Electron beam experiments at FAST in 2017

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Outline

1. Introduction and updates
   - Experiments at FAST in 2016
2. Canonical Angular Momentum (CAM) dominated beams
   - Theoretical background
   - Beam moments gymnastics
   - Round-to-flat transformation
3. Experimental plan for Run 2017
   - Flat beam generation
   - THz radiation generation
4. Additional materials

Introduction

IOTA/FAST facility - high-brightness 300 MeV electron beams

- Under comissioning (linac will be ready in 2017)
- Collaboration with Northern Illinois University
- Several experiments planned in 2017

Snapshot of recent work

Future experiments

- Magnetized and flat beam generation
- Flat beam compression
- THz radiation generation from compressed flat beams

1.3 GHz SRF accelerating cavity transport studies:

- Analysis and Measurement of the Transfer Matrix of a 9-cell 1.3-GHz Superconducting Cavity // arXiv:1701.08187; accepted in Phys. Rev. Accel. & Beams (2017)
- A High-Level Python Interface to Fermilab ACNET Control System // Proc. of NAPAC16, in press (2016)

Channeling radiation experiment:

- Commissioning and First Results From Channeling Radiation At FAST // Proc. of NAPAC16, in press (2016)

UV laser shaping experiments:

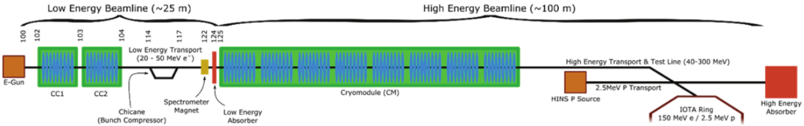
- Generation of homogeneous and patterned electron beams using a microlens array laser-shaping technique //FERMILAB-TM-2634-APC
- A Simple Method for Measuring the Electron-Beam Magnetization // Proc. of NAPAC16, in press (2016)

Simulations and potential experiments:

- Cascade Longitudinal Space-Charge Amplifier at FAST// Nucl. Instrum. Meth A 819, **144** (2016)
- Numerical Study of Three Dimensional Effects in Longitudinal Space-Charge Impedance// Proc. of IPAC15, p. 1853 (2015)

and MORE...

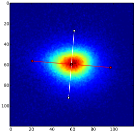
FAST beamline



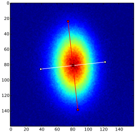
- FAST injector - 1.3 GHz SRF linac
- Charge range: 10 fC - 3.2 nC per pulse (Cs:Te cathode)
- Nominal bunch length 5 ps
- Includes chicane and skew-quadrupole adapter (RTFB)
- Detailed description of the facility: Antipov, S., *et al*, JINST, **12**, T03002 (2017).

Emittance measurements summary

Electron beam emittance was meassured via simple geometrical ($\epsilon = \frac{\sigma_1}{z}\sqrt{\sigma_2^2 - \sigma_1^2}$) and quadrupole scan technique

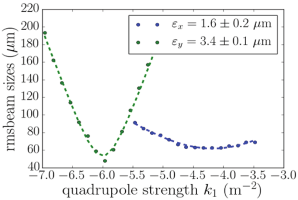


X120



X111

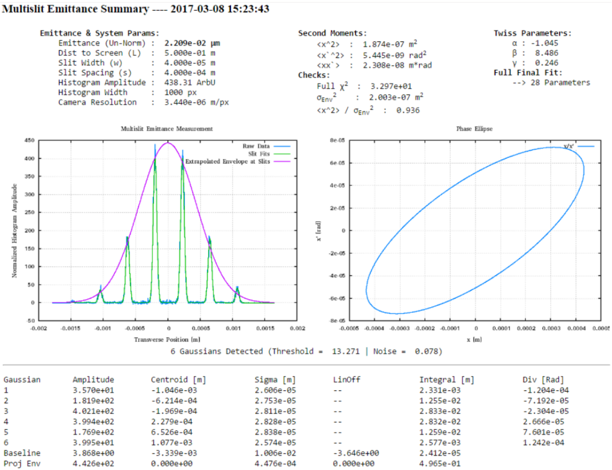
Charge, Q	ϵ_{nx}, μm	ϵ_{ny}, μm
<1 pC	0.25 ± 0.1	0.3 ± 0.1
50 pC	1.6 ± 0.2	3.4 ± 0.1



Reference: Data by A. Romanov, P. Piot; Proc. of NAPAC16: TUPOA19; Green, A. MS Thesis, NIU (2016)

- Emittance is not yet optimized (**will be**)
- Quadrupole scan data analysis in progress; will be reported separately
- Multislit method will be used to confirm/update

New multislit tool



Multislit Emittance Summary ---- 2017-03-08 15:23:43

Emittance & System Params:
Emittance (Un-Norm) : **2.209e-02 µm**
Dist to Screen (L) : 5.000e-01 m
Slit Width (w) : 4.000e-05 m
Slit Spacing (s) : 4.000e-04 m
Histogram Amplitude : 438.31 ArbU
Histogram Width : 1000 px
Camera Resolution : 3.440e-06 m/px

