Design of a RoboCup Shooting Mechanism

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Introduction

Last year the idea of joining RoboCup has risen at the Department of Mechanical Engineering at the Technische Universiteit Eindhoven, TU/e. A team should be ready to participate on the RoboCup Middle Size League tournament of 2006 in Eindhoven with other teams. Until then a lot of work has to be done, including designing a shooting mechanism.

RoboCup is an international project to promote robotics and subjects related like Artificial Intelligence. It is founded to make a contribution to Artificial Intelligence and intelligent robotics research. RoboCup chose to use a soccer game competition, because of the great complexity of this game. The final goal is to be able to win against the human world champion team in soccer in the year 2050.

Meanwhile the RoboCup Committee uses a restricted version of the FIFA rules which can be found at the RoboCup website, www.robocup.org. Those adapted rules will be reduced slowly to correspond to the FIFA rules as soon as technology allows.

In this report the choice and development of the best shooting mechanism for RoboCup Middle size league will be taken into account. The first chapter contains an overview of already used mechanisms by other teams. The next chapter contains demands and the best mechanism will be chosen. This mechanism will be studied in depth in the following chapters followed by a design.

1. Mechanisms used by other teams

This chapter contains an overview of mechanisms which are used by competing RoboCup teams. Almost every team has developed there own unique shooting device. They can be subdivided into 3 categories which will be dealt in this chapter.
The three types of mechanisms are judged at 10 points.

- Shooting Power
- Costs
- Simplicity
- Power modulation
- Weight
- Space required
- Time between shots
- Number of shots
- Safety

1.1 Spring Mechanisms

The first category contains systems based on mechanical stored energy in a spring. This system is a very simple mechanism. A spring is wound up, held, and released at certain moment of time. This mechanism was used in Lissabon 2004 by Agilo, Philips CFT, Tkumsu and Win-Kit. It is applied in various configurations. Varying from basic spring systems to crossbow based mechanisms. Figure 1 contains a simplified model of a standard spring mechanism.

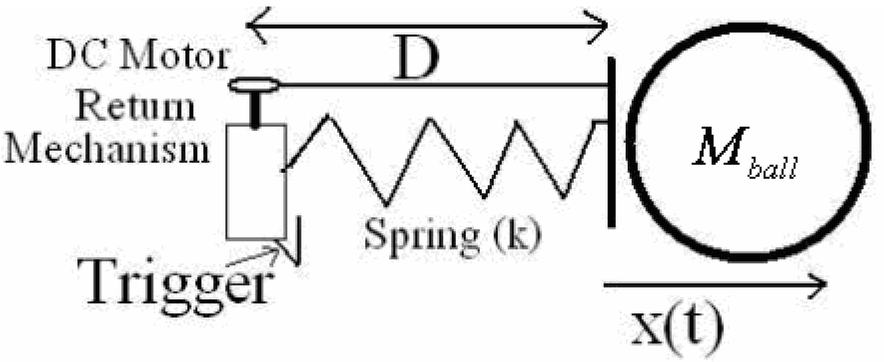

Figure 1.1: Schematic model of a spring-based shooting mechanism

For this simple model the equation of motion holds.

$$\ddot{x} = -kx \cdot m_{ball}{}^{-1} \qquad (1.1)$$

With Initial Values:

$$x(0) = D \qquad (1.2)$$

$$\left.\frac{dx}{dt}\right|_{t=0} = 0 \qquad (1.3)$$

The most advanced example known in this category is the shooting mechanism which is used by the Philips CFT team (figure 2). It was the most powerful mechanism for a long time. It can shoot up to 8 m/s.

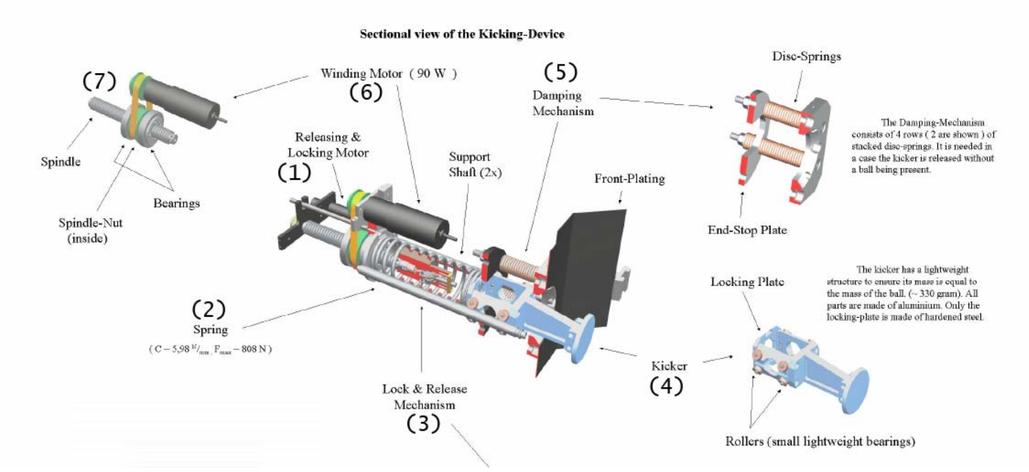

Figure 1.2: A sectional view of the Philips CFT shooting mechanism

The design is very well-thought. The spring **(2)** is wound up by a spindle **(7)** with screw thread which is attached at a dc motor **(6)**. A small mechanism **(3)** to lock and unlock the kicker **(4)** is placed inside the spindle with thread. In initial condition (before a kick) the kicker is locked on the spindle and holds the spring. In an elastic collision energy transfer is optimal with equal masses thus the kicker mass is almost equal to the ball mass. The motor starts turning and stops as the kicker is almost at maximum stroke. To fire, the motor starts again and presses the release-plate **(1)** against an obstacle. This unlocks the kicker and is driven forward by the spring. At the end of stroke is a simple damping mechanism of disc-springs **(5)** to prevent damage when the ball is not present in a shooting action.

This system is very powerful, because much energy can be stored in a spring. For the Philips shooting device is this approximately in the order of 40 [J] It is able to shoot the ball with high velocity, 8 m/s. The number of shots is almost unlimited, because it works on battery power. However the system has also several disadvantages: It takes a lot of space, weights several kg's and it takes about 6 [s] to reload.

It is also very hard to control the shooting power. There are 2 ways to obtain variable shooting power, by varying the springs displacement or by taking energy away with a variable damper. These are difficult solutions and is rather impossible to achieve variable shooting power "on demand" without any time lag.

Spring Based systems	
Shooting power	**+**
Costs	**+**
Simplicity	**-**
Power modulation	**-**
Weight	**-**
Space required	**-**
Time between shots	**-**
Number of Shots	**+**
Safety	**+**

Table 1.1: Overview Spring Based Systems

1.2 Pneumatic Systems

Most teams use shooting mechanisms which are based on pneumatic pressure. This is also a very basic technology. A large gas tank is placed somewhere in the robot and is brought on pressure before a match. At the front are one or more pneumatic cylinders connected with tubes to the air tank. In the tube(s) are solenoid valve's which can operate as a "switch" or they can be controlled so they can regulate the airflow and shooting power.

Shooting force depends on the pressure in the gas tank. High pressure is needed for a decent shooting force en thus a strong and heavy tank is needed. The number of shots depends on the size of the gas tank. 15 shots at 247 [n] with a 3.6 [l] tank according to Searock et. al.

Pneumatic Based systems	
Shooting power	-
Costs	+
Simplicity	+
Power modulation	0
Weight	+
Space required	-
Time between shots	+
Number of Shots	-
Safety	+

Table 1.2: Overview Pneumatic Based systems

1.3 Solenoids

The third principle used for shooting devices is self-inductance. By sending a current trough a turn of wire a magnetic field can be build. As the number of turns or current increases, the magnetic field increases too. With magnetism ferromagnetic materials can be attracted or repulsed. This phenomenon is used in a solenoid, which is used in RoboCup by Minho, JiAO Long and 5DPO.

Solenoids are widely available in store, but these solenoids are not suitable for a kicking device. Those solenoids are low voltage and are very slow due to the timeconstant (paragraph 3.4). High voltage solenoids are not available at this moment. For RoboCup the solenoid has to be really fast, because it travels 10 [cm] in about 10 [ms] when shooting at 10 m/s. All teams who use a solenoid have build one themselves.

As written before, team Minho uses also a solenoid. It is a powerful and silent weapon. A schematic model can be found below.

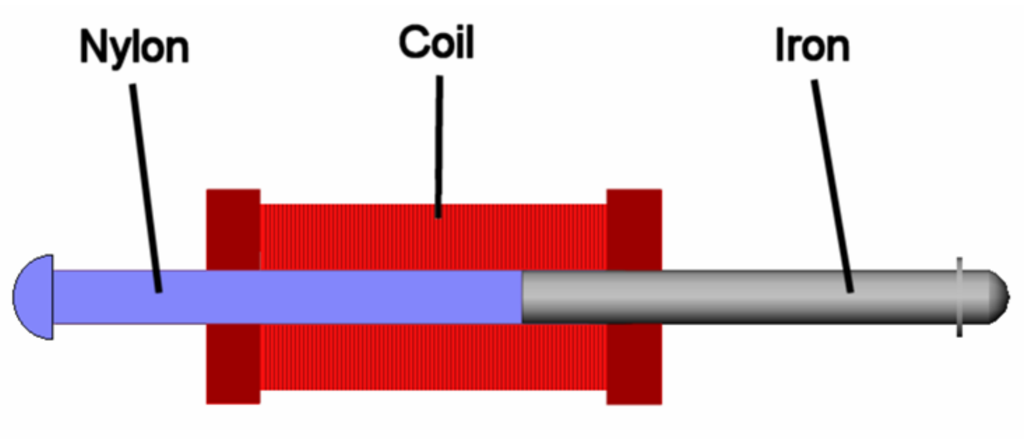

Figure 1.3: The Team Minho Solenoid

Characteristics	
Max. charging time	12 seconds
Max. voltage discharge	400 Volts
Equivalent capacitance	4,3 mF
Coil inductance	55 mH
Coil resistance	6 Ω
Max. energy consumption by kick	174 Joule
Weight	2 Kg
Minimum discharging time (weak kick)	1 ms
Maximum discharging time (strong kick)	25 ms
Ball distance	50 meters

Table 1.3: Characteristics Team Minho Solenoid

This design takes advantage of the property that a solenoid has a ferromagnetic core which is attracted into the coil centre. The piece of nylon which is attached to the iron bar is a non-ferro and shoots outwards and hits the ball.

It is able to shoot very fast. 10 m/s when about 800 turns and a current of 60 [A] are applied. It is rather small (length is about 20 cm and about 5 cm diameter) and lightweight (2 [kg]). Only a transformer, a capacitor, some resistors and a switch is used so it is in theory very reliable. And most important shooting power can be varied by varying the time of the applied current.

The disadvantage of the use of a solenoid is that it operates at a high voltage and current, so it can be quite dangerous. This can be solved by hiding dangerous parts in a black box. It also uses a lot of power for a really short time, so a capacitor is needed to supply high voltage and current. Due to internal resistance, heat is generated when activated (paragraph 3.6). This has to be taken into account in a design.

Solenoid Based systems	
Shooting power	**+**
Costs	**+**
Simplicity	**+**
Power modulation	**+**
Weight	**+**
Space required	**+**
Time between shots	**+**
Number of Shots	**+**
Safety	**-**

Table 1.4: Overview Solenoid Based systems

1.4 Other mechanisms

There are a lot of other mechanisms that can be used. But in practice those devices don’t work properly or have some side-effects. For instance rack and pinion systems (figure 4b) and rotating systems (figure 4a). The first one requires a motor with huge power-ratings. The second one is too dangerous especially for referees. They can easily be injured by the rotating parts when a fault is committed and the ball has to be taken out of the game.

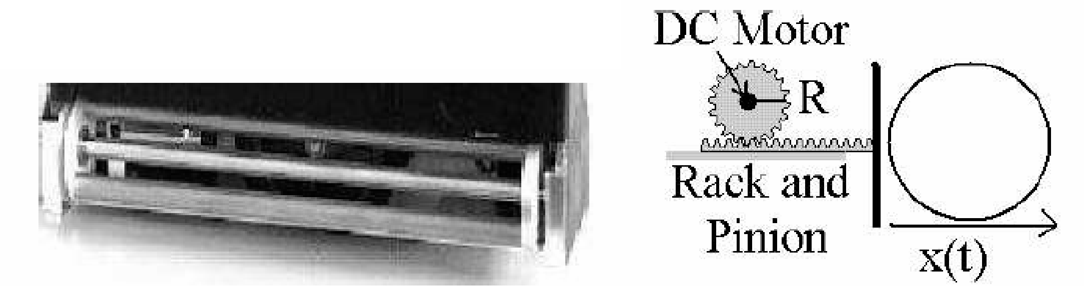

Figure 1.4: Schematic model of rotating system (left) and a rack and pinion system (right)

2. Comparison

2.1 Demands

Now the several types of shooting mechanisms are introduced and the pro's and con's are known, a comparison can be made. At first the demands for our mechanism have to be determined. The demands are decreasing in importance, so the first one is the most important one. The best shooting mechanism, will be researched in depth in following chapters.

