


Normal Conducting CW RF Photoinjector for CW Microtron, XFEL, and ERL Facilities

Yujong Kim†, J. Wang, T. Andrews, C. Eckman S. Saitiniyazi M. Mayierjiang, M. Titberidze, D. Dale, A. Hunt, D. Wells

Idaho State University, Pocatello, ID 83209, USA

†Jefferson Lab, Newport News, VA 23606, USA

yjkim@isu.edu, http://www.isu.edu/~yjkim

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Outline

- The Idaho Accelerator Center (IAC) at Idaho State University (ISU)
  - Various Accelerators @ IAC & Users' Strong Demand on CW Accelerators

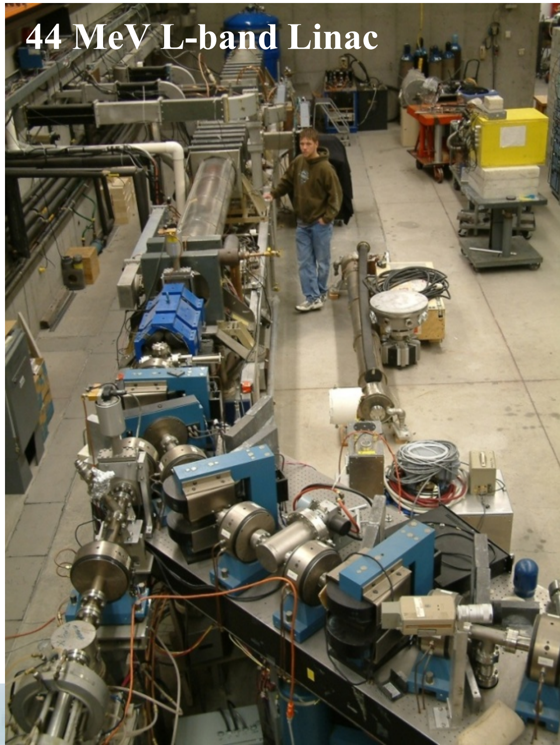
- Design Concepts of 3 MeV, 28 fC CW Injector for 6 MeV CW Microtrons
  - A New Microtron by using Existing Dipole Magnets
  - RF Photoinjector, RF Source, Gun Driving Laser, Booster Linac Structures
  - ASTRA Simulation Results

- Design Concepts of 6 MeV, 20 pC CW Injector for XFEL and ERL Facilities
  - RF Power Dissipation, Selection of Single Bunch Charge Vs. Low Gradient
  - Emittance Compensation after the Injector
  - High Average Current Operation for ERL Facilities
  - High Peak Current Operation for XFEL Facilities

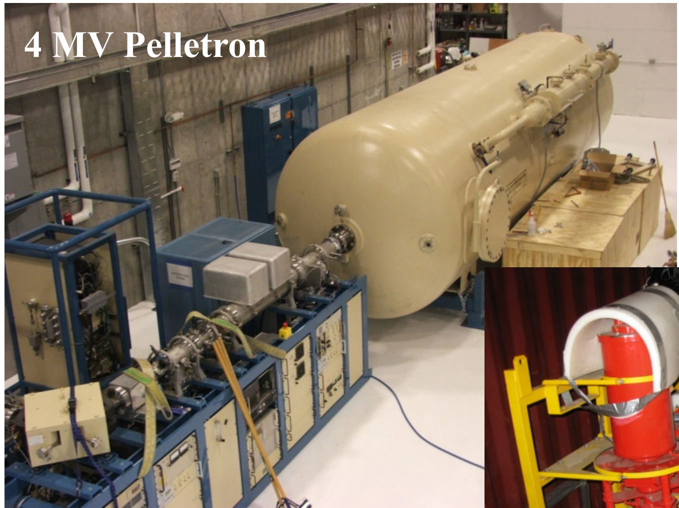
- Summary & Acknowledgements

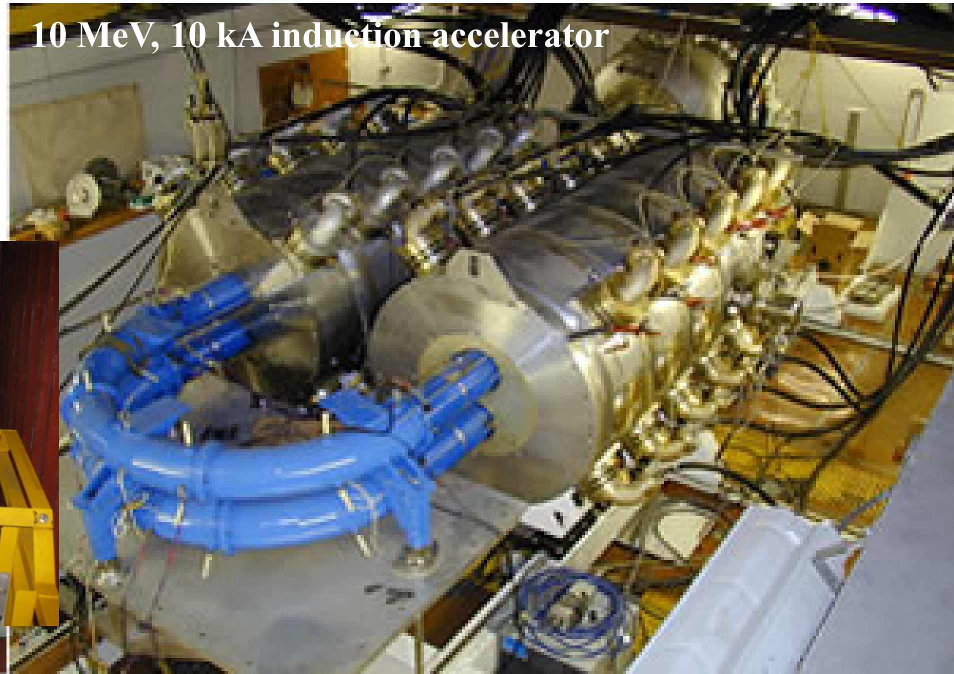
Various Accelerators @ IAC

- Electrons/Gammas
  - 10 MeV Induction Accelerator (~10 kA)
  - Four 25 MeV S-band electron Linacs
  - High Rep-Rate 15 MeV S-band Linac - 1 kHz operation
  - 44 MeV, 6 kW Short Pulse L-band Linac - LCS
  - Newly coming High power Linac - 50 MeV, 40 kW (max)
  - In Storage: Boeing FEL L-band Linac (100 MeV, 100 mA, 1MW)
- Light Ions
  - 2 MV Positive-Ion Van de Graaff
  - 4 MV Tandem Pelletron
- Accelerators & Parts in Storage
  - Twenty P, L, S, and X-band Electron Linacs
  - 18 MeV Cyclotron, 20 MeV Betatron, and Tandetron
  - Two Chicanes for Bunch compressors
  - So many L-band, S-band klystron tubes and RF parts.

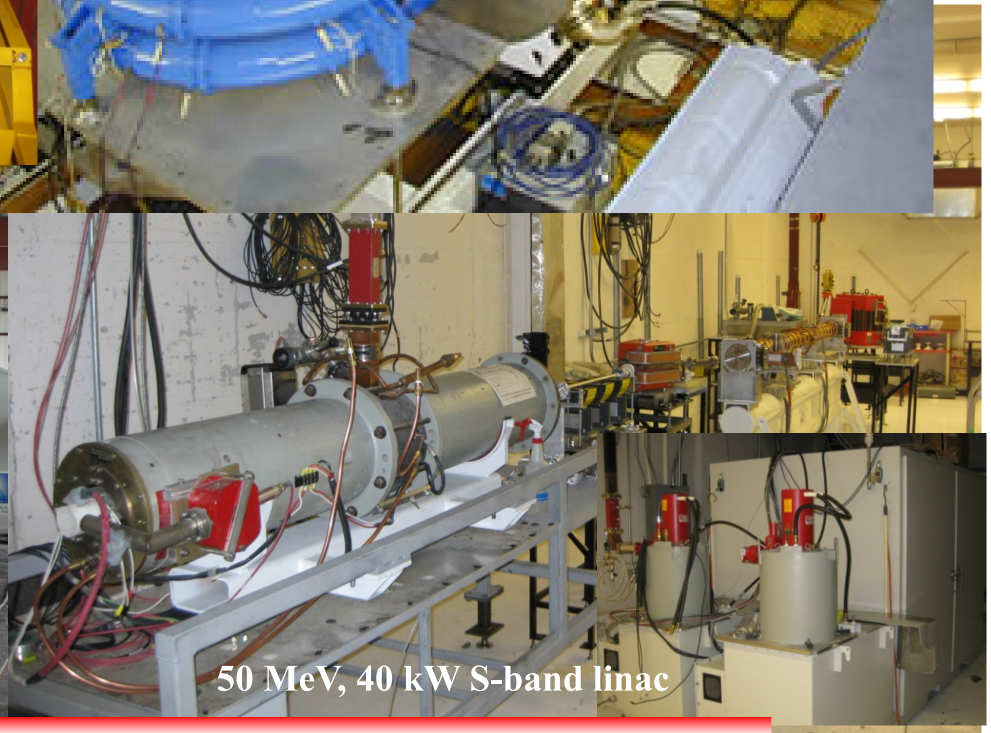


Various Accelerators @ IAC


4 MV Pelletron


10 MeV, 10 kA induction accelerator

Cargo Container Scanning Test Facility


50 MeV, 40 kW S-band linac

IAC Users' Strong Demand on CW Accelerators

It seems that many IAC projects (photon tagging, DoD positron project, LCS, JLab CEBAF positron source project) require a new advanced accelerator which can supply;

- **high duty factor : 10% (initial) - 100% (very promising)**
- **high average current : 1 μA (nominal) - 50 mA (max)**
- **high beam energy: 6 MeV (min) - 20 MeV (nominal) - 50 MeV (max)**
- **good or high average beam power : 20 W (nominal) - 300 kW (max)**
- **low rms energy spread: smaller than 0.1% (nominal)**
- **low normalized rms emittance < 10 mm.mrad**

But we are feeling difficulties to choose Superconducting based accelerator and/or storage ring due to its big construction budget (at least $10M range).

We may consider Continuous Wave (CW) microtrons to satisfy IAC users' strong demand.

Working Principle of Racetrack Microtron

A racetrack microtron (RTM) use two wide dipoles to bend electron beams by 360 degree per turn. After each turn, electron beams re-accelerated at an RF cavity or a linac structure between two dipoles.

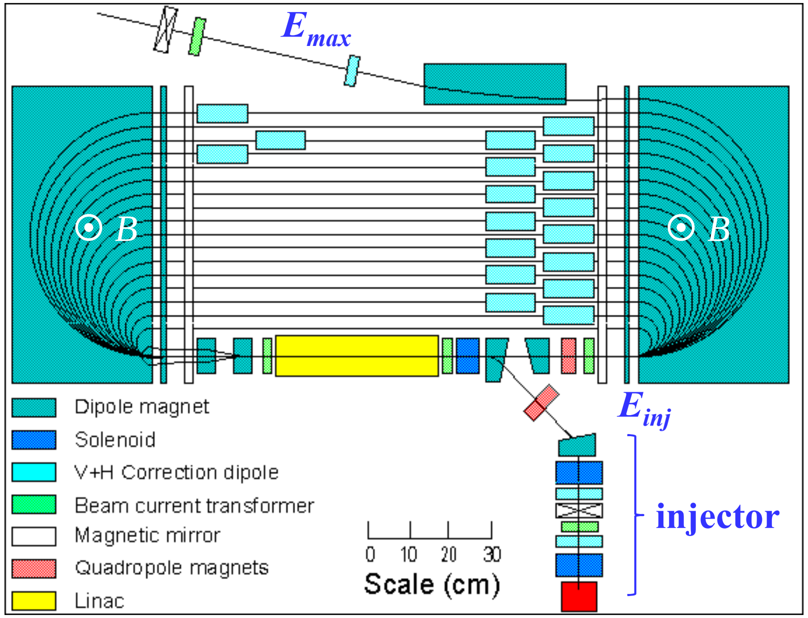
Since electron beam energy is continuously increased whenever electron beams go through the linac or the RF cavity, the bending radius of electron beams becomes bigger at the next turn.

$$p(\mathrm{GeV}/c) \approx 0.2998 B(\mathrm{T}) \rho(\mathrm{m})$$

Since beam energy is repeatedly increased at a short linac or RF cavity, we can build a compact and economic accelerator.

Note that beam energy should be a certain value to avoid any colliding with the linac at the first several turns. → an external injector with a beam energy of several MeV is required for a high E_{max}.

