Charge separation for the muon collider

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MAP Secondary Meeting

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Introduction

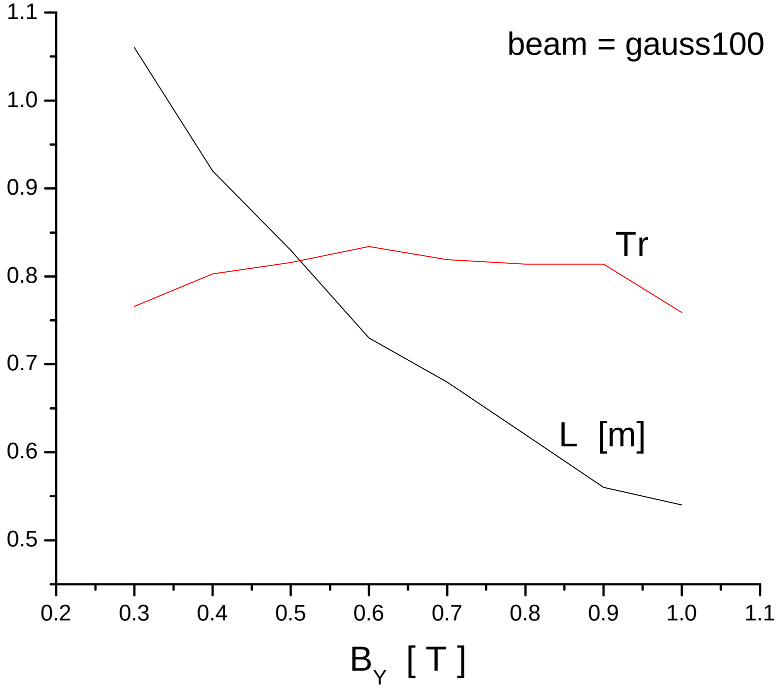
- made preliminary investigation of three possible methods for charge separation (CS)
  1. dipoles
  2. RF deflection cavities
  3. bent solenoids
- idea: identify most promising approach first
  make more detailed studies later
- results on dipoles & RF cavities adapted from my NFMCC Friday talk (5 June 2009)
- results on bent solenoids
  some results adapted from the talk
  some more recent simulations
- earlier study used "HEMC parameters": ε_{TN}= 12 mm, ε_{LN}= 41 mm
  ≈NF front end with some transverse cooling

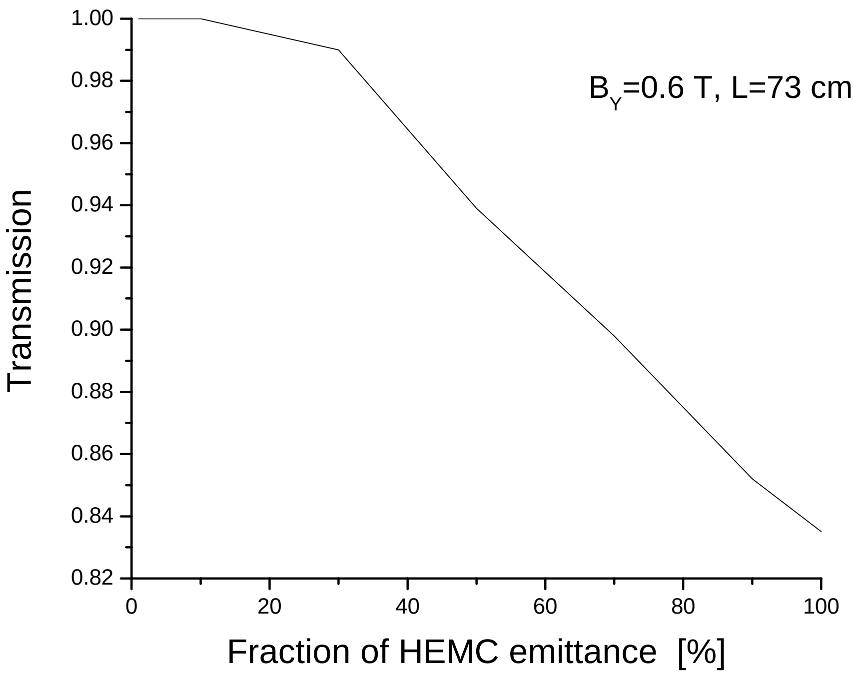
1. Dipole model

- ICOOL is not an ideal tool for this example
  - uses Frenet-Serret coordinate system
  - one sign follows the curvature in the coordinate system
  - other sign has distorted looking distribution
- wrote new cartesian tracking routine for this study

  (I would just use G4Beamline for this now)
- started with uniform rectangular dipole field
  - entrance beam normal to face
  - no vertical focusing
- used 30 cm radius exit holes for the two separated beams
- adjusted dipole B L to get ±31 cm center separation

