Heat sources

NPTEL Online course on
Analysis and modeling of welding

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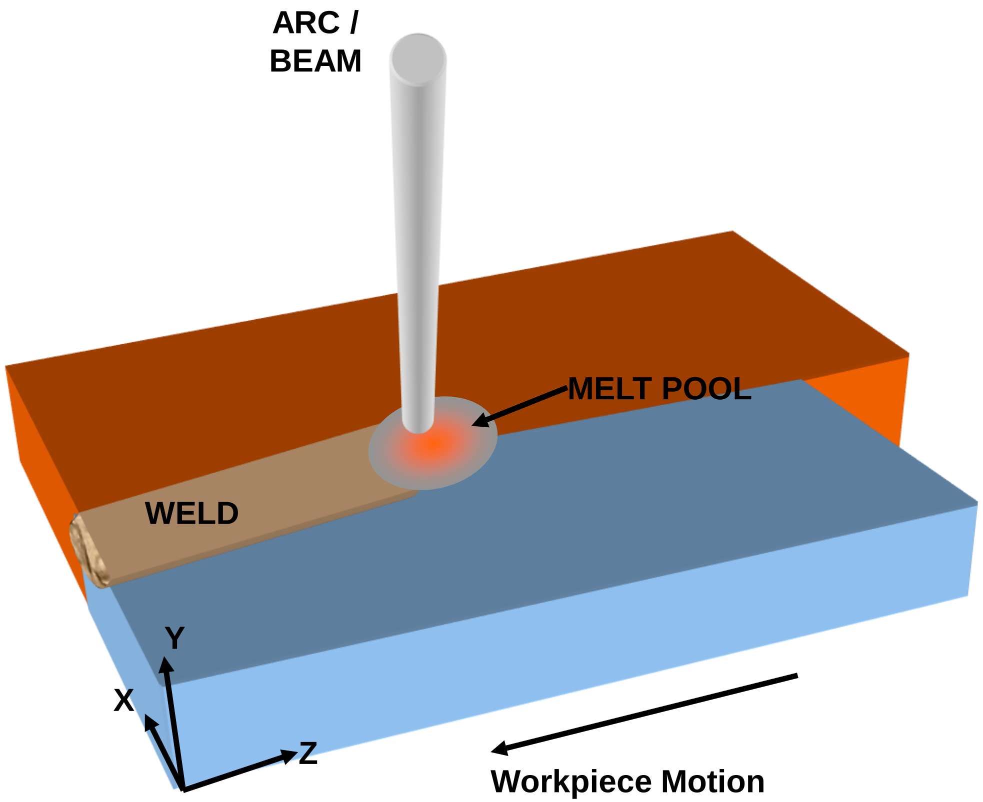
Joining



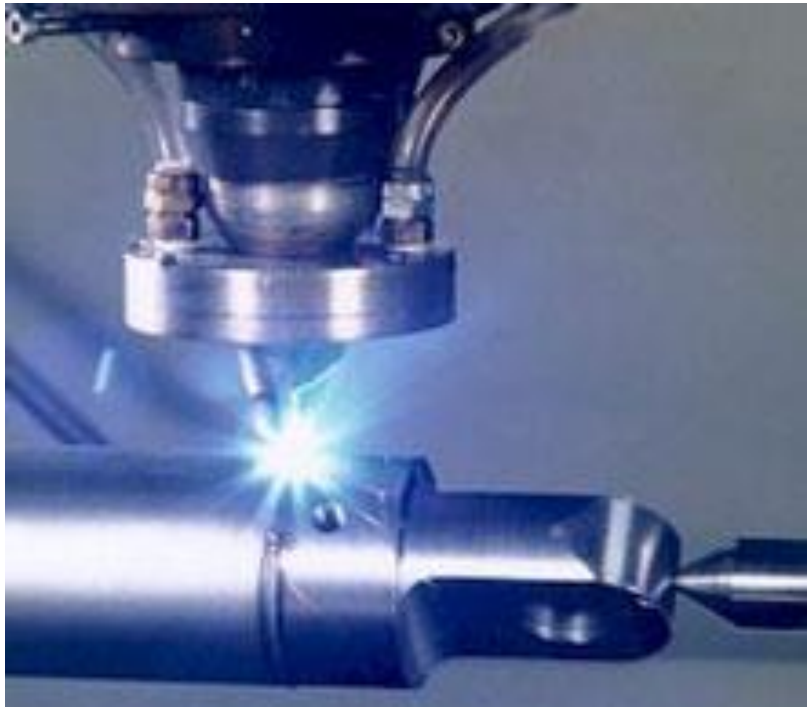


Figure courtesy: Internet

Cladding / Weld overlay

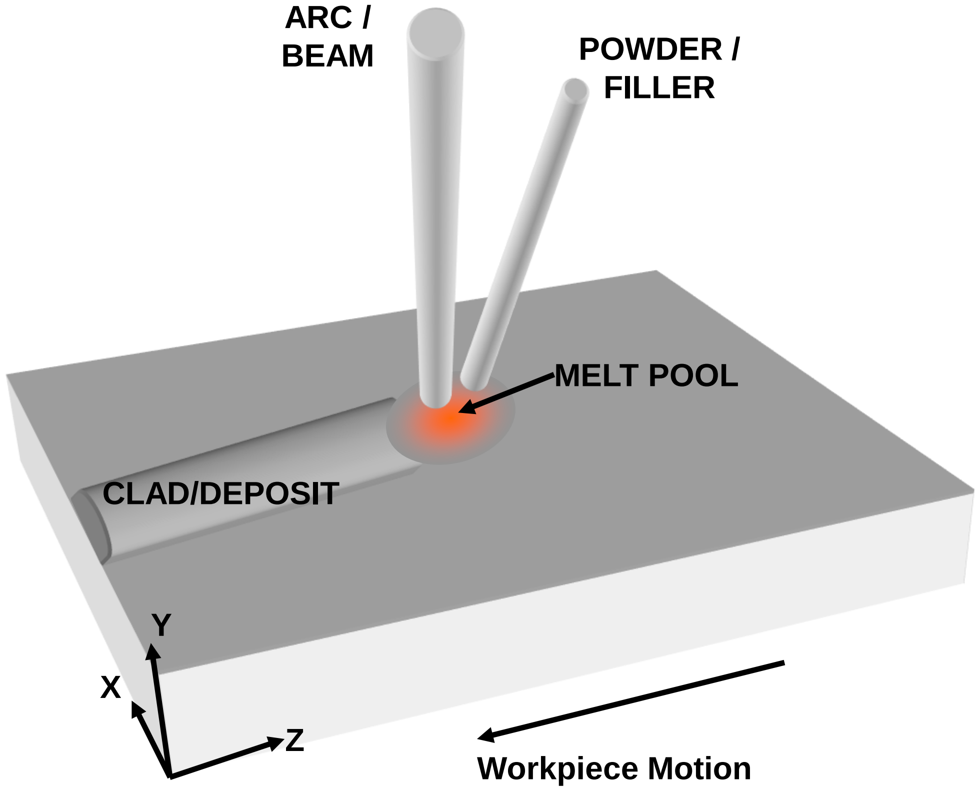


Figure courtesy: Internet

Boundary conditions

Gaussian heat flux

$$q = \frac{Q}{\pi r^2} \exp\left\{ -\frac{(x - x_0)^2 + (y - y_0)^2}{r^2} \right\}$$

Convective loss

$$h(T - T_\infty)$$

Radiative loss

$$\varepsilon\sigma(T^4 - T_\infty^4)$$

Physical processes

- Heat transfer
- Fluid flow
- Mass transfer

-decouple-

- Phase transformations
- Stress effects

Heat transfer

- Heat gain from welding source
- Heat grain from leading heat source
- Heat loss from external heat sinks
- Heat loss by convective mode
- Heat loss by radiation
- Heat loss by conduction in the base metal
- Enhanced heat extraction through water cooled backing setup
- Formation of compounds through exothermic reaction

- Heating of base metal
- Melting
- Possible vaporization
- Solidification
- Cooling to ambient temperature

Heat sources

- Arc
- Plasma
- Electrons
- Lasers (Nd:YAG, CO_2, Excimer, Diode)
- Infrared sources (Image Furnace)

+

- Filler (powder / wire)

Characteristics of a heat source

- Nature of distribution : surface or volumetric
- Power distribution : spatial variation
- Absorption efficiency : dependency on material, temperature etc.
- Temporal changes : pulsing effects
- Traverse rate : velocity of heat source
- Path : raster or arc oscillation

Heat source efficiency

$$\eta = \frac{Q}{Q_{\mathrm{nominal}}}$$

Q is the amount of heat transferred to the base material.
$Q_{nominal}$ is known from the welding process.
Eg., Voltage * Current for arc welding processes, Power setting for Laser welding etc.

η is often less than 1 → not all heat is received by the base material.

