ILC 9mA tests at FLASH

Past results and future plans

Julien Branlard
ILC 9mA tests at FLASH
DESY, 02.07.2012
Overview

I. The International Linear Collider
   - ILC main specification
   - The 9mA collaboration
   - ILC challenges

II. Simple key-concepts to understand the 9mA studies
   - Single-klystron multiple-cavities
   - Vector sum regulation
   - Pk / Qi control

III. Flattening cavity gradients
   - Analytical approach
   - Accuracy assessment

IV. Conclusions:
   - Summary of the 9mA run last year (Feb. 2011)
   - Outlook on the next 9mA run (Feb. 2012)
I. The International Linear Collider

> ILC main accelerating parameters

<table>
<thead>
<tr>
<th>Accel. Params</th>
<th>ILC</th>
<th>FLASH</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity tech.</td>
<td>super conducting</td>
<td>super conducting</td>
<td></td>
</tr>
<tr>
<td>RF freq.</td>
<td>1.3</td>
<td>1.3</td>
<td>GHz</td>
</tr>
<tr>
<td>Rep. rate</td>
<td>5</td>
<td>5-10</td>
<td>Hz</td>
</tr>
<tr>
<td>Beam current</td>
<td>9</td>
<td>1-9</td>
<td>mA</td>
</tr>
<tr>
<td>Average gradient</td>
<td>31.5</td>
<td>26</td>
<td>MV/m</td>
</tr>
<tr>
<td>RF station</td>
<td>10 MW klystron for 26 cavities</td>
<td>10 MW klystron for 16 cavities</td>
<td></td>
</tr>
</tbody>
</table>

Main Linacs

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>2x 250GeV</td>
</tr>
<tr>
<td>Cavities (9-cell)</td>
<td>14,560</td>
</tr>
<tr>
<td>Cryomodules</td>
<td>1680</td>
</tr>
<tr>
<td>RF Units</td>
<td>560</td>
</tr>
<tr>
<td>Cavities per RF Unit</td>
<td>26</td>
</tr>
</tbody>
</table>

Courtesy: J.Cawardine
I. The International Linear Collider

- The reference design RF unit: klystron power distribution scheme

![Diagram of linear RF power distribution with circulator & stub or EH tuner for every cavity input]

<table>
<thead>
<tr>
<th>Klystron</th>
<th>10MW MBK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavities per RF Unit</td>
<td>26 (9+8+9)</td>
</tr>
<tr>
<td>Avg. gradient</td>
<td>31.5MV/m</td>
</tr>
<tr>
<td>Gradient spread (post RDR)</td>
<td>+/-20% p-p (26-38MV/m)</td>
</tr>
</tbody>
</table>

- Beam current parameters

<table>
<thead>
<tr>
<th></th>
<th>XFEL</th>
<th>iLC</th>
<th>FLASH Free-Electron Laser in Hamburg</th>
<th>FLASH 9mA experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch charge</td>
<td>nC</td>
<td></td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td># bunches</td>
<td>3250*</td>
<td>2625</td>
<td>7200*</td>
<td>2400</td>
</tr>
<tr>
<td>Pulse length</td>
<td>μs</td>
<td></td>
<td>650</td>
<td>900</td>
</tr>
<tr>
<td>Current</td>
<td>mA</td>
<td></td>
<td>5</td>
<td>9</td>
</tr>
</tbody>
</table>

Courtesy: J.Cawardine

Julien Branlard | ILC 9mA tests at FLASH | 02.07.2012 | Page 4
I. The ILC 9mA collaboration

> DESY
  - Nick Walker
  - Siegfried Scheiber
  - Bart Faartz
  - Katja Honkavaara
  - Holger Schlarb
  - Valeri Ayvazyan
  - Mariusz Grecki
  - Wojciech Jalmuzna
  - Wojciech Cichalewski
  - Tim Wilksen
  - Olaf Hensler
  - Christian Schmidt
  - Julien Branlard
  - … and many others

> ANL
  - Ned Arnold
  - John Cawardine

> FNAL
  - Brian Chase
  - Gustavo Cancelo
  - Warren Schappert
  - Yuriy Pischalnikov

