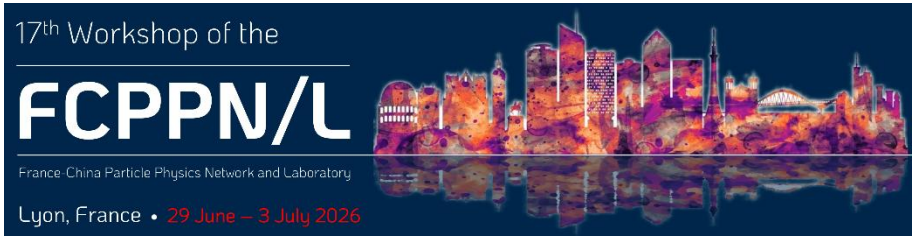


Development of the upgraded Belle II vertex detector

17th France–China Particle Physics Network/Laboratory Workshop
(FCPPN/L 2026)
June 29 – July 3, 2026, Lyon

Yunpeng Lu

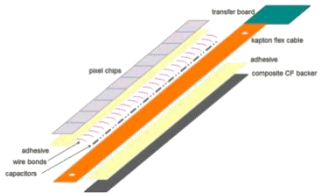
on behalf of the VTX development teams

Overview of collaboration

- Starting from 2010, common R&D efforts of MAPS for the e^+e^- collider experiments: ***BES III upgrade, ILC/CEPC, BELLE II upgrade***

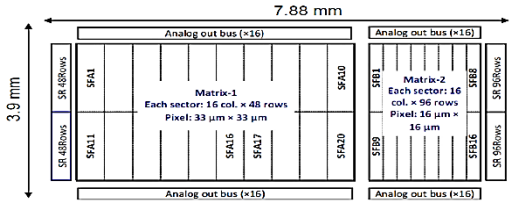
1、The prototype of CMOS pixel detector for the upgrade of BESIII-inner tracker

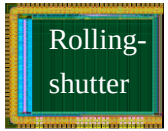
- ✓ Development of pixel detector ladder based on the MIMOSA28 sensors from IPHC
- ✓ common participation of beam test at DESY, to validate the ladder performance, space resolution, material budget, …

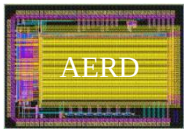


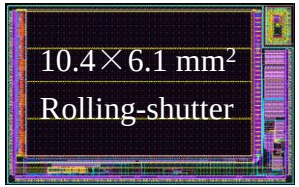
Ref.: *NIMA924(2019)287-292, NIMA986(2021)164810*

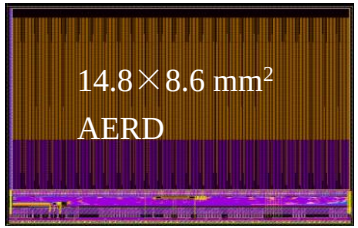
2、CMOS Pixel Sensors R&D for future e^+ e^- colliders: *pixel sensor and double-sided ladder development*
Since 2015, **four engineering runs** have been shared with TJ 180 nm CIS process











2015: JadePix-1 → 2017: JadePix-2/MIC4 → 2020: JadePix-3 → 2022: JadePix-4/MIC5

Outline

- Introduction
  - VTX upgrade proposal for Belle II
- Participation of China group
  - Physics performance
  - Optimized BELle II pIXel sensor (OBELIX)
  - Backend electronics and TDAQ system
- Summary

Physics program @ SuperKEKB with Belle II

- Thorough test of Std Model
- DIrect/indirect search for New Physics
- Hadronic Physics

} with billions of $B\bar{B}, c\bar{c}, \tau\bar{\tau}$ pairs In "clean" environment of B-factory

⇒ The Belle II physics book PTEP 12 (2019) 123C01

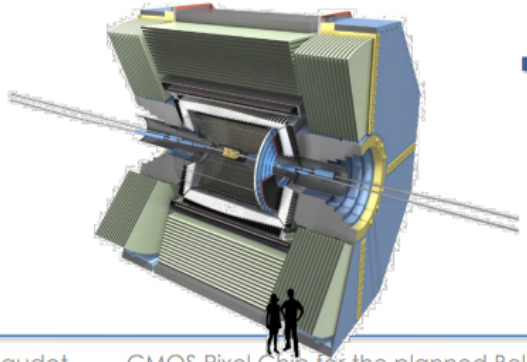
- Based on accumulation of 50 ab^{-1} of e^+e^- at $\sqrt{s} = M_{\Upsilon(4S)}$
  - requires instantaneous luminosity close to $6x10^{35}$ $cm^{-2}.s^{-1}$