According to the RoboCup rules the robot has to fit in specified dimensions. Robot and actuators may not exceed a square of size 50 [cm] x 50 [cm] and this may be extended to a limit of 60 [cm] x 60 [cm] for a short time, e.g. when kicking or dribbling. Thus the maximum stroke of our shooting device may not exceed 10 [cm].

The shooting device has to be able to vary shooting power. Our RoboCup team should be to pass from the beginning or in the near future. Because a pass has a lower velocity then a regular goal attempt power modulation is necessary. To prevent major hardware changes in the near future, the shooting device has to be able to met this demand..

The shooting device also has to be able to shoot the ball 10 [m/s] to keep up with other competitors and to improve scoring chances. A good aimed shot is almost always a goal at this speed, because the keepers are not fast enough to analyze the shot and move to the aimed position before the ball hits the goal. The amount of energy needed for one shot at 10 m/s is calculated with formula 2.1. All ball properties can also be found in the RoboCup rules.

To calculate the ball velocity some assumptions are made. At first the ball is fully rolling after the shot. Secondly the collision between plunger and ball is fully elastic. And losses like air drag and rolling resistance are neglected.

$$\frac{1}{2} m_{plunger} v_{plunger}{}^{2} = \frac{1}{2} m_{ball} v_{ball}{}^{2} + \frac{1}{2} J_{ball} \omega^{2} \qquad (2.1)$$

With

$$V_{ball} = 10 \quad [m \cdot s^{-1}]$$

$$m_{ball} = 0.45 \ [kg]$$

$$r_{ball} = 0.11 \ [m]$$

$$J_{ball} = \frac{2}{3} m_{ball} r_{ball} = 363 \cdot 10^{-3} \quad [kg \cdot m2]$$

$$\omega = Vball \ / \ r \qquad [rad / s]$$

Gives 42.5 [J] to be supplied by the solenoid.

To ensure maximum safety for team-members, RoboCup-staff and supporters the device has to be as safe as possible in idle state and when actuated.

Because a robot sometimes has to shoot again shortly after one shot, the reload time until next shot should be as small as possible.

The space taken by actuator and components is preferred to be low, because at bottom level where actuator will be placed are also motors and a ball handling mechanism and it has to fit in previous specified dimensions.

To be able to shoot many times in one match, the device has to be efficient with available resources and energy.

The actuator may not interfere with other components like control hardware. In current plans a control laptop will be placed inside the robot and our shooting device may not create conditions in which the laptop is not able to operate

The device has to be lightweight because the robot should be as light as possible to make it really fast and very agile.

A simple design with minimum parts is preferred to prevent hardware fail and to be able to fix it with fewer tools and in a short time.

Costs are also taken into account. These are not very important but are kept to a minimum.

2.2 Choice

A complete overview has been created in previous chapter and demands are specified in previous paragraph thus a shooting method can be chosen. All data is add in table 2.1 and the three devices can be compared.

Properties	**Spring**	**Pneumatic**	**Solenoid**
Shooting power	**+**	**-**	**+**
Costs	**+**	**+**	**+**
Simplicity	**-**	**+**	**+**
Power modulation	**-**	**0**	**+**
Weight	**-**	**+**	**+**
Space required	**-**	**-**	**+**
Time between shots	**-**	**+**	**+**
Number of Shots	**+**	**-**	**+**
Safety	**+**	**+**	**-**

Table 2.1: Overview of all mechanisms

After adding up all factors it’s obvious the solenoid is the best option. In next chapters the solenoid will be analyzed in detail.

3. Solenoid Design

When designing a solenoid a number of variables should be taken into account. Variables that determine the behaviour of solenoids are among other things inductance, response time, resistance, force, dimensions and core-material. Moreover operating voltage should be kept in mind, because of limited power supply.

To design a good solenoid these parameters should be balanced carefully. In this chapter this parameters will be explained

3.1 Self-Inductance

Self-inductance of solenoids is stipulated by the number of windings, coil length and diameter. It can be calculated with Wheeler's formula (3.1) [4]. This formula holds for coils in which core isn't present inside the coil but it is a good indication for the solenoid.

Self-inductance will not remain constant in the case of a solenoid kicker due to the moving core. Self-inductance will increase when the core moves inside.

$$L[mH] = \frac{0.0315 \cdot N^2 \cdot \left(\frac{R_1 + R_2}{2}\right)^2}{6 \cdot \frac{R_1 + R_2}{2} + 9 \cdot l_{coil} + 10 \cdot (R_2 - R_1)} \qquad (3.1)$$

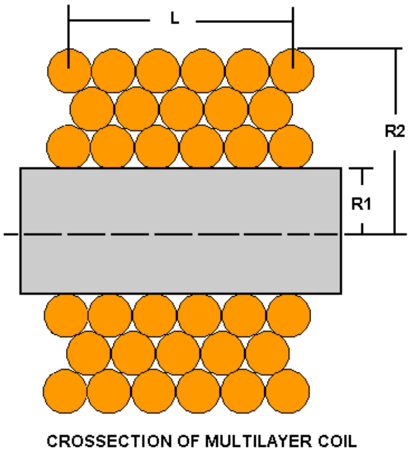

Figure 3.1: Crossection of a Solenoid

With:

N	=	Number of Turns	[-]
R_1	=	Inside radius	[m]
R_2	=	Outside radius	[m]
l_{coil}	=	Length	[m]
L	=	Self-inductance	[mH]

Self-inductance is also proportional to magnetic flux, which is proportional to flux intensity.

3.2 Resistance

Resistance of solenoids is stipulated by the specific resistance of the wire material, diameter and wire length. Wire length can be calculated with formula (3.2).

$$l = 2\pi \cdot \left(R_1 + \frac{(R_2 - R_1)}{2} \right) \cdot N \qquad (3.2)$$

With:

R_1	=	Inside radius	[m]
R_2	=	Outside radious	[m]
N	=	Number of Turns	[-]
l_{wire}	=	Wire length	[m]

Solenoids contain often copper winding wire, because it is a very good conductor, not being magnetised and good availability. Winding wire manufacturers always supply resistance by unit length. In that case resistance can be calculated by formula (3.3).

$$R = \rho \cdot l_{wire} \tag{3.3}$$

With:

R	=	Resistance	[Ω]
ρ	=	Resistance by unit length	[$\Omega\ m^{-1}$]
l_{wire}	=	Wire length	[m]

Resistance is stipulated by wire cross-sectional area. Resistance can be decrease by increasing area. A table with resistance by unit length for several winding wire diameters can be found in attachment 1.

3.3 Force

The acting force at the core can be calculated with Lorentz formula (3.4). In this formula, force is proportional to flux density.

$$F = B \cdot I \cdot l \tag{3.4}$$

With:

B	=	Flux density	[T]
I	=	Current	[A]
l	=	Length	[m]

Flux density B is proportional to current and force also is to both, thus force is proportional to I^2. For high currents saturation appears. This means that almost all small particles inside the core are in an optimum state by which flux density no longer increases. According to (3.4) force is proportional to I for high currents.

Because much energy is needed for one shooting action, the solenoid will be operating in high current domain only. This implies within the saturation area and so proportionality to I.

The Lorentz formula is only applicable for limited conditions but is a very good indication for the generated force. Lorentz holds for solenoids without shielding, because a magnetic shield adds external flux density increasing material. As told in previous chapter no interference with control hardware (like hard disks) is allowed, so magnetic shielding is crucial. In this case the magnetic field co-energy can be used for force calculation. Co-energy is the amount of energy which the magnetic field contains. This can be calculated numerically. Force can be calculated by differentiating co-energy to place. More about this in chapter 5.

Of course it isn't necessary to calculate force directly because the kinetic energy of the plunger is the most important variable. But force-stroke diagrams give a clear view about the boundary effects. A research with the influence of several solenoid parameters to force is done in Chapter 6.

3.4 Time constant

Solenoids have a time constant. This is the value of L/R. A large time constant decreases the reaction time of the solenoid. This time constant causes a delay in applied current in both on and off-switching. In general it takes 5 times the time-constant to build and break down the current. An example is shown in figure 3.2. After 5 units L/R current reaches maximum. Current is switched of and it takes again 5 units L/R to decay.

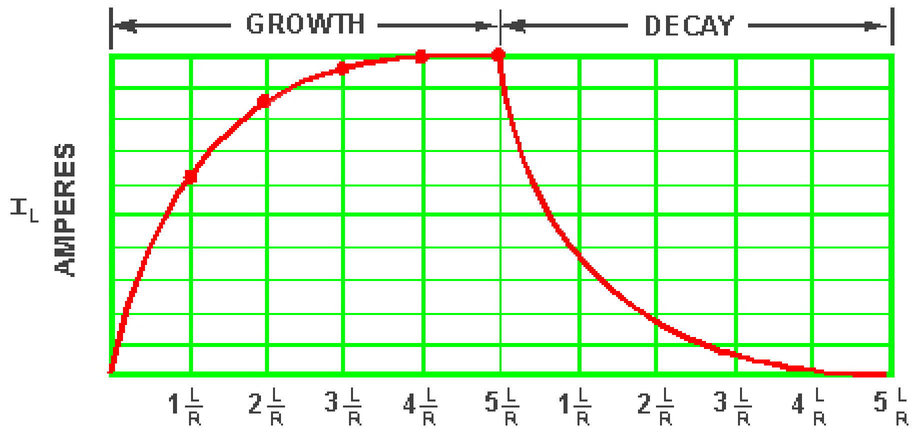

Figure 3.2: Time constant example

This current delay is caused by Faraday's law which creates an e.m.f. as current is turned on. According to Lenz law it's a back e.m.f. and opposes the change of current. This is a very unwanted effect because it takes some time until the solenoid operates at full power.

To lower the time constant a low self-inductance and / or a high resistance can be chosen. A low self-inductance can be created by decreasing the number of turns and increasing current. But increasing current causes a quadratic increase of power losses due to resistance $P = I^2R$. More heat will be dissipated, thus there is a limit.

The other option is to design with highest resistance. A high resistance is unwanted because of the higher power losses due to resistance and also more heat will be dissipated.

Thus a compromise is necessary to achieve the lowest time constant. The solenoid should be designed with the thinnest wire (means high resistance) and highest current applicable (means low self-inductance).

3.5 Dimensions

To create a concentrated magnetic field the solenoid should be designed as compact as possible in de radial direction. This means that the coil is positioned as close to the core as possible with a minimum of supporting material and space.

The length of the coil should be equal to the core length. Now the centre of the coil, which contains concentrated field lines, is completely filled with the core.

3.6 Temperature

The RoboCup solenoid has to deliver lots of energy in a very short time thus a high power is needed. Heat will be generated due to resistance. This will be a limited amount of energy, because one shooting action takes only about 10 [ms]. In that case very high currents can be applied without melting.

The robot will use the shooting mechanism incidentally in a match, so an incidental heating can be assumed. This implies that enough time to cool down between shooting actions is available. Now convection and radiation can be neglected and all energy will heat up the material. To be sure the solenoid works also on very extreme circumstances for RoboCup, the maximum temperature rise is set to 10˚C after one shooting action.

If all energy will heat up the material, following equation can be used.

$$Q = m_c \cdot c \cdot (T_2 - T_1) \tag{3.5a}$$

For Q the resistance energy loss can be taken. The mass of copper, m_c, is equal to the wire cross-sectional area times length times the mass density of copper. Now formula (3.5b) can be rewritten in formula (3.6).

$$I^2 \cdot R \cdot \Delta t = \frac{\pi}{4} d_{wire} \cdot l_{wire} \cdot \rho_{wire} \cdot c_{copper} (T_2 - T_1) \tag{3.6}$$

4. Shielding

To improve the solenoid a magnetic shield is applied. Shielding can be done just with adding a shell of steel (a pipe) on the outside and two cylindrical plates with a hole at both solenoid ends. Adding shields decreases the reluctance at outer solenoid positions.

Reluctance is like electric resistance. A high reluctance means that a high amount of magnetic energy is stored inside. To be sure most energy will be available in the solenoid core the reluctance of the air gap inside the solenoid has to be much higher than reluctance at the outer solenoid positions. For good shielding air gap reluctance has to be at least ten times larger then at outer positions

The reluctance is defined with a standard formula.

$$\Re = \frac{\text{length}}{\text{cross-section}} \cdot \frac{1}{\mu} \tag{4.1}$$

The airgap is a cylinder with diameter $2r_{gap}$ and length l_{gap}. The relative permeability of air is equal to 1, so the absolute permeability is equal to μ_0. Applying this formula in formula (4.1) gives:

$$\Re_{gap} = \frac{l_{gap}}{\pi r_{gap}^{2}} \frac{1}{\mu_0} \tag{4.2}$$

For the cylindrical shell with inside radius r_{shell}, wall-thickness t_{shell} and length l_{shell} formula (4.1) becomes:

$$\Re_{shell} = \frac{l_{shell}}{\pi\left(r_{shell} + t_{shell}\right)^2 - \pi r_{shell}^{2}} \cdot \frac{1}{\mu} \tag{4.3}$$

For the cylindrical plates with hole radius r_{hole}, outside radious r_{plate} and thickness t_{plate} formula (4.1) has to be adapted. The cross-sectional area changes with r and thus the reluctance has to be calculated with infinitesimal steps which are add up together. This is equal to an integral which gives for reluctance:

$$\Re_{plate} = \int_{r_{hole}}^{r_{plate}} \frac{1}{2\pi r \cdot t_{plate} \cdot \mu} dr = \frac{1}{2\pi \cdot t_{plate} \cdot \mu} \left(\ln\left(\frac{r_{plate}}{r_{hole}} \right) \right) \tag{4.4}$$

For a specified solenoid design are all radii known thus the only unknown parameters for the shield are the thicknesses of the components. To create a good shield the reluctance of both shell and washer have to be much smaller then the reluctance of the airgap. In practice a factor 10 is used. Now also maximum reluctance is known thicknesses can be calculated.

