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

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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.

http://www.iac.isu.edu
Various Accelerators @ IAC

4 MV Pelletron

10 MeV, 10 kA induction accelerator

Cargo Container Scanning Test Facility

50 MeV, 40 kW S-band linac

Yujong Kim @ Idaho State University and Thomas Jefferson National Accelerator Facility, USA
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.
A racetrack microtron (RTM) uses two wide dipoles to bend electron beams by 360 degrees per turn. After each turn, electron beams are 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.

\[ p(\text{GeV} / c) \approx 0.2998 B(T) \rho(\text{m}) \]

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 \( E_{\text{max}} \).

\[ n \lambda_{\text{RF}} = \frac{2\pi \Delta \rho}{ecB} \rightarrow n \lambda_{\text{RF}} = \frac{2\pi \Delta E}{ecB} \text{ for RTM} \]

\[ n = \text{any integer} \]

\( \Delta E = \text{energy gain per turn in RF cavity} \)

\( \lambda_{\text{RF}} = \text{RF wavelength} \)

\( B = \text{magnetic field in microtron dipole} \)

\( \Delta \rho = \text{increment of bending radius} \)

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Yujong Kim @ Idaho State University and Thomas Jefferson National Accelerator Facility, USA
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: \(0.2 \text{ m} \, \odot \, E_{\text{max}}\)
- Field uniformity in working area: 10 Gauss
- Dimension: \(729 \, (D) \times 740 \, (W) \times 620 \, (H) \, \text{mm}^3\)
- Bending radius \(E = 55 \, \text{MeV}\): 18.5 cm

If \(E_{\text{max}} = 20 \, \text{MeV}\), \(\rho_{\text{max}} = 0.2 \, \text{m}\) → \(B = 0.334 \, \text{T}\)
∴ bending radius \(E_{\text{inj}} = 3.4 \, \text{MeV}\) → 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 \(E_{\text{max}} = 6 \, \text{MeV}\), \(\rho_{\text{max}} = 0.2 \, \text{m}\) → \(B = 0.100 \, \text{T}\)
∴ bending radius \(E_{\text{inj}} = 3.4 \, \text{MeV}\) → 11.3 cm
→ wide gap to avoid colliding
→ we may reach 6 MeV in 5 turns if \(E_{\text{inj}} = 3.4 \, \text{MeV}\) & \(\Delta E = 0.5 \, \text{MeV}\) (CW single cell cavity).
→ we may consider a linac structure with multi-cells to increase \(\Delta E\) and \(E_{\text{max}}\).
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 Cs₂Te, Cs:GaAs, K₂CsSb 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$_2$Te or Copper
- 2.5 cells
- Gradient = 14.15 MV/m
- $Q = 29 \text{ fC}$
- Q.E. < 20%
- $E_{kf} = 300 \text{ keV}$
- $f_{RF} = 2450 \text{ MHz}$
- 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
- $L = 0.726 \text{ m}$
- $E_{k0} = 300 \text{ keV}$
- $E_{kf} = 1.301 \text{ MeV}$
- $f_{RF} = 2450 \text{ MHz}$

### Boosting Linac-II
- 13 cells
- $\beta \sim 1$
- Cell length ~ 6.1 cm
- Gradient = 1.91 MV/m
- RF phase = -17 deg
- $L = 0.793 \text{ m}$
- $E_{k0} = 1.3 \text{ MeV}$
- $E_{kf} = 2.813 \text{ MeV}$
- $f_{RF} = 2450 \text{ MHz}$
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 $\approx$ 10 ps (FWHM)
- wavelength = 266 nm
- maximum single bunch charge $\approx$ 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.
Components - Boosting Linac-I with $\beta < 1$

- Both linacs used in this design are standing wave (SW) type linacs due to its high shunt impedance ($\sim 85 \, \text{M}\Omega/\text{m}$).

- 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.

\[
f_{RF} = 2450 \, \text{MHz} \\
T = \frac{1}{f_{RF}} = 408 \, \text{ps} \\
\pi \text{ mode SW cavity} \\
\rightarrow T / 2 = 204 \, \text{ps}
\]

\[
\text{cell length} = \beta \lambda_{RF} / 2
\]

S-band side-coupled SW linac structure
Components - Boosting Linac-I with $\beta < 1$

