Machine Protection and Interlock Systems – Linear Machines

Marc Ross, SLAC

An Example:

- The idea:
  - Develop a **high power accelerator** to operate in conjunction with an **actinide reactor**.
- The problem:
  - Providing enough beam power with the required stability
- The questions:
  - What is the practical limit to beam power?
  - What are the trade offs between power and stability?
  - How are these limits addressed?
  - What is a reasonable goal?

This Talk

20 years ago – the **accelerator** was deemed to be impractical
*BECAUSE **MACHINE PROTECTION** WAS NOT MATURE*

Recommendation to terminate development:

Mid-1990's DoE review

Former SLAC Director
Burton Richter

symmetry I March 2012

letter

March 01, 2012

Reliability of accelerator driven systems

I was the chairman of the committee that recommended to the DOE that the Accelerator Driven Systems (ADS) approach to dealing with the long-lived component of spent nuclear fuel be terminated. It was, indeed, an accelerator issue but not the one implied in your article ("Taking the Heat out of Nuclear Waste," February 2012).

Reliable Machine Operation

Burton Richter's 2012 retrospective comments:

" There are still important safety issues. One of them is related to the frequency of accelerator trips. Frequent starting and stopping of a reactor, even a subcritical facility driven by an accelerator, stress the reactor. The standard fission reactors we use today trip very infrequently and each is investigated to find out why before permission to restart is given. I know of no analysis of allowable trip frequency versus down time that would be acceptable…. Clearly an outage of one second does not change temperature much and would not be a problem. Outages of minutes would begin to be."

Reaction to Richter from proponents (2012):

"Regarding the question of accelerator reliability, SNS operation has demonstrated …

SNS performance has also demonstrated that, at one megawatt, beam losses are well within acceptable limits.

While beam losses are difficult to accurately estimate, the experience gained with SNS operation lends confidence that beam losses will remain acceptable at the higher powers in excess of 10 megawatts that are needed for ADS applications. "

Reaction to Richter from proponents continued (2012):

"Dr. Richter is correct that current accelerator reliability is insufficient to meet the requirements needed for reliable delivery of electricity to the grid, and research and development of higher reliability accelerator systems are needed to meet this mission. … allowable trip rates are within the range of what a new accelerator should be able to meet. … concluded that the demanding requirements needed for transmutation could be met with further R&D and with the incorporation of redundancy and modern reliability engineering principles to the design of the accelerator system, something which has never before been done for a high-energy particle accelerator…"

Theme:

- High field storage ring magnets allow **very high energy (5e8 *J*)** to be circulated / stored

- High gradient / low-loss cavities allow **very high power (1e7 *W*)** linacs
  - Match this with protection-systems (1) / operations strategies (2)

- Technological potential should be matched with equivalent protection system

Bottom Line:

- After personnel safety is fully realized …
- Machine Protection seeks to balance

1. Cost / performance (mitigation)
   - (Component cost and MPS cost) vs
2. Risk
   - (likelihood of failure) vs
3. Uptime
   - (including impact of time-to-recover)

Goal: Acceptable risk with cost-effective performance that meets or exceeds specified uptime

Bottom Line (2):

Three example questions:

- What is the expected damage resulting from the failure?
- How long would it take to repair the damage?
- How likely is the failure (i.e. how often do we expect it to occur)?

- So:

a failure mode that damages a vacuum section which would require a few days to repair might be deemed acceptable if the failure is only like to happen once every few years (on average)

Outline(1)

Machine Protection and Interlock Systems – Linear Machines

- **Linacs**
  - Basics
  - Technical Developments
  - High performance superconducting RF
  - ***Taking full advantage of available technology***
- **What protections are needed?**
- **Protection Systems**

Outline(2)

Machine Protection and Interlock Systems – Linear Machines

- **Linacs**
- **What protections are needed?**
  - single bunch damage
  - average power loss
  - radiation dose (prompt / residual)
  - a protection collimator system
  - ***Key to viable, long-lived systems***
- **Protection Systems**

Outline(3)

Machine Protection and Interlock Systems – Linear Machines

- **Linacs**
- **What protections are needed?**
- **Protection Systems:**
  - a beam permit system / restart ramp sequence → operations
  - series of abort kickers and low power dumps,
  - a sequencing system that provides for the appropriate level of protection depending on machine mode or state
  - a strategy for limiting the *rate-of-change* of magnetic fields and insertion device positions
  - fault analysis recorder system,
- **Recovery / Reliability- *Operations → 12 November***

Machine Protection and Interlock Systems – Linear Machines

MPS ≡ collection of devices intended to keep the beam from damaging machine components.

- ***both*** **from damage caused by a**
  - single bunch and the residual radiation or
  - heating caused by small (fractional) losses of many bunches
- **Includes Recovery / Diagnosis systems**
- **Also: technical system redundancy**

Overview of protection systems – JAS keywords

- How to stop beam in pulsed machines? What is required (e.g. time constant)?
- How to deposit the beam energy? Beam dumping systems.
- Elements to stop beam: Beam dump system (kickers, beam dump block, …) + choppers + foils + faraday cups, mitigation devices
- Interlock system to connect all protection systems
- Design principles for machine protection systems (e.g. electronics, other equipment)
- What checks can be done pulse by pulse, timescales, criticality, etc.
- Practical design principles for protection and safety systems?
- COTS for protection (e.g. PLCs)
- Taking over standards from Industry, e.g. IEC61508: why, what parts, what impact does it have
- Risk and reliability/availability analysis throughout the lifecycle
- Burning in of equipment

Outline(1)

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- **Linacs**
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- **Protection Systems**

High Power Linacs – Technical Developments

Electrons

A. FEL / ERL
B. Linear Colliders
C. Small-scale devices

Protons (and related)

- Fixed target (LBNF)
- Spallation sources
- Radioactive beams
- Accelerator/Reactor I

LCLS-II (*1.2 MW*)
ILC (*22 MW*)
Single cavity / single structure (~*1 MW*)

Neutrino (*>2 MW*)
SNS/ESS (*2-5 MW*)
FRIB (*0.4 MW*)
ADS (*50-100 MW*)

Superconducting RF Technology (SCRF)

Linacs

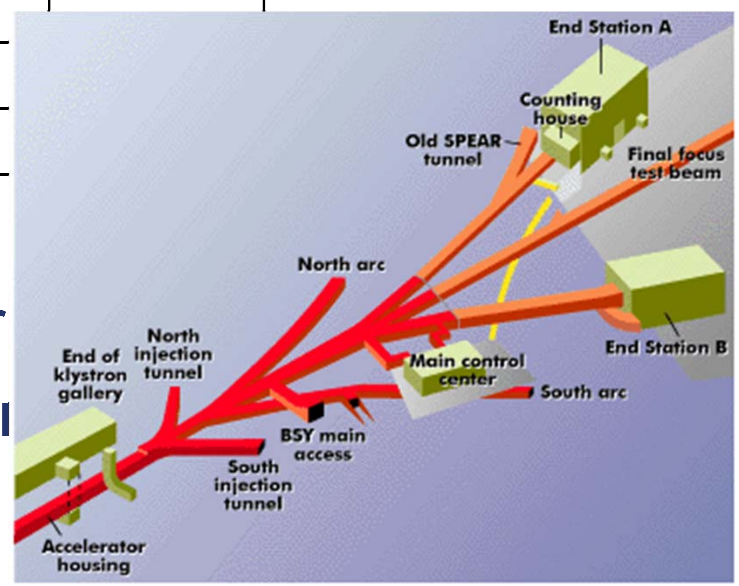
- **Basics**
  - ***Linacs from the Machine Protection point-of-view***
  - Energy flow / Energy Density
  - Examples: LCLS-II, ILC, and small-scale systems
- **Technical Developments**
  - Superconducting RF →
  - 3 to 4 x improvement in cryogenic heat-load since 2012
  - ***The bar has been raised!***

Basics

- **Linac is a *transformer:***
  - Power flows directly from mains to beam.
  - LCLS-II (SLAC):

	Power		Energy	Current
Beam	MW	MW	GeV	mA
	1.2		4.0	0.3
Utility	8.0			
RF		3		
Cryo		4		
Other		1		
Efficiency	15%			

- **Each pulse is different**
  - No intrinsic physical stability cr
- **Linac systems can be fully bifu**



Electron Linacs (1)

Power = Charge * Energy * Rate

(A) LCLSII:

- **Average beam power 1.2 MW**
- **1 MHz bunches with 2e9 ppb (CW);**
- **300 micro-amp average current**
- **Beam sizes 50 to 100 micron (σ)**

(B) ILC:

- **average beam power of 22 MW (11/beam)**
  - 16 seconds to deliver 360 MJ (LHC single-beam)
  - (LHC takes a long time to re-load)
- **consisting of 14000 bunches of 2e10 ppb each per second,**
- **beam sizes 10 x 1 micron,**

Electron Linacs (2)

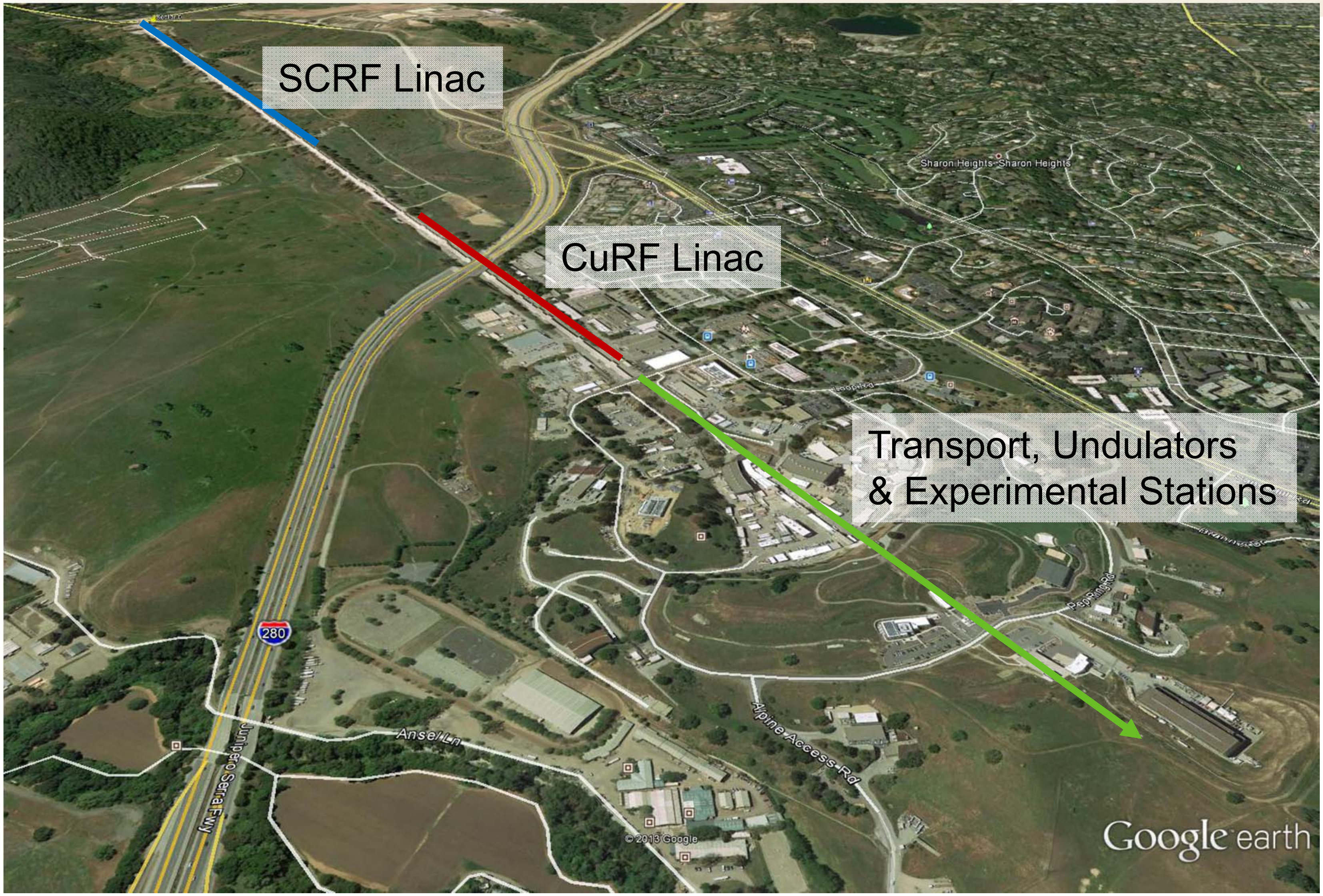
(C) Commercial applications:

- **Very high current (~100 mA)**
- **Low Energy (~10 MeV)**
  - 1 MW in a very small foot-print!!
  - Minimal cryo load; multi-MW RF source
- **CW**

Key Technological ingredient: *Energy Recovery Linac* R&D

  - (Cornell, KEK, HZ Berlin,…)
  - CW 1.3 GHz, 100 mA average current, 2 ps, 77 pC (every RF bucket), 10 to 15 MeV (Linac 2010)

(A) LCLS-II Concept
Use 1st km of SLAC linac for CW SCRF linac

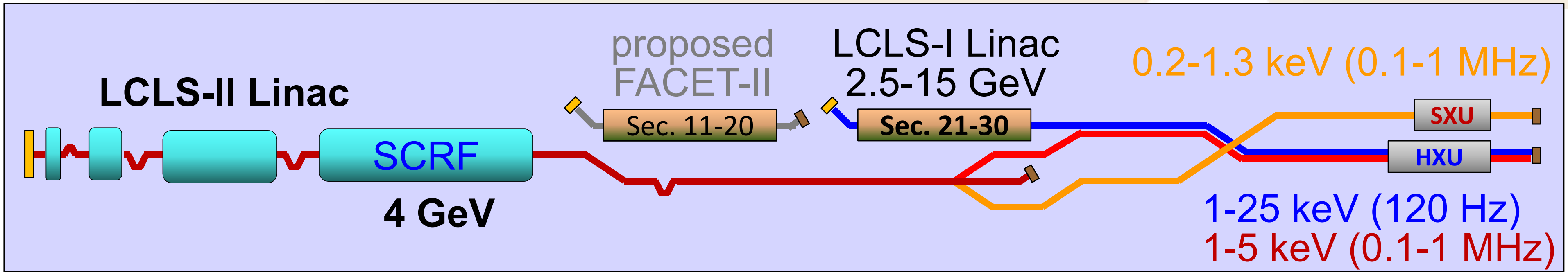


(A)
LCLS-II Accelerator Design

SLAC has strong FEL design experience

- What is new in LCLS-II?
  - CW, high rep rate beam:
    - → SCRF technology and beam dynamics
    - → Injector
    - → Diagnostics and feedback
  - High beam power:
    - → Beam heating, collimation and losses
    - → Beam dumps
  - Longitudinal phase space control
    - → Generate uniform beams for manipulation
- Building on SRF work done by others

(A)
LCLS-II Accelerator Layout and Modifications



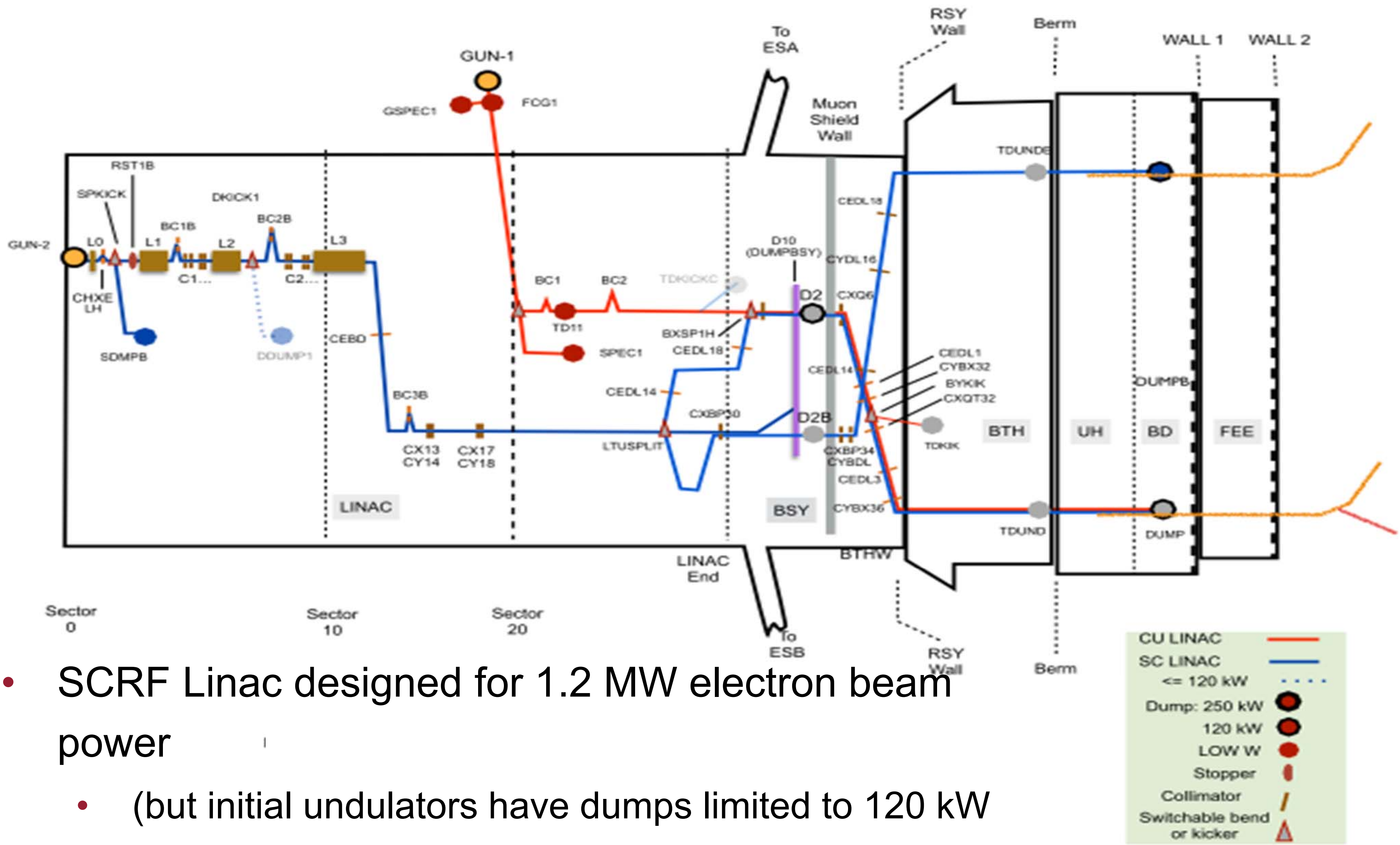
- New Injector, SCRF linac, and extension installed in Sectors 0-10
- Use existing Bypass line from Sector 10 → Beam Switch Yard (BSY)
- Re-use existing high power dump in BSY and add rf spreader to direct beams to dump, SXR or HXR
- Install new variable gap HXR (replacing LCLS-I) and SXR
- Re-use existing transfer line (LTU) to HXR; modify HXR dump
- Construct new LTU to SXR and new dump line
- Modify existing LCLS-I X-ray optics and build new SXR X-ray line

