17TH ADVANCED BEAM DYNAMICS WORKSHOP ON

FUTURE LIGHT SOURCES

WG2 Summary Viewgraphs

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Working Group II:
Linac-Based, High-Gain FELs
Ilan Ben-Zvi

Presentations:

FEL Theory	Li Hua Yu
Wake Fields	Karl Bane
Compression	Paul Emma
Photoinjector	Bruce Carlsten
" simulations	Massimo Ferrario
SR/FEL properties	Max Zolotorev
FEL numerics simul.	Heinz-Dieter Nuhn
" " "	Sven Reiche
Harmonics/code comp.	Henry Freund
CSR Results	Courtland Bohn
1 GV/m pulsed gun	Triveni Srinivasan-Rao
General considerations	Stephen Milton
Effect of $d\gamma/dz$	H.-D. Nuhn

The FEL:

Universal ~~se~~scaling gain function

(Yu et al. PRL 64 3011 (90

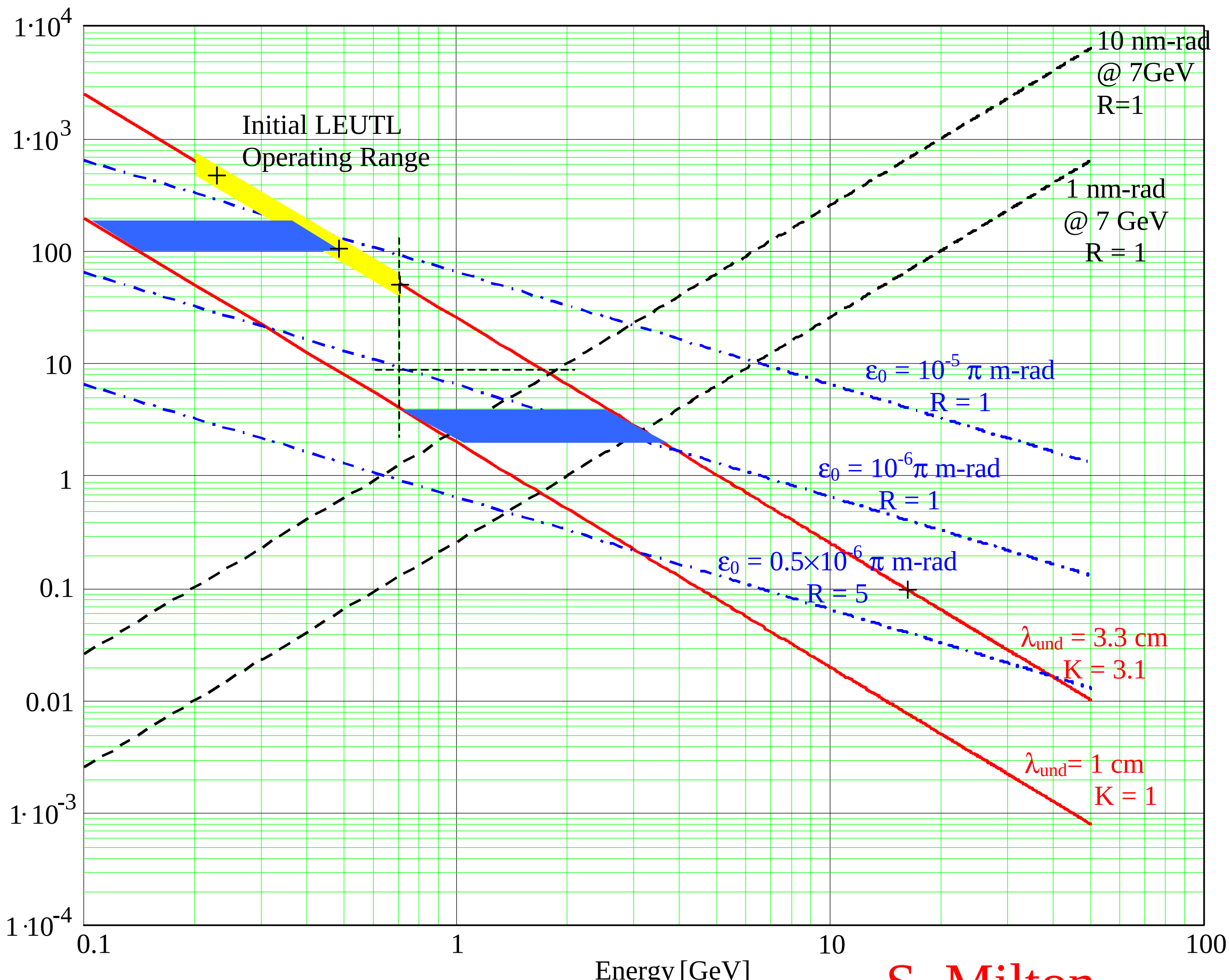
$$\frac{1}{L_G} = k_w D \, G\left(k_s \epsilon, \frac{\sigma_r}{\gamma D}, \frac{k_\beta}{k_w D}, \frac{K}{\gamma}\right)$$

$$D \propto \sqrt{\frac{I}{\gamma}} \qquad \epsilon = \frac{\epsilon_n}{\gamma}$$

$$k_s = k_w \frac{2\gamma^2}{1+K^2/2}$$

- Shorter λ implies larger γ, larger I and smaller k_w.

- For a given λ, smaller ϵ_n implies smaller γ and larger k_w



S. Milton

Undulator Resonant Condition: $$\lambda_L = \frac{\lambda_{und}}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

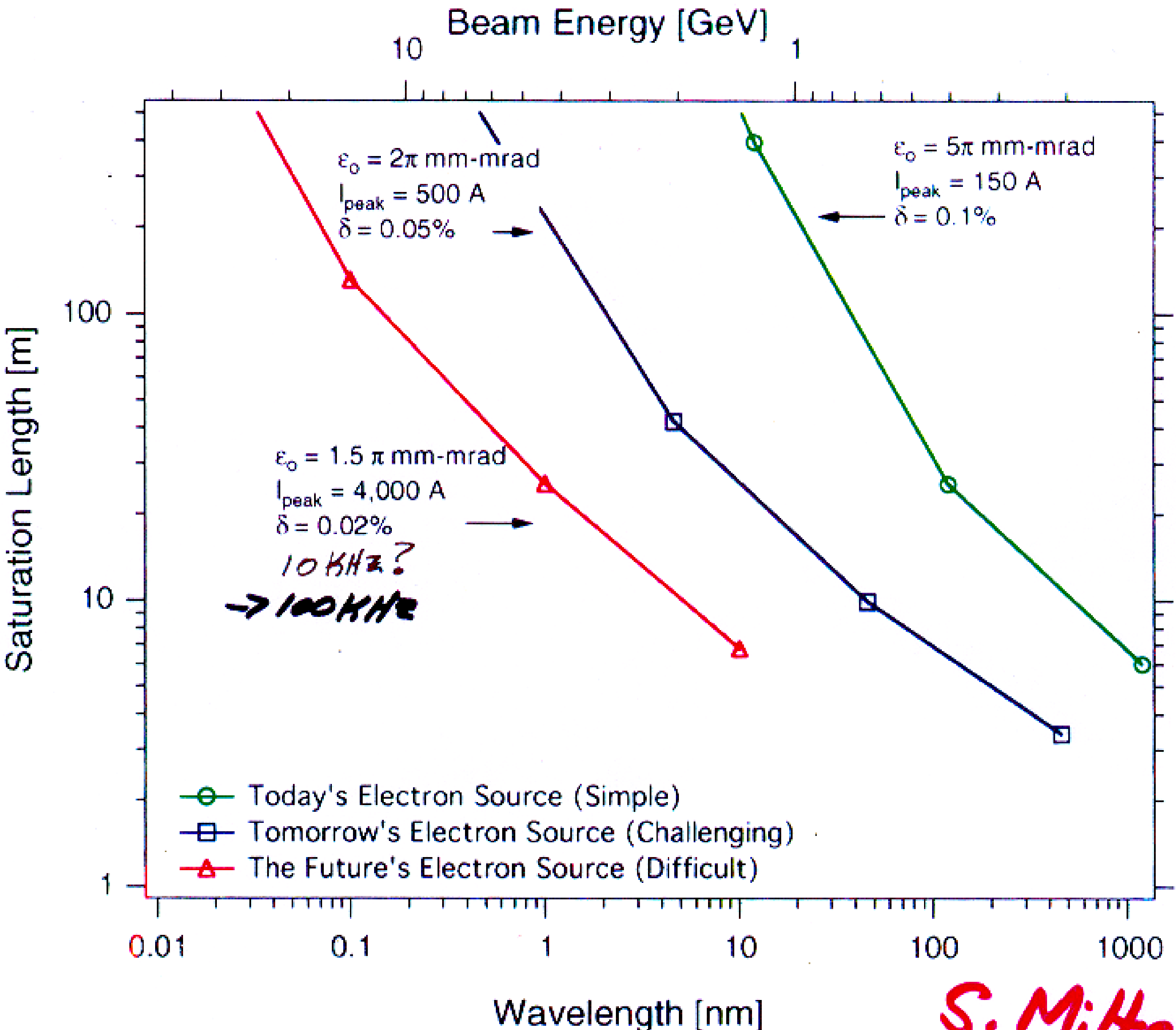
Diffraction Limit Requirement: $$\lambda_L > \lambda_{diff} = \frac{4\pi\varepsilon}{R}$$

