Simulation Study of Final Cooling Channel using Lithium Lens

UCLA

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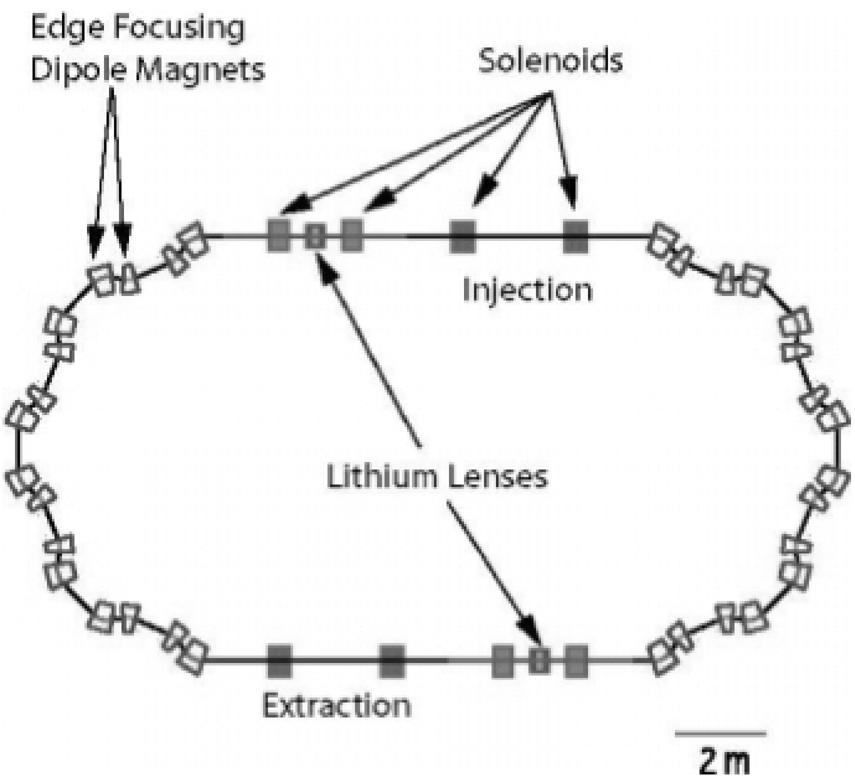
BNL Muon Collider Design Workshop

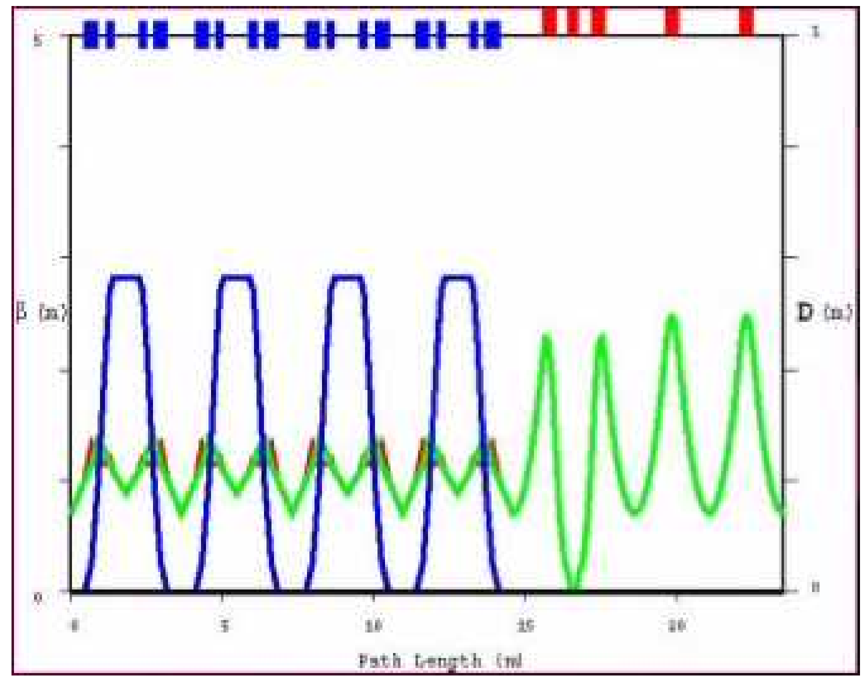
December 1-3, 2009

Previous Studies with Lithium lens

- Curved Li lens (~2004-current) by Y. Fukui
- Cooling Ring studies (~2002-2004) using Li lens by A. Garren and Y. Fukui
- Initial engineering considerations for a liq. Li lens (2008) with some inputs from J.P. Morgan and T. Leveling at Fermilab and BINP papers

Li Lens Cooling Ring in ~2004





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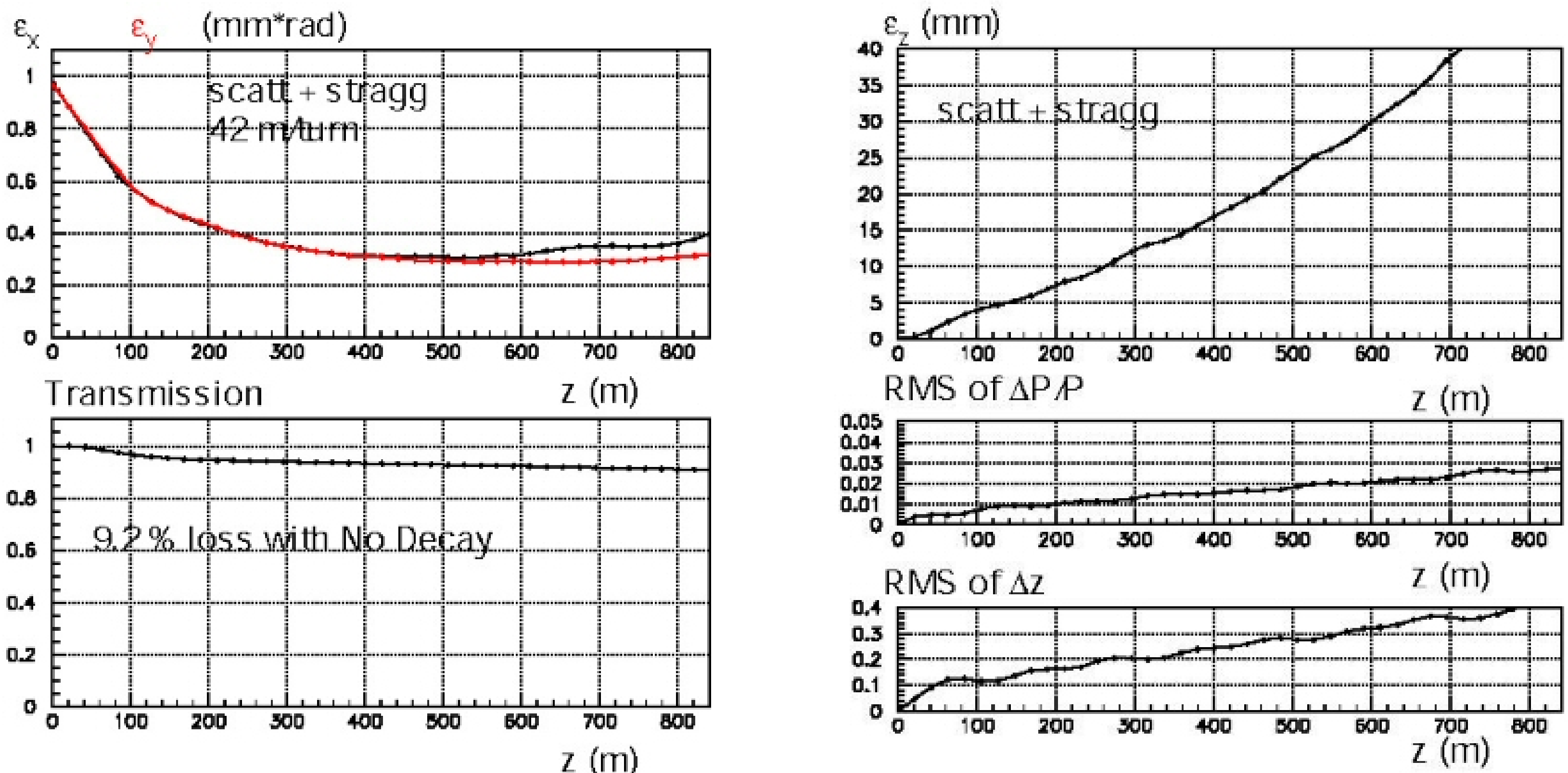
A. Garren

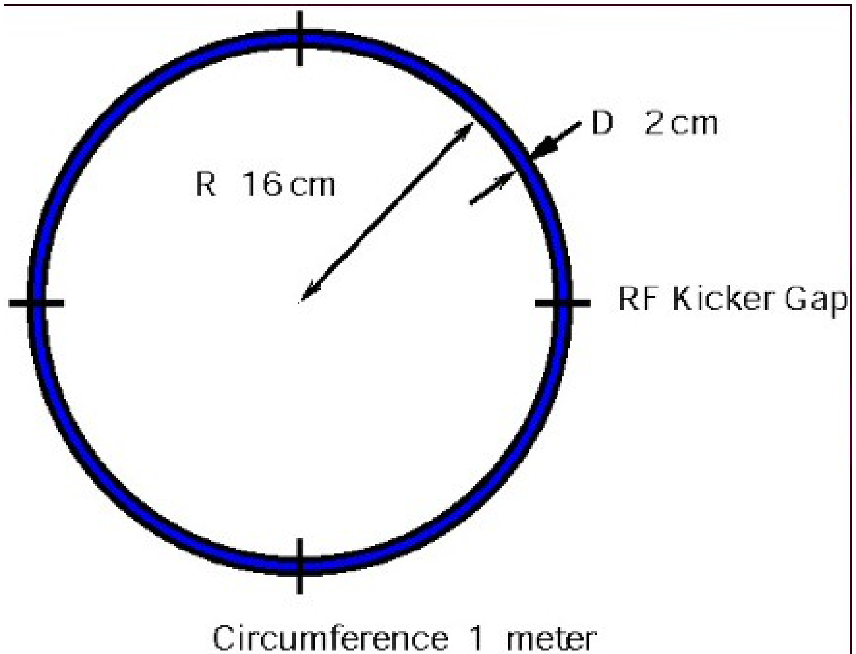
Results for Cooling Ring w/ Straight Lens