100 MeV ISA RTM Microtron



$$n\lambda_{RF} = 2\pi\Delta\rho \;\rightarrow\; n\lambda_{RF} = 2\pi\frac{\Delta E}{ecB} \quad \text{for RTM}$$

n = any integer

ΔE = energy gain per turn in RF cavity

λ_{RF} = RF wavelength

B = magnetic field in mictron dipole

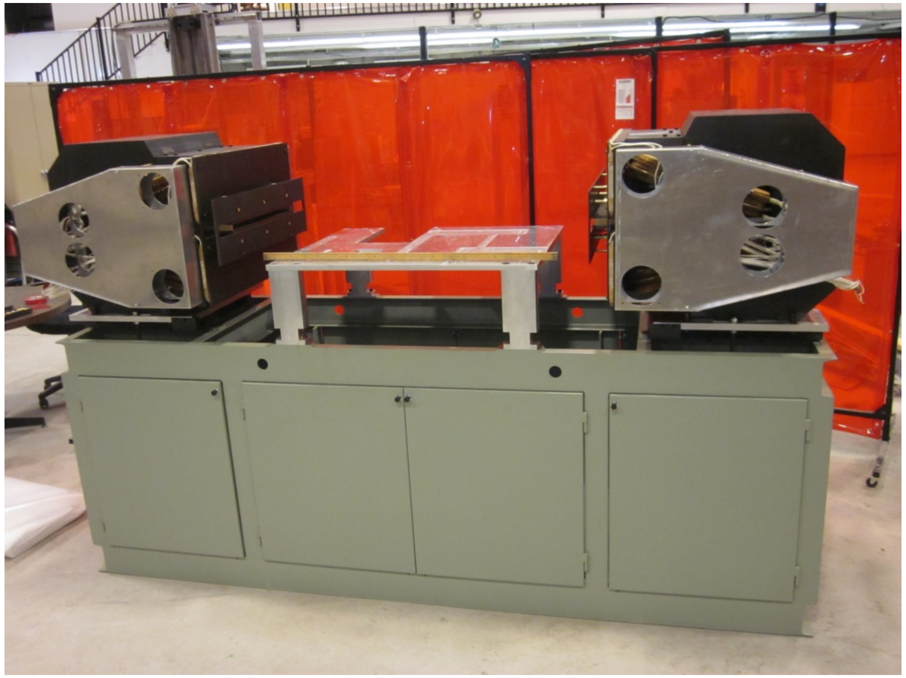
$\Delta\rho$ = increment of bending radius

Existing IAC Microtron Dipoles and Girder

IAC has two dipoles for a 55 MeV pulsed mode racetrack microtron!

bending angle of one dipole : 180 degree
nominal magnet field for 50 MeV pulsed mode operation : 1.0 T
energy gain per tune (pulsed mode) : 5 MeV
dipole gap height : 20 mm
max bending radius ~ 0.2 m @ E_{max}
field uniformity in working area : 10 Gauss
dimension : 729 (D) × 740 (W) × 620 (H) mm^3
bending radius @ 55 MeV : 18.5 cm

$$p(\mathrm{GeV}/c) \approx 0.2998 B(\mathrm{T}) \rho(\mathrm{m})$$



Dipoles and Girder of IAC Microtron

If E_{max} = 20 MeV, ρ_{max} = 0.2 m → B = 0.334 T
∴ bending radius @ E_{inj} = 3.4 MeV → 3.4 cm
→ too narrow to avoid colliding with the cavity
→ we need a higher energy gain in the cavity or a higher injection energy, or wider dipoles.

If E_{max} = 6 MeV, ρ_{max} = 0.2 m → B = 0.100 T
∴ bending radius @ E_{inj} = 3.4 MeV → 11.3 cm
→ wide gap to avoid colliding
→ we may reach 6 MeV in 5 turns if E_{inj} = 3.4 MeV & ΔE = 0.5 MeV (CW single cell cavity).
→ we may consider a linac structure with multi-cells to increase ΔE and $E_{max.}$

Design Concepts of the IAC 3 MeV CW Injector

Idaho Accelerator Center

To generate high quality beams with a low emittance and a low energy spread, we choose a 2.5 cell S-band RF Gun instead of DC gun.

The RF gun based injector is also very helpful to control space charge force, bunch length, and the total length of injector due to no chopper or no buncher. (length of DC gun based CW injector ~ 6 m for IFUSP CW microtron).

After CW operation, beam kinetic energy at the end of the gun ~ 300 keV for about 30 kW RF input power.

By choosing a high power CW laser from Time-Bandwidth, we may also generate beams with a high frequency (frequency ~ 350 - 2500 MHz).

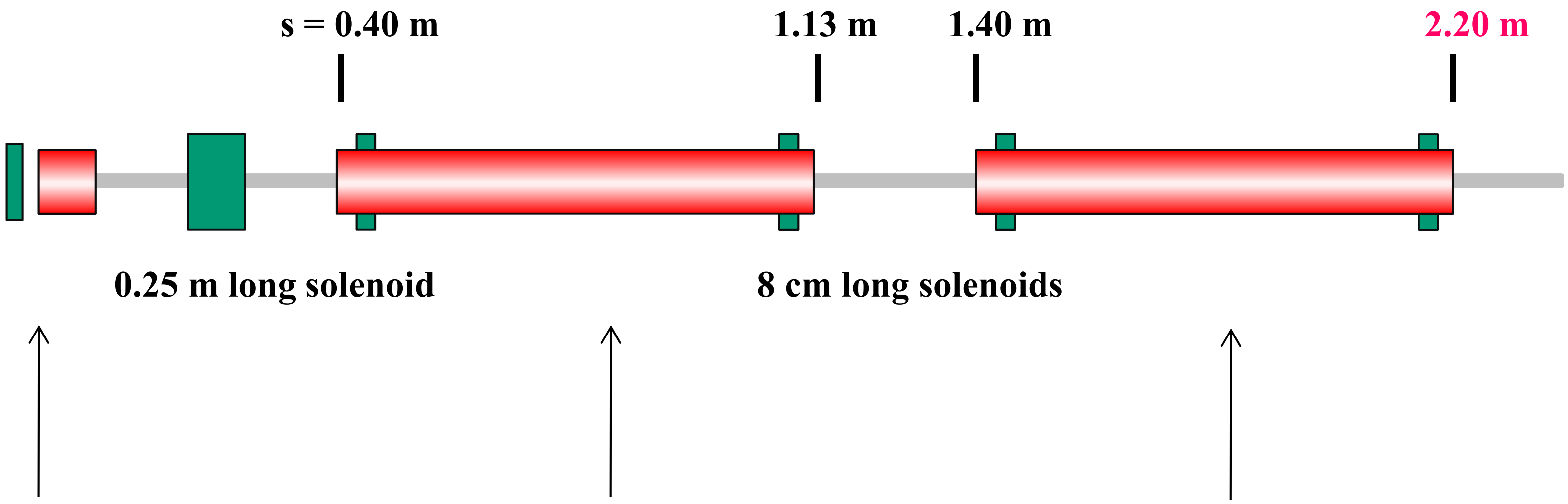
To reduce needed laser power during a high frequency operation, we can choose a cathode with a high quantum efficiency (several % with Cs_2Te, Cs:GaAs, K_2CsSb cathode) @ 532 nm.

$$Q = \eta \times \frac{\lambda_L E_L}{124}$$

To increase beam energy up to 3 MeV, we add two boosting linac structures with $\beta < 1$ and $\beta \sim 1$.

To control Twiss parameters, we add four solenoids along booster linac structures.

Layout of the IAC 3 MeV CW Injector



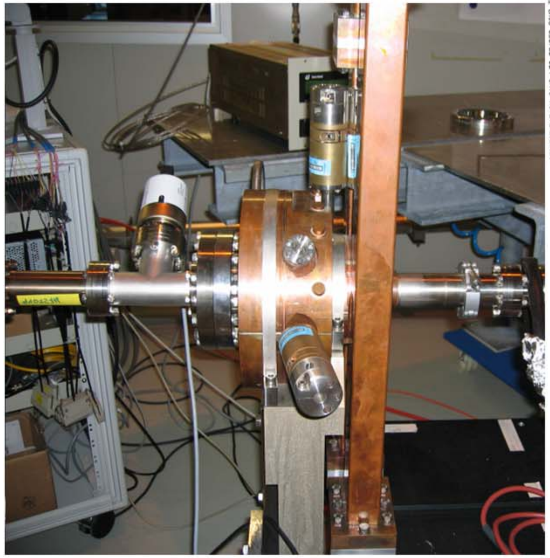
Photoinjector Gun
Cathode: Cs_2Te or Copper
2.5 cells
gradient = 14.15 MV/m
Q = 29 fC
Q.E. < 20%
E_{kf} = 300 keV
f_{RF} = 2450 MHz
350 MHz Nd:YVO4
CW gun driving laser

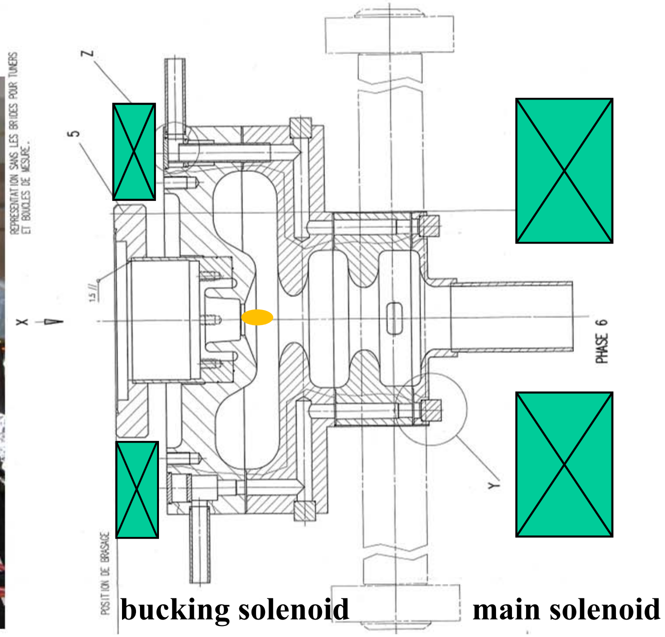
Boosting Linac-I
13 cells
$\beta < 1$
cell length = 4.9 cm - 5.9 cm
gradient = 1.38 MV/m
RF phase = -40 deg
L = 0.726 m
E_{k0} = 300 keV
E_{kf} = 1.301 MeV
f_{RF} = 2450 MHz

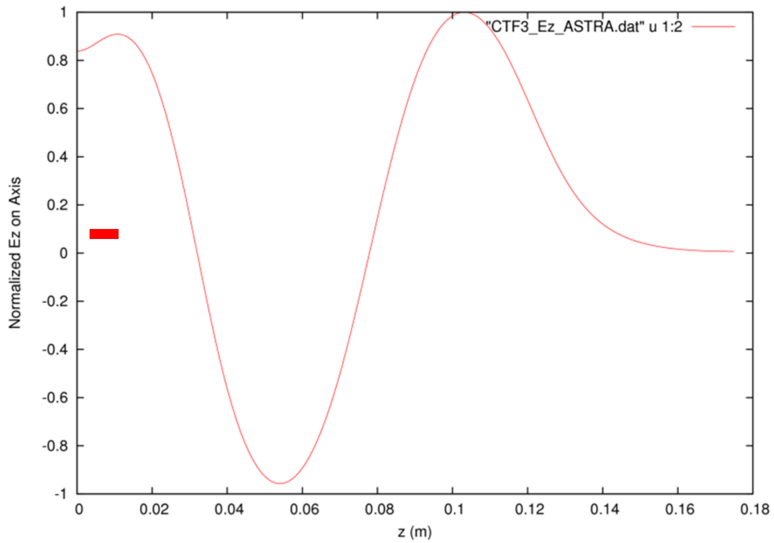
Boosting Linac-II
13 cells
$\beta \sim 1$
cell length ~ 6.1 cm
gradient = 1.91 MV/m
RF phase = -17 deg
L = 0.793 m
E_{k0} = 1.3 MeV
E_{kf} = 2.813 MeV
f_{RF} = 2450 MHz

Components of the IAC 3 MeV CW Injector - Gun

PSI CTF3 2.5 Cell S-band RF Gun
cathode wall angle = 20 degree
cathode loading hole : yes
cell = 2.5 cells (one TM02 + Two TM01)
dual feed for RF dipole mode but no racetrack shape
π & π/2 mode separation ~ 12 MHz
power for 120 MV/m ~ 25 MW (4.5 μs) for about 8 MeV







Components - CPI CW RF Power Source

CPI 2450 MHz VKS-7975A, 120 kW CW S-band Klystron Amplifier ~ $ 1.0 M
CPI 2450 MHz VKS-8269, 500 kW CW S-band Klystron Amplifier ~ $ 2.0 M
→ RF Frequency = 2450 MHz CW

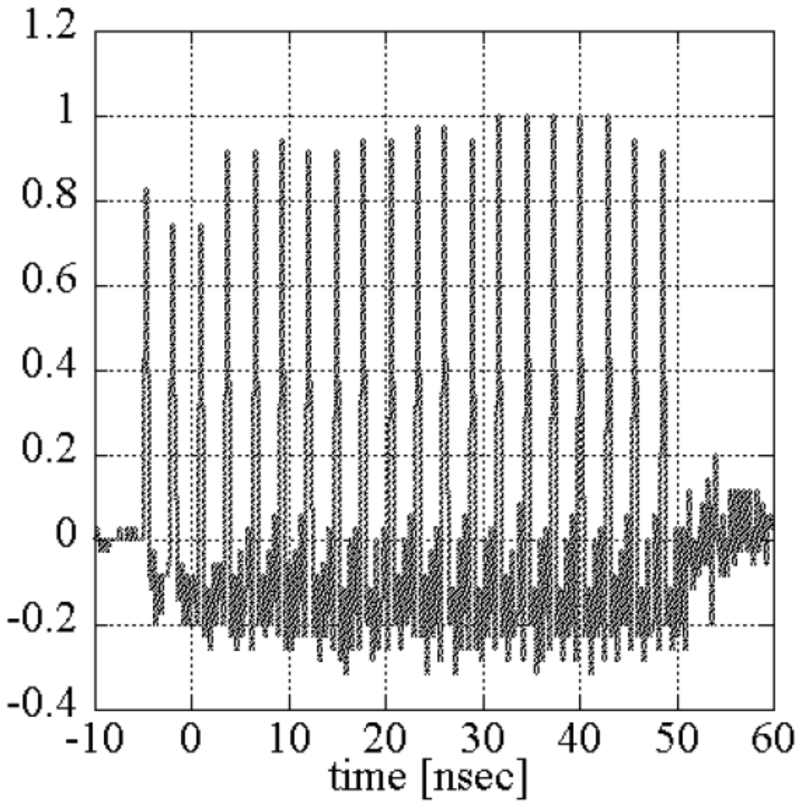
Components - Gun Driving Laser

KEK ATF Nd:YVO_4 laser from Time-Bandwidth

- max repetition frequency = 357 MHz
- pulse spacing = 2.8 ns
- energy per pulse = several μJ
- laser pulse ≈ 10 ps (FWHM)
- wavelength = 266 nm
- maximum single bunch charge ≈ 5 nC

- DESY FLASH has a similar operating laser.

