Electron beam experiments at FAST in 2017

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Northern Illinois University

Outline

1. Progress: Electron beam shaping and its applications
2. Canonical Angular Momentum (CAM) dominated beams at FAST
   - Theoretical background
   - Round-to-flat transformation
   - CAM beam generation
   - Flat beam generation
3. Transverse beam shaping and emittance-exchange setup

Progress: Year 1

The Joint University-Fermilab Doctoral Program acceptance

Main focus: Longitudinal instabilities due to space-charge; longitudinal space-charge amplifier at FAST
Results: Proposed experimental setup for LSCA at FAST

Papers:

1. Simulation of a cascaded longitudinal space charge amplifier for coherent radiation generation, NIMA, 819, (2016) 144-153

Conferences:

1. Numerical study of three dimensional effects in longitudinal space charge impedance, IPAC2015, FERMILAB-CONF-15-225-APC
2. Numerical investigation of a cascaded longitudinal space charge amplifier at the Fermilab's Advanced Superconducting Test Accelerator, IPAC2015, FERMILAB-CONF-15- 226-APC
3. Simulation of Cascaded Longitudinal Space Charge Amplifier at the Fermilab Accelerator Science and Technology (FAST) Facility, FEL2015, FERMILAB-CONF-15- 370-APC

Seminars:

1. APC seminar (Fermilab), CAD seminar (BNL)

Progress: Year 2

Main focus: 1.3 GHz SRF accelerating cavity transport measurement;
microlens array laser shaping; channeling radiation
Results: Confirmation of Chambers' model;
comissioning of microlens array setup;

Papers:

1. Analysis and Measurement of the Transfer Matrix of a 9-cell 1.3-GHz Superconducting Cavity, Phys. Rev. Accel. Beams 20, 4, 040102 (2017)
2. Spatial control of photoemitted electron beams using a microlens-array transverse-shaping technique, Phys. Rev. Accel. Beams 20, 103404 (2017)

Conferences:

1. A Simple Method For Measuring The Electron-beam Magnetization, NAPAC2016, FERMILAB-CONF-16-460-APC
2. Measurement Of The Transverse Beam Dynamics In A Tesla-type Superconducting Cavity, LINAC2016, FERMILAB-CONF-16-398-APC
3. Generation of Homogeneous and Patterned Electron Beams using a Microlens Array Laser-Shaping Technique, IPAC2016, THPOW021

Seminars:

1. Budker seminar 1/2 (Fermilab)

Progress: Year 3 (current)

Main focus: CAM dominated and flat beams at FAST; EEX+MLA experiments

Results: CAM beam generation at FAST (*in progress*); transverse cathode imaging in time domain

Papers:

1. Magnetized and Flat beam generation at FAST (*in progress*) (2017)
2. Tunable bunch train generation in EEX+MLA setup (*in progress*) (2017)

Conferences:

1. Magnetized and flat beam experiment at FAST, IPAC2017, FERMILAB-CONF-17-172-APC
2. IPAC18 abstracts in preparation

Seminars:

1. Budker seminar 3 (Fermilab)

Miscellaneous projects

Future experiments

- THz radiation generation from compressed flat beams
- Arbitrary emittance partitioning (flat beam + EEX)
- Flat beam compression + acceleration (ILC type beam)

Computational geometry in beam physics:

- Application of Voronoi diagram to mask-based intercepting phase-space measurements, IPAC2017, FERMILAB-CONF-17-171-APC

Channeling radiation experiment:

- Commissioning and First Results From Channeling Radiation At FAST, NAPAC2016, arXiv:1612.07358

CTR generation from transversely modulated electron beams:

- Coherent transition radiation from transversely modulated electron beams, FEL2017, FERMILAB-CONF-17-337-APC

and MORE...

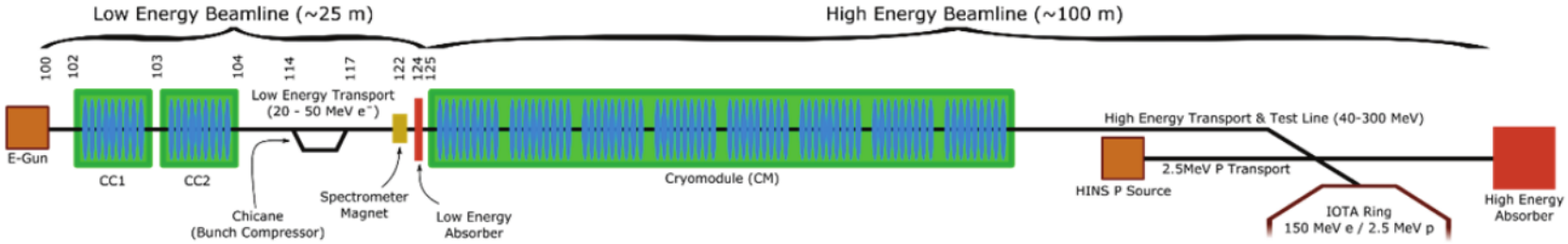
IOTA/FAST facility

High-brightness 300 MeV electron beams (Elog: 120200)

- Linac completed in 2017, ring will be completed in 2018
- Collaboration with Northern Illinois University
- Several experiments performed during Run 2017

FAST beamline

- FAST injector - 1.3 GHz SRF linac (two CC $\rightarrow$ 52 MeV + cryomodule $\rightarrow$ 300 MeV)
- 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).



Beam parameters

Parameter	Value	Units
Initial emittance (norm.)	<1	μm
Beam energy	50	MeV
Slice energy spread	<5	keV
Nominal charge	250	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 emittance summary