⇒ SuperKEKB collider implementing the nano-beam scheme @ high currents

⇒ High collision rate High beam-induced bkg

The Belle II experiment

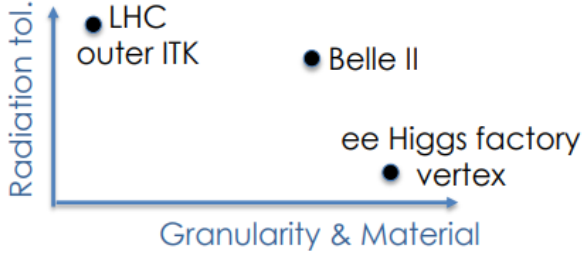
- "classical" B-factory detector + enhanced features



The vertex detector (VXD)

- Better vertexing ← lower boost
  Smarter tracking ← higher hit rate

+ Harsher radiation environment
+ Belle II trigger rate ~ 30 KHz

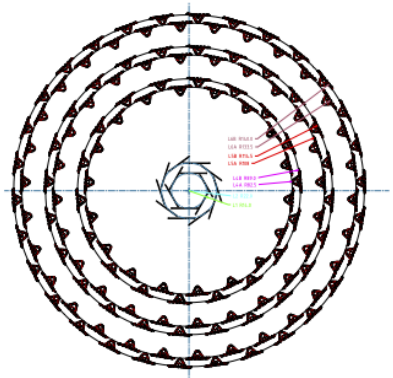


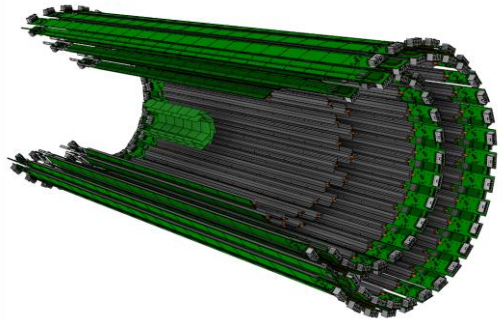
➔ Proposal for replacement of VXD = PXD (DEPFET sensors) + SVD(Double Sided Strip Detector) by VTX detector.

VTX proposal

Proposed BELLE II VXT upgrade scheme

- 5 straight layers with **D**epleted **M**onolithic **A**ctive **P**ixel **S**ensors
- Identical chips on all layers: Optimized BELle II pIXel (OBELIX) sensor
- ~1m² silicon surface





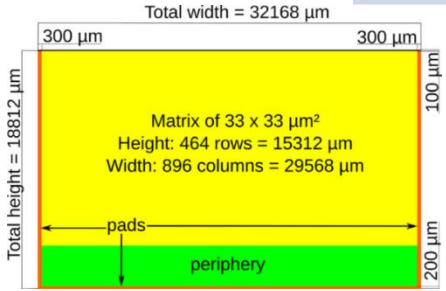
From simulations	Belle II VTX
Spatial res.	<10-15µm
Total material budget Inner-outer layers	0.1 – 0.8 %Xo
Max hit rate	120MHz/cm²
Time precision	<100ns
Trigger (freq.) (delay)	30 kHz 5-10µs
Rad. hard. (TID) (fluence)	<100 kGy/year <50x10^{12}n$_{eq}$cm^{-2}/year
Power	<200mW/cm²

OBELIX

– Tower 180 nm process

– Extension of TJ-Monopix2 → OBELIX sensor

– <40 µm pitch, 100 ns integration



Key sensor specifications:

- Pixel pitch: *30-40 µm*
- Integration time: *≲100 ns*
- Power dissipation: *≲200 mW/cm²*

Belle II VTX Organization

Steering board

Resource manager
A. Bevan

Project coordination
J. Baudot

Publications & Speakers
J. Serrano & WG leaders

WG1: Performance
V. Vobbilisetti
- Software
- Tracking
- Track-triggering
- Benchmarking

