OVERVIEW OF FELS UNDER CONSTRUCTION INCLUDING FELS AT

Giuseppe Penco

Acknoledgement

- T. Shintake and Spring-8 team
- L. Giannessi, M. Ferrario and SPARC team
- FERMI@Elettra commissioning team

Reference:

[1] "Conceptual Design Report" for the FERMI@Elettra project (2007).
[2] P .Emma, LCLS-TN-01-1, November 14,2001.
[3] Z. Huang et al., Phys. Rev. ST Accel. Beams 13, 020703 (2010).
[4] P. Craievich at al., Proc. of the DIPAC 2007 conference.
[5] M.Cornacchia et al., Phys. Rev. ST Accel. Beams 9, 120701 (2006).
[6] G. Penco et al., Proc. of EPAC 2008 Conf., Italy
[7] G. Penco et al., Proc. of IPAC 2010, TUOARA02, Kyoto, Japan. 555-559.
[8] S. Di Mitri et al., Proc. of the FEL 2010 Conf., Malm ¨ o, Swe- den.
[9] M. Veronese et al., Proc of the FEL 2010 Conf., Malm ¨ o, Sweden.
[10] E. Allaria et al., Proc of FEL 2009 conference, Liverpool, UK.
[11] D. Alesini et al., Nucl. Instrum. Methods Phys. Res., Sect. A 507, 345 (2003).
[12] L. Giannessi et al. Nuclear Instruments and Methods in Physics Research Section A, Vol. 593, Issue 1-2, p. 132-136.
[13] M. Ferrario et al., "Recent results of the SPARC FEL ex- periments", Proc. of the FEL 2009 conference, Liverpool, UK.
[14] L. Poletto et al., EUROFEL-Report-2005-DS4-008 (2005), https://www.eurofel.org/e693/e1009/.
[15] L. Palumbo et al., "Status of SPARX Project", Proc. of the FEL 2009 conference, Gyeongju,Korea.
[16] M. Ferrario et al., Phys. Rev. Lett. 104, 054801 (2010).
[17] D. Alesini et al., Proc of DIPAC 2009, Basel, Switzerland.
[18] L. Giannessi et al.,"FEL EXPERIMENTS AT SPARC: OP- ERATION IN SEEDED AND CHIRPED MODE", Proc. of the FEL 2010 conference, Malmo, Sweden.
[19] L. Giannessi et al.,"FEL EXPERIMENTS AT SPARC: SEEDING WITH HARMONICS GENERATED IN GAS", Proc. of the FEL 2010 conference, Malmo, Sweden.
[20] A.Bacci et al., Nuclear Instruments and Methods in Physics Research Section A, Vol. 608, Issue 1, Supplement 1, Pages S90-S93, 2009.
[21] D. Filippetto et al., "Velocity bunching experiment at SPARC", Proc. of the FEL 2009 conference, Liverpool, UK.
[22] E. L. Saldin, E. A. Schneidmiller, and M.V. Yurkov, PRST- AB 9, 050702 (2006)
[23] T. Shintake and XFEL/SPring-8 Joint Team, "Status report on Japanese XFEL construction project at SPring-8", Proc. of the IPAC 2010, Japan.
[24] K.Togawa et al., Phys. Rev. ST Accel. Beams 10, 020703 (2007).
[25] C. Lejeune and J. Aubert, in Applied Charged Particle Op- tics, edited by A. Septier, Advances in Electronics and Elec- tron Physics Supplement 13A (Academic Press, San Diego, 1980), pp. 159 259.
[26] T. Shintake et al., Nature Photonics, Vol. 2, Sept. 2008, pp. 555-559.
[27] T.Shintake et al., "Compact Klystron modulator for XFEL/SPring-8", Proc. of the IPAC 2010, Japan.
[28] T. Hasegawa et al., "Status of precision temperature reg- ulation system for C-band accelerator in XFEL/SPring-8", Proc. of the IPAC 2010, Japan.
[29] H.Hanaki et al., "Construction of Injector System for SPring-8 X-FEL",Proc. of this conference.

FERMI@Elettra project

Accelerator Layout, e-beam param. and undulators have been choosen to allow:

- Multiple FEL schemes -> maximize number and type of experiments
- Flexible FEL output -> output tuning
- Machine upgrades -> shorter wavelengths

Electron bunch:

- E=1.5GeV
- Ipeak =800A
- FW=1ps
- ε_{slice} = 1 mm mrad
- $\sigma_{E,slice}$=150keV

Seeded FEL utilizing HGHG:

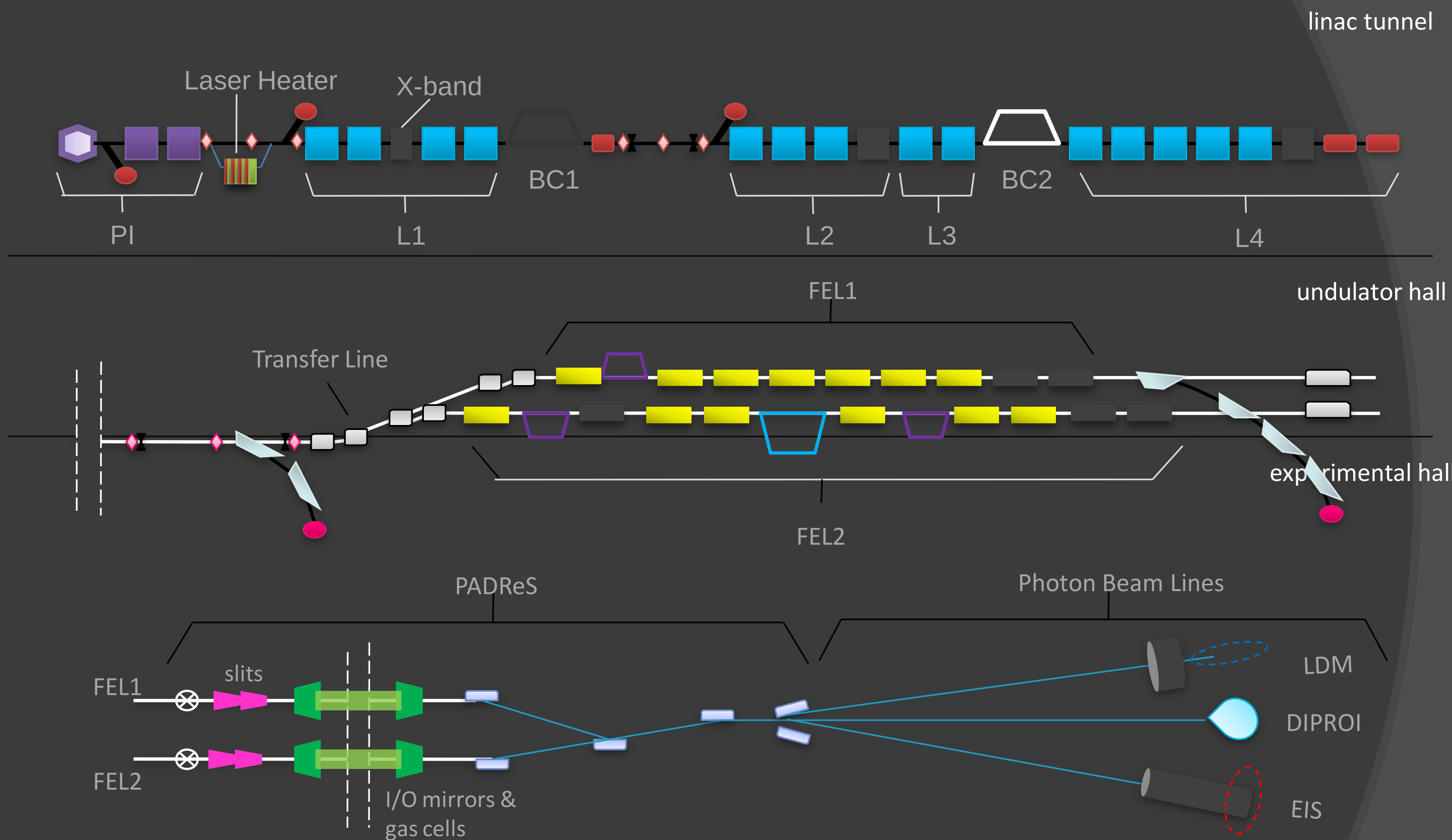
Parameters	**FEL-1**	**FEL-2**
HGHG stages	1	2 (fresh bunch in 2nd stage)
λ range (nm)	**80 to 20**	**20 to 4 (1.4 at 3rd harm.)**
RMS pulse length (fs)	< 100	20-100 (<10 future goal)
RMS Bandwidth (meV)	17 @40nm	100 @4.2nm
Polarization	**Fully variable**	**Fully variable**
Repetition rate (Hz)	50	50
Peak Power (GW)	1 to >5	0.5-2
Harm. P_{peak} (% of fund.)	~2%	~0.2% (@4.2nm)
Photons per pulse	10^{14} (@40nm)	$2*10^{12}$ (@4.2nm)
Pulse-to-pulse stability	<30%	~40%
Pointing stab (μrad)	<20	<20
Virtual waist size (μm)	250 @40nm	120
Divergence (rms) μrad	50 @40nm	10 @4.2nm

Civil Engineering

- Civil Construction
  - "Linac Building Extension" completed
  - "Main FERMI" construction began 25 March 2009
    - *Completed by June 2010*
    - *FEL1 beamline installed in Aug. 2010*
    - *FEL1 undulators will be installed in Oct-Nov. '10*

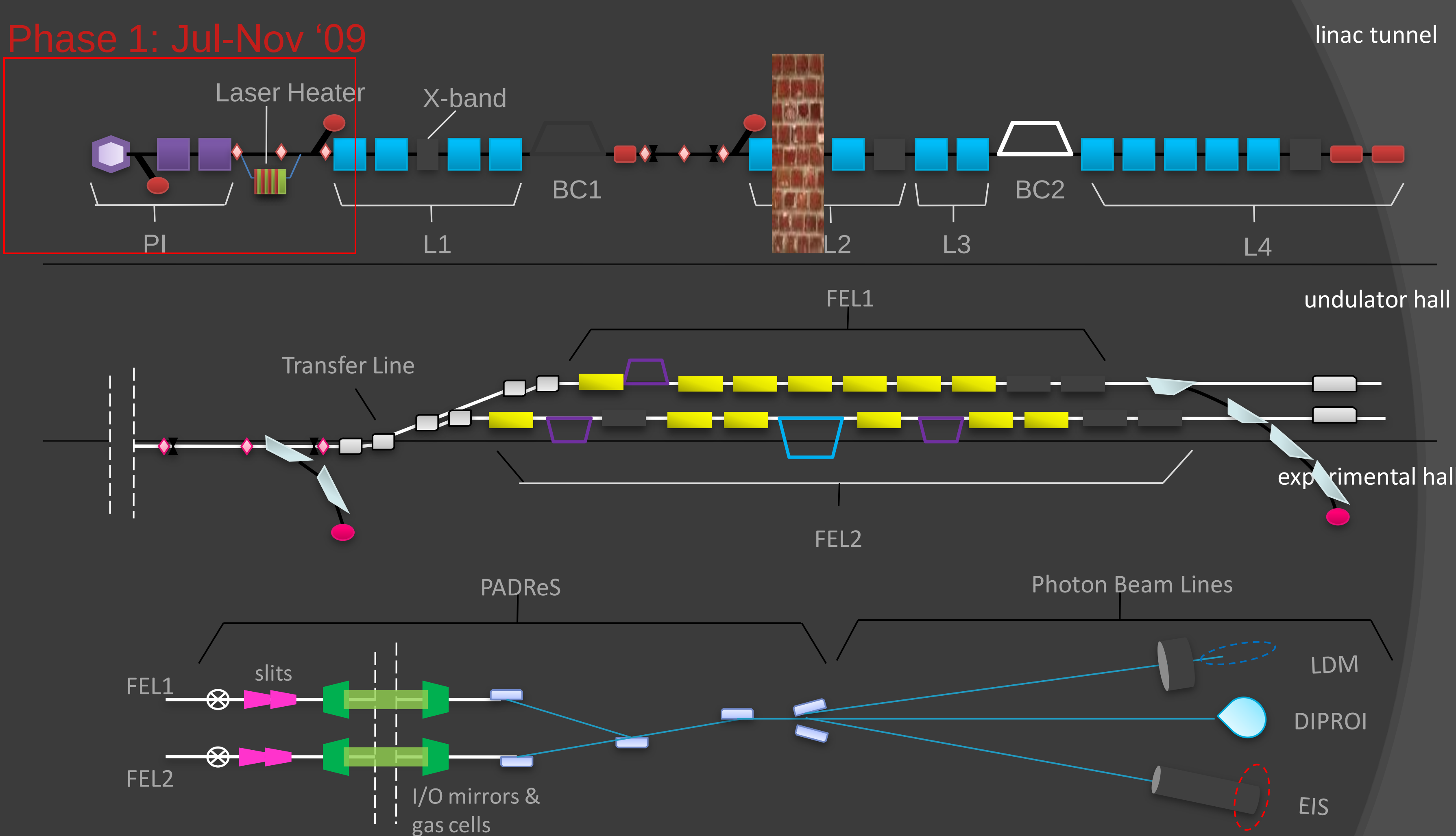
(ref. S. Noe')