5. Model Shaping

5.1 FEMM

To analyse solenoids a finite element method is used. This method is integrated in a program called FEMM. FEMM stands for Finite Element Method Magnetics. This program is developed by Dr. David Meeker of the University of Virginia.
FEMM is developed to solve 2-dimensional time-independent magnetic problems. The Maxwell equations are used to solve these problems. Axi-symmetric problems can also be analysed, which is very handy for cylindrical solenoids.

FEMM is Freeware and can be downloaded at http://femm.foster-miller.net/cgi-bin/efileman/efileman.cgi

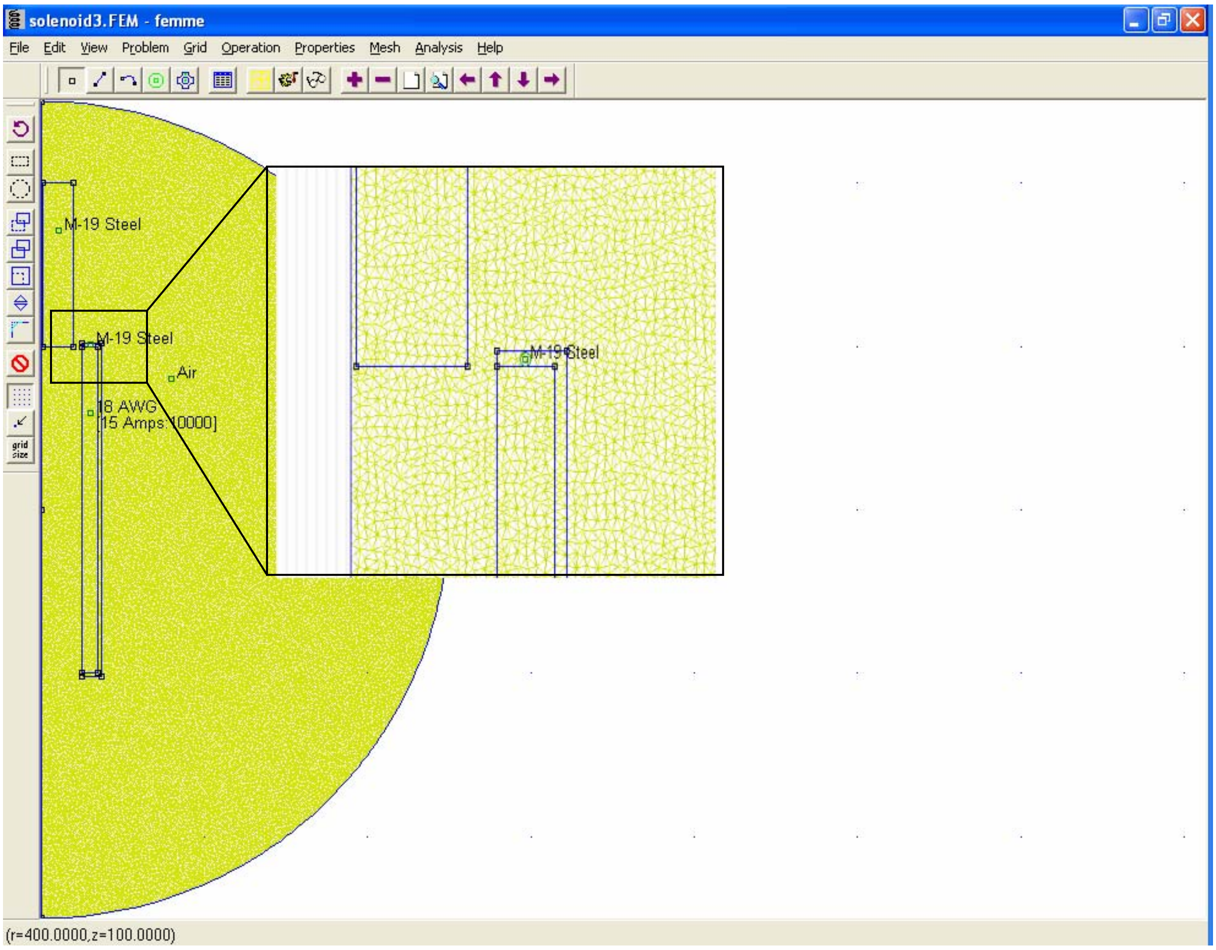

Figure 5.1: Screenshot of FEMM with a solenoid design

Figure 4.1 contains a screenshot of the interface of FEMM. The placed in square is a magnification of the area around the core to show the mesh. By placing nodes en connecting them together lines can be drawn. Almost every form can be created. These forms have to contain closed surfaces. Different properties can be attached to surfaces, like material properties, circuit properties, geometric properties, boundary conditions and mesh conditions.

The program also contains a library with common used materials. This library contains winding-wire, different core materials and air. All relevant material parameters are included, both linear and non-linear.

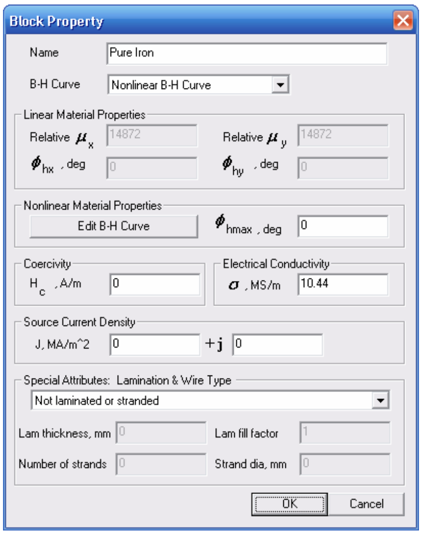

Figure 5.2: Screenshot of material properties

The linear properties contain permeability. The non-linear section contains a table with saturation data, also known as the B-H curve. In figure 4.3 displays the B-H curve of iron. The effects of saturation are clearly visible. Iron begins to saturate at 1.5 Tesla. The user can decide either to solve linear or to solve non-linear in the materials property menu.

In the boundary conditions menu six different boundary conditions can be chosen. Only a mixed boundary condition is used in the solenoid case to approximate an unbounded open space. This is a approximation to simulate the solenoid in free air circumstances in where it looks that there is no boundary. For more information about the other boundary conditions I refer to the FEMM manual [9].

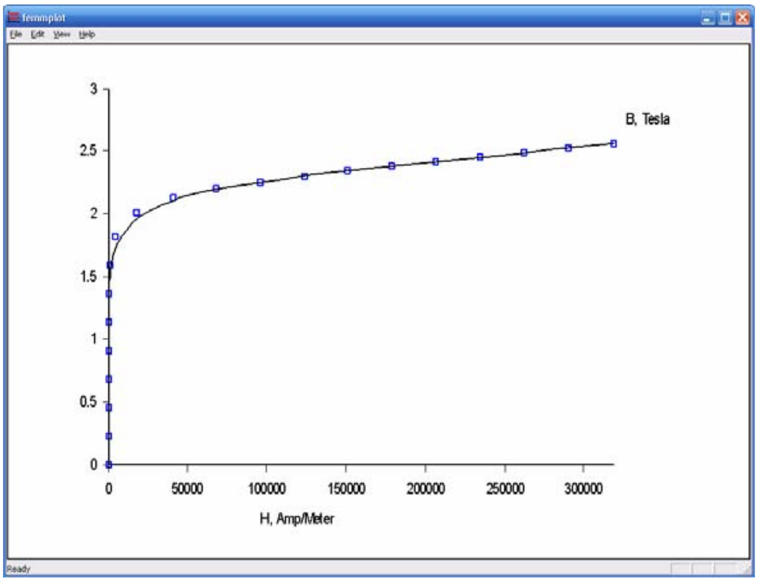

Figure 5.3: B-H curve of iron

When all properties are applied a mesh can be created and the problem can be solved. When the solver is ready, results can be viewed in a new window. Several parameters can be calculated. In the solenoid case only the Lorentz force and magnetic field co-energy are used.

FEMM also contains a post- and pre-processor. It is possible to create scriptfiles and change your model with the pre-processor and to calculate automatically with the postprocessor. With these scriptfiles a loop of calculations can be made with changed conditions. With a pre-processor scriptfile the plunger can be moved automatically with small steps to calculate energy-stroke data for example. The programming language which is used in the scriptfiles is lua. More information and a detailed documentation about this language can be found at www.lua.org.

5.2 Solving method

A modelled RoboCup solenoid is a time independent magnetostatic problem. In This situation following equation holds for flux density B.

$$\nabla \bullet B = 0 \tag{5.1}$$

And for field intensity (H):

$$\nabla \times H = J \tag{5.2}$$

When using lineair media, flux density B must satisfy:

$$B = \mu H \tag{5.3}$$

And in non-linear (saturated) media permeability satisfies:

$$\mu = \frac{B}{H(B)} \tag{5.4}$$

FEMM goes about finding a field that satisfies equation (5.1) until (5.3) via a magnetic vector potential (A) approach.

Flux density is related to this vector with:

$$B = \nabla \times A \tag{5.5}$$

Equation (5.5) always satisfies equation (5.1) and now equation (5.2) can be rewritten.

$$\nabla \times \left(\frac{1}{\mu(B)} \nabla \times A \right) = J \tag{5.6}$$

With this equation the vector a can be calculated. Vector A contains 3 values in a 3D problem, but in a 2D axi-symmetric problem 2 out of 3 are equal to zero. After vector A is known flux density and field intensity can be calculated by differentiating and substituting in the upper equations.

5.3 Magnetic Field Energy Calculations:

When the values for B and H are know many properties of the solenoid can be calculated. In our case only the energy is relevant. For energy is known that:

$$W_c = \int \left(\int_0^H B(H')dH' \right) dV \tag{5.7}$$

After calculating the co-energy for a number of positions within the solenoid force estimation can be done with formula (5.8).

$$F = \frac{W_c(x+\delta) - W_c(x)}{\delta} \tag{5.8}$$

When δ -> 0 this is mathematical equal to differentiating F with respect to place

6. Solenoid Tests

Because the magnetic field force determines the amount of kinetic energy, it is important to know how force changes by changing several parameters. There are two parameters which can be adapted easily, current, amount of core material and material used. This should be proportional for a infinitely long solenoid according to chapter 3.

6.1 Current

At first a free chosen solenoid is modelled in FEMM. This solenoid has 10000 turns of 18 AWG wire, see also appendix 1. The core contains an bar of M19 steel with radius 20 [mm]. Between core and coil is a gap of 1[mm] and they both have a length of respectively 100[mm] and 200[mm]. The solenoid is shielded with a shell of 2 mm thickness.

For the boundary an asymptotic boundary conditions is chosen to simulate an unbounded open space to model the solenoid in a limited area with open space behaviour.

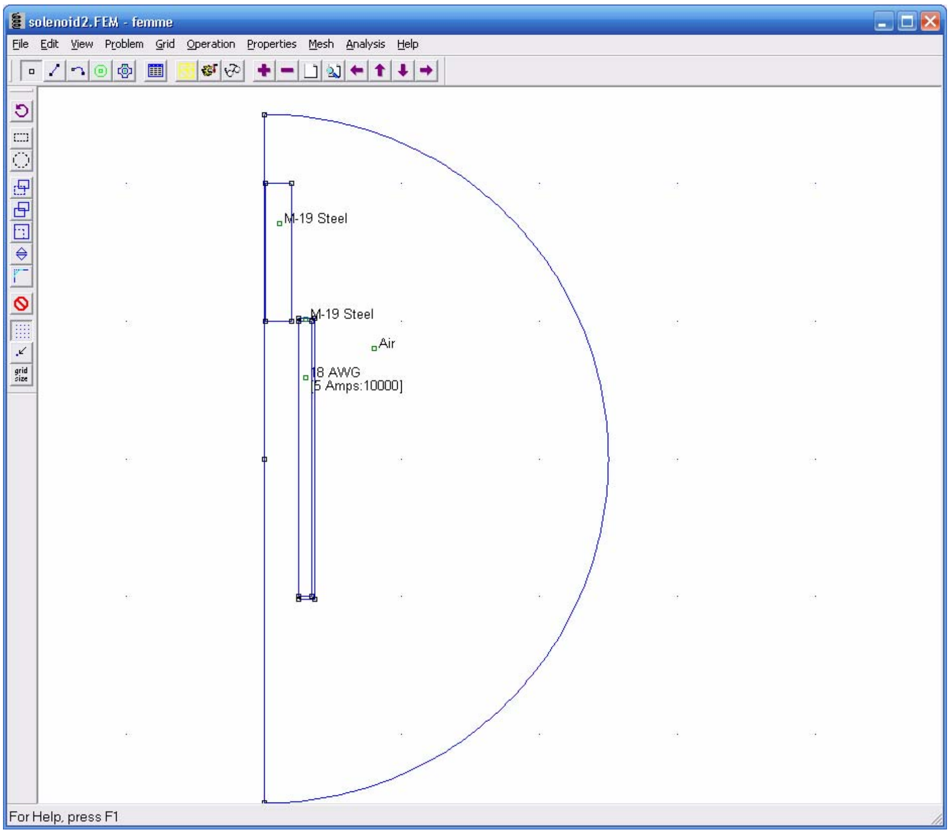

Figure 6.1: The modelled solenoid

The model is simulated with a current of 5, 10, 15 [A]. The results are plot in figure 6.2. The dotted pink line represents the 10 [A] current force/stroke line divided by 2, which should be equal to the 5 [A] current when force is proportional to current. This holds when the largest part of the core is inside the coil ($-100 \leq stroke \leq 100$), but not for larger strokes due to side effects.