Second Moments:
<x^2> : 1.874e-07 m^2
<x`^2> : 5.445e-09 rad^2
<xx`> : 2.308e-08 m*rad
Checks:
Full χ^2 : 3.297e+01
σ_{Env}^2 : 2.003e-07 m^2
<x^2> / σ_{Env}^2 : 0.936

Twiss Parameters:
α : -1.045
β : 8.486
γ : 0.246
Full Final Fit:
--> 28 Parameters

6 Gaussians Detected (Threshold = 13.271 | Noise = 0.078)

```
Gaussian    Amplitude    Centroid [m]    Sigma [m]    LinOff       Integral [m]    Div [Rad]
1           3.570e+01    -1.046e-03      2.606e-05    --           2.331e-03       -1.204e-04
2           1.819e+02    -6.214e-04      2.753e-05    --           1.255e-02       -7.192e-05
3           4.021e+02    -1.969e-04      2.811e-05    --           2.833e-02       -2.304e-05
4           3.994e+02    2.279e-04       2.828e-05    --           2.832e-02       2.666e-05
5           1.769e+02    6.526e-04       2.838e-05    --           1.259e-02       7.601e-05
6           3.995e+01    1.077e-03       2.574e-05    --           2.577e-03       1.242e-04
Baseline    3.868e+00    -3.339e-03      1.006e-02    -3.646e+00   2.412e-05
Proj Env    4.426e+02    0.000e+00       4.476e-04    0.000e+00    4.965e-01
```

D. Edstrom, FAST meeting 03/10/2017 slides

Why CAM beams?

1. Conventional application - electron cooling (Derbenev, Ya., UM-HE-98-04-A); proposed for JLEIC and other facilities
2. Emittance partitioning via flat beams (interest of ILC group)
3. Supressing microbunching instabilities in IOTA (collaboration with R. Li, JLab)
4. Several possible radiation experiments (dielectric structures, microundulators, channeling, etc.) can be done at FAST

CAM beams production at FAST is an important first step

Motivation and goals

Motivation: *flat-beam generation, compression, and application to the generation of tunable THz narrowband radiation.*

Goals:

1. Produce canonical angular momentum dominated (CAM) beams (pionereed at Fermilab A0)
2. Set up and optimize on the fly the round-to-flat beam transformer (RTFB)
3. Generate extreme eigen-emittances ratio (> 300) (**NEW**)
4. Demonstrate compression of flat beam and investigate emittance dilution during the process (**NEW**)
5. Demonstrate the use of flat beam to generate THz radiation using the mask method (**NEW**)

Busch's theorem

Relativistic Hamiltonian of the particle $(m, q, \mathbf{P})$:

$$H = c(m^2c^2 + (\mathbf{P} - q\mathbf{A})^2)^{1/2} + q\phi - mc^2,$$

where $\phi, \mathbf{A}$ - scalar (vector) potential.

Note, that:

$$-\frac{\partial H}{\partial \theta} = \frac{dP_\theta}{dt} = 0,$$

therefore θ is a cyclic variable and P_θ is a **constant of motion**.

$$P_\theta = \gamma m r^2 \dot{\theta} + qrA_\theta = const$$

Conservation of canonical angular momentum or Busch's theorem

CAM conservation

Total canonical angular momentum
of a charged particle in symmetric magnetic field is conserved

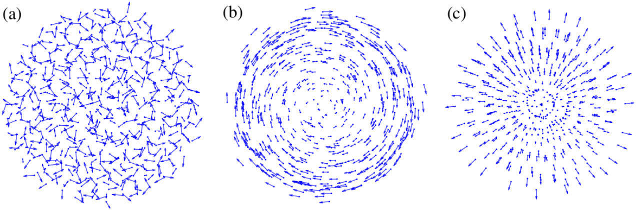
$$L = \gamma m r^2 \dot{\theta} + \frac{1}{2} e B_z(z) r^2 \tag{1}$$

The norm of $|\vec{L}|$ can be computed as $L = |\vec{r} \times \vec{p}| = x p_y - y p_x$.
Redefine as $< L >= e B_{0z} \sigma_0^2$:

$$\mathcal{L} \equiv < L > / 2\gamma mc = const$$

where B_{0z} is the field at the cathode, σ_0 is the RMS spot at the cathode and σ is the RMS beam size.
The particle total mechanical momentum $\vec{p} = p_r \widehat{\mathbf{r}} + p_\theta \widehat{\theta} + p_z \widehat{\mathbf{z}}$ has non-zero $\widehat{\theta}$-component resulting in **CAM-dominated beam**.