FERMI-FEL1 commissioning



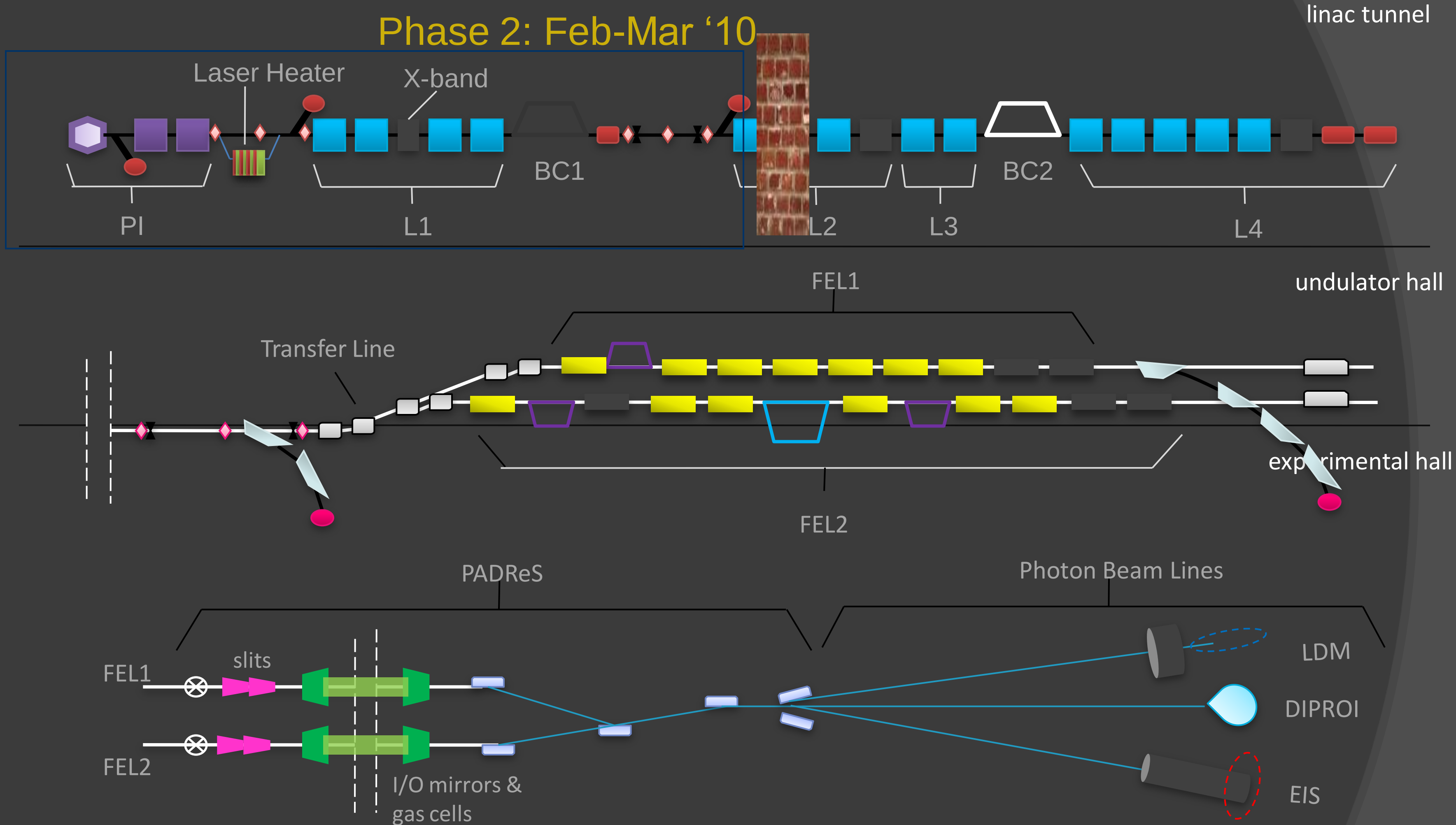
G. Penco

FERMI-FEL1 commissioning

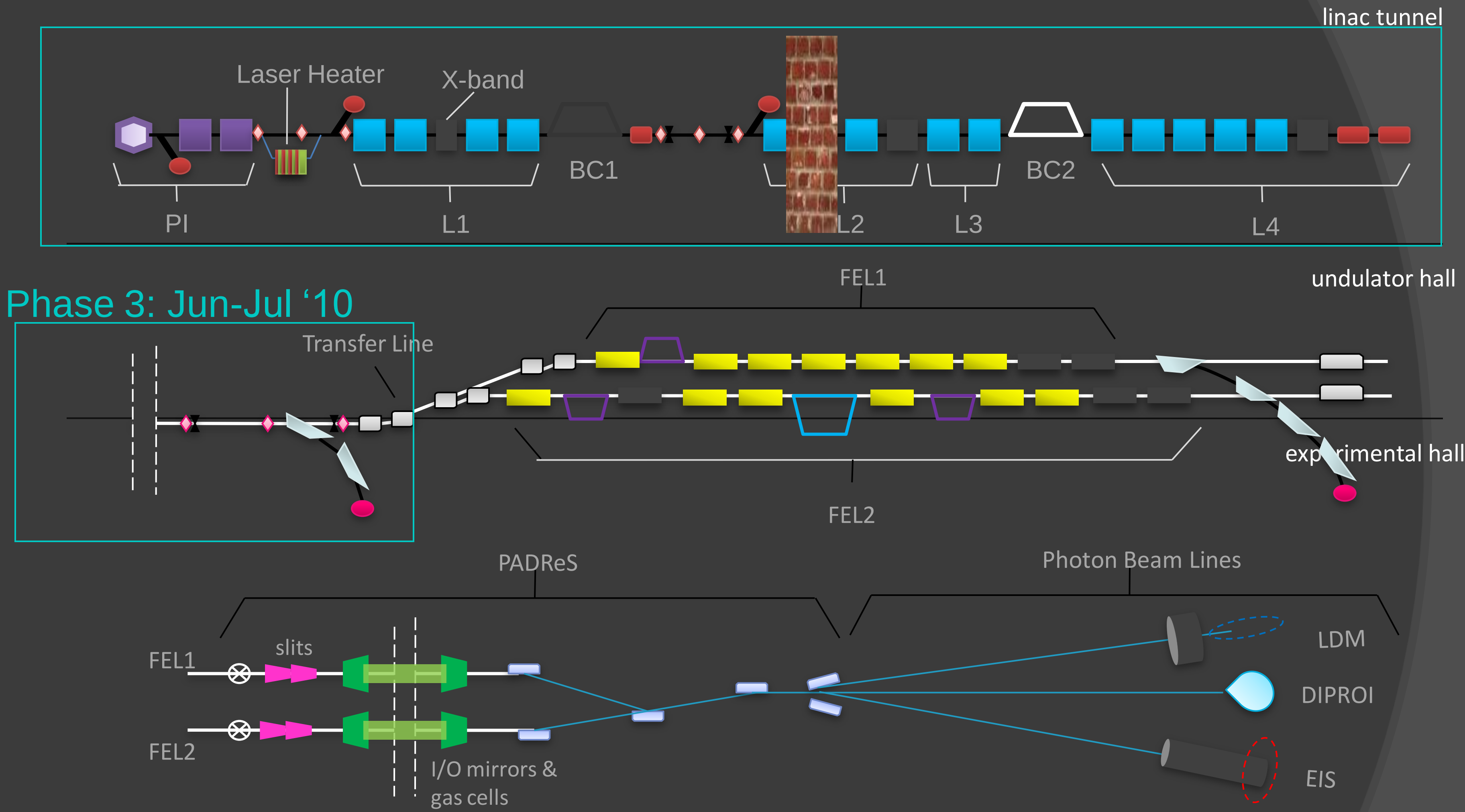


G. Penco

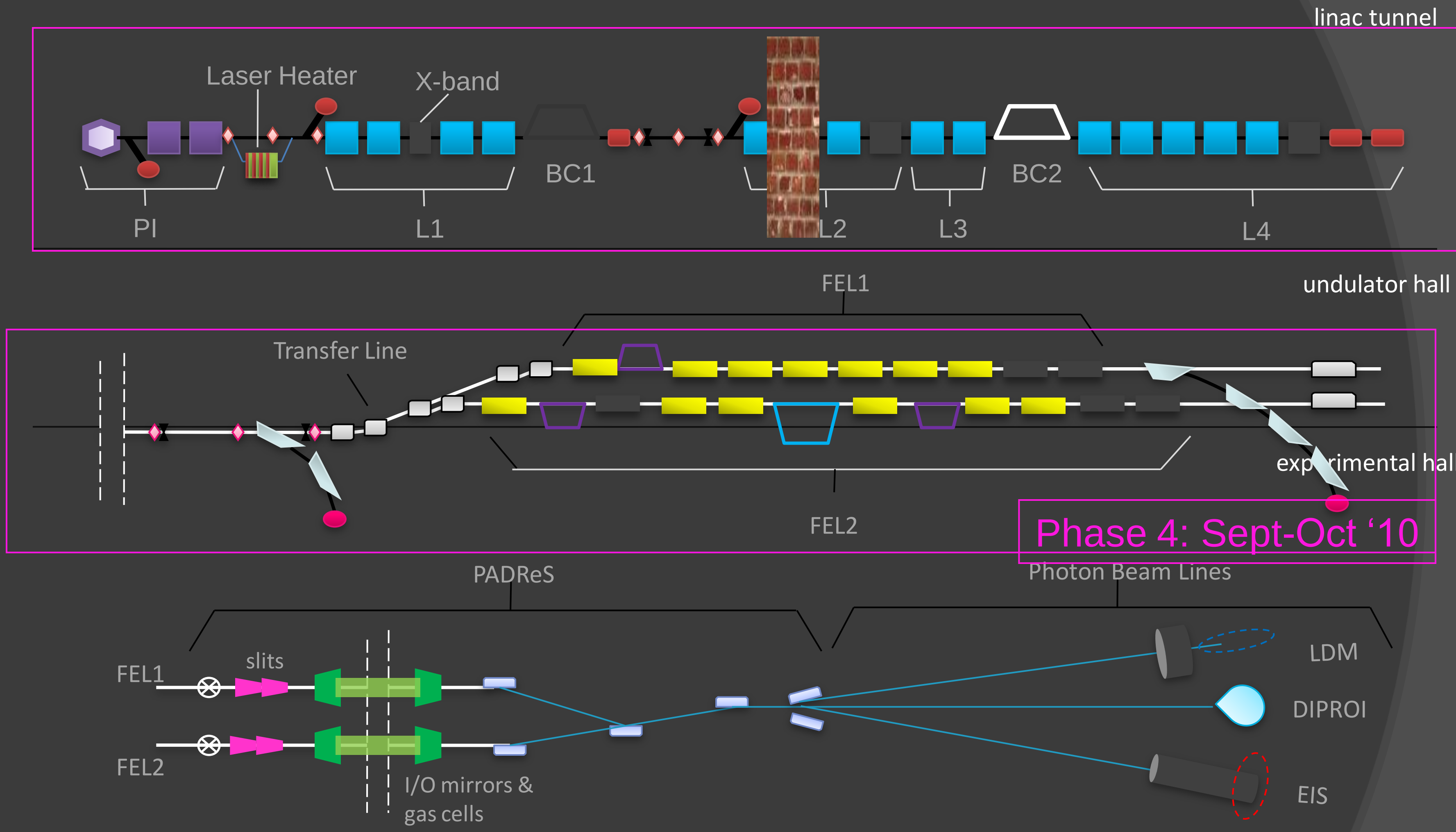
FERMI-FEL1 commissioning



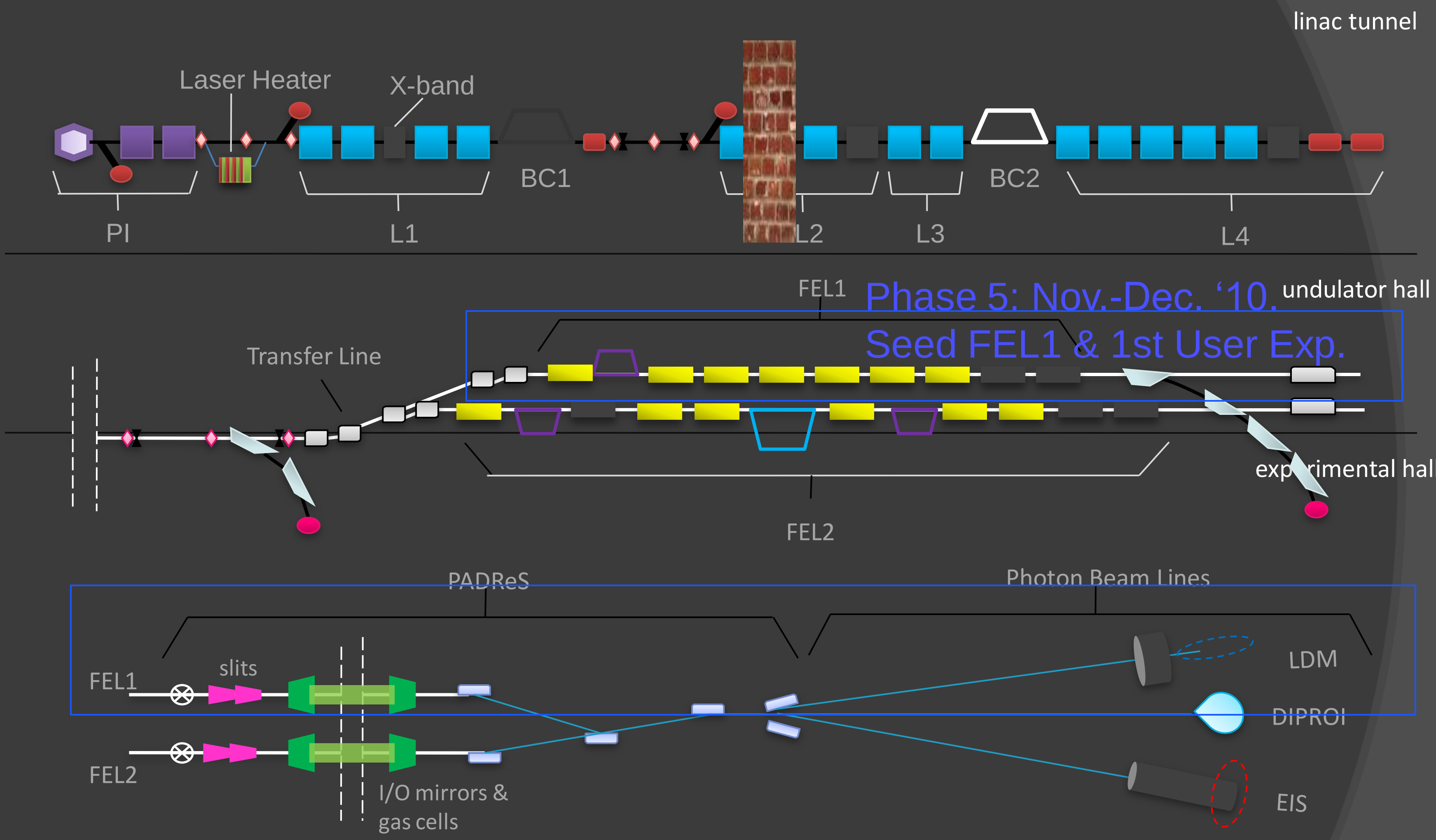
FERMI-FEL1 commissioning



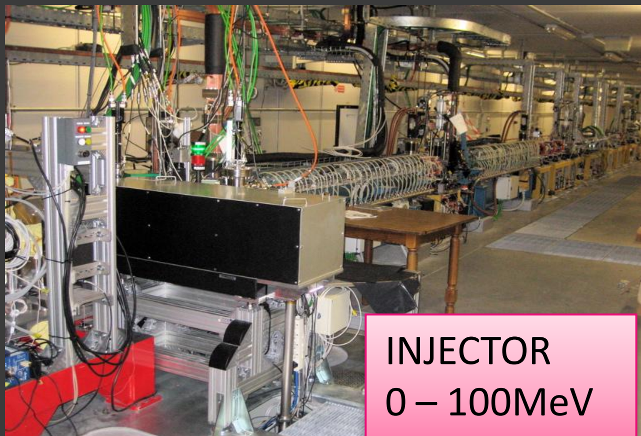
FERMI-FEL1 commissioning



FERMI-FEL1 commissioning



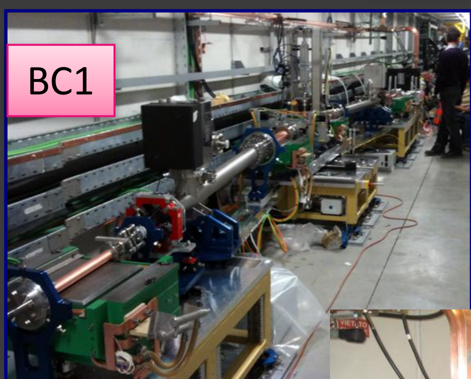
Accelerator



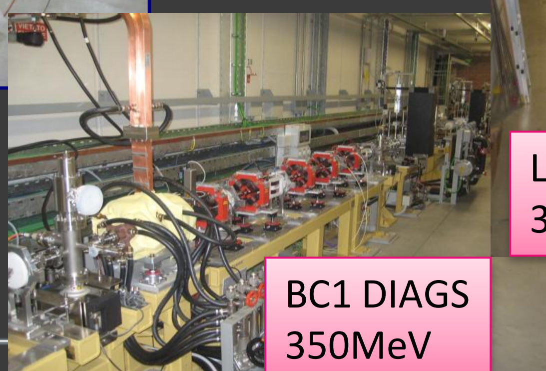
INJECTOR
0 – 100MeV

LASER HEATER
100MeV

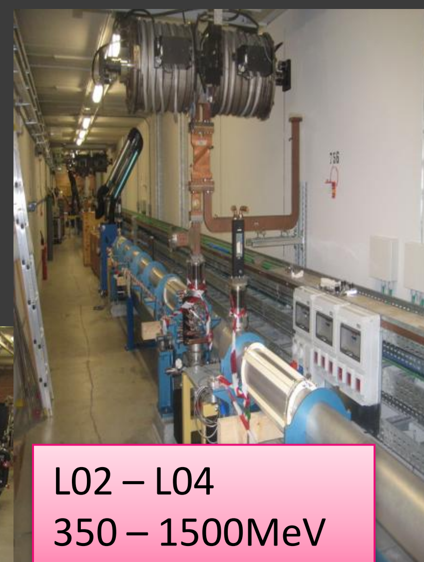
L01
100 – 350MeV



BC1



BC1 DIAGS
350MeV



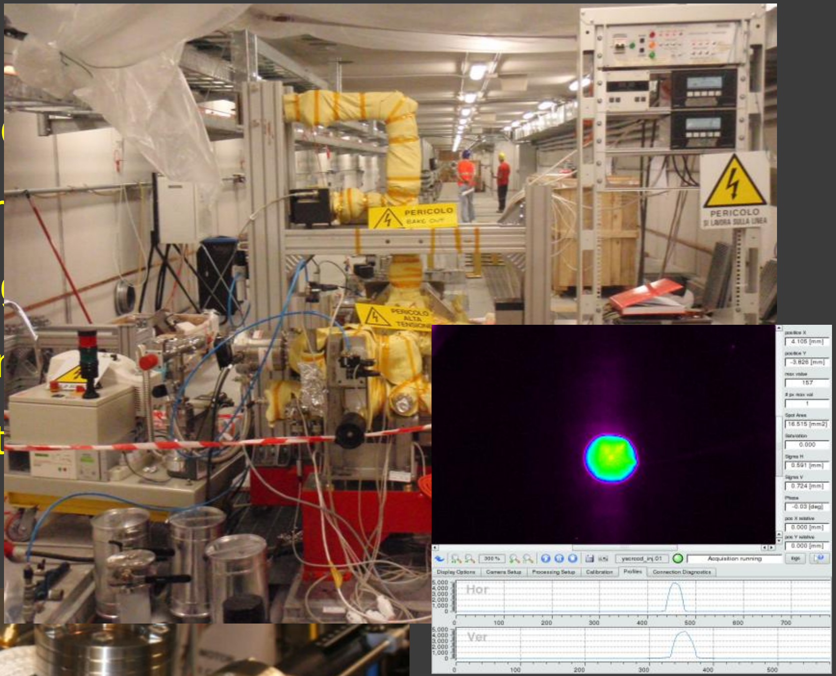
L02 – L04
350 – 1500MeV

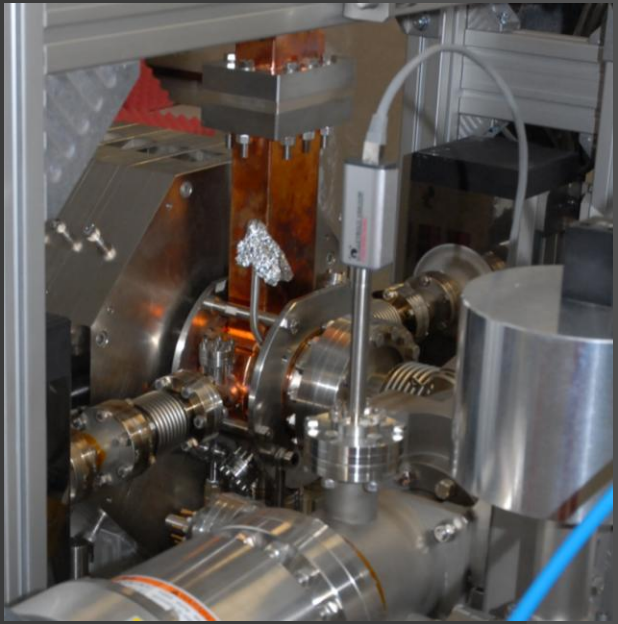
FEL1 beamline

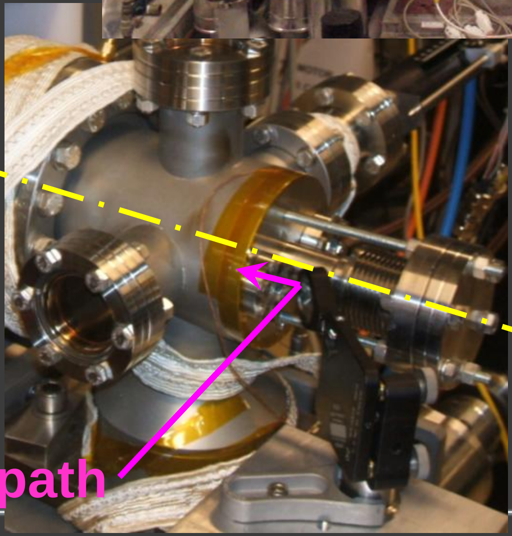
1.6 cell RF gun

MILESTONE:

- Oct. 2006 coll. U
- 03/19/08: Gun ar
- 03/08 - 04/09: Hi
- 05/09: installatior
- 19th Aug. 09: 1st







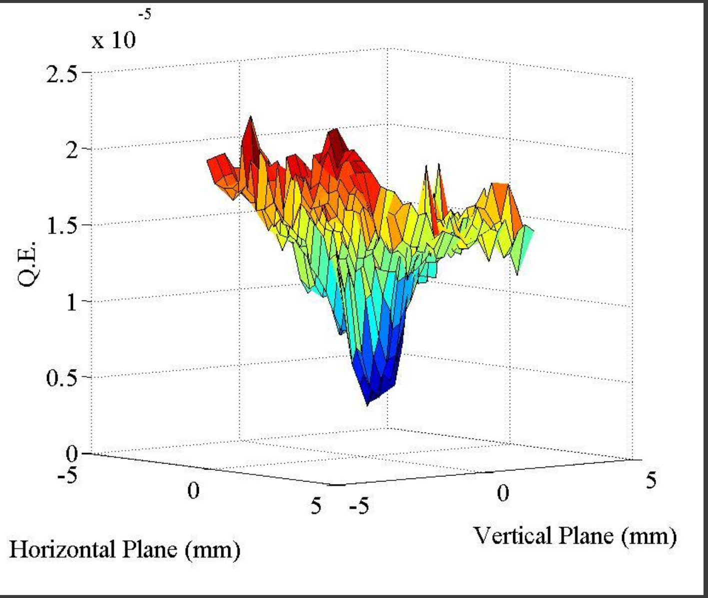
e$^-$ beam axis

Laser path

Keep out the chamber the last UV mirror.
Wakefields effects studied: negligible
<u>Advantage:</u>
The twin windows are useful for the laser pre-alignment

Cu cathode Q.E.

Ref: M.Trovo'

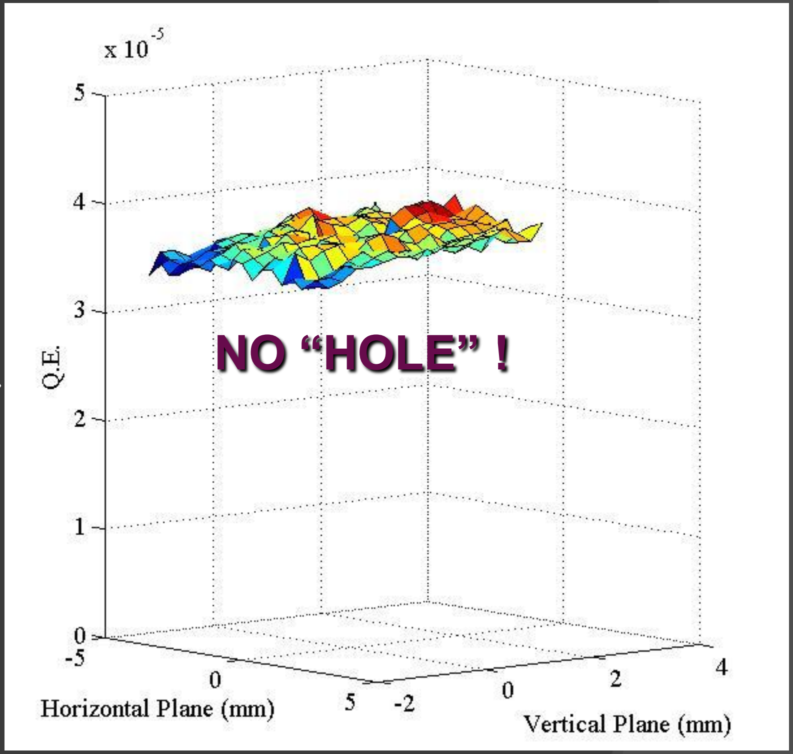


In Aug. 2009 Q.E. ~ 3e-5, which deteriorated progressively after few weeks of operation.

After 3 months with 250μJ, a 200pC bunch was extracted (@ -30deg)

During the shut-down, a cleaning procedure was performed: venting the RF gun with Ozone gas for few hours and baking out for 2 days

The Q.E. degradation re-appeared but with a slower rate: after 2 months lost "only" a factor 2.