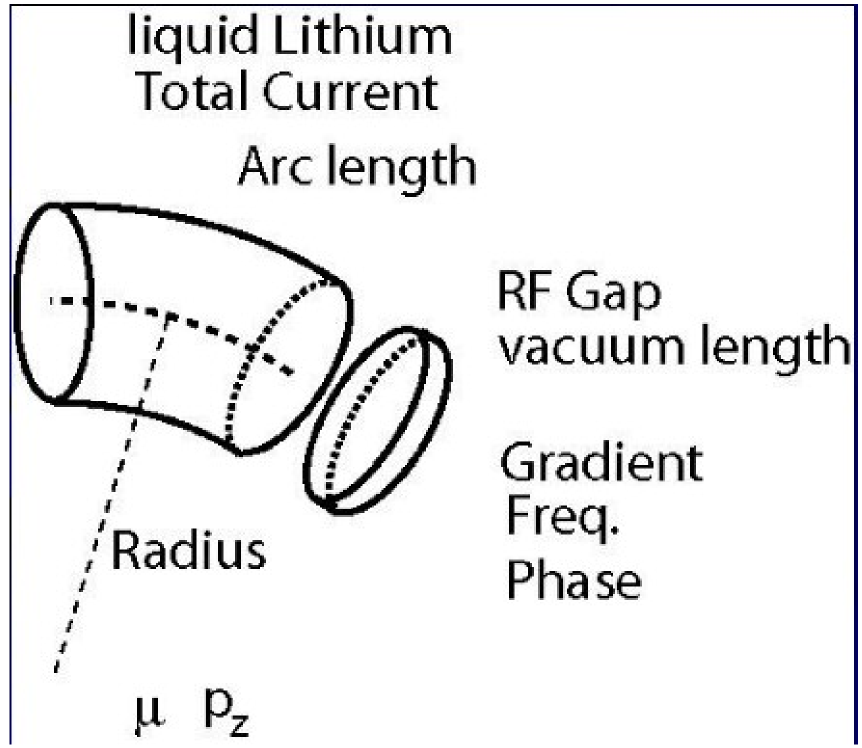


Y. Fukui et. al, Proceedings of **2005** Particle Accelerator Conference, Knoxville, Tennessee,

IEEE01591401

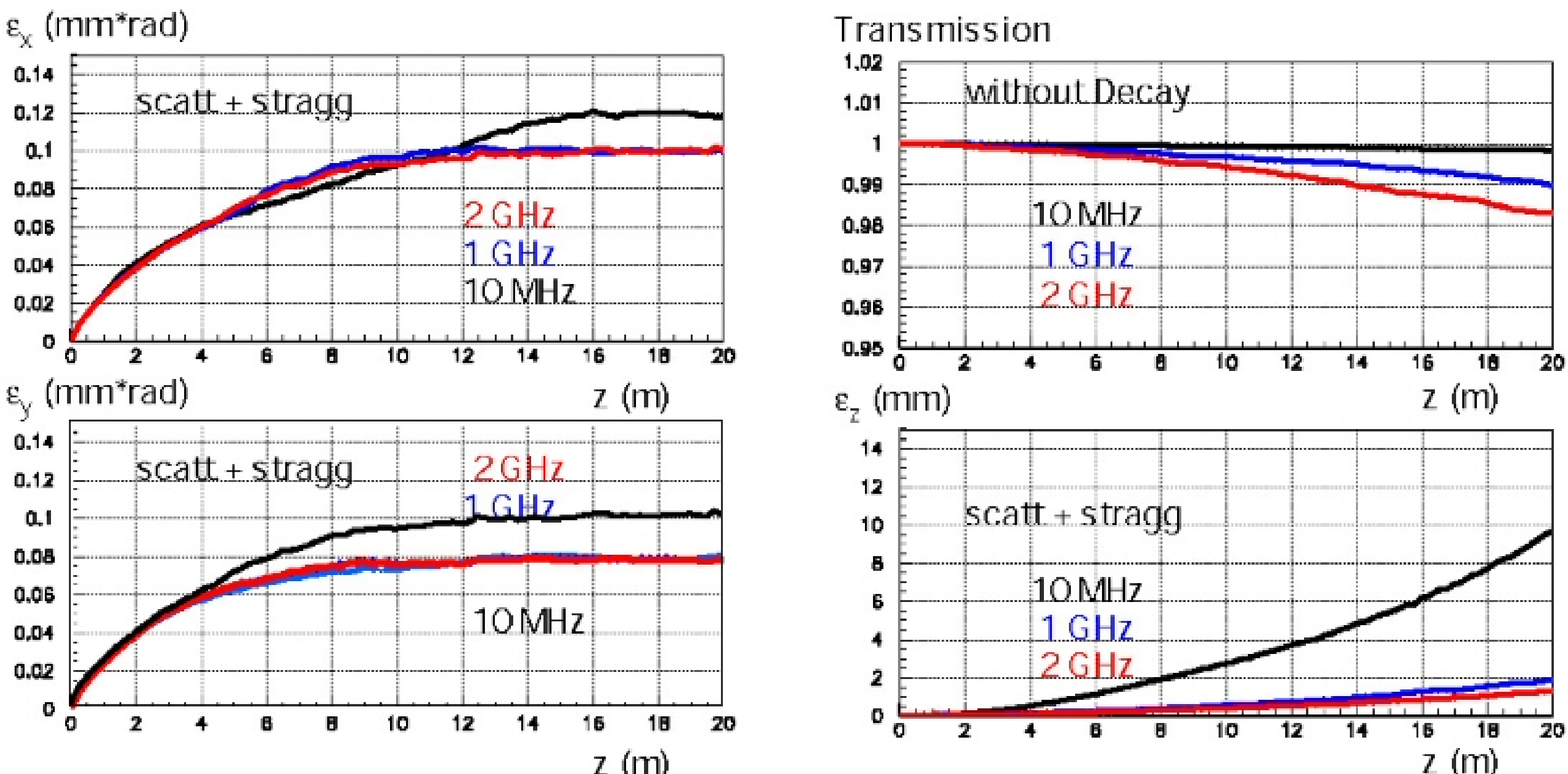
Curved Lithium Lens Cooling Ring





f_0 = 278.3 MHz for 250 MeV/c

Results for Cooling Ring w/ Curved Lens



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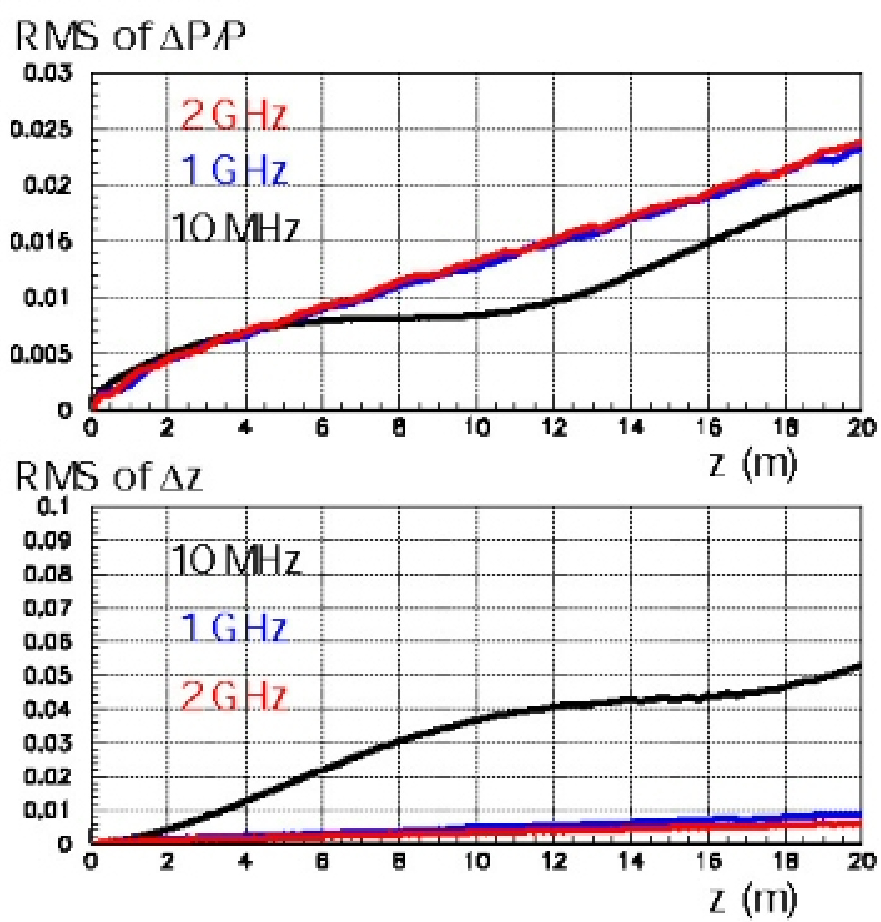
Results for Cooling Ring w/ Curved Lens



Y. Fukui et. al, Proceedings of **2005** Particle Accelerator Conference, Knoxville, Tennessee,

IEEE01591401

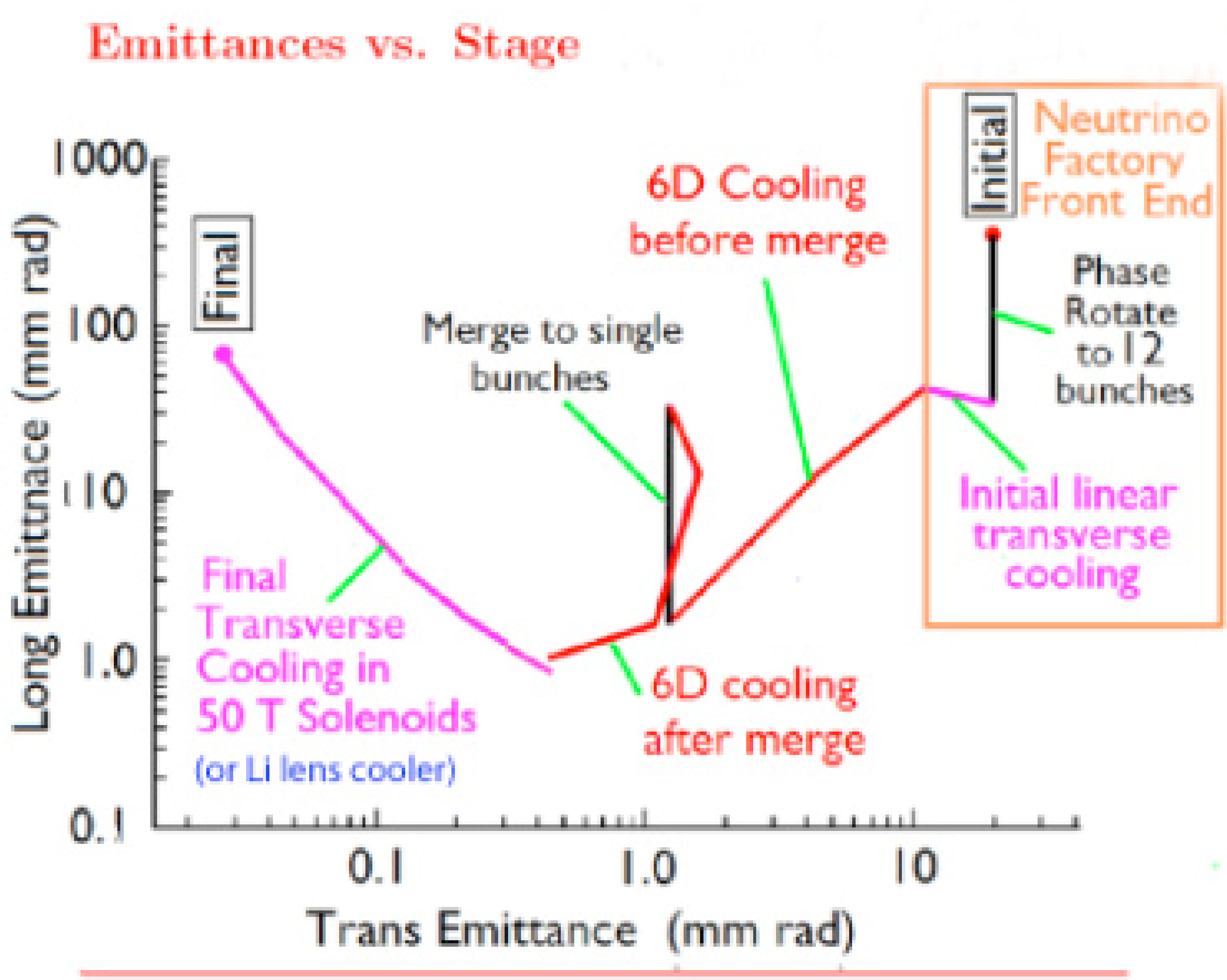
Current Simulation Study for the Final Cooling Stage

•Previous work shows transverse emitt. cooling especially by the curved Li lens

•Objective is to find a channel that can cool the transverse emittance to below 0.1 mm-rad from about 0.5 to 1 mm-rad

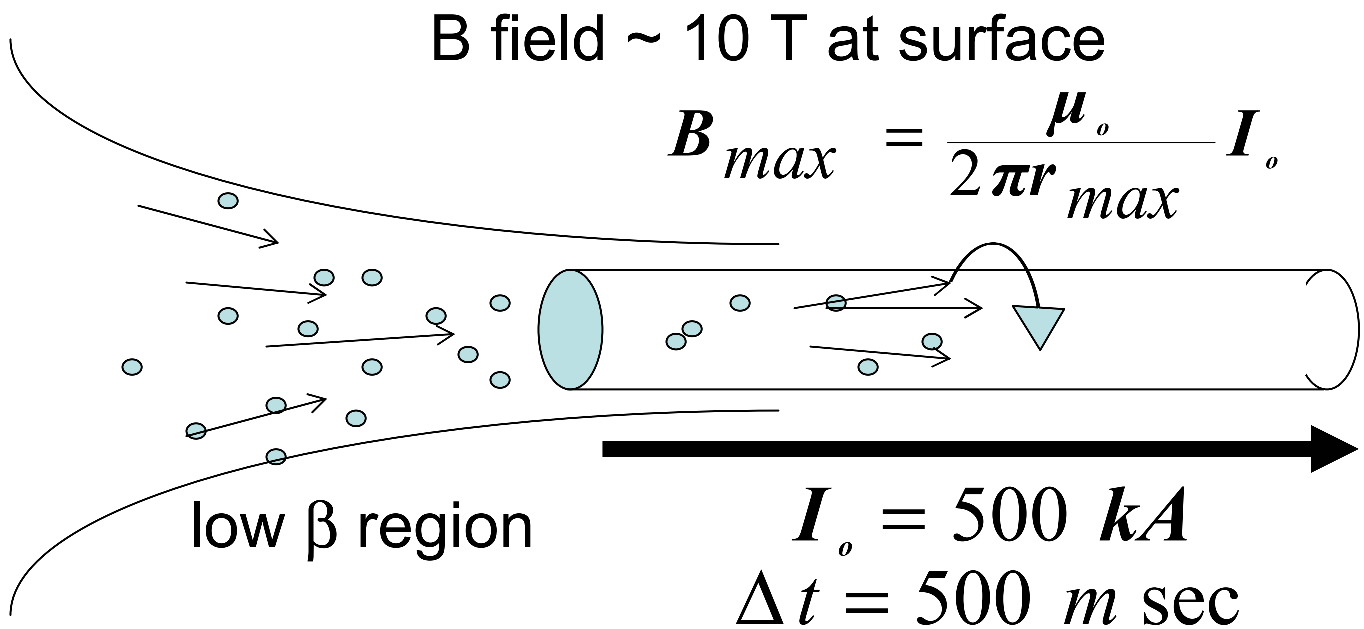
•The channel must be mechanically feasible and likely as liquid lithium lens