Electron beam emittance is now meassured with multislits X107

```
Emittance & System Params:
    Emittance (Un-Norm) :  7.995e-03 µm
    Dist to Screen (L)  :  7.379e+00 m
    Slit Width (w)      :  4.000e-05 m
    Slit Spacing (s)    :  4.000e-04 m
    Histogram Amplitude :  15.19 ArbU
    Histogram Width     :  2049 px
    Camera Resolution   :  9.300e-06 m/px
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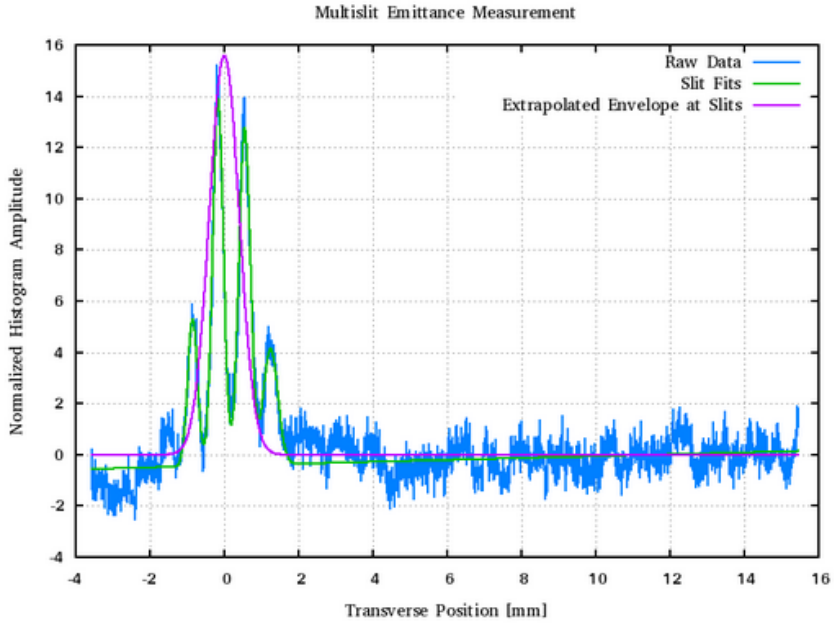


Reference: Data by D. Edstrom, A. Romanov, P. Piot

Charge, Q	ϵ_{nx}, μm	ϵ_{ny}, μm
<1 pC	0.25 ± 0.1	0.3 ± 0.1
250 pC	0.56 ± 0.2	0.64 ± 0.2

- Emittance is optimized with solenoid and σ_{cath}
- Not the lowest value yet (*takes time*)
- Multislit at X118 will help in studies

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**)

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

CAM conservation

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

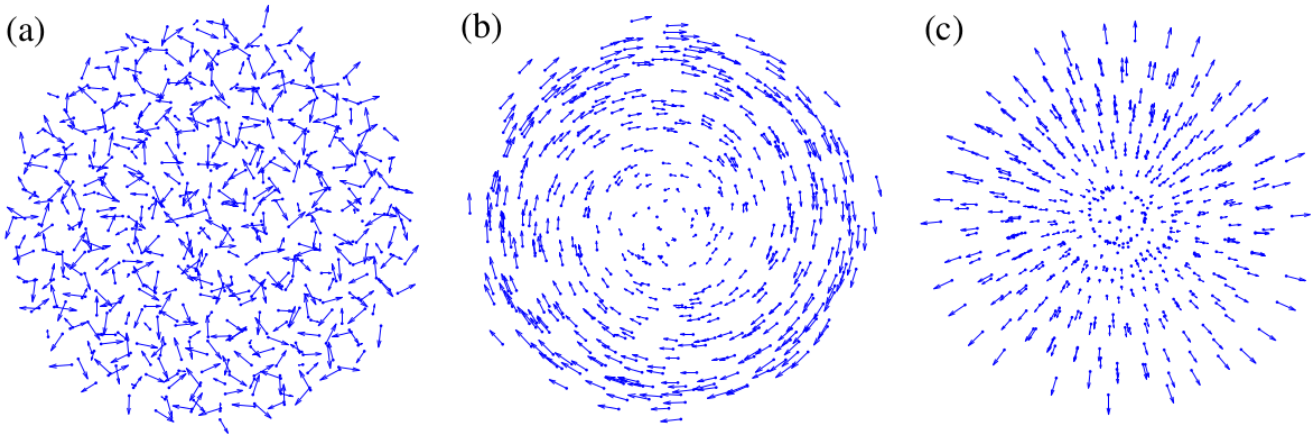
$$L = \gamma m r^2 \dot{\theta} + \frac{1}{2} e B_z(z) r^2 \tag{1}$$

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

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

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 $\epsilon_{4D} = \sqrt{|\Sigma|}$, then:

$$\Sigma_0 = \begin{pmatrix} \sigma^2 & 0 & 0 & \kappa\sigma^2 \\ 0 & \kappa^2\sigma^2 + \sigma'^2 & -\kappa\sigma^2 & 0 \\ 0 & -\kappa\sigma^2 & \sigma^2 & 0 \\ \kappa\sigma^2 & 0 & 0 & \kappa^2\sigma^2 + \sigma'^2 \end{pmatrix},$$

where $\epsilon_u = \sigma\sigma'$, $\kappa = \mathcal{L}/\sigma^2$, $\epsilon_{4D} = \sqrt{\epsilon_u^2 + \mathcal{L}^2}$

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:

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

