Laser Heater Integration into XFEL. Update.

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XFEL Beam Dynamics Meeting
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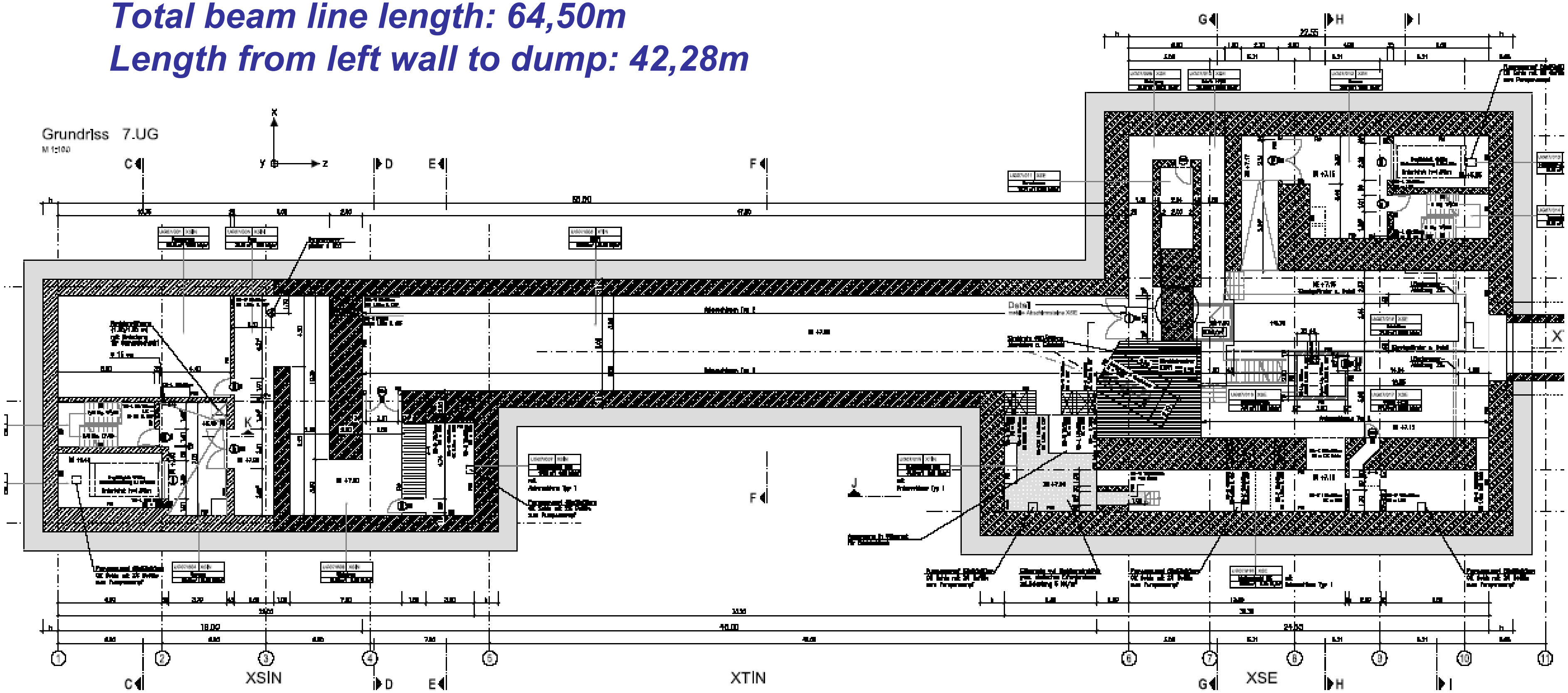
Outline

- **Overview about the main components and space margins**
- **Optics at the laser heater and diagnostics**
- FODO + parabola-like β at the heater
- FODO + const β
- Drift with parabola-like β
- Phase advance between the OTRs in the drift solution
- Beam sizes at the OTRs
- **Estimations of the laser heater specifications**
- Formulas
- Assumptions and requirements
- Maximum energy modulation
- Laser peak power for different configurations
- Energy distribution after the interaction with the laser heater
- **Summary**

Injector Building Plan

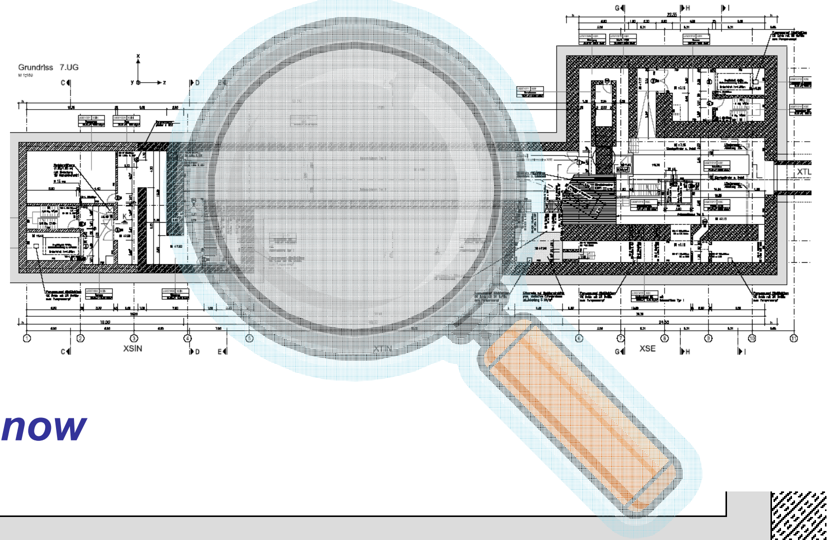
Injector is divided by reinforced concrete wall (Shielding) in two unequal parts:
- left one is used for injection tuning
- in the right one the beam is matched by means of Dogleg into the Linac

Total length: 73,80m
Total beam line length: 64,50m
Length from left wall to dump: 42,28m

