Application of X-band Linacs

Gerardo D'Auria

Elettra - Sincrotrone Trieste

LINAC12

XXVI Linear Accelerator Conference

Tel Aviv, Israel, September 9-14, 2012

Outline

- **Overview and historical remarks**
- ***The X-band technology***
- ***X-band applications:***
  - ***Linear collider***
  - ***Photon sources***
  - ***Beam diagnostics and manipulation***
  - ***Industrial and medical applications***
- ***Conclusion***

Considering the vastness of the subject to be treated, I am presenting only a selection of ongoing activities at laboratories that provided me with information and data about their X-band projects. The talk is not exhaustive and unfortunatley many applications will not be mentioned. For this I apologize in advance

Overview and Historical Remarks

Already in the mid 60's, the Slac "Blue book" reports a clear interest in the accelerator community for X-band technology.

Table 6-2 Design parameters of 20-GeV accelerator at three frequencies[a]

Parameter	Frequency (L-Band) 1000 MHz	(S-Band) 3000 MHz	(X-Band) 9000 MHz
Shunt impedance r (megohms/meter)	31	53	92
RF loss factor (Q)	2.25×10^4	1.3×10^4	0.75×10^4
Filling time t_F (μsec)	4.31	0.83	0.16
Total RF peak power (MW)	9216	5320	3072

....

- ***From the late 1980's to 2004, groups from SLAC, KEK and Fermilab began a dedicated development of X-band technology (@11.4 GHz) for a TeV-scale Linear Collider. The frequency choice (four times that of SLAC) was motivated by cost benefits:***
  - ***high gradients → shorter and cheaper linacs***
    → lower energy per pulse
- ***In 2004, the International Technology Review Panel (ITRP) selected L-band superconducting RF technology for the International Linear Collider (ILC) which led to a slowdown in X-band activities.***
- ***In 2007 CERN decided to lower the Compact Linear Collider (CLIC) frequency to 12 GHz (previously at 30 GHz) producing a new interest in X-band and the CERN-SLAC-KEK collaboration on HG X-band structure development.***

Pros/Cons of High Frequency NC Linacs

Advantages:

- Higher operating gradients
  - X-band is capable up to 80-100 MV/m
  - S-band is limited to about 20-24 MV/m
  - C-band is limited to about 32-35 MV/m
- Higher energy efficiency, especially for short pulse operation
  - Important for lightly loaded operation
  - Opens possibility of higher repetition rates , i.e. kHz X-ray FELs

Drawbacks:

- Larger wakefields*
  - Need larger iris radius to reduce the short-range wakes
  - Need HOM damping to reduce the long-range wakes
- Very tight alignment tolerances

*Generally small for X-FELs operating with short bunches (≤ 100 fs) and low bunch charge < 250 pC

X-band Applications

The driving force behind the X-band technology development has been, and is, the scientific interest for the construction of a Multi TeV e^+e^- linear collider. First with the collaboration SLAC-KEK (for NLC-GLC), then with the CERN proposal for a collider at 12 GHz based on the TBA concept) CLIC.(
In addition to this application, X-band technology is now rapidly expanding for the multiple uses that it can satisfy. In particular:

- *Very compact X-ray FELs and photon sources, based on few tens of MeV up to multi GeV linacs.*
- *High gradient photo-injectors for extremely high brightness beams production.*
- *Diagnostics for X-ray FELs:*
  - *transverse deflecting cavities for bunch length measurements and beam phase space characterization with extremely high resolution.*
- *Beam manipulation:*
  - *energy linearizer, already in use at LCLS and FERMI@Elettra FELs, planned for SwissFEL.*
  - *crab cavities for beam luminosity improvement at collider IP (CLIC).*
- *Medical and industrial applications:*
  - *linacs for proton and carbon ion therapy, IORT…*
  - *low energy compact linacs for radiographies and non-destructive inspections.*

CLIC Collaboration

http://clic-study.org/accelerator/CLIC-ConceptDesignRep.php

Successfully tested T24 and TD24 accel. struct. to CDR specifications:

E_a > 100 MV/m
T_{RF} > 170 ns flat top
BDR/m < 3 x 10^{-7}


SLAC-R-985
KEK Report 2012-1
PSI-12-01
JAI-2012-001
CERN-???
12 July 2012

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

A MULTI-TEV LINEAR COLLIDER BASED ON CLIC TECHNOLOGY

CLIC CONCEPTUAL DESIGN REPORT, VOLUME 1

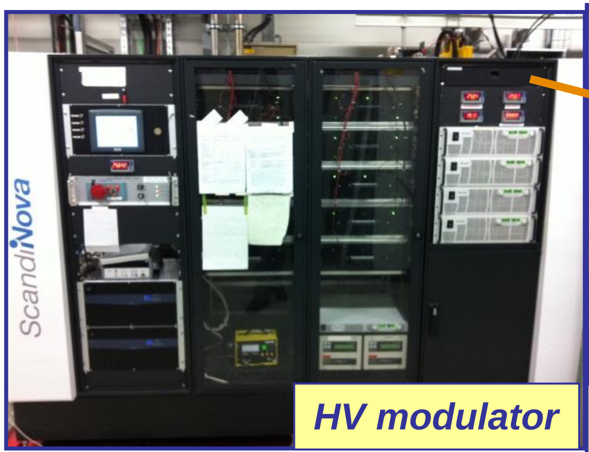
GENEVA
2012

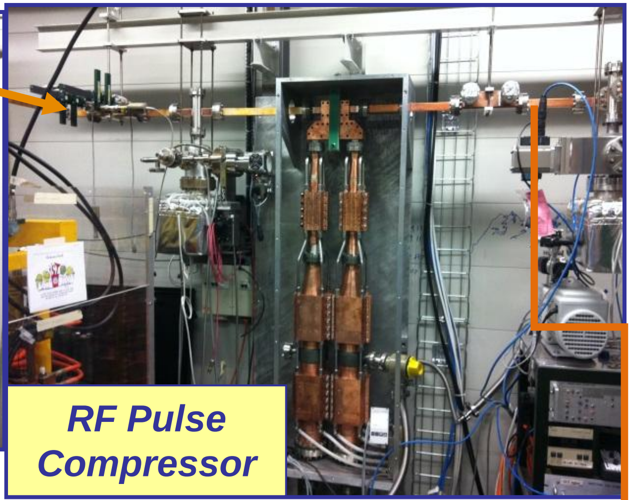
CERN 12 GHz High Power Test Stand

Status at 08-2012

RF power operation

- XL5 Klystron conditioned up to 40MW, 500ns, 50Hz with loads (50MW peak, 300ns, 50Hz)
- Started CLIC structure condit. without pulse compressor, reached 88 MV/m, 170 ns at a BDR of 10^{-6}/pulse.



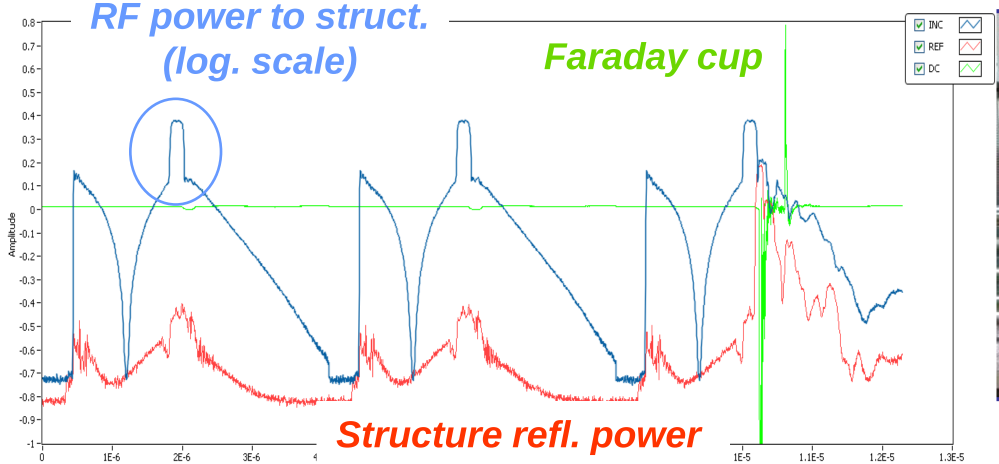


Gallery

Bunker

Max RF power into RF Pulse Compressor:
12 MW, 1.5 μs, 50 Hz

RF power into struct:
31 MW, 140 ns, 50 Hz



Courtesy of
J. Kovermann

X-band activities at SLAC

From the late 80's SLAC has pioneered the X-band technology development with a major contribution from KEK and later from FNAL for the accelerating structures.
The important R&D effort brought the development of many high power RF components at 11.424 GHz, i.e. klystron, HG structures, WG components.

Actually SLAC is very active in supporting many accelerator-based laboratory programs:

- *CERN for the Linear Collider program*
- *Lawrence Livermore National Laboratory*
  - *MEGa-ray, with a 250 MeV X-band linac for Inverse Compton Scattering (ICS)*
  - *ELI-NP proposal (Extreme Light Infrastructure – Romania based on ICS)*
- *SincrotroneTrieste, FERMI@Elettra, for X-band linearizer and possible FEL extension*
- *PSI, SwissFEL, for X-band linearizer*
- *NLS, studies for a possible NC linac option based on an X-band linac*

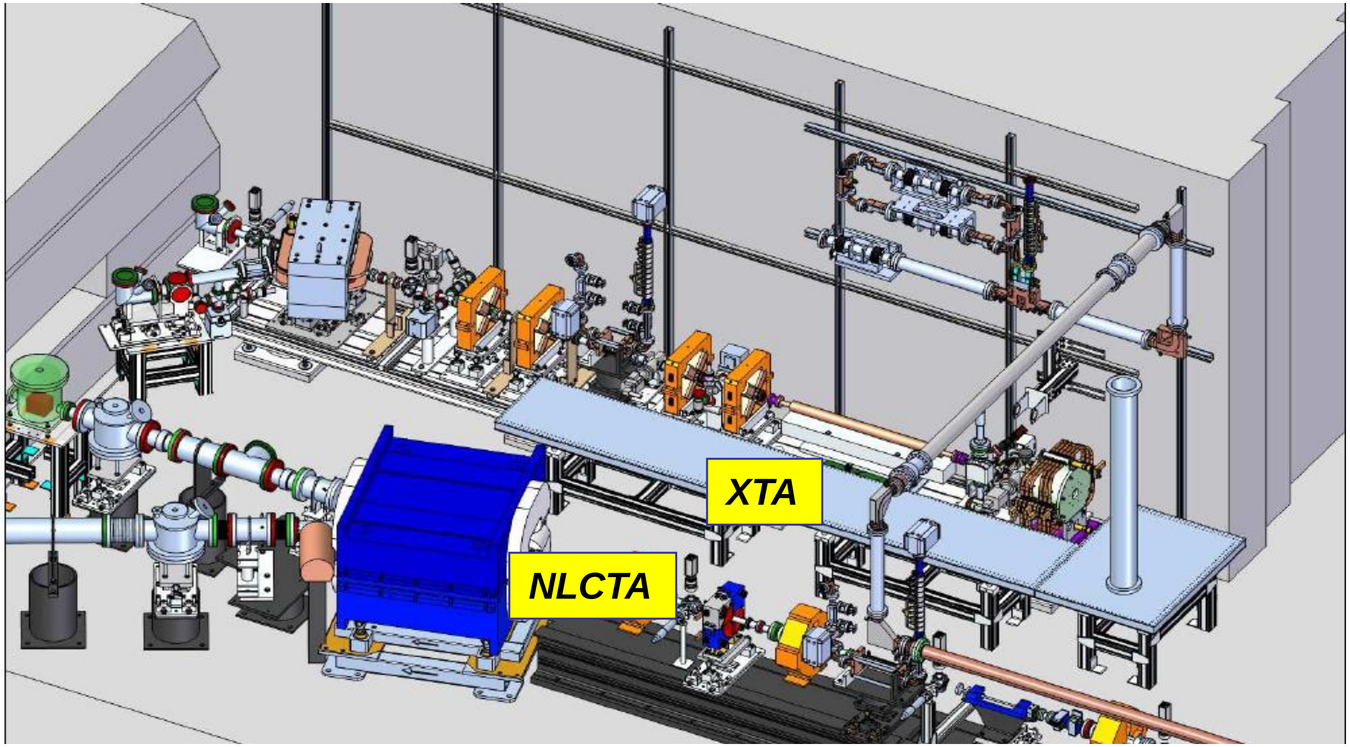
Internal developments:

- *X-band beam diagnostics for LCLS*
- *X-band Gun Test Area (XTA)*
- *NLCTA and ASTA Test Areas, mostly dedicated to photon science*
- *Studies and simuilations for X-ray FELs based on very compact X-band linacs*

  (Y. Sun et al., PRST 15, 030703 (2012).

