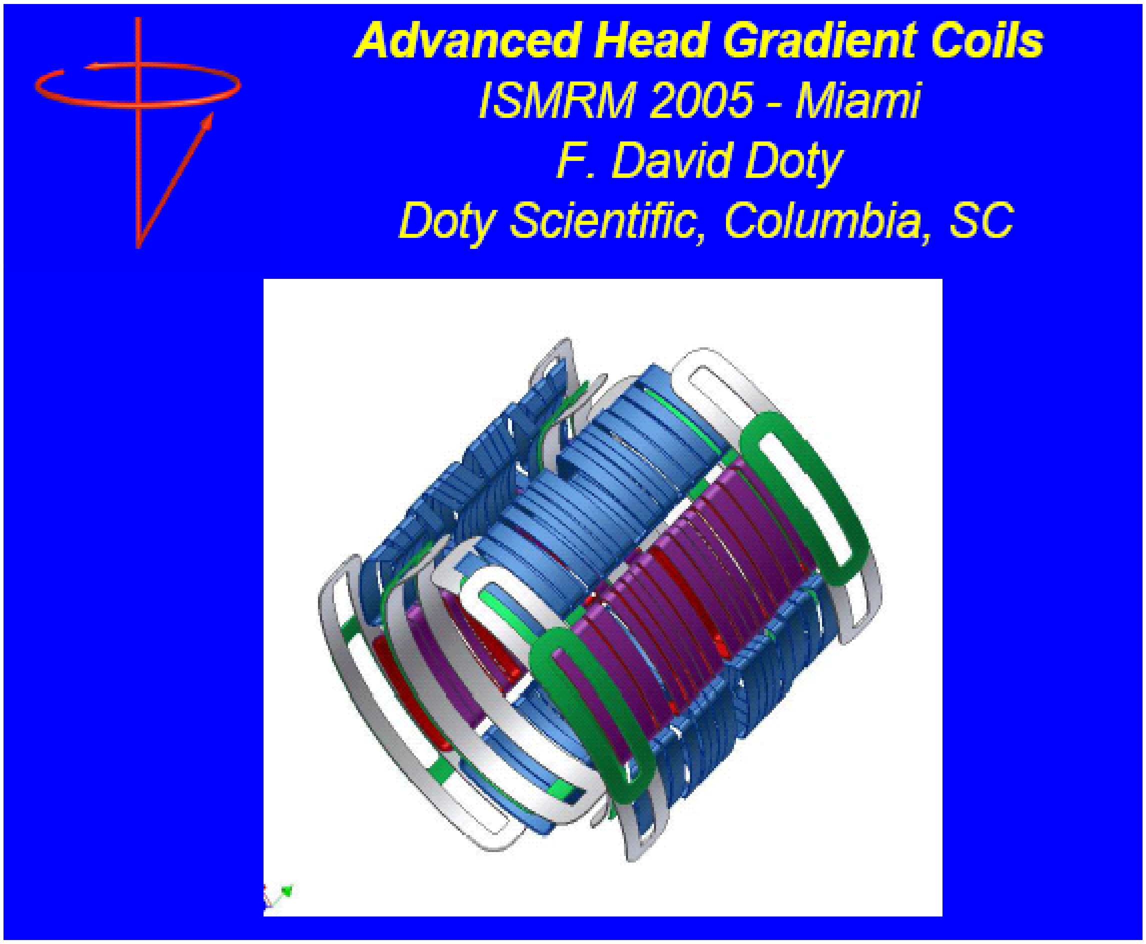
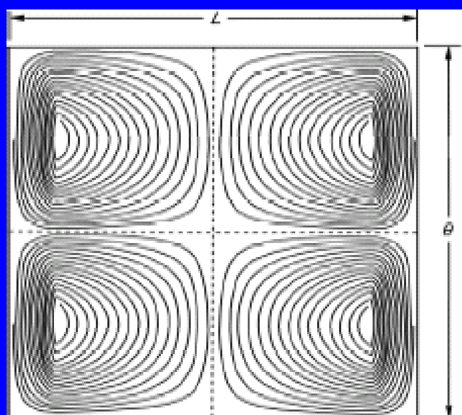


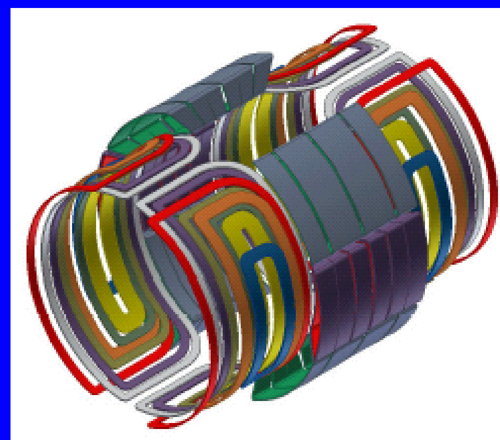
First, I'd like to thank the organizers for inviting me to present a brief update on our progress at Doty Scientific, from Columbia South Carolina, in the development of a high-performance head gradient coil. The approach is based on 3D winding geometries (not constrained to cylindrical surfaces) and it applies a balanced weighting to all the important parameters.