Laser absorption efficiency

- Metallic surfaces are like mirrors
- Absorption depends on:
  - Metal
  - Wavelength of laser
  - Temperature
  - Phase
  - Surface condition : oxides, coatings
  - Surface structure

Ref: Laser Heating of Metals by A. M. Prokhorov et al., Adam Hilger (1990) ISBN: 075030040X

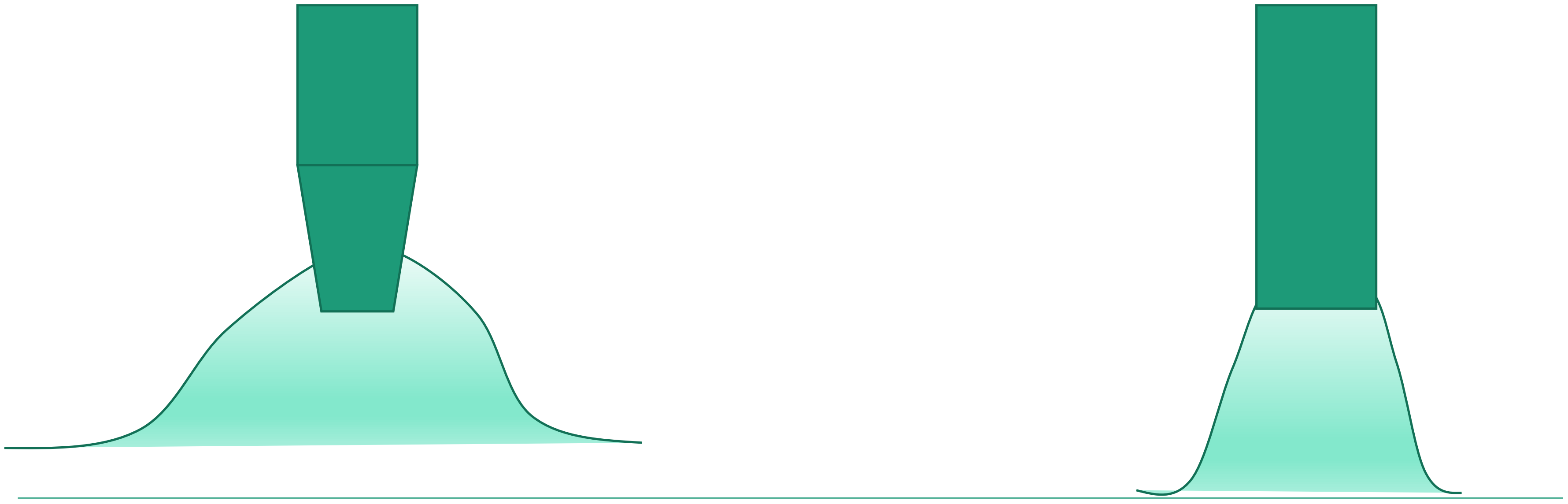
Typical heat source efficiencies

Process	Typical efficiency	Reasons
Laser Beam Welding	<0.1	High reflectivity of metals
Plasma Arc Welding	0.5 – 0.7	Heat loss to water cooled constriction nozzle
Gas Tungsten Arc Welding (DCEN)	0.6 – 0.8	Both work function and kinetic energy are released to the work piece
Shielded Metal Arc Welding	0.7 – 0.9	Heat transferred to electrode reaches the work piece back via the droplets
Gas Metal Arc Welding	0.7 – 0.9	Heat transferred to electrode reaches the work piece back via the droplets
Submerged Arc Welding	0.75 – 0.9	Arc is covered by flux which prevents heat loss
Electron Beam Welding	0.8 – 0.95	Keyhole acts as a black body

Ref: Welding Metallurgy, 2nd Edition by Sindo Kou

Effect of electrode tip angle

- Blunt tip → diameter of arc decreases → power density increases
- Weld aspect (depth/width) ratio increases with increasing conical tip angle of the electrode



Gaussian heat source

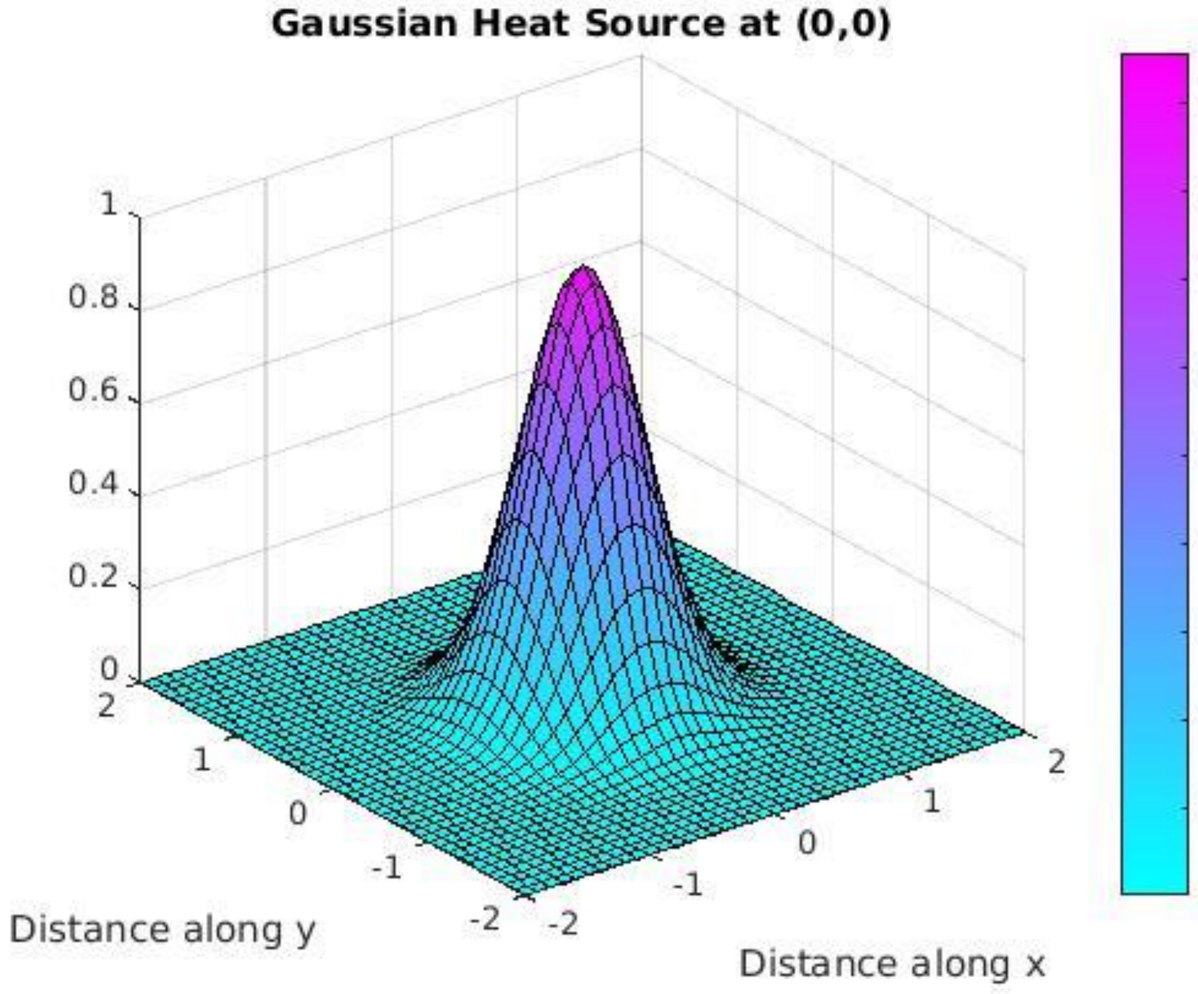
$$q(x, y) = \frac{3Q}{\pi r_0^2} \exp\left(-3\frac{r^2}{r_0^2}\right)$$

$$r^2 = (x - x_0)^2 + (y - y_0 - vt)^2$$

v Velocity of torch along *y*

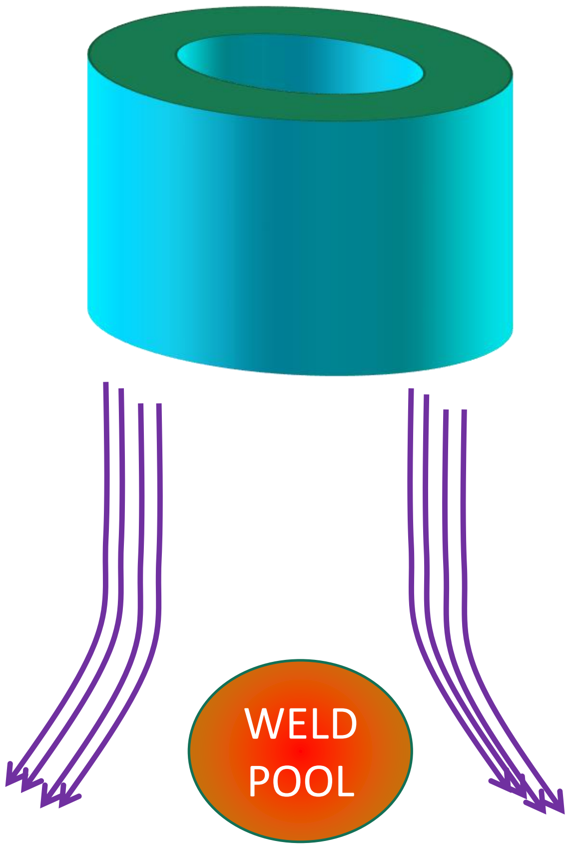
(x_0, y_0) Initial location of the torch