SLAC X-band Test Area (XTA)

Characterization of X-Band photoinjector



High power tests with Mark-0 gun

- **Dark current studies**
- **Peak brightness for various charges (250pC, 20pC, … , 1pC)**

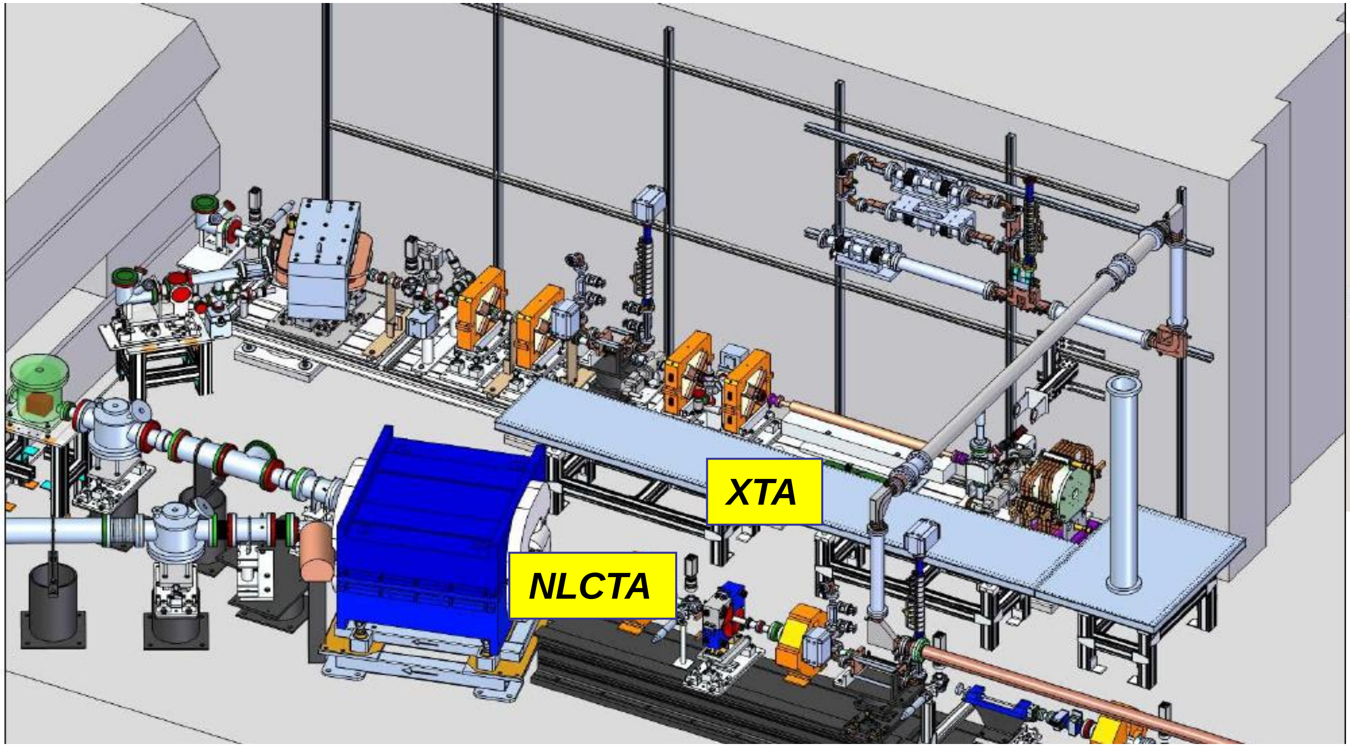
Tests with Mark-1 gun

- **Multi-bunch feasibility: starting with 2-bunch**
- **Higher repetition rate exploration: from beam dynamics perspective**

Courtesy of C.Limborg

SLAC X-band Test Area (XTA)

Characterization of X-Band photoinjector



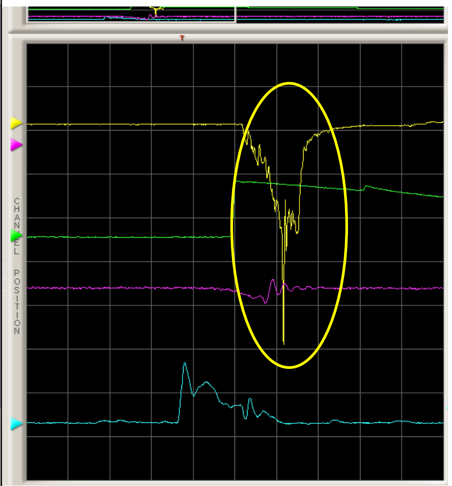


Photo e-beam commissioning started July 30.

First beam: spike on yellow trace

High power tests with Mark-0 gun

- Dark current studies
- Peak brightness for various charges (250pC, 20pC, … , 1pC)

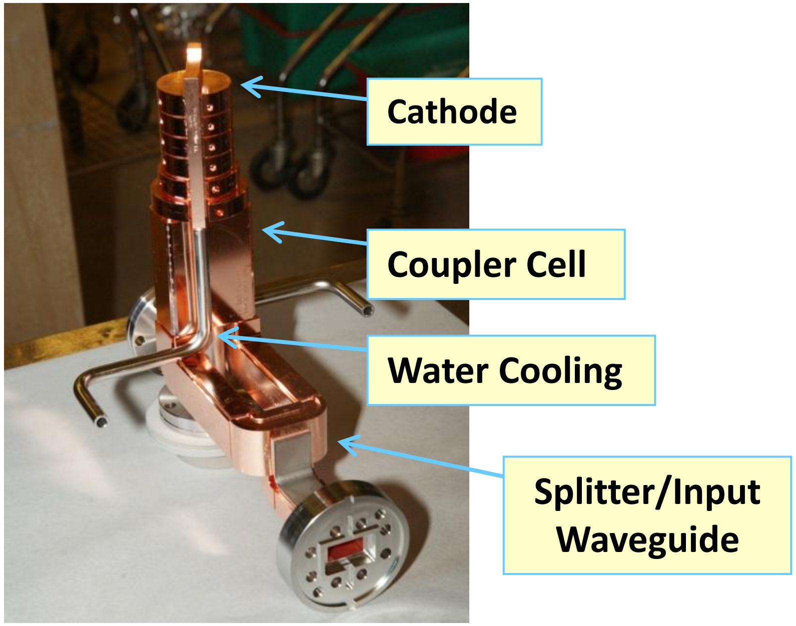
Tests with Mark-1 gun

- Multi-bunch feasibility: starting with 2-bunch
- Higher repetition rate exploration: from beam dynamics perspective

Courtesy of C.Limborg

Mark-0 X-band photo-injector

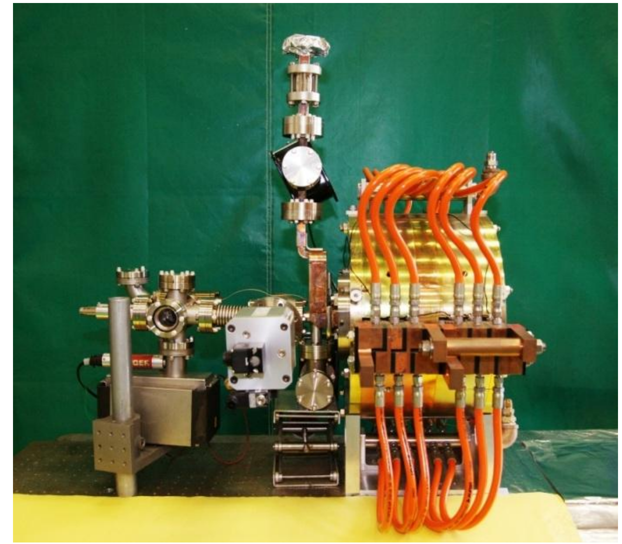
5.5 cell RF Gun



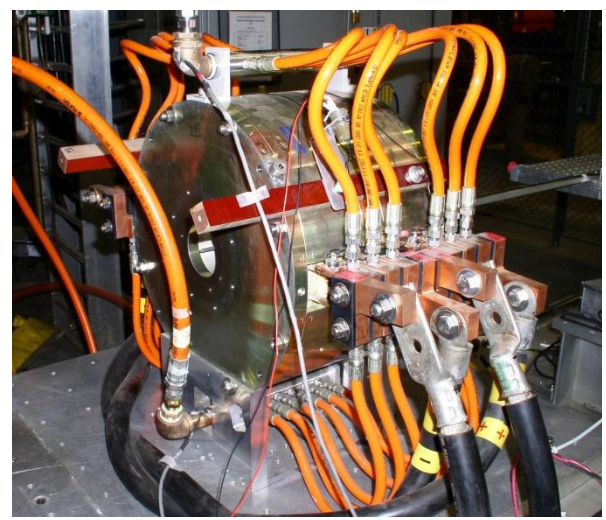
- *F = 11.424 GHz, 5.5 cells, π-mode*
- *Earlier version tested at 200 MV/m with 250 ns RF pulse.*
- *Coupling factor β ≈ 1.7*

Improved version under construction → MARK-1
- *5.59 cells*
- *> 25 MHz mode separations*
- *elliptical irises*
- *racetrack coupler*

Photo-injector assembly



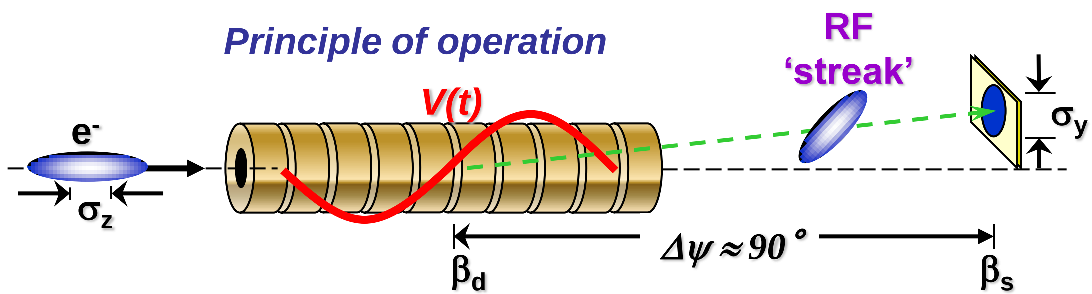
6 kG Solenoid Magnet



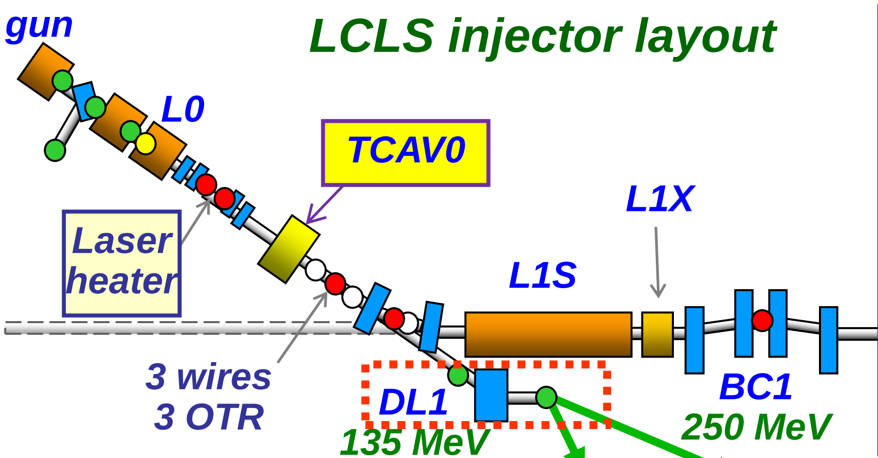
Courtesy of A. Vlieks

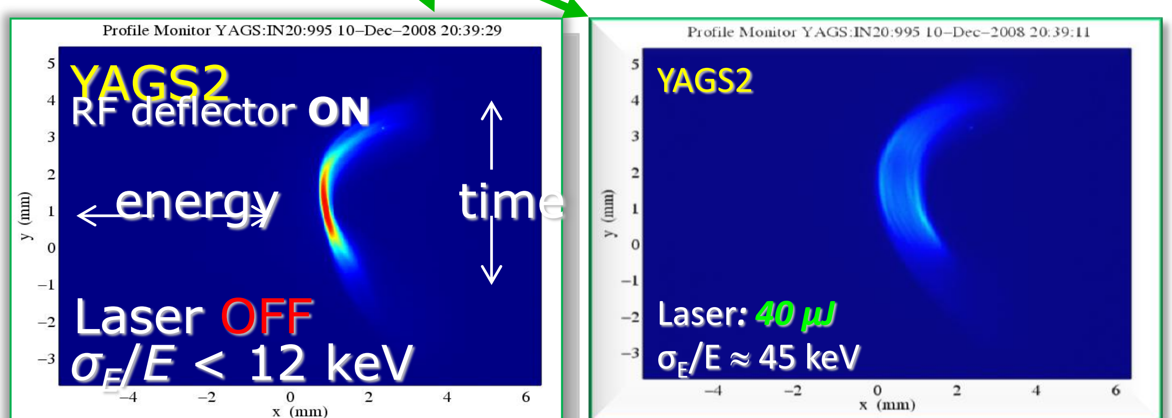
Transverse Cavity Diagnostics

The Transverse Cavity (TCAV) technique is now a well established diagnostic tool at the X-ray FELs to measure sub-ps temporal bunch profiles.



The diagnostics is further enhanced if the deflected beam is observed on an energy spectrometer screen, where the energy dispersion is in the plane perpendicular to the RF deflection. The dispersion properties of the dipole allow for the complete characterization of the energy distribution of each bunch slice reconstructing the longitudinal phase space.





Energy profile and slice energy spread measurements with TCAV at LCLS

Courtesy of
P. Krejcik, P. Emma, H. Loos

New X-band Transverse Cavity at LCLS

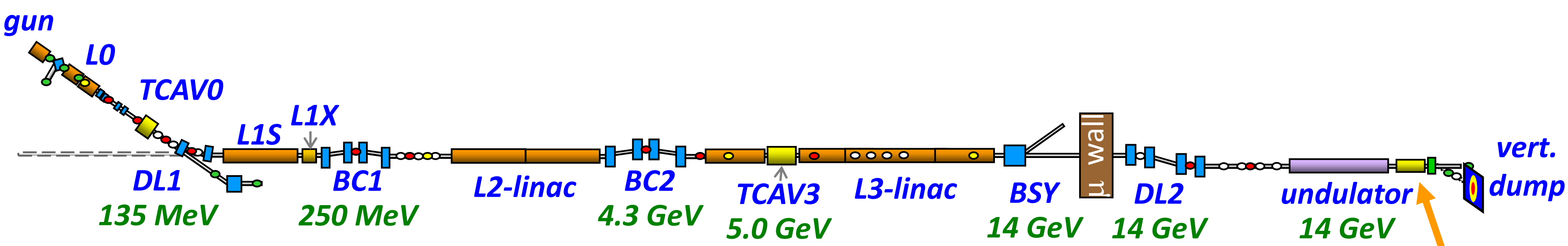
Ratio of beam size on the screen σ_y to bunch length σ_z:

$$S = \frac{\sigma_y}{\sigma_z} = \frac{eV_0}{E_e}\frac{2\pi}{\lambda_{RF}}\sqrt{\beta_d\beta_s}\left|\sin\Delta\psi\right|$$

Measurement resolution

$$\sigma_{t,R} = \frac{\sigma_{y0}}{S} = \sqrt{\frac{\varepsilon_{n,y}}{\gamma\beta_d}}\frac{\lambda_{RF}E_e}{eV_0\left|\sin\Delta\psi\right|}$$

The dependence on wavelength and gradient suggest that going from S to X band the resolution can be improved by a factor of 4 from the wavelength (10 cm → 2.5 cm) and at least another factor of 2 from the gradient!!!