CAM-dominated beams



a) Emittance-dominated beam (ϵ_u)
b) CAM-dominated beam (magnetization $\mathcal{L} \equiv < L > /2\gamma mc$)
c) Space charge dominated beam (space charge parameter K)

$$\sigma'' + k_l^2\sigma - \frac{K}{4\sigma} - \frac{\epsilon_u^2}{\sigma^3} - \frac{\mathcal{L}^2}{\sigma^3} = 0,$$

$k_l = eB_z(z)/2\gamma mc$ is Larmor wavenumber, $K = 2I/I_0\gamma^3$ is the perveance, I and I_0 are the beam and Alfven current respectively

4D-emittance, ϵ_u

Define 4D-emittance as $\epsilon_{4D} = \epsilon_u^2 = \sqrt{|\Sigma|}$, then:

$$\Sigma_i = \begin{pmatrix} \sigma^2 & 0 & 0 & \kappa\sigma^2 \\ 0 & \kappa^2\sigma^2 + \sigma'^2 & -\kappa\sigma^2 & 0 \\ 0 & -\kappa\sigma^2 & \sigma^2 & 0 \\ \kappa\sigma^2 & 0 & 0 & \kappa^2\sigma^2 + \sigma'^2 \end{pmatrix},$$

where $\epsilon_u = \sigma\sigma'$ (doesn't depend on κ) and $\kappa = \mathcal{L}/\sigma^2$.

Total 4D-emittance is conserved

$$det(J\Sigma - i\epsilon_\pm I) = 0,$$

where I and J are respectively unit and symplectic unit matrix.

Emittance ratio

Eigenemittances:

$$\epsilon_\pm = \sqrt{\epsilon_u^2 + \mathcal{L}^2} \pm \mathcal{L} \to \epsilon_+ \approx 2\mathcal{L}; \epsilon_- \approx \frac{\epsilon_u^2}{2\mathcal{L}}$$

Emittance ratio or "flatness":

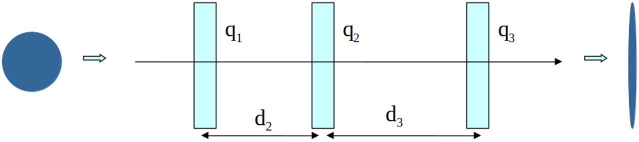
$$\frac{\epsilon_+}{\epsilon_-} = \frac{4\mathcal{L}^2}{\epsilon_u^2} = \frac{1}{p_z^2} e^2 B_{0z}^2 \frac{\sigma_0^2}{\sigma_0'^2}$$

Example calculation: $\sigma_+ = \sqrt{\beta_{x,y}\epsilon_+} \to \epsilon_u$=2 μm $\to \epsilon_+ = 40\mu$m, $\epsilon_- = 0.1\mu$m $\to \beta_{x,y} = 8$m, $\sigma_+ = 1.8$mm and $\sigma_- = 0.09$mm

*Burov, A., Phys. Rev. E **66**, 016503 (2002)*
*Kim, KJ., PRSTAB, **6**, 104002 (2003).*

RTFB transfomer

Round-To-Flat Beam transformer



Let the transformer be described by $R'_{RTFB} = Q_3 D_3 Q_2 D_2 Q_1$, where $D_i = \begin{pmatrix} 1 & d_i \\ 0 & 1 \end{pmatrix}$ and $Q_i = \begin{pmatrix} 1 & 0 \\ \pm q_i & 1 \end{pmatrix}$ drift and quadrupole transfer matrix respectively.

Consider three quadrupoles skewed at 45 deg. as $R_{RTFB} = M_{-45} R'_{RTFB} M_{45}$, *where* M_ϕ *is rotation matrix*

Beam moments gymnastics

Let the RTFB transfomer transport be described by $R = \begin{pmatrix} A & B \\ C & D \end{pmatrix}$

A,B,C,D - are 2×2 matrices. Then beam matrix $\Sigma_i = \begin{pmatrix} \Sigma_{XX} & \Sigma_{XY} \\ \Sigma_{YX} & \Sigma_{YY} \end{pmatrix}$ is transformed as $\Sigma_f = R\Sigma_i\tilde{R}$. Setting $\Sigma_{XY} = 0$ leads to:

$$A\Sigma_{XX}\tilde{C} + A\Sigma_{XY}\tilde{D} + B\tilde{\Sigma}_{XY}\tilde{C} + B\Sigma_{YY}\tilde{D} = 0 \qquad (2)$$

Round beam → $\Sigma_{XX} = \Sigma_{YY} = \Sigma_0$ and $\Sigma_C = -\tilde{\Sigma}_{XY}$

Σ-matrix diagonalization

4×4 matrix R_{RTFB} can be also represented in 2×2 block form as:

$$R_{RTFB} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} a+b & a-b \\ a-b & a+b \end{pmatrix}$$

or in non-rotated coordinate system:

$$R'_{RTFB} = \begin{pmatrix} a & 0 \\ 0 & b \end{pmatrix}$$

Then rewrite Eq. 2 as: $A\Sigma_0\tilde{B} + B\Sigma_0\tilde{A} + A\Sigma_C\tilde{A} + B\tilde{\Sigma}_C\tilde{B} = 0.$

Guess solution $A_+ = A + B$ and $A_- = A - B$ such that
$A_- = A_+ S$, where S some **symplectic** matrix
(can be defined by Σ_{XX}, Y. Sun PhD thesis, FNAL (2005))