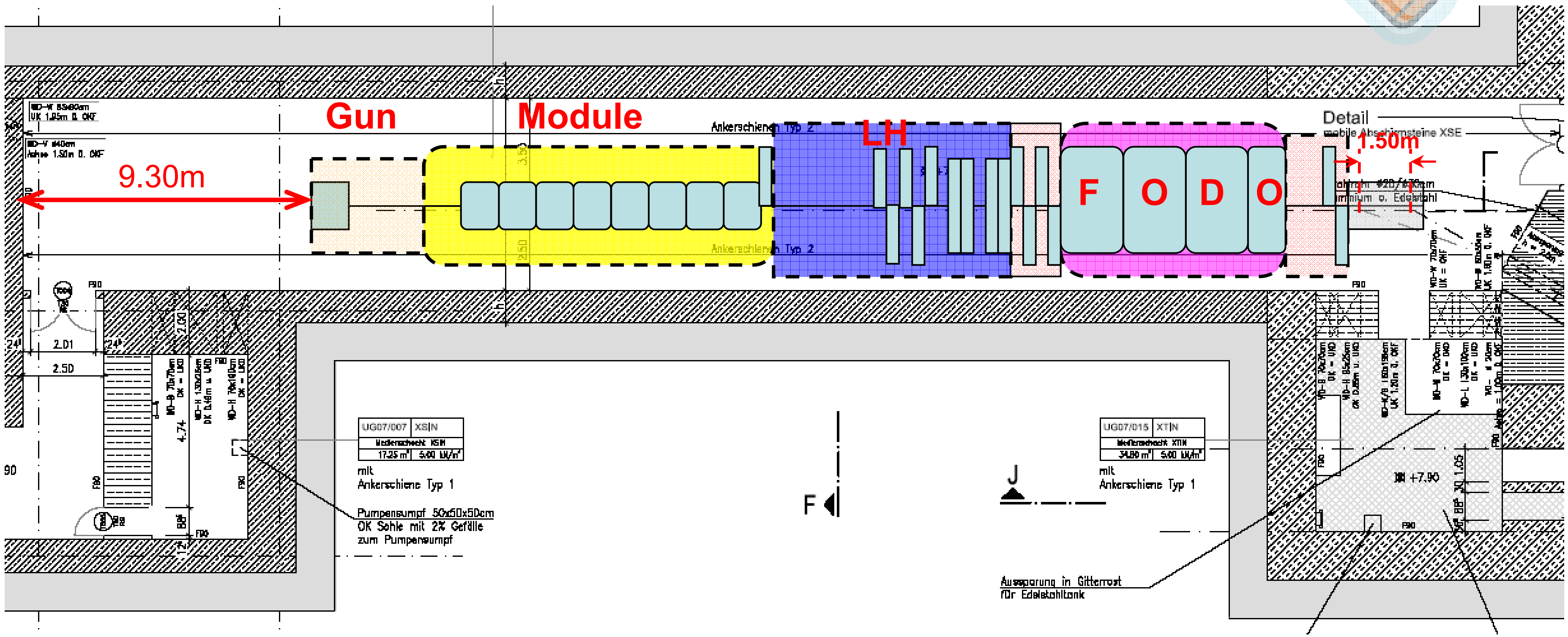


Point of Interest: from Gun to Dump

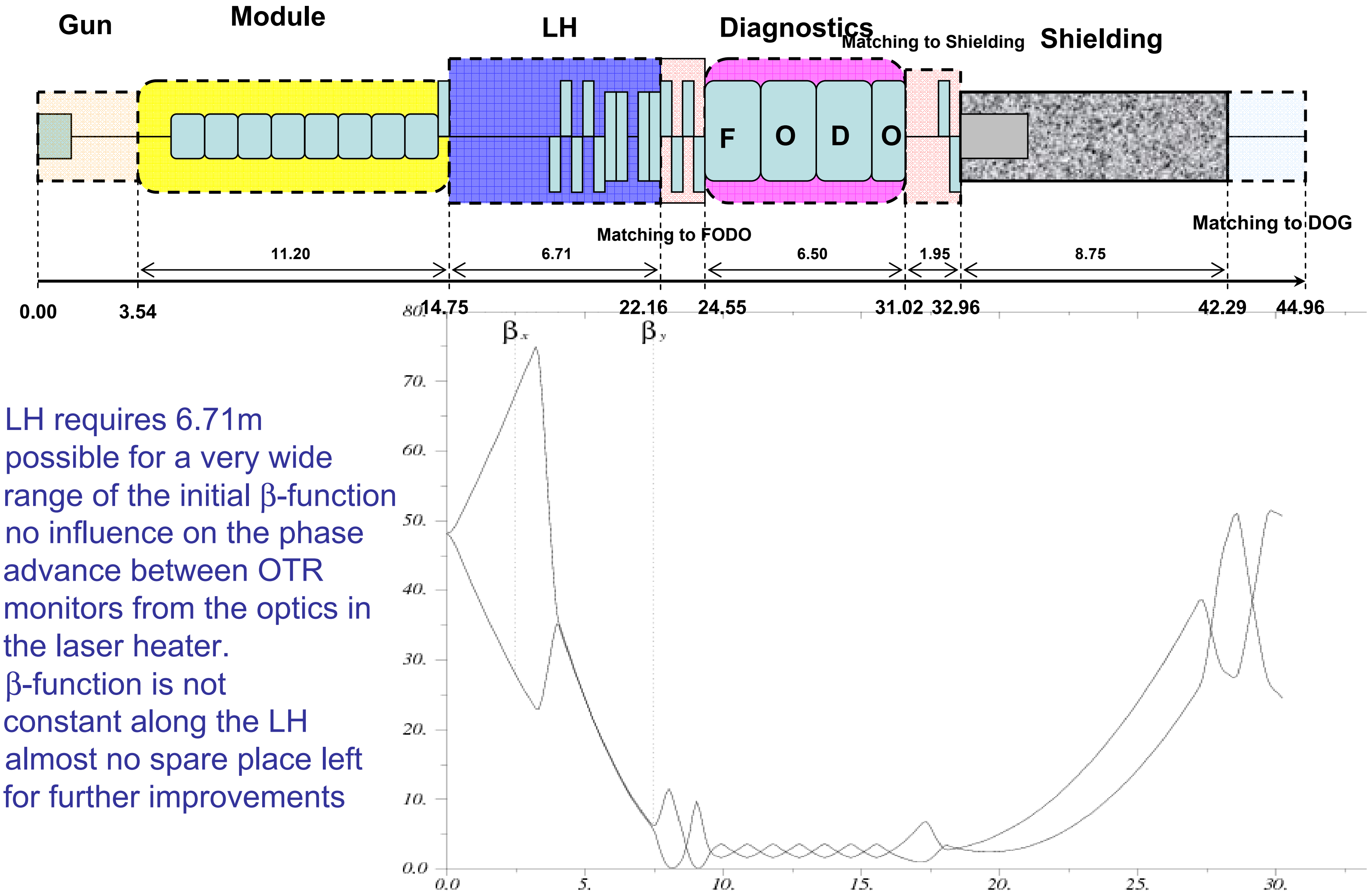
Boundary conditions:
The wall on the left ←→Dump dipole on the right.
All diagnostics have to be be placed there.