$\pi$ mode SW cavity
$\rightarrow T / 2 = 204$ ps

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

<table>
<thead>
<tr>
<th>Cell #</th>
<th>Length(cm)</th>
<th>$E_k$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell 1</td>
<td>4.9</td>
<td>.377</td>
</tr>
<tr>
<td>Cell 2</td>
<td>5.2</td>
<td>.454</td>
</tr>
<tr>
<td>Cell 3</td>
<td>5.3</td>
<td>.531</td>
</tr>
<tr>
<td>Cell 4</td>
<td>5.4</td>
<td>.608</td>
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<tr>
<td>Cell 5</td>
<td>5.5</td>
<td>.685</td>
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<tr>
<td>Cell 6</td>
<td>5.6</td>
<td>.762</td>
</tr>
<tr>
<td>Cell 7</td>
<td>5.7</td>
<td>.839</td>
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<td>Cell 9</td>
<td>5.8</td>
<td>.993</td>
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<tr>
<td>Cell 10</td>
<td>5.8</td>
<td>1.07</td>
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<tr>
<td>Cell 11</td>
<td>5.8</td>
<td>1.147</td>
</tr>
<tr>
<td>Cell 12</td>
<td>5.8</td>
<td>1.224</td>
</tr>
<tr>
<td>Cell 13</td>
<td>5.9</td>
<td>1.301</td>
</tr>
</tbody>
</table>

S-band side-coupled SW linac structure
Components - Boosting Linac-I with $\beta < 1$

fieldmap of 2450 MHz SW Linac-I
$\beta < 1$
total No. of cell = 13
cell length ~ 4.9 - 5.9 cm

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</tbody>
</table>
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 $\sim 6.1$ cm

**Fieldmaps of Linac-I & Linac-II**
- Linac-I: green
- Linac-II: red
$Q = 29 \text{ fC}$

- thermal emittance with the copper cathode $\sim 0.032 \ \mu\text{m}$ (K.E. $= 0.63 \text{ eV}$)
- laser spotsize $\sim 35 \ \mu\text{m}$ (rms) or $140 \ \mu\text{m}$ (diameter)
- laser pulse length $= 3.13 \ \text{ps}$ (FWHM) with rising/falling time $= 1.0 \ \text{ps}$
ASTRA Simulation Results along Injector

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

$\varepsilon_n \sim 0.040 \ \mu m$

$\sigma_{xy} \sim 271 \ \mu m$
ASTRA Simulation Results along Injector

- $Q = 29 \text{ fC}$
- thermal emittance with the copper cathode $\sim 0.032 \ \mu\text{m} \ (\text{K.E.} = 0.63 \ \text{eV})$
- laser spotsize $\sim 35 \ \mu\text{m} \ (\text{rms})$ or $140 \ \mu\text{m} \ (\text{diameter})$
- laser pulse length = 3.13 ps (FWHM) with rising/falling time = 1.0 ps

rms bunch length = 2.05 ps
momentum = 3.4 MeV/c
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)

For CW Microtron facilities

- injector energy ~ 6 MeV
- \( E_{\text{max}} \approx 40 \) MeV
- \( \Delta E \approx 1.8 \) 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 structures) 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 \( \varepsilon_{\text{lsc}} \) and \( \varepsilon_{\text{nsc}} \), are controllable though the gun gradient \( E \) is lower if charge is much lower and bunch length is longer. Here \( \varepsilon_{\text{rf}} \) is also ignorable.

\[
\varepsilon_{\text{nx,ny}} = \sqrt{\varepsilon_{\text{th}}^2 + \varepsilon_{\text{lsc}}^2 + \varepsilon_{\text{nsc}}^2 + \varepsilon_{\text{rf}}^2 + \varepsilon_{\text{optics}}^2} \quad \varepsilon_{\text{slice}} \geq \varepsilon_{\text{th}}
\]

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

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

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

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

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

\( k_B = 8.617 \times 10^{-5} \text{ eV/K} \)

\( \varepsilon_{\text{th}} \approx 0.24 \mu\text{m} \) for \( \text{LaB}_6 \) cathode with \( \sigma_{x,y} = 0.445 \text{ mm}, T = 1700 \text{ K} \)

### Selection of Charge - from SwissFEL Injector

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

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

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

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

For a much higher $Q$, $\varepsilon_{\text{projected}} > \varepsilon_{\text{slice}} >> \varepsilon_{\text{thermal}}$ 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

one gun cavity → divided into several long RF structures

CW RF Photoinjector
6.5 cells $\beta = 0.687 - 0.906$
cathode: Cs:GaAs or K$_2$CsSb
Q.E. ~ 10% @ 532 nm
$\varepsilon_{th}$ ratio = 0.22 $\mu$m/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$_4$
gradiant ~ 2 MV/m
length $L = 0.367$ m
$\Delta E_k = 700$ keV
$E_T = 1.211$ MeV
$f_{RF} = 2450$ MHz
$R_{sh} \sim 85$ $\Omega$/m
power dissipation ~ 23 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
$\Delta E_k = 1.634$ MeV
$E_{kf} = 2.334$ MeV
$E_T = 2.845$ MeV
$f_{RF} = 2450$ MHz
$R_{sh} \sim 85$ $\Omega$/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
$\Delta E_k = 1.700$ MeV
$E_{kf} = 4.034$ MeV
$E_T = 4.545$ MeV
$f_{RF} = 2450$ MHz
$R_{sh} \sim 85$ $\Omega$/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
$\Delta E_k = 1.800$ MeV
$E_{kf} = 5.834$ MeV
$E_T = 6.345$ MeV
$f_{RF} = 2450$ MHz
$R_{sh} \sim 85$ $\Omega$/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

