ELETTRA Users' Meeting Satellite Workshop :

"Prospects for FELs in the VUV and Soft X-ray Region as Sources for Scientific Research"

A Proposal for a Linac Based SASE-FEL Source Operating in the VUV-X region

Alberto Renieri - on behalf of the

SPARX Study Group

A collaboration among
CNR - ENEA - INFN - Univ. di Roma 2 "Tor Vergata"

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SUMMARY

1. Introduction
2. High Gain FEL Regime: General Description and Key-parameters
3. The LINAC
4. Possible Localization in Rome Area

Which Linac for what FEL λ_r ?

- **The study group decided to start a broad band investigation to compare different schemes and technologies**
- **The aim was to develop a program able to reach a wavelength range of interest (i.e. with a good scientific case), consistent with the available budget (67 MEUR + 5 MEUR + 29 MEUR)**
- **The project is meant to be evolutionary, that is compatible to a long term upgrade expected to reach the *final goal* of a 1 Å Coherent Radiation Source**

The Scientific Case
in the 10 nm $\Rightarrow$ 1 nm range

High Peak Brightness (> 10^{30}), Ultra-short (< 100 fs) radiation pulses are of great interest in various areas:

1. **molecular physics** (vibrational modes, bond breaking and formation at λ=10-1 nm, λ<1 Å)
2. **physics of the clusters** (phase transitions at λ=10-1 nm, λ<1 Å)
3. **surface and interfaces** (real time dynamics and phase transitions, λ=10-1 nm)
4. **time resolved chemical reactions** (metastable and transition states, magnetic scattering, confined systems, λ=10-1 nm, λ<1 Å)

$\Rightarrow$ **first step at 10 and 1.5 nm, paving the road toward 1 Å (and below)**

HIGH GAIN FEL REGIME: GENERAL DESCRIPTION AND KEY-PARAMETERS

SASE FEL DYNAMICS

SASE FEL DYNAMICS

- the spectral region and the brightness quoted in the s.c. cannot be achieved with conventional SR sources or SR-FELs. They require the use of FEL devices of the SASE type (self-amplified-spontaneous-emission-type)
- FELs operating in the SASE regime requires e-beams with high current and high qualities providing the necessary conditions to reach the saturation in one undulator passage with the appropriate coherence properties

SASE FEL DYNAMICS

- THE SASE PROCESS IS CHARACTERIZED BY 3 PHASES
- 1) THE RADIATION GROWS INITIALLY INCOHERENTLY
- 2) THE SYSTEM ORGANIZES THE COHERENCE AND GROWS WITH EXPONENTIAL GAIN
- 3) THE POWER HAS GROWN SUFFICIENTLY TO DETERMINE THE SATURATION

REQUIREMENTS

- PEAK BRIGHTNESS 10^{30} OR LARGER
- RELATIVE BANDWIDTH 0.1%
- PULSE DURATION <100 fs
- WAVELENGTH 10-0.1nm
- SATURATION LENGTH 50m

KEY NUMBERS AND PARAMETERS

THE CRUCIAL PARAMETER OF SASE DEVICES IS

$$\rho = \frac{1}{4\pi}\left(\frac{\pi g}{N^3}\right)^{1/3}$$

g=small-signal gain coefficient

SASE FEL DYNAMICS

The saturated Power $$P_s \approx \rho P_e$$

The relative bandwidth $$\frac{\Delta \varpi}{\varpi} = \rho$$

The saturation length $$L_s = \frac{\lambda_u}{\rho}$$

HIGH GAIN FREE ELECTRON LASERS

- INTENSITY GROWTH RATE

$$G = \frac{1}{9}\exp(4\sqrt{3}\pi\rho \mathrm{N})$$

- GAIN REDUCTION PARAMETERS

$$\mu_\varepsilon = \frac{2\sigma_\varepsilon}{\rho} < 1 \qquad \mu_{x,y} = \frac{1}{\rho}\frac{K}{1+\frac{K^2}{2}}\frac{\gamma\pi\varepsilon_n}{\lambda_u}$$

SASE FEL DYNAMICS

- BY CHOOSING JUST TO FIX IDEAS

$$N\rho=1$$

WE OBTAIN AN AMPLIFICATION FACTOR

$$G=\frac{1}{9}\exp(4\sqrt{3}\pi)=3.15\cdot 10^{8}$$

- CORRESPONDING TO A SMALL SIGNAL GAIN COEFFICIENT

$$g_0=\frac{(4\pi)^2}{\pi} \qquad g_0 \approx 6.3\cdot 10^{2}$$

SASE FEL DYNAMICS

- The current values are also fixed by the initial requirements on the optical pulse duration

$$Q \cong 1nc\ ,\ \tau \approx (100 - 300)\ fs$$

$$I \geq 2kA$$

SASE FEL DYNAMICS

- The requirement on the bandwith suggests that

$$\rho \cong 10^{-3}$$

- As consequence

$$N \cong 10^{3}$$

$$L_u < 50 \Leftrightarrow \lambda_u < 5cm$$

SASE FEL DYNAMICS

- IN ANY FEL DEVICE THERE ARE TWO CRUCIAL PARAMETERS
- a) The small signal gain coefficient

$$g_0$$

- b) The Saturation Intensity

$$I_s\left(\frac{MW}{cm^2}\right) = 6.9 \cdot 10^2 \left(\frac{\gamma}{N}\right)^4 \frac{1}{[\lambda_u[cm]Kf_b(K)]^2}$$

SASE FEL DYNAMICS

- LASER POWER

$$I_L = \frac{1}{2} g_0 I_S = \frac{1}{2N} P_e$$

- High Gain FEL ρ–PARAMETER

$$\rho = \frac{1}{4\pi} \left(\frac{\pi g_0}{N^3}\right)^{\frac{1}{3}}$$

SASE FEL DYNAMICS

- LASER POWER

$$I_L = 1.26 \cdot 10^3 I_s$$

- By recalling that

$$g_0 = \frac{(4\pi)^2}{\pi} \quad (g_0 = \frac{16\pi}{\gamma} \lambda_r L_u \frac{JN^2}{1.7 \cdot 10^4} \xi \cdot f_b(K))$$

- We can obtain the conditions on J

SASE FEL DYNAMICS

- The use of the condition

$$\varepsilon < \frac{\lambda}{4\pi}$$

- Provides the following extimation of the attainable laser power density

$$I_L\left[\frac{MW}{cm^2}\right] \cong F(K)\frac{1}{N^4(\varepsilon[mrad])^2},$$

$$F(K) = .13\left[\frac{1+\frac{K^2}{2}}{Kf_b(K)}\right]^2$$

SASE FEL DYNAMICS

- COLLECTING THE VARIOUS NUMBERS WE GET

$$I \cong (2-3)KA$$

$$\sigma_{\varepsilon} \cong 10^{-3},$$

$$\varepsilon_{n} \cong \pi \cdot mm \cdot mrad$$

$$E \geq 2GeV$$

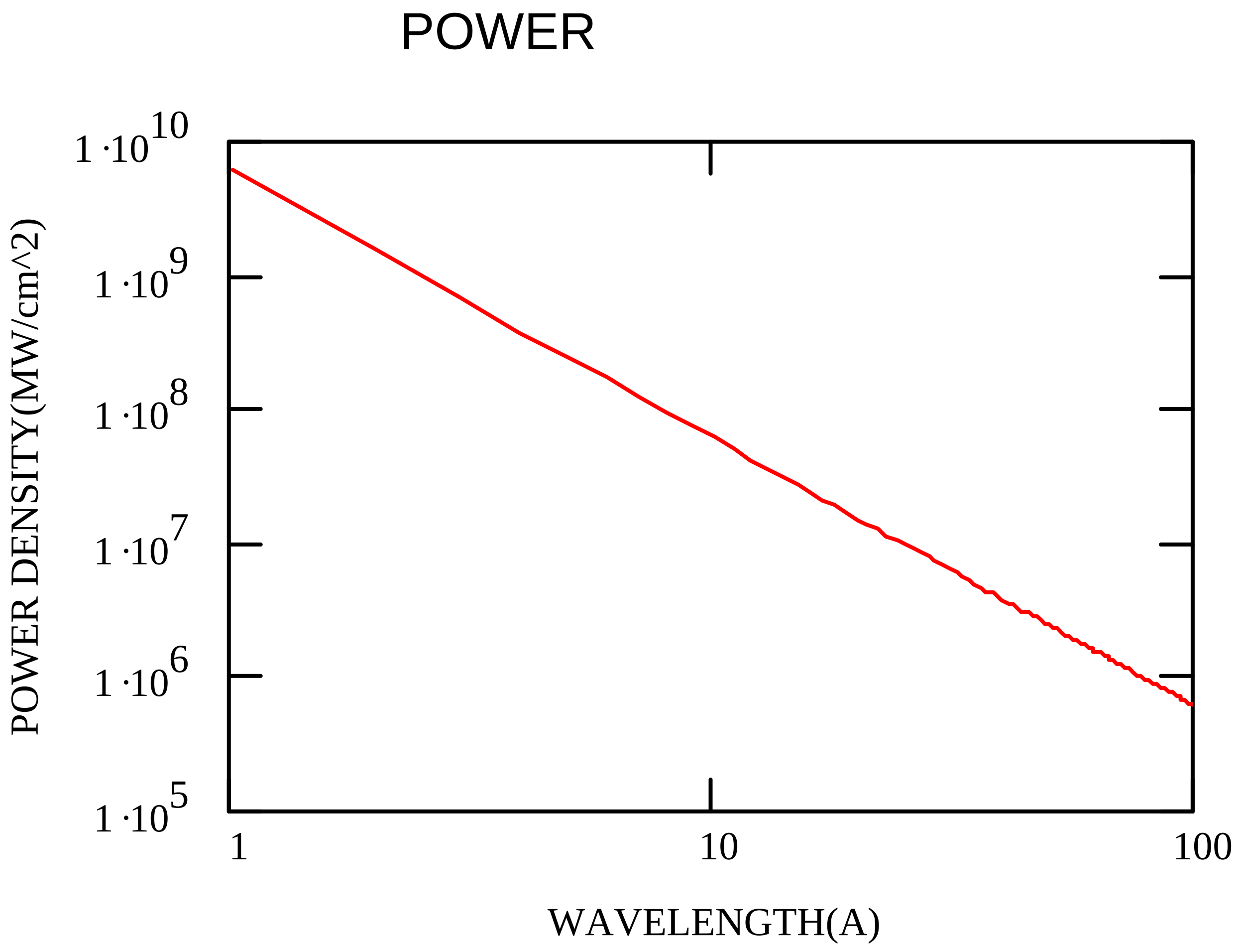
CODES

- PROMETEO (1d-numerical)
- PERSEO (1d-numerical)
- MEDUSA(3d-numerical)
- GINGER (3d-numerical)
- PARSIFEL (analytical)

INTERNATIONAL CODE BENCHMARKING:

- EXOTICA (Coordinator Sandra G. Biedron, ARGONNE)

PARSIFEL: Diffraction limited operation
(λ_u = 2 cm, *k* = 1, $\rho = 10^{-3}$, *N* = 1000)



