BEAM MATCHING IN PARTICLE ACCELERATORS

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PARTICLE ACCELERATORS

What are they?

Quite simply, accelerators give high energy to subatomic particles, which then collide with targets. Out of this interaction come many other subatomic particles that pass into detectors. From the information gathered in the detectors, physicists can determine properties of the particles and their interactions. The higher the energy of the accelerated particles, the more closely we can probe the structure of matter.

Particle accelerators come in two basic designs, linear (linac) and circular (synchrotron). The longer a linac is, the higher the energy of the particles it can produce. A synchrotron achieves high energy by circulating particles many times before they hit their targets.

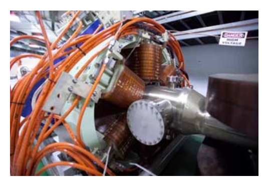
What are they for?

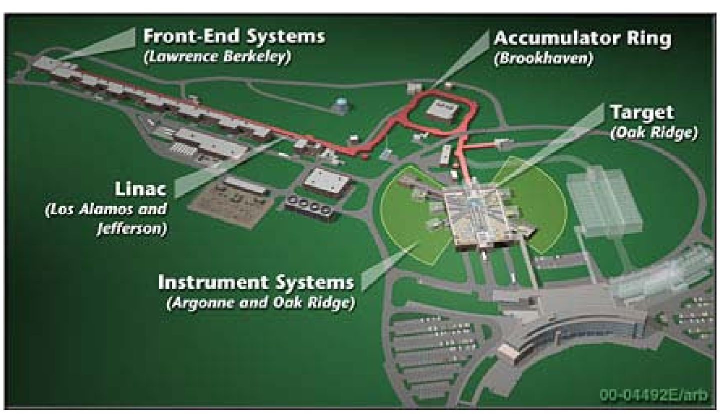
Linacs are used in medicine, high energy physics research, neutron scattering (material science).

PARTICLE ACCELERATORS

The Spallation Neutron Source (SNS), being built in Oak Ridge, Tennessee, by the U.S. Department of Energy with a cost of $1.4 billion, is the most intense accelerator-based neutron source in the world.

SPALLATION NEUTRON SOURCE

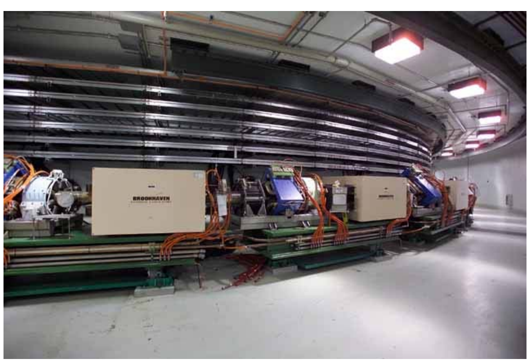


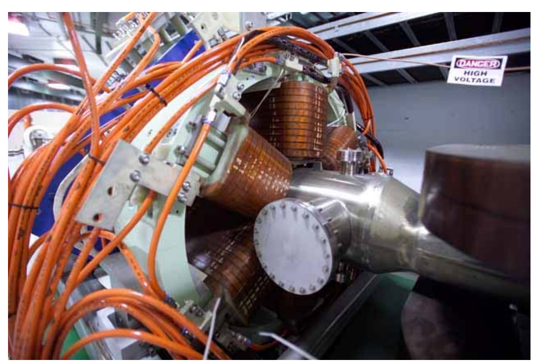


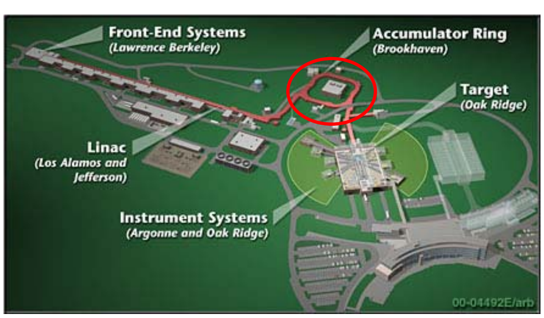
SNS - LINAC

• The linac is a superposition of normal conducting and super-conducting radio-frequency cavities that accelerate the beam and magnetic lattices that provide focusing and steering.
• Accelerates the H- beam from 2.5 Mev to 1 GeV.
• Diagnostic elements provide information about the beam current, shape, and timing, as well as other information necessary to ensure that the beam is suitable for injection into the accumulator ring and to allow the high-power beam to be controlled safely.

