X-FEL photoinjector concept

In collaboration with: Fermi National Accelerator Laboratory (USA)
North Illinois Center for Accelerator and Detector Development (USA)
Laboratori Nazionali di Frascati (Italy)

Overview

›Electron bunches required to drive a a SASE-FEL must have a high phase space density: typical requirements on transverse normalized emittances are in the mm-mrad regimes, and the bunch duration has to be sub-picosecond.
›Because of the required bunch brightness, the XFEL injector incorporates a photo-emission electron source based on an rf-gun.
›The phase space can (generally) only deteriorate downstream of the injector. The best achievable beam parameters at the FEL-undulator are thus determined by the injector performance.

Beam dynamics

Overview:
›A thorough optimization of the injector was performed using simple models, and various numerical simulations based on `HOMDYN` (a program based on a multi-slice model of the bunch), and `Astra` (that incorporates a particle-on-grid space charge algorithm).
›The chosen operating charge (consistent with SASE-FEL requirements) is Q=1 nC

Transverse phase space manipulation:
›The disadvantage of generating the bunch with a long photocathode laser pulse (20 ps) is rf-induced longitudinal emittance growth ($\varepsilon_z \propto \sigma_z^3$)
›Most of the longitudinal emittance is coming from rf-induced curvature

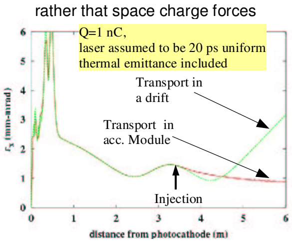
$$\delta(z) = \frac{V_{rf}(\cos(kz+\varphi) - \cos(\varphi))}{E_g + V_{rf}\cos\varphi} \approx \alpha_1 z + \alpha_2 z^2 + O(z^3)$$

›It can be corrected using higher-order accelerating field (e.g. 3[rd] order)

Transverse phase space manipulation:
›Transverse emittance of beam induced in rf-gun is correlated ➔ possible to partially reduce emittance
›``Emittance compensation'' scheme realized by focusing with a solenoid
›Downstream of the gun, the beam is injected in a booster linac
›Booster linac field amplitude is properly tuned (one solution being the so-called ``invariant envelope match'') so to shift the emittance minimum, that usually occurs in a drift downstream of the gun, at high energy:

$$\sigma_r = \frac{2}{\gamma}\sqrt{\frac{I}{3I_A\gamma_g}}, \quad \text{and} \quad \sigma_r' = 0.$$

›At high energy the beam transport is dominated by "emittance pressure" rather that space charge forces

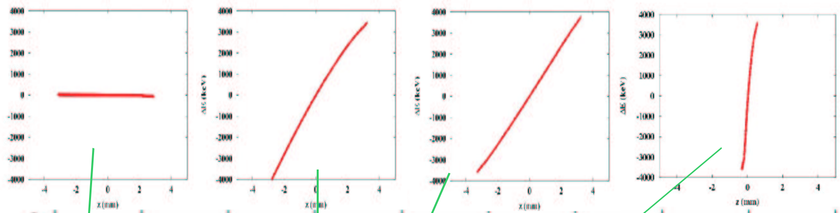


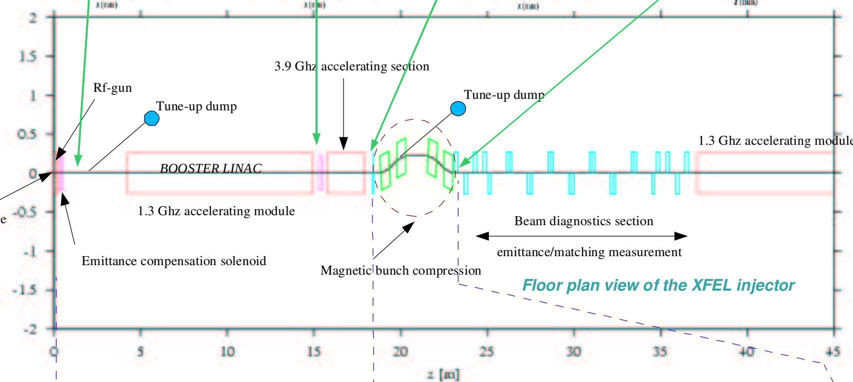
Required operating points for components

	parameter	nom. value	tolerance	unit
laser	σ_r	0.75	±0.05	mm
	L_t	20.0	±1.0	ps
	rise time	-	≤2	ps
	Q	1.0	±10%	-
	r-distrib.	Uniform	-	-
	t-distrib.	Uniform	-	-
gun	E_o	60	±0.3	MV/m
	ϕ	44	±2	°
solen.	$\hat{B}$	198	±1	mT

e 1: Requirements and tolerances on parameters settings for various elements of the electron source.