- We can use a similar Time-bandwidth Argos laser for our CW injector.

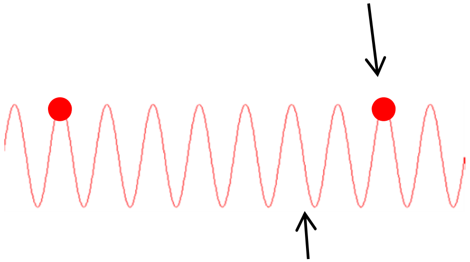


structure of micro bunches
M. Kuriki *et al.*, EPAC2004

Components - Gun Driving Laser

- **RF Frequency of 2450 MHz**
- **Time-Bandwidth Argos CW laser (10 W @ 350 MHz, 532 nm) - 0.7 M$**
- **There is also a similar 2.5 GHz Time-Bandwidth GE-100 CW laser.**
- **If the laser pulse frequency is 350 MHz, an electron bunch will be generated at every 7 RF periods in a CW mode.**

350 MHz laser pulse

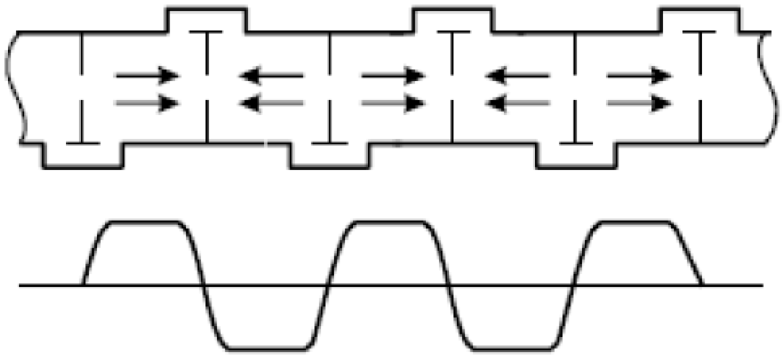


2450 MHz RF pulse

$$\frac{2450\,\mathrm{MHz}}{350\,\mathrm{MHz}} = 7$$

Components - Boosting Linac-I with β < 1

- **Both linacs used in this design are standing wave (SW) type linacs due to its high shunt impedance (~ 85 MΩ/m)**
- **Linac-I:**
  - **The size of each cell is determined by speed of electron beam (see next page).**
  - **Beam traveling time for a cell should be 204 ps.**



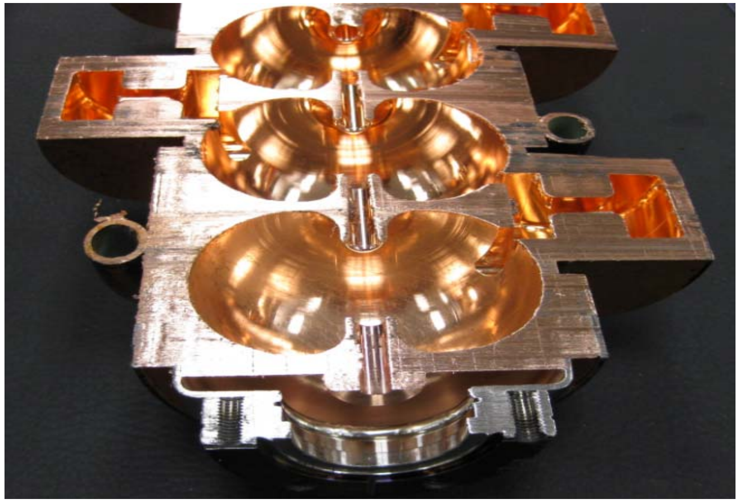
$f_{RF} = 2450$ MHz

$T = 1/f_{RF} = 408$ ps

π mode SW cavity

$\rightarrow T/2 = 204$ ps

cell length $= \beta\lambda_{RF}/2$



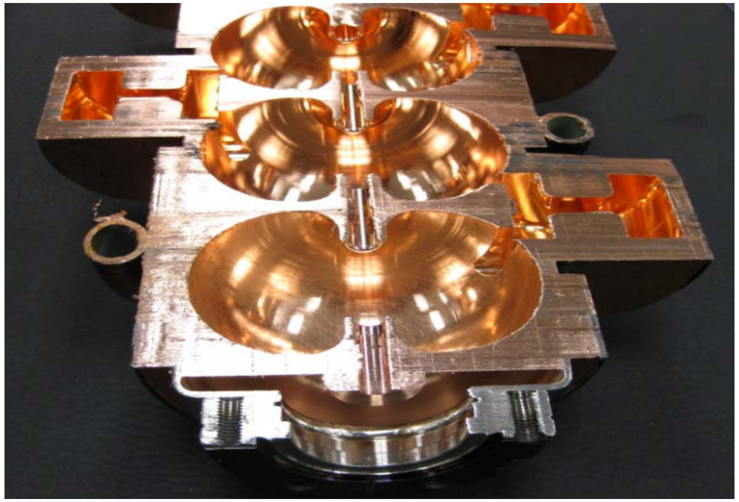
S-band side-coupled SW linac structure

Components - Boosting Linac-I with β < 1

π mode SW cavity

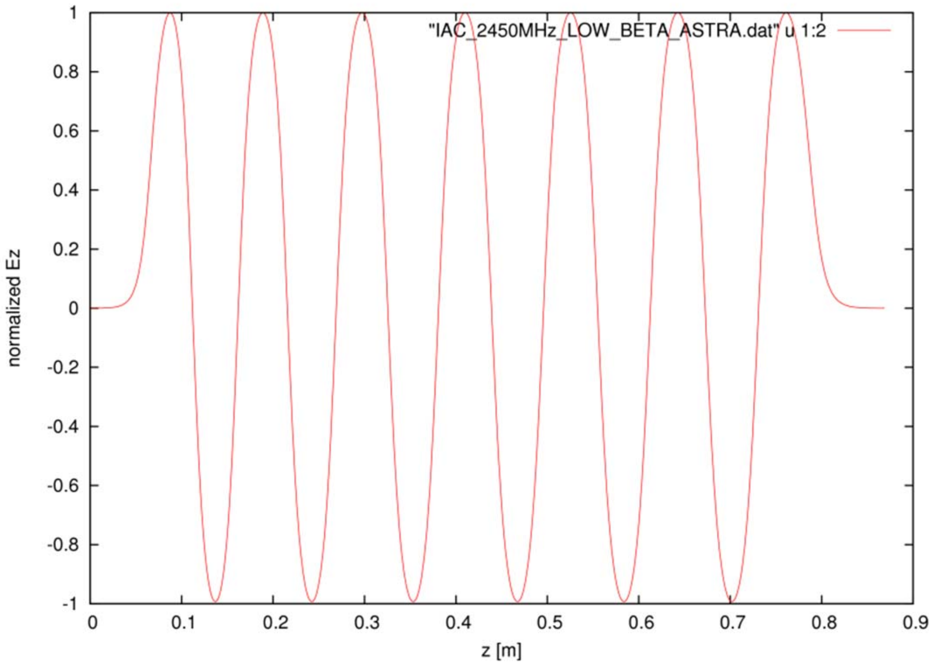
$\rightarrow T/2 = 204$ ps

cell length $= \beta\lambda_{RF}/2 = 4.9 - 5.9$ cm


S-band side-coupled SW linac structure

Cell #	Length(cm)	E_k (MeV)
Cell 1	4.9	.377
Cell 2	5.2	.454
Cell 3	5.3	.531
Cell 4	5.4	.608
Cell 5	5.5	.685
Cell 6	5.6	.762
Cell 7	5.7	.839
Cell 8	5.7	.916
Cell 9	5.8	.993
Cell 10	5.8	1.07
Cell 11	5.8	1.147
Cell 12	5.8	1.224
Cell 13	5.9	1.301

Components - Boosting Linac-I with β < 1



fieldmap of 2450 MHz SW Linac-I

β < 1
total No. of cell = 13
cell length ~ 4.9 - 5.9 cm

Cell #	**Length(cm)**	**E_k (MeV)**
Cell 1	4.9	.377
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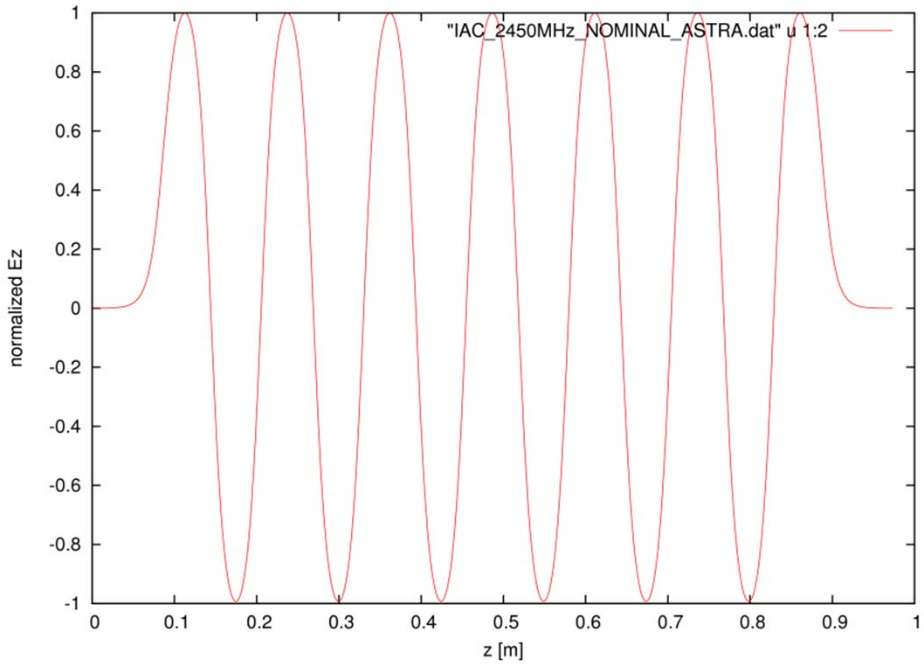
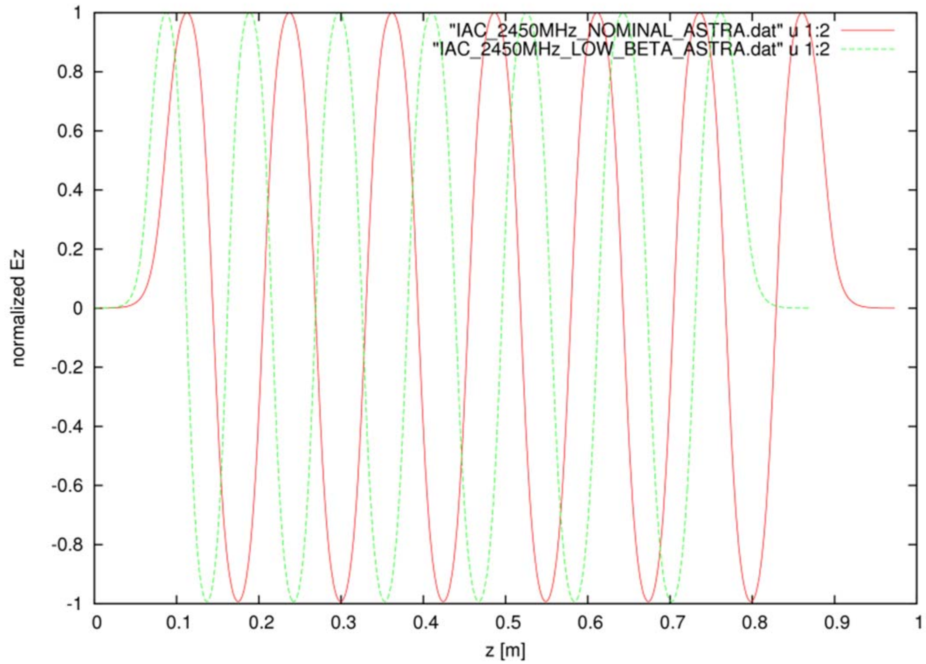
Components - Boosting Linac-II with $\beta \sim 1$