Emittance ratio or "flatness":

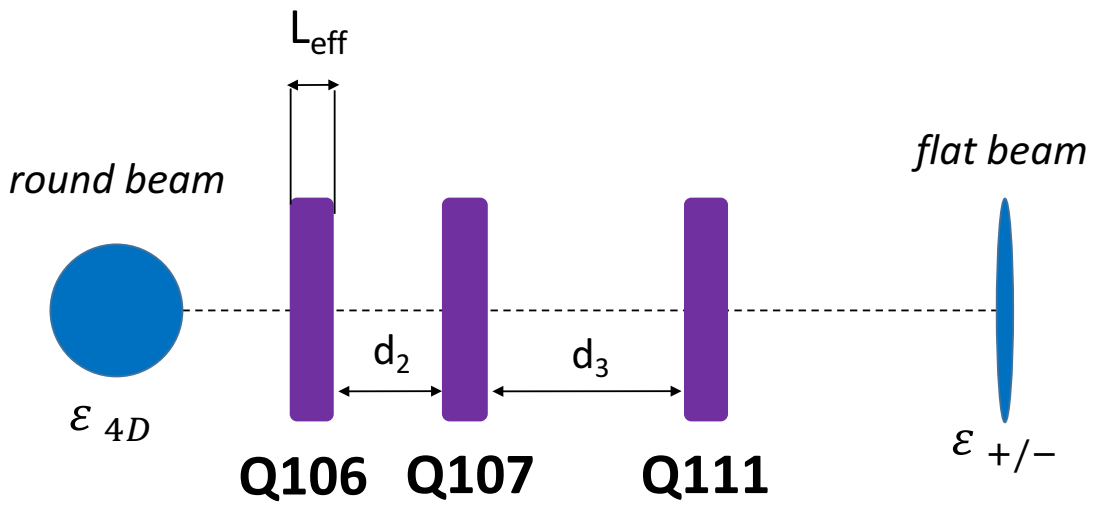
$$\frac{\epsilon_+}{\epsilon_-} = \frac{4\mathcal{L}^2}{\epsilon_u^2} = \frac{1}{p_z^2} e^2 B_{0z}^2 \frac{\sigma_0^2}{\sigma_0'^2}$$

Example calculation: $\sigma_+ = \sqrt{\beta_{x,y}\epsilon_+} \rightarrow \epsilon_u$=2 μm $\rightarrow \epsilon_+ = 40\mu$m, $\epsilon_- = 0.1\mu$m $\rightarrow \beta_{x,y} = 8$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.

Beam moments gymnastics

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

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 $\rightarrow \Sigma_{XX} = \Sigma_{YY} = \Sigma_0$ 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: $K = (10.135 \times 40\, I_q)/(1.8205 \times p\,[MeV/c])$,
$L_{eff} = 17cm$

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

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

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

Numerical optimization 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:

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

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

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

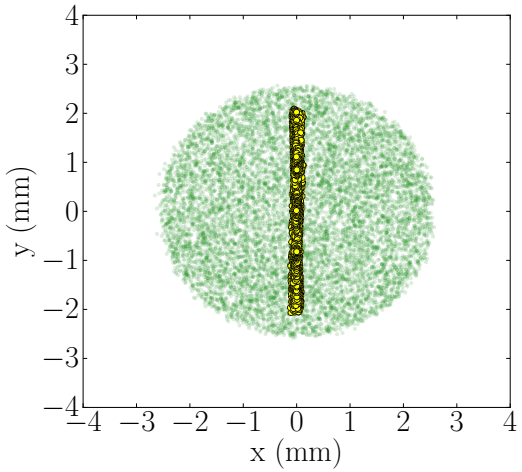
(Proof can be found in Y. Sun PhD thesis, FNAL (2005))

$$S = \mp\begin{pmatrix} -\alpha & -\beta \\ (\alpha^2+1)/\beta & \alpha \end{pmatrix}$$

RTFB solutions: Example

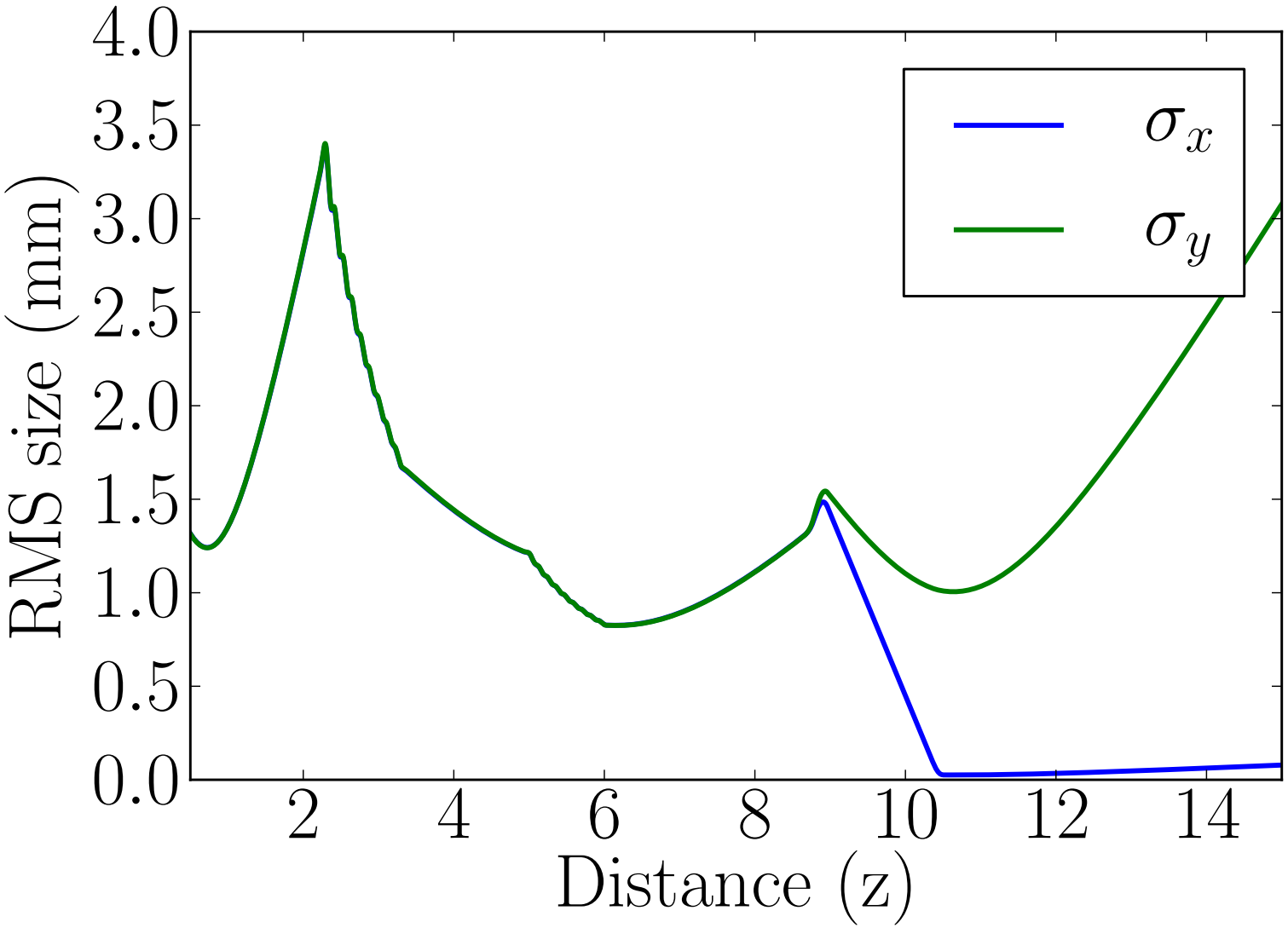
$$Case : S = \begin{pmatrix} 0 & -1.28 \\ 0.781 & 0 \end{pmatrix}$$

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
MagnetOptimizer (10000 p.)	1.89	-1.41	0.20



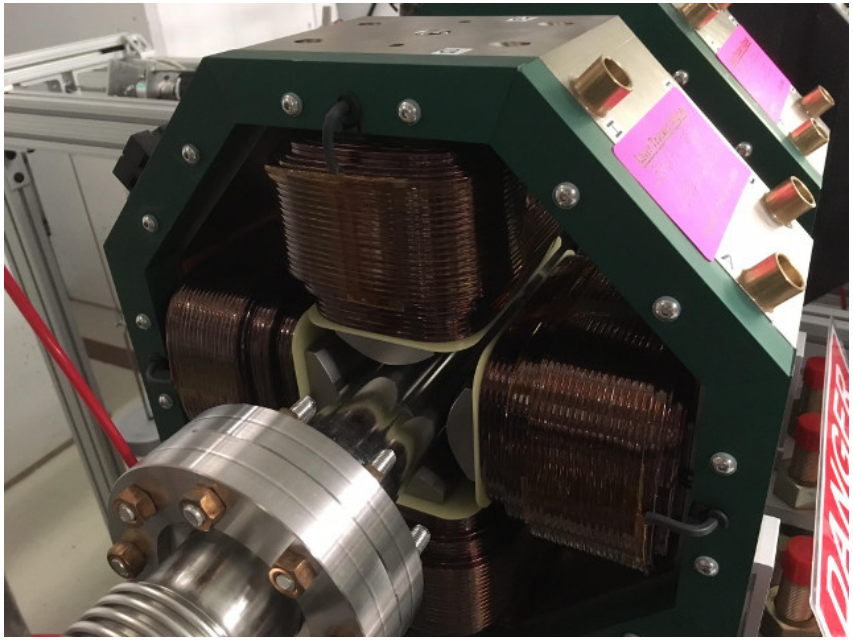
- Linear model gives a good first guess
