Target Shock Wave Study

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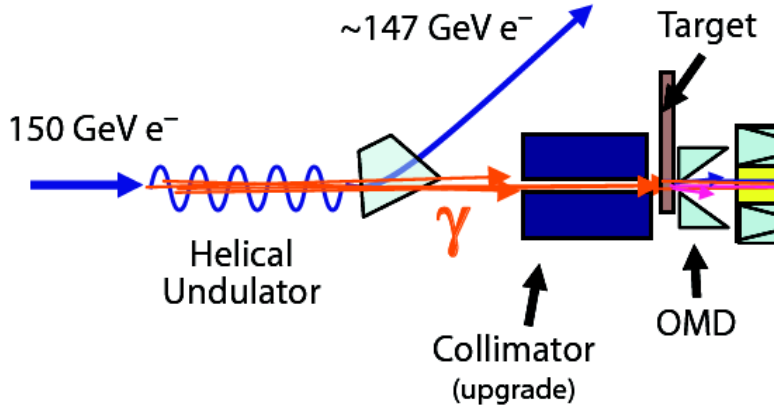
Outline

- Introduction
- Thermal shocks in target
- Hydrodynamical model
- Simulations with FlexPDE
- Discussion
- Conclusions and outlook

Introduction

- Positron source, e.g. ILC RDR:



- Polarized γ on target $\Rightarrow$ polarized e^+
- Leading production process: e^+e^- pair creation
  - Quasi-classical approximations
  - Simulation with e.g. GEANT, FLUKA $\rightarrow$ tested against data
- Possible problems: heat load, thermal shocks in target, . . .
- Rotating wheel targets
- Prototype in Daresbury (Ti alloy) [Ian's talk]
- Alternatives: Liquid metals (Bi-Pb, Hg) [e.g. A.A. Mikhailichenko, CBN06-1, 2006]

Thermal shocks in target

- Rapid energy deposition of γ beam $\Rightarrow$ pressure shock wave
- Hydrodynamical model [e.g. A.A. Mikhailichenko, CBN06-1, 2006]

  $\rightarrow$ Temperature $T = T(\vec{x}, t)$, pressure $P = P(\vec{x}, t)$

  described by hydrodynamical equations
- Simulations at LLNL and Cornell

  [talks at Argonne meeting, Sept. 2007, by T. Piggott and A.A. Mikhailichenko, respectively]
- Cornell simulations
  - FlexPDE
  - Large negative pressure at $\mathcal{O}(10^{-10}$ s) at target exit
  - Results: *"Ti target not surviving with present margins"*

Hydrodynamical model

Model used for Cornell simulations

[A.A. Mikhailichenko, CBN06-1, 2006, talk at Argonne meeting]

- Temperature: $\nabla(k\nabla T) + \dot{Q} = \rho c_V \dot{T}$

  $\dot{Q}(\vec{x}, t)$: density of energy deposition

  k: thermal conductivity; c_V: heat capacity; ρ: density

- Pressure: $\ddot{P} - \nabla(c_0^2 \nabla P) = \Gamma / V_0 \ddot{Q}$

  c_0: speed of sound; $\Gamma = \Gamma(V) = V/c_V(\partial P/\partial T)_V$: Grüneisen coefficient

- Gaussian distribution of energy deposition:

$$\dot{Q} = \sum_j \frac{2cQ_{\text{bunch}}}{\pi\sqrt{\pi}\sigma_z\sigma_\perp^2 l_T} \frac{z}{l_T} \exp\left(-\frac{(z + z_0 - c(t - jt_0))^2}{\sigma_z^2}\right) \exp\left(-\frac{r^2}{\sigma_\perp^2}\right)$$

  $\int \dot{Q}(\vec{x}, t) dV dt = Q_{\text{bunch}}$; $\sigma_z, \sigma_\perp$: bunch size; l_T: target thickness

- Density of energy distribution: $Q(\vec{x}) = \int \dot{Q}(\vec{x}, t) dt$

Simulations with FlexPDE

- FlexPDE 6.12 available in Zeuthen [S. Riemann, A. Schälicke, A. Ushakov]
- Solves Partial Differential Equations (PDEs)
- Target materials
  - Ti: $k = 0.0067\ \frac{\mathrm{W}}{\mathrm{mm\,K}}$, $c_V = 0.5263\ \frac{\mathrm{J}}{\mathrm{g\,K}}$, $\rho = 4.43 \cdot 10^{-3}\ \frac{\mathrm{g}}{\mathrm{mm}^3}$, $c_0 = 5 \cdot 10^6\ \frac{\mathrm{mm}}{\mathrm{s}}$, $\Gamma = \Gamma_0 = 1.18$
  - Pb: $k = 0.033\ \frac{\mathrm{W}}{\mathrm{mm\,K}}$, $c_V = 0.1287\ \frac{\mathrm{J}}{\mathrm{g\,K}}$, $\rho = 11.34 \cdot 10^{-3}\ \frac{\mathrm{g}}{\mathrm{mm}^3}$, $c_0 = 1.28 \cdot 10^6\ \frac{\mathrm{mm}}{\mathrm{s}}$, $\Gamma = \Gamma_0 = 2.46$
- Bunch size
  - RDR: $\sigma_z = 0.3$ mm, $\sigma_\perp = 1.5$ mm
  - Small bunch: $\sigma_z = 0.05$ mm, $\sigma_\perp = 0.25$ mm
- Length unit in mm $\Rightarrow$ pressure in MPa

Simulations with FlexPDE

- 2-dim description of target via cylinder coordinates

  $\longrightarrow$ boundaries used: $z = 0 \longrightarrow 15$ mm

  $r = 0 \longrightarrow 15$ mm for RDR bunch size

  $r = 0 \longrightarrow 3$ mm for small bunch size

- Boundary conditions:

  $P = 0$ and $T = 300$ K on target surface ($z = 0$, $z = 15$ mm)

  Natural boundary conditions "inside" target ($r = 0$, $r = r_{\text{max}}$)