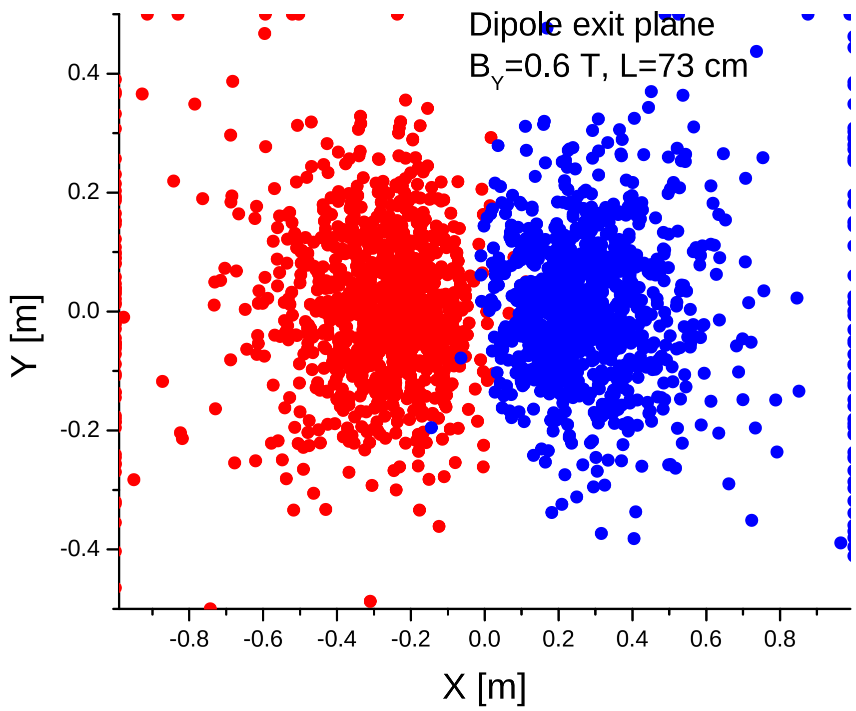
Optimization

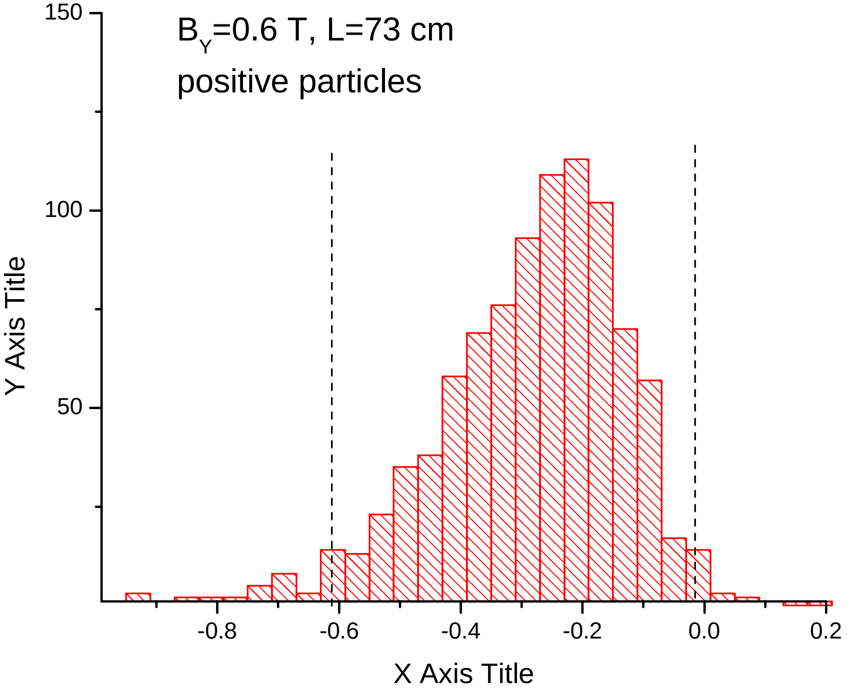




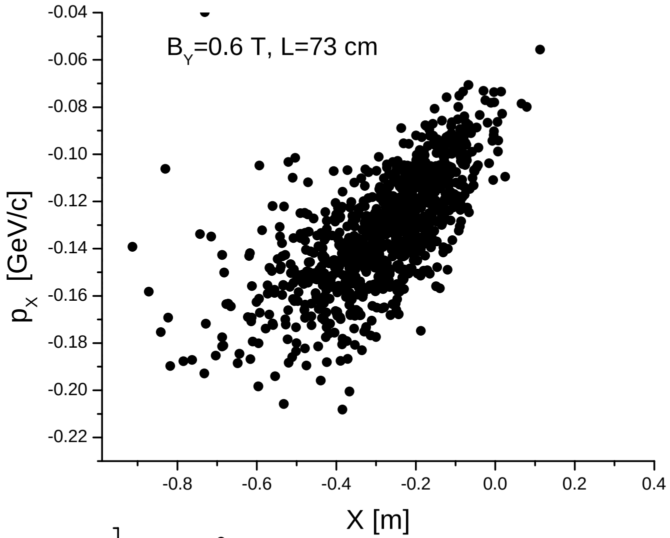
• reasonable separation acceptance (~84%) for HEMC beam

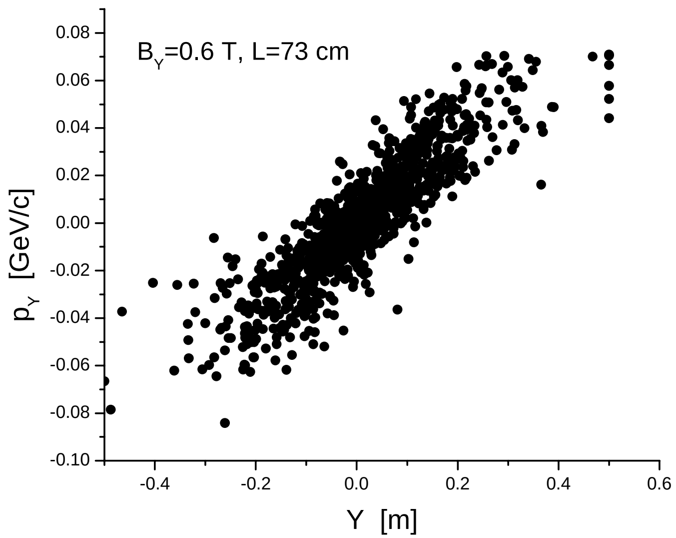
Exit plane distribution

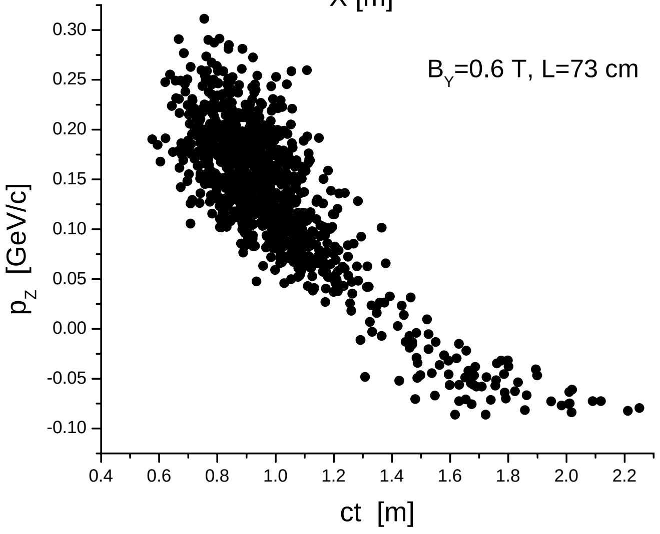




Phase space at exit window

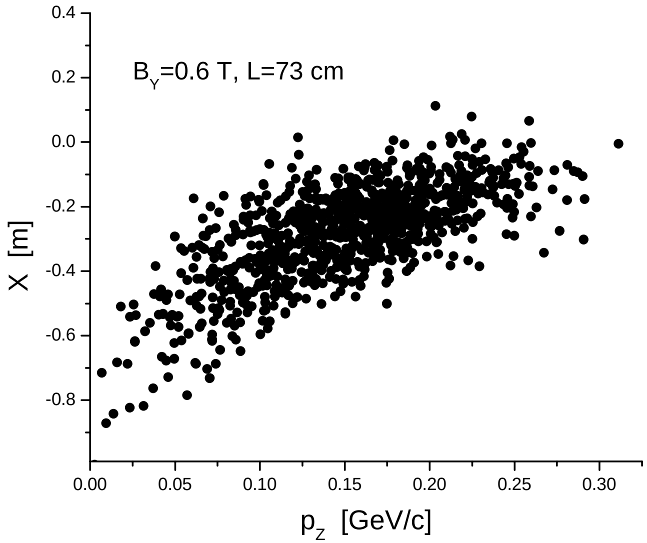


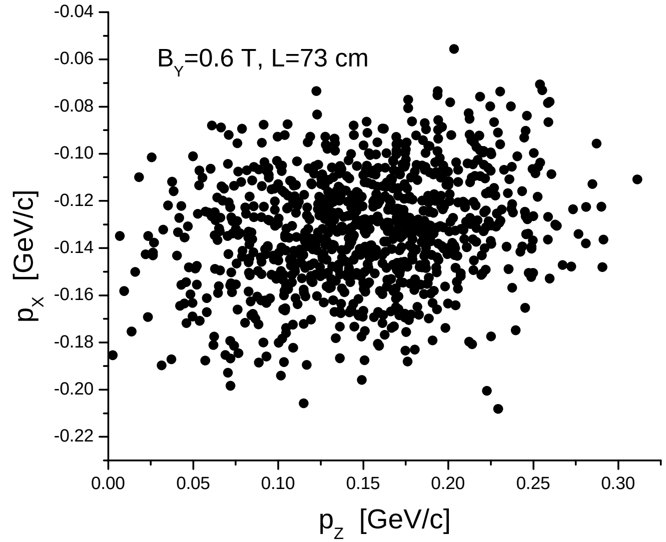




needs focusing, but that hurts separation ?
needs RF or longitudinal preconditioning,
but that stretches system out ?