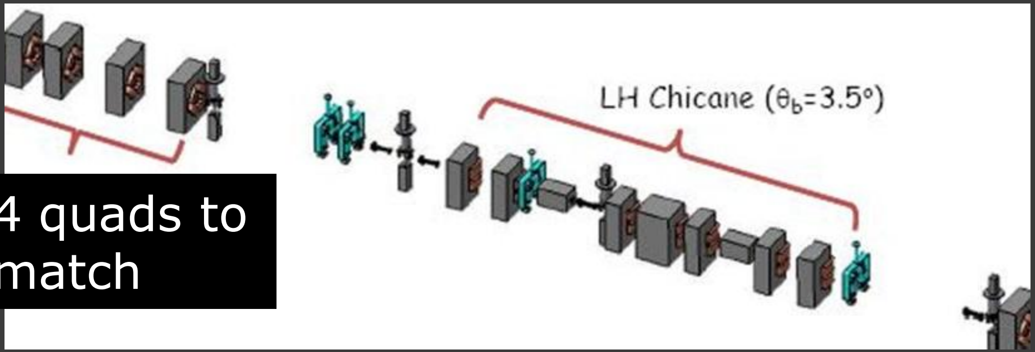


Low charge option

In order to have by Dec. 2010 the first Seeded-FEL radiation at 60nm (without BC2 and X-band cavity):

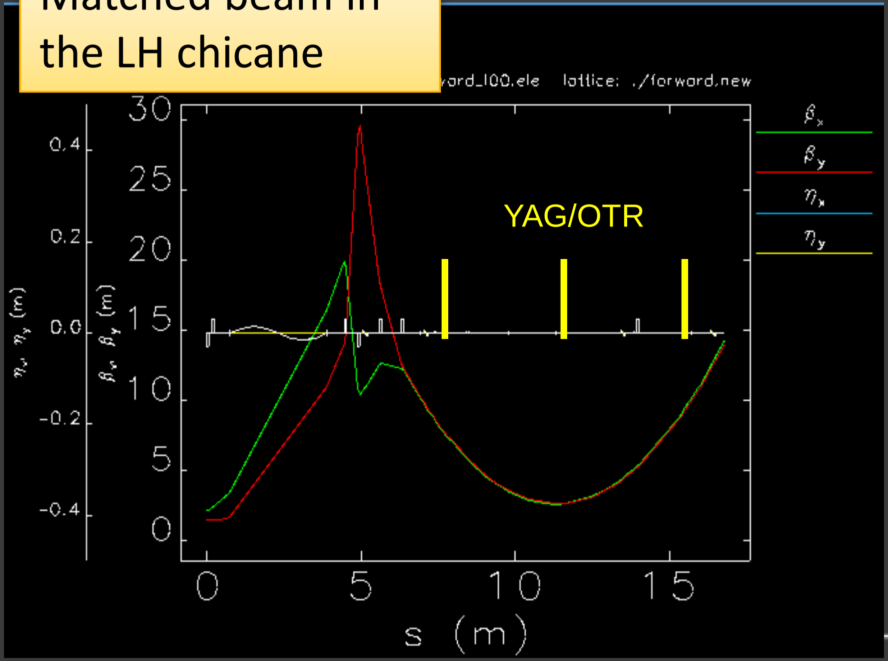
- Q=250pC
- Laser: 5ps (full width), Flat-top (diam=1.3mm)
- Bunch compressed a factor ~5, (full width~1ps) at 1.2GeV, ε_{slice}<1.5 mm mrad, $\sigma_{E,slice}$<400 keV

100-MeV diagnostics station



4 quads to match

Matched beam in the LH chicane



- Measure Twiss parameters and the projected emittance.
- Optimization by changing the gun solenoid, RF phase, etc.
- Use ELEGANT to match the real beam to the nominal machine optics (Matlab tool): after few iteration the matching procedure converge

Mismatch in LH:

X= 1.005 ± 0.003 ; Y= 1.001 ± 0.002

Mismatch in BC1:

X= 1.030 ± 0.004 ; Y= 1.117 ± 0.124

Normalized emittance (~100%):

Best found: 0.90 mm mrad

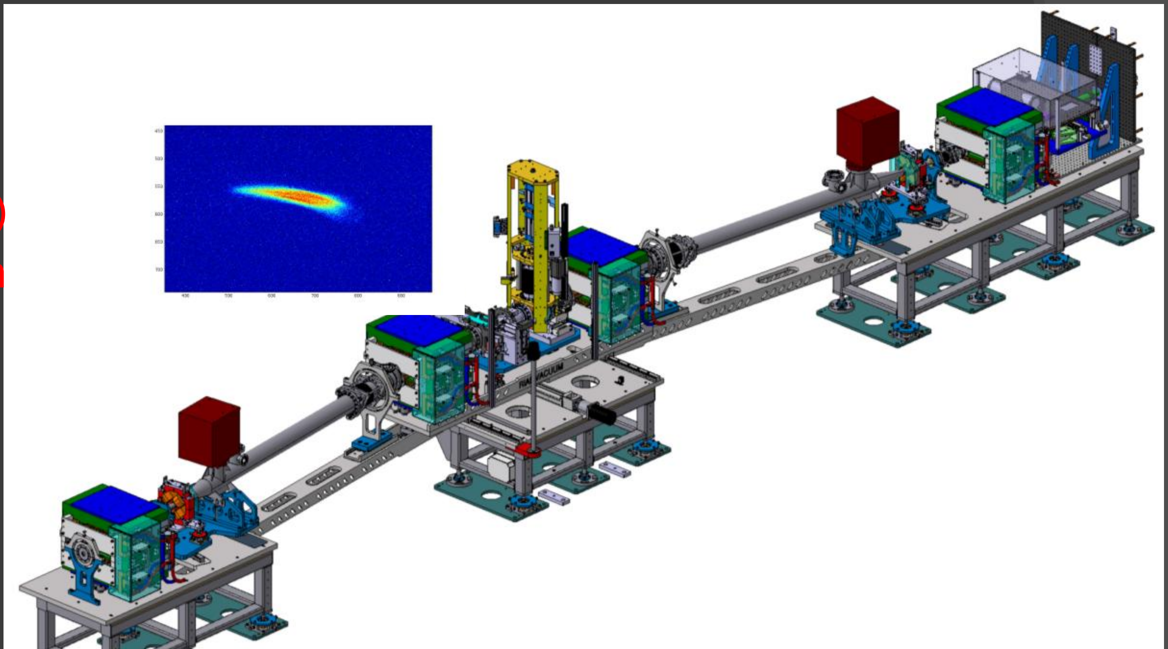
Routinely: 1.2-1.7 mm mrad

Bunch compressor

The FERMI@Elettra Bunch Compressor is a 4 dipoles, variable angle symmetric chicane. Diagnostic devices and "trim" quadrupoles follow the chicane movement, therefore they stay centered to the electron beam for any chicane angle.

Bunch Compressor main characteristics:

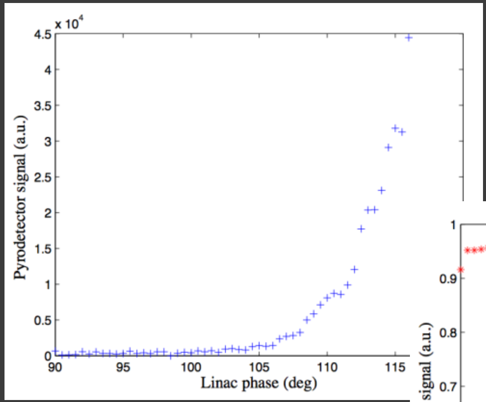
- Diagnostic installed on the central movable sled: Scraper, BPM and Multi-screen
- Transv. displacement: ≈ 370mm (max defl angle = 7°)
- Movement accuracy: ± 50μm
- Total length: ≈ 8m
- Movable vacuum chambers
- 1-DOF movement system
- Residual traj. distortion < 10μm
- Trim coils correct to the level of 20μm

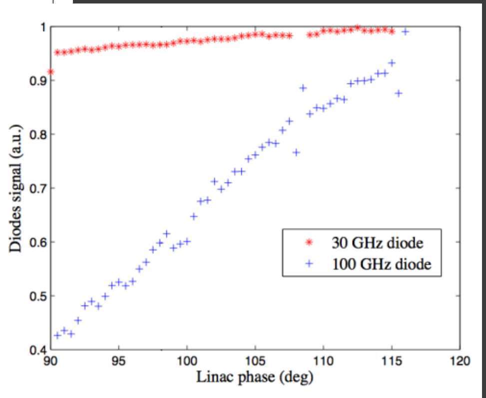


Courtesy of D. La Civita

Bunch length measurements (preliminary results)

Bunch Length Monitor :
Based on the detection of the edge radiation coming from the last dipole of BC1 and detected by a pyrodetector, and the diffraction radiation coming from a ceramic gap, that is collected by 3 electromagnetic horns and detected by 3 RF diodes (bw=30-100-300GHz)

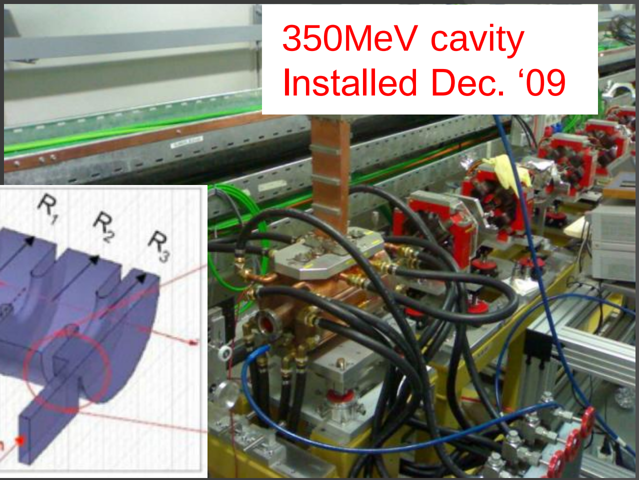


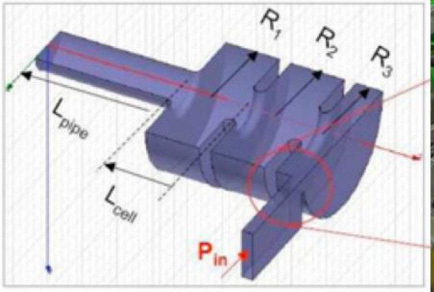


Excellent agreement between meas. with the theory for gap radiation emission signal vs. linear CF

Ref: R.Appio et al. Proc of FEL 2010

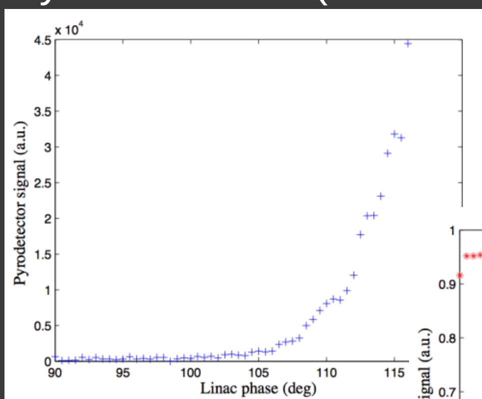
RF deflecting cavity after BC1 (350MeV) and at the end of the linac (1.2GeV)

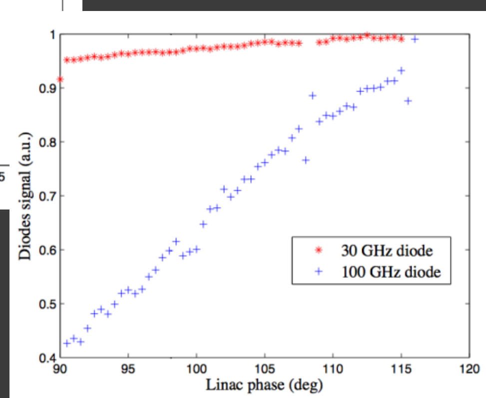




Bunch length measurements (preliminary results)

Bunch Length Monitor :
Based on the detection of the edge radiation coming from the last dipole of BC1 and detected by a pyrodetector, and the diffraction radiation coming from a ceramic gap, that is collected by 3 electromagnetic horns and detected by 3 RF diodes (bw=30-100-300GHz)



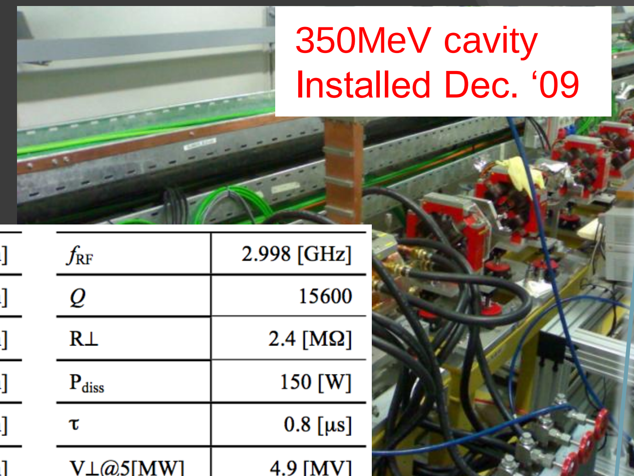


Excellent agreement between meas. with the theory for gap radiation emission signal vs. linear CF

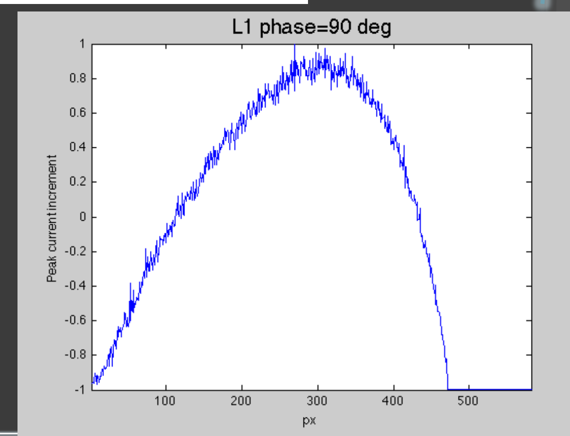
Ref: R.Appio et al. Proc of FEL 2010

RF deflecting cavity after BC1 (350MeV) and at the end of the linac (1.2GeV)

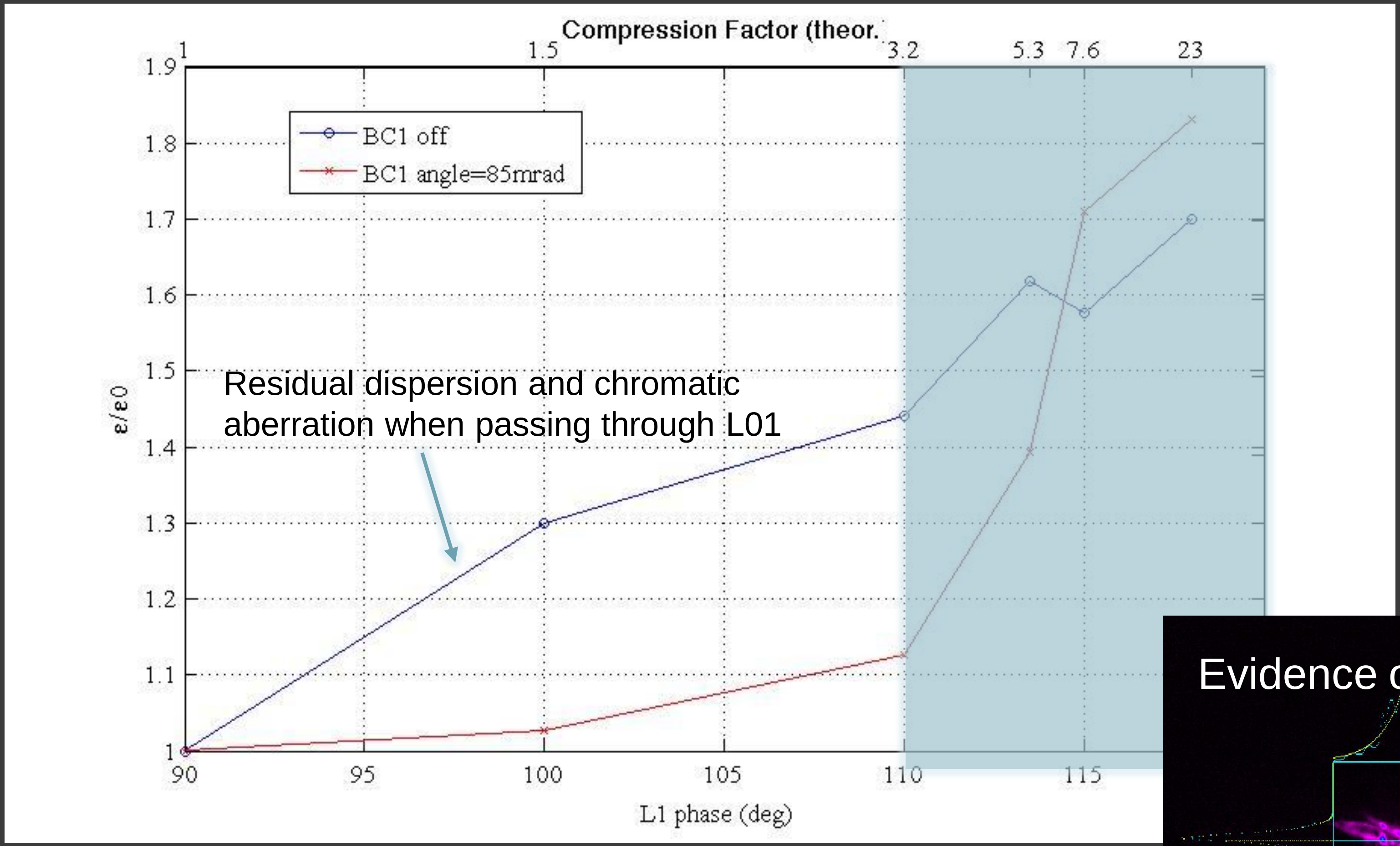
Ref: P.Craievich, IPAC 2010

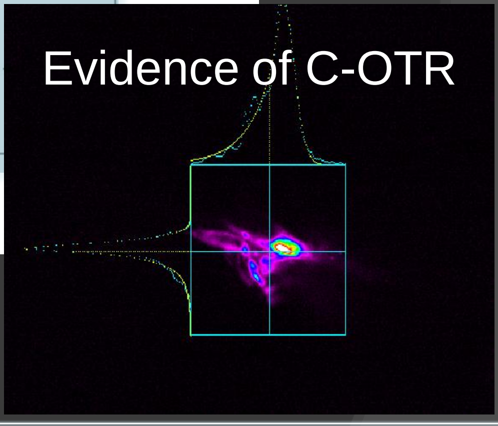


L_{cell}	50 [mm]	f_{RF}	2.998 [GHz]
R_1	58.25 [mm]	Q	15600
R_2	57.6 [mm]	R⊥	2.4 [MΩ]
R_3	57.45[mm]	P_{diss}	150 [W]
a	18 [mm]	τ	0.8 [μs]
x_w	8 [mm]	V⊥@5[MW]	4.9 [MV]
y_w	19.5 [mm]		
t	9.5 [mm]		



Emittance vs compression factor (CF)

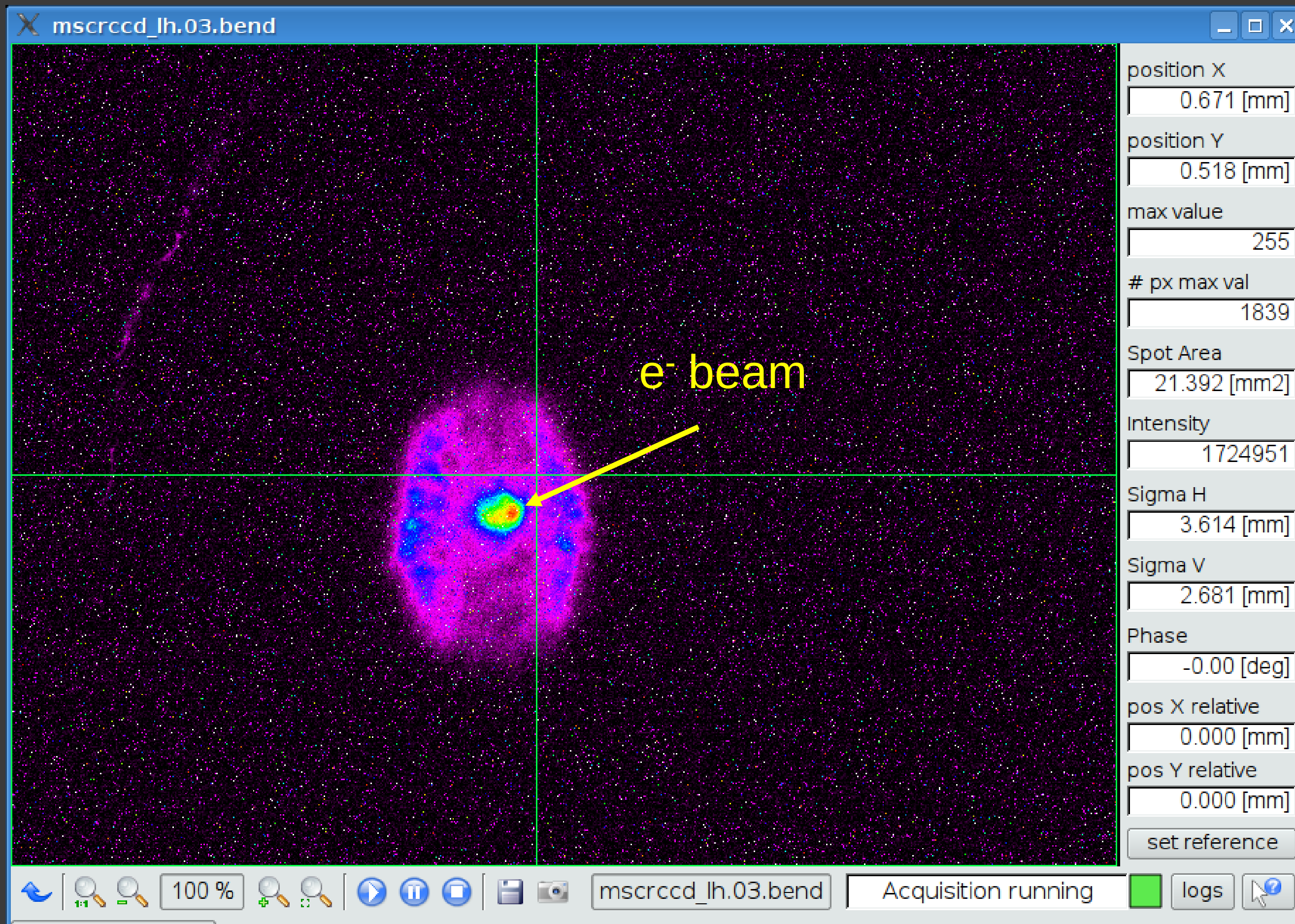




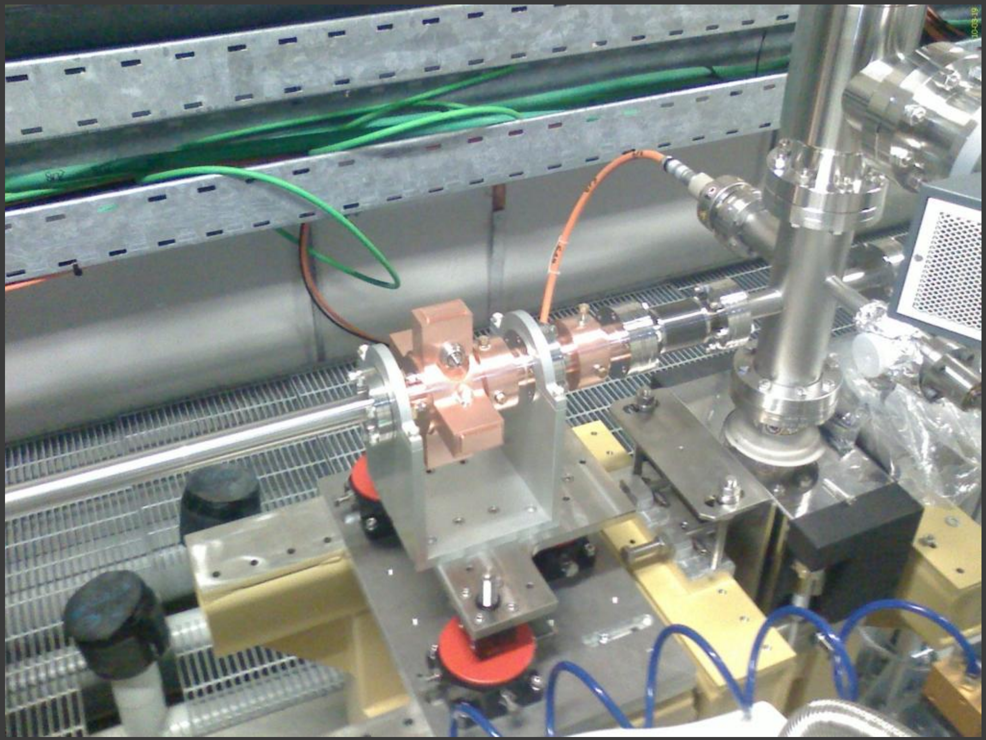
-Non linearized long. phase space at the entrance of BC1 leads to a 1 kA-current spike for CF>3.
- Microbunching instabilities influences