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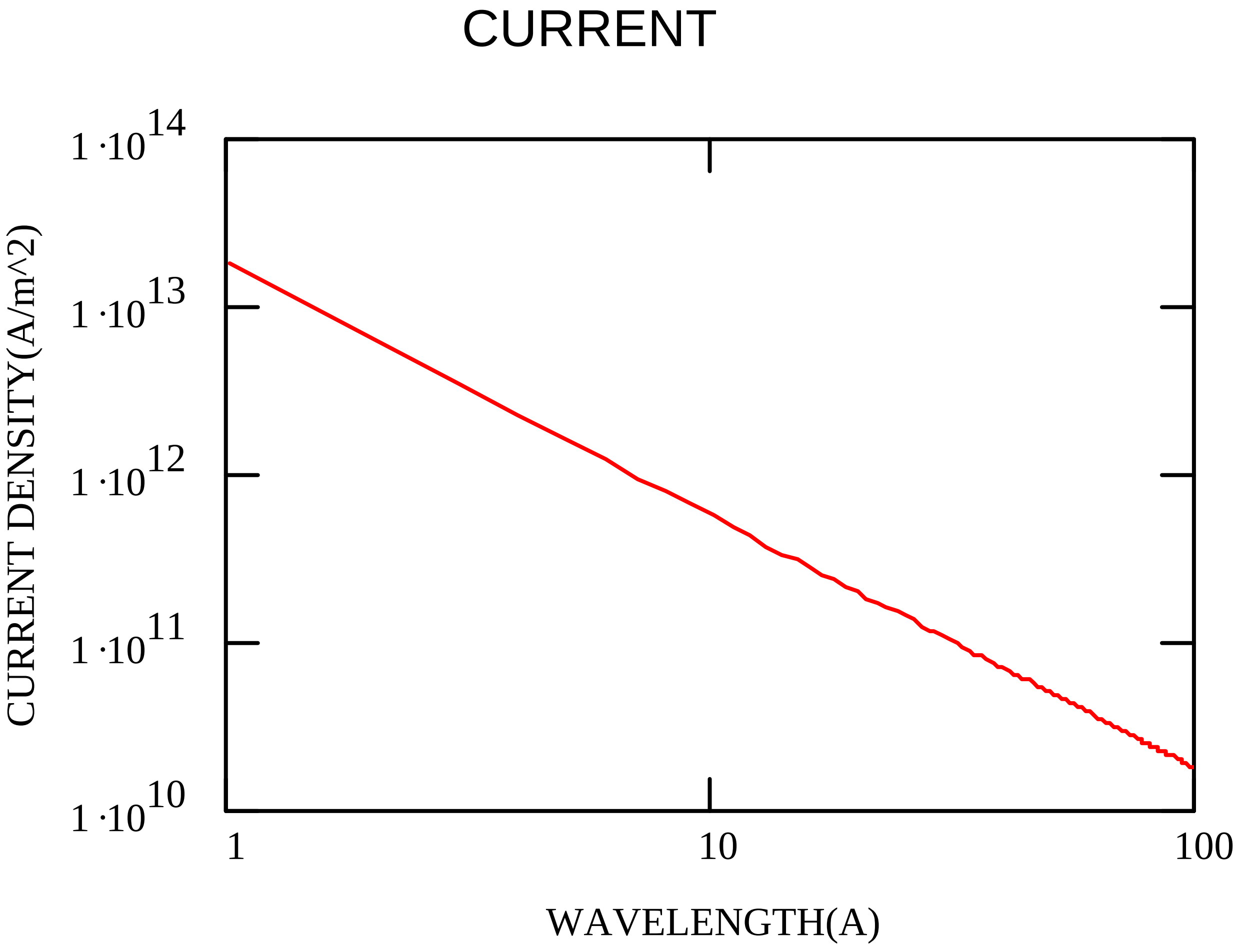
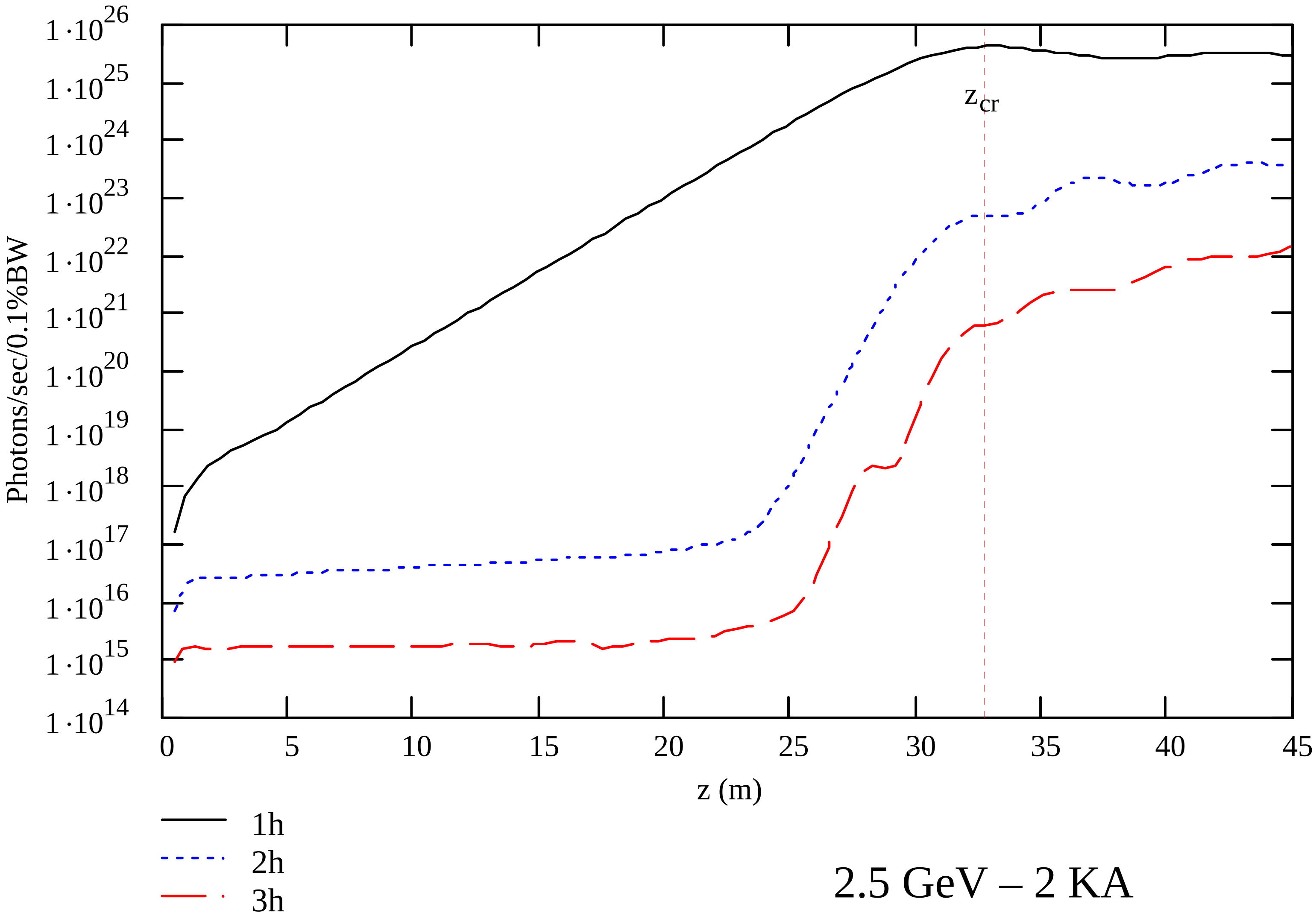
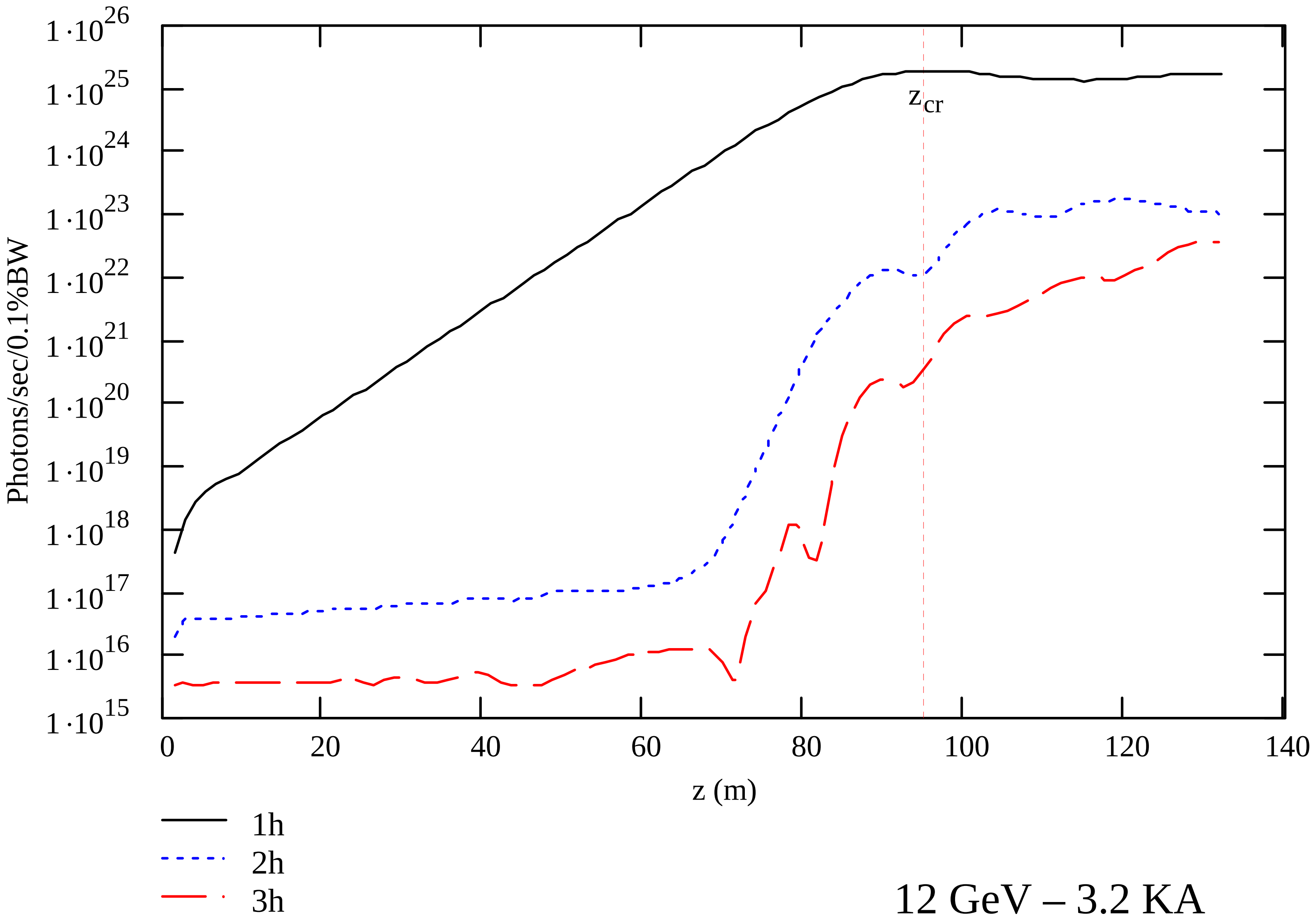




PROMETEO-PERSEO

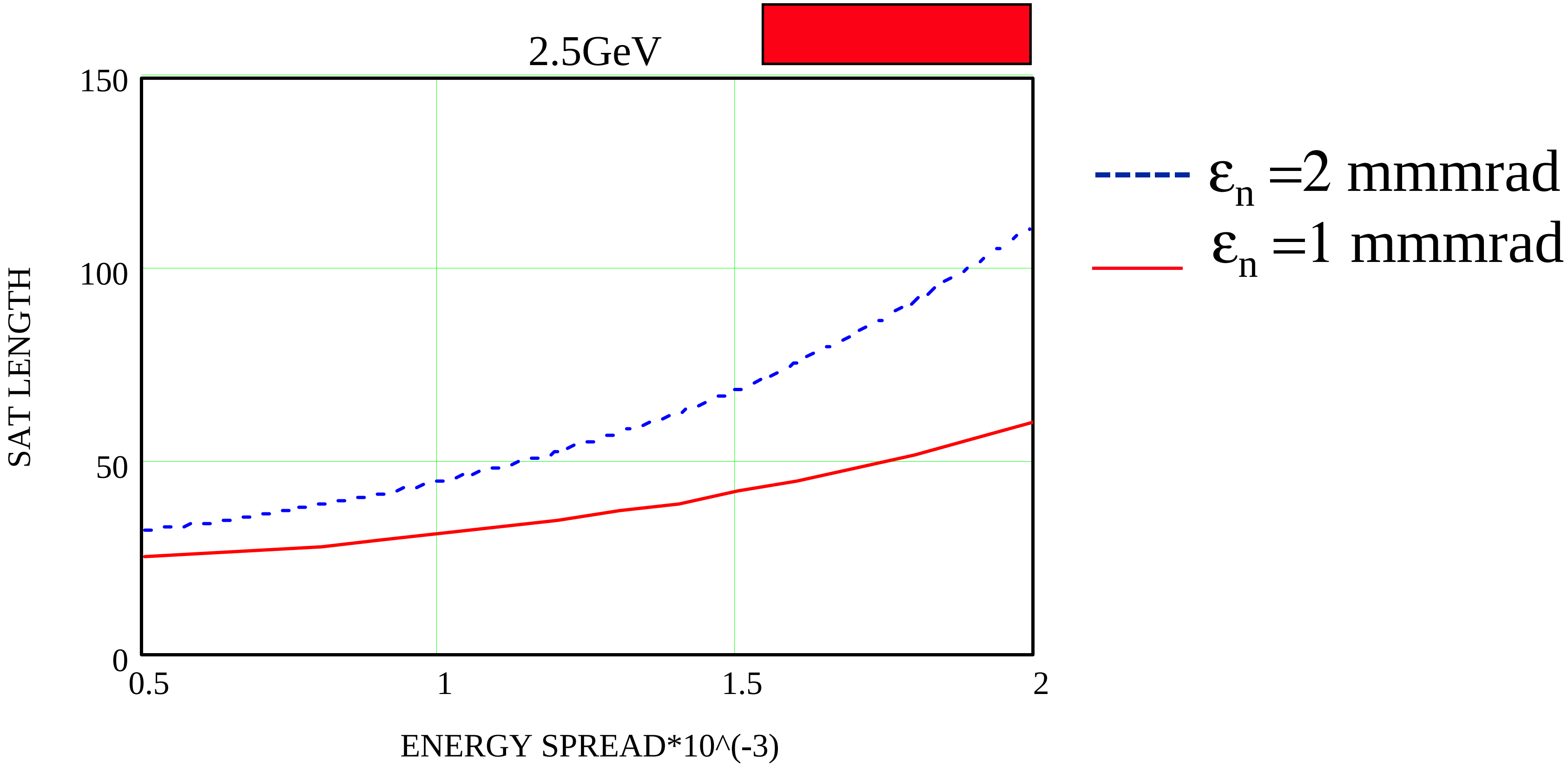
2.5 GeV – 2 KA
0.1% energy spread
1 mm mrad emittance