Head Gradient Coil Design Objectives

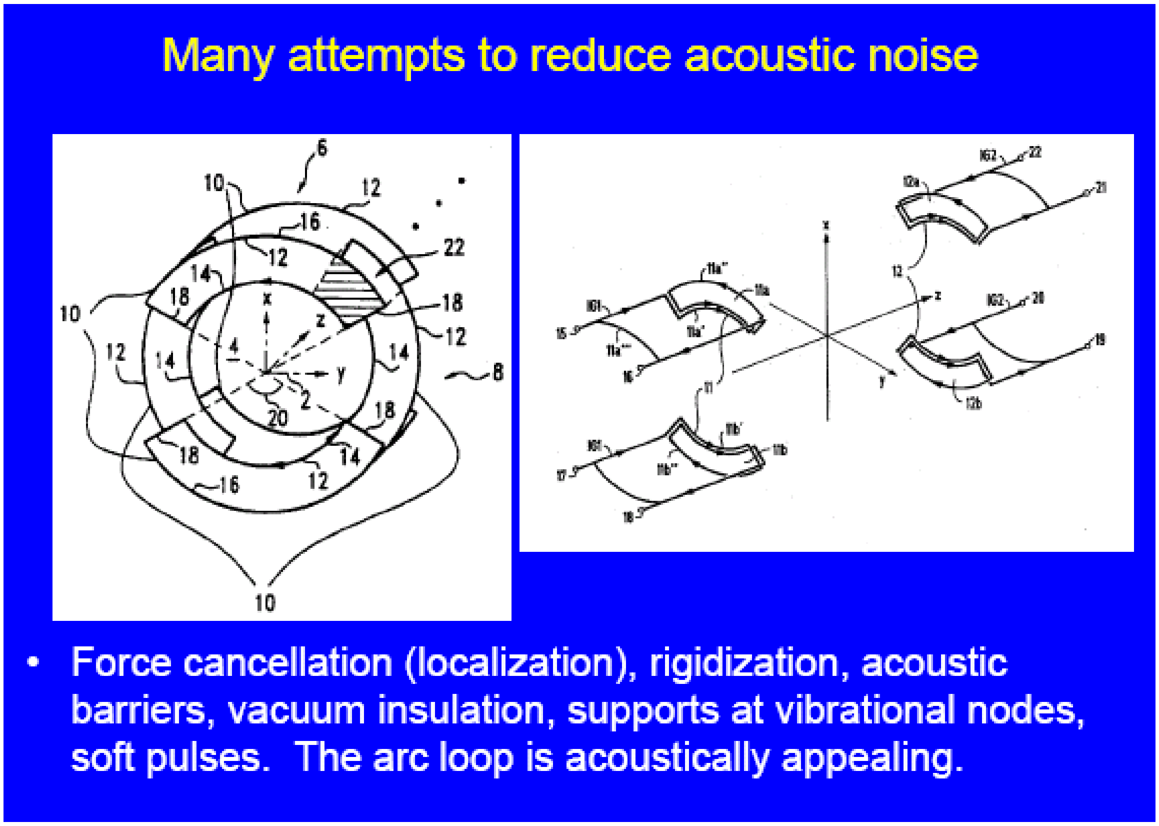
- Maximize continuous gradient capability (70 mT/m)
- Reduce acoustic noise
- Minimize nerve stimulation
- Improve reliability in very high fields (3-9.4 T)
- Reduce settling time
- 24 cm dsv ROU (Region of Uniformity)
- ROU extending to within 9 cm of shoulder edge
- Accommodate larger rf coils (36 cm grad coil ID)
- Incorporate high-order shims (Z2, Z3, Z4)
- Limit system cost (drivers plus coil)
- Symmetric, for generalized magnet compatibility