WG2: Sensor design
H. Pham
- Analog
- Digital
- Verification

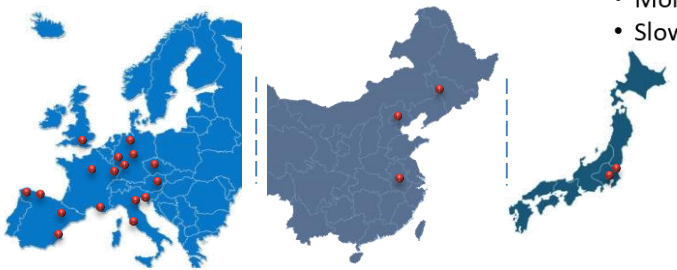
WG3: Characterization and test system
G. Rizzo
- Irradiations
- Lab tests
- Beam tests

WG4: Layer development
S. Bettarini
- iVTX Electrical
- oVTX Electrical
- iVTX Thermomechanics
- oVTX Thermomechanis

WG5: System integration
C. Irmler
- Readout
- Track trigger
- Power & Grounding
- Cooling services
- Monitoring
- Slow control

WG6: Demonstrator
C. Marinas
- Full chain system
- High level tests
- Beam telescope

Participation from Belle II China Group:
WG1: tracking
WG2: Verification
WG5: Backend data and trigger readout, powering



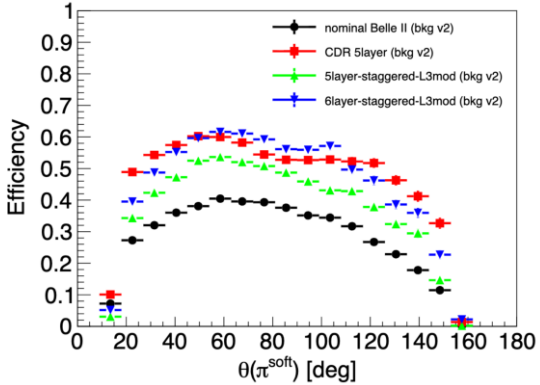
9 countries,
25 institutions

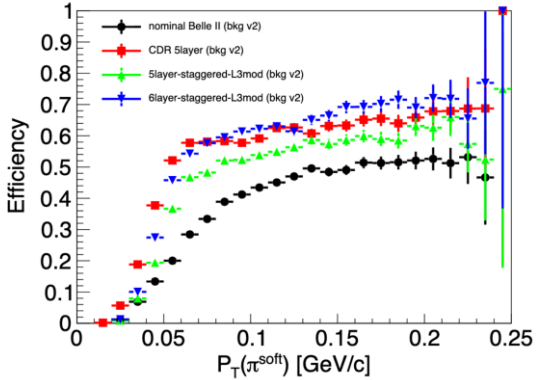
Slow pion performance study

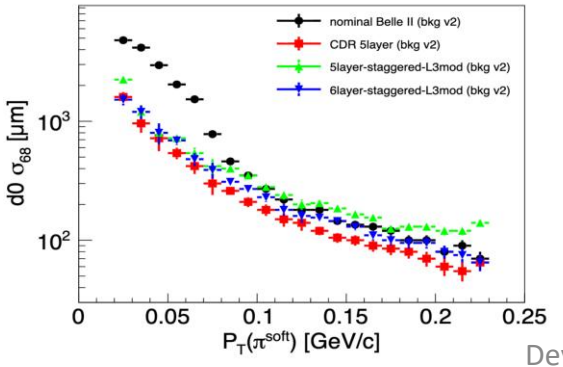
Jilin University: Weiming Song

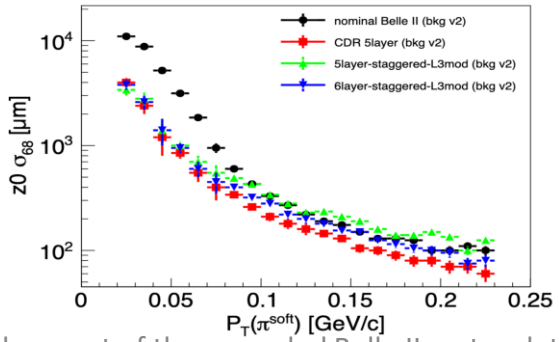
Study is based on the Monte Carlo samples of following two decay processes