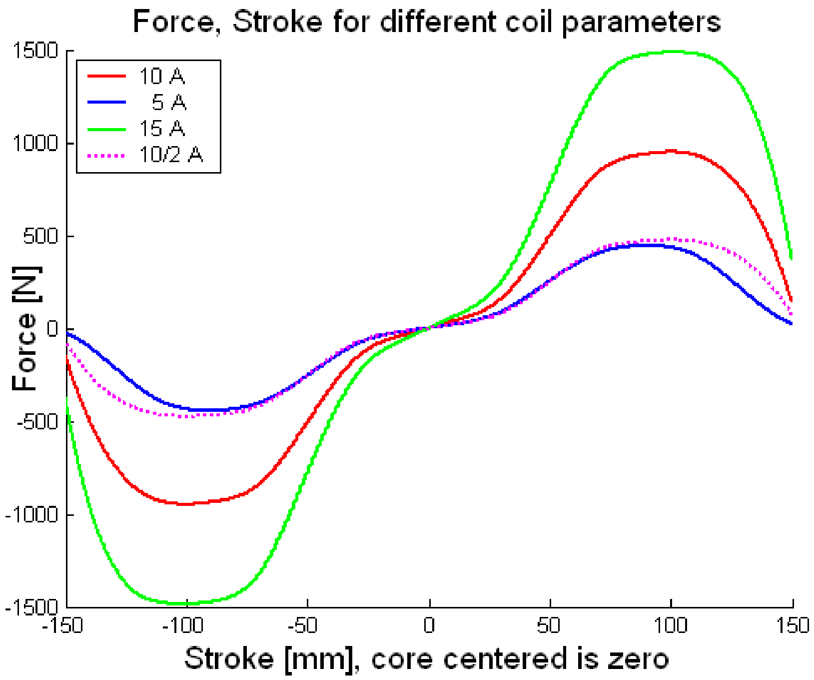

Figure 6.2: Force, stroke for different currents

6.2 *Amount of Material*

A similar test is done for the amount of material. It is the same solenoid as in the previous test, but now with a fixed current and with variable core dimensions. Current is set to 10 [A] and results are calculated for a full and a half size core. The results are plot in figure 6.3 with the results of the previous test. The outcome is clear, the force in the inside region ($-100 \le stroke \le 100$) with a half core is the same as the force with a full core but half current thus force is also proportional to amount of material.

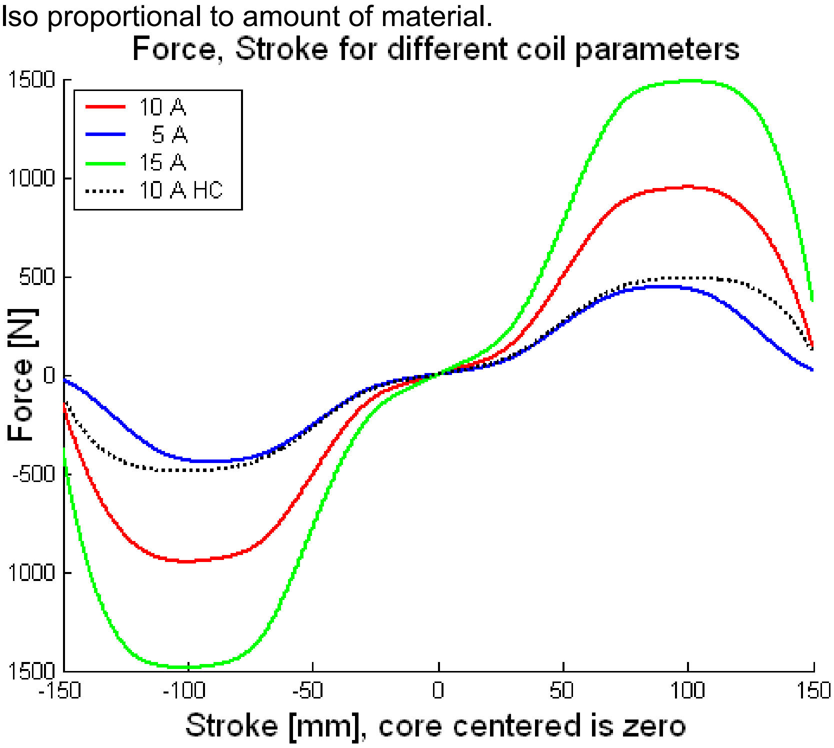

Figure 6.3: Force, stroke for different cores

7. Final design

As seen in previous chapters there are some parameters that should be taken into account. The most important parameters are temperature, the time constant and availability of components for the solenoid circuit board. These are explained In chapter 3.

The time constant is the major parameter for the RoboCup solenoid. To keep this constant low, inductance must be kept low and a minimal wire thickness should be used without melting. To create enough force high current is needed through these thin wires. This results in a very high voltage because of Ohm's law.

A large capacitor is needed as an energy buffer. These capacitors become more expensive as rated voltage increases. Above 450V are suitable capacitors not anymore available. So the maximum voltage is set to 450V for our solenoid.

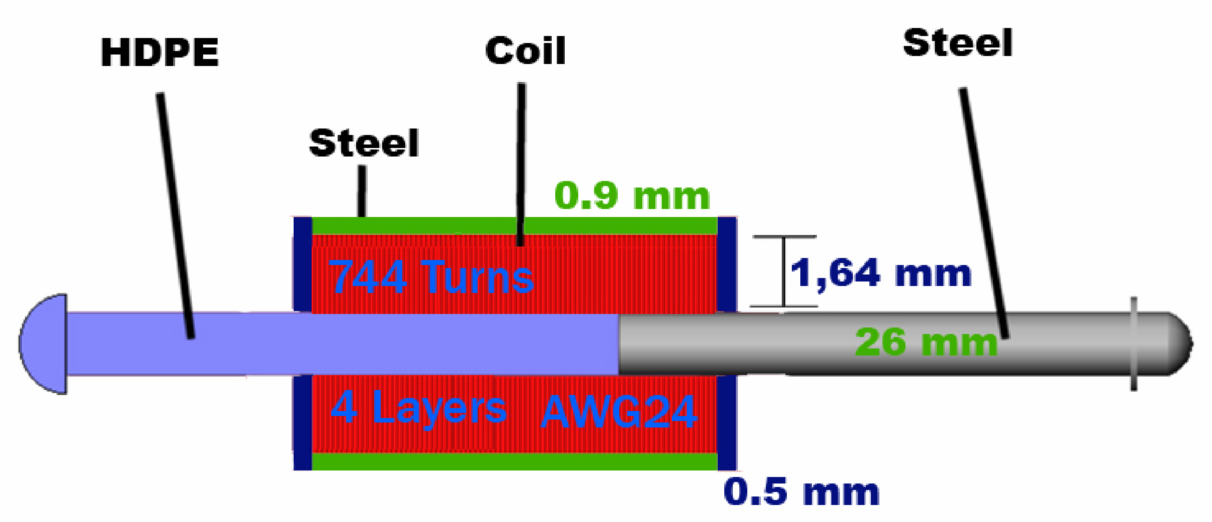

Figure 7.1 Solenoid

To create at least 42.5 [J] at full power the number of turns is set to 744 in 4 layers with current of 68 [A]. This is the result of optimisation in Femm. The maximum voltage may not raise the 450 [V] barrier, because there are no electric components available above that voltage. Resistance is kept high, by using less windings with a high current, to create a low time constant. But heat generation is also taken in account.

Each layer contains 186 turns with a winding factor of 0.95. AWG 24 wire is used thus the coil-resistance becomes 5.56 [Ohm] (See appendix [1]). Self-Inductance can be calculated with formula (3.1). This gives 3790 [uH]. The time constant L/R is thus 0.68 [ms]. The solenoid length is 10 [cm], due to the maximum stroke set by the Robocup Rules. All other dimensions are shown in figure 7.1.

A bar of 1018 steel with a HDPE bar attached is used with a diameter of 26 [mm] as a core. 1018 steel is chosen because it has the highest magnetic performance in FEMM. The B-H curve can be found in figure 7.3. HDPE is chosen because it has the right density to give the complete bar an equal mass with respect to the ball. Between the coil and core is an little gap of 1mm to reserve space for a pipe or something similar to wind the coil on to.

The shield thickness is calculated with the reluctance formula's in chapter 4. A higher thickness then needed is used for the (blue) endplates, because otherwise they were very thin and fragile. The (green) outer shell reluctance is equivalent to the end plates when a thickness of 0.9 [mm] is used.

A FEMM model is made with this design. The final solenoid graph is shown in figure 7.1. The average plunger velocity is 9.09 [m/s] thus the core travels from end to centre in 11 milliseconds with constant current thus one shooting action uses 336 [J]. The maximum plunger speed becomes 14.12 [m/s] and the ball reaches 10.93 [m/s] according to the energy calculation in chapter 2.1

A remark has to be made, because all simulations are done with constant current. It is the average current supplied by the circuit. But In practice current varies in time because of the time constant so the final plunger speed is in practice a little bit lower.

This solenoid is not able to reverse it's movement, because the plunger is in a dead point after a shot. Thus another measure is required to bring the solenoid after actuation back. The easiest and cheapest way is to connect a little spring at the steel bar's end. The spring should have a spring constant which is just high enough to overcome friction.

An overview with all solenoid properties can be found in table 7.1.

Solenoid Properties	
Energy consumption per shot [J]	336
Inductance [mH]	37.9
Capacitor [mF]	4.7
Transistor Switch	International Rectifier IRG4PC50FD
Windings per layer [-]	186
Layers [-]	4
Winding factor [-]	0.95
Wire Size [AWG]	24
Solenoid Length [mm]	100
Coil Resistance [Ohm]	5.56
Core Diameter [mm]	26
Core Material [-]	1018 Steel and HDPE
Shielding Shell Thickness [mm]	0.9
Shielding End Plates Thickness [mm]	0.5
Theoretical Ball Speed [m/s]	10.9
Voltage [V]	450