- ***Two 1 meter long X-band deflecting structures, located downstream the undulator, just before the electrons are bent down to the dump, are being installed at LCLS for an ultra-short e-bunch and X-ray temporal diagnostics.***
- ***Operation of the XTCAV is non invasive to photon user operation.***

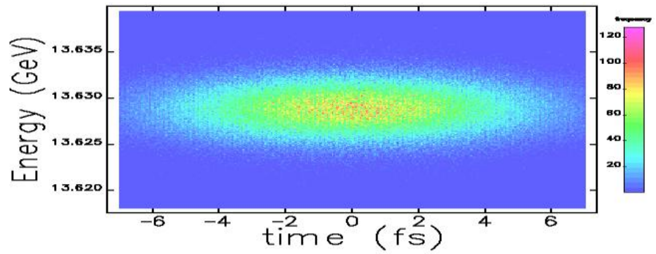
New XTCAV

Courtesy of P. Krejcik

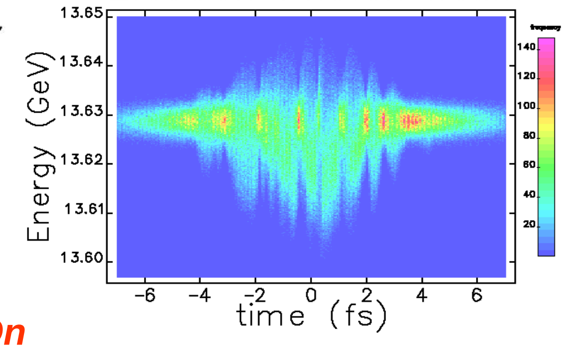
Simulation Studies

Only those parts of the bunch that do lase lose energy and increase their energy spread

FEL Off
E-beam only

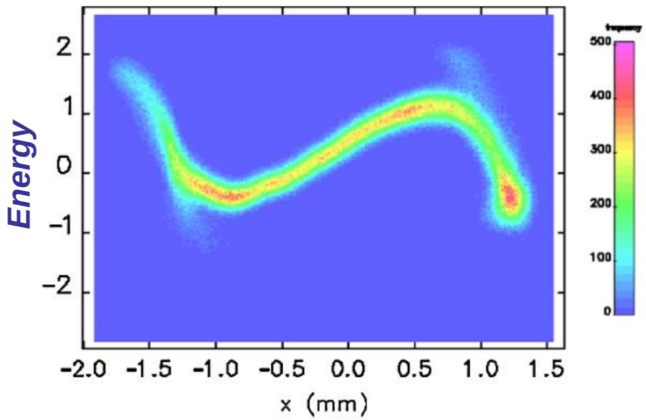


FEL On
Electron+Photon beam

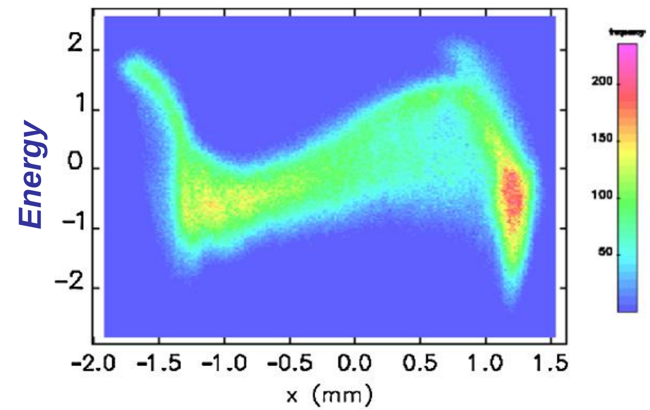


@13.6 GeV
250 pC
3 kA

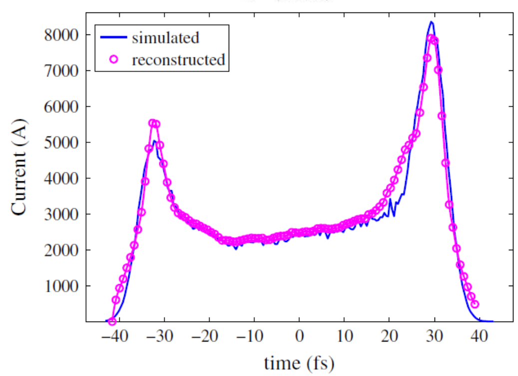
FEL Off

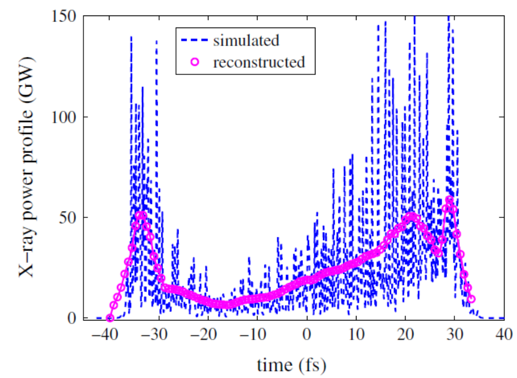


FEL On



Reconstructed electron beam profile





Reconstructed photon beam profile

Y. Ding et al.,
PRST 14, 120701 (2011)

LCLS X-band TDCs Installation

X-band transverse cavity main parameters

- *Fabrication and testing of the X-band structures completed*
- *Beamline installation is underway*
- *High power RF installation and in-situ testing are expected to be completed for the end of the year*
- *First beam commissioning early 2013*

Parameter	Symbol	Value	Unit
rf frequency	f	11.424	GHz
Deflecting structure length	L	2×1	m
rf input power	P	40	MW
Deflecting voltage (on crest)	V_0	48	MV
Soft x-ray (e-beam 4.3 GeV)			
Calibration factor	S	400	
Temporal resolution (rms)	$\sigma_{t,r}$	~ 1	fs
Energy resolution (rms)	$\sigma_{E,r}$	56	keV
Hard x-ray (e-beam 14 GeV)			
Calibration factor	S	128	
Temporal resolution (rms)	$\sigma_{t,r}$	~ 2	fs
Energy resolution (rms)	$\sigma_{E,r}$	100	keV

Deflector Structures at SLAC

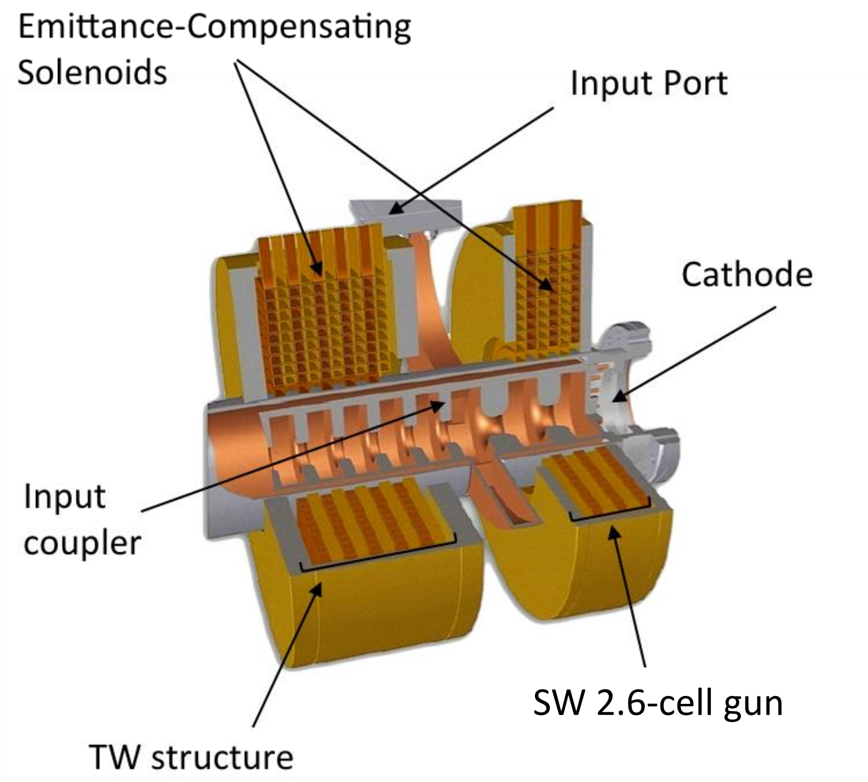
- *Two at NLCTA for ECHO*
- *FACET recently installed a 1-m version*
- *LCLS will install two*

Courtesy of P. Krejcik C. Adolphsen, T. Raubenheimer

UCLA Hybrid Photoinjector

SW high gradient RF gun section
+
TW low gradient section

both fed on-axis
with a common coupling cell

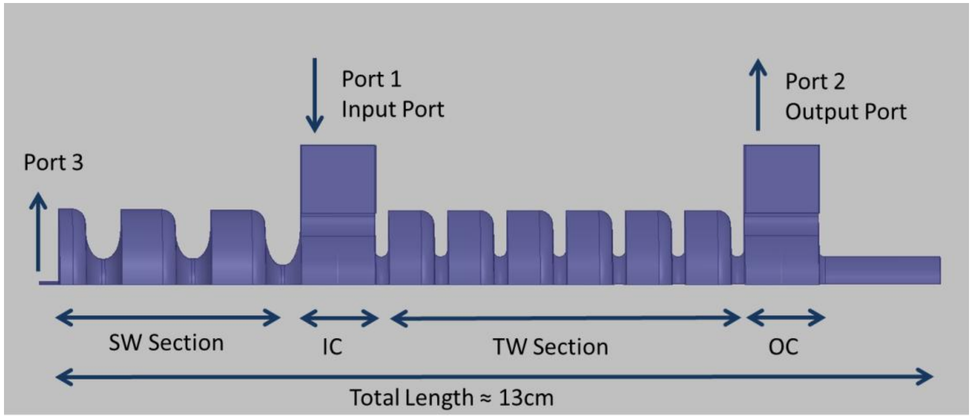


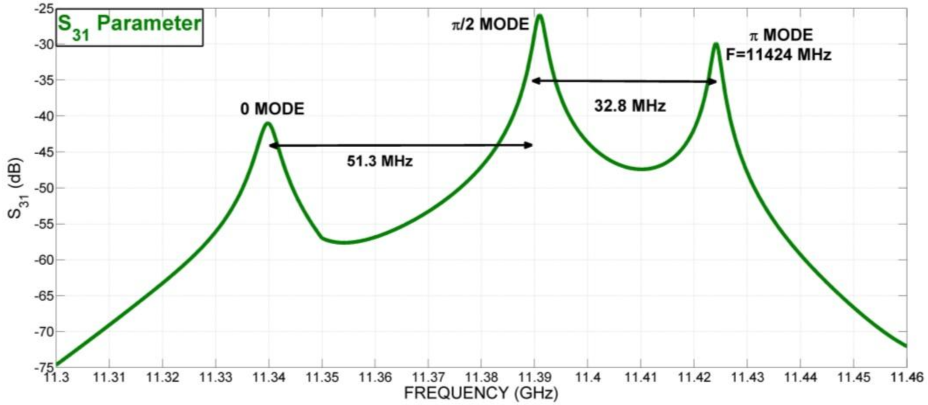
- *More compact than a split system*
- *Nearly RF matched – no isolator*
- *Avoids post-gun bunch lengthening*
- *Strongly longitudinally focused with the TW section performing as velocity bunching (90° phase shift between SW cell and input coupler)*

- *High accelerating field on axis, 200 MV/m peak → very high brightness beams.*
- *X-band scaled from an existing S-band unit, preserving acceleration and transverse dynamics.*
- *Tens of fs beams at 3.5 MeV with sub-0.1 mm-mrad emittance at 7 pC*
- *Applications: PWFA, coherent Cerenkov rad., electron diffraction*

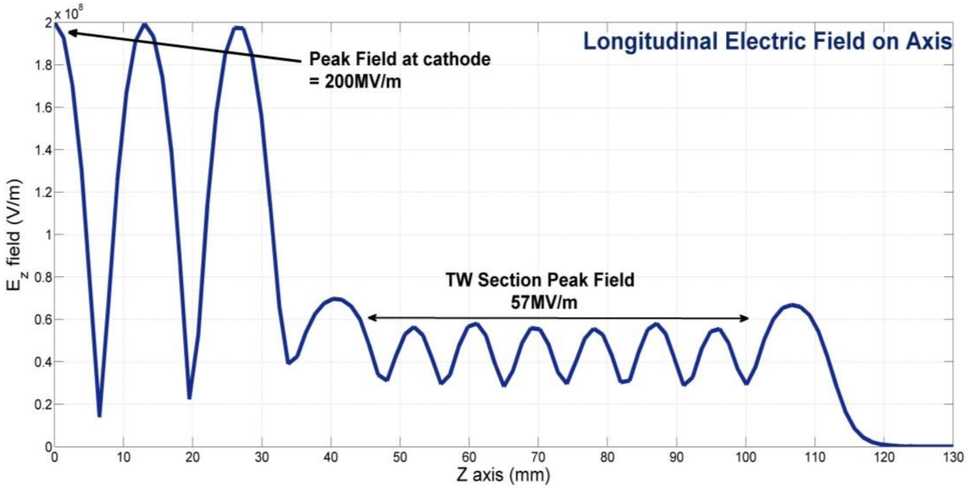
Courtesy of A. Valloni, J. Rosenzweig

RF Design

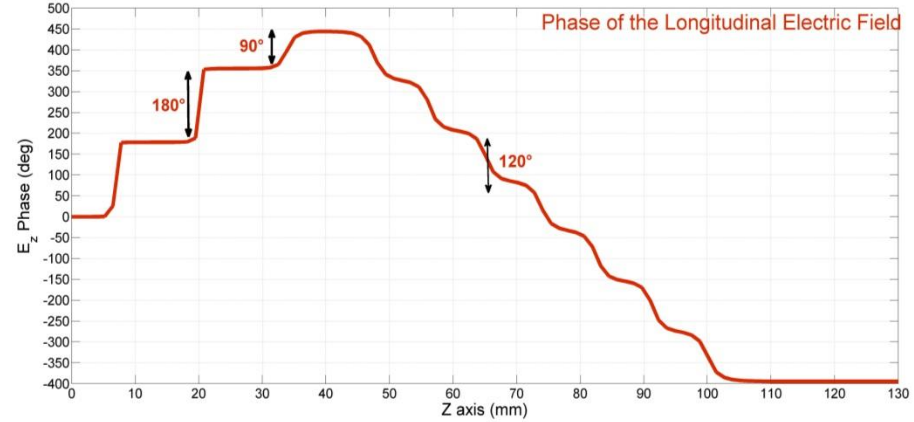




S31 between the gun and the WG input port



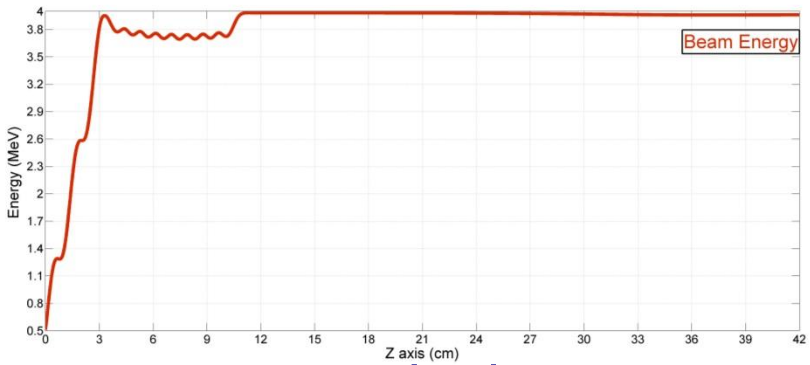
Amplitude of the Accelerating Electric Field on axis