- Elegant simulations account for chromaticity
- MagnetOptimizer (https://github.com/NIUaard/MagnetOptimizer) based on thick-lens model
- Calculation can be done for bunch slice (include analytical SRF cavity model)
- Note it is different from Thrane, E., *et al*, Proc. of LINAC02

Beam size evolution: Example



Preparations during Run 2017

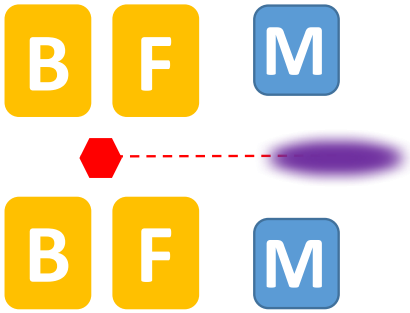
1. Optimized round beam emittance via multislit tool
2. Up to $B_{0z} \approx 0.1$ T at the cathode achieved
3. Chicane comissioned, CC1/CC2 total 35 MeV
4. X107 and X118 slits are not ready
5. Only pyro detector for CTR, no bolometer

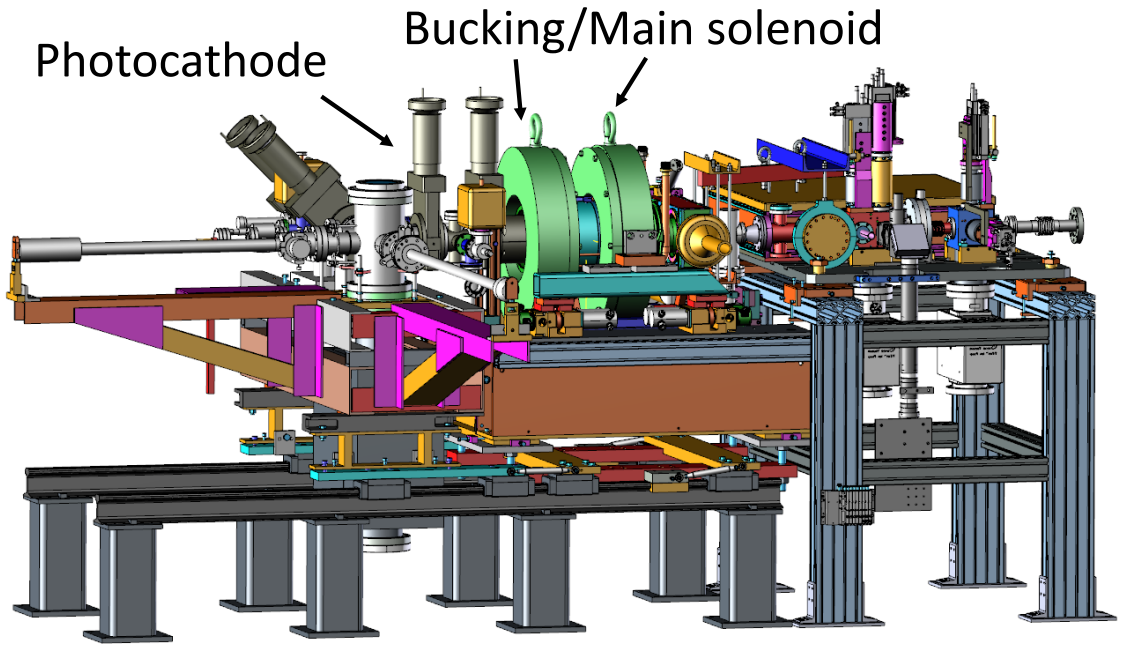


CAM generation (exp.)

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

$$\mathcal{L} = \frac{eB_{0z}\sigma^2}{2mc} \approx 2.93 \cdot 10^{-8}[Gauss^{-1}\mu m^{-1}]B[Gauss]\sigma^2[\mu m^2]$$

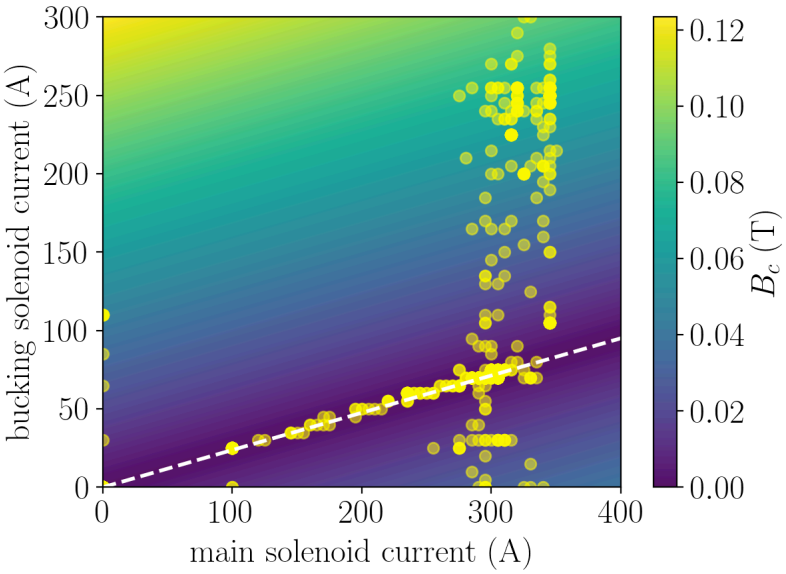


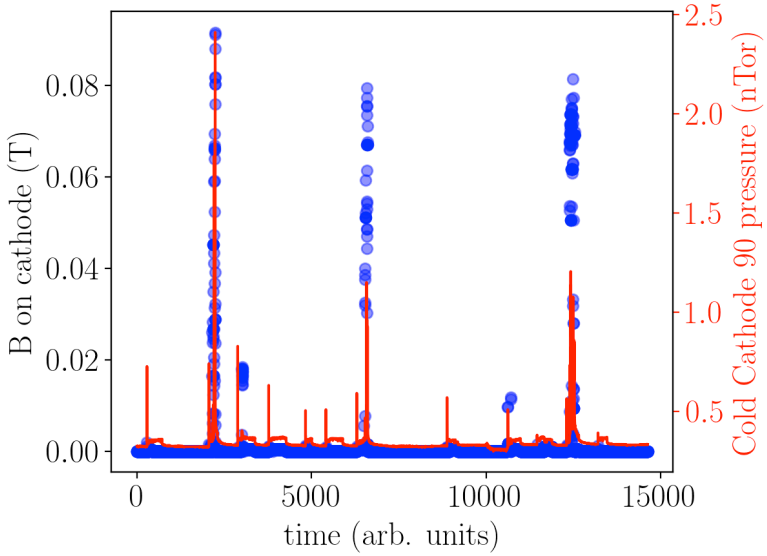


Traditional RF-gun **FAST RF-gun**

RF-Gun conditioning

- Vacuum activity with increasing Bucking solenoid current
- Activity decreases with time (conditioning)
- FAST RF-gun is able to run with $I_B < 300$A





- On 11/17/2017 no vacuum activity at I_B=250A

MAM 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)

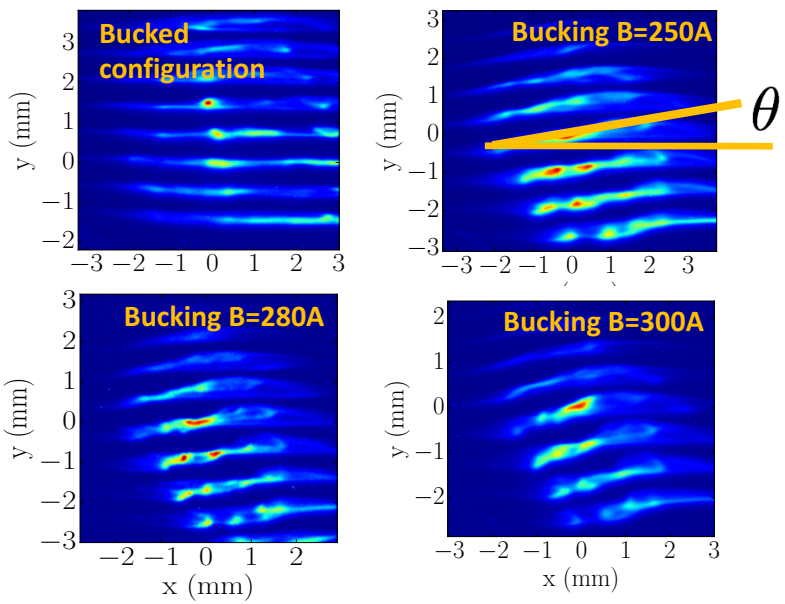
Two methods of measuring CAM:

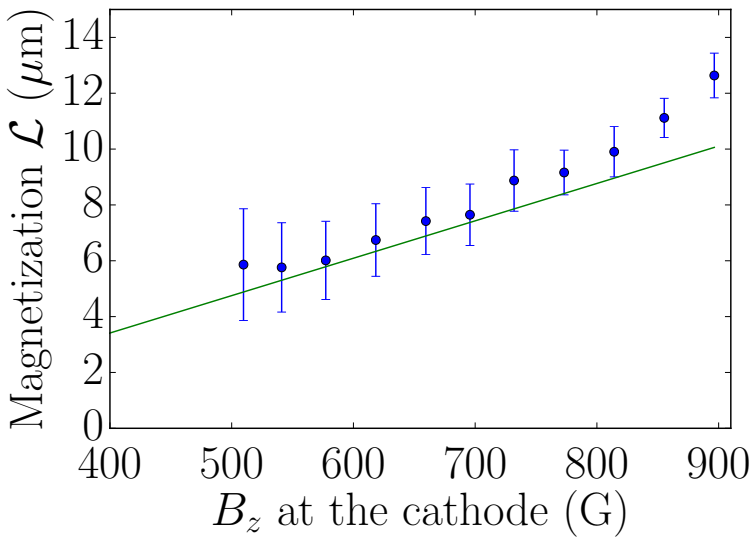
1. Using multi-slits, observe relative shear of the beamlets
2. Using microlens arrays, produce multi-beam and observe rotation (currently not available at FAST)

MAM measurement (slits)

$< L >= 2p_z \frac{\sigma_1^2 M \sin\theta}{D}$, where p_z is momentum, D is the drift length, $\sigma_1 = (n-1) * d/5$, $M = \sigma_2/\sigma_1$ - magnification factor