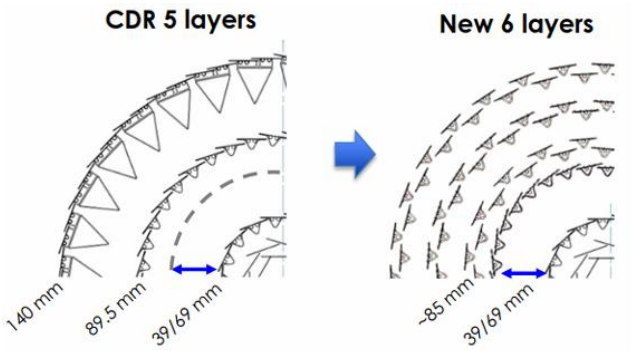
- $B^0 \to D^{*-}\mu\nu$ with $D^{*-} \to \bar{D}^0\pi^-_{soft}$ and $\bar{D}^0 \to K^+\pi^-$
- $B^0 \to D^{*-}\pi^+$ with $D^{*-} \to \bar{D}^0\pi^-_{soft}$ and $\bar{D}^0 \to K^+\pi^-$









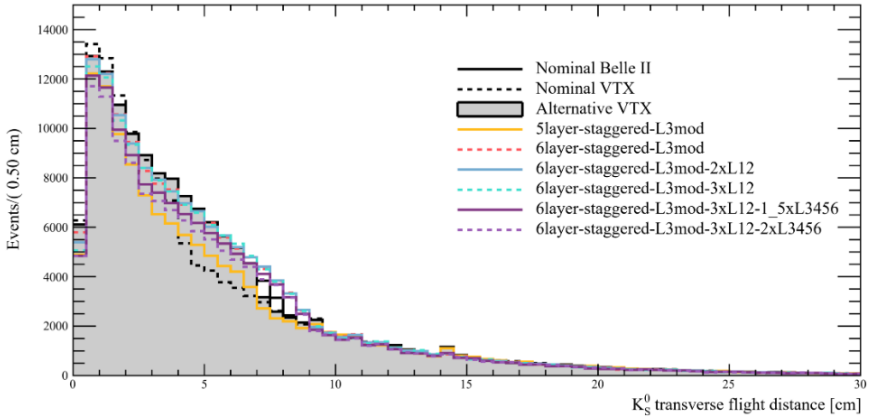


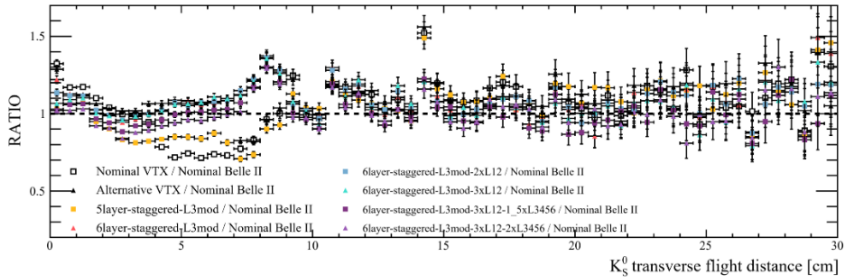
- Significant improvement in VTX compared by nominal Belle II
- Performance of 6 layer VTX is great than 5 layer in same conditions (but also constrained by the installation space)
- Details can be found at this link
- Useful in finalizing the VTX geometry, and checking the impact of different material budgets

Vertex reconstruction performance

Jilin University: Weiming Song

With the Monte Carlo sample of $B^0 \to J/\psi K_S^0\,(J/\psi \to e^+e^- or \mu^+\mu^-, K_S^0 \to \pi^+\pi^-$





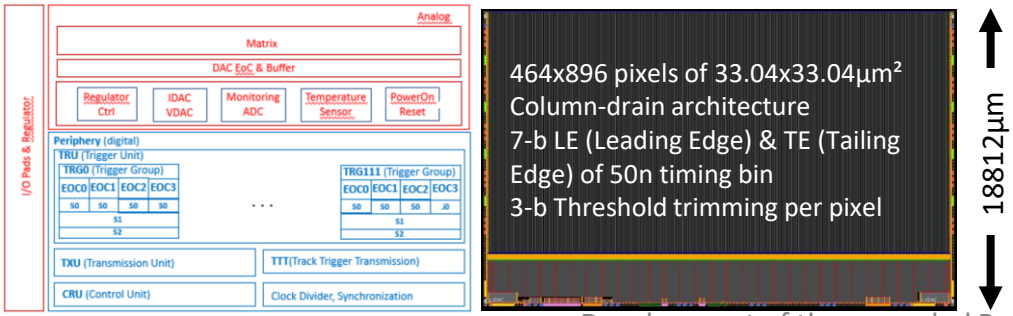
B_{sig} z vertex resoluton (μm)	Bkg(v1)	Bkg(v2)	Bkg(v3)
Belle II	20.9	22.3	24.5
Nominal VTX	13.9	14.0	13.9
Alternative VTX	13.7	13.7	13.6
5layer-staggered-L3mod	16.7	16.9	17.1
6layer-staggered-L3mod	16.1	16.1	16.4
6layer-staggered-L3mod-2xL12		17.8	
6layer-staggered-L3mod-3xL12		19.0	
6layer-staggered-L3mod-3xL12-1_5xL3456		19.0	
6layer-staggered-L3mod-3xL12-2xL3456		19.1	