Beamline length from Gun to Dump: 32,40m
9.30m spare place from the wall to gun foreseen now

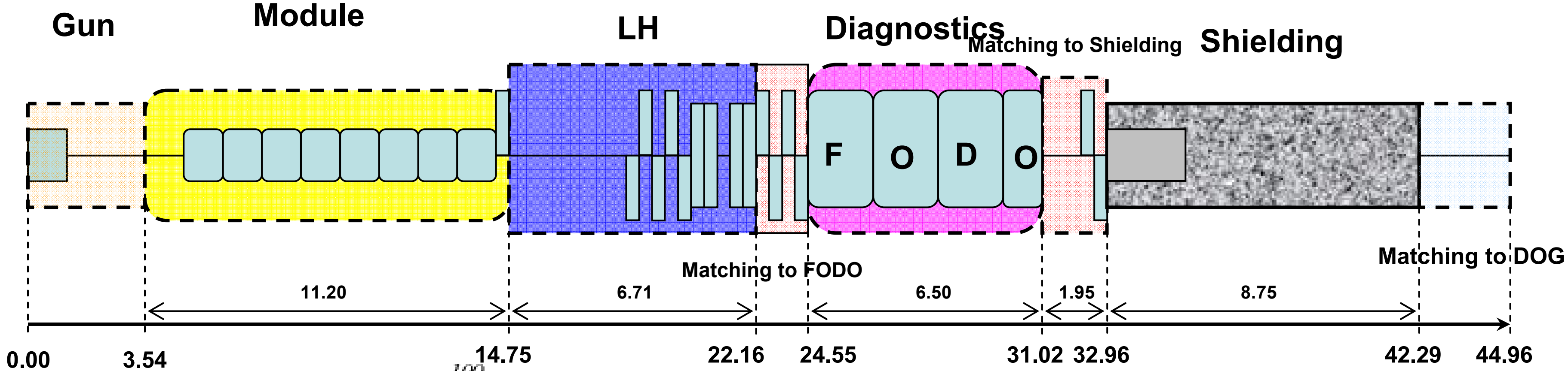


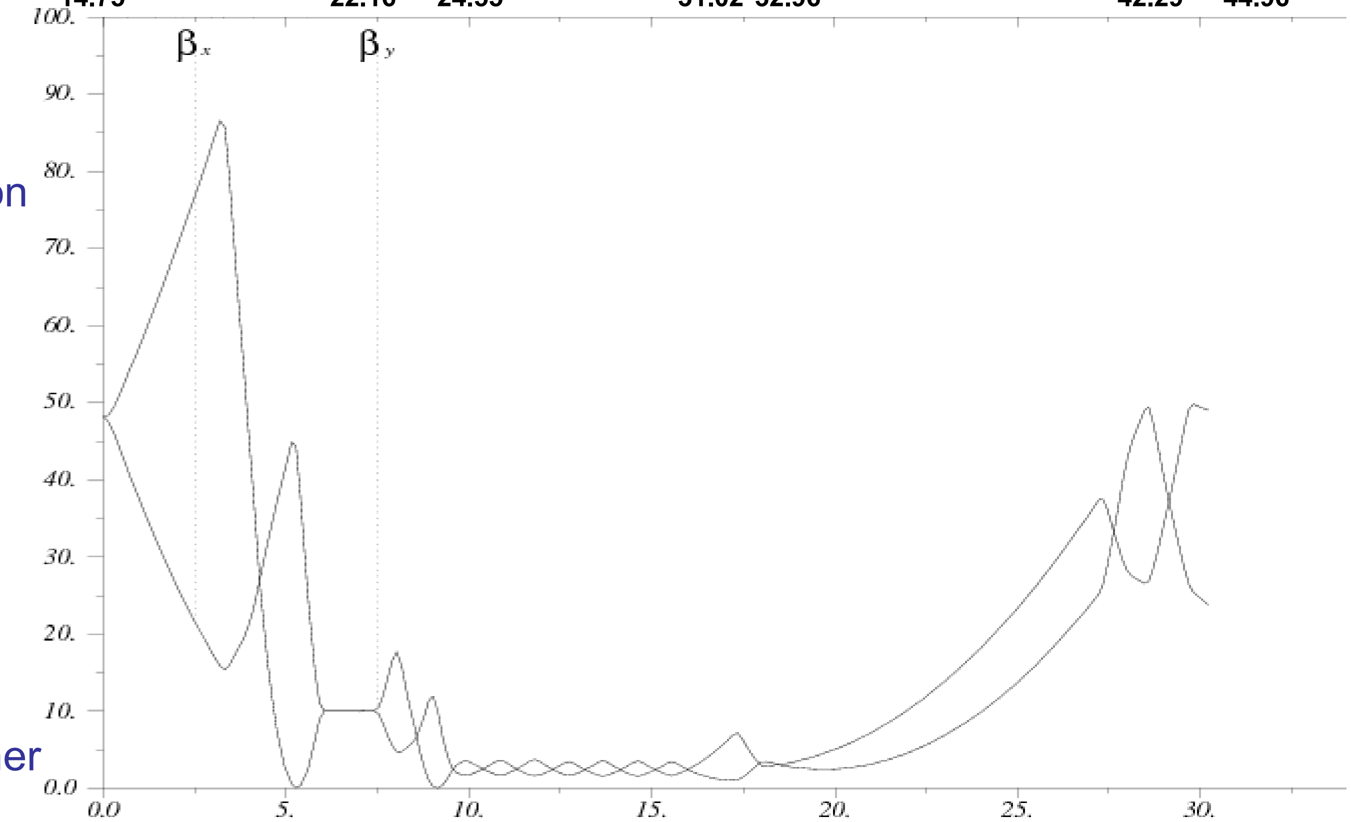
Laser Heater Integration: FODO + Parabola-like β at the Heater



- LH requires 6.71m
- possible for a very wide range of the initial β-function
- no influence on the phase advance between OTR monitors from the optics in the laser heater.
- β-function is not constant along the LH
- almost no spare place left for further improvements

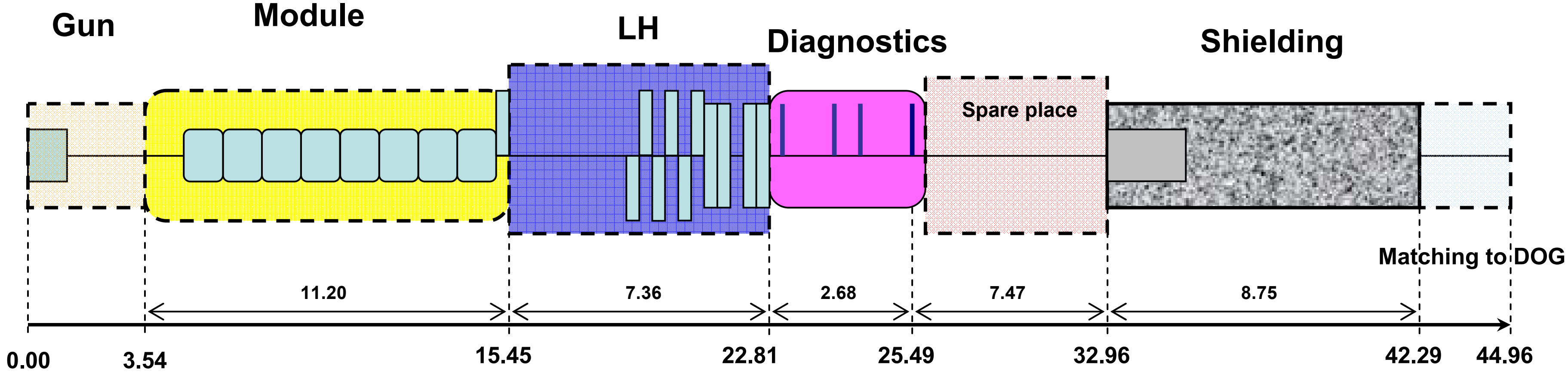
Laser Heater Integration: FODO + const β at the Heater