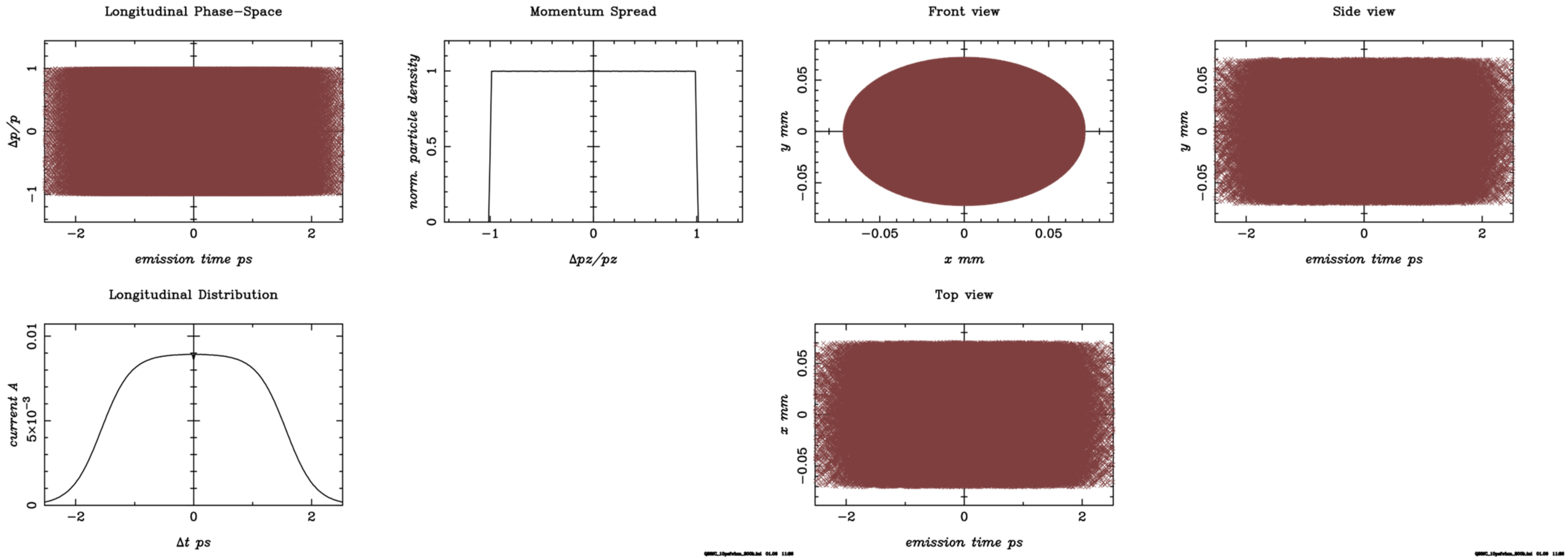
fieldmap of 2450 MHz SW Linac-II

$\beta \sim 1$
total No. of cell = 13
cell length ~ 6.1 cm

fieldmaps of Linac-I & Linac-II

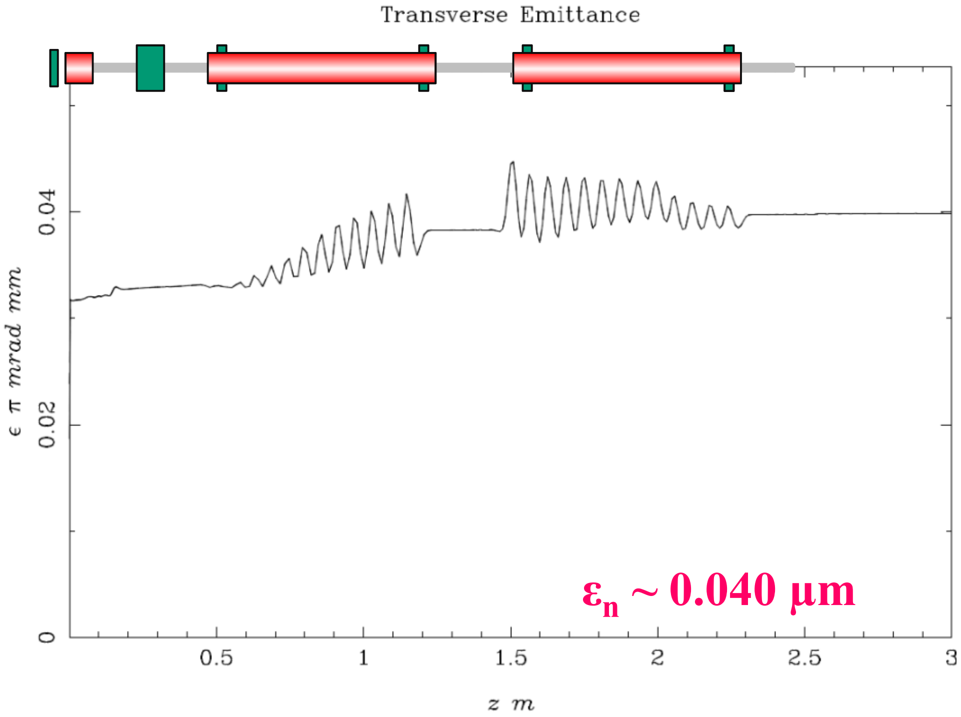
Linac-I : green
Linac-II : red

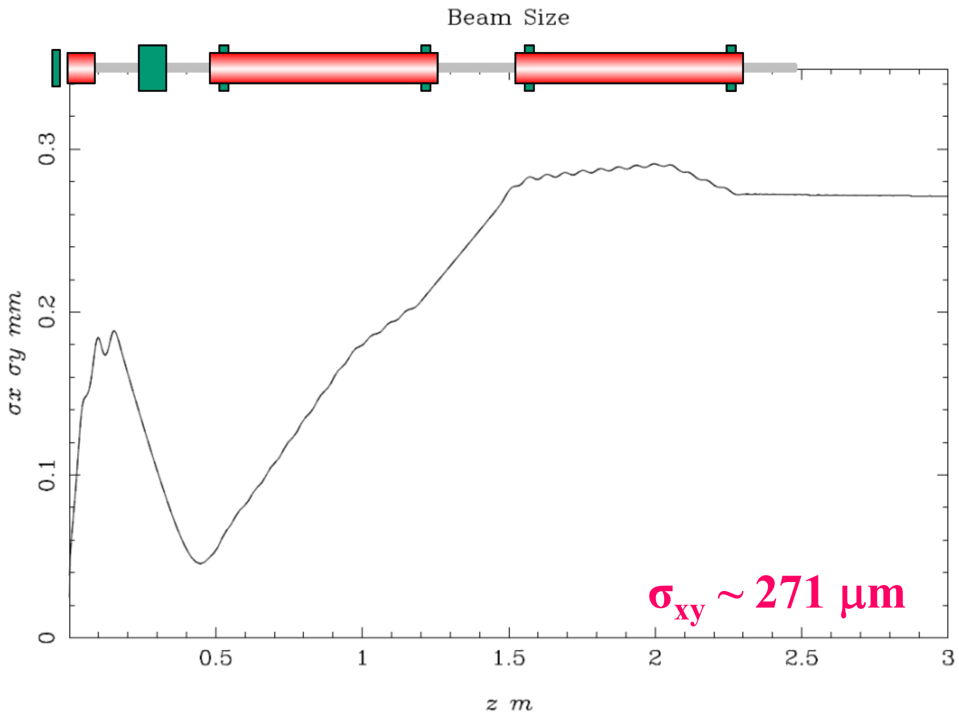
ASTRA Simulation - Gun Driving Laser



- *Q* = 29 fC
- thermal emittance with the copper cathode ~ 0.032 μm (K.E. = 0.63 eV)
- laser spotsize ~ 35 μm (rms) or 140 μm (diameter)
- laser pulse length = 3.13 ps (FWHM) with rising/falling time = 1.0 ps

ASTRA Simulation Results along Injector





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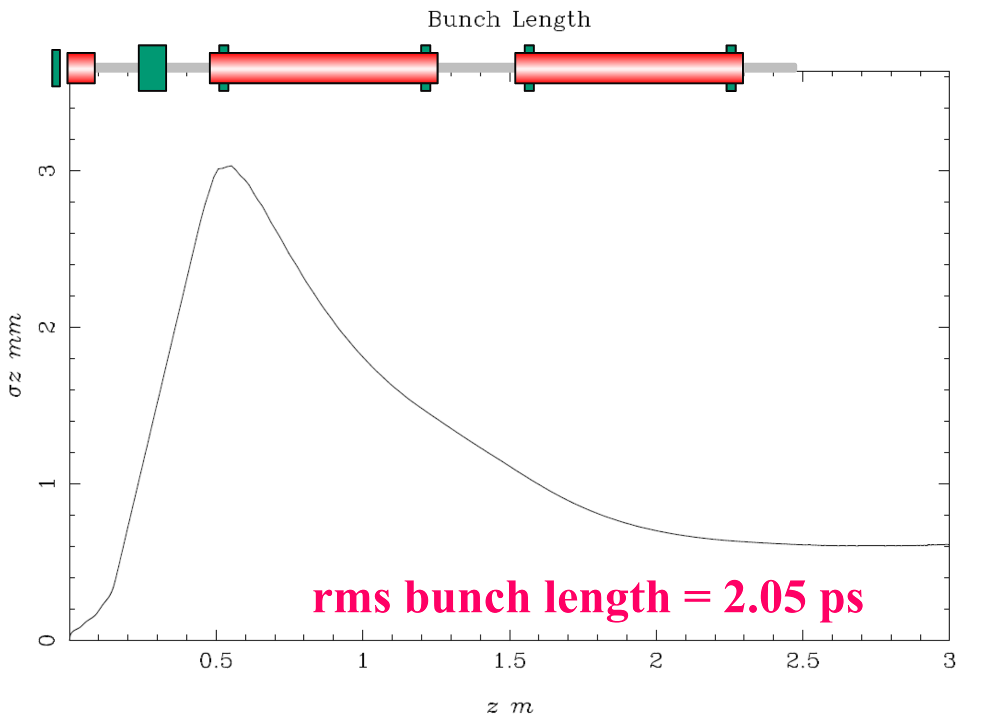