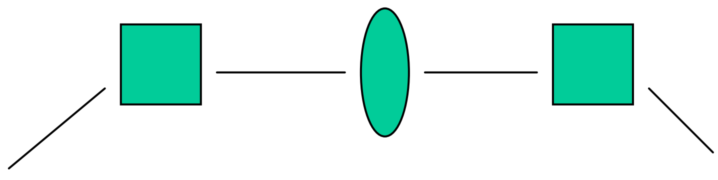
Dispersion at exit window





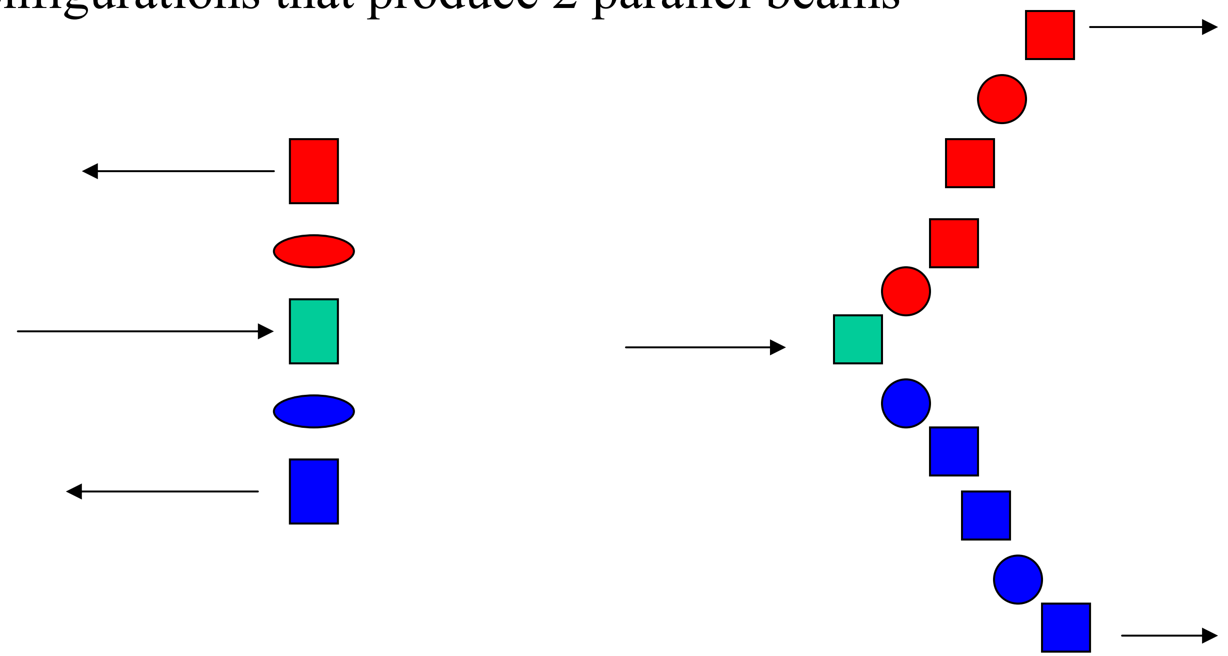
accepted beam is dispersive

Removing the dispersion (quads)



classic achromat
both bends must be in same direction
e.g. LQ=20 cm, BQ=0.34 kGs, rQ=30 cm
LD=64 cm, BD=7 kGs, d=20 cm

Configurations that produce 2 parallel beams



long channels
also need to include
focussing
RF cavities

Dipole summary

- this is a possible approach
- further work needs a more realistic dipole model
  - fringe field
  - edge focusing
- need to incorporate focusing and RF into the channel
- need to have proper matching from solenoid channel to dipole-quad channel and back again
- must include other parts of the system
  - matching beam to external channels
  - transporting beams apart
  - removing dispersion
- needs a lot more work

2. Deflection cavity model

• avoids difficulty of introducing RF in other methods

• looked at several arrangements of TE and TM cavities

(1) string of TE cavities doesn't work

violates Panofsky-Wenzel Theorem

confirmed in simulations using TE_{011} rectangular cavities

constant E field along x

(2) continuous string of TM cavities

(3) TM cavities with drift spaces in Alvarez-like arrangement

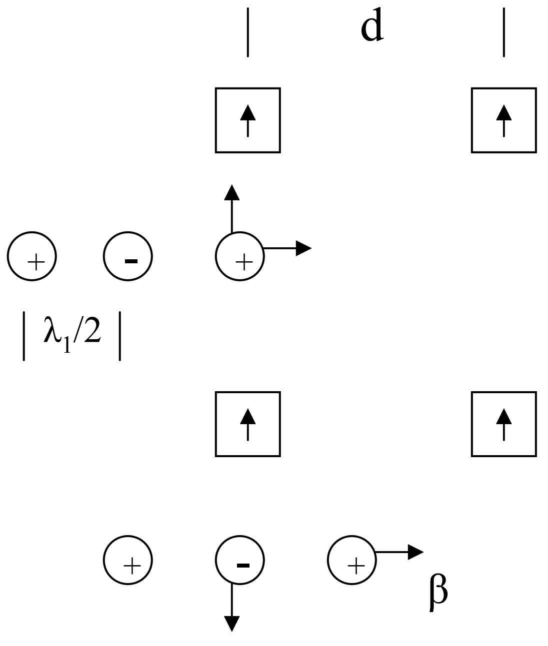
this scheme works best

$$\mathbf{p}_\perp = -\frac{e}{v}\int_0^d \left[\left(\frac{\partial}{\partial t}+\mathbf{v}\cdot\boldsymbol{\nabla}\right)\mathbf{A}_\perp - \boldsymbol{\nabla}_\perp(\mathbf{v}\cdot\mathbf{A})\right]dz, \tag{2}$$

$$= e\left\{[\mathbf{A}_\perp(z=0)-\mathbf{A}_\perp(z=d)]+\int_0^d \boldsymbol{\nabla}_\perp A_z dz\right\}. \tag{3}$$

The first term will vanish for any cavity with ends perpendicular to its axis. The second term will *vanish identically* for a TE mode, but can be evaluated for a TM mode as follows: From the usual

Alvarez layout



- shield out field reversals with drift spaces

$$\lambda_1 / 2\beta c = n\,T$$
$$d / \beta c = m\,T$$

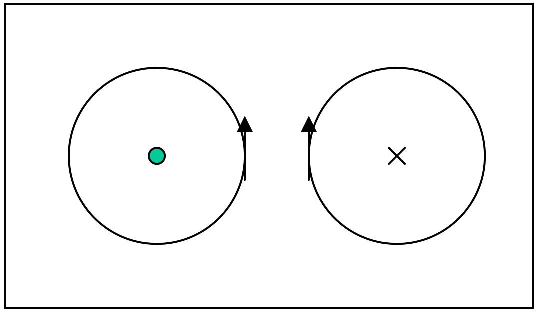
e.g. $m = n = 1$
$$d = \lambda_1 / 2$$
$$T = \lambda_1 / 2\beta c$$

$\lambda_1 = 1.492$ m $= c$ / 201 MHz

TM cavities

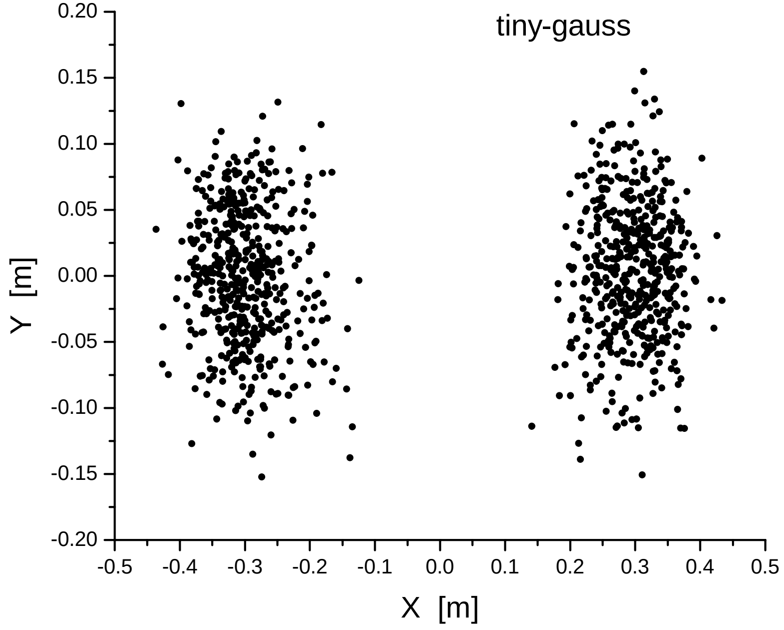
- try TM_{210} rectangular cavities
  has B_Y field along particle axis
- same cavity mode used for crab crossing, but shifted in phase
- needs $w > \lambda$ for resonance
- for 200 MeV/c f=355 MHz, λ=84 cm
- cavity dimensions: d=25 cm, w=100 cm, h=77 cm
- each cell = 25 cm cavity + 50 cm drift
- problem: after particle is deflected it sees E_Z => Δp_Z => phase error

