World-Wide Experience with SRF facilities

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Outline

- Maximum Gradients
- Operating Gradients
- Integrated Operating Experience
- SRF Survey
- Fast RF Trips
- Conclusion

Maximum Gradients

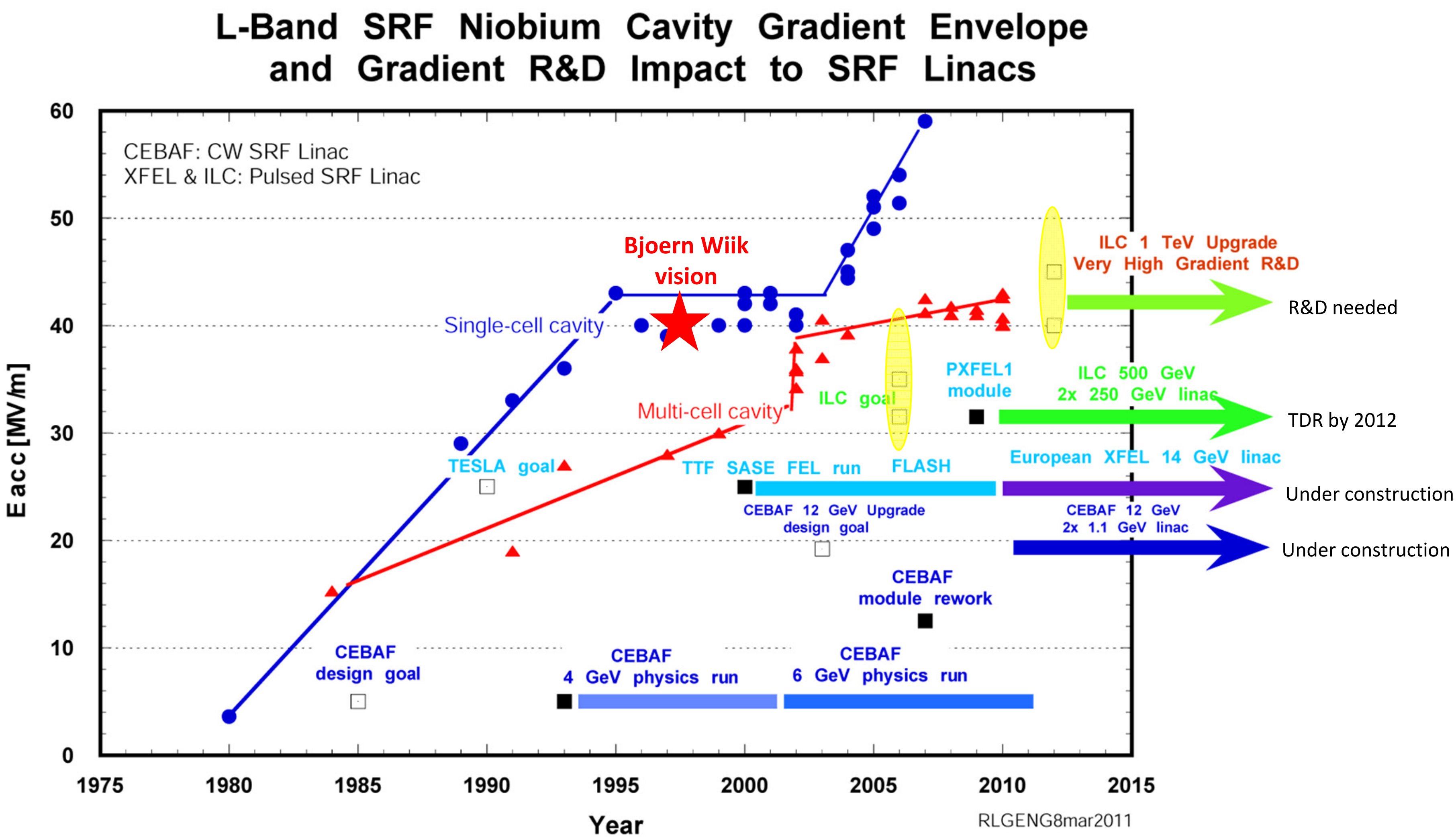
Introduction

- SRF has a long history
  - HEPL, Stanford in the sixties
    - ⮡ Plans for ILC
- There are two main areas of utilization
  - Linacs
    - CW for stable beams
    - Pulsed for maximum energy
  - Rings
    - High beam currents up to several Amps

Maximum Gradients

- Early cavities operated at a gradient of a few MV/m
  - Recent cavities produced for the International Linear Collider (ILC) are achieving 35 MV/m
- Limit of pure Niobium is probably around 50-60 MV/m
  - Depends on detailed cavity shape
- Other materials or thin films are under study
  - Not operational yet

