LEG PSI Free Electron Laser
Low Emittance Gun

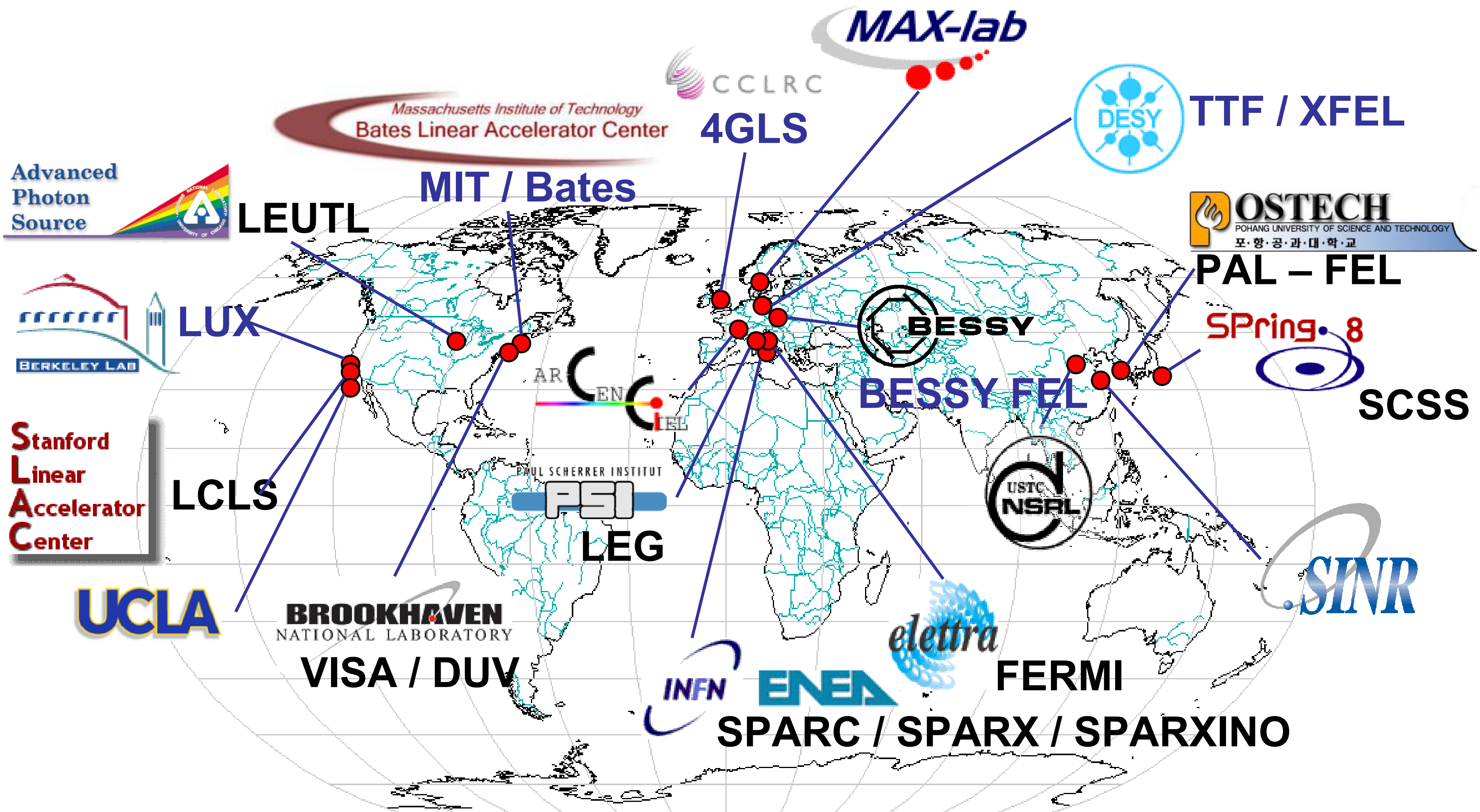
0.1 nm compact FEL project

A challenge as well for the RF systems.

Thanks to René Bakker who provided many slides for this presentation

http://leg.web.psi.ch

Single Pass FEL Activity



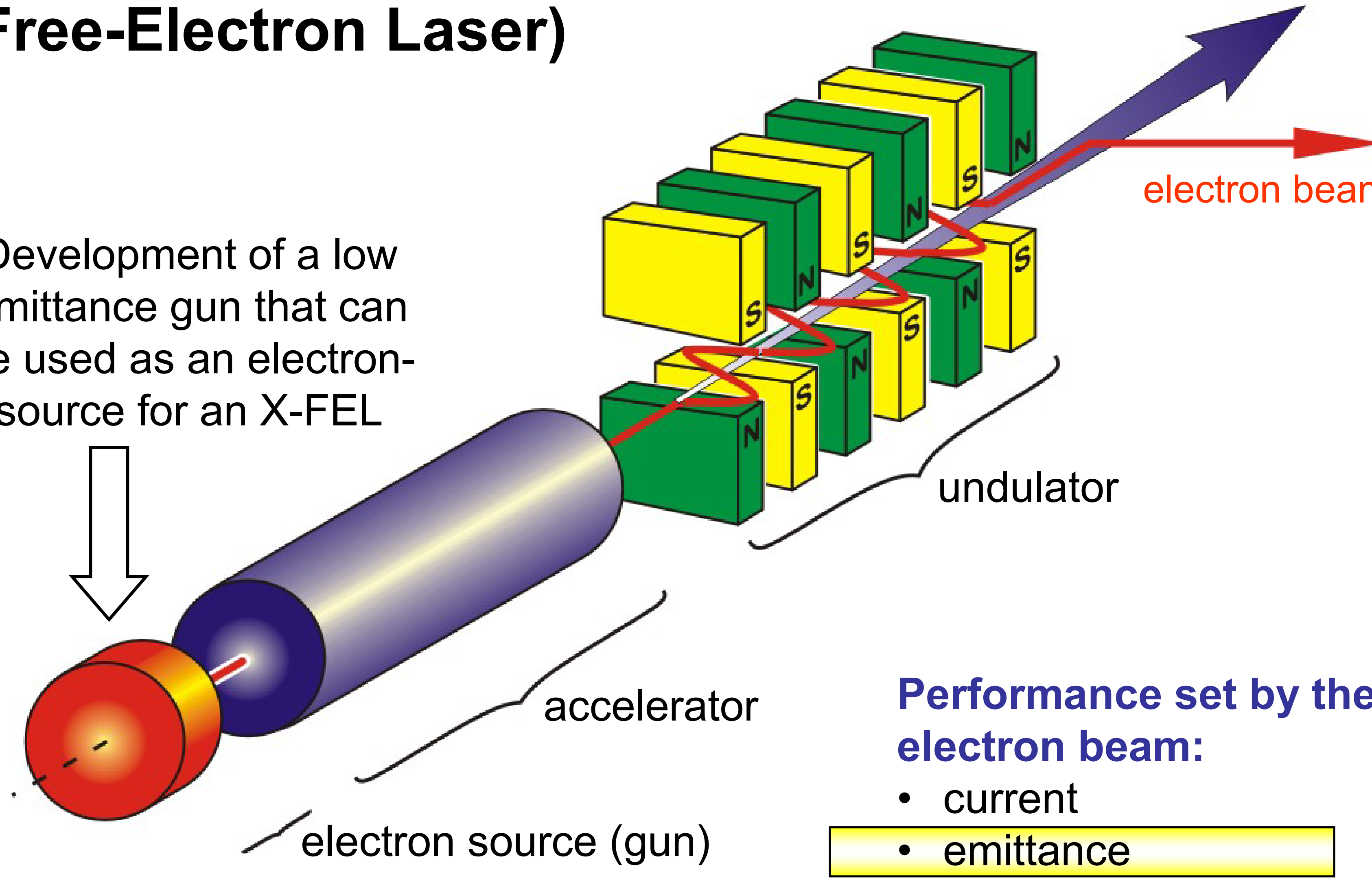
SC technology / NC technology

Outline

- Overview of the project
- Activities:
  - Electron-source development
  - High-voltage generation
  - Accelerator concepts and RF systems
- Summary

Single-Pass FEL (Free-Electron Laser)

Development of a low emittance gun that can be used as an electron-source for an X-FEL



Performance set by the electron beam:

- current
- emittance
- energy spread

Still Missing for hard X ray sources:

- Demonstration of lasing at 0.1 nm, i.e., projects like:
  - LCLS (SLAC, USA)
  - European X-FEL (DESY, Hamburg, Germany)
  - SCSS (SPring8, Sayo-gun , Japan)

Status: FLASH (DESY) with lasing down to 13 nm

Europe

X-FEL – DESY	**2012**	**1000 MEU**	***(L-band SC linac)***

Japan

SCSS – SPring8	**2010**	**300 MEU**	***(C-band NC linac)***

USA

LCLS - SLAC	**2009**	**325 MEU**	***(existing NC S-band linac)***

X-ray FELs are expensive machine the main driving cost being:

The Linac energy & The undulator length

Two basic condition to fulfill for the high gain regime

$$\lambda_s = \frac{\lambda_u}{2\gamma^2}\left(1 + K_{rms}^2\right)$$

Resonant condition
With usually K_{rms}~1

LEG LOW EMITTANCE GUN PROJECT

$$\varepsilon_n < \frac{\beta}{L_G}\frac{\gamma\lambda_s}{2\pi}$$

~Diffraction limit strongly affect the FEL ρ parameter.

$$L_g \approx \frac{\lambda_u}{4\pi\rho\left(\varepsilon_n\right)}$$

High gain regime

$$\rho = \frac{1}{\gamma}\sqrt[3]{\frac{I}{I_A}\left(\frac{K\lambda_u f(\xi)}{8\sqrt{2}\pi\sigma_{xy}}\right)^2}$$

$$\sigma_{x,y} = \sqrt{\varepsilon\beta_{x,y}}$$

$$f(\xi) = J_0(\xi) - J_1(\xi)$$

$$\xi = \frac{1}{2}\frac{K^2}{2+K^2}$$

Reduction of the normalized emittance leads to a reduction of the linear accelerator and undulator length.

Cost reduction would allow medium size research institute to realize FEL based light sources at wavelength down to 0.1 nm.

LOW EMITTANCE GUN PROJECT

FEL PARAMETERS

Wavelength	λ_{rad}	0.1	nm
Photon energy	$\hbar\omega_{rad}$	12.4	keV
Electron Beam			
Beam energy	E	5.8	GeV
Peak current	I	1.5	kA
Bunch charge	Q	0.2	nC
Norm. Emittance[a]	ε_n	≤ 0.1	mm mrad
Energy spread[a]	σ_E	≤ 0.6	MeV/ ps
Undulator Section			
Undulator period	λ_u	15 (12)	mm
Undulator type		planar	-
Undulator strength	K	1.19	-
Average β-function	β	15	m
FEL Performance[b]			
Pierce parameter	ρ_{1D}	$5.4 \cdot 10^{-4}$	-
Gain length	L_g	1.0	m
Saturation Length	L_{sat}	20	m
Peak power	P	6	GW
Pulse Energy	E_{ph}	0.4	mJ
Peak brilliance	B	$1.1 \cdot 10^{33}$	–[c]
Photons per pulse	N	$1.9 \cdot 10^{11}$	-

[a] Slice parameters

[b] Based on analytical estimates [5]

[c] photons/sec/mm^2/mrad^2/0.1% bw

The Low Emittance Gun Project

- **Development of a low emittance gun**
  - Sufficient current **≥ 5.5 A** (0.2 nC)
  - Low emittance **<0.1 mm mrad** (normalized)
- **Low emittance acceleration concept for an FEL**
  - Preservation of the emittance from the source
  - Increase of the peak current

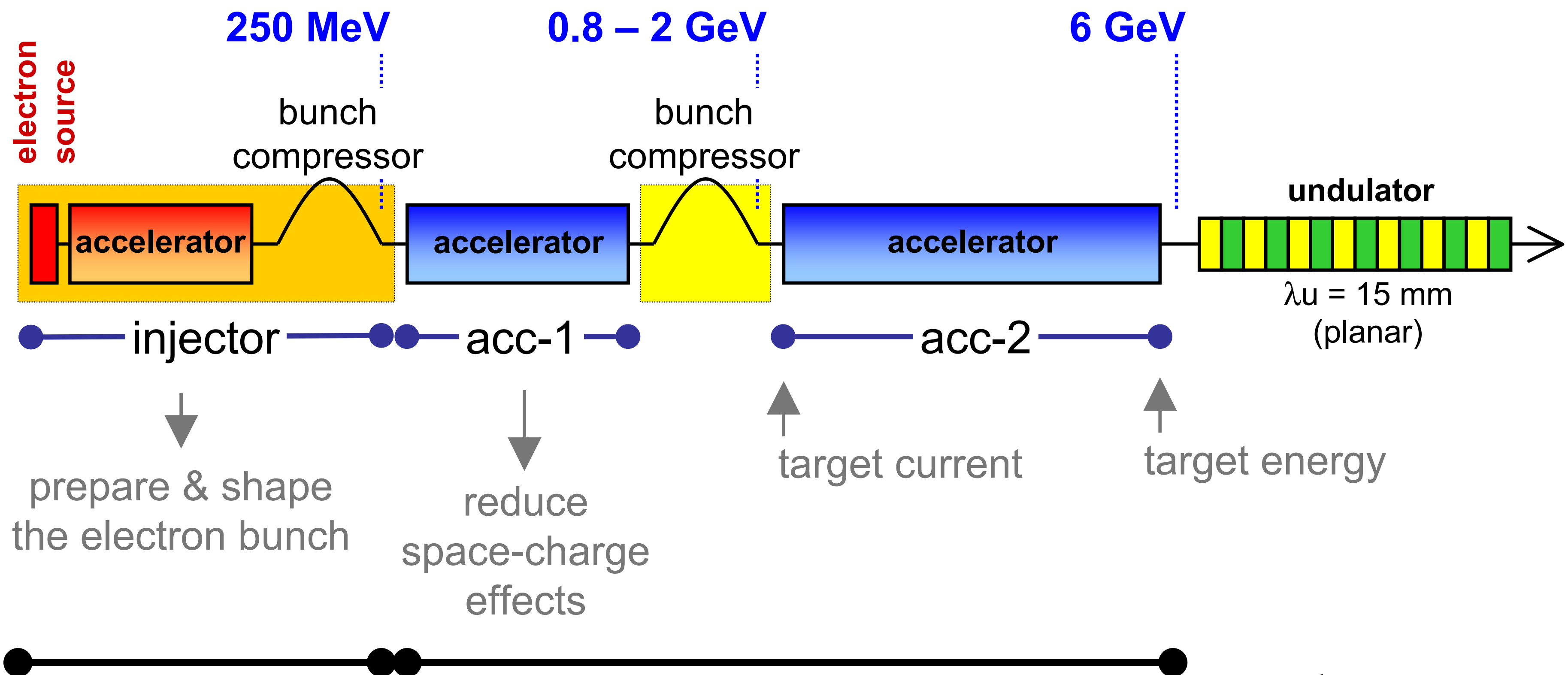
Low emittance ⇨ low current ⇨ long pulses (40-60 ps) ⇨ *choice of RF frequency*