SNS – ACCUMULATOR RING







• Accumulator ring bunches and intensifies the ion beam for delivery onto the mercury target to produce the pulsed neutron beams.
• The H- pulse from the linac is wrapped into the ring through a stripper foil that strips the electrons from the negatively charged hydrogen ions to produce the protons (H +) that circulate in the ring.
• Around 1200 turns are accumulated, and then all these protons are kicked out at once, producing a short and sharp pulse less than 1 millionth of a second (10^{-6} seconds) in duration that is delivered to the target (needed for neutron-scattering research).

SNS - TARGET

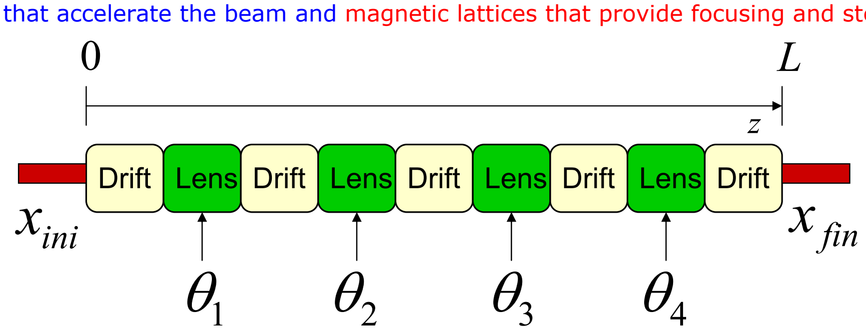
• The SNS will be the first scientific facility to use pure mercury as a target for a proton beam: (1) it is not damaged by radiation, as are solids; (2) it has a high atomic number; and (3), because it is liquid at room temperature, it is better able than a solid target to dissipate the large, rapid rise in temperature and withstand the shock effects arising from the rapid high-energy pulses.

• The neutrons coming out of the target must be turned into low-energy neutrons suitable for research.

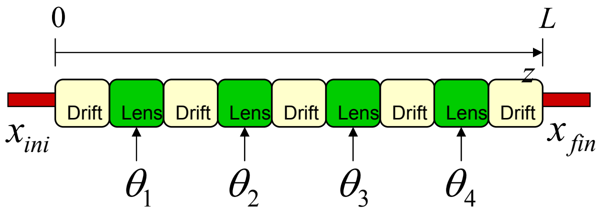
• Two “thermal” moderators and two “cold moderators will be used to service 18 beam lines.

BEAM MATCHING CHANNEL

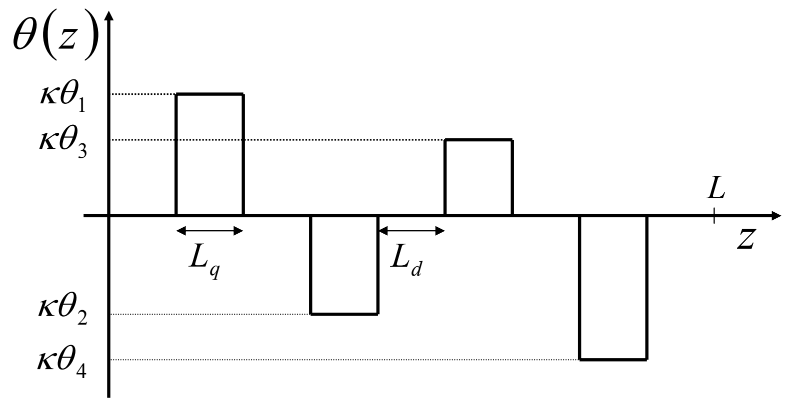
“The linac is a superposition of normal conducting and super-conducting radio-frequency cavities that accelerate the beam and magnetic lattices that provide focusing and steering.”