(A) LCLS-II (SCRF) Baseline Parameters

Parameter	symbol	nominal	range	units
Electron Energy	E_f	**4.0**	2.0 - 4.14	GeV
Bunch Charge	Q_b	**100**	10 - 300	pC
Bunch Repetition Rate in Linac	f_b	**0.62**	0 - 0.93	MHz
Average e^- current in linac	I_{avg}	**0.062**	0.0 - 0.3	mA
Avg. e^- beam power at linac end	P_{av}	**0.25**	0 - 1.2	MW
Norm. rms slice emittance at undulator	$\gamma\varepsilon_{\perp\text{-}s}$	**0.45**	0.2 - 0.7	μm
Final peak current (at undulator)	I_{pk}	**1000**	500 - 1500	A
Final slice E-spread (rms, w/heater)	σ_{Es}	**500**	125 - 1500	keV
RF frequency	f_{RF}	**1.3**	-	GHz
Avg. CW RF gradient (powered cavities)	E_{acc}	**16**	-	MV/m
Avg. Cavity Q0	$Q0$	**2.7e10**	1.5 - 5e10	-

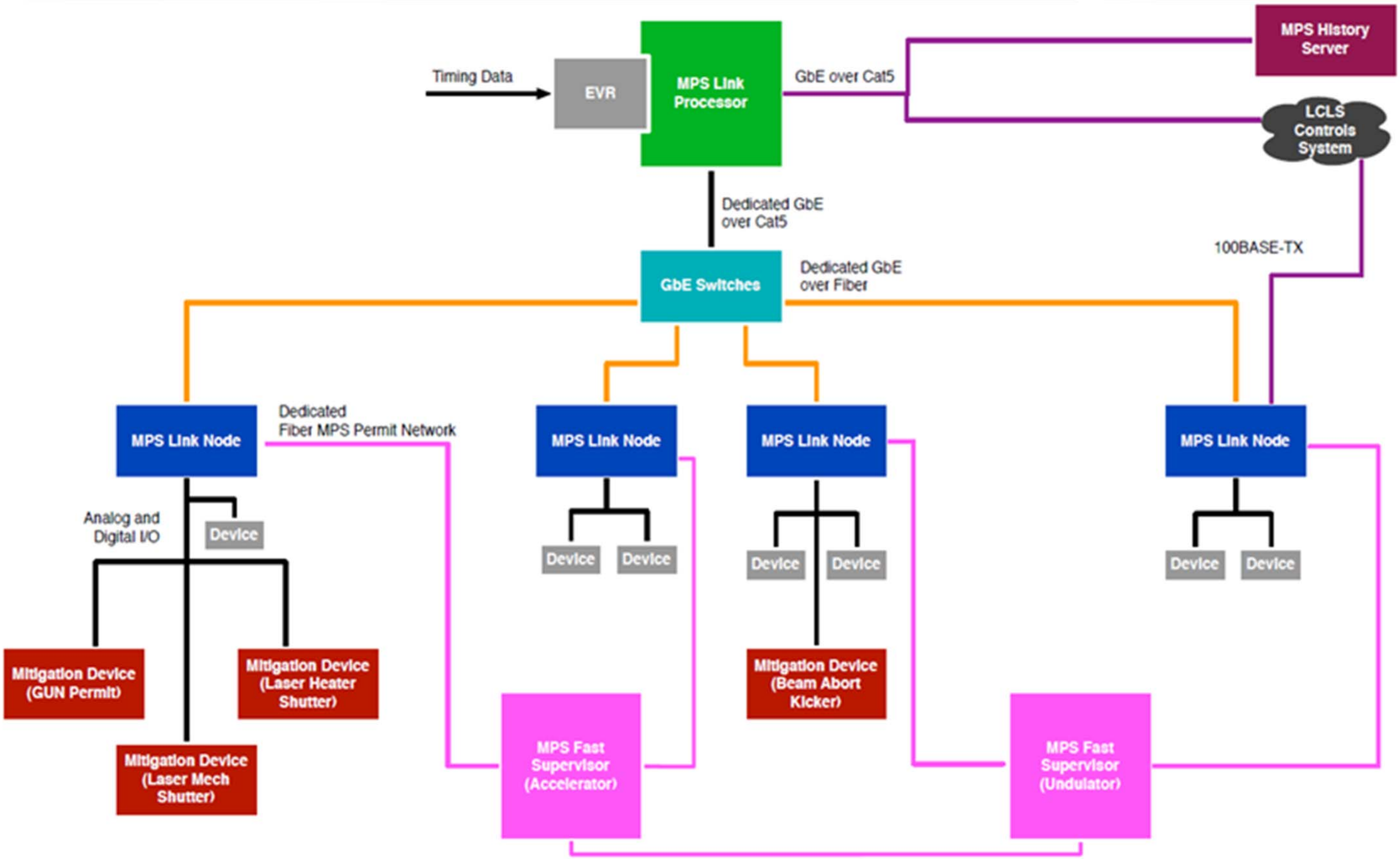
- **1 MHz bunches w/2e9 e+/e- each**
- **σ** *x,y,z* **= 100 x 50 x 10 microns**

(A)
LCLS Complex showing switching and dumps; (BYKIK)



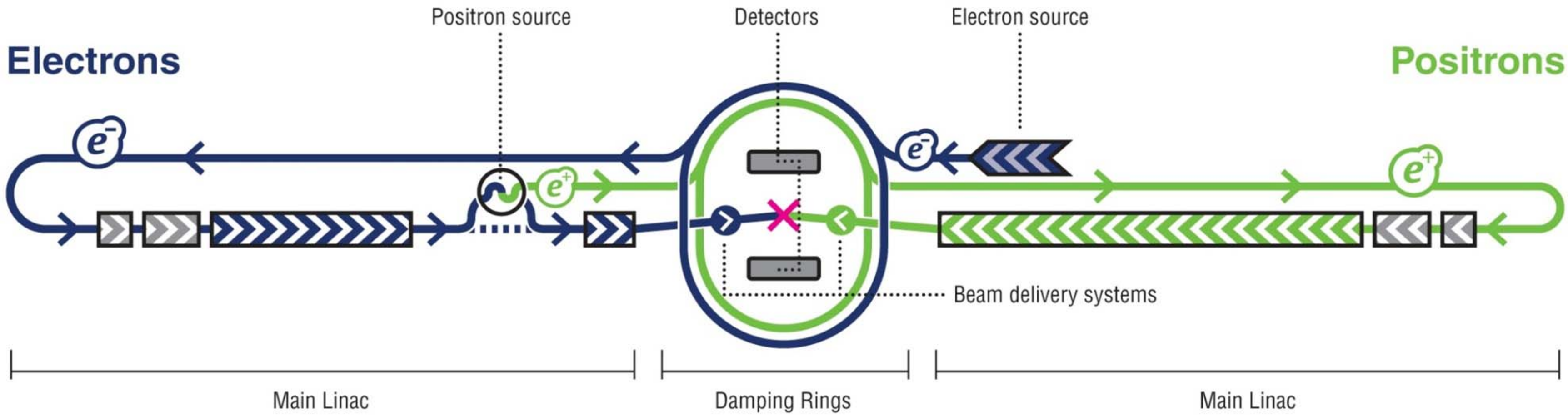
- SCRF Linac designed for 1.2 MW electron beam power
  - (but initial undulators have dumps limited to 120 kW
- Collimation and (~5) dumps; developing operation models including beam halo and losses as well as tuning strategies

(A)
LCLS MPS



MPS History Server
Timing Data
EVR
MPS Link Processor
GbE over Cat5
LCLS Controls System
Dedicated GbE over Cat5
100BASE-TX
GbE Switches
Dedicated GbE over Fiber
MPS Link Node
Dedicated Fiber MPS Permit Network
MPS Link Node
MPS Link Node
MPS Link Node
Analog and Digital I/O
Device
Device
Device
Device
Device
Device
Device
Mitigation Device (GUN Permit)
Mitigation Device (Laser Heater Shutter)
Mitigation Device (Beam Abort Kicker)
MPS Fast Supervisor (Accelerator)
MPS Fast Supervisor (Undulator)
Mitigation Device (Laser Mech Shutter)

(B) ILC Schematic



- **Collisions require high energy, high intensity and high beam 'quality'**
  - Linacs produce an intrinsically better beam than rings
- **The collisions are so intense the beam 'quality' is destroyed**

(B) ILC beam

Intensity:

- **1300 bunches w/2e10 e+/e- each**
  - (6 mA pulse current; 0.5% duty factor)
- **11 MW average / beam**
  - Site power consumption 165 MW (60% for linac)

Size at collision point:

- **σ *x,y,z* = 0.5 x 0.005 x 300 microns**

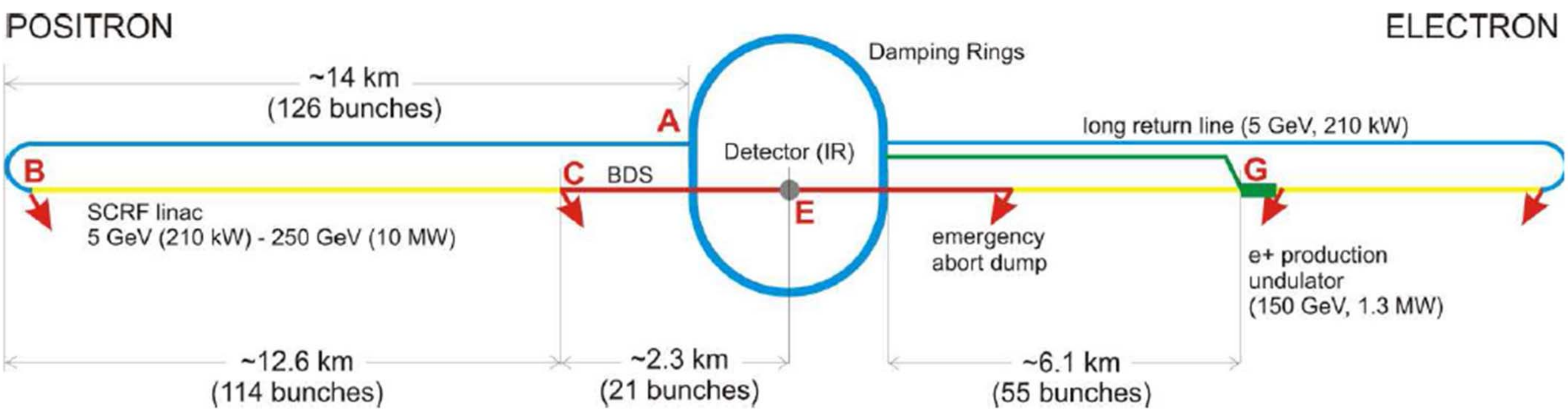
Typical damped beam size:

- **σ *x,y,z* = 10 x 1 x 300 microns**

ILC beam abort-lines and dumps

- **Take-off 'beam abort-lines' allow a segmented tune-up process**
  – Typically between major systems
- **No abort systems along the linac**

Will return to this point



(B) ILC Beam shut-off points

	Region name	Begin	End
1	e- injector	Source (gun)	e- Damping ring injection (before)
2	e- damping ring	Ring injection	e- Ring extraction (after)
3	e- RTML	Ring extraction	e- Linac injection (before)
4	e- linac	Linac injection	Undulator (before)
5	Undulator	Undulator	BD; e+ target
6	e- BDS	BD start	e- Main dump
7	e+ target	e+ target	e+ damping ring injection
8	e+ damping ring	Ring injection	e+ ring extraction
9	e+ RTML	ring extraction	e+ linac injection
10	e+ linac	linac injection	e+ BDS
11	e+ BDS	e+ BDS	e+ main dump

Table 1: beam shut off points. Each of these segmentation points is capable of handling the full beam power, i.e. both a kicker and dump are required. These systems also serve as fast abort locations for single bunch damage mitigation.

International Linear Collider

Centre-of-mass energy	E_{cm}	**GeV**	**250**	**500**	**1000**
					A1
Beam energy	E_{beam}	GeV	125	250	500
Beam average power	P_{beam}	MW	5.5	11	14
Collision rate	f_{rep}	Hz	5	5	4
Electron linac rate	f_{linac}	Hz	10	5	4
Number of bunches	n_b		1312	2625	2450
Electron bunch population	N_-	$\times 10^{10}$	2.0	2.0	1.74
Positron bunch population	N_+	$\times 10^{10}$	2.0	2.0	1.74
Bunch separation	Δt_b	ns	554	366	366
Bunch separation $\times f_{\mathrm{RF}}$	$\Delta t_b f_{\mathrm{RF}}$		720	476	476
Pulse current	I_{beam}	mA	5.8	8.75	7.6
Horizontal emittance	$\gamma\varepsilon_x$	µm	10	10	10
Vertical emittance	$\gamma\varepsilon_y$	nm	35	35	30
IP RMS horizontal beam size	σ_x*	nm	729	474	481
IP RMS veritcal beam size (no TF)	σ_y*	nm	7.7	5.9	2.8

(B) ILC Beam dumps (e-/e+)

DUMPS

MPD	e-1	SC TUNE UP DUMP	311 KW**
MPD	e-2	EDRX TUNE UP DUMP	220 KW
MPD	e-3	RTML TUNE UP DUMP	220 KW
HPD	e-4	BDS TUNE UP DUMP	14 MW
HPD	e-5	PRIMARY e-DUMP	14 MW*
MPD	e-6	RTML TUNE UP DUMP	220 KW
MPD	e-7	ELECTRON FAST ABORT DUMP	250 KW

MPD	e+2	PDRX TUNE UP DUMP	220 KW
MPD	e+3	RTML TUNE UP DUMP	220 KW
HPD	e+4	BDS TUNE UP DUMP	14 MW
HPD	e+5	PRIMARY e+DUMP	14 MW*
MPD	e+6	RTML TUNE UP DUMP	220 KW
MPD	e+7	TARGET DUMP	200 KW*

LEGEND

(HPD) HIGH POWER BEAM DUMP
(MPD) MID POWER BEAM DUMP
* INDICATES NON-STOP DUMP (
** INDICATES 45KW ALWAYS ON

(B) ILC MPS Key components: Proposed Abort kickers and dumps

- Abort systems protect SCRF from single bunch damage.
  - single bunch impact on a niobium iris will leave a small hole, roughly the diameter of the beam, through which the helium will flow.
- Minimal abort:
  - spoiler / collimator / absorber block (copper) and a kicker.
- Kicker rise time should guarantee displacement of more than the pipe radius in an inter-bunch interval (300 ns)
  - ~ 450 bunches on the copper block.
- Block surface marred with many small impact holes,
  - would not fracture and would not require cooling.
- Assume block is thick enough to absorb the full shower
  - the energy of 450 bunches <400kJ (250 GeV)
  - $\Delta T \sim 4$ degrees.

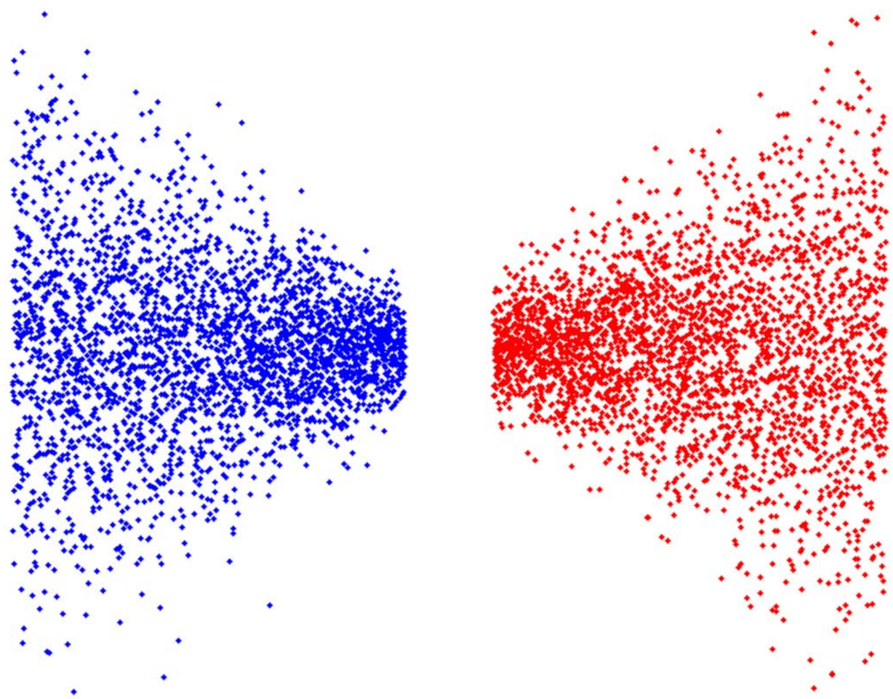
(B) ILC MPS Key components: Abort kickers and dumps

- Each abort precedes
  - cool down interval,
  - post-mortem evaluation of the fault,
  - response to the fault and
  - restart sequence,
  - ~1 minute; the average power should be very low.
- Care must be taken to avoid a rapid sequence of identical fault events.
  - block thermal interlock
- The block volume should be more than one cubic foot.

Machine Protection and Interlock Systems – Linear Machines

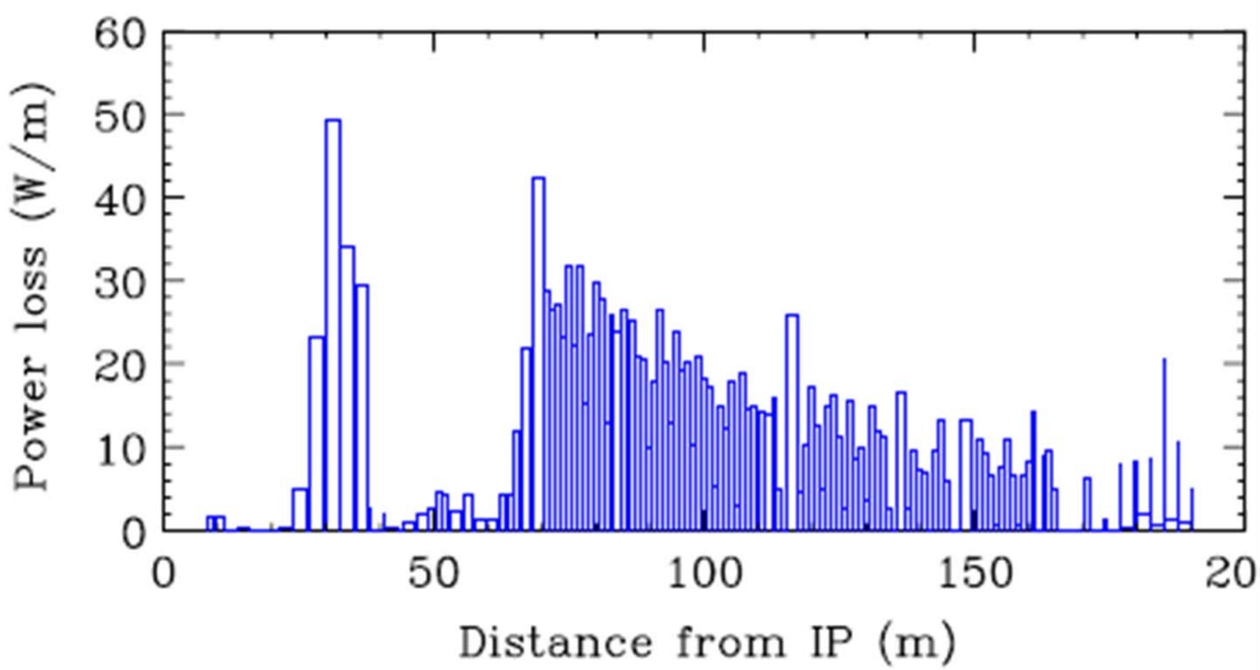
- Five abort systems are needed on the electron side (four on the e+ side) ***→ see further analysis***
  - (~1 per kilometer of linac)
  - Required kicker deflection is 10 mm.
- With a kicker volume of 20 * 20 mm, about 25 MW of peak power would be required for a 50 m long kicker system!
  - Total length associated with abort systems is 200 m per side.
  - Can be integrated with the tune up dumps.
- The abort system must be trigger-able during the train, if a serious trajectory distortion is detected.
- The kickers must be triggered as close as possible to the preceding bunch so that no bunch is kicked incompletely.