Slit images at X111





MAM measurement (quad)

$$\Sigma_0 = \begin{pmatrix} \sigma^2 & < xx' > & 0 & L/2 \\ < x'x > & \sigma'^2 & -L/2 & 0 \\ 0 & -L/2 & \sigma^2 & < yy' > \\ L/2 & 0 & < y'y > & \sigma'^2 \end{pmatrix},$$

$< x^2 >=< y^2 >= \sigma^2$, $< xy' >=< y'x >= L/2$ and
$< x'y >=< yx' >= -L/2$
$< xx' >=< yy' >=< x'x >=< y'y >$ and
$< x'^2 >=< y'^2 >= \sigma'^2$.

If waist at "0", $< xx' >=< x'x >=< yy' >=< y'y >\equiv 0$. The directly measurable elements : $< x^2 >, < y^2 >, < xy >$. The beam moments matrix is transformed as:

$$\Sigma_1 = \mathbf{R}\Sigma_0\mathbf{R}^T,$$

where $\mathbf{R}$ is the linear transfer matrix.

MAM measurement (quad) cont.

Normal quad

$$
\begin{aligned}
< x^2 > &= 2 < xx' > d(dq+1) + d^2\sigma'^2 + \sigma^2(dq+1)^2 \\
< y^2 > &= -2 < yy' > d(dq-1) + d^2\sigma'^2 + \sigma^2(dq-1)^2 \\
< xy > &= Ld^2q.
\end{aligned}
$$

$$L =< xy > /d^2q$$

Skew quad

$$
\begin{aligned}
< x^2 > &= d^2(-Lq + q^2\sigma^2 + \sigma'^2) + 2d < xx' > +\sigma^2 \\
< y^2 > &= d^2(Lq + q^2\sigma^2 + \sigma'^2) + 2d < yy' > +\sigma^2 \\
< xy > &= dq\left(d(< xx' > + < yy' >) + 2\sigma^2\right)
\end{aligned}
$$

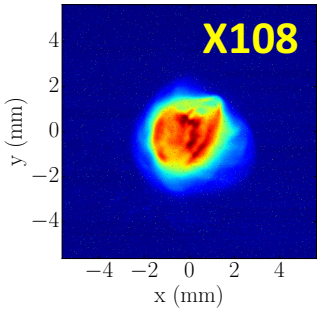
$$L = | < x^2 > - < y^2 > |/2d^2q$$

Experimental results (Nov. 17)

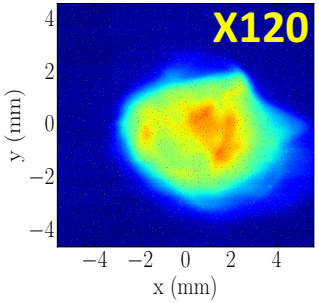
First RTFB transformation at FAST ($\epsilon_x = 0.743\mu$m, $\epsilon_y = 30.9\mu$m)

Round beam

(MagnetOptimizer)



Low-charge
(no SC)



Msol = 310 A
Bsol = 250 A
Bz = 0.1 Tesla

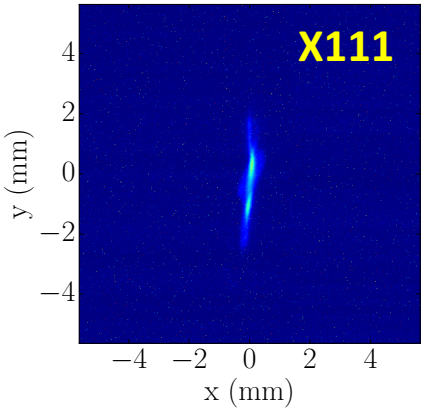
RTFB

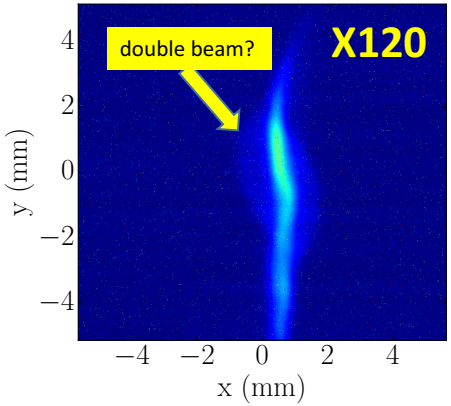
$K \sim \mathcal{L}$

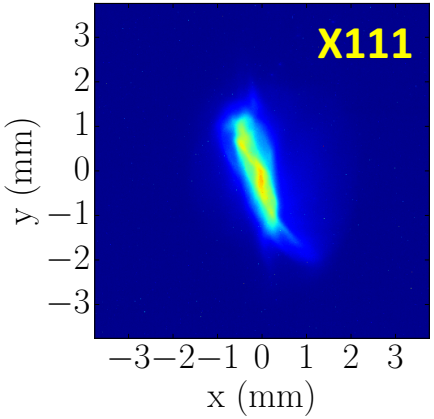
this can be optimized

