Stress issues at the ILC target
(status report Hamburg+DESY)

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for
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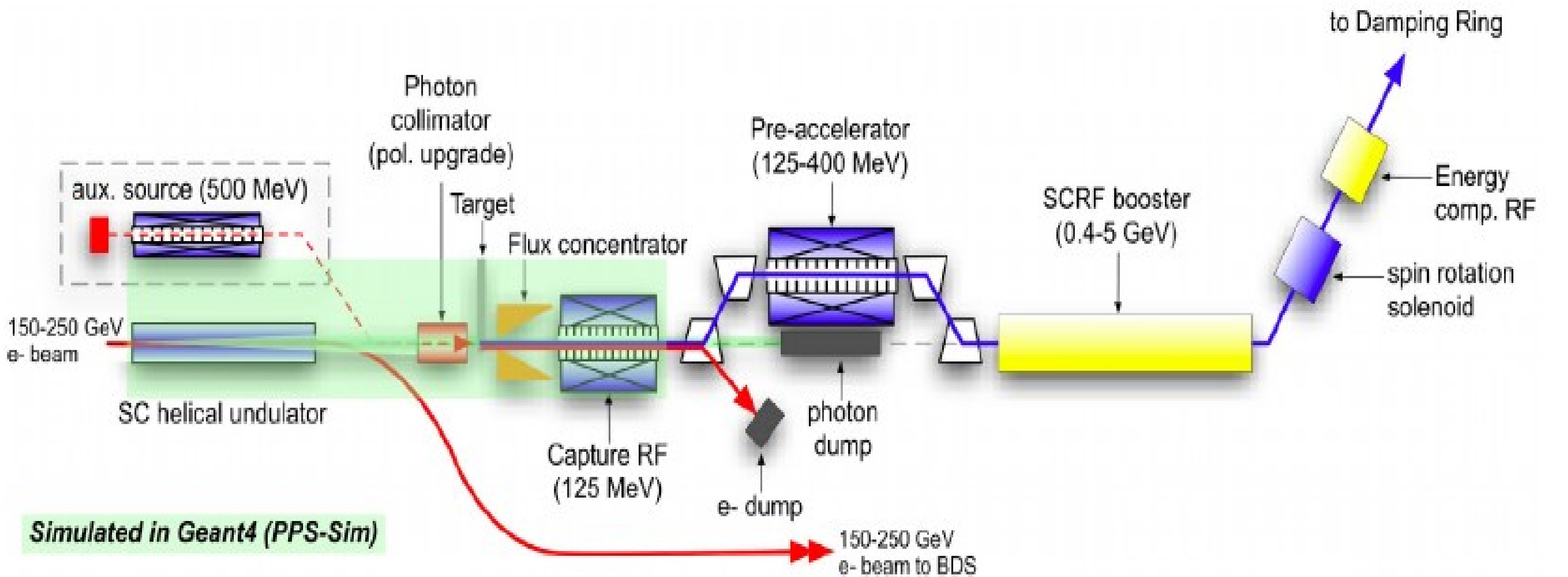
- **Short intro**
- **Current status**
- **Future plans of DESY and Hamburg**

LINEAR COLLIDER COLLABORATION

ILC Positron Target

- •`Positron Source is the only area of ILC where real R&D is still remaining' (K. Yokoya)



- **0.4 X_0 thickness, Ti6Al4V rotating rim,100 m/s tangential speed**
- **e+ yield: 1.5 e+/e- (50% safety margin)**

Technical facts

- P(e+) (always yield ≥1.5 imposed)

P(e-) ~ 80-90%

√s=240 GeV: 120 GeV e- drive beam

– Undulator with 231 m (K=0.92, λ=11.5 mm), collimator r=3.5 mm

– P(e+)~ 40%

√s=350GeV: 175 GeV e- drive beam

– Collimator with r=1.2 mm,P(e+)~ 56%

√s=500GeV: 250 GeV e- drive beam

– Undulator with 144 m, coll. r=0.7mm

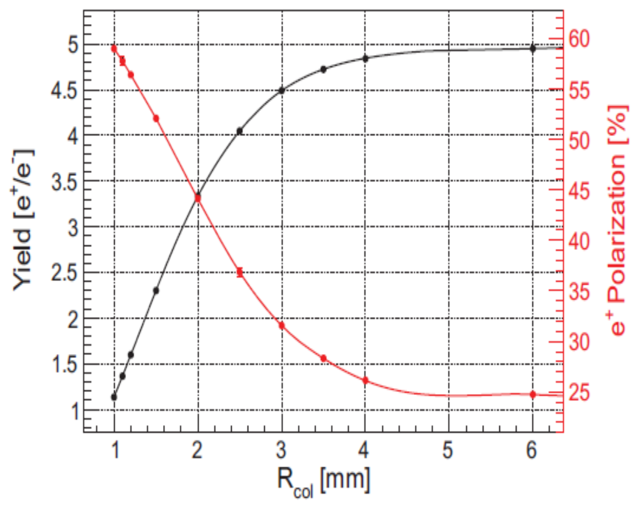
– P(e+)~59%

√s=1 TeV: 500 GeV e- drive beam

– λ_u = 4:3 cm, 176 m length, coll r=0.9mm, K=2.5

– P(e+)~54%

Eb=175 GeV



A. Ushakov, LC note

Energy deposition at the ILC e+ source

Sabine

Energy deposition in targets

- photon target, Ti wheel, Ø = 1m, 2000rpm
  - PEDD per bunch train: 67.5 J/g (101.3 J/g h.lumi) ⇔ ΔT_{max} = 130K (195K)
    - Energy deposition per bunch: 0.31 … 0.72J ⇔ $\Delta T \approx O(1K)$
    - Polarization upgrade to 50% or 60% increases E_{dep} and PEDD
  - Fatigue limit in Ti : $\Delta T \sim 600K$ (340MPa)
- 300Hz target; tungsten
  - Peak energy deposited density (PEDD) per triplet below 30J/g (35J/g)

Energy deposition in collimator

- Collimator is partial γ beam dump, absorbs up to 50% of γ beam power
- Design strongly coupled to drive e- beam energy

Dynamic response to energy deposition

- energy deposition, instantaneous temperature rise ⇔ stress waves
- After few (tens) microseconds stress becomes quasistatic

Material response depends on

- beam energy, bunch/pulse length,
- deposited energy, material parameters

Andriy

Energy deposition at target at 120 GeV drive beam

Source Parameters:

- 120 GeV e- beam
- Undulator K = 0.92
- Optimal phase of capture RF
- 8.5 mm aperture radius of FC
- 192.5 m undulator active length
- 266.5 m undulator lattice length
- 412 m between undulator and target

Photons on Target:

E_1 ph = 6.4 MeV

(Eph)= 6.8 MeV

(Pph) = 54.1 kW

Energy Deposited in Target:

(E_{dep}) = 9.2% (5 kW)