Quiet, High-Performance Gradient Coils

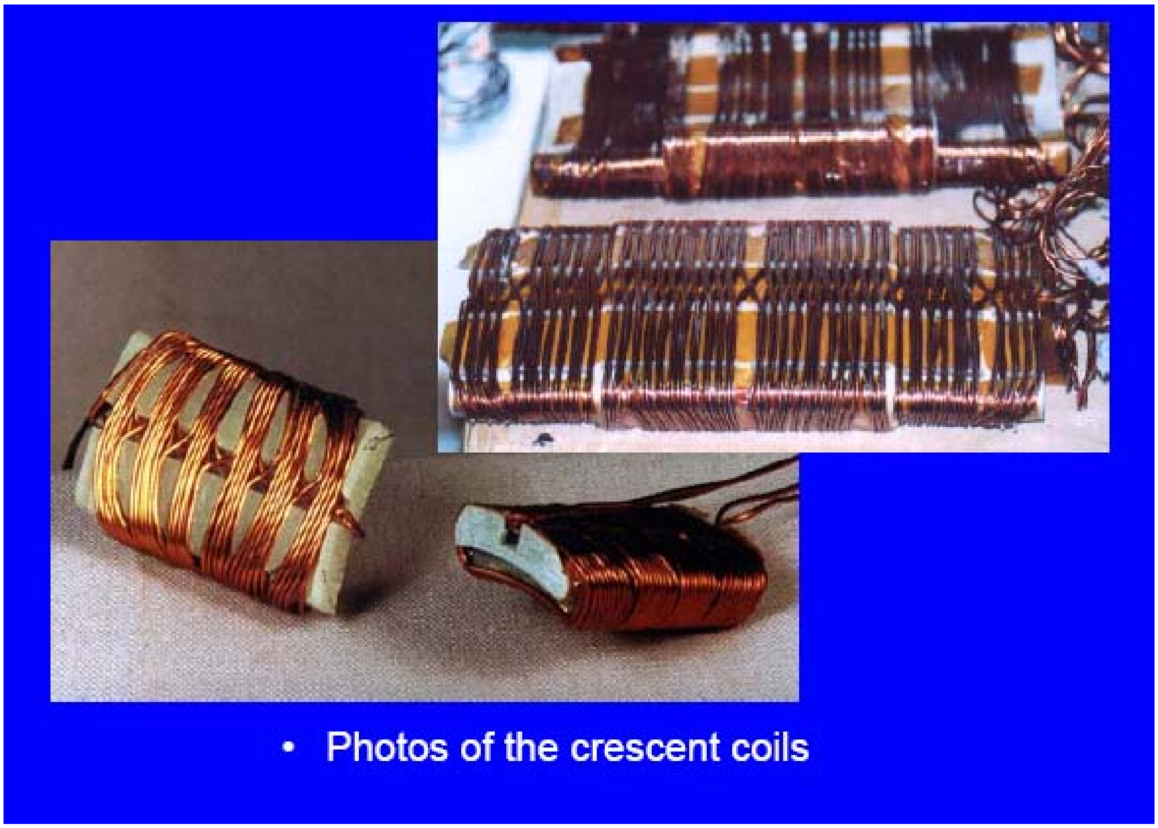




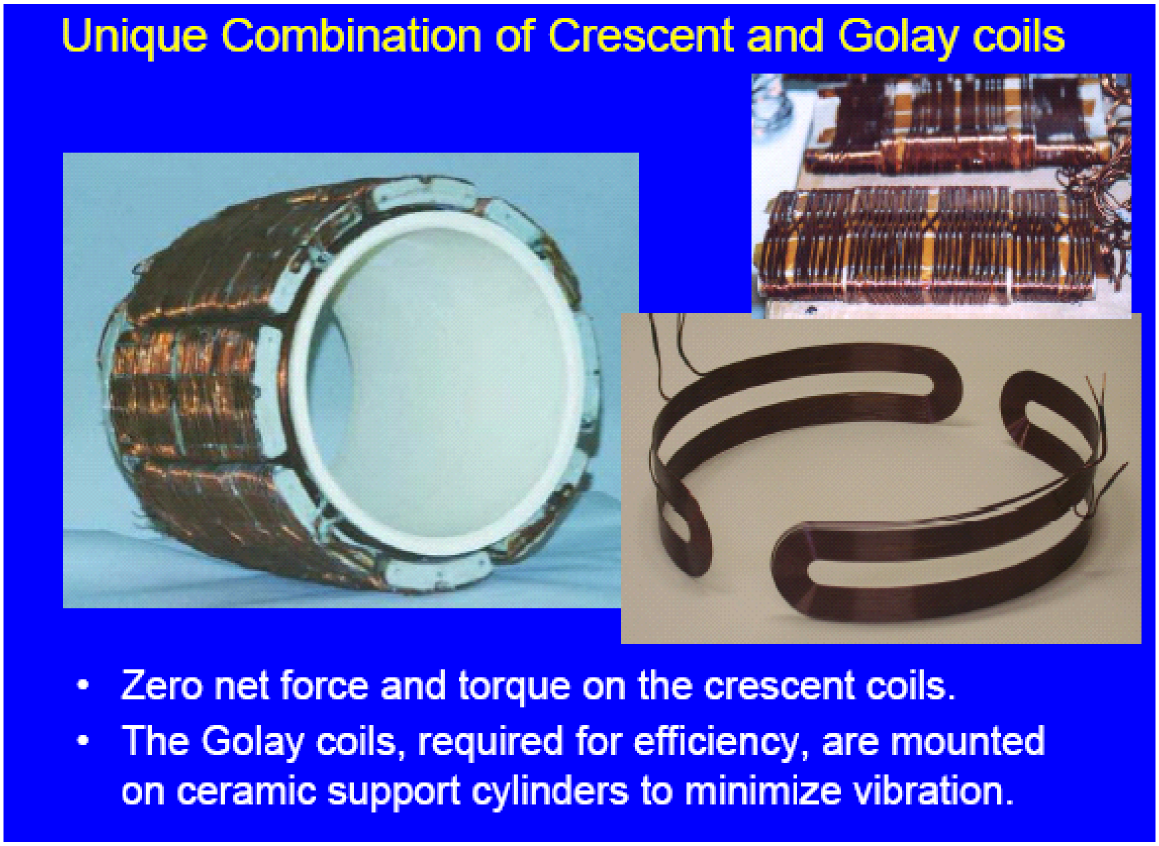
- Limitations from conventional gradient coils, constrained to cylindrical surfaces, arise from hot spots and acoustic noise. The combination of 3D arc-loops and Golay coils allows reductions in noise and improved efficiency for constrained lengths.



The appeal of the arc loop is that the net forces and torques vanish on an arbitrary loop in a plane whose normal is aligned with B0.



Our approach uses a combination of solenoidal-like coils, which we call crescent coils, along with heavy Golay coils, or saddle coils, to achieve improved performance for the constrained length case. Several examples of these crescent coils are shown here.