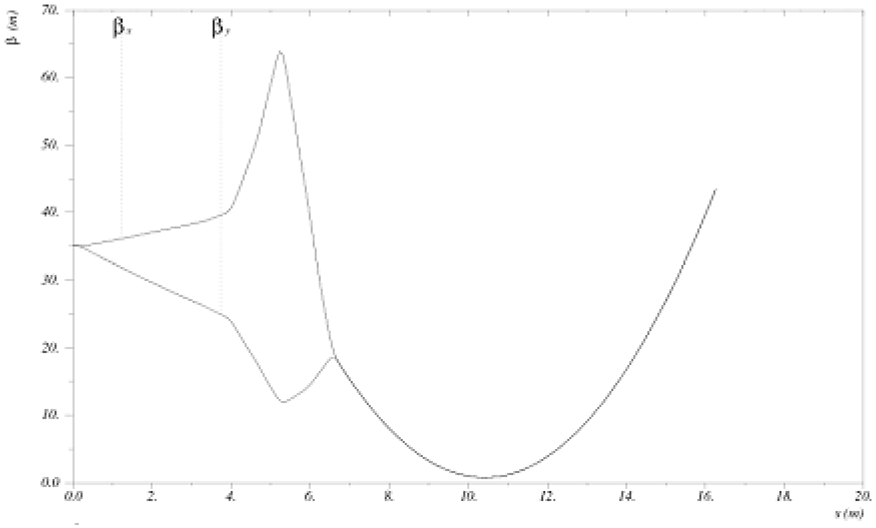


- LH requires 6.71m
- possible for a very wide range of the initial β-function
- no influence on the phase advance between OTR monitors from the optics in the laser heater.
- β-function is <u>constant</u> along the LH
- the best conditions for operating the laser heater.
- places with extremely flat beam unavoidable.
- no spare place left for further improvements

Laser Heater Integration: Drift with Parabola-like β



- LH requires 7.36m
- desired phase advance of 45° between OTRs for initial β-function between 30m and 65m achievable
- additional 7.47m of spare place.
- only OTR monitors are to be installed in the diagnostics section.
  no other stuff required.
- β-function is not constant along the heater



Phase Advances between OTRs in the Drift Solution

Phase advances between OTR monitors for different intial values of β-function

initial beta	min beta	phase advances
20	1.267	42.5 - 29.2 - 42.5
24	1.008	44.6 - 36.0 - 44.6
26	0.920	44.6 - 39.6 - 44.6
28	0.840	45.0 - 42.8 - 45.0
30	0.800	45.0 - 45.0 - 45.0
65	0.800	45.0 - 45.0 - 45.0
70	0.780	45.4 - 45.7 - 45.4
75	0.728	45.0 - 48.6 - 45.0

Desired phase advance of 45° is achievable in the range of the initial β-function between 30m and 65m
Expected initial β-function: 20-70m → regions 20-30m and 65-70m could be critical.

Expected beam sizes at the OTR monitors

	OTRs in the FODO solution		OTRs 1&4 in the drift solution		OTRs 2&3 in the drift solution	
Assumed emittance, mm mrad	β, m	Beam size range, μm	β, m	Beam size range, μm	β, m	Beam size range, μm
1.0-1.5	2.435	98.9 - 121.2	5.50	148.7 - 182.1	0.935	61.3 - 75.1

- **FODO solution provides the constant β-function at the OTR monitors, leading to the same beam size**
- **Drift solution: different betas at exterior and interior OTRs → different beam sizes**
- **The smallest expected beam size at the OTR is about 61μm, still comfortable above the tolerance limit of the OTR monitor (10μm).**

Main Formulas for the Estimation of the Laser Heater Specifications

Distribution function after the interaction with the laser heater

$$f_0(z_0,\Delta\gamma_0,r)=\frac{I_0}{ec\sqrt{2\pi}\sigma_{\gamma_0}}\exp\left\{-\frac{[\Delta\gamma_0-\Delta\gamma_L(r)\sin k_L z_0]^2}{2\sigma_{\gamma_0}^2}\right\}\frac{1}{2\pi\sigma_x^2}\exp\left(-\frac{r^2}{2\sigma_x^2}\right)$$

$$f_0(z_0,\Delta\gamma_0,r)=\frac{1}{\sqrt{2\pi}\sigma_{\gamma_0}}\frac{N\sqrt{\left(\frac{l_b}{2}\right)^2-z_0^2}}{\pi\left(\frac{l_b}{2}\right)^2}\exp\left\{-\frac{\left[\Delta\gamma_0-\Delta\gamma_L(0)\cdot e^{-\frac{r^2}{2\sigma_r^2}}\sin k_L z_0(1+q\sin k_s z_0)\right]^2}{2\sigma_{\gamma_0}^2}\right\}\frac{1}{2\pi\sigma_x^2}\exp\left(-\frac{r^2}{2\sigma_x^2}\right)$$

Laser peak power

$$P_L=P_0\left(\Delta\gamma_L(0)\frac{\gamma_0\sigma_r}{KL_u}\right)^2\left[J_0\left(\frac{K^2}{4+2K^2}\right)-J_1\left(\frac{K^2}{4+2K^2}\right)\right]^{-1}$$

$$P_0=\frac{I_A mc^2}{e}\approx 8.7GW$$

σ_x – transverse beam size
σ_r – laser beam size rms
$\Delta\gamma_L$ – energy modulation
σ_{γ_0} – initial energy spread

Assumptions and Requirements for the Estimations

➢ **Energy spread considerations:**

- Desired uncorrelated energy spread after the acceleration: 2.5MeV rms.
- BC1 and BC2 with the compression of 20x5=100

→Uncorrelated energy spread after the laser heater should be below 25keV
→Laser Heater should provide the uncorrelated energy spread of the beam up to 25keV.

➢**Beam size at the laser heater:**

- Normalized beam emittance range: 1.0-1.5mm mrad
- Depends on the solution for the diagnostics section after the heater.
- FODO solution: β–function is constant along the laser heater and assumes the value of 10m.