Laser heater preliminary test

Spontaneous emission (783nm), produced when the bunch passes through the chicane undulator, closed to the nominal gap, reflected by OTR screen



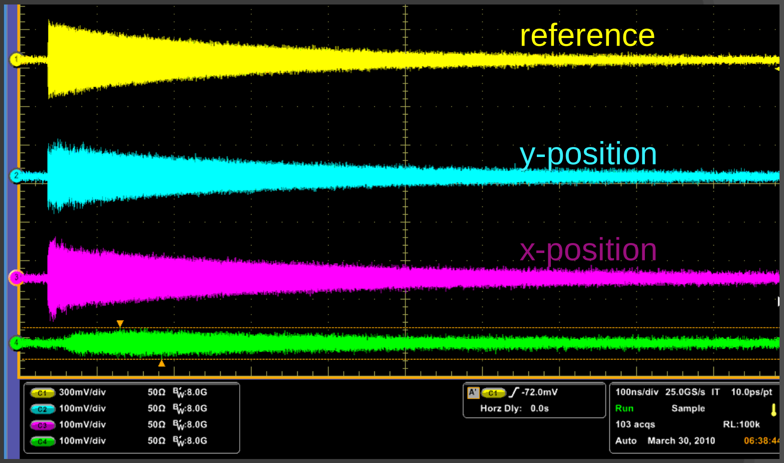
Cavity BPM



Cavity BPM signal when close BPMs read x=0, y=0:

Q=270pC, cross-talking ~ -40dB

Test on Electronics in lab on going



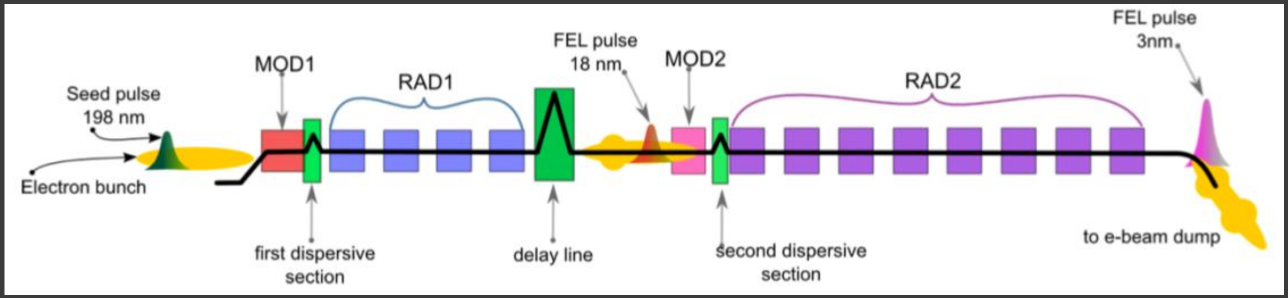
RF parameters: Freq=6.5GHz, Q=7000.

RF pulse signal (amplitude and length) in agreement with simulation.

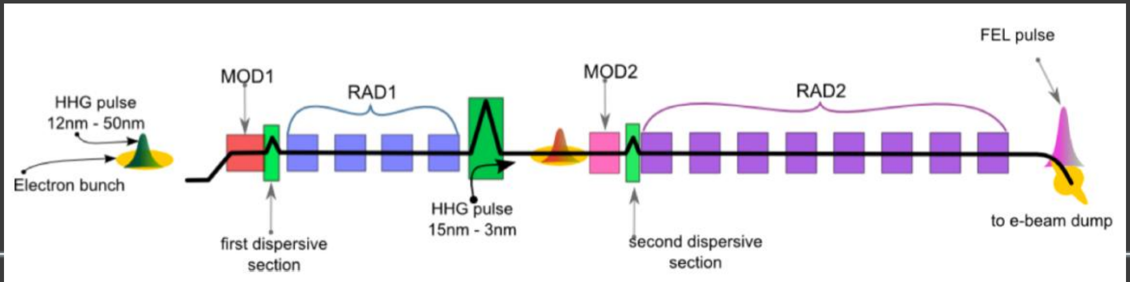
10 cavity BPMs are installed in the FEL intra-undulators sections

Next steps

- Dec. 2010: Beam at 1.2GeV, e<1.5 mm mrad:
  - Radiator tuned @60nm and tuning of the phase shifter to have SASE
  - Generation and optimization of **HG @60nm** (4th harmonic)
- In 2011: BC2 and X-band installed.
  - 800pC-bunch optimized for HGHG scheme @ 20nm
  - Installation of FEL2 beam-line: maybe first laser by the end of year at 4.2nm and 3rd harm. (1.4nm), through **HGHG double cascade**

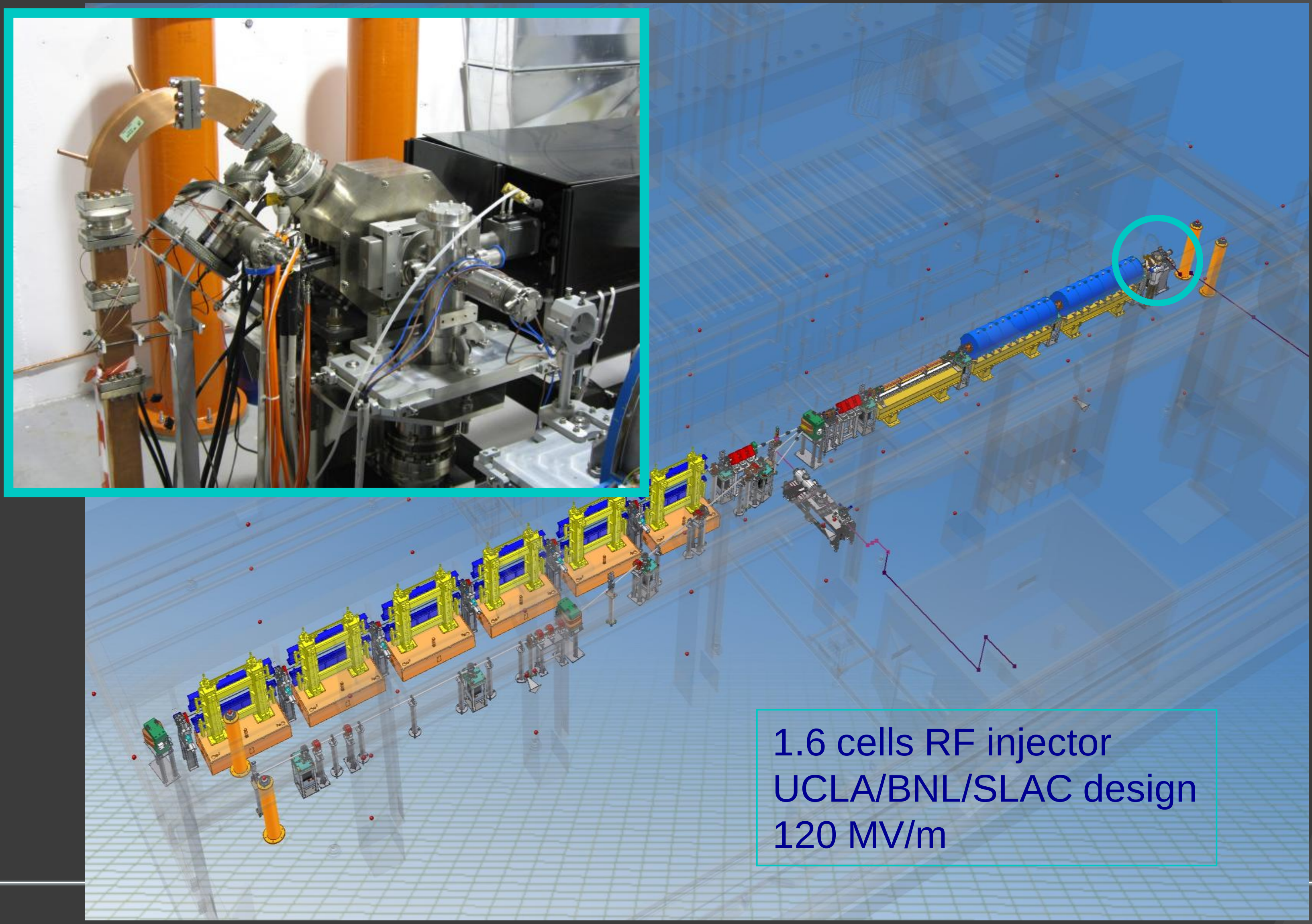


- Compatible with a change to **HHG-seeding** at some point in the future if HHG power levels for <50 nm become sufficiently strong