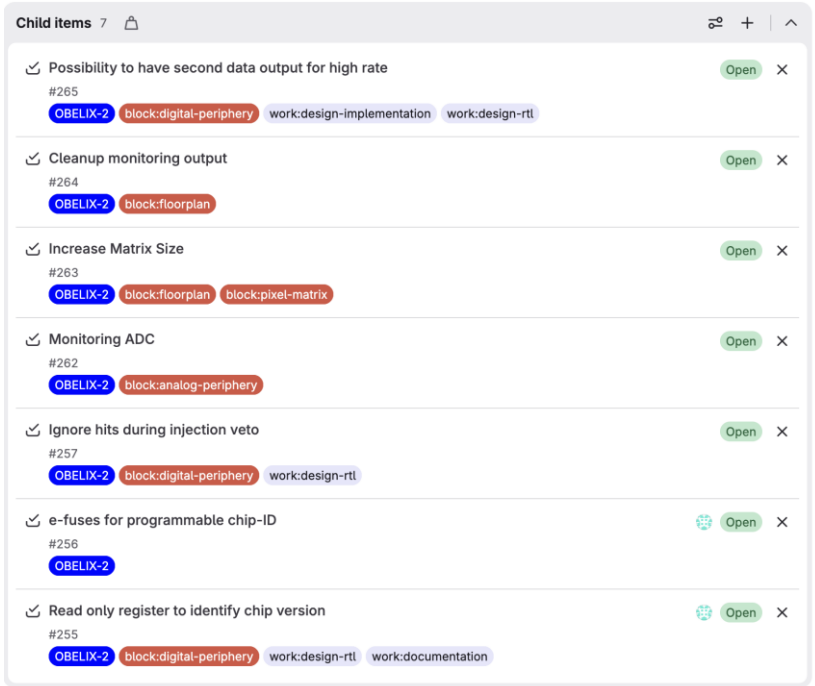
- Vertex resolution and K_S^0 efficiency are compared between different VTX configuration and Nominal Belle II performance.
- Material budget chosen: 0.3% X0 for L1 and L2; 0.8% X_0 for L3-6 to be realistic.
- Details are provided at this link

OBELIX (Optimized for BELle II pIXell)

- Developed from **TJ-Monopix2 sensor** (*Developed for ATLAS-ITK: doi: 10.1016/j.nima.2020.164460*)
- Increase **active area** from 17x17 mm² to 15x29,6 mm²
- OBELIX-1 has been submitted now with wafers expected back around October 2026
  - the lack of person power to verify all the functionalities
- OBELIX-2 design is starting
  - a strong need for more verification
  - And more anticipated verification with new features

Design collaboration: IPHC, CPPM, MBI Vienna, KEK, INFN, University of Bergamo, University of Pavia, University of Pisa, University of Applied Sciences and Arts Dormund, University of Bonn, University of Valencia





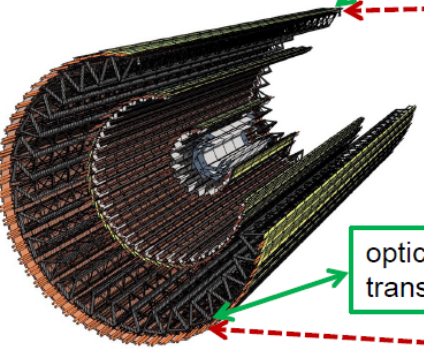
OBELIX-2 contribution from IHEP

- Possible activities: RTL, verification
- Solution for NDA and PDK (access to the process) confirmed
- **Design share agreement** under discussion
- A PHD student will work on the design and verification
  - EDA Tool chain ready for use
  - Hands on experience in digital design flow