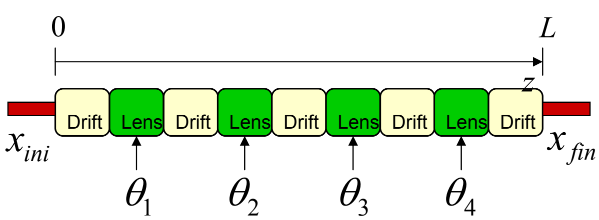
BEAM MATCHING CHANNEL



$$\begin{aligned} X'' - \theta(z)X - \frac{2K}{X+Y} - \frac{\varepsilon_X^2}{X^3} = 0 \\ Y'' + \theta(z)Y - \frac{2K}{X+Y} - \frac{\varepsilon_Y^2}{Y^3} = 0 \end{aligned}$$



BEAM MATCHING OPTIMIZATION



$$x_{ini} = \begin{bmatrix} X_{ini} \\ X'_{ini} \\ Y_{ini} \\ Y'_{ini} \end{bmatrix}, x_{fin} = \begin{bmatrix} X_{fin} \\ X'_{fin} \\ Y_{fin} \\ Y'_{fin} \end{bmatrix}, x_{tar} = \begin{bmatrix} X_{tar} \\ X'_{tar} \\ Y_{tar} \\ Y'_{tar} \end{bmatrix}$$

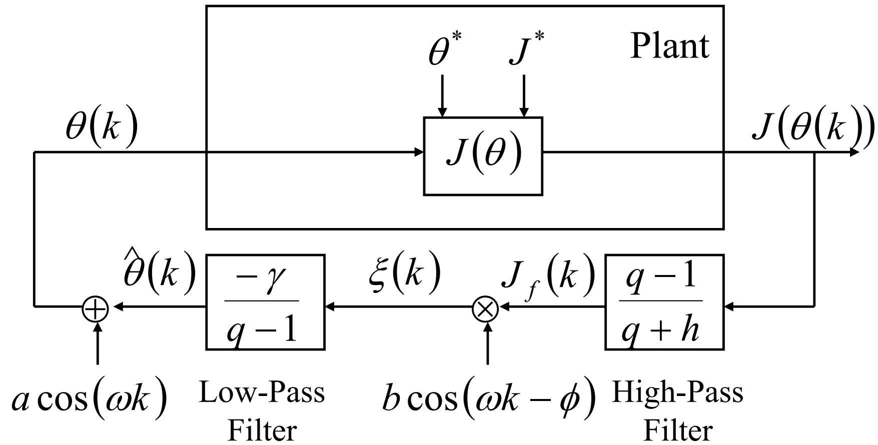
$$\boxed{J = k_1 J_1 + k_2 J_2 + k_3 J_3}$$

$$J_1 = K_X \left(X_{fin} - X_{tar}\right)^2 + K_Y \left(Y_{fin} - Y_{tar}\right)^2$$

$$J_2 = K_{dX} \left(X'_{fin} - X'_{tar}\right)^2 + K_{dY} \left(Y'_{fin} - Y'_{tar}\right)^2$$

$$J_3 = \int_o^L w(z)\left[K_{iX}\left(X(z) - X_{des}(z)\right)^2 + K_{iY}\left(Y(z) - Y_{des}(z)\right)^2\right]dz$$

