# Comparison of final focus magnetic systems for the Assisted Pinched Transport and the RPD-2002

J. Barnard, G. Sabbi, S. Yu,

Lawrence Berkeley National Laboratory

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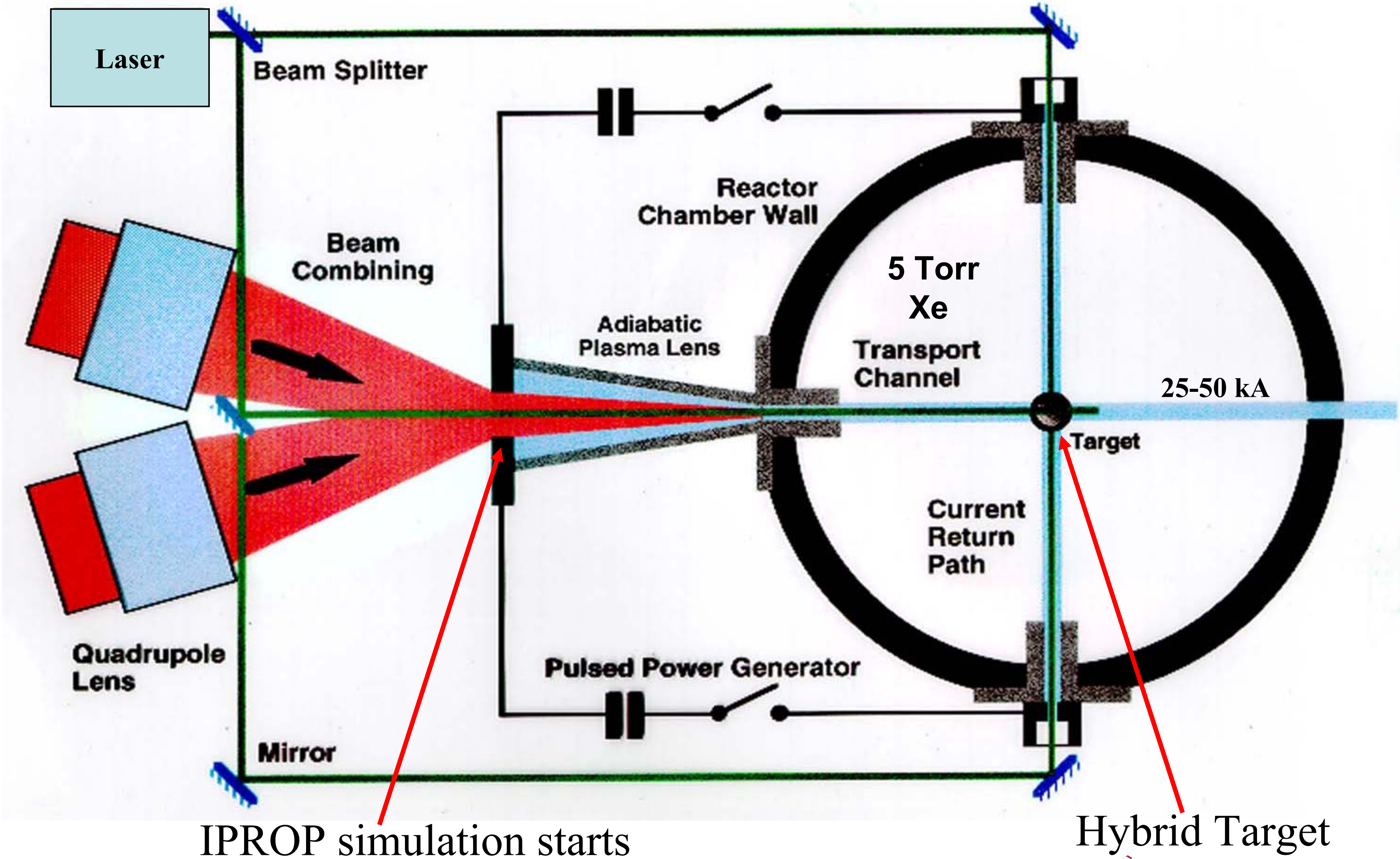
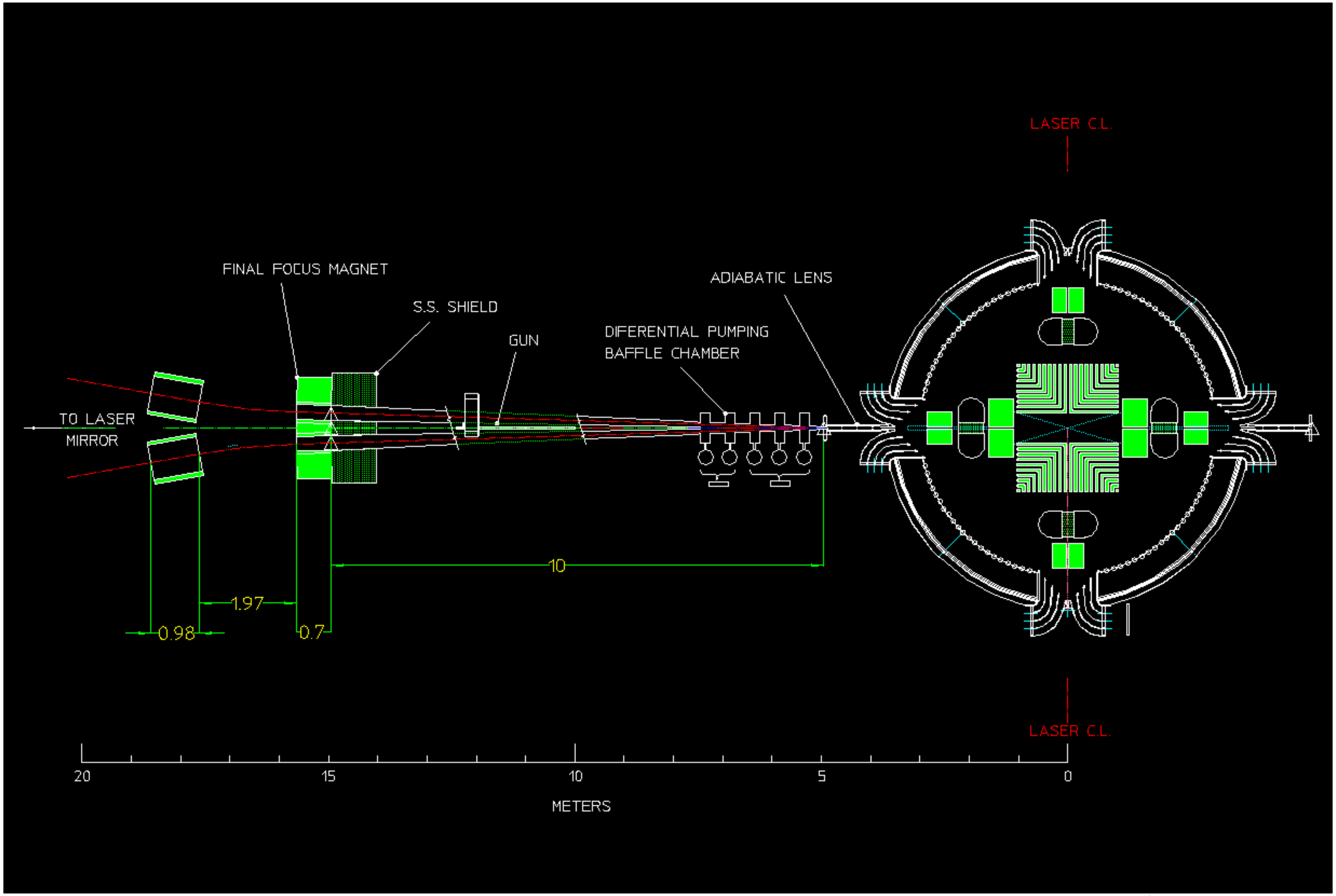
# Z Pinched Transport can reduce chamber focus requirements and reduce driver costs.