【1】Specification & Module Partitioning
【2】RTL Coding ←→ **UVM Verification (Environment/Testcase/Simulation/Coverage)**
【3】Logic Synthesis → **Gate-level UVM Simulation** → Formal Verification → STA → DFT
【4】Floorplan → Placement → CTS → Routing → Parasitic Extraction (PEX)
【5】**UVM Post-Simulation (With RC Parasitics)**
【6】Backend Analysis + Physical Verification (DRC/LVS/ERC)
【7】ECO Revision → UVM Regression Test
【8】Tape-Out (GDSII Export)
【9】Wafer Fabrication & Packaging
【10】ATE Test → Mass Production & Delivery

UVM in Digital Design flow

VTX Readout Concept



optical transceiver

optical transceiver

Dock Box

DC/DC converters

Dock Box

DC/DC converters

optical transceiver

Back-end electronics

Belle II DAQ

Belle II trigger & clock (TTD)

L1 trigger

Run control

Slow control & config

Power supplies

power

e-link: data, cfg, clock, trigger

Optical transceivers placed as close to the modules as possible

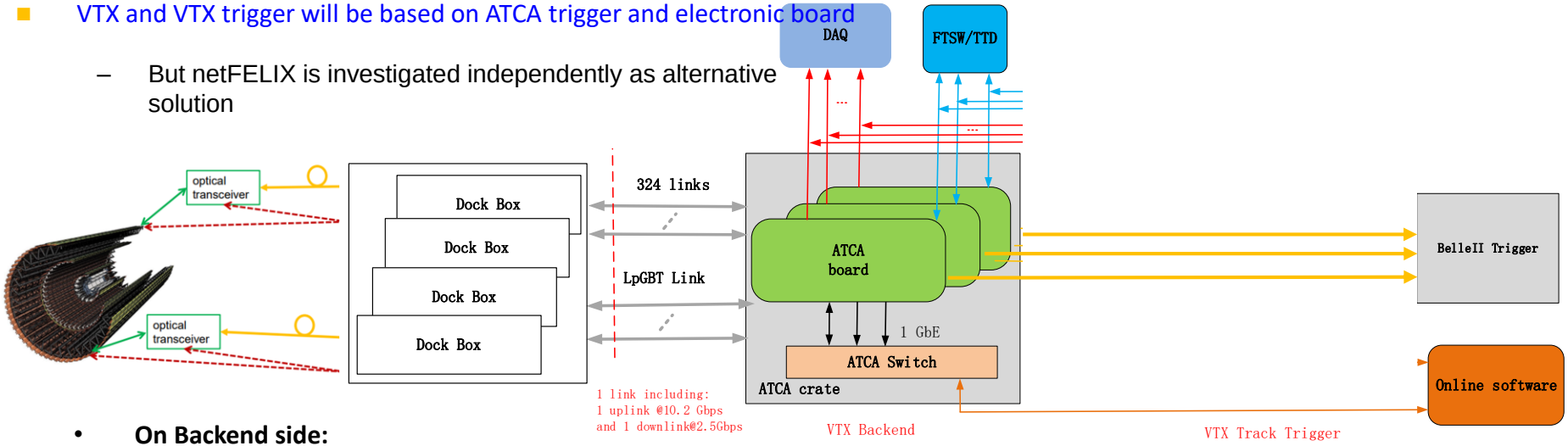
radiation hard components

commercial components

IHEP: Jingzhou Zhao

VTX Backend IHEP Proposal

- VTX and VTX trigger will be based on ATCA trigger and electronic board
  - But netFELIX is investigated independently as alternative solution