- Target rotated with 100 m/s tangential speed
- 554 ns bunch spacing

Peak Energy Deposition Density

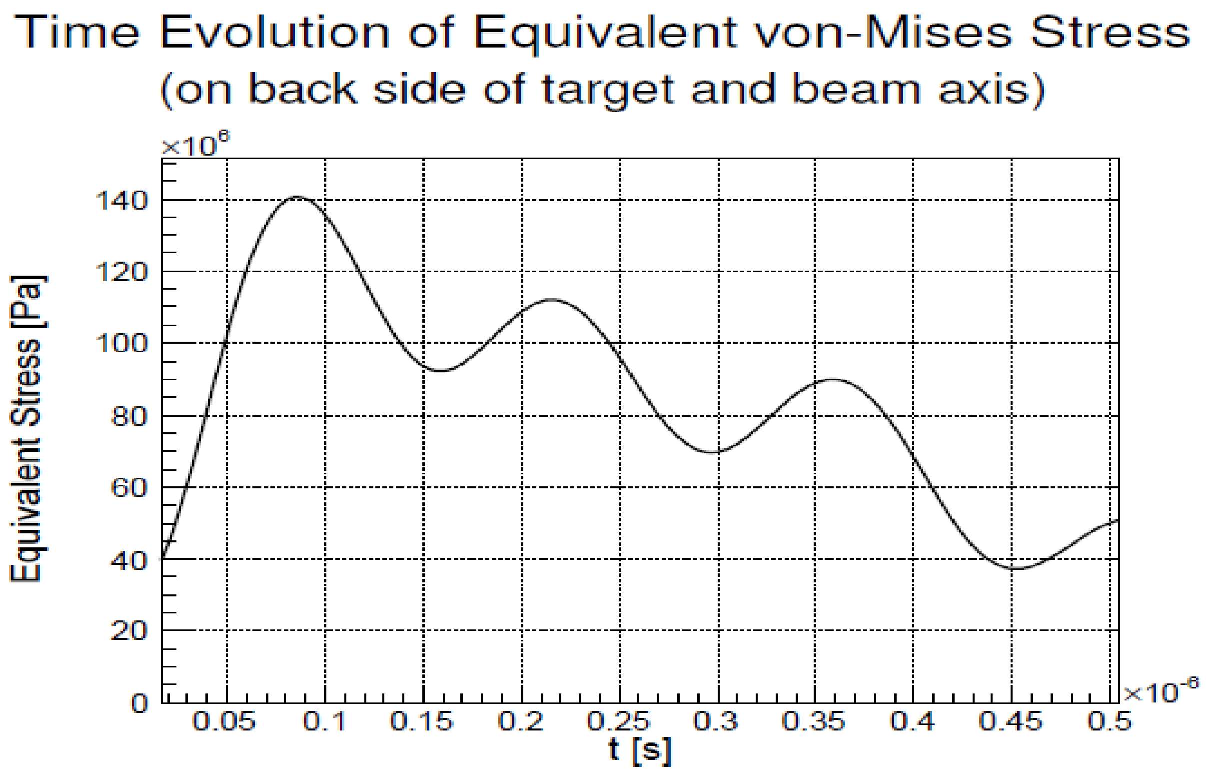
PEDD ~44 J/g

Temperature Rise

ΔT ~84 K per pulse

Andriy

Thermal Target Stress at 120 GeV drive beam (ANSYS)



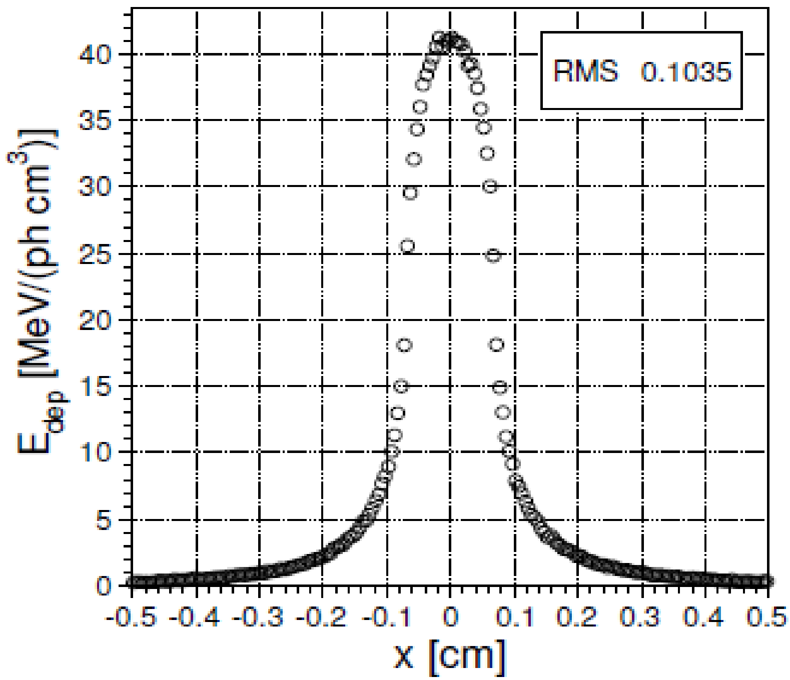
- **Max. Equivalent Stress: 140 MPa (27.5% of Fatigue Strength)**
- **Ti6Al4, Fatigue Strength (Unnotched 10M Cycles): 510 MPa**

Stress at E_b=250~GeV

Andriy

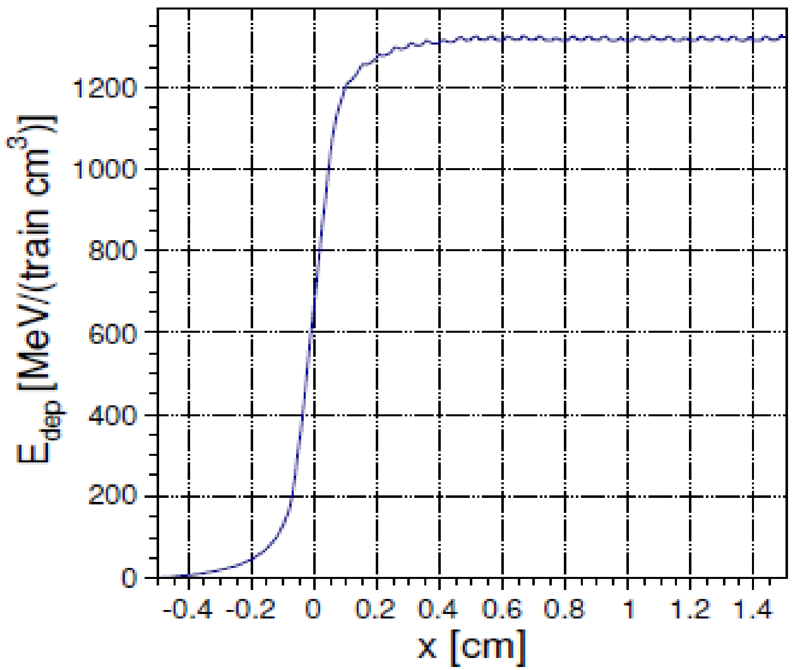
250 GeV e^-, $K = 0.92$, $R_c = 0.7$ mm,
554 ns bunch spacing, 100 m/s rot. speed

Energy Deposition after Bunch



E_{max} = 1.6 J/(g bunch)

Energy Deposition after Bunch Train



E_{max} = 52 J/(g train)

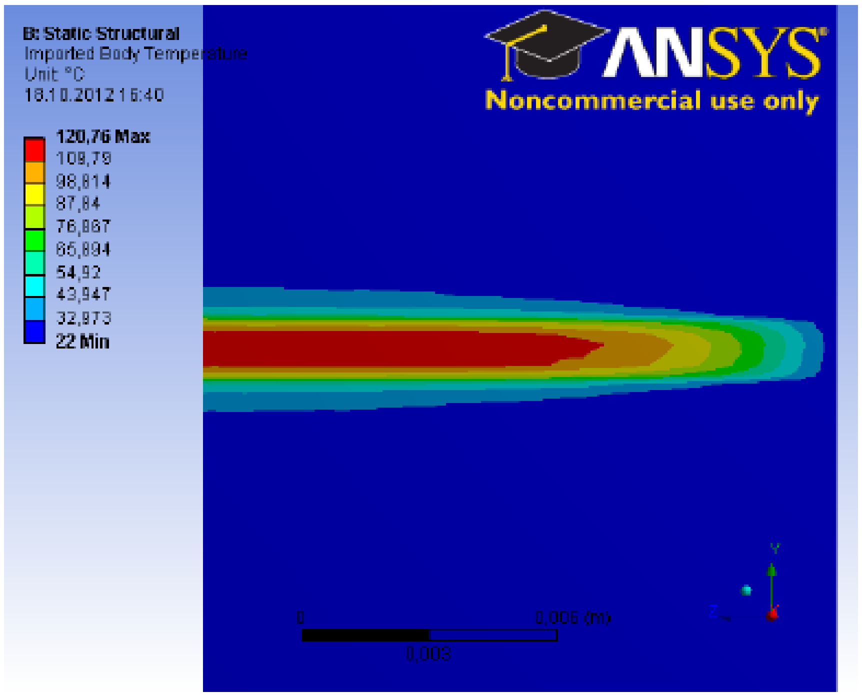
Bunch Overlapping Factor $\equiv E_{max\ Train}/E_{max\ Bunch} = 32.5$

