The A0 photoinjector program in Accelerator Science Research and Education: Recent Achievements and Migration to NML

P. Piot, DOE meeting, FNAL, August 23rd, 2010

A0 photoinjector (A0PI)

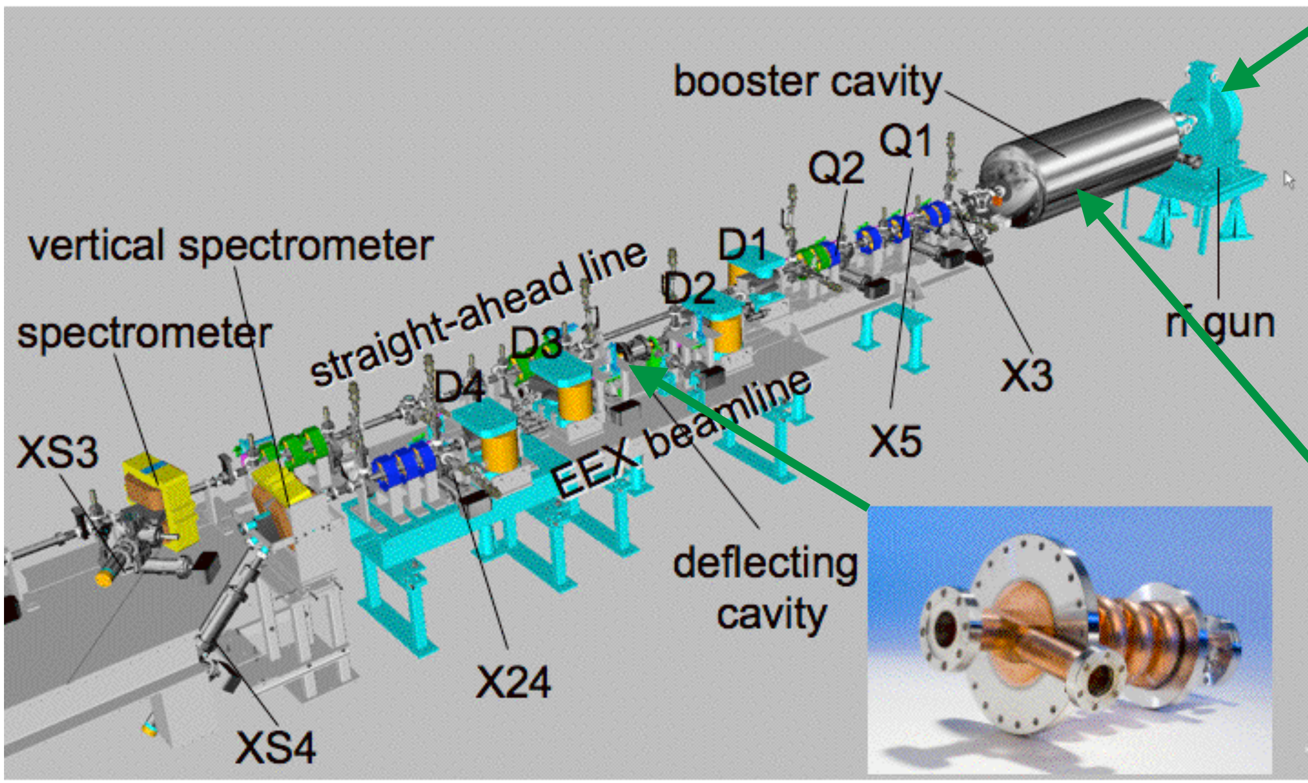
- Started as a vision (by a small group of people) ~15 years ago to get FNAL involved in the TESLA collaboration.
- Current goals/achievements:
  - **Technical**:
    - Low level radiofrequency control systrem R&D
    - Development of subsystems (cathode lasers, diagnostics) for NML
    - R&D on 3.9 GHz cavity for phase space linearization
    - Polarized electron source (w. DULY, AES)
  - **Scientific**:
    - Beam manipulation: flat beams, transverse-to-longitudinal phase space exchange, beam shaping (esp. current profile)
    - Beam diagnostics
  - **Education**:
    - Trained 1/3 of the total number of FNAL students who graduated in Accelerator Science

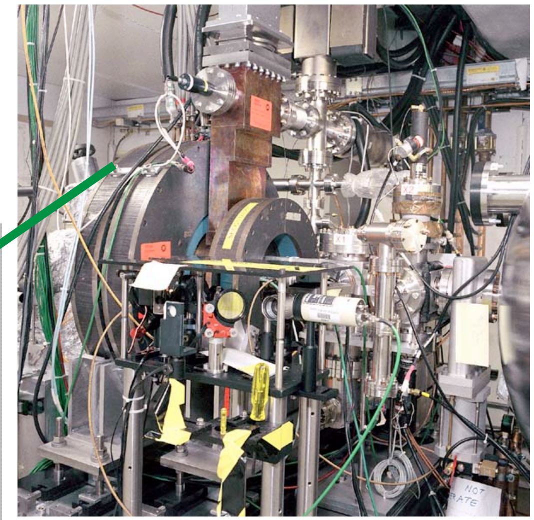
Historical achievements at A0PI

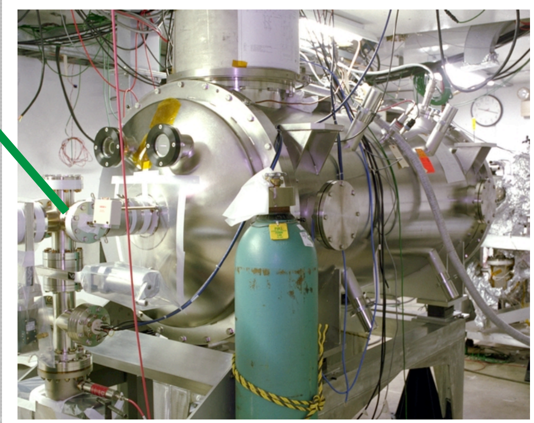
- Education
  - Contributed to the training of ~10 PhD students
- Technology
  - Designed, built, delivered an injector (rf-gun + injector beamline components) for TESLA test facility (TTF-1) at DESY
  - Laser capable of providing ILC-type macropulse format
- Science:
  - Characterization of a L-band gun over a wide range of operating parameter (1999)
  - Observation of wakefield via electro-optical imaging (2000)
  - Generation of angular-momentum dominated beams (2002)
  - Proof-of principle of flat beam production in a photoinjector (2000-2003)
  - Plasma-wakefield acceleration and plasma lens in under-dense regime, (2003-2004)
  - Emittance exchange between the horizontal and longitudinal degrees of freedom (2008)
  - Pulse shaping with emittance-exchanger beamline (2010)

A0PI setup

- 1.3 GHz rf-gun with CsTe photocathode → Q< 10 nC (up to 100 bunches)
- TESLA SCRF cavity (f=1.3 GHz) → E=16 MeV
- Emittance exchange beam line $(\varepsilon_x, \varepsilon_z) \rightarrow (\varepsilon_z, \varepsilon_x)$
- Extensive diagnostics: emittance measurements, screens, streak camera, Michelson interferometers)





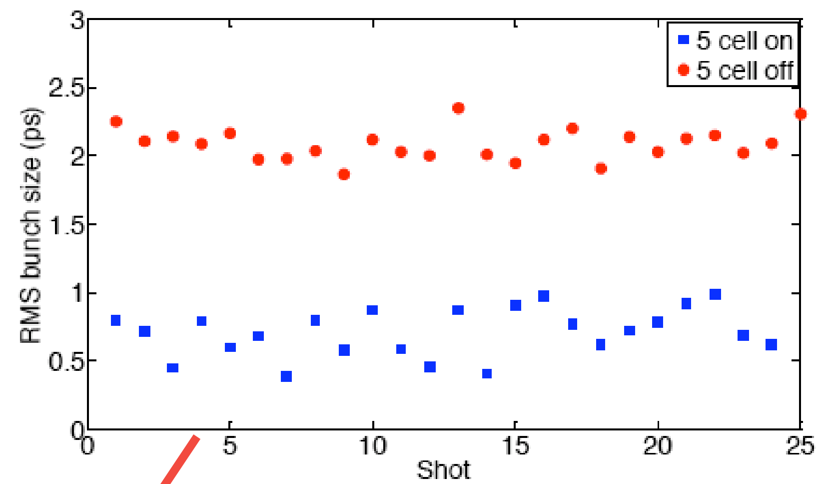


Recent work @ A0PI: emittance exchange

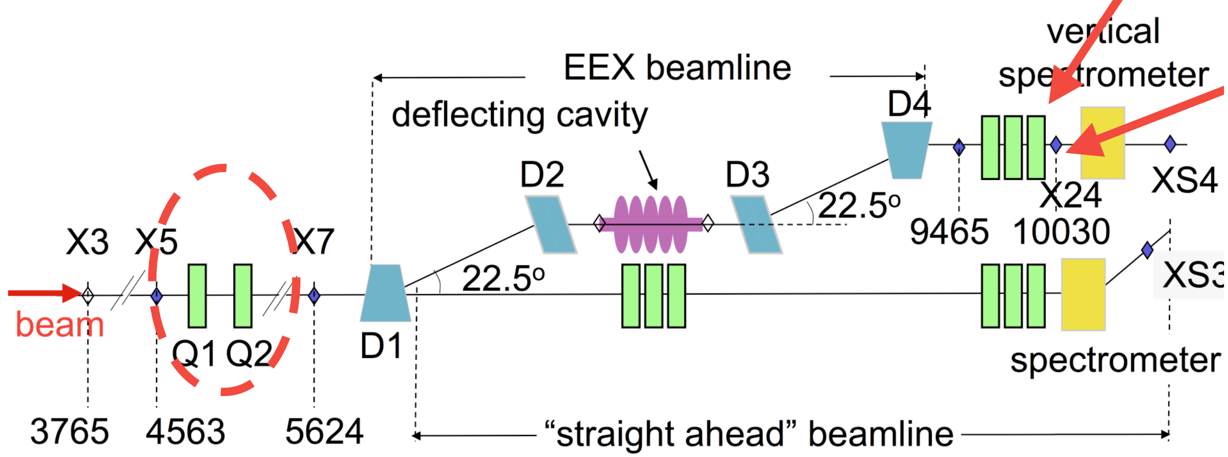
- Observed emittance exchange between the horizontal and the longitudinal phase spaces

