Challenges of Linac Driven Light Sources

Carlo J. Bocchetta
ELETTRA

Limits of Ring Based Light Sources

	ϵ_x [nmrad]	E [GeV]	ϵ_x/E^2		ϵ_x [nmrad]	E [GeV]	ϵ_x/E^2
USRLS	0.3	7	0.006	SLS	4.4	2.4	0.763
PETRA III	1	6	0.027	ELETTRA	7	2.4	1.215
SPring-8	3.4	8	0.053	BESSY II	6	1.9	1.66
APS	3	7	0.061	Spear III	18	3	2
ESRF	3.9	6	0.108	MAX II	9	1.5	4
Diamond	2.5	3	0.2	ANKA	41	2.5	6.56
Soleil	3	2.5	0.48	DORIS III	450	4.5	22.2

From PETRA-III TDR Feb/04

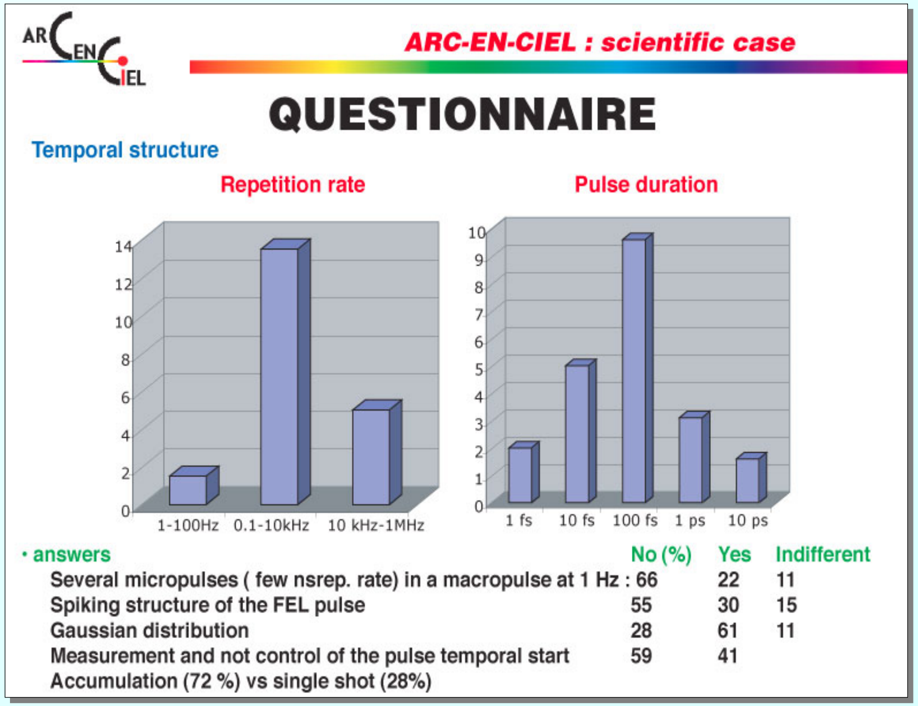
Minimum emittance ~ few nm-rad, 0.1% coupling
Brilliance ~ 10^{22} (ph/s/mm^2/mrad^2/0.1%bw)
Lifetime ~ 10's hours to infinity (top-up)
Pulse length ~ 10's ps (slicing possible but low flux)
Stability ~ 10^{-2} beam size
Partial coherence

Users ask for shorter brighter pulses for new types of experiment

User Requirements from New Sources

Shorter pulse lengths ~ 100 fs to 100 as (or less)
Flexible time structure ~ 10’s Hz to 10 kHz and CW
Higher Brilliance ~ 10^{32} ph/s/mm^2/mrad^2/0.1% bw
High Average Flux per pulse ~ 10^6-10^{13} ph/pulse/0.1% bw
High Peak Power ~ 10’s GW
Fully coherent radiation - spatial and temporal
Tuneability and synchronisation to external lasers ~ to 10 fs
Fully tuneable polarised light
Broad spectral range ~ 100 - 0.1 nm
Shot to Shot Reproducibility

Courtesy: M. E. Couprie



Linac Based Light Source

Beam properties determined by the injector - transverse & longitudinal

Peak currents tailored by bunch compressors

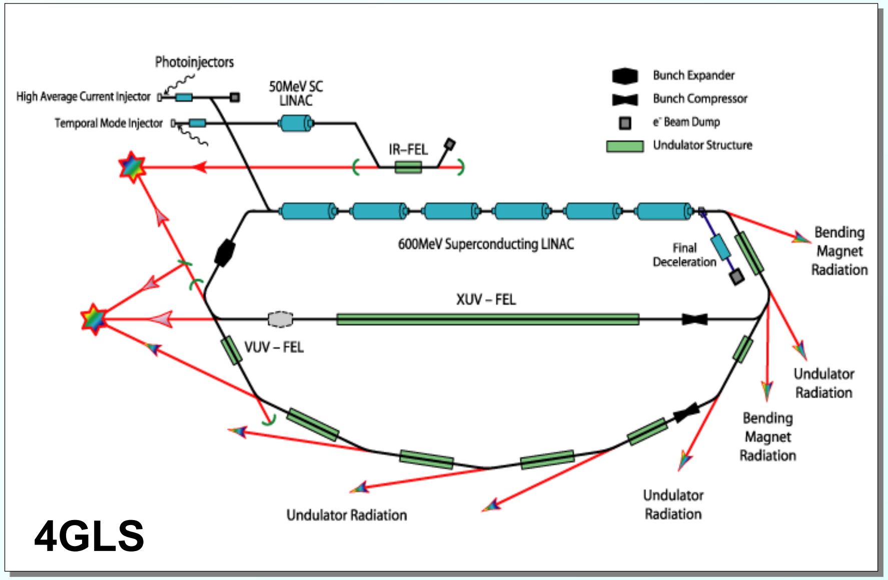
Single (or few) passes through the machine - no equilibrium state

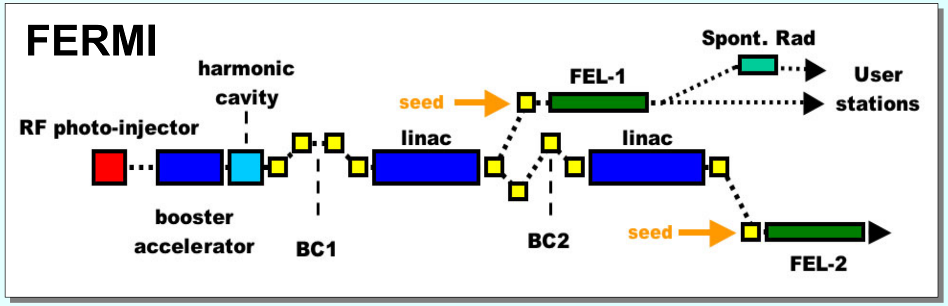
No lifetime issues (vacuum or IBS). Different class of instabilities BBU,CSR,LSC

Flexible operation modes - Laser control or fast kickers

SASE or seed schemes (i.e., HGHG) for FELs

For high current CW machines energy recovery is possible





Electron Beam Source

The electron gun is the most important component of a linac based light source

The photo-cathode gun is the candidate for most projects
An topic of intense R&D

Beam qualities produced are
- Emittances of a few mm-mrad or less
- High charge in a short pulse 100 to 1nc
- Pulse lengths ~ 1 to 10s ps