Table 7.: Solenoid Properties

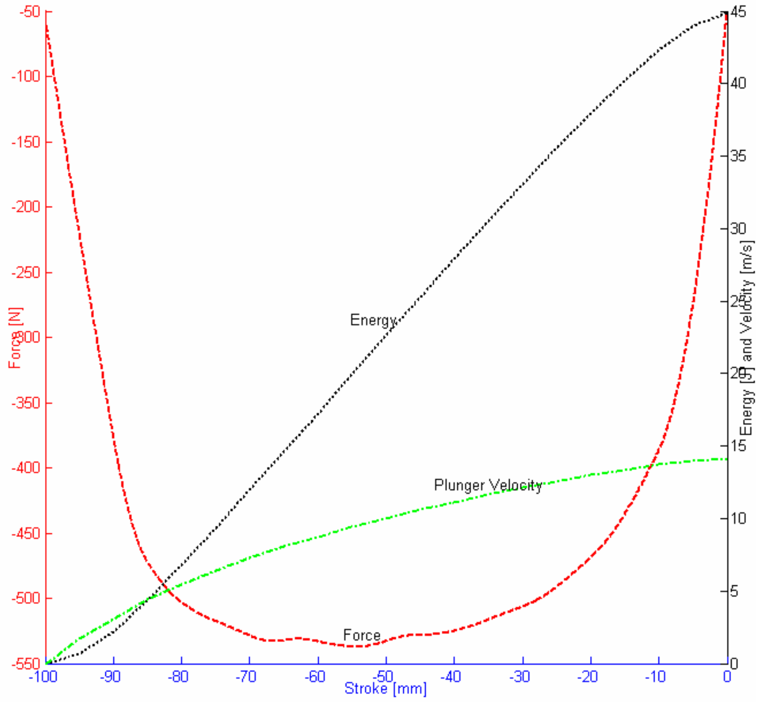

Figure 7.2: Final Solenoid diagram

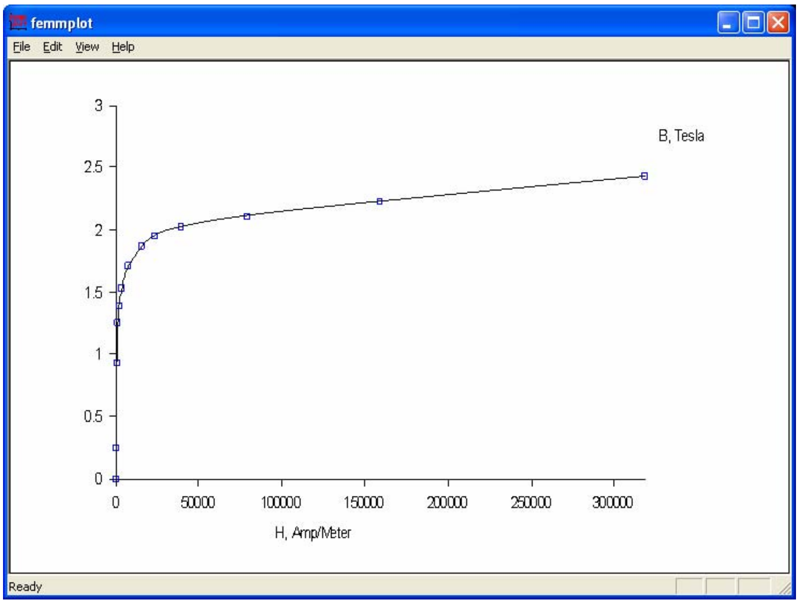

Figure 0.3: B-H Curve of 1018 steel

8. Circuit Design

The in the previous chapter designed solenoid needs a very fast switching circuit otherwise the solenoid will melt due to generated heat. Active cooling is not an option because the solenoid has a Power of 30 kW. The circuit must also contain a capacitor to slowly store energy in idle state and release it fast over the solenoid. An adapted RLC circuit (Figure 8.1) is used and analyzed in Pspice.

The first component is a dc/dc converter to convert the available battery power to 450 volt.

The Second component is a resistance which determines the load speed of the capacitor. The capacitor has a capacity of 4.7 [mF] and is rated for 450V. This is enough to shoot once at full power and once at half power without reloading. It takes 10 seconds to reload after one full power shot.

Parallel to the capacitor is the solenoid, modeled with a coil and a resistance with the values of the RoboCup solenoid.

The solenoid is connected to a transistor which is controlled by a pulse source. The transistor can handle high currents and is manufactured by the International Rectifier Group, item nr IRG4PC50FD.When the source-signal is high the transistor is closed (solenoid is activated), when low it is open (solenoid is idle). The transistor opens in 380 [ns] and closes in 70 [ns]. Specification sheet is available in attachment 2.

Parallel to the solenoid is a diode with a resistance to “catch” the back-current generated when turning of the solenoid (see also paragraph 3.5).

Analysis is done in PSpice. At t=0 is the capacitor empty and is switch open. At t=14.1 is the capacitor full and the switch closes. In figure 8.2 is the current applied on the solenoid shown. Figure 8.3 contains the load diagram of the capacitor.

In figure 8.3 can be seen that the capacitor is filled in 14 seconds, because the current over the capacitor is almost zero. Then a shot is simulated. The applied current on the solenoid is shown in figure 8.2. The start- and endeffects of the time constant are present after applying current and after removing the current. When the shot starts, the capacitor starts immediately to reload after 7 seconds is it filled again. But when there is not enough time to reload there is enough energy available to shoot one more time at half power.

The solenoid shooting force can also be modulated with this circuit when Pulse Width Modulation is applied to the pulse source. With PWM current can be turned off at every moment and the solenoid stops with generating energy. So the plunger will not accelerate anymore.

The circuit with capacitor should be placed in a “black box” to guarantee safety for all. It is very dangerous because of high voltage and high current. The capacitor contains also a huge amount of electric energy. People can get injured or be killed when touching the wrong parts, so this safety measure is required.

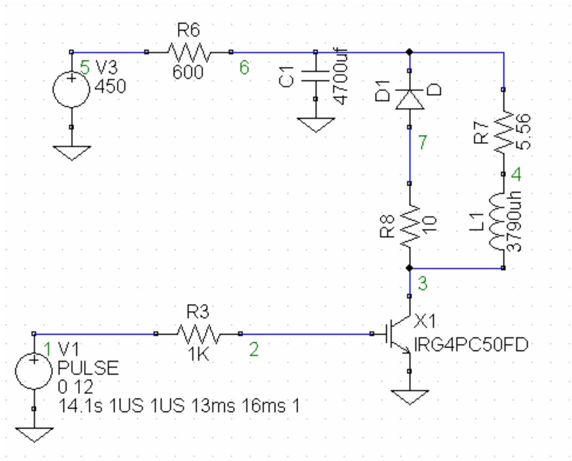

Figure 8.1: Solenoid circuit design

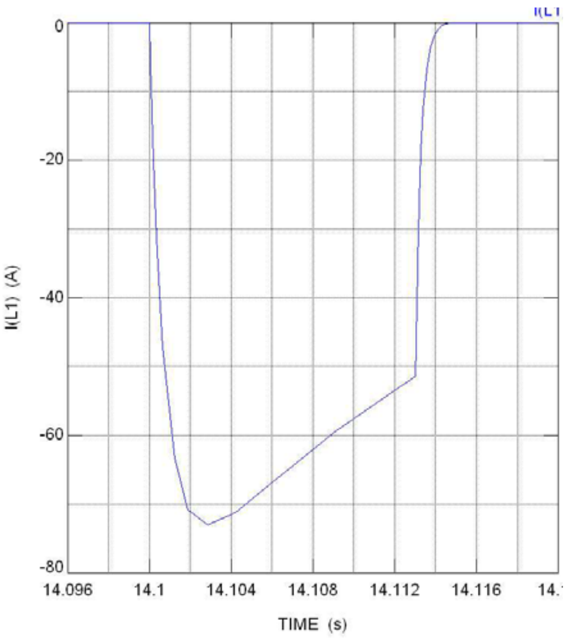

Figure 8.2: Current Applied on Solenoid

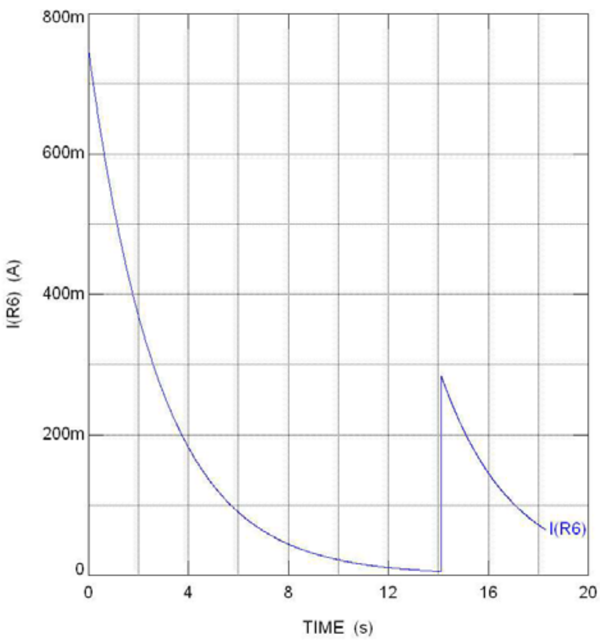

Figure 8.3: Capacitor Load

Conclusion

The solenoid is the best option for a RoboCup shooting device. It is powerful, not very expensive, robust, lightweight and small. It is also able to modulate shooting power by applying pulse width modulation on the pulse source in the control circuit.

It is the best option but also the most dangerous one because of the use of high power electric components. This should also be taken into account, because people can get seriously injured. But when good safety measures are applied, by placing the dangerous components in a shielded box, nobody would get harmed.

The shooting device is also ready for the near future in the RoboCup competition. It's expected (and one of our goals) that in the near future robots can pass to other robots. Power modulation and thus different ball speeds are required for good passing. Power modulation is possible with the solenoid, so this should not be a problem.

The design made in chapter 7 is able to meets also Tech United's requirement to shoot with 10 m//s and is, together with the electric circuit, ready to be build.

Further research recommendations:

- To build this prototype
- Research controllability

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List of Symbols

$\ddot{x}$	Acceleration [m/s^2]
x	Distance [m]
K	Spring Constant [N/m]
m	Mass [Kg]
t	Thickness [m]
$m_{plunger}$	Plunger Mass [Kg]
$v_{plunger}$	Plunger Velocity [m/s]
m_{ball}	Ball Mass [Kg]
v_{ball}	Ball Velocity [m/s]
J_{ball}	Moment of inertia of Ball [Kg m^2]
ω	Rotational Speed [rad/s]
r_{ball}	Ball radius [m]
$E_{solenoid}$	Solenoid Energy [J]
L	Self-Inductance [mH]
N	Number of Turns [-]
R_1	Inner Coil radius [m]
R_2	Outer Coil radius [m]
l_{coil}	Coil length [l]
l_{wire}	Wire length [l]
R	Resistance [Ohm]
ρ	Specific Resistance [Ohm/m]
F	Force [N]
B	Flux Density [T]
I	Current [A]
l	Length [l]
P	Power [W]
Q	Generated Heat [J]
m_c	Copper Mass [Kg]
c	Specified heat coefficient [J/Kg/K]
T_2	Begin Temperature [K]
T_1	End Temperature [K]
d_{wire}	Wire Diameter [m]
ρ_{wire}	Density Wire [Kg/m^3]
c_{copper}	Specified heat coefficient copper [J/Kg/K]
$\Re$	Reluctance [AN]
$\Re_{gap}$	Airgap Reluctance [AN[
$\Re_{shell}$	Shell Reluctance [AN]
$\Re_{plate}$	Plate Reluctance [AN]
μ	Permeability [Hm^{-1}]
μ_0	Permeability of vacuum [Hm^{-1}]
μ_r	Relative permeability [Hm^{-1}]
l_{gap}	Airgap length [m]
r_{gap}	Airgap radius [m]
l_{shell}	Shell length [m]
r_{shell}	Shell radius [m]

t_{shell}	Shell Thickness [m]
t_{plate}	Endplate thickness [m]
r_{hole}	Hole radius [m]
r_{plate}	Endplate radius [m]
H	Field Strength [A/m]
J	Current Density [A/m^2]
A	Area [m^2]
W_c	Magnetic Field Co-Energy

Attachment 1: Resistance Values for AWG wire sizes

14-23 AWG

AWG	Bare Copper				Area Circ. Mils NOM	Recom. Winding Tension (grams)	Heavy Build		
	Diameter (inches)		Resistance* (ohms/1000 ft)				Min Increase (inches)	Overall Dia. (inches)	
	NOM	MIN MAX	NOM	MIN MAX				NOM	MIN MAX
14	.0641	.0635 .0347	2.524	2.477 2.572	4,109	17,690	.0032	.0675	.0667 .0682
15	.0571	.0565 .0577	3.181	3.115 3.249	3,260	14,061	.0030	.0602	.0595 .0609
16	.0508	.0530 .0513	4.019	3.941 4.099	2,581	10,886	.0029	.0539	.0532 .0545
17	.0453	.0448 .0458	5.054	4.944 5.167	2,052	8,618	.0028	.0482	.0476 .0488
18	.0403	.0399 .0407	6.386	6.261 6.514	1,624	6,804	.0026	.0431	.0425 .0437
19	.0359	.0355 .0363	8.047	7.871 8.229	1,289	5,443	.0025	.0386	.0380 .0391
20	.0320	.0317 .0323	10.13	9.941 10.32	1,204	4,354	.0023	.0346	.0340 .0351
21	.0285	.0282 .0288	12.77	12.50 13.04	812.3	3,447	.0022	.0309	.0304 .0314
22	.0253	.0250 .0256	16.20	15.82 16.59	640.1	2,767	.0021	.0276	.0271 .0281
23	.0226	.0224 .0228	20.31	19.95 20.67	510.8	2,177	.0020	.0249	.0244 .0253

24-33 AWG

AWG	Bare Copper				Area Circ. Mils NOM	Recom. Winding Tension (grams)	Heavy Build		
	Diameter (inches)		Resistance* (ohms/1000 ft)				Min Increase (inches)	Overall Dia. (inches)	
	NOM	MIN MAX	NOM	MIN MAX				NOM	MIN MAX
24	.0201	.0199 .0202	25.670	25.417 26.189	404	1,450	.0019	.0233	.0218 .0227
25	.0179	.0177 .0180	32.368	32.009 33.104	320	1,175	.0018	.0199	.0195 .0203
26	.0159	.0157 .0159	41.023	40.512 42.076	253	950	.0017	.0178	.0174 .0182
27	.0142	.0141 .0143	51.433	50.717 52.167	202	770	.0016	.0161	.0157 .0164
28	.0126	.0125 .0127	65.325	64.302 66.376	159	630	.0016	.0144	.0141 .0147
29	.0113	.0112 .0114	81.220	79.801 82.679	128	540	.0015	.0130	.0127 .0133
30	.0100	.099 .0101	103.71	101.67 105.82	100	400	.0014	.0116	.0113 .0119
31	.0089	.088 .0090	130.9	128.0 133.90	79.21	315	.0013	.0105	.0101 .0108
32	.0080	.0079 .0081	162.0	158.1 166.20	64.00	270	.0012	.0095	.0091 .0098
33	.0071	.0070 .0072	205.7	200.1 211.7	50.41	225	.0011	.0084	.0081 .0088