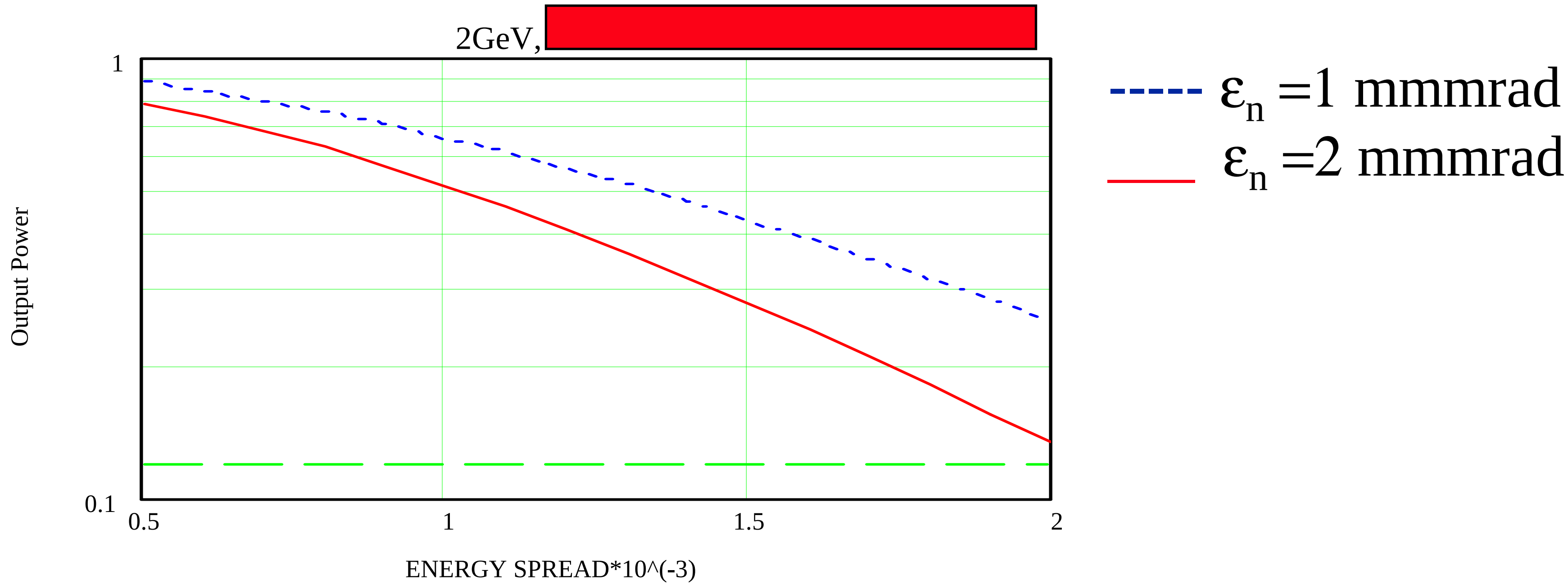
12 GeV – 3.2 KA
0.05% energy spread
1 mm mrad emittance

PROMETEO-PERSEO

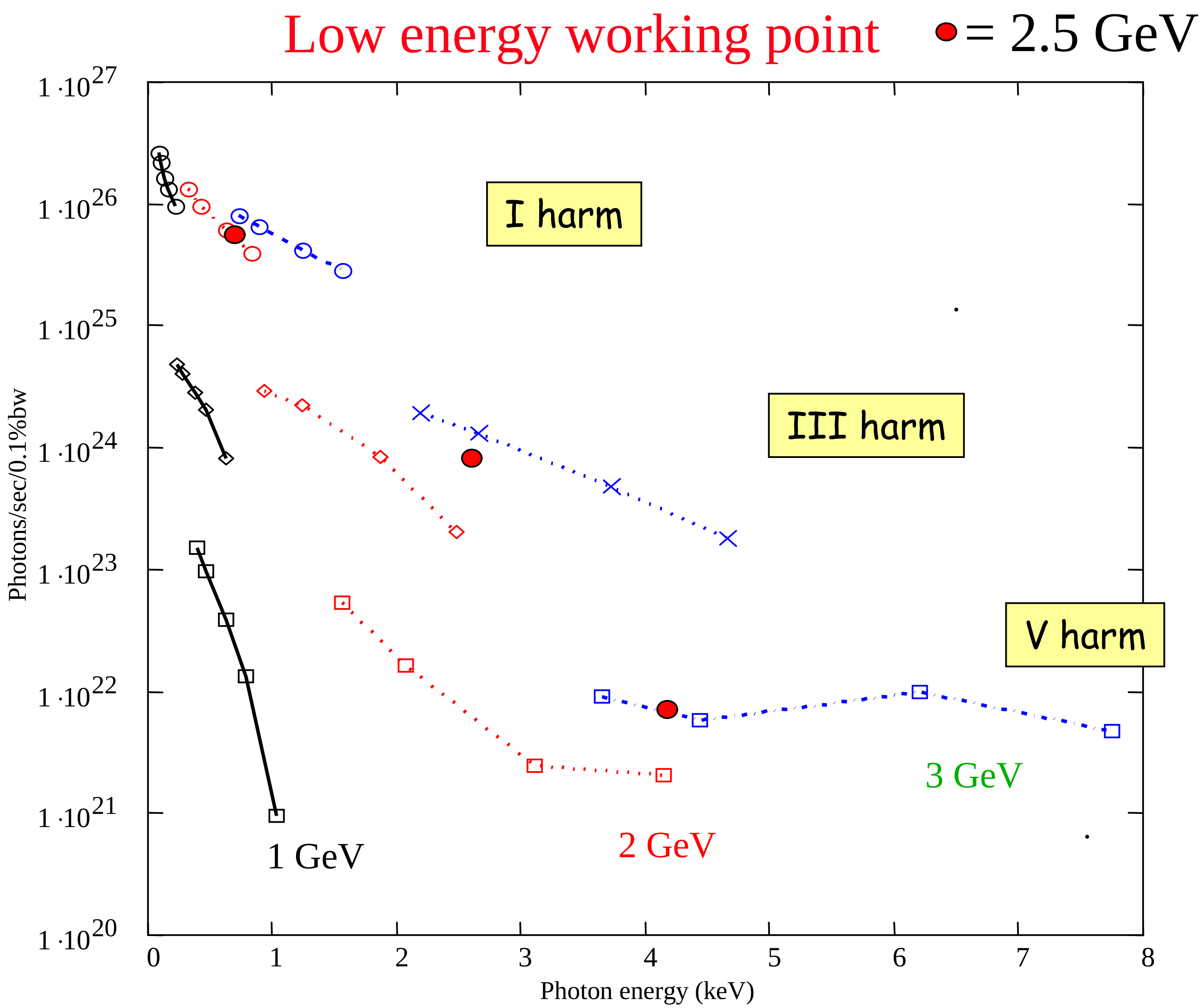
PARSIFEL: Energy spread sensitivity



PARSIFEL: Energy spread sensitivity



PERSEO



Low energy working point
= 2.5 GeV
I harm
III harm
V harm
1 GeV
2 GeV
3 GeV
Photons/sec/0.1%bw
Photon energy (keV)
1 ·10^27
1 ·10^26
1 ·10^25
1 ·10^24
1 ·10^23
1 ·10^22
1 ·10^21
1 ·10^20
0
1
2
3
4
5
6
7
8

The LINAC for a FEL SASE DEVICE

Which technology for a 2 GeV Linac with long term evolution toward 10 GeV ?

- 2 GeV is consistent with λ = 1.5 nm

	10 nm	1.5 nm $\Rightarrow$	1 Å
I [kA]	2	2	3-5
ε_n [μm]	2 (1)	2(1)	$\cong$ 1
$\Delta\gamma/\gamma$ [%]	$\leq$ 0.3	$\leq$ 0.1	$\cong$ 0.07
T [GeV]	2	2	$\cong$ 10

A bird view over the challenges in generating high brightness electron beams

$$B_n = \frac{2I}{\varepsilon_n^2}$$

- **Peak Brightness demands exceed capabilities of modern beam sources, i.e. advanced photoinjectors (plasma gun ?)**
- **No cooling mechanism is available in a Linac for the rms normalized transverse emittance ε_n**
- **Need of a device to boost the brightness via bunch compression (peak current increase over the natural 50-100 A delivered by the source)**

Continue on challenges

$$B_n = \frac{2I}{\varepsilon_n^2}$$

Three Major Tasks to accomplish

1) Minimize all mechanisms leading to degradation of the rms normalized transverse emittance ε_n

2) Peak current enhancement by a factor 20-100

3) Damp the beam energy spread below the threshold $\Delta\gamma/\gamma < \rho$

DESIGN CRITERIA

1) Optimum Emittance Correction accomplished in initial 150 MeV (laminar regime)

a) matching to Invariant Envelope

b) tuning of emittance oscillations

2) Optimum Magnetic Compressor Design

a) minimize $R_{56} = \delta L / (\Delta\gamma/\gamma)$

b) integrate bunch compression into laminar regime using velocity bunching

3) Control $\Delta\gamma/\gamma$ via short range longitudinal wake-fields and adiabatic damping

DESIGN CRITERIA

KEY FACTS:

A) Brightness scales up with RF frequency of photoinjector

B) Emittance growth due to CSR scales up with R_{56}

Maximizing Brightness in Laminar Beams

$$B_n = \frac{2I}{\varepsilon_n^2}$$

A beam is laminar when

$$\gamma \le \frac{(I/I_0)}{\varepsilon_{nth}\gamma'\sqrt{1+4\Omega^2}} \quad ; \quad \gamma_{lam} = 300 \;\; in \;\; LCLS$$

Maximum brightness is reached @ $\gamma = \gamma_{lam}$ when the beam is matched on the Invariant Envelope

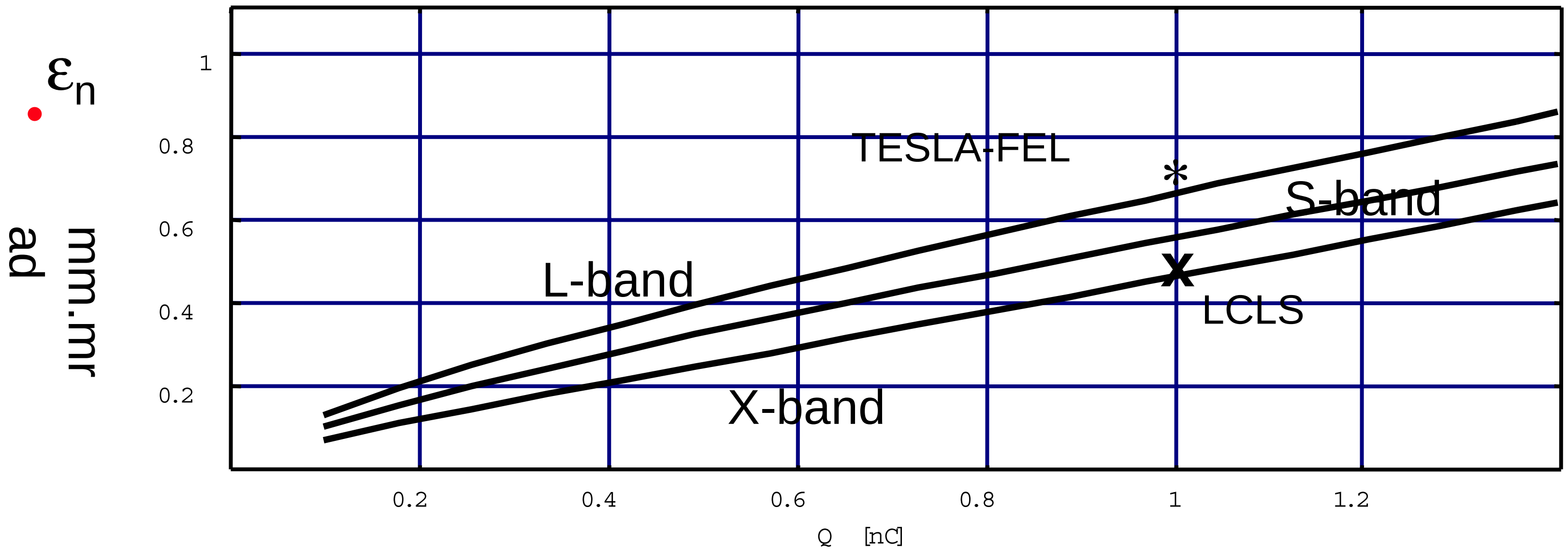
$$\sigma_{INV} = \frac{1}{\gamma'}\sqrt{\frac{2I/I_0}{\gamma\left(1+4\Omega^2\right)}}$$