Note: 500 kV Pulsed HV gun development at SPring-8 Compact SASE Source (SCSS)
CeB_6 cathode heated to 1500 °C
1 A peak current in 3μs pulse, 60 Hz
Measured ε_n ~ 1.1 πmm-mrad

Courtesy T. Shintake

DC-Guns

High repetition rate, good vacuum conditions with low electric fields

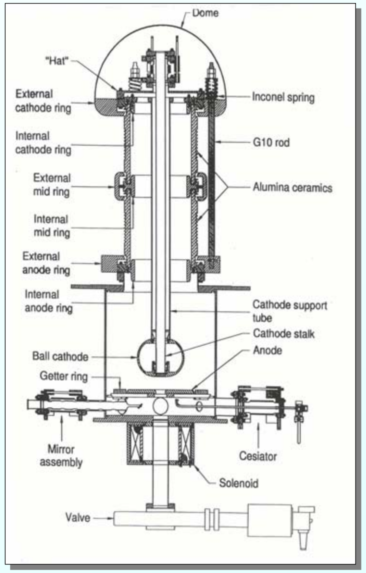
State of the art FEL gun at JLAB

High repetition rate up to 75 MHz

$\varepsilon_{N,rms}$~7-15 mm-mrad for Q~ 60 –135 pC

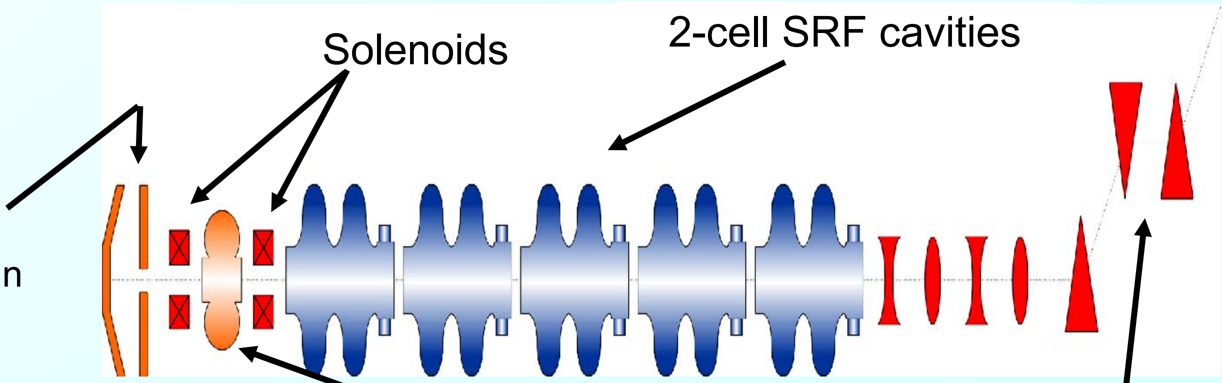
Average current up to 9 mA

Cathode voltage: 350 – 500 kV



Similar gun being constructed at ERLP, Daresbury

Cornell ERL Prototype Injector proposal



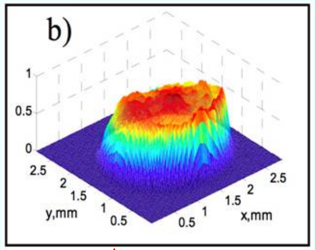
5-15 MeV, L-band

ε_n ~ 1 mm-mrad, 77 pC, 3ps

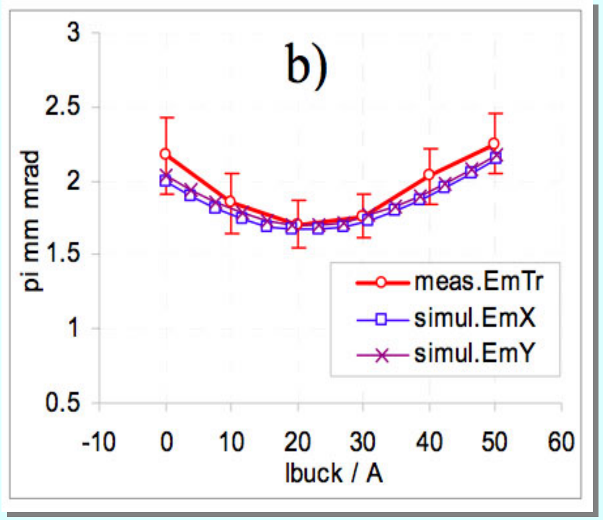
RF-Guns

NC pulsed RF guns - Low repetition rate
Routinely used for high intensity and high electric fields
Up to 120-140 MV/m S-band, 40-80 MV/m L-Band

Example: Pitz Gun - Installed in VUV-FEL
Cesium Telluride cathode
L-Band, 1-10 Hz, 900 μs RF Pulse, 42 MV/m
Max average power 27 kW
ε_n ~ 1.7 π mm-mrad, 1 nC
Laser pulse ~20 ps, ~7ps rise time



Laser quality is fundamental for good emittance
Good understanding of the beam dynamics



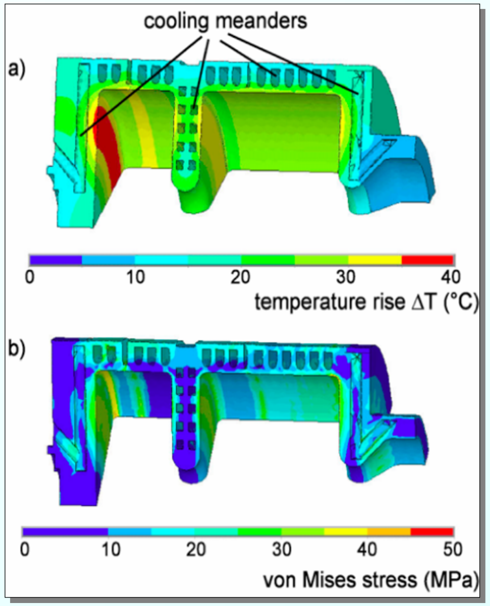
Future developments - for 0.9 π mm-mrad, 10Hz, 650 μs
- Improved transverse laser profile
- Improved longitudinal laser pulse, better rise times 2ps
- Increased accelerating gradient to 60 MV/m

RF-Guns

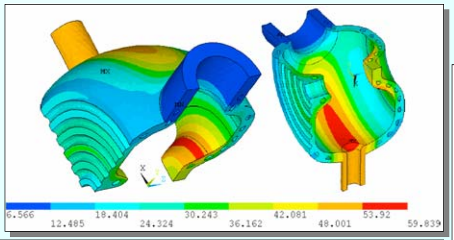
At kHz repetition rates the power dissipated in a NC gun can be very large

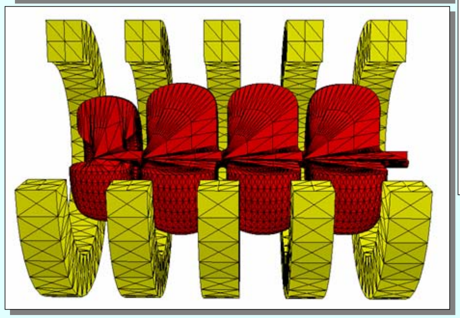
- Thermal drifts produce RF phase and amplitude mismatch
- Requires well optimised cooling and/or power extraction

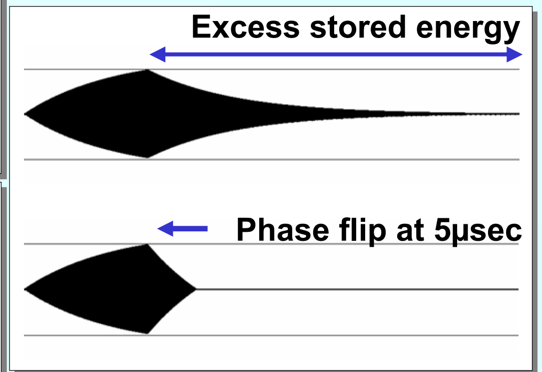
Modification of **PITZ Gun** (1.3 GHz) for the **BESSY FEL**
1 kHz,6μs Bunch train, 40 MV/m,
75 kW average power in gun.
Thermal optimisation.