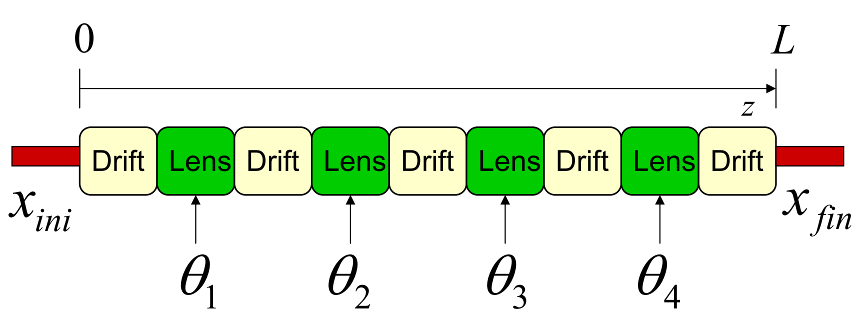
BEAM MATCHING OPTIMIZATION



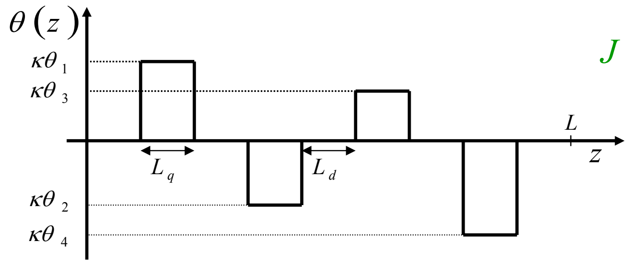
$$\boxed{\begin{aligned} J_f(k) &= -hJ_f(k-1) + J(k) - J(k-1) \\ \xi(k) &= J_f(k)b\cos(\omega k-\phi) \\ \hat{\theta}(k+1) &= \hat{\theta}(k) - \gamma\xi(k) \\ \theta(k+1) &= \hat{\theta}(k+1) + a\cos(\omega(k+1)) \end{aligned}}$$

BEAM MATCHING OPTIMIZATION

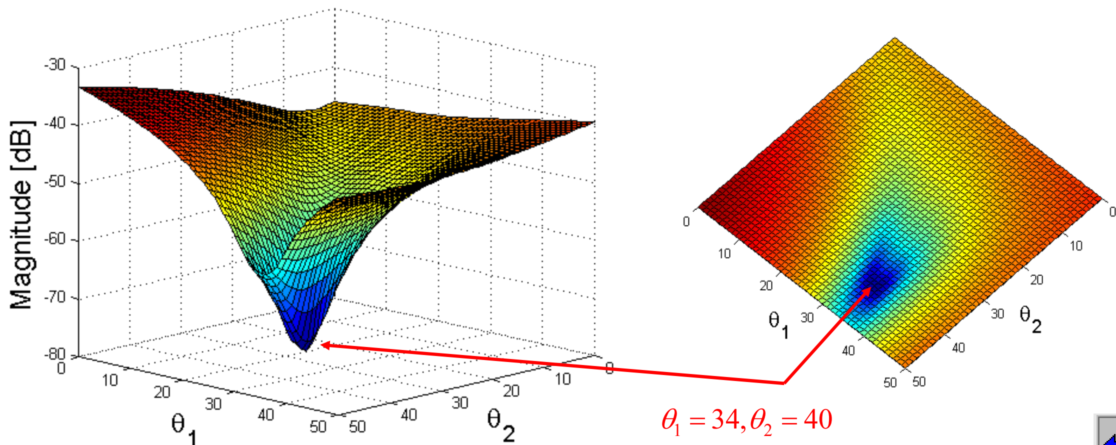
$$x_{ini} = \begin{bmatrix} 0.001474 \\ -0.006013 \\ 0.002014 \\ 0.007686 \end{bmatrix}, \quad x_{tar} = \begin{bmatrix} 0.001094 \\ -0.007864 \\ 0.003290 \\ 0.011726 \end{bmatrix}, \quad \theta(0) = \begin{bmatrix} 25 \\ -25 \\ 25 \\ -25 \end{bmatrix}$$