Linac Emittance Scaling: $$\varepsilon = \frac{\varepsilon_o}{\gamma}$$

$$\gamma = \frac{E}{m_e c^2}$$

Storage Ring Emittance Scaling: $$\varepsilon \propto \gamma^2$$

Undulator Saturation Length vs. Photon Wavelength and Beam Energy



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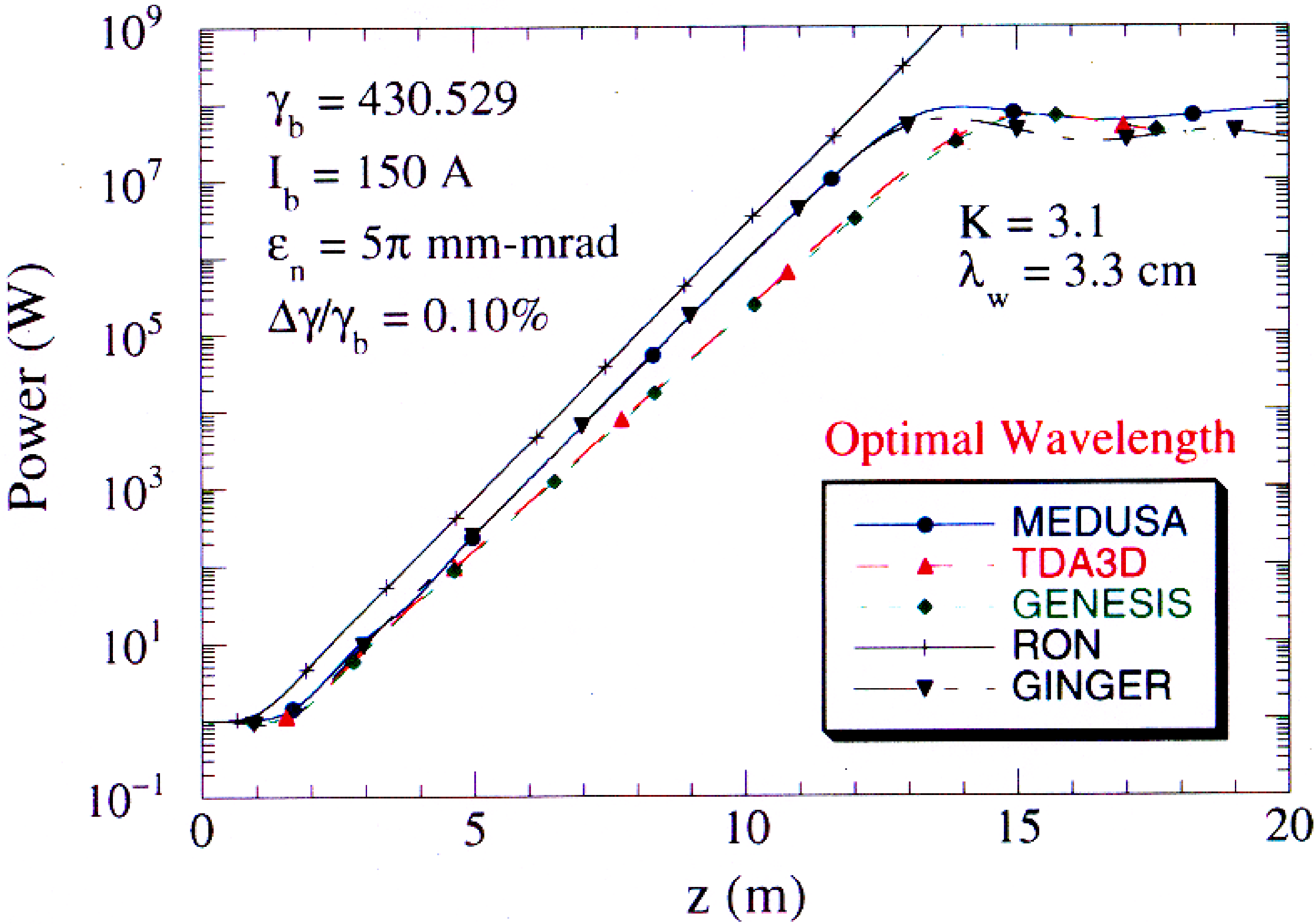
LINAC Based FEL Working Group II

FEL Theory and Simulations Subgroup Report.

- Sensitivity of the FEL Working Point to Parameter Changes.
- Electron Beam Halos.
  - Emittance good Figure of Merit ?
- Trajectory Error Simulations.

  Simulation Codes indicate:
    - Required wiggler error tolerances are achievable.
    - More research is need in comparing several simulation codes and in comparing simulations with experiment.
- Code-Code Comparisons
  - Initial Comparisons have been started with good agreement in emittance, energy spread and peak current dependence.



γ_b = 430.529
I_b = 150 A
ε_n = 5π mm-mrad
$\Delta\gamma/\gamma_b$ = 0.10%
K = 3.1
λ_w = 3.3 cm
Optimal Wavelength
MEDUSA
TDA3D
GENESIS
RON
GINGER
Power (W)
z (m)
10^9
10^7
10^5
10^3
10^1
10^{-1}
0
5
10
15
20

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FEL Theory and Simulations Subgroup Report.

- Linear 3D FEL Theory
  - Two Models
    - Waterbag Model
    - Gaussian Model
  - Good agreement with simulation codes.
- Code-Experiment Comparison
  - Few experiments available for test:
    - Livermore (8 mm, 2mm)
    - MIT (600 micron)
    - UCLA/LANL (12 micron)
    - BNL/APS (5micron)
  - Good agreement between experiment and simulation code from the mm to the rinfrared regime was found.
- Slice Parameters

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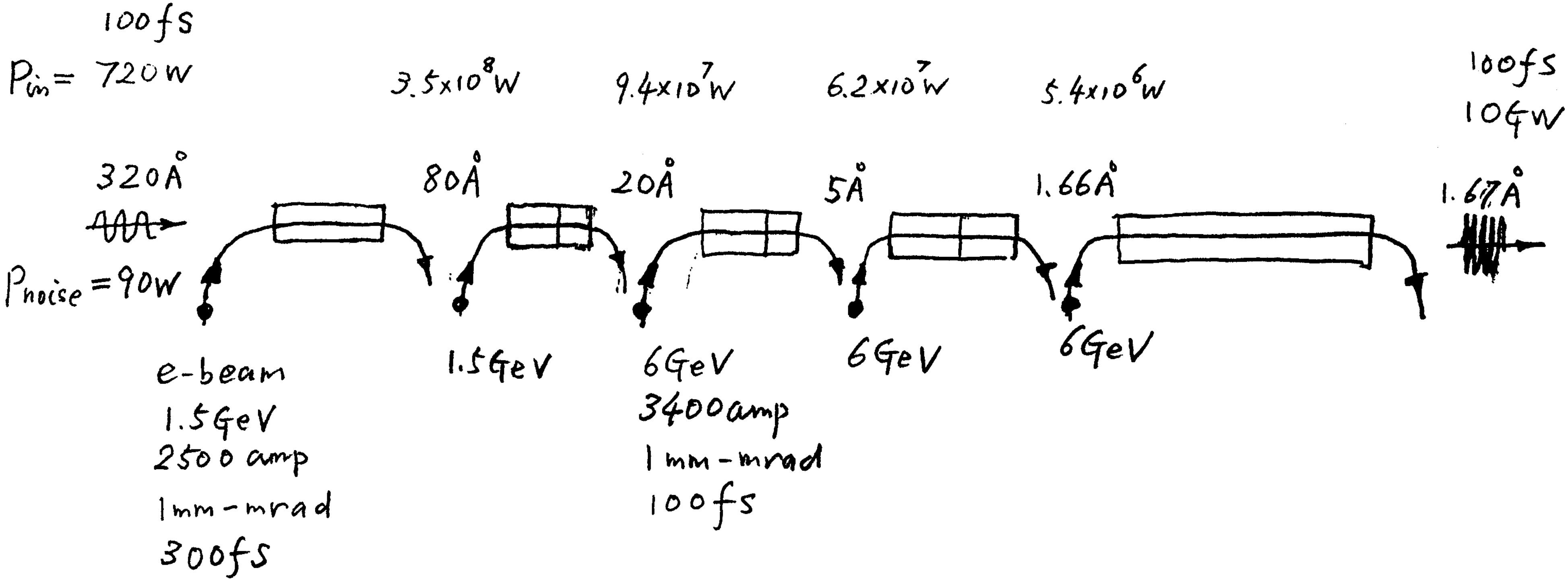
FEL Theory and Simulations Subgroup Report.