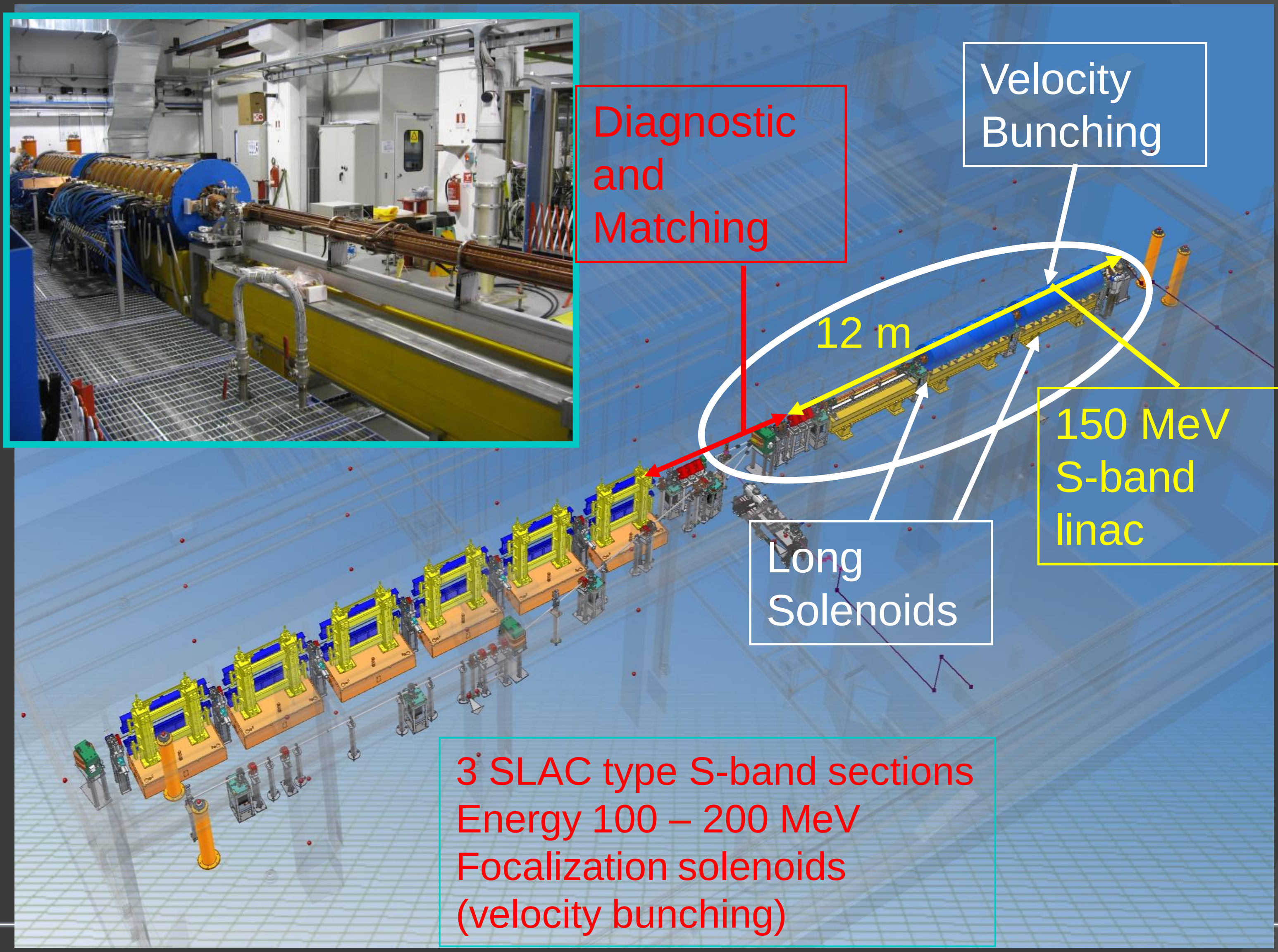


SPARC

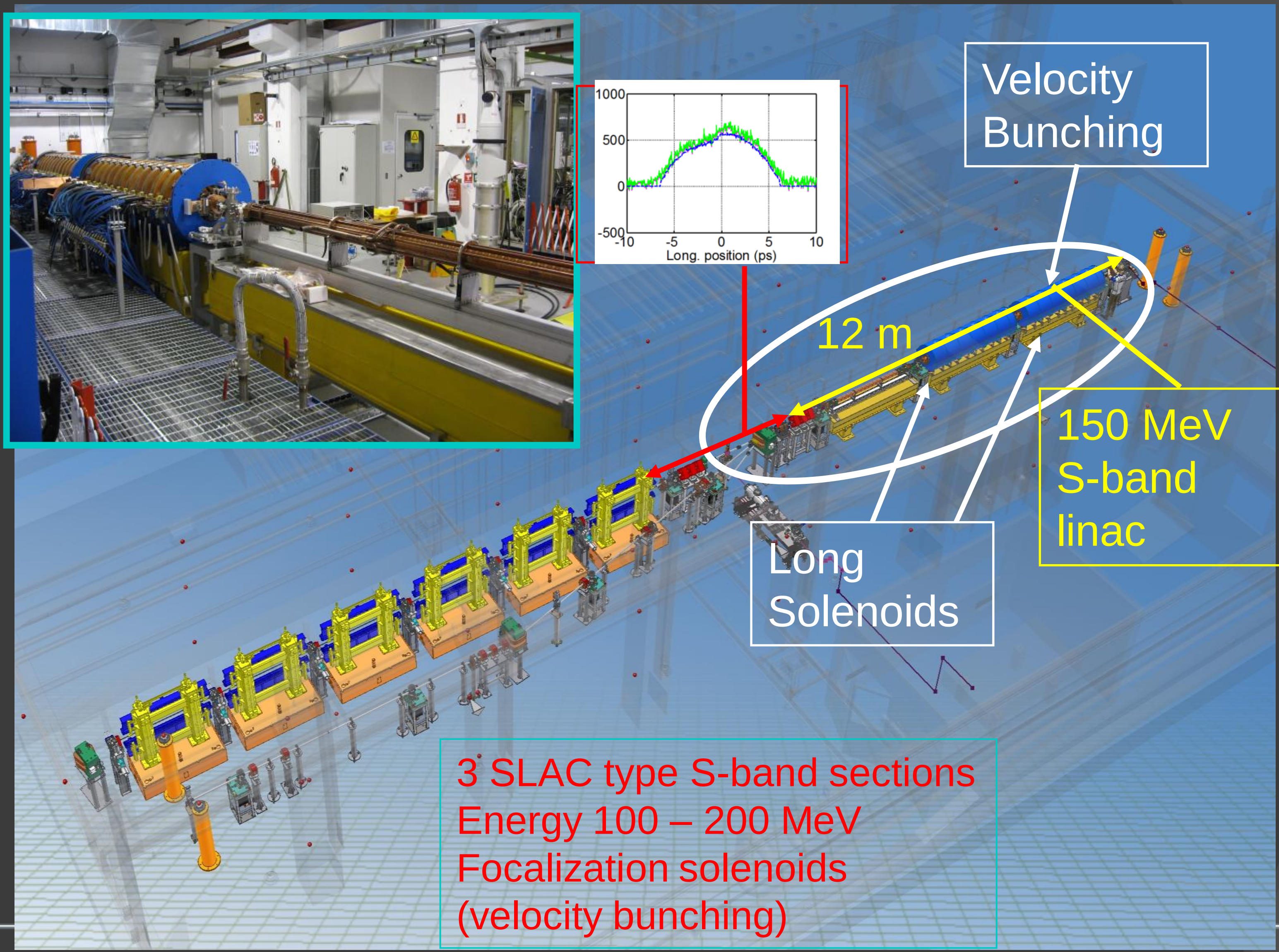
SPARC - layout



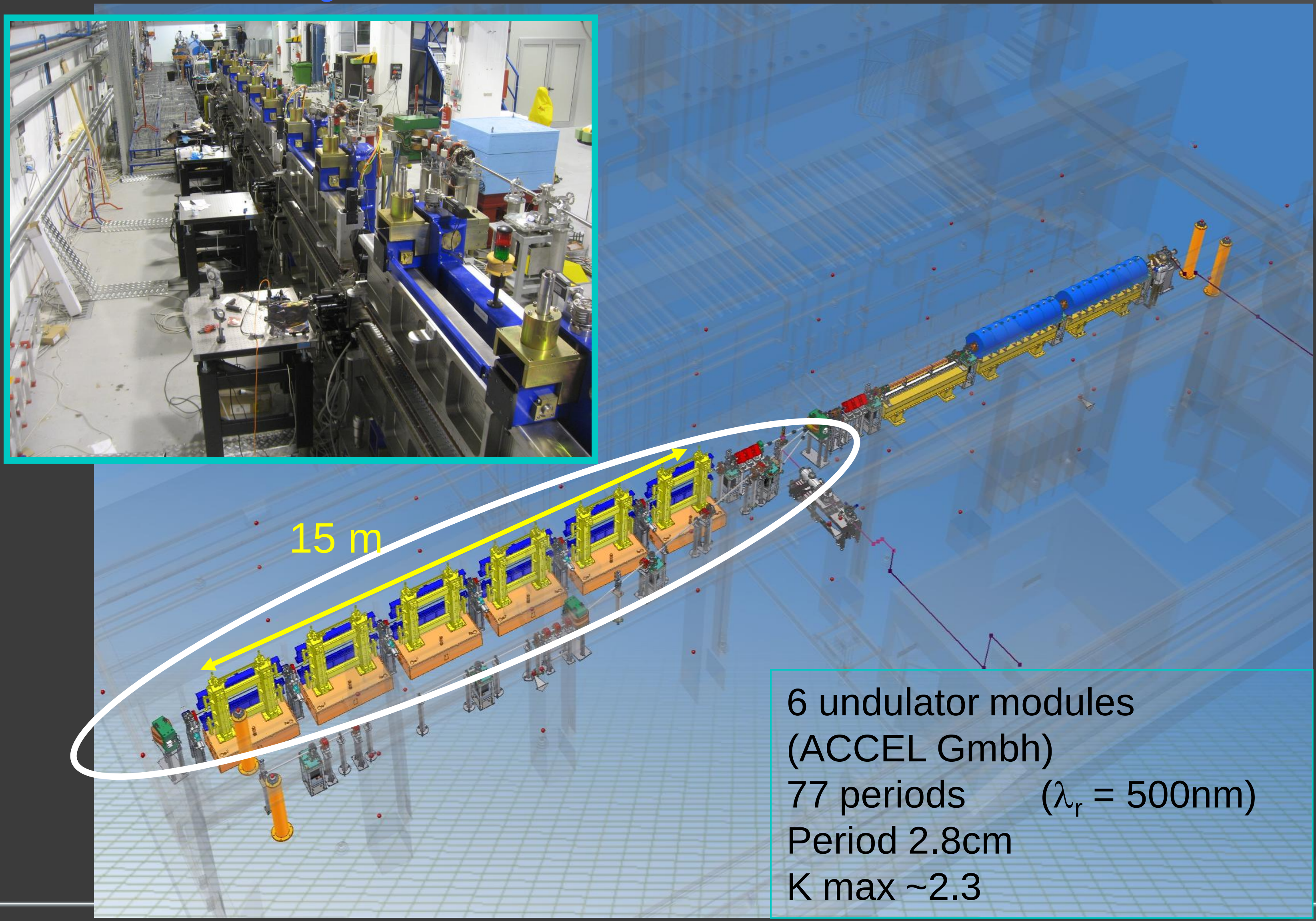
SPARC - layout



SPARC - layout

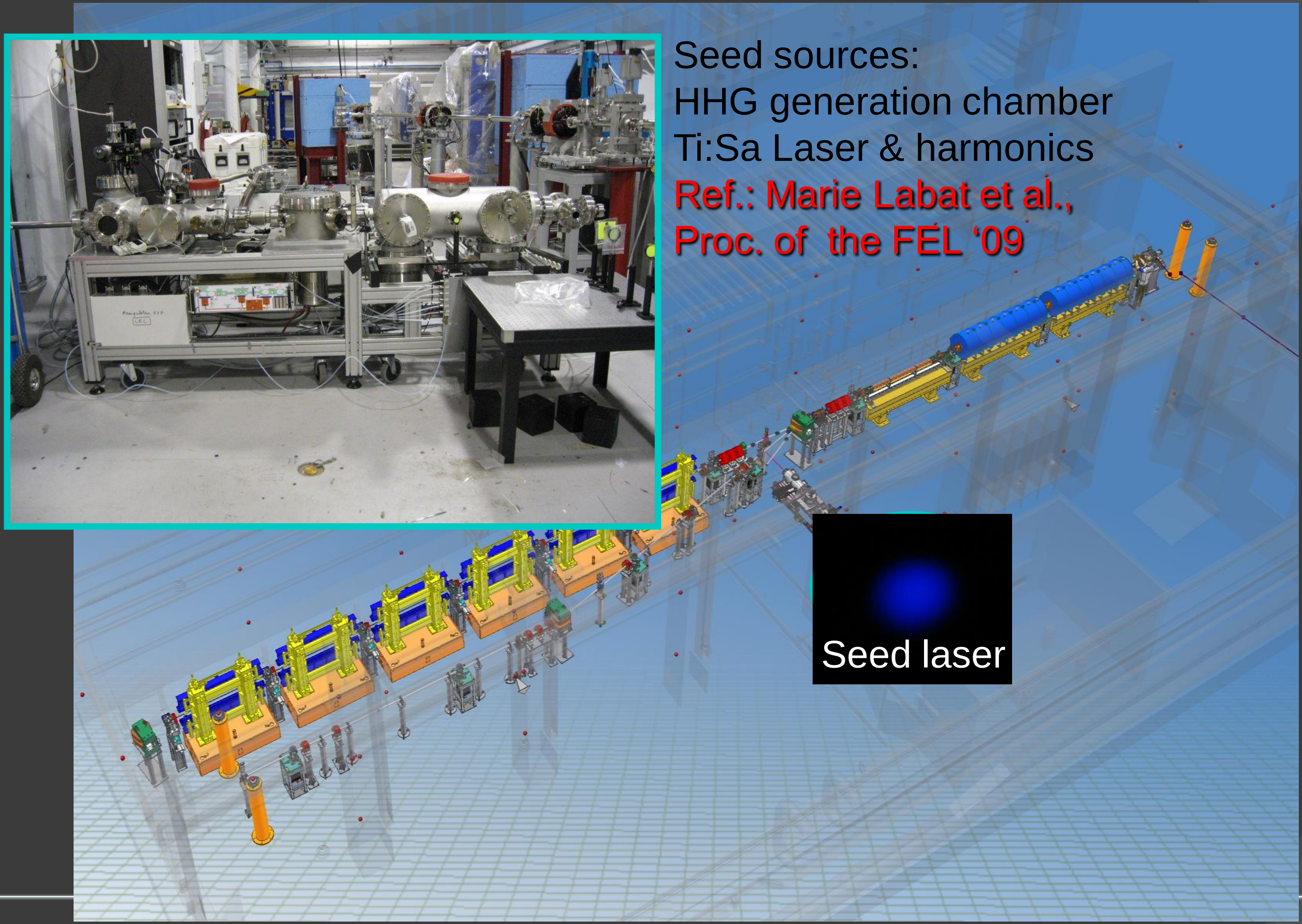


SPARC - layout



6 undulator modules
(ACCEL Gmbh)
77 periods (λ_r = 500nm)
Period 2.8cm
K max ~2.3

SPARC - layout



Seed sources:
HHG generation chamber
Ti:Sa Laser & harmonics
Ref.: Marie Labat et al.,
Proc. of the FEL '09

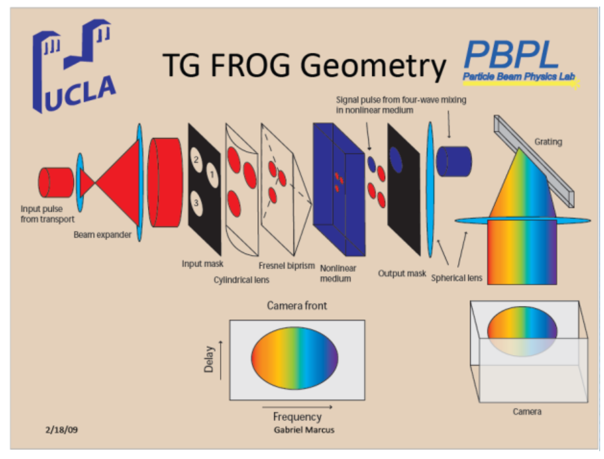
SPARC - layout

Streak Camera
In vacuum spectrometer (Luxor)

Laboratory for UV and X-ray Optical Research — LUXOR CNR-INFM

in the next future … FROG

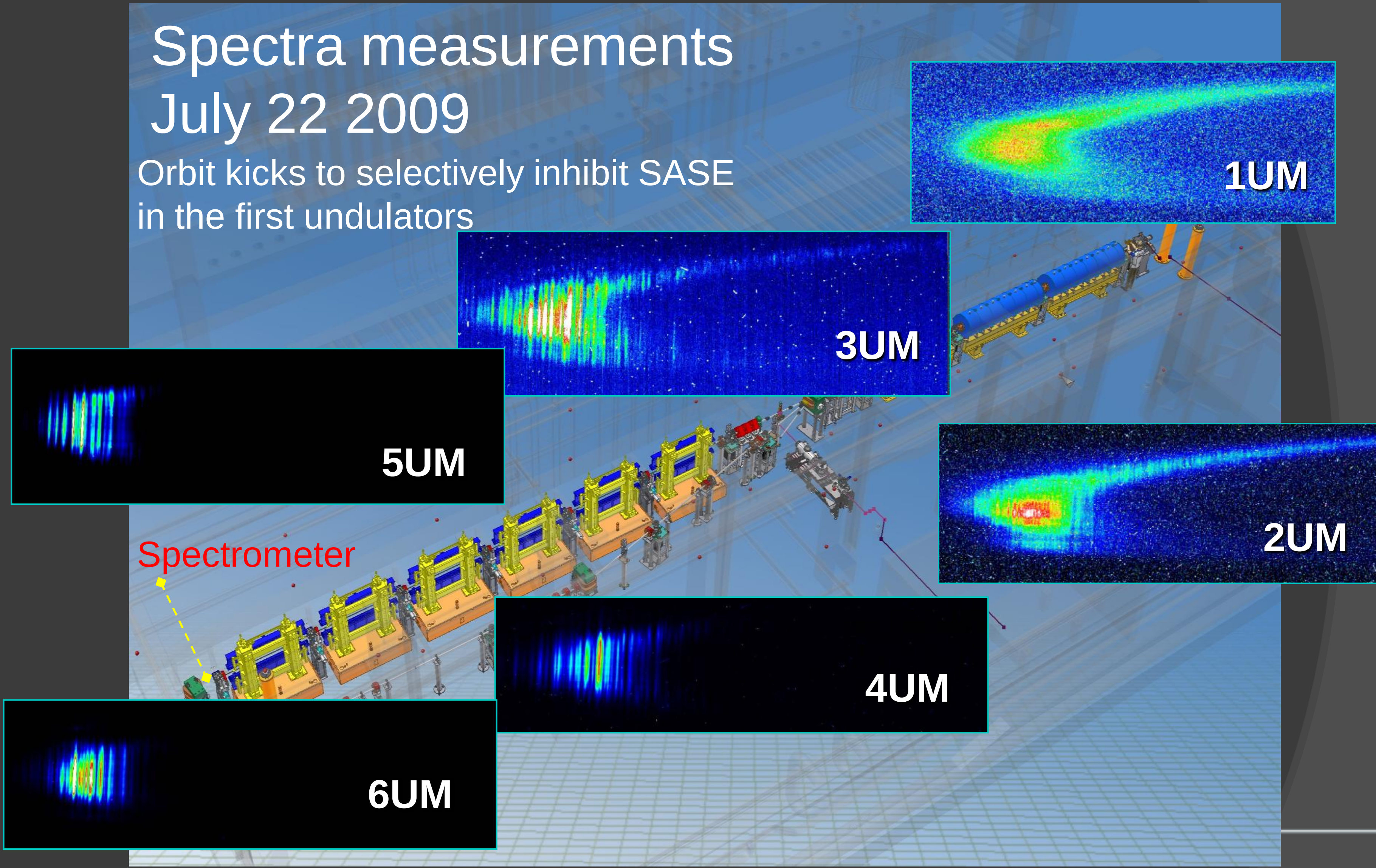
Particle Beam Physics Laboratory



SPARC - layout

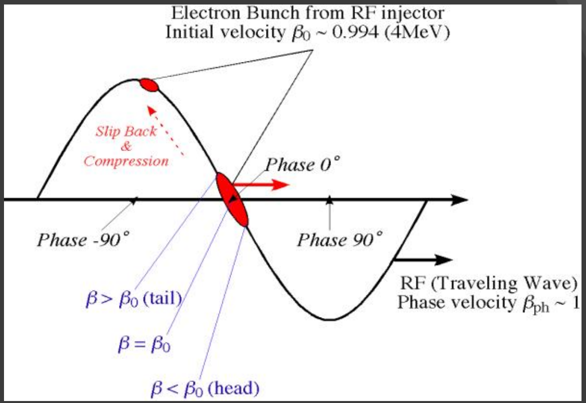
Spectra measurements July 22 2009

Orbit kicks to selectively inhibit SASE in the first undulators



Velocity bunching

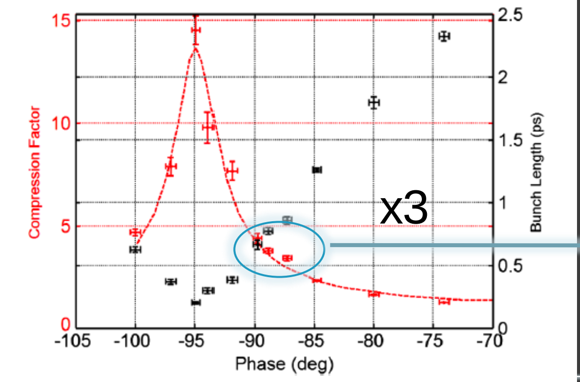
If the beam injected in a long accelerating structure at the 0 crossing field phase and it is slightly slower than the phase velocity of the RF wave, it will slip back to phases where the field is accelerating, but at the same time it will be chirped and compressed.

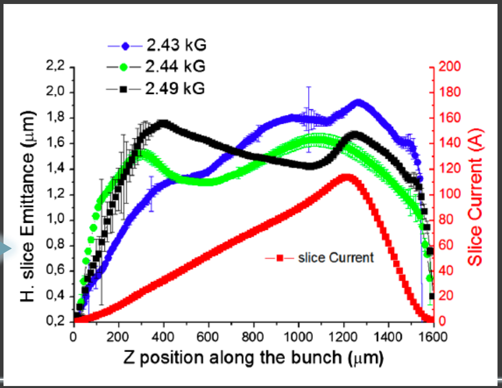


PRL **104,** 054801 (2010) PHYSICAL REVIEW LETTERS week ending 5 FEBRUARY 2010

Experimental Demonstration of Emittance Compensation with Velocity Bunching

M. Ferrario,[1] D. Alesini,[1] A. Bacci,[3] M. Bellaveglia,[1] R. Boni,[1] M. Boscolo,[1] M. Castellano,[1] E. Chiadroni,[1] A. Cianchi,[2] L. Cultrera,[1] G. Di Pirro,[1] L. Ficcadenti,[1] D. Filippetto,[1] V. Fusco,[1] A. Gallo,[1] G. Gatti,[1] L. Giannessi,[4] M. Labat,[4] B. Marchetti,[2] C. Marrelli,[1] M. Migliorati,[1] A. Mostacci,[1] E. Pace,[1] L. Palumbo,[1] M. Quattromini,[4] C. Ronsivalle,[4] A. R. Rossi,[3] J. Rosenzweig,[5] L. Serafini,[3] M. Serluca,[6] B. Spataro,[1] C. Vaccarezza,[1] and C. Vicario[1]





Compression with "Velocity Bunching" for SPARC:

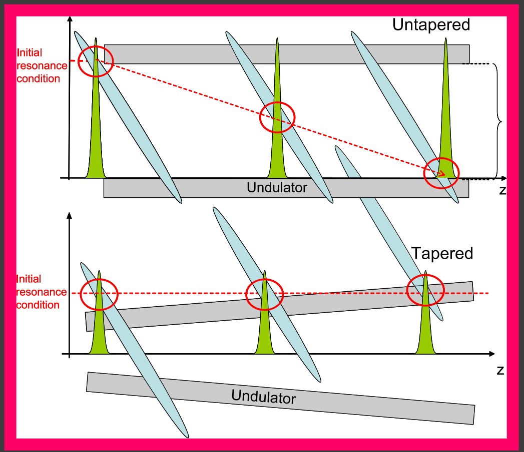
PRO: **High peak current (up to 380 A) without CSR effects as in the magnetic chicanes**

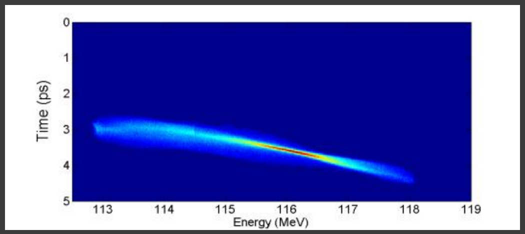
CON: **Strong chirp / energy spread in the longitudinal phase space**

Undulator tapering

Compensation of the chirp with UM Taper:

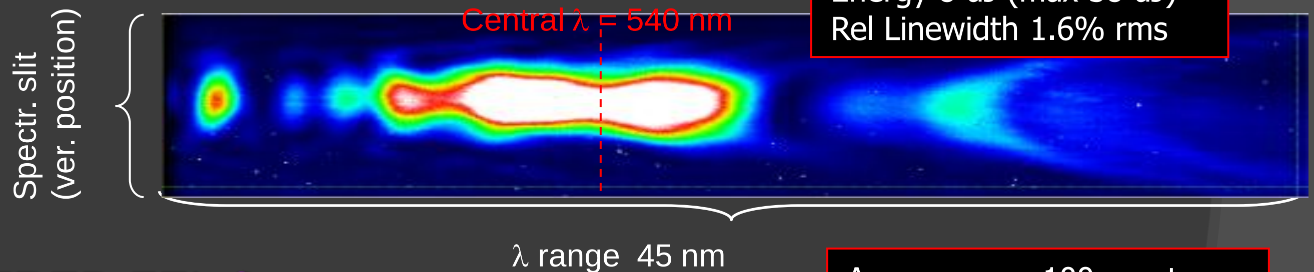
E. L. Saldin, E. A. Schneidmiller, and M.V. Yurkov, PRST - AB 9, 050702 (2006)





Beam Energy=117MeV

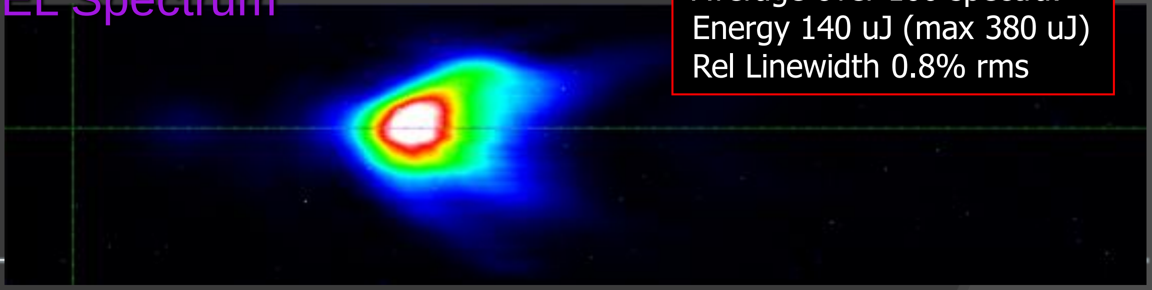
UNTAPERED FEL Spectrum



Average over 100 spectra
Energy 8 uJ (max 38 uJ)
Rel Linewidth 1.6% rms

Details in Proc of the FEL 2010

TAPERED FEL Spectrum



Average over 100 spectra:
Energy 140 uJ (max 380 uJ)
Rel Linewidth 0.8% rms

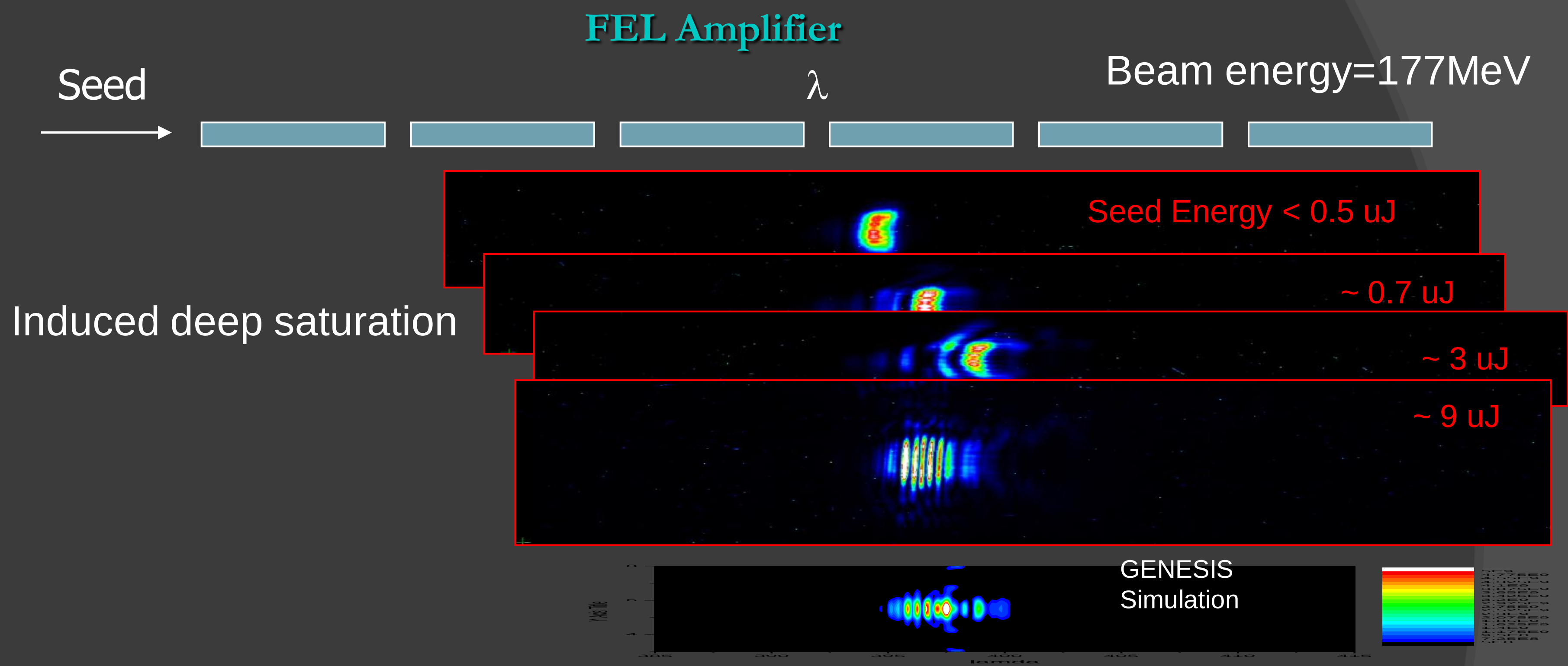
Single cooperation length observed in many spectra
Average energy per pulse 18 times higher in a narrower bandwidth (~1/2)

XXV LINEAR ACCELERATOR CONFERENCE
LINAC10
TSUKUBA, JAPAN
SEPTEMBER 12 - 17, 2010

G. Penco

Sparc 2: Direct seeding HHG and superradiance

Ref. : "Generation of high harmonics" (Giannessi et al. JAP 98 043110 – 2005)