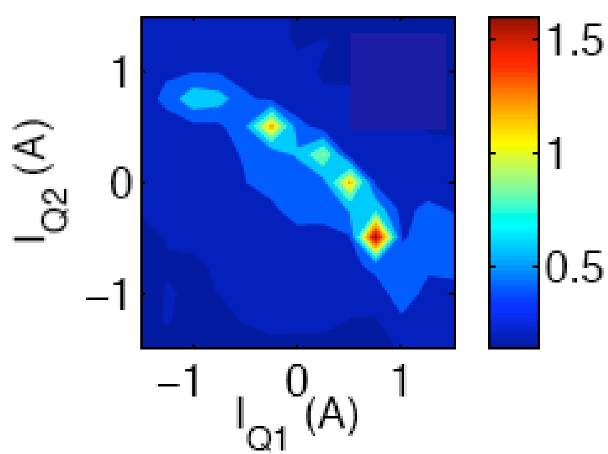
$$\varepsilon^n{}_x = 2.6 \pm 0.3 \text{ mm mrad} \rightarrow 11 \pm 2 \text{ mm mrad}$$
$$\varepsilon^n{}_z = 11.5 \pm 1.5 \text{ mm mrad} \rightarrow 5 - 6 \text{ mm mrad}$$
$$\varepsilon^n{}_y = 2.5 \pm 0.3 \text{ mm mrad} \rightarrow 3.7 \pm 0.3 \text{ mm mrad}$$

Bunch duration measurement with streak camera



- Made significant improvements on beam diagnostics



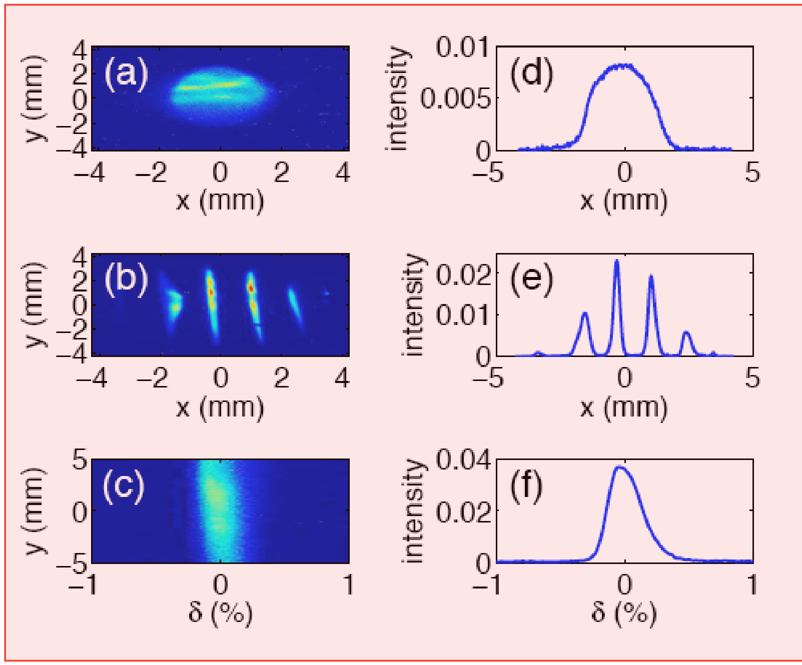


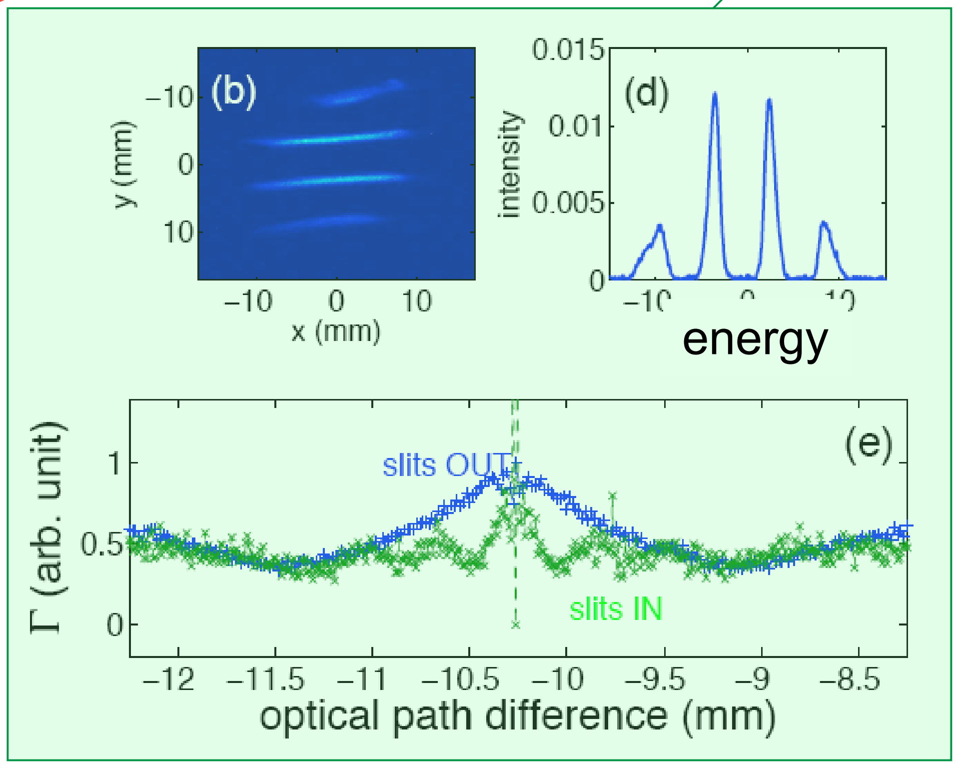
CTR Power versus Q1 & Q2 settings

Recent work @ A0PI: current shaping

- Generated a **train of microbunches with sub-ps separation** using slits

Transversely-shaped beam → EEX beamline → Longitudinally-shaped beam



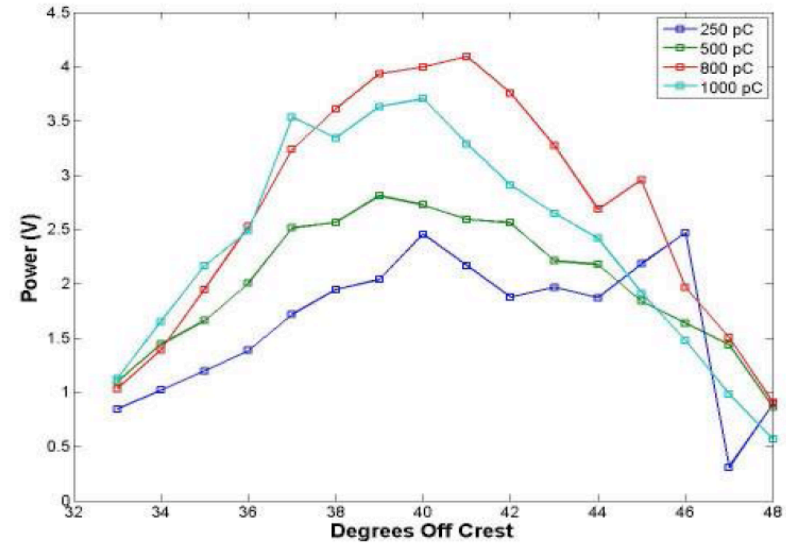


- Applications:
  - generation of narrow-band coherent transition radiation,
  - Resonant excitation of wake -fields in PWFA and DWFA

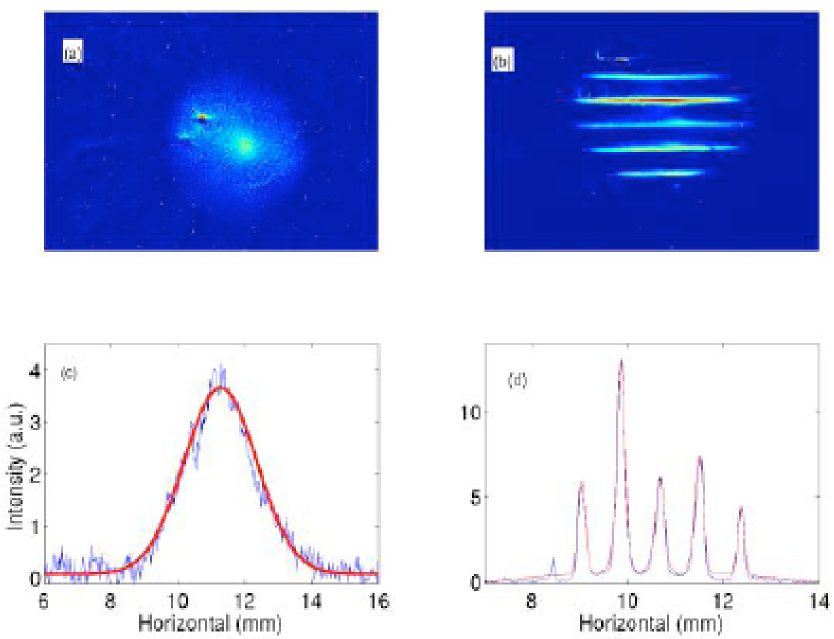
•Method can be used to produce any type of current profiles (trapezoidal, linearly- ramped,…)

Recent work @ A0PI: other

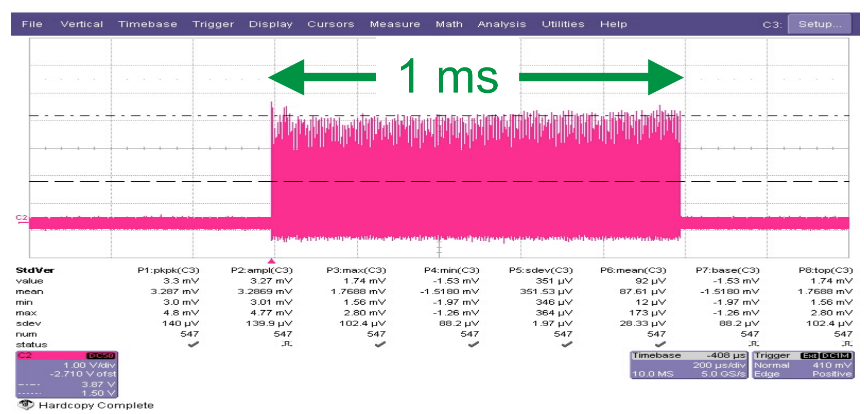
- Measurement of effects of coherent synchrotron radiation
- Commissioning of a long-pulse photocathode laser system
- Exploration of long-pulse operation LLRF stability