Attachment 2: Transistor Data Sheet

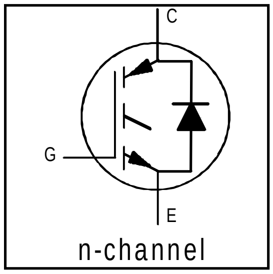
PD 91469B

International
IOR Rectifier

IRG4PC50FD

INSULATED GATE BIPOLAR TRANSISTOR WITH ULTRAFAST SOFT RECOVERY DIODE

Fast CoPack IGBT



V_{CES} = 600V

$V_{CE(on)\,typ.}$ = 1.45V

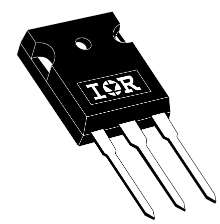
@V_{GE} = 15V, I_C = 39A

Features

- Fast: Optimized for medium operating frequencies (1-5 kHz in hard switching, >20 kHz in resonant mode).
- Generation 4 IGBT design provides tighter parameter distribution and higher efficiency than Generation 3
- IGBT co-packaged with HEXFRED™ ultrafast, ultra-soft-recovery anti-parallel diodes for use in bridge configurations
- Industry standard TO-247AC package

Benefits

- Generation -4 IGBT's offer highest efficiencies available
- IGBT's optimized for specific application conditions
- HEXFRED diodes optimized for performance with IGBT's . Minimized recovery characteristics require less/no snubbing
- Designed to be a "drop-in" replacement for equivalent industry-standard Generation 3 IR IGBT's



TO-247AC

Absolute Maximum Ratings

	Parameter	Max.	Units
V_{CES}	Collector-to-Emitter Voltage	600	V
I_C @ T_C = 25°C	Continuous Collector Current	70	A
I_C @ T_C = 100°C	Continuous Collector Current	39	
I_{CM}	Pulsed Collector Current ①	280	
I_{LM}	Clamped Inductive Load Current ②	280	
I_F @ T_C = 100°C	Diode Continuous Forward Current	25	
I_{FM}	Diode Maximum Forward Current	280	
V_{GE}	Gate-to-Emitter Voltage	± 20	V
P_D @ T_C = 25°C	Maximum Power Dissipation	200	W
P_D @ T_C = 100°C	Maximum Power Dissipation	78	
T_J T_{STG}	Operating Junction and Storage Temperature Range	-55 to +150	°C
	Soldering Temperature, for 10 sec.	300 (0.063 in. (1.6mm) from case)	
	Mounting Torque, 6-32 or M3 Screw.	10 lbf•in (1.1 N•m)	

Thermal Resistance

	Parameter	Min.	Typ.	Max.	Units
$R_{\theta JC}$	Junction-to-Case - IGBT	------	------	0.64	°C/W
$R_{\theta JC}$	Junction-to-Case - Diode	------	------	0.83	
$R_{\theta CS}$	Case-to-Sink, flat, greased surface	------	0.24	------	
$R_{\theta JA}$	Junction-to-Ambient, typical socket mount	-----	-----	40	
Wt	Weight	------	6 (0.21)	------	g (oz)

12/30/00

Electrical Characteristics @ T_J = 25°C (unless otherwise specified)

	Parameter	Min.	Typ.	Max.	Units	Conditions	
$V_{(BR)CES}$	Collector-to-Emitter Breakdown Voltage③	600	----	----	V	V_{GE} = 0V, I_C = 250µA	
$\Delta V_{(BR)CES}/\Delta T_J$	Temperature Coeff. of Breakdown Voltage	----	0.62	----	V/°C	V_{GE} = 0V, I_C = 1.0mA	
$V_{CE(on)}$	Collector-to-Emitter Saturation Voltage	----	1.45	1.6	V	I_C = 39A	V_{GE} = 15V
		----	1.79	----		I_C = 70A	See Fig. 2, 5
		----	1.53	----		I_C = 39A, T_J = 150°C	
$V_{GE(th)}$	Gate Threshold Voltage	3.0	----	6.0		V_{CE} = V_{GE}, I_C = 250µA	
$\Delta V_{GE(th)}/\Delta T_J$	Temperature Coeff. of Threshold Voltage	----	-14	----	mV/°C	V_{CE} = V_{GE}, I_C = 250µA	
g_{fe}	Forward Transconductance ④	21	30	----	S	V_{CE} = 100V, I_C = 39A	
I_{CES}	Zero Gate Voltage Collector Current	----	----	250	µA	V_{GE} = 0V, V_{CE} = 600V	
		----	----	6500		V_{GE} = 0V, V_{CE} = 600V, T_J = 150°C	
V_{FM}	Diode Forward Voltage Drop	----	1.3	1.7	V	I_C = 25A	See Fig. 13
		----	1.2	1.5		I_C = 25A, T_J = 150°C	
I_{GES}	Gate-to-Emitter Leakage Current	----	----	±100	nA	V_{GE} = ±20V	

Switching Characteristics @ T_J = 25°C (unless otherwise specified)

	Parameter	Min.	Typ.	Max.	Units	Conditions		
Q_g	Total Gate Charge (turn-on)	----	190	290	nC	I_C = 39A		
Qge	Gate - Emitter Charge (turn-on)	----	28	42		V_{CC} = 400V	See Fig. 8	
Q_{gc}	Gate - Collector Charge (turn-on)	----	65	97		V_{GE} = 15V		
$t_{d(on)}$	Turn-On Delay Time	----	55	----	ns	T_J = 25°C		
t_r	Rise Time	----	25	----		I_C = 39A, V_{CC} = 480V		
$t_{d(off)}$	Turn-Off Delay Time	----	240	360		V_{GE} = 15V, R_G = 5.0Ω		
t_f	Fall Time	----	140	210		Energy losses include "tail" and		
E_{on}	Turn-On Switching Loss	----	1.5	----	mJ	diode reverse recovery.		
E_{off}	Turn-Off Switching Loss	----	2.4	----		See Fig. 9, 10, 11, 18		
E_{ts}	Total Switching Loss	----	3.9	5.0				
$t_{d(on)}$	Turn-On Delay Time	----	59	----	ns	T_J = 150°C,	See Fig. 9, 10, 11, 18	
t_r	Rise Time	----	27	----		I_C = 39A, V_{CC} = 480V		
$t_{d(off)}$	Turn-Off Delay Time	----	400	----		V_{GE} = 15V, R_G = 5.0Ω		
t_f	Fall Time	----	260	----		Energy losses include "tail" and		
E_{ts}	Total Switching Loss	----	6.5	----	mJ	diode reverse recovery.		
L_E	Internal Emitter Inductance	----	13	----	nH	Measured 5mm from package		
C_{ies}	Input Capacitance	----	4100	----	pF	V_{GE} = 0V		
C_{oes}	Output Capacitance	----	250	----		V_{CC} = 30V	See Fig. 7	
C_{res}	Reverse Transfer Capacitance	----	49	----		f = 1.0MHz		
t_{rr}	Diode Reverse Recovery Time	----	50	75	ns	T_J = 25°C	See Fig.	
		----	105	160		T_J = 125°C	14	I_F = 25A
I_{rr}	Diode Peak Reverse Recovery Current	----	4.5	10	A	T_J = 25°C	See Fig.	
		----	8.0	15		T_J = 125°C	15	V_R = 200V
Q_{rr}	Diode Reverse Recovery Charge	----	112	375	nC	T_J = 25°C	See Fig.	
		----	420	1200		T_J = 125°C	16	di/dt 200A/µs
$di_{(rec)M}/dt$	Diode Peak Rate of Fall of Recovery	----	250	----	A/µs	T_J = 25°C	See Fig.	
	During t_b	----	160	----		T_J = 125°C	17	

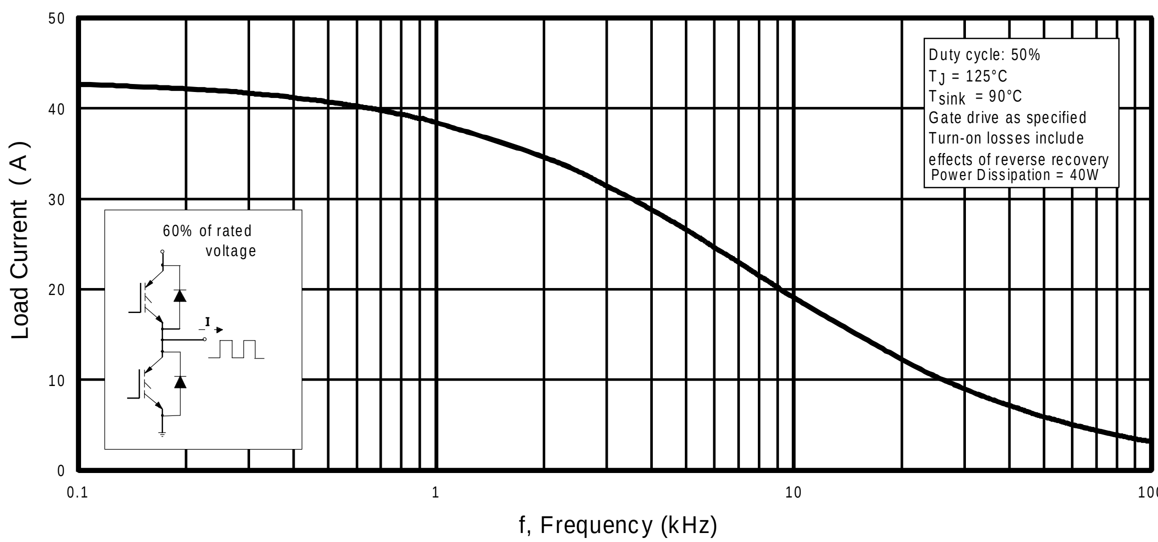


Fig. 1 - Typical Load Current vs. Frequency
(Load Current = I_{RMS} of fundamental)