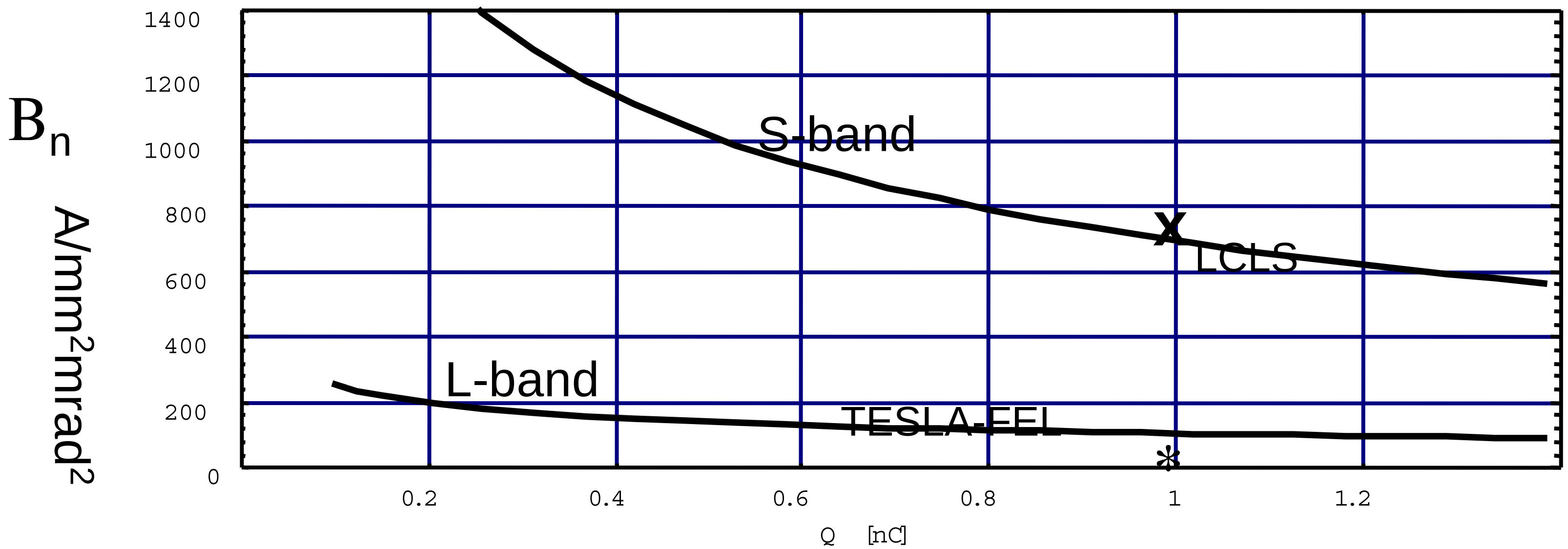
Implying a condition at the photocathode

$$\frac{I}{\left(E_0^{RF} R_{cat}\right)^2} = \cos t$$

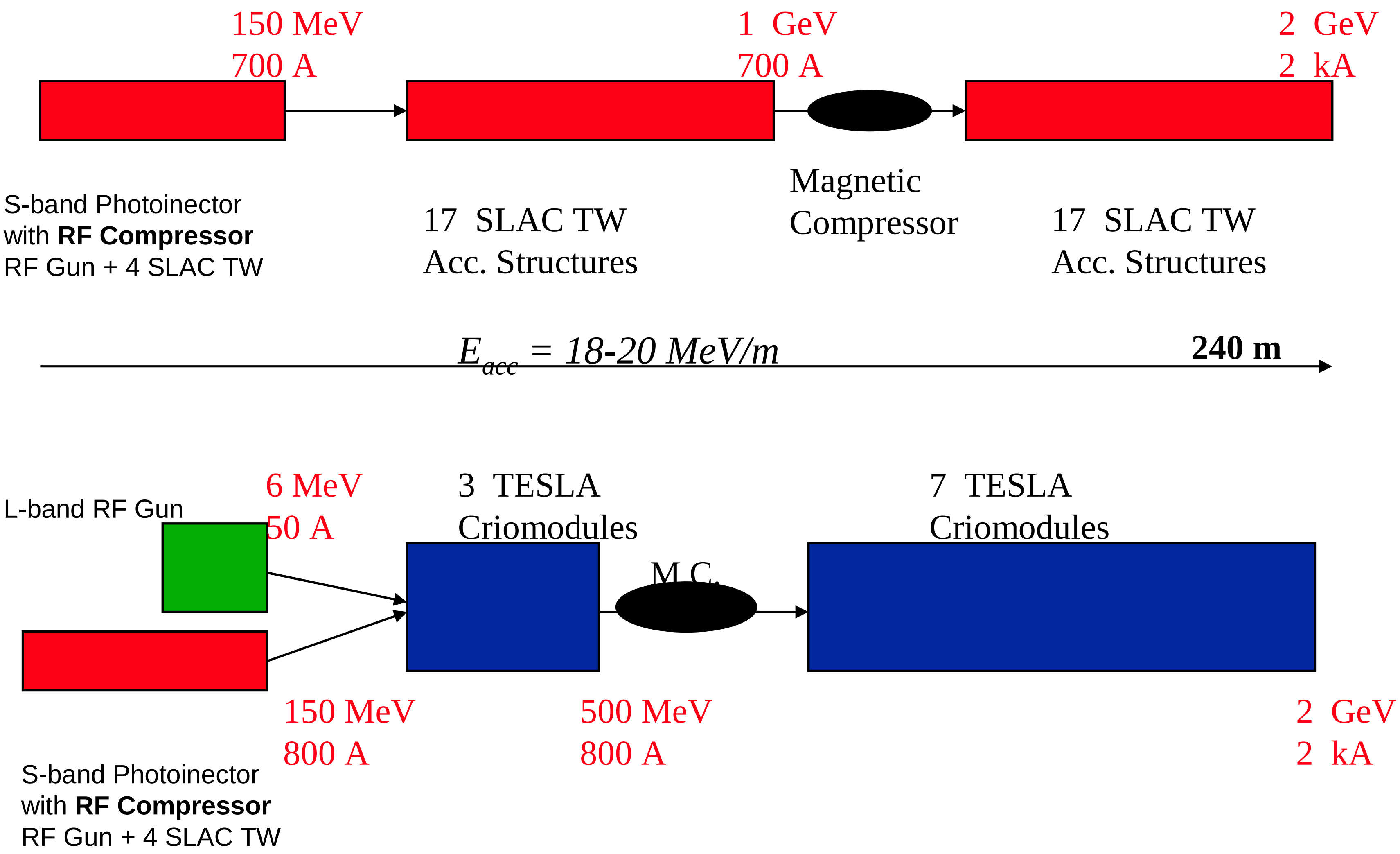
nat. scaling $\begin{cases} R_{cat} \propto \lambda_{RF} \\ E_0^{RF} \propto \lambda_{RF}^{-1} \end{cases}$

Emittance and brightness scaling





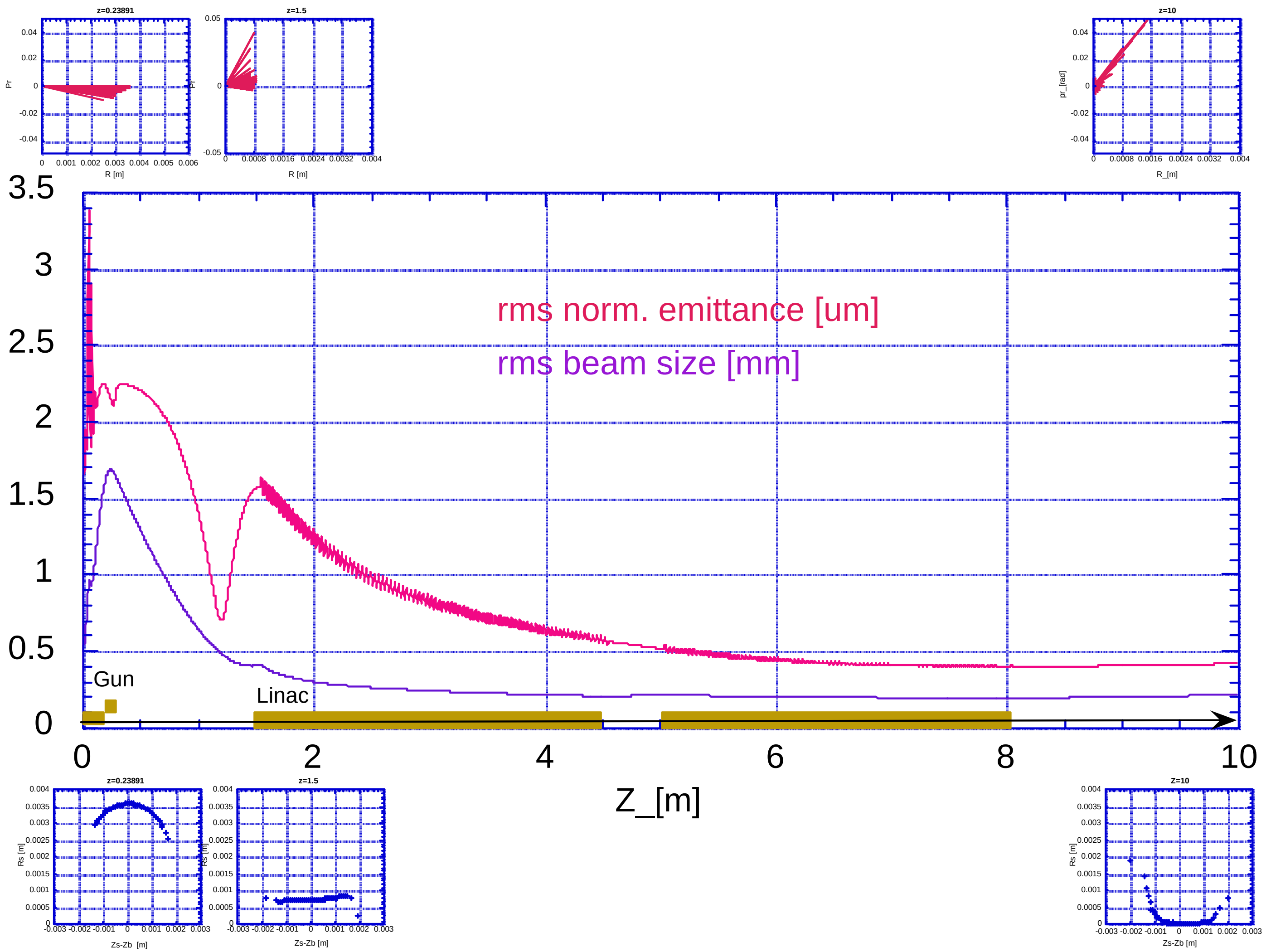
TWO OPTIONS:
S-band Room-Temperature
L-band Super-Conducting



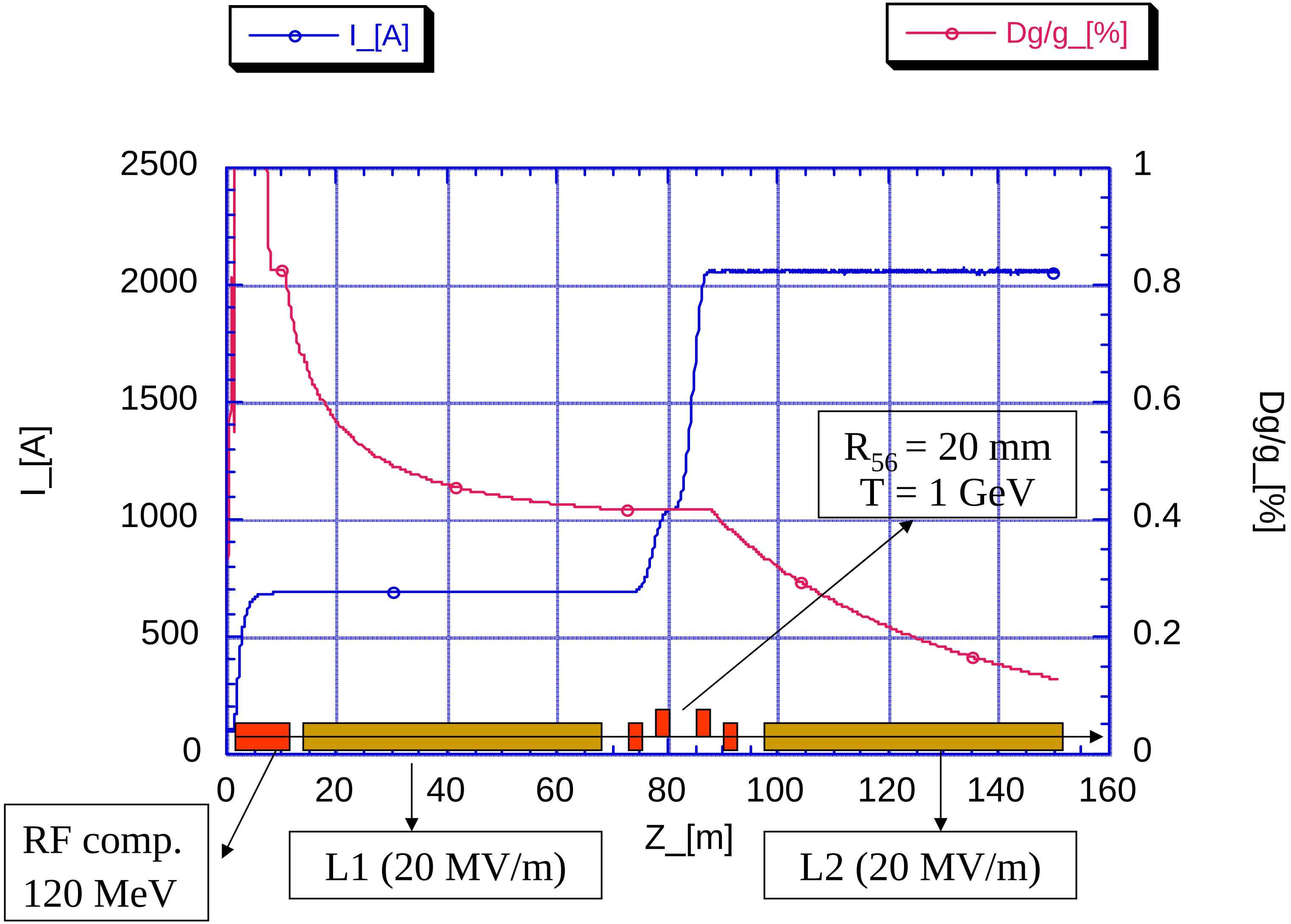
S-band photoinjector up to 150 MeV, HOMDYN simulation

(RF Gun + 2 Traveling Wave Structures)