RTFB solutions

FAST quadrupoles: $K = (10.135 \times 40\, I_q)/(1.8205 \times p\,[MeV/c])$, $L_{eff} = 17cm$

$$q_1 = \pm\sqrt{\frac{-d_2(d_T s_{21} + s_{11}) + d_T s_{22} + s_{12}}{d_2 d_T s_{12}}},$$

$$q_2 = \frac{(d_2 + d_3)(q_1 - s_{21}) - s_{11}}{d_3(d_2 q_1 s_{11} - 1)},$$

$$q_3 = \frac{d_2(q_2 - q_1 q_2 s_{12}) - s_{22}}{d_2(d_3 q_2 s_{22} + q_1 s_{12} - 1) + d_3(s_{12}(q_1 + q_2) - 1)}$$

Least-squares method can be used for correcting (q_1, q_2, q_3) for chromaticities and other second order effects

S matrix definition

Matrix S can be defined as correlation:

$$Y = SX \to S = \Sigma_{YX}\Sigma_{XX}^{-1}$$

where X, Y are 2×1 phase space vectors.
Alternatively, it can be defined as:

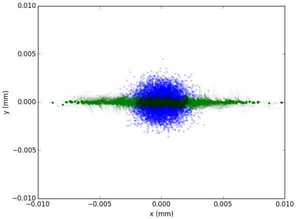
$$S = \pm\frac{1}{|\Sigma_{XX}|}J\Sigma_{XX}^{-1} = \mp\frac{1}{\epsilon}\begin{pmatrix} 0 & -\sigma^2 \\ \kappa^2\sigma^2 + \sigma'^2 & 0 \end{pmatrix}$$

(Proof can be found in Y. Sun PhD thesis, FNAL (2005))

RTFB solutions: Example

$$Case : S = \begin{pmatrix} 0 & -1.28 \\ 0.781 & 0 \end{pmatrix}$$

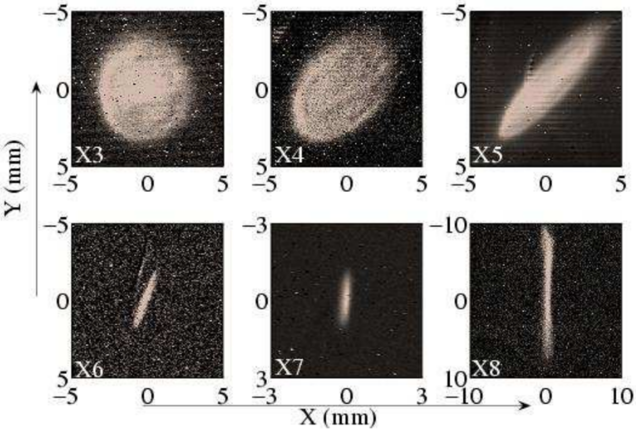
Model	$q_1,\ m^{-1}$	$q_2,\ m^{-1}$	$q_3,\ m^{-1}$
Linear model	1.84	-1.2	0.23
Elegant simplex (1000 p.)	1.88	-1.39	0.20



- Linear model gives a good first guess
- Elegant simulations account for chromaticity
- Quadrupole solutions based on statistical properties of the distribution
- Calculation can be done for bunch slice (include analytical SRF cavity model)
- Note it is different from Thrane, E., *et al*, Proc. of LINAC02

CAM removal example

Fermilab A0 CAM removal demonstration:

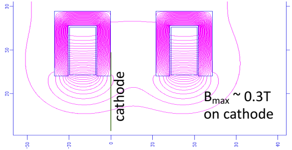


Plan for Run 2017

1. Optimize round beam emittance via multislit tool
2. Start with low B_{0z} value and demonstrate RTFB transformation
3. Switch to high B_{0z} configuration and optimize RTFB adapter
4. Produce highly asymmetric beams at 2.2 nC (interest of JLEIC group)
5. Study flat beam compression in the chicane by using multislits at X107 and X118 locations
6. Proceed to THz radiation generation using multislit in bunch compressor

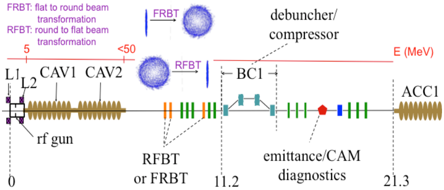
FAST flat beam experiment

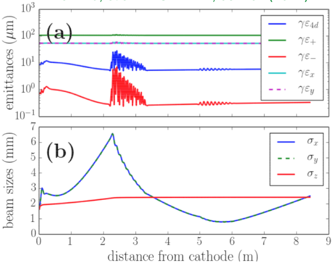
- **Experiment will primarily focus on RTFB**
- Characterization of magnetized beams will be a byproduct (many applications)
- Beam parameters comparable to required for electron cooling
- B_{max}=0.3 Tesla (**strong!**)