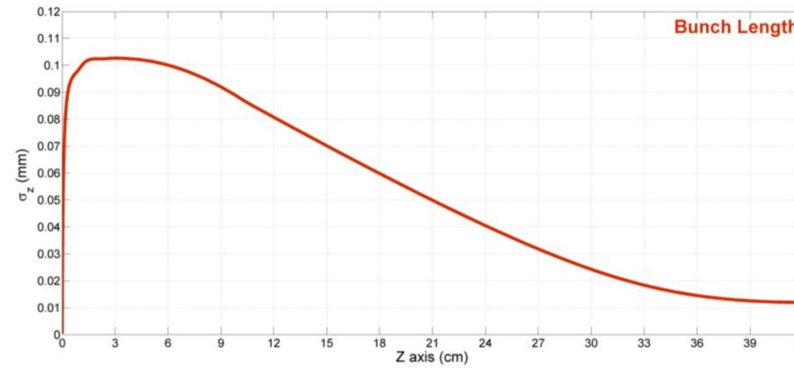
Operating frequency	**11.424 GHz**
Q factor (SW section)	**8100**
Shunt impedance (SW section)	**110 MΩ/m**
Peak field at cathode	**200 MV/m**
Average field in the TW section	**49 MV/m**

Courtesy of
A. Valloni, J. Rosenzweig

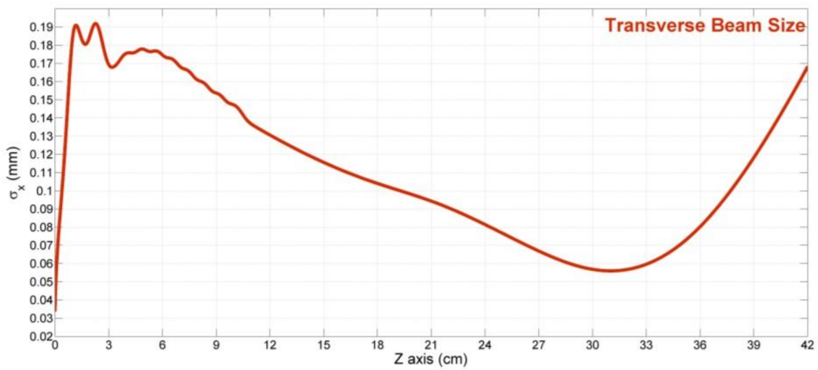
Beam Dynamics



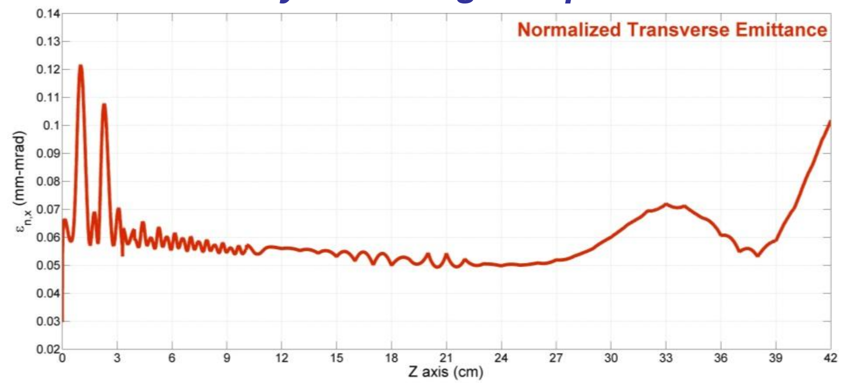
Acceleration



Velocity bunching compression



Beam Size Controlled with Solenoids



Well Compensated Emittance

Input beam	
Charge	6.75 pC
Radius	67.5 μm
Length	416 fs
Thermal emittance	0.03 mm mrad

Output beam @30 cm	
Energy	4 MeV
Transverse size	58 μm
Length	80 fs
Norm. transv. emitt.	0.065 mm
Energy spread	0.60%

"Six-dimensional phase space compensation"

Courtesy of
A. Valloni, J. Rosenzweig

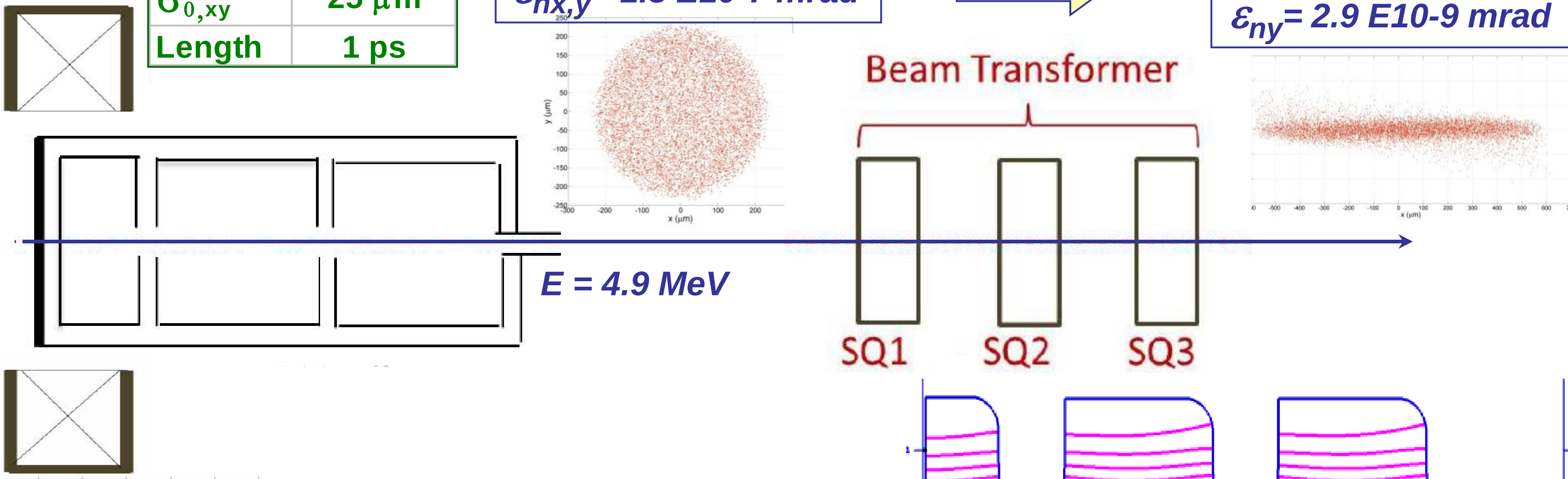
Asymmetric emittance beam photoinjector

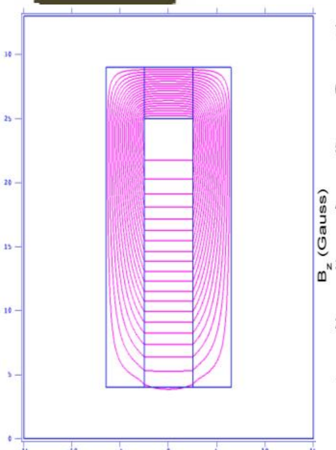
Charge	1 pC
$\sigma_{0,xy}$	25 μm
Length	1 ps