- $Q_{\text{bunch}} = 0.53$ J: deposited energy energy by one bunch

  estimated from FLUKA simulations

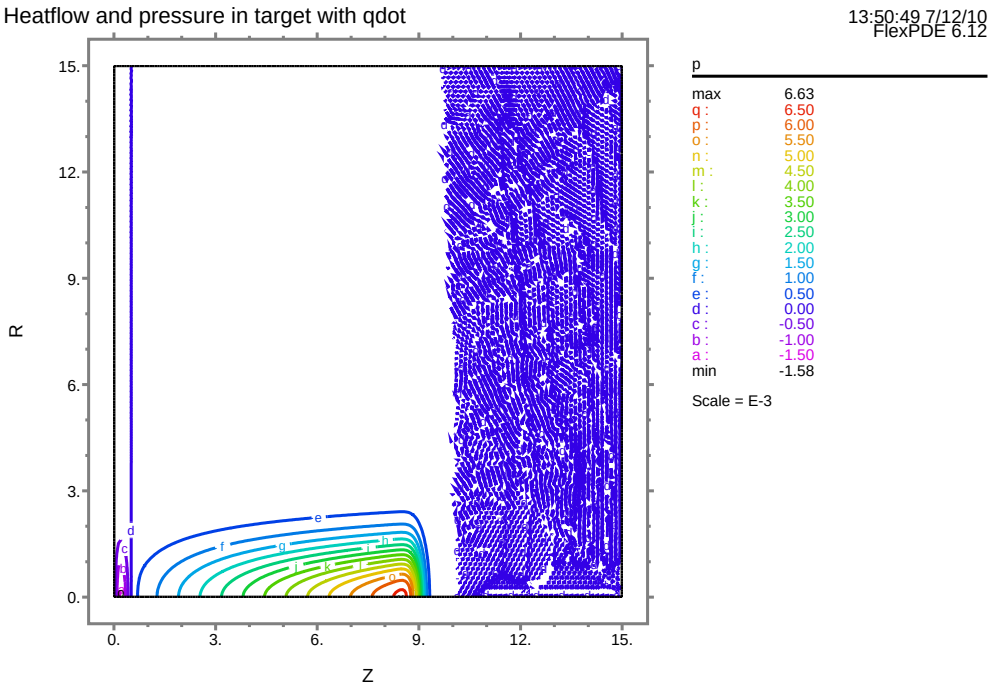
  [Zeuthen group: S. Riemann, A. Schälicke, A. Ushakov]

Simulations with FlexPDE

Pressure P

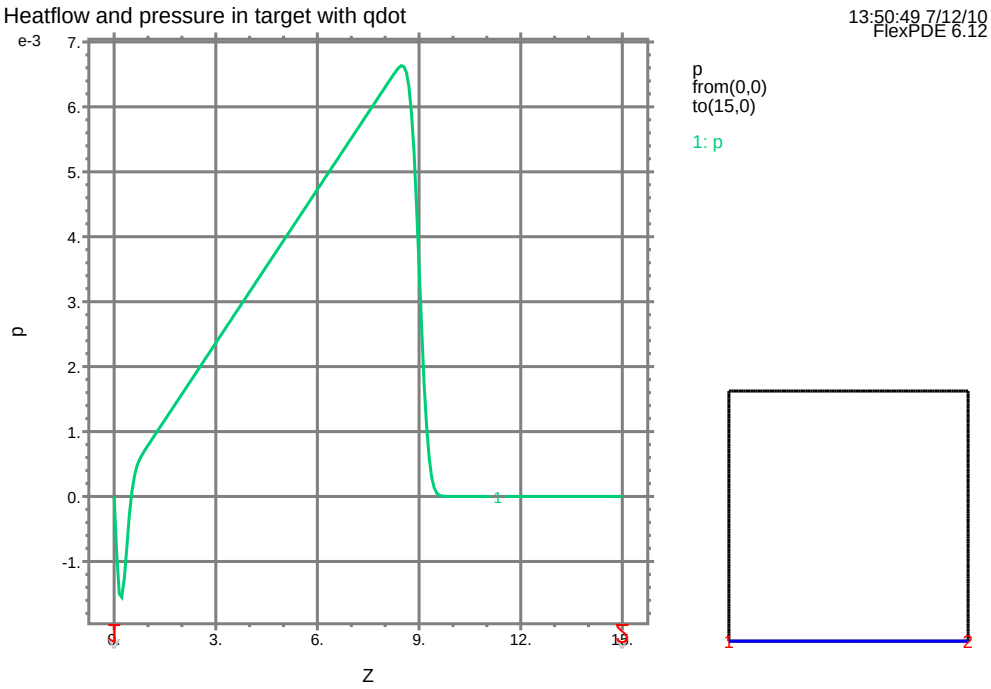
Ti target, RDR bunch size, $t = 3 \times 10^{-11}$ s

Contours of P in MPa



pressure_qdot5_1.2: Cycle=665 Time= 3.0000e-11 dt= 4.2376e-14 P2 Nodes=44405 Cells=22002 RMS Err= 5.2e-9
Vol_Integral= 0.221388

