Results of the CC2 transverse matrix measurements in 2016 and 2017 plans

A. Halavanau and P. Piot

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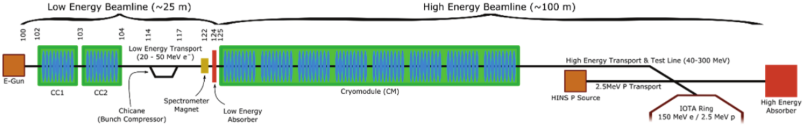
Northern Illinois University

Outline

- 1.3 GHz SRF accelerating cavity transfer studies
- Complimentary experiments and studies
- Planned experiments in 2017

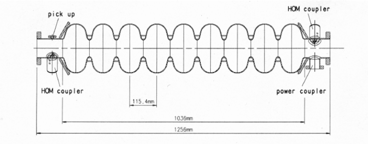
FAST beamline



- 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).

1.3 GHz SRF accelerating cavity

Goal: Study beam dynamics of FAST low energy beamline

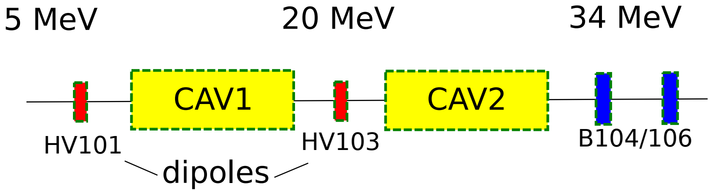


The transverse-focusing properties of such a cavity and non-ideal transverse-map effects introduced by field asymmetries in the vicinity of the input and high-order-mode radiofrequency (RF) couplers play a crucial role in transverse beam dynamics

1. Compare the experimental transverse transfer matrix with analytical model
2. Attempt to characterize the effects discussed above

Experimental setup (2016)

Schematics of the experiment



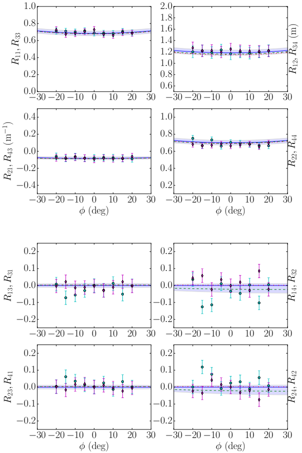
Advantages

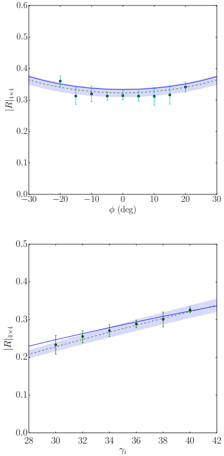
1. Overall better laser performance in 2016
2. Improved instrumentation (BPM jitter $<$ 80 um)

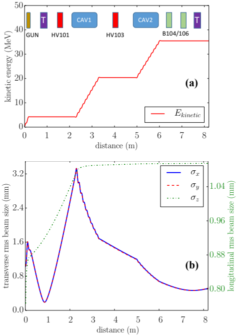
Issues

1. Strong focusing in CAV1 (need to lower the gradient)
2. CAV1 in place, need to adjust the beam size

Results







Each data point is inferred from 80 reference orbits

(left) transfer matrix R elements; (middle) determinant $R_{4\times4}$ as a funciton of phase (ϕ) and injected γ_i; (right) beam dynamics in low energy section.

1.3 GHz SRF transport summary

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)

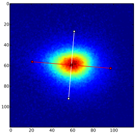
Outcomes:

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

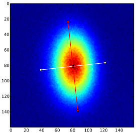
Halavanau, A., Phys. Rev. Accel. Beams ***20****, 040102 (2017)*

Emittance measurements summary

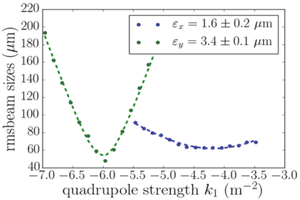
Electron beam emittance was meassured via simple geometrical $(\epsilon = \frac{\sigma_1}{z}\sqrt{\sigma_2^2 - \sigma_1^2})$ and quadrupole scan technique



X120



X111



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

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

- 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

Moving on - 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

Experimental plan

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

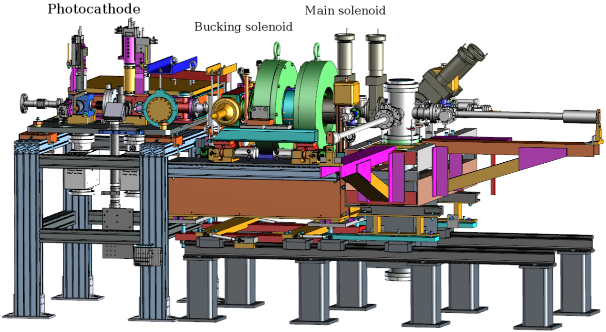
Goals:

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

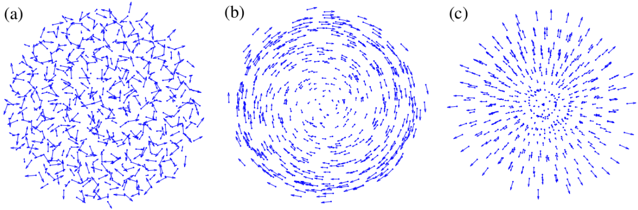
Total canonical angular momentum
of a charged particle in symmetric magnetic field is conserved

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



FAST RF-gun setup

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

Emittance ratio

Eigenemittances:

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

Emittance ratio or “flatness”:

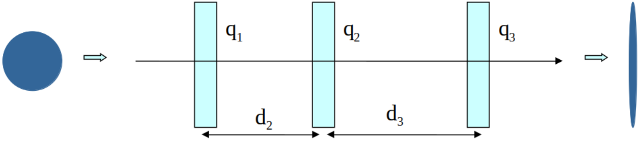
$$\frac{\epsilon_+}{\epsilon_-} = \frac{4\mathcal{L}^2}{\epsilon_u^2} = \frac{1}{p_z^2} e^2 B_{0z}^2 \frac{\sigma_0^2}{\sigma_0'^2}$$

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.

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

RTFB solutions

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

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

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

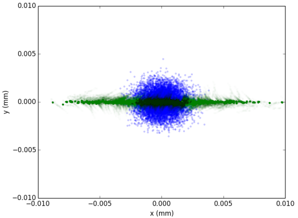
$$q_3 = \frac{d_2(q_2 - q_1 q_2 s_{12}) - s_{22}}{d_2(d_3 q_2 s_{22} + q_1 s_{12} - 1) + d_3(s_{12}(q_1 + q_2) - 1)}$$

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

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

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

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

Thank you for your attention!

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))

Measurement algorithm

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

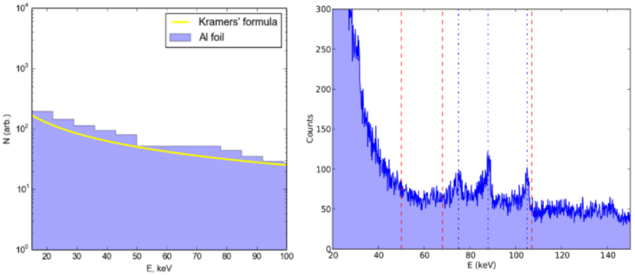
Assumption:

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

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**)