# Z Pinch Point Design (1997)

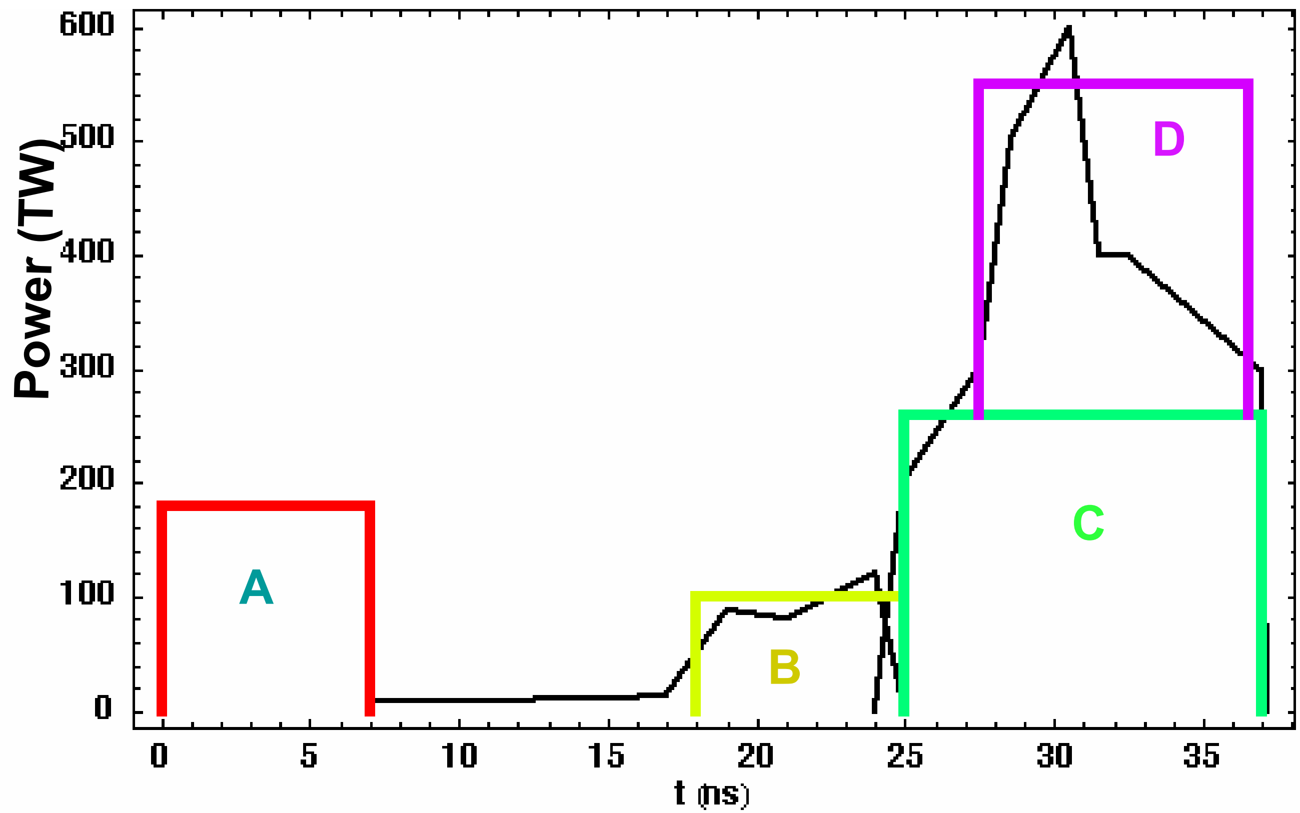


# Beam parameters for the Robust Point Design were obtained from D. Callahan

- Total beam energy = 7.0 MJ; Main pulse = 5.22 MJ; Foot pulse = 1.77 MJ
- Number of beams = 120; amu = 209 (Bismuth); q = 1.
- final ion energy(main) = 4.0 GeV ($\beta$=0.200); final energy (foot)=3.3 GeV ($\beta$=0.182)
- normalized emittance (going into final focus) = 2 $\pi$ mm-mrad (normalized)

| Block | Power (TW) | $\tau$ (ns) | No. of beams | Power/ beam (TW) | Charge/ beam ($\mu$C) | Energy (all beams) (MJ) | Perv./1 $0^{-4}$ |
|---|---|---|---|---|---|---|---|
| A (Foot) | 70 | 6.5 | 16 | 4.375 | 8.62 | 0.455 | 0.646 |
| B (Foot) | 20 | 38.3 | 16 | 1.25 | 14.5 | 0.766 | 0.185 |
| C (Foot) | 53 | 10.1 | 16 | 3.31 | 10.1 | 0.545 | 0.489 |
| D (Main) | 130 | 13.7 | 24 | 5.43 | 18.6 | 1.78 | 0.494 |
| E (Main) | 370 | 9.3 | 48 | 7.70 | 17.9 | 3.44 | 0.701 |