Temperatur distribution and maximal stress

Andriy

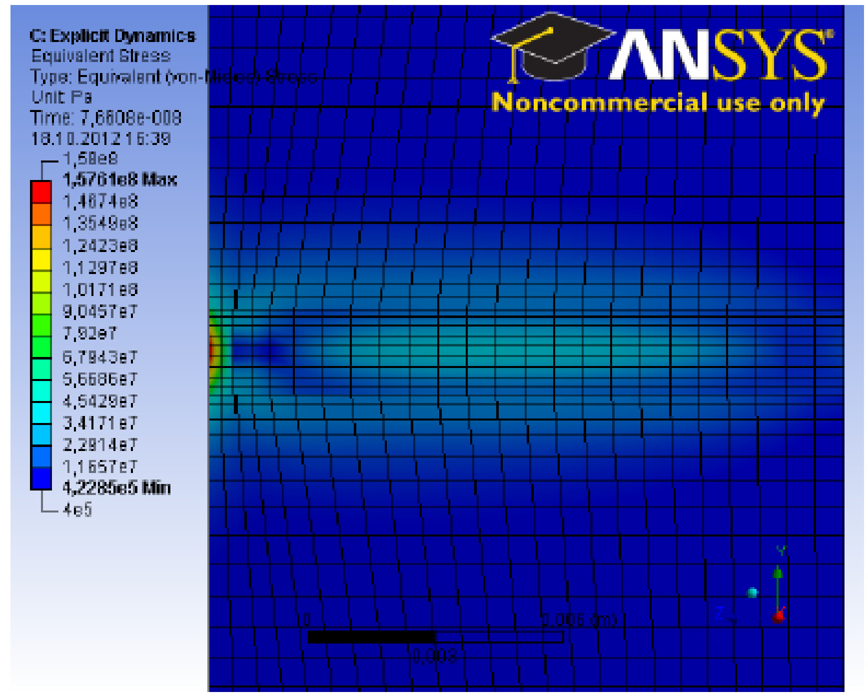
250 GeV e⁻, $K = 0.92$, $L_u = 143.5$ m (active), $R_c = 0.7$ mm

Temperature Map after Bunch Train



$\Delta T_{max} \simeq 100$ K

Max. Dynamic Stress in Target



$\sigma_{max} \simeq 160$ MPa

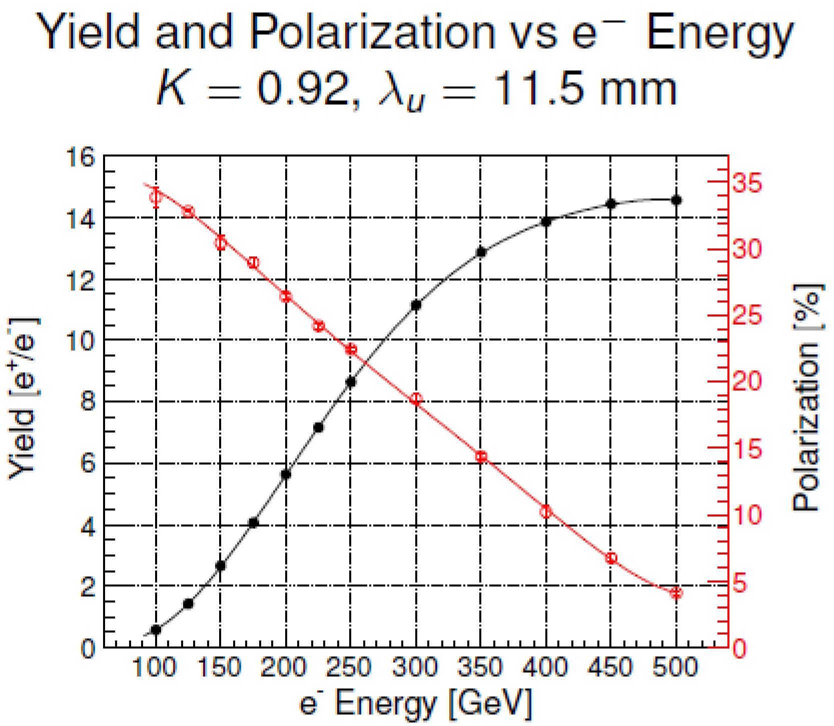
www.matweb.com – Ti6Al4V (Grade 5), Annealed:
Tensile Yield Strength = **880 MPa**, Fatigue Strength = **510 MPa** at 10^7 Cycles

Base-Line Undulator at High Energies

Andriy

Increase of e- beam energy results in

- ➢ **Higher energy of photons (~E^2)**
- • **Bigger e+ yield**
- • **Bigger energy spread**
- • **More difficult to capture**
- ➢ **Smaller angle of photons (~E^{-1})**
- • **Higher photon density**
- • **Higher PEDD per bunch**
- ➢ **Smaller e+ polarization**



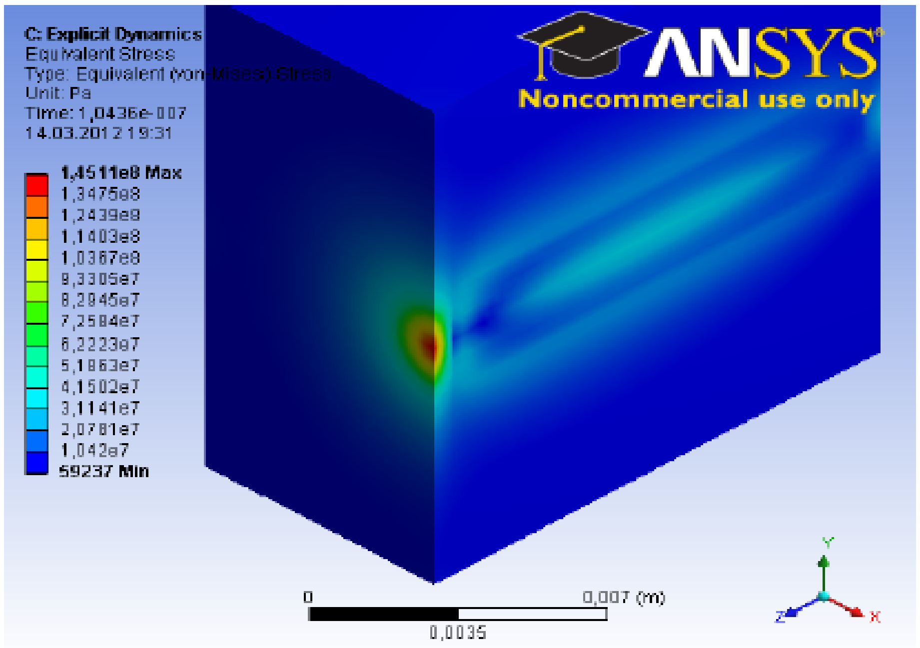
Suggestion for ILC 1 TeV upgrade:

- **Use another SC helical undulator with bigger period (λu = 4.3 cm, same NbTi technology), that will keep energy of photons "small" (Eph ~λ_u^{-2})**

Maximal Thermal Stress (at 100 ns after pulse end)