$$Q = \eta V I$$



Influence of shielding gases

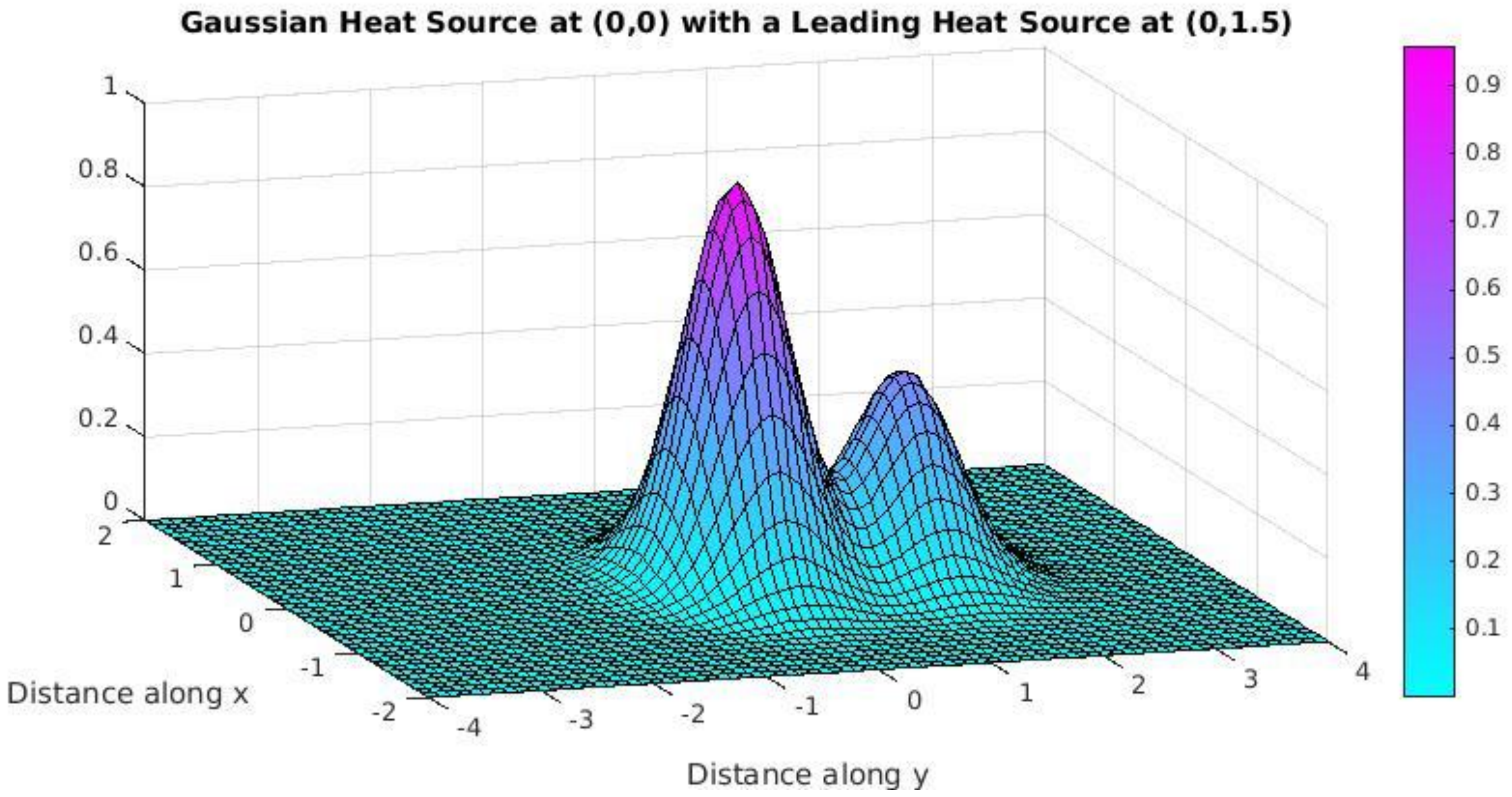
- Thermal conductivity of the shielding gas
- Flow rate
- Geometric constriction for flow
- Height of nozzle from workpiece
- Angle of nozzle
- Gas curtain



Combining heat sources

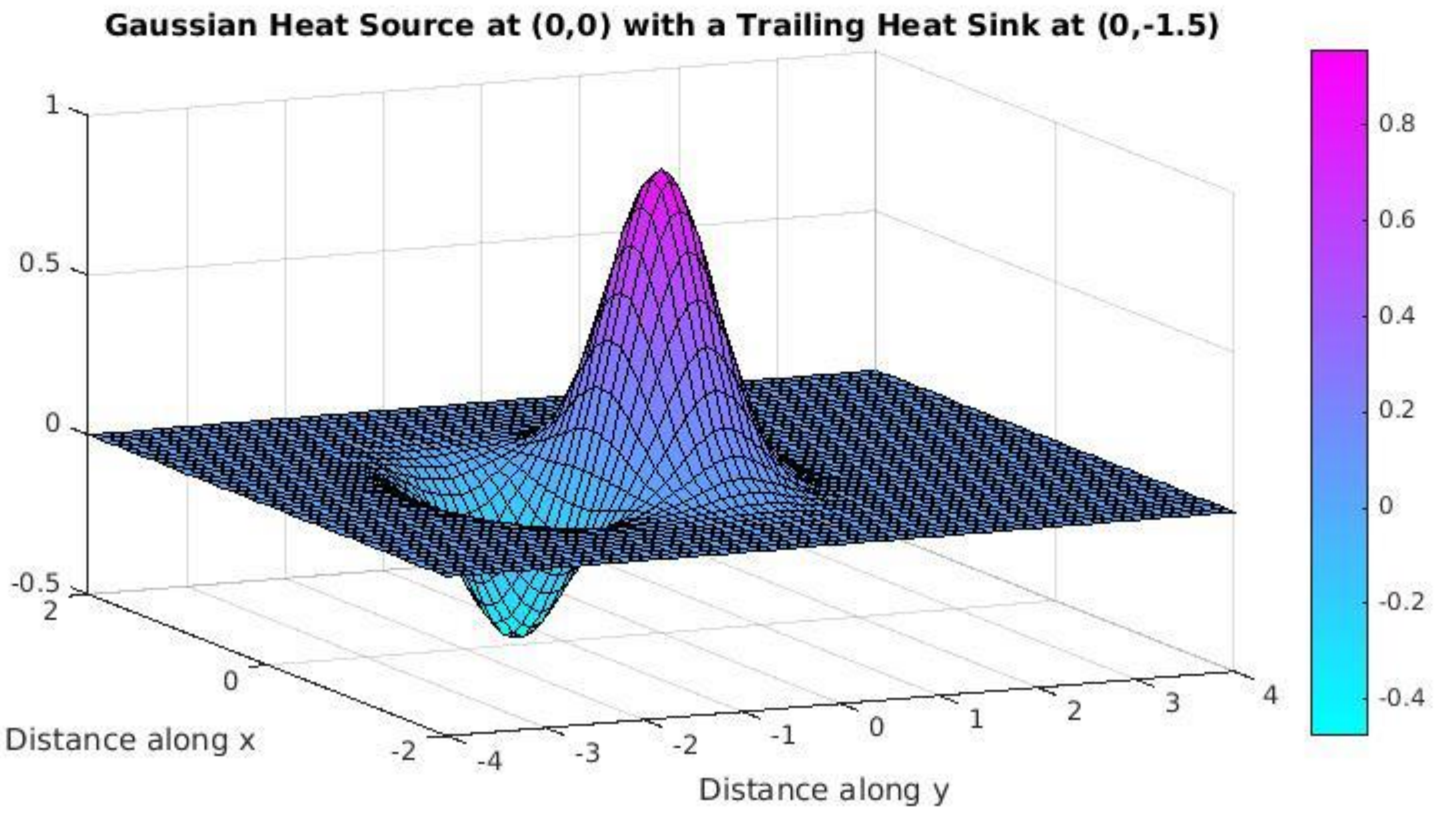
- Apart from the welding torch / beam, there are other sources / sinks too.
- Heat sinks or sources could be trailing or leading the weld torch / beam
- Leading heat source: preheat, hybrid process
- Trailing heat sink: distortion control
- Heat sinks are same as heat sources – except for the sign
- Heat removal processes are treated separately

Combining heat sources : A leading heat source



Sum of two Gaussian profiles with different origins and strengths

Combining heat sources : A trailing heat sink



Sum of two Gaussian profiles with different origins and strengths (one positive and the other negative)

Modes of welding

Conduction Mode

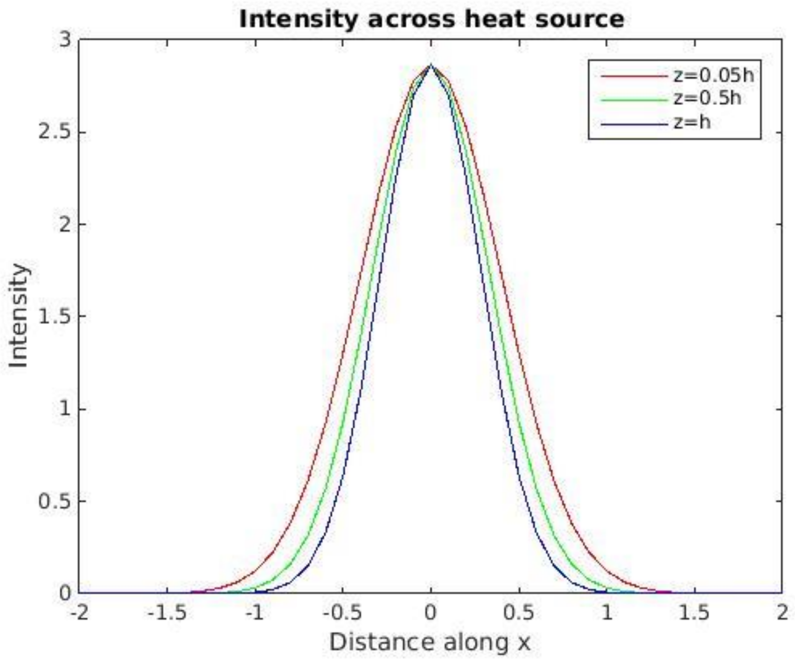
Shallow and wide pools
Low heat source intensity processes

