





## LLRF system for the Fermilab PIP-II Superconducting LINAC

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PIP-II is a partnership of:

US-DOE
India-DAE
Italy-INFN
UK-STFC-UKRI
France-CEA, CNRS/IN2P3
Poland-WUST, WUT, TUL



## Outline

- 1. PIP2-LINAC Accelerator Components
- 2. Physics Requirements LLRF Specifications
- 3. LLRF Systems
  - a) RFQ
  - b) Bunchers 1-4
  - c) HWR Cryomodule
  - d) SSR1 Cryomodule
  - e) HB650 Cryomodule
- 3. LLRF Testing at CMTF and STC
- 4. EPICS User Interface
- 5. Results and system performance



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## **Fermilab Accelerator Complex**



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## **PIP-II** Superconducting RF CW Linac, 800 MeV Consists of



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#### **PIP2-IT Accelerator Components**



lon Source RFQ, B1 VXI Crate 2 MFC cards Buncher2,3 1 SOCMFC Chassis

HWR 4 SOCMFC Chassis 1 Tuner Signal Cond Module

SSR1 4 SOCMFC Chassis 2 Resonance Control Chassis

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#### **PIP2 LLRF Systems**

| CM<br>type | Cavities<br>per CM | Number<br>of CMs | CM config-<br>uration <sup>+</sup> | CM length<br>(m) | $Q_0 \text{ at } 2 \text{K} \ (10^{10})$ | Surface resistance, $(n\Omega)$ | Loaded $Q^{\triangle}$<br>(10 <sup>6</sup> ) |
|------------|--------------------|------------------|------------------------------------|------------------|--|---------------------------------|--|
| HWR        | 8                  | 1                | 8×(sc)                             | 5.93             | 0.5                                      | 9.6 (2.75 <sup>†</sup> )        | 2.32   |
| SSR1       | 8                  | 2                | 4×(csc)                            | 5.53             | 0.6                                      | 14 (10 <sup>‡</sup> )           | 3.02   |
| SSR2       | 5                  | 7                | SCCSCCSC                           | 6.3*             | 0.8                                      | 14.4                            | 5.05   |
| LB650      | 4                  | 9                | cccc                               | 5.52*            | 2.15                                     | 9.0                             | 10.36  |
| HB650      | 6                  | 4                | cccccc                             | 9.92*            | 3  | 8.7                             | 9.92   |

|           | Station | Total |
|-----------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|-------|
|           | 1       | 2       | 3       | 4       | 5       | 6       | 7       | 8       | 9       | 10      | 11      |       |
|           | RFQ,    | HWR     | SSR1-   | SSR2-   | SSR2-   | SSR2-   | LB650-  | LB650-  | LB650-  | HB650-  | HB650-  |       |
|           | B1-4    |         | 1,2     | 1,2,3   | 4,5     | 6,7     | 1,2,3   | 4,5,6   | 7,8,9   | 1,2     | 3,4     |       |
| Number of | 6       | 8       | 16      | 15      | 10      | 10      | 12      | 12      | 12      | 12      | 12      | 125   |
| cavities  |         |         |         |         |         |         |         |         |         |         |         |       |
| RF Freq   | 162.5   | 162.5   | 325     | 325     | 325     | 325     | 650     | 650     | 650     | 650     | 650     |       |
| (MHz)     |         |         |         |         |         |         |         |         |         |         |         |       |



S4-S11 – SSR2 (7), LB650 (9), HB650 (4)

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## 4-cavity LLRF Station Rack – Components 1





8-Channel Downconverter

4-Channel Upconverter

UC/DC Power Supply

LLRF Controller

LLRF Controller

**Resonance Controller** 

**RCC Power Supply** 

LBL-Marble RFS Xilinx – Kintex





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**PIP-II LLRF System** 

**FNAL- LLRF Controller** 

Intel – Arria10 SOC

## **4-cavity LLRF Station Rack – Components 2**

JLAB/FNAL

(Marble FPGA) Xilinx – Kintex



#### 1320 MHz Clock Distribution

LO Distribution

**Reference Distribution** 

**Dual Temperature Controller** 

8-Channel Downconverter

8-Channel Downconverter

4-Channel Upconverter

UC/DC Power Supply

LLRF Controller

LLRF Controller

**Resonance Controller** 

**RCC Power Supply** 

**Resonance Controller** 



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## **PIP2 4-Cavity RF Station**