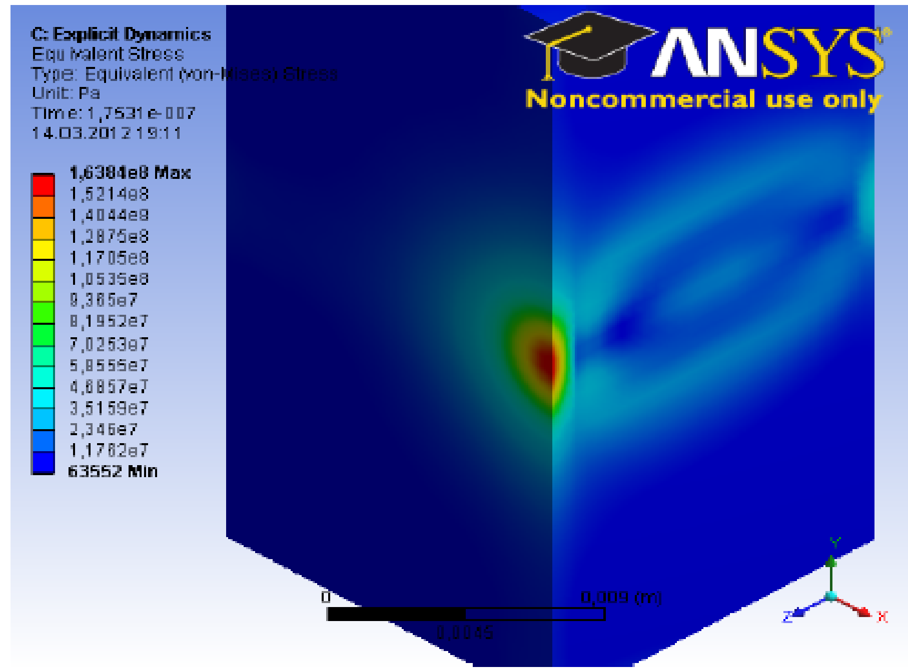
Andriy

500 GeV e^-, $K = 2.0$, $\lambda = 4.3$ cm, $R_{col} = 0.8$ mm



$\sigma_{max} = 145$ MPa

150 GeV e^-, $K = 0.92$, $\lambda = 1.15$ cm, $R_{col} = 2$ mm



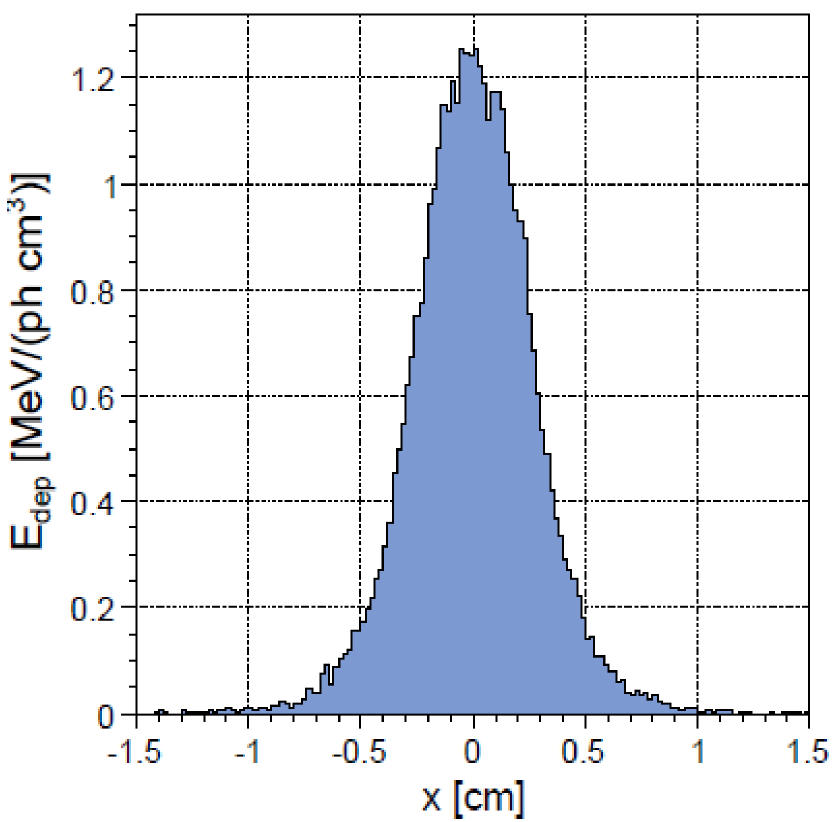
$\sigma_{max} = 164$ MPa

- ***Dynamical stress in target should be at acceptable level***

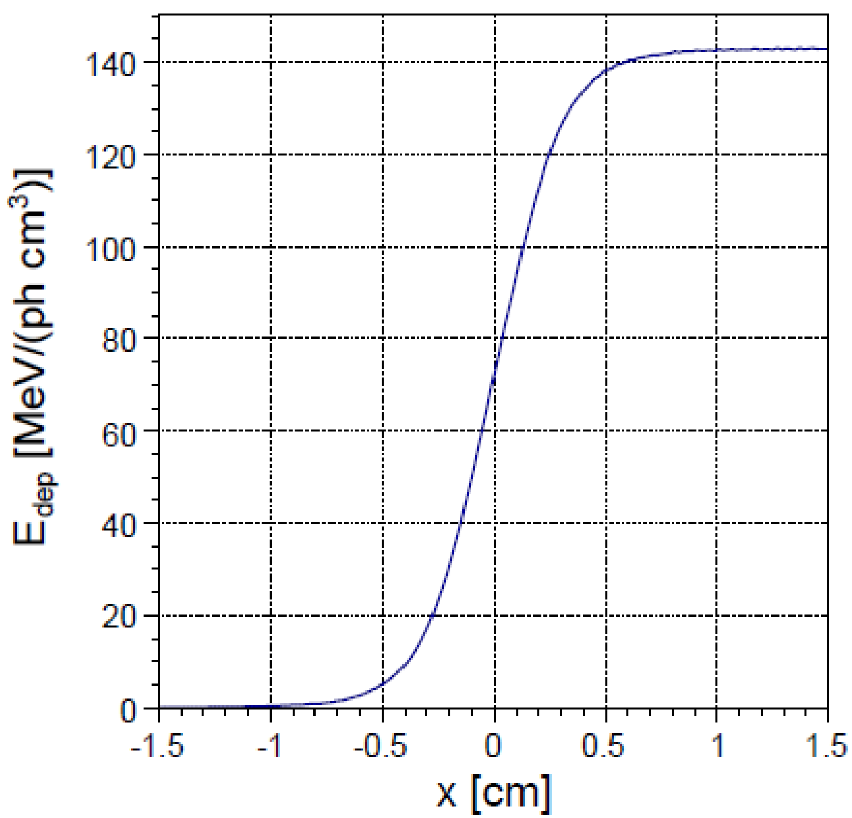
Deposited Energy in Target

Andriy

Deposited Energy by **Bunch**



Deposited Energy by **Bunch Train**



$\sigma_x \simeq 2.5$ mm; Bunch Shift = 55.4 μm

Bunch Overlapping Factor = **114**

Andriy

Used: simplified ANSYS Model

- "Instantaneous" spacial distribution of $E_{MeV/ph}(x,y,z)$
  max $E_{MeV/ph} = 1.2$ MeV/(phcm^3)
- Bunch Overlaping Factor (BOF): 114 bunches/train
- $N_{ph/"train"} = N_{e-/bunch}\ Y_{ph/(e-m)}\ L_u\ BOF = 8.5 \times 10^{14}$
- PEDD = max $E_{MeV/ph}\ N_{ph/"train"} \approx 44$ J/g
  $\Delta T_{max} \approx 84$ K
- $\Delta t_{"train"} = 554$ ns * BOF = 63.2 s
- Heat Rate $\Delta Q(x,y,z)/\Delta t = E_{MeV/ph}(x,y,z)\ N_{ph/"train"} / \Delta t_{"train"}$
  $(\Delta Q/\Delta t)_{max} = 3.1 \times 10^{12}$ W/m^3

ANSYS Heat Source:

$\Delta Q(x,y,z)/\Delta t$, for $t < \Delta t_{"train"}$

0 , for $t > \Delta t_{"train"}$

➢ *Task: to find max. stress shortly after the end of bunch train*

Analytical approach

- *Can we 'understand' the model ANSYS uses ? Potential for improvement?*

Instantaneous stress induced by abrupt change of temperature is propagated as a 'stress-wave' with a speed of sound

- Analytical approach:
  - Major work done already by Peter Sievers
  - Important calculation be Vlevoshkaja
  - Ongoing calculation by Kikuchi (+ Peter)
- Our appoach (PhD student: Olufemi Adeyemi):
  - Use continuum medium
  - Calculate stress tensor via Cauchy equation
  - Solve partial differential equation for pressure

Analytical equations

Olufemi

1. **Energy deposition causes stress in material:**

Partial Differential Equation:

$$\frac{\partial^2 P}{\partial t^2} - \nabla \cdot (c_s^2 \nabla P) = \frac{\Gamma}{V} \frac{\partial^2 Q}{\partial t^2}$$

–Solution depend on assumptions for energy deposition

–Solution depends crucially on boundary conditions

2. **Energy deposition gets dissipated: heat diffusion**

Partial Differential Equation:

$$\frac{\partial T}{\partial t} = \chi \nabla^2 T + \frac{1}{V \rho c_p} \frac{\partial Q}{\partial t}$$