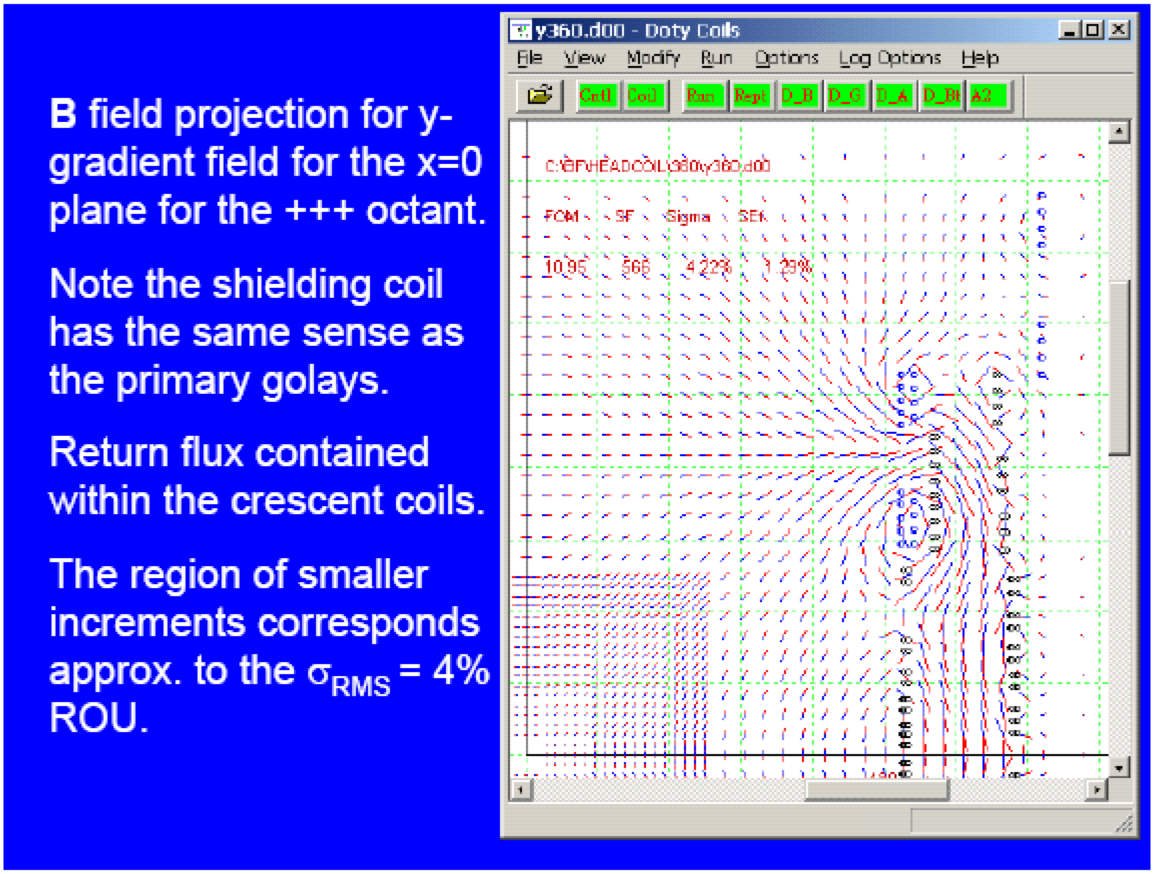


A unique combination of crescent and golay coils is required to achieve optimum performance. Here you see the complete assembly, with 8 crescent coils mounted around the perimeter of the former. Golay coils, as shown here, actually, two layers for each axis, are mounted on the ceramic former at each end. The crescent coils have an increased inner diameter at their ends so that they overlap the golay coils near the ends. In the central region, their inner diameter comes down to that of the ceramic former. The power dissipation is roughly equally divided between the crescent coils and the golay coils. The crescent coil produce little noise because of force cancellation, and the golay coils produce less noise because of the use of an alumina ceramic former.

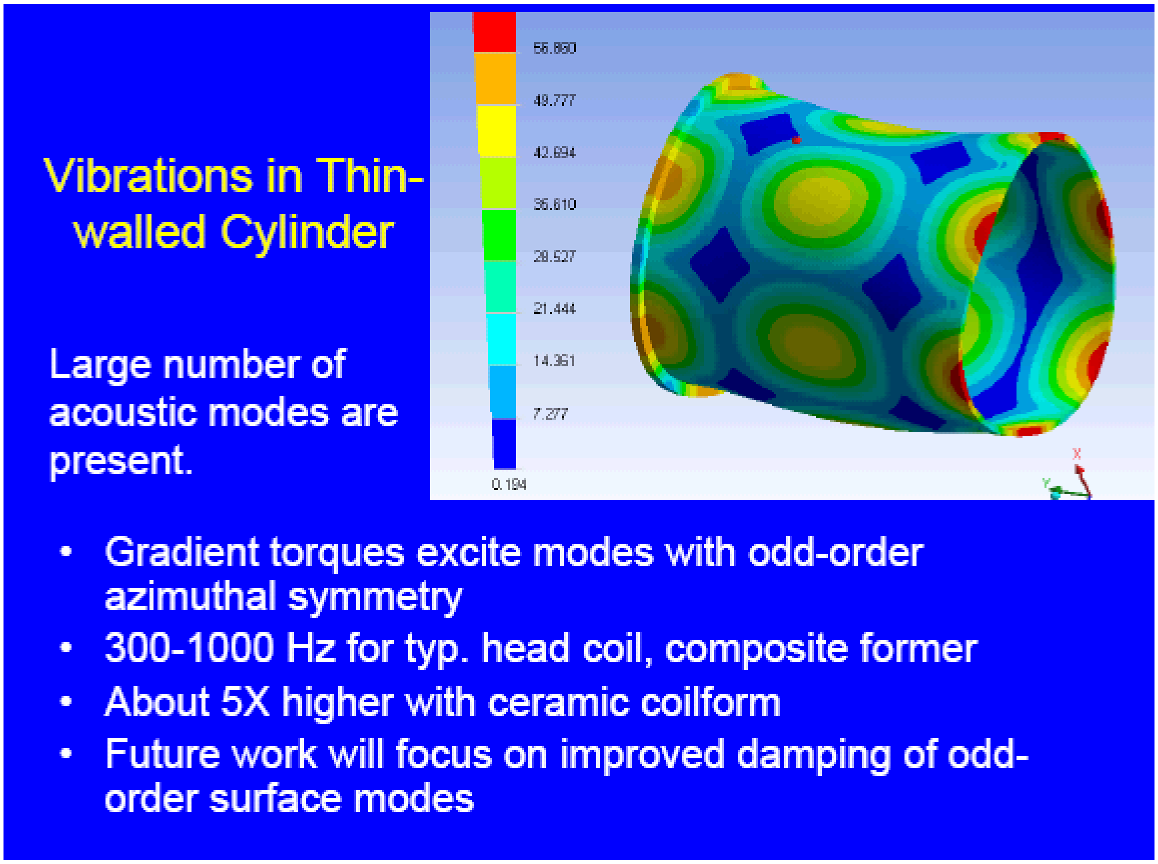
Full-parameter-set, Dimensionless Optimizations

- Biot-Savart $$d\mathbf{B}(\mathbf{r}_f) = \frac{\mu_0}{4\pi}\left(\frac{I_i d\mathbf{l}_i x(\mathbf{r}_f - \mathbf{r}_i)}{|\mathbf{r}_f - \mathbf{r}_i|^3}\right)$$
- Switching Efficiency, η_S $$\eta_S = \frac{\alpha^2 d_S^3 h_S^2}{\mu_0 L}$$
-
- DC efficiency: $$\eta_L = \frac{200\alpha^2 d_S^3 h_S}{\mu_0 R_E}$$
- Shielding effectiveness – ratio of magnetic energy within the ROU to energy outside the cryostat radius