(B) ILC Collisions: Travelling focus



After colliding: extraction to the high-power dump

Loss per meter vs distance (design)
(100 W/m is the activation limit for electrons/positrons)



Storage Ring vs. Linac

LHC

- LHC can deliver all energy in one turn
- Refilling LHC takes a very long time
  - **Average beam power is quite small**
- Truly enormous component stored energy

ILC

- Linac can deliver energy continuously
- Linac beam sizes typically much smaller
  - **Power / unit area**
- Segmentation is practical
  - **Stepwise approach**
  - **Bifurcated complex**
  - **Logically independent**

Machine Protection: LHC / ILC

- LHC:
  - 3000 bunches each with 1e11 protons
  - Damage at 3e-5 of nominal I
  - Loss of a small fraction of each bunch is a concern
- ILC
  - 3000 bunches each with 2e10 e+/e-
  - Damage at 3e-6 of nominal I
  - Loss of a single bunch (with I > 1% of nominal) is a concern
    - e.g. first bunch…
- Difference is emittance, stored energy vs single pass

(C)
Small Scale Systems

Recent success reducing SCRF cryogenic loss will enable further development of low cryo-power linacs

- May improve feasibility of small-scale applications,

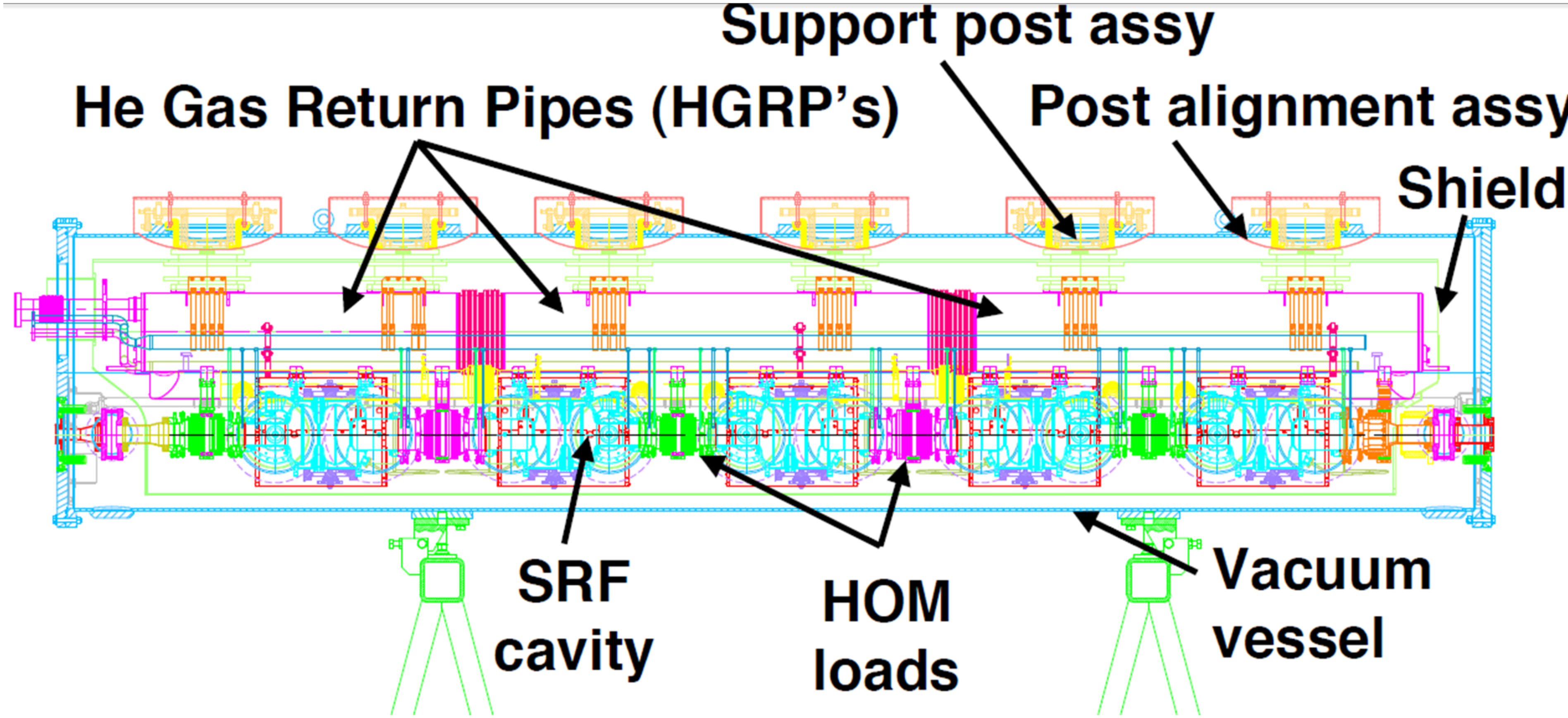
For example:

- Cornell Energy Recovery Linac Injector:
  - ***15 MeV x 100 mA = 1.5 MW***
  - http://www.lns.cornell.edu/~liepe/webpage/docs/TU303.pdf

Numb. of cavities / HOM loads	5 / 6
Accelerating voltage per cavity	1 - 3 MV
Fundamental mode frequency	1.3 GHz
R/Q (circuit definition) per cavity	111 Ohm
Loaded quality factor	4.6×10^4 to 10^6
RF power installed per cavity	120 kW
Required amplit. / phase stab. (rms)	1×10^{-3} / $0.1°$
Maximum beam current (design)	100 mA
Total 2K / 5K / 80K loads	$\approx$ 26 / 60 / 700 W
Overall length	5.0 m

Cornell Energy Recovery Linac

- **ERL very high current injector Cryomodule**



Linde Kryotechnik AG

A model of performance and efficiency.

Capacities of L70/LR70, L140/LR140, L280/LR280

The L Series will dazzle you with its excellent performance (13 bar at 4.4 K).

	Without LN_2 precooling	With LN_2 precooling
L70	20 – 35 l/h	40 – 70 l/h
L140	45 – 70 l/h	90 – 140 l/h
L280	100 – 145 l/h	200 – 290 l/h
LR70	please inquire	130 – 190 Watt
LR140	210 – 290 Watt	255 – 400 Watt
LR280	445 – 640 Watt	560 – 900 Watt

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Niowave announces $200 million medical radioisotope facility near Capital Region airport

By Brandon Howell | brhowell@mlive.com
Email the author | Follow on Twitter
on November 20, 2013 at 4:05 PM, updated November 20, 2013 at 7:18 PM

Print

LANSING -- Superconducting electron accelerator manufacturer Niowave plans to build a new multimillion-dollar facility for radiopharmaceutical production, creating at least 90 jobs in the Lansing area.

Speaking Wednesday before the Michigan Strategic Fund board, Niowave founder and President Terry Grimm said the new building will eventually be a $200 million facility and create about 120 jobs. The board signed off on a $3 million performance-based loan for the project, which Niowave has agreed to pay back in full - plus an additional $250,000 - with annual payments beginning in 2018.

Niowave had been offered incentives by the Illinois Accelerator Research Center to place its new facility in Illinois.

Grimm told the board most radiopharmaceutical production occurs in Canada in Europe, through a process that typically requires highly enriched uranium. Niowave will use its supercollider to produce radiopharmaceuticals, though, eliminating the need for uranium or a nuclear reactor.

Superconducting Electron Linac Radioisotope Production

NIOWAVE
www.niowaveinc.com

We are building a **40 MeV, 2.5 mA, 100 kW** superconducting linac for isotope production:

- Photonuclear production
  - (γ,p)
  - (γ,n)
- Photofission
  - (γ,f)

- **Same beam power as initial phase of LCLS-II**

Linacs

- **Basics**
  - ***Linacs from the Machine Protection point-of-view***
  - Energy flow / Energy Density
  - Examples: LCLS-II, ILC, and small-scale systems
- **Technical Developments**
  - Superconducting RF →
  - 3 to 4 x improvement in cryogenic heat-load since 2012
  - ***The bar has been raised!***

High Q0 R&D

- Recent work (2012) has demonstrated a novel cavity surface N-doping preparation technique
  - ***~three-fold improvement of mid-field Q0 at 2.0 K***
  - (Q0 is a surrogate that represents *1/ cryo heat-load*)
- The goal of the LCLS-II High Q0 R&D Program is:
- *to define and subsequently demonstrate the reliability of modifications to the Baseline Recipe as needed to achieve very high Q0*.
  - (Baseline Recipe => E-XFEL, ILC, CEBAF 12 GeV)

Jefferson Lab Colloquium Announcement:

Colloquium: Charlie Reece **Wed, Oct 22, 2014**

Description:
"The Pursuit of Better SRF Cavities - The Bar has been Raised"

Abstract:

Superconducting niobium rf cavities provide a remarkably efficient way to accelerate charged particles, especially for CW applications. Practical cost pressures continue to motivate development of ever more energy efficient and lower capital cost systems. The push to realize reliably SRF cavity surfaces with very low surface resistance (also known as high Q 0) with maximally high surface fields is the constant challenge for SRF technology R&D. Recent developments have dramatically changed what we understand to be "ideal" theoretical performance and have also opened the door to practical realization of accelerators with cryogenic heat budget cut by over 60%. Both theory and experiment point to a surprising decrease in surface resistance with increasing RF field amplitude. A collaborative effort involving JLab, FNAL, Cornell, and HZB has made significant progress characterizing and learning to manage this phenomena. The LCLS-II project is already committed to exploiting these new developments to minimize cryogenic capital and operating costs. These new understandings and associated challenges will be reviewed in their historical international and JLab context.

Fermilab-developed ‘gas-doping’ process →

Fermilab has developed a cavity processing recipe that results in ***high quality factors (>3E10)*** at operating gradients between 10 and 20 MV/m.

In 2014 Fermilab, Cornell, and Jlab developed this technology.

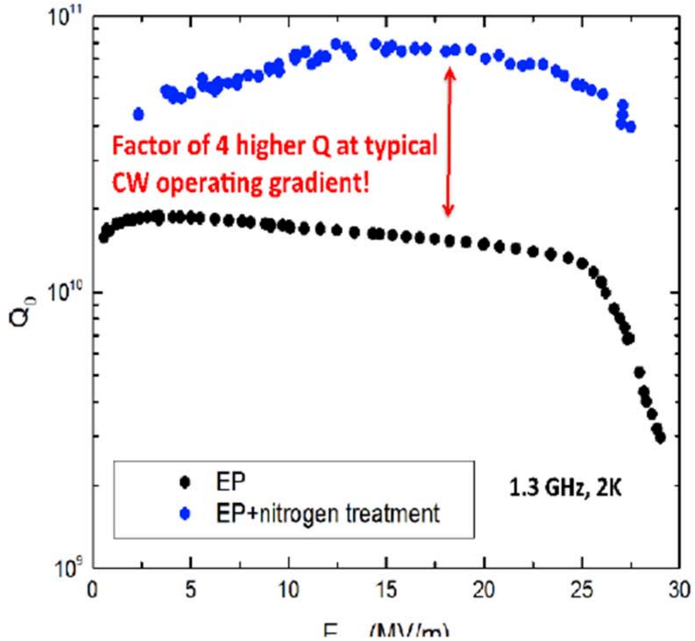
The primary goal was to develop a reliable and industrially compatible processing recipe to achieve an average Q0 of 2.7E10 at 16 MV/m in a practical cryomodule.

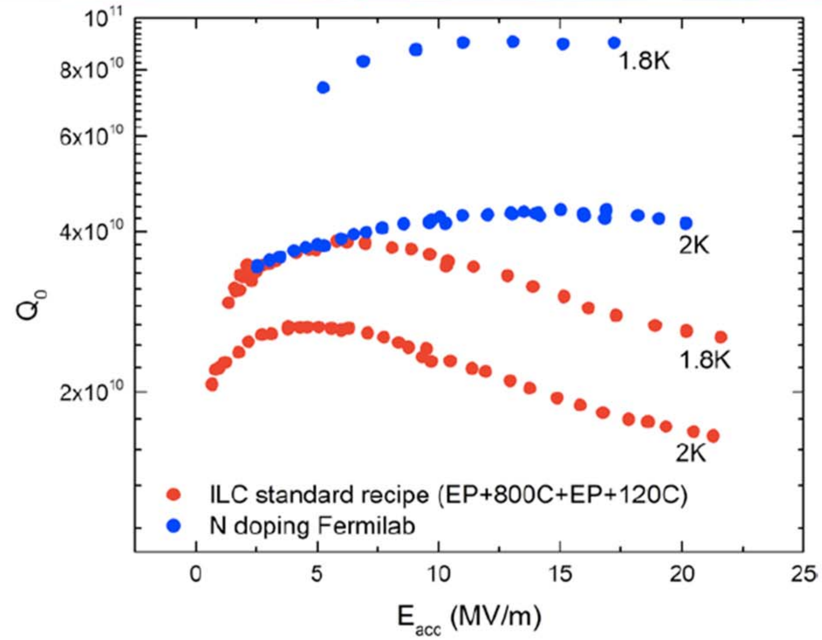
To reach this goal, the collaborating institutions processed and tested single-cell and 9-cell 1.3 GHz cavities in a successive optimization cycle.

The deliverable is industrial capability and cost-effective production yield.

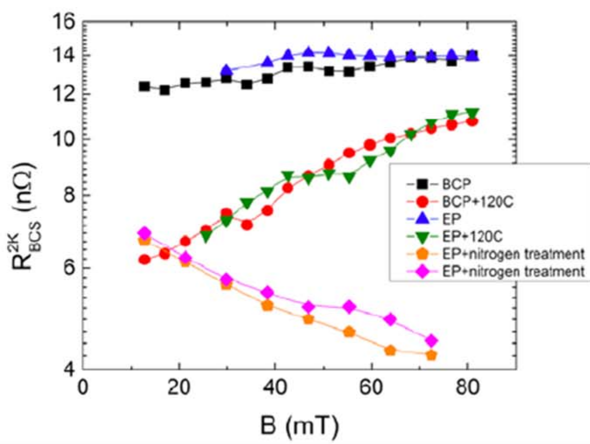
- Supporting the choice of a single 4.5 degree K cold-box for LCLS-II.

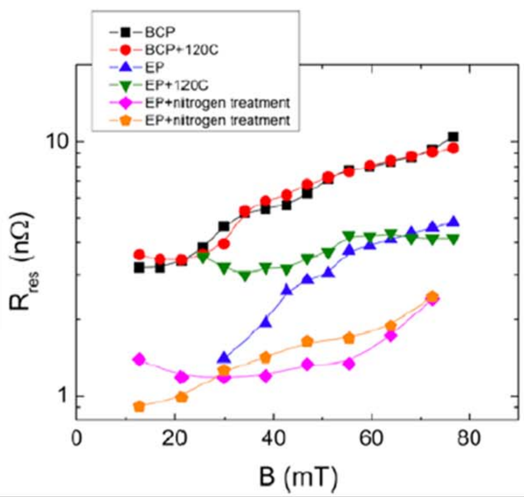
Nitrogen doping





Use the temperature dependence to separate R_s components





A. Grassellino, FNAL

Outline(2)

Machine Protection and Interlock Systems – Linear Machines

- **Linacs**
- **What protections are needed?**
  A. single bunch damage →
  B. average power loss →
  C. radiation dose (prompt/residual) →
  D. a protection collimator system
  – ***To ensure viable, long-lived systems***

ILC linac example		
C	R	T
Δ	O	Δ
◎	◎	Δ
O	O	Δ

- **Protection Systems**

Cost to mitigate?, Risk (likelihood)?, Time-to-repair?

In 'reverse': 1) kinds of damage, 2)impact, 3) causes

What protections are needed?

A. single bunch damage

- first micro-bunch of a new machine pulse;
- start-up after interrupt
- *No prior warning from control system / BLM .. But serious impact* →

Energy Density = BeamCharge × BeamSize^{-1} × dE/dx (ionisation loss)
Destructive capacity: determined by BeamCharge × BeamSize^{-1} not Beam Power

- ***Beam size at impact***
- ***Electron beam emittances (x,y) can be very small***
  - *Low energy machines are capable of micron-sized beams*

Beam size at impact

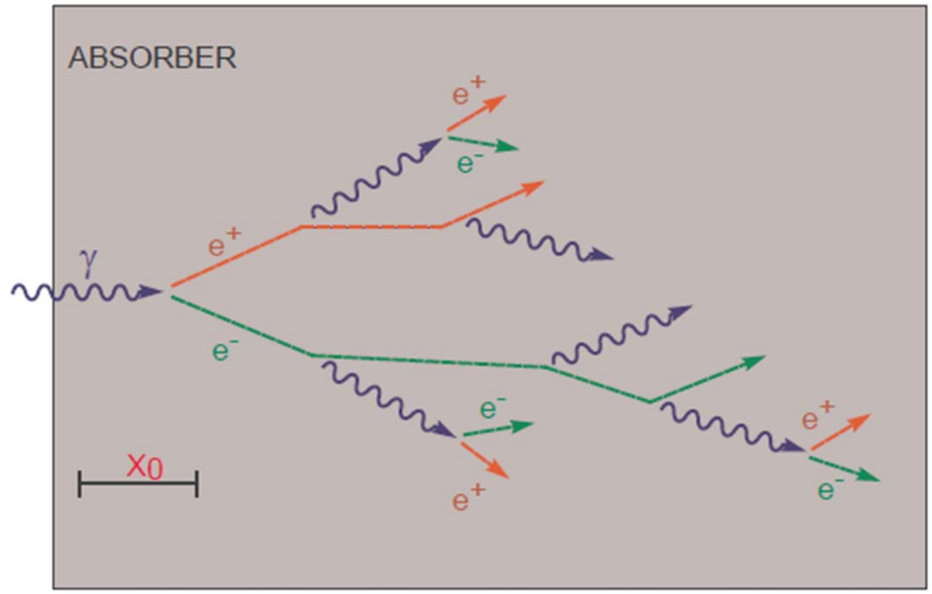
Particle interaction with matter

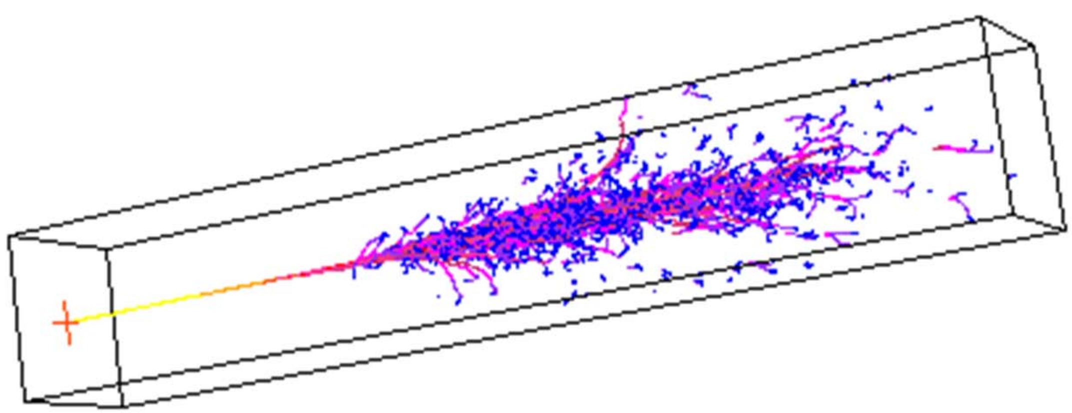
Energy density substantially reduced after ~3 X0

Typical X0 is 'long' (14 mm Cu)

Size at impact gives destructive capacity

Normal incidence / grazing incidence





Beam Power and destructive capacity

Michael Jonker

Beam Power = BeamCharge × ParticleEnergy × CyclingRate

Drive Beam: 2 × 70 MWatt   Main Beam: 2 × 14 MWatt

this makes a sustained disposal of this power a challenging task.