Final Cooling Stages

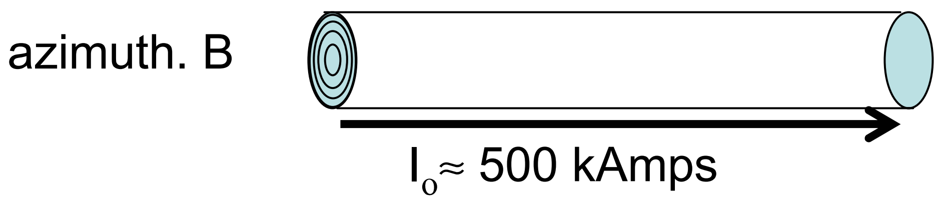


Li Lens Properties

- Strongly focusing
- Low Z material for ionization cooling



Cooling in an ideal Li Lens



Beam focusing parameter in the azimuthal B field

$$\hat{\beta} = \sqrt{\left[\frac{p}{eG}\right]} = \sqrt{\frac{p r_{max}}{3B_{max}}}$$

(cm, MeV/c, T)

Equilibrium beam parameters

$$\varepsilon_{eq} \approx 0.0085\hat{\beta} \approx 0.005\sqrt{\frac{p r_{max}}{B_{max}}}$$

(cm, MeV/c, T)

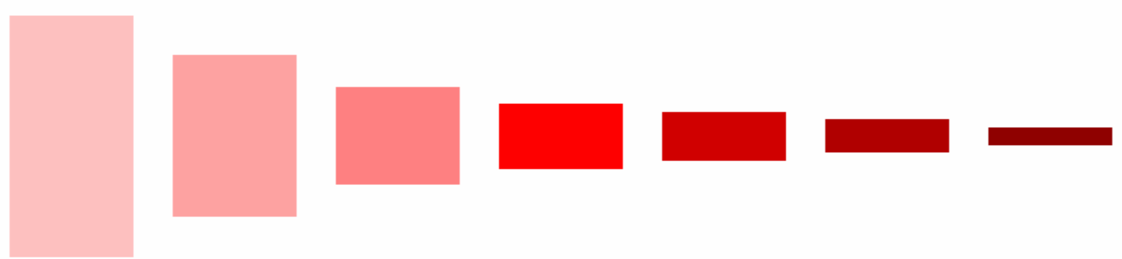
$$r_{eq} = \sqrt{\hat{\beta}\varepsilon_{eq} / \beta\gamma} \approx \sqrt{\frac{0.3 r_{max}}{B_{max}}}$$

(cm, T)

V. Balbekov, Aug. 2006

Idealized multi-lens cooling channel

In an optimized multi-lens cooling channel, the lens field should increase, and the lens length should decrease by the same factor step by step.



If all the lenses have the same length, a constant increase/decrease factor has to be applied.

Exponential transverse cooling is achieved by this, in spite of scattering.

Transverse decrement in the lens is about $0.66 / \beta^4\gamma$ per meter.

Longitudinal increment in the lens is about $1.3 / \beta^4\gamma^3$ per meter.

Example: 7 x 154 cm Li lens channel

The lens field increases, and the radius decreases by factor 1.6 / cell.

Muon momentum drops from 317 MeV/c to 211 MeV/c in any lens.

Beta function, equilibrium transverse emittance and beam radius are given at 211 MeV/c.

Lense #	1	2	3	4	5	6	7
r_{max} (cm)	7.50	4.69	2.93	1.83	1.14	.715	.447
B_{max} (T)	.881	1.41	2.26	3.61	5.78	9.24	14.8
$\hat{\beta}$ (cm)	24.5	15.3	9.55	5.97	3.73	2.33	1.46
ε_{eq} (cm)	0.21	0.13	.081	.051	.032	.020	.012
r_{eq} (cm)	1.60	1.00	0.60	0.39	0.24	0.15	.095

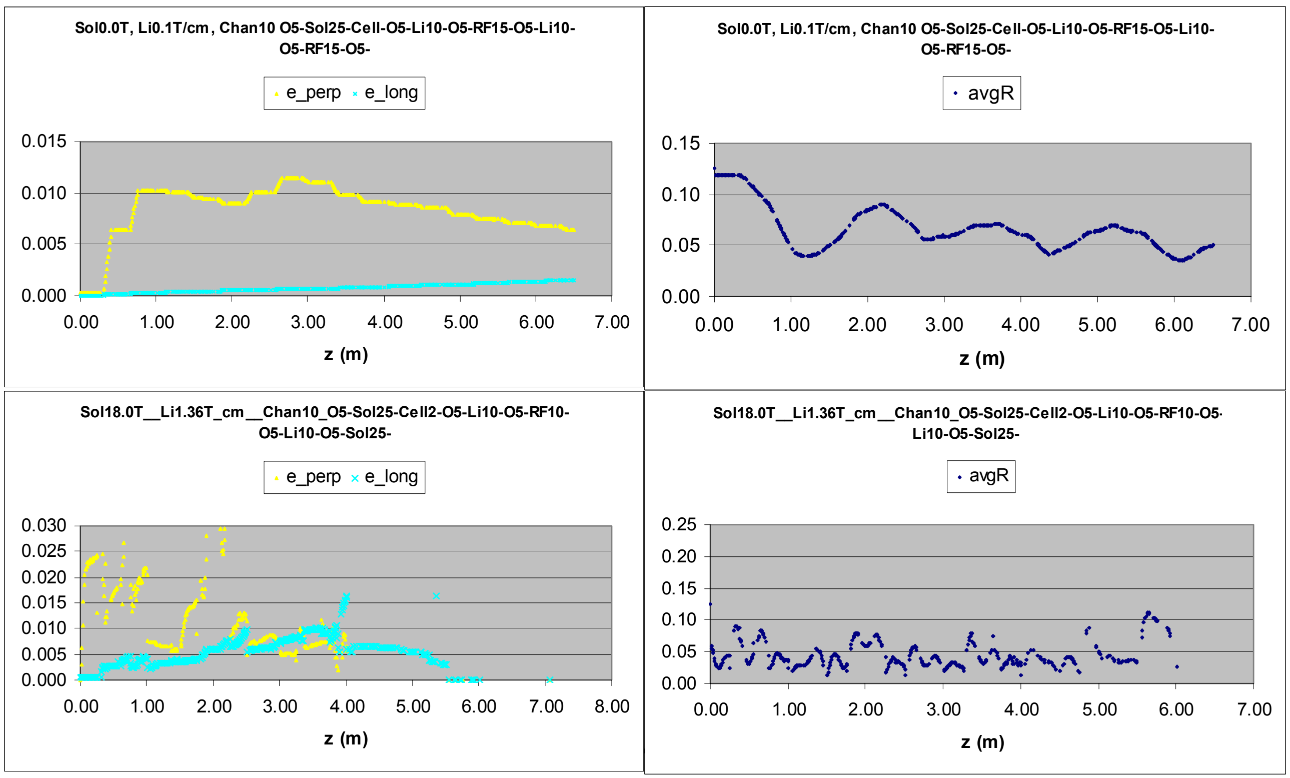
ICOOL Simulation Parameters

- Li lens 10 cm radii $\times$ 60 cm length
- Beam input parameters
  - $(\sigma_x, \sigma_y, \sigma_z)$=(1 cm,1 cm, 2 cm)
  - $(\sigma_{Px}, \sigma_{Py}, \sigma_{Pz})$= (0.00025, 0.00025, 0.00025 GeV/c)

- B_{max}=15 to 150 T or G ~ 10 T/cm
- Physics interactions
  - dElev=2; straglev=4; scatlev=4

Ionization Cooling with Very Large Beam

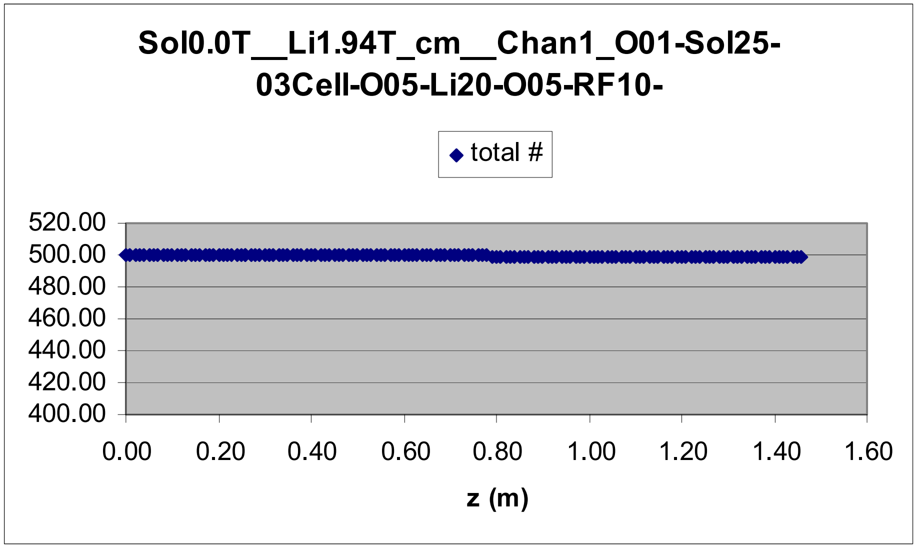
- ICOOL simulations show beam cooling in the straight channel Li lens w/o solenoids
- The Li lens channel show trend of cooling out to 6 m for a parrallel beam of 10 cm radius.
- strag=on; scatt=on