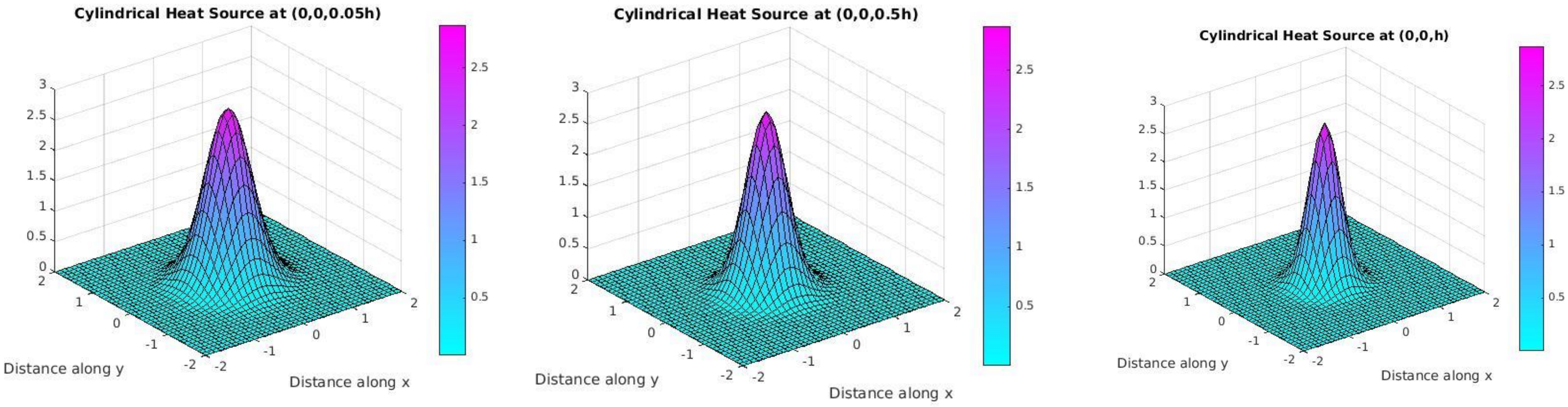
Keyhole Mode

Narrow and deep pools
Full depth penetration
Single pass welds of thick plates
High heat source intensity processes

Cylindrical heat source

$$Q(x,y,z) = \frac{9Q_0}{\pi h r_0^2} \exp\left[-\frac{3(x^2+y^2)}{r_0^2}\left(1+\frac{z}{h}\right)\right]$$



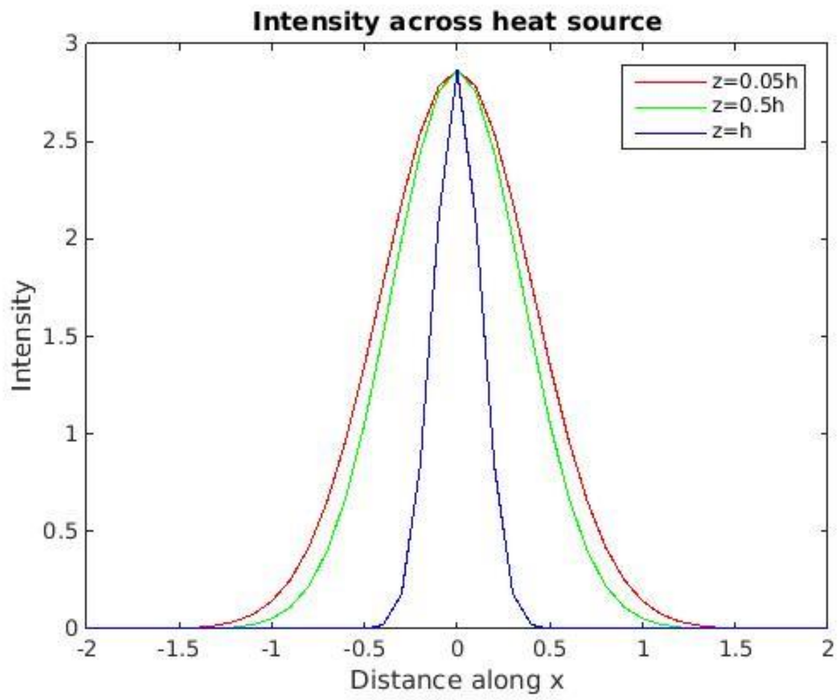


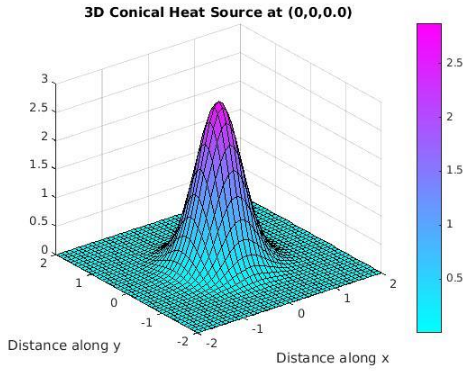
Heat source get slightly narrower with increasing depth

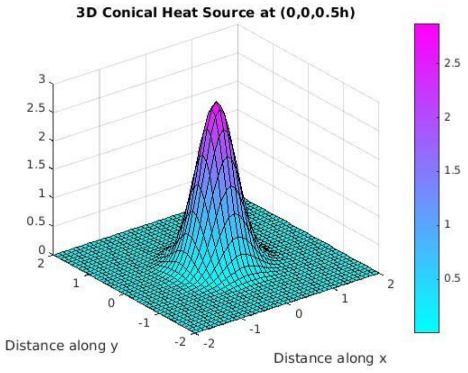
3D conic volume heat source

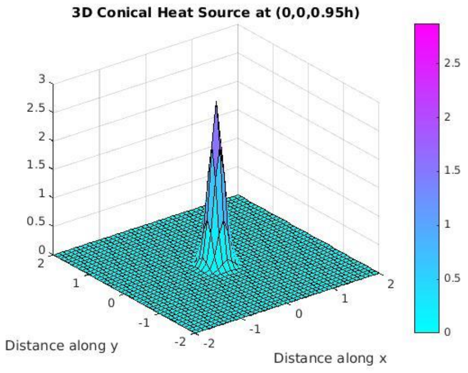
$$Q(x, y, z) = \frac{9Q_0}{\pi h r_0^2} \exp\left(-\frac{3(x^2+y^2)}{r_0^2}\frac{h^2}{(h^2-z^2)}\right)$$

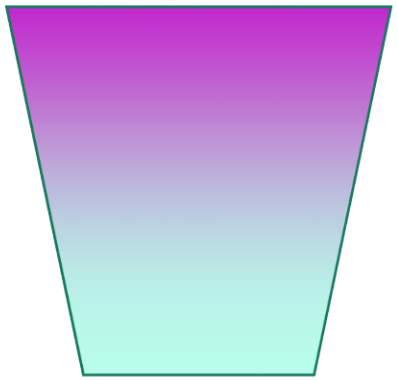
h is effective beam penetration depth











Gaussian Rod

$$Q(r,z) = \frac{Q}{\pi r_0^2 d} \exp\left(-\frac{r^2}{r_0^2}\right) u(z)$$

To account for deep penetration weld

d is the maximum keyhole depth

$u(z) = 1$ for $0 \leq z \leq d$ else $u(z) = 0$

Ref: R. Mueller in Proceedings of the ICALEO 94, pg. 509 (1994)

Internal heat source

To account for deep penetration weld

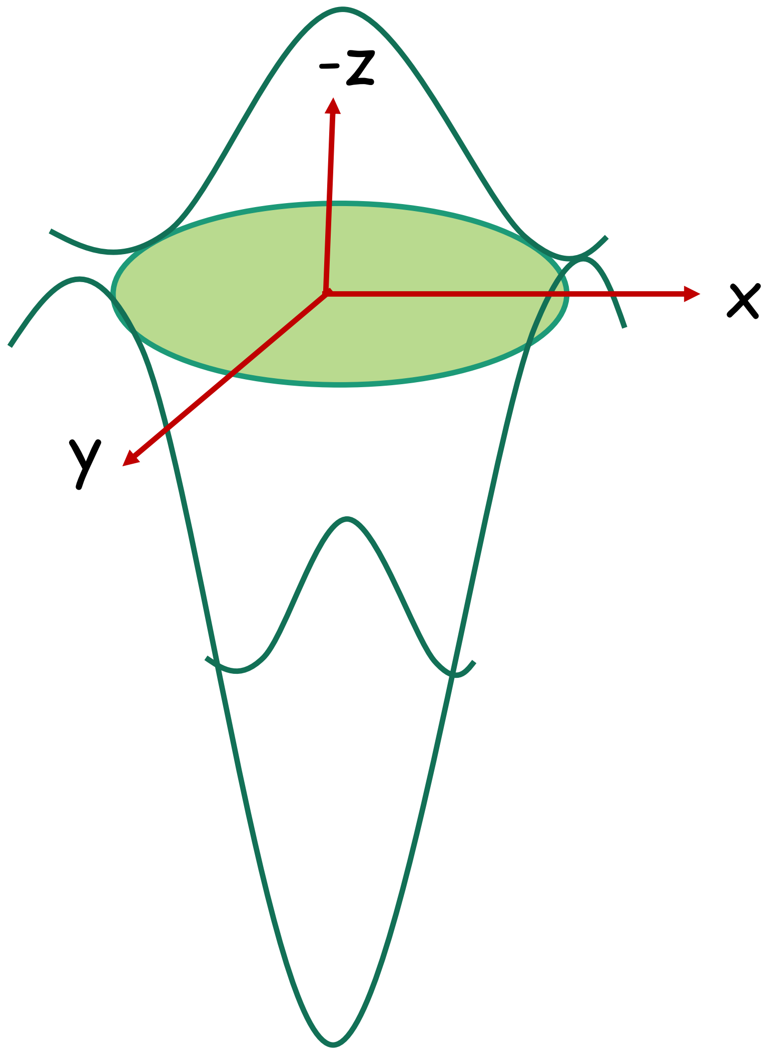
$$Q(r,z) = \frac{2\beta Q}{\pi r_0^2} \exp\left(-2\frac{r^2}{r_0^2} - \beta z\right)$$