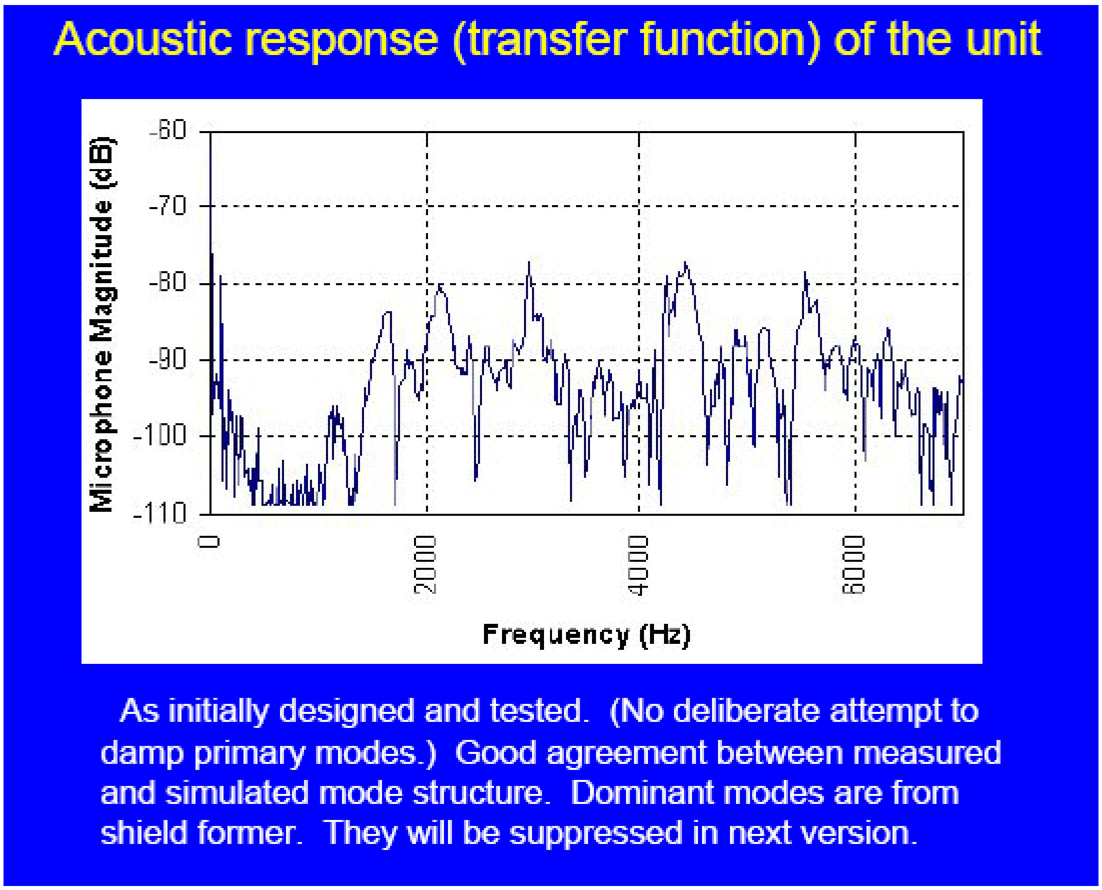
We begin by calculating the B field for all points in space, from which we calculate the values of six dimensionless figures of merit that go into a weighted objective function to be optimized. Probably the three most important are switching efficiency, shielding effectiveness, and DC efficiency. Switching efficiency is defined as the ratio of magnetic energy within the ROU to the total magnetic energy. It is quadratic with gradient gain, alpha, mT/m/A, proportional to the 5/3 power of the ROU volume, and inverse with inductance. DC efficiency is also quadratic with gradient gain, but inverse with resistance and proportional to the 4/3 power of ROU volume. We define a shielding effectiveness as the ratio of magnetic energy within the ROU to energy outside the cryostat radius.



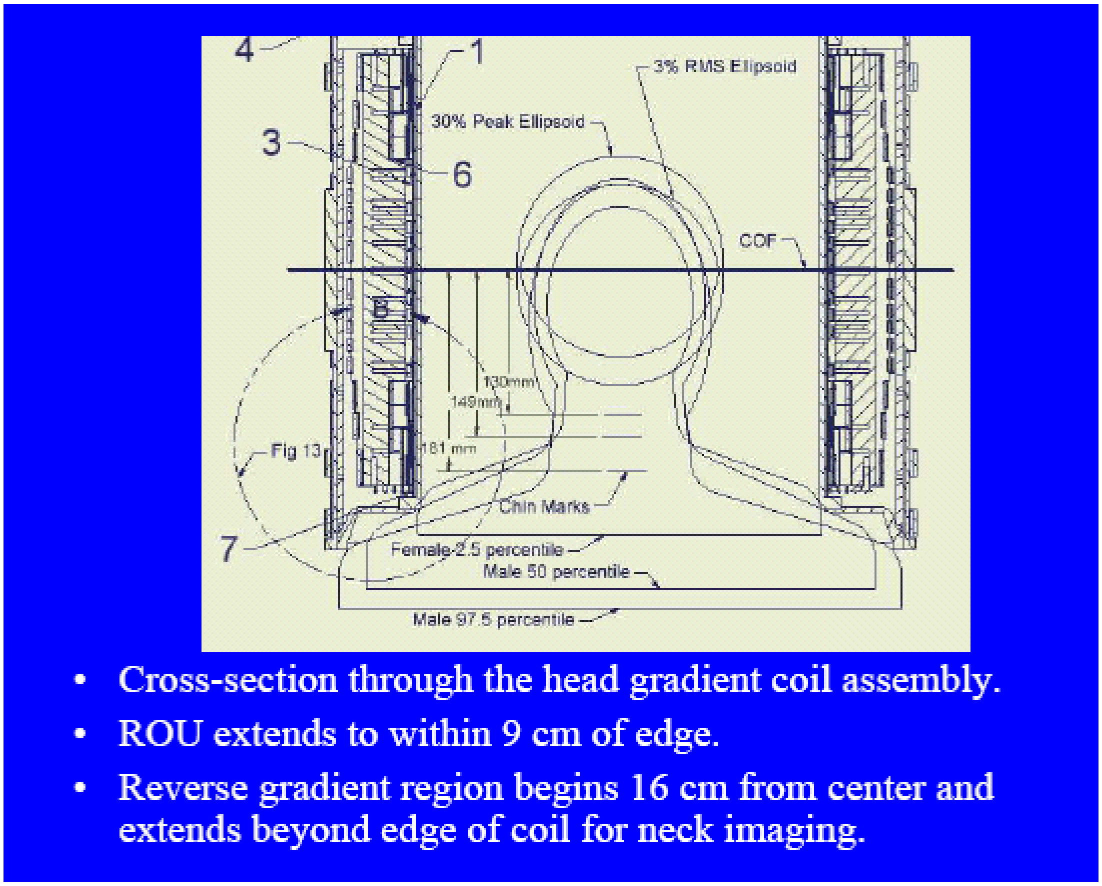
Here we see one octant of the B field projection calculations. The primary golay coils are here, near the ends. You can see that the crescent coils act to contain the return flux. The shielding golay coil, here, actually has the same field direction as that of the primary golays.