Energy Density = BeamCharge × BeamSize^{-1} × dE/dx (ionisation loss)

Destructive capacity: determined by BeamCharge × BeamSize^{-1} **not** Beam Power.

	Particle Energy [GeV]	Pulse Charge [μC]	Beam Size [mm²]	Energy Density in copper [J g⁻¹]	
				Incident Beam	Shower Core
Drive Beam Train (1 of 24)	2.4	25	1	**3.4 10^3**	40
Main Beam @ Damping Ring	2.8	0.20	125 10^{-6}	**1.8 10^5**	0.34
Main Beam @ β collimation	1.5 10^3	0.18	40 10^{-6}	**6.7 10^5**	120

Energy density in shower core is less significant than energy density of the incident beam.

Main beam already **unsafe** in the **damping ring** even with low beam power**.**

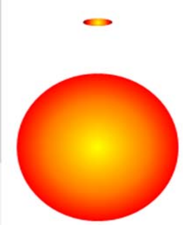
Particle energy is not the primary worry, however, no doubt **at 1.5 TeV you 'drill' deeper holes**.

Safe Beam:: yield limit in copper **(62 J g^{-1})**

Main Beam : 10000 × 'safe beam'

Drive Beam : 100 × 'safe beam'

Main beam:



Incident Beam size ~100 μm²

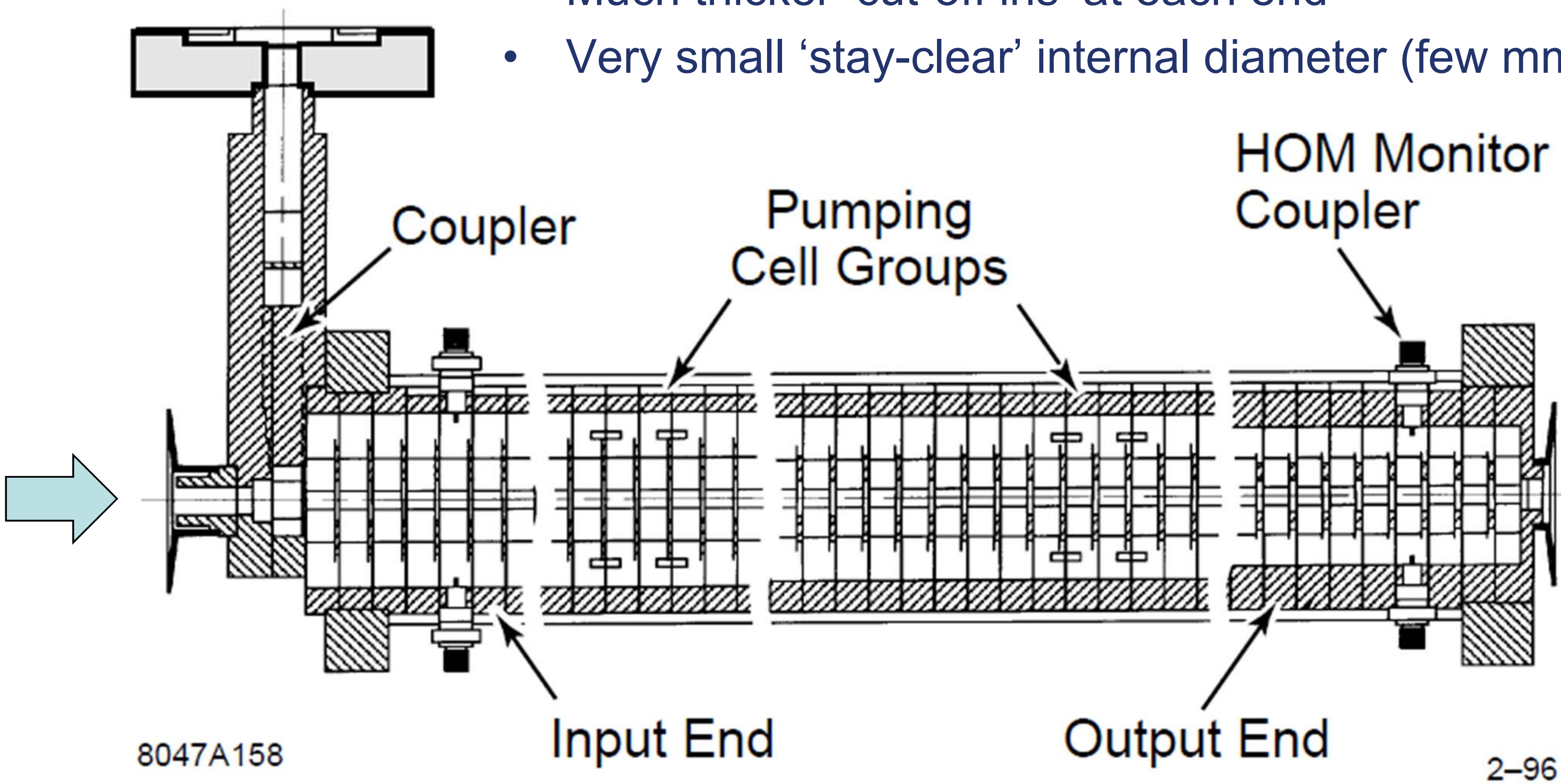
Shower core (@shower max)

- Size ~100 mm² x ~10^6
- $N_{particles}$ x ~10^3

⇒ E density x ~10^{-3}

X-Band Accelerator 'Structure'

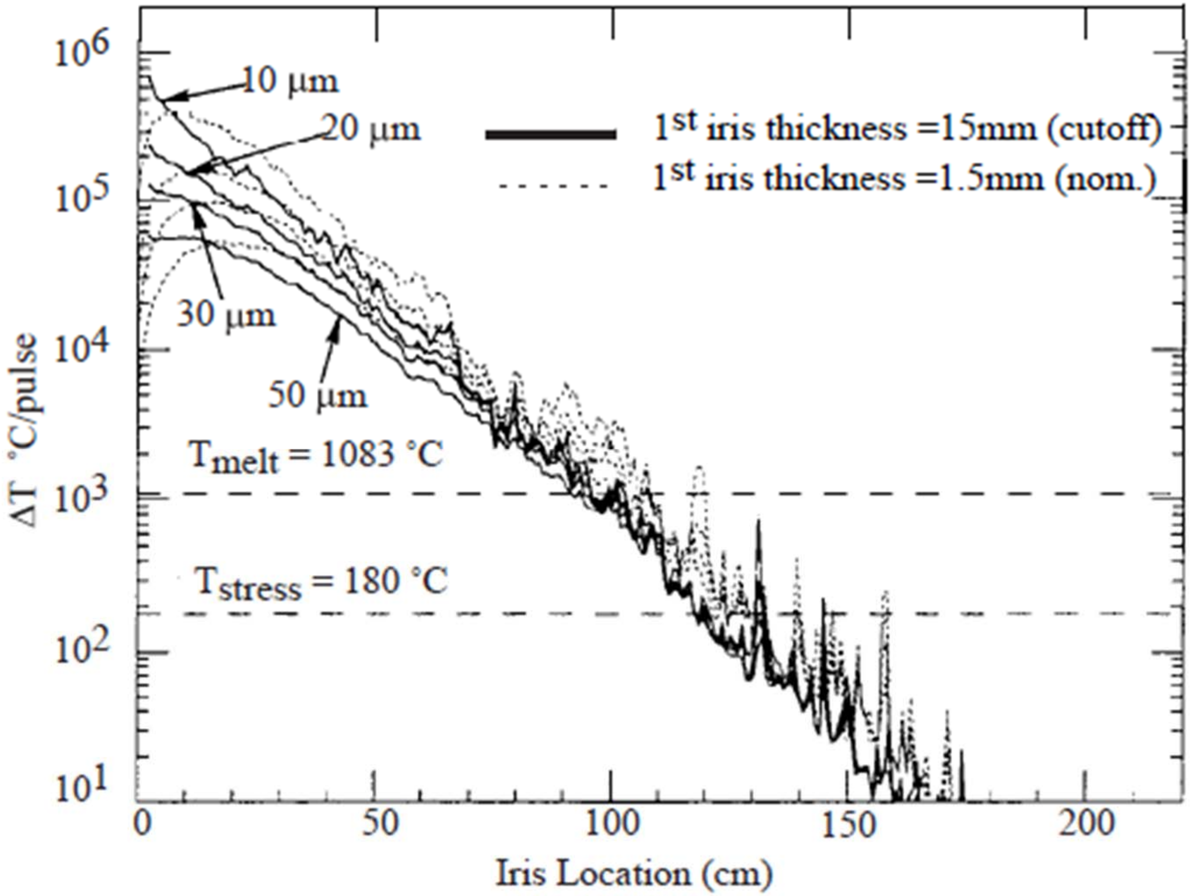
- A sheaf of 1.4mm-thick Cu plates spaced by 10mm
  - Near-normal impact can occur
- Much thicker 'cut-off iris' at each end
- Very small 'stay-clear' internal diameter (few mm)



Predicted maximum temperature rise – X band structure

ΔT in Irises of an X-band accelerating structure vs distance (nominal 10^12 ppp at 500 GeV)

(dashed lines show melting point and thermal stress limit in fully annealed copper)

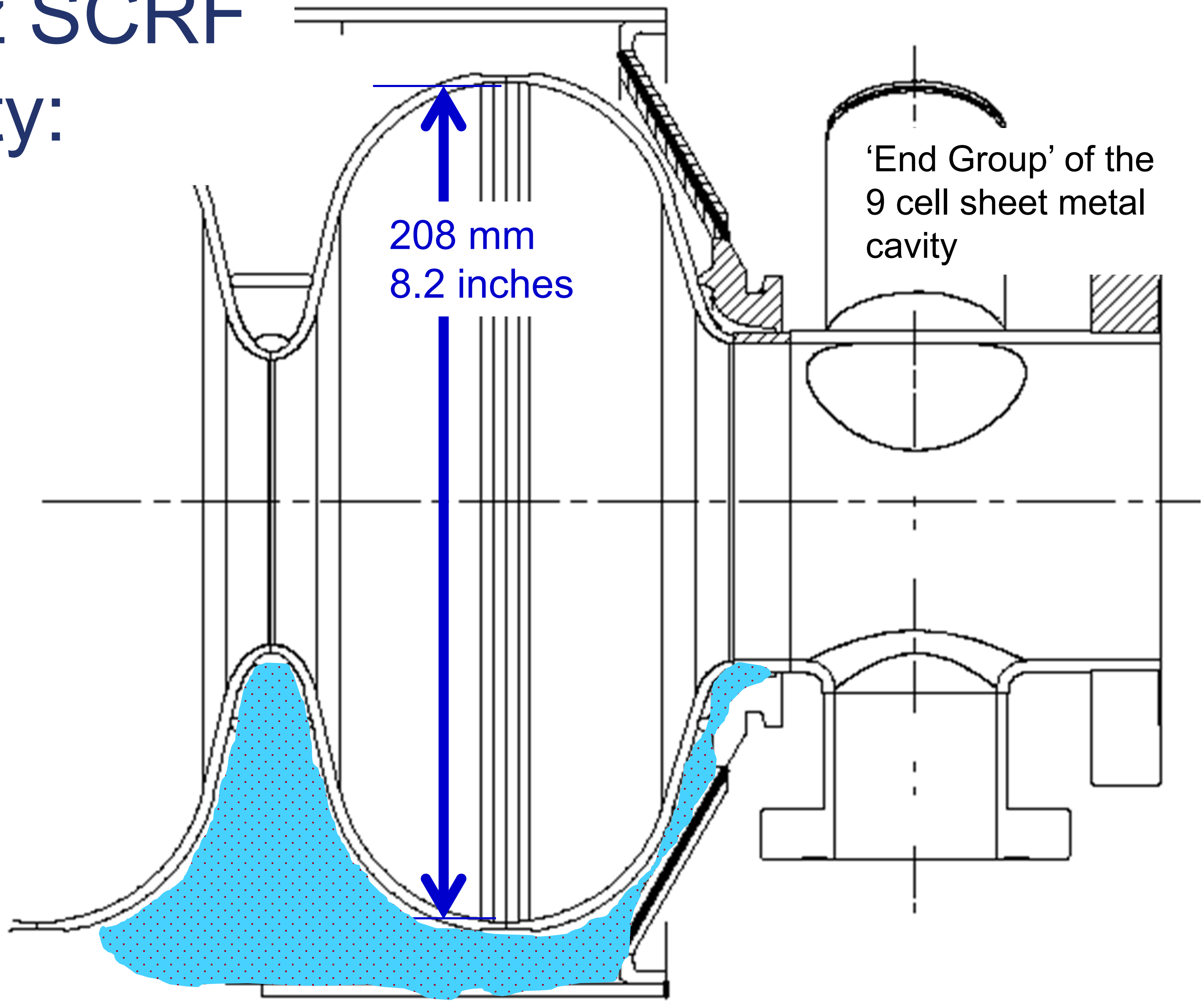


1300 MHz SCRF Cavity:

2.8 mm thick niobium sheet

2.0 K superfluid helium coolant just behind Nb sheet

Penetrating through-hole might allow liquid to drain into beam duct



Single Bunch Damage:

1. **will be mitigated by systems that check the preparedness before each pulse.**
2. **Mitigation is only necessary in the 'damped-beam' section of the ILC, where the beam area is less than 50 micron^2 (2e10).**
3. **mitigation will be done using two basic subsystems:**

LHC equivalents

1) a leading benign pilot bunch and
2) a beam permit system that surveys all appropriate devices before damping ring beam extraction begins and provides a permit if each device is in the proper state.

In addition, some exceptional devices will need fast monitoring systems and redundancy.

(damping ring RF and extraction kickers for example)

Pilot Bunch: Mitigating Single Bunch Damage

The pilot bunch is:

- 1% I_nom; 10 usec ahead start of nominal train.
- must traverse the machine before the train is allowed
- resolution requirements: BPM's must have resolution and systematic offsets not more than 10 times worse at the low end of the intensity range 2e9 ppb to 2e10 ppb.

If an errant trajectory is sensed, the nearest upstream abort system is triggered.

Pilot Bunch Timing:

- To ensure an abort kicker can be turned on quickly enough to dump the high intensity bunches that follow the pilot bunch:
- Assuming the latency for detecting the fault is 500 ns,
- the upstream signal effective propagation speed is 0.7 c,
- and the abort kicker latency time is 1 us, the maximum kicker spacing should be 1000m.

- 0.5 + 3 + 4.3 + 1 micro-seconds = 8.8 → nominally 25 bunches

- Only those bunches extracted from the damping ring before the abort signal is sensed and received at the ring need to be dumped and the damping ring extraction sequence will be terminated, leaving what is left of the partially extracted beam train stored. Given that the time needed for the beam to go from the damping ring to the main beam dump is 67 us, in the worst case, (when the downstream most sensor detects a fault condition from the pilot), and the signal return time to the damping ring is another 100 us, roughly 450 bunches need to be dumped.

Pilot Bunch Generation:

- The injector complex must include systems that reliably generate the pilot bunch.
- Extraction from the ring should not begin unless the pilot is within allowed limits; its intensity should be high enough for the trajectory sensors to read and respond reliably yet below the single damage threshold, expected to be around 1% for bunches which are intended for the whole machine.
- (There may also be a need for a benign pilot bunch of nominal intensity but much larger emittance)

Validation: Demonstrate single-bunch damage

- Beam tests were performed in the SLAC Final Focus Test Beam area, near the focal point in the system, where the beams can be made quite small.
- Wire scanners positioned a coupon in the beam path.
- A magnet near the entrance to the linac was used to allow beam through to the FFTB, one pulse at a time, such that the coupon could be moved exactly 200 µm between pulses.
- Seven micron wires allowed
  - precise positioning of the beam wrt coupon
  - And provided measurements of beam size.

Coupon mover w/wires to measure σ (x,y)

Copper Coupon Test		
Impact set #	Beam intensity (e10)	σ (x,y) microns
1	1	8x6
2	1.2	8x6
3	1.4	8x6
4	1.6	8x6
5	1.8	8x6
6	2.0	8x6
7	2.0	16x13
8	2.0	8x11
9	2.0	9x8
10	0.3	8x6
11	0.7	8x6

- **1.4 mm soft copper coupon**
  - (same as structure iris)
- **Subjected to sets of beam-impacts with different parameters**
  - Size (x, y), intensity
- **Entrance / Exit holes *mirrored!* showing beam shape**