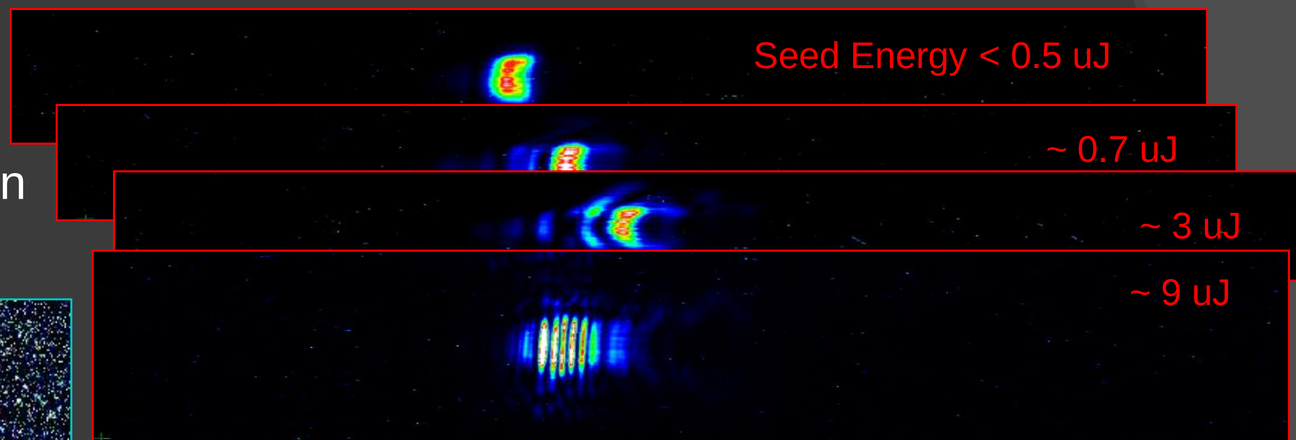
Sparc 2: Direct seeding HHG and superradiance

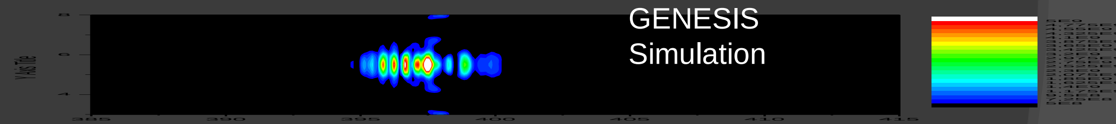
Ref. : "Generation of high harmonics" (Giannessi et al. JAP 98 043110 – 2005)

FEL Amplifier

Beam energy=177MeV

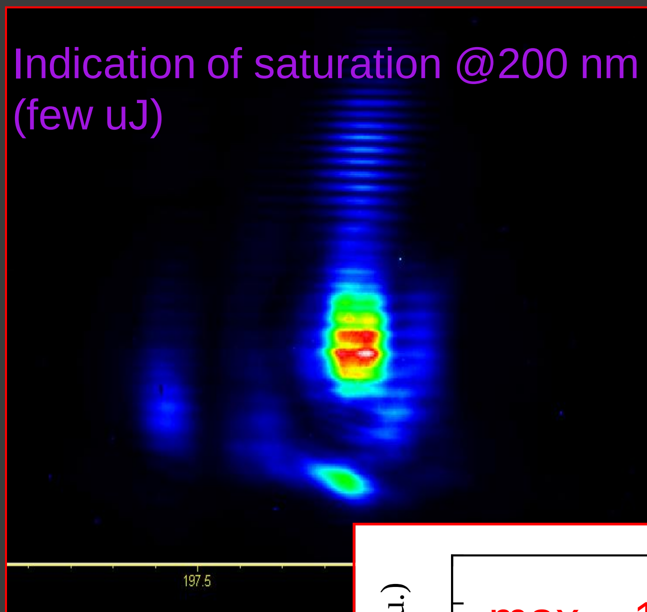
Induced deep saturation



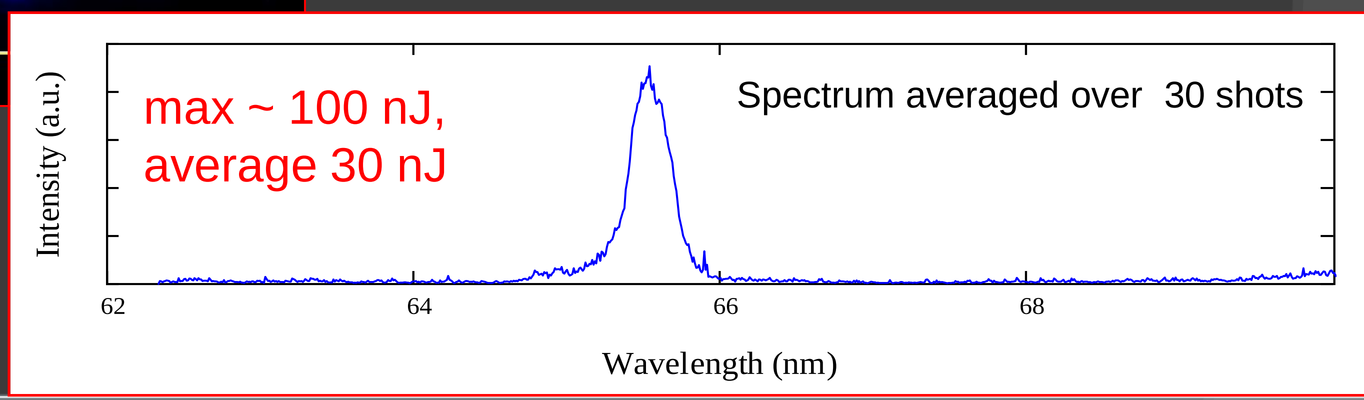


G. Penco

SPARC 3: cascade operating at saturation

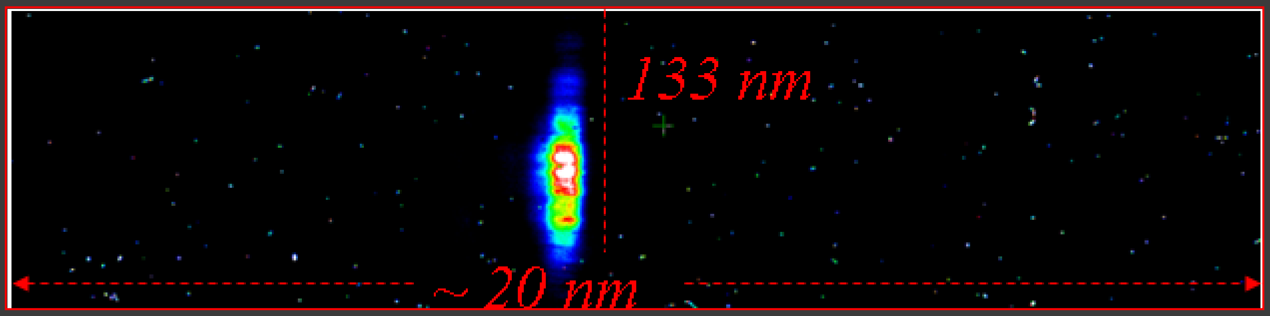


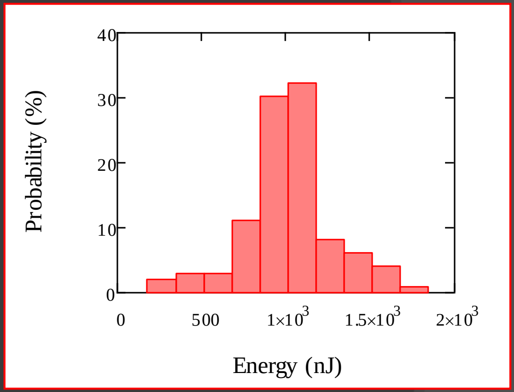
3° harmonic
of the radiator (66nm)



SPARC 4: seeding with HG in gas

Seed @ 266 nm → 133 nm



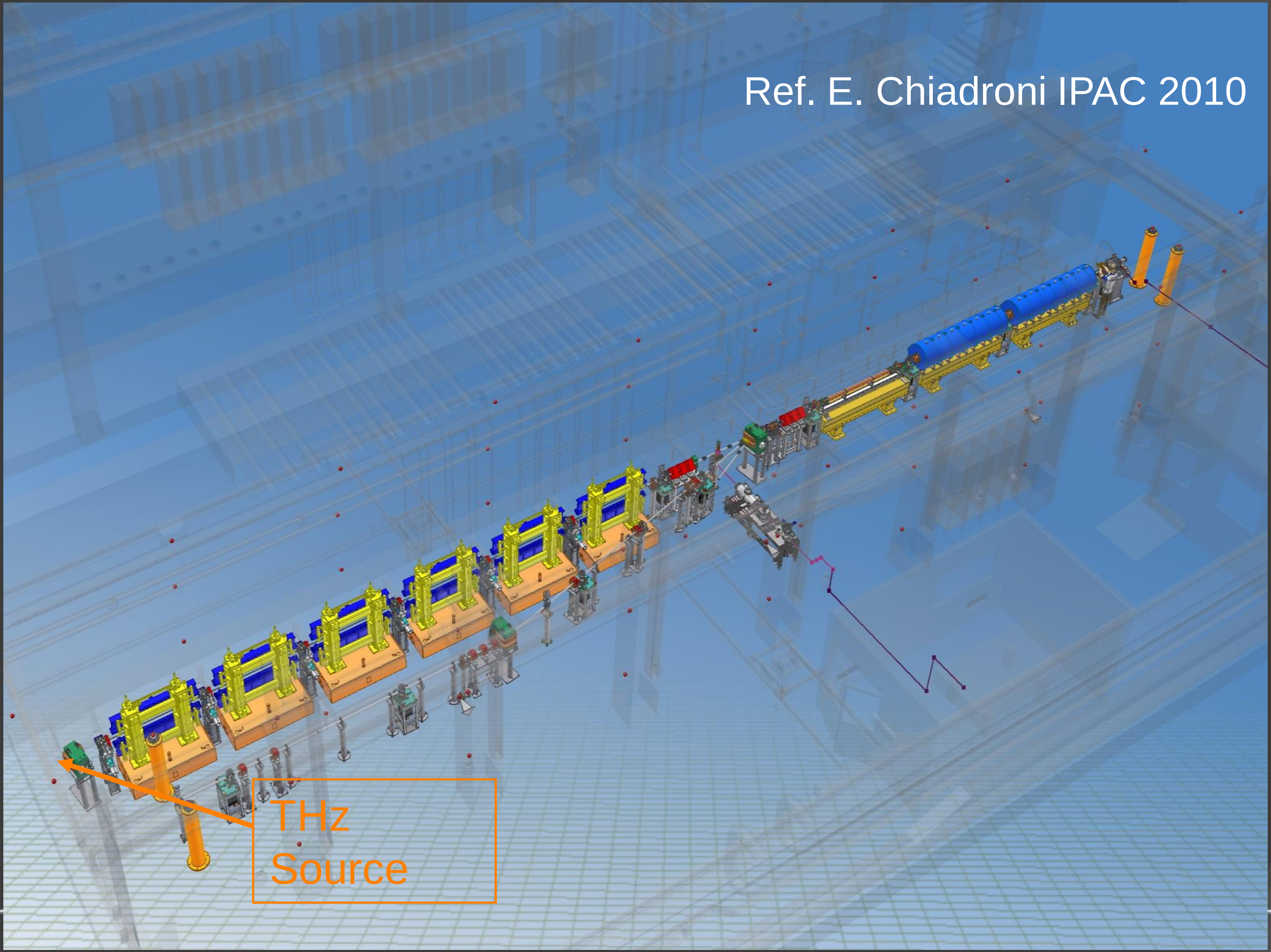


Studied the cascade changing the number of modulators/radiators

50 nJ 5-4-3 UM tuned @ 266 nm – 1-2-3 UM tuned @133 nm

Demonstrated Direct seeding @ 160nm

SPARC – THz radiation



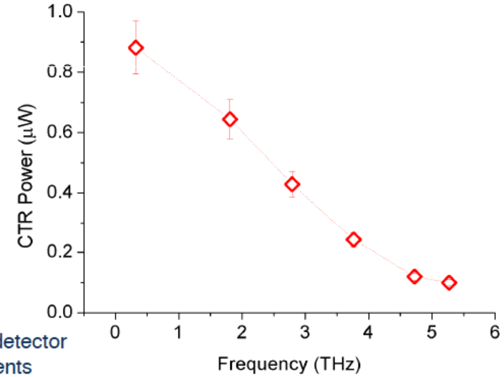
XXV LINEAR ACCELERATOR CONFERENCE
LINAC10
TSUKUBA, JAPAN
SEPTEMBER 12 - 17, 2010

G. Penco

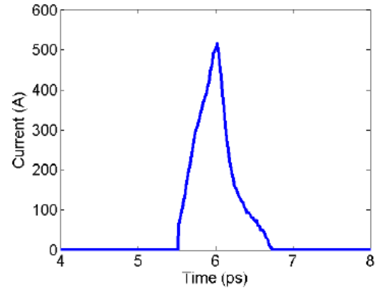
SPARC – THz radiation

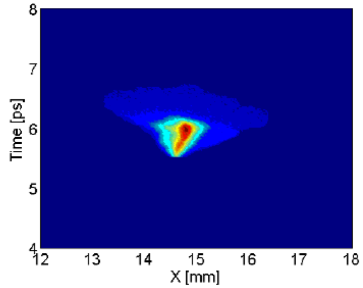
Velocity bunching with compression factor 14 and emittance compensated

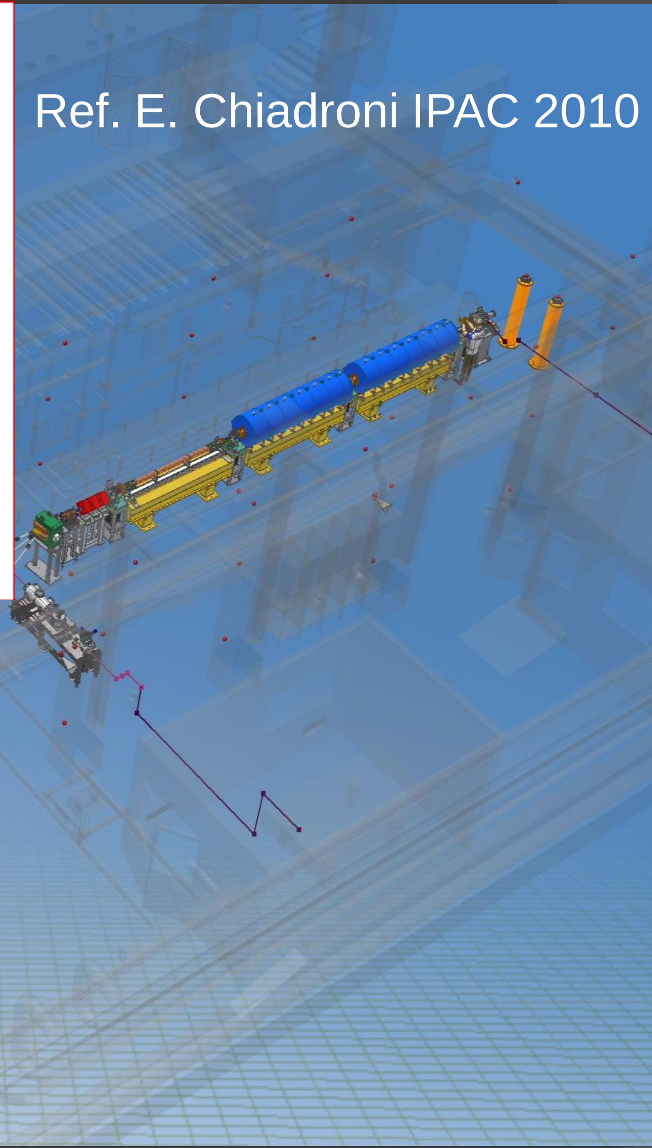
Q = 260 pC
σ_t = 260 fs (after compression)
Beam Energy= 100 MeV