P on beam axis



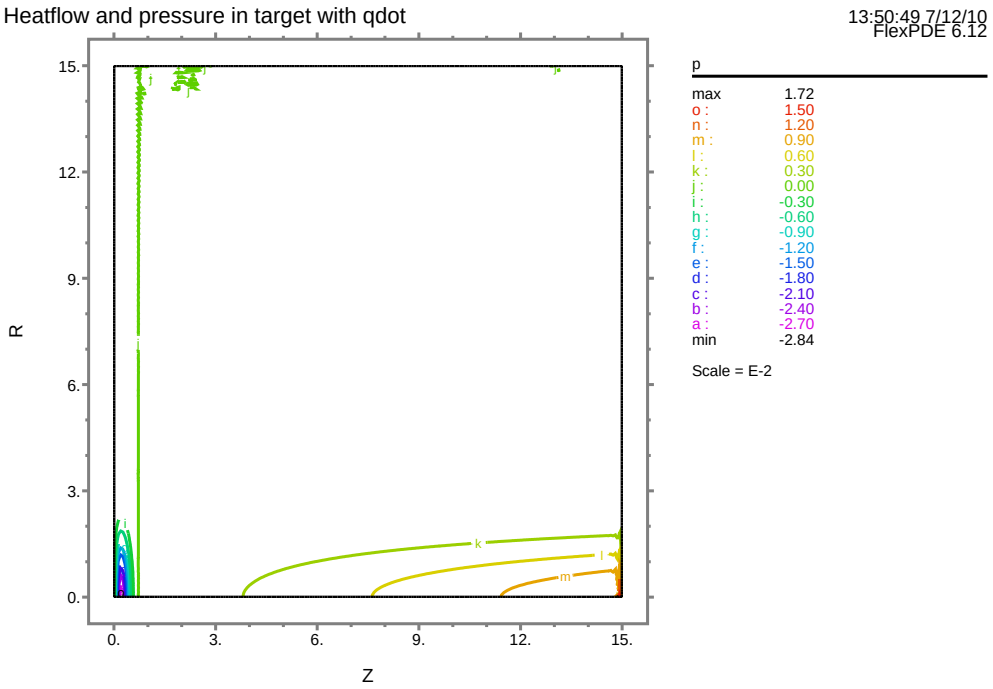
pressure_qdot5_1.2: Cycle=665 Time= 3.0000e-11 dt= 4.2376e-14 P2 Nodes=44405 Cells=22002 RMS Err= 5.2e-9
Surf_Integral= 1.968436e-6

Simulations with FlexPDE

Pressure P

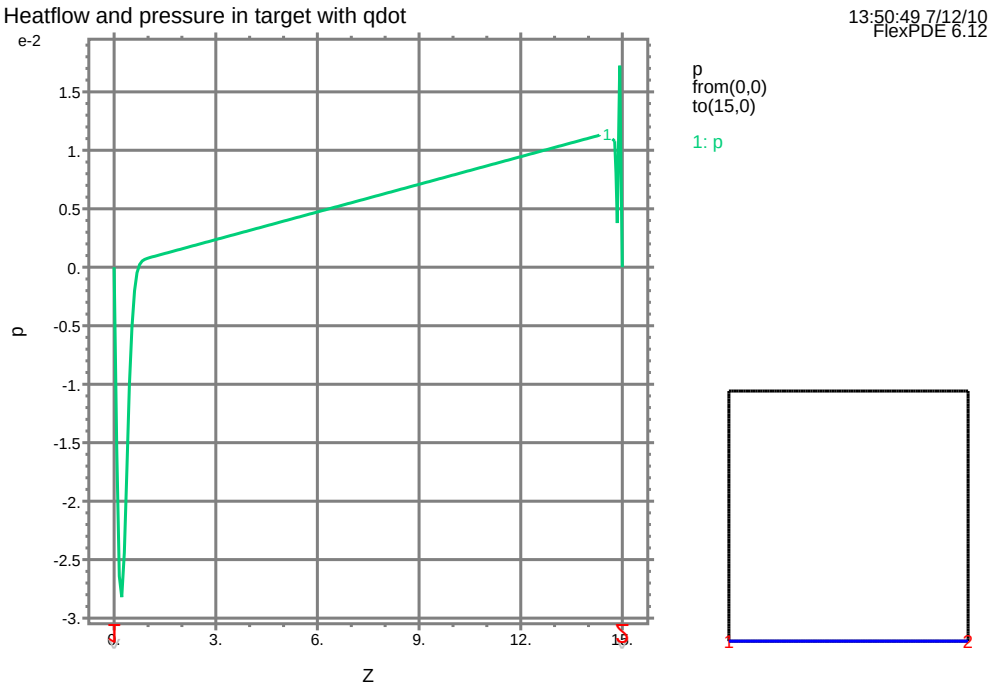
Ti target, RDR bunch size, $t = 5 \times 10^{-10}$ s

Contours of P in MPa



pressure_qdot5_1.2: Cycle=10065 Time= 5.0000e-10 dt= 4.2376e-14 P2 Nodes=44405 Cells=22002 RMS Err= 1.e-11
Vol_Integral= 0.553077

P on beam axis



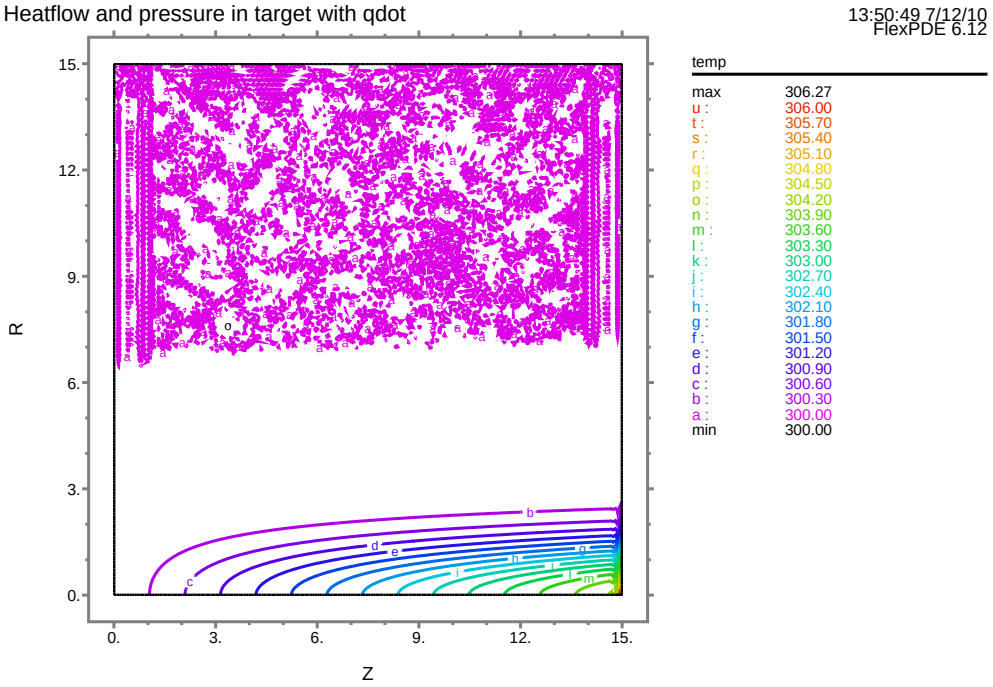
pressure_qdot5_1.2: Cycle=10065 Time= 5.0000e-10 dt= 4.2376e-14 P2 Nodes=44405 Cells=22002 RMS Err= 1.e-11
Surf_Integral= 4.904573e-6