- High Gain Harmonic Generation.
  - Will reduce undulator length by factor two.
  - Reduced effects of wavelength.
- SASE FEL with powerful simultaneous emission of multiple higher harmonics.
- Longitudinal Coherence
  - Ideas exist for increasing longitudinal coherence (Two undulator schemes with monochromatization.)

5 Bunches Scheme



λ (Å)	320	80	80	20	20	5	5	1.67	1.67
λ_w (cm)	3.6	2.6	2.6	1.8	3.4	2.5	2.5	1.8	1.8
L_w (m)	7	1	2.4	2	10	4	16	12	49
L_G (m)	0.4	0.5	0.5	0.75	1.3	2	2	5	5

$L_{total} = 103\,m$

$$\frac{\Delta\lambda}{\lambda} = \frac{\lambda}{\ell} = \frac{1.67\times10^{-10}\,m}{30\,\mu m} \cong 5\times10^{-6}$$ (Fourier trans. limited)

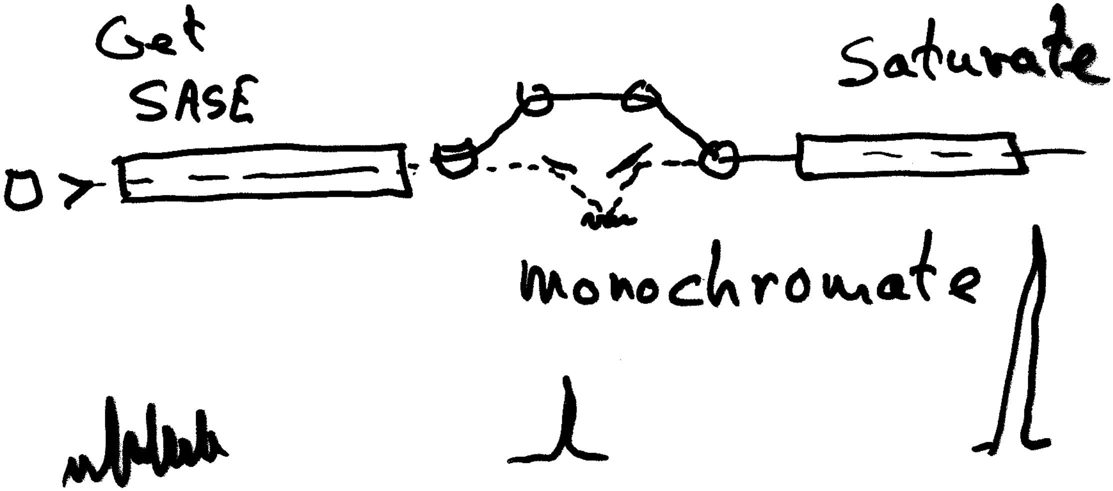
$$W = 10\,GW \times 100\,fs = 1\,mJ$$ (8×10^{11} photons, 1.67Å)

Summary of the Estimate

	SASE	2-Stage	HGHG single bunch	HGHG 5 bunch
pulse length (fs)	100	100	10	100
band width $\frac{\Delta\lambda}{\lambda}$	4×10^{-4}	5×10^{-5}	5×10^{-5}	5×10^{-6}
Fourier limit	5×10^{-6}	5×10^{-6}	5×10^{-5}	5×10^{-6}
pulse energy (mJ)	1	1	0.1	1
# photons	8×10^{11}	8×10^{11}	8×10^{10}	8×10^{11}
peak power (GW	10	10	10	10
fluctuation	5%	10%-20%	5%	5%
Spon. power in fundamental (GW)	1	–	0.4	0.4
beam size			~30 μm	
divergence			~0.5 μrad	

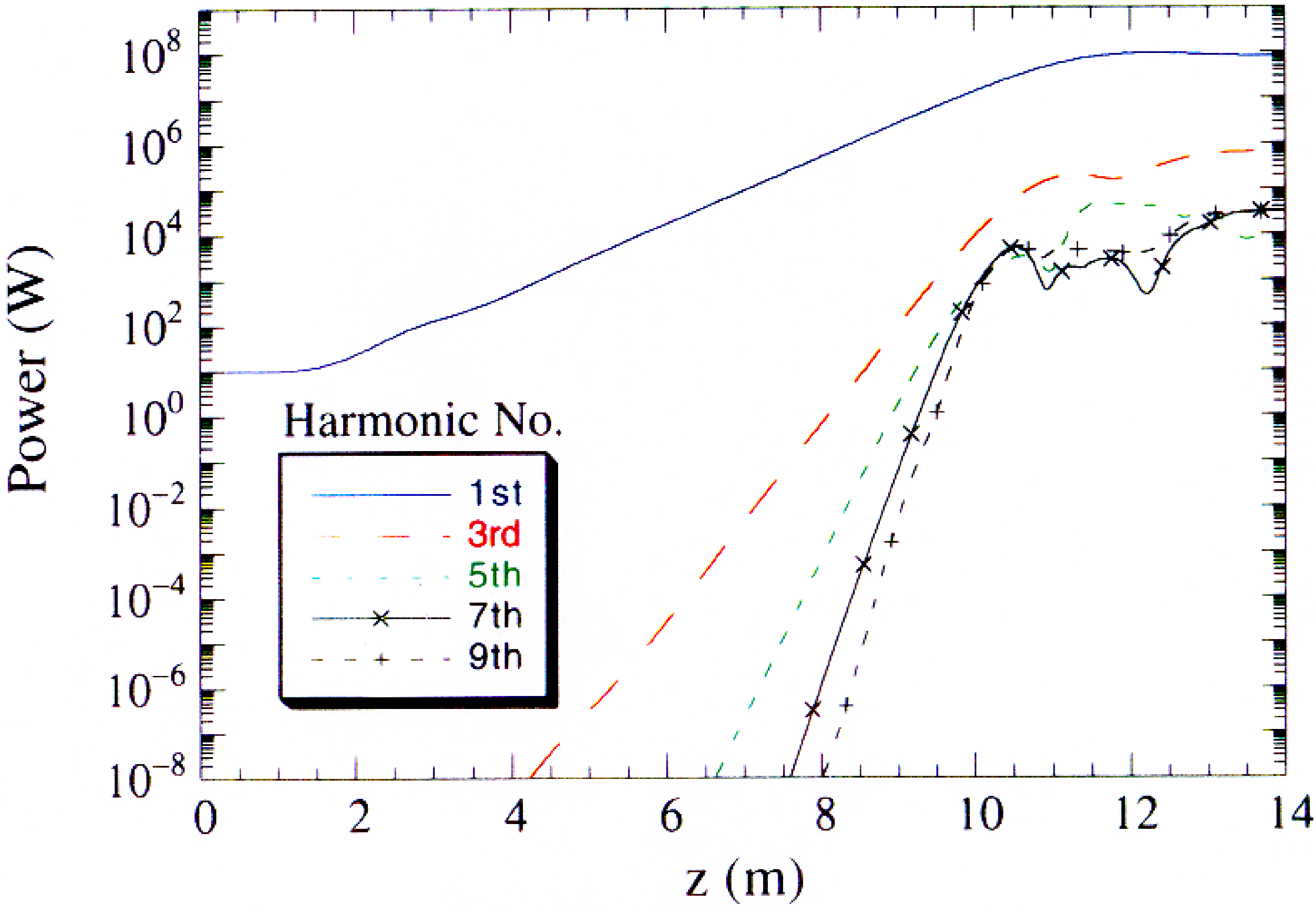
Narrow bandwidth from SASE (DESY)

(S. Reiche)



Narrow bandwidth / coherence

improved shot to shot stability



Power (W)
10^8
10^6
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
0
2
4
6
8
10
12
14
z (m)
Harmonic No.
1st
3rd
5th
7th
9th

HARMONIC POWERS & GAIN LENGTHS

The scaling of the powers and gain lengths for the fundamental and harmonics are shown in the Table. To within a very good approximation, the gain lengths scale inversely with the harmonic number. The odd harmonic powers are substantial and drop off relatively slowly with increasing harmonic number, while the even harmonic powers are relatively small. This is expected for planar wiggler geometries.