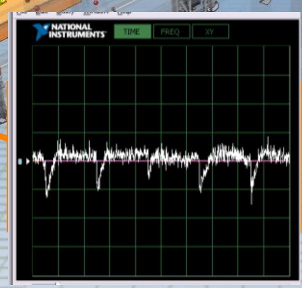


Golay cell detector measurements



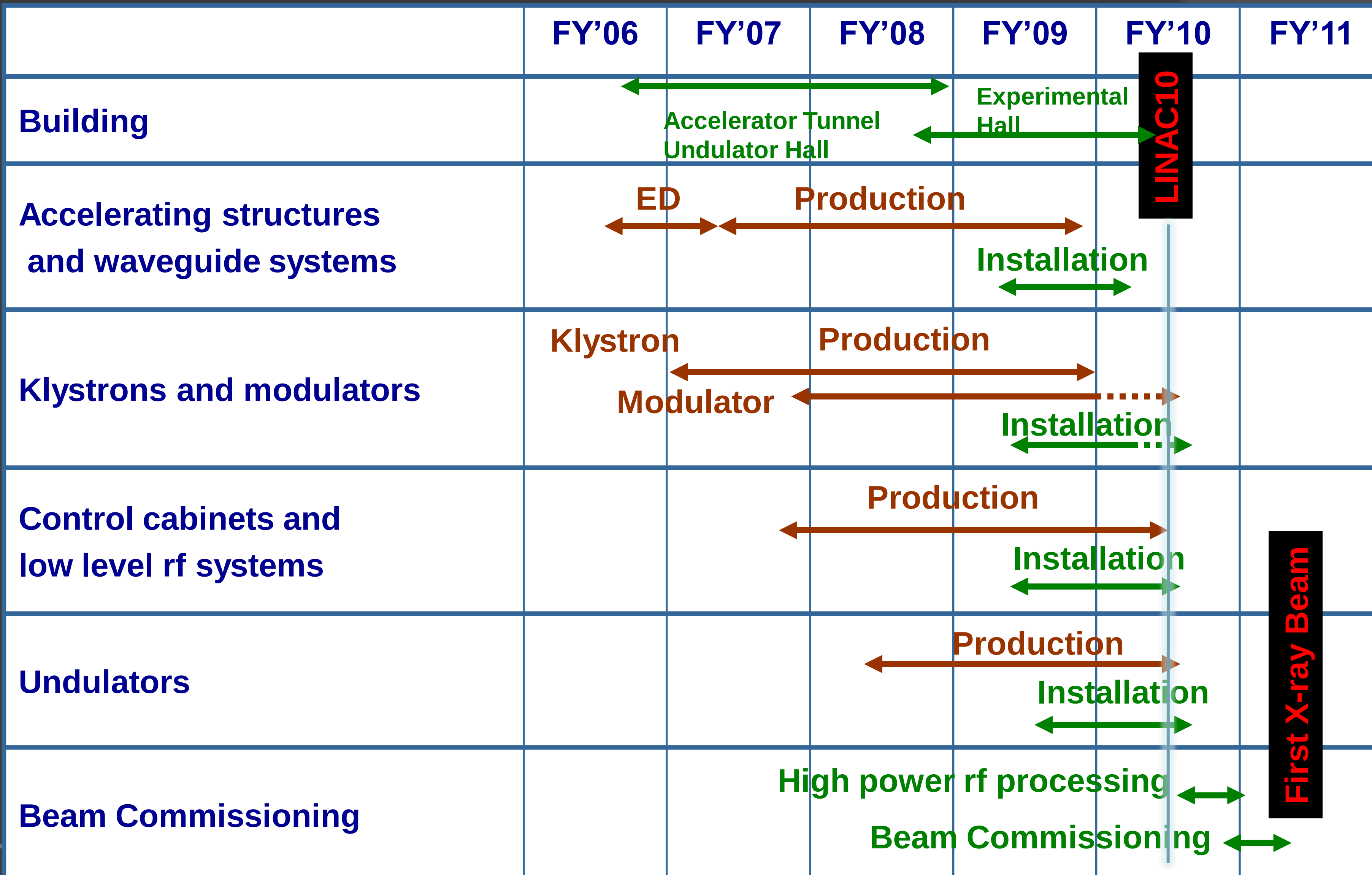




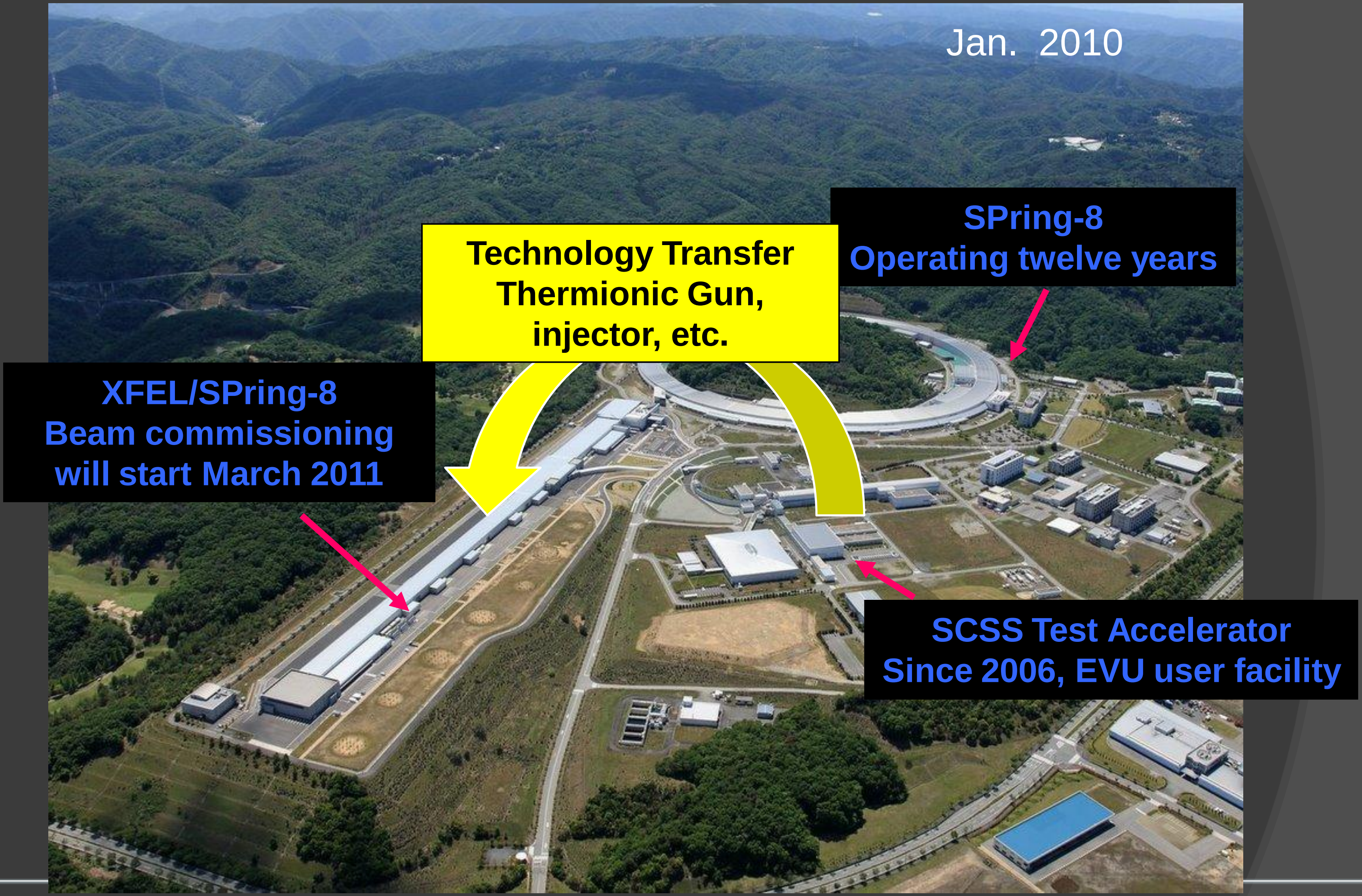


XFEL/SPring-8

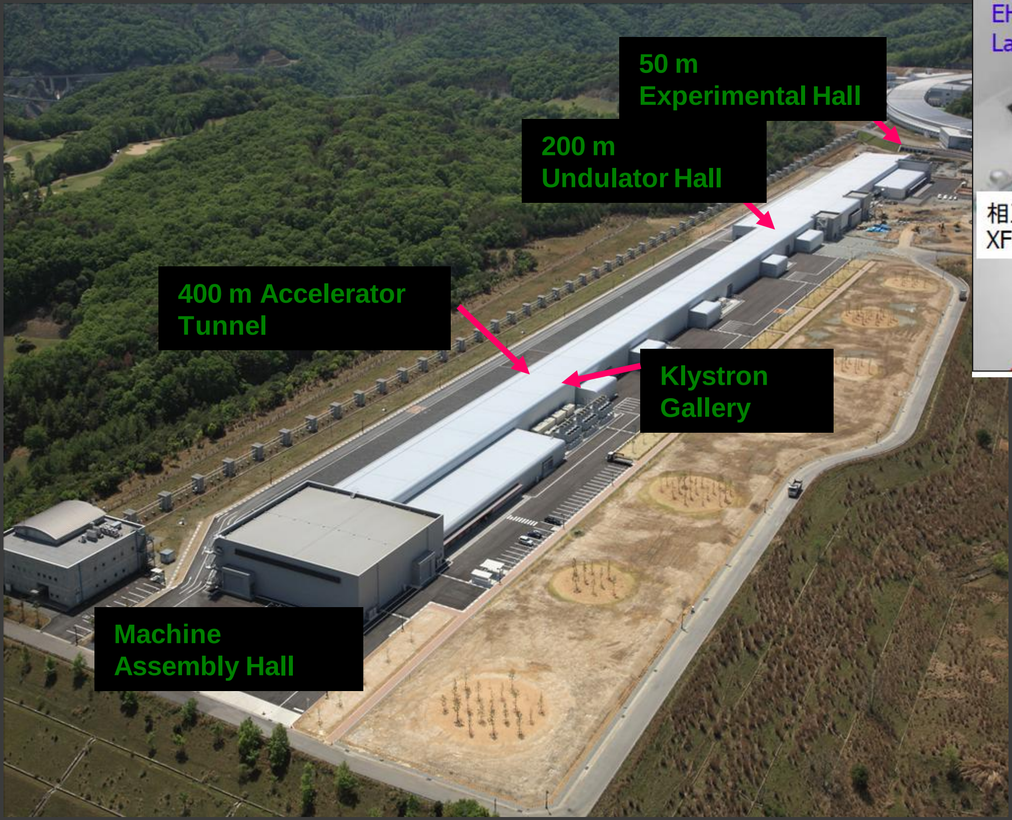
Status of XFEL/Spring-8 construction



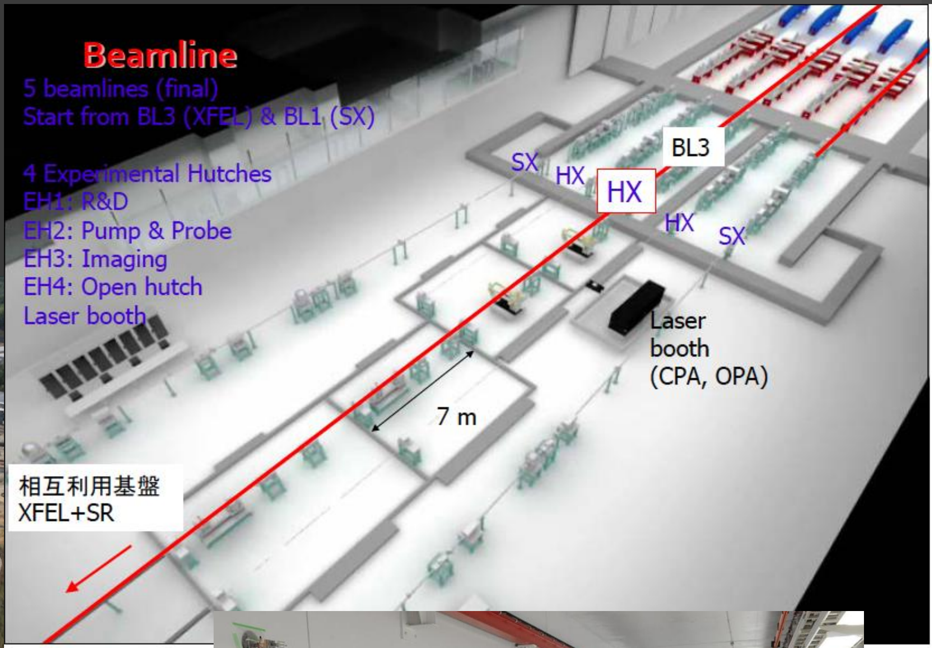
Spring-8/XFEL and SCCS



Layout



50 m
Experimental Hall
200 m
Undulator Hall
400 m Accelerator
Tunnel
Klystron
Gallery
Machine
Assembly Hall

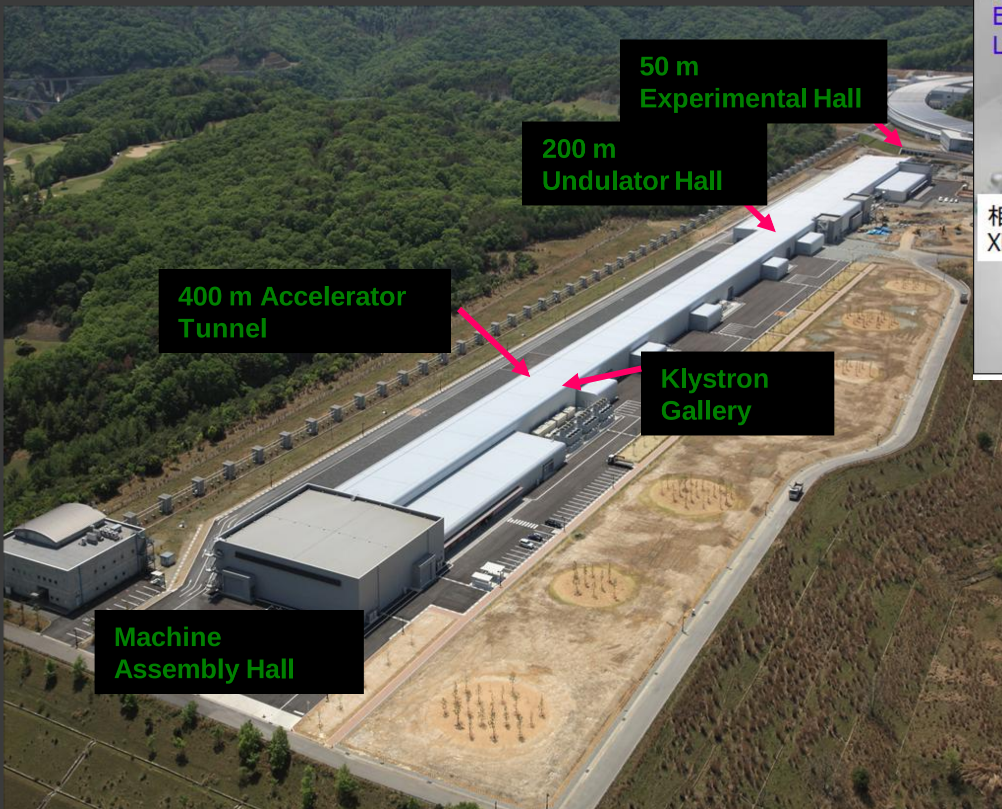


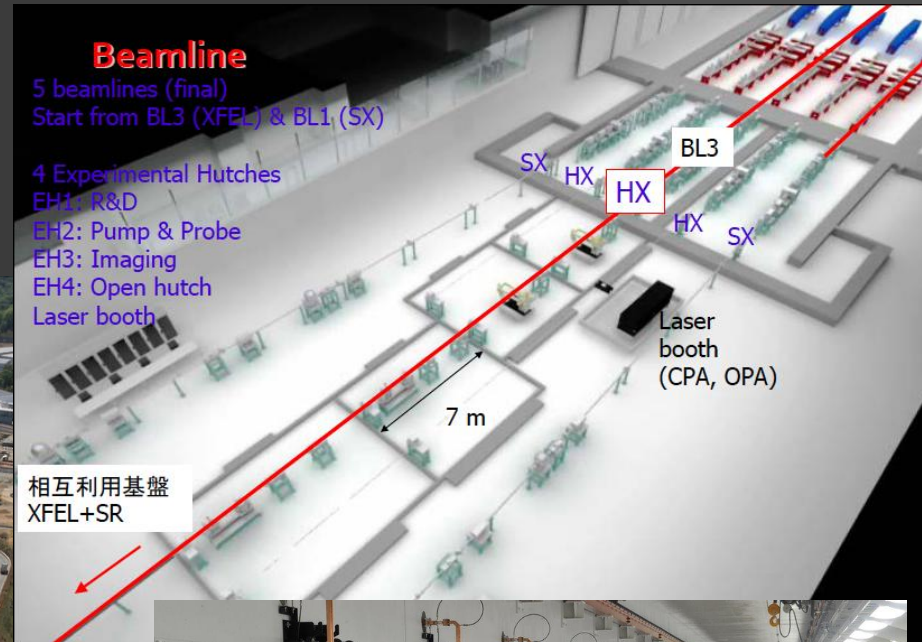
Beamline
5 beamlines (final)
Start from BL3 (XFEL) & BL1 (SX)
4 Experimental Hutches
EH1: R&D
EH2: Pump & Probe
EH3: Imaging
EH4: Open hutch
Laser booth
BL3
SX
HX
HX
HX
SX
Laser
booth
(CPA, OPA)
7 m
相互利用基盤
XFEL+SR

Accelerator
installation Aug. '09

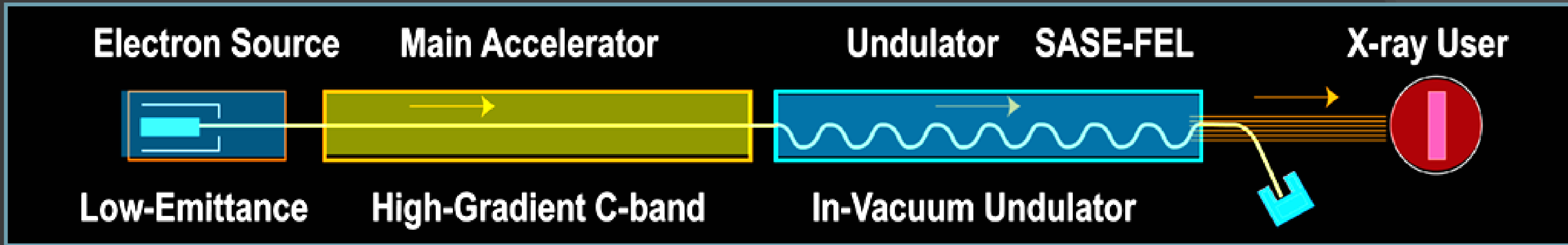
Layout

T. Inagaki, "Construction of 8-GeV C-band Accelerator for XFEL/SPring-8", Proc. of FEL 2010 conference





SCCS: Spring-8 Compact SASE Source



- **Short Period Undulator** → **Lower Beam Energy**

  In-Vacuum Undulator : λu= 18 mm, K=1.9, λx < 1 Å → E= 8 GeV,

  SLAC-LCLS : λu= 30 mm, K=3.7, λx~ 1.5 Å → E= 14 GeV

  Euro-XFEL : λu= 36 mm, K=3.3, λx < 1 Å → E= 17.5 GeV

- **High Gradient Accelerator** → **Short Accelerator Length**

  8 GeV, C-band 35 MV/m → 230 m

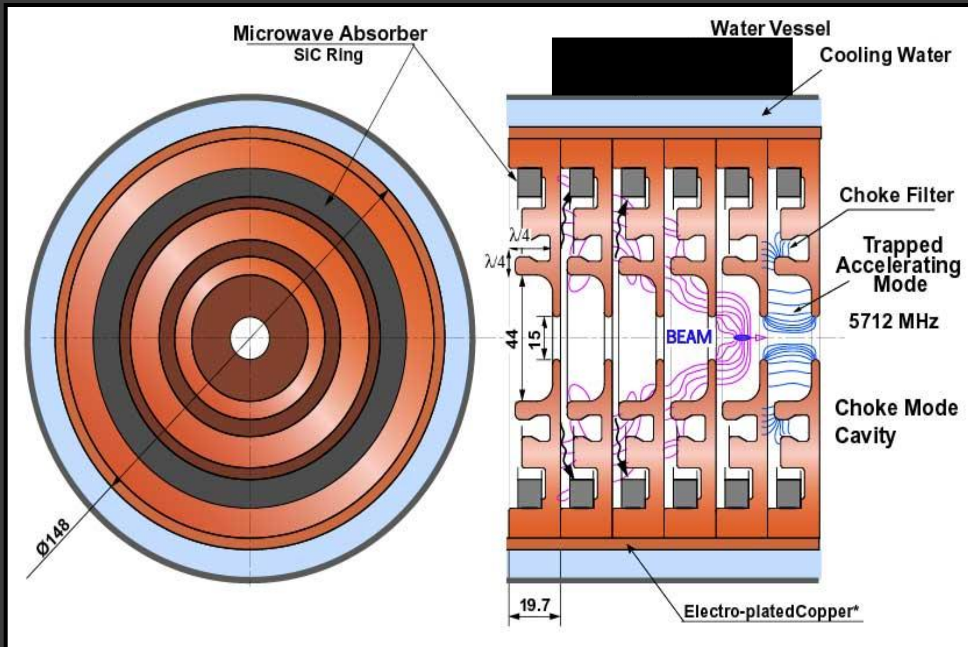
  SLAC-LCLS : S-band 19 MV/m → 740 m

- **Thermionic Electron Source** → **Short Saturation Length**

  Thermionic gun + velocity bunching → 0.8 π.mm.mrad @ 3k A, 8GeV

  → multi-bunch operation, smooth & quiet beam for seeding

C-band accelerator for multi-bunch option



13,000 cells are under mass production.

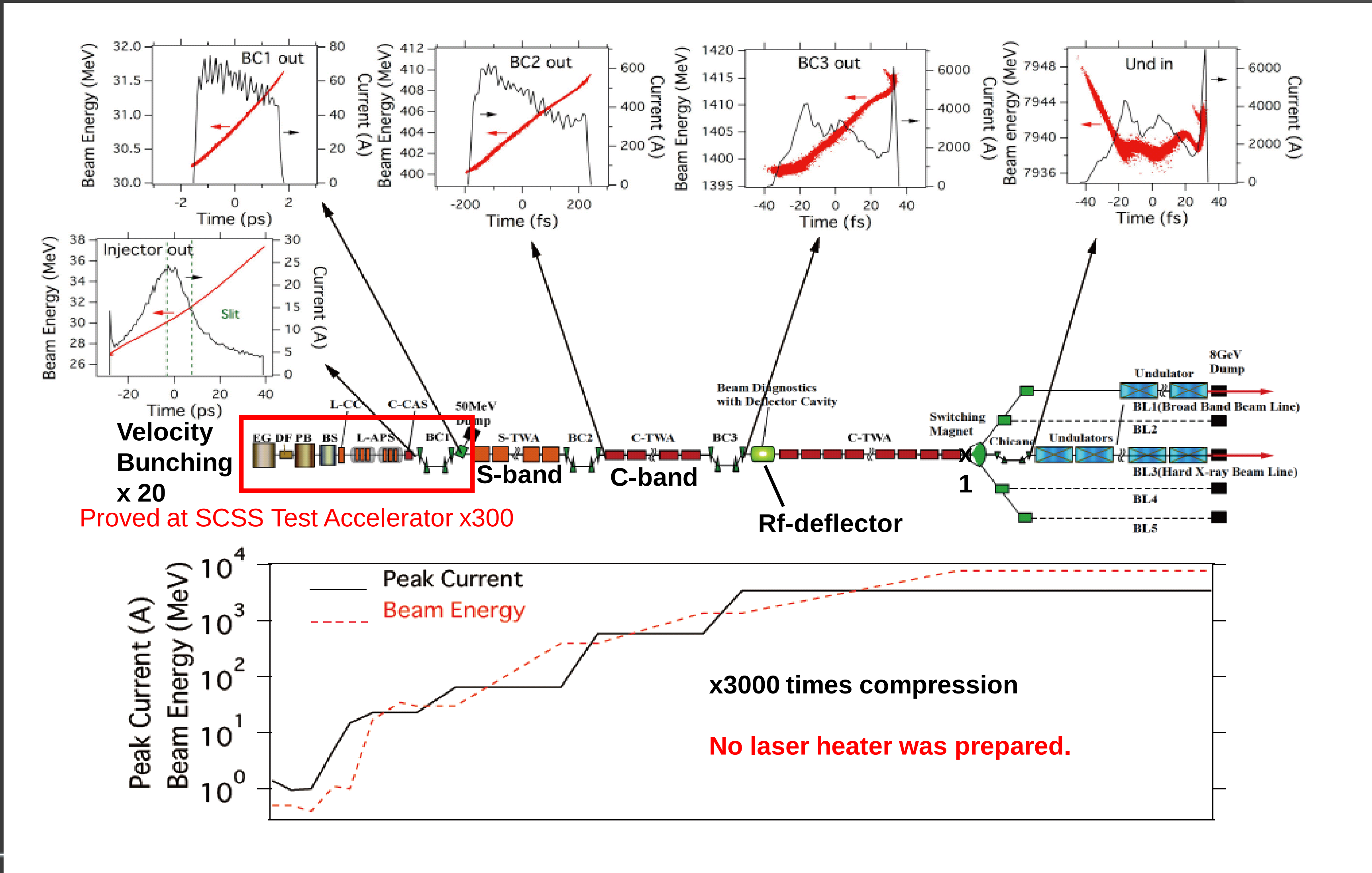
T. Shintake, "Choke Mode Cavity",
Jpn. J. Appl. Phys. Vol. 31 pp. L1567-L1570, November 19

Sadao Miura, MITSUBISHI Heavy Ind, April 2008

Higher Order Mode Damping for Multi-bunch operation.
Maximum 50 bunches x 1 nC, at 4.2 nsec spacing

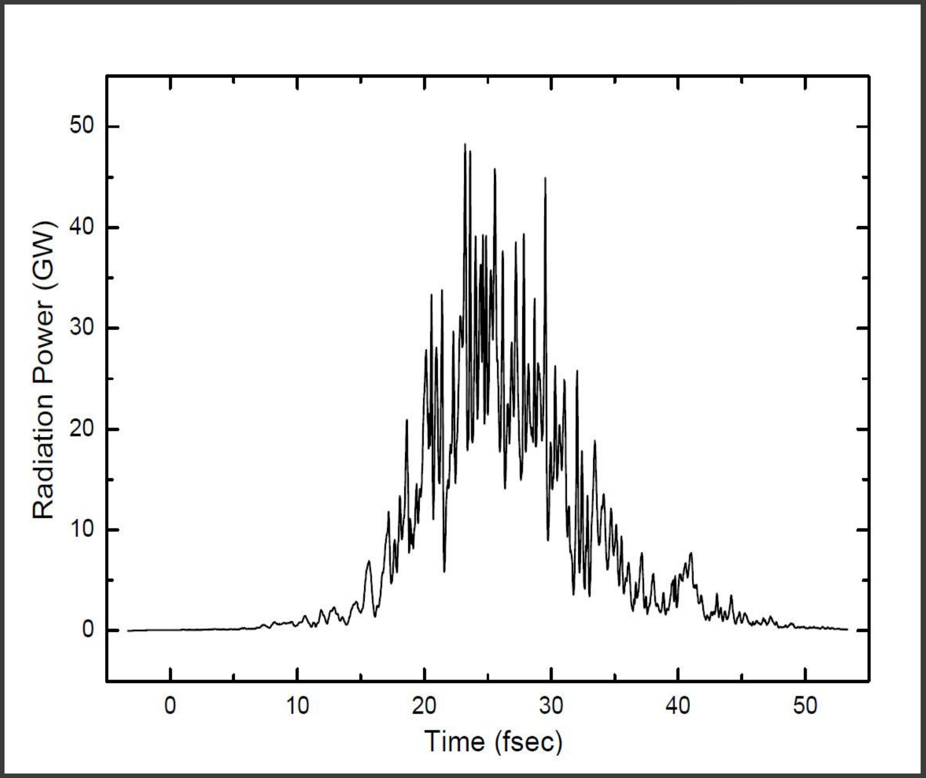
X-ray 4.2 nsec x 50 bunches will be key for
Single bio-molecule imaging to improve Luminosity.