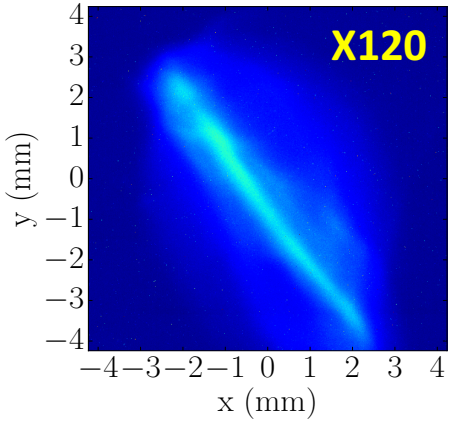
$\sigma_c \simeq 690\mu$m

$\mathcal{L} \sim {\sigma_c}^2$

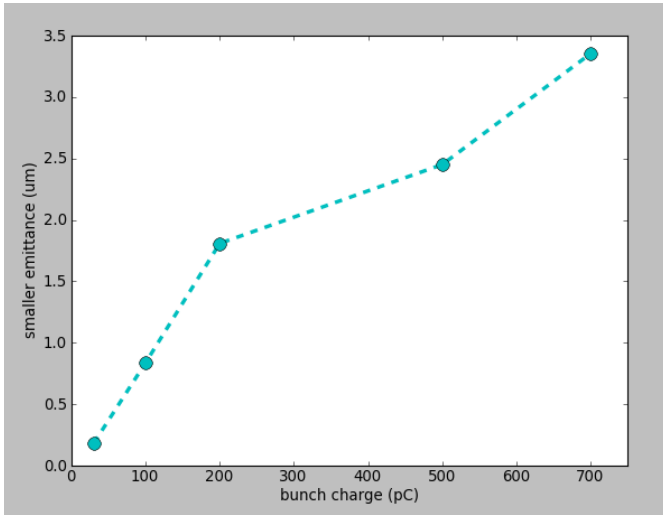


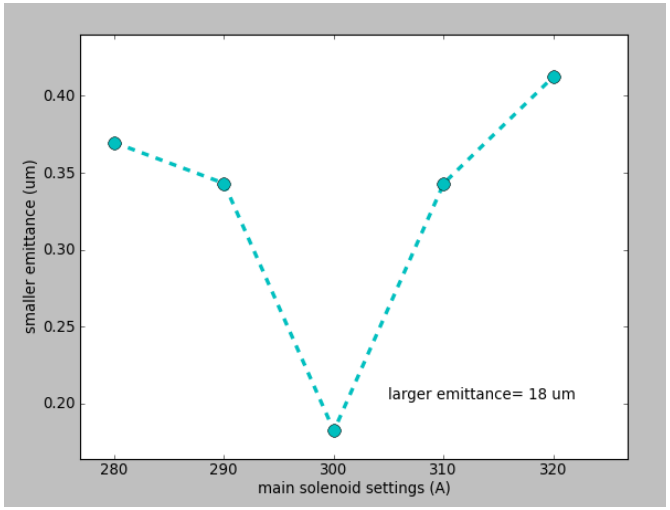




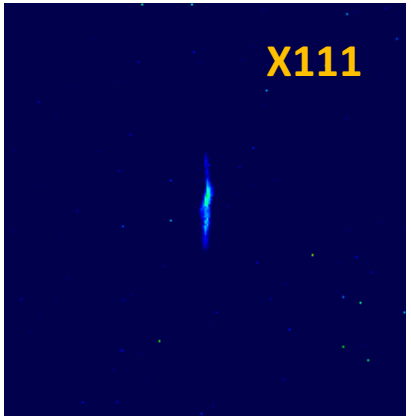


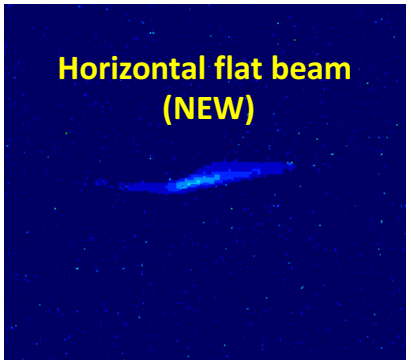
Experimental results (Nov. 19)

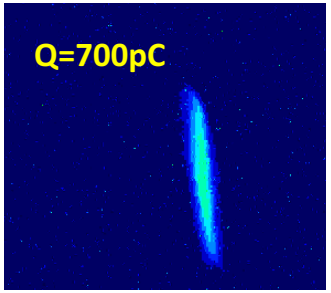


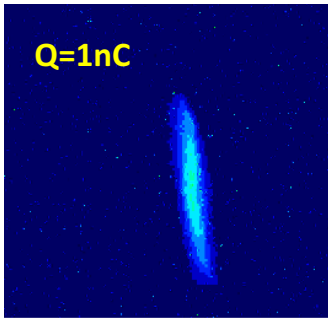


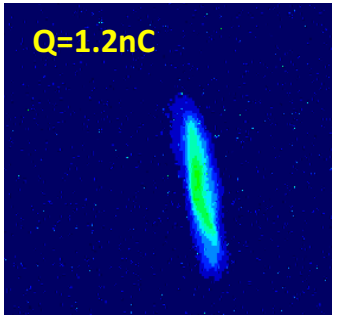
Optimized flat beam at low charge



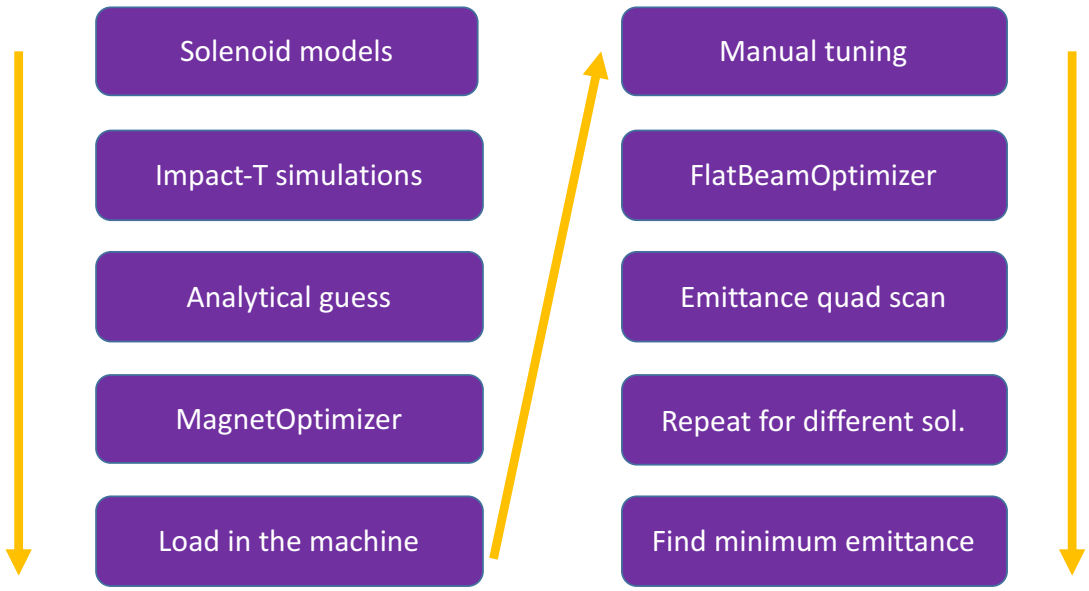








Flat beam generation



MagnetOptimizer – minimize off-diagonal elements of covariance matrix

FlatBeamOptimizer – minimize ratio of histograms at the screen

Better way – minimize multislit width

Lowest emittance so far 0.2 μm at 50 pC and $\sigma_0 \approx$ 1mm (close to the limit of quad scan); room for optimization

Experimental program

1. Magnetization $\mathcal{L}$: measurement of $\mathcal{L}(B_{0z})$ and possibly vs σ_{cath} [X107 is *not* ready to use]
2. Flat beam:
   - Dynamics in the RFTB, demonstrate decorrelation process, use X111 and X120 to demonstrate flat beam is produced
   - Measure $\epsilon(\mathcal{L})$, quadrupole scan [X118 is *not* ready to use]
   - Parametric study of ϵ versus energy chirp
3. Compressed flat beam: for the best flatness (smallest emittance achieved) demonstrate the generation of a compressed bunch.
   - Michelson interferometer is operational, can quote a peak current in addition to the emittance
   - Measure ϵ versus energy chirp with compressor on (J. Zhu 2014 paper)

Comparison and verdict

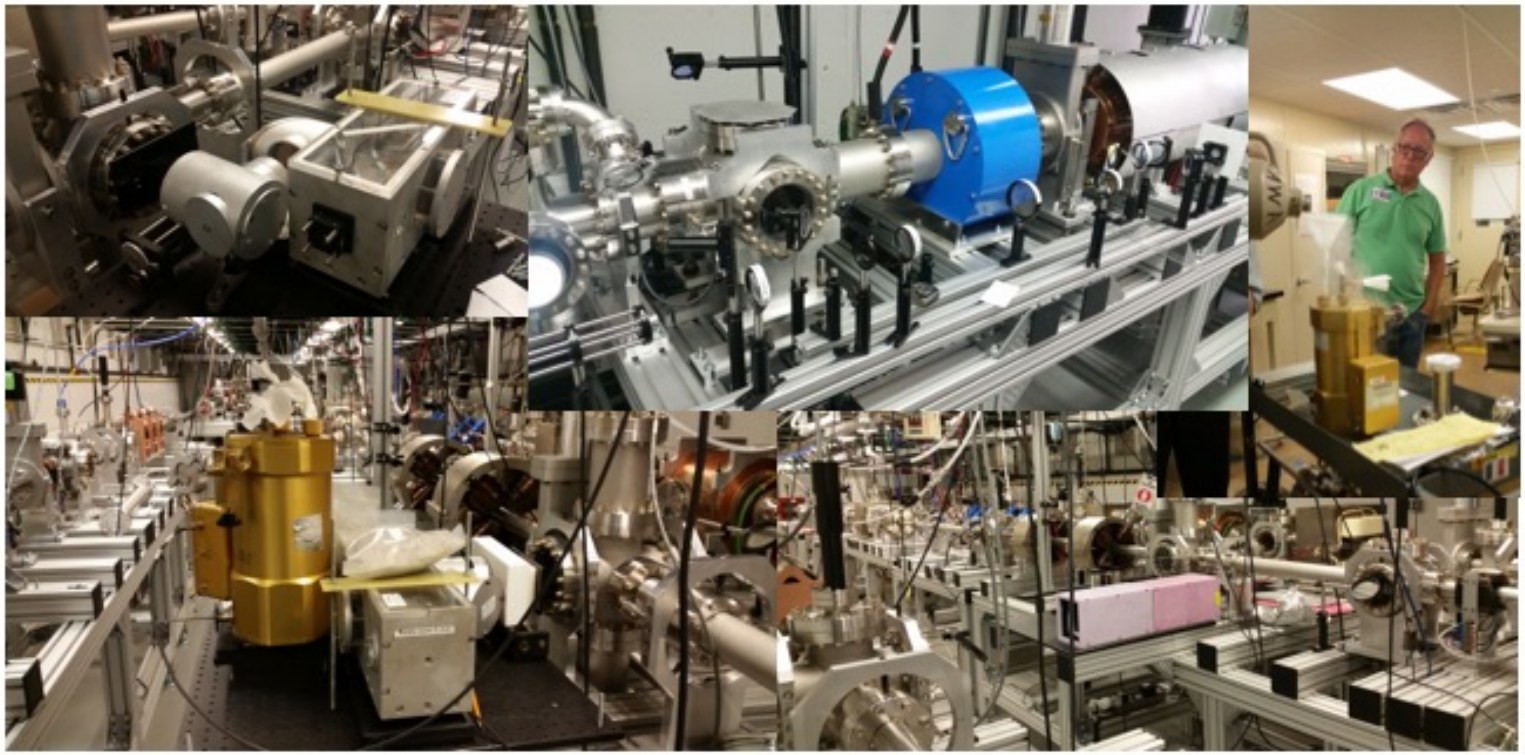
- ***Study in progress***
- CAM beams were produced at FAST at 35 MeV