# The intensity profile on the hybrid target is approximated by four blocks of beams with constant intensity




| Block | Power (TW) | Time (ns) |
|---|---|---|
| A (foot) | 180 | 7 |
| B (foot) | 100 | 7 |
| C (main) | 260 | 12 |
| D (main) | 290 | 9 |

# Beam parameters for the hybrid design

- Total beam energy = 7.7 MJ; Main pulse = 5.7 MJ; Foot pulse = 2.0 MJ
- Number of beams = 128;  amu = 209 (Bismuth);  q = 1.
- final ion energy(main) = 4.0 GeV ($\beta$=0.200); final energy (foot)=3.3 GeV ($\beta$=0.182)
- normalized emittance (going into final focus) = 2 $\pi$ mm-mrad (normalized)

| Block | Power (TW) | $\tau$ (ns) | No. of beams | Power/ beam (TW) | Charge/ beam ($\mu$C) | Energy (all beams) (MJ) | Perv./1 $0^{-4}$ |
|---|---|---|---|---|---|---|---|
| A (Foot) | 180 | 7 | 32 | 5.625 | 11.9 | 1.26 | 0.83 |
| B (Foot) | 100 | 7 | 32 | 3.125 | 6.6 | 0.7 | 0.46 |
| C (Main) | 260 | 12 | 32 | 8.125 | 24.3 | 3.12 | 0.74 |
| D (Main) | 290 | 9 | 32 | 9.0625 | 20.4 | 2.61 | 0.82 |

# Final focus system in Assisted Pinch and Robust Point Designs allow for beams of variable perveance and energy

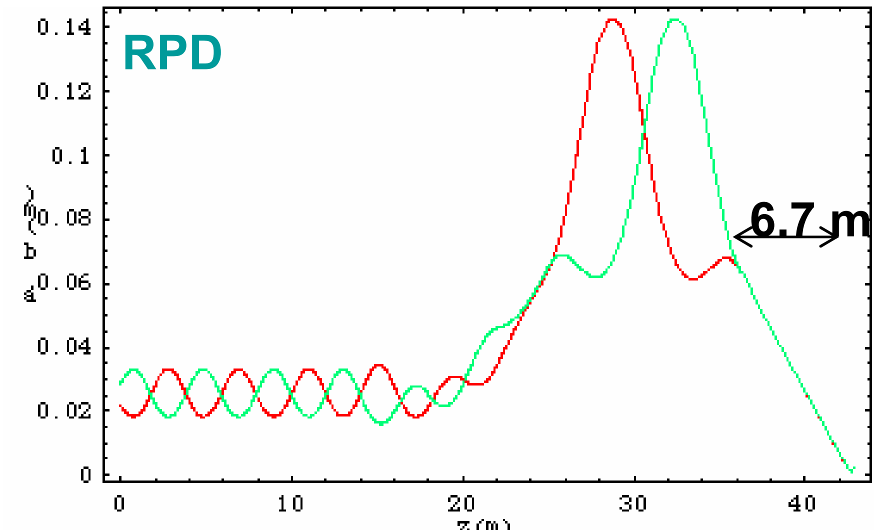
**Final four magnets have same magnetic field gradient and aperture for all beam lines (with varying energy and perveance). This allows flux sharing in a magnet array (transverse) analogous to the arrays within the accelerator.**

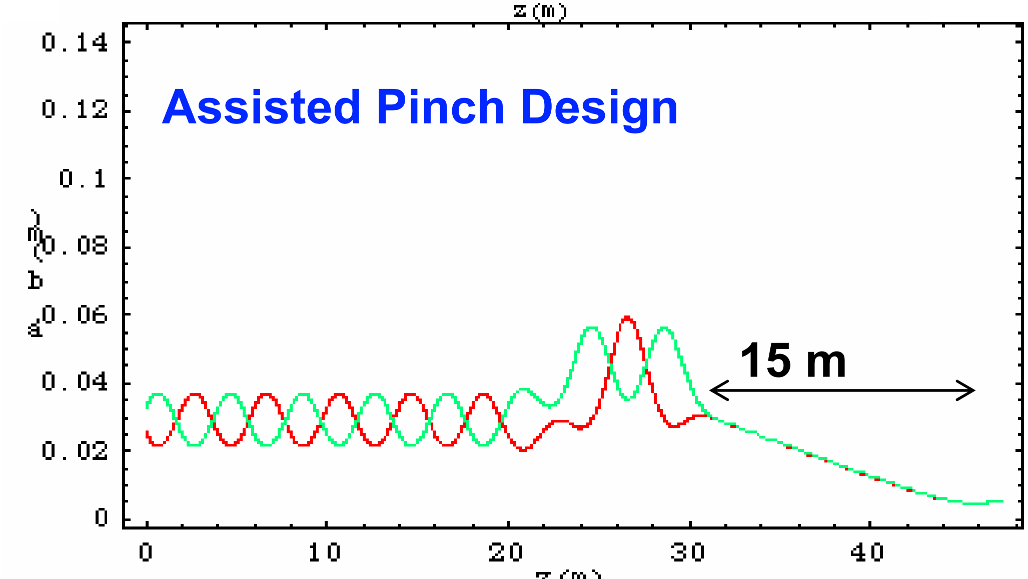
**Six to eight "Matching" magnets that precede final magnets will be well separated transversely; each matching magnet gradient is tuned to the particular beam energy and perveance needed for each block of beams.**

**Maximum allowed field at aperture is 6 T in assisted pinch and 4 T in RPD. (Higher beam current was assumed in hybrid design).**

**Final angle of high perveance beams held constant ( 2 mrad for Blocks C and D in assisted pinch and 10 mrad for blocks D and E in RPD.) Lower perveance beams have lower final focusing angles associated with lower emittance growth predicted in chamber.**

# Comparison of RPD with Assisted Pinch Design




| | RPD | APD |
|---|---|---|
| Spot radius (mm) | 2.2 | 10.0 |
| Standoff distance (m) | 6.7 | 15.0 |
| Angle between beamlines (deg) | 5.4 | 0.75 |
| Gradient (max) (T/m) | 19.1 | 75.1 |
| Radius of inner winding (m) | 0.259 | 0.099 |
| Max ($8B'^2 R^3$) (FOD) ($T^2$-m) | 50.7 | 43.8 |