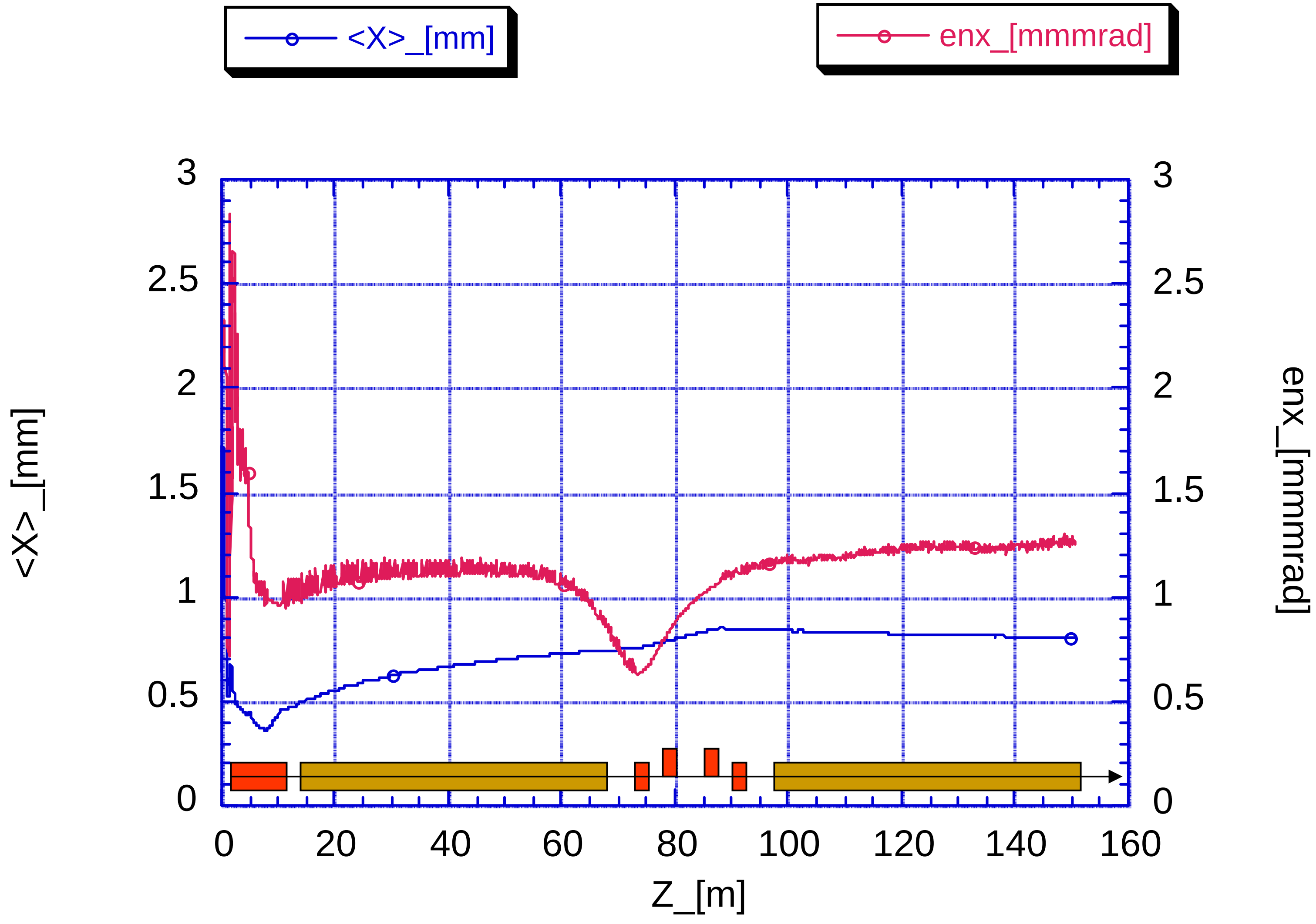
Q=1nC, L=10ps, R=1 mm, Gun E_{peak}=140 MV/m, TW E_{acc} = 25 MV/m



S-band SPARX Linac preliminary layout,
(RF compressor + Linac 1 + Magnetic Compressor + Linac 2)
HOMDYN simulation up to 2 GeV



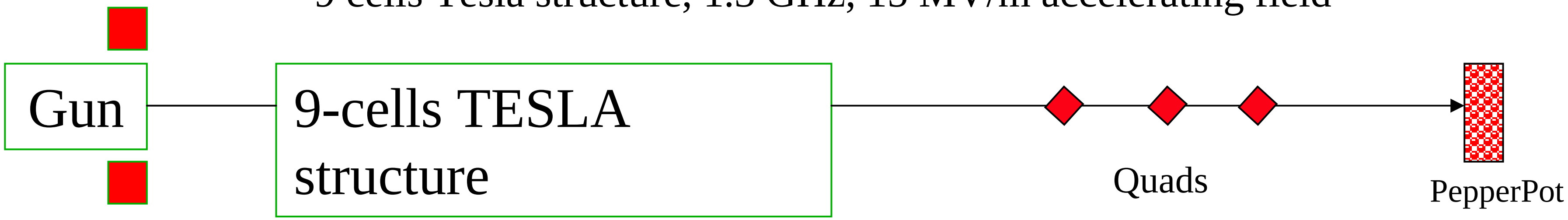
Emittance compensation along the linac not yet optimised



Experimental validation at the A0 photoinjector (FERMILAB)
(Jean Paul Carneiro et al.)

1.6 cells gun, 1.3 GHz, 40 MV/m peak field, 1.3 KG solenoid

9 cells Tesla structure, 1.3 GHz, 15 MV/m accelerating field



Solenoid Scan @ 8nC

Emittance (mm-mrad) computed by HOMDYN and PARMELA/Orsay

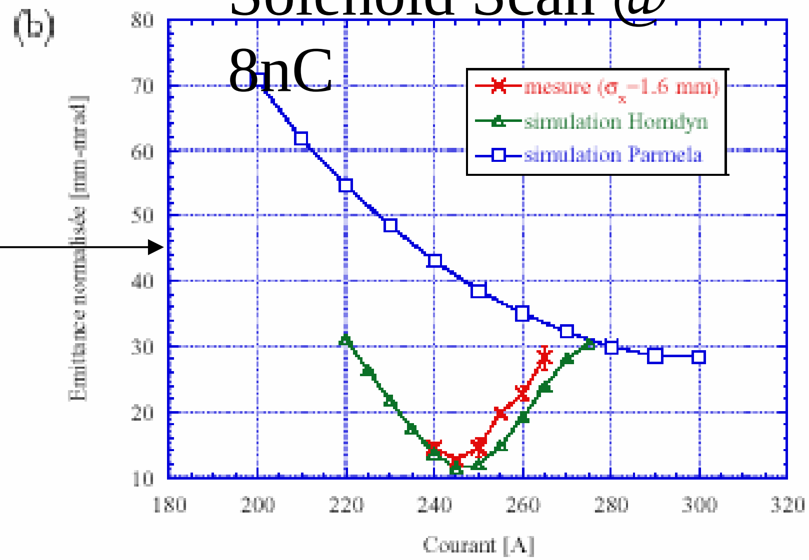
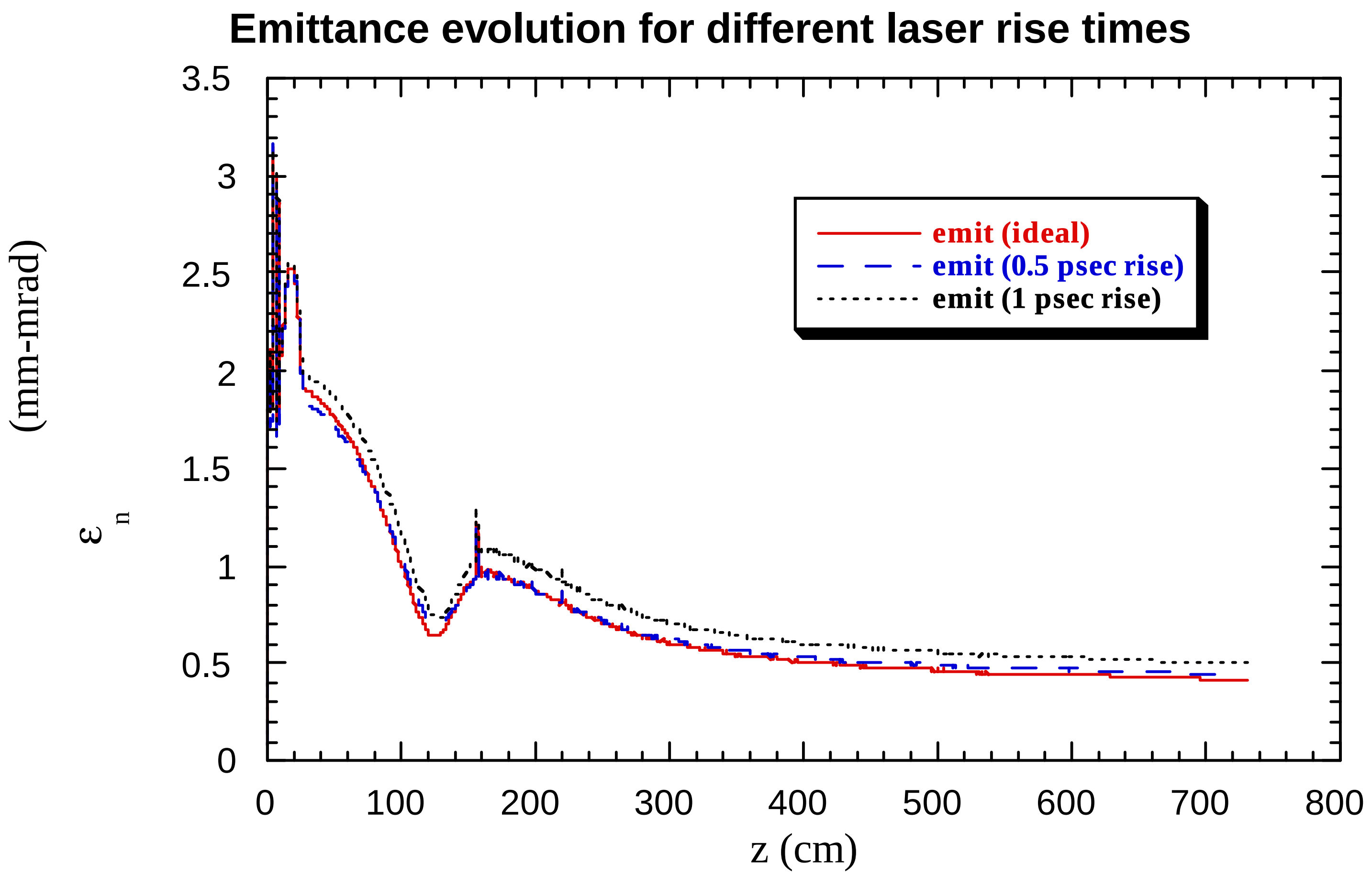


Figure 6.10: (a) mesure de l'émittance verticale normalisée ϵ_y pour un faisceau de charge Q=8 nC nC à z=3.8 m en fonction du courant dans les solénoïdes pour trois dimensions transverses σ_x de la tache laser sur la cathode et (b) comparaison du cas σ_x=1.6 mm avec les codes de simulations Homdyn et Parmela.

Comparison with PARMELA/UCLA

==> good agreement



Beam Time Structure

S-band option

RF Pulse	350 ns
Bunch per Pulse	1-10
Rep. Rate	10-100 Hz

L-band option

RF Pulse	1 ms
Bunch per Pulse	10^4 (10^4/sec in CW)
Rep. Rate	5 Hz

S-band inj. + L-band option

RF Pulse	5 μs
Bunch per Pulse	1-40
Rep. Rate	10-100 Hz

Max rep. rate from freq. Match 4 MHz with nat. freq. (260 MHz with 2860 and 1300)

Conclusions

We have an *innovative solution* for the Linac lay-out which appears to *relax the criticality of beam compression*

We have identified two possible options :

1) S-band Linac: technologically simpler and less expensive

2) L-band Linac with add. S-band injector: requires a stronger effort and larger cost, but offers more flexibility w.r.t. the evolution toward 1 Å in terms of:

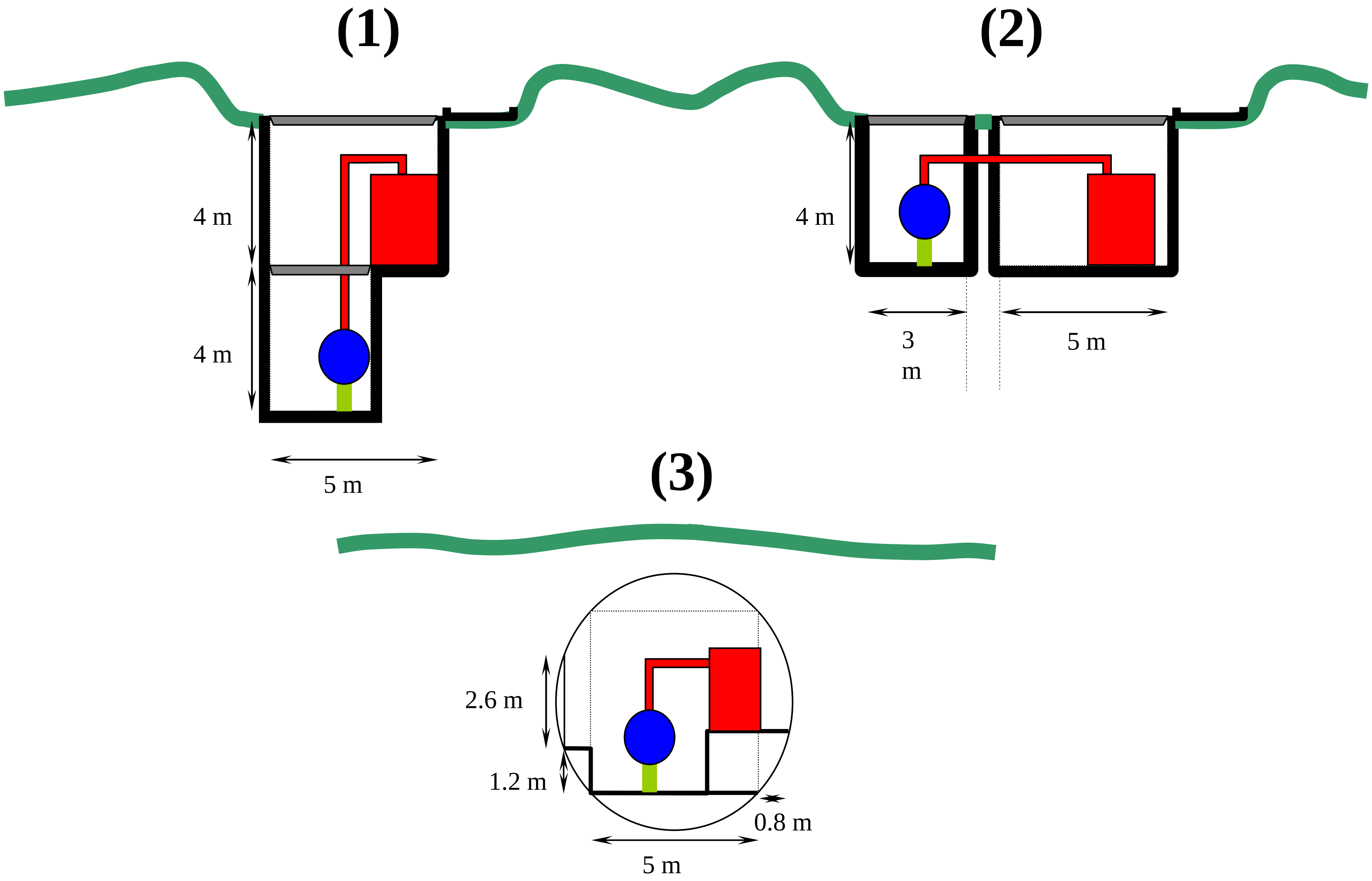
Conclusions (cont.)