Since the final aim is an FEL user-facility, the project focuses on 'stable' technology:

- 'conventional' undulator technology
- 'conventional' accelerator technology

} no plasma/laser accelerators or undulators

Acceleration & FEL Concept - MULTI FREQUENCY RF



L/S/X-band
(1.5/3.0 GHz)
250 MeV

S or C-band
(3 or 6 GHz)*
5.8 GeV

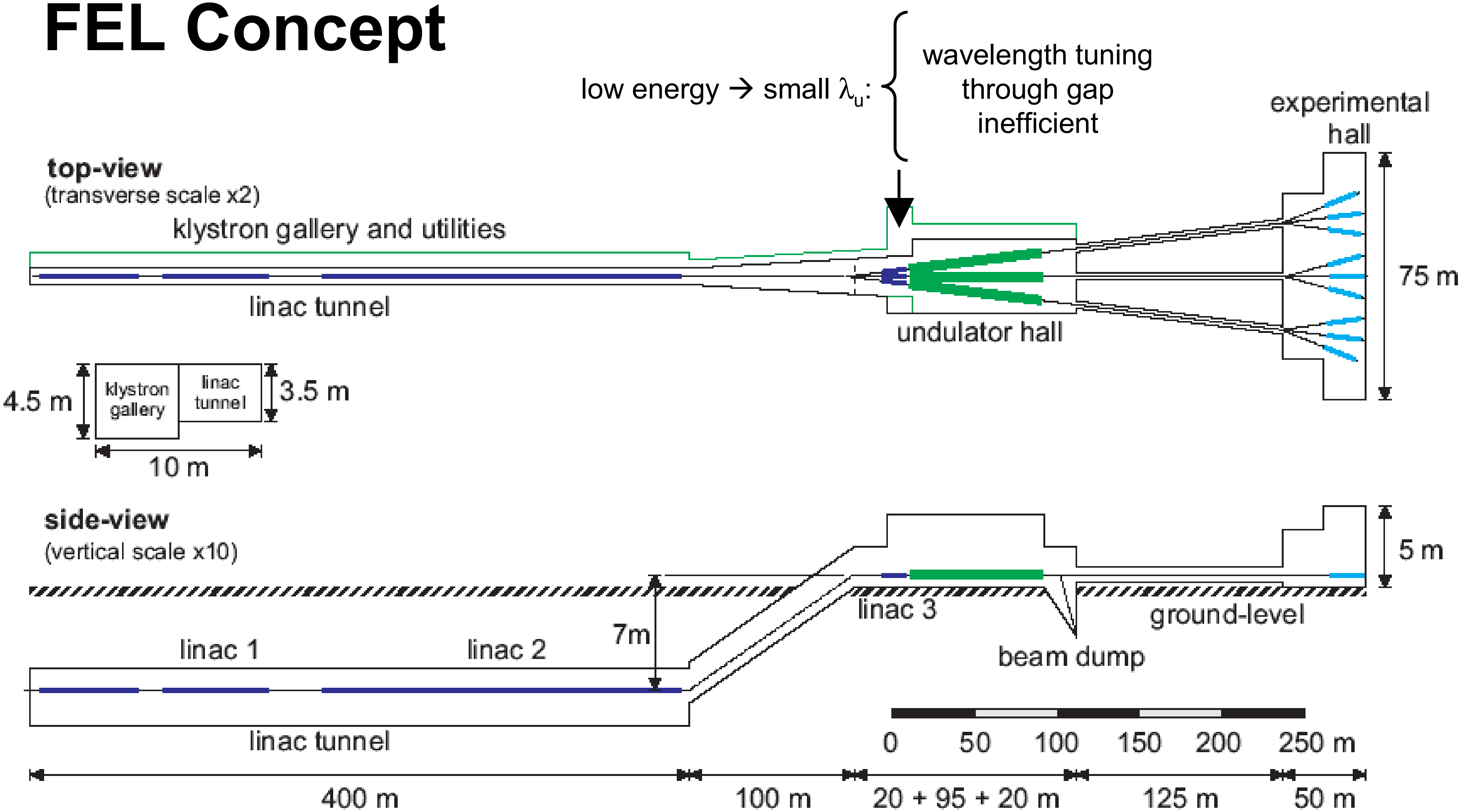
→ **room temperature**

gun:
- single-pulse
- 10 Hz

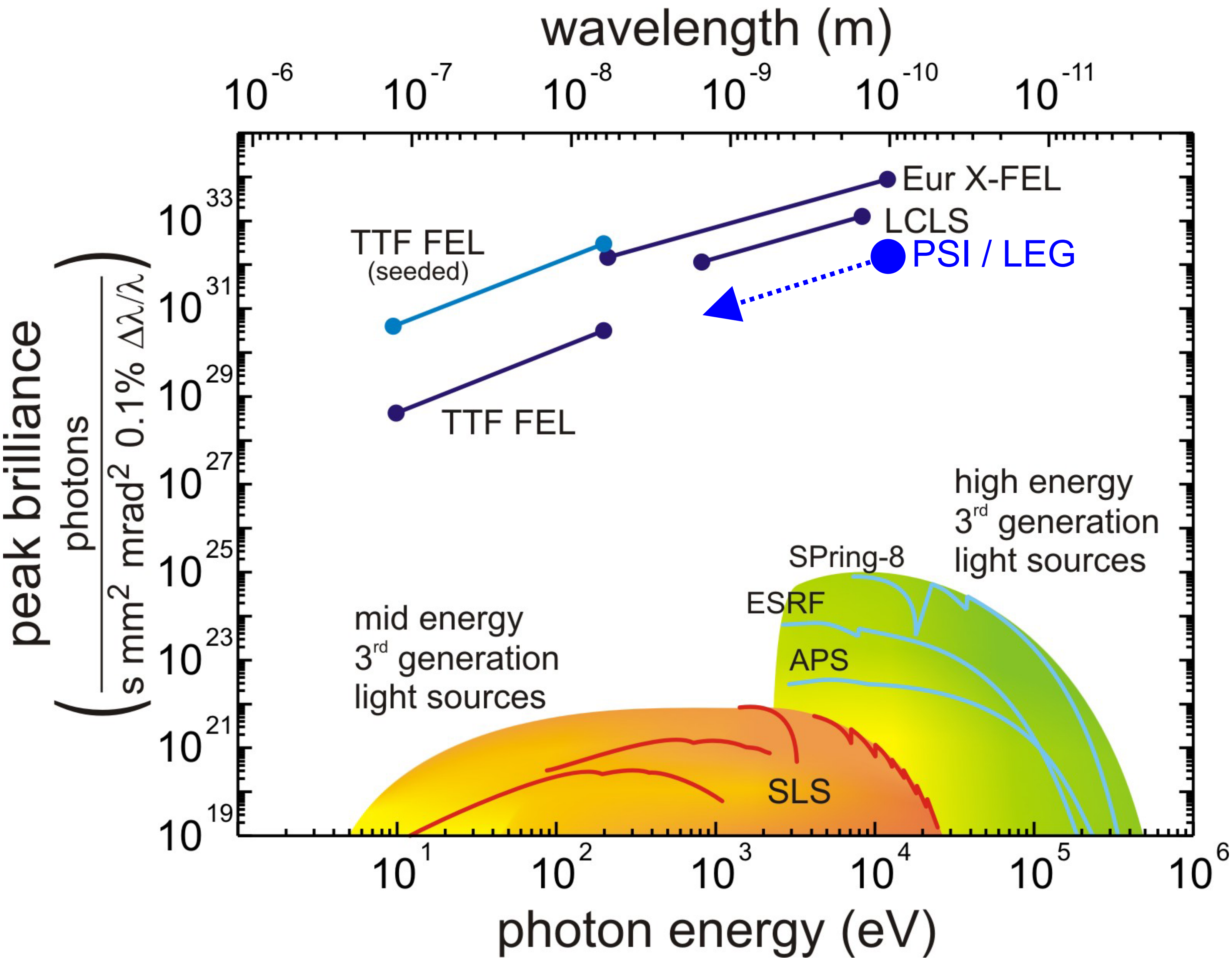
Capture and compression L band
Acceleration S band
Compressor X band (linearization)

critical to maintain the emittance

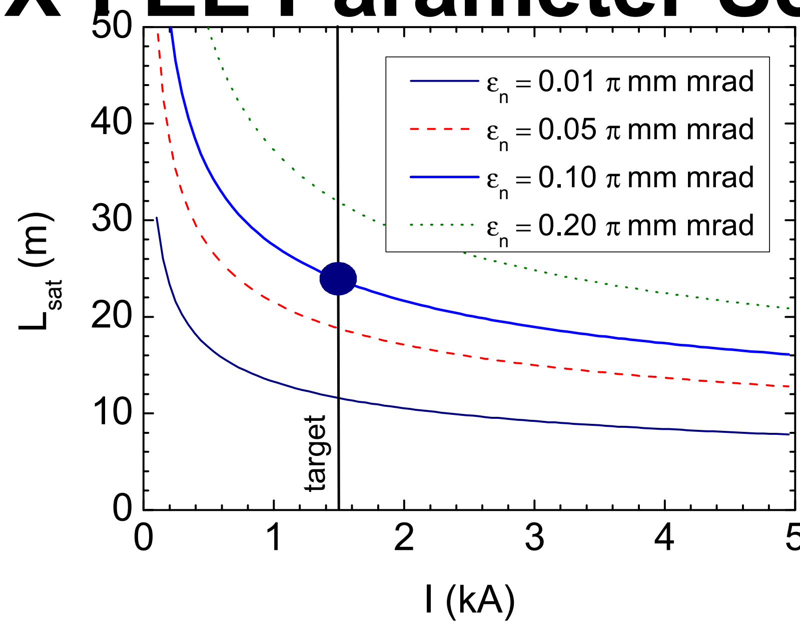
FEL Concept

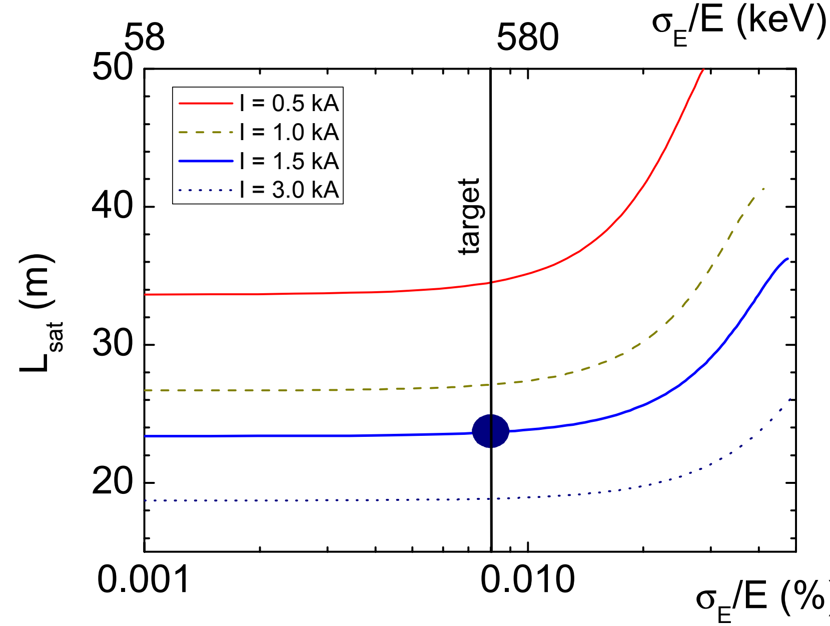


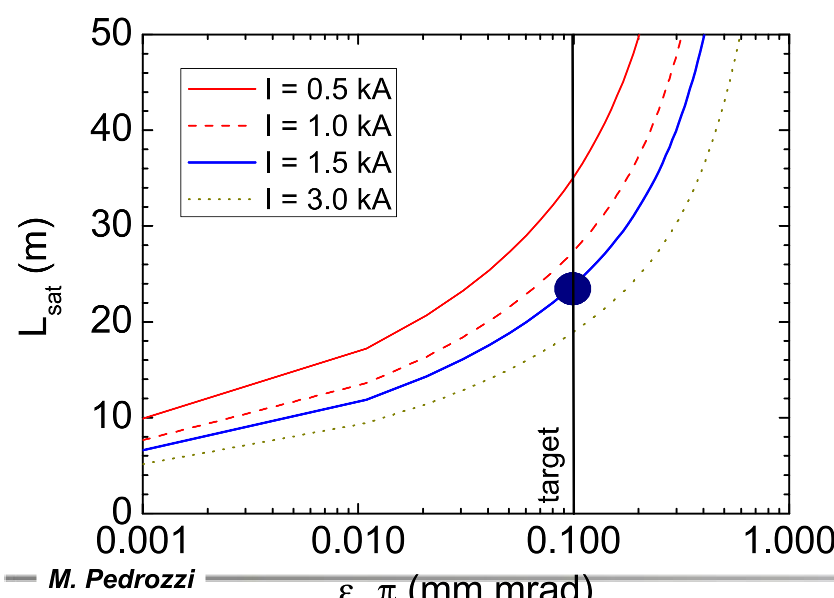
~ 800 m (500 m of RF stations)


wavelength (m)
10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11}
peak brilliance
$\left(\frac{\text{photons}}{\text{s mm}^2\ \text{mrad}^2\ 0.1\%\ \Delta\lambda/\lambda}\right)$
10^{19} 10^{21} 10^{23} 10^{25} 10^{27} 10^{29} 10^{31} 10^{33}
Eur X-FEL
LCLS
PSI / LEG
TTF FEL
(seeded)
TTF FEL
high energy
3rd generation
light sources
SPring-8
ESRF
APS
mid energy
3rd generation
light sources
SLS
10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}
photon energy (eV)