# Assisted Pinch Parameters

*Variable lattice length design:*

| Quad | B'(T/m) | B(rp)(T) | Rp(cm) | l(m) | ldrift*(m) |
|---|---|---|---|---|---|
| last | 76.7 | 3.82 | 4.98 | 0.348 | 15 |
| 2nd | -107.4 | -5.98 | 5.57 | 0.697 | 0.3 |
| 3rd | 94.8 | 6.39 | 6.74 | 1.05 | 0.45 |
| 4th | -84 | -6.21 | 7.41 | 1.26 | 0.54 |

*Fixed lattice length design:*

| Quad | B'(T/m) | B(rp)(T) | Rp(cm) | l(m) | ldrift*(m) |
|---|---|---|---|---|---|
| last | 26.9 | 1.66 | 6.2 | 1.39 | 15 |
| 2nd | -61.4 | -4.95 | 8.1 | 1.39 | 0.598 |
| 3rd | 75.1 | 6.32 | 8.4 | 1.39 | 0.598 |
| 4th | -62.3 | -5.03 | 8.1 | 1.39 | 0.598 |

*ldrift is the distance after the last magnet

# Assisted Pinch vs. RPD-02

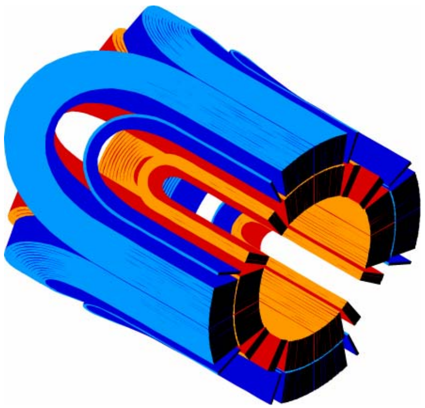
Assisted Pinch has several advantages from the magnet design standpoint:

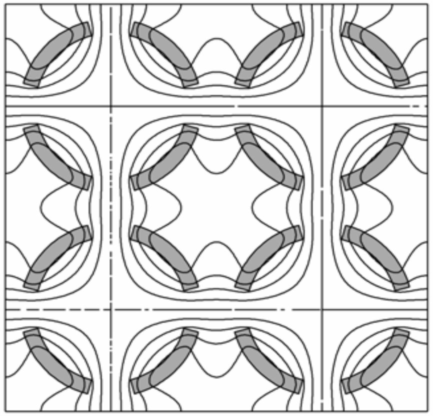
- Smaller beam aperture (max $R_{pipe}$ is 8.4 cm vs. 19.6 cm)
- Lower radiation load → no radial buildup for shielding (5 cm)
- Smaller coil aperture (max $R_{coil}$ is 9.9 cm vs. 26.6 cm)
- Comparable peak field due to larger gradient
- Parameters are closer to present "state of the art" magnets
- Smaller beam convergence angle allows parallel coil axis

# Coil geometry & array layout options

<u>Shell type (cos 2θ):</u>

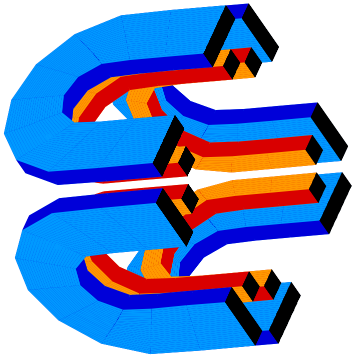
- magnetically more efficient
- need individual coil support, radial & azimuthal

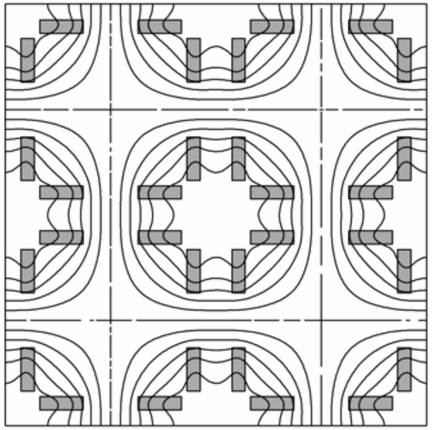




<u>Block/racetrack:</u>

- mechanical support advantages
- larger transverse force/stress
- tight transverse packing possible
- common structure required





# Magnet #3 parameters

$Nb_3Sn$ racetrack coils in array configuration can meet specs:

- Design (short sample) gradient: 90 T/m (20% margin)
- Required average current density: 430 A/mm$^2$
- 2D coil peak field @ short sample: 13.7 T
- 3D peak field (expected): 15.0 T
- Required $Nb_3Sn$ Jc @ 15 T: 1.1-1.3 kA/mm$^2$
- Available $Nb_3Sn$ Jc @ 15 T: 1.5 kA/mm$^2$

Shell-type coils are magnetically more efficient, but do not allow tight transverse packing

Magnet #3 parameters appear quite reasonable relative to "state of the art" $Nb_3Sn$ magnet R&D (LHC IR quads)

# Second-generation LHC IR quads (90 mm bore)

*Operating Gradient: 205 T/m (FOD=30.6)*

Assuming $J_c$ (12T, 4.2K) = 3 kA/mm$^2$ $T_{op}$=1.9K

Maximum gradient

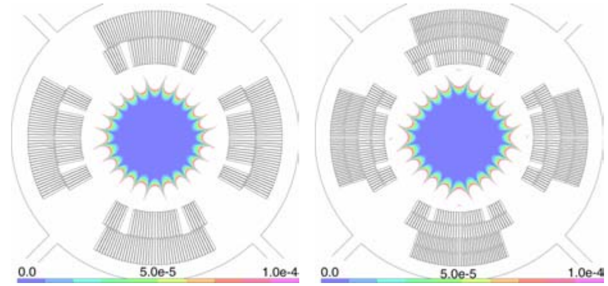
- 260 T/m (2-layer)
- 285 T/m (4 layer)