Single Bunch Damage in 1.4 mm Cu

Average human hair – 70 microns

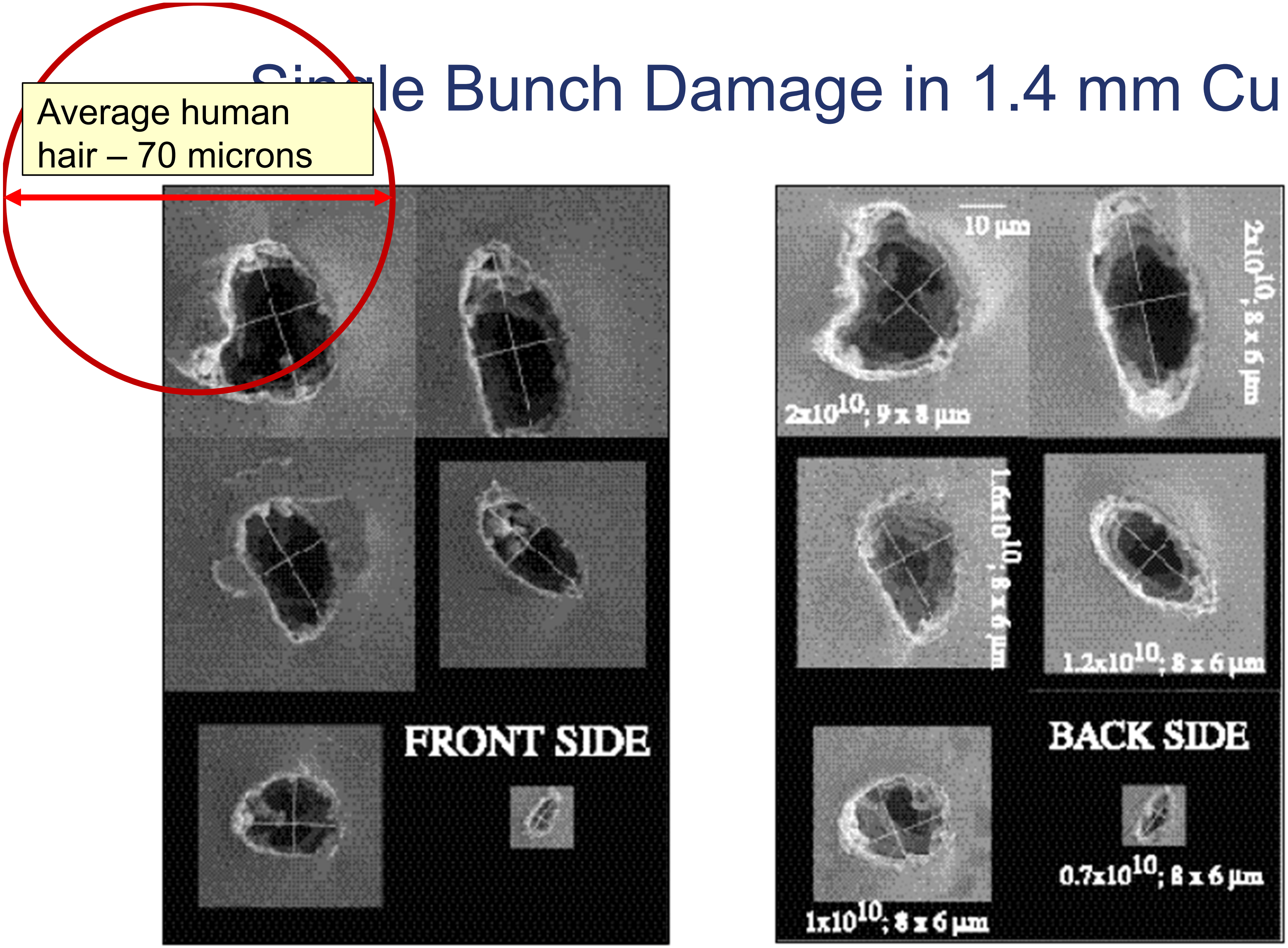
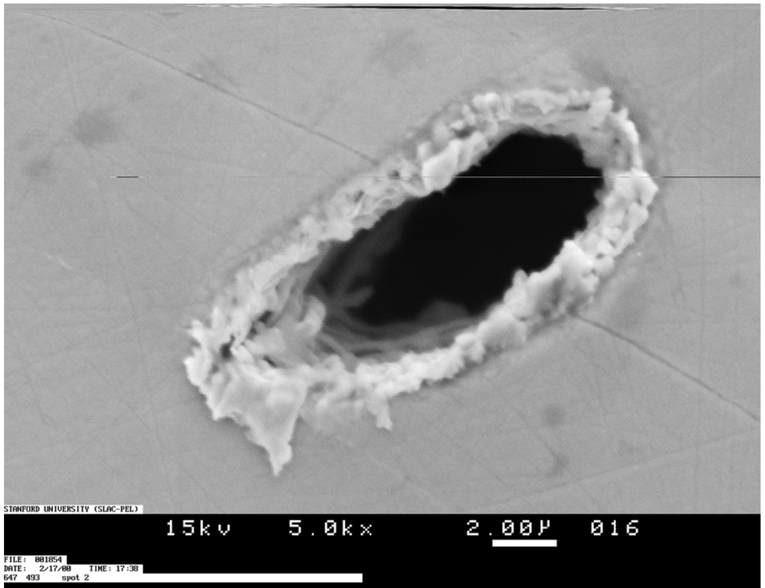
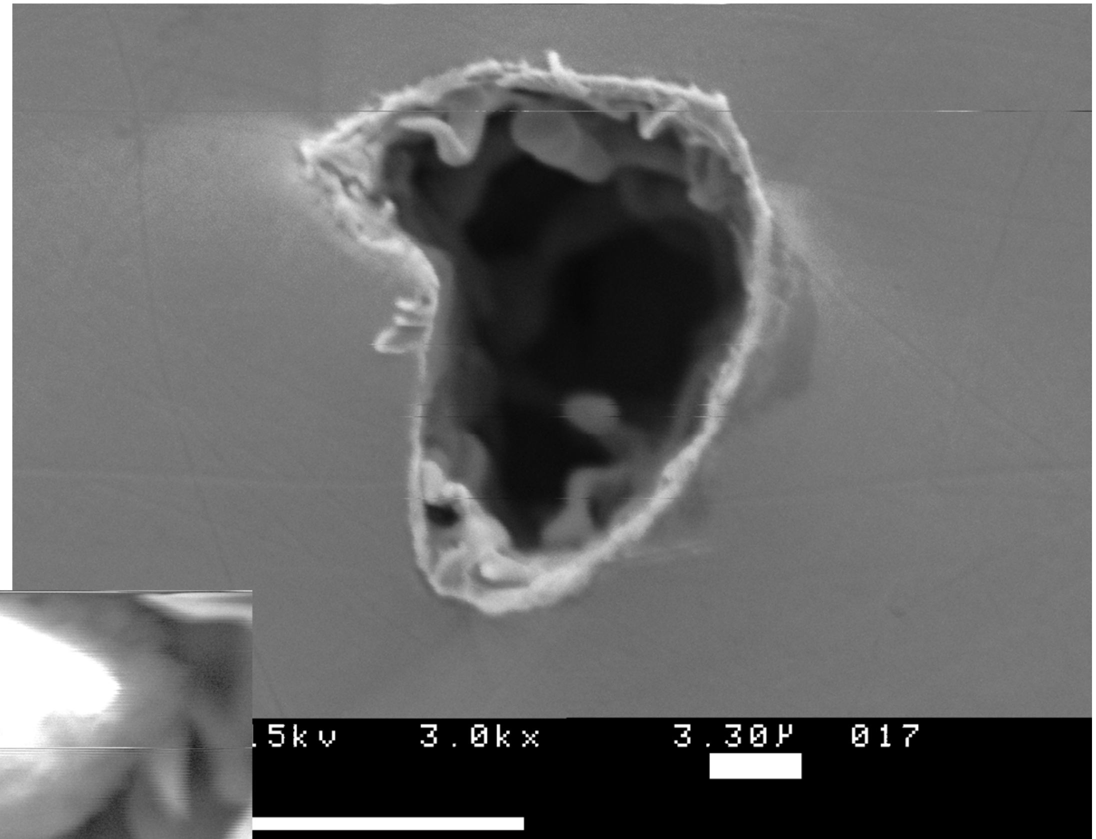
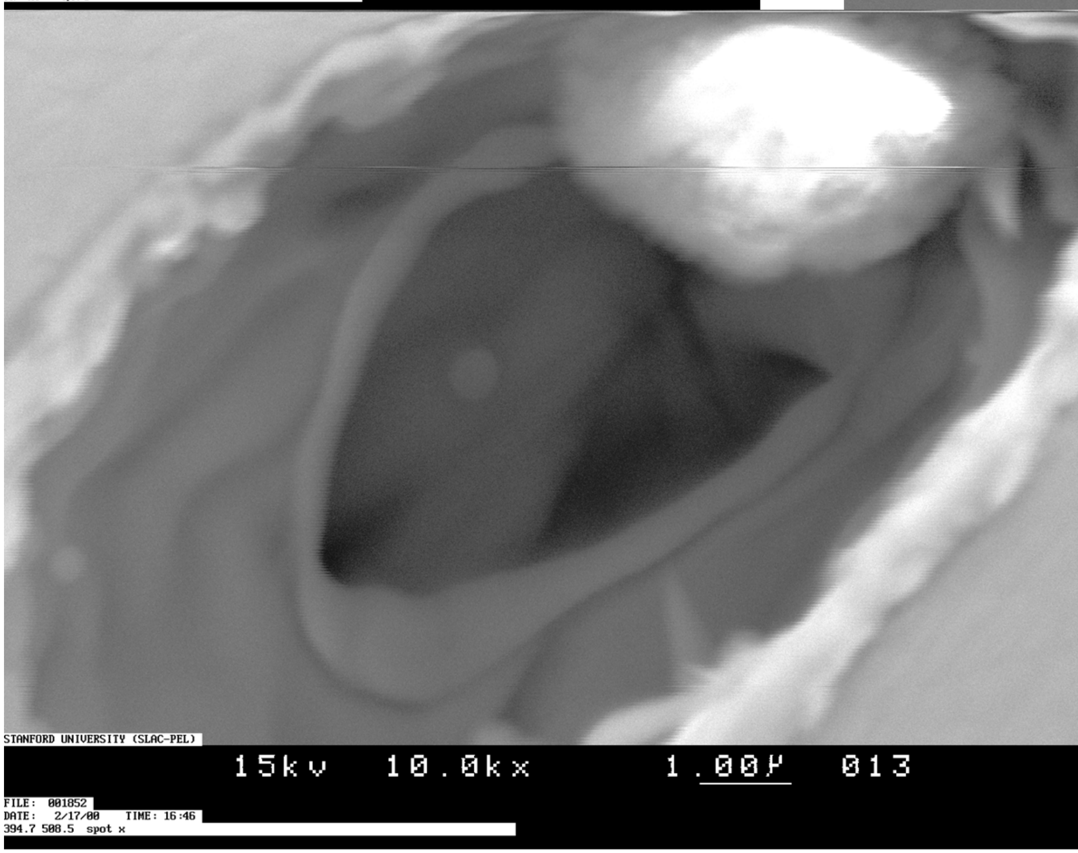


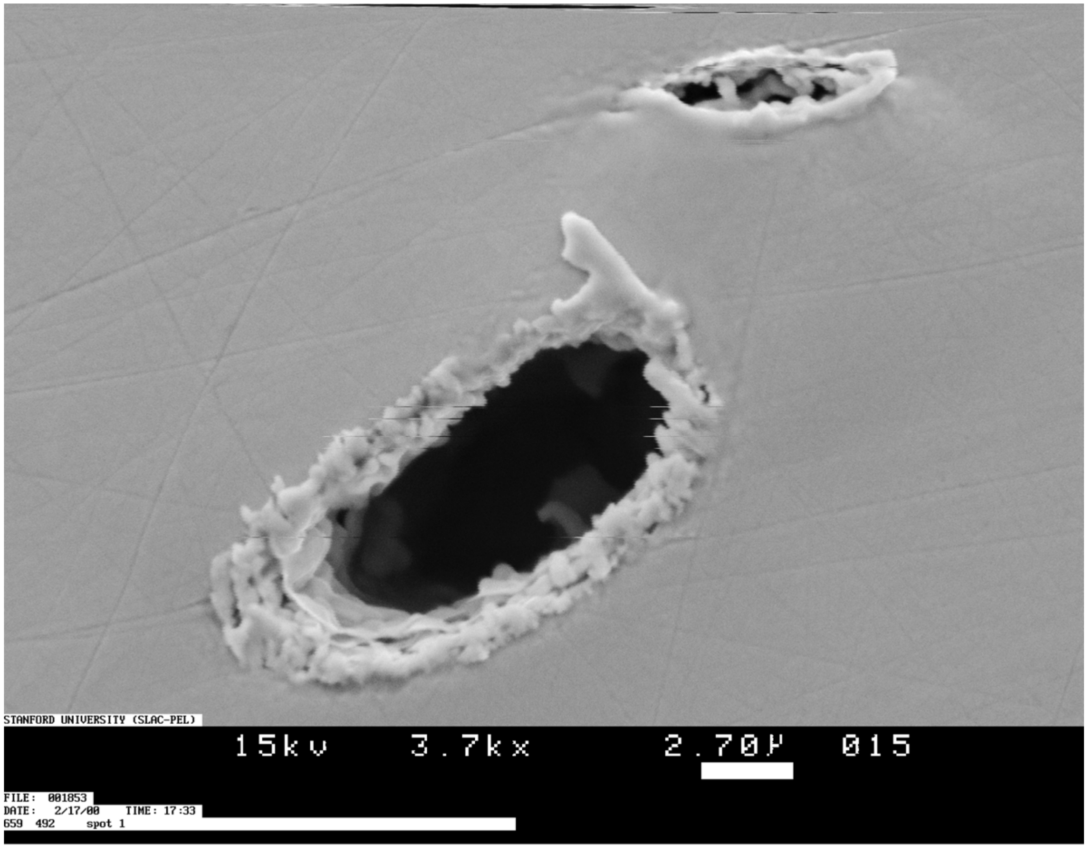
Figure 1: Scanning electron microscope (SEM) images of the entrance (left) and exit (right) points on the copper coupon. The faint lines drawn in the figure were used to estimate the impact point size. All of the images in the montage have the same scale.







Single Bunch Damage in 1.4 mm Cu (2)



Critical density ~1pC/μm^2 ~10^{13}/mm^2.
(CLIC use ~0.4 pC/μm^2 for Cu).
Grazing incidence (~1 mrad) will help.

Single Bunch Damage in 1.4 mm Cu (3)

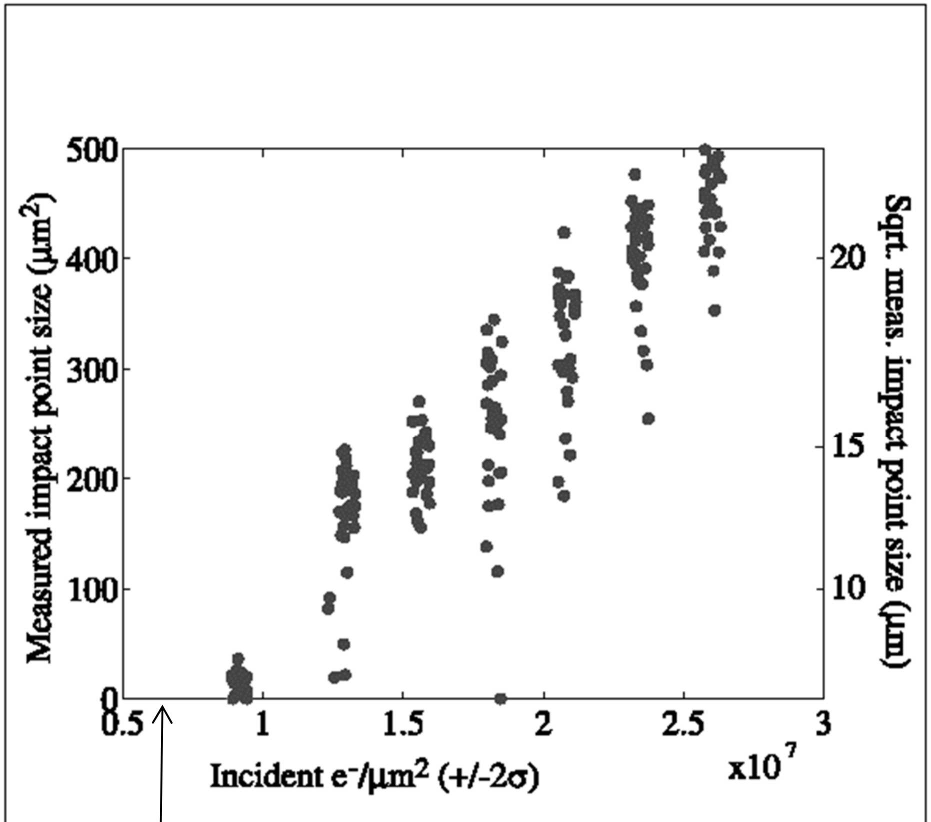


Figure 3: Measured impact point sizes vs beam density.

1 pC/um^2

leak detector showed small, (10-8 torr/liter/sec) leaks through the coupon in the region of the larger IPs.

Single Bunch Damage in Cu Summary

- Extreme heating followed by rapid cooling is evident on each impact point (IP)
- some of the material is missing, leaving a substantial pit whose depth is comparable to its size.

→high pressure in the material along the path of the beam, with force enough to eject the liquid at the surface.

- Some copper was in gas phase; predictions did not indicate enough heat for full vaporization.

Single Bunch Damage: Collective Effect

- Short bunches (~micron), small (x,y) dimension beam (micron) have extremely high electric field at 1 σ and extremely high peak current (~ kA).
- 100pC, 10 µm (x,y,z) (LCLS-II)

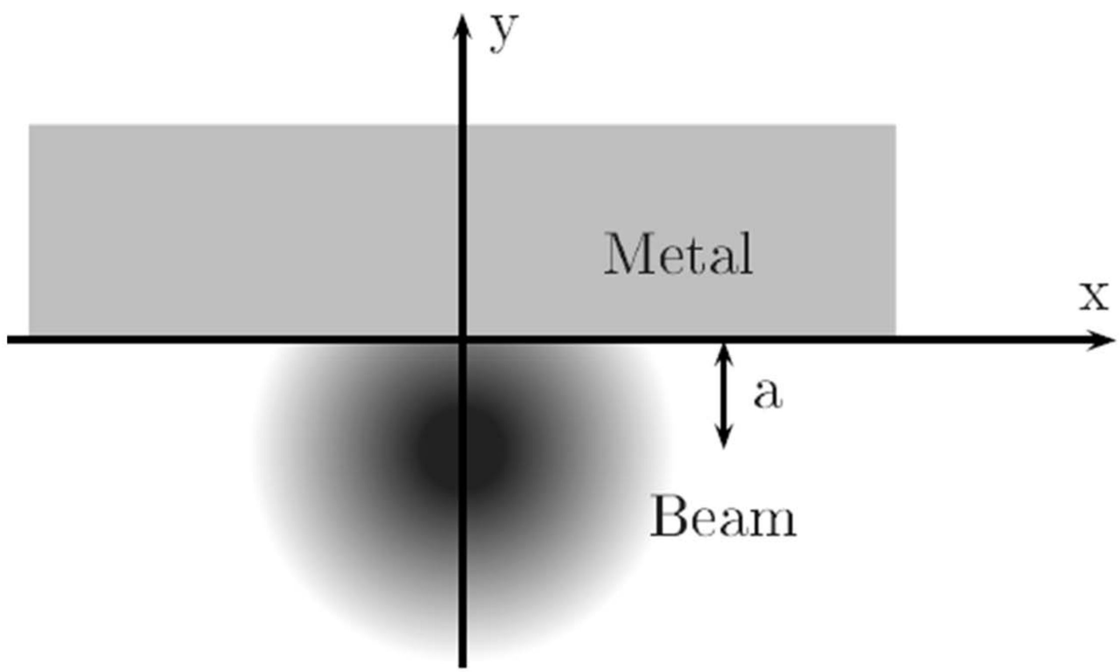


Image Current Heating

Image Current Heating on Metal Surface Due to Charged Bunches

Xintian E. Lin and David H. Whittum

Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

(Dated: February 18, 2000)

When charged particles pass through a metal pipe, they are accompanied by an image current on the metal surface. With intense short bunches passing near the metal surface, the peak image current density can be very high. This current may result in substantial temperature rise on the surface, especially in multi-bunch operation. In this paper, we derive an explicit formula for the surface temperature rise due to this previously unrecognized effect, and show that it should be taken into account in structure and collimator design for future accelerators.