X-FEL Parameter Scan







Values are slice-parameters

- Very tight emittance budget
- Tight peak-current budget
- “Relaxed” energy-spread budget

(λ = 0.1 nm, *E* = 5.8 GeV)

PROJECT STEPS

Low emittance GUN – high gradient diode

↓

Low emittance GUN – high gradient diode + 2 frequency post acceleration cavity

↓

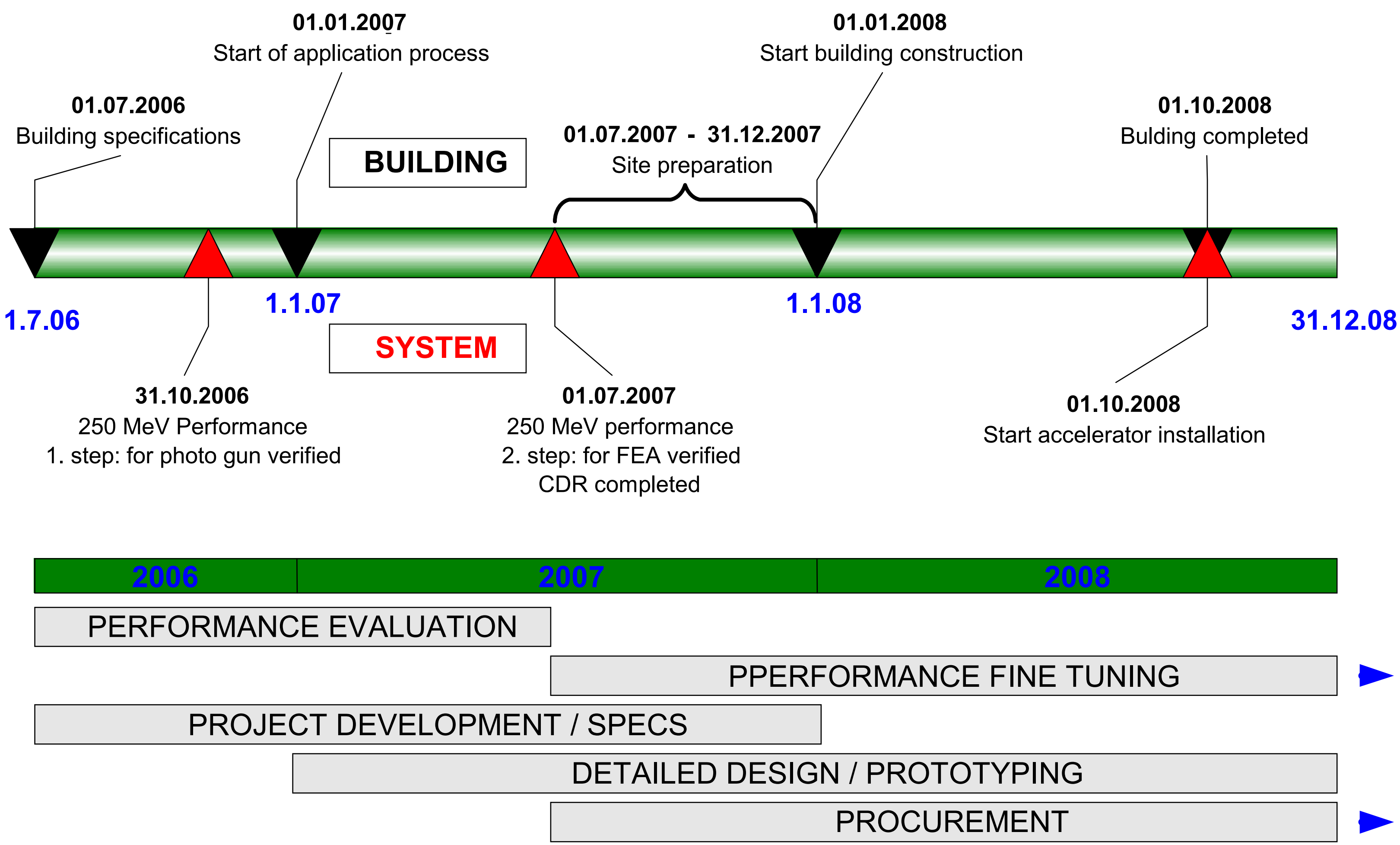
250 MeV injector test stand

↓

6 GeV FEL facility

But many activities going on in parallel

PSI-FEL 250 MeV Injecor / EVALUATION



If the injector results are good: Project approval January 2011

The Low Emittance Gun Project

- **Basic concept for the low emittance gun.**

The work concentrate mainly on:

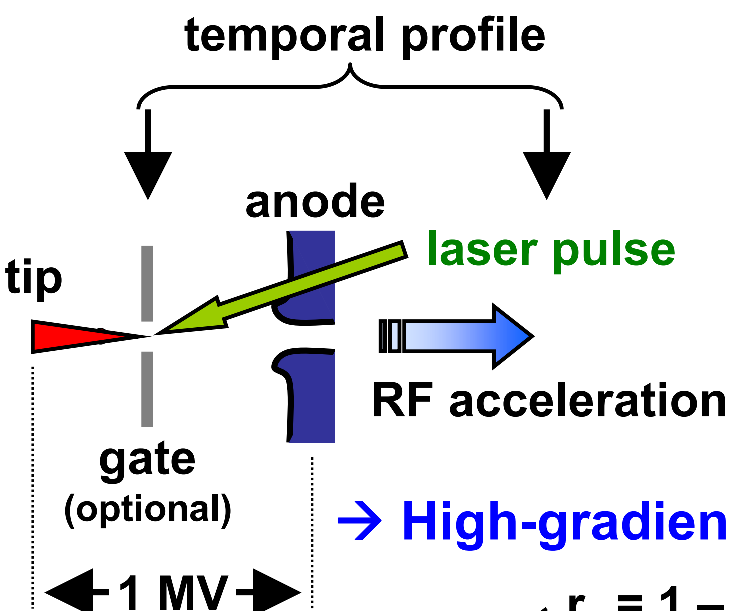
-the cathode (intrinsic emittance must be reduced)

$$\varepsilon_n = \frac{\gamma r_c}{2}\sqrt{\frac{E_{r,kin}}{m_o c^2}}$$

-The low emittance beam transport (large RF contribution)

$$\varepsilon_n << \frac{\beta}{L_G}\frac{\gamma\lambda_s}{2\pi}$$

The Field Emitter (FE) concept



+ easy to obtain / fabricate

- high current density on the tip

Target:
Φ ≥ 250 MV/m

→ **High-gradient pulsed acceleration**

$r_e = 1 - 5\ \mu m$

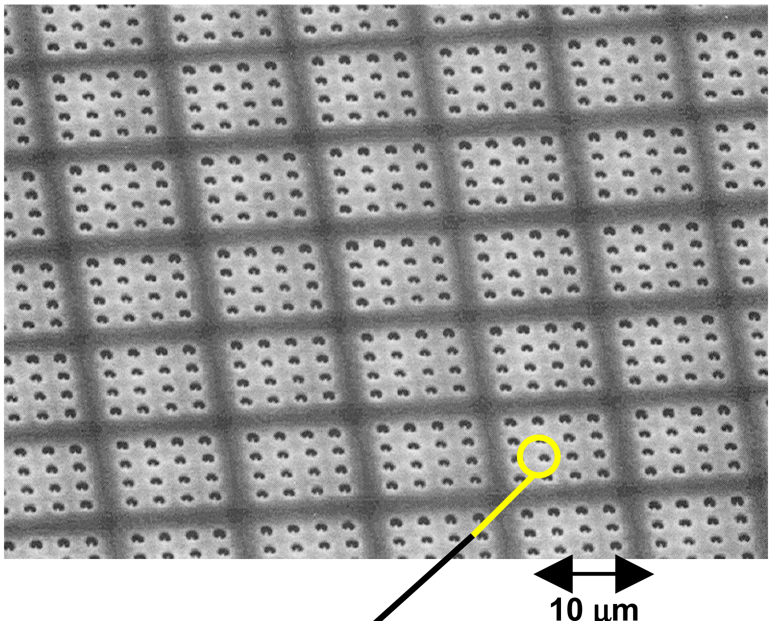
$$\frac{\varepsilon_n}{\gamma} = \frac{r_e}{2}\sqrt{\frac{E_{kin}}{m_e c^2}}$$

room temperature:
$\varepsilon_n \approx 6 \cdot 10^{-10}$ m rad

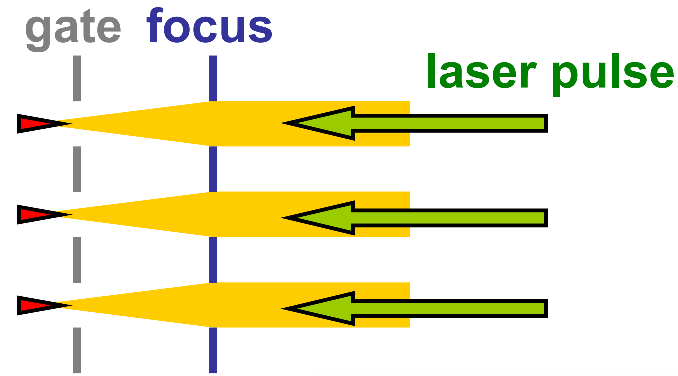
Target:
$Q =$ 0.2 nC
$I \geq$ 5.5 A
$\varepsilon_n \leq 5 \cdot 10^{-8}$ m rad

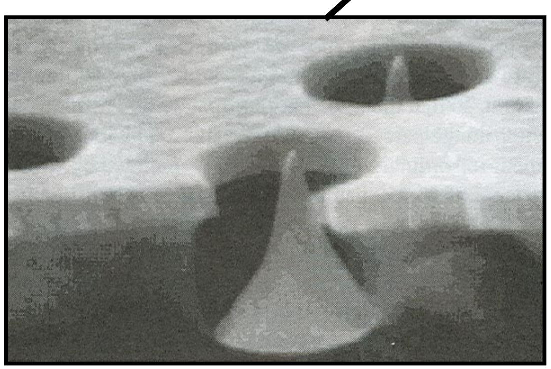
ZrC, HfC tips from Etched Wire

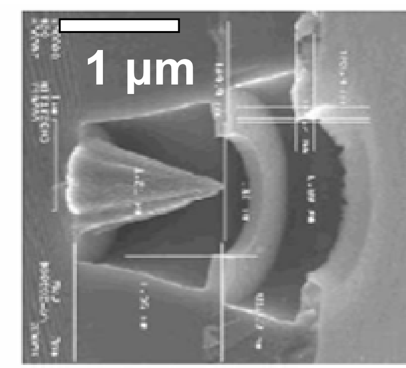
The Field Emitter Array (FEA) Concept



Spindt field-emitter cathode array







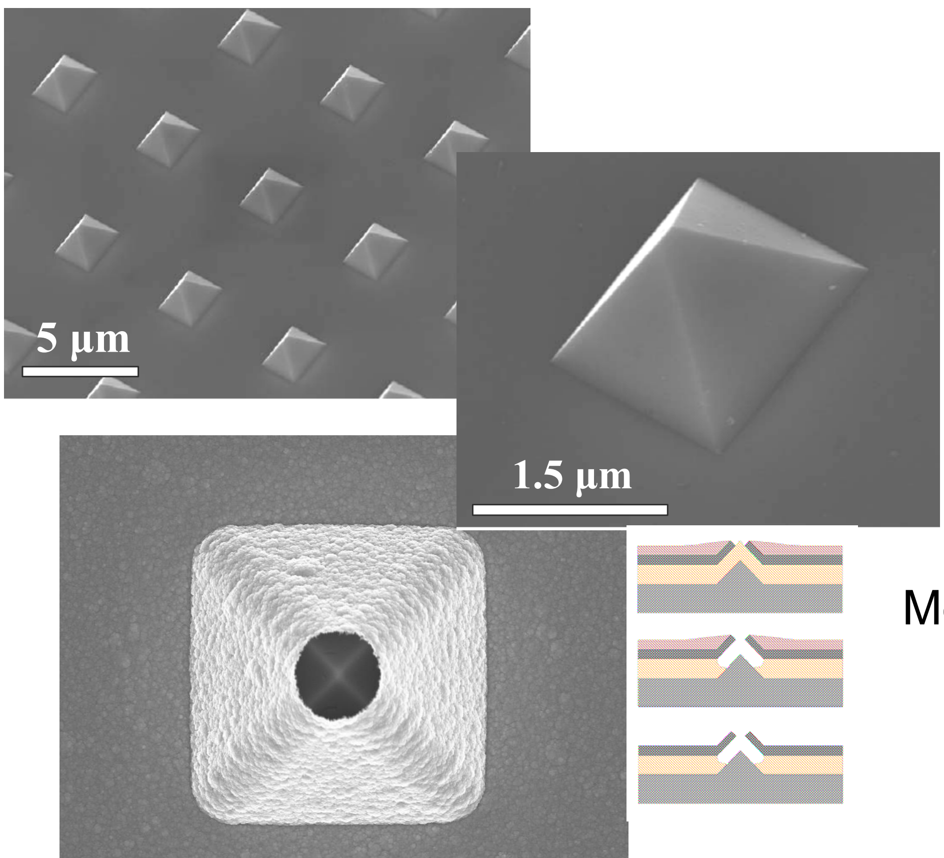
Courtesy
A. Akinwande (MIT)