→ beam size rms: 200-246 μm

- Drift solution: β–function varies from 12 to 8m along the laser heater.

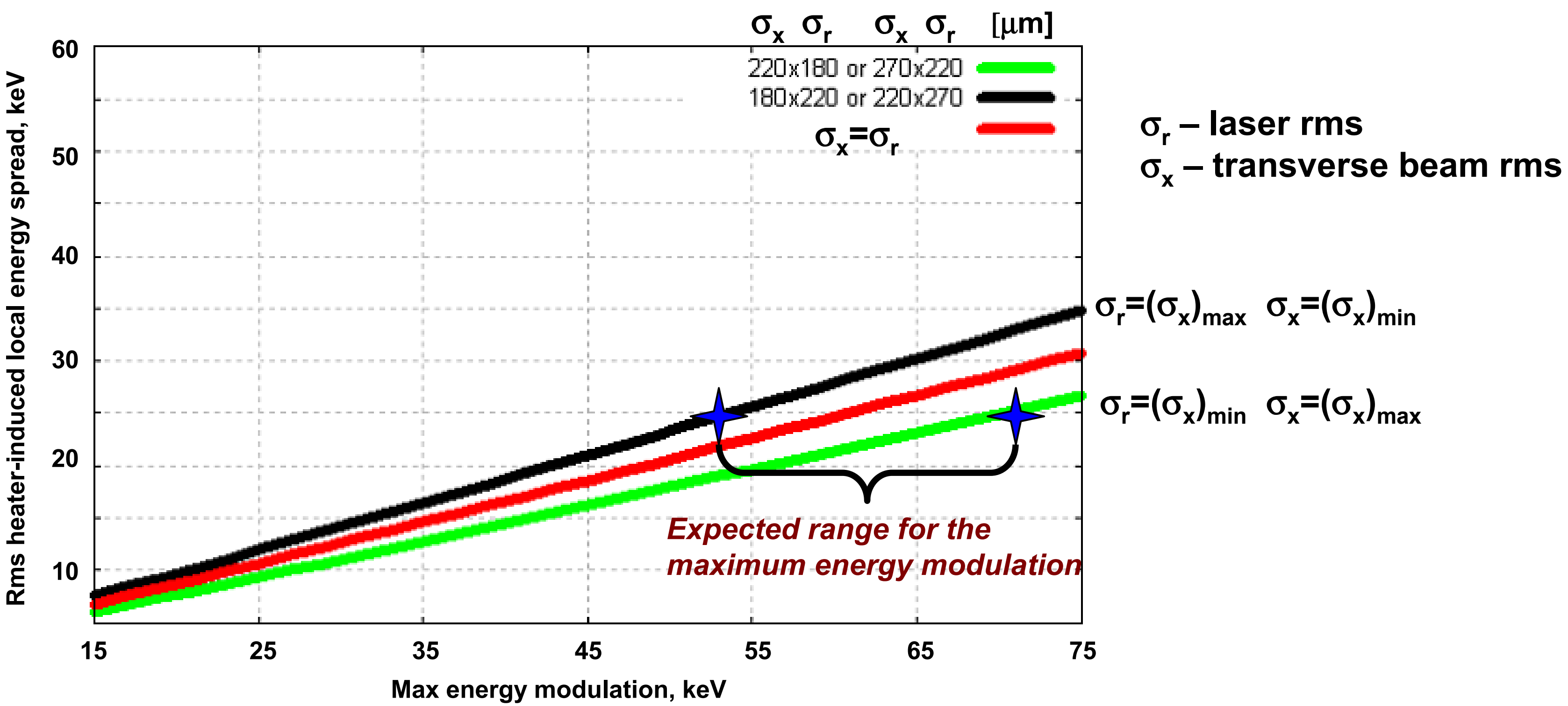
→beam size rms: from 180-220 μm to 220-270 μm

➢ **Average beam size at the heater for the drift solution:**

$$\sigma_x = \sqrt{\varepsilon\beta} = \sqrt{\varepsilon \cdot \left(\beta^* + \frac{s^2}{\beta^*}\right)} \approx s\sqrt{\frac{\varepsilon}{\beta^*}}$$