3. **Incorporation of multi-bunch effect**

Models for spatial energy deposition

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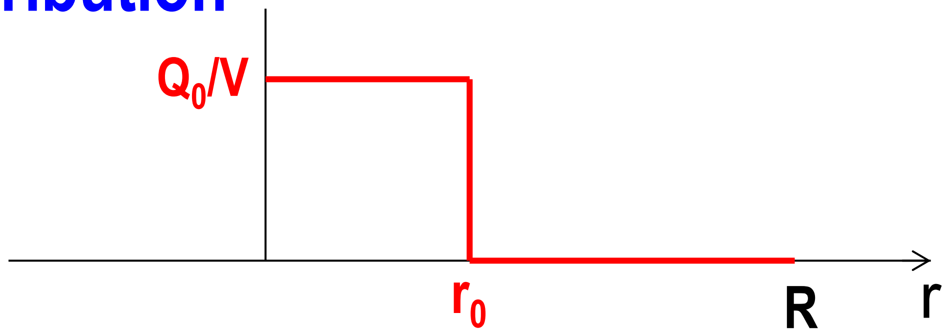
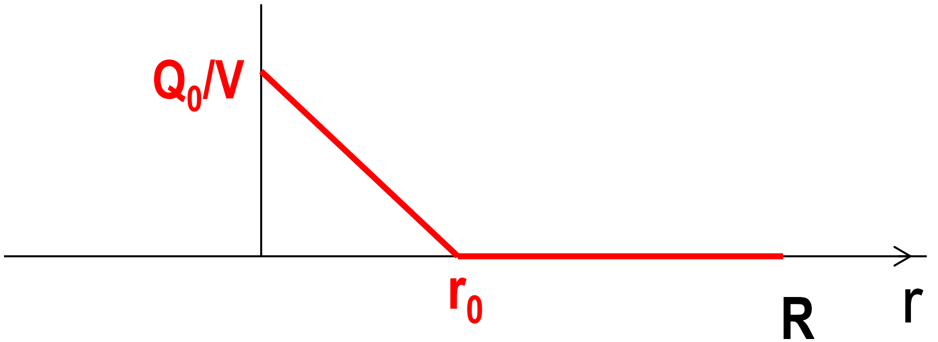
- **Rectangular (uniform) distribution**



- **Triangular (linear) distribution**



- **Gaussian (normal) distribution**
  - as normal

Boundary Conditions

Olufemi

- **Dirichlet problem:**

Initial condition:

Pressure

Grüneisen coeff.

$$P(z,0) = \frac{\Gamma}{V} Q(z),$$

Dep. Energy

Volume

$$\left.\frac{\partial P}{\partial t}\right|_{t=0} = 0,$$

Boundary condition: the pressure at both end is zero at all time

$$P(0,t) = 0,$$

$$P(L,t) = 0,$$

Boundary Conditions

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- **von Neumann problem:**

Initial condition:

$$P(z,0) = \frac{\Gamma}{V} Q(z),$$

$$\left.\frac{\partial P}{\partial t}\right|_{t=0} = 0,$$ ⟵ **Same as for Dirichlet**

and boundary conditions:

$$\left.\frac{\partial P}{\partial z}\right|_{z=0} = 0 = \left.\frac{\partial P}{\partial z}\right|_{z=L}$$

Target geometry

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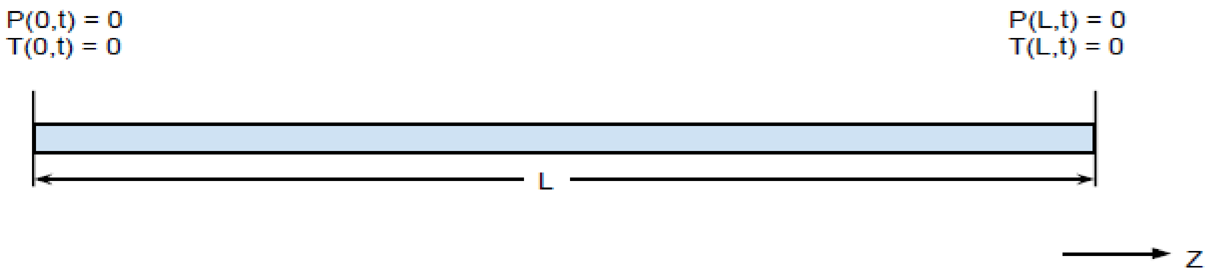
- **Case 1: Thin rod**



- **Case 2: Thin disc**
  - Radius R
- **Case 3: The cylinder** (2 dim, since axial symmetric)
  - Radius R and longitudinal z

➢ ***We have analytical solutions for all 3 cases for both boundary classes***

Some results for a thin disc

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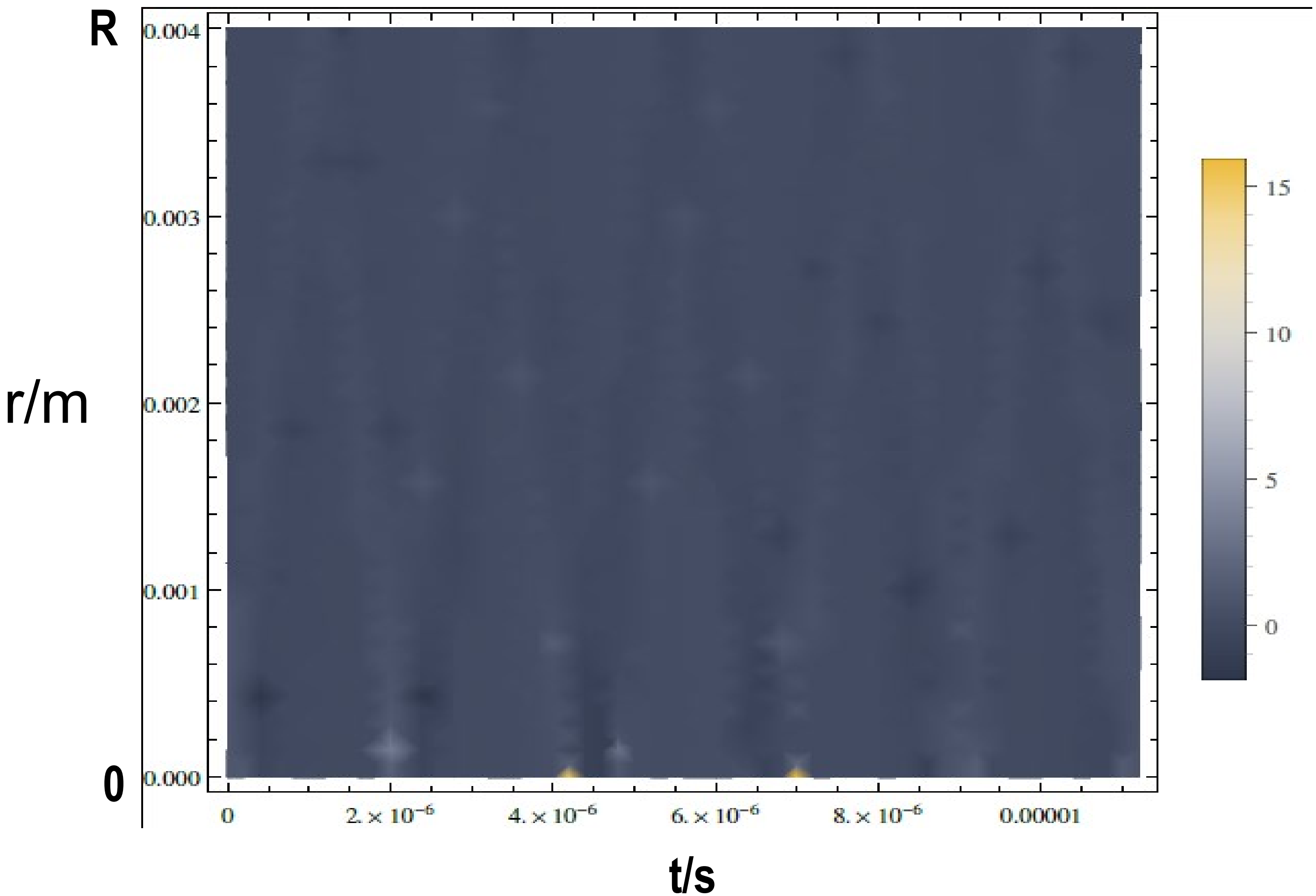
- v. Neumann boundaries + uniform energy deposition