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Cavity3,4 Detuning (Fiber)



## LLRF System Architecture 1 - Amp/Phs Control



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#### **SEL System Architecture**



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## LLRF System Architecture 2 – I/Q Control



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## **Resonance Controller Architecture**

Resonance Controller FPGA Block Diagram



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## **Resonance Control Processing**





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## **HWR LLRF System with Pneumatic Tuner Control**





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#### **HWR Resonance Control Design**

em: sys6d juency (Hz): 0.0748

10-1

8-1440

e -2880 -4320



**Physical Model** 



#### **Controller Implementation**





#### **Control System Simulation**

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## **HWR Control Performance**

| HWR Amplite                      | ude and   | Phase Re  | egulatio  | n         |           |
|----------------------------------|-----------|-----------|-----------|-----------|-----------|
|                                  | Cavity4   | Cavity5   | Cavity6   | Cavity7   | Cavity8   |
| Cavity Field Setpoint (MV/m)     | 2.89      | 6.04      | 8.94      | 8.5       | 8         |
| Amplitude Regulation (rms) %     | 0.0135    | 0.0106    | 0.0101    | 0.0081    | 0.0103    |
| Phase Regulation (rms) deg       | 0.0228    | 0.0065    | 0.0056    | 0.0055    | 0.0062    |
| Feedback Proportional Gain       | 1000      | 1000      | 1000      | 1000      | 1000      |
| Feedback Integral Gain (rad/sec) | 1,000,000 | 1,000,000 | 1,000,000 | 1,000,000 | 1,000,000 |





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#### **PIP-II Specifications**

- Energy Stability(Linac) < 0.01%
- Amplitude Regulation(individual cavity) < 0.06 rms %
- Phase Regulation
- Maximum detuning

< 20 Hz

< 0.06 rms deg



## **RF Cavity Parameters and Feedback Gains**

| Cavity Type          | $Q_L$              | $f_0$ | $f_H$              | $K_P$ |
|----------------------|--------------------|-------|--------------------|-------|
|                      |                    | (MHz) | (Hz)               |       |
| Warm Cavity          | 3000               | 53    | $8.83	imes10^3$    | 15    |
| $\operatorname{RFQ}$ | 15000              | 162.5 | $5.542 	imes 10^3$ | 23    |
| Buncher Cavity       | 10000              | 162.5 | $8.125 	imes 10^3$ | 16    |
| HWR Cavity           | $2.32 \times 10^6$ | 162.5 | 35                 | 3548  |
| SSR1 Cavity          | $3.02 	imes 10^6$  | 325   | 53.8               | 2317  |
| SSR2 Cavity          | $5.05 	imes 10^6$  | 325   | 32.2               | 3846  |
| LB650 Cavity         | $10.36 	imes 10^6$ | 650   | 31.4               | 3935  |
| HB650 Cavity         | $9.92 	imes 10^6$  | 650   | 32.76              | 3801  |
| LCLSII Cavity        | $4 	imes 10^7$     | 1300  | 16.25              | 7600  |

Maximum Feedback Gains computed for Stability with a 45 degree phase Margin with 1 us Loop delay



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## **SSR1 LLRF System with Piezo Tuner Control**



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## **SSR1 Cryomodule Testing**

|                                  | SSR       | 1 Amplitud | de and Pha | se Regula | tion      |           |           |           |
|----------------------------------|-----------|------------|------------|-----------|-----------|-----------|-----------|-----------|
|                                  | Cavity1   | Cavity2    | Cavity3    | Cavity4   | Cavity5   | Cavity6   | Cavity7   | Cavity8   |
|                                  |           |            |            |           |           |           |           |           |
| Cavity Field Setpoint (MV/m)     | 4.88      | 4.63       | 4.78       | 7.32      | 7.8       | 7.56      | 7.32      | 10        |
| Amplitude Regulation (rms) %     | 0.0194    | 0.0289     | 0.0219     | 0.0157    | 0.014     | 0.0158    | 0.0147    | 0.0124    |
| Phase Regulation (rms) deg       | 0.0116    | 0.0164     | 0.0118     | 0.0091    | 0.0088    | 0.0093    | 0.0092    | 0.0076    |
| Feedback Proportional Gain       | 1600      | 1600       | 1600       | 1600      | 1600      | 1600      | 1600      | 1600      |
| Feedback Integral Gain (rad/sec) | 3,000,000 | 3,000,000  | 3,000,000  | 3,000,000 | 3,000,000 | 3,000,000 | 3,000,000 | 3,000,000 |