→ Linear with s → varies from 200 to 245μm

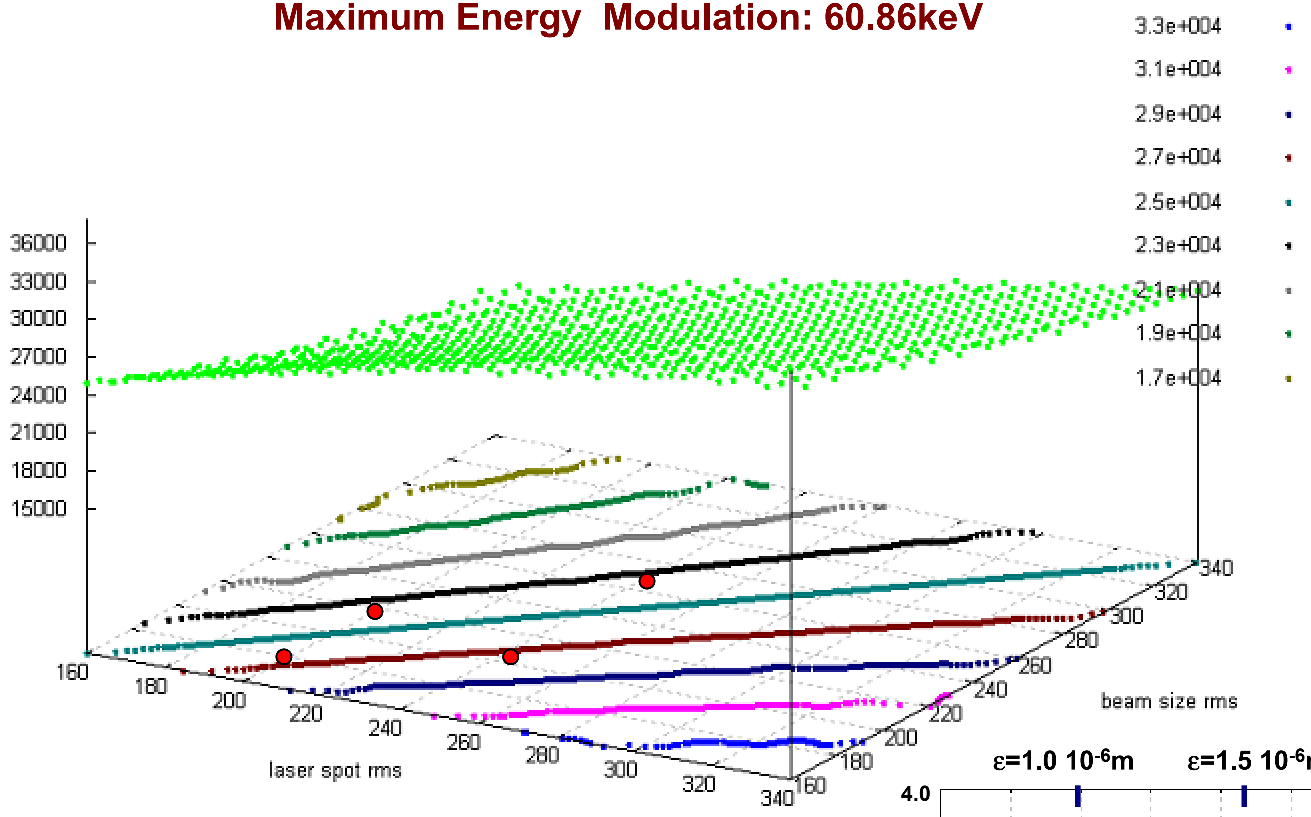
Rms Heater-Induced Local Energy Spread



Rms heater-induced energy spread depends crucial on the ratio σ_x/σ_r
Transverse beam size varies by about 20% along the laser heater.
If the energy spread of 25keV desired, the maximum energy modulation is expected to be in the range of 53.56 - 70.31keV.
For $\sigma_x=\sigma_r$ the energy modulation of 60.86keV needed

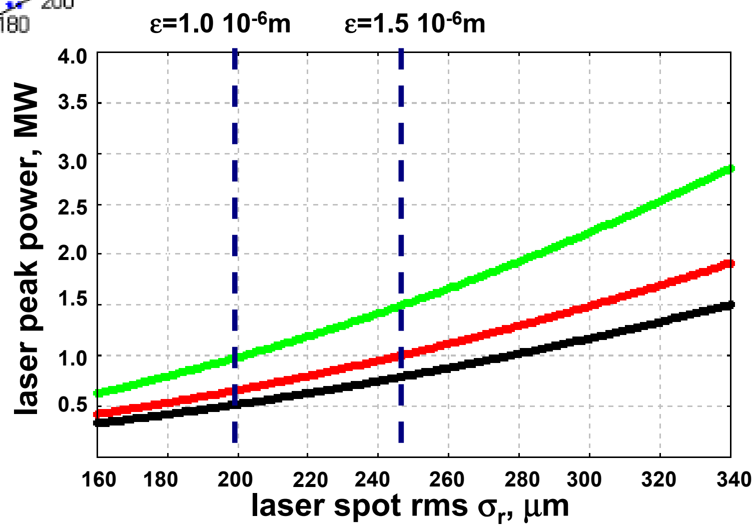
Uncorrelated Energy Spread after the Interaction with the Laser Beam

Maximum Energy Modulation: 60.86keV



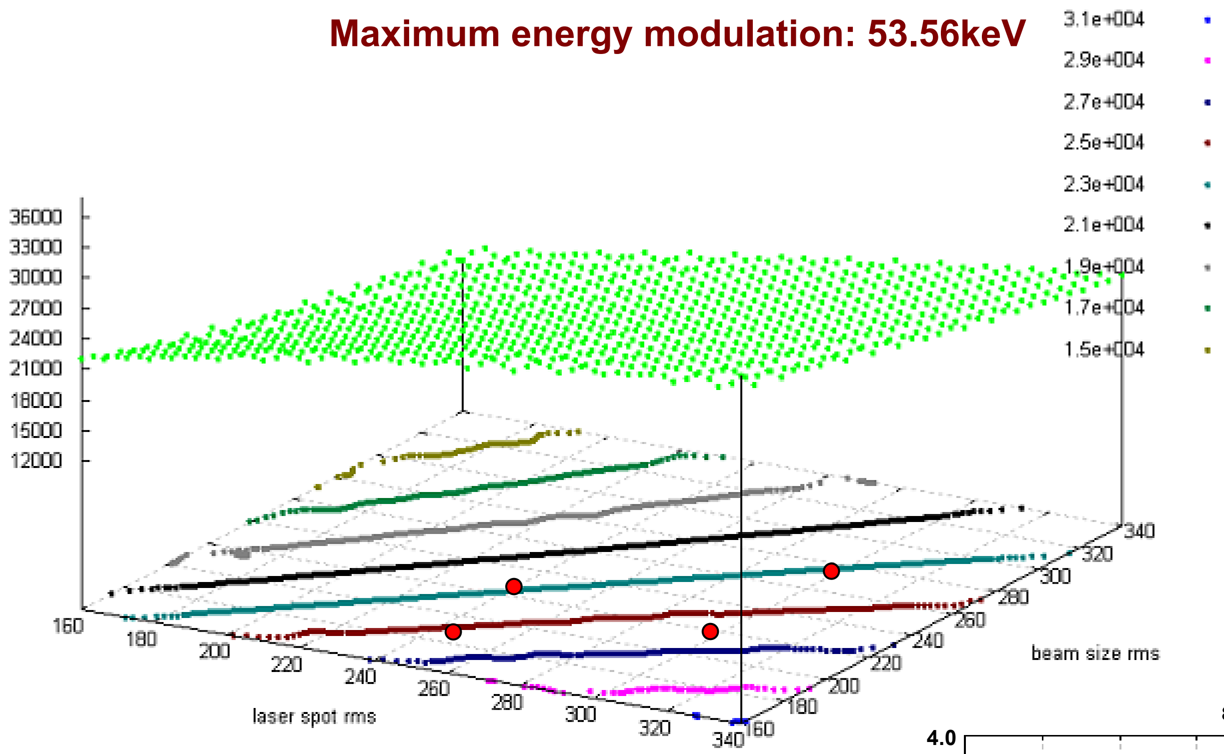
Laser peak power for different wave lengths, MW (undulator field 0.33T)

λ, nm	λ_u	K	peak power for σ_r=200μm (ε=1.0mm mrad)	peak power for σ_r=245μm (ε=1.5mm mrad)
527	0.0383	1.18	0.99	1.48
800	0.0476	1.47	0.66	0.99
1054	0.0543	1.67	0.52	0.78