- Flat beams were produced with RTFB transformer
- Optimized flat beams were made at high charge $Q = 1.2nC$

Long-term goals

1. 10 nm horizontal emittance (below thermal) at FAST
2. 300 MeV flat beam acceleration
3. THz radiation generation using multislits in the chicane and flat beams
4. Possible neural network RTFB optimizer (with A. Edelen)

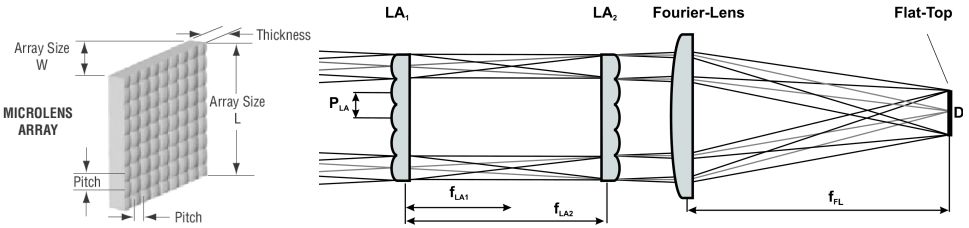
Argonne Wakefield Accelerator

72 MeV photoinjector + EEX beamline

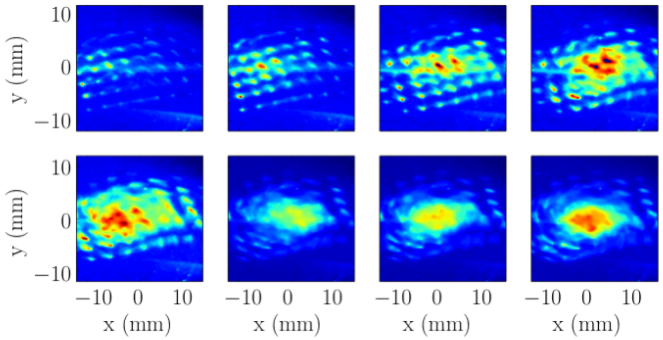


Microlens array setup

Microlens array (MLA) setup at AWA



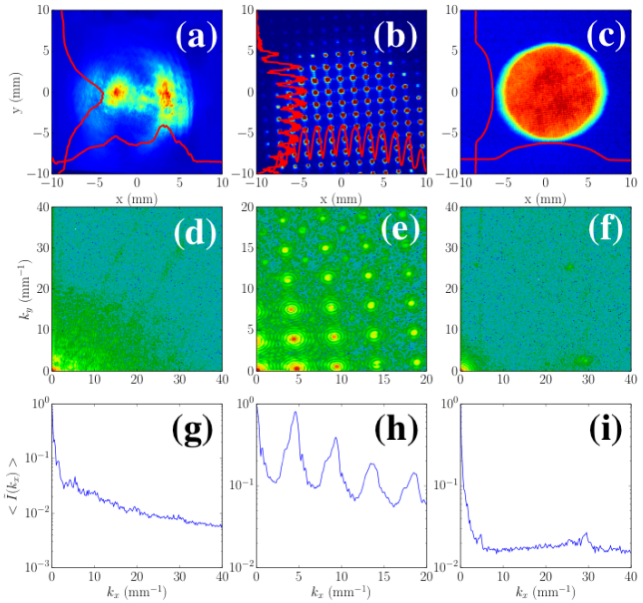
Multi beam at 50 MeV



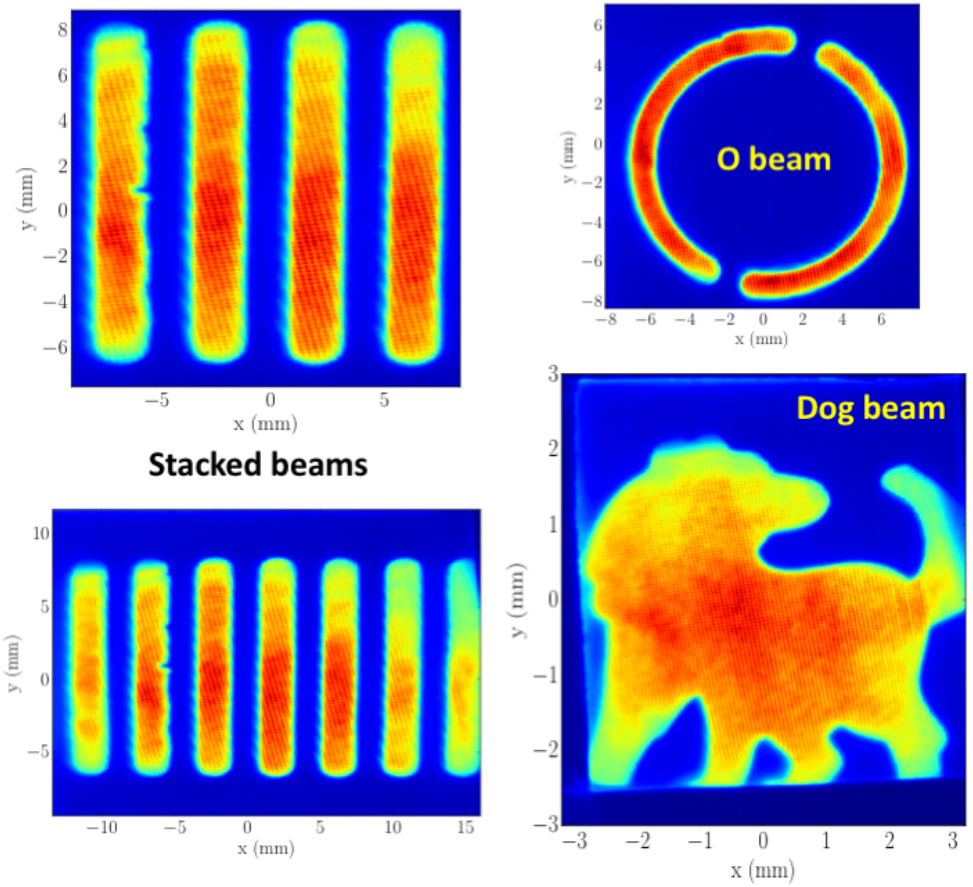
https://arxiv.org/abs/1707.08448 (accepted in PRAB)

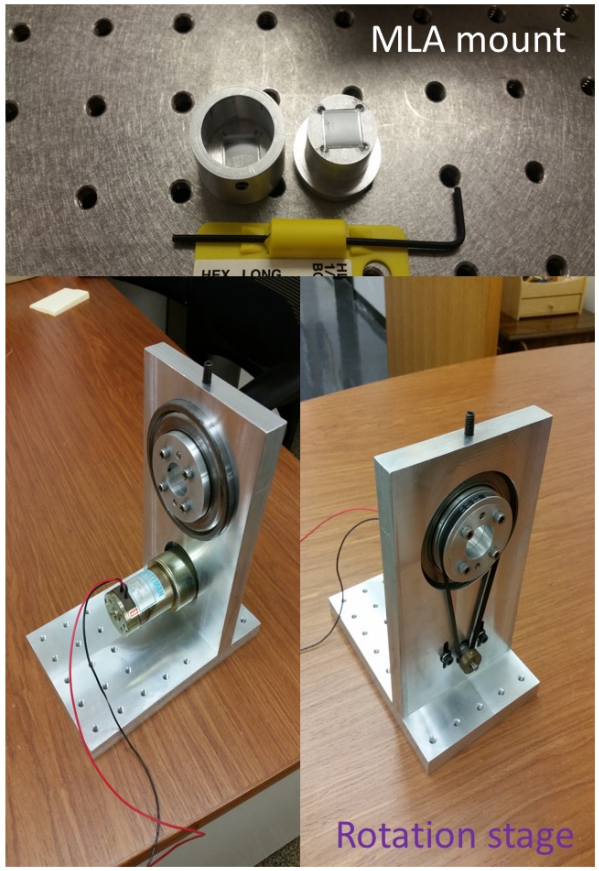
AWA UV laser

Regular beam | Multi beam | Uniform beam



MLA laser shaper

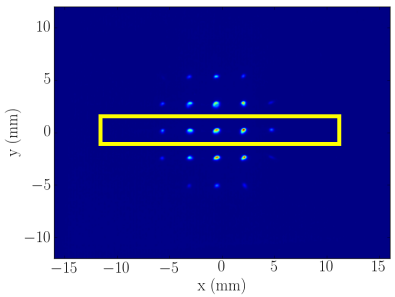




Arbitrary laser transverse profile for different applications

Emittance exchange setup

Experiment schematics: (MLA + EEX)

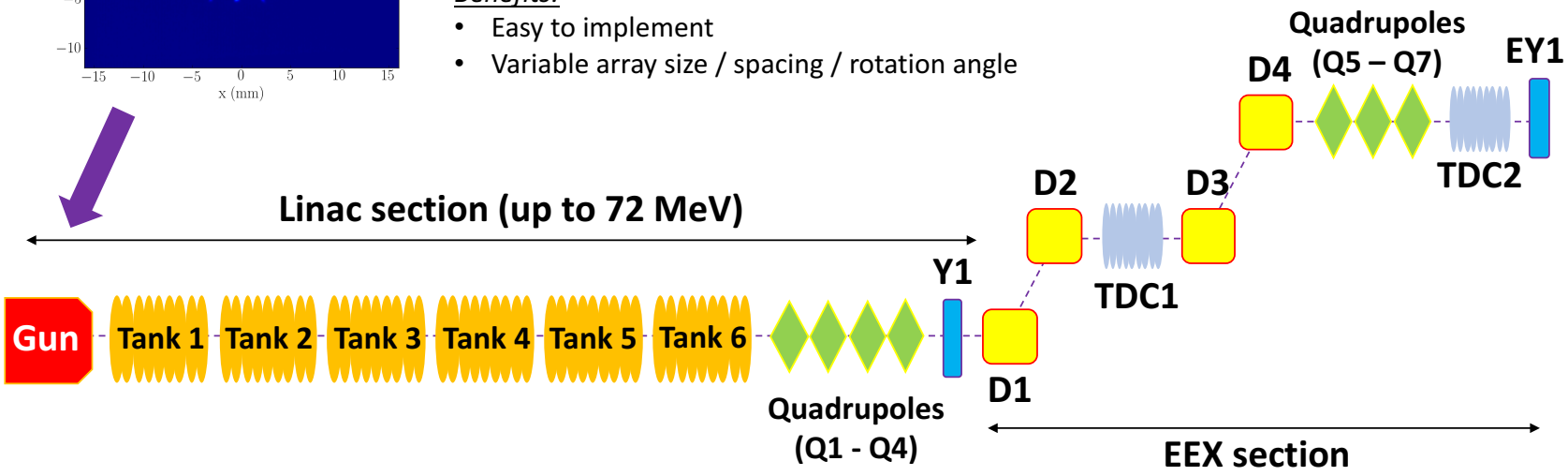


<u>Goal:</u> Combine MLA multi-beams with EEX to generate bunch trains

- MLA setup can shape laser spot to create multi-beams
- Additionally, a line of laser dots can be selected

<u>Benefits:</u>

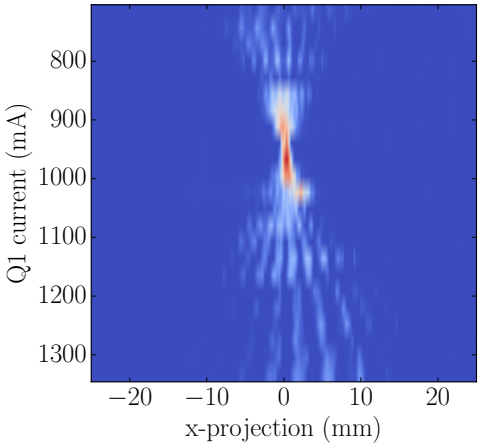
- Easy to implement
- Variable array size / spacing / rotation angle



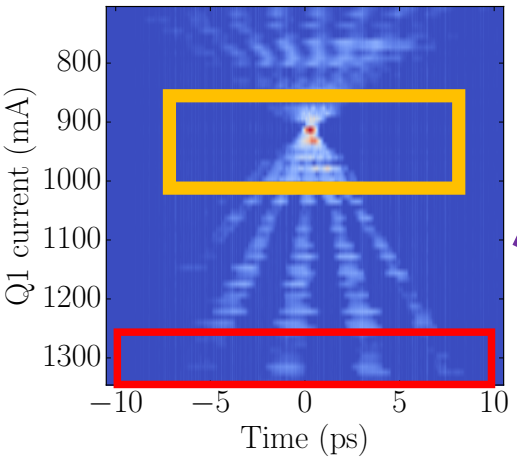
Quadrupole matching

Quadrupole matching (tunable bunch train)

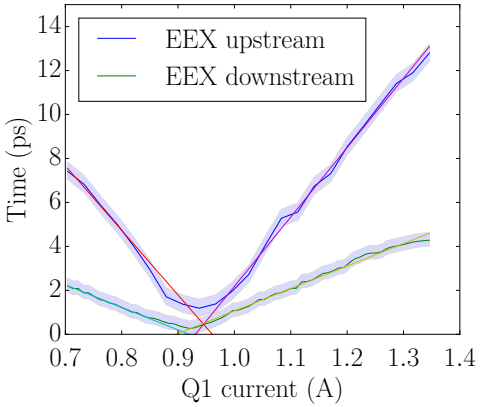
- Select line of beamlets (for simplicity)
- Vary quadrupole upstream of the EEX
- Achieve desired separation of bunch train
- Demonstrate 1:1 imaging from cathode to time-domain!