- **Stability in energy jitter**
- **Multi-user facility (higher RF duty cyle, beam duty cycle is limited by laser / photocathode system performances)**

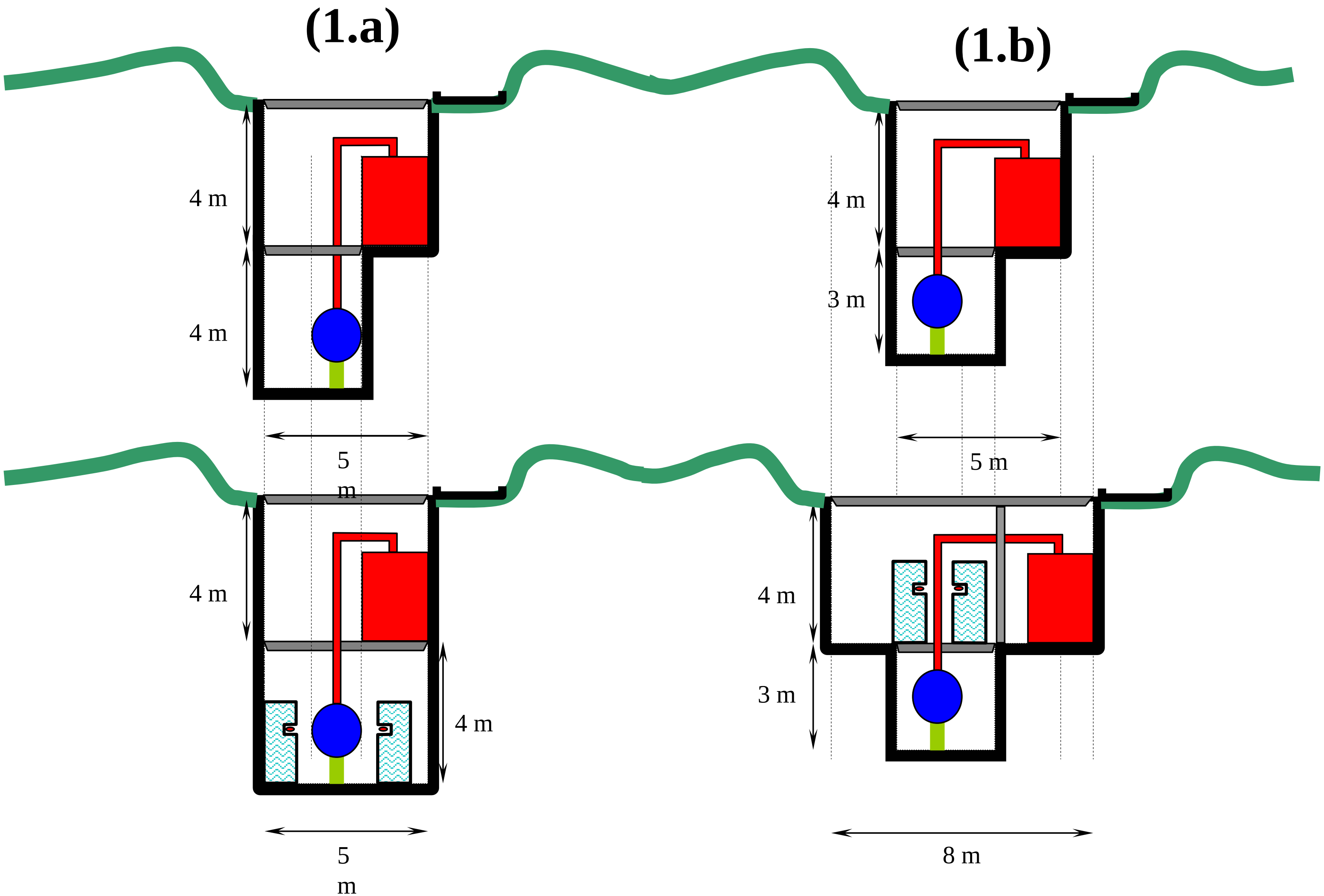
- **Better suited for future potentialities of Super-Conducting Photoinjectors**

DEVICE LAYOUT

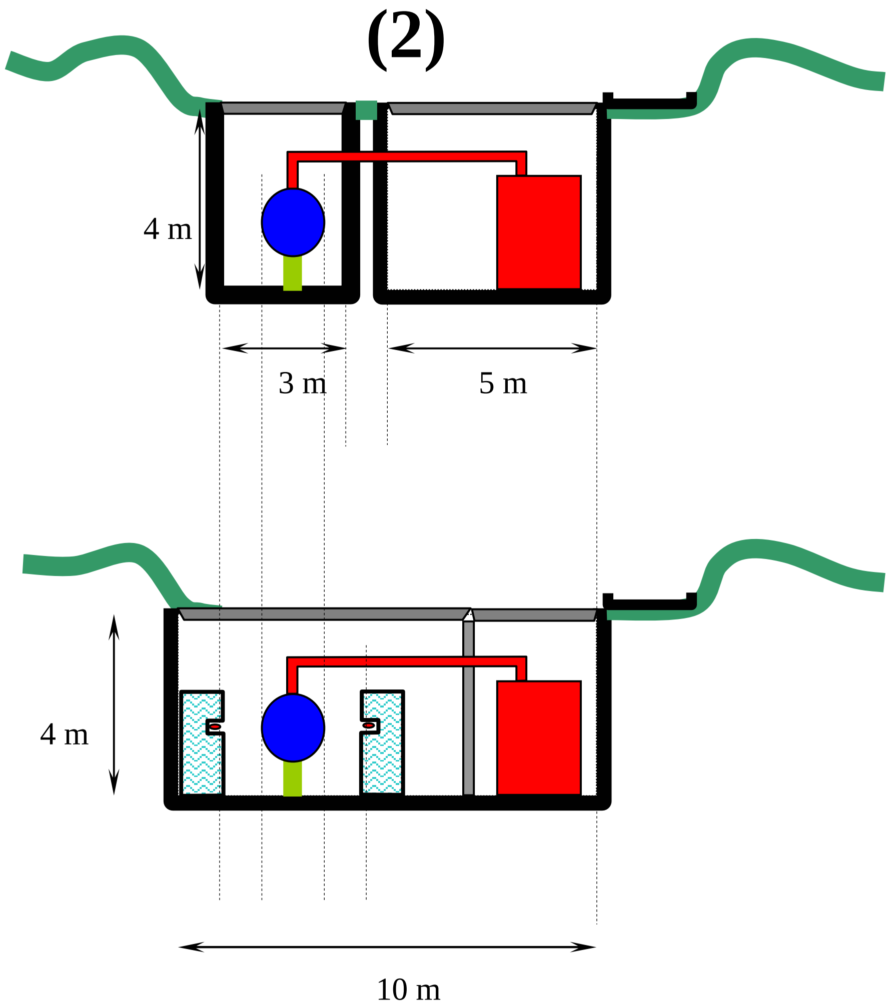
Three possible layout for SPARX



FEL Area and beam-lines: Scheme (1)

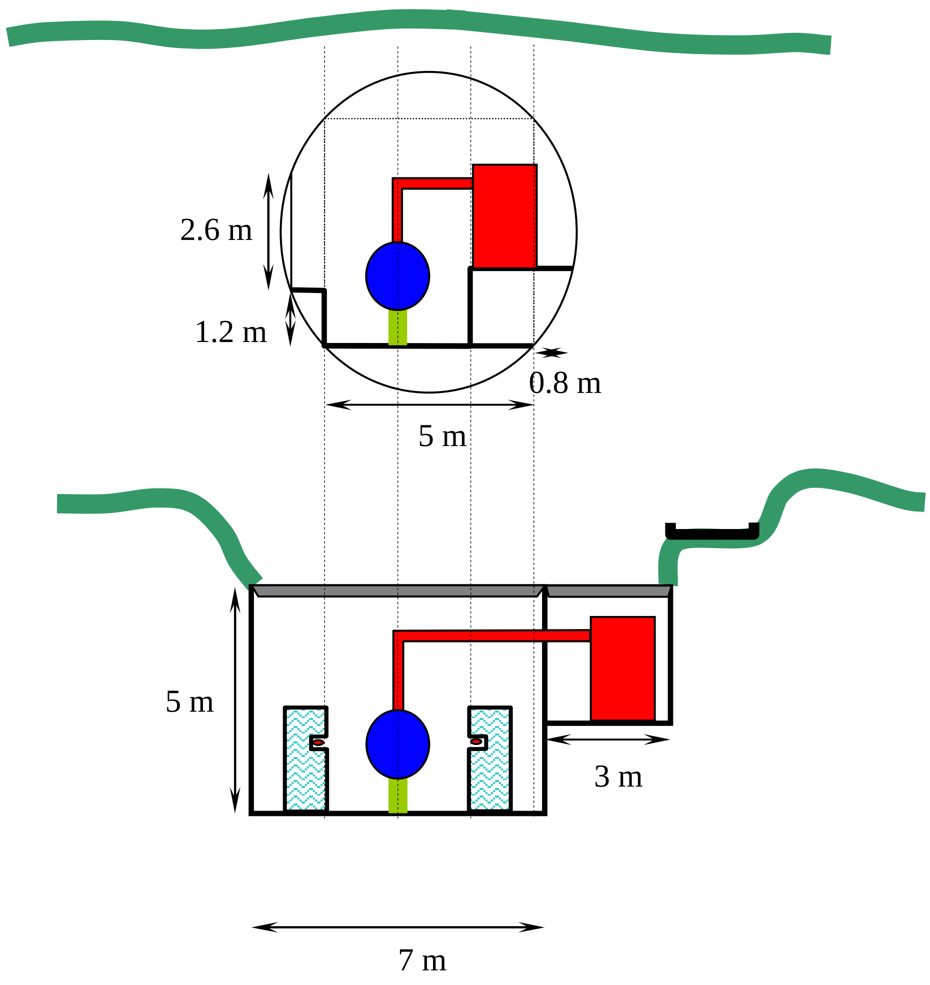


FEL Area and beam-lines: Scheme (2)



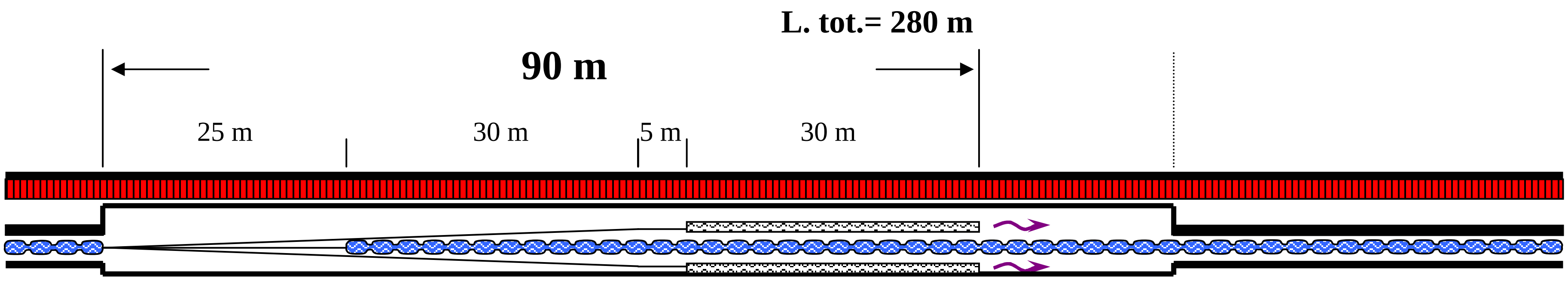
FEL Area and beam-lines: Scheme (3)