Conductor peak field

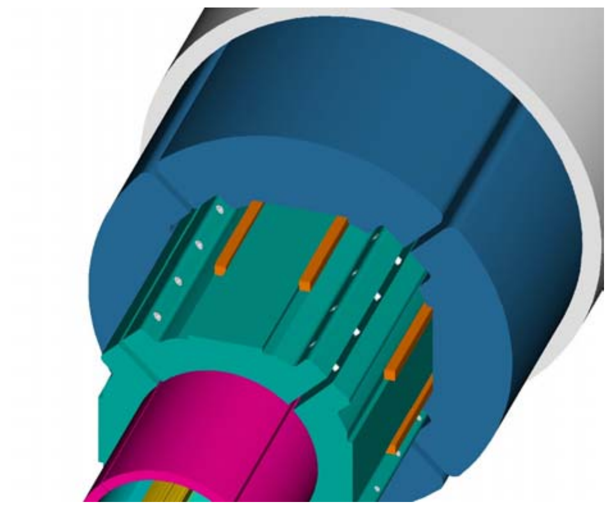
- 13.3 T (2-layer)
- 14.4 T (4 layer)

Stress analysis

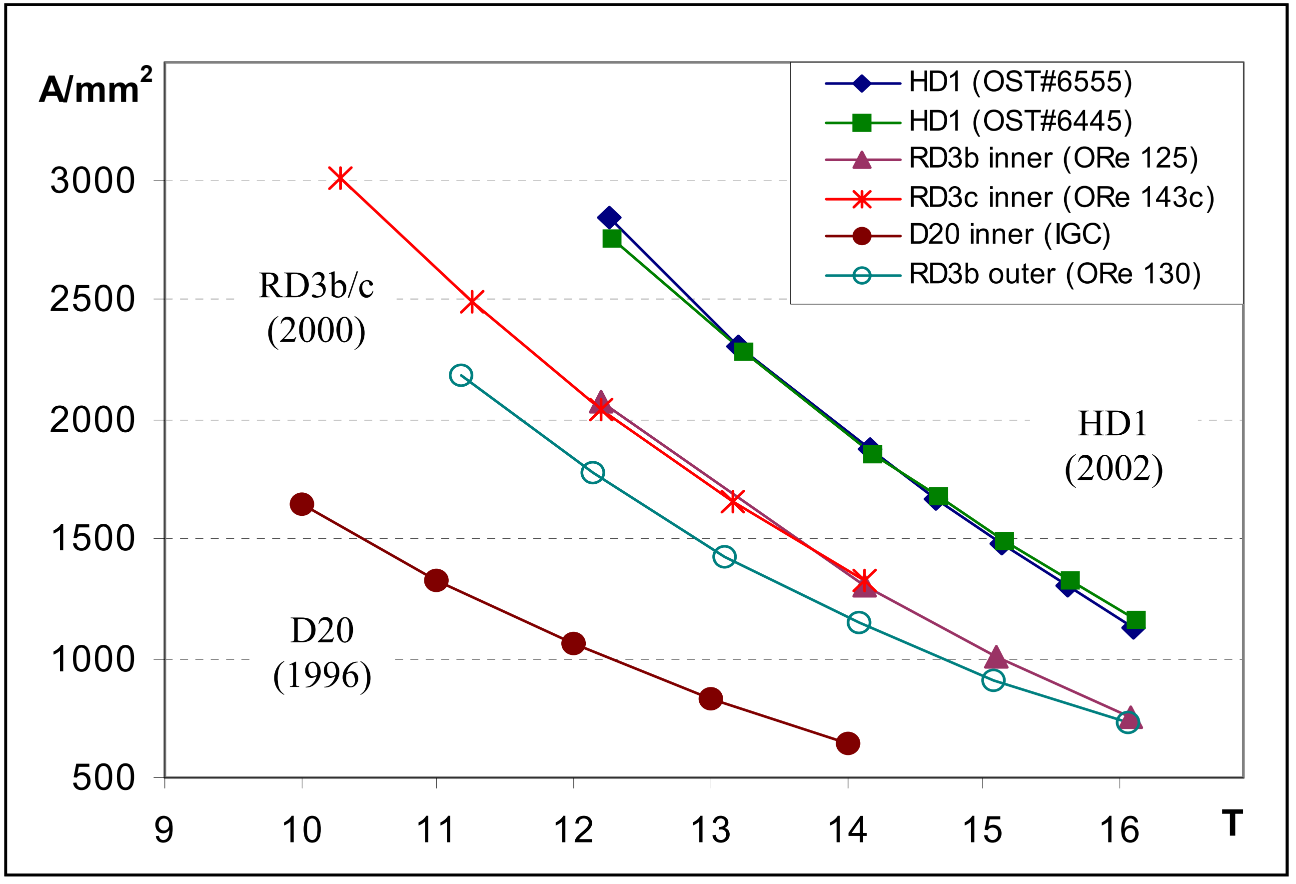
| | Inner (MPa) | | Outer (MPa) | |
|---|---|---|---|---|
| | Midpl. | Pole | Midpl. | Pole |
| 2-layer (270 T/m) | 130 | 11 | 138 | 4 |
| 4-layer (300 T/m) | **162** | 14 | **170** | 5 |



Two or four layer designs


Bladder and key assembly

# $Nb_3Sn$ current density



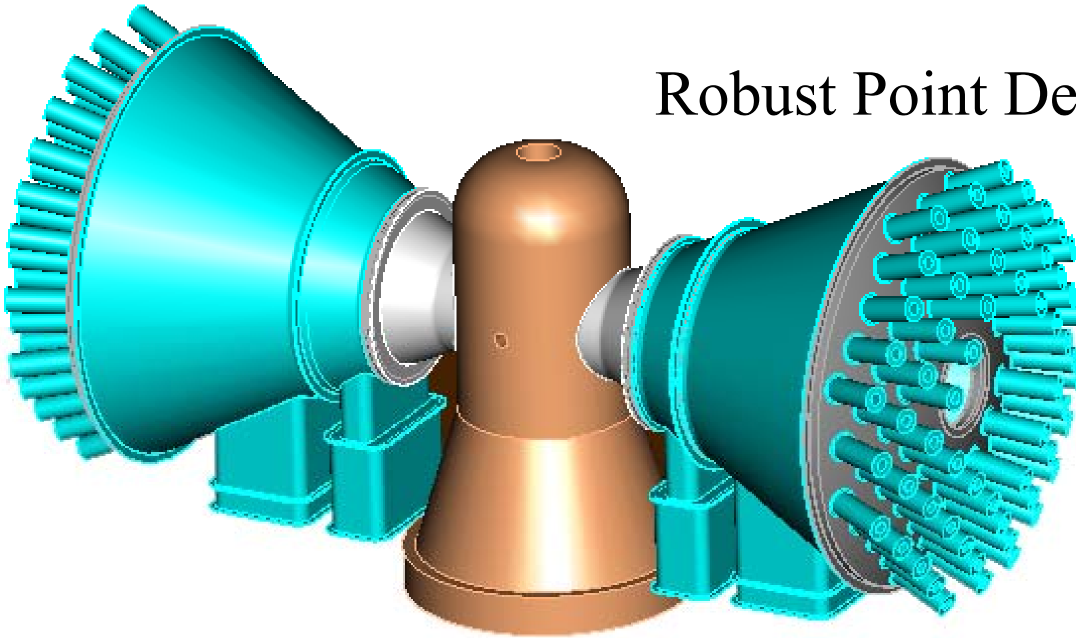
# Array size (magnet #3)