> KEK
  - Shinichiro Michizono
  - Toshihiro Matsumoto

> SLAC
  - Chris Adolphsen
  - Shilun Pei
I. Specific objectives for the 9mA study

- **Operation with gradient spread from a single source**
  - operating gradient spread for ACC67 around +/-25%

- **Operation with high beam current**
  - gain experience with beam loading

- **Operate as close as possible to the quench limit**
  - challenges linked to low RF overhead

- **Focus on ACC67**
  - highest gradient
  - piezo
  - $Q_L$ motors
I. Specific objectives for the 9mA study

> Long bunch-trains with high beam loading (9mA)
  - 800µs pulse with 2400 bunches at 3MHz, 3nC per bunch
  - Vector Sum control of up to 16 cavities, with +/- 20% gradient spread
  - Beam energy 700-1000MeV with +/- 0.1% energy stability
  - Beam-based adjustments/optimization

> Operation (very) close to cavity quench limits (1MV/m or less)
  - Robust automation of tuning (Ql, piezo, tuners, etc..)
  - Cavity gradients approaching quench limits
  - Quench detection/recovery, exception handling

> Characterize operational limits
  - Low klystron power overhead
  - Klystron saturation regime
  - Saturation of control loop
  - Energy stability limitations and trade-offs
I. Specific objectives for the 9mA study

- Long-pulse + high-current: achieved parameter space

![Diagram showing parameter space and timeline for 9mA studies.](image-url)
II. Some key concepts to understand the ILC study

- Gradient spread

- Power distribution

![Gradient Spread Diagram](image1)

![Power Distribution Diagram](image2)
II. Some key concepts to understand the ILC study

> Vector sum control

Single-klystron multiple-cavities
II. Some key concepts to understand the ILC study

> Beam loading

BEAM OFF

BEAM ON

> Why do we care about individual flat gradients?

- “Effect of Cavity Tilt and RF Fluctuations to Transverse Beam Orbit Change in ILC Main Linac” K. Kubo, Jan. 2010
II. Some key concepts to understand the ILC study

> Beam loading tilts scale linearly with beam current

Simulated gradient tilts in ACC6, for a 800 usec flat top with current FLASH $Q_L$ setup
II. Some key concepts to understand the ILC study

> Single klystron + beam loading = gradient tilts
II. Some key concepts to understand the ILC study

> Loaded quality factor: $Q_L$

- Cold coax
- Warm coax
- Wave guide
- Qext tuner motor
- Vacuum connection
- Wave guide spark detector
- Temperature sensor, 300K and 70K

Diagram:

- Klystron
- Fixed
- Fixed
- Fixed
- LLRF
- $P_{k1}$
- $Q_{L1}$
- Cavity 1
- $P_{k2}$
- $Q_{L2}$
- Cavity 2
- $P_{kN}$
- $Q_{LN}$
- Cavity N

Courtesy: W.D. Möller
III. Analytical solution: Pk / Ql

> “Solutions” to flatten cavity gradient with beam

- “RF Distribution Optimization in the Main Linacs of the ILC”, Bane, Adolphsen, Nantista – PAC07
- “Optimal Coupler and Power Settings for Superconductive Linear Accelerators”, Branlard, Chase - LINAC08
- “Pseudo-Pk/Ql control for ACC6/7 at FLASH”, Michizono, unpublished 2010
III. Analytical solution: “pseudo Pk” / QL

> Analytical ‘solution’ for optimal $Q_L$

$$e^{-\frac{t_0 \omega_0}{2Q_{Li}}} - \sqrt{\frac{1}{4Q} \frac{Q_{Li} I_B^2}{P_{Ki}}} = 1 - r$$

→ assumes “perfect” tuning
→ solve for $Q_{Li}$ when possible

$cavity\ i$ loaded $Q$
$cavity\ i$ forward power during fill time [W]
DC beam current [A]
fill time (~ beam arrival time) [s]
fill time to flat top voltage ratio (including beam compensation)
III. Analytical solution: SIMCAV, cavity simulator
III. Analytical solution: SIMCAV, cavity simulator
1. Load $V_{cav}$ from DAQ