LUX Gun - to provide 20-30 ps pulses, 1 nC, 2 πmm-mrad at **10 kHz**, Acc Field 64 MV. 5 μs pulse. **RF Dissipated power 31.3 kW** (surface power 98 W/cm^2).
Propose to use SLED type power removal by change phase of the klystron.

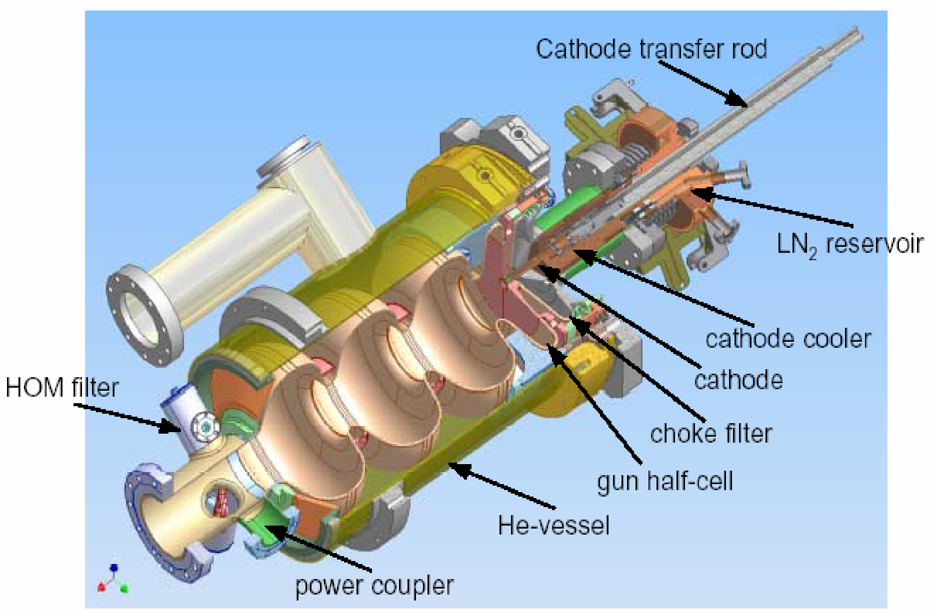






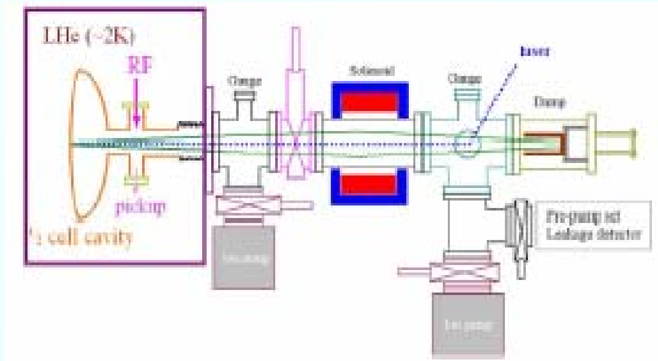
RF-Guns

SRF is the solution for CW high RF fields - Important R&D topic

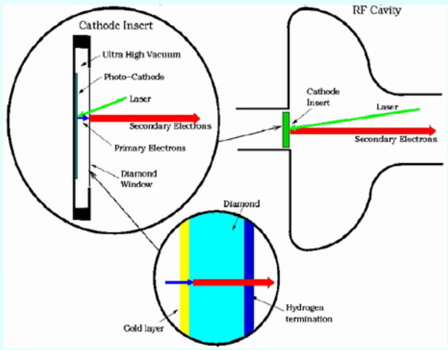


3 + 1/2 Cell ELBE Gun
CsTe Cathode
1.3 GHz, 10 MeV
77 pC at 13 MHz and 1 nC at < 1 MHz

First RF tests in early 2005



BNL/AES/JLAB development
High I_{ave} & brightness gun under test:
1.3 GHz 1/2-cell Nb cavity at 2K

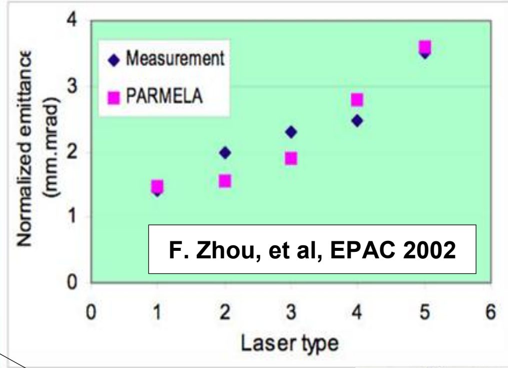


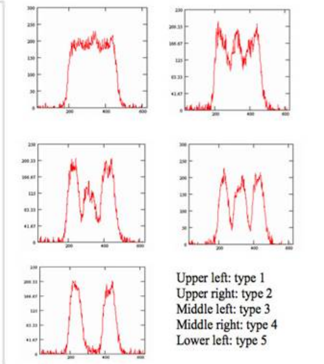
BNL Proposal
SRF gun
with diamond
amplified cathode
Q.E. ~ 1000%

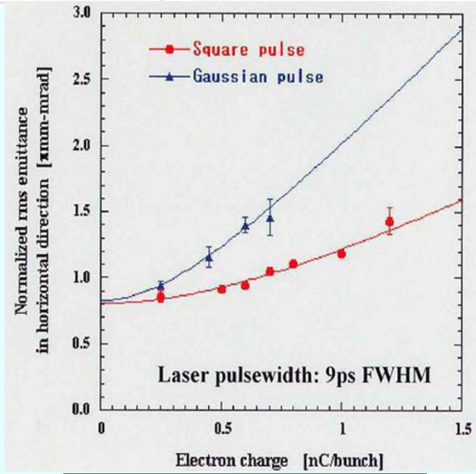
Laser System - Profile

- Control of the properties of the photocathode laser is mandatory for the generation and preservation of low emittance beams.
- Requires transverse and longitudinal homogeneous pulses (10s ps) with fast rise and fall times (~ 2ps)

- Several techniques exist: Spectral Pulse Shaping, Acousto-Optic Programmable Dispersive Filter (Dazzler) Area of R&D