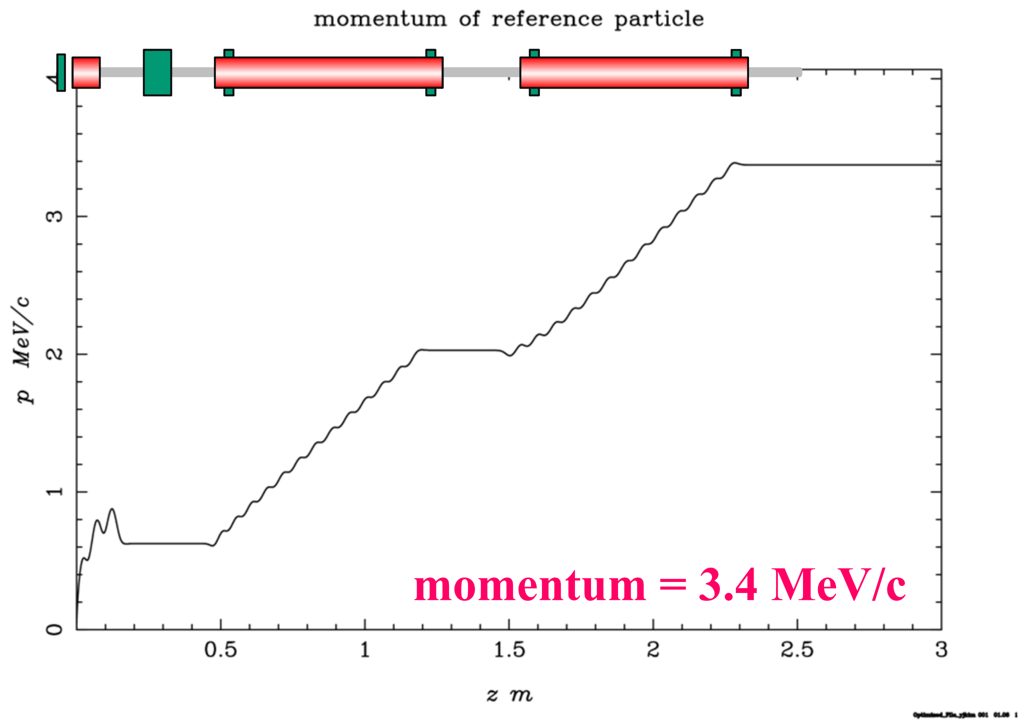

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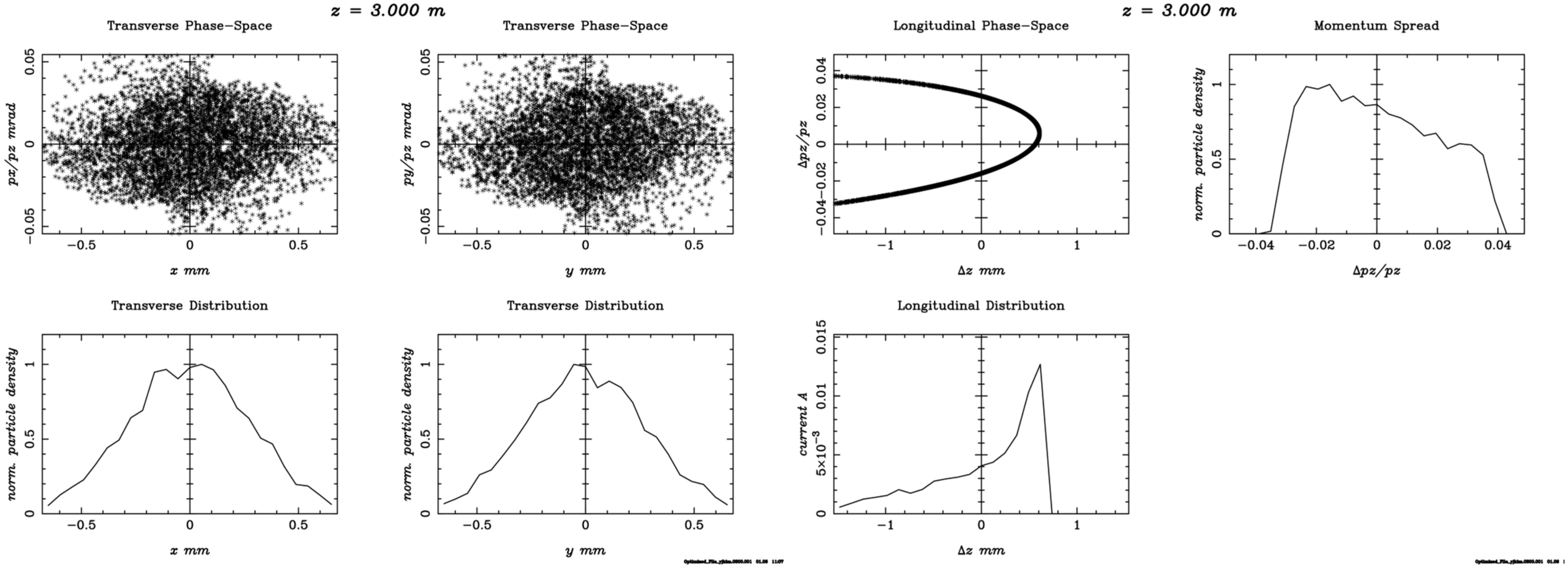
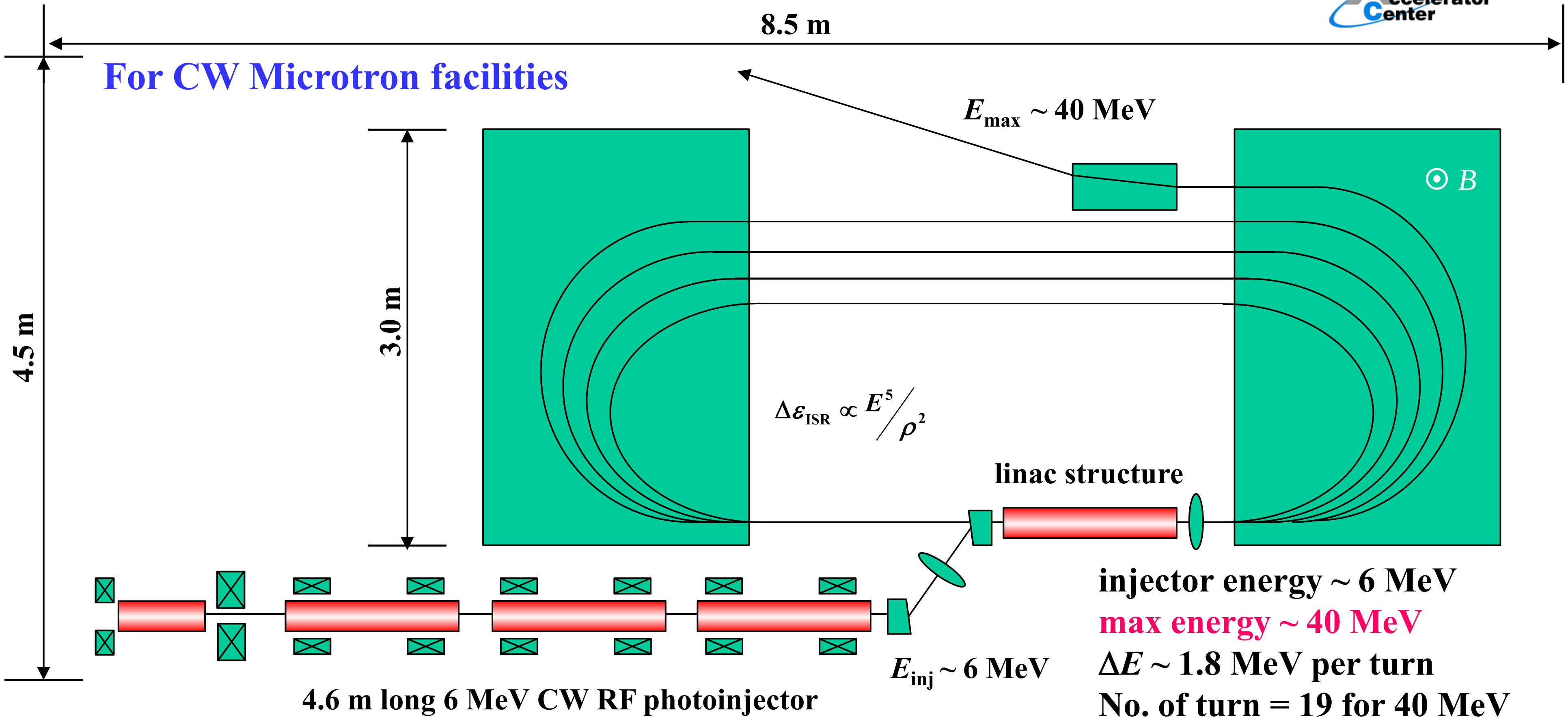
ASTRA Simulation Results at the end of Injector



- total beam energy at the end of injector ~ 3.4 MeV
- normalized emittance at the end of injector ~ 0.04 μm for 29 fC / ~ 3.0 μm for 20 pC with Cu cathode
- average beam current ~ 10 μA (CW) for 29 fC / 7 mA for 20 pC
- relative rms energy spread at the end of injector ~ 2.2%
- rms bunch length at the end of injector ~ 2 ps
- promising parameters.
- We may get better results if the initial pulse length of gun driving laser is optimized further.

IAC 40 MeV CW Race Track Microtron (RTM)

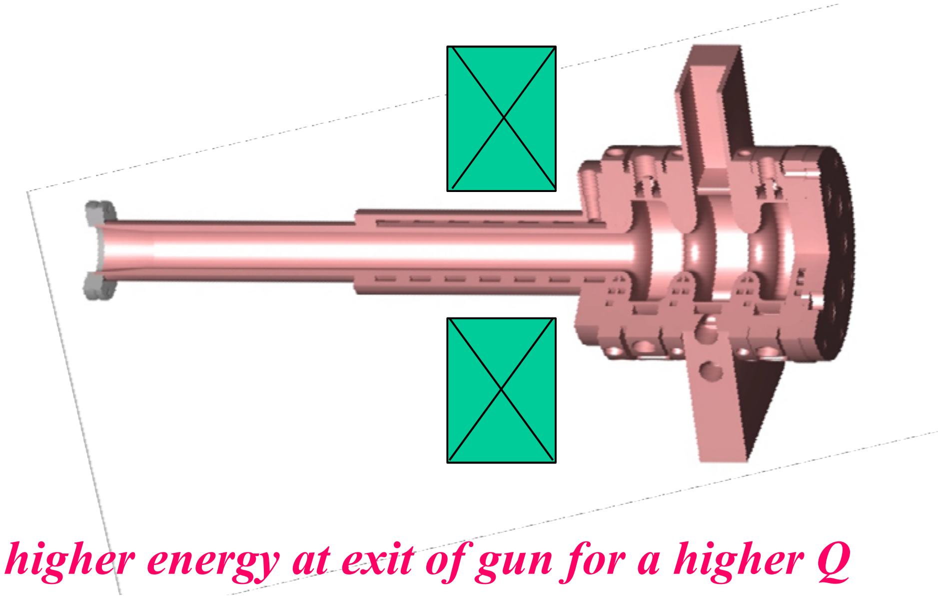


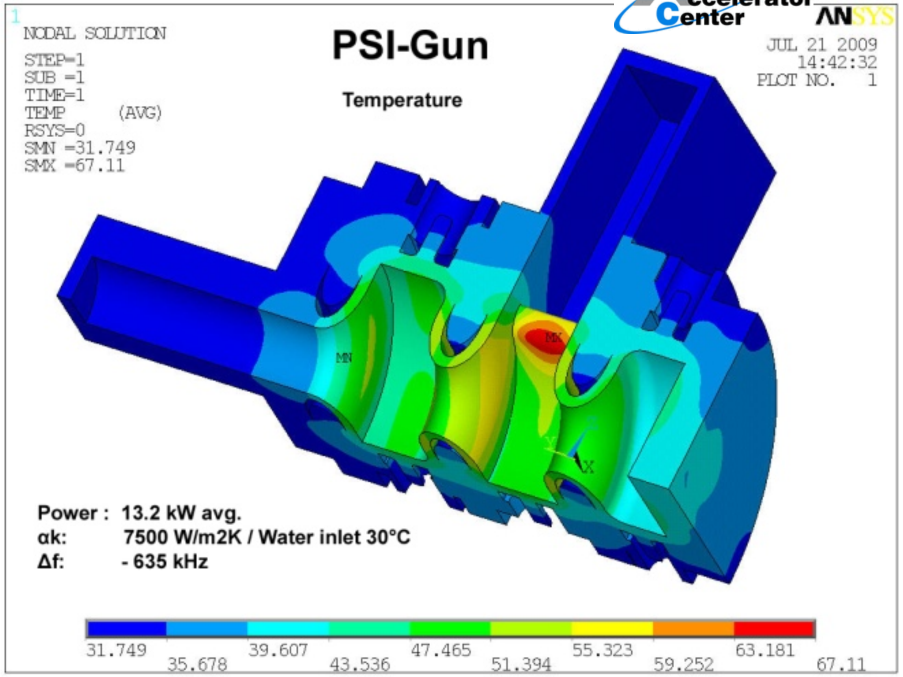
injector energy ~ 6 MeV
max energy ~ 40 MeV
ΔE ~ 1.8 MeV per turn
No. of turn = 19 for 40 MeV
uniform B field region = 2.5 m
max B field strength = 0.5 T
nominal B field strength = 0.107 T
max bending radius = 1.25 m
x-norm. emittance < 5 mm.mrad
y-norm. emittance < 1 mm.mrad

Total Construction Budget ~ $5-6 M
Average Beam Current ~ 7 mA with 20 pC
Average Beam Power ~ 280 kW (max)
RF Frequency = 2450 MHz CW
Total Required RF Power ~ 270 kW CW
Beam Repetition Rate = 350 MHz CW

Concepts of CW gun for XFEL/ERL Facilities

Heat load of SwissFEL gun for 400 Hz operation





higher energy at exit of gun for a higher Q

With a single RF structure for CW operation, RF power dissipation to the cavity is too high (> 100 kW) to accelerate electron beams up to several MeV range. To keep power dissipation of the cavity within a control level (≤ 30 kW), we divide a single cavity into several longer RF structures (gun and boosting linac strutures) to reach a few MeV range.

Gradient is much lower but we do not need a high gradient for a much lower single bunch charge. Instead of choosing a higher charge and a higher gradient, we chose a lower charge but its beam repetition frequency is much higher (350 MHz - 2450 MHz) to keep a high average beam current (7 - 50 mA), which is possible with status-art-lasers.