Disc: uniform deposition

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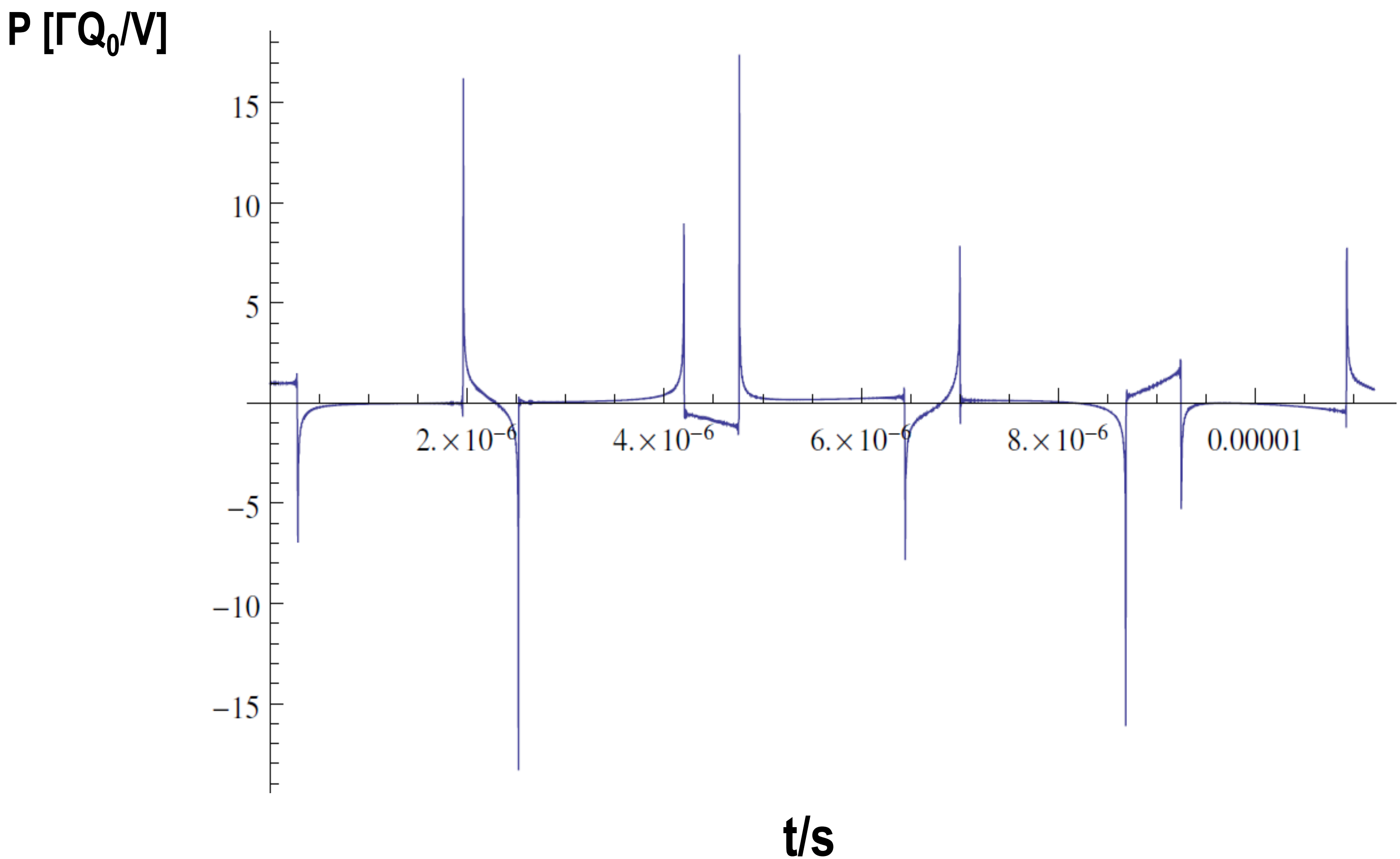
At r=0:



Disc: uniform deposition

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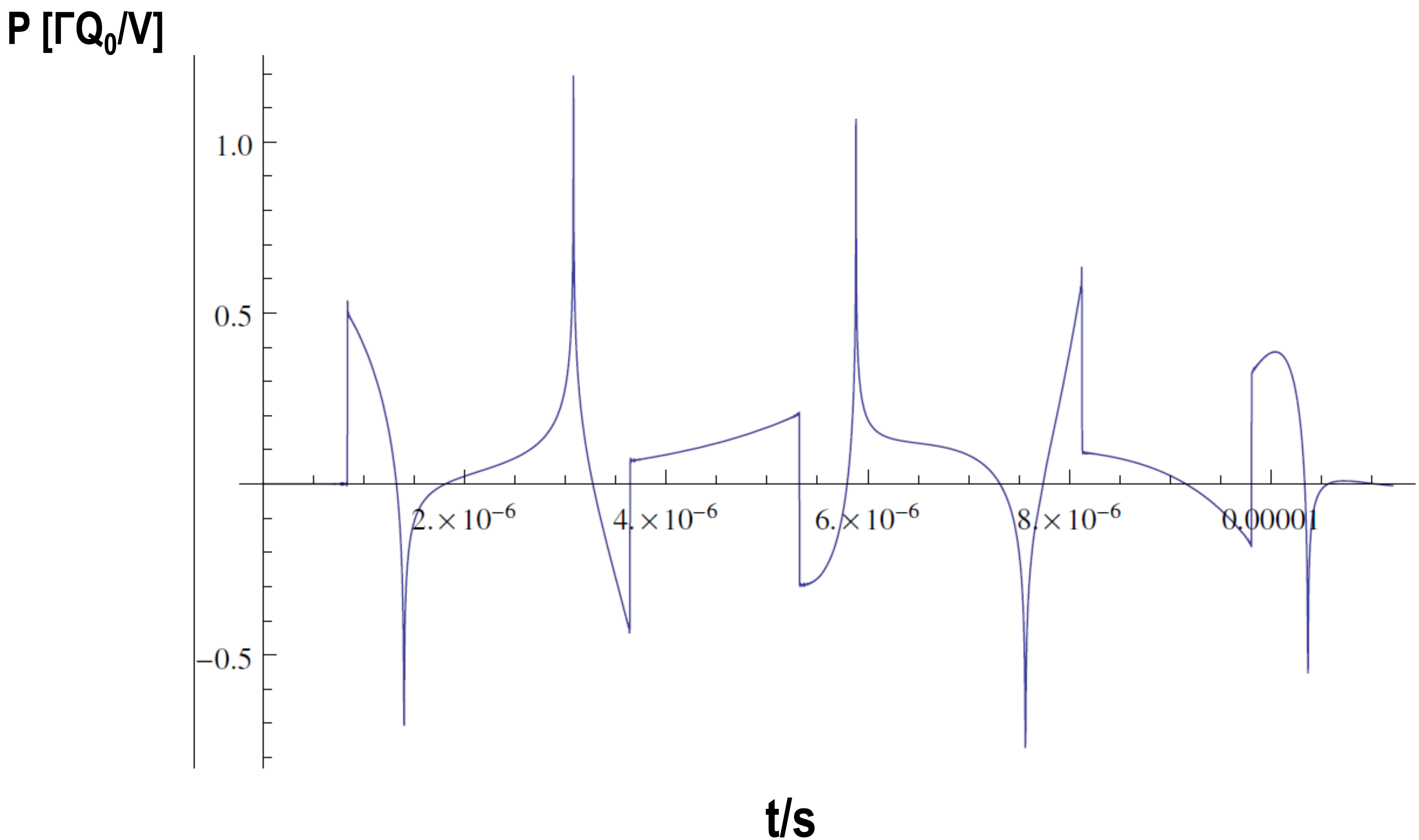
At r=R:



Disc: Linear Deposition

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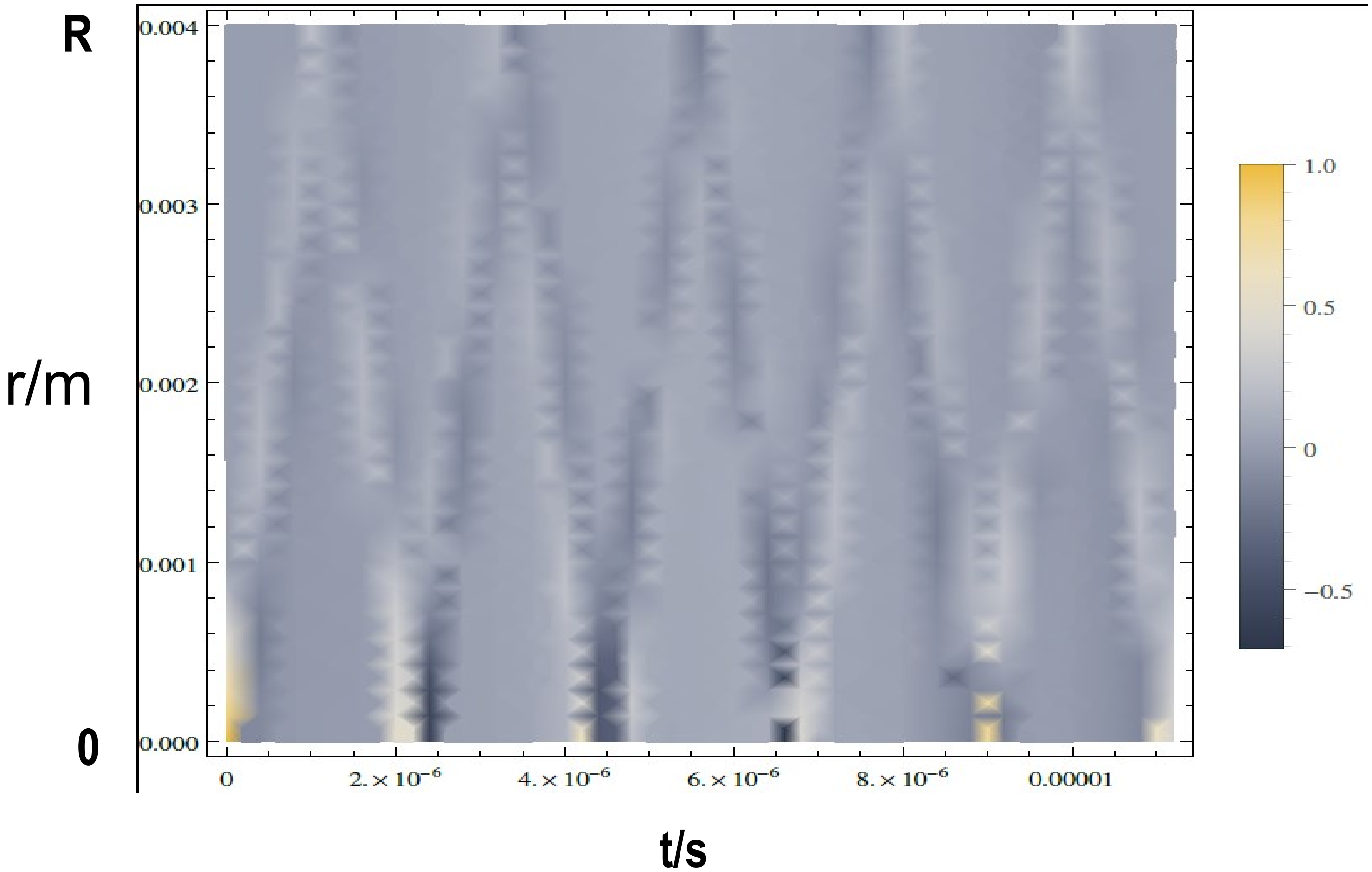

Disc: Linear Deposition

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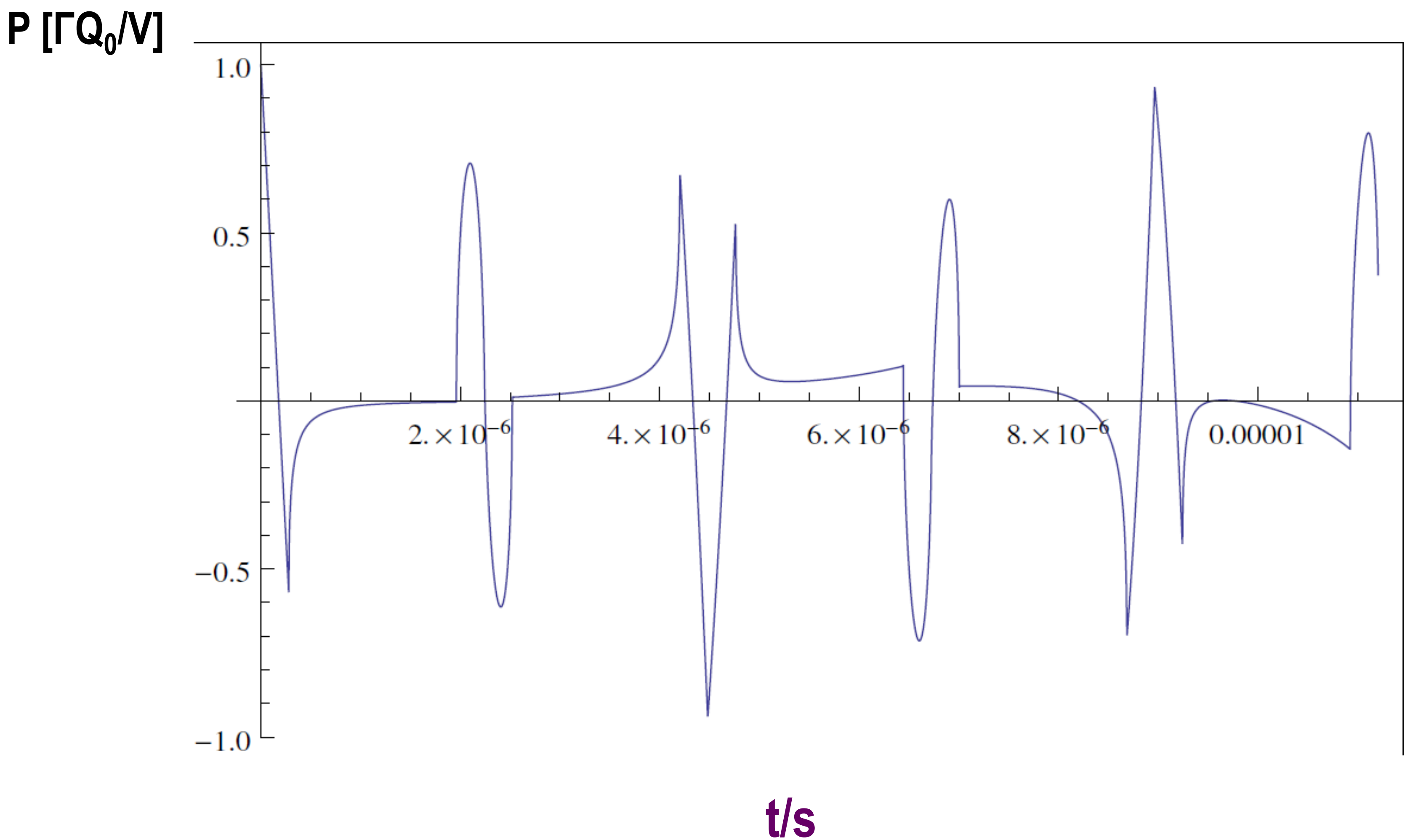
At r=0:



Disc: Linear Deposition

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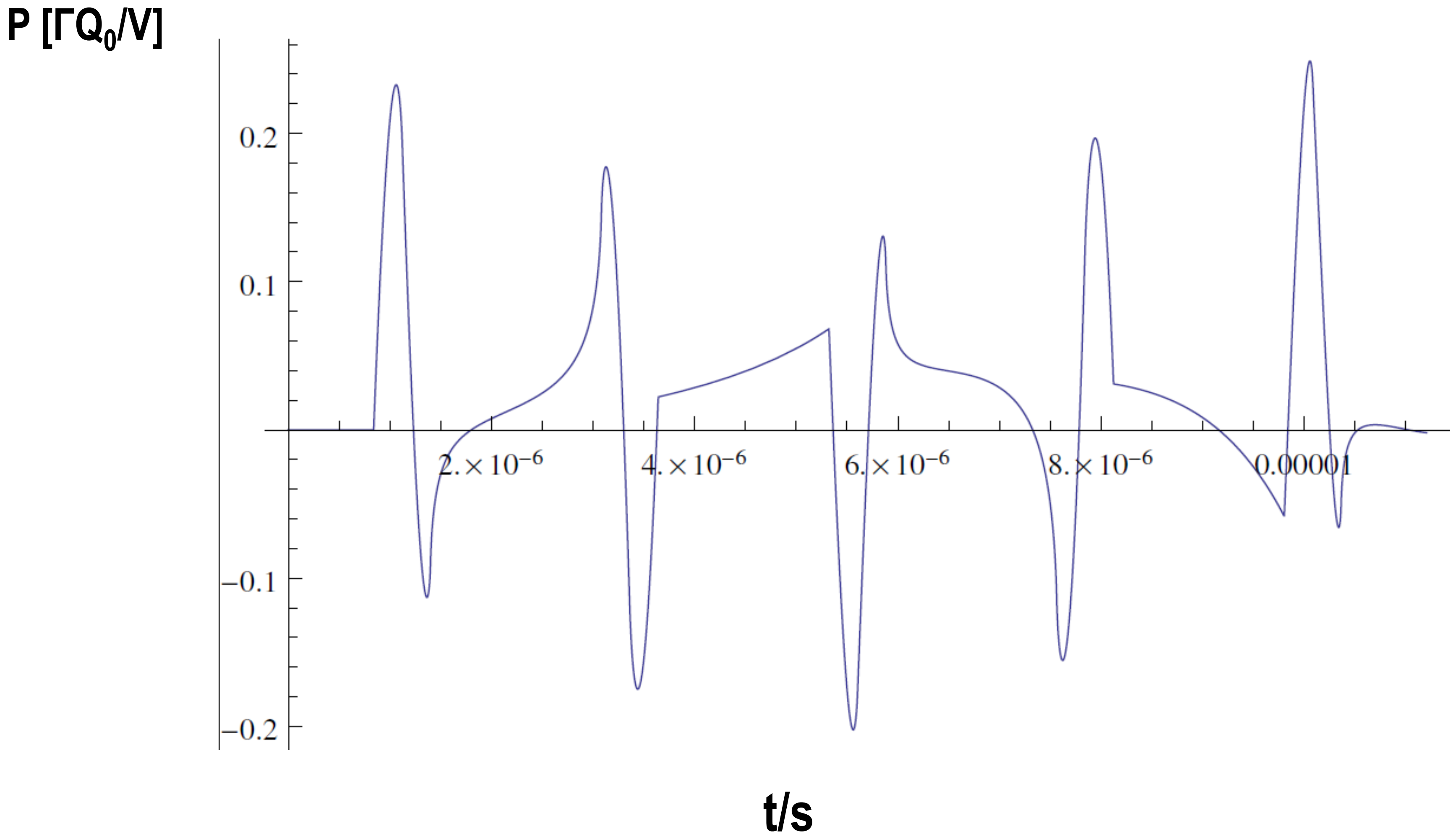
At r=R:



Next steps

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- Inclusion of damping effects

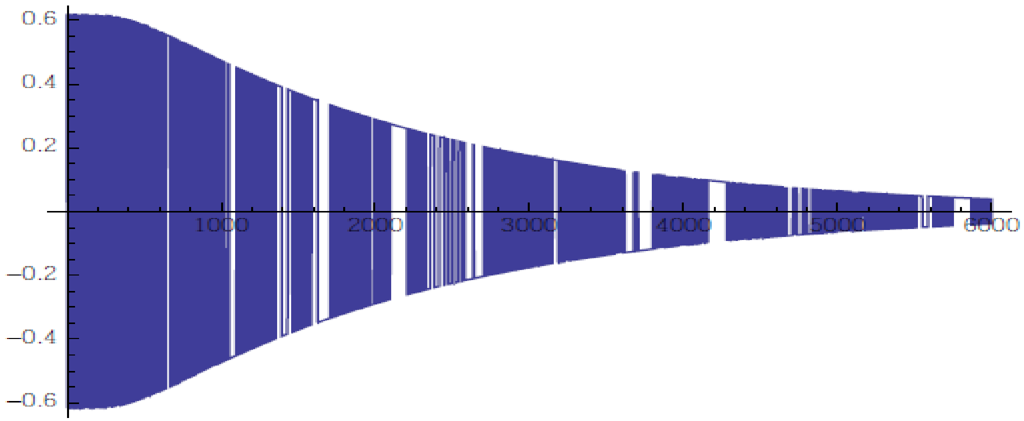


Figure: $\left(\frac{4\Gamma^2 Q_0 L^2 T_0 c_p \rho}{V\pi^2}\right) \times$ P[Pa] vs. t[s]

- Inclusion of multi-bunch effect
- If possible: numerical evaluation of analytical solutions of cylinder case in 2-dim
- Finishing writing the thesis,….

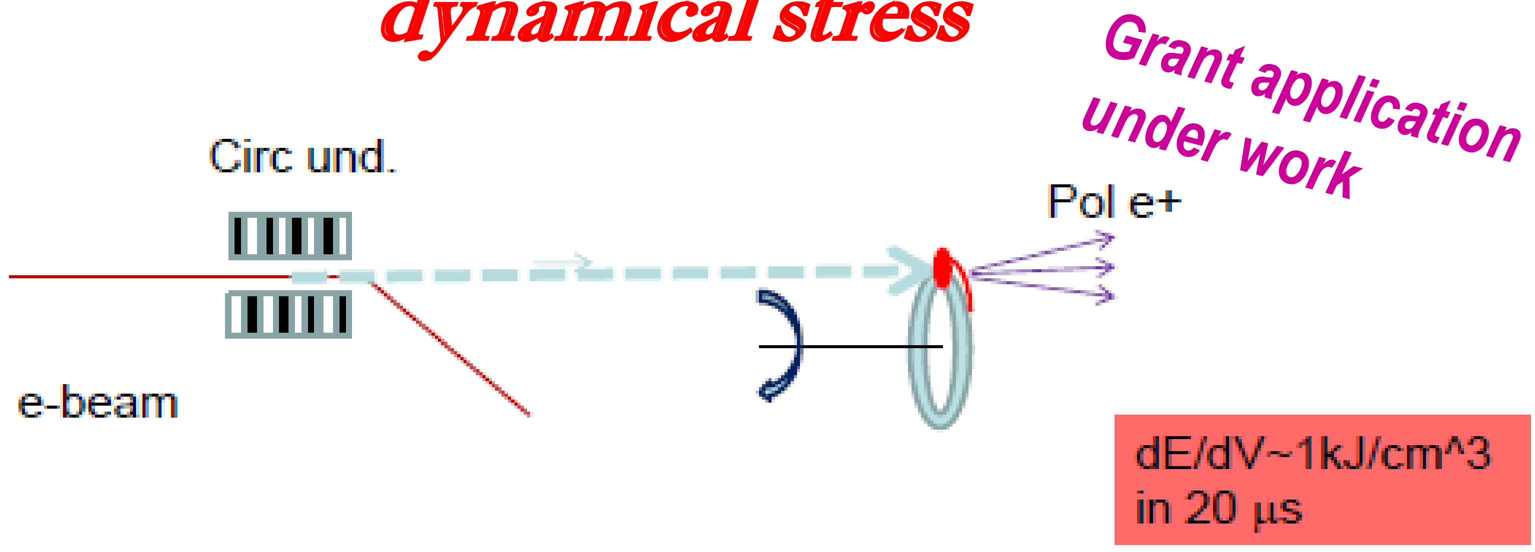
Further plans

- Test of thermo-mech. dynamics of target materials
- Different material tests
- Simulation of alternative cooling methods
- Optimization of optics

Target tests might be crucial!

- Experiment:
  - mimick high power γ's by pulse e- (bunch spacing shorter!)
  - smashing on target materials
  - About same heat deposition as at ILC target
  - Due to c.w.: any repition rate possible ⟶ artificial aging

Planned: material test experiments: for dynamical stress



- γ-radiation **heats target without steep gradient**
- No powerful γ-source available → mimick by **electron pulses**
- Check if (non-moving) material gets destroyed (single pulse+fatigue)
- Electrons mainly ionize the (thin) material if $E_{beam}<E_{krit}\sim 10$MeV.
- Reduce beam size and target thickness until dE/dV is achieved for available electron beam
- MAMI c.w. injector: 1mA/3.5MeV
- At MAMI typical beam spot **size is 0.1 mm (ILC~mm)**
- Due to c.w. capability arbitrary repetition rate possible → „artificial aging"

Conclusions

- **Detailed simulations (ANSYS) and involved analytical evaluations under work**
  - **Dynamical stress should be at an acceptable level for all drive beam energies**
  - **So far: konservative model used in ANSYS (rotation not yet included, etc.)**
  - **Analytical calculations promising: solutions exist for both boundary conditions and several target geometries**
  - **Damping and multi-bunch effect still missing in analytical approach**
- **Concrete plans for involved target material tests planned**
  - **Should provide reliable info about dynamics of thermic stress at LC target**