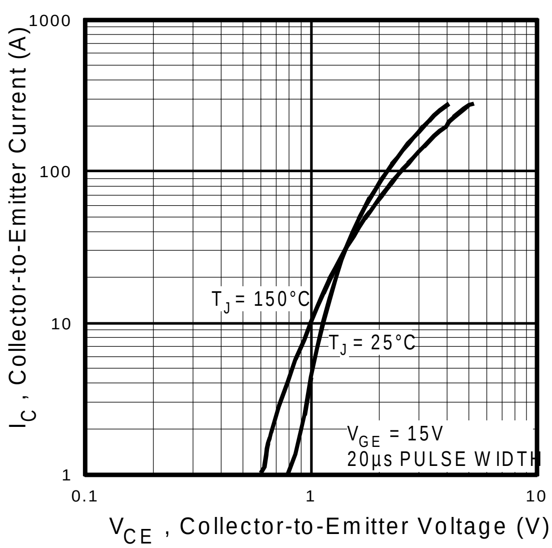


Fig. 2 - Typical Output Characteristics

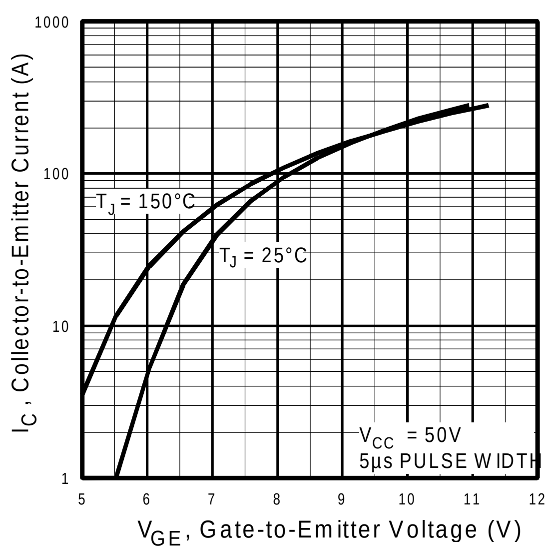


Fig. 3 - Typical Transfer Characteristics

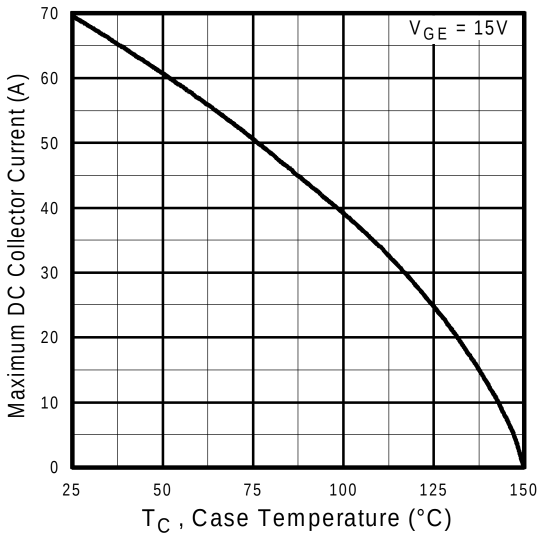


Fig. 4 - Maximum Collector Current vs. Case Temperature

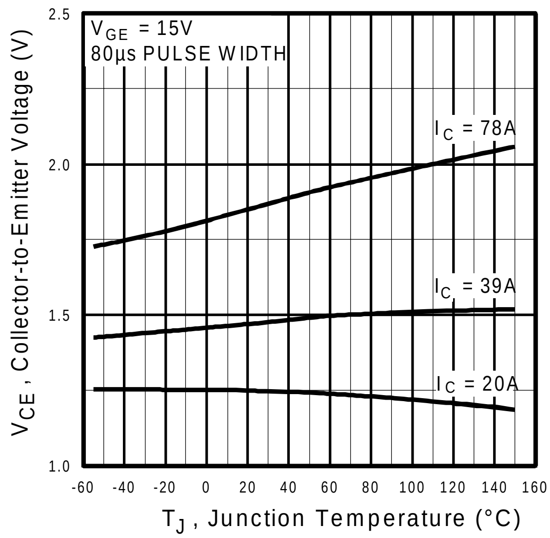


Fig. 5 - Typical Collector-to-Emitter Voltage vs. Junction Temperature

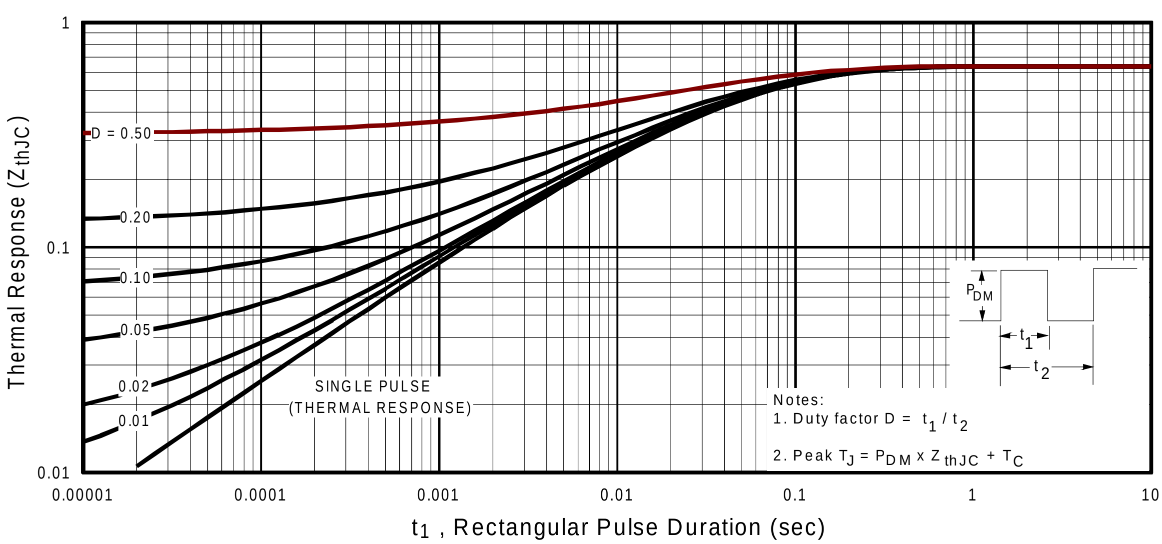


Fig. 6 - Maximum IGBT Effective Transient Thermal Impedance, Junction-to-Case

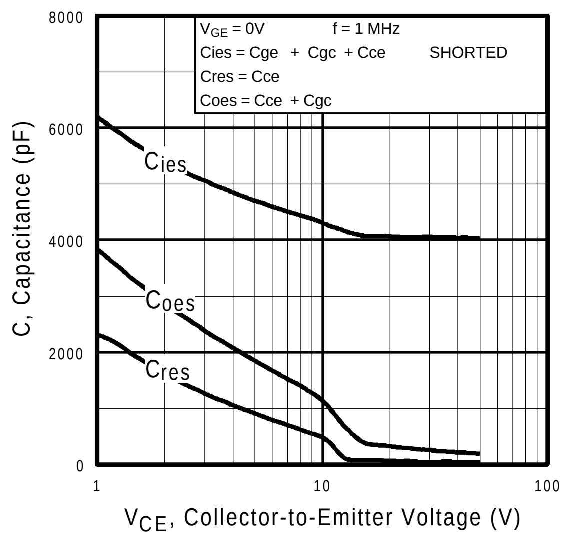


Fig. 7 - Typical Capacitance vs. Collector-to-Emitter Voltage

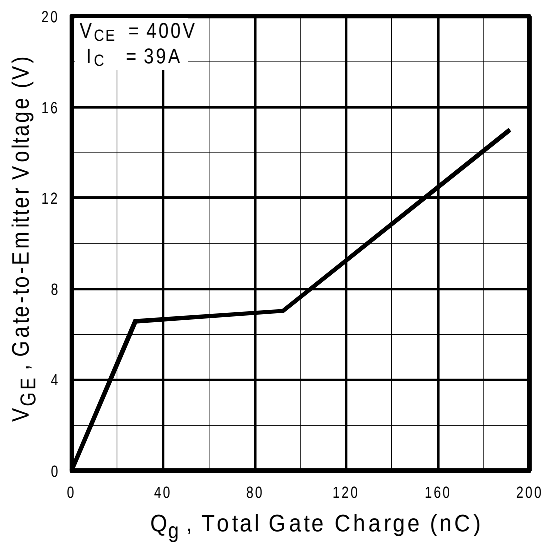


Fig. 8 - Typical Gate Charge vs. Gate-to-Emitter Voltage

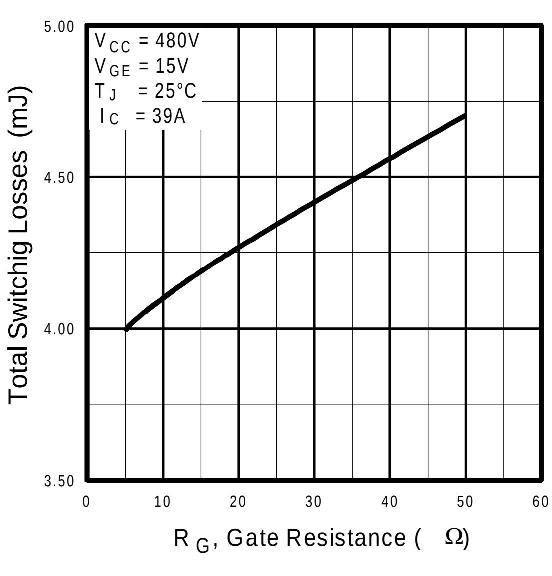


Fig. 9 - Typical Switching Losses vs. Gate Resistance

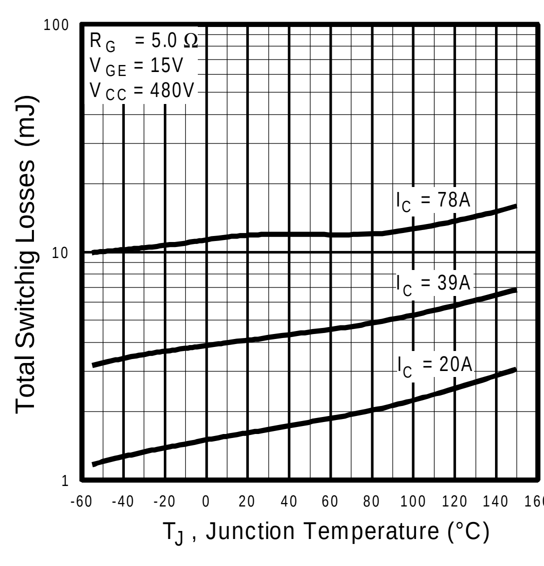


Fig. 10 - Typical Switching Losses vs. Junction Temperature

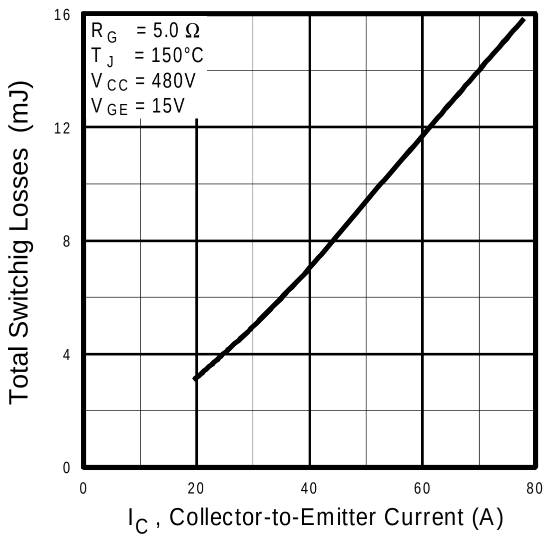


Fig. 11 - Typical Switching Losses vs. Collector-to-Emitter Current

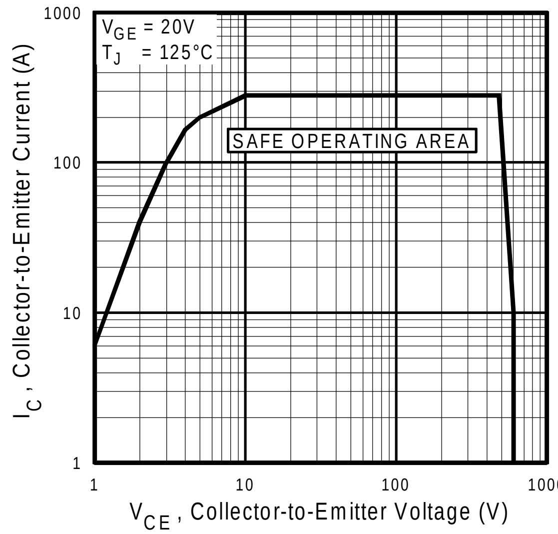


Fig. 12 - Turn-Off SOA

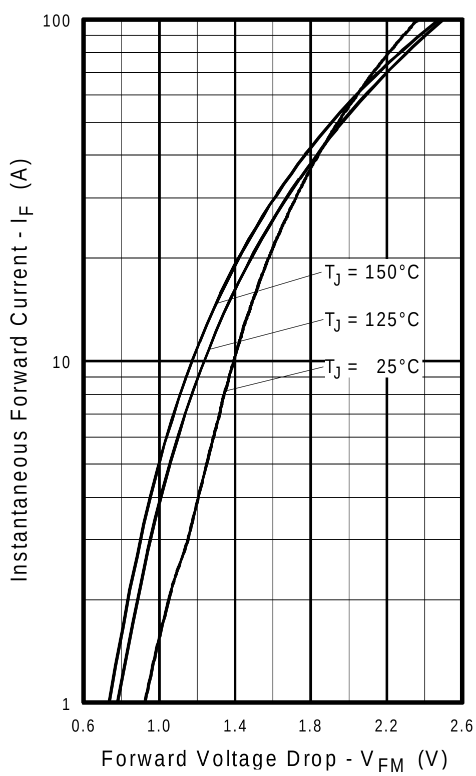


Fig. 13 - Maximum Forward Voltage Drop vs. Instantaneous Forward Current

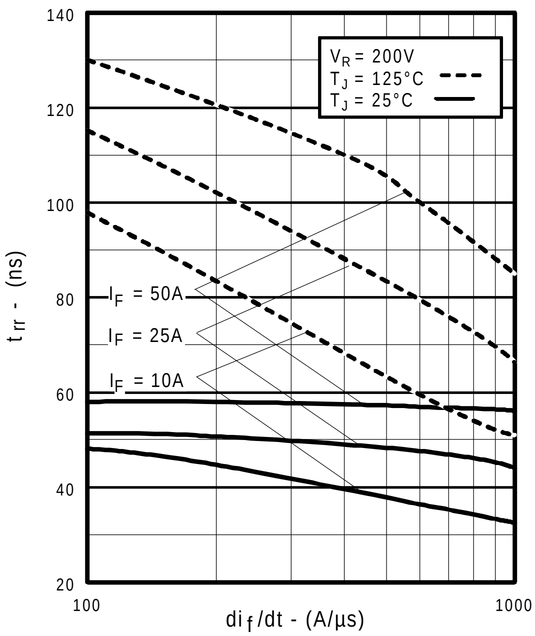


Fig. 14 - Typical Reverse Recovery vs. di_f/dt

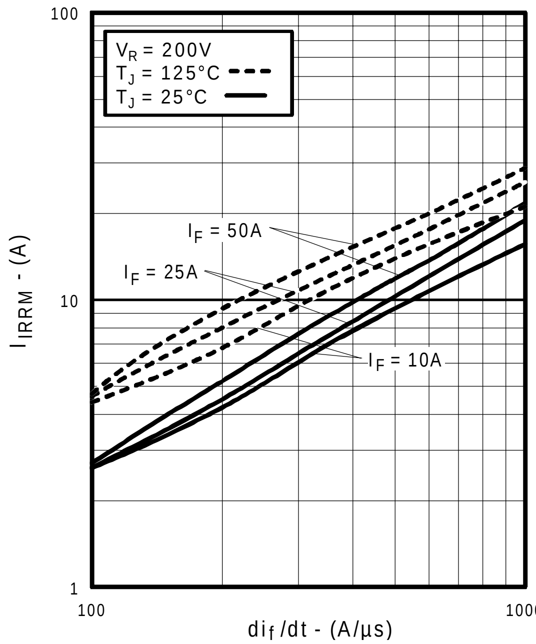


Fig. 15 - Typical Recovery Current vs. di_f/dt

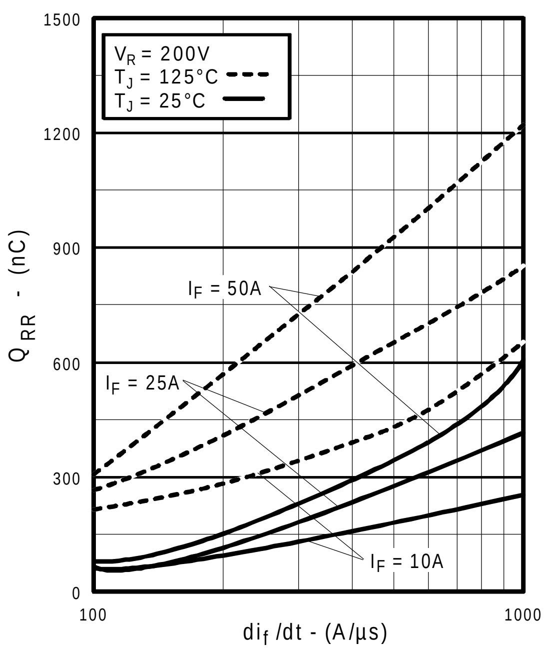


Fig. 16 - Typical Stored Charge vs. di_f/dt

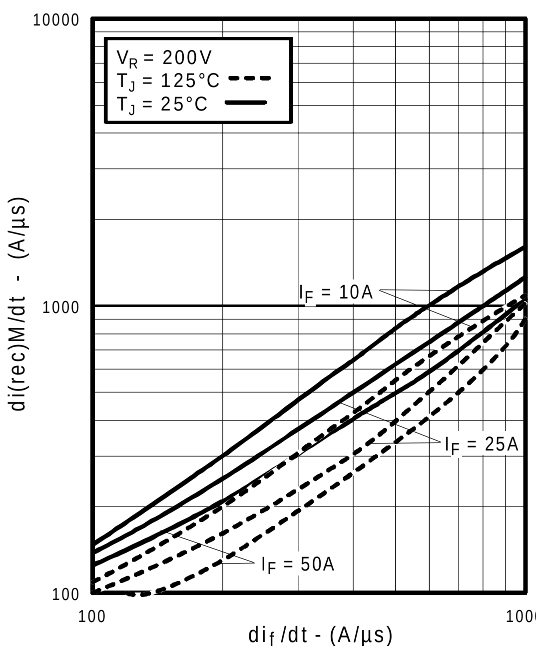


Fig. 17 - Typical $di_{(rec)M}/dt$ vs. di_f/dt

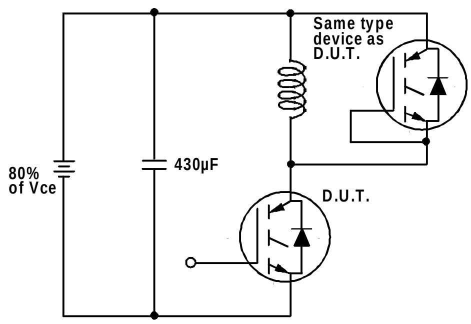


Fig. 18a - Test Circuit for Measurement of I_{LM}, E_{on}, $E_{off(diode)}$, t_{rr}, Q_{rr}, I_{rr}, $t_{d(on)}$, t_r, $t_{d(off)}$, t_f

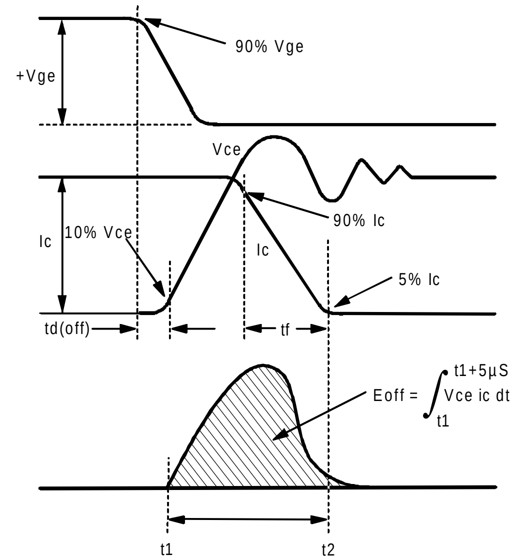


Fig. 18b - Test Waveforms for Circuit of Fig. 18a, Defining E_{off}, $t_{d(off)}$, t_f

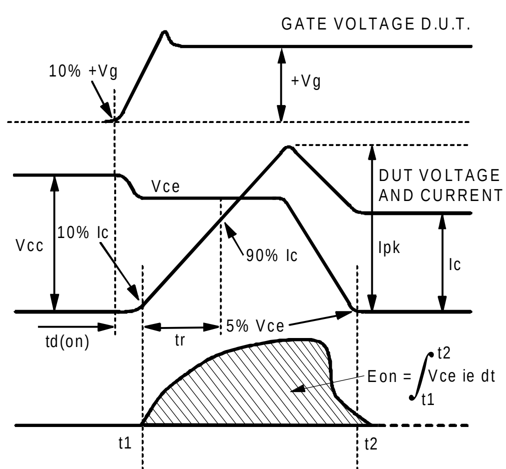


Fig. 18c - Test Waveforms for Circuit of Fig. 18a, Defining E_{on}, $t_{d(on)}$, t_r

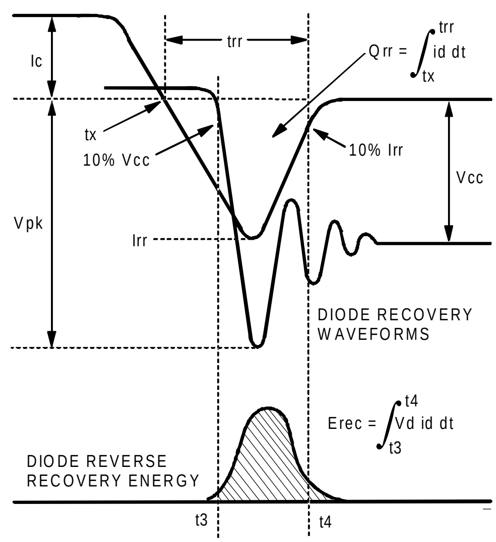


Fig. 18d - Test Waveforms for Circuit of Fig. 18a, Defining E_{rec}, t_{rr}, Q_{rr}, I_{rr}

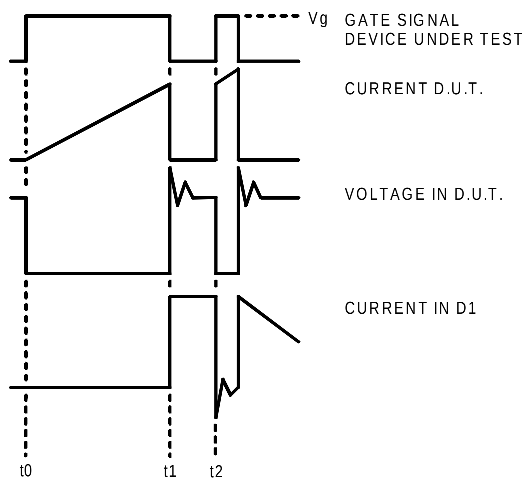


Figure 18e. Macro Waveforms for Figure 18a's Test Circuit

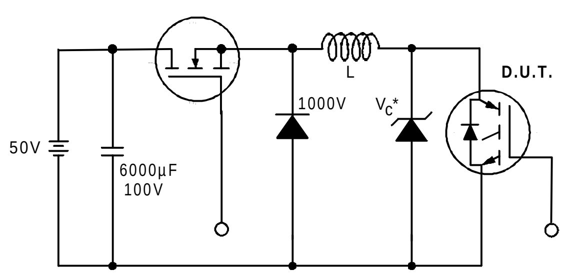


Figure 19. Clamped Inductive Load Test Circuit