Measurement of CSR emission versus bunch compression for different charges



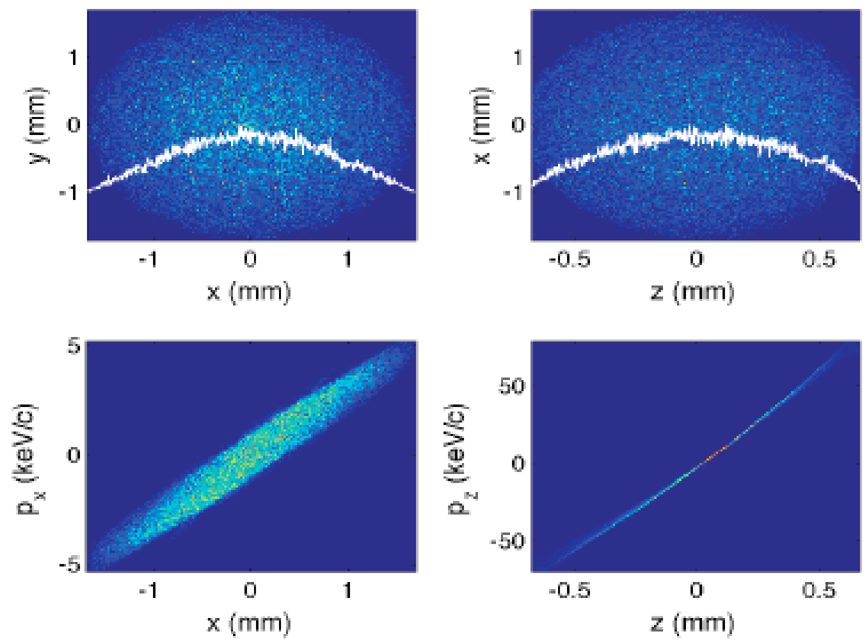
Improvement of emittance measurement usingYaG:Ce screens



New laser system for NML: pulse after multi-pass amplifier

Near-term plans until decommissioning

- Emittance exchange:
  - Explore single-particle regime w. very low charge → understand the exchange process in detail
  - Generation of ramped bunches from a semiconductor cathode
  - EEX with ellipsoidal bunches
  - Combine flat beam with EEX → ultra-low-emittance beams



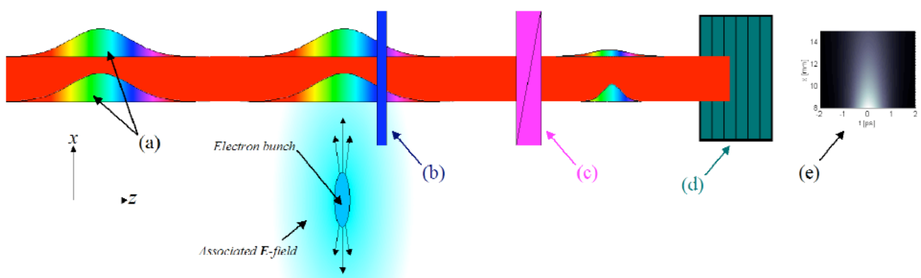


Figure 1: Illustration of simultaneous spectral and spatial encoding. (a) Chirped laser pulse (profiles along minimum and maximum x extent of laser pulse shown), (b) Electro-optic crystal, (c) Polarizer, (d) Cylindrical diffraction grating focusing out of page, (e) Resulting ideal image of bunch-field squared in x-z plane.

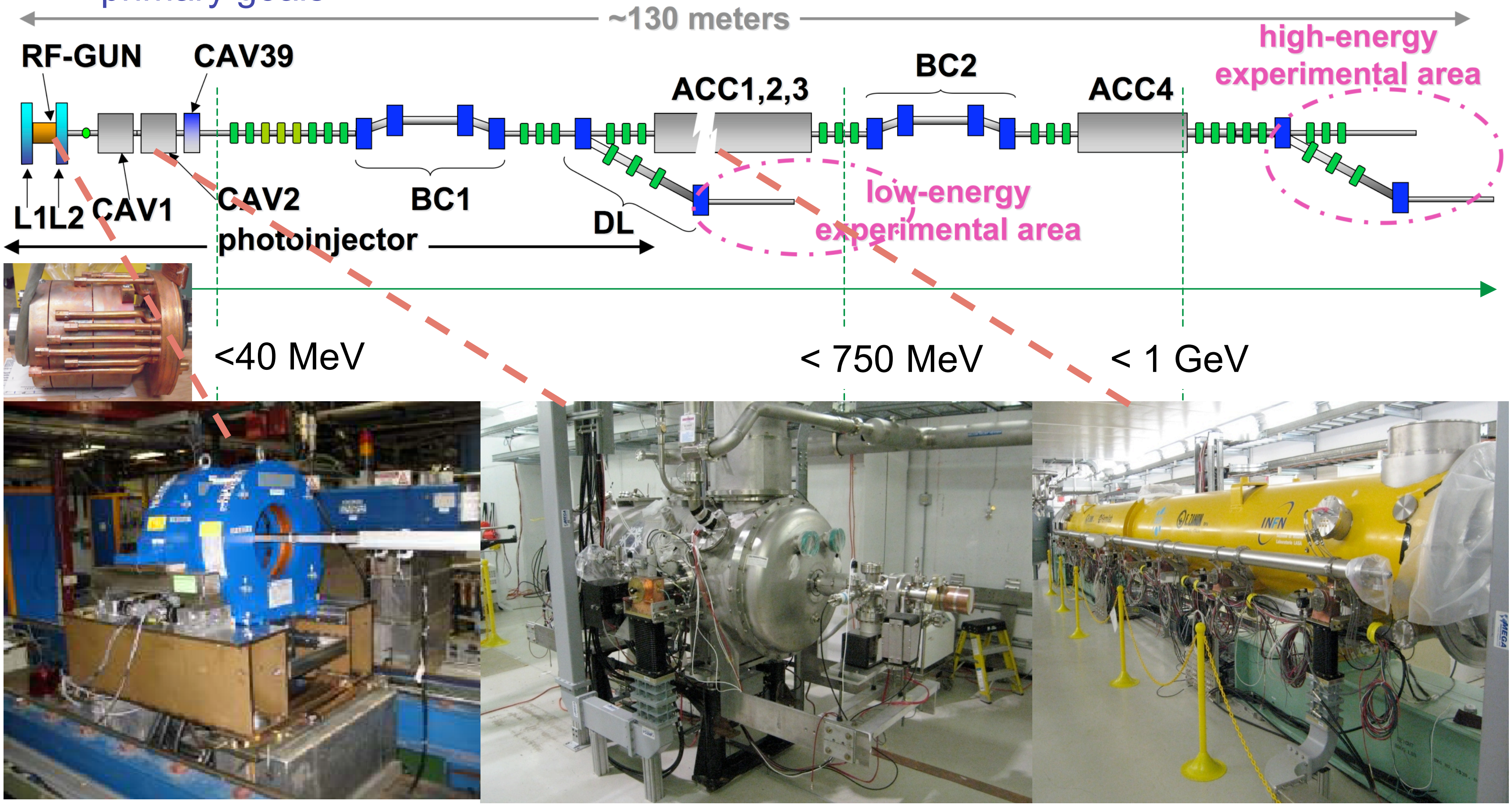
•Generation and characterization of ellipsoidal bunches using the “blow-out technique”

•Sub-ps tilt monitor: POP experiment [PhD, T. Maxwell, NIU]

- A0 will be decommissioned end of FY11 part of the components will be moved to NML. The A0 vault → high brightness e- source development lab

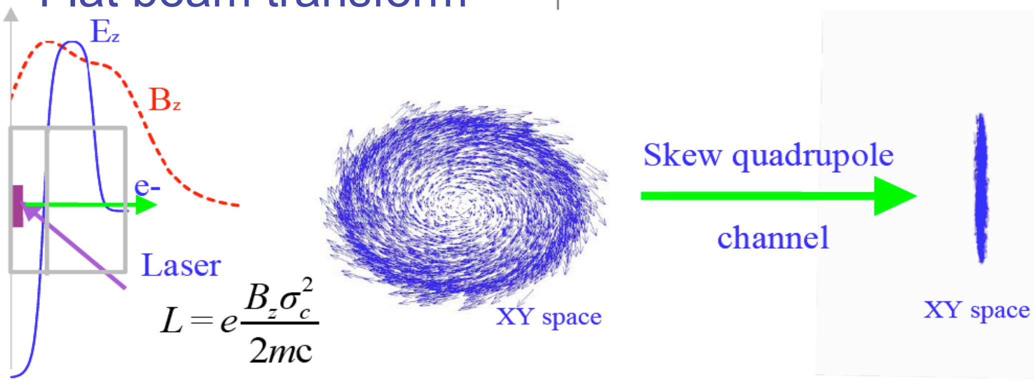
NML setup

- NML will support research and education in Accelerator Science in parallel to its primary goals

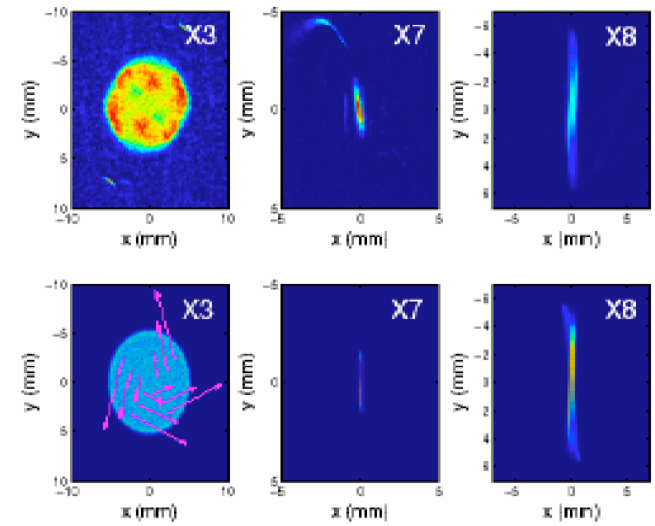


NML capabilities

- Flat beam transform

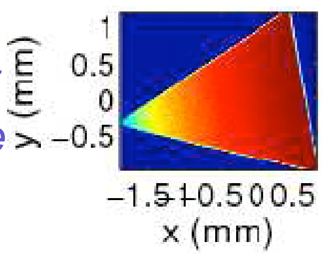


measurements at A0

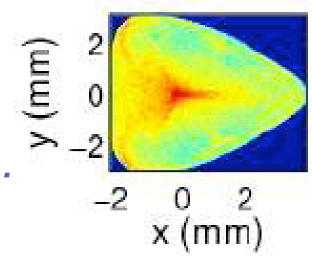


simulations

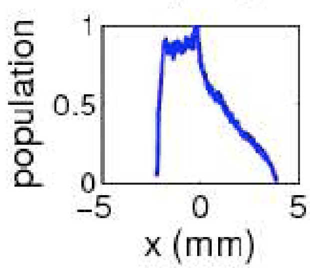
Laser spot on cathode



Electron beam distrib.