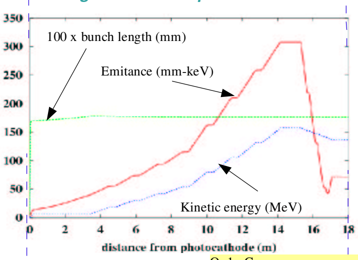
Longitudinal phase space manipulation

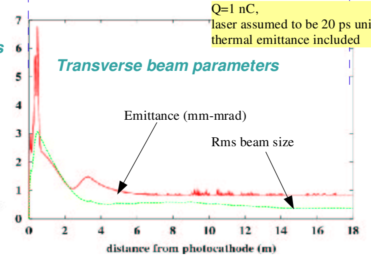




Floor plan view of the XFEL injector

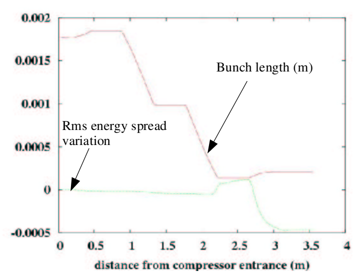
Longitudinal beam parameters





Transverse beam parameters

Magnetic bunch compression issues:
As the beam is being compressed in a magnetic chicane, the bunch may self-interact via its radiative self-field (coherent synchrotron radiation). The investigation of this intricate beam dynamics has been conducted with `CsrTrack` a self consistent tracking program that include bunch self-interaction via radiative effects.

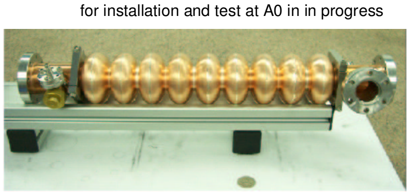


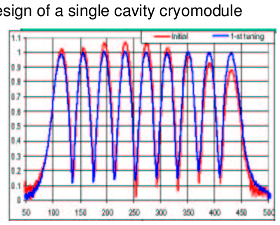
The bunch compression does not significantly impact the beam quality (projected transverse horizontal emittance growth is kept at about 10 % and slice emittance is not significantly affected)

On-going R&D toward the X-FEL photoinjector

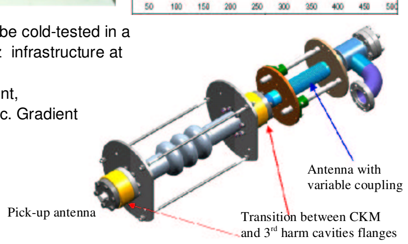
›**L-band accelerator test facilities in DESY-Zeuthen (PITZ) and FNAL (A0-photoinjector) for benchmarking numerical model used to simulate the dynamics of high brightness beam**

›**On-going R&D on 3.9 Ghz accelerating structure at FNAL:**
- a copper model has been produced
- field measurements have been performed (both accelerating field and HOM fields)
- a Niobium model is under realization and the design of a single cavity cryomodule for installation and test at A0 in in progress

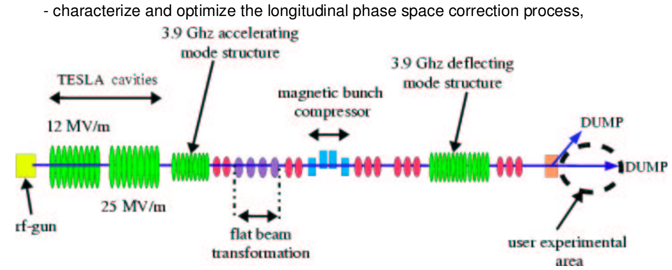




- 3-cell prototype cavity will will be cold-tested in a vertical cryostat of the 3.9 Ghz infrastructure at FNAL. The goals are:
  - Q vs accelerating gradient,
  - Maximum achievable acc. Gradient
  - Lorentz force detuning



› **Upgrade of the A0-photoinjector to include a high-gradient TESLA cavity, a 3.9 Ghz accelerating cavity and a deflecting cavity will provide a unique facility (within approximately one year from now) to study:**
- time-dependence (within the bunch) of the beam parameters,
- gain experience with simultaneous operation of rf-systems at 1.3 and 3.9 GHz,
- characterize and optimize the longitudinal phase space correction process,



The proposed upgrade for A0-photoinjector : "a ~1/4 scaled version of the X-FEL" injector

Conclusion

An XFEL injector was proposed in the frame work of the 2001 TESLA Design report. There is currently efforts at DESY (PITZ photo-injector) and Fermilab (A0-photoinjector) to study, optimize and benchmark numerical models pertaining to the dynamics of high brightness bunches produces in photoinjectors. Fermilab is also currently developing a Nb prototype for the 3.9 Ghz accelerating section required to linearize the longitudinal phase space. This cavity will also be tested with beam in A0-photoinjector.

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