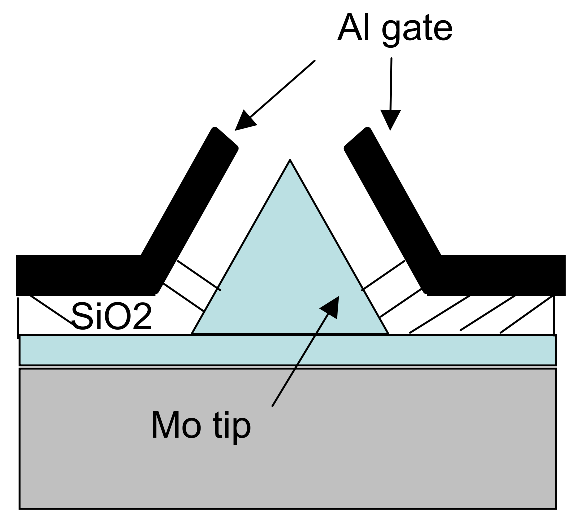
+ low current density

- difficult fabrication process
- fragile

Field Emitters: Activities

1. Fabrication of Field Emitter Arrays (FEA)





Molding Process

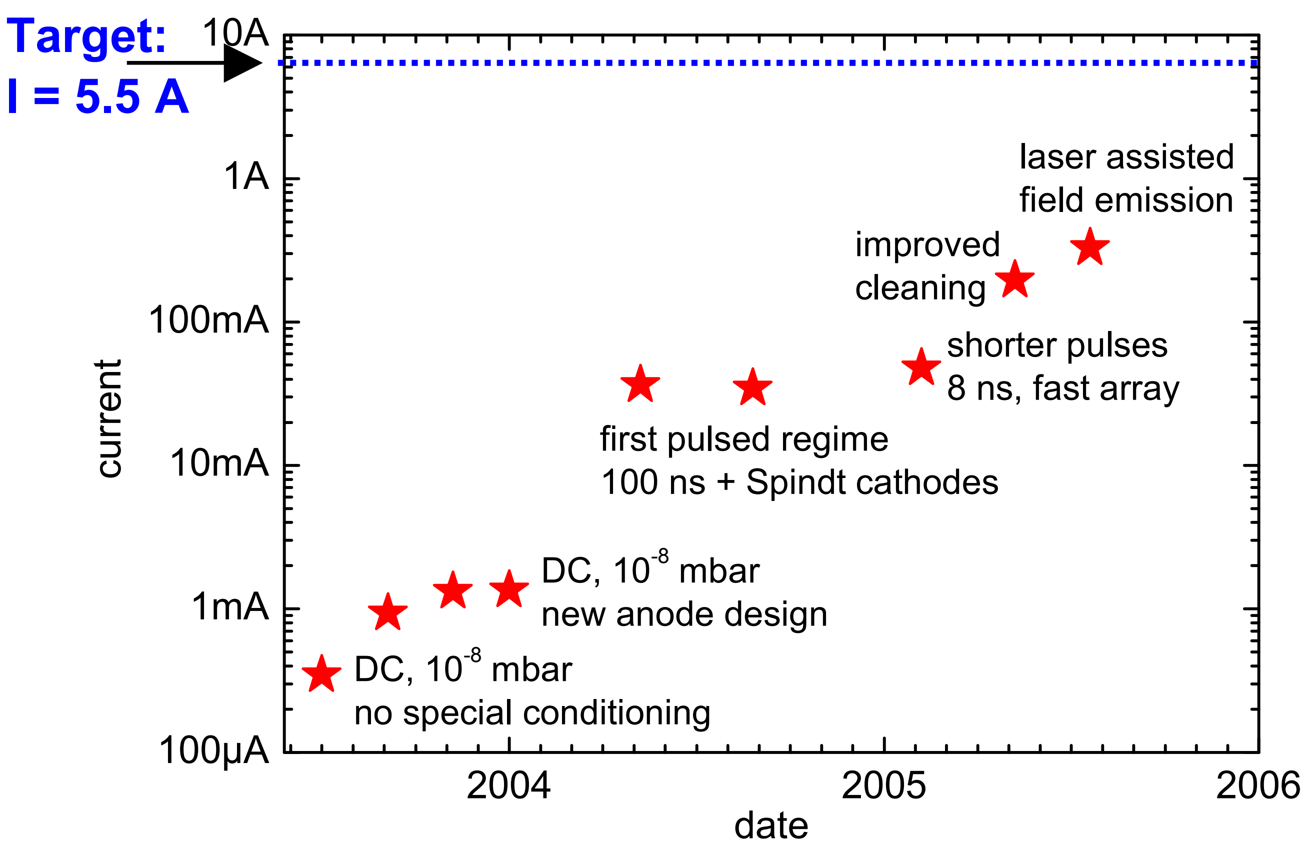
⇨ Pyramidal Tips

http://lmn.web.psi.ch

Laboratory for Micro- and Nanotechnology

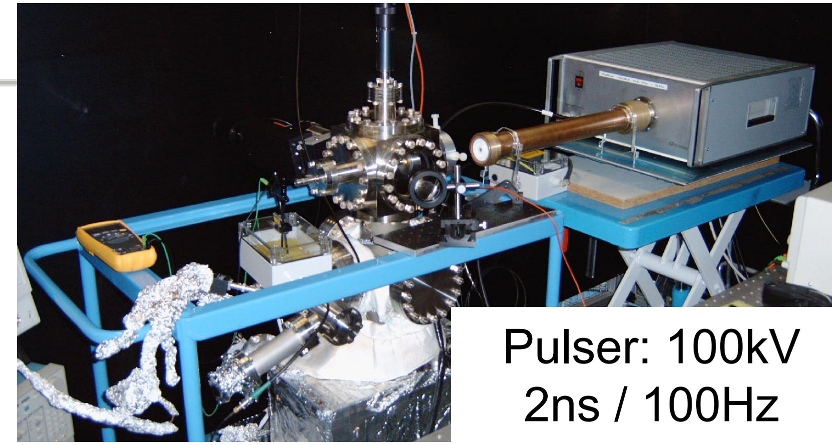
Field Emitters: Activities

2. Drawing sufficient current

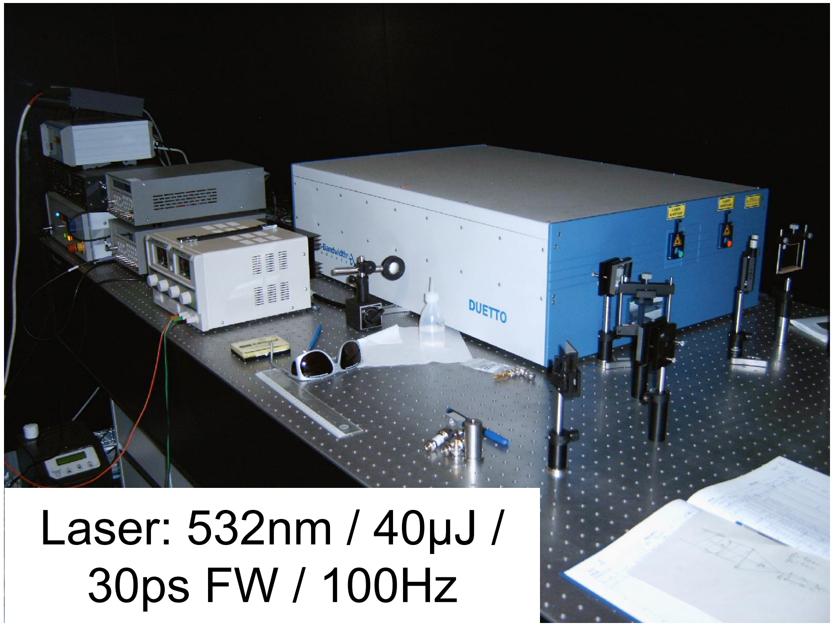


13.04.06
Laser assisted emission
On ZrC single tip
(*Explosive emission*)

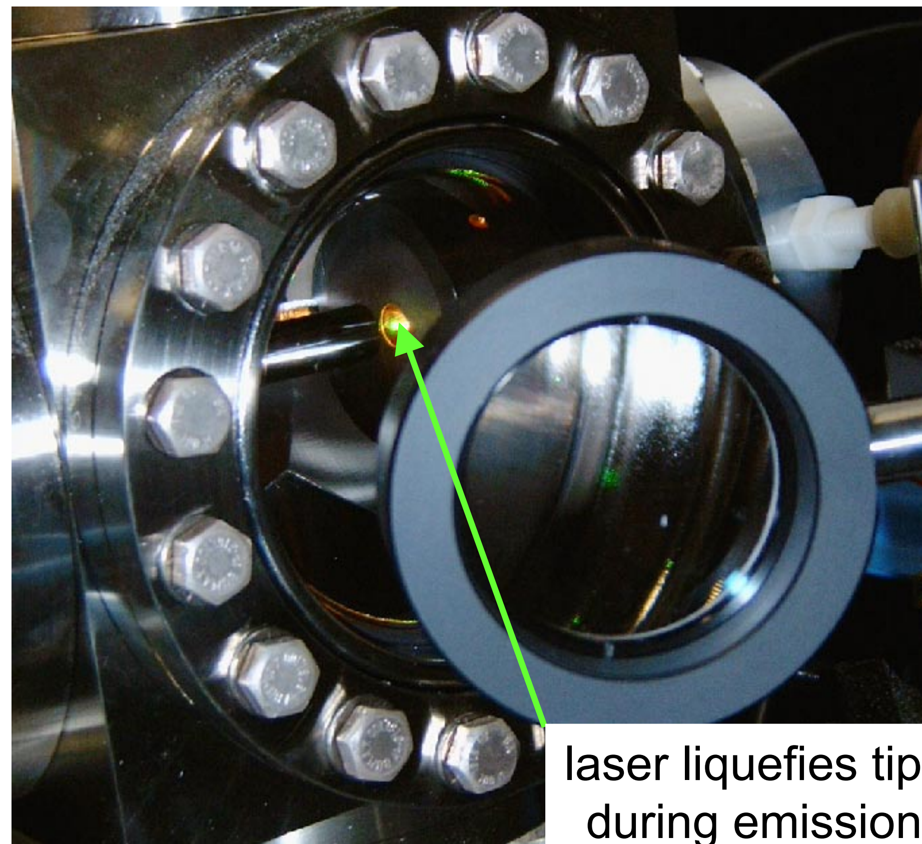
- higher voltage
- shorter pulses
- good vacuum
- laser