Beam Accelerator and Compression



Expected perfomance

Wavelength	< 0.1 nm
Peak Power	~ 20 GW
X-ray Pulse Length	200 fs ~ 20 fs
X-ray Pulse Energy	Max 0.4 mJ
Photon Flux	2 x 10^{11} p/pulse
Peak Brightness	1 x 10^{33} p/mm^2/mrad^2/0.1% BW
X-ray Pulse Repetition	10 ~ 3000 pps (50 bunch x 60 Hz)
Bunch per Pulse	1 ~ 50 (4.2 nsec spacing)
e Beam	8 GeV x 0.3 nC 0.8 πmm.mrad, 3 kA

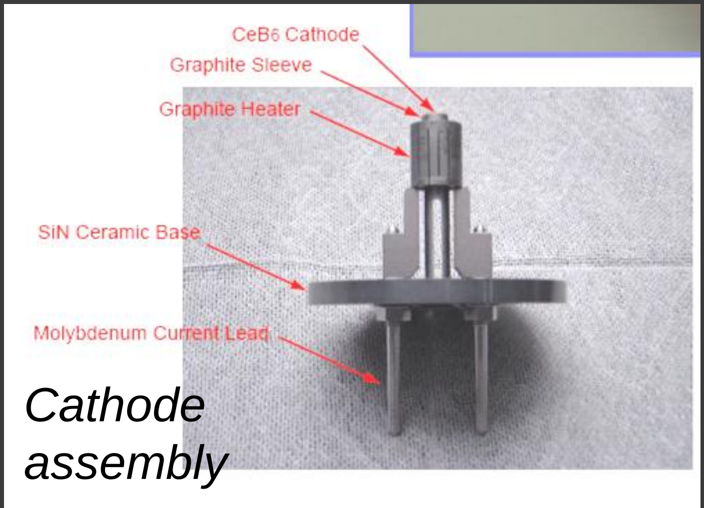


Expected X-ray pulse of 0.1 nm (SIMPLEX simulation)

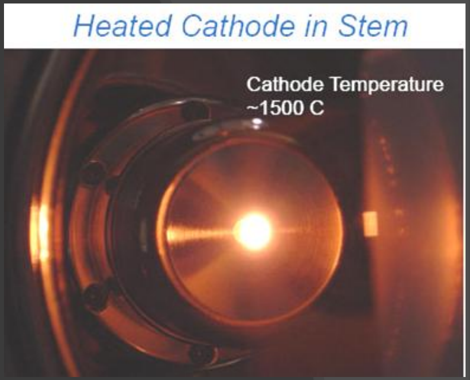
CeB6 thermionic electron gun

Use Small Cathode ϕ=3mm -> ε_{th} ~ 0.4 π mm mrad

Current density= 14~30 A/cm^2

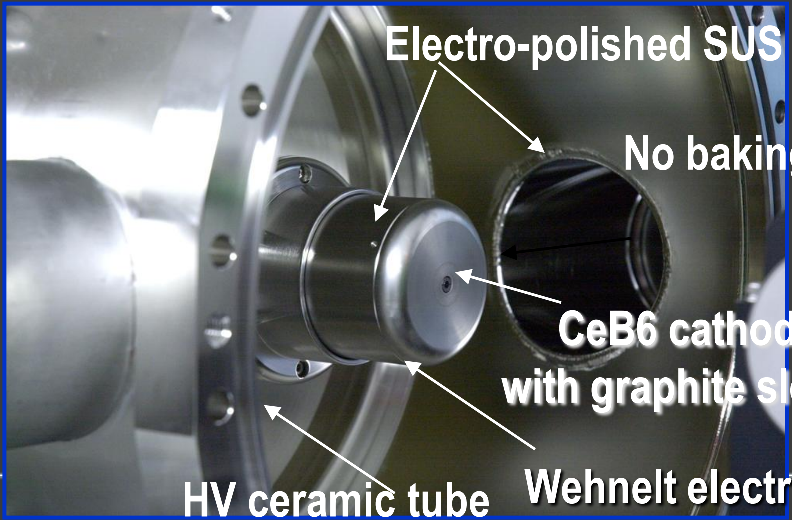


Cathode assembly



Ref. K. Togawa Phys. Rev ST-AB 10, 020703 (2007)

- **Applying 500 kV pulse.**
- **3 micro-sec pulse driven by klystron modulator.**
- **Gun sits inside HV pulse tank, filled with oil.**

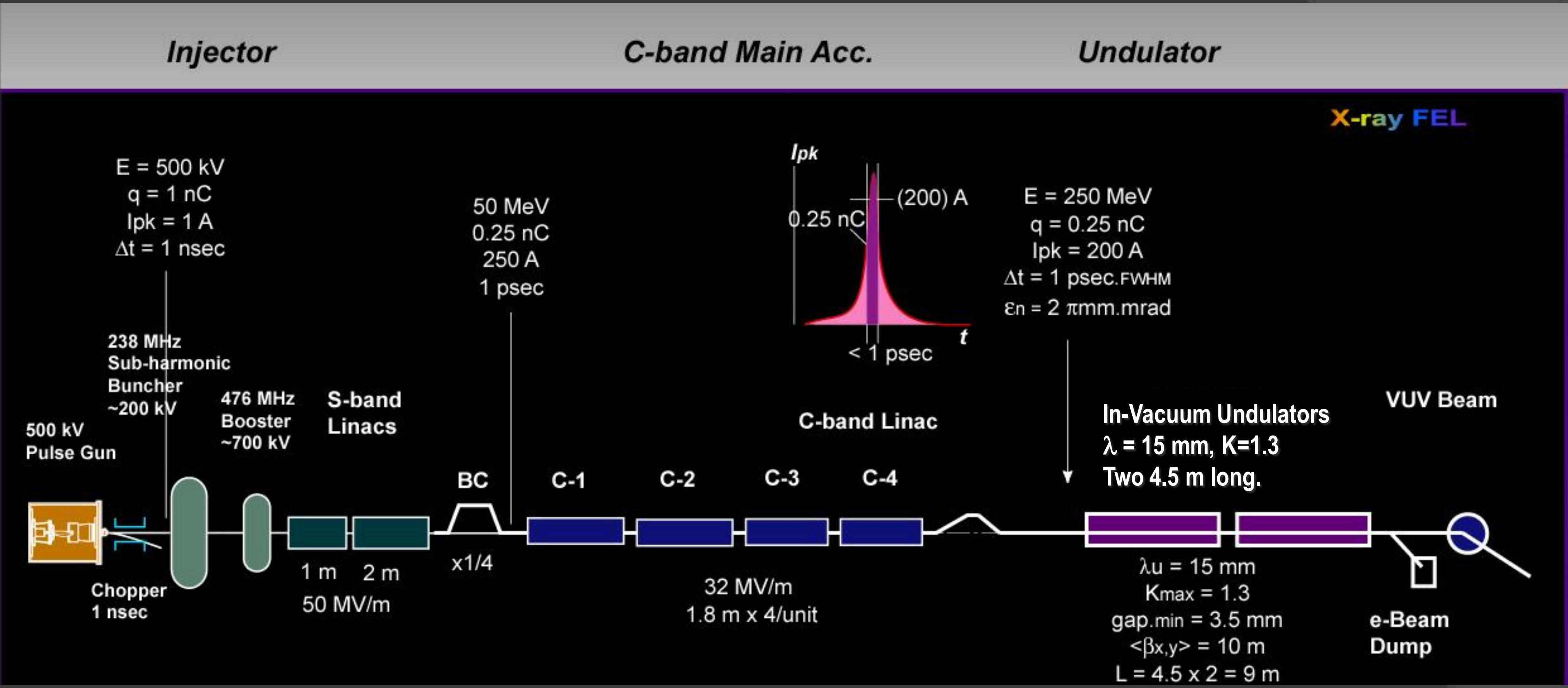


✓ No HV breakdown at 500 kV for 4 years, daily operation
✓ measured emit at the gun exit: 0.6 mm mrad (90% electrons)

XXV LINEAR ACCELERATOR CONFERENCE LINAC10 TSUKUBA, JAPAN SEPTEMBER 12 - 17, 2010

G. Penco

Test Accelerator Configuration

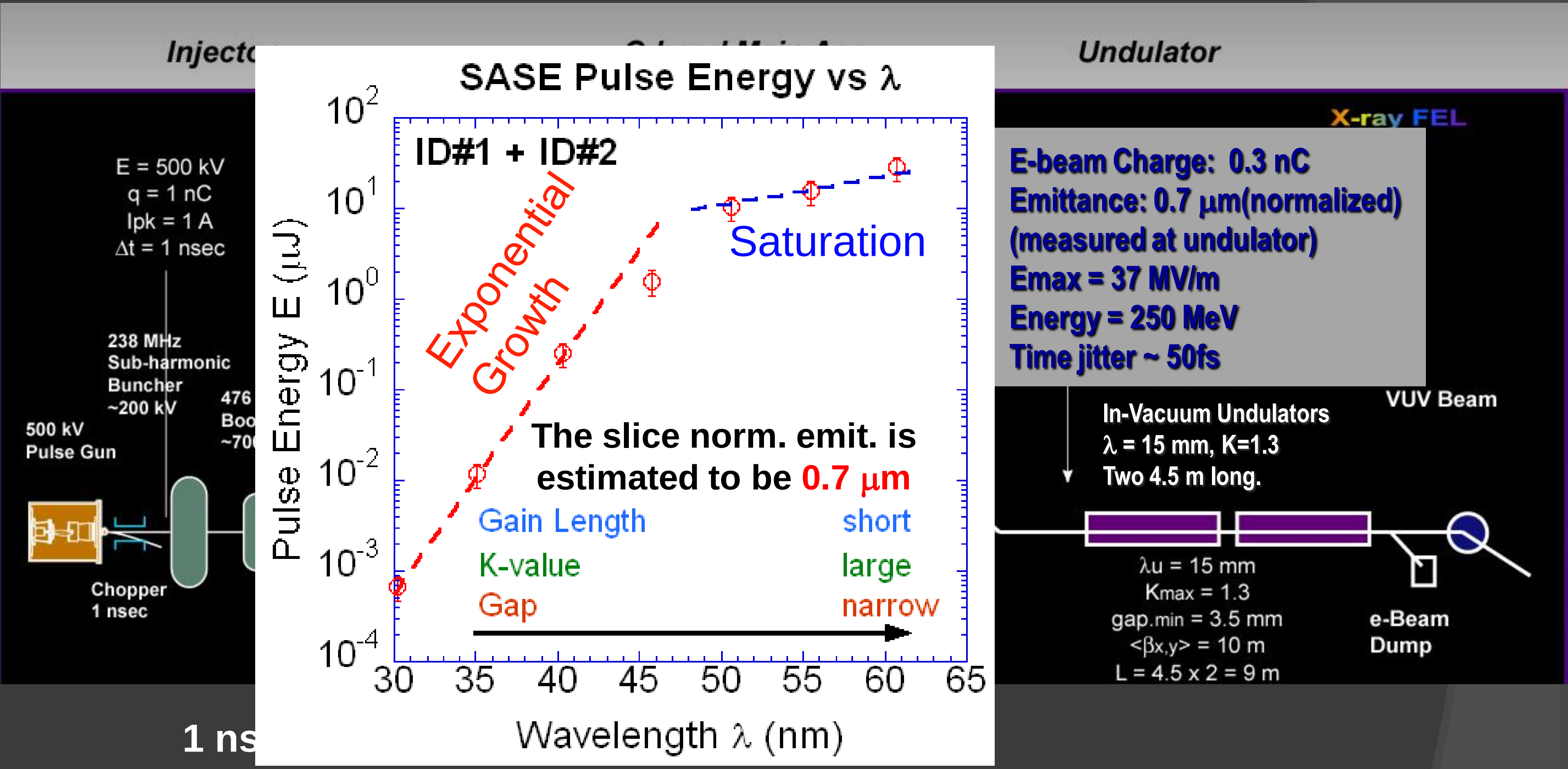


1 nsec (chopper)

1 A, 3 usec gun → **1 A, 1 nsec** → **300 ~ 800 A**
200 fs ~ 70 fs

Velocity Bunching x 100 ~ x 300

Test Accelerator Configuration

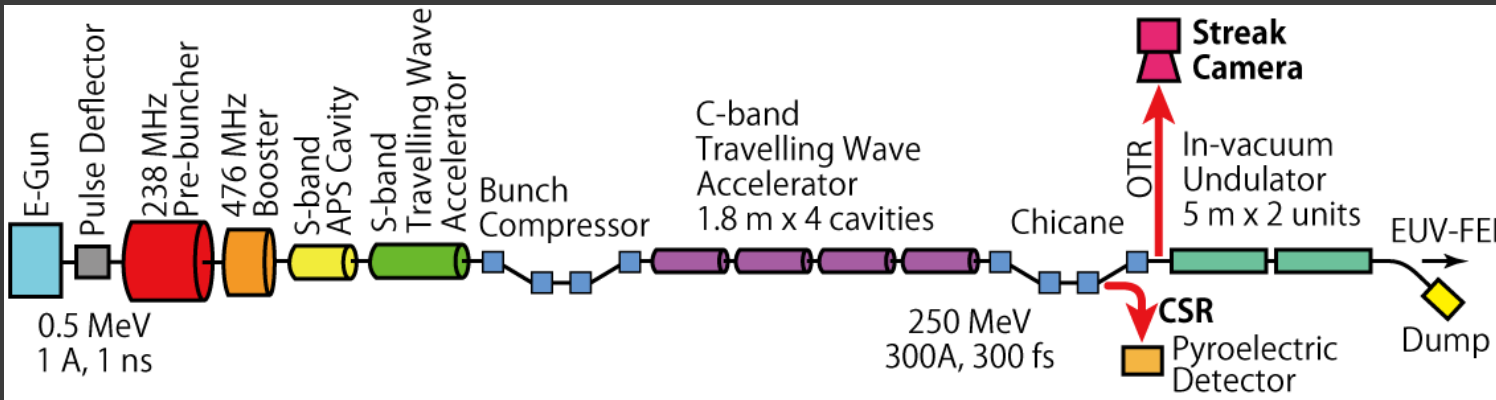


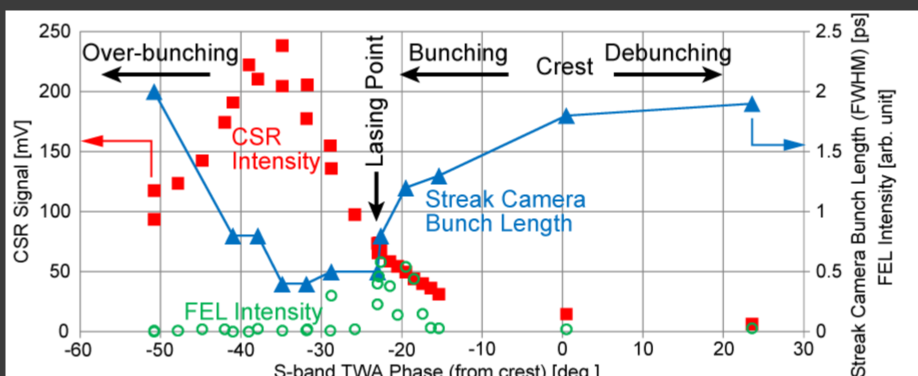
1 A, 3 usec gun → **1 A, 1 nsec** → **300 ~ 800 A**
200 fs ~ 70 fs

Velocity Bunching x 100 ~ x 300

Bunch length and timing jitter

Bunch length was monitored by a CSR monitor and a streak camera at the SCSS test accelerator. (ref. : H. Maesaka *et al, Fel 2010)*





- R56 = 20 mm in bunch compressor at 45 MeV.
- Incoming bunch length = 2 psec (0.6 mm)
- Max energy chirp 0.6 mm/20 mm = 3% at 45 MeV, 0.6% at 250 MeV
- Bunch compression factor x 1 ~ x 5

Thermionic cathode & velocity bunching system can generate short bunch (<50fs and in XFEL case <5fs) with small jitter (<50fs and in XFEL case <5fs+residual)

XXV LINEAR ACCELERATOR CONFERENCE LINAC10 TSUKUBA, JAPAN SEPTEMBER 12 - 17, 2010

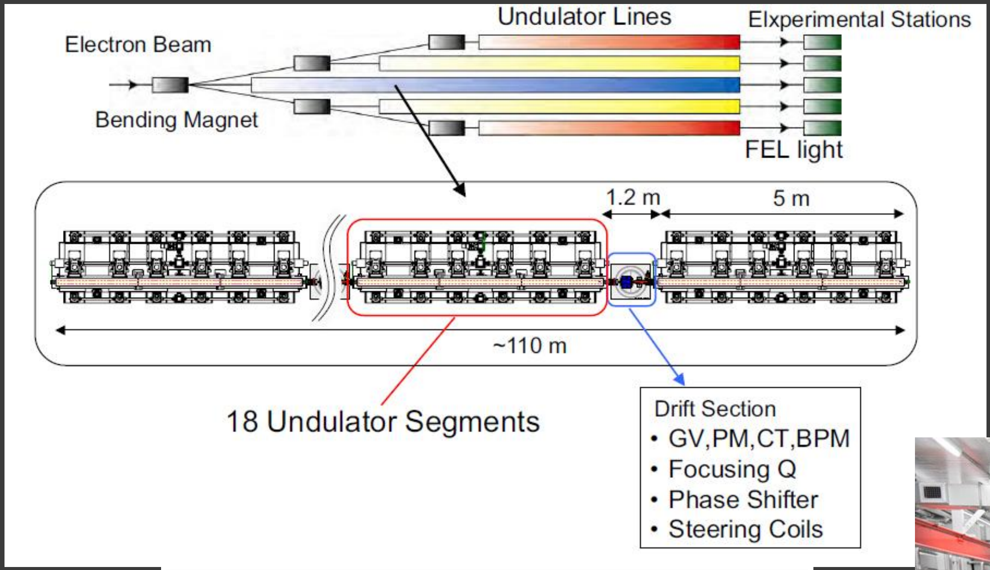
G. Penco

Thermionic gun produces "smooth beam"

- No CSR instability was observed.
- OTR, CSR radiations at chicane magnet are stable, for wide range of bunch compression change.
- → conclusion: there is no density modulation on incoming bunch into chicane compressor
- → **No laser heater is required for this system**

- Moreover, the CeB6 cathode has a long lifetime (>10,000 hours ~ 2 years)

Undulator line arranged for XFEL/Spring-8



Undulator Type		In-Vacuum Planer Undulator
Active Length		5 m
Undulator Period		18 mm
Magnetic Circuit		Hybrid (NdFeB+Permendur)
Peak Field	Maximum	1.31 T
	Nominal	1.13 T
K	Maximum	2.2
	Nominal	1.9
Gap	Minimum	3.5 mm
	Nominal	4.5 mm
Maximum Attractive Force		~ 6 ton

Summary and Schedule

- 2010 Sept. Complete installation.
- 2010 Oct. ~ 2011 Feb. High power processing.
- 2011 March First beam to the undulator.
- 2011 April - July ..... Beam commissioning, and the first FEL Lasing?

Thank you for your attention