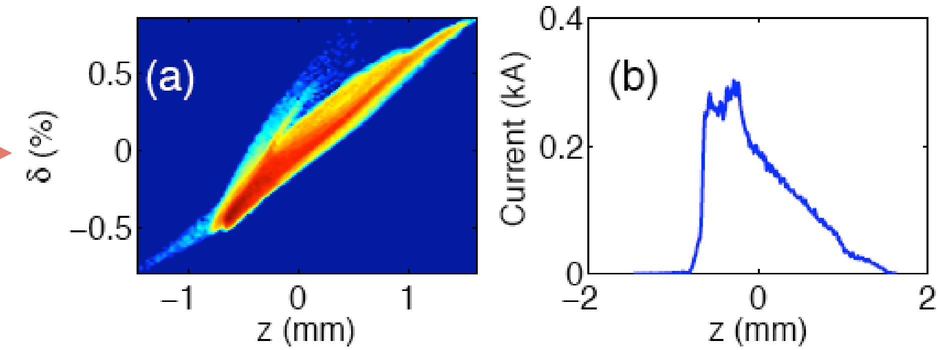


Horizontal profile



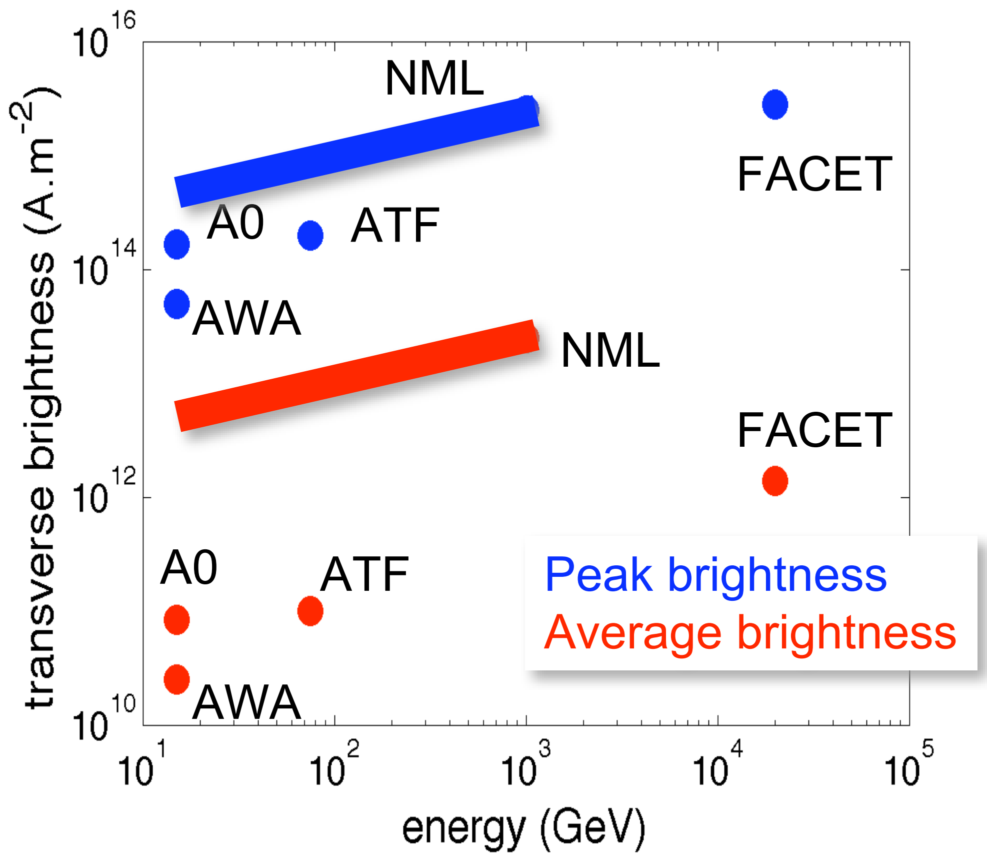
•Transverse-to-longitudinal emittance exchange in a versatile BC2 bunch compressor (preparing STTR w. Radiabeam LLC)

EEX



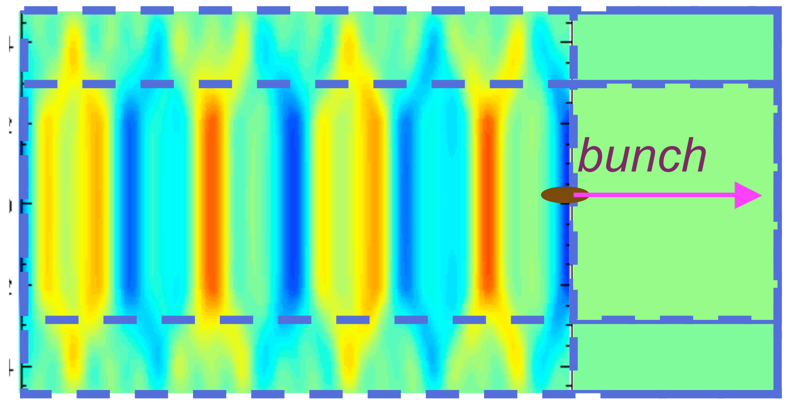
NML as an AARD facility

- Variable energy from ~40 (injector beamlines) to ~1 GeV,
  1st experiment maybe located in injector at 40 MeV and eventually relocated to the HE line
- High-repetition rate (1-ms trains),
  dynamical effect in structures (pulse heating, dielectric breakdown, multi-bunch dynamics?)
- L-band SCRF linac
  large rf wavelength accommodates drive-witness pulses experiments,
- Photoinjector source
  low phase space volume, easy con-trol of bunch train format (up to 3000)
- Arbitrary emittance partition
  match the beam to the structure size,
- Tailored current profiles,
  enhancement of transformer ratio, drive+witness pulses,

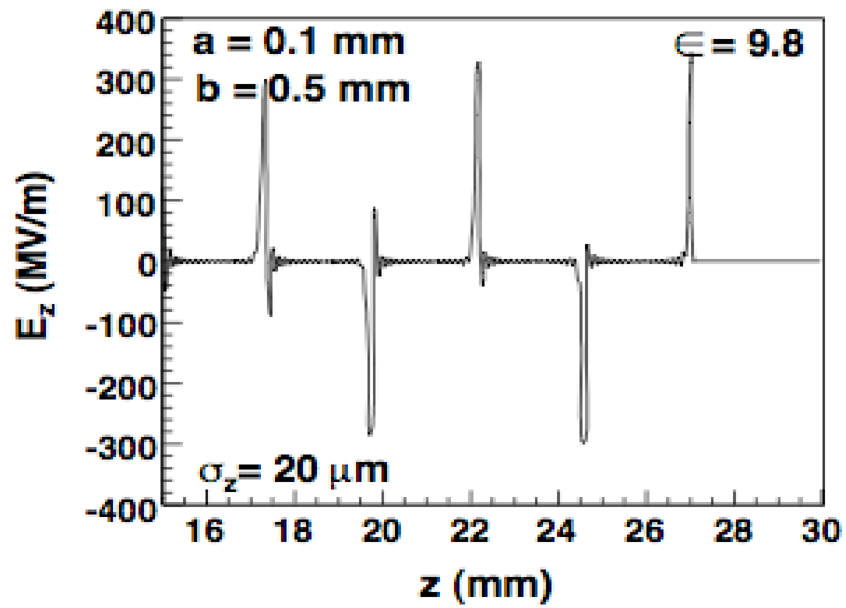


Proposal for DWFA experiment

- Simple experiment use all the "bell and whistle" capabilities of NML (flat beams, emittance exchange, current pulse shaping)
- The emphasis is on
  - transplanting and commissioning the manipulations developed at A0
  - Developing a generic setup that could be used by other interested parties
- **As a first experiment we chose dielectric wakefield acceleration in slab structure**
  - Simple,
  - Novel and well matched to NML capabilities,
  - Promise is great E_z>*0.3* GV/m,
  - Leverage on local ANL expertise,
  - NIU and Tech-X obtained funding from DTRA to model, design and perform such an experiment.

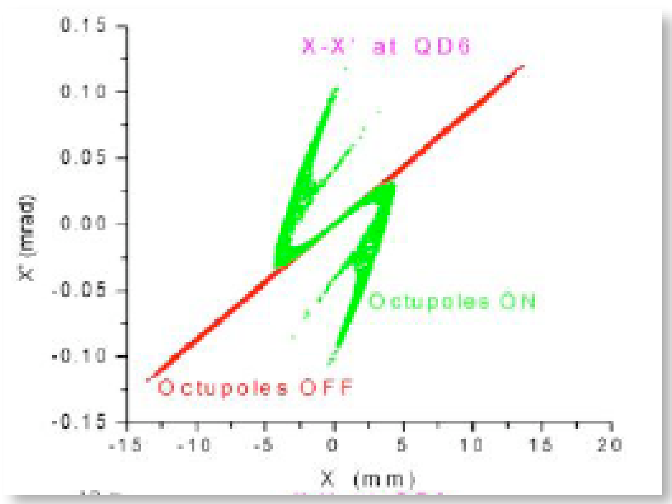


VORPAL

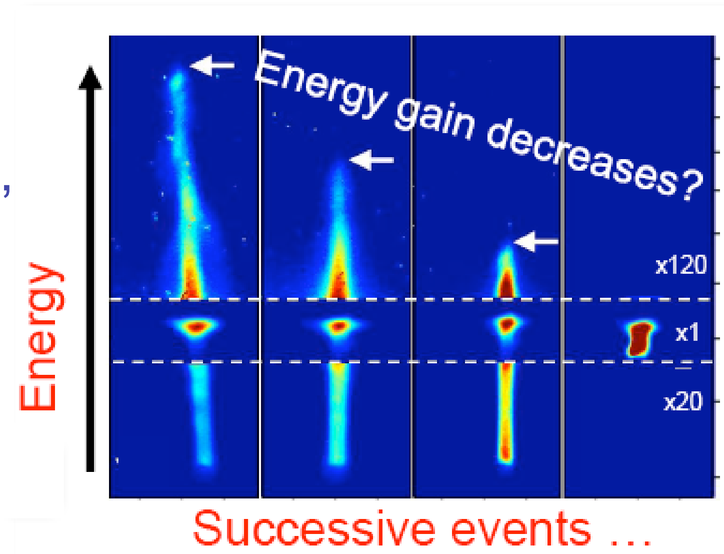


Possible Opportunities/Interests

- Two mini-worshop were held to explore interest in NML
  - November 2007 at Fermilab,
  - June 2009 in Lake Geneva.
- These workshops attracted many participants nationwide
- Example of experiments include PWFA, Muon generation, non-linear manipulation to reduce halo tails, positron sources R&D, …