SRF Cavity Gradient Progress



Steady progress in SRF cavity gradient makes SRF an enabling technology
SRF based electron linacs (CW & pulsed) have track record of successful operations

Courtesy Rong-Li Geng

Operating Gradients

Operating Gradients

- The optimum operating gradient is determined by:
  - Maximum capability of the cavity
  - Cryogenic load
  - Reliability demanded by the Users
- Linacs
  - Pulsed – ILC spec is **31.5 MV/m** average
  - CW – JLab 12 GeV Upgrade spec is **19 MV/m** average
    - Focus on minimizing duration of trips
- Rings – KEKB operates at around **4.5 MV/m**
  - Focus on minimizing frequency of trips

Linacs

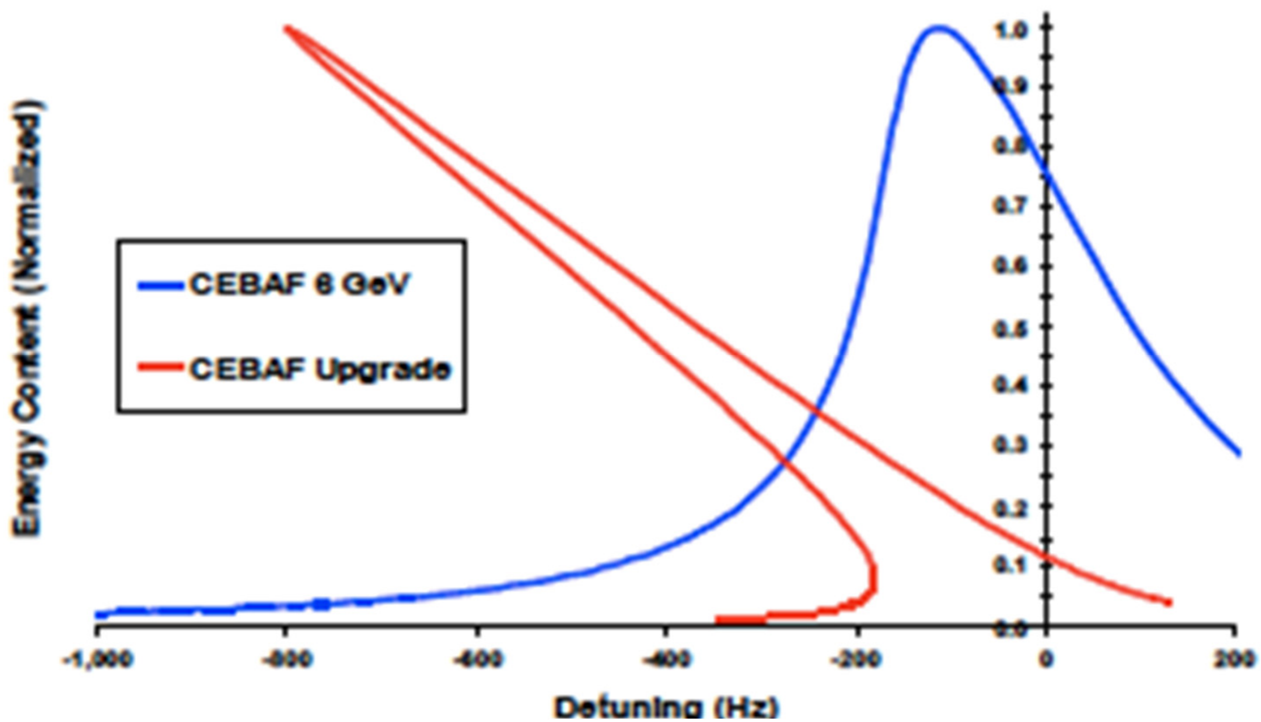
- Provide accelerated particles as an injector or for fixed target experiments
- Over-riding concern has been to increase gradient, often at the expense of availability
  - In CEBAF, the requirements of the experiments are to keep the RF trip rate below 15 per hour
    - Operating energy is adjusted accordingly
- CEBAF now operates with energy 50% above design
  - Maximizes physics experimentation

Pulsed versus CW Operation

- In Linacs, SRF cavities operate pulsed or CW
- Higher gradients can be achieved operationally in pulsed operation than in CW operation
  - Primarily driven by cryogenic capacity
    - Dynamic cryogenic losses proportional to gradient for a given maximum energy
  - SNS, FLASH, XFEL
- CW operation provides better beam stability
  - CEBAF, future light sources