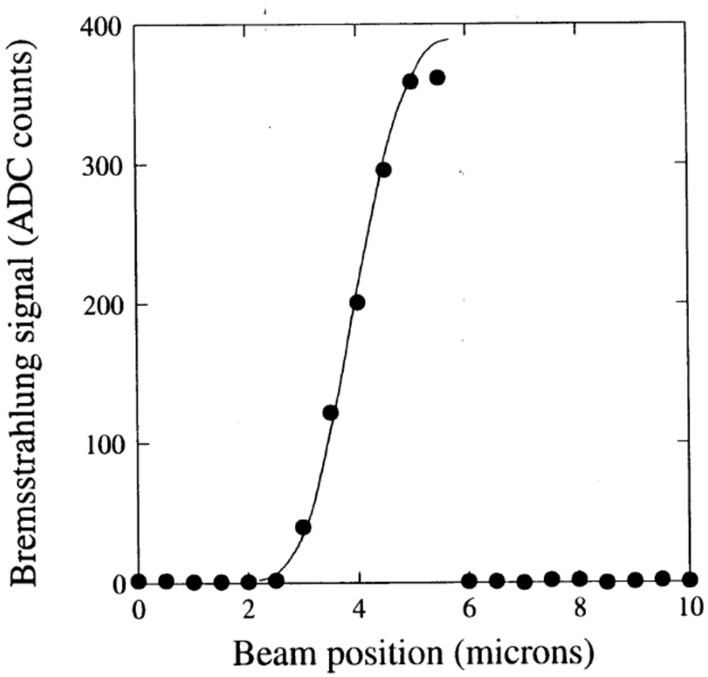
Image Current Examples:

I^2R heating – peak current squared

	nC	Beam size	Material	ΔT_rad	ΔT_i
LC	Multi-bunch	60x60x160	Ti	728	66
LCLS-I	1nC	38x38x20	Ti	34	390
			SS	45	324
XFEL	1	18x18x23	Ti	150	900

LHC (large beams) – LC (small beams)

- **Sliced wire – sheaf**



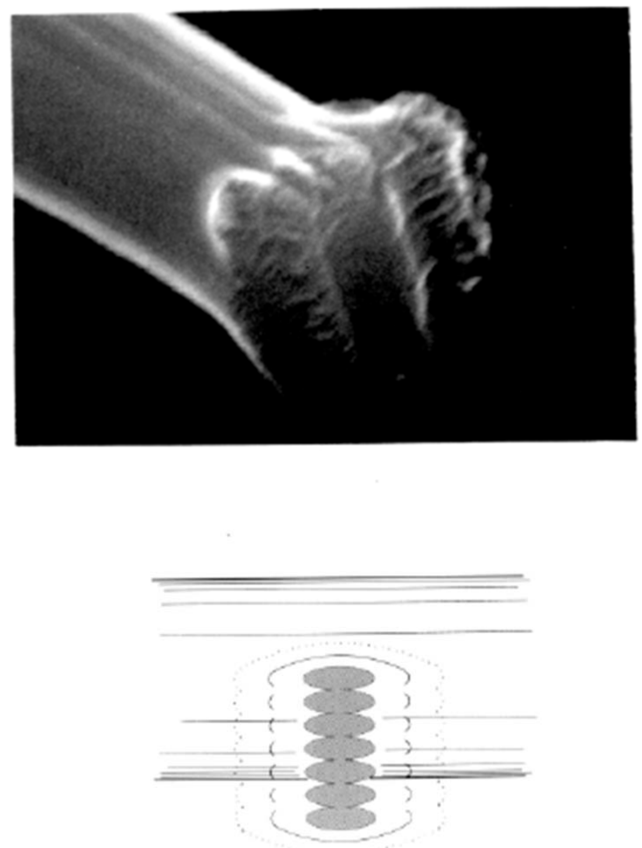


FIGURE 4. Failed 4 μm carbon wire with inset showing the progression of successive beam pulses scanning across the wire. This wire was broken at the point of intersection with a beam of 3 x 10^9 particles/μm^2.

Average beam loss

- limited using a combination of radiation, thermal, beam intensity and other special sensors.
- similar to other machines, such as SLC, LHC, SNS and Tevatron.
- exceeded exposure limits during the passage of the train, ring extraction or source production (e+/e-) is stopped.
- For stability, it is important to keep as much of the machine operating at a nominal power level.
- Done by segmenting into MPS regions.
- Since the fault response can (and will) occur during the train, and since there will be 9 full power shut-off points, each with an extraction system and a full capacity dump,
- The average beam loss MPS will be applied throughout the complex, including the source, damping ring injector and the damping ring itself.

Radiation (prompt and residual) Protons v Electrons

Protons

- 1 W/m → Not to exceed to limit personnel exposure to residual activity
- Prompt radiation typically less

Electrons

- 100 W/m equivalent
  - **(1/α)**
- Prompt radiation can be very high – w/o causing unmanageable exposure

Beam loss Mechanisms

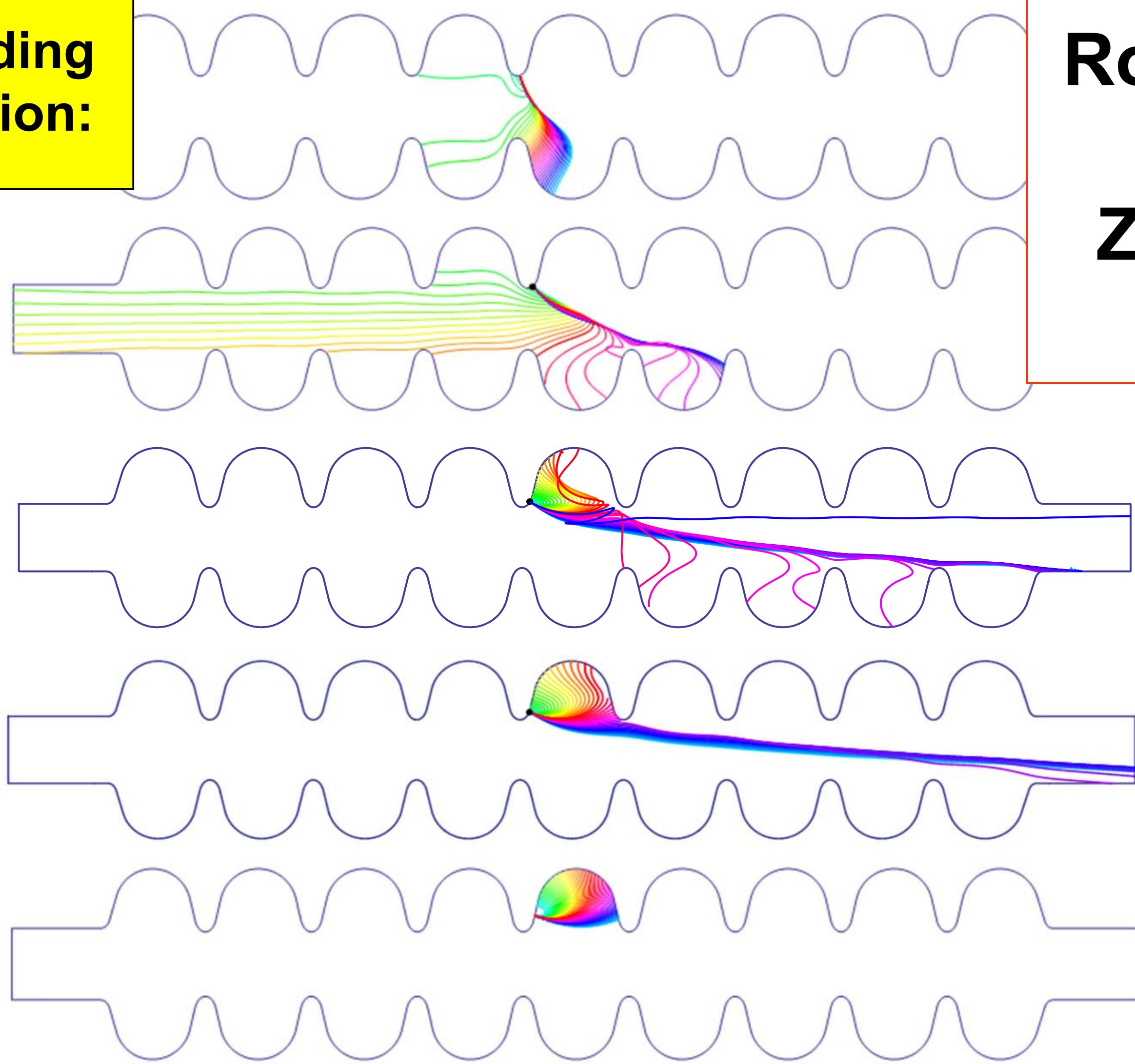
Covered in previous talks

- **Halo formation**
  - Particle processes : gas scattering, (quasi) elastic and inelastic Bremsstrahlung, thermal photon, etc..
  - Optics related : mismatch, coupling, dispersion, non-linearities - requires tracking for the “real” machine
  - Various : noise and vibrations, dark current, wakefields - currently not simulated for halo
- **Dark Current and Radiation generated and accelerated by cavities (major source)**

Example: Trajectories from different Emitters

Understanding field emission:

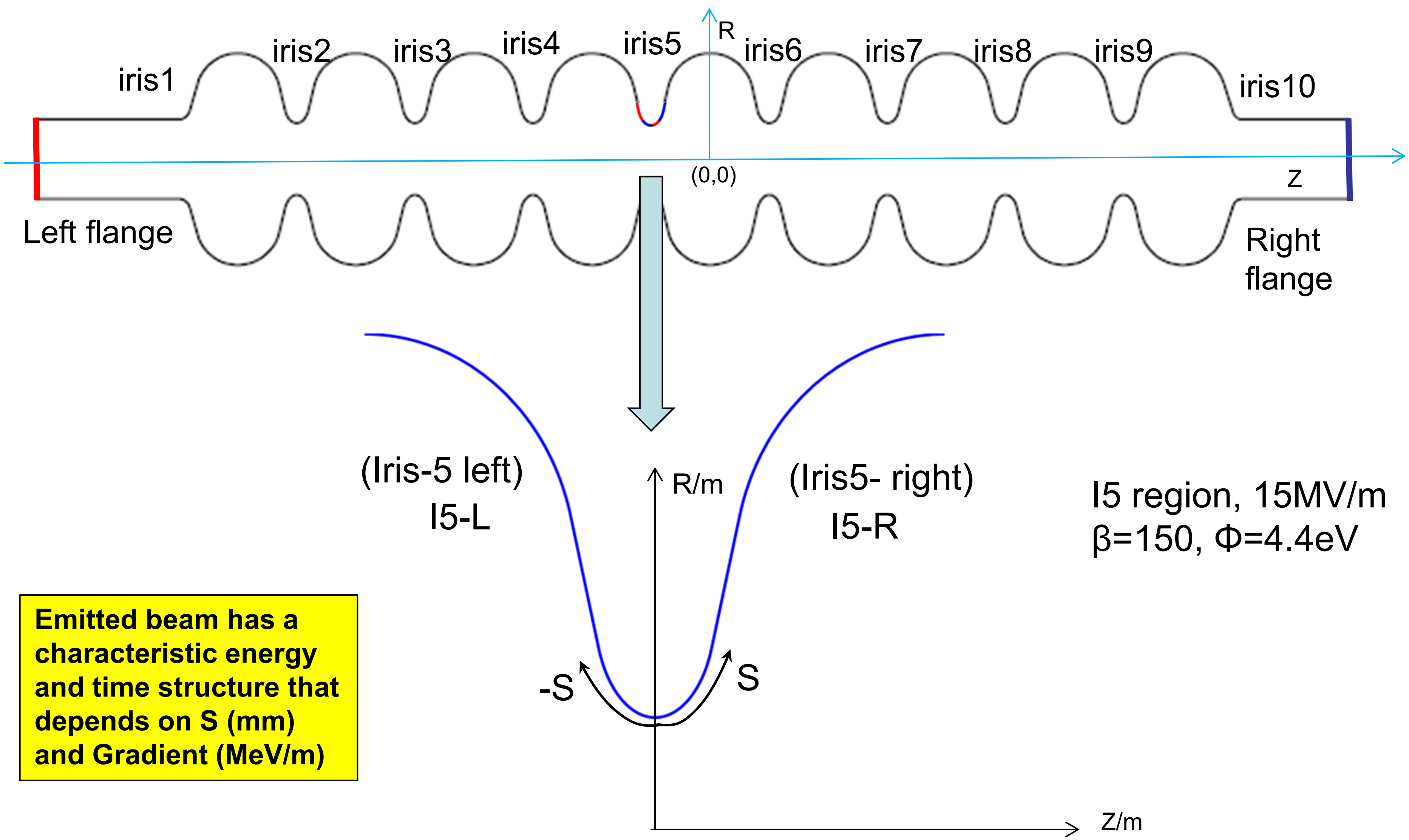
Rongli Geng, Jlab
Zenghai Li, SLAC



A field emission point is a 'diode'

Field emission sites are defects

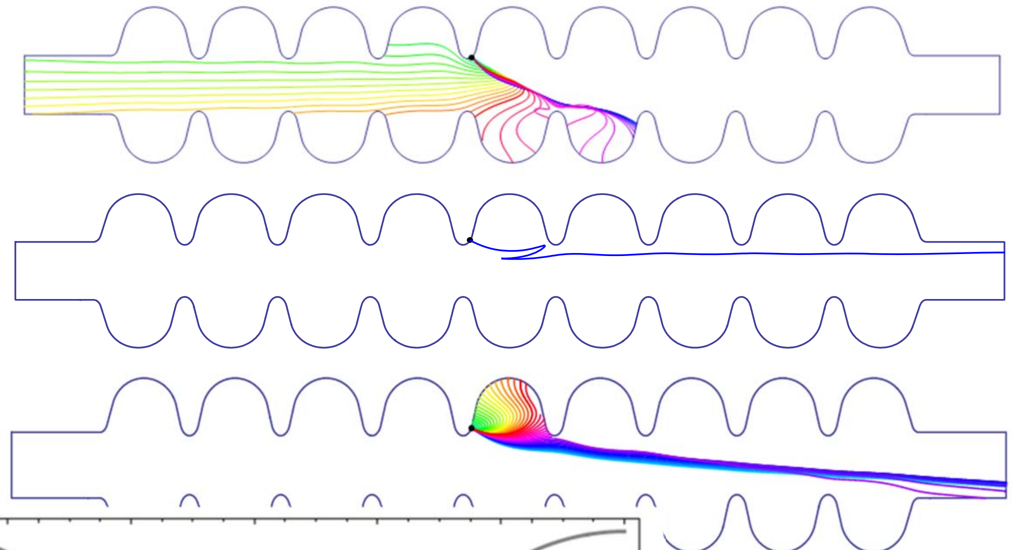
9-cell Model and Definition of Coordinate



I5 region, 15MV/m
β=150, Φ=4.4eV

Emitted beam has a characteristic energy and time structure that depends on S (mm) and Gradient (MeV/m)

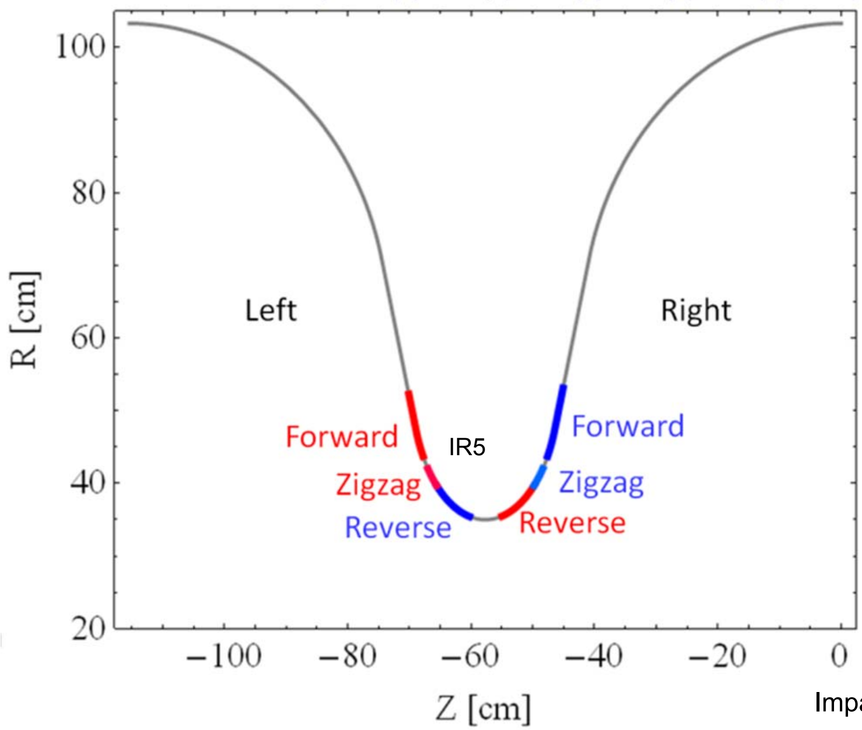
3 Types of "Long Range" Trajectories

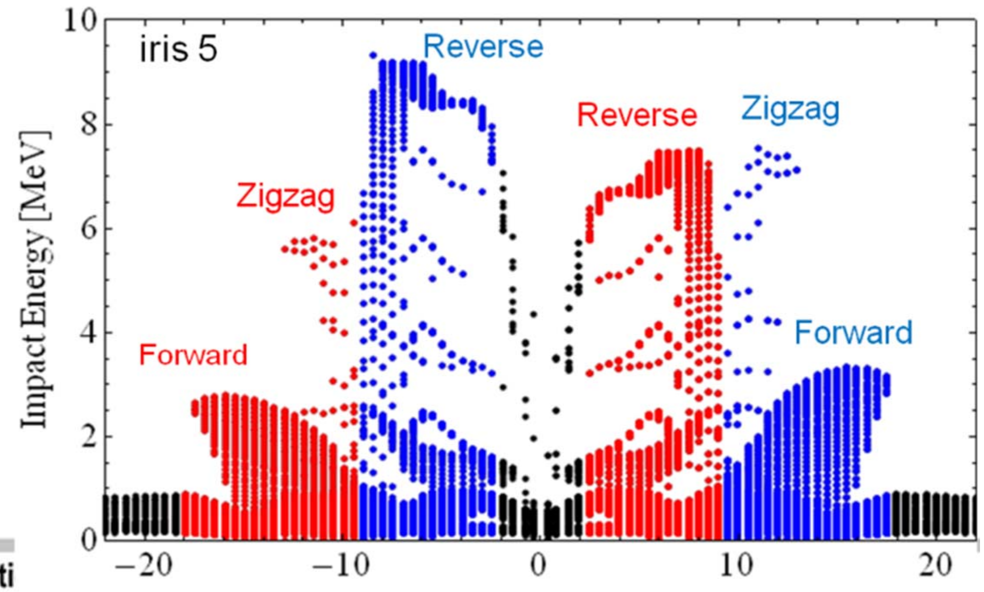


Emission in region
>>> "Reverse type"

Emission in region
>>> "Zigzag type"

Emission in region
>>> "Forward type"





Impact position VS impact energy distribution

Dark Current

- From both the TESLA TDR, and the US LC Technology Options Study, the total (Static + Dynamic) **2 K cryo-load** at 35 MV/m is:

~ 2.5 W/cavity

at a nominal $Q_0 = 5 \cdot 10^9$ and with a 50% margin on the cryo-plant capacity.