Beam tail folding using octupole [Courtesy of N. Mokov, FNAL]



*How does PWFA behave with high-repetition-rate accelerator? [Courtesy of P. Muggli, USC -- **this is a fictive image made from experimental data**]*

Summary

- Fermilab has pioneered novel phase space manipulations
- Since their invention and experimental demonstration at A0, these phase space manipulations have found many applications in, e.g., beam-driven wakefield acceleration, and novel light source concepts
- The NML facility currently in construction will include most of these manipulations thereby enabling the production of high-brightness beam with arbitrary emittance partition and current profile
- A FNAL-NIU collaboration is preparing a DWFA experiment at NML
- The DWFA experiment is simple to implement and most of the work focus on the beam preparation (e.g. production of shaped current profile, witness + drive bunches)
- The techniques to be developed in support to our DWFA experiment will be **valuable and available** to other AARD experiments (PWFA, FEL's R&D, etc…)
- Two workshops organized by Fermilab have generated a great interest in NML from possible user community,
- A recent external review (accelerator advisory committee) supported the use of NML as an AARD user-oriented facility
- We are currently assembling an NML review committee that will advise us and eventually serve as a review panel for experiment proposals.

Pending/funded proposal related to NML

- Funded:
  - P. Piot, NIU-Tech-X contract with DTRA, “Numerical and experiment investigation of dielectric wakefield accelerators”, 0.6 M$/3 years
  - P. Piot, K.-J. Kim, University of Chicago - Fermilab - Argonne strategic initiative, “Generation and characterization of low-charge electron beams at the NML facility with application to next generation x-ray free-electron lasers”, 56k$ (year 1) + 55k$ (year 2).

- Pending
  - P. Piot, NIU renewal proposal to DOE HEP, “Phase space manipulation”, **pending** requested (322 k$/3 years).
  - Y.-E Sun, FNAL, “A novel solution to the generation of arbitrary electron beam current profile”, early carrer pre-proposal to DOE.

ADDITIONAL MATERIAL: SPECIFICS on A0

A0 Current effort

- Physicist
  - Students:
    - Current: 2 graduate students (both FNAL/NIU)
    - Average: 2 per year, 1 supported through FNAL phD program
  - Postdoctoral associate
    - Currently: 2 Peoples' fellow (Yin-e Sun and Charles Thangaraj)
    - Average: 2 per year (FNAL-supported + visitor)
  - Staff
    - Current:
      - 1 full time application physicist,
      - 25% of FNAL-NIU joint appointee
      - 50% physicist acting as facility manager (include photoinjector and other activities in the A0 building
- Technical staff:
  - 1 engineer,
  - 2 part-time technicians.

A0 statistics

- Operation:
  - 3 days/week in average
  - Other days are downtimes due to operation of north cave (SCRF R&D in A0 building), coupler conditioning
  - 2 experiments ran simultaneously -- currently
    - Emittance exchanges
    - Generation of train of microbunches

Education at A0 (and **NML**)

- **Graduated:**
  1. Eric Colby, PhD, UCLA, 1997 (J. Rosenzweig)
  2. Alan Fry, PhD, U. of Rochester, 1998 (A. Melissinos)
  3. Michael Fitch, PhD, U. of Rochester, 2000 (A. Melissinos)
  4. Jean-Paul Carneiro, PhD, U. Paris XI France, 2001 (J. Le Duff)
  5. Matt Thompson, PhD, UCLA, 2004 (J. Rosenzweig)
  6. Dan Bollinger, MS, Northern Illinois University, 2005 (C. Bohn)
  7. Yin-e Sun, PhD, U. of Chicago, 2005 (K.-J. Kim)
  8. R. Tikhoplav, PhD, U. of Rochester, 2006 (A. Melissinos)
  9. M. Thompson, PhD, UCLA, 2007 (J. Rosenzweig)
  10. Arthur Paytan, MS, Yerevan State University (Armenia), 2008 (E. Laziev)
  11. Timothy Koeth, PhD, Rutgers University, 2009 (S. Schnetzer)
- **Present:**
  1. T. Maxwell, Northern Illinois University (P. Piot)
  2. A. Johnson, FNAL-technician at Northern Illinois University (P. Piot)
  3. **C. Prokop, Northern Illinois University [NML, sponsored by LANL] (P. Piot)**
  4. **M. Radwan, Norhern Illinois University [NML, DWFA, sponsored by DTRA] (P Piot)**
- **People Fellows:**
  - Markus Huening, 2002-2004 (from DESY, now at DESY)
  - Philippe Piot, 2002-2005 (from DESY, now at NIU-FNAL)
  - Yin-e Sun, since 2008 (from Argonne)
  - Charles Thangaraj, since 2010 (from U. Maryland)
- **Undergraduates:**
  - summer students from SIST, Sup-Areo Toulouse, Politecnico Milano, Uni. Torino

* ***Sponsored by the Fermilab/universities PhD program in accelerator physics***

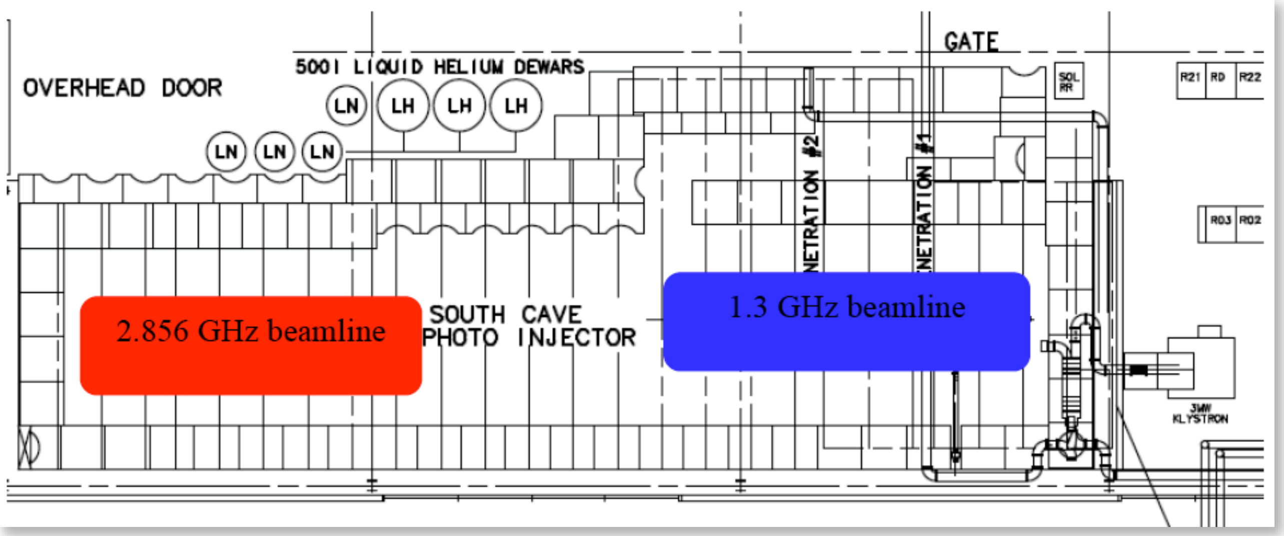
A0 Publications/Preprints (2010)

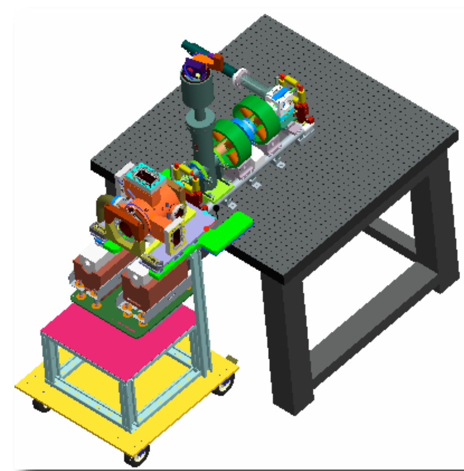
1. Y.-E Sun et al., “Formation of train of sub-picosecond bunches with variable spacing using a transverse to longitudinal phase space exchange”, submitting to PRL (2010).
2. A. Lumpkin, et al., “Upgrades of beam diagnostics in support of emittance-exchange experiments at the FNAL A0 photoinjector”, Proc. FEL10 (2010).
3. P. Piot et al., “Transverse-to-longitudinal phase space exchange: a versatile tool for shaping the current and energy profile of relativistic electron bunches”, Proc. AAC10 (2010).
4. T. Thangaraj, et al., “Experimental study of coherent synchrotron radiation in the emittance-exchange line of the A0 photoinjector”, Proc. AAC10 (2010).
5. P. Piot et al., “Generation of relativistic electron bunches with arbitrary current distribution via transverse-to-longitudinal phase space exchange”, ArXiv:1007.4499, submitted PRSTAB (2010).
6. Y.-E Sun, et al., “Experimental Generation of Longitudinally-modulated Electron Beams using an Emittance-exchange Technique”, Proc. IPAC10, 4313 (2010).
7. M. Thompson, et al., “Observations of low-aberration plasma lens focusing of relativistic electron beams at the underdense threshold”, Phys. Plasmas **17**, 073105 (2010).
8. A. Johnson, et al., “Demonstration of Transverse-to-longitudinal Emittance Exchange at the Fermilab Photoinjector”, Proc. IPAC10, 4614 (2010).
9. Y.-E Sun, et al., “Conversion of a transverse density modulation into a longitudinal modulation using a emittance exchange technique”, Proc, HBEB09, ArXiV:1003.3126 (2010).
10. A. Lumpkin, et al., “OTR polarization effects in beam-profile monitor at the A0 photoinjector”, Proc. BIW10 (2010).