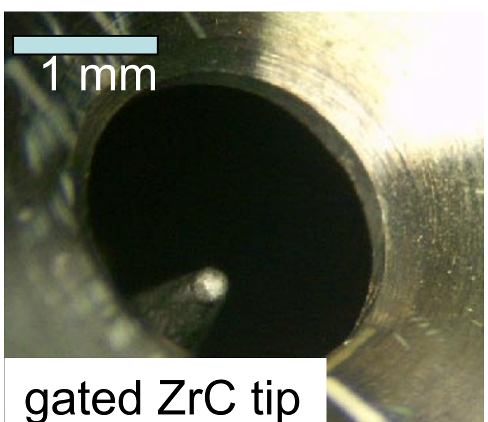
Pulser: 100kV
2ns / 100Hz



Laser: 532nm / 40µJ /
30ps FW / 100Hz

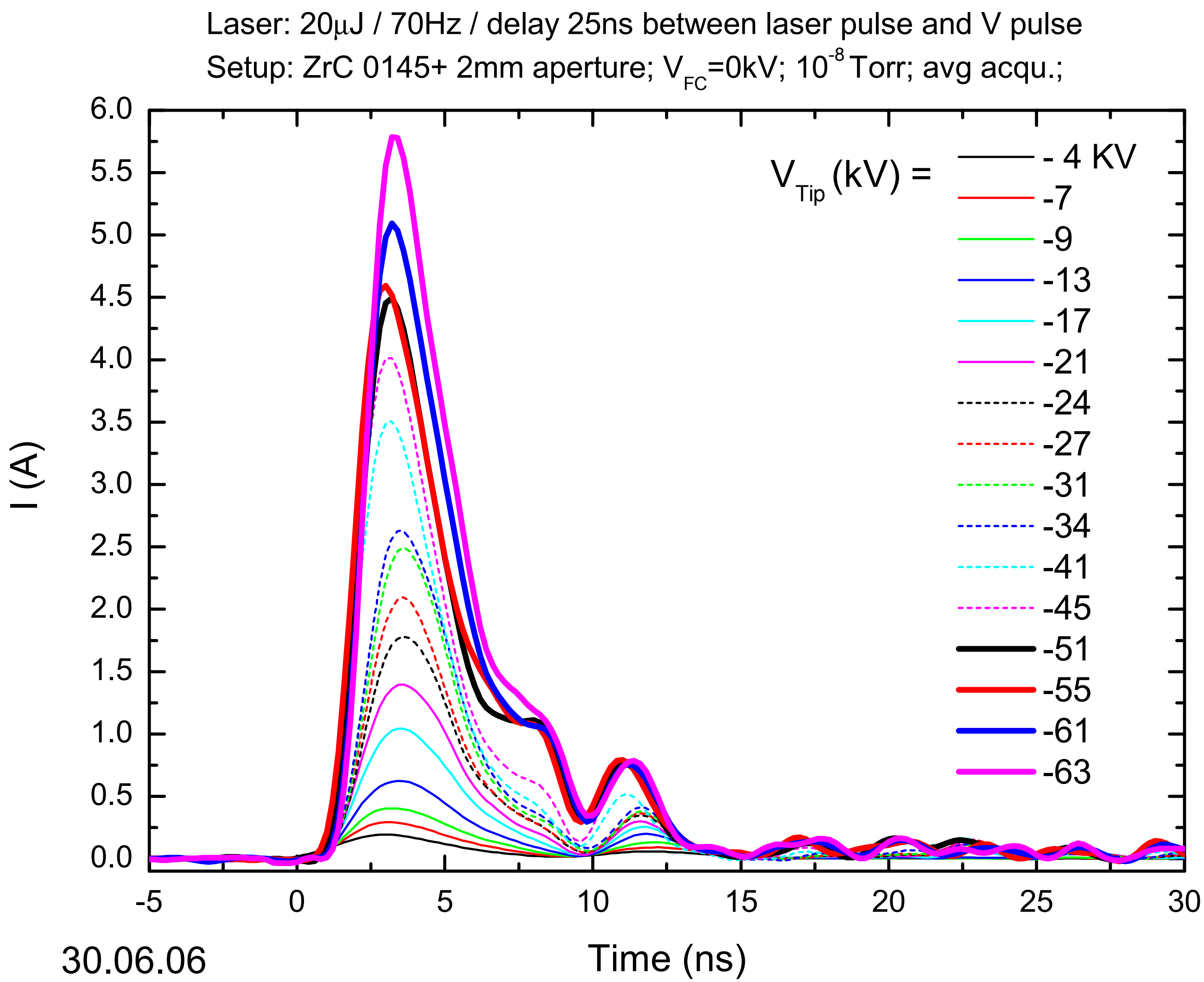


laser liquefies tip
during emission



gated ZrC tip

width of pulse determined by speed of the detector and transmission line

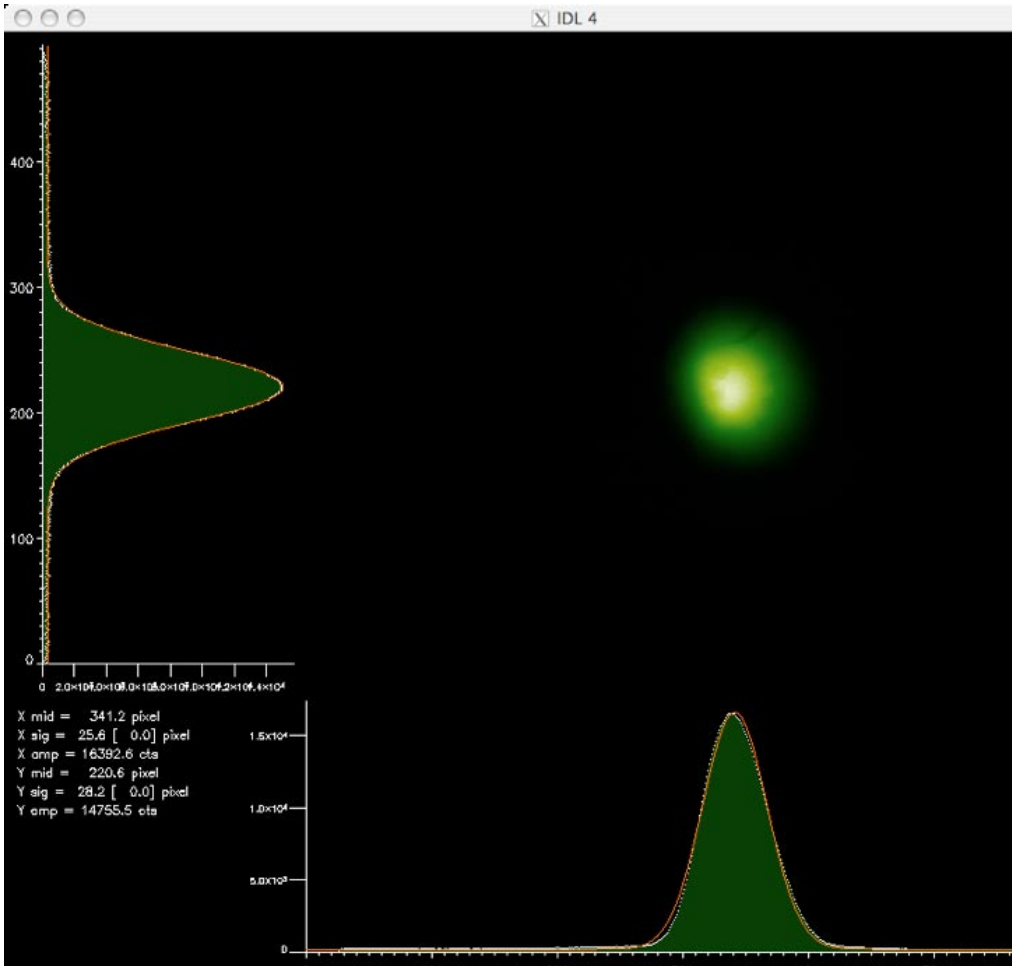


tip after experiment:

- -Very stable emission observed
- - Goal current achieved

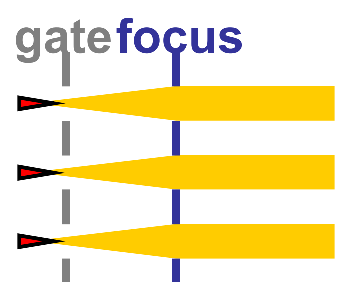
100 kV Emittance measurement

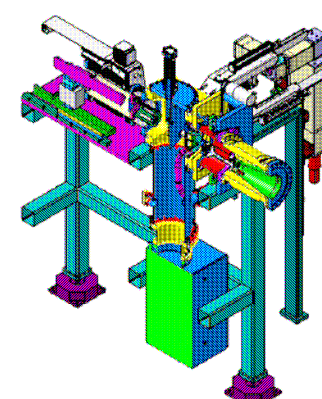
first results with industrial FEA *(single gate, no focus)*



ε_n = 0.6 mm mrad
Q = 0 – 60 pC
I ≈ 1.5 mA

single-gated
field-emitter array
(no focusing layer)





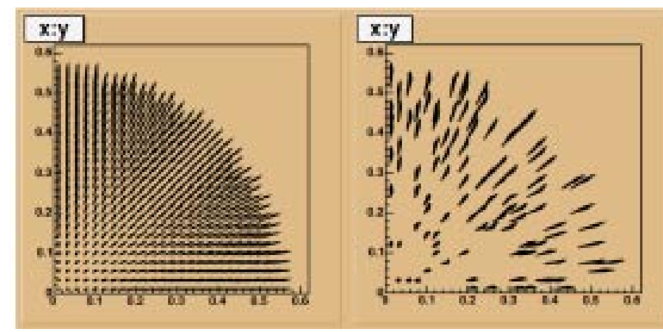
S. Leemann

Field Emitters: Activities

1. **Fabrication of Field Emitter Arrays**
2. **Drawing sufficient current**
3. **Checking homogeneity of FEA's**
4. **100 kV test-stand**
5. **Theoretical design and verification**

PSI Parallel Maxwell Solver "Capone"

Full Tip array Simulation (Granularity)



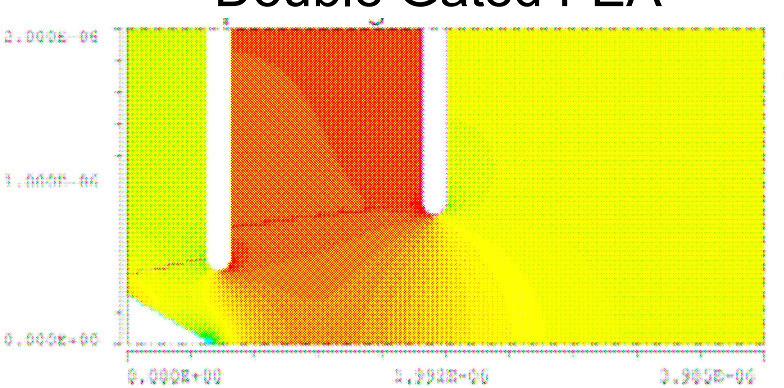
Uniform emission:

$\varepsilon_n \leq 5.10^{-8}$ m.rad

Non-uniform emission:

$\varepsilon_n \geq 2.10^{-7}$ m·rad

MAFIA simulation
Double Gated FEA

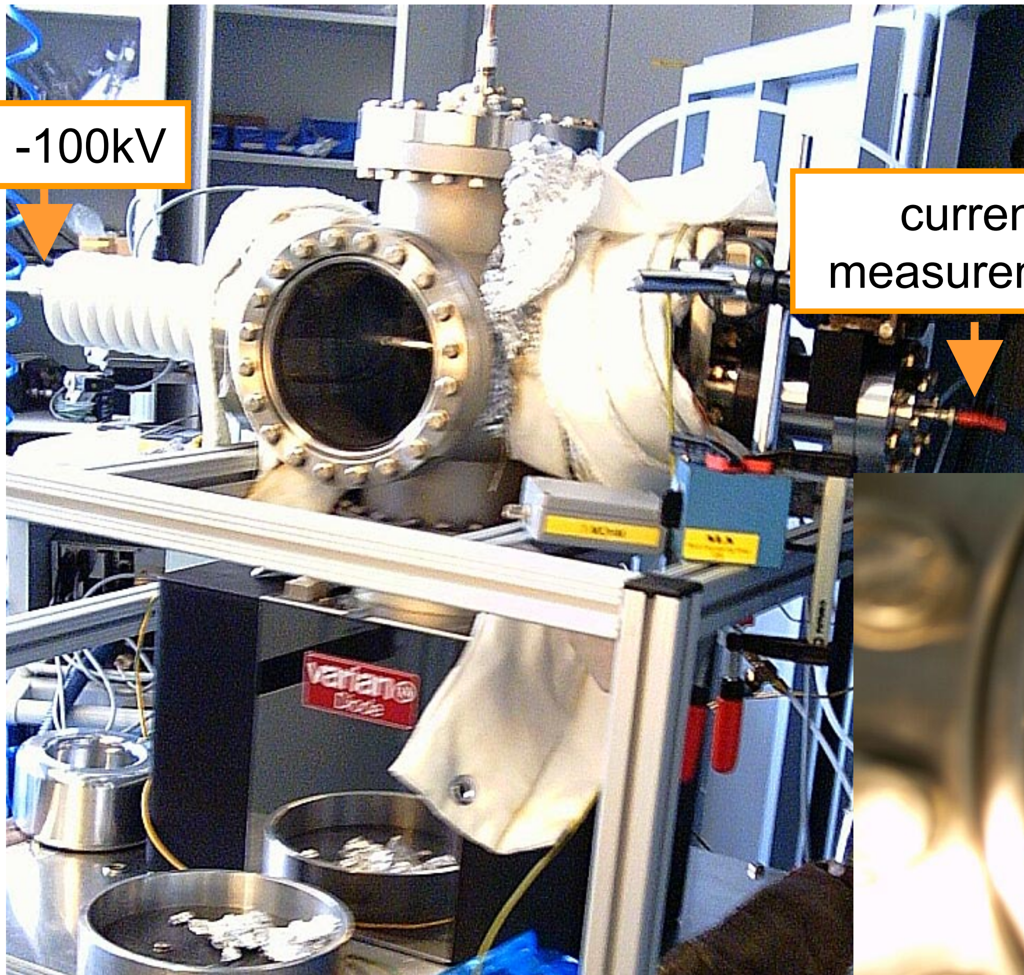


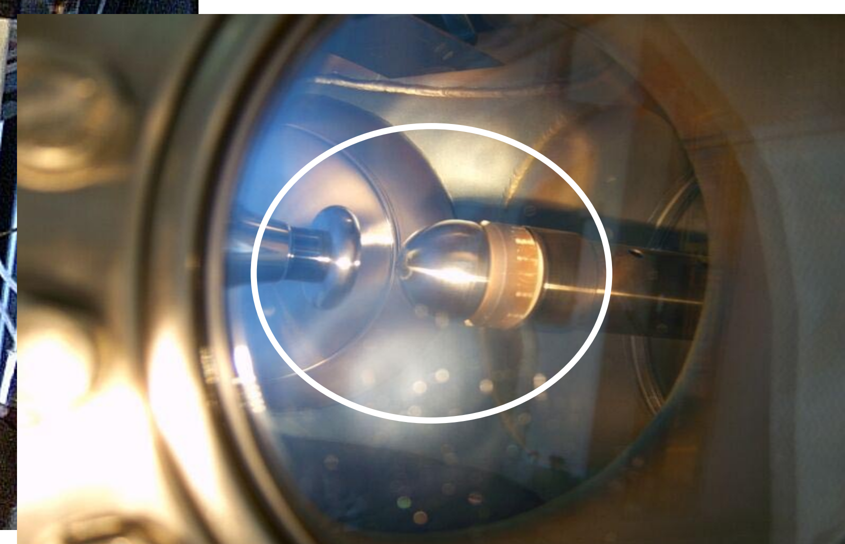
ε_n = $3\cdot10^{-10}$ m.rad (projected)