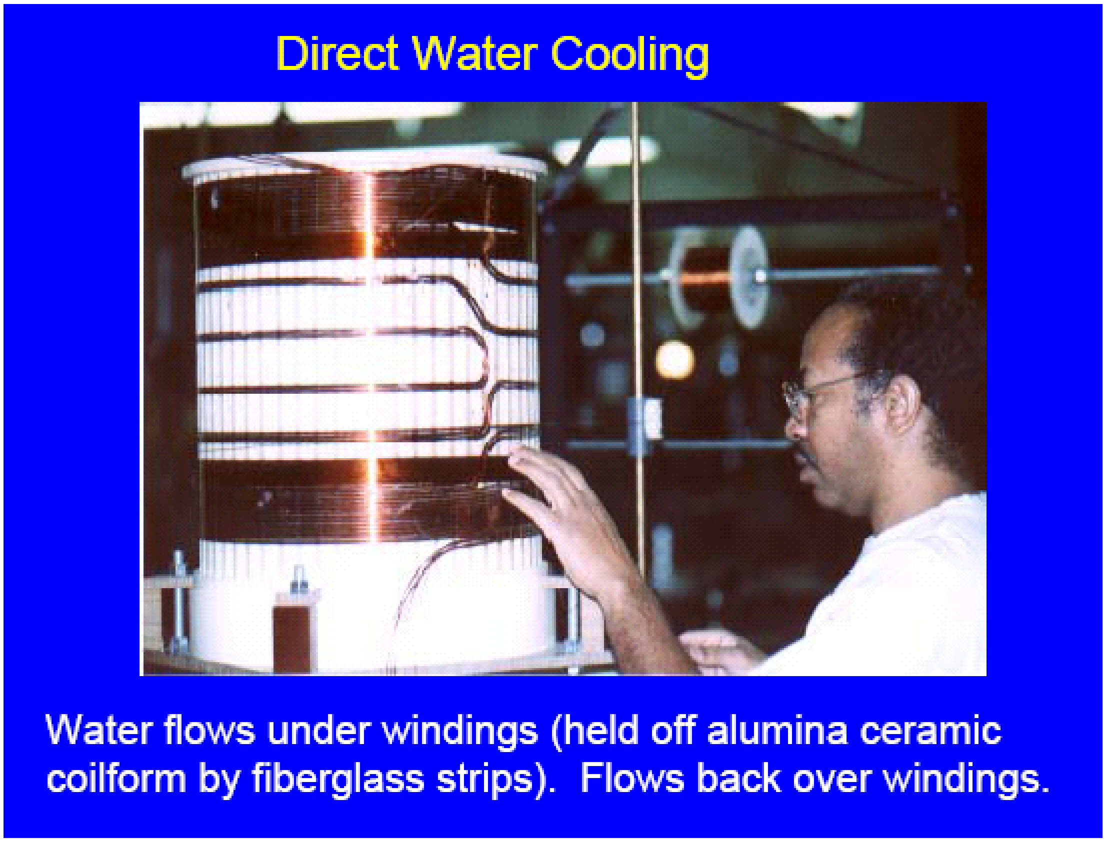
A very large number of vibrational modes are possible in thin-walled cylinders. The gradient torques tend to excite those that have odd-order azimuthal symmetry, such as that shown here. The use of a ceramic former increases their frequencies by about a factor of five compared to what one often finds with composite formers. Our composite golay coil structure also tends to damp many modes, including the one shown here.