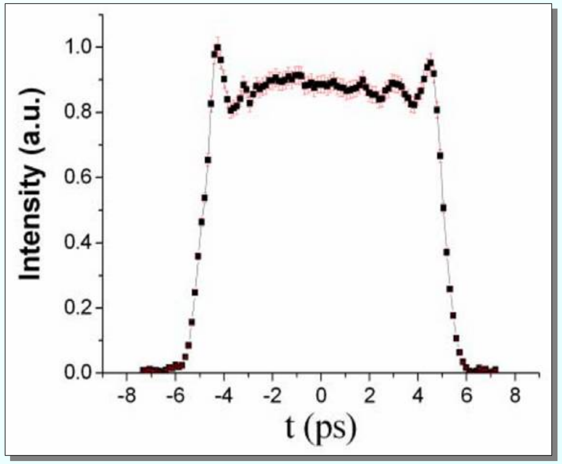


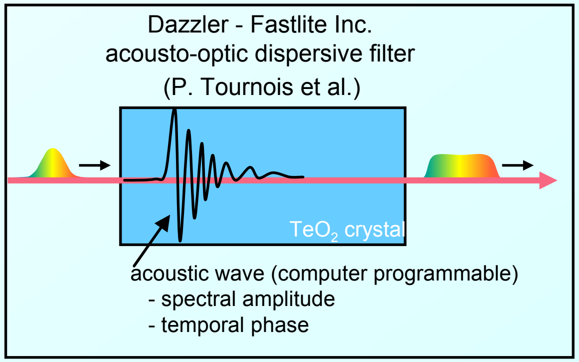


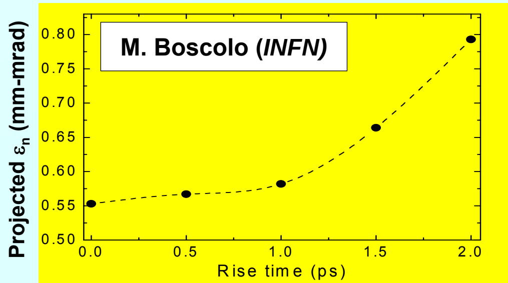


F. Sakai, ICFA 2002, SPring8

INFN Group for SPARC (C. Vicario, EPAC04)
Rise/fall times < 1ps, overshoot < 15%



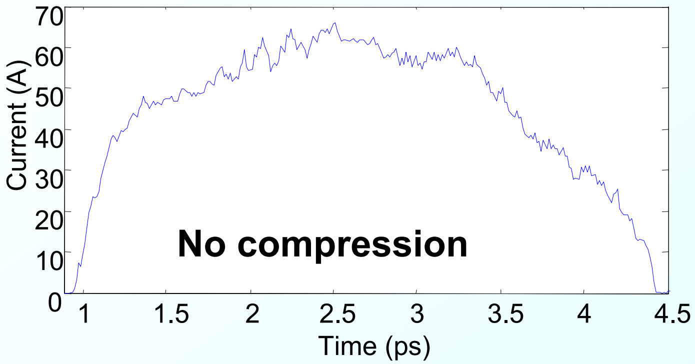


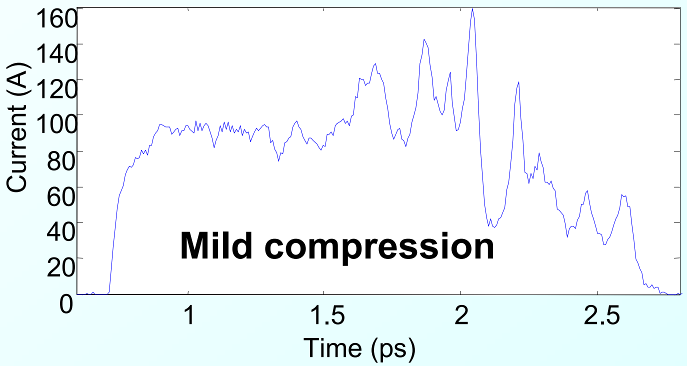


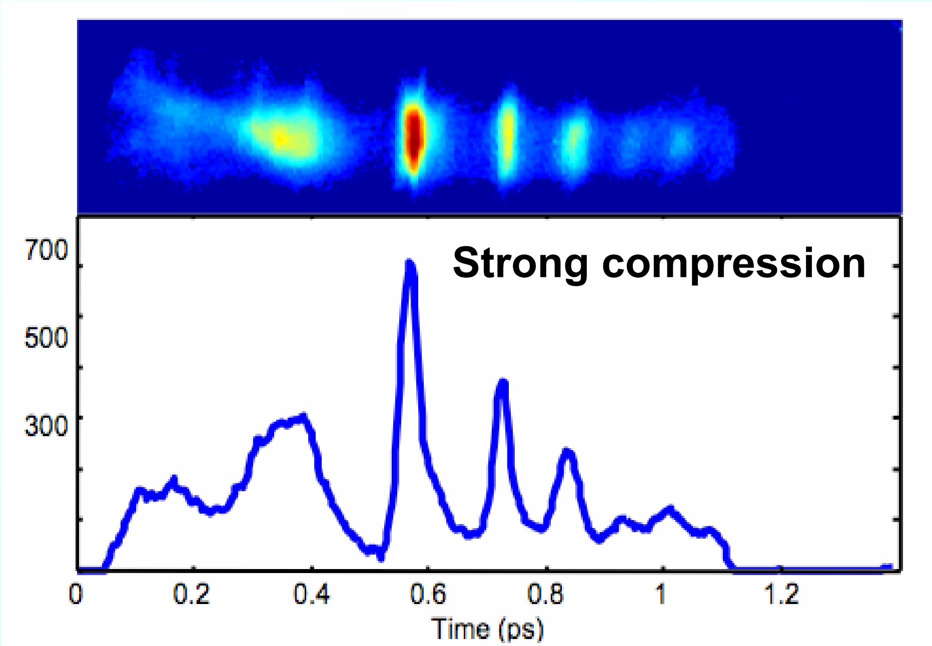
Generating High Peak Currents

To generate kA need to compress the beam, but have to consider induced μ-bunching instabilities generated by Coherent Synchrotron Radiation (CSR), Longitudinal Space Charge (LSC) and Linac wakefields

Microbunching and beam break-up in DUV-FEL Accelerator
T. Shaftan *et al*., PAC 2003







Generating High Peak Currents

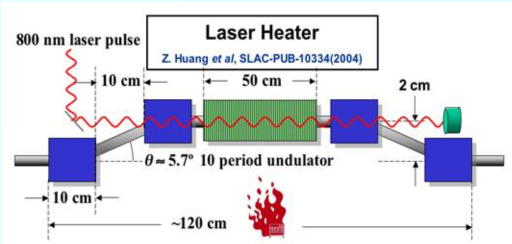
CSR
Generates microbunching in BC's.

Challenge: Reduce density spikes use Higher Harmonic sections.
'Multiple' Optimised BC's (weak bends, stronger compression in earlier BC's)
Slow wave compression (*need to consider space charge*)

LSC
Oscillations between current density & particle energy at low energy.
Modulations freeze at high energy and are strongly amplified in BC's.
Source is laser in-homogeneities.

Challenge: Flat-top laser pulse, transversally homogeneous.