I = 1 mA / tip

High Gradient Pulsed Acceleration

1. Dark current test stand

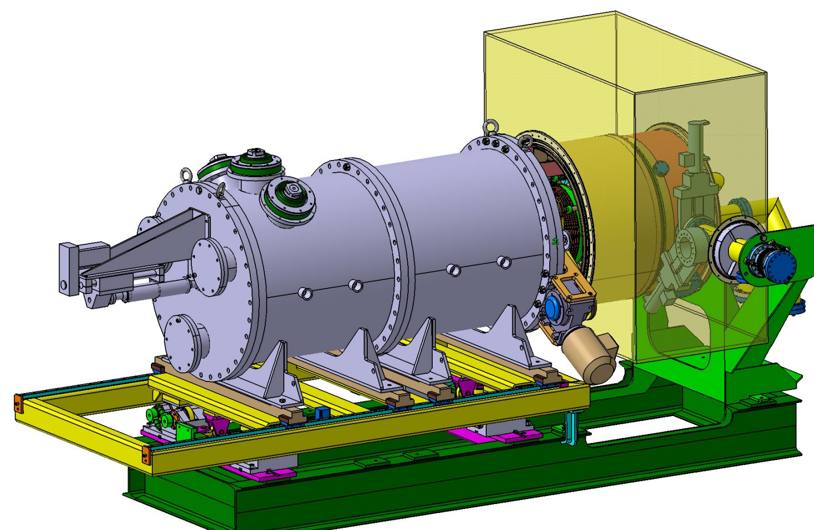




Goal: 250 MV/m

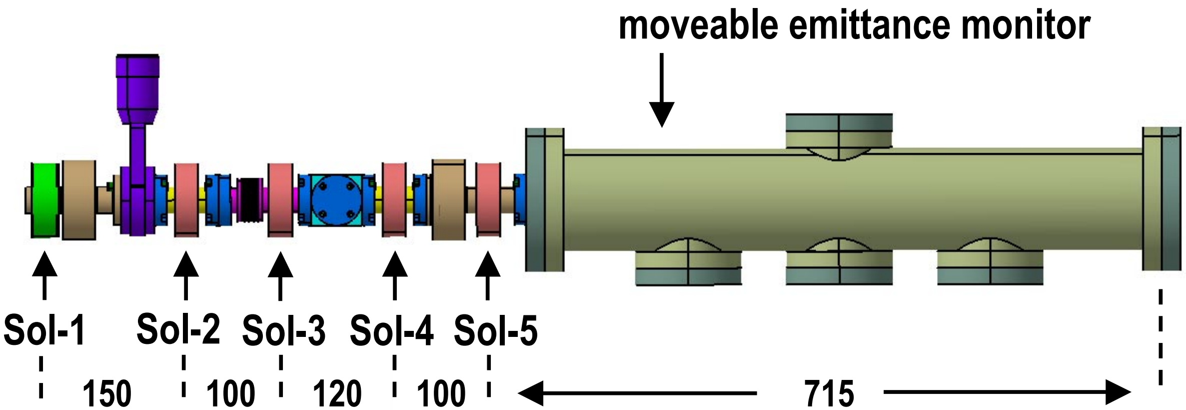
High Gradient Pulsed Acceleration

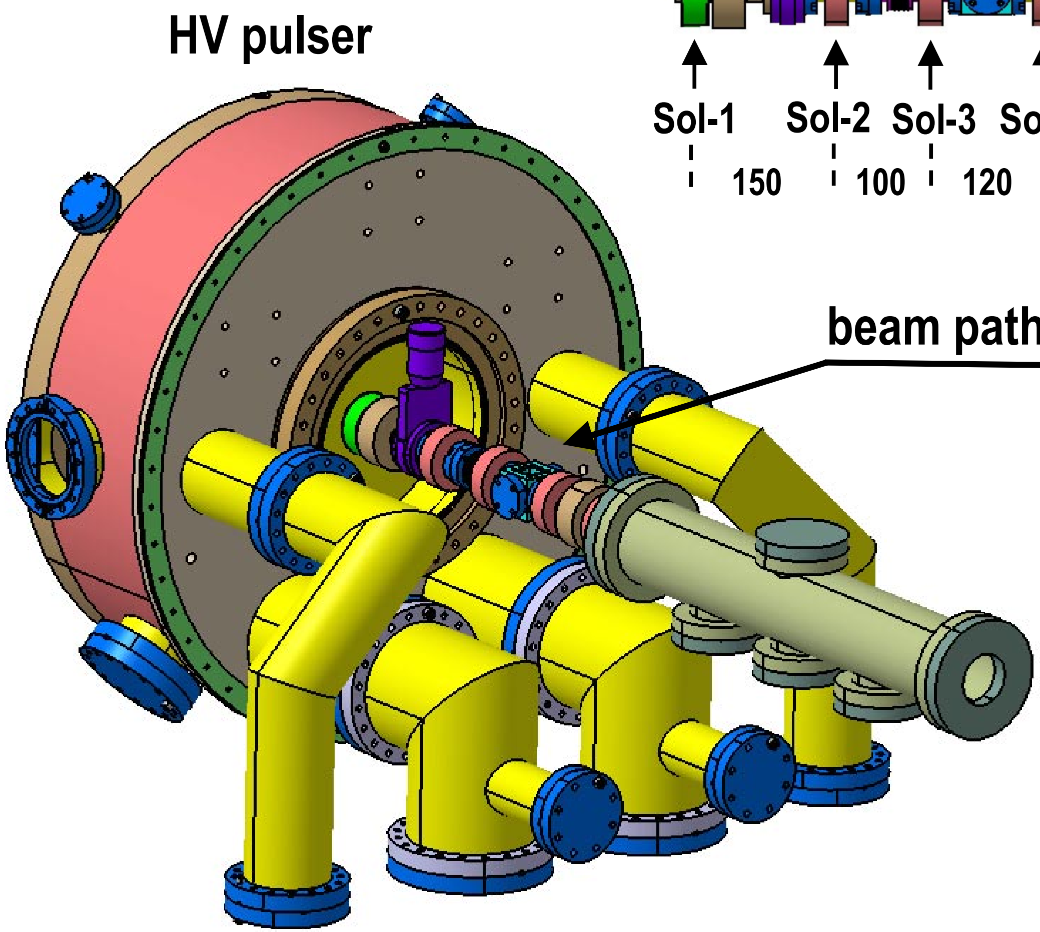
1. Dark current test stand
2. **500 kV test-stand:** 500 kV - 250 ns - 10 Hz



C. Gough

Schematic Overview of 500 keV LEG Test

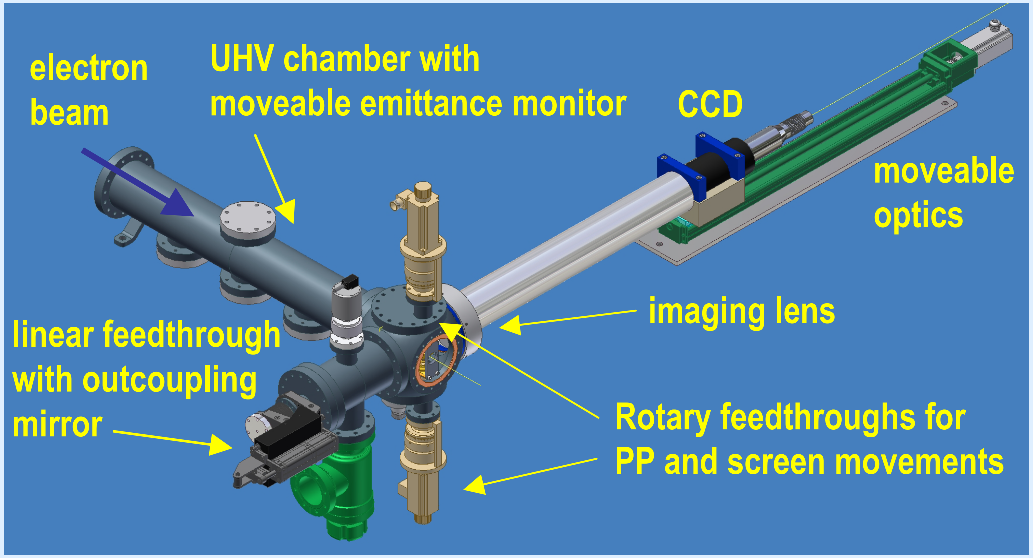




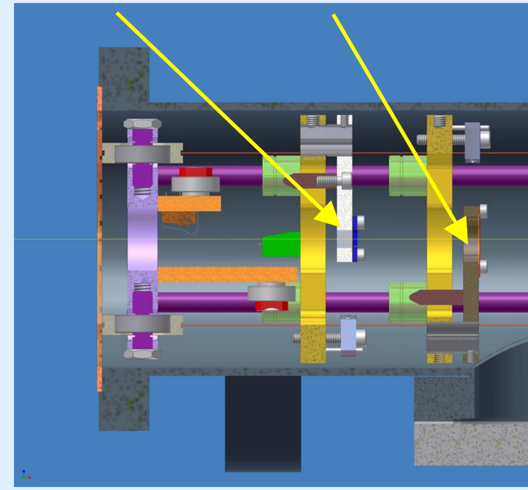
- 5 solenoids for variable focusing of large dynamic range of beam currents

under construction

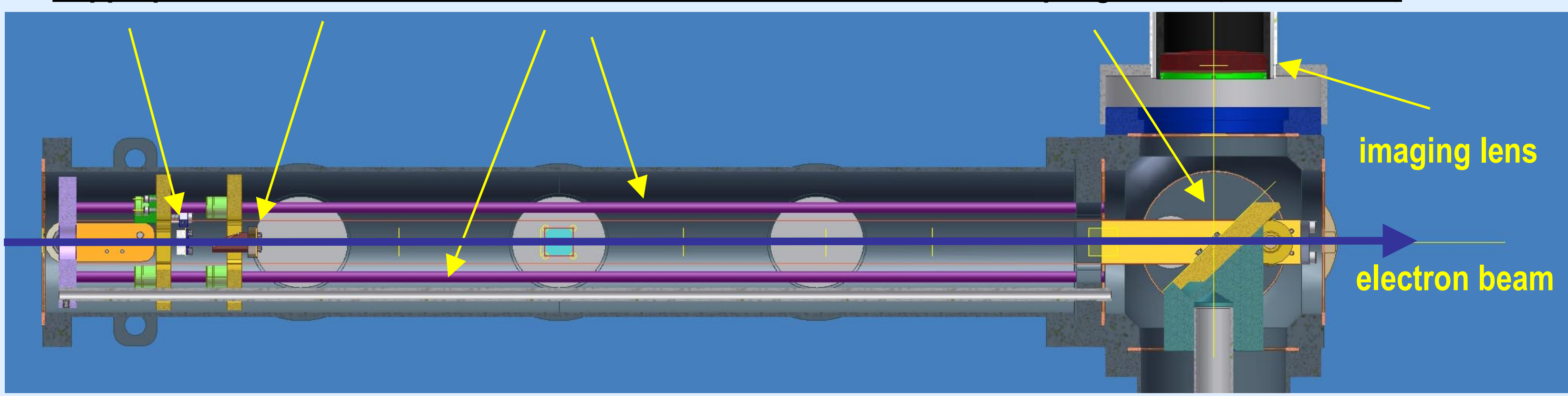
Emittance Measurement IV - Flexible Emittance Monitor (in collaboration with BESTEC company)



Pepperpot and YAG:Ce Screen (side view)

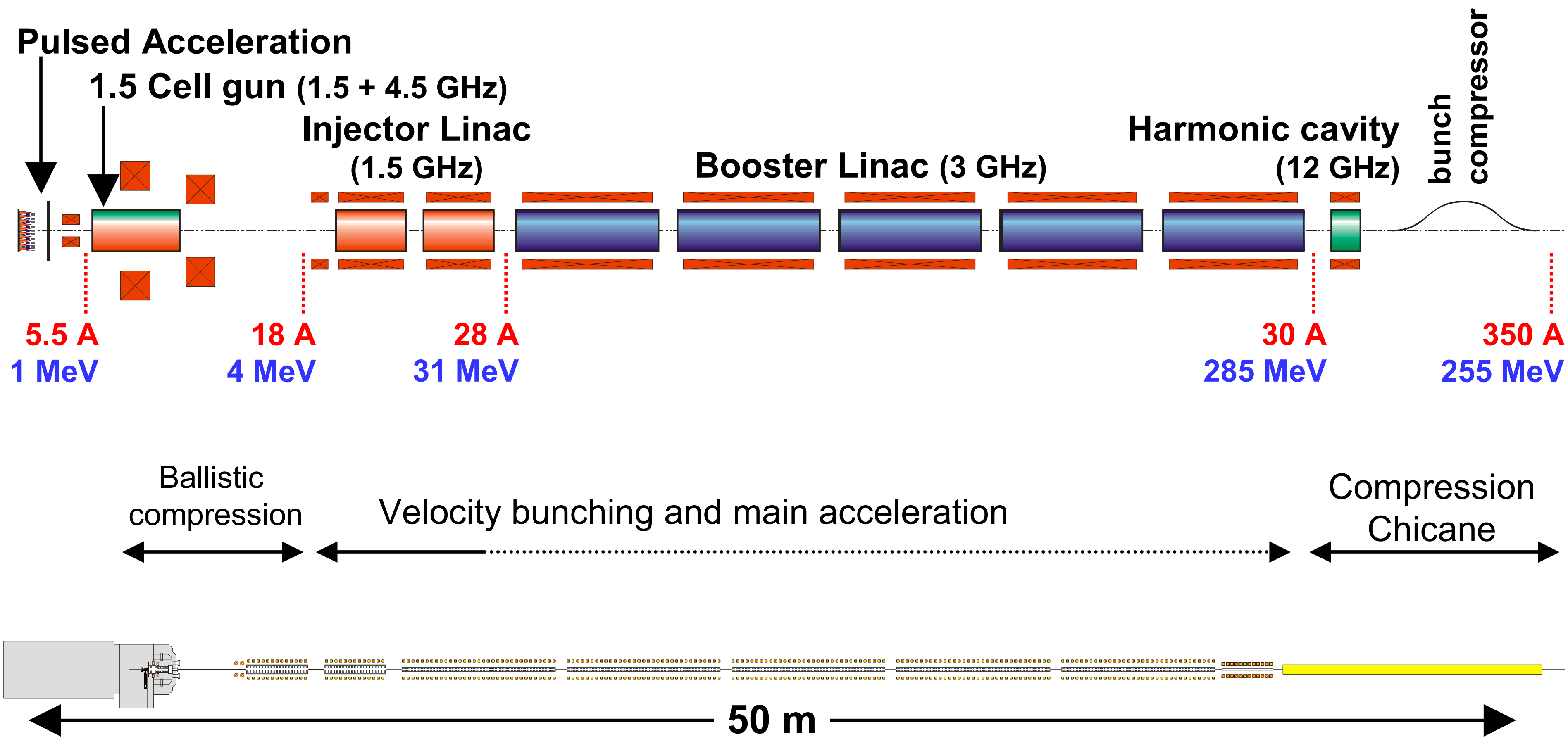


Pepperpot and YAG:Ce screen on sliders in UHV chamber with out-coupling mirror (side view / cut)