The scaling of the gain with the harmonic number is characteristic of the nonlinear mechanism, and is a well-known phenomenon in TWTs. Of course, the linear gain lengths decrease with increasing harmonic number.

Harmonic No.	Gain Length (m)	Power
1	0.592	95.5 MW
2	0.335	4.28 kW
3	0.201	797 kW
4	0.165	1.57 kW
5	0.124	47.5 kW
6	0.098	175 W
7	0.089	32.5 kW
8	0.065	144 W
9	0.072	31.8 kW

Photoinjector Summary

• Identified important issues:

1. What happens if charge goes less than 1 nC
2. Effect of bunch longitudinal shape on FEL performance
3. What is minimum slice emittance and what are the growth mechanisms?
4. New photoinjector ideas
5. "Capturing" the smallest emittance
6. Stability of drive laser

$$\epsilon \sim 1.4 \left(0.38 Q^{4/3} + \ldots\right)^{1/2}$$

- Photoinjectors are a mature technology

  ⇒ 1.3 mm mrad slice emittance demonstrated at S-band & L-band already

- Thermal emittance ~ 0.3 mm mrad/mm radius

- 1μm surface roughness does not impact thermal emittance

- RMS emittance probably not best figure of merit for predicting beam quality relevant to lasing

- Can reduce minimum slice emittance by flat-topping or nonlinear radial laser profile

- Electron beam is space-charge dominated essentially throughout LCLS machine. Potential emittance growth from nonlinear free energy, but beam should not thermalize, except for some minor wave-breaking in halo.

Photoinjector Stability

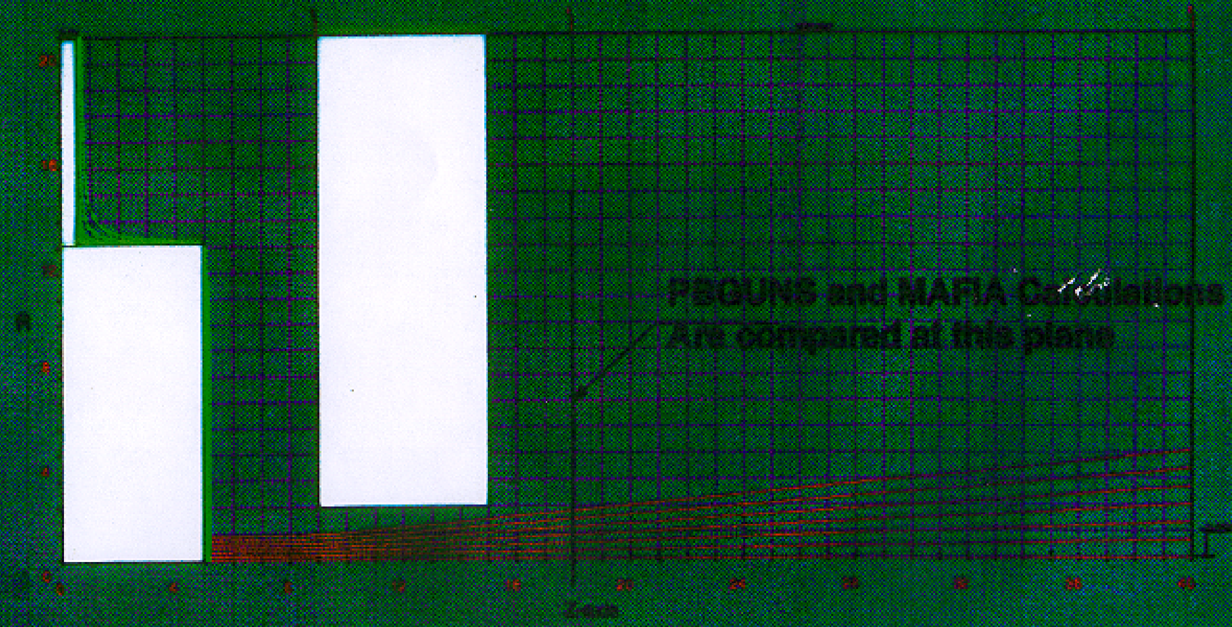
- Pulse-to-pulse jitter serious issue with existing photoinjector "physics" experiments
- BNL has demonstrated 2% rms amplitude stability, thinks 1/2 % possible
- Major experiments will probably be able to provide enough support to maintain good stability
- LCLS needs ~1 ps timing, ~1-2% amplitude stability

Stability helped by:
- controlling vibrations in drive Laser room (fans, etc)
- temperature control, including beam path
- humidity control

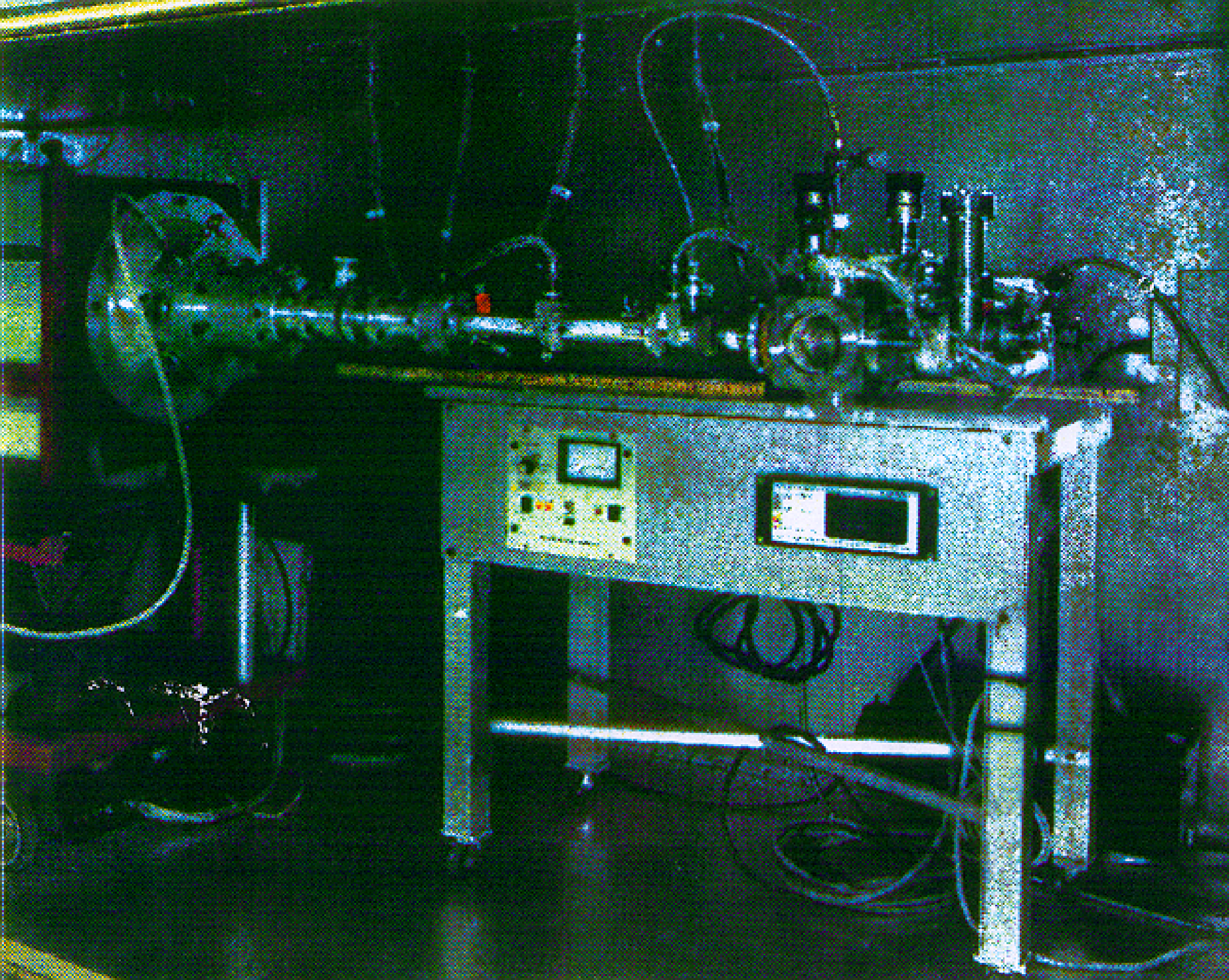
- BNL demonstrated 10 μm pointing stability over 30 m
- Workshop on drive lasers liked use of Ti Sapphire laser

Geometry for Simulation

- 1 mm gap
- .5 mm radius anode hole
- .25 mm emitting spot, uniform current density
- 1 MV potential, 1 GV/m gradient