P. Piot, IPAC13 (2013)

J. Zhu, et al. PRSTAB 17, 084401 (2014)



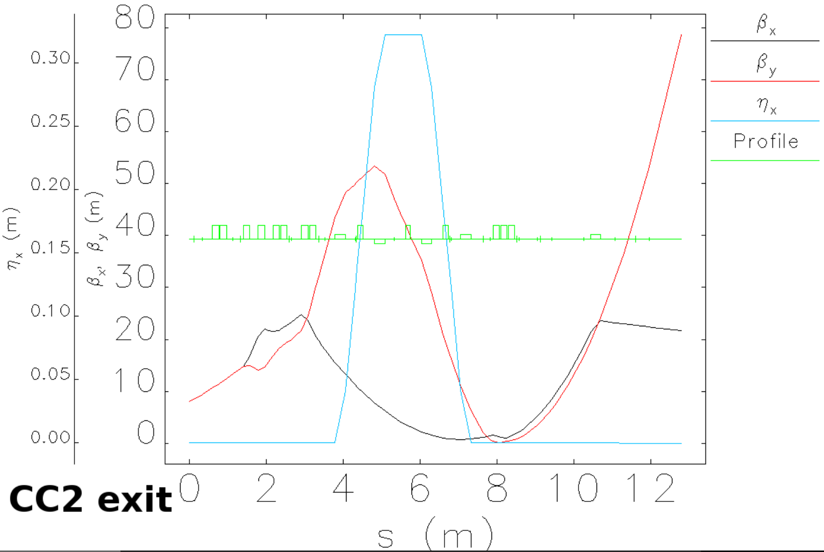


Beam parameters

Parameter	**Value**	**Units**
Initial emittance (norm.)	<2	μm
Beam energy	50	MeV
Slice energy spread	<5	keV
Charge	200	pC
Bunch length	5	ps
Beta-function (CC2 exit)	8	m
Dipole bending radius	0.958	m
Dipole length	0.301	m
Dipole angle	18	degrees
R_{56}	-0.18	m

Beam-based alignment: Romanov, A., arXiv:1703.09757 [physics.acc-ph]

Beam optics: Example



CC2 exit

Measurement algorithm

$$\text{MAM} \rightarrow \text{CAM} \rightarrow \mathcal{L} \rightarrow \Sigma \rightarrow \text{RTFB} \rightarrow \epsilon_+/\epsilon_-$$

Assumption:

Canonical Angular Momentum (CAM) is fully trasferred to Mechanical Angular Momentum (MAM)

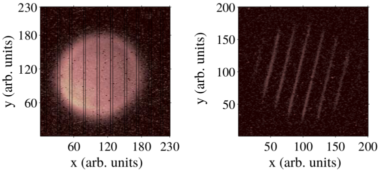
Two methods of measuring CAM:

1. Using multi-slits, observe relative shear of the beamlets
2. Using microlens arrays, produce multi-beam and observe rotation

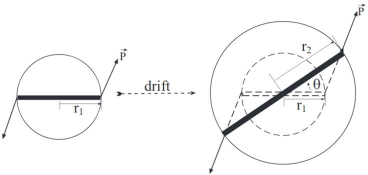
MAM measurement (A0 method)

Fermilab A0 2004 Run (PRSTAB **7**, 123501 (2004)):

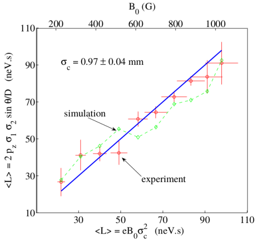
Multislit beamlets



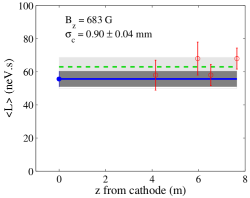
Angular sheering



$< L >= 2p_z \frac{\sigma_1\sigma_2 \sin\theta}{D}$, where p_z is momentum, D is the drift length



Conservation of $\mathcal{L}$

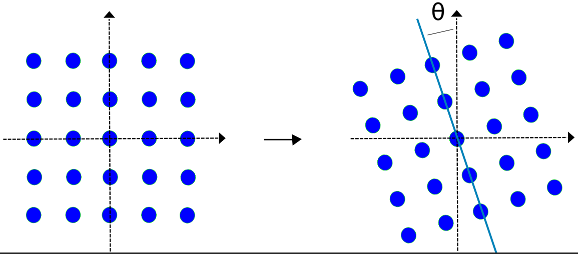


MAM measurement (NEW method)

Goal: Measure CAM without inserting any diagnostic hardware in the beamline except YAG viewers

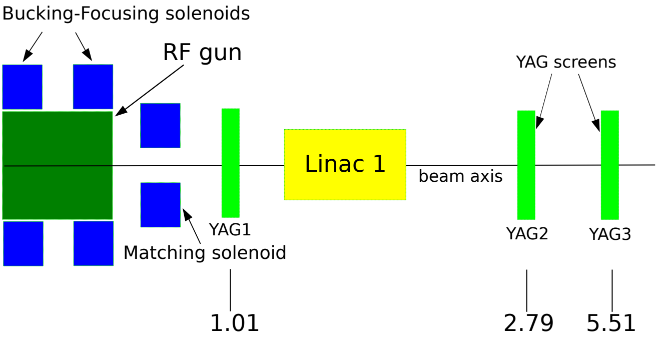
Method:

1. Create electron beam that looks like array of thin dots
2. "Magnetize" the beam with solenoids at the cathode
3. Infer mechanical momentum by measuring the rotation on the screen



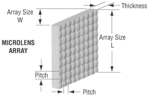
Verification at AWA (ANL)

AWA 2016/17 Run (submitted to PRAB):

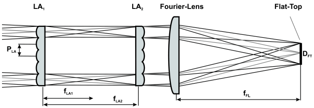


Multi-beam projected on the cathode, two YAG screens used to determine relative rotation → calculate $\mathcal{L}$.

Method to make multi-beam



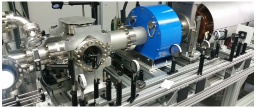
MLA plate



Layout for laser homogenizer

Resulting distribution can be flat-top or multi-beam

Joint collaboration with Northern Illinois University



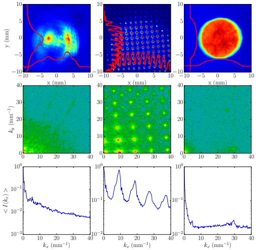
Optical transport requires custom imaging solution

Advantages of the MLA:

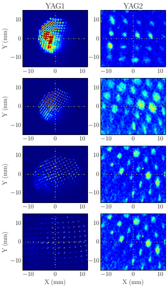
1) Flat-top homogenized laser spot
2) Reduction of beam emittance by factor of 3!
3) Multi-beam pattern generation
4) Available off-shelf!

Homogenized beam **More intensity!**

Regular beam clipped with iris



Multi-beam



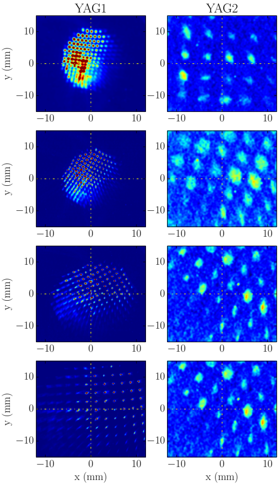
Both beams were produced at 18/50 MeV

References:

FERMILAB-TM-2634-APC (arXiv:1609.01661), FERMILAB-CONF-16-460-APC (Proc. of NAPAC'16)

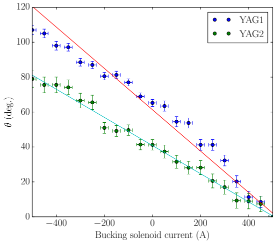
Experimental results

Multi-beam shearing

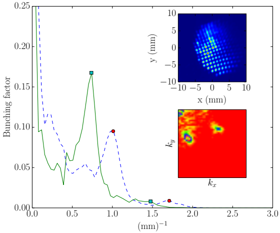


- Multi-beams are generated via microlens array laser shaping technique (submitted to PRAB)
- Beam is magnetized at the cathode and observed at two locations
- Angle of rotation and beamlet spacing is calculated
- $L = \frac{p_z}{D}\left[\left(\frac{n}{2}a_1\right)\right]^2(m\sin\theta)$, n is number of beamlets, a_1 beamlet pitch, $m = a_2/a_1$ is the magnification, θ is skew angle.

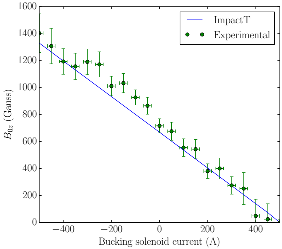
Experimental results cont.



Skew angle θ



Resulting value of B_{0z} compared with IMPACT-T simulations



- Easy setup (laser only)
- Rough estimate even with one YAG screen
- Due individual beam dynamics of each beamlet (30 fC), error bars are big (can be reduced)
- Improvement: use only central portion of the beamlet formation

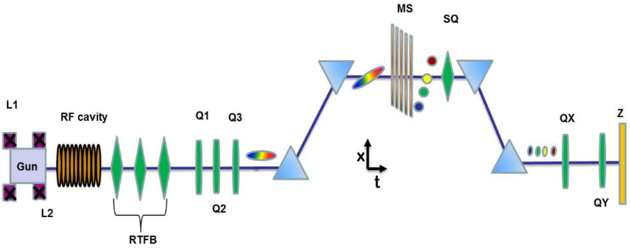
Comparison and verdict

- Both methods provide a way of measuring $\mathcal{L}$, so the resulting settings for RTFB can be computed
- Method 1 is *default* for Run 2017 (assuming hardware installation is completed)
- Method 2 verified experimentally (details in Halavanau, A., FERMILAB-CONF-16-460-APC)
- Implementation of Method 2 at FAST is relatively straightforward