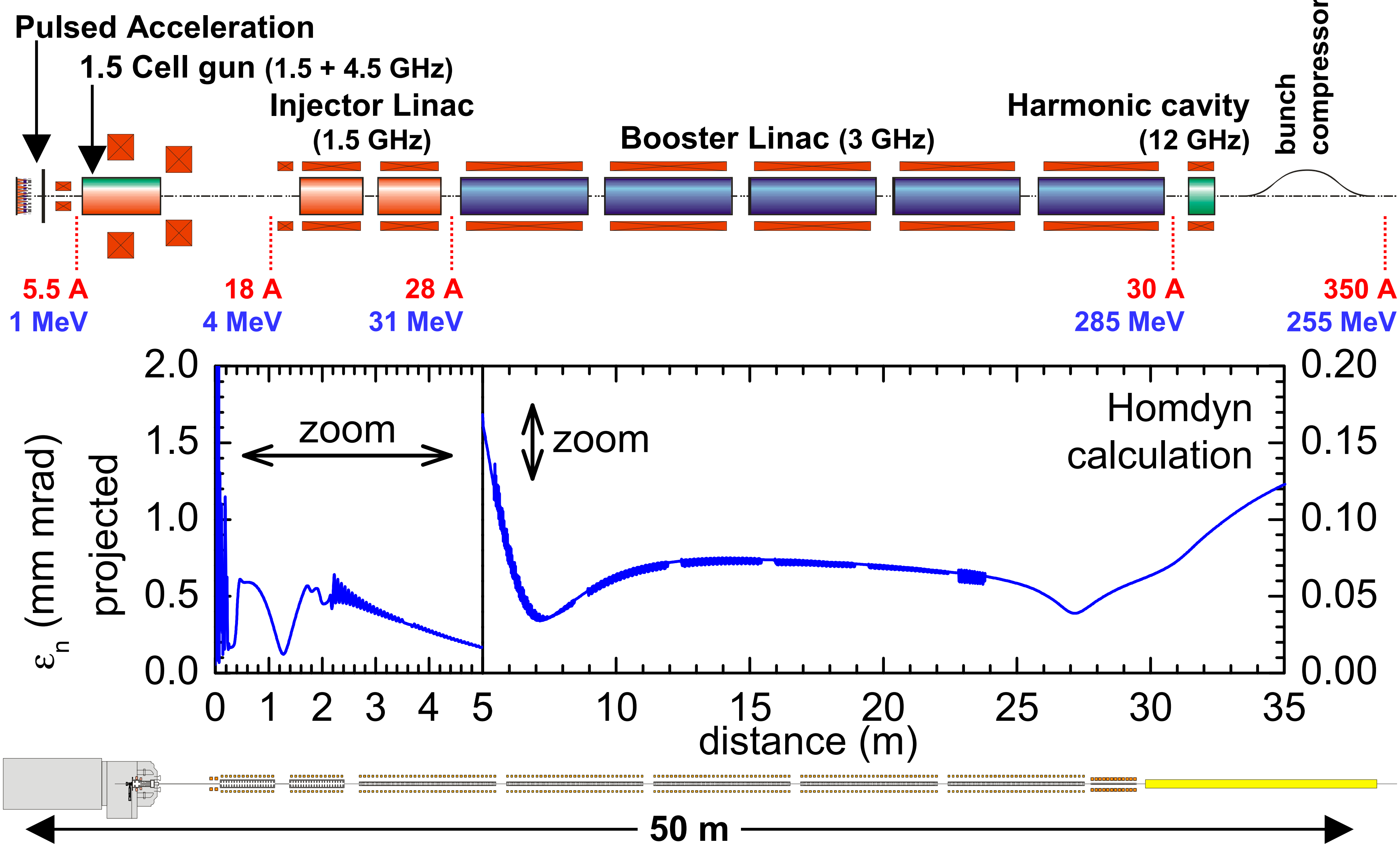


Layout 250 MeV Test Accelerator

The FEL injector is the most sensitive section of the accelerator.

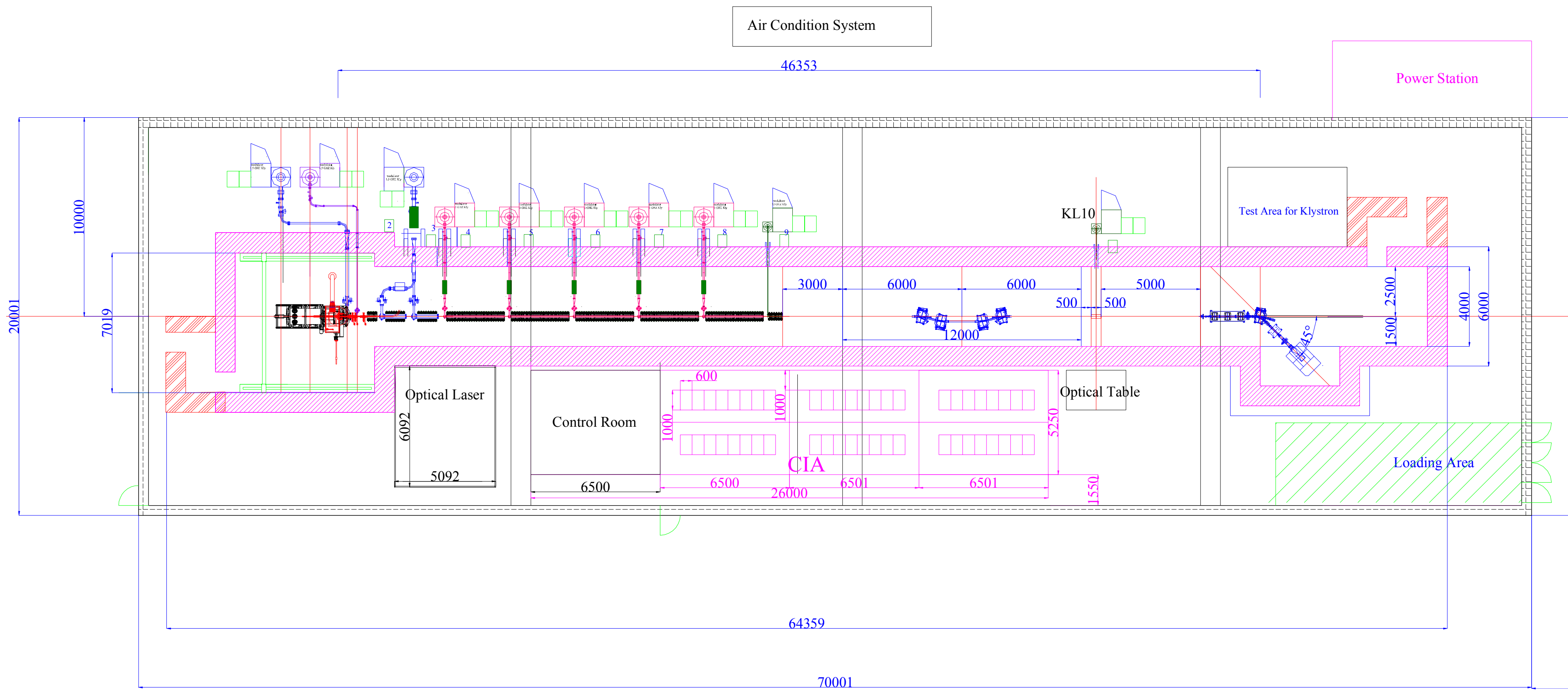


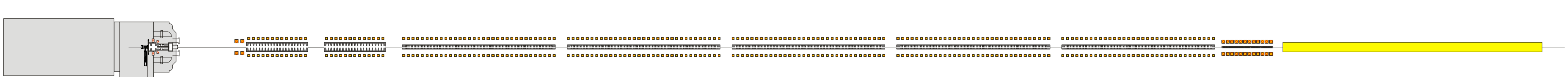
Layout 250 MeV Test Accelerator



Building Concept (Fuqiang WEI)

70 m





50 m


POSSIBLE BUILDING LOCATION

RF systems 250 MeV injector

Single bunch 10-100Hz rep rate - Normal conducting technology

Post acceleration 1.5 or 2 cell cavity

2 frequency cavity 1.5 GHz - 4.5 GHz

Velocity bunching

TW section 1.5 GHz

Acceleration

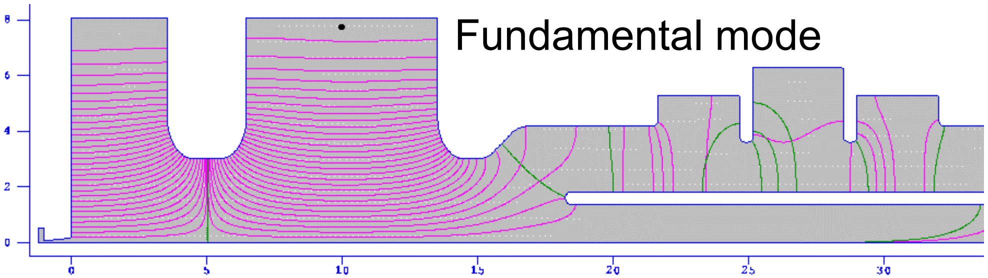
TW sections 3 GHz

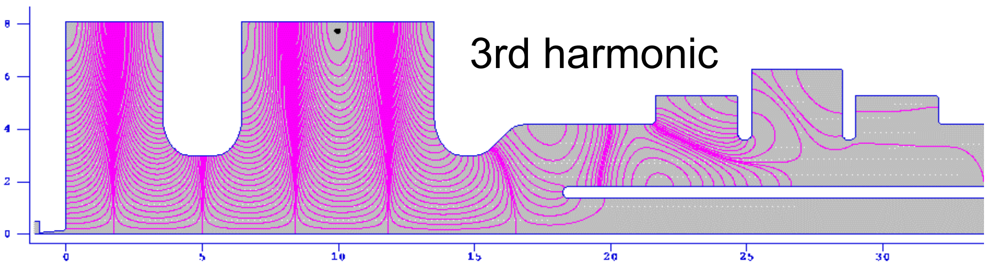
Longitudinal phase space linearization for compression chicane

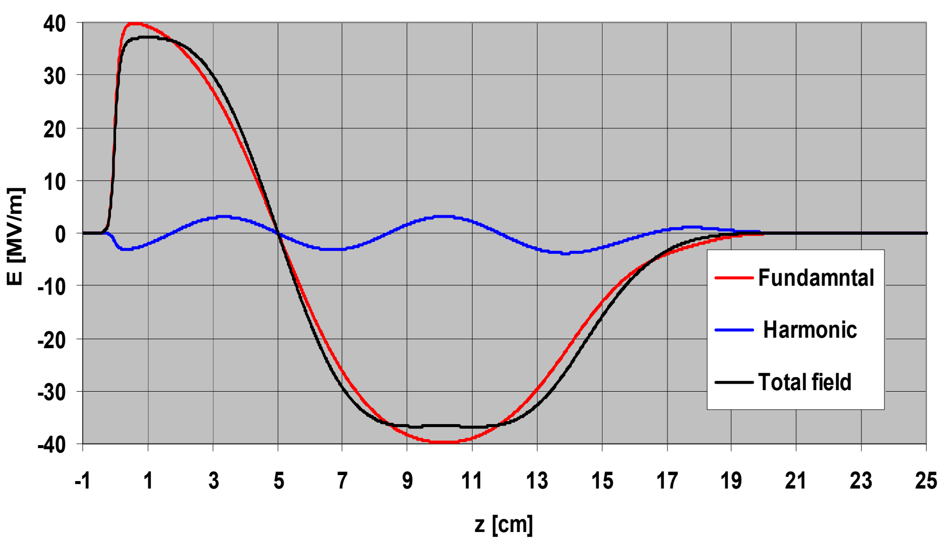
Harmonic cavity at 12 GHz

Two freq. RF gun *1.5 GHz – 4.5 GHz -* RF design

2-frequency RF gun [J.-Y. Raguin]