Combining Gaussian heat source and internal absorption by Beer-Lambert's Law

Ref: N. Sonti and M.F. Amateau, Numerical Heat Transfer A, 16:351 (1989)

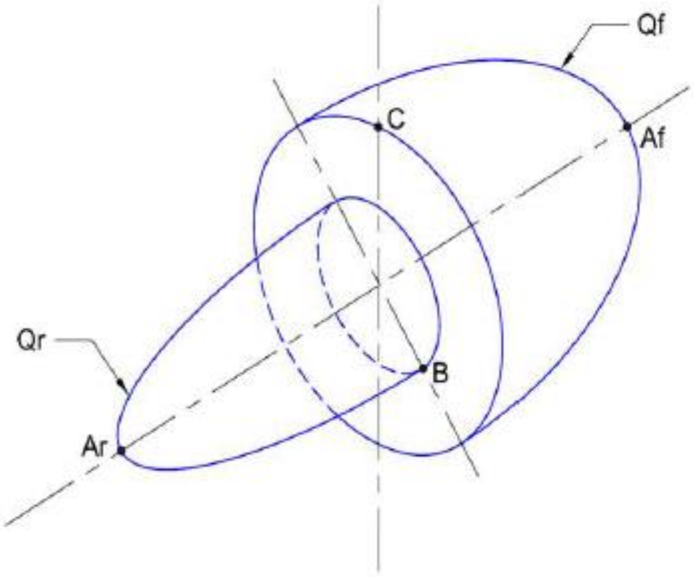
Rotary Gaussian heat source

$$Q(x, y, z) = \frac{9Q_0}{\pi h r_0^2} \exp\left[\frac{3 f_s r^2}{r_0^2 \log(z/h)}\right]$$

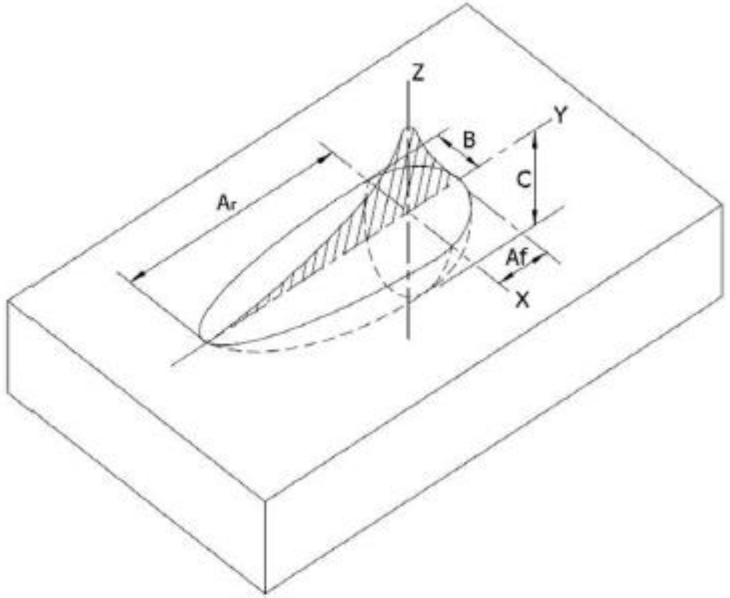


Ref: H. Wang et al., Journal of Physics D : Applied Physics, 39:4722 (2006)

Double ellipsoidal heat source



(a)



(b)

Ref: Goldak J. et al., Metallurgical Transactions B, 15B 299-305 (1984)
Figure Courtesy: Kala Shirish R., Ph.D. Thesis, IIT Madras (2013)

Double ellipsoidal heat source

Front half:

$$Q_f(x,\xi,z) = \frac{6\sqrt{3}Q}{A_f BC\pi\sqrt{\pi}} \exp\left(-3\frac{x^2}{A_f^2} - 3\frac{\xi^2}{B^2} - 3\frac{z^2}{C^2}\right)$$

Rear half:

$$Q_r(x,\xi,z) = \frac{6\sqrt{3}Q}{A_r BC\pi\sqrt{\pi}} \exp\left(-3\frac{x^2}{A_r^2} - 3\frac{\xi^2}{B^2} - 3\frac{z^2}{C^2}\right)$$

$$Q = \eta VI \qquad \xi = y - v(\tau - t)$$

v = Velocity of Torch

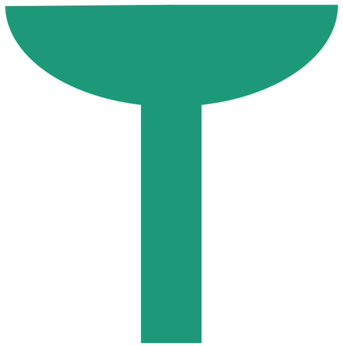
τ = Lag factor

Two quarters (one front and one rear) make for the heat source

4+ parameters !

Nail head heat source

Superposition of a line and point sources can describe a keyhole



$$I(x, y) = \eta I_0 \exp\left(-2\frac{r^2}{r_0^2}\right)$$ Gaussian

$$P_z = \lambda(T_v - T_0)f(Pe)$$ Empirical Form

$$Pe = \frac{vr}{\alpha}$$ Peclet Number

Ref: Kazemi and Goldak, Computational Materials Science, 44:841-849 (2009)

Summary of heat sources

Profile	Number of parameters	Comments
Gaussian	1	Radius
Cylindrical, 3D Conic body Gaussian Rod	2	Radius, Depth
Internal Heat Source	2	Radius, Absorption Coefficient
Rotary Gaussian	3	Radius, Depth, f_s
Double Ellipsoid	4+	A_f, A_r, B, C
Nail head	?	Radius, Pz(Pe)

Characterization of laser source

- Heat: Spatial distribution (TEM00, TEM01*, Top-hat etc.,) and Temporal distribution (continuous, pulsed)
- Momentum: (buoyancy, Marangoni)
- Mass: (surface flux, distributed flux, redistribution)

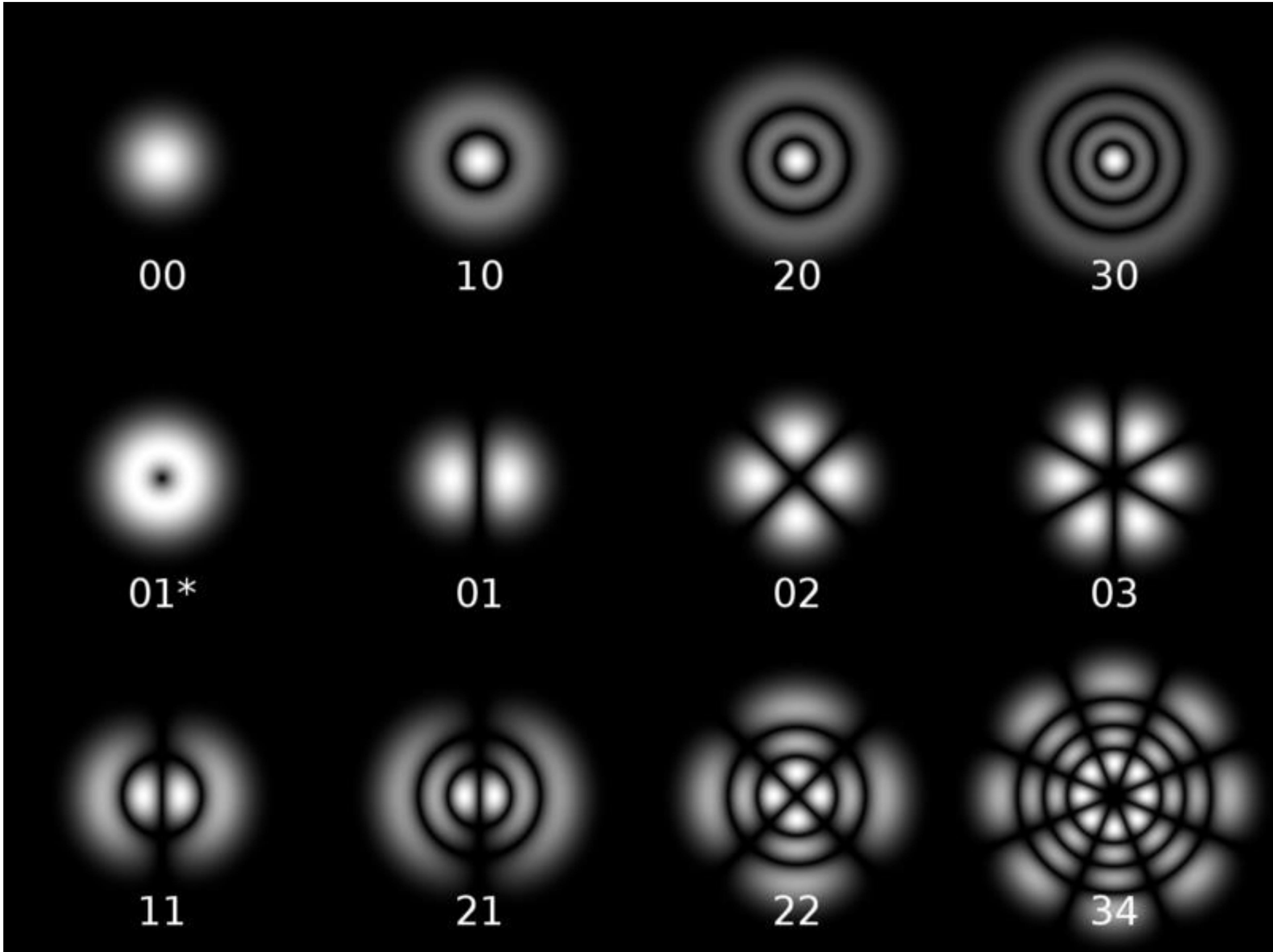
TEM modes

- Transverse electro magnetic modes / Laser modes
- Rectangular:
  - A distribution TEM_{mn} has m and n minima along x- and y- directions
  - Analytical expressions given by Hermite Polynomials
- Cylindrical:
  - A distribution TEM_{pl} has p minima and l modes
  - Analytical expressions given by Laguerre Polynomials
- TEM_{00} is Gaussian for both the geometries
- TEM_{01*} is doughnut shaped distribution