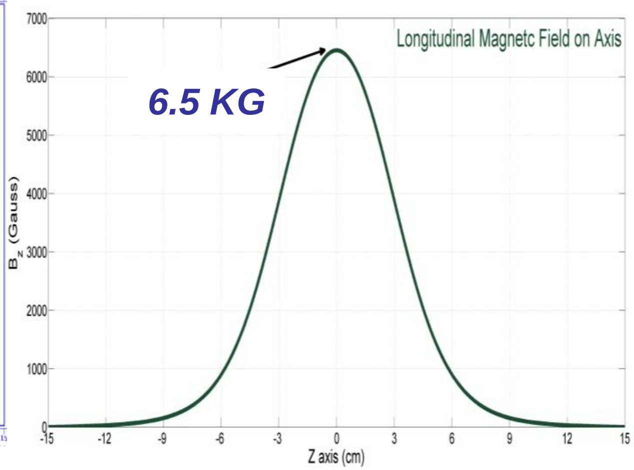
$\varepsilon_{nx,y}$= 1.3 E10-7 mrad

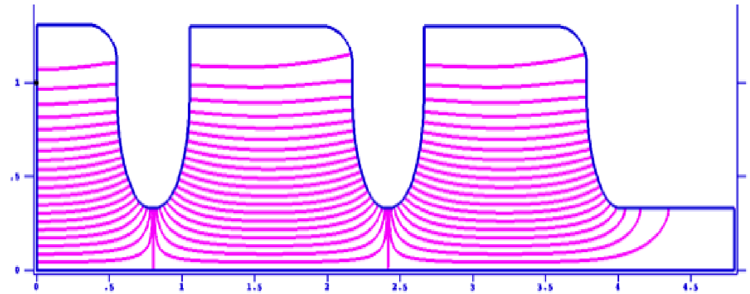
ε_{nx}= 2.6 E10-7 mrad

ε_{ny}= 2.9 E10-9 mrad





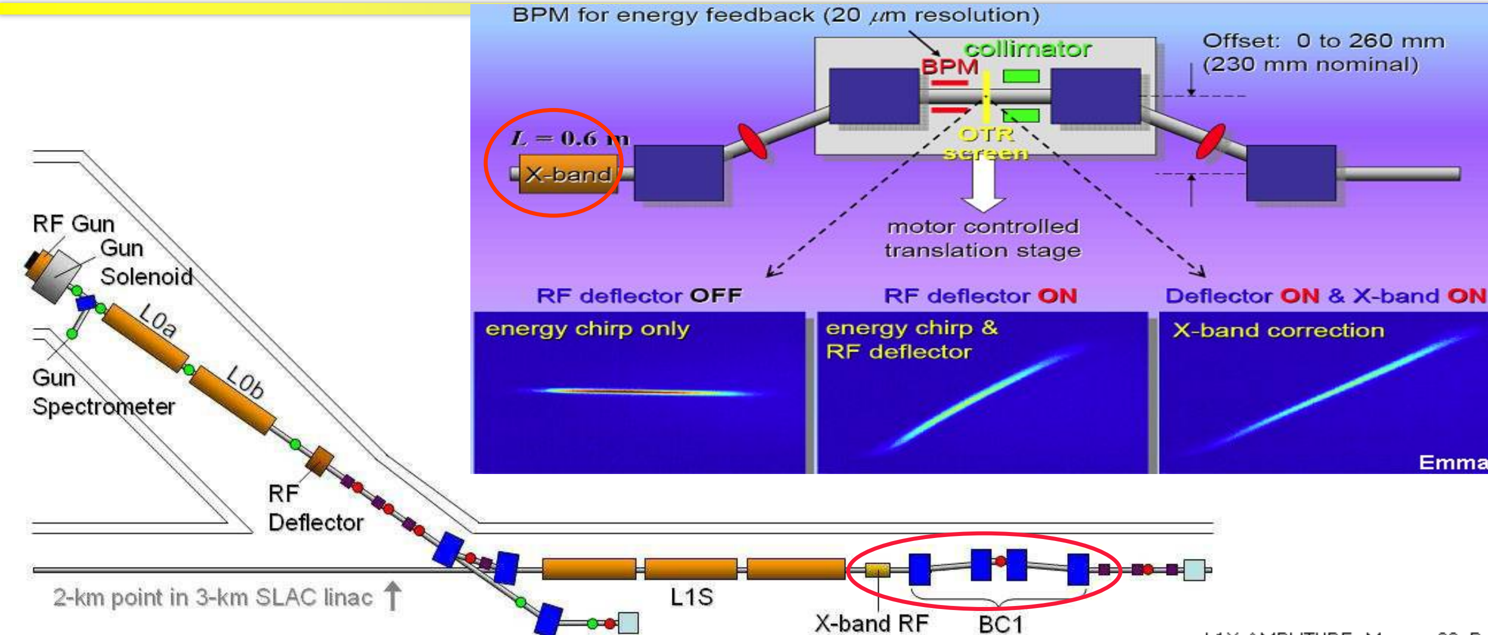


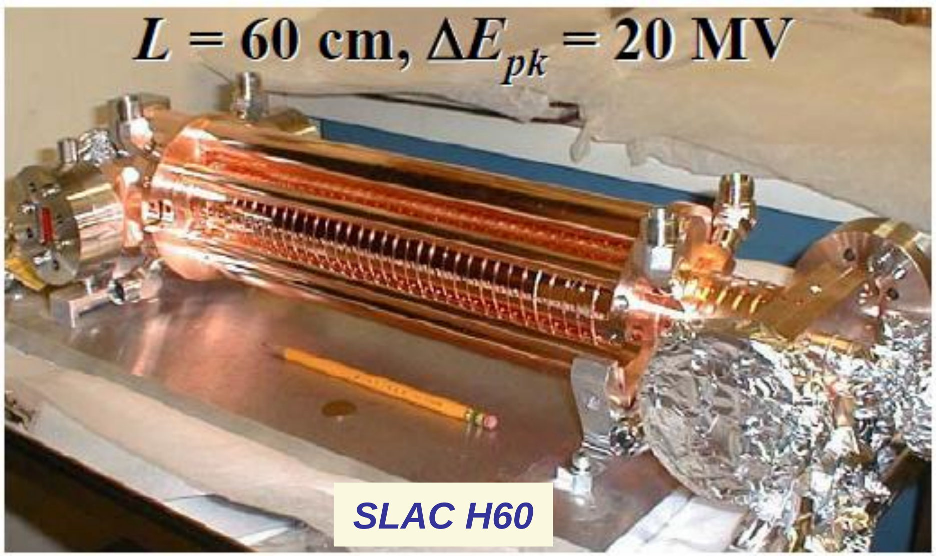


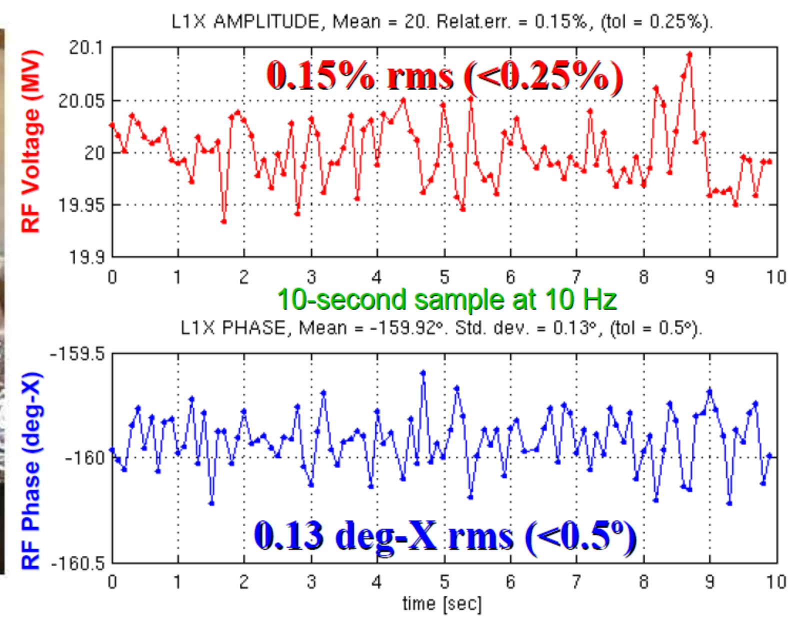
Operating frequency	*9.3 GHz*
Shunt impedance	*145 M Ω/m*
Q factor	*10000*
Peak field at cathode	*160 MV/m*
Power dissipation	*3.5 MW*