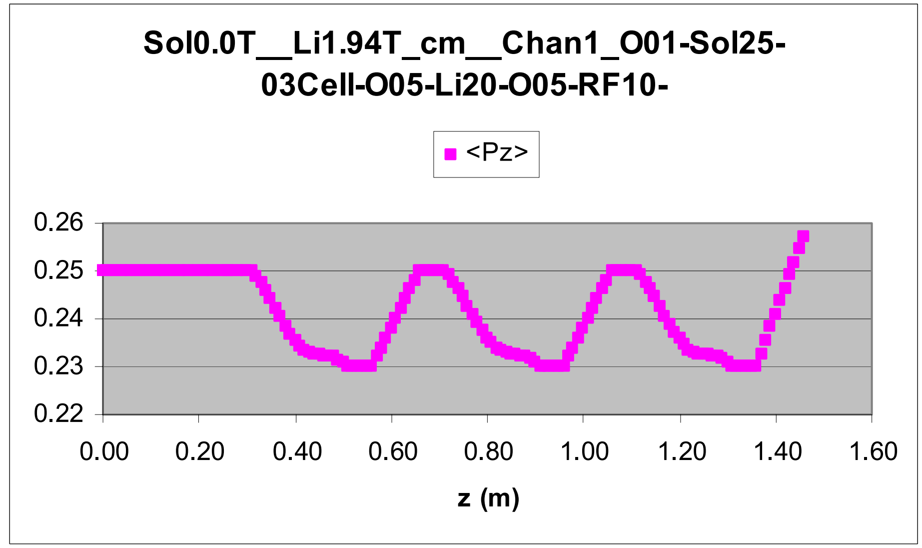


Li lens channel w/o solenoid

Li lens channel w/ solenoids

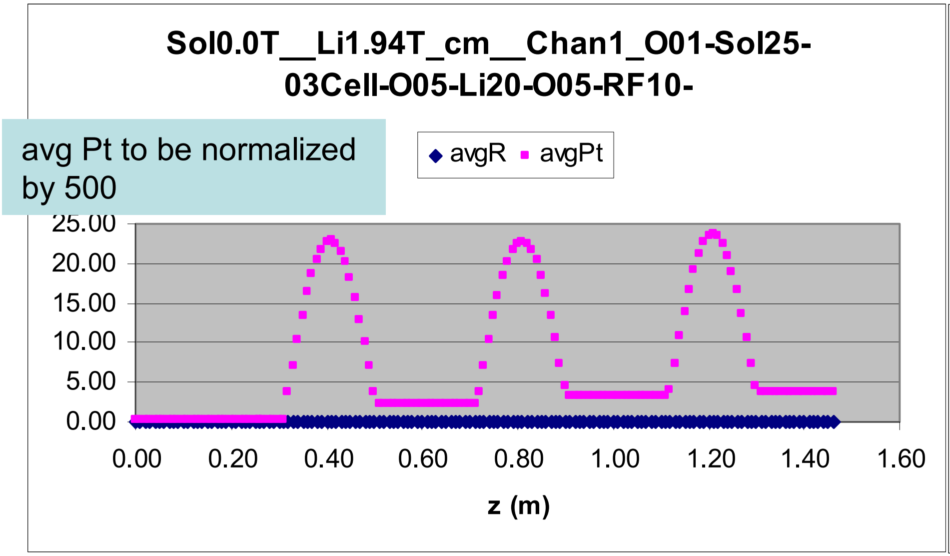
ICOOL Simulation Diagnostics

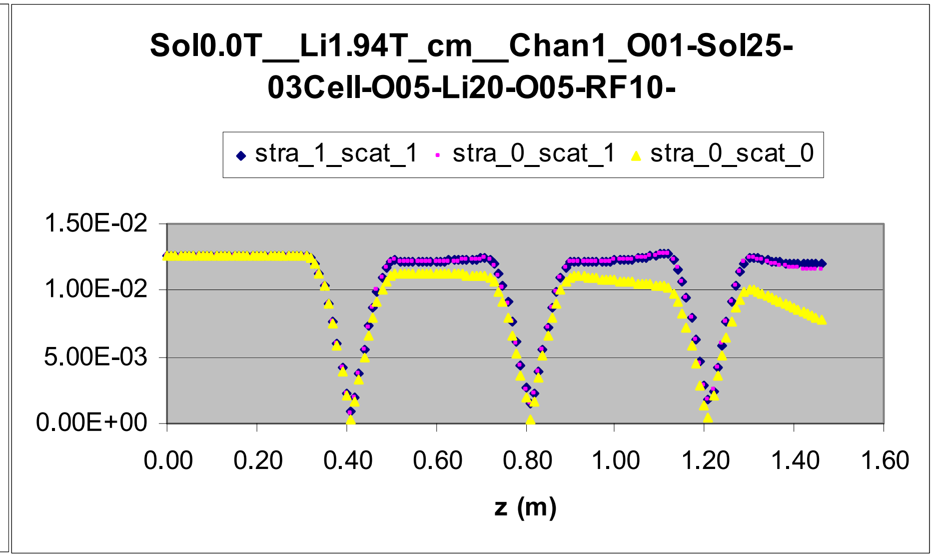




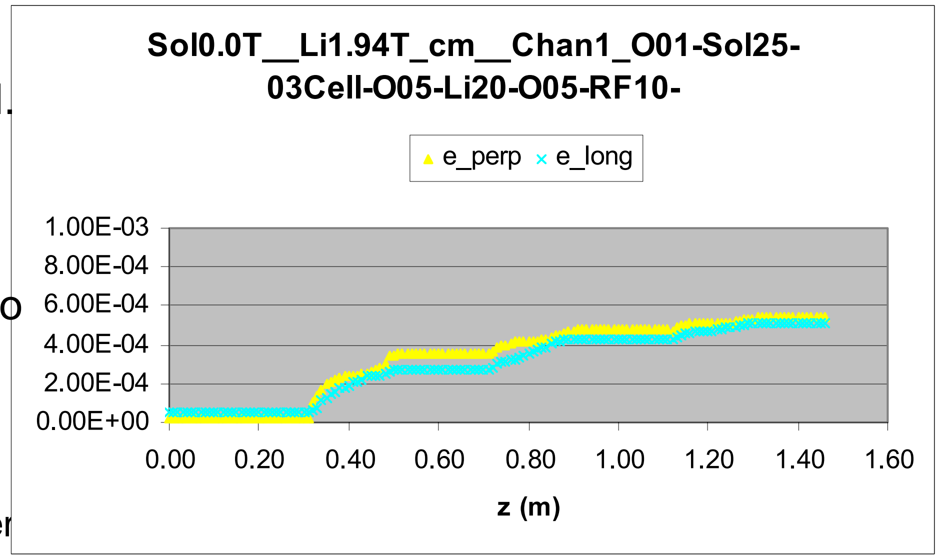
- Channel
  - Li Lens 10 cm × 20 cm length and RF 10 cm cavities
  - 03Cell-O05-Li20-O05-RF10-
  - strag=on; scatt=on;
  - (σx, σy, σz)=(1 cm,1 cm, 2 cm); (σPx, σPy, σPz)= (0.00025, 0.00025, 0.00025 GeV/c)
- Almost no particle lost
- P_z restored by 185 keV/cm RF to 0.25 GeV/c

ICOOL Simulation Results





- Beam gets a large kick at entrance; avg P_t swings to maximum and down to minimal level.
- avg R is flat or almost flat at exit of each lens
- Beam emitt. almost zero for parallel beam at entrance and increasing. Scattering appears to increase the avg P_t gradually.



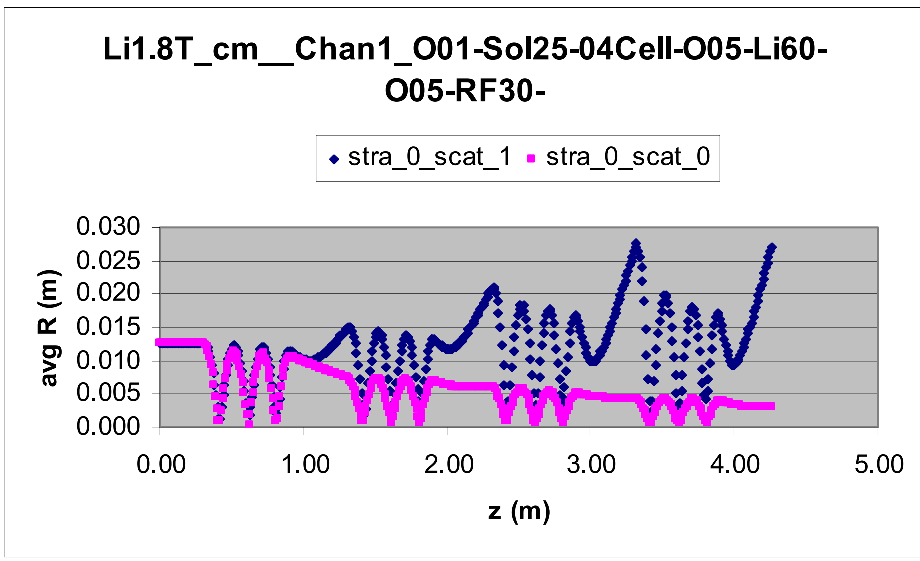
Channel with Four 10 cm x 60 cm Lens

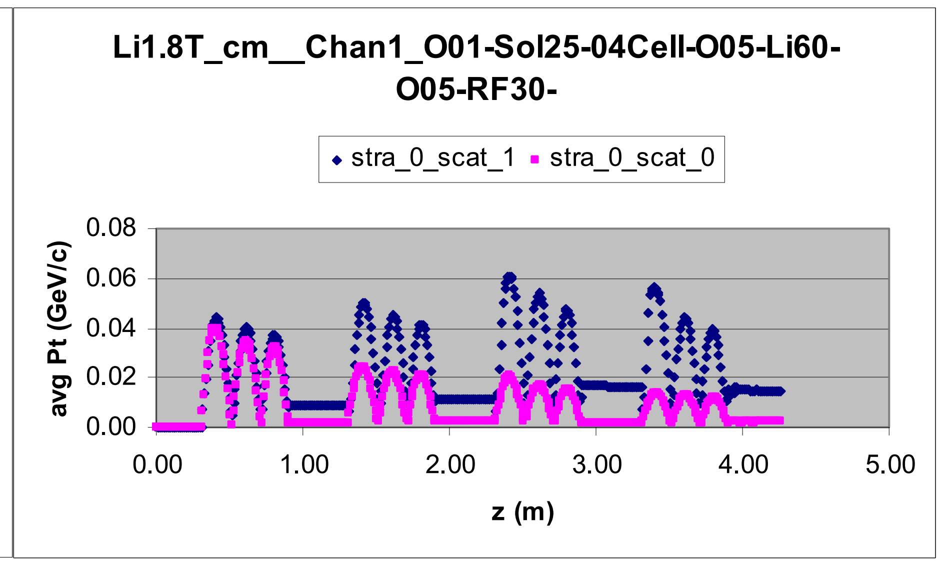
Comparison for Scattering On and Off

emit001b:

(σx, σy, σz)=(1 cm,1 cm, 2 cm)

(σ_{Px}, σ_{Py}, σ_{Pz})= (0.00025, 0.00025, 0.00025 GeV/c)





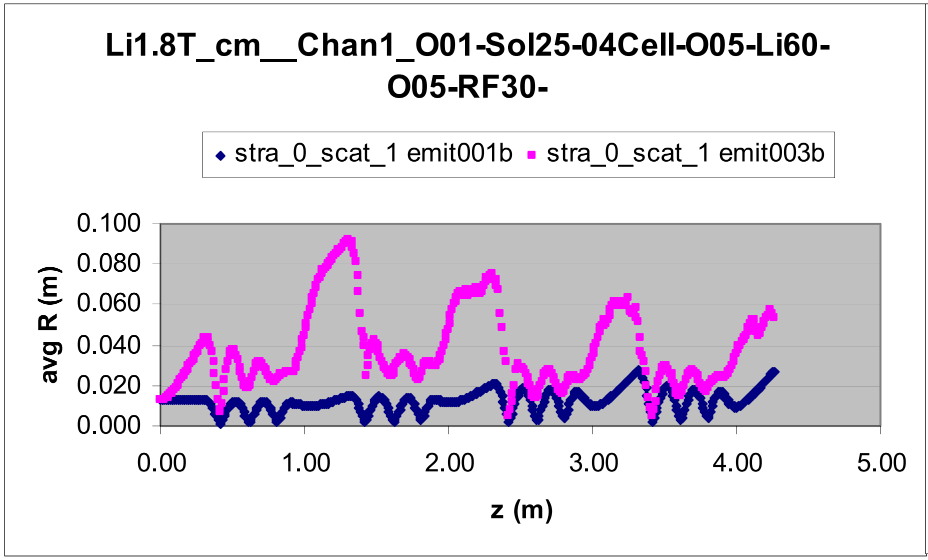
Channel with Four 10 cm x 60 cm Lens

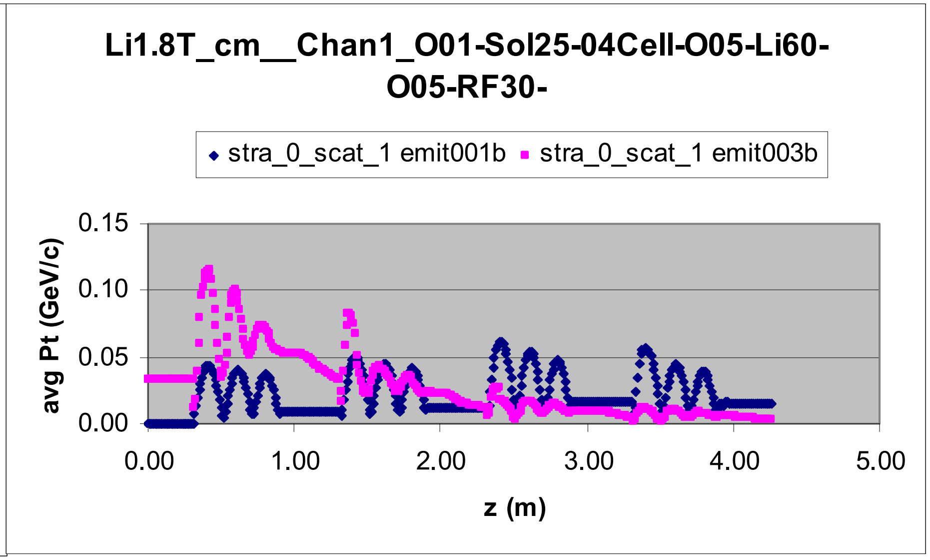
Comparison for different beam profiles

Both: (σx, σy, σz)=(1 cm,1 cm, 2 cm)

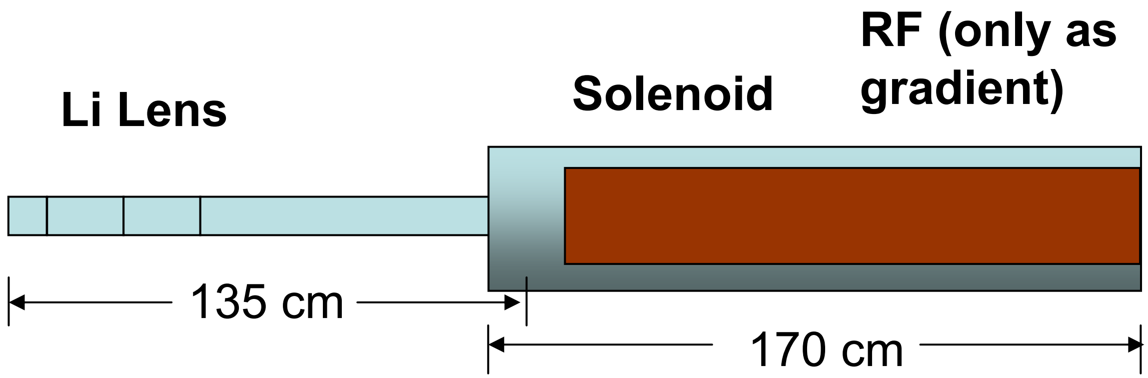
emit001b: (σ_{Px}, σ_{Py}, σ_{Pz})= (0.00025, 0.00025, 0.00025 GeV/c)

emit003b: (σ_{Px}, σ_{Py}, σ_{Pz})= (0.025, 0.025, 0.025 GeV/c)





Channel with One 10 cm x 135 cm Lens



Li Lens:

10 cm 1.79 T/cm

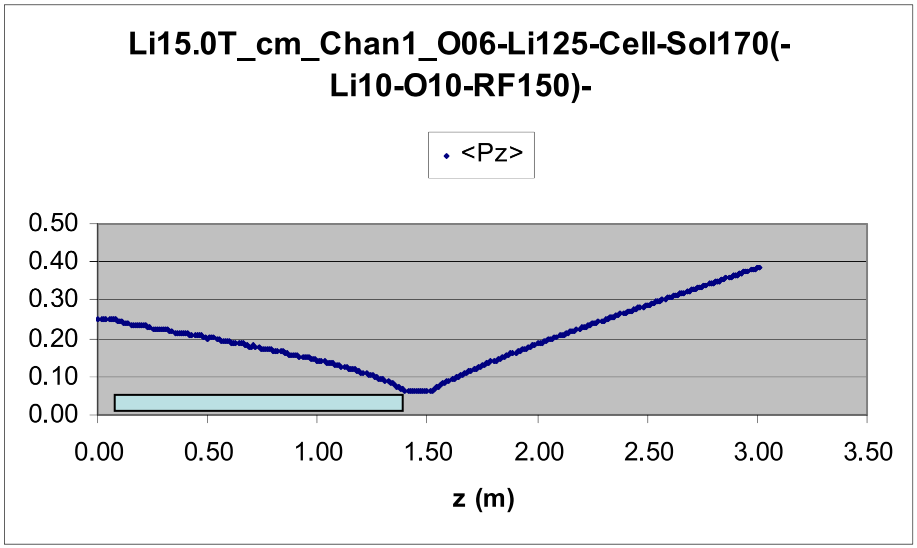
20 cm 7.60 T/cm

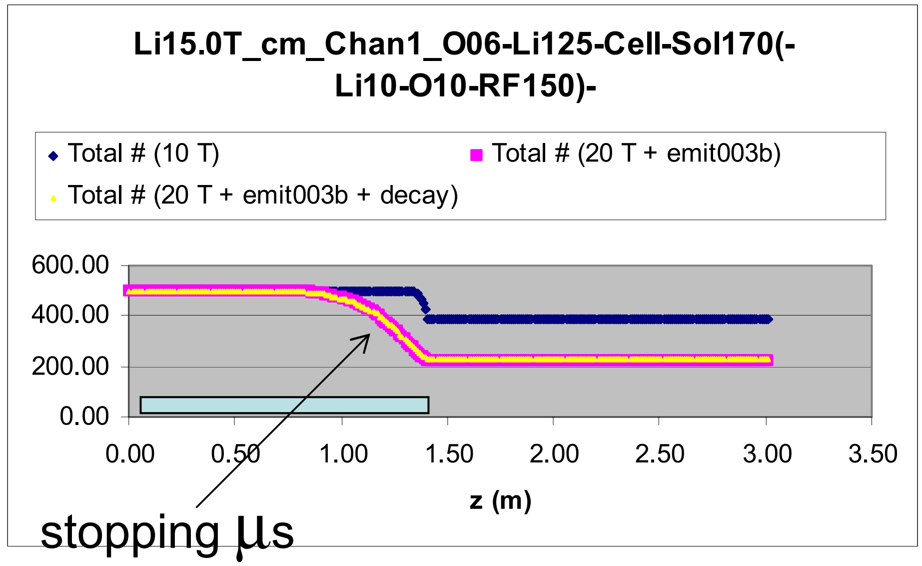
20 cm 15.0 T/cm

75 cm 15.0 T/cm

10 cm 15.0 T/cm

RF: 185 keV/cm



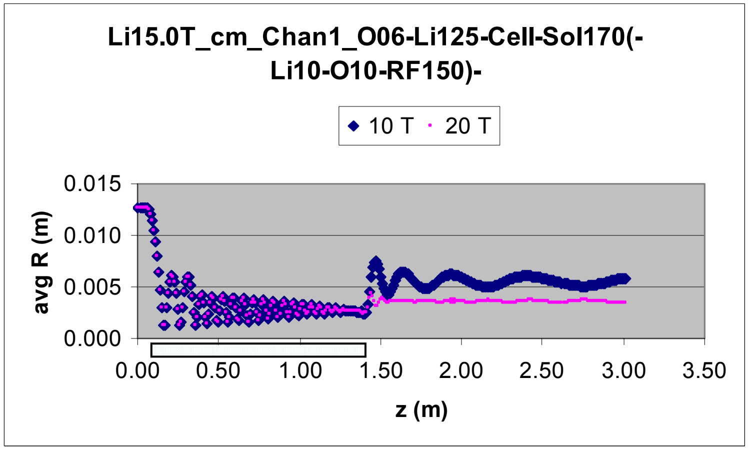


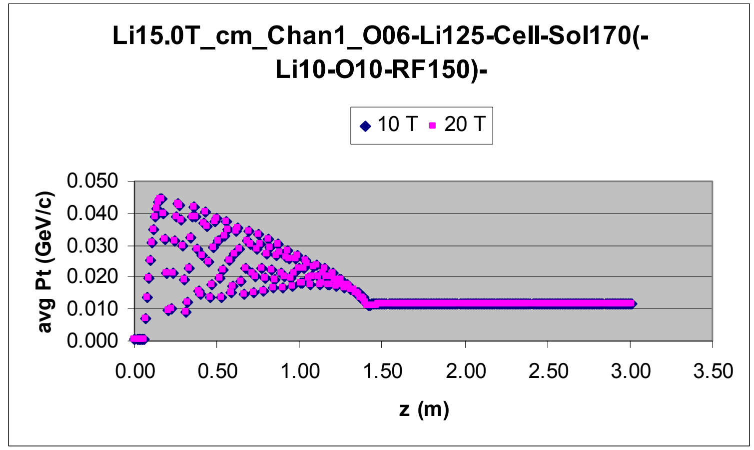
List of beam parameters

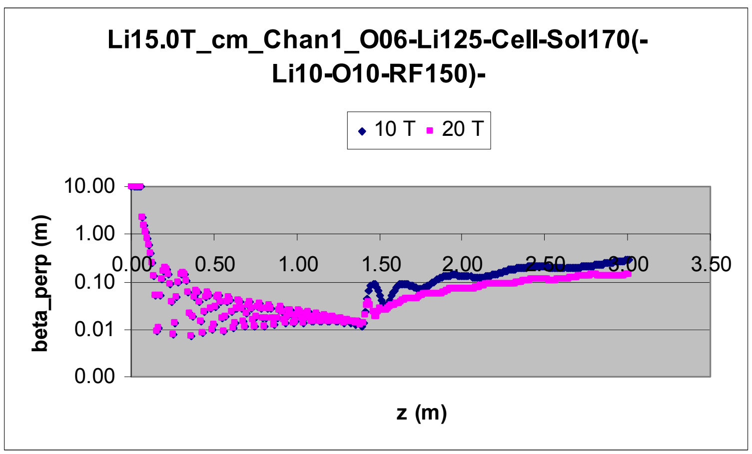
	$(\sigma_x, \sigma_y, \sigma_z)$ [m]	$(\sigma_{Px}, \sigma_{Py}, \sigma_{Pz})$ [GeV/c]		$(\sigma_x, \sigma_y, \sigma_z)$ [m]	$(\sigma_{Px}, \sigma_{Py}, \sigma_{Pz})$ [GeV/c]
001a	$(1.0,1.0,2.0)\times10^{-1}$	$(2.5,2.5,2.5)\times10^{-4}$	**003a**	$(1.0,1.0,1.0)\times10^{-1}$	$(2.5,2.5,2.5)\times10^{-2}$
001b	$(1.0,1.0,2.0)\times10^{-2}$	$(2.5,2.5,2.5)\times10^{-4}$	**003b**	$(1.0,1.0,1.0)\times10^{-2}$	$(2.5,2.5,2.5)\times10^{-2}$
001c	$(1.0,1.0,2.0)\times10^{-3}$	$(2.5,2.5,2.5)\times10^{-4}$	**003c**	$(1.0,1.0,1.0)\times10^{-3}$	$(2.5,2.5,2.5)\times10^{-2}$
002a	$(1.0,1.0,2.0)\times10^{-1}$	$(2.5,2.5,2.5)\times10^{-1}$	**004a**	$(1.0,1.0,2.0)\times10^{-1}$	$(5.0,5.0,5.0)\times10^{-2}$
002b	$(1.0,1.0,2.0)\times10^{-2}$	$(2.5,2.5,2.5)\times10^{-1}$	**004b**	$(1.0,1.0,2.0)\times10^{-2}$	$(5.0,5.0,5.0)\times10^{-2}$
002c	$(1.0,1.0,2.0)\times10^{-3}$	$(2.5,2.5,2.5)\times10^{-1}$	**004c**	$(1.0,1.0,20.0)\times10^{-3}$	$(5.0,5.0,5.0)\times10^{-2}$