Impact of Low Gun Gradient on Beam Quality

- note that ε_{lsc} and ε_{nsc}, are controllable though the gun gradient E is lower if charge is much lower and bunch length is longer. Here ε_{rf} is also ignorable.

$$\varepsilon_{nx,ny} = \sqrt{\varepsilon_{th}^2 + \varepsilon_{lsc}^2 + \varepsilon_{nsc}^2 + \varepsilon_{rf}^2 + \varepsilon_{optics}^2} \qquad \varepsilon_{slice} \geq \varepsilon_{th}$$

$$\varepsilon_{th} \approx \sigma_{x,y}\sqrt{\frac{2K_{ave}}{3m_e c^2}} = \sigma_{x,y}\sqrt{\frac{k_B T}{m_e c^2}}, \quad \text{for thermionic emission}$$

$$\varepsilon_{th} \to \sigma_{x,y}\sqrt{\frac{\hbar\omega - \phi_{eff}}{3m_e c^2}} = \sigma_{x,y}\sqrt{\frac{\hbar\omega - \phi_w + \phi_{schottky}}{3m_e c^2}} \quad \text{for photo emission}$$

Here $K_{ave} \approx (3/2)\times k_B T$ for thermal emission

$K_{ave} \approx (1/2)\times(\hbar\omega - \phi_w + \phi_{schottky})$ for photo emission

$\phi_{schottky} \sim 3.7947\times 10^{-5}\sqrt{E(\text{V/m})}$ eV

$k_B = 8.617\times 10^{-5}$ eV/K

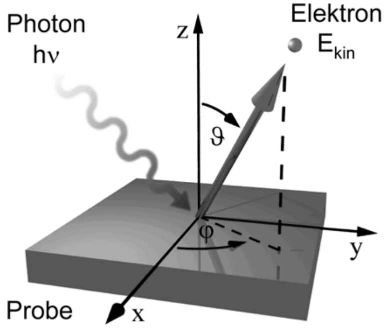
$\varepsilon_{th} \sim 0.24$ μm for LaB_6 cathode with $\sigma_{x,y} = 0.445$ mm, $T = 1700$ K

$$\varepsilon_{lsc} \propto \frac{Q}{(2\sigma_r + \sigma_z)E}$$

$$\varepsilon_{nsc} \propto \frac{FQ}{\sigma_r^2 \sigma_z}$$

$$\varepsilon_{rf} \propto f_{rf}^2 \sigma_r^2 \sigma_z^2 E$$

$$\varepsilon_{optics} \propto \frac{\sigma_\delta \sigma_r^2}{f_{sol}}$$



Y. Kim *et al.*, FEL2006, Y. Kim *et al*, FEL2008, D. H. Dowell *et al.*, PRST-AB 9, 063502 (2006)
K. Togawa *et al.*, PRST-AB, 10, 020703 (2007), K. L. Jensen *et al.*, JAP 102, 074902 (2007), C. Travier *et al.*, NIMA 340, 26 (1994)

Selection of Charge - from SwissFEL Injector

ASTRA Simulation Results : CTF3 RF Gun based SwissFEL Injector for various Charges

Q	laser length (FWHM)	$I_{peak, cathode}$	laser $\sigma_{x,or\ y}$	$\varepsilon_{thermal}$	$\varepsilon_{slice}/\varepsilon_{projected}$
200 pC	9.9 ps	22 A	270 μm	0.195 μm	0.320/0.350 μm
150 pC	9.0 ps	18 A	245 μm	0.177 μm	0.272/0.283 μm
100 pC	7.9 ps	14 A	214 μm	0.155 μm	0.220/0.233 μm
50 pC	6.2 ps	8.7 A	170 μm	0.123 μm	0.160/0.174 μm
20 pC	4.6 ps	4.7 A	125 μm	0.091 μm	0.108/0.122 μm
10 pC	3.7 ps	3.0 A	100 μm	0.072 μm	0.080/0.096 μm
5 pC	2.9 ps	1.9 A	79 μm	0.057 μm	0.062/0.074 μm
2 pC	2.1 ps	1.0 A	58 μm	0.042 μm	0.044/0.054 μm

~ 2 times brighter

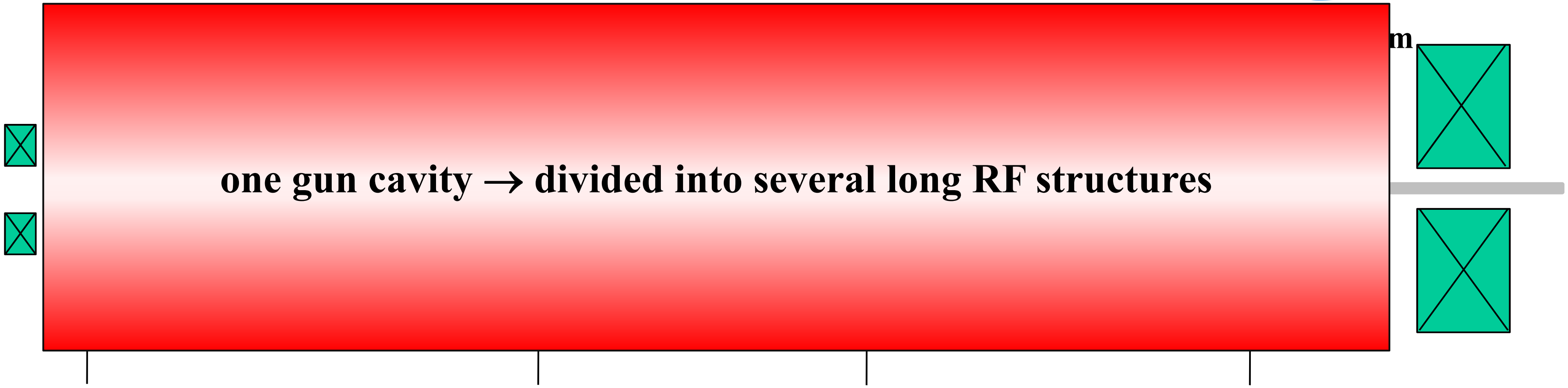
Final beam parameters are at the exit of the 2nd S-band structure (130 MeV - 172 MeV).
Gun max gradient = 100 MV/m, assumed K_{ave} = 0.4 eV with copper cathode.

For only $Q \leq 2$ pC, $\varepsilon_{projected} \approx \varepsilon_{slice} \approx \varepsilon_{thermal}$

For a much higher Q, $\varepsilon_{projected} > \varepsilon_{slice} >> \varepsilon_{thermal}$ due to the nonlinear space charge force.

From experiences of the 18 SwissFEL linac optimizations and LCLS low charge operation, we chose 20 pC for the single bunch charge of the CW injector for XFEL/ERL facilities.

Concept of CW gun for XFEL/ERL Facilities



CW RF Photoinjector
6.5 cells $\beta = 0.687 - 0.906$
cathode: Cs:GaAs or K_2CsSb
Q.E. ~ 10% @ 532 nm
ε_{th} ratio = 0.22 μm/mm (rms spot)
max average current ~ 7 mA
Q = 20 pC for 7 mA @ 350 MHz
laser repetition = 350 MHz CW
laser oscillator = 10 W Nd:YVO_4
gradient ~ 2 MV/m
length L = 0.367 m
ΔE_k = 700 keV
E_T = 1.211 MeV
f_{RF} = 2450 MHz
R_{sh} ~ 45 MΩ/m
power dissipation ~ 29 kW

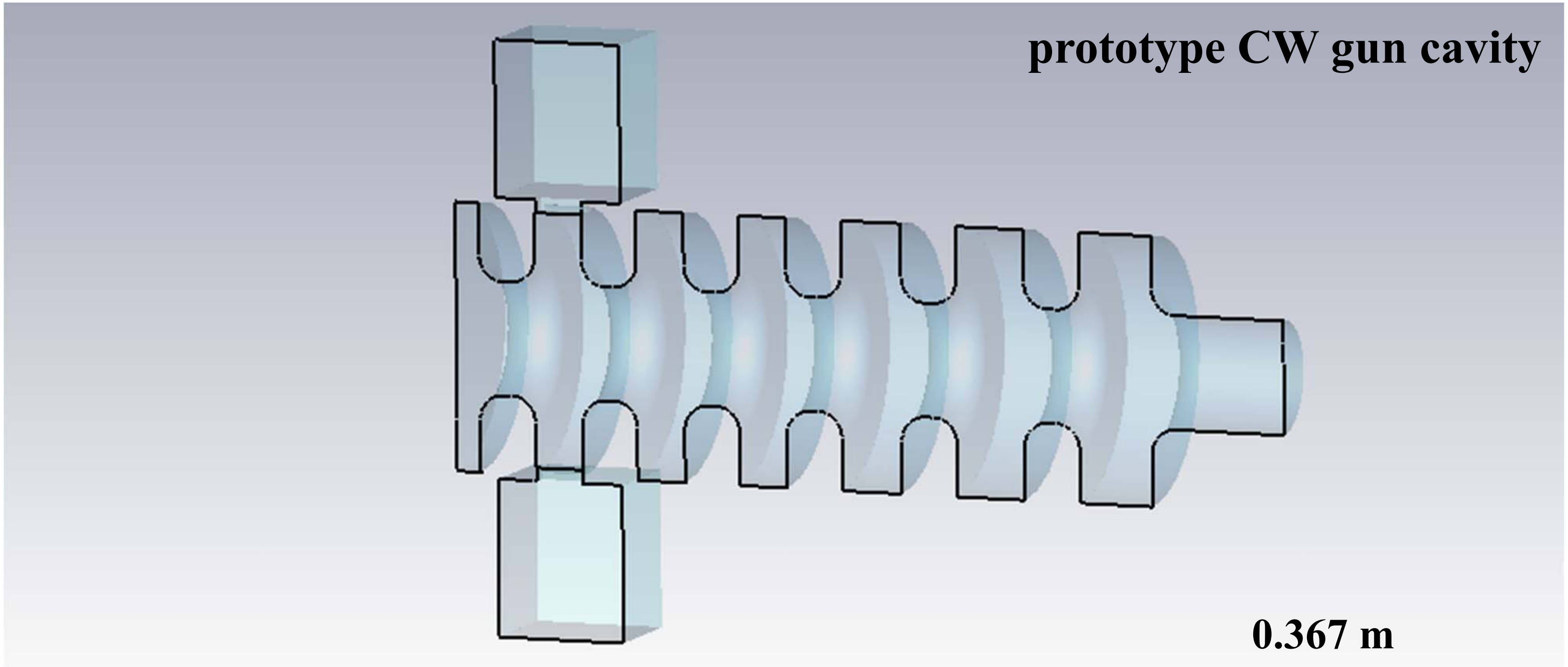
Booster Linac-I
21 cells $\beta = 0.906 - 0.984$
cell length = 5.53 - 6.00 cm
gradient = 1.18 MV/m
L = 1.389 m
ΔE_k = 1.634 MeV
E_{kf} = 2.334 MeV
E_T = 2.845 MeV
f_{RF} = 2450 MHz
R_{sh} ~ 85 MΩ/m
power dissipation ~ 23 kW

Booster Linac- II
21 cells $\beta = 0.984 - 0.994$
cell length = 6.00 - 6.06 cm
gradient = 1.12 MV/m
L = 1.454 m
ΔE_k = 1.700 MeV
E_{kf} = 4.034 MeV
E_T = 4.545 MeV
f_{RF} = 2450 MHz
R_{sh} ~ 85 MΩ/m
power dissipation ~ 22 kW

Booster Linac-III
21 cells $\beta = 1$
cell length ~ 6.1 cm
gradient = 1.22 MV/m
L = 1.472 m
ΔE_k = 1.800 MeV
E_{kf} = 5.834 MeV
E_T = 6.345 MeV
f_{RF} = 2450 MHz
R_{sh} ~ 85 MΩ/m
power dissipation ~ 26 kW

power dissipation at each RF structure < 26 kW
power dissipation at all RF structures < 100 kW