Simulations with FlexPDE

Temperature T

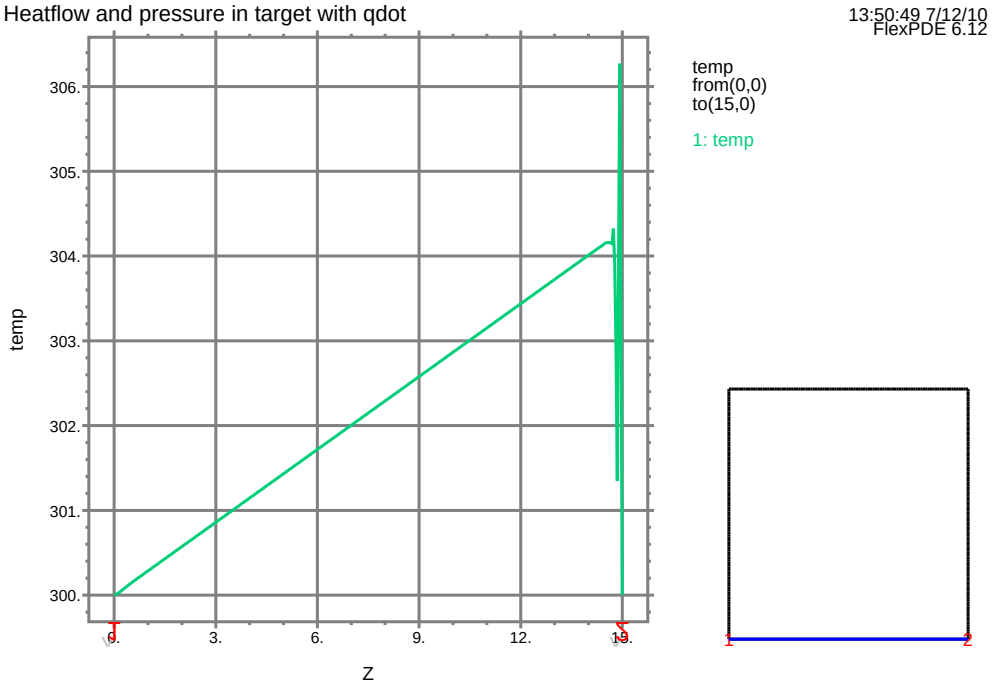
Ti target, RDR bunch size, $t = 5 \times 10^{-10}$ s

Contours of T in K



pressure_qdot5_1.2: Cycle=10065 Time= 5.0000e-10 dt= 4.2376e-14 P2 Nodes=44405 Cells=22002 RMS Err= 1.e-11
Vol_Integral= 3181089.

T on beam axis



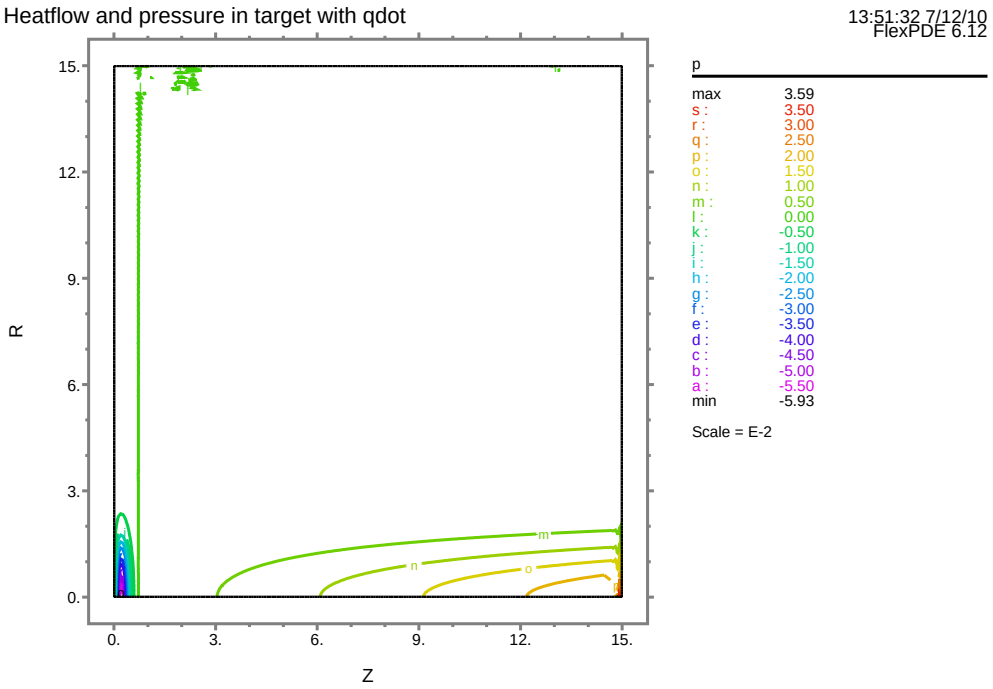
pressure_qdot5_1.2: Cycle=10065 Time= 5.0000e-10 dt= 4.2376e-14 P2 Nodes=44405 Cells=22002 RMS Err= 1.e-11
Surf_Integral= 0.284753