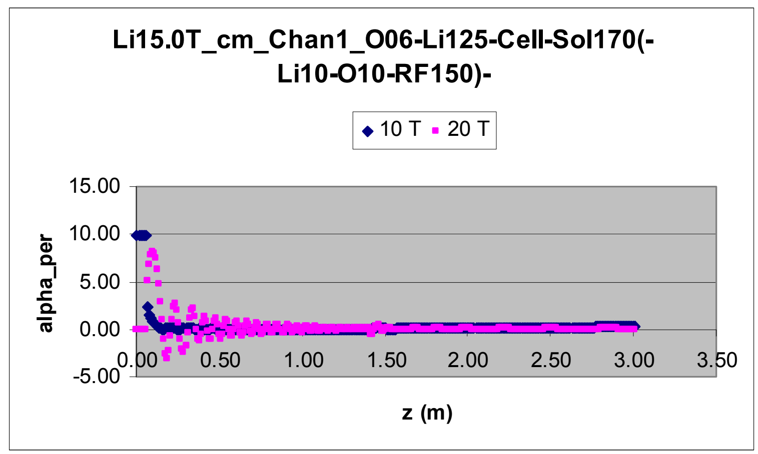
Channel with One 10 cm x 135 cm Lens

Comparison between 10 T and 20 T exit solenoid



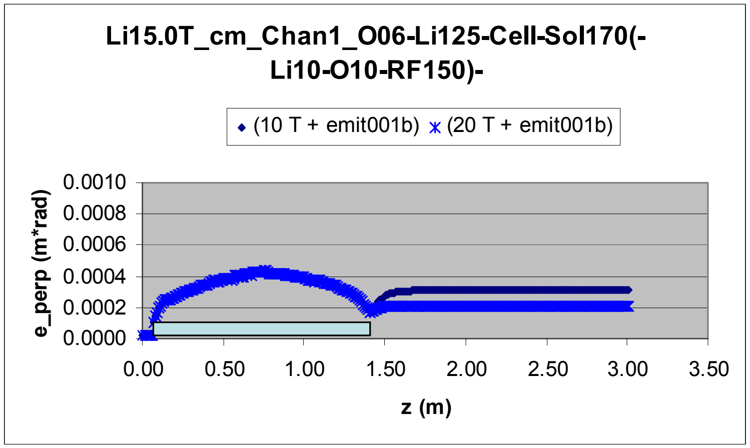


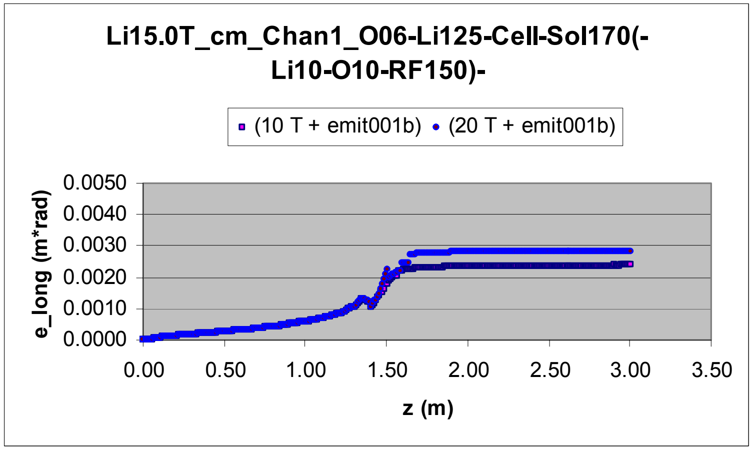


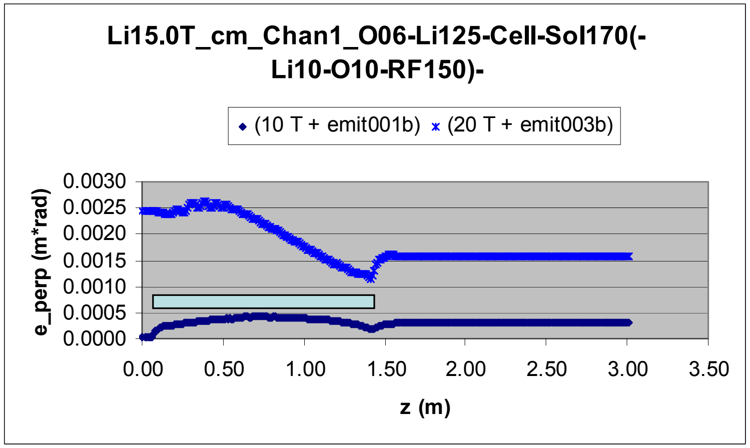


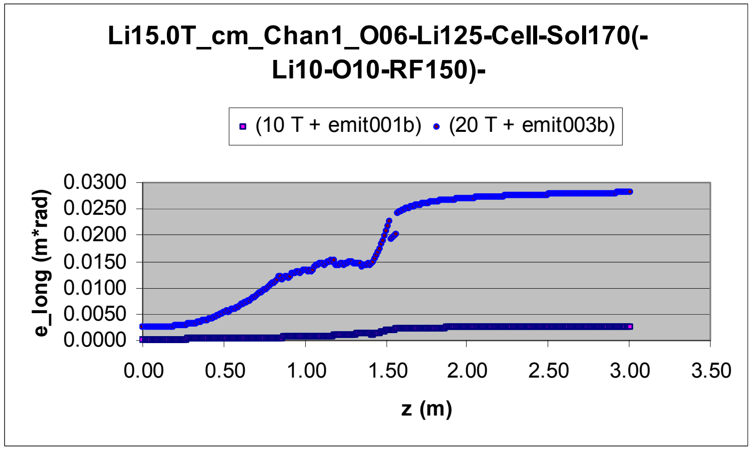
Channel with One 10 cm x 135 cm Lens

Comparison between 10 T and 20 T exit solenoid

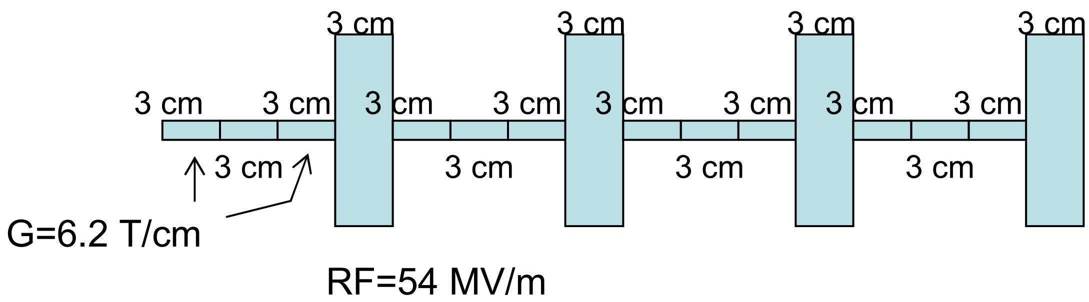


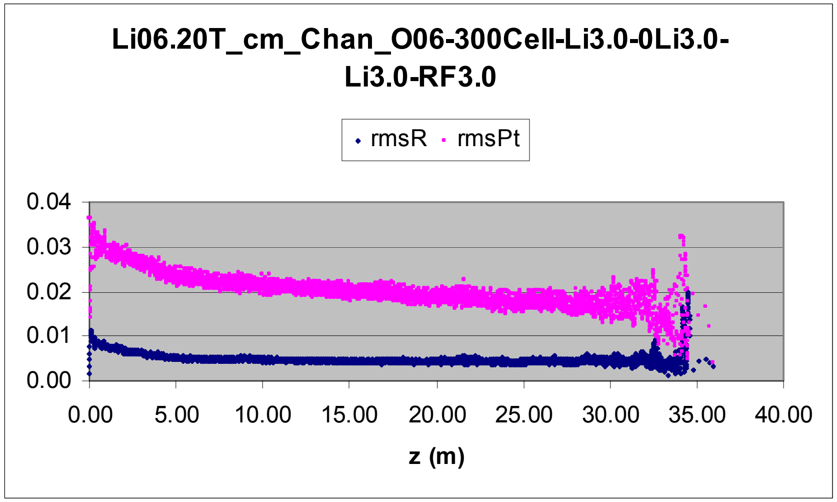






Series of 9 cm Li lens Channel of 300 cells





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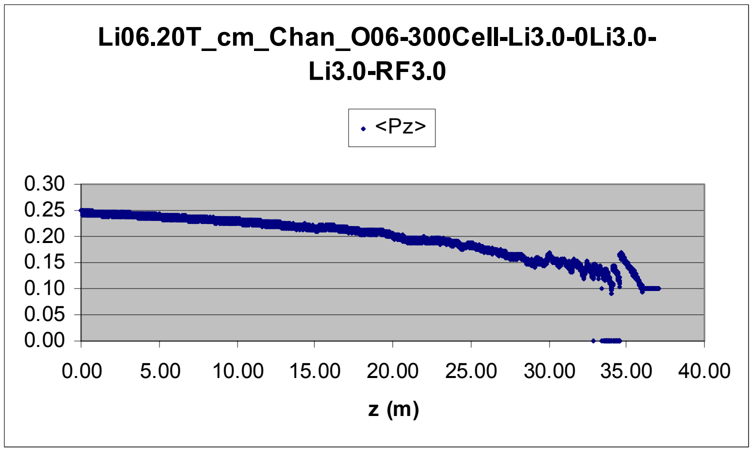
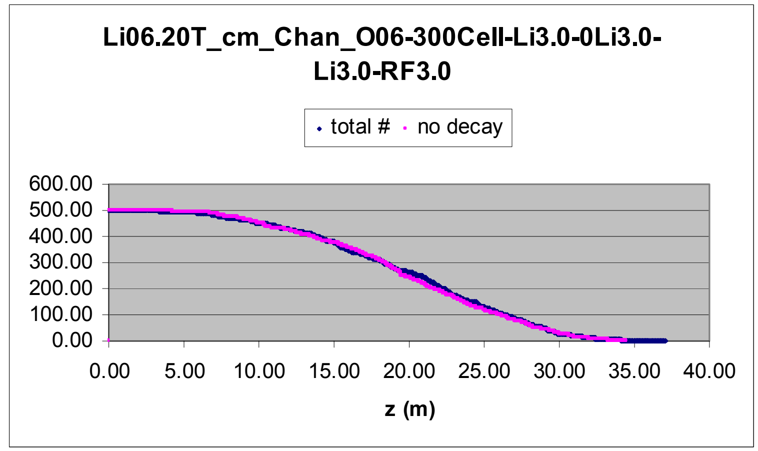
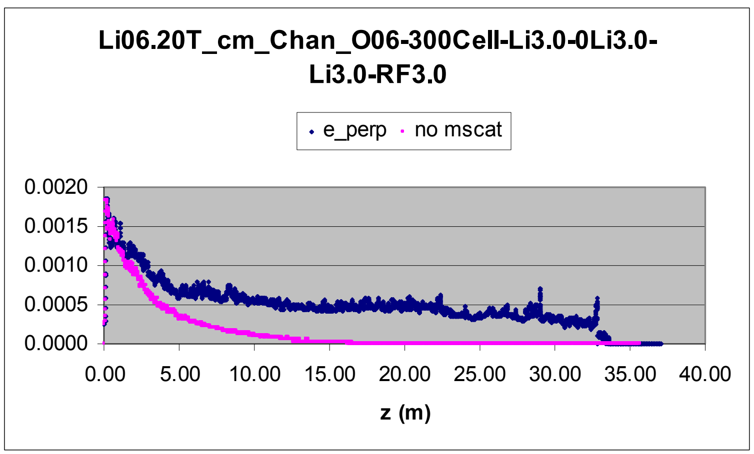
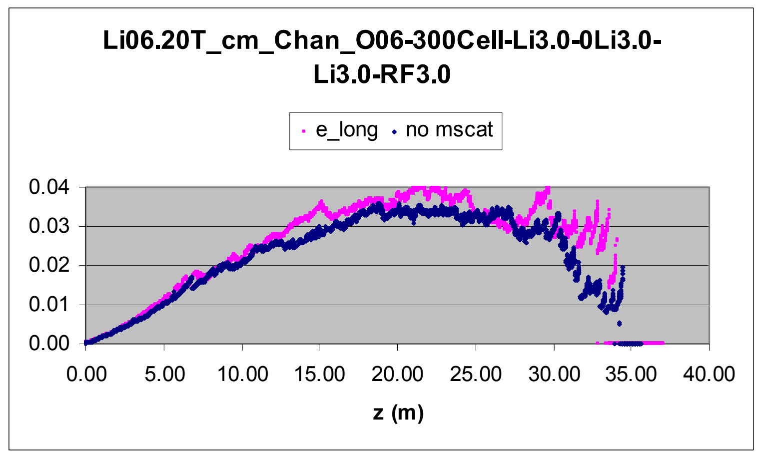
Series of 9 cm Li lens Channel

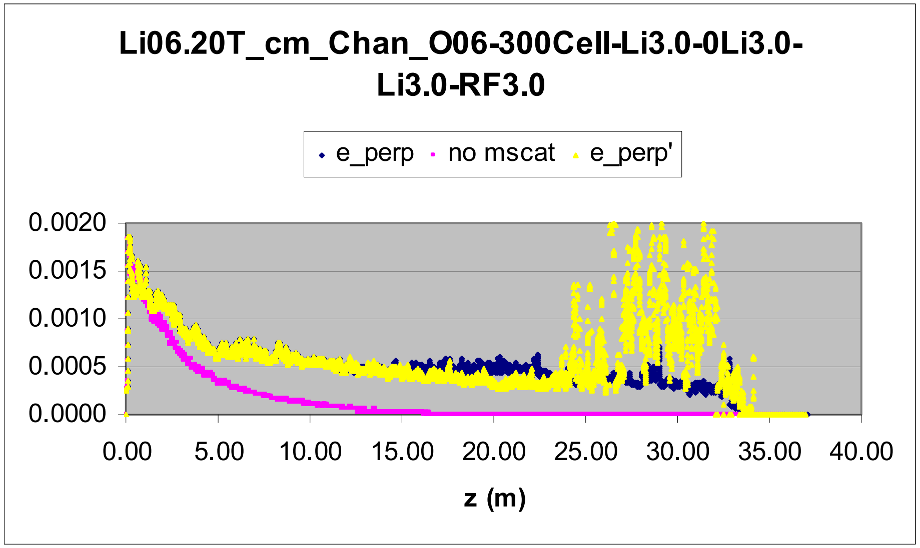








Series of 9 cm Li lens Channel



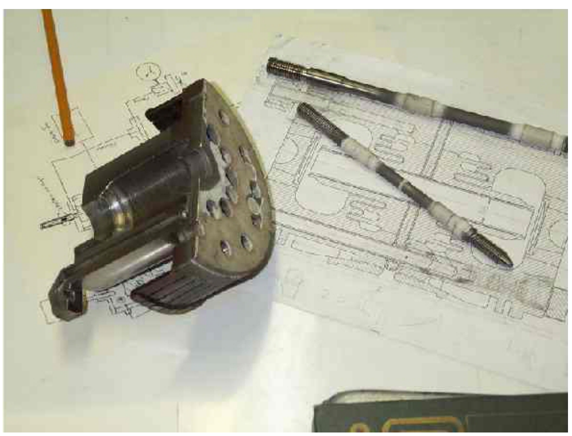
Summary

- Parallel beam used for adjusting Li Lens gradient for beam matching between components
- Achieved a cooling factor 1.7 from 2.5 mm*rad down to 1.5 mm*rad in a channel with a single 10 cm x 135 cm Li Lens with field gradient steps from 1.8 T/cm to 15 T/cm.
- With the capture solenoid at 10 T (or 20 T), significant beam loss at the transition into the RF system
- Strong coupling between the transverse and longitudinal motion, revisit the short length lens and cooling to 500 mm·mrad; continue to explore this channel using stronger gradients successfully in ICOOL simulations

Liquid Li Lens Development at BINP

- The Li lens work by Dr. Silvestrov et. al at BINP was for use at the Tevatron anti-proton source (accord w/ Fermilab for run II) and at CERN.
- The lens survived < 100k pulses at 7.5 T (design was 10M and 13 T).
- Shock waves in the Li and cracking of the Ti septum.