Concept of CW gun for XFEL/ERL Facilities

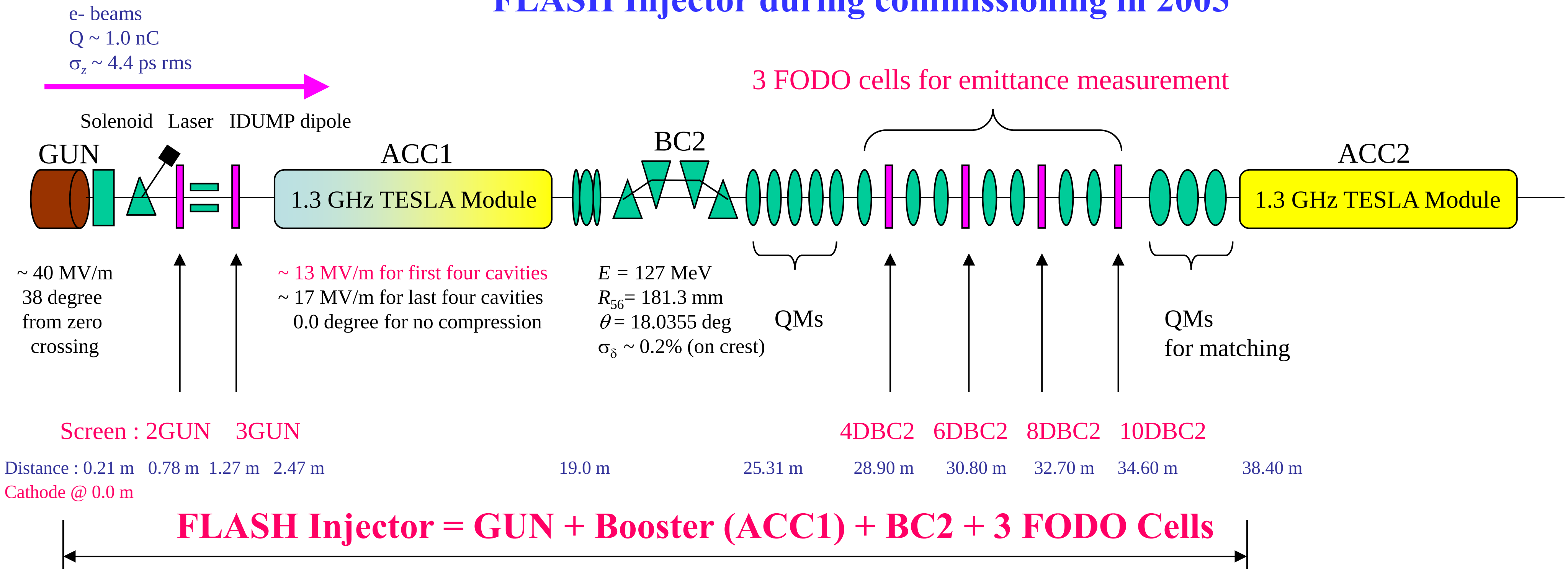


IAC 6.5 cell RF gun cavity for CW operation

f_{RF} = 2450 MHz
β = 0.687 - 0.906
half cell length = 2.09535 cm
length of the 1st - 3rd full cells = 4.1907 cm
length of the sixth cell = 5.5266 cm
power dissipation ~ 29 kW for ΔE_k = 700 keV

Emittance Compensation @ DESY FLASH Facility

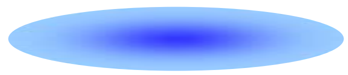
FLASH Injector during commissioning in 2005

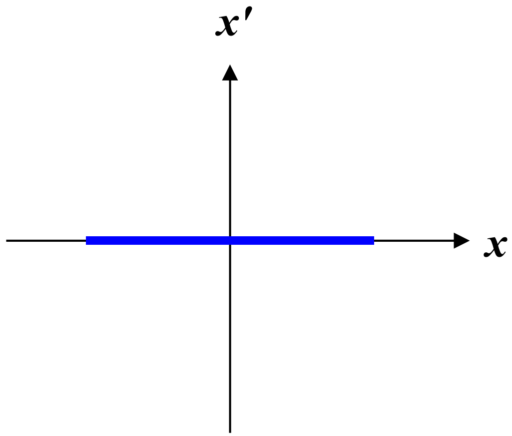


By optimizing TTF2/FLASH injector properly, we could get an excellent emittance at the injector. Without any bunch length compression, projected normalized emittance is about 1.1 μm for 90% beam intensity in 1.0 nC and 4.4 ps (rms) long bunch.

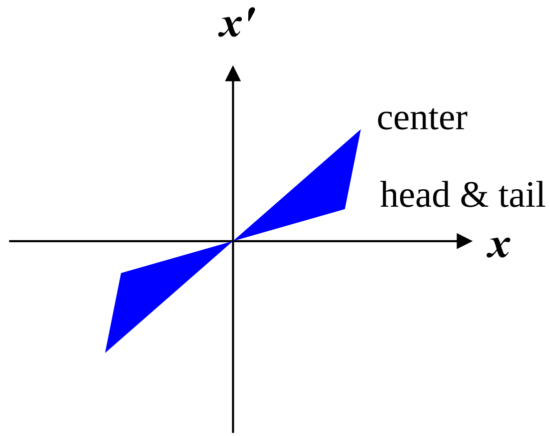
Invariant Envelope Matching & Emittance Damping

emitted electron bunch

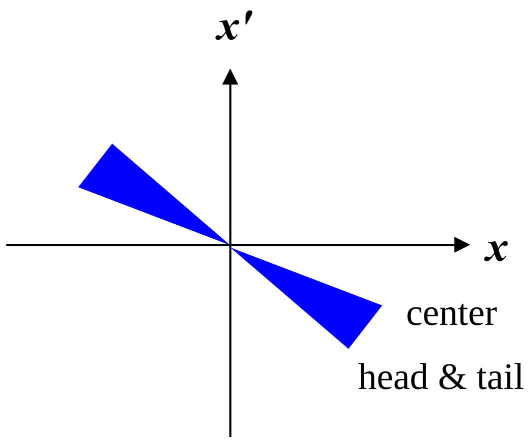




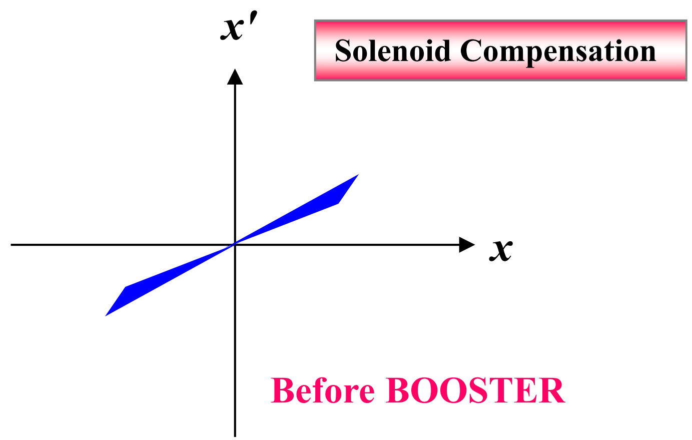
initial zero emittance just after emission from cathode



increased emittance due to space chare force

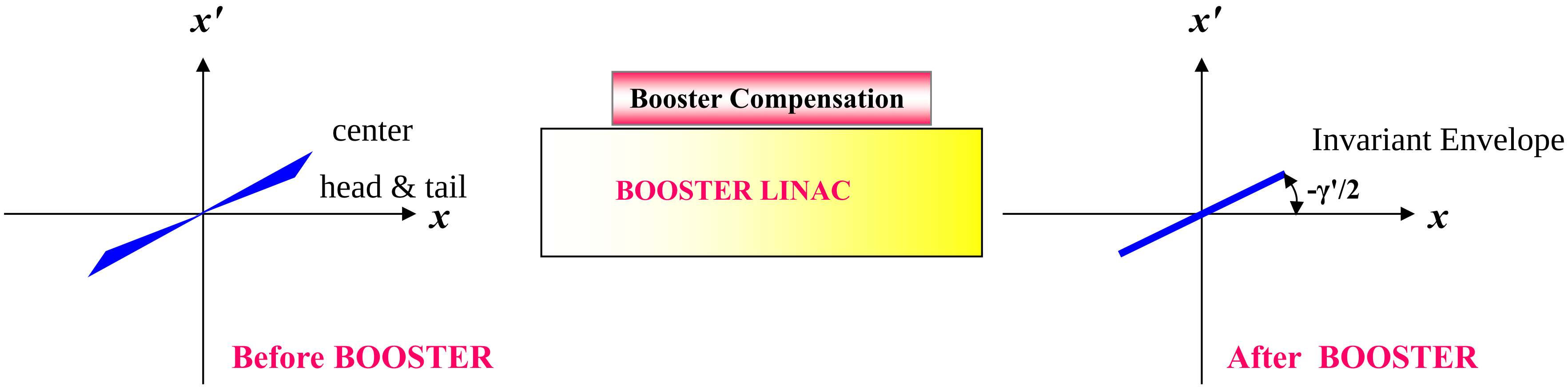


rotated phase space by an external focusing solenoid



compensation by reaction of space charge force after some drift

Invariant Envelope Matching & Emittance Damping



Space charge force induces oscillations in envelope and emittance.
The emittace and envelope oscillation around an ideal invariant envelope can be damped by accelerating beams in booster. (L. Serafini and J. Rosenzweig PRE Vol 55, Page 7565)

$$\varepsilon_n \approx \frac{\left(\sigma_r - \sigma_{r,INV}\right)}{\gamma'} \sqrt{\frac{I}{3 I_0 \gamma}} \left| \cos\psi - \sqrt{2}\sin\psi \right|, \quad \psi = \frac{1}{\sqrt{2}} \ln\left(\frac{\gamma}{\gamma_0}\right)$$

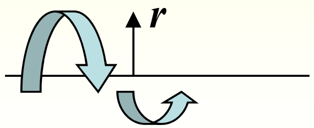
Invariant envelope is an ideal case which makes a constant slope (-γ'/2) for all different slices in the phase space by the acceleration of booster. In this case, beam spot size as well as transverse momentum are reduced together due to reduced space charge force in booster. Projected (and even slice) emittance damping in booster !!!

Conditions for Invariant Envelope Matching

Pondermotive RF Focusing (PRE Vol. 47, page 2031, 1993)

Periodic longitudinal accelerating electric field E_z induces periodic transverse Lorentz force and electron's periodical transverse motion. Due to nonzero spatial gradient of the force, the net momentum transfer (or total effective focusing strength) for one periodic cycle is not zero, which is the ponderomotive RF focusing force.

$$\overline{F_r} \approx -r\frac{(eE_o)^2}{8\gamma mc^2} \text{ for fundamental mode in SW linac}$$



To avoid space charge effects in the drift space and to avoid too strong pondermotive RF focusing in the booster linac, at the entrance of booster, (PRE Vol 55, Page 7565, SLAC-PUB-8400)

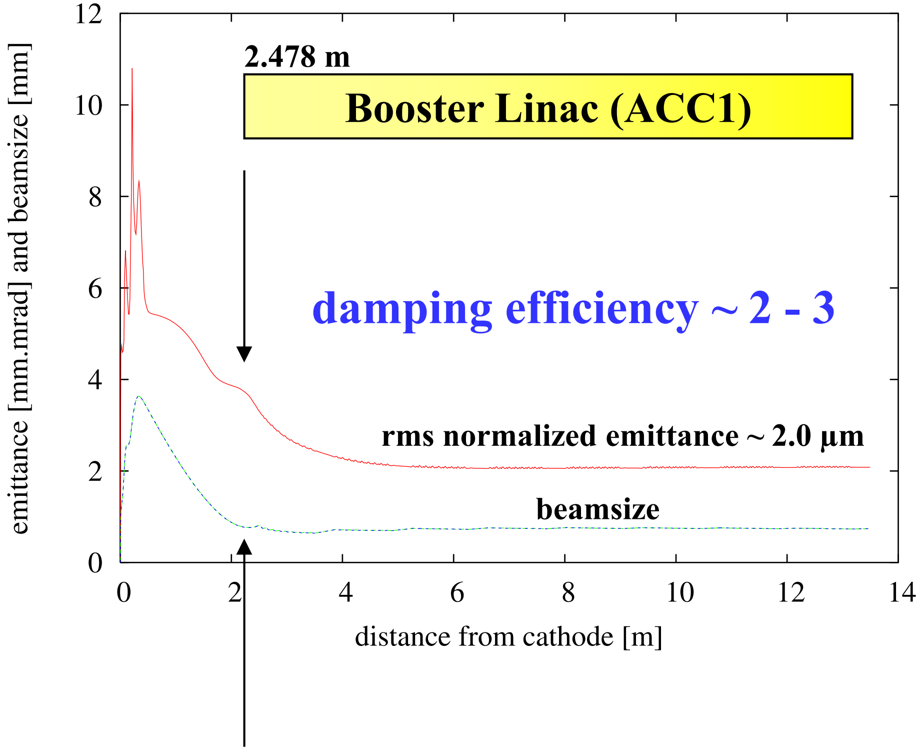
$$\sigma' = 0 \quad \text{(laminar waist)}$$

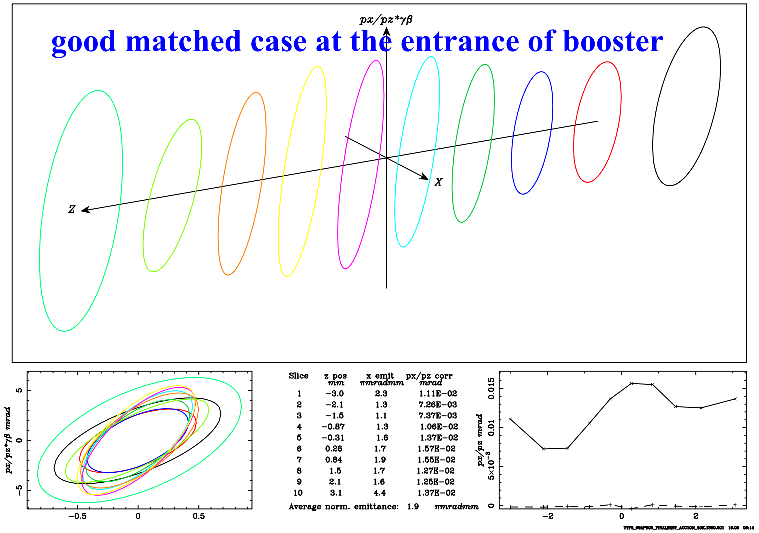
$$\gamma' = \frac{2}{\sigma_w}\sqrt{\frac{\hat{I}}{3I_o\gamma}} \quad \text{for SW linac (invariant envelope), } I_o = 17 \text{ kA.}$$