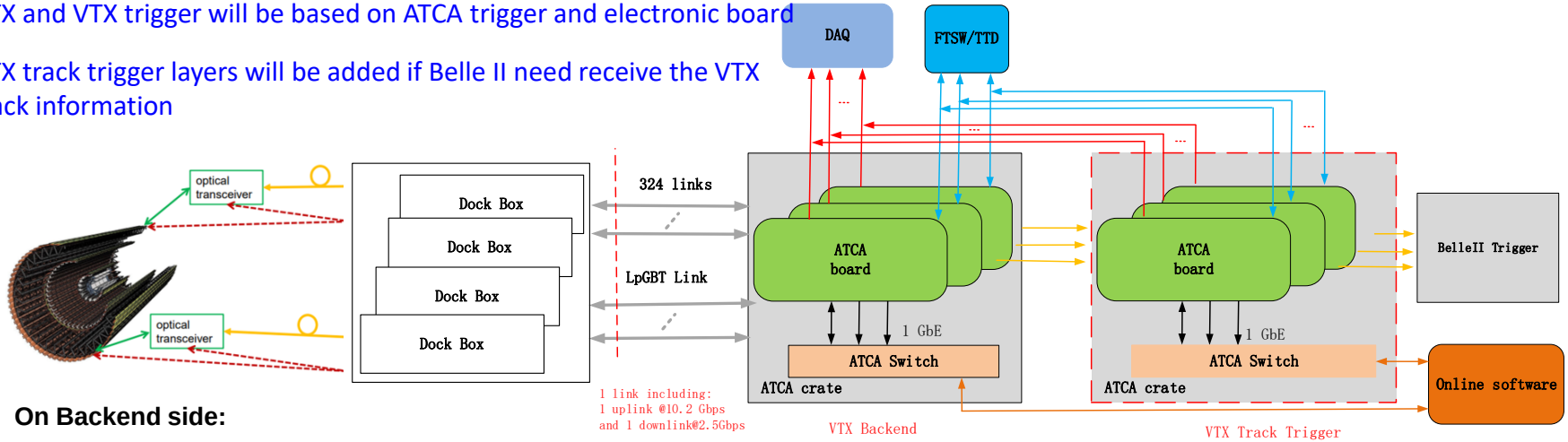


- **On Backend side:**
  - Receive and decode TTC signals from FTSW and feedback BUSY and Error signal to FTSW
  - Separate the hit data and trigger data;
  - Generate the cluster Trigger Primitive(TP)
  - Send TP data to VTX tracker in pipeline way
  - Package the hit data and TP data based on L1
  - Send data package to DAQ via TPC/RDMA
  - ATCA Switch board as a 1GbE Ethernet switch for Online connection with ATCA board for Slow control

IHEP: Jingzhou Zhao

VTX Backend IHEP Proposal (con't)

- VTX and VTX trigger will be based on ATCA trigger and electronic board
- VTX track trigger layers will be added if Belle II need receive the VTX track information



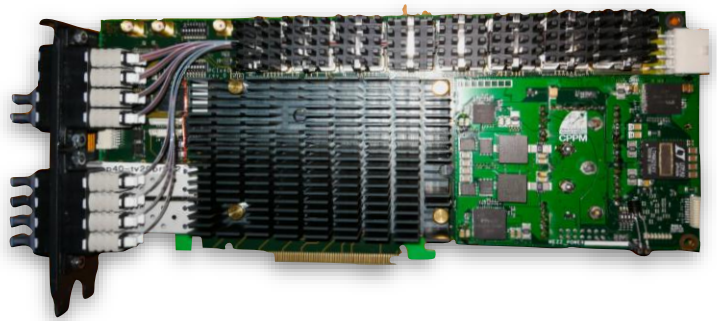
- **On Backend side:**
  - Receive and decode TTC signals from FTSW and feedback BUSY and Error signal to FTSW
  - Separate the hit data and trigger data;
  - Generate the cluster Trigger Primitive(TP)
  - Send TP data to VTX tracker in pipeline way
  - Package the hit data and TP data based on L1
  - Send data package to DAQ via TPC/RDMA
  - ATCA Switch board as a 1GbE Ethernet switch for Online connection with ATCA board for Slow control

- **On Track trigger side(If needed):**
  - Receive and decode TTC signals from FTSW and feedback BUSY and Error signal to FTSW
  - Receive Cluster TP data and do track finding in section;
  - Send track data to Belle II trigger based on BelleII trigger transmission Protocol
  - Package the TP data and Track data based on L1
  - Send data package to DAQ via TPC/RDMA
  - ATCA Switch board as a 1GbE Ethernet switch for Online connection with ATCA board for Slow control

Firmware development for backend

IHEP: Jingzhou Zhao
Shandong University: Qidong Zhou
Jilin Univerity: Weiming Song

- The link protocol of lpGPT from frontend to backend
- User logic on backend
- **Clustering algorithm (if needed on the backend)**
- **Trigger algorithm (interest, collaboration with trigger group)**
- A pocket DAQ system with PCIe40 at Shandong Univ.
- It is planned to setup a testbench with frond-end and back-end boards