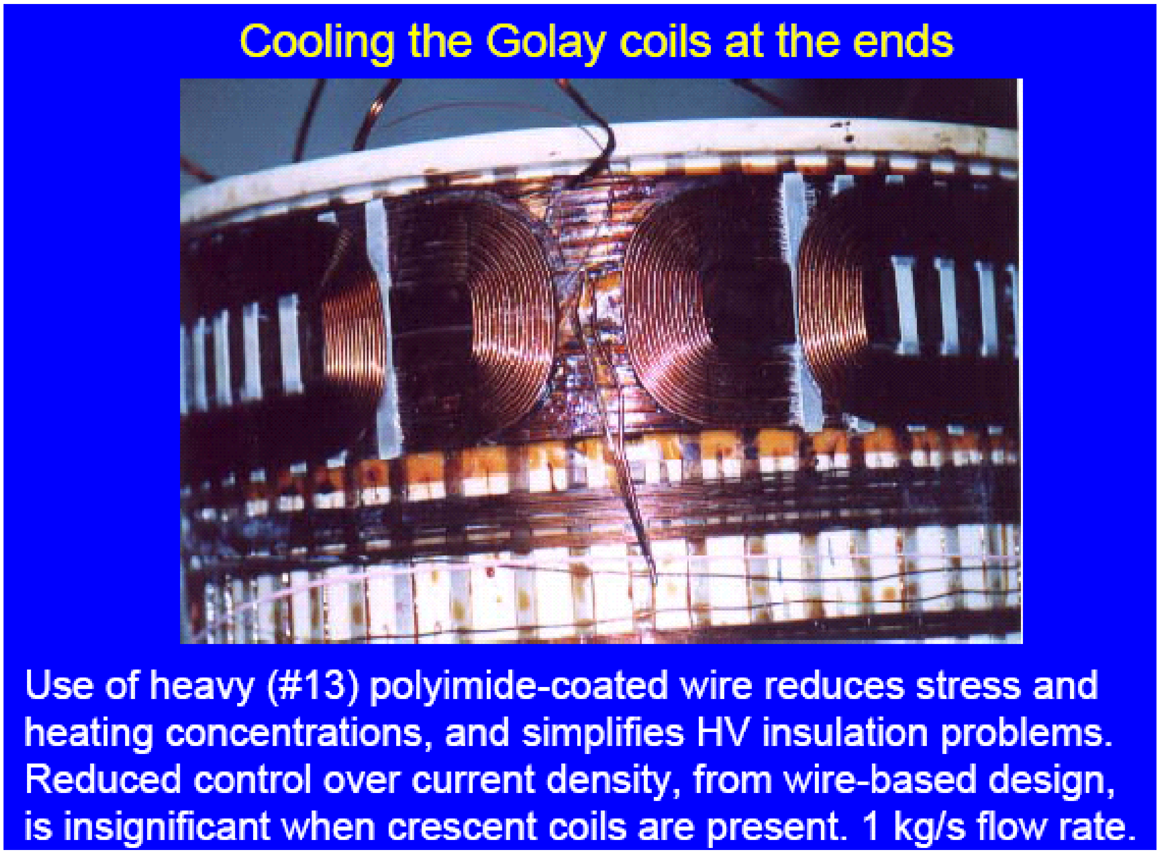
Here we see the acoustic response, or transfer function, of the complete unit, as initially tested with no deliberate attempt to damp the acoustic modes. We are still rather early in our simulations of the acoustic problem, but we are getting fairly good agreement between predicted acoustic response and measured response. We expect to be able to very effectively kill most of the resonances shown here without creating new ones. (Bandwidth of excitation pulse began rolling off above 6 kHz. RF coil and foam liner were present.)



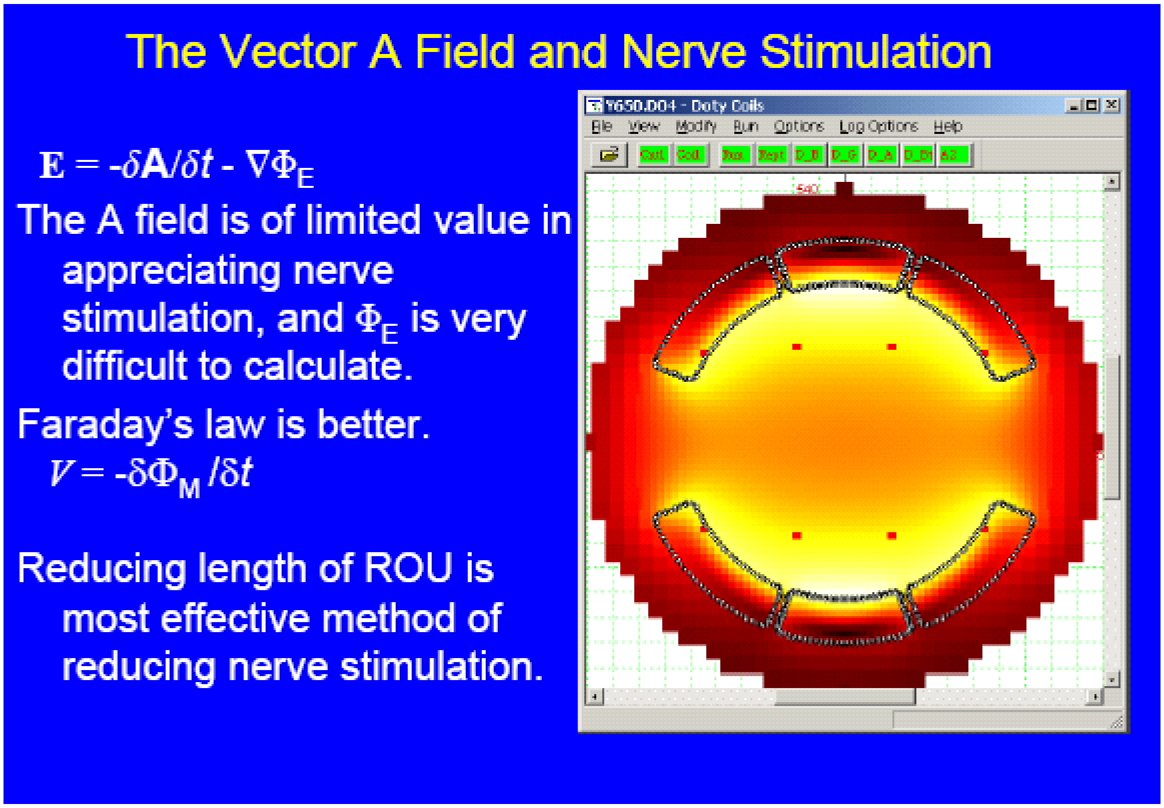
Here we see the complete assembly in cross section with profiles of large and small patients superimposed.