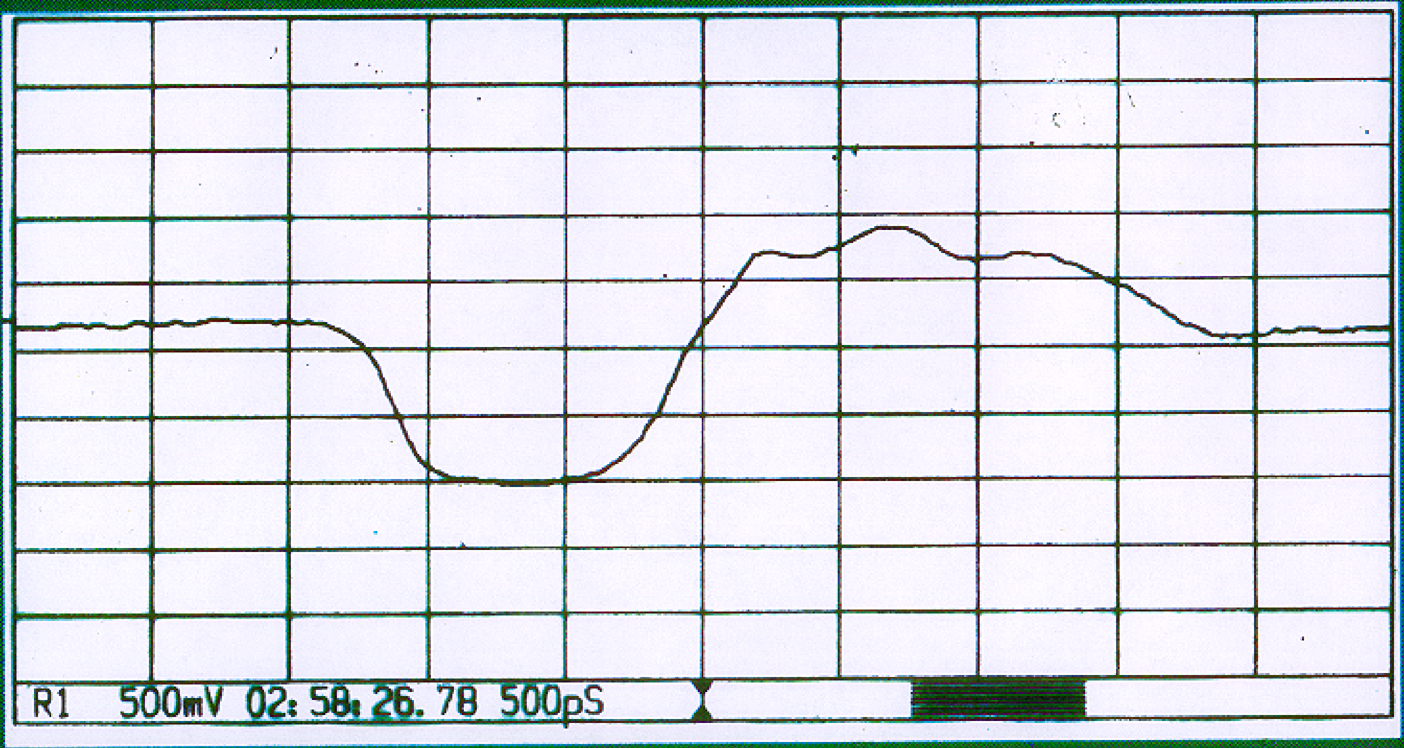


Current	Charge	Bunch length	Emittance	Brightness
A	nC	ps	π mm mrad	$\frac{A}{(mm-mrad)^2}$
100	1	10	0.16734	3571
100	0.3	3	0.0882	12854
100	0.1	1	0.062	26014
100	0.03	0.3	0.0728	18868
500	0.5	1	0.207	11668
250	0.25	1	0.132	14348
50	0.05	1	0.0386	33557
10	0.01	1	0.0446	5027



Voltage Trace from MV pulser

1 ns duration, with 100 ps rise and fall



"Capturing" smallest emittance:

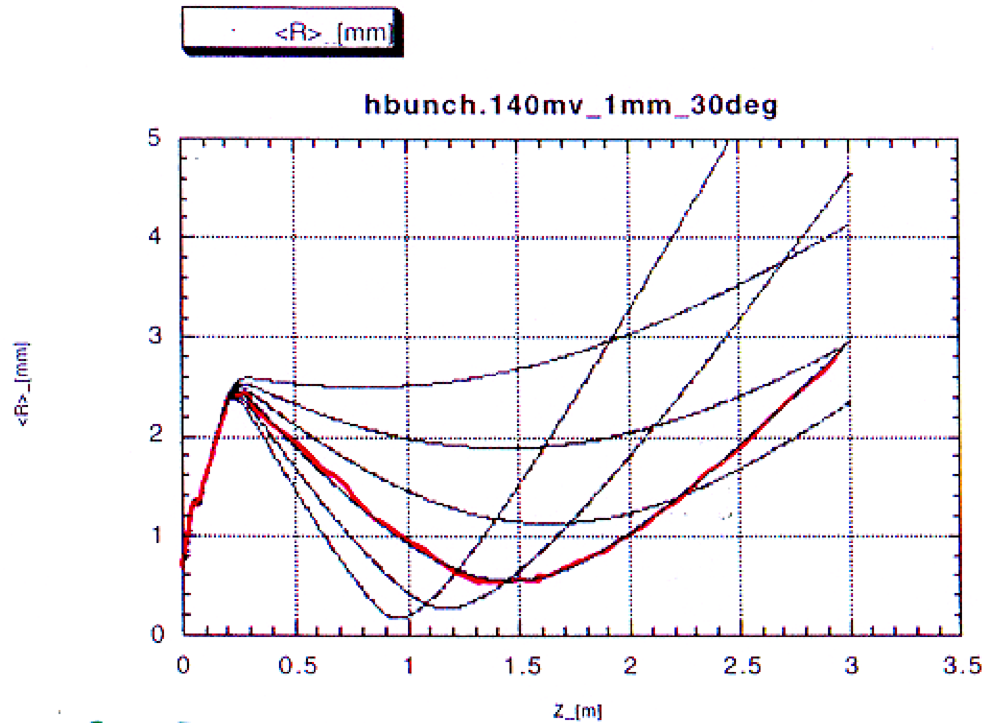
Beam slices oscillate about Invariant envelope
(Rosenzweig, Serafini)

- Invariant envelope matching done where $r'=0$
  - Two options – r_{max} or r_{min} lead to varying requirements on linac.

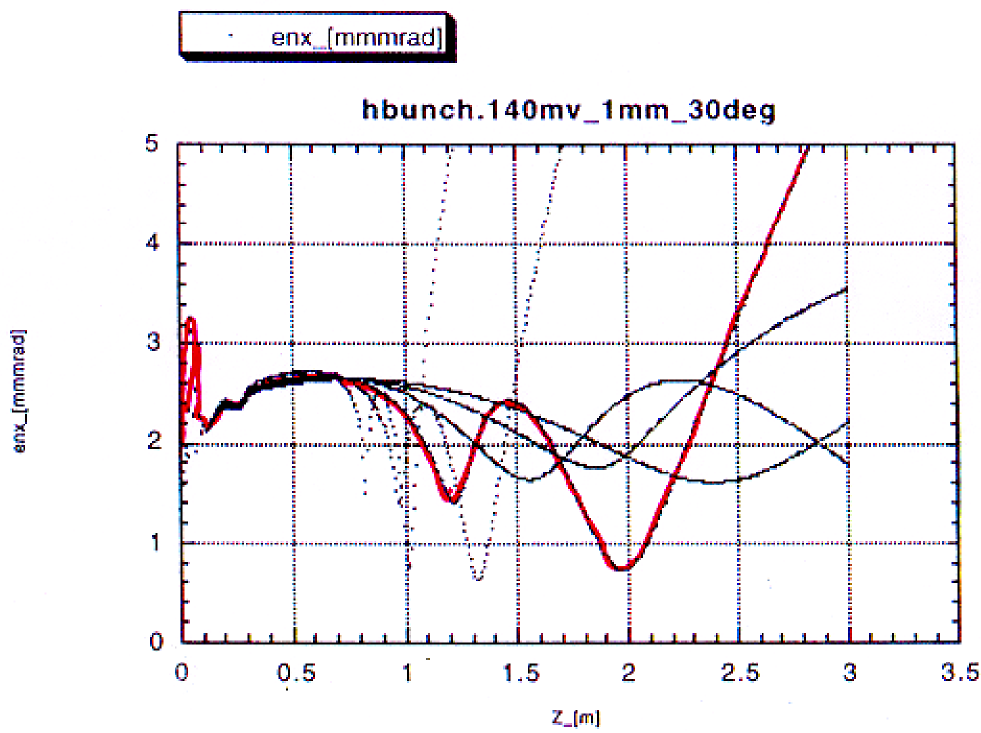
- Proper matching to invariant envelope can lead to extremely low emittances
(Ferrario)
1 nC ~ 0.3 mm mRad

- Possibility of individual "tuning" of slices by laser.