Simulations with FlexPDE

Pressure P

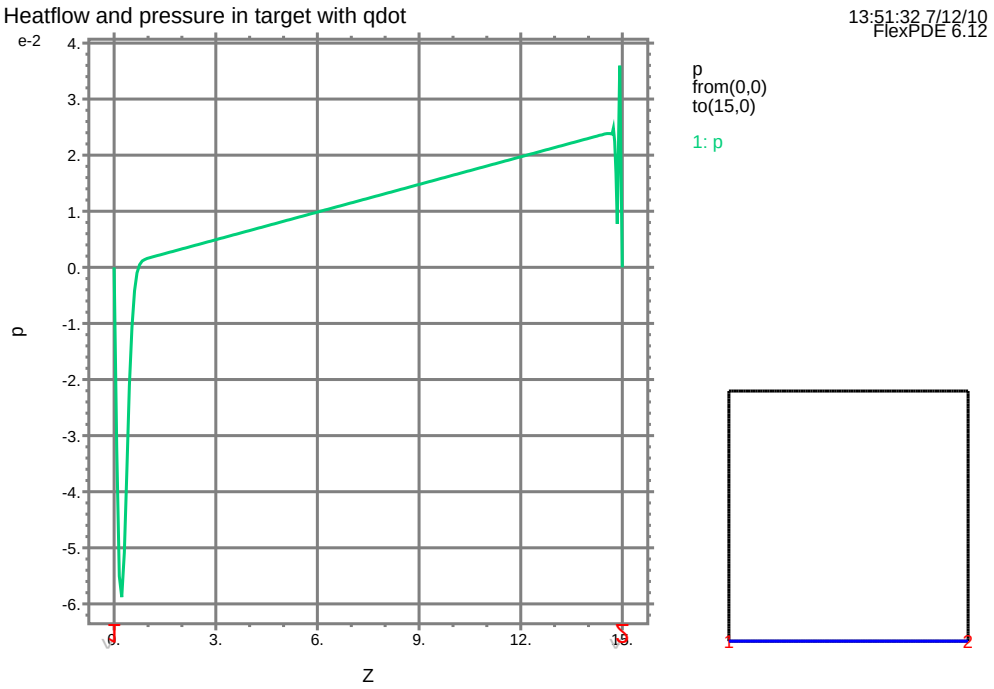
Pb target, RDR bunch size, $t = 5 \times 10^{-10}$ s

Contours of P in MPa



pressure_qdot5_Pb_1.2: Cycle=10065 Time= 5.0000e-10 dt= 4.2376e-14 P2 Nodes=44405 Cells=22002 RMS Err= 9.e-12
Vol_Integral= 1.153018

P on beam axis



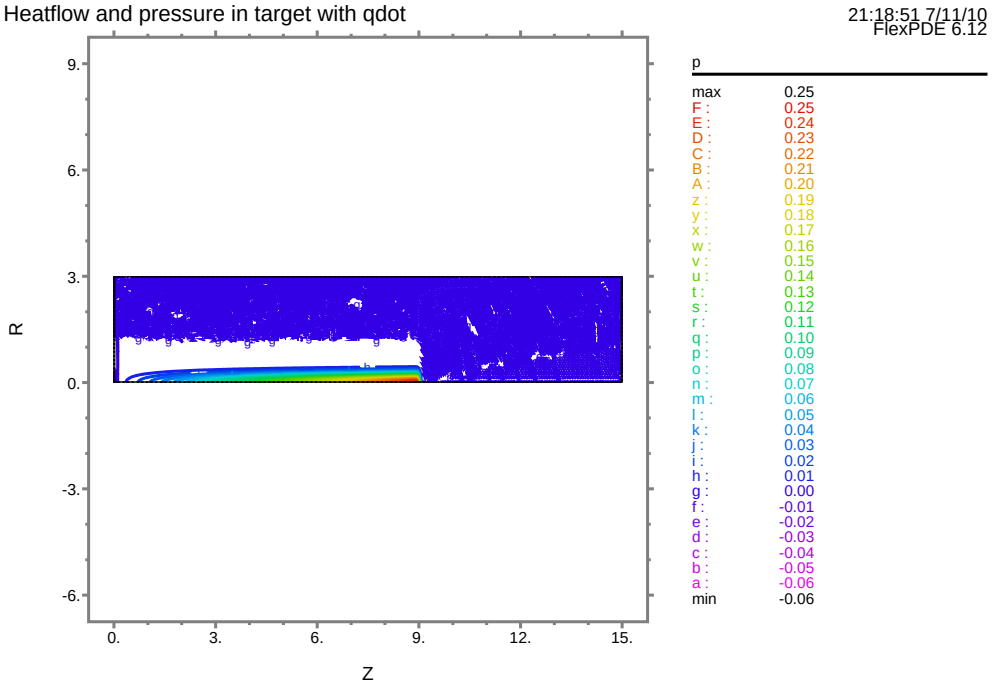
pressure_qdot5_Pb_1.2: Cycle=10065 Time= 5.0000e-10 dt= 4.2376e-14 P2 Nodes=44405 Cells=22002 RMS Err= 9.e-12
Surf_Integral= 1.022426e-5

Simulations with FlexPDE

Pressure P

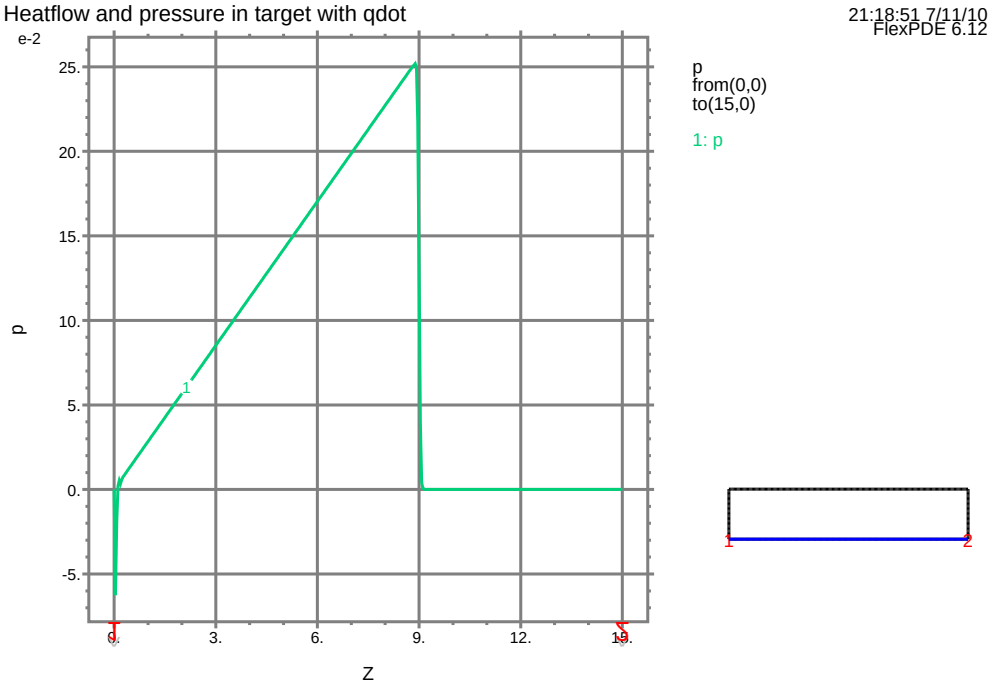
Ti target, small bunch size, $t = 3 \times 10^{-11}$ s