beam's eye view



Small emittance beam

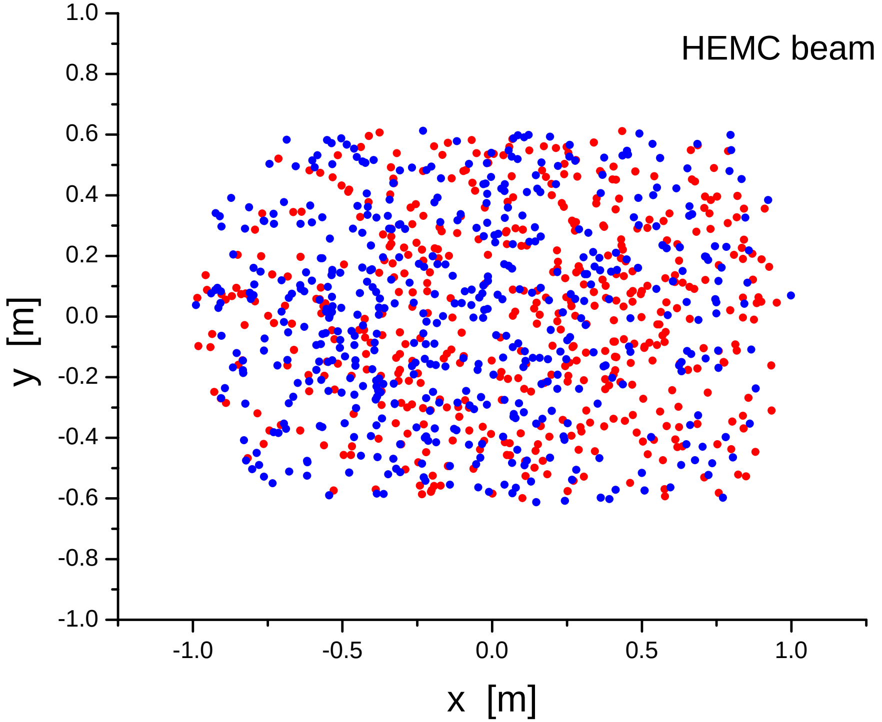
ε_{TN}=0.12 mm, ε_{LN}=0.41 mm
single bunch-pair



good separation along x
Tr = 99%

• to get good separation for a train of 20 bunches
had to reduce emittances to ε_{TN}=0.05 mm, ε_{LN}=0.03 mm

Full gaussian beam



ε_{TN}=12 mm, ε_{LN}=41 mm
single bunch-pair

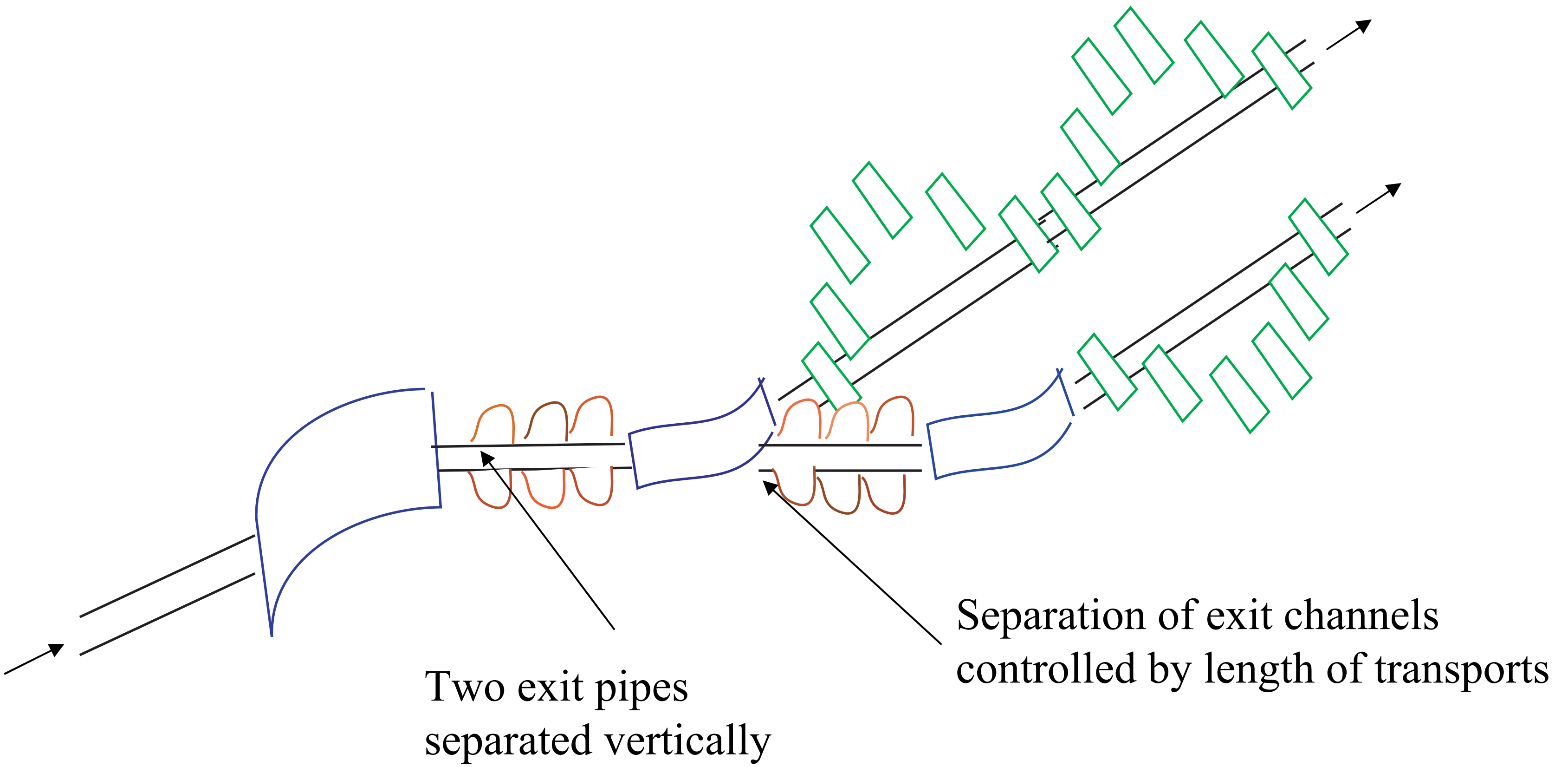
no separation !!