Alleviate μbunching effects by:
Extensive optimisation (Needs **continual** work on program codes)
Increase local energy spread at injector
laser heater SLAC →



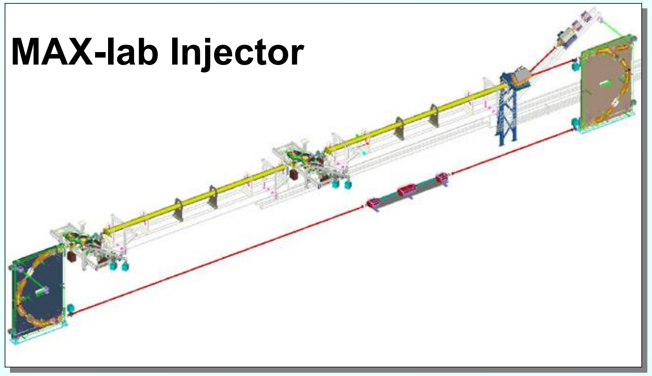
Reconsider types & numbers of BC's in view of μbunching (normal 4 magnet chicane performs better than S-Chicane, XFEL)

Recirculating Linac - Optics & ER

Optics have to guarantee

360° Transportation (with phase shift for deceleration)

Optimisation of longitudinal & transverse phase space for Photon production and beam dump



- **Take into account incoherent and coherent SR** - ***TBA optics for HE machines***
- **Tuning of (arc) optics (R56 and R566) for bunch compression/decompression**
- **Correction of non-linear effects from acceleration (Higher Harmonic cavities)**
- **Compensation of FEL disrupted beams (~10% $\Delta E/E$)**
- **Maintain nm structured beams for distribution (LUX)**

Challenges

Correction of non-linear phase space distortions for minimum bunch length and ER

Minimise emittance growth (incoherent & coherent radiation)

Operational control of transporting beams with $E_{final}/E_{injected}$ > 50 in same channel

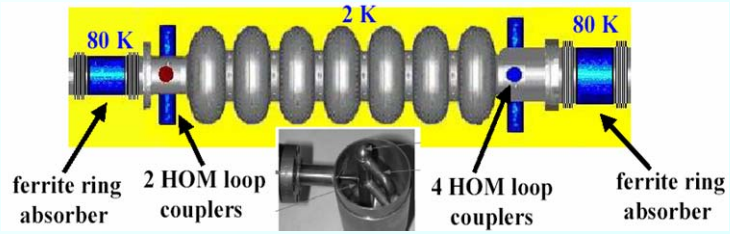
(successful CEBAF E_{final}(1GeV)/$E_{injected}$(20 MeV) ~ 50 in 2003 - no ε degradation)

Energy Recovery Linacs - High Current

Higher Order Mode power dissipation

High average currents, short bunch length beams excite HOMs
HOMs extend to high frequencies ~ 100 GHz
Places a load on the cryogenic system (~100s W)
HOM damping and efficient HOM extraction at cryogenic temperatures is required

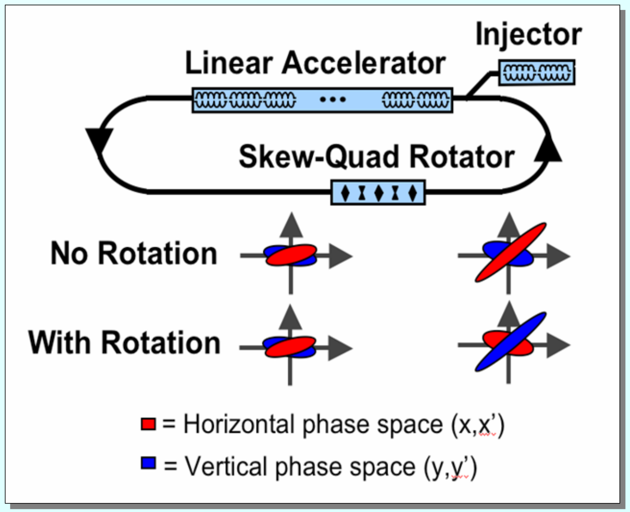
HOM damping scheme for the Cornell ERL



Beam Break Up

A transversely offset beam in a high Q SC cavity excites HOMs that interact on return path.
Can limit maximum current: $I_{threshold}$ ~ 100 mA
Challenge: avoid BBU

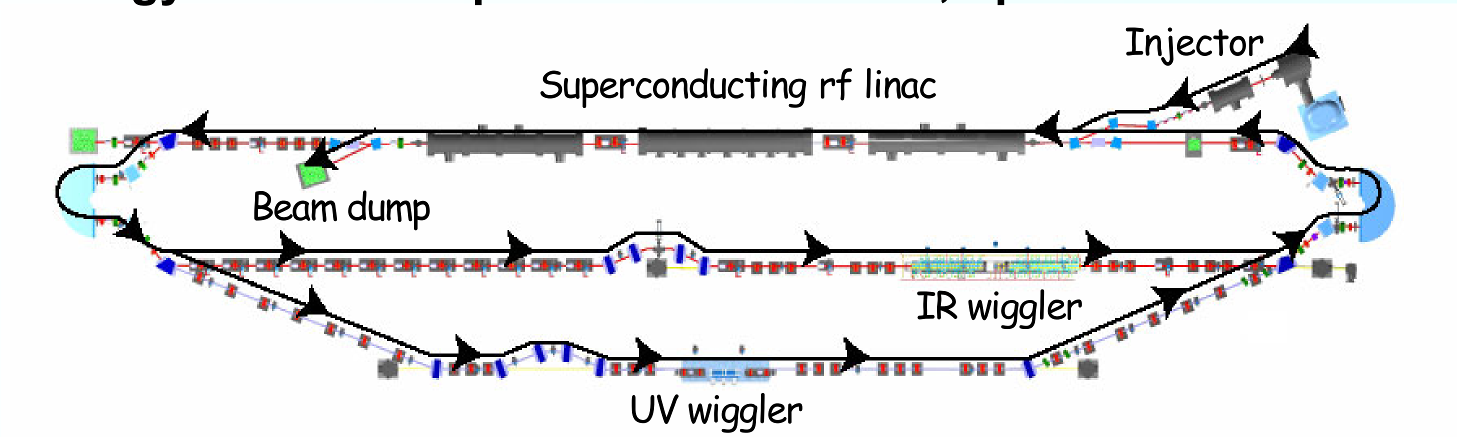
- Rotating Beam Optics at JLab
- Lower frequency SRF 700 MHz -> 1 A threshold
- 'bunch by bunch' Feedback Systems

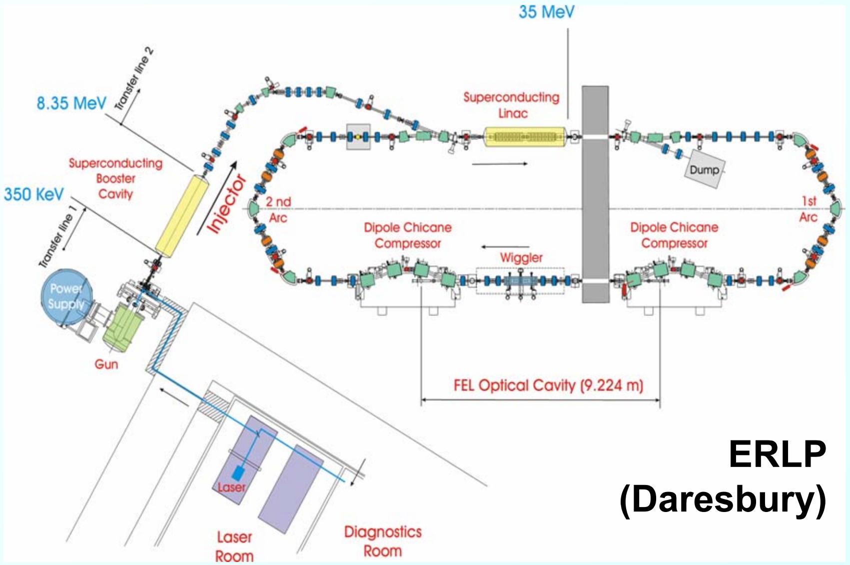


Courtesy L. Merminga

ERL Example Activities

JLab 10kW IR FEL and 1 kW UV FEL
Achieved 8.5 kW CW IR power on June 24, 2004
Energy recovered up to 5mA at 145 MeV, up to 9mA at 88 MeV





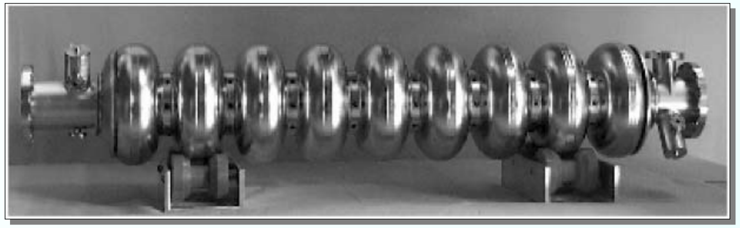
ERLP (Daresbury)

ERLP - First EU ERL - In construction
Prototype to test ER, guns, compression, effects of FEL operation, arc optics, ...