BNL/SLAC/UCLA GUN (1.6 CELL) + DRIFT



SOLENOID SCAN



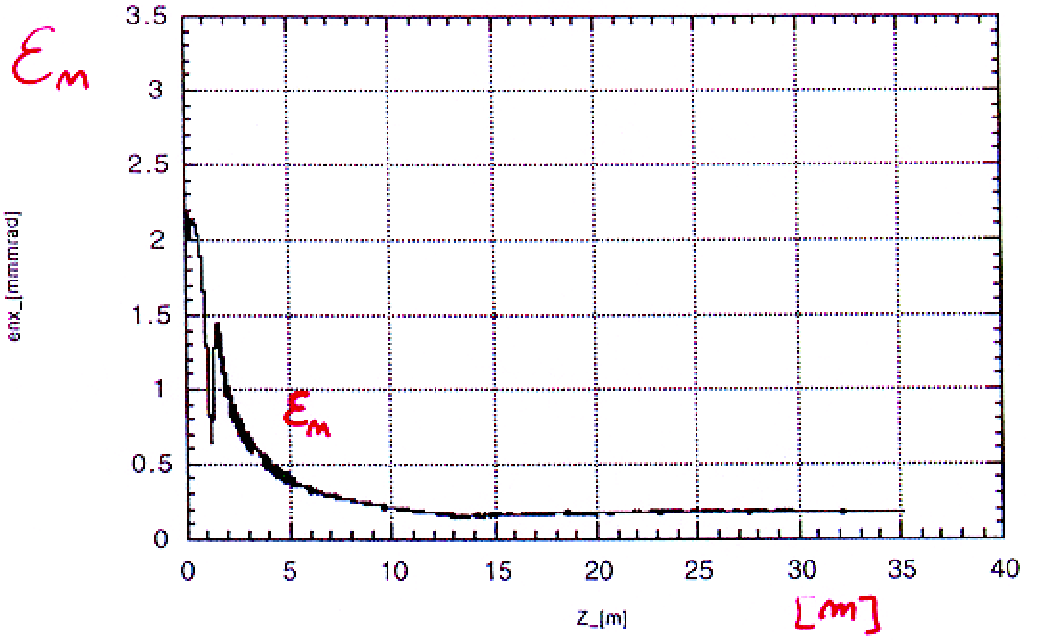
S-BAND

140 MV/m

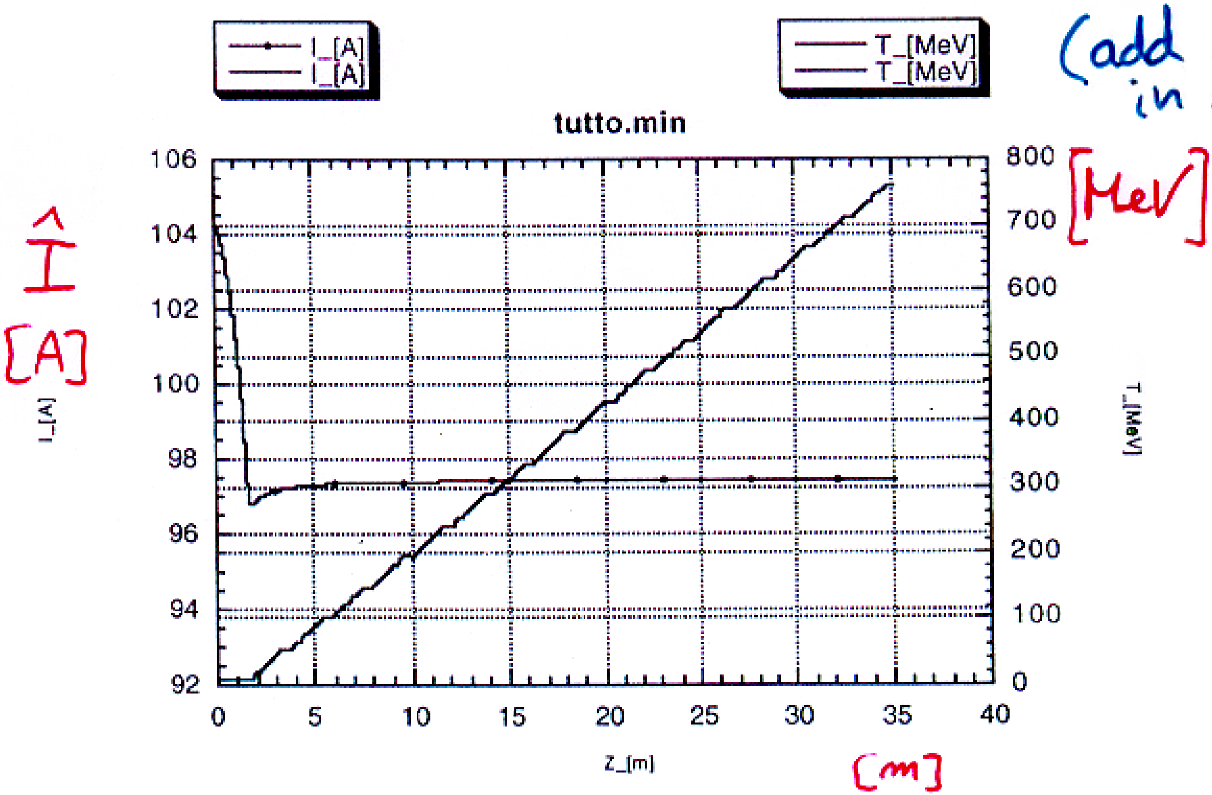
10ps FLAT TOP LASER

R_{CAT} = 1 mm

C1

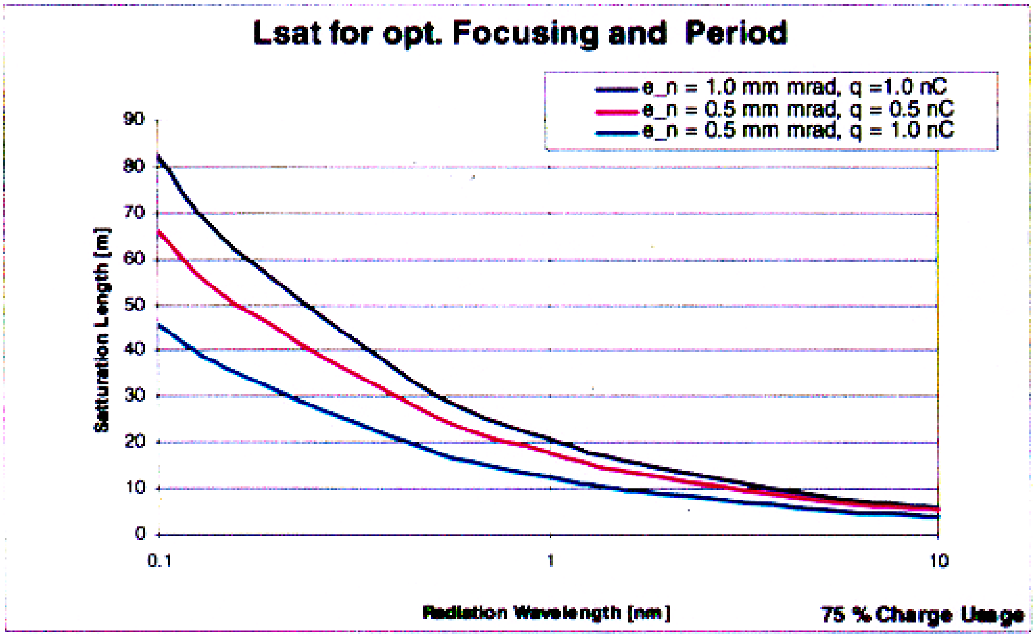


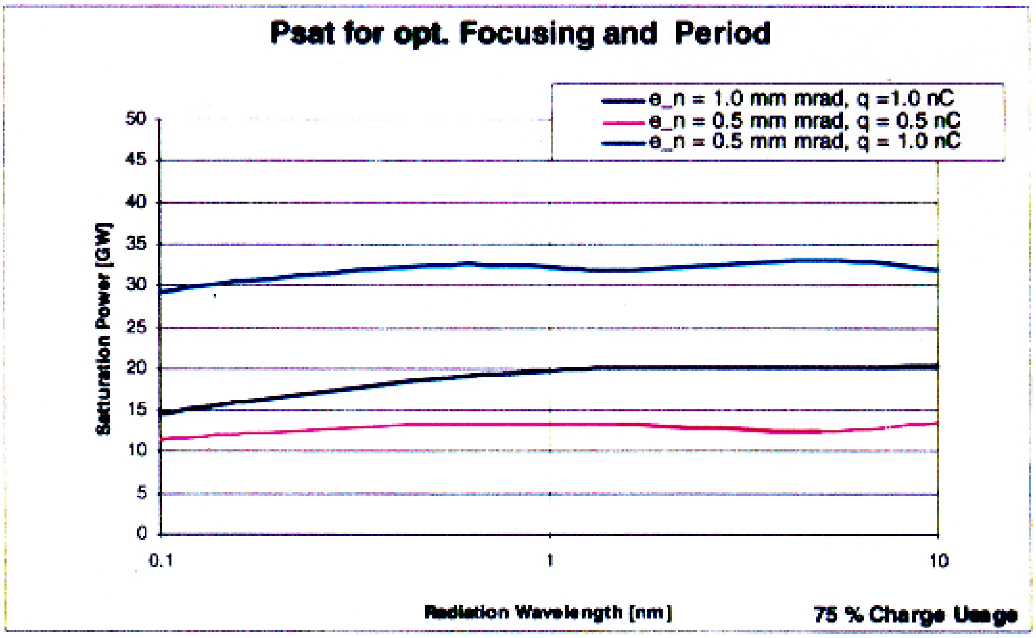
1 nC
0.3 mm mRad
No thermal
(add 0.3 in quad.



LINAC Based FEL Working Group II

FEL Theory and Simulations Subgroup Report.





BUNCH COMPRESSION ISSUES

- EFFECTS OF COHERENT SYNCH. RAD. (CSR) STILL UNDER STUDY
  - FUTURE AND PRELIMINARY EXPERIMENTS (JLAB-FEL, CLIC-TF, TTF, LANL, SDL, ATF, APS...)
  - CODE "BENCH-MARKING" STARTED
  - COMPENSATION DESIGNS EXIST (NOT TESTED)
  - SHIELDING SOMETIMES IMPRACTICAL
- PULSE-TO-PULSE JITTER SENSITIVITES CAN DRIVE COMPESSOR DESIGN (Δt, N, ϕ_{rf}) ← IMPORTANT ISSUE
- LOWER CHARGE/BUNCH BIG HELP FOR e^- DYNAMICS IN ACCELERATOR, AND UNDULATOR (CSR, WAKES, E-SPREAD)

- INCOHERENT SYNCH. RAD. (ISR)
  AN ISSUE AT HIGH ENERGY ("GeV.")
  (INCREASES SLICE EMITTANCE & E-SPREAD)

- NO FUNDAMENTAL LIMITATIONS —
  NEED LOW LONGITUDINAL EMITTANCE
  FROM INJECTOR — DESIGNS MUST
  RESPOND TO MANY CHALLENGES ...