Method is no good for us

3. Bent solenoid model

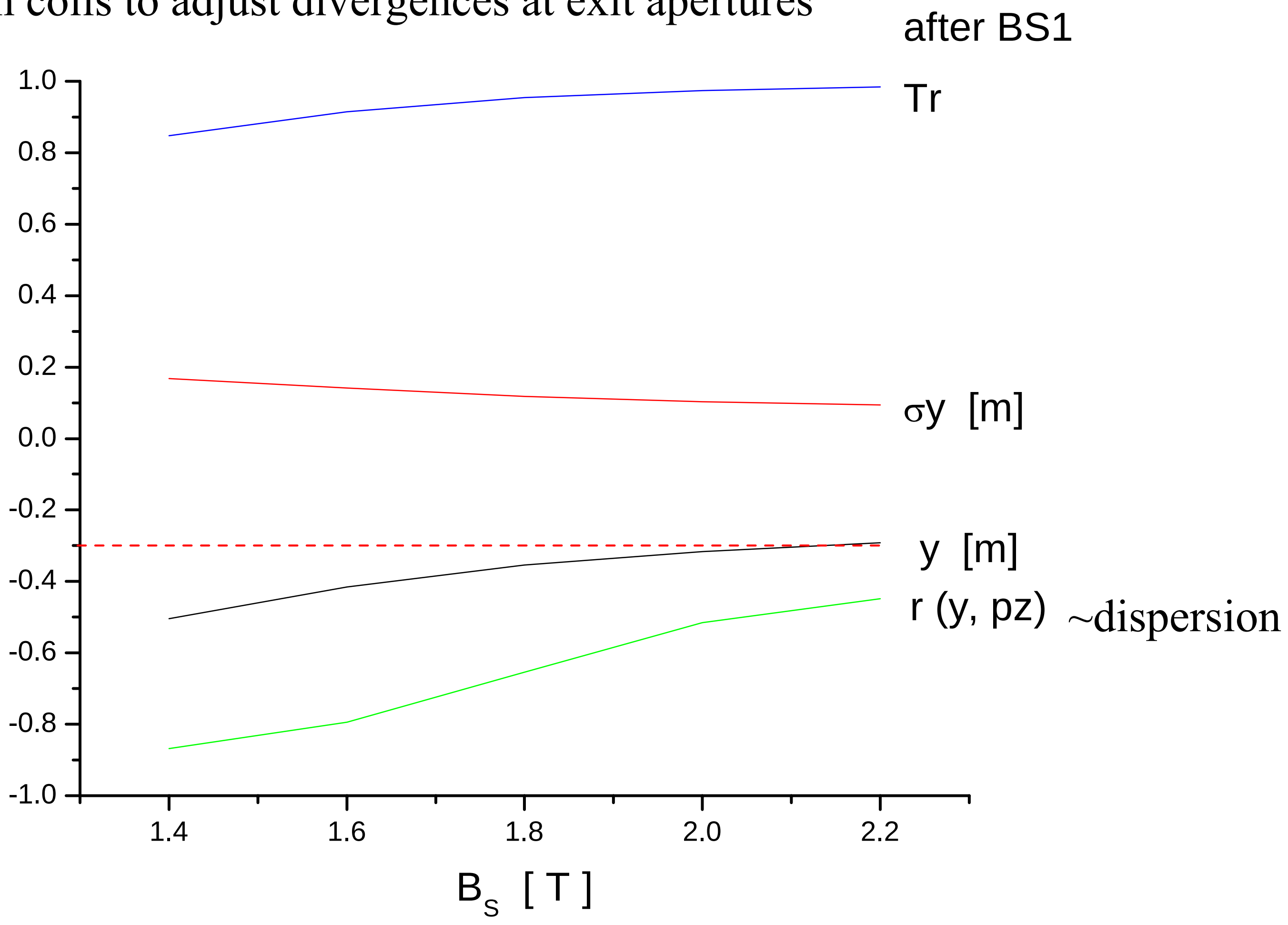
- tried using simple bent solenoid, ICOOL model BSOL(2)
- on-axis fields have Δtanh(s) (or constant) dependence
- off-axis fields comes from multipole expansions
- looked at channels with pairs of bent solenoids
  - first bent solenoid does the separation
  - second bent solenoid removes dispersion

Schematic horizontal layout



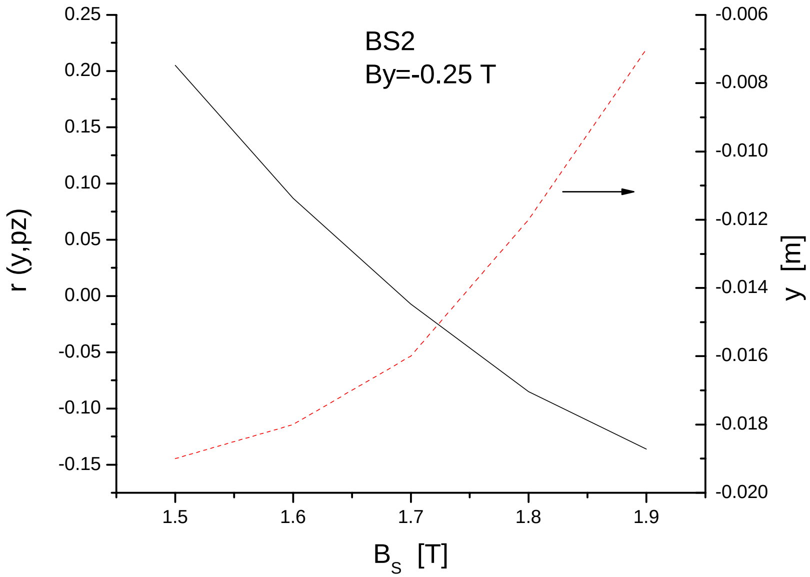
1^{st} bent solenoid optimization

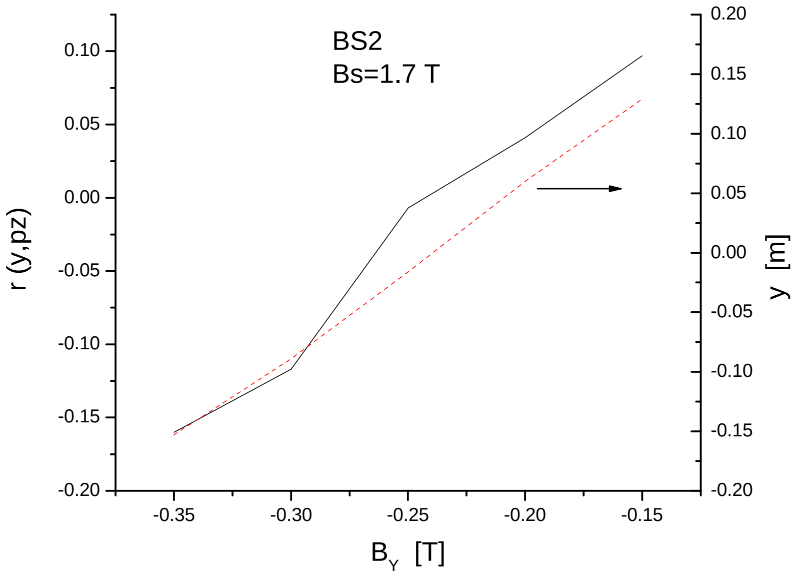
- used BSOL model 2 in ICOOL (use version ≥3.17)
- constant solenoid strength, no dipole field
- assumed trim coils to adjust divergences at exit apertures



2^{nd} bent solenoid optimization

- linear correlation coefficient **r** (y, pz) is proportional to dispersion
- use B_S to statistically remove dispersion
- use B_Y to keep central momentum at fixed y (not required)





Bent solenoid results with old HEMC beam

- separation and transmission looked good
- Tr = 90% of entrance beam
- could statistically remove dispersion
- main issue was emittance growth

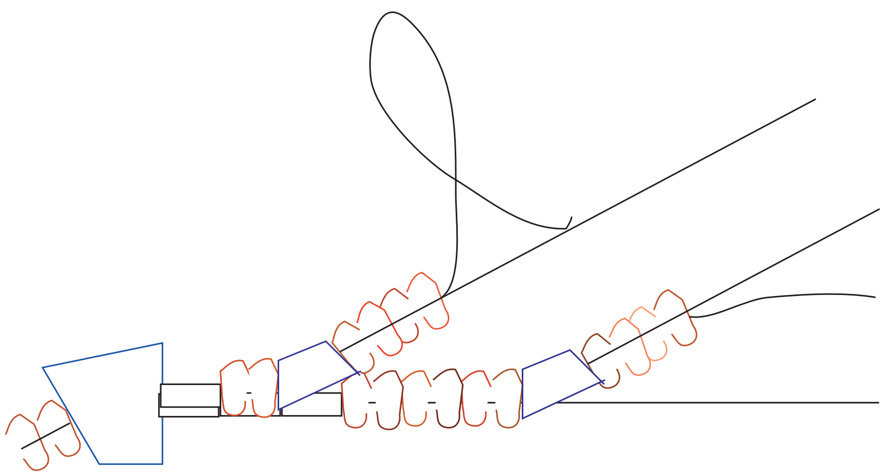
ε_{XN} : 12 → 24 mm
ε_{YN} : 12 → 23 mm
ε_{ZN} : 41 → 54 mm