Lorentz Detuning

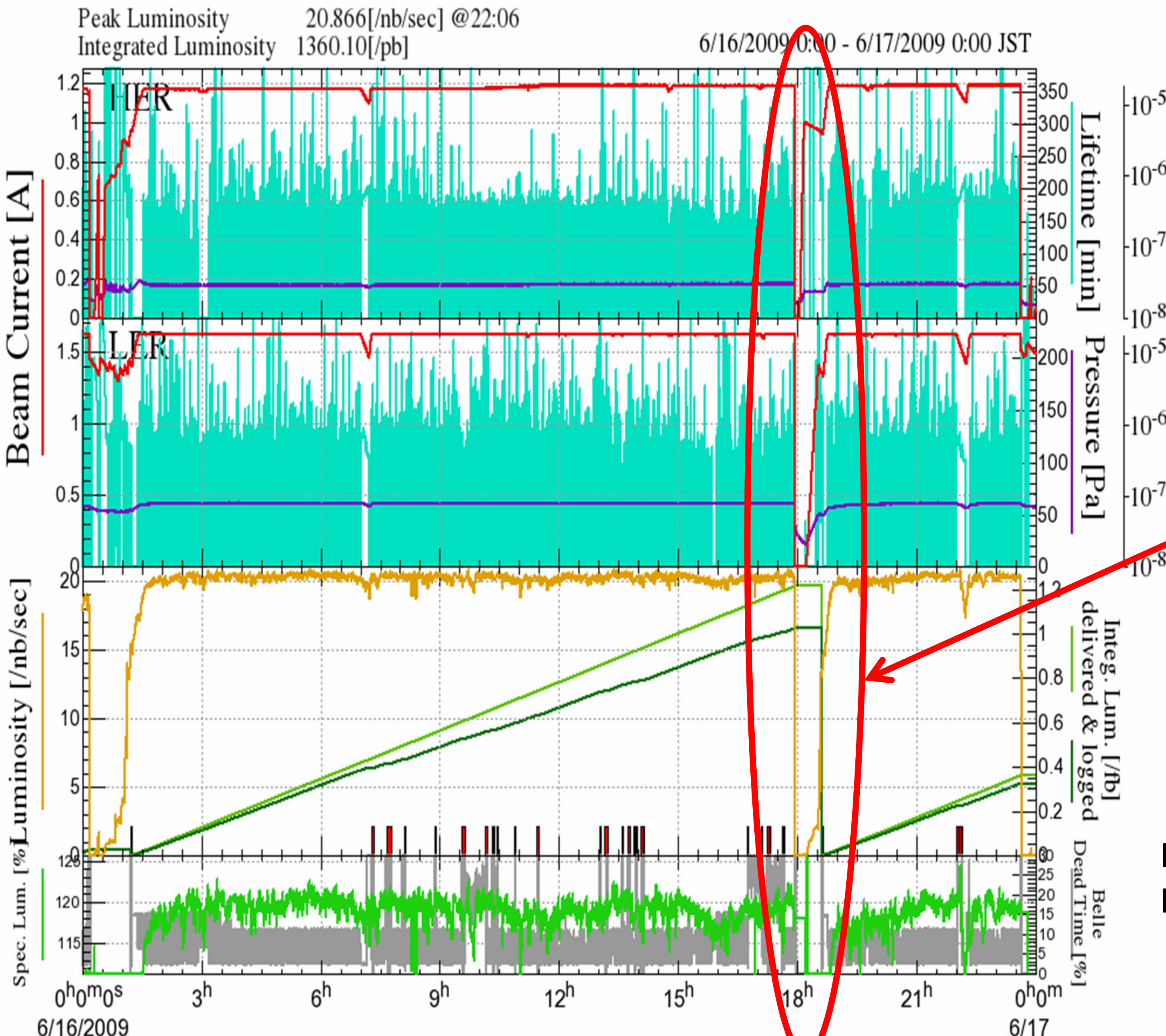
- Gradients in SRF cavities are now so high that Lorenz detuning is a real problem
  - Control algorithms become complicated
    - Pulsed operation requires feed-forward



Rings

- Modern storage rings, operate in top-up mode
  - Both colliding beam experiments and synchrotron light sources
  - Continuous injection maintains beam current constant
    - Must avoid losing the stored beam
- RF trip leads to a loss of the stored beam
  - Refilling the stored beam leads to a significant loss of operating time
  - Optimum average operating gradient is lower than in Linacs to keep the trip rate at an acceptable level

KEK One Day Data



Impact of trip

Plot courtesy of
Katsunori Akai, KEK

Integrated Operating Experience

Operating Experience

- Define a unit – the Cryomodule Century (CC)
  - Ten cryomodules operating for a decade, or 50 of them operating for two years, yield 1 CC

- Total world's integrated SRF operating experience in the world is about **20 CC**

Integrated Operating Experience

Facility	Cryomodule Centuries
ATLAS at ANL	3
CEBAF at JLab	6
CESR at Cornell	1
FLASH/TTF at DESY	1
HERA at DESY	1
KEKB at KEK	1
LEP-II at CERN	4
Tristan at KEK	1
TOTAL	**~20**