Contours of P in MPa



pressure_qdot5_2.4: Cycle=1291 Time= 3.0000e-11 dt= 2.4472e-14 P2 Nodes=36633 Cells=18076 RMS Err= 2.7e-4
Vol_Integral= 0.224345

P on beam axis



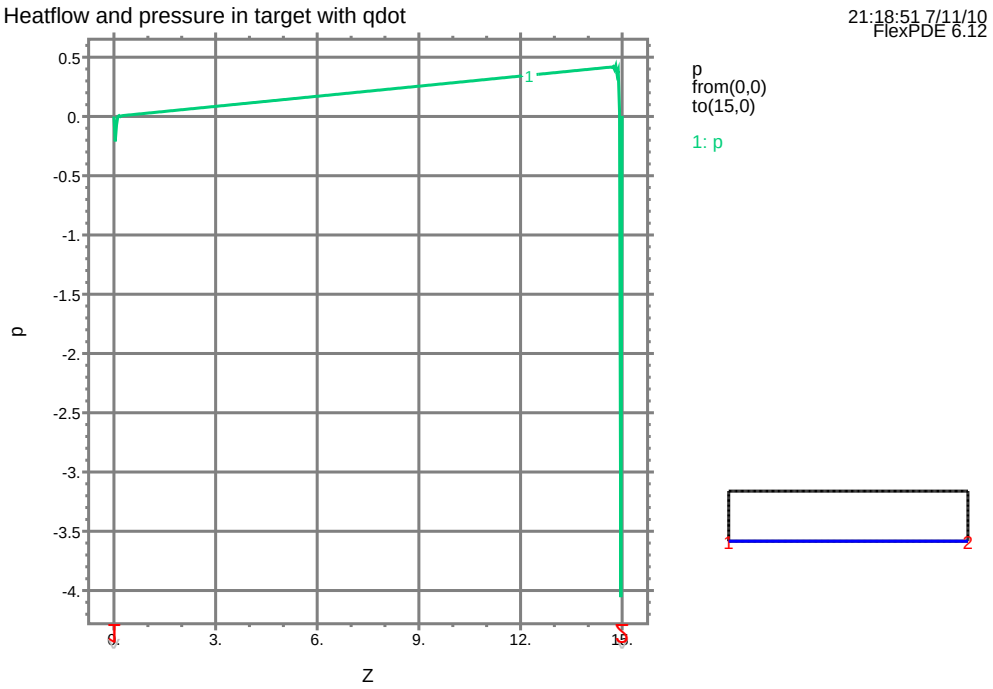
pressure_qdot5_2.4: Cycle=1291 Time= 3.0000e-11 dt= 2.4472e-14 P2 Nodes=36633 Cells=18076 RMS Err= 2.7e-4
Surf_Integral= 7.206122e-5

Simulations with FlexPDE

Pressure P **Temperature T**

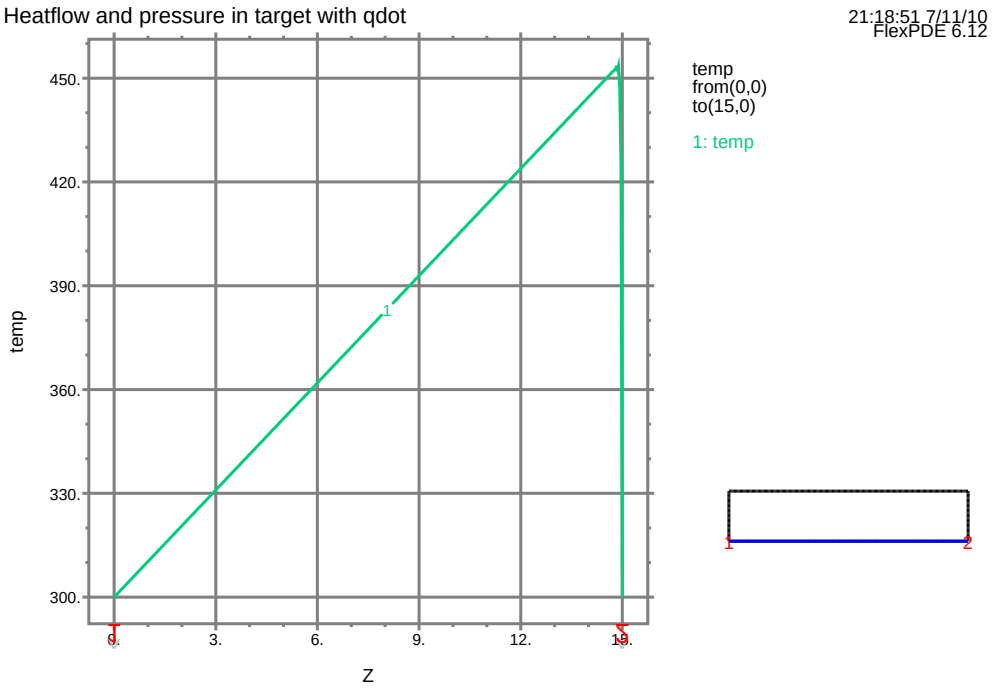
Ti target, small bunch size, $t = 10^{-10}$ s