Recent simulations

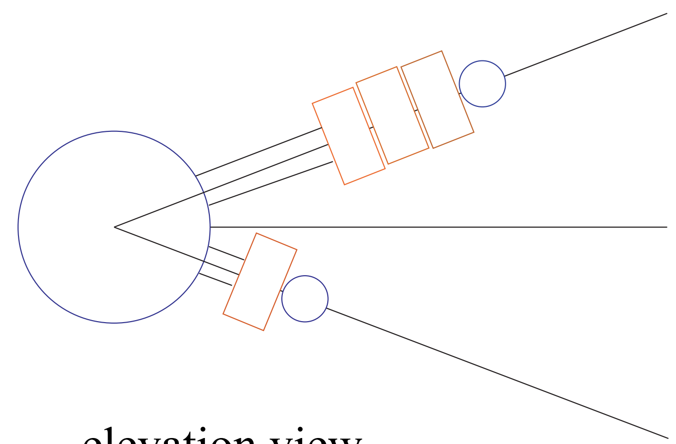
- looked at charge separation later in the HEMC collider scenario
- assumed we have initial 6D cooling with a FOFO-snake
- start separation when $\varepsilon_{TN} \sim 6$ mm and $\varepsilon_{LN} \sim 11$ mm
- used bent solenoid to do separation
- used analytic ICOOL model BSOL(2)
- assumed constant solenoid field strength along whole channel

Layout

- both charges: RF(2) + BS1(3) = 5 m
- positive channel: D(1) + RF(1) = 2 m
- negative channel: D(3) + RF(3) = 6 m
- both charges: BS2(3) + RF(2) = 5 m



plan view



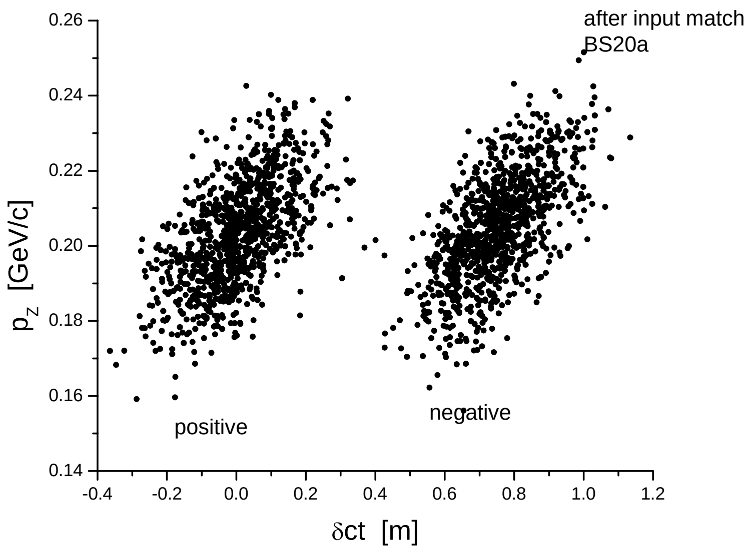
elevation view

Input match

- 2 m with 201 MHz RF and 1.9 T solenoid
- use RF cavities

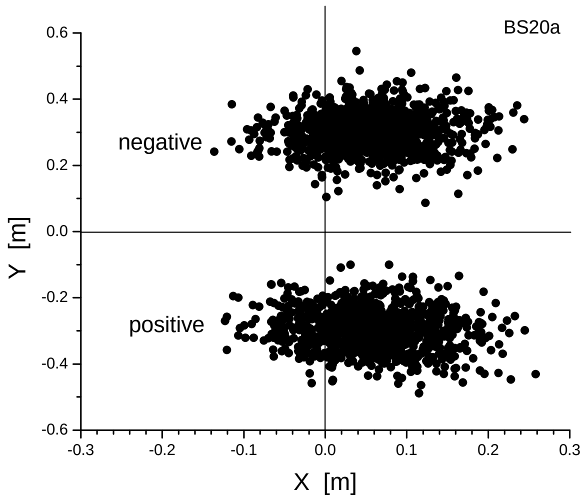
  to keep momentum fixed at 200 MeV/c

  to get upright longitudinal ellipse after BS1

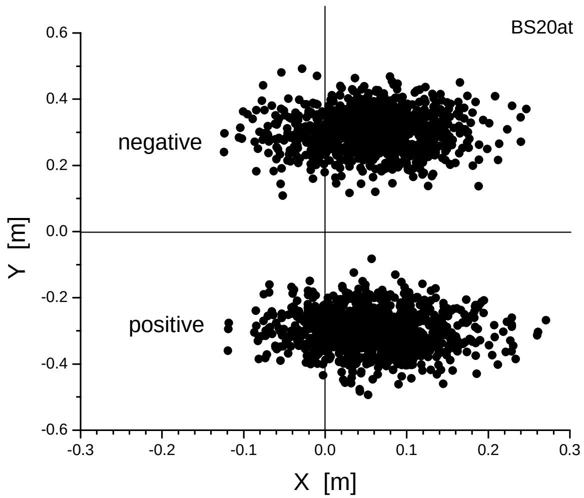


BS1 properties

- $L = 3$ m, B_S=1.9 T, B_D=0, h=0.30 m^{-1}
- exit holes have radius of 25 cm
- 12 cm separation between edges of positive and negative holes
- introduces dispersion on beam



single bunch pair



train of 20 bunch pairs

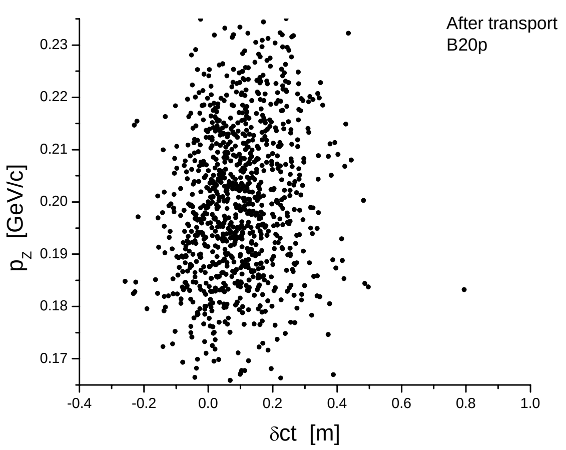
~100% separation

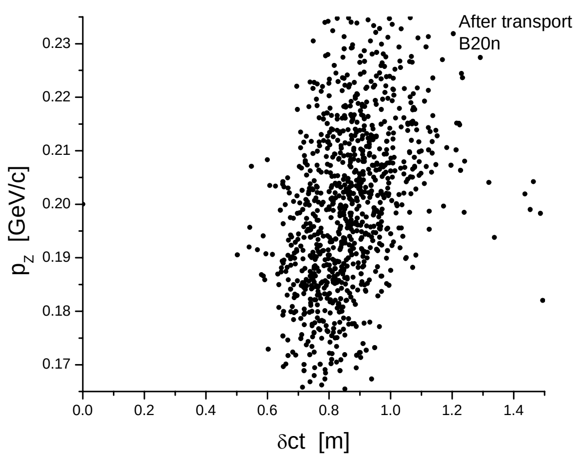
Transport properties

- want final beams ~3 m apart transversely
- use drifts to get away from congested areas
- then use RF cavities

  to keep momentum fixed

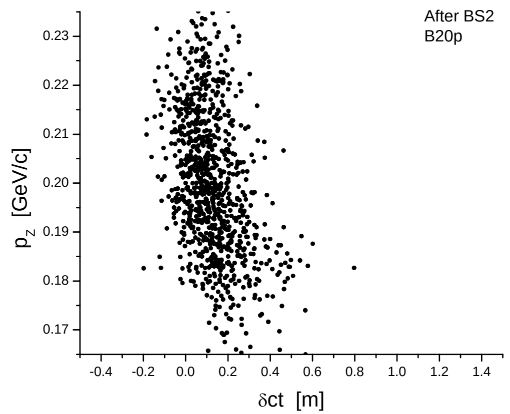
  to get upright longitudinal ellipse after BS2