  (CSR, WAKEFIELDS, STABILITY ...)

Impedance Effects on Lasing.

* Major consideration – affects emittance, compression, limits on wiggler gap and peak current.
* Impedances in linac are generally well understood.
* Impedance due to surface roughness in narrow-gap undulator is an issue
  - concerned about emittance in the slices, energy spread
  - too large dr/dz will suppress gain (H.-D. Nuhn)

Resonator model (K. Bane)
leads to pessimistic estimate:

$\sim 10\,nm$ roughness

could be more like $\gtrsim 100\,nm$ if "bumps" are well separated.

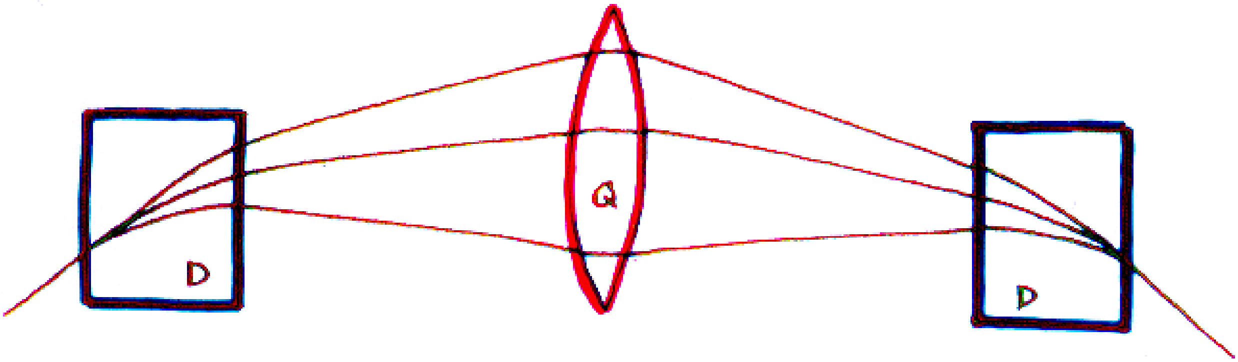
SLAC is measuring roughness. Electro-polished surfaces can reach $\sim 20\,nm$, low "frequency" of aspect ratio.

Both SLAC and DESY have proposed to measure wake effects by passing beam through narrow chambers with specially prepared rough surfaces

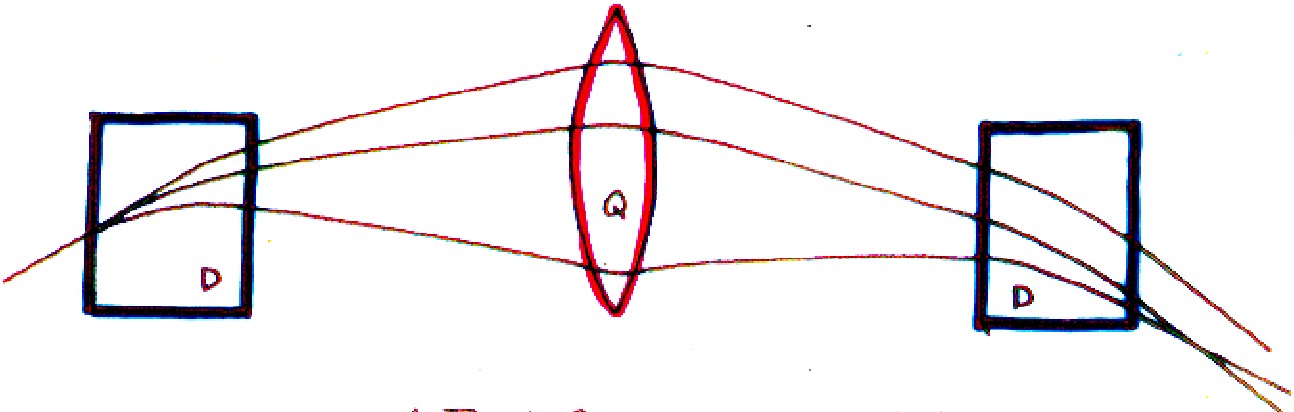
INDUCED ENERGY SPREAD AND EMITTANCE GROWTH

Example: Achromatic bend through angle θ.

Let ΔE = particle's energy change during bend.



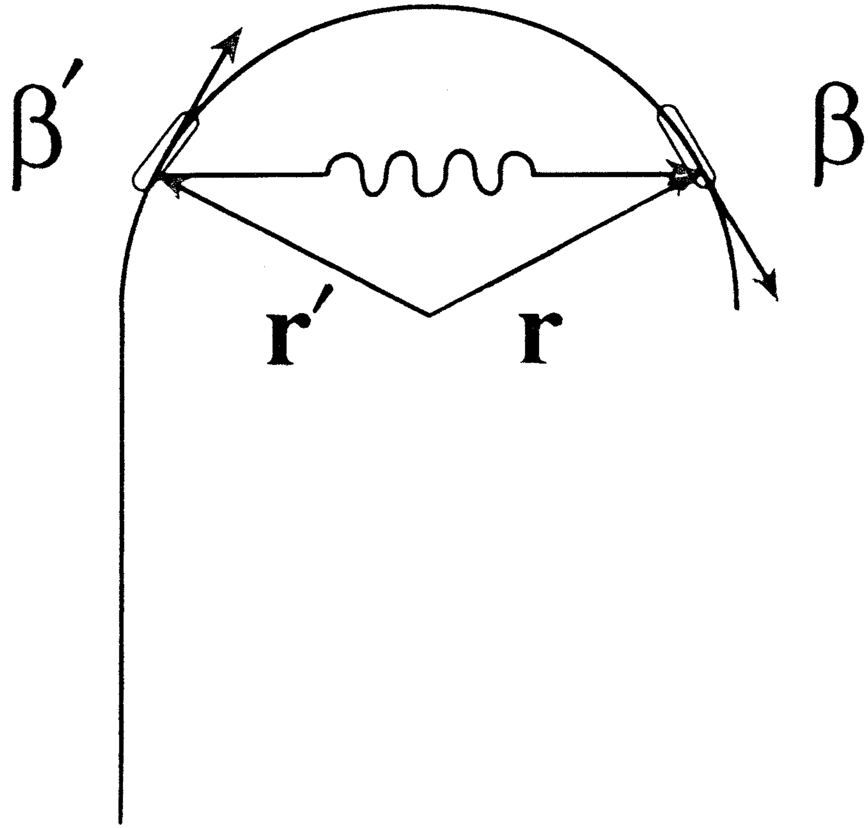
$\Delta E = 0$ (ideal case) $\Delta\theta = 0$