Courtesy of A. Valloni, J. Rosenzweig

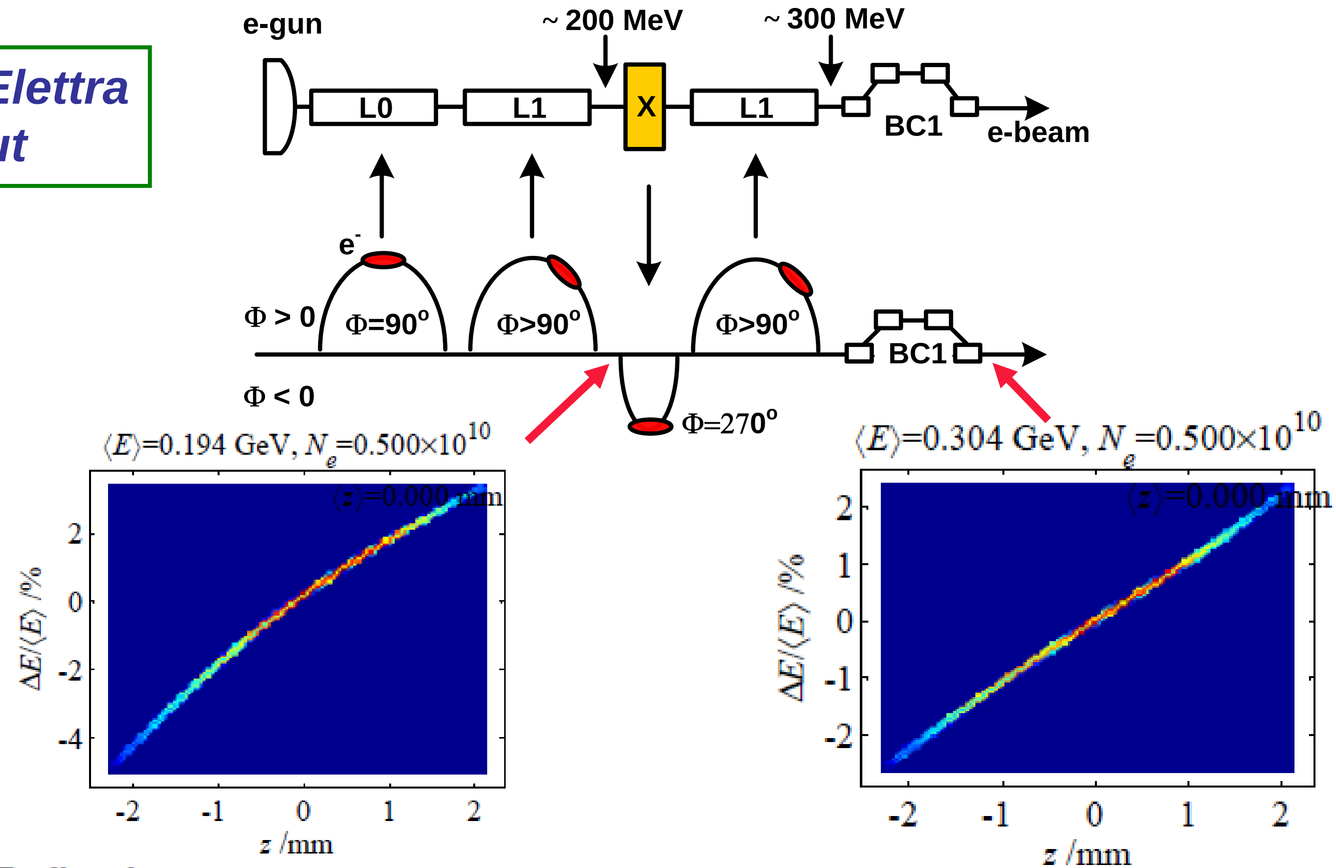
LCLS Linearizer



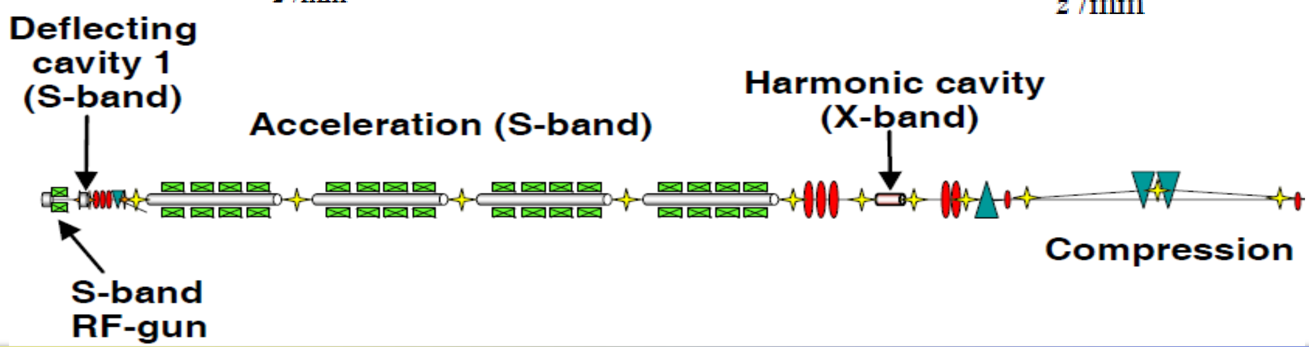




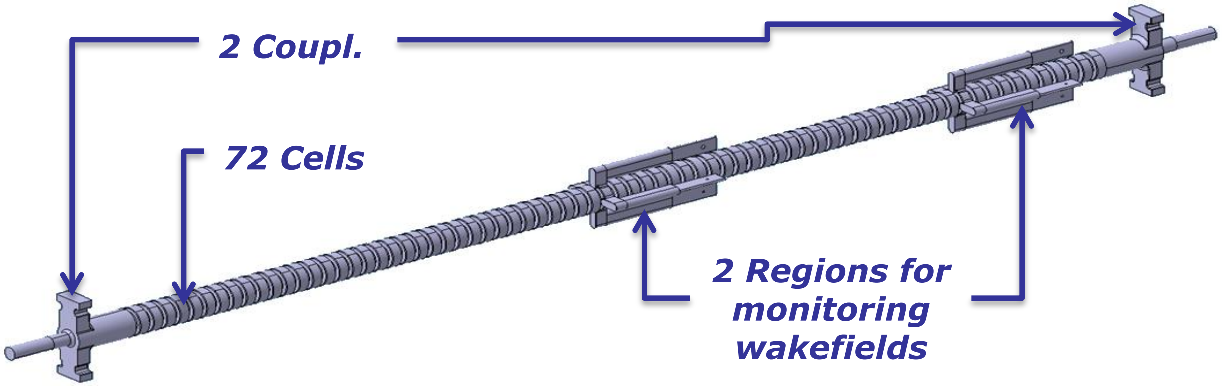
FERMI@Elettra layout

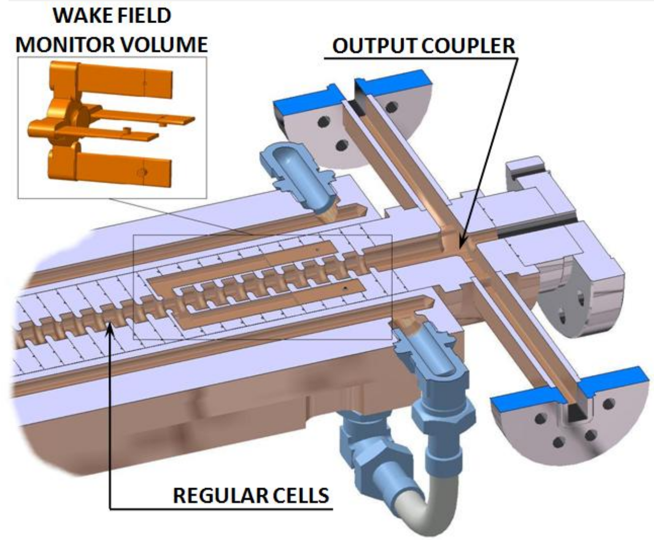


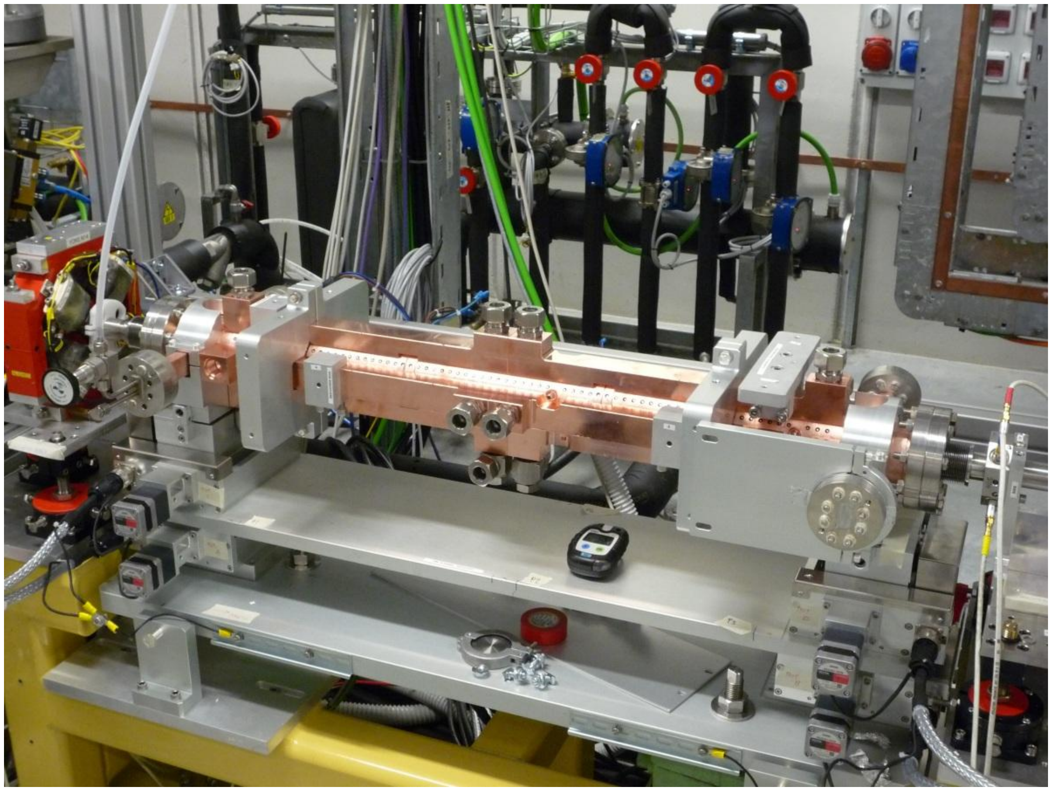
SwissFEL layout



Accelerating Structure

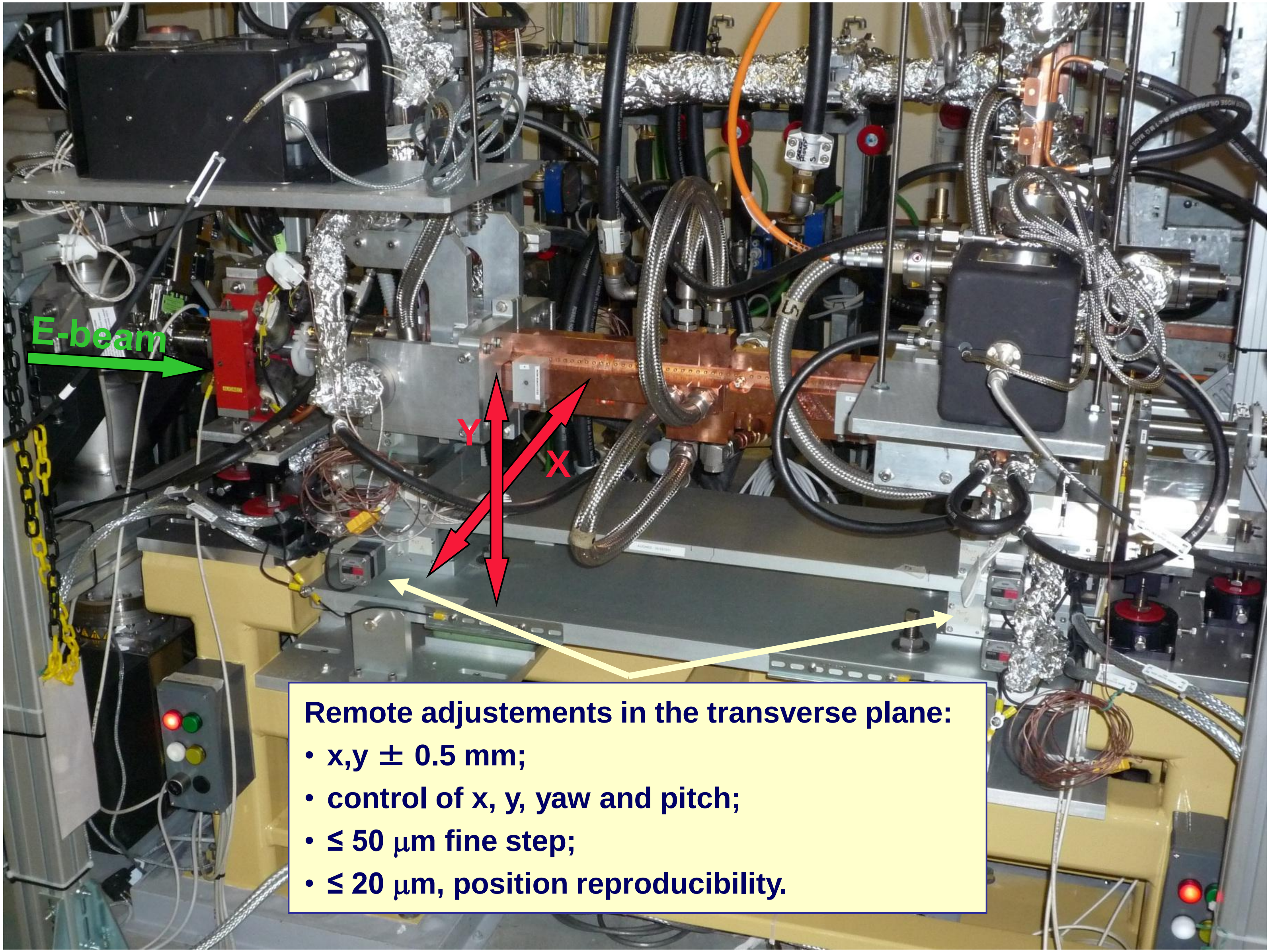






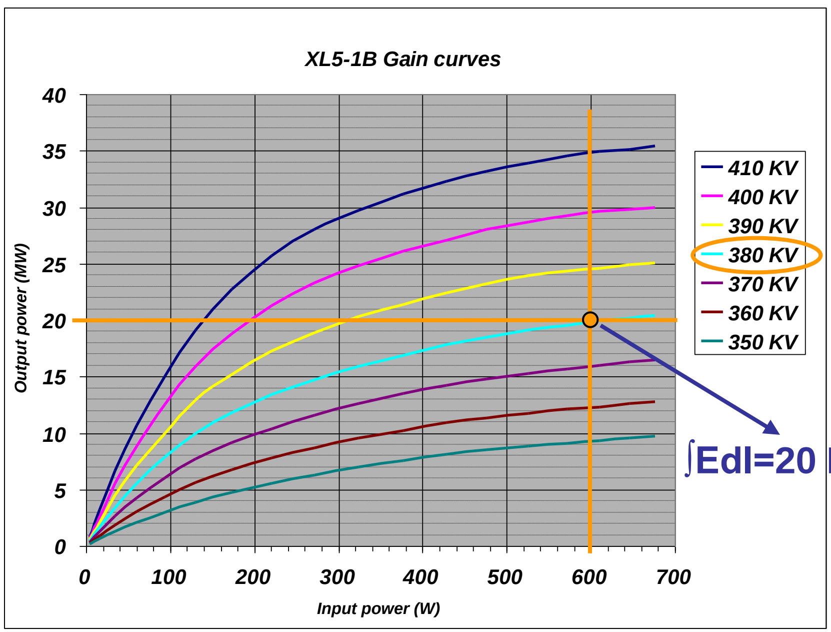
Parameter	Value	Units
Structure type	72 cells, CG, 5/6 π, no HOM damping	
Working frequency	11.992	GHz
Overall length	0.965	m
Active length	0.75	m
Iris diameter (average)	9.1	mm
Group velocity variation	1.6 - 3.7	%
Average grad. with 29 MW RF	40	MV/m
Filling time	100	ns
Pulse repetition rate	50	Hz

FERMI X-band Linearizer



SLAC_XL5 klystron

XL5 main parameters		
RF Frequency	11.992	GHz
RF output power (peak)	≥ 50	MW
Max RF pulse length	1.5	μs
Pulse repetition rate (max)	100	Hz
Gain	≥ 50	dB
Efficiency	≥ 40	%
Klystron voltage (max)	450	KV
Perveance (typ)	1.1	μP
HV pulse length FWHM (max)	3.2	μs



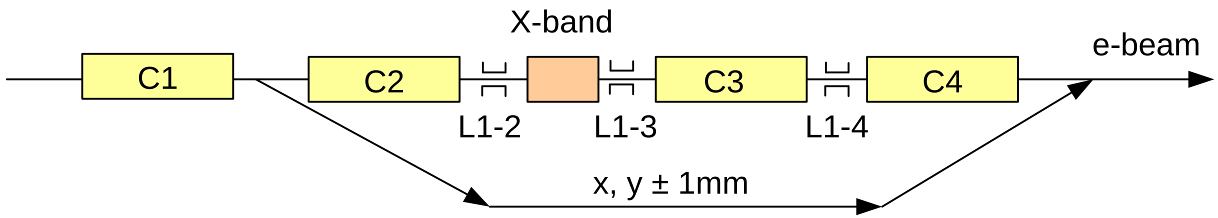
$\int E dl = 20$ MV

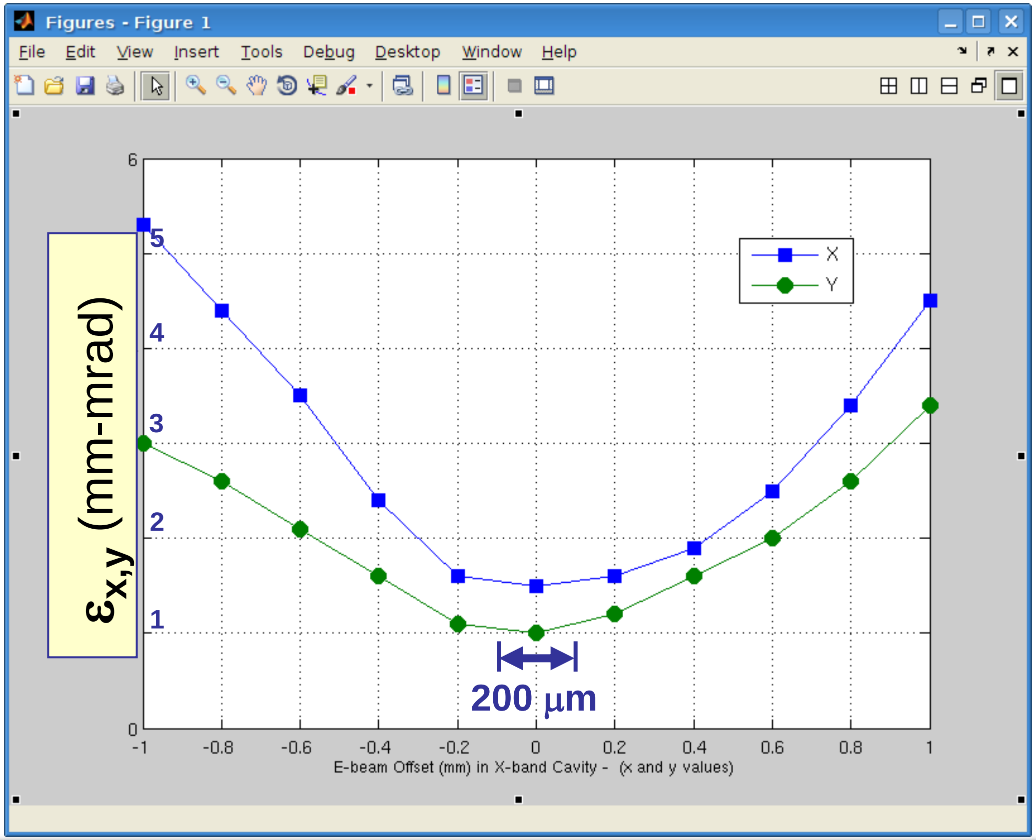
A total of five XL5 tubes assembled:
- 1 for CERN
- 2 for ELETTRA
- 2 for PSI

XL5 Klystron at SLAC

X-band Beam Effects

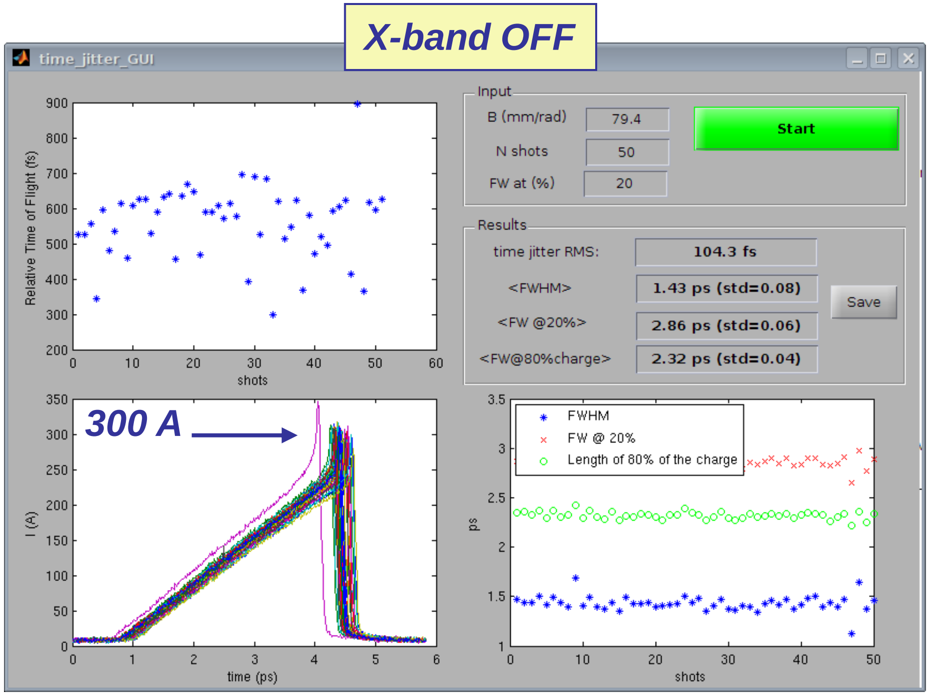
Measured ε_x and ε_y as we moved the beam (6.5 ps_fwhm, 350 pC) along a line from ±1 mm in x-y, through the X-band structure (passive, no RF)