P [MPa] on beam axis



pressure_qdot5_2.4: Cycle=3108 Time= 1.0000e-10 dt= 4.1240e-14 P2 Nodes=36662 Cells=18089 RMS Err= 4.1e-6
Surf_Integral= 1.876539e-4

T [K] on beam axis



pressure_qdot5_2.4: Cycle=3108 Time= 1.0000e-10 dt= 4.1240e-14 P2 Nodes=36662 Cells=18089 RMS Err= 4.1e-6
Surf_Integral= 0.355437

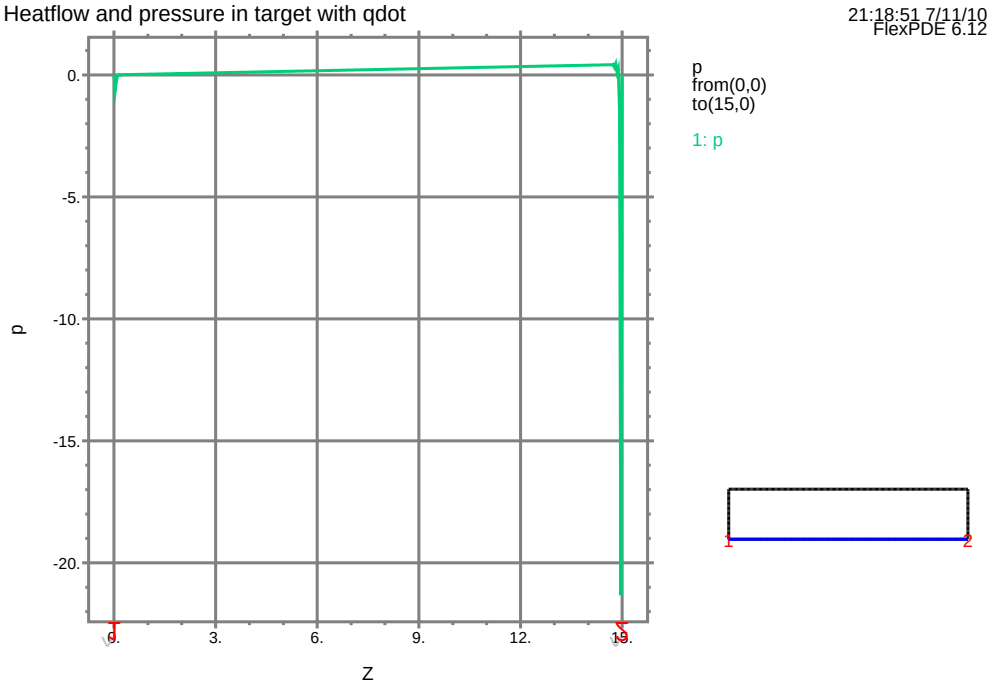
Simulations with FlexPDE

Pressure P

Ti target, small bunch size

$t = 3 \times 10^{-10}$ s

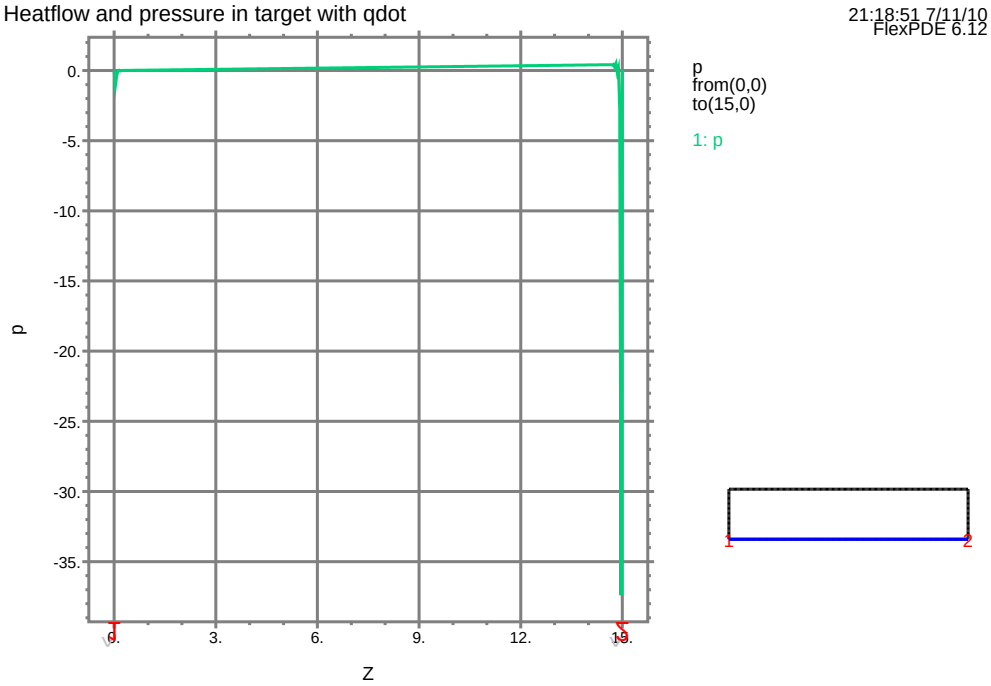
P [MPa] on beam axis



pressure_qdot5_2.4: Cycle=7108 Time= 3.0000e-10 dt= 4.1240e-14 P2 Nodes=36662 Cells=18089 RMS Err= 8.5e-7
Surf_Integral= 1.405651e-4

$t = 5 \times 10^{-10}$ s

P [MPa] on beam axis



pressure_qdot5_2.4: Cycle=11108 Time= 5.0000e-10 dt= 4.1240e-14 P2 Nodes=36662 Cells=18089 RMS Err= 5.1e-7
Surf_Integral= 9.667806e-5