- Taking **10% of this value**, namely 250 mW/cavity, as a safe limit for the 2 K cryo-load induced by the Dark Current we obtain:

~ 50 nA/cavity

This v

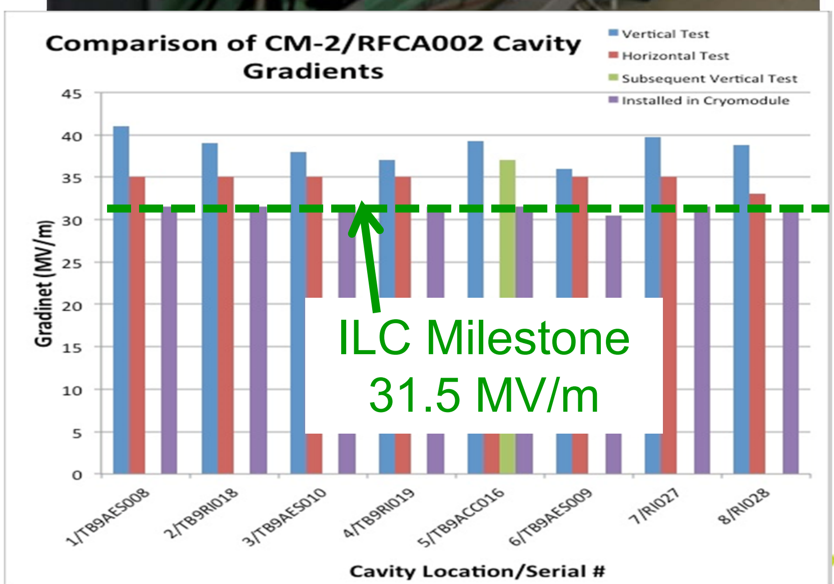
LCLS-II: CW SCRF 25 pA limit

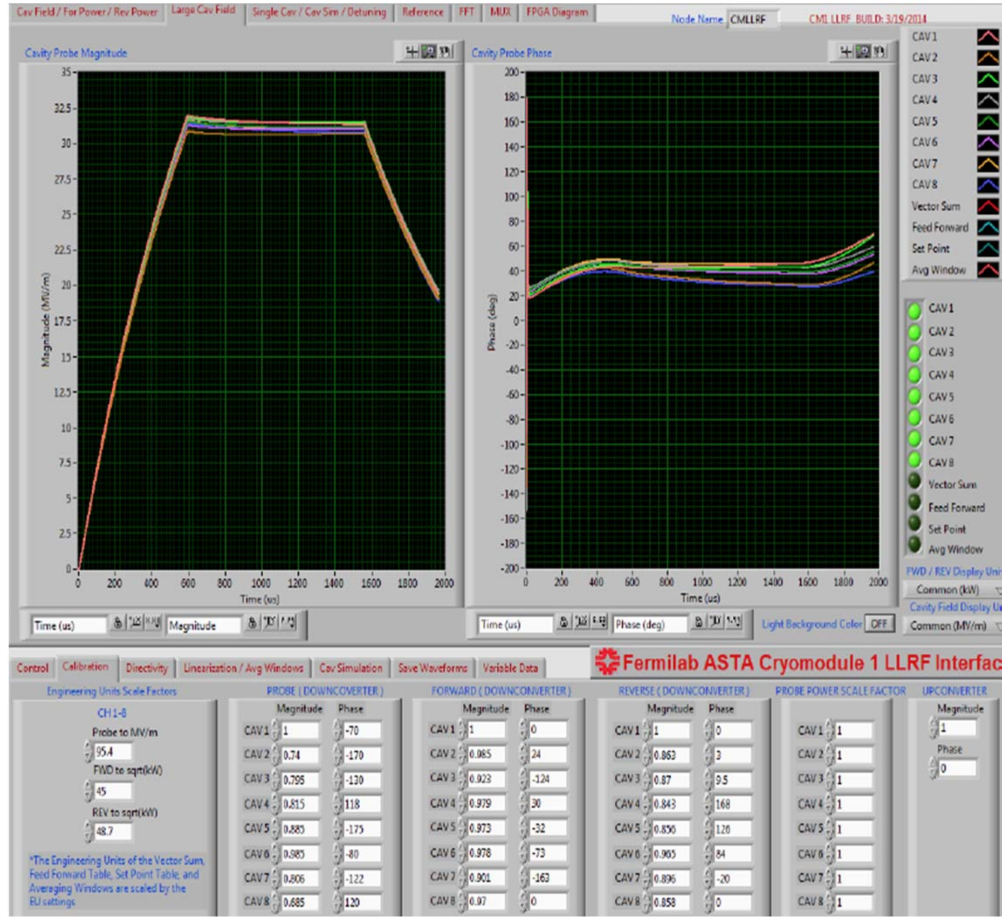
- 1 GeV as average energy gained by DC electrons
  (value that has been shown to be conservative for E_{acc} = 35 MV/m)
- 5 Hz operation with 1 ms pulses

250 mW = 50 nA · 1 GeV/e · 0.005

Carlo Pagani 4 ITRP Meeting Five Caltech, 28 June 2004

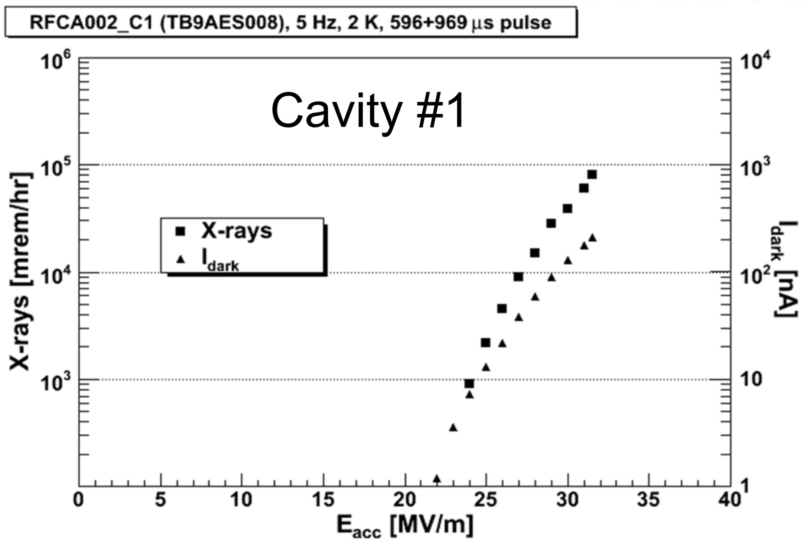
FNAL CM2 performance

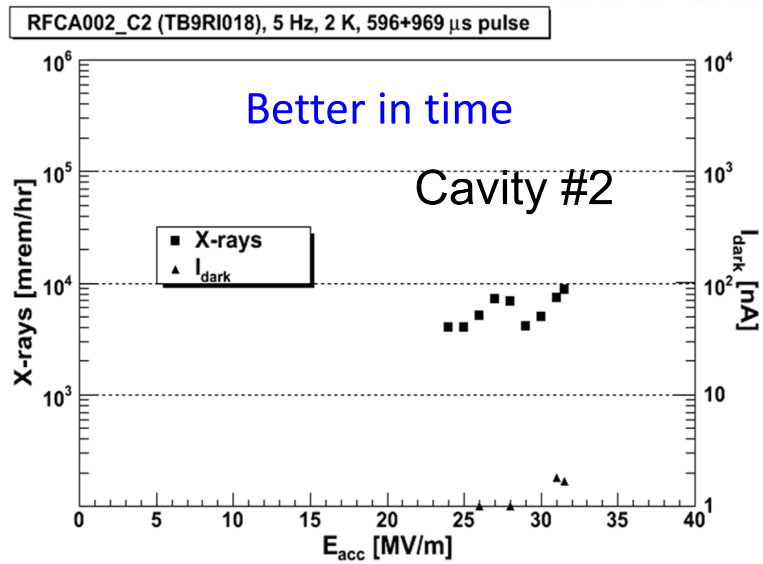




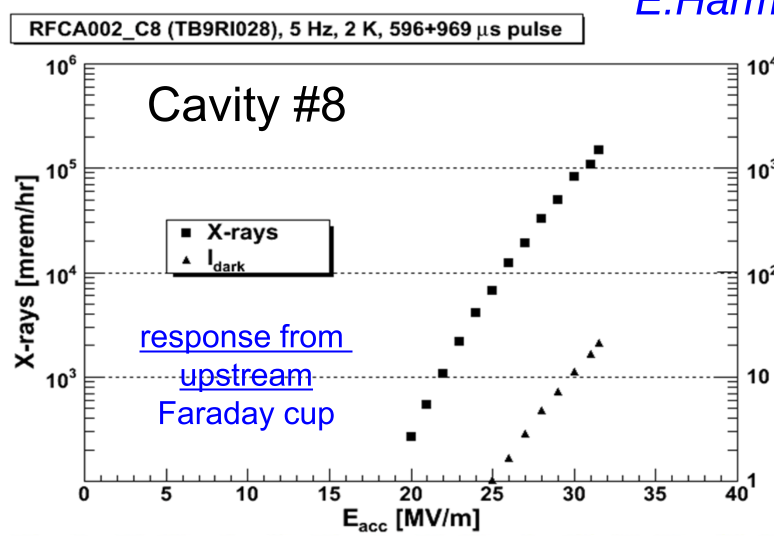
- 2°K; QL=3.5e6; Total Voltage = 252 MeV
- pulse:1.6 ms = 0.59 fill + 0.97 flattop
- 5 Hz repetition rate

FNAL CM-2 Radiation and Dark current data

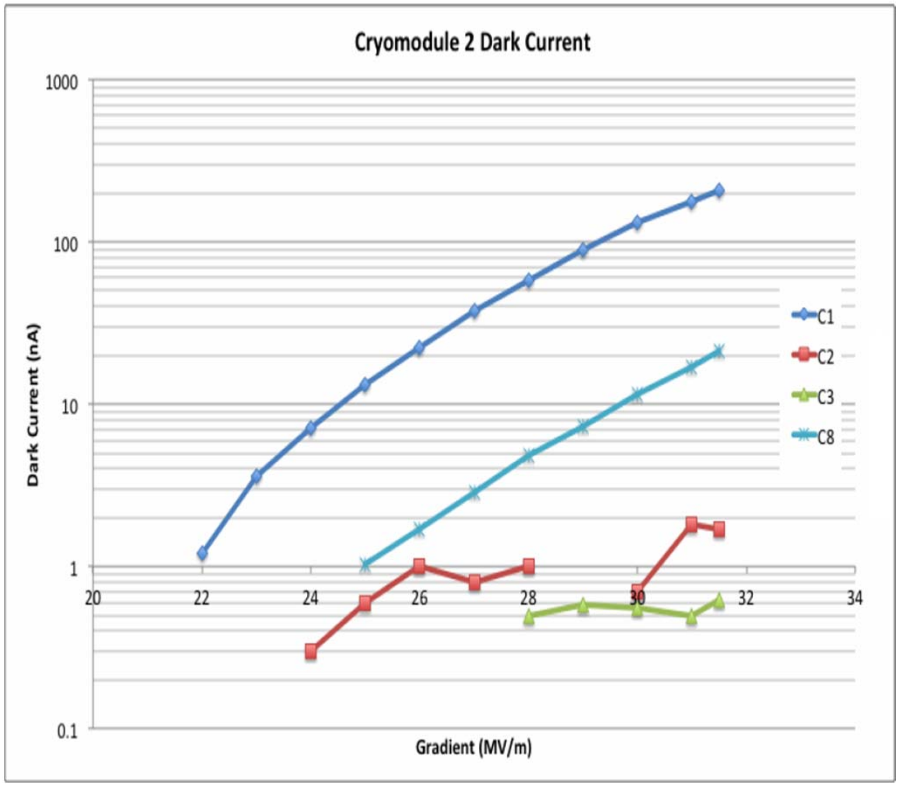


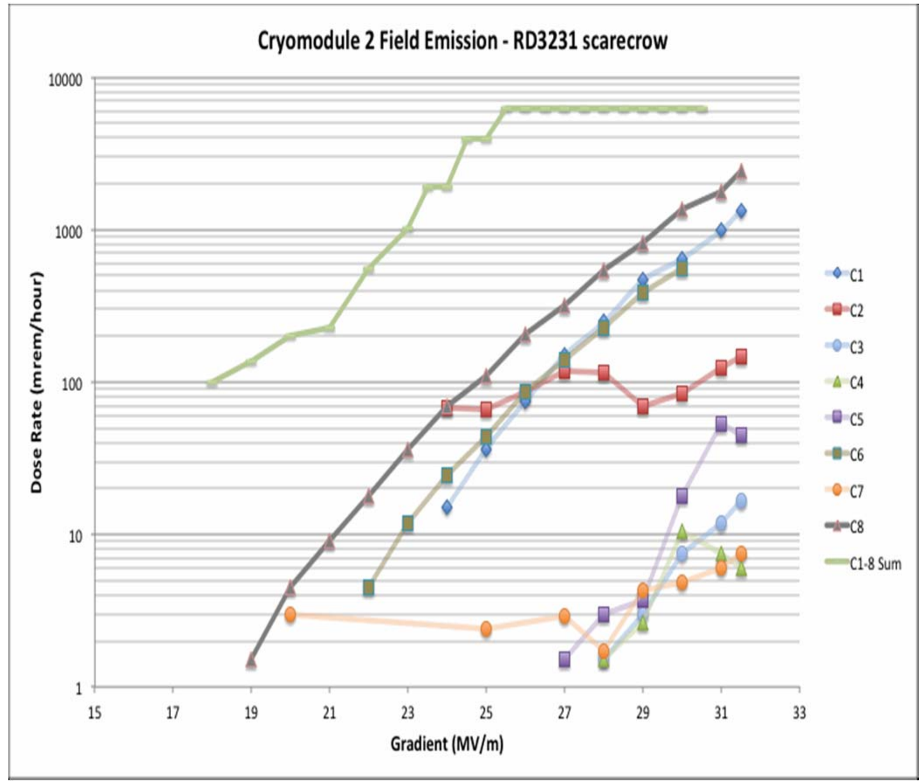


E.Harms talk



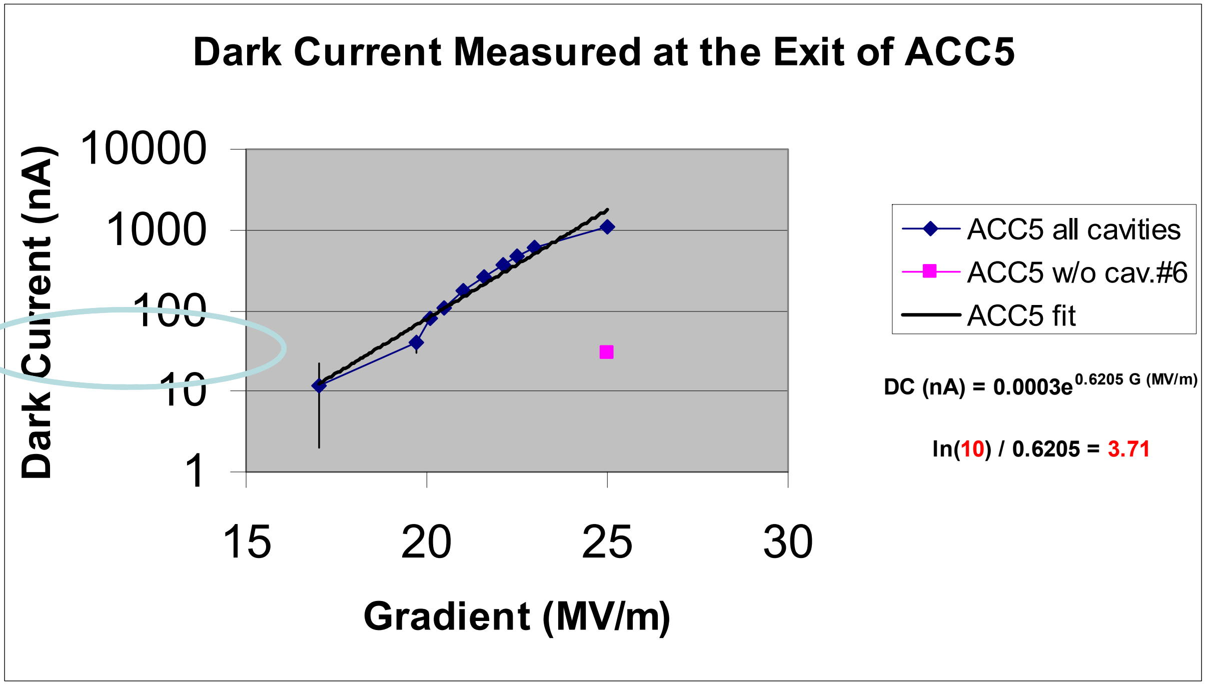
- Radiation and dark current mostly in cav1, less in cav8 & #2.
- Much less from others.
- Response from upstream Faraday cup x5 higher than downstream
- Powered individually, No beam





- Threshold for production ~20 MV/m
- No external radiation seen
- Variety of detection means available
- TLM’s are promising option for rad. meas.

From FLASH/DESY (H. Weise) - 2004



Gradient (MV/m)	d.c. (nA)	error / noise (nA)
17	12	10
19.7	39.7	10
20.1	80	10
20.5	110	10
21	175	10
21.6	260	20
22.1	370	20
22.5	470	20
23	610	20
25	1100	50

d.c. was averaged between 600μs and 1200 μs

the fit shows an increase by a factor 10 for each 3.71 MV/m gradient step

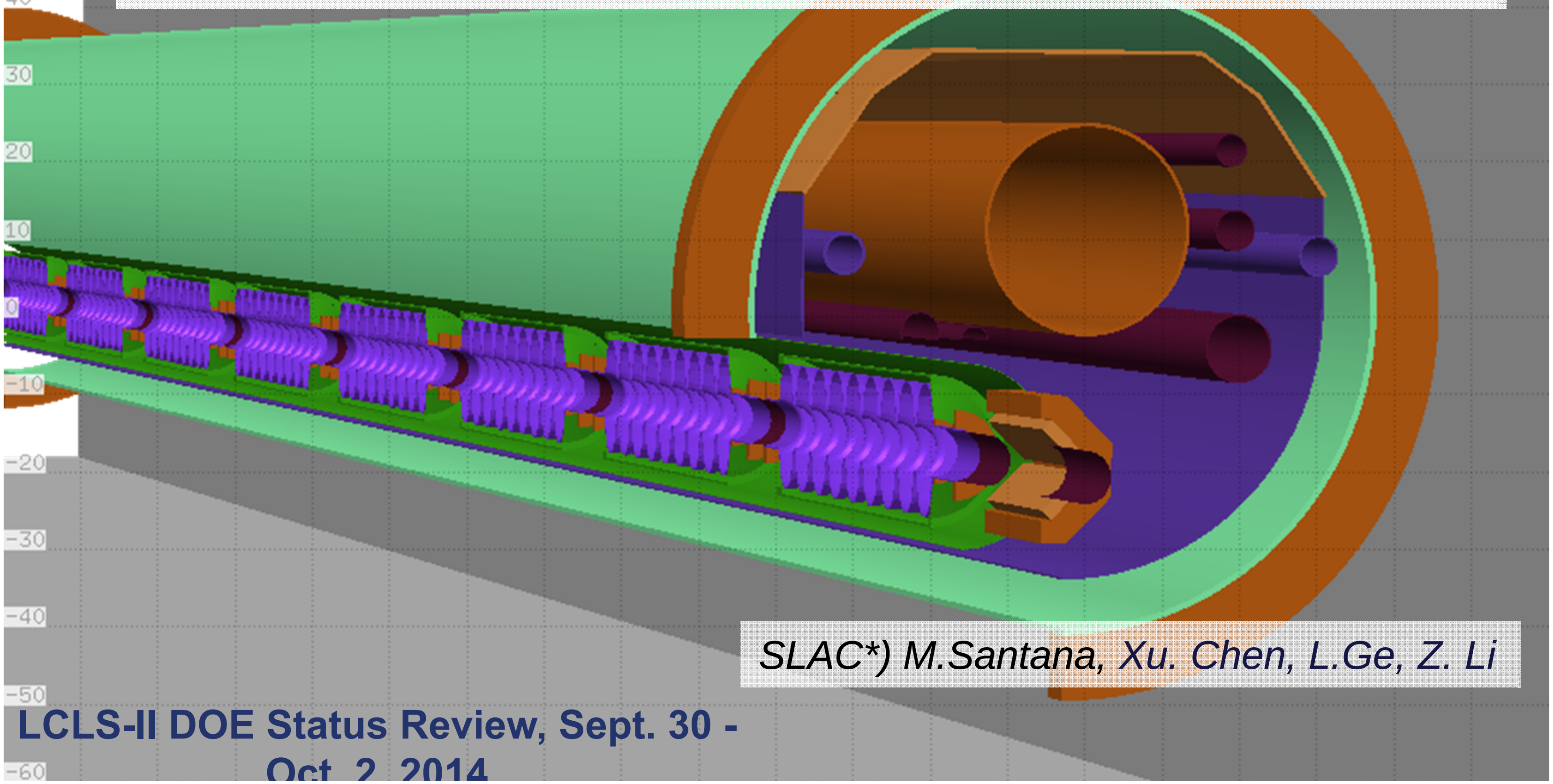
average is slightly too low due to the frequency detuning in llrf feed forward mode; the above fit might be better

LCLS-II: Radiation in SRF Linac (FLUKA)

Dark current and radiation studies, e.g. [Studies of electromagnetic cascade showers development in the TESLA main linac initiated by electron field emission in RF cavities](#) (TESLA-report 2003-10)