Future Operations

- The XFEL at DESY will accumulate 10 CC in the first decade of operation
  - Half the total experience to date
  - Similar to what JLab will have accumulated by then
    - Present experience is valid
- ILC will accumulate 186 CC in the first decade
  - Order of magnitude greater than present experience
  - Need to extrapolate present experience to plan ILC

SRF Survey

SRF Survey

- In preparation for this paper, an SRF Survey was prepared to gather information on the current state of worldwide SRF technology use
- The primary focus of the survey was on the availability and reliability of the main SRF technology
  - SRF cavities and cryomodules
  - Supporting technologies
    - Cryogenics, RF, vacuum, protection systems
- Secondary focus was performance and pervasiveness of SRF technology

SRF Survey

- The survey was split into two separate questionnaires, one brief and one in-depth
- The brief questionnaire was designed to assess the use of SRF technology in laboratories around the world
- The in-depth questionnaire focused on:
  - Number of cryomodules
  - Installation date
  - Particles accelerated
  - Performance information
  - Reliability information

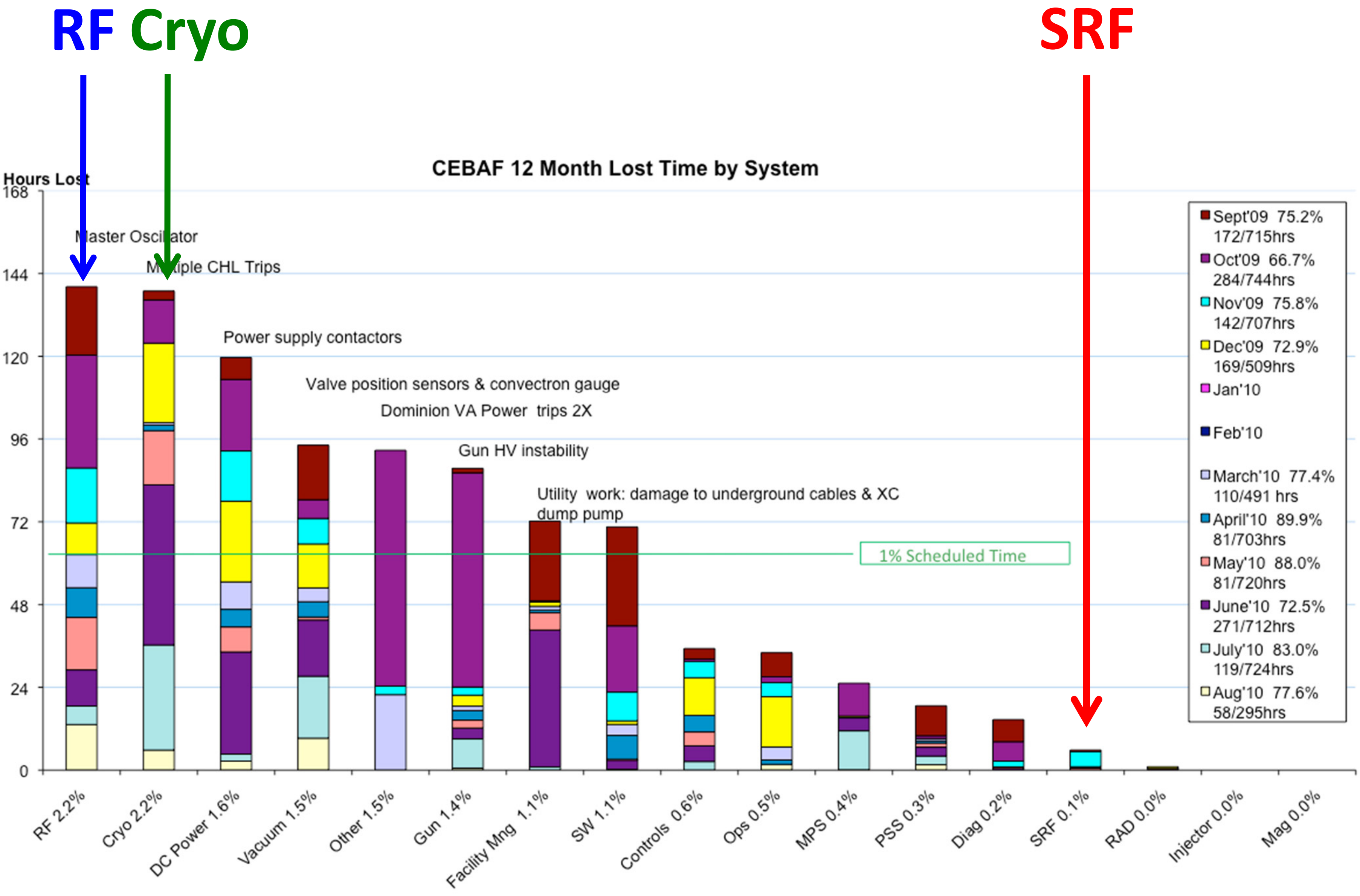
Survey Responses

Number of Surveys sent out	**67**
Number of Responses Received	22
Number of Laboratories not using SRF	16
Number of laboratories using SRF	4
Number of laboratories planning to use SRF	2