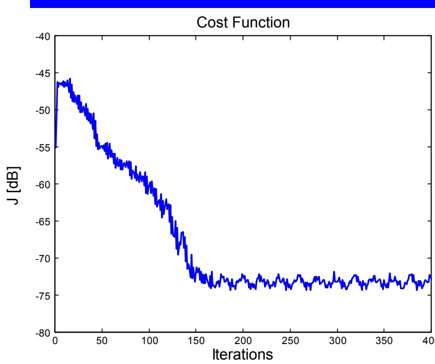
BEAM MATCHING OPTIMIZATION – 2D

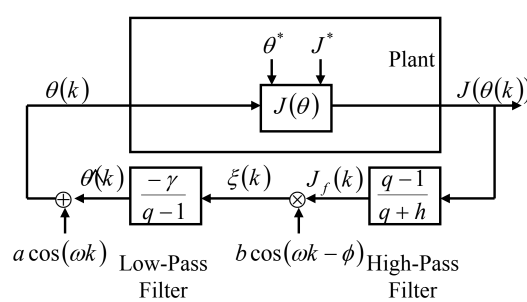


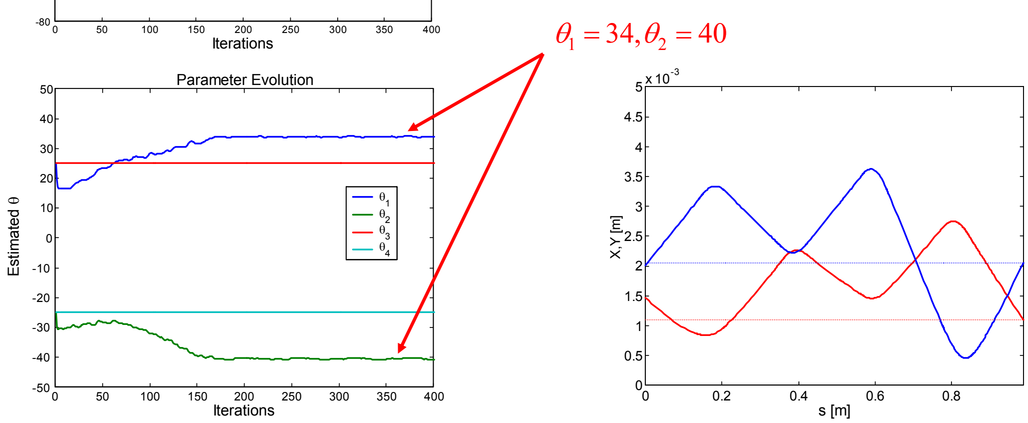
$$J = \sqrt{\left(X_f - X_{\text{target}}\right)^2 + \left(Y_f - Y_{\text{target}}\right)^2}$$



BEAM MATCHING OPTIMIZATION – 2D





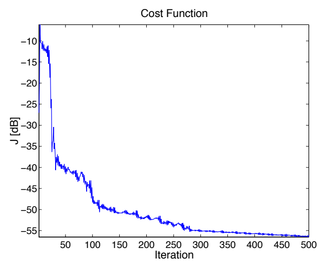


BEAM MATCHING OPTIMIZATION – 4D

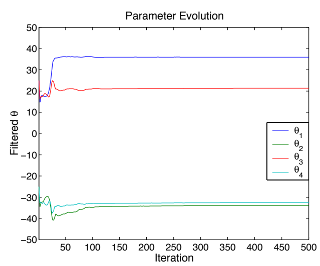
$$x_{tar} = \begin{bmatrix} 0.001094 \\ -0.007864 \\ 0.003290 \\ 0.011726 \end{bmatrix} \quad x_{fin} = \begin{bmatrix} 0.001070 \\ -0.006730 \\ 0.003289 \\ 0.011034 \end{bmatrix}$$

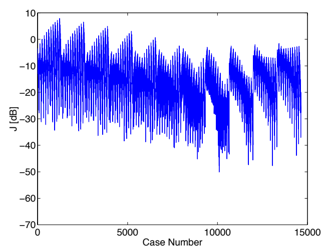
TERMINAL CONSTRAINTS ONLY

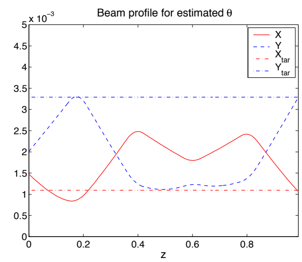
$K_X = 2000,\ K_Y = 1000,\ K_{dX} = 1,\ K_{dY} = 1, K_{iX} = K_{iY} = 0,$
$k_1 = 1,\ k_2 = 1,\ k_3 = 0.$