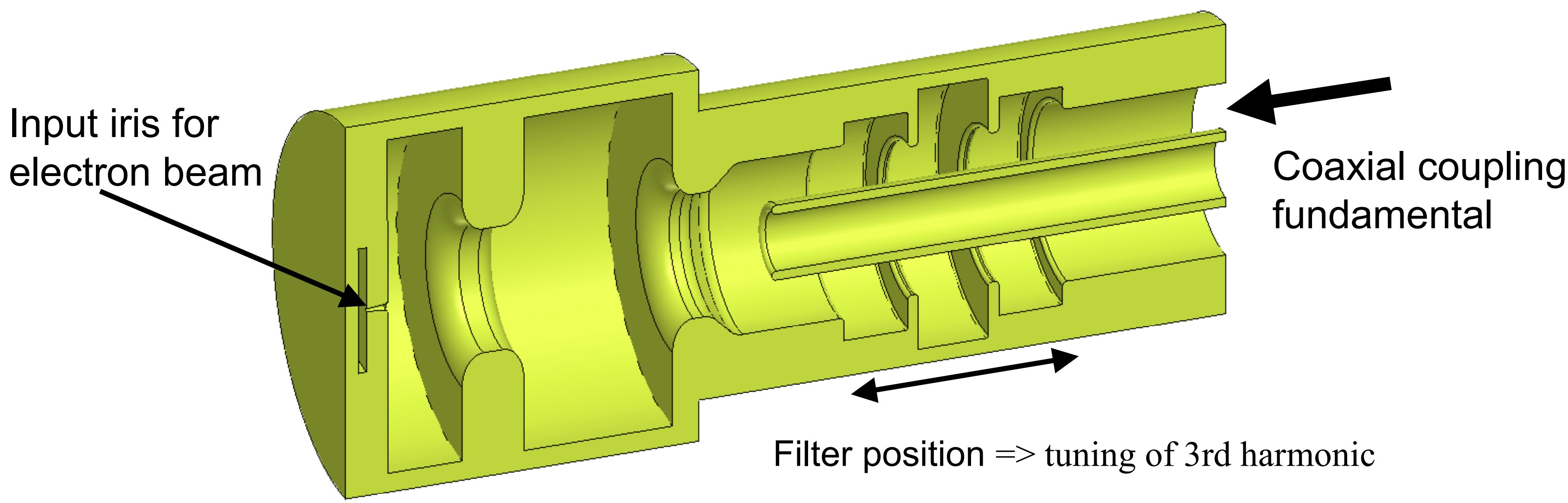


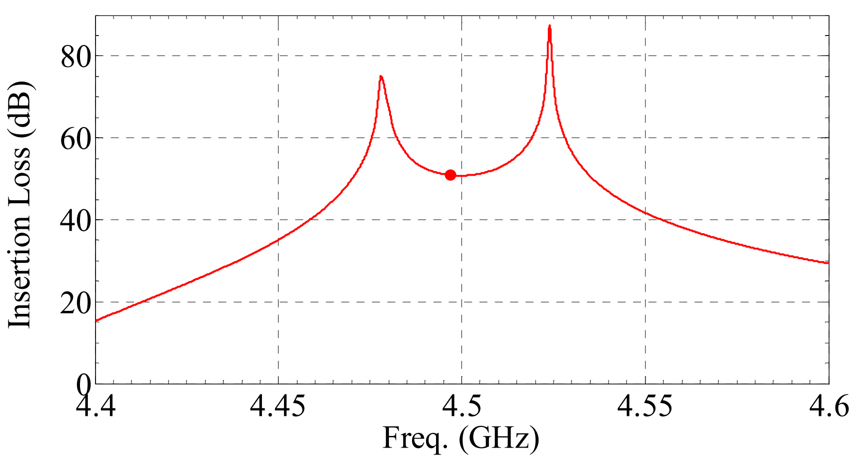


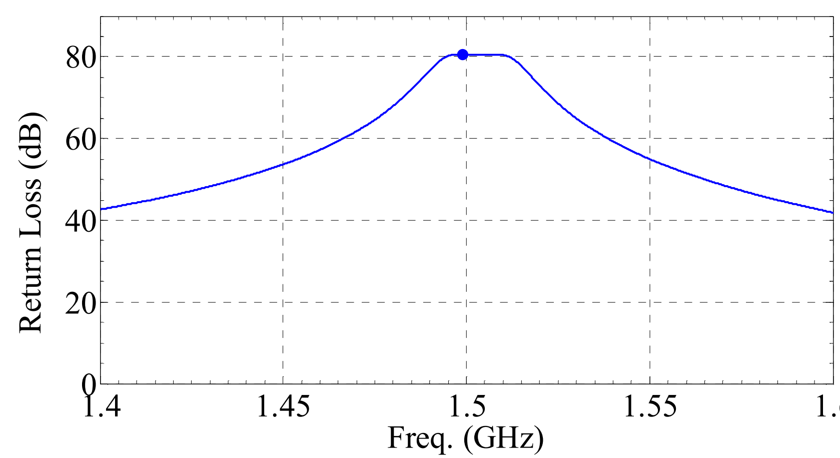
SUPERFISH simulations

Fundamental freq. (MHz)	**1498.956**
π-O mode separation (MHz) *(Optimized for large mode separation)*	**12**
Qo fundamental O mode	**11260**
Q loaded fund. π mode	**9340**
Qo harmonic (~TM_{012})	**19840**
Peak on axis field (MV/m)	**40**
Peak surface field (MV/m)	**48.1**
Peak input power π mode (MW)	**3.3**
Peak input power harmonic (kW)	**280**

Coaxial coupling with 3rd harmonic filter – RF design

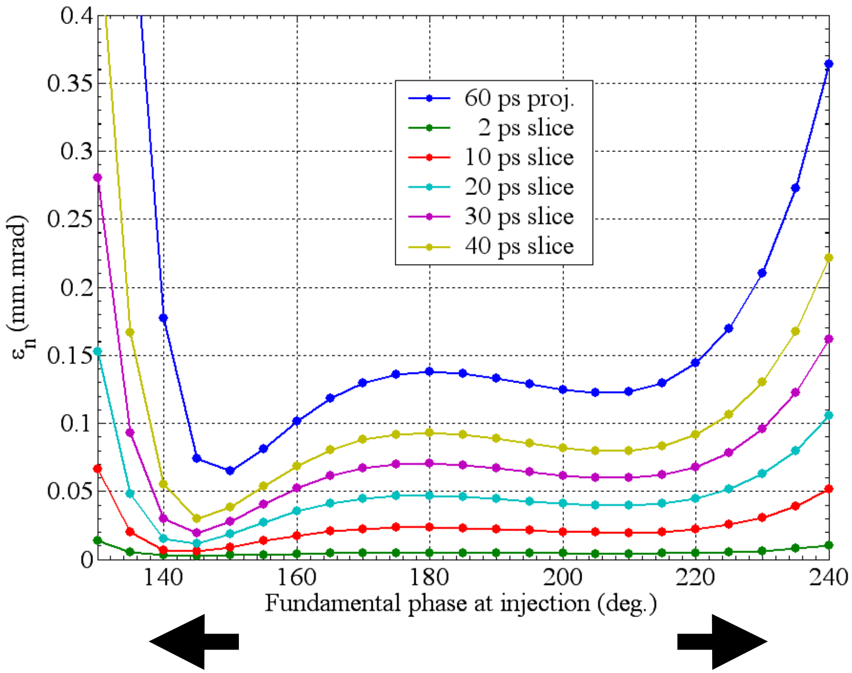






Parmela simulation 1 - Zero current – possible compensation of RF emittance dilution for long pulses (dilution effect reduces if the beam size can be kept "small").

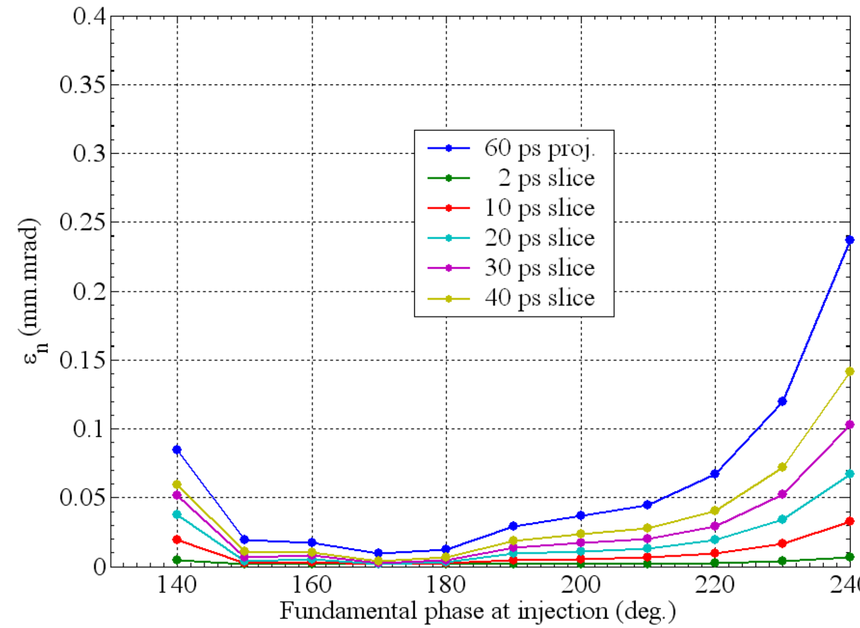
Fundamental alone



Bunching

De-bunching

Fundamental + optimized 3rd harm.



Injection phase ≡ theRF phase of the fubdamental when the first particle of the 60 ps pulse is entering the diode Transit angle for the bunch center to reach the cavity backplane is 26.5 deg.

The emittance dilution due to the RF with long pulses can be compensated. The third harmonic make the bunching regime accessible from the emittance point of view.

Power sources for 2 frequency cavity

1.5 GHz:

Thales klystron TH2170 – 20 MW – 5 us – 100 Hz

To be delivered in November 2006

Modulator ordered by the company PPT

To be delivered beginning 2007

Standard Stangenes Tank

To be ordered

4.5 GHz:

No MW klystrons available at this frequency

Klystron 1 MW – 100 Hz at least needed
under discussion with CPI, Thales, Toshiba and IEAC*
To be ordered

Both power plants will be installed in the old SLS test stand facility

****Institute of Electronics, Chinese Academy of Sciences Beijing, China***

Power sources TW cavity

1.5 GHz:

Thales klystron TH2170 – 20 MW – 5 us – 100 Hz

Modulator and tank technology to be discussed (possible synergies with other labs)

3 GHz:

~32 MW – 100Hz – 4.5 us needed

Possible solution with 45 MW Thales klystrons (TH2100B or TH2155).
One Plant with SLED cavity to test the accelerating structure and acquire experience for the FEL linac.
Possible solution with Toshiba klystrons. It requires a frequency retune and collector designfor 100 Hz.

12 GHz:

~40 MW – 100Hz needed

Toshiba out of the game (not enough resources to modify the existing tube)

Thales waiting for an answer. No tube available.

To be investigated a collaboration with SLAC and other laboratories (ELETTRA, INFN, …)

TW accelerating structures

Injector:

L band / 1.25 m: 10 MV/m accelerating gradient
S band / 3 m: 19 MV/M (25 MV/m for FEL) accelerating gradient

FEL options:

~77 S band / 3.0 m: 25 MV/m, RF length 231 m (power/structure ~58MW)
~80 C band / 1.8 m : 40 MV/m, RF length 144 m, power/structure ~80MW)

Short structures preferable to avoid mechanical deformations (bend)
5m structure ~optimal in term of energy gain / power plant
C-band option probably expensive …

Possible suppliers and early information:

ACCEL:

S-band already produced (Desy design)
prototype + power test ~1 Year (then 1/month for the first 3 structures)
Delivery ~4 Years for 80 structures (main Linac)

Mitsubishi:

Experienced supplier, S-band guaranteed for 30 MV/m,
waiting for an offer (one structure at SPARCX)

IHEP*:

Getting experience, offer in house (good price/quality factor).
Available SLAC scaling, if more new design required.
Delivery 10 month for 8 structures (L,S,X band) after order award.
Delivery ~2 Years for 80 structures (main Linac)

*Institute of High Energy Physics, Beijing, CHINA

Summary - RF trivial complications

- Phase and amplitude stability:

Definitive estimation not available now, should be close to the canonical 0.1 deg for the phase and 0.2% for the amplitude.

Phase and amplitude loops hard to implement because of the short pulse length. The injector test stand will be used to investigate the RF-LLE.

- Use of SLED cavities and large accelerating gradients in the main Linac.

- Large number of power plants in the main Linac

50 to 80 depending on the configuration

- High RF Cost:

~6MEU for the injector

>50 MEU for the main Linac (depending on the config.)

For 5750 MeV Linac and 25 MV /m - 231 m RF active length	For 5750 MeV Linac and 40 MV /m - 144m RF active length
6.0m (~23 MV/m): 138.0 MeV/section, 42 sections and 42 klystrons + sleds (100 MW)*	2.5m (~40 MV/m): 100.0 MeV/section, 58 sections and 58 klystrons + sleds (111 MW)
5.2m (~25 MV/m): 130.0 MeV/section, 44 sections and 44 klystrons + sleds (99 MW)	2.0m (~40 MV/m): 80.0 MeV/section, 72 sections and 72 klystrons + sleds (89 MW)
4.0m (~25 MV/m): 100.0 MeV/section, 56 sections and 56 klystrons + sled (76 MW)	1.8m (~40 MV/m): 72.0 MeV/section, 80 sections and 80 klystrons + sled (80 MW)
3.5m (~25 MV/m): 87.5 MeV/section, 66 sections and 66 Klystrons + sled (67 MW)	1.5m (~40 MV/m): 60.0 MeV/section, 96 sections and 48 Klystrons + sled (67 MW)
3.0m (~25 MV/m): 75.0 MeV/section, 77 sections and 72 klystrons + sled (57 MW)	1.0m (~40 MV/m): 40.0 MeV/section, 144 sections and 72 klystrons (45 MW)
* actve length 250 m	

Summary - Other RF requirements

- **Low emittance acceleration seems possible but ……**
  - sophisticated modeling still required (HOMDYN is semi-analytical and needs cross-check with MAFIA, PARMELA, GPT, IMPACT…….)
  - Tolerance studies
  - Optimization
  - Including diagnostics
  - …………………

- **Need for a conceptional/technical design report for a 250 MeV test accelerator (mile stone 01.07.2007)**

Outlook / Required

2006	2007	2008	2009	2010	2011

electron source

- gun current estimate
- field-emitter array development
- 100 kV performance measurements
  - single gated field-arrays
  - single tips
- 500 kV performance measurements
- 4 MeV performance measurements OBLA

250 MeV linac

- Building location and layout
- CDR for a 250 MeV Accelerator
- operation

ToDo: Project Planning