SRF Availability

- Downtime from SRF <u>and support systems</u> was compared to operating time
  - Average downtime was 3.7%
  - Highest downtime was CEBAF 7.5%
- Downtime appears to scale with number of cavities
  - CEBAF 338
  - SNS 80
  - CESR 4
- Downtime primarily from support systems
  - SRF cavities and cryomodules a small fraction

CEBAF Downtime from All Sources



Common Issues with Support Systems

- High-voltage modulators that supply power
  - Results in downtimes from <1 hour to <1 week
- RF control instabilities
- Vacuum valve and pump failures
- Cryogenics issues
  - Failed turbines
  - Unstable cryogenic liquid levels
- Fast shut down or protection interlock trips

Future Reliability Direction

- Focus on improving support systems will increase reliability more than the total time lost due to failures with the cavities and cryomodules
  - Will be the next major push to improve reliability of SRF based accelerators
- Survey still open at at https://cebaf.jlab.org/srf-survey/main_survey
- Results, including raw data, available at https://cebaf.jlab.org/srf-survey/home

Fast RF Trips

Requirements for ADS

Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production

White Paper Working Group Report

- A Table of trip requirements for an ADS accelerator was produced by the Working Group for this White Paper

Trip Requirements for ADS

	Transmutation Demonstration	Industrial Scale Transmutation	Industrial Scale Power Generation with Energy Storage	Industrial Scale Power Generation without Energy Storage
Beam Power	1-2 MW	10-75 MW	10-75 MW	10-75 MW
Beam Energy	0.5-3 GeV	1-2 GeV	1-2 GeV	1-2 GeV
Beam Time Structure	CW/pulsed (?)	CW	CW	CW
Beam trips (t < 1 sec)	N/A	< 25000/year	<25000/year	<25000/year
Beam trips (1 < t < 10 sec)	< 2500/year	< 2500/year	<2500/year	<2500/year
Beam trips (10 s < t < 5 min)	< 2500/year	< 2500/year	< 2500/year	< 250/year
Beam trips (t > 5 min)	< 50/year	< 50/year	< 50/year	< 3/year
Availability	> 50%	> 70%	> 80%	> 85%

Initial requirement per cryomodule per year is 100 trips< 10 seconds, 100 trips <5 minutes, 2 per year >5 min

Fast Shut-Down Systems at CEBAF

- CEBAF has a complex Machine Protection System (MPS) to protect the SRF cavities during operation
  - All other SRF installations have similar systems
- The MPS includes a suite of automated Fast Shut Down (FSD) procedures
  - Designed to detect the presence of an arc
  - Remove RF power and the electron beam before the cavity is damaged
    - Both of these sources can supply enough energy to the cavity to maintain an arc indefinitely