*Racetrack design:*

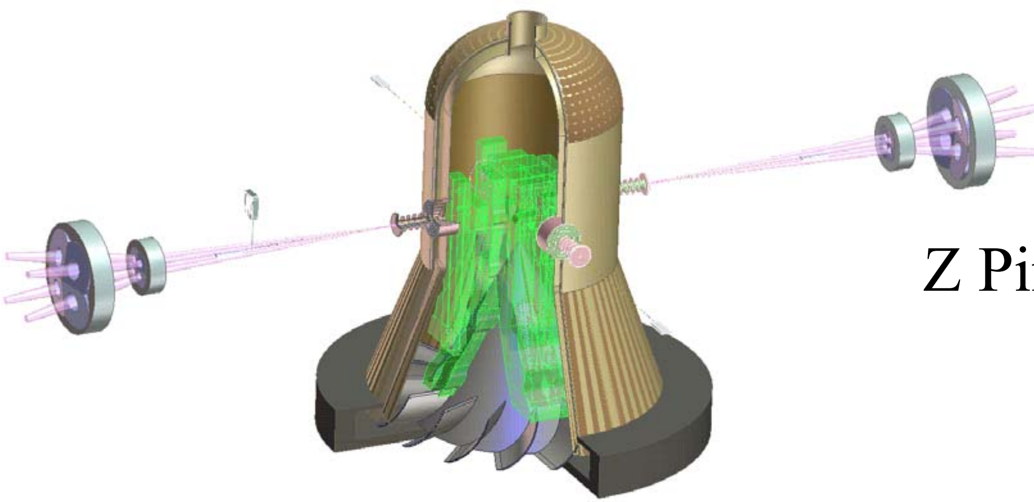
- Radial buildup: $R_{pipe}$=8.4 cm, $R_{coil}$=9.9 cm, $R_{cell}$=12 cm
- 2.2 m total transverse size (without support structure)

*Shell design:*

- Requires individual coil support (collars or outer shell)
- Collars have smaller radial buildup (a few cm) but are difficult to implement in Nb3Sn magnets
- Yoke+shell provides good support but results in large radial buildup



Robust Point Design (RPD-2002)



Z Pinch Point Design (1997)

# Advantages of Z Pinch Transport

A. Chamber Protection
  - 4 small holes for channel entry and return
  - Complete shielding of target entry port
  - Few nozzles

B. Compact Final Focus Array
  - Array angle 2º - 3º (vs 24º for RPD)
  - Array diameter 1m (vs 6 to 10m for RPD)

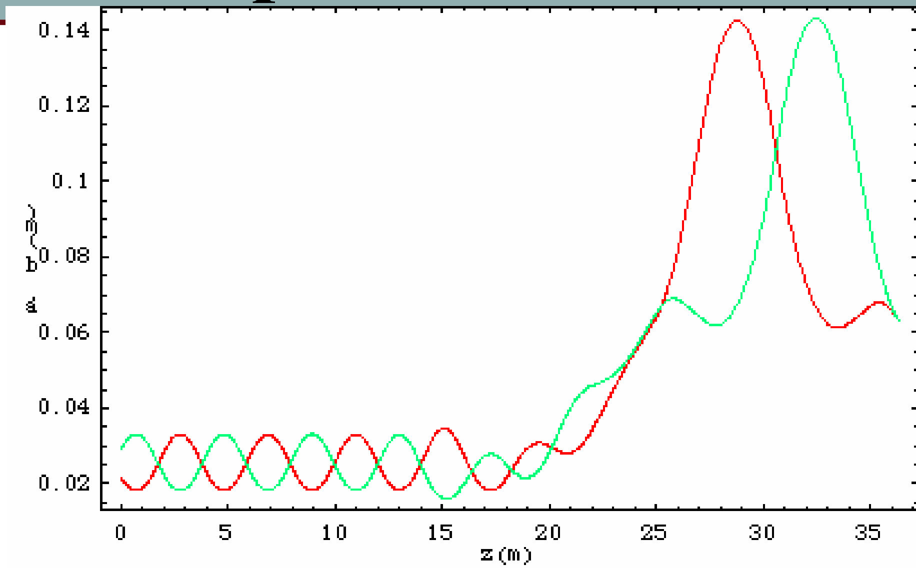
C. Relaxed Drift Compression
  - $\Delta p/p$ relaxed by one order of magnitude
  - $\Delta I/I$ similarly relaxed
  - Expensive correction pulsers minimized

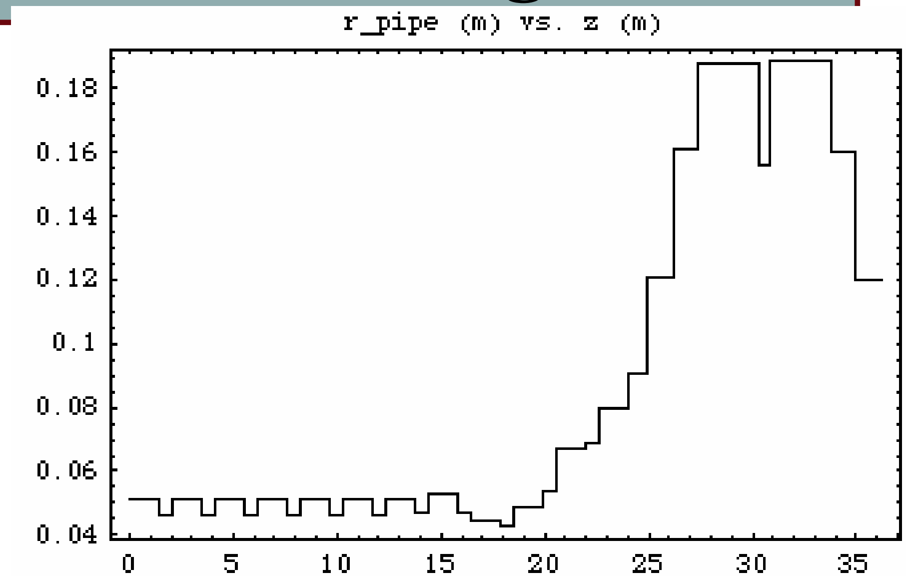
D. Many driver options
  - Low mass OK
  - Many beams or few beams