Power supplies for VTX

USTC: Lailin Xu, Jiajun Qin

- DC-DC Specific requirement
  - Radiation dose (<56 Mrad), magnetic field (1.5 T)
  - Output Current up to 8A
- Survey on DC-DC chips
  - Commercial DC-DC converters (< 100 krad) cannot meet the TID requirement
  - CERN radiation-hardened DC-DC converters
    - ✓ bPOL12V, bPOL2V5 and bPOL48V are widely applied.
    - ✓ bPOL12V has reliability issues in certain situations, particularly after irradiation, thermal cycling, and repeated enable/disable operations.

	Model	Vin	Vout	Output Current/Power	TID	MAG (Gauss)
CERN	FEAST2.1/FEAST2.3	5 ~ 12 V	0.9 ~ 5 V	0~4 A	>200 Mrad(Si)	40000
CERN	bPOL48V_V2	13 ~ 48 V	0.6 ~ 24 V	0~10 A	>50 Mrad(Si)	40000
CERN	bPOL12V_V6	5.5 ~ 12 V	0.63 ~ 5 V	0~4 A	>150 Mrad(Si)	40000
CERN	bPOL2V5_V3.3	2.1 ~ 2.5 V	0.6 ~ 1.5 V	0~3 A	>100 Mrad(Si)	40000
CERN	AMIS2	6 ~ 11 V	1.2/1.8/2.5/3.3/5 V	0~3 A	300 Mrad(Si)	40000
MAGICS	MAG-PSU00001-NP	5~11 V	0.9~5 V	0~4 A / 0~10 W	> 100Mrad(Si)	40000

Back-end power units

Manufacturer	Model	Output voltage	Output current	Output channels	Ripple
CAEN	A2551	0–8 V	12A	8	<5 mVpp
CAEN	A2552	0–16 V	6A	8	<5 mVpp
CAEN	A2553	0–32 V	3A	8	< 8 mVpp
CAEN	A2554	0–64 V	1.5 A	8	< 8 mVpp
CAEN	A3006	4–16 V	6A	6	<20 mV pp on 10 µF // 0.1 µF 10 Hz-15 MHz

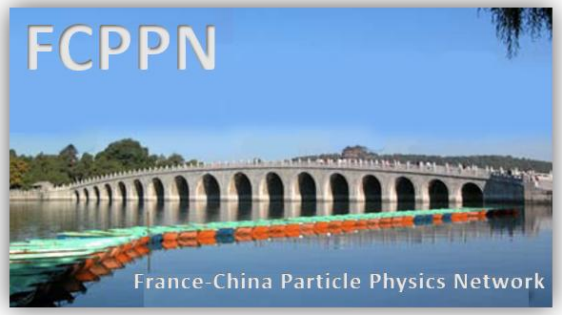
FCPPN/L joint project

- A dedicated channel to strengthen the VTX collaboration
  - Based on the participation of VTX upgrade from French and Chinese side
  - WG1: IPHC and Jilin University
  - WG2: IPHC, CPPM and IHEP
  - WG5: CPPM, IHEP, Shandong University and USTC

French Group			Chinese Group		
Name	Status	Affiliation (institute)	Name	Status	Affiliation (institute)
Leader BAUDOT JEROME	PR	IPHC	Leader LU Yunpeng	PR	IHEP
BARBERO Marlon	PR	CPPM	SONG Weimin	PR	Jilin University
PANGAUD Patrick	Ing.	CPPM	XU Lailin	PR	USTC
BREUGNON Patrick	Ing.	CPPM	ZHOU Qidong	PR	Shandong Univ.
XU Danwei	PhD	CPPM	OUYANG Qun	PR	IHEP
MARGUIN Jérémy	Master	IPHC	GAO Xu	PhD	Jilin university
MAUSHART Mattéo	PhD	IPHC	YU Han	PhD	IHEP
GOFFE Mathieu	Ing.	IPHC			

Summary

- 4 Chinese teams involved in the BELLE II VTX upgrade
  - Jilin University contributed to the physics performance study
  - IHEP is starting to participate the OBELIX-2 sensor design
  - 3 universities Shandong, Jilin, USTC and IHEP participated WG5 and devoted to the backend
  - Joint project and annual workshop in the FCPPN/L framework



Thank you for your time!