CEBAF RF Trip Analysis

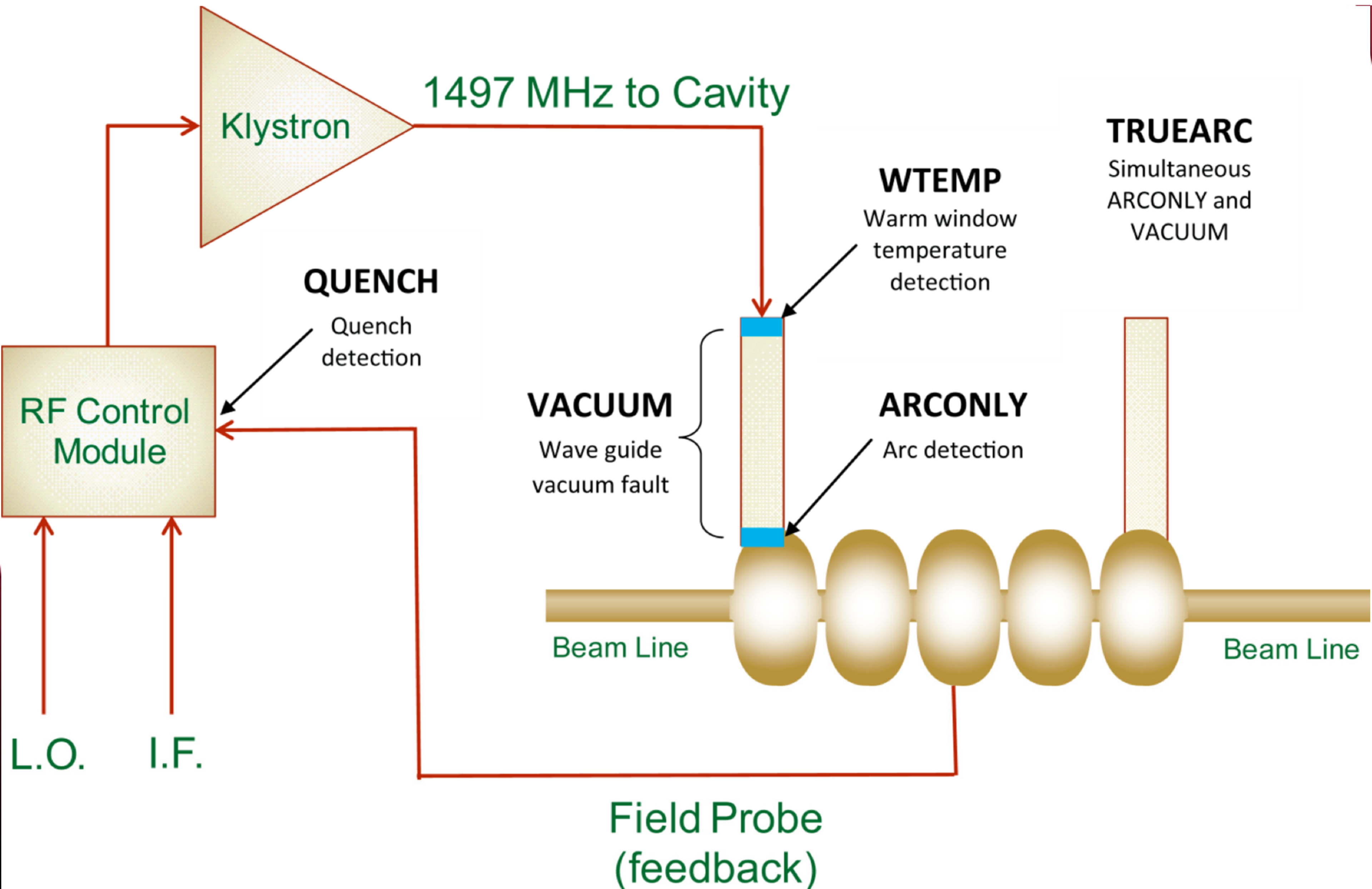
- FSDs evaluated for a one-year period from August 2009 to September 2010.
- CEBAF was operating with:
  - **29** of the original C-20 cryomodules
    - Designed for a total acceleration of 20 MV each
  - **9** C-50 cryomodules producing 50 MV each
    - Original cryomodules that were reworked to:
      - Increase the average accelerating gradient
      - Modify the input power waveguides to prevent field-emitted electrons from hitting RF window

Total FSD Trip Rate

- CEBAF was operating at 50% above design (6 GeV)
- C-20 cryomodules had an average gradient of 9.4 MV/m
  - Average trip rate: **516.3** per cryomodule per year
- C-50 cryomodules operate at around 12.1 MV/m
  - Average trip rate: **579** per cryomodule per year
- Difference is not statistically significant
- Operationally, gradients evolved to equalize FSD trip rates

Compare to ADS requirement of <100 per cryomodule per year

FSD Schematic



FSD Inputs

- **ARCONLY** faults – signal from a photodiode, to detect an arc flash at the cryomodule window
- **WTEMP** faults – increase in cryomodule window temperature
- **QUENCH** faults - sudden change in field in the SRF cavities implying a loss of superconductivity
- **VACUUM** faults - pressure increase in the RF waveguide
- **TRUEARC** faults are those that have triggered both ARCONLY and VACUUM faults simultaneously
  - Two independent systems – real arc
    - But others may be real arcs too!