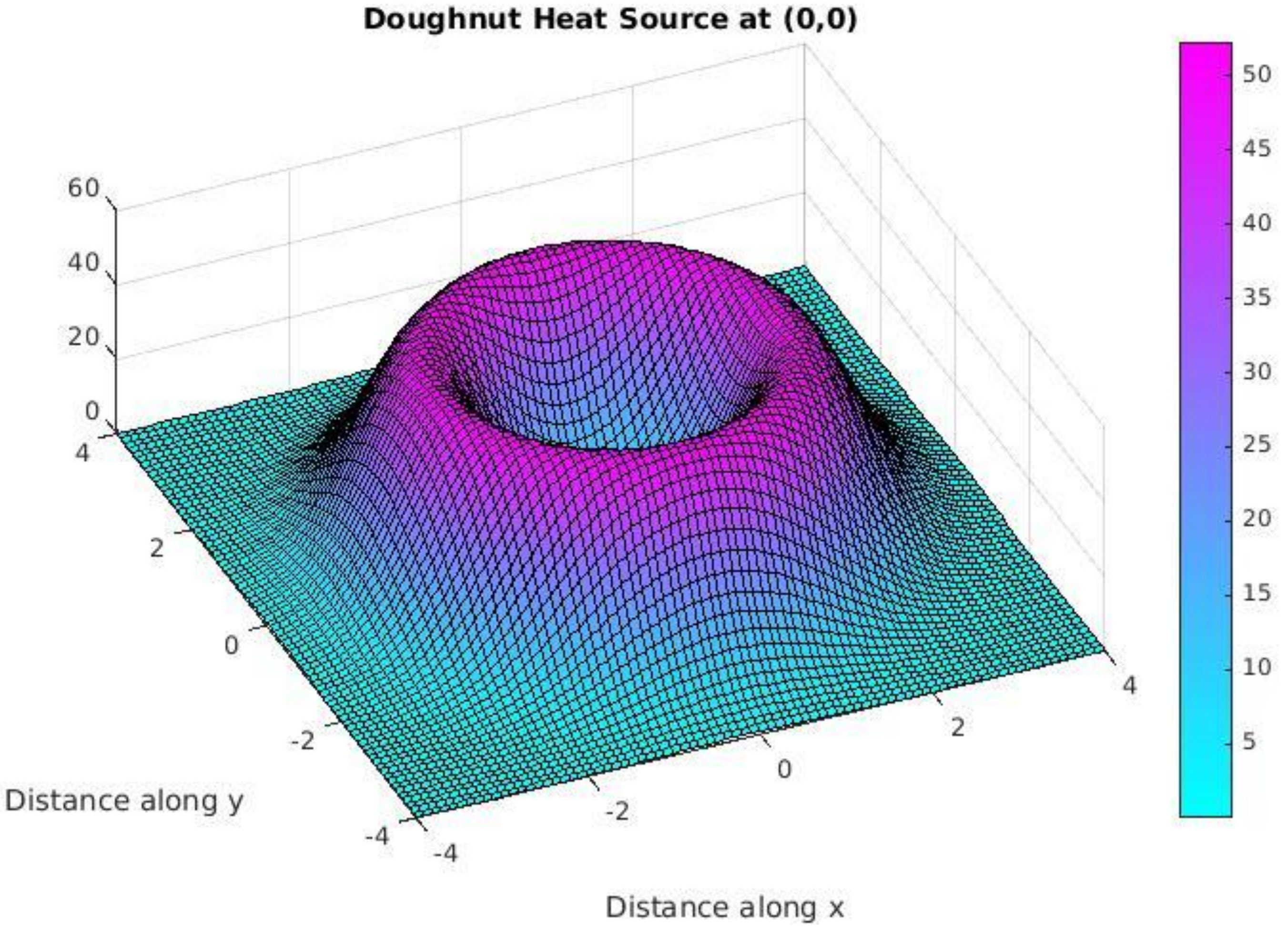
TEM_{pl} Modes

Cylindrical Geometry

Ref: Wikipedia, public domain

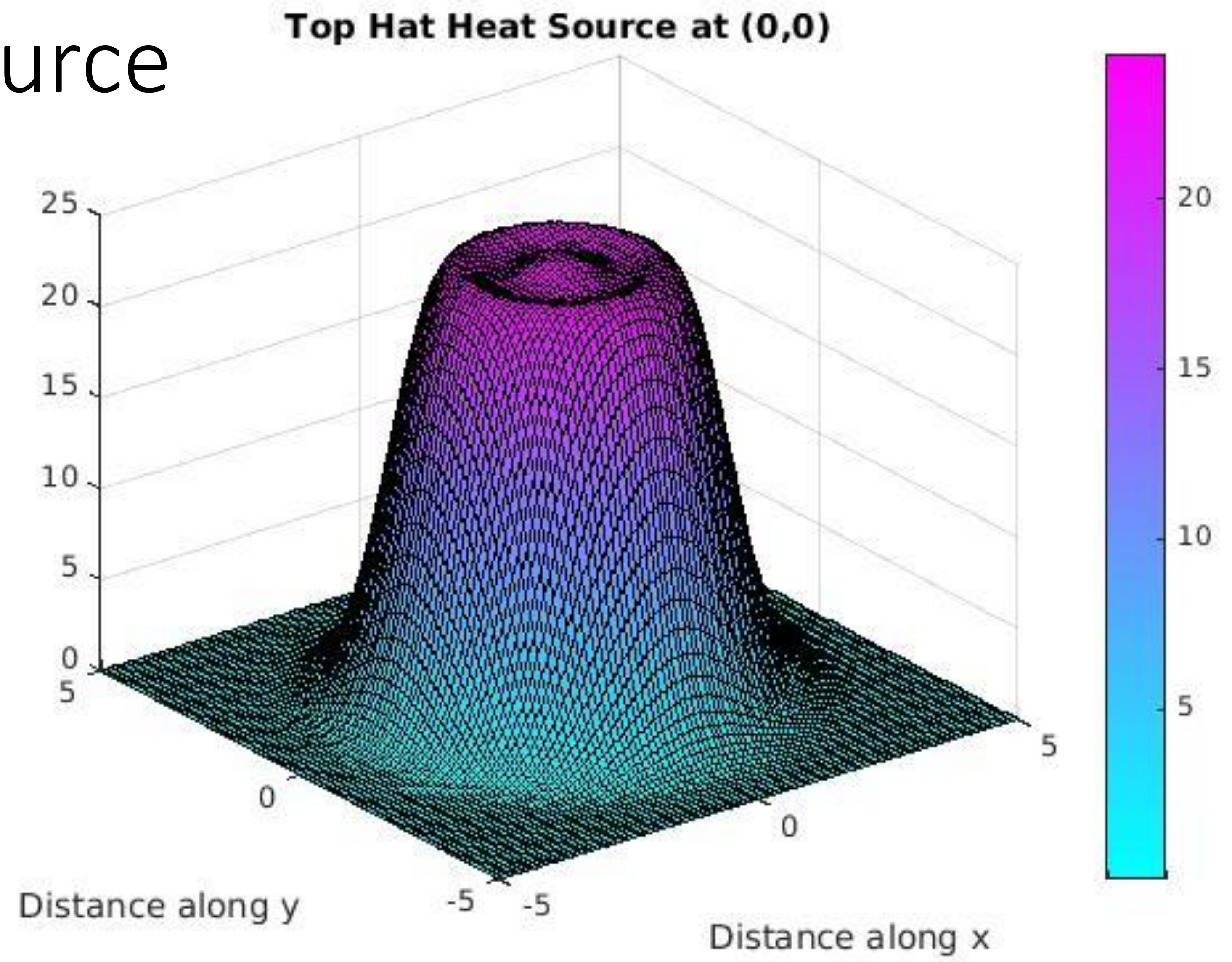


Doughnut heat source



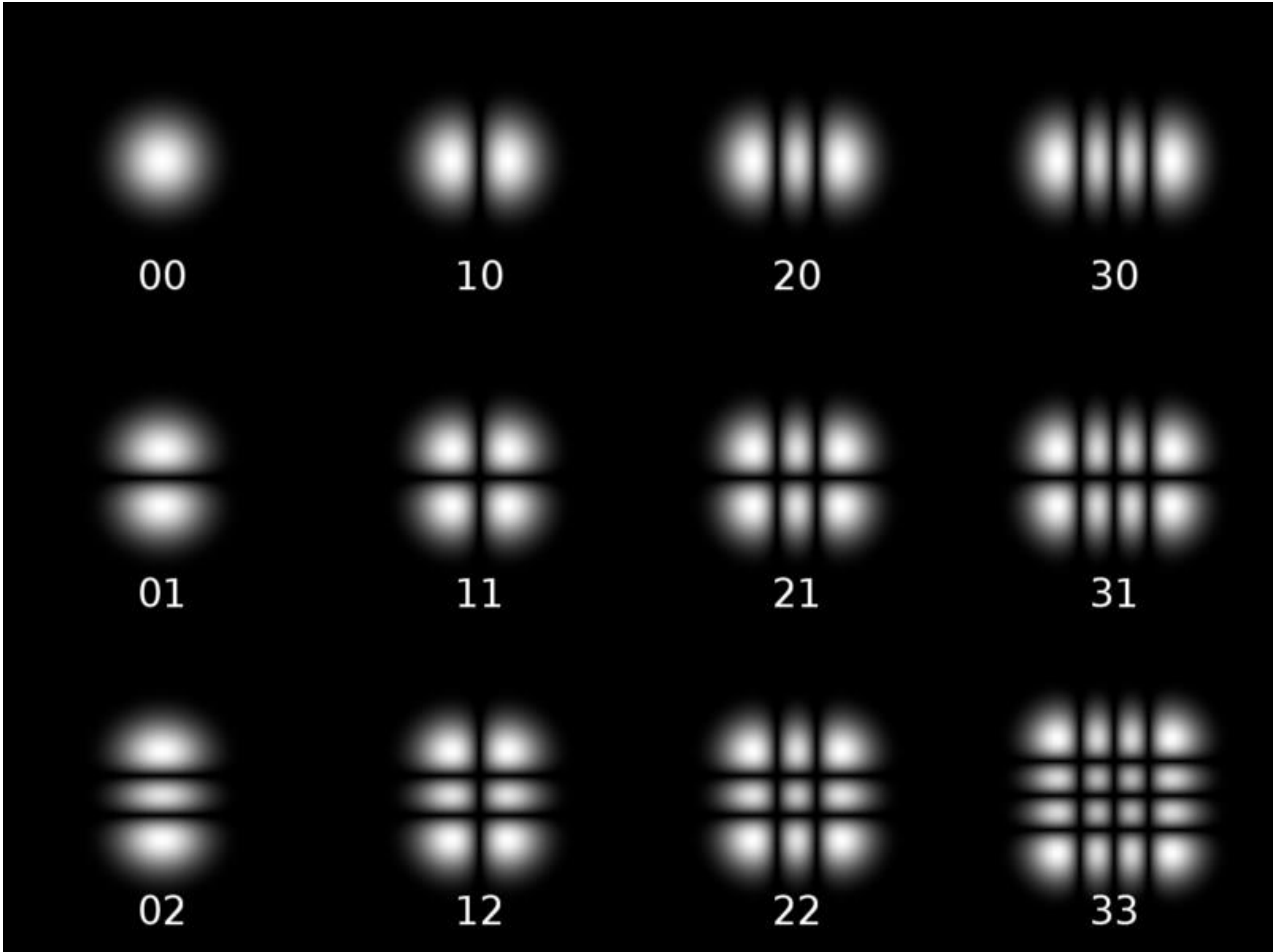
Top hat heat source

You can add a doughnut heat source to a Gaussian Heat Source