Similar activities envisaged at KEK and Cornell (100 mA)

TESLA SC Accelerating Modules

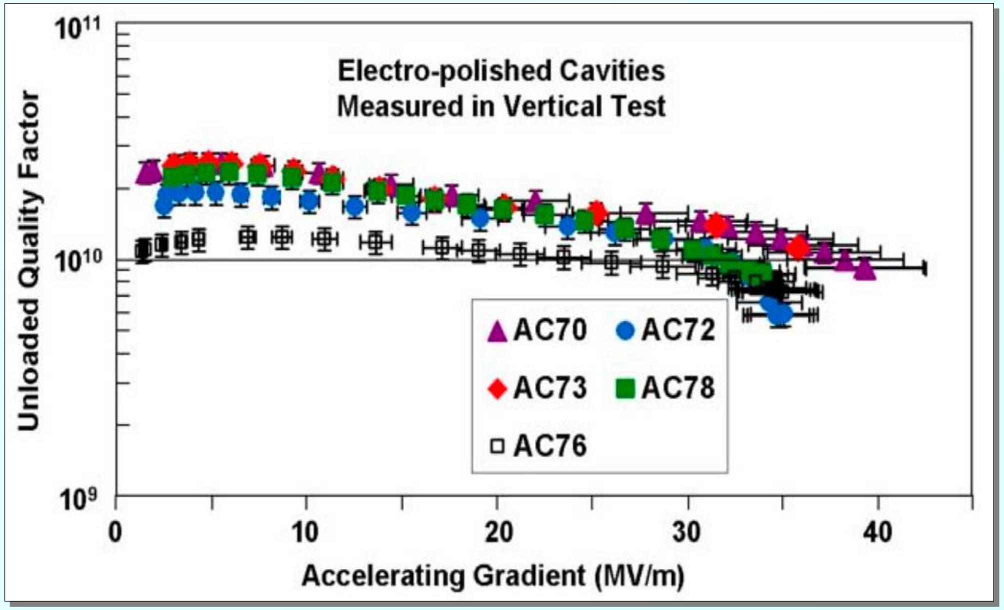
Many Projects are based on the TESLA cavities and cryomodules
Taking advantage of extensive LC activities.



XFEL, VUV-FEL, 4GLS, ERLP, LUX, BESSY-FEL, MIT, ARC-EN-CIEL, KEKP, ...

Electro-Polished Cavities have reached up to 39 MV/m.
One cavity installed in VUV-FEL and has accelerated beam at 35 MV/m ($Q_0 \sim 10^{10}$)

An area of continual activity
- Higher Gradients
- Compensation of Lorentz detuning - mechanical or piezoelectric/feedforward
- Design & assembly procedures for Industrial mass production



TESLA SC Accelerating Modules - CW

CW Operation permits high repetition rates, fully flexible bunch patterns and higher beam stability

Need to consider heat load dissipation
Modifications to TESLA cryomodules are required
CW Cryogenic costs lessened by operating at lower gradients ~ 15-20 MV/m

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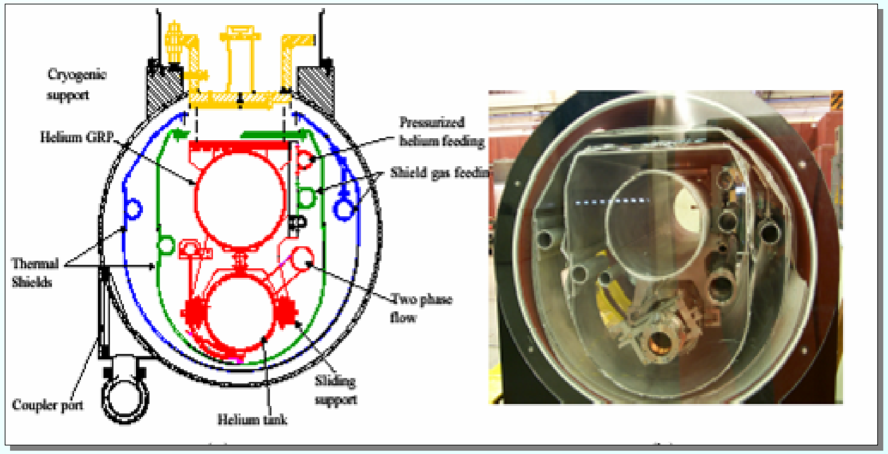
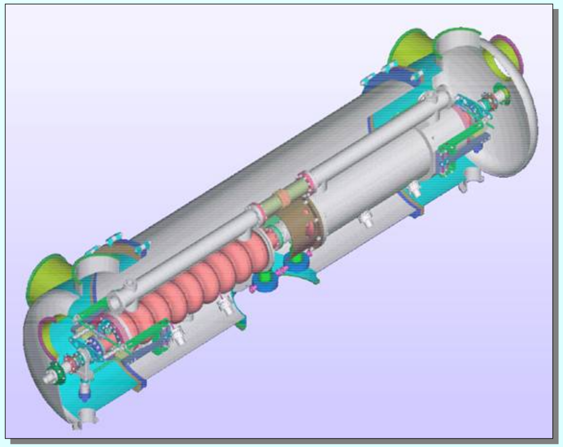
BESSY-FEL
Modifications to TESLA cryomodule
at the 2pHe-line and "chimney" to cope with the ~25 W heat load at field of 16 MV/m



ERLP - Daresbury
Will use a modified ELBE cryostat containing 2 9-cell cavities.
15 MV/m, 50 W dynamic load



BESSY HoBiCat - Teststand

Will address technological issues related to near CW FEL operation and also to quantify industrial production.

RF control at high loaded Q
Causes and impact of microphonics
Tuner characterization
Fast piezo tuning
Pressure stability and cryogenic operation
CW operation of input coupler
Q measurements as f(*T*)
Determination of optimum bath temperature
etc.