Summary of RF Trip Data

	C-20	C-50
Total	516.3	579.0
TRUEARC	278.4	24.8
VACUUM	66.4	166.0
ARCONLY	81.75	20.0
QUENCH	100.71	359.9
WTEMP	16.2	17.1

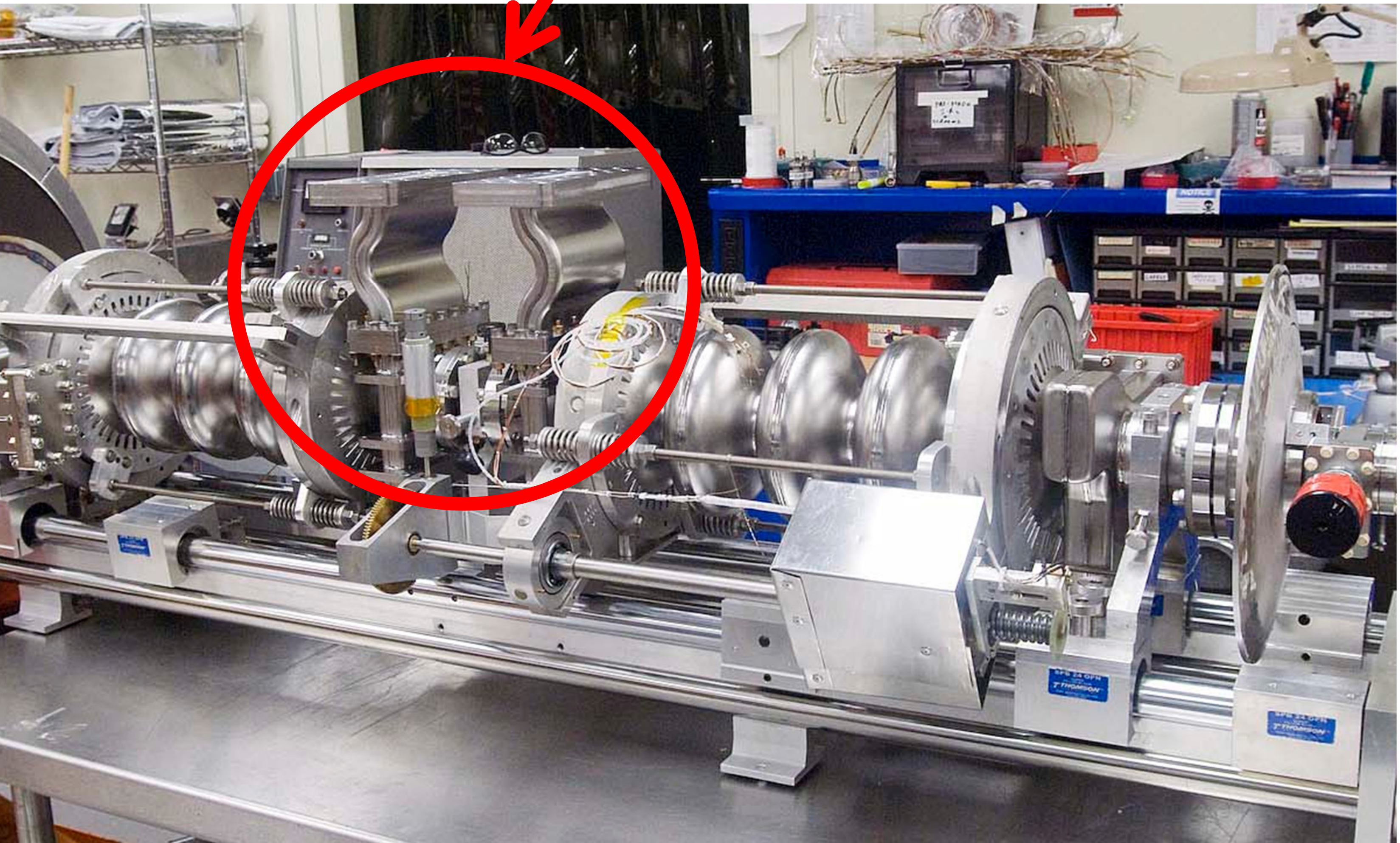
Arc Trips

- **TRUEARC** faults were significantly lower in C-50 cyomodules compared to C-20 cryomodules
  - C-20 **278.3** trips per cryomodule per year
  - C-50 **24.8** trips per cryomodule per year
- This was due to the addition of a “dogleg to prevent electrons emitted in the cavity from striking the waveguide window
  - Modification was successful!