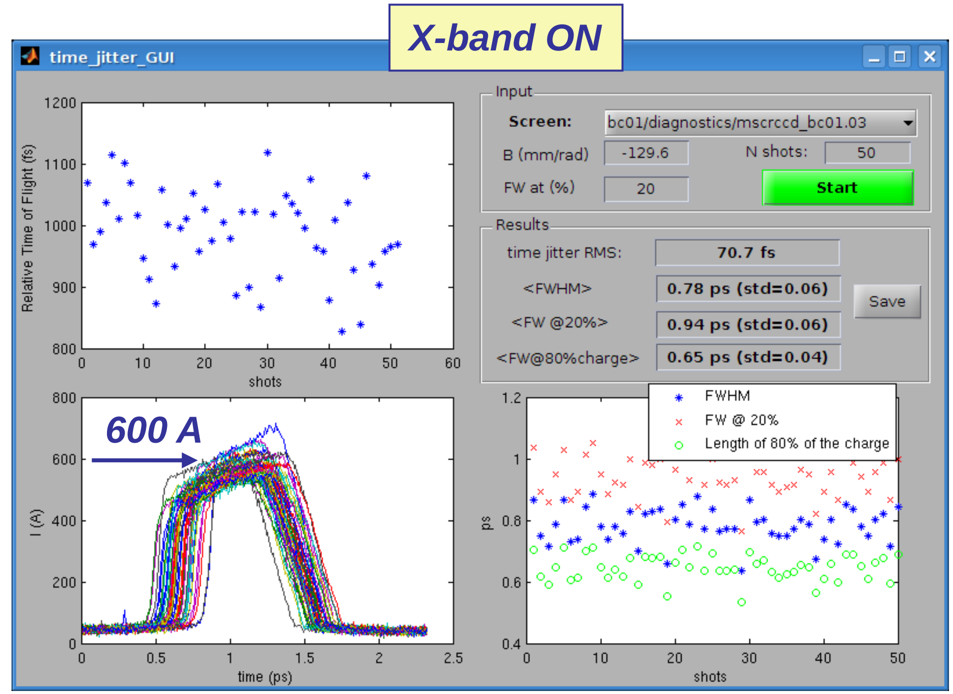




Courtesy of S. Di Mitri

Beam Compression Tests



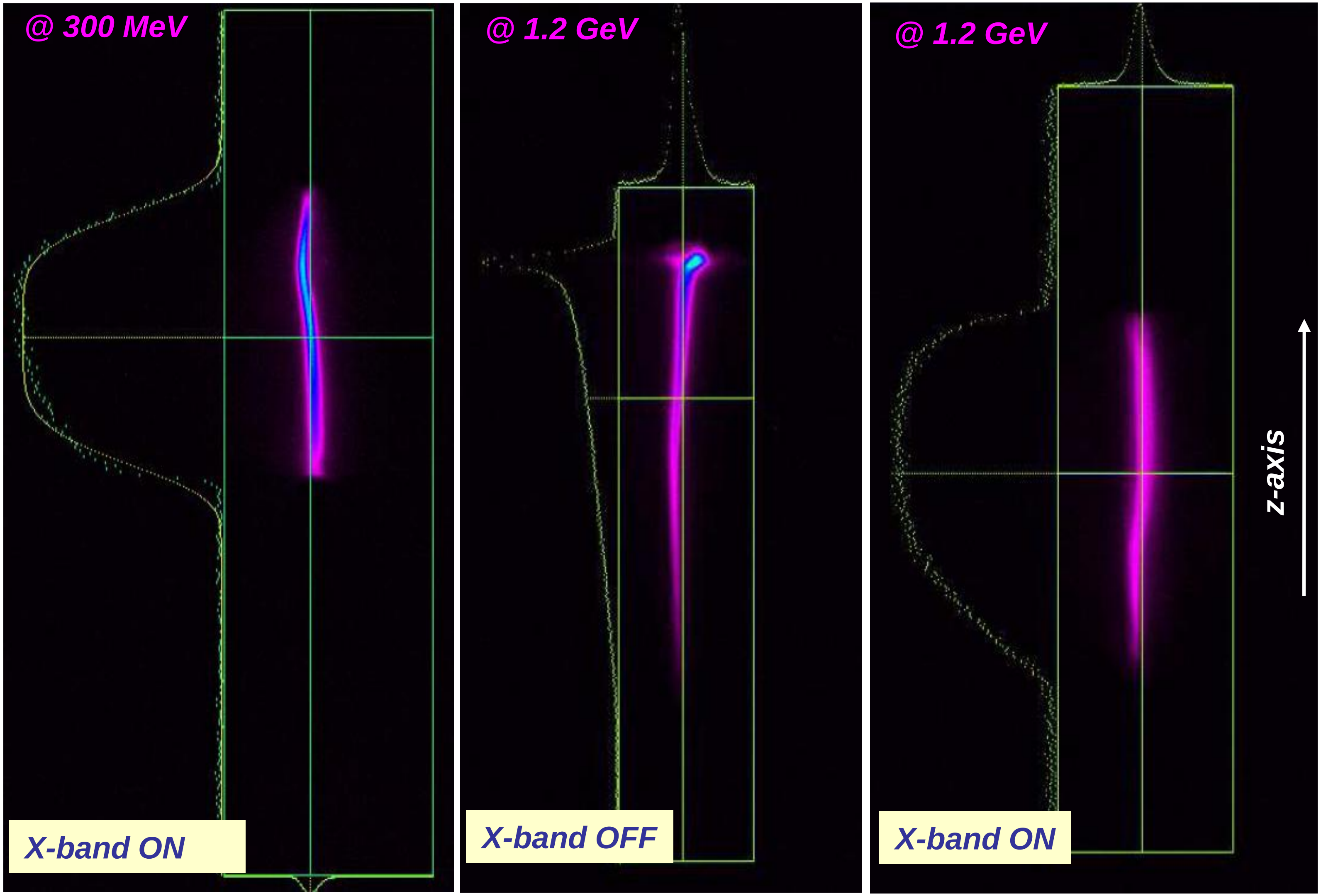


Bunch temporal profiles with and without X-band downstream BC1, using a TDC@300 MeV. Analysis on 50 shots

Courtesy of S. Di Mitri

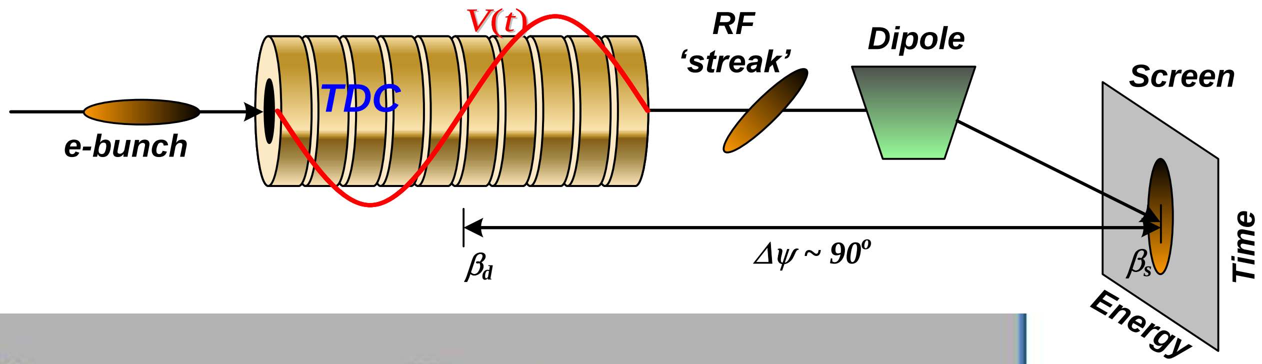
Bunch charge distribution

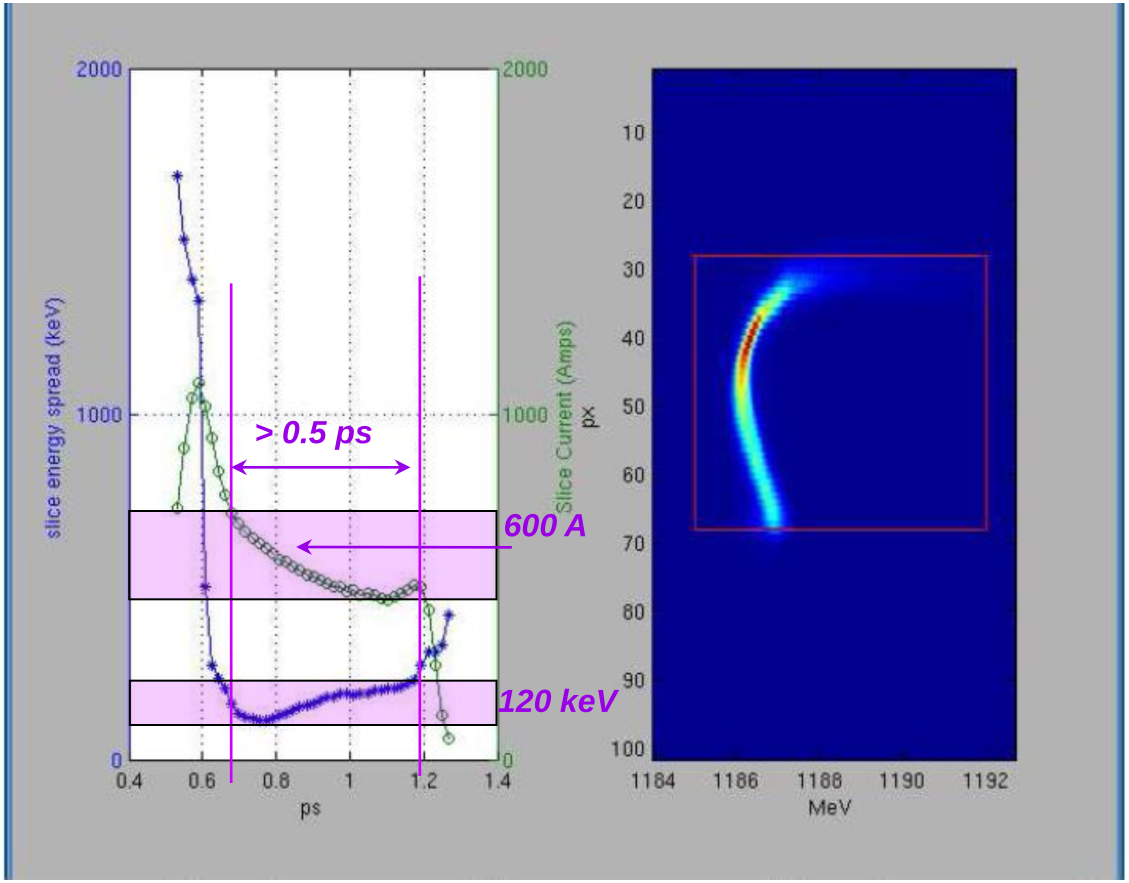
Analysis performed using transverse deflecting cavities @ 300 MeV and 1.2 GeV (note: the vertical coordinate is the z-axis)



Slice Measurements

Slice beam analysis made @1.2 GeV using a high energy TDC

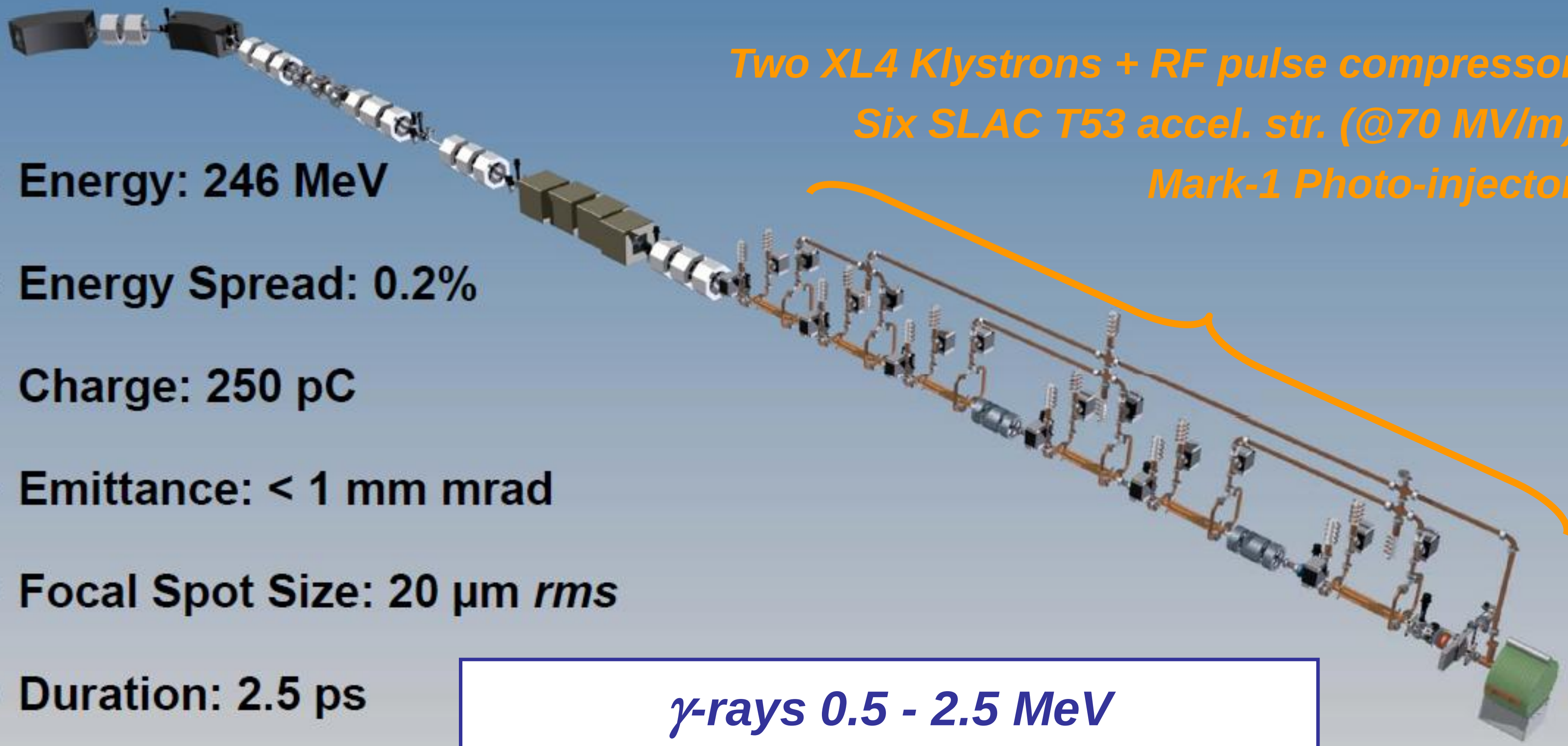




Courtesy of G. Penco

VELOCIRAPTOR 250 MeV X-band Linac

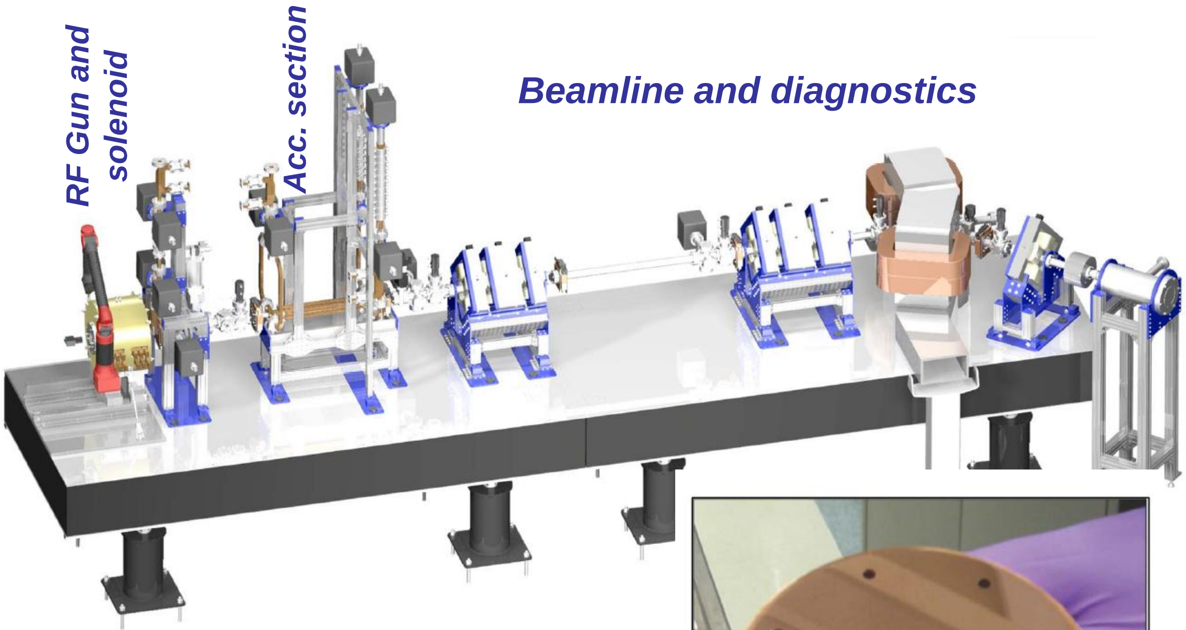
- Energy: 246 MeV
- Energy Spread: 0.2%
- Charge: 250 pC
- Emittance: < 1 mm mrad
- Focal Spot Size: 20 μm *rms*
- Duration: 2.5 ps