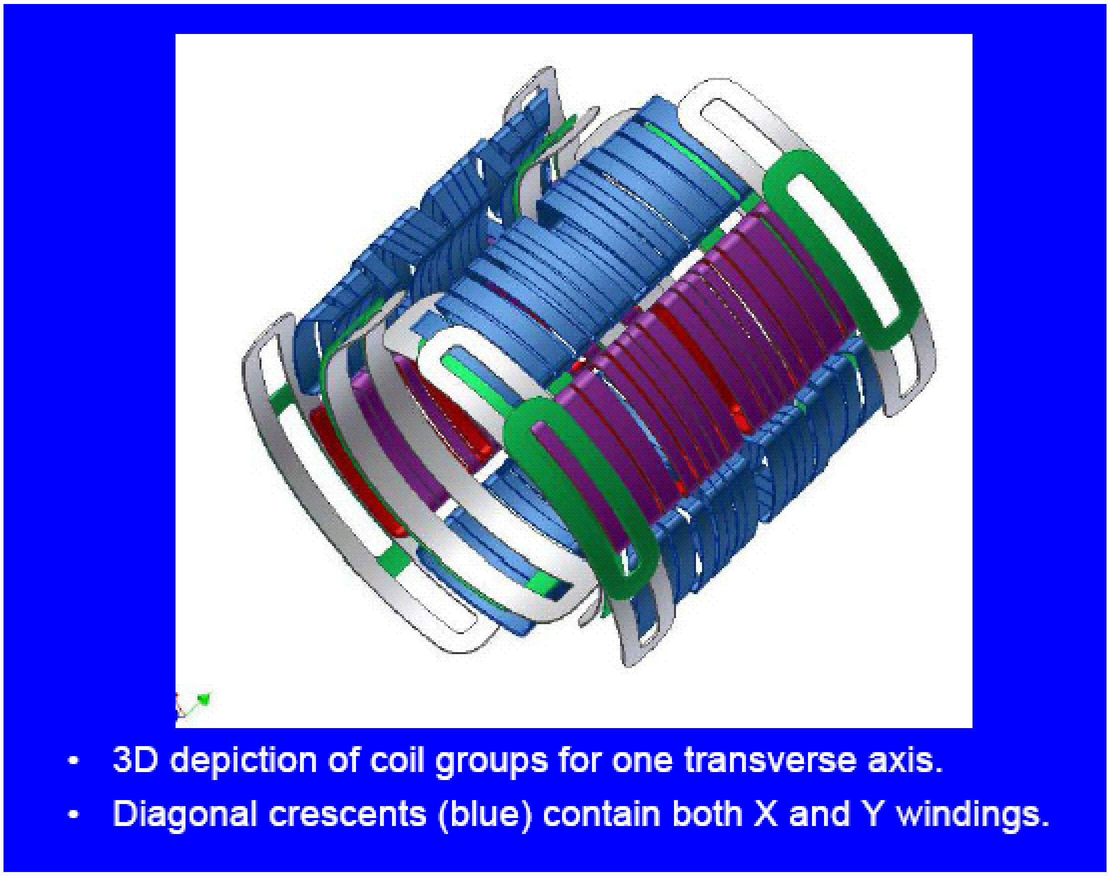
Direct water cooling of the windings is required to achieve very high gradient strength. The windings are held off the ceramic former by spaced-apart strips of fiber glass, and the water begins by flowing under the windings.



Here, we get a better look at the heart of the cooling problem. Water flows under, between, and over these heavy windings. The use of heavy (13 gage) polyimide-coated wire reduces stress and heating concentrations, and simplifies HV insulation problems, but Parylene coatings are also essential. Peak temperatures are under 90C (inter-winding) at maximum continuous current. A flow rate of about 20 gal/min (about 1 kg/s) is required when operating at the maximum rating. The reduced control over the current density, from the wire-based construction approach, is insignificant when crescent coils are present.



Of course, it is important to minimize nerve stimulation, and the most effective means to that end is to limit the length of the gradient region. In fact, this may be one of the strongest justifications for the use of a dedicated head gradient coil – it allows substantial reduction in nerve stimulation. The A vector field, shown here, is interesting for looking at localized stimulation fields in some cases, but Faraday's law is the best way to analyze stimulation potential.



Here we see a 3D depiction of the coil groups for one transverse axis. The diagonal crescent coils, shown in blue, will also contain windings for the other transverse axis when it is added.

**Acoustic Noise for EPI, 3 T, 20 mT/m,
120 mT/m/ms, 24 cm FOV, 64x64**

Coil	Ref	ID	Waveform	f_0	SPL
		cm		Hz	dB
Siemens, Sonata	1	68	Trapezodal	780	114
Varian, head	2	35	Trapezodal	~800	117
Bowtell, head	3	35	Sinusoidal	1920	128
Doty, this work		36	Trapezodal	780	110

1. CK Mechefske et al, *Mat. in Physics,* 2002.
2. DL Price et al, *JMRI,* 2001.
3. JR Foster et al, *JMRI,* 2000.

Here we tabulate some acoustic noise data from several better performing coils for a typical EPI sequence. Our first prototype is quieter by 7 dB than the best published data we've seen on a head gradient coil, and we believe there will be substantial further improvement in the near future with focused work on more effective damping, especially of the shield windings.

Performance, Head Gradient Coils - 36 cm ID x 54 cm OD					
Parameters	**Units**	**Roemer**	**Mansfield**	**Siemens**	**Doty**
Grad. gain, α	**mT/Am**	**.138**	**.084**	**0.08**	**0.138**
L	**µH**	**240**	**354**	**160**	**255**
R_E	**Ω**	**0.22**	**0.25**	**0.1**	**0.17**
Slew ($V\alpha/L$) @ 670 V	**T/m/s**	**379**	**156**	**335**	**365**
Continuous grad., G_C	**mT/m**	**20**	**10**	**35**	**70**
Rise time to 20 mT/m	**µs**	**56**	**140**	**68**	**55**
Shielding, RRG	**%**	**2.5**	**38.0**		**0.1**
Gradient null point, $\pm z_0$	**mm**	**147**	**182**		**158**
Front edge to σ_P =30%	**mm**	**96**	**54**		**90**
Dia. d_2 for σ_{RMS} = 9%	mm	240	240	~230	240
Lgh., h_2 for σ_{RMS} = 9%	mm	235	260	~220	240
S.Eff.: η_S for 9% ellips	**%**	**4.97**	**1.38**	~2	**5.57**
Copper mass (3 axes)	kg	32	22		44

Finally, we tabulate some data for several head gradient coil designs. Of course, there are far too many numbers here go over in detail, but I would draw your attention to several primary objectives. Our coil is extremely well shielded. It achieves about twice the continuous gradient capability of the best prior designs. It is quieter – soon, we expect it to be much quieter. And it is large enough to more efficiently accommodate transmit-receive coils for phased arrays or double resonance coils.

Doty Scientific, Inc., Columbia, SC

Thank You