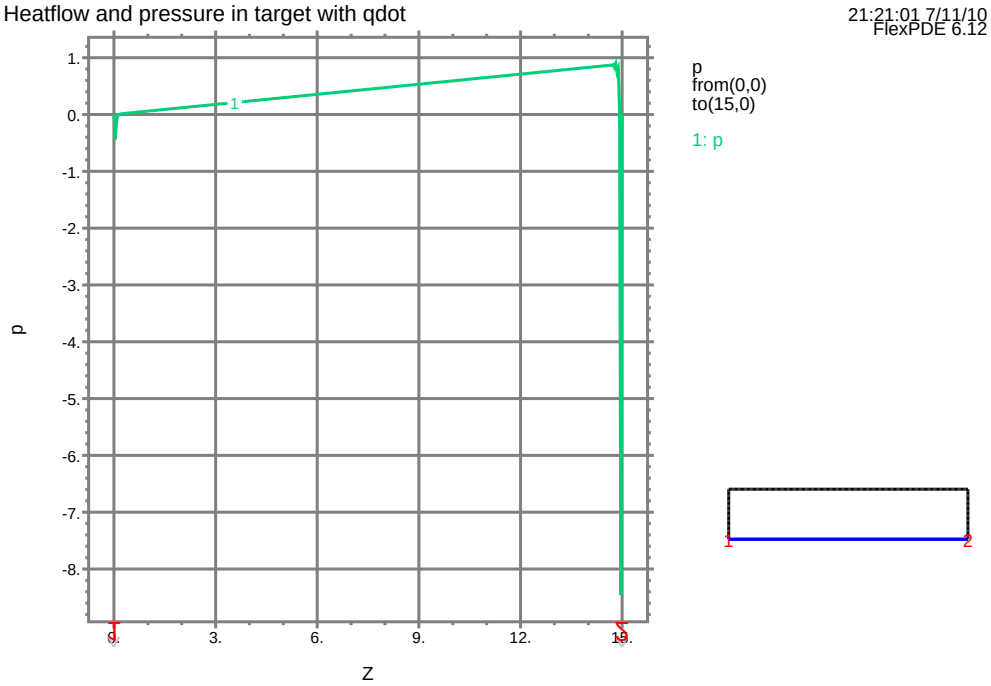
Simulations with FlexPDE

Pressure P

Pb target, small bunch size

$t = 10^{-10}$ s

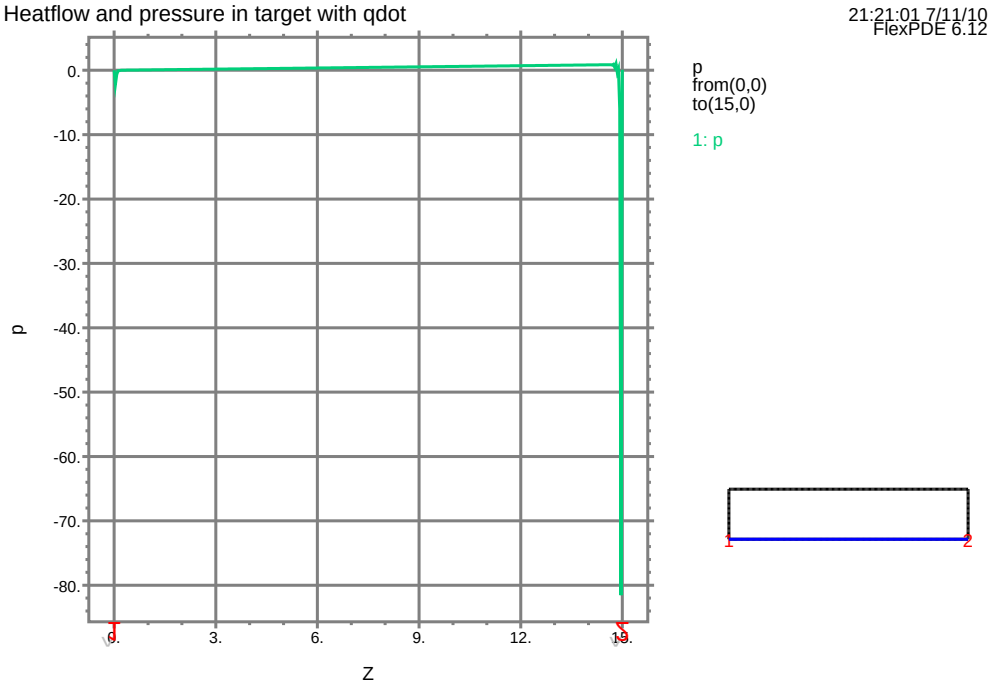
P [MPa] on beam axis



pressure_qdot5_Pb_2.4: Cycle=3112 Time= 1.0000e-10 dt= 4.1240e-14 P2 Nodes=36662 Cells=18089 RMS Err= 4.1e-6
Surf_Integral= 3.911995e-4

$t = 5 \times 10^{-10}$ s

P [MPa] on beam axis



pressure_qdot5_Pb_2.4: Cycle=11112 Time= 5.0000e-10 dt= 4.1240e-14 P2 Nodes=36662 Cells=18089 RMS Err= 4.6e-7
Surf_Integral= 1.920456e-4

Discussion

- Results:
  - Large negative pressure at target exit for small bunch size
    P = $\mathcal{O}$(10–100 MPa)
  - So far simulated until $t = 10^{-9}$ s: P keeps growing
  - Effect seems absent (or at least weaker?) for RDR bunch size

- Tensile strengths: Ti: 965 MPa
  Pb: 18.0 MPa

- Is Ti target for RDR bunch size safe?

Conclusions and outlook

For final conclusions need to test:

- What is maximum negative pressure?
  - PDE for P: $\ddot{P} - \nabla(c_0^2 \nabla P) = \Gamma / V_0 \ddot{Q}$
  - Need to simulate until $t \sim 10^{-6}$ s?
- For what bunch size does effect set in?
  - Need to test other bunch sizes
  - How is it related to beam intensity $\leftrightarrow Q_{\text{bunch}}$
- Improve model
  - Include volume effects ($\Gamma = \Gamma(V)$)
  - Compression pressure P_c