A0 future as a source development Lab

- The vaults would incorporate two beamlines: both beamlines would initially provide low energies (~5 MeV) electron beams.

S-band beamline: pursue high-risk university-driven R&D (e.g. novel cathodes (FEA), bunch shaping, multifrequency guns,…)





S-band facility, Courtesy from ME dept NIU

L-band beamline: perform R&D in support to the NML facility (new 1.3 GHz gun geometry, higher E-field guns, bunch shaping, cathode studies)

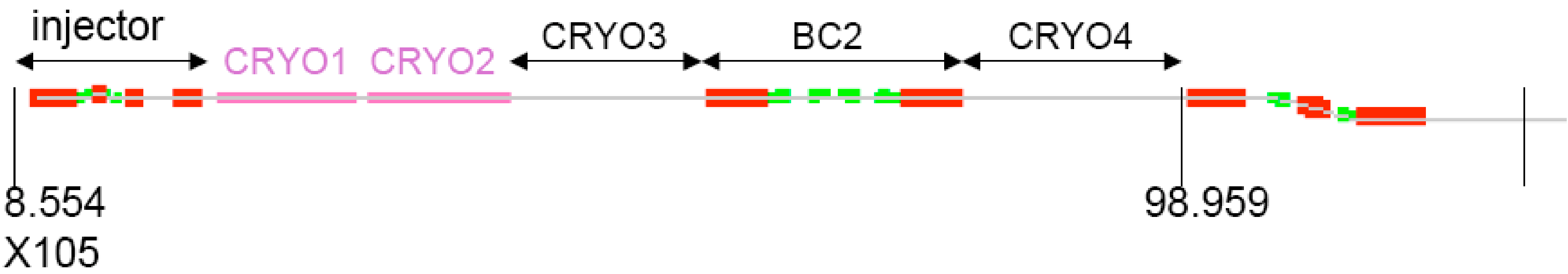
Non-photoinjector activities

Aside from housing the photoinjector, other activities are ongoing in the A0 building:

- Superconducting RF Cavity Development
  - R&D on 1.3 GHz and 3.9 GHz single cell cavities - 13 runs in FY10 to date
  - Evaluation of 3.9 GHz 9-cell cavities provided for DESY's FLASH facility
  - Preparation of spare cavities for same
- Cold (2K) vacuum evaluation of explosively bonded Nb-SS pipe assemblies as part of an agreement with JINR (Dubna) & INFN for possible future SRF pipe assemblies
- Warm coupler conditioning of prototype 3.9 GHz input couplers for the European XFEL (only facility in the world to support this effort)
- Development of 2nd Sound/Oscillating Superleak Transducers to identify quench locations

ADDITIONAL MATERIAL: SPECIFICS on NML

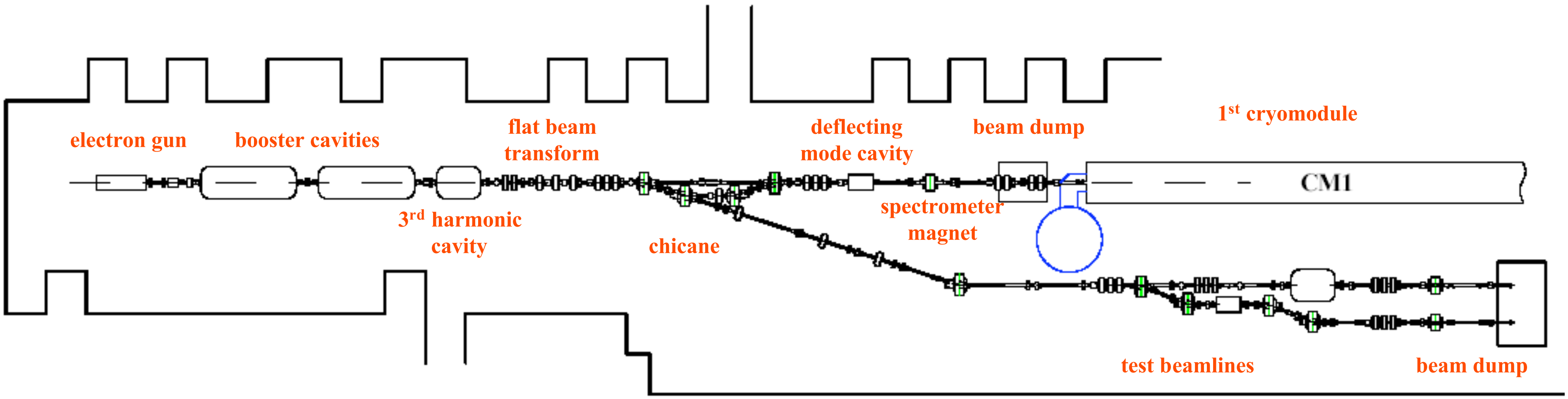
NML phases

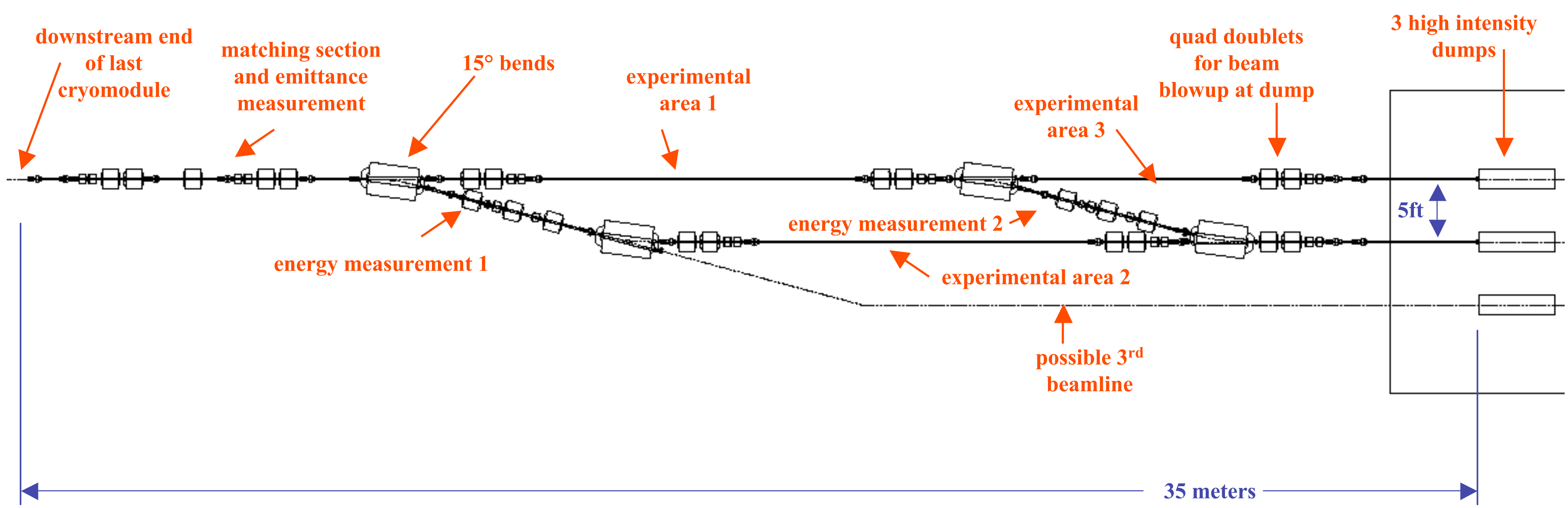


- Phase 1 (first beam): two cryomodules
- Phase 2: 3 cryomodules +BC2 (?)
- Phase 3: 3 cryomodules + BC2 + 4th crymodule