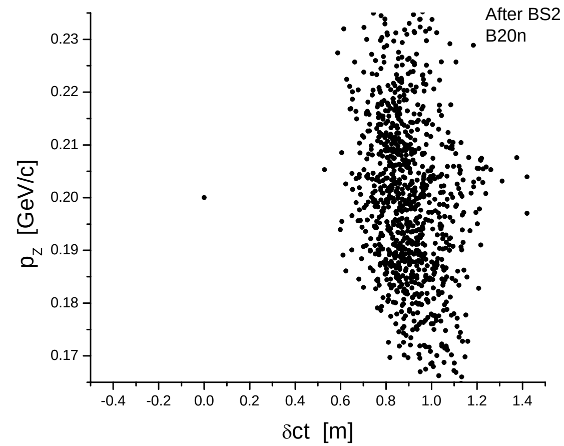


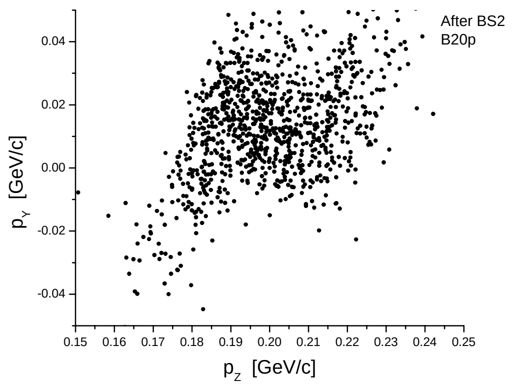
BS2 properties

- L=3 m, B_S=1.9 T, h=-0.30 m^{-1}
- B_D has Δtanh(s) shape
- B_D = -0.25 T for positives, =+0.25 T for negatives

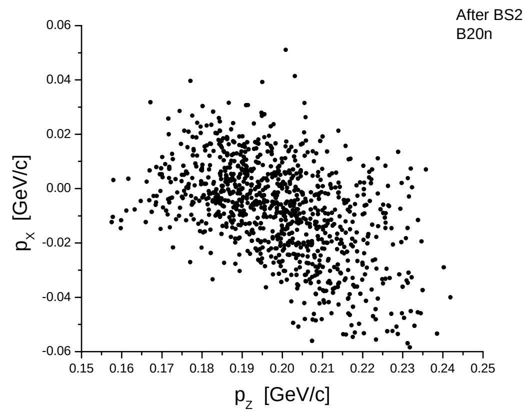


longitudinal phase space



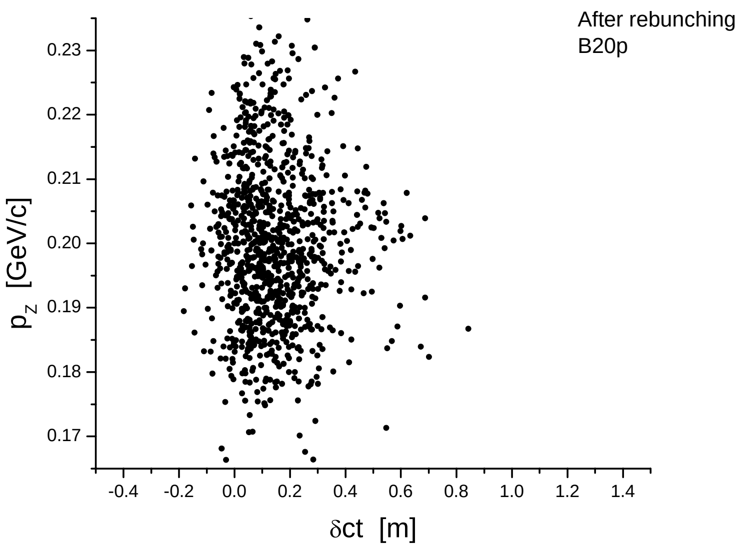


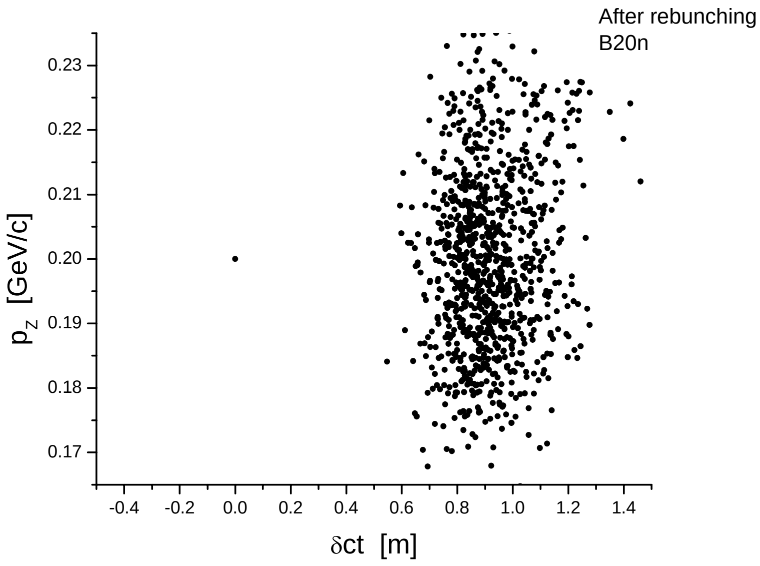
worst dispersions



Output match

- use 2 m of RF
- f=201 MHz, r=25 cm
- want upright longitudinal phase space at end