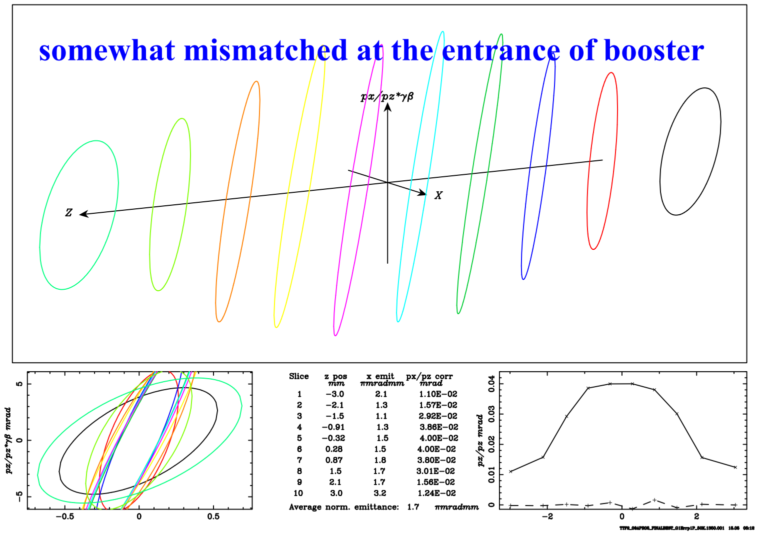
These means that at the entrance of booster linac, emittance should be its 2nd maximum, and beamsize should be its minimum. If these two conditions are satisfied, envelope is oscillated around the invariant envelope and we can get continuous emittance damping in booster linac.

Conditions for Invariant Envelope Matching

ASTRA Simulation Results on FLASH Injector







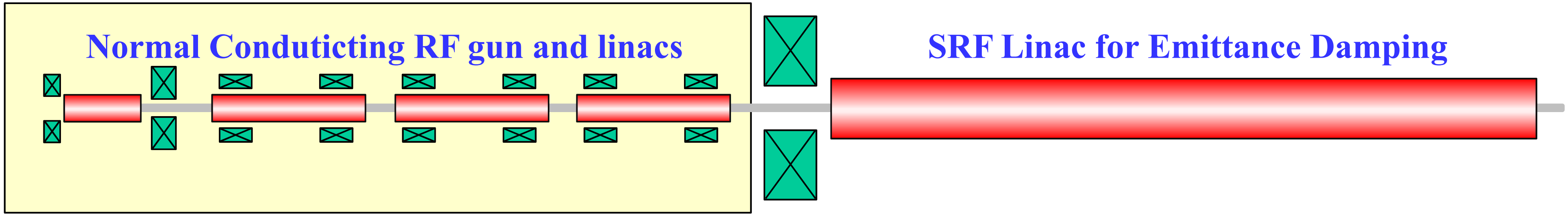
At the entrance of booster, invariant envelope concept based matching conditions should be satisfied to get emittance damping in booster !

- local maximum emittance
- local minimum beamsize

Layout of CW Injector for XFEL/ERL Facilities

Idaho Accelerator Center

We can consider this normal conducting RF injector as a big RF gun in normal injectors for the XFEL projects. Therefore, we can compensate projected emittance by optimizing strength of a new bigger solenoid and the gradient of superconducting booster linac (Invariant Envelope Matching).



a big CW gun system for XFEL/ERL projects **solenoid for emittance compensation**

<u>Before Emittance Compensation</u>

Q = 20 pC
average current ~ 7 mA
peak current ~ 1.5 A
bunch length ~ 5.3 ps (rms)
e-beam repetition = 350 - 2450 MHz CW
E ~ 3-6 MeV
ε_n < 0.8 μm
(Cs:GaAs cathode with a lower ε_{th} and longer bunch)

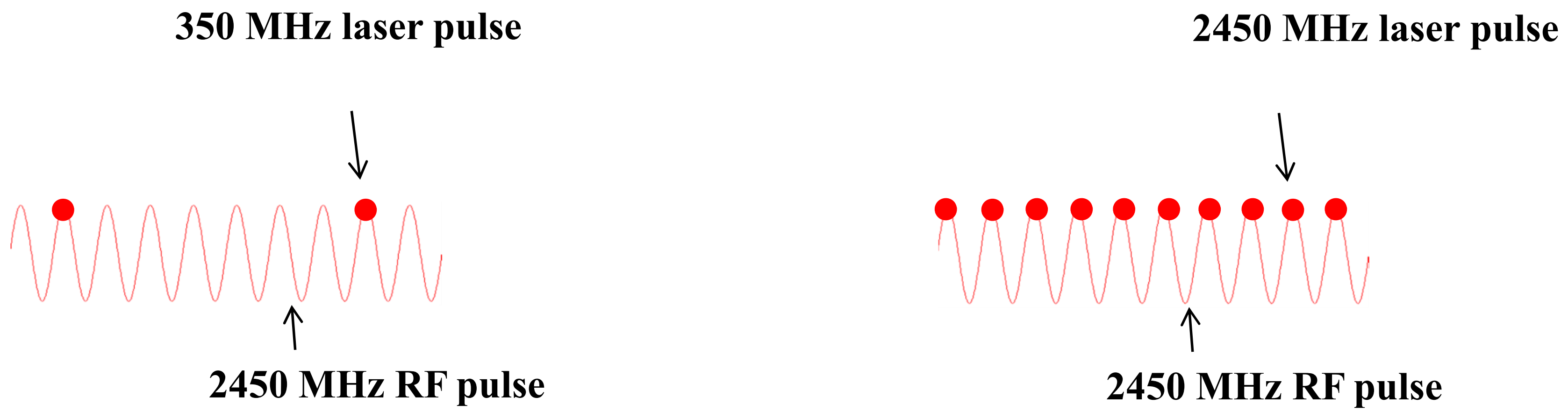
<u>After emittance Compensation</u>

Q = 20 pC
average current ~ 7 mA
peak current ~ 1.5 A
bunch length ~ 5.3 ps (rms)
e-beam repetition = 350 - 2450 MHz CW
E > 120 MeV
ε_n < 0.4 μm

This layout is a similar to the FLASH injector! Detailed optimizations are on going now!

For a Higher Average Current Operation ~ 50 mA

For CW ERL facilities

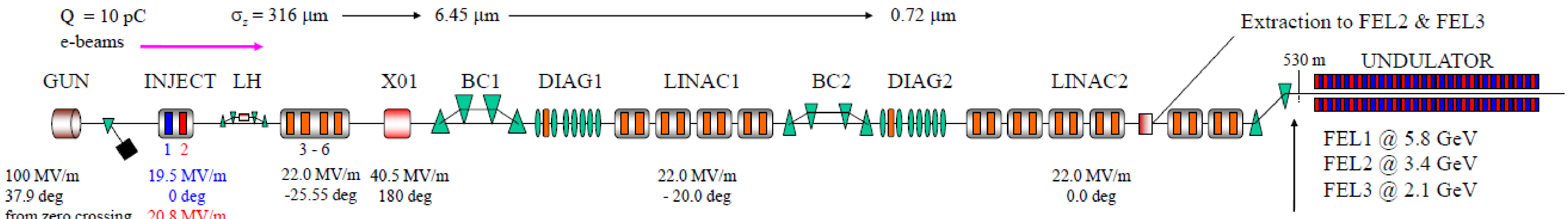


Q = 20 pC
average current ~ 7.14 mA
laser repetition = 350 MHz CW
e-beam repetition = 350 MHz CW
f_{RF} = 2450 MHz
$\varepsilon_n < 0.4\ \mu$m
(after emittance compensation)

Q ~ 20 pC
average current ~ 50 mA
laser repetition = 2450 MHz CW
e-beam repetition = 2450 MHz CW
f_{RF} = 2450 MHz
$\varepsilon_n < 0.4\ \mu$m
(after emittance compensation)

For a Higher Peak Current Operation ~ a few kA

SwissFEL Linac Optimization-XI with New Injector for 10 pC Single Spike Mode



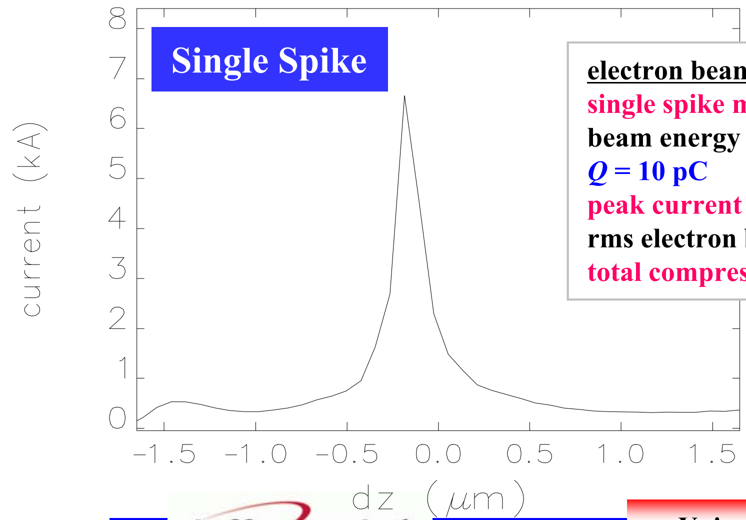
E = 450.7 MeV
σ_δ ~ 0.673%
R_{56} = 45.98 mm
θ = 3.8 deg

E = 1963.7 MeV
σ_δ ~ 0.161%
R_{56} = 3.17 mm
θ = 1.0 deg

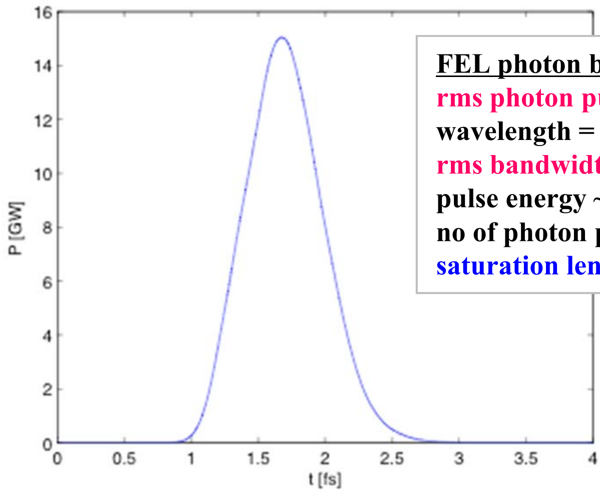
For CW XFEL facilities

E = 5800 MeV, σ_δ = 0.053%
σ_x = 13.0 μm, σ_y = 13.0 μm, σ_z = 0.72 μm
ε_{nx} ~ 0.240 μm, ε_{ny} ~ 0.097 μm
I_{peak} < 7 kA, $\varepsilon_{n,core,slice}$ < 0.150 μm
$\sigma_{dE,slice}$ < 800 keV for whole bunch

initial 3.0 A becomes 7.0 kA by a strong compression!
ultra-tight RF jitter tolerances are required.



electron beam for Optimization-XI
single spike mode (0.7 nm ~ 7 nm)
beam energy ~ 3.4 GeV
Q = 10 pC
peak current ~ 7 kA
rms electron bunch length ~ 2.4 fs
total compression factor = 2400



FEL photon beam for Optimization-XI
rms photon pulse length ~ 330 as
wavelength = 0.7 nm with K = 1.05
rms bandwidth ~ 0.35% for 7 kA
pulse energy ~ 9 μJ
no of photon per pulse ~ 3.1×10^{10}
saturation length ~ 25 m for 7 kA

Summary & Acknowledgements

- There are strong user' demands on CW accelerators at the Idaho Accelerator Center (IAC), where about 15 accelerators are under operating.
- The IAC chose the CW microtron to supply CW electron beams to users.
- The CW injector for the IAC CW microtron was designed with following design concepts, which can also be used for CW ERL and XFEL facilities:
  - choosing the normal RF technology for easy maintenance.
  - choosing RF photoinjector to remove a long buncher.
  - dividing one RF gun cavity into several longer RF structures to keep RF power dissipation within control range (≤ 30 kW) during the CW mode operation.
  - beam quality dilution due to a lower gun gradient can be compensated by choosing a lower charge (~ 20 pC) and longer bunch length.
  - by adding a solenoid and a superconducting booster linac, the projected emittance can be damped down further with the well known invariant envelope matching concept.
  - average current can be increased further (~ 50 mA) by increasing repetition rate of the gun driving laser.
  - peak current can be increased further (~ a few kA) by compressing bunch length strongly at bunch compressors.

- Many thanks to Jefferson Lab colleagues and N. Peterson and Dr. Cole for some slides.