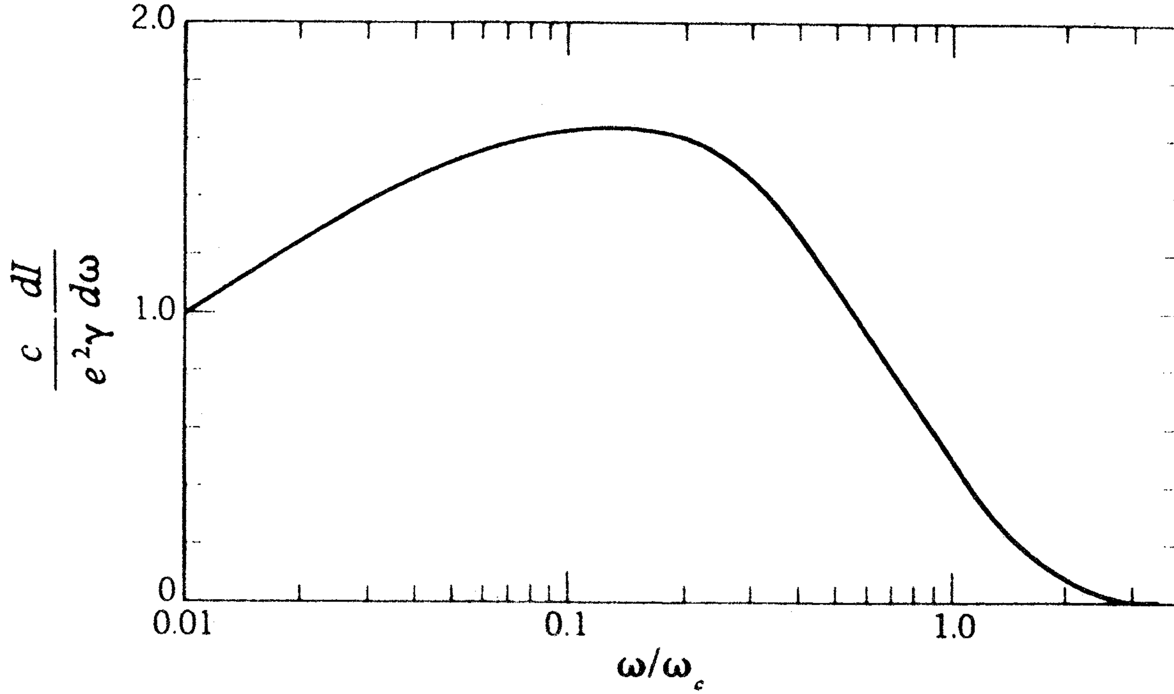
$\Delta E \neq 0$ $\Delta\theta = \theta(\Delta E/E)$

Naively expect emittance growth $\propto \Delta E_{rms}$.

BUNCH SELF-INTERACTION



Synchrotron Radiation Spectrum for Circular Motion



$$\omega_c = 3\gamma^3 \frac{c}{R} \longleftrightarrow \lambda_c = \frac{2\pi}{3\gamma^3} R.$$

IR Demo: $E = 42$ MeV $\Rightarrow \gamma = 83$, $R = 1$ m, $\sigma \sim 1$ ps.

$$\Rightarrow \lambda_c = 3.6\,\mu m \simeq 0.01\,ps.$$

For $\lambda \gtrsim \sigma \gg \lambda_c$ (**CSR regime**),

$$\frac{dI}{d\omega} \simeq 3.25 \frac{e^2}{c}\left(\frac{\omega R}{c}\right)^{1/3} \Rightarrow \underline{\gamma\text{-independent.}}$$

Example Application

"Canonical" assumptions:

① rigid-line-charge gaussian bunch,
② CSR is principally dispersive,
③ long magnet ($\Rightarrow$ steady state),
④ big vacuum chamber ($\rightarrow$ free space).

Result: $\epsilon = \sqrt{\epsilon_0^2 + (\Delta\epsilon)^2}$;

$$\boxed{|\Delta\epsilon(\text{mm-mrad})| = 0.039\, Q(\text{pC})\, \sigma_x(\text{mm}) \left[\frac{R(\text{m})}{\sigma^4(\text{mm})}\right]^{1/3} |g(\theta)|;}$$

$|g(\theta)| = |\theta \sin\theta + \cos\theta - 1|$,

θ = bend angle,

Q = bunch charge,

σ_x = rms transverse bunch size,

R = bend radius,

σ = rms bunch length.

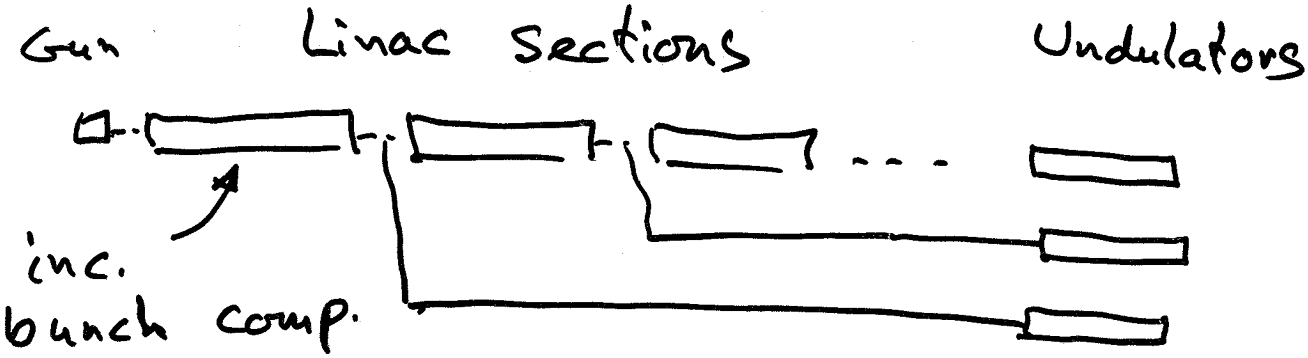
For IR Demo 180° magnet with "average" bunch profile:

$\epsilon_0 \sim 8$ mm-mrad, $\sigma \sim 2.5$ mm, $Q = 135$ pC,
$\sigma_x \sim 7.5$ mm, $R \doteq 1$ m, $\theta = \pi$

$\Rightarrow$ $|\Delta\epsilon| = 23$ mm-mrad $\Rightarrow$ $\epsilon = 24$ mm-mrad.

Independent Wavelength Control in Multiuser Facility

change λ thru γ, $\lambda \sim \frac{1}{\gamma^2}$



Kick out beam at a number of points downstream of the bunch compressors.

Must have energy reserve. The degree of energy reserve determines the tuning range.

Energy redistribution can be made fast, transport elements are slower, but 10 sec time scale can be done.

Multiple pulses

Can be produced with variable pulse separation [~~mod~~ At multiples of linac period (350 ps for LCLS)]

Maximum separation - linac rf macropulse. Need to examine long range wake field.

Problem - provide dual / multiple pulse only ~~to~~ to one user - can be solved.

Macropulse Length:

300 ns @ LCLS

1 ms @ TTF FEL

Conclusions

1. Need to improve emittance, reduce peak current.

2. Compression – must deal with CSR.

3. Rough surface wake field is still an open problem

4. Need for experiments
   - Detailed FEL study to saturation (VISA, LEUTL SOL, TTF-FEL)
   - CSR (preliminary results reported)
   - Rough surface wake

5. Need for ultra-stabe drive laser

5. Photoinjector, Linac, FEL theory — mature fields.

But:

New photoinjectors appear. (GV/m pulsed diode)

New phenomena being discovered (CSR, rough surface wake)

New possibilities exist (HGHG)

"The year of the experimental results"

VISA, HGHG, LEUTL, TTF-FEL
RAFEL