$$\boxed{\begin{array}{l} a_{1,2,3,4} = [2.25 \quad 2 \quad 1.75 \quad 1.5] \ \ if \ \text{-}40dB \le J \\ a_{1,2,3,4} = [0.25 \quad 0.75 \quad 0.5 \quad 0.5] \ \ if \ \text{-}50dB \le J \ < \ \text{-}40dB \\ a_{1,2,3,4} = [0.1 \quad 0.25 \quad 0.1 \quad 0.1] \ \ if \ \text{-}55dB \le J \ < \ \text{-}50dB \\ a_{1,2,3,4} = [0.05 \quad 0.05 \quad 0.05 \quad 0.05] \ \ if \ \text{-}60dB \le J \ < \ \text{-}55dB \\ a_{1,2,3,4} = [0.01 \quad 0.01 \quad 0.025 \quad 0.025] \ \ if \ J \ < \ \text{-}60dB \end{array}}$$





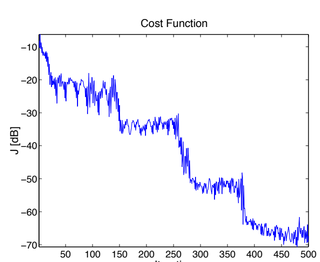


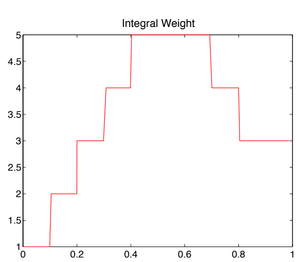
BEAM MATCHING OPTIMIZATION – 4D

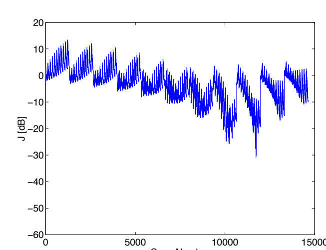
$$x_{tar} = \begin{bmatrix} 0.001094 \\ -0.007864 \\ 0.003290 \\ 0.011726 \end{bmatrix} \quad x_{fin} = \begin{bmatrix} 0.001095 \\ -0.007871 \\ 0.003291 \\ 0.011725 \end{bmatrix}$$

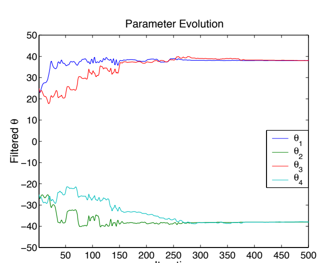
REAL TRAJECTORY AS DESIRED TRAJECTORY

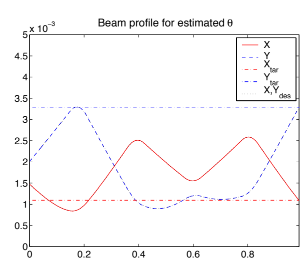
$K_X = 200,\ K_Y = 200,\ K_{dX} = 1,\ K_{dY} = 1, K_{iX} = K_{iY} = 1000,$
$k_1 = 1,\ k_2 = 1,\ k_3 = 1.$