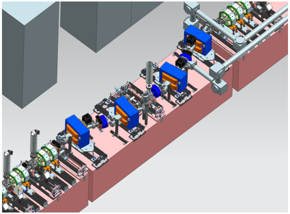
Flat beam conclusions

1. 20 nm horizontal emittance (below thermal) at FAST
2. Analytical model for RTFB with online optimization via Elegant
3. Start-to-end full bunch simulations on NIU GAEA cluster (**work in progress**)
4. Parameter space study via IMPACT-T on NIU NICADD cluster (**work in progress**)
5. Possible neural network RTFB optimizer (with A. Edelen)

Round beam compression



Schematics of the experiment



Bunch compressor

- Beam is focused by triplet ($Q1$, $Q2$, $Q3$) into the chicane
- Multislit mask (MS) is inserterd to introduce energy modulation
- Energy modulation is converted into density modulation
- Slit spacing is in THz range
- FAST has interferometer and detector installed at X121 location

Theoretical considerations

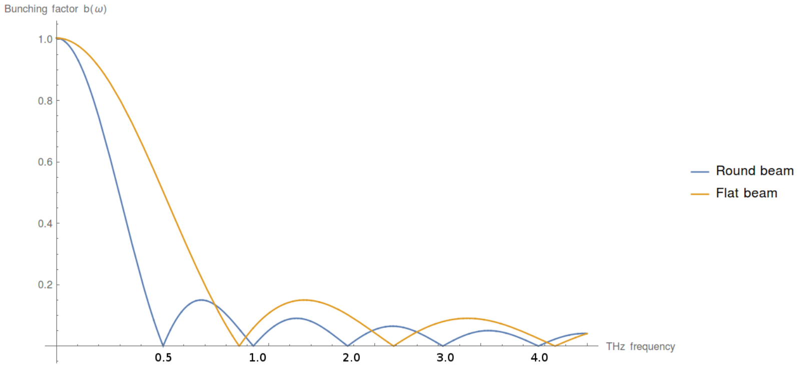
Bunching factor: $b(\omega) = \frac{1}{N} | \sum_n \exp(-i\omega t_n)|$. N - total number of particles, n - particle index number. Radiation spectrum:

$$\left(\frac{d^2 W}{d\omega d\Omega} \right)_{total} = [N + N(N-1) b(\omega)^2] \left(\frac{d^2 W}{d\omega d\Omega} \right)_e ,$$

where $\left(\frac{dW}{d\omega d\Omega} \right)_e$ represents the single-electron radiation spectral fluence associated to the considered electromagnetic process (*Transition Radiation*).

Further analytical consideration **in progress**

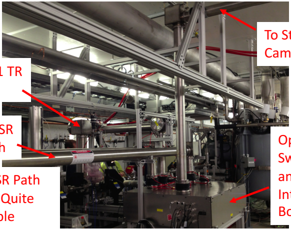
Single bunch contribution



- Lower emittance results in enhancement and detection of:
- With existing detector (up to 3.5 THz)
- With bolometer (10 THz and more)

Frequency-domain LPS diagnostics

- Streak Camera
- Martin-Puplett Interferometer
- 1 Transition Radiation Source
- 2 Synch. Radiation Sources
- Ceramic Gap Schottky Diode
- Bolometer



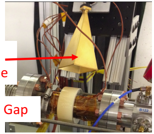
To Streak Camera

X121 TR Path

D3 SR Path

D4 SR Path Not Quite Visible

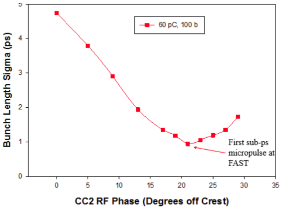
Optical Switching and Interferometer Box