to give an approximately a Top Hat heat source



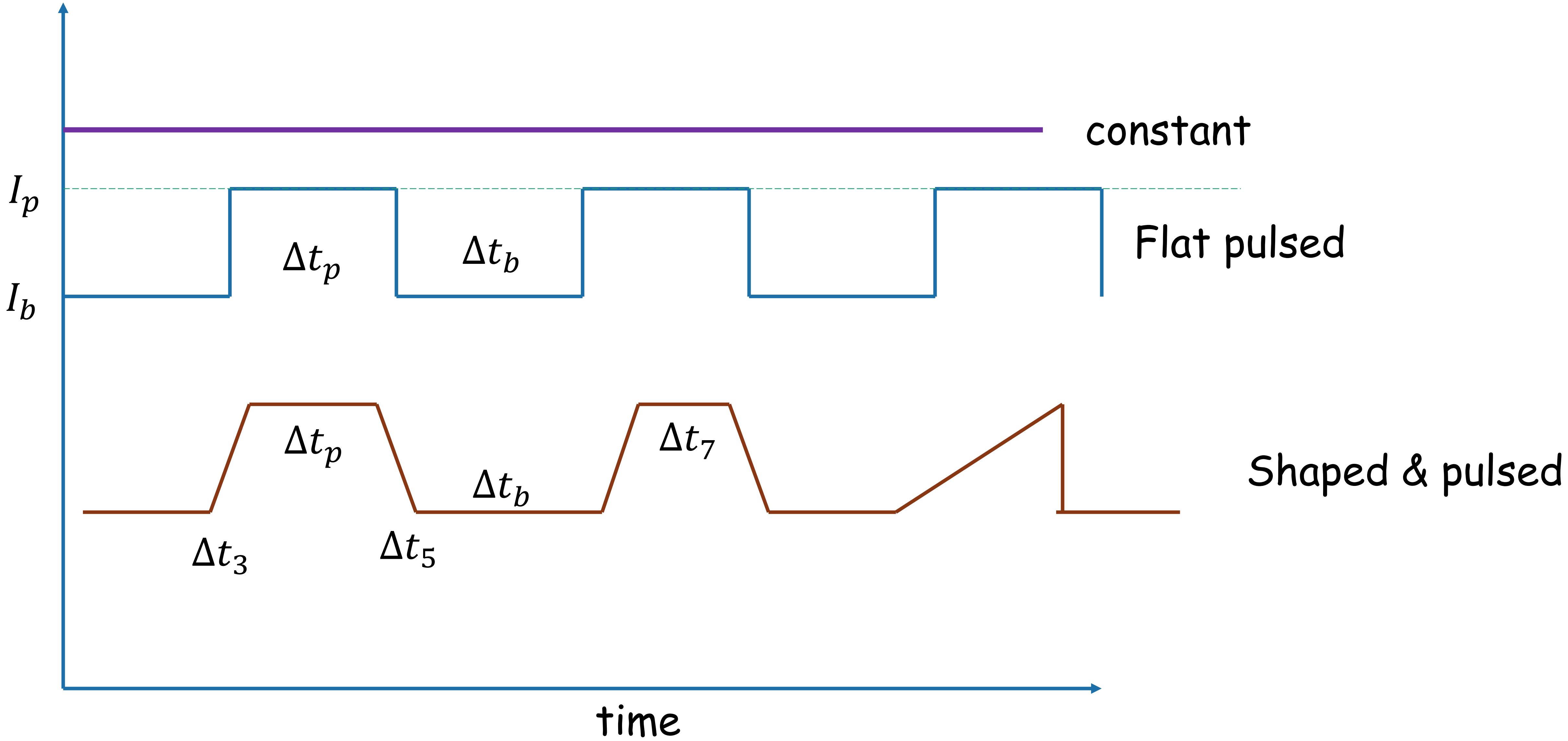
TEM_{mn} Modes

Rectangular Geometry



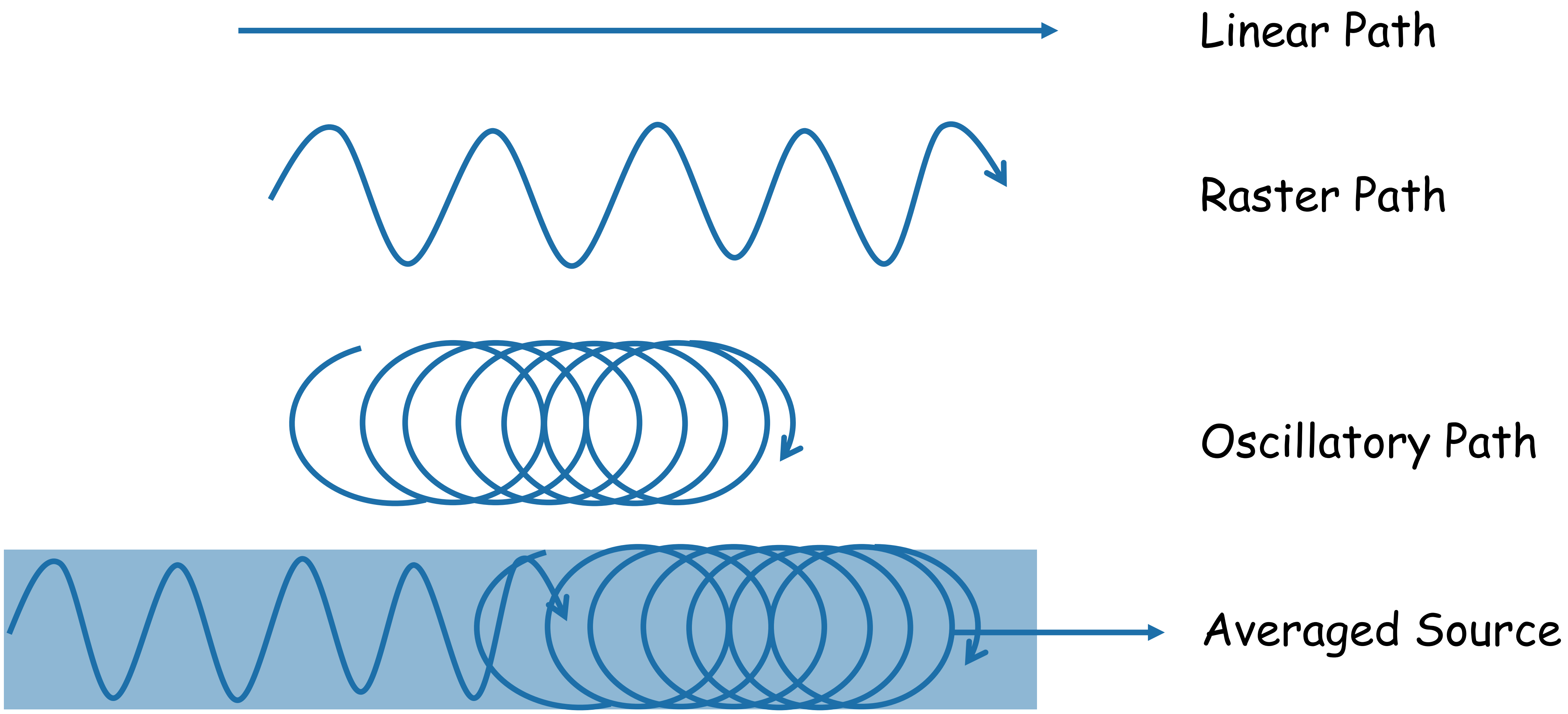
Ref: Wikipedia, public domain

Pulsing



constant
I_p
I_b
Δt_p
Δt_b
Flat pulsed
Δt_p
Δt_7
Δt_b
Δt_3
Δt_5
Shaped & pulsed
time