(3)



two degrees horizontal deflection of the 2 GeV electron beam

Layout



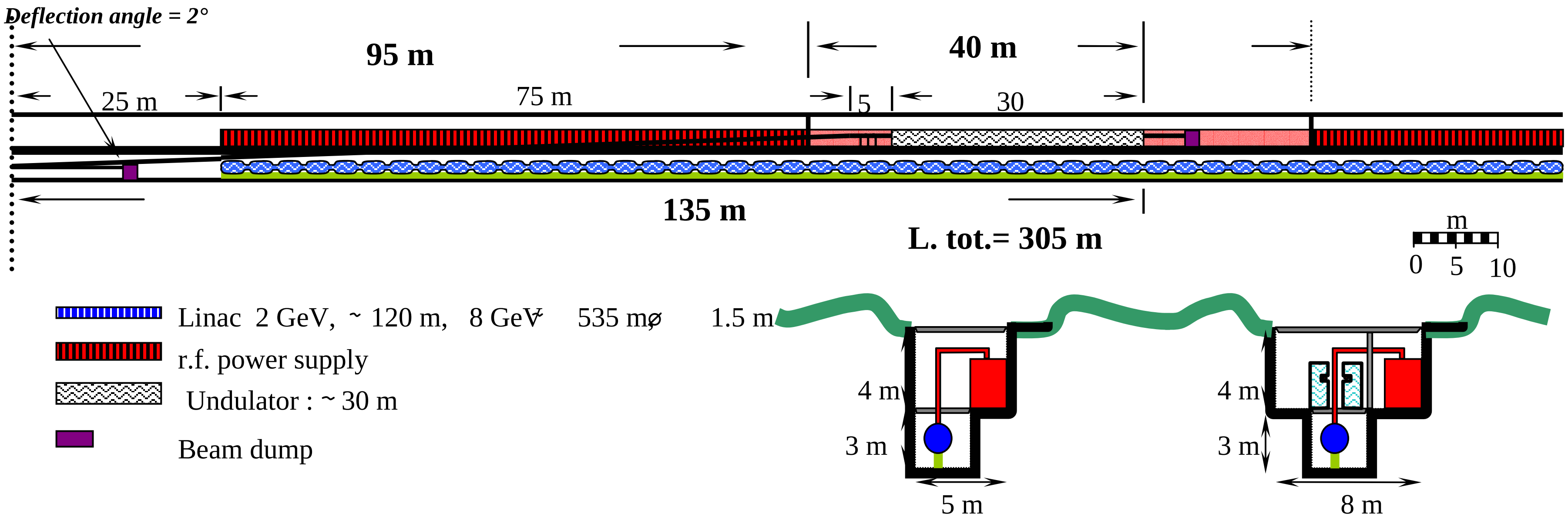
Linac 2 GeV, ~ 120 m, 8 GeV ~ 535 m, 1.5 m

r.f. power supply

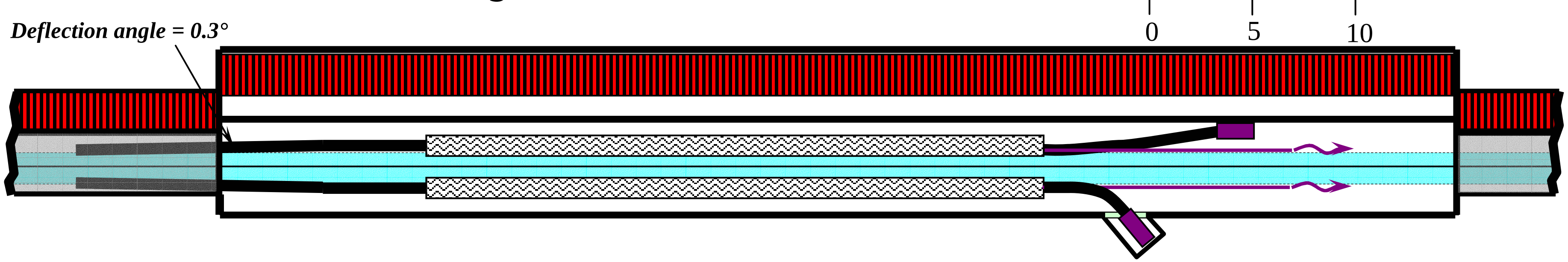
Undulator: ~30 m

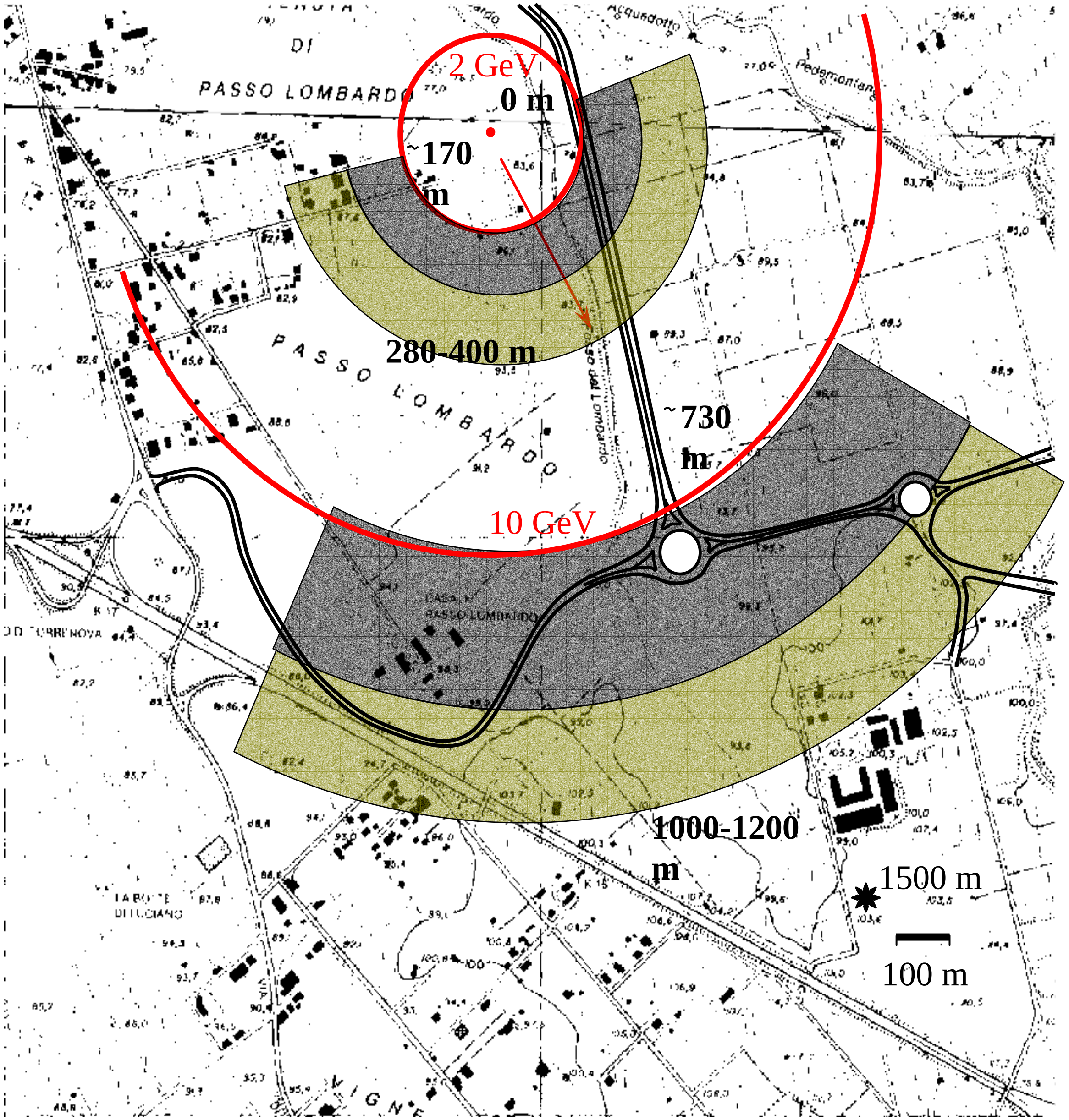
two degrees vertical deflection of the 2 GeV electron beam