γ-rays 0.5 - 2.5 MeV
(10^{20} ph/sec/mm^2/mrad^2/0.1%bw)
for
Nuclear Resonance Fluorescence (NRF)

Courtesy of C. Barty

LLNL X-band test station

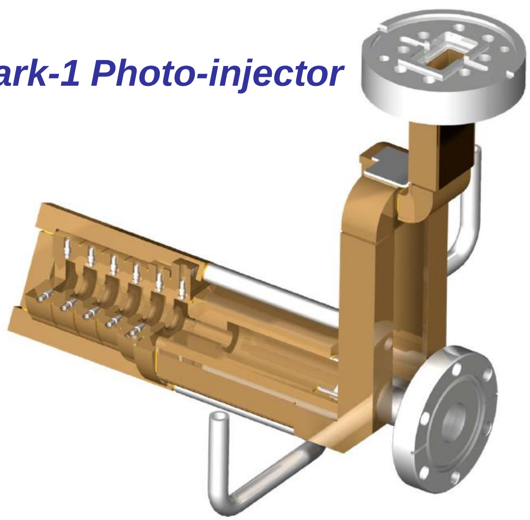


Charge	250 pC
Bunch Duration	2 ps
Bunch Rise/Fall	<250 fs
Normalized Emittance	<1 mm mrad
Gun Energy	7 MeV
Cathode Field	200 MV/m
Coupling β	1.7
Section Gradient	~70 MV/m
Final Energy	30–50 MeV

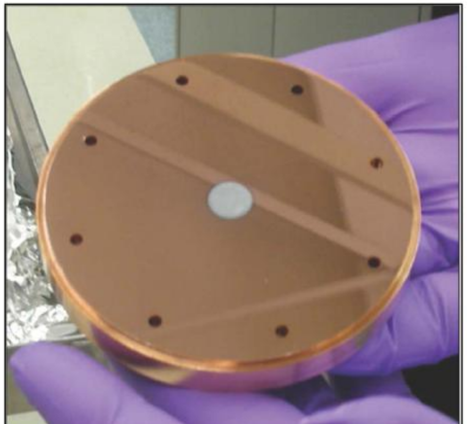
Parameter	Cu Cathode	Mg Cathode
Quantum Efficiency	1.0×10^{-5}	1.0×10^{-4}
Micropulses/macropulse	1000	1000
Micropulse Specifications		
Repetition Rate	11.424 GHz	
Pulse Width	250 fs	
Energy @ 260 nm	5 μJ	0.5 μJ
Energy @ 1040 nm	50 μJ	5 μJ
Energy variation	3%	
Macropulse Specifications		
Repetition Rate	120 Hz	
Pulsetrain Length	87.5 ns	
Energy @ 260 nm	5 mJ	0.5 mJ
Energy @ 1040 nm	50 mJ	5 mJ
Energy variation	1%	

D. Gibson et al., IPAC'12 WEPPD060

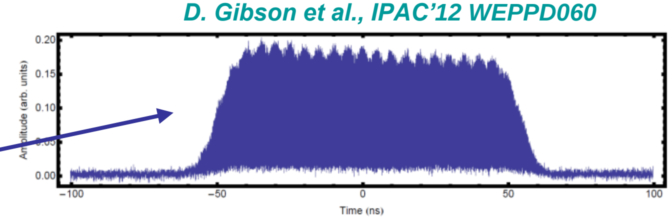
Mark-1 Photo-injector



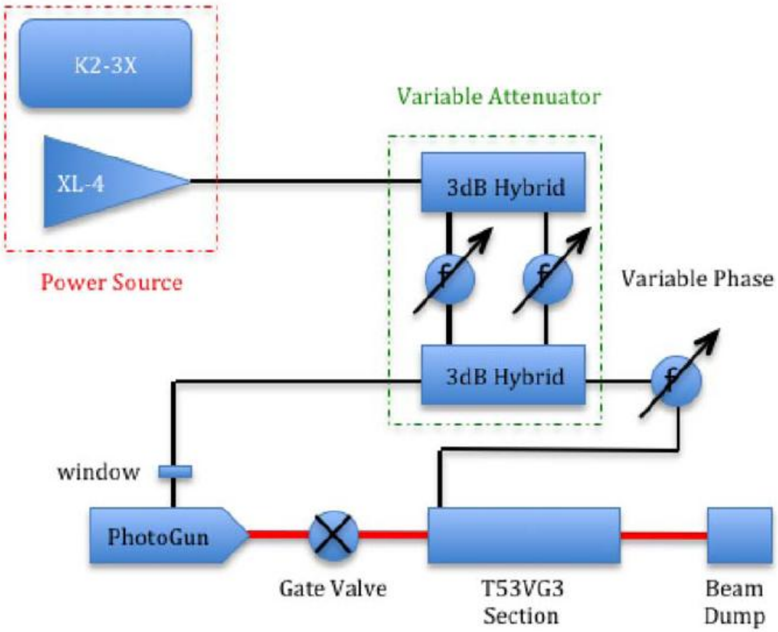
R. Marsh, IPAC'12 THYA02



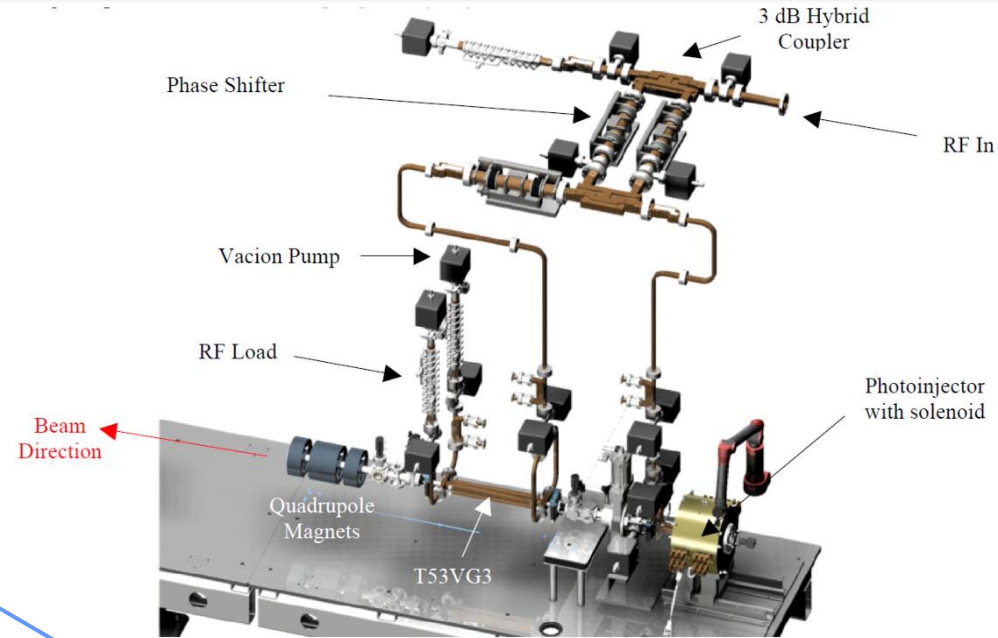
2 µm of Mg is sputtered in a 1 cm diameter spot on the Cu back plane of the photoinjector

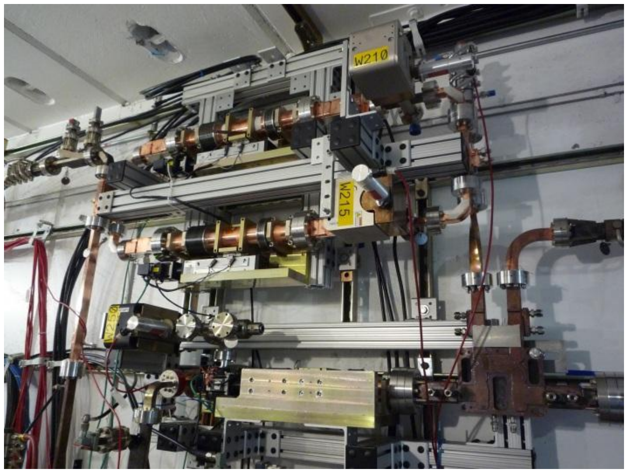


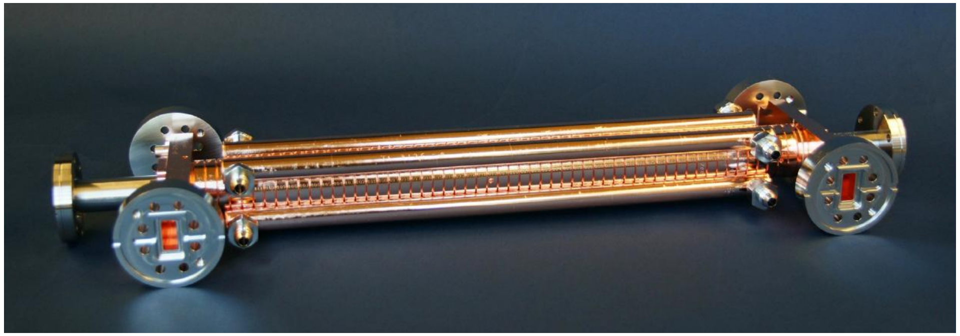
Laser macropulse recorded using a 12 GHz photodiode (100 ns macropulse@1 MHz)



WG distribution layout







SLAC T53 accelerating structure

Existing WG distribution system at XTA

R. Marsh, IPAC'12 THYA02

Industrial and Medical applications

X-band advantages (compared to S-C bands)

- *compactness, reduced weight*
- *ease in handling and control*
- *higher shunt imped./breakdown voltages*
- *shorter filling time*
- *possibility to have "self-shielded machines"*

Main industrial applications:

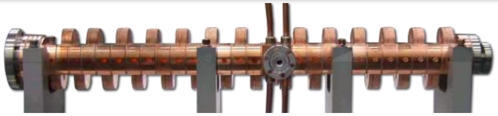
- *on-site inspections*
  i.e. bridges, chemical plants, pipe lines
- *non-destructive analysis*
  cargo screening, food processing

Medical applications

- *Intra-Operative Radiation Therapy (IORT)*
- *Stereotactic Radiosurgery*

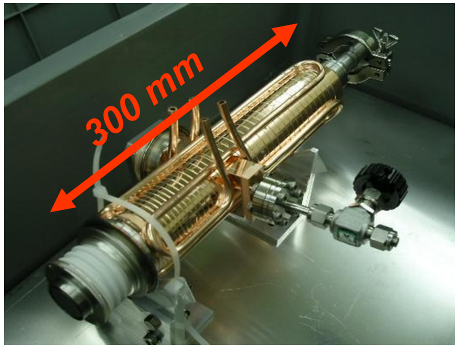
Considered also for Hadrontherapy

- *"single room facilities" with the proton linac rotating around the patient*



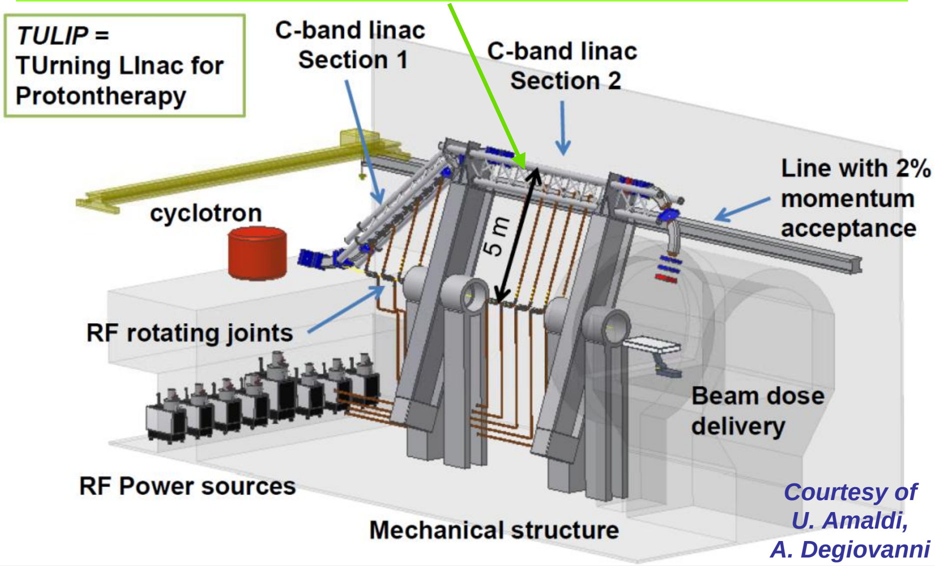
50 cm, 6 MeV 9.3GHz linac for Micro-beam Pinpoint 4-dimensional Therapy System

950 keV linac for on-site inspections



Courtesy of M. Uesaka

An option with X-band is also being considered



Courtesy of U. Amaldi, A. Degiovanni

Conclusion

- ***X-band technology in linacs is rapidly expanding due to its great potential already shown in different areas of particle acceleration.***
- ***Recent results (CLIC) regarding accelerating gradients demonstrate the feasibility of 100 MV/m operation with NC accelerating structures at 12 GHz.***
- ***The development of very high brightness X-band photo-injectors are very promising (SLAC,UCLA)***
- ***Very challenging R&D programs with X-band linacs have been undertaken to increase the average power of the machines - multibunch operations (LLNL-SLAC).***
- ***The use of X-band structures for diagnostics and beam manipulation at FEL linacs is continuously evolving (SLAC, PSI, ELETTRA).***
- ***In the last two years the interest of industry in the X-band technology has grown significantly: two 50 MW, 12 GHz klystrons are currently at an advanced stage of manufacturing.***

Acknowledgements

Thanks to:

U. Amaldi, S. Döbert, A. Degiovanni, J. Kovermann, G. McMonagle, I. Syratchev, W. Wuensch (CERN)

C. Adolphsen, C. Limborg, P. Krejcik, T. Raubenheimer, S. Tantawi, A. Vlieks (SLAC)

C. Barty, R. Marsh (LLNL)

J. Rosenzweig (UCLA)

A. Valloni (UCLA - Univ. "La Sapienza" Rome)

B. Spataro (INFN-LNF)

M. Uesaka (University of Tokyo)

E. Tanabe (AET Inc.)

A. Tafo (Accuray)

F. Manelli (Elekta)

for providing me the material for this presentation

The members of linac group and Fermi commissioning team (Elettra-Sincrotrone Trieste)