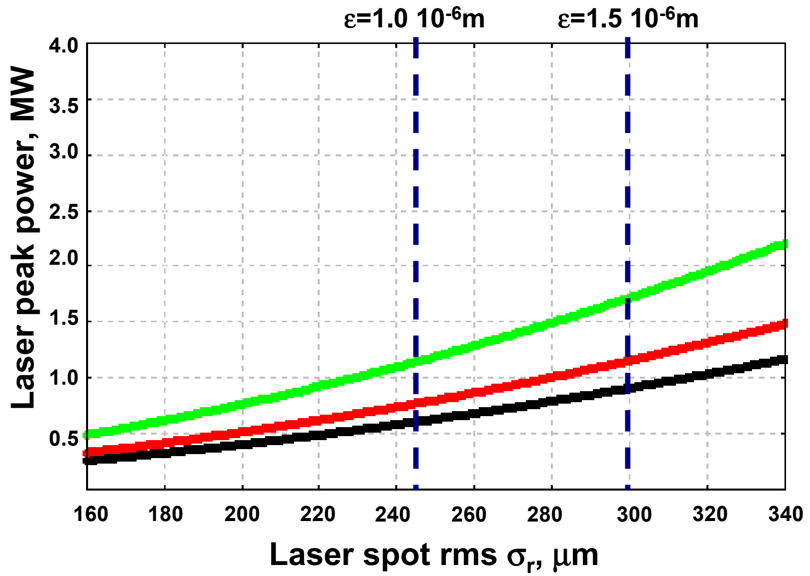
Uncorrelated Energy Spread after the Interaction with the Laser Beam

Maximum energy modulation: 53.56keV



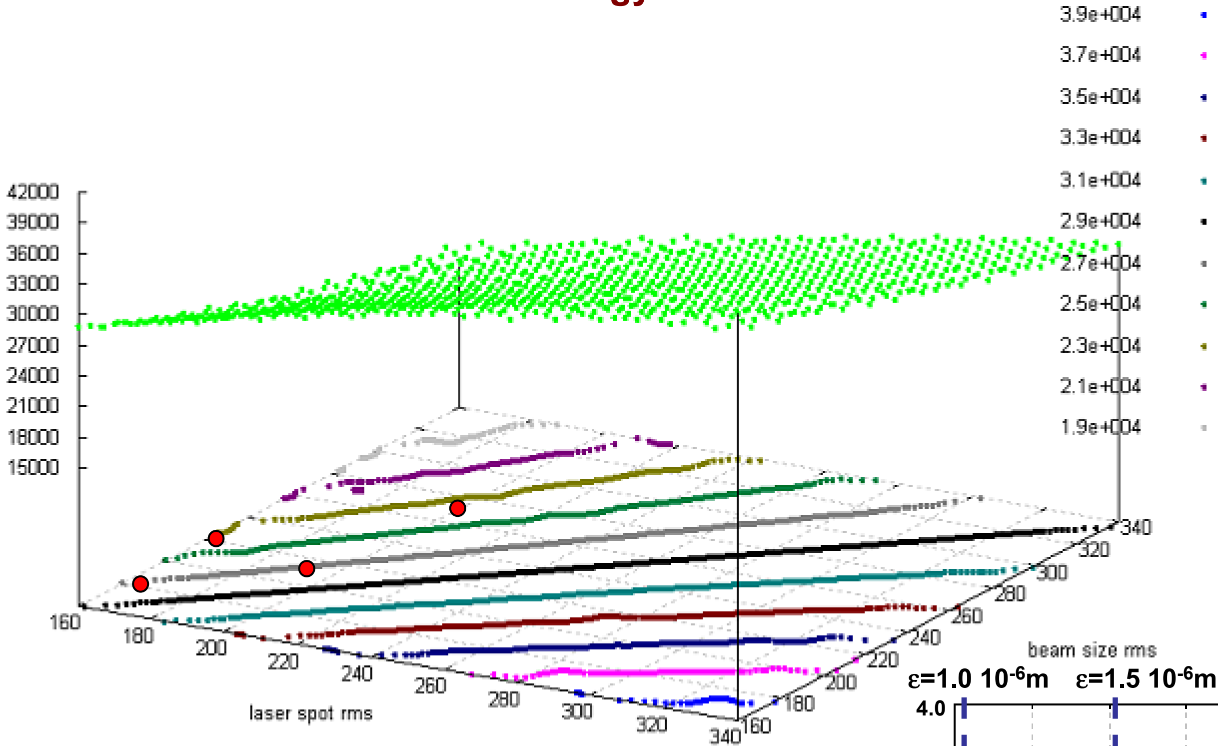
Laser peak power for different wave lengths, MW (undulator field 0.33T)

λ, nm	λ_u	K	peak power for σ_r=245μm (ε=1.0mm mrad)	peak power for σ_r=300μm (ε=1.5mm mrad)
527	0.0383	1.18	1.15	1.72
800	0.0476	1.47	0.77	1.15
1054	0.0543	1.67	0.61	0.91



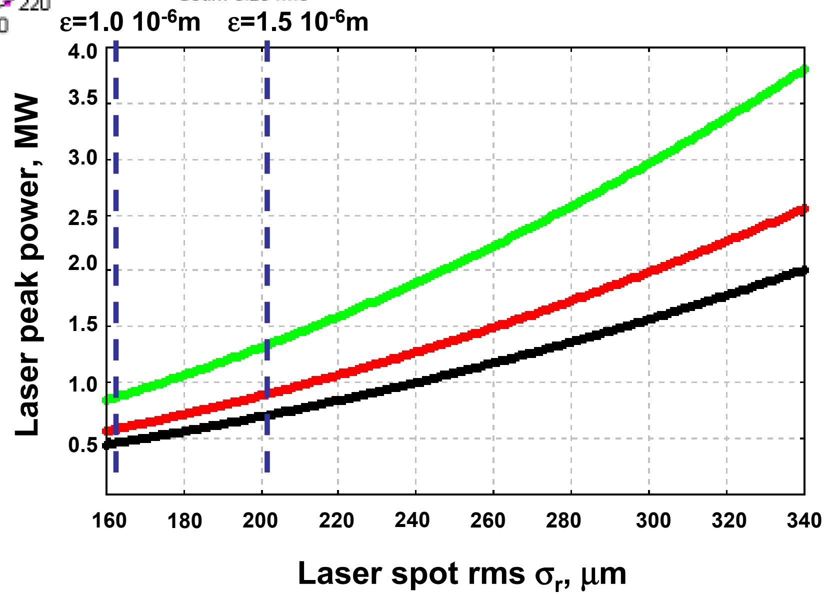
Uncorrelated Energy Spread after the Interaction with the Laser Beam