BINP Li Lens



BINP liquid lithium lens, opened lens lithium vessel and the entire system.

http://www-bdnew.fnal.gov/pbar/Projects/liquidlilens/liquidli.htm

Properties of Lithium Metal

Density [gm/cm³]

$$\rho_{\text{solid}} = 533 \cdot \left(1 - 1.8\times10^{-4} \cdot (\text{T} - 273.2)\right)\left[\text{kg/m}^3\right]$$

$$\rho_{\text{liquid}} = 540.43 - 0.02729 \cdot \text{T} - 8.0035 \cdot \text{T}^2 \times 10^{-5} + 3.799 \cdot \text{T}^3 \times 10^{-3} [\text{kg/m}^3]$$

Resistivity [10^{-6} Ω-m]

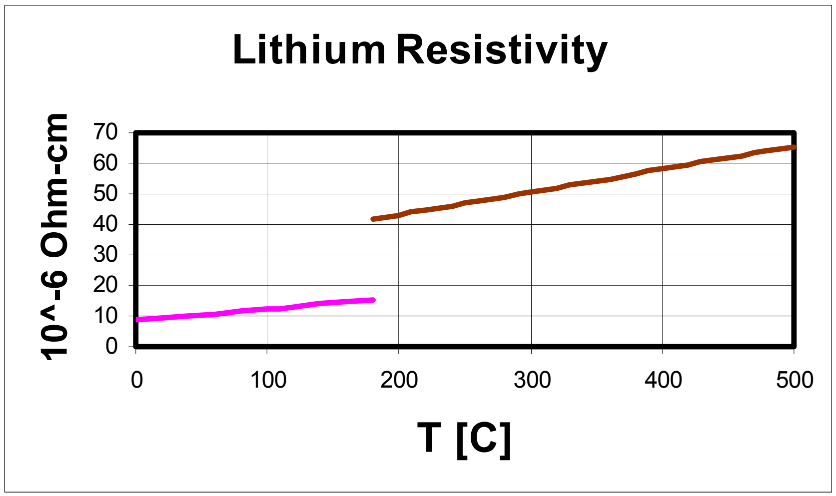
$$\rho_{solid} = 8.55\times10^{-2} \cdot \left(1 + 4.46\times10^{-3} \cdot (T - 273.2)\right)\left[10^{-6}\Omega \cdot m\right]$$

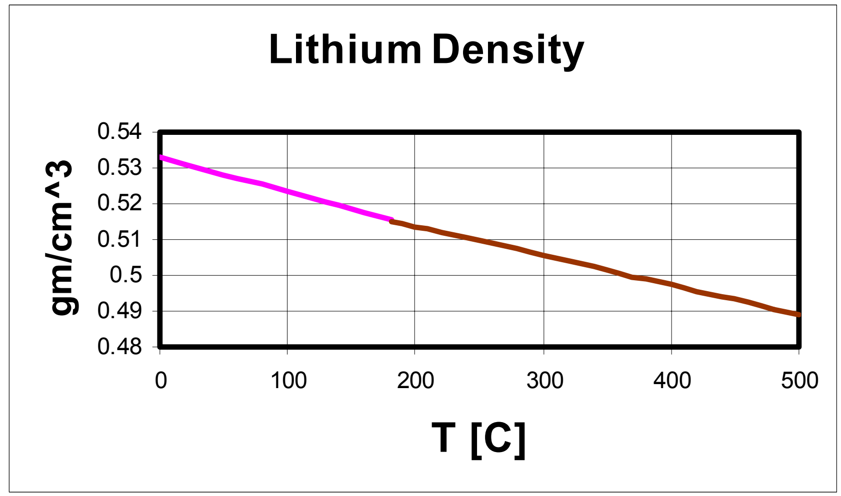
$$\rho_{liquid} = 27.884\times10^{-2} \cdot \left(1 + 2.7\times10^{-3}(T - 273.2)\right)\left|10^{-6}\Omega \cdot m\right|$$

BINP Li Lens Technology

http://www-bdnew.fnal.gov/pbar/Projects/liquidlilens/liquidli.htm

Properties of Lithium Metal





BINP Li Lens Technology

http://www-bdnew.fnal.gov/pbar/Projects/liquidlilens/liquidli.htm

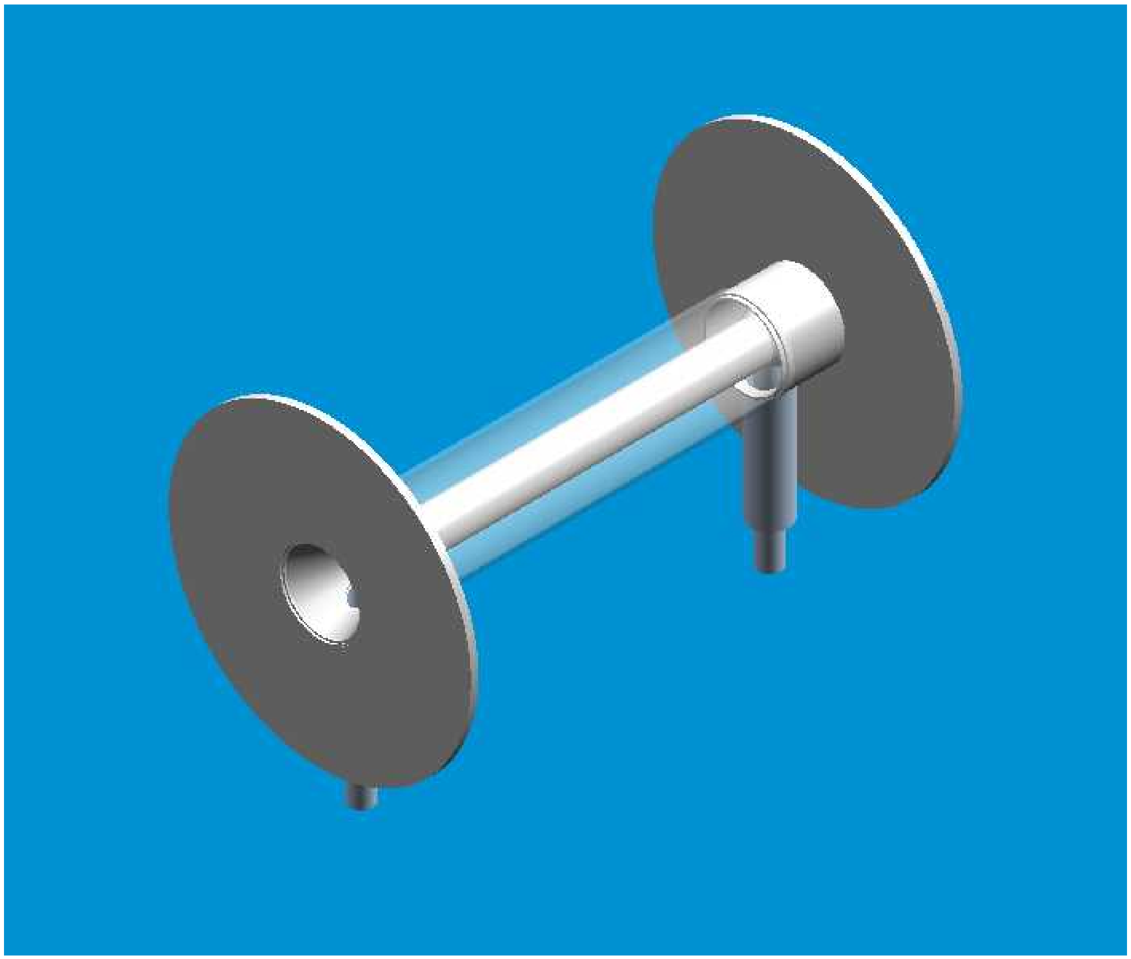
Observed Fermilab Li Lens Lifetime

B grad (T/m)	Avg. Life Time (Pulses)
1,000	<500,000 (1.9 wk)
900	1,000,000 (3.8 wk)
800	3,000,000 (5.7 wk)
740	9,000,000 (17 wk)
700	>10,000,000 (19 wk)

J. Morgan

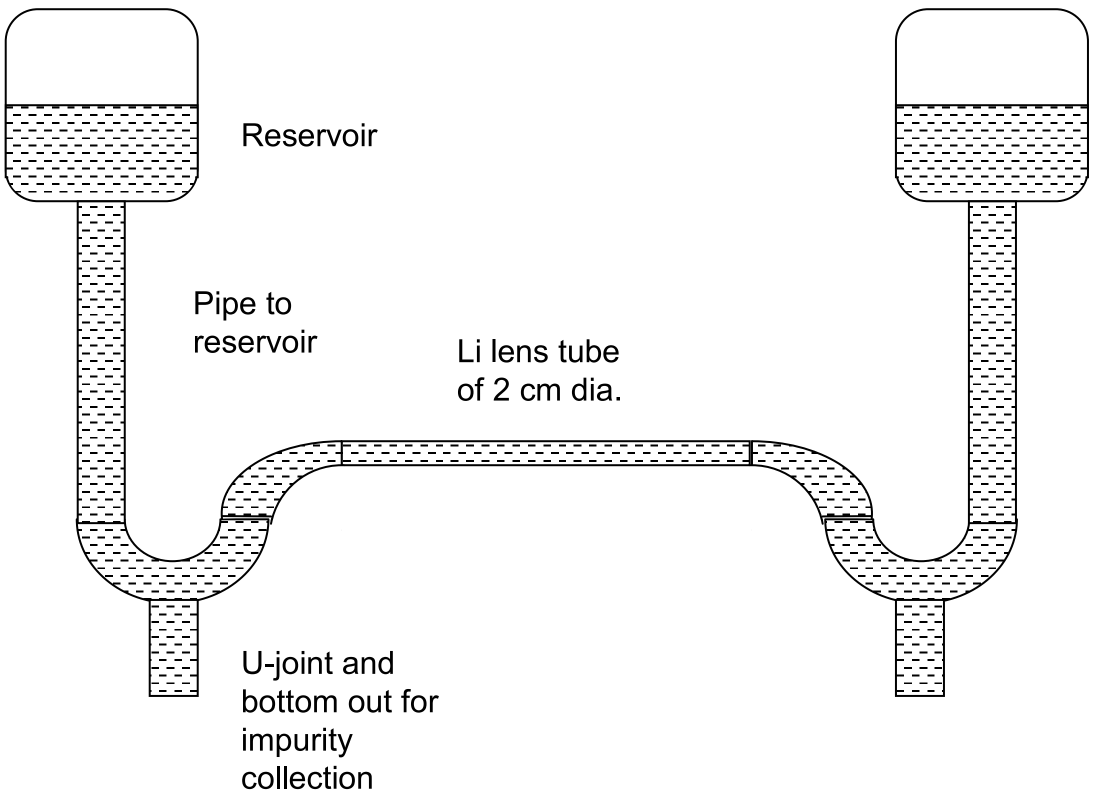
Lens Upgrade Note

Initial Mechanical Design



- D 2.54cm × L 30cm
- Outer tube for heated oil above 200 C
- Double layered tubes for liquid Li and heated oil

Push-Pull Flow of Liquid Li

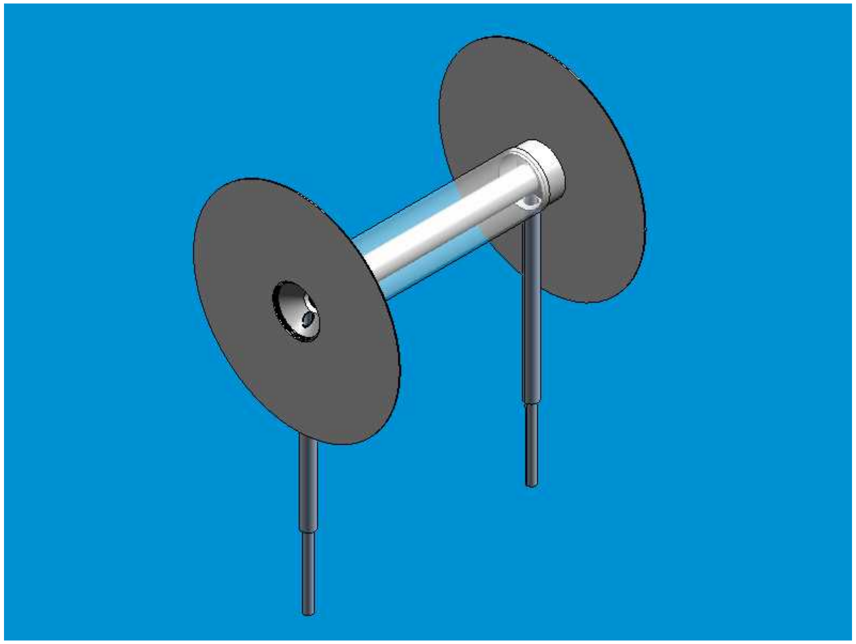


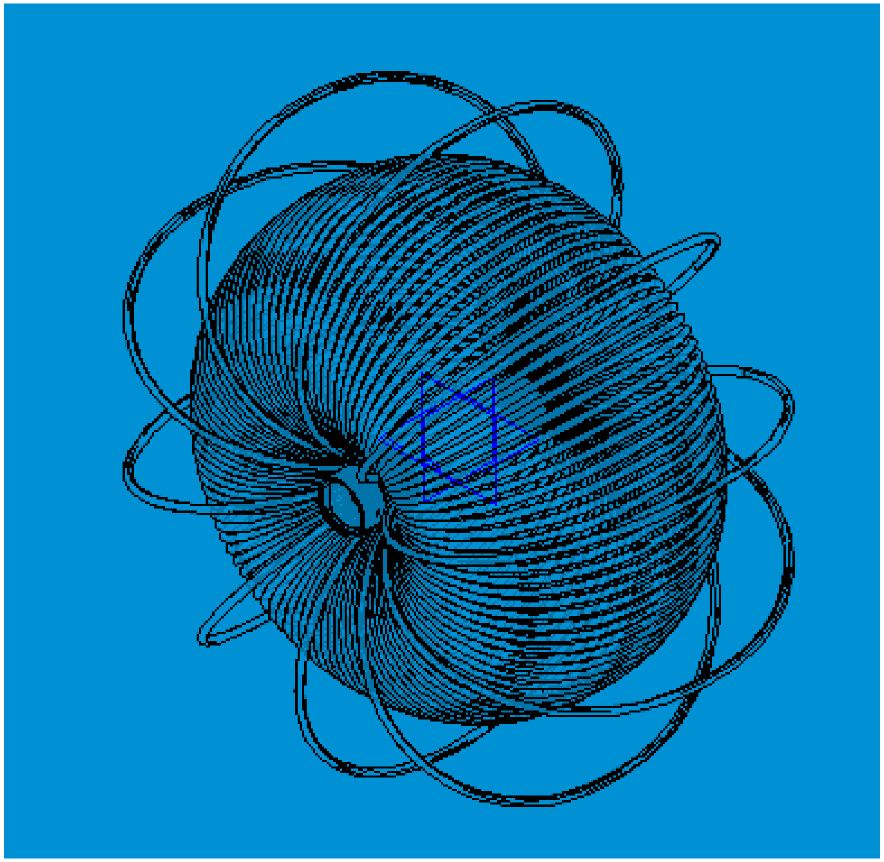
Conceptual Design w/ two reservoirs for push-pull thermal cooling action.