\[ f_{RF} = 2450 \text{ MHz} \]
\[ \beta = 0.687 - 0.906 \]
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 \( \sim 29 \text{ kW} \) for \( \Delta E_k = 700 \text{ keV} \)
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

- initial zero emittance just after emission from cathode
- increased emittance due to space charge force
- rotated phase space by an external focusing solenoid
- compensation by reaction of space charge force after some drift

Yujong Kim @ Idaho State University and Thomas Jefferson National Accelerator Facility, USA
Space charge force induces oscillations in envelope and emittance. The emittance 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)

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

Invariant envelope is an ideal case which makes a constant slope (-\(\gamma'/2\)) 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.

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

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

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

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

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.
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

**Booster Linac (ACC1)**

- 2.478 m
- damping efficiency ~ 2 - 3
- rms normalized emittance ~ 2.0 µm
- beamsize

**ASTRA Simulation Results on FLASH Injector**

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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).

**Before Emittance Compensation**
- \( Q = 20 \) pC
- average current ~ 7 mA
- peak current ~ 1.5 A
- bunch length ~ 5.3 ps (rms)
- e-beam repetition = 350 - 2450 MHz CW
- \( E \approx 3-6 \) MeV
- \( \varepsilon_n < 0.8 \) \( \mu m \)
- (Cs:GaAs cathode with a lower \( \varepsilon_{th} \) and longer bunch)

**After emittance Compensation**
- \( Q = 20 \) 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
- \( \varepsilon_n < 0.4 \) \( \mu m \)

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

350 MHz laser pulse

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

2450 MHz laser pulse

2450 MHz RF pulse

2450 MHz laser pulse

2450 MHz RF pulse

\[ Q \sim 20 \text{ pC} \]
\[ \text{average current} \sim 50 \text{ mA} \]
\[ \text{laser repetition} = 2450 \text{ MHz CW} \]
\[ \text{e-beam repetition} = 2450 \text{ MHz CW} \]
\[ f_{RF} = 2450 \text{ MHz} \]
\[ \varepsilon_n < 0.4 \ \mu m \]
\[ (\text{after emittance compensation}) \]
For a Higher Peak Current Operation ~ a few kA

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

\( E = 5800 \text{ MeV}, \ \sigma_\delta = 0.053\% \)

\( \sigma_x = 13.0 \text{ \(\mu\)m}, \ \sigma_y = 13.0 \text{ \(\mu\)m}, \ \sigma_z = 0.72 \text{ \(\mu\)m} \)

\( \epsilon_{nx} \sim 0.240 \text{ \(\mu\)m}, \ \epsilon_{ny} \sim 0.097 \text{ \(\mu\)m} \)

\( I_{\text{peak}} < 7 \text{ kA}, \ \epsilon_{n,\text{core},\text{slice}} < 0.150 \text{ \(\mu\)m} \)

\( \sigma_{dE,\text{slice}} < 800 \text{ keV for whole bunch} \)

**Single Spike**

- Electron beam for Optimization-XI
  - Single spike mode \((0.7 \text{ nm} \sim 7 \text{ nm})\)
  - Beam energy \(\sim 3.4 \text{ GeV}\)
  - \(Q = 10 \text{ pC}\)
  - Peak current \(< 7 \text{ kA}\)
  - RMS electron bunch length \(< 2.4 \text{ fs}\)
  - Total compression factor \(= 2400\)

**FEL photon beam for Optimization-XI**

- RMS photon pulse length \(< 330 \text{ as}\)
- Wavelength \(= 0.7 \text{ nm with } K = 1.05\)
- RMS bandwidth \(< 0.35\% \text{ for 7 kA}\)
- Pulse energy \(< 9 \text{ \(\mu\)J}\)
- No of photons per pulse \(< 3.1 \times 10^{10}\)
- Saturation length \(< 25 \text{ m for 7 kA}\)

For CW XFEL facilities

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

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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 ($\leq 30$ kW) during the CW mode operation.
  - beam quality dilution due to a lower gun gradient can be compensated by choosing a lower charge ($\sim 20$ 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 ($\sim 50$ mA) by increasing repetition rate of the gun driving laser.
  - peak current can be increased further ($\sim$ 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.