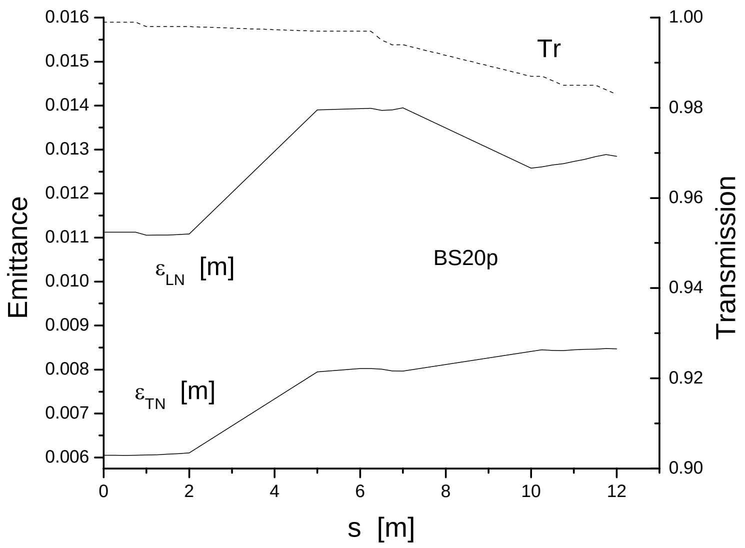


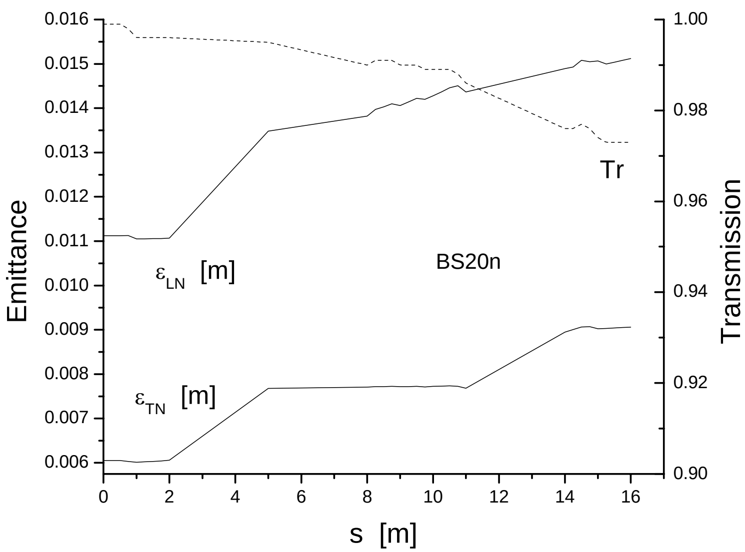


Effect on performance

- no problem with transmission
- issue is <u>emittance growth</u>

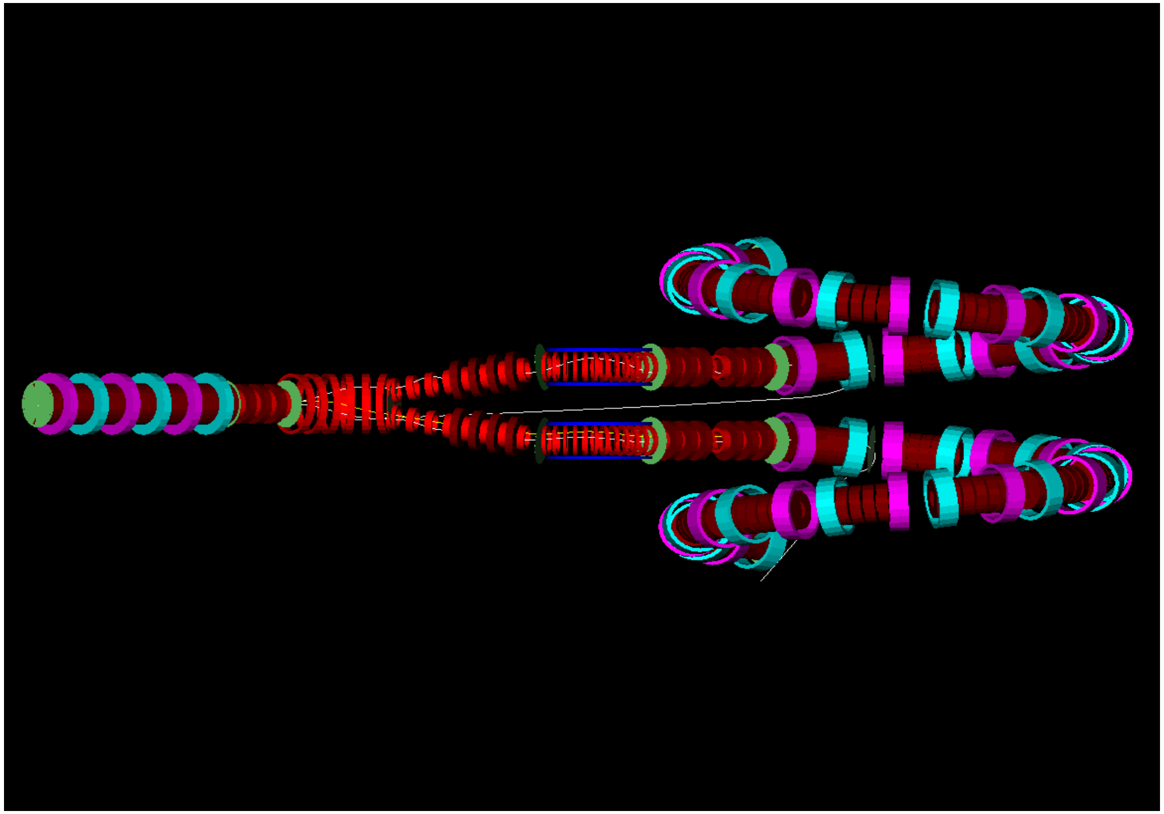
model	L	ε_{TN}	ε_{LN}	Tr
	[m]	[mm]	[mm]	[%]
BS20p	12	6.1 → 8.5	11.1 → 12.9	98.3
BS20n	16	6.1 → 9.1	11.1 → 15.1	97.3





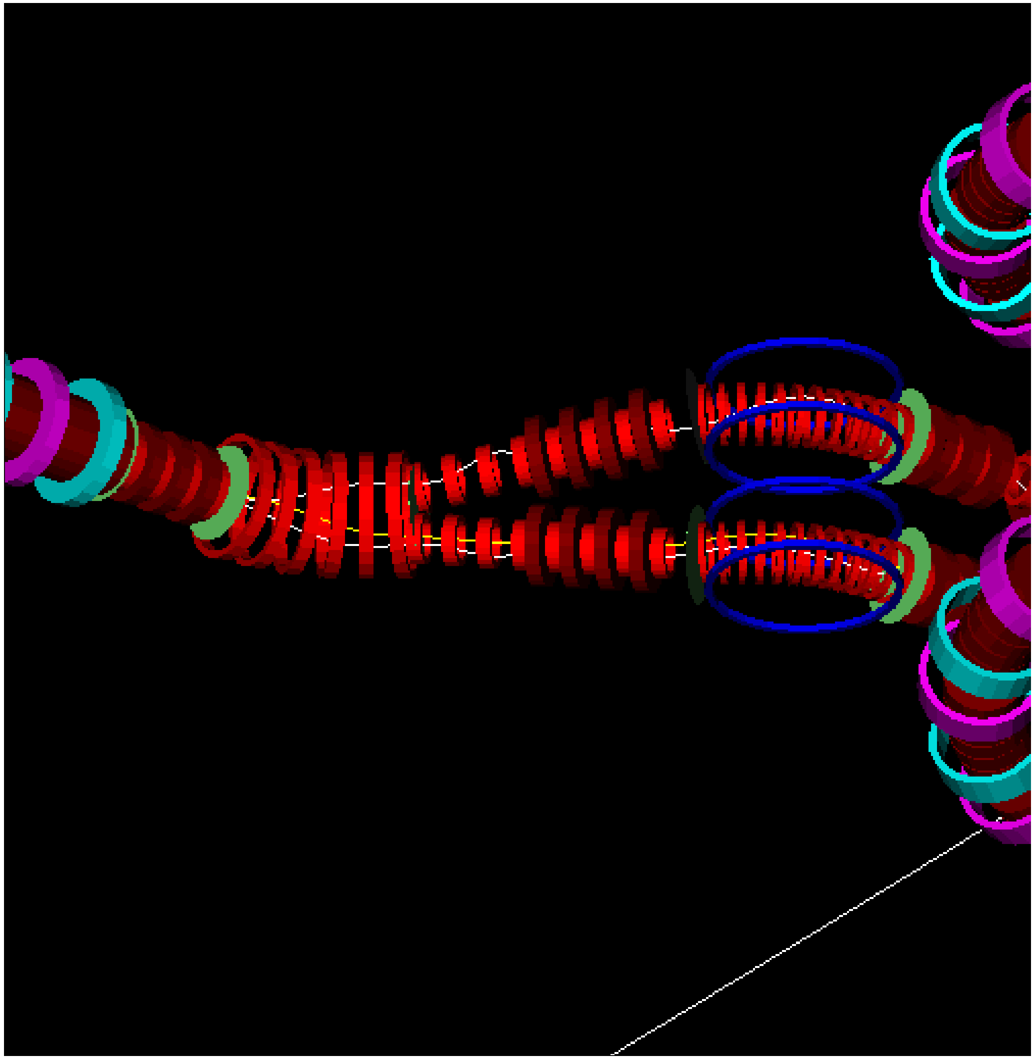
G4Beamline layout

H-FOFO
snake



Guggenheims

Details of bent solenoids



Conclusions

- a dipole system is possible
  - but needs a lot more work
  - there is no clear advantage over using bent solenoids
- RF separation is not suitable for our large emittance beams
- bent solenoid channels look most promising for our problem
  - incorporate focusing with separation in a natural way
- issues for bent solenoid simulations
  - how to reduce the emittance growth? cf. Bob's talk
  - how realistic is the BSOL(2) model in ICOOL?
    - eventually need a G4Beamline simulation