Maximum energy modulation: 70.31keV

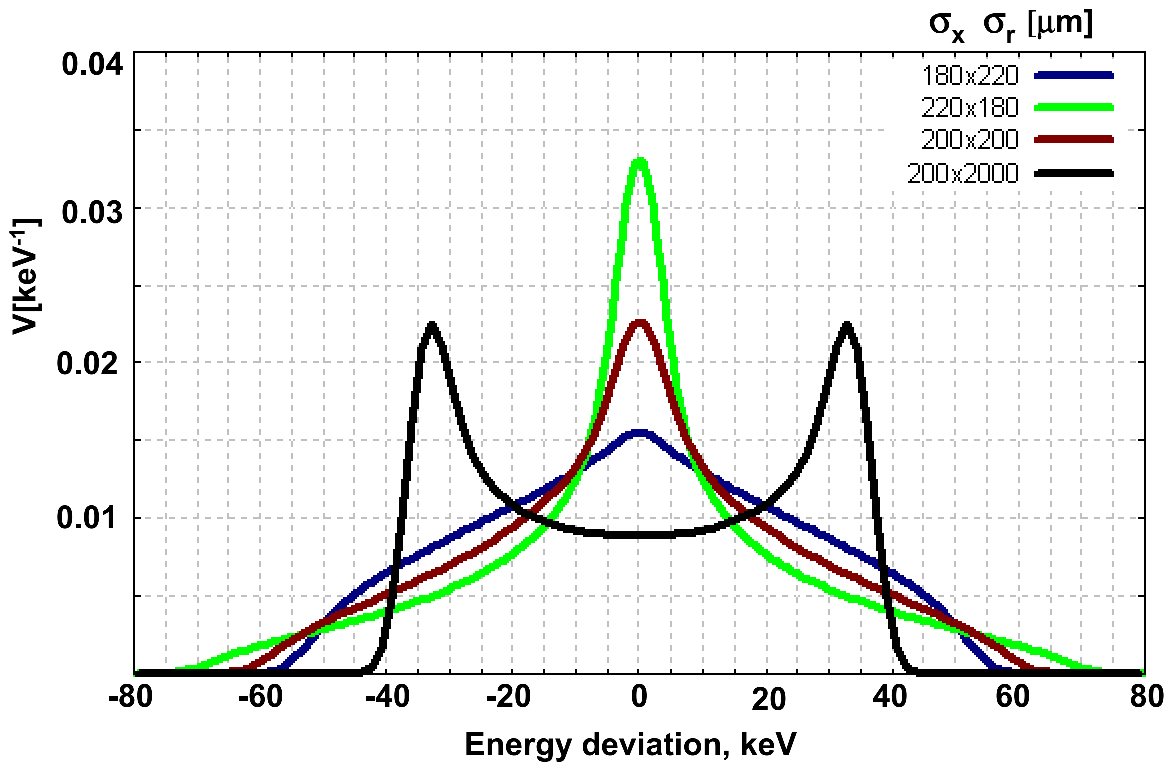


Laser peak power for different wave lengths, MW (undulator field 0.33T)

λ, nm	λ_u	K	peak power for σ_r=164μm (ε=1.0mm mrad)	peak power for σ_r=200μm (ε=1.5mm mrad)
527	0.0383	1.18	0.88	1.32
800	0.0476	1.47	0.59	0.88
1054	0.0543	1.67	0.47	0.70



Energy Distribution after the Interaction with the Laser Beam



All distributions have the same energy spread, but different form

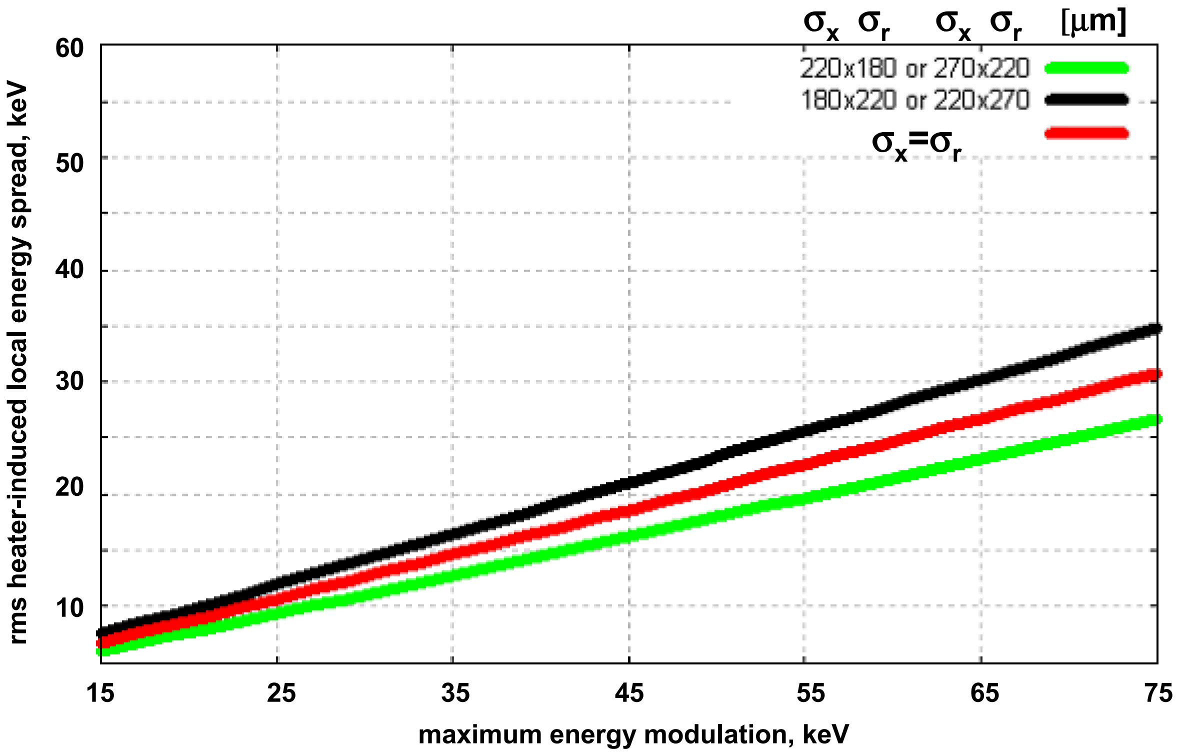
σ_r – laser rms
σ_x – transverse beam rms

The ratio σ_x/σ_r has impact on the final form of the energy distribution:
Case one: $\sigma_r < \sigma_x$ → sharp spike with long tails
Case two: $\sigma_r = \sigma_x$ → more or less gaussian distribution
Case three: $\sigma_r > \sigma_x$ → approx. like a water bug
Case four: $\sigma_r >> \sigma_x$ → double horn structure.

Perfectly matched laser beam size or slightly above the electron beam rms provides the most convenient form of the energy distribution.

Summary

- Three different optics have been calculated for the implementation of the laser heater and the diagnostics.
- Optics with the drift solution for the diagnostics allows to save about 7m space. Constant phase advance between OTRs can be provided, however, only for a range of initial β 30-65m.
- Optics with the FODO solution for the diagnostics requires more place, but makes the phase advances beteewn OTRs independent from the intial β.
- Beam sizes at the OTRs are well above the tolerance limits of the monitors.
- Laser heater specifications have been calculated for the laser wave lengths of 527, 800 and 1054 nm.
- Uncorrelated energy spread of the bunch after the interaction with the laser heater has been calculated for different ratios σ_r/σ_x.
- Perfectly matched laser beam size or laser beam slightly larger than the electron beam provides the most preferable energy distribution.



Expected range for t
maximum energy m