Compare to ADS requirement of <100 per cryomodule per year

C-50 Waveguide Modification

"Dogleg" prevents field emitted electrons from hitting the waveguide window



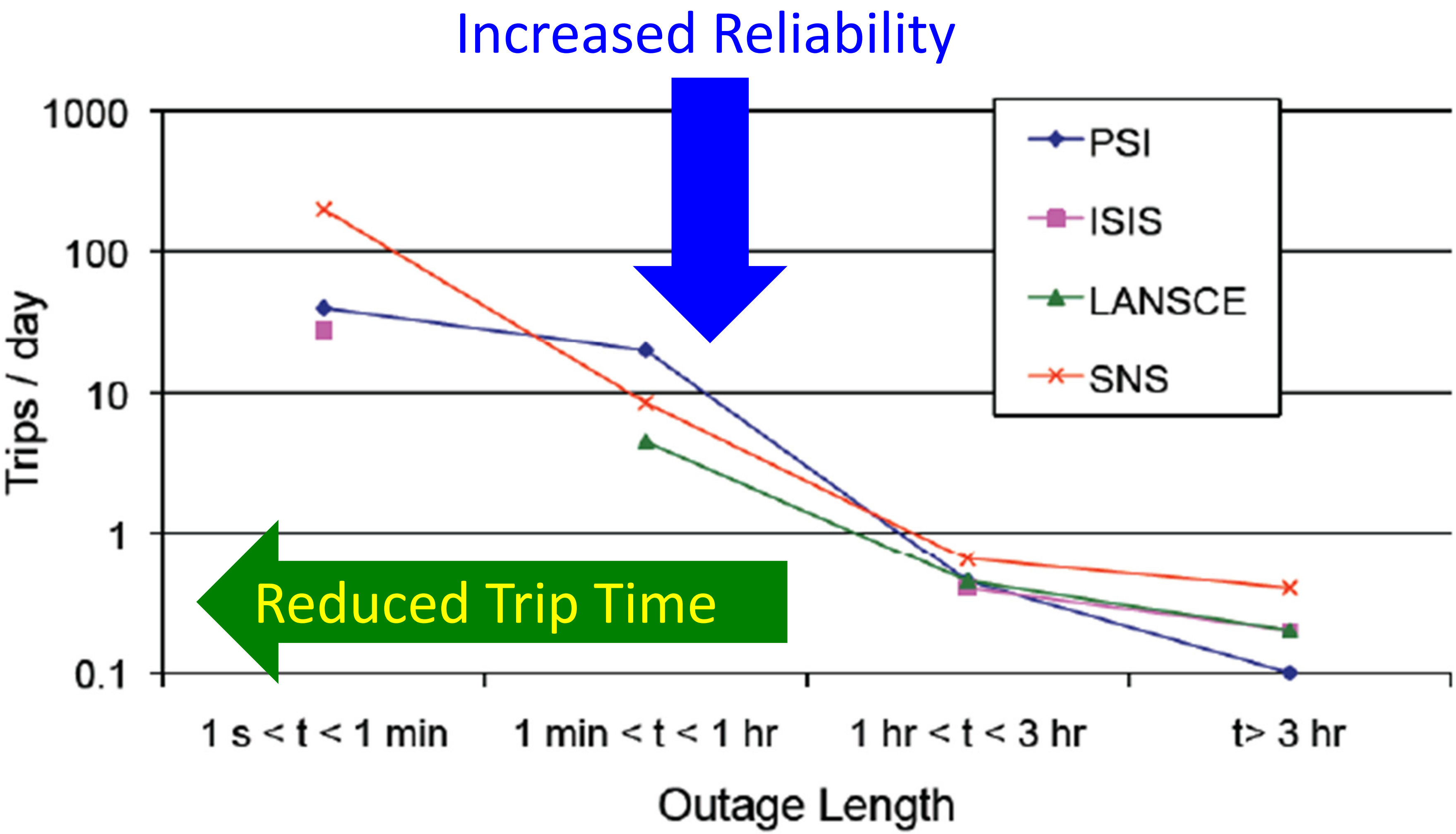
Quench Faults

- **QUENCH** faults account for **20.0** percent of all **C-20** trips and **62.2** percent of all **C-50** trips
- Maximum cavity gradient is limited to 1 MV/m below the gradient at which each cavity quenches, as recorded during commissioning,
  - It is unlikely that they are real quenches
- Increased QUENCH faults are likely due to the greater stress placed on the RF power sources of the C-50 cryomodules
  - QUENCH faults will be targeted for future reliability and performance enhancements

Vacuum and Waveguide Temperature Faults

- **VACUUM** faults account for **13.2** percent of all C-20 trips and **28.7** percent of all C-50 trips
  - The increased VACUUM faults are a mystery
  - The implication is that some new behavior may be present, e.g.
    - Arcing in the cavity where the arc sensor is blind
    - Erroneous readings (unlikely to be so widespread)
    - Something else?
- **WTEMP** faults remained relatively constant and represent only a minor amount of all faults

Trip Frequency for Proton Accelerators



J. Galambos, T. Koseki and M. Seidel, Proc. 2008 ICFA Workshop on High-Intensity High-Brightness Hadron Beams (HB2008), p. 489

Conclusions 1

- SRF has become a widespread technology
- Future projects that will use SRF include
  - 12 GeV Upgrade at JLab (under construction)
  - FRIB at MSU
  - Project X at Fermilab
  - SNS Power Upgrade Project at ORNL
  - SuperKEKB at KEK (under construction)
  - XFEL at DESY (under construction)
  - European Spallation Source at Lund
  - ILC
  - ADS accelerators?

Conclusions

- The operating experience that has already been accumulated is invaluable to help plan future projects
- Problem areas will be different
  - We will fix the things we know
  - We will find new limitations!
- Availability and trip rates can be reduced to acceptable levels if the requirement is sufficiently strong
  - Ring experience supports this
- New projects should plan on replacing ~1-2% of accelerating gradient each year of operation

A big thank you to everyone who filled in the Survey

It's not too late if you haven't!