- Five user areas:
  - 2 at low energy (~ 40 MeV)
  - 3 at high energy

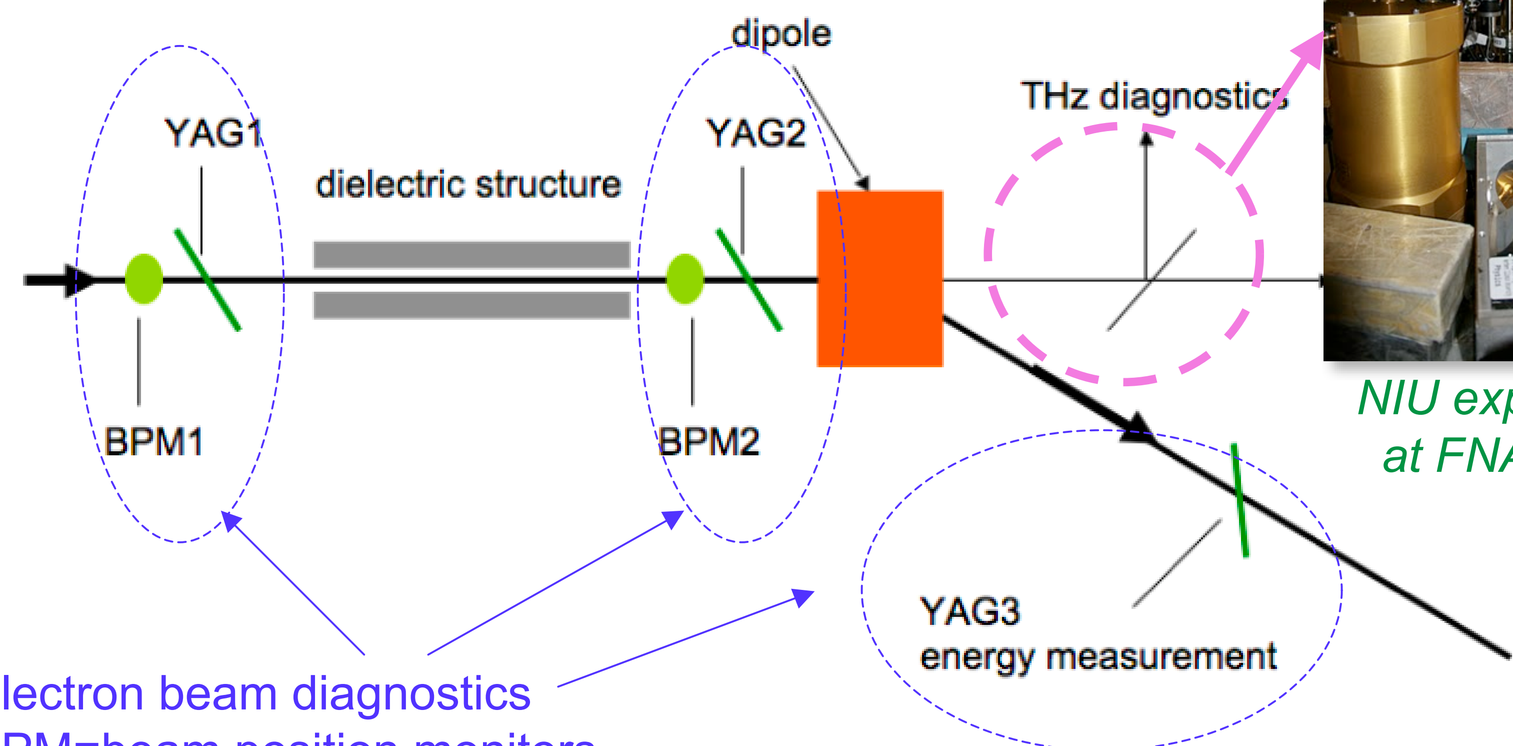
NML user areas

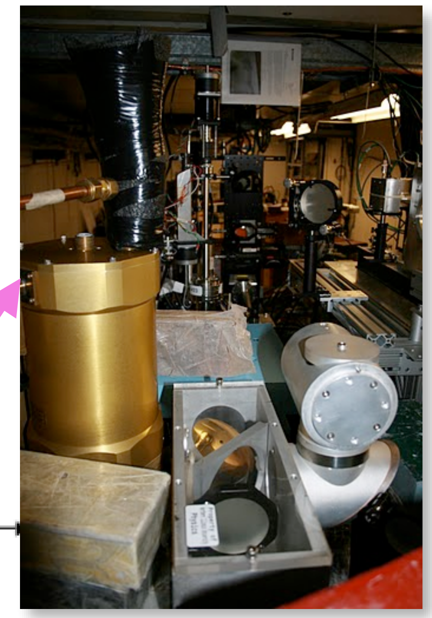




Generic acceleration test

- Diagnostics
  - energy gain and loss
  - Cherenkov radiation





NIU experiment at FNAL's A0

Electron beam diagnostics
BPM=beam position monitors
YAG= Ce-doped Yttrium Aluminum Garnet or Optical transition radiation screens

Anticipated parameters

parameter	ILC RF unit test	range	comments
bunch charge	3.2 nC	10's of pC to >20 nC	minimum determined by diagnostics thresholds; maximum determined by cathode QE and laser power
bunch spacing	333 nsec	<12 nsec to 0.1 sec	lower laser power at minimum bunch spacing; max is 1 bunch per bunch train
bunch train length	1 msec	1 bunch to 1 msec	maximum limited by modulator and klystron power
bunch train repetition rate	5 Hz	0.1 Hz to 5 Hz	minimum may be determined by gun temperature regulation and other stability considerations
norm. transverse emittance	~30 mm-mrad	<1 mm-mrad to ~100 mm-mrad	maximum will be limited by aperture and beam losses; without bunch compression emittance is ~5 mm-mrad @ 3.2 nC
RMS bunch length	1 ps	~30 fs to ~20 ps	minimum obtained with Ti:Sa laser; maximum obtained with laser pulse stacking
peak bunch current	3 kA	10 kA (?)	depends on performance of bunch compressor
injection energy	40 MeV	~5 (?) MeV – 50 MeV	may be difficult to transport 5 MeV to the dump; maximum is determined by booster cavity gradients
high energy	810 MeV	40 (?) MeV – 1500 MeV	may be difficult to transport 40 MeV through the cryomodules; radiation shielding issues limit the maximum

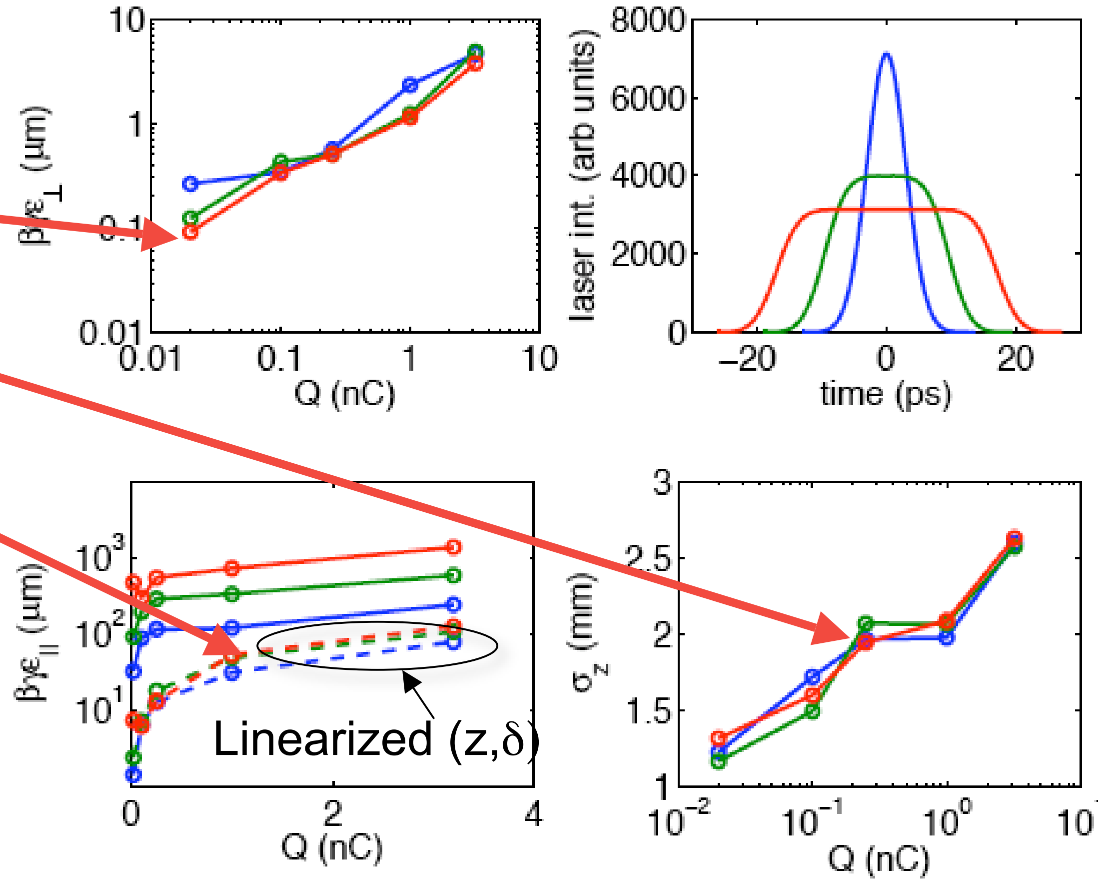
Photoinjector performances

- Optimization of NML Injector supports the production of bright electron beams
- Scaling for Gaussian laser distribution is

$$\varepsilon_\perp \approx 2.11 Q^{0.69}$$

$$\sigma_z \approx 2.18 Q^{0.13}$$

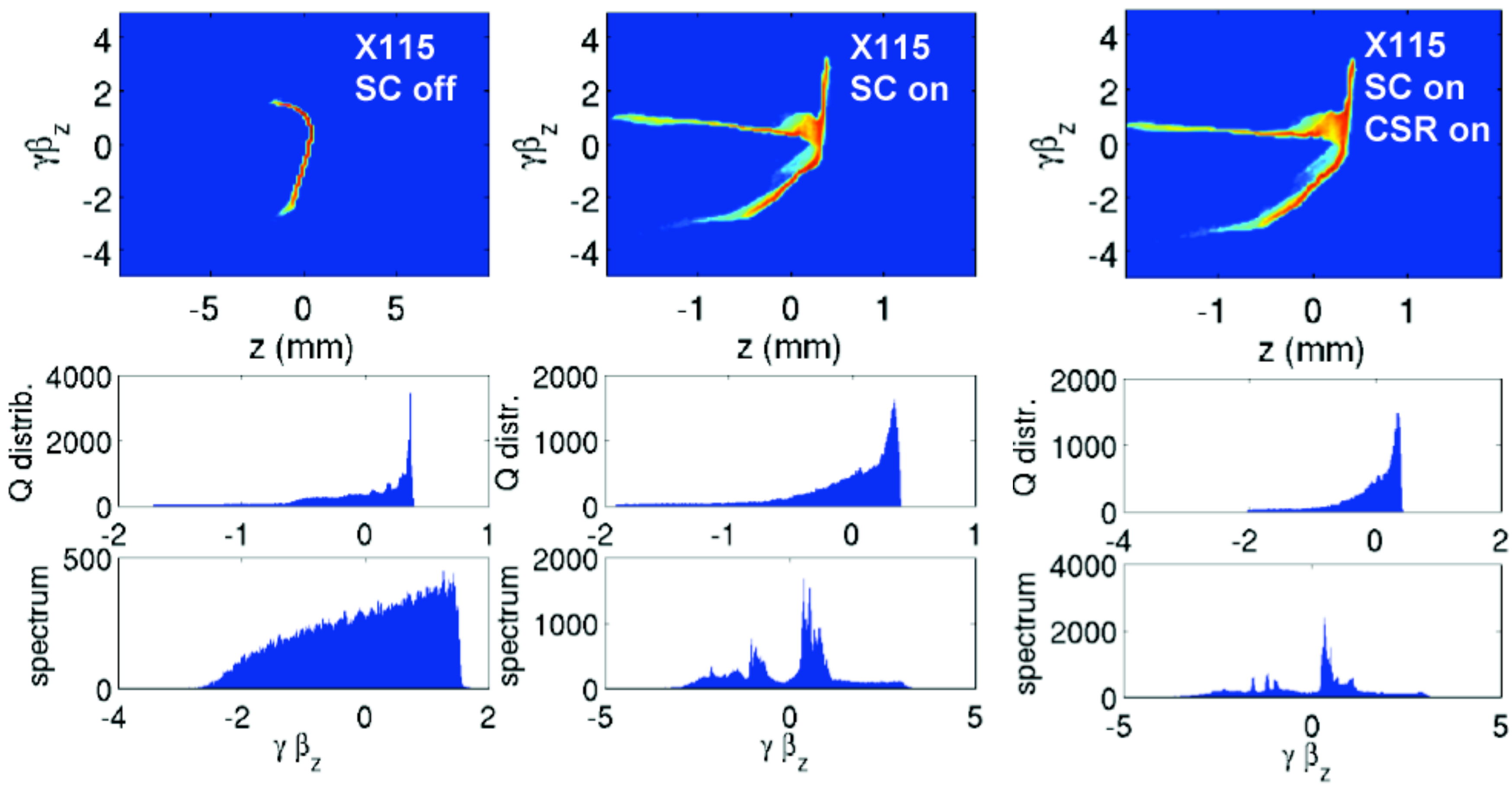
$$\varepsilon_z \approx 30.05 Q^{0.84}$$