Properties of Related Elements

	Melting pt. [C]	Density [g/cc]
Li	180.54	0.54
Al	660.32	2.7
Be	1,287	1.85
Ti	1,668	4.51
Steel	1,370	7.874 [Fe]
Li_2O	1,570	2.01
Li_3N	813	1.27

Initial Design of Liquid Li Lens





Lens assembly w/ current discs and the primary and secondary coils

Li D = 2.54 cm; L = 30.0 cm

Thermal Cooling w/ static Li in Lens

Li Lens Parameters:
D = 2.54 cm; L = 30.0 cm; Wall Thickness = 1.06 mm (~41mil)

I_{DC} = 64.0 kAmps; $B_{Surface}$ = 1.00 T; DC Heat Load = 1.77 MW; too high

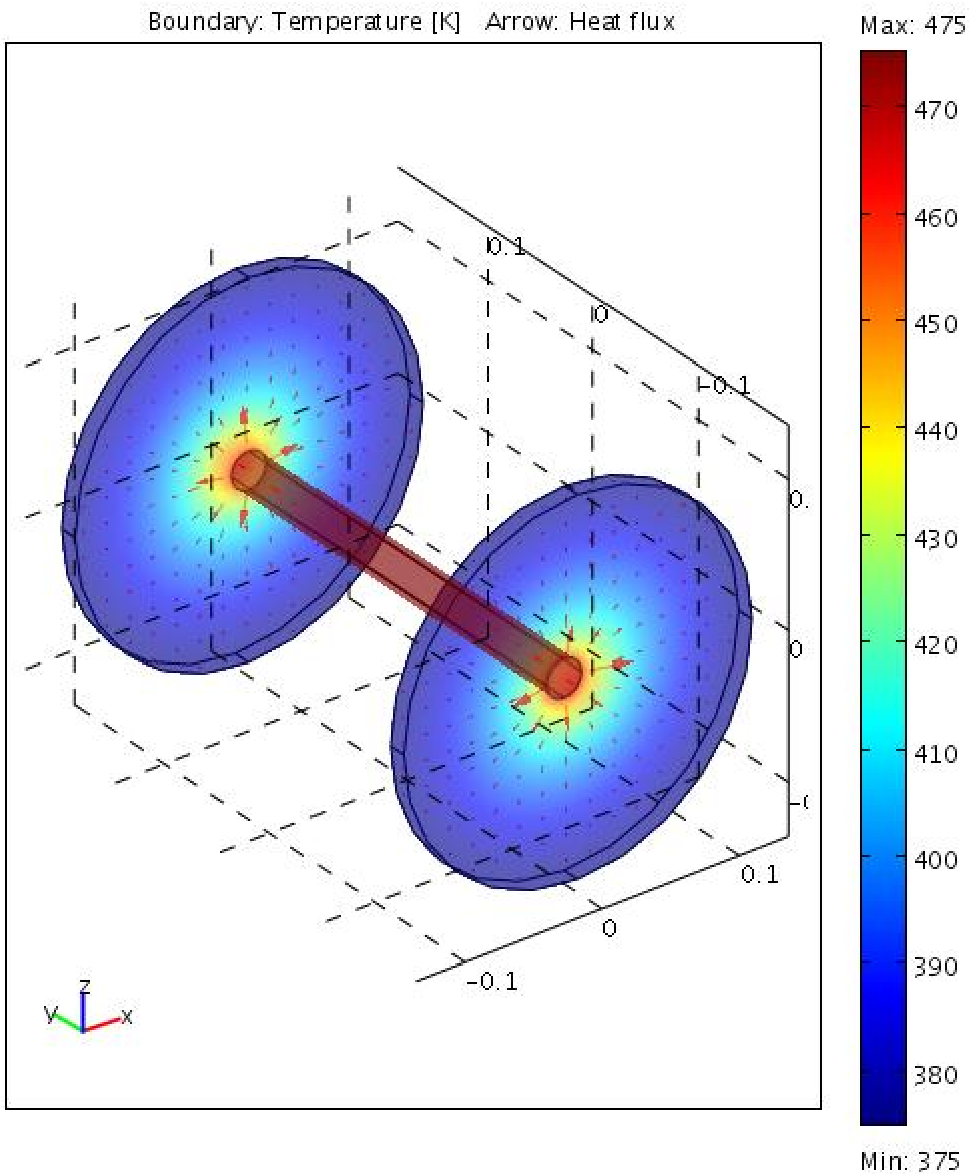
@15 Hz of 10 msec pulses, Heat Load = 70 kW; manageable

Be Tube [k@20C = 190 W/m/K]: Outer T = 200 C; **Inner T = 210 C**

Ti Tube [k@20C = 22 W/m/K]: Outer T = 200 C; **Inner T = 285 C**

Oil Sp. Heat Capacity c_P@20C ~ 2 kJ/kg/K: **Flow ~ 13 L/min**

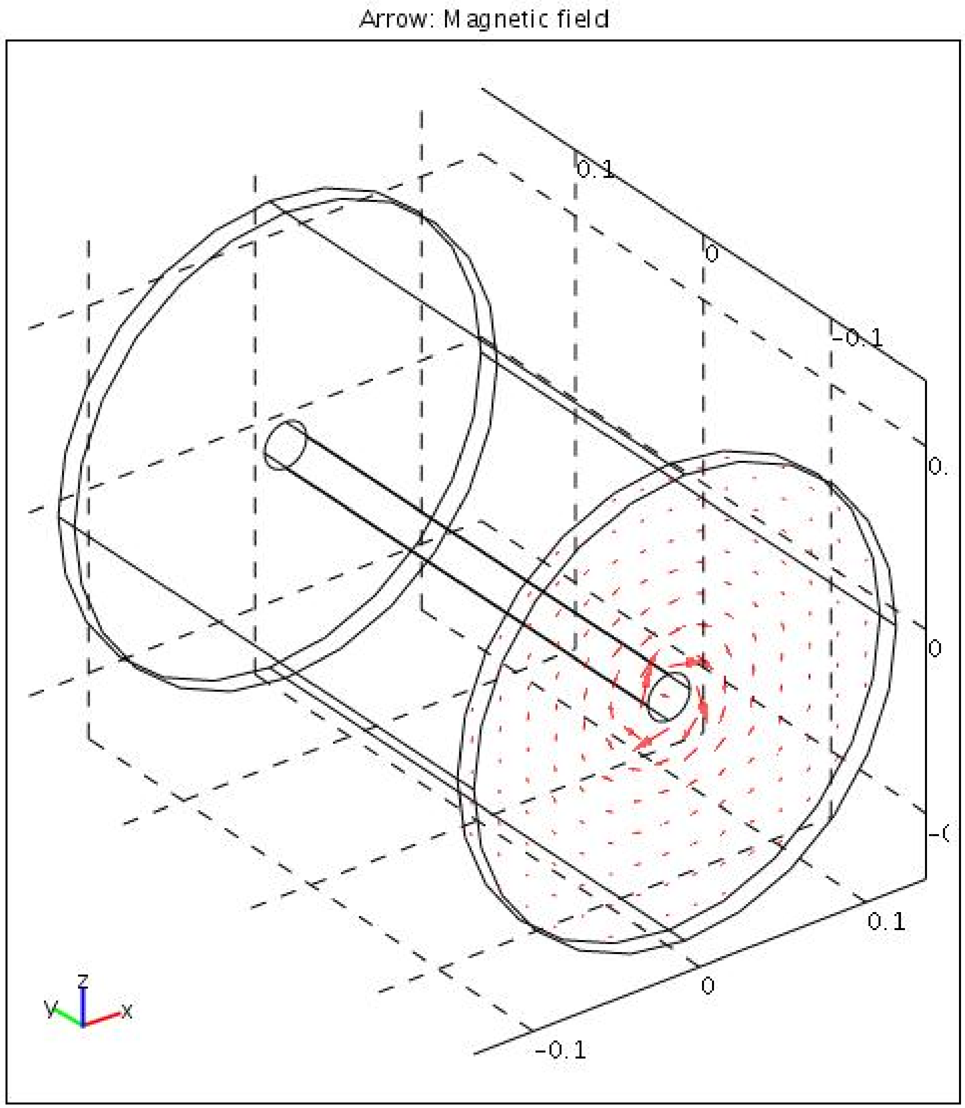
Steady State Heat Transfer



- Current enters in the left disc and exit in the right disc.
- Temperature on tube is maintained at ~200 C.

COMSOL3.4 (trial license)

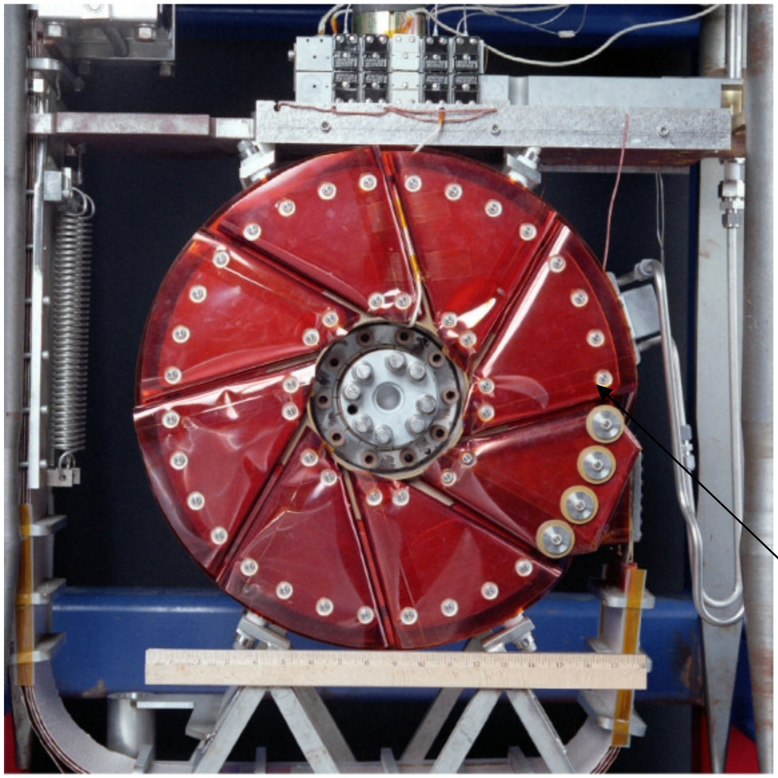
B Field at the Current Disc



B field map at the disc

COMSOL3.4 (trial license)

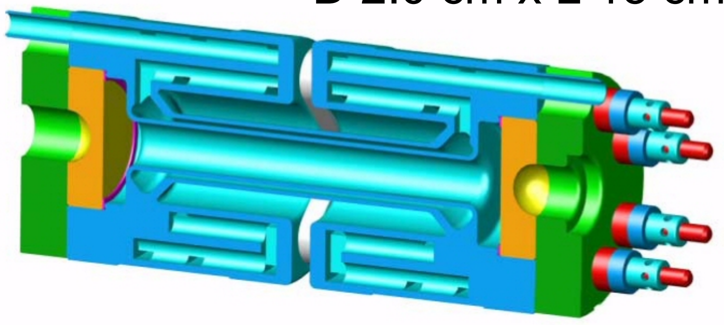
Fermilab Solid Li Lens (Recent Design)



Induction Coils

High Gradient Solid Lens
Prototype Design

D 2.0 cm x L 15 cm



BNL Muon Collider Design Workshop
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J. Morgan

Lens Upgrade Note

Summary to the Liquid Lithium Lens

to work on designing the liquid Li lens in 2010, if we receive funding, collaborating with Fermilab people.