Commissioning started spring 2004

Courtesy: Dieter Krämer

Diagnostics

Fundamental for

- **Machine optimisation & protection**
- **Optimisation of the light production (FELs) and tuning**
- **User Experiments**

Challenges: Many diagnostics are still R&D

- **Timing and Synchronization required to 10's of fs**
- **Measure electron bunch slice parameters (100 fs bunch lengths)**
- **Measure photon pulse duration & temporal structure**
- **On-line non-destructive pulse to pulse characterisation (for feedback)**

Some techniques are (J. Feldhaus EPAC04 for VUV-FEL diagnostics review)

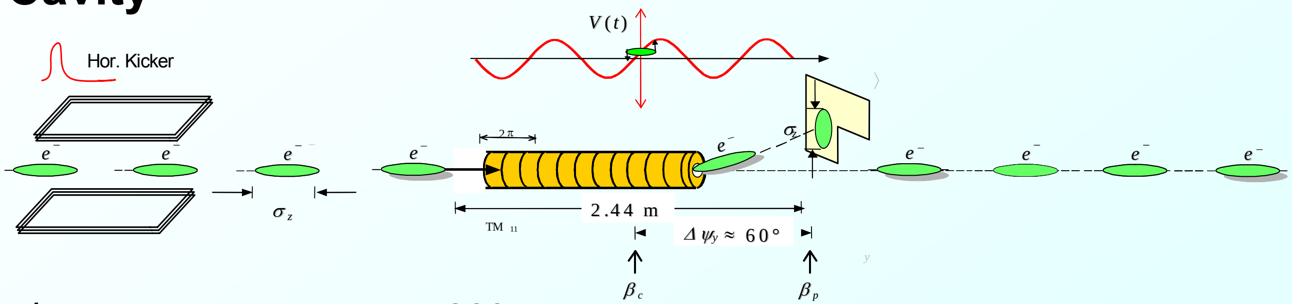
- **e-bunch laser interaction EOS**
- **Transverse Deflecting Cavities**
- **Coherent FIR**
- **Gas Ionisation detector**
- **VLS spectrometer**

Many diagnostic techniques will be implemented and tested at VUV-FEL and the SPARC test-facility

Diagnostics - Examples from VUV-FEL

Transverse Deflecting Cavity

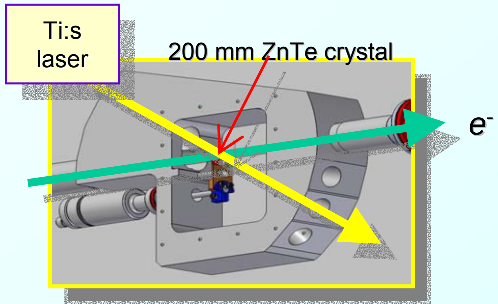
Intra Beam Streak Camera
“Easy” to synchronize
Uses direct beam image
Most straight forward



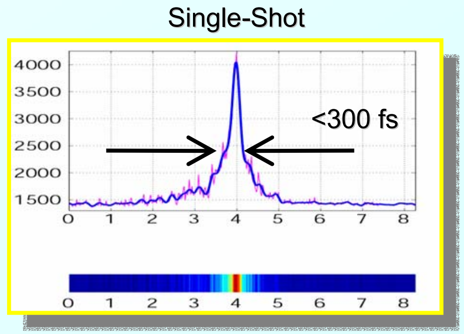
DESY/SLAC collaboration - Testing on VUV-FEL autumn 2004

Electro Optical Sampling

Non-intercepting bunch length measurements.
Can measure bunch profile and timing.



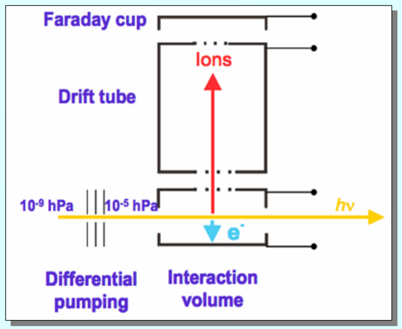
e^- temporal information is encoded on transverse profile of laser beam



DESY/SLAC/U. Mich collaboration - Will be installed on VUV-FEL, Commissioning at SPPS

Gas Ionisation Detector

Photon Pulse Energy Measurement
Transparent
Large dynamic range
Absolute calibration
Independent of beam position, can measure beam position

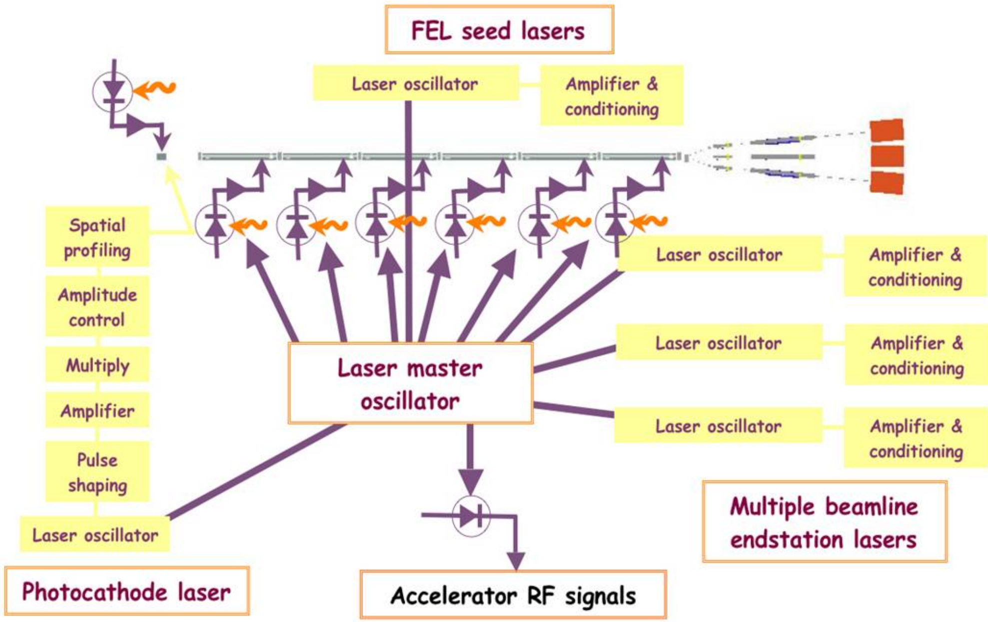


Timing & Synchronization

- **A timing system is required to trigger accelerator systems, provide waveforms for rf systems and synchronization of experiments.**
- **Synchronization is required for pump-probe experiments/diagnostics and needs a stable timing distribution system.**
- **Lasers are an integral part of timing and synchronization**

LUX - Example minimisation of jitter between pump laser and X-ray pulse via:

- Stable optical master oscillator
- Actively stabilised optical fibre distribution
- Phase locking all lasers to master oscillator
- RF signals from master oscillator