- At 1 nC we estimate $\varepsilon_x/\varepsilon_y$=31/0.06 ~ 500 σ_δ=1.7x10^{-4} (40 MeV)

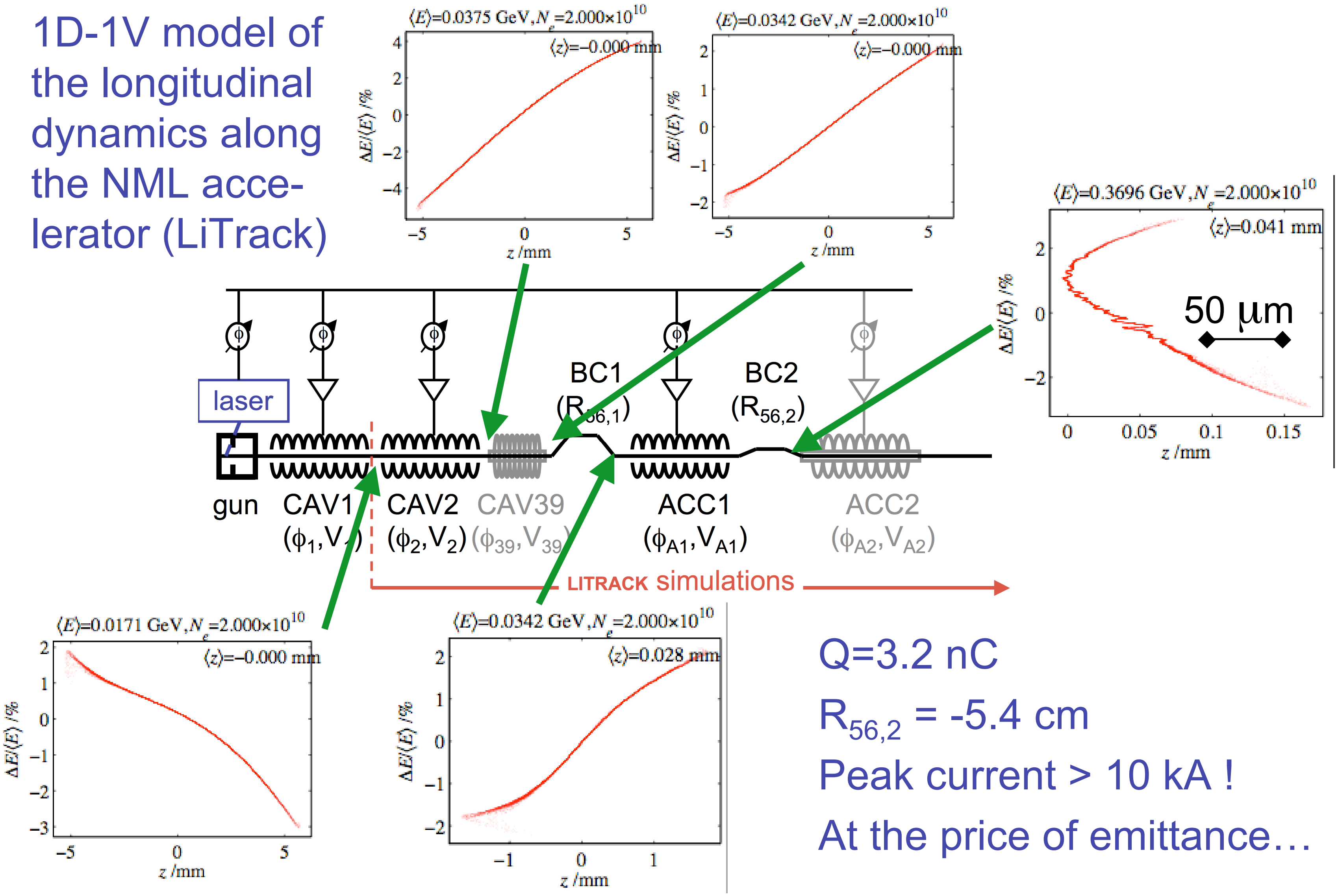
Single-stage compression : issues

- Fully compressing the beam at 40 MeV results in large phase space dilutions due to collective effects (predominantly space charge).



Two-stage compression

- 1D-1V model of the longitudinal dynamics along the NML accelerator (LiTrack)



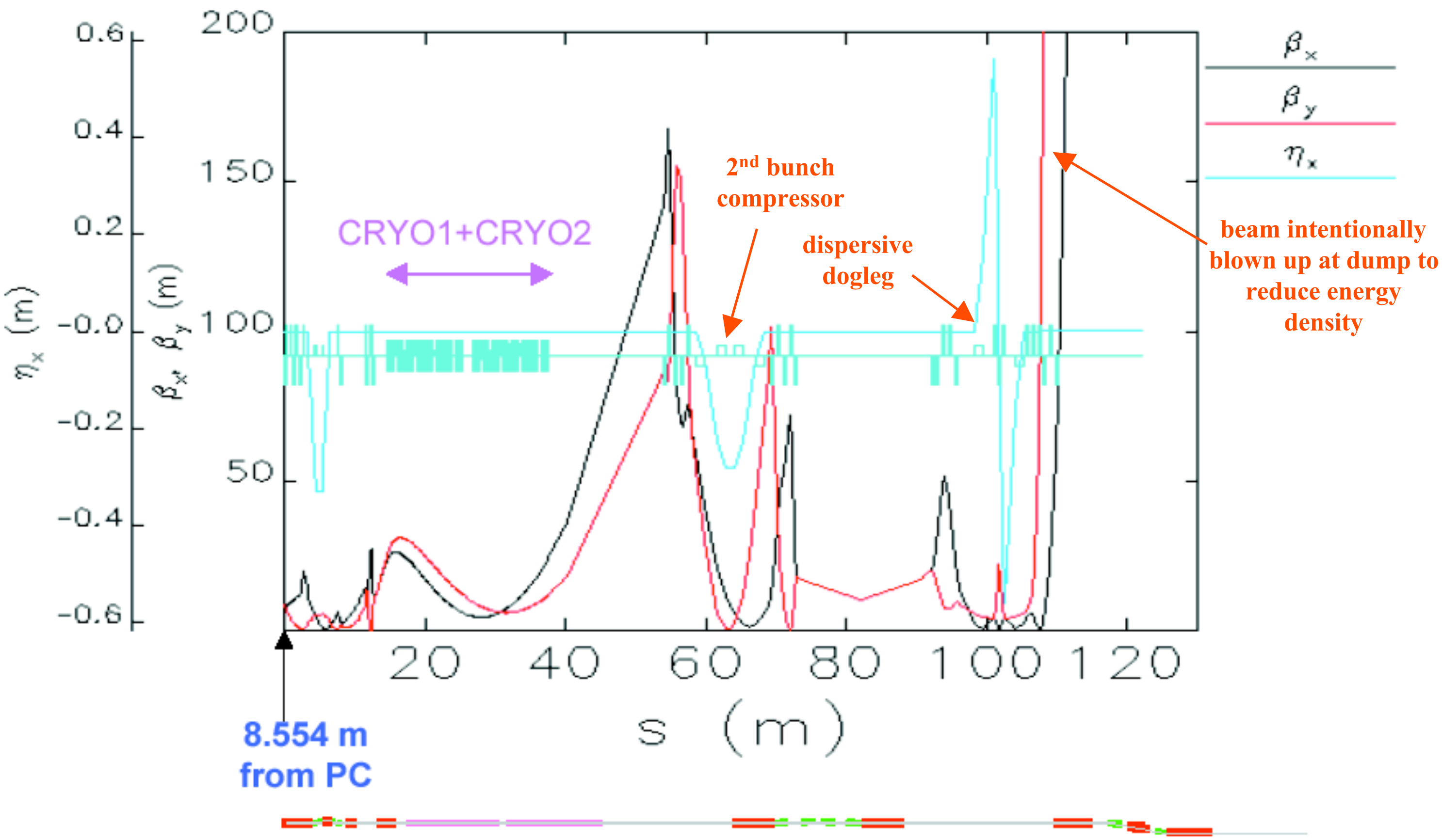
Q=3.2 nC

$R_{56,2}$ = -5.4 cm

Peak current > 10 kA !

At the price of emittance…

Optics with two cryomodules (phase 1)



Example of proposed experiments (1)

NEED high-peak-current low-emittance beam

WOULD benefit from compressed beam with low emittance

Experiment	Energy	proponent	Motivation/ application
Long. → transverse EEX	low	FNAL/ANL	Proof-of-principle; possible application in FELs and X-ray sources
Slit microbunching generation	low	FNAL	For wakefield investigations;
Ellipsoidal beam generation	low (egun)	NIU/FNAL	Low emittance beams
Microbunching investigations	low, high?	ANL/FNAL	Beam physics; diagnostics
ODR instrumentation development	high	ANL/FNAL	Non-invasive emittance diagnostic
Flat beam transform and image charge undulator	low	FNAL/NIU	Compact UV/ soft X-ray source
Flat beam transform	high	LANL	Proof-of-principle for MaRIE
Emittance exchange	high	LANL	Proof-of-principle for MaRIE
6-D muon cooling	high	IIT/FNAL	Proof-of-principle for muon collider
Optical stochastic cooling	high	IIT	Proof-of-principle; muon collider
γ-ray enhancement by crystal channeling	high	ANL	Unpolarized e^+ source
High gradient wakefield acceleration with dielectric structures	Low?, high?	ANL/NIU	many

Example of proposed experiments (2)

Experiment	Energy	proponent	Motivation/ application
PIC lattice test	high	FNAL/Muons Inc	Muon collider
Reverse emittance exchange	Low?, high?	FNAL/Muons Inc	Muon collider
Dielectric Wall Accelerator section	Low? high?	FNAL	Muon collider; induction linac
Measure plasma wakes with long bunch trains	high	USC	Application to 2-beam plasma acceleration
Measure plasma wakes with laser interferometry	high	USC	Application to 2-beam plasma acceleration
Photoproduction of muons @ 300 MeV	high	FNAL	Homeland security; verify production model
Test of integrable beam optics	high	FNAL	Proof-of-principle; future high current proton machines