Beamlet projection upstream of the EEX



Resulting bunch train



Compression ratio is found to be 1/3

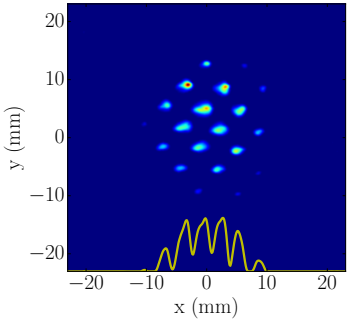
Sub-ps structure: easy to generate THz radiation

Separation corresponds to initial multi-beam separation at the cathode in time!

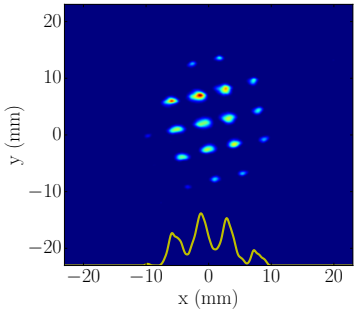
MLA rotation + EEX

High-frequency modulation generation

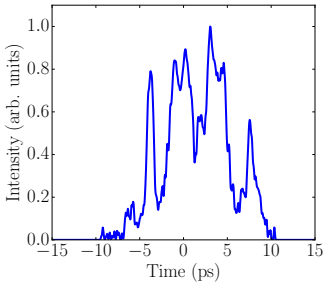
Quadrupole compression is limited due to space-charge effects at waist. What if rotate the multi-beam?

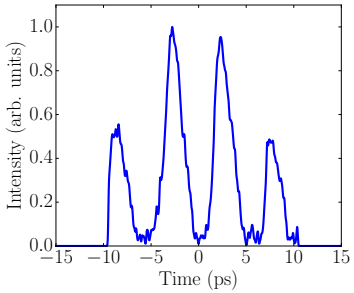


45 deg

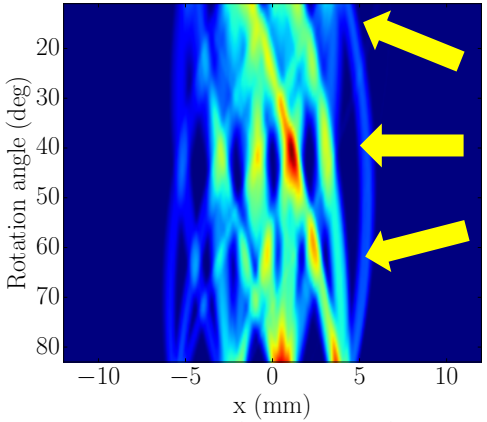


15 deg





MLA mounted on rotatable stage



Projection as a function of rotation angle

Vary bunch train separation via simple rotation!

Conclusions

1. CAM beam generation is a byproduct with many outcomes
2. Ratio of 90 has been achieved; room for optimization
3. Lowest emittance below thermal (NEW)
4. FAST flat beam configuration can be used for numerous radiation generation experiments
5. Analytical considerations for RTFB transfomer work for both horizontal and vertical flat beams
6. Semi-automatic flat beam generation
7. Various tools and instruments developed and will be reused

Credits

Acknowledgements:

- P. Piot (NIU, Fermilab) for supervising this research
- A. Valishev and V. Shiltsev (Fermilab) for valuable suggestions
- A. Romanov (Fermilab) for his help with beam alignment at FAST and useful comments
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- D. Ratner and S. Li (SLAC) for interest in MLA applications
- A. Edelen (Fermilab, Colorado State for interest in optimizers and neural network flat beam generation

Thank you for your attention!