J. Corlett - http://www-ssrl.slac.stanford.edu/lcls/xfel2004/index.html

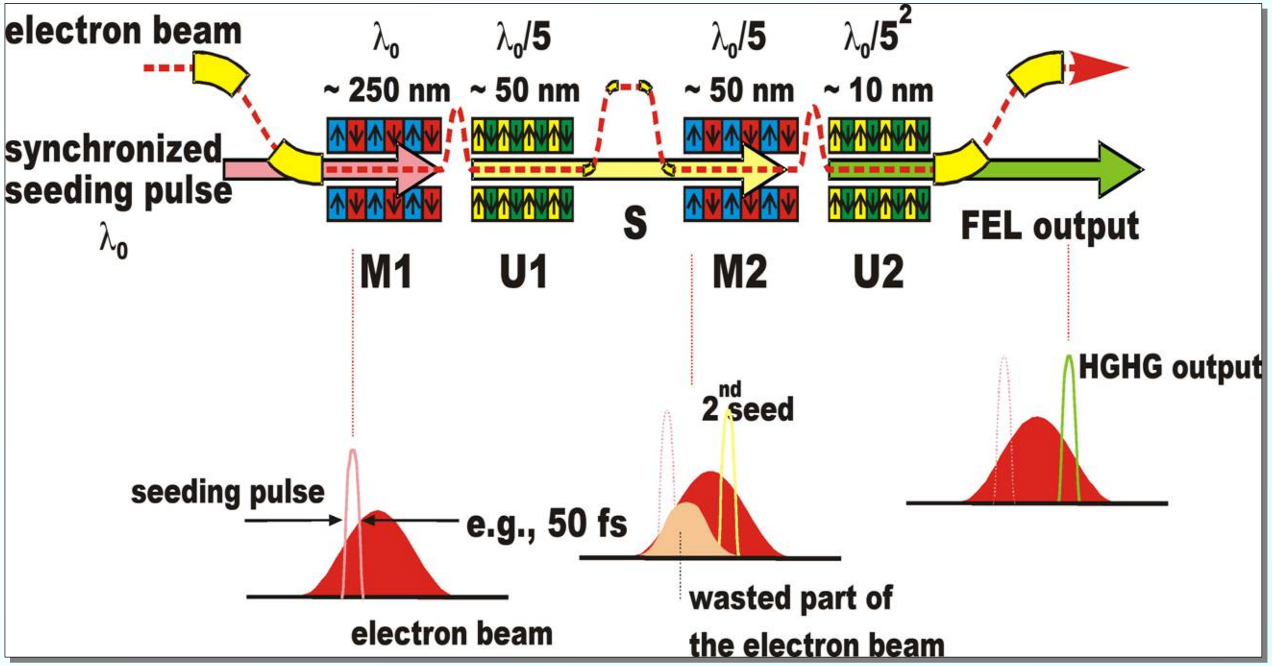
Although two lasers can be synchronised to < fs, we need

- **Demonstration of ultra-stable timing to 10s fs based on optical fibre distrib.**

High Gain Harmonic Generation

Many VUV - Soft X-ray machines adopting a seeding scheme for FEL radiation

More compact and fully temporally coherent source, short pulses & greater control of spectral parameters.



FERMI 40 to 10 nm FEL - 2-stage cascaded HGHG

DUV-FEL
A. Doyuran, *et al*., PAC 03

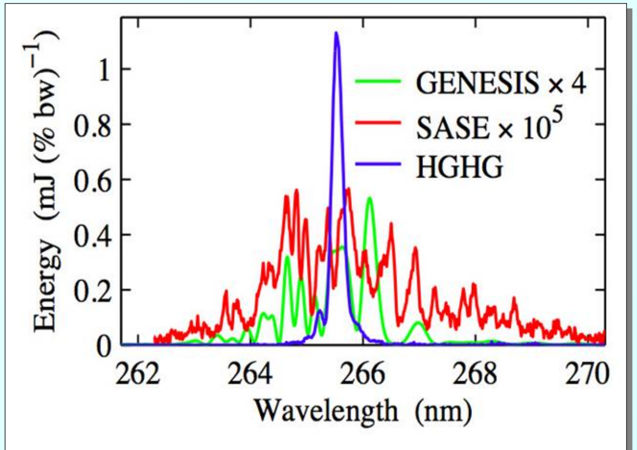


FIG. 4: Single shot HGHG spectrum for 30 MW seed (blue), single shot SASE spectrum measured by blocking the seed laser (red) and simulation the SASE spectrum after 20 m of NISUS structure (green). The average spacing between spikes in the SASE spectrum is used to estimate the pulse length.

High Gain Harmonic Generation

Challenges & Studies

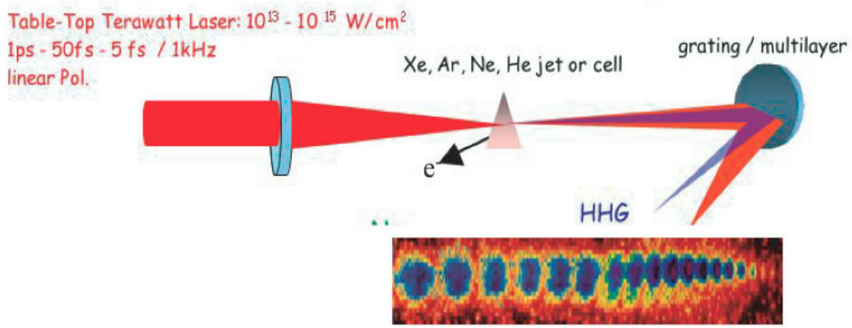
Arrival time jitter of the electron bunch of ~20 fs is required for HGHG machines
Machine optimization must be performed with jitter sensitivities included
Control of RF phases/voltages (attained phase ~0.07°LCLS, 0.1° VUV-FEL, need 0.01°)
Studies of bunch micro-structure effects in modulator sections
Trajectory errors can halve the output power - studies of transverse beam stability
Further R&D into gas jet lasers - reduces complexity (fewer cascades)

ARC-EN-CIEL : light sources

LASER SOURCES

Infra-red laser system Ti:Sa, mJ, 1-10 kHz, frequency conversion

High Gain Harmonic Generation in gas



linear polarisation
tuneability
spatial and temporal coherence

Courtesy: M.E. Couprie

soft X ray region
80-45 nm : RIKEN, Saclay, ISSP, 0.2-10 μJ/pulse
35-25 nm : RIKEN, 100 nJ/pulse
30-20 nm : LLNL, 10-1 nJ/pulse

XUV region
30-10 nm : RIKEN, 10-100 nJ/pulse
30-20 nm : Saclay, 0.1-1 nJ/pulse
30-12 nm : Vienne, 0.02 nJ/pulse
10-4 nm : 0.1-1 pJ/pulse

RIKEN group :
Ne target, 13.5 nm, 25 nJ, DV = 0.35 mrad
He target, 8.9 nm, 1 nJ, DV = 0.3 mrad
E. J. Takahashi et al., Appl. Phys. Lett. 84, 4 (2004)
E.Takahashi et al, Opt. Lett 27, 1920 (2002)
E. Takahashi et al. Phys. Rev. A 68, 023808 (2003)

EUROFEL

FP6 Design Study Programme

<u>Tasks:</u>

1. **Photo-guns and injectors**
2. **Beam dynamics**
3. **Synchronization**
4. **Seeding and harmonic generation**
5. **Superconducting CW and near-CW linacs**
6. **Cryomodule technology transfer**
7. **Coordination**

		DS1	*DS2*	*DS3*	*DS4*	*DS5*	*DS6*	*DS7*
1	*DESY*	■	■	■		■	■	■
2	*BESSY*	■			■	■	■	
3	*CCLRC*	■	■	■	■	■		
4	*CEA*	■	■	■	■	■		
5	*CNRS*	■		■				
6	*ELETTRA*	■	■	■	■			
7	*ENEA*	■	■	■	■			
8	*FZR*					■		
9	*INFN*	■	■	■		■		
10	*MAX-lab*			■	■			
11	*MBI*	■						
12	*SOLEIL*		■		■			
13	*TEMF-TUD*	■	■					
14	*UniHH*				■			
15	*URLS*	■	■					
16	*USTRAT*				■			

Recent Approval ~ 9 MEuro package, undergoing final negotiations

Courtesy J. Feldhaus

Conclusions

Many Challenges but Great Rewards

Significant work being done in many laboratories worldwide

It promises to be an exciting and fulfilling future

Acknowledgments

Marie-Emmanuelle Couprie (CEA)
John Corlett (LBL)
Paul Emma (SLAC)
Josef Feldhaus (DESY)
Luca Gianessi (ENEA)
Dieter Krämer (BESSY)
Lia Merminga (TJNAF)
Hywel Owen (Daresbury)
Tsumoru Shintake (RIKEN)
Frank Stephan (DESY)
Sverker Werin (MAX-Lab)