#### **RF Detune Calibration**



$$\begin{split} \ddot{\mathbf{V}}(t) &+ \frac{\omega_0}{Q_L} \dot{\mathbf{V}}(t) + \omega_0^2 \mathbf{V}(t) = \frac{\omega_0 R_L}{Q_L} \dot{\mathbf{I}}(t) \\ &\frac{d\vec{V}}{dt} = (-\omega_{1/2} + j\Delta\omega)\vec{V} + R_L \omega_{1/2}\vec{I} \\ &\frac{d\vec{V}}{dt} = a\vec{V} + b\vec{K}_1 \\ &a = \frac{1}{\vec{M}_V} \cdot \left[\frac{d\vec{M}_V}{dt} - \beta\vec{M}_K\right] \end{split}$$

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- The cavity is operated in pulse mode with a cavity field ~ 1/2 FS magnitude and the cavity probe and forward waveforms are recorded.
- Numerical analysis of the acquired data provides cavity parameters such as half bandwidth and the detuning constants



#### **Cavity Quench Detection/ Overdrive Protection**



- Quench Detection is based on computing the dissipated power in the cavity. The dissipated power is compared against a threshold for quench detection
- RF overdrive is detected when the controller output saturation persists beyond a specified time (~ 1 sec)

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## HB650 and LB650 Cavity Testing at STC

- HB650, beta=0.9, B9A-AES-001
- January-March 2020
- STC commissioning for 650 MHz operations
- Prototype coupler/tuner validation/testing
- Prototype cavity characterization



• HB650, beta=0.92, **B92D-RRCAT-502** 

HB650 B92D-RRCAT-502

- October-November 2021
- Prototype coupler/tuner validation/testing
- Prototype cavity characterization, qualification for prototype HB650 cryomodule assembly



- June-September 2022
- · Preproduction coupler/tuner testing
- · Prototype cavity characterization





Bare HB650 Cavity



LB650 Cavity on ANL EP stand

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## **LB650 Cavity Measurements**



4/5π Mode, 625 kHz





3/5π Mode, 2.125 MHz



Suppression with notch filters



LFD Coefficient = 2.4



#### **Detuning Spectrogram**

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### **HB650 Cavity Measurements**



#### GDR Mode 15 MV/m



Piezo Tuner Controls



#### **Tuner Waveforms**





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#### **Piezo Transfer Function**

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#### **Prototype HB650 Cryomodule Testing at CMTF**



#### pHB650 Cryomodule





#### 40 kW SSA

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**SSA** Calibration



#### SELAP Mode at 7 MV/m

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## **Prototype HB650 Cryomodule Testing at CMTF**





#### **Piezo Waveforms**

#### GDR Mode at 5MV/m

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#### **User Interfaces**

|  |  |  |  | • × • |
|--|--|--|--|-------|
| File Edit Operate Tools Window Help  | 15   |  |  | 2     |
| 🔿 @ 😑  |  |  |  | 1     |
| Waveform / Scalar / FFT Display Full Speed Waveform /FFT Disp  | olay   System Timing   Ql Analysis   Cavity C  | alculations Example MATLA8 scripts   | SSR1 LABVIEW BUILD: 10/14/20   | 20 ^  |
| Waterier     Calibration (PTD Day)     Data Specific Neutrino (PTD Day)       Days /s. However Neutrino (PTD Day)     Non-     Non-       Non-     Non-     Non-  | (a)     (b)     (b) <td>State     Experimentation       0     State     State       0     State     State</td> <td>Stot Linderwice AULD: 10:101       Hermit The Store Autom       Hermit The Store Autom       Store Autom       Difference Autom</td> <td></td> | State     Experimentation       0     State     State  | Stot Linderwice AULD: 10:101       Hermit The Store Autom       Hermit The Store Autom       Store Autom       Difference Autom |       |
| Terre Loo (a) 24/55 (Annahue) (a) 25/55 (c) 25 | Chiptry A Type Select<br>Workform Piot. ~~<br>ar Dicaply Range (nc)  | Time (u) 1/2/1/2/ Amplitude<br>Credy Sidelar "-Bu (AVVI) Constrained and the set office<br>(a) 2000 (a) 20 | ad bigling hypeds<br>rad between every<br>ty Sand 30.<br>Served Weederms<br>Sared Weederms   | sR1   |
| CLUERSSEL, MAD, Denksill, MAD, Andréa, JMAD, Andréa, JMAD, Parkell, S., MAD, Andréa, JMAD, Andréa, J | W0 (fear, frinin dat )   | HeACKE<br>Number of sendering spirits<br>Number of sendering (FG conscious exertisme)<br>Wordsom time set (FG collection<br>Certy to SR collection<br>Certy to SR collection<br>Field to applicate allocation<br>Field to applicate allocation<br>Field to applicate allocation<br>Field to applicate allocation   | Concey May Minimi<br>Concey May Minimi<br>Concey May Concey Caracy<br>Server Preser (1994)<br>For Preser (1994)   |       |