2. Compute actual $Q_L$, $P_K$ and $\Delta_f$ from DAQ data

3. Type in $Q_L$, $P_K$ and $\Delta_f$ into simulator

4. Check agreement between simulated and FLASH data

5. Adjust $Q_L$ in simulator to flatten tilts

6. Implement $Q_L$ corrections in FLASH

7. Check gradient flatness
III. Analytical solution: procedure

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III. Analytical solution: procedure

1. Load $V_{cav}$ from DAQ
2. Compute actual $Q_L$, $P_K$ and $\Delta \tau$ from DAQ data
3. Type in $Q_L$, $P_K$ and $\Delta \tau$ into simulator
4. Check agreement between simulated and FLASH data
5. Adjust $Q_L$ in simulator to flatten tilts
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![Simulated data vector sum graph]
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1. Load $V_{cav}$ from DAQ
2. Compute actual $Q_L$, $P_K$ and $\Delta_f$ from DAQ data
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III. Analytical solution: procedure

1. Load \( V \) from DAQ
2. Compute actual \( Q_L \), \( P_K \), and \( \Delta f \) from DAQ data
3. Type in \( Q_L \), \( P_K \), and \( \Delta f \) into simulator
4. Check agreement between simulated and FLASH data
5. Adjust \( Q_L \) in simulator to flatten tilts
6. Implement \( Q_L \) corrections in FLASH
7. Check gradient flatness

![Graph showing gradient flatness over time]
III. Accuracy assessments

> Q_L scan

→ Keep beam current constant but walk Q_L's around optimized value

> I_B scan

→ Keep optimized Q_L's but ramp beam up/down
III. Accuracy assessments

> $Q_L$ scan

→ Keep beam current constant but walk $Q_L$'s around optimized value

> $I_B$ scan

→ Keep optimized $Q_L$ but ramp beam up/down
III. Accuracy assessments

In the ideal case, all cavities have zero tilts at the same exact beam current.

Errors in QL or in detuning will cause cavities to have zero tilts at different beam currents.

Courtesy: J. Cawardine
III. Accuracy assessments

Before freq. tuner adjustments

- **AMPLITUDE**
  - Gradient: \( Q_L = 1.58 \times 10^6 \)
  - Phase: \( \Delta f = 70 \text{ Hz} \)

After freq. tuner adjustments

- **AMPLITUDE**
  - Gradient: \( Q_L = 1.58 \times 10^6 \)

**~ 0.1 MV/m**
III. Accuracy assessments

> $Q_L$ settings are limited: no solution yet for 9mA!

![Graph showing $Q_L$ solutions and ILC specs: 9 mA!](image)
IV. Conclusions: last 9mA run at FLASH (Feb. 2011)

What went well

> Motorized couplers / tuners
> Analytical approach proved to be useful
> Predicted optimized $Q_L$ values were accurate $\rightarrow$ to $0.2e6$
> Successfully implemented the tuning plan $\rightarrow$ tilts $< 0.1MV/m$

What we’ve learnt

> Cavity resonance control is crucial for gradient tilts
> Limitations to the analytical approach:
  - How accurately can we compensate for LFD
  - How accurately can we measure and set $Q_L$’s $\rightarrow +/- 2$ to $5\%$

What is still unanswered

> No proposed solution for high beam currents (>6mA) implementable at FLASH
> There is not always a solution to flatten all cavities (especially when gradient spread is large) $\rightarrow$ ACC6.C5 and C6
> No solution to bring up the machine at its highest gradient
IV. Conclusions: upcoming 9mA test at FLASH (Feb. 2012)

> Machine automation
- Automatic $Q_L$ settings
- Automatic quench detection
- Automatic piezo compensation

> Machine operation scenarios
- Tuning strategies
- How to ramp up the beam
- How to ramp up the gradient
- How to recover from a quench

> RF power overhead study
- Simulate klystron saturation regime
- Field control regulation saturation

Further reading:
- FLASH 2011 Highlights

Thank You!