E. Good match to hybrid target
  - Large spot, small angle

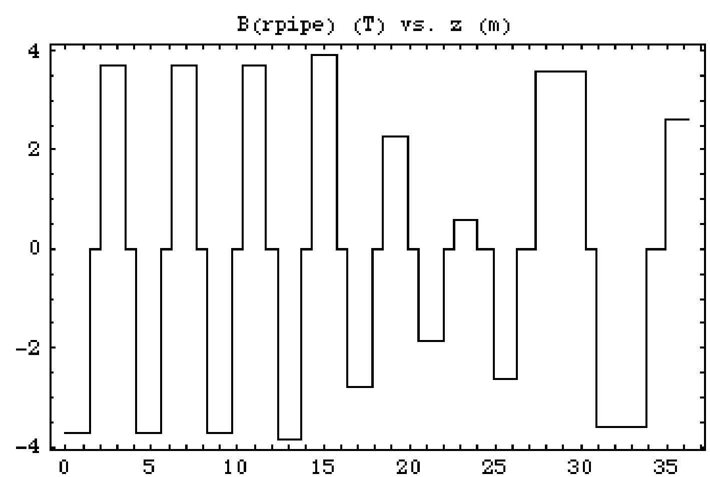
# Backup Slides

# Final four magnets based on 4.38TW beam parameters of Robust Point Design



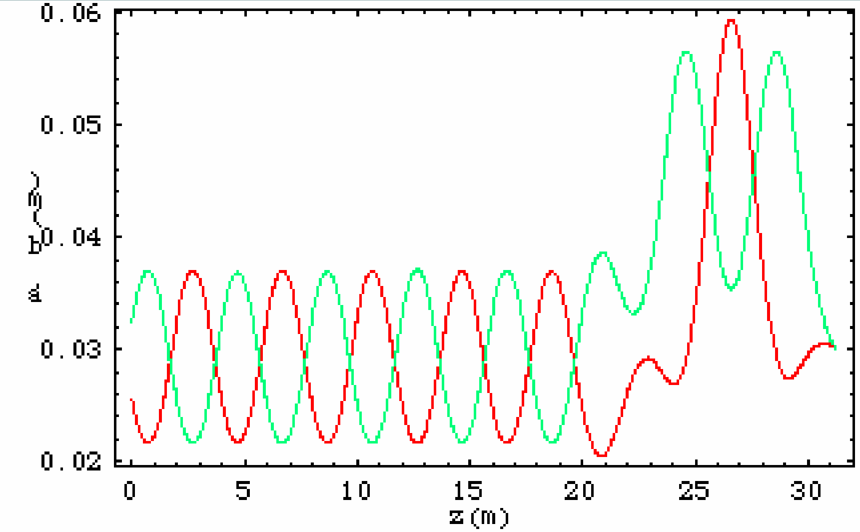



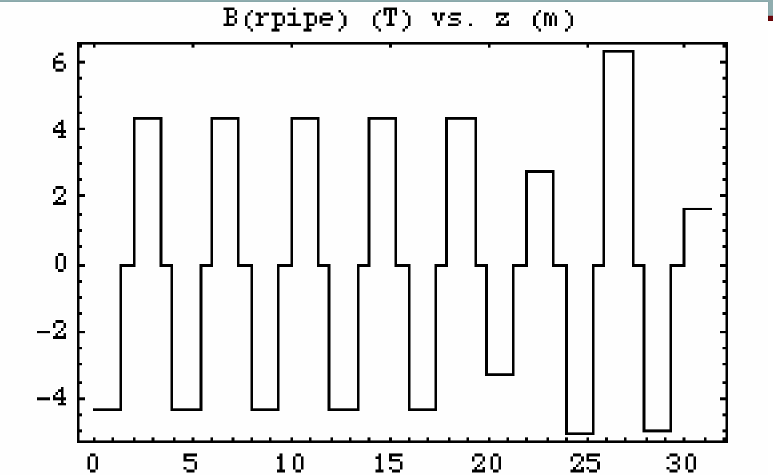

| quad | B'(T/m) | $B(r_p)$(T) | $r_p$(cm) | l(m) | ldrift*(m) |
|---|---|---|---|---|---|
| last | 21.8 | 2.61 | 12.0 | 1.33 | 6.33 |
| 2nd | -19.1 | -3.60 | 18.9 | 3.00 | 1.10 |
| 3rd | 19.1 | 3.79 | 19.9 | 3.00 | 0.50 |
| 4th | -21.8 | -3.09 | 14.2 | 1.33 | 1.10 |