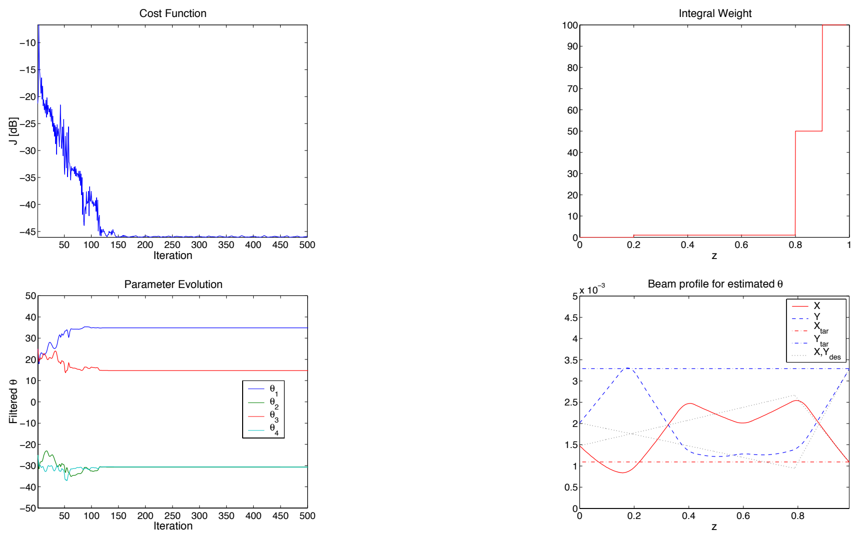


BEAM MATCHING OPTIMIZATION – 4D

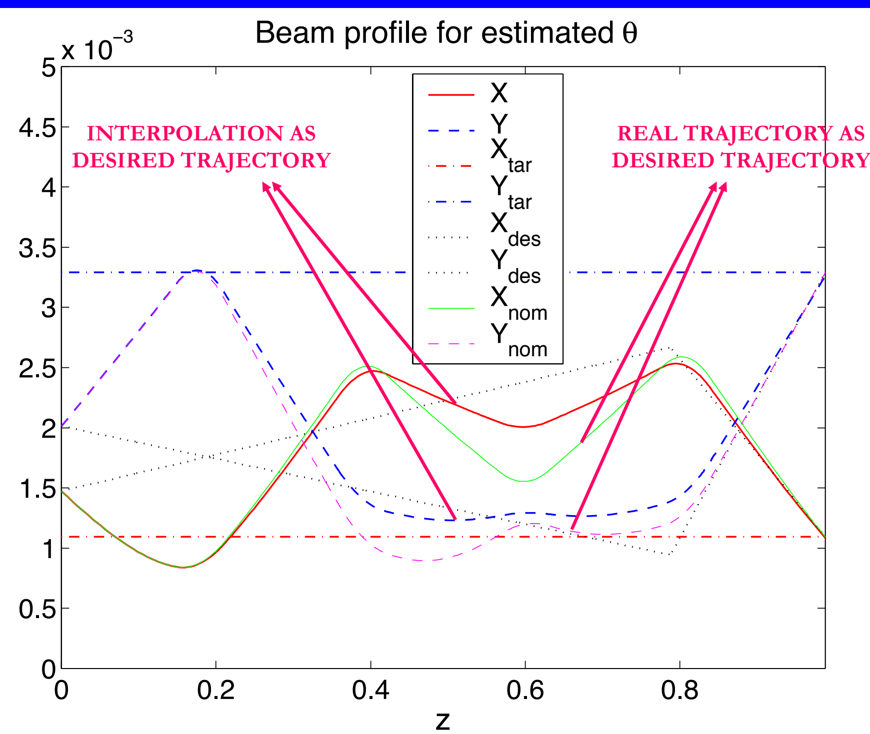
$$x_{tar} = \begin{bmatrix} 0.001094 \\ -0.007864 \\ 0.003290 \\ 0.011726 \end{bmatrix} \quad x_{fin} = \begin{bmatrix} 0.001093 \\ -0.007343 \\ 0.003280 \\ 0.010630 \end{bmatrix}$$

INTERPOLATION AS DESIRED TRAJECTORY

$K_X = 2000,\ K_Y = 2000,\ K_{dX} = 1,\ K_{dY} = 1,\ K_{iX} = K_{iY} = 50,$
$k_1 = 1,\ k_2 = 1,\ k_3 = 1.$



BEAM MATCHING OPTIMIZATION – 4D



CONCLUSIONS

A multi-parameter extremum seeking procedure has been implemented, and successfully tested in simulations, for the tuning of the lens strengths in a 4-lens matching channel.

Although the scheme shows a very fast convergence, considering that we are tuning simultaneously four parameters, it is not clear at this point if the scheme can be used for real-time optimization.

However, based on the promising results obtained in the simulation study, it is anticipated that the scheme can play an important role in an off-line design process.

We must highlight at this point the capability of the scheme of avoiding getting stuck in local minima with relatively large values of the cost function. The modification of the amplitude of the sinusoidal excitation as a function of the value of the cost function is key in this achievement.