#### EPICS

#### Labview



| 🗙 РА РЗО | LLRF/H | IPRF Cont | rol <n< th=""><th>loSets</th><th>&gt;<dp< th=""><th>M-DP</th><th>M03 (1%):</th><th>•</th><th></th><th></th><th>-</th><th>-</th><th></th><th></th></dp<></th></n<> | loSets | > <dp< th=""><th>M-DP</th><th>M03 (1%):</th><th>•</th><th></th><th></th><th>-</th><th>-</th><th></th><th></th></dp<> | M-DP         | M03 (1%):       | •        |              |      | -          | -   |      |     |
|----------|--------|-----------|---|--------|--|--------------|-----------------|----------|--------------|------|------------|-----|------|-----|
| P30 SSR  | 1 CA\  | /ITY5 C   | ALIE  | BRAT   | IONS   |              | SE              | T        | D/A          | A7   | Com        | -U  | Pgm_ | Too |
|          | *5н•   | X-H/U     | X=  | TWF    |  | Y=Z          | NENUM           | , Z : NI | -UUI ,.      | 2:NX | MUHI,Z     |     | CHLC |     |
| COMMHNU  |        | Eng-U     | 1=  | ×.     |  | 1=           | ,               | , 20     | 07000,       | 250  | , ;        | 280 | 2000 |     |
| -<14>+   | r_eo   | HUTU      | F = 1   | . 1    |  | F= .         | 2009000         | , 20     | 19000,       | 200  |            | 200 | 9000 |     |
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| : DOWNC  | CMG    | CIER UH   | 0.101   | CON    |  | Mad          |                 |          |              |      |            |     | 0.1  |     |
| -P:335CD | CPU    |           | 00  | COV    | DC   | Diag         |                 | 27       |              |      | 1          |     |      |     |
| -P.33500 | CMG    |           | 05  | ELID   | DC   | Mad          | -               | -37      |              |      | 4          |     |      |     |
| -P:335FD | CMD    |           | CE  | FWD    | DC   | nag<br>Dhaei |                 | _97      | =            |      | т<br>97 Б  |     | ded  |     |
| -P:335FU | CMB    |           | CE  | DEV    | DC   | Mad          | 3               | -07      |              |      | 4          |     | 0-1  |     |
| -P:335RU | CDU    |           | 05  | DEV    |  | mag          | _               | 1 1 1    |              |      | 1<br>445 5 |     | dod  |     |
| D. SSORU | DCM    |           | 00  | DEE    | DC   | Mad          |                 | -110     |              |      | 4          |     |      |     |
| D. CODRF | DCP    |           | 00  | DEE    | DC   | Dhae         |                 | -        |              |      | ~          |     | ded  |     |
| LUNTT    |        | DATTON    | C0  | REF    | υC   | Filasi       |                 | 0        |              |      |            |     | ueg  |     |
| D. SSECS | TMV    | INTEL ON  |   | COV    | 801  | to           | 45.7            |          |              |      | 2 6000     | 000 |      |     |
| -P:33503 | TEO    |           | 0   | CAV    | 201  | to 1         | nv<br>Sant (UI) | 3.0      | 209999       | 9    | 3.0099:    | 999 |      |     |
| P: 55505 | EN     |           | 00  | COV    | 1.001  | - 4 lo -     | 5գու(ա)         |          | NE.          |      |            |     |      |     |
| -P:33500 | TEO    |           | CE  | ELID   | Sel  | g uni        | East (11)       | . 20     | 20<br>504    |      | 1 626      |     | 1.1  |     |
| -P:335F3 | 130    |           | 05  | DEV    | 301  | to :         | Sqrt(W)         | 1.0      | 20           |      | 1.020      |     |      |     |
| P:SSER   | 130    |           | CE  | Eno    | - Tm   | L 0 5        | syrt(w)         | _ 24     | 50<br>524000 |      | 26240      |     |      |     |
| -P:335F1 | 102    |           | 0   | Cou    | 4 11   | K UT<br>01   | r 10 H2         | 30       | 251333       | 9 -  | 400000     | 222 |      |     |
| -P:555CH | VQL    |           | 60  | Lav.   | Lug  | ωL           |                 | 400      | 000000       |      | 400000     |     |      |     |