***ldrift is the distance after magnet**

# Final four magnets in assisted pinch design based on 8.125 TW beam parameters, final focus angle of 2 mrad-(const. L)




| quad | B'(T/m) | $B(r_p)$(T) | $r_p$(cm) | l(m) | ldrift*(m) |
|---|---|---|---|---|---|
| last | 26.9 | 1.66 | 6.2 | 1.39 | 15 |
| 2nd | -61.4 | -4.95 | 8.1 | 1.39 | 0.598 |
| 3rd | 75.1 | 6.32 | 8.4 | 1.39 | 0.598 |
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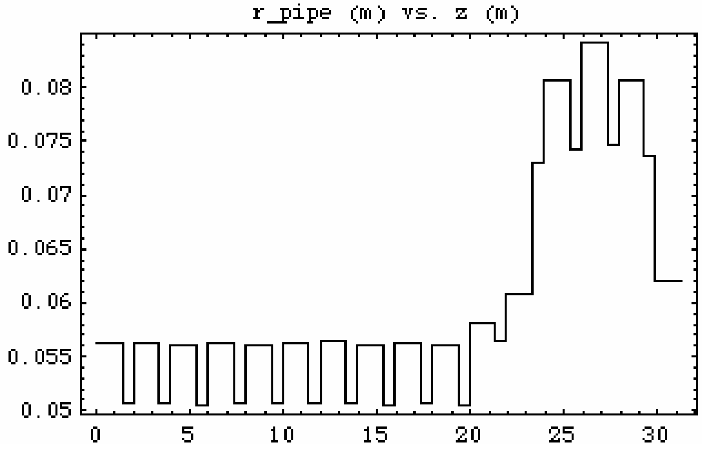
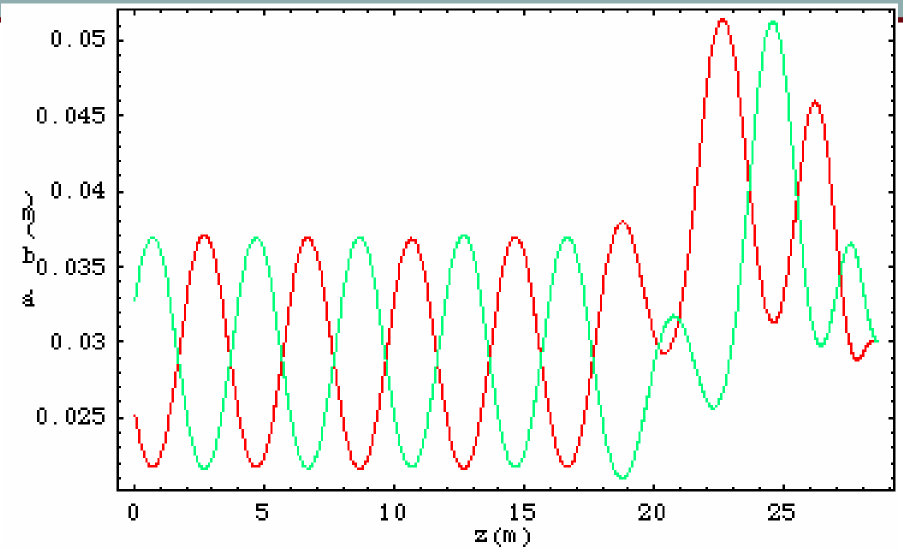
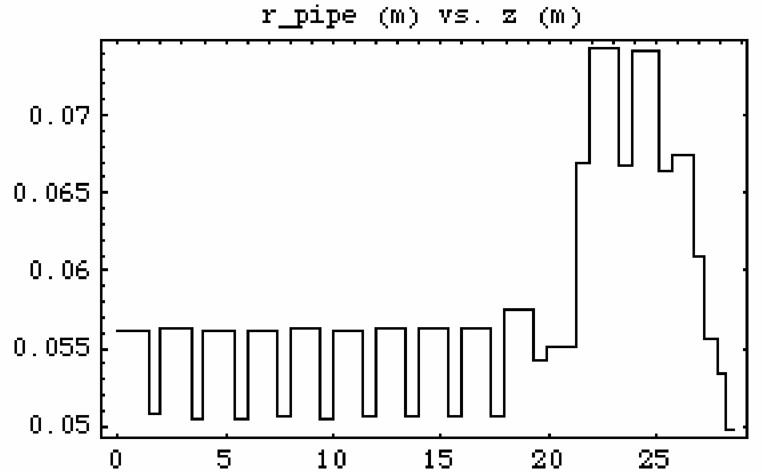


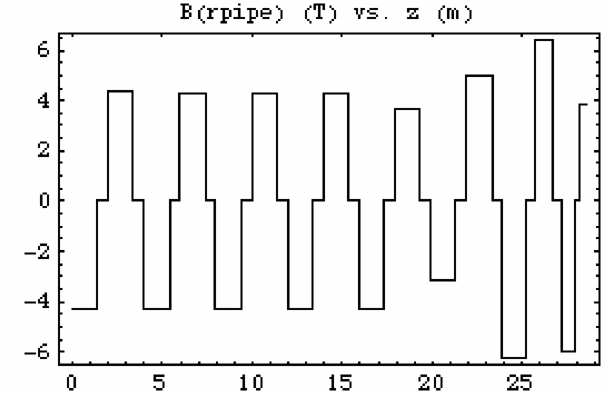

*ldrift is the distance after magnet

# Final four magnets in assisted pinch design based on 8.125 TW beam parameters, final angle of 2 mrad-(varied L)




| quad | B'(T/m) | $B(r_p)$(T) | $r_p$(cm) | l(m) | ldrift*(m) |
|---|---|---|---|---|---|
| last | 76.7 | 3.82 | 4.98 | 0.348 | 15 |
| 2nd | -107.4 | -5.98 | 5.57 | .697 | 0.30 |
| 3rd | 94.8 | 6.39 | 6.74 | 1.05 | 0.45 |
| 4th | -84.0 | -6.21 | 7.41 | 1.26 | 0.54 |




*ldrift is the distance after magnet

# Fixed lattice length vs Variable lattice length

*"Fixed length" is preferred option from magnet design standpoint*

- Better longitudinal spacing (min. $L_{drift}$ 0.6 m vs. 0.3 m)
- Magnet requirements for #1, #2, #4 are easier to meet (magnet #3 requirements comparable for both cases)

Variable lattice length

| Mag | Gop [T/m] | Rcoil (*) [cm] | FOD (#) [$T^2$m] |
|---|---|---|---|
| #1 | 76.7 | 6.48 | **12.8** |
| #2 | 107.4 | 7.07 | **32.6** |
| #3 | 94.8 | 8.24 | **40.2** |
| #4 | 84 | 8.91 | **39.9** |

Fixed lattice length

| Mag | Gop [T/m] | Rcoil (*) [cm] | FOD (#) [$T^2$m] |
|---|---|---|---|
| #1 | 26.9 | 7.7 | **2.6** |
| #2 | 61.4 | 9.6 | **26.7** |
| #3 | 75.1 | 9.9 | **43.8** |
| #4 | 62.3 | 9.6 | **27.5** |

*(*) assuming 1.5 cm radial buildup $R_{pipe}$ to $R_{coil}$ - consistent with RPD-02*
*(#) FOD (figure of difficulty) is defined as $G^2D^3$*

- Better length to aperture ratio