Raster or Oscillations



Benchmarking heat sources

- Separate out what is used for calibration and what is used for validation or prediction
- Eg., typically fusion zone shape is used for calibration and thermal profiles away from fusion zone are used for validation and prediction
- Ability to closely match the fusion zone shape is also part of validating the heat source form
- Peak temperatures to be realistic and validated
- Trends for small changes in heat source parameters to be verified

Methods to validate thermal profiles

- Thermocouple measurements
- Two colour IR pyrometers
- IR Thermography

Thermocouple measurements

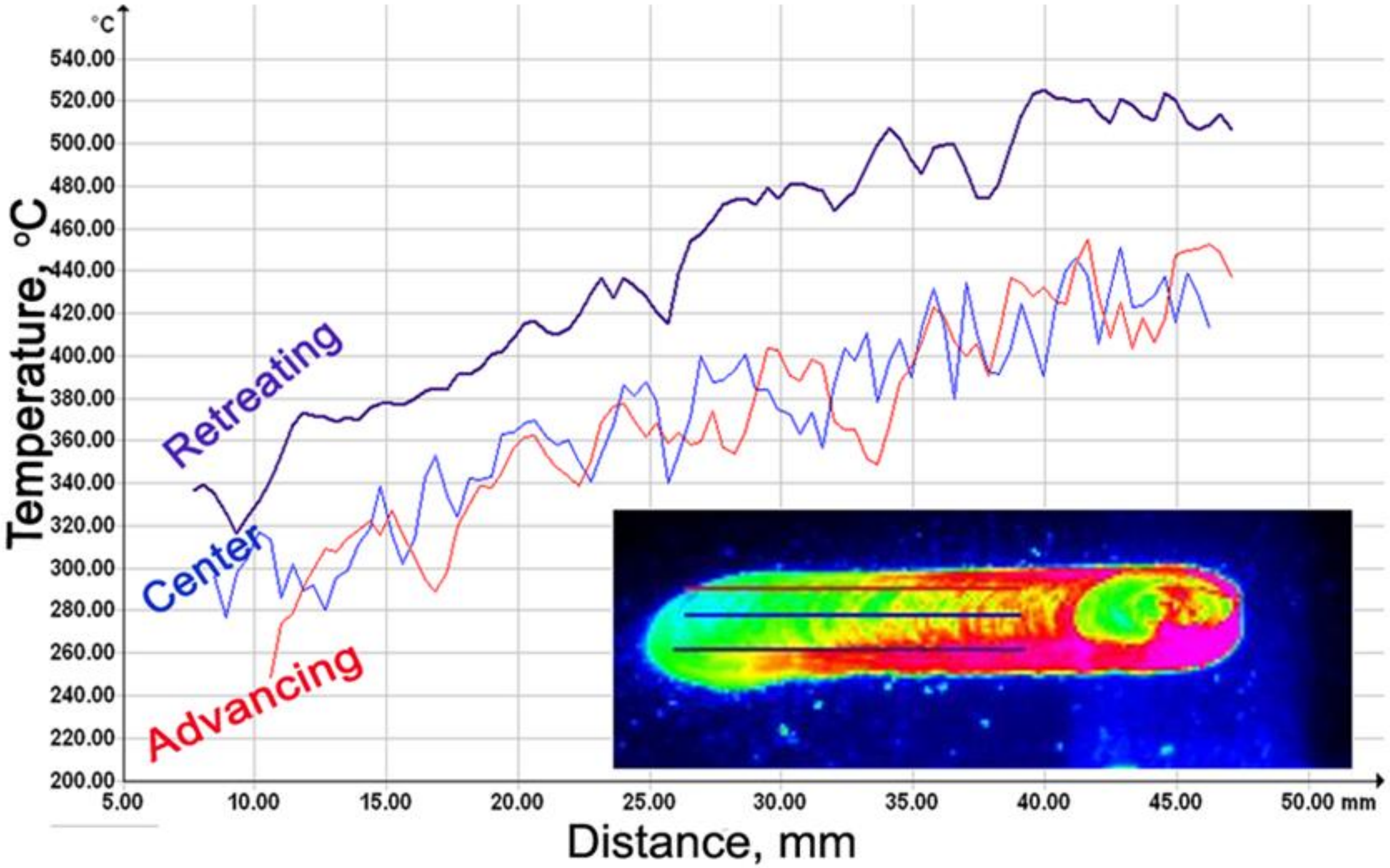
Position(s)

Contact
Electric Connections

Thermocouple thickness
Acquisition Speed
Signal Conditioner

Actual image of GTAW + Thermocouple DAQ facility at Materials Joining Laboratory, Dept. of MME, IIT Madras

IR Thermography



Ref: Snapshop from IR Thermography Video of a friction surface deposit
Ph.D. Thesis, H. Khalid Rafi, IIT Madras (2011)

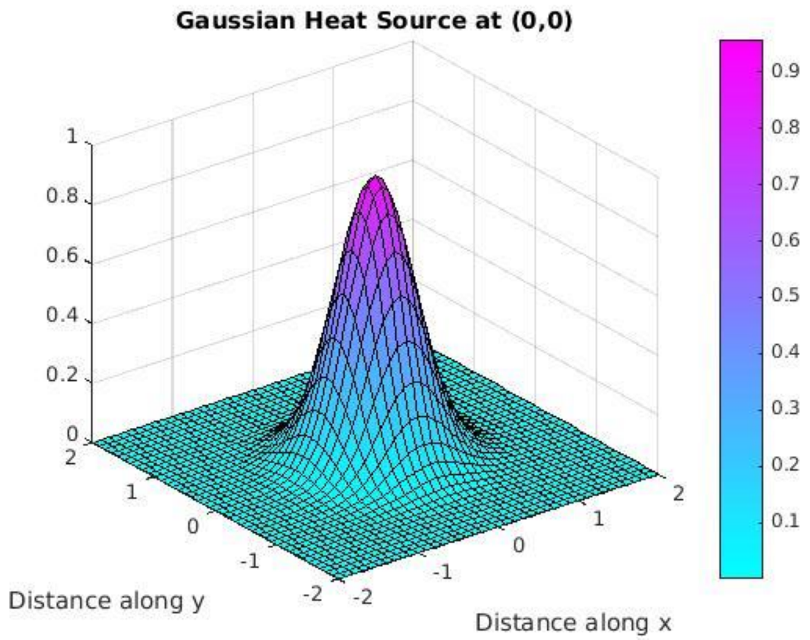
Methods to validate thermal profiles

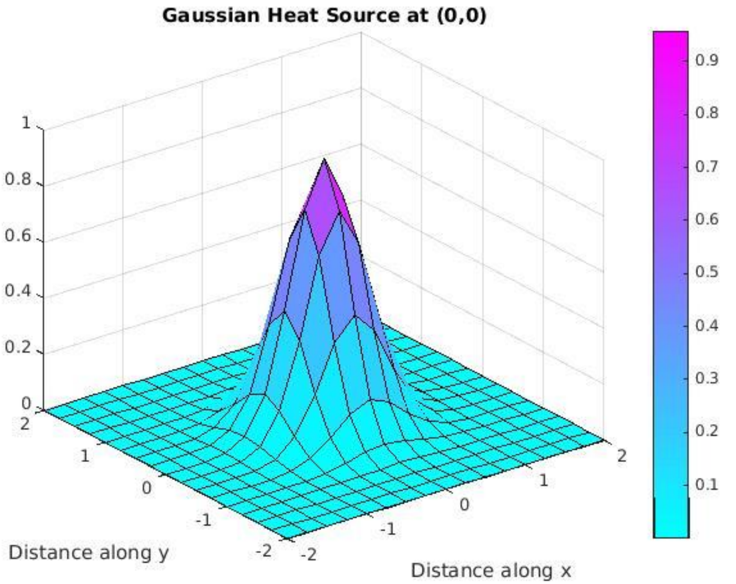
- Thermocouple measurements – high speed data acquisition at a location inside the sample. Multiple thermocouples possible.
- Two colour IR pyrometers – high speed data acquisition at a location on the surface of the sample.
- IR visualization for surface temperature distribution. Frame rate often less than thermocouple measurements. Array of data available at each time step.
- Microstructure can be used as a marker to verify the zones (FZ, PMZ, HAZ)

- Calibration of Thermocouples and IR sensors

Points to take care

- Integral of heat source distribution over the top surface of workpiece should match total input actually given
- Fine grid points inside the heat source to capture it well
- Small time steps to avoid missing phase change





Summary

- Heat source is to be modelled as close to actual process as possible
- Number of parameters, their sensitivity to the intensity
- Integral to be calibrated to equal unity

- You get only as much as you put in !

End of Lesson on Heat Sources