| ! AVERA  | GING   | WINDOW    | IS !  |        |  |              |                 |          |              |      |            |     |      |     |
| P:SS5CA  | VST    |           | C5  | CAV    | Âv⊴  | Gat          | e Start         | 100      | 00           |      | 1000       |     | us   |     |
| P:SS5CA  | VWD    |           | C5  | CAV    | Ave  | Gat          | e ⊎idth         | 100      | 00           |      | 1000       |     | us   |     |
| -P:SS5FA | VST    |           | C5  | FWD    | Ave  | Gat          | e Start         | 100      | 00           |      |            |     | us   |     |
| -P:SS5FA | VWD    |           | C5  | FWD    | Ave  | Gat          | e Width         | 100      | 00           |      | 1000       |     | us   |     |
| -P:SS5RA | VST    |           | C5  | REV    | Ave  | Gat          | e Start         | 100      | 00           |      |            |     | us   |     |
| -P:SS5RA | VWD    |           | сs  | REV    | Ave  | Gat          | e Width         | 100      | 00           |      | 1000       |     | us   |     |
|          |        |           |   |        |  |              |                 |          |              |      |            |     |      |     |
| ! SCALA  | R REF  | DBACKS    |   |        |  |              |                 |          |              |      |            |     |      |     |
| P:SS5CA  | VMG    |           | C5  | CAV    | Mag  |              |                 |          |              |      | .00123     | 59  | MV/m |     |
| P:SS5CA  | VPH    |           | C5  | CAV    | Pha  | se           |                 |          |              |      | 10.024     | 592 | deg  |     |
| P:SS5CA  | VPP    |           | C5  | CAV    | Pro  | be P         | ω               |          |              |      |            |     | Watt |     |
| P:SS5FW  | MG     |           | C5  | FWD    | Pow  | Mag          |                 |          |              |      | . 00000    | 004 | kW   |     |
| P:SS5FW  | PH     |           | C5  | FWD    | Pow  | Pha          | зе              |          |              |      | 3.1749     | 376 | deg  |     |
| P:SS5RV  | MG     |           | С5  | REV    | Pow  | Mag          |                 |          |              |      | . 00000    | 006 | ĸω   |     |
| P:SS5RV  | PН     |           | C5  | REV    | Pow  | Pha          | зе              |          |              |      | 17.323     | 978 | deg  |     |
| P:SS5CA  | VET    |           | C5  | CAV    | Fre  | a Tr         | acking          |          |              |      | .72439     | 998 | Hz   |     |
| P:SS5RE  | SER    |           | C5  | Res    | onan   | ce Fr        | rea Err         | or       |              |      | 2          |     | Hz   |     |

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#### **Summary**

- PIP-II LLRF System is in the Final Design Review Stage
- The design is closely aligned with the LCLS-II LLRF system
- Various hardware/software components have been tested at PIP2-IT and STC
- The LLRF systems at PIP2-IT met the project requirements
- All the different cavity types(7) have been tested with the LLRF system
- Final design prototypes will continue to be tested at both facilities

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- The EPICS user interface has been used in the test stands
- The Final Design Review is expected in early 2024

# Thank You!

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## **RFQ and B1 LLRF System**









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#### **Beam Loading Compensation – B2**







RE<sub>2</sub>

LOW LEVEL RADIO FREQUENCY WORKSHOP 2023

023

PIP-II

ww

LLRF2023

OCTOBER 22-27, 2023 IN GYEONGJU, REPUBLIC OF KOREA

## $Q_L$ Measurement



**PIP-II LLRF System** 

#### HWR Cavity 5, *Q*<sub>*L*</sub> = 2.07e6



SSR1 Cavity 5, *Q*<sub>*L*</sub> = 4.11e6