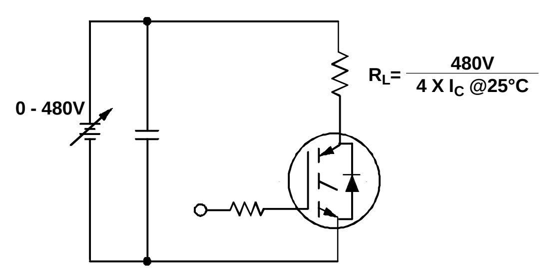


Figure 20. Pulsed Collector Current Test Circuit

Notes:

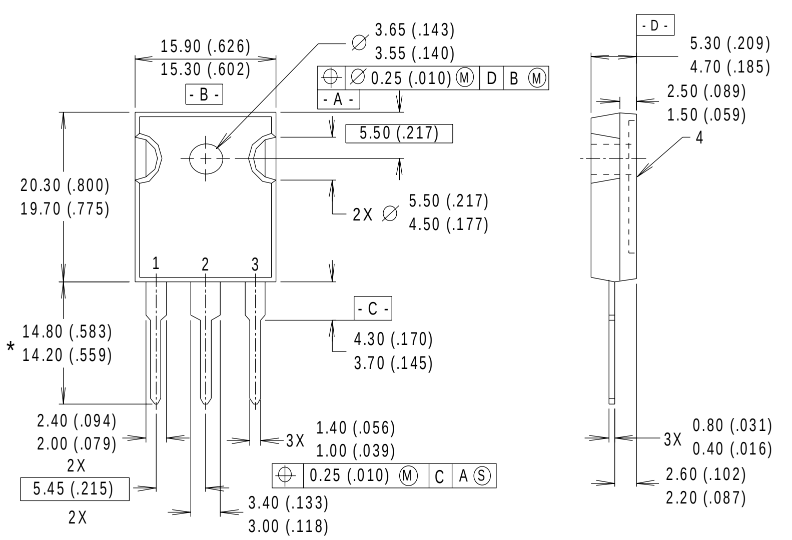
① Repetitive rating: V_{GE}=20V; pulse width limited by maximum junction temperature (figure 20)

② V_{CC}=80%(V_{CES}), V_{GE}=20V, L=10µH, R_G = 5.0Ω (figure 19)

③ Pulse width ≤ 80µs; duty factor ≤ 0.1%.

④ Pulse width 5.0µs, single shot.

Case Outline — TO-247AC



NOTES:
1. DIMENSIONS & TOLERANCING PER ANSI Y14.5M, 1982.
2. CONTROLLING DIMENSION : INCH.
3. DIMENSIONS ARE SHOWN MILLIMETERS (INCHES).
4. CONFORMS TO JEDEC OUTLINE TO-247AC.

LEAD ASSIGNMENTS
1 - GATE
2 - COLLECTOR
3 - EMITTER
4 - COLLECTOR

* LONGER LEADED (20mm) VERSION AVAILABLE (TO-247AD) TO ORDER ADD "-E" SUFFIX TO PART NUMBER

CONFORMS TO JEDEC OUTLINE TO-247AC (TO-3P)
Dimensions in Millimeters and (Inches)

International
IOR Rectifier

IR WORLD HEADQUARTERS: 233 Kansas St., El Segundo, California 90245, USA Tel: (310) 252-7105
TAC Fax: (310) 252-7903
Visit us at www.irf.com for sales contact information.

Data and specifications subject to change without notice. 12/00

Attachment 3: FEMM Pre- and PostProcessor Files

Preprocessor file: Solenoid1.lua

```
project = "Solenoid"
outfile = project .. "_results.txt"
start_time = date()

-- Save model under new name
save_femm_file("temp2.fem")

-- Prepare for selecting and moving the group of points in the projectile.
seteditmode("group")

-- Loop through the sizes of projectile; each one is 'increment' larger
-- Loop through all the projectile positions along firing tube

for n=1,21 do
   -- Save current position for post-processor
   handle = openfile("tempfile","w")
   pos = 105-5*n
   write(handle, pos)
   closefile(handle)

   -- Solve and save results
   showmesh()
   analyse()
   run_post("solenoid.lua")

   -- Nudge projectile downward by 50mm
   selectgroup(1)
   move_translate(0,-5)
end
```

Postprocessor file: Solenoid.lua

```
outfile = "solenoidpost.txt"

-- read projectile's position at its centerpoint
handle = openfile("tempfile", "r")
position = read(handle, "*n")
closefile(handle)

-- Select the solenoid coil, to prepare for integration
groupselectblock(2)

force = blockintegral(12)

-- Output volume and force to results file
handle = openfile(outfile,"a")
write(handle, position, "\t", force, "\n")
closefile(handle)

exitpost()
```