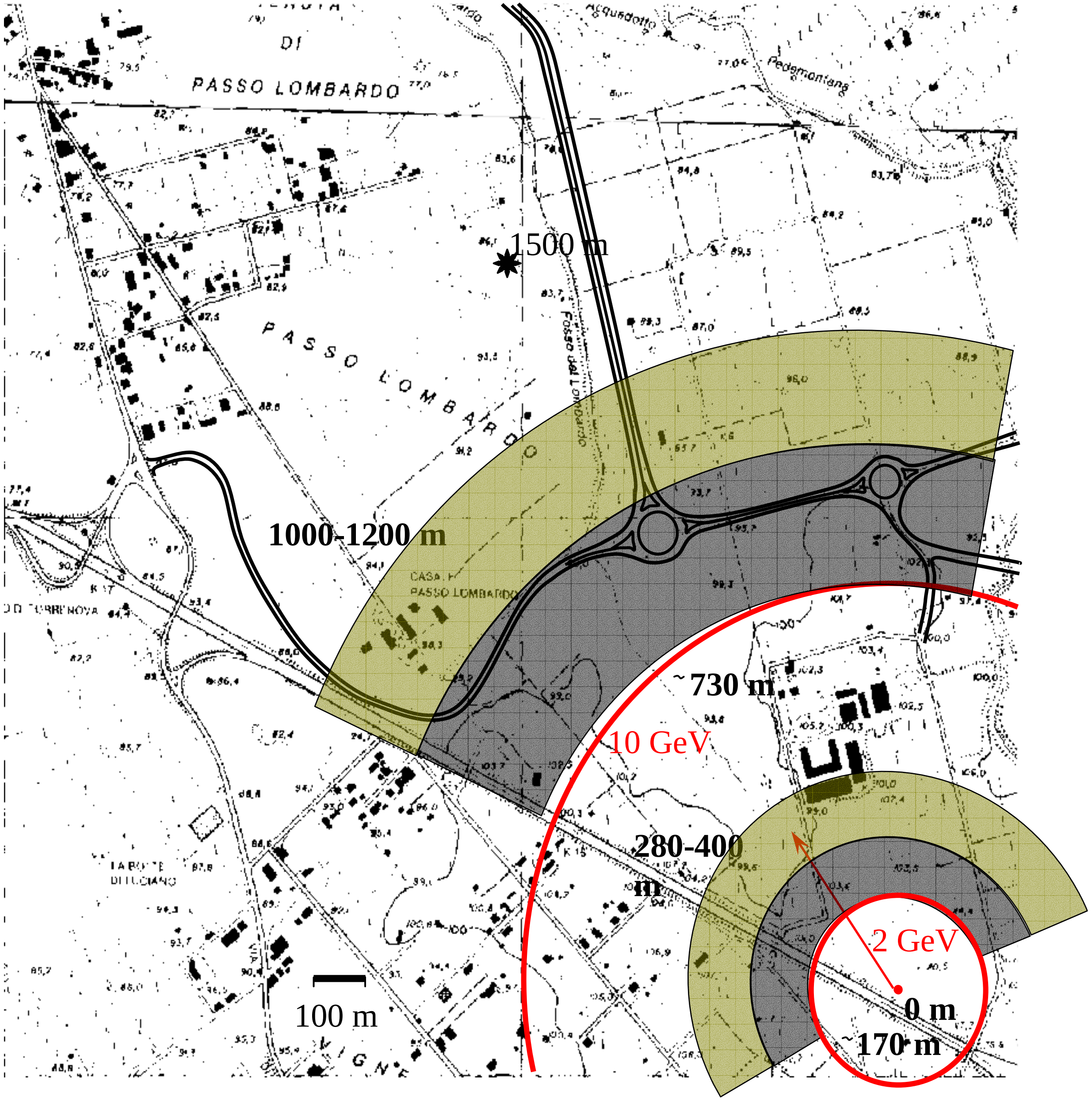
Longitudinal cross-section



Enlarged view




2 GeV
0 m
~170 m
280-400 m
~730 m
10 GeV
1000-1200 m
1500 m
100 m
PASSO LOMBARDO
CASA PASSO LOMBARDO



1500 m
1000-1200 m
~730 m
10 GeV
280-400 m
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0 m
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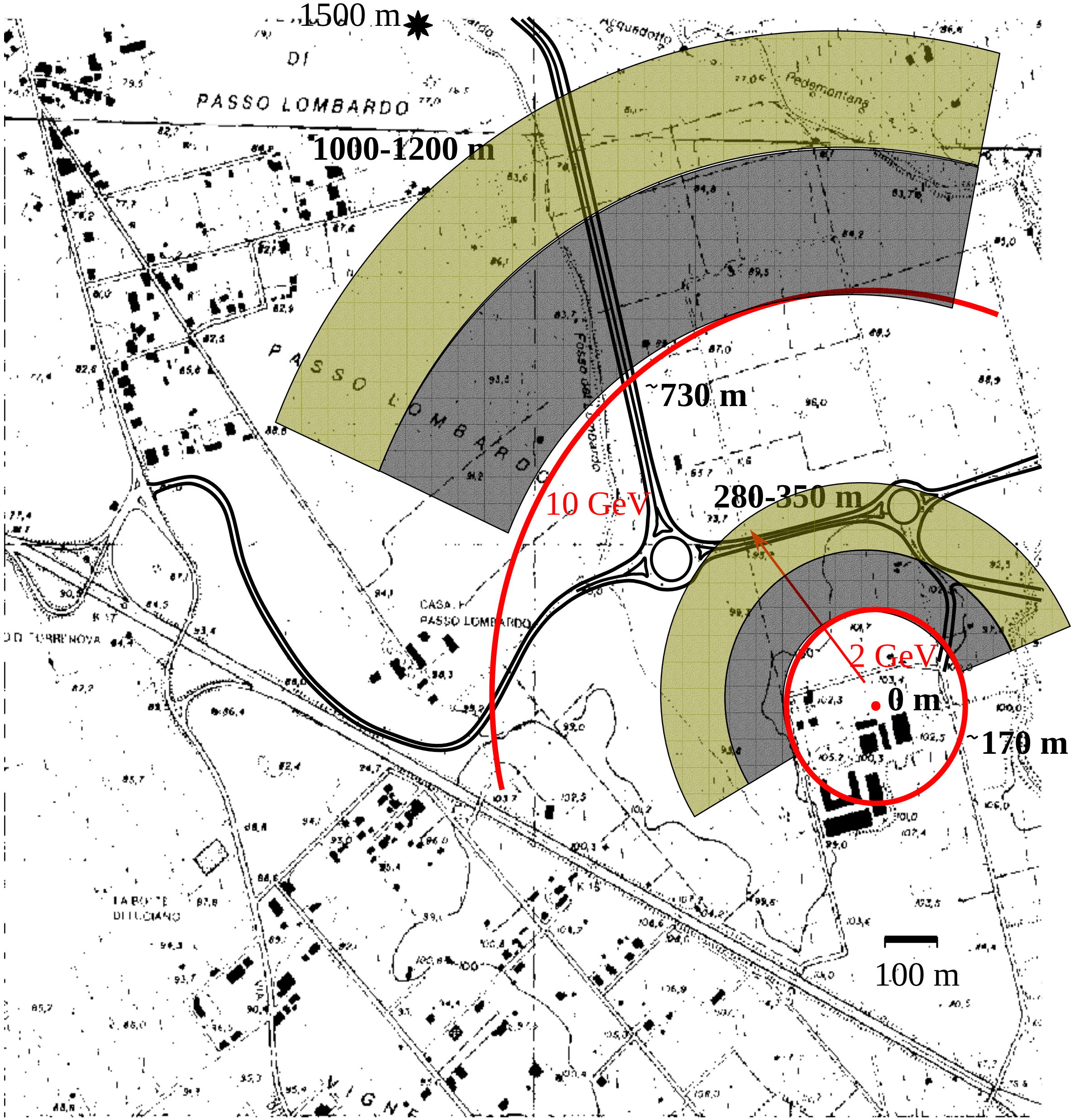
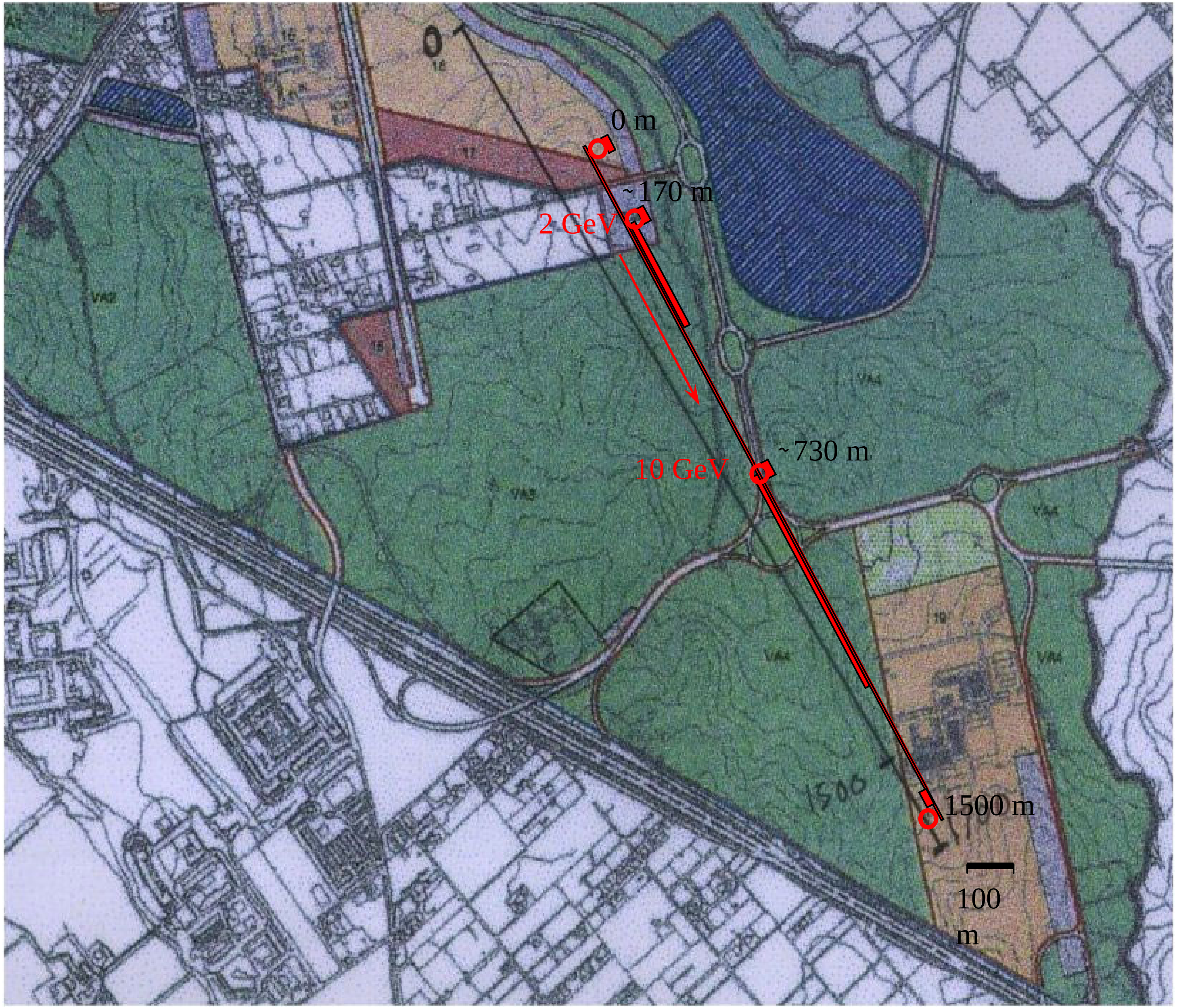
PASSO LOMBARDO



1500 m
PASSO LOMBARDO
1000-1200 m
~730 m
10 GeV
280-350 m
2 GeV
0 m
~170 m
100 m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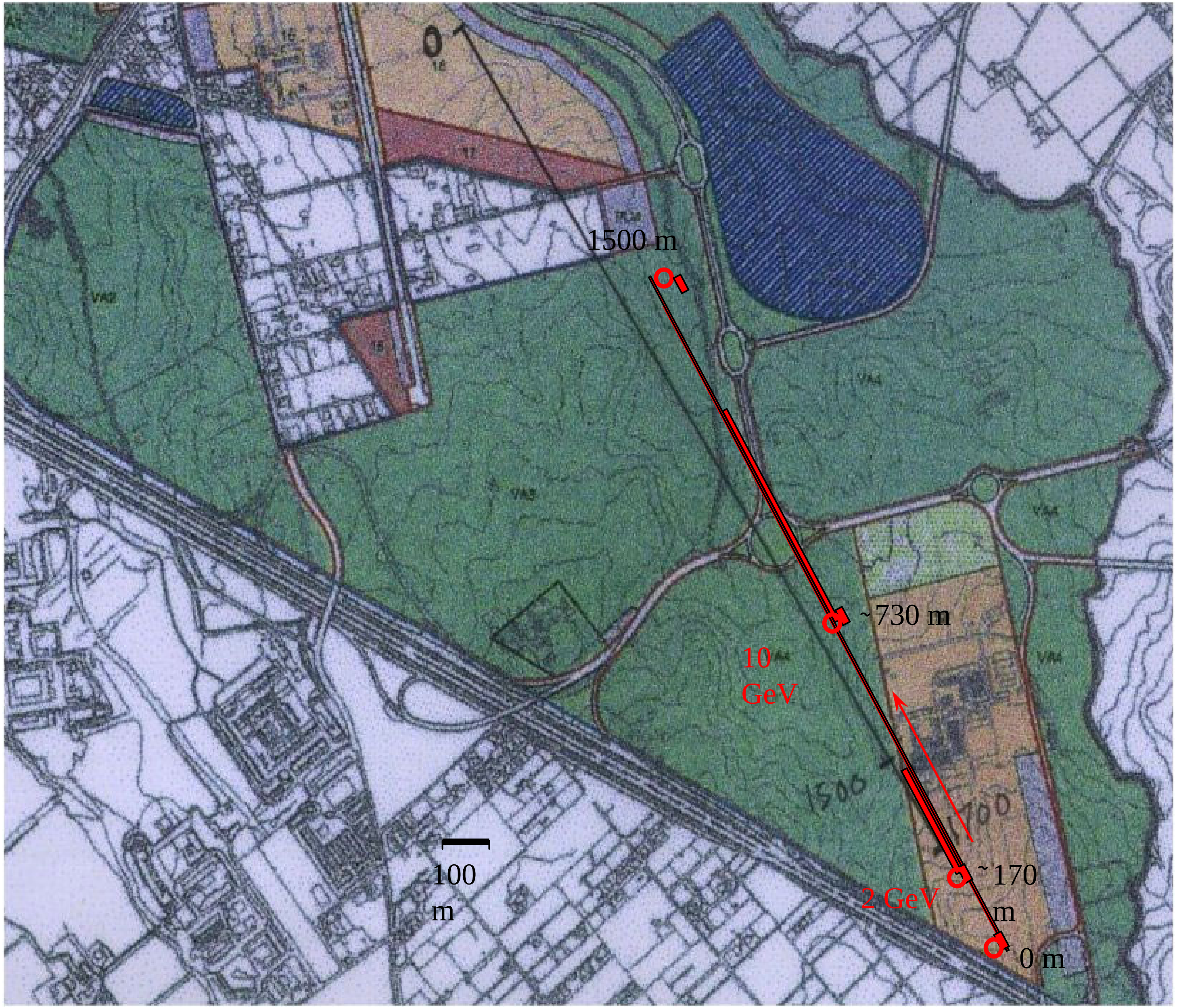
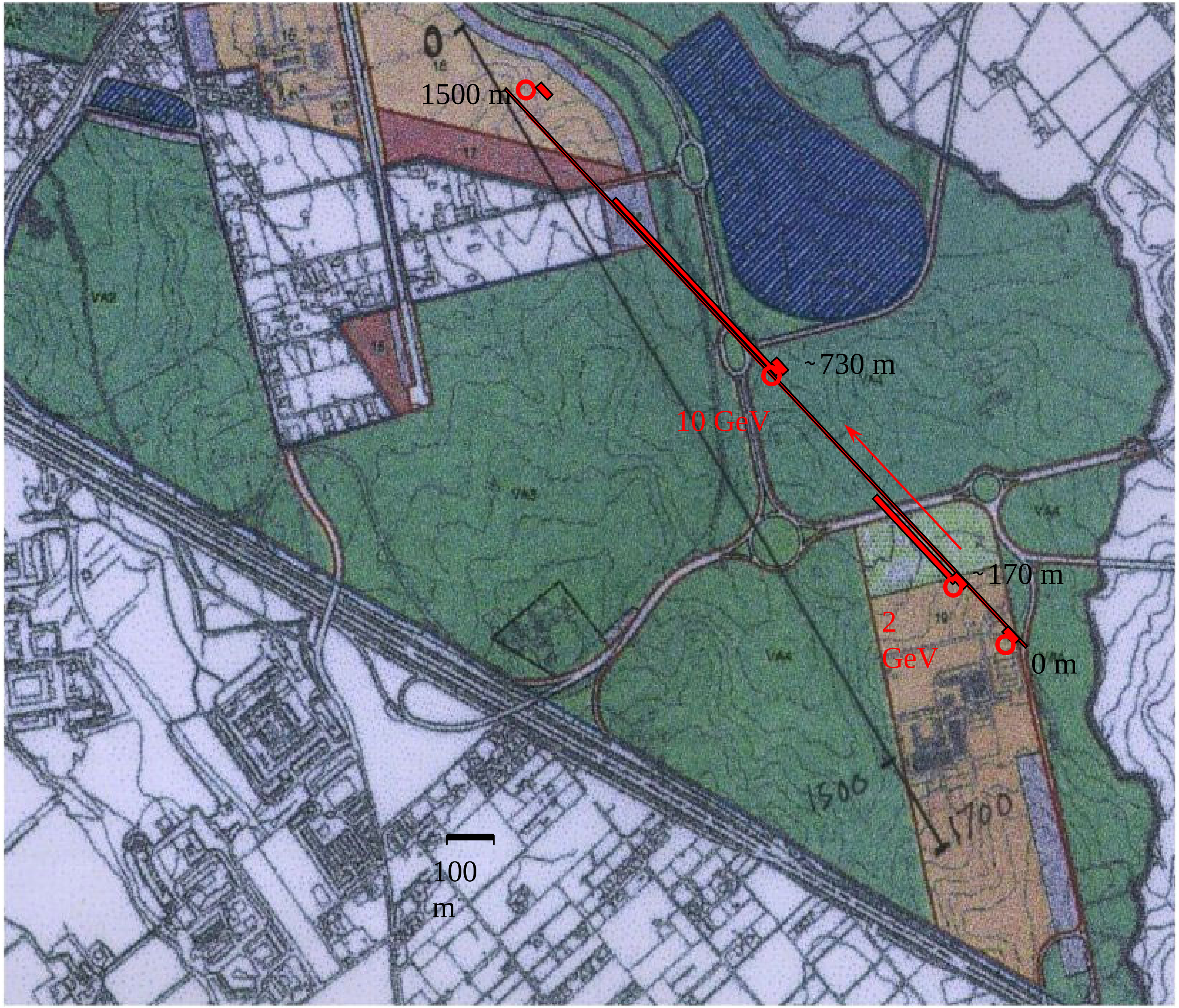

1500 m
~730 m
10
GeV
~170
m
2 GeV
0 m
100
m



1500 m
~730 m
10 GeV
~170 m
2 GeV
0 m
100 m
1500
1700