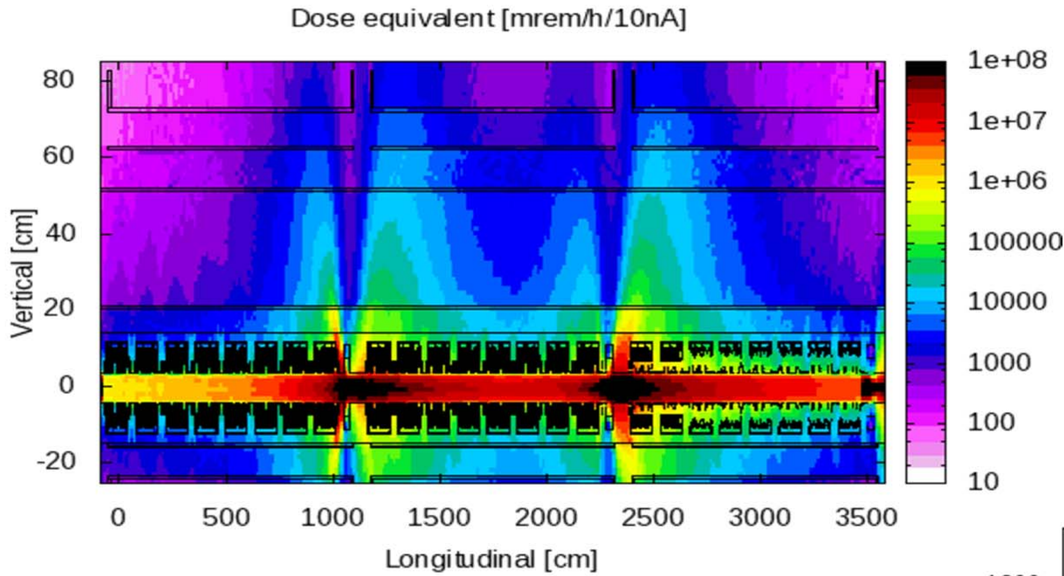
Recent re-evaluation of radiation studies for LCLS-II project (CW SCRF linac)

- Field emission simulated with Track3P*
- RP simulates transport from cavities through quadrupoles and CM's to define:
  - **Rad leakage to klystron gallery**
  - **Tunnel activation**
  - **Dose to components: Nb, quads, electronics**
  - **Dark current propagation?**
- Results (FLUKA) are normalized to the captured field emission(@16 MV/m) : **0.25-10 nA/CM**



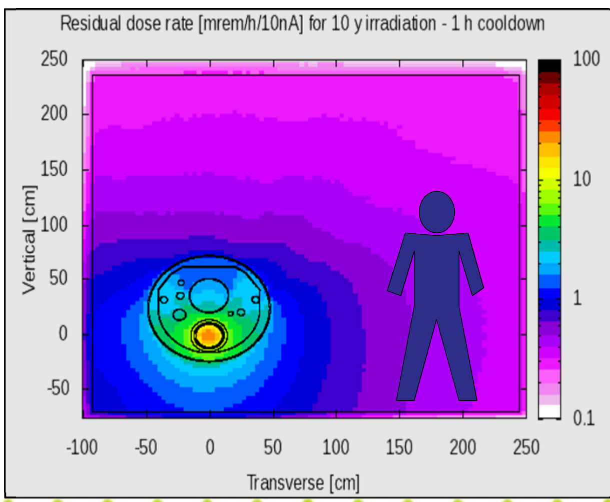
SLAC) M.Santana, Xu. Chen, L.Ge, Z. Li*

Radiation in SCRF LINAC\ dose to KG & components

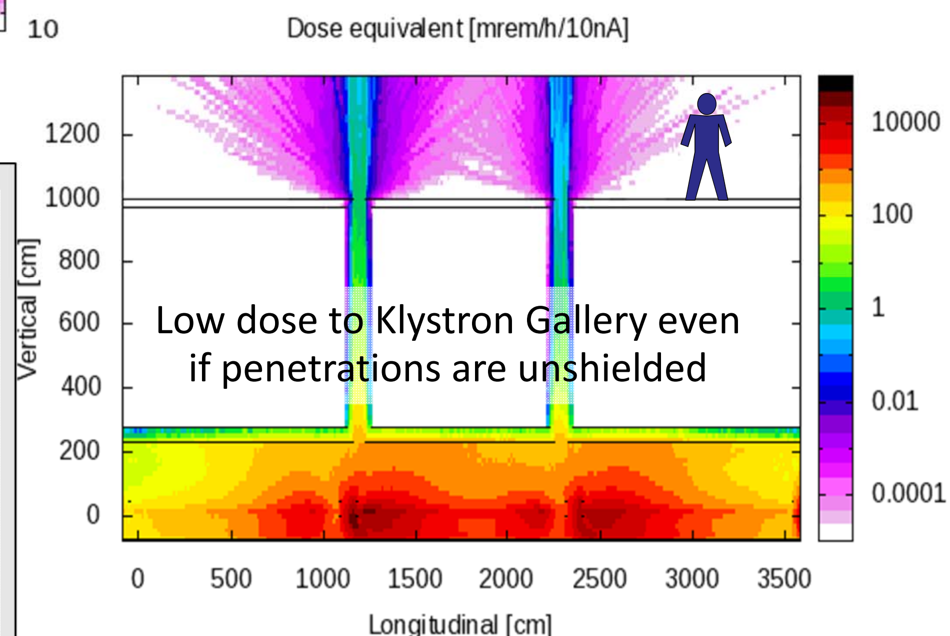


🡸 Potential high dose to components, e.g. quads @10 nA (reqs 50 times lower)

LCLS-II DOE Status Review, Sept. 30 - Oct. 2, 2014

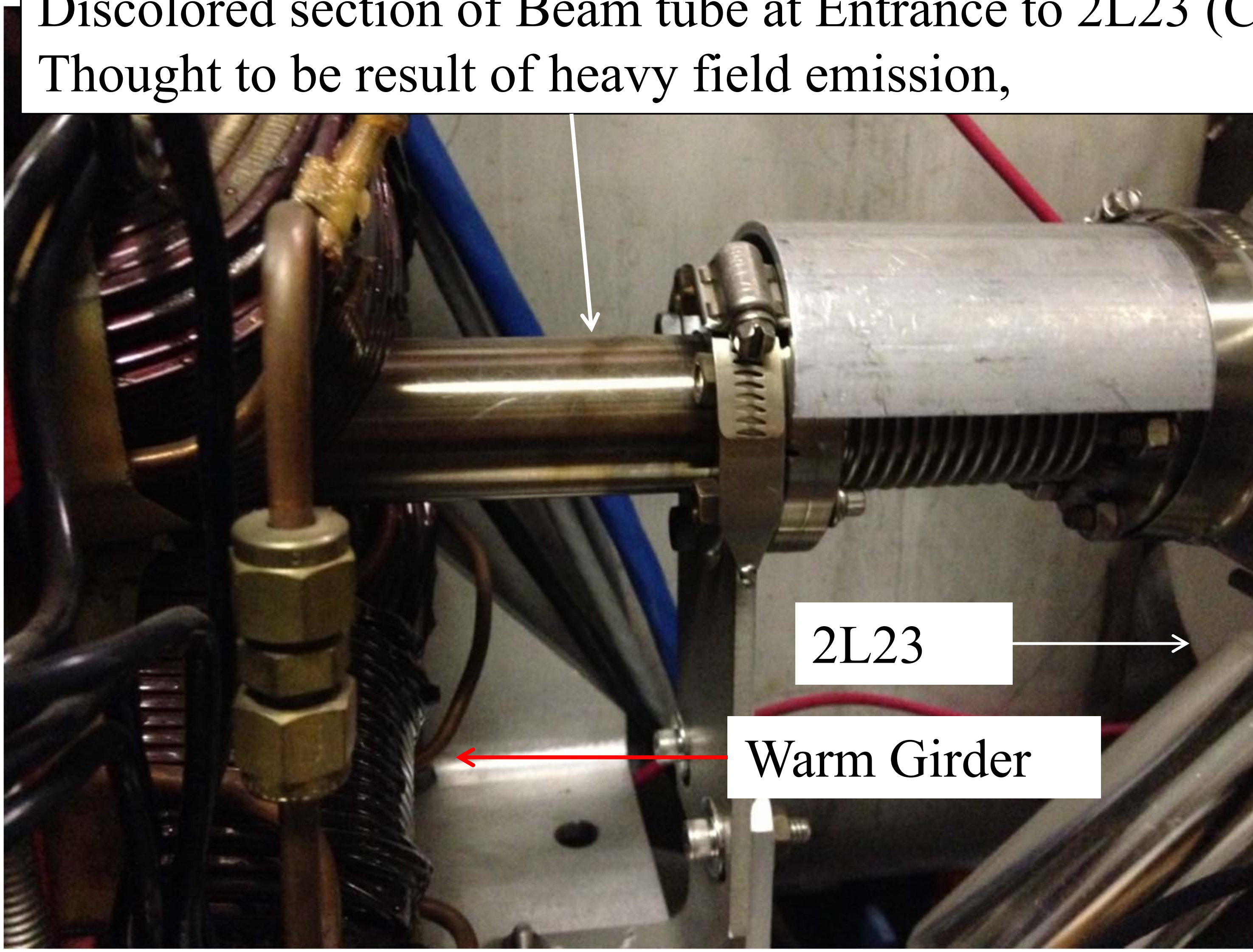


- Residual dose rates in the tunnel due to SCRF field emission seem low (< 1 mrem/h)
- First results suggest SCRF field emission does not pose an RP issue



FE Effect

Discolored section of Beam tube at Entrance to 2L23 (C100-5)
Thought to be result of heavy field emission,



DARK CURRENT REFERENCES

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Outline(3)

Machine Protection and Interlock Systems – Linear Machines

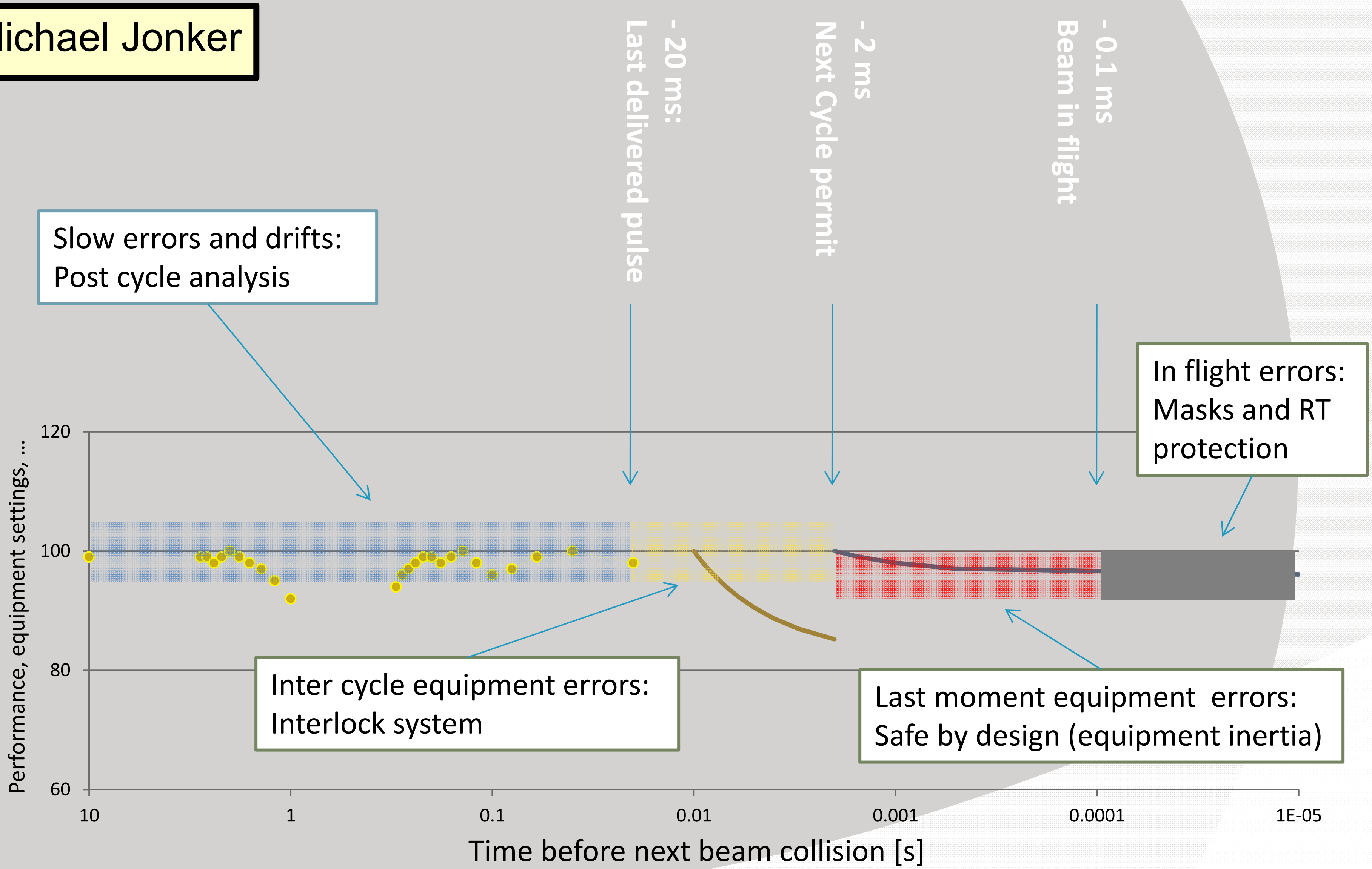
- **Linacs**
- **What protections are needed?**
- **Protection Systems:**
  - series of abort kickers and low power dumps,
  - a beam permit system / restart ramp sequence → operations
  - fault analysis recorder system,
  - a strategy for limiting the *rate-of-change* of magnetic fields and insertion device positions
  - a sequencing system that provides for the appropriate level of protection depending on machine mode or state
- **Recovery / Reliability- *Operations***

Linac Cycles:

- LCLS: CW 1 MHZ
  - Preferred; constant beam-surveillance
  - (But low power operation will be at much lower rates)
- SNS: 60 Hz with 1 ms macro pulses
- E-XFEL: 10 Hz with 1 ms macro pulse; ~10 MHz bunch-rate
  - Low power operation by reducing 10 MHz (factor 1e-4)
- ILC: 5 Hz with 1 ms macro pulse; 3 MHz bunch-rate
- CLIC: 100 Hz with 100 ns macro pulses; ~ 1GHz bunch-rate →

Machine Protection Timeline

Michael Jonker



Failure types and Protection strategies

Michael Jonker

Slow Failures

Time scale larger than the machine cycle period (10 ~ 20 ms) .

- Temperature drifts
- Alignment drifts
- Beam feedback saturations.

N.B.: Normally, the beam feedback system should keep drifts under control. Any deviation of the expected behaviour is potentially dangerous.

Inter-Cycle Failures

Time scale comparable to machine cycle period (10 ~ 20 ms).

- Power supply failures
- Positioning system failures
- Vacuum system failures

Last moment Equipment Failures

As above but to late for the Interlock system to react (< 2 ms)

Fast Failures

Time scale of beam flight time through the accelerator complex (*in flight < 0.2 ms*).

- RF breakdown: (transversal kicks...)
- Kicker misfiring: (damage to septum magnet).
- RF klystron trip. (disrupt beam, large losses)

N.B. the drive beam linac: 1.5 drive beam train in the pipeline: i.e. two orders above damage level.

Next Cycle Permit

Safe by construction

Post Cycle Analysis

Equipment Interlock

Static Protection

Next Cycle Permit

- Systematically **revoked after every cycle**
- **Re-established** if predefined beam and equipment **quality checks** have passed: ≈10 ~ 20 ms to analyse the previous cycle and to decide if OK for next cycle.

Static Protection

In flight failures:

- Difficult to detect beam failures and dump the misbehaving beam.
- Impossible for the head of the beam (causality, speed of light).

Passive protection: masks and spoilers.

Make passive protection robust enough to provide full protection for the whole pulse.

Many of the systems are already designed along this principle.

Locations (mostly associated with kickers)

- Extraction channels damping ring
- Extraction from combiner rings
- Drive Beam turn around

Protective masks. (Picture of an LHC Collimator)

4 ...

minal).

Decision time: 2 ms before next pulse

Protection/Interlock Systems:

- series of abort kickers and low power dumps,
- a beam permit system / restart ramp sequence → operations
- fault analysis recorder system,
- a strategy for limiting the *rate-of-change* of magnetic fields and insertion device positions
- a sequencing system that provides for the appropriate level of protection depending on machine mode or state

The MPS interlocks consists of:

1) a single bunch damage mitigation system,
2) an average beam loss limiting system,
3) a series of abort kickers and low power dumps,
4) a restart ramp sequence,
5) a beam permit system,
6) a fault analysis recorder system,
7) a strategy for limiting the rate with which magnetic fields (and insert-able device positions) can change,
8) a sequencing system that provides for the appropriate level of protection depending on machine mode or state, and
9) a protection collimator system.

Rapidly changing fields / devices – Slew rate limits and locks

- Some critical devices have fields (or positions) that can change *quickly*
  - during the pulse, or between pulses.
- Need:
  - 1) special controls protocols,
  - 2) redundancy or
  - 3) external stabilization and verification systems.
- *Depending on the state* of the machine
  - programmed (perhaps at a very low level) ramp rate limits
- Example: dipole magnet is not allowed to change its kick by more than a small fraction of the aperture between beam pulses
  - (full power operation)
- (may have an impact on the speed of beam based feedback)
- Some devices, such as collimators should be effectively frozen in position at the highest beam power level

Michael Jonker

Fast Failures

These failures occur at time scales corresponding to the

Critical, high power, high speed devices will need some level of redundancy in order to reduce the consequence of failure. For example the bunch compressor RF will have more than one klystron / modulator system powering a given cavity through a tee.

- RF breakdown. An RF breakdown could potentially produce enough transversal kick to send the drive beam or the main beam off trajectory into some accelerator component.
- Kicker misfiring. A misfiring of a kicker can send the beam off trajectory into the extraction channel (most critical element: the septum magnet).
- Klystron trip. A klystron trip in the drive beam linac

In the case of the extraction kicker, this will be done by having a sequence of independent power supplies and stripline magnets that have minimal common mode failure mechanisms.

Common mode failures

- **Timing and phase distribution system need specially engineered controls.**
- **Linac common phase cannot change drastically compared to some previously defined reference,**
  - even if commanded to do so by the controls, unless the system is in the benign – beam tune up mode.

some MPS ‘rules’ (starting from the hardest)

1. Critical component control through high level software should be 'keyed' through MPS modes, so that various controls are severely limited or disabled. Feedback must also be subject to these controls.
2. An assessment is needed to balance the beamline design and MPS response. e.g. it is foolish to place a large number of small apertures in the linac and then expect a omniscient MPS to keep them all happy and safe. This assessment must be made numerical for very expensive choices, like the one in the example.

3. parallel beam diagnostic and device monitoring MPS paths are needed.

some MPS ‘rules’ (2)

4. **Every attempt should be made to make individual components as robust as possible.**
5. **Device controller responsibilities should have as much responsibility as possible. This includes reporting field changes (even if requested) and OOT. This will have the effect of de-centralizing the MPS - see LHC abort kicker set-point monitor threshold controls**
6. **MPS itself must include routine test procedures, some with beam.**
7. **beam dynamics - related failures deserve additional consideration and controls. These are especially important for the DR.**
8. **generic design rules controlling rate/bunch number transitions, management of diagnostic bunches, integration.**