kz	- - + +
sin 2kz	+ - + -

cooling performance similar for all
huge Δp and small D

Other focusing lattices could be explored

SFOFO can have an even larger Δp pass band
shape of field is additional parameter that can be tuned


cos ϑ
+ − − +
sin ϑ
+ + − −
sin 2ϑ
+ − + −
cos 2ϑ
+ + + +

Conclusions

- maximum μ / p achieved so far is 0.051 at exit of RFOFO

  these simulations do not include windows

  to be competitive with Study 2 we need ~ 0.22 x 1.3 = 0.29

- still things to try
  1) try to reduce bunch train length
     shorten buncher below 50 m
     raise maximum G at 201 MHz above 12 MV/m
  2) try to better flatten momentum range of selected bunches
  3) try to cool better before injecting into RFOFO
     different focusing channel
        e.g. SFOFO, helix
     longer
        expensive, more decays
  4) improve matching between stages
  expect small improvements, but recovering factor x6 is unlikely

- if we abandon the adiabatic buncher
  1) multiturn injection
     6 x 50 ns bunches separated by 130 ns
     implications for proton driver and target?
     can a cooling ring also stack efficiently?
  2) use low frequency buncher near target
  3) use preceding bunch compression ring

- the bottom line

may not be feasible to use the adiabatic buncher together with present ring coolers

possible alternatives look expensive
=> ring coolers may not be useful for neutrino factories
=> ring coolers are still important for muon colliders