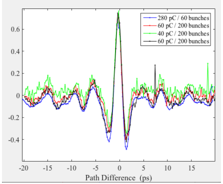
Horn Antenna with Waveguide

Ceramic Gap

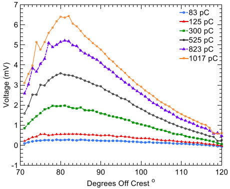
Streak Camera Bunch Length vs. RF Phase



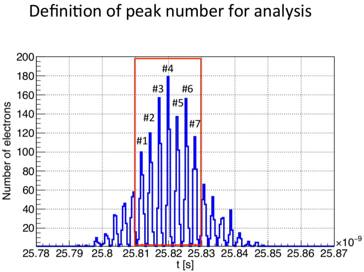
Interferometer Autocorrelation Traces



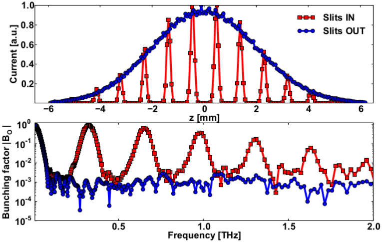
Ceramic Gap Signal vs. RF Phase



LPS simulations



Definition of peak number for analysis



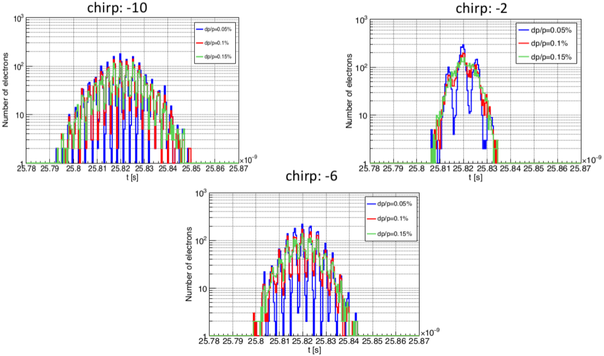
Transmission rate through mask: 33%

LPS simulations

Longitudinal distribution after chicane

Energy chirp: -10, -6, -2

Δp/p : 0.05%, 0.1%, 0.15%



Energy chirp can be used as a parameter knob

Conclusions

1. CAM beam generation is a byproduct with many outcomes
2. FAST flat beam configuration can be used for numerous radiation generation experiments
3. THz radiation generation using multislits in the chicane will be attempted during Run2017
4. Analytical considerations for RTFB transfomer and flat beam compression are in progress
5. Various tools and instruments developed and will be reused

Credits

Acknowledgements:

- P. Piot (NIU, Fermilab) for supervising this research
- J. Power (ANL, AWA), Q. Gao (Tsinghua U.) and G. Ha (POSTECH) for their significant contribution to the MLA research
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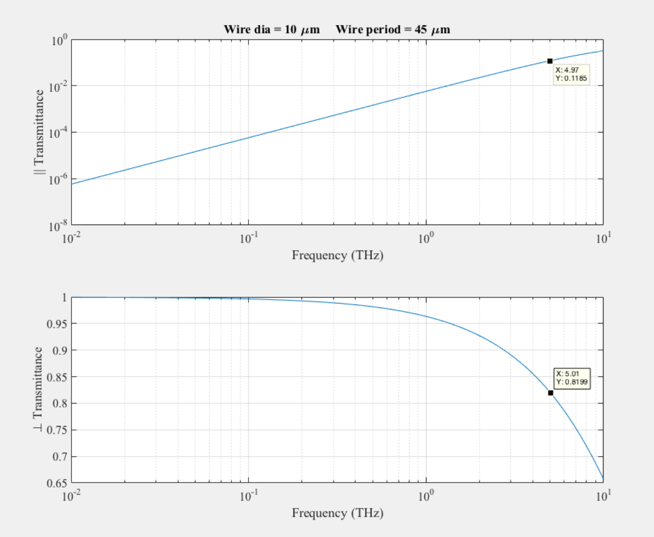
- A. Romanov (Fermilab) for his help with beam alignment at FAST and useful comments
- A. Valishev and V. Shiltsev (Fermilab) for valuable suggestions

Thank you for your attention!

MPI transmission



1.3 GHz SRF transport summary

Accelerating cavity properties were studied during Run2016

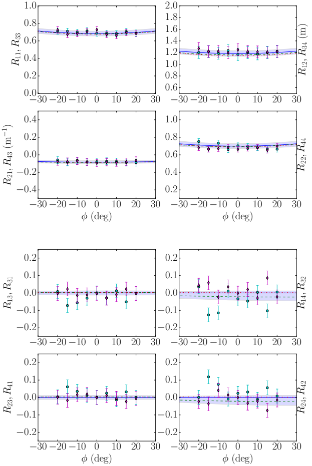
Conclusions:

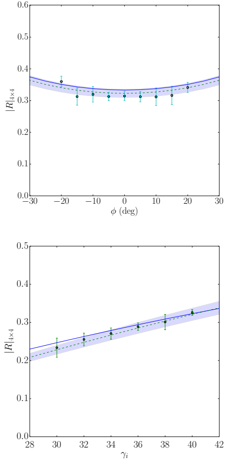
- Chambers' model is accurate on FAST energy scale (34 MeV)
- HOM coupler kick has parametric dipole component
- Beam-based alignment can be done via minimization procedure (experimentally confirmed for CG-method)

Outcomes:

- Better understanding of low energy round beam dynamics
- Improved analytical model of RTFB transformer
- Tools (pyACL)

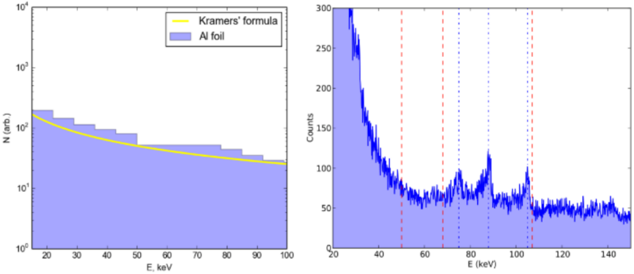
Cavity measurements





(left) transfer matrix R elements; (right) determinant $R_{4\times4}$ as a funciton of phase (ϕ) and injected γ_i (See FERMILAB-PUB-17-020-APC for details)

Channeling radiation summary



(left) Braking radiation spectrum of Al; (right) Diamond ($C - 110$) response to electron beam

1. First attempt at FAST
2. Detector alignment procedure has to be improved (**